LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION
KAGRA COLLABORATION

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The LSC-Virgo-KAGRA Observational Science White Paper (Autumn 2022 edition)

The LSC-Virgo-KAGRA Observational Science Working Groups

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Contents

1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC), Virgo Collaboration and KAGRA Collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for and studies signals from merging neutron stars and black holes by filtering the data with waveform templates. The **Burst** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin.

These groups also collaborate with the **Detector Characterization (DetChar)** group, which interfaces with the detector commissioning teams and works to improve GW signal searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals, as well as with the **Calibration** and **Computing & Software** teams.

The LSC, Virgo Collaboration and KAGRA Collaboration are separate entities but work together closely, especially on data analysis. We often refer to the LSC and Virgo together as 'LVC', and refer to the LSC-Virgo-KAGRA combination as 'LVK'.

This ***LSC-Virgo-KAGRA Observational Science White Paper*** describes the planned activities of the members of the four astrophysical search working groups, including science goals and methods. The subsections in sections 2 through 10 contain "activity plans" with a wide range of themes. Each activity plan has a prefix which associates it with either Section 2 or Section 4 of the LIGO Scientific Collaboration 2022 Program:

- Section 2, *Scientific Operations and Scientific Results* (prefix "ST-"), includes activities to complete the publication of results from the most recent observing run (O3), to prepare for the next observing run (O4) which is expected to begin in March 2023, and to carry out analyses of the O4 data. "ST" activities that also qualify as Infrastructure and Operations (InfraOps) activities according to Section 2 are indicated by the suffix -**OPS**.
- Section 4, *Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics: Enhanced Analysis Methods* (prefix "LT-") includes longer-term developments which we will pursue to advance the scientific frontiers of GW observational science.

The LSC Program Committee and Virgo Core Program Committee set specific goals for collaboration work on an annual basis, using this white paper and other inputs. While this white paper concerns the activities of the four astrophysical search groups, LSC, Virgo and KAGRA activities in the domains of Commissioning, Calibration, Computing, Detector Characterization, LSC Fellows program, and Run Planning can be found in the *LSC-Virgo-KAGRA Operations White Paper* (LIGO-T2200381, VIR-?????-22, JGW-T221????) **[to do: update Virgo, KAGRA links to 2022 versions]**.

Achieving the direct detection of gravitational waves was the result of decades of development of both instrumentation and data analysis methods. Substantial advances were made using data collected by the initial LIGO detectors (2002–2010) and the initial Virgo detector (2007–2011), but no GW signals were detected. The era of GW detection, GW astronomy and astrophysics was enabled by the Advanced LIGO and Advanced Virgo upgrades. The first Advanced LIGO observing run, O1, began in September 2015 and immediately yielded the first detected event, GW150914. The second observing run (O2) took place in 2016–17, starting with just the two Advanced LIGO detectors but with Advanced Virgo joining the run for the month of August 2017. The third observing run (O3) began on April 1, 2019, with both LIGO detectors and the Virgo detector collecting data with better sensitivity than ever before, and ended on March 27, 2020. At the time of writing this white paper, the LVK observational science working groups have released approximately 85% of the planned papers from the O3 run and are expecting to release the remaining ones before the start of O4. Working group effort has already shifted focus to preparing for O4 data analysis, with O4 expected to begin in March 2023.

Epoch	Run Name	Run Duration	Typical Binary Neutron Star (BNS) Range (Mpc)			$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		
			LIGO	Virgo	KAGRA	LIGO	Virgo	
2015–16	O1	4 months	80	–	–	50	–	actual
2016–17	O2	9 months	100	30	–	60	25	actual
2019–20	O3	11 months	110–130	50	1	80–90	35	actual
2023–24	O4	12 months	160–190	80–115	1–10	110–120	65–80	projected
2026–28	O5	TBD	240–325	150–260	25–128	210	100–155	projected

Table 1: Observing schedule, actual and projected sensitivities for the Advanced LIGO, Advanced Virgo and KAGRA detectors. Adapted from *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA* (LIGO-P1200087, VIR-0288C-12, and published in Living Reviews in Relativity), curated by the LVK Joint Run Planning Committee. Projected BNS ranges for O4 and O5 are updated by using publicly announced information https://dcc.ligo.org/LIGO-G2002127/public and LIGO-G2002127-v13.

Scientific Operations and Observational Results

LSC-Virgo-KAGRA data analysis activities for Observing run 4 (very similar to the activities for O3) are summarized in Table 2, by search group, and prioritized in three categories:

- **Highest priority:** searches most likely to make detections or yield significant astrophysical results.
- **High priority:** promising extensions of the highest priority goals that explore larger regions of parameter space or can further the science potential of LIGO, Virgo and KAGRA.
- **Additional priority:** sources with lower detection probability but high scientific payoff.

Computing needs and resource allocations are derived, in part, from the science priorities presented in this table. Scientific motivations, details on methods and strategies for result validation are provided in the **activity plans** included in the later sections of this white paper.

We note that the LSC and Virgo Collaboration have adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for astrophysical results to be validated with a different analysis, using independent methods and tools when possible. In some cases this may require the same data to be analyzed by more than one pipeline for the same science target.

	LSC-Virgo-KAGRA Observational Science Working Group			
	Burst	CBC (compact binaries)	Continuous Wave	Stochastic Background
Highest priority	Search for short-duration GW bursts (both online and offline)	Responding to exceptional compact binary coalescence detections	Targeted searches for high-interest known pulsars, e.g. Crab, Vela	Searches for an isotropic stochastic GW background
	Search for long-duration GW bursts	Cataloging detections of coalescence of neutron star and black hole binaries and their meaured parameters	Narrow-band searches for high-interest known pulsars	Directional searches for anisotropic stochastic GW backgrounds from point sources
	Responding to exceptional GW burst and multi-messenger detections	Characterizing the astrophysical distribution of compact binaries	Directed searches for high-interest point sources, e.g. Cassiopeia A, Scorpius X-1	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Searches without templates from GWs from binary black holes	Testing General Relativity with compact binaries	All-sky searches for unknown sources, either isolated or in binary systems	All-sky search for extended sources using spherical harmonic analysis
	GW burst signal characterization	Low-latency searches to enable multimessenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	SGWB implications and modeling
		Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	Development of python SGWB search pipeline
		Measuring the properties of extreme matter, e.g. the neutron star equation of state	Detector characterization, data preparation, scientific software maintenance	
		Determination of the Hubble constant		
High priority	Multimessenger searches for GW bursts associated with GRBs, fast radio bursts, core-collapse supernovae, magnetar flares and high-energy neutrinos.	Improved searches for intermediate mass black hole binaries and intermediate mass-ratio inspirals	Targeted searches for other known pulsars, and non-tensor polarisations	Data folding for efficient SGWB searches
	Search for BNS post-merger signals	Search for sub-solar mass compact binary coalescences	Targeted searches for CW signals with non-tensor polarizations	
	All-sky cosmic string search	Search for gravitationally lensed signals from compact binary coalesceces	Directed searches for other point sources of interest	
	Optimized algorithms for non-vanilla binary black hole mergers (eccentric, parabolic, or hyperbolic orbits).	Improved waveform models for signals expected during the O4 run	Long-transient searches for emission from distant post-merger neutron stars	
		Multimessenger searches for binary mergers associated with fast radio bursts and high energy neutrinos		
Additional priority		Optimized search for stochastic background of GWs from CBCs	Searches for long-lived transient emission following a known pulsar glitch	Analysis to separate components of a stochastic GW background
			Continuous GW emission from ultra-light boson clouds around black holes	Search for very long transients ($\sim$ 10 hr − days)
			Direct detection of dark photon dark matter	Search for SGWB-EM sky correlations

Table 2: **Scientific Operations and Observational Results:** Priorities of the LIGO Scientific Collaboration, Virgo Collaboration and KAGRA, for the four astrophysical search working groups. Targets are grouped into three categories (highest priority, high priority, additional priority) based on their detection potential. There is no additional ranking within each category in this table.

Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

Longer term developments which are pursued to advance the scientific frontiers of GW observational science are summarized in Table 3, by search group, and classified in two categories:

- **Essential:** developments considered necessary steps for enhancing the scientific return of future observing runs.
- **Exploratory:** developments which can further the science potential of future observing runs.

Depending on the course of development, these enhancements may be used in the analysis of the O4 data, or may be used farther in the future.

	LSC-Virgo-KAGRA Observational Science Working Group			
	Burst	CBC (compact binaries)	Continuous Wave	Stochastic Background
Essential	Improvement of existing pipelines and methods for GW burst searches	Parameter estimation acceleration	Further improvement and optimization of existing data analysis pipelines	Implement optimal method to search for stochastic background from CBC events
	Plans for the detection of exceptional multi-messenger sources	Essential improvements to waveform models	Development of model-robust/agnostic data analysis methods	
		Improved models of population inference		
		Improvements to statistical measurement of the Hubble constant		
		Essential enhancements to all-sky searches		
Exploratory	Development of new methods for GW burst searches	Research and development in parameter estimation methodology	Development of new and potentially more sensitive data analysis methods	Cross-correlation search for intermittent background
		New tests for exotic black hole physics	Use mock data challenges to compare data analysis pipelines	Component separation using narrowband maps
		Long-term improvements to waveform models		Models for anisotropic backgrounds
		Robust population inference with marginal events		
		Real-time cosmology calculation		
		Exploratory enhancements to all-sky searches		

Table 3: **Enhanced Analysis Methods for Advancing Frontiers**: longer term R&D activities of the LIGO Scientific Collaboration, Virgo Collaboration and KAGRA, for the four astrophysical search groups: Burst, Compact Binary Coalescence (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into two categories (essential, exploratory). There is no ranking within each category in this table.

1.1 Searches for Generic Transients, or Bursts

FTE-months: 12.0 (Burst group co-chairs)
FTE-months: 4.0 (Burst review chairs)

The mission of the burst group is to detect GW transients, or *bursts*, and to gain new information on populations, emission mechanisms, and source physics of the associated astrophysical objects. Central to the burst group philosophy is the assumption of minimal information on the source, so that searches for GW bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the GW signature. Burst searches are, therefore, sensitive to GW transients from a wide range of progenitors, ranging from known sources such as binary black hole (BBH) mergers, in particular the most massive and loudest ones, to poorly-modeled signals such as core-collapse supernovae (CCSN) as well as gravitational-wave transients that are currently unknown to science such as cosmic strings, neutron star instabilities, fast radio burst and magnetars. We refer to this as the “eyes wide open" approach.

For example, the complexity of supernovae makes it difficult to reliably map the dynamics of a CCSN into a GW signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces GW transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts (GRBs) could be associated with a GW transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, the group employs data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

The burst group implements a variety of methods to identify instances of statistically significant excess power, localized in the time-frequency domain. To discriminate between GWs and noise fluctuations, each search requires the signal to appear coherently in multiple detectors. The confidence of a candidate event is established by repeating the analysis on many instances of background, obtained by shifting the data from different detectors with non-physical delays.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefit from considering how they perform for plausible astrophysical signals. A variety of targeted searches are designed to increase sensitivity to expected classes of signals. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling, and numerical relativity communities.

Many potential GW burst sources should also be observable in other astronomy channels, including γ-ray, X-ray, optical, radio, and neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a GW burst can be used to increase the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a GW burst detection. Most importantly, joint *multi-messenger* studies of complementary data enable scientific insight that cannot be accessed through GWs or other messengers alone. Therefore, in addition to searches using only the GW data, a significant part of the burst group's science program involves connecting with other observations and working closely with the astronomy and astrophysics communities. An important component of this connection utilizes burst searches running in low- and medium-latency, from minutes to hours, and providing information on transient GW candidates to the astronomical community. The first BBH detection, GW150914, and the binary neutron star merger GW170817 illustrated the scientific value of this approach.

Once a confident GW transient is identified, characterizing its properties becomes an important goal of the group. This includes producing waveform reconstruction, polarization, and source localization estimates for all observed transients (CBC, CCSN, cosmic strings, etc.) This information can then be used to learn about the nature of the astrophysical source and test different astrophysical scenarios.

1.1.1 *Scientific Operations and O4 Observational Results*

The Scientific Operations and O4 Observational Results priorities of the burst group are:

1. **Highest Priority**
    - **Search for short-duration GW bursts (both online and offline):** The burst group will search for a broad class of short-duration transients. Deliverables include low-latency triggers for EM follow-up, and papers describing search results. [Section ST-2.1]
    - **Search for long duration GW bursts:** The burst group will search for a broad class of long-duration transients. Deliverables include papers describing the search results. [Section ST-2.2]
    - **Responding to exceptional GW burst and multi-messenger detections (CCSN, BNS, GRB, FRB, Magnetar Flare, Neutrino):** In the event of an exceptional GW burst or astrophysical event with a reasonable expectation for detecting GWs, the group will deliver a detection statement (or non-detection statement) in a timely manner, as well as waveform reconstruction and signal interpretation. Examples include a galactic core-collapse supernova, an unusually close binary neutron star merger or gamma-ray burst, or a highly energetic magnetar flare. [Sections ST-2.5, ST-6.2, ST-2.6, ST-6.4]
    - **Searches without templates for GWs from binary black holes:** Although most expected BBH mergers will also be detected with CBC searches, burst algorithms are sensitive to a range of features not included in current template banks, including higher order modes, eccentricity, and spin precession. This is important to detect some classes of BBH events. Deliverables include the results of searches targeting both stellar mass and intermediate mass ($M > 100\ M_{\odot}$) black hole systems, with results to be included in papers written jointly with the CBC group. [Sections ST-2.3, ST-6.1]
    - **GW burst signal characterization:** For detected transients, a coherent waveform reconstruction, polarization estimates, and source localization enable many potential investigations. Deliverables include producing waveform reconstructions and localizations for all detected transients. [Section ST-2.4]
2. **High Priority**
    - **Multi-messenger searches (CCSN, GRB, Magnetar Flare, Neutrino, Fast Radio Burst):** Using a known astrophysical event as a target can increase the sensitivity of a GW search. The group will pursue a number of searches, both triggered and untriggered. This includes some sub-threshold searches. Deliverables include papers describing the search results. [Sections ST-2.5, ST-6.2, ST-2.6, ST-6.4, ST-6.3]
    - **Search for BNS post-merger signals:** Following a BNS detection, the group will search for a post-merger signal. Finding (or limiting) such a signal provides a powerful equation-of-state measurement. Deliverables include the result of a search for a post-merger signal after each nearby BNS detection. [Section ST-6.2]
    - **All-sky cosmic string search:** The group will search for signals from cosmic strings, and interpret any upper limits as constraints on string parameters. Deliverables include papers describing search results. [Section ST-7.1]

- **Optimized algorithms for BBH mergers with features well-suited to unmodeled searches.** The group will optimize burst algorithms to search for new populations of non-vanilla BBH mergers, such as systems with high eccentricity, hyperbolic and parabolic encounters. Deliverables include offline searches for these systems and papers describing the search results. [Sections ST-2.3]

Several of these science targets – including BBH mergers, gamma-ray bursts, and low-latency trigger production – overlap with the CBC group, while others – including long transient and cosmic string searches – overlap with the stochastic group. Joint teams are working together across the multiple groups on these targets.

1.1.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The two main levels of longer term R&D activities of the burst group comprise:

1. **Essential**
    - **Improvement of existing pipelines and methods for GW burst searches:** The group will maintain and improve the pipelines employed in GW burst searches and the methods used to produce high-priority results. Deliverables include technical notes and papers describing these improvements.
    - **Plans for the detection of exceptional multi-messenger sources:** In advance of an exceptional astrophysical event, the group will make plans for what types of statements to make in case of a multi-messenger detection, including the quantification of the significance of a candidate multi-messenger detection of cosmic events, and further develop software that will be used to produce the results.
2. **Exploratory**
    - **Development of new methods for GW burst searches:** The group will develop new methods and software to look for GW burst signals. Deliverables include technical notes and papers describing the algorithms and data analysis methods.

1.2 Searches for Signals from Compact Binary Coalescences

FTE-months: 12.0 (CBC group co-chairs)

FTE-months: 4.0 (CBC review chairs)

As of this writing, the O3 run has completed and a multitude of new events have been detected. These are in addition to the several binary black hole coalescences and a binary neutron star merger that were observed in O1 and O2.

The O3a and O3b catalog reporting significant events discovered during O3 along with several companion papers are completed, pending peer review. These papers contain significant events, and include more detailed estimation of population distributions of binary masses and spins, more sensitive tests of general relativity using a much larger statistical sample of signals, and improved measurements of the Hubble constant through direct and statistical methods. Furthermore, we reported the discovery of another binary neutron star merger as well as the detection of two coalescing systems comprising likely a neutron star and a black hole.

During O4, we anticipate a compact binary coalescence detection rate approaching one per day. This will pose a significant challenge to the group in analysing the data and producing scientific publications. But, the scientific payoff will be substantial. The larger population uncovered will help to answer fundamental questions raised by tentative hints seen so far. High-SNR events will yield new insights into the nature of black holes. With additional neutron star mergers, we will be able to make more precise measurements of the neutron star equation of state. The Compact Binary Coalescence (CBC) group aims to discover additional compact binary mergers and to use the gravitational wave signals to advance our understanding of fundamental physics and astrophysics.

The range of scientific activities pursued by the CBC group requires us to prioritize our goals. In the regime of increasing detection frequency over the coming observing runs, we must strike a balance between exploitation of established classes of sources and preparing for detection of new source classes. Achieving these goals requires the group to prioritize the continued research and development of our tools and methods for source detection, estimation of parameters, inference of rates and populations, probing fundamental physics and modeling of waveforms with analytical and numerical relativity. We will continue to develop our search pipelines to improve their sensitivity to quiet sources by improvements in detection statistics, understanding of the noise background and rigorous understanding of data quality. A tremendous human effort is required to develop, deploy, run and interpret the results of low-latency and offline searches in the context of evolving detector sensitivity and data quality. Additionally, the CBC group maintains an active collaboration with a broader community to enhance the impact of our discoveries on theoretical astrophysics and the electromagnetic and astroparticle observing communities.

1.2.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the CBC group are:

1. **Highest priority**

   - **Responding to exceptional events**.

     We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include new detections of binary neutron stars, intermediate-mass or sub-solar mass binary systems. We also anticipate examples in which measurement of a source's parameters (e.g., masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g., the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass). Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, improved measurement of the nuclear equation of state. Binaries with observed electromagnetic counterparts can significantly improve our estimate of Hubble constant using the standard-siren distance estimate.

   - **Producing a catalogue of detected compact binaries**.

     We will produce a summary of all compact binaries detected during each observing run in order to provide a reference for the astrophysics community with details of the detected source's physical parameters, notable properties, and waveform estimates. This requires a good understanding of systematic errors, including waveform modelling errors. We will continue to reduce our sources of systematic errors by improving our waveform modeling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals along with their estimated significance and sky-localization in order to enable subthreshold multimessenger searches.

Eccentric binary systems are another potential class of source where the searches and waveforms are less mature. Templated searches and unmodeled searches can be combined to allow for more robust searches over a range of eccentricity.

Along similar lines, the concrete possibility of detection of hyperbolic captures will require the development of models to be used in templated searches to be run in synergy with unmodeled searches.

- **Characterizing the astrophysical distributions of compact objects**.

  As the number of detections increases, we will build a clearer picture of the astrophysical distribution of compact binaries in terms of their masses and spins. This will set novel empirical constraints on the astrophysics of binary evolution. To accurately learn these distributions we need the ability to infer the physical properties of our detected sources and estimate their distribution taking into account the selection effects of our detectors and pipelines.

- **Testing general relativity**.

  The final stages of compact binary coalescence provide a unique window into the behaviour of gravity in the strong-field, high-velocity regime. We will continue to develop the range of tests we are able to perform on our detections, ensuring their robustness through comparison to numerical relativity simulations where possible. We will develop methods of combining multiple detections to place better constraints on the theory, and test specific predictions from general relativity such as the no-hair, area theorems and the general nature of merger remnants, local Lorentz invariance and the mass of the graviton, and the speed of gravitational waves. As more detectors are added to the network we will also be able to make improved tests of the polarization states of gravitational waves.

- **Low-latency and early warning searches to enable multimessenger astronomy**.

  Observations of an electromagnetic or neutrino counterparts to a gravitational wave signal are of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by searching data in near-real-time and providing public alerts to the astronomical community. This requires the continued development of low-latency pipelines for detection, localization, and estimation of parameters of sources. We will also deploy early warning pipelines in O4 providing pre-merger alerts for binary neutron stars and neutron star black holes in order to capture any prompt emission associated with such events. (The Operations White Paper describes other essential components of this effort, including data quality checks and the infrastructure associated with collating information and distributing alerts.)

- **Multimessenger search for gravitational waves associated with gamma-ray bursts**.

  The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact observations in the compact binary field. We will continue performing a deep coherent search for gravitational waves focused on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational-wave and GRB signals.

- **Probing the properties of matter in the extremes of physical limits**.

  Binary coalescences involving neutron stars are a unique laboratory for studying the behaviour of matter at super-nuclear densities and pressures. We will refine methods of constraining the neutron star equation of state by measuring its observable effects on the inspiral, merger and post-merger phases of the coalescence signal, and apply these to forthcoming neutron star merger observations.

- **Determination of the Hubble constant**.

  Gravitational waves provide a new way to measure the distance of extra-galactic binary coalescences. When these events are also observed electromagnetically, and the redshift of the host galaxy is measured, an estimate of the Hubble constant can be obtained. As such observations accumulate, this method is expected to provide a competitive and independent method for obtaining the Hubble constant. In addition, a statistical approach involving spatial correlations with a galaxy catalog can be used for merger events when no identified counterpart is available. With new observations, we will improve our estimate of the Hubble constant.

To enable these highest-priority activities we will engage in research and development in compact binary coalescence search pipelines and parameter estimation, externally-triggered searches, waveform modelling, rate and population inference, tests of general relativity, measurement of cosmological parameters, and measurement of neutron star equation of state.

2. **High priority**

High priority activities are those which are less certain to produce a significant result in the near term, but where the potential payoff would be high.

- **Improved searches for intermediate mass black hole binaries & intermediate mass-ratio inspirals**.
  A goal of the CBC group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of refined searches for intermediate-mass-ratio inspirals and waveforms to describe them.
- **Search for sub-solar mass compact binary coalescences**.
  A speculative source is black hole binaries (or other compact object binaries) having component masses below one solar mass. Primordial black holes could be one channel by which such systems are formed, but there are other possibilities. Such systems might possibly constitute some fraction of the dark matter. A search for sub-solar mass binaries could reveal the existance of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.
- **Search for gravitationally lensed binary coalescences**.
  Gravitational lensing of gravitational waves can result in magnification of gravitational wave signals as well as multiple images, which has the effect that the same source is seen as multiple events separated in time. Lensing can also alter the gravitational waveform in ways that could allow us to determine that a signal has been lensed. Detection of a lensed signal would allow us to make inferences about cosmology and population of compact binaries and would allow us to perform improved tests of the number of gravitational wave polarization states.
- **Improved waveform models**.
  The O4 run is likely to produce additional interesting CBC events, possibly with higher signal-to-noise ratio or in new regions of parameter space. Development and validation of improved waveform models may be needed to robustly interpret the detected signal or signals.
- **Multimessenger search for gravitational waves associated with fast radio bursts**.
  It is possible that fast radio bursts are produced during compact binary coalescence. The method for performing deep searches for gravitational waves associated with gamma-ray bursts can be extended to explore periods of time around triggers produced by fast radio bursts. Though the methods are similar, the time window to be explored will need to be reassessed.

- **Multimessenger search for gravitational waves associated with high-energy neutrinos**.
  High-energy neutrinos can be produced during compact binary coalescence. The catalog of compact binary coalescence candidates including the subthreshold trigger list with sky localization information will used to search for joint sources of gravitational waves and high-energy neutrinos around astrophysically motivated time window.

3. **Additional priority**

   Additional priority activities are activities that the Compact Binary Coalescence (CBC) group will undertake if resources are available.

   - **Stochastic background of gravitational waves from compact binary coalescences**.
     The superposition of a large number of weak signals arising from compact binary coalescences in the distant universe will produce a stochastic background of gravitational radiation. Such a background produced by binary black hole mergers is not truly continuous, though, as it originates from discrete signals that are not fully overlapping in time, and an optimized statistical search for such sub-threshold signals will be pursued.

1.2.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The two main levels of longer term R&D activities of the CBC group comprise:

1. **Essential**

   - **Parameter Estimation Acceleration and Automation**.
     Parameter estimation engines need to be modernized and optimized to increase their utility, computational performance, and ease of use, in order to handle the future onslaught of events. This will entail management, archiving and interfacing with workflows from other analyses as well as an increase in the level of automation of existing and future pipelines.

   - **Essential Improvements to Waveform Models**.
     With increasing sensitivity we will become increasingly dependent on highly accurate waveform models. Waveform models that capture sub-dominant modes of emission, improved models of precession, and eccentricity will be developed. In addition, inclusion of additional matter effects, e.g., during the merger and post-merger phases, will be needed for modeling neutron star binary systems. A new and flexible interface for waveform models will be implemented to harvest the power of modern hardware, like GPUs, and software, such as Machine Learning methods. Such interface will help the need improvements in the computational performance of waveform simulations to enable faster parameter estimation on the scale necessary for O4.

   - **Improved Models of Population Inference**.
     As the census of compact binary coalescences grows, more sophisticated models of the astrophysical population will become possible (e.g., with redshift evolution). New methods of population inference will be introduced to exploit the large number of detections anticipated.

   - **Improvements to Statistical Measurement of the Hubble Constant**.
     There are a number of potentially biasing systematic effects present in the statistical method of measuring the Hubble constant. These effects will be studied and methods for mitigating them with be implemented in the cosmology code.

- **Essential Enhancements to All-Sky Searches**.
  As the network of detectors grows with the addition of KAGRA, and with improvements in the detector sensitivity curves, search pipelines need to be enhanced to make optimal use of the available data. This continued development will improve the search sensitivity of both online and offline pipelines.

2. **Exploratory**

- **Research and Development in Parameter Estimation Methodology**.
  Investigation of new algorithms and optimization has the potential to greatly improve the speed of the parameter estimation code and add scalability to allow for increasing number of parameters and more complex signal models.
- **New Tests for Exotic Black Hole Physics**.
  Tests for exotic speculative physics such as black hole mimickers or late time gravitational wave echos from black holes will be explored.
- **Long-Term Improvements to Waveform Models**.
  In the long term, we seek waveforms containing the full set of possible physics, capable of modeling the inspiral, merger, and post-merger of precessing, eccentric (even hyperbolic), systems including, where applicable, matter effects and disruption.
- **Robust Population Inference with Marginal Events**.
  Additional information about the astrophysical population of compact binary coalescences can be gleaned by inclusion of marginal events, whose astrophysical origin is not certain. New methods for including marginal events in population inference will be explored.
- **Real-Time Cosmology Calculation**.
  As we move toward larger signal rates and longer stretches of continuous operation, a cosmology calculation that updates in real time as events occur (with or without a counterpart) will be a boon.
- **Exploratory Enhancements to All-Sky Searches**.
  Novel methods can be incorporated into the all-sky search pipelines. For example, searches using templates modelling precessing and sub-dominant emission modes; fully-coherent searches; and the use of machine learning to improve event ranking and detector characterization.

1.3 Searches for Continuous-Wave Signals

FTE-months: 12.0 (CW group co-chairs)

FTE-months: 4.0 (CW review chairs)

The Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal, and extremely weak. Such signals are believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including rotation with elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous GW and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program. Other possible astrophysical CW sources include boson clouds around black holes and low-mass compact binaries during early inspiral, and CW detection methods can also be used for dark matter directly interacting with interferometric detectors.

For known pulsars with measured spin frequencies, frequency derivatives (also known as *spindowns*) and distances, energy conservation sets an upper limit on GW strain amplitude, known as the *spindown limit*, albeit with significant uncertainties. Searches of LIGO and Virgo data have obtained high-confidence upper limits well below the spindown limits for many pulsars, including the Crab and Vela pulsars; as detector sensitivities improve the number of pulsars for which the spindown limit has been surpassed will continue to increase, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

There is much astrophysical uncertainty surrounding CW emission mechanisms, in part because (i) electromagnetic astronomers have detected only a small fraction (a few thousand) of the population of neutron stars in the galaxy (believed to be 10^8–10^9), and (ii) modeling the physics of the interiors of neutron stars, particularly beyond nuclear densities, is extremely difficult. To try to mitigate these uncertainties, the CW group maintains a broad program to search for GW emission from several distinct source categories, as described below. The CW group also encourages active research and development into further improvements to existing search pipelines, as well as formulating ideas for new search methods. In addition, mock data challenges can be useful tools to rigorously compare the performance of data analysis pipelines targeting a particular source category.

The primary categories of searches pursued by the CW group are ordered below by decreasing prior information known about the sources, which generally leads to decreased sensitivity of the associated searches:

Searches for known pulsars use known ephemerides from radio, X-ray or γ-ray timing measurements, and can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans. Of high interest are those pulsars with spindown limits within factors of a few of the achievable sensitivities. For these high-interest targets it is desirable to also perform complementary searches which forego a small part of the sensitivity and, relaxing the strict assumption of phase coherence between the GW signal and the measured ephemeris, perform a search in small frequency and spindown bands around their nominal values. It is also of interest to search for evidence of non-tensor polarizations, which if detected would imply a violation of general relativity.

Directed searches use known sky locations of interesting astrophysical point sources but lack prior frequency or spindown information. They are therefore less sensitive than searches for known pulsars due to the computational expense and trials factor associated with searching over several parameters: the GW frequency, and potentially higher-order spindowns; and, if the target astrophysical source has a binary companion, parameters of the binary orbit where unknown. This typically precludes using fully-coherent matched filtering over the year-long time spans of an observing runs. Semi-coherent methods – which partition the data set into shorter segments and incoherently combine the results from these – make the computational problem tractable, but sacrifice additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Important astrophysical sources in this category are: galactic supernova remnants which may contain a young neutron star, e.g. Cassiopeia A; low-mass X-ray binaries (LMXBs) where accretion could over time have built up a detectable non-axisymmetry, e.g. Scorpius X-1; the region of the Galactic center, which may contain a large population of neutron stars not detectable by electromagnetic surveys; and nearby globular clusters, where older neutron stars may acquire a detectable non-axisymmetry through debris accretion, e.g. NGC 6544.

All-sky searches use no astrophysical priors, and instead perform broad surveys for undiscovered neutron stars. The sensitivity achievable with all-sky searches is further limited, with respect to directed searches, by the need to make sky-location-dependent corrections for the Doppler modulation of the detected source frequency due to the Earth's daily rotation and yearly orbit. The number of sky directions that must be searched to maintain accurate demodulation grows rapidly with the time span of the data set being analyzed, and the associated increase in computational cost is typically severe enough to require shorter coherence times than in directed searches. Finally, to be sensitive to neutron stars with a binary companion, the parameters of the binary orbit must also be searched over, further enlarging the search parameter space and computational cost.

In addition to the categories above, the CW group is also interested in searching for GWs from several other sources. Searches for *long-lived transients*, in collaboration with the Burst and Stochastic working groups (Section ST-2.2), could target emission from e.g. a remnant neutron star formed in a binary neutron star coalescence, or following a pulsar glitch. *Ultra-light boson clouds around black holes* may also produce long-lived CW signals and can be searched for in both directed and all-sky modes. *Compact binaries* can also be CW sources during their early inspiral phase, and for certain mass ranges, such as pairs of low-mass primordial black holes, can be covered by CW search methods with the LVK network. A direct detection of *dark matter* with GW detectors, under various models that allow for direct interaction with the interferometers, is also being pursued using CW data analysis methods, and in collaboration with the Stochastic working group (Section ST-10.2).

1.3.1 Scientific Operations and O4 Observational Results

The input data to any CW analysis pipeline must be carefully characterized and prepared before use. Improperly calibrated data, or data that is otherwise contaminated with excess noise, must be excised from the input data, otherwise analysis results may be affected by large numbers of spurious outliers. Work on identification and mitigation of spectral noise artifacts (lines or combs) coupling into the calibrated strain channel benefits from a close interaction with the detector characterization working group and the site commissioning staff. A small set of data quality flags, produced by the detector characterization working group, are applied to the calibrated detector data so that the most egregious data are discarded. Frequent, large transient glitches seen beginning in the O3 observing run have motivated the use of data cleaning methods to excise them. The detector response is also validated via "hardware injection" recovery, that is, via the successful reconstruction of signals injected into the interferometer data by radiation pressure actuation on the test masses. A set of such signals are monitored daily, weekly and cumulatively during observing runs, and are essential to validate the detector calibration, data cleaning, and other post-processing steps.

The CW group is undertaking a comprehensive search program using data from the O4 observing run, which is reflected in the following list of priority activities. The prioritization of each activity into different classes is arrived at by considering a number of factors: the prior likelihood of detecting a particular category of source; the sensitivity achievable by searches targeting that source category, which in many cases is restricted by their computational cost; and available human resources needed to produce a vetted observational result.

It is important to note that these factors contain several uncertainties. Prior likelihoods of detection are difficult to quantify and may be re-assessed over time. The sensitivity and computational cost of a particular search is often influenced by the specific data set under consideration, including its spectral noise, which may be hard to predict before the data is examined in detail. The availability of human resources, in particular to bring new analysis methods under development to maturity, may also be uncertain. For those reasons, the prioritization of activities that follows is a best guess at the time of writing, and is subject to change when extrapolated into the future. Finally, note that the ordering of activities within the same priority class in the list below does *not* imply any further prioritization *within* that class.

The categorisation into **key/other** from 2022 LSC programme (ADD LINK) is related to the following **highest**, **high** and **additional** priorities in such a way that we call the **highest** and **high** papers **key** and

additional priorities are categorised as **other**.

1. **Highest priority**
    - Targeted searches (Section ST-4.1) for all known pulsars for which upper limits within a factor of two of the spindown limit are likely to be achieved, e.g. the Crab and Vela pulsars. These searches will include searching at once and twice the pulsar spin frequency.
    - Narrow-band searches (Section ST-4.2) for high-interest pulsars, as above, which explore small frequency and spindown bands around the nominal parameters given by the known ephemerides.
    - Directed searches targeting as many high-interest astrophysical point sources as resources allow, in particular Cassiopeia A (Section ST-4.4), Scorpius X-1 (Section ST-4.5). and the Galactic center (Section ST-4.7).
    - All-sky searches for undiscovered neutron stars, either isolated (Section ST-4.9) or in binary systems (Section ST-4.10).
    - Long- and short-transient searches for GWs from post-merger neutron stars (Section ST-4.11) where the estimated distance is similar to or closer than GW170817.
    - Searches for long-lived transient GWs following a pulsar glitch (Section ST-4.12) where indirect upper limits based on measured glitch parameters are expected to be surpassed.
    - Follow-up searches of any promising CW candidates found by other searches (Section ST-4.15).
    - Support for CW searches through detector characterization (see the Operations White Paper), data preparation (Section ST-4.16), and scientific software maintenance (Section ST-4.17).
2. **High priority**
    - Targeted searches (Section ST-4.1) for known pulsars for which the spindown limit is unlikely to be surpassed, [1] including searches sensitive to non-tensor polarizations.
    - Searches for CW emission from r-modes from known pulsars, especially PSR J0537–6910 (Section ST-4.3).
    - Narrow-band searches for CWs from Accreting Millisecond X-ray Pulsars (AMXPs) (Section ST-4.6), which are neutron stars in LMXBs with known spin frequency.
    - Searches for a direct detection of dark matter from various models, in collaboration with the Stochastic working group (Section ST-10.2).
3. **Additional priority**
    - More robust, but less sensitive all-sky searches for more generic CW-like signals (Section ST-4.8).
    - Directed searches for other point sources of interest, including but not limited to: additional galactic supernova remnants (Section ST-4.4), sources in LMXBs (Section ST-4.5) with unknown spin frequency other than Scorpius X-1, and sources in nearby globular clusters.
    - All-sky and directed searches for CWs from ultra-light boson clouds around black holes (Section ST-4.13).
    - Follow-up of candidates from directional stochastic searches, in collaboration with the Stochastic working group (Section ST-10.1).
    - Long- and short-transient searches for GW from post-merger neutron stars (Section ST-4.11) at estimated distances larger than GW170817.
    - Searches for long-lived transient GWs following a pulsar glitch (Section ST-4.12) where indirect upper limits are unlikely to be surpassed.

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[1] Note that, due to the maturity and insignificant computational cost of the targeted search pipelines, there is virtually no practical benefit to separating the high-interest targets from the others and delivering two separate sets of results.

- Searches for transient CW-like emission from low-mass primordial black-hole binaries (Section ST-4.14).

1.3.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The search for CWs is a challenging scientific problem. In particular, when parameters of the sources are unknown and therefore must be searched for over wide parameter spaces, the achievable sensitivity compared to the theoretically-optimal method (e.g. matched filtering) is severely limited by finite computational resources. Sub-optimal but computationally-cheaper algorithms must be utilized. The problem of determining the most sensitive search method, given a fixed computational budget, is not easily solved – yet its solution may prove critical to a first CW detection. Furthermore, many sources may exhibit behaviors which deviate from the usual CW signal model, e.g. spin wandering in LMXBs, or sources with intermittent gravitational emission. Investment in *optimization of existing pipelines*, as well as *development of new, potentially more sensitive and/or robust methods*, is therefore of critical importance.

The CW group aims to support at least two independent search methods/pipelines for each search type; more may be supported as resources allow. This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimal handling of instrumental artifacts.

1. **Essential**
   - Further improvement and optimization of existing data analysis pipelines (Section LT-4.18).
   - Development of model-robust/agnostic data analysis methods (Section LT-4.19).
2. **Exploratory**
   - Development of new and potentially more sensitive data analysis methods (Section LT-4.20).
   - Use mock data challenges to compare data analysis pipelines (Section LT-4.21).

1.4 Searches for Stochastic Backgrounds

FTE-months: 24.0 (SGWB group co-chairs)
FTE-months: 6.0 (SGWB review chairs)

A stochastic gravitational-wave background (SGWB) is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually. The prime objective of the SGWB group is to measure this background, which can arise from cosmological sources such as inflation, cosmic strings, and phase transition models or from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The measured rate of binary black hole (BBH) and binary neutron star (BNS) mergers indicates that, at design sensitivity, Advanced LIGO may detect an astrophysical background. This detection will be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity. Meanwhile, the detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The stochastic searches are built on the cross-correlation infrastructure, which was originally designed to carry out searches for an isotropic stochastic background, but has been adapted to also search for directional stochastic backgrounds and transient GW signals.

Although no SGWB was detected during O1, O2 and O3, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 1.7 \times 10^{-8}$ at 95% confidence. When the Advanced detectors reach design sensitivity, we expect to be as low as 6×10^{-10}.

The isotropic search has been extended to include a test of General Relativity (GR) by searching for a background of non-tensor polarizations. This extension provides a tool for model selection between a tensor and non-tensor background signal, as well as an estimate of the background energy density from tensor, vector, and scalar polarizations. It is also important to estimate the individual contributions of distinct sources of the background, which may be described by distinct spectral shapes. Independent methods have been developed to consider all physically allowed spectral shapes using either a mixing matrix deconvolution or Bayesian parameter estimation. Bayesian parameter estimation techniques are also used to estimate or constrain the average chirp mass and merger rate of the binary black hole population. Significant model development will be necessary for understanding and interpretating the observational results. To support the interpretation of the results, mock data challenges with different sources, such as compact binaries and cosmic strings, will be pursued. Additionally, search pipelines targeting popcorn backgrounds are being developed using both the traditional cross-correlation approach as well as the fully Bayesian techniques.

The directional searches provide a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power. The group employs both a radiometer algorithm and a spherical harmonic decomposition to generate sky maps (and strain spectra) that can be used to identify cosmological or local anisotropies as well as point sources. The spherical harmonic decomposition provides an estimate of the energy density of the SGWB from extended sources over the sky. It can also be applied to search for a GW background with parameterized anisotropy, for example anisotropies associated with the compact binary black hole background or cosmic strings. To further study anisotropies in the astrophysical background, GW sky maps can be cross correlated with electromagnetic observables. The broadband radiometer measures the background energy density from point-like sources over the sky, and provides an important tool for GW astronomy when there is significant uncertainty in the phase evolution of a continuous-wave signal. As an application, a narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. Using a compressed data set folded over a sidereal day, the radiometer can be applied to perform an unmodeled search for persistent sources over all frequencies and sky locations. Directional searches are performed separately for multiple spectral indices in standard LIGO analyses but it may be possible to deconvolve the skymaps to constrain backgrounds of multiple spectral components. Exploration studies are being performed, initially considering two or three power-law spectral indices. We also investigate models of SGWB anisotropies, such as compact binaries and cosmic strings, which we can test against our results. We will test these models with mock data challenges. Continuous-wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable either via the stochastic radiometer or via methods being developed in the CW group. The Stochastic group continues to develop these searches, in consultation with the CW Group.

It may be possible for neutron stars to emit transient gravitational waves on time scales lasting hours to weeks. Moreover, exotic models allow for the possibility of a seemingly persistent signal to start or stop during an observing run, also leading potentially to very long transient signals. The Stochastic group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients on these time scales. Applications of this search include the ability to establish whether an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time; and an understanding of the behaviour of detector artefacts on timescales of days to weeks. There is overlap between the very long transient search and searches being carried out in the Burst and Continuous Waves search groups.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background. However, a background from unresolvable binary BH mergers, for example, is likely to be detected first by the Stochastic group even though it will not be stationary and is unlikely to be Gaussian. Non-Gaussian stochastic background signals have been studied using software injections and analyses on mock data. A search for an astrophysical background from unresolved compact binary coalescences is being pursued in conjunction with the CBC group. The joint activity will develop and implement a Bayesian search strategy that is optimally suited to handle the non-stationarity of the expected background from BBH mergers. We note that collecting information from unresolved binaries at large luminosity distance will also help test the Primordial Black Hole scenario, whose merger rate evolution with redshift is expected to be significantly different from the one of astrophysical black holes.

The Stochastic group is actively involved in detector characterization efforts, with overlap with the Detector Characterization (DetChar) group. For example, the SGWB group relies on magnetic field measurements to estimate and mitigate contamination due to Schumann resonances. There are also plans to study how intermittent signals from (instrumental, environmental, or astrophysical) transients may bias stochastic analyses using software injections. The group has also developed and maintains a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

1.4.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the Stochastic group are:

1. **Highest priority**

    - **Search for an isotropic background.** Analyze the O4 data for an isotropic stochastic gravitational-wave background, looking as well for evidence of non-GR polarization modes; constrain relevant astrophysical and cosmological models of isotropic gravitational-wave backgrounds; investigate the effect of correlated magnetic noise on the search.

    - **Directional searches for anisotropic backgrounds .** Analyze the O4 data using the radiometer method to generate sky maps for point sources of an anisotropic gravitational-wave background; Produce the O4 data folded to one sidereal day to facilitate applications of more computationally-expensive stochastic searches like the all-sky all-frequency radiometer and searches for parameterized anisotropy; optimize the search sensitivity in terms of angular resolution, regularization bias, and frequency band used in search; perform an unmodeled search for potentially interesting persistent gravitational-wave sources from specific sky locations; perform modelled searches targeting specific anisotropy in the sky, such as in the galactic plane.

    - **Data quality and detector characterization studies.** Investigate the effect of non-stationarity and coherent lines in the O4 data on the stochastic searches, and pursue approaches to mitigate these sources of noise.

    - **Spherical harmonic analysis for anisotropic background.** Perform all-sky search for extended gravitational wave background sources using spherical harmonic decomposition method applied to O4 data; constrain astrophysical and cosmological models of anisotropic gravitational-wave backgrounds, using angular spectra for both auto-power in gravitational wave background and for the cross-power between the gravitational-wave background and electromagnetic observables.

    - **Development of python-based pipeline for isotropic stochastic background search.** Implement and vet the cross-correlation based search algorithm for the isotropic stochastic gravitational-wave background in python, taking advantage of the existing infrastructure.

    - **Implications and gravitational-wave background modeling.** Develop more accurate theoretical models of astrophysical and cosmological gravitational-wave backgounds; perform mock data challenges to test the recovery of simulated backgrounds corresponding to different theoretical models, using Bayesian model selection or parameter estimation.

2. **High priority**

    - **Dark matter searches.** Searches for dark photon dark matter in collaboration with Continuous Wave working group.

3. **Additional priority**

    - **Component separation.** Implement frequentist or Bayesian component separation methods to determine the individual spectral contributions to an isotropic gravitational-wave background.

    - **Search for very long transients.** Analyze the O4 data for very-long transient events, thus assessing the temporal distribution of the SGWB. In the case of a BNS or a BHNS detection, the search for a very long duration signal from a merger remnant will be promoted to the rank of highest priority.

    - **GW-EM Correlations.** Develop techniques for measuring possible correlations between GW anisotropy maps and maps of matter structure obtained through electromagnetic approaches (galaxy counts, gravitational lensing and others).

1.4.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

1. **Essential**

    - **Stochastic background from compact binary coalescences.** Implement and test an optimal Bayesian search for the nonstationary background produced by individually unresolvable CBC events (e.g., BBH mergers) throughout the universe.

    - **Cross-Correlation Based Search for Intermittent Gravitational-wave Backgrounds.** Develop a search for intermittent (i.e., popcorn-like) stochastic GW backgrounds by modifying the standard cross-correlation search for a stationary-Gaussian background to target short intermittent “bursts" of correlated GW signals.

2. **Exploratory**

    - **Component separation using narrowband maps.** Develop and implement component separation methods for anisotropic gravitational-wave backgrounds.

    - **Models for anisotropic backgrounds.** Develop theoretical models of astrophysical backgrounds.

1.5 Working Group Leadership Roles

Each of the four observational science working groups (CBC, Burst, CW, SGWB) is led by Co-Chairs, with at least one from each collaboration. As the collaborations complete analyses from the full O3 data run and prepare to analyze O4 data when it is collected, KAGRA working group chairs will expand their role to lead the joint groups on a more equal basis with the LSC and Virgo co-chairs, and to help all LVK members contribute to a unified science program.

Because the working groups have many active members and encompass a large scientific scope, the Co-Chair role demands a considerable amount of time and energy.

Some of the working groups have defined formal subgroups devoted to developing and maintaining specific technical capabilities and pursuing various science goals. Several of these subgroups span two or more working groups where the science suggests overlap in sources or methods.

Each paper being prepared has a designated Editorial Team (or Paper Writing Team), formed at the onset of paper preparation, and a paper project manager (or co-manager).

Internal review of science results is led and coordinated by a pair of Review Co-Chairs (one each from the LSC and Virgo) for each of the four astrophysical search groups.

Each collaboration also appoints a Data Analysis (or Observational Science) Coordinator. The Data Analysis Coordinators facilitate the overall process of planning, producing and reviewing scientific analyses and papers, and lead weekly Data Analysis Coordination (DAC) meetings, among other tasks.

FTE-months: 8.0 (DAC co-chairs)

2 Burst Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the CBC, and Stochastic groups in sections 6 and 7, respectively.

ST-2.1 Search for short-duration GW bursts

All-sky searches for short-lived (lasting $\lesssim$ 10 s) transient astrophysical signals not amenable to template-based methods.

Motivation and methods

A wide range of highly energetic astrophysical phenomena are expected to be accompanied by emission of gravitational-wave transients lasting from milliseconds to several seconds within the instruments' frequency band. For some transient sources, especially compact binary systems made up of neutron stars and/or black holes, their expected gravitational-wave emission is modeled sufficiently well over most of their parameter space that matched filter techniques using waveform templates can be used to optimally retrieve astrophysical signals from the interferometer data. However, there exists a range of plausible sources of short-duration gravitational-wave emission for which their signal morphologies are poorly modeled or even unknown, and for which no matched filter techniques can be effectively employed. Such sources, e.g., core-collapse supernovae, long-duration gamma-ray bursts, soft gamma repeaters and neutron star glitches. The all-sky search for short-duration bursts targets this wide class of sources. For this reason, the all-sky search invokes general transient-finding methods with minimal assumptions on signal morphology. This also provides the opportunity to identify unanticipated sources and signals.

Since O1, the search for unmodeled transients has benefited from independent implementations of burst analysis pipelines [1, 2, 3]. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to identify coincident or coherent excess power in the data from multiple detectors (cWB [4], oLIB [5] and BayesWave [6]). These analyses use gravitational-wave strain data from all available detectors to solve the inverse problem for the impinging gravitational-wave signal by using maximum likelihood and Bayesian statistics approaches. Multi-instrument analysis is essential for the robust detection of unmodeled gravitational-wave transients; coincident or fully coherent methods have been shown to perform well at rejecting noise transients while recovering relatively weak signals. We plan to continue using multiple burst pipelines in the foreseeable future. Independent searches for the same science targets present the opportunity for direct comparisons of the analysis, an ability to validate search results, and often leads to search innovation. Multiple, independent searches may also better cover the signal parameter space.

In addition to offline analyses, an all-sky search for transient events is performed in low-latency and successfully produces triggers with as short as a few minutes of time delay to allow for rapid follow-up multi-messenger observations. The ability to quickly identify triggers from generic transient events complements current targeted searches for compact binaries, remaining sensitive to a wider variety of sources.

We note that because of the generic waveforms targeted by these searches, there is sometimes significant overlap with results from other, more narrowly focused search methods.

Gravitational-wave transient searches benefit from data quality information provided by detector experts. That especially includes the findings of the detector characterization groups to identify and understand the origin of the non-stationary noise sources. In particular, data quality vetoes are provided by detector characterization groups to exclude noise outliers and improve the burst search snsitivities.

Critical tasks and major deliverables for O4

ACTIVITY ST-2.1-A-**OPS**: LOW-LATENCY SEARCHES FOR PUBLIC ALERTS

TASK ST-2.1-A(i): CWB ONLINE PIPELINE OPERATION

FTE-months: 4.0

Prepare, deploy and maintain the cWB online search for gravitational-wave bursts for O4. This activity includes all flavors of low-latency searches that generate burst alerts (all-sky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK ST-2.1-A(ii): BAYESWAVE FOLLOW-UP ANALYSES FOR LOW-LATENCY SEARCH

FTE-months: 4.0

Prepare, deploy and maintain the BayesWave analysis to follow-up online gravitational-wave burst candidates. Online detection of burst candidates by cWB shall be characterized using the BayesWave pipeline. This activity includes the determination of Bayes factors as well as the inference of the source waveform.

TASK ST-2.1-A(iii): OLIB ONLINE PIPELINE OPERATION

FTE-months: 2.0

Prepare, deploy and maintain the oLIB online search for gravitational-wave bursts for O4. This activity includes all flavors of low-latency searches that generate burst alerts (all-sky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK ST-2.1-A(iv): MLY ONLINE PIPELINE OPERATION

FTE-months: 2.0

Prepare, deploy and maintain the MLy online search for gravitational-wave bursts for O4. This activity includes all flavors of low-latency searches that generate burst alerts (all-sky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK ST-2.1-A(v): DEFINITION OF BURST LOW-LATENCY ALERTS

FTE-months: 1.0

Discuss and decide the nature of the all-sky burst alerts during O4.

TASK ST-2.1-A(vi): STRATEGY TO FOLLOW-UP BURST EVENTS DETECTED ONLINE

FTE-months: 2.0

Decide and implement a strategy to follow-up burst-only candidates. This procedure should include detector characterization studies and parameter estimation using all existing burst waveforms.

TASK ST-2.1-A(vii): ONLINE DATA QUALITY FOR BURST SEARCH

FTE-months: 2.0

Online search pipelines shall include a mechanism to integrate data quality products delivered with low latency. This information shall be used to define valid analysis segments and to reject detector glitches.

TASK ST-2.1-A(viii): ONLINE BACKGROUND TRIGGERS FOR BURST SEARCH

FTE-months: 2.0

Deliver the most-limiting background triggers found by online searches to the detector characterization groups. This shall be done on a regular basis during the observing run. In return, safe and relevant data quality products are delivered to burst pipelines with low latency to reject noise outliers.

ACTIVITY ST-2.1-B-**OPS**: SEARCH FOR SHORT-DURATION GRAVITATIONAL-WAVE TRANSIENT SIGNALS IN LIGO, VIRGO, AND KAGRA O4 DATA

TASK ST-2.1-B(i): RUN THE ALL-SKY BURST SEARCH ON O4 DATA

FTE-months: 4.0

Run cWB, oLIB, MLy and BayesWaves pipelines on O4 data set and produce results.

TASK ST-2.1-B(ii): SIGNAL INJECTIONS FOR ALL-SKY BURST SEARCH FTE-months: 2.0

Perform burst signal injections to assess the pipeline efficiency following the methodology developed for previous runs.

TASK ST-2.1-B(iii): OFFLINE BACKGROUND TRIGGERS FOR ALL-SKY BURST SEARCH FTE-months: 2.0

Deliver the most-limiting background triggers found by offline search pipelines to the detector characterization groups. In return, safe and relevant data quality vetoes are delivered to burst pipelines to reject noise outliers.

TASK ST-2.1-B(iv): FOLLOW-UP DETECTION CANDIDATES FROM ALL-SKY BURST SEARCH FTE-months: 3.0

Use codes designed to evaluate gravitational-wave candidate significance. Employ models to test significance of candidates as astrophysical versus “glitch” (detector artifact) models. As needed, employ techniques to remove glitches from the data near a gravitational-wave candidate – to be used by parameter estimation or other follow-up analyses. Test all existing burst waveforms to match the data and assess the astrophysical origin of the event.

TASK ST-2.1-B(v): REPORT RESULTS AND REVIEW ALL-SKY BURST SEARCH FTE-months: 2.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results. Reporting should be made within working groups and periodically to the burst group.

TASK ST-2.1-B(vi): PUBLISH RESULTS FROM ALL-SKY BURST SEARCH FTE-months: 2.0

Work toward publishing a collaboration paper reporting any signals found by the short-duration search in the O4 data, and place limits on some classes of sources.

ACTIVITY ST-2.1-C-**OPS**: SUBGROUP ADMINISTRATION

Management of the short-duration GW burst subgroup.

TASK ST-2.1-C(i): SUBGROUP LEADERSHIP: ALL-SKY SHORT-DURATION BURST SEARCH FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.1 Search for short-duration GW bursts R&D (Long Term)

ACTIVITY LT-2.1-A: ALTERNATIVES TO GENERAL RELATIVITY

In addition to searching for generic transient gravitational-wave events, we also plan to search for gravitational-wave bursts with alternative polarizations. While Einstein’s general theory of relativity (GR) predicts that gravitational waves will have a tensor polarization, some alternative theories of gravity predict gravitational waves with other polarizations (namely scalar and vector polarizations). Using data from LIGO, Virgo and KAGRA detectors makes it possible to distinguish between polarizations of a gravitational-wave signal and to search for these alternative polarizations. We plan to use one or more burst pipeline to search for gravitational-wave signals with non-GR polarizations, and to quantify the consistency between recovered signals and GR polarizations.

TASK LT-2.1-A(i): INVESTIGATE ALTERNATIVES TO GR USING SHORT-DURATION BURST SEARCH

ACTIVITY LT-2.1-B: PIPELINE IMPROVEMENTS

Continue to investigate improvements to pipelines. For example, machine learning tools can be used at the post-processing stage to try to overcome the issue of the non-Gaussian transients hampering the search.

TASK LT-2.1-B(i): INVESTIGATE PIPELINE IMPROVEMENTS FOR SHORT-DURATION BURST SEARCH

ST-2.2 Search for long-duration GW bursts

All-sky searches for 10 – 1000 s long transient astrophysical signals not amenable to template-based methods.

Motivation and methods

Unmodeled long-lived gravitational-wave transients (lasting $\gtrsim$ 10–1,000 s) are an exciting class of signals for advanced detectors. Such long-lived transients have been predicted to originate at the death of massive stars. In one class of models, gravitational waves are emitted by a rapidly spinning protoneutron star, which may be spun up through fallback accretion. In another class of models, the signal comes from the motion of clumps in an accretion disk. In either case, the signals are long-lived, narrowband, and may occur with a sufficiently high rate so as to be observed with advanced detectors. Other possible scenarios for long-lived gravitational-wave emission include protoneutron star convection, rotational instabilities in merger remnants, r-mode instabilities associated with glitching pulsars, type I bursts from accreting pulsars, and eccentric binary systems. Searches [7, 8, 9] for these sources use minimal assumptions about the signal waveform, so unpredicted sources are detectable as well. The burst group long-duration transient search, carried out by the cWB [4], pySTAMPAS [10, 11], pyXel, and CoCoA [12] pipelines, focuses on signals that last up to several hundreds of seconds while other searches (see LT-5.3 and ST-4.11) target signals lasting up to several weeks.

Critical tasks and major deliverables for O4

ACTIVITY ST-2.2-A-**OPS**: SEARCH FOR LONG-DURATION GRAVITATIONAL-WAVE TRANSIENT SIGNALS IN O4 DATA

TASK ST-2.2-A(i): CONFIGURE AND RUN THE ALL-SKY LONG-DURATION BURST SEARCHES

FTE-months: 4.0

Search for gravitational-wave signals in LIGO, Virgo and KAGRA O4 data with cWB, pySTAMPAS, pyXel and CoCoA. Estimate the significance of the most promising gravitational-wave candidates and estimate the search sensitivity.

TASK ST-2.2-A(ii): WAVEFORM CATALOG DEVELOPMENT FOR LONG-DURATION BURST SEARCHES

FTE-months: 2.0

Continue to enhance the long-duration transient waveform catalogue with astrophysically motivated sources. A selection of the most interesting waveforms will be done for the O4 search results publication.

TASK ST-2.2-A(iii): FOLLOW-UP DETECTION CANDIDATES FROM LONG-DURATION BURST SEARCHES

FTE-months: 3.0

Evaluate the significance of a candidate against the hypothesis of a noise event. Study the data quality and the signal properties (sky localization etc). Use a Bayesian parameter estimation algorithm that tests signal waveform models.

TASK ST-2.2-A(iv): REPORT RESULTS AND REVIEW OF LONG-DURATION BURST SEARCHES

FTE-months: 1.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results.

TASK ST-2.2-A(v): BACKGROUND TRIGGERS FOR LONG-DURATION BURST SEARCH FTE-months: 2.0

Deliver the most-limiting background triggers found by search pipelines to the detector characterization groups. In return, safe and relevant data quality products (vetoes and/or spectral lines) are delivered to reject noise outliers.

TASK ST-2.2-A(vi): PUBLISH RESULTS FROM LONG-DURATION BURST SEARCH FTE-months: 2.0

Work toward publishing a collaboration paper reporting any signals found by the long-duration search in the O4 data, and place limits on some classes of sources.

ACTIVITY ST-2.2-B-**OPS**: SUBGROUP ADMINISTRATION

Management of the long-duration GW burst subgroup.

TASK ST-2.2-B(i): SUBGROUP LEADERSHIP: ALL-SKY LONG-DURATION BURST SEARCH FTE-months: 1.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.2 Search for long-duration GW bursts R&D (Long Term)

ACTIVITY LT-2.2-A: PIPELINE IMPROVEMENTS

TASK LT-2.2-A(i): CWB PIPELINE IMPROVEMENTS FOR LONG-DURATION BURST SEARCHES

Investigate options to improve the cWB sensitivity to long-duration burst signals.

TASK LT-2.2-A(ii): PYSTAMPAS PIPELINE IMPROVEMENTS FOR LONG-DURATION BURST SEARCHES

Investigate options to improve the pySTAMPAS sensitivity to long-duration burst signals.

TASK LT-2.2-A(iii): PYXEL PIPELINE IMPROVEMENTS FOR LONG-DURATION BURST SEARCHES

Investigate options to improve the pyXel sensitivity to long-duration burst signals.

TASK LT-2.2-A(iv): COCOA PIPELINE IMPROVEMENTS FOR LONG-DURATION BURST SEARCHES

Investigate options to improve the CoCoA sensitivity to long-duration burst signals.

ACTIVITY LT-2.2-B: PARAMETER ESTIMATION

TASK LT-2.2-B(i): SOURCE RECONSTRUCTION FOR ALL-SKY LONG-DURATION BURST EVENTS

Investigate modeled and unmodeled source reconstruction methods for long transients. It includes to adapt and test the Bayesian parameter estimation code for long-duration signals with the different models of long-duration GW transient sources.

ACTIVITY LT-2.2-C: ONLINE SEARCH

Develop and test a pipeline to search for long-duration burst transient signals with low latency.

TASK LT-2.2-C(i): ONLINE ALL-SKY LONG-DURATION BURST SEARCH

ST-2.3 Search without templates for GWs from binary black holes

All-sky Burst searches applied to BBH systems.

Motivation and methods

The binary black hole (BBH) systems in the normal stellar mass range (total mass less than about $100\,\mathrm{M}_\odot$ have been efficiently detected in observing runs O1, O2, and O3 with the matched filter searches using quasi-circular CBC templates, as described in the CBC section. However, other types of potential of CBC systems covering a larger range of component masses, spins and eccentricities should also be considered. Detection of such systems would provide information regarding the viability of several proposed binary formation mechanisms and would help discriminate among different formation models. Targeting this wider parameter space of CBC sources with a burst analysis method, which does not rely on templates, creates a search which is robust to a variety of features including high mass ratios, higher order modes, mis-aligned spins, eccentric orbits, or deviations from general relativity. These may create mismatch between the observed signal and CBC matched-filter search templates.

There are foreseen two major types of BBH systems for which the Burst searches are especially informative, IMBH and non-circular BBHs. We briefly discuss these two cases below.

High-mass BBH systems

The GW190521 discovery [13] in O3a, representing the first black hole with mass in the pair instability mass gap and the first definitive IMBH, promises to revolutionize this topic. Previously, stellar-mass black holes, originating from core collapse of massive stars, have been observed in the mass range up to $\sim 65\,\mathrm{M}_\odot$. Due to the pair instability, it is expected that normal stellar evolution will not result in black holes with mass roughly in the range 65 to 100 $\mathrm{M}_\odot$. Meanwhile, massive black holes, exceeding $10^5\,\mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) occupy the mass range between these two. IMBHs exceeding the $65\,\mathrm{M}_\odot$ mass limit of stellar-mass black holes may form in dense stellar environments upon the merger of multiple stellar-mass black holes [14, 15, 16]. These IMBHs may then form binaries and merge with stellar-mass black holes in dense environments. Several channels for IMBH formation were explored in the GW190521 "implications" paper [17].

IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [18, 19]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [20], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [21]. A large number of IMBH mergers may be a generic feature of some mechanisms of structure formation, although these are likely to occur at high redshifts [22]. Binaries including two IMBHs could also form as a result of evolution of isolated binaries with very high initial stellar masses [23]. Hence, detections of additional IMBH systems may serve as probes of globular cluster dynamics, and, potentially, as probes of structure formation and growth of super-massive black holes.

The searches are carried out both with matched filter algorithms using CBC templates and Burst algorithms, which do not rely on templates. The matched filter technique yields the optimal detection efficiency for signals of known form in stationary, Gaussian noise and thus requires a sufficiently accurate signal waveform model for use as a template. The IMBH Burst search is robust to a variety of features that may create mis-match between the observed signal and BBH template banks, including high mass ratios, mis-aligned spins, eccentricity, precession, deviations from general relativity, or detector noise artifacts. Therefore, the IMBH search benefits from the combination of the two complementary analysis techniques.

Non-circular BBH systems

The all-sky Burst searches represent a viable detection method for BBH systems over a wide range of their potential parameter space. A particularly interesting case is that of eccentric (eBBH) systems. Theoretical work has suggested that galactic nuclei and globular clusters may be promising settings for the formation of dynamical capture binaries. Since these systems can form with large eccentricities and very small initial separations, there is good reason to expect that significant eccentricity will persist when the binaries evolve into the LIGO/Virgo detection band. Current CBC searches using quasi-circular waveforms from stellar-mass binaries will not efficiently detect these systems for eccentricities of $e \approx 0.05$ or more[24], therefore dedicated burst searches for these potential sources represent a viable alternative [25]. In practice, the eccentric BBH (eBBH) analysis uses a variation of the generic binary stellar mass black hole search carried out with the cWB pipeline [4] which is optimized for such systems. Finally, it is expected that for O4 there will sufficient coverage of eBBH waveforms available to allow application of standard parameter estimation techniques for eBBH candidates.

Other potential non-quasi-circular BBH systems include close hyperbolic encounters (CHE) or BBH captures. Numerical relativity waveforms are starting to become available for such systems, which allows the evaluation of detection efficiencies for Burst searches. Because these waveforms morphologically resemble the class of instrumental artifacts known as “blip glitches," it will be important to evaluate these searches in the presence of real detector noise.

In recent years, the proposal that there is a large population of black holes living in dense clusters has been gaining popularity, both in the context of primordial black hole (PBH) clusters [26] and dense globular clusters with a large amount of stellar remnants [27]. One natural consequence of these dense clusters is that the black holes inside them will gravitationally scatter off each other in hyperbolic encounters [28], and if they get close enough, they will emit bremsstrahlung gravitational waves that can be detected by the LVK interferometers [29]. To date, no systematic search looking for CHE has been published, which if detected could give information about the dynamics of the clusters in which black holes live.

BBH captures are characterised by a close encounter between 2 objects, which become bound at high eccentricities if a critical amount of angular momentum and energy loss occur. Under such conditions there is not enough time for the binary to circularise, and hence BHs merge with high eccentricity. Various scenarios can lead to capture, such as single-single interactions in galactic nuclei, in regions around supermassive BHs [30], and single-single [31], binary-single [32] and binary-binary interactions [33] in globular clusters. Work by [34, 30] suggests that single-single interactions in galactic nuclei produce the highest rate of eccentric stellar mass BH capture events, with most encounters being parabolic and forming within the LIGO/Virgo band. Binary-single capture events are most common in globular clusters, possibly accounting for $\sim 10\%$ of all BBH mergers formed in these environments [32]. Recent simulations have shown that these waveforms are similar to signals detectable by burst search [35], thus it is important for us to characterize the sensitivity of burst searches to such sources.

Given the complementary nature of Burst and CBC searches for BBH systems, a joint Burst-CBC all-sky effort has been organized and is briefly discussed in Section ST-6.1.

Major deliverables and critical tasks for O4

ACTIVITY ST-2.3-A-**OPS**: BURST BBH SEARCH

TASK ST-2.3-A(i): OFFLINE SEARCH

FTE-months: 4.0

Prepare and run the O4 search pipelines. Report results in a timely manner. Provide feedback on data quality issues to detector characterization.

TASK ST-2.3-A(ii): FOLLOWING-UP DETECTION CANDIDATES

FTE-months: 1.0

Prepare and use codes designed to evaluate GW candidate significances. Employ models to test significance of candidates as astrophysical versus “glitch” (detector artifact) models. As needed, employ techniques to remove glitches from the data near a GW candidate – to be used by parameter estimation or other follow-up analyses.

TASK ST-2.3-A(iii): EVALUATION OF SENSITIVE PARAMETER SPACE FTE-months: 1.0

Use injections to evaluate the sensitivity of the search for ranges of BBH system parameters, including mass ratio, spin, precession, higher-order modes, etc. Compare with the CBC templated searches.

TASK ST-2.3-A(iv): REPORTING RESULTS AND REVIEW FTE-months: 1.0

Report intermediate results in a timely manner as data becomes available during engineering runs and in the O4 observing run. Reporting should be made within the BBH group, the joint Burst-CBC group, and periodically to the Burst group.

TASK ST-2.3-A(v): CONTRIBUTE TO GW TRANSIENT CATALOG AND RELATED PAPERS FTE-months: 1.0

The all-sky team should work with the catalog team to agree on thresholds for GW detection candidates. They should oversee any necessary follow-up studies for evaluating candidates.

ACTIVITY ST-2.3-B-**OPS**: ECCENTRIC BBH (EBBH) SEARCH

The following activities and tasks for O4 apply specifically to eccentric BBH systems, as well as hyperbolic BBH encounters or BBH captures.

TASK ST-2.3-B(i): THE O3 SEARCH FTE-months: 3.0

Complete the O3 eBBH analysis and prepare the collaboration paper.

TASK ST-2.3-B(ii): SEARCH OPTIMIZATION FTE-months: 2.0

Optimize the eBBH search for O4.

TASK ST-2.3-B(iii): ECCENTRIC WAVEFORMS FTE-months: 2.0

Evaluate eccentric BBH waveforms or hyperbolic BBH encounter waveforms for use in O4 analyses. This includes waveform sensitivity tests and implementation in the analysis.

TASK ST-2.3-B(iv): REPORTING RESULTS AND REVIEW FTE-months: 3.0

Report intermediate results in a timely manner as data becomes available during engineering runs and in the O4 observing run. Reporting should be made within working groups and periodically to the Burst group.

A significant eBBH detection will result in an exceptional event paper.

ACTIVITY ST-2.3-C-**OPS**: SUBGROUP ADMINISTRATION

Management of the BBH Burst subgroup.

TASK ST-2.3-C(i): SUBGROUP LEADERSHIP FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership. This will include maintaining close ties with the relevant Burst and CBC sub-groups.

LT-2.3 Search without templates for GWs from binary stellar mass black holes R&D (Long Term)

ACTIVITY LT-2.3-A: DEVELOPMENT OF ECCENTRIC WAVEFORMS POST-O4

TASK LT-2.3-A(i): WAVEFORM DEVELOPMENT

Continue to monitor the development of waveform models for IMBH, eBBH systems, hyperbolic BBH encounters, or BBH captures. Test and evaluate their impact.

ACTIVITY LT-2.3-B: IMPROVEMENT OF SEARCH SENSITIVITY

TASK LT-2.3-B(i): OPTIMIZING THE BBH SEARCH

Optimize the non-templated all-sky searches for any BBH system beyond O4.

TASK LT-2.3-B(ii): METHODS FOR IMPROVING THE NON-CIRCULAR BBH SEARCH SENSITIVITY

Investigate options to improve the burst search sensitivity to eccentric black hole signals by using different clustering algorithms and time-frequency graphs obtained from relevant signal models. Same for hyperbolic encounters or BBH captures.

TASK LT-2.3-B(iii): METHODS FOR LOW-MASS CHIRP SYSTEMS.

Investigate methods for improving the Burst BBH search sensitivity for systems with chirp mass less than 10 $M_\odot$.

TASK LT-2.3-B(iv): ECCENTRICITY RECONSTRUCTION

Investigate methods for reconstructing the eccentricity of BBH mergers for any eccentricity.

ST-2.4 GW burst signal characterization

Waveform reconstruction and interpretation.

Motivation and methods

One of the exciting features of gravitational-wave astrophysics is the observation of signals directly tied to the flow of energy and momentum within a source [36]. This signal can be extremely rich in the information it contains. For compact object mergers, it encodes the source masses, spins, distance, and orientation. An observed gravitational-wave signature from a galactic supernova would probe the stellar core, and would give valuable clues to the supernova explosion mechanism, angular momentum, and other dynamic variables. The gravitational waveform from an oscillating neutron star would constrain the neutron star equation of state. For new classes of signals, the waveform will provide a unique path towards understanding the astrophysical source. Even without an astrophysical model, it may be possible to constrain some source parameters based on time-scale and energy arguments.

Reconstructing the waveform of a detected CBC or burst signal with minimal assumptions is a non-trivial process, involving data from multiple detectors, knowledge of detector positions and responses, and a statistical framework for evaluating a best-fit waveform and properties of the detector noise [6, 37, 38]. Quantifying the uncertainty on reconstructed CBC or burst waveforms is also critical to allow comparisons between measured signals and proposed source models, as well as test different astrophysical scenarios such as CCSN, neutron star equation of state, and cosmic strings models.

During O1, O2 and O3, reconstructed waveforms were seen to agree with models for expected signals from binary compact objects coalescences [39]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [38]. Meaningful polarization measurements are possible with three or more detectors in the network.

Closely related to the best-fit waveform is an estimate of the source's direction [40, 41, 42]. The angular position reconstruction of a gravitational wave source, or "skymap", enables searches for coincident emission by a wide range of electromagnetic and particle observatories. This includes both searches of archival data from all-sky instruments or serendipitous observations, and attempts to rapidly respond to low-latency GW triggers by slewing radio, optical, and X-ray instruments.

Critical tasks and major deliverables for O4

ACTIVITY ST-2.4-A-**OPS**: PARAMETER ESTIMATION FOR THE GW TRANSIENT CATALOG AND PAPERS

TASK ST-2.4-A(i): PERFORM WAVEFORM RECONSTRUCTIONS

FTE-months: 2.0

Deliver waveform reconstructions, with uncertainty, for all detected sources during O4. Compare waveform reconstructions with best templates used in CBC searches.

TASK ST-2.4-A(ii): PRODUCTION OF SKYMAPS

FTE-months: 1.0

Deliver position reconstruction skymaps for all detected sources during O4.

TASK ST-2.4-A(iii): EVALUATE WAVEFORM MODELS

FTE-months: 2.0

Test available burst waveform models against data. Examples include CCSN ST-2.5, cosmic strings ST-7.1, pulsar glitches, close hyperbolic encounters of two black holes, etc. For a given GW event, this analysis shall be able to prefer one waveform model against another.

TASK ST-2.4-A(iv): CONTRIBUTE TO O4 CATALOGS AND PAPERS

FTE-months: 1.0

Deliver waveform reconstructions, waveform matching results and reconstructed skymaps to the GWTC for O4, and to the corresponding catalog papers. Maintain a close working relationship with the catalog paper editorial teams (PET).

TASK ST-2.4-A(v): REPORTING RESULTS AND REVIEW

FTE-months: 0.5

Report progress and results in a timely manner as data becomes available during the observing run. Reporting should be made within working groups and periodically to the burst group.

LT-2.4 GW burst signal characterization R&D (Long Term)

ACTIVITY LT-2.4-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-2.4-A(i): IMPROVING WAVEFORMS AND SKY LOCALIZATION RECONSTRUCTION

Continue development of improved methods for waveform reconstruction, waveform comparisons, and sky localization.

TASK LT-2.4-A(ii): POLARIZATION STUDIES

Provide measurement and interpretation of the polarization patterns for GW events detected with the LIGO-Virgo-KAGRA network.

ACTIVITY LT-2.4-B: IMPACT OF CALIBRATION ERROR ON BURST SEARCHES

TASK LT-2.4-B(i): IMPACT OF CALIBRATION ERROR ON SKY LOCALIZATION AND WAVEFORM RECONSTRUCTION OF BURST SOURCES

Development of methods to quantify the impact of calibration error on burst searches. For example, how relative calibration error between the detectors impact the sky localization of the sources.

ST-2.5 Search for GWs from core-collapse supernova

Search around the inferred stellar collapse times of nearby core-collapse supernovae.

Motivation and methods

Once a star with mass $M \gtrsim 10 M_\odot$ exhausts its fuel, its core collapses to a hot proto-neutron star. The proto-neutron star cools by emitting neutrinos. A shock wave is promptly formed from the proto-neutron star and plows through the stellar mantle. If it breaks out of the star's surface, it lights up the star in a supernova explosion. The neutrinos and/or EM radiation herald a core-collapse supernova, and can be used to trigger a search for GW bursts. GWs are produced by bulk aspherical accelerated motion of matter; in the CCSN context they are a direct probe of the uncertain degree of asymmetry of the supernova engine.

GW signals from CCSN are typically much weaker than signals from binary mergers. Numerical simulations have shown that CCSN signals can span frequencies up to few kHz and durations up to a few seconds, making them hard to detect because their energy is spread over a large area in the time-frequency domain. The current burst searches are not designed to detect such signals and can miss a Galactic CCSN with signal-to-noise ratio below 30. Thus pipeline developments are needed to improve the detection efficiency of CCSN searches.

The strategies for these searches can vary according to detection of different messengers. It may happen that GWs are produced while no electromagnetic or neutrino counterpart is detected, in which case a CCSN-specific all-sky burst search would be the best search strategy. In case we observe only light from a nearby supernova an optically-triggered search is performed, as was performed for O1-O2 [43]. In case we observe low-significance neutrinos, then a sub-threshold neutrino search may be performed. But special attention is placed when an SNEWS alert reports the detection by neutrinos of a galactic or nearby extragalactic supernova, like supernova SN1987A.

Major deliverables and critical tasks for O4

ACTIVITY ST-2.5-A-**OPS**: SEARCHES FOR GW ASSOCIATED TO CCSNE

TASK ST-2.5-A(i): COLLECT TRIGGERS

FTE-months: 0.5

Review the identification of candidate CCSNe within roughly 20 Mpc from electromagnetic observations. Work with external groups (e.g., DLT40 and AS-SSN) to determine the best estimates for the time of core collapse and nature of the progenitor.

TASK ST-2.5-A(ii): RUN A TARGETED GW SEARCH

FTE-months: 1.0

Run a targeted search for CCSN within roughly 20 Mpc with the CCSN time and sky position using dedicated pipelines (e.g., cWB [4], X-pipeline). In case of non-detection, provide an estimate of the upper limits found by the search.

TASK ST-2.5-A(iii): RUN A CCSN-SPECIFIC ALL-SKY GW SEARCH

FTE-months: 1.0

Run an all-sky search specifically targeted at CCSN waveforms. Evaluate GW candidate significances and follow-up astrophysical candidates. In case of non-detection, provide upper limits for various CCSN models.

TASK ST-2.5-A(iv): REPORTING RESULTS AND REVIEW

FTE-months: 1.0

Report progress and the final results of these searches in a timely manner. Reporting should be made within the working groups and to the burst group.

ACTIVITY ST-2.5-B-**OPS**: CCSN EXTRAORDINARY EVENT

TASK ST-2.5-B(i): FORMULATE AND IMPLEMENT A PLAN FOR AN EXTRAORDINARY DETECTION

Formulate and implement a plan to respond to a near-galactic CCSN in O4, including searches triggered by neutrino and/or electromagnetic observations.

TASK ST-2.5-B(ii): RUN THE SEARCH

FTE-months: 4.0

Run all search pipelines (including the pipelines described in ST-2.5-A(iii)) associated to the external trigger and determine its significance.

TASK ST-2.5-B(iii): PARAMETER ESTIMATION

FTE-months: 4.0

Employ parameter estimation methods to determine the CCSN parameters and possible explosion mechanism.

TASK ST-2.5-B(iv): REPORTING RESULTS AND REVIEW

FTE-months: 2.0

Report progress and the results of the search in a timely manner. Report final results. Reporting should be made within the CCSN group and to the Burst group.

TASK ST-2.5-B(v): PUBLISHING RESULTS

FTE-months: 2.0

Publish a collaboration paper reporting any signals found by the search.

ACTIVITY ST-2.5-C-**OPS**: SUBGROUP ADMINISTRATION

Management of the CCSN subgroup.

TASK ST-2.5-C(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.5 Search for GWs from core-collapse supernova R&D (long term)

ACTIVITY LT-2.5-A: DEVELOPMENT ACTIVITIES

The following are continuing developments.

TASK LT-2.5-A(i): PIPELINE DEVELOPMENT AND OPTIMIZATION

Continue to develop and optimize current pipelines for CCSN targeted or all-sky searches. Evaluate improved pipeline sensitivities.

TASK LT-2.5-A(ii): CCSN WAVEFORM DEVELOPMENT

Continue to procure and catalog CCSN waveforms and use them to develop waveform reconstruction and parameter estimation techniques for use in targeted or all-sky CCSN searches.

TASK LT-2.5-A(iii): WAVEFORM RECONSTRUCTION AND PARAMETER ESTIMATION

Develop techniques to distinguish CCSN models in search data and infer the properties of the supernova dynamics, for example parameters of the proto-neutron star.

TASK LT-2.5-A(iv): SUB-THRESHOLD NEUTRINO-GW COINCIDENT SEARCH

Develop a joint sub-threshold neutrino/GW search.

TASK LT-2.5-A(v): STATISTICAL SIGNIFICANCE OF CCSN SEARCH TRIGGERS

Develop methods to separate CCSN signals from non-astrophysical detector noise artifacts and assess the statistical significance of astrophysical candidates. Develop noise reduction techniques to increase the significance of astrophysical triggers, e.g., with signal processing or machine learning algorithms.

TASK LT-2.5-A(vi): SINGLE-INTERFEROMETER DETECTION

Develop methods for detecting CCSN with data from a single GW detector.

ST-2.6 Search for GW transients from magnetar flares and neutron star glitches

Opportunistic search for Burst or CBC signals associated with magnetar flares or timing glitches.

Motivation and methods

Violent phenomena associated with neutron stars, such as flaring activity in magnetars [44, 45, 46] and pulsar glitches, may result in the excitation of various oscillatory modes which leads to transient gravitational wave emission. The energetics involved with phenomena such as magnetar flares or pulsar glitches makes detection of an associated gravitational wave burst rather speculative with current detectors. The science pay-off, however, would be tremendous; the detection and characterization of GWs associated with neutron star oscillations holds the potential for GW neutron star asteroseismology, while neutron star oscillation mode identification and characterization leads to constraints on the equation of state.

In O3, there was exceptional magnetar-related phenomena lead to a collaboration O3 paper [47]. The first was the observation of a fast radio burst (FRB) associated with the galactic magnetar SGR 1935+2154 (see Section ST-6.3). While the FRB occurred just after the end of O3, this magnetar was active in x-ray flares earlier during O3. The second was the discovery of a young galactic magnetar J1818 in March 2020, during O3 observations.

Our goals for science deliverables are focused on the improvement of O3 GW emission upper limits [47], development of novel searches and techniques, and the deployment of morphology-independent searches, waveform reconstructions, and parameter estimation follow-ups to *extraordinary* events. Past searches targeting such events include [48, 49, 50, 51, 52]. The methods employed overlap with the long-duration burst searches (Section ST-2.2) and the GRB group (Section ST-6.2).

ACTIVITY ST-2.6-A-**OPS**: COMPLETE THE O3 PUBLICATION PROCESS

TASK ST-2.6-A(i): COMPLETE THE O3 PUBLICATION PROCESS

FTE-months: 0.1

The O3 paper has been submitted for publication. Complete the O3 publication process by responding to referees (if needed), check and return proofs.

ACTIVITY ST-2.6-B-**OPS**: PREPARE FOR AN O4 MAGNETAR SEARCH

An exceptional magnetar flare, providing for a possible GW detection or an astrophysically interesting limit, would provide motivation for a collaboration paper.

TASK ST-2.6-B(i): MONITOR FLARES DATA

FTE-months: 1.0

Monitor the reported x-ray flare activity reported by external groups such as Swift or Fermi.

TASK ST-2.6-B(ii): RUN TRIGGERED SEARCHES

FTE-months: 2.0

Run pipelines similar to those used in O3 in early O4 data to check for sensitivity and any important data quality issues.

ACTIVITY ST-2.6-C-**OPS**: O4 MAGNETAR ANALYSIS

TASK ST-2.6-C(i): CARRY OUT THE O4 ANALYSIS

FTE-months: 3.0

Carry out the triggered GW burst analyses associated with O4 x-ray magnetar flares. This is to include searches for both short and long duration GW bursts, with X-pipeline and the STAMP pipeline, respectively. This will include development of appropriate on-source and off-source windows and the stacking analysis.

TASK ST-2.6-C(ii): REPORTING RESULTS AND REVIEW

FTE-months: 2.0

Report progress and the results of these searches in a timely manner during the observing run. Report final results. Reporting should be made within the GRB group and periodically to the Burst group.

TASK ST-2.6-C(iii): PUBLISHING RESULTS

FTE-months: 2.0

If there is an extraordinary event(s) – e.g. a giant galactic flare, an associated FRB, or a very nearby ($\sim$ 1 kpc) normal flare – or a significant improvement in upper limits compared to O3, publish a collaboration paper reporting the search results.

LT-2.6 Search for GW transients from isolated neutron stars R&D (Long Term)

ACTIVITY LT-2.6-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-2.6-A(i): METHODS AND MODELING STUDIES

Continue to develop improved search and analysis methods. A new stacking search, analogous to that developed previously [49] but based on X-pipeline, is being prepared for O4. Anticipating the possibility of a GW detection from the magnetar searches, methods are being developed to characterize an observed signal in astrophysical terms. For example, we can determine if a candidate GW signal is consistent with f-mode excitations from a realistic neutron star at the location provided by the x-ray flares.

3 CBC Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst and Stochastic groups in sections 6 and 8.

ST-3.1 CBC Parameter Estimation R&D (Short Term)

Development of tools for characterizing CBC sources in terms of their parameters (short term).

Motivation and methods

The primary task of the parameter estimation (PE) group is to develop, improve, and maintain the techniques and tools necessary for characterizing compact binaries. For each detected event the PE group delivers posterior estimates for the physical characteristics of each binary, using sophisticated models available for both signal and noise. To this end, the PE group's primary research tasks are focused on developing the tools and techniques necessary to take advantage of new signal models that account for more physical effects (e.g., eccentricity, matter effects) as they become available. The group also maintains infrastructure to support tests of general relativity. The group is also working on improved noise models that will relax assumptions made about the stationarity of the detectors' noise. Finally, the group assesses the improvement in parameter inference from such models, guides gravitational-wave model developments and science cases for future gravitational-wave measurements, and informs instrument design.

Major aspects and methods for this activity

ACTIVITY ST-3.1-A-**OPS**: DEVELOPMENT OF PARAMETER ESTIMATION CODE

Incremental improvements of the parameter estimation code will be made in preparation for O4, to improve parameter estimation accuracy and performance.

TASK ST-3.1-A(i): MARGINALIZATION OVER FREQUENCY-DEPENDENT DETECTOR CALIBRATION ERRORS AND PSD UNCERTAINTIES

FTE-months: 3.0

During O1, O2 and O3 frequency-dependent but instrument-agnostic models for calibration errors were used for the purposes of marginalization, and estimates of the noise PSD computed from on-source data were used for each analysis. We plan to move toward physically motivated models for calibration errors, and to marginalize over uncertainties in the estimated noise PSDs.

TASK ST-3.1-A(ii): FASTER CONVERGENCE WITH IMPROVED SAMPLING ALGORITHMS AND PARALLELIZATION

FTE-months: 20.0

Working closely with the CBC waveform models R&D group (Sec. ST-3.4), accelerate PE convergence using a variety of methods, including reduced-order-quadrature (ROQ) techniques, heterodyning, multibanding, machine learning techniques, improvements to traditional sampling algorithms, and through the implementation and maintenance of CPU- and GPU-parallelized algorithms. One key goal is to test, review, and select an approach for very low-latency PE for use in O4.

TASK ST-3.1-A(iii): IMPROVEMENTS TO POST-PROCESSING

FTE-months: 2.0

The outputs of the post-processing routines from the PE group are now used by many scientists in and outside of the LIGO, Virgo and KAGRA collaborations. These tools are in need of 1) improvements to the presentation of critical results, 2) additional statistical tests, 3) better usability by other CBC subgroups (e.g., numerical relativity follow-ups, rates and population), 4) adaptation to the open-data era and public releases.

TASK ST-3.1-A(iv): IMPROVEMENTS TO LIBRARY INFRASTRUCTURE FTE-months: 18.0

To better facilitate the goals outlined above, we will continue to improve and maintain the code bases used by the PE group. This includes the continued migration of various libraries and functionalities from C to Python to become more development-friendly, and tighter integration of the various code bases.

TASK ST-3.1-A(v): RAPID LOCALIZATION WITH HIGHER ORDER MODES FTE-months: 2.0

Rapid localization codes, including BAYESTAR, which are designed to enable electromagnetic followup of CBC signals, will be extended to incorporate higher order multipole contributions to the gravitational-wave signal, possibly in concert with extensions to the interface between ultra-low latency codes and online search pipelines.

ACTIVITY ST-3.1-B-**OPS**: EVALUATION OF PARAMETER ESTIMATION METHODS

The PE methods will be evaluated to understand potential biases.

TASK ST-3.1-B(i): USING AND ASSESSING MORE ACCURATE WAVEFORMS FTE-months: 4.0

As more faithful waveform models and more numerical relativity simulations become available (see Sec. ST-3.4) which include and explore more physical effects (e.g., multi-modal effects, amplitude corrections, eccentricity), studies will be required to determine the impacts of the inclusion of such physical effects on PE. Studies will also be required to assess the potential for these waveform models to enable new discoveries and to achieve the scientific goals of the collaboration.

TASK ST-3.1-B(ii): BETTER MEASUREMENT OF WAVEFORM SYSTEMATIC ERRORS FTE-months: 6.0

Coordinating closely with waveform group efforts to quantify systematic errors in the waveform models to be developed for and used in O4, the PE group will continue to investigate and quantify the impact of waveform systematics on parameter estimation, especially for exceptional source classes which may be detected in O4.

TASK ST-3.1-B(iii): STUDY THE BIASES TO PE CAUSED BY NON-STATIONARY NOISE FTE-months: 2.0

Current PE analyses assume the detector noise to be stationary over intermediate timescales, 1 to 100's times the length of a detected signal. We know the noise is not always stationary on these timescales, thus we must characterize the biases introduced in parameter estimates due to this false assumption.

TASK ST-3.1-B(iv): REQUIREMENTS AND CONSTRAINTS FROM CALIBRATION UNCERTAINTY FTE-months: 2.0

The use of marginalisation over uncertanties in the data calibration connects the astrophysical and instrumental inference. Therefore, investigating what requirements on the calibration uncertanties are, for both low- and high-latency analyses, in order to ensure unbiased astrophysical PE results. This also includes accounting for potential systematic errors in the calibration. The work is to be done in coordination with the calibration groups in LIGO, Virgo and KAGRA.

ACTIVITY ST-3.1-C-**OPS**: DEPLOYMENT AND MAINTENANCE OF PARAMETER ESTIMATION CODE

Parameter estimation libraries will be deployed and maintained for both online and offline usage during O4.

TASK ST-3.1-C(i): DEPLOYMENT OF ONLINE PARAMETER ESTIMATION CODE

FTE-months: 6.0

The parameter estimation pipeline and configuration will be deployed and integrated into the low-latency infrastructure in preparation for and during O4.

TASK ST-3.1-C(ii): DEPLOYMENT OF OFFLINE PARAMETER ESTIMATION CODE

FTE-months: 6.0

The parameter estimation libraries will be maintained and deployed on collaboration computational clusters for use in preparation for and during O4.

ACTIVITY ST-3.1-D-**OPS**: PARAMETER ESTIMATION ANALYSIS, INTEGRATION AND AUTOMATION

As the number of GW event candidates increase, a greater focus on automation and standardization of the PE analysis is required.

TASK ST-3.1-D(i): AUTOMATION OF GENERATING PE CONFIGURATION FILES

FTE-months: 3.0

We will continue to develop automated methods for generating a configuration file for offline PE using inputs from searches and low-latency PE.

TASK ST-3.1-D(ii): AUTOMATION OF COLLATION OF INPUT DATA TO PE ANALYSES

FTE-months: 1.0

We will continue to ensure that the collation of additional inputs to parameter estimation is done in an automated and integrated fashion. These include PSDs, calibration uncertainty envelopes, and the appropriate frame files.

TASK ST-3.1-D(iii): AUTOMATION OF INITIALIZATION AND MONITORING OF PE ANALYSES

FTE-months: 6.0

The PE group will continue to develop and maintain methods for automatically initializing and monitoring PE analyses. This includes further development and maintenance of overview boards where ongoing analyses can be monitored.

TASK ST-3.1-D(iv): AUTOMATION OF POSTPROCESSING OF PE ANALYSES

FTE-months: 3.0

For a completed PE analysis, the group will continue to archive the finalized results in an automated, centralized, and version controlled way. The group will continue to develop and improve these procedures, and strive to make results easily accessible to all groups within the collaborations. This task also includes generation of comparisons and diagnostics of the analyses to ensure convergence of the samples, and also to avoid problematic railing against prior bounds. This is also a requirement for improvements to the overall PE review process.

ACTIVITY ST-3.1-E-**OPS**: PE WITH MATTER EFFECTS

LIGO/Virgo made the first detection of a binary neutron star (BNS) merger in 2017, with one more certain BNS detection in O3 together with two neutron star-black hole (NSBH) candidates. The detected GWs allow for novel measurements of matter effects in the binary mergers, including the neutron star equation of state. Developing good techniques for measuring these effects is an active area of research, and the most recent developments of this work need to be implemented in LIGO's Parameter Estimation code libraries. All of these activities will be carried out in close coordination with the Extreme Matter and Rates & Populations subgroups.

TASK ST-3.1-E(i): PARAMETERIZED EQUATION OF STATE ESTIMATION

FTE-months: 3.0

Implement new matter equation of state parameterizations, for example, spectral parameterizations, and incorporate them into the parameter estimation engines.

TASK ST-3.1-E(ii): NON-PARAMETRIC EQUATION OF STATE ESTIMATION

FTE-months: 3.0

Implement non-parametric methods for equation of state estimation into the parameter estimation engines.

TASK ST-3.1-E(iii): PARAMETER ESTIMATION ON MULTIPLE EVENTS

FTE-months: 1.0

Since the equation of state is believed to be universal, it can be better constrained by analyzing multiple events together. Coordinating closely with the Rates & Populations subgroup, implement and improve methods to do a multiple event equation of state estimation.

ACTIVITY ST-3.1-F-**OPS**: PARAMETER ESTIMATION REVIEW

Review of changes to parameter estimation code and deployment configuration.

TASK ST-3.1-F(i): PARAMETER ESTIMATION CODE REVIEW

FTE-months: 12.0

Review modifications to parameter estimation code.

TASK ST-3.1-F(ii): PARAMETER ESTIMATION ONLINE PIPELINE REVIEW

FTE-months: 6.0

Review of deployment, configuration, and integration of the online parameter estimation engine.

TASK ST-3.1-F(iii): PARAMETER ESTIMATION AUTOMATION REVIEW

FTE-months: 6.0

Review of pipelines which perform automated parameter estimation and postprocessing of results.

ACTIVITY ST-3.1-G-**OPS**: SUBGROUP ADMINISTRATION

Management of the Parameter Estimation subgroup.

TASK ST-3.1-G(i): SUBGROUP LEADERSHIP

FTE-months: 4.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.1 CBC Parameter Estimation R&D (Long Term)

Development of tools for characterizing CBC sources in terms of their parameters (long term).

Major aspects and methods for this activity

ACTIVITY LT-3.1-A: FASTER PE (UP TO LOW-LATENCY)

Results from stochastic samplers can often take hours to days to obtain, with the lowest-latency analyses making simplifying assumptions (e.g., spins aligned with the orbital angular momentum). We aim to reduce latency, particularly for the more physically accurate and computationally expensive waveform models (e.g., including precession effects). Development along multiple avenues for accelerating PE will continue, including improvement of parallelized sampling algorithms, ROQs, heterodyning, multibanding, and machine learning approaches.

TASK LT-3.1-A(i): INVESTIGATE FASTER PE

ACTIVITY LT-3.1-B: INVESTIGATIONS OF WAVEFORM SYSTEMATICS ON PARAMETER ESTIMATION

Coordinating closely with waveform group efforts to quantify systematic errors in the waveform models, the PE group will continue to investigate and quantify the impact of waveform systematics on parameter estimation, especially in challenging regions of parameter space

Task LT-3.1-B(i): Investigate waveform systematics on PE

Activity LT-3.1-C: Marginalisation Over Waveform Uncertainty

The systematic differences between waveform models can be incorporated in a statistical model that allows for uncertainty in the waveforms as well as in the parameter of the signal itself. This will allow us to mitigate the effect of waveform systematic errors in the estimation of source properties. This is particularly important for regions of parameter space where numerical simulations are sparse, and there is less data to calibrate waveform models.

Task LT-3.1-C(i): Marginalisation over waveform uncertainty

Activity LT-3.1-D: Analyzing Background Events

Though not an official task of the PE group, as the most rigorous stage of signal characterization, PE is often looked to for verification of a trigger's status as signal vs. noise. To better inform the collaboration on such matters, we must conduct complete studies of PE analyses of background events to better understand the behavior of posteriors and detection-related statistics (e.g., coherent vs. incoherent Bayes factor) on foreground and background. This work is coordinated with the CBC detection and search R&D group (Sec. ST-3.7).

Task LT-3.1-D(i): PE analyses of background events

Activity LT-3.1-E: Developing Fully Bayesian Searches

For many sources of GWs we expect a stochastic background, which need not be persistent or Gaussian. The use of Bayesian inference to detect a population of sub-threshold events could lead to the detection of such a stochastic background. This work is coordinated with the binary coalescence Rates and Population R&D group (Sec. ST-3.5) and the Stochastic group (Sec. 8).

Task LT-3.1-E(i): Developing Fully Bayesian Searches: PE angle

Activity LT-3.1-F: Use of Bayes Factors in Low Latency to Help Inform Detections

The production of Bayes factors, which can be useful as detection statistics, currently takes too long to be useful for decisions made in low latency. The fact that such analyses can include physical effects not accounted for in searches (e.g., precession) means that obtaining such statistics on shorter timescales could allow PE to provide crucial new information at the time of detection. This work is coordinated with the CBC detection and search R&D group (Sec. ST-3.7).

Task LT-3.1-F(i): Use of Bayes factors in low latency

Activity LT-3.1-G: Research and Development of New Techniques

We will continue to investigate the use of new algorithms or hardware-specific optimization (e.g., GPUs and/or machine learning techniques) for CBC parameter estimation, to support the desire to lower overall latency until final results are obtained, but also to allow codes to scale to increasing numbers of parameters and/or complex signal models.

Task LT-3.1-G(i): Research and development of new PE techniques

ST-3.2 Tests of General Relativity R&D (Short Term)

Short-term research and development on tests of general relativity using compact binary coalescences.

Motivation and methods

The Testing General Relativity group is primarily responsible for testing the consistency of the GW signals observed by LIGO, Virgo, and KAGRA with predictions of GR and for developing the associated data analysis infrastructure. Due to the lack of reliable waveform models in alternative theories, so far the group's primary focus has been on "null" tests, which aim to put constraints on deviations from GR predictions without assuming specific alternative theories. Several other aspects of strong gravity, such as the true nature of black holes, the possible existence of exotic compact objects are also explored within the group. Whenever possible, interpretations of our results will be given, by mapping any observational constraints derived from our analyses onto bounds on alternative models.

Major aspects and methods for this activity

ACTIVITY ST-3.2-A-**OPS**: GRAVITATIONAL-WAVE PROPERTIES

TASK ST-3.2-A(i): TESTING THE MULTIPOLAR STRUCTURE OF GRAVITATIONAL WAVES

FTE-months: 2.0

Develop methods that test the consistency of the amplitudes of different GW multipoles beyond the (l=2,m=2) mode with the predictions of general relativity for compact binaries.

TASK ST-3.2-A(ii): SEARCHES FOR NON-STANDARD POLARIZATIONS

FTE-months: 1.0

Further develop and improve model agnostic and theory-specific analyses for non-tensorial polarizations.

TASK ST-3.2-A(iii): TESTING THE PROPERTIES OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 2.0

Develop and improve analyses that will look for signs of modified GW propagation, like dispersion or birefringence related to spacetime symmetry breaking mechanisms.

TASK ST-3.2-A(iv): EXPLORING ACCELERATION EFFECTS ON GRAVITATIONAL WAVEFORM

FTE-months: 2.0

Develop analysis to look for signs of line-of-sight acceleration that a binary may undergo when coalescing in the vicinity of a massive object.

ACTIVITY ST-3.2-B-**OPS**: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Sufficiently loud signals from massive compact objects will allow us to test their immediate environments. These tests can be either 1. agnostic with respect to the progenitor, 2. inspiral-informed with respect to progenitor parameters for sampling the prior of remnant parameters, or 3. inspiral-informed with respect to the progenitor with a joint likelihood computation.

TASK ST-3.2-B(i): TESTS OF THE NATURE OF THE MERGER REMNANT

FTE-months: 6.0

Develop and improve tests of the nature of merger remnants through measurements of parametrized deviations from GR predictions on complex frequencies and cross-comparison of various modes.

TASK ST-3.2-B(ii): PROBING THE NEAR-HORIZON STRUCTURE

FTE-months: 4.0

Develop and improve searches for echoes, signs of anomalous flux or Hawking radiation and other features that probe the near-horizon structure of the merger remnant or BHs of the progenitor, using template-based and model-agnostic approaches.

ACTIVITY ST-3.2-C-**OPS**: CONSTRAINING THE PARAMETER SPACE OF VARIOUS BLACK HOLE MIMICKERS

There are theoretical proposals of exotic alternatives to black holes, which can be massive and compact enough to be confused with black holes. Several distinct signatures in the emission of gravitational waves can help distinguish between these objects and black holes, such as finite-size effects on the phase evolution, resonant excitations, etc.

TASK ST-3.2-C(i): CONSTRAINING FINITE-SIZE EFFECTS OF BLACK HOLE MIMICKERS

FTE-months: 3.0

We will be able to constrain the parameter space of some models of black hole mimickers based on measurements of the tidal deformability and spin-induced quadrupole moment, and aim to extend this analysis to include other finite-size effects.

ACTIVITY ST-3.2-D-**OPS**: INTERPRETATION OF TGR ANALYSES RESULTS AND IMPLICATIONS FOR THEORY

TASK ST-3.2-D(i): MAPPING CONSTRAINTS TO PARAMETER SPACES OF SELECTED THEORIES

FTE-months: 1.0

Identify alternative theory frameworks for which a mapping can be drawn between our observational constraints on measured parameters and the theory parameter space. Investigate the regime of validity for such mappings and combine with other observational or theoretical constraints.

ACTIVITY ST-3.2-E-**OPS**: INFRASTRUCTURE MAINTENANCE AND IMPROVEMENT

Working in close coordination with the PE and Waveforms R&D groups, we will improve our data analysis code libraries for testing GR and perform incremental upgrades to meet the state-of-the-art in performance, robustness, and automation.

TASK ST-3.2-E(i): IMPROVEMENTS TO LIBRARY INFRASTRUCTURE

FTE-months: 2.0

Improve the base code for testing-GR data analysis pipelines and bring them up to speed with PE standards. This includes integration with Python libraries, inclusion of the most sophisticated waveform models, in coordination with the Waveforms R&D group, and integration with the central CBC data management system.

TASK ST-3.2-E(ii): PACKAGING AND MAINTENANCE OF TGR PIPELINE CODES

FTE-months: 2.0

Collect TGR libraries as plugins to standard packages like Bilby, PESummary, and BayesWave, when applicable. Package and ensure streamlined installation on computing clusters, centrally managed via IGWN.

TASK ST-3.2-E(iii): PIPELINE AUTOMATION

FTE-months: 3.0

In anticipation of a much higher rate of GW detections in O4 and beyond, develop a framework to automate the processes of job submission and resubmission, monitoring, post-processing, and review for each testing-GR pipeline. This will be done in line with the best practices adopted by the PE R&D group and the CBC group at large.

ACTIVITY ST-3.2-F-**OPS**: MOCK DATA CHALLENGES AND ANALYSIS READINESS FOR O4

TASK ST-3.2-F(i): GLITCH MOCK DATA CHALLENGE

FTE-months: 4.0

Set up and run campaigns on sets of simulated signals overlapping with different types of glitches. Examine the different TGR pipelines' ability to distinguish between the presence of a glitch or a violation of GR in the data and their response to different types of glitches and glitch-removal/data-cleaning processes.

TASK ST-3.2-F(ii): WAVEFORM SYSTEMATICS MOCK DATA CHALLENGE FTE-months: 4.0

Set up and run campaigns on sets of simulated signals generated using waveform models that incorporate different physics (precession, higher harmonics) and assess the response of TGR analyses.

TASK ST-3.2-F(iii): MOCK DATA CHALLENGE ON GR-VIOLATING SIGNALS FTE-months: 4.0

Set up and run campaigns of analyses on a diverse, selected set of simulated GR-violating signals. Examine impact on detectability by search pipelines.

TASK ST-3.2-F(iv): REVIEW OF NEW PIPELINES FTE-months: 14.0

Participate in the review of the implementation of TGR pipelines destined to run in O4a and/or O4b. A final readiness test will be performed for each candidate pipeline that will run on O4 data.

ACTIVITY ST-3.2-G-**OPS**: COMBINING CONSTRAINTS FROM MULTIPLE EVENTS

Several of the tests described in this section can benefit from the combination of the observed data coming from different GW events and electromagnetic counterparts, thus leading to stronger constraints. In most cases however, there is not a single statistically robust way of doing so. We will explore Bayesian methods such as hierarchical or nonparametric models to establish the optimal way of combining information for each test of GR.

TASK ST-3.2-G(i): COMBINING TGR CONSTRAINTS FROM MULTIPLE EVENTS FTE-months: 2.0

ACTIVITY ST-3.2-H-**OPS**: SUBGROUP ADMINISTRATION

Management of the Testing General Relativity subgroup.

TASK ST-3.2-H(i): SUBGROUP LEADERSHIP FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.2 Tests of General Relativity R&D (Long Term)

Long-term research and development on tests of general relativity using compact binary coalescences.

Major aspects and methods for this activity

We will develop methods to perform the following tests of general relativity and assessment of systematics.

ACTIVITY LT-3.2-A: CHARACTERIZATION OF WAVEFORM SYSTEMATICS

Missing physics, including eccentricity, higher-order modes, spin precession, black-hole charge, and non-vacuum environments, have the ability to mimic deviations of GR. A systematic exploration of the impact of inaccuracies and missing physics in waveform templates on various tests of GR will be conducted.

TASK LT-3.2-A(i): CHARACTERIZATION OF WAVEFORM SYSTEMATICS FOR TGR

ACTIVITY LT-3.2-B: IMPROVEMENTS OF ANALYSIS ON RESIDUALS

TASK LT-3.2-B(i): IDENTIFYING DEVIATIONS FROM GR BY CORRELATING RESIDUALS

Develop a method for detecting and characterizing deviations from GR (or systematic effects) by projecting cross-correlated residuals onto templates.

ACTIVITY LT-3.2-C: IMPROVEMENT OF ANALYSIS PIPELINES AND THEIR PERFORMANCE

TASK LT-3.2-C(i): SPEED-UP USING REDUCED-ORDER-QUADRATURE METHODS

TASK LT-3.2-C(ii): SPEED-UP USING MULTIBANDING METHODS

TASK LT-3.2-C(iii): SPEED-UP USING MACHINE-LEARNING TECHNIQUES

ACTIVITY LT-3.2-D: BEYOND-GR EFFECTS ON THE GW WAVEFORM AND TESTS OF GR

Effects beyond GR will manifest themselves in all stages of the gravitational waveform, including the inspiral, merger, ringdown, and possible echoes. Different tests of GR will respond differently to different classes of effects. We will explore models of beyond-GR effects on the GW waveform and tests of GR, including those motivated by general classes of modified theories (e.g. described by an effective-field-theory framework).

TASK LT-3.2-D(i): BEYOND-GR EFFECTS ON GW WAVEFORM AND TGR

ACTIVITY LT-3.2-E: INTERACTION WITH ADJACENT WORKING GROUPS

TASK LT-3.2-E(i): WAVEFORMS

Continuously liaise with the Waveforms group to keep the TGR pipelines up to date with the most state-of-the-art waveform models available in terms of accuracy and features.

TASK LT-3.2-E(ii): CONTINUOUS WAVES

Explore potential for collaborations on tests of GR, such as searches for non-tensorial polarizations.

TASK LT-3.2-E(iii): STOCHASTIC

Explore potential for collaborations on tests of GR, such as searches for non-tensorial polarizations.

TASK LT-3.2-E(iv): COSMOLOGY

Collaborate on analyses for which there is common scope and expertise, such as modified propagation at cosmological distances (e.g., cases where there is both dispersion and a modification to the luminosity distance) and tests of ΛCDM cosmology with bright or dark sirens.

TASK LT-3.2-E(v): GRAVITATIONAL LENSING

Develop model agnostic and theory-specific analyses to test for the gravitational-wave polarization and massive gravity with strongly lensed gravitational waves.

TASK LT-3.2-E(vi): RATES AND POPULATIONS

Transfer of knowledge regarding expected event rates, detection rates, and impact of GR-violating features on the latter. Set-up of realistic injection datasets for MDCs that will inform our decisions on setting our selection criteria for TGR pipelines.

ST-3.3 Studies of Extreme Matter R&D (Short Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures.

Motivation and goals

An outstanding issue in nuclear physics is the unknown equation of state (EOS) of neutron-star matter. This has two impacts on gravitational-wave science: First, we must understand (and address) any impact the presence of matter may have on statements from CBC searches and parameter estimation. Second, using both CBC and Burst methods, we hope to learn about the equation of state of matter at extreme densities from LIGO/Virgo detections.

The detection and parameter estimation of binary neutron star (BNS)/neutron star black hole binary (NSBH) systems employ templates that include the late stages of inspiral, where neutron stars will be tidally deformed and possibly even tidally disrupted. The extent of this deformation is highly dependent on the mass of the star and the EOS of the nuclear matter inside the neutron star, so measuring the tidal parameters of the merging binary will constrain the EOS. In certain BNS scenarios—such as extremely large-radius stars or nonlinear couplings—these tidal interactions may also lead to the loss of signals if they are not incorporated into CBC searches.

Measurement of tidal parameters is immediately possible with post-Newtonian waveforms, however systematic errors are large and will limit the strength of the statements LIGO/Virgo can make. The ability to measure matter effects is constrained by the accuracy and speed of inspiral waveforms. Avenues for improvement include improved waveform models and high-frequency follow-up parameter estimation with numerical simulations. Improvements in EOS constraint may also result from optimally combining information from multiple detections, or from constraining equation-of-state parameters directly.

Astrophysical gravitational waves will also include the merger and high-frequency post-merger, which will be challenging for current-generation detectors to measure but carry additional information about neutron-star matter. Burst follow-up of CBC detections is needed to confirm or constrain the presence or absence of these post-merger signals and measure their properties. Data analysis methods that span the inspiral to post-merger stage of BNS events would strengthen overall statements about the EOS.

Multiple BNS/BHNS detections, giving a distribution of measured masses and/or coincident gravitational-wave and electromagnetic counterpart detections, are in themselves relevant for equation of state constraints. In particular, large measured NS masses could constrain more exotic forms of nuclear matter. Any signature of matter in an observed compact binary merger could also confirm whether one component object is a neutron star instead of a black hole. Therefore, tidal parameter measurement within CBC, identification of electromagnetic counterparts, and burst follow-up results can inform rates and population statements about the categories of observed mergers.

Major aspects and methods for this activity

ACTIVITY ST-3.3-A-**OPS**: SUBGROUP ADMINISTRATION

Management of the Extreme Matter subgroup.

TASK ST-3.3-A(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

TASK ST-3.3-A(ii): EDITORIAL TEAM LEADERSHIP AND PAPER MANAGEMENT

FTE-months: 2.0

Administrative and managerial tasks associated with collaboration papers led by the Extreme Matter subgroup.

ACTIVITY ST-3.3-B-**OPS**: CODE DEVELOPMENT AND DEPLOYMENT FOR O4 MATTER ANALYSES

Extension, maintenance and implementation of the infrastructure for matter-related studies during O4.

TASK ST-3.3-B(i): MATTER-RELATED PARAMETER ESTIMATION

FTE-months: 36.0

With the transition from LALInference to bilby, it is essential to ensure the availability of matter-related pipelines for O4. Maintenance and modernization of infrastructure, algorithms, and code are continuously required as short-term goals. Necessary studies include among others: the usability of accurate TOV solvers for astrophysical results, methods for tidal parameter estimation, a working infrastructure for spectral and piecewise-polytropic EOS inference, the inference of non-linear tidal effects, and rapid inferencing infrastructure for combining multiple events with and without multi-messenger observations to constrain the equation of state.

TASK ST-3.3-B(ii): EOS INFRASTRUCTURE

FTE-months: 12.0

Extension of the available EOS infrastructure and table database. Revisiting the accuracy of existing EOS tables. Updating and maintaining the EOS constraint information derived from GW and external observations for use across LVK subgroups.

TASK ST-3.3-B(iii): CONSTRAINTS ON RADII, EOS AND REMNANT PROPERTIES

FTE-months: 24.0

Development, maintenance and deployment of infrastructure for matter analyses that are downstream from parameter estimation. Critical analyses include among others: generation of radius constraints, a working infrastructure for non-parametric EOS inference, inferences of ejecta and the fate of the remnant.

TASK ST-3.3-B(iv): PAPER WRITING AND CURATION OF DATA PRODUCTS

FTE-months: 12.0

Contributions to the writing of collaboration papers with Extreme Matter subgroup involvement. Development and implementation of standardized formats for Extreme Matter data releases. Curation of data products to ensure they are easily accesible and usable for public release.

ACTIVITY ST-3.3-C-**OPS**: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The tools and results produced by the extreme matter group depend on and can influence the research direction of other groups and projects.

TASK ST-3.3-C(i): IMPACT OF EOS ON ALERTS

FTE-months: 6.0

Coordinating with the low-latency subgroup to inform rapid classification and EM bright statements with up-to-date information about neutron star properties.

TASK ST-3.3-C(ii): IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE

FTE-months: 6.0

Coordinating with the waveform and parameter estimation groups to quantify the impact of model systematics on EOS constraints.

TASK ST-3.3-C(iii): EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS

FTE-months: 6.0

Coordinating with the parameter estimation and rates and population groups for source classification, prior assumptions, and joint EOS and population inferences (see also Task **??**). EOS inference is influenced by population assumptions, in particular when multiple signals are considered.

TASK ST-3.3-C(iv): EOS DEGENERACY WITH TESTS OF GR

FTE-months: 2.0

Providing knowledge about EOS information to quantify degeneracies between modifications to GR and uncertain neutron star EOS properties.

LT-3.3 Studies of Extreme Matter R&D (Long Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures (long term).

Major aspects and methods for this activity

ACTIVITY LT-3.3-A: SYSTEMATIC ERROR ASSESSMENT

Statements about tidal parameters are limited by uncertainties in the waveform evolution. Waveform injection and parameter estimation studies will be performed to assess the systematic errors in the measured tidal parameters. These studies will explore the impact of differences in waveform model, spin priors, and calibration errors.

TASK LT-3.3-A(i): SYSTEMATIC ERROR ASSESSMENT FOR EXTREME MATTER

ACTIVITY LT-3.3-B: WAVEFORM DEVELOPMENT AND COMPARISON

The ability to measure tidal parameters is limited by uncertainties in both point-particle and matter-dependent contributions to the waveform evolution. A detailed analysis of the differences between state-of-the-art waveforms for systems with tides, as well as differences with numerical simulations, is required to inform the waveform development outlined in ST-3.4.

Inspiral waveforms for compact binary coalescences involving beyond-standard-model matter effects (e.g. massive scalar fields, axions) or exotic compact objects (e.g. boson stars) will be developed to constrain dark matter candidates and non-GR matter interactions.

TASK LT-3.3-B(i): WAVEFORM DEVELOPMENT AND COMPARISON FOR EXTREME MATTER

ACTIVITY LT-3.3-C: RAPID ANALYSIS METHODS

Parameter estimation for systems containing neutron stars is not possible for some of the currently implemented tidal effective one body models due to their long evaluation time. Improvements such as surrogate waveform models for the aligned spin waveforms with tidal interactions will be produced.

TASK LT-3.3-C(i): RAPID ANALYSIS METHODS FOR EXTREME MATTER

ACTIVITY LT-3.3-D: BNS POST-MERGER REMNANT AND SIGNAL PROPERTIES

A number of modeled and unmodeled data analysis techniques for constraining the energetics and spectral content of BNS postmerger signals have been proposed and some applied to GW170817. The efficacy and optimization of such methods will be studied further using numerical simulations of BNS mergers. Techniques to combine information from pre- and post-merger observations, as well as combining measurements from multiple events (i.e., “stacking”) will be developed. Further detector characterization studies will be pursued in an effort to improve high frequency instrumental sensitivity and to refine and optimize analyses of high frequency data.

Studies will be performed to investigate whether the post-merger waveform associated with the NS resulting from the merger event in the presence of massive scalar fields can provide further constraints on both the axion field and the nuclear equation of state.

Development of waveform models for the post-merger can also be used to complement the inspiral, working towards obtaining a unified inspiral-merger-postmerger model.

TASK LT-3.3-D(i): BNS POST-MERGER REMNANT AND SIGNAL PROPERTIES

ACTIVITY LT-3.3-E: RESONANT MODE IMPLICATIONS FOR NEUTRON STAR COALESCENCES

Various mode excitations through the inspiral to merger of neutron stars provide useful modeling frameworks and astrophysical implications. This include p-g mode instabilities in inspiral, resonant r-mode excitations, and approach to f-mode in the final stages of merger. Methods for identifying the presence and significance of such energy transfers will be developed.

TASK LT-3.3-E(i): RESONANT MODE IMPLICATIONS FOR NS COALESCENCES

ACTIVITY LT-3.3-F: MULTI-SIGNAL UNDERSTANDING OF COMMON CHARACTERISTICS

As a population of neutron-star signals is revealed, methods for usefully combining the information from a full catalog to learn about the underlying physics of dense matter will be developed and implemented.

Methods for identifying effective EOS variability in the population, e.g. due to accumulation of particle dark matter or a subpopulation of exotic compact objects, will be developed.

TASK LT-3.3-F(i): MULTI-SIGNAL UNDERSTANDING OF CHARACTERISTICS OF DENSE MATTER

ACTIVITY LT-3.3-G: CONNECTIONS WITH NUCLEAR PHYSICS AND HIGH-ENERGY ASTROPHYSICS

Extreme matter constraints also stem from investigations of terrestrial nuclear physics experiments, nuclear and QCD theory, and other astronomical observations of neutron stars. LIGO/Virgo analyses will continually need updating to incorporate state-of-the-art methods and models from these fields; for example new equation of state models and constraints and observations of neutron stars used to set our priors.

TASK LT-3.3-G(i): CONNECTIONS WITH NUCLEAR PHYSICS AND HIGH-ENERGY ASTROPHYSICS

ST-3.4 CBC Waveform Models R&D (Short Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (short term).

Motivation and methods

The waveforms group aims to provide the collaboration with waveform models for template-based analyses of gravitational wave events, most importantly for compact binary coalescence events. Our long-term vision foresees waveform models which include all physical effects that may influence our GW analyses, and which can be evaluated sufficiently quickly for all GW-analysis purposes. Furthermore, we strive to quantify errors that arise from model approximations and from neglected physical effects. These goals require a combination of analytical and numerical modeling of CBC waveforms, as well as acceleration techniques to speed up evaluation of waveform models.

Major aspects and methods for this activity

The following activities are critical for generating O4 results.

ACTIVITY ST-3.4-A-**OPS**: NEW WAVEFORM MODELS

Improve / add waveform models expanding parameter ranges or introducing new physics.

TASK ST-3.4-A(i): IMPROVE BH-BH WAVEFORM MODELS

FTE-months: 36.0

Waveform models for BBH systems that include the effects of precession and sub-dominant multipoles have been developed, implemented and reviewed in collaboration code. We aim to further develop BBH models, delivering improvements in terms of accuracy, physical content and computational efficiency. This may include the development of new models as well as the refinement of existing models, e.g., through a re-calibration of IMR waveforms to larger NR data sets. A particular focus will be the parameter space of high mass ratios.

TASK ST-3.4-A(ii): IMPROVE NS-NS WAVEFORM MODELS

FTE-months: 36.0

This includes improved modelling of BNS tidal and spin effects by comparison to numerical relativity simulations or improved analytical understanding, as well as modelling sub-dominant multipoles. We aim to develop models that include as many of these effects as possible.

TASK ST-3.4-A(iii): IMPROVE BH-NS WAVEFORM MODELS

FTE-months: 36.0

This includes improved modelling on NS tidal and spin effects, improved modelling of sub-dominant multipoles and the accurate modelling of the merger/disruption of the NS. We aim to develop models that include as many of these effects as possible.

TASK ST-3.4-A(iv): INCLUDE ECCENTRICITY IN BH-BH WAVEFORM MODELS

FTE-months: 36.0

Eccentric waveform models are required to quantify search sensitivity, and to estimate or bound the eccentricity of observed CBC events. We aim to have an IMR model for BH-BH systems with moderate eccentricity and aligned spins implemented in LAL and reviewed by O4. Further work will address effects of spin precession and subdominant modes on eccentric IMR waveforms.

TASK ST-3.4-A(v): IMPROVED NR-CALIBRATED FITS FOR SPECIFIC BH-BH, BH-NS AND NS-NS PROPERTIES

FTE-months: 24.0

In addition to full waveform models, there is continued need in parameter estimation and testing-GR applications for more accurate and general NR-calibrated fits for BBH properties such as final mass, final spin, radiated energy, kicks, peak luminosity and frequency. New developments can include both conventional fits and surrogate models, with a particular focus on the full precessing parameter space.

We also aim to implement in LAL accurate NR-calibrated fits for tidally interacting binaries that include the remnant black hole mass and spin, radiated energy, peak luminosity and postmerger frequencies fits.

TASK ST-3.4-A(vi): EXPAND THE NR WAVEFORM CATALOG AS BASELINE DATA FOR A VARIETY OF WAVEFORM/PE/TESTINGGR/BURST PROJECTS

FTE-months: 12.0

For BBH: Convert to LVC-NR format and add to the LVC-NR repository additional BBH waveforms. Of particular priority are NR waveforms with validated sub-dominant modes of sufficient accuracy even at high SNR; eccentric simulations; simulations at sparsely explored regions of high mass-ratio, high spin or both; long simulations to validate transition to analytical inspiral waveforms; and detailed coverage of merger/ringdown for high-mass systems. We also plan to expand simulation coverage supporting comparisons of GW measurements directly to the NR waveform catalog, without the need for an intermediary model.

For BH-NS, NS-NS systems: Convert to LVC-NR format and add to the LVC-NR repository waveforms for BH-NS and NS-NS systems which are either publicly available, or contributed by NR groups.

ACTIVITY ST-3.4-B-**OPS**: EVALUATION OF WAVEFORM MODELS

TASK ST-3.4-B(i): IMPROVE UNDERSTANDING OF WAVEFORM MODEL ERRORS AND ATTENDANT SYSTEMATICS

FTE-months: 6.0

Improve understanding of waveform model errors and attendant systematics by cross-comparisons between different waveform models and numerical relativity simulations. In particular at significantly unequal mass-ratios and/or high spins, and also paying attention to sub-dominant modes.

ACTIVITY ST-3.4-C-**OPS**: ALGORITHMIC AND COMPUTATIONAL IMPROVEMENTS TO WAVEFORM MODELS

TASK ST-3.4-C(i): OPTIMIZATIONS OF IMPORTANT WAVEFORM MODELS

FTE-months: 12.0

The evaluation time of waveform models needs to be low enough to i) be used in parameter estimation of long signals, ii) be run multiple times on the same event to study the impact of analysis hyperparameters, and finally iii) to cope with the large number of events expected.

We will pursue methods to speed up existing waveform models, e.g., through the use of surrogate/reduced-order-modelling or the reduced-order-quadrature method.

ACTIVITY ST-3.4-D-**OPS**: WAVEFORM REVIEW

TASK ST-3.4-D(i): REVIEWS OF WAVEFORM CODE

FTE-months: 36.0

Review of implementation of waveform models, including code review, correctness of results across domain of applicability, and conformance to waveform conventions.

ACTIVITY ST-3.4-E-**OPS**: CODE MAINTENANCE AND INFRASTRUCTURE IMPROVEMENT

TASK ST-3.4-E(i): LALSIMULATION CODE MAINTENANCE

FTE-months: 6.0

Rapid response to LALSimulation bug fixes, code changes and feature requests that are required to carry out the Collaboration's science tasks. Maintenance of LALSimulation code interfaces with common file formats. Maintenance and development of spin evolution codes, including both PN and EOB evolutions.

TASK ST-3.4-E(ii): IMPROVEMENT OF COMMON INFRASTRUCTURE

FTE-months: 10.0

Examples: Development of common waveform tools, e.g., to aid in waveform reviews. Standardized waveform conventions across models. Increase support for eccentric waveforms, e.g., in the numerical relativity injection infrastructure.

TASK ST-3.4-E(iii): SUPPORT FOR EXTERNAL CODES AND PYTHON INFRASTRUCTURE

FTE-months: -

Draft, implement and review new waveforms interface that will help integrate Python-based model development for O4. Strengthen support for existing external codes (e.g., gwsurrogate).

ACTIVITY ST-3.4-F-**OPS**: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The Waveforms group is often required to produce recommendations for preferred waveform models or to produce statements regarding waveform systematics. We list projects within the scope of the Waveforms group that have impact on and overlap with other R&D groups.

TASK ST-3.4-F(i): IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE AND POPULATION STUDIES

FTE-months: 3.0

Coordinating with both the Parameter Estimation and R&P groups to assess impact of waveform systematics on parameter estimation and population inference. This task includes event specific systematics studies, recommendations for preferred waveform models and studies in support of catalog and exceptional event papers.

ACTIVITY ST-3.4-G-**OPS**: SUBGROUP ADMINISTRATION

Management of the Waveforms subgroup.

TASK ST-3.4-G(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.4 CBC Waveform Models R&D (Long Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (long term).

Motivation and methods

Our ultimate goal is a plurality of waveform models for systems which may include precession, eccentricity and matter effects all together. Specific aspects toward this ultimate goal are articulated in the major aspects for this activity (below).

Major aspects and methods for this activity

ACTIVITY LT-3.4-A: ECCENTRIC WAVEFORM MODELS FOR CBC SYSTEMS: PRECESSION, SUB-DOMINANT MODES, TIDAL EFFECTS, OPTIMIZATION, SPIN EVOLUTION

Include effects of spin-precession, sub-dominant modes and matter in the development of signal models for binary coalescence with orbital eccentricity (BH-BH, NS-NS and NS-BH systems). Improve evaluation speed of eccentric waveform models. Incorporate eccentricity into spin evolution codes.

TASK LT-3.4-A(i): ECCENTRIC WAVEFORM MODELS FOR CBC SYSTEMS

ACTIVITY LT-3.4-B: WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

Develop waveform models for hyperbolic and parabolic encounters.

TASK LT-3.4-B(i): WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

ACTIVITY LT-3.4-C: ACCURATE AND LONG NUMERICAL RELATIVITY SIMULATIONS

Perform numerical relativity simulations for all types of CBC systems with sufficient accuracy and length to quantify waveform modeling errors at sensitivities of future GW detectors.

TASK LT-3.4-C(i): PERFORM ACCURATE AND LONG NR SIMULATIONS

ACTIVITY LT-3.4-D: INVESTIGATE APPLICATION OF NEW MATHEMATICAL TOOLS TO WAVEFORM MODELING

Exploration of novel methods that may lead to the development of models that include more physical effects, or that may significantly speed up existing waveform models, but do not necessarily lead to deliverable waveforms in the short term.

TASK LT-3.4-D(i): INVESTIGATE NEW MATHEMATICAL TOOLS FOR WAVEFORM MODELING

ACTIVITY LT-3.4-E: CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS

Cross-validation between different NR codes for BH-BH, NS-NS and BH-NS systems to assess the accuracy and reliability of NR waveforms to confirm NR waveforms are of sufficient quality for their use in studies as varied as search-efficiency, parameter recovery bias, and waveform model development.

TASK LT-3.4-E(i): CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS

ACTIVITY LT-3.4-F: CONTINUE PER-EVENT NR FOLLOW-UP AS NEEDED

Improve the accuracy of observational statements and/or test systematic biases using NR simulations in response to suitable detection candidates. Develop and improve NR follow-up methods.

TASK LT-3.4-F(i): PER-EVENT NR FOLLOW-UP TO DETECTION CANDIDATES

ST-3.5 Binary Coalescence Rates and Population R&D (Short Term)

Estimate the astrophysical rates of various classes of compact binary coalescences, characterize their population properties via both parameterized models and unmodeled methods, with the objective to uncover features of their astrophysical formation and evolution.

Motivation and methods

The objective of Rates and Population analysis is to infer the astrophysical merger rate (mergers per time per comoving volume) of compact binary systems and their population distribution using the outputs of all-sky searches and individual event parameter estimation analyses. Populations are presently defined over the spaces of binary masses, spin geometry, and redshifts. Inference of the compact binary population is performed by defining models of the underlying population, and then measuring the parameters of these models via comparison against the outputs of CBC and Burst Group searches and parameter estimation.

Binary merger events can be astrophysically classified as binary black hole (BBH), BNS, and NSBH, each of which are currently observed with a non-zero event rate. The limits or boundaries between these categories are not precisely defined a priori, and may be adjusted based on future observations. These categories are furthermore not exhaustive; additional theorized classes include intermediate mass black hole (IMBH) and sub-solar-mass binaries. No sub-solar-mass candidates have been identified to date, however, and although the source of GW190521 could include an IMBH component, this event appears consistent with the bulk BBH population.

The rates and ensemble properties within each category offer information about the range of astrophysical processes governing compact binary evolution. As the binary merger census expands in number and cosmological reach, an increasing number of population features are becoming observationally accessible, in turn offering more powerful observational constraints on astrophysical binary evolution. With several hundred events, we may aim to resolve distinct compact binary sub-populations, probe correlations between binary masses, spins, and redshifts, and determine details concerning the origin of compact binary progenitors.

In addition to the interfacing with CBC and Burst searches and parameter estimation, and with other subgroups studying individual binary mergers (CBC Waveforms, CBC Extreme Matter), we also expect Rates and Population activities to influence the structure of future search catalogs and associated data products, both as downstream users of these data products as inputs to population analyses and as a provider of upstream astrophysical information (such as refined definitions of source categorizations). Rates and Populations work will further interface with other science groups leveraging the ensemble properties of compact binaries. The Stochastic Group, for example, uses the output of Rates and Populations analyses to estimate the unresolved gravitational-wave background; stochastic searches can also provide independent constraints on the rate of high-redshift binary mergers.

Major aspects and methods for this activity

ACTIVITY ST-3.5-A-**OPS**: MEASUREMENT OF SEARCH SENSITIVITY TO BINARY POPULATIONS

Develop and maintain methods to efficiently measure the sensitivity of searches over the network of interferometers to a broad range of possible CBC populations, delineated by source parameters, redshift, and/or non-GR modifications; integrate such estimates with population inference codes, and ensure they achieve the accuracy required for science goals; publish associated data products for both internal LVK and external consumers. The main estimation methods are Monte Carlo via direct injection of simulated signals into real data, to be searched with all-sky pipelines, which fully accounts for non-ideal features in the data and in search methods; or, 'semi-analytic' via synthetic injections, with expected SNR used as a proxy for detection probability.

TASK ST-3.5-A(i): SIMULATED SIGNAL CAMPAIGNS

FTE-months: 4.0

Decide on distributions of simulated CBCs to cover the relevant binary parameter spaces and create simulation sets, specifying sufficiently accurate waveforms to measure selection effects with accuracy comparable to (or better than) other statistical and systematic errors affecting population analysis. Create and curate data products resulting from analyzing simulations with search pipelines.

TASK ST-3.5-A(ii): LOW-LATENCY SIMULATED SIGNAL CAMPAIGNS

FTE-months: 2.0

Investigate production of simulated signal campaigns for low-latency searches. The distributions should closely mimic the distributions produced for the final population analyses. The injections sets should be available before the data taking so they can be analyzed in real time.

TASK ST-3.5-A(iii): ONLINE & SEMI-ANALYTIC SENSITIVITY ESTIMATION

FTE-months: 3.0

For preliminary investigation of population features and checks on intrinsic rates, a rolling estimate of current integrated sensitivity over the O4 run, accounting for the variability of detector and network sensitivity over time, is desirable. Implement and test such a low/medium latency estimate, likely based on semi-analytic synthetic injections. Quantify and correct for the biases of semi-analytic estimates by calibrating/regressing against the outputs of full large-scale injection runs from the previous task.

TASK ST-3.5-A(iv): INTERFACE WITH POPULATION INFERENCE

FTE-months: 2.0

Any method designed to measure sensitivity to specific populations must be integrated into analyses which require selection function estimates over binary source parameters and/or population hyperparameters. This interface may require additional fitting, resampling or reweighting steps which must be computationally efficient without introducing unwanted biases. Various machine learning methods may be applicable.

ACTIVITY ST-3.5-B-**OPS**: PARAMETRIC AND NON-PARAMETRIC MERGER RATE ESTIMATION

TASK ST-3.5-B(i): SIGNIFICANCE ESTIMATION USING MODELLED BINARY POPULATIONS

FTE-months: 3.0

For known (fixed) source populations, astrophysically-informed significance estimates of signal candidates may be derived directly from the outputs of search pipelines via a signal-noise mixture model [53], using the results of injection campaigns (reweighted if appropriate) to estimate the signal distribution and the search sensitivity. For classes of event with no clear detections, rate upper limits for given populations may be set via a simpler method [54]. Maintain and update such methods to account for refinements in search pipelines and target populations, including intermediate mass and sub-solar mass black hole populations. The impact of population uncertainty on rate may be partly incorporated by evaluating the effect on search sensitivity, however see Task ST-3.5-D(v) for a more complete treatment.

TASK ST-3.5-B(ii): NON-PARAMETRIC RATE ESTIMATES

FTE-months: 3.0

For source classes with a small number of detected events, typically up to 3, non-parametric methods based on the measured parameters of the events [55] are used to provide alternative data-driven rate estimates. Implementation requires targeted evaluation of the search sensitivity using event parameter samples, plus calibration to large-scale injection campaigns. Application to intermediate-mass and sub-solar mass black hole binaries if appropriate.

ACTIVITY ST-3.5-C-**OPS**: POPULATION ASTROPHYSICS

As compact binary catalogs grow in size and scope, we will perform increasingly detailed studies targeting finer phenomenological details of the compact binary population, and/or linking these details to underlying astrophysical phenomena and evolutionary mechanisms.

TASK ST-3.5-C(i): MASS DISTRIBUTION MODELS

FTE-months: 8.0

Develop and refine models describing the masses of merging binaries, either descriptive or connected to various possible formation channels. Continue to extend existing single-component modeling of BBH to multiple components / mixtures, with inclusion of more physical content in models as appropriate. Extend the modelling framework to include possible intermediate-mass and sub-solar mass black hole components, as well as primordial black hole components with cosmologically motivated distributions.

TASK ST-3.5-C(ii): SPIN DISTRIBUTION MODELS

FTE-months: 8.0

Develop and refine models describing the spin geometry of merging binaries (targeting either component spins or phenomenological effective spin parameters) and apply results of model inference to distinguish formation scenarios.

TASK ST-3.5-C(iii): REDSHIFT EVOLUTION AND SPATIAL DEPENDENCE OF MERGER POPULATION

FTE-months: 4.0

Develop and refine models to infer the dependence of the binary merger rate and ensemble properties (e.g. masses and spins) on redshift. Implement methods to measure or place limits on potential anisotropies in the merger distribution.

TASK ST-3.5-C(iv): INFERENCE ON ASTROPHYSICALLY MOTIVATED POPULATION PROPERTIES FTE-months: 4.0

Identify features in mass / spin / redshift-dependent event distributions which arise from astrophysical processes. Interpretation and inference on these within the framework of phenomenological and physically motivated models in the literature.

ACTIVITY ST-3.5-D-**OPS**: COMMON CODE AND DATA PRODUCT PLATFORM DEVELOPMENT

To support the ongoing and future activities of the R&P group, we will continue to develop a common set of codes and data product formats. Several of these codes will also benefit from a single source of information needed by inference codes, such as event sample ingestion and computation of detection selection effects and surveyed volume. In the longer term we may benefit from integration of codebases using similar methods (notably, hierarchical population inference) into a single pipeline.

TASK ST-3.5-D(i): HIERARCHICAL INFERENCE FOR PARAMETERIZED MODELS FTE-months: 6.0

Maintain and optimize codebases for Bayesian hierarchical inference on population model hyperparameters using MCMC or other sampling methods. Extend the inference framework to include mixture models and address resulting issues of priors and sampling.

TASK ST-3.5-D(ii): INFERENCE ON NON-PARAMETRIC MODELS FTE-months: 6.0

Maintain and extend methods for non-parametric models to explore features of the binary merger population without imposing physically motivated functional forms (e.g. binned mass/spin models, spline/KDE, Gaussian mixture).

TASK ST-3.5-D(iii): MODEL CHECKING AND OUTLIER IDENTIFICATION FTE-months: 3.0

Maintain and refine methods for checking consistency of modeled populations with actual recovered detection sets (e.g. posterior population checks, cumulative distribution tests) and for detecting possible population outliers, i.e. events apparently inconsistent with current models.

TASK ST-3.5-D(iv): MID-LATENCY POPULATION UPDATES FTE-months: 4.0

In order to identify exceptional events at/beyond the boundaries of known populations, spot significant emerging population features and enable preliminary exploration of astrophysical implications, we will periodically update inferences during observing runs using current population models. Maintain infrastructure to collect preliminary search sensitivity and parameter estimation outputs on a few-week cadence, and to update population inferences for masses, spins, rates and redshift evolution.

TASK ST-3.5-D(v): INCLUSION OF MARGINAL EVENTS IN RATE/POPULATION INFERENCE FTE-months: 4.0

Implement and refine methods to quantify and account for noise event contamination in population inferences by leveraging search pipeline estimates of background event distributions. For rate estimation this corresponds to existing two- or more-component Poisson mixture methods.

TASK ST-3.5-D(vi): CURATION OF DATA PRODUCTS FTE-months: 4.0

Develop and implement standardized formats for R&P analyses. This includes infrastructure for ingesting standardized data produced by parameter estimation (see Task ST-3.1-D(iv)), as well as the production and curation of standardized output files containing the results of population analyses. Ensure that data products are easily accessible and usable for public release.

ACTIVITY ST-3.5-E-**OPS**: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The tools and results produced by the R&P group are dependent on, and can influence the development of other groups and projects. We list tasks carried out primarily by other groups where R&P input is required either for science motivation or technical requirements and support.

TASK ST-3.5-E(i): RATE/POPULATION INPUTS TO CLASSIFICATION OF SEARCH EVENTS

FTE-months: 2.0

All-sky search pipelines will produce estimates of terrestrial origin and astrophysical source origin, for candidates seen both in low latency and in searches of archival data for catalog publication. These estimates may be based on specific assumed models of CBC merger rates and source distributions. The R&P group will liaise and advise on such assumptions. Such 'population prior' models may also be incorporated into search ranking statistics and significance estimates, where the CBC All Sky Search group is responsible for detailed implementation.

TASK ST-3.5-E(ii): LIAISON ON SIMULATION CAMPAIGNS

FTE-months: 2.0

Carrying out large-scale injection campaigns requires consultation with the CBC Waveforms and All Sky Search groups, as well as with project (paper writing) teams, to determine technical requirements and limitations bearing on the accuracy and deployment of the injections.

TASK ST-3.5-E(iii): ROLE OF WAVEFORM SYSTEMATICS IN RATE/POPULATION INFERENCE

FTE-months: 1.0

Coordinating with the CBC Waveform and Parameter Estimation groups to assess the impact of model systematics on population inference. A handle on such systematics is available by repeating population analysis with parameter estimates arising from different waveform models. This requires multiple reviewed catalogs of event parameters: the CBC Parameter Estimation group is primarily responsible for implementation.

TASK ST-3.5-E(iv): EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS

FTE-months: 2.0

Coordinating with the CBC Parameter Estimation and Extreme Matter groups, population studies with neutron star components will incorporate and contribute to understanding of the equation of state of neutron star matter. See also Task ST-3.3-C(iii).

TASK ST-3.5-E(v): REEXAMINING EVENTS WITH POPULATION PRIORS

FTE-months: 2.0

Coordinating with the Parameter Estimation and Extreme Matter groups, individual events should be reexamined with priors corresponding to constraints implied by the current knowledge of the population (e.g. mass and spin reweighting). This will impact our understanding of their properties in the context of the population.

TASK ST-3.5-E(vi): POPULATION IMPACTS ON COSMOLOGY AND LENSING

FTE-months: 1.0

'Standard siren' methods for measuring the expansion history of the Universe require accurate accounting for selection effects, and thus modeling of relevant populations over mass, spin and redshift. Thus, the current best knowledge of the binary merger population should be applied. Similar considerations apply to studies of strongly lensed GW events. The Cosmology and Lensing groups are responsible for implementation, however a R&P liaison may be required.

TASK ST-3.5-E(vii): POPULATION INFORMATION FOR STOCHASTIC BACKGROUND SEARCH

FTE-months: 1.0

Estimates of the stochastic background from CBC sources (see Section ST-5.1) require information on merger rate and population distributions. The Stochastic group is primarily responsible for implementation, however a liaison from R&P may be required.

TASK ST-3.5-E(viii): POPULATION INFORMATION FOR TESTS OF GENERAL RELATIVITY FTE-months: 2.0

Tests of General Relativity based on the combination of data from multiple events may rely upon methods and data products developed in the Rates and Populations group. This may include hierarchical inference frameworks as well as injection-based sensitivity estimates. While the Testing General Relativity group is responsible for coordinating and performing these analysis, a liaison from the R&P group may be required.

ACTIVITY ST-3.5-F-**OPS**: RATES AND POPULATIONS METHODS AND CODE REVIEW

TASK ST-3.5-F(i): REVIEW OF PARTICULAR METHOD FTE-months: 8.0

Integrated method and code review for particular methods used in LVC publications.

ACTIVITY ST-3.5-G-**OPS**: SUBGROUP ADMINISTRATION

Management of the Rates and Populations subgroup.

TASK ST-3.5-G(i): SUBGROUP LEADERSHIP FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.5 Binary Coalescence Rates and Population R&D (Long Term)

This section highlights developments that may *optionally* be deployed during the O4 run, or further in future, and thus are not required to be tested before O4 data taking.

Major aspects and methods for this activity

ACTIVITY LT-3.5-A: METHODS TO MEASURE SEARCH SENSITIVITY

Extend Monte Carlo or similar methods to estimate selection effects to so far neglected effects on binary signals and regions of parameter space.

TASK LT-3.5-A(i): SIMULATED SIGNAL CAMPAIGNS FOR ECCENTRIC BINARIES FTE-months: 2.0

Create and perform simulation campaigns for binary coalescences including significant non-zero orbital eccentricity. This relies on the existence of sufficiently accurate waveform models, which are largely not available at present: see ST-3.4.

TASK LT-3.5-A(ii): SIMULATED SIGNAL CAMPAIGNS FOR SUB-SOLAR-MASS BINARIES FTE-months: 2.0

Create and perform simulation campaigns for binary coalescences including at least one sub-solar-mass compact object.

ACTIVITY LT-3.5-B: COMMON CODE AND DATA PRODUCT DEVELOPMENT

TASK LT-3.5-B(i): MIXTURE MODEL FOR SIGNAL AND NOISE POPULATIONS FTE-months: 4.0

Implement a fully self-consistent mixture model analysis that can simultaneously infer the population and rate of both foreground (astrophysical) and background (noise) events, using data from binary merger searches, DetChar and parameter estimation. This will allow for distinguishing terrestrial noise events without biasing our inferences by assuming all candidate events above an arbitrary threshold to be real.

TASK LT-3.5-B(ii): COMMON TOOLKIT AND COMMUNITY CODE DEVELOPMENT

FTE-months: 4.0

Continued development of other open codes or tools for use by the Rates and Populations community.

ACTIVITY LT-3.5-C: POPULATION ASTROPHYSICS

TASK LT-3.5-C(i): IDENTIFICATION AND EXPLOITATION OF BBH MASS SCALES FOR COSMOLOGY

FTE-months: 4.0

Identify and calibrate mass scales in the BBH mass distribution as an independent measure of merger redshifts and explore cosmological constraints that can be obtained from the BBH population.

TASK LT-3.5-C(ii): BAYESIAN MODEL SELECTION WITH PRIMORDIAL BLACK HOLE MERGERS

FTE-months: 4.0

Develop Bayesian model selection analyses for models including PBH components (versus astrophysical scenarios without such components) based on the merger rate and mass distribution.

ST-3.6 CBC Cosmology R&D (Short Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (short term).

Motivation and methods

The cosmology group is responsible for obtaining estimates of cosmological parameters such as the Hubble constant H_0, matter density of the Universe, dark energy equation of state, as well as testing alternative theories of gravity from GW signals detected by LIGO-Virgo-KAGRA. The methods involved include identification of a set of possible hosts using an observed EM counterpart, statistical redshift association using galaxy catalogs and exploitation of the features present in the source frame mass spectrum. Since a precise estimate requires combining information from multiple events, correcting for any systematic bias that is expected to accumulate over observations is crucial. Selection effects are known to play an important role even with only a few observations. Redshift uncertainties and other effects coming from the EM sector will become increasingly significant. Smaller effects like GW waveform and calibration uncertainties may eventually also become important. A large part of the research and development involves developing methods to understand and account for such effects.

Major aspects and methods for this activity

ACTIVITY ST-3.6-A-**OPS**: COSMOLOGY PIPELINE

A precise measurement of cosmological parameters, such as the Hubble constant, requires combining information from multiple GW observations, with or without transient electromagnetic counterparts. The fact that gravitational wave interferometers have a finite detection threshold introduces a systematic selection bias. Additionally, for the statistical analysis with galaxy catalogues, the incompleteness of the catalogue is expected to introduce further biases. Near future cosmological measurements will be limited by assumptions about the underlying astrophysical source population and so it is necessary to work toward simultaneous fitting of cosmological and astrophysical parameters. Further development in this direction will require methodological studies and close links with other groups, in particular Rates and Populations.

The cosmology group develops and maintains two pipelines for the estimation of cosmological parameters from multiple GW observations, taking into account selection effects. These are GWCOSMO and ICAROGW. The former pipeline makes use of galaxy catalogues, while the latter can handle simultaneous fitting of astrophysical population parameters for empty catalogues. Future development effort will focus on merging the functionality of the two pipelines and including further robustness to systematics by marginalising over additional uncertainties.

TASK ST-3.6-A(i): IMPROVE CODE PERFORMANCE

FTE-months: 16.0

Improve the current pipelines' speed and computational efficiency to allow for easier extensions into inference for a higher number of parameters.

TASK ST-3.6-A(ii): COMBINED COSMOLOGICAL AND POPULATION INFERENCE INCLUDING GALAXY CATALOG INFORMATION

FTE-months: 20.0

Inclusion of galaxy catalogs with simultaneous fitting of cosmological and population properties of compact binary coalescence.

TASK ST-3.6-A(iii): EXTENDED GW POPULATION MODELS

FTE-months: 12.0

Extend the treatment of GW population models by including more complex mass and rate evolution models, spin models, etc.

TASK ST-3.6-A(iv): IMPROVEMENTS TO THE EM COUNTERPART METHOD

FTE-months: 10.0

Improved EM counterpart analysis by including optional EM information (eg inclination angle from jet and peculiar velocity information).

TASK ST-3.6-A(v): EXTENSION BEYOND ΛCDM

FTE-months: 6.0

Develop extended versions of the cosmological pipelines to produce inference of beyond-ΛCDM and beyond-GR cosmological models by exploiting possible GW propagation effects.

ACTIVITY ST-3.6-B-**OPS**: GALAXY CATALOGS

TASK ST-3.6-B(i): IMPROVING CURRENT GALAXY CATALOGS FOR USE WITH COSMOLOGICAL PIPELINES

FTE-months: 18.0

Extending current galaxy catalogs used by the cosmological pipelines to include data from various publicly available wide-angle spectroscopic and photometric surveys. Verify the fidelity of the input galaxy catalogs, especially photometric redshift catalogs, which can increase the completeness of the catalog..

TASK ST-3.6-B(ii): ASSESSMENT OF GALAXY CATALOG INCOMPLETENESS

FTE-months: 12.0

Establish the limiting magnitude of such catalogs over the sky, compute the luminosity functions of the galaxies which are deemed to be reliable, and make them usable as reliable inputs for the cosmological pipelines.

TASK ST-3.6-B(iii): ADDITIONAL EM DATA TO IMPROVE CURRENT GALAXY CATALOGS

FTE-months: 8.0

Investigate the potential improvement from targeted EM follow-up for well-localised GW sources. Assess the viability of working with EM partners with proprietary galaxy catalogs or expertise for specific galaxy surveys.

ACTIVITY ST-3.6-C-**OPS**: ASSESSMENT/MITIGATION OF SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Since a precise estimate of cosmological parameters requires combining information from multiple events, even small systematic effects can lead to biases in measurements. In addition to the impact of selection effects already discussed above, systematic biases can be present in redshift estimates in galaxy catalogues, which can be significant if photometric catalogues are being used. Incorrect assumptions about the astrophysical population of sirens (both bright and dark sirens) and the evolution of the merger rate and the mass distribution, with redshift which can also lead to biases in the measured cosmological parameters. Moreover GW calibration effects and GW waveform uncertainties are also expected to become important as the precision of measurement becomes tighter with an increasing number of observations. Other effects such as galaxy clustering or correlations between BNS mergers and the properties of their host galaxies might also lead to systematic biases if ignored, but could also be exploited to improve the power of the statistical method. We plan to investigate and attempt to understand these effects thoroughly and compute the requirements (on both statistical uncertainties and systematic biases) necessary to achieve any given specified accuracy in the estimation of cosmological parameters.

TASK ST-3.6-C(i): UNDERSTANDING KEY GALAXY CATALOG SYSTEMATICS

FTE-months: 16.0

Assessment of importance of systematics arising from galaxy clustering, photometric redshift uncertainties, K corrections, and Schechter function parameter uncertainties. Development of mitigation/marginalization strategies in analysis pipelines for these systematic effects.

TASK ST-3.6-C(ii): UNDERSTANDING KEY GW POPULATION SYSTEMATICS

FTE-months: 16.0

Understanding the impact of redshift dependence of the mass, spin and merger rate of the GW sources. Exploring presence of underlying astrophysical correlation between these parameters that can cause any selection bias.

TASK ST-3.6-C(iii): UNDERSTANDING KEY EM COUNTERPART SYSTEMATICS

FTE-months: 6.0

Understanding the selection effects due to the inclination angle of the bright sirens.

ACTIVITY ST-3.6-D-**OPS**: COSMOLOGY MOCK DATA CHALLENGE

Validation of current and future versions of the cosmology pipeline on simulated universes via a mock data challenge.

TASK ST-3.6-D(i): MOCK DATA CHALLENGE: CONSTRUCTION OF MOCK DATA SET

FTE-months: 20.0

One or more datasets (complete galaxy catalog, incomplete galaxy catalog, observed events) will be generated that include additional physical population features. MDCs will include both BBH and BNS sources and will also include the clustered population of sources rather than just uniform distribution by using cosmological simulations to capture the large scale structure. MDCs will also include Blind tests, as in cosmological analyses of other experimental data. Preparation of the MDC on simulated galaxy catalogs, real galaxy observations, understanding the impact of photo-z errors, k-correlation, etc.

TASK ST-3.6-D(ii): MOCK DATA CHALLENGE: VALIDATION OF COSMOLOGY PIPELINE

FTE-months: 12.0

Improvements to the cosmology pipeline will be validated by running on the previously mentioned mock datasets.

ACTIVITY ST-3.6-E-**OPS**: REVIEW OF COSMOLOGY PIPELINE

Continuing method and code review of the cosmology pipeline.

TASK ST-3.6-E(i): REVIEW OF COSMOLOGY PIPELINE

FTE-months: 12.0

All code review activities, including review of new statistical methods or features adopted in the cosmology pipeline; review of the implementation of new statistical methods/features in the cosmology code; and review of the performance of the cosmology code on the mock data challenge.

ACTIVITY ST-3.6-F-**OPS**: H_0 PUBLIC WEBSITE CALCULATOR

Produce a low-latency measurement of H0 in the event of an EM counterpart, using only publicly available data, to be displayed on a public website in order to promote the LVK's cosmological work, as well as raising awareness of the nuances that go into a rigorous estimate of H0 in the EM counterpart case.

TASK ST-3.6-F(i): H_0 WEBSITE

FTE-months: 12.0

Create, develop and maintain a public website presenting the latest H0 posteriors calculated with publicly available GW and EM counterpart data. The H_0 results on the website will be updated as soon as possible after any unambiguous EM counterpart has been spotted and its redshift measured. The website will also contain descriptions and general information to educate both the scientific community and the larger public on the details of cosmological GW measurements (in collaboration with the LVK EPO group).

ACTIVITY ST-3.6-G-**OPS**: SUBGROUP ADMINISTRATION

Management of the Cosmology subgroup.

TASK ST-3.6-G(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.6 CBC Cosmology R&D (Long Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (long term).

Motivation and methods

With a large number of events, precision cosmology will be possible using gravitational wave observations of CBCs, combining those with optical counterparts with those without. As the precision of the measurement increases, it will become necessary to fully understand potential systematic sources of error.

Major aspects and methods for this activity

ACTIVITY LT-3.6-A: DEVELOP A COMPLETE UNDERSTANDING OF SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Investigations of the importance of all systematic effects, including those not mentioned explicitly in the ShortTerm section.

TASK LT-3.6-A(i): ASSESSMENT OF PECULIAR VELOCITY SYSTEMATICS

FTE-months: 6.0

A crucial strength of GW standard sirens is that they provide distances that bypass completely the traditional EM "distance ladder" that combines primary and secondary distance indicators. For low-redshift sources, however, the peculiar velocity of the siren host galaxy can require significant correction, as was the case for GW170817. While most BBH sirens are likely to be sufficiently distant that these peculiar velocity corrections are not important, we propose to investigate thoroughly the potential impact of systematic errors in the peculiar velocity correction for nearby sources. We will investigate the effects on the inference of cosmological parameters due to mismodelling of peculiar velocity corrections.

TASK LT-3.6-A(ii): STUDY OTHER SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

FTE-months: 6.0

Investigation of all possible systematic effects affecting the inference of cosmological parameters, for example waveform, calibration, population model systematics.

ACTIVITY LT-3.6-B: DEVELOPMENT FOR CROSS-CORRELATION TECHNIQUE

GW sources are expected to follow the underlying matter distribution and should exhibit spatial clustering with other tracers of large-scale structures such as galaxies. The exploration of the spatial clustering between GW sources and spectroscopic/photometric galaxy samples will make it possible to infer the redshift of the GW sources. This kind of redshift estimation can be referred to as 'clustering redshift' estimation. One of the key quantities of spatial clustering is the GW bias parameter which takes into account the population of GW sources and the connection of GW sources with the dark matter distribution. We will set up a Bayesian framework that will use cross-correlation between GW sources and galaxies and will give a joint estimation on cosmological parameters such as H_0, the matter fraction the matter fraction Ω_m, the dark energy equation-of-state parameters w_o, w_a, along with the GW bias parameters and its redshift evolution.

TASK LT-3.6-B(i): DEVELOP CROSS-CORRELATION TECHNIQUE FOR COSMOLOGY MEASUREMENTS

FTE-months: 18.0

Develop pipelines for cross-correlating GW sources with large scale structure surveys on simulated galaxy catalog and real galaxy catalog.

ACTIVITY LT-3.6-C: SYNERGIES WITH OTHER COSMOLOGICAL PROBES

Gravitational wave constraints on cosmological parameters are just one of many methods for understanding the large scale structure and evolution of the Universe. It has been frequently demonstrated that different probes can provide orthogonal constraints which, when combined, are much stronger than any one probe in isolation. As gravitational wave constraints improve, the impact on cosmological inference will be greatest when combined with other data sets. The purpose of this project is to understand how GW observations fit into this wider context. We will identify which other types of data are most complementary to the information coming from the GW observations and how constraints can be improved by combining data sets. Other data sets that we will consider will include type Ia supernovae, Baryon Acoustic Oscillations, strong lensing (e.g., HOLICow), surface brightness fluctuation measurements and others.

Another aspect of this project will be to explore how these combined analyses can improve our understanding of other cosmological probes. An example of this is to use GW measurements to improve calibration of type IA supernovae.

TASK LT-3.6-C(i): CATALOGUE CONSTRUCTION FOR SUPERNOVAE CALIBRATION

FTE-months: 2.0

A binary neutron star coalescence event could be used to validate the distance to a galaxy or a cluster in which a supernova is known to have occurred and hence provide an independent calibration of the supernova luminosity. The GW measurement would be better than other distance estimators if the event was within 100 Mpc. We will explore how such measurements might influence measurements of H0 using supernovae. Using the population of standard sirens, it may also be possible to cross-calibrate other methods such as Type Ia SNe or BAO. This will be particularly useful as a way to look for systematic errors. Assemble a catalogue of all nearby (< 1 Gpc) supernovae, focussing especially on clusters and SNe type Ia.

TASK LT-3.6-C(ii): MOCK DATA CHALLENGE FOR SUPERNOVA CALIBRATION

FTE-months: 6.0

Set up a mock data challenge for coincident observation of a binary neutron star event and a SNe Ia.

TASK LT-3.6-C(iii): COMPARISON OF STANDARD SIREN CONSTRAINTS WITH OTHER METHODS

FTE-months: 3.0

Situate standard siren constraints within the landscape of cosmological constraints, focusing especially on Type Ia supernovae and strong lensing time delay constraints.

ACTIVITY LT-3.6-D: TESTS OF ΛCDM

The propagation of GWs over cosmological distances may be affected by deviations from ΛCDM, in particular if gravity is no longer well described by GR at large scales as predicted by some modified gravity models of dark energy. Standard sirens, with or without an EM counterpart, can be used to test these deviations and thus to place constraints on beyond-ΛCDM theories. The scope of this activity is to develop model-independent pipelines to test deviations from ΛCDM, and in particular from GR, in the propagation of GWs.

TASK LT-3.6-D(i): TESTING DEVIATIONS FROM ΛCDM FROM GW PROPAGATION

FTE-months: 15.0

Expand cosmological pipelines to test phenomenological deviations in the standard ΛCDM propagation of GWs at cosmological distances, including e.g. the frictional term and its redshift evolution, from GW sources with/without EM counterparts.

ACTIVITY LT-3.6-E: BUILDING IMPROVED GALAXY CATALOGUES

Undertake investigations to improve the galaxy catalogues used by cosmological pipelines by utilizing the latest EM surveys and assessing the potential sources of systematics from them.

TASK LT-3.6-E(i): IMPROVED GALAXY CATALOGUES FOR COSMOLOGY MEASUREMENTS

FTE-months: 18.0

Develop pipelines for compiling appropriate galaxy catalogs to be used for cosmology with gravitational waves. This will include gathering data from various wide-angle spectroscopic and photometric surveys and merging them into a homogenous dataset that could be used for further processing by cosmology pipeline.

In parallel to galaxy catalogs, explore the use of galaxy cluster catalogs in GW cosmology. Assess the survey limitations and quantify the catalog incompleteness. Develop a model analogous to luminosity weighting to enable the use of these catalogs in the cosmological pipelines and study the robustness / quantify the systematic effects of the unknown astrophysics that goes into the model(s). Exploring future galaxy catalogs (such as SPHEREx, Euclid, Rubin, Roman) which will be available and how and which one of those are going to be useful for the LVK analysis in future.

ACTIVITY LT-3.6-F: PRIMORDIAL BLACK HOLES AND DARK MATTER

Develop methods for constraints and model selection of primordial black hole (PBHs) based on CBC observations. Develop or extend techniques and methods to constrain particle dark matter models from CBC observations in combination with continuous waves and stochastic GW limits.

Gravitational-wave observations provide a novel way to probe the nature and origin of dark matter in cosmology as well as primordial black holes (PBHs) expected to be formed due to inhomogeneities in the early universe. The methods involved in PBH searches and constraints include the computation of the GW signatures (e.g. mass function, rates in different binary formation channels, spin distributions) in different PBH scenarios. Additionally, statistical methods for model selection (PBH versus astrophysical models) would constrain the theoretical PBH models. In several models of dark matter, new particles or fields can leave imprints in the GW signals from CBCs or produce continuous waves or stochastic GW backgrounds.

TASK LT-3.6-F(i): EXTENSION OF SUB-SOLAR SEARCH TO MORE EXTREME MASS RATIOS

FTE-months: 12.0

The search for sub-solar black hole binaries with a maximal component mass of $2M_\odot$ is the subject of another section of this white paper. This activity rather consists in extending that search to binaries with a larger primary component mass (dubbed as sub-solar binaries with higher mass ratios below). Methods include the production of new template banks for this mass range, running searches, setting new limits of the merger rate of such binaries, and interpretation of these limits in terms of constraints on the possible PBH mass function, abundance and binary formation channels.

Related work will include: design a template bank for sub-solar black holes with higher mass ratios, develop a search pipeline for sub-solar black holes with higher mass ratios, develop methods for using search results to set new limits on the rate of PBHs and constraints on PBH mass function, abundance, and binary formation channels.

TASK LT-3.6-F(ii): MODEL SELECTION OF PBH VS ASTROPHYSICAL SCENARIOS, BASED ON THE CBC MASS AND SPIN DISTRIBUTIONS

FTE-months: 4.0

Development or extension of statistical methods for the Bayesian selection of PBH models versus astrophysical scenarios, based on the rate, mass and spin distributions of CBC observations. Computation of improved constraints on viable PBH models. Develop tools for Bayesian model selection of PBH models versus astrophysical scenarios based on the inferred rate and mass distributions.

TASK LT-3.6-F(iii): POSSIBLE PBH INTERPRETATION OF EXCEPTIONAL OR SPECIAL EVENTS

FTE-months: 4.0

For exceptional CBC events, the component masses and spins as well as the inferred merger rates could hint to a primordial origin rather than an astrophysical one. Assuming a primordial origin, the implications of these events for PBH scenarios could be investigated. Methods would include CBC parameter estimations and merger rate inference based on PBH-inspired mass functions instead of ones expected for neutron stars or astrophysical black holes. Develop tools that can be used to identify an exceptional event as a PBH candidate.

TASK LT-3.6-F(iv): SYNERGIES BETWEEN CBC OBSERVATIONS AND LIMITS ON CWS AND THE SGWB

FTE-months: 4.0

The PBH scenarios able to explain CBC observations can be further tested against the limits on continuous GWs from inspiralling light PBH binaries, set by all-sky or targetted searches, and on the stochastic GW background from PBH binaries (primordial or in PBH clusters), close encounters and formation in the early universe. Moreover synergy between CBC observations and continuous waves and / or the stochastic background lead the way to other aspects of dark matter science. Superradiance from (scalar, vector or tensor) ultra-light boson clouds has an effect on the black hole spins. It is therefore possible to set limits on models with ultra-light bosons from spin measurements in black hole mergers. Limits on CW signals from all-sky or directed searches (towards galactic center, known X-ray binaries, or dwarf galaxies) is another way to constrain these models. Stochastic and continu- ous wave techniques can further be used to constrain the dark photon – the dark photon is expected to couple to the baryons in the detector mirrors, inducing a quantum-mechanical force that can be interpreted as a GW strain. Develop methods for joint inference using CBC, CW, and SGWB search results.

ACTIVITY LT-3.6-G: DEVELOPMENT FOR DARK SIREN METHOD WITH SINGLE HOST

BBH sources which are well localised in the plane of the sky can be used to measure the Hubble constant. Such sources may contain a single galaxy in the field of view. A targeted search in the localisation region can identify the host galaxy. Subsequent EM measurements can be undertaken to measure the redshift of the host. This will yield a measurement of the Hubble constant.

TASK LT-3.6-G(i): DEVELOP SINGLE-HOST DARK SIREN METHOD FOR H_0 MEASUREMENT

FTE-months: 6.0

Develop methods to marginalise H_0 over sub-luminous galaxies. Evaluate the accuracy with which H_0 can be inferred in the presence of higher order modes and spin precession. Develop methods to identify host galaxy.

ST-3.7 CBC All Sky Search ShortTerm R&D

Short term development and tuning of search pipelines for online/offline running; generate template banks; assess data quality issues relevant to CBC detection. Requirements for going into O4 operations.

Motivation and methods

The online and offline detection and search technical development groups work to develop sensitive and computationally efficient pipelines to identify compact binary merger signals in strain data, and manage the generation of search results via running the pipelines on LIGO-Virgo-KAGRA data. These pipelines generally operate in "all-sky" mode, i.e., searching all available data after non-analyzable times have been identified and removed, as distinct from "externally triggered" searches for GWs from reported astrophysical events such as GRBs.

Offline searches run with a latency of order a few days to weeks on a stable and carefully selected data set, to provide reproducible results for publication including precise evaluation of the significance and pastro classification of candidate events and the sensitivity of the search to populations of realistic binary merger signals. Online / low-latency searches run primarily to generate triggers for follow-up including initial evaluation of trigger significance, mass and spin values and extrinsic parameters relevant to sky localization and p-astro classification. Development of methods for low latency data selection and estimation of search sensitivity is motivated by the desirability of convergence of results between online and offline searches if possible.

Major aspects and methods for this activity

ACTIVITY ST-3.7-A-**OPS**: O4 PIPELINE DEVELOPMENT

As the detector sensitivity curves change, and as the network of gravitational wave detectors grow, it is necessary to update aspects of the search pipelines to optimize search efficiency.

Changes to template banks are needed in order to respond to changes in detector sensitivity curves as well as changes to the parameter space of signals being targeted.

During O3 3-detector operations were the norm, and we expect that O4 will be first 4-detector observing run of the advanced detector era. Pipelines must be ready to handle this multi-detector data in O4.

In addition a number of the most important observations have been made with data from only a single detector. Reliably estimating single-detector significance is challenging and a number of pipelines are working to develop methods to estimate significance of events seen in only a single observatory.

TASK ST-3.7-A(i): CONSTRUCTION OF A TEMPLATE BANK FOR GSTLAL

FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes. Tune and test the template bank's performance in simulations and real data.

TASK ST-3.7-A(ii): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR GSTLAL

FTE-months: 12.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK ST-3.7-A(iii): CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY FOR O4

FTE-months: 12.0

Incremental improvements to the GstLAL pipeline's search sensitivity in preparation of the O4 run.

TASK ST-3.7-A(iv): CONTINUE OPTIMIZING THE GSTLAL P-ASTRO CALCULATION FOR O4

FTE-months: 12.0

Improvements to the GstLAL pipeline's p-astro computation in preparation of the O4 run.

TASK ST-3.7-A(v): CONTINUE OPTIMIZING THE GSTLAL COMPUTATIONAL PERFORMANCE FOR O4

FTE-months: 12.0

Incremental improvements to the GstLAL pipeline's computational performance in preparation of the O4 run.

TASK ST-3.7-A(vi): CONTINUE OPTIMIZING THE GSTLAL ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

FTE-months: 12.0

Improvements to GstLAL online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK ST-3.7-A(vii): GSTLAL DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

FTE-months: 3.0

Any development or optimisation effort needed specifically for the SSM search.

TASK ST-3.7-A(viii): CONSTRUCTION OF A TEMPLATE BANK FOR MBTA

FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK ST-3.7-A(ix): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR MBTA

FTE-months: 6.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK ST-3.7-A(x): CONTINUE OPTIMIZING THE MBTA SEARCH SENSITIVITY FOR O4

FTE-months: 12.0

Incremental improvements to the MBTA pipeline's search sensitivity in preparation of the O4 run.

TASK ST-3.7-A(xi): CONTINUE OPTIMIZING THE MBTA P-ASTRO CALCULATION FOR O4

FTE-months: 12.0

Improvements to the MBTA pipeline's p-astro computation in preparation of the O4 run.

TASK ST-3.7-A(xii): CONTINUE OPTIMIZING THE MBTA COMPUTATIONAL PERFORMANCE FOR O4

FTE-months: 3.0

Incremental improvements to the MBTA pipeline's computational performance in preparation of the O4 run.

TASK ST-3.7-A(xiii): CONTINUE OPTIMIZING THE MBTA ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

FTE-months: 12.0

Improvements to MBTA online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK ST-3.7-A(xiv): MBTA DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

FTE-months: 3.0

Any development or optimisation effort needed specifically for the SSM search.

TASK ST-3.7-A(xv): CONSTRUCTION OF A TEMPLATE BANK FOR PYCBC

FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK ST-3.7-A(xvi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR PYCBC

FTE-months: 12.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK ST-3.7-A(xvii): CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY FOR O4

FTE-months: 12.0

Incremental improvements to the PyCBC pipeline's search sensitivity in preparation of the O4 run.

TASK ST-3.7-A(xviii): CONTINUE OPTIMIZING THE PYCBC P-ASTRO CALCULATION FOR O4

FTE-months: 12.0

Improvements to the PyCBC pipeline's p-astro computation in preparation of the O4 run.

TASK ST-3.7-A(xix): CONTINUE OPTIMIZING THE PYCBC COMPUTATIONAL PERFORMANCE FOR O4

FTE-months: 4.0

Incremental improvements to the PyCBC pipeline's computational performance for the O4 run.

TASK ST-3.7-A(xx): CONTINUE OPTIMIZING THE PYCBC ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

FTE-months: 12.0

Improvements to PyCBC online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK ST-3.7-A(xxi): PYCBC DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

FTE-months: 3.0

Any development or optimisation effort needed specifically for the SSM search.

TASK ST-3.7-A(xxii): CONSTRUCTION OF A TEMPLATE BANK FOR SPIIR FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK ST-3.7-A(xxiii): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR SPIIR FTE-months: 6.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK ST-3.7-A(xxiv): CONTINUE OPTIMIZING THE SPIIR SEARCH SENSITIVITY IN PREPARATION OF O4 FTE-months: 8.0

Incremental improvements to the SPIIR pipeline's search sensitivity in preparation of the O4 run.

TASK ST-3.7-A(xxv): CONTINUE OPTIMIZING THE SPIIR P-ASTRO CALCULATION FOR O4 FTE-months: 12.0

Improvements to the SPIIR pipeline's p-astro computation in preparation of the O4 run.

TASK ST-3.7-A(xxvi): CONTINUE OPTIMIZING THE SPIIR COMPUTATIONAL PERFORMANCE FOR O4 FTE-months: 3.0

Incremental improvements to the SPIIR pipeline's computational performance for the O4 run.

TASK ST-3.7-A(xxvii): CONTINUE OPTIMIZING THE SPIIR ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE FTE-months: 12.0

Improvements to SPIIR online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

ACTIVITY ST-3.7-B-**OPS**: O4 PIPELINE DEPLOYMENT

Search pipelines must be deployed and maintained on collaboration computer clusters for O4 online and offline analyses.

TASK ST-3.7-B(i): DEPLOYMENT OF GSTLAL PIPELINE FOR ONLINE RUNNING FTE-months: 12.0

Deploy, monitor, and maintain the GstLAL online pipeline for low-latency trigger generation (possibly including SSM search).

TASK ST-3.7-B(ii): DEPLOYMENT OF GSTLAL PIPELINE FOR OFFLINE RUNNING FTE-months: 12.0

Deploy and maintain the GstLAL pipeline for deeper offline searches.

TASK ST-3.7-B(iii): DEPLOYMENT OF MBTA PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the MBTA online pipeline for low-latency trigger generation (possibly including SSM search).

TASK ST-3.7-B(iv): DEPLOYMENT OF MBTA PIPELINE FOR OFFLINE RUNNING FTE-months: 8.0

Deploy and maintain the MBTA pipeline for deeper offline searches.

TASK ST-3.7-B(v): DEPLOYMENT OF PYCBC PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the PyCBC online pipeline for low-latency trigger generation.

TASK ST-3.7-B(vi): DEPLOYMENT OF PYCBC PIPELINE FOR OFFLINE RUNNING FTE-months: 8.0

Deploy and maintain the PyCBC pipeline for deeper offline searches.

TASK ST-3.7-B(vii): DEPLOYMENT OF SPIIR PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the SPIIR online pipeline for low-latency trigger generation.

TASK ST-3.7-B(viii): DEPLOYMENT OF SPIIR PIPELINE FOR OFFLINE RUNNING FTE-months: 8.0

Deploy and maintain the SPIIR pipeline for deeper offline searches.

ACTIVITY ST-3.7-C-**OPS**: O4 EARLY WARNING PIPELINE DEPLOYMENT

Early warning pipelines will be deployed and maintained on collaboration computer clusters for O4 online analyses.

TASK ST-3.7-C(i): DEPLOYMENT OF GSTLAL EARLY WARNING PIPELINE FTE-months: 12.0

Deploy, monitor, and maintain the GstLAL early warning pipeline for pre-merger trigger generation.

TASK ST-3.7-C(ii): DEPLOYMENT OF MBTA EARLY WARNING PIPELINE FTE-months: 12.0

Deploy, monitor, and maintain the MBTA early warning pipeline for pre-merger trigger generation.

TASK ST-3.7-C(iii): DEPLOYMENT OF PYCBC EARLY WARNING PIPELINE FTE-months: 12.0

Deploy, monitor, and maintain the PyCBC early warning pipeline for pre-merger trigger generation.

TASK ST-3.7-C(iv): DEPLOYMENT OF SPIIR EARLY WARNING PIPELINE FTE-months: 12.0

Deploy, monitor, and maintain the SPIIR early warning pipeline for pre-merger trigger generation.

O4 Early Warning Pipeline Deployment

ACTIVITY ST-3.7-D-**OPS**: O3/O4 PIPELINE REVIEW

Review of final O3 results/configurations and review of O4 pipelines.

TASK ST-3.7-D(i): REVIEW OF GSTLAL PIPELINE FTE-months: 2.0

Review of changes to the GstLAL offline pipeline. Both changes to code and to configurations will be reviewed.

TASK ST-3.7-D(ii): REVIEW OF MBTA PIPELINE FTE-months: 2.0

Review of changes to the MBTA offline pipeline. Both changes to code and to configurations will be reviewed.

TASK ST-3.7-D(iii): REVIEW OF PYCBC PIPELINE FTE-months: 2.0

Review of changes to the PyCBC offline pipeline. Both changes to code and to configurations will be reviewed.

TASK ST-3.7-D(iv): REVIEW OF SPIIR PIPELINE FTE-months: 2.0

Review of changes to the SPIIR offline pipeline. Both changes to code and to configurations will be reviewed.

ACTIVITY ST-3.7-E-**OPS**: CBC-RELATED DETECTOR CHARACTERIZATION TASKS

Development and maintenance of tools to characterize the impact of detector state on CBC searches and identify possible veto times was ongoing since O3 and will continue through O4 to adapt to new detector characterization challenges encountered.

TASK ST-3.7-E(i): DETCHAR FOLLOWUP OF GSTLAL TRIGGERS

FTE-months: 2.0

Investigate gstlal single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

TASK ST-3.7-E(ii): DETCHAR FOLLOWUP OF MBTA TRIGGERS

FTE-months: 2.0

Investigate MBTA single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

TASK ST-3.7-E(iii): DETCHAR FOLLOWUP OF PYCBC TRIGGERS

FTE-months: 2.0

Investigate PyCBC single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

ACTIVITY ST-3.7-F-**OPS**: SUBGROUP ADMINISTRATION

Management of the all-sky pipelines subgroup.

TASK ST-3.7-F(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.7 CBC All Sky Search R&D (Long Term)

Long term development and tuning of search pipelines for online/offline running.

Motivation and methods

As well as continuing to run online and offline searches in O4, we must start to consider the problems that future improvements to the detector, and the inclusion of additional detectors, will bring (All with next to no personpower). We specifically want to consider expanding the search parameter space to include "exotic" sources, which our current searches are not sensitive to. We want to consider how to efficiently search a network of detectors, and we want to start to consider how we will address the computational challenges that 3G-networks will pose.

Major aspects and methods for this activity

ACTIVITY LT-3.7-A: OFFLINE SEARCH FOR CBC INVOLVING AT LEAST ONE SUB-SOLAR-MASS COMPACT OBJECT

TASK LT-3.7-A(i): CONSTRUCTION OF A TEMPLATE BANK FOR GSTLAL SSM SEARCH

FTE-months: 2.0

Construct a template bank that covers the sub-solar-mass search parameter space.

TASK LT-3.7-A(ii): CONSTRUCTION OF A TEMPLATE BANK FOR MBTA SSM SEARCH

FTE-months: 2.0

Construct a template bank that covers the sub-solar-mass search parameter space.

TASK LT-3.7-A(iii): CONSTRUCTION OF A TEMPLATE BANK FOR PYCBC SSM SEARCH

Construct a template bank that covers the sub-solar-mass search parameter space.

FTE-months: 2.0

TASK LT-3.7-A(iv): DEPLOYMENT OF GSTLAL PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the GstLAL pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

FTE-months: 6.0

TASK LT-3.7-A(v): DEPLOYMENT OF MBTA PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the MBTA pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

FTE-months: 4.0

TASK LT-3.7-A(vi): DEPLOYMENT OF PYCBC PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the PyCBC pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

FTE-months: 4.0

ACTIVITY LT-3.7-B: SEARCHING FOR NOVEL OR "EXOTIC" SOURCE TYPES

Current search techniques necessarily make assumptions about the signal model to reduce the computational cost. These assumptions lead to certain types of rare, but astrophysically very rewarding, systems potentially being missed. This includes systems exhibiting strong precessional dynamics, systems where subdominant modes have a significant contribution, systems on significantly eccentric orbits and signals emitted from compact objects whose behaviour significantly deviates from GR predictions. New methods have been proposed to search for some of these sources, but significant work on implementation and tuning of a search will be required to obtain results. Hopefully some of these features could be searched for already in O4.

TASK LT-3.7-B(i): SEARCH FOR NOVEL OR EXOTIC CBC SOURCE TYPES

ACTIVITY LT-3.7-C: COHERENT ALL-SKY SEARCH WITH 3+ DETECTORS

CBC searches currently look for coincident triggers, with the exception of the coherent GRB analysis. In the long term, a network of 3+ detectors of comparable sensitivity will motivate the development of fully coherent search algorithms. Considerable work remains to be done in optimisation to extend the methods pioneered in the coherent GRB analysis to cover the all-sky, all-time parameter space in a computationally efficient manner. This research will continue throughout the O4 timeframe, with the aim of reaching maturity in time for design sensitivity detector networks.

TASK LT-3.7-C(i): COHERENT ALL-SKY CBC SEARCH WITH 3+ DETECTORS

ACTIVITY LT-3.7-D: NOVEL SEARCH OPTIMIZATION TECHNIQUES

To address the computational challenge that the 3G era, and to a lesser extent, a 5-detector 2G network at design sensitivity, will pose, we must consider how to reduce the computational cost of our searches. A number of methods have been proposed for this, including reducing the template count by using a reduced basis, using multi-banding to achieve a similar affect and computational optimization of existing codes. Additionally it has been proposed that convolutional neural networks might achieve similar sensitivity to traditional matched-filtering searches. Given the wide range of methods and the requirements of this activity is expected to be an area of research for some time to come, with the implementation and review of practical methods likely to be during O4 or beyond.

TASK LT-3.7-D(i): NOVEL OPTIMIZATION TECHNIQUES FOR CBC SEARCHES

ACTIVITY LT-3.7-E: NOVEL SEARCH SENSITIVITY IMPROVEMENTS

As we learn more about the search parameter space, we should continue to think about how we can most effectively find the compact binary merger signals buried in our data. This broad item covers a number of techniques that might be considered to improve search sensitivity. This ranges from using improved signal-based classifiers to better separate noise from signal, using better glitch identification techniques to remove non-Gaussianities from the data that can particularly harm the search to including better knowledge of the types of compact binary in the Universe to better identify "sub-threshold" events.

TASK LT-3.7-E(i): NOVEL SENSITIVITY IMPROVEMENTS FOR CBC SEARCHES

ST-3.8 Lensing R&D (Short Term)

Research and development on searches for lensing of gravitational waves.

Motivation and methods

The Lensing group is primarily responsible for searching for signatures of gravitational lensing of gravitational waves in the LIGO–Virgo–KAGRA data, and for developing the associated data analysis infrastructure. Depending of the type of lens, gravitational lensing offers a rich phenomenology. Within the Lensing group we search this broad spectrum: from multiple images produced in gravitational waves strongly lensed by a galaxy or galaxy cluster, to interference and wave effects when the lenses sizes are comparable to the wavelengths of the gravitational waves. Other searches for lensing include search for highly magnified events, signatures in the stochastic background, as well as modeling of the gravitational lenses and their population, and constraints on the population of sources. In addition to perform the mentioned searches, we will improve the analysis techniques and develop methods to assess the systematics and detection thresholds. The LVK Collaborations want to be ready for gravitationally lensed detections. Thus, the short-term lensing R&D development develops critical infrastructure to detect gravitational-wave lensing.

Major aspects and methods for this activity

ACTIVITY ST-3.8-A-**OPS**: SEARCHES FOR MULTIPLE IMAGES

TASK ST-3.8-A(i): MACHINE LEARNING MULTI-IMAGE SEARCH PIPELINE

FTE-months: 3.0

Infrastructure development to improve machine learning algorithms targeting lensed multiple images. Particularly the accuracy of the machine learning pipelines will require further improvements in order to confidently detect strong lensing.

TASK ST-3.8-A(ii): POSTERIOR-BASED SEARCH PIPELINE FOR STRONG LENSING

FTE-months: 1.0

Infrastructure development to analyse strong lensing candidates with a postprocessing step. Particularly the efficiency of the pipeline and the KDE reconstruction will require further development.

TASK ST-3.8-A(iii): FACTORIZED JOINT PARAMETER ESTIMATION PIPELINE

FTE-months: 3.0

Infrastructure development for factorized joint parameter estimation using importance sampling and pre-computed look-up tables to perform "factorized" joint parameter estimation. Particularly the mapping from image properties to lens properties, inclusion of better population models, and inclusion of posterior Odd computations, are crucial to strong lensing detections.

TASK ST-3.8-A(iv): JOINT PARAMETER ESTIMATION PIPELINE

FTE-months: 3.0

Infrastructure development towards joint parameter estimation searches using template-based approaches. Particularly improving the efficiency of the pipeline as well as including more advanced lensing statistical models will be crucial.

TASK ST-3.8-A(v): SUB-THRESHOLD SEARCH PIPELINE

FTE-months: 4.0

Infrastructure development towards searches for weak multiple-image counterparts to strong lensing candidates. Better identification procedures through the inclusion of sky maps as well as strong lensing time delays will be crucial to correctly identify candidates below the noise threshold.

ACTIVITY ST-3.8-B-**OPS**: SEARCH FOR INTERFERENCE AND WAVE EFFECTS

TASK ST-3.8-B(i): MICROLENSING SEARCH PIPELINE

FTE-months: 3.0

Infrastructure development to target microlensed events and to combine strong lensing analyses with microlensing analyses for both isolated and population of microlenses. Particularly the inclusion of more advanced microlens models going beyond isolated microlenses is crucial for microlensing detections and follow-up analysis of strong lensing candidates.

TASK ST-3.8-B(ii): MILLILENSING SEARCH PIPELINE

FTE-months: 3.0

Infrastructure development towards a new model-independent inference for millilensing based on geometrical optics approximation. A model-independent approach will allow for a follow-up analysis of the strong lensing candidates. Full development of the model-independent search PE framework as well as a mapping from image parameters to millilensing parameters will be crucial to millilens identification and follow-up analysis.

ACTIVITY ST-3.8-C-**OPS**: WAVEFORM SYSTEMATICS STUDIES

Study the impact of using waveforms from different modelling approaches and with different physics content (e.g. precession, higher modes) in the searches, parameter estimation and model selection methods used for identifying lensing signatures of all types. Understanding waveform systematics is critical to distinguish lensed detections from mimickers.

TASK ST-3.8-C(i): PERFORM WAVEFORM SYSTEMATICS STUDIES

FTE-months: 3.0

ACTIVITY ST-3.8-D-**OPS**: LENS MODEL SELECTION EFFECTS

TASK ST-3.8-D(i): SELECTION EFFECTS FOR STRONG-, MILLI- AND MICRO-LENS POPULATION

FTE-months: 3.0

Development for connecting strong-, milli- and micro-lens detections with lens modelling and their selection effects given the lens and source populations.

TASK ST-3.8-D(ii): SELECTION EFFECTS FROM LENS POPULATION OF COMPACT OBJECTS

FTE-months: 2.0

Development of improved selection effects when the lenses are compact objects as dark matter. Particularly the inclusion of more advanced primordial black hole models as well as a better connection between the parameter inference pipelines and the follow-up compact object analyses is critical to new dark matter constraints.

ACTIVITY ST-3.8-E-**OPS**: BUILDING COMMON INFRASTRUCTURE FOR LENSING FIRST DETECTION

Develop and review infrastructure in preparation for upcoming runs. This includes: (i) Development of tools for automating lensing analyses together with the Testing General Relativity Group; (ii) Coordination of pipeline improvements via development calls; (iii) Mock data challenge to test the efficiency and accuracy of the lensing pipelines; and (iv) Development of the lensing infrastructure for the cbcflow pipeline.

TASK ST-3.8-E(i): BUILDING COMMON INFRASTRUCTURE FOR LENSING FIRST DETECTION

FTE-months: 13.0 (includes all aspects of the preparations listed)

ACTIVITY ST-3.8-F-**OPS**: SEARCHING FOR EXCEPTIONAL LENSED CANDIDATES AT LOW AND MEDIUM LATENCIES

TASK ST-3.8-F(i): DEPLOY THE POSTERIOR OVERLAP PIPELINE

FTE-months: 1.0

The Posterior Overlap pipeline will provide a computationally efficient low-latency way to identify strongly lensed candidate pairs in the data.

TASK ST-3.8-F(ii): DEPLOY THE MACHINE LEARNING PIPELINE

FTE-months: 1.0

The Machine Learning pipeline will provide a computationally efficient low-latency way to identify strongly lensed candidate pairs in the data.

TASK ST-3.8-F(iii): DEPLOY THE GOLUM PIPELINE

FTE-months: 2.0

The GOLUM pipeline will provide a computationally efficient medium-latency way to identify strongly lensed candidate pairs in the data.

TASK ST-3.8-F(iv): DEPLOY THE RAPID HANABI PIPELINE

FTE-months: 3.0

The Rapid Hanabi pipeline will provide a computationally efficient medium-latency way to identify strongly lensed candidate pairs in the data.

TASK ST-3.8-F(v): DEPLOY THE SUB-THRESHOLD LENSING PIPELINE

FTE-months: 3.0

The Sub-threshold pipeline will provide a computationally efficient medium-latency way to identify strongly lensed pairs with one event being sub-threhold.

TASK ST-3.8-F(vi): DEPLOY THE TYPE II IMAGE LENSING PIPELINE

FTE-months: 1.0

The Type II image pipeline will provide a computationally efficient medium-latency way to identify strongly lensed type II images by their waveform distortions.

TASK ST-3.8-F(vii): DEPLOY THE MICROLENSING PIPELINE

FTE-months: 2.0

The Microlensing pipeline will provide a computationally efficient medium-latency way to identify wave effects due to lensing by compact lenses.

TASK ST-3.8-F(viii): DEPLOY THE MILLILENSING PIPELINE

FTE-months: 2.0

The Millilensing pipeline will provide a computationally efficient medium-latency way to identify interference effects due to lensing by compact lenses.

TASK ST-3.8-F(ix): FOLLOW-UP ANALYSIS OF INTERESTING CANDIDATES

FTE-months: 2.0

For any interesting candidate, we will perform a focus study to investigate its potential for being a lensed candidate.

ACTIVITY ST-3.8-G-**OPS**: SUBGROUP ADMINISTRATION

Management of the Lensing subgroup.

TASK ST-3.8-G(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 2.0

LT-3.8 Lensing R&D (Long Term)

Long-term research and development on searches for lensing of gravitational waves.

Major aspects and methods for this activity

ACTIVITY LT-3.8-A: STUDY DETECTION THRESHOLDS AND FALSE ALARM PROBABILITIES

The goal is to determine solid thresholds for the first identification of lensing of gravitational waves in its different regimes. This includes among other things performing background studies, mock data challenges.

TASK LT-3.8-A(i): DETECTION THRESHOLDS AND FALSE ALARMS

ACTIVITY LT-3.8-B: MODELING OF LENS POPULATIONS

Improve the modeling of lens populations and lensing rates and investigate the use of improved lens models in data analysis pipelines.

TASK LT-3.8-B(i): MODELING LENS POPULATION

ACTIVITY LT-3.8-C: INFERENCE TOOLS

Improve the inference tools to detect and characterize lensing signatures from existing detections, including the investigation of microlensing/millilensing effects and multiple images, prior choices, and selection effects.

TASK LT-3.8-C(i): INFERENCE TOOLS

ACTIVITY LT-3.8-D: INFERENCE OF THE LENS AND SOURCE POPULATION

Develop methods to make astrophysical inference (e.g., nature of dark matter) from lensing signatures in gravitational-wave signals, as well as develop methods to infer properties of the source population from detections of lensed gravitational-wave signals as well as the stochastic background.

TASK LT-3.8-D(i): INFERENCE SOURCE POPULATION

ACTIVITY LT-3.8-E: SUBTHRESHOLD SEARCHES

Improve sub-threshold search pipelines to detect lensed counterparts of transient gravitational-wave signals.

TASK LT-3.8-E(i): SUB-THRESHOLD

ACTIVITY LT-3.8-F: MULTI-MESSENGER SIGNALS OF LENSING

Study the enhancement in the identification of strongly lensed gravitational wave using electromagnetic observations via searching for lensed counterparts or background objects lensed by the same lens. This also includes predicting the time delay from images of host galaxies of CBCs as a means to enhance early-warning and using catalogs of lensed galaxies to help identify lensed CBCs

TASK LT-3.8-F(i): MULTI-MESSENGER LENSING

TASK LT-3.8-F(ii): STRONG LENSING IDENTIFICATION WITH CROSS-MATCHING WITH EM CATALOGS

Leverage the EM imaging and catalogs to extract corresponding image properties such as time-delays, to enhance GW early-warning, and improve significance and inference of the candidate lensed GW event pairs.

ACTIVITY LT-3.8-G: PROBES ON FUNDAMENTAL PHYSICS AND COSMOLOGY

TASK LT-3.8-G(i): TESTING GENERAL RELATIVITY WITH GRAVITATIONAL LENSING

Develop model agnostic and theory-specific analyses to test for the gravitational-wave polarization and massive gravity with strongly lensed gravitational waves.

TASK LT-3.8-G(ii): COSMOLOGICAL INFERENCE

Explore the cosmological inference using gravitational wave lensing and the impact of weak lensing in standard siren methods. This task is to be undertaken in collaboration with the TGR/Cosmology CBC sub-group

TASK LT-3.8-G(iii): MICROLENSING MIMICKERS

To study whether the non-inclusion of certain physical effects in the waveform model can mimic microlensing

TASK LT-3.8-G(iv): GR VIOLATIONS

Explore the possibility that lensed waveforms can show biases in various tests of General Relativity

ST-3.9 CBC Service Roles

These tasks represent critical CBC service roles that are transient in nature and may be appointed positions.

Motivation and methods

Management of the CBC group requires teamwork between appointed and elected leaders along with a host of volunteers who contribute to the review and dissemination of scientific results. Here we capture a few broad classes of these types of service roles.

Major aspects and methods for this activity

ACTIVITY ST-3.9-A-**OPS**: SERVING AS CBC CO-CHAIR

Future co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the CBC working group.

TASK ST-3.9-A(i): STANDING FOR ELECTION AS CBC CO-CHAIR

FTE-months: -

ACTIVITY ST-3.9-B-**OPS**: SERVING AS CBC SUBGROUP LEAD

Subgroup leads are appointed by CBC co-chairs to lead R&D groups.

TASK ST-3.9-B(i): ACCEPTING CBC SUBGROUP LEAD APPOINTMENT FTE-months: -

ACTIVITY ST-3.9-C-**OPS**: SERVING AS CBC TECHNICAL REVIEWER

Technical reviewers agree to review code or techniques for scientific soundness.

TASK ST-3.9-C(i): ACCEPTING A CBC TECHNICAL REVIEWER APPOINTMENT OR VOLUNTEERING FOR TECHNICAL REVIEW TASKS IF CALLED UPON FTE-months: -

ACTIVITY ST-3.9-D-**OPS**: SERVING AS CBC PAPER REVIEWER

Paper reviewers agree to review papers for correctness, e.g., checking numbers and the validity of basic statements which interpret the results of the technical analysis.

TASK ST-3.9-D(i): ACCEPTING A CBC PAPER REVIEWER APPOINTMENT OR VOLUNTEERING FOR PAPER REVIEW TASKS IF CALLED UPON FTE-months: -

ACTIVITY ST-3.9-E-**OPS**: SERVING ON A CBC "KEY PAPER" TEAM

CBC paper team members write or manage CBC papers.

TASK ST-3.9-E(i): ACCEPTING A CBC PAPER TEAM APPOINTMENT OR VOLUNTEERING FOR PAPER TASKS IF CALLED UPON FTE-months: -

ACTIVITY ST-3.9-F: SERVING ON A CBC "OTHER PAPER" TEAM

CBC paper team members write or manage CBC papers.

TASK ST-3.9-F(i): ACCEPTING A CBC PAPER TEAM APPOINTMENT OR VOLUNTEERING FOR PAPER TASKS IF CALLED UPON FTE-months: -

ST-3.10 O4a and O4b Catalog of Compact Binaries

Produce a catalog of compact binary coalescence candidate signals observed during O4a and O4b (separately) along with parameter estimates and rate estimates. The catalog would include a binary merger found by a burst search, with template-based parameter estimation.

Motivation and goals

The Catalog represents the list of definitive and marginal compact binary coalescences identified by the LIGO/Virgo/KAGRA Collaborations along with search results, data quality statements, source classification, parameter estimates, and summary statements on tests of general relativity, equation of state inference, and rates and population inference.

Major aspects and methods for this activity

Providing a comprehensive summary of the detected systems will be one of the main publication goals of the CBC group. To this end, we will catalogue our detections made during O4 and release a detailed description of all detected systems, covering their detection and physical parameters, inferred using the best available waveform models.

In O4 data we will conduct a deep search for compact objects from $1\,M_{\odot}$ to a maximum mass dictated by the instrument sensitivity (likely not to exceed $\sim 1000\,M_{\odot}$). For detection, spins aligned with the orbital angular momentum will be considered. For components below 2 $M_\odot$, spin magnitudes up to 0.04 will be searched for. Otherwise, up to maximal spins of 1 will be considered. Three independent search codes, gstlal, pycbc, and MBTA, will be run on the data. In addition, the cWB burst search will be run, which is capable of detecting higher-mass binary black hole systems.

For all signals above a pre-determined threshold, we will provide estimates of the physical parameters of the source using the best available waveform models, including the statistical errors. We will also provide an estimate of the systematic error by comparing parameter estimation using different waveform families or through comparison to numerical relativity simulations. This information is an input to the study of astrophysical rates and distributions.

The published results from this project should represent the best available information on the detected sources during O4, using the latest versions of data quality and calibration at the time of the analysis. In coordination with the Gravitational Wave Open Science Center we will produce an electronic data release to go alongside the publication.

ACTIVITY ST-3.10-A-**OPS**: OFFLINE SEARCHES

Perform searches of gravitational wave data for compact binary coalescences using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK ST-3.10-A(i): GSTLAL PIPELINE OPERATION

FTE-months: 12.0

Offline running of the GstLAL search over O4a and O4b data chunks.

TASK ST-3.10-A(ii): PYCBC PIPELINE OPERATION

FTE-months: 12.0

Offline running of the PyCBC search over O4a and O4b data chunks.

TASK ST-3.10-A(iii): MBTA PIPELINE OPERATION

FTE-months: 6.0

Offline running of the MBTA search over O4a and O4b data chunks.

TASK ST-3.10-A(iv): SPIIR PIPELINE OPERATION

FTE-months: 6.0

Offline running of the SPIIR search over O4a and O4b data chunks.

TASK ST-3.10-A(v): CWB PIPELINE OPERATION

FTE-months: 7.0

Offline running of the cWB search over O4a and O4b data chunks.

ACTIVITY ST-3.10-B-**OPS**: DATA QUALITY

Obtain data quality statements for each detection candidate identified by the offline searches.

TASK ST-3.10-B(i): DETECTOR CHARACTERIZATION ROTA

FTE-months: 2.0

Produce a data quality report for each candidate event. This task is identical to task O.C.2.1 in the LSC-Virgo Operations White Paper.

ACTIVITY ST-3.10-C-**OPS**: OFFLINE PARAMETER ESTIMATION

Perform parameter estimation on significant detection candidates identified by the offline searches, with the goal of using at least two waveform models where possible.

Note: requires calibrated data at times of events.

TASK ST-3.10-C(i): PRODUCTION PARAMETER ESTIMATION ANALYSIS FTE-months: 12.0

Produce final posteriors on events detected in O4 for release and secondary analysis. This analysis will take initial parameter estimation from the rota as an input, and will be initialized, monitored, and curated using automated software systems with expert input.

TASK ST-3.10-C(ii): PARAMETER ESTIMATION EVENT ROTA FTE-months: 12.0

As required, follow up on automated low-latency parameter estimation analysis with further initial runs. The rota will produce preliminary results and analysis settings for production parameter estimation.

TASK ST-3.10-C(iii): PARAMETER ESTIMATION EXPERT ROTA FTE-months: 12.0

Supervise parameter estimation event rota effort, organize regular meetings to monitor rota analysis during assigned period, and certify preliminary results.

TASK ST-3.10-C(iv): PARAMETER ESTIMATION RESULTS CURATION FTE-months: 4.0

Collect the output of parameter estimation, including preferred posterior samples, configuration files, PSDs, calibration envelopes, etc. from required runs for each candidate event. If necessary, produce additional runs and catalog the results in an accessible way for downstream analysis.

TASK ST-3.10-C(v): WAVEFORM RECONSTRUCTION FTE-months: 0.5

Perform waveform reconstruction to enable consistency/residual tests.

ACTIVITY ST-3.10-D-**OPS**: SENSITIVITY ESTIMATION

Provide high-level sensitivity statements for various source categories (BNS, NSBH, BBH, etc.) using common injection sets analyzed by all search pipelines, and applying consistent thresholds on significance (either false alarm rate or astrophysical probability)

TASK ST-3.10-D(i): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR GSTLAL FTE-months: 1.0

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold

TASK ST-3.10-D(ii): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR PYCBC FTE-months: 1.0

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold

TASK ST-3.10-D(iii): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR MBTA FTE-months: 1.0

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold

TASK ST-3.10-D(iv): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR SPIIR FTE-months: 1.0

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold

TASK ST-3.10-D(v): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR CWB FTE-months: 1.0

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold

TASK ST-3.10-D(vi): SENSITIVITY CURATION FTE-months: 1.0

Collect the results from all search pipelines into a standardised format for further analsysis.

ACTIVITY ST-3.10-E-**OPS**: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.10-E(i): PROJECT MANAGEMENT FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.10-E(ii): PAPER WRITING COORDINATION FTE-months: 6.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK ST-3.10-E(iii): FIGURE PREPARATION FTE-months: 3.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.10-E(iv): TABLE PREPARATION FTE-months: 3.0

- Prepare production-quality tables.
- Prepare data-behind-tables for public dissemination.

TASK ST-3.10-E(v): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 1.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY ST-3.10-F-**OPS**: TECHNICAL REVIEW

TASK ST-3.10-F(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0

Coordinate technical review activities.

TASK ST-3.10-F(ii): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of GstLAL search results: candidate lists, background estimation, sensitivity.

TASK ST-3.10-F(iii): REVIEW OF PYCBC PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of PyCBC search results: candidate lists, background estimation, sensitivity.

TASK ST-3.10-F(iv): REVIEW OF MBTA PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of MBTA search results: candidate lists, background estimation, sensitivity.

TASK ST-3.10-F(v): REVIEW OF SPIIR PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of SPIIR search results: candidate lists, background estimation, sensitivity.

TASK ST-3.10-F(vi): REVIEW OF CWB PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK ST-3.10-F(vii): REVIEW OF PARAMETER ESTIMATION RESULTS FTE-months: 3.0

Review of Parameter Estimation results, including posterior samples.

TASK ST-3.10-F(viii): REVIEW OF WAVEFORM RECONSTRUCTION AND CONSISTENCY CHECKS FTE-months: 1.0

Review of Waveform Reconstruction results.

ACTIVITY ST-3.10-G-**OPS**: PAPER REVIEW

TASK ST-3.10-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK ST-3.10-G(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

ACTIVITY ST-3.10-H-**OPS**: DATA FLOW COORDINATION

TASK ST-3.10-H(i): DEVELOPMENT FTE-months: 1.0

Develop methods to coordinate the handling of data products between different analysts

TASK ST-3.10-H(ii): OPERATION FTE-months: 2.0

Operate the data flow coordination tool during the catalogue preparation

Expected products and/or outcomes

- Catalog publication of events in O4a and O4b.
- Strain data release surrounding catalog events in O4a and O4b.
- Posterior samples for catalog events in O4a and O4b.
- Data behind the figures appearing in O4a and O4b Catalog.
- Curated summary of injection analysis results

ST-3.11 O4a and O4b Astrophysical Distribution of Compact Binaries

Determine the astrophysical mass and spin distributions of compact binary systems, and rate estimates for observations up to and including O4b.

Motivation and goals

With the addition of new detections during O4a and O4b, stronger constraints on the BBH, BNS, and NSBH populations are possible and may lead to new insights on compact binary formation and evolution. Three papers will be produced analyzing the compact binary population in O4. A single O4a paper will summarize our knowledge of the binary population after the first half of the fourth observing run, acting as an update to the O3b Astrophysical Distributions Paper. This will be followed by two O4b papers: an O4b "high mass" paper concerning the distribution of binary black holes and an O4b "low mass" paper studying the population of BNS and NSBH events. The activities below are applicable to both the O4a and combined "high" & "low mass" O4b paper efforts.

Major aspects and methods for this activity

ACTIVITY ST-3.11-A-**OPS**: BINARY NEUTRON STAR POPULATION INFERENCE

Inference on the population of binary neutron stars, including "joint" analyses characterizing the combined population of one or more CBC classes. These tasks will contribute towards the O4a and O4b "low mass" Astrophysical Distributions papers.

TASK ST-3.11-A(i): PARAMETRIC BNS POPULATION INFERENCE

FTE-months: 4.0

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for BNS events in the O4a and O4b catalogs.

TASK ST-3.11-A(ii): NON-PARAMETRIC BNS POPULATION INFERENCE

FTE-months: 4.0

Perform non-parametric hierarchical inference using PE posteriors and sensitivity estimates for BNS events in the O4a and O4b catalogs.

ACTIVITY ST-3.11-B-**OPS**: NEUTRON STAR-BLACK HOLE POPULATION INFERENCE

Inference on the population of neutron star-black hole mergers, including "joint" analyses characterizing the combined population of one or more CBC classes. These tasks will contribute towards the O4a and O4b "low mass" Astrophysical Distributions papers.

TASK ST-3.11-B(i): PARAMETRIC NS-BH POPULATION INFERENCE

FTE-months: 4.0

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for NSBH events in the O4a and O4b catalogs.

TASK ST-3.11-B(ii): NON-PARAMETRIC NS-BH POPULATION INFERENCE

FTE-months: 4.0

Perform non-parametric hierarchical inference using PE posteriors and sensitivity estimates for NSBH events in the O4a and O4b catalogs.

ACTIVITY ST-3.11-C-**OPS**: BLACK HOLE MASS DISTRIBUTION

Inference on the mass distribution of binary black holes observed, including "joint" analyses characterizing the combined population of one or more CBC classes. These tasks will contribute towards the O4a and O4b "high mass" Astrophysical Distributions papers.

TASK ST-3.11-C(i): PARAMETRIC INFERENCE OF THE BBH MASS DISTRIBUTION

FTE-months: 5.0

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for BBH events in the O4a and O4b catalogs, using a variety of phenomenological models to extract different physical features.

TASK ST-3.11-C(ii): NON-PARAMETRIC INFERENCE OF THE BBH MASS DISTRIBUTION

FTE-months: 5.0

Produce non-parametric estimates of the BBH mass distribution using PE posteriors and sensitivity estimates for BBH events in the O4a and O4b catalogs.

ACTIVITY ST-3.11-D-**OPS**: REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE POPULATION

Estimate the merger rate and/or ensemble properties of binary black holes as a function of redshift and test for spatial isotropy of mergers. These tasks will contribute towards the O4a and/or O4b "high mass" Astrophysical Distributions papers.

TASK ST-3.11-D(i): INFERENCE ON REDSHIFT EVOLUTION OF THE BBH POPULATION FTE-months: 4.0

Quantify possible evolution of the BBH merger rate and ensemble properties as a function of redshift

TASK ST-3.11-D(ii): MEASUREMENT AND BOUNDS ON ANISOTROPY FTE-months: 2.0

Constrain the spatial (directional) dependence of BBH mergers and quantify any possible anisotropy in spatial distribution or binary orientation.

ACTIVITY ST-3.11-E-**OPS**: BLACK HOLE SPIN DISTRIBUTION

Inference on the spin distributions of binary black hole mergers. These tasks will contribute towards the O4a and O4b "high mass" Astrophysical Distributions papers.

TASK ST-3.11-E(i): PARAMETRIC INFERENCE OF THE BBH SPIN DISTRIBUTION FTE-months: 5.0

Parametrically infer the binary black hole spin distribution using PE posteriors and sensitivity estimates for BBH events in the O4a and O4b catalogs, using a variety of phenomenological models to extract different physical features.

TASK ST-3.11-E(ii): NON-PARAMETRIC INFERENCE OF THE BBH SPIN DISTRIBUTION FTE-months: 3.0

Non-parametrically infer the binary black hole spin distribution using PE posteriors and sensitivity estimates for BBH events in the O4b Catalog.

ACTIVITY ST-3.11-F-**OPS**: MODEL CHECKING AND OUTLIER TESTS

Evaluate the goodness-of-fit of the mass, spin, and redshift distribution models and identify potential outliers in the set of events.

TASK ST-3.11-F(i): COMPARE POSTERIOR PREDICTIVE DISTRIBUTIONS TO OBSERVATIONS FTE-months: 4.0

Check the consistency of the parameterized models with the observations and look for potential tensions between the model and the data.

TASK ST-3.11-F(ii): OUTLIER IDENTIFICATION FTE-months: 4.0

Identify outliers in the population by various methods including leave-one-out analyses to test the robustness of the population results against the targeted exclusion of individual events.

ACTIVITY ST-3.11-G-**OPS**: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.11-G(i): PROJECT MANAGEMENT FTE-months: 1.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.11-G(ii): PAPER WRITING COORDINATION FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.

- Incorporate / address comments.

TASK ST-3.11-G(iii): FIGURE PREPARATION

FTE-months: 2.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.11-G(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 3.0

- Write science summary.
- Prepare data public release on Zenodo, DCC, and/or GWOSC

ACTIVITY ST-3.11-H-**OPS**: TECHNICAL REVIEW

TASK ST-3.11-H(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK ST-3.11-H(ii): REVIEW OF BINARY NEUTRON STAR POPULATION INFERENCE RESULTS

FTE-months: 0.5

Review of the parametric and non-parameteric population inference results.

TASK ST-3.11-H(iii): REVIEW OF THE NEUTRON STAR-BLACK HOLE POPULATION INFERENCE RESULTS

FTE-months: 0.5

Review of the parametric and non-parameteric population inference results.

TASK ST-3.11-H(iv): REVIEW OF BBH MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric and non-parameteric mass distribution results.

TASK ST-3.11-H(v): REVIEW OF REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE POPULATION

FTE-months: 0.5

Review of the non-evolving BBH rate estimation and redshift evolution.

TASK ST-3.11-H(vi): REVIEW OF BLACK HOLE SPIN DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric hierarchical inference of spins.

TASK ST-3.11-H(vii): REVIEW OF MODEL CHECKING RESULTS

FTE-months: 0.5

Review of the posterior predictive checks and outlier analyses, including data behind figures.

ACTIVITY ST-3.11-I-**OPS**: PAPER REVIEW

TASK ST-3.11-I(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Review of scientific content in Astrophysical Distributions paper.

TASK ST-3.11-I(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Astrophysical Distributions paper.

TASK ST-3.11-I(iii): REVIEW OF PUBLIC DATA RELEASE

FTE-months: 0.5

Review of public data release products, the archival of analysis outputs, figure generation scripts, and/or other supplemental data.

Expected products and/or outcomes

- O4a Astrophysical Distributions companion paper.
- O4b "low-mass" Astrophysical Distributions companion paper.
- O4b "high-mass" Astrophysical Distributions companion paper.
- Public hyperposterior samples produced by hierarchical population analyses
- Data products describing the detector sensitivity that can be used for independent population analyses.
- Data behind the figures appearing in the O4a and O4b Astrophysical Distributions papers.

ST-3.12 O4a and O4b Strong-Field Tests of General Relativity

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves, using events in the O4a and O4b catalogs.

Motivation and goals

LIGO's initial crop of binary black hole mergers has allowed us, for the first time, to test the predictions of general relativity in the highly relativistic, strong-field regime [56, 57]. Using these events we set limits on the deviation from the post-Newtonian (PN) description of the inspiral phase, mass of the graviton and dispersion relationship for GWs. Moreover, we have shown that the final remnant's mass and spin are mutually consistent, and that the data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole. With the first detection in O2, we also started constraining dispersive gravitational wave propagation [58]. Additionally, most of these constraints were further improved by combining detections [57, 59].

The first detection of a binary neutron star merger, GW170817 [60], had a long inspiral phase from which we were able to conduct a phenomenological test for dipole radiation and improve the constraints on some other low-order PN coefficients [61]. GW170817 was also detected in conjunction with electromagnetic information, which has given us information beyond what can be measured with just a gravitational-wave signal, such as the redshift of the source and the time difference between the gravitational-wave and electromagnetic signal. These additional pieces of information have allowed us to place tight constraints on the speed of gravity and also constrain some Standard Model Extension coefficients [62]. They have also given us the ability to put constraints on alternative theories of gravity that predict large deviations between the gravitational-wave and electromagnetic signal, and insight into the polarization modes of gravitational waves [61].

In O3, we have also observed events with unequal masses that require descriptions beyond the dominant quadrupole moment [63, 64], allowing us to test additional predictions of GR. We have also made the first NSBH detection and found that it is also consistent with GR. Additionally, we have added additional tests for the consistency of the binary black hole signals with Kerr spin-induced quadrupole moments and of the consistency of the ringdown phase with the predictions for a Kerr black hole, as well as constraints on echoes after the end of the signal, and a more general framework for constraining alternative gravitational wave polarizations [65, 66].

In O4, we expect new detections of BBHs, BNSs, and NSBHs, which will further tighten the existing constraints. There are also a number of new analyses proposed, though we only list the established analyses that have contributed to previous papers below. We also only list single O4a and O4b testing GR papers for simplicity, but plan to split up each of these into three separate papers to keep them from becoming too large and to allow us to better advertise the individual results.

Due to the lack of waveform models arising from alternative theories of gravity, in the near future our phenomenological tests will continue to follow the “top-down" methodology which will allow us to detect deviations from GR, but not necessarily to identify the underlying alternative theory. However, there are efforts underway to provide benchmarks for, e.g., the tests of post-Newtonian coefficients in terms of specific alternative theories and to reinterpret the modified dispersion results in terms of constraints on dark energy theories. Below we list the priority science results anticipated from GW observations in the O4 observing run.

Major aspects and methods for this activity

ACTIVITY ST-3.12-A-**OPS**: CONSISTENCY TESTS OF GR

Look for inconsistency between observed results and GR predictions for the events in the O4a and O4b Catalogs.

TASK ST-3.12-A(i): RESIDUALS TEST

FTE-months: 2.0

Subtract best fit waveforms from data surrounding each event and look for excess residuals. Apply this test to all confident detections.

TASK ST-3.12-A(ii): INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST

FTE-months: 2.0

Compare predicted final mass and spin of each event, as determined from the inspiral, with the values inferred from the post-inspiral stages, according to GR. Apply this test to all confident high-mass BBH events satisfying the test’s selection criteria.

ACTIVITY ST-3.12-B-**OPS**: GRAVITATIONAL-WAVE PROPERTIES

Testing gravitational-wave properties, including generation and propagation, in the O4a and O4b Catalogs.

TASK ST-3.12-B(i): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN INSPIRAL AND POST-INSPIRAL

FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in the inspiral, merger and ringdown stages.

TASK ST-3.12-B(ii): TEST FOR MODIFIED DISPERSION RELATION

FTE-months: 2.0

Perform parameter estimation on all events in the Catalogs while allowing for dephasing potentially caused by a modified dispersion relation.

TASK ST-3.12-B(iii): TEST FOR NON-TENSORIAL POLARIZATIONS

FTE-months: 2.0

Perform model selection between various polarization hypotheses (all combinations of tensor, vector, and scalar) for events observed by at least two detectors.

TASK ST-3.12-B(iv): SPEED OF GRAVITY

FTE-months: 1.0

Constrain the speed of gravity through comparison with the arrival time of a counterpart GRB.

ACTIVITY ST-3.12-C-**OPS**: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Probe the immediate environment of remnant compact objects in O4a and O4b.

TASK ST-3.12-C(i): TESTS OF THE NATURE OF THE MERGER REMNANT

FTE-months: 4.0

Test the nature of the merger remnant through measurements and cross-comparison of various quasi-normal modes.

TASK ST-3.12-C(ii): PROBING THE NEAR-HORIZON STRUCTURE

FTE-months: 2.0

Search for near-horizon effects such as late-time echoes using template-based and model-independent approaches.

ACTIVITY ST-3.12-D-**OPS**: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.12-D(i): PROJECT MANAGEMENT

FTE-months: 4.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.12-D(ii): PAPER WRITING COORDINATION

FTE-months: 4.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK ST-3.12-D(iii): FIGURE PREPARATION

FTE-months: 1.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.12-D(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 2.0

- Write a science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY ST-3.12-E-**OPS**: TECHNICAL REVIEW

TASK ST-3.12-E(i): TECHNICAL REVIEW COORDINATION

FTE-months: 2.0

Coordinate technical review activities.

TASK ST-3.12-E(ii): REVIEW OF RESIDUALS TEST

FTE-months: 0.5

Review of the residuals consistency test results.

TASK ST-3.12-E(iii): REVIEW OF IMR TEST

FTE-months: 0.5

Review of the IMR consistency test results.

TASK ST-3.12-E(iv): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE GENERATION

FTE-months: 0.5

Review of the parameterized test of gravitational wave generation results.

TASK ST-3.12-E(v): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 0.5

Review of the modified dispersion relation test results.

TASK ST-3.12-E(vi): REVIEW OF POLARIZATION TEST

FTE-months: 0.5

Review of the polarization test results.

TASK ST-3.12-E(vii): REVIEW OF SPEED OF GRAVITY

FTE-months: 0.5

Review of the speed of gravity analysis.

TASK ST-3.12-E(viii): REVIEW OF QUASI-NORMAL MODES TESTS

FTE-months: 0.5

Review of the quasi-normal modes tests' results.

TASK ST-3.12-E(ix): REVIEW OF SEARCH FOR LATE TIME ECHOES

FTE-months: 0.5

Review of the search for late time echoes results.

TASK ST-3.12-E(x): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY ST-3.12-F-**OPS**: PAPER REVIEW

TASK ST-3.12-F(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in O4a and O4b Testing GR companion papers.

TASK ST-3.12-F(ii): EDITING

FTE-months: 0.5

Editorial Board review of paper quality in O4a and O4b Testing GR companion papers.

Expected products and/or outcomes

- O4a Testing GR companion paper.
- Posterior samples from each analysis in O4a Testing GR paper.
- Data behind the figures appearing in O4a Testing GR paper.
- O4b Testing GR companion paper.
- Posterior samples from each analysis in O4b Testing GR paper.
- Data behind the figures appearing in O4b Testing GR paper.
- Low-latency speed of gravity paper (if there is a high-significance detection with a GRB counterpart)

ST-3.13 O4a and O4b Inference of Cosmological Parameters with Observational Data

Measure cosmological parameters, in particular the Hubble constant, using both GW events for which a reliable EM counterpart is observed and an associated redshift measurement is obtained, and statistical associations with a galaxy catalog and/or features in the source population mass distribution for events without EM counterparts.

Motivation and goals

Gravitational waves from the binary neutron star merger GW170817 along with its uniquely identified host galaxy led to a first "standard siren" measurement of the Hubble parameter independent of the cosmological distance ladder. The identification of the host galaxy was possible because of the coincident optical counterpart to GW170817. Similar observations in O4 of binaries involving a neutron star with identified electromagnetic counterparts will improve the precision of the measurement. The statistical method of combining gravitational-wave distance estimates with catalogues of potential host galaxies, as well as the population method employing features of the mass distribution of GW sources to infer cosmological constraints, are expected to provide observational results once a significant number of events have been observed in O4 and have been reported in the associated O4(a/b) catalog (i.e., towards the second half of 2023 or later). There may be an exception for particularly well-localised GW events, or events for which an EM counterpart (which cannot be associated with a specific host galaxy) allows the sky localisation of the event to be significantly improved. The main results from the two methods mentioned above, statistical and mass features method, will be used to provide a new update on the constraint of H_0 and, where possible, other cosmological parameters following O4(a/b).

Major aspects and methods for this activity

ACTIVITY ST-3.13-A-**OPS**: MEASUREMENT OF COSMOLOGICAL PARAMETERS

Obtain a combined estimate on cosmological parameters, in particular on H_0, from compact binaries with identified electromagnetic counterparts.

TASK ST-3.13-A(i): COUNTERPART ONLY MEASUREMENT OF COSMOLOGICAL PARAMETERS FROM O4

FTE-months: 6.0

Analyze events with EM counterparts to obtain a joint measurement on the Hubble constant, and if possible on other cosmological parameters.

TASK ST-3.13-A(ii): STATISTICAL ONLY MEASUREMENT OF H_0 FROM O4

FTE-months: 12.0

Analyze events without EM counterparts to obtain a joint statistical measurement on the Hubble constant, other cosmological parameters (where possible), and GW population parameters from O4 data.

TASK ST-3.13-A(iii): ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

FTE-months: 6.0

Investigate the effect of potential systematic uncertainties on statistical measurements of cosmological parameters, by varying parameters such as the luminosity function, the GW mass model, galaxy catalog observation band, etc.

ACTIVITY ST-3.13-B-**OPS**: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.13-B(i): PROJECT MANAGEMENT

FTE-months: 4.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.13-B(ii): PAPER WRITING COORDINATION FTE-months: 6.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK ST-3.13-B(iii): FIGURE PREPARATION FTE-months: 2.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.13-B(iv): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 1.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY ST-3.13-C-**OPS**: TECHNICAL REVIEW

TASK ST-3.13-C(i): TECHNICAL REVIEW COORDINATION FTE-months: 3.0

Coordinate technical review activities.

TASK ST-3.13-C(ii): REVIEW OF MEASUREMENTS OF COSMOLOGICAL PARAMETERS FTE-months: 4.0

Review of all cosmological measurements, with or without EM counterparts, including review of posterior sample chains and systematic uncertainty studies. In particular review of results of the O4(a/b) cosmology paper and possible O4 EM counterpart papers.

ACTIVITY ST-3.13-D-**OPS**: PAPER REVIEW

TASK ST-3.13-D(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in cosmological papers.

TASK ST-3.13-D(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in cosmological papers.

Expected products and/or outcomes

- O4(a/b) cosmology companion paper (review and publication).
- Data behind the results and figures appearing in the O4(a/b) cosmology paper.
- Cosmological results for O4 EM counterpart CBC paper(s) + associated data.

ST-3.14 O4a and O4b Search for Lensed Gravitational Waves

Search for gravitational-wave lensing signatures following O4a and O4b

Motivation and goals

Gravitational waves can be gravitationally lensed by intervening galaxies, galaxy clusters, or smaller lenses such as compact objects. Lensing can result in multiple images separated in time, and modifications to the waveform due to microlensing. Here we will look for signatures of lensing in O4 data.

Major aspects and methods for this activity

ACTIVITY ST-3.14-A: MULTIPLE IMAGE ANALYSES

Search for evidence that two or more gravitational wave observations might have a common lensed source.

TASK ST-3.14-A(i): RAPID IDENTIFICATION WITH MACHINE LEARNING FTE-months: 2.0

Use machine learning techniques to rapidly identify lensed candidate pairs.

TASK ST-3.14-A(ii): POSTERIOR OVERLAP ANALYSIS FTE-months: 2.0

Analyze all the O4 events to identify lensed multi-image candidate pairs using a fast posterior-overlap-based method.

TASK ST-3.14-A(iii): FACTORIZED JOINT PARAMETER ESTIMATION FTE-months: 4.0

Perform factorized joint parameter estimation on event pairs by replacing the prior in the second event analysis with the posterior of the first event and pre-computing waveforms.

TASK ST-3.14-A(iv): JOINT PARAMETER ESTIMATION ANALYSES FTE-months: 4.0

Perform joint parameter estimation on event pairs to compute the Bayes factor of lensed vs. unlensed hypotheses.

TASK ST-3.14-A(v): SUB-THRESHOLD SEARCH FTE-months: 4.0

Search for sub-threshold candidates that could be lensed images associated with other, confidently detected events.

TASK ST-3.14-A(vi): TYPE II IMAGE SEARCH FTE-months: 2.0

Search for waveform distortions induced in type II images

TASK ST-3.14-A(vii): LENS MODEL SELECTION FTE-months: 1.0

For any candidate lensed events, utilize model selection to determine the properties of the gravitational lens.

TASK ST-3.14-A(viii): ASSESSMENT OF UNCERTAINTIES FTE-months: 2.0

Investigate the systematic uncertainties of the methods targeting multiple images through mock data studies and investigations of waveform systematics.

ACTIVITY ST-3.14-B: INTERFERENCE AND WAVE-EFFECTS

Search for evidence of frequency-dependent distortion of signals that could arise from lensing either by isolated or a population of small lenses.

TASK ST-3.14-B(i): SEARCH FOR MICROLENSING EFFECTS FTE-months: 4.0

Perform parameter estimation on events to determine if there is evidence of microlensing distortions.

TASK ST-3.14-B(ii): SEARCH FOR MILLILENSING EFFECTS FTE-months: 3.0

Perform parameter estimation on events to determine if there is evidennce of milli-imaging of gravitational waves.

TASK ST-3.14-B(iii): MICROLENSING AND MILLILENSING ANALYSIS OF STRONG LENSING CANDIDATES

FTE-months: 3.0

For any candidate strongly lensed event, combine the strong lensing images to study microlensing.

TASK ST-3.14-B(iv): ASSESSMENT OF UNCERTAINTIES

FTE-months: 2.0

Investigate the systematic uncertainties of the methods targeting distorted signals through mock data studies and investigations of waveform systematics.

ACTIVITY ST-3.14-C: INFERENCE ON LENS AND SOURCE POPULATIONS

The objective is to derive the rate of observable strong gravitational-wave lensing and to derive constraints on the lensed event rates and populations based on the (non-)detection of gravitational-wave lensing.

TASK ST-3.14-C(i): GRAVITATIONAL-WAVE LENSING RATES BASED ON KNOWN MODELS

FTE-months: 2.0

Estimate the gravitational-wave lensing rate and multi-image time-delays based on current knowledge of the populations of binary black holes and lenses. This will enable us to estimate the prior odds of gravitational-wave lensing, which is useful as input for joint parameter estimation.

TASK ST-3.14-C(ii): DERIVE BOUNDS ON GRAVITATIONAL-WAVE LENSING

FTE-months: 2.0

Use the (non-)detection of lensed gravitational waves and limits from the stochastic background, to set constraints on the gravitational-wave lensing rate and the population of lensed binaries.

TASK ST-3.14-C(iii): CONSTRAIN COMPACT DARK MATTER

FTE-months: 2.0

Using the microlensing search results, set constraints on the compact dark matter fraction.

ACTIVITY ST-3.14-D: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.14-D(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.14-D(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK ST-3.14-D(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.14-D(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 1.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY ST-3.14-E-**OPS**: TECHNICAL REVIEW

TASK ST-3.14-E(i): TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

FTE-months: 1.0

TASK ST-3.14-E(ii): REVIEW OF POSTERIOR OVERLAP ANALYSIS

Review of the posteror overlap analysis study.

FTE-months: 0.5

TASK ST-3.14-E(iii): REVIEW OF MACHINE LEARNING ANALYSIS

Review of the machine learning analysis study.

FTE-months: 0.5

TASK ST-3.14-E(iv): REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION ANALYSES

Review of the factorized joint parameter estimation analyses.

FTE-months: 0.5

TASK ST-3.14-E(v): REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES

Review of the posterior samples from the factorized joint parameter estimation analyses.

FTE-months: 0.5

TASK ST-3.14-E(vi): REVIEW OF JOINT PARAMETER ESTIMATION ANALYSES

Review of the joint parameter estimation analyses.

FTE-months: 0.5

TASK ST-3.14-E(vii): REVIEW OF JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES

Review of the posterior samples from the joint parameter estimation analyses.

FTE-months: 0.5

TASK ST-3.14-E(viii): REVIEW OF SUB-THRESHOLD SEARCH

Review of the sub-threshold search for lensed images.

FTE-months: 1.0

TASK ST-3.14-E(ix): REVIEW OF TYPE II IMAGE SEARCHES

Review of the type II image search.

FTE-months: 1.0

TASK ST-3.14-E(x): REVIEW OF MICROLENSING STUDIES

Review of the search for microlensing effects and associated posterior samples.

FTE-months: 1.0

TASK ST-3.14-E(xi): REVIEW OF MILLILENSING STUDIES

Review of the search for millilensing effects and associated posterior samples.

FTE-months: 1.0

TASK ST-3.14-E(xii): REVIEW OF POPULATION INFERENCE STUDIES

Review of the studies of lensing statistics.

FTE-months: 0.5

ACTIVITY ST-3.14-F-**OPS**: PAPER REVIEW

TASK ST-3.14-F(i): REVIEW OF PAPER SCIENTIFIC CONTENT

Publications & Presentations review of scientific content in the lensing paper.

FTE-months: 0.5

TASK ST-3.14-F(ii): EDITING

Editorial Board review of paper quality in the lensing paper.

FTE-months: 0.2

Expected products and/or outcomes

- O4a and O4b Lensing companion paper.
- Posterior samples from joint parameter estimation analyses.
- Data behind the figures appearing in the O4a and O4b Lensing paper.

ST-3.15 O4a and O4b Search for Sub-Solar-Mass Compact Binary Coalescences

Search for compact binary coalescences with a component having mass below a solar mass

Motivation and goals

Compact objects with masses below $\sim 1\ M_{\odot}$ are not expected to be generated as endpoints of stellar evolution. The lowest mass neutron stars are expected to have masses above the Chandrasekhar mass [67] less the gravitational binding energy. Current models and observations place the minimum neutron star mass near $\sim 1.15\ M_{\odot}$ [68, 69, 70]. The lightest black holes are constrained by the maximum non-rotating neutron star mass, which is currently believed to be $\sim 2\ M_{\odot}$ [71].

There are several models that predict the formation of sub-solar mass black holes. One class posits that sub-solar mass primordial black holes could have formed via the prompt collapse of large overdensities in the early universe [72]. The size and abundance of primordial black holes is closely related to the early universe equation of state and the scale of the primoridal perturbations [73, 74, 75, 76]. Another class of models links sub-solar mass black holes to particulate dark matter, either via a complex particle spectrum [77] or nuclear interactions with neutron stars [78, 79, 80, 81, 82, 83, 84].

O4 deliverables

- Carry out a thorough search for sub-solar mass compact binary mergers in O4 data

ACTIVITY ST-3.15-A: O4 SEARCH FOR SUB-SOLAR MASS COMPACT BINARY MERGERS

TASK ST-3.15-A(i): DETERMINE SEARCH PARAMETERS

FTE-months: 1.0

Design, generate, and test coverage of a bank of template waveforms for sub-solar mass compact binaries.

TASK ST-3.15-A(ii): RUN SEARCH PIPELINE

FTE-months: 5.0

Carry out a matched filter based search using the template bank designed to recover sub-solar mass compact binaries.

ACTIVITY ST-3.15-B: INTERPRETATIONS OF SEARCH RESULTS

In the event of a detection, we will perform parameter estimation. For a null result, we will provide rate upper limits and discuss other ways to meaningfully present constraints on the abundance of sub-solar mass compact objects/binaries.

TASK ST-3.15-B(i): RATE ESTIMATION

FTE-months: 2.0

For a null result, we will provide rate upper limits and discuss other ways to meaningfully present constraints on the abundance of sub-solar mass compact objects/binaries.

TASK ST-3.15-B(ii): PARAMETER ESTIMATION

FTE-months: 2.0 ((only for detection))

In the event of a detection, we will perform parameter estimation.

ACTIVITY ST-3.15-C: EDITORIAL TEAM

Paper project management and writing.

TASK ST-3.15-C(i): PROJECT MANAGEMENT

FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK ST-3.15-C(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK ST-3.15-C(iii): FIGURE PREPARATION

FTE-months: 1.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK ST-3.15-C(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 1.0

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY ST-3.15-D-**OPS**: TECHNICAL REVIEW

TASK ST-3.15-D(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK ST-3.15-D(ii): REVIEW OF SEARCH RESULTS

FTE-months: 1.0

Review of search results: candidate lists, background estimation, sensitivity.

TASK ST-3.15-D(iii): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES

FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY ST-3.15-E-**OPS**: PAPER REVIEW

TASK ST-3.15-E(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK ST-3.15-E(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

ST-3.16 Characterizing exceptional CBC events

Prepare / write a paper to discuss in detail any compact binary coalescence that is deemed to be of particular relevance and meriting its own publication. This complements the catalog concept. (This paper could include Burst content if found by a burst search.)

Motivation and goals

In future observing runs, we expect to detect a broad range of compact object merger scenarios. A fraction of these will be exceptional events in the context of previous observations. Such systems will warrant specific attention to be determined only once confirmed. Further, there is a possibility that the first detection of CBC signals with KAGRA can be achieved during O4 altough it depends on the sensitivity KAGRA can achieve. If that happens, it is a major milestone of KAGRA and the gravitational wave astronomy.

Some examples of exceptional events would be one that yields:

- a binary with a sub-solar-mass component;
- other astrophysically interesting component masses (large mass ratio, large black hole mass, large neutron star mass, etc.);
- clear statement on neutron star equation of state;
- measurement of a high-spin system;
- clear evidence of orbital eccentricity;
- a multi-messenger counterpart (externally-triggered or in electromagnetic/neutrino follow-up searches);
- substantial improvement in the measurement of the Hubble constant;
- clear evidence of deviation from general relativity;
- a gravitationally lensed gravitational wave detection;
- clear indication of a particular formation channel.
- first detection with KAGRA.

Major aspects and methods for this activity

Activities and tasks will come into scope upon the identification of an exceptional event. Here we give a generic placeholder for future accounting purposes.

ACTIVITY ST-3.16-A-**OPS**: AD HOC ACTIVITY

Placeholder for an ad hoc activity. Activities will be defined upon the occurrence of an exceptional event.

TASK ST-3.16-A(i): AD HOC TASK

Placeholder for an ad hoc task. Tasks will be defined upon the occurrence of an exceptional event.

FTE-months: 12.0 (12 months per exceptional event paper)

Expected products and/or outcomes

A detailed analysis of exceptional events with parameter estimation and astrophysical interpretation.

4 CW Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Stochastic group in section 10. For these activities, some combination of data from LIGO, Virgo and KAGRA will be used as deemed appropriate in each case.

ST-4.1 Targeted searches for known pulsars

Motivation

Rapidly spinning neutron stars in our galaxy may emit CWs if they are not perfectly symmetric about their spin axis. Our searches target a subset of sources for which pulses are observed in radio, X-ray, or other electromagnetic radiation bands. Pulsar timing through electromagnetic observations can tell us precise sky positions, frequencies, frequency evolution, and binary orbital parameters (if applicable) of these objects, so that targeted analyses need search only a small parameter space (sometimes only a single phase template) and are not computationally limited. Electromagnetic observations also set an upper limit on the GW strain we could see from a known pulsar, by assuming that all of its observed spin-down is due to GW emission (see Equation 5 of [85]).

The standard searches assume GW emission from a triaxial neutron star, with the electromagnetic and GW components rotating as one unit. This would lead to GW emission at twice the rotation frequency ($2f$) of the star. Detecting such emission would represent the first ever measurement of the difference between the two (equatorial) components of the inertia tensor. This would provide important information on the strength and strain profile of the solid phase of the star (the crust, or possibly a solid core) and/or information on the nature of the internal magnetic field. Emission from other mechanisms is possible and can lead, for example, to a signal at a star's rotation frequency, f [86]. Hence, we also search for signals at either f, or both f and $2f$, whose detection would give further insight into the coupling between the crust and core of a neutron star.

Traditional searches for CWs targeted at known pulsars assume that sources emit the tensorial plus and cross GW polarizations predicted by the general theory of relativity. It is conceivable, however, that due to a departure from general relativity neutron stars may generate scalar and vector polarizations, on top or instead of tensor ones. If so, power in those extra modes would have been largely missed by standard targeted searches. In contrast, a search for non-tensorial continuous signals from known pulsars would be capable of detecting and classifying those alternative modes in a theory-independent way [87, 88, 89].

Generic metric theories of gravity may support up to six gravitational polarizations: two scalar modes (breathing and longitudinal), two vector modes (x and y) and two tensor modes (plus and cross). Because general relativity makes the unambiguous prediction that only the two tensor modes may exist, the presence of any of the tensorial modes, no matter how weak, would be fatal for the theory. Although it is not possible to use the current LIGO–Virgo network to carry out this important test of general relativity with transient signals, this can be done with long-lived CWs.

Methods

Three mature analysis pipelines for targeted searches are the time-domain Bayesian pipeline [90, 91], the 5-vector method [92], and the time-domain $\mathcal{F}/\mathcal{G}$-statistic method [85]. All three pipelines will be used for high-value targets for which the spin-down limit can be, or could nearly be, surpassed. The remaining sources will be searched for with the time-domain Bayesian pipeline. Searches will target emission at both f and $2f$. For calculating realistic values of the spin down limits, using improved intrinsic spin frequency derivative values, work by [93] can be used.

One search for non-tensorial CWs from known pulsars expands the time-domain Bayesian targeted analysis [90] to be sensitive to signals of any polarization content at a given frequency, without assuming any specific theory of gravity or emission mechanism. If a signal is detected, rigorous Bayesian methods will allow us to determine whether there is evidence of a departure from general relativity. Another search for scalar GW radiation predicted by Brans-Dicke theory adapts the $\mathcal{F}$-statistic to search for this particular GW signal.

Activities for O4

ACTIVITY ST-4.1-A-**OPS**: EARLY-O4 HIGH-VALUE TARGETED PULSAR SEARCHES

A selection of the most promising targets, consisting of both millisecond and young pulsars, will be targeted using the first six months of data from the O4 run. This will lead, for example, to surpassing the spin-down limit for PSR J0737−3039A, the mildly recycled pulsar in the famous "double pulsar" system, and producing limits on the ellipticity of a handful of MSPs to levels of just a few $\times 10^{-9}$. We will produce a paper, aimed at a high profile journal, describing a search for signals from these selected targets.

TASK ST-4.1-A(i): OBTAIN PULSAR EPHEMERIDES FTE-months: 3.0

Obtain timing ephemerides from electromagnetic observers for the selected pulsars that are coherent over the run.

TASK ST-4.1-A(ii): RUN TIME-DOMAIN BAYESIAN PIPELINE FTE-months: 3.0

Run the time-domain Bayesian pipeline on the selected targets, searching at the two harmonics of the pulsar spin frequency: f and $2f$.

TASK ST-4.1-A(iii): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE FTE-months: 3.0

Search for GWs from the selected pulsars analyzing data from the network of detectors (LIGO, Virgo and KAGRA). Search at two harmonics of the pulsar spin frequency: f and $2f$.

TASK ST-4.1-A(iv): RUN THE 5-VECTOR PIPELINE FTE-months: 3.0

Search for GWs from the selected pulsars. Independent searches at f and $2f$.

TASK ST-4.1-A(v): WRITE PAPER FTE-months: 3.0

Write a paper describing the results of the search, with an emphasis on the astrophysical significance of surpassing the spin-down limit for any pulsars.

ACTIVITY ST-4.1-B-**OPS**: FULL-O4 TARGETED PULSAR SEARCHES

As with previous runs (e.g. [94, 89]), we will perform a search for all pulsars with rotation frequencies greater than 10 Hz for which we have a reliable timing ephemeris spanning the run. The search will target emission at either, or both, once and twice the stellar rotation frequency. From the results we will make inferences on the underlying ellipticity distributions of populations of pulsars.

TASK ST-4.1-B(i): OBTAIN PULSAR EPHEMERIDES FTE-months: 3.0

Obtain timing ephemerides from electromagnetic observers for pulsars with rotation frequencies greater than 10 Hz that are coherent over the run.

TASK ST-4.1-B(ii): RUN TIME-DOMAIN BAYESIAN PIPELINE FTE-months: 3.0

Run the time-domain Bayesian pipeline on all the targets.

TASK ST-4.1-B(iii): RUN THE 5-VECTOR PIPELINE FTE-months: 3.0

Search for GWs from all the pulsars for which updated ephemerides will be available. Independent searches at f and $2f$.

TASK ST-4.1-B(iv): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE FTE-months: 3.0

Search for GWs from the tens of known pulsars for which the spin-down limit can be surpassed or nearly surpassed. Analyze data from the network of detectors. Search at two harmonics of the pulsar spin frequency.

TASK ST-4.1-B(v): POPULATION INFERENCE CODE DEVELOPMENT AND REVIEW FTE-months: 3.0

Review the code to be used to perform the population inference on the pulsar ellipticity distributions.

TASK ST-4.1-B(vi): POPULATION INFERENCE FTE-months: 3.0

Perform population inference on the ellipticity distribution of pulsars, splitting the population between "young" and millisecond pulsars.

TASK ST-4.1-B(vii): WRITE PAPER FTE-months: 3.0

Write a paper describing the results of the search.

ACTIVITY ST-4.1-C-**OPS**: O4 TARGETED PULSARS NON-TENSORIAL ANALYSIS

We will perform a search for CW signals from a selection of known pulsars in which we allow their polarization state to contain non-tensorial modes. This search will be performed on data using the same set of pulsars as for the standard targeted pulsar search (Section ST-4.1). It will expand upon the analysis done on previous data by allowing the signals to have emission at both once and twice the source rotation frequency.

TASK ST-4.1-C(i): CODE UPDATE FTE-months: 1.0

Update the Bayesian parameter estimation code to allow the inclusion of components of the non-tensorial signal at both f and $2f$.

TASK ST-4.1-C(ii): CODE REVIEW FTE-months: 1.0

Review the code updates to confirm they perform as expected.

TASK ST-4.1-C(iii): RUN TIME-DOMAIN BAYESIAN PIPELINE FTE-months: 3.0

Run the time-domain Bayesian pipeline on all targets, making use of the pulsar ephemerides and heterodyned data products already obtained for the standard known pulsar search.

TASK ST-4.1-C(iv): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE FTE-months: 3.0

For around 30 known pulsars for which the spin down limit can be surpassed or nearly surpassed, search for for scalar radiation predicted by Brans-Dicke theory.

TASK ST-4.1-C(v): PAPER CONTRIBUTION FTE-months: 1.0

Add these results to the full targeted search paper.

ST-4.2 Narrow-band searches for known pulsars

Motivation

These searches are an extension of targeted searches for known pulsars (Section ST-4.1) in which the position of the source is assumed to be accurately known while allowing for uncertainties in the rotational parameters [95]. This type of search is generally computationally heavier with respect to targeted searches, but still cheaper than directed or all-sky searches. In general, narrow-band searches allow one to take into account a possible mismatch between the CW signal parameters and the rotation parameters inferred from electromagnetic observations. For instance, the GWs could be emitted by the core of the neutron star which may have a slightly different rotational frequency with respect to the magnetosphere.

Methods

Two pipelines, one based on the 5-vector method [96] used in targeted searches, and one based on the frequency-domain $\mathcal{F}$-statistic [97], can be used for narrow-band searches. The basic idea is to explore a range of frequency and spin-down values around the electromagnetic-derived values by properly applying barycentric and spin-down corrections to the data in such a way that a signal would appear as monochromatic apart from the sidereal modulation. Of the order of 10^7 points in the parameter space are typically explored in a narrow-band search.

Activities for O4

ACTIVITY ST-4.2-A-**OPS**: EARLY-O4 SEARCHES

Using 4 months and then 8 months of data, we will search for CWs from known pulsars for which we expect to surpass or approach the spindown limit. If no updated ephemeris will be available, we will use the ones of O3 propagated to an O4 reference time.

TASK ST-4.2-A(i): RUN SEARCHES

FTE-months: 3.0

Run the search using the 5-vector method and the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK ST-4.2-A(ii): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 3.0

Check for the presence of noise lines close to each outlier taking into account the modulation due to the motion of the Earth.

TASK ST-4.2-A(iii): OUTLIERS FOLLOWUP – TARGETED SEARCHES

FTE-months: 3.0

Check the nature of the outliers by performing several targeted searches using more and more data for each outlier. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary. Follow-ups with other analysis methods, including those testing for transient properties, should also be performed (see Section ST-4.15).

TASK ST-4.2-A(iv): SENSITIVITY STUDIES

FTE-months: 3.0

We will compute upper limits on CW emission from a subset of the pulsars in different frequency bands, in order to check our sensitivity.

TASK ST-4.2-A(v): REVIEW SEARCH RESULTS

FTE-months: 1.0

Review of any updated part of the codes and the search results.

TASK ST-4.2-A(vi): PUBLISH RESULTS

FTE-months: 1.0

Results will be either included in the O4a high-value pulsars paper together with targeted search results, or as comparison results in the full-O4 narrow-band paper.

ACTIVITY ST-4.2-B-**OPS**: FULL-O4 NARROW-BAND SEARCHES

We will search for CWs from ∼40 known pulsars for which we expect to surpass or approach the spindown limit using the entire data. If no interesting outliers are present, we will set upper limits on GW strain. We expect to surpass the spindown limit for 4–5 additional pulsars at frequencies lower than 100 Hz and to improve our previous constraints in [98, 99].

TASK ST-4.2-B(i): RUN SEARCHES

FTE-months: 3.0

Run the search using the 5-vector method and the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK ST-4.2-B(ii): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 3.0

Check for the presence of noise lines close to each outlier taking into account the modulation due to the motion of the Earth. Compare the outliers with the Early searches outliers.

TASK ST-4.2-B(iii): OUTLIERS FOLLOWUP – TARGETED SEARCHES

FTE-months: 3.0

Check the nature of the outliers by performing several targeted searches using more and more data for each. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary, and do follow-ups with other analysis methods, including those testing for transient properties (see Section ST-4.15).

TASK ST-4.2-B(iv): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, we will put upper limits on GW strain.

TASK ST-4.2-B(v): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review of any updated part of the codes and the search results.

TASK ST-4.2-B(vi): PUBLICATION

FTE-months: 3.0

Produce a publication with the results of each pipeline.

ST-4.3 Searches for r-modes from known pulsars

Motivation

PSR J0537–6910 is a young (1–5 kyrs) energetic X-ray pulsar, rotating at a spin frequency $\nu = 62$ Hz [100], in the Large Magellanic Cloud at a distance of 49.6 kpc [101]. PSR J0537–6910 (hereafter J0537) has been the subject of a number of studies, starting from its first detection with the *Rossi X-ray Timing Explorer* (*RXTE*; [102]) up to recent observations starting in 2017 with the *Neutron Star Interior Composition Explorer* (*NICER*; [103]). J0537 is intriguing for several reasons. Not only is it the fastest spinning young pulsar known, but measurements of its spin evolution also reveal J0537 to be the most prolific glitcher known. J0537 is, however, unique, as it is the only glitching pulsar that shows a strong correlation between the size of a glitch and the waiting time to the next glitch [104, 105, 106, 107], which suggests that a threshold has to be reached to trigger the glitch mechanism (see [108] for a review of pulsar glitch models). One can try to understand the impact of glitches on the spin evolution of J0537 by comparing its long-term spin evolution, i.e., the trend over a number of years and consequently over many glitches, to its short-term spin evolution between glitches. [105] studied the spin evolution over a 13-year span of *RXTE* data (1999–2011) and determined a long-term second frequency derivative $\ddot{\nu} = -7.7 \times 10^{-22}$ Hz s^{-2} (and $\dot{\nu} \approx -1.99 \times 10^{-10}$ Hz s^{-1}), which leads to a braking index $n = \nu\ddot{\nu}/\dot{\nu}^2 = -1.22 \pm 0.04$. Similar estimates were obtained by [106] and more recently by [107] The braking index n is obtained by assuming a power-law spin-down mechanism for the neutron star of the form $\dot{\nu} \propto -\nu^n$, where $n = 3$ if magnetic dipole radiation (at constant magnetic field strength and inclination) is the dominant spin-down mechanism. A negative value of n thus describes an unusual spin evolution, which may be a consequence of the cumulative effect of glitches during the more than 20-year time span of monitoring observations since 1999 (see discussions in [105, 107]). In order to test this hypothesis, it is of interest to study the braking index between glitches. This allows us to understand if, far from a glitch, it is possible to extract an 'intrinsic' braking index that can provide information on the physical spin-down mechanism for J0537. A detailed analysis of post-glitch relaxations shows that, while the inter-glitch braking index is large for days after a glitch, it tends to an asymptotic value of $n \approx 7.4$ for longer times [109]. Similar values of n are also obtained independently by [106] and from analysis of recent *NICER* observations [107, 110]. Such a value may be indicative of the spin evolution of J0537 not being driven by electromagnetic wave emission but by gravitational-wave (GW) emission due to a constant amplitude r-mode oscillation for which $n \approx 7$ [109]. Furthermore previous theoretical analysis of the r-mode instability curve have already singled out J0537 as young enough to be in the region of parameter space where the r-mode is unstable and emitting GWs [111], thus providing additional motivation for the search.

Methods

There are two mature pipelines to perform the r-mode search from pulsar J0537: the 5-vector method and time domain $\mathcal{F}/\mathcal{G}$-statistic method. Both methods involve coherent analysis of the data between the glitches of the pulsar. As the position of J0537 is known very accurately, a directed search is performed and the pipelines search a parameter space of frequency and frequency derivatives. The r-mode GW emission frequency $f_{\rm GW}$ depends on the pulsar spin frequency ν and on the neutron star structure (e.g., [112, 113]). We adopt search parameter ranges in frequency recently updated in [**?**] and its derivatives following the analysis of [114]. The 5-vector method also involves incoherent addition of the statistic from the coherent analysis of inter-glitch segments, whereas the $\mathcal{F}/\mathcal{G}$-statistic method searches also for the second frequency derivative. Both methods were used in the search for r-mode GW emission from J0537 in O3 data [115] using the timing obtained from the *NICER* mission.

Activities for O4

ACTIVITY ST-4.3-A-**OPS**: O4 SEARCH FOR R-MODES FROM PSR J0537−6910

We perform the search for r-mode GW emission from J0537 using the two pipelines and using the ephemeris of J0537 from the *NICER* mission.

TASK ST-4.3-A(i): OBTAIN EPHEMERIS OF J0537

FTE-months: 3.0

Obtain the ephemeris of J0537 from the *NICER* mission observations covering the whole O4 data span.

TASK ST-4.3-A(ii): RUN THE 5-VECTOR PIPELINE

FTE-months: 3.0

TASK ST-4.3-A(iii): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

FTE-months: 3.0

TASK ST-4.3-A(iv): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 1.0

Check for the presence of noise lines close to each outlier taking into account the modulation due to the motion of the Earth.

TASK ST-4.3-A(v): OUTLIERS FOLLOWUPS

FTE-months: 1.0

Check the nature of the outliers by performing targeted searches and other pipelines (see Section ST-4.15). Compare these results with software injections if necessary.

TASK ST-4.3-A(vi): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, we will set upper limits on the GW emission from r-modes, upper limits on the r-mode amplitude and constraints on the mass of pulsar J0537.

TASK ST-4.3-A(vii): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review of any updated part of the codes and the search results.

TASK ST-4.3-A(viii): PUBLICATION

FTE-months: 3.0

Produce a joint publication with the results of each pipeline.

ST-4.4 Directed searches targeting Galactic supernova remnants

Motivation

Young neutron stars may be the strongest isolated radiators of gravitational waves. Supernova kicks indicate that neutron stars are born with some asymmetry, and spin-downs of young pulsars are generally more rapid than those of old pulsars, allowing for more gravitational wave emission as a possible part of that spin-down. Mountains may settle on long timescales with no plate tectonics to revive them, and r-modes (long-lived fluid oscillations) eventually succumb to viscosity as the star cools. Many of the youngest neutron stars in the galaxy are known not as pulsars, but as non-pulsing X-ray point sources embedded in young supernova remnants, such as the current record holder Cassiopeia A at ~ 300 years old. Small pulsar wind nebulae and extremely young supernova remnants without true point sources, e.g., SNR 1987A, also merit consideration.

For these targets the sky direction is known but there is no timing solution, so the searches cover wide bands of frequency (hundreds of Hz) and frequency derivatives. The parameter space is still small enough compared to all-sky surveys that time spans of order one-to-several weeks can be coherently integrated; and semi-coherent techniques can integrate longer time spans.

Methods

Most previous searches have been based on the $\mathcal{F}$-statistic [116], either as fully coherent [117, 118, 119] or semi-coherent [120] methods. Hidden Markov model techniques can also be used to track the unknown signal frequency in a young supernova remnant as it wanders due to secular spin-down and un-modeled stochastic timing noise [121], and are a computationally cheap supplement to other techniques. An extended application of the hidden Markov model technique allows tracking both once and twice the spin frequency of the star, producing better sensitivities in the case that the signal contains two frequency components [122].

Another way of looking for these signals is to use the FrequencyHough transform as already done for all-sky searches. A re-adaptation of the full all-sky Frequency Hough transform to a new directed search pipeline, is done within the Band-Sampled-Data framework [123]. The pipeline is a semi-coherent method where the coherent part is covered by the BSD heterodyned data while the incoherent part is performed through the production of “peakmaps” and Frequency Hough maps.

The computationally intensive Weave-based search (semi-coherent $\mathcal{F}$-statistic) will focus on a handful of the most promising sources and use multi-day coherence times to dig deep in the noise, assuming a signal model with smooth frequency evolution. Outliers from the initial search stage will be followed up in a multi-stage analysis that requires increasing SNR for increasing coherence time.

The fully coherent Drill search (also based on the $\mathcal{F}$-statistic) will target a complementary set of the most promising sources, focusing on those where long coherence times are feasible.

Activities for O4

For O4, there will be analyses of various targets with several pipelines, and at least two publications (quick-turnaround O4a results and full-O4 results). Which pipeline contributes to which publication and on which subset of targets will be assessed based on run progress, data quality and available resources.

ACTIVITY ST-4.4-A-**OPS**: O4 SUPERNOVA REMNANT SEARCHES

We will run directed searched for selected supernova remnants using some of the available pipelines, e.g. Viterbi, BSD-directed, Weave and/or Drill. This first activity lists the tasks needed for both the O4a and Full-O4 searches, while tasks for running the actual searches are listed separately below.

TASK ST-4.4-A(i): SOURCE SELECTION

FTE-months: 3.0

Select a list of sources for directed searches. These sources will likely include all of those sought in the O3a searches (Cassiopeia A, Vela Jr, ...) in addition to SN 1987A and perhaps other new sources of interest.

TASK ST-4.4-A(ii): DATA QUALITY STUDIES

FTE-months: 1.0

Any data quality studies needed to veto or confirm candidates from the searches.

TASK ST-4.4-A(iii): REVIEW CODES AND SEARCH RESULTS

FTE-months: 3.0

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section LT-4.18); for both the O4a and Full-O4 searches.

ACTIVITY ST-4.4-B-**OPS**: O4A DIRECTED SUPERNOVA REMNANTS PUBLICATION

TASK ST-4.4-B(i): RUN SEARCH AND POST-PROCESSING

FTE-months: 6.0

Run directed searches using multiple pipelines, identify and follow up candidates.

TASK ST-4.4-B(ii): SET UPPER LIMITS

FTE-months: 6.0

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK ST-4.4-B(iii): PUBLICATION

FTE-months: 3.0

Produce a single publication either presenting the detection of CWs from one or more supernova remnants or comparing upper limits from the search pipelines that were used.

ACTIVITY ST-4.4-C: FULL-O4 DIRECTED SUPERNOVA REMNANTS PUBLICATION

TASK ST-4.4-C(i): RUN SEARCH AND POST-PROCESSING

FTE-months: 6.0

Run directed searches using multiple pipelines, identify and follow up candidates.

TASK ST-4.4-C(ii): SET UPPER LIMITS FTE-months: 6.0

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK ST-4.4-C(iii): PUBLICATION FTE-months: 3.0

Produce a single publication either presenting the detection of CWs from one or more supernova remnants or comparing upper limits from the search pipelines that were used.

ST-4.5 Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries

Motivation

Accretion in a binary system leads to recycling, where the neutron star spins up to near-kHz frequencies. In the torque balance scenario, the gravitational radiation reaction torque balances the accretion torque, which is proportional to the X-ray flux, in turn implying a limit on the characteristic wave strain proportional to that flux [124]. Torque balance is one possible explanation for the observed fact that the spin frequencies of low-mass X-ray binaries (LMXBs) are systematically lower than predicted. Directed searches for accreting binaries are a high priority because the sources are relatively powerful if they are emitting near the torque balance limit. A CW detection would shed light on several important astrophysical questions: by combining CW and electromagnetic data, one could tie down the emission mechanism, produce equation-of-state information, and probe the physics of the X-ray emission mechanism and of any differential rotation between the interior and crust.

Methods

A number of largely independent algorithms have been developed which can be used to search for LMXBs: cross-correlation [125, 126, 127], doubly-Fourier transformed data (TwoSpect; [128]), hidden Markov models (Viterbi; [129, 130, 131, 132, 133]), coherent summation of matched-filter sidebands (Sideband; [134]), and a resampling procedure, which is a generalization of the 5-vector method [135], and F-statistic based semicoherent procedure with known sky-localization of the source (BinaryWeave; [136, 137]). The central challenge facing these searches is that the spin frequency and orbital parameters are in general unknown. Furthermore the spin frequency is likely to wander stochastically in response to the fluctuating torque [138].

Activities for O4

ACTIVITY ST-4.5-A-**OPS**: O4 SCORPIUS X-1 SEARCHES

We will run a directed search for continuous gravitational waves from Scorpius X-1 using at least the cross-correlation and Viterbi search pipelines. The BinaryWeave pipeline will also be used if it can be implemented and reviewed on an appropriate timescale. In the event of a detection, we will publish results from all pipelines, as well as detailed follow up; otherwise we will set upper limits.

TASK ST-4.5-A(i): RUN INCREMENTAL VITERBI SEARCHES FTE-months: 1.0

Run Viterbi search to analyze data as soon as calibrated, cleaned, and gated data becomes available – even if these products are only subsets of the full run – to generate a list of candidates to follow up.

TASK ST-4.5-A(ii): RUN VITERBI SEARCH FTE-months: 3.0

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK ST-4.5-A(iii): ESSENTIAL OPTIMIZATION OF THE CROSS-CORRELATION SEARCH CODE FTE-months: 3.0

Planned improvements over the O3 pipeline to deliver a faster search include use of resampling [139] to speed up the computation at lower frequencies, and re-optimization of the choice of coherence times as a function of frequency and orbital parameters.

TASK ST-4.5-A(iv): RUN CROSS-CORRELATION SEARCH FTE-months: 3.0

Run cross-correlation search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK ST-4.5-A(v): UPDATE AND PREPARE BINARYWEAVE FOR REAL DATA FTE-months: 4.0

Update BinaryWeave pipeline for searching real detector data with noise, add/incorporate noise vetos and instrumental line detections.

TASK ST-4.5-A(vi): PERFORM PARAMETER SPACE OPTIMIZATION FTE-months: 2.0

Perform Sco X-1 parameter space optimization for BinaryWeave with updated astrophysical constraints and electromagnetic data to maximize search sensitivity.

TASK ST-4.5-A(vii): RUN BINARYWEAVE SEARCH FTE-months: 3.0

Run BinaryWeave search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK ST-4.5-A(viii): FOLLOW UP STATISTICAL OUTLIERS – VETOES FTE-months: 3.0

Follow up statistical outliers from each search using line-lists and tests of the efficacy of each candidate source. This may be done collectively or by each individual search.

TASK ST-4.5-A(ix): FOLLOW UP STATISTICAL OUTLIERS – PARAMETER ESTIMATION FTE-months: 3.0

Statistical outliers that pass vetoes in the above task should be analyzed with a denser set of matched-filter templates if possible and followed up using more-sensitive, but computationally intensive search methods like that used for the targeted known pulsar search.

TASK ST-4.5-A(x): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, each pipeline sets upper limits on gravitational-wave emission from Scorpius X-1.

TASK ST-4.5-A(xi): REVIEW CODES AND SEARCH RESULTS FTE-months: 3.0

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section LT-4.18).

TASK ST-4.5-A(xii): PUBLICATION FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from Scorpius X-1 or comparing upper limits from the search pipelines that were used.

ACTIVITY ST-4.5-B: O4 SEARCHES FOR OTHER LMXBS

Time and personpower permitting, we may run directed searches for other low mass X-ray binary (LMXB) targets with unknown spin frequency, besides Sco X-1, and as opposed to accreting millisecond X-ray pulsars with known spin frequencies (Section ST-4.6).

TASK ST-4.5-B(i): TARGET LIST

Identify a list of LMXB targets.

FTE-months: 3.0

TASK ST-4.5-B(ii): RUN VITERBI SEARCH

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

FTE-months: 3.0

TASK ST-4.5-B(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOS

We will use the same veto procedure as applied in the Scorpius X-1 search to follow up any statistical outliers.

FTE-months: 3.0

TASK ST-4.5-B(iv): PUBLICATION

Produce publication presenting the LMXB search results, potentially as part of the Sco-X1 paper.

FTE-months: 3.0

TASK ST-4.5-B(v): REVIEW CODES AND SEARCH RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section LT-4.18).

FTE-months: 3.0

ST-4.6 Narrowband directed searches targeting accreting millisecond X-ray pulsars

Motivation

Accreting millisecond X-ray pulsars (AMXPs) are accreting neutron stars in which outbursts are observed, providing constraints on the neutron star spin frequency. This allows a deeper and faster search than the all-frequency search for LMXBs such as Sco X-1 (Section ST-4.5).

Methods

The search for GWs from AMXPs has been conducted [140, 141] using a Hidden Markov Model (Viterbi pipeline) [129, 130].

Activities for O4

ACTIVITY ST-4.6-A-**OPS**: O4 SEARCHES FOR AMXPS

We will run a narrowband search for a selection of accreting millisecond X-ray pulsars (AMXPs), which are low mass X-ray binaries (LMXBs) with electromagnetic constraints on the neutron star rotation frequency. We will use the Viterbi search pipeline initially, however other search pipelines could also be used if person and computational resources allow.

TASK ST-4.6-A(i): TARGET LIST

Identify a list of AMXP targets.

FTE-months: 3.0

TASK ST-4.6-A(ii): RUN VITERBI SEARCH

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

FTE-months: 3.0

TASK ST-4.6-A(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOS

We will use the same veto procedure as applied in the previous AMXP searches, and the Scorpius X-1 Viterbi search, to follow up any statistical outliers.

FTE-months: 2.0

TASK ST-4.6-A(iv): SET UPPER LIMITS

FTE-months: 1.0

In the event of no detection, we will put upper limits on GW strain, and convert to astrophysical parameters, such as ellipticity and r-mode amplitude.

TASK ST-4.6-A(v): REVIEW CODE AND SEARCH RESULTS

FTE-months: 1.0

Review of any updated part of the codes and the search results.

TASK ST-4.6-A(vi): PUBLICATION

FTE-months: 3.0

Produce publication presenting AMXP search results.

ST-4.7 Directed searches targeting the Galactic center

Motivation

All-sky CW searches are computationally limited because of the rapid increase in computational cost with coherence time of the search. Hence there is a trade-off between searching the largest sky area at reduced sensitivity, or searching a smaller sky region with increased sensitivity. There are regions in the sky that are thought to host high concentrations of the types of objects that might be emitting detectable CWs; the Galactic center and globular clusters are both regions of interest. Several independent lines of evidence suggest the presence of a large number of NSs in the few inner parsecs of the Milky Way and may also explain the EM excess measured by astronomical surveys which are not emitted by resolved sources [142, 143, 144, 145, 146]. Nevertheless, the dark matter interpretation for the origin of this excess cannot be ruled out. In this search three different sources of CW (and CW-like) signals will be searched for: isolated NSs, boson clouds around spinning BHs, and small compact (dark) objects binaries (e.g. primordial black holes) with masses below $10^{-3}\ M_{\odot}$. The results can also be reinterpreted taking into account the possibility that the signals may come from a larger distance behind the galactic center and have been lensed by the supermassive black hole.

Methods

The idea is to explore a wide frequency and spin-down/spin-up parameter space, limiting–where possible–the computational cost of the search. The BSD-directed search pipeline [147], pointing to the sky position of Sgr A*, will be used. The BSDs are complex time series sampled at 0.1 s and divided into frequency bands of 10 Hz [123]. For the search for CW signals the time series is heterodyned, partially removing the Doppler effect. From this time series we build "peakmaps", which consist in a collection of time-frequency peaks selected from the average spectrum. The peakmap will be the input of the FrequencyHough transform which will map the time-frequency peaks into the intrinsic frequency/spin-down values of the source. Selected candidates, if significant enough, will be followed up with methods similar to those used in all-sky searches. The BSD-directed search pipeline will be used for the search of standard isolated NSs, while a modified version of the same pipeline will be used for the search of small dark compact objects. The semi-coherent 5-vector method will be used for the search of boson clouds.

Activities for O4

ACTIVITY ST-4.7-A-**OPS**: O4 GALACTIC CENTER SEARCH

Pending on person power, we will run a directed search(es) for the Galactic center using some of the available pipelines, e.g. BSD-directed and semi-coherent 5-vector method

TASK ST-4.7-A(i): RUN SEARCH AND POST-PROCESSING FTE-months: 3.0

Run directed search(es), identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK ST-4.7-A(ii): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK ST-4.7-A(iii): REVIEW SEARCH CODE AND RESULTS FTE-months: 3.0

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section LT-4.18).

TASK ST-4.7-A(iv): PUBLICATION FTE-months: 3.0

Produce a publication presenting the results.

ST-4.8 All-sky searches for unknown generic continuous-wave sources

Motivation

CW searches largely focus on signals expected from specific gravitational wave sources or source classes. However, we also need to consider sources that produce quasi-sinusoidal gravitational waves but with a time evolution that does not fit with our expectations. Non- (or low-) parametric search techniques can explore the parameter space beyond the regions covered by semi-coherent methods and with competitively similar sensitivities. With slight modification, these techniques can also be used to identify and distinguish instrumental artefacts.

Methods

SOAP [148] is a non-parametric search pipeline which is computationally cheap, returning results within $\mathcal{O}(\text{hours})$ after SFTs are generated. The non-parametric nature of the search makes it sensitive to many different signal types which may not follow the standard CW frequency evolution. The SOAP pipeline is now mature, and recent developments have enabled it to return sky localisation estimates as well as identifying a possible signal. By its nature, SOAP can only set upper limits if a signal model is assumed, so the fully-generic search is purely a detection pipeline. However, when a search sensitivity can be set, on (say) isolated neutron stars with a constant rate of spindown, its sensitivity is comparable to semi-coherent searches with coherence times of 30 minutes.

Activities for O4

ACTIVITY ST-4.8-A: O4A GENERIC ALL-SKY SEARCH

TASK ST-4.8-A(i): RUN SEARCH FTE-months: 1.0

SOAP is computationally cheap, and will be run continuously throughout O4a with an update cadence of one week.

TASK ST-4.8-A(ii): OUTLIERS FOLLOWUP – ASTROPHYSICAL PLAUSIBILITY FTE-months: 1.0

We will also check the astrophysical plausibility of the Viterbi track.

TASK ST-4.8-A(iii): PUBLICATION FTE-months: 3.0

Produce a publication that includes the results of the pipeline.

ACTIVITY ST-4.8-B-**OPS**: O4A GENERIC ALL-SKY SEARCH - DATA QUALITY STUDIES AND CODE REVIEW

TASK ST-4.8-B(i): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 2.0

As SOAP is a non-parametric search, a full interpretation of its results requires human intervention to assess data quality and the spectral environment.

TASK ST-4.8-B(ii): REVIEW SEARCH CODE AND RESULTS

FTE-months: 3.0

Review of any updated part of the codes and the search results.

ACTIVITY ST-4.8-C: FULL-O4 GENERIC ALL-SKY SEARCH

TASK ST-4.8-C(i): RUN SEARCH

FTE-months: 1.0

SOAP is computationally cheap, and will be run continuously throughout O4 with an update cadence of one week.

TASK ST-4.8-C(ii): OUTLIERS FOLLOWUP – ASTROPHYSICAL PLAUSIBILITY

FTE-months: 1.0

We will also check the astrophysical plausibility of the Viterbi track.

TASK ST-4.8-C(iii): PUBLICATION

FTE-months: 3.0

Produce a publication that includes the results of the pipeline.

ACTIVITY ST-4.8-D-**OPS**: FULL-O4 GENERIC ALL-SKY SEARCH - DATA QUALITY STUDIES AND CODE REVIEW

TASK ST-4.8-D(i): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 2.0

As SOAP is a non-parametric search, a full interpretation of its results requires human intervention to assess data quality and the spectral environment.

TASK ST-4.8-D(ii): REVIEW SEARCH CODE AND RESULTS

FTE-months: 1.0

Review of any updated part of the codes and the search results.

ST-4.9 All-sky searches for unknown isolated sources

Motivation

While other CW searches explore regions of potentially high interest, e.g. known pulsars and directed search targets, it is prudent to conduct comprehensive searches of the entire parameter space so as not to miss an unexpected source, one for which electromagnetic emission has not yet been detected. Theory suggests that fractional deformations or *ellipticities* of neutron stars as high as 10^{-5} could be sustained by neutron star crusts. On the other hand, there are observed neutron stars with ellipticities smaller than 10^{-8}, and it may well be that still smaller ellipticities are common. As our searches struggle to touch ellipticities of 10^{-7} at the top of the explored frequency range, it is likely that the first discovered source would have an unusually high ellipticity.

Methods

There are several pipelines in the CW group that have been optimized for different search scenarios, data quality and analysis speed. PowerFlux [149] can be used to carry out broad all-sky searches over the entire frequency space with the aim of producing results as promptly as possible. It is the only pipeline that performs direct estimation of GW power. The loosely coherent pipeline [150] is capable of improved sensitivity at greater computational cost. FrequencyHough [151] and SkyHough [152] are based on different implementations of the Hough transform algorithm and inherit its resilience to contaminated data. The time-domain $\mathcal{F}$-statistic pipeline [153] is based on a method with a long coherence time. This makes it resilient to many artifacts affecting pipelines with shorter coherence lengths. All pipelines have experience with processing large numbers of outliers with streamlined follow-up methods and vetoes. For the non-parametric SOAP [148] pipeline, see (Section ST-4.8).

Activities for O4

For O4, there will be several analyses with these pipelines, and at least two publications (quick-turnaround O4a results and full-O4 results). Which pipeline contributes to which publication will be assessed based on run progress, data quality and available resources.

ACTIVITY ST-4.9-A-**OPS**: O4 ALL-SKY ISOLATED SEARCHES

TASK ST-4.9-A(i): RUN THE SKYHOUGH SEARCH

FTE-months: 3.0

Run the SkyHough search code on multi-interferometer data, produce a large list of candidate sources, and post-process the results with a number of vetoes and follow-ups.

TASK ST-4.9-A(ii): RUN TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE

FTE-months: 3.0

Run the time domain F-statistic pipeline for the detector network. Search a broad frequency range divided into time-frequency segments using the two-step procedure. First search the segments coherently using the $\mathcal{F}$-statistic and then search for coincidences among candidates in each narrow ($\sim$1 Hz frequency band.

TASK ST-4.9-A(iii): RUN THE FREQUENCYHOUGH SEARCH

FTE-months: 3.0

Run the FrequencyHough search code on data from the LIGO and Virgo detectors to search for significant outliers. If person power is available, we will perform a follow-up based on the standard approach (computation of a set of FrequencyHough maps with higher coherence time), plus – for a subset of them – the new semi-coherent 5-vector method to further increase the coherence time. In any case, O4a outliers will be used for coincidences with O4b outliers.

TASK ST-4.9-A(iv): RUN THE POWERFLUX SEARCH

FTE-months: 3.0

Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers. Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers. Loose coherence will be used to follow up outliers in multiple stages, requiring improved SNR with each stage of increased effective coherence time.

TASK ST-4.9-A(v): FOLLOW UP STATISTICAL OUTLIERS

FTE-months: 3.0

Follow up statistical outliers from each search using longer coherent integration times. This may be done collectively or by each individual search.

TASK ST-4.9-A(vi): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, each pipeline sets averaged population based upper limits on the gravitational-wave strain amplitude and derives astrophysical implications.

TASK ST-4.9-A(vii): REVIEW

FTE-months: 3.0

Review search setups and results, as well as any recent search method improvements and optimizations (Section LT-4.18).

ACTIVITY ST-4.9-B-**OPS**: O4A ALL-SKY ISOLATED SEARCH PUBLICATION

TASK ST-4.9-B(i): PUBLICATION

FTE-months: 3.0

Produce a single publication either presenting the detection of CWs from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

ACTIVITY ST-4.9-C-**OPS**: FULL-O4 ALL-SKY ISOLATED SEARCH PUBLICATION

TASK ST-4.9-C(i): PUBLICATION

FTE-months: 3.0

Produce a single publication either presenting the detection of CWs from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

ACTIVITY ST-4.9-D-**OPS**: INVESTIGATE FEASIBILITY OF A SKYHOUGH SEARCH USING THE $\mathcal{F}$-STATISTIC

An optional improvement for either the O4a or full-O4 analysis, that would significantly improve sensitivity. Based on existing code infrastructure, improve and optimize codes to adapt the SkyHough search pipeline to use demodulation (via the $\mathcal{F}$-statistic), increasing the time baseline of the coherent step and, consequently, the depth of the search. The basic data products produced by SkyHough are equivalent to those without demodulation, meaning the new code will benefit from any improvements on the already existing SkyHough pipeline.

TASK ST-4.9-D(i): IMPROVEMENT AND OPTIMIZATION OF EXISTING HIERARCHICAL DATA ANALYSIS PIPELINES

FTE-months: 9.0

TASK ST-4.9-D(ii): REVIEW OF ANY UPDATED PART OF THE CODES

FTE-months: 3.0

TASK ST-4.9-D(iii): ACQUISITION OF COMPUTING RESOURCES

FTE-months: 1.0

The use of GPUs is crucial for the optimization of this pipeline. The search will leverage the use of internal computing resources of the collaboration on the LDG with external resources from the OSG and acquired through competitive allocation calls.

TASK ST-4.9-D(iv): DEFINE THE PARAMETER SPACE OF THE SEARCH DEPENDING ON COMPUTATIONAL RESOURCES

FTE-months: 2.0

TASK ST-4.9-D(v): RUN THE SEARCH CODE

FTE-months: 3.0

TASK ST-4.9-D(vi): FOLLOW UP STATISTICAL OUTLIERS

FTE-months: 1.0

ACTIVITY ST-4.9-E-**OPS**: IMPROVEMENTS IN THE TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE

Improvements in the multi-stage pipeline include extending the 2nd-stage coincidences procedure to more general model-agnostic signal types, rewriting the signal injection/upper limits part of the pipeline, and followup of outliers by a ML procedure to study the $\mathcal{F}$-statistic distribution for a given sky position.

TASK ST-4.9-E(i): EXTENSION OF THE COINCIDENCES PROCEDURE

FTE-months: 9.0

Currently only strictly continous almost-monochromatic signals are being search for. By taking into account signal types with e.g. amplitude variation, the triggers found by the 1st stage of the pipeline may be used in search for transient signals.

TASK ST-4.9-E(ii): SIGNAL INJECTIONS/UPPER LIMITS

FTE-months: 6.0

We perform signal injections in each time-domain segment and each band to establish coincidences and set search upper limits. This part of the pipeline needs a technical rewrite, and additional improvements e.g., using ML methods to optimally chose injection amplitudes for a given frequency band (relate the ULs as a function of frequency with the sensitivity curve of the detectors).

TASK ST-4.9-E(iii): OUTLIER FOLLOWUP BY STUDYING THE $\mathcal{F}$-STATISTIC DISTRIBUTION IN f-$\dot{f}$ PLANE

FTE-months: 6.0

For outliers found by first stages of the pipeline, we plan to confirm their astrophysical nature (or instrumental nature) by studying the distribution of $\mathcal{F}$-statistic values on the dense grid in the f-$\dot{f}$ plane (i.e., for a given sky position). This task will be enhanced by ML techniques.

ST-4.10 All-sky searches for unknown sources in binaries

Motivation

CW emission from neutron stars in binary systems (see also Section ST-4.5) is of particular interest because of recycling, where a neutron star accretes matter from a companion star, gaining angular momentum and speeding up. Most millisecond pulsars observed in radio, X-rays and/or γ rays reside in or once resided in systems where the accretion has stopped, but where the neutron stars retain a high angular velocity. Accretion can provide a natural mechanism to impart asymmetries in the neutron star moment of inertia, thus causing the star to emit continuous gravitational waves, even after accretion has subsided.

Neutron stars in unknown binary systems present an extreme challenge for CW searches because the unknown orbital characteristics produce unknown modulations of the source frequency in the Solar System Barycenter (SSB), in addition to calculable modulations due to the Earth's motion with respect to the SSB. As is well known, even the calculable modulations for an assumed source frequency make an all-sky search for unknown isolated stars a formidable computational challenge, and adding the unknown binary orbital modulations makes the problem all the more difficult.

Methods

The TwoSpect method [154], which relies on doubly-Fourier transformed data, was the first method applied to LIGO and Virgo data to perform an all-sky search for unknown sources in binaries [155]. TwoSpect allows for a broad parameter space range to be covered while maintaining computational efficiency.

The BinarySkyHough is a pipeline [156] developed from the SkyHough method, one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. BinarySkyHough is an extension of this method, which allows to search for signals from neutron stars in binary systems, which have an extra Doppler modulation. Due to the highly increased computational cost, BinarySkyHough requires GPUs in order to have a feasible computational cost. This pipeline was previously employed to analyse O2 open data [157] and early O3 data [158].

Activities for O4

Whether searches will be performed and published based on O4a only, or on the full O4 data set, will be assessed based on run progress, data quality and available resources.

ACTIVITY ST-4.10-A-**OPS**: O4 ALL-SKY SEARCH FOR CWS FROM NSS IN BINARIES

The BinarySkyHough semicoherent pipeline will be used to search for CW signals from sources in circular binary systems in O4 data, using GPUs to analyze wide frequency bands in an all-sky search. The results are analyzed using a newly developed suite of vetoes and follow-up strategies.

TASK ST-4.10-A(i): ACQUISITION OF COMPUTING RESOURCES

FTE-months: 1.0

The use of GPUs is crucial to perform the main stage of the search, which uses a highly efficient implementation of the Hough transform to analyze wide parameter-space regions with an increased level of robustness against spectral artifacts [156]. The search will leverage the use of internal computing resources of the collaboration on the LDG with external resources from the OSG and acquired through competitive allocation calls.

TASK ST-4.10-A(ii): RUN THE SEARCH

FTE-months: 3.0

Run the BinarySkyHough search code on multi-interferometer data, and produce a large list of candidate sources.

TASK ST-4.10-A(iii): POST-PROCESSING AND VETOES

FTE-months: 2.0

The main results of the search are toplists containing the most significant parameter-space points for each of the analyzed frequency bands. A recently improved clustering algorithm groups together candidates with a common origin, effectively reducing the amount of parameter-space point to be taken care of [159]. After selecting the most significant clusters, a first set of veotes comparing search outliers to known instrumental artifacts will further reduce the amount of outliers to follow-up.

TASK ST-4.10-A(iv): FOLLOW-UP CANDIDATES

FTE-months: 2.0

The default follow-up strategy will use an MCMC-based $\mathcal{F}$-statistic search implemented in the PyFstat Python package [160, 161]. The flexibility of this procedure allows for the application of several follow-up strategies, either based on detector-consistency vetoes, as done in [158], or using hierarchical schemes to compare the behaviour of a CW candidate as the coherence time increases [162].

TASK ST-4.10-A(v): REVIEW

FTE-months: 3.0

This will include code review as well as reviewing search results.

TASK ST-4.10-A(vi): PUBLICATION

FTE-months: 3.0

A paper on these results will be written and submitted for publication.

ACTIVITY ST-4.10-B-**OPS**: INVESTIGATE FEASIBILITY OF A TWOSPECT SEARCH

FTE-months: 3.0

Pending availability of person power and computing resources, investigate the feasibility of a search using the mature TwoSpect algorithm. This would require running the search, resuming and concluding review efforts, and publication of results.

TASK ST-4.10-B(i): INVESTIGATE FEASIBILITY OF A TWOSPECT SEARCH

ST-4.11 Searches for transient emission from post-merger neutron stars

Motivation

CW-derived analysis methods can also be used to search for long-duration transient GWs from newborn neutron stars with rapid spindown, including signals from neutron star remnants of nearby binary neutron star (BNS) mergers [163] such as GW170817 [60]. In particular, while shorter remnant signals on the order of milliseconds to hundreds of seconds can also be effectively searched for with methods derived from burst and stochastic searches [164], longer signals associated with the rapid spindown of a supramassive or long-lived young neutron star are well suited for CW-derived methods [165]. These remnant searches can play a crucial role in constraining the nature of the remnant and thus the nuclear physics properties of the involved objects [166, 167].

On the other hand, for a hypermassive NS remnant that collapses to a black hole in less than 1 s, simulations show that the post-merger GW emission is dominated by the quadrupolar f-mode with frequency in the range of around 2–4 kHz with broad secondary and tertiary peaks in the 1.8–4 kHz range. This signal typically lasts a few tens of milliseconds. The postmerger signal is quite complex, but it can be well approximated by a damped sinusoid resembling a ringdown signal. The search for such a postmerger signal associated with the GW170817 event has been previously carried out using the cWB pipeline [168]. There was no detection and upper limits on GW strain have been established.

The same methods can also apply to newborn neutron stars from the regular core-collapse supernova channel; see (Section LT-4.20) for investigations into that case.

Methods

Even for long-duration postmerger signals, the parameter space [169, 170], signal morphology and data quality requirements are quite different from other CW searches. Available methods include adaptations of the hidden-Markov-model Viterbi tracking algorithm [171, 172] and the two semi-coherent Hough algorithms [152, 173, 174, 175] to the rapid-spindown waveform model from [176]. It is also possible to combine some of these methods, with a cheaper, more generic method as a first-stage search and a semi-coherent modelled algorithm as a follow-up stage.

The selection of worthwhile BNS candidates for long-duration post-merger searches depends on the rate of increase in detector sensitivity, on the distances at which such events are found, on the inferred total mass of each binary, and on how well they are localized.

For the shorter f-mode signals, a new pipeline is under development based on matched filtering. It approximates the postmerger signal by an exponentially damped sinusoid with frequency f_2 and frequency drift γ. To detect the signal, one derives a likelihood-ratio statistic called the $\mathcal{P}$-statistic, similar to the well-known $\mathcal{F}$-statistic [116]. The $\mathcal{P}$-statistic depends only on the intrinsic parameters – frequency f_2, frequency drift γ, and damping time τ. Its performance is tested with typical postmerger signals from the CoRe data base [177][2] added both to Gaussian noise and to real data, with a loss of 10 to 20% in SNR with respect to a perfectly matched signal. There are methodological similarities in the implementation of the $\mathcal{P}$-statistic with the $\mathcal{F}$-statistic: the $\mathcal{P}$-statistic can be expressed as a Fourier transform and the grid in the frequency – frequency drift parameter space can be constructed as in CW directed searches [178].

Activities for O4

ACTIVITY ST-4.11-A-**OPS**: ONGOING COORDINATION WITH OTHER WORKING GROUPS

FTE-months:
- (3 FTE-mo
listed 2019-20)

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[2] The most recent release of the database contains 264 entries including an extensive set of simulations targeted to the event GW170817; see `http://www.computational-relativity.org/`)

During current and future observing runs, post-merger experts from the CW group will be on standby to coordinate, in the event of an interesting nearby BNS detection, with other working groups and the observatory heads/operators about search plans and required stand-down times in detector interventions to maximize science opportunities. Nominal thresholds for this have been agreed, but continued coordination will be beneficial.

TASK ST-4.11-A(i): ONGOING COORDINATION WITH OTHER WORKING GROUPS ON POSTMERGER SEARCHES

ACTIVITY ST-4.11-B-**OPS**: OPPORTUNISTIC LONG-DURATION POST-MERGER SEARCHES DURING O4 (ON STANDBY)

Pending on person power and event rates, we will run a directed search for long-duration signals from a possible remnant of any sufficiently nearby, low-mass and well-localized BNS merger, using some of the available pipelines: Viterbi [171, 172], Adaptive Transient Hough [173] or updated versions of it, and/or Generalized Frequency Hough [175].

TASK ST-4.11-B(i): CANDIDATE IDENTIFICATION AND LIAISON WITH CBC PARAMETER ESTIMATION

FTE-months: 1.0

When a promising candidate has been identified based on low-latency CBC parameter estimates (distance, masses and sky localization), CW analysts will liaise with the CBC parameter estimation experts to follow the progress of refined inference runs to obtain the best estimates for informing our decision to run a search and on details of the search setups.

TASK ST-4.11-B(ii): COORDINATION WITH SHORT-DURATION PUBLICATION PLANS

FTE-months: - (3 FTE-mo listed 2019-20)

The planning of these searches and the eventual publication will require coordination with members of the CBC, burst and stochastic groups to ensure full exploitation of all post-merger science opportunities, proper folding-in of prior information from the inspiral phase, efficient data quality studies, and a streamlined publication schedule.

TASK ST-4.11-B(iii): RUN SEARCHES

FTE-months: - (3 FTE-mo listed 2019-20)

Run different existing search pipelines, post-process results, and in the event of interesting outliers produce a list of candidate signals.

TASK ST-4.11-B(iv): VETOES AND CANDIDATE FOLLOW-UP

FTE-months: - (3 FTE-mo listed 2019-20)

Follow up candidates from each search, either collectively or by each individual search team.

TASK ST-4.11-B(v): DATA QUALITY STUDIES

FTE-months: - (3 FTE-mo listed 2019-20)

Data around and after the merger needs to be studied for gaps, nonstationarities, transient line features etc; both in advance to determine optimal search setups, and in more detail if outliers are found.

TASK ST-4.11-B(vi): SET UPPER LIMITS

FTE-months: - (3 FTE-mo listed 2019-20)

In the event of no detection, each pipeline sets upper limits through injection of simulated signals.

TASK ST-4.11-B(vii): REVIEW SEARCH RESULTS

FTE-months: - (3 FTE-mo listed 2019-20)

This will include code review of any updated parts of the search pipelines, as well as reviewing their search configurations and results.

Task ST-4.11-B(viii): Publication

FTE-months:
- (3 FTE-mo
listed 2019-20)

Either produce a single stand-alone publication presenting results of the different search pipelines and/or incorporate the results as a brief summary in a more general paper on the BNS event.

Activity ST-4.11-C-**OPS**: Opportunistic short-duration post-merger searches during O4 (on standby)

Task ST-4.11-C(i): Test of the pipeline with GW170817 postmerger data

The time-domain $\mathcal{P}$-statistic pipeline for short-duration BNS postmerger signals will be applied to search data after the GW170817 merger, of duration of a few tens of milliseconds. The sensitivity of the pipeline will be tested by injections into real data of the postmerger waveforms from the CoRe database.

Task ST-4.11-C(ii): Obtain parameters of the BNS signals form CBC pipelines

FTE-months:
1.0

We shall obtain parameters of each BNS merger signal detected by CBC pipelines. In particular merger times in each detectors, masses, tidal parameters, extrinsic parameters (polarization angles and distance to the source), and positions of the sources in the sky.

Task ST-4.11-C(iii): Run the time-domain $\mathcal{P}$-statistic postmerger pipeline

FTE-months:
3.0

We shall search with our pipeline a few tens of milliseconds of data after each BNS merger reported by CBC pipelines.

Task ST-4.11-C(iv): Determine sensitivity of the serach

FTE-months:
3.0

In the case of no detection, determine sensitivity of the search by injections of numerical-relativity postmerger waveforms from the CoRe database.

Task ST-4.11-C(v): Review search results

FTE-months:
3.0

Review of the code and the search results.

Task ST-4.11-C(vi): Publication

FTE-months:
3.0

Produce a publication with the results of the searches for the whole O4 or incorporate the results as a brief summary in papers on a significant nearby BNS events.

ST-4.12 Searches for long-transient emission following a pulsar glitch

Motivation

The CW group is primarily focused on searching for truly *continuous* GWs: periodic signals lasting at least as long as an observation run. However, electromagnetic observations of transient neutron star phenomena, such as pulsar glitches, raise the possibility that neutron stars also emit GW signals on time scales of hours–months due to short-lived deformations [179, 180]. The mechanisms behind pulsar glitches are still poorly understood [181] and post-glitch GW observations (including upper limits) could yield valuable insights complementary to radio and other EM observations.

Methods

Many CW search algorithms can be adapted to search for long-duration transients by studying their intermediate, time-dependent data products or running separate analyses on shorter time intervals. For quasi-monochromatic transients during the post-glitch relaxation phase, the transient $\mathcal{F}$-statistic [179, 182] is an efficient method with demonstrated performance on real data [183, 99]. Searches with this method can be cheaply run for several targets, with additional development and/or the use of GPUs [182, 160] allowing for broader searches or covering more targets. For shorter signals with nontrivial frequency evolution, more immediately associated with the glitch event itself, methods similar to those for post-merger searches [171, 172, 173, 175], based on machine learning, or from the burst and stochastic domains [6, 184, 38] could also be employed.

Similar to post-merger searches, post-glitch searches face unusual data quality and candidate validation challenges. For example, periods of no or degraded data due to environmental effects degrade transient search performance more strongly than for full-run CW searches, and transient instrumental lines that would be too weak to affect a year-long analysis can produce strong spurious candidates in a transient search. Once statistical outliers are found in a search, the standard approach of increasing coherence time is not always helpful for transients, and follow-up must instead rely on data quality studies, varying the time steps used in the analysis, generalizing the signal model, and grid-less MCMC methods [185, 160].

Activities for O4

ACTIVITY ST-4.12-A-**OPS**: OPPORTUNISTIC SEARCHES AFTER PULSAR GLITCHES DURING O4 (ON STANDBY)

The case for a paper targeting transients from pulsar glitches depends on the number of such events observed in EM timing of nearby pulsars with frequencies matching the detectors' sensitivity band (assuming the usual factor of 2 for the dominant GW emission frequency) and the predicted chance of surpassing the energy-based indirect upper limits on GW strain (depending on frequency, glitch size and pulsar distance, [179, 186]). A standalone paper will be pursued if at least one large, nearby glitch (e.g. from the Vela pulsar) promises a first surpassing of such limits, while combination with the full-O4 known pulsar or narrowband papers (Sections ST-4.1, ST-4.2) is the fallback for less promising targets.

TASK ST-4.12-A(i): MONITOR AND SELECT TARGETS

FTE-months: 3.0

Data on promising glitches in nearby pulsars needs to be collected and used to prioritise search targets. This will be based on the work of EM observers under the MoUs already in place for targeted CW searches (Section ST-4.1) and public literature and databases. How promising a glitch is as a search target will be estimated based on indirect energy upper limits [179, 186], the precision of available ephemerides, and the duty cycle and data quality around and after the glitch.

TASK ST-4.12-A(ii): COORDINATION WITH OTHER WORKING GROUPS

FTE-months: 1.0

For large glitches from nearby pulsars (e.g. Vela), and if a sufficient number of detectors were in observing mode close to the glitch, additional short-duration transient searches may be pursued by other working groups (e.g. Section ST-2.6), and CW group members will coordinate with the analysis leads from those groups to exchange information, coordinate data quality studies, and potentially merge paper plans.

TASK ST-4.12-A(iii): CODE REVIEW

FTE-months: 3.0

The transient $\mathcal{F}$-statistic code in LALSuite is based on intermediate data products from the reviewed CW $\mathcal{F}$-statistic code, and the version as reviewed for O3 can be reused for O4. The PyFstat package [161] can be used for more flexible searches, including MCMCs and GPU usage. Enhancements to both codes may require some addition review effort, as will the run- and target-specific search setup scripts. Any additional analysis codes joining this activity will likely be based on existing codes reviewed for other applications, but require additional review in their application to the post-glitch case.

TASK ST-4.12-A(iv): DATA PREPARATION AND DATA QUALITY STUDIES

FTE-months: 3.0

The total time interval covered by each search depends on the pattern of usable science quality data segments. SFTs for these intervals and the relevant frequency bands are extracted from the standard broadband SFTs. Shorter-duration SFTs may need to be generated for some follow-up studies. Strong transient instrumental lines need to be identified in advance and cleaned from the data.

TASK ST-4.12-A(v): SEARCH

FTE-months: 3.0

For each glitch target, a search of several months of data covering a small frequency band (similar to the searches in Section ST-4.2) must be performed. The detailed search setup can be chosen based on the number of promising targets, the uncertainties in pulsar ephemerides, and the available person-power and computing budget. To identify promising candidates, the distribution of search outputs can be modelled [187].

TASK ST-4.12-A(vi): CANDIDATE FOLLOW-UP

FTE-months: 3.0

Statistical outliers will be first subjected to data quality scrutiny and anything that cannot be attributed to instrumental lines must be followed up with variations in the search setup and through independent pipelines, including MCMC methods [185, 160, 91].

TASK ST-4.12-A(vii): SET UPPER LIMITS

FTE-months: 3.0

If no promising detection candidates survive, upper limits can be set through injections of simulated signals. For large glitches in nearby pulsars, beating the indirect energy upper limit [179, 186] may be possible.

TASK ST-4.12-A(viii): REVIEW SEARCH RESULTS

FTE-months: 3.0

In addition to the main search code review, the target list, search configurations and results will require review.

TASK ST-4.12-A(ix): PUBLICATION

FTE-months: 3.0

As discussed above, a single paper (or contribution to a joint CW-transient known pulsar / narrowband paper) can describe the search results for any number of glitches targeted during the run, or a standalone paper may be written first on an exceptional event. Coordination with short-duration transient searches for the same targets will be beneficial.

ST-4.13 Searches for continuous emission from ultra-light boson clouds around black holes

Motivation

Ultra-light boson clouds forming around BHs are expected to emit CW-like signals over long times. According to theoretical predictions, which are based on several approximations, the emitted signal is monochromatic with a small spin-up. The actual signal could be more complicated due to matter accretion, presence of a binary companion, unpredicted physics, etc. For this reason it is important to develop robust methods that are able to detect long-lasting signals, with (small) spin-up and a finite unknown coherence time. In the case of vector boson clouds, the signal amplitudes are expected to be higher than scalar boson signals, but the signals have a shorter lifetime with a higher spin-up. While we have in mind BH/ultra-light boson cloud systems as a reference source, similar methods can be used to search for other signals with similar characteristics.

The search for CW signals from boson clouds around spinning BHs is conceptually similar to "standard" searches of CWs from asymmetric spinning neutron stars. Therefore the core data analysis techniques can be shared among them. There are, however, some specificities that we can take into account to improve the boson cloud search. The following points support performing the searches for boson clouds and asymmetrically rotating neutron stars separately.

First, in all-sky searches, the simple idea of working with FFT databases of different length allows us to deal with non-monochromatic signals, potentially providing a significant gain in sensitivity, with respect to the standard choice of a fixed FFT duration, as shown in [188]. The feasibility of this approach for boson cloud searches is guaranteed by the small range of frequency derivative values we need to consider. For standard CW searches for spinning neutron stars, the large spin-down range we need to cover prevents us from using this method, due to computational cost constraints. Second, in all-sky searches, candidates are selected with a "top list" criterion according to which for every frequency band (e.g 0.1 Hz), and every sky position, the two most significant candidates, across the whole spin-down/up range, are chosen. Now, if we should consider the boson cloud search as a particular case of a standard all-sky search, we would select candidates over a spin-down/up range much larger than needed. As a result, there would be a very high probability to select candidates much stronger than those we could choose by running the search only on the restricted spin-up range suitable for boson clouds. This, clearly, implies a net loss in sensitivity: by running a search specifically for bosons we can select weaker candidates, i.e. go "deeper". Finally, for directed searches, the targets are of course different from those of CW searches for spinning neutron stars. Improved semi-coherent search methods are also developed to cover larger spin-up rate in directed searches, especially for vector signals.

Methods

A simple semi-coherent procedure, in which data are analyzed using various collections of FFTs of durations from hundreds to thousands seconds, has been developed [188]. The procedure is computationally cheap (relative to standard all-sky CW searches) and is designed for an all-sky search. In the last search, carried on O3 data, the variable FFT duration has been obtained by applying a moving average, with varying width, to time-frequency maps built with a fixed FFT duration [189]. Another method is a semi-coherent directed search for such systems based on hidden Markov model tracking, which is robust against potentially slow frequency variations of the signals due to the expected intrinsic evolutions and astrophysical interactions [190]. The first observational constraints on the mass of ultra-light scalar bosons have been set in all-sky [191] and directed [192] searches carried out on LIGO O2 data. New all-sky constraints are obtained in O3 [189]. A new hidden Markov model based method is being developed and will be used in O4 to track more rapidly evolving vector boson signals (e.g., on a timescale of hours to months). A more accurate, numerically calculated waveform model will be used as theoretical predictions to interpret the O4 results and derive the constraints [193]. We will also continue to improve the accuracy of the superradiance waveform model, and use it as an aid in designing future searches.

Activities for O4

We will run two searches, one all-sky search for scalar boson clouds, and a directed search for vector boson clouds, targeting promising post-merger black holes and potentially a few interesting galactic black holes. A directed search for scalar boson clouds around post-merger black holes will be also carried out, pending person power and identification of interesting targets. These analyses will be collectively described in two observational papers, one for scalar bosons (all-sky search and possibly additional directed searches) and the other for vector bosons (directed searches only).

ACTIVITY ST-4.13-A: O4 ALL-SKY AND DIRECTED SEARCHES FOR ULTRA-LIGHT SCALAR BOSON CLOUDS

We will run an all-sky search for scalar boson cloud continuous signals, relying on the semi-coherent all-sky pipeline method described above [188], as well as further developments introduced in [189]. Candidate follow-up will be based on the FrequencyHough [151], the Viterbi tracking [190] and a new semi-coherent method based on 5-vectors. Directed searches for scalar boson clouds around some specific nearby black holes, black holes in globular clusters, and post-merger black holes may get added.

TASK ST-4.13-A(i): RUN SEARCH FTE-months: 3.0

Run the search and identify candidates.

TASK ST-4.13-A(ii): OUTLIER FOLLOWUP – OTHER STUDIES FTE-months: 1.0

TASK ST-4.13-A(iii): SET CONSTRAINTS FTE-months: 1.0

In the event of no detection, interpret results and set constraints on scalar ultra-light boson mass and other properties.

TASK ST-4.13-A(iv): PUBLICATION FTE-months: 1.0

Produce a publication presenting the results.

ACTIVITY ST-4.13-B-**OPS**: O4 ALL-SKY AND DIRECTED SEARCHES FOR ULTRA-LIGHT SCALAR BOSON CLOUDS - DATA QUALITY STUDIES AND REVIEW

TASK ST-4.13-B(i): OUTLIER FOLLOWUP – DATA QUALITY STUDIES FTE-months: 1.0

Veto outliers caused by instrumental artifacts.

TASK ST-4.13-B(ii): REVIEW SEARCH CODE AND RESULTS FTE-months: 2.0

Review some portions of the analysis pipeline and search results.

ACTIVITY ST-4.13-C: O4 DIRECTED SEARCHES FOR ULTRA-LIGHT BOSON CLOUDS

We will run a directed search for vector boson clouds following up nearby and well-localized merger remnants observed in O4, using a newly developed semi-coherent methods based on hidden Markov model tracking (in prep). We will use the sky localization and remnant black hole properties inferred from the merger events to guide the choice of parameter space and search configurations. We also plan to run a directed search for scalar boson clouds using the semi-coherent method of a collection of FFTs [188] plus the new semi-coherent 5-vector method mentioned above. The best targets for this search are Cygnus X-1, LMC X-1 and GRO J1665-40, where a detection or constraint in the region spanning $\sim$ 30–100 Hz is possible. In contrast to the all-sky search for scalar bosons, we know the sky position and the orbital parameters of these X-ray binaries, which means that we are able to correct for the expected frequency modulations. We can therefore create a collection of FFTs that are overall longer than those for the all-sky scalar boson search, thus providing (in principle) better sensitivity. Pending on person power and identification of interesting sources, we will also run a directed search for scalar bosons from selected CBC merger remnants, which are well localized and close in distance, using the Viterbi pipeline [190]. Galactic newly discovered black holes and known globular clusters are also interesting targets for scalar/vector searches.

TASK ST-4.13-C(i): RUN SEARCH AND POST-PROCESSING

FTE-months: 3.0

Run the search, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK ST-4.13-C(ii): SET CONSTRAINTS

FTE-months: 1.0

In the event of no detection, interpret results and set constraints on ultra-light boson mass and other properties.

TASK ST-4.13-C(iii): PUBLICATION

FTE-months: 1.0

Produce a publication presenting the results.

ACTIVITY ST-4.13-D-**OPS**: O4 DIRECTED SEARCHES FOR ULTRA-LIGHT BOSON CLOUDS - REVIEW

TASK ST-4.13-D(i): REVIEW SEARCH CODE AND RESULTS

FTE-months: 1.0

Review some portions of the analysis pipeline and search results. Note that the core analysis code of the FFT-based method is the same as for the all-sky search. The semi-coherent 5-vector method is under review right now (expected conclusion within 2-3 months). The core code of the Viterbi pipeline for vector bosons is similar to other Viterbi versions, and the Viterbi pipeline for scalar bosons has been reviewed in previous CW analyses.

ST-4.14 Searches for light primordial black-hole binaries

Motivation

The rates, progenitor masses and low effective spins of black hole mergers detected by LVK [39, 194] have revived interest in primordial black holes (PBHs) that comprise at least one solar mass [195, 196, 197]. Furthermore, PBHs with masses well below a solar mass, i.e. between $[10^{-7} - 10^{-1}]M_{\odot}$, remain plausible for certain PBH formation scenarios [198]. For such systems, the signals emitted by PBH binaries slowly inspiraling towards each other resemble (transient) continuous gravitational waves, lasting for $\mathcal{O}(\text{hours} - \text{days})$ at the high-end of the mass range quoted, and $\mathcal{O}(\text{years})$ at the low end. These planetary-mass systems are well-motivated observationally as well as theoretically. There have been recent detections of stellar and quasar microlensing events [199, 200, 201] that suggest compact objects or PBHs with masses $[10^{-6}, 10^{-5}]M_{\odot}$ could constitute a fraction of dark matter of order $f_{\text{PBH}} \sim 0.01$, which is consistent within the unified scenario for PBH formation presented in [202], but greater than expected for floating planets [203]. It has even been hypothesized that Planet 9 could be a PBH with a mass of $10^{-6}M_{\odot}$ that was captured by the solar system [204], motivating the development of methods to detect the accretion of small Oort cloud objects [205]. However, astrophysical uncertainties plague these observations, e.g. due to the clustering properties of PBHs [206, 207, 208, 209, 209, 210, 211], underlining the importance of probing these mass regimes using complementary and independent observational methods that could help to distinguish PBHs from other sources.

At the moment, LVK analyses search for sub-solar mass black holes only down to $0.1M_\odot$ (Section ST-3.15), due to computational restrictions intrinsic to matched filtering that prevent the generation of such long waveforms for masses below $0.1M_\odot$. It is therefore necessary to devise methods that can search for PBHs below $0.1M_\odot$, which can be done by adapting CW methods [152, 151, 212, 175, 171, 173, 165, 213, 172]. These methods must also be robust against noise disturbances and be able to handle gaps in the data, since the signals will be long enough such that the detector noise spectrum will change. Already, constraints on asteroid-mass PBH binaries exist based on the results of all-sky CW searches [214, 215]; however, to obtain stringent constraints in the PBH mass parameter space, dedicated searches need to be performed. The results of such an investment in this kind of science will be the first-ever GW constraints of planetary-mass PBHs, or a potential detection of a very elusive compact object.

Methods

The methods employed to perform these kinds of searches are based on CW methods that look for isolated neutron stars after a supernova or BNS merger. One such method is the Generalized Frequency-Hough [175, 216], that tracks power-law time–frequency evolutions using a particularly efficient implementation of the Hough Transform. This method can handle searches for PBH inspirals between roughly $10^{-6} - 10^{-2}M_\odot$, which would correspond to signals spanning hours–days. Furthermore, machine learning methods [212, 213] could also be applied to this problem, as well as particular implementations of matched filtering in restricted portions of the parameter space between $10^{-4} - 10^{-1}M_\odot$. Matched filtering could be used to enhance the sensitivity of the Generalized Frequency-Hough to higher masses closer to $10^{-1}M_\odot$. Furthermore, we can consider the case of asymmetric mass ratio binaries, which the Generalized Frequency-Hough could directly constrain, assuming circular orbits. However, we plan to improve methods , based on more precise waveform modelling, to search for so-called mini extreme mass ratio inspirals [217], for which the circular orbit approximation will fail. These kinds of methods will also serve as prototypes for searches in future ground-based and space-based detectors, when the signals will last a lot longer even for the canonical sources of GWs.

Activities for O4

ACTIVITY ST-4.14-A-**OPS**: DEVELOP SEARCH METHODS FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

TASK ST-4.14-A(i): DEVELOP EXTENDED CW SEARCH

FTE-months: 6.0

Determine constraints on $\dot{f}$, determine if blind injections are needed, and determine required SNR threshold for upper limits.

TASK ST-4.14-A(ii): DEVELOP MATCHED FILTERING SEARCH

FTE-months: 6.0

Create truncated template bank which looks for partial, high-frequency portion of chirps in mass range $10^{-4} - 10^{-1}M_\odot$. The start frequency will determine the range truncation, and will in turn will be determined by maximum template duration limitation from computational resources. Determine if the same SNR can be used when using a truncated frequency range. Determine how to combine SNR or upper limits for masses whose low-frequency part is being searched by CW methods. Essentially, develop the formalism for a hybrid search pipeline.

ACTIVITY ST-4.14-B: O4 SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

TASK ST-4.14-B(i): RUN SEARCH

FTE-months: 3.0

TASK ST-4.14-B(ii): OUTLIER FOLLOWUP – OTHER STUDIES FTE-months: 1.0

TASK ST-4.14-B(iii): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, we will put upper limits on the GW emission.

TASK ST-4.14-B(iv): PUBLICATION FTE-months: 3.0

Produce a publication with the results of each pipeline.

ACTIVITY ST-4.14-C-**OPS**: O4 SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES - DATA QUALITY STUDIES AND REVIEW

TASK ST-4.14-C(i): OUTLIER FOLLOWUP – DATA QUALITY STUDIES FTE-months: 1.0

TASK ST-4.14-C(ii): REVIEW SEARCH CODE AND RESULTS FTE-months: 3.0

Review of any updated part of the codes and the search results.

ST-4.15 Support for continuous wave searches: Follow-up of interesting candidates

Motivation

A candidate for the first detection of continuous gravitational waves will need to be vigorously vetted by many different pipelines. Since many wide-parameter-space searches produce very large numbers of candidates, follow-up pipelines which can efficiently deal with a long list of targets will be necessary.

Methods

Naturally, the pipelines used to search for known pulsars (Sections ST-4.1, ST-4.2) may also be used for candidate follow-up; particularly via the CWInPy package [91] and the 5-vector method. Follow-up pipelines have also been developed as part of many of the directed (Sections ST-4.4, ST-4.5, ST-4.7) and all-sky (Sections ST-4.9, ST-4.10) search methods. A highly-optimized semi-coherent $\mathcal{F}$-statistic search code [218] was found to be more effective for candidate follow-up compared to other implementations [219]. A semi-coherent follow-up (and directed search) method using 5-vectors [92] has been recently developed, extending a simpler procedure used in BSD-based directed searches [147], and is currently under review (and a method paper is in preparation). Other methods have been developed more specifically for candidate follow-up. A general-purpose follow-up tool based on MCMC methods [185, 160] has been described recently in [162]. A long-transient add-on to semi-coherent analyses is also available for intermediate follow-up steps [220].

The follow-up of outliers from CW searches will generally be accompanied by manual investigation of the detector noise to check for any spectral artifacts that may be responsible for the outliers (see the Operations White Paper).

Activities for O4

ACTIVITY ST-4.15-A-**OPS**: UPDATE FOLLOW-UP METHODS AND IMPLEMENT LATEST DEVELOPMENTS FTE-months: 3.0

Follow-up methods are continuously being improved in order to fullfil different trade-offs regarding sensitivity and robustness against instrumental artifacts. At the same time, LALSuite routines evolve in order to fix issues identified during production time of the previous run, meaning specific follow-up implementations need to be maintained in order to be actively used in production for the next time.

TASK ST-4.15-A(i): IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

PyFstat [160, 161] is a package for $\mathcal{F}$-statistic-based data analysis, aimed mostly at candidate followup for both standard CWs and long-duration transients (Section ST-4.12). Ongoing and planned development includes closer interfacing with existing LALPulsar functionality, better support for CW sources in binaries, and addition of utility functions for hierarchical followup schemes [162].

TASK ST-4.15-A(ii): UPDATE OTHER FOLLOW-UP METHODS AND IMPLEMENT LATEST DEVELOPMENTS

TASK ST-4.15-A(iii): REVIEW OF THE UPDATED PACKAGES

ACTIVITY ST-4.15-B-**OPS**: FOLLOW-UP OF INTERESTING CONTINUOUS WAVE CANDIDATES

FTE-months: 3.0

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline continuous wave searches, with the goal to confirm or reject their continuous nature. The use of a broad set of tools may require to re-generate data in different formats in order to suit the technical requirements of different pipelines. This includes, for example, the re-generation of SFT data files using different baseline durations. The interpretation of follow-up results will also form a key part of LVK search results publications.

TASK ST-4.15-B(i): PRODUCE DATA PRODUCTS IN THE REQUIRED FORMAT

TASK ST-4.15-B(ii): FOLLOW-UP OF INTERESTING CW CANDIDATES

TASK ST-4.15-B(iii): REVIEW OF THE FOLLOW-UP RESULTS

TASK ST-4.15-B(iv): CONTRIBUTE TO RESULTS PAPER

ACTIVITY ST-4.15-C-**OPS**: FOLLOW-UP OF INTERESTING LONG-TRANSIENT CANDIDATES

FTE-months: 3.0

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline long-transient searches, or to study transient properties of candidates found in CW searches but found in a previous follow-up stage to not follow the expected CW behaviour. In a similar vein to the previous task, this may require to re-generate data in different formats to suit the technical requirements of the different involved pipelines. The interpretation of follow-up results will also form a key part of LVK search results publications.

TASK ST-4.15-C(i): PRODUCE DATA PRODUCTS IN THE REQUIRED FORMAT

TASK ST-4.15-C(ii): FOLLOW-UP OF INTERESTING LONG-TRANSIENT CW CANDIDATES

TASK ST-4.15-C(iii): REVIEW OF THE FOLLOW-UP RESULTS

TASK ST-4.15-C(iv): CONTRIBUTE TO RESULTS PAPER

ST-4.16 Support for continuous wave searches: Data preparation

Motivation

Since continuous GWs are nearly monochromatic in the Solar System Barycenter reference frame, it is useful for most CW search pipelines to pre-process the $h(t)$ strain time series into a few common data products ready for analysis by the different pipelines. Common data products include: Short Fourier Transforms (SFTs), Short Fourier Transform Database (SFDB), Band-Sampled Data (BSD), and heterodyned data. Different data products are needed because different analysis pipelines are optimized for knowledge of a putative source (e.g., targeted, directed, or all-sky).

Methods

Data products generated for CW searches generally rely on well known digital data analysis methods, such as the Fast Fourier Transform, heterodyning, or resampling. These algorithms are coded and used within the LALSuite library and the Virgo PSS C code and the Matlab software Snag.

In conjunction with characterising every observing run data set, an appropriate set of data quality flags are used to select time intervals of high-quality $h(t)$ data and used as input for these data products. In addition, self-gating of $h(t)$ may be required to deal with very loud glitches which contaminate the spectrum when Fourier-transformed. Once appropriate data is selected, the data is processed and is stored in common computing locations (e.g., distributed to LVK computing clusters via LDR).

The time-domain Bayesian [90] and $\mathcal{F}/\mathcal{G}$-statistic [85] targeted pulsar searches require narrowband time series for each pulsar. The production of these time series makes use of pulsar timing ephemerides that provide a coherent phase solution for each pulsar signal over the course of an observing run. For each pulsar the phase evolution is used to heterodyne the raw $h(t)$, which is subsequently low-pass filtered and downsampled [221]. This gives a complex time series, with a sample rate of one per minute, which can then be used for further analysis.

Activities for O4

ACTIVITY ST-4.16-A-**OPS**: DETERMINE APPROPRIATE TIME SEGMENTS TO ANALYZE

FTE-months: 3.0

Before producing common data products, it is important to identify time segments for which data is reliable. Data quality flags will be chosen in such a way to eliminate truly bad data.

TASK ST-4.16-A(i): DETERMINE APPROPRIATE TIME SEGMENTS FOR CW SEARCHES TO ANALYZE

ACTIVITY ST-4.16-B-**OPS**: IMPROVE DATA PREPARATION INFRASTRUCTURE AND SOFTWARE

FTE-months: 3.0

Parts of the data preparation infrastructure and software tools have been in use for a long time and for O4 will require updates to improve code maintainability, adherence to modern coding standards, and usability. This will also enable the tools to support more flexible requirements from analysis pipelines, and to improve interoparability with modern data storage and distribution solutions.

TASK ST-4.16-B(i): MODERNISATION OF SFT PRODUCTION SOFTWARE

The SFT specification [222] will be updated to record the window function (if any) applied to SFTs. A more prescriptive filename and directory naming convention will also be developed for “public” (i.e. published and distributed SFTs); in particular, O4 production SFT filenames will be globally unique to facilitate replication with Rucio and other tools. The `MakeSFTs` executable in LALSuite will be upgraded to modern coding standards, as well as to implement the new “public” SFT filename convention.

TASK ST-4.16-B(ii): IMPROVE DATA PREPARATION INFRASTRUCTURE AND SOFTWARE FOR CW SEARCHES

Broadband Tukey-windowed SFTs for analysis will be generated daily on the Caltech cluster, along with derived spectral plots (daily and cumulative) and numerical data for detector characterization studies. This infrastructure will be a consolidation of the weekly SFT generation of SFTs for analysis at Caltech during O3 and some of the daily spectral analysis using Fscan products carried out during O3 at the observatories. The same set of O4 SFTs will be used for producing daily CW-focused figures of merit for the Detchar Daily Summary pages and for monitoring of CW hardware injections.

ACTIVITY ST-4.16-C-**OPS**: PRODUCE FOURIER TRANSFORM FILES

FTE-months: 3.0

TASK ST-4.16-C(i): VET GATED $h(t)$ FRAMES

Vet gated $h(t)$ frames for any issues before starting SFT/SFDB production.

TASK ST-4.16-C(ii): PRODUCE SFTS

SFT files will be produced for a variety of coherence times and at least two windowing choices (Tukey, Hann). Vet produced SFT files for any issues.

TASK ST-4.16-C(iii): PRODUCE SFDB

SFDB files will be produced at the CNAF computing center with four different coherence times: 8192 s, 4096 s, 2048 s, 1024 s for the frequency bands [10 - 128] Hz, [128 - 512] Hz, [10 - 1024] Hz, [10 - 2048] Hz, respectively. Data are overlapped by the halfh and a window cosine flat (similar to Tuckey) is used. Strong glitches in the data, in time domain, are identified and substracted from the data, before constructing the FFTs. SFDB data can be distributed to different LVK computing centers, if this will be needed. The production of the h reconstructed channel will be done on a monthly basis. BSD files (see below) are produced from SFDB files.

TASK ST-4.16-C(iv): DISTRIBUTE DATA PRODUCTS

SFT data products will be distributed to different LSC computing clusters via LDR, and SFDBs will be transferred to other Virgo clusters as well as the Caltech LSC cluster.

ACTIVITY ST-4.16-D-**OPS**: PRODUCE TIME SERIES FILES

FTE-months: 3.0

TASK ST-4.16-D(i): PRODUCE BSD

BSD files [123] will be produced on a monthly base. Each file contains a complex, reduced analytic time series covering a 10 Hz frequency band. Each file contains the auxiliary information needed for the analyses.

TASK ST-4.16-D(ii): PRODUCE NARROWBAND HETERODYNED TIME SERIES

The narrowband heterodyned time series will be produced for a range of pulsars with rotation frequencies $\gtrsim 10$ Hz for which ephemerides can be obtained from electromagnetic observers.

ST-4.17 Support for continuous wave searches: Scientific software maintenance

Motivation

The software used and developed by the CW group are maintained in version-controlled repositories in different locations, including public as well as internal repositories, and generally are managed by the code authors themselves. One exception is the more centralized LALSuite repository [223], which contains important CW core routines and data, such as the antenna patterns as a function of time and sky location and the Sun and Earth ephemeris files. To ensure that this software base is maintained with standard good practice procedures, contributions to the main LALSuite repository [3] are restricted to a merge request model.

Methods

Maintainers from the CW group assist the LALSuite librarian in vetting and approving merge requests to the main repository, to ensure code is well documented and tested, maintains backward compatibility as much as possible, and to reduce the likelihood of introducing new bugs. Issues potentially relevant to the whole group, as well as recently-approved merge requests, are discussed in the weekly teleconferences. Code contributions from external authors (defined as those who are not LVK members) are also supported through an e-mail service desk system.[4]

Activities for O4

ACTIVITY ST-4.17-A-**OPS**: MAINTENANCE OF CW SOFTWARE IN LALSUITE

FTE-months: 3.0

Address issues and approve merge requests to CW software in the LALSuite repository, and keep the CW group informed of any important changes or bugs. Occasionally, larger upgrades to keep CW software modernised, maintainable, and to support new use cases and packaging requirements may be needed.

TASK ST-4.17-A(i): MAINTENANCE OF CW SOFTWARE IN LALSUITE

ACTIVITY ST-4.17-B-**OPS**: SUPPORT FOR LALSUITE REPOSITORY MANAGEMENT

FTE-months: 3.0

Work with the LALSuite librarian to ensure the contribution model, code review, continuous integration and other aspects of the repository management continue to evolve and are suitable for the scientific needs of the working group. Work to ensure timely releases of LALSuite, and support CW analysts in using released software versions for improved reproducibility.

TASK ST-4.17-B(i): CW-RELATED SUPPORT FOR LALSUITE REPOSITORY MANAGEMENT

ACTIVITY ST-4.17-C-**OPS**: SUPPORT FOR OTHER SHARED SOFTWARE TOOLS AND ANALYSIS PACKAGES

FTE-months: 3.0

Support of other packages outside of LALSuite, but often building on it, whose use is shared across CW analysis pipelines and projects, ensuring their robustness and interoparability. This includes for example data input/output libraries for different formats, interfaces to detector characterization information, and follow-up packages.

TASK ST-4.17-C(i): SUPPORT FOR SHARED CW-REALTED SOFTWARE TOOLS AND ANALYSIS PACKAGES

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[3] `https://git.ligo.org/lscsoft/lalsuite`

[4] contact+lscsoft-lalsuite-1438-issue-@support.ligo.org

LT-4.18 Further improvement and optimization of existing data analysis pipelines

Motivation

The most efficient use of limited computing resources is essential to the scientific goals of the CW group. Typically, the codes used by the CW group are highly optimized, due to the demanding computational nature of many searches, but further improvements may still be possible. Time spent on optimization will need to be weighed against the potential reduction in run time of the analysis in question, as well as the time needed to review the new version of the code. Code improvement also includes refactoring to better work with modern hard- and software technologies, adapting to broader or more specific astrophysical source classes and priors, inclusion of data quality information, and other enhancements.

Activities

ACTIVITY ST-4.18-A-**OPS**: PIPELINE OPTIMIZATION REPORTS AND WORK WITH COMPUTING GROUP

At the request of the IGWN computing chairs, the CW group may periodically produce optimization reports to ensure responsible use of LVK computing resources. When requested, pipelines that are found to be the highest users of computing resources will produce optimization reports and work with the IGWN computing optimization team to reduce the computing load.

TASK ST-4.18-A(i): PREPARE OPTIMIZATION REPORTS (ON REQUEST)

TASK ST-4.18-A(ii): IMPLEMENT OPTIMIZATIONS SUGGESTED BY IGWN COMPUTING TEAM

ACTIVITY LT-4.18-B: ASTROPHYSICALLY-INFORMED PARAMETER SPACE SELECTION

All-sky searches for unknown CW sources are extremely computationally expensive. It is therefore important to find ways of using the available computational and man-power resources most efficiently. This can be achieved through analysis of existing catalogues of pulsars, supernova remnants and galactic structure, and/or through Monte Carlo-type modelling of the Galactic neutron star population, to build an astrophysically-informed picture of where in parameter space detections are most likely to be made. This knowledge could then be used to make decisions as to how to allocate resources, in terms of sky locations and spin-down parameters.

TASK LT-4.18-B(i): ASTROPHYSICALLY-INFORMED PARAMETER SPACE SELECTION FOR CW SEARCHES

ACTIVITY LT-4.18-C: FURTHER IMPROVEMENT AND OPTIMIZATION OF SKYHOUGH AND RELATED CODES

The SkyHough method is one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. SkyHough has been used to analyze O1, O2 and O3 data [224, 225, 226]. Another search code derived from SkyHough are BinarySkyHough [156] for all-sky searches of unknown neutron stars in binary systems.

TASK LT-4.18-C(i): FURTHER IMPROVEMENT AND OPTIMIZATION TO $\mathcal{F}$-STATISTIC VERSION OF SKYHOUGH CODE

This covers work beyond that needed for direct O4 application as discussed in (Section ST-4.9).

TASK LT-4.18-C(ii): FURTHER IMPROVEMENT AND OPTIMIZATION OF SKYHOUGH CODE

Refactoring and modernization of the standard SkyHough code to profit from improvements to the demodulated ($\mathcal{F}$-statistic) version, for better use of modern technologies such as GPUs, and algorithmic improvements.

TASK LT-4.18-C(iii): FURTHER IMPROVEMENT AND OPTIMIZATION OF BINARYSKYHOUGH CODE

Refactoring and modernization for better use of modern technologies such as GPUs and algorithmic improvements.

ACTIVITY LT-4.18-D: FURTHER IMPROVEMENT AND OPTIMIZATION OF ADAPTIVETRANSIENTHOUGH

AdaptiveTransientHough [173] is a search code for long-duration CW-like signals for newborn neutron stars with rapid spindown. Envisaged improvements include refactoring and modernization for better use of modern technologies such as GPUs, and algorithmic and grid placement improvements.

TASK LT-4.18-D(i): FURTHER IMPROVEMENT AND OPTIMIZATION OF ADAPTIVETRANSIENTHOUGH CODE

ACTIVITY LT-4.18-E: IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

The transient $\mathcal{F}$-statistic method [179, 182] is well suited for quasi-monochromatic long transients after pulsar glitches (Section ST-4.12). It is computationally cheap as long as applied only to narrow frequency bands around twice the pulsar rotation frequency and simple, rectangular transient window functions. However, the search can be made more robust and general with several improvements over the simple type of setup as it was used in [183]. The method itself can easily support generic transient amplitude evolutions [179], e.g. exponential decay, but the LALSuite code [223] is very slow for these. A much faster GPU implementation is available [182, 160, 161] but will require some (limited) amount of additional work to integrate it in the full search pipeline, plus additional review. The easiest way to run a transient $\mathcal{F}$-statistic search is to reuse the standard 1800 s SFTs produced for other CW searches (Section ST-4.9), but extension of the search space to shorter transients and a detailed follow-up with denser coverage of transient parameters can be achieved with generating and analyzing multiple sets of SFTs with different baselines. Better methods in the time and/or frequency domain to find, clean or mitigate instrumental artifacts will improve the robustness of the search and reduce the effort required for follow-up and review of outliers. Machine-learning methods (Section LT-4.20) can make the searches faster and more robust to different amplitude and frequency evolutions.

TASK LT-4.18-E(i): IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

ACTIVITY LT-4.18-F: OPTIMIZATION OF THE FREQUENCYHOUGH PIPELINE

The main target is to port the heaviest parts of the code to use GPUs. The core FrequencyHough routine has been already ported and reviewed. The capability of running a full all-sky search on new LIGO-Virgo data will depend on the availability of enough GPU resources. The porting will be based on the TensorFlow framework. Extensive tests and comparisons with old code will be done in order to verify the new code behaves properly. An exploratory analysis, over a reduced parameter space, will be run using O2 data. A paper describing the new implementation and the pilot analysis will be written. New pieces of the code, not previously reviewed, will be subject to a review.

TASK LT-4.18-F(i): OPTIMIZATION OF THE FREQUENCYHOUGH PIPELINE

ACTIVITY LT-4.18-G: FURTHER IMPROVEMENT AND OPTIMIZATION OF THE TIME-DOMAIN $\mathcal{F}$-STATISTIC SEARCH

The Time-Domain $\mathcal{F}$-statistic method is one of the semi-coherent pipelines able to perform all-sky searches for CW signals in many-days time-domain segments, as well as sensitivity upper limits calculations via software signal injections, with a moderate computational cost [153]. However, some technical code optimization as well as improvements in the post-processing stages of the pipeline are still possible.

TASK LT-4.18-G(i): OPTIMIZATION TO COINCIDENCES BETWEEN TRIGGERS FOUND IN TIME-DOMAIN SEGMENTS

Technical code optimization of task described in (Section ST-4.9).

TASK LT-4.18-G(ii): OPTIMIZATION TO SIGNAL INJECTIONS PROCEDURE/UPPER LIMITS CALCULATION

Technical code optimization of task described in (Section ST-4.9).

ACTIVITY LT-4.18-H: FURTHER OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

CrossCorr is the most sensitive pipeline to search for Sco X-1 (Section ST-4.5). Since the sensitivity is determined by the coherence time, which is tied to computing cost, the search is computationally limited: any further improvements (beyond those discussed in (Section ST-4.5)) which allow the code to run faster enable us to run a more sensitive search.

TASK LT-4.18-H(i): FURTHER OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

ACTIVITY LT-4.18-I: EXPLORE FURTHER TWOSPECT ANALYSIS IMPROVEMENTS

TwoSpect provides a framework for analysis of CW sources in binary systems, and is especially powerful when the neutron star or binary parameters are unknown. Pending person power, explore new analysis strategies with the goal of improvements in TwoSpect detection capabilities; this would prove very useful for future all-sky searches for unknown neutron stars in binary systems.

TASK LT-4.18-I(i): EXPLORE FURTHER TWOSPECT ANALYSIS IMPROVEMENTS

ACTIVITY LT-4.18-J: FURTHER IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

Potential developments of the PyFstat [160, 161] package beyond those discussed above (Section ST-4.15) include the possible migration of the MCMC-based followup methods [185] to newer sampling backends.

TASK LT-4.18-J(i): IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

ACTIVITY LT-4.18-K: IMPACTS OF CALIBRATION SYSTEMATIC ERROR AND UNCERTAINTY ON CW SEARCHES

Improved understanding of calibration systematic error and uncertainty is increasingly important, especially when performing parameter estimation on a source signal. It is also important to understand how time- and frequency- dependent errors impact results from CW search pipelines, especially when systematic error may be poorly quantified. We intend to research the impact of calibration error and uncertainty, as currently understood, in the Viterbi/HMM pipeline. We expect this kind of study could be expanded to include other pipelines. The conclusions of such studies will enable better understanding on usage of different calibration versions and impacts on CW analysis results.

TASK LT-4.18-K(i): IMPACTS OF CALIBRATION SYSTEMATICS AND UNCERTAINTY ON CW SEARCHES

ACTIVITY LT-4.18-L: DEPLOY THE SOAP PIPELINE FOR INSTRUMENTAL LINE IDENTIFICATION.

SOAP [148] can also be applied in detector characterisation, where it can be used to identify instrumental lines. We aim to run this search on advanced LIGO observing runs and integrate this tool into existing instrumental line searches.

TASK LT-4.18-L(i): DEPLOY SOAP PIPELINE FOR INSTRUMENTAL LINE IDENTIFICATION

ACTIVITY LT-4.18-M: INTEGRATE PE FOLLOWUP FOR SOAP

SOAP [148] has been extended to generate posterior distributions on the doppler parameters of an isolated neutron star signal. This needs to be fully integrated into the SOAP pipeline to run in future advanced LIGO observing runs.

TASK LT-4.18-M(i): DEPLOY PE SOAP PIPELINE

LT-4.19 Development of model-robust/agnostic data analysis methods

Motivation

Given the limited knowledge of neutron star physics, particularly beyond nuclear densities, it is conceivable that the usual continuous quasi-sinusoidal model of a CW signal may not entirely reflect nature, and that not accounting for such deviations could prevent detection. In general, without knowledge of what form such deviations could take, this is a difficult issue to address. Relaxing the assumption of phase lock between gravitational and electromagnetic emission is a key motivation for the narrow-band pulsar searches (Section ST-4.2). The stochastic wandering of the spin frequency of LMXBs is a key consideration for directed searches (Section ST-4.5), although the timescale of the wandering is difficult to quantify. The lack of knowledge of the behavior of long-transient signals, such as from a post-merger neutron star remnant (Section ST-4.11) or a pulsar glitch (Section ST-4.12) motivates the development of robust pipelines for such sources. Same arguments apply to all-sky searches (Section ST-4.9), (Section ST-4.8). Signals which are not truly continuous, but are intermittent on some timescale, present a particular challenge by expanding the parameter space to include the start and end time of any gravitational-wave emission as a subset of an observing run. New methods based on traditional statistics and on machine learning [227] can contribute to solving these challenges.

Activities

ACTIVITY LT-4.19-A: POST-MERGER NEUTRON STAR SEARCH METHODS WITH IMPROVED SENSITIVITY AND/OR ROBUSTNESS

Post-merger neutron star searches are a relatively new area of activity in the CW group. While a number of pipelines have been successfully developed so far, further improvements in analysis methods may still be possible. For instance, the likely rapid spindown and uncertain signal model for post-merger neutron stars present numerous challenges to obtaining optimal sensitivity, which new methods development could potentially address.

TASK LT-4.19-A(i): POST-MERGER NS CW SEARCH METHOD IMPROVEMENTS

ACTIVITY LT-4.19-B: MACHINE LEARNING FOR LESS MODEL-DEPENDENT CW AND TRANSIENT-CW SEARCHES

Many CW and transient CW searches are optimized for very specific signal models, which means that we are bound to find only signals we expect. Machine Learning methods can help to alleviate this problem by training the algorithms on signals following the standard model plus allowing for some variations, and then benefiting from the method's robustness to deviating signals.

TASK LT-4.19-B(i): MACHINE LEARNING FOR LESS-MODEL-DEPENDENT CW AND TRANSIENT-CW SEARCHES

This task will investigate application of ML methods to perform signal searches, with aim of comparable senstivity and decreased computational cost.

TASK LT-4.19-B(ii): MACHINE LEARNING POST-PROCESSING OF TRIGGERS FOUND BY SEARCH PIPELINES

ML clustering may be applied to trigger parameters found in coherent searches (i.e., in time-domain data segments of specific duration, as used in the Time-Domain F-statistic) in order to train the algorithm a specific (or general) behavior, e.g., frequency evolution or amplitude evolution. Alternatively, these methods may be used to veto outlier signal candidates obtained in the coincidences procedure.

LT-4.20 Development of new and potentially more sensitive data analysis methods

Motivation

The CW group welcomes work on significant improvements to existing methods that open new scientific opportunities, as well as blue-sky research into completely new ideas for search methods which may yield increased sensitivity or new scientific scope with respect to current algorithms. Many ideas used in CW data analysis have been imported from other fields of astronomy which also analyze long time series, such as radio pulsar astronomy, as well as from more general trends in data analysis, e.g., the use of Bayesian inference. Other successful ideas have come from engineering fields, such as the Viterbi algorithm used in digital communications.

Activities

ACTIVITY LT-4.20-A: ALTERNATIVE METHODS FOR COMPUTATIONALLY EXPENSIVE SEARCHES

The sensitivity of many CW searches, such as directed and all-sky searches, are fundamentally limited by their computational cost, which typically scales steeply with observation time. It is therefore important to pursue "blue skies" research into alternative analysis methods that are fundamentally less computationally expensive and/or scale more shallowly with observation time, thereby permitting more sensitive searches. Outcomes in this area are difficult to predict, nevertheless success could potentially be vital to a first CW detection.

TASK LT-4.20-A(i): ALTERNATIVE METHODS FOR COMPUTATIONALLY EXPENSIVE CW SEARCHES

ACTIVITY LT-4.20-B: ELLIPTICITY DISTRIBUTION INFERENCE

For any individual pulsar targeted by a CW search one can estimate the parameters defining the gravitational-wave signal. The amplitude of the signal, as observed at Earth, is defined by the mass quadrupole of the source and its distance from us. The mass quadrupole can itself be parameterized by the ellipticity of the star under assumptions about the equation of state and moment of inertia. For a population of sources it is interesting to understand the distribution of ellipticities across all pulsars, which may help constrain the underlying physics that gives rise to such a distribution. We will expand on the works in [228] to combine results from the targeted pulsar searches to infer the properties of various parameterized ellipticity distributions, and how these might vary for different sub-populations of pulsars, e.g., "young" versus recycled millisecond pulsars. It will be tested on results from published known pulsar analyses as a short author project. In addition, it will be compared with an independent method, described in [229], that combines results from the targeted pulsar searches using the 5n-vector method.

TASK LT-4.20-B(i): ELLIPTICITY DISTRIBUTION INFERENCE

ACTIVITY LT-4.20-C: MACHINE LEARNING FOR EFFICIENT ANALYSIS OF CWS AND TRANSIENT-CWS

In addition to making CW and transient-CW searches less model-dependent (Section LT-4.19), machine learning can also help to reduce the amount of resources needed to find and study signals. For example, searches using convolutional neural networks take orders of magnitude less time than traditional methods, and can approach their sensitivity both for signals that follow our models and even ones that do not. Moreover, machine learning has the capabilities to estimate the parameters of transient CW signals. Finally, it does not necessarily have to be used to detect signals; rather, it can be used to generate waveforms [230, 231], to veto likely false candidates, etc. We plan to continue efforts to use machine learning to run searches [213], perform parameter estimate [232, 233], and to apply it in new ways. We also plan to continue the work of [234] in order to better understand how machine learning methods respond specifically to noise disturances, so that we can quote reliable false alarm probabilities, sensitivities in the presence of non-Gaussianities, and actually apply more of them to real searches.

TASK LT-4.20-C(i): MACHINE LEARNING FOR EFFICIENT ANALYSIS OF CWS AND TRANSIENT-CWS

ACTIVITY LT-4.20-D: FURTHER IMPROVEMENTS TO BINARYWEAVE PIPELINE

Accreting neutron stars in low-mass X-ray binary systems (LMXB), particularly Sco X-1, are one of the strongest candidates for the future detection of CW signals. A new detection pipeline, namely BinaryWeave, has been developed that is suitable for searching for CW signals from spinning neutron stars in binary systems with known sky position over a wide parameter space. (Section ST-4.5). Further development and characterization of the pipeline is ongoing.

TASK LT-4.20-D(i): FURTHER IMPROVEMENTS TO BINARYWEAVE PIPELINE

ACTIVITY LT-4.20-E: NEW TECHNIQUES FOR FOLLOW-UP AND PARAMETER ESTIMATION OF CW CANDIDATES

There is so far a limited set of methods available to do Bayesian sampling on CW signal candidates, both for follow-up with enhanced coherence times (Section ST-4.15) and especially for full parameter estimation. But many modern sampling algorithms and software packages have been developed in the wider GW, astrophysics and data science communities. Implementing and characterizing these for CW applications is a crucial step towards the robust identification and scientific exploitation of CW signals from a wide range of searches (from all-sky to targeted).

TASK LT-4.20-E(i): IMPLEMENT AND CHARACTERIZE NEW SAMPLERS FOR CW APPLICATIONS

ACTIVITY LT-4.20-F: EXPANDED PARAMETER ESTIMATION AND ASTROPHYSICAL INFERENCE FOR NEWLY-DISCOVERED CW SOURCES

If a known radio or X-ray pulsar is seen to be a continuously emitting gravitational wave source, its mass quadruple can be readily estimated from the signal strain and the distance to the pulsar. This distance is usually known reasonably well from dispersion or parallax measurements. If however the source of the gravitational waves is not radio or X-ray loud we need another way to determine its distance if we are to progress further than a simple strain and frequency measurement. For close, bright GW sources we can apply the same annual parallax method used in radio to gravitation observations. The current targeted parameter estimation code can be adapted to include frequency and its derivative, sky position and parallax (or distance) as constrained parameters, returning estimates of the neutron star's mass quadruple and distance. Of course this process is sensitive to the signal-to-noise ratio and will become increasingly important in A+ and beyond.

TASK LT-4.20-F(i): EXPANDED PARAMETER ESTIMATION FOR NEWLY-DISCOVERED CW SOURCES

ACTIVITY LT-4.20-G: EFFICIENT SEARCHES FOR LONG-DURATION TRANSIENTS FROM UNKNOWN SOURCES

Search techniques for long-duration CW-like signals, such as post-merger (Section ST-4.11) and post-glitch (Section ST-4.12) signals, are so far severely computationally limited and only run on targets with known sky position and approximately known starting time. As for CWs, all-sky searches over broad frequency ranges are even more expensive, though the sky needs to be covered less densely for shorter durations. Searching for arbitrary transients with starting time anywhere within an observing run gives another huge scaling factor. New approaches are needed to meet this computational challenge for "all-sky all-frequency all-time" searches.

TASK LT-4.20-G(i): DEVELOP AND CHARACTERIZE HIGHLY EFFICIENT METHODS FOR FINDING TRANSIENTS FROM UNKNOWN SOURCES

ACTIVITY LT-4.20-H: ASTROPHYSICAL IMPLICATIONS AND MULTI-MESSENGER STUDIES OF CW DETECTIONS

The first CW detections will require detailed astrophysical interpretation. At least in the case of our main targets, neutron stars, there is also a rich range of opportunities for multi-messenger combined analysis of electromagnetic and GW data on the same sources. Testing for consistency of GW-inferred source parameters and those known from EM observations has been identified as an important step in CW candidate validation, and optimal Bayesian methods for combined inference can be useful contributions to exploiting LVK detections.

TASK LT-4.20-H(i): DEVELOP METHODS FOR SYSTEMATIC ASTROPHYSICAL INTERPRETATION AND COMBINED ELECTROMAGNETIC AND GW STUDIES OF CW DETECTIONS

ACTIVITY LT-4.20-I: STUDYING GRAVITATIONALLY LENSED CWS

Directed searches towards the galactic center can potentially detect CWs that undergo gravitational lensing by the supermassive black hole [235]. Strong lensing will create multiple copies of the signal with a time delay, which will interfere with each other. If the time delay is constant, the interfered signal would be indistinguishable from an unlensed CW. However, if the relative motion between the source and the lens is sufficiently large, the lensing time delay can vary with time. This will result in the modulation of the amplitude and phase of the lensed CW signals, rendering them distinguishable. Observation of lensed CWs could enable unique probes of the properties of the supermassive black hole as well as the astrophysical environment of the galactic center.

TASK LT-4.20-I(i): DEVELOP METHODS TO REINTERPRET STANDARD CW UPPER LIMITS UNDER THE LENSING HYPOTHESIS

TASK LT-4.20-I(ii): DEVELOP DEDICATED SEARCH METHODS FOR LENSED CWS

ACTIVITY LT-4.20-J: INVESTIGATE SEARCHES FOR LONG-DURATION TRANSIENT SEARCHES FOR NEWBORN NEUTRON STARS

The methods as discussed in (Section ST-4.11) for the case of BNS merger remnants can also be applied to newborn neutron stars from the regular core-collapse supernova formation channel. The event rates, parameter space and search setup details need to be investigated before designing practical searches.

TASK LT-4.20-J(i): STUDY THE ASTROPHYSICAL RATES AND PRIORS ON PARAMETER SPACE FOR NEWBORN NEUTRON STARS

TASK LT-4.20-J(ii): IMPLEMENT SEARCH PROCEDURES FOR NEWBORN NEUTRON STARS

LT-4.21 Use mock data challenges to compare data analysis pipelines

Motivation

Mock data challenges (MDCs) can be a useful tool for comparing different data analyses pipelines. By subjecting each pipeline to a common set of tests, the benefits and costs of each pipeline can be rigorously assessed. In the past, successful mock data challenges organized within the CW group have compared pipelines for directed searches for Scorpius X-1 [236] and all-sky searches for isolated sources [237]. Since most CW pipelines have been in a mature state for many years, and taking into account constrained human resources, currently no extensive MDCs are planned as essential run preparation, but the CW group still welcomes and supports such efforts as person power and resources allow.

Methods

Commonly, simulated data containing signals of varying strengths whose parameters are unknown to the analysts are prepared by a neutral party, and each pipeline is assessed based on the number of simulated signals it found. This can be done both as fully blind mock data challenges, or as simpler coordinated injection sets shared across different pipelines, which any multi-pipeline analysis project can benefit from.

Activities

ACTIVITY LT-4.21-A: SIMULATION INVESTIGATION FOR SCO X-1

The performance of CW pipelines to search for Sco X-1 may be tested with simulated signals injected into O3 data. In particular, simulations may be generated with varying amounts of spin wandering to check the practical limitations of CW pipelines. Results and conclusions would be reported in a short-author paper.

TASK LT-4.21-A(i): DESIGN OF A SIMULATION INVESTIGATION FOR SCO X-1

TASK LT-4.21-A(ii): PIPELINE PARTICIPATION IN SIMULATION INVESTIGATION FOR SCO X-1

TASK LT-4.21-A(iii): EVALUATION OF A SIMULATION INVESTIGATION FOR SCO X-1

ACTIVITY LT-4.21-B: TARGETED MDCS FOR CANDIDATE FOLLOW-UP AND HANDOVER

The seamless handover of CW detection candidates from first-stage searches to independent follow-up pipelines (Section ST-4.15) has been identified as an important task for validating such candidates.

Targeted MDCs (in the sense of covering specific parameter space regions, where interesting candidates are expected or have already been observed) can be a useful tool to exercise and characterise such handover procedures, including the setting of follow-up priors based on search results and their uncertainty estimates, as well as the choice of appropriate false-dismissal / false-alarm operating points for the follow-up pipelines.

TASK LT-4.21-B(i): DESIGN OF TARGETED MDCS FOR CANDIDATE FOLLOW-UP AND HANDOVER

TASK LT-4.21-B(ii): PIPELINE PARTICIPATION IN TARGETED MDCS

TASK LT-4.21-B(iii): EVALUATION OF TARGETED MDCS FOR CANDIDATE FOLLOW-UP AND HANDOVER

ACTIVITY LT-4.21-C: OTHER MDCS

The CW group supports the design and implementation of any other MDCs that answer a clear question on comparing the sensitivity, robustness or parameter space coverage of several CW analysis methods or pipelines, as long as these clearly contribute to the group deliverables on O4 or to improving CW science in future observing runs.

TASK LT-4.21-C(i): DESIGN OF MDCS

TASK LT-4.21-C(ii): PIPELINE PARTICIPATION MDCS

TASK LT-4.21-C(iii): EVALUATION OF MDCS

5 Stochastic Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, CBC, DetChar and CW groups in sections 7, 8, 9 and 10, respectively.

ST-5.1 Search for an isotropic stochastic gravitational-wave background (short term)

ST-5.1.1 Scientific Case

The stochastic isotropic search targets the stochastic gravitational-wave background, which arises from a superposition of a variety of cosmological and astrophysical gravitational-wave sources. Potential cosmological sources include the amplification of vacuum fluctuations following inflation [238], phase transitions in the early universe [239, 240], and cosmic (super)strings [241, 242, 243, 244]. Astrophysical contributions to the stochastic background consist of an incoherent superposition of sources that are unresolved or too weak to be detected individually. The most promising contribution for terrestrial detectors comes from the population of compact binaries such as binary neutron stars [245], binary black holes [246], or black-hole–neutron stars. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysical background would also be of great interest as it would give important constraints on the star formation history and the evolution of the mass distributions with redshift. The implication from Advanced LIGO/Virgo's first and second observing runs is that the stochastic gravitational-wave background from binary black holes and binary neutron stars is consistent with optimistic predictions, and is potentially observable with advanced detectors [246, 245, 247].

General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [248, 249], $f(R)$ gravity [250, 251], bimetric [252] and massive [253] gravity theories, generically predict up to four additional vector and scalar polarization states. The direct measurement of gravitational-wave polarizations may therefore serve as a powerful phenomenological test of gravity.

ST-5.1.2 Methodology

The primary goal of the isotropic search is to estimate the energy density of the stochastic background:

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f}\,, \tag{1}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the universe, and f is the frequency. This is accomplished through a well-established cross-correlation procedure, documented in [254, 255], which has served as the basis for all previous LIGO/Virgo stochastic searches [256, 257, 258, 259, 260, 261]. The stochastic pipeline estimates $\Omega_{\rm GW}(f)$ given some assumed power law $\Omega_{\rm GW}(f) \propto f^{\alpha}$. Cosmological sources such as inflation and cosmic string backgrounds are predicted to have $\alpha = 0$, while $\alpha = 2/3$ is appropriate for the signal from binaries.

ACTIVITY ST-5.1-A-**OPS**: SEARCH FOR AN ISOTROPIC STOCHASTIC BACKGROUND

TASK ST-5.1-A(i): O4 ANALYSIS

FTE-months: 25.0 (includes all aspects of the search, review, and paper writing)

(i) Measure (or set upper limits on) the energy density of the isotropic stochastic background for different power laws and non-GR polarizations using the combined O1, O2, O3, and O4 data from Advanced LIGO (LHO and LLO), Advanced Virgo, and (possibly) KAGRA; (ii) Using these measurements or upper limits, constrain theoretical models for the isotropic stochastic background, e.g., binary black holes, binary neutron stars and neutron star-black hole binaries (see below), (iii) Implement a method to mitigate loud glitches in O3. (iv) Constrain the presence of magnetic noise.

TASK ST-5.1-A(ii): PREPARATIONS FOR O4

FTE-months: 25.0 (includes all aspects of the preparations listed)

Develop and review infrastructure that will support O4 analyses. This includes: (i) Extending the parameter estimation modules of the new python-based pipeline for isotropic stochastic background search, pygwb, to investigate the implications on new astrophysical and cosmological models, and (ii) performing mock data challenges to verify the detection capabilities of the stochastic search and test the model prediction.

TASK ST-5.1-A(iii): IMPLICATIONS FOR ASTROPHYSICAL MODELS

FTE-months: 15.0 (includes all aspects of the preparations listed)

Our measurements of the energy density of the stochastic gravitational-wave background will allow us to place observational constraints on specific theoretical models of the background. For example, applying the Bayesian parameter estimation techniques outlined in [262, 245, 263], we can estimate or place upper limits on the average chirp mass and merger rate of the binary black hole population. Understanding the observational implications also requires us to develop more accurate astrophysical models of the binary black hole. This work is coordinated with the binary coalescence Rates and Population group (Sec. ST-3.5). We will develop methods to infer properties of the underlying compact binary population from a detection of an astrophysical stochastic background, such as the merger rate as a function of redshift. Mock data challenges will be used to test the recovery of simulated backgrounds. We expect the implications for astrophysical stochastic background to be included in the O4 isotropic background search paper.

TASK ST-5.1-A(iv): IMPLICATIONS FOR COSMOLOGICAL MODELS

FTE-months: 35.0 (includes all aspects of the preparations listed)

With the measurements or upper limits on the energy density, we can explore the implications of these results for isotropic stochastic background due to cosmological models. We will develop methods and carry out a program to compute implications of our observations for models of interest in cosmology, such as phase transitions, cosmic strings, domain walls, parity violation, dark matter candidates (primordial black holes, axion-like particles, dark photon), and inflationary models. We will also consider extensions to backgrounds that have circular polarization. The implications for cosmological stochastic background models will be explored in a separate isotropic search publication.

LT-5.1 Search for an isotropic stochastic gravitational-wave background (long term)

In addition to our standard isotropic analysis, there are several additional activities underway to improve the sensitivity of our search.

ACTIVITY LT-5.1-A: COMPONENT SEPARATION

An important extension of the standard isotropic search is to estimate the individual contributions of distinct sources of the background, because the true background is unlikely to be fully described as a single power law. Even if there is one strong (detectable) power law component, the upper limits on the weaker components will be affected by the strong one(s). One should perform a joint analysis considering all the physically allowed spectral shapes together. A "component separation" method was recently developed to put joint upper limits on the amplitudes of multiple spectral shapes [264]. This method uses the results produced by the isotropic search for each spectral shape and estimates the joint upper limit by deconvolving them via a mixing matrix. In addition to the component separation method, we also will implement a related approach using Bayesian parameter estimation to study more general models such as broken power laws. This analysis can be applied in post-processing, using the measured cross-correlation spectrum as the fundamental data product.

TASK LT-5.1-A(i): COMPONENT SEPARATION FOR ISOTROPIC STOCHASTIC SEARCHES

ACTIVITY LT-5.1-B: A CROSS-CORRELATION BASED SEARCH FOR INTERMITTENT GRAVITATIONAL-WAVE BACKGROUNDS

To better search for intermittent (i.e., popcorn-like) stochastic GW backgrounds (most-likely produced by astrophysical sources such as stellar-mass binary black hole mergers), efforts are currently underway to modify the standard cross-correlation search for a stationary-Gaussian background to target short intermittent “bursts" of correlated GW signals. The search is based on a mixture-likelihood formalism involving the duty cycle of the signals, analogous to the fully-Bayesian search for BBH mergers. But rather than marginalize over the parameters of deterministic chirp signals, this new method looks for evidence of excess correlated $f^{-7/3}$ GW power, as expected for binary inspiral signals. Although suboptimal compared to the fully-Bayesian search for BBH mergers, the cross-correlation-based search is computationally efficient, using cross-correlation frequency spectra and their variances as sufficient statistics for the analysis. Preliminary testing on simple toy models indicate that the cross-correlation-based search is a promising strategy for intermittent GW signals. Additional testing on more realistic simulated data sets containing injected BBH merger signals and noise transients is needed before this method can be run with confidence on real LIGO-Virgo data. The hope is to complete this testing in time for the search to be ready around the start of O4.

TASK LT-5.1-B(i): CORSS-CORRELATION BASED SEARCH FOR INTERMITTENT GW BACKGROUNDS

ST-5.2 Directional searches for persistent gravitational waves (short term)

ST-5.2.1 Scientific Case

While most prescriptions of the SGWB predict an isotropic signal, there are mechanisms that could introduce anisotropy [244, 265, 266, 267, 268, 269, 270]. For example, a confusion background may arise from binary mergers [262, 271, 272], core-collapse supernovae [273, 274], neutron-star excitations [275, 276], persistent emission from neutron stars [277, 278], and compact objects around supermassive black holes [279, 280]. Depending on the rate and redshift distribution of these objects, the corresponding SGWB could be isotropic or anisotropic. Such an anisotropic signal may appear with greater statistical significance in the anisotropic search than in the isotropic search.

The directional search provides information on the angular content of the SGWB in the form of a map of the gravitational-wave sky, and is therefore a powerful tool for distinguishing among different possible sources of the SGWB. The stochastic directional search provides a crucial follow-up to characterize anisotropies present in stochastic GW signals detected by the isotropic search; it facilitates the detection of highly anisotropic stochastic sources (e.g., clustered in the Galactic plane) that might be missed by the isotropic search; it provides a robust and sensitive search for narrowband point sources from interesting persistent sources (such as accreting binary systems like Sco X-1, young neutron stars like SN1987A, or unknown neutron stars such as a localised population at the galactic center [281]); and it provides a possibility of cross-correlating the SGWB anisotropies with anisotropies in electromagnetic observations (galaxy counts, gravitational lensing) to extract further information on the origin and composition of the SGWB.

ST-5.2.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [282]:

$$\Omega_{\rm GW}(f,\Theta) \equiv \frac{1}{\rho_c}\frac{d^3\rho_{\rm GW}}{d\ln f d^2\Theta} = \frac{2\pi^2 f^3}{3H_0^2}\,H(f)P(\Theta), \quad \Omega_{\rm GW}(f) = \int d\Theta\Omega_{\rm GW}(f,\Theta), \tag{2}$$

for Hubble parameter H_0 and sky location Θ. The frequency spectrum is typically assumed to be a power law in the frequency band of GW detectors: $H(f) = (f/f_0)^{\alpha-3}$. For a given value of the power index α (for example, $\alpha = 0$ for inflation and cosmic strings, $\alpha = 2/3$ for compact binaries, and $\alpha = 3$ gives a fiducial value for other astrophysical backgrounds such as supernovae), the objective of the search is to estimate $P(\Theta)$. Two approaches are pursued. In the radiometer algorithm, we assume the signal is characterized by a point source

$$P(\Theta) = \eta(\Theta_0)\delta^2(\Theta,\Theta_0), \tag{3}$$

and in the spherical harmonic decomposition (SHD) algorithm we assume that the signal can be written as a superposition of spherical harmonics

$$P(\Theta) = \sum_{lm} P_{lm}Y_{lm}(\Theta). \tag{4}$$

Likelihood maximization leads to estimators of the angular content of the SGWB for the radiometer ($\hat{\eta}_\Theta$) and spherical harmonic ($\hat{P}_{lm}$) cases:

$$\hat{\eta}_\Theta = (\Gamma_{\Theta\Theta})^{-1}X_\Theta \tag{5}$$

$$\hat{P}_{lm} = \sum_{l'm'}(\Gamma^{-1})_{lm,l'm'}X_{l'm'}. \tag{6}$$

The Fisher matrix $\Gamma(f,t)$ encodes the uncertainty associated with deconvolving the raw cross-correlation measurement for different directions on the sky (see [283, 282, 284] for further description and details on its inversion).

In [285], it was demonstrated that the data compression using sidereal folding [286] significantly improves the computational speed of directional analyses. Hence directional analyses are carried out using folded data.

ACTIVITY ST-5.2-A-**OPS**: DIRECTIONAL SEARCH FOR PERSISTENT GRAVITATIONAL WAVES

TASK ST-5.2-A(i): MOCK DATA CHALLENGE

FTE-months: 12.0

Conduct an extensive Mock Data Challenge (MDC) to: (i) understand the angular resolution of the directional searches for the stochastic background, both in the case of detection and in the case of parameter estimation; (ii) study the Fisher matrix regularization schemes and their bias on the estimates of the angular power spectrum; (iii) determine the optimal choice for the frequency band to be used in directional searches; (iv) explore how all of the above change as a function of the detector network; and (v) perform parameter estimation targeted for modeled skymaps such as kinematic dipole and galactic plane. Results of this MDC will guide the choices to be made in searches for anisotropic stochastic background using O4 data.

TASK ST-5.2-A(ii): PREPARATION FOR O4

FTE-months: 20.0

Develop and review a fully python-based code infrastructure for O4 directional analyses. This will include (i) organizing the exisiting code base of `PyStoch`, (ii) folding data generation using intermediate data products from new python-based isotropic code infrastructure `pyGWB`, (iii) extending `PyStoch` to perform spherical harmonic analysis in python, (iv) python-based post processing codes to calculate significance and upper limits, (v) improving the upper limit calculation using better Bayesian priors, (vi) improving data quality cuts for directional analyses, and (vii) demonstrating the efficiency of detection checklist and readiness for the first detection.

TASK ST-5.2-A(iii): O4 DIRECTIONAL ANALYSIS

FTE-months: 23.0 (includes all aspects of the search, review, and paper writing)

(i) Identify data quality issues in O4 data specifically relevant for directional analyses; (ii) Generate folded data for directional searches; (iii) Perform all-sky search for measuring (or constraining) the energy flux on the sky from point sources (narrowband and broadband radiometer analysis) for different power-law indices and produce GW sky maps. The maps can be used to identify patches on the sky to follow up with CW searches [See Section ST-10.1]; (iv) Perform an unmodeled search for potentially interesting persistent GW sources from specific sky locations or from the galactic plane; (v) Constrain published models of anisotropic GW backgrounds, for example due to millisecond pulsars in the Milky Way.

TASK ST-5.2-A(iv): O4 SPH ANALYSIS

FTE-months: 15.0 (includes all aspects of the search, review, and paper writing)

(i) Perform all-sky search for extended sources using spherical harmonic decomposition for different power-law spectral indices applied to O4 data. (ii) Identify data quality issues affecting the SpH analysis; (iii) Constrain published models of anisotropic GW backgrounds, for example from cosmic strings or compact binaries, using angular spectra for both auto-power in gravitational wave background and for the cross-power between the gravitational-wave background and electromagnetic observables.

LT-5.2 Directional searches for persistent gravitational waves (long term)

In addition to our standard directional analysis, there are several extensions planned or already in production.

ACTIVITY LT-5.2-A: COMPONENT SEPARATION USING NARROWBAND MAPS

Like the isotropic search, directional searches are also performed separately for multiple spectral indices in standard analyses. A method is being developed to generate skymaps for multiple spectral components. However, deconvolution of skymaps, even with one index poses serious challenges, which only gets amplified when multiple components are present. Exploration studies are being performed, initially considering two or three power-law spectral indices.

TASK LT-5.2-A(i): COMPONENT SEPARATION FOR DIRECTION SEARCHES USING NARROWBAND MAPS

ACTIVITY LT-5.2-B: IMPLICATIONS AND PARAMETER ESTIMATION FOR MODELS OF ANISOTROPIC BACKGROUNDS

Observation of anisotropy in the SGWB could indicate structure between now and the surface of last scattering, the scale of which could be used to inform models of our cosmological history. Recent theoretical developments have established the framework for estimating anisotropies in cosmological and astrophysical SGWB models [266, 268], and have applied the formalism to specific cases of the models due to BBH mergers [267, 269, 270, 287, 288, 289, 289, 290] and due to cosmic string networks [268]. We will develop methods of using the measured SGWB anisotropies to constrain theoretical SGWB models. We will employ a recently developed method for estimating the angular spectrum of anisotropies that gives an unbiased estimate of the true, astrophysical spectrum, removing the offset due to shot noise [287, 290]. We also investigate ways of correlating SGWB anisotropy measurements with electromagnetic proxies for the evolution of structure in the universe (galaxy counts, gravitational lensing, cosmic infrared background) so as to extract information about the evolution and composition of the SGWB. Finally, we plan to use the spherical harmonic search to study parameterized models of anisotropy, for example arising from neutron stars in the galactic plane [265, 291, 292] or in the galactic center [281].

TASK LT-5.2-B(i): PARAMETER ESTIMATION TARGETED FOR MODELED SKYMAPS

(i) Search for anisotropic distribution of GW background using pixel-based skymap templates and constrain the amplitude of the background (ii) Perform Bayesian parameter inference for several skymap models, such as kinematic dipole and galactic plane to place constraints on model parameters, e.g. amplitude, spectral index. (iii) Perform Bayesian parameter inference for angular power spectrum C_ℓ for astrophysical GW background, for example, compact binary coalescence and cosmic strings.

TASK LT-5.2-B(ii): GW-EM CORRELATION

(i) Estimate correlations of anisotropy in the stochastic gravitational wave background and anisotropy in electromagnetic tracers of the structure in the universe (galaxy counts, weak lensing, cosmic microwave background, cosmic infrared background) by measuring angular power spectra between skymaps. (ii) Develop techniques for estimating these correlations in both *clean* and *dirty* space, as well as techniques for minimizing the impact of regularization of the Fisher matrix. (iii) Develop frameworks for parameter estimation in astrophysical models of SGWB-EM correlations. (iv) Include the effect of spatial and temporal shot noise in the above parameter estimation frameworks.

LT-5.3 Search for very-long transient gravitational-wave signals

LT-5.3.1 Scientific Case

The long transient search looks for very long-lived transient signals ($\gtrsim 10$ hr, to as long as months) that might be otherwise overlooked or mistaken as an apparent stationary stochastic signal. There are several potential astrophysical sources for gravitational-wave transients on these time scales. For example, in Ref. [293], several scenarios associated with neutron stars are suggested, including non-axisymmetric Ekman flow occuring after a glitch and emission from free precession (with a damping time possibly lasting from weeks to years) [116, 294, 295]. Remnants of BNS mergers are particularly interesting as potential sources of very long transient signals. Futhermore, it is worthwhile to be prepared for a surprise: a very long-lived transient signal from an unexpected source. Recent work studying gravitational-wave emission from gravitationally bound axion clouds [296], potentially starting and stopping on the timescale of a few years, serves to illustrate this possibility. Finally, regardless of the specific source, one or more long-lived transient signals (or coherent long-duration noise) can produce an apparent signal in the isotropic and directional stochastic searches, while simultaneously evading detection in searches for short-duration transients. As a result, a dedicated search is necessary to understand the origin of apparent stochastic signals.

LT-5.3.2 Methodology

The transient searches will constrain the energy density $\Omega_{\rm gw}$ [254] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector

Pipeline (STAMP) [297, 298, 299, 300, 301]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [297]. Gravitational-wave signals appear as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [297, 302, 300, 301, 303]) in order to identify statistically significant clusters of pixels. Highly-parallel seedless clustering algorithms are available [300, 301], taking advantage of GPUs and multi-core CPUs for dramatic speed-ups [301]. Seedless clustering was used in the analysis of the Advanced LIGO O1 data. The results of an all-sky search for long transients using O1 and O2 data are presented in [7, 8].

We will analyze data on timescales of $\approx$ 10 hr–1 month in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We have run STAMP in all-sky mode on O1/O2 data used in the stochastic search, and we will run the same pipeline on the O4 data. In order to analyze these very long signals, we have added an extra stage of pre-processing in which the data are compressed through time-averaging as described in [304]. As an application of the STAMP very-long-transient pipeline, we will work in collaboration with the Burst group (Section ST-2.2) and CW group (Section ST-4.11) to search for post-BNS-merger gravitational-wave signals. Such a search for a long-lived remnant of GW170817 was conducted [165], with the STAMP pipeline being run as a directed unmodeled search, and we plan to repeat similar searches for remnants of any BNS mergers observed in O4.

The STAMP code package has also produced spin-off technology that has proven useful for detector characterization [305, 306] and follow-up/visualization of CBC triggers [303]. We expect continued development and maintenance of STAMP will be broadly useful for the Stochastic Group activities and the wider LSC/Virgo community.

ACTIVITY LT-5.3-A: SEARCH FOR VERY LONG TRANSIENTS

TASK LT-5.3-A(i): VLT CONTRIBUTION TO Ω_{gw}

Measure (or set upper limits on) the energy density of the very long transient signals and their contribution to the overall Ω_{gw} using O4 data. If a stochastic background is observed, contribute to developing the energy budget of the observed background by estimating the contribution of the very long transients.

TASK LT-5.3-A(ii): STUDY OF BNS MERGER REMNANTS

Apply the search for very long transients to data following mergers of binary neutron stars observed in O4 observing run. Coordinate the search and the publication with similar searches conducted in the burst and CW groups.

TASK LT-5.3-A(iii): MACHINE LEARNING APPROACH TO IDENTIFYING LONG TRANSIENTS

Explore the use of modern Machine Learning algorithms to parse the cross-power spectrograms with the goal of improving the sensitivity and computational efficiency of the search.

6 Burst+CBC Joint Activity Plans

ST-6.1 Search for GWs from black hole binaries

Search for binary black hole systems using CBC and Burst methods.

Motivation and goals

Binary black hole (BBH) systems in the normal stellar mass range have been efficiently detected in observing runs O1, O2, and O3 with matched filter searches using quasi-circular CBC templates. However, for high-mass systems in the IMBH range (total mass of about $100\,\mathrm{M}_\odot$ or more), we expect Burst searches, which do not rely on templates, to perform similarly to the CBC searches. Furthermore, if there exist BBH systems not currently well described by quasi-circular waveforms, we would expect the Burst searches to provide good detection capability. The GW190521 discovery [13] in O3a, representing the first IMBH detection, is an example where CBC and Burst searches found the signal with similar significance. On the other hand, for non-circular BBH systems, such as eccentric binaries (with $e > 0.05$) or hyperbolic encounters, templated CBC searches are not currently expected to be competitive with Burst searches, although we do not yet have evidence that such systems exist at a detectable rate within the LIGO-Virgo-KAGRA horizon.

Given the complementarity of the Burst and CBC searches, for O4 we will utilize a more uniform organizational structure for carrying out the all-sky searches for BBH systems. In particular, the CBC all-sky group has been generalized to a combined CBC-Burst group with joint leadership. Results are to be reported in exceptional event papers, if appropriate, but more typically in the GWTC catalogs, astrophysical populations, and testing GR papers.

The methods, targets and goals for the all-sky searches are described separately in the CBC and Burst sections of this White Paper.

ACTIVITY ST-6.1-A-**OPS**: SUBGROUP ADMINISTRATION

Management of the joint all-sky subgroup.

TASK ST-6.1-A(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 3.0

ST-6.2 Multimessenger search for GWs and GRBs

Follow up GRB alerts with deeper searches for simultaneous GW (CBC or burst) signals: communicate online associations and perform sub-threshold analyses. Includes joint analysis of sub-threshold candidates with GRB missions.

Motivation and goals

Gamma-ray bursts (GRBs) are extremely energetic bursts of gamma-rays from cosmological sources observed by orbiting satellite detectors at a rate of about one per day. Two phenomenologically recognized categories have been identified [307]: short-duration (< 2 s) GRBs with generally harder spectra, and long-duration (> 2 s) GRBs with generally softer spectra. Astrophysical evidence has led to the hypothesis that these categories herald the creation of a compact object [a black hole (BH) or a neutron star (NS)] by way of two distinct pathways, both of which involve the emission of transient gravitational waves.

The NS-NS and NS-BH coalescences have been invoked as a short GRB progenitor candidates for decades [308, 309, 310, 311, 312]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [62]. Any future coincident observations of GWs and short GRBs would also be a major scientific result, demanding a rapid publication. A possible association should be communicated with low latency to enable follow-up observations of the GRB of interest. Finally, the nature of the post-merger remnant (hypermassive/supramassive NS or BH) can be investigated via searches for post-merger GWs similar to those carried out for the case of GW170817/GRB 170817A [164].

Long GRBs are associated with the gravitational collapse of massive stars. The wide range of observable properties they display has led to the speculation that there may be sub-classes involving different mechanisms, with astrophysical details far from being fully understood. Any significant GW detection would presumably contribute to our understanding of the underlying astrophysics. Some models predict GW emission associated with the accretion disk itself, or with a post-collapse proto-NS, which would give rise to long-duration ($\lesssim 1\,\mathrm{s}$) GW emission. The observation of X-ray "plateaus" following the GRB on timescales of tens of minutes to hours after the main burst has suggested that GRB central engines may live longer ($\sim 1000\,\mathrm{s}$) than previously thought.

Methodology

To search for gravitational waves associated with GRBs, we use triggered (using GRB time and sky position), coherent algorithms that target either NS-NS and NS-BH binary inspiral signals [313] in the case of short GRBs, or generic GW burst signals [314] for all GRBs. These searches are more sensitive than the corresponding all-sky ones and are run offline. We use an additional algorithm [315] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs. These methods were applied to the full sample of GRBs which occurred during O1 [316], O2 [317], and O3 [318, 319]; the offline, triggered searches were also used to process GRBs which occured during the first joint observation of the KAGRA detector with GEO 600 [320].

We continue to develop methods to utilize sub-threshold GW triggers, sub-threshold GRB triggers, or both. An offline search using sub-threshold all-sky CBC triggers to search for coincident GRBs with Fermi was established with the O1 publication [321].

An offline cross-correlation algorithm[12] targeting long-duration GWs from the remnants of exceptional short or long GRBs, potentially in association with EM plateaus, will be used for opportunistic searches.

ACTIVITY ST-6.2-A-**OPS**: TRIGGERED GRB SEARCH AND PUBLICATIONS - OFFLINE

The following tasks are necessary for implementing the standard offline, triggered GRB search and to report results. The main activities will be to prepare and run the O4 searches.

TASK ST-6.2-A(i): CATALOG THE GRBS

FTE-months: 2.0

Collect and catalog the GRBs from Swift and Fermi from early O4 running to be used in the triggered searches. Determine if IPN will be used to provide triggers for O4 and, if so, set up procedures for collecting the IPN information.

TASK ST-6.2-A(ii): PREPARE THE SEARCH PIPELINES FOR O4

FTE-months: 3.0

Prepare to run the Burst and CBC pipelines on the appropriate GRB triggers, as catalogued above.

TASK ST-6.2-A(iii): RUN THE O4 SEARCH

FTE-months: 3.0

Run the O4 offline search.

TASK ST-6.2-A(iv): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW

FTE-months: 3.0

Report results and prepare publications for O4.

ACTIVITY ST-6.2-B-**OPS**: ONLINE SEARCHES

TASK ST-6.2-B(i): PREPARE THE MEDIUM LATENCY SEARCH FOR O4

FTE-months: 3.0

Prepare the infrastructure required to run the Burst and CBC search algorithms in medium latency for O4. The pipeline review was completed just before the end of O3, but will presumably need to be re-reviewed prior to O4.

TASK ST-6.2-B(ii): RUN THE O4 SEARCH

FTE-months: 3.0

Run the O4 medium latency search.

ACTIVITY ST-6.2-C-**OPS**: SUB-THRESHOLD SEARCHES - O3 AND O4 PREPARATIONS

Complete the programs described in the MOUs with the Fermi and Swift collaborations for exploiting potential associations of (sub-threshold) GW triggers with (sub-threshold) Fermi-GBM or Swift triggers. Prepare for O4.

TASK ST-6.2-C(i): TARGETED SEARCHES

FTE-months: 3.0

Complete the O3 search and publication. Prepare for O4.

TASK ST-6.2-C(ii): UNTARGETED SEARCHES

FTE-months: 3.0

Complete the O3 search and publication. Prepare for O4.

ACTIVITY ST-6.2-D: SUB-THRESHOLD SEARCHES - O4

Run the O4 Sub-threshold searches jointly with the Fermi and Swift collaborations.

TASK ST-6.2-D(i): RUN THE O4 SEARCHS

FTE-months: 3.0

Run the O4 Sub-threshold searches.

ACTIVITY ST-6.2-E-**OPS**: PIPELINE DEVELOPMENT FOR O4

Some pipeline development activities are needed well in advance of O4 in order to allow time for testing and review by the start of the run.

TASK ST-6.2-E(i): PYGRB PIPELINE

FTE-months: 3.0

Complete development and review of a targeted, coherent matched-filter CBC search which is consistent with the PYCBC framework.

TASK ST-6.2-E(ii): X-PIPELINE

FTE-months: 1.0

Complete development and review of the O4 version of X-PIPELINE.

ACTIVITY ST-6.2-F-**OPS**: SUBGROUP ADMINISTRATION

Management of the GRB subgroup.

TASK ST-6.2-F(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-6.2 Multimessenger search for GWs and GRBs R&D

ACTIVITY LT-6.2-A: GW-GRB PIPELINE IMPROVEMENTS

Continue improvements of the PYGRB and X pipelines for use beyond O4, especially to speed up execution times and to improve sensitivity by background reduction.

TASK LT-6.2-A(i): GW-GRB PIPELINE IMPROVEMENTS

Improve the PYGRB and X pipelines.

ACTIVITY LT-6.2-B: MEDIUM LATENCY GRB PIPELINE

Continue development and updating of the infrastructure to run the GRB medium latency pipeline.

TASK LT-6.2-B(i): MEDIUM LATENCY GRB PIPELINE

Develop and update the infrastructure of the GRB medium latency pipeline.

ACTIVITY LT-6.2-C: LONG-DURATION SEARCH

For the cross-correlation search, test the feasibility of parameter estimation analyses aimed at ensuring understanding of any parameter correlations, and establishing appropriate probability coverage.

TASK LT-6.2-C(i): GRB LONG-DURATION CROSS-CORRELATION SEARCH

Development work for GRB long-duration cross-correlation search

ACTIVITY LT-6.2-D: SUB-THRESHOLD SEARCHES

Continue development of methods to exploit sub-threshold GRBs (from Fermi, Swift) and/or sub-threshold GW triggers.

TASK LT-6.2-D(i): GRB SUB-THRESHOLD SEARCHES

Development work for exploiting sub-threshold GRBs and/or GW triggers.

ST-6.3 Multimessenger search for GWs and fast radio bursts

Follow up FRBs with coherent Burst and CBC searches, similarly to the GRB-GW method.

Motivation and methods

Since the publication in summer 2013 of four Fast Radio Bursts (FRBs) identified in Parkes Telescope data [322] there has been considerable scientific interest in these millisecond-scale radio transients which, based on their observed dispersion measures, appear to mostly occur at cosmological distance scales. A multitude of FRBs have been published so far [323], including repeating sources [324], and an increasing number of radio telescopes are becoming involved in FRB identification, most notably the CHIME detector[325].

In 2020, an MOU agreement between LIGO/Virgo and CHIME was reached, which has allowed on order 10^2 FRB triggers within a plausible GW horizon distance to become available for the O3 run. Results for the FRBs that occured in O3a are available in a preprint [326], while the O3b analyses is currently (November 2022) ongoing.

Currently, while numerous papers have suggested plausible sources for these radio transients, their origin is unclear. Observations indicate two possible classes – repeaters and non-repeaters – and it may be that there are multiple progenitor types. Not all plausible mechanisms for emission of FRBs are likely to result in simultaneous gravitational wave emission at detectable frequencies. However, compact binary coalescences, neutron star asteroseismology, and cosmic string cusps are all proposed mechanisms for production of both gravitational waves and short duration radio transients in the frequency ranges of interest. See [327] and references therein for descriptions of the relevant models. Identification of a clear coincidence between an FRB and a transient gravitational wave, while challenging at current sensitivities, would be of tremendous scientific value in determining the nature of FRBs in addition to being a major achievement in the field of gravitational-wave astronomy.

Recently, there was potentially an important clue in the FRB story. In April 2020, galactic magnetar SGR 1935+2154 became very active in x-ray emission. And on April 28 an FRB was observed[328] from this source. The observed fluence provided an estimate for the intrinsic FRB energy which was 1 to 6 orders of magnitude less energetic than previously observed (cosmological) FRBs, but otherwise closely resembled previous FRBs. While this provides credence to the magnetar model of FRBs, it is still unclear how many FRB progenitor classes actually exist in nature.

Given the unknown nature of FRBs, it is appropriate to apply both CBC and Burst pipelines in triggered searches, essentially mirroring the externally triggered GRB searches, except for the choice of triggers and on-source windows.

ACTIVITY ST-6.3-A-**OPS**: O3 ANALYSES AND PUBLICATIONS

TASK ST-6.3-A(i): CARRY OUT THE O3B SEARCH

FTE-months: 4.0

Define the CHIME triggers in range (within $\approx$ 400 Mpc) which occurred during O3b. Carry out the same analysis methods used for O3b. Prepare the corresponding O3b collaboration paper.

ACTIVITY ST-6.3-B-**OPS**: PREPARE THE O4 SEARCH

Prepare for an O4 search. The methods are currently assumed to be very similar to those used in O3.

TASK ST-6.3-B(i): COLLECT THE FRB TRIGGERS

FTE-months: 2.0

Arrange for the collection of FRB triggers. Determine if any MOU agreements are required, in particular with the CHIME collaboration. Make a selection on the triggers using available dispersion measure methods, if necessary, to select the triggers within the plausible O4 GW horizon.

TASK ST-6.3-B(ii): RECONFIGURE, TEST AND RUN THE SEARCH PIPELINES

FTE-months: 3.0

Reconfigure (if necessary), test, and run the Burst and CBC pipelines over triggers from early O4 running. Determine if additional changes are needed and react to any new data quality issues.

TASK ST-6.3-B(iii): EXCEPTIONAL EVENTS

FTE-months: 4.0

In the event of a GW-FRB detection or an astrophysically interesting upper limit, make the case for a single-event publication.

ST-6.4 Multimessenger search for GWs and high-energy neutrinos

Perform searches for joint sources of GWs and high-energy neutrinos.

Motivation and methods

Some dynamical processes with strong GW emission, such as compact binary mergers or stellar core-collapse with rapidly rotating cores, can drive relativistic outflows that result in the emission of high-energy neutrinos (HEN) [329, 330]. Detecting both messengers from a common source would provide the unique opportunity to develop and fine-tune our understanding of the connection between the central engine [331], its surroundings [332], and the nature of relativistic outflows [333, 334]. A joint search also increases the sensitivity compared to GW-only or neutrino-only searches, and can be especially interesting for sources that are difficult to detect electromagnetically [335, 336, 337].

In O1 and O2, we worked closely with the IceCube and ANTARES collaborations to develop and perform sensitive multimessenger analyses to search for neutrinos associated with GW candidates, and in particular with GW150914 [338], LVT151012 and GW151226 [339], and GW170817 [340]. No coincident neutrinos were found. The results were used to constrain the neutrino flux from these sources. Additionally, we have looked for coincidences of sub-threshold events in both the neutrino and GW detectors [341, 342], including the coincident subthreshold analysis for the O1 observing period [343].

The method employed uses temporal and spatial coincidence between the GW and HEN triggers to identify detection candidates. Additionally, it evaluates the significance of joint candidates by incorporating astrophysical priors through a Bayesian framework [344] while also including LIGO-Virgo as well as neutrino detector characteristics. The Bayesian framework is extendable to include additional messengers [345].

The same pipeline (LLAMA) is used in both offline and in low-latency mode [346]. The major tasks are to complete the O3 offline analysis/paper and to prepare for O4.

Critical tasks and major deliverables for O4

ACTIVITY ST-6.4-A-**OPS**: COMPLETE THE O3 SEARCH

Perform the multimessenger search between GW events and high-energy neutrinos. The O3 online search was complete at the end of O3. What remains is the offline search using sub-threshold CBC and Burst triggers to be provided by the CBC and Burst pipelines together with sky-localization information. The offline pipeline is essentially the same as the online one.

TASK ST-6.4-A(i): COMPLETE THE O3 ANALYSIS FTE-months: 2.0

Wrap up the GW-HEN analysis with the LLAMA pipeline. Report results and publish O3 results.

TASK ST-6.4-A(ii): PIPELINE REVIEW FTE-months: 2.0

Complete the review of the LLAMA pipeline for the O3 offline analysis. The reviewed pipeline will be used for the O4 analysis.

ACTIVITY ST-6.4-B-**OPS**: SEARCH FOR GW-HEN COINCIDENT EVENTS IN O4 DATA

TASK ST-6.4-B(i): CONFIGURE AND RUN THE LOW-LATENCY GW-HEN COINCIDENT ANALYSIS FTE-months: 3.0

Configure the LLAMA pipeline to analyze the data with low latency. Perform the coincident analysis between Burst/CBC GW triggers and HEN triggers uploaded to GraceDB with low latency. Estimate the significance of the coincident events. Prepare to send alerts for interesting GW+HEN associations, including sub-threshold events.

TASK ST-6.4-B(ii): REPORT SEARCH RESULTS DURING O4 FTE-months: 1.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results.

TASK ST-6.4-B(iii): EXCEPTIONAL EVENTS

FTE-months: 4.0

In the event of a GW+HEN detection or an astrophysically interesting upper limit, make the case for a single-event publication. This would include an extended time window search for neutrinos in the direction of a confirmed EM counterpart.

TASK ST-6.4-B(iv): MOUS

FTE-months: 1.0

Prepare or update MOU agreements with IceCube and KM3NeT.

LT-6.4 Multimessenger search for GWs and high-energy neutrinos R&D (Long Term)

ACTIVITY LT-6.4-A: PREPARE FOR THE POSSIBILITY OF A TRIPLE-MESSENGER EVENT

Improve the LLAMA pipeline to include the statistical treatment of multimessenger events with three (GW, neutrino, and EM) messengers.

TASK LT-6.4-A(i): PREPARE FOR TRIPLE MESSENGER EVENT

ACTIVITY LT-6.4-B: INCORPORATE AUGER

Incorporate high energy cosmic ray triggers from the Pierre Auger Observatory into the low-latency GW+HEN coincidence analysis, along with IceCube.

TASK LT-6.4-B(i): INCORPORATE AUGER IN GWHEN

7 Burst+Stochastic Joint Activity Plans

ST-7.1 Search for GWs from cosmic strings

Motivation and methods

Cosmic strings [347] are one-dimensional topological defects, formed after a spontaneous symmetry phase transition characterized by a vacuum manifold with non-contractible loops [348]. These objects are expected to be generically formed in the context of Grand Unified Theories [349]. Their obervational consequences offer a tool to probe particle physics beyond the Standard Model at energies far above the ones reached at accelerators. More recently it was realized that strings can also be produced within the framework of string-theory-inspired cosmological models and grow to cosmic scales [350, 351, 352, 353]. Cosmic strings produced in string-theory-motivated models (dubbed “cosmic superstrings”) have received much attention since they could provide observational signatures of string theory [354, 355].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational-wave emission from loops [356, 357] and long strings [358]. When two string segments meet, they may exchange partners. When a string intercommutes with itself, a closed loop breaks off. The loop oscillates, radiates gravitationally, and eventually decays. Special points on the cosmic string loop play an important role: cusps and kinks. Cusps are points along the string with large Lorentz boosts. They are transient and produce a beam along a single direction. Kinks are loop discontinuities that form every time intercommuting occurs. They propagate around the string, beaming over a fanlike range of directions. Since long (super-horizon) strings are not straight due to the existence of kinks, they also emit gravitational radiation [358]. Both cusps and kinks produce powerful bursts of gravitational waves [359]. In addition, left- and right-moving colliding kinks will produce a GW spectrum emitted in all directions, this is the dominant mechanism for fairly wiggly strings [360].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [361, 259]. The two searches are conducted over LIGO-Virgo data and provide complementary results. In particular, observational constraints on cosmic string models are given as bounds on the string tension $G\mu (c = 1)$, where G is Newton’s constant and μ the mass per unit length. These bounds are then used to drive further theoretical developments and constrain particle physics beyond the Standard Model as well as early Universe cosmological models.

Critical tasks and major deliverables for O4

ACTIVITY ST-7.1-A-**OPS**: O4 SEARCH FOR GRAVITATIONAL-WAVE BURSTS

TASK ST-7.1-A(i): RUN THE SEARCH PIPELINE AND REVIEW RESULTS

FTE-months: 1.0

Run the templated search for gravitational-wave bursts from cosmic strings over O4 data. Test all gravitational-wave production mechanisms: cusp alone, kink alone, or kink-kink collision.

TASK ST-7.1-A(ii): FOLLOW UP GW CANDIATES

FTE-months: 2.0

If a gravitational-wave event is significant, estimate the cosmic string parameters considering up-to-date loop distribution models. Interpret cosmologically the results.

TASK ST-7.1-A(iii): SET UPPER LIMITS ON COSMIC STRING MODELS

FTE-months: 1.0

Constrain cosmic string parameters for specific models/simulations predicting the loop distribution. Derive the expected rate of gravitational-wave events from cosmic strings and compare it with the rate measured with signal injections. If no clear gravitational-wave event is detected, set upper limits on cosmic string parameters.

TASK ST-7.1-A(iv): DEVELOP A STRATEGY TO FOLLOW-UP UNMODELLED BURST CANDIDATES

FTE-months: 1.0

If a short-duration unmodeled burst candidate is detected by the all-sky searches (see Sec ST-2.1), a procedure shall be in place to assess the astrophysical nature of the event. A cosmic string scenario must be examined and the possibility of this scenario must be quantified.

ACTIVITY ST-7.1-B-**OPS**: O4 STOCHASTIC BACKGROUND SEARCH

TASK ST-7.1-B(i): DETERMINE MODEL PARAMATERS

FTE-months: 3.0

Consider up-to-date cosmic string loop distribution models supported by numerical simulations for Goto-Nambu strings. Follow also an agnostic approach, interpolating between theoretical models, for example based on [362].

TASK ST-7.1-B(ii): PARAMETER ESTIMATION

FTE-months: 3.0

For the chosen cosmic string models, perform the parameter estimation using the latest (O4) results of the stochastic searches to compute excluded or preferred regions of the parameter space (string tension and number of kinks).

LT-7.1 Search for gravitational waves from cosmic strings R&D (Long Term)

ACTIVITY LT-7.1-A: BURST ALGORITHM DEVELOPMENT

TASK LT-7.1-A(i): FINALIZE THE DEVELOPMENT OF A "DETECTION-READY" SEARCH PIPELINE

Finalize the development of a search pipeline based on GstLAL methods. This new pipeline shall be able to produce detection statements (as opposed to upper-limits). Moreover, this potentially enables a more powerful noise rejection, as well as a better memory management and execution speed.

TASK LT-7.1-A(ii): MITIGATE BLIP GLITCHES TO IMPROVE THE SEARCH SENSITIVITY

Recent searches for gravitational-wave bursts from cosmic strings have been limited by noise artifacts, specifically the so-called "blip glitches." Determining how to mitigate the effects of such artifacts in the search is crucial for improving upper limits or for making a detection claim.

ACTIVITY LT-7.1-B: IMPROVED MODELS

TASK LT-7.1-B(i): IMPROVED MODELS FOR COSMIC STRING SEARCHES

It is expected that theoretical developments will continue to provide the impetus towards new types of cosmic string related phenomena and/or to improve cosmic string templates for gravitational-wave burst searches. It is expected that soon we will be able to improve considerably the cosmic string models we are using and include further effects.

8 Stochastic+CBC Joint Activity Plans

LT-8.1 Search for the stochastic background from unresolvable binary black hole mergers

LT-8.1.1 Scientific Case

The recent detections of binary black-hole (BBH) mergers by aLIGO and aVirgo suggest the near-term possibility of detecting the stochastic background of weaker, unresolvable BBH signals out to large redshift. Rate estimates predict one such event every ~ 2 minutes on average, with each merger lasting $\mathcal{O}(1\ \text{second})$. Thus, the duty cycle is $\lesssim 10^{-2}$, implying a "popcorn-like" *highly non-stationary* stochastic signal. Although the standard cross-correlation search can be used to search for such a background, the low duty cycle of the expected signal renders the standard (Gaussian-stationary) search *sub-optimal*, since most of the segments analyzed will consist of only detector noise. Here we propose a joint activity between the stochastic and compact binary coalescence (CBC) groups to develop and implement a Bayesian search strategy (originally proposed by Smith and Thrane [363]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

LT-8.1.2 Methodology

The search methodology is based on Smith et al. [363] which applies Bayesian parameter estimation to all available data. The search uses the output of parameter estimation code (e.g., Bilby [364]) to construct a probability density on the *astrophysical duty cycle* which we take to be the fraction of analyzed data segments which contain a CBC signal

$$p(\xi|d) = \prod_{i=1}^{N} \left[\xi \mathcal{Z}_s^i + (1-\xi)\mathcal{Z}_n^i + \text{glitch terms}\right] . \tag{7}$$

The data d are broken up into N segments d_i, each of duration T; ξ denotes the probability that a particular segment contains a signal, which is related to the rate R via $R = \xi/T$; $\mathcal{Z}_s^i$ and $\mathcal{Z}_n^i$ are respectively the signal and noise evidences of the i^{th} data segment and are the outputs of Bilby. For readability, the glitch-model terms have been omitted. The search treats non-Gaussian glitches in the data as uncorrelated CBC-like signals in two or more detectors. These glitch terms are also outputs of Bilby and this particular glitch model was shown in [363] to yield unbiased estimates of the astrophysical duty cycle in O1 background data. Using Bayesian inference, one can then calculate the Bayes factor for the signal+noise to noise-only models, which can be used as a detection statistic, e.g.,

$$B = p(\xi > 0|d)/p(\xi = 0|d) \tag{8}$$

to estimate the rate of BBH events. It is the *mixture* form of the likelihood that allows one to handle the non-stationarity.

Because the search applies Bayesian parameter estimation to compute the signal and noise evidences of the data, we also obtain posterior PDFs of the CBC parameters (such as masses and spins) irrespective of whether the data contains a signal or not. The PDFs from each data segment can, in principle, be combined in a Bayesian way to infer the properties of the whole population of CBC signals.

The proposed search in O4 will focus on searching for "high-mass" BBH systems, which we take to be BBH systems with chirp masses in the range $12 M_\odot \leq M_c \leq 45 M_\odot$. This enables us to keep computational costs manageable as it only requires analyzing data segments that are up to 4s in duration.

It was estimated in [363] that the BBH background can be detected using around one day of design sensitivity data. Subsequent work has investigated how the signal from unresolved binaries is distributed in redshift [365]. The same study develops tools to extract the population parameters of unresolved binaries;

see also [366]. Meanwhile, in [367] it was shown that it will be necessary to marginalize over uncertainty in the noise power spectral density to avoid bias in the estimate of duty cycle. We expect that using O4 data we can make a confident detection using around one week of data. While the computational cost of the search is high (due to the application of Bayesian parameter estimation), we expect to be able to analyze data in real time using a modest fraction of the LIGO Data Grid computing resources.

ACTIVITY LT-8.1-A: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION

1. Develop a set of data analysis routines to implement the above search such that it is both computationally feasible and robust against non-Gaussian features in the detector noise.
2. Perform a large-scale mock data challenge (MDC) of the proposed search method on synthetic data and O3 background data, including tests of its efficacy relative to the standard Gaussian-stationary search.
3. Develop the necessary computational tools to be able to search for weak BBH signals at cosmological distances (luminosity distances greater than ~ 15 Gpc).
4. Publish the results of the MDC.

TASK LT-8.1-A(i): THE BAYESIAN SEARCH IMPLEMENTATION AND MDC VALICATION

Assuming that the above activities are performed successfully, we can then move to applying this search to O4 data.

ACTIVITY LT-8.1-B: O4 ANALYSIS

1. Run the search on O4 data. Detect the background of BBH mergers and measure the astrophysical duty cycle.
2. Perform inference on the population properties of the BBH background, such as the mass spectrum, spin and redshift distributions.
3. Prepare full collaboration paper on search results.

TASK LT-8.1-B(i): THE BAYESIAN SEARCH O4 ANALYSIS

9 Stochastic+DetChar Joint Activity Plans

ST-9.1 Data quality investigations for stochastic searches

ST-9.1.1 Scientific Case

The stochastic searches assume that the detector noise is Gaussian, stationary, and uncorrelated between different sites. However, in reality, detector noise can break all of these assumptions. Correlated noise can arise due to instrumental effects such as electronic lines coherent between sites, or due to environmental effects such as geophysical Schumann resonances, or the superposition of individually correlated lightning strikes. Understanding and accounting for these effects is crucial to making astrophysical statements about the stochastic background with LIGO/Virgo data. Throughout this section we include references to codes in the Detector Characterization section of the LSC-Virgo Operations White Paper (Section 4). During O3, individual detector's strain data was subject to relatively frequent and loud low-frequency glitches, often without known causes. The procedure that eliminates these effects and their detrimental impact on PSD estimates for CW and Stochastic searches is known as *gating*. The mitigation of glitches via gating, and assessing the impact of this procedure on the stochastic analyses pipelines implies extra tasks and dedicated personpower.

ST-9.1.2 Methodology

The stochastic searches rely on cross correlating data from different detectors. Common noise lines at two sites can occur due to similar equipment in the laboratory, electronics that have been synchronized by GPS, or common data acquisition systems [368, 369]. A strong line in one interferometer, along with a large random fluctuation in the other, can also produce an apparent narrowband signal in the stochastic search pipeline. We use several tools to identify and determine the causes of noise lines (codes O.RD.1.1, O.RD.1.2, O.C.1.4). First, we have developed several key tools for data quality and detector characterisation (code O.C.5), including WITSPEC, STAMP-PEM and the coherence tool, physical environment monitors that study subsystem coherence at different frequency resolutions, and StochMon, an online coherence monitoring tool that is updated hourly and includes standard result plots as well as diagnostic plots such as coherence spectra. During engineering and observing runs StochMon is regularly monitored by members of the stochastic group. In addition, we will continue to work with the detector characterization and continuous wave groups to identify and find the sources of noise lines using all available tools. Noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the observing runs, and possibly addressed at the sites [370, 368].

Also, the elimination of glitches via gating is coordinated between the DetChar groups, the CW group and the Stochastic group. During O3, this effort was extensive and has been summarized in LIGO-P2000546, and LIGO-T2000384.

We have previously observed correlated broadband magnetic fields in magnetometer channels at widely separated detectors [371, 372, 373, 374, 375]. The primary sources of these correlated fields are geophysical Schumann resonances [371] at low frequencies, and the supperposition of individually correlated lightningstrikes at high frequencies [375]. Investigations are in progress to determine how well the magnetometers at LIGO and Virgo sites can measure the correlated Schumann resonance noise, and whether more antennas dedicated to Schumann resonance observations are needed (codes F.C.2.7, F.C.3.3) . Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied [373]. Regular monitoring of the magnetic coupling also forms a crucial part in understanding the effect of these correlated magnetic noise sources on stochastic searches. This contains both the outside-to-inside and inside-to-DARM magnetic coupling function. The latter uses injection coils inside the building to estimate the effect on DARM, whereas the former estimates the effect from building shielding and can for instance be estimated using distant lightning strikes as injections [375] If the correlated Schumann resonance magnetic fields are limiting the stochastic search, then it will be necessary to directly measure the Schumann resonance magnetic fields at each interferometer site and implement noise subtraction techniques. Another approach being pursued is to use Bayesian parameter estimation to measure the noise contribution from Schumann resonances at the same time as the gravitational-wave background [376].

Finally, while the stochastic searches target persistent stochastic gravitational-wave backgrounds from broadband and narrowband sources, they are sensitive to intermittent signals from transients, which can arise from environmental or instrumental sources, or even astrophysical ones. We will simulate software signals characteristic of transients, and then analyze this using the stochastic search pipeline. The results will inform interpretation of a signal.

ACTIVITY ST-9.1-A-**OPS**: DETECTOR CHARACTERIZATION FOR STOCHASTIC SEARCHES

TASK ST-9.1-A(i): INSTRUMENTAL CORRELATIONS BETWEEN DETECTORS

FTE-months: 8.0

Perform studies of instrumental and environmental correlations between detectors. This includes searches for broadband correlations, e.g, using environment sensors, as well as narrowband correlations, e.g., induced by GPS synchronization across sites. The studies will result in lists of correlated frequency bins that will need to be excluded from stochastic searches, including how these bins evolve over run time. In addition, the studies will result in a list of contaminated run times that should be excluded from the stochastic searches.

TASK ST-9.1-A(ii): CORRELATED MAGNETIC NOISE

FTE-months: 8.0

Perform measurements of the coupling of magnetic fields to the strain channels at all detectors, and study how they vary over time and how they depend on the location and orientation of magnetic injections. Estimate the contribution of the correlated magnetic noise to the measurement of $\Omega_{\rm gw}$ and use parameter estimation formalism to separate this contribution from the true stochastic background contributions, and thereby mitigate this effect. Explore possibilities of removing the correlated magnetic noise from the strain data, e.g., using the developed Wiener filtering techniques and magnetometer data.

TASK ST-9.1-A(iii): MEASURMENT OF THE MAGNETIC COUPLING

FTE-months: 14.0

To understand the effect of magnetic noise on stochastic searches we need measurments of both the outside-to-inside as well as the inside-to-DARM magnetic coupling function. Both have to be monitored regularly to study possible time dependent features. Estimate the effect of correlated magnetic noise on different types of anisotropic stochastic searches.

TASK ST-9.1-A(iv): STUDY OF NOISE IMPACT ON STOCHASTIC SEARCHES

FTE-months: 2.0

Perform a set of simulations that include the stochastic background and various forms of transient noise sources, and study the effect these noise sources have on the stochastic searches.

TASK ST-9.1-A(v): STUDY OF GATING PROCEDURES AND THEIR IMPACT ON STOCHASTIC SEARCHES

FTE-months: 8.0

Coordinate with the DetChar group and CW group on the use of pre-gated data, cross check the impact of the gating on various analysis pipelines, and adopt where necessary.

TASK ST-9.1-A(vi): STUDY OF NON-LINEAR NOISE SUBTRACTION METHODS AND THEIR IMPACT ON STOCHASTIC SEARCHES

FTE-months: 12.0

Coordinate with the DetChar group on the use of non-linear noise subtraction methods, cross check the impact of these methods on various analysis pipelines, and adopt where necessary.

LT-9.1 Data quality investigations for stochastic searches (long term)

In addition to the above, there are long-term activities that will be needed for long-term improvements in the sensitivity of the stochastic searches.

ACTIVITY LT-9.1-A: CALIBRATION UNCERTAINTY ASSESSMENT

Perform a set of analytical and numerical studies to understand the impacts of the frequency-dependent systematic error in the calibration estimate on the stochastic searches. This includes the isotropic and directional stochastic searches, as well as estimation of parameters in favored models of the stochastic background. Identify what level of calibration uncertainty starts to dominate the sensitivity of the stochastic searches and of the parameter estimation studies, and identify the frequency band(s) in which understanding the calibration errors is particularly important.

TASK LT-9.1-A(i): CALIBRATION UNCERTAINTY ASSESSMENT FOR STOCHASTIC SEARCHES

ACTIVITY LT-9.1-B: DATA POSTPROCESSING ASSESSMENT

Study alternatives for delta sigma cut and Median PSD estimation instead of mean PSD estimation, to reduce data loss and in function of future detection sensitivity.

TASK LT-9.1-B(i): DATA POSTPROCESSING ASSESSMENT

10 Stochastic+CW Joint Activity Plans

ST-10.1 Identification and follow-up of outliers in stochastic directional analysis skymaps

Motivation

Performing all-sky searches for continuous gravitational wave sources is an important goal of gravitational wave astronomy. Significant trade-offs between sensitivity against computational costs must be considered. Continuous wave analyses carry out optimal targeted searches for known sources or use a variety of different hierarchical search strategies, depending on the amount of information known for a putative source. Unmodeled, radiometer-style searches reaching maturity in stochastic gravitational wave searches are comparatively computationally inexpensive. A novel technique to aid rapid analysis of detector data is to combine CW and stochastic searches in a hierarchical search. This can be achieved by utilising the sky-maps produced by the stochastic directional analysis [285] on folded data [286].

Methodology

The goal is to perform fast (“quick-look”) all-sky analysis for continuous wave signals, even though the expected sensitivity will be less than other, dedicated searches. The directional analysis carried out using `PyStoch` [377] produces a full GW sky- map at every frequency bin. Those regions of parameter space (sky locations and frequencies) that produce interesting outliers could be passed to continuous wave searches for follow up under the assumption that the outlier may be due to a rapidly rotating neutron star or possibly a boson cloud surrounding a black hole.

It is expected that model-agnostic continuous wave searches (such as the Viterbi/Hidden Markov Model searches) will be used to first confirm or reject the outliers, any remaining candidates would be subsequently followed up using analyses that place further constraints on the long duration waveform coherence.

ACTIVITY ST-10.1-A-**OPS**: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION

TASK ST-10.1-A(i): IDENTIFICATION OF OUTLIERS IN STOCHASTIC DIRECTIONAL ANALYSIS

Development of a reliable statistic to identify patches on the sky for follow up and share the coordinates of the patches in a readily usable format. This may depend on the parameters used for the searches. It may be possible make the information more robust by combining results of activities with similar goals.

TASK ST-10.1-A(ii): FOLLOW-UP OF OUTLIERS AND SET UPPER LIMITS

Develop and implement a sensible strategy to follow up outliers using CW searches, especially to understand how much parameter space to explore around a given outlier. Explore methods to put more stringent upper limits on physical parameters. Understand the upper limit procedure.

ACTIVITY ST-10.1-B-**OPS**: O4 ANALYSIS

TASK ST-10.1-B(i): ANALYZE STOCHASTIC DIRECTIONAL SEARCH FOR OUTLIERS

FTE-months: 3.0

Using the ranking statistic developed using mock data validation, identify outliers and parameter space to be passed to the CW stage for follow up

TASK ST-10.1-B(ii): FOLLOW UP OUTLIERS USING CW ANALYSES

FTE-months: 3.0

Process the outliers using the follow up procedures developed using the mock data validation.

TASK ST-10.1-B(iii): SET UPPER LIMITS

In the event of no detection, set an averaged population based upper limit on the gravitational-wave strain amplitude and derive astrophysical implications.

FTE-months: 2.0

TASK ST-10.1-B(iv): REVIEW

Review search set up, code, scripts, and results.

FTE-months: 2.0

TASK ST-10.1-B(v): PUBLICATION

Prepare the results for the inclusion into O4 directional paper or other relevant publication.

FTE-months: 1.0

ST-10.2 Dark matter direct interaction searches

Motivation

Gravitational wave interferometers can also be used to search for the existence of dark matter that could couple directly to the detector.

Scalar, dilaton DM would cause time-dependent oscillations of the values of fundamental constants, such as the electron mass and fine structure constant[378, 379, 380]. Physically, the Bohr radius would change, causing time-varying changes in the size and index of refraction of the beam splitter [381]. Since the light from each cavity would traverse a slightly different path on the surface of the beam splitter, a differential phase would result whose magnitude is independent of the length of the arms. The phase sensitivity depends on the amount of quantum noise at high frequencies and depends on many other factors overall, including cavity finesse etc. As shown in Ref. [382], the most sensitive detector at high frequencies currently is actually GEO600, since it employs squeezed vacuum light that greatly reduces quantum noise compared to LIGO/Virgo/KAGRA. LIGO/Virgo/KAGRA can provide additional independent constraints above 100 Hz, and competitive constraints below 100 Hz [382]. This same scalar DM will also cause a change in length of the reference cavity which is used for pre-stabilizing the laser in LIGO, in turn resulting in a relative frequency shift between the reference cavity and the IMC-CARM system [382]. This frequency shift can be read out in the auxilliary channel and can provide most competitive limits below 100 Hz [382]. Additionally, axions could couple to the laser light and alter the phase velocities of left- and right-hand circularly polarized light [383]. In this case, the birefringence in the interferometer, i.e. optical path difference between p- and s-polarized lights, has to be measured using some additional optics that would need to be added to the interferometers that do not affect the sensitivity to gravitational waves [383].

Vector dark matter, such as dark photons arising from e.g. the misalignment mechanism [384] or cosmic string network decays [385], would interact with baryons in the input and end mirrors, causing oscillatory forces on them that can be formulated as arising from a “dark electric field”, analogously to the ordinary photon [386]. Since the dark matter field sees each of the mirrors in a different location with respect to its propagation direction, each one experiences a slightly different force, leading to different travel times for light down each arm and hence a differential strain [386]. Furthermore, an additional contribution to the differential strain arises due to the finite amount of time light takes to traverse each arm, a “common-mode motion” effect [387]. Tensor dark matter [388], arising as a modification to gravity that could also play the role of DM [389], could also cause a differential strain analogously to GWs by stretching and squeezing the spacetime around the mirrors [390].

All of these types of dark matter would mimic a GW signal in a very narrow frequency band. Because the distance between detectors is much smaller than the coherence length of the dark-matter signal, the LIGO/Virgo/KAGRA detectors experience nearly the same dark matter background; thus their observable signals are highly correlated.

Methodology

A straightforward analysis pipeline was developed and results have been obtained from LIGO O1 data [391]. A semi-coherent method was recently developed within the Band-Sampled Data (BSD) framework [392] that carefully varies the fast Fourier Transform length to account for the expected frequency spread of the signal. This method was applied to the O3 data resulting in stringent upper limits on the dark photon signal, as summarized in [393]. These limits improve upon existing ones from O1 because they account for the contribution to the strain due to the finite light travel time [387]. Furthermore, a search of GEO600 was performed for scalar, dilaton dark matter using the LPSD method that varies, bin by bin, the fast Fourier Transform length, resulting in extremely stringent constraints on the coupling of dilatons to photons and electons [394]. A method to follow-up potential dark matter candidates using the Wiener filter has also been developed, and would allow not just to rule out candidates resulting from spurious detector artifacts, but actually confirm the existence of a dark matter particle and distinguish amongst models for these particles [395].

Two new methods to search for dark matter interacting with other parts of the interferometers have been proposed: one looks for a dilaton signal in the reference cavity and LIGO beam splitters [382], another looks for correlations in multiple non-strain channels in the GW detectors caused by vector bosons [396]. Finally, axions could be searched for jointly with KAGRA and LIGO for "unwanted" polarizations in the interferometers [383], though methods to better estimate calibration errors in the polarization rotation angle are needed.

Activities for O4

ACTIVITY ST-10.2-A-**OPS**: O4 DARK MATTER SEARCH FTE-months: 18.0

TASK ST-10.2-A(i): DEVELOP REFCAV PIPELINE FTE-months: 6.0

These pipelines will be applied to carry out an analysis of O4 data. The refcav/dilaton pipeline needs significant development - lowering noise in IMC-F, detchar, calibration, and then search.

TASK ST-10.2-A(ii): DEVELOP CALIBRATION METHOD SEARCH FTE-months: 6.0

This method to search KAGRA and LIGO data for unwanted polarizations induced by axions needs significant development. Estimation of polarization rotation angle is needed.

TASK ST-10.2-A(iii): DATA PREPARATION FTE-months: 0.5

SFDBs and BSDs will need to be produced up to 8192 Hz, and LIGO SFTs will be employed as well for most methods.

TASK ST-10.2-A(iv): RUN SEARCH FTE-months: 3.0

Run the various pipelines on the prepared detector data.

TASK ST-10.2-A(v): OUTLIER FOLLOWUP AND DATA QUALITY STUDIES FTE-months: 3.0

Follow-ups of potentially interesting signals will be performed by varying the FFT length, looking for coincidences in various detectors, and applying the Wiener filter method.

TASK ST-10.2-A(vi): SET UPPER LIMITS FTE-months: 3.0

Realistically, the output of this search will be upper limits on the strength to which dark matter couples to standard model particles – baryons, baryon-lepton, electrons or photons.

TASK ST-10.2-A(vii): REVIEW SEARCH METHODS AND RESULTS

FTE-months: 3.0

The cross correlation and BSD excess power pipelines are fully developed and reviewed. The follow-up method using the Wiener filter to confirm or deny the presence of dark matter signals, and distinguish between different models, needs review.

The multi-channel method, beam splitter search method, and the calibration methods all need review.

TASK ST-10.2-A(viii): PUBLICATION

FTE-months: 3.0

Produce a publication with the results of each pipeline.

A Total FTE Commitments

Activity Plan		FTE-months Op	LT
Overview and Executive Summary		86.0	-
ST-2.1:	Search for short-duration GW bursts	36.0	-
LT-2.1:	Search for short-duration GW bursts R&D (Long Term)	-	-
ST-2.2:	Search for long-duration GW bursts	15.0	-
LT-2.2:	Search for long-duration GW bursts R&D (Long Term)	-	-
ST-2.3:	Search without templates for GWs from binary black holes	20.0	-
LT-2.3:	Search without templates for GWs from binary stellar mass black holes R&D (Long Term)	-	-
ST-2.4:	GW burst signal characterization	6.5	-
LT-2.4:	GW burst signal characterization R&D (Long Term)	-	-
ST-2.5:	Search for GWs from core-collapse supernova	17.5	-
LT-2.5:	Search for GWs from core-collapse supernova R&D (long term)	-	-
ST-2.6:	Search for GW transients from magnetar flares and neutron star glitches	10.1	-
LT-2.6:	Search for GW transients from isolated neutron stars R&D (Long Term)	-	-
Subtotal for Burst Group Activity Plans		105.1	-
ST-3.1:	CBC Parameter Estimation R&D (Short Term)	119.0	-
LT-3.1:	CBC Parameter Estimation R&D (Long Term)	-	-
ST-3.2:	Tests of General Relativity R&D (Short Term)	58.0	-
LT-3.2:	Tests of General Relativity R&D (Long Term)	-	-
ST-3.3:	Studies of Extreme Matter R&D (Short Term)	108.0	-
LT-3.3:	Studies of Extreme Matter R&D (Long Term)	-	-
ST-3.4:	CBC Waveform Models R&D (Short Term)	256.0	-
LT-3.4:	CBC Waveform Models R&D (Long Term)	-	-
ST-3.5:	Binary Coalescence Rates and Population R&D (Short Term)	91.0	-
LT-3.5:	Binary Coalescence Rates and Population R&D (Long Term)	-	20.0
ST-3.6:	CBC Cosmology R&D (Short Term)	199.0	-
LT-3.6:	CBC Cosmology R&D (Long Term)	-	104.0
ST-3.7:	CBC All Sky Search ShortTerm R&D	345.0	-
LT-3.7:	CBC All Sky Search R&D (Long Term)	-	20.0
ST-3.8:	Lensing R&D (Short Term)	60.0	-
LT-3.8:	Lensing R&D (Long Term)	-	-
ST-3.9:	CBC Service Roles	-	-
ST-3.10:	O4a and O4b Catalog of Compact Binaries	122.2	-
ST-3.11:	O4a and O4b Astrophysical Distribution of Compact Binaries	61.2	-
ST-3.12:	O4a and O4b Strong-Field Tests of General Relativity	36.0	-
ST-3.13:	O4a and O4b Inference of Cosmological Parameters with Observational Data	45.2	-
ST-3.14:	O4a and O4b Search for Lensed Gravitational Waves	54.2	-
ST-3.15:	O4a and O4b Search for Sub-Solar-Mass Compact Binary Coalescences	21.2	-
ST-3.16:	Characterizing exceptional CBC events	12.0	-
Subtotal for CBC Group Activity Plans		1588.0	144.0

Activity Plan		FTE-months Op	 LT
ST-4.1:	Targeted searches for known pulsars	45.0	-
ST-4.2:	Narrow-band searches for known pulsars	32.0	-
ST-4.3:	Searches for r-modes from known pulsars	20.0	-
ST-4.4:	Directed searches targeting Galactic supernova remnants	37.0	-
ST-4.5:	Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries	49.0	-
ST-4.6:	Narrowband directed searches targeting accreting millisecond X-ray pulsars	13.0	-
ST-4.7:	Directed searches targeting the Galactic center	12.0	-
ST-4.8:	All-sky searches for unknown generic continuous-wave sources	18.0	-
ST-4.9:	All-sky searches for unknown isolated sources	67.0	-
ST-4.10:	All-sky searches for unknown sources in binaries	17.0	-
ST-4.11:	Searches for transient emission from post-merger neutron stars	14.0	-
ST-4.12:	Searches for long-transient emission following a pulsar glitch	25.0	-
ST-4.13:	Searches for continuous emission from ultra-light boson clouds around black holes	15.0	-
ST-4.14:	Searches for light primordial black-hole binaries	26.0	-
ST-4.15:	Support for continuous wave searches: Follow-up of interesting candidates	9.0	-
ST-4.16:	Support for continuous wave searches: Data preparation	12.0	-
ST-4.17:	Support for continuous wave searches: Scientific software maintenance	9.0	-
LT-4.18:	Further improvement and optimization of existing data analysis pipelines	-	-
LT-4.19:	Development of model-robust/agnostic data analysis methods	-	-
LT-4.20:	Development of new and potentially more sensitive data analysis methods	-	-
LT-4.21:	Use mock data challenges to compare data analysis pipelines	-	-
Subtotal for CW Group Activity Plans		420.0	-
ST-5.1:	Search for an isotropic stochastic gravitational-wave background (short term)	100.0	-
LT-5.1:	Search for an isotropic stochastic gravitational-wave background (long term)	-	-
ST-5.2:	Directional searches for persistent gravitational waves (short term)	70.0	-
LT-5.2:	Directional searches for persistent gravitational waves (long term)	-	-
LT-5.3:	Search for very-long transient gravitational-wave signals	-	-
Subtotal for Stochastic Group Activity Plans		170.0	-
ST-6.1:	Search for GWs from black hole binaries	3.0	-
ST-6.2:	Multimessenger search for GWs and GRBs	33.0	-
LT-6.2:	Multimessenger search for GWs and GRBs R&D	-	-
ST-6.3:	Multimessenger search for GWs and fast radio bursts	13.0	-
ST-6.4:	Multimessenger search for GWs and high-energy neutrinos	13.0	-
LT-6.4:	Multimessenger search for GWs and high-energy neutrinos R&D (Long Term)	-	-
Subtotal for Burst+CBC Joint Activity Plans		62.0	-
ST-7.1:	Search for GWs from cosmic strings	11.0	-
LT-7.1:	Search for gravitational waves from cosmic strings R&D (Long Term)	-	-

Activity Plan		FTE-months	
		Op	LT
Subtotal for Burst+Stochastic Joint Activity Plans		11.0	-
LT-8.1:	Search for the stochastic background from unresolvable binary black hole mergers	-	-
Subtotal for Stochastic+CBC Joint Activity Plans		-	-
ST-9.1:	Data quality investigations for stochastic searches	52.0	-
LT-9.1:	Data quality investigations for stochastic searches (long term)	-	-
Subtotal for Stochastic+DetChar Joint Activity Plans		52.0	-
ST-10.1:	Identification and follow-up of outliers in stochastic directional analysis skymaps	11.0	-
ST-10.2:	Dark matter direct interaction searches	45.5	-
Subtotal for Stochastic+CW Joint Activity Plans		56.5	-
Grand Total		2550.6	144.0

References

[1] Benjamin P. Abbott et al. All-sky search for short gravitational-wave bursts in the first Advanced LIGO run. *Phys. Rev. D*, 95(4):042003, 2017.

[2] B. P. Abbott et al. All-sky search for short gravitational-wave bursts in the second Advanced LIGO and Advanced Virgo run. *Phys. Rev. D*, 100(2):024017, 2019.

[3] R. Abbott et al. All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run. *Phys. Rev. D*, 104(12):122004, 2021.

[4] S. Klimenko et al. A coherent method for detection of gravitational wave bursts. *Class. Quantum Grav.*, 25(11):114029, June 2008.

[5] Ryan Lynch, Salvatore Vitale, Reed Essick, Erik Katsavounidis, and Florent Robinet. Information-theoretic approach to the gravitational-wave burst detection problem. *Phys. Rev. D*, 95(10):104046, 2017.

[6] Neil J. Cornish and Tyson B. Littenberg. Bayeswave: Bayesian inference for gravitational wave bursts and instrument glitches. *Classical and Quantum Gravity*, 32(13):135012, July 2015.

[7] B. P. Abbott et al. All-sky search for long-duration gravitational wave transients in the first Advanced LIGO observing run. *Classical and Quantum Gravity*, 35(6):065009, 2018.

[8] B. P. Abbott et al. All-sky search for long-duration gravitational-wave transients in the second Advanced LIGO observing run. *Phys. Rev. D*, 99(10):104033, 2019.

[9] R. Abbott et al. All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run. *Phys. Rev. D*, 104(10):102001, 2021.

[10] Adrian Macquet, Marie-Anne Bizouard, Nelson Christensen, and Michael Coughlin. Long-duration transient gravitational-wave search pipeline. *Phys. Rev. D*, 104(10):102005, 2021.

[11] E. Thrane, S. Kandhasamy, C. D. Ott, W. G. Anderson, N. L. Christensen, M. W. Coughlin, S. Dorsher, S. Giampanis, V. Mandic, A. Mytidis, T. Prestegard, P. Raffai, and B. Whiting. Long gravitational-wave transients and associated detection strategies for a network of terrestrial interferometers. *Phys. Rev. D*, 83(8):083004, April 2011.

[12] Eric Sowell, Alessandra Corsi, and Robert Coyne. Multiwaveform cross-correlation search method for intermediate-duration gravitational waves from gamma-ray bursts. *Physical Review D*, 100(12), December 2019.

[13] R. Abbott et al. GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$. *Phys. Rev. Lett.*, 125(10):101102, September 2020.

[14] D. Gerosa and E. Berti. Are merging black holes born from stellar collapse or previous mergers? *Phys. Rev. D*, 95(12):124046, June 2017.

[15] M. Fishbach, D. E. Holz, and B. Farr. Are LIGO's Black Holes Made from Smaller Black Holes? *Astrophys. J. Lett.*, 840:L24, May 2017.

[16] Yang Yang, Imre Bartos, V. Gayathri, Saavik Ford, Zoltan Haiman, Sergey Klimenko, Bence Kocsis, Szabolcs Márka, Zsuzsa Márka, Barry McKernan, and Richard O'Shaugnessy. Hierarchical Black Hole Mergers in Active Galactic Nuclei. *arXiv e-prints*, page arXiv:1906.09281, June 2019.

[17] R. Abbott et al. Properties and Astrophysical Implications of the 150 $M_\odot$ Binary Black Hole Merger GW190521. *Astrophys. J. Lett.*, 900(1):L13, September 2020.

[18] M. C. Miller and E. J. M. Colbert. Intermediate-Mass Black Holes. *International Journal of Modern Physics D*, 13:1–64, January 2004.

[19] Nathan W. C. Leigh, Nora Lützgendorf, Aaron M. Geller, Thomas J. Maccarone, Craig Heinke, and Alberto Sesana. On the coexistence of stellar-mass and intermediate-mass black holes in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 444(1):29–42, 2014.

[20] J. M. Fregeau, S. L. Larson, M. C. Miller, R. O'Shaughnessy, and F. A. Rasio. Observing IMBH-IMBH Binary Coalescences via Gravitational Radiation. *Astrophys. J. Lett.*, 646:L135–L138, August 2006.

[21] P. Amaro-Seoane and M. Freitag. Intermediate-Mass Black Holes in Colliding Clusters: Implications for Lower Frequency Gravitational-Wave Astronomy. *Astrophys. J. Lett.*, 653:L53–L56, December 2006.

[22] Jonathan R. Gair, Ilya Mandel, M. Coleman Miller, and Marta Volonteri. Exploring intermediate and massive black-hole binaries with the Einstein Telescope. *General Relativity and Gravitation*, 43(2):485–518, February 2011.

[23] K. Belczynski, A. Buonanno, M. Cantiello, C. L. Fryer, D. E. Holz, I. Mandel, M. C. Miller, and M. Walczak. The Formation and Gravitational-wave Detection of Massive Stellar Black Hole Binaries. *Astrophys. J.*, 789:120, July 2014.

[24] E. A. Huerta and D. A. Brown. Effect of eccentricity on binary neutron star searches in Advanced LIGO. *Phys. Rev. D*, 87(12):127501, 2013.

[25] B.P. Abbott et al. Search for Eccentric Binary Black Hole Mergers with Advanced LIGO and Advanced Virgo during their First and Second Observing Runs. *Astrophys. J.*, 883(2):149, 2019.

[26] Jose María Ezquiaga and Juan García-Bellido. Quantum diffusion beyond slow-roll: implications for primordial black-hole production. *Journal of Cosmology and Astroparticle Physics*, 2018(08):018–018, Aug 2018.

[27] Fabio Antonini, Mark Gieles, and Alessia Gualandris. Black hole growth through hierarchical black hole mergers in dense star clusters: implications for gravitational wave detections. *Monthly Notices of the Royal Astronomical Society*, 486(4):5008–5021, May 2019.

[28] Manuel Trashorras, Juan García-Bellido, and Savvas Nesseris. The clustering dynamics of primordial black boles in n-body simulations. *Universe*, 7(1):18, Jan 2021.

[29] Juan García-Bellido and Savvas Nesseris. Gravitational wave energy emission and detection rates of primordial black hole hyperbolic encounters. *Physics of the Dark Universe*, 21:61–69, Sep 2018.

[30] László Gondán and Bence Kocsis. High Eccentricities and high masses characterize gravitational-wave captures in galactic nuclei as seen by earth-based detectors. *arXiv*, 28(November):1–28, 2020.

[31] Johan Samsing, Daniel J. D'Orazio, Kyle Kremer, Carl L. Rodriguez, and Abbas Askar. Single-single gravitational-wave captures in globular clusters: Eccentric deci-Hertz sources observable by DECIGO and Tian-Qin. *Physical Review D*, 101(12):1–16, 2020.

[32] Johan Samsing. Eccentric black hole mergers forming in globular clusters. *Physical Review D*, 97(10), 2018.

[33] Michael Zevin, Johan Samsing, Carl Rodriguez, Carl Johan Haster, and Enrico Ramirez-Ruiz. Eccentric black hole mergers in dense star clusters: The role of binary-binary encounters. *arXiv*, 2019.

[34] Ryan M. O'leary, Bence Kocsis, and Abraham Loeb. Gravitational waves from scattering of stellar-mass black holes in galactic nuclei. *Monthly Notices of the Royal Astronomical Society*, 395(4):2127–2146, 2009.

[35] Yeong-Bok Bae, Hyung Mok Lee, Gungwon Kang, and Jakob Hansen. Gravitational radiation driven capture in unequal mass black hole encounters. *Phys. Rev. D*, 96(8):084009, October 2017.

[36] K. S. Thorne. Multipole Expansions of Gravitational Radiation. *Rev. Mod. Phys.*, 52:299–339, 1980.

[37] Tyson B. Littenberg and Neil J. Cornish. Bayesian inference for spectral estimation of gravitational wave detector noise. *Phys. Rev. D*, 91(8):084034, 2015.

[38] S. Klimenko et al. Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors. *Phys. Rev. D*, 93(4):042004, 2016.

[39] R. Abbott et al. GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. 11 2021.

[40] B. P. Abbott et al. Implementation and testing of the first prompt search for gravitational wave transients with electromagnetic counterparts. *Astron. Astrophys.*, 539:A124, 2012.

[41] Bence Bécsy, Peter Raffai, Neil J. Cornish, Reed Essick, Jonah Kanner, Erik Katsavounidis, Tyson B. Littenberg, Margaret Millhouse, and Salvatore Vitale. Parameter estimation for gravitational-wave bursts with the BayesWave pipeline. *Astrophys. J.*, 839(1):15, 2017. [Astrophys. J.839,15(2017)].

[42] Reed Essick, Salvatore Vitale, Erik Katsavounidis, Gabriele Vedovato, and Sergey Klimenko. Localization of short duration gravitational-wave transients with the early Advanced LIGO and Virgo detectors. *Astrophys. J.*, 800(2):81, 2015.

[43] B.P. Abbott et al. Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced LIGO and advanced Virgo. *Phys. Rev. D*, 101(8):084002, 2020.

[44] E. P. Mazets, S. V. Golentskii, V. N. Ilinskii, R. L. Aptekar, and I. A. Guryan. Observations of a flaring X-ray pulsar in Dorado. *Nature*, 282:587–589, December 1979.

[45] Y. T. Tanaka, T. Terasawa, N. Kawai, A. Yoshida, I. Yoshikawa, Y. Saito, T. Takashima, and T. Mukai. Comparative Study of the Initial Spikes of Soft Gamma-Ray Repeater Giant Flares in 1998 and 2004 Observed with Geotail: Do Magnetospheric Instabilities Trigger Large-Scale Fracturing of a Magnetar's Crust? *Astrophys. J. Lett.*, 665:L55–L58, August 2007.

[46] T. Terasawa, Y. T. Tanaka, Y. Takei, N. Kawai, A. Yoshida, K. Nomoto, I. Yoshikawa, Y. Saito, Y. Kasaba, T. Takashima, T. Mukai, H. Noda, T. Murakami, K. Watanabe, Y. Muraki, T. Yokoyama, and M. Hoshino. Repeated injections of energy in the first 600ms of the giant flare of SGR1806 - 20. *Nature*, 434:1110–1111, April 2005.

[47] R. Abbott et al. Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run. 10 2022.

[48] B. Abbott et al. Search for gravitational-wave bursts from soft gamma repeaters. *Phys. Rev. Lett.*, 101(21):211102, 2008.

[49] B. P. Abbott et al. Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm. *Astrophys. J. Lett.*, 701:L68–L74, August 2009.

[50] J. Abadie et al. Search for Gravitational Wave Bursts from Six Magnetars. *Astrophys. J. Lett.*, 734:L35, 2011.

[51] J. Abadie et al. A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar. *Phys. Rev. D*, 83:042001, 2011.

[52] B. P. Abbott et al. Search for Transient Gravitational-wave Signals Associated with Magnetar Bursts during Advanced LIGO's Second Observing Run. *Astrophys. J.*, 874(2):163, 2019.

[53] W. M. Farr, J. R. Gair, I. Mandel, and C. Cutler. Counting and confusion: Bayesian rate estimation with multiple populations. *Phys. Rev. D*, 91(2):023005, January 2015.

[54] Rahul Biswas, Patrick R. Brady, Jolien D. E. Creighton, and Stephen Fairhurst. The Loudest Event Statistic: General Formulation, Properties and Applications. *Class. Quantum Grav.*, 26:175009, 2009.

[55] C. Kim, V. Kalogera, and D. R. Lorimer. The Probability Distribution of Binary Pulsar Coalescence Rates. I. Double Neutron Star Systems in the Galactic Field. *Astrophys. J.*, 584:985–995, February 2003.

[56] B. P. Abbott et al. Tests of general relativity with GW150914. *Phys. Rev. Lett.*, 116(22):221101, 2016.

[57] B. P. Abbott et al. Binary Black Hole Mergers in the First Advanced LIGO Observing Run. *Phys. Rev. X*, 6(4):041015, October 2016.

[58] Benjamin P. Abbott et al. GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.*, 118(22):221101, 2017.

[59] B.P. Abbott et al. Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1. *Phys. Rev. D*, 100(10):104036, 2019.

[60] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, 2017.

[61] B. P. Abbott et al. Tests of General Relativity with GW170817. *Phys. Rev. Lett.*, 123(1):011102, Jul 2019.

[62] B. P. Abbott et al. Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.*, 848:13, 2017.

[63] GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses. 4 2020.

[64] R. Abbott et al. GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. *Astrophys. J. Lett.*, 896(2):L44, 2020.

[65] R. Abbott et al. Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog. *Phys. Rev. D*, 103(12):122002, 2021.

[66] R. Abbott et al. Tests of General Relativity with GWTC-3. 12 2021.

[67] Subrahmanyan Chandrasekhar. The maximum mass of ideal white dwarfs. *Astrophys. J.*, 74:81–82, 1931.

[68] F. X. Timmes, S. E. Woosley, and Thomas A. Weaver. The Neutron star and black hole initial mass function. *Astrophys. J.*, 457:834, 1996.

[69] J. G. Martinez, K. Stovall, P. C. C. Freire, J. S. Deneva, F. A. Jenet, M. A. McLaughlin, M. Bagchi, S. D. Bates, and A. Ridolfi. Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry. *Astrophys. J.*, 812(2):143, 2015.

[70] Yudai Suwa, Takashi Yoshida, Masaru Shibata, Hideyuki Umeda, and Koh Takahashi. On the minimum mass of neutron stars. *Mon. Not. Roy. Astron. Soc.*, 481(3):3305–3312, 2018.

[71] John Antoniadis, Paulo C.C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, et al. A Massive Pulsar in a Compact Relativistic Binary. *Science*, 340(6131):1233232, 2013.

[72] Bernard J. Carr. The Primordial black hole mass spectrum. *Astrophys. J.*, 201:1–19, 1975.

[73] Karsten Jedamzik. Primordial black hole formation during the qcd epoch. *Phys. Rev. D*, 55:5871–5875, 1997.

[74] Peter Widerin and Christoph Schmid. Primordial black holes from the QCD transition? *Preprint: arXiv astro-ph/9808142*, 1998.

[75] Julian Georg and Scott Watson. A Preferred Mass Range for Primordial Black Hole Formation and Black Holes as Dark Matter Revisited. *JHEP*, 09:138, 2017.

[76] Christian T. Byrnes, Mark Hindmarsh, Sam Young, and Michael R. S. Hawkins. Primordial black holes with an accurate QCD equation of state. *JCAP*, 1808(08):041, 2018.

[77] Sarah Shandera, Donghui Jeong, and Henry S. Grasshorn Gebhardt. Gravitational Waves from Binary Mergers of Subsolar Mass Dark Black Holes. *Phys. Rev. Lett.*, 120(24):241102, 2018.

[78] Chris Kouvaris and Peter Tinyakov. Constraining Asymmetric Dark Matter through observations of compact stars. *Phys. Rev. D*, 83:083512, 2011.

[79] Arnaud de Lavallaz and Malcolm Fairbairn. Neutron Stars as Dark Matter Probes. *Phys. Rev. D*, 81:123521, 2010.

[80] Itzhak Goldman and Shmuel Nussinov. Weakly interacting massive particles and neutron stars. *Phys. Rev. D*, 40:3221–3230, November 1989.

[81] Joseph Bramante and Fatemeh Elahi. Higgs portals to pulsar collapse. *Phys. Rev. D*, 91(11):115001, 2015.

[82] Joseph Bramante and Tim Linden. Detecting Dark Matter with Imploding Pulsars in the Galactic Center. *Phys. Rev. Lett.*, 113(19):191301, 2014.

[83] Joseph Bramante, Tim Linden, and Yu-Dai Tsai. Searching for dark matter with neutron star mergers and quiet kilonovae. *Phys. Rev. D*, 97(5):055016, 2018.

[84] Chris Kouvaris, Peter Tinyakov, and Michel H. G. Tytgat. NonPrimordial Solar Mass Black Holes. *Phys. Rev. Lett.*, 121(22):221102, 2018.

[85] J. Aasi et al. Gravitational Waves from Known Pulsars: Results from the Initial Detector Era. *Astrophys. J.*, 785(2):119, 2014.

[86] D.I. Jones. Gravitational wave emission from rotating superfluid neutron stars. *Monthly Notices of the Royal Astronomical Society*, 402:2503–2519, March 2010.

[87] Maximiliano Isi, Matthew Pitkin, and Alan J. Weinstein. Probing dynamical gravity with the polarization of continuous gravitational waves. *Phys. Rev. D*, 96:042001, August 2017.

[88] B. P. Abbott et al. First Search for Nontensorial Gravitational Waves from Known Pulsars. *Phys. Rev. Lett.*, 120(3):031104, January 2018.

[89] R. Abbott et al. Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs. *Astrophys. J.*, 935(1):1, 2022.

[90] Matthew Pitkin, Maximiliano Isi, John Veitch, and Graham Woan. A nested sampling code for targeted searches for continuous gravitational waves from pulsars. *arXiv*, 1705.08978, May 2017.

[91] Matthew Pitkin. CWInPy: A Python package for inference with continuous gravitational-wave signals from pulsars. *J. Open Source Softw.*, 7(77):4568, 2022.

[92] P. Astone, S. D'Antonio, S. Frasca, and C. Palomba. A method for detection of known sources of continuous gravitational wave signals in non-stationary data. *Classical and Quantum Gravity*, 27(19):194016, 2010.

[93] Dhruv Pathak and Debarati Chatterjee. Improving the spin-down limits for the continuous gravitational waves emitted from pulsars as triaxial rotators. *arXiv e-prints*, page arXiv:2210.10355, October 2022.

[94] B. P. Abbott et al. Searches for Gravitational Waves from Known Pulsars at Two Harmonics in 2015-2017 LIGO Data. *Astrophys. J.*, 879:10, July 2019.

[95] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, T. Adams, et al. Narrow-band search of continuous gravitational-wave signals from Crab and Vela pulsars in Virgo VSR4 data. *Phys. Rev. D*, 91(2):022004, January 2015.

[96] S Mastrogiovanni, P Astone, S D'Antonio, S Frasca, G Intini, P Leaci, A Miller, C Palomba, O J Piccinni, and A Singhal. An improved algorithm for narrow-band searches of continuous gravitational waves. *Classical and Quantum Gravity*, 34(13):135007, 2017.

[97] B. Abbott et al. Beating the Spin-Down Limit on Gravitational Wave Emission from the Crab Pulsar. *Astrophys. J. Lett.*, 683:L45, August 2008.

[98] B. P. Abbott et al. Narrow-band search for gravitational waves from known pulsars using the second LIGO observing run. *Phys. Rev. D*, 99:122002, June 2019.

[99] R. Abbott et al. Narrowband Searches for Continuous and Long-duration Transient Gravitational Waves from Known Pulsars in the LIGO-Virgo Third Observing Run. *Astrophys. J.*, 932(2):133, 2022.

[100] F. E. Marshall, E. V. Gotthelf, W. Zhang, J. Middleditch, and Q. D. Wang. Discovery of an Ultrafast X-Ray Pulsar in the Supernova Remnant N157B. *Astrophys. J. Lett.*, 499(2):L179–L182, June 1998.

[101] G. Pietrzyński, D. Graczyk, A. Gallenne, W. Gieren, I. B. Thompson, B. Pilecki, P. Karczmarek, M. Górski, K. Suchomska, M. Taormina, B. Zgirski, P. Wielgórski, Z. Kołaczkowski, P. Konorski, S. Villanova, N. Nardetto, P. Kervella, F. Bresolin, R. P. Kudritzki, J. Storm, R. Smolec, and W. Narloch. A distance to the Large Magellanic Cloud that is precise to one per cent. *Nature*, 567(7747):200–203, March 2019.

[102] H. V. Bradt, R. E. Rothschild, and J. H. Swank. X-ray timing explorer mission. A&AS, 97(1):355–360, January 1993.

[103] Keith C. Gendreau, Zaven Arzoumanian, and Takashi Okajima. The Neutron star Interior Composition ExploreR (NICER): an Explorer mission of opportunity for soft x-ray timing spectroscopy. In Tadayuki Takahashi, Stephen S. Murray, and Jan-Willem A. den Herder, editors, *Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray*, volume 8443 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 844313, September 2012.

[104] J. Middleditch, F. E. Marshall, Q. D. Wang, E. V. Gotthelf, and W. Zhang. Predicting the Starquakes in PSR J0537-6910. *Astrophys. J.*, 652(2):1531–1546, December 2006.

[105] D. Antonopoulou, C. M. Espinoza, L. Kuiper, and N. Andersson. Pulsar spin-down: the glitch-dominated rotation of PSR J0537-6910. *MNRAS*, 473(2):1644–1655, January 2018.

[106] R. D. Ferdman, R. F. Archibald, K. N. Gourgouliatos, and V. M. Kaspi. The Glitches and Rotational History of the Highly Energetic Young Pulsar PSR J0537-6910. *Astrophys. J.*, 852(2):123, January 2018.

[107] Wynn C. G. Ho, Cristóbal M. Espinoza, Zaven Arzoumanian, Teruaki Enoto, Tsubasa Tamba, Danai Antonopoulou, Michał Bejger, Sebastien Guillot, Brynmor Haskell, and Paul S. Ray. Return of the Big Glitcher: NICER timing and glitches of PSR J0537-6910. *MNRAS*, 498(4):4605–4614, September 2020.

[108] Brynmor Haskell and Andrew Melatos. Models of pulsar glitches. *International Journal of Modern Physics D*, 24(3):1530008, January 2015.

[109] N. Andersson, D. Antonopoulou, C. M. Espinoza, B. Haskell, and W. C. G. Ho. The Enigmatic Spin Evolution of PSR J0537-6910: r-modes, Gravitational Waves, and the Case for Continued Timing. *Astrophys. J.*, 864(2):137, September 2018.

[110] R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, A. Adams, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, and et al. Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910. *arXiv e-prints*, page arXiv:2012.12926, December 2020.

[111] Mark G. Alford and Kai Schwenzer. Gravitational Wave Emission and Spin-down of Young Pulsars. *Astrophys. J.*, 781(1):26, January 2014.

[112] Ashikuzzaman Idrisy, Benjamin J. Owen, and David I. Jones. R -mode frequencies of slowly rotating relativistic neutron stars with realistic equations of state. *Phys. Rev. D*, 91(2):024001, January 2015.

[113] Suprovo Ghosh, Dhruv Pathak, and Debarati Chatterjee. Relativistic correction to the r-mode frequency in light of multi-messenger constraints. *arXiv e-prints*, page arXiv:2209.11941, September 2022.

[114] Santiago Caride, Ra Inta, Benjamin J. Owen, and Binod Rajbhandari. How to search for gravitational waves from r -modes of known pulsars. *Phys. Rev. D*, 100(6):064013, September 2019.

[115] R. Abbott and et al. Constraints from ligo o3 data on gravitational-wave emission due to r-modes in the glitching pulsar psr j0537â€“6910. *The Astrophysical Journal*, 922(1):71, nov 2021.

[116] P. Jaranowski, A. Królak, and B. F. Schutz. Data analysis of gravitational-wave signals from spinning neutron stars: The signal and its detection. *Phys. Rev. D*, 58(6):063001, 1998.

[117] J. Abadie et al. First Search for Gravitational Waves from the Youngest Known Neutron Star. *Astrophys. J.*, 722:1504, 2010.

[118] J. Aasi et al. Searches for Continuous Gravitational Waves from Nine Young Supernova Remnants. *Astrophys. J.*, 813:39, November 2015.

[119] B. P. Abbott et al. Searches for Continuous Gravitational Waves from 15 Supernova Remnants and Fomalhaut b with Advanced LIGO. *Astrophys. J.*, 875(2):122, April 2019.

[120] S. J. Zhu, M. A. Papa, H.-B. Eggenstein, R. Prix, K. Wette, B. Allen, O. Bock, D. Keitel, B. Krishnan, B. Machenschalk, M. Shaltev, and X. Siemens. Einstein@Home search for continuous gravitational waves from Cassiopeia A. *Phys. Rev. D*, 94(8):082008, 2016.

[121] L. Sun, A. Melatos, S. Suvorova, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from young supernova remnants. *Phys. Rev. D*, 97:043013, February 2018.

[122] Ling Sun, Andrew Melatos, and Paul D. Lasky. Tracking continuous gravitational waves from a neutron star at once and twice the spin frequency with a hidden Markov model. *Phys. Rev. D*, 99:123010, June 2019.

[123] O. J. Piccinni, P. Astone, S. D'Antonio, S. Frasca, G. Intini, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, and A. Singhal. A new data analysis framework for the search of continuous gravitational wave signals. *Classical and Quantum Gravity*, 36:015008, 2019.

[124] L. Bildsten. Gravitational Radiation and Rotation of Accreting Neutron Stars. *Astrophys. J. Lett.*, 501:L89, 1998.

[125] Sanjeev Dhurandhar, Badri Krishnan, Himan Mukhopadhyay, and John T. Whelan. Cross-correlation search for periodic gravitational waves. *Phys. Rev. D*, 77:082001, 2008.

[126] John T. Whelan, Santosh Sundaresan, Yuanhao Zhang, and Prabath Peiris. Model-based cross-correlation search for gravitational waves from Scorpius X-1. *Phys. Rev. D*, 91:102005, 2015.

[127] B. P. Abbott et al. Upper Limits on Gravitational Waves from Scorpius X-1 from a Model-Based Cross-Correlation Search in Advanced LIGO Data. *Astrophys. J.*, 847(1):47, 2017.

[128] Grant David Meadors, Evan Goetz, Keith Riles, Teviet Creighton, and Florent Robinet. Searches for continuous gravitational waves from Scorpius X-1 and XTE J1751-305 in LIGO's sixth science run. *Phys. Rev. D*, 95(4):042005, 2017.

[129] S. Suvorova, L. Sun, A. Melatos, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from a neutron star with wandering spin. *Phys. Rev. D*, 93(12):123009, June 2016.

[130] S. Suvorova, P. Clearwater, A. Melatos, L. Sun, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from a binary neutron star with wandering spin. II. Binary orbital phase tracking. *Phys. Rev. D*, 96:102006, November 2017.

[131] B. P. Abbott et al. Search for gravitational waves from Scorpius X-1 in the first Advanced LIGO observing run with a hidden Markov model. *Phys. Rev. D*, 95(12):122003, 2017.

[132] B. P. Abbott et al. Search for gravitational waves from Scorpius X-1 in the second Advanced LIGO observing run with an improved hidden Markov model. *Phys. Rev. D*, 100(12):122002, December 2019.

[133] R. Abbott et al. Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data. *Phys. Rev. D*, 106(6):062002, September 2022.

[134] J. Aasi et al. Directed search for gravitational waves from Scorpius X-1 with initial LIGO data. *Phys. Rev. D*, 91(6):062008, March 2015.

[135] P. Astone, K. M. Borkowski, P. Jaranowski, M. Pietka, and A. Królak. Data analysis of gravitational-wave signals from spinning neutron stars. V. A narrow-band all-sky search. *Phys. Rev. D*, 82(2):022005, July 2010.

[136] Arunava Mukherjee, Reinhard Prix, and Karl Wette. Implementation and characterization of BinaryWeave: A new search pipeline for continuous gravitational waves from Scorpius X-1. *arXiv e-prints*, page arXiv:2207.09326, July 2022.

[137] Paola Leaci and Reinhard Prix. Directed searches for continuous gravitational waves from binary systems: Parameter-space metrics and optimal Scorpius X-1 sensitivity. *Phys. Rev. D*, 91(10):102003, May 2015.

[138] Arunava Mukherjee, Chris Messenger, and Keith Riles. Accretion-induced spin-wandering effects on the neutron star in Scorpius X-1: Implications for continuous gravitational wave searches. *Phys. Rev. D*, 97:043016, February 2018.

[139] Grant David Meadors, Badri Krishnan, Maria Alessandra Papa, John T. Whelan, and Yuanhao Zhang. Resampling to accelerate cross-correlation searches for continuous gravitational waves from binary systems. *Phys. Rev. D*, 97:044017, February 2018.

[140] Hannah Middleton, Patrick Clearwater, Andrew Melatos, and Liam Dunn. Search for gravitational waves from five low mass x-ray binaries in the second Advanced LIGO observing run with an improved hidden Markov model. *Phys. Rev. D*, 102(2):023006, July 2020.

[141] R. Abbott et al. Search for continuous gravitational waves from 20 accreting millisecond x-ray pulsars in O3 LIGO data. *Phys. Rev. D*, 105(2):022002, January 2022.

[142] Fermi-LAT Collaboration. Characterizing the population of pulsars in the inner Galaxy with the Fermi Large Area Telescope. *arXiv*, 1705.00009, 2017.

[143] A. Abramowski et al. Acceleration of petaelectronvolt protons in the Galactic Centre. *Nature*, 531:476, 2016.

[144] Samuel K. Lee, Mariangela Lisanti, Benjamin R. Safdi, Tracy R. Slatyer, and Wei Xue. Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy. *Phys. Rev. Lett.*, 116:051103, 2016.

[145] Richard Bartels, Suraj Krishnamurthy, and Christoph Weniger. Strong support for the millisecond pulsar origin of the Galactic center GeV excess. *Phys. Rev. Lett.*, 116:051102, 2016.

[146] D. Hooper, I. Cholis, and T. Linden. TeV Gamma-Rays from Galactic Center Pulsars. *Physics of the Dark Universe*, 21:40, 2018.

[147] Ornella J. Piccinni, P. Astone, S. D'Antonio, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. Miller, and C. Palomba. Directed search for continuous gravitational-wave signals from the galactic center in the Advanced LIGO second observing run. *Phys. Rev. D*, 101:082004, April 2020.

[148] Joe Bayley, Graham Woan, and Chris Messenger. SOAP: A generalised application of the Viterbi algorithm to searches for continuous gravitational-wave signals. *Phys. Rev. D*, March 2019.

[149] B. Abbott et al. All-sky search for periodic gravitational waves in LIGO S4 data. *Phys. Rev. D*, 77:022001, January 2008.

[150] Vladimir Dergachev. Description of PowerFlux 2 algorithms and implementation. Technical Report T1000272-v5, LIGO, 2010.

[151] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba. Method for all-sky searches of continuous gravitational wave signals using the frequency-Hough transform. *Phys. Rev. D*, 90(4):042002, August 2014.

[152] B. Krishnan, A. M. Sintes, M. A. Papa, B. F. Schutz, S. Frasca, et al. The Hough transform search for continuous gravitational waves. *Phys. Rev. D*, 70:082001, 2004.

[153] J. Aasi et al. Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data. *Classical and Quantum Gravity*, 31(16):165014, August 2014.

[154] E. Goetz and K. Riles. An all-sky search algorithm for continuous gravitational waves from spinning neutron stars in binary systems. *Classical and Quantum Gravity*, 28:215006, 2011.

[155] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, T. Accadia, F. Acernese, K. Ackley, et al. First all-sky search for continuous gravitational waves from unknown sources in binary systems. *Phys. Rev. D*, 90:062010, May 2014.

[156] P. B. Covas and Alicia M. Sintes. New method to search for continuous gravitational waves from unknown neutron stars in binary systems. *Phys. Rev. D*, 99:124019, June 2019.

[157] P. B. Covas and Alicia M. Sintes. First all-sky search for continuous gravitational-wave signals from unknown neutron stars in binary systems using Advanced LIGO data. *Phys. Rev. Lett.*, 124:191102, May 2020.

[158] R. Abbott et al. All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems. *Phys. Rev. D*, 103(6):064017, 2021.

[159] Rodrigo Tenorio, David Keitel, and Alicia M. Sintes. Time-frequency track distance for comparing continuous gravitational wave signals. *Phys. Rev. D*, 103(6):064053, 2021.

[160] David Keitel, Rodrigo Tenorio, Gregory Ashton, and Reinhard Prix. PyFstat: a Python package for continuous gravitational-wave data analysis. *J. Open Source Softw.*, 6(60):3000, 2021.

[161] Gregory Ashton, David Keitel, Reinhard Prix, and Rodrigo Tenorio. Pyfstat, April 2021. `https://doi.org/10.5281/zenodo.3967045`.

[162] Rodrigo Tenorio, David Keitel, and Alicia M. Sintes. Application of a hierarchical MCMC follow-up to Advanced LIGO continuous gravitational-wave candidates. May 2021.

[163] Nikhil Sarin and Paul D. Lasky. The evolution of binary neutron star post-merger remnants: a review. *Gen. Rel. Grav.*, 53(6):59, 2021.

[164] B. P. Abbott et al. Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817. *Astrophys. J. Lett.*, 851(1):L16, 2017.

[165] B. P. Abbott et al. Search for Gravitational Waves from a Long-lived Remnant of the Binary Neutron Star Merger GW170817. *Astrophys. J.*, 875(2):160, April 2019.

[166] Andreas Bauswein, Oliver Just, Hans-Thomas Janka, and Nikolaos Stergioulas. Neutron-star radius constraints from GW170817 and future detections. *Astrophys. J. Lett.*, 850(2):L34, 2017.

[167] Ben Margalit and Brian D. Metzger. Constraining the Maximum Mass of Neutron Stars From Multi-Messenger Observations of GW170817. *Astrophys. J. Lett.*, 850(2):L19, 2017.

[168] B. P. Abbott and et al. Search for post-merger gravitational waves from the remnant of the binary neutron star merger gw170817. *The Astrophysical Journal Letters*, 851(1):L16, dec 2017.

[169] Nikhil Sarin, Paul D. Lasky, Letizia Sammut, and Greg Ashton. X-ray guided gravitational-wave search for binary neutron star merger remnants. *Phys. Rev. D*, 98(4):043011, 2018.

[170] Shunke Ai, He Gao, Zi-Gao Dai, Xue-Feng Wu, Ang Li, Bing Zhang, and Mu-Zi Li. The allowed parameter space of a long-lived neutron star as the merger remnant of GW170817. *Astrophys. J.*, 860(1):57, 2018.

[171] Ling Sun and Andrew Melatos. Application of hidden Markov model tracking to the search for long-duration transient gravitational waves from the remnant of the binary neutron star merger GW170817. *Phys. Rev. D*, 99:123003, June 2019.

[172] Sharan Banagiri, Ling Sun, Michael W. Coughlin, and Andrew Melatos. Search strategies for long gravitational-wave transients: Hidden Markov model tracking and seedless clustering. *Phys. Rev. D*, 100:024034, July 2019.

[173] Miquel Oliver, David Keitel, and Alicia M. Sintes. Adaptive transient Hough method for long-duration gravitational wave transients. *Phys. Rev. D*, 99:104067, May 2019.

[174] C. Palomba, P. Astone, and S. Frasca. Adaptive Hough transform for the search of periodic sources. *Classical and Quantum Gravity*, 22:S1255–S1264, 2005.

[175] Andrew Miller, Pia Astone, Sabrina D'Antonio, Sergio Frasca, Giuseppe Intini, Iuri La Rosa, Paola Leaci, Simone Mastrogiovanni, Federico Muciaccia, Cristiano Palomba, Ornella J. Piccinni, Akshat Singhal, and Bernard F. Whiting. Method to search for long duration gravitational wave transients from isolated neutron stars using the generalized frequency-Hough transform. *Phys. Rev. D*, 98:102004, November 2018.

[176] P. D. Lasky, N. Sarin, and L. Sammut. Long-duration waveform models for millisecond magnetars born in binary neutron star mergers. Technical Report LIGO-T1700408, LIGO, 2017.

[177] Tim Dietrich, David Radice, Sebastiano Bernuzzi, Francesco Zappa, Albino Perego, Bernd BrĂĽgmann, Swami Vivekanandji Chaurasia, Reetika Dudi, Wolfgang Tichy, and Maximiliano Ujevic. CoRe database of binary neutron star merger waveforms. *Classical and Quantum Gravity*, 35(24):24LT01, nov 2018.

[178] Andrzej Pisarski, Piotr Jaranowski, and Maciej Pietka. Banks of templates for directed searches of gravitational waves from spinning neutron stars. *Phys. Rev. D*, 83:043001, Feb 2011.

[179] Reinhard Prix, Stefanos Giampanis, and Chris Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[180] Garvin Yim and D. I. Jones. Transient gravitational waves from pulsar post-glitch recoveries. *Mon. Not. Roy. Astron. Soc.*, 498(3):3138–3152, 2020.

[181] Brynmor Haskell and Andrew Melatos. Models of Pulsar Glitches. *Int. J. Mod. Phys.*, D24(03):1530008, 2015.

[182] David Keitel and Gregory Ashton. Faster search for long gravitational-wave transients: GPU implementation of the transient $\mathcal{F}$-statistic. *Classical and Quantum Gravity*, 35(20):205003, 2018.

[183] David Keitel, Graham Woan, Matthew Pitkin, Courtney Schumacher, Brynley Pearlstone, Keith Riles, Andrew G. Lyne, Jim Palfreyman, Benjamin Stappers, and Patrick Weltevrede. First search for long-duration transient gravitational waves after glitches in the Vela and Crab pulsars. *Phys. Rev. D*, 100(6):064058, 2019.

[184] Eric Thrane, Vuk Mandic, and Nelson Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91(10):104021, 2015.

[185] G. Ashton and R. Prix. Hierarchical multistage MCMC follow-up of continuous gravitational wave candidates. *Phys. Rev. D*, 97(10):103020, May 2018.

[186] Joan Moragues, Luana M. Modafferi, Rodrigo Tenorio, and David Keitel. Prospects for detecting transient quasi-monochromatic gravitational waves from glitching pulsars with current and future detectors. 10 2022.

[187] Rodrigo Tenorio, Luana M. Modafferi, David Keitel, and Alicia M. Sintes. Empirically estimating the distribution of the loudest candidate from a gravitational-wave search. *Phys. Rev. D*, 105(4):044029, 2022.

[188] S. D'Antonio, C. Palomba, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. Miller, F. Muciaccia, O. J. Piccinni, and A. Singhal. Semicoherent analysis method to search for continuous gravitational waves emitted by ultralight boson clouds around spinning black holes. *Phys. Rev. D*, 98:103017, November 2018.

[189] R. Abbott et al. All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data. *Phys. Rev. D*, 105(10):102001, May 2022.

[190] Maximiliano Isi, Ling Sun, Richard Brito, and Andrew Melatos. Directed searches for gravitational waves from ultralight bosons. *Phys. Rev. D*, 99:084042, April 2019.

[191] C. Palomba, S. D'Antonio, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. Miller, F. Muciaccia, O. J. Piccinni, L. Rei, and F. Simula. Direct constraint on the Ultralight Boson Mass from Searches of Continuous Gravitational Waves. *Phys. Rev. Lett.*, 123:171101, October 2019.

[192] L. Sun, R. Brito, and M. Isi. Search for ultralight bosons in Cygnus X-1 with Advanced LIGO. *Phys. Rev. D*, 101:063020, March 2020.

[193] Nils Siemonsen, Taillte May, and William E. East. SuperRad: A black hole superradiance gravitational waveform model. 11 2022.

[194] R. Abbott et al. The population of merging compact binaries inferred using gravitational waves through GWTC-3. 11 2021.

[195] Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess. Did LIGO detect dark matter? *Phys. Rev. Lett.*, 116(20):201301, 2016.

[196] Sebastien Clesse and Juan García-Bellido. The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO. *Phys. Dark Univ.*, 15:142–147, 2017.

[197] Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama. Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914. *Phys. Rev. Lett.*, 117(6):061101, 2016. [Erratum: Phys.Rev.Lett. 121, 059901 (2018)].

[198] Anne M. Green and Bradley J. Kavanagh. Primordial Black Holes as a dark matter candidate. *J. Phys. G*, 48(4):043001, 2021.

[199] Hiroko Niikura, Masahiro Takada, Shuichiro Yokoyama, Takahiro Sumi, and Shogo Masaki. Constraints on Earth-mass primordial black holes from OGLE 5-year microlensing events. *Phys. Rev. D*, 99(8):083503, 2019.

[200] M. R. S. Hawkins. The signature of primordial black holes in the dark matter halos of galaxies. *Astron. Astrophys.*, 633:A107, 2020.

[201] Saloni Bhatiani, Xinyu Dai, and Eduardo Guerras. Confirmation of planet-mass objects in extragalactic systems. *The Astrophysical Journal*, 885(1):77, 2019.

[202] Sebastien Clesse and Juan García-Bellido. Seven hints for primordial black hole dark matter. *Physics of the Dark Universe*, 22:137–146, 2018.

[203] C Sivaram, Kenath Arun, and OV Kiren. Primordial planets predominantly of dark matter. *Earth, Moon, and Planets*, 122(3):115–119, 2019.

[204] Jakub Scholtz and James Unwin. What if Planet 9 is a Primordial Black Hole? *Phys. Rev. Lett.*, 125(5):051103, 2020.

[205] Amir Siraj and Abraham Loeb. Searching for Black Holes in the Outer Solar System with LSST. *Astrophys. J. Lett.*, 898(1):L4, 2020.

[206] Juan García-Bellido and Sebastien Clesse. Constraints from microlensing experiments on clustered primordial black holes. *Phys. Dark Univ.*, 19:144–148, 2018.

[207] Josh Calcino, Juan Garcia-Bellido, and Tamara M. Davis. Updating the MACHO fraction of the Milky Way dark halowith improved mass models. *Mon. Not. Roy. Astron. Soc.*, 479(3):2889–2905, 2018.

[208] Konstantin M. Belotsky, Vyacheslav I. Dokuchaev, Yury N. Eroshenko, Ekaterina A. Esipova, Maxim Yu. Khlopov, Leonid A. Khromykh, Alexander A. Kirillov, Valeriy V. Nikulin, Sergey G. Rubin, and Igor V. Svadkovsky. Clusters of primordial black holes. *Eur. Phys. J. C*, 79(3):246, 2019.

[209] Bernard Carr, Sebastien Clesse, Juan García-Bellido, and Florian Kühnel. Cosmic conundra explained by thermal history and primordial black holes. *Phys. Dark Univ.*, 31:100755, 2021.

[210] Manuel Trashorras, Juan García-Bellido, and Savvas Nesseris. The clustering dynamics of primordial black boles in N-body simulations. *Universe*, 7(1):18, 2021.

[211] V. De Luca, V. Desjacques, G. Franciolini, and A. Riotto. The clustering evolution of primordial black holes. *JCAP*, 11:028, 2020.

[212] Antonis Mytidis, Athanasios Aris Panagopoulos, Orestis P. Panagopoulos, Andrew Miller, and Bernard Whiting. Sensitivity study using machine learning algorithms on simulated r-mode gravitational wave signals from newborn neutron stars. *Phys. Rev. D*, 99(2):024024, 2019.

[213] Andrew L. Miller et al. How effective is machine learning to detect long transient gravitational waves from neutron stars in a real search? *Phys. Rev. D*, 100(6):062005, 2019.

[214] Andrew L. Miller, Nancy Aggarwal, Sébastien Clesse, and Federico De Lillo. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational-wave searches. *Phys. Rev. D*, 105(6):062008, 2022.

[215] R. Abbott et al. All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data. 1 2022.

[216] Andrew L. Miller, Sébastien Clesse, Federico De Lillo, Giacomo Bruno, Antoine Depasse, and Andres Tanasijczuk. Probing planetary-mass primordial black holes with continuous gravitational waves. *Phys. Dark Univ.*, 32:100836, 2021.

[217] Huai-Ke Guo and Andrew Miller. Searching for Mini Extreme Mass Ratio Inspirals with Gravitational-Wave Detectors. 5 2022.

[218] K. Wette, S. Walsh, R. Prix, and M. A. Papa. Implementing a semicoherent search for continuous gravitational waves using optimally constructed template banks. *Phys. Rev. D*, 97:123016, June 2018.

[219] Sinéad Walsh, Karl Wette, Maria Alessandra Papa, and Reinhard Prix. Optimizing the choice of analysis method for all-sky searches for continuous gravitational waves with Einstein@Home. *Phys. Rev. D*, 99:082004, April 2019.

[220] David Keitel. Robust semicoherent searches for continuous gravitational waves with noise and signal models including hours to days long transients. *Phys. Rev. D*, 93:084024, April 2016.

[221] Réjean J. Dupuis and Graham Woan. Bayesian estimation of pulsar parameters from gravitational wave data. *Phys. Rev. D*, 72(10):102002, November 2005.

[222] Continuous Waves Search Group. SFT Data Format Version 2 Specification. Technical Report T040164-v1, LIGO, 2004.

[223] LIGO Scientific Collaboration. LIGO Algorithm Library - LALSuite. Free software (GPL), doi:10.7935/GT1W-FZ16, 2018.

[224] B. P. Abbott et al. Full band all-sky search for periodic gravitational waves in the O1 LIGO data. *Phys. Rev. D*, 97:102003, May 2018.

[225] B. P. Abbott et al. All-sky search for periodic gravitational waves in the O1 LIGO data. *Phys. Rev. D*, 96:062002, September 2017.

[226] B. P. Abbott et al. All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data. *Phys. Rev. D*, 100:024004, July 2019.

[227] Elena Cuoco et al. Enhancing Gravitational-Wave Science with Machine Learning. *Mach. Learn. Sci. Tech.*, 2(1):011002, 2021.

[228] M. Pitkin, C. Messenger, and X. Fan. Hierarchical Bayesian method for detecting continuous gravitational waves from an ensemble of pulsars. *Phys. Rev. D*, 98(6):063001, September 2018.

[229] Luca D'Onofrio, Rosario De Rosa, Luciano Errico, Cristiano Palomba, Valeria Sequino, and Lucia Trozzo. $5n$-vector ensemble method for detecting gravitational waves from known pulsars. *Phys. Rev. D*, 105:063012, Mar 2022.

[230] Joongoo Lee et al. A Deep Learning Model on Gravitational Waveforms in Merging and Ringdown Phases of Binary Black Hole Coalescence. Technical Report LIGO-P1900207, LIGO, 2019.

[231] Paul J. Easter, Paul D. Lasky, Andrew R. Casey, Luciano Rezzolla, and Kentaro Takami. Computing Fast and Reliable Gravitational Waveforms of Binary Neutron Star Merger Remnants. *Phys. Rev. D*, 100(4):043005, 2019.

[232] Daniel George and EA Huerta. Deep neural networks to enable real-time multimessenger astrophysics. *Phys. Rev. D*, 97(4):044039, 2018.

[233] Hunter Gabbard, Michael Williams, Fergus Hayes, and Chris Messenger. Matching matched filtering with deep networks for gravitational-wave astronomy. *Phys. Rev. Lett.*, 120(14):141103, 2018.

[234] Takahiro S. Yamamoto, Andrew L. Miller, Magdalena Sieniawska, and Takahiro Tanaka. Assessing the impact of non-Gaussian noise on convolutional neural networks that search for continuous gravitational waves. *Phys. Rev. D*, 106(2):024025, 2022.

[235] Soummyadip Basak, Aditya Kumar Sharma, Shasvath J. Kapadia, and Parameswaran Ajith. Prospects for the observation of continuous gravitational waves from spinning neutron stars lensed by the galactic supermassive black hole. 4 2022.

[236] C. Messenger, H. J. Bulten, S. G. Crowder, V. Dergachev, D. K. Galloway, E. Goetz, R. J. G. Jonker, P. D. Lasky, G. D. Meadors, A. Melatos, S. Premachandra, K. Riles, L. Sammut, E. H. Thrane, J. T. Whelan, and Y. Zhang. Gravitational waves from Scorpius X-1: A comparison of search methods and prospects for detection with advanced detectors. *Phys. Rev. D*, 92(2):023006, July 2015.

[237] S. Walsh, M. Pitkin, M. Oliver, S. D'Antonio, V. Dergachev, A. Królak, P. Astone, M. Bejger, M. Di Giovanni, O. Dorosh, S. Frasca, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, M. A. Papa, O. J. Piccinni, K. Riles, O. Sauter, and A. M. Sintes. Comparison of methods for the detection of gravitational waves from unknown neutron stars. *Phys. Rev. D*, 94(12):124010, December 2016.

[238] E. W. Kolb & M. S. Turner. *The Early Universe*. Westview Press, 1994.

[239] A. A. Starobinskii. Spectrum of relic gravitational radiation and the early state of the universe. *JETP Lett.*, 30, 1979.

[240] R. Bar-Kana. Limits on Direct Detection of Gravitational Waves. *Phys. Rev. D*, 50, 1994.

[241] T. W. B. Kibble. Topology of cosmic domains and strings. *J. Phys. A*, 9, 1976.

[242] T. Damour & A. Vilenkin. Gravitational radiation from cosmic (super)strings: bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71, 2005.

[243] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[244] S. Olmez, V. Mandic, and X. Siemens. Anisotropies in the Gravitational-Wave Stochastic Background. *J. Cosmol. Astropart. Phys.*, 2012:009, 2011.

[245] Benjamin P. Abbott et al. GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences. *Phys. Rev. Lett.*, 120(9):091101, 2018.

[246] B. P. Abbott et al. Gw150914: Implications for the stochastic gravitational-wave background from binary black holes. *Phys. Rev. Lett.*, 116:131102, March 2016.

[247] B. P. Abbott et al. Search for the isotropic stochastic background using data from Advanced LIGO's second observing run. *Phys. Rev. D*, 100:061101(R), 2019.

[248] C. Brans and R.H. Dicke. Mach's principle and a relativistic theory of gravitation. *Phys. Rev.*, 124:925–935, 1961.

[249] Y. Fujii and K. Maeda. *The Scalar-Tensor Theory of Gravitation*. Cambridge Monograph on Mathematical Physics. Cambridge University Press, Cambridge, 2002.

[250] Thomas P. Sotiriou and Valerio Faraoni. f(R) Theories Of Gravity. *Rev. Mod. Phys.*, 82:451–497, 2010.

[251] Antonio De Felice and Shinji Tsujikawa. f(R) Theories. *Living Rev. Relativity*, 13(3), 2010.

[252] Matt Visser. Mass for the graviton. *General Relativity and Gravitation*, 30(12):1717–1728, 1998.

[253] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley. Resummation of massive gravity. *Phys. Rev. Lett.*, 106:231101, June 2011.

[254] Bruce Allen and Joseph D. Romano. Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys. Rev. D*, 59:102001, 1999.

[255] N Christensen. Measuring the Stochastic Gravitational Radiation Background with Laser Interferometric Antennas. *Phys. Rev. D*, 46:5250, 1992.

[256] B Abbott et al. Searching for a Stochastic Background of Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory. *Astrophys. J.*, 659:918, 2007.

[257] J. Abadie et al. Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz. *Phys. Rev. D*, 85:122001, 2012.

[258] B. Abbott et al. Searching for Stochastic Gravitational Waves with LIGO. *Nature*, 460:990, 2009.

[259] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009-2010 LIGO and Virgo Data. *Phys. Rev. Lett.*, 113:231101, 2014.

[260] J. Aasi et al. Searching for stochastic gravitational waves using data from the two colocated LIGO Hanford detectors. *Phys. Rev. D*, 91:022003, 2015.

[261] Benjamin P. Abbott et al. Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 118(12):121101, 2017.

[262] C. Wu, V. Mandic, and T. Regimbau. Accessibility of the gravitational-wave background due to binary coalescences to second and third generation gravitational-wave detectors. *Phys. Rev. D*, 85:104024, 2012.

[263] V Mandic, E Thrane, S Giampanis, and T Regimbau. Parameter Estimation in Searches for the Stochastic Gravitational-Wave Background. *Phys. Rev. Lett.*, 109:171102, 2012.

[264] Abhishek Parida, Sanjit Mitra, and Sanjay Jhingan. Component Separation of a Isotropic Gravitational Wave Background. *JCAP*, 1604(04):024, 2016.

[265] D. Talukder, E. Thrane, S. Bose, and T. Regimbau. Measuring neutron-star ellipticity with measurements of the stochastic gravitational-wave background. *Phys. Rev. D*, 89(12):123008, June 2014.

[266] G. Cusin, C. Pitrou, and J.-P. Uzan. Anisotropy of the astrophysical gravitational wave background i: analytic expression of the angular power spectrum and correlation with cosmological observations. *Phys. Rev. D*, 96:103019, 2017.

[267] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. First Predictions of the Angular Power Spectrum of the Astrophysical Gravitational Wave Background. *Phys. Rev. Lett.*, 120(23):231101, June 2018.

[268] Alexander C. Jenkins and Mairi Sakellariadou. Anisotropies in the stochastic gravitational-wave background: Formalism and the cosmic string case. *Phys. Rev. D*, 98(6):063509, September 2018.

[269] Alexander C. Jenkins, Mairi Sakellariadou, Tania Regimbau, and Eric Slezak. Anisotropies in the astrophysical gravitational-wave background: Predictions for the detection of compact binaries by LIGO and Virgo. *Phys. Rev. D*, 98(6):063501, 2018.

[270] Alexander C. Jenkins, Richard O'Shaughnessy, Mairi Sakellariadou, and Daniel Wysocki. Anisotropies in the astrophysical gravitational-wave background: The impact of black hole distributions. *Phys. Rev. Lett.*, 122(11):111101, 2019.

[271] T Regimbau & B Chauvineaux. A stochastic background from extra-galactic double neutron stars. *Class. Quantum Grav.*, 24:627, 2007.

[272] A. J. Farmer & E. S. Phinney. The gravitational wave background from cosmological compact binaries. *Mon. Not. R. Ast. Soc.*, 346:1197, 2003.

[273] E Howell et al. The gravitational wave background from neutron star birth throughout the cosmos. *Mon. Not. R. Ast. Soc.*, 351:1237, 2004.

[274] V Ferrari & S Matarrese & R Schneider. Gravitational wave background from a cosmological population of core-collapse supernovae. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[275] V Ferrari & S Matarrese & R Schneider. Stochastic background of gravitational waves generated by a cosmological population of young, rapidly rotating neutron stars. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[276] G Sigl. Cosmological gravitational wave background from phase transitions in neutron stars. *J. Cosmol. Astropart. Phys.*, JCAP04:002, 2006.

[277] T Regimbau & J A de Freitas Pacheco. Cosmic background of gravitational waves from rotating neutron stars. *Astron. Astrophys.*, 376:381, 2001.

[278] T Regimbau & J A de Freitas Pacheco. Gravitational wave background from magnetars. *Astron. Astrophys.*, 447:1, 2006.

[279] L Barack & C Cutler. Confusion noise from LISA capture sources. *Phys. Rev. D*, 70:122002, 2004.

[280] G Sigl & J Schnittman & A Buonanno. Gravitational-wave background from compact objects embedded in AGN accretion disks. *Phys. Rev. D*, 75:024034, 2007.

[281] Francesca Calore, Tania Regimbau, and Pasquale Dario Serpico. Probing the Fermi-LAT GeV Excess with Gravitational Waves. *Phys. Rev. Lett.*, 122(8):081103, March 2019.

[282] B Abbott et al. Directional limits on persistent gravitational waves using LIGO S5 science data. *Phys. Rev. Lett.*, 107:271102, 2011.

[283] E Thrane, S Ballmer, J D Romano, S Mitra, D Talukder, S Bose, and V Mandic. Probing the anisotropies of a stochastic gravitational-wave background using a network of ground-based laser interferometers. *Phys. Rev. D*, 80:122002, 2009.

[284] B. P. Abbott et al. Directional Limits on Persistent Gravitational Waves from Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 118(12):121102, March 2017.

[285] E Thrane, S Mitra, N Christensen, V Mandic, and A Ain. All-sky, narrowband, gravitational-wave radiometry with folded data. *Accepted in Phys. Rev. D*, 2015.

[286] A. Ain, P. Dalvi, and S. Mitra. Fast gravitational wave radiometry using data folding. *Phys. Rev. D*, 92(2):022003, July 2015.

[287] Alexander C. Jenkins and Mairi Sakellariadou. Shot noise in the astrophysical gravitational-wave background. *arXiv*, 1902.07719, 2019.

[288] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. Stochastic gravitational wave background anisotropies: astrophysical dependencies in the LIGO/Virgo and LISA bands. *arXiv*, 1904.07757, 2019.

[289] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. Properties of the stochastic astrophysical gravitational wave background: Astrophysical sources dependencies. *Phys. Rev. D*, 100(6):063004, September 2019.

[290] Alexander C. Jenkins, Joseph D. Romano, and Mairi Sakellariadou. Estimating the angular power spectrum of the gravitational-wave background in the presence of shot noise. *arXiv*, 1907.06642, 2019.

[291] Deepali Agarwal, Jishnu Suresh, Vuk Mandic, Andrew Matas, and Tania Regimbau. Targeted search for the stochastic gravitational-wave background from the galactic millisecond pulsar population. *Phys. Rev. D*, 106:043019, Aug 2022.

[292] Leo Tsukada, Santiago Jaraba, Deepali Agarwal, and Erik Floden. Bayesian parameter estimation for targeted anisotropic gravitational-wave background. *arXiv:2208.14421*, 2022.

[293] R Prix, S Giampanis, and C Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[294] D I Jones and N Andersson. Gravitational waves from freely precessing neutron stars. *Mon. Not. R. Ast. Soc.*, 331:203, 2002.

[295] L. Gualtieri, R. Ciolfi, and V. Ferrari. Structure, deformations and gravitational wave emission of magnetars. *Classical and Quantum Gravity*, 28(11):114014, June 2011.

[296] A Arvanitaki, M Baryakhtar, and X Huang. Discovering the qcd axion with black holes and gravitational waves. *Phys. Rev. D*, 91:084011, 2015.

[297] E Thrane, S Kandhasamy, C D Ott, et al. Long gravitational-wave transients and associated detection strategies for a network of terrestrial interferometers. *Phys. Rev. D*, 83:083004, 2011.

[298] T. Prestegard, E. Thrane, et al. Identification of noise artifacts in searches for long-duration gravitational-wave transients. *Class. Quantum Grav.*, 29:095018, 2012.

[299] J Aasi et al. Search for long-lived gravitational-wave transients coincident with long gamma-ray bursts. *Phys. Rev. D*, 88:122004, 2013.

[300] E Thrane and M Coughlin. Searching for gravitational-wave transients with a qualitative signal model: seedless clustering strategies. *Phys. Rev. D*, 88:083010, 2013.

[301] E. Thrane and M. Coughlin. Seedless clustering in all-sky searches for gravitational-wave transients. *Phys. Rev. D*, 89:063012, 2014.

[302] T. Prestegard and E. Thrane. Burstegard: a hierarchical clustering algorithm, 2012. Technical report LIGO-L1200204, `https://dcc.ligo.org/LIGO-L1200204/public`.

[303] M. Coughlin, E. Thrane, and N. Christensen. Detecting compact binary coalescences with seedless clustering. *Phys. Rev. D*, 90(8):083005, 2014.

[304] E Thrane, V Mandic, and N Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91:104021, 2015.

[305] P. Meyers, M. W. Coughlin, and J. Luo. Investigating Environmental Noise Using the Stochastic Transient Analysis Multi-Detector Pipeline (STAMP-PEM), 2014.
Technical report LIGO-G1400354, `https://dcc.ligo.org/LIGO-G1400354`.

[306] M. Coughlin for the LIGO Scientific Collaboration and the Virgo Collaboration. Identification of long-duration noise transients in LIGO and Virgo. *Class. Quantum Grav.*, 28:235008, 2011.

[307] E. Nakar. Short-hard gamma-ray bursts. *Physics Reports*, 442:166–236, April 2007.

[308] S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev. Exploding Neutron Stars in Close Binaries. *Soviet Astronomy Letters*, 10:177–179, April 1984.

[309] Bohdan Paczynski. Gamma-ray bursters at cosmological distances. *Astrophys. J. Lett.*, 308:L43–L46, 1986.

[310] D Eichler, M Livio, T Piran, and D Schramm. *Nature*, 340:126, 1989.

[311] Bohdan Paczynski. Cosmological gamma-ray bursts. *Acta Astron.*, 41:257–267, 1991.

[312] R Narayan, Paczynski, and T Piran. *Astroph. J.*, 395:L83, 1992.

[313] A. R. Williamson, C. Biwer, S. Fairhurst, I. W. Harry, E. Macdonald, D. Macleod, and V. Predoi. Improved methods for detecting gravitational waves associated with short gamma-ray bursts. *Phys. Rev. D*, 90(12):122004, 2014.

[314] Patrick J. Sutton, Gareth Jones, Shourov Chatterji, Peter Michael Kalmus, Isabel Leonor, et al. X-Pipeline: An Analysis package for autonomous gravitational-wave burst searches. *New J. Phys.*, 12:053034, 2010.

[315] Alex L. Urban. *Monsters in the Dark: High Energy Signatures of Black Hole Formation with Multi-messenger Astronomy*. Ph.D. dissertation, University of Wisconsin-Milwaukee, May 2016.

[316] B. P. Abbott et al. Search for Gravitational Waves Associated with Gamma-Ray Bursts During the First Advanced LIGO Observing Run and Implications for the Origin of GRB 150906B. *Astrophys. J.*, 841(2):89, 2017.

[317] B. P. Abbott, B. P. and others. Search for Gravitational-wave Signals Associated with Gamma-Ray Bursts during the Second Observing Run of Advanced LIGO and Advanced Virgo. *The Astrophysical Journal*, 886(1):75, November 2019.

[318] R. Abbott et al. Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift During the LIGO-Virgo Run O3a. *Astrophys. J.*, 915(2):86, 2021.

[319] R. Abbott et al. Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift during the LIGO–Virgo Run O3b. *Astrophys. J.*, 928(2):186, 2022.

[320] R. Abbott et al. First joint observation by the underground gravitational-wave detector KAGRA with GEO 600. *PTEP*, 2022(6):063F01, 2022.

[321] E. Burns et al. A Fermi Gamma-ray Burst Monitor Search for Electromagnetic Signals Coincident with Gravitational-Wave Candidates in Advanced LIGO's First Observing Run. *Astrophys. J.*, 871(1):90, 2019.

[322] D. Thornton, B. Stappers, M. Bailes, B. Barsdell, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, D. J. Champion, P. Coster, N. D'Amico, A. Jameson, S. Johnston, M. Keith, M. Kramer, L. Levin, S. Milia, C. Ng, A. Possenti, and W. van Straten. A Population of Fast Radio Bursts at Cosmological Distances. *Science*, 341:53–56, July 2013.

[323] E. Petroff, E. D. Barr, A. Jameson, E. F. Keane, M. Bailes, M. Kramer, V. Morello, D. Tabbara, and W. van Straten. FRBCAT: The Fast Radio Burst Catalogue. *Pub. Astron. Soc. Aust.*, 33:e045, September 2016.

[324] L. G. Spitler, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, M. A. McLaughlin, S. Chatterjee, F. Crawford, J. S. Deneva, V. M. Kaspi, R. S. Wharton, B. Allen, S. Bogdanov, A. Brazier, F. Camilo, P. C. C. Freire, F. A. Jenet, C. Karako-Argaman, B. Knispel, P. Lazarus, K. J. Lee, J. van Leeuwen, R. Lynch, A. G. Lyne, S. M. Ransom, P. Scholz, X. Siemens, I. H. Stairs, K. Stovall, J. K. Swiggum, A. Venkataraman, W. W. Zhu, C. Aulbert, and H. Fehrmann. Fast Radio Burst Discovered in the Arecibo Pulsar ALFA Survey. *The Astrophysical Journal*, 790(2):101, 2014.

[325] CHIME/FRB collaboration. The CHIME Fast Radio Burst Project: System Overview. *The Astrophysical Journal*, 863(48), 2018.

[326] R. Abbott et al. Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO–Virgo Observing Run O3a. 3 2022.

[327] B. P. Abbott et al. Search for transient gravitational waves in coincidence with short-duration radio transients during 2007–2013. *Phys. Rev. D*, 93:122008, June 2016.

[328] B.C. Andersen et al. A bright millisecond-duration radio burst from a Galactic magnetar. *arXiv:2005.10324*, 2020.

[329] S. Ando, B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, A. Dietz, C. Donzaud, D. Eichler, C. Finley, D. Guetta, F. Halzen, G. Jones, S. Kandhasamy, K. Kotake, A. Kouchner, V. Mandic, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Piran, T. Pradier, G. E. Romero, P. Sutton, E. Thrane, V. Van Elewyck, and E. Waxman. Colloquium: Multimessenger astronomy with gravitational waves and high-energy neutrinos. *Reviews of Modern Physics*, 85:1401–1420, October 2013.

[330] I. Bartos, P. Brady, and S. Márka. How gravitational-wave observations can shape the gamma-ray burst paradigm. *Classical and Quantum Gravity*, 30(12):123001, June 2013.

[331] B. Baret et al. Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts. *Astroparticle Physics*, 35:1–7, August 2011.

[332] I. Bartos, B. Dasgupta, and S. Márka. Probing the structure of jet-driven core-collapse supernova and long gamma-ray burst progenitors with high-energy neutrinos. *Phys. Rev. D*, 86(8):083007, October 2012.

[333] I. Bartos, A. M. Beloborodov, K. Hurley, and S. Márka. Detection Prospects for GeV Neutrinos from Collisionally Heated Gamma-ray Bursts with IceCube/DeepCore. *Physical Review Letters*, 110(24):241101, June 2013.

[334] K. Murase, K. Kashiyama, K. Kiuchi, and I. Bartos. Gammy-Ray and Hard X-Ray Emission from Pulsar-aided Supernovae as a Probe of Particle Acceleration in Embryonic Pulsar Wind Nebulae. *Astrophys. J.*, 805:82, May 2015.

[335] B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, C. Donzaud, M. Drago, C. Finley, G. Jones, S. Klimenko, A. Kouchner, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Pradier, G. Prodi, P. Raffai, V. Re, J. Rollins, F. Salemi, P. Sutton, M. Tse, V. Van Elewyck, and G. Vedovato. Multimessenger science reach and analysis method for common sources of gravitational waves and high-energy neutrinos. *Phys. Rev. D*, 85(10):103004, May 2012.

[336] M. W. E. Smith, D. B. Fox, D. F. Cowen, P. Mészáros, G. Tešić, J. Fixelle, I. Bartos, P. Sommers, A. Ashtekar, G. Jogesh Babu, S. D. Barthelmy, S. Coutu, T. DeYoung, A. D. Falcone, S. Gao, B. Hashemi, A. Homeier, S. Márka, B. J. Owen, and I. Taboada. The Astrophysical Multimessenger Observatory Network (AMON). *Astroparticle Physics*, 45:56–70, May 2013.

[337] Shigeo S. Kimura, Kohta Murase, Imre Bartos, Kunihito Ioka, Ik Siong Heng, and Peter Mészáros. Transejecta high-energy neutrino emission from binary neutron star mergers. *Phys. Rev. D*, 98(4):043020, Aug 2018.

[338] S. Adrián-Martínez, A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, J.-J. Aubert, T. Avgitas, B. Baret, J. Barrios-Martí, et al. High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube. *Phys. Rev. D*, 93(12):122010, June 2016.

[339] A. Albert et al. Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube. *Phys. Rev. D*, 96(2):022005, July 2017.

[340] A. Albert, M. André, M. Anghinolfi, M. Ardid, J.-J. Aubert, J. Aublin, T. Avgitas, B. Baret, J. Barrios-Martí, S. Basa, and et al. Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory. *Astrophys. J. Lett.*, 850:L35, December 2017.

[341] S. Adrián-Martínez et al. A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007. *Journal of Cosmology and Astroparticle Physics*, 2013(06):008, 2013.

[342] M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D. Altmann, T. Anderson, C. Arguelles, T. C. Arlen, and et al. Multimessenger search for sources of gravitational waves and high-energy neutrinos: Initial results for LIGO-Virgo and IceCube. *Phys. Rev. D*, 90(10):102002, November 2014.

[343] A. Albert et al. Search for multimessenger sources of gravitational waves and high-energy neutrinos with advanced LIGO during its first observing run, ANTARES, and IceCube. *The Astrophysical Journal*, 870(2):134, jan 2019.

[344] Imre Bartos, Doğa Veske, Azadeh Keivani, Zsuzsa Márka, Stefan Countryman, Erik Blaufuss, Chad Finley, and Szabolcs Márka. Bayesian multimessenger search method for common sources of gravitational waves and high-energy neutrinos. *Phys. Rev. D*, 100(8):083017, October 2019.

[345] Doğa Veske, Zsuzsa Márka, Imre Bartos, and Szabolcs Márka. How to Search for Multiple Messengers—A General Framework Beyond Two Messengers. *Astrophys. J.*, 908(2):216, February 2021.

[346] Stefan Countryman, Azadeh Keivani, Imre Bartos, Zsuzsa Marka, Thomas Kintscher, Rainer Corley, Erik Blaufuss, Chad Finley, and Szabolcs Marka. Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) with Gravitational-Wave and High-Energy Neutrino Candidates. *arXiv e-prints*, page arXiv:1901.05486, January 2019.

[347] A. Vilenkin and E. Shellard. *Cosmic strings and other Topological Defects*. Cambridge University Press, 2000.

[348] T. W. B. Kibble. Topology of Cosmic Domains and Strings. *J. Phys. A*, 9:1387–1398, 1976.

[349] Rachel Jeannerot, Jonathan Rocher, and Mairi Sakellariadou. How generic is cosmic string formation in SUSY GUTs. *Phys. Rev. D*, 68:103514, 2003.

[350] Andrei D. Linde. Hybrid inflation. *Phys. Rev. D*, 49:748–754, 1994.

[351] Edmund J. Copeland, Andrew R. Liddle, David H. Lyth, Ewan D. Stewart, and David Wands. False vacuum inflation with Einstein gravity. *Phys. Rev. D*, 49:6410–6433, 1994.

[352] G.R. Dvali, Q. Shafi, and Robert K. Schaefer. Large scale structure and supersymmetric inflation without fine tuning. *Phys. Rev. Lett.*, 73:1886–1889, 1994.

[353] Saswat Sarangi and S.H. Henry Tye. Cosmic string production towards the end of brane inflation. *Phys. Lett. B*, 536:185–192, 2002.

[354] Edward Witten. Cosmic superstrings. *Physics Letters B*, 153:243 – 246, 1985.

[355] Edmund J. Copeland, Levon Pogosian, and Tanmay Vachaspati. Seeking String Theory in the Cosmos. *Class. Quant. Grav.*, 28:204009, 2011.

[356] Thibault Damour and Alexander Vilenkin. Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71:063510, 2005.

[357] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[358] M. Sakellariadou. Gravitational waves emitted from infinite strings. *Phys. Rev. D*, 42:354–360, 1990. [Erratum: Phys.Rev.D 43, 4150 (1991)].

[359] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cosmic strings. *Phys. Rev. Lett.*, 85:3761–3764, 2000.

[360] Christophe Ringeval and Teruaki Suyama. Stochastic gravitational waves from cosmic string loops in scaling. *JCAP*, 12:027, 2017.

[361] J. Aasi, J. Abadie, B.P. Abbott, R. Abbott, T. Abbott, et al. Constraints on cosmic strings from the LIGO-Virgo gravitational-wave detectors. *Phys. Rev. Lett.*, 112:131101, 2014.

[362] Pierre Auclair, Christophe Ringeval, Mairi Sakellariadou, and Daniele Steer. Cosmic string loop production functions. *JCAP*, 06:015, 2019.

[363] Rory Smith and Eric Thrane. The optimal search for an astrophysical gravitational-wave background. *Phys. Rev. X*, 8(2):021019, 2018.

[364] Gregory Ashton, Moritz Hübner, Paul D. Lasky, Colm Talbot, Kendall Ackley, Sylvia Biscoveanu, Qi Chu, Atul Divakarla, Paul J. Easter, Boris Goncharov, Francisco Hernandez Vivanco, Jan Harms, Marcus E. Lower, Grant D. Meadors, Denyz Melchor, Ethan Payne, Matthew D. Pitkin, Jade Powell, Nikhil Sarin, Rory J. E. Smith, and Eric Thrane. Bilby: A user-friendly bayesian inference library for gravitational-wave astronomy. *The Astrophysical Journal Supplement Series*, 241(2):27, April 2019.

[365] Rory J E Smith, Colm Talbot, Francisco Hernandez Vivanco, and Eric Thrane. Inferring the population properties of binary black holes from unresolved gravitational waves. *Monthly Notices of the Royal Astronomical Society*, 496(3):3281–3290, 06 2020.

[366] S. M Gaebel, J. Veitch, T. Dent, and W. M. Farr. Digging the population of compact binary mergers out of the noise. *Monthly Notices of the Royal Astronomical Society*, 484(3):4008–4023, January 2019.

[367] C. Talbot and E. Thrane. Gravitational-wave astronomy with an uncertain noise power spectral density. *arXiv:2006.05292*, 2020.

[368] D Davis et al. LIGO detector characterization in the second and third observing runs. *Classical and Quantum Gravity*, 38(13):135014, June 2021.

[369] F. Acernese and et al. Virgo detector characterization and data quality: results from the o3 run, 2022.

[370] Irene Fiori, Federico Paoletti, Maria Concetta Tringali, Kamiel Janssens, Christos Karathanasis, Alexis Menéndez-Vázquez, Alba Romero-Rodríguez, Ryosuke Sugimoto, Tatsuki Washimi, Valerio Boschi, Antonino Chiummo, Marek Cieślar, Rosario De Rosa, Camilla De Rossi, Francesco Di Renzo, Ilaria Nardecchia, Antonio Pasqualetti, Barbara Patricelli, Paolo Ruggi, and Neha Singh. The hunt for environmental noise in Virgo during the third observing run. *Galaxies*, 8(4), 2020.

[371] E Thrane, N Christensen, and R Schofield. Correlated magnetic noise in global networks of gravitational-wave interferometers: observations and implications. *Phys. Rev. D*, 87:123009, 2013.

[372] E. Thrane, N. Christensen, R. M. S. Schofield, and A. Effler. Correlated noise in networks of gravitational-wave detectors: subtraction and mitigation. *Phys. Rev. D*, 90(2):023013, 2014.

[373] Michael W. Coughlin et al. Measurement and subtraction of schumann resonances at gravitational-wave interferometers. *Phys. Rev. D*, 97:102007, May 2018.

[374] Michael W. Coughlin et al. Subtraction of correlated noise in global networks of gravitational-wave interferometers. *Class. Quant. Grav.*, 33(22):224003, 2016.

[375] Kamiel Janssens et al. Correlated 1-1000 Hz magnetic field fluctuations from lightning over earth-scale distances and their impact on gravitational wave searches. 9 2022.

[376] Patrick M. Meyers, Katarina Martinovic, Nelson Christensen, and Mairi Sakellariadou. Detecting a stochastic gravitational-wave background in the presence of correlated magnetic noise. *Phys. Rev. D*, 102:102005, November 2020.

[377] Anirban Ain, Jishnu Suresh, and Sanjit Mitra. Very fast stochastic gravitational wave background map-making using folded data: PyStoch. *arXiv*, 1803.08285, 2018.

[378] Yevgeny Stadnik and Victor Flambaum. Searching for Dark Matter and Variation of Fundamental Constants with Laser and Maser Interferometry. *Physical Review Letters*, 114:161301, 2015.

[379] Yevgeny Stadnik and Victor Flambaum. Can Dark Matter Induce Cosmological Evolution of the Fundamental Constants of Nature? *Physical Review Letters*, 115:201301, 2015.

[380] Yevgeny Stadnik and Victor Flambaum. Enhanced effects of variation of the fundamental constants in laser interferometers and application to dark-matter detection. *Physical Review A*, 93:063630, 2016.

[381] Hartmut Grote and YV Stadnik. Novel signatures of dark matter in laser-interferometric gravitational-wave detectors. *Physical Review Research*, 1(3):033187, 2019.

[382] Evan Hall and Nancy Aggarwal. Advanced LIGO, LISA, and Cosmic Explorer as dark matter transducers. 10 2022.

[383] Koji Nagano, Tomohiro Fujita, Yuta Michimura, and Ippei Obata. Axion Dark Matter Search with Interferometric Gravitational Wave Detectors. *Phys. Rev. Lett.*, 123(11):111301, 2019.

[384] Ann E Nelson and Jakub Scholtz. Dark light, dark matter, and the misalignment mechanism. *Physical Review D*, 84(10):103501, 2011.

[385] Andrew J Long and Lian-Tao Wang. Dark photon dark matter from a network of cosmic strings. *Physical Review D*, 99(6):063529, 2019.

[386] Aaron Pierce, Keith Riles, and Yue Zhao. Searching for Dark Photon Dark Matter with Gravitational Wave Detectors. *Phys. Rev. Lett.*, 121(6):061102, 2018.

[387] Soichiro Morisaki, Tomohiro Fujita, Yuta Michimura, Hiromasa Nakatsuka, and Ippei Obata. Improved sensitivity of interferometric gravitational wave detectors to ultralight vector dark matter from the finite light-traveling time. *Phys. Rev. D*, 103(5):L051702, 2021.

[388] Luca Marzola, Martti Raidal, and Federico R. Urban. Oscillating Spin-2 Dark Matter. *Phys. Rev. D*, 97(2):024010, 2018.

[389] Katsuki Aoki and Kei-ichi Maeda. Condensate of Massive Graviton and Dark Matter. *Phys. Rev. D*, 97(4):044002, 2018.

[390] Juan Manuel Armaleo, Diana López Nacir, and Federico R. Urban. Searching for spin-2 ULDM with gravitational waves interferometers. *JCAP*, 04:053, 2021.

[391] Huai-Ke Guo, Keith Riles, Feng-Wei Yang, and Yue Zhao. Searching for dark photon dark matter in LIGO O1 data. *Communications Physics*, 2(1):155, December 2019.

[392] Andrew L. Miller et al. Probing new light gauge bosons with gravitational-wave interferometers using an adapted semi-coherent method. *Phys. Rev. D*, 103(10):103002, 2021.

[393] R. Abbott et al. Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run. *arXiv e-prints*, page arXiv:2105.13085, May 2021.

[394] Sander M Vermeulen et al. Direct limits for scalar field dark matter from a gravitational-wave detector. *Nature*, 600(7889):424–428, 2021.

[395] Andrew L. Miller, Francesca Badaracco, and Cristiano Palomba. Distinguishing between dark-matter interactions with gravitational-wave detectors. *Phys. Rev. D*, 105(10):103035, 2022.

[396] Hiromasa Nakatsuka, Soichiro Morisaki, Tomohiro Fujita, Jun'ya Kume, Yuta Michimura, Koji Nagano, and Ippei Obata. Stochastic effects on observation of ultralight bosonic dark matter. 5 2022.