LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION
KAGRA COLLABORATION

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The LSC-Virgo-KAGRA Observational Science White Paper (Summer 2021 edition)

The LSC-Virgo-KAGRA Observational Science Working Groups

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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 Program 2020-2021:

- Section 2, *Scientific Operations and Scientific Results* (prefix "Op-"), 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 the second half of 2022, and to carry out analyses of the O4 data.
- 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 and Virgo activities in the domains of Commissioning, Calibration, Computing, Detector Characterization, LSC Fellows program, and Run Planning can be found in the *LSC-Virgo Operations White Paper* (LIGO-T2100304, VIR-0790A-21, JGW-T2113065).

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 completed roughly half of the planned analyses from the O3 run and are expecting to complete most or all of the remaining ones before the end of 2021. Working group members will then focus on preparing for O4 data analysis until the O4 run begins, currently expected to be no earlier than June 2022.

			Typical Binary Neutron Star (BNS) Range (Mpc)			$E_{\mathrm{GW}} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		
Epoch	Run Name	Run Duration	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
2021–23	O4	12 months	160–190	90–120	25–130	110–120	65–80	projected
2024–26	O5	TBD	330	150–260	130+	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.

Scientific Operations and Observational Results

LSC-Virgo 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 and Virgo.
- **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	CW	SGWB
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
	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 all-frequency search for unmodeled persistent sources
	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, 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	Search for very long transients ($\sim$ 10 hr – days)
	Search for BNS post-merger signals	Search for sub-solar mass compact binary coalescences	Targeted searches for CW signals with non-tensor polarizations	Data folding for efficient SGWB searches
	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 binary black hole mergers with features well-suited to unmodeled searches.	Improved waveform models for signals expected during the O4 run	Long-transient searches for emission from distant post-merger neutron stars	
Additional priority		Multimessenger searches for binary mergers associated with fast radio bursts and high energy neutrinos	Searches for long-lived transient emission following a known pulsar glitch	Analysis to separate components of a stochastic GW backgroun
		Optimized search for stochastic background of gravitational waves from CBCs	Continuous emission from ultra-light boson clouds around black holes; direct detection of dark photon dark matter	Searching for SGWB-EM sky correlations

Table 2: **Scientific Operations and Observational Results** priorities of the LIGO Scientific Collaboration and Virgo Collaboration, 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 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	CW	SGWB
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 and Virgo Collaboration, 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 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 Op-2.1]

    - **All-sky long duration search:** The burst group will search for a broad class of long-duration transients. Deliverables include papers describing the search results. [Section Op-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 Op-2.5, Op-6.2, Op-6.4, Op-6.6]

    - **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 Op-2.3, Op-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 Op-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 Op-2.5, Op-6.2, Op-6.4, Op-6.6, Op-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 Op-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 Op-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 Op-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 latter event was observed nearly simultaneously in gamma-rays, and, within a day, an optical counterpart was discovered; this was followed by observations across the entire electromagnetic spectrum.

An O3a catalog reporting significant events discovered during the first half of O3 along with several companion papers are completed and are not included in this white paper. We are preparing for the next major update to the catalog, which will contain significant events detected during the second half of O3 (O3b). We are preparing to do 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 a neutron star and a black hole. During O4, we anticipate several detections of compact binary coalescences, and, 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.

     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 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. (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.

3. **Additional priority**

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

   - **Multimessenger search for gravitational waves associated with fast radio bursts and high-energy neutrinos**.
     It is possible that fast radio bursts and high-energy neutrinos 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 or high-energy neutrinos. Though the methods are similar, the time window to be explored will need to be reassessed.

- **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. The 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 gravitational wave and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives (also known as *spindowns*) and distances, energy conservation sets an upper limit on gravitational wave 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 continuous wave 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 gravitational wave 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. Mock data challenges are carried out to rigorously compare the performance of data analysis pipelines targeting a particular source category.

The primary gravitational wave source categories targeted 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 forego a small part of the sensitivity and, relaxing the strict assumption of phase coherence between the gravitational wave 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 gravitational wave frequency, and potentially higher-order spindowns; and, if the target astrophysical source has a binary companion, parameters of the binary orbit where unknown. 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 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 pulsars 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 prior astrophysical parameters, 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 severe enough to preclude all-sky searches using fully-coherent matched filtering over the typical year-long time spans of observational runs. The use of semi-coherent methods – which partition the data set into shorter segments, perform matched filtering on each segment individually, then incoherently combine filters from each segment – makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Finally, in order 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 gravitational waves from several other sources. Searches for *long-lived transients*, in collaboration with the Burst and Stochastic working groups (Section Op-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 continuous wave signals. A direct detection of *dark photon dark matter* in interferometric gravitational wave detectors is being pursued in collaboration with the Stochastic working group (Section Op-10.2).

1.3.1 Scientific Operations and O3/O4 Observational Results

The input data to any continuous gravitational wave 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 $h(t)$ 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 observational 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 O3 and O4 observing runs, 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 produced 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.

1. **Highest priority**
   - Targeted searches (Section Op-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 Op-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 Op-4.4) and Scorpius X-1 (Section Op-4.5).
   - All-sky searches for undiscovered sources, either isolated (Section Op-4.7) or in binary systems (Section Op-4.8).
   - Long-transient searches for emission from post-merger neutron stars (Section Op-4.9) where the estimated distance is similar to or closer than GW170817.

- Follow-up searches of any promising continuous wave candidates found by other searches (Section Op-4.12).
- Support CW searches through detector characterization (see the Operations White Paper), data preparation (Section Op-4.13), and scientific software maintenance (Section Op-4.14).

2. **High priority**
    - Targeted searches (Section Op-4.1) for known pulsars for which the spindown limit is unlikely to be surpassed. [1]
    - Targeted searches for known pulsars sensitive to non-tensor polarizations (Section Op-4.3).
    - Directed searches for other point sources of interest, including but not limited to: galactic supernova remnants (Section Op-4.4), sources in low-mass X-ray binaries (Section Op-4.5), sources near the Galactic center (Section Op-4.6), and sources in nearby globular clusters.
    - Long-transient searches for emission from post-merger neutron stars (Section Op-4.9) at estimated distances larger than GW170817.
3. **Additional priority**
    - Searches for long-lived transient emission following a pulsar glitch (Section Op-4.10).
    - Searches for continuous emission from ultra-light boson clouds around black holes (Section Op-4.11).
    - Searches for a direct detection of dark photon dark matter, in collaboration with the Stochastic working group (Section Op-10.2).

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

The search for continuous gravitational waves sources 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 of the theoretically-optimal method (e.g. matched filtering) is severely limited by finite computational resources. Sub-optimal but computationally-cheaper algorithms must therefore 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 detection of continuous waves. Furthermore, many sources may exhibit behaviors which deviate from the usual continuous wave signal model, e.g. spin wandering in low-mass X-ray binaries, 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 source target; 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-4.15).
    - Development of model-robust/agnostic data analysis methods (Section LT-4.16).
2. **Exploratory**

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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.

- Development of new and potentially more sensitive data analysis methods (Section LT-4.17).
- Use mock data challenges to compare data analysis pipelines (Section LT-4.18).

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 both the radiometer and spherical harmonic decomposition methods to generate sky maps for both point sources and extended sources of an anisotropic gravitational-wave background; 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; constrain relevant astrophysical and cosmological models of anisotropic backgrounds.

- **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.

- **All-sky all-frequency search for unmodeled persistent sources.** Implement an all-sky, all-frequency extension of the narrow-band radiometer search that can look for unmodeled persistent GW point sources not conforming to the assumptions made by standard template-based searches.

- **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**

    - **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.

    - **Folded data set.** Fold the O4 data to a single sidereal day to speed up analyses by a factor of ~ 100. This will facilitate the application of more computationally-expensive stochastic searches like the all-sky all-frequency radiometer and searches for parameterized anisotropy.

3. **Additional priority**

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

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

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

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.

2. **Exploratory**

- **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.

- **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; use the measured SGWB anisotropies to constrain such models; and search for parametrized models of anisotropic 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.

Op-2.1 Search for short-duration GW bursts

All-sky searches for short-lived 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]. 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 [3], oLIB [4] and BayesWave [5]). 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 Op-2.1-A: LOW-LATENCY SEARCHES FOR PUBLIC ALERTS

TASK Op-2.1-A(i): cWB ONLINE PIPELINE OPERATION FTE-months: 1.0

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 Op-2.1-A(ii): BAYESWAVE FOLLOW-UP ANALYSES FTE-months: 1.0

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 Op-2.1-A(iii): oLIB ONLINE PIPELINE OPERATION FTE-months: 2.0

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 Op-2.1-A(iv): DEFINITION OF BURST LOW-LATENCY ALERTS FTE-months: 1.0

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

TASK Op-2.1-A(v): 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 Op-2.1-A(vi): ONLINE DATA QUALITY FTE-months: 0.5

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 Op-2.1-A(vii): ONLINE BACKGROUND TRIGGERS FTE-months: 0.5

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

TASK Op-2.1-B(i): RUN THE ALL-SKY BURST SEARCH FTE-months: 1.0

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

TASK Op-2.1-B(ii): SIGNAL INJECTIONS FTE-months: 0.5

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

TASK Op-2.1-B(iii): OFFLINE BACKGROUND TRIGGERS

FTE-months: 0.5

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 Op-2.1-B(iv): FOLLOW-UP DETECTION CANDIDATES

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 Op-2.1-B(v): REPORT RESULTS AND REVIEW

FTE-months: 0.5

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 Op-2.1-B(vi): PUBLISH RESULTS

FTE-months: 0.5

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 Op-2.1-C: SUBGROUP ADMINISTRATION

Management of the short-duration GW burst subgroup.

TASK Op-2.1-C(i): SUBGROUP LEADERSHIP

FTE-months: 1.0

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.

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.

Op-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 [6, 7] 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 [3], stampas [8], pyXel, and CoCoA [9] pipelines, focuses on signals that last up to several hundreds of seconds while other searches (see Op-5.3 and Op-4.9) target signals lasting up to several weeks.

Critical tasks and major deliverables for O4

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

TASK Op-2.2-A(i): RUN THE ALL-SKY LONG-DURATION BURST SEARCH

FTE-months: 1.0

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

TASK Op-2.2-A(ii): WAVEFORM CATALOG DEVELOPMENT

FTE-months: 0.5

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 Op-2.2-A(iii): FOLLOW-UP DETECTOR CANDIDATES

FTE-months: 1.0

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 like magnetars.

TASK Op-2.2-A(iv): REPORT RESULTS AND REVIEW

FTE-months: 0.5

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

TASK Op-2.2-A(v): BACKGROUND TRIGGERS

FTE-months: 0.5

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 Op-2.2-A(vi): PUBLISH RESULTS

FTE-months: 0.5

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 Op-2.2-B: SUBGROUP ADMINISTRATION

Management of the long-duration GW burst subgroup.

TASK Op-2.2-B(i): SUBGROUP LEADERSHIP

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: TOWARDS A 4-DETECTOR NETWORK

FTE-months: 0.5

Analyze KAGRA data with the existing pipelines. This integration is already in place for some pipelines, but still needs to be done for others.

ACTIVITY LT-2.2-B: PIPELINE IMPROVEMENTS

TASK LT-2.2-B(i): CWB

FTE-months: 0.5

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

TASK LT-2.2-B(ii): STAMPAS

FTE-months: 1.0

Test the performance and review the new python based stampas pipeline.

TASK LT-2.2-B(iii): PYXEL

FTE-months: 1.0

Compare the performace of pyXel with other long-duration pipelines. Consider including pyXel upper limits in the final result and publication.

TASK LT-2.2-B(iv): COCOA

FTE-months: 1.0

Compare the performace of CoCoA with other long-duration pipelines. Consider including CoCoA upper limits in the final result and publication.

ACTIVITY LT-2.2-C: PARAMETER ESTIMATION

TASK LT-2.2-C(i): SOURCE RECONSTRUCTION

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

ACTIVITY LT-2.2-D: ONLINE SEARCH

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

Op-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 [10] 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 [11, 12, 13]. 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 [14].

IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [15, 16]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [17], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [18]. 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 [19]. Binaries including two IMBHs could also form as a result of evolution of isolated binaries with very high initial stellar masses [20]. 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[21], therefore dedicated burst searches for these potential sources represent a viable alternative [22]. 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 [3] 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 [23] and dense globular clusters with a large amount of stellar remnants [24]. One natural consequence of these dense clusters is that the black holes inside them will gravitationally scatter off each other in hyperbolic encounters [25], and if they get close enough, they will emit bremsstrahlung gravitational waves that can be detected by the LVK interferometers [26]. 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 [27], and single-single [28], binary-single [29] and binary-binary interactions [30] in globular clusters. Work by [31, 27] 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 [29]. Recent simulations have shown that these waveforms are similar to signals detectable by burst search [32], 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 n Section Op-6.1.

Major deliverables and critical tasks for O4

ACTIVITY Op-2.3-A: BURST BBH SEARCH

TASK Op-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 Op-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 Op-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 Op-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 Op-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 Op-2.3-B: 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 Op-2.3-B(i): THE O3 SEARCH

FTE-months: 3.0

Complete the O3 eBBH analysis and prepare the collaboration paper.

TASK Op-2.3-B(ii): SEARCH OPTIMIZATION

FTE-months: 2.0

Optimize the eBBH search for O4.

TASK Op-2.3-B(iii): ECCENTRIC WAVEFORMS

FTE-months: 2.0

Evaluate eccentric BBH waveforms or hyperbolic BBH encounter waveforms for use in O4 analyses.

TASK Op-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 would presumably result in an exceptional event paper.

ACTIVITY Op-2.3-C: SUBGROUP ADMINISTRATION

Management of the BBH Burst subgroup.

TASK Op-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

FTE-months: 3.0

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

Op-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 [33]. 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 [5, 34, 35]. 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 [36, 37]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [35]. 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 [38, 39, 40]. 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.

Major deliverables for O4

ACTIVITY Op-2.4-A: PARAMETER ESTIMATION FOR THE GW TRANSIENT CATALOG AND PAPERS

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

FTE-months: 1.0

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

TASK Op-2.4-A(ii): EVALUATE WAVEFORM MODELS

FTE-months: 2.0

Test available burst waveform models against data. Examples include CCSN (Op-2.5), cosmic strings (Op-7.1), pulsar glitches, close hyperbolic encounters of two black holes, etc.

TASK Op-2.4-A(iii): PRODUCTION OF SKYMAPS

FTE-months: 1.0

Deliver position reconstruction skymaps for all detected sources during O4.

TASK Op-2.4-A(iv): CONTRIBUTE TO O4 GW 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 Op-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 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.

Op-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 $M \gtrsim 10M_\odot$ 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 GW 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 [41]. 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 Op-2.5-A: SEARCHES FOR GW ASSOCIATED TO CCSNE

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

FTE-months: 0.5

Run a targeted search for CCSN within roughly 20 Mpc with the CCSN time and sky position using dedicated pipelines (e.g., cWB [3], X-pipeline). In case of non-detection, provide an estimate of the upper limits found by the search.

TASK Op-2.5-A(iv): RUN A CCSN-SPECIFIC ALL-SKY GW SEARCH FTE-months: 0.5

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 Op-2.5-A(v): REPORTING RESULTS AND REVIEW FTE-months: 0.5

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.

TASK Op-2.5-A(vi): PUBLISHING RESULTS (UPPER LIMITS)

Organize and write collaboration papers reporting any upper limits found by these searches in O4 in case of significant improvements compared to existing limits.

ACTIVITY Op-2.5-B: CCSN EXTRAORDINARY EVENT

TASK Op-2.5-B(i): RUN THE SEARCH

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

TASK Op-2.5-B(ii): PARAMETER ESTIMATION

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

TASK Op-2.5-B(iii): REPORTING RESULTS AND REVIEW

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 Op-2.5-B(iv): PUBLISHING RESULTS

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

ACTIVITY Op-2.5-C: SUBGROUP ADMINISTRATION

Management of the CCSN subgroup.

TASK Op-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.

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.

Op-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 Op-3.1-A: 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 Op-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 Op-3.1-A(ii): FASTER CONVERGENCE WITH IMPROVED SAMPLING ALGORITHMS

FTE-months: 18.0

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

TASK Op-3.1-A(iii): PARALLELIZED SAMPLING ALGORITHMS

FTE-months: 1.0

Implement and maintain CPU-parallelized algorithms for parameter estimation, for use on exceptional candidate events which warrant expensive cutting-edge signal models.

TASK Op-3.1-A(iv): 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 Op-3.1-A(v): 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 Op-3.1-A(vi): RAPID LOCALIZATION WITH HIGHER ORDER MODES

FTE-months: 3.0

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 Op-3.1-B: EVALUATION OF PARAMETER ESTIMATION METHODS

The PE methods will be evaluated to understand potential biases.

TASK Op-3.1-B(i): USING MORE ACCURATE WAVEFORMS

FTE-months: 3.0

As more faithful waveform models and more numerical relativity simulations become available (see Sec. Op-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.

TASK Op-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 were seen in O3 and may be detected in O4.

TASK Op-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 Op-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 Op-3.1-C: DEPLOYMENT OF PARAMETER ESTIMATION CODE

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

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

FTE-months: 3.0

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

FTE-months: 3.0

Since the equation of state is believed to be universal, it can be better constrained by analyzing multiple events together. Implement and improve methods to do a multiple event equation of state estimation.

ACTIVITY Op-3.1-F: PARAMETER ESTIMATION REVIEW

Review of changes to parameter estimation code and deployment configuration.

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

FTE-months: 8.0

Review modifications to parameter estimation code.

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

FTE-months: 8.0

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

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

FTE-months: 8.0

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

ACTIVITY Op-3.1-G: SUBGROUP ADMINISTRATION

Management of the Parameter Estimation subgroup.

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

FTE-months: 3.0

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.

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

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.

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. Op-3.7).

ACTIVITY LT-3.1-E: ANALYZING POPULATIONS OF SUB-THRESHOLD EVENTS

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. Op-3.5) and the Stochastic group (Sec. 8).

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. Op-3.7).

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.

Op-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 observed GW signals by LIGO and Virgo with predictions of GR, and for developing the associated data analysis infrastructure. Due to the lack of reliable waveform models in alternative theories, currently the group's primary focus is 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 and gravitational lensing, are also pursued within thegroup.

Major aspects and methods for this activity

ACTIVITY Op-3.2-A: GRAVITATIONAL-WAVE PROPERTIES

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

FTE-months: 2.0

Develop tests that use the multipolar structure of gravitational waves to test their consistency with general relativity.

TASK Op-3.2-A(ii): SEARCHES FOR NON-STANDARD POLARIZATION PROPERTIES

FTE-months: 1.0

Develop model agnostic and theory-specific analyses for non-tensorial polarizations and vacuum birefringence.

ACTIVITY Op-3.2-B: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Sufficiently loud signals from massive compact objects will allow us to test their immediate environments.

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

FTE-months: 3.0

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

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

FTE-months: 6.0

Develop and improve searches for echoes and other features that probe the near-horizon structure of the merger remnant, using template-based and model-agnostic approaches.

ACTIVITY Op-3.2-C: 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 Op-3.2-C(i): CONSTRAINING FINITE-SIZE EFFECTS OF BLACK HOLE MIMICKERS

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 Op-3.2-D: 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 Op-3.2-D(i): IMPROVEMENTS TO LIBRARY INFRASTRUCTURE

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 and

TASK Op-3.2-D(ii): PIPELINE AUTOMATION

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

ACTIVITY Op-3.2-E: GRAVITATIONAL LENSING

The gravitational-wave lensing sub-group under the Testing General Relativity group is primarily responsible for finding signatures of gravitational-wave lensing within the GW signals observed by LIGO and Virgo, and for developing associated data analysis and modeling infrastructure. These include (but are not limited to) searches for lensing magnification, multiple images produced by strong lensing, micro/millilensing beating patterns and diffraction effects, as well as modeling of the gravitational lenses and their population, stochastic background, and other modeling of gravitational-wave lensing.

TASK Op-3.2-E(i): MACHINE LEARNING - BASED SEARCH PIPELINE

FTE-months: 3.0

Develop and improve machine learning algorithms to search for lensed multiple images.

TASK Op-3.2-E(ii): POSTERIOR-BASED SEARCH PIPELINE

FTE-months: 1.0

Develop and improve posterior-based parameter estimation searches for lensed multiple images.

TASK Op-3.2-E(iii): FACTORIZED JOINT PARAMETER ESTIMATION PIPELINE

FTE-months: 3.0

Develop and improve factorized joint parameter estimation searches using importance sampling and pre-computed look-up tables.

TASK Op-3.2-E(iv): JOINT PARAMETER ESTIMATION PIPELINE

FTE-months: 3.0

Develop and improve joint parameter estimation searches using template-based approaches.

TASK Op-3.2-E(v): SUB-THRESHOLD SEARCH PIPELINES

FTE-months: 3.0

Update template-based sub-threshold search pipelines for application to the O4 data set.

TASK Op-3.2-E(vi): MICROLENSING SEARCH PIPELINE

FTE-months: 3.0

Develop templates and parameter estimation methodologies to target microlensed events and to combine strong lensing analyses with microlensing analyses for both isolated and population of microlenses.

TASK Op-3.2-E(vii): TESTING GENERAL RELATIVITY WITH GRAVITATIONAL LENSING

FTE-months: 2.0

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

TASK Op-3.2-E(viii): LENSING MODEL SELECTION

FTE-months: 2.0

Develop methodologies to do template-based model selection with gravitational lenses.

ACTIVITY Op-3.2-F: SUBGROUP ADMINISTRATION

Management of the Testing General Relativity subgroup.

TASK Op-3.2-F(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.

ACTIVITY LT-3.2-B: 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).

ACTIVITY LT-3.2-C: 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.

ACTIVITY LT-3.2-D: GRAVITATIONAL LENSING

1) Improve the modeling of lens populations and lensing rates. 2) Investigate the use of improved lens models in data analysis pipelines. 3) Develop methods to infer properties of the source population from detections of lensed gravitational-wave signals as well as the stochastic background. 4) Improve the inference tools to detect and characterize lensing signatures from existing detections, including the investigation of microlensing effects and multiple images, prior choices, and selection effects. 5) Improve sub-threshold search pipelines to detect lensed counterparts of transient gravitational-wave signals. 6) Develop methods to make astrophysical inference (e.g., nature of dark matter) from lensing signatures in gravitational-wave signals.

Op-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 constraint. 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 Op-3.3-A: SUBGROUP ADMINISTRATION

Management of the Extreme Matter subgroup.

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

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

ACTIVITY Op-3.3-B: PREPARATION TOWARDS THE NEXT OBSERVING RUN

Extension of the infrastructure to ensure matter-related studies for the next observing run.

TASK Op-3.3-B(i): MAINTENANCE AND DEVELOPMENT OF MATTER-RELATED PARAMETER ESTIMATION INFRASTRUCTURE

FTE-months: 48.0

With the transition from LALInference to bilby, it is essential to ensure the availability of matter-related pipelines for the upcoming observing runs. 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, a working infrastructure for spectral, piecewise-polytropic, non-parametric EOS Inference, generation of radius constraints, and the inference of non-linear tidal effects.

Task Op-3.3-B(ii): EOS Infrastructure FTE-months: 24.0

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.

Activity Op-3.3-C: 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 Op-3.3-C(i): Impact of EOS on alerts FTE-months: 12.0

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

Task Op-3.3-C(ii): Impact of waveform systematics on inference FTE-months: 3.0

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

Task Op-3.3-C(iii): EOS measurements in populations of neutron stars FTE-months: 2.0

Coordinating with the parameter estimation and rates and population groups for source classification and prior assumptions. EOS inference is influenced by population assumptions, in particular when multiple signals are considered.

Task Op-3.3-C(iv): EOS degeneracy with tests of GR FTE-months: 1.0

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.

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 Op-3.4.

Inspiral waveforms for NS-NS systems in the presence of massive scalar fields to be used to constrain the mass and decay constant of the axion or axion-like particles will be developed.

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.

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 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.

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.

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.

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

Extreme matter constraints also stem from investigations of terrestrial nuclear physics experiment, 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.

Op-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 Op-3.4-A: NEW WAVEFORM MODELS

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

TASK Op-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 Op-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 Op-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 Op-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 Op-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 Op-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 Op-3.4-B: EVALUATION OF WAVEFORM MODELS

TASK Op-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 Op-3.4-C: ALGORITHMIC AND COMPUTATIONAL IMPROVEMENTS TO WAVEFORM MODELS

TASK Op-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 Op-3.4-D: WAVEFORM REVIEW

TASK Op-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 Op-3.4-E: CODE MAINTENANCE AND INFRASTRUCTURE IMPROVEMENT

TASK Op-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 Op-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 Op-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 Op-3.4-F: 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 Op-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 Op-3.4-G: SUBGROUP ADMINISTRATION

Management of the Waveforms subgroup.

TASK Op-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.

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

Develop waveform models for hyperbolic and parabolic encounters.

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.

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.

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.

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.

Op-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 defined over the binary masses, spins, and spatial/redshift distribution. Models of such population properties are compared with the outputs of CBC searches and of parameter estimation algorithms to perform inference and to categorize and establish the significance of new events as they arise. Typically, population inference on simple models may start to yield informative results with 3 or more detected events; with increasing statistics and more detailed modeling, inference on relevant physical quantities affecting populations will be incorporated.

Binary merger events are considered in the astrophysical categories of binary black hole (BBH), BNS, and NSBH, which are currently observed with a non-zero event rate; for the intermediate mass black hole binary (IMBHB) category, we establish upper limits on the rate (note though that the source of GW190521 could include an intermediate mass black hole (IMBH) component), and likewise for possible binaries with containing sub-solar-mass components of cosmological origin. The limits or boundaries of the categories are not precisely defined a priori, and may be adjusted based on future observations. The distributions of events within each category are influenced by a range of astrophysical phenomena which we wish to explore. With the 39 new events reported in GWTC-2, we began to probe features in the distributions of CBC masses, spins, and redshifts.

As the binary merger census expands in number and cosmological reach, additional population features are becoming measurable and subpopulations may become resolvable. With a few hundred events, we are likely able to determine details about the origin of the components, as well as probe correlations between mass and spin distributions. In addition to the interface with CBC searches and parameter estimation, and with other subgroups quantifying properties of individual binary mergers (CBC Waveforms, CBC Extreme Matter), we also expect Rates/Population work to influence the structure of future catalogs of compact binaries and associated data products.

This group may also interface with communities developing astrophysical model simulations (for instance population synthesis or cluster dynamics) in various contexts, and may undertake opportunistic investigations of specific astrophysical processes or properties which are otherwise inaccessible.

Major aspects and methods for this activity

ACTIVITY Op-3.5-A: 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 and redshift; 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 Op-3.5-A(i): SIMULATED SIGNAL CAMPAIGNS

FTE-months: 3.0

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 Op-3.5-A(ii): 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 Op-3.5-A(iii): 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 Op-3.5-B: PARAMETRIC AND NON-PARAMETRIC MERGER RATE ESTIMATION

TASK Op-3.5-B(i): RATE ESTIMATION FOR MODELLED BINARY POPULATIONS

FTE-months: 3.0

For known (fixed) source populations, merger rates may be derived directly from the outputs of search pipelines via a signal-noise mixture model [42], 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 [43]. 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 Op-3.5-D(v) for a more complete treatment.

TASK Op-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 [44] 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 Op-3.5-C: POPULATION ASTROPHYSICS

As more fine-grained features and properties of the population become measurable, we will make more detailed studies linking them with potential underlying physical phenomena and mechanisms.

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

FTE-months: 4.0

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 Op-3.5-C(ii): COMPONENT SPIN DISTRIBUTION MODELS

FTE-months: 4.0

Develop and refine models describing the spin magnitudes and orientations of merging binaries and apply results of model inference to distinguish formation scenarios.

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

FTE-months: 2.0

Continue to refine models required to infer rate and mass spectrum dependence on redshift. Implement methods to test for, measure and place limits on potential anisotropies in the merger distribution.

TASK Op-3.5-C(iv): INFERENCE ON ASTROPHYSICALLY MOTIVATED POPULATION PROPERTIES

FTE-months: 3.0

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 Op-3.5-D: 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 Op-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. Implement hierarchical inference based on direct (non-Markov-Chain) likelihood estimates as in the `rapid_pe` pipeline.

TASK Op-3.5-D(ii): INFERENCE ON NON-PARAMETRIC MODELS FTE-months: 4.0

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 Op-3.5-D(iii): MODEL CHECKING AND OUTLIER IDENTIFICATION FTE-months: 2.0

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 Op-3.5-D(iv): MID-LATENCY POPULATION UPDATES FTE-months: 3.0

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 Op-3.5-D(v): INCLUSION OF MARGINAL EVENTS IN RATE/POPULATION INFERENCE FTE-months: 2.0

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 Op-3.5-D(vi): CURATION OF DATA PRODUCTS FTE-months: 2.0

Decide on and implement common formats for collecting data products from R&P activities, ensuring the data products are easily accessible and usable for public release.

ACTIVITY Op-3.5-E: 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 Op-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 Op-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 Op-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 Op-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.

TASK Op-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 Op-3.5-E(vi): POPULATION IMPACTS ON COSMOLOGY AND LENSING FTE-months: 0.5

'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 Op-3.5-E(vii): POPULATION INFORMATION FOR STOCHASTIC BACKGROUND SEARCH FTE-months: 0.5

Estimates of the stochastic background from CBC sources (see Section Op-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.

ACTIVITY Op-3.5-F: RATES AND POPULATIONS METHODS AND CODE REVIEW

TASK Op-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 Op-3.5-G: SUBGROUP ADMINISTRATION

Management of the Rates and Populations subgroup.

TASK Op-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 Op-3.4.

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): RATES AND POPULATION COMMON TOOLKIT FTE-months: 4.0

Integrated package of search-independent and flexible tools for inference over merger rates and populations. `https://git.ligo.org/RatesAndPopulations/lvc-rates-and-pop/`

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.

Op-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 parameter H_0 from GW signals detected by LIGO-Virgo. The methods involved include identification of a set of possible hosts using an observed EM counterpart to the GW event and statistical cross-correlation of the GW distance estimate with catalogues of potential host galaxies in the absence of a counterpart. 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. Smaller effects like redshift uncertainties and GW calibration uncertainties could become important with an increasing number of observations. 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 Op-3.6-A: COSMOLOGY PIPELINE

A precise measurement of cosmological parameters, such as the Hubble parameter, 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 limited 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 Op-3.6-A(i): COSMOLOGY CODE IMPROVEMENTS

FTE-months: 24.0

Development activity for one of the Cosmology group's active pipelines, including performance improvements to enable better exploration of systematics, and treatment of more general astrophysical and cosmological models.

TASK Op-3.6-A(ii): INPUT GALAXY CATALOGS

FTE-months: 12.0

Verify the fidelity of the input galaxy catalogs, especially photometric redshift catalogs, which can increase the completeness of galaxies to be cross-correlated against the gravitational wave events. Determine the quality of the photometric redshift estimates as a function of the galaxy magnitudes in terms of the biases, errors and catastrophic failure rates and the allowed tolerance given the statistical precision of the current observations. 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 gwcosmo.

ACTIVITY Op-3.6-B: 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 and the evolution of the merger rate with redshift 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 Op-3.6-B(i): UNDERSTANDING KEY SYSTEMATICS FTE-months: 24.0

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

ACTIVITY Op-3.6-C: COSMOLOGY MOCK DATA CHALLENGE

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

TASK Op-3.6-C(i): MOCK DATA CHALLENGE: CONSTRUCTION OF MOCK DATA SET FTE-months: 12.0

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.

TASK Op-3.6-C(ii): MOCK DATA CHALLENGE: VALIDATION OF COSMOLOGY PIPELINE FTE-months: 6.0

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

ACTIVITY Op-3.6-D: REVIEW OF COSMOLOGY PIPELINE

Continuing method and code review of the cosmology pipeline.

TASK Op-3.6-D(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 Op-3.6-E: SUBGROUP ADMINISTRATION

Management of the Cosmology subgroup.

TASK Op-3.6-E(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). 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.

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.

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.

Major aspects and methods for this activity

ACTIVITY LT-3.6-A: IMPORTANCE OF PECULIAR VELOCITY CORRECTIONS AS A FUNCTION OF DISTANCE

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 sources within the Local Supercluster, 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, particularly "golden" NS binaries within 100 Mpc. We will use mock galaxy catalogues derived from n-body simulations to study this, with particular focus on systematics arising from possible non-Gaussian peculiar velocity residuals.

TASK LT-3.6-A(i): MARGINALIZATION OVER THE NON-GAUSSIAN PECULIAR VELOCITY POSTERIOR

FTE-months: 6.0

We will develop the existing code for the measurement of H0 from sources with the EM counterpart by including a module that will marginalize over the peculiar velocity posterior. The module will read the peculiar velocity PDF from an external file. This will be implemented for nearby sources redshift $z \leq 0.05$.

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

Investigations of the importance of other systematic effects not mentioned explicitly in the InfraOps section.

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

FTE-months: 18.0

GW sources are expected to follow the underlying matter distribution and should exhibit a spatial clustering with other tracers of large-scale structures such as galaxies. The exploration of the spatial clustering between GW sources and spectroscopic/photometric galaxies 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, Ω_m, w_o, w_a along with the GW bias parameters.

ACTIVITY LT-3.6-D: 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. 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 100Mpc. We will explore how such measurements might influence measurements of H_0 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.

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

FTE-months: 3.0

Assemble a catalogue of all nearby (< 1 Gpc) supernovae, focussing especially on clusters and SNe type Ia.

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

FTE-months: 9.0

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

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

FTE-months: 12.0

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-E: 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-E(i): TESTING DEVIATIONS FROM ΛCDM FROM GW PROPAGATION

FTE-months: 18.0

Expand cosmological pipelines to test model-independent 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-F: BUILDING IMPROVED GALAXY CATALOGUES

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 gwcosmo codebase and study the robustness / quantify the systematic effects of the unknown astrophysics that goes into the model(s).

ACTIVITY LT-3.6-G: EXTENSION OF SUB-SOLAR SEARCH TO MORE EXTREME MASS RATIOS

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.

TASK LT-3.6-G(i): SUB-SOLAR BLACK HOLE TEMPLATE BANK WITH HIGHER MASS RATIOS

FTE-months: 4.0

Design a template bank for sub-solar black holes with higher mass ratios.

TASK LT-3.6-G(ii): SEARCH FOR SUB-SOLAR BLACK HOLES WITH HIGHER MASS RATIO

FTE-months: 4.0

Develop a search pipeline for sub-solar black holes with higher mass ratios.

TASK LT-3.6-G(iii): METHODS OF INTERPRETATION OF SEARCHES FOR SUB-SOLAR BLACK HOLES WITH LOW MASS RATIO

FTE-months: 4.0

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.

ACTIVITY LT-3.6-H: MODEL SELECTION OF PBH VS ASTROPHYSICAL SCENARIOS, BASED ON THE CBC MASS AND SPIN DISTRIBUTIONS

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.

TASK LT-3.6-H(i): BAYESIAN MODEL SELECTION FOR PBHS

FTE-months: 4.0

Develop tools for Bayesian model selection of PBH models versus astrophysical scenarios based on the inferred rate and mass distributions.

ACTIVITY LT-3.6-I: POSSIBLE PBH INTERPRETATION OF EXCEPTIONAL OR SPECIAL EVENTS

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.

TASK LT-3.6-I(i): METHODS FOR IDENTIFYING PBHS IN EXCEPTIONAL EVENTS

FTE-months: 4.0

Develop tools that can be used to identify an exceptional event as a PBH candidate.

ACTIVITY LT-3.6-J: SYNERGIES BETWEEN CBC OBSERVATIONS AND LIMITS ON CWS AND THE SGWB

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 continuous 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.

TASK LT-3.6-J(i): JOINT INFERENCE

FTE-months: 4.0

Develop methods for joint inference using CBC, CW, and SGWB search results.

Op-3.7 CBC All Sky Search InfraOps 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 Op-3.7-A: 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 Op-3.7-A(i): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR GSTLAL

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

FTE-months: 12.0

TASK Op-3.7-A(ii): CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY FOR O4

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

FTE-months: 12.0

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

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

FTE-months: 12.0

TASK Op-3.7-A(iv): CONTINUE OPTIMIZING THE GSTLAL COMPUTATIONAL PERFORMANCE FOR O4

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

FTE-months: 12.0

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

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

FTE-months: 12.0

TASK Op-3.7-A(vi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR MBTA

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

FTE-months: 6.0

TASK Op-3.7-A(vii): CONTINUE OPTIMIZING THE MBTA SEARCH SENSITIVITY FOR O4

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

FTE-months: 12.0

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

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

FTE-months: 12.0

TASK Op-3.7-A(ix): CONTINUE OPTIMIZING THE MBTA COMPUTATIONAL PERFORMANCE FOR O4

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

FTE-months: 3.0

TASK Op-3.7-A(x): CONTINUE OPTIMIZING THE MBTA ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

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

FTE-months: 12.0

TASK Op-3.7-A(xi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR SPIIR

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

FTE-months: 6.0

TASK Op-3.7-A(xii): CONTINUE OPTIMIZING THE SPIIR SEARCH SENSITIVITY IN PREPARATION OF O4

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

FTE-months: 8.0

TASK Op-3.7-A(xiii): CONTINUE OPTIMIZING THE SPIIR P-ASTRO CALCULATION FOR O4

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

FTE-months: 12.0

TASK Op-3.7-A(xiv): CONTINUE OPTIMIZING THE SPIIR COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the SPIIR pipeline's computational performance for the O4 run.

FTE-months: 3.0

TASK Op-3.7-A(xv): CONTINUE OPTIMIZING THE SPIIR ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

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

FTE-months: 12.0

TASK Op-3.7-A(xvi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR PYCBC

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

FTE-months: 12.0

TASK Op-3.7-A(xvii): CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY FOR O4

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

FTE-months: 12.0

TASK Op-3.7-A(xviii): CONTINUE OPTIMIZING THE PYCBC P-ASTRO CALCULATION FOR O4

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

FTE-months: 12.0

TASK Op-3.7-A(xix): CONTINUE OPTIMIZING THE PYCBC COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the PyCBC pipeline's computational performance for the O4 run.

FTE-months: 4.0

TASK Op-3.7-A(xx): CONTINUE OPTIMIZING THE PYCBC ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

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

FTE-months: 12.0

ACTIVITY Op-3.7-B: REMAINING O3 AND INITIAL O4 PIPELINE DEPLOYMENT

Search pipelines must be deployed and maintained on collaboration computer clusters for remaining O3 offline analyses and the initial O4 online and offline analyses.

TASK Op-3.7-B(i): DEPLOYMENT OF GSTLAL PIPELINE FOR ONLINE RUNNING

Deploy, monitor, and maintain the GstLAL online pipeline for low-latency trigger generation.

FTE-months: 12.0

TASK Op-3.7-B(ii): DEPLOYMENT OF GSTLAL PIPELINE FOR OFFLINE RUNNING

Deploy and maintain the GstLAL pipeline for deeper offline searches.

FTE-months: 12.0

TASK Op-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.

TASK Op-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 Op-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 Op-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 Op-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.

ACTIVITY Op-3.7-C: O3/O4 PIPELINE REVIEW

Review of final O3 results/configurations and review of O4 pipelines.

TASK Op-3.7-C(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 Op-3.7-C(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 Op-3.7-C(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.

ACTIVITY Op-3.7-D: 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 Op-3.7-D(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 Op-3.7-D(ii): 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 Op-3.7-E: SUBGROUP ADMINISTRATION

Management of the all-sky pipelines subgroup.

TASK Op-3.7-E(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 O3 and 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: 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.

ACTIVITY LT-3.7-B: 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.

ACTIVITY LT-3.7-C: 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.

ACTIVITY LT-3.7-D: 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.

Op-3.8 CBC Service Willingness

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 Op-3.8-A: WILLINGNESS TO SERVE 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 Op-3.8-A(i): WILLINGESS TO STAND FOR ELECTION OF CBC CO-CHAIR

FTE-months: -

ACTIVITY Op-3.8-B: WILLINGNESS TO SERVE AS CBC SUBGROUP LEAD

Subgroup leads are appointed by CBC co-chairs to lead R&D groups.

TASK Op-3.8-B(i): WILLINGNESS TO ACCEPT CBC SUBGROUP LEAD APPOINTMENT

FTE-months: -

ACTIVITY Op-3.8-C: WILLINGNESS TO SERVE AS CBC TECHNICAL REVIEWER

Technical reviewers agree to review code or techniques for scientific soundness.

TASK Op-3.8-C(i): WILLINGNESS TO ACCEPT CBC TECHNICAL REVIEWER APPOINTMENT OR TO VOLUNTEER FOR TECHNICAL REVIEW TASKS IF CALLED UPON

FTE-months: -

ACTIVITY Op-3.8-D: WILLINGNESS TO SERVE 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 Op-3.8-D(i): WILLINGNESS TO ACCEPT CBC PAPER REVIEWER APPOINTMENT OR TO VOLUNTEER FOR PAPER REVIEW TASKS IF CALLED UPON

FTE-months: -

ACTIVITY Op-3.8-E: WILLINGNESS TO SERVE ON CBC PAPER TEAM

CBC paper team members write or manage CBC papers.

TASK Op-3.8-E(i): WILLINGNESS TO ACCEPT CBC PAPER TEAM APPOINTMENT OR TO VOLUNTEER FOR PAPER TASKS IF CALLED UPON

FTE-months: -

Op-3.9 O4a Catalog of Compact Binaries

Produce a catalog of compact binary coalescence candidate signals observed during O4a 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 Collaboration 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 O4a 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 O4a, 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 Op-3.9-A: OFFLINE SEARCHES

Perform searches of gravitational wave data for compact binary coalescences using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK Op-3.9-A(i): GSTLAL PIPELINE OPERATION

FTE-months: 12.0

Offline running of the GstLAL search over O4a data chunks.

TASK Op-3.9-A(ii): PYCBC PIPELINE OPERATION FOR BROAD SEARCH

FTE-months: 6.0

Offline running of the PyCBC broad parameter search over O4a data chunks.

TASK Op-3.9-A(iii): PYCBC PIPELINE OPERATION FOR BBH-FOCUSED SEARCH

FTE-months: 6.0

Offline running of the PyCBC BBH-focused search over O4a data chunks.

TASK Op-3.9-A(iv): MBTA PIPELINE OPERATION FTE-months: 6.0

Offline running of the MBTA search over O4a data chunks.

TASK Op-3.9-A(v): cWB PIPELINE OPERATION FTE-months: 7.0

Offline running of the cWB search over O4a data chunks.

ACTIVITY Op-3.9-B: DATA QUALITY

Obtain data quality statements for each detection candidate identified by the offline searches.

TASK Op-3.9-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 Op-3.9-C: 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 Op-3.9-C(i): PARAMETER ESTIMATION AUTOMATED ANALYSIS FTE-months: 12.0

Run an automation pipeline to setup initial runs in a standardised framework.

TASK Op-3.9-C(ii): PARAMETER ESTIMATION EVENT ROTA FTE-months: 12.0

Taking initial output form the automated analysis, run the parameter estimation pipeline(s) on each candidate event to produce a preliminary set of results.

TASK Op-3.9-C(iii): PARAMETER ESTIMATION EXPERT ROTA FTE-months: 12.0

Supervise parameter estimation event rota efforts and certify preliminary results.

TASK Op-3.9-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 Op-3.9-C(v): WAVEFORM RECONSTRUCTION FTE-months: 1.0

Perform waveform reconstruction estimation and use this to enable consistency/residual tests.

ACTIVITY Op-3.9-D: 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 Op-3.9-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 Op-3.9-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 Op-3.9-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 Op-3.9-D(iv): 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 Op-3.9-D(v): SENSITIVITY CURATION

FTE-months: 1.0

Collect the results from all search pipelines into a standardised format for further analsysis.

ACTIVITY Op-3.9-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.9-E(i): PROJECT MANAGEMENT

FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.9-E(ii): PAPER WRITING COORDINATION

FTE-months: 6.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.9-E(iii): FIGURE PREPARATION

FTE-months: 3.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.9-E(iv): TABLE PREPARATION

FTE-months: 3.0

- Prepare production-quality tables.
- Prepare data-behind-tables for public dissemination.

TASK Op-3.9-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 Op-3.9-F: TECHNICAL REVIEW

TASK Op-3.9-F(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.9-F(ii): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of GstLAL search results: candidate lists, background estimation, sensitivity.

TASK Op-3.9-F(iii): REVIEW OF PYCBC PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of PyCBC search results: candidate lists, background estimation, sensitivity.

TASK Op-3.9-F(iv): REVIEW OF MBTA PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of MBTA search results: candidate lists, background estimation, sensitivity.

TASK Op-3.9-F(v): REVIEW OF CWB PIPELINE SEARCH RESULTS FTE-months: 1.0

Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK Op-3.9-F(vi): REVIEW OF PARAMETER ESTIMATION RESULTS FTE-months: 3.0

Review of Parameter Estimation results, including posterior samples.

TASK Op-3.9-F(vii): REVIEW OF WAVEFORM RECONSTRUCTION AND CONSISTENCY CHECKS FTE-months: 1.0

Review of Waveform Reconstruction results.

ACTIVITY Op-3.9-G: PAPER REVIEW

TASK Op-3.9-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.9-G(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Catalog publication of events in O4a.
- Strain data release surrounding catalog events in O4a.
- Posterior samples for catalog events in O4a.
- Data behind the figures appearing in O4a Catalog.
- Curated summary of injection analysis results

Op-3.10 O4a 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 O4a.

Motivation and goals

With the addition of new detections during O4a, stronger constraints on the BBH, BNS, and NSBH populations are possible and may lead to new insights on compact binary formation and evolution. This paper is an update to the O3b Astrophysical Distribution of Compact Binaries work.

Major aspects and methods for this activity

ACTIVITY Op-3.10-A: BINARY NEUTRON STAR POPULATION INFERENCE

Inference on the population of binary neutron stars.

TASK Op-3.10-A(i): PARAMETRIC BNS MERGER RATE ESTIMATE

FTE-months: 1.0

Estimate the rate of BNS mergers using FGMC or a fixed threshold, with a parametric mass model.

TASK Op-3.10-A(ii): NON-PARAMETRIC BNS MERGER RATE ESTIMATE

FTE-months: 1.0

Estimate the rate of BNS mergers using the KKL method based on the parameters of observed events.

ACTIVITY Op-3.10-B: NEUTRON STAR-BLACK HOLE POPULATION INFERENCE

Inference on the population of neutron star-black hole mergers.

TASK Op-3.10-B(i): PARAMETRIC NS-BH MERGER RATE ESTIMATE

FTE-months: 1.0

Constrain the rate of NS-BH mergers, assuming a parameterised mass distribution or distributions.

TASK Op-3.10-B(ii): NON-PARAMETRIC NS-BH MERGER RATE ESTIMATE

FTE-months: 1.0

Constrain the rate of NS-BH mergers, using a non-parameteric method (e.g. the KKL method).

ACTIVITY Op-3.10-C: BLACK HOLE MASS DISTRIBUTION

Inference on the mass distribution of binary black holes observed.

TASK Op-3.10-C(i): PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

FTE-months: 6.0

Perform parametric hierarchical inference using PE posteriors for BBH events in the O4a Catalog, using a variety of phenomenological models to extract different physical features.

TASK Op-3.10-C(ii): NON-PARAMETRIC INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

FTE-months: 2.0

Produce non-parametric estimates of the BBH mass distribution using PE posteriors for BBH events in the O4a Catalog.

ACTIVITY Op-3.10-D: REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE MERGER RATES

Estimate the merger rate of binary black holes as a function of redshift and test for spatial isotropy of mergers.

TASK Op-3.10-D(i): NON-EVOLVING RATE ESTIMATION

FTE-months: 2.0

Estimate the merger rates under the different mass and spin models, assuming that the rate does not evolve with redshift.

TASK Op-3.10-D(ii): INFERENCE ON REDSHIFT EVOLUTION

FTE-months: 3.0

Quantify possible evolution of the BBH merger rate and mass and spin distribution as a function of redshift

TASK Op-3.10-D(iii): MEASUREMENT AND BOUNDS ON ANISOTROPY

FTE-months: 2.0

Constrain the spatial (direction) dependence of BBH mergers and quantify any possible anisotropy.

ACTIVITY Op-3.10-E: BLACK HOLE SPIN DISTRIBUTION

Inference on the spin distributions of binary black holes observed.

TASK Op-3.10-E(i): PARAMETRIC HIERARCHICAL INFERENCE OF SPINS FROM OBSERVED BBH EVENTS

FTE-months: 6.0

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O4a Catalog, using a variety of phenomenological models to extract different physical features.

ACTIVITY Op-3.10-F: 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 Op-3.10-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 Op-3.10-F(ii): OUTLIER IDENTIFICATION

FTE-months: 4.0

Identify outliers in the population by various methods including leave-one-out analyses to test the robusntess of the population results against the targeted exclusion of individual events.

ACTIVITY Op-3.10-G: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.10-G(i): PROJECT MANAGEMENT

FTE-months: 1.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.10-G(ii): PAPER WRITING COORDINATION

FTE-months: 1.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.10-G(iii): FIGURE PREPARATION

FTE-months: 2.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.10-G(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 1.5

- Write science summary.

- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.10-H: TECHNICAL REVIEW

TASK Op-3.10-H(i): TECHNICAL REVIEW COORDINATION
FTE-months: 1.0
Coordinate technical review activities.

TASK Op-3.10-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 Op-3.10-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 Op-3.10-H(iv): REVIEW OF BBH MASS DISTRIBUTION RESULTS
FTE-months: 0.5
Review of the parametric and non-parameteric mass distribution results.

TASK Op-3.10-H(v): REVIEW OF REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE MERGE RATES
FTE-months: 0.5
Review of the non-evolving BBH rate estimation and redshift evolution.

TASK Op-3.10-H(vi): REVIEW OF BLACK HOLE SPIN DISTRIBUTION RESULTS
FTE-months: 0.5
Review of the parameteric hierarchical inference of spins.

TASK Op-3.10-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 Op-3.10-I: PAPER REVIEW

TASK Op-3.10-I(i): REVIEW OF PAPER SCIENTIFIC CONTENT
FTE-months: 0.5
Publications & Presentations review of scientific content in Astrophysical Distributions paper.

TASK Op-3.10-I(ii): EDITING
FTE-months: 0.2
Editorial Board review of paper quality in Astrophysical Distributions paper.

Expected products and/or outcomes

- O4a Astrophysical Distributions companion paper.
- Posterior samples from posterior distributions.
- Data products describing the detector sensitivity that can be used for independent population analyses.
- Data behind the figures appearing in the O4a Astrophysical Distributions paper.

Op-3.11 O3b and O4 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 O3b and O4 catalogs.

Motivation and goals

LIGO's first 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 [45, 46]. 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, that data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole. Most of these constraints were further improved by combining detections [46, 37, 47].

In addition, the first detection of a binary neutron star merger, GW170817, had a long inspiral phase from which we were be able to conduct a phenomenological test for dipole radiation [48]. 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 given us the ability to put constraints on the specific alternative theories of gravity that predict large deviations between the gravitational-wave and electromagnetic signal, and insight into the polarisation modes of gravitational waves [49].

In O3, we have also observed events that require descriptions beyond the dominant quadrupole moment [50]. This has broadened the scope for us to test fundamental aspects of gravitational-wave generation, including the consistency between the dominant and higher-order moments. We have also seen the first candidate events that match the NSBH profile.

In O4, we expect new detections of BBHs and BNSs, and anticipate detections of NSBH systems, which will further tighten the existing constraints. 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. Below we list the priority science results anticipated from GW observations in the O3b and O4 observing runs.

Major aspects and methods for this activity

ACTIVITY Op-3.11-A: CONSISTENCY TESTS OF GR

Look for inconsistency between observed results and GR predictions for the events in the O3b and O4 Catalogs.

TASK Op-3.11-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 Op-3.11-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 BBH events.

ACTIVITY Op-3.11-B: GRAVITATIONAL-WAVE PROPERTIES

Testing gravitational-wave properties, including generation and propagation, in the O3b and O4 Catalogs.

TASK Op-3.11-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 Op-3.11-B(ii): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN THE MULTIPOLAR STRUCTURE

FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in the multipolar structure of the inspiral.

TASK Op-3.11-B(iii): TEST FOR LORENTZ-INVARIANCE VIOLATIONS

FTE-months: 2.0

Perform parameter estimation on all events in the Catalogs while allowing for dephasing potentially caused by violation of Lorentz invariance.

TASK Op-3.11-B(iv): TEST FOR NON-TENSORIAL POLARIZATIONS

FTE-months: 2.0

Perform parameter estimation allowing for non-tensor polarization content (vector or scalar) on events that are well localized by detection in three detectors.

TASK Op-3.11-B(v): SPEED OF GRAVITY

FTE-months: 1.0

Constrain the speed of gravity by comparing the arrival time of signals between a network of detectors, or through comparison of the arrival time of a counterpart.

TASK Op-3.11-B(vi): EXTRA DIMENSIONS

FTE-months: 1.0

Constrain effects of large extra dimensions on the gravitational-wave propagation behaviour.

ACTIVITY Op-3.11-C: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Probe the immediate environment of remnant compact objects in O3b and O4.

TASK Op-3.11-C(i): TESTS OF THE NATURE OF THE MERGER REMNANT

FTE-months: 6.0

Test the nature of the merger remnant through measurements and cross-comparison of various quasi-normal modes.

TASK Op-3.11-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 Op-3.11-D: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.11-D(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.11-D(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.11-D(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.11-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 Op-3.11-E: TECHNICAL REVIEW

TASK Op-3.11-E(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.11-E(ii): REVIEW OF RESIDUALS TEST

FTE-months: 0.5

Review of the residuals consistency test results.

TASK Op-3.11-E(iii): REVIEW OF IMR TEST

FTE-months: 0.5

Review of the IMR consistency test results.

TASK Op-3.11-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 Op-3.11-E(v): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 0.5

Review of the Lorentz-invariance violation test results.

TASK Op-3.11-E(vi): REVIEW OF POLARIZATION TEST

FTE-months: 0.5

Review of the polarization test results.

TASK Op-3.11-E(vii): REVIEW OF QUASI-NORMAL MODES TESTS

FTE-months: 0.5

Review of the quasi-normal modes tests results.

TASK Op-3.11-E(viii): REVIEW OF SEARCH FOR LATE TIME ECHOES

FTE-months: 0.5

Review of the search for late time echoes results.

TASK Op-3.11-E(ix): REVIEW OF COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

FTE-months: 0.5

Review of the comparison of gravitational waves with electromagnetic waves.

TASK Op-3.11-E(x): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.11-F: PAPER REVIEW

TASK Op-3.11-F(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.8

Publications & Presentations review of scientific content in O3b and O4 Testing GR companion papers.

TASK Op-3.11-F(ii): EDITING

FTE-months: 0.4

Editorial Board review of paper quality in O3b and O4 Testing GR companion papers.

Expected products and/or outcomes

- O4a Testing GR companion paper.
- Posterior samples from each analysis in O3b Testing GR paper.
- Data behind the figures appearing in O4a Testing GR paper.
- O4 Testing GR companion paper.
- Posterior samples from each analysis in O4 Testing GR paper.
- Data behind the figures appearing in O4 Testing GR paper.

Op-3.12 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 cross correlation of 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 not expected to provide observational results before the first O4 catalog of detected sources will be completed (not expected before 2023). An exception may be provided by detections for which an EM counterpart is observed but it cannot be associated to a unique host galaxy. In this case the reduced sky localisation, due to the EM counterpart observation, may yield relevant constraints on cosmological parameters with the statistical method. On the other hand the two methods mentioned above, statistical and mass features method, will be used to provide a new update on the constraint of H_0 obtained with the complete O3 observational data.

Major aspects and methods for this activity

ACTIVITY Op-3.12-A: MEASUREMENT OF COSMOLOGICAL PARAMETERS

Obtain a combined estimate on cosmological parameters, in particular on H_0, from binary neutron stars with identified electromagnetic counterparts.

TASK Op-3.12-A(i): COUNTERPART ONLY MEASUREMENT OF COSMOLOGICAL PARAMETERS FROM O4

FTE-months: 0.5

Analyze events with EM counterparts to obtain a joint measurement on the Hubble constant, and if possible on other cosmological parameters.

TASK Op-3.12-A(ii): STATISTICAL ONLY MEASUREMENT OF H_0 FROM O3

FTE-months: 2.0

Analyze events without EM counterparts to obtain a joint statistical measurement on the Hubble constant from O3 data.

TASK Op-3.12-A(iii): PRELIMINAR STATISTICAL-ONLY ANALYSIS WITH O4 DATA

FTE-months: 2.0

Preliminary application of the cosmological inference pipelines to available O4 data and assessment of unforeseen problematics.

TASK Op-3.12-A(iv): ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

FTE-months: 3.0

Investigate the effect of potential systematic uncertainties on statistical measurements of cosmological parameters, by varying parameters such as the luminosity cutoff, the underlying mass distribution used in the selection function, the galaxy catalog completeness, etc.

ACTIVITY Op-3.12-B: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.12-B(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.12-B(ii): PAPER WRITING COORDINATION

FTE-months: 4.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.12-B(iii): FIGURE PREPARATION

FTE-months: 2.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.12-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 Op-3.12-C: TECHNICAL REVIEW

TASK Op-3.12-C(i): TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

FTE-months: 2.0

TASK Op-3.12-C(ii): REVIEW OF MEASUREMENTS OF COSMOLOGICAL PARAMETERS

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 O3 statistical H0 paper and possible O4 EM counterpart papers.

FTE-months: 6.0

ACTIVITY Op-3.12-D: PAPER REVIEW

TASK Op-3.12-D(i): REVIEW OF PAPER SCIENTIFIC CONTENT

Publications & Presentations review of scientific content in cosmological papers.

FTE-months: 0.5

TASK Op-3.12-D(ii): EDITING

Editorial Board review of paper quality in cosmological papers.

FTE-months: 0.2

Expected products and/or outcomes

- O3 H_0 companion paper (review and publication).
- Posterior samples from posterior distributions.
- Data behind the figures appearing in the O3 H_0 paper.
- Provisional O4 EM counterpart paper(s) + associated data
- Preliminary analysis for O4 statistical cosmological constraints

Op-3.13 O4a Search for Lensed Gravitational Waves

Search for gravitational-wave lensing signatures following LIGO/Virgo run O4a

Motivation and goals

Gravitational waves can be gravitationally lensed by intervening galaxies, galaxy clusters, or microlenses. Lensing can result in magnified images, multiple images (separated in time), and modifications to the waveform due to microlensing. Here we will look for signatures of lensing in O4a data. The analyses will include I) Lensing statistics, II) Lensing magnification studies for chosen events, III) Multiple images, IV) Microlensing.

Major aspects and methods for this activity

ACTIVITY Op-3.13-A: LENSING STATISTICS

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 Op-3.13-A(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 Op-3.13-A(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.

ACTIVITY Op-3.13-B: LENSING MAGNIFICATION STUDIES

If a gravitational wave is strongly lensed, it will receive a magnification μ defined such that the gravitational-wave amplitude is increased by a factor $\mu^{1/2}$. If unaccounted for, the magnification will bias the measurement of luminosity distance and source-frame mass such that the binary appears more massive and closer to us than it actually is.

TASK Op-3.13-B(i): PERFORM MAGNIFICATION ESTIMATES ON THE MASSIVE OBSERVATION RUN O4A EVENTS

FTE-months: 1.0

Analyze O4a events that are outliers with respect to an expected unlensed mass distribution and estimate the required magnification under the lensing hypothesis.

TASK Op-3.13-B(ii): SEARCH FOR EVIDENCE OF LENSING MAGNIFICATION THROUGH TIDAL MEASUREMENTS

FTE-months: 1.0

Perform parameter estimation on O4a events with tidal measurements to search for evidence of gravitational-wave lensing magnification. Lensing magnification is fully degenerate with the measurement of the luminosity distance, and biases the source-frame masses. However, when combined with the neutron star equation-of-state, measurement of the tidal effects can break this degeneracy.

ACTIVITY Op-3.13-C: MULTIPLE IMAGE ANALYSES

Search for evidence that two or more gravitational wave observations might have a common lensed source.

TASK Op-3.13-C(i): RAPID IDENTIFICATION WITH MACHINE LEARNING

FTE-months: 2.0

Use machine learning techniques to rapidly identify lensed candidate pairs.

TASK Op-3.13-C(ii): POSTERIOR OVERLAP ANALYSIS

FTE-months: 2.0

Analyze all the O4a events to identify lensed multi-image candidate pairs using a fast posterior-overlap-based method.

TASK Op-3.13-C(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 Op-3.13-C(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 Op-3.13-C(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 Op-3.13-C(vi): TESTS OF GRAVITATIONAL-WAVE POLARIZATION

FTE-months: 1.0

For any candidate lensed event, perform follow-up analysis of its gravitational-wave polarization content.

TASK Op-3.13-C(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 Op-3.13-C(viii): ASSESSMENT OF UNCERTAINTIES

FTE-months: 1.0

Investigate the systematic uncertainties of the methods targeting multiple images through mock data studies.

ACTIVITY Op-3.13-D: MICROLENSING

Search for evidence of frequency-dependent distortion of signals that could arise from microlensing either by isolated or a population of microlenses.

TASK Op-3.13-D(i): SEARCH FOR MICROLENSING EFFECTS

FTE-months: 4.0

Perform parameter estimation on events to determine if there is evidence of microlensing distortions.

TASK Op-3.13-D(ii): MICROLENSING ANALYSIS OF STRONG LENSING CANDIDATES

FTE-months: 2.0

For any candidate strongly lensed event, combine the strong lensing images to study microlensing.

TASK Op-3.13-D(iii): CONSTRAIN COMPACT DARK MATTER

FTE-months: 2.0

Using the microlensing search results, set constraints on the compact dark matter fraction.

ACTIVITY Op-3.13-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.13-E(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.13-E(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.13-E(iii): FIGURE PREPARATION FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.13-E(iv): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 1.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.13-F: TECHNICAL REVIEW

TASK Op-3.13-F(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.13-F(ii): REVIEW OF LENSING STATISTICS STUDIES FTE-months: 0.5

Review of the studies of lensing statistics.

TASK Op-3.13-F(iii): REVIEW OF LENSING MAGNIFICATION STUDIES FTE-months: 0.5

Review of the studies of lensing magnification.

TASK Op-3.13-F(iv): REVIEW OF POSTERIOR OVERLAP ANALYSIS FTE-months: 0.5

Review of the posteror overlap analysis study.

TASK Op-3.13-F(v): REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION ANALYSES FTE-months: 0.5

Review of the factorized joint parameter estimation analyses.

TASK Op-3.13-F(vi): REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES FTE-months: 0.5

Review of the posterior samples from the factorized joint parameter estimation analyses.

TASK Op-3.13-F(vii): REVIEW OF JOINT PARAMETER ESTIMATION ANALYSES FTE-months: 0.5

Review of the joint parameter estimation analyses.

TASK Op-3.13-F(viii): REVIEW OF JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES FTE-months: 0.5

Review of the posterior samples from the joint parameter estimation analyses.

TASK Op-3.13-F(ix): REVIEW OF SUB-THRESHOLD SEARCH FTE-months: 1.0

Review of the sub-threshold search for lensed images.

TASK Op-3.13-F(x): REVIEW OF MICROLENSING STUDIES FTE-months: 1.0

Review of the search for microlensing effects and associated posterior samples.

ACTIVITY Op-3.13-G: PAPER REVIEW

TASK Op-3.13-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in the lensing paper.

TASK Op-3.13-G(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in the lensing paper.

Expected products and/or outcomes

- O4a Lensing companion paper.
- Posterior samples from joint parameter estimation analyses.
- Data behind the figures appearing in the O4a Lensing paper.

Op-3.14 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 [51] less the gravitational binding energy. Current models and observations place the minimum neutron star mass near $\sim 1.15\ M_\odot$ [52, 53, 54]. The lightest black holes are constrained by the maximum non-rotating neutron star mass, which is currently believed to be $\sim 2\ M_\odot$ [55].

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 [56]. 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 [57, 58, 59, 60]. Another class of models links sub-solar mass black holes to particulate dark matter, either via a complex particle spectrum [61] or nuclear interactions with neutron stars [62, 63, 64, 65, 66, 67, 68].

O4 deliverables

- Carry out a thorough search for sub-solar mass compact binary mergers in O4 data

ACTIVITY Op-3.14-A: O4 SEARCH FOR SUB-SOLAR MASS COMPACT BINARY MERGERS

TASK Op-3.14-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 Op-3.14-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 Op-3.14-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 Op-3.14-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 Op-3.14-B(ii): PARAMETER ESTIMATION

FTE-months: 2.0 ((only for detection))

In the event of a detection, we will perform parameter estimation.

ACTIVITY Op-3.14-C: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.14-C(i): PROJECT MANAGEMENT

FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.14-C(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.14-C(iii): FIGURE PREPARATION

FTE-months: 1.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.14-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 Op-3.14-D: TECHNICAL REVIEW

TASK Op-3.14-D(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.14-D(ii): REVIEW OF SEARCH RESULTS

FTE-months: 1.0

Review of search results: candidate lists, background estimation, sensitivity.

TASK Op-3.14-D(iii): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES

FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-3.14-E: PAPER REVIEW

TASK Op-3.14-E(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.14-E(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Op-3.15 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.

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;
- clear indication of a particular formation channel.

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 Op-3.15-A: AD HOC ACTIVITY

Placeholder for an ad hoc activity. Activities will be defined upon the occurrence of an exceptional event.

TASK Op-3.15-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.

Op-4.1 Targeted searches for known pulsars

Motivation

Rapidly spinning neutron stars in our galaxy may emit gravitational waves 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 gravitational-wave strain we could see from a known pulsar, by assuming that all of its observed spindown is due to gravitational-wave emission (see Equation 5 of [69]).

The searches assume gravitational-wave emission from a triaxial neutron star, with the electromagnetic and gravitational-wave components rotating as one unit. This would lead to gravitational-wave 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 [70]. Detecting signals at either f, or both f and $2f$, would give further insight into the coupling between the crust and core of a neutron star.

Methods

Three mature analysis pipelines for targeted searches are the time-domain Bayesian pipeline [71], the 5-vector method [72], and the time-domain $\mathcal{F}/\mathcal{G}$-statistic method [69]. All three pipelines will be used for high-value targets for which the spin-down limit has, 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 $2f$.

Activities for O3 and O4

ACTIVITY Op-4.1-A: EARLY TARGETED PULSAR PAPER

Using data from the first half of O3 (O3a), the spin-down limit for two recycled millisecond pulsars (J0437−4715 and J0711−6830) was surpassed for the first time [73]. The analysis also provided updated constraints on the emission from the high-value young targets of the Crab and Vela pulsars. A selection of the most promising targets, consisting of both millisecond and young pulsars will be targeted using the first few months of data from the O4 run, leading, for example, to surpassing the spin-down limit for PSR J0737-3039A, the mildly recycled pulsar in the famous "double pulsar" system. We will produce a paper, aimed at a high profile journal, describing a search for signals from these selected targets.

TASK Op-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 Op-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 Op-4.1-A(iii): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

FTE-months: 3.0

Search for gravitational waves from the selected pulsars analyzing data from network of detectors (LIGO, Virgo and KAGRA). Search at two harmonics of the pulsar spin frequency: f and $2f$.

TASK Op-4.1-A(iv): RUN THE 5-VECTOR PIPELINE

FTE-months: 3.0

Search for gravitational waves from the selected pulsars. Independent searches at f and $2f$.

TASK Op-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 Op-4.1-B: FULL TARGETED PULSAR PAPER

As with previous runs (e.g. [74]), 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 Op-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 Op-4.1-B(ii): RUN TIME-DOMAIN BAYESIAN PIPELINE

FTE-months: 3.0

Run the time-domain Bayesian pipeline on all the targets.

TASK Op-4.1-B(iii): RUN THE 5-VECTOR PIPELINE

FTE-months: 3.0

Search for gravitational waves from all the pulsars for which updated ephemerides will be available. Independent searches at f and $2f$.

TASK Op-4.1-B(iv): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

FTE-months: 3.0

Search for gravitational waves from around 30 known pulsars for which 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 Op-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 Op-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 Op-4.1-B(vii): WRITE PAPER

Write a paper describing the results of the search.

FTE-months: 3.0

Op-4.2 Narrow-band searches for known pulsars

Motivation

These searches are an extension of targeted searches for known pulsars (Section Op-4.1) in which the position of the source is assumed to be accurately known while the rotational parameters are slightly uncertain [75]. This type of search is generally computationally heavier with respect to targeted searches. In general, narrow-band searches allow one to take into account a possible mismatch between the gravitational wave rotational parameters and those inferred from electromagnetic observations. For instance, the gravitational wave 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 [76] used in target searches, and one based on the $\mathcal{F}$-statistic [77], 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 O3 and O4

ACTIVITY Op-4.2-A: EARLY 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 O2.

TASK Op-4.2-A(i): RUN SEARCHES

Run the search using the 5-vector method and the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

FTE-months: 3.0

TASK Op-4.2-A(ii): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

Check for the presence of noise lines close to each outlier taking into account the modulation due to the Earth motion. Compare the outliers with the Early searches outliers.

FTE-months: 3.0

TASK Op-4.2-A(iii): OUTLIERS FOLLOWUP – TARGETED SEARCHES

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 up from potential more sensitive searches should also be performed (see Section Op-4.12).

FTE-months: 3.0

TASK Op-4.2-A(iv): SENSITITVITY STUDIES

We will compute upper-limits on CW emission from a subset of the pulsars in different frequency bands, in order to check our sensitivity.

FTE-months: 3.0

ACTIVITY Op-4.2-B: FULL NARROW-BAND SEARCH

We will search for continuous GWs 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 the GWs emission. We expect to surpass the spindown limit for additional 4-5 pulsars at frequencies lower than 100 Hz and improve our previous constraints in [78].

TASK Op-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 Op-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 Earth motion. Compare the outliers with the Early searches outliers.

TASK Op-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.

TASK Op-4.2-B(iv): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, we will put upper limits on the GW emission.

TASK Op-4.2-B(v): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review of any updated part of the codes and the search results.

TASK Op-4.2-B(vi): PUBLICATION

FTE-months: 3.0

Produce a publication with the results of each pipeline.

Op-4.3 Targeted searches for non-tensorial emission from known pulsars

Motivation

Traditional searches for CWs targeted at known pulsars (Sections Op-4.1, Op-4.2), assume that sources emit the tensorial plus and cross gravitational-wave 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 [79, 80].

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

The search for non-tensorial CWs from known pulsars expands the time-domain Bayesian targeted analysis [71] 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. The search for scalar GW radiation predicted by Brans-Dicke theory adapts the $\mathcal{F}$-statistic to search for this particular GW signal.

Activities for O3 and O4

ACTIVITY Op-4.3-A: FULL TARGETED PULSAR PAPER

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 Op-4.1). It will expand upon the analysis of O1 data by allowing the signals to have emission at both once and twice the source rotation frequency.

TASK Op-4.3-A(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 Op-4.3-A(ii): CODE REVIEW

FTE-months: 1.0

Review the code updates to confirm they perform as expected.

TASK Op-4.3-A(iii): RUN TIME-DOMAIN BAYESIAN PIPELINE

FTE-months: 3.0

Run the time-domain Bayesian pipeline on the all targets, making use of the pulsar ephemerides and heterodyned data products already obtained for the standard known pulsar search.

TASK Op-4.3-A(iv): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

FTE-months: 3.0

For around 30 known pulsars for which spin down limit can be surpassed or nearly surpassed, search for for scalar radiation predicted by Brans-Dicke theory.

TASK Op-4.3-A(v): WRITE PAPER

FTE-months: 1.0

Add these results to the full targeted search paper (Section Op-4.1).

Op-4.4 Directed searches targeting Cassiopeia A and other 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 Cas A at $\sim$ 300 years old. Extremely young extragalactic sources without an associated electromagnetic point source, 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 [81], either as fully coherent [82, 83, 84] or semi-coherent [85] 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 [86], 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 [87].

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 [88]. 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.

Activities for O3 and O4

ACTIVITY Op-4.4-A: EARLY SUPERNOVA REMNANTS PAPER

We will run a directed search for selected supernova remnants using some of the available pipelines, e.g. Viterbi, BSD-directed.

TASK Op-4.4-A(i): SOURCE SELECTION

Select a list of sources for directed searches.

FTE-months: 3.0

TASK Op-4.4-A(ii): RUN SEARCH AND POST-PROCESSING

Run directed searches using multiple pipelines, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

FTE-months: 3.0

TASK Op-4.4-A(iii): SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

FTE-months: 3.0

TASK Op-4.4-A(iv): REVIEW SEARCH RESULTS

Review the search procedure and results.

FTE-months: 3.0

TASK Op-4.4-A(v): PUBLICATION

Produce a publication presenting the results.

FTE-months: 3.0

Op-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 [89]. 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 [90, 91, 92], doubly-Fourier transformed data (TwoSpect; [93]), hidden Markov models (Viterbi; [94, 95, 96]), coherent summation of matched-filter sidebands (Sideband; [97]), and a resampling procedure, which is a generalization of the 5-vector method [98]. 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 [99].

Activities for O3 and O4

ACTIVITY Op-4.5-A: FULL SCORPIUS X-1 PAPER

We will run a directed search for continuous gravitational waves from Scorpius X-1 using the cross-correlation, Viterbi, and TwoSpect search pipelines. 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 Op-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 Op-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 Op-4.5-A(iii): 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 Op-4.5-A(iv): 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 Op-4.5-A(v): 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 Op-4.5-A(vi): 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 Op-4.5-A(vii): 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 Op-4.5-B: FULL OTHER LMXBS / AMSPS PAPER

We will run a directed search for a selection of low mass X-ray binary (LMXB) targets for which there are electromagnetic constraints on the neutron star rotation frequencies. Accreting millisecond pulsars (AMSPs) will be our prime targets in this search due to their well constrained rotation frequencies. We will use the Viterbi search pipeline initially, however other search pipelines could also be used if person and computational resources allow.

TASK Op-4.5-B(i): TARGET LIST

FTE-months: 3.0

Identify a list of LMXBs / AMSPs targets.

TASK Op-4.5-B(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 Op-4.5-B(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOS

FTE-months: 3.0

We will use the same veto procedure as applied in the Scorpius X-1 search to follow up any statistical outliers.

TASK Op-4.5-B(iv): PUBLICATION

FTE-months: 3.0

Produce publication presenting the LMXBs / AMSPs search results.

Op-4.6 Directed searches targeted the Galactic center

Motivation

All-sky searches for continuous gravitational waves 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 continuous GWs; the Galactic center and globular clusters are both regions of interest. Several independent lines of evidence suggest the presence of a large number of NS 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 [100, 101, 102, 103, 104].

Methods

The idea is to explore a wide frequency and spin-down parameter space, limiting–where possible–the computational cost of the search. The BSD-directed search pipeline [105], 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 [88]. 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.

Activities for O3 and O4

ACTIVITY Op-4.6-A: EARLY GALACTIC CENTER PAPER

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.

TASK Op-4.6-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 Op-4.6-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 Op-4.6-A(iii): REVIEW SEARCH RESULTS FTE-months: 3.0

Review the search procedure and results.

TASK Op-4.6-A(iv): PUBLICATION FTE-months: 3.0

Produce a publication presenting the results.

Op-4.7 All-sky searches for isolated sources

Motivation

While other CW searches explore regions of potentially high interest, e.g. known pulsars and directed 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 pulsations have 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 [106] can be used to carry out broad all-sky searches over entire frequency space with the aim of producing results as promptly as possible. It is the only pipeline that performs direct estimation of gravitational wave power. The loosely coherent pipeline [107] is capable of improved sensitivity at greater computational cost. FrequencyHough [108] and SkyHough [109] are based on different implementations of the Hough transform algorithm and inherit its resilience to contaminated data. The time-domain $\mathcal{F}$-statistic pipeline [110] 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 number of outliers with streamlined follow-up methods and vetoes. SOAP [111] is a non-parametric search pipeline which is computationally cheap, returning results within $\mathcal{O}$(hours) after SFTs are generated. The non-parametric nature of the search allows it to identify many different signal types which may not follow the standard CW frequency evolution.

Activities for O3 and O4

ACTIVITY Op-4.7-A: FULL ALL-SKY ISOLATED PAPER

TASK Op-4.7-A(i): RUN THE SKYHOUGH SEARCH FTE-months: 3.0

Run the SkyHough search code for single and multiple interferometer data, using the data of the two most sensitive detectors, produce a large list of candidate sources and post-process the results, either by checking coincidences among different data sets (among different detector or between first and second half of the run) and/or implementing a number of vetoes.

TASK Op-4.7-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 frequency band.

TASK Op-4.7-A(iii): RUN THE FREQUENCYHOUGH SEARCH FTE-months: 3.0

Run the FrequencyHough search code for the detector network, produce a large list of candidate sources and post process the results, either by checking coincidences among different data sets (among different detector or between first and second half of the run) and/or implementing a number of vetoes.

TASK Op-4.7-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.

TASK Op-4.7-A(v): RUN THE SOAP PIPELINE FTE-months: 3.0

Run the SOAP search code on data from the detector network to potentially find CW signals which may not follow the standard frequency evolution.

TASK Op-4.7-A(vi): 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 Op-4.7-A(vii): 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 Op-4.7-A(viii): REVIEW FTE-months: 3.0

Review search set up and results, as well as any recent search method improvements and optimizations (Section LT-4.15).

TASK Op-4.7-A(ix): PUBLICATION FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

ACTIVITY Op-4.7-B: EARLY ALL-SKY ISOLATED PAPER

TASK Op-4.7-B(i): RUN THE SKYHOUGH SEARCH

FTE-months: 3.0

Define the parameter space of the search depending on computational resources. Estimate the depth of the search by means of software injected simulated signals in the data. Run the SkyHough search code for single and multiple interferometer data, using the first 6 months of data from the two most sensitive detectors, and post process the results by checking coincidences and implementing a number of vetoes. Produce a list of candidate sources. Depending on the achieved sensitivity, results will be presented or not for publication.

TASK Op-4.7-B(ii): 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.

TASK Op-4.7-B(iii): REVIEW

FTE-months: 3.0

Review search set up and results.

TASK Op-4.7-B(iv): PUBLICATION

FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

Op-4.8 All-sky searches for unknown sources in binaries

Motivation

CW emission from neutron stars in binary systems (see also Section Op-4.5) are 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 CWs 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 [112], 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 [113]. TwoSpect allows for a broad parameter space range to be covered while maintaining computational efficiency.

The BinarySkyHough is a pipeline [114] 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 [115] and early O3 data [116].

Activities for O3 and O4

Activity Op-4.8-A: All-sky binary CW search paper

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 Op-4.8-A(i): Acquisition of computing resources

FTE-months: 3.0

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 [114]. 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 Op-4.8-A(ii): 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 [117]. 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 Op-4.8-A(iii): 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 [118, 119]. The flexibility of this procedure allows for the application of several follow-up strategies, either based on detector-consistency vetoes, such as done in [116], or using hierarchical schemes to compare the behaviour of a CW candidate as the coherence time increases [120].

Task Op-4.8-A(iv): Review

FTE-months: 3.0

This will include code review as well as reviewing search results.

Task Op-4.8-A(v): Publication

FTE-months: 3.0

A paper on these results will be written and submitted for publication.

Activity Op-4.8-B: 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.

Op-4.9 Searches for long-transient emission from a post-merger neutron star

Motivation

CW-derived analysis methods can be used to search for a long-lived neutron star remnant from nearby binary neutron star (BNS) mergers [121] such as GW170817 [48]. While shorter remnant signals on the order of milliseconds to hundreds of seconds can be effectively searched for with methods derived from burst and stochastic searches [122], longer signals associated with the rapid spindown of a young massive neutron star are well suited for CW-derived methods [123]. 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 [124, 125].

Methods

The parameter space [126, 127], 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 [128, 129] and the two semi-coherent Hough algorithms [109, 130, 131, 132] to the rapid-spindown waveform model from [133]. 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.

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.

Activities for O3 and O4

ACTIVITY Op-4.9-A: ONGOING COORDINATION WITH OTHER WORKING GROUPS

FTE-months:
- (3 FTE-mo listed 2019-20)

During current and future observing runs, CW post-merger experts 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.

ACTIVITY Op-4.9-B: OPPORTUNISTIC LONG-DURATION POST-MERGER PAPER (ON STANDBY)

Pending on person power and event rates, we will run a directed search for the remnant of any sufficiently nearby and well localized BNS merger using some of the available pipelines: Viterbi, adaptive transient Hough, and/or generalized frequency-Hough transform.

TASK Op-4.9-B(i): 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 Op-4.9-B(ii): RUN SEARCHES

FTE-months:
- (3 FTE-mo listed 2019-20)

Run different existing search pipelines, post-process results, and in the event of statistical outliers produce a list of candidate signals.

TASK Op-4.9-B(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOES

FTE-months:
- (3 FTE-mo listed 2019-20)

Follow up statistical outliers from each search, either collectively or by each individual search.

TASK Op-4.9-B(iv): 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 Op-4.9-B(v): 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 Op-4.9-B(vi): 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 Op-4.9-B(vii): 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 CBC paper on the BNS event.

Op-4.10 Searches for long-transient emission following a pulsar glitch

Motivation

The CW group is primarily focused on searching for truly *continuous* gravitational waves: 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 gravitational wave signals on time scales of hours–months due to short-lived deformations [134, 135]. The mechanisms behind pulsar glitches are still poorly understood [136] 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 [134, 137] is an efficient method with demonstrated performance on real data [138]. A simple search based on the transient $\mathcal{F}$-statistic method and a setup similar to [138] can be cheaply run for several such targets, with additional development and/or the use of GPUs [137, 118] allowing for deeper 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 [128, 129, 130, 132] or from the burst and stochastic domains [5, 139, 35] 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 [140].

Activities for O3 and O4

ACTIVITY Op-4.10-A: OPPORTUNISTIC GLITCH PAPER (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).

TASK Op-4.10-A(i): MONITOR AND SELECT TARGETS FTE-months: 3.0

Data on promising glitches in nearby pulsars needs to be collected and prioritised as search targets. This will be based on the work of EM observers under the MoUs already in place for targeted CW searches (Section Op-4.1) and public literature and databases.

TASK Op-4.10-A(ii): CODE REVIEW FTE-months: 3.0

The transient $\mathcal{F}$-statistic code in the LALSuite is based on a simple re-use of intermediate data products from the reviewed CW $\mathcal{F}$-statistic code. The PyFstat package [119] can be used for more flexible searches, including MCMCs and GPU usage. Both still require some review effort for production searches.

TASK Op-4.10-A(iii): 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 Op-4.2) must be performed. The detailed search setup can be chosen based on the number of promising targets and the available person-power and computing budget.

TASK Op-4.10-A(iv): 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 MCMC methods.

TASK Op-4.10-A(v): 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, strong transient instrumental lines need to be identified in advance and cleaned from the data, and statistical outliers need to be subjected to deeper checks.

TASK Op-4.10-A(vi): 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 [134] may be possible.

TASK Op-4.10-A(vii): 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 Op-4.10-A(viii): PUBLICATION FTE-months: 3.0

A single paper can describe the search results for any number of glitches targeted during the run. Coordination with short-duration transient searches for the same targets will be beneficial. If the number of promising targets turns out to be limited, inclusion of search results in one of the targeted or narrow-band papers is also an option.

Op-4.11 Searches for continuous emission from ultra-light boson clouds around black holes

Motivation

Ultra-light boson clouds forming around BH are expected to emit continuous wave (CW) 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. While we have in mind BH/ultra-light boson cloud systems as a reference source, the method can be used to search for other signals with similar characteristics.

The search for CW signals from boson clouds around spinning black holes 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 [141]. 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 methodology, 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.

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. The procedure is computationally cheap (relative to standard all-sky CW searches) and is designed for an all-sky search [141]. 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 [142]. The first observational constraints on the mass of ultra-light scalar bosons have been set in all-sky [143] and directed [144] searches carried out on LIGO O2 data.

Activities for O3 and O4

We will run two searches, one all-sky search for scalar boson clouds and a directed search for vector boson clouds, targeting a few potentially interesting galactic black holes. A directed search for scalar boson clouds around post-merger black holes will be also carried out on, pending person power and identification of interesting targets. These analyses will be collectively described in a single observational paper.

ACTIVITY Op-4.11-A: FULL ULTRA-LIGHT SCALAR BOSON CLOUD ALL-SKY SEARCH

We will run an all-sky search for scalar boson cloud continuous signals, relying on the semi-coherent all-sky pipeline method described above [141], as well as further developments. Candidate follow-up will be based on the Viterbi tracking [142].

TASK Op-4.11-A(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 Op-4.11-A(ii): 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 Op-4.11-A(iii): REVIEW SEARCH RESULTS FTE-months: 2.0

Review some portions of the analysis pipeline and search results.

TASK Op-4.11-A(iv): PUBLICATION FTE-months: 1.0

Produce a publication presenting the results.

ACTIVITY Op-4.11-B: FULL ULTRA-LIGHT BOSON CLOUD DIRECTED SEARCH

We are planning to run a directed search for vector boson clouds using the same semi-coherent method of a collection of FFTs [141]. 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 [142].

TASK Op-4.11-B(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 Op-4.11-B(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 Op-4.11-B(iii): REVIEW SEARCH RESULTS FTE-months: 1.0

Review some portions of the analysis pipeline and search results. Note that for the vector boson search the core analysis code is the same as for the all-sky search. Note also that the Viterbi pipeline has been reviewed in previous CW analyses.

TASK Op-4.11-B(iv): PUBLICATION FTE-months: 1.0

Produce a publication presenting the results.

Op-4.12 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 Op-4.1, Op-4.2) may also be used for candidate follow-up. Follow-up pipelines have also been developed as part of many of the directed (Sections Op-4.4, Op-4.5, Op-4.6) and all-sky (Sections Op-4.7, Op-4.8) search methods. A highly-optimized semi-coherent $\mathcal{F}$-statistic search code [145] was found to be more effective for candidate follow-up compared to other implementations [146]. Other methods have been developed more specifically for candidate follow-up. A general-purpose follow-up tool based on MCMC methods [140, 118] has been described recently in [120]. A long-transient add-on to semi-coherent analyses is also available for intermediate follow-up steps [147].

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 O3 and O4

ACTIVITY Op-4.12-A: 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.

ACTIVITY Op-4.12-B: 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.

Op-4.13 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 $h(t)$ 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 an 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 LSC computing clusters via LDR).

The time-domain Bayesian [71] and $\mathcal{F}/\mathcal{G}$-statistic [69] 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 [148]. This gives a complex time series, with a sample rate of one per minute, which can then be used for further analysis.

Activities for O3 and O4

ACTIVITY Op-4.13-A: 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.

ACTIVITY Op-4.13-B: 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.

ACTIVITY Op-4.13-C: PRODUCE FOURIER TRANSFORM FILES

FTE-months: 3.0

TASK Op-4.13-C(i): VET GATED $h(t)$ FRAMES

Vet gated $h(t)$ frames for any issues before starting SFT/SFDB production.

TASK Op-4.13-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 Op-4.13-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.

TASK Op-4.13-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 Op-4.13-D: PRODUCE TIME SERIES FILES

FTE-months: 3.0

TASK Op-4.13-D(i): PRODUCE BSD

BSD files will be produced on a monthly base. Each file contains a complex time series covering a 10 Hz frequency band.

TASK Op-4.13-D(ii): PRODUCE NARROWBAND HETERODYNED TIME SERIES

The narrowband heterodyned time series will be produced for a range of pulsars with rotation frequencies $\gtrsim 10\,\mathrm{Hz}$ for which ephemerides can be obtained from electromagnetic observers.

Op-4.14 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 [149], 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 [2] 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.[3]

Activities for O3 and O4

ACTIVITY Op-4.14-A: 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.

ACTIVITY Op-4.14-B: 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.

ACTIVITY Op-4.14-C: 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.

LT-4.15 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.

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[2] `https://git.ligo.org/lscsoft/lalsuite`

[3] contact+lscsoft-lalsuite-1438-issue-@support.ligo.org

At the request of the LSC and Virgo computing teams, the CW group may periodically produce optimization reports to ensure responsible use of LVC/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 LSC computing optimization team to reduce the computing load.

Activities

ACTIVITY LT-4.15-A: ASTROPHYSICALLY-INFORMED PARAMETER SPACE SELECTION

All-sky searches for unknown continuous wave 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 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.

ACTIVITY LT-4.15-B: FURTHER IMPROVEMENT AND OPTIMIZATION OF THE SKYHOUGH CODE FOR ALL-SKY SEARCHES

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 [150, 151, 152]. Basic improvement includes refactoring the existing SkyHough executable in lalapps into a Python package in order to simplify any further developments, such as the extension to different source types, the use of an arbitrary number of detectors and the introduction of new detection statistics into the basic workflow. Core LALSuite functionalities, such as the lalpulsar library, can be accessed using the SWIG bindings [153]. This first refactoring will ease the implementation of further improvements to the pipeline, such as the use of GPU computing or the setup of machine learning algorithms to perform outlier selection. Review of new codes would be required.

ACTIVITY LT-4.15-C: IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

The transient $\mathcal{F}$-statistic method [134, 137] is well suited for quasi-monochromatic long transients after pulsar glitches (Section Op-4.10). 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 [138]. The method itself can easily support generic transient amplitude evolutions [134], e.g. exponential decay, but the LALSuite code [149] is very slow for these. A much faster GPU implementation is available [137, 118, 119] 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 all-sky CW searches (Section Op-4.7), 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.

ACTIVITY LT-4.15-D: 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.

ACTIVITY LT-4.15-E: OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

CrossCorr is the most sensitive pipeline to search for Sco X-1 (Section Op-4.5). Since the sensitivity is determined by the coherence time, which is tied to computing cost, the search is computationally limited: anything which allows the code to run faster enables us to run a more sensitive search. Improvements to the O1 pipeline include: use of resampling [154] to speed up the computation at lower frequencies; more efficient template lattices to cover the orbital parameter space; re-optimization of the choice of coherence times as a function of frequency and orbital parameters.

ACTIVITY LT-4.15-F: 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.

ACTIVITY LT-4.15-G: IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

PyFstat [118, 119] is a package for $\mathcal{F}$-statistic-based data analysis, aimed mostly at candidate followup (Section Op-4.12) and long-duration transients (Section Op-4.10). Ongoing and planned development includes closer interfacing with existing LALPulsar functionality, better support for CW sources in binaries, addition of utility functions for hierarchical followup schemes [120], and possibly migration of the MCMC-based followup methods [140] to the flexible Bilby parameter estimation package [155].

ACTIVITY LT-4.15-H: 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.

ACTIVITY LT-4.15-I: DEPLOY THE SOAP PIPELINE FOR INSTRUMENTAL LINE IDENTIFICATION.

SOAP [111] 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.

LT-4.16 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 Op-4.2). The stochastic wandering of the spin frequency of LMXBs is a key consideration for directed searches (Section Op-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 Op-4.9) or a pulsar glitch (Section Op-4.10) motivates the development of robust pipelines for such sources. 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.

Activities

ACTIVITY LT-4.16-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.

ACTIVITY LT-4.16-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 tihs 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 devaiting signals.

LT-4.17 Development of new and potentially more sensitive data analysis methods

Motivation

The CW group welcomes blue-sky research into new ideas for search methods which may yield increased sensitivity 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-4.17-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.

ACTIVITY LT-4.17-B: IMPLEMENT THE SKYHOUGH CODE FOR DEMODULATED DATA

Develop and optimize codes to adapt the SkyHough search pipeline to run on demodulated data, 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 in non-demodulated data, meaning the new code will benefit from any improvements on the already existing SkyHough pipeline.

ACTIVITY LT-4.17-C: 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 work in [156] 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.

ACTIVITY LT-4.17-D: MACHINE LEARNING FOR EFFICIENT ANALYSIS OF CWS AND TRANSIENT-CWS

In addition to making CW and transient-CW searches less model-dependent (Section LT-4.16), 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 are just as sensitive to the 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 [157, 158], to veto likely false candidates, etc. We plan to continue efforts to use machine learning to run searches [159], perform parameter estimate [160, 161], and to apply it in new ways.

ACTIVITY LT-4.17-E: NEW SEMI-COHERENT METHOD FOR DIRECTED SEARCHES FOR CONTINUOUS WAVES FROM NEUTRON STARS IN BINARY SYSTEMS

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, is being 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. Development and characterization of the pipeline is ongoing. Depending upon its performance, the pipeline would be used in production searches for Sco X-1 and other targets.

ACTIVITY LT-4.17-F: EXPANDED PARAMETER ESTIMATION 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.

LT-4.18 Use mock data challenges to compare data analysis pipelines

Motivation

Mock data challenges are a useful tool for comparing different data analyses pipeline. By subjecting each pipeline to a common set of tests, the benefits and costs of each pipeline can be rigorously assessed. Commonly, simulated data containing signals of varying strengths whose parameters are unknown to the analyst are prepared by a neutral party, and each pipeline is assessed based on the number of simulated signals it found. Successful mock data challenges organized within the CW group compared pipelines for directed searches for Scorpius X-1 [162] and all-sky searches for isolated sources [163].

Activities

ACTIVITY LT-4.18-A: SIMULATION INVESTIGATION FOR SCO X-1

The performance of CW pipelines to search for Sco X-1 will be tested with simulated signals injected into O3 data. In particular, simulations will be generated with varying amounts of spin wandering to check the practical limitations of CW pipelines. Results and conclusions will be reported in a short-author paper.

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.

Op-5.1 Search for an isotropic stochastic gravitational-wave background (short term)

Op-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 [164], phase transitions in the early universe [165, 166], and cosmic (super)strings [167, 168, 169, 170]. 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 [171], binary black holes [172], 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 [172, 171, 173].

General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [174, 175], $f(R)$ gravity [176, 177], bimetric [178] and massive [179] 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.

Op-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 [180, 181], which has served as the basis for all previous LIGO/Virgo stochastic searches [182, 183, 184, 185, 186, 187]. 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 Op-5.1-A: SEARCH FOR AN ISOTROPIC STOCHASTIC BACKGROUND

TASK Op-5.1-A(i): O4 ANALYSIS

FTE-months: 20.0 (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 Op-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) Development of a python-based pipeline for isotropic stochastic background search that will leverage the existing python infrastructure, for example for strain data manipulation and for parameter estimation. The pipeline will produce cross- and auto-correlation spectra that will then be used for the isotropic search as well as be compatible for use in producing folded data (to one sidereal day) and for searches for anisotropic stochastic background; (ii) Development and review of a general parameter estimation infrastructure that can support O4 analyses, which can be used for inference of stochastic backgrounds of any spectral shape (astrophysical and cosmological), and for magnetic noise; and (iii) performing mock data challenges to verify the detection capabilities of the stochastic search.

TASK Op-5.1-A(iii): IMPLICATIONS FOR ASTROPHYSICAL AND COSMOLOGICAL 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 [188, 171, 189], 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 background. 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. We will also 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, 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. Mock data challenges can be used to test the recovery of simulated backgrounds corresponding to different theoretical models. We expect the implications for astrophysical stochastic background to be included in the O4 isotropic background search paper, while implications for cosmological stochastic background models to be explored in a separate 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 [190]. 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.

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.

Op-5.2 Directional searches for persistent gravitational waves (short term)

Op-5.2.1 Scientific Case

While most prescriptions of the SGWB predict an isotropic signal, there are mechanisms that could introduce anisotropy [170, 191, 192, 193, 194, 195, 196]. For example, a confusion background may arise from binary mergers [188, 197, 198], core-collapse supernovae [199, 200], neutron-star excitations [201, 202], persistent emission from neutron stars [203, 204], and compact objects around supermassive black holes [205, 206]. 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 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 [207]); 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.

Op-5.2.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [208]:

$$\Omega_{\rm GW}(f,\Theta) \equiv \frac{1}{\rho_c}\,\frac{d^3\rho_{\rm GW}}{d\ln f\, d^2\Theta} = \frac{2\pi^2 f^3}{3H_0^2}\, H(f)P(\Theta), \quad \Omega_{\rm GW}(f) = \int d\Theta\,\Omega_{\rm GW}(f,\Theta), \tag{2}$$

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 [209, 208, 210] for further description and details on its inversion).

ACTIVITY Op-5.2-A: DIRECTIONAL SEARCH FOR PERSISTENT GRAVITATIONAL WAVES

TASK Op-5.2-A(i): MOCK DATA CHALLENGE

FTE-months: 30.0

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; and (iv) explore how all of the above change as a function of the detector network. Results of this MDC will guide the choices to be made in searches for anisotropic stochastic background using O4 data.

TASK Op-5.2-A(ii): PREPARATION FOR O4

FTE-months: 30.0

Develop and review a fully python-based code infrastructure for O4 directional analyses. This will include (i) folding data generation using intermediate data products from new python-based isotropic code infrastructure, (ii) performing spherical harmonic analysis in python, (iii) python-based post processing codes to calculate significance and upper limits, (iv) improving the upper limit calculation using better Bayesian priors, (v) improving data quality cuts for directional analyses, and (vi) demonstrating the efficiency of detection checklist and readiness for the first detection.

TASK Op-5.2-A(iii): O4 ANALYSIS

FTE-months: 20.0 (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 broadband all-sky search for measuring (or constraining) the energy flux on the sky from point sources (broadband radiometer analysis) and extended sources (spherical harmonic decomposition analysis) for different power-law spectral indices. (iv) Constrain published models of anisotropic GW backgrounds, for example from cosmic strings or compact binaries.

TASK Op-5.2-A(iv): TARGETED SEARCHES FOR POINT SOURCES AND EXTENDED SOURCES

FTE-months: 20.0 (includes all aspects of the search, review, and paper writing)

(i) Perform an unmodeled search for potentially interesting persistent GW sources from specific sky locations or from the galactic plane. (ii) Constrain published models of anisotropic GW backgrounds, for example population properties of neutron stars.

TASK Op-5.2-A(v): ALL-SKY ALL-FREQUENCY (ASAF) SEARCH FOR UNMODELED SOURCES

FTE-months: 20.0 (includes all aspects of the search, review, and paper writing)

Recent work [211] demonstrates that data compression using sidereal folding [212] can facilitate an extremely efficient narrowband search looking in all directions and at all frequencies. The all-sky, all-frequency extension to the point-source radiometer targets unknown neutron stars in binary systems as well as all other narrowband sources, providing a sensitive tool for discovering *any* persistent point source, which does not conform to the assumptions made by template-based searches. The search method has been tested by injecting and recovering synthetic signals in the presence of instrumental artifacts, using time-shifted O1 data [213]. Additionally, new methods have been introduced to produce sky maps in a highly efficient way by taking advantage of the compactness of the folded data and HEALPix pixelization tools for further standardization and optimization, as implemented in the code `PyStoch` [214]. They have been used in directional and ASAF searches using O3 and O4 data. Building on these developments, we plan to perform an all-sky, all-frequency radiometer search using O4 data. The maps can be used to identify patches on the sky to follow up with CW searches [See Section Op-10.1].

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.

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 [192, 194], and have applied the formalism to specific cases of the models due to BBH mergers [193, 195, 196, 215, 216, 217, 217, 218] and due to cosmic string networks [194]. We will develop a method 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 [215, 218]. 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 [191] or in the galactic center [207].

Op-5.3 Search for very-long transient gravitational-wave signals

Op-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. [219], 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) [81, 220, 221]. 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 [222], 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.

Op-5.3.2 Methodology

The transient searches will constrain the energy density $\Omega_{\rm gw}$ [180] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [223, 224, 225, 226, 227]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [223]. Gravitational-wave signals appear as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [223, 228, 226, 227, 229]) in order to identify statistically significant clusters of pixels. More recently, a highly-parallel seedless clustering algorithm [226, 227] was implemented, and recent work [227] demonstrates that GPUs and multi-core CPUs facilitate dramatic speed-ups. 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 [6, 7].

We will analyze data on timescales of ≈ 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 [230]. As an application of the STAMP very-long-transient pipeline, we will work in collaboration with the Burst group (Section Op-2.2) and CW group (Section Op-4.9) to search for post-BNS-merger gravitational-wave signals. Such a search for a long-lived remnant of GW170817 was conducted [123], 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 [231, 232] and follow-up/visualization of CBC triggers [229]. We expect continued development and maintenance of STAMP will be broadly useful for the Stochastic Group activities and the wider LSC/Virgo community.

ACTIVITY Op-5.3-A: SEARCH FOR VERY LONG TRANSIENTS

TASK Op-5.3-A(i): VLT CONTRIBUTION TO $\Omega_{\rm gw}$

FTE-months: 5.0

Measure (or set upper limits on) the energy density of the very long transient signals and their contribution to the overall $\Omega_{\rm gw}$. 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 Op-5.3-A(ii): STUDY OF BNS MERGER REMNANTS

FTE-months: 5.0

Apply the search for very long transients to data following mergers of binary neutron stars. Coordinate the search and the publication with similar searches conducted in the burst and CW groups.

LT-5.3 Search for very-long transient gravitational-wave signals (Long Term)

TASK LT-5.3-(i): 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

Op-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 [10] 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, we will generalize the CBC all-sky group to be 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 Op-6.1-A: SUBGROUP ADMINISTRATION

Management of the joint all-sky subgroup.

TASK Op-6.1-A(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 3.0

Op-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 [233]: 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 [234, 235, 236, 237, 238]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [239]. 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 [122].

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 ($\lesssim 1$ 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 (~ 1000 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 [240] in the case of short GRBs, or generic GW burst signals [241] for all GRBs. These searches are more sensitive than the corresponding all-sky ones. We run them both online (few-hour latency) and offline. We use an additional algorithm [242] 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 O2[243].

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 [O1 sub-th paper].

An offline cross-correlation algorithm[9] 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 Op-6.2-A: TRIGGERED GRB SEARCH AND PUBLICATIONS - OFFLINE

The following tasks are necessary for implementing the standard offline, triggered GRB search and to report results. With the O3b search and publication winding down, the main activity will be to ready the searches for O4.

TASK Op-6.2-A(i): COMPLETE THE O3B ANALYSIS

FTE-months: 3.0

Complete the O3b analysis and collaboration publication.

TASK Op-6.2-A(ii): 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 Op-6.2-A(iii): 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 Op-6.2-A(iv): EXCEPTIONAL EVENTS

FTE-months: 4.0

Follow up any exceptional event candidates identified in O4 in the all-sky Burst or CBC searches, or resulting from the above triggered searches. Follow-up will include consideration of any opportunistic search for long duration GWs from GRB remnants. Make the case for or against a single-event publication.

ACTIVITY Op-6.2-B: ONLINE SEARCHES

TASK Op-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.

ACTIVITY Op-6.2-C: SUB-THRESHOLD SEARCHES

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 Op-6.2-C(i): TARGETED SEARCHES

FTE-months: 3.0

Complete the O3 search and publication. Prepare for O4.

TASK Op-6.2-C(ii): UNTARGETED SEARCHES

FTE-months: 3.0

Complete the O3 search and publication. Prepare for O4.

ACTIVITY Op-6.2-D: 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 Op-6.2-D(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.

ACTIVITY Op-6.2-E: SUBGROUP ADMINISTRATION

Management of the GRB subgroup.

TASK Op-6.2-E(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: CBC-GRB PIPELINE

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.

ACTIVITY LT-6.2-B: MEDIUM LATENCY GRB PIPELINE

Continue development and updating of the infrastructure to run the GRB pipelines online.

ACTIVITY LT-6.2-C: NS FLARES

Develop method for follow-up of compact binary merger triggers with targeted Fermi-GBM search for orbitally-modulated NS flares [244].

ACTIVITY LT-6.2-D: 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.

ACTIVITY LT-6.2-E: SUB-THRESHOLD SEARCHES

Continue development of methods to exploit sub-threshold GRBs (from Fermi, Swift) and/or sub-threshold GW triggers.

Op-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 [245] 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 [246], including repeating sources [247], and an increasing number of radio telescopes are becoming involved in FRB identification, most notably the CHIME detector[248].

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. Given the delay in reaching an approved MOU, the O3 analyses are currently (June 2021) ongoing. The collaboration paper for O3a is expected soon, with the O3b paper expected to follow by early Fall 2021.

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 [249] 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[250] 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 Op-6.3-A: O3 ANALYSES AND PUBLICATIONS

TASK Op-6.3-A(i): COMPLETE THE O3A PUBLICATION

Complete the O3a GW analyses and the corresponding collaboration paper.

FTE-months: 3.0

TASK Op-6.3-A(ii): CARRY OUT THE O3B SEARCH

Define the CHIME triggers in range (within ≈ 400 Mpc) which occurred during O3b. Carry out the same analysis methods used for O3b. Prepare the corresponding O3b collaboration paper.

FTE-months: 4.0

ACTIVITY Op-6.3-B: PREPARE THE O4 SEARCH

Prepare for an O4 search. The methods are currently assumed to be very similar to those used in O3.

TASK Op-6.3-B(i): COLLECT THE FRB TRIGGERS

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.

FTE-months: 2.0

TASK Op-6.3-B(ii): RECONFIGURE, TEST AND RUN THE SEARCH PIPELINES

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.

FTE-months: 3.0

TASK Op-6.3-B(iii): EXCEPTIONAL EVENTS

In the event of a GW-FRB detection or an astrophysically interesting upper limit, make the case for a single-event publication.

FTE-months: 4.0

Op-6.4 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 [251, 252, 253] 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. Our goals for science deliverables are focused on the improvement of O1-O2 GW emission upper limits [254], 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 [255, 256, 257, 258, 254]. The methods employed overlap with the long-duration burst searches (Section Op-2.2) and the GRB group (Section Op-6.2).

In O3, there was exceptional magnetar-related phenomena which has spurred a proposed collaboration O3 paper. This was recently (June 2021) approved by the LSC and Virgo collaborations and is in progress. The first was the observation of a fast radio burst (FRB) associated with the galactic magnetar

SGR 1935+2154 (see Section Op-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.

ACTIVITY Op-6.4-A: O3 MAGNETAR ANALYSIS

TASK Op-6.4-A(i): CARRY OUT THE O3 ANALYSIS

FTE-months: 3.0

Carry out the triggered GW burst analyses associated with the O3 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.

TASK Op-6.4-A(ii): COMPLETE THE O3 PAPER

FTE-months: 3.0

Complete the O3 paper describing the search and results. The paper should be released prior to the O3b public data release.

ACTIVITY Op-6.4-B: 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 Op-6.4-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 Op-6.4-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.

TASK Op-6.4-B(iii): 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 Op-6.4-B(iv): 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-6.4 Search for GW transients from isolated neutron stars R&D (Long Term)

ACTIVITY LT-6.4-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-6.4-A(i): METHODS AND MODELING STUDIES

Continue to develop improved search methods. Develop parameter estimation techniques. Progress may require new developments in theoretical modeling or new neutron star observations.

Op-6.5 O3GK Observation Paper

Search for compact binary coalescences, short duration GW bursts, and targeted search for GRBs in GEO and KAGRA data during the O3GK data taking period.

ACTIVITY Op-6.5-A: COMPLETE THE O3GK PAPER

The analyses and paper writing are currently (June 2021) well under way. The White Paper from a year ago gave a detailed description of the activities and tasks. The main activities remaining are simply to complete the ongoing work. Since we expect KAGRA to be fully integrated for O4, there will be no need for a similar paper.

TASK Op-6.5-A(i): COMPLETE THE ANALYSES

FTE-months: 4.0

Complete the offline data analyses and reviews.

TASK Op-6.5-A(ii): COMPLETE THE PAPER

FTE-months: 4.0

Complete the collaboration paper and release it for publication. Prepare data release and science summary.

Op-6.6 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) [259, 260]. 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 [261], its surroundings [262], and the nature of relativistic outflows [263, 264]. 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 [265, 266, 267].

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 [268], LVT151012 and GW151226 [269], and GW170817 [270]. 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 [271, 272], including the coincident subthreshold analysis for the O1 observing period [273].

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 [274] while also including LIGO-Virgo as well as neutrino detector characteristics. The Bayesian framework is extendable to include additional messengers [275].

The same pipeline (LLAMA) is used in both offline and in low-latency mode [276]. The major tasks are to complete the O3 offline analysis/paper and to prepare for O4.

ACTIVITY Op-6.6-A: COMPLETE 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 Op-6.6-A(i): PIPELINE REVIEW

FTE-months: 2.0

Complete the review of the LLAMA pipeline for O3 offline analysis. This will allow its results to be made public as LVK products.

TASK Op-6.6-A(ii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW

FTE-months: 4.0

Collect and/or catalog triggers from IceCube and ANTARES from the O3 run. Collect the sub-threshold GW triggers with sky-localization from the CBC and Burst teams. Run the LLAMA pipeline in offline mode. Report results and prepare a publication for O3.

TASK Op-6.6-A(iii): EXCEPTIONAL EVENTS

FTE-months: 2.0

In the event of a GW-HEN detection or an astrophysically interesting upper limit, make the case for a single-event publication.

ACTIVITY Op-6.6-B: PREPARE THE O4 SEARCH

TASK Op-6.6-B(i): ONLINE SEARCH

FTE-months: 5.0

Prepare to send alerts for interesting GW+HEN associations, including sub-threshold events.

TASK Op-6.6-B(ii): MOUS

FTE-months: 1.0

Prepare or update MOU agreements with IceCube and KM3NeT.

TASK Op-6.6-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.

LT-6.6 Multimessenger search for GWs and high-energy neutrinos R&D

ACTIVITY LT-6.6-A: INCORPORATE AUGER AND KM3NET TRIGGERS

FTE-months: 2.0

Incorporate high energy cosmic ray triggers from the Pierre Auger Observatory as well as from KM3Net into the low-latency GW+HEN coincidence analysis, along with IceCube.

ACTIVITY LT-6.6-B: PREPARE FOR THE POSSIBILITY OF A TRIPLE MESSENGER EVENT

FTE-months: 4.0

Develop the extended framework for the proper statistical treatment of multimessenger events with at least three (GW, neutrino, and EM) messengers.

7 Burst+Stochastic Joint Activity Plans

Op-7.1 Search for GWs from cosmic strings

Motivation and methods

Cosmic strings [277] are one-dimensional topological defects, formed after a spontaneous symmetry phase transition characterized by a vacuum manifold with non-contractible loops [278]. These objects are expected to be generically formed in the context of Grand Unified Theories [279]. 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 [280, 281, 282, 283]. Cosmic strings produced in string-theory-motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [284, 285].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational-wave emission from loops [286, 287] and long strings [288]. 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 [288]. Both cusps and kinks produce powerful bursts of gravitational waves [289]. 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 [290].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [291, 185]. 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.

Major deliverables for this activity

ACTIVITY Op-7.1-A: O4 SEARCH FOR GRAVITATIONAL-WAVE BURSTS

TASK Op-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. If a gravitational-wave event is significant, estimate the cosmic string parameters considering up-to-date loop distribution models.

TASK Op-7.1-A(ii): SET UPPER LIMITS ON COSMIC STRING MODELS

FTE-months: 1.0

Decide which models/simulations predicting the loop distribution should be used to constrain cosmic string parameters. 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 Op-7.1-A(iii): DEVELOP A NEW BURST PIPELINE

FTE-months: 1.0

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 Op-7.1-A(iv): DEVELOP A STRATEGY TO FOLLOW-UP UNMODELLED BURST CANDIDATES

FTE-months: 1.0

If a short-duration unmodelled burst candidate is detected by the all-sky searches (see Sec Op-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 Op-7.1-B: O4 STOCHASTIC BACKGROUND SEARCH

TASK Op-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 [292].

TASK Op-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

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

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 [293]), 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. [293] which applies Bayesian parameter estimation to all available data. The search uses the output of parameter estimation code (e.g., Bilby [294]) 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 [293] 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 O3/O4 will focus on searching for "high-mass" BBH systems, which we take to be BBH systems with chirp masses in the range $12M_\odot \leq M_c \leq 45M_\odot$. 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 [293] 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 [295]. The same study develops tools to extract the population parameters of unresolved binaries;

see also [296]. Meanwhile, in [297] 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 O3/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.

Assuming that the above activities are performed successfully, we can then move to applying this search to O3/O4 data.

ACTIVITY LT-8.1-B: O3/O4 ANALYSIS

1. Run the search on O3 and O4 data. The choice of dataset will depend on what data are available when the pipeline is ready for application to 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.

9 Stochastic+DetChar Joint Activity Plans

Op-9.1 Data quality investigations for stochastic searches

Op-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. 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 manpower.

Op-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. 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 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 [298, 299].

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 [300]. The primary sources of these correlated fields are geophysical Schumann resonances [300]. 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 [301]. 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 [302].

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 Op-9.1-A: DETECTOR CHARACTERIZATION FOR STOCHASTIC SEARCHES

TASK Op-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 Op-9.1-A(ii): SCHUMANN RESONANCES

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 Schumann resonances 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 Schumann resonances contributions from the strain data, e.g., using the developed Wiener filtering techniques and magnetometer data.

TASK Op-9.1-A(iii): 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 Op-9.1-A(iv): 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.

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.

10 Stochastic+CW Joint Activity Plans

Op-10.1 Identification and follow-up of outliers in All-Sky All-Frequency (ASAF) 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 ASAF analysis [211] on folded data [212].

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 ASAF radiometer search is presently being carried out on folded O3 data using `PyStoch` [214] which produces a full sky- map at every frequency bin. Those regions of parameter space (sky locations and frequencies) that produce interesting outliers will 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.

Activities for O3

ACTIVITY Op-10.1-A: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION

TASK Op-10.1-A(i): IDENTIFICATION OF ASAF OUTLIERS

FTE-months: 8.0

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 Op-10.1-A(ii): FOLLOW-UP OF ASAF OUTLIERS AND SET UPPER LIMITS

FTE-months: 12.0

Develop and implement a sensible strategy to follow up ASAF 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 Op-10.1-B: O3 ANALYSIS

TASK Op-10.1-B(i): ANALYZE THE ASAF 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 Op-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 Op-10.1-B(iii): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, set an averaged population based upper limit on the gravitational-wave strain amplitude and derive astrophysical implications.

TASK Op-10.1-B(iv): REVIEW

FTE-months: 3.0

Review search set up, code, scripts, and results.

TASK Op-10.1-B(v): PUBLICATION

FTE-months: 3.0

In the event of interesting results (such as a candidate signal) prepare a stand-alone publication with input from both the CW and Stochastic groups. Otherwise, prepare for inclusion into relevant publication, perhaps the full-O3 all-sky CW paper and/or an O3 all-sky radiometer paper.

Op-10.2 Dark photon dark matter searches

Motivation

Gravitational wave interferometers can also be used to search for the existence of dark photon dark matter directly [303]. Such a dark matter background will induce displacements of test masses and mimic a GW signal in a very narrow frequency band. Because they are nearly aligned, the two LIGO 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 [304]. A semi-coherent method was recently developed within the Band-Sampled Data (BSD) framework [305] 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 [306]. These limits improve upon existing ones from O1 because they account for the contribution to the strain due to the finite light travel time [307].

Activities for O4

ACTIVITY Op-10.2-A: DARK PHOTON SEARCH

FTE-months: 3.0

These pipelines will be applied to carry out an analysis of O4 data.

A Total FTE Commitments

Activity Plan		FTE-months Op	 LT
Overview and Executive Summary		86.0	-
Op-2.1:	Search for short-duration GW bursts	15.0	-
LT-2.1:	Search for short-duration GW bursts R&D (Long Term)	-	-
Op-2.2:	Search for long-duration GW bursts	5.0	-
LT-2.2:	Search for long-duration GW bursts R&D (Long Term)	-	4.0
Op-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)	-	3.0
Op-2.4:	GW burst signal characterization	5.5	-
LT-2.4:	GW burst signal characterization R&D (Long Term)	-	-
Op-2.5:	Search for GWs from core-collapse supernova	4.0	-
LT-2.5:	Search for GWs from core-collapse supernova R&D (long term)	-	-
Subtotal for Burst Group Activity Plans		49.5	7.0
Op-3.1:	CBC Parameter Estimation R&D (Short Term)	116.0	-
LT-3.1:	CBC Parameter Estimation R&D (Long Term)	-	-
Op-3.2:	Tests of General Relativity R&D (Short Term)	34.0	-
LT-3.2:	Tests of General Relativity R&D (Long Term)	-	-
Op-3.3:	Studies of Extreme Matter R&D (Short Term)	92.0	-
LT-3.3:	Studies of Extreme Matter R&D (Long Term)	-	-
Op-3.4:	CBC Waveform Models R&D (Short Term)	256.0	-
LT-3.4:	CBC Waveform Models R&D (Long Term)	-	-
Op-3.5:	Binary Coalescence Rates and Population R&D (Short Term)	66.0	-
LT-3.5:	Binary Coalescence Rates and Population R&D (Long Term)	-	18.0
Op-3.6:	CBC Cosmology R&D (Short Term)	93.0	-
LT-3.6:	CBC Cosmology R&D (Long Term)	-	90.0
Op-3.7:	CBC All Sky Search InfraOps R&D	268.0	-
LT-3.7:	CBC All Sky Search R&D (Long Term)	-	-
Op-3.8:	CBC Service Willingness	-	-
Op-3.9:	O4a Catalog of Compact Binaries	111.7	-
Op-3.10:	O4a Astrophysical Distribution of Compact Binaries	43.2	-
Op-3.11:	O3b and O4 Strong-Field Tests of General Relativity	34.7	-
Op-3.12:	Inference of cosmological parameters with observational data	25.7	-
Op-3.13:	O4a Search for Lensed Gravitational Waves	46.2	-
Op-3.14:	Search for sub-solar-mass compact binary coalescences	21.2	-
Op-3.15:	Characterizing exceptional CBC events	12.0	-
Subtotal for CBC Group Activity Plans		1219.6	108.0
Op-4.1:	Targeted searches for known pulsars	36.0	-
Op-4.2:	Narrow-band searches for known pulsars	30.0	-
Op-4.3:	Targeted searches for non-tensorial emission from known pulsars	9.0	-

Activity Plan		FTE-months	
		Op	LT
Op-4.4:	Directed searches targeting Cassiopeia A and other Galactic supernova remnants	15.0	-
Op-4.5:	Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries	31.0	-
Op-4.6:	Directed searches targeted the Galactic center	12.0	-
Op-4.7:	All-sky searches for isolated sources	39.0	-
Op-4.8:	All-sky searches for unknown sources in binaries	16.0	-
Op-4.9:	Searches for long-transient emission from a post-merger neutron star	-	-
Op-4.10:	Searches for long-transient emission following a pulsar glitch	24.0	-
Op-4.11:	Searches for continuous emission from ultra-light boson clouds around black holes	13.0	-
Op-4.12:	Support for continuous wave searches: Follow-up of interesting candidates	6.0	-
Op-4.13:	Support for continuous wave searches: Data preparation	12.0	-
Op-4.14:	Support for continuous wave searches: Scientific software maintenance	9.0	-
LT-4.15:	Further improvement and optimization of existing data analysis pipelines	-	-
LT-4.16:	Development of model-robust/agnostic data analysis methods	-	-
LT-4.17:	Development of new and potentially more sensitive data analysis methods	-	-
LT-4.18:	Use mock data challenges to compare data analysis pipelines	-	-
Subtotal for CW Group Activity Plans		252.0	-
Op-5.1:	Search for an isotropic stochastic gravitational-wave background (short term)	60.0	-
LT-5.1:	Search for an isotropic stochastic gravitational-wave background (long term)	-	-
Op-5.2:	Directional searches for persistent gravitational waves (short term)	120.0	-
LT-5.2:	Directional searches for persistent gravitational waves (long term)	-	-
Op-5.3:	Search for very-long transient gravitational-wave signals	10.0	-
LT-5.3:	Search for very-long transient gravitational-wave signals (Long Term)	-	-
Subtotal for Stochastic Group Activity Plans		190.0	-
Op-6.1:	Search for GWs from black hole binaries	3.0	-
Op-6.2:	Multimessenger search for GWs and GRBs	27.0	-
LT-6.2:	Multimessenger search for GWs and GRBs R&D	-	-
Op-6.3:	Multimessenger search for GWs and fast radio bursts	16.0	-
Op-6.4:	Search for GW transients from magnetar flares and neutron star glitches	13.0	-
LT-6.4:	Search for GW transients from isolated neutron stars R&D (Long Term)	-	-
Op-6.5:	O3GK Observation Paper	8.0	-
Op-6.6:	Multimessenger search for GWs and high-energy neutrinos	18.0	-
LT-6.6:	Multimessenger search for GWs and high-energy neutrinos R&D	-	6.0
Subtotal for Burst+CBC Joint Activity Plans		85.0	6.0
Op-7.1:	Search for GWs from cosmic strings	10.0	-
LT-7.1:	Search for gravitational waves from cosmic strings R&D (Long Term)	-	-
Subtotal for Burst+Stochastic Joint Activity Plans		10.0	-

Activity Plan		FTE-months Op	 LT
LT-8.1:	Search for the stochastic background from unresolvable binary black hole mergers	-	-
Subtotal for Stochastic+CBC Joint Activity Plans		-	-
Op-9.1:	Data quality investigations for stochastic searches	26.0	-
LT-9.1:	Data quality investigations for stochastic searches (long term)	-	-
Subtotal for Stochastic+DetChar Joint Activity Plans		26.0	-
Op-10.2:	Dark photon dark matter searches	38.0	-
Subtotal for Stochastic+CW Joint Activity Plans		38.0	-
Grand Total		1956.1	121.0

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