LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

Document Type **LIGO–T1700214-v1**
VIR-0435A-17

The LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics (2017-2018 edition)

The LSC-Virgo Data Analysis Council
including the LSC-Virgo Data Analysis Working Groups
and the Detector Characterization Working Group

WWW: http://www.ligo.org/ and http://www.virgo.infn.it

Processed with LaTeX on 2017/06/20

Contents

1 Overview and Executive Summary

Gravitational wave searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo collaboration are organized by astrophysical source classification into four working groups. The **Compact Binary Coalescence (CBC)** group searches for signals for merging neutron stars or black holes by filtering the data with waveform templates. The **Burst (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 (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin. Joint teams across two or more working groups exist where the science suggests overlap between sources or methods. In addition, the **Detector Characterization (Detchar)** group collaborates with the detector commissioning teams and works to improve searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals.

The *LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics*, which is updated yearly, describes the astrophysical search plans of the LSC-Virgo working groups. For each group, it provides a mission statement and scientific priorities in the Advanced Detector Era, as well as statements from the Detector Characterization, Calibration and Hardware Injection teams.

The Advanced Detector Era (ADE) is the epoch of Advanced LIGO and Advanced Virgo science data acquisition, which began in September 2015 and has already yielded the first direct observation of gravitational waves by the Advanced LIGO detectors [PRL 116, 131103 (2016), PRL 116, 241103 (2016)]. Table 1 shows the past and planned schedule of science runs, as provided by the LSC-Virgo Joint Run Planning Committee, which includes representatives from the laboratories, the commissioning teams and search groups.

Epoch	Run Duration	Run Name	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		Binary Neutron Star Range (Mpc)		Number of Binary Neutron Star Detections	
			LIGO	Virgo	LIGO	Virgo		
2015–16	4 months	O1	20 – 30	–	68 – 78	–	–	actual [1,2]
2016–17	8 months	O2	25 – 35	20 – 40	70 – 90	20 – 40	0.006 – 20	in progress [3]
2018–19	12 months	O3	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	projected [3]

Table 1: Plausible observing schedule and expected sensitivities for the Advanced LIGO and Virgo detectors. The O1 Burst range is for ~ 150 Hz signals, from [1 – arXiv:1611.02972] . The O1 BNS range is from [2 – arXiv:1607.07456]. The O2 LIGO BNS range is from public status updates on the ligo.org web site. Projected sensitivity for Virgo in the last months of O2 and for LIGO and Virgo in O3 will be strongly dependent on commissioning progress [3 – Living Rev. Relativity 19 (2016), 1].

The LSC-Virgo scientific priorities for ADE observations are summarized in Table 2, by search group, 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 low detection probability but high scientific payoff.

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

We note that the LSC-Virgo Collaboration has adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for all astrophysical results to be validated with a different analysis, using independent methods and

	Burst	CBC	CW	SGWB
Highest priority	All-sky search for generic GW transients, in low latency for EM followup and deep, offline for 4σ detection confidence	Detecting the coalescence of neutron star and black hole binaries and measuring their parameters	All-sky search for isolated neutron stars, both as a *quick-look* on owned resources and as a deep/broad search on Einstein@Home	Searches for an isotropic stochastic GW background
	Parameter estimation for the astrophysical interpretation of detected burst events	Characterizing the astrophysical distribution of compact binaries	Targeted search for high value, known pulsars	Directional searches for stochastic GW backgrounds
	Search for GW bursts triggered by outstanding GRB alerts	Responding to exceptional CBC detections	Directed searches for most promising isolated stars (Cas A, Vela Jr etc.)	Search for very long transients ($\sim$ 10 hr $-$ days)
	Searches triggered by outstanding astrophysical events (a galactic supernova, neutron star transients, an exceptional high energy neutrino alert)	Multi-messenger astronomy with compact binaries	Directed searches for X-ray binaries SCO-X1 and J1751-305	Data folding for efficient SGWB searches
	Search for cosmic string kinks and cusps	Searching for CBC-GRB coincidences		Searches for non-Gaussian backgrounds
		Testing General Relativity with Compact Binaries		Data quality and detector characterisation studies
High priority	Searches triggered by high energy neutrinos, extragalactic supernovae, and GRB observations	All sky search for spinning binary neutron star systems (deep and low latency)	Targeted search for other known pulsars	Long transient follow up of CBC and burst candidates
	Burst search for intermediate mass ratio and eccentric black hole binary systems	Matched filtered search for intermediate mass black hole binary systems	Directed searches for other isolated stars and X-ray binaries	
	All-sky search for long bursts of > 10 s duration			
Additional priority	GRB-triggered search for long-duration bursts and plateaus	Exploring effects of detector noise on parameter estimation	All sky search for isolated stars (alternative approaches)	
	Hypermassive neutron star followup	Searching for sub-solar mass CBC signals	All-sky search for binaries	
	Burst searches triggered by radio transients and by SGR/SGR-QPO	Developing searches for CBC signals with generic spins	Spotlight deep sky-patch search	
	Burst tests of alternative gravity theories **		Search for continuous wave transients	
			Search for Supernova post birth signals **	

Table 2: Science priorities of the LIGO-Virgo collaboration, for the four astrophysics search groups: Bursts, Compact Binary Coalescences (CBC), Continuous Waves (CW), and Stochastic Gravitational Wave Background (SGWB). The targets are grouped in three categories (highest priority, high priority, additional priority), based on their detection potential with Advanced Detectors. There is no additional ranking within each category in this table. Critical for accomplishing these science priorities are the detector characterization, calibration and injection activities described in this document.
** Future searches under development, not included in ongoing production computing requests.

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.

[Below here, each of the four search groups, plus Detchar and Calibration, has up to two pages to describe the mission of the group, the types of signals being sought, and the rationale behind the group's priorities.]

1.1 Searches for Generic Transients, or Bursts

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and gain new information on populations and emission mechanisms of the associated astrophysical objects, as well as to test theories of gravity. Central to the Burst group philosophy is the assumption of minimal information on the source, so that searches for gravitational wave bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the gravitational wave signature. Burst searches are, therefore, sensitive to gravitational wave transients from a wide range of progenitors, ranging from known sources such as binary black-hole mergers (in particular the most massive and loudest ones) to poorly-modelled signals such as core-collapse supernovae as well as transients that are currently unknown to science. 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 core-collapse into a gravitational wave signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces gravitational wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, we need 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 gravitational waves and noise fluctuations, the analysis 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. In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star ring-downs, a search can be done using matched filtering with a bank of templates.

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. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities.

Many gravitational wave burst sources should also be observable in more traditional channels, from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational wave 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 gravitational-wave burst detection. Most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational wave 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.

1. **Highest priority**

   The Burst group is focused on an *eyes wide open* approach to detecting gravitational wave transients. To maximize its discovery potential, the Burst group employs a strategy of multiple searches, overlapping in parameter space to allow for cross-validation of search outputs. Highest priority goals for the analysis of advanced detector data include:

   - a statement on the transient gravitational wave sky, with population studies if we have several detections, a rare-event detection significance if we have one candidate or an upper limit on the rate of gravitational wave bursts if there is no detection;

- deployment of multiple analyses for cross validation of the all-sky search results, including verifying the significance of any observed events, across a wide parameter space. This is especially important for events that are not matched to a specific source model;
- the astrophysical interpretation of any detected signals, leveraging signal characterization and parameter estimation;
- a prompt analysis, trigger production and sky localization, to enable the electromagnetic follow-up of gravitational wave transients;
- prompt reports on astrophysically significant events, such as nearby gamma ray bursts, soft gamma repeater hyperflares, galactic supernovae as well as exceptional bursts of low (MeV) or high (GeV–PeV) energy neutrinos;
- a dedicated search for gravitational wave bursts originating from cosmic strings.

2. **High priority**

   The Burst group will extend the parameter space of the all-sky search to include longer duration transients ($\geq 10\,\mathrm{s}$) which may originate from various astrophysical sources such as long gamma-ray bursts. Long-duration burst searches share similar complexities with their short-duration counterparts. Since the long-duration search is not as mature as the short-duration one, multiple analyses will be deployed to cross-validate the results.

   The Burst group will also pursue, with the burst analysis approach, some classes of compact binary coalescence sources that are not well covered by the current waveform template banks. These include intermediate mass binary black holes, binary black holes with eccentric orbits and intermediate mass ratio inspirals.

   Finally, the Burst group will pursue multi-messenger searches for gravitational wave bursts in conjunction with signatures such as generic gamma ray bursts, fast radio transients, low- and high-energy neutrino observations, and electromagnetic observations of nearby core-collapse supernovae. The Burst group will use information on the astrophysical event to reduce the parameter space over which searches must be performed, leading to a reduction in the false alarm rate and, consequently, an improvement in search sensitivities.

3. **Additional Priority**

   Additional priorities include the search for gravitational waves in association with neutron star transients (eg. pulsar glitches, type I X-ray bursts and soft gamma ray repeater flares) and testing alternative theories of gravity with gravitational wave bursts.

Several of these science targets – intermediate mass black hole binaries, GRBs, electromagnetic followup – overlap with the CBC group, and joint teams are working together across the two groups on these targets.

1.2 Searches for Signals from Compact Binary Coalescences

On September 14, 2015, one-hundred years after gravitational waves were first predicted, the advanced LIGO experiment detected gravitational waves from the merger of two black holes. This discovery was followed by a second confirmed binary black hole detection on December 26, 2015. The second observing run (Nov 2016 - summer 2017) yielded the discovery of GW170104, firmly establishing the existence of stellar-mass binary black hole mergers as a primary source population for Advanced LIGO and Advanced Virgo. Furthermore, we anticipate discovery of entirely new source classes such as coalescing binary systems containing neutron stars within the next few years. The Compact Binary Coalescence group aims to discover new 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 compact binary coalescence 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. We expect a tremendous human effort will be required to develop, deploy, run and interpret the results of low-latency and offline searches as in the context of evolving detector sensitivity and data quality. Additionally, the compact binary coalescence 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. With this in mind we have outlined the following projects which cover the goals of the group in the coming year.

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 the first detection of binary neutron-star, neutron-star black-hole binary or intermediate 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, measurement of the nuclear equation of state could be made
    - **Producing a catalogue of detected compact binaries**. We will produce a summary of all compact binaries detected during each science 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 modelling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals such as LVT151012, along with their estimated p-value.
    - **Characterizing the astrophysical distributions of compact objects**. As the number of de-

tections increases, we will begin to build a 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 a compact binary coalescence provide a unique window into the behavior 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 in general relativity such as the no-hair and area theorems.
- **Multimessenger astronomy and astrophysics**. The observation of an electromagnetic or neutrino counterpart to a gravitational wave signal will be of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by providing alerts to our observing partners. This requires the continued development of low-latency pipelines for detection and localization of sources, and the infrastructure associated with collating and distributing information about detection candidates.
- **Gamma-ray bursts**. The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact discoveries possible in the compact binary field. We will continue performing a deep coherent search for gravitational waves focussed 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 develop 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.

2. **High Priority**

High priority activities are those which are less certain to produce a significant result in the time-scale of the coming year, but where the potential payoff would be high.

- **Intermediate mass black hole binaries & intermediate mass-ratio inspirals**. A goal of the compact binary coalescence 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 searches for intermediate-mass ratio inspirals and waveforms to describe them.
- **Eccentric binaries**. Eccentric binary systems are another potential class of source where the searches and waveforms are less mature and templated searches and unmodelled searches can be combined to allow for the range of eccentricity and robustness of our models.
- **Spinning binary neutron stars**. Searching for neutron star binaries with significant component spin is also a high priority. Although neutron stars in binary systems have been observed to have small spin, some isolated neutron stars are known to spin significantly. If neutron stars with significant spins do exist in binary systems, then opportunities to detect them could be lost without a dedicated search.

3. **Additional Priority**

   Building more accurate noise models for parameter estimation techniques can dramatically mitigate the effects of non-stationary, non-Gaussian noise on the fidelity of parameter inference. It is a priority to conduct a simulation campaign to study improved noise models for parameter estimation.

   The compact binary parameter space searched in higher priorities is not complete. It covers a plausible range of physical parameters based on observation and stellar evolution models. However, there are other interesting but less plausible parameter spaces which would have a dramatic impact if discovered. Given additional resources, we would consider searching for compact objects below one solar mass. It is possible that neutron stars or black holes could exist with masses down to fractions of a solar mass and be in detectable binary systems. Additionally, although parameter estimation techniques use waveforms that account for orbital precession, detection searches do not presently include precession effects in the templates. Work is ongoing to develop such a search, and with additional resources, we would conduct a precessing binary search in the future.

1.3 Searches for Continuous-wave Signals

The LSC/Virgo Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal and extremely weak, believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including 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 and distances, energy conservation allows setting an upper limit on gravitational wave strain amplitude, known as the *spindown* limit, albeit with significant uncertainties due to poorly understood neutron star astrophysics. Previous searches in LIGO and Virgo data have obtained 95% confidence upper limits well below the spindown limits for the Crab and Vela pulsars. As interferometer sensitivities improve in the Advanced Detector Era, several dozen more known pulsars will become spindown-accessible, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or on 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.

Because there is so much astrophysical uncertainty in continuous gravitational wave emission and because electromagnetic astronomers have detected about 2500 of the O(10^{8-9}) neutron stars believed to populate our galaxy, the CW group has established a broad program to search for gravitational wave emission from five distinct source categories, ordered below by decreasing *a priori* information known about the sources: 1) known pulsars with well measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) known or suspected binary neutron star systems; 4) unknown isolated stars in any direction; and 5) unknown binary stars in any direction.

This ordering of categories corresponds to ordering by source strain sensitivity. Targeted searches using known ephemerides from radio, X-ray or γ-ray timing measurements can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans with minimal trials factor corrections. Directed searches using known sky locations but having no *a priori* frequency information (e.g., *Cassiopeia A*) are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched). The sensitivity achievable with all-sky searches is still further limited by the need to make sky-location-dependent corrections for Doppler modulations of detected source frequency due to the Earth's motion (daily rotation and orbital motion). The number of sky points to search to maintain accurate demodulation grows rapidly with coherence time used in the search (time scale over which the signal is assumed to follow a precise phase model). The effect is severe enough to preclude all-sky searches using coherence times equal to the full observation spans of data runs. Adopting semi-coherent summing of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Directed searches for suspected neutron stars in binary systems with unknown source frequency must make similar sensitivity tradeoffs, and all-sky searches for sources in unknown binary systems define the current extreme in sensitivity tradeoff for tractability.

In the case of known objects, we have identified sources that seem to be the most promising, and should priorities need to be set because of limited resources (labor or computing), those sources will receive the highest priority. With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories, with the following priorities:

1. **Highest priority**

   - Targeted searches for the Crab and Vela pulsars and any other stars for which the spindown limit is likely to be beaten to within a factor of two. High-interest stars likely to fall in this category include PSR J0537–6910 and PSRJ1813–1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.
   - Directed search for Cassiopeia A which is the youngest known neutron star in the galaxy, but for which the spin frequency is unknown. (This choice of primary source is under reconsideration; Vela Jr. may be more promising, under some astrophysical assumptions.)
   - Directed searches for the X-ray binaries Scorpius X–1, Cygnus X–3, PSR J1751–305 and 4U 1636-536. The first two are especially bright in X-rays, and in the torque-balance model, GW luminosity scales with X-ray luminosity, while there is evidence in the last two objects for sharp X-ray periodicities that may indicate an r-mode oscillation.
   - All-sky searches for unknown isolated stars. These searches necessarily suffer from degraded strain sensitivity relative to what can be achieved in the targeted and directed searches, but they cast a very wide net, offering a reasonable prospect of discovery.

2. **High priority**

   - Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten, according to conventional theory, but which are extreme astrophysical objects of great interest.
   - Directed searches for young supernova remnants other than Cassiopeia A, including Supernova 1987A, for sources near the galactic center, for sources in nearby globular clusters and for unidentified γ-ray sources with pulsar-like spectra.
   - Directed searches for additional X-ray binaries.

3. **Additional priority**

   - All-sky searches for unknown binary stars. Because of the additional unknown orbital parameter space to search, these searches are most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability.
   - All-sky searches for unknown isolated stars, using alternative algorithms.

For every type of search, the CW group supports at least two independent methods (pipelines). This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimum handling of instrumental artifacts. The robustness against incorrect signal modeling is especially important for accreting sources, such as Scorpius X–1, where the time span over which the coherence of the signal model can be safely assumed is uncertain. In fact, that time scale is likely to vary in response to fluctuations in accretion rate.

There is some overlap in the CW search space with searches carried out in the Burst and Stochastic working groups. Long-lived transients can be considered to be short-lived CW sources. A small joint subgroup with members from both the CW and Burst groups is carrying out work in this area. CW sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the "radiometer" method in use by the Stochastic group. Tradeoffs among search methods for such sources are being explored in a joint CW/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.4 Searches for Stochastic Backgrounds

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 pre-Big-Bang models or from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The measured rate of BBH 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 and transient SGWB signals.

Although no SGWB was detected during O1, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 1.7 \times 10^{-7}$ at 95% confidence. When advanced detectors reach design sensitivity, we expect to be sensitive to an energy density as low as $\Omega_0 < 6 \times 10^{-10}$. The isotropic search has been extended to include a test for 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, since the true background may not be fully described by a single power law. Independent methods have been developed to consider all physically allowed spectral shapes using a 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 the understanding and interpretation of the implications observational results. Additionally, a fully-Bayesian analysis for an isotropic SGWB is being developed using BayesWave. This analysis is capable of estimating noise power spectra and modelling glitches in the data, allowing a simultaneous estimate of both detector noise and GW background contributions to observed data in a fully-Bayesian manner.

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 will also be applied to search for an anisotropic GW background estimated from pulsars in the galactic plane. 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 unmodelled 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, which we can test against our results. Continuous wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable via the stochastic radiometer, or 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 Wave search groups.

It has been demonstrated that data compressed using sidereal folding can be used to facilitate extremely efficient searches over long observing times. The stochastic group is producing a combined extended data set folded data set for the O1/O2 observing runs. This data set will be utilised by the all-sky all-frequency radiometer, by the very long transient search, and by the galactic pulsar search.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background, however a background for example from unresolvable binary BH mergers, which is likely to be detected first by the stochastic group, 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 coalscences 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.

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. **Highest priority**

   The stochastic group places highest priority on activities that are essential for detecting and interpreting the stochastic background. The isotropic analysis is the original *raison d'être* for the SGWB working group, and the detection of a stochastic background is the SGWB group's most compelling scientific deliverable. We include in the **isotropic searches** recent and planned extensions including a search for non-GR polarisations, parameter estimation and model development, and a fully-Bayesian search for an isotropic power-law background. The standard **directional searches** employ 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. Extensions to the directional searches include an all-sky all-frequency radiometer search for unmodelled persistent GW signals, a search for an anisotropic background from Galactic pulsars, component separation using narrowband maps and models of anisotropic backgrounds will provide a detailed picture of an observable background. The **search for very long transients** assesses the temporal distribution of the SGWB. The production of a combined extended **folded data set** facilitates the application of the very-long transient search, the all-sky all-frequency radiometer and the galactic pulsar search. The **non-Gaussian searches** will handle the non-stationarity of an astrophysical background. **Data quality and detector characterisation studies** are essential to the understanding and interpretation of results for all of the group's activities.

2. **High priority**

   We assign high priority to a software injection study on intermittent transients, to investigate how such signals may bias the stochastic analyses.

1.5 Characterization of the Detectors and their Data

LIGO: LIGO's sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Continued detection, the vetting of candidate signals, and the accuracy of parameter estimation is *crucially* dependent on the quality of the data searched and the collaboration's knowledge of the instrument and environment. The LIGO Detector Characterization group is focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to clean the data sets, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the early Advanced LIGO detectors to help to identify data quality issues early enough that they can be addressed in the instruments to improve future instrument and search performance.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that have a negative impact on astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Coalescing Binaries and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data must be cleaned of transient data quality issues. The primary forms of data quality information that must be delivered to the astrophysical search groups are: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; *veto segments* that indicate periods of poor quality data; and *data quality triggers* that identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use veto segments and data quality triggers to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave and stochastic backgrounds searches, frequency bins that are contaminated by non-astrophysical disturbances must be identified and removed, and low-level, broadband contamination from correlated magnetic noise must be mitigated.

Automation of Data Quality assessment: With the anticipated signal rate for O2, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must develop automated approaches to respond to items on the Detection Checklist. The objective is to reduce to a minimum the amount of manual sorting through signals, flagging of problems, and identification of sources of defects in the data. This will be the main focus of the group during O2, with partners in the astrophysical search groups collaborating on both identifying pipeline needs and sensitivities to data defects.

aLIGO Instrument Characterization: The Detector Characterization group works with the detector commissioning and engineering groups to identify and resolve issues in the aLIGO subsystems related to glitch and noise contamination, channel signal fidelity and robustness, etc. This work has led to early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to facilitate aLIGO detections by ensuring that the detectors are well understood and that fixes for data quality issues are aggressively pursued.

1. **Highest priority.** The highest priority of the LIGO Detector Characterization group is to provide timely data quality information to the LSC-Virgo search groups that designate what data should be analyzed, remove egregious data quality issues, and identify periods/frequencies of poor data quality. Automation is central to success in this activity.

2. **High priorities.** Complement and collaborate on commissioning with tools and insights to help find sources of transient and CW data defects. Use the non-interferometer sensors to find, quantify, and mitigate coupling to the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.

3. **Priorities.** Develop improved methods to uncover the causes of the noise transients which most impact the searches, with the goal of mitigating them or producing vetoes. Pursue, when motivated, exploration of new approaches to data quality issues.

To accomplish these priorities, the LIGO Detector Characterization group requires

- search group participation to call out sensitivities in the pipelines to data defects
- data quality experts to identify data defects and establish relationships to instrument events
- code developers to establish both infrastructures and specific modules to recognize and flag defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients, and to identify mitigation where needed

Virgo

Noise mitigation, spectral lines identification, glitch reduction and data quality vetoes are the main tasks of the Virgo detector characterization group. Responsibilities include working with the commissioning team to track down any limitation to the detector's sensitivity, working with the calibration team to maintain the calibration and timing accuracy to an acceptable level for GW searches, and providing noise information and vetoes to the data analysis groups and commissioning team. During past science runs and commissioning periods, the Virgo detector characterization team has provided several investigation and monitoring tools, and data quality vetoes which impacted positively both commissioning activity and astrophysical searches.

Search Data Quality: A new Virgo data quality model has been developed and is currently implemented. This model defines workflows and procedures the group will follow to provide data quality products to searches. In particular, emphasis is made to produce and deliver search-specific data quality vetoes. On top of this, a new and ambitious online architecture is being implemented to provide vetoes to online search pipelines. We have developed with LIGO a common data quality segment database, to benefit Burst and CBC groups. It has been moved to production. Additional data quality needs specific to CW and Stochastic search groups include the identification of noise source contributions to spectral lines or non stationary and non linear features. For this, we use automatic spectral lines identification tools already well tested, and a line database.

Early AdvVirgo Characterization: The Virgo detector characterization team will begin noise and glitch studies on each commissioned sub-system as soon as they come online, in close collaboration with sub-system hardware coordinators and commissioners. A system of shifts has been organized. Periodically, a team of two shifters is on watch. They study transient and spectral noise using analysis tools developed by the group.

1. **Highest priority**
   The highest priority of the Virgo Detector Characterization is to find and mitigate the sources of noise and to provide data quality information to the LSC-Virgo search groups in order to reduce the impact of the remaining noises.

2. **High priority**
   Our current high priorities are the development of useful tools for commissioning and an early characterization of each sub-system of Advanced Virgo in order to reduce the need of vetoes in future searches. This will imply a coherent system of monitoring web pages, a spectral line database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Additional priority**
   Additional priorities for Virgo detector characterization are to develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches, and to implement automated noise classification tools.

1.6 Data Calibration

1.6.1 LIGO Calibration

LIGO calibration includes all work to produce the calibrated strain time series that is used by all astrophysical analyses. This necessary work includes:

- creating the accurate models of the detector to calibrate the data
- maintaining the necessary infrastructure and performing the physical measurements needed to calibrate the detector models
- tracking and correcting for time-varying changes in detector configuration and performance
- providing an error budget on the calibration that astrophysical analyses use to establish uncertainties in measured quantities
- producing a calibrated detector time series in low-latency for multi-messenger astronomy
- providing infrastructure to re-calibrate the detector data with improved measurements and correcting problems with the low-latency calibration
- providing scientific support for the collaboration's astrophysical analyses on matters of detector calibration and its accuracy.

Since the calibration of the detector changes in response to its day-to-day environmental and physical state, and in response to planned commissioning changes that improve its sensitivity, calibration of the data is an ongoing task that requires continuous activity both during and between observing runs.

1.6.2 Virgo Calibration

During the Virgo science runs, the calibration measurements have been automated and extended to have some redundant data. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration output are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the h(t) strain digital time series and (iii) for the hardware injections. Independent cross-check of the reconstruction has been done systematically during VSR4 using a photon calibrator.

The methods used for Virgo will still apply for AdV after some tuning for the new configuration. Simulations have been carried on for the a priori most challenging measurements, i.e. the measurement of the mirror actuation response. They confirm that the Virgo methods can still be applied, putting some constraints on the minimum force to be applied on the AdV arm mirrors. In parallel a conceptual design of the new photon calibrator to be developed for AdV is being finalized before the setup is built and then installed in 2015. Critical calibration activities are:

1. development and improvement of instrumental measurements (in particular with the digital demodulation electronics of the photodiode readout),
2. prototyping and installation of a photon calibrator,
3. development of online tools to monitor the Virgo timing permanently,

4. upgrade the h(t) reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

1.6.3 LIGO and Virgo Hardware Injections

Hardware injections are simulated gravitational wave signals added to LIGO and Virgo strain data by physically actuating on the test masses. They provide an end-to-end validation of our ability to detect gravitational waves: from the detector, through data analysis pipelines, to the interpretation of results. The hardware injection group is tasked with the development, testing, and maintenance of hardware injection infrastructure. This includes on-site software to carry out the injections at specified times. We also work with the search groups to maintain the software that generates gravitational waveforms suitable for injection.

Each data analysis group works with the hardware injection team, in different ways: Burst and CBC groups provide transient waveforms and determine suitable injection rates, the CW group selects the parameters for neutron star signals, which persist throughout the science run, and the SGWB group typically carries out one or two $\approx$[10] min injections during each science run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up, and the results of these studies are reported back to the hardware injection team so that adjustments can be made.

While most injections are known to the LSC, there are also blind injections, for a blind test of the analysis. Although blind injections are performed by a separate team, the hardware injection group is in charge of maintaining the blind injection infrastructure, nearly identical to the regular injection one, and provides training.

1.6.4 LIGO Timing Diagnostics

Traceable and closely monitored timing performance of the detectors is mission critical for reliable interferometer operation, astrophysical data analysis and discoveries. The advanced LIGO timing distribution system provides synchronized timing between different detectors, as well as synchronization to an absolute time measure, UTC. Additionally, the timing distribution system must provide synchronous timing to subsystems of the detector. Timing distribution system's status is monitored, and periodically tested in-depth via timing diagnostics studies.

Critical timing tasks include:

1. verifying traceable performance of the timing distribution system,
2. verifying the validity and accuracy of the recorded time-stamp,
3. verifying the accuracy of the distributed timing signals,
4. expanding the capabilities of data monitoring tools related to timing,
5. availability of timing diagnostics for various subsystems,
6. measuring and documenting the timing performance,
7. reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.

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.

2.1 Search for short-duration GW bursts

A wide range of highly energetic astrophysical phenomena are expected to be accompanied by emission of gravitational-wave transients lasting from milli-seconds to several seconds within the instruments' frequency band. For some transient sources, especially binary compact systems made up of neutron stars and black holes, their expected gravitational-wave emission is modelled well enough over most of their parameter space so that matched filter techniques can be used to seek them in data from ground-based laser interferometers. However, there exists a range of plausible sources of short-duration gravitational-wave emission for which their signal morphologies are poorly modelled or even unknown and for which no matched filter techniques can be employed in an effective way. Such sources include core-collapse supernovae, long gamma-ray bursts, soft-gamma repeaters as well as 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; a noteworthy goal given the current early stages of gravitational-wave astronomy.

The all-sky search for transients was one of the first searches pursued when interferometric data first became available in 2001 [1]. Since then, all data from the LIGO and Virgo detectors have been searched for bursts, using a variety of techniques [2, 3, 4, 5, 6]. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to project the signal onto and identify excess power in the time-frequency decomposition of single detector data [7, 8, 9]. Multi-instrument analysis is essential for the robust detection of unmodelled gravitational-wave transients; fully coherent methods have been shown to perform well rejecting noise transients while recovering relatively weak signals. They use multiple measurements from an arbitrary number of interferometric detectors to solve the inverse problem for the impinging gravitational-wave signal. They use maximum likelihood or explicitly Bayesian frameworks to define an optimal solution. For candidate transients, statistical significance is evaluated by repeating the analysis using data that is cleansed of real signals through unphysical time-slides. In order to evaluate search sensitivity and place upper-limits, the pipelines are run over data that contains sets of simulated astrophysical signals.

The search for unmodelled transients has benefited from independent implementations; we plan to continue with this 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.

There is strong motivation for performing all-sky transiet searches in low latency; recent science runs have utilized triggers produced with only a few minutes of lag time. Prompt identification of detection candidates allows for rapid follow-up observations using electromagnetic telescopes, and also can inform detector characterization and operations.

O2/O3 Deliverables

- Produce rapid alerts for event candidates by running low-latency search pipelines.
- Draft a comprehensive paper reporting final search results within 3-months from the end of the run.
- Produce data quality flags and vetoes to use for both the low-latency and off-line searches.
- Quantify improvement in search sensitivity gained by including Virgo data

- Deliver mid-run results at set intervals

2.2 Search without templates for GWs from binary black holes

Compact binary coalescences (CBC), containing some combination of neutron stars (NS) and black holes (BH), are the most promising sources for first detection with advanced gravitational wave (GW) detectors. Compact binaries formed from stellar binary progenitors, which have historically been considered the most probable sources, are expected to circularize due to gravitational-wave emission prior to reaching the sensitive band of advanced detectors. However, other types of dynamically formed CBC sources covering a large range of component masses, spins and eccentricities are also possible. For example, dynamically formed compact binaries may retain significant residual eccentricity when they enter the sensitive band of Advanced LIGO and Advanced Virgo. The inspiral and merger-ringdown (IMR) of these eccentric binary black holes (eBBH) may therefore be a promising candidate for gravitational-wave detection. A detection of these sources would provide information regarding the viability of several proposed dynamical formation mechanisms, and a measurement of the eccentricity would help discriminate among those scenarios. However, standard CBC searches using quasi-circular IMR waveforms from stellar-mass binaries will not detect these systems for eccentricities $e >\sim 0.05$ [10], so a dedicated search for these potential sources is required. Targeting this parameter space with a burst method, which does not rely on templates, creates a search which 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, and/or deviations from general relativity.

The focus of previous gravitational-wave searches for compact-object (CO) binaries has centered on quasicircular systems, since gravitational waves are known to circularize binaries, and there is ample time to circularize if the system was formed from a stellar binary progenitor. However, more recent 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 a significant amount of eccentricity will remain when the binaries evolve into the Advanced LIGO (aLIGO) band. In galactic centers, mass segregation around the central massive BH can lead to large densities of stellar mass BHs. The Fokker-Planck model used in [11] suggests that our galactic nucleus should have ~ 2000 BHs and ~ 400 NSs in the central 0.1 pc. In [12, 13], the event rate for the formation of BH-BH binaries from GW capture in this setting was estimated to be between 0.01 and 1.0 yr^{-1} Gpc^{-3}, with corresponding Advanced LIGO detection rates of $\approx 1 - 10^2$ yr^{-1}. The formation of BH-NS binaries is estimated to be $\sim 1\%$ of this rate [12].

Dynamical capture binaries may also form in globular clusters (GCs) that undergo core collapse [14, 15]. In [16], it was estimated that binary formation through tidal capture would result in a NS-NS tidal capture rate that would peak at ~ 50 yr^{-1} Gpc^{-3} at $z = 0.7$, falling to ~ 30 yr^{-1} Gpc^{-3} by $z = 0$. They also provide a scaling to BH-NS and BH-BH mergers which gives rates that peak at ~ 70 yr^{-1}Gpc^{-3} and ~ 20 yr^{-1}Gpc^{-3} for BH-NS and BH-BH mergers, respectively.

There is also the possibility that eccentric mergers could result from hierarchical triples through the Kozai mechanism. This has been suggested to occur in BH-BH mergers in GCs [17, 18, 19] and CO mergers around supermassive BHs in galactic nuclei [20], as well as in coevolved or dynamically formed BH-NS or NS-NS binaries [21]. Efforts to understand this mechanism in the general-relativistic regime are ongoing (see e.g. [22]), and the event rates of these systems are not well known (though see [23]).

To estimate the fraction of dynamical capture binaries that retain high eccentricity, we first note that the relationship between impact parameter b and pericenter distance r_p is $r_p \approx b^2 v^2/2M$. In other words, the cross section $\sigma \propto b^2$ scales *linearly* with r_p, rather than quadratically as one might expect. If the initial periapse is $r_{p,i}$, and we consider the repeated burst phase to end at a periapse of $r_{p,f}$ with eccentricity e_f, then from [24], $r_{p,i} \approx 0.57 r_{p,f}(1 + e_f)e_f^{-12/19}[1 + O(e_f^2)]$. For example, if a binary with $e_f > 0.1$ by $r_{p,f} = 10M$ can be considered to have a significantly eccentric inspiral phase, then this corresponds to all systems with $r_{p,i} < 27M$. In galactic nuclei, this is between 60% and 80% for mass ratio $q = 1 - 0.1$, so the majority of systems from the aforementioned rate estimates will have significant eccentricity with a repeated burst phase occurring in band. This fraction is significantly lower in globular clusters due to the smaller velocity dispersion, such that more systems will form with large periapses.

For all of these scenarios, the event rates for Advanced LIGO are very uncertain, and range from effectively zero to exceeding the predicted event rate for quasicircular binaries. A null result will significantly constrain the efficiency of the aforementioned mechanisms, and the fact that a very large event rate remains a viable possibility necessitates a concerted effort to search for these specific signals.

O2/O3 Deliverables

- Deliver rate estimate or limit on eccentric binary black hole mergers
- Report results on detected BBH in catalog paper and/or discovery paper

2.3 GW burst waveform reconstruction and source localization

One of the exciting features of gravitational-wave astrophysics is the observation of signals directly tied to the kinematic motion of the source. 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 be provide a unique path towards understanding the astrophysical source.

Reconstructing the waveform of a detected signal 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. Quantifying the uncertainty on reconstructed waveforms is also critical to allow comparisons between measured signals and proposed source models. During O1, reconstructed waveforms were seen to agree with models for expected signals from binary black hole mergers.

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

O2/O3 Deliverables

- Deliver waveform reconstruction, with uncertainty, for all detected sources.
- Deliver position reconstruction skymaps for all detected sources, including low-latency skymaps.

2.4 Search for GW transients from isolated neutron stars

Violent phenomena associated with NSs, such as flaring activity in magnetars [25, 26, 27] and binary coalescence, 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 and pulsar glitches, and the low rate of nearby binary neutron star mergers 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 NS oscillations holds the potential for GW neutron astereoseismology, whereby NS oscillation mode identification and characterization leads to constraints on the equation of state. Our goals for science deliverables in O2/O3 are, therefore, focussed towards the development of novel searches and techniques, and the deployment of morphology-independent waveform reconstructions and parameter estimation follow-ups to *extraordinary* events. Past searches targeting such events include [28, 29, 30, 31].

O2/O3 Deliverables

Long-duration signals associated with magnetar flares: A targeted, broadband, offline search for gravitational waves associated with quasi-periodic oscillations observed in X-ray light-curves following magnetar flaring activity. Full results from such a search have not previously been published so we aim for a publication reporting the results of the analysis ~ 6 months after the end of O2.

Extraordinary events in galactic sources: For extraordinary events such as the 2004 hyper-flare in SGR 1806-20:

1. **Low-latency analysis (∼minutes–hours):** Initial check for temporal and spatial coincidence of triggers arising from the online burst or CBC analysis with the electromagnetic trigger.
2. **Higher latency analysis (∼week–month):** Upon confirmation of the galactic and extraordinary nature of a magnetar event, analyses will be performed offline. Deliver targeted searches for both long duration (> 10 seconds) and short duration bursts from 10's of Hz up to ~ 4. Short-duration candidates will be followed-up and characterized with burst parameter estimation (PE) tools.

Confirmed detection of a binary neutron star merger :

1. **Low-latency analysis (∼minutes–hours):** initial check for temporal and spatial coincidence of triggers arising from the online burst analysis with a low-latency CBC GW trigger. We shall also perform a manual, targeted high-frequency burst analysis of the latter portion of the signal.
2. **Higher latency analysis (∼week–month):** follow-up studies using burst waveform reconstruction, with the goal of constraining the neutron star equation of state.

2.5 Triggered search for GWs from core collapse supernovae

Once a massive star (about $10\times$ the mass of the Sun or more) 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. If the protoneutron star accrets enough mass (which is likely for very massive progenitors) a BH is formed instead and the star fails to explode (and the GW emission is expected to be abruptly truncated). It is theorized that the shock wave is powered by the absorption of a small fraction ($\sim$10%) neutrinos within the first second of the proto-neutron star's life. The neutrinos heat up the material above the proto-neutron star. This drives convection where hot buoyant bulk material rise and colder material sinks. This convection in turns leads to the emission of GWs mostly through the excitation of motion in the newly formed neutron star. If the star's core is spinning, then also a burst of GWs that lasts for a few milliseconds is emitted when the proto-neutron star is first formed (the GW emission of the later phases of a rapidly rotating progenitor is less understood than the case of slowly rotating one).

Neutrinos were detected from supernova SN1987A, which exploded in the Large Magellanic Cloud, a neighbor galaxy of the Milky Way. At the time, no detector with sufficient sensitivity to detect GWs from a supernova was operational. Supernovae are rare events in the local universe: 1 or 2 events per century are estimated in our galaxy and about 4 per year within 20Mpc [ref].

The next galactic (core-collapse) supernova ([CC]SN) will be a an exciting astronomical event, and the world will look to the LIGO Scientific Collaboration and the Virgo Collaboration for statements about its GW emission. Multimessenger observations in photons, neutrinos, and gravitational waves of the next nearby CCSN will revolutionize our understanding of massive star structure and angular momentum distribution, of core collapse dynamics, of the still uncertain CCSN explosion mechanism, of explosive nucleosynthesis and mixing of synthesized elements in the explosion, and of fundamental physics such as the equation of state of nuclear matter and neutrino interactions.

GWs are produced by bulk aspherical accelerated motion of mass-energy; in the CCSN context they are a direct probe of the uncertain degree of asymmetry of the supernova engine. GWs are expected to be emitted by a broad range of processes (e.g., [32, 33]) many of which can be directly associated with particular explosion mechanisms. For example, the GW signal from neutrino-driven convection can be connected to the neutrino mechanism or the strong signal from rotating core collapse can be linked to magnetorotational explosions (e.g., [34, 35]). GWs from rotating core collapse can be used to measure the angular momentum of the collapsing core [36, 37]. GWs from neutrino-driven convection and the standing accretion shock instability can be used (1) to infer the moment of the onset of explosion and (2) to constrain the structure of the nascent neutron star and in this way put constraints on the nuclear equation of state (in combination with neutrino information; e.g., [38, 39, 40]). An abrupt end of GW and neutrino emission would unambiguously herald the formation of a black hole (e.g., [41, 42]).

Recently, the LVC has organized a systematic interaction with the SN modeling community with a series of SN theory calls and a focused workshop on CCSNe [43]. Of particular interest is the summary of the aspects of CCSNe modeling that are considered, to date, robust by the CCSN modeling community as a whole. This activity is expected to continue.

O2/O3 Deliverables

- SNEWS trigger: estimate significance of the coincident loudest GW candidate, provide reconstructed waveforms of identified candidate and estimate parameters of the GW candidate.
- O1-O2 SN search paper: provide detection and non-detection statements for optically observed supernovae within roughly 20Mpc (the exact distance depends on the SN trigger being able to contribute to the model exclusion probabilities), constrain the most extreme emission models GW emission, set up upper limits on emitted GW energy in specific time frequency regions (for example the one expected from SASI).
- Develop noise reduction techniques for burst searches, including [44].
- Create a statistical framework for detection statements using multiple supernovae. Realistic GW signals from CCSNe from outside the galaxy are predicted to be weak, so seeking a population of weak signals may improve the chance of discovery.
- Develop a methodology for evaluating statistical significance of a GW trigger associated with a supernova.
- Establish veto procedures specific to SN searches.
- Develop a method for detecting GWs in coincidence with a SN using data from only a single GW detector.
- Quantify the impact of calibration errors on detection statistics and parameter estimation/waveform reconstruction measures using hardware injections.

- Publish a study of SN science targets using third generation GW detectors
- Develop a subprime neutrino triggered search

2.6 Multimessenger search for GWs and fast radio bursts

Since the publication in summer 2013 of four Fast Radio Bursts (FRBs) identified in Parkes Telescope data [45] there has been considerable scientific interest in these millisecond-scale radio transients which, based on their observed dispersion measures, appear to occur at cosmological distance scales. A total of 22 FRBs have been published so far [46], including one repeating source [47], and an increasing number of radio telescopes are becoming involved in FRB identification.

Currently, while numerous papers have suggested plausible sources for these radio transients, their origin (or origins if there are distinct classes) is unclear. 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 [48] 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. Searches with initial detector data in coincidence with known FRBs have already been conducted [48], and work is underway to continue analysis using Advanced detector data.

O2/O3 Deliverables

- Develop and test analysis methods for FRB searches using externally triggered unmodelled transient and matched filter methods, including analysis approaches suitable for both short and long-duration coincidence windows
- Publish the results of searches for coincident GW/FRB events in Advanced Detector data using data coincident with identified FRBs. The next radio transient LIGO/Virgo publication will utilize data from O1 and O2 and, depending on the availability of sufficient coincident FRB triggers, may also utilize O3 and the corresponding Advanced Virgo run(s).
- Coordinate with radio astronomy community to facilitate necessary exchange of information to make reasonably prompt completion of above publication possible. Where needed, this may involve development of additional MoUs with relevant radio astronomy partners.

2.7 Service and technical activities for Burst searches

Several Burst searches are supported by transversal technical activities that provide support and tools and/or make the link with the LSC and Virgo detector characterization groups.

- Software injections: Search pipelines use simulated signals to test and characterise their performance. For Burst searches, a typical set of simulated signals used for assessing pipeline performance consists of sine-gaussian, gaussian pulse, ringdown and white noise burst waveforms. Other examples of simulated Burst signals are those based on theoretical emission models (eg. accretion disk instabilities) and/or numerical relativity simulations (core collapse supernovae). These simulations are being generated to act as input waveforms for hardware injections and create a population of simulated signals stored in frame files for Mock Data Challenges (MDCs). The waveforms and corresponding parameters of simulated signal populations for MDCs are defined by the goals of search activity for which the MDCs are created.

O2 Deliverables

For O2, MDCs will be created for the following searches:

  - Short-duration all-sky search.
  - O1-O2 core collapse supernova search.

- Hardware injections: The MDC infrastructure will also be used to generate input waveforms for hardware injections. In particular, there are plans for a number of hardware injections using core collapse supernova waveforms.

  O2 Deliverables

  - Gather and condition all waveforms that the Burst group decides to inject during a run.
  - Work closely with the LIGO hardware team to succeed in injecting broadband (-high frequency) core collapse supernove signals using the photon calibrator that should circumvent the actuators saturation issue observed when applying a force directly to a Fabry-Perot cavity entry mirror.

- Detector characterization: Almost all GW transient searches benefit from data quality information provided by the detectors' experts. That especially includes the findings of the LSC and Virgo detector characterization groups to identify and understand the origin of the non stationary noise sources. The ability to estimate the significance of candidates at least the level of 3-σ requires to remove the main noise artefacts from the data. Safe data quality vetoes (data quality flags stored in DQsegDB and auxiliary channels based vetoes) are used by burst searches to remove a large fraction of noise outliers that pass multiple interformeter coincidence and coherence tests. The search leaders and search DQ liaisons must work with detector characterization Burst experts to define the most efficient list of vetoes.

  O2 Deliverables

  - Provide a regularly updated and customized list of data quality flags and hVeto and UPV vetoes for each Burst search.
  - Provide feedback regularly to the burst and detector characterization groups.

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, respectively.

3.1 CBC parameter estimation R&D

Development of tools for characterizing CBC sources in terms of their parameters.

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 the most sophisticated models possible 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 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.

Short term goals

1. *PE with matter effects:* When LIGO/Virgo finally makes the first detections of binary neutron star and neutron star-black hole mergers, the detected GWs will allow for novel measurements of matter effects in the binary mergers, including the neutron star equation of state. Effective 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 library, LALInference.

2. *Marginalization over frequency-dependent detector calibration errors and PSD uncertainties:* During O1 and O2, frequency-dependent but instrument-agnostic models for calibration errors were used for the purposes of marginalization, and point 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 possible noise PSDs.

3. *Better measurement of waveform systematic errors:* Thus far the variance between posterior estimates obtained using multiple approximants (e.g. SEOBNRv3 and IMRPhenomPv2) have been used as a proxy for quantifying systematic uncertainties in parameter estimates. We must develop more robust and meaningful ways to quantify systematic errors associated with the use of our approximate waveforms.

4. *Study the biases to PE caused by non-stationary noise:* 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.

5. *Gravitationally lensed events:* A non-negligible fraction of BBH merger events to be observed by LIGO can undergo strong gravitational lensing. The strong lensing can produce multiple triggers of the same event with time delays varying from weeks to months. Identification of such events can help us to study the properties of gravitational lenses.

6. *Using more accurate waveforms:* As more faithful waveform models become available (e.g., multi-modal effects, amplitude corrections), studies will be required to determine the impacts of the inclusion of such physical effects on PE.

7. *Faster convergence with improved sampling algorithms:* The group goals related to low latency analyses will require (in part) improvements to our sampling algorithms.

8. *Improvements to post-processing:* The outputs of the post-processing routines from the PE group are now used by many scientists in and outside of the LIGO-Virgo collaboration. These tools are in need of 1) improvements to the presentation of critical results, 2) additional statistical tests, and 3) better usability by other CBC subgroups (e.g., numerical relativity follow-ups, rates and population).

9. *Improvements to library infrastructure:* To better facilitate the goals outlined above, the LALInference code base is in need of infrastructural updates. This includes the migration of the library from C to Python to become more development-friendly.

Long term goals

1. *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 models (e.g., including precession effects), and pursue the direct use of waveforms produced by numerical relativity simulations

2. *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.

3. *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 LALInference to detect a population of sub-threshold events could lead to the detection of such a stochastic background.

4. *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.

5. *Recover binary properties at the time of formation:* Parameter estimates obtained for events thus far correspond to the binaries' properties at some reference frequency, typically when the signal enters band. To better understand formation scenarios for these binaries, we will need methods to evolve such constraints backward to earlier times.

3.2 Tests of General Relativity R&D

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, possible existence of exotic compact objects, etc., are also pursued within the group.

Short term goals

1. *:*

Long term goals

1. *:*

3.3 CBC waveform models R&D

Development of waveforms to faithfully model physics in binary coalescence for searches and parameter estimation.

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 are waveform-models which include all physical effects that may influence the expected waveforms enough to impact the output of 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.

Short term goals (for end-of O2 and O3)

1. *Include sub-dominant modes in BBH waveform models*: We aim to extend our waveform models of spinning, non-precessing BBH systems by including the effects of subdominant harmonic modes. Two independent models will be used for cross-comparisons. We also plan to provide functionality to compare GW-measurements directly to spinning, non-precessing numerical simulations, without the need for an intermediary model.

2. *Improve precessing BBH waveform models* by extensively tuning/testing against precessing NR simulations. We also aim to have initial prototype models of precessing binaries with subdominant modes.

3. *Include eccentricity in BBH waveform models*: Eccentric waveform-models are important for estimating or bounding the eccentricity of any observed CBC event. We aim to develop models for modest eccentricity that cover non-spinning and subsequently aligned-spin binaries.

4. *Inspiral waveforms for NS-NS and BH-NS systems that include NS-tides and NS-spin effects*.

5. *Investigate opportunities to use post-merger NS-NS waveform information to characterize NS-NS systems*.

6. *Cross-checks and validation*: Perform cross-validation between different NR codes for precessing BBH systems to assess the accuracy and reliability of precessing NR waveforms. Assess BBH

waveform-model accuracies, especially at more extreme parameters, namely mass-ratios expected for BH-NS binaries, and/or high spins.

7. *Expand the NR waveform catalog as baseline data for a variety of waveform/PE/testingGR/burst projects*: improve parameter space coverage, and consider extension to BH-NS, NS-NS

8. *Continue per-event NR follow-up as needed:* Improve the accuracy of observational statements and/or test systematic biases by perfoming dedicated NR simulations in response to detection candidates.

9. *Investigate application of new mathematial tools to waveform modelling*: Such tools may lead to the development of models that include more physical effects (e.g. deep learning or gaussian process regression), or that may significantly speed up existing waveform models (e.g. reduced-order models).

Long term goals (for beyond O3)

1. *Precessing IMR-waveform-models for BH with subdominant modes*, where all modes are tuned/tested against precessing NR simulations.

2. *Precessing and eccentric IMR waveform-models*

3. *Accurate NS-BH and BH-BH waveform models for precessing systems including EoS effects and subdominant modes*

4. *Develop aligned spin BH-NS waveform models that include merger/disruption of the NS.*

5. *Waveform-models for hyperbolic encounters*

3.4 CBC offline search R&D

Perform offline searches; develop and tune offline pipelines; generate template banks; assess offline data quality.

See text in next subsection, which discusses both offline and online search R&D.

3.5 CBC online search R&D

Develop, maintain, and staff online searches, including sky-localization, low-latency GRB searches, and CBC-specific R&D for online analysis within the EM-Followup effort.

Motivation and methods

The online and offline 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 data. These pipelines 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 such as GRB. Online searches are designed to perform matched filtering and consistency checks within simtens of seconds of the data being available, in order to enable sky localization and rapid EM follow-up of candidate events. They can also provide single-detector triggers for checking data quality and identifying issues in detector operation with rapid turnover. Offline searches run with a latency of order a few weeks on a stable and carefully selected data set, to provide reproducible results for publication with precise evaluation of the significance of candidate events and the sensitivity of the search to a population of realistic binary merger signals.

Short term goals

1. *Results for broad parameter space CBC search in O2 data:* The current standard search space encompasses BNS, NSBH, BBH and IMBHB sources with a range of non-precessing component spins. Maintaining and running existing pipelines to produce a list of candidates with significance derived from background estimates and evaluate the sensitivity of the search to simulated signals (injections) over the full space, including precessing spins and higher-mode/NR signals as appropriate given availability of waveforms.

2. *Single-detector/Multi-detector searches:* Virgo is about to join the O2 run and engineering runs are underway to test and validate online pipelines with 3-detector running. Depending on the development of Virgo sensitivity offline runs may also be Given the likelihood that some signals will occur in single-detector time the development and optimization of a search over such time is motivated. As a medium term goal methods to optimally search heterogeneous data (i.e. with different networks at different times) are required.

3. *Source-dependent results for rate calculations:* To infer the rates of sources which inhabit only a subset of the broad CBC search space (e.g. BNS, NSBH) it is desirable to produce results which are weighted or otherwise restricted to promote events originating from specific source types and downrank/exclude others. Timescale to implement is end of O2, intersects with Rates/Pop. work.

4. *Optimization of computing cost and search sensitivity:* Construction of template banks to cover the very broad parameter space from BNS to IMBHB may be further streamlined and it is likely that more effective methods of signal-background discrimination can be developed with further study, particularly for the IMBHB region.

Long term goals

1. *Precessing and higher mode template searches:*

2. *BNS with nonlinear tides:*

3. *Coherent all-sky search with 3 or more detectors:*

3.6 Binary coalescence rates and population R&D

Provides the means to estimate the astrophysical rate of various classes of compact binary coalescences, and to estimate their mass and spin distributions.

Motivation and methods

The charge of the Rates and Population subgroup is to measure and maintain a set of population based event rates for compact binary mergers with gravitational-wave observations. At the top level, this is encapsulated in the posterior on the event rate per unit space-time volume per category. With an ad-hoc division of four event categories, only one category (binary black hole (BBH)) is currently measured with a non-zero rate. The other three, binary neutron star (BNS), neutron star black hole binary (NSBH), and intermediate mass binary black hole (IMBBH) all have event rate densities which are upper limits. Current developments revolve around refinements to rate measurement technology (e.g. hierarchical population inference, parameterized property dependent rate models), refined assessments of the astrophysical significance of event candidates, and improved integration of these techniques with existing searches. Beyond these goals, we also expect that collection of more events will allow us to develop a picture of the properties of the *population*, e.g. their formation channels and properties in aggregate. It is expected that the infrastructure developed in the context of BBH is flexible enough to encompass more event categories as they are discovered. In addition to the interface with Compact Binary Coalescence (CBC) searches, we also expect work here to influence both the structure and data products exposed in the catalog of compact binaries.

Short term goals

1. *Source-dependent template weighting methods to evaluate CBC rates:* (end of O2) To enable rate estimates over different categories of binary mergers (e.g. BNS vs NSBH vs BBH), the current FGMC based hierarchical foregroun/background model must be expanded to allow for several categories of foreground. The gstlal ranking statistic will be leveraged to implement "mass weighting", that is, to asses the relative probability of an event belonging to any one category of merger. The pycbc search will also generate a set of restricted template ranges to provide the basis for rate limits on each source categorization.

2. *Rapid source classification and p-astro calculation of low-latency triggers:* (post O2) Consuming the outputs of low latency CBC searches to calculate the astrophysical significance of each event candidate as it is produced. This will interface with the LVAlert and gracedb event brokers.

3. *Automated rate calculation within pycbc* (end O2) Formalize and standardize injection sets and use the existing pycbc workflow to automate the generation of rate statements within pycbc. Explore how to reuse the results of injection campaigns to most effectively cover the parameter space.

4. *Mixture model for signal and noise populations* (end 2017) Develop a mixture model analysis that can simultaneously infer the population and rate of both foreground (astrophysical) and background (noise) events. This will allow for distinguishing terrestrial noise events without biasing our inferences by assuming signals to be real.

5. *Empirical distributions — Binned mass distributions:* (ongoing) Investigate the component mass distribution using a regularized Gaussian process fit to a binned mass distribution. This expands on the current single-parameter power law primary mass hierarhhical inference.

6. *Empirical distributions II — GMMs and MCMCs for mass and spin distributions:* (end O2) Determine parameter dependent event rates using both parameteric and nonparametric methods. Planned for low latency operation.

7. *Hierarchical inference engine with the `rapid_pe` toolkit* (end O2) The `rapid_pe` pipeline allows for non-Markovian evaluation of the GW event likelihood function. This is specially suited to hierarchical inference since it avoids some of the complications of priors required to evaluate the hierarchical likelihood.

8. *Evaluation of mass and spin distributions by the use of phenomenological and/or parameterized models* (post O2) Develop phenomenological and/or parameterized models to fit observational data, and simultaneously derive the rates.

9. *Redshift Evolution of Rates and Mass Distributions* (post O2) Current publications implicitly assume flat distribution of rates with respect to redshift. This project will develop out the infrastructure needed to infer rate and mass spectrum dependence on redshift.

10. *Population Synthesis Model Selection* (end O2) Fuse real and synthetic data to perform model selection with binary evolution.

11. *Distinguishing Formation Scenarios Using Spins* (ongoing) Applying the results of spin measurements from GW observations to distinguish BBH fornation scenarios.

Long term goals

1. *Rates and Pop. Toolkit Development* (ongoing) Develop a set of search-independent and fleixible tools to facilitate population rates and inference. `https://git.ligo.org/RatesAndPopulations/lvc-rates-and-pop/`

3.7 Catalog of compact binaries

Produce a catalog of compact binary coalescence candidate signals 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

Stellar-mass BBHs were directly measured by Advanced LIGO to merge with a rate of approximately $9\ \mathrm{Gpc^{-3}yr^{-1}}$ to $240\ \mathrm{Gpc^{-3}yr^{-1}}$ [49]. Advanced LIGO established two confirmed binary black hole detections, GW150914 and GW151226 and a strong third candidate LVT151012 [49] , with an overall range of masses $\sim 7\,\mathrm{M}_\odot$ to $36\,\mathrm{M}_\odot$. From these observations, the mass distribution of black holes in binary systems was estimated to be a power law with the primary mass m_1 distribution $p(m) \propto m_1^{-2.5}$ [49], although the power law index is still very uncertain with so few observations. To date, spins have been difficult to constrain from gravitational waves, but are consistent with small effective spins.

The detection in O2 of the black hole binary coalescence GW170104 has allowed us to further expand our catalog of sources. While the masses involved (31 and 20 $M_\odot$) are similar to GW150914, this sources was the most distant detected by Advanced LIGO at a redshift of $z \sim 0.2$. The inclusion of this source allows us to update the merger rate estimate to approximately $12\ \mathrm{Gpc^{-3}yr^{-1}}$ to $213\ \mathrm{Gpc^{-3}yr^{-1}}$, and the power law for the primary mass distribution to $p(m) \propto m_1^{-2.3}$ [**?**]

The binary massess detected through gravitational wave observations are larger than those of black hole candidates identified by X-ray observations, which yield BH masses $5 \leq M_\bullet/\mathrm{M}_\odot \leq 20$, confirmed with dynamical mass measurements for 16 BHs. An apparent lack of BH masses in the range $3\,\mathrm{M}_\odot$ to $5\,\mathrm{M}_\odot$ (the "mass gap") [50, 51, 52] has been ascribed to the supernova explosion mechanism [53, 54]. Further BBH observations with advanced GW detectors will begin to give us a clearer picture of the mass distribution of coalescing BBHs, allowing comparisons to be made with Galactic BH distributions and probing the existence of a mass gap. Population synthesis based on recent stellar wind models allows for isolated black hole masses up to $\sim 80\,\mathrm{M}_\odot$ [54, 55]. Common envelope binary evolution [56] may reduce the maximum expected component mass and total mass to $\lesssim 100\,\mathrm{M}_\odot$ [57], however stellar BH with mass above $100\,\mathrm{M}_\odot$ are conceivable [58], overlapping the range associated with intermediate mass black holes (IMBHs) formed by repeated mergers.

X-ray observations of accreting black holes indicate a fairly uniform distribution of spins over the entire range allowed by general relativity, $0 \leq S/m^2 \leq 1$ [59, 60, 61, 62, 63, 64, 65]; both low ($\sim$0.1) [66] and high (> 0.85) values [67] are represented. The microquasar XTE J1550-564 [68] and population synthesis models [69] indicate small spin-orbit misalignment in field binaries. For massive field binary progenitors, the common envelope phase and mass transfer [70] are expected to cause strong correlations between spins and masses of the two BHs in field binaries [71]. However, no such correlations are expected for dynamically formed BBH.

Population synthesis models constrained by radio observations of double neutron star (NS) systems in the Milky Way, provide an indirect estimate of the GW-driven BNS merger rate of $10\ \mathrm{Gpc^{-3}yr^{-1}}$ to

$10\,000~\mathrm{Gpc^{-3}yr^{-1}}$. While no BNS systems were detected during the O1 science run, we were able to put an upper limit on the merger rate for these systems of $< 12\,600~\mathrm{Gpc^{-3}yr^{-1}}$ [**?**]. The detection or non-detection of BNS systems in O2 and future observing runs will allow us to constrain the models of the BNS rate.

The masses of known NSs are reported to be in the range $0.7~\mathrm{M_\odot}$ to $2.7~\mathrm{M_\odot}$ with a mean mass of $\sim 1.4~\mathrm{M_\odot}$ [72], though the lower value, $0.7~\mathrm{M_\odot}$, comes from an imprecise measurement of a single system that is also consistent with a higher mass. NSs in BNS systems have a more narrow observed mass distribution of $(1.35 \pm 0.13)~\mathrm{M_\odot}$ [72]. Theoretical models support the production of a population of NSs formed in binaries through electron-capture collapse of O-Ne-Mg cores, and predict masses which are consistent with these observations [73, 74]. Lower mass Fe cores are predicted to lead to NSs with masses almost as low as $1~\mathrm{M_\odot}$ [75].

Current astrophysical understanding indicates that the older NS in a binary system can be spun up through mass-transfer from its companion, which can increase the spindown timescale. However, this process is not completely understood, and it is not clear how efficient the spin-up process can be. The observed dimensionless spins (J/m^2) for NSs in BNS systems (e.g., J0737-3039) are ≤ 0.04 [76], however the fastest known NS spin is 0.4 [77].

NSs contain the highest densities of matter in the observable universe. The internal structure of NSs is constrained by nuclear experiments and astrophysical mass-radius measurements, which help to constrain the possible equation of state (EOS) of nuclear matter [78]. As binary NSs coalesce, the EOS will determine both tidal interactions during late inspiral and matter effects during merger. These effects are encoded in the gravitational waveform [79]. In cases where an electromagnetic (EM) counterpart can be identified, further information can be used to understand the physics of the merger [80, 81]. There are several plausible EM counterparts to BNS mergers [82].

Neutron star - black hole binary systems are thought to be efficiently formed in one of two ways: either through the stellar evolution of field binaries or through dynamical capture of a neutron star by a black hole [83, 84, 85, 86]. Though no NSBHs systems are known to exist, one likely progenitor has been observed [87]. Rates for the coalescence of NSBH systems are not well known, however a "realistic" estimate from population synthesis of field binaries is given as $30~\mathrm{Gpc^{-3}yr^{-1}}$ [88]. A "pessimistic" estimate is given as $0.6~\mathrm{Gpc^{-3}yr^{-1}}$ and an "optimistic" estimate as $1000~\mathrm{Gpc^{-3}yr^{-1}}$ [88]. These yield observation rates for Advanced LIGO and Advanced Virgo of 0.2 - 300 $\mathrm{yr^{-1}}$.

The mass distribution of NSBH systems is not well constrained. However, it is possible to place estimates on the mass and spin ranges by using the properties of neutron stars and black holes observed in other systems, such as the NS and BH systems described above. The microquasar XTE J1550-564 [68] and population synthesis models [69] indicate small spin-orbit misalignment in field binaries. Dynamically formed NSBH systems, in contrast, are expected to have no correlation between the spins and the orbit.

Fully general-relativistic numerical simulations of NSBH systems have been performed (for e.g. [89, 90, 91, 92, 93, 94]) and show that certain combinations of mass, spin, and NS equation of state (EOS) parameters can cause the neutron star to tidally disrupt before coalescence. These systems could power the central engines of short gamma ray bursts (GRBs) or produce other types of prompt or delayed electromagnetic (EM) counterparts [95].

Major aspects and methods for this activity

In the O2 observing run we expect to detect around ten compact binaries. 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 O2 and release a detailed description of all detected systems, covering their detection and physical parameters, inferred using the best available waveform models.

In O2 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. For parameter estimation, waveform models that capture the most complete dynamics available of any binary system will be used. Two independent search codes, pycbc and gstlal, will be run on the data. In O1 we conducted a joint search with the burst group for IMBH systems separately from BNS, NSBH and stellar mass BBH. In O2 we will include binary black holes detected by burst pipelines in the catalogue alongside those detected with modeled CBC pipelines.

For each event, both clear and marginal detections, we will provide estimates of the physical parameters of the source using the best available waveform models, and provide an estimate of the systematic error through 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 O2, using final vesions of data quality and calibration. In coordination with the LIGO Open Science Center we will produce an electronic data release to go alongside the publication.

O2 deliverables

1. A publication detailing significant signals detected during O2. These will include
   - clear detections,
   - marginal events which cannot be invalidated through data quality or other means,
   - and may also include single-detector events which have significant probability of being true signals.
2. Parameter estimates for each event, including an eventual electronic data release
3. Probability of astrophysical origin for each event
4. Estimates of the gravitational waveform for each event, including in electronic format

3.8 Astrophysical distribution of compact binaries

Determine the astrophysical mass and spin distributions of BBHs, and rate estimates.

Motivation and goals

The detection of GW150914, GW151226 and GW170104 firmly established the existence of stellar-mass BBHs, with a coalescence rate of $9\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ to $240\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, high enough to make them a primary source for future observing runs. In the O2 run we expect to detect between 1 and 10 such events, depending on detector performance, duty cycle and the actual rate of BBHs. Binary black holes can be produced by several astrophysical formation channels including isolated binary evolution and dynamical formation in dense stellar environments. The direct observation of BBHs using GWs allows us to measure the mass and spin of individual systems. Combining these individual detections into a statement about the population requires knowledge of the selection function of the GW detectors, searches and parameter estimates. The resulting knowledge of the astrophysical population can be used to improve models of binary evolution and determine the relative importance of the various formation channels.

O2 deliverables

1. A catalogue of detected events in coordination with the Catalogue project
2. Astrophysical event rates
   (a) Up to date compact binary event rate estimates including all feasible sources of uncertainty and, if possible and mature, $\frac{dN}{dV dM}$.
   (b) Constraints on BNS and NSBH rates in lieu of detection.
3. Astrophysical mass distribution of coalescing binary black holes
4. Astrophysical spin distribution of coalescing binary black holes
5. Data release of BBH population

3.9 Analyses testing 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.

Motivation and goals

LIGO's first crop of binary black hole mergers – GW150914, GW151226 and GW170104 – allowed us, for the first time, to test the predictions of general relativity in the highly relativistic, strong-field regime. GW150914 was the most massive binary among all LIGO events, and while we saw the end of the inspiral, most of the information came from the merger-ringdown. Using this event we set limits on the deviation from the post-Newtonian (PN) description of the inspiral phase, and from the the phenomenological GR model of the merger-ringdown. In addition, the GW150914 analysis established that the final remnant's mass and spin, as determined from the low-frequency (inspiral) and high-frequency (post-inspiral) phases of the signal, are mutually consistent. Furthermore, the data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole. This event also allowed us to constrain the mass of the graviton [96].

Most of these constraints were further improved by combining the GW150914 results with GW151226 [97] and GW170104 [**?**]. In addition, GW170104 allowed us to put bounds on a more general dispersion relation for GWs. In O3 and the remaining period of O2, we expect new detections of BBHs, and anticipate detections of BNS and BHNS 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 O2 and O3 observing runs.

O2 deliverables

1. *Constraining deviations from GR during the PN inspiral phase:* Lower mass BBH, as well as BNS and BHNS sources, will have longer inspiral phases. Combining posteriors from multiple events in O2 should allow us to progressively strengthen the constraints on deviations from PN theory.
2. *Constraining deviations from GR during the merger-ringdown phase:* More massive binaries should produce most of the detectable SNR in the merger-ringdown phase. By using improved IMR and EOB

waveforms, we should be able to place tighter constraints on the phenomenological parameters that govern the merger-ringdown.

3. *Consistency between the inspiral, merger and ringdown:* A consistency test between the mass and spin of the remnant black hole estimated from the inspiral and post-inspiral parts of massive BBHs will allow us to detect certain departures from GR. Combining posteriors from multiple inspiral-merger-ringdown events should allow us to strengthen these constraints.

4. *Bound on the mass of the graviton and constraining Lorentz violation*: A further constraint on the graviton mass from the increased number of events and constraints on generic Lorentz violations, by considering modified dispersion relations for propagating GWs.

5. *Dipole radiation:* With signals that provide a long inspiral phase, we should be able to conduct a phenomenological test for dipole radiation. If dipole radiation exists, its effects would be visible at the -1PN order in the phase and frequency of the waveforms. An ideal source for testing for dipole radiation will be the inspiral phase of a BNS.

6. *Study of waveform systematics:* By combining results from multiple events, we will be able to put more precise constraints on various deviations from GR. We anticipate that various systematic errors in the waveform models to dominate our results at some point. Thus, characterizing the effect of waveform systematics on various tests of GR is a high priority task. Preliminary investigations will be carried out by the end of O2. A systematic exploration is targeted in O3.

O3 deliverables

In addition to the results listed above, we anticipate the following additional science results from O3 data.

1. *Measurement of quasi-normal modes:* Sufficiently loud signals from massive BBHs should provide conclusive evidence of quasi-normal modes. Measurement of multiple quasi-normal modes will allow us constrain the no-hair theorem of GR.

2. *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. We will be able to constrain the parameter space of some of these models based on constraints on the tidal deformability, spin-induced quadrupole moment, etc.

3. *Search for late time echos of BBH merger signals:* Some of the quantum gravity inspired alternatives to black hole horizons predict late-time echoes of GW signals in BBH mergers. These can be constrained, or detected, using upcoming BBH observations.

4. *Characterization of waveform systematics:* A systematic exploration of the impact of inaccuracies and missing physics in waveform templates on various tests of GR is targeted to complete by the end of O3.

3.10 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. Many of these will be exceptional events, e.g., the first confirmed neutron star binary, systems with definitive spin precession, etc. Such systems will warrant specific attention to be determined only once confirmed.

Some examples of exceptional events would be one that yields:

- the first detection of a binary neutron star, neutron star + black hole binary, or an intermediate-mass black-hole binary;
- measurement of the highest/lowest neutron star mass, or the highest stellar-mass black hole mass;
- clear statement on neutron star equation of state;
- clear evidence of a black hole in a predicted mass gap;
- clear evidence of unequal mass ratio;
- clear evidence of spin-induced precession;
- measurement of a high-spin system;
- measurement of black hole quasi-normal modes;
- measurement of higher-order gravitational wave emission modes;
- clear evidence of orbital eccentricity;
- a multi-messenger counterpart (externally-triggered or in electromagnetic/neutrino follow-up searches);
- measurement of the Hubble constant;
- clear evidence of deviation from general relativity;
- clear indication of a particular formation channel.

Expected products and/or outcomes

A detailed analysis of exceptional events with parameter estimation and astrophysical interpretation.

4 CW Group Activity Plans

4.1 Targeted searches for known isolated and binary pulsars

Rapidly spinning neutron stars in our galaxy may emit gravitational waves if they are not perfectly symmetric about their spin axis. They are the most promising sources of continuous-wave gravitational signals in the LIGO and Virgo frequency band. Their quadrupole deviation from such axisymmetry is usually characterized by a parameter called the *ellipticity* of the neutron star which, for example, might be as large as 10^{-6} for a broad, 1-cm-high *bulge* across the surface of the 20-km-diameter star.

Searches have been carried out for continuous gravitational wave signals from 200 known pulsars using data from the LIGO and Virgo gravitational wave detectors [Abbott et al., Ap. J, 839, 2017]. No signals have been detected from these stars, but upper limits on their ellipticities have been obtained reaching as low as 10^{-8}.

Motivation and goals

Our searches target a subset of sources for which pulsations 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, e.g., Equation 5 of [Aasi et al., Ap. J., 785, 2014]). Analysis of data from Advanced LIGO's first observing run (O1) has surpassed this upper limit for eight pulsars, with another 32 within only a factor of ten of their spindown limits [Abbott et al., Ap. J, 839, 2017].

The search mentioned above assumed 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 [Jones, MNRAS, 402, 2010]. 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, however such searches have not extensively been performed.

Methods and major aspects of this activity

The principal work will be the analysis of data from Advanced LIGO's second observing run (O2) to search for continuous gravitational wave signals from $\mathcal{O}(200)$ known pulsars under the assumption that their gravitational wave phase evolution is tightly linked to their rotation. This will initially require coordination with a range of electromagnetic pulsar astronomers to obtain rotational phase models of pulsars for which there are observations overlapping with O2. If coherent phase models are available spanning both O1 and O2, then data from both runs will be coherently combined, otherwise an incoherent combination of independent O1 and O2 searches will be performed. These searches will produce probability distributions for each pulsar's gravitational wave emission amplitude, h_0, and orientation (inclination to the line-of-sight, polarization angle, and initial phase). In the absence of significant evidence for signals the probability distributions on h_0 will be used to set upper limits, and equivalent limits on the neutron star mass quadrupole moment and fiducial ellipticity will be derived.

The search will use three existing, and very mature, analysis pipelines: the *Time domain Bayesian Pipeline*, the *5-vector method*, and the *Time domain $\mathcal{F}/\mathcal{G}$-statistic method* (see, e.g., [Aasi et al., Ap. J., 785, 2014]). These pipelines will require very little additional development when performing searches for gravitational wave signals closely locked to twice the stars' rotational frequencies. All three pipelines will be used for several, $\mathcal{O}(10)$, high-value targets for which the spin-down limit has, or could nearly be, surpassed. The rest of sources will be searched for with the *Time domain Bayesian Pipeline*.

In addition to the search for signals at twice the rotational frequency, the O2 analysis will also include searches at the rotational frequency. Previous LVC analyses have not targeted f, although the pipelines can all be adapted for this through minor adjustments to their standard $2f$ searches. Reviews of these differences will be required, but otherwise the search will be entirely in parallel with the $2f$ search. The *Time domain Bayesian Pipeline* will use Bayesian model selection to determine the preference for signals at either frequency, both frequencies, or neither.

Methods are being developed to use the posterior distributions of gravitational wave amplitude, combined with knowledge of pulsar distances (and their uncertainties), to infer the underlying population distribution of pulsar ellipticities. This will use a hierarchical Bayesian method very similar to that used to infer mass and spin population distributions for the observed black-hole binary mergers (see Appendix D of [Abbott et al., PRX, 6, 041015, 2016]). This could be applied post-hoc to O1 data, and incorporated into O2 and O3 analyses. This work, and an extension of the 5-vector method, are being developed as a method to detect an ensemble of pulsar signals when no individual sources give rise to a significant detection.

The all-sky and directed continuous gravitational wave searches (see, e.g., Sections 4.7, 4.5, and 4.3) will produce a selection of signal candidates. Investigations will proceed in applying the targeted pulsar search pipelines to such candidate signals in a systematic way. This will include producing background distributions on the Bayesian odds (comparing the signal hypothesis to a noise and/or incoherent signal hypothesis) that reflect real instrumental noise, and can be compared to the true odds values. One method to achieve this is "de-sourcing", namely producing a background distribution by assuming random sky locations at the inference stage; this would quickly uncorrelated any astrophysical signals, given the long observation times, but would preserve non-Gaussian noise features.

By monitoring the simulated continuous gravitational wave hardware injections the known pulsar search has proved very useful in checking the amplitude and phase calibration of the LIGO detectors over previous science runs. This will continue to the end of O2 and will again be used during any engineering runs leading up to O3.

Expected products and/or outcomes

The main product will be a single O2 (or combined O1 and O2) paper describing the search for gravitational waves from $\mathcal{O}(200)$ at both f and $2f$. As described above, this will make use of mature pipelines that require little additional review. Provided electromagnetic pulsar observations are able to be gathered on a 3-6 month timescale, and no significant signal is observed, then a search paper could be submitted by mid-Spring 2018. The target journal would be *The Astrophysical Journal* with the novel aspect of the paper being the new search at f. If significant signals are observed their will be a concerted effort to ensure that they are astrophysical in origin, which could delay a paper by several months. If the signals prove to be real they will most likely still be published with the full set of results, although will be very prominently highlighted. If they do not turn out to meet our detection claim requirements they will be published as upper limits.

A methods paper describing the ellipticity population distribution estimation is expected by late 2017. Depending on successful review of the method the aim would be to apply it to O2 and either include it in the main O2 results paper, or produce a stand-alone collaboration paper by mid-2018.

4.2 Search for non-tensorial continuous GWs from known pulsars

Traditional searches for continuous waves targeted at known pulsars assume that sources emit the tensorial plus and cross gravitational-wave polarizations predicted by the general theory of relativity in accordance with the triaxial-source emission mechanism. However, it is conceivable 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, the search for non-tensorial continuous signals from known pulsars is capable of detecting and classifying those alternative modes in a theory-independent way [Isi et al. 2017].

Motivation and goals

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 continuous waves.

The search for non-tensorial continuous waves from known pulsars expands the time-domain Bayesian targeted analysis to be sensitive to signals of any polarization content at a given frequency (usually twice the rotational frequency of the source), without assuming any specific theory of gravity or emission mechanism. Once a signal is detected, rigorous Bayesian methods will allow us to determine whether there is evidence of a departure from general relativity. We can also measure or place upper-limits on the values of the strain amplitudes of the non-tensorial polarizations, which can be turned into constraints of alternative theories of gravity. These would be the first ever direct observational statements about the nature of gravitational-wave polarizations.

Major aspects and methods for this activity

Since development of this pipeline is basically complete and the code has been reviewed, the focus of this activity will be to analyze O2 data for the same pulsars targeted by the regular targeted search (Section 4.1). O1 and O2 data will be analyzed jointly whenever coherent timing solutions exist for both runs, and will otherwise be combined incoherently using Bayes factors. The analysis will also be expanded to search for GW signals at the rotational frequency of the source, and to support gravitational wave speeds different from that of light; this will require minimal changes to the code. As we have done in the past, we will also follow up on any signal candidates found by other pipelines.

Expected products and/or outcomes

Results from the search of O1 data for signals from $\mathcal{O}(200)$ pulsars at twice the source rotational frequency have been reviewed and will be published in the next few months. The analysis of O2 data at once and twice the rotational frequency will be presented in another paper to be released in the same timescale as the O2 standard targeted search paper (Section 4.1).

4.3 Narrowband searches for GWs from known and poorly known isolated pulsars

In the case of a neutron star with a mass quadrupole rotating about one of its principal axes of inertia, the signal frequency is twice the star rotation frequency. In the case of a spinning neutron star with an active r-mode (long-lived fluid oscillation), however, the signal frequency is roughly 4/3 the stellar rotation frequency, depending on the star's mass and equation of state. If the phase evolution of the NS can be accurately computed, i.e. if the source parameters are known with high accuracy e.g. from electromagnetic observations, data analysis techniques based on matched filtering can be used. Looking for continuous gravitational waves using electromagnetic-based templates means that the electromagnetic and gravitational signals are assumed to be phase-locked. This assumption, if not true, can prevent a possible detection.

Motivation and goals

Narrow-band mass quadrupole searches are an extension of targeted searches, see 4.1, in which the position of the source is assumed to be accurately known while the rotational parameters are slightly uncertain (Aasi et al. PRD 91, 022004, 2015). This type of search can still be based on matched filtering but, of course, is 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.

Narrow-band r-mode searches are also extensions of targeted searches, searching a somewhat less narrow band of order 10% of the pulsar rotation frequency to allow for the uncertainty of the r-mode frequency (Idrisy et al., PRD 91, 024001, 2015) due to the star's mass (which is not known for these pulsars) and the equation of state (which is not known in general).

Major aspects and methods for this activity

The narrow-band mass quadrupole search is performed using a pipeline based on the *5-vector method* (used since a long time for targeted searches, see sec. 4.1) and, in particular, its latest implementation, fully described in (Mastrogiovanni et al. CQG 34, 135007, 2017). The basic idea is that of exploring 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. The most interesting candidates are further analyzed in a follow-up stage.

In the past, a narrow-band quadrupole search has been done for Crab and Vela pulsars (Aasi et al. PRD 91, 022004, 2015). More recently, using Advanced LIGO O1 data (paper in preaparation), we have searched for continuous gravitational waves in a narrow-band region for 11 known pulsars. No evidence for true signals has been found so we have computed upper limits on the signal strain, finding for 8 pulsars values below the spin-down limit. In particular, for the Crab and Vela pulsars the upper limits significantly improve with respect to past analyses.

The r-mode narrowband search is based on the $\mathcal{F}$-statistic, searching over a band of frequencies as described above, with the frequency derivatives determined by the ratio of r-mode frequency to stellar rotation frequency. Hence the code pipeline is a simple adaptation of that used for most directed searches of supernova remnants and other non-pulsing pointlike sources described in Section 4.4.

Expected products and/or outcomes

As done for O1, we will apply the 5-vector narrow-band search pipeline to the entire O2 data set searching for the same targets already considered in O1 (and, possibly, to other potentially interesting known pulsars). Due to the detector sensitivity improvement and to the longer run duration, we expect an improvement in the overall search sensitivity, which could allow us to beat the spin-down limit for 2-3 more pulsars. In case of no detection an observational paper describing the O2 narrow-band search will be ready in early spring 2018 and submitted to PRD. Otherwise, more time could be needed to make deeper analyses in order to confirm a possible detection.

In the next year we will publish a search of all the O1 data for r-modes from the Crab pulsar. It should beat the spin-down limit slightly, although not enough to account for the braking index (information from the first and second frequency derivatives) of the pulsar which already indicates that r-modes are responsible for at most a small fraction of the spin-down. This will serve as a prototype for future searches of the Crab and other pulsars young enough to still be emitting via r-modes.

4.4 Directed search for GWs from supernova remnants and interesting point sources

Motivation and goals

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 only 300 years old. Extremely young extragalactic sources without an associated electromagnetic point source, e.g., SNR 1987A, also merit consideration. Some young supernova remnants and pulsar wind nebulae without pulsars are small enough to search with a single sky position. The goal here is to use the sky locations provided by non-pulsing electromagnetic markers of likely young neutron stars (such as supernova remnants) to perform point searches at greater sensitivity than the all-sky surveys, though not quite at the same sensitivity as searches for known pulsars.

Major aspects and methods for this activity

For these targets the sky direction is known but there is not even an approximate 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. Most previous searches have been based on existing implementations of the F-statistic code used in many LSC and Virgo searches. Further work is needed on improving this and on integrating the faster resampling algorithm and semi-coherent methods, used so far in only one LSC-Virgo publication each.

The CW group plans to perform a directed search for long transient (days-weeks) r-mode signals based on their exact waveforms. Such a type of a search has never been done, and is very valuable because a constrain on the r-mode saturation amplitude can provide a lot of information about the equation of state of a neutron star. A machine learning algorithm (MLA) is being developed to this purpose (see Sec. 4.9). The algorithm relies heavily on existing machinery from CW groups, and will be used to analyse the upcoming advanced detector data.

Expected products and/or outcomes

In the next year we will publish at least one results paper on point sources, mostly supernova remnants, searching O1 data. Approximately twenty targets are feasible, meaning that we can achieve sensitivities enough to potentially detect a signal given an analog of the spin-down limit for known pulsars, and not spend too much computing power in doing so. If there is a detection the information will be used outside the LSC and Virgo to hunt for a radio or x-ray pulsar, and comparison between any pulsar frequency and the gravitational wave frequency will be used to constrain the neutron star equation of state. If there is no detection the upper limits will not constrain the equation of state.

We will also improve the algorithms and incorporate advances in disparate pipelines, and begin searching O2 data shortly after the run is complete later this year.

We will run a directed, 'template' search from supernova remnants within the next couple of years using MLA, and we will write at least a methodological paper within 2018.

4.5 Directed searches for isolated stars

Motivation and goals

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 tradeoff between searching the largest sky area with reduced sensitivity, and pushing for sensitivity in a smaller region.

There are regions in the sky that are thought to host high concentrations of the types of objects that might be emitting detectable continuous gravitational waves. For instance known radio pulsars tend to cluster along the spiral arms, in globular clusters, and in other star-forming regions. To increase the chances of discovering a continuous gravitational wave signal we select regions where one can expect a clustering of neutron star sources in line-of-sight cones determined by the search area and sensitivity reach of the detector. We refer to these as "spotlight searches". Examples of regions that we have explored with spotlight searches are the Galactic Center and the Orion spur.

These interesting regions may also comprise a single point in the sky, being associated to single objects, like known pulsars and supernova-remnants (see 4.4), or to point-like regions like close globular clusters.

Methods and major aspects of this activity

Potentially all existing all-sky search algorithms can be used to perform spot-light searches. In practice only the Powerflux pipeline and semi-coherent stack-slide pipeline have been used.

A new directed search pipeline, based on the so called Band-Sample-Data (BSD) collection, is under development. The BSD data guarantee a more flexible data handling and a computationally fast application of the barycentric corrections needed in this type of search.

Expected products and/or outcomes

We expect a methodological paper describing the BSD collection to be delivered within 2018.

In O2 we can expect one or two "spotlight papers". It is hard at this moment to say much more because it is unclear what searches will make most sense to perform. The trade-offs in a run like O2 that has sensitivity not better than O1, a longer observation time with respect to O1 but with long interruptions, are not trivial. The extended interruptions, in particular, extend the spanned observation time, which is very costly for the computational budget of any search (the grid spacings depend on a high power of the spanned observation time), without any gain in sensitivity, which depends on the actual amount of data.

4.6 Directed searches for Sco X-1 and other known or suspected binary sources.

Motivation and goals

Accretion in a binary system leads to recycling, in which the neutron star spins up to near-kHz frequencies, and its magnetic field reduces to $\sim 10^8$ G. Directed searches for accreting binaries are a high priority because (i) the sources are relatively powerful if they are emitting near the indirect (torque balance) limit, and (ii) a CW detection can be combined with X-ray data to infer important astrophysical information about the accretion physics, as well as structure and evolution of the compact object. The central challenge facing these searches is that the spin frequency f_0 and orbital parameters are in general unknown. Furthermore the spin frequency is likely to wander stochastically in response to the fluctuating torque. In the torque balance scenario, the gravitational radiation reaction torque balances the accretion torque, which is proportional to the X-ray flux F_X, implying a limit on the characteristic wave strain given by $h_0 = 5.5 \times 10^{-27}(F_X/10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}})^{1/2}(f_0/300\,\mathrm{Hz})^{-1/2}$, independent of the distance to the source. Torque balance is one explanation for the observed fact that the spin frequencies of low-mass X-ray binaries (LMXBs) are systematically lower than accretion theory predicts (cf. $\sim 1.4\,\mathrm{kHz}$).

A CW detection will shed light on several important astrophysical questions: By combining CW and electromagnetic data, one can tie down the emission mechanism, produce equation-of-state information, probe the physics of the X-ray emission mechanism, differential rotation between the interior and crust; by measuring the distance independently, from the sphericity of the CW fronts, one can infer the size of the stellar deformation, and so on.

Aside from known binary sources, there are also interesting sky locations where a non-accreting binary source might reside and for which no spin frequency or orbital parameter is known. Examples include unidentified Fermi gamma-ray sources at high galactic latitude, the cores of nearby globular clusters and the galactic center region. Although the all-sky binary search covers these cases with some sensitivity, exploiting the precise localization allows improved sensitivity.

Methods and major aspects of this activity

The CW group is currently involved in developing various analysis pipelines suited to directed searches for LMXBs. Most of the pipelines operate in the frequency domain on data in the form of Short Fourier Transforms. The pipelines use largely independent algorithms from a signal processing viewpoint, e.g. cross-correlation [B. P. Abbott et al., arXiv:1706.03119], doubly-Fourier transformed data [TwoSpect, G. D. Meadors et al., PRD 95, 042005 (2017)], hidden Markov models [Viterbi, B. P. Abbott et al., arXiv:1704.03719], coherent summation of matched-filter sidebands [Sideband, J. Aasi et al., PRD 91, 062008 (2015)], and a resampling procedure, which is a generalization of the 5-vector method [P. Astone et al., PRD 82, 022005 (2010)]. A metric-lattice-based StackSlide search code ("Weave") that is currently under development will also allow searching over LMXB parameter spaces. Several of the pipelines participated formally in the first Scorpius X-1 Mock Data Challenge (MDC), which was performed on simulated data without instrumental artifacts or spin wandering [C. Messenger et al., PRD 92, 023006 (2015)].

The CW group will devote some efforts to refine the current pipelines, such as (i) including resampling in the Cross-correlation pipeline, (ii) using a coherent tracking of the orbital phase (Viterbi), (iii) reducing number of sidebands, (iv) incorporate improvements from noise line mitigation into all pipelines. An ongoing effort is being carried out to speed up the 5-vector resampling method. In targeting interesting sky locations for which no orbital information is known, a refined version of TwoSpect is under development, using a new statistic which permits efficient sparse sampling of the parameter space.

Expected products and/or outcomes

The products of the activities outlined above include a paper on the results of a second MDC (including signals with spin wandering added to instrumental noise from previous runs), at least one O2 search paper, and methods papers on improvements to the current search methods. Specifically, (i) a paper on using resampling to speed up the cross-correlation search (and thereby enable longer coherence times), (ii) a paper on a coherent extension to the Viterbi method, and (iii) a methodological paper describing the generalization of the resampling 5-vector method. All three improved methods expect to accomplish code review and analyze observational data within 2018. A paper on astrophysically characterizing the "spin-wandering" of Sco X-1 due to fluctuations in the accretion torque is currently being finalized. Furthermore, the CW group plans also to perform directed searches for the X-ray binaries Scorpius X-1, Cygnus X-3 and PSR J1751-305. The first two are especially bright in X-rays and in the torque-balance scenario, while there is evidence in the third object for a sharp X-ray periodicity that may indicate an r-mode oscillation. Other LMXBs should also be considered once ephemerides are refined. Searches will be carried out for one or more interesting sky locations for which no orbital parameters are known.

4.7 All-sky search for GWs from isolated compact stars

Motivation and goals

Continuous gravitational waves are expected to be emitted by neutron stars with a non-zero equatorial ellipticity. Theory shows that ellipticity as high as 10^{-5} could be sustained by neutron star crusts. However, there are observed neutron stars with ellipticities of smaller than 10^{-8} hence it may well be that small ellipticity values 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.

The mechanisms to form high-ellipticity sources are not understood well enough to predict rates of such an occurrence. While other searches explore regions of potentially high concentrations of neutron stars (such as globular clusters, galactic center, etc) it makes sense to conduct comprehensive searches of the entire parameter space so as not to miss an unexpected source nearby.

Major aspects and methods for this activity

There are several pipelines in CW group that have been optimized for different search scenarios, data quality and analysis speed.

- The Einstein@Home infrastructure is able to utilize computation power donated by volunteers around the globe. Because of this its computational budget is approximately 10x of other pipeline. This pipeline will carry out deep searches in somewhat narrower parameter spaces than the other pipelines.
- PowerFlux will be used to carry out broad all-sky searches over entire frequency space with the aim of producing results within several months to a year of run completion. It is the only pipeline that performs direct estimation of gravitational wave power.
- FrequencyHough and SkyHough are based on different implementation of the Hough transform algorithm and inherit its resilience to contaminated data. This was particularly useful during O1.
- TimeDomain F-statistic pipeline is based on method with a long coherence time. This makes it resilient to many artifacts affecting pipelines with shorter coherence lengths.

All pipelines had to contend with extremely large outlier sets during O1, as well as outliers that were coherent between interferometers. The knowledge gained from this will be folded into the analysis of O2 data which, so far, appears to be better behaved. Work will continue to further develop effective follow-up schemes.

All of the pipelines are computationally limited and work continues on algorithm optimizations. A separate focus is extending upper limit coverage to highly contaminated parameter space in order to produce comprehensive upper limits through the entire frequency range.

Work also continues on extending coverage to non-standard sources, such a long-period binaries, intermittent sources and others. This is especially important during followup as short-coherence all-sky pipelines are sensitive to wider range of sources that are not accessible by present followup methods. Note, however, that successful discovery of non-standard source places stringent demands on data quality that might not be available in O2.

Expected products and/or outcomes

The quality of O2 data is impossible to judge until the data collection is complete. This is because most all-sky pipelines use the entire data set for integration which exposes detector artifacts invisible on a day-to-day basis.

The larger timebase of O2 and the interruptions present a special challenge as they greatly increase parameter space compared to the same amount of data obtained in a contiguous chunk.

- Einstein@Home will perform a deep search on O2 data
- PowerFlux will perform an all-sky blind search covering entire frequency range 20-2000 Hz. Some regions of parameter space might be excluded if the performance is not as good as O1.
- FrequencyHough will use the same pipeline as in O1 to perform an all-sky search.
- SkyHough will perform an all-sky search
- TimeDomain F-statistic will perform a search on most sensitive subset of the data.

Depending on data quality the first paper can be shown to the collaboration with a year of run completion. Note, however, that this is conditioned on relatively well-behaved data. Presence of artifacts coherent between detectors (such as happened in O1) can greatly complicate the analysis as it is very difficult to distinguish such artifacts from true signals.

4.8 All-sky search for GWs from binary compact stars

Motivation and goals

Continuous gravitational wave emission from neutron stars in binary systems are of particular interest because of the phenomenon of "recycling" in which a companion star accretes matter onto the neutron star, imparting angular momentum to it and speeding it up. Such accretion is observed, for example, in low mass X-ray binary systems, such as Scorpius X-1, and most observed millisecond pulsars observed in radio, X-rays and gamma rays, reside in or once resided in systems where the accretion has stopped, but where the neutron stars retain a high angular velocity. The fraction of known millisecond pulsars ($f_{\rm rot} > 100$ Hz) that are binary is more than half, and the fraction of pulsars with $f_{\rm rot} > 400$ Hz that are binary is more than 3/4. The fraction of all known binary pulsars that are millisecond pulsars is $\sim$70%. 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, however, also present extreme challenges for continuous waves 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.

Major aspects and methods for this activity

Two methods have been developed to search for continuous gravitational waves from sources in unknown binary systems: 1) a method that relies on doubly-Fourier transformed data [E. Goetz and K. Riles, CQG 2011]; and 2) a method that produces correlations with filters described by a polynomial functional form of the putative gravitational wave phase [S. van der Putten, J. of Phys. Conf. Ser. 2010]. The former method has reached a mature state and the first search carried out on data from LIGO's sixth science run and Virgo's second and third science runs [J. Aasi, et al., PRD 2014]. Although the latter method is still under development, we expect that a search will be run on Advanced LIGO and Advanced Virgo data in the future.

In the near term, the mature, former analysis pipeline will be run on Advanced LIGO data from ongoing and future observing runs. The sensitivity of adding Virgo data into the LIGO network will need to be assessed, however, before proceeding to include it in future observing run analyses. This work will require setting up and preparing calibrated detector data for analysis–producing the first required data product, short Fourier transformed data–and deciding on the parameter space to be searched. Data will be analyzed on LSC computing clusters, with the output of the search being a list of outliers exceeding statistical threshold tests and upper limits on gravitational wave strain.

Analysis outliers are first assessed within the constraints of the pipeline. Further follow up of interesting candidates will be performed by more specialized algorithms, optimized for directed searches, and having higher sensitivity than all-sky search methods. Understanding the possible parameter uncertainty in the all-sky search is important so that the full range of possible parameter values can be tested by the more sensitive follow up analysis.

In addition to performing the analysis, pipeline development will continue on both algorithms in order to further enhance the sensitivity to continuous gravitational waves and to bring the development pipeline into maturity. Since sensitivity is often a trade-off with computational costs, exploratory studies for new, efficient methods is encouraged. The continuous waves group, however, will balance computing costs and sensitivity to signals for both old and new methods.

Expected products and/or outcomes

The main goal of these searches is to observe continuous gravitational waves from unknown neutron stars in binary systems. In conjunction with improved detector sensitivity as well as methods improvements in algorithms (e.g. [E. Goetz and K. Riles, CQG 2016]), the continuous waves group is well positioned for detections of these types of sources. Upper limits on gravitational wave strain are a standard output from each analysis. The continuous waves group anticipates publication of at least one pipeline paper for each observing run, provided the new data would yield added improvement over previously published results.

4.9 Search for long (days to weeks) transient CW signals

Motivation and goals

Other activities in Section 4 pertain to neutron stars emitting truly *continuous* gravitational waves: periodic signals lasting longer than an observation run. However, there are transient neutron star phenomena observed electromagnetically (e.g. pulsar glitches and x-ray bursts), which raise the possibility that neutron stars also emit gravitational wave signals on time scales of hours–weeks due to short-lived deformations or oscillations [Prix et al., PRD 84.023007 (2011)]. This activity includes development of new search algorithms for transient continuous-wave-like signals (tCWs) and methods to follow up potential transient candidates from standard CW searches. CW data analysis relies on integrating weak signals over long observation times; for transients, we can only accumulate signal power during the signal's lifetime. Dedicated tCW analyses can extract more of that limited signal power without averaging it out over the full data set.

Major aspects and methods for this activity

Assuming that tCW signals have waveforms similar to standard continuous waves, we can adapt detection methods developed for continuous waves. In particular, many matched-filter continuous-wave analyses already split the data set into discrete blocks of time, from a few hundred seconds (for Short Fourier Transforms) up to several days (for the segments of semi-coherent searches). Simple tCW searches then analyze the distribution of continuous-wave detection statistics over these individual time blocks. Current developments include both coherent and semicoherent tCW searches for known and unknown neutron stars. The theory and software tools are maturing, but still undergoing optimization and characterization. These methods can be used either as standalone searches, or as follow-up tools for interesting candidates from continuous-wave searches: candidates deviating from the standard expectation of continuity could otherwise be dismissed as due to transient detector artifacts.

Other developments involve completely new search methods, e.g. machine learning algorithms (MLAs) that recognize and classify patterns, where our patterns are gravitational wave signal behaviors in the time/strain or time/frequency planes. MLAs need to be trained with a sufficient number of examples, but then can also identify patterns that are similar, though maybe not exactly like, the patterns on which they have been trained. Specifically, training will involve templates for r-mode oscillations [Owen et al., PRD 58.084020 (1998)], including frequency evolution, and the machinery of existing all-sky searches can be used to provide time/frequency maps as input to neural networks and random forests.

Expected products and/or outcomes

Grid- and Monte-Carlo-based matched-filter transient routines will be characterized (in one or more methods papers) to follow up the candidates from blind searches, thus contributing to all-sky and directed search papers from O2 and later. A tCW add-on to semicoherent analyses is also available for intermediate follow-up steps [Keitel, PRD 93.084024 (2016)]. For known pulsars, a new transient analysis and methods paper are under development, and this is intended as part of future targeted search papers. Contingent on progress in methods optimization and studies of the detector noise background, we intend to perform a dedicated O2 search for transient signals triggered by EM observations of glitches in known pulsars, which can eventually be developed into an untriggered search for transients from any nearby glitching and accreting systems. The MLA approach will also lead to a methods paper, and we plan to use it in a targeted search for r-modes from astrophysically promising objects. Once trained, MLAs are computationally cheap and can also be used to generate triggers for follow-up by other methods. The detection of tCW signals, through probing neutron star dynamics, would yield information about neutron star composition and evolution [Bennett et al., MNRAS 409(4):1705-1718 (2010)], while even for non-detections the derived upper limits on signal strengths and rates in individual sources or populations could constrain glitch and burst mechanisms.

4.10 Detector and data characterization, software maintenance, and code optimization

Overview of the tasks

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. The continuous wave working group therefore must work closely with the detector characterization working group and the site commissioning staff to determine the best way to achieve these goals.

In addition, the software used by the continuous wave working group must be maintained in the LALSuite software repository. For reviewed search codes and for shared library and applications software used within the group it is essential to maintain them in a vetted and functional state, while at the same time allowing for continued code development. *Code development* typically encompasses bug fixes, but also additions of new and improved methods, added functionalities to existing search codes, and code optimizations. The standard operating procedure is for each code patch to undergo internal vetting to ensure compatibility and reduce the likelihood of introducing new bugs.

Finally, the continuous waves working group is periodically requested to produce optimization reports to ensure responsible use of LVC computing resources. Estimates of required computing resources are needed for each observing run. 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. Typically, the codes used by the working group are already highly optimized due to the demanding computational nature of many searches. These requests will also need to be weighed against the potential time cost for improving code optimization as well as the time to review the new version of the code.

Methods and work required

Several tools are used to validate and characterize detector data during observing runs. Depending on the person power available, volunteers from the continuous waves working group will monitor detector data on a weekly basis, checking to see if new contaminations have appeared that may impact the astrophysical results that the group can deliver. Potentially, if some contamination disappears, this might also indicate a noise coupling source that can be reported back to the site commissioning staff. This team will utilize the tools already produced, and, when necessary, work on new tools that can better handle particular data quality needs. The results of this data monitoring will be reported back to the detector characterization working group.

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. Some data quality flags are only needed for short duration searches, whereas the coherent time interval for most continuous wave searches negates the need for most "glitch" transient flags. The continuous waves group will validate which data quality flags are needed and which can be safely ignored.

The continuous waves group uses the LIGO-Virgo Redmine tracking system [`https://bugs.ligo.org/redmine/projects/lalsuite-lalpulsar`] to manage code patches, requests, and bug reports. Members of the group work together to submit issues and cross-check and verify patches uploaded to Redmine. Redmine issues potentially relevant to the whole group are discussed in the weekly teleconferences, in order to inform users of affected codes about bugs found and fixed, or of upcoming changes and extensions, in order to avoid unintended conflicts or surprises.

As requested from the LSC and Virgo computing teams, the continuous waves group will sometimes be tasked to verify and optimize the algorithms requiring the largest computing resources. Pipeline developers will need to produce observing run estimates for computing resources required. Periodically, those pipelines identified as most computationally demanding will have their authors work closely with the computing team to benchmark and optimize the code used in the analysis.

Expected results

As a result of these efforts, the continuous waves group will, first, work to identify spectral artifacts in the calibrated detector output. Ideally, this work will also result in mitigation of noise sources. These identified artifacts will make up a so-called "lines list" that can be used to discard outliers or to "clean" the data before a search is performed, as done for the Einstein@Home data. Second, data quality flags will be identified and used to exclude the most egregiously contaminated detector data. Third, the continuous waves group will work together to track and manage code patches, requests, and fix bugs using the Redmine system. Lastly, computing request estimates and occasional code optimizations will be performed in order to reduce the computational burden of the largest analysis requests.

5 Stochastic Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, CBC and Detchar groups in sections 7, 8 and 9, respectively.

5.1 Search for an Isotropic Stochastic Gravitational Wave background

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 [98], phase transitions in the early universe [99, 100], cosmic strings [101, 102, 103, 104], and pre-Big Bang models [105, 106]. Astrophysical contributions to the stochastic background consist of an incoherent superposition of sources too weak to detect individually, such as binary neutron stars [107] or binary black holes [108]. 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 is not unlikely and would also be of great interest. The implications from Advanced LIGO's first observing run are that the stochastic gravitational-wave background from binary black holes is consistent with optimistic predictions, and is potentially observable with advanced detectors [108].

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 [109, 110], which has served as the basis for all previous LIGO/Virgo stochastic searches [111, 112, 113, 114, 115, **?**]. The stochastic pipeline estimates $\Omega_{\rm GW}(f)$ given some assumed power law $\Omega_{\rm GW}(f) \propto f^{\alpha}$. Cosmological sources such as the inflation and cosmic string backgrounds are predicted to have $\alpha = 0$ limits, while $\alpha = 2/3$ is appropriate for the signal from binaries. We will carry out this search on O2 data. We expect increased sensitivity relative to O1, due to both the longer integration time, and increased detector sensitivity. In the event of a detection, we will employ consistency checks, spectral fitting, and tests of isotropy in order to study the origin of the signal; see [116]. Otherwise, we will report upper limits for arbitrary spectral indices [113, 116].

We can study the observational implications for specific theoretical models for the stochastic background. For example, applying the Bayesian parameter estimation techniques outlined in [117, 116] to search results, 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 will also require developing better models for the background. This includes more accurate astrophysical models of the binary black hole background,and studies of inflationary models.

In addition to carrying out this search, we will develop several extensions to the standard isotropic analysis, to maximize the information obtained from the advanced detectors.

Mixed power-law spectra. 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 method was recently developed to put joint upper limits on the amplitudes of multiple spectral shapes [?]. 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. We also propose to implement a related approach using Bayesian parameter estimation to place upper limit contours in a parameter space containing multiple power law backgrounds simultaneously.

Fully Bayesian search. The standard isotropic analysis uses a hybrid of Bayesian and frequentist techniques to measure the background. This leaves open the possibility that some information is lost in the standard analysis. We propose to use BayesWave [?] to do a fully-Bayesian search for an isotropic stochastic gravitational-wave background. BayesWave is a set of Bayesian inference routines that are optimized for the detection and estimation of un-modeled gravitational-wave bursts. It is also capable of estimating noise power spectra and modeling glitches in the data, using a trans-dimensional reversible jump Markov chain Monte Carlo algorithm to determine the optimal number of parameters (and their values) needed to model these sources. BayesWave has recently been extended to estimate the amplitude and spectral index of a common correlated gravitational-wave component to the covariance matrix for a network of detectors. This allows us to use BayesWave to simultaneously estimate both the detector noise and gravitational-wave background contributions to the observed data in a fully Bayesian manner. By comparing the fully Bayesian approach with the standard isotropic pipeline, we will be able to see if the standard approach is losing information by working solely with the cross-correlation statistic (which ignores the auto-correlation terms).

Non-tensor polarizations. While general relativity allows only for two kind of tensorial polarizations, a generic prediction of extended gravitational theories, such as scalar-tensor theories [118, 119], $f(R)$ gravity [120, 121], bimetric [122] and massive [123] gravity theories, is the presence of other physical degrees of freedom, with scalar and/or vector polarizations. An extension to the isotropic pipeline which searches for a background of non-tensor polarizations has recently been developed and validated [?]. The search for nonstandard polarizations uses the same pipeline as the standard isotropic search, with minimal modifications which take into account the different coherence structure of the expected signal, parameterized by the overlap reduction function. We have developed a sophisticated post processing layer to perform model selection and parameter estimation. We compare the Bayesian evidence of signal to noise. In the case of a detection of a stochastic background, we compare the evidence of a pure tensor background to a background containing one or more non-tensor modes. We can also perform Bayesian parameter estimation on the amplitudes and spectral indices of different polarization components. It should be noted that the possibility of separating in a model independent way different contributions is greatly improved by using a network with more than one pair of detectors. A search using O1 data is ongoing.

5.1.3 Deliverables

1. Combined O1/O2 search results on the stochastic background (Late 2017). This includes:
    - Measurements or upper limits of the energy density in the stochastic background for different power laws.
    - Implications for theoretical models for the stochastic background, e.g. binary black holes.
    - Joint multi-component upper limits derived from the standard search results.
    - A comparison of the amplitudes and spectral indices for an isotropic stochastic background estimated from O1 data, using both BayesWave and the standard cross-correlation analysis methods.

2. Search results from O1 for the background from non-tensor polarizations (Mid 2017). This includes:
   - model selection between GR and non-GR background signal.
   - estimate of the background energy density from tensor, vector, and scalar polarizations.
3. Investigations of BayesWave as a tool for estimating the parameters of a stochastic gravitational-wave background (Early 2018).

5.2 Directional searches for persistent gravitational waves

5.2.1 Scientific Case

While most prescriptions of the SGWB predict an isotropic signal, there are mechanisms that could introduce anisotropy [104, 124]. For example, a confusion background may arise from binary mergers [117, 125, 126], core-collapse supernovae [127, 128], neutron-star excitations [129, 130], persistent emission from neutron stars [131, 132], and compact objects around supermassive black holes [133, 134]. 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; and 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 centre).

5.2.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [135]:

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

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 (typically $\alpha = 0$ for cosmological models and $\alpha = 3$ for astrophysical models), the objective of the search is to estimate $P(\Theta)$. Two approaches are pursued. In the radiometer algorithm, we assume the signals 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:

$$\hat{\eta}_\Theta = (\Gamma_{\Theta\Theta})^{-1} X_\Theta \quad (5)$$

$$\hat{P}_{lm} = \sum_{l'm'} (\Gamma^{-1})_{lm,l'm'} X_{l'm'}. \quad (6)$$

The Fisher matrix $\Gamma_\mu(f,t)$ encodes the uncertainty associated in deconvolving the raw cross-correlation measurement with different directions on the sky and the angular decomposition of the overlap reduction function (see [136, 135, **?**] for further description and details on its inversion).

There are also several extensions to the direction searches planned or already in production.

All-sky all-frequency search for unmodelled persistent GW sources. Recent work [137] demonstrates that data compressed using sidereal folding [138] 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 we 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.

Galactic Pulsar Search. The spherical harmonic search for broadband extended sources can be applied to search for an anisotropic GW background from pulsars in the galactic plane [**?**]. Population synthesis studies of millisecond and normal pulsars suggest that each population can be separately described by an anisotropic background with a certain power law [124]. However, the total background is a superposition of the backgrounds from each population, and the relative strength of the backgrounds for the two populations in the LIGO frequency band is not known. We extend the spherical harmonic search to perform parameter estimation on the amplitude and spatial distribution of multiple pulsar populations simultaneously.

Component separation using narrowband maps. Like the isotropic search, directional searches are also performed separately for multiple spectral indices in standard LIGO 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.

Models for 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. We investigate the possibility of correlations between the scale of anisotropies in the microwave and GW backgrounds and make predictions to test against observations. We also investigate other sources of anisotropy, such as BBH mergers or cosmic string networks, for the angular distribution or the level of anisotropy can be estimated for example with simulation studies.

5.2.3 Deliverables

1. Sky maps of the SGWB, including:
   - measurements (or constraints) on the energy flux from point sources and energy density from extended sources across the sky
   - measurements (or constraints) on the anisotropy of the SGWB
   - joint upper limit skymaps for two or three power-law spectral indices

2. Unmodeled search for potentially interesting persistent GW sources, including:
   - directed search for persistent GWs from specific sky locations
   - measurements (or constraints) on the GW strain amplitude from persistent GW sources
3. Combined O1/O2 folded data to facilitate all-sky search for persistent narrowband point sources over all frequencies
4. A search for an anisotropic GW background from pulsar emission in the galactic plane, including measurement of (or constraints on) the energy density and spatial distribution of such a signal.
5. Models of anisotropic GW backgrounds

5.3 Search for very long transient gravitational wave signals

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. [139], 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) [140, 141, 142]. 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 [143], 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.

5.3.2 Methodology

The transient searches will constrain the energy density $\Omega_{\rm gw}$ [109] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [144, 145, 146, 147, 148]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [144]. Gravitational-wave signals appears as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [144, 149, 147, 148, 150]) in order to identify statistically significant clusters of pixels. Recently, a highly-parallel seedless clustering algorithm [147, 148] was implemented, and recent work [148] 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 data are presented in [**?**].

We will analyze data on timescales of $\approx$[$10]hr$–[$1]month$ in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We will run STAMP in all-sky mode on all O1 and O2 data used in the stochastic search. In order to analyze these very long signals, we will add an extra stage of pre-processing in which the data are compressed through time-averaging as described in [151]. This new pre-processing step will require minimal new infrastructure/review.

The STAMP code package has also produced spin-off technology that has proven useful for detector characterization [152, 153] and follow-up/visualization of CBC triggers [150]. We expect continued development and maintenance of STAMP will be broadly useful for Stochastic Group activities and the wider LSC/Virgo community.

5.3.3 Deliverables

1. Search results using O1 and O2 data (early Spring 2018), including
   - Measurement (or upper limits) on $\Omega_{\rm gw}$ due to transient sources.
   - If a stochastic signal is observed, then this search will allow us to measure or put upper limits on the contribution from transient signals.

5.4 Data Folding for Efficient Searches of Stochastic Gravitational Wave Background

5.4.1 Scientific Case

Searches for a persistent Stochastic Gravitational Wave Background involves processing of cross-spectral density data from pairs of detectors with optimal spectral and spatial filters that maximise the signal-to-noise ratio. It was observed that the spatial part of the filter is periodic in time, it repeats itself after every sidereal day, and the time dependent component of spectral filters and data are otherwise treated in the same way for all stochastic searches for persistent sources. These two symmetries can be utilized in order to *fold* stochastic cross-spectral data (a.k.a. Stochastic Intermediate Data or SID) over one or more observing runs into a time-frequency map over a single sidereal day. This process of folding data does not involve any additional approximation (apart from the ones that are used in the standard searches) and it can also incorporate complex corrections that arise from the application of overlapping windows for preprocessing of data. The theory, implementation and validation of folding on real S5 data was presented in [138]. Folded data not only save enormous amount of computation time, but they introduce many other advantages to perform stochastic analyses in a convenient way as listed below:

- The computation time required to perform an analysis on n sidereal days worth of data is reduced by a factor n when using folded data. Hence the speed-up to analyse S5 data was by a factor of ~ 300.
- The folded data size is small. For a frequency bin size of 0.25 Hz and upper cut-off of 2 kHz, the data size is little more than a GigaByte. So the whole data set can comfortably fit in a laptop's memory.
- Once the folded data has been produced, all other analyses can follow from the same dataset, providing a good opportunity for cross-validation of results.

5.4.2 Methodology

Folding essentially stacks time-frequency maps of data segments (typically few tens of seconds long) for the same sidereal time of every sidereal day of the dataset. The implementation described in [138] also incorporates complex corrections to account for overlapping window functions. The code was implemented in MATLAB as part of matapps. Scripts were also written to generate condor/DAG submission files, though the code is so fast that a serial mode run in an interactive session is often sufficient. The code has the ability to apply data quality cuts on the fly in multiple ways. However, in order to ensure consistency of the results, it may better to use quality cuts applied by one standard search. The group is considering a modular approach where once a full analysis, perhaps the isotropic search, is done and data quality cuts are finalised, a common set of folded data would be created for all other long duration stochastic searches.

The efficiency and convenience to use folded data has motivated a new map making code that enables making skymaps on a normal laptop and provides narrowband maps as an intermediate product. It uses PyCBC and healpy, in order to use HEALPix pixelisation and other tools which make it very easy to analyse anisotropic maps. This code also includes some additional computational tricks, which makes it possible to produce skymaps on a laptop in just few minutes.

In summary, the folding code and the new map making code are well equipped to provide compressed datasets in multiple ways, which can be readily used for different analyses at a much reduced computational cost and in a very conveniently on portable computers.

5.4.3 Deliverables

1. Folded data, perhaps one set per week/month and one master set for the whole run
2. Maps from folded data (the planned analyses of these maps are discussed in the other sections)

6 Burst+CBC Joint Activity Plans

6.1 Search for GWs from intermediate mass black hole binaries

Stellar-mass black holes, originating from core collapse of massive stars, have been observed in the mass range up to $\sim 65\,\mathrm{M}_\odot$. Massive black holes, exceeding $10^5\,\mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) are postulated to occupy the mass range between these two. IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [154, **?**]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [155], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [156]. 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 [157]. IMBH binaries could also form as a result of evolution of isolated binaries with very high initial stellar masses [158].

No IMBHs in the mass range of interest ($\lesssim 1000\,\mathrm{M}_\odot$ for Advanced detectors) have been detected so far. Thus, a single detection will be revolutionary, as it will prove unambiguously that black holes exist in the mass range between stellar-mass and super-massive black holes. IMBH binary detections will also serve as probes of globular cluster dynamics, and, potentially, as probes of structure formation and growth of super-massive black holes. IMBH binary measurements could also inform our understanding of the formation and evolution of the most massive stars. On the other hand, the lack of confident IMBH observations to date and the complexity of modeling the evolution of very massive stars means that little is known about these objects. It is impossible to quote lower limits on the IMBH binary merger rate, which may, in fact, be zero.

If IMBHs in this mass range do merge in binaries, little is known about their mass distribution. However, we do expect that merger and ringdown will make a very significant contribution to the signal-to-noise ratio of observed gravitational waves from such systems, because most or all of the inspiral for massive systems will occur at frequencies below the detector band. Similarly, little is known about the spin distribution of IMBHs; they may have high spins, and because of the dynamical interactions likely involved in IMBH binary formation, the spins are likely to be misaligned, leading to precession. Moreover, higher order modes may play a significant role for IMBHB systems with large mass ratios. Therefore, waveforms that not only include merger and ringdown phases, but also precession and higher order modes (both NR and non-NR waveforms), will be necessary to accurately model IMBH binaries.

We can very crudely estimate optimistic IMBH binary merger rate predictions as follows. For IMBH binary mergers in globular clusters, it is very unlikely to have more than $O(1)$ merger per history of globular cluster. The space density of globular clusters is approximately 3 Mpc^{-3}, and a typical cluster is about 10 Gyr old, leading to an upper limit on the IMBH binary merger rate of $0.3\times$ Gpc^{-3} yr^{-1}. IMBH binary formation from very massive isolated stellar binaries in galactic fields could yield rates a few times higher than this, but there are many uncertainties. This optimistic rate is a factor of several hundred lower than the upper limits obtained in previous LIGO-Virgo searches [159].

A search for IMBH binaries would thus have a chance of yielding a detection if the space-time volume of the search is more than $\sim 3\times$ Gpc$^3\cdot$ yr (comoving volume $\cdot$ surveyed time). Current sensitivities of Advanced LIGO create this possibility. For example, the O1 IMBH search [160] probed roughly this space-time volume, placing meaningful constraints on the IMBH merger rate for the first time. IMBH binaries with a "redshifted" mass of $M(1+z) \sim 260\,\mathrm{M}_\odot$ could be detected to a luminosity horizon distance [1] of ~ 4.8 Gpc. Larger detection volumes are possible for spin-aligned systems. The horizon distance for these sources is expected to grow as Advanced LIGO approaches design sensitivity over the next few years.

This search will be conducted both with matched filter algorithms using CBC templates and burst algorithms, which do not rely on templates. The matched filter yields the optimal detection efficiency for signals of known form in stationary, Gaussian noise and thus requires a sufficiently accurate signal wave-

[1] An approximate upper bound on the reach of a modeled search for IMBHBs.

form model for use as a template. The IMBHB 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, and/or deviations from general relativity. Therefore, the IMBHB search benefits from the combination of the two complementary analysis techniques.

O2 Deliverables

- Conduct the IMBHB search on the O2 data
- Report events detected by the search in the catalog paper and/or discovery paper if an IMBHB source is identified
- Deliver a paper on the astrophysical interpretation on the estimated rate limits on intermediate mass black hole mergers
- In collaboration with numerical relativity (NR) community develop a set of IMBHB NR waveforms for interpretation of the O1+O2 results

O3 Deliverables
Adopt the same publication procedure reported above and in addition we will do the following:

- Improve and upgrade the burst IMBHB search algorithms before the O3 data taking run
- Conduct the IMBHB searches on the O3 data
- Perform population studies for existing IMBHB formation models and include them into the astrophysical interpretation of the O3 IMBHB results

6.2 Studies of extreme matter with pre-merger and post-merger GWs

Report on 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

One of the outstanding issues in nuclear physics is the EOS of nuclear matter. The detection and parameter estimation of BNS/NSBHsystems will require templates that include modelling of the late inspiral, where it is possible that neutron stars may be tidally deformed or even tidally disrupted. The extent of this deformation, and the final state of matter in the system is highly dependent on the EOS of the nuclear matter inside the NS.

Currently the ability to measure matter effects is constrained by the accuracy and speed of inspiral waveforms and by the lack of data analysis methods for the post-merger stage of BNS events.

Multiple BNS/NSBH detections will allow us to further constrain these models. An accurate estimation of the NS mass will also allow us to constrain more exotic forms of nuclear matter.

O2 deliverables

1. *Systematic errors:* The ability to measure the tidal parameters is limited by uncertainties in the point-particle and tidal contributions to the waveform evolution. Waveform injection and parameter estimation studies will be performed to assess the systematic errors in the measured tidal parameters resulting from differences in the waveform model spin priors, and calibration errors.

2. *Waveform comparison:* A detailed analysis of the differences between several versions of the EOB formalism for systems with tides as well as numerical simulations is not currently available. The impact of these uncertainties on the measured tidal parameter will be assessed.

3. *Surrogate models:* Parameter estimation for systems containing NSs is not possible with currently implemented effective one body models due to their long evaluation time. A surrogate waveform model for the aligned spin waveforms with tidal interactions (TEOBv2 and TEOBv4) will be produced.

4. *BNS post-merger remnant:* Methods for identifying and measuring the peak frequency of a potential BNS post-merger signal are not currently available. Pipelines using BayesWave and CWB[[?]] will be developed to do this.

5. *Nonlinear tides:* A potential p-g-mode coupling during the early inspiral of BNS systems has the potential to significantly bias the recovered binary parameters and cause current detection pipelines to miss these signals. A more detailed analysis of their impact and a search for systems with nonlinear tides will be developed.

6. With multiple detections of BNS/BHNS, a constraint statement on the EOS of nuclear matter can be made.

6.3 Multimessenger search for GWs and gamma-ray bursts

Follow up GRB alerts with deeper searches for simultaneous CBC and burst triggers: 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 [161]: 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 or neutron star) by way of two distinct pathways, both of which involve the emission of transient gravitational waves.

The coalescence of a neutron star with a neutron star or black hole is a probable candidate to be the progenitor of short gamma-ray bursts (sGRBs). A detection of GWs in coincidence with a GRB would be a major scientific result, confirming this progenitor model and demanding a rapid publication. Any possible association should be communicated to MOU porters with low latency to enable follow-up observations of any GRB of interest.

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. The observable range in GWs of basic stellar collapse is (near-)galactic, but could reach ~ 200 Mpc when the collapse leads to core fragmentation or rotational instabilities. The estimated rate for long GRBs within 100 Mpc is $\sim 1\,\mathrm{yr}^{-1}$ [162, 163]. A hypothesized sub-population of low-luminosity long GRBs, including GRB 980425 observed at 35 Mpc [164], is predicted to occur at rates sufficiently high [165] to expect many 10s of events per year within 100 Mpc. Some models predict GW emission associated with the accretion disk itself, or with a post-collapse proto-neutron star, 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.

The association between GWs and GRBs has a number of other impacts in multiple fields. For example, the speed of gravity can be probed to $\sim 10^{-16}$, and “dark matter emulator” models can be effectively ruled out with a coincident GRB-GW event [166]. A population of GW and short GRB joint observations could provide a measurement of the low-z Hubble parameter H_0 to a few % [167]. Finally, multiple observations of compact binary merger sources — both with and without GRB counterparts — can constrain the average short GRB beaming angle. Past searches for coincident observation of gravitational waves and GRBs include [168, 169, 170].

Methodology

To search for gravitational waves associated with GRBs, we use triggered (using GRB time and sky position), coherent algorithms that either target NS-NS or NS-BH binary inspiral signals [171] for short GRBs, or target generic GW burst signals [172] for all GRBs. These searches are more sensitive than the corresponding all-sky ones. We run these searches both online (few-hour latency) and offline. We use an additional algorithm [173] to search online (minutes latency) for coincidences of low-latency, all-sky GW triggers and GRBs. In O1 we successfully ran triggered search pipelines for BNS and NSBH progenitors in online mode, and provided results with a latency of a few hours. We also analysed our data offline to provide a final collection of results for the O1 GRB search. We will continue this plan in O2. Finally, methods are in development to search for gravitational waves in coincidence with “sub-threshold” GRBs.

O2 and O3 deliverables

1. Communication of online search results to MOU partners. This will require the following:
    (a) Continue to run low- (RAVEN) and medium-latency (X and pyGRB) pipelines, as for O1, but with updates.
    (b) Continue to use the online frame files at Caltech, as for O1.
    (c) Complete the infrastructure to communicate online results to MOU partners via approval processor, etc (in progress as of Oct 17, 2016)
    (d) Adding Virgo data (sometime in O2) needs to be tested. X and pyGRB successfully ran with Virgo in S6, so not a problem, in principle.
2. Rapid publication of a GW detection associated with a GRB.
    (a) Communications with MOU partners would give best, vetted, but perhaps not final, results available at that time.
    (b) The group should develop a publication template.
    (c) Significant non-detections would presumably also fall into this category, but presumably with faster collaboration approval; and we have several paper templates from GRB 070211, GRB 051103, and GRB 150916B.
3. Publication of complete set of GRB search results. This may result in two papers:
    (a) A “classic" upper limits paper which includes promptly available GRBs, typically those published in the public GCN plus IPN GRBs if available quickly.

   (b) A second results paper which includes results from the emerging sub-threshold analyses using the Fermi GBM or possibly other detectors, such as the Integral-only GRBs. If the IPN GRBs are not available promptly, they would also be included in this paper. The sub-threshold analyses would require new reviewing efforts.

4. Complete development of a targeted, coherent matched-filtering CBC search.

5. Follow-up of compact binary merger triggers with targeted Fermi/GBM search for orbitally-modulated NS flares.

6. Complete development of cross-correlation search for longer duration GWs targeting GRBs with X-ray plateaus (testing in O2, running in O3).

6.4 Multimessenger search for GWs and high-energy neutrinos

Some dynamical processes with strong gravitational-wave (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 [174, 175]. 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 [176], its surroundings [177], and the nature of relativistic outflows [178, 179]. 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 [180, 181].

In O1 we worked closely with the IceCube and ANTARES collaborations to perform a sensitive search for neutrinos associated with the GW150914 [182], LVT151012, and GW151226 [183]. No coincident neutrinos were found, and the results were used to constrain the neutrino flux from these sources. Past searches have also looked for coincidences of sub-threshold events in both the neutrino and gravitational wave detectors [184].

O2/O3 Deliverables

- Develop, enhance and perform multimessenger GW+neutrino searchs in low-latency, utilizing the baseline GW+neutrino search pipeline, and rapidly share the results with astronomy and other partners through, e.g., the LIGO/Virgo event database (GraceDB), and other brokers.

- Facilitate electromagnetic follow-up of multimessenger GW+neutrino detections by providing suitable data products and maintaining information sharing with astronomy and other partners.

- Write publications for O2 and (separately) O3 describing the results and methods of the multimessenger search between low-threshold GW events and high-energy neutrinos.

- Write publications on results of multimessenger searches corresponding to significant GW or neutrino events for the cases in which no significant counterpart was identified, if non-detection represent a novel and/or significantly improved ($\times 3$) constraint or involve new/improved (astro)physics.

- Write publication(s) describing the results of the multimessenger search corresponding to significant GW or neutrino signals for the cases in which a multimessenger signal was detected.

6.5 Astronomical (EM+neutrino) follow-up campaign

Motivation and goals

The National Science Foundation has recently named “Window on the Universe: The Era Multi-Messenger Astrophysics” as one of its “big ideas”. Gravitational waves along with electromagnetic and astroparticle observations could help us to unravel the mystery of some of the Universe’s most spectacular transient phenomena. Identifying the electromagnetic or neutrino signature of the transient gravitational-wave sources, like the coalescence of compact object systems and the core-collapse of massive stars, will have strong impact on many astrophysical fields, going from fundamental physics to stellar evolution and nuclear astrophysics, shedding light on the equation of state of neutron stars, birth and evolution of neutron stars and black holes, and the processes that power multi-messenger emissions.

Major aspects and methods for this activity

Unmodeled and compact binary coalescence matched-filter searches have been developed aiming at detecting and localizing transient gravitational-wave sources in low latency for a rapid neutrino and electromagnetic follow-up. These searches started early in the initial LIGO and Virgo 2009-2010 science runs and continued during the first and second run of the Advanced detectors. Prompt identification and validation of gravitational-wave candidate signals enable to generate and send rapid alerts containing sky position, preliminary significance, distance, and basic classification to the observers. Parameter estimation follow-ups are then performed to send updates and support the electromagnetic and neutrino counterpart search. The notable improvement in sensitivity and lifetime of the LIGO and Virgo network planned for the third observation run is expected to increase the number of alerts. A major change will be the open release for event candidates of high confidence (FAR $<$ 1/100 years) expected to be sent within a few minutes to the entire astronomical community. This will drive development, improvement and organization of software and infrastructures to generate, validate and send gravitational-wave candidate signals with the goal of a rapid communication to the astronomical community.

Expected products and/or outcomes

- Validate and distribute low-latency alerts to the scientific community during the third run of the Advanced detectors. This will require 1) to improve the robustness of the low-latency trigger generation, their organization and the required infrastructure; 2) to automatize data quality and vetoes as much as possible, to incorporate them in low latency and reduce the alert latency to order of few minutes; 3) to improve latency of parameter estimation follow-ups of the gravitational-wave candidates to support electromagnetic and neutrino observational strategies and data analysis;

- Support the astronomers for the usage and interpretation of alert contents. This will be done by developing tools (with astronomical standard format) to easily manage the gravitational-wave observational products shared with the astronomers, improving documents and communication with the astronomical community;

- Perform studies to address the scientific question of how to assess/interpret any sub-threshold candidate with an apparent counterpart;

- Improving the communication with the astronomical community to plan current and future multi-messenger astronomy with the goal to: 1) identify requirements and policy to maximize joint observations and data analysis results and 2) to participate in projects and develop science cases for future electromagnetic/neutrino and gravitational-wave observatories;

- Publication and/or reports describing the low-latency analysis, candidate selection and data analysis results transmitted in the GCNs, as well as summary of all the distributed alerts and EM follow-up response for O2 are planned as LVC and short-author list papers. Papers identifying the science value of marginal candidates with electromagnetic and neutrino candidate counterparts are considered interest of LVC. Contributions of the electromagnetic and neutrino observers are highly valuable and to be stimulated.

7 Burst+Stochastic Joint Activity Plans

7.1 Search for long-duration GW bursts

Unmodeled long-lived gravitational-wave transients (lasting $\gtrsim$ 10–$[\,10,000]s$) 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 for these sources use minimal assumptions about the signal waveform, so unpredicted sources are detectable as well. The most promising source classes are described below. A search for long duration transients was published using initial LIGO data [185].

- Protoneutron stars: The first scenario relies on the formation of a protoneutron star. If the protoneutron star is born spinning rapidly, it may develop an instability (e.g., a bar mode), leading to the strong emission of long-lived, narrowband gravitational waves [186]. A protoneutron star can also be spun up through accretion of stellar remnant fallback such that an instability sets in [187]. The resulting gravitational-wave emission can last for $\approx$ 40–$[\,3100]s$ [188]. Advanced LIGO / advanced Virgo might detect rotational instability signals from protoneutron stars out to distances of up to $\approx [\,40]Mpc$ [147, 148]. The rate of observed supernovae in this volume is on the order of $\approx$ 10–$[\,30]yr^{-1}$ [188], though the fraction of these stellar explosions that might result in an accretion fallback signal is currently unknown. Nonetheless, a single such detection would provide an unparalleled glimpse into the moments following stellar collapse and the birth of a neutron star or black hole.

- Accretion disks: The second scenario relies on the formation of an accretion disk following stellar collapse. A central spinning black hole drives turbulence in the accretion torus, which leads to the formation of clumps. The motion of these clumps emits long-lived narrowband gravitational waves [189, 190, 191], on the time-scale reaching 10^3 sec. Alternatively, clumps may form through accretion disk fragmentation, also leading to the production of gravitational waves [192]. The rate and energy budget of accretion disk instability signals are debated. However, we estimate that advanced LIGO / advanced Virgo can observe accretion disk instability events out to distances of $[\,540]Mpc\,(E_{\rm gw}/0.1M_{\odot})^{1/2}$ where $E_{\rm gw}$ is the gravitational-wave energy budget [147, 148]. We note that long gamma ray-bursts are observed at a rate of about $[\,0.3]yr^{-1}$ within this radius (and many are likely to be missed due to beaming) [146].

  A single detection would provide unprecedented information about the environment following the collapse of a massive star and could shed light on the mechanics of long gamma-ray bursts.

- Other sources: Other scenarios for the production of long-lived gravitational waves include protoneutron star convection [193], rotational instabilities in merger remnants [144], and eccentric binary systems [194]. While these sources are associated with signals on the time-scale of 1 minute to 1 hour, much longer transient signals (on the time-scale of days) are also possible, for example in glitching pulsars or in accreting fast millisecond pulsars. The subfield of theoretical investigations into long-lived transients is fluid, and it is prudent to have a search dedicated to whatever long-lived transient signals may be awaiting discovery: predicted models, yet-to-be-predicted models, and total surprises.

Relationship to other searches. This activity plan is closely related to a number of other efforts within the LVC. It complements the burst all-sky search for short-duration signals by extending the parameter space to longer durations. It overlaps with triggered searches for long-lived transients described in the GRB activity plan (section 6.3) and the neutron star transient activity plan (magnetars) (section 2.4). Finally, it is also related to efforts in the CW group to look for long-lived transient signals from neutron stars. A cross-correlation based pipeline [195] to search for intermediate duration signals bridging the gap between continous waves and transient searches has been proposed. Along the same lines, a hours/days/weeks long duration GW signals search is performed by the stochastic background group [196]. We coordinate with the CW and stochastic background groups to identify overlapping interests, and identify the advantages and complementarities of different pipelines. The two projects are complementary as they focus on different time scales, and the stochastic search is primarily concerned with the effect of transient phenomena (astrophysical or due to noise) on the stochastic background search, whereas this search is concerned with studying astrophysical long-lived transient signals.

O2/O3 Deliverables

- Deliver low-latency triggers from burst pipelines for use by the astronomy community.
- Deliver a search paper reporting any signals found by the long-duration search, and place limits on some classes of sources.
- Enhance the long transient waveforms catalogue.

7.2 Search for GWs from cosmic strings

A cosmic network of strings may form as a result of phase transitions in the early Universe [197]. When a U(1) symmetry is broken in multiple causally disconnected spacetime regions, one-dimensional topological defects, i.e. strings, are expected to form [198]. 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 [199, 200, 201, 202, 203]. Cosmic strings produced in string theory motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [204, 205].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational wave (GW) emission from loops [206, 207]. 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. Kinks are loop discontinuities that forms in particular every time intercommuting occurs. Both cusps and kinks produce powerful bursts of gravitational radiation [208].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [209, 210]. 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 constraints are then used to drive the theoritical developments and cosmic string network simulations.

O2/O3 Deliverables

- Identify a cosmic string GW signal or produce limits on cosmic string parameters
- Publish the results of a search for cosmic string cusps and kinks in O2 and O3 data, including results from both the burst and stochastic analyses

- Decide which models/simulations predicting the loop distribution should be used to constrain cosmic string parameters

8 Stochastic+CBC Joint Activity Plans

8.1 Search for the stochastic background from unresolvable binary black hole mergers

8.1.1 Scientific case

The recent detections by aLIGO of several binary black-hole (BBH) mergers suggests 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 ~ 15 minutes on average, with each merger lasting $\lesssim 1$ second. Thus, the duty cycle is $\lesssim 10^{-3}$, 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 an Bayesian search strategy (originally proposed by Thrane, Rosado, and Smith [**?**]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

8.1.2 Methodology

The key observation of Thrane et al. [**?**] is that the likelihood function for the non-stationary signal+noise model $\mathcal{M}_1$ has the form

$$p(d|\xi, \theta_s, \theta_n, \mathcal{M}_1) = \prod_{I=1}^{N} \left[\xi p_n(d_I - s(\theta_s)|\theta_n) + (1-\xi) p_n(d_I|\theta_n)\right] , \tag{7}$$

where the two terms on the right-hand side correspond to the foreground (i.e., signal present) and background (i.e., noise-only) distributions. Here, 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 $R = \xi/T$; θ_s, θ_n denote the signal and noise parameters; and $p_n(n|\theta_n)$ is the probability distribution for the detector noise. Using Bayesian inference, one can then calculate either a Bayes factor for the signal+noise to noise-only models, which can be used as a detection statisic, or marginalized posteriors, e.g.,

$$p(\xi|d, \mathcal{M}_1) = \int d\theta_s \int d\theta_n \, p(\xi, \theta_s, \theta_n|d, \mathcal{M}_1) \tag{8}$$

to estimate the rate of BBH events. It is the *mixture* form of the likelihood that allows one to handle the non-stationarity.

The above method is *optimal* for the assumed signal and noise distributions. But to implement this analysis in practice will be challenging due to: (i) the computational costs of performing a fully-Bayesian analysis over the duration of an observing run, and (ii) non-stationary features in the detector noise (e.g., glitches) that could mimic BBH mergers. Thus, it may be necessary to consider simplified signal models or to include glitch modeling in the noise model to implement this search on real aLIGO data.

8.1.3 Deliverables

1. Develop a set of data analysis routines to implement the above search, which is both computationally feasible and robust against non-Gaussian features in the detector noise.

2. A study of the proposed search method on synthetic data, including tests of its efficacy relative to the standard Gaussian-stationary search.

9 Stochastic+Detchar Joint Activity Plans

9.1 Data quality investigations for stochastic searches

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.

9.1.2 Methodology

The stochastic searches rely on cross correlating the data from different detectors. Common noise lines at two sites can occur due to similar equipment in the laboratory, 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). First, we have developed several key tools for data quality and detector characterisation (code O.C.5.3), including STAMP-PEM, a real-time physical environment monitor to study subsystem coherence 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 monitored by members of the stochastic group as part of "stochastic monitoring shifts." Second, 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 science runs, and possibly addressed at the sites.

We have previously observed correlated broadband magnetic fields in magnetometer channels at widely separated detectors [211]. The primary sources of these correlated fields are geophysical Schumann resonances [211]. 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.2.1, F.C.3.3) . Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied. 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 masure the noise contribution from Schumann resonances at the same time as the gravitational-wave background.

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.

9.1.3 Deliverables

1. Studies of instrumental correlations between detectors, which used by all stochastic searches.
2. A measurement of or upper limit on correlated magnetic noise from Schumann resonances, along with studies of mitigating the effect of correlated magnetic noise.

3. Simulations studying the bias that long transient noise sources can have on stochastic searces.

10 Characterization of the Detectors and Their Data

10.1 LSC Detector Characterization

10.2 Detailed LIGO Detector Characterization priorities

The detector characterization (detchar) group has the dual responsibilities of investigating and mitigating misbehavior in the instrument, and providing data quality information to the gravitational-wave searches to reduce the impact of artifacts in the data. In addition, the detchar group must help to validate the quality of the data around the time of candidate detections. The remainder of this section lays out in a sparse format the priorities for the work in 2016-2017.

10.3 Overarching goals

- Automate as much as possible of the data quality assessment process, in low latency
- Document and make available codes used to the whole group, and aim for interoperability of codes
- Validate new methods on recent data
- Rigorously show that a search is improved by the data quality information

10.4 Characterizing Instrumental Artifacts

There are three main areas of investigation: Ongoing work (Physical and Environmental Monitoring (PEM), subsystem characterization, DQ shifts), focused but open-ended investigations (find particular noise source or cause of glitch), and method development (ETGs, statistics and classifiers)

10.4.1 Highest Priorities

- Characterize data quality around the time of event candidates – at low- and offline-latency; and for transient and for CW/Stochastic sources
- Support commissioners from offsite
- Undertake subsystem characterization and documentation
- Maintain and document PEM monitors, characterize environmental couplings

10.4.2 Priorities

- Develop human resources (esp. mentors), and perform DQ shifts to identify changes in or problems with the instruments and to maintain currency in understanding of the instrument in the DetChar group
- Search for causes of short isolated glitches which are the largest background of the transient searches
- Mitigate spectral lines and features which are coherent/coincident between the two sites
- Investigate variations in the noise floor, and attempt to predict noise performance based on instrument state

10.4.3 Suggested papers as outcomes of these studies

- Tracking and Mitigating Scattered Light
- RF Interference in aLIGO (may include either or both of RF beatnotes/RF45 modulation troubles)
- Investigating Causes of Short Transient Artifacts in aLIGO
- Mitigation of Line Features in aLIGO
- Mitigation of Coherent Noise between Detectors due to GPS Synchronization
- Predicting Spectral Variations of aLIGO Noise from Varying Instrument State and Alignment

- Isolation of aLIGO from the Local Environment

10.4.4 Additional thoughts

Developing a deep and current understanding of each component subsystem is crucial to enabling diagnosis of instrumental and environmental artifacts as well as data quality veto development. For each subsystem the subsystem leads are jointly responsible for:

- Ensuring a complete, meaningful, and representative set of auxiliary channels is included in the detector characterization channel list
- Monitoring subsystem states accurately and robustly
- Checking signal fidelity of channels included in the detector characterization channel list and the science frames
- Maintaining documentation of the subsystems and the relevant channels for detector characterization reference
- Interfacing with commissioners and instrument experts to propagate instrument changes and developments to detector characterization investigations and monitoring

In addition to focusing on noise artifacts in h(t), the detector characterization group will characterize the performance of the component subsystems, particularly any behavior that is potentially limiting to interferometer performance. For example:

- Improving monitors for excess mirror motion leading to scattered light
- Improving monitoring and reporting of digital and analog overflows, reaching software limits, and other kinds of saturations; monitoring and reporting of real-time data handling errors (timing, dropped data, etc.)
- Searching for causes of short isolated glitches which are the largest background of the transient searches
- Searching for causes of non-stationary noise and of excess low and mid frequency noise
- Searching for physical causes of lines and spectral combs which harm continuous-wave searches

The detector characterization portion of the detection checklist is essential in demonstrating that the candidate signal cannot be due to global coincident noise and is unlikely to be due to other non-astrophysical noise. The detection checklist, refined by the O1 experience, requires detector characterization experts to evaluate key studies and tests of the data surrounding the time of a candidate event.

10.5 Improving search data quality

The over-arching goals here are to rigorously evaluate the effect of data quality on the searches and parameter estimation, and to target our attention on making the largest possible gains in detection rate and detection confidence.

10.5.1 Highest Priorities

- Identify outliers and artifacts which are most damaging to the primary gravitational-wave searches
- Provide data quality in low-latency to the EM followup searches
- Provide effective, documented offline data quality information for searches

10.5.2 Priorities

- Develop rigorous criteria for evaluating effect of data quality on search performance
- Develop methods for cleaning data of artifacts
- Quantify effects of bad data quality on parameter estimation

10.5.3 Suggested Papers

- Which Data Artifacts are Most Detrimental to [Search]
- Optimally Cleaning Data of Loud Outliers / Lines
- Effects of Varying Background on the Performance of [Search]
- Can Data Artifacts Subtly Affect Estimated Parameters of Detected Signals?
- Optimizing Signal-Based Vetoes Based on Knowledge of Likely Glitches
- How does Search Sensitivity Compare to Ideal Case of Stationary Gaussian Noise?

10.5.4 Additional Thoughts

Data quality shifts and detection validation are key to improving the performance of the astrophysical searches and enabling confident detection statements.

Data quality shifts will be the primary means of ensuring full coverage of h(t) data quality analysis for both detectors during O2, including limiting factors to interferometer performance such as weather or earthquakes. Data quality shifters must invest first in training, and a qualified mentor must be identified.

Additional investigations might include:

- Looking into worst offenders from single-detector or time-slid backgrounds
- Investigating effects of possible data quality issues on the search: isolated glitch, scattered light, non-stationary PSD, wandering lines

10.6 Essential Software and Automation

Fundamentally necessary software:

- The summary pages
- The DMT (including the new low-latency DMT DQ vector infrastructure)
- The segment database
- Omicron triggers, including in low-latency, delivered with very high reliability
- Robustly accurate Guardian states, including for configuration changes made between or during lock stretches (i.e. SEI blend filter state or suspension damping state)

High priority software:

- Automated low latency data quality checks (iDQ, automated Omegascans)
- GWpy
- ligoDV web
- Omegascans
- Channel Information System
- VET
- Suite of remote access tools (remote MEDM, remote EPICS, remote DataViewer)
- ODC (or potentially an alternative for key information at low latency)
- Mapping of overflow channels
- LigoCAM

Low latency tier-3 automation tasks requiring additional personpower ahead of O2:

- Automatically look at the spectrum in the neighborhood of the trigger
- Drops in range
- Glitch rate summary from multiple ETGs

The summary pages are fundamental to data quality shifts, the launching point for investigations into data quality features, and an invaluable resource in the control rooms and for a remote view of interferometer performance and the behavior of the data. The summary pages infrastructure also enables automation of key tool results and plot generation is critical in order to support both effective data quality shifts and viably efficient checks on candidate events.

In addition there are a number of tools which continue to be of use, such as stamp-pem automated coherence, FScans and auxiliary post-processing scripts, and NoEMi, that the group will maintain.

This list relies on software dependencies maintained by DASWG, low latency data streaming, the Virgo Collaboration, the remote data access group, and the Guardian. While those software elements are not in the scope of DetChar, they are of the highest priority to enable LIGO science

Low latency automation tasks requiring additional personpower ahead of O2:

- Automatically look at the spectrum in the neighborhood of the trigger
- Drops in range
- Glitch rate summary from multiple ETGs

https://wiki.ligo.org/DetChar/DetCharProductsForAndInterfaceWithEMFollowActivities

10.7 Development of New Methods

This section includes longer-term projects that should be explored as secondary priorities.

- Citizen science for identifying new instrumental features
- Development of Event Trigger Generators
- New veto methods and advanced signal processing
- Machine learning
- Computing support for new methods

Citizen Science: GravitySpy is a citizen-science prjoect, operating on the Zooniverse platform. It allows volunteers from outside the LSC to look at glitches in the gravtiational-wave channel and attempt to classify them into categories. These classifications are then available to seed detchar investigations, or for training machine-learning classifiers. The detchar group should get involved by providing feedback to the GravitySpy people on how to best select and represent glitches for classification. In addition, the detchar group should apply its standard veto generators to single categories of classified glitches, in the hopes that a purified list of one type of glitches will make it possible to identify causes of those glitches.

ETG development: The detchar group uses a few different algorithms to detect glitches and other short transients in the gravitational-wave and auxiliary channels. The primary method is the sine-Gaussian basis used by Omega and Omicron. Further development can still be done on better methods for pre-processing and whitening the data before it is used in the ETG, different tilings for placing the sine-Gaussian tiles, better methods for clustering significant tiles into a single description of a glitch, and on improved visual display of the data. Along the same lines, the BayesWaveBurst method uses a similar decomposition with a Bayesian method for reconstructing glitches in the detector. The detchar group should continue to use this method to reconstruct interesting glitches and find their intrinsic shape uncorrupted by noise.

Veto methods: Evidently new veto methods will be needed, both to deal with news kinds of data defects (which will certainly appear as the instruments are improved), and to improve the reliability and speed of identification of currently recognized data defects. Methods should be brought to bear, in prototype form, on real data early in the 'lifetime' of the development process; success should be demonstrated before significant human or computing resources are committed.

Machine learning: Machine learning and 'big data' are very popular topics today. These methods can be useful in detchar, as long as certain considerations are respected. The features input to the classfiers must be carefully chosen and conditioned to extract only the useful information in those channels. The classifiers must optimize a reasonable cost function, so that they are targeted at identifying important glitch classes or data quality effects, and providing information that maximally improves the search sensitvity.

Computing support for new methods: As new Detector Characterization methods become more mature, they will need to be incorporated into our suite of automated tools and checks. This requires integration with the summary pages, and the online and offline generation of data quality products in an efficient and stable manner. Additionally, as new methods increase in complexity and scale, particularly with application machine learning codes, effort will be required to optimize these codes to ensure efficient use of computing resources.

10.7.1 Suggested publications

- Improved clustering of LIGO Triggers
- Tuning [ETG] for improved performance on [important glitch class]
- An Optimized Cost Function for Machine Learning to Improve [Search]
- Interesting Instrument Behaviors Identified by GravitySpy
- Mechanical Couplings Identified by a Machine Learning Algorithm
- Using Machine Learning to Identify Sources of Excess Noise in O1
- A Comparison of ML Classifiers against a Single Glitch Dataset
- Generating Good Features for Training ML for Detchar

10.8 Ongoing Tasks

These are tasks that require constant time commitment of people throughout the run. The DQ shifts are the primary way for new people (or people without much detchar experience) to contribute. In addition, support is needed from experienced DQ shifters to mentor and train new people.

10.8.1 DQ shifts

Data quality shifts and detection validation are key to improving the performance of the astrophysical searches and enabling confident detection statements.

Data quality shifts will be the primary means of ensuring full coverage of h(t) data quality analysis for both detectors during O2, including limiting factors to interferometer performance such as weather or earthquakes. New data quality shift volunteers must invest first in training, and a qualified mentor must be identified; the data quality shift policy is LIGO-L1500110. A list of data quality shift volunteers, and where they are in their training, is kept on the detchar wiki (https://wiki.ligo.org/DetChar/DataQuality/DQShiftVolunteers). Volunteers liaise with LSC Fellows who can provide real time support in identifying egregious features in the interferometer data. This close relationship proved extremely useful during O1, bridging the gap between the LIGO sites and the broader LSC.

10.8.2 Validating detections

The detector characterization portion of the detection checklist is essential in demonstrating that the candidate signal cannot be due to global coincident noise and is unlikely to be due to other non-astrophysical noise. The detection checklist requires detector characterization experts to evaluate key studies and tests of the data surrounding the time of a candidate event.

10.8.3 Rapid Response to validate EM Triggers

Detector characterization will field appointed representatives to the Rapid Response Team, responsible for evaluating and signing off on data quality at the time of an identified low-latency candidate event, as was provided in O1. This effort relies on the support of low latency data quality tools such as iDQ and the automation of tools like Omegascan.

10.9 Roles

There are many active roles within the LIGO detector characterization group, and often some people have more than just one role either due to expertise or people limitations. There are two LIGO detchar co-chairs who oversee and steer the entire group. Working alongside them are a small committee who chair the data quality and instrumentation sub-groups. Within the instrumentation sub-group are subsystem leads, each of whom are responsible for understanding and maintaining the eleven subsystems from the detchar perspective. Each subsystem typically has one lead person; however the more complicated subsystems have two leads. There is also a small group of people who oversee, maintain and develop the key software required by the detchar group. The structure of the detchar group is viewable in the LSC Organisation Chart LIGO-M1200248.

11 Calibration

For the LIGO interferometers, *calibration* involves converting data streams from channels that monitor the feedback control loop that maintains the differential arm length into a derived time series that represents the inferred differential arm length variations, h(t), which is normalized to the average arm length, approximately 4000m. h(t) is referred to as *interferometer strain* or just *strain*. The analog and digital filters used in h(t) production are first produced in the frequency domain by the calibration and commissioning team.

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. As such, the LSC created in its bylaws a Calibration Committee, separate from the Detector Characterization group. The goal of the Calibration Committee is to provide calibrated h(t) with sufficiently small uncertainties in amplitude and phase. The current tentative goal is to have maximum calibration errors of roughly 10 percent in amplitude and a few degrees in phase.

Calibration of a detector is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. The time-domain calibrated data is the main data product, and its generation is sufficiently complex that it needs a dedicated team for calibration and another one for review. The Calibration Committee is therefore co-chaired by a time-domain chair and an experimental chair, and includes LIGO Laboratory and other LSC scientists. It works along with a dedicated Calibration Review Committee which provides advice and vetting of this work. The Calibration Committee's results are posted and documented on a web page[212] available to the LSC, and as with previous science runs, will continue to be recorded in the electronic logs, software repositories, and LIGO documents[213].

Estimation and reduction of the errors in the calibration data products will be a major effort in aLIGO. Towards that end multiple methods of calibration will be used, including a method using auxiliary laser pressure actuation ("photon calibrator")[**?**] and a method using interferometer laser frequency modulation[**?**], both of which were used in initial LIGO science runs. The aLIGO photon calibrator subsystem has been installed and has been used successfully as the primary calibrator during aLIGO's early observing runs. The photon calibrator will remain the primary source for calibration accuracy and precision in upcoming observing runs.

Production and analysis of the time-dependent calibration coefficients is an essential tool for calibration validations. They can be used to estimate the systematic and statistical uncertainties of the calibration as well as the time offset changes. These studies will be continued in the future. Development of on-line tools to monitor the time-dependent calibration factors, and more generally h(t) data quality, is essential.

Phase calibration and end-to-end interferometer model verification (performed e.g., through direct test mass excitation using the photon calibrator[214]) are important. If the interferometer model used for calibration is incorrect, it could skew the phase of LIGO data. Therefore the calibration group's tasks include developing and testing injection techniques, and characterization of analog modules in order to determine accuracy of the interferometer model for calibration.

The Calibration Committee's membership has been augmented in recent years by graduate students and scientists alike from several LSC institutions. Each site will have a dedicated LIGO lab person responsible for the calibration, but the Calibration Committee expects additional manpower of about 3 people per site, on time scales of 6-8 weeks per year, to be necessary to get calibration out and vetted in a timely manner around science runs. This manpower would be in addition to those working on the calibration software pipelines and those maintaining close communication with various aLIGO subsystem groups. This work provides students valuable instrumental training. It would be highly desirable to sustain this broad participation.

In anticipation of the aLIGO science runs we will be creating and maintaining communication channels between aLIGO and other projects' calibration teams and reviewers. In collaboration with Virgo and GEO, the calibration team will also work on improving h(t) generation techniques, and the development of preprocessed h(t) products such as whitened, cleaned, and coherent data streams. Also important is an exchange of ideas about the review process.

The work of the calibration team is currently focused on preparations for the advanced detector era. New techniques are being commissioned to produce h(t) data with second and sub-second latencies. These techniques include moving the generation of h(t) to the front end of the interferometer (CDS) and a gstreamer-based algorithm. In addition, online tools to monitor the quality of the data produced on the fly, and the development of pre-processed h(t) products (e.g. whitened, cleaned, and coherent data streams) are being developed.

The front end calibration effort is intended to develop the necessary code to perform time domain calibration on the CDS computers that directly run the interferometer. This code is directly embedded in the controls code. This method has the advantage of providing the lowest latency possible as it works directly with the data before it is sent on to be recorded, and can thus be included directly in the recorded frame data. The disadvantage of this method is that has difficultly handling the effects of poles and zeros in the actuation and sensing functions above the nyquist frequency that the front end models run at.

The calibration team is commissioning a low-latency gstreamer-based pipeline for time domain calibration in aLIGO. This is a robust pipeline with both frame file and shared memory I/O capabilities, thus allowing for the same pipeline to run for both online and offline calibration. The online infrastructure required for the aLIGO gstreamer-based calibration pipeline was the primary producer for h(t), both in low-latency and offline, during aLIGO's first observing run. The calibration team is continuing to commission and improve the infrastructure required for and the inner-workings of the low-latency aLIGO time domain calibration pipeline.

The current plan for the second observing run is to combine the front end calibration code outputs with the low-latency gststreamer pipline, as was done during the first observing run. The front end code was easy for the calibrators on site, who did the calibration measurements of the interferometer, to keep up to date with changes in the actuation and sensing of the interferometer. The low-latency gstlal calibration pipeline is able to take data products from that front end code and properly apply poles and zeros above the nyquist frequency, as well as properly handle time delay, and generate the final h(t) stream. In the case where calibration needs to be recalculated after data taking due to errors, the offline gstreamer pipeline is capable of producing from just the raw differential arm control signals the same data products as the front end code. This mode of operation was used successfully and compared to the front end calibration code during the first observing run.

11.1 LIGO timing diagnostics

Traceable and closely monitored timing performance of the GW detectors is mission critical for reliable interferometer operation, astrophysical data analysis, and discoveries. For example, (a) timing jitter of digitization of the GW signal could directly contribute to the noise level degrading the astrophysical reach of the LIGO interferometers, (b) coincident and coherent observation using the network of GW detectors is only possible if the absolute timing of the data streams agree within a high degree of accuracy, (c) a network of interferometric GW detectors can only recover both the polarization and sky direction information for a detected event if the absolute timing of their data-streams are known, and (d) multimessenger astronomy with external observatories also require traceable and accurate absolute timing.

The Timing Group includes scientists from both the LSC and the LIGO Laboratory. The group is responsible for (a.) the availability and diagnostics of timing information and signals provided for various subsystems (e.g., LSC, OMC, etc.), (b.) measuring and documenting the timing performance, (c.) the documented certification of the software implementation of precise timing information by the timing distribution system, (d.) documentation of timing related parts, (e.) verifying that the precision of the distribution of timing is according to specification.

The timing distribution system extends until it passes the timing pulses to the advanced LIGO data acquisition system. (Please note that the accuracy of subsystem components beyond the boundaries of the timing distribution system can introduce errors that factor into the phase calibration or data recording of aLIGO detectors and those studies are the responsibility of the calibration and CDS teams.)

The construction and testing of the timing distribution system as well as the associated timing diagnostics tasks have already provided fertile ground for undergraduate and graduate student research involvement and diversity in the program is strongly encouraged for the future.

Critical timing diagnostic tasks in the era of regular gravitational-wave detections are the following:

- verifying traceable performance of the timing distribution system
- checking the status of the independent timing diagnostic hardware, and providing upgrades when necessary,
- assuring the availability of timing witness signals,
- verifying the validity and accuracy of the recorded time-stamp
- verifying the accuracy of the distributed timing signals
- expanding the capabilities of data monitoring tools related to timing,
- availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance,

- reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.

References

[1] B. Abbott et al. First upper limits from LIGO on gravitational-wave bursts. *Physical Review D*, 69:102001, 2004.

[2] B. Abbott et al. First joint search for gravitational-wave bursts in LIGO and GEO 600 data. *Classical & Quantum Gravity*, 25:245008, 2008.

[3] B. Abbott et al. Search for high frequency gravitational-wave bursts in LIGO data from the fifth science run. *Physical Review D*, 80(10):102002, 2009.

[4] B. Abbott et al. All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run. *Physical Review D*, 81(10):102001, 2010.

[5] J. Abadie et al. All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run. *Phys. Rev.*, D85:122007, 2012.

[6] Benjamin P. Abbott et al. All-sky search for short gravitational-wave bursts in the first Advanced LIGO run. *Phys. Rev.*, D95(4):042003, 2017.

[7] S. Klimenko et al. A coherent method for detection of gravitational wave bursts. *Class. Quantum Grav.*, 25(11):114029–+, June 2008.

[8] Ryan Lynch, Salvatore Vitale, Reed Essick, Erik Katsavounidis, and Florent Robinet. Information-theoretic approach to the gravitational-wave burst detection problem. *Phys. Rev.*, D95(10):104046, 2017.

[9] Neil J. Cornish and Tyson B. Littenberg. BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches, 2014.

[10] E. A. Huerta and D. A. Brown. Effect of eccentricity on binary neutron star searches in advanced LIGO. *Phys. Rev. D*, 87(12):127501, 2013.

[11] C. Hopman and T. Alexander. The Effect of Mass Segregation on Gravitational Wave Sources near Massive Black Holes. *Astrophys. J.*, 645:L133–L136, July 2006.

[12] Ryan M. O'Leary, Bence Kocsis, and Abraham Loeb. Gravitational waves from scattering of stellar-mass black holes in galactic nuclei. *Mon. Not. Roy. Astron. Soc.*, 395:2127–2146, 2009.

[13] Bence Kocsis and Janna Levin. Repeated bursts from relativistic scattering of compact objects in galactic nuclei. *Phys. Rev. D*, 85:123005, Jun 2012.

[14] A. C. Fabian, J. E. Pringle, and M. J. Rees. Tidal capture formation of binary systems and X-ray sources in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 172:15P–+, August 1975.

[15] D. Pooley, W. H. G. Lewin, S. F. Anderson, H. Baumgardt, A. V. Filippenko, B. M. Gaensler, L. Homer, P. Hut, V. M. Kaspi, J. Makino, B. Margon, S. McMillan, S. Portegies Zwart, M. van der Klis, and F. Verbunt. Dynamical Formation of Close Binary Systems in Globular Clusters. *Astrophys. J.*, 591:L131–L134, July 2003.

[16] W. H. Lee, E. Ramirez-Ruiz, and G. van de Ven. Short Gamma-ray Bursts from Dynamically Assembled Compact Binaries in Globular Clusters: Pathways, Rates, Hydrodynamics, and Cosmological Setting. *Astrophys. J.*, 720:953–975, September 2010.

[17] Linqing Wen. On the Eccentricity Distribution of Coalescing Black Hole Binaries Driven by the Kozai Mechanism in Globular Clusters. *Astrophys. J.*, 598:419–430, 2003.

[18] M. Coleman Miller and Douglas P. Hamilton. Four-body effects in globular cluster black hole coalescence. *Astrophys. J.*, 576(2):894, 2002.

[19] S. J. Aarseth. Mergers and ejections of black holes in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 422:841–848, May 2012.

[20] Fabio Antonini and Hagai B. Perets. Secular evolution of compact binaries near massive black holes: Gravitational wave sources and other exotica. *Astrophys. J.*, 757(1):27, 2012.

[21] T. A. Thompson. Accelerating Compact Object Mergers in Triple Systems with the Kozai Resonance: A Mechanism for "Prompt" Type Ia Supernovae, Gamma-Ray Bursts, and Other Exotica. *Astrophys. J.*, 741:82, November 2011.

[22] S. Naoz, B. Kocsis, A. Loeb, and N. Yunes. Resonant Post-Newtonian Eccentricity Excitation in Hierarchical Three-body Systems. *Astrophysical Journal*, 773:187, August 2013.

[23] B. Katz and S. Dong. The rate of WD-WD head-on collisions may be as high as the SNe Ia rate. *ArXiv e-prints*, November 2012.

[24] P. C. Peters. Gravitational radiation and the motion of two point masses. *Phys. Rev.*, 136:B1224–B1232, 1964.

[25] E. P. Mazets, S. V. Golentskii, V. N. Ilinskii, R. L. Aptekar, and I. A. Guryan. Observations of a flaring X-ray pulsar in Dorado. *Nature*, 282:587–589, December 1979.

[26] Y. T. Tanaka, T. Terasawa, N. Kawai, A. Yoshida, I. Yoshikawa, Y. Saito, T. Takashima, and T. Mukai. Comparative Study of the Initial Spikes of Soft Gamma-Ray Repeater Giant Flares in 1998 and 2004 Observed with Geotail: Do Magnetospheric Instabilities Trigger Large-Scale Fracturing of a Magnetar's Crust? *Astrophysical Journal Letters*, 665:L55–L58, August 2007.

[27] T. Terasawa, Y. T. Tanaka, Y. Takei, N. Kawai, A. Yoshida, K. Nomoto, I. Yoshikawa, Y. Saito, Y. Kasaba, T. Takashima, T. Mukai, H. Noda, T. Murakami, K. Watanabe, Y. Muraki, T. Yokoyama, and M. Hoshino. Repeated injections of energy in the first 600ms of the giant flare of SGR1806 - 20. *Nature*, 434:1110–1111, April 2005.

[28] B. Abbott et al. Search for gravitational-wave bursts from soft gamma repeaters. *Physical Review Letters*, 101(21):211102, 2008.

[29] B. P. Abbott et al. Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm. *Astrophysical Journal Letters*, 701:L68–L74, August 2009.

[30] J. Abadie et al. Search for Gravitational Wave Bursts from Six Magnetars. *Astrophys. J.*, 734:L35, 2011.

[31] J. Abadie et al. A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar. *Phys. Rev.*, D83:042001, 2011.

[32] K. Kotake. Multiple physical elements to determine the gravitational-wave signatures of core-collapse supernovae. *Comptes Rendus Physique*, 14:318, 2013.

[33] C. D. Ott. TOPICAL REVIEW: The gravitational-wave signature of core-collapse supernovae. *Class. Quantum Grav.*, 26:063001, 2009.

[34] C. D. Ott. Probing the core-collapse supernova mechanism with gravitational waves. *Class. Quant. Grav.*, 26(20):204015, October 2009.

[35] J. Logue, C. D. Ott, I. S. Heng, P. Kalmus, and J. Scargill. Inferring Core-Collapse Supernova Physics with Gravitational Waves. *Physical Review D*, 86(4):044023, 2012.

[36] E. Abdikamalov, S. Gossan, A. M. DeMaio, and C. D. Ott. Measuring the angular momentum distribution in core-collapse supernova progenitors with gravitational waves. *Physical Review D*, 90(4):044001, 2014.

[37] W. J. Engels, R. Frey, and C. D. Ott. Multivariate regression analysis of gravitational waves from rotating core collapse. *Physical Review D*, 90(12):124026, December 2014.

[38] J. W. Murphy, C. D. Ott, and A. Burrows. A Model for Gravitational Wave Emission from Neutrino-Driven Core-Collapse Supernovae. *Astrophysical Journal*, 707:1173, 2009.

[39] B. Müller, H.-T. Janka, and A. Marek. A New Multi-dimensional General Relativistic Neutrino Hydrodynamics Code of Core-collapse Supernovae. III. Gravitational Wave Signals from Supernova Explosion Models. *Astrophysical Journal*, 766:43, 2013.

[40] K. N. Yakunin, P. Marronetti, A. Mezzacappa, S. W. Bruenn, C.-T. Lee, M. A. Chertkow, W. R. Hix, J. M. Blondin, E. J. Lentz, O. E. Bronson Messer, and S. Yoshida. Gravitational waves from core collapse supernovae. *Class. Quantum Grav.*, 27:194005, October 2010.

[41] T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer. The neutrino signal from protoneutron star accretion and black hole formation. *Astronomy & Astrophysics*, 499:1–15, 2009.

[42] C. D. Ott, C. Reisswig, E. Schnetter, E. O'Connor, U. Sperhake, F. Löffler, P. Diener, E. Abdikamalov, I. Hawke, and A. Burrows. Dynamics and Gravitational Wave Signature of Collapsar Formation. *Phys. Rev. Lett.*, 106:161103, 2011.

[43] https://wiki.ligo.org/LSC/2017SupernovaeWorkshop.

[44] S. Mukherjee and L. Salazar. New Method for Enhanced Efficiency in Detection of Gravitational Waves from Supernovae Using Coherent Network of Detectors. *LIGO-P1400116*, 2014.

[45] D. Thornton, B. Stappers, M. Bailes, B. Barsdell, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, D. J. Champion, P. Coster, N. D'Amico, A. Jameson, S. Johnston, M. Keith, M. Kramer, L. Levin, S. Milia, C. Ng, A. Possenti, and W. van Straten. A Population of Fast Radio Bursts at Cosmological Distances. *Science*, 341:53–56, July 2013.

[46] E. Petroff, E. D. Barr, A. Jameson, E. F. Keane, M. Bailes, M. Kramer, V. Morello, D. Tabbara, and W. van Straten. Frbcat: The fast radio burst catalogue. *arXiv:1601.03547*.

[47] L. G. Spitler, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, M. A. McLaughlin, S. Chatterjee, F. Crawford, J. S. Deneva, V. M. Kaspi, R. S. Wharton, B. Allen, S. Bogdanov, A. Brazier, F. Camilo, P. C. C. Freire, F. A. Jenet, C. Karako-Argaman, B. Knispel, P. Lazarus, K. J. Lee, J. van Leeuwen, R. Lynch, A. G. Lyne, S. M. Ransom, P. Scholz, X. Siemens, I. H. Stairs, K. Stovall, J. K. Swiggum, A. Venkataraman, W. W. Zhu, C. Aulbert, and H. Fehrmann. Fast Radio Burst Discovered in the Arecibo Pulsar ALFA Survey. *The Astrophysical Journal*, 790(2):101, 2014.

[48] B. P. Abbott et al. Search for transient gravitational waves in coincidence with short-duration radio transients during 2007–2013. *Phys. Rev. D*, 93:122008, Jun 2016.

[49] B. P. Abbott et al. *Phys. Rev. X*, 6:041015, Oct 2016.

[50] Feryal Ozel, Dimitrios Psaltis, Ramesh Narayan, and Jeffrey E. McClintock. The Black Hole Mass Distribution in the Galaxy. *Astrophys.J.*, 725:1918–1927, 2010.

[51] W. M. Farr, N. Sravan, A. Cantrell, L. Kreidberg, C. D. Bailyn, I. Mandel, and V. Kalogera. The Mass Distribution of Stellar-mass Black Holes. *Astrophysical Journal*, 741:103, November 2011.

[52] Laura Kreidberg, Charles D. Bailyn, Will M. Farr, and Vassiliki Kalogera. Mass Measurements of Black Holes in X-Ray Transients: Is There a Mass Gap? *Astrophys. J.*, 757:36, 2012.

[53] K. Belczynski, G. Wiktorowicz, C. Fryer, D. Holz, and V. Kalogera. Missing Black Holes Unveil The Supernova Explosion Mechanism. 2011.

[54] C.L. Fryer, K. Belczynski, G. Wiktorowicz, M. Dominik, V. Kalogera, et al. Compact Remnant Mass Function: Dependence on the Explosion Mechanism and Metallicity. *Astrophys.J.*, 749:91, 2012.

[55] Krzysztof Belczynski et al. On The Maximum Mass of Stellar Black Holes. *Astrophysical Journal*, 714:1217–1226, 2010.

[56] Michal Dominik, Krzysztof Belczynski, Christopher Fryer, Daniel Holz, Emanuele Berti, et al. Double Compact Objects I: The Significance Of The Common Envelope On Merger Rates. 2012.

[57] Michal Dominik and Krzysztof Belczynski. Private communication. 2012.

[58] Krzysztof Belczynski, Alessandra Buonanno, Matteo Cantiello, Chris L. Fryer, Daniel E. Holz, Ilya Mandel, M. Coleman Miller, and Marek Walczak. The Formation and Gravitational-Wave Detection of Massive Stellar Black-Hole Binaries. *Astrophys. J.*, 789(2):120, 2014.

[59] J.M. Miller, C.S. Reynolds, A.C. Fabian, G. Miniutti, and L.C. Gallo. Stellar-mass Black Hole Spin Constraints from Disk Reflection and Continuum Modeling. *Astrophys.J.*, 697:900–912, 2009.

[60] R. Shafee, J. E. McClintock, R. Narayan, S. W. Davis, L.-X. Li, and R. A. Remillard. Estimating the Spin of Stellar-Mass Black Holes by Spectral Fitting of the X-Ray Continuum. *Astrophysical Journal Letters*, 636:L113–L116, January 2006.

[61] Jeffrey E. McClintock et al. The Spin of the Near-Extreme Kerr Black Hole GRS 1915+105. *Astrophysical Journal*, 652:518–539, 2006.

[62] J. Liu, J. E. McClintock, R. Narayan, S. W. Davis, and J. A. Orosz. Erratum: "Precise Measurement of the Spin Parameter of the Stellar-mass Black Hole M33 X-7". *Astrophysical Journal Letters*, 719:L109, August 2010.

[63] L. Gou, J. E. McClintock, J. Liu, R. Narayan, J. F. Steiner, R. A. Remillard, J. A. Orosz, S. W. Davis, K. Ebisawa, and E. M. Schlegel. A Determination of the Spin of the Black Hole Primary in LMC X-1. *Astrophysical Journal*, 701:1076–1090, August 2009.

[64] S. W. Davis, C. Done, and O. M. Blaes. Testing Accretion Disk Theory in Black Hole X-Ray Binaries. *Astrophysical Journal*, 647:525–538, August 2006.

[65] L.-X. Li, E. R. Zimmerman, R. Narayan, and J. E. McClintock. Multitemperature Blackbody Spectrum of a Thin Accretion Disk around a Kerr Black Hole: Model Computations and Comparison with Observations. *ApJS*, 157:335–370, April 2005.

[66] Jeffrey E. McClintock, Ramesh Narayan, Shane W. Davis, Lijun Gou, Akshay Kulkarni, et al. Measuring the Spins of Accreting Black Holes. *Class. Quantum Grav.*, 28:114009, 2011.

[67] Jeffrey E. McClintock, Ramesh Narayan, and James F. Steiner. Black Hole Spin via Continuum Fitting and the Role of Spin in Powering Transient Jets. *Space Sci. Rev.*, pages 1–28, July 2013.

[68] James F. Steiner and Jeffrey E. McClintock. Modeling the Jet Kinematics of the Black Hole Microquasar XTE J1550-564: A Constraint on Spin-Orbit Alignment. *Astrophys.J.*, 745:136, 2012.

[69] T. Fragos, M. Tremmel, E. Rantsiou, and K. Belczynski. Black Hole Spin-Orbit Misalignment in Galactic X-ray Binaries. *Astrophysical Journal Letters*, 719:L79–L83, August 2010.

[70] Krzysztof Belczynski, Matthew Benacquista, and Tomasz Bulik. Double Compact Objects as Low-frequency Gravitational Wave Sources. *Astrophys.J.*, 725:816–823, 2010.

[71] V. Kalogera. Spin-orbit misalignment in close binaries with two compact objects. *Astrophysical Journal*, 541:042003, 2000.

[72] Bulent Kiziltan, Athanasios Kottas, and Stephen E. Thorsett. The Neutron Star Mass Distribution. 2010.

[73] Ph. Podsiadlowski, N. Langer, A. J. T. Poelarends, S. Rappaport, A. Heger, and E. Pfahl. The effects of binary evolution on the dynamics of core collapse and neutron star kicks. *The Astrophysical Journal*, 612(2):1044, 2004.

[74] E. P. J. van den Heuvel. Double neutron stars: Evidence for two different neutron-star formation mechanisms. *AIP Conference Proceedings*, 924(1):598–606, 2007.

[75] S.E. Woosley, A. Heger, and T.A. Weaver. The evolution and explosion of massive stars. *Rev.Mod.Phys.*, 74:1015–1071, 2002.

[76] M. Kramer and N. Wex. The double pulsar system: a unique laboratory for gravity. *Classical and Quantum Gravity*, 26:073001, 2009.

[77] Jason W.T. Hessels, Scott M. Ransom, Ingrid H. Stairs, Paulo Cesar Carvalho Freire, Victoria M. Kaspi, et al. A radio pulsar spinning at 716-hz. *Science*, 311:1901–1904, 2006.

[78] J. M. Lattimer. The Nuclear Equation of State and Neutron Star Masses. *Annual Review of Nuclear and Particle Science*, 62:485–515, November 2012.

[79] Jocelyn S. Read, Luca Baiotti, Jolien D. E. Creighton, John L. Friedman, Bruno Giacomazzo, et al. Matter effects on binary neutron star waveforms. *Phys.Rev.*, D88:044042, 2013.

[80] Paul D. Lasky, Brynmor Haskell, Vikram Ravi, Eric J. Howell, and David M. Coward. Nuclear Equation of State from Observations of Short Gamma-Ray Burst Remnants. *Phys.Rev.*, D89:047302, 2014.

[81] M. Tanaka, K. Hotokezaka, K. Kyutoku, S. Wanajo, K. Kiuchi, Y. Sekiguchi, and M. Shibata. Radioactively Powered Emission from Black Hole-Neutron Star Mergers. *Astrophysical Journal*, 780:31, January 2014.

[82] B. D. Metzger and E. Berger. What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? *Astrophysical Journal*, 746:48, February 2012.

[83] Jonathan Grindlay, Simon Portegies Zwart, and Stephen McMillan. Short gamma-ray bursts from binary neutron star mergers in globular clusters. *Nature Physics*, 2:116–119, 2006.

[84] Aleksander Sadowski, Krzysztof Belczynski, Tomasz Bulik, Natalia Ivanova, Frederic A. Rasio, et al. The Total Merger Rate of Compact Object Binaries In The Local Universe. *Astrophys.J.*, 2007.

[85] William H. Lee, Enrico Ramirez-Ruiz, and Glenn van de Ven. Short gamma-ray bursts from dynamically-assembled compact binaries in globular clusters: pathways, rates, hydrodynamics and cosmological setting. *Astrophys.J.*, 720:953–975, 2010.

[86] Matthew J. Benacquista and Jonathan M.B. Downing. Relativistic Binaries in Globular Clusters. 2011.

[87] Krzysztof Belczynski, Tomasz Bulik, Ilya Mandel, B.S. Sathyaprakash, Andrzej A. Zdziarski, et al. Cyg X-3: a Galactic double black hole or black hole-neutron star progenitor. *Astrophys.J.*, 764:96, 2013.

[88] J. Abadie et al. Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors. *Classical & Quantum Gravity*, 27:173001, 2010.

[89] Emmanouela Rantsiou, Shiho Kobayashi, Pablo Laguna, and Frederic Rasio. Mergers of Black Hole – Neutron Star binaries. I. Methods and First Results. 2007.

[90] Koutarou Kyutoku, Hirotada Okawa, Masaru Shibata, and Keisuke Taniguchi. Gravitational waves from spinning black hole-neutron star binaries: dependence on black hole spins and on neutron star equations of state. *Phys.Rev.*, D84:064018, 2011.

[91] Zachariah B. Etienne, Vasileios Paschalidis, and Stuart L. Shapiro. General relativistic simulations of black hole-neutron star mergers: Effects of tilted magnetic fields. *Phys.Rev.*, D86:084026, 2012.

[92] Francois Foucart, Matthew D. Duez, Lawrence E. Kidder, Mark A. Scheel, Bela Szilágyi, et al. Black hole-neutron star mergers for 10 solar mass black holes. *Phys.Rev.*, D85:044015, 2012.

[93] Francois Foucart, M. Brett Deaton, Matthew D. Duez, Lawrence E. Kidder, Ilana MacDonald, et al. Black hole-neutron star mergers at realistic mass ratios: Equation of state and spin orientation effects. *Phys.Rev.*, D87:084006, 2013.

[94] Francois Foucart, Luisa Buchman, Matthew D. Duez, Michael Grudich, Lawrence E. Kidder, et al. First direct comparison of nondisrupting neutron star-black hole and binary black hole merger simulations. *Phys.Rev.*, D88(6):064017, 2013.

[95] Luciano Rezzolla, Bruno Giacomazzo, Luca Baiotti, Jonathan Granot, Chryssa Kouveliotou, et al. The missing link: Merging neutron stars naturally produce jet-like structures and can power short Gamma-Ray Bursts. *Astrophys.J.*, 732:L6, 2011.

[96] B. P. Abbott et al. Tests of general relativity with GW150914. *Phys. Rev. Lett.*, 116(22):221101, 2016.

[97] B. P. Abbott et al. Observation of Black Hole Binary Mergers in Advanced LIGO's First Run. 2016. `https://dcc.ligo.org/LIGO-P1600088/public/main`.

[98] E. W. Kolb & M. S. Turner. *The Early Universe*. Westview Press, 1994.

[99] A. A. Starobinskii. Spectrum of relic gravitational radiation and the early state of the universe. *JETP Lett.*, 30, 1979.

[100] R. Bar-Kana. Limits on Direct Detection of Gravitational Waves. *Phys. Rev. D*, 50, 1994.

[101] T. W. B. Kibble. Topology of cosmic domains and strings. *J. Phys.*, A9, 1976.

[102] T. Damour & A. Vilenkin. Gravitational radiation from cosmic (super)strings: bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71, 2005.

[103] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[104] S. Olmez, V. Mandic, and X. Siemens. Anisotropies in the Gravitational-Wave Stochastic Background. *J. Cosmol. Astropart. Phys.*, 2012:009, 2011.

[105] A. Buonanno. Spectrum of relic gravitational waves in string cosmology. *Phys. Rev. D*, 55, 1997.

[106] V. Mandic & A. Buonanno. Accessibility of the Pre-Big-Bang Models to LIGO. *Phys. Rev. D*, 73, 2006.

[107] T. Regimbau. The astrophysical gravitational wave stochastic background. *Research in Astronomy and Astrophysics*, 11:369–390, April 2011.

[108] B. P. Abbott et al. Gw150914: Implications for the stochastic gravitational-wave background from binary black holes. *Phys. Rev. Lett.*, 116:131102, Mar 2016.

[109] Bruce Allen and Joseph D. Romano. Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys.Rev.*, D59:102001, 1999.

[110] N Christensen. Measuring the Stochastic Gravitational Radiation Background with Laser Interferometric Antennas. *Phys. Rev. D*, 46:5250, 1992.

[111] B Abbott et al. Searching for a Stochastic Background of Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory. *Astrophys. J.*, 659:918, 2007.

[112] J. Abadie et al. Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz. *Phys. Rev. D*, 85:122001, 2012.

[113] B. Abbott et al. Searching for Stochastic Gravitational Waves with LIGO. *Nature*, 460:990, 2009.

[114] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational–Wave Background from 2009–2010 LIGO and Virgo Data. *prl*, 113:231101, 2014.

[115] J. Aasi et al. Searching for stochastic gravitational waves using data from the two colocated LIGO Hanford detectors. *prd*, 91:022003, 2015.

[116] V Mandic, E Thrane, S Giampanis, and T Regimbau. Parameter Estimation in Searches for the Stochastic Gravitational-Wave Background. *Phys. Rev. Lett.*, 109:171102, 2012.

[117] C. Wu, V. Mandic, and T. Regimbau. Accessibility of the gravitational-wave background due to binary coalescences to second and third generation gravitational-wave detectors. *Phys. Rev. D*, 85:104024, 2012.

[118] C. Brans and R.H. Dicke. Mach's principle and a relativistic theory of gravitation. *Phys.Rev.*, 124:925–935, 1961.

[119] Y. Fujii and K. Maeda. *The Scalar-Tensor Theory of Gravitation*. Cambridge Monograph on Mathematical Physics. Cambridge University Press, Cambridge, 2002.

[120] Thomas P. Sotiriou and Valerio Faraoni. f(R) Theories Of Gravity. *Rev.Mod.Phys.*, 82:451–497, 2010.

[121] Antonio De Felice and Shinji Tsujikawa. f(R) Theories. *Living Rev. Relativity*, 13(3), 2010.

[122] Matt Visser. Mass for the graviton. *General Relativity and Gravitation*, 30(12):1717–1728, 1998.

[123] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley. Resummation of massive gravity. *Phys. Rev. Lett.*, 106:231101, Jun 2011.

[124] D Talukder, E Thrane, S Bose, and T Regimbau. Measuring neutron-star ellipticity with measurements of the stochastic gravitational-wave background. *Accepted for publication in Phys. Rev. D*, 2014. `http://arxiv.org/abs/1404.4025`.

[125] T Regimbau & B Chauvineaux. A stochastic background from extra-galactic double neutron stars. *Class. Quantum Grav.*, 24:627, 2007.

[126] A. J. Farmer & E. S. Phinney. The gravitational wave background from cosmological compact binaries. *Mon. Not. R. Ast. Soc.*, 346:1197, 2003.

[127] E Howell et al. The gravitational wave background from neutron star birth throughout the cosmos. *Mon. Not. R. Ast. Soc.*, 351:1237, 2004.

[128] V Ferrari & S Matarrese & R Schneider. Gravitational wave background from a cosmological population of core-collapse supernovae. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[129] V Ferrari & S Matarrese & R Schneider. Stochastic background of gravitational waves generated by a cosmological population of young, rapidly rotating neutron stars. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[130] G Sigl. Cosmological gravitational wave background from phase transitions in neutron stars. *J. Cosmol. Astropart. Phys.*, JCAP04:002, 2006.

[131] T Regimbau & J A de Freitas Pacheco. Cosmic background of gravitational waves from rotating neutron stars. *Astron. Astrophys.*, 376:381, 2001.

[132] T Regimbau & J A de Freitas Pacheco. Gravitational wave background from magnetars. *Astron. Astrophys.*, 447:1, 2006.

[133] L Barack & C Cutler. Confusion noise from LISA capture sources. *Phys. Rev. D*, 70:122002, 2004.

[134] G Sigl & J Schnittman & A Buonanno. Gravitational-wave background from compact objects embedded in AGN accretion disks. *Phys. Rev. D*, 75:024034, 2007.

[135] B Abbott et al. Directional limits on persistent gravitational waves using LIGO S5 science data. *Phys. Rev. Lett.*, 107:271102, 2011.

[136] E Thrane, S Ballmer, J D Romano, S Mitra, D Talukder, S Bose, and V Mandic. Probing the anisotropies of a stochastic gravitational-wave background using a network of ground-based laser interferometers. *Phys. Rev. D*, 80:122002, 2009.

[137] E Thrane, S Mitra, N Christensen, V Mandic, and A Ain. All-sky, narrowband, gravitational-wave radiometry with folded data. *Accepted in Phys. Rev. D*, 2015.

[138] A Ain, P Dalvi, and S Mitra. Fast gravitational wave radiometry using data folding. 2015. `http://xxx.tau.ac.il/abs/1504.01714`.

[139] R Prix, S Giampanis, and C Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[140] P Jaranowski, A Kr'olak, and B F Schutz. Data analysis of gravitational-wave signals from spinning neutron stars: The signal and its detection. *Phys. Rev. D*, 58:063001, 1998.

[141] D I Jones and N Andersson. Gravitational waves from freely precessing neutron stars. *Mon. Not. R. Ast. Soc.*, 331:203, 2002.

[142] L Gualtieri, R Ciolfi, and V Ferrari. Structure, deformations and gravitational wave emission of magnetars, 2010. Prepared for 19th International Conference on General Relativity and Gravitation (GR19), Mexico City, Mexico, July 5-9, 2010, arxiv/1011.2778.

[143] A Arvanitaki, M Baryakhtar, and X Huang. Discovering the qcd axion with black holes and gravitational waves. *Phys. Rev. D*, 91:084011, 2015.

[144] E Thrane, S Kandhasamy, C D Ott, et al. Long gravitational-wave transients and associated detection strategies for a network of terrestrial interferometers. *Phys. Rev. D*, 83:083004, 2011.

[145] T. Prestegard, E. Thrane, et al. Identification of noise artifacts in searches for long-duration gravitational-wave transients. *Class. Quantum Grav.*, 29:095018, 2012.

[146] J Aasi et al. Search for long-lived gravitational-wave transients coincident with long gamma-ray bursts. *Phys. Rev. D*, 88:122004, 2013.

[147] E Thrane and M Coughlin. Searching for gravitational-wave transients with a qualitative signal model: seedless clustering strategies. *Phys. Rev. D*, 88:083010, 2013.

[148] E. Thrane and M. Coughlin. Seedless clustering in all-sky searches for gravitational-wave transients. *Phys. Rev. D*, 89:063012, 2014.

[149] T. Prestegard and E. Thrane. Burstegard: a hierarchical clustering algorithm. *LIGO DCC*, page L1200204, 2012. `https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=93146`.

[150] M. Coughlin, E. Thrane, and N. Christensen. Detecting compact binary coalescences with seedless clustering. *Phys.Rev.*, D90(8):083005, 2014.

[151] E Thrane, V Mandic, and N Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91:104021, 2015.

[152] P. Meyers, M. W. Coughlin, and J. Luo. Investigating Environmental Noise Using the Stochastic Transient Analysis Multi-Detector Pipeline (STAMP-PEM), 2014. `https://dcc.ligo.org/LIGO-G1400354`.

[153] M. Coughlin for the LIGO Scientific Collaboration and the Virgo Collaboration. Identification of long-duration noise transients in LIGO and Virgo. *Class. Quantum Grav.*, 28:235008, 2011.

[154] M. C. Miller and E. J. M. Colbert. Intermediate-Mass Black Holes. *International Journal of Modern Physics D*, 13:1–64, January 2004.

[155] J. M. Fregeau, S. L. Larson, M. C. Miller, R. O'Shaughnessy, and F. A. Rasio. Observing IMBH-IMBH Binary Coalescences via Gravitational Radiation. *Astrophysical Journal Letters*, 646:L135–L138, August 2006.

[156] P. Amaro-Seoane and M. Freitag. Intermediate-Mass Black Holes in Colliding Clusters: Implications for Lower Frequency Gravitational-Wave Astronomy. *Astrophysical Journal Letters*, 653:L53–L56, December 2006.

[157] Jonathan R. Gair, Ilya Mandel, M. Coleman Miller, and Marta Volonteri. Exploring intermediate and massive black-hole binaries with the Einstein Telescope. 2009.

[158] K. Belczynski, A. Buonanno, M. Cantiello, C. L. Fryer, D. E. Holz, I. Mandel, M. C. Miller, and M. Walczak. The Formation and Gravitational-wave Detection of Massive Stellar Black Hole Binaries. *Astrophysical Journal*, 789:120, July 2014.

[159] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, T. Accadia, F. Acernese, K. Ackley, C. Adams, T. Adams, and et al. Search for gravitational radiation from intermediate mass black hole binaries in data from the second LIGO-Virgo joint science run. *Physical Review D*, 89(12):122003, June 2014.

[160] Benjamin P. Abbott et al. Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO. 2017.

[161] E. Nakar. Short-hard gamma-ray bursts. *Physics Reports*, 442:166–236, April 2007.

[162] I. Leonor, P. J. Sutton, R. Frey, G. Jones, S. Marka, et al. Estimating detection rates for the LIGO-Virgo search for gravitational-wave burst counterparts to gamma-ray bursts using inferred local GRB rates. *Class.Quant.Grav.*, 26:204017, 2009.

[163] D. Wanderman and T. Piran. The luminosity function and the rate of Swift's Gamma Ray Bursts. *Mon. Not. Roy. Astron. Soc.*, 406:1944–1958, 2010.

[164] F. Daigne and R. Mochkovitch. The low-luminosity tail of the GRB distribution: the case of GRB 980425. *Astronomy & Astrophysics*, 465:1–8, April 2007.

[165] E. J. Howell and D. M. Coward. A redshift-observation time relation for gamma-ray bursts: evidence of a distinct subluminous population. *MNRAS*, 428:167–181, January 2013.

[166] S. Desai, E.O. Kahya, and R.P. Woodard. Reduced time delay for gravitational waves with dark matter emulators. *Phys.Rev.*, D77:124041, 2008.

[167] N. Dalal, D. E. Holz, S. A. Hughes, and B. Jain. Short GRB and binary black hole standard sirens as a probe of dark energy. *Phys.Rev.*, D74:063006, 2006.

[168] J. Abadie, B. P. Abbott, T. D. Abbott, R. Abbott, M. Abernathy, C. Adams, R. Adhikari, C. Affeldt, P. Ajith, B. Allen, and et al. Implications for the Origin of GRB 051103 from LIGO Observations. *Astrophysical Journal*, 755:2, August 2012.

[169] B. P. Abbott, R. Abbott, F. Acernese, et al. Search for gravitational-wave bursts associated with gamma-ray bursts using data from ligo science run 5 and virgo science run 1. *The Astrophysical Journal*, 715(2):1438, 2010.

[170] B. P. Abbott et al. Search for Gravitational Waves Associated with Gamma-Ray Bursts During the First Advanced LIGO Observing Run and Implications for the Origin of GRB 150906B. *Astrophys. J.*, 841(2):89, 2017.

[171] A. R. Williamson, C. Biwer, S. Fairhurst, I. W. Harry, E. Macdonald, D. Macleod, and V. Predoi. Improved methods for detecting gravitational waves associated with short gamma-ray bursts. *Phys. Rev.*, D90(12):122004, 2014.

[172] Patrick J. Sutton, Gareth Jones, Shourov Chatterji, Peter Michael Kalmus, Isabel Leonor, et al. X-Pipeline: An Analysis package for autonomous gravitational-wave burst searches. *New J.Phys.*, 12:053034, 2010.

[173] Alex L. Urban. *Monsters in the Dark: High Energy Signatures of Black Hole Formation with Multi-messenger Astronomy*. Ph.D. dissertation, University of Wisconsin-Milwaukee, May 2016.

[174] S. Ando, B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, A. Dietz, C. Donzaud, D. Eichler, C. Finley, D. Guetta, F. Halzen, G. Jones, S. Kandhasamy, K. Kotake, A. Kouchner, V. Mandic, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Piran, T. Pradier, G. E. Romero, P. Sutton, E. Thrane, V. Van Elewyck, and E. Waxman. Colloquium: Multimessenger astronomy with gravitational waves and high-energy neutrinos. *Reviews of Modern Physics*, 85:1401–1420, October 2013.

[175] I. Bartos, P. Brady, and S. Márka. How gravitational-wave observations can shape the gamma-ray burst paradigm. *Classical and Quantum Gravity*, 30(12):123001, June 2013.

[176] B. Baret et al. Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts. *Astroparticle Physics*, 35:1–7, August 2011.

[177] I. Bartos, B. Dasgupta, and S. Márka. Probing the structure of jet-driven core-collapse supernova and long gamma-ray burst progenitors with high-energy neutrinos. *Phys. Rev. D*, 86(8):083007, October 2012.

[178] I. Bartos, A. M. Beloborodov, K. Hurley, and S. Márka. Detection Prospects for GeV Neutrinos from Collisionally Heated Gamma-ray Bursts with IceCube/DeepCore. *Physical Review Letters*, 110(24):241101, June 2013.

[179] K. Murase, K. Kashiyama, K. Kiuchi, and I. Bartos. Gammy-Ray and Hard X-Ray Emission from Pulsar-aided Supernovae as a Probe of Particle Acceleration in Embryonic Pulsar Wind Nebulae. *ApJ*, 805:82, May 2015.

[180] B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, C. Donzaud, M. Drago, C. Finley, G. Jones, S. Klimenko, A. Kouchner, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Pradier, G. Prodi, P. Raffai, V. Re, J. Rollins, F. Salemi, P. Sutton, M. Tse, V. Van Elewyck, and G. Vedovato. Multimessenger science reach and analysis method for common sources of gravitational waves and high-energy neutrinos. *Phys Rev D*, 85(10):103004, May 2012.

[181] M. W. E. Smith, D. B. Fox, D. F. Cowen, P. Mészáros, G. Tešić, J. Fixelle, I. Bartos, P. Sommers, A. Ashtekar, G. Jogesh Babu, S. D. Barthelmy, S. Coutu, T. DeYoung, A. D. Falcone, S. Gao,

B. Hashemi, A. Homeier, S. Márka, B. J. Owen, and I. Taboada. The Astrophysical Multimessenger Observatory Network (AMON). *Astroparticle Physics*, 45:56–70, May 2013.

[182] S. Adrián-Martínez, A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, J.-J. Aubert, T. Avgitas, B. Baret, J. Barrios-Martí, and et al. High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube. *Phys. Rev. D*, 93(12):122010, June 2016.

[183] A. Albert, M. Andre, M. Anghinolfi, G. Anton, M. Ardid, J.-J. Aubert, T. Avgitas, B. Baret, J. Barrios-Marti, S. Basa, and et al. Search for High-energy Neutrinos from Gravitational Wave Event GW151226 and Candidate LVT151012 with ANTARES and IceCube. *ArXiv e-prints*, March 2017.

[184] S. Adrián-Martínez et al. A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007. *Journal of Cosmology and Astroparticle Physics*, 2013(06):008, 2013.

[185] B. P. Abbott et al. All-sky search for long-duration gravitational wave transients with initial LIGO. *Phys. Rev.*, D93(4):042005, 2016.

[186] A. Corsi and P. Mészáros. Gamma-ray burst afterglow plateaus and gravitational waves: multi-messenger signature of a millisecond magnetar? *Astrophys. J.*, 702:1171, 2009.

[187] A. L. Piro and C. D. Ott. Supernova fallback onto magnetars and propeller-powered supernovae. *Astrophys. J.*, 736:108, 2011.

[188] A. L. Piro and E. Thrane. Gravitational Waves from Fallback Accretion onto Neutron Stars. *Astrophys. J.*, 761:63, 2012.

[189] K Kiuchi, M Shibata, P J Montero, and J A Font. Gravitational waves from the Papaloizou-Pringle instability in black hole-torus systems. *Phys. Rev. Lett.*, 106:251102, 2011.

[190] M. H. P. M. van Putten. Proposed Source of Gravitational Radiation from a Torus around a Black Hole. *Phys. Rev. Lett.*, 87:091101, 2001.

[191] M. H. P. M. van Putten. Gravitational Waveforms of Kerr Black Holes Interacting with High-Density Matter. *Astrophys. J. Lett.*, 684:91, 2008.

[192] A. L. Piro and E. Pfahl. Fragmentation of Collapsar Disks and the Production of Gravitational Waves. *Astrophysical Journal*, 658:1173, April 2007.

[193] C. D. Ott. The gravitational-wave signature of core-collapse supernovae. *Class. Quantum Grav.*, 26:063001, 2009.

[194] R. M. O'Leary, B. Kocsis, and A. Loeb. Gravitational waves from scattering of stellar-mass black holes in galactic nuclei. *Mon. Not. R. Ast. Soc.*, 395:2127, 2009.

[195] Robert Coyne, Alessandra Corsi, and Benjamin J. Owen. Cross-correlation method for intermediate duration gravitational wave searches associated with gamma-ray bursts. *Phys. Rev.*, D93(10):104059, 2016.

[196] Eric Thrane, Vuk Mandic, and Nelson Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. 2015.

[197] T. W. B. Kibble. Topology of Cosmic Domains and Strings. *J.Phys.A*, A9:1387–1398, 1976.

[198] A. Vilenkin and E. Shellard. *Cosmic strings and other Topological Defects*. Cambridge University Press, 2000.

[199] Andrei D. Linde. Hybrid inflation. *Phys.Rev.*, D49:748–754, 1994.

[200] Edmund J. Copeland, Andrew R. Liddle, David H. Lyth, Ewan D. Stewart, and David Wands. False vacuum inflation with Einstein gravity. *Phys.Rev.*, D49:6410–6433, 1994.

[201] G.R. Dvali, Q. Shafi, and Robert K. Schaefer. Large scale structure and supersymmetric inflation without fine tuning. *Phys.Rev.Lett.*, 73:1886–1889, 1994.

[202] Saswat Sarangi and S.H. Henry Tye. Cosmic string production towards the end of brane inflation. *Phys.Lett.*, B536:185–192, 2002.

[203] Rachel Jeannerot, Jonathan Rocher, and Mairi Sakellariadou. How generic is cosmic string formation in SUSY GUTs. *Phys.Rev.*, D68:103514, 2003.

[204] Edward Witten. Cosmic superstrings. *Physics Letters B*, 153(4???5):243 – 246, 1985.

[205] Edmund J. Copeland, Levon Pogosian, and Tanmay Vachaspati. Seeking String Theory in the Cosmos. *Class.Quant.Grav.*, 28:204009, 2011.

[206] Thibault Damour and Alexander Vilenkin. Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational windows. *Phys.Rev.*, D71:063510, 2005.

[207] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys.Rev.*, D81:104028, 2010.

[208] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cosmic strings. *Phys.Rev.Lett.*, 85:3761–3764, 2000.

[209] J. Aasi, J. Abadie, B.P. Abbott, R. Abbott, T. Abbott, et al. Constraints on cosmic strings from the LIGO-Virgo gravitational-wave detectors. *Phys.Rev.Lett.*, 112:131101, 2014.

[210] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009âĂŞ2010 LIGO and Virgo Data. *Phys. Rev. Lett.*, 113(23):231101, 2014.

[211] E Thrane, N Christensen, and R Schofield. Correlated magnetic noise in global networks of gravitational-wave interferometers: observations and implications. *Phys. Rev. D*, 87:123009, 2013.

[212] LIGO calibration web page.
`http://blue.ligo-wa.caltech.edu/engrun/Calib_Home/`.

[213] R. Adhikari *et al.*, "Calibration of the LIGO Detectors for the First LIGO Scientific Run", LIGO-T030097 (2003);
G. Gonzalez *et al.*, "Calibration of the LIGO Detectors for S2", LIGO-T040060 (2004);
G. Gonzalez *et al.*, "Calibration of the LIGO Detectors for S3", LIGO-T050059 (2005);
A. Dietz *et al.*, "Calibration of the LIGO detectors for S4", LIGO-T050262-01-D (2006).

[214] Y. Aso et al. Accurate measurement of the time delay in the response of the ligo gravitational wave detectors. *Classical and Quantum Gravity*, 26(5):055010, 2009.