

LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

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The LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics (Summer 2018 edition)	
The LSC-Virgo Data Analysis Council including the LSC-Virgo Data Analysis Working Groups and the Detector Characterization and Calibration Working Groups	

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1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo Collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for signals from merging neutron stars or black holes by filtering the data with waveform templates. The **Burst** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin. 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 priorities and plans of the members of these four working groups, along with statements from the Detector Characterization and Calibration teams. (The LSC Program Committee and Virgo Program committee will set specific goals for collaboration work on an annual basis, using this white paper and other inputs.)

The Advanced Detector Era (ADE) is the epoch of Advanced LIGO and Advanced Virgo science data acquisition, which began in September 2015 with the first Advanced LIGO observing run (O1). The second run (O2) took place in 2016–17, including Advanced Virgo’s first science data in August 2017. Besides the binary black hole mergers detected during the O1 run, as of this writing (June 2018) four GW events detected during the O2 run have been published. This includes the first binary neutron star merger, GW170817 [Phys. Rev. Lett. (PRL) 119, 161101 (2018)], which was remarkable for having a very rich and well-studied electromagnetic counterpart.

Table 1 shows the past and planned schedule of observing 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	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		Binary Neutron Star (BNS) Range (Mpc)		
			LIGO	Virgo	LIGO	Virgo	
2015–16	4 months	O1	40 – 60	–	68 – 78	–	actual
2016–17	9 months	O2	60 – 75	20–40	55 – 95	22 – 28	actual
2019–20	12 months	O3	75–90	40–50	120 – 170	60 – 85	projected

Table 1: Observing schedule, actual and expected sensitivities for the Advanced LIGO and Virgo detectors. The O2 LIGO BNS range is from public status updates on the ligo.org web site, as well as internal monitoring of actual ranges. The sensitivities for LIGO and Virgo achieved in O3 will depend on ongoing commissioning progress [Living Rev. Relativity 21:3 (2018)].

Current LSC-Virgo scientific priorities 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 lower detection probability but high scientific payoff.

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

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

1.1 Searches for Generic Transients, or Bursts

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and to gain new information on populations, emission mechanisms, and source physics of the associated astrophysical objects. Central to the Burst group philosophy is the assumption of minimal information on the source, so that searches for 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-modeled signals such as core-collapse supernovae (CCSN) 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 ($\geq 100 M_{\odot}$) produces gravitational-wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts (GRBs) could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, the group employs data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

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

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

Many potential gravitational-wave burst sources should also be observable in other astronomy channels, including γ -ray, X-ray, optical, radio, and neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a 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 *multi-messenger* 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. An important component of this connection utilizes burst searches running in low-latency, with latencies of minutes to hours, and providing information on transient GW candidates to the astronomical community. The binary neutron star merger GW170817 illustrated the scientific value of this approach.

Once a confident gravitational-wave transient is identified, characterizing its properties becomes an impor-

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LSC-Virgo Astrophysics Search Working Group				
	Burst	CBC	CW	SGWB
Highest priority	All-sky short duration search (both online and offline)	Detecting the coalescence of neutron star and black hole binaries and measuring their parameters	All-sky search for isolated neutron stars, both as a <i>quick-look</i> on owned resources and as a deep/broad search on Einstein@Home	Searches for an isotropic stochastic GW background
	Untemplated searches targeting binary black holes	Characterizing the astrophysical distribution of compact binaries	Targeted search for high value, known pulsars, including narrowband searches	Directional searches for stochastic GW backgrounds
	Plan for exceptional multi-messenger sources	Responding to exceptional CBC detections	Directed searches for the most promising point sources (Cas A, Vela Jr etc.) and follow-ups of interesting BNS/SN events	Search for non-stationary compact binary black hole background
	All-sky long duration search	Multi-messenger astronomy with compact binaries	Directed searches for X-ray binaries Sco X-1 and XTE J1751–305	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Signal characterization	Searching for CBC-GRB coincidences	Searches for unknown continuous wave sources in unknown binary systems	
		Testing General Relativity with compact binaries		
		Measuring the neutron star equation of state		
	Determination of the Hubble constant			
High priority	Search for BNS post-merger signal	Matched filter search for intermediate mass black hole binary systems	Targeted search for other known pulsars	Search for very long transients (~ 10 hr – days)
	Triggered multi-messenger searches	Search for sub-solar mass compact binary coalescences	Directed searches for other isolated compact stars and X-ray binaries	Data folding for efficient SGWB searches
	All-sky cosmic string search			
Additional priority	Search for GW memory effects	CBC searches for binary mergers associated with fast radio bursts and high energy neutrinos	Alternative approaches for all-sky searches for isolated/binary compact stars	
	Search for GW bursts with non-GR polarization	Optimized statistical search for a weak background of signals from binary mergers	Searches for emission from glitching objects	
			Searches for emission from axion clouds around black holes	
			Novel techniques using machine learning and model-agnostic techniques	

Table 2: Science priorities of the LIGO Scientific Collaboration and Virgo Collaboration, for the four astrophysics search groups: Burst, Compact Binary Coalescence (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into three categories (highest priority, high priority, additional priority) based on their detection potential. There is no additional ranking within each category in this table. Critical for accomplishing these science priorities are the detector characterization and calibration activities described in this document.

tant goal of the group. This includes producing waveform reconstruction, polarization, and source localization estimates for all observed transients. This information can then be used to learn about the nature of the astrophysical source.

1. Highest Priority

- **All-sky short duration search (both online and offline):** The Burst group will search for a broad class of short duration transients. Deliverables include low-latency triggers for EM follow-up, and papers describing search results. [Sections 2.1, 6.1]
- **Untemplated searches targeting binary black holes:** Although most expected BBH mergers will also be detected with CBC searches, burst algorithms are sensitive to a range of features not included in current template banks, including higher order modes, eccentricity, and spin precession. This is important to detect some classes of BBH events. Deliverables include the results of searches targeting both stellar mass and intermediate mass ($M > 100 M_{\odot}$) black hole systems, with results to be included in papers written jointly with the CBC group. [Sections 2.2, 7.3]
- **Plan for exceptional multi-messenger sources (CCSN, BNS, GRB, Magnetar Flare, Neutrino):** In the event of an exceptional astrophysical event, where there is a reasonable expectation for detectable gravitational waves, the group will deliver a detection statement (or non-detection statement) in a timely manner, as well as waveform reconstruction and signal interpretation. Examples include a galactic core-collapse supernova, an unusually close binary neutron star merger or gamma-ray burst, or a highly energetic magnetar flare. In advance of this, deliverables include making plans for what types of statements to make, and developing software that will be used to produce the results. [Sections 2.5, 2.4, 7.2, 7.4, 7.6, Sections 7.7, 7.1]
- **All-sky long duration search:** The Burst group will search for a broad class of long-duration transients. Deliverables include papers describing the search results. [Sections 8.1]
- **Signal characterization:** For detected transients, a coherent waveform reconstruction, polarization estimates, and source localization enable many potential investigations. Deliverables include producing waveform reconstructions and localizations for all detected transients. [Sections 2.3]

2. High Priority

- **Search for BNS post-merger signal:** Following a BNS detection, the group will search for a post-merger signal. Finding (or limiting) such a signal provides a powerful equation-of-state measurement. Deliverables include the result of a search for a post-merger signal after each nearby BNS detection. [Sections 7.7, 7.1]
- **Triggered multi-messenger searches (CCSN, GRB, Magnetar Flare, Neutrino, Fast Radio Burst):** Using a known astrophysical event as a target can increase the sensitivity of a GW search, typically by 10-30% in range. The group will pursue a number of triggered searches. This includes some sub-threshold searches. Deliverables include papers describing the search results. [Sections 2.5, 2.4, 7.2, 7.4, 7.6, 7.5]
- **All-sky cosmic string search:** The group will search for signals from cosmic strings, and interpret any upper limits as constraints on string parameters. Deliverables include papers describing

search results. [Sections 8.2]

3. Additional Priority

- **Search for GW memory effects:** Searches for GW memory effects are in development.
- **Search for GW bursts with non-GR polarization:** Searches for GW bursts with polarization states not allowed by General Relativity are in development.

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

1.2 Searches for Signals from Compact Binary Coalescences

As of this writing, analyses of the first observing run (O1) and the second observing run (O2) have yielded the detection of several binary black hole coalescences and a binary neutron star merger. The latter event was observed nearly simultaneously in gamma-rays, and, within a day, an optical counterpart was discovered; this was followed by observations across the entire electromagnetic spectrum. In preparation for the third observing run (O3) we are actively preparing open public alerts to enable electromagnetic follow-up of compact binary coalescences. We are also preparing to do more detailed estimation of population distributions of binary masses and spins and more sensitive tests of general relativity using a much larger statistical sample of signals; more precise measurements of neutron star (NS) equation of state through measurement of tidal interactions of neutron star binaries; and improved measurements of the Hubble constant through direct and statistical methods. Furthermore, we anticipate discovery of entirely new source classes such as coalescing black-hole + neutron-star binaries within the next few years, and we also target more speculative sources such as intermediate mass binary black holes and sub-solar mass binary black holes. The Compact Binary Coalescence (CBC) group aims to discover additional compact binary mergers and to use the gravitational wave signals to advance our understanding of fundamental physics and astrophysics.

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

1. Highest priority

- **Responding to exceptional events.** We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include

new detections of binary neutron stars, the first detection of a neutron-star + black-hole binary, or intermediate-mass or sub-solar mass binary systems. We also anticipate examples in which measurement of a source’s parameters (e.g. masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g. the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass). Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, improved measurement of the nuclear equation of state. Binaries with observed electromagnetic counterparts can significantly improve our estimate of Hubble constant using the standard-siren distance estimate.

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

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

- **Characterizing the astrophysical distributions of compact objects.** As the number of detections 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 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 from general relativity such as the no-hair and area theorems, Lorentz violations of the graviton, and the speed of gravitational waves. As more detectors are added to the network we will also be able to make improved tests of the polarization states of gravitational waves.
- **Public alerts to enable multimessenger astronomy.** Observations of an electromagnetic or neutrino counterparts to a gravitational wave signal are of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by providing public alerts to the astronomical community. This requires the continued development of low-latency pipelines for detection, localization, and estimation of parameters of sources, automatic detector quality checks, and the infrastructure associated with collating and distributing information about detection candidates.
- **Multimessenger search for gravitational waves associated with gamma-ray bursts.** The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact observations in the compact binary field. We will continue performing a deep coherent search for gravitational waves focused on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational-wave and GRB signals.

- **Probing the properties of matter in the extremes of physical limits.** Binary coalescences involving neutron stars are a unique laboratory for studying the behaviour of matter at super-nuclear densities and pressures. We will refine methods of constraining the neutron star equation of state by measuring its observable effects on the inspiral, merger and post-merger phases of the coalescence signal, and apply these to forthcoming neutron star merger observations.
- **Determination of the Hubble constant.** Gravitational waves provide a new way to measure the distance of extra-galactic binary coalescences. When these events are also observed electromagnetically, and the redshift of the host galaxy is measured, an estimate of the Hubble constant can be obtained. As such observations accumulate, this method is expected to provide a competitive and independent method for obtaining the Hubble constant. In addition, a statistical approach involving spatial correlations with a galaxy catalog can be used for merger events when no identified counterpart is available. With new observations, we will improve our estimate of the Hubble constant.

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

2. High priority

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

- **Intermediate mass black hole binaries & intermediate mass-ratio inspirals.** A goal of the CBC group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of searches for intermediate-mass-ratio inspirals and waveforms to describe them.
- **Search for sub-solar mass compact binary coalescences.** A speculative source is black hole binaries (or other compact object binaries) having component masses below one solar mass. Primordial black holes could be one channel by which such systems are formed, but there are other possibilities. Such systems might possibly constitute some fraction of the dark matter. A search for sub-solar mass binaries could reveal the existence of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.

3. Additional priority

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

- **Multimessenger search for gravitational waves associated with fast radio bursts and high-energy neutrinos.** It is possible that fast radio bursts and high-energy neutrinos are produced during compact binary coalescence. The method for performing deep searches for gravitational waves associated with gamma-ray bursts can be extended to explore periods of time around

triggers produced by fast radio bursts or high-energy neutrinos. Though the methods are similar, the time window to be explored will need to be reassessed.

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

1.3 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 rotation with elastic deformations, magnetic deformations, unstable r -mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous gravitational wave and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives and distances, energy conservation allows setting an upper limit on gravitational wave strain amplitude, known as the *spindown* limit, albeit with significant uncertainties. Previous searches in LIGO and Virgo data have obtained high-confidence upper limits well below the spindown limits for several pulsars, including the Crab Pulsar and Vela. 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 only 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. We note that due to the trials factor, the lack of *a priori* information on the waveform leads to decreased sensitivity of the associated searches. The five source categories are: 1) known pulsars with well-measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) unknown isolated stars; 4) known or suspected binary neutron star systems with no timing information; and 5) unknown binary stars. In more detail:

- 1) 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. Among these, of high-interest are those with spindown limits within factors of a few of the achievable sensitivities. For these high-interest targets it is mandatory to forego a small part of the sensitivity and, relaxing the strict assumption of phase coherence between the gravitational wave signal and the electromagnetic pulsation, perform a search in a small frequency band around the nominal value.
- 2) Directed searches using known sky locations but having no *a priori* frequency information (e.g., Casiopeia 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).
- 3) The sensitivity achievable with all-sky searches is 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 combination of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space.

4) Directed searches for suspected neutron stars in binary systems with unknown source frequency must make similar sensitivity tradeoffs, and

5) all-sky searches for sources in unknown binary systems define the current extreme in sensitivity tradeoff for tractability.

Additionally the group maintains an active research program which constantly scopes out new ideas in order to improve the existing searches and/or to expand the scope of the existing ones.

With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories. The priorities presented below represent our “must deliver” scale and are determined by: 1) convolving the estimated priors on the likelihood of a detection from sources in a certain category with the cost/benefit of the searches (their computational and “human” cost); 2) their sensitivity; and 3) the timeline for extracting a vetted observational result. It should be noted that priors on the signal parameters are highly uncertain and are often re-assessed in time, and the cost/benefit of a search is influenced by the specific data set under consideration, including its spectral noise, which may be hard to predict. Some of the investigations that are now quite far from being applied to yield or support any observational result will mature and move up the prioritisation list. So our prioritisation, as described below, is to be taken as our best-effort at the time of writing that becomes less certain the further in time it is extrapolated.

We finally note that the ordering within the same priority class does *not* indicate any prioritisation within the class:

1. Highest priority

- Targeted searches for the Crab and Vela pulsars as well as 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 PSR J1813–1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.
- Searches for the Crab and Vela pulsars as well as other high-interest targets exploring a small frequency band around the nominal one at twice the rotation frequency.
- Directed searches for point sources as broadly and widely as resources allow. It should be noted that these searches include follow-ups to neutron star-neutron star mergers, targeting “long-duration transient signals”.
- All-sky searches for signals from 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.
- Directed searches for the X-ray binary Scorpius X–1 and other X-ray binaries as resources allow.
- All-sky searches for signals from unknown stars in binary systems. Because of the additional unknown orbital parameter space to search, these searches are the most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability. At time of writing we do not have a lot of resources devoted to this endeavor.

2. High priority

- Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten, according to conventional theory. It must be noted that, due to the way that the targeted searches are now streamlined and to their insignificant computational cost, there is virtually no practical benefit to separating the high-interest targets from the others and delivering two separate sets of results.
- Directed searches for remaining young supernova remnants, 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 promising gamma-ray and X-ray binaries that were not covered in the highest priority, e.g. Cygnus X-3, XTE 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. For the latter two objects there is evidence for sharp X-ray periodicities that may indicate an r -mode oscillation.

3. Additional priority

- Development of alternative/improved methods for all-sky searches for unknown isolated neutron stars and neutron stars in binary systems.
- Searches for emission from glitching objects.
- Searches for emission from axion clouds around black holes.
- Scoping out new techniques and/or “blue-sky” developments to existing pipelines. At the time of writing these include the use of neural networks/deep learning algorithms to carry out searches and new Viterbi-based techniques.

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 (see Sec. 8.1) may also present as 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 binary black hole (BBH) and binary neutron star (BNS) mergers indicates that, at design sensitivity, Advanced LIGO may detect an astrophysical background. This detection will be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity. Meanwhile, the detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The stochastic searches are built

on the cross-correlation infrastructure, which was originally designed to carry out searches for an isotropic stochastic background, but has been adapted to also search for directional 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 of General Relativity (GR) by searching for a background of non-tensor polarizations. This extension provides a tool for model selection between a tensor and non-tensor background signal, as well as an estimate of the background energy density from tensor, vector, and scalar polarizations. It is also important to estimate the individual contributions of distinct sources of the background, 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 either a mixing matrix deconvolution or Bayesian parameter estimation. Bayesian parameter estimation techniques are also used to estimate or constrain the average chirp mass and merger rate of the binary black hole population. Significant model development will be necessary for understanding and interpreting the observational results. To support the interpretation of the results, mock data challenges with different sources, such as compact binaries and cosmic strings, will be pursued. Additionally, a fully-Bayesian analysis for an isotropic SGWB is being developed using BayesWave. This analysis is capable of estimating noise power spectra and modeling 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 can also be applied to search for a GW background with parameterized anisotropy, for example anisotropies associated with the compact binary black hole background or cosmic strings. To further study anisotropies in the astrophysical background, GW sky maps can be cross correlated with electromagnetic observables. The broadband radiometer measures the background energy density from point-like sources over the sky, and provides an important tool for GW astronomy when there is significant uncertainty in the phase evolution of a continuous-wave signal. As an application, a narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. Using a compressed data set folded over a sidereal day, the radiometer can be applied to perform an unmodeled search for persistent sources over all frequencies and sky locations. Directional searches are performed separately for multiple spectral indices in standard LIGO analyses but it may be possible to deconvolve the skymaps to constrain backgrounds of multiple spectral components. Exploration studies are being performed, initially considering two or three power-law spectral indices. We also investigate models of SGWB anisotropies, such as compact binaries and cosmic strings, which we can test against our results. We will test these models with mock data challenges. Continuous-wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable either via the stochastic radiometer or via methods being developed in the CW group. The Stochastic group continues to develop these searches, in consultation with the CW Group.

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

of the behaviour of detector artefacts on timescales of days to weeks. This method will be used to search for a remnant to the binary neutron star merger GW170817. There is overlap between the very long transient search and searches being carried out in the Burst and Continuous Waves 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 folded data set for the O1 and O2 observing runs. This data set will be utilised by the all-sky all-frequency radiometer.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background. However, a background from unresolvable binary BH mergers, for example, is likely to be detected first by the Stochastic group even though it will not be stationary and is unlikely to be Gaussian. Non-Gaussian stochastic background signals have been studied using software injections and analyses on mock data. A search for an astrophysical background from unresolved compact binary coalescences is being pursued in conjunction with the CBC group. The joint activity will develop and implement a Bayesian search strategy that is optimally suited to handle the non-stationarity of the expected background from BBH mergers.

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 polarizations, 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. The maps can be cross-correlated with maps of electromagnetic observables. **Non-Gaussian searches** will address the possible non-stationarity of an astrophysical background. **Data quality and detector characterization studies** are essential to the understanding and interpretation of results for all of the group's activities.

2. **High priority** We assign high priority important activities which, however, are not strictly required to complete the highest priority tasks. 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 all-sky all-frequency radiometer and searches for parameterized anisotropy.

1.5 Characterization of the Detectors and their Data

The detector characterization teams are largely separate for LIGO and Virgo, but there are some common tools and ongoing exchange of ideas.

1.5.1 LIGO

LIGO’s sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Robust detection of signals, 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 instruments and their environment. The LIGO Detector Characterization group (DetChar) is focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to avoid bad data, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the Advanced LIGO (aLIGO) detectors to help to identify data quality issues that can be addressed in the instruments to improve future instrument and search performance.

There are three top priorities: 1) contributing key work to the upcoming O3 observing run and search results, 2) supporting the upgrade and commissioning of the detectors during the commissioning break, and 3) preparing for future observing runs. In preparing for and contributing to the upcoming observing run, the highest priorities are automating event candidate validation, producing data quality infrastructure for low-latency EM alerts, developing key tools, monitoring data quality issues in the detector, vetting GW event candidates, and producing data quality products throughout O3. During the commissioning break, a high priority is conducting on-site and off-site investigations of interferometer and environment behavior to support the upgrade and commissioning efforts. The highest priorities in preparing for future observing runs are improved automation of key tools and event candidate validation, and improvement of monitors of known data quality features. Other high priorities are characterization of interferometer subsystems and auxiliary channels before O3, and curating data quality information for public data releases.

In parallel, there are a number of research and development tasks which have the potential to enhance the detector characterization mission. The highest priorities are investigation of which instrumental artifacts have the most severe impacts on each astrophysical search, development of existing machine learning and citizen science methods to identify the causes of noise transients, and the integration of various detector characterization tools into a central framework with common data formats. Longer-term goals are development of new methods, or improvement of existing methods, for noise identification and mitigation. This includes exploration of machine learning techniques and transient noise identification methods. All new methods should be tested with a data set and performance goals outlined by the DetChar group.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that adversely affect the astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Binary Coalescence and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data analysis must account for 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; and *veto segments* that indicate periods of poor quality data or identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use state segments to identify data suitable for analysis. Searches will use veto segments to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave (CW) and stochastic background 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 O3, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must develop automated approaches to identify the causes of instrumental problems and to provide data quality information in low-latency with minimal human supervision. This will be the main focus of the group during this period, 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 and auxiliary channel signal fidelity and robustness. 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 instrumental fixes for data quality issues are aggressively pursued. While the detectors are being upgraded, the DetChar group will provide commissioners with off-site assistance in any needed investigations as well as characterize changes in instrumental subsystems.

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, identify periods/frequencies of poor data quality, and vet event candidates. Automation is central to success in this activity.
2. **High priority.** Complement and collaborate on commissioning to help identify sources of data defects that limit sensitivity to transient and CW gravitational wave sources. Use auxiliary sensors to find, quantify, and mitigate coupling between the gravitational wave strain data and the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.
3. **Additional Priority.** 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 exploration of well-motivated new approaches to data quality issues.

To accomplish these priorities, the LIGO Detector Characterization group requires:

- astrophysical search group participation to report sensitivities in the analysis pipelines to data defects
- data quality experts to identify data defects and investigate their source as well as vet event candidates
- code developers to support and build key infrastructure and develop specific modules to recognize and flag data defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients between the gravitational wave data, the instrumentation, and the environment, and to identify mitigation strategies where needed

1.5.2 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 the Burst and CBC groups, and it has been moved to production. Additional data quality needs specific to the 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 Advanced Virgo 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 team is to find and mitigate 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 for 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, Hardware Injection, and Timing Diagnostics

1.6.1 LIGO Calibration

LIGO calibration includes all work to produce the calibrated strain time series, $h(t)$, that is used by all astrophysical analyses. This necessary work includes:

- creating accurate models of the detectors 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 uncertainty estimates on the calibration that can be used by astrophysical analyses to establish uncertainties in measured quantities
- producing a calibrated detector time series in low-latency
- providing infrastructure to re-calibrate the detector data using improved measurements or to correct 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 a GW 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.

Current LIGO calibration team activities are organized into two categories:

- **Essential:** These are items that must be accomplished in order to produce a calibrated data stream and associated data products required for all downstream analyses of LIGO $h(t)$ data.
- **Research and development:** These are items that are critical for improving LIGO calibration infrastructure and ensuring that LIGO calibration uncertainty is not the limiting factor in downstream astrophysical analysis results.

The current activities falling into each of these categories are listed below.

1. Essential

- Measure and understand the O3 interferometers
- Maintain and upgrade the photon calibrator system
- Revitalize and improve the calibration model software for better workflow from calibration measurements to uncertainty estimation
- Revitalize and improve the software for determining calibration uncertainty estimates
- Maintain and operate the low- and high-latency $h(t)$ data production software, currently both `gstreamer` based software and LIGO front-end based software
- Maintain the LIGO calibration monitoring tools used for reviewing and diagnosing calibration issues

2. Research and development

- Improve the detector calibration above 1 kHz
- Resolve any potential systematic error in the overall scale of the calibration and improve LIGO calibration precision and accuracy
- Integrate LIGO calibration uncertainty estimates seamlessly into astrophysical analyses
- Automate the generation of standard calibration precision and accuracy checks for more constant and effortless review
- Advance and improve the low- and high-latency `gstreamer` and front-end based calibration software

1.6.2 Virgo Calibration

An important activity after O2 has been to improve Advanced Virgo calibration and reconstruct the O2 $h(t)$ channel with better precision. An online version of the reconstructed channel $h(t)$ was available during O2 for low-latency searches. An updated O2 $h(t)$ channel was released in September 2017 with improved calibration models and frequency noise subtraction. A second update was released in January 2018 with the addition of monitoring cavity finesses variations and better frequency noise subtraction. This version is being used for the latest and on-going O2 analysis. The estimated uncertainties for the second versions are 5.1% in amplitude and $40 \times 10^{-3} + 2\pi f(20 \times 10^{-6})$ rad in phase.

The goals for O3 are to provide a better online $h(t)$ reconstructed channel for low-latency analysis and provide the estimated uncertainties before the start of the run, aiming at 5% online uncertainty. This

requires the calibration measurement to be done well in advance with an interferometer configuration stable during the four weeks preceding the start of O3. Weekly calibration shifts are planned in the commissioning planning, as well as nightly automated standard measurements. Additional improvements are planned for the photon calibrators.

A prototype Newtonian (gravitational) calibration system (NCal) has been successfully tested around O2 and has given results consistent with the standard calibration. Going further with NCal is planned for O3 and beyond to improve the calibration precision and to cross-calibrate the LIGO and Virgo detectors.

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 observing run, and the SGWB group typically carries out one or two ≈ 10 min injections during each observing 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.

The photon calibrator setup is being improved to overcome some slow calibration variations observed during O2 at the level of 20%, probably due to beam polarization variations. Cross-calibration of photon calibrators between detectors is being planned before O3.

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. The timing distribution system's status is monitored continuously and is periodically tested in-depth via timing diagnostics studies.

Critical timing tasks include:

- verifying traceable performance of the timing distribution system,
- 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.

2 Burst Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the CBC, DetChar, and Stochastic groups in sections 6, 7, and 8, respectively.

2.1 Search for short-duration Gravitational-Wave (GW) bursts

A wide range of highly energetic astrophysical phenomena are expected to be accompanied by emission of gravitational-wave transients lasting from milliseconds to several seconds within the instruments' frequency band. For some transient sources, especially binary compact systems made up of neutron stars and black holes, their expected gravitational-wave emission is modeled 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 modeled 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 and neutron star glitches. The all-sky search for short-duration bursts targets this wide class of sources. For this reason, the all-sky search invokes general transient-finding methods with minimal assumptions on signal morphology. This also provides the opportunity to identify unanticipated sources and signals; 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, searches for generic transients have been implemented in all of LIGO's and Virgo's science and observing runs. These searches have used a variety of techniques, and have been reported in publications at the end of data taking periods [2, 3, 4, 5, 6].

In O1 and O2, the search for unmodeled transients has benefited from independent implementations of burst analysis pipelines. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to identify coherent excess power in the data from multiple detectors [7, 8, 9]. Multi-instrument analysis is essential for the robust detection of unmodeled gravitational-wave transients; fully coherent methods have been shown to perform well at rejecting noise transients while recovering relatively weak signals. These analyses use GW strain data from all available detectors to solve the inverse problem for the impinging gravitational-wave signal by using maximum likelihood and Bayesian statistics approaches. We plan to continue using multiple burst searches 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. Additionally, combining the results of multiple pipelines can provide an increased sensitivity over any individual pipeline.

For candidate transients, statistical significance is evaluated by repeating the analysis using data that is cleansed of real signals through unphysical time-slides. This time-slide method is used to establish the significance of exceptional events, as well as to search for a possible population of low significance events. In order to evaluate search sensitivity and place upper limits, the pipelines are run over data that contains sets of simulated astrophysical signals based on both GR-based templates, as well as generic signals meant to test the pipelines' abilities to detect gravitational waves from a broad range of sources.

The all-sky search for transient events has been performed in low-latency in the first two observing runs, and successfully produced triggers with as short as a few minutes of time delay. The ability to quickly identify triggers from generic transient events complements current targeted searches for compact binaries, remaining sensitive to a wider variety of sources. For future observing runs we foresee this low-latency search to continue to be of high importance to allow for rapid follow-up observations with electromagnetic telescopes.

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

O2 Deliverables

- **Publish** a comprehensive paper reporting final search results of the short-duration GW burst search.

O3 Deliverables

- Produce rapid alerts for event candidates by running low-latency search pipelines.
- **Publish** a comprehensive paper reporting final search results of the short-duration GW burst search.
- Produce data quality flags and vetoes to use for both the low-latency and offline searches.
- Improve and update the all-sky burst searches for the analysis of O3 data.

2.2 Search without templates for GWs from binary black holes

Compact binary coalescences (CBC), containing combinations of neutron stars (NS) and black holes (BH), are among the most efficient emitters of gravitational waves. Compact binaries formed from stellar mass progenitors have historically been considered the most probable sources. The binary black hole systems recently discovered by LIGO have started to probe the emerging CBC population. The binary black hole (BBH) systems detected so far have close component masses, have little evidence for component spins, and exhibit no deviations from circular orbits. Such sources can be efficiently detected with the matched filter searches using quasi-circular CBC templates. However, other potential types of CBC sources covering a large range of component masses, spins and eccentricities are also possible. Detection of any such sources would provide information regarding the viability of several proposed binary formation mechanisms and would help discriminate among different formation models. Targeting this wider parameter space of CBC sources with a burst analysis method, which does not rely on templates, creates a search which is robust to a variety of features including high mass ratios, higher order modes, misaligned spins, eccentric orbits and/or deviations from general relativity, that may create mismatch between the observed signal and CBC matched-filter search templates.

The focus of previous gravitational-wave searches for CBC sources has centered on quasicircular systems, because there is ample time to circularize the orbit 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. Current CBC searches using quasi-circular CBC waveforms from stellar-mass binaries will not efficiently detect these systems for eccentricities $e > \sim 0.05$ [10], therefore dedicated burst searches for these potential sources would be a viable alternative.

There are several formation models describing dynamical capture binaries [11, 12, 13]. In [11] it is suggested that galactic nuclei 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 $1.0 \text{ Gpc}^{-3} \text{ yr}^{-1}$, with corresponding Advanced LIGO detection rates of $\approx 1 - 10^2 \text{ yr}^{-1}$. 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 $\sim 50 \text{ Gpc}^{-3} \text{ yr}^{-1}$ at $z = 0.7$, falling to $\sim 30 \text{ Gpc}^{-3} \text{ yr}^{-1}$ by $z = 0$. They also provide a scaling to BH-NS and BH-BH mergers which gives rates that peak at $\sim 70 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $\sim 20 \text{ Gpc}^{-3} \text{ yr}^{-1}$ 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]).

For all of these scenarios, the event rates for Advanced LIGO are very uncertain, however, measurable rates are plausible. Detection and identification of dynamical capture binaries would help to discriminate between different formation models and the null result will constrain the models parameters. Burst analysis methods provide a viable option to search for these specific signals.

Relation to other searches

This activity plan is closely related to a number of other efforts within the LSC and Virgo. It executes a burst search, which targets CBC systems (i.e. with chirp mass $M_{chirp} < 50 M_{\odot}$), that may not be well detected by the template CBC searches. The heavier systems (typically $M_{chirp} > 50 M_{\odot}$) are targeted by a dedicated intermediate mass black hole binary (IMBHB) burst search conducted jointly with the modeled CBC algorithms as described in 7. Both burst searches are designed and executed in a different way to maximize their performance in the low ($M_{chirp} < 50 M_{\odot}$) and high ($M_{chirp} > 50 M_{\odot}$) chirp mass regions. However, the high mass ratio systems (1:10 and more) may have IMBH as the heavier component. Therefore, the low chirp mass burst search may yield a first IMBH detection in the part of the mass parameter space not accessible by the dedicated IMBHB searches. This search will use simulated eccentric binary waveforms developed by the LSC and Virgo for estimation of the detection efficiency and interpretation of the search results. Results of the burst search for stellar-chirp-mass CBC systems will be reported in the CBC catalog paper.

O1/O2 Deliverables

- **Publish** a paper on the astrophysical interpretation of the search results in the context of models considering dynamical capture in dense stellar environment with residual eccentricity in the sensitivity band.
- Conduct burst search for stellar mass CBC mergers in the O1 and O2 runs.
- Report events detected by the search in the catalog paper and/or discovery paper if an unusual CBC source is identified.

O3 Deliverables

- Extend the burst search sensitivity to lower chirp masses, $M_{chirp} < 10 M_{\odot}$.
- Investigate options to improve the burst search sensitivity to eccentric black hole signals by using different clustering algorithms and time-frequency graphs obtained from relevant signal models [24].

2.3 GW burst signal characterization

One of the exciting features of gravitational-wave astrophysics is the observation of signals directly tied to the flow of energy and momentum within a source [25]. This signal can be extremely rich in the information it contains. For compact object mergers, it encodes the source masses, spins, distance, and orientation. An observed gravitational-wave signature from a galactic supernova would probe the stellar core, and would give valuable clues to the supernova explosion mechanism, angular momentum, and other dynamic variables. The gravitational waveform from an oscillating neutron star would constrain the neutron star equation of state. For new classes of signals, the waveform will provide a unique path towards understanding the astrophysical source. Even without an astrophysical model, it may be possible to constrain some source parameters based on time-scale and energy arguments.

Reconstructing the waveform of a detected 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 and properties of the detector noise [9, 26, 27]. Quantifying the uncertainty on reconstructed waveforms is also critical to allow comparisons between measured signals and proposed source models. During O1 and O2, reconstructed waveforms were seen to agree with models for expected signals from binary compact objects coalescences [28, 29]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [27]. Meaningful polarization measurements are possible with three or more detectors in the network.

Closely related to the best-fit waveform is an estimate of the source’s direction [30, 31, 32]. The angular position reconstruction of a gravitational wave source, or “skymap”, enables searches for coincident emission by a wide range of electromagnetic and particle observatories. This includes both searches of archival data from all-sky instruments or serendipitous observations, and attempts to rapidly respond to low-latency GW triggers by slewing radio, optical, and X-ray instruments.

O3 Deliverables

- Deliver waveform reconstruction, with uncertainty, for all detected signals.
- Deliver position reconstruction skymaps for all detected sources, including low-latency skymaps.
- Provide measurement and interpretation of the polarization patterns for GW events detected with the LIGO-Virgo network.

2.4 Search for GW transients from isolated neutron stars

Violent phenomena associated with NSs, such as flaring activity in magnetars [33, 34, 35] and pulsar glitches, may result in the excitation of various oscillatory modes which leads to transient gravitational wave emission. The energetics involved with phenomena such as magnetar flares and pulsar glitches makes detection of an associated gravitational wave burst rather speculative with current detectors. The science pay-off, however, would be tremendous; the detection and characterization of GWs associated with NS oscillations holds the potential for GW neutron asteroseismology, 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, focused 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 [36, 37, 38, 39].

O2/O3 Deliverables

- **Publish** a targeted, broadband, offline search for gravitational waves associated with magnetar flaring activity, including several flares observed during O2.
- For extraordinary O3 events, comparable to the 2004 hyper-flare in SGR 1806-20, provide:
 - **Low-latency analysis** (\sim minutes–hours): Check for temporal and spatial coincidence of triggers arising from the online burst or CBC analysis with the electromagnetic trigger.
 - **Higher latency analysis** (\sim week–month): Deliver targeted searches for both long-duration (> 10 seconds) and short-duration bursts from 10’s of Hz up to ~ 4 kHz. Short-duration candidates will be followed up and characterized with burst parameter estimation (PE) tools.
- Pursue further offline searches for gravitational waves associated with magnetar flaring activity in O3.

2.5 Searches for GWs from core-collapse supernova

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 accretes 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). 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 20 Mpc [40].

GWs are produced by bulk aspherical accelerated motion of matter; in the core-collapse supernova (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., [41, 42]) 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., [43, 44]). GWs from rotating core collapse can be used to measure the angular momentum of the collapsing core [45, 46]. 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., [47, 48, 49]). An abrupt end of GW and neutrino emission would unambiguously herald the formation of a black hole (e.g., [50, 51]).

The strategies for GW searches can vary according to detection of different messengers. It may happen that GW are produced while no electromagnetic or neutrino counterpart is detected. In case we observe only light from a nearby supernova a triggered search is performed. In case we observe low-significance neutrinos then a subprime neutrino search may be performed. Dedicated searches can target robust emission processes, like g-mode oscillations. Special attention is placed when an SNEWS alert reports the detection of a galactic or nearby extragalactic supernova, like 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.

The next galactic core-collapse supernova will be 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.

Recently, the LSC and Virgo initiated a more systematic interaction with the CCSN modeling community with a series of CCSN theory calls and a focused workshop on CCSNe [52]. Of particular interest is the summary of the aspects of CCSNe modeling and waveforms that are considered, to date, robust by the CCSN modeling community as a whole. This activity is expected to continue and evolve accordingly to the needs of the SN and Burst groups, and in respect to the LVC procedures.

O1/O2/O3 Deliverables

- **Publish** an O1-O2 SN search paper, providing detection and non-detection statements for optically observed supernovae within roughly 20 Mpc. The results should constrain the most extreme GW emission models and set upper limits on emitted GW energy in specific time-frequency regions (for example the one expected from SASI).
- Publish a paper in case of an SNEWS alert associated with a CCSN. Estimate significance of a GW trigger, provide reconstructed waveforms of identified candidate and estimate parameters of the GW candidate.
- Conduct a dedicated CCSN O3 search corresponding to the most realistic multidimensional simulations.

R&D

- Develop a method for assessing statistical significance of GW triggers associated with one or more supernovae [40].
- Develop a method for detecting GWs in coincidence with a CCSN 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.
- Perform a study of CCSN science targets using third generation GW detectors.
- Develop noise reduction techniques for CCSN searches.
- Develop a subprime neutrino triggered search.
- Develop techniques to infer proto-neutron star properties.

2.6 Service and technical activities for Burst searches

Several Burst searches are supported by a range of technical activities that provide support, tools, and/or coordination with other groups.

Software injections: Search pipelines use simulated signals to test and characterize their performance. For Burst searches, a typical set of simulated signals 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 (e.g., accretion disk instabilities) and/or numerical relativity simulations (core-collapse supernovae). These simulations are used to create populations of simulated signals, known as Mock Data Challenges (MDCs).

O3 Deliverables

- MDCs generation for the short-duration all-sky search.
- MDCs generation for the core collapse supernova search.

Hardware injections: Hardware injections are simulated signals added directly to the detector data, by actuating on the interferometer test masses (i.e., signals added through the detector hardware). The MDC software tools will also be used to generate input waveforms for hardware injections.

O3 Deliverables

- Gather and condition all waveforms that the Burst group decides to inject during a run.
- Work closely with the LIGO hardware injection team to perform and record hardware injections.

Detector characterization: Almost all GW transient searches benefit from data quality information provided by detector 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. Safe data quality vetoes are used by burst searches to remove a large fraction of noise outliers. The search leaders and search data quality liaisons must work with detector characterization Burst experts to define the most efficient list of vetoes.

O3 Deliverables

- Provide a regularly updated and customized list of data quality flags and vetoes for each family of Burst searches.
- Provide regularly feedback to the Burst and detector characterization groups.
- Burst search pipelines will produce and provide triggers as needed for the purpose of detector characterization studies.

3 CBC Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, DetChar, and Stochastic groups in sections 6, 7, and 9, 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 also maintains infrastructure to support tests of general relativity. The group is also working on improved noise models that will relax assumptions made about the stationarity of the detectors’ noise. Finally, the group assesses the improvement in parameter inference from such models, guides gravitational-wave model developments and science cases for future gravitational-wave measurements, and informs instrument design.

Short term goals

1. *PE with matter effects:* LIGO/Virgo made the first detection of a binary neutron star (BNS) merger in 2017. In O3, it is possible that LIGO/Virgo may detect ten or more BNS mergers, and also one or more neutron star-black hole (NSBH) mergers. The detected GWs allow for novel measurements of matter effects in the binary mergers, including the neutron star equation of state. Developing good techniques for measuring these effects is an active area of research, and the most recent developments of this work need to be implemented in LIGO’s Parameter Estimation code libraries.
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. Coordinating closely with waveform group efforts to quantify systematic errors in the waveform basis, we must develop more robust and meaningful ways to quantify the impact of systematic errors associated with the use of our approximate waveforms on parameter inferences. Coordinating with applications groups (the Tests of General Relativity R&D group [Sec. 3.2], the Binary coalescence rates and population R&D group [Sec. 3.4], and the Studies of extreme matter with pre-merger and post-merger GWs R&D group [Sec. 7.1]), the group will develop metrics to assess the extent to which systematics propagate into their science deliverables, such as population parameters or identification of non-GR parameters, or otherwise impair the ability to identify potentially highly-informative parameters at all (e.g., eccentricity, tides).

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 and more numerical relativity simulations become available (see Sec. 3.3) which include and explore more physical effects (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 and Virgo collaborations. These tools are in need of 1) improvements to the presentation of critical results, 2) additional statistical tests, 3) better usability by other CBC subgroups (e.g., numerical relativity follow-ups, rates and population), 4) adaptation to the open-data era and public releases.
9. *Improvements to library infrastructure:* To better facilitate the goals outlined above, the LALInference code base and `rapid_pe` are in need of infrastructural updates. This includes the continued migration of the library from C to Python to become more development-friendly, and the tighter integration of `rapid_pe` and LALInference.
10. *Hybridization and surrogates:* Working closely with the CBC waveform models R&D group (Sec. 3.3) as needed for hybridization and/or surrogates, and simulation groups for targeted follow-up, we will enhance readiness for O3 for direct comparison of GWs from massive BBHs with generic numerical relativity simulations
11. *Readiness for O3:* Ensure readiness for O3 by maintaining production codes and completing code review.

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. This work is coordinated with the CBC detection and search R&D group (Sec. 3.6).

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. This work is coordinated with the Binary coalescence rates and population R&D group (Sec. 3.4) and the Stochastic group (Sec. 9).
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. This work is coordinated with the CBC detection and search R&D group (Sec. 3.6).
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 the sensitive frequency band of the detectors. To better understand formation scenarios for these binaries, we will need methods to evolve such constraints backward to earlier times.
6. *Research and development of new techniques:* We will continue to investigate the use of new algorithms or hardware-specific optimization (e.g., GPUs) for CBC parameter estimation, to support the desire to lower overall latency until final results are obtained, but also to allow codes to scale to increasing numbers of parameters and/or complex signal models.

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

Short term goals

Short term goals are the continuation of support for the O2 deliverables of the O2 TGR project and the development of analyses for O3, as outlined in section 3.9.

Long term goals

Furthermore, we will develop the capacity to deliver the following additional science results on an O3 timescale.

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 to 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.

3.3 CBC waveform models R&D

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

Motivation and methods

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

Short term goals

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 to allow improved parameter estimation. Two independent models (EOBNRv4HM and IMRPhenomHM) will be implemented and fully reviewed for O3 analyses and for cross-comparisons.
2. *Improve precessing BBH waveform models* by extensively tuning/testing against precessing numerical relativity (NR) simulations. We also aim to have initial prototype models of precessing binaries with subdominant modes for improved Bayesian inference of precessing binaries.
3. *Include eccentricity in BBH waveform models:* Eccentric waveform models are required to quantify search sensitivity, and to estimate or bound the eccentricity of observed CBC events. We aim to develop models for moderate eccentricity that cover non-spinning and subsequently aligned-spin binaries. Specifically, we aim to have the model `Enigma-EccentricIMR` implemented in LAL and reviewed for O3.
4. *Improve 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. *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. Of particular priority are NR waveforms with validated sub-dominant modes of sufficient accuracy even at high

SNR; simulations at sparsely explored regions of high mass-ratio, high spin or both; long simulations to validate transition to analytical inspiral waveforms; and detailed coverage of merger/ringdown for high-mass systems. We also plan to provide functionality to compare GW measurements directly to the NR waveform catalog, without the need for an intermediary model.

7. Perform *cross-validation between different NR codes for CBC systems* to assess the accuracy and reliability of NR waveforms to confirm NR waveforms are of sufficient quality for their use in studies as varied as search-efficiency, parameter recovery bias, and waveform model development. Of particular priority are: precessing BBH; a comparison of sub-dominant modes; and NS-NS simulations.
8. *Continue per-event NR follow-up as needed*: Improve the accuracy of observational statements and/or test systematic biases by performing dedicated NR simulations in response to detection candidates.
9. Improve understanding of *waveform model errors and attendant systematics* by cross-comparisons between different waveform models or parameterized models. In particular at significantly unequal mass-ratios and/or high spins, and also paying attention to sub-dominant modes.
10. Improve *evaluation speed of important waveform models* for faster turn-around of parameter estimation, most notably tidal NS-NS waveforms and EOB models.
11. *Investigate application of new mathematical tools to waveform modeling*: Such tools may lead to the development of models that include more physical effects (e.g. surrogate models, deep learning or Gaussian process regression), or that may significantly speed up existing waveform models (e.g. reduced-order models).

Long term goals

Our ultimate goal is a plurality of waveform models for systems which may include precession, eccentricity and matter effects all together. Specific aspects toward this ultimate goal are

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 equation-of-state effects and sub-dominant modes*.
4. *Develop BH-NS waveform models that include merger/disruption of the NS*.
5. *Waveform models for hyperbolic encounters*.
6. Compute NR waveforms for all types of CBC systems with sufficient accuracy and length to quantify waveform modeling errors at sensitivities of future GW detectors.

3.4 Binary coalescence rates and population R&D

Provide the means to estimate the astrophysical rate of various classes of compact binary coalescences, and to estimate model-driven distributions of their properties. Further develop interpretative superstructure to infer astrophysics which is sensitive to the distribution of their properties.

Motivation and methods

The charge of the Rates and Population (Rates/Pop.) 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, two categories (binary black hole (BBH), and binary neutron star (BNS)) are currently measured with a non-zero rate. The other two, neutron star black hole binary (NSBH), and intermediate mass black hole binary (IMBHB) all have event rate densities which are upper limits. With two categories of compact binaries now detected, an extension to the current rates and significance infrastructure — a mixture model of foreground and background fit empirically to search distributions — is being developed to better address ambiguities in detected binary categorization and self-consistently handle the estimation of rates over all categories. Additional 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 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:* (post O2) To enable rate estimates over different categories of binary mergers (e.g., BNS vs NSBH vs BBH), the current FGMC [53] based hierarchical foreground/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 assess 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 LVAAlert 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:* (mid 2018) 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 hierarchical 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 a flat distribution of rates with respect to redshift. This project will develop the infrastructure needed to infer rate and mass spectrum dependence on redshift.
10. *Distinguishing formation scenarios using spins:* (ongoing) Applying the results of spin measurements from GW observations to distinguish BBH formation scenarios.

Long term goals

1. *Rates and Population Toolkit development:* (ongoing) Develop a set of search-independent and flexible tools to facilitate population rates and inference. <https://git.ligo.org/RatesAndPopulations/lvc-rates-and-pop/>

3.5 CBC cosmology R&D

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

Motivation and methods

The cosmology group is responsible for obtaining estimates of cosmological parameters such as the Hubble parameter H_0 from GW signals detected by LIGO-Virgo. The methods involved include identification of a set of possible hosts using an observed EM counterpart to the GW event and statistical cross-correlation of the GW distance estimate with catalogues of potential host galaxies in the absence of a counterpart. Since a precise estimate requires combining information from multiple events, correcting for any systematic bias that is expected to accumulate over observations is crucial. Selection effects are known to play an important role even with only a few observations. Smaller effects like redshift uncertainties and GW calibration uncertainties could become important with an increasing number of observations. A large part of the research and development involves developing methods to understand and account for such effects.

Short term goals

1. *Pipeline to obtain estimates of the Hubble parameter from multiple GW observations taking into account selection effects:* A precise measurement of the Hubble parameter requires combining information from multiple GW observations, with or without transient electromagnetic counterparts. The fact that gravitational wave interferometers have a finite detection threshold introduces a systematic selection bias. Additionally, for the statistical analysis with galaxy catalogues, the incompleteness of the catalogue is expected to introduce further biases. We aim to put together a pipeline to estimate H_0 from multiple GW observations, taking into account the above selection effects.

Long term goals

1. *Importance of peculiar velocity corrections as a function of distance:* A crucial strength of GW standard sirens is that they provide distances that bypass completely the traditional EM “distance ladder” that combines primary and secondary distance indicators. For sources within the Local Supercluster, however, the peculiar velocity of the siren host galaxy can require significant correction, as was the case for GW170817. While most BBH sirens are likely to be sufficiently distant that these peculiar velocity corrections are not important, we propose to investigate thoroughly the potential impact of systematic errors in the peculiar velocity correction for nearby sources, particularly “golden” NS binaries within 100 Mpc. We will use mock galaxy catalogues derived from n -body simulations to study this, with particular focus on systematics arising from possible non-Gaussian peculiar velocity residuals.
2. *Standard sirens as calibrators for nearby distance ladders:* Precision cosmology requires accurate calibration of luminosities of supernova that occur in a nearby galaxy or a galaxy cluster (e.g., Virgo or Coma). This requires a precise measurement of the distance to the host galaxy of a supernova using Cepheid variables or other measures of distance. Alternatively, a binary neutron star coalescence event could be used to validate the distance to a galaxy or a cluster in which a supernova is known to have occurred. In order for GW observations to beat the accuracy of distance measurement by other methods, the coalescence event has to be within about 50 or 100 Mpc. By measuring the distance to a known supernova host accurately, we can provide an independent calibration of supernova luminosities. We will estimate the accuracy with which distances to nearby galaxies can be measured in O3 and the late Advanced-LIGO/Virgo era and how these measurements might influence measurements of H_0 using supernovae.
3. *Develop a complete understanding of systematic effects in measurement of cosmological parameters:* Since a precise estimate of cosmological parameters requires combining information from multiple events, even small systematic effects can start biasing our measurements. In addition to some of the major effects already discussed above, systematic biases can be present in redshift estimates in galaxy catalogues, which can be significant if photometric catalogues are being used. Moreover GW calibration effects are also expected to become important as the precision of measurement becomes tighter with an increasing number of observations. We plan to understand these effects thoroughly and propose to compute requirements (on both statistical uncertainties and systematic biases) necessary to achieve any given specified accuracy in the estimation of cosmological parameters.

3.6 CBC detection and search R&D

Perform all-sky offline and online (low-latency) searches; develop and tune search pipelines; generate template banks; assess data quality issues relevant to CBC detection.

Motivation and methods

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

Offline searches run with a latency of order a few days to weeks on a stable and carefully selected data set, to provide reproducible results for publication including precise evaluation of the significance of

candidate events and the sensitivity of the search to populations of realistic binary merger signals. Online / low-latency searches run primarily to generate triggers for follow-up including initial evaluation of trigger significance, mass and spin values and extrinsic parameters relevant to sky localization. Development of methods for low latency data selection and estimation of search sensitivity is motivated by the desirability of convergence of results between online and offline searches if possible.

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. Rate estimation methods as used in O1 are to be integrated into pipelines by end O2. Candidates will be used in the Catalog project described in Sec. 3.7.
2. *Single-detector/Multi-detector searches:* Virgo joined the last month of the O2 run from August 1, 2017. Given the state of the detector's sensitivity and data quality it was not an immediate priority to incorporate Virgo data in offline searches, however the data around LIGO detected candidates were filtered in low latency with the resulting SNR time series used to significantly improve low-latency sky localization estimates over the two-detector case. As Virgo sensitivity is expected to significantly improve in O3, offline searches are developing the capability to perform 3-detector coincident event identification, and corresponding ranking and background estimation methods. 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. Development/maintenance of the coherent matched filter pipeline for GRB search is also 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. The timescale to implement this is the end of O2, and it intersects with Rates/Pop. work, Sec. 3.4.
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 any opportunities to further reduce the computational cost of searches should be pursued for application to final O2 results. More effective methods of signal-background discrimination are to be investigated using recent data, particularly for the IMBHB region. Proposed methods using Bayesian parameter-estimation analysis (Sec. 3.1) to exclude events of instrumental origin should be coordinated and compared with detection pipeline ranking statistic calculations to assess improvements in sensitivity.
5. *CBC-related Detector Characterization tasks:* Development and maintenance of tools to characterize the impact of detector state on CBC searches and identify possible veto times was ongoing through O2 and will ramp up through data replays and engineering runs into O3.

Long term goals

1. *Precessing and higher mode template searches:* New methods of constructing banks for CBC signals showing precession and subdominant modes have been proposed and significant work on implemen-

tation and tuning of a search will be required to obtain results.

2. *BNS with nonlinear tides:* For some models of BNS internal structure, tidal effects could significantly alter the inspiral waveform from the point-particle case. Loss of sensitivity due to such effects in the standard search should be quantified and alternative templates deployed if needed. Intersects with the Extreme Matter project, Sec. 7.1.
3. *Coherent all-sky search with 3 or more detectors:* CBC searches currently look for coincident triggers, with the exception of the coherent GRB analysis. In the long term, a network of 3+ detectors of comparable sensitivity will motivate the development of fully coherent search algorithms. Considerable work remains to be done in optimisation to extend the methods pioneered in the coherent GRB analysis to cover the all-sky, all-time parameter space in a computationally efficient manner. This research will continue throughout the O3 timeframe, with the aim of reaching maturity in time for design sensitivity detector networks.
4. *Use of machine learning in event ranking and detector characterization:* Novel machine learning methods can be applied to the classification of triggers into signal and noise categories. These have the potential to improve the speed and sensitivity of a search, especially for signals of short duration where traditional χ -squared discriminators are known to be less effective. Machine learning may also make use of a range of auxiliary data channels to better identify environmental disturbances. Given the wide range of methods and the requirements of training both machines and humans this activity is expected to be an area of research for some time to come, with the implementation and review of practical methods likely to be during O3 or beyond.

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

In the O1 observing run, stellar-mass BBHs were directly measured by Advanced LIGO to merge with a rate of approximately $9 \text{ Gpc}^{-3}\text{yr}^{-1}$ to $240 \text{ Gpc}^{-3}\text{yr}^{-1}$ [54]. From that run, Advanced LIGO established two confirmed binary black hole detections, GW150914 and GW151226 and a strong third candidate LVT151012 [54], with an overall range of masses $\sim 7 M_{\odot}$ to $36 M_{\odot}$. 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 $p(m) \propto m_1^{-2.5}$ [54], 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 source 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 $12 \text{ Gpc}^{-3}\text{yr}^{-1}$ to $213 \text{ Gpc}^{-3}\text{yr}^{-1}$, and the power law for the primary mass distribution to $p(m) \propto m_1^{-2.3}$ [29]

The binary masses detected through gravitational wave observations are larger than those of black hole candidates identified by X-ray observations, which yield BH masses $5 \leq M_{\bullet}/M_{\odot} \leq 20$, confirmed with dynamical mass measurements for 16 BHs. An apparent lack of BH masses in the range $3 M_{\odot}$ to $5 M_{\odot}$ (the “mass gap”) [55, 56, 57] has been ascribed to the supernova explosion mechanism [58, 59]. 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 $\sim 80 M_{\odot}$ [59, 60]. Common envelope binary evolution [61] may reduce the maximum expected component mass and total mass to $\lesssim 100 M_{\odot}$ [62], however stellar BH with mass above $100 M_{\odot}$ are conceivable [63], 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, $0 \leq S/m^2 \leq 1$ [64, 65, 66, 67, 68, 69, 70]; both low (~ 0.1) [71] and high (> 0.85) values [72] are represented. The microquasar XTE J1550-564 [73] and population synthesis models [74] indicate small spin-orbit misalignment in field binaries. For massive field binary progenitors, the common envelope phase and mass transfer [75] are expected to cause strong correlations between spins and masses of the two BHs in field binaries [76]. 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 $10 \text{ Gpc}^{-3} \text{ yr}^{-1}$ to $10\,000 \text{ Gpc}^{-3} \text{ yr}^{-1}$. While no BNS systems were detected during the O1 observing run, we were able to put an upper limit on the merger rate for these systems of $< 12\,600 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [77]. The detection of the BNS event GW170817 near the end of the O2 observing run was a milestone for GW science, as well as for multi-messenger astronomy and astrophysics. Further detections of BNS systems in 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 $0.7 M_{\odot}$ to $2.7 M_{\odot}$ with a mean mass of $\sim 1.4 M_{\odot}$ [78], though the lower value, $0.7 M_{\odot}$, 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 $(1.35 \pm 0.13) M_{\odot}$ [78]. 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 [79, 80]. Lower mass Fe cores are predicted to lead to NSs with masses almost as low as $1 M_{\odot}$ [81].

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 [82], however the fastest known NS spin is 0.4 [83].

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 [84]. 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 [85]. In cases where an electromagnetic (EM) counterpart can be identified, further information can be used to understand the physics of the merger [86, 87]. There are several plausible EM counterparts to BNS mergers [88].

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 [89, 90, 91, 92]. Though no NSBH systems are known to exist, one likely progenitor has been observed [93]. Rates for the coalescence of NSBH systems are not well known, however a “realistic” estimate from population synthesis of field binaries is given as $30 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [94]. A “pessimistic” estimate is given as $0.6 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and an “optimistic” estimate as $1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [94]. These yield observation rates for Advanced LIGO and Advanced Virgo of $0.2 - 300 \text{ yr}^{-1}$.

The mass distribution of NSBH systems is not well constrained. However, it is possible to place es-

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 [73] and population synthesis models [74] 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. [95, 96, 97, 98, 99, 100]) 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 [101].

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 data we will conduct a deep search for compact objects from $1 M_{\odot}$ to a maximum mass dictated by the instrument sensitivity (likely not to exceed $\sim 1000 M_{\odot}$). For detection, spins aligned with the orbital angular momentum will be considered. For components below $2 M_{\odot}$, spin magnitudes up to 0.04 will be searched for. Otherwise, up to maximal spins of 1 will be considered. 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 and beyond 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 versions 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 and GW151226 firmly established the existence of stellar-mass binary black holes (BBH), with a coalescence rate of 12-213 $\text{Gpc}^{-3} \text{yr}^{-1}$, high enough to make them a primary source for future observing runs. In the O2 run we have collected three additional BBH events (GW170104, GW170608, and GW170814) and expect a few additional such events (excluding sub-threshold “LVT” designated candidates), 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 their natal environments.

The collaboration has published the results of a hierarchical analysis which infers the exponent of a power law governing the distribution of the primary mass of BBH systems. While this may be an incomplete description of a more complicated distribution, the current bound of $\alpha = -2.35$ is useful in ruling out models with flatter or steeper distributions in mass. Features such as a minimum or maximum black hole mass (e.g., the edges of “mass gaps”) have been probed with more sophisticated models, and their early results show promise for independent methods to explore these topics. However, additional confident detections are needed to place more detailed constraints on the distribution of binary physical parameters, such as the spin magnitude and orientation of the component objects. As additional detections are collected, this information can be used to measure relative contributions from different formation channels as well as measure finer details about the models that represent the formation channels. This has immeasurable value to the astrophysics community, since those models can often have many free parameters which are not constrained well by other observations.

O2 deliverables

1. Parametric model-driven interpretation of 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, $\frac{dN}{dVdM}$.
 - (b) Constraints on NSBH rates in lieu of detection, as well as the first gravitational-wave probe into the core-collapse supernova black hole mass gap.
3. Astrophysical mass distribution of coalescing binary black holes in the form of constraints on a power law governing the distribution of the masses of binary black hole mergers.
4. Astrophysical spin distribution of coalescing binary black holes
5. Data release of BBH population

3.9 Strong-field tests of General Relativity

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves.

Motivation and goals

LIGO’s first crop of binary black hole mergers has allowed us, for the first time, to test the predictions of general relativity in the highly relativistic, strong-field regime. 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 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 [102]. Most of these constraints were further improved by combining detections so far [103, 29].

In addition, GW170104 allowed us to put bounds on a more general dispersion relation for GWs. The first detection of a binary neutron star merger, GW170817, had a long inspiral phase from which we were able to conduct a phenomenological test for dipole radiation.

GW170817 was also detected in conjunction with electromagnetic information. This has given us information beyond what can be measured with just a gravitational-wave signal, such as the redshift of the source and the time difference between the gravitational-wave and electromagnetic signal. These additional pieces of information have given us the ability to put constraints on the specific alternative theories of gravity that predict large deviations between the gravitational-wave and electromagnetic signal, and insight into the polarisation modes of gravitational waves.

In O3, we expect new detections of BBHs and BNSs, and anticipate detections of 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 the O3 observing run and beyond.

O3 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. *Bounding beyond-GR effects*: Further constraints on beyond-GR effects including the graviton mass, generic Lorentz violations and dipolar radiation from the increased number of events
5. *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.

3.10 Hubble constant measurements

Measure the Hubble constant using both EM associations and statistical associations with a galaxy catalog.

Motivation and goals

Gravitational waves from the binary neutron star merger GW170817 along with its uniquely identified host galaxy led to a first “standard siren” measurement of the Hubble parameter independent of the cosmological distance ladder. The identification of the host galaxy was possible because of the coincident optical counterpart to GW170817. Similar observations in O3 of binaries involving a neutron star with identified electromagnetic counterparts will improve the precision of the measurement. Additionally, the statistical method of cross correlation of gravitational-wave distance estimates with catalogues of potential host galaxies, can be used in the absence of a uniquely identified counterpart. In particular it will be possible to do this for well-localized binary black hole mergers, a good number of which are expected in O3. Intermediate between these two is the case where an electromagnetic counterpart is observed but it cannot be associated to a unique host galaxy. Such events can also be used to improve cosmological constraints.

O3 deliverables

1. Combined H_0 estimate from binary neutron stars with identified electromagnetic counterparts, and other binary coalescences (neutron stars or black holes) without uniquely identified counterparts.

3.11 Search for sub-solar-mass compact binary coalescences

Search for compact binary coalescences with a component having mass below a solar mass

Motivation and goals

Compact objects with masses below $\sim 1 M_\odot$ are not expected to be generated as endpoints of stellar evolution, but could have a primordial origin.

O1/O2 deliverables

- Conduct a prototype search for sub-solar-mass compact binary mergers on O1 data, and extend to O2 data

O3 deliverables

- Carry out a thorough search for sub-solar mass compact binary mergers in O3 data

3.12 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 black hole + 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 neutron star + black hole binary, a binary with a sub-solar-mass component, 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);
- substantial improvement in the 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 [104]. 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 [105]). 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 [104].

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 [106]. 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., [105]). 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 [107]). 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.

Other directed and all-sky continuous gravitational wave searches (see, e.g., Sections 4.3, 4.4, and 4.6) 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 uncorrelate any astrophysical signals, given the long observation times, but would preserve non-Gaussian noise features. The candidates will also be analysed using a new Bayesian-block method developed to test for intermittent emission, distinguishing between weak truly continuous and stronger, discontinuous candidates.

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.

A methods paper describing the Bayesian-block analysis will be presented 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 [108].

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 [109]. 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 [110] 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 [111]. 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 [109]. More recently, using Advanced LIGO O1 data (paper in preparation), 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 4.5.

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 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 leverages computation power donated by volunteers around the globe. Running for about 5 months on this platform, and with a computational budget ≈ 10 times that of other pipelines, the Einstein@Home searches can afford much longer coherent observation times than the other searches and are the deepest surveys that we carry out.
- PowerFlux and/or Loosely Coherent code will be used to carry out broad all-sky searches over entire frequency space with the aim of producing results as promptly as possible. It is the only pipeline that performs direct estimation of gravitational wave power. The Loosely Coherent code capable of all-sky searches is more sensitive, but has not been reviewed yet.
- 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 a large number of outliers, especially at low frequency, in O1 data, some of which were coherent between interferometers. Much of the work went in the streamlining of follow-up schemes and vetoes. That experience will be folded into the analysis of O2 data and extended as necessary.

All of the pipelines are computationally limited, and work also 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.

All-sky searches for signals from isolated sources have a non-negligible sensitivity to certain classes of signals from objects in binary systems. We want to leverage this feature in the follow-up of the all-sky searches. Note, however, that successful discovery of non-standard source places stringent demands on data quality.

The quality of O2 data is improved with respect to that of O1 data, but spectral contamination especially at low frequencies is still significant. At fixed computational cost (for the follow-ups) this results in a higher detection threshold and hence in lower sensitivity across all searches.

Interruptions in data taking negatively affect large parameter-space searches: The longer time span of O2 compared to O1 brings better signal parameter resolution (finer search grids) and hence a higher computing cost. This is a price we are happy to pay because longer time span usually means more data and hence higher sensitivity. However any interruption in data taking, such as in O2, offset this advantage, because the time-span of the observation and hence the parameter space resolution remains the same, but there is not as much gain in sensitivity due to the missing data.

Expected products and/or outcomes

- Einstein@Home will perform a deep search on O2 data in the frequency range 20-500 Hz and with spindowns down to -3×10^{-9} Hz/s.
- PowerFlux and/or Loosely Coherent search code will perform an all-sky blind search covering the 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 the most sensitive subset of the data.

Typically results from these searches have been presented in two separate observational papers: one from the fast-turnaround pipelines (Powerflux, the Houghs and the time-domain F-statistic) and one from the Einstein@Home search. We foresee a similar cadence of papers in O2, with the fast-turn-around paper well before the Einstein@Home one, and within a year of the full data set being available for analysis. Note, however, that this timeline is conditioned by the quality of the 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.

4.5 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 the coherent or semi-coherent F-statistic. Hidden Markov model (HMM) techniques can also be used to track the unknown signal frequency in a young SNR, as it wanders due to secular spin-down and stochastic timing noise [112]. An HMM search represents a computationally cheap supplement to other coherent and semi-coherent O2 searches and is robust against unmodeled timing noise.

Extensive parameter space surveys (broad frequency and spin-down ranges) with long integration times can still be very computationally expensive. For these it is worthwhile to consider how astrophysical priors can inform an optimisation scheme [113] which determines what targets are the most promising to search and what is the most efficient search set-up. The Einstein@Home searches have employed such optimisation procedures [114].

Expected products and/or outcomes

In the next year we will publish at least two observational papers on point sources, mostly supernova remnants, searching O1 data:

- an extensive survey of several point sources for which we can achieve sensitivities enough to detect a signal at the analog of the spin-down limit for known pulsars, and not spend too much computing power in doing so.
- a deep Einstein@Home search aiming at Vela Jr, Cas A and G347 [114].

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 complete a directed, “templated” search for signals from supernova remnants using MLA by March 2020, and we will write at least a methodological paper by the end of 2018.

4.6 Spotlight searches: directed searches for isolated stars in interesting regions

4.6.1 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 GWs. 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 wave gravitational source 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. Interesting regions may comprise a single point in the sky.

Methods and major aspects of this activity

Potentially all existing all-sky search algorithms can be used to perform spot-light searches. In practice 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

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.

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

4.7 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 $h_0 = 5.5 \times 10^{-27} (F_X/10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1})^{1/2} (f_0/300 \text{ Hz})^{-1/2}$, independent of the distance to the source. Torque balance is one possible explanation for the observed fact that the spin frequencies of low-mass X-ray binaries (LMXBs) are systematically lower than accretion theory predicts (cf. ~ 1.4 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 [115], doubly-Fourier transformed data (TwoSpect; [116]), hidden Markov models (Viterbi; [117]), coherent summation of matched-filter sidebands (Sideband; [118]), and a resampling procedure, which is a generalization of the 5-vector method [119]. Extension of the Weave semicoherent search pipeline [120] to allow searching over LMXB parameter spaces, using the parameter-space metric of [121], is also under development. 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 [122].

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 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 an orbital-phase tracking 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 written by CW group members on astrophysically characterizing the “spin-wandering” of Sco X-1 due to fluctuations in the accretion torque was recently published [123]. 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.

4.8 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 ($f_{\text{rot}} > 100$ Hz) that are binary is more than half, and the fraction of pulsars with $f_{\text{rot}} > 400$ 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 [124]; and 2) a method that produces correlations with filters described by a polynomial functional form of the putative gravitational wave phase [125]. 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 [126]. 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. [124]), 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 Sec. 4 pertain to neutron stars emitting truly *continuous* gravitational waves: periodic signals lasting at least as long as an observation run. However, electromagnetic observations of transient

neutron star phenomena (e.g., pulsar glitches and X-ray bursts) raise the possibility that neutron stars also emit gravitational wave signals on time scales of hours–weeks due to short-lived deformations [127]. Transient emission due to the impulsive excitation of oscillation modes is also of interest, including r -mode oscillations [128, 129]. Signals from young, rapidly spinning down neutron stars may also only be observable for a similar time scale; the special case of post-merger remnants is discussed separately in Sec. 4.12 but overlaps in methodology with the wider science case discussed here.

This activity includes development and prototyping 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 transient continuous-waves 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 search algorithms 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 [130], 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 are being characterized to follow up the candidates from blind searches, thus contributing to all-sky and directed search papers from O2 and later. A general-purpose followup tool has been described recently in [131] and additional transient-focused methods papers may follow. A tCW add-on to semicoherent analyses is also available for intermediate follow-up steps [132]. 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 searches 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 [133], 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 Post-merger remnant searches

Overview of the tasks

With the first observed binary neutron star (BNS) merger GW170817 [134] happening relatively close to Earth at ~ 40 Mpc, interest has arisen in using CW-derived analysis methods to search for a long-lived neutron star remnant of this unprecedented event and of any additional nearby BNSs encountered during future observing runs. While shorter remnant signals on the order of milliseconds to hundreds of seconds can be effectively searched for with methods derived from burst and stochastic searches [135], longer signals associated with the rapid spindown of a young massive neutron star are well suited for CW-derived methods. However, the parameter space, signal morphology and data quality requirements are still quite different from other CW searches, and significant development is taking place to adapt existing pipelines to long transients. While the limited high-frequency sensitivity of the LIGO and Virgo detectors during O2 means that a detection of postmerger GWs from GW170817 is, while not impossible, rather unlikely, this event also serves as an initial test case for these new methods. For future BNS observations with improved high-frequency detector sensitivity, these remnant searches can play a crucial role in constraining the nature of the remnant and thus the nuclear physics properties of the involved objects [136, 137].

Methods and work required

Current development efforts concentrate on adapting the hidden-Markov-model Viterbi tracking algorithm [112] and the two semi-coherent Hough algorithms [138, 139] (see also Sec. 4.4) to the waveform model of “magnetar” power-law spindown [140]. (Through a variable braking index, this model includes spindown dominated by magnetic fields, GW emission, or mixtures thereof). Another development will extend the Weave semicoherent search pipeline [120] to allow searching for very-rapid-spindown CW signals, including potential postmerger signals; this project will first derive the parameter-space metric appropriate to a generic power-law spindown model. Other CW pipelines such as those based on the PowerFlux algorithm or the \mathcal{F} -statistic may also be adapted to this waveform model in the future.

Searching for transients on the order of minutes to weeks also imposes unique challenges on the data quality and detector characterisation side, as, e.g., transient lines that would be too weak to affect a year-long analysis can produce strong spurious candidates in a transient search; investigations are shared with other long-duration transient searches discussed in Sec. 4.9. The optimal exploration of the powerlaw-spindown waveform model’s parameter space and direct comparison of upper limits derived from the various pipelines is also a challenge where reasonable working solutions have been found, but an optimal and robust scheme may still require further development.

Expected results

A multi-pipeline analysis of the post-GW170817 data, i.e. the last \sim week of O2 data, is ongoing and will be published as a combined paper of stochastic and CW results, complementing the previous shorter-duration remnant search paper [135]. Methods development will continue with the goal of having a mature set of pipelines, similar to the situation for all-sky and targeted CW searches, that can be routinely employed on any sufficiently nearby BNS events during O3 and future observations, in order to extract physical constraints on the remnant properties.

4.11 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. Part of this work benefits from a close interaction with the detector characterization working group and the site commissioning staff, as well as informing noise mitigation actions.

The software used and developed by the continuous wave working group is not all maintained within the same infrastructure. There are pipelines maintained in semi-private repositories, including ones of the Virgo Collaboration. A large chunk of the used software is, however, in the LALSuite software repository. Such repository contains important core routines and data, such as the antenna patterns as a function of time and sky location and the Ephemeris files. Contributions to this software base are regulated with standard good practice procedures. The CW LALSuite repository has a librarian who enforces such practices.

Independently of the environment where different pipelines are developed, all search software is vetted and kept in a functional state, while at the same time it is worked on and enhanced.

Code development typically encompasses bug fixes, but also additions of new and improved methods, added functionalities to existing search codes, and code optimizations. The operating procedure for LALSuite software is for each code patch to undergo internal vetting to ensure compatibility and reduce the likelihood of introducing new bugs.

We periodically 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. 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 use the tools already produced (which include spectral averaging with fine resolution, spectral line finding, spectral comb finding and data folding on integer-second intervals), 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.

Reports on line contamination identified in search results or/and as part of data preparation is also provided to the detector characterization team.

The continuous waves group uses a fork of the LALSuite repository on GitLab¹ to manage bug reports, issues, and merge requests related to LALSuite continuous-wave codes. Members of the group work together to submit issues and cross-check and verify merge requests to the master branch of LALSuite. Issues potentially relevant to the whole group, as well as recently-approved merge requests, 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 GitLab issue tracking system. Lastly, computing request estimates and occasional code optimizations will be performed in order to reduce the computational burden of the largest analysis requests.

4.12 New developments and exploratory work

Excess continuous power search and deep neural networks/machine learning

All-sky searches for CW signals are dominated by template-matching techniques, but there merit in performing non-parametric searches for continuous narrow-band excess power in $h(t)$. A new Viterbi-based algorithm, SOAP, has been developed which is sensitive to a wide range of continuous gravitational-wave signals and which is computationally cheap. Another alternative approach to template-matching is that of deep learning neural networks.

Methods and work required: Methods papers are under development and will be submitted in 2018 Q2 (SOAP) and 2019 Q1 (neural networks).

Expected results: SOAP is not currently considered an end-to-end pipeline, but it is sensitive (and can distinguish between) both instrumental lines and putative CW signals, generating candidates for further investigation with parametric methods. A SOAP search can be performed very rapidly, with negligible computational load and will be run on current and past science runs to build up our experience of it data products, contribute to line lists and generate detection candidates. The feasibility of using neural networks as alternatives to matched filtering for continuous gravitational wave searches needs to be established. This is the main goal of this work for the next 12 months.

Search for CW signals from BH/axion cloud systems

Axion clouds forming around BH are expected to emit CW signals over long times. According to theoretical predictions, which are based on several approximations, the emitted signal is exactly monochromatic. We do not want to rely on this strong assumption and aim at developing a robust method for CW signals

¹<https://git.ligo.org/CW/lalsuite>

with zero or very small spin-down (-up) and a finite unknown coherence time. While we have in mind BH/axion cloud systems as a reference source, the method can be used to search for other signals with similar characteristics.

Methods and work required: Currently we have developed a simple semi-coherent procedure in which data are analyzed using various collections of FFTs of different duration (from hundreds to thousand seconds). The procedure is computationally relatively cheap and is suited to an all-sky search. We plan to produce a method paper by Q3 2018. We are also developing a semi-coherent directed search for such systems based on hidden Markov model tracking as well as using the semi-coherent Fstat-stacking approach. The former method is robust against potentially slow frequency variations of the signals due to the expected intrinsic evolutions and astrophysical interactions. The latter method may be more sensitive in the absence of such variations.

Expected results: We aim at applying the method to O3 data. Alternative methodologies are being investigated. Even in case of non-detection, a constraint on axion masses can be established. Method demonstrations for the Fstat-stacking approach might be carried out on open O1 data.

Search for r-mode emission from glitching objects, such as J0537

The presence of glitches disrupts the phase coherence of the signal and reduces the SNR gains when using longer coherent times. Further, it has been suggested that r-mode emission may be driving the inter-glitch phase evolution of the “big glitcher” J0537. These two facts have generated renewed interest in developing searches to that look for emission in-between glitches. When no information on the time of occurrence of the glitches is available, this effectively results in the introduction of two new parameters in the search. Method demonstrations might be carried out on open O1 data.

Search for continuous signals from objects in binary systems

Even though they are among the highest priority searches in our program, searches for continuous signals from objects in binary systems have not received much attention, due to the inherent difficulty of designing a search that could be sensitive enough to yield interesting results. We will attempt to remedy this.

Developing a glitch-robust parameter estimation tool

All-sky and directed searches for signals from isolated sources have a non-negligible chance of finding signals from a source undergoing non-negligible (spin) glitches. If neglected during the follow-up and vetting of signals, this could lead to either bias in the inferred parameters or false dismissal of the candidates.

Methods and work required: Work has been done to develop an MCMC-based glitch-robust parameter estimation method which can be applied to candidates identified by all-sky or directed searches. Work is required to improve predictions for the size and rate of glitches in potential candidates and understand the sensitivity of pipelines to such signals. Future work is needed to develop a complete glitch-robust semi-coherent to fully coherent pipeline.

Expected results: The MCMC-based glitch-robust detection statistic will be applied to any interesting candidates arising from all-sky and directed searches

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 8, 9 and 10, 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 [141], phase transitions in the early universe [142, 143], cosmic strings [144, 145, 146, 147], and can also arise in pre-Big Bang models [148, 149]. Astrophysical contributions to the stochastic background consist of an incoherent superposition of sources too weak to detect individually, such as binary neutron stars [150] or binary black holes [151]. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysical background would also be of great interest. The implications from Advanced LIGO’s first observing run are that the stochastic gravitational-wave background from binary black holes and binary neutron stars is consistent with optimistic predictions, and is potentially observable with advanced detectors [151, 150].

5.1.2 Methodology

The primary goal of the isotropic search is to estimate the energy density of the stochastic background:

$$\Omega_{\text{GW}}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \ln f}, \quad (1)$$

where ρ_{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 [152, 153], which has served as the basis for all previous LIGO/Virgo stochastic searches [154, 155, 156, 157, 158, 159]. The stochastic pipeline estimates $\Omega_{\text{GW}}(f)$ given some assumed power law $\Omega_{\text{GW}}(f) \propto f^\alpha$. Cosmological sources such as the inflation and cosmic string backgrounds are predicted to have $\alpha = 0$, while $\alpha = 2/3$ is appropriate for the signal from binaries. We have carried out this search on O1 data, and O2 results are currently in preparation. We will also carry out this search on O3 data. We expect increased sensitivity in O3 relative to O1 and O2, 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 [160]. Otherwise, we will report upper limits for arbitrary spectral indices [156, 160].

We can study the observational implications for specific theoretical models for the stochastic background. For example, applying the Bayesian parameter estimation techniques outlined in [161, 150, 160], 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 “component separation” method was recently developed to put joint upper limits on the amplitudes of multiple spectral shapes [162]. This method uses the results produced by the isotropic search for each spectral shape and estimates the joint upper limit by deconvolving them via a mixing matrix. In addition to the component separation method, we also will implement a related approach using Bayesian parameter estimation to study more general models. This analysis can be applied in post-processing, using the measured cross-correlation spectrum as the fundamental data product. This Bayesian method can be applied to any spectral shape (not necessarily a power law).

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 [163] 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 present in the likelihood of the fully Bayesian approach [164]).

Non-tensor polarizations. General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [165, 166], $f(R)$ gravity [167, 168], bimetric [169] and massive [170] gravity theories, generically predict up to four additional vector and scalar polarization states. The direct measurement of gravitational-wave polarizations may therefore serve as a powerful phenomenological test of gravity. The isotropic pipeline has recently been extended to additionally search for a stochastic background of non-standard polarizations [171]. This modification adds support for the vector and scalar overlap reduction functions, which parametrize the expected Hanford-Livingston strain coherence in the presence of a vector- or scalar-polarized background. A Bayesian post-processing code has also been developed to perform model selection and parameter estimation on the background. We can use Bayesian odds ratios to distinguish between signal and noise hypotheses (e.g., to claim a detection of the background), and between non-GR and GR hypotheses (to claim a detection of scalar and/or vector polarization content). As a by-product of computing the Bayesian evidence, we obtain posteriors on the amplitudes and spectral indices of the tensor, vector, and scalar contributions to the stochastic background. Search results using O1 data have been recently published [172] and O2 results are in preparation. It should be noted that additional detectors greatly improve prospects for measuring the polarization content of the stochastic background [171]. Future searches in O3 and beyond will therefore benefit from the use of Advanced Virgo data.

5.1.3 Deliverables

1. A paper describing the combined O1 and O2 search results on the stochastic background (Fall 2018). 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 study of correlated magnetic noise.
2. O3 search results on the stochastic background (2020).
3. Investigations of BayesWave as a tool for estimating the parameters of a stochastic gravitational-wave background.

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 [147, 173, 174, 175, 176]. For example, a confusion background may arise from binary mergers [161, 177, 178], core-collapse supernovae [179, 180], neutron-star excitations [181, 182], persistent emission from neutron stars [183, 184], and compact objects around supermassive black holes [185, 186]. Depending on the rate and redshift distribution of these objects, the corresponding SGWB could be isotropic or anisotropic. Such an anisotropic signal may appear with greater statistical significance in the anisotropic search than in the isotropic search.

The directional search provides information on the angular content of the SGWB in the form of a map of the gravitational-wave sky, and is therefore a powerful tool for distinguishing among different possible sources of the SGWB. The stochastic directional search provides a crucial follow-up to characterize anisotropies present in stochastic signals detected by the isotropic search; it facilitates the detection of highly anisotropic stochastic sources (e.g., clustered in the Galactic plane) that might be missed by the isotropic search; it provides a robust and sensitive search for narrowband point sources from interesting persistent sources (such as accreting binary systems like Sco X-1, young neutron stars like SN1987A, or unknown neutron stars such as a localised population at the galactic center); and it provides a possibility of cross-correlating the SGWB anisotropies with anisotropies in electromagnetic observations (galaxy counts, gravitational lensing) to extract further information on the origin and composition of the SGWB.

5.2.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [187]:

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

for Hubble parameter H_0 and sky location Θ . The frequency spectrum is typically assumed to be a power law in the frequency band of GW detectors: $H(f) = (f/f_0)^{\alpha-3}$. For a given value of the power index α (for example, $\alpha = 0$ for inflation and cosmic strings, $\alpha = 2/3$ for compact binaries, and $\alpha = 3$ gives a fiducial value for other astrophysical backgrounds such as supernovae), the objective of the search is to estimate

$P(\Theta)$. Two approaches are pursued. In the radiometer algorithm, we assume the signal is characterized by a point source

$$P(\Theta) = \eta(\Theta_0)\delta^2(\Theta, \Theta_0), \quad (3)$$

and in the spherical harmonic decomposition (SHD) algorithm we assume that the signal can be written as a superposition of spherical harmonics

$$P(\Theta) = \sum_{lm} P_{lm} Y_{lm}(\Theta). \quad (4)$$

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 $\Gamma(f, t)$ encodes the uncertainty associated with deconvolving the raw cross-correlation measurement for different directions on the sky (see [188, 187, 189] for further description and details on its inversion).

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

All-sky all-frequency search for unmodeled persistent GW sources. Recent work [190] demonstrates that data compression using sidereal folding [191] can facilitate an extremely efficient narrowband search looking in all directions and at all frequencies. The all-sky, all-frequency extension to the point-source radiometer targets unknown neutron stars in binary systems as well as all other narrowband sources, providing a sensitive tool for discovering *any* persistent point source, which does not conform to the assumptions made by template-based searches. The search method has been tested by injecting and recovering synthetic signals in the presence of instrumental artifacts, using time-shifted O1 data [192]. Additionally, new methods have been introduced to produce sky maps in a highly efficient way by taking advantage of the compactness of the folded data and HEALPix pixelization tools for further standardization and optimization, as implemented in the code `PyStoch` [193]. Building on these developments, we plan to perform an all-sky, all-frequency radiometer search using O1 and O2 data.

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. Recent theoretical developments have established the framework for estimating anisotropies in cosmological and astrophysical SGWB models [174], and have applied the formalism to specific cases of the models due to BBH mergers [175] and due to cosmic string networks [176]. We use the measured SGWB anisotropies to constrain theoretical SGWB models. We also investigate ways of correlating SGWB anisotropy measurements with electromagnetic proxies for the evolution of structure in the universe (galaxy counts, gravitational lensing, cosmic infrared background) so as to extract information about the evolution and composition of the SGWB. Finally, we plan to use the spherical harmonic search to study parameterized models of anisotropy, for example arising from neutron stars in the galactic plane.

5.2.3 Deliverables

1. A paper including sky maps of the SGWB using O2 data, with:
 - 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 at unknown sky locations
3. Measurements or upper limits on published models of anisotropic GW backgrounds, for example from cosmic strings or compact binaries.
4. Search results for O3 data.

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. [194], several scenarios associated with neutron stars are suggested, including non-axisymmetric Ekman flow occurring after a glitch and emission from free precession (with a damping time possibly lasting from weeks to years) [195, 196, 197]. Furthermore, 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 [198], 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 Ω_{gw} [152] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [199, 200, 201, 202, 203]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [199]. Gravitational-wave signals appears as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [199, 204, 202, 203, 205]) in order to identify statistically significant clusters of pixels. Recently, a highly-parallel seedless clustering algorithm [202, 203] was implemented, and recent work [203] 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 [206].

We will analyze data on timescales of ≈ 10 hr–1 month in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We have run STAMP in all-sky mode on O1 and O2 data used in the stochastic search, and will complete this search. We will also run the same pipeline on the upcoming O3 data. In order to analyze these very long signals, we have added an extra stage of pre-processing in which the data are compressed through time-averaging as described in [207]. As an application of the STAMP very-long-transient pipeline, we will work in collaboration with the Burst group (Section 8.1) and CW group (Section 4.10) to search for post-BNS-merger gravitational-wave signals. This will include a search for a long-lived remnant of GW170817, with the STAMP pipeline being run as a directed unmodeled search.

The STAMP code package has also produced spin-off technology that has proven useful for detector characterization [208, 209] and follow-up/visualization of CBC triggers [205]. 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, including
 - measurement (or upper limits) on Ω_{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.
2. Search results with O3 data.

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 (called 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 [191]. Using a folded data set not only saves an enormous amount of computation time, but it allows many other advantages for performing 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 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 [191] 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 be 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 of using 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 is very convenient for portable computers.

5.4.3 Deliverables

1. Folded data set, perhaps one set per week/month and one master set for the whole run.
2. Skymaps from folded data, for use in the anisotropic search described in Section 5.2.

6 Burst+CBC+DetChar Joint Activity Plans

6.1 Low-Latency searches for GW transients for EM follow-up

Develop, maintain, and staff online searches, including sky-localization, low-latency GRB searches, and Burst, CBD, and DetChar R&D for online analysis within the EM follow-up effort.

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.

Online searches are designed to perform matched filtering and consistency checks within \sim tens 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.

Research and development on the online search pipelines is closely coupled with the development of the offline pipelines, and so many of the activities described in Sec. 3.6. Here the Online-specific R&D activities are described.

Deliverables

- *Perform Online Searches for transients during O2* The current standard search space is pipeline-dependent but overall encompasses BNS, NSBH, BBH and IMBHB sources. Maintaining and running existing pipelines to identify candidates with significance derived from background estimates which are used by the EM follow-up and Multimessenger Astronomy projects, e.g., Sec. 7.4.
- *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. Given the likelihood that some

signals will occur in single-detector time the development and optimization of a search over such time is motivated.

- *Source-type identification:* For rapid source type identification (e.g., plausibly EM-bright BNS or NSBH systems vs. likely EM-dark BBH systems) the weighted rate calculations in the Offline R&D work can be used to assign relative probabilities of each source type for online candidates, and the overall probability that the candidate is astrophysical. Timescale to implement is end of O2, intersects with Rates/Pop. work, Sec. 3.4.
- 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;

7 Burst+CBC Joint Activity Plans

7.1 Studies of extreme matter with pre-merger and post-merger GWs R&D

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

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

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

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

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

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

O3 deliverables

1. *Systematic error assessment* : Statements about tidal parameters are limited by uncertainties in the waveform evolution. Waveform injection and parameter estimation studies will be performed to assess the systematic errors in the measured tidal parameters. These studies will explore the impact of differences in waveform model, spin priors, and calibration errors.
2. *Waveform development and comparison*: The ability to measure tidal parameters is limited by uncertainties in both point-particle and matter-dependent contributions to the waveform evolution. A detailed analysis of the differences between state-of-the-art waveforms for systems with tides, as well as differences with numerical simulations, is required to inform the waveform development outlined in 3.3.

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

3. *Surrogate models:* Parameter estimation for systems containing neutron stars is not possible with currently implemented tidal effective one body models due to their long evaluation time. Surrogate waveform models for the aligned spin waveforms with tidal interactions (TEOBv2 and TEOBv4) will be produced.
4. *BNS post-merger remnant:* a number of modeled and unmodeled data analysis techniques for constraining the energetics and spectral content of BNS postmerger signals have been proposed and some applied to GW170817. The efficacy and optimization of such methods will be studied further using numerical simulations of BNS mergers. Techniques to combine information from pre- and post-merger observations, as well as combining measurements from multiple events (i.e., “stacking”) will be developed. Further detector characterization studies will be pursued in an effort to improve high frequency instrumental sensitivity and to refine and optimize analyses of high frequency data.
 Studies will be performed to investigate whether the post-merger waveform associated with the NS resulting from the merger event in the presence of massive scalar fields can provide further constraints on both the axion field and the nuclear equation of state.
5. *Extreme tides:* Large tidal effects, such as the potential p-g-mode coupling during the early inspiral of BNS systems, have 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 extreme tides will be developed.

7.2 Externally-triggered searches for GWs R&D

Research and development of triggered searches for transient GWs associated with external triggers such as GRBs, fast radio bursts (FRBs), and high-energy neutrinos.

Methodology

To search for gravitational waves associated with external triggers, we use targeted (using the trigger’s time and sky position), coherent algorithms that either target NS-NS or NS-BH binary inspiral signals [210] for short GRBs and FRBs, or target generic GW burst signals [211] for all GRBs and FRBs. 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 [212] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs or high-energy neutrinos. 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 [213] and the final O2 GRB search results are under preparation. Finally, methods are in development to search for gravitational waves in coincidence with “sub-threshold” GRBs.

Short term goals

Long term goals

7.3 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 $\sim 65 M_{\odot}$. Massive black holes, exceeding $10^5 M_{\odot}$, 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 [214, 215]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [216], or

as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [217]. 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 [218]. IMBH binaries could also form as a result of evolution of isolated binaries with very high initial stellar masses [219].

No IMBHs in the mass range of interest ($\lesssim 1000 M_{\odot}$ 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 $0.3 \times \text{Gpc}^{-3} \text{ yr}^{-1}$. 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 [220].

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 $\sim 3 \times \text{Gpc}^3 \cdot \text{yr}$ (comoving volume \cdot surveyed time). Current sensitivities of Advanced LIGO create this possibility. For example, the O1 IMBH search [221] 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 $M(1+z) \sim 260 M_{\odot}$ could be detected to a luminosity horizon distance ² of $\sim 4.8 \text{ Gpc}$. 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 waveform 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

- **Publish** a paper on the astrophysical interpretation on the estimated rate limits on intermediate mass black hole mergers

²An approximate upper bound on the reach of a modeled search for IMBHBs.

- 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
- 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

7.4 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 [222]: short-duration (< 2 s) GRBs with generally harder spectra, and long-duration (> 2 s) GRBs with generally softer spectra. Astrophysical evidence has led to the hypothesis that these categories herald the creation of a compact object [a black hole (BH) or a neutron star (NS)] by way of two distinct pathways, both of which involve the emission of transient gravitational waves.

The NS-NS and NS-BH coalescences have been invoked as a short GRB progenitor candidates for decades [223, 224, 225, 226, 227]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [228]. Any future coincident observations of GWs and short GRBs would also be a major scientific result, demanding a rapid publication. Any possible association should be communicated 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 $\sim 1 \text{ yr}^{-1}$ [229, 230]. A hypothesized sub-population of low-luminosity long GRBs, including GRB 980425 observed at 35 Mpc [231], is predicted to occur at rates sufficiently high [232] 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-NS, which would give rise to long-duration ($\lesssim 1$ s) GW emission. The observation of X-ray “plateaus” following the GRB on timescales of tens of minutes to hours after the main burst has suggested that GRB central engines may live longer (~ 1000 s) than previously thought.

The association between GWs and a GRBs has a number of other impacts in multiple fields. For example, the first coincident GW-GRB observation probed the speed of gravity down to $\sim 10^{-16}$ precision [228], effectively ruling out a large family of modified gravity models, including “dark matter emulators” and many dark energy theories [233]. A population of GW and short GRB joint observations could provide a measurement of the low- z Hubble parameter H_0 to a few % [234]. 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 GWs and GRBs include [235, 236, 213].

Methodology

To search for gravitational waves associated with GRBs, we use triggered (using GRB time and sky position), coherent algorithms that target either NS-NS and NS-BH binary inspiral signals [210] in the case of short GRBs, or generic GW burst signals [211] for all GRBs. These searches are more sensitive than the corresponding all-sky ones. We run them both online (few-hour latency) and offline. We use an additional algorithm [212] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs. In O2 we successfully ran both triggered search pipelines in online mode, and provided results with a latency of a few hours. We are in the process of analyzing our data offline to provide a final collection of results for the O2 GRB search. Lastly, we are developing methods to search for GWs in coincidence with “sub-threshold” GRB events. Especially for the current CBC analysis, the large sky-location errors and the large number of “sub-threshold” GRBs is a computational issue.

O2 and O3 deliverables

1. **Publication** of complete set of GRB search results. This may result in two papers:
 - (a) An upper-limits paper which includes promptly available GRBs (public GCN plus IPN GRBs)
 - (b) A second paper which includes results from the emerging sub-threshold analyses using the *Fermi*-GBM or possibly other detectors, such as *INTEGRAL*.
2. Communication of online search results publicly. This will require the following:
 - (a) Continue to run low- (RAVEN) and medium-latency (X and pyGRB) pipelines, as for O2, but with updates.
 - (b) Continue to use the online frame files at Caltech, as for O2.
 - (c) Test the infrastructure to communicate online results to via approval processor, etc
3. Rapid publication of a GW detection associated with a GRB – joint GRB/GW170817 paper as starting point
 - (a) Communications with MOU partners would give best, vetted, but perhaps not final, results available at that time.
 - (b) Significant non-detections also fall into this category; we have several examples in the literature: GRB 070211, GRB 051103, and GRB 150906B.
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 [237].
6. Complete development of cross-correlation search for longer duration GWs targeting GRBs with X-ray plateaus (testing in O2, running in O3).

7.5 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 [238] 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. Over 30 FRBs have been published so far [239], including one repeating source [240], 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 [241] 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 [241], and work is underway to continue analysis using Advanced detector data.

O3 Deliverables

- **Publish** the results of searches for coincident GW/FRB events in Advanced Detector data using data coincident with identified FRBs. Given the anticipated increases in the rates of FRB detection, the paper is planned to focus on FRB coincident searches in O3, although the handful of detected FRBs coincident with O1 or O2 data will be included as part of the set of FRBs considered for analysis.
- Develop and test analysis methods for FRB searches using externally triggered unmodeled transient and matched filter methods, including analysis approaches suitable for both short and long-duration coincidence windows
- 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.

7.6 Multimessenger search for GWs and high-energy neutrinos

Some dynamical processes with strong GW emission, such as compact binary mergers or stellar core-collapse with rapidly rotating cores, can drive relativistic outflows that result in the emission of high-energy neutrinos [242, 243]. 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 [244], its surroundings [245], and the nature of relativistic outflows [246, 247]. 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 [248, 249].

In O1 and O2 we worked closely with the IceCube and ANTARES collaborations to develop and perform sensitive multimessenger analyses to search for neutrinos associated with GW candidates, and in particular with GW150914 [250], LVT151012 and GW151226 [251], and GW170817 [252]. No coincident neutrinos were found. 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 GW detectors [253], and we are finalizing the coincident sub-threshold analysis for the O1 observing period.

O2/O3 Deliverables

- **Publish** analysis for O2 and (separately) O3 describing the results and methods of the multimessenger search between low-threshold GW events and high-energy neutrinos.
- Develop, enhance and perform multimessenger GW+neutrino searches 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.
- Incorporate the Pierre Auger Observatory into the low-latency GW+neutrino coincidence analysis, along with IceCube and ANTARES.
- 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.

7.7 Measuring the nuclear equation of state from pre-merger and post-merger GWs

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

O2/O3 deliverables

1. With detections of BNS/BHNS, a constraint (or non-constraint) statement on the EOS of nuclear matter will be made. It will include CBC estimation of tidal parameters.
2. Following an extraordinary BNS detection (such as GW170817), provide targeted follow-up analyses of putative high-frequency post-merger gravitational wave emission using unmodeled and, where available, model-based parameter estimation techniques to:
 - Identify or reject plausible emission models by measuring or constraining the energetics of the post-merger emission.
 - Constrain the EOS via spectral analysis of the post-merger signal.

Note that studies targeting long-duration (days-months) post-merger signals are being coordinated between the long burst/stochastic and the CW group and will lead to a companion publication (see section 4.12 for CW contribution and full paper discussion).

8 Burst+Stochastic Joint Activity Plans

8.1 Search for long-duration GW bursts

Unmodeled long-lived gravitational-wave transients (lasting $\gtrsim 10\text{--}10,000$ 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 [254] and O1 data [255].

- **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 [256]. A protoneutron star can also be spun up through accretion of stellar remnant fallback such that an instability sets in [257]. The resulting gravitational-wave emission can last for $\approx 40\text{--}3100$ s [258]. Advanced LIGO / advanced Virgo might detect rotational instability signals from protoneutron stars out to distances of up to ≈ 40 Mpc [202, 203]. The rate of observed supernovae in this volume is on the order of $\approx 10\text{--}30$ yr⁻¹ [258], 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 [259, 260, 261], on the time-scale reaching 10^3 sec. Alternatively, clumps may form through accretion disk fragmentation, also leading to the production of gravitational waves [262]. 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 $(E_{\text{gw}}/0.1M_{\odot})^{1/2}$ where E_{gw} is the gravitational-wave energy budget [202, 203]. 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) [201]. 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 [263], rotational instabilities in merger remnants [199], and eccentric binary systems [264]. 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 LSC-Virgo efforts. 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 7.4) and the neutron star transient activity plan (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 [265] to search for intermediate duration signals bridging the gap between continuous 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 [266]. The Burst group coordinates 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 the burst and CW groups are concerned with studying astrophysical long-lived transient signals.

O2/O3 Deliverables

- Deliver a search paper reporting any signals found by the long-duration search, and place limits on some classes of sources.
- Continue to enhance the long transient waveforms catalogue with astrophysically motivated waveforms.
- Investigate options to improve the coherent Waveburst sensitivity to long-duration burst signals. One of the options is to use the Wavegraph clustering algorithm, and develop the time-frequency graphs for the signal models specified in this proposal [24].
- Investigate using ft-map based source reconstruction methods for long transients.

8.2 Search for GWs from cosmic strings

A cosmic network of strings may form as a result of phase transitions in the early Universe [267]. When a U(1) symmetry is broken in multiple causally disconnected spacetime regions, one-dimensional topological defects, i.e. strings, are expected to form [268]. 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 [269, 270, 271, 272, 273]. Cosmic strings produced in string theory motivated models (dubbed “cosmic superstrings”) have received much attention since they could provide observational signatures of string theory [274, 275].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational wave emission from loops [276, 277]. 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 [278].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [279, 280]. 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 theoretical 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

9 Stochastic+CBC Joint Activity Plans

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

9.1.1 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 ~ 2 minutes on average, with each merger lasting $\mathcal{O}(1)$ second). Thus, the duty cycle is $\lesssim 10^{-2}$, implying a “popcorn-like” *highly non-stationary* stochastic signal. Although the standard cross-correlation search can be used to search for such a background, the low duty cycle of the expected signal renders the standard (Gaussian-stationary) search *sub-optimal*, since most of the segments analyzed will consist of only detector noise. Here we propose a joint activity between the stochastic and compact binary coalescence (CBC) groups to develop and implement a Bayesian search strategy (originally proposed by Smith and Thrane [281]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

9.1.2 Methodology

The search methodology is based on Smith et al. [281] which applies Bayesian parameter estimation to all available data. The search uses the output of `lalinference_nest` to construct a probability density on the *astrophysical duty cycle* which we take to be the fraction of analyzed data segments which contain a CBC signal

$$p(\xi|d) = \prod_{i=1}^N [\xi \mathcal{Z}_s^i + (1 - \xi) \mathcal{Z}_n^i + \text{glitch terms}] . \quad (7)$$

The data d are broken up into N segments d_i , each of duration T ; ξ denotes the probability that a particular segment contains a signal, which is related to the rate R via $R = \xi/T$; \mathcal{Z}_s^i and \mathcal{Z}_n^i are respectively the signal and noise evidences of the i^{th} data segment and are the outputs of `lalinference_nest`. For readability, the glitch-model terms have been omitted. The search treats non-Gaussian glitches in the data as uncorrelated CBC-like signals in two or more detectors. These glitch terms are also outputs of `lalinference_nest` and this particular glitch model was shown in [281] to yield unbiased estimates of the astrophysical duty cycle in O1 background data. 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 statistic, e.g.,

$$B = p(\xi > 0|d)/p(\xi = 0|d) \quad (8)$$

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

Because the search applies Bayesian parameter estimation to compute the signal and noise evidences of the data, we also obtain posterior PDFs of the CBC parameters (such as masses and spins) irrespective of whether the data contains a signal or not. The PDFs from each data segment can, in principle, be combined in a Bayesian way to infer the properties of the whole population of CBC signals.

The proposed search in O3 will focus on searching for “high-mass” BBH systems, which we take to be BBH systems with chirp masses in the range $12M_\odot \leq M_c \leq 45M_\odot$. This enables us to keep computational costs manageable as it only requires analyzing data segments that are up to 4s in duration.

It was estimated in [281] that the BBH background can be detected using around one day of design sensitivity data. We expect that using O3 data we can make a confident detection using around one week of data. While the computational cost of the search is high (due to the application of Bayesian parameter

estimation), we expect to be able to analyze data in real time using a modest fraction of the LIGO Data Grid computing resources.

9.1.3 O3 Deliverables

1. Develop a set of data analysis routines to implement the above search such that it is both computationally feasible and robust against non-Gaussian features in the detector noise.
2. Perform a large-scale mock data challenge (MDC) of the proposed search method on synthetic data and O2 background data, including tests of its efficacy relative to the standard Gaussian-stationary search. Compare the performance of this proposed search to the existing CBC all-sky search and rate estimation techniques.
3. Develop tools to extract CBC-population parameters, e.g., mass spectrum.
4. Develop the necessary computational tools to ensure `lal inference_nest` is capable of searching for weak BBH signals at cosmological distances (luminosity distances greater than ~ 15 Gpc).
5. Publish the results of the MDC.
6. Run the search on O3 data. Detect the background of BBH mergers and measure the astrophysical duty cycle.
7. Perform inference on the population properties of the BBH background, such as the mass spectrum, spin and redshift distributions.
8. Prepare full collaboration paper on search results.

10 Stochastic+DetChar Joint Activity Plans

10.1 Data quality investigations for stochastic searches

10.1.1 *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.

10.1.2 *Methodology*

The stochastic searches rely on cross correlating data from different detectors. Common noise lines at two sites can occur due to similar equipment in the laboratory, electronics that have been synchronized by GPS, or common data acquisition systems. A strong line in one interferometer, along with a large random fluctuation in the other, can also produce an apparent narrowband signal in the stochastic search pipeline. We use several tools to identify and determine the causes of noise lines (codes O.RD.1.1, O.RD.1.2), as described in detail in [?]. First, we have developed several key tools for data quality and detector characterisation (code O.C.5.3), including STAMP-PEM and the coherence tool, physical environment monitors that study subsystem coherence at different frequency resolutions, and StochMon, an online coherence monitoring tool that is updated hourly and includes standard result plots as well as diagnostic plots such as coherence spectra. During engineering and observing runs StochMon is 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 observing runs, and possibly addressed at the sites.

We have previously observed correlated broadband magnetic fields in magnetometer channels at widely separated detectors [282]. The primary sources of these correlated fields are geophysical Schumann resonances [282]. 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 [283]. If the correlated Schumann resonance magnetic fields are limiting the stochastic search, then it will be necessary to directly measure the Schumann resonance magnetic fields at each interferometer site and implement noise subtraction techniques. Another approach being pursued is to use Bayesian parameter estimation to measure the noise contribution from Schumann resonances at the same time as the gravitational-wave background.

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.

10.1.3 *Deliverables*

1. Studies of instrumental correlations between detectors, which is 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 searches.

11 Characterization of the Detectors and Their Data

11.1 LSC Detector Characterization

Detailed LIGO Detector Characterization priorities

The LIGO detector characterization (DetChar) group has the dual responsibilities of investigating and mitigating misbehavior in the instrument, and providing data quality (DQ) information to the gravitational-wave searches to reduce the impact of artifacts in the data. In addition, the detector characterization group must help to validate the quality of the data around the time of candidate detections.

Overarching goals

- Continue to vet gravitational wave events and provide high caliber data quality products to astrophysical searches, particularly data quality flags based on physical noise couplings, for the third LIGO-Virgo observing run (O3).
- Enabling investigations and innovation for future observing runs.
- Characterization of the LIGO gravitational wave detectors ahead of the third observing run.
- Automation of LIGO detector characterization tool and tasks and improved centralization and accessibility of tools and documentation.

The following sections outline the priorities for LIGO detector characterization work in 2018-2019 in terms of **O3**, or tasks necessary for the third LIGO-Virgo observing run, and **future observing runs**, or tasks required for the success of the next observing run and beyond.

LIGO detector characterization priorities are also specified as **central** or **critical research and development** tasks. **Central** tasks are any task required for the delivery of DQ products to the astrophysical searches and the public, and engagement in the detector commissioning. **Critical research and development** tasks are those undertaken to address noise sources problematic for a particular astrophysical search or search method, techniques that don't contribute directly to generating DQ vetoes, or exploratory research and development which is not yet certain to have a direct application to the central DetChar scope.

O. The third aLIGO observing run - O3

O.C. Prioritized list of central tasks

Highest priority tasks

O.C.1: DQ products for the astrophysical searches

- O.C.1.1. Developing, testing, and documenting offline DQ flags.
- O.C.1.2. Producing offline veto definer files, which define the DQ flags that are used to veto data for each individual astrophysical search.
- O.C.1.3. Reviewing offline veto definer files.
- O.C.1.4. Noise line studies to characterize line artifacts that impact searches for long duration gravitational waves.
- O.C.1.5. Support of online DQ products; low latency state information, data quality flags, and veto definitions.

- O.C.1.6. Review of DQ products used to generate and evaluate DQ flags.
- O.C.1.7. Post-run investigation of worst offender noise sources. Particularly:
 - Blip glitches
 - Mid-frequency noise (i.e., 60-200 Hz non-stationary 'blue mountains')
 - Anomalous environmental coupling (i.e. airplanes, thunderstorms, periscope motion, beam clipping)
 - *See LIGO DCC P1600110 for more information on the noise sources.*
- O.C.1.8 Produce $h(t)$ frames that have noise contributions linearly subtracted, when noise sources with auxiliary witnesses exist.

O.C.2: Vetting GW event candidates

- O.C.2.1. Producing and reviewing full event detection checklists to vet the data quality around gravitational wave event candidates, including evaluating environmental couplings.
- O.C.2.2. Field a DetChar rapid response team to vet the data quality for low-latency gravitational wave candidate events.

O.C.3: Monitoring known or new DQ issues

- O.C.3.1. Contributing to conducting or mentoring DQ shifts: 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 for new volunteers.
- O.C.3.2. Mentoring and training scientists participating in the LSC fellows program, which supports LSC scientists working at the site to improve the detector data.
- O.C.3.3. Maintenance and characterization of the Physical Environment Monitor (PEM) sensors.

O.C.4: Commissioning support

- O.C.4.1. Tracking issues that affect interferometer uptime, such as seismic motion.
- O.C.4.2. Investigating noise sources that limit detector sensitivity; for example, hour-scale correlations between $h(t)$ and auxiliary channels or jumps in detector binary neutron star range.

O.C.5: Maintaining key tools

- O.C.5.1. Support of key tools, including user feedback and documentation for key infrastructure as listed in O.C.5.3.
- O.C.5.2. Review of key tools, particularly those used to generate vetoes.
- O.C.5.3. List of key infrastructure and tools:
 - Fundamentally necessary services:
 - * The summary pages; an invaluable set of webpages containing key plots that describe the state and behavior of the LIGO detectors and their environment
 - * The Data Monitoring Tool (DMT), including the low-latency DMT DQ vector infrastructure

- * The segment database; which stores state and DQ flag information used by the astrophysical searches
- * Omicron triggers, which identify transient noise triggers, including in low-latency, delivered with very high reliability
- * Robustly accurate interferometer states, including for configuration changes made between or during lock stretches (i.e., suspension damping state)
- Highest priority software and services
 - * Automated data quality checks for candidate events: the Data Quality Report (DQR)
 - * iDQ
 - * GWpy
 - * Stochmon
 - * STAMP-PEM
 - * Hveto
 - * ligoDV web
 - * Omegascans
 - * Channel Information System
 - * VET
 - * Offline noise subtraction code
 - * 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
 - * GravitySpy
 - * FScans and dependent programs / scripts
 - * NoEMi

This list relies on software dependencies maintained by the LIGO Laboratory (e.g. Guardian), the LSC Computing and Software Committee (e.g. low-latency data distribution), the LSC Remote Access group (e.g. NDS2), and the Virgo Collaboration (e.g. Omicron, NoEMi). While those software elements are not in the scope of DetChar, continued maintenance of the software, adaptation for use on LIGO data, and operations on LIGO data are of the highest priority to enable LIGO science

- O.C.5.4. Improvement of Codebase to meet the following development standards
 - Code should be open source
 - Code should be hosted on github.com or git.ligo.org to enable a github-flow-style development cycle
 - Code should include web-accessible documentation
 - Code should include unit testing
 - Code should include clear and complete installation instructions
 - Code configuration files will be available and up to date
 - Python is recommended for development to maximize compatibility with existing tools, reducing duplication-of-effort and redundancy

O.C.6: Interfacing with commissioners, site staff, and search groups

- Interfacing with commissioners and instrument experts to propagate instrument changes and developments to detector characterization investigations and monitoring.
- Using the Fault Reporting System (FRS) and the electronic logs (alogs) to communicate results and request tests.
- DQ liaisons identified by each pipeline should identify and report sensitivities in the pipelines to data defects.

O.RD. Prioritized list of critical Research and Development tasks

Highest priority tasks

O.RD.1: Investigation of the search backgrounds

- O.RD.1.1. Studying how instrumental artifacts affect the sensitivity of a specific search or search method.
- O.RD.1.2. Developing search-specific techniques for noise mitigation.
- O.RD.1.3. Investigating the loudest background outliers for a specific search or search method.

The standardized metric for assessing the impact of DQ information on a particular search will be search volume-time (VT), measured by the effect on the background of each search and on recoverability of signals.

O.RD.2: Machine learning and citizen science for O3

- O.RD.2.1. Gravity Spy citizen science and machine learning classification to identify instrumental causes for glitch classes.
- O.RD.2.2. Machine learning classification studies targeting known O2 noise sources, e.g. scattering.

Future observing runs

F.C. Prioritized list of central tasks for future observing runs

Highest priority tasks

F.C.1: Automation of key tools

- F.C.1.1. Automation of a data quality report for vetting the data quality of offline gravitational wave candidate events, including evaluating environmental couplings.
- F.C.1.2. Automation of studies to measure the coupling between $h(t)$ and auxiliary channels, or *safety* studies.
- F.C.1.3. Automation of DQ veto performance testing.
- F.C.1.4. Development of low latency DQ for fully-automated EM alerts.
- F.C.1.5. Further automation of low-latency event DQ reports, particularly targeting:
 - Producing a plot of the spectrum at the time of the trigger
 - Identifying sharp decreases in binary neutron star inspiral range near the event

- Checking for an increase in the rate of transient noise

F.C.2: Characterization of interferometer and auxiliary channels ahead of O3

- F.C.2.1. Evaluate the environmental couplings of the interferometers ahead of LIGO's third observing run, O3.
- F.C.2.2. Characterization and documentation of interferometer subsystems.
- F.C.2.3. Maintenance of lists of auxiliary channels useful for DetChar studies.
- F.C.2.4. Maintenance of summary page content.
- F.C.2.5. Signal fidelity studies of auxiliary channels.
- F.C.2.6. Auxiliary channel safety studies ahead of O3.
- F.C.2.7. Development and improvement of PEM sensors and sensor characterization.

The LIGO Detector Characterization subsystem leads will play a critical role here.

F.C.3: Improve monitors of known DQ features

- F.C.3.1. 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).
- F.C.3.2. Improving monitors for excess mirror motion leading to scattered light.
- F.C.3.3 Schumann resonance studies.
- F.C.3.4 Develop tool to query stochastic monitors to find which auxiliary channels are coherent with the gravitational wave strain data at a given frequency.
- F.C.3.5. Optic suspension resonance 'violin mode' monitoring.

F.C.4: Curation of DQ information for public data releases LOSC

- F.C.4.1. Development of documentation of PEM sensors and code examples for the LIGO Open Science Center (LOSC).

F.C.5: Integration of machine learning glitch classification into low-latency event DQ information

- F.C.5.1. Develop low latency machine learning classification (i.e., GravitySpy) that informs the DetChar rapid response team of GW event classifications and likelihoods.

High priority tasks

Predict noise performance based on instrument state using machine learning

- F.C.6.1. Change point detection

FRD. Prioritized list of critical Research and Development tasks for future observing runs

Highest priority tasks

F.RD.1: Develop improved clustering for Omicron

- F.RD.1.1. Improve Omicron clustering scheme to more accurately report timing, frequency, SNR of excess power.

F.RD.2: Integration of key tools to be cross-compatible

- The summary pages, hveto, VET, omegascan, others should all share the same well-maintained, well-documented, and accessible codebase.
- All triggers and data products (e.g. Omicron, GSpY classifications, lines and coherences, FEC states, saturations and overflows) will be stored in appropriate common data formats and will be discoverable with common tools. For instance, any data product should be accessible in a single function call in GWpy on the site cluster.)
- Improve documentation and support of key tools: All DetChar tools in common use should be fully and centrally documented, accessible on the LDAS clusters (or easy to install), and well supported by responsive experts.

High priority tasks

F.RD.3: Quantify the impact of transient noise on parameter estimation

- F.RD.3.1 - test the effects of transient noise on recovered source properties
- F.RD.3.2 - develop and test methods to reconstruct and remove from $h(t)$ isolated glitches and other noise types without auxiliary witnesses

F.RD.4: Research and development of new methods for noise identification/mitigation

Any new methods are to be tested and validated on recent Advanced LIGO data in a performance test outlined by the DetChar group.

Additional priority tasks

F.RD.5: Development of improvements to existing tools/pipelines for noise identification/mitigation

For example, exploration of supplementary machine learning techniques for spectrogram image-based glitch classification or supplementary event trigger generators outside of software listed in O.C.5.3. Any new methods are to be tested and validated on recent Advanced LIGO data in a performance test outlined by the DetChar group.

LIGO DetChar Tools Policy

The major goals of this plan are to establish a framework for LIGO DetChar tools that maximizes the ease and efficiency of comparison of techniques as well as access to results. This plan should serve as a guide to facilitate involvement that will be maximally useful to LIGO detector characterization. This policy seeks to promote the application of tools and techniques to improve the data of the LIGO detectors.

Requirements for the DetChar group

- An infrastructure supporting common data formats should be developed, well-documented, well-advertised, and supported. A ‘data format’ committee is charged with this task and updating the DetChar group regularly.
- Evaluation metrics and ‘mock data challenges’ featuring common data sets and training sets to be used for testing should be supported for tools in development, including supervised and unsupervised machine learning work. These mock data challenge data sets should be well documented and well advertised to the group.
- Standardized safety protocol should be developed for all tools that use auxiliary channels.

Requirements for tool developers

- No restrictions or requirements will be made on methods or techniques for development, or input formats to these methods, with the exception of requiring use of standardized auxiliary channel safety information (where applicable).
- All DetChar tool developers are responsible for producing code and technique documentation, including the code itself and usable instructions for running the code.
- All DetChar tools should make results available for use by the DetChar group in the appropriate common data format(s).
- All DetChar tools that make use of auxiliary channels are required to use the standardized auxiliary channel safety protocol from the earliest stages of development.
- All DetChar machine learning and classification tools should produce results for DetChar evaluation metrics and mock data challenges in the common data format.

Any tools or techniques that meet the indicated requirements will be eligible to be counted as service work for MOU reports (pending agreement by the MOU review committee), eligible to be included in any LSC-all DetChar technique comparison papers, and the work will be counted as ‘applied to LIGO data’ for MOU reports and statements made in talks or papers that go through internal LIGO Presentations and Publications review.

LIGO DetChar Roles

There are many active roles within the LIGO detector characterization group, and often some people have more than just one role. There are two DetChar chairs at present who oversee and steer the entire group. Working alongside them is a small committee who co-chair the hardware injections, 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. The review chair of the LIGO DetChar group manages the review of critical DetChar code and coordinates code configuration control with other working groups for observing runs. A small group of people also oversee, maintain and develop the key software required by the DetChar group. The structure of the DetChar group is viewable in the LSC Organization Chart LIGO-M1200248.

12 Calibration

12.1 LIGO 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*.

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 group, separate from the Detector Characterization group. The goal of the Calibration group is to provide calibrated $h(t)$ with sufficiently small uncertainties in amplitude and phase in both low and high latency, with the high latency calibration typically providing the smallest uncertainty.

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 and its associated uncertainty 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 group 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 group results are posted and documented on a web page[284] available to the LSC, and as with previous observing runs, will continue to be recorded in the electronic logs, software repositories, LIGO documents [285], and peer-reviewed articles [286, 287, 288, 289, 290, 291, 292].

As the interferometers improve in sensitivity, the era of precision gravitational-wave measurements will continue to intensify. The Calibration group is responding with intensified efforts to understand and reduce calibration uncertainty as well as to provide the most accurate calibrated data in low-latency as possible. The need for a more precise high-latency calibrated data product is expected to remain in upcoming observing runs, however.

Activities planned for Advanced LIGO's third observing run include:

- **Calibration model software:** The calibration model software will be revitalized and improved in an effort to improve the workflow from calibration measurements, to model parameters, to generation of FIR and IIR calibration filters, to uncertainty estimation for a given gravitational-wave event. The new model software will be written in the Python programming language and will be based off of the Matlab calibration software used in the first and second observing runs.
- **Calibration uncertainty estimate software:** The calibration uncertainty estimate software will be revitalized and improved moving into the next observing run. Notable improvements include automated generation of calibration uncertainty estimates with each significant gravitational-wave candidate and automated review checks on the calibration surrounding the time of each significant gravitational-wave candidate.
- **Calibration pipeline software:** The low and high latency calibration pipeline software requires constant maintenance to ensure smooth operation. Currently, the calibration pipeline software is a combination of front-end code and a `gstlal`-based code in low latency and `gstlal`-based code in high latency [292]. Planned improvements to the `gstlal`-based software include
 - correcting for two known time-varying, frequency-dependent calibration parameters (the coupled cavity pole frequency and the signal recycling cavity optical spring parameters) in both low and high latency

- improving the efficiency of on-the-fly FIR filter calculations where possible
- improving the computational speed and resource consumption of the pipeline
- separating out the UIM and PUM time-dependent scalar correction calculations into two separate factors
- subtracting calibration lines from a strain output channel
- subtracting the 60 Hz lines and harmonics lines from a strain output channel.

Planned improvements for the front-end based software include

- implementing FIR filtering routines
- implementing compensation for both scalar and frequency-dependent time-varying calibration factors.

If FIR filtering routines cannot reasonably be implemented, the Calibration group will implement a solution to include DARM loop characteristics currently only modeled in FIR filters into IIR filters. If time-varying calibration factors cannot be included in the front-end based software for the next observing run, the Calibration group will ensure the time-varying calibration factors computed in the `gstlal`-based software are displayed in the LIGO control rooms for real-time review purposes.

- **Calibration monitoring tools:** The LIGO summary pages are used as the primary monitoring tool of the LIGO calibration outside of the control rooms. These pages need constant maintenance and upgrades to keep up with any changes and evolving checks on the calibration. For the next observing run, the Calibration group will be including the low-latency testing calibration data stream where new software changes are being prototyped onto the summary pages.
- **Interaction of calibration with astrophysical analyses:** As more precise astrophysical and cosmological measurements are made from gravitational-wave events, calibration systematic error could become the dominant systematic error in these measurements. The Calibration group is partnering closely with astrophysical analysis groups to conclude what systematic errors could plague estimates of cosmological or astrophysical parameters. The tool being developed for these studies is the integration of calibration uncertainty estimates into the astrophysical parameter estimation pipelines. Feedback from studies on the effect of calibration systematic errors on astrophysical and cosmological measurements will inform how to proceed in improving the LIGO calibration. Additionally, studies that investigate the possibility of corroborating detector calibration using astrophysical signals, such as a binary neutron star event with an electromagnetic counterpart, are being revitalized.
- **Automate and standardize regular review checks:** The calibration review process is on-going as the calibration continues to evolve with the interferometers. In order to facilitate easier and faster review of the evolving calibration, the Calibration group will be automating calibration checks such as response function comparison plots, ASD comparisons between different calibration pipelines, ratios of the PCAL/DARM response at calibration line frequencies, and time-series plots of the calibration correction factors. In addition, the Calibration group will continue to maintain a repository of sensitivity curves that are vetted by members of the group.

12.2 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 outputs are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the GW 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. 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 GW strain $[h(t)]$ reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

12.3 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 observing run, and the SGWB group typically carries out one or two 10 min injections during each observing 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.

13 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) and multimessenger astronomy projects with external observatories also require and depend on 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.

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