LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

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EXECUTIVE SUMMARY
from 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. This document is its executive summary. (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	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	Binary Neutron Star (BNS) Range (Mpc) 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 full version 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 ($\geq 100\,\mathrm{M}_{\odot}$) 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-

	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 *quick-look* 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 ($\sim$ 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 **??**, **??**]

    - **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 **??**, **??**]

    - **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 **??**, **??**, **??**, **??**, **??**, Sections **??**, **??**]

    - **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 **??**]

    - **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. **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 **??**, **??**]

    - **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 **??**, **??**, **??**, **??**, **??**, **??**]

    - **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 **??**]

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 deteciton 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 measurment 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 developemnt 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 existance of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.

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., Cassiopeia A) are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched).
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 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 interpretating the observational results. To support the interpretation of the results, mock data challenges with different sources, such as compact binaries and cosmic strings, will be pursued. Additionally, 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 succesfully 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 $\approx$10 min injections during each observng 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.