# LIGO SCIENTIFIC COLLABORATION

LIGO-M1800085

# PROGRAM 2018-19

## PREFACE

In 2018, the LIGO Scientific Collaboration (LSC) appointed a Program Committee charged with formulating the Science Program of the LSC, identifying the current priorities of the Collaboration necessary to fulfill the LSC mission as described in the LSC charter[1].

The LSC Program will be updated annually as a public document outlining the Collaboration's priorities for the research and development, design, commissioning and operation plans of current and future ground-based gravitational wave detectors; the development, implementation and interpretation of gravitational-wave searches and observations; and the services and management necessary for the operation of the collaboration.

This is the first edition of the LSC Program, approved by the LSC Council, describing goals for the year that started in August 2018, and is published in `https://dcc.ligo.org/LIGO-M1800085/public`.

The members of the 2018 Program Committee were G. González (chair), S. Fairhurst (deputy chair), S. Ballmer, P. Brady, A. Corsi, P. Fritschel, B. Iyer, J. Key, S. Klimenko, D. McClelland, L. Nuttall, F. Ohme, K. Riles, S. Rowan, and the LIGO directorate: D. Shoemaker (LSC spokesperson), L. Cadonati (LSC deputy spokesperson), D. Reitze (LIGO Laboratory executive director), and A. Lazzarini (deputy executive director).

We invite feedback and comments to help define the next year's program, by using the electronic address program-committe@ligo.org

*Cover photograph by N. Kijbunchoo*

[1]https://dcc.ligo.org/LIGO-M980279/public

# Contents

# 1 Overview

## 1.1 The LIGO Scientific Collaboration's Scientific Mission

The charter approved in 2005 [1] describes briefly our mission: "The LIGO Scientific Collaboration (LSC) is a self-governing collaboration seeking to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery. The LSC works toward this goal through research on, and development of techniques for, gravitational wave detection; and the development, commissioning and exploitation of gravitational wave detectors."

After the first detection of gravitational waves from merging black holes on September 14 2015 [2] and the others that followed [3, 4, 5, 6], including the discovery of merging neutron stars [7] producing gravitational and electromagnetic waves [8, 9], the LSC mission is at the core of a new era of multi-messenger gravitational wave astronomy.

The LSC operates the Advanced LIGO gravitational wave detectors at Hanford, WA and Livingston, LA, and the GEO600 detector in Hannover, Germany. The LIGO detectors are laser interferometric gravitational wave detectors with suspended mirrors, with laser beams traveling 4 km in perpendicular arms in each detector, above ground and in vacuum [10].

The LSC is engaged to bring its advanced detectors to their design sensitivity, undertake observing runs, and collect calibrated gravitational wave data. The collaboration develops, maintains, and updates/optimizes complex software to identify times of poor data quality and perform searches for gravitational wave signals in the LIGO data, using theoretical calculations or numerical simulations that provide models of the expected signals. Searches for gravitational waves are performed, some in near real time, and alerts are issued to the broader astronomical community to enable multi-messenger observations of gravitational wave events. The LSC extracts the details of the gravitational wave signals from the data and, using the measured properties of the signal, presents in publications the astrophysical implications of the observations.

The LSC works closely with the Virgo and KAGRA collaborations operating gravitational wave detectors to ensure the coordinated operation of the global network of ground-based detectors. It also communicates closely with collaborations developing space-based gravitational wave detectors and operating pulsar timing arrays.

Following a proprietary period, the LIGO data are made public, enabling other scientists to independently search the data. The collaboration is engaged in activities aimed at making gravitational wave science accessible to the broader community, including resources for educating school children.

The LSC works to develop new instrumental techniques to improve the sensitivity of the LIGO detectors beyond the Advanced LIGO design, to bring them to the best sensitivity possible within the limits of the LIGO facilities. Among other research, this includes reducing the thermal noise due to optical coating of mirrors, manipulating the quantum nature of the light in the interferometers to reduce the quantum noise in the measurement, and attenuating further the effect of seismic noise. The LSC will also build the LIGO detector in India and bring it to a comparable sensitivity to the other LIGO detectors to expand the global network, as well as participate in the planning of a future generation of gravitational wave detectors.

The LSC has over 1,200 members from about 100 institutions in 20 countries; so there is significant infrastructure required to ensure that the collaboration operates smoothly. This includes collaboration leadership and management, provision of the communications resources enabling the collaboration to work across multiple time-zones, provision of computing hardware and software to enable gravitational wave searches, and outreach to funding agencies to secure long-term funding for gravitational wave astronomy.

The LSC presents in this program details about its goals, the activities it intends to perform in 2018-2019, and results it intends to deliver to the broader scientific community in pursuit of its mission. More complete details, and a more exhaustive list of activities pursued by LSC working groups can be found in the Collaboration white papers [11, 12, 13].

## 1.2 LSC Science Goals: Gravitational Wave Targets

The Advanced LIGO detectors took data between September 2015 and January 2016 in their first Observing run (O1) following a major upgrade from 2010-2015 [10], and then again with improved sensitivity in O2, between November 2016 and August 2017; there have been five detections of signals from black hole mergers [2, 3, 4, 5, 6] and many other results published to date. Virgo joined O2 on August 1st 2017, and that allowed much better localization of the detections of a black hole merger on August 14, 2017 [6], and more spectacularly, of a merger of neutron stars, on August 17, 2017 [7]. The improved localization and rapid alerts allowed the detection of an electromagnetic counterpart to the binary neutron star merger [8, 9]. This counterpart, spanning all bands of the electromagnetic spectrum, allowed the first direct association between a binary neutron star merger and a short gamma-ray burst, and the first unambiguous identification of a kilonova. It provided evidence for theories of the origin of heavy elements, and much detail about the nuclear equation of state.

During 2018, intensive commissioning work of the Advanced LIGO detectors is on-going to improve their sensitivity and allow more detections of compact binary mergers, as well as potential new discoveries of other astrophysical sources. During this time, the GEO600 detector takes data in "AstroWatch" mode to follow up possible nearby gravitational wave emission found from electromagnetic observations, *e.g.*, from galactic supernovae. It is expected that the Advanced LIGO and Virgo detectors will begin taking data again in their third Observing run O3, starting early 2019 and lasting about a year.

We list below the gravitational wave targets that we are searching for in LIGO and Virgo data. *We will publish high impact results from each class of targets in O2 and O3 data as soon as possible after data become available, and before the data become public (February 2019 for O2).*

- **Gravitational waves emitted during the coalescence of compact binaries**. We will search for mergers of compact binaries that produce gravitational waves in the sensitive frequency range of the LIGO detectors, including binary systems with neutron stars and stellar-mass black holes. These searches have been developed over the history of the collaboration and are now mature. They are run in low latency to provide alerts to electromagnetic observers. Despite their maturity, these searches will benefit from improvements, *e.g.*, using more accurate waveforms, or incorporating additional physical effects into the search waveforms, such as the presence of matter in mergers of neutron stars, or eccentricity and precession in black hole mergers. The searches must also deal, at times, with poor data quality, especially for brief transients, such as from high mass black hole mergers. Upgrading search programs to handle these complications can improve search sensitivity.

- **Searches for unmodelled transient gravitational wave signals.** We will search for transients with durations from a few milliseconds up to hours or days. Expected sources include core-collapse supernovae, soft gamma repeaters, neutron star glitches, proto-neutron stars and accretion disks, and cosmic string cusps. These searches will also allow the discovery of previously unknown sources. Searches for short transients will be run in low latency. Searches for unmodelled transients are hampered by noise transients and non-stationarities in the LIGO data, for which detector characterization is critical.

- **Gravitational waves associated with known astronomical transients.** We will search for transient gravitational wave signals around known electromagnetic transients such as gamma-ray bursts, fast radio bursts, supernovae, and magnetar flares. By using the known times and sky locations of these electromagnetic transients and, where applicable, the expected gravitational wave signals, we will perform targeted gravitational wave searches with improved sensitivity over blind all-sky searches. Some of these searches will be performed in low-latency mode to allow for alerts to be issued to the broader community.

- **Gravitational waves emitted by previously unknown non-axisymmetric neutron stars.** We will search for continuous gravitational wave emission from fast-spinning galactic neutron stars, both isolated and in binary systems. These searches are the most computationally demanding we carry out and necessarily require sensitivity tradeoffs for tractability; the most sensitive results may be published after the data are made public. Improving computational efficiency to improve sensitivity is an active research area.

- **Continuous gravitational waves emitted by known pulsars and other promising sources.** We will search in greater depth for continuous gravitational waves from sources for which we can exploit astrophysical measurements, such as the frequency evolution of known pulsars and/or the locations of other promising sources, such as recent supernovae and known X-ray binaries.

- **Searches for astrophysical and cosmological gravitational wave backgrounds.** We will search for an isotropic, stochastic gravitational wave background from unresolved binary mergers, cosmic string cusps and kinks, or of cosmological origin. We will also search for an anisotropic background, where the anisotropy could arise if the background is of astrophysical origin and may be correlated with structure in the local Universe.

### 1.3 LSC Science Goals: Gravitational Wave Astronomy

The following list describes the measurements to be carried out for gravitational wave detections and potential conclusions to be drawn from non-detections, again with the expectation to publish high impact results with O2 and O3 data before the data become public.

- **Signal Characterization.** We will extract the physical properties of the observed gravitational wave signals. For events where the source is well modelled, such as a binary merger, we will extract the physical parameters of the source. Where the signal morphology is not well modelled, we will reconstruct the waveforms. Where possible, we will determine best-fit maps of sky position and distance.

- **Public alerts.** We will issue prompt and open public alerts of significant gravitational wave events in O3 to allow for follow-up observations with electromagnetic and neutrino observatories.

- **Astrophysical rates and populations.** We will use the observed individual events, primarily compact binary coalescences of black holes and neutron stars, to determine the underlying population of sources in the universe, taking into account selection effects. We will interpret the detected populations in terms of existing models of compact binary formation and evolution. This can be done both with detections and non-detections as the latter can set upper limits on the rates of sources, and more generally constrain astrophysical population properties. We will also determine the implications of stochastic background search results for various cosmological and astrophysical models, including models based on cosmic string cusps and kinks, inflationary models, models due to mergers of binary neutron stars and/or black holes, models due to magnetars, and others.

- **Testing gravitational wave properties.** In General Relativity (GR), gravitational waves propagate at a constant speed, independent of frequency, equal to the speed of light. Gravitational wave observations, both with and without electromagnetic counterparts, can be used to look for variations of the speed of gravity (either from the speed of light or as a function of gravitational wave frequency). Gravitational waves in GR have two transverse polarizations. Observations of gravitational wave transients or stochastic gravitational waves in a network of detectors, or of continuous gravitational waves in one or more detectors, allow us to probe the polarization content of the signal and look for the existence of additional polarizations.

- **Strong-field tests of general relativity.** Precise predictions of gravitational waveforms from binary mergers are made using Einstein's equations. Thus, observations allow us to test for deviations from GR. These may occur during the inspiral as deviations from post-Newtonian coefficients. They may also occur during the merger and ringdown, where the signal must be compared to numerically derived waveforms. Deviations from the expected black hole physics waveform could arise too from violations of the black hole uniqueness theorems or from the presence of a boundary rather than a horizon. We will search for these effects, both in individual signals and by coherently analyzing the population of observed signals.

- **Probing extremes of matter.** Observations of neutron stars, either in binary mergers or through continuous gravitational-wave emission, allow us to probe the underlying structure of the neutron stars, often parametrized via the neutron-star equation of state. The neutron star structure affects the waveform emitted during the inspiral and the post-merger waveform. Since the coalescences of binary systems involving neutron stars produce electromagnetic waves, combining electromagnetic and gravitational wave observations can yield insight into the mechanisms for prompt and post-merger electromagnetic burst generation. In the fortunate event of a nearby supernova, combining neutrino and gravitational wave observations can yield insight into the explosion mechanism. Observations of continuous gravitational wave signals from neutron stars can also constrain the equation of state. Electromagnetic observations of the star could be especially helpful in establishing distance (and hence absolute signal strength) and in relating potential electromagnetic pulse phase to gravitational wave signal phase (relevant to interpreting the neutron star non-axisymmetry).

- **Gravitational wave cosmology.** The gravitational waveform emitted during a binary merger can be used to obtain a measurement of the luminosity distance to the binary. Thus, gravitational wave observations provide a new cosmic distance ladder. Given an accurate measurement of the source redshift, it is possible to probe the expansion history of the universe and, concretely, to measure the Hubble constant. The redshift measurement can either be from an electromagnetic observation, directly from the properties of the gravitational wave signal (*e.g.*, merger physics in neutron star mergers) or statistically derived from overlaying a galaxy catalog on the source localization.

# 2 LIGO Scientific Operations

LIGO Scientific Operations enable gravitational wave science by ensuring a stable and ever-improving LIGO detector, producing good quality and calibrated data to be combed for astrophysical signals. Data are taken in "Observing runs"; O2 was held between November 30, 2016 and August 25, 2017; O3 is expected to start early 2019, and last for about a year. The LSC commissions the detectors in between runs to improve the sensitivity, plans the dates of observing runs in consultation with Virgo, and operates the detectors during the runs. The LSC also makes sure the acquired gravitational wave data are properly calibrated and characterized to be used in analysis algorithms.

This section describes the activities carried out for operations at the observatories, commissioning and detector improvements, as well as activities needed for the data calibration and characterization.

## 2.1 LIGO Observatory Operations

The LIGO Laboratory has primary responsibility for the operation and maintenance of the LIGO Hanford and Livingston Observatories through a Cooperative Agreement with the US National Science Foundation.

There are many detector-related activities at the LIGO Hanford and Livingston observatories to support Observatory Scientific Operations. Facilities operations comprise a large number of ongoing maintenance activities throughout the year. In 2018, detector engineering and control-room operator groups will lead the incursion into the vacuum envelope in corner and end stations, installing upgrades in all chambers, and later carrying out diagnostic and maintenance activities for the detectors (and sub-components).

Detection coordination efforts for 2018 concentrate on exploiting O2 to maximize the science output of that observation run, plus preparing for O3, with an enhanced reach for gravitational wave sources and the associated increase in detection rate. O2 analyses and O3 preparations will require on-site investigations into artefacts in the data intrinsic to the detector, as well as couplings from external sources. Preparation for O3 will include revisions to protocols such as low latency response and alerts for electromagnetic follow up, including considerations of how to accommodate the expected high rate of detections.

The LIGO Laboratory System, Optical and Mechanical Engineering groups are central to the success of the commissioning and vacuum refurbishment efforts. Current activities focus on particulate control, suspension improvements, squeezed light injection engineering, vacuum system recovery, and commissioning/observatory support.

The LIGO Laboratory Control and Data Systems (CDS) group maintains and updates the CDS suite of software used in real-time control and data acquisition systems deployed to the LIGO sites and R&D facilities. In 2018 and 2019, CDS is preparing to make changes to the software suite based primarily on changes in software packages not developed in-house and computer technologies (software improvement) and provides support in the area of electronics design, fabrication, test and maintenance (electronics improvements).

The GEO Collaboration is responsible for the operation and maintenance of the GEO600 Observatory, taking data in "AstroWatch" mode while the LIGO detectors are being commissioned. Many technology developments to be implemented are first tested in GEO600, as was the case for the use of squeezing, now being installed in Advanced LIGO.

## 2.2 LSC Detector Commissioning and Detector Improvement activities

Detector Commissioning includes all activities involved in bringing the detectors to their target design sensitivity and operating robustly. Examples include diagnosing and reducing technical noise sources, improving the interferometer controls, characterizing the optical behavior of the system, and improving the duty cycle for low-noise operation. Most commissioning work is performed at the observatories, but remote contributions are also made by analyzing test and performance data, or modeling the interferometer behavior, in preparation for observation runs. Careful observations of the detector while running also give valuable information on possible detector improvements. Detector characterization activities (described below) contribute to the commissioning described here.

While LIGO Detector Commissioning and Detector Improvements at the Observatories are the responsibility of the LIGO Laboratory, there are also important contributions from other LSC institutions. These activities are managed by the LIGO Laboratory Commissioning Leader and the local LIGO Hanford and LIGO Livingston Commissioning Leaders. The commissioning team will continue improving the detectors' performance, with the primary goal for 2018 being preparing the interferometer for O3.

Detector Commissioning efforts will focus on assisting post-O2 in-vacuum detector work, preparing for commissioning activities, and then improving sensitivity and reliability to support O3. In 2018, some of the expected commissioning activities are increasing the laser power sent into the interferometer, implementing squeezed-light injection, and reaching stable operation for O3 in 2019. A more detailed list of activities is included in the 2018 Instrument Science white paper [11].

Detector Improvements involve new hardware or software that is intended to improve detector performance and supports the commissioning effort. Detector Improvements are managed by the LIGO Chief Engineer, and any proposed improvement projects must follow the processes for approval and implementation defined by LIGO Laboratory. Contributions in this category are in the form of the development, fabrication, or integration of approved Detector Improvement projects. Although most contributions are from LIGO Laboratory personnel, other LSC institutions make important contributions as well: a recent example is the Beam Rotation Sensors used to reduce seismic motion at very low frequencies.

## 2.3 Detector Calibration and Data Timing

Timely, accurate calibration of each detector's differential arm length channels into equivalent gravitational-wave strain is essential to extracting gravitational wave science from the LIGO detectors' data.

The task involves producing a calibrated data stream for each detector, called $h(t)$, of sufficient quality to support both the on-line gravitational-wave searches and the off-line analysis of gravitational-wave signals or null results. Analyzing and providing uncertainty estimates are also part of the calibration task.

The data calibration uses the known displacement produced by radiation pressure ("photon calibration") to track calibration at certain frequencies, and a model for the detector's frequency-dependent sensitivity to produce time-dependent calibration and estimated uncertainties. The model is vetted with measurements before, during and after each observing run. There is an on-line calibration that allows low latency analysis, and an offline calibration that is used in final analyses of the data.

The activities required for calibration are:

- maintenance and improvement (as necessary) of the photon calibrator system, the calibration model code, and the code for determining calibration uncertainties,
- measurement of transfer functions required for the calibration model,
- maintenance and operation of the low- and high-latency $h(t)$ data production software, and
- maintenance of calibration monitoring tools used for reviewing and diagnosing calibration issues.

Calibrated data and associated uncertainty estimates should be produced with sufficient quality for publication of final results within 2 months of data collection, and for public data release within 12 months of data collection.

Traceable and closely monitored timing performance of the detectors is critical for reliable interferometer operation and astrophysical data analysis. 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 sub-systems of the detector. The timing distribution system's status is monitored, and periodically tested in-depth via timing diagnostics studies.

### 2.4 Detector Characterization

Robust detection of signals, the vetting of candidate signals, and the accuracy of parameter estimation are crucially dependent on the quality of the data searched. The LSC's knowledge of the LIGO detectors and their environment is essential to deliver data quality information to the astrophysical searches which will avoid data with known issues, veto false positives, and allow candidate follow up. Characterization of the LIGO detectors themselves help to identify data quality issues that can be addressed at the instrument to improve instrument and search performance.

The LSC will perform the following critical tasks:

- characterize the LIGO detector subsystems, with the aim to quantify their contribution to detector performance and identify strategies to mitigate instrumental issues as they arise;
- provide timely data quality information to the astrophysical searches to designate what data should be analyzed, remove untrustworthy data due to quality issues, and identify periods/frequencies of poor data quality;
- identify sources of data defects that limit sensitivity to transient and continuous gravitational-wave sources;
- develop improved methods to uncover the causes of noise which most impact astrophysical search performance, with the goal of mitigating these causes in the instrument;
- undertake vetting of event candidates for potential instrumental origins; and
- maintain and extend the software infrastructure required to provide needed data quality information to the astrophysical searches and monitoring of the LIGO detectors.

With the anticipated event rate in O3 and beyond, automation is essential to achieve many of these tasks. This will be a particular focus of the LSC over the next year. The activities described require expertise in both the astrophysical searches and instrumentation.

### 2.5 A+ Upgrade Project

The "A+ detector" project is a major upgrade to the existing Advanced LIGO detectors, beginning in 2019 and expected to continue through the end of 2023. The A+ project in 2019 will be carried out in parallel with the O3 observing run.

Activities related to A+ operations are: testing frequency dependent squeezing at 1064 nm; designing measurement and implementation methods for Newtonian noise reduction; testing low noise control of the homodyne readout; reliability testing for higher stress silica fibers; and studying production of fused silica suspension fibers to ensure that frequencies of violin modes are sufficiently matched.

Results from these tests are expected to be implemented in A+, using frequency dependent squeezing with a 300 m filter cavity, balanced homodyne readout, implementation of lower loss coatings when developed, and installation of new test masses from upgraded pulling and welding systems for fused silica fibers. Details on A+ can be found in the LSC Instrument white paper [11].

## 2.6 LIGO-India

LIGO-India is a project of the Government of India with primary responsibilities to build facilities and assemble, install, commission and operate an advanced LIGO detector provided by LIGO and the US National Science Foundation. Formal approval by the Cabinet of the Government of India for LIGO-India was granted on February 17, 2016. Several important activities are expected to be completed in 2018-19: submission of a detailed proposal to the Indian funding agency and initiation of funding for R&D activities; completion of site acquisition; long-term seismological study; and initiation of site construction activities and vacuum infrastructure prototyping. The LSC is also engaged in developing and training the LIGO-India scientific workforce and planning the integration of LIGO-India data into the full detector network.

## 2.7 LSC Fellows Program

LSC Fellows are scientists and engineers who are resident at the LIGO observatories for extended periods of time [14]. The program is supported via contributions from LSC groups, including the LIGO Laboratory. Serving as an LSC Fellow at one of the LIGO observatories is a critical LSC activity . LSC Fellows can engage in a variety of operations activities, including: detection coordination efforts during observing runs; detector commissioning; installation of detector improvements; detector calibration; detector characterization.

LSC Fellows are participating in commissioning efforts and noise investigations prior to O3. During O3 in 2019, LSC Fellows will monitor the quality of the data and participate in investigations with the commissioning and detector characterization groups. As members of the local rapid response teams at each site LSC Fellows will perform investigations related to publicly announced event candidates. LSC Fellows work with on-site mentors or liaisons depending on their initial level of expertise and the nature of their project.

## 2.8 Roles in LSC organization

The LSC has a complex organization, with many members serving different roles, such as leadership and management of working groups, participation in committees, performing non-science needed activities, etc.

There is a wide range of activities undertaken by collaboration members which are organizational roles. Some of these have scientific elements, and some are simply necessary to maintain and propel the collaboration. The activities listed below are critical to the smooth running of the Collaboration:

- Chairing, or co-chairing or serving as secretary of LSC Bodies, Working Groups, and Committees described in the by-laws [15];
- Participating in committees or chairing subgroups as detailed in the LSC organizational chart LIGO-M1200248 as well as in ad-hoc Study Teams charged by the Spokespersons;
- Participation in reviews of the LSC activities e.g., reviews of LSC groups agreements (MoUs), reviews by funding agencies, presentations to LIGO's Program Advisory Committee;
- Administrative support to the LSC organization (setting up e.g., MoU meetings, maintaining spreadsheets and LSC activity documentation, LSC Activities accounting and invoicing);
- Management (by group leaders or their delegates) of LSC member groups.

# 3 Exploiting the LIGO Data

The success of the LSC in exploiting the LIGO data depends directly upon the use and development of specialized data analysis tools (detection and reconstruction methods, search algorithms and waveform simulation software) for identifying gravitational waves in the LIGO/Virgo data and producing scientific results. These tools are used to search in the data for the astrophysical targets and to achieve gravitational wave astronomy objectives listed in Section 1.

This section describes the development activities needed to exploit the LIGO O3 data, and the use, or operation, of analysis tools to obtain scientific results from O2 and O3. The future, long term, development activities beyond the O3 run are discussed in Section 5. Note that analysis activities are performed jointly with the Virgo Collaboration and use data from LIGO and Virgo detectors; it may also include KAGRA data by the end of O3.

## 3.1 Development of data analysis tools to search and interpret the gravitational wave data

The LSC has carried out gravitational wave searches on the O1 and/or O2 data to identify most of the targets listed in section 1.2 and to extract the gravitational wave science detailed in section 1.3. Nonetheless, further development and review of analysis tools is required prior to the start of O3 to ensure timely and effective searches of the data and extraction of gravitational wave events. It is vital that this work be completed, and reviewed, prior to the start of the O3 run to enable rapid identification of events, issuing of public alerts and publication of scientific results. Any development of analysis tools after the start of the observing run is only encouraged if motivated by expectations of significant impact to the scientific outcome of the analysis, and if the additional review can completed in a timely manner. Details of development and maintenance activities are available in the Data Analysis white paper [12]. Examples of those required in preparation for O3 include:

(A) **Automation of detection and parameter estimation pipelines.** With increased sensitivity during the O3 run, it is likely that the rate of gravitational wave detections will be one event per week or possibly higher. Therefore, any procedures to identify, vet and follow-up candidate gravitational wave events must be increasingly automated to allow for the analyses to keep up with observations.

(B) **Development of tools to characterize gravitational wave populations.** As the number of gravitational wave observations increases, it will become increasingly important and interesting to provide details of the underlying gravitational wave population, taking into account selection effects. Efficient tools to regularly update rate and population information during the observing run are required.

(C) **Development of tools for issuing public alerts of gravitational wave events.** The LSC is committed to providing public alerts for significant event candidates observed by its low-latency pipelines. The infrastructure must be developed, tested and reviewed before the beginning of the O3 run. It needs to incorporate methods of handling alerts from multiple search algorithms, and correctly prioritize the right information to provide in the alerts.

(D) **Devising and implementing operation plans for the long O3 observing run.** This is critical to enable sustainable use of both human and computational resources in delivering gravitational wave science from the data. The work includes the ongoing efforts to optimize gravitational wave search and parameter extraction analyses for computational efficiency and run-time.

(E) **Enhancements of existing analyses.** The LIGO detectors will have an improved sensitivity, over a broader frequency range, compared to previous runs. In addition, the Virgo detector will take part in the full O3 run, and the KAGRA detector may join near the end of O3. Developments of the existing analyses will be required to handle the improved sensitivity, for example through larger template banks in an enlarged network. In addition, refined methods for applying information on data quality and accounting for detector non-stationarity may be required to maintain search sensitivity.

(F) **Improvements to existing waveform models.** With increased detector sensitivity, it is likely that signals will be observed with greater signal-to-noise ratio. Consequently, increasingly accurate gravitational waveforms are required to ensure that any systematic uncertainties arising from discrepancies in model waveforms remain less significant than statistical uncertainties. Additionally, generation of waveforms can be the computationally dominant part of parameter estimation routines, so optimization work is required to speed them up.

## 3.2 The operations of data analysis search, simulation and interpretation pipelines

The main objective of the data analysis operations is the processing of the gravitational wave data with reviewed search pipelines, identification of gravitational wave signals in the data, and the production of scientific results and the LSC publications. With the growing number of detectors participating in the global gravitational wave network and the increasing volume of gravitational wave data, the data analysis activities become increasingly time consuming and require significant human and computing resources. Specifically, the following activities are critical for the effective and timely analysis of the gravitational wave data:

(A) **Maintenance of production search software.** Although the search algorithms and waveforms should be reviewed and tested before use in production, there are often maintenance activities needed to address bugs, security and unforeseen problems.

(B) **Operation of the low latency searches.** Ensure continuous 24/7 operation of the low latency searches for transient gravitational wave signals during the data taking runs. Perform rapid parameter estimation of detected signals and measurements of the source sky-maps. Provide public alerts for significant events. Accommodate for changing run conditions, detector sensitivity and non-stationary detector noise.

(C) **Prompt response to the real-time events.** Run the follow-up analysis of candidate gravitational wave events for better estimation of the false alarm rates, signal parameters and refined source sky maps. Perform rapid analysis of exceptional gravitational wave events, followed by LSC publications on those events.

(D) **Data conditioning and validation.** Coordinate closely the data analysis work with the data quality and calibration efforts. Perform timely integration of the data quality information into the LSC searches. Using the search pipelines, perform monitoring and mitigation of the environmental and instrumental glitches affecting the search performance. Apply subtraction of known noise contributions algorithms to improve detection and parameter estimation of observed gravitational wave signals.

(E) **Running the gravitational wave searches on archived data.** Preparation and execution of the searches for all gravitational wave targets on archived data, with final calibration and data quality. These searches will be run with reviewed analyses for O2 archived data, and during O3, to identify candidate gravitational wave events. Searches will be run on all collected data passing validity and quality checks from the LIGO, Virgo and KAGRA detectors. Processing of data from such a heterogeneous network of detectors with different sensitivity, duty cycle and varying run conditions is time consuming and requires significant resources. Therefore, we would generally expect to run no more than two analyses for a given source, or a region of the parameter space, following the LSC-Virgo multiple pipeline policy [16]. This is particularly important for long data taking runs and when Virgo and KAGRA detectors join the observations, which significantly increases the number of the detector combinations that need to be processed by the searches.

(F) **Production of the search results.** Final estimation of the detection significance for candidate events and the parameter estimation of detected signals. Processing of simulation data sets for estimation of the search sensitivity and interpretation of the search results with the astrophysical models. Estimation of the astrophysical rates and the source population studies.

(G) **Multi-messenger searches.** Conduct multi-messenger observations and interpretation of astrophysical events triggered by the gravitational wave detectors or by other electromagnetic or neutrino instruments. In most cases, this work requires observations and expertise outside the LSC and Virgo collaborations, and activities are regulated by the signed agreements with the external partners. Current examples include low threshold gravitational wave triggers shared with the Fermi GBM collaboration, and joint searches with the neutrino detectors.

(H) **Publication and review of results.** Prompt and thorough review of the analysis results and of the LSC publications, publishing high impact results as soon as possible and before data become public.

## 3.3 Operating computing systems and services for modeling, analysis, and interpretation

The timely production of LSC results requires significant computing resources. In particular, the following services are required:

(A) **Provision of computational hardware for analyses.** Several large-scale computing clusters are provided within the LSC for gravitational wave analyses. The computing clusters must remain secure, have the appropriate gravitational wave software installed, provide access to LSC and Virgo members, storage and web space for posting results. Usage of the clusters is tracked.

(B) **Data handling services.** Each LIGO observatory generates 25 MBytes/s of data from a combination of instrumental and environmental monitors. Data handling services include: automated data transfer infrastructure to support both low-latency analysis and batch processing for less time-sensitive analyses; data discovery services; remote data access services; databases (and associated web services) to store and access metadata about the instruments, the data, and gravitational-wave signals; and, finally, a summary service that presents an overview of important information about the instrument and data that can be viewed by date.

(C) **Engineering and operations of computing environments.** Provide users seamless and efficient access to computing resources and services, as well as a coherent, high-quality and well-managed suite of tools and infrastructure for development and production work. Engineering and operations includes: system provisioning and maintenance; operating and maintaining automated build and test tools/systems; packaging software for easy installation by users; providing gateways to use external computing resources for LSC science; monitoring the globally distributed computing systems and accounting of usage; optimization of the most computationally costly LSC analyses to enable more efficient use of resources and more timely results.

(D) **Collaboration operations support.** Identity and access management services underpin the ability of the LSC to interact and operate efficiently across the globe. Users require services to manage their LIGO.ORG identity and their access to LIGO.ORG resources; these range from a user enrollment and group management platform, through certificate management resources to group membership management tools. Federated identity management and additional group management tools are needed to support collaborative relationships between the LSC, other collaborations, and other scientists. The LSC requires tools to effectively collaborate and communicate including: mailing lists, wikis, web pages, document preparation and management systems, version control repositories, a messaging system, a voting system, problem reporting systems, interfaces with needed non-LSC documentation services, and teleconference system.

(E) **Curation and preservation of the LIGO data.** As described in the LIGO Data Management Plan [17] LIGO maintains a copy of all LIGO gravitational-wave interferometer data up to and including O2 data in the central data archive at Caltech with remote backups at the observatories.

## 3.4 Dissemination of LIGO data and scientific results

LSC scientific results and data are disseminated to fellow scientists in a number of ways:

(A) **Gravitational Wave Alerts.** In previous observing runs, low latency alerts were shared with many astronomy groups that had MoUs with the LSC and Virgo. Beginning with O3, there will be open public alerts for significant transient event candidates; preparations for the needed infrastructure, the vetting, and possible retractions of these alerts will be performed in 2018, in readiness for the start of O3.

(B) **Publication of Scientific Papers:** We commit to publish papers on all of our main gravitational wave targets in a timely manner following an observing run, and within six months for notable gravitational wave events identified in the data. We will review the correctness of results and scientific content of papers before sharing those with the broader community. We intend to publish results from searches in O2 data for all gravitational wave targets (except possibly from our most sensitive blind searches of continuous gravitational-wave signals) before the O2 data are made public in February 2019. This may require strategic planning and prioritization of collaboration-wide publications, to be done jointly with Virgo.

(C) **Release of Data at times of Gravitational Wave Transients:** At the time when the details of a new gravitational-wave transient are first published, the LSC makes the data containing the event public; typically about one hour of data around the event is released. The data have been released for all events observed to date and will continue to be made available for all O3 events.

(D) **Bulk Release of LIGO Data:** As described in the LIGO Data Management Plan [17], the LSC will make public the calibrated data taken in observation runs; this has been done with O1 and the final two initial LIGO scientific runs (S5 and S6), and it will be done with O2 in February 2019 (18 months after the end of O2 in August 2017). In addition to data release, the LSC provides tools to allow the community to access and search the gravitational wave data.

## 3.5 Outreach to the public and the scientific community

Activities that are important for the LSC to broadcast its mission and results are related to several aspects listed below. More details can be found in the LSC Education and Public Outreach (EPO) white paper [13].

(A) **Observatory EPO**: We will expand the Science Education Center (SEC) capability for conducting virtual tours and field trips and continue efforts to secure funding for a future LIGO Hanford Science Outreach Center as well as organize a yearly International Physics and Astronomy Educator Program at LIGO Hanford, building on the 2018 pilot program.

(B) **Formal and Higher Education**: We will develop new classroom units for high schools aligned with Next Generation Science Standards (NGSS) and other appropriate international school standards, including updates and revisions of existing classroom activities. We will work with APS to develop a Physics Quest experiment and Spectra comic book about LIGO for middle-school students, develop high-school teacher training materials that can be tested and evaluated prior to use, conduct professional development with high-school teachers at local, regional, national, and international venues, and develop new classroom and laboratory activities on LIGO-related data analysis and experimental topics, suitable for use in introductory astronomy and/or physics classes.

(C) **Informal EPO**: We will maintain and renovate the ligo.org website for informal users. We will continue worldwide outreach and communication through social media (@LIGO, Facebook, Instagram) including educational primers for O3 science and alerts. We will continue answering question@ligo.org queries, developing efficient approaches to curate and organize them. We will develop printed material and multi-lingual resources including science summaries for collaboration papers and promote development of audio, video, VR, web/phone apps, video games, planetarium shows, and other innovative approaches that communicate LIGO science. We will support the Humans of LIGO initiative, Gravity Spy, other relevant citizen science initiatives, and the Gravitational Wave Open Science Center (GWOSC) including a possible GWOSC User Group. We will develop and curate a bank of approved graphics and multimedia on all aspects of gravitational-wave science, suitable for LSC and Virgo colleagues to use in public lectures, and support LSC presence at major science festivals, exhibitions and other high-profile public events that attract large audiences.

(D) **Professional Outreach**: We will maintain and renovate the ligo.org website for professional users. We will work with the LSC Spokesperson Team to establish a US Government Relations working group and promote outreach to scientists at professional conferences and meetings, where appropriate in collaboration with other gravitational wave communities, including development of flexible and easily portable resources that can be used at exhibitions as well as other informal education and outreach events.

# 4 Advancing frontiers of Gravitational-Wave Astrophysics, Astronomy and Fundamental Physics: Improved Gravitational Wave Detectors

LIGO envisages three detector epochs spread over the next 20 years. The first epoch is defined by enhancements to the Advanced LIGO room temperature detector, in part to bring it to the Advanced LIGO design sensitivity and in part to go beyond the Advanced LIGO design with detector upgrades such as A+ described in Section 2.5. The second epoch, currently organized around the LIGO Voyager concept, entails a new detector in the existing facilities possibly enabled by cryogenic operation of the optics and new low-mechanical-loss coatings materials. The final epoch involves the 3rd Generation Detectors, such as Cosmic Explorer and the Einstein Telescope which require new facilities.

R&D is required to improve the performance of the ground based, suspended mass, laser interferometer subsystems, improve their integration into more and more sensitive instruments, develop new control architectures and explore new topologies. Beyond A+, upgrades to interferometric detectors' sensitivities require pushing the limits of all interferometer technologies with the possibility of operation at low temperatures.

R&D activities in the LSC program must have a clear vision for how such developments can be applied in, and/or improve the performance of, suspended-mass interferometric gravitational wave detectors. Important R&D studies and activities include those listed below; more details can be found in the LSC Instrument White Paper [11].

## 4.1 Substrates

For future detectors or detector upgrades operating at room temperature, mirror substrates formed from fused silica are of interest. Particularly needed are larger diameter substrates for heavier test masses. Such larger diameter substrates should facilitate the use of laser beams of larger diameter at the test mass face, thereby reducing effects of thermal noise on detector sensitivity.

For further improvements to detector sensitivity, substrates compatible with low noise operation at cryogenic temperatures are envisaged. As such, silicon forms an important candidate material for study.

(A) **Silica substrates:** Research across a range of areas is required to develop larger fused silica test masses in the range of approximately 80 - 200 kg. For example, such larger substrates require an improved surface figure error over the larger mirror face, controlling the residual substrate fixed lens, and maintaining the figure error despite elastic distortion when suspended. In addition research to mitigate the effects of charging noise and parametric instabilities on detector operation is necessary.

(B) **Crystalline substrates:** Critical R&D activities include the study and optimization of the optical and thermo-mechanical material properties of crystalline (silicon or sapphire) substrates, and the scaling of those substrates to the diameter required by future detectors - on the order of 80 cm. For example, techniques for super-polishing and surface figuring large silicon substrates need to be developed.

## 4.2 Suspensions and seismic isolation

Test mass suspensions need to provide adequate seismic isolation and maintain low thermal noise levels while allowing alignment and control of the interferometer optics.

(A) **Suspensions of lower thermal noise:** The final stages of the suspended optics require suspension elements of appropriate design to give improved levels of thermal noise, influencing requirements for specific geometry and intrinsic dissipation levels of such elements. Such R&D has a constructive interaction with characterization and monitoring of the in situ performance of suspensions currently installed in Advanced LIGO. Required research includes R&D on room temperature fused silica suspensions operating at higher fiber stress, able to support heavier test masses (approximately 80-200 kg), as well as R&D to improve the thermal noise performance of other portions of the suspension system, including lower thermal noise cantilever springs and bonds with mechanical loss, strength and vacuum-compatibility properties appropriate for new suspensions. Moving to cryogenic temperatures as envisaged for future developments requires development of crystalline suspension fibers (ribbons/fibers) with associated characterization of the thermo-mechanical properties of cryogenic materials (thermal expansion, thermal conductivity) and equivalent R&D as mentioned for silica suspensions, but translated to the cryogenic regime. In addition, studies are required of the application of techniques for cooling the optics via radiative and/or conductive processes.

(B) **Isolation, alignment and control:** Operation of interferometric detectors requires appropriate levels of isolation of the interferometer components from mechanical disturbance, necessitating research on mechanical design and active control systems. This incorporates a set of activities including: R&D to improve the stable operation of observatories through measures to increase the robustness of the detector systems to *e.g.*: high winds or seismic events, via use of enhanced sensing and control systems. Use of heavier test masses will require studies to optimise overall suspension performance, enabling seismic isolation and suspension control of a nature allowing movement of the lower end of the detection band to below 10 Hz. This needs to be done without violating the load limits of the existing seismic isolation tables for more immediate upgrades, and attention needs to be given to developments in sensors, mechanical design and control to provide appropriate low-noise seismic isolation in the cryogenic regime.

(C) **Newtonian noise reduction:** Finally, to benefit from improved seismic and thermal noise levels, the LSC will perform R&D targeted at methods of seismic and atmospheric Newtonian noise cancellation and/or design of a low-noise infrastructure.

## 4.3 Optical Coatings

Studies of the properties of the optical coatings applied to the test masses of ground-based, suspended mass gravitational-wave detectors are required to enable sensitivities beyond that of current detectors, notably in the most sensitive frequency range of the instruments. This topic covers a wide range of optical and materials R&D, from atomistic simulation of coating materials, through development of techniques for enhanced coating deposition and creation of new materials to characterization of the macroscopic properties of coatings (both optical and thermo-mechanical) in the laboratory and in situ, at room and cryogenic temperatures.

Examples of where these R&D areas are required include:

(A) **Continued development of improved amorphous coatings:** R&D is required to understand the sources of, and further reduce, mechanical loss of coatings materials whilst achieving suitably low levels of optical absorption and scatter. This could include for example materials modeling, design, development, deposition and characterization of properties of coatings (optical and thermo-mechanical). Coatings suitable for operation at 1064 nm (for room temperature operation) and at longer wavelengths are required. The LSC is working intensely to obtain prompt results to be implemented in A+.

(B) **Technology challenges for manufacturing coatings for large diameter optics:** For the larger size test mass substrates being studied elsewhere in the program will require appropriate coatings with uniformity of thickness and homogeneity of properties across large diameters. Thus research is needed to understand the relevant tolerances on coating properties and develop deposition techniques meeting required tolerances.

(C) **Development of large crystalline multi-layer coatings:** Promising alternative coating production techniques involving small-scale production of crystalline coatings materials have been demonstrated, however R&D is required to develop techniques that can produce such coatings on large-scale optics and to demonstrate their performance.

## 4.4 Cryogenics

Cryogenic interferometers are an attractive approach to lower the test mass thermal noise, but require a whole spectrum of new technological developments, from seismically quiet cooling systems, to new substrates and coatings, stable sensing and control systems, and different laser wavelength. R&D on testing the implementation of these in cryogenic interferometer technology in prototypes is therefore essential.

## 4.5 Lasers and Squeezers

Advanced LIGO sensitivity will ultimately be limited in a broad band of frequencies by quantum noise (shot noise and radiation pressure). In O3 and A+, higher laser power quantum manipulation of the light ("squeezing") will be used to improve the astrophysical reach. Lasers and squeezed light sources are critical subsystems in current and future detectors, where higher laser powers, enhanced levels of stabilization and sub-standard-quantum-limit sensing are required. Further, material choices for core optics components and coatings currently suggest that a change of operating wavelength will be desirable or even essential to achieve improved sensitivity levels. Areas of required research and development include:

(A) **Laser Development**: It is still necessary to achieve a high power (200 W) pre-stabilized laser with understood noise coupling into the interferometer in Advanced LIGO, including alternatives as power fiber amplifiers or coherently combined solid state amplifiers. For future detectors, pre-stabilized lasers at longer wavelength (1.5 or 2 microns) operating at 200 W and above are needed. The use of low-noise, high power handling and high quantum efficiency photodiodes will improve the sensitivity of detectors, especially if using squeezed light.

(B) **Squeezed light sources and systems**: Development and optimization of crystal squeezers is needed at longer wavelengths; as well as methods reducing losses in the injection and internal coupling of squeezed states. The application of squeezing to reduce the broadband noise requires filter cavities; frequency-dependent squeezing without such cavities would make implementation more practical. There are novel squeezed state generation concepts (e.g. ponderomotive squeezing) that require investigation for possible use in detectors.

## 4.6 Auxiliary Systems

Auxiliary systems are those technologies used in the interferometer not described in previous sections, such as Faraday isolators, electro-optics modulators, auxiliary lasers, and auxiliary cavities (input and output mode cleaners). The requirements for such systems often change in response to other design choices, such as cryogenic operation, test mass substrate materials, laser wavelength and squeezing operation. R&D activities include high power modulators; low-loss and high power isolators; arm length stabilization using a non-harmonically related laser wavelength; thermal correction systems for use at high power operation; and active wavefront control.

## 4.7 Topologies

While subsystem improvements can separately enhance interferometer performance, interferometer topologies can combine these subsystems together in ways that further increase signal (or signal bandwidth) and/or reduce noise coupling. Topologies that reduce quantum back-action noise fall under a class of experiments known as Quantum Non-Demolition (QND). Areas of focus include speed meters; enhancing the test masses mechanical response to the gravitational waves using dynamical back-action of light; intra-cavity nonlinear devices for internal modification of quantum states; high-frequency sensitivity improvement using negative-dispersion medium in the interferometer; and control systems and deep learning optimization.

Proof of concepts requires the development of prototype interferometers of appropriate scale.

# 5 Advancing frontiers of Gravitational-Wave Astrophysics, Astronomy and Fundamental Physics: Enhanced Analysis Methods

The LSC has, over the years, developed a diverse suite of detector characterization tools, gravitational-wave searches, and parameter estimation routines and tools to interpret gravitational-wave observations. In the future, as gravitational-wave detectors become more sensitive, as the global network expands, and as our understanding of gravitational waveforms and gravitational astrophysics improves, significant effort will be required to enhance the existing analyses and to develop improved methods to identify and interpret signals in the LIGO data. In this section, we outline the LIGO Scientific Collaboration's plans for longer-term development of analyses.

## 5.1 Development of searches for future runs and improved detectors

Future development activities include new R&D projects, major search program upgrades and the optimization of existing tools. Future development must account for the evolving gravitational-wave network with additional detectors and improving sensitivity, along with advances in the gravitational-wave source modeling and inclusion of the latest astrophysical models.

The development of new projects, or major upgrades to existing searches, take a significant amount of human and computing resources. Currently proposed development activities are listed in the LSC-Virgo white paper [12]. The LSC will prioritize projects taking into account the scientific scope of the proposed development, potential applications, relevance to the LSC publications, the human and computing resources required, and the necessary support and review the new tools. Development of a new search algorithm, or a major upgrade to an existing analysis, will be considered part of the LSC program if at least one of the following requirements is met:

(A) **A new gravitational-wave target.** The new algorithm targets a specific astrophysical source or phenomena from the list of the LSC gravitational-wave target classes (see section 1.2) not covered by the existing pipelines;

(B) **Improved scientific output.** The new algorithm has the potential to do significantly better science with the LSC gravitational-wave target classes than algorithms in operation;

(C) **Second, independent pipeline.** The new algorithm searches for a particular gravitational-wave target class with a second, independent pipeline of comparable sensitivity when only one pipeline exists;

(D) **Computational efficiency.** The new algorithm is computationally more efficient, and permits computationally limited searches to achieve significantly improved detection and/or reconstruction of gravitational-wave sources.

## 5.2 Theoretical and computational research supporting gravitational-wave analysis software

The search and interpretation of binary merger signals benefit directly from accurate theoretical and numerical models of the gravitational waveform emitted by those sources. Searches for coalescence of binary systems use template waveforms to separate astrophysical signals from noise. Estimating source parameters and their uncertainties is based on comparing the data with millions of modeled signals, and testing the strong-field gravitational-wave regime relies profoundly on accurate predictions of the expected gravitational-wave signature. Research in the areas of improved analytical and numerical modeling, carried out by researchers inside and outside the LSC, is an important building block towards improved analyses of gravitational-wave data.

The LSC will ensure in a collaborative effort that modeling advances supporting the LSC's science goals (as described in section 1 and presented in detail in [12]) are appropriately implemented and tested in its analyses. Here, modeling is taken to include both analytical and numerical predictions of the gravitational waveform. In particular, this includes:

- the implementation of new models and incremental model improvements into the appropriate LSC analysis software;
- waveform model improvements targeted for application in LSC analyses, provided these activities lead to a fully implemented model within two years;
- review of model implementations and tests of the LSC's analysis sensitivity and performance under model changes;
- production of numerical waveform data that are readily usable by the LSC's analysis software;
- maintenance of waveform-related LSC infrastructure;
- general interactions and knowledge transfer between modeling experts and analysts, in support of the LSC's observational results.

### 5.3 Development of tools for scientific interpretation of gravitational-wave observations

The gravitational-wave astronomical measurements discussed in section 1.3 require interpreting the results of searches and parameter estimation in light of current gravitational, astrophysical, cosmological or subatomic theory. Ensuring that our publications are well informed by current theory is important, as is incorporating relevant models driven by theory into LSC algorithms. The primary goal of the LSC is to make well grounded interpretations from new gravitational-wave signals, guided by published theory, especially where gravitational waveforms, including signal times of arrival, are critical to interpretation. The LSC currently plans to further develop and exploit tools for interpretation in the following topics:

(A) **Populations of merging compact binary systems.** The LSC will integrate existing population models into its gravitational-wave searches and use them for interpretation of the search results, including parametric population modeling of redshift-dependent mass functions and merger rates for black holes; and parametric modeling of black hole and neutron star spin distributions to help make statements about binary formation channels.

(B) **Tests of GR and searches for deviations from GR predictions for well understood sources.** The LSC will maintain a suite of tests for both gravitational-wave data alone (*e.g.*, deviations of waveforms from GR predictions for inspiral, merger and ringdown phases of binary systems; evidence of dispersion in the waveform), and where possible, when electromagnetic signals are seen, tests of the speed of gravitational radiation relative to that of light. Polarization measurements can be carried out from multi-detector compact binary coalescence detections, and in the event of a continuous-wave signal detection, it should be possible to extract highly precise polarization measurements of the signal, allowing tests for tiny deviations from GR predictions.

(C) **Measurements of matter effects in merging binary systems and properties of neutron star matter.** The LSC will establish a systematic program of testing inspiral waveforms for evidence of tidal effects, along with seeking and interpreting gravitational-wave signals from potential postmerger remnants (*e.g.*, hypermassive neutron stars). For detections of coalescing binary systems coincident with gamma ray bursts, we will work with gamma ray observers to interpret the burst phenomenology. Similarly, in the event of a nearby supernova, we will work with neutrino observers to interpret the collapse and explosion phenomenology. Further, the LSC will establish systematic interpretation of any detected continuous-wave signal (ideally, also using electromagnetic signals) to constrain the structure of the source star and hence the equation of state.

(D) **Measurements of the expansion history of the universe.** In principle, the Hubble constant $H_0$ can be determined from gravitational-wave distance measurements of individual binary neutron star or neutron star-black hole signals combined with counterpart redshifts measured electromagnetically. In practice, however, there is a large uncertainty in the inferred distance and non-negligible uncertainties

in relating the redshift measured for the source (or host galaxy) to the redshift characteristic of the local Hubble flow because of peculiar velocity corrections. Alternatively, the Hubble constant can be inferred with some precision from a statistical ensemble of compact binary mergers, including from binary black hole events, by using galaxy catalogs and sky localization of the mergers.
The LSC will work to improve measurements of counterpart standard siren cosmology. This will require developing tools to improve measurements of distance and inclination using higher-order gravitational-wave modes, where measurable; strengthening the expertise to make peculiar velocity or other redshift corrections with better precision; and collaborating with electromagnetic observers and modelers to incorporate available follow-up observations that inform inclination determination and to establish and exploit improved galaxy catalogs.

(E) **Interpretation of potential new physics effects beyond the Standard Model of particle physics.** It is possible that gravitational-wave interferometer signals will bring evidence of entirely new physics beyond the Standard Model of elementary particles. Examples include cosmic string cusps (detected individually or stochastically from an ensemble), stochastic gravitational radiation from exotic processes in the early Universe, direct dark matter detection (clumped or background field, primordial black holes), or superradiance induced by a condensate of new, ultra-light bosons, such as axions created by extracting energy from a fast-spinning black hole. The LSC will interpret detected signals, or lack thereof, in light of such predictions from the literature.

## 5.4 Development of calibration and detector characterization resources

Research and development in both calibration and detector characterization is needed to fully exploit the increasing sensitivity of gravitational-wave detectors and searches. Details on these activities are found in the white paper [12].

For example, as stronger signals are observed and the gravitational-wave detector network grows, improved detector calibration is required to accurately obtain parameter estimates, sky location and perform precision tests of general relativity. Examples of planned future calibration activities include:

(A) **Improvement of the detector calibration above 1 kHz.** Investigate and accurately model the response of the detectors above 1kHz which will benefit studies of the post merger signal and high-frequency burst-like signals;

(B) **Integration of LIGO calibration uncertainty estimates into astrophysical analyses.** Incorporate the calibration uncertainty at the time of a gravitational-wave event in to the astrophysical analyses to accurately accommodate for the changing response of the detector over time;

(C) **Improvement of LIGO calibration precision and accuracy.** Resolve any potential systematic error in the overall scale of the calibration and augment the precision and accuracy;

(D) **Automation of standard calibration precision and accuracy checks.** Automate the current methods to track and report the calibration precision and accuracy for more constant and effortless review;

(E) **Improvement of the calibration software.** Advance and augment the low- and high-latency production calibration pipeline and front-end based calibration software.

Detector characterization remains vital to accurate identification and interpretation of signals in the gravitational-wave data. Examples of planned detector characterization activities include:

(A) **Investigation of the search background.** Study how instrumental artefacts affect the sensitivity of a specific search or method and develop search-specific techniques for noise mitigation;

(B) **Machine learning and citizen science.** Research and development of machine learning, citizen science and/or new methods to identify and/or mitigate instrumental causes of noise;

(C) **Improvements to production trigger generators.** Enhance the performance of production trigger generators to more accurately report timing, frequency and signal-to-noise ratio of excess power;

(D) **Integration of key tools to be cross-compatible.** Ensure all essential tools, triggers and data products share the same well-maintained, well-documented and accessible codebase;

(E) **Quantifcation of the impact of transient noise on parameter estimation.** Evaluate the effects of transient noise on recovered source parameters and develop methods to reconstruct and remove transient noise form the strain channel without the use of auxiliary witnesses.

## 5.5 Development of computational resources for future runs and improved detectors

In addition to developing new data-analysis software, it is also important to develop plans to deliver computing for future observing runs. This includes, for example:

(A) **Future computing requirements.** Accurate accounting of the evolution of computational requirements as detector sensitivity, network size and rate of observed signals increases;

(B) **Optimization of analyses.** Identification and assessment of potential new software and hardware that could be used to further optimize gravitational-wave searches;

(C) **Code portability.** Evaluation of the utility of grid and cloud resources for LSC analyses, and software packaging, virtual machines and containers for increased portability of LSC software packages.

(D) **Identity and Access management.** Development of new identity and access management tools to facilitate the smooth running of collaboration services.

## References


[1] The LIGO-Virgo Collaboration. The LIGO Scientific Collaboration Charter, 2005. LIGO-M980279.

[2] B. P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116(6):061102, 2016.

[3] B. P. Abbott et al. GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 116(24):241103, 2016.

[4] B. P. Abbott et al. GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.*, 118(22):221101, 2017.

[5] B. P. Abbott et al. GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence. *Astrophys. J.*, 851(2):L35, 2017.

[6] B. P. Abbott et al. GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 119(14):141101, 2017.

[7] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, 2017.

[8] B. P. Abbott et al. Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J.*, 848(2):L13, 2017.

[9] B. P. Abbott et al. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophys. J.*, 848(2):L12, 2017.

[10] The LIGO Scientific Collaboration. Advanced LIGO. *Classical and Quantum Gravity*, 33:134001, 2016.

[11] The LIGO Scientific Collaboration. The LIGO Scientific Collaboration Instrument Science White paper 2018, 2018. LIGO-T1800133.

[12] The LIGO-Virgo Collaboration. The LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics, 2018. LIGO-T1800058.

[13] The LIGO Scientific Collaboration. LSC EPO White Paper 2018-19, 2018. LIGO-T1800322.

[14] The LIGO Scientific Collaboration. LSC Fellows Program, 2014. LIGO-M1400310.

[15] The LIGO Scientific Collaboration. LIGO Data Management Plan: June 2017, 2017. LIGO-M1000066.

[16] The LIGO Scientific Collaboration and the Virgo Collaboration. The LSC-Virgo Policy on Multiple Pipelines, 2015. LIGO-M1500027.

[17] The LIGO Scientific Collaboration. Bylaws of the LIGO Scientific Collaboration, 2015. LIGO-M050172.