PROJECT SUMMARY

Overview:

The Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US and the Virgo detector in Europe have ushered in a new era in the exploration of the Universe. In addition to resolving decades old questions in physics and astronomy they have begun to reveal a population of astronomical objects no one suspected to exist. Yet, observing the Universe with gravitational waves is still in its infancy. The next generation of ground-based detectors currently being conceived – in particular, the Cosmic Explorer (CE) in the US and Einstein Telescope (ET) in Europe – will compile a census of sources in almost the entire Universe, with the hope of answering many questions in fundamental physics and cosmology. However, data from a network of such detectors will pose analysis challenges that will take years to resolve. A series of progressively more difficult data challenges is proposed to confront data analysis hurdles presented by the next generation of gravitational-wave detectors (3G). These challenges will (i) inform the progress that would need to be made in the development of new algorithms for efficient detection and parameter inference, (ii) help estimate the computational resources required to fully exploit the science potential of 3G detectors and (iii) build and engage a community of researchers that is ready to explore the Universe with this new observational window.

Intellectual Merit:

LIGO and Virgo discoveries are impacting many areas of astrophysics and fundamental physics. We now have a new tool for measuring cosmological parameters and observing neutron stars and black holes throughout the cosmos and inferring their population properties. Gravitational waves could inform us about the state of matter in extremely dense regions and key to Multimessenger Astronomy. Mergers of stellar-mass black holes and neutron stars have allowed the most stringent tests of Einstein's theory of gravity. Current detectors are only sensitive to sources in a small volume of the local Universe. It is difficult to overstate discoveries that will be made with detectors that are able to survey almost the entire Universe for compact binary mergers. Such improvements in sensitivity are unprecedented in astronomy but opportunities for resolving some of the fundamental questions in physics today are huge. These include the discovery of new particles and fields beyond the Standard Model, understanding the equation of state of dense matter, finding black holes that may have formed in the primeval Universe and detecting signals from the earliest moments of the Big Bang, to name a few. The proposal will provide an opportunity to check if science results from the signal-rich data of future detectors can be reliably extracted and trigger research in the development of new analysis and inference algorithms that can deal with overlapping multiple signal types and strengths, of varying duration and cadence, all buried in data with nonstationarities and gaps.

Broader Impacts:

LIGO discoveries have the potential to attract school students to STEM subjects. However, not everyone is benefitting from this surge in new discoveries. In rural PA schools lack adequate resources to train in computer science, which hinders the education of key concepts in science and math. This is counter to the nation's need for a workforce with skills in computing to pursue careers where STEM subjects drive innovation and wealth creation. Students from underrepresented minorities and women are most affected by this imbalance. The objective is to provide access to high-performance computing in school districts in rural Pennsylvania, especially women and underrepresented minorities. Central to this proposal is also the training of graduate students. The existing partnership between Syracuse University and California State University Fullerton (CSUF) aims to significantly increase the number of students from underrepresented groups, in particular Hispanic and Latino/a students, in gravitational-wave astrophysics. The proposed research will provide support and training for CSUF students who wish to engage in third-generation detector research, and provide opportunities at MIT, Penn State and Syracuse. PIs will also work with undergraduate students to prepare the next generation of scientists and they will take part in simple data challenges. Students will be recruited, e.g., via the MIT UROP, which encourages undergraduates to become involved with research as early as possible. We will actively work to specifically recruit students from underrepresented minorities, low socioeconomic and first generation backgrounds. The proposed work naturally presents opportunities to train in Bayesian inference, machine learning, etc., skill sets of a successful scientist and pave the way to multiple, well-sought after jobs.

Project Description–Collaborative Proposal: A Data Challenge for the Next Generation of Ground-Based Gravitational Wave Detectors[‡]

1 Overview

The objective of this collaborative proposal is to develop a *mock data challenge* for the next generation of ground-based gravitational-wave observatories (3G) Cosmic Explorer (CE) [2] and the Einstein Telescope (ET) [3]. 3G observatories will have unprecedented sensitivity to detect compact binary mergers from an epoch when the Universe was still in its infancy and will routinely detect sources with stupendously large signal-to-noise ratios bringing precision to gravitational-wave astronomy [4–6].[7] An order of magnitude greater redshift reach and access to extremely high-fidelity signals will deliver new discoveries while allowing independent precision tests of nuclear physics, cosmological models, alternative gravity theories, and astrophysical scenarios of compact-object formation and evolution [8]. Beyond the hundreds of thousands of binary coalescence signals that 3G observatories will detect each year, they will observe weak but persistent radiation from isolated neutron stars, rare bursts from supernova, and other transient sources and stochastic backgrounds. Current analysis tools, waveform models and detector calibration will not be adequate in the 3G era. The sheer volume of observed signals will demand novel algorithms for extracting the science in signal-rich 3G data set. The algorithms must be able to keep up with the rate of detection and must handle the challenges of overlapping signals that range from very weak to extremely loud. The impact of statistical and systematic errors and the computational costs of 3G data analysis must be studied and quantified. Addressing these technical challenges is essential if 3G detectors are to deliver science at the forefront of fundamental physics and astronomy[6].

Mock Data Challenges The 3G network will consist of observatories of different topologies and sensitivities, distributed in different parts of the globe. Mimicking data with astrophysical signals that encode the expected physical effects and from a global network of detectors is a complex task. Challenge data must simulate the proposed 3G network as closely as possible, with non-stationary and non-Gaussian detector noise to develop analysis algorithms that are robust against such artifacts. We have assembled a team that has the deep understanding of detector responses, source dynamics, waveform models, cosmological effects, astrophysical evolution and distributions of sources needed to deliver the proposed challenge data (see, in particular, Sec. 4). We propose producing data sets of increasing complexity over the period of the proposed research and making these data freely available to the global scientific community. *Playground data* sets will be provided that allow scientists to develop and tune algorithms and *challenge data sets* with specific scientific objectives will allow participants to test their analysis pipelines. We will also provide tools for data access and simple investigations on the data sets.

The proposed data challenges will stimulate the development of the new algorithms that are necessary to ensure that 3G observatories can deliver their promised scientific goals [9–12]. These goals that will form the core objectives of the challenges include: extracting the equation of state of ultra high-density matter,[13] probing quark deconfinement phase transitions,[14] measuring the dark energy density and equation of state parameters [9, 15], ability to detect and characterize black hole mergers at redshifts as large as $z \sim$ 10–50 [5, 16],[12] determining the star formation rate as a function of redshift [17, 18], and discovering any violations of general relativity (GR) [11]. The challenges will also allow more accurate estimates of the computational resources needed to deliver these scientific goals [19].

Impact The project is designed benefit a range of researchers at different stages of their careers, with junior scientists encouraged to participate. We expect the project to trigger new discoveries in data science (e.g. combining Bayesian inference and machine learning to measure the parameters of thousands of signals[20]), to improve modelling of waveforms,[21] and identify subtle physical effects (e.g. non-general

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[‡] See Ref. [1] for citation convention (blue and red square brackets and superscripts) used in this proposal.

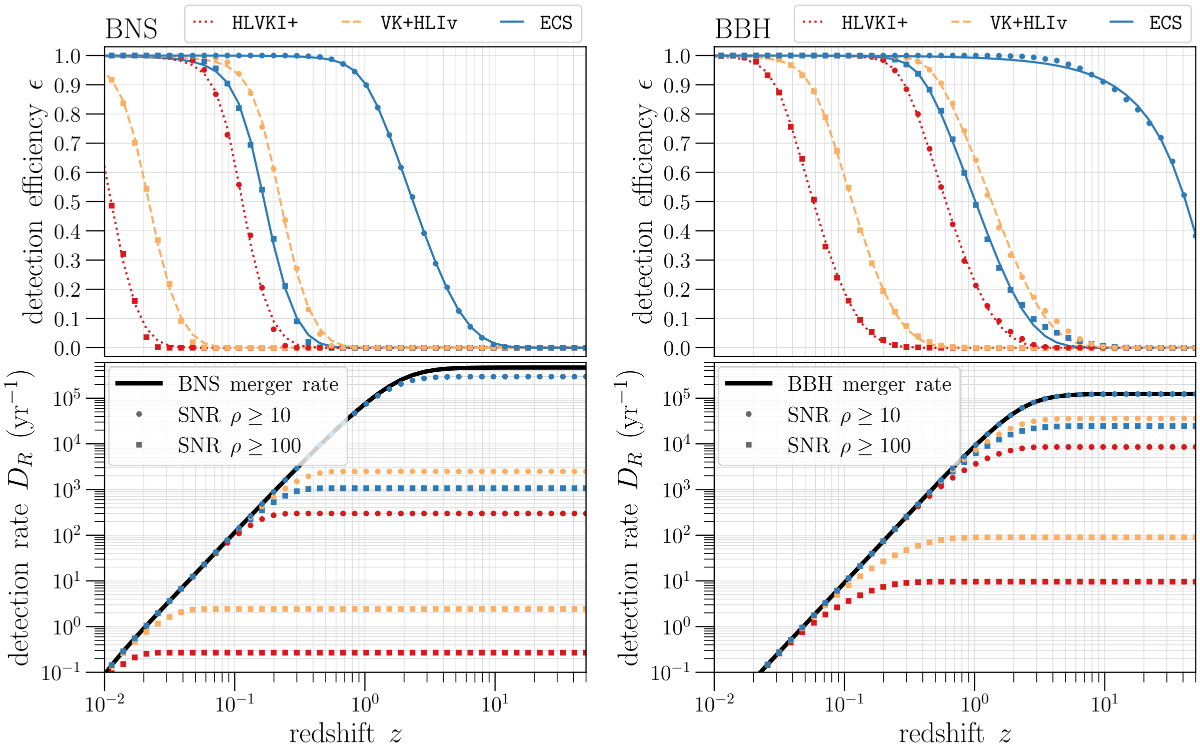

Figure 1: Detection efficiencies ϵ (i.e., fraction of all signals detected at a given distance) and rates D_R of an upgraded version of the LIGO-Virgo-KAGRA network in Advanced+ sensitivity (HLVKI+), the same but with LIGO detectors in Voyager sensitivity(VK+HLIv) and a 3G network (ECS) plotted vs redshift z. The circles (squares) are for events with SNR $\rho \geq 10$ ($\rho \geq 100$). The thick, black lines are the cosmic BNS and BBH merger rates.

relativistic propagation, tidal effects in neutron stars, cosmological acceleration) buried in the shape of the extracted signals. Simpler challenges will also be a training ground for STEM students in high school who are currently Freshmen but would be leading the analysis of data when 3G observatories come online. In summary, the proposed research will train a new generation of graduate, undergraduate and school students in the frontier area of gravitational-wave astronomy. The statistical tools and analysis techniques used in the training will be applicable in many other areas of physical and biological sciences and engineering.

2 Intellectual Merit

Gravitational-wave observations have ushered in a new era of discoveries in physics and astronomy. The hundreds of binary coalescence events detected[22–26] by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo observatory have already had a massive impact on our understanding of the Universe: the discovery of *heavy* black holes with masses in excess of 50 $M_\odot$,[27–30] large mass ratios[31] and neutron star-black holes[32] have challenged astrophysical models of their formation. Constraint on the relative speeds of electromagnetic and gravitational waves have ruled out many[33] modified theories of gravity invoked to explain dark energy, setting new directions for research.[34–37] Double neutron star coalescences are unique laboratories for exploring the nature of ultradense matter [38, 39],[13,40,41] including the discovery of new phases of quarks beyond hadrons.[14,42] Compact binaries are standard sirens, giving us a new tool for accurately measuring distances[43–47] and an independent tool for cosmography. New, strong-field tests of GR have so far vindicated the theory in a regime where it was never tested before.[48–51]

This is just the beginning. The detectors that are currently operating[52] and their planned upgrades,[53,54] are only able to survey the local Universe $z < 1$ for mergers of binary neutron stars and $z < 3$ for black holes (see Fig. 1). 3G observatories have the potential to observe black hole mergers beyond the epoch of the formation of first stars at $z \sim$10–50 and binary neutron stars from epochs when the Universe was only a few hundred million years old. A network of CE and ET observatories will provide a crystal clear picture of sources in the near-by Universe—for example, reveal many subtle signatures of dynamical spacetimes and state of matter at the highest densities anywhere in the Cosmos—and at the same time survey binary black holes when the Universe was only fifty million years old. Such a leap in sensitivity is unprecedented in astronomy and it is difficult to imagine the landscape of discoveries and the potential to unveil new physics.

With the CE *Horizon Study Document* now complete [6] and ET included in the *European Strategy Forum on Research Infrastructures* Roadmap,[55] the time is now ripe for a quantitative understanding of the data analysis challenges posed by 3G observatories. The endorsement of R&D for Cosmic Explorer by the recently concluded *Decadal Survey for Astronomy and Astrophysics 2020* (Astro2020)[56] is testament to strong community support for the next steps in the design of CE. With a series of increasingly sophisticated data challenges, the goal of this proposal is also to mobilize the global gravitational-wave community to engage in the design of new search algorithms, source characterization techniques and computational paradigms that are suitable for a signal-rich data in the 3G era.

3 Proposed Research

The main objective of this proposal is the production of data that mimics the output of a 3G observatory network, which will be fundamentally different from what we have encountered so far. The Gravitational-Wave International Committee recommended a series of 3G data challenges.[57] In its priority area *New Windows on the Dynamic Universe*, the Astro2020 Decadal Survey states that "new, coordinated advances in several areas are required to unlock the workings of the dynamic universe" including:[56]

> *Strong software and theoretical foundations to numerically interpret the gravitational wave signals from merging compact objects to extract new physics in the extremes of density and gravity, and ensure easy user access to the wealth of data on the dynamic universe and to model and interpret astronomical sources whose physical conditions cannot be replicated in laboratories on Earth.*

This proposal is a critical step towards accomplishing this task. It would be impossible to mimic the full complexity of a 3G data set but we will simulate data containing an astrophysical population of different signal types and strengths, lasting for varied amounts of time, embedded in instrumental and environmental noise artifacts. We will set up a series of data challenges to vet that key science goals can be extracted from data that contains overlapping signals, non-stationarities and gaps and understand the algorithmic and computational needs of a 3G network. The deliverables of this effort (Sec. 3.7) would advance our understanding of the true potential of 3G observatories and inform where future efforts would be needed.

3.1 State of the Art

Mock data challenges have played an essential role in validating analysis pipelines, understanding systematics, and identifying unforeseen problems. The most comprehensive challenges to date are (i) Numerical Injection Analysis (or NINJA) [58, 59], (ii) Mock LISA (Laser Interferometer Space Antenna) Data Challenges (MLDCs)[60] [61, 62], and (iii) the ET Mock Data Challenges [63, 64].

NINJA The NINJA project was critical in integrating numerical simulations of binary black holes in data analysis. Without these efforts understanding LIGO's seminal discovery[65] would have been far from complete. The large masses of the companion black holes in GW150914 meant that the signal in the LIGO band was dominated by the merger phase of the evolution which is captured accurately only with numerical relativity simulations. Furthermore, this effort led to a systematic calibration of analytical models against numerical simulations that led to tests of GR in regimes of the theory that were unexplored before.[49,66] It is important to note that the first efforts began almost a decade before the discovery.

LISA data challenges MLDCs began a decade before the then LISA's launch date and helped identify a number of problems in a signal-rich data set. Specifically, the importance of *global fitting* to multiple signals[67] was recognized and now forms the backbone of LISA data analysis strategy.[68] They also demonstrated the significance of higher multipole modes in resolving the sky position [69] of sources and their luminosity distance, both critical for precision cosmology [70]. With a launch date in 2034, LISA Data Challenges[71] have restarted to develop software tools that will form the basis of a future data analysis system. Our proposed effort with the help of collaborators deeply involved in the MLDCs will help identify where algorithms developed for LISA data analysis can inform the development of 3G algorithms. However, the data-analysis challenges faced by the 3G network are very different from those posed by LISA. The science challenges that we propose (e.g. extracting the dense matter equation-of-state, population properties of neutron stars and stellar-mass black holes) are distinct from LISA science and require a separate dedicated effort. 3G algorithms will need to cope with a data set containing $\sim$ one binary merger every few minutes, creating a "popcorn" background of signals. These signals sweep over the entire detection band from a few Hz to a kHz, whereas in LISA signals from most white dwarf binaries—the main source of confusion background—remain in single frequency bins over the entire observation period. 3G data will contain occasional bursts from intermediate-mass binary mergers, supernovae, magnetar quakes, etc., in a data set containing thousands of weak binary coalescence signals. Extracting these rare events is critical as they could bring us a wealth of information from sources that cannot be observed in other ways. The ability of analysis algorithms to identify and measure the parameters of rare events in 3G data needs to be demonstrated, and this task is distinct from those of the MLDC.

ET Mock Data Analysis ET mock data challenges have been relatively modest. They have largely focused on demonstrating the detection of compact binary coalescence signals and stochastic backgrounds in an array of three detectors in the ET triangular configuration but avoided analysis challenges posed by a detector network or the motion of the Earth. Even so, it helped demonstrate that detection of overlapping signals will not be a serious challenge [63], while identifying problems posed by long-duration signals. In particular, it showed the difficulty of filtering data at frequencies as low as $\sim$ few Hz when binary neutron star inspirals last for tens of hours. This was solved in the second data challenge [64]. Recently, several studies have been carried out to assess how the problem of parameter estimation is affected by the presence of one or more overlapping signals.[72–74] However, so far there is no clear understanding of the challenges posed by parameter estimation of *hundreds* of overlapping signals nor of extracting specific science targets such as cosmological parameters, the equation of state of dense matter, etc. The current proposal aims to address precisely these latter set of questions together with collaborators involved in ET.

3.2 Objectives

Compact binaries are the loudest gravitational-wave sources and the only ones observed so far. These sources will, therefore, be the dominant population in the mock data challenges. However, we also aim to simulate other signals such as supernova bursts, continuous waves and 'surprise' sources to challenge analysis algorithms. In order not to overwhelm the participants, we will begin with simple challenges consisting of only one source type and progressively increase the complexity. Each data challenge will ask participants to answer specific questions as discussed in Sec. 3.4-3.6. The specific objectives of the proposal are to release and evaluate three data challenges:

1. **Challenge A:** Three data sets, each one year long, containing only compact binary signals: (a) binary neutron stars, (b) binary black holes, (c) neutron star-black hole binaries.
2. **Challenge B:** Three, year-long data sets, containing binary merger signals but with different cosmological parameters; also supernova bursts and continuous waves but not part of the challenge.
3. **Challenge C:** Same as Challenge B but add continuous waves and supernova burst signals to the challenge and non-general relativistic signals aimed at totally new discoveries.

3.3 Methods and Implementation Plan

3G network and response functions This Section introduces common elements of the challenges in Sec. 3.4-3.6. For the purpose of data challenges we assume that the 3G network consists of two CE detectors at fiducial locations in the US and Australia and one ET at the current location of the Virgo detector in Italy[75] but it will be possible to assess single-detector detection strategies. The outcome of this study will be insensitive to the actual locations of the detectors. The data sets will properly account for detector locations and orientations, their noise spectral densities and deploy appropriate antenna patterns and response functions e.g., ET would consist of responses for the three V-shaped detectors in ET's triangular topology.[76] The detector response will account for the motion of the detector relative to the sky and include gaps in the data to mimic detector down times, and constructed in the long-wavelength approximation.[77]

Noise background The statistical nature of the noise background is determined by detector sub-systems, the physical environment of the detector, and a myriad other factors. To capture this complexity, we will use both simulated noise data sets as also the publicly available LIGO/Virgo data to mimic the types of gaps and noise transients seen in real data. These data can be time reversed to remove signals and recolored to mimic the expected noise spectrum of 3G detectors. Collaborator Craig Cahillane will help us to generate a data that that will mimic 3G detectors as closely as possible. Cahillane is a research scientist at the LIGO Hanford Observatory and an expert on calibration, detector noise, and detector performance [78–80]. The LIGO Laboratory has committed one month of Cahillane's time, supported by Caltech funds available for 3G research, to work on this project (see letter from Reitze). While the noise background in detectors at geographically well-separated locations can be assumed to be uncorrelated, the background in the three ET responses will not be so due to common seismic oscillations and gravity gradient fluctuations.[81] We will work with the ET instrument science team to simulate the expected correlations.

Waveform families: An important element of the challenges is the family of waveforms added to the data. For a given signal family, we will use the models that incorporate most of the physics. For example, in the case of black hole binaries this would mean the inclusion of higher modes, spin precession, merger and ringdown phases of the signal[82] and, possibly, overtones in the ringdown[83,84] or eccentric orbits[85] for some of the challenges. Binary neutron star waveforms will initially include tidal effects[86] and then extend to include post-merger signals in later challenges.[87] The neutron star-black hole waveform family will include precession, as would binary black holes and maximum allowed mass ratios.[88] Continuous waves would be monotonic with a slowly varying first and second derivatives of the frequency.[89] Burst signals will be sampled from a catalog of supernova waveforms.[90–94] In some cases, we will alter the waveforms depending on the specific data challenge: e.g., propagation effects different from GR, tidal effects from different equations of state, or alternative polarizations, as the challenge demands and deploy the most sophisticated waveform models available at the time.

Distribution of intrinsic and extrinsic parameters While significant uncertainty still exists, the discoveries of the LIGO and Virgo detectors have already provided clues about the mass and spin distribution of black holes in binaries.[22] Less is known about the distribution of mass and spins of neutron stars in binaries, owing to the smaller number that have been discovered to date. We will use the most up-to-date knowledge at the time of data generation to inform the distribution of the intrinsic parameters of the compact binaries we simulate. For binary black holes, we will consider at least three sub-populations, mimicking formation in galactic fields, dynamical environments, and black holes formed from Population III stars. Formation in dynamical environments will include the possibility of repeated mergers, which can result in a tail of the population with higher mass and higher spins [28].[95–97] The mass distribution of binary neutron stars will reflect the fact that most neutron stars have masses in the range $[1, 2]\ M_\odot$.[98–100]

Whenever possible, our choice for the spin distributions will be informed by population synthesis codes.[101,102] In particular, we will assume that compact binaries formed in galactic fields will have spin vectors which are roughly aligned with the orbital angular momentum, whilst dynamical formation can yield any spin direction with the same probability. The most uncertain distribution we have to fix is that of the spin magnitudes, a quantity that LIGO and Virgo's data is only starting to offer a handle on. We will consider a distribution of the spin magnitude consistent with the data from LIGO/Virgo's entire third observing run, which should be published before this award starts. The spin magnitude of neutron stars will be uniform up to the spin magnitude of the fastest pulsar discovered to date (716Hz, for B1937+21[103]). Both the orbital orientation and the sky position of the sources will be uniform on the sphere.

Merger rates: Compact binary sources in the data set will have redshift distributions informed both by theory and numerical simulations, and by the measurements made with 2G detectors. Specifically, we will assume that the formation rate of compact objects in galactic fields follows the Madau-Dickinson star-formation rate.[104] A time-delay distribution informed by population synthesis codes will be implemented to account for the delay between the formation and the merger of a binary.[105] Different prescriptions will be used for time-delay distribution of black hole and neutron star binaries.[106-108] We will use numerical simulations of globular clusters as a probe for the merger rate history in dynamical environments.[109] Similarly, the rate of mergers from Population III stars will be informed by published numerical analysis[110] and peak at redshifts larger than 5.[111] The redshift of each source will be converted into a luminosity distance—necessary for the evaluation of the gravitational-wave signal that is added to the data—using the most recent cosmological model of the Planck collaboration,[112] save for some of the data sets in Challenges B and C below, where three different cosmologies will be considered as a part of the data challenge. The value of the local merger rate for compact binary coalescences will be informed by the most recent constraints[113, 114] or revised ones that may become available at the time of data challenges.

Organization and evaluation of data challenges We plan three data releases, in the 9th, 15th, and 21st months of the grant period. Accompanying each release will be a specific set of challenges (see Sections 3.4-3.6). The first challenge will last for 6 months, while the second and third, being more complex, will last for 9 months each. The signal-rich mock data will provide ample opportunities to explore the science potential of single and multiple detectors alike, check when multiple detectors are critical and investigate what science would be lost without a network. Participants will be asked to report on at least one of the four specific challenges to qualify for evaluation, but they will also be encouraged to report as many other findings as they wish. The CE consortium wiki pages will be used to communicate details of the challenges with a clear description of how the data sets were generated, what waveform models were used for injections, the location and orientation of detectors, a list of star formation models etc.

We will develop criteria and tools for evaluating and ranking the submissions, taking into account expected systematic biases, accuracy with which the findings agree with the injections but also the computational resources used in the analysis. The outcome of the evaluation will be reported in the CE consortium web page. Each challenge will be summed up in a collaboration publication and participants will be encouraged to write papers describing their own analysis in greater detail. Publications resulting from this effort could be used to justify the science case of future 3G proposals.

Playground and challenge data sets Two months before each data release, a playground set, together with the software used to generate it, will be published to facilitate participants to generate their own stationary or non-stationary data to test their software and to fix any bugs found during the testing period. We will also publish the parameters of a subset of loud and quiet injected events in challenge data sets but revealing only a range of times and parameters instead of the actual values. This is because not all participants will be interested in running a search pipeline some would want to draw inferences from detected signals. This strategy would mean inference runs can begin immediately after data release without waiting for signals to be identified by search pipelines. At the same time there will be enough ambiguity in the information revealed that search pipelines would still be useful in addressing analysis issues. Data sets will each be year long to allow for the discovery of continuous waves and stochastic backgrounds but participants will be able to accomplish most challenges with smaller amount of data.

Data formats, access, storage and curation Challenge data sets will be created and distributed in two formats widely used in the field: HDF5 and Frame format. These formats are used by the Gravitational-Wave Open Science Center[115] to distribute the public data from the LIGO and Virgo observatories and so are well documented and widely supported by open-source software. All data sets will be published into the CERN Virtual Machine File System (CVMFS)[116] at Syracuse University for wide dissemination and access. Distribution via CVMFS will allow the data to be accessed from any Open Science Grid, LIGO Data Grid, or XSEDE computing centers used by participants in the challenge. CVMFS also provides support for installation on desktop machines, allowing challenge participants to directly explore the data sets without the need to access a computing center. CVMFS separates the distribution of file metadata from the data, allowing the full data set to be indexed with very little bandwidth and then transferring (via the widely-supported http protocol) the data when it is accessed. Caching pins the requested data to the physical storage of the requesting device for fast and efficient access. The data set will be preserved for at least three years beyond the end of the mock data challenge, or longer if storage allows.

Analysis tools to be made available The data sets will be developed using existing open-access analysis toolkits (e.g. PyCBC [117], GstLAL,[118] and LALSuite[119]). Libraries and algorithms developed to create the data sets will be released to the community through these open source libraries. Public repositories on the Cosmic Explorer GitHub will be used to host any software that falls outside the scope of existing open-scource data analysis tools (e.g. high-level codes specific to the preparation of the data sets, or codes used to analyse and compare data challenge results). Challenge participants will be required to make the software that they use to analyze the data available with the results of their analysis to encourage open and public dissemination of methods as well as results.

3.4 Challenge A

The first challenge will be a fairly simple one to encourage wider engagement but also to allow participants to test their pipelines on specific detection and measurement problems. It should be possible for the challenges in this set to be tackled by adapting open-access software, e.g. PyCBC [117], and GstLAL[118] especially since Challenge A will avoid overlapping signals by choosing a low merger rate. As an example, for a lower frequency cutoff of 5 Hz, a pair of $1.4\,M_\odot$ neutron stars at $z = 2$ coalesces in $\sim 10^3$ s. Given that the median rate of binary neutron star mergers is[113] $\mathcal{R} = 320\,\mathrm{yr}^{-1}\,\mathrm{Gpc}^{-3}$, there will be a signal in band once every five minutes within that redshift and thousands of overlapping signals in a year's worth of data. A twenty times smaller rate assures that less than $\sim 1\%$ of signals overlap and yet provide thousands of events to study the population and tens of events with signal-to-noise ratio in excess of 200 for a careful study. The same event at $z = 0$ would last for hours but occur less frequently. Thus, the merger rate would need to be chosen carefully to avoid overlapping signals. Challenge A goals are given in the box below.

CHALLENGE SET A:

Three data sets, each containing only one population of compact binary merger signals: Binaries composed of (i) two neutron stars, (ii) two black holes, and (iii) a neutron star and a black hole.

1. Recover the properties of ten loudest events in different data sets (e.g., masses, spins, sky position, polarization, and distance).
2. Determine merger rates and reconstruct the star formation rate as a function of redshift.
3. Demonstrate low-latency analysis to generate early warning alerts.
4. Identify any binary black hole merger events beyond a redshift of $z = 10, 20, 50$.

Parameter recovery Bayesian parameter estimation [120] of long-duration binary neutron star events is algorithmically straightforward but computationally demanding [121] and require acceleration techniques.[122] Signals that begin at lower frequencies stay longer in band and break certain parameter degeneracies. Binaries with black hole companions would display spin-induced precession and excite higher modes, both of which are readily observable in longer signals. Such effects help measure spin magnitudes, orbital orientation and luminosity distance—parameters that are crucial to test binary formation models.[123]

Star formation rate 3G observatories could accurately determine the merger rate as a function of redshift.[124] To derive the star formation rate from the merger rate requires a 'transfer function' that folds in a lot of unknown physics [17]. Mock data will be based on one of several competing star formation models[124] and the challenge will be to determine which one was used in the simulation.

Low-latency analysis Observing electromagnetic emissions right at the onset of a binary neutron star merger would have a massive scientific payoff[125] and vigorously pursued.[125,126] Binary neutron stars at 400 Mpc would last for a couple of hours in 3G detectors and can be detected several minutes before coalescence compared to tens of seconds that is possible with the current generation of detectors. This challenge will require not only detecting the events before merger but also determining their sky position.[127] This challenge will be streamed to mimic online analysis possibly repeated in Challenge B/C.

Events at high redshift One of the biggest puzzles in cosmology is the origin of supermassive black holes that are suspected to reside at galactic cores.[128] The first black holes might be the end product of population III stars.[129] 3G observatories should be able to detect binary black hole mergers from that era. The challenge would be to not only detect them but to unambiguously determine their redshift from the luminosity distance and ascertain that they are indeed low-mass black holes at high redshift and not more massive ones in the nearby Universe [16].

3.5 Challenge B

Challenge B will continue with compact binary coalescence signals but increases complexity in two ways: (i) the merger rates will match the best estimates at the time of the challenge, and (ii) data sets will contain all three classes of compact binary coalescence events and bursts and continuous waves. This implies that the fraction of overlapping signals will be far greater than in Challenge A, requiring more sophisticated data analysis tools. Challenge B will comprise three different data sets, each with distinct cosmologies and neutron star equations of state.

CHALLENGE SET B:

Three data sets corresponding to universes with distinct cosmological models, containing compact binary merger signals of all types at the expected rates, supernova bursts and continuous waves.

1. Estimate the parameters of overlapping binary coalescence signals.
2. Measure cosmological parameters used in the three different data sets.
3. Estimate the strength of the stochastic background due to the population of merger events.
4. Find the cold equation-of-state of dense matter used in different data sets.

Overlapping signals 3G data will contain thousands of overlapping signals from compact binary mergers. This is an entirely different analysis challenge than what is currently encountered but similar to what is expected in LISA[130,131] or future upgrades of LIGO and Virgo. This data set will allow to propose and test source characterization algorithms that can account for the simultaneous presence of several signal classes in a segment of data being analyzed. Such algorithms must also be able to properly characterize the noise spectral density of the detectors, removing or accounting for foreground contamination. Continuous waves and supernova bursts are included as a warm up exercise but are not part of this challenge.

Cosmological parameters The scientific community has started using gravitational-wave data to set constraints on the Hubble parameter[44,45,132–137] [138], though not yet in way that is competitive with electromagnetic-based methods.[112,139] Owing to the large number and high signal-to-noise ratio of sources in 3G detectors, we expect far better constraints. At the same time, the much larger reach of 3G detectors implies that one can measure the Hubble parameter and also determine the dark matter and dark energy densities, and the dark energy equation of state. Challenge B will include the release of 3 data sets, each with a different value of the cosmological parameters: one set consistent with the latest Planck measurement,[112] one consistent with the SHOES measurement,[139] and one in between. The community will have to show if and how accurately one can measure the cosmological parameters, dealing with selection effects arising in gravitational-wave[140,141] and electromagnetic-wave[142] measurements.

Neutron star equation of state The late inspiral phase of the a binary merger involving a neutron star offers precious insights into the equation of state of dense nuclear matter [38,39].[13,40,41,143] Some of the binaries in the data set will have signal-to-noise ratios of the order of thousands, enabling precise measurement of the neutron star equation of state.[144] This challenge will allow the community to verify how precisely and accurately one can measure the equation of state of neutron stars, and how that information is correlated with other quantities of interest such as the neutron star mass distribution,[145] as well as quantify any observed biases due to the presence of other signals.

Astrophysical foreground The sum of all the sources (especially binary neutron stars) which are too weak to be individually resolved, will create an astrophysical background that might hinder studying or setting upper limits on the cosmological gravitational-wave background.[146] This foreground must thus be removed, or at least accounted for, to measure the properties of a primordial background. Various methods have been proposed to perform this measurement in advanced detectors data.[122,147–149] These data sets will enable extensive testing of next-generation algorithms on a large and realistic data set.

3.6 Challenge C

The final challenge will build on the experiences gained in the first two challenges, extend to new classes of gravitational-wave sources, and introduce deviations from current models to test the community's ability to probe new physics with 3G detectors. Core-collapse supernovae signals will be included and binary neutron star signals will be extended to add post-merger signatures based on available numerical simulations. A data set will be provided in which the signals and their propagation deviates from GR. The third data release will also provide an opportunity to release or re-release data sets based on lessons learned from the first two challenges The main goals of Challenge C are listed in the box below.

CHALLENGE SET C:

Same as set B but data sets will in addition contain short bursts, weak continuous waves and one or more data sets might could contain signals that violate GR.

1. Discover and measure the parameters of supernova signals and continuous waves.
2. Look for quark-deconfinement phase transitions and explore the hot equation-of-state with binary neutron star events.
3. Verify if GR is consistent with the data sets (e.g. polarization different from GR).

Supernovae and continuous signals 3G observatories will be able to observe the gravitational waves from neutrino-driven core collapse supernovae out to a few hundred kiloparsecs and the magnetorotationally driven explosion signals out to 2 Mpc.[90–94] A variety of methods for the extraction of information from supernovae signals have been proposed that target the bounce signature, the post-bounce neutron star running, and longer term effects like the standing accretion shock instability or ring-up of the protoneutron star.[150–156] A challenge data set will be released that contains a variety of core-collapse signals from available numerical simulations, to explore the ability of 3G detectors to measure the differential rotation profile of the progenitor stars, the nuclear equation of state, and the physics of the core collapse mechanism. The problem of detecting persistent radiation from deformed neutron stars is well understood.[157] The challenge, however, is if such algorithms would work with frequent and loud foreground transients.

Phase transitions and the hot equation of state A binary neutron star can have four possible outcomes: (i) the prompt formation of a black hole, (ii) the formation of a hypermassive neutronstar that collapses to a black hole; (iii) the formation of a supramassive neutron star that collapses to a black hole; or (iv) the formation of a stable neutron star. The post-merger signature provides additional constraints on the properties of the merging stars, the nature of any electromagnetic counterpart, and unique insight into the hot nuclear equation of state. If a first-order hadron-quark phase transition at supranuclear densities exists, it may give rise to a stable extended quark matter core in the postmerger remnant and will change the gravitational wave signature of the post merger.[42] Numerical simulation of neutron star mergers remains challenging, but enough information exists to allow the creation of signals that stitch post-merger signatures to inspiral signals. Challenge C will include a data release that tests the ability of 3G detectors to extract physics from the post-merger waveform.

Deviations from GR 3G detectors could detect deviations from GR, e.g., in loud binary black hole mergers, which will be measured with exquisite precision, or in the most distant mergers as gravitational waves propagate through the observable universe [158–160].[161–164] Challenge C will include binary black hole signals that deviate from GR by including e.g. scalar-tensor modes, dispersion effects, or “hairy” black holes whose modes and/or overtones deviate from those predicted by GR.[165] The data set will challenge the community to find small but presently not excluded deviations[166] and evidence for new physics.

3.7 Deliverables, Work Plan, Measure of Success

The main deliverables are the data challenges, associated software and publications. The postdoctoral fellow (P) and graduate students (G1, G2) will collaborate on common tasks but also work on distinct problems. Their involvement is shown in parenthesis against each task in the box below. The postdoctoral fellow is expected to work concurrently on multiple tasks. It is possible that publications, especially from Challenge C, will take longer than envisaged and pursued after the grant period.

SCHEDULE AND DELIVERABLES

Y1	**Mo 1-3**	Develop or adapt tools for data generation and validation. (P, G1, G2)
	Mo 4-6	Prepare Challenge A data set, release playground data for practice. (P, G1, G2)
	Mo 7-9	Test integrity of set A and release Challenge A. (G1, G2)
	Mo 7-12	Develop evaluation criteria and verification tools. (P)
	Mo 10-12	Prepare Challenge B data set, release playground data. (P, G1, G2)
Y2	**Mo 13-15**	Test integrity of set B and release Challenge B. (P, G1, G2)
	Mo 16-18	Evaluate Challenge A submissions. (P)
	Mo 16-21	Prepare Challenge C data set test its integrity and release. (P, G1, G2)
	Mo 18-24	Write up Challenge A publications. (P, G1, G2)
Y3	**Mo 25-27**	Evaluate Challenge B submissions. (P)
	Mo 25-30	Write up Challenge B publications. (P, G1, G2)
	Mo 31-33	Evaluate Challenge C submissions. (P)
	Mo 31-36	Write up Challenge C publications. (P, G1, G2)

Risks and Mitigation Risks are inevitable in a collaborative project that depends on many factors. Here we provide main risks involved and our plan to mitigate them.

- **Risk:** Large number of tasks could derail some of the projects. **Mitigation:** At the beginning of the project develop a tangible schedule. Meet project personnel regularly to review progress.
- **Risk:** Implementation and testing gets delayed. **Mitigation:** Identify the most critical aspects of the project and prioritize their implementation. Retain projects that are close to completion and drop others; even if two of the three proposed challenges get completed that would be worthwhile.
- **Risk:** The proposed data challenges require inputs from multiple people. **Mitigation:** Provide plenty of advance notice to all participants. Keep enough buffer time to mitigate unexpected delays. Organize periodic meetings with collaborators to make steady progress.
- **Risk:** Challenge does not attract participants: **Mitigation:** Engage with the community from the start; offer participant support at workshops; encourage publications on challenges by individual groups.

Communicating with the participants The CE project has set up a global consortium of scientists who are interested in contributing to the R&D that is essential to design subsystems, address analysis challenges and work on theoretical issues. The monthly consortium calls on theory and data analysis will be the main vehicle for communicating the mock data challenges. At the start of the project we will layout a detailed plan of the schedule of mock data releases, challenge periods, evaluation criteria and receive feedback frequently on the program. Participants will be encouraged to publish their analyses in short-author-list papers to increase the visibility of the CE project and have a public record of the findings.

Coordination of tasks MIT, Penn State and Syracuse are already collaborating as part of the CE project. They will have weekly zoom calls to discuss progress on technical tasks, plan data releases and evaluations, attendance and presentation at conferences and writing of reports and publications. Additionally, a Slack channel will be set up for easy, fast and secure messaging amongst project members. We also envisage quarterly in-person visits for collaborative work when the pandemic situation improves.

Measure of success We will evaluate progress each quarter against the work plan. The success of the project will be measured against (i) timely delivery of data and software products, (ii) broad participation in the data challenges, (iii) innovation in computing and algorithmic research for 3G and (iv) participation of underrepresented minorities and early career scientists, all periodically reviewed by the PIs. The NSF report at the end of the grant will not only include a summary of the research outcomes but outline lessons learnt and future steps necessary to assure that 3G observatories can reach their full science potential.

4 Expertise Relevant to the Proposal at Collaborating Institutions

Penn State: For over a decade Sathyaprakash has been involved in developing the vision for the next generation of ground-based detectors [4, 9–12, 54, 167]. His research highlights relevant to the proposal are the following: He derived the *stationary phase approximation* to the Fourier transform of binary coalescence waveforms [168] and developed an *optimal algorithm* to search for compact binaries [168–172] both central to gravitational-wave discoveries [65, 66]. As the chair of the *Working Group on the Science Case* of the Einstein Telescope project *he organized two mock data challenges* [63, 121]. He took part in the *analysis of mock LISA data* [62, 173] and contributed to the NINJA effort [58, 59], that validated the data analysis pipelines for the space-based LISA observatory and ground-based detectors, respectively. He contributed to the idea of generating *early-warning alerts* so that astronomers could potentially observe binary neutron stars right at the onset of merger [125] and conceived and directed a project on subtracting compact binary signals in 3G data to reveal cosmological backgrounds [174]. His work on testing general relativity [175–178] [158, 179–181], measuring cosmological parameters [15] and inferring neutron star equation of state [182], will be pivotal in setting up the proposed data challenges.

MIT: Vitale is one of the six original developers of *LALInference* [120], a suite of compact binary source characterization algorithms. *LALInference* has been the parameter estimation software of reference within the LIGO-Virgo collaboration during the first three observing runs. He has worked on multiple topics related to the characterization of compact binary coalescences and their use in astrophysics including the measurement of black hole parameters [183–190] and their use to probe formation channels of compact binaries [28, 191, 192]; characterization of binary neutron stars [193–195], including their sky localization and electromagnetic counterparts [196–199]; the impact of Bayesian priors in the interpretation of LIGO and Virgo's discoveries [200, 201]; cosmological measurements [138, 202]; axion searches with gravitational waves [203, 204]; and studies of tidal effects in neutron stars [145, 205]. He has also worked on tests of GR, introducing one of the methods currently used by the collaboration in its publications [187, 206–209]. He has also worked on the astrophysical potential of 3G detectors [5, 17, 188, 210][16, 18, 211, 212] and on networks 3G and A+ detectors [213], and also worked on topics at the interface between data analysis and instrument development [214–221].
Syracuse University: Brown was the primary author of one of the algorithms used to detect gravitational waves from binary mergers [222], played a leading role in the development of the PyCBC toolkit for searches [223,224] and parameter estimation [225]. He participated in many of the early LIGO Mock Data Challenges [226] and has experience in gravitational-wave detector calibration [78,227,228] and validation using the injection of simulated signals [225, 229]. He was a lead organizer of the NINJA projects [59, 230, 231], Syracuse hosting the projects' data sets. Brown served on the executive committee of the Numerical Relativity–Analytical Relativity (NRAR) project[232] and participated in the early MLDCs [233, 234]. Brown has expertise in large-scale scientific workflows and cyberinfrastructure for gravitational-wave analysis [235–239] and in the reproducibility and replicability of computational analyses [240,241]. He contributed to the adoption of CVMFS by LIGO [116] and the Gravitational-Wave Open Science Center. Since January 2018, the Brown group has been pursuing research in multimessenger astronomy and nuclear astrophysics using public data from the LIGO and Virgo observatories [26,38,39,242–247] and the development of the CE Horizon Study [54].
Roles of External Collaborators and their *principal* interests in the data challenge tasks and analysis is shown in the Table below. Some of the collaborators will directly help with the production of challenge data sets and waveform models. A number of them are interested in the analysis of mock data and understanding how well we can answer the science promise of the next generation of gravitational-wave detectors.

Task	**Collaborators**
Noise modelling/data sets	Cahillane, Cuoco, Evans, Hild, Regimbau, Stahl, Veitch, Weinstein
Waveform models	Ajith, Buonanno, Chatziioannou, Heng, Pfeiffer,
GW search pipelines	Cannon, Creighton, Harry, Heng, Littenberg, Marka, Nerella, Nitz, Woan
Parameter estimation	Chatziioannou, Berry, Gupta, Singer, Smith, Woan, Zaldarriaga
Dense matter, dark matter	Berti, Chatziioannou, Creighton, Gupta, Lasky, Read
Cosmology	Berry, Gair, Farr, Hendry, Messenger, Regimbau, Zaldarriaga
Tests of GR	Ajith, Berti, Buonanno, Nitz, Pfeiffer, Van Den Broeck, Veitch
Astrophysical models	Ajith, Bailes, Fairhurst, Farr, Harry, Mandel, Marka, Nerella, Woan

5 Results from Prior NSF Support

The NSF award relevant to the current proposal for all the PIs is *Collaborative Research: The Next Generation of Gravitational Wave Detectors*, August 15, 2018–July 31, 2021 awarded as Brown PHY-1836702 ($240,006), Sathyaprakash PHY-1836779 ($253,940), and Vitale PHY-1836814, ($1,154,304). The main deliverable of this award is the *Horizon Study Document* [6]. The study includes the science goals for

CE and the results of a trade study to understand, with quantitative metrics, the cost-to-benefit ratio of hundreds of different 3G networks, largely based on the Fisher Information Matrix formalism [248, 249]. A logical next step is to validate the study with mock data challenges of this proposal.

Intellectual Merit **PI Sathyaprakash**, postdoctoral fellow Anuradha Gupta and graduate student Ssohrab Borhanian worked on defining the science case and the vision for a global detector network. They studied some of the science opportunities presented by 3G observatories and how detector configurations can impact the ability to realize those opportunities. Borhanian developed a python package to benchmark hundreds of different detector networks, using it for a cost-benefit analysis of candidate 3G networks [248] and has made the package public [249]. The group helped define quantitative metrics for a network's discovery potential, in addition to studying several specific science questions that could be addressed with CE [75, 158, 179, 250–253] and analysis issues that would need to be tackled [125, 174].

Broader Impacts Gupta mentored by Sathyaprakash is now a faculty member at the University of Mississippi. Borhanian defended his PhD in the summer of 2021 and now a postdoctoral fellow at Jena, Germany. Sathyaprakash organized the *Physics and Astronomy at the eXtreme* (PAX) workshop in 2018, 2019, and 2021, and a week-long inaugural *Cosmic Explorer Conference* in 2020. He presented the science potential of CE at 12 international conferences and workshops and spoke at three public events. He is a member of the *3G Sub-Committee*[57] and a co-chair of its *Science Case Team*. He contributed to five *Astro2020 Decadal Survey White Papers* on the science capability of 3G observatories [9–12, 54]. He is a convener of the Snowmass21's[254] topical group on *Cosmic Probes of Fundamental Physics*.[255]

Intellectual Merit: **PI Vitale** and graduate student Ken Ng have worked on various topics related to the scientific potential of CE (more broadly, 3G gravitational-wave detectors). Ng and Vitale collaborated with Borhanian in ensuring that GWBENCH used to benchmark 3G networks is reliable, by cross checking its results against more expensive Markov Chain Monte Carlo simulations. They have shown how 3G detectors can measure the merger rate of black holes across cosmic history [17] [16, 18], and the time-delay distribution of neutron star binaries [212]. Ng and Vitale have also shown how 3G detectors have the potential to yield significant constraints on the existence of ultralight bosons, when used jointly with the space-based LISA observatory [211].

Broader Impacts: Vitale supervises a group of 3 students and 3 postdocs (2 of which are NASA Einstein/Hubble fellows), with a gender ratio of 50%. Ken Ng is the only student partially supported by this grant. By the time he graduates, a significant part of his work will be about astrophysics with 3G detectors. Ng and Vitale have given several talks partially or entirely about the scientific potential of next-generation detectors, including an invited talk at the April 2018 APS meeting. Vitale has been involved with the writing of several white papers related to 3G detectors [8, 11, 54, 256], for the Astro2020 Decadal.

Intellectual Merit: **PI Brown** worked on the detection and measurement of core collapse supernovae with CE. With Adam Burrows, Brown determined how to optimize 3G detectors to maximize the range to detect core-collapse supernovae [94]. Brown's student Chaitanya Afle has used supernovae simulations that explore a variety of progenitor core rotation rates and nuclear equations of state[257] to examine the ability of current and future observatories to determine these properties using gravitational-wave parameter estimation [156]. Brown was one of the lead writers for the CE Astro2020 Decadal Survey submission.[54]

Broader Impacts: Brown's five most recent Ph.D. students are from underrepresented backgrounds and include three women of color and two Hispanic men. Two of these students currently hold prize postdoctoral fellowships (Los Alamos National Laboratory Directors Fellowship and Stephen Hawking Fellowship), two hold data science positions in industry (iRobot and Johns Hopkins Applied Physics Laboratory), and one is a postdoc with the N3AS NSF Physics Frontier Center. Brown was the lead organizer for the 2019 Kavli Institute for Theoretical Physics Program "The New Era of Gravitational-Wave Physics and

Astrophysics" that brought together a diverse group of scientists to study multimessenger observations of merging binaries. Brown manages the computing infrastructure for the CE Consortium.

6 Broader Impacts

Gravitational-wave astronomy is triggering new research in black holes, astrophysics and cosmology, areas that are popular amongst school teachers, students, and the general public. We will enhance the broader impact of this emerging area by: (i) establishing a cloud-based access to high performance computing resources for K-12 teachers and students, (ii) facilitating education and research in undergraduates, schools students, particularly underrepresented minorities and (iii) continuing to host the PAX series of workshops.

HPC access to K-12 School Students and Teachers For precollege education, current frameworks in K-12 STEM,[258] computer science (CS)[259] and math[260] education promote engaging students in the disciplinary practices of professionals in order to learn important concepts. Recent reporting suggests that students' access to high-quality CS and STEM education varies significantly, and that, too often, students of color, low socioeconomic status students, and girls have less access to opportunities than those available for their wealthier, white, and male peers.[261]

While the number of Pennsylvania high schools offering CS classes has remained consistent, the most commonly reported challenges include a lack of qualified teachers.[262] Secondary teachers with little experience in research find the shift to incorporating CS into STEM instruction to be challenging, but teacher education and professional development programs can respond to this need. Access to adequate computing resources and effective professional learning programs will enable teachers to deepen their content and pedagogical knowledge as well as opportunities to practice new instructional approaches in their classrooms, which can lead to improved student achievement.[263,264] Three primary objectives for programmatic success will guide our activities and evaluation:

HPC ACCESS TO STUDENTS AND TEACHERS

1. Expand infrastructure for broader impacts by establishing web-based access to high-performance computing resources to secondary-level teachers and students.
2. Enhance teachers' understanding of the practices of STEM (+C) research, particularly in the areas of astronomy and physics through a summer workshop.
3. Improve teachers' ability to use the practices of researchers to teach content, aligned with current STEM standards by involving them in simple data challenges.

In collaboration with Penn State's Institute for Computational and Data Sciences (ICDS) and the Center for Science and the Schools (CSATS) (partly funded by NSF grant PHY-2012083), Sathyaprakash has initiated the establishment of cloud-based access to high-performance computing (HPC) resources for K-12 teachers and students and we will contribute to that effort by including simple data challenges (e.g., matched filtering) in that program. Since many Pennsylvania school districts have outdated computer resources or have purchased less expensive devices, students are often limited to class-room projects that require limited to no computing power. This is counter to the nation's needs of a prepared future workforce in STEM fields. In collaboration with CSATS we will conduct summer workshops to train teachers in the use of HPC and the data challenges. Teachers who express interest in implementing the workshop activities in their classrooms will be supported by the PIs, postdoc and CSATS faculty.

ICDS will provide access to 100 cores and 5 TB of storage to K-12 students and teachers to accomplish the goals stated in the box above. The resources will also include dual port 40/100GB Ethernet connectivity, authentication for login to ensure security, secure login via a web based interface for accessibility, access to software licenses and software stack, support for administration of equipment and software.

Undergraduate education and outreach As the scientific part of the proposed work aims at helping the scientific community be ready for the prospects and challenges of the next generation of GW detectors, PIs will work with undergraduate students to prepare the next generation of scientists. While some students will be recruited, e.g., via the MIT UROP program,[265] which encourages undergraduates to become involved with research as early as possible, we will actively work to specifically recruit students from underrepresented minorities, low socioeconomic and first generation backgrounds. Vitale will recruit through the MIT Summer Research Program[266] (MSRP) whose mission is to increase the number of URM students in STEM. MSRP students are selected from colleges across the USA, and spend one summer doing active research at MIT. Vitale will also reach out to various MIT student associations (e.g. MIT's African Students' Associations and MIT Association of Puerto Rican Students) to encourage students from those groups to get involved with undergraduate research in his group.

Data analysis methods, and tools such as machine learning, are assuming a more prominent role in the skill set of a successful scientist and pave the way to multiple, well-sought after jobs. The proposed work naturally presents many opportunities to learn and apply these methods. All students will be invited to join weekly group meetings of the collaboration where they will interact with the broader group and present updates on their work. Reaching out to the general public will be a key part of the proposed work. Once a year for the duration of the proposal, Vitale will hold an online or in-person lecture for the general public, targeting youth and families and advertised through MIT's outreach page[267] as well as through the network of high school teachers that Vitale has built in the context of his CAREER award.

Including students from underrepresented backgrounds Central to this proposal is the training of graduate students. Co-PI Brown has actively worked to recruit and mentor women and students of color in his research group. Brown is a co-PI of the NSF PAARE award "Catching a New Wave: the CSUF-Syracuse Partnership for Inclusion of Underrepresented Groups in Gravitational-wave Astronomy." This partnership between Syracuse University and California State University Fullerton (CSUF) aims to significantly increase the number of students from underrepresented groups, in particular Hispanic and Latino/a students.The PAARE is in its sixth year and has provided funding that supported four Hispanic men and one Black woman to earn their Ph.D. in physics from Syracuse University. After fellowships in their early years, PAARE students are hired as research assistants supported by other NSF awards. This proposal will provide support and training for underrepresented students who wish to engage in 3G research, and broaden opportunities for students to include MIT and Penn State.

Challenge Workshops and Training The success of this project relies largely on the participation of external collaborators. We will host yearly, 4-day workshops with the dual goal of offering training to and receiving feedback from challenge participants. They will consist of lectures and tutorials on data cleaning, search pipelines, Bayesian inference, machine learning, etc. Lectures will be delivered by project personnel and collaborators working at the forefront of data analysis. The project will partially support the attendance of about 20 participants, especially early career scientists and underrepresented minorities. Additionally, the annual PAX meetings will be a forum to debate the results of data challenges with a broader audience. Participants will be offered mentoring throughout the challenge period. A ticketing system will be used to address problems and answer questions.

Evaluation of Broader Impacts Evaluation of the proposed program will provide an in-depth view of the impact of the educational programming for K-12 students and teachers. The Guskey model will be used to evaluate professional development (PD) of teachers at multiple levels and to gauge the success of this program.[268] Using this model, we examine teachers' reactions to the PD, learning from the PD, and translation of that learning into their professional practice. Public lectures will be evaluated by asking the attendees to fill out an online questionnaire whose results will be used to improve the next iteration.

References

[1] When citing references, we will cite references in red **[...]** for publications supported by previous NSF awards, in blue **[...]** for the rest of our publications and a superscript for all other papers, URLs, etc., including publications by the LIGO and Virgo Collaborations where we are co-authors.

[2] Benjamin P Abbott et al., LIGO Scientific Collaboration , *Exploring the Sensitivity of Next Generation Gravitational Wave Detectors*, *Class. Quant. Grav.* **34** (2017) 044001 [`1607.08697`].

[3] M Punturo, M Abernathy, F Acernese, B Allen, N Andersson, K Arun, F Barone, B Barr, M Barsuglia, M Beker, N Beveridge, S Birindelli, S Bose, L Bosi, S Braccini, C Bradaschia, T Bulik, E Calloni, G Cella, E Chassande Mottin, S Chelkowski, A Chincarini, J Clark, E Coccia, C Colacino, J Colas, A Cumming, L Cunningham, E Cuoco, S Danilishin, K Danzmann, G De Luca, R De Salvo, T Dent, R De Rosa, L Di Fiore, A Di Virgilio, M Doets, V Fafone, P Falferi, R Flaminio, J Franc, F Frasconi, A Freise, P Fulda, J Gair, G Gemme, A Gennai, A Giazotto, K Glampedakis, M Granata, H Grote, G Guidi, G Hammond, M Hannam, J Harms, D Heinert, M Hendry, I Heng, E Hennes, S Hild, J Hough, S Husa, S Huttner, G Jones, F Khalili, K Kokeyama, K Kokkotas, B Krishnan, M Lorenzini, H Lück, E Majorana, I Mandel, V Mandic, I Martin, C Michel, Y Minenkov, N Morgado, S Mosca, B Mours, H Müller–Ebhardt, P Murray, R Nawrodt, J Nelson, R Oshaughnessy, C D Ott, C Palomba, A Paoli, G Parguez, A Pasqualetti, R Passaquieti, D Passuello, L Pinard, R Poggiani, P Popolizio, M Prato, P Puppo, D Rabeling, P Rapagnani, J Read, T Regimbau, H Rehbein, S Reid, L Rezzolla, F Ricci, F Richard, A Rocchi, S Rowan, A Rüdiger, B Sassolas, B Sathyaprakash, R Schnabel, C Schwarz, P Seidel, A Sintes, K Somiya, F Speirits, K Strain, S Strigin, P Sutton, S Tarabrin, A Thüring, J van den Brand, C van Leewen, M van Veggel, C van den Broeck, A Vecchio, J Veitch, F Vetrano, A Vicere, S Vyatchanin, B Willke, G Woan, P Wolfango, and K Yamamoto, *The Einstein Telescope: A third-generation gravitational wave observatory*, *Class. Quant. Grav.* **27** (2010) 194002.

[4] B Sathyaprakash, M Abernathy, F Acernese, P Ajith, B Allen, P Amaro-Seoane, N Andersson, S Aoudia, K Arun, P Astone, B Krishnan, L Barack, F Barone, B Barr, M Barsuglia, M Bassan, R Bassiri, M Beker, N Beveridge, M Bizouard, C Bond, S Bose, L Bosi, S Braccini, C Bradaschia, M Britzger, F Brueckner, T Bulik, H J Bulten, O Burmeister, E Calloni, P Campsie, L Carbone, G Cella, E Chalkley, E Chassande-Mottin, S Chelkowski, A Chincarini, A Di Cintio, J Clark, E Coccia, C N Colacino, J Colas, A Colla, A Corsi, A Cumming, L Cunningham, E Cuoco, S Danilishin, K Danzmann, E Daw, R De Salvo, W Del Pozzo, T Dent, R De Rosa, L Di Fiore, M Di Paolo Emilio, A Di Virgilio, A Dietz, M Doets, J Dueck, M Edwards, V Fafone, S Fairhurst, P Falferi, M Favata, V Ferrari, F Ferrini, F Fidecaro, R Flaminio, J Franc, F Frasconi, A Freise, D Friedrich, P Fulda, J Gair, M Galimberti, G Gemme, E Genin, A Gennai, A Giazotto, K Glampedakis, S Gossan, R Gouaty, C Graef, W Graham, M Granata, H Grote, G Guidi, J Hallam, G Hammond, M Hannam, J Harms, K Haughian, I Hawke, D Heinert, M Hendry, I Heng, E Hennes, S Hild, J Hough, D Huet, S Husa, S Huttner, B Iyer, D I Jones, G Jones, I Kamaretsos, C Kant Mishra, F Kawazoe, F Khalili, B Kley, K Kokeyama, K Kokkotas, S Kroker, R Kumar, K Kuroda, B Lagrange, N Lastzka, T G F Li, M Lorenzini, G Losurdo, H Lück, E Majorana, V Malvezzi, I Mandel, V Mandic, S Marka, F Marin, F Marion, J Marque, I Martin, D Mc Leod, D Mckechan, M Mehmet, C Michel, Y Minenkov, N Morgado, A Morgia, S Mosca, L Moscatelli, B Mours, H Müller-Ebhardt, P Murray, L Naticchioni, R Nawrodt, J Nelson, R O' Shaughnessy, C D Ott, C Palomba, A Paoli, G Parguez, A Pasqualetti, R Passaquieti, D Passuello, M Perciballi, F Piergiovanni, L Pinard, M Pitkin, W Plastino, M Plissi, R Poggiani, P Popolizio, E Porter, M Prato, G Prodi, M Punturo, P Puppo, D Rabeling, I Racz, P Rapagnani, V Re, J Read,

T Regimbau, H Rehbein, S Reid, F Ricci, F Richard, C Robinson, A Rocchi, R Romano, S Rowan, A Rüdiger, A Samblowski, L Santamaría, B Sassolas, R Schilling, P Schmidt, R Schnabel, B Schutz, C Schwarz, J Scott, P Seidel, A M Sintes, K Somiya, C F Sopuerta, B Sorazu, F Speirits, L Storchi, K Strain, S Strigin, P Sutton, S Tarabrin, B Taylor, A Thürin, K Tokmakov, M Tonelli, H Tournefier, R Vaccarone, H Vahlbruch, J F J van den Brand, C Van Den Broeck, S van der Putten, M van Veggel, A Vecchio, J Veitch, F Vetrano, A Vicere, S Vyatchanin, P Weßels, B Willke, W Winkler, G Woan, A Woodcraft, and K Yamamoto, *Scientific Objectives of Einstein Telescope*, *Class. Quant. Grav.* **29** (2012) 124013 [`1206.0331`].

[5] Salvatore Vitale and Matthew Evans, *Parameter estimation for binary black holes with networks of third generation gravitational-wave detectors*, *Phys. Rev.* **D95** (2017) 064052 [`1610.06917`].

[6] Matthew Evans, Rana X Adhikari, Chaitanya Afle, Stefan W. Ballmer, Sylvia Biscoveanu, Ssohrab Borhanian, Duncan A. Brown, Yanbei Chen, Robert Eisenstein, Alexandra Gruson, Anuradha Gupta, Evan D. Hall, Rachael Huxford, Brittany Kamai, Rahul Kashyap, Jeff S. Kissel, Kevin Kuns, Philippe Landry, Amber Lenon, Geoffrey Lovelace, Lee McCuller, Ken K. Y. Ng, Alexander H. Nitz, Jocelyn Read, B. S. Sathyaprakash, David H. Shoemaker, Bram J. J. Slagmolen, Joshua R. Smith, Varun Srivastava, Ling Sun, Salvatore Vitale, and Rainer Weiss, *A Horizon Study for Cosmic Explorer: Science, Observatories, and Community*, [`2109.09882`].

[7] Michele Maggiore, Chris Van Den Broeck, Nicola Bartolo, Enis Belgacem, Daniele Bertacca, Marie Anne Bizouard, Marica Branchesi, Sebastien Clesse, Stefano Foffa, Juan García-Bellido, Stefan Grimm, Jan Harms, Tanja Hinderer, Sabino Matarrese, Cristiano Palomba, Marco Peloso, Angelo Ricciardone, and Mairi Sakellariadou, *Science Case for the Einstein Telescope*, *JCAP* **03** (2020) 050 [`1912.02622`].

[8] David Reitze, LIGO Laboratory: California Institute of Technology, LIGO Laboratory: Massachusetts Institute of Technology, LIGO Hanford Observatory, and LIGO Livingston Observatory, THE LIGO LABORATORY , *The US Program in Ground-Based Gravitational Wave Science: Contribution from the LIGO Laboratory*, *Bull. Am. Astron. Soc.* **51** (2019) 141 [`1903.04615`].

[9] Bangalore Sathyaprakash, Enis Belgacem, Daniele Bertacca, Chiara Caprini, Giulia Cusin, Yves Dirian, Xilong Fan, Daniel Figueroa, Stefano Foffa, Evan Hall, Jan Harms, Michele Maggiore, Vuk Mand ic, Andrew Matas, Tania Regimbau, Mairi Sakellariadou, and Eric Thrane, *Cosmology and the Early Universe*, [`1903.09260`].

[10] Bangalore Sathyaprakash, Matthew Bailes, Mansi M. Kasliwal, Samaya Nissanke, Shreya Anand, Igor Andreoni, Monica Colpi, Michael Coughlin, Evan Hall, Vicky Kalogera, Dan Kasen, and Alberto Sesana, *Multimessenger Universe with Gravitational Waves from Binaries*, [`1903.09277`].

[11] Bangalore Sathyaprakash, Alessandra Buonanno, Luis Lehner, Chris Van Den Broeck, P. Ajith, Archisman Ghosh, Katerina Chatziioannou, Paolo Pani, Michael Puerrer, Thomas Sotiriou, Salvatore Vitale, Nicolas Yunes, K. G. Arun, Enrico Barausse, Masha Baryakhtar, Richard Brito, Andrea Maselli, Tim Dietrich, William East, Ian Harry, Tanja Hinderer, Geraint Pratten, Lijing Shao, Nicola Tamanini, Maaretn van de Meent, Vijay Varma, Justin Vines, Huan Yang, and Miguel Zumalacarregui, *Extreme Gravity and Fundamental Physics*, [`1903.09221`].

[12] Vicky Kalogera, Christopher P. L. Berry, Monica Colpi, Steve Fairhurst, Stephen Justham, Ilya Mandel, Alberto Mangiagli, Michela Mapelli, Cameron Mills, B. S. Sathyaprakash, Raffaella Schneider, Thomas Tauris, and Rosa Valiante, *Deeper, Wider, Sharper: Next-Generation Ground-Based Gravitational-Wave Observations of Binary Black Holes*, [1903.09220].

[13] James M. Lattimer, *Neutron Star Mass and Radius Measurements*, *Universe* **5** (2019) 159.

[14] Andreas Bauswein, Niels-Uwe Friedrich Bastian, David Blaschke, Katerina Chatziioannou, James Alexander Clark, Tobias Fischer, Hans-Thomas Janka, Oliver Just, Micaela Oertel, and Nikolaos Stergioulas, *Equation-of-state Constraints and the QCD Phase Transition in the Era of Gravitational-Wave Astronomy*, *AIP Conf. Proc.* **2127** (2019) 020013 [1904.01306].

[15] B. S. Sathyaprakash and B. F. Schutz, *Physics, Astrophysics and Cosmology with Gravitational Waves*, *Living Rev. Rel.* **12** (2009) 2 [0903.0338].

[16] Ken K. Y. Ng, Shiqi Chen, Boris Goncharov, Ulyana Dupletsa, Ssohrab Borhanian, Marica Branchesi, Jan Harms, Michele Maggiore, B. S. Sathyaprakash, and Salvatore Vitale, *On the single-event-based identification of primordial black hole mergers at cosmological distances*, [2108.07276].

[17] Salvatore Vitale, Will M. Farr, Ken Ng, and Carl L. Rodriguez, *Measuring the star formation rate with gravitational waves from binary black holes*, *Astrophys. J. Lett.* **886** (2019) L1 [1808.00901].

[18] Ken K. Y. Ng, Salvatore Vitale, Will M. Farr, and Carl L. Rodriguez, *Probing multiple populations of compact binaries with third-generation gravitational-wave detectors*, *Astrophys. J. Lett.* **913** (2021) L5 [2012.09876].

[19] Amber K. Lenon, Duncan A. Brown, and Alexander H. Nitz, *Eccentric binary neutron star search prospects for Cosmic Explorer*, *Phys. Rev. D* **104** (2021) 063011 [2103.14088].

[20] Kaze W. K. Wong and Davide Gerosa, *Machine-learning interpolation of population-synthesis simulations to interpret gravitational-wave observations: a case study*, *Phys. Rev.* **D100** (2019) 083015 [1909.06373].

[21] Stefano Schmidt, Matteo Breschi, Rossella Gamba, Giulia Pagano, Piero Rettegno, Gunnar Riemenschneider, Sebastiano Bernuzzi, Alessandro Nagar, and Walter Del Pozzo, *Machine Learning Gravitational Waves from Binary Black Hole Mergers*, [2011.01958].

[22] R. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run*, [2010.14527].

[23] R. Abbott et al., LIGO SCIENTIFIC, VIRGO, KAGRA , *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*, [2111.03606].

[24] Barak Zackay, Tejaswi Venumadhav, Liang Dai, Javier Roulet, and Matias Zaldarriaga, *Highly spinning and aligned binary black hole merger in the Advanced LIGO first observing run*, *Phys. Rev.* **D100** (2019) 023007 [1902.10331].

[25] Tejaswi Venumadhav, Barak Zackay, Javier Roulet, Liang Dai, and Matias Zaldarriaga, *New binary black hole mergers in the second observing run of Advanced LIGO and Advanced Virgo*, *Phys. Rev.* **D101** (2020) 083030 [1904.07214].

[26] Alexander H. Nitz, Collin Capano, Alex B. Nielsen, Steven Reyes, Rebecca White, Duncan A. Brown, and Badri Krishnan, *1-OGC: The first open gravitational-wave catalog of binary mergers from analysis of public Advanced LIGO data*, *Astrophys. J.* **872** (2019) 195 [1811.01921].

[27] R. Abbott et al., LIGO SCIENTIFIC, VIRGO , *GW190521: A Binary Black Hole Merger with a Total Mass of* $150 M_{\odot}$, *Phys. Rev. Lett.* **125** (2020) 101102 [2009.01075].

[28] Katerina Chatziioannou, Roberto Cotesta, Sudarshan Ghonge, Jacob Lange, Ken K. Y. Ng, Juan Calderón Bustillo, James Clark, Carl-Johan Haster, Sebastian Khan, Michael Pürrer, Vivien Raymond, Salvatore Vitale, Nousha Afshari, Stanislav Babak, Kevin Barkett, Jonathan Blackman, Alejandro Bohé, Michael Boyle, Alessandra Buonanno, Manuela Campanelli, Gregorio Carullo, Tony Chu, Eric Flynn, Heather Fong, Alyssa Garcia, Matthew Giesler, Maria Haney, Mark Hannam, Ian Harry, James Healy, Daniel Hemberger, Ian Hinder, Karan Jani, Bhavesh Khamersa, Lawrence E. Kidder, Prayush Kumar, Pablo Laguna, Carlos O. Lousto, Geoffrey Lovelace, Tyson B. Littenberg, Lionel London, Margaret Millhouse, Laura K. Nuttall, Frank Ohme, Richard O'Shaughnessy, Serguei Ossokine, Francesco Pannarale, Patricia Schmidt, Harald P. Pfeiffer, Mark A. Scheel, Lijing Shao, Deirdre Shoemaker, Bela Szilagyi, Andrea Taracchini, Saul A. Teukolsky, and Yosef Zlochower, *On the properties of the massive binary black hole merger GW170729*, *Phys. Rev.* **D100** (2019) 104015 [1903.06742].

[29] Barak Zackay, Liang Dai, Tejaswi Venumadhav, Javier Roulet, and Matias Zaldarriaga, *Detecting Gravitational Waves With Disparate Detector Responses: Two New Binary Black Hole Mergers*, [1910.09528].

[30] R. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *GW190521: A Binary Black Hole Merger with a Total Mass of* $150 M_{\odot}$, *Phys. Rev. Lett.* **125** (2020) 101102 [2009.01075].

[31] R. Abbott et al., LIGO SCIENTIFIC, VIRGO , *GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object*, *Astrophys. J. Lett.* **896** (2020) L44 [2006.12611].

[32] R. Abbott et al., LIGO SCIENTIFIC, KAGRA, VIRGO , *Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences*, *Astrophys. J. Lett.* **915** (2021) L5 [2106.15163].

[33] Jose María Ezquiaga and Miguel Zumalacárregui, *Dark Energy After GW170817: Dead Ends and the Road Ahead*, *Phys. Rev. Lett.* **119** (2017) 251304 [1710.05901].

[34] David Langlois, Ryo Saito, Daisuke Yamauchi, and Karim Noui, *Scalar-tensor theories and modified gravity in the wake of GW170817*, *Phys. Rev.* **D97** (2018) 061501 [1711.07403].

[35] M. A. Green, J. W. Moffat, and V. T. Toth, *Modified Gravity (MOG), the speed of gravitational radiation and the event GW170817/GRB170817A*, *Phys. Lett.* **B780** (2018) 300 [1710.11177].

[36] Claudia de Rham and Scott Melville, *Gravitational Rainbows: LIGO and Dark Energy at its Cutoff*, *Phys. Rev. Lett.* **121** (2018) 221101 [1806.09417].

[37] Luca Amendola, Dario Bettoni, Guillem Domènech, and Adalto R. Gomes, *Doppelgänger dark energy: modified gravity with non-universal couplings after GW170817*, *JCAP* **1806** (2018) 029 [`1803.06368`].

[38] Soumi De, Daniel Finstad, James M. Lattimer, Duncan A. Brown, Edo Berger, and Christopher M. Biwer, *Tidal Deformabilities and Radii of Neutron Stars from the Observation of GW170817*, *Phys. Rev. Lett.* **121** (2018) 091102 [`1804.08583`].

[39] Collin D. Capano, Ingo Tews, Stephanie M. Brown, Ben Margalit, Soumi De, Sumit Kumar, Duncan A. Brown, Badri Krishnan, and Sanjay Reddy, *Stringent constraints on neutron-star radii from multimessenger observations and nuclear theory*, *Nature Astron.* **4** (2020) 625 [`1908.10352`].

[40] B. P. Abbott et al., LIGO Scientific Collaboration, Virgo Collaboration , *GW170817: Measurements of neutron star radii and equation of state*, *Phys. Rev. Lett.* **121** (2018) 161101 [`1805.11581`].

[41] David Radice, Albino Perego, Francesco Zappa, and Sebastiano Bernuzzi, *GW170817: Joint Constraint on the Neutron Star Equation of State from Multimessenger Observations*, *Astrophys. J. Lett.* **852** (2018) L29 [`1711.03647`].

[42] Andreas Bauswein, Niels-Uwe F. Bastian, David B. Blaschke, Katerina Chatziioannou, James A. Clark, Tobias Fischer, and Micaela Oertel, *Identifying a first-order phase transition in neutron star mergers through gravitational waves*, *Phys. Rev. Lett.* **122** (2019) 061102 [`1809.01116`].

[43] Bernard F. Schutz and Clifford M. Will, *Black hole normal modes: A semianalytic approach*, *Astrophys. J.* **L291** (1985) 33.

[44] Daniel E. Holz and Scott A. Hughes, *Using gravitational-wave standard sirens*, *Astrophys. J.* **629** (2005) 15 [`astro-ph/0504616`].

[45] B. P. Abbott et al., LIGO Scientific Collaboration, Virgo Collaboration, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER , *A gravitational-wave standard siren measurement of the Hubble constant*, *Nature* **551** (2017) 85 [`1710.05835`].

[46] Daniel J. Mortlock, Stephen M. Feeney, Hiranya V. Peiris, Andrew R. Williamson, and Samaya M. Nissanke, *Unbiased Hubble constant estimation from binary neutron star mergers*, *Phys. Rev.* **D100** (2019) 103523 [`1811.11723`].

[47] Kenta Hotokezaka, Ehud Nakar, Ore Gottlieb, Samaya Nissanke, Kento Masuda, Gregg Hallinan, Kunal P. Mooley, and Adam.T. Deller, *A Hubble constant measurement from superluminal motion of the jet in GW170817*, *Nat. Astron.* **3** (2019) 940 [`1806.10596`].

[48] Nicolas Yunes, Kent Yagi, and Frans Pretorius, *Theoretical Physics Implications of the Binary Black-Hole Mergers GW150914 and GW151226*, *Phys. Rev.* **D94** (2016) 084002 [`1603.08955`].

[49] B. P. Abbott et al., LIGO Scientific Collaboration, Virgo Collaboration , *Tests of general relativity with GW150914*, *Phys. Rev. Lett.* **116** (2016) 221101 [`1602.03841`].

[50] B. P. Abbott et al., LIGO Scientific Collaboration, Virgo Collaboration , *Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1*, *Phys. Rev.* **D100** (2019) 104036 [`1903.04467`].

[51] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *Tests of General Relativity with GW170817*, *Phys. Rev. Lett.* **123** (2019) 011102 [`1811.00364`].

[52] B. P. Abbott et al., KAGRA, LIGO SCIENTIFIC, VIRGO, VIRGO , *Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA*, *Living Rev. Rel.* **21** (2018) 3 [`1304.0670`].

[53] Parameters of the A+ design curve: `https://dcc.ligo.org/LIGO-T1800042/public`.

[54] David Reitze, Rana X. Adhikari, Stefan Ballmer, Barry Barish, Lisa Barsotti, GariLynn Billingsley, Duncan A. Brown, Yanbei Chen, Dennis Coyne, Robert Eisenstein, Matthew Evans, Peter Fritschel, Evan D. Hall, Albert Lazzarini, Geoffrey Lovelace, Jocelyn Read, B. S. Sathyaprakash, David Shoemaker, Joshua Smith, Calum Torrie, Salvatore Vitale, Rainer Weiss, Christopher Wipf, and Michael Zucker, *Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO*, *Bull. Am. Astron. Soc.* **51** (2019) 035 [`1907.04833`].

[55] European Strategy for Research Infrastructures: `https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021`.

[56] Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021) `https://www.nap.edu/read/26141/chapter/1`.

[57] Reports of the 3G subcommittee of the Gravitational-Wave International Committee can be found at: `https://gwic.ligo.org/3Gsubcomm/documents.shtml`.

[58] Laura Cadonati, Benjamin Aylott, John G Baker, William D Boggs, Michael Boyle, Patrick R Brady, Duncan A Brown, Bernd Brügmann, Luisa T Buchman, Alessandra Buonanno, Jordan Camp, Manuela Campanelli, Joan Centrella, Shourov Chatterji, Nelson Christensen, Tony Chu, Peter Diener, Nils Dorband, Zachariah B Etienne, Joshua Faber, Stephen Fairhurst, Benjamin Farr, Sebastian Fischetti, Gianluca Guidi, Lisa M Goggin, Mark Hannam, Frank Herrmann, Ian Hinder, Sascha Husa, Vicky Kalogera, Drew Keppel, Lawrence E Kidder, Bernard J Kelly, Badri Krishnan, Pablo Laguna, Carlos O Lousto, Ilya Mandel, Pedro Marronetti, Richard Matzner, Sean T McWilliams, Keith D Matthews, R Adam Mercer, Satyanarayan R P Mohapatra, Abdul H Mroué, Hiroyuki Nakano, Evan Ochsner, Yi Pan, Larne Pekowsky, Harald P Pfeiffer, Denis Pollney, Frans Pretorius, Vivien Raymond, Christian Reisswig, Luciano Rezzolla, Oliver Rinne, Craig Robinson, Christian Röver, Lucía Santamaría, Bangalore Sathyaprakash, Mark A Scheel, Erik Schnetter, Jennifer Seiler, Stuart L Shapiro, Deirdre Shoemaker, Ulrich Sperhake, Alexander Stroeer, Riccardo Sturani, Wolfgang Tichy, Yuk Tung Liu, Marc van der Sluys, James R van Meter, Ruslan Vaulin, Alberto Vecchio, John Veitch, Andrea Viceré, John T Whelan, and Yosef Zlochower, *Status of NINJA: The Numerical INJection Analysis project*, *Class. Quant. Grav.* **26** (2009) 114008 [`0905.4227`].

[59] Benjamin Aylott, John G Baker, William D Boggs, Michael Boyle, Patrick R Brady, Duncan A Brown, Bernd Brügmann, Luisa T Buchman, Alessandra Buonanno, Laura Cadonati, Jordan Camp, Manuela Campanelli, Joan Centrella, Shourov Chatterji, Nelson Christensen, Tony Chu, Peter Diener, Nils Dorband, Zachariah B Etienne, Joshua Faber, Stephen Fairhurst, Benjamin Farr, Sebastian Fischetti, Gianluca Guidi, Lisa M Goggin, Mark Hannam, Frank Herrmann, Ian Hinder, Sascha Husa, Vicky Kalogera, Drew Keppel, Lawrence E. Kidder, Bernard J Kelly, Badri

Krishnan, Pablo Laguna, Carlos O Lousto, Ilya Mandel, Pedro Marronetti, Richard Matzner, Sean T McWilliams, Keith D Matthews, R Adam Mercer, Satyanarayan R P Mohapatra, Abdul H Mroué, Hiroyuki Nakano, Evan Ochsner, Yi Pan, Larne Pekowsky, H arald P Pfeiffer, Denis Pollney, Frans Pretorius, Vivien Raymond, Christian Reisswig, Luciano Rezzolla, Oliver Rinne, Craig Robinson, Christian Röver, Lucía Santamaría, Bangalore Sathyaprakash, Mark A Scheel, Erik Schnetter, Jennifer Seiler, Stuart L Shapiro, Deirdre Shoemaker, Ulrich Sperhake, Alexander Stroeer, Riccardo Sturani, Wolfgang Tichy, Yuk Tung Liu, Marc van der Sluys, James R van Meter, Ruslan Vaulin, Alberto Vecchio, John Veitch, Andrea Viceré, John T Whelan, and Yosef Zlochower, *Testing gravitational-wave searches with numerical relativity waveforms: Results from the first Numerical INJection Analysis (NINJA) project*, *Class. Quant. Grav.* **26** (2009) 165008 [`0901.4399`].

[60] Keith A. Arnaud, Stanislav Babak, John G. Baker, Matthew J. Benacquista, Neil J. Cornish, Curt Cutler, Shane L. Larson, B. S. Sathyaprakash, Michele Vallisneri, Alberto Vecchio, and Jean-Yves Vinet, *The Mock LISA Data Challenges: An overview*, *AIP Conf. Proc.* **873** (2006) 619 [`gr-qc/0609105`].

[61] Stanislav Babak, John G Baker, Matthew J Benacquista, Neil J Cornish, Jeff Crowder, Shane L Larson, Eric Plagnol, Edward K Porter, Michele Vallisneri, Alberto Vecchio, Keith Arnaud, Leor Barack, Arkadiusz Błaut, Curt Cutler, Stephen Fairhurst, Jonathan Gair, Xuefei Gong, Ian Harry, Deepak Khurana, Andrzej Królak, Ilya Mandel, Reinhard Prix, B S Sathyaprakash, Pavlin Savov, Yu Shang, Miquel Trias, John Veitch, Yan Wang, Linqing Wen, and John T Whelan, *The Mock LISA Data Challenges: From Challenge 1B to Challenge 3*, *Class. Quant. Grav.* **25** (2008) 184026 [`0806.2110`].

[62] Stanislav Babak, John G Baker, Matthew J Benacquista, Neil J Cornish, Shane L Larson, Ilya Mandel, Sean T McWilliams, Antoine Petiteau, Edward K Porter, Emma L Robinson, Michele Vallisneri, Alberto Vecchio, Matt Adams, Keith A Arnaud, Arkadiusz Błaut, Michael Bridges, Michael Cohen, Curt Cutler, Farhan Feroz, Jonathan R. Gair, Philip Graff, Mike Hobson, Joey Shapiro Key, Andrzej Królak, Anthony Lasenby, Reinhard Prix, Yu Shang, Miquel Trias, John Veitch, and John T Whelan, MOCK LISA DATA CHALLENGE TASK FORCE , *The Mock LISA Data Challenges: From Challenge 3 to Challenge 4*, *Class. Quant. Grav.* **27** (2010) 084009 [`0912.0548`].

[63] Tania Regimbau, Thomas Dent, Walter Del Pozzo, Stefanos Giampanis, Tjonnie G. F. Li, Craig Robinson, Chris Van Den Broeck, Duncan Meacher, Carl Rodriguez, B. S. Sathyaprakash, and Katarzyna Wójcik, *A Mock Data Challenge for the Einstein Gravitational-Wave Telescope*, *Phys. Rev.* **D86** (2012) 122001 [`1201.3563`].

[64] Duncan Meacher, Kipp Cannon, Chad Hanna, Tania Regimbau, and B. S. Sathyaprakash, *Second Einstein Telescope Mock Data and Science Challenge: Low Frequency Binary Neutron Star Data Analysis*, *Phys. Rev.* **D93** (2016) 024018 [`1511.01592`].

[65] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *Observation of Gravitational Waves from a Binary Black Hole Merger*, *Phys. Rev. Lett.* **116** (2016) 061102 [`1602.03837`].

[66] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence*, *Phys. Rev. Lett.* **116** (2016) 241103 [`1606.04855`].

[67] Neil J. Cornish and Jeff Crowder, *LISA data analysis using MCMC methods*, *Phys. Rev.* **D72** (2005) 043005 [`gr-qc/0506059`].

[68] S. Teukolsky and M. Vallisneri, *Architecture of LISA Data Analysis*: `https://kiss.caltech.edu/final_reports/LISA_Final_Report.pdf`.

[69] K. G. Arun, Stas Babak, Emanuele Berti, Neil Cornish, Curt Cutler, Jonathan Gair, Scott A. Hughes, Bala R. Iyer, Ryan N. Lang, Ilya Mand el, Edward K. Porter, Bangalore S. Sathyaprakash, Siddhartha Sinha, Alicia M. Sintes, Miquel Trias, Chris Van Den Broeck, and Marta Volonteri, *Massive Black Hole Binary Inspirals: Results from the LISA Parameter Estimation Taskforce*, *Class. Quant. Grav.* **26** (2009) 094027 [`0811.1011`].

[70] K. G. Arun, Bala R. Iyer, B. S. Sathyaprakash, Siddhartha Sinha, and Chris Van Den Broeck, *Higher signal harmonics, LISA's angular resolution and dark energy*, *Phys. Rev.* **D76** (2007) 104016 [`0707.3920`].

[71] LISA Data Challenge: `https://lisa-ldc.lal.in2p3.fr/`.

[72] Anuradha Samajdar, Justin Janquart, Chris Van Den Broeck, and Tim Dietrich, *Biases in parameter estimation from overlapping gravitational-wave signals in the third-generation detector era*, *Phys. Rev. D* **104** (2021) 044003 [`2102.07544`].

[73] Elia Pizzati, Surabhi Sachdev, Anuradha Gupta, and Bangalore Sathyaprakash, *Bayesian inference of overlapping gravitational wave signals*, [`2102.07692`].

[74] Philip Relton and Vivien Raymond, *Parameter estimation bias from overlapping binary black hole events in second generation interferometers*, *Phys. Rev. D* **104** (2021) 084039 [`2103.16225`].

[75] Ssohrab Borhanian, Arnab Dhani, Anuradha Gupta, K. G. Arun, and B. S. Sathyaprakash, *Dark Sirens to Resolve the Hubble-Lemaître Tension*, [`2007.02883`].

[76] S. Hild, M. Abernathy, F. Acernese, P. Amaro-Seoane, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker, N. Beveridge, S. Birindelli, S. Bose, L. Bosi, S. Braccini, C. Bradaschia, T. Bulik, E. Calloni, G. Cella, E. Chassande Mottin, S. Chelkowski, A. Chincarini, J. Clark, E. Coccia, C. Colacino, J. Colas, A. Cumming, L. Cunningham, E. Cuoco, S. Danilishin, K. Danzmann, R. De Salvo, T. Dent, R. De Rosa, L. Di Fiore, A. Di Virgilio, M. Doets, V. Fafone, P. Falferi, R. Flaminio, J. Franc, F. Frasconi, A. Freise, D. Friedrich, P. Fulda, J. Gair, G. Gemme, E. Genin, A. Gennai, A. Giazotto, K. Glampedakis, C. Gräf, M. Granata, H. Grote, G. Guidi, A. Gurkovsky, G. Hammond, M. Hannam, J. Harms, D. Heinert, M. Hendry, I. Heng, E. Hennes, J. Hough, S. Husa, S. Huttner, G. Jones, F. Khalili, K. Kokeyama, K. Kokkotas, B. Krishnan, T. G. F. Li, M. Lorenzini, H. Lück, E. Majorana, I. Mandel, V. Mandic, M. Mantovani, I. Martin, C. Michel, Y. Minenkov, N. Morgado, S. Mosca, B. Mours, H. Müller-Ebhardt, P. Murray, R. Nawrodt, J. Nelson, R. Oshaughnessy, C. D. Ott, C. Palomba, A. Paoli, G. Parguez, A. Pasqualetti, R. Passaquieti, D. Passuello, L. Pinard, W. Plastino, R. Poggiani, P. Popolizio, M. Prato, M. Punturo, P. Puppo, D. Rabeling, P. Rapagnani, J. Read, T. Regimbau, H. Rehbein, S. Reid, F. Ricci, F. Richard, A. Rocchi, S. Rowan, A. Rüdiger, L. Santamaría, B. Sassolas, B. Sathyaprakash, R. Schnabel, C. Schwarz, P. Seidel, A. Sintes, K. Somiya, F. Speirits, K. Strain, S. Strigin, P. Sutton, S. Tarabrin, A. Thüring, J. van den Brand, M. van Veggel, C. van den Broeck, A. Vecchio, J. Veitch, F. Vetrano, A. Vicere, S. Vyatchanin, B. Willke, G. Woan, and K. Yamamoto, *Sensitivity Studies for Third-Generation Gravitational Wave Observatories*, *Class. Quant. Grav.* **28** (2011) 094013 [`1012.0908`].

[77] K S Thorne, *Gravitational radiation*, in *Three hundred years of gravitation*, S. W. Hawking and W. Israel, eds., (Cambridge), pp. 330–458, Cambridge University Press, (1987).

[78] Craig Cahillane, Joe Betzwieser, Duncan A. Brown, Evan Goetz, Evan D. Hall, Kiwamu Izumi, Shivaraj Kandhasamy, Sudarshan Karki, Jeff S. Kissel, Greg Mendell, Richard L. Savage, Darkhan Tuyenbayev, Alex Urban, Aaron Viets, Madeline Wade, and Alan J. Weinstein, LIGO SCIENTIFIC , *Calibration uncertainty for Advanced LIGO's first and second observing runs*, *Phys. Rev.* **D96** (2017) 102001 [`1708.03023`].

[79] Craig Cahillane, Georgia Mansell, and Daniel Sigg, *Laser Frequency Noise in Next Generation Gravitational-Wave Detectors*, [`2107.14349`].

[80] A. Buikema, C. Cahillane, G. L. Mansell, C. D. Blair, R. Abbott, C. Adams, R. X. Adhikari, A. Ananyeva, S. Appert, K. Arai, J. S. Areeda, Y. Asali, S. M. Aston, C. Austin, A. M. Baer, M. Ball, S. W. Ballmer, S. Banagiri, D. Barker, L. Barsotti, J. Bartlett, B. K. Berger, J. Betzwieser, D. Bhattacharjee, G. Billingsley, S. Biscans, R. M. Blair, N. Bode, P. Booker, R. Bork, A. Bramley, A. F. Brooks, D. D. Brown, K. C. Cannon, X. Chen, A. A. Ciobanu, F. Clara, S. J. Cooper, K. R. Corley, S. T. Countryman, P. B. Covas, D. C. Coyne, L. E. H. Datrier, D. Davis, C. Di Fronzo, K. L. Dooley, J. C. Driggers, P. Dupej, S. E. Dwyer, A. Effler, T. Etzel, M. Evans, T. M. Evans, J. Feicht, A. Fernandez-Galiana, P. Fritschel, V. V. Frolov, P. Fulda, M. Fyffe, J. A. Giaime, K. D. Giardina, P. Godwin, E. Goetz, S. Gras, C. Gray, R. Gray, A. C. Green, E. K. Gustafson, R. Gustafson, J. Hanks, J. Hanson, T. Hardwick, R. K. Hasskew, M. C. Heintze, A. F. Helmling-Cornell, N. A. Holland, J. D. Jones, S. Kandhasamy, S. Karki, M. Kasprzack, K. Kawabe, N. Kijbunchoo, P. J. King, J. S. Kissel, Rahul Kumar, M. Landry, B. B. Lane, B. Lantz, M. Laxen, Y. K. Lecoeuche, J. Leviton, J. Liu, M. Lormand, A. P. Lundgren, R. Macas, M. MacInnis, D. M. Macleod, S. Márka, Z. Márka, D. V. Martynov, K. Mason, T. J. Massinger, F. Matichard, N. Mavalvala, R. McCarthy, D. E. McClelland, S. McCormick, L. McCuller, J. McIver, T. McRae, G. Mendell, K. Merfeld, E. L. Merilh, F. Meylahn, T. Mistry, R. Mittleman, G. Moreno, C. M. Mow-Lowry, S. Mozzon, A. Mullavey, T. J. N. Nelson, P. Nguyen, L. K. Nuttall, J. Oberling, Richard J. Oram, B. O'Reilly, C. Osthelder, D. J. Ottaway, H. Overmier, J. R. Palamos, W. Parker, E. Payne, A. Pele, R. Penhorwood, C. J. Perez, M. Pirello, H. Radkins, K. E. Ramirez, J. W. Richardson, K. Riles, N. A. Robertson, J. G. Rollins, C. L. Romel, J. H. Romie, M. P. Ross, K. Ryan, T. Sadecki, E. J. Sanchez, L. E. Sanchez, T. R. Saravanan, R. L. Savage, D. Schaetzl, R. Schnabel, R. M. S. Schofield, E. Schwartz, D. Sellers, T. Shaffer, D. Sigg, B. J. J. Slagmolen, J. R. Smith, S. Soni, B. Sorazu, A. P. Spencer, K. A. Strain, L. Sun, M. J. Szczepańczyk, M. Thomas, P. Thomas, K. A. Thorne, K. Toland, C. I. Torrie, G. Traylor, M. Tse, A. L. Urban, G. Vajente, G. Valdes, D. C. Vander-Hyde, P. J. Veitch, K. Venkateswara, G. Venugopalan, A. D. Viets, T. Vo, C. Vorvick, M. Wade, R. L. Ward, J. Warner, B. Weaver, R. Weiss, C. Whittle, B. Willke, C. C. Wipf, L. Xiao, H. Yamamoto, Hang Yu, Haocun Yu, L. Zhang, M. E. Zucker, and J. Zweizig, ALIGO , *Sensitivity and performance of the Advanced LIGO detectors in the third observing run*, *Phys. Rev. D* **102** (2020) 062003 [`2008.01301`].

[81] Einstein Telescope Conceptual Design Study Document: `https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf`.

[82] Sebastian Khan, Frank Ohme, Katerina Chatziioannou, and Mark Hannam, *Including higher order multipoles in gravitational-wave models for precessing binary black holes*, *Phys. Rev.* **D101** (2020) 024056 [`1911.06050`].

[83] Matthew Giesler, Maximiliano Isi, Mark A. Scheel, and Saul Teukolsky, *Black Hole Ringdown: The Importance of Overtones*, *Phys. Rev.* **X9** (2019) 041060 [`1903.08284`].

[84] Pierre Mourier, Xisco Jimenez-Forteza, Daniel Pook-Kolb, Badri Krishnan, and Erik Schnetter, *Quasi-normal modes and their overtones at the common horizon in a binary black hole merger*, [`2010.15186`].

[85] Antoine Klein, Yannick Boetzel, Achamveedu Gopakumar, Philippe Jetzer, and Lorenzo de Vittori, *Fourier domain gravitational waveforms for precessing eccentric binaries*, *Phys. Rev.* **D98** (2018) 104043 [`1801.08542`].

[86] Tanja Hinderer, Benjamin D. Lackey, Ryan N. Lang, and Jocelyn S. Read, *Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral*, *Phys. Rev.* **D81** (2010) 123016 [`0911.3535`].

[87] Kentaro Takami, Luciano Rezzolla, and Luca Baiotti, *Spectral properties of the post-merger gravitational-wave signal from binary neutron stars*, *Phys. Rev.* **D91** (2015) 064001 [`1412.3240`].

[88] Roberto Cotesta, Stanislav Babak, Tim Dietrich, Roland Haas, Ian Hinder, Harald P. Pfeiffer, Michael Pürrer, Charles J. Woodford, Michael Boyle, Lawrence E. Kidder, Mark A. Scheel, and Béla Szilágyi, *Multipolar Effective-One-Body Waveforms for Precessing Binary Black Holes: Construction and Validation*, *Phys. Rev.* **D102** (2020) 044055 [`2004.09442`].

[89] Reinhard Prix, *Gravitational Waves from Spinning Neutron Stars*, *Astrophys. Space Sci. Lib.* **357** (2009) 651.

[90] Hans-Thomas Janka, *Explosion Mechanisms of Core-Collapse Supernovae*, *Ann. Rev. Nucl. Part. Sci.* **62** (2012) 407 [`1206.2503`].

[91] B. Müller, *Neutrino Emission as Diagnostics of Core-Collapse Supernovae*, *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 253 [`1904.11067`].

[92] Chris L. Fryer and Kimberly C. B. New, *Gravitational waves from gravitational collapse*, *Living Rev. Rel.* **14** (2011) 1.

[93] Adam Burrows, *Colloquium: Perspectives on core-collapse supernova theory*, *Rev. Mod. Phys.* **85** (2013) 245 [`1210.4921`].

[94] Varun Srivastava, Stefan Ballmer, Duncan A. Brown, Chaitanya Afle, Adam Burrows, David Radice, and David Vartanyan, *Detection Prospects of Core-Collapse Supernovae with Supernova-Optimized Third-Generation Gravitational-wave Detectors*, *Phys. Rev.* **D100** (2019) 043026 [`1906.00084`].

[95] Chase Kimball, Colm Talbot, Christopher P. L. Berry, Matthew Carney, Michael Zevin, Eric Thrane, and Vicky Kalogera, *Black Hole Genealogy: Identifying Hierarchical Mergers with Gravitational Waves*, *Astrophys. J.* **900** (2020) 177 [`2005.00023`].

[96] Davide Gerosa and Emanuele Berti, *Are merging black holes born from stellar collapse or previous mergers?*, *Phys. Rev.* **D95** (2017) 124046 [`1703.06223`].

[97] Maya Fishbach, Daniel E. Holz, and Ben Farr, *Are LIGO's Black Holes Made From Smaller Black Holes?*, *Astrophys. J. Lett.* **840** (2017) L24 [`1703.06869`].

[98] John Antoniadis, Thomas M. Tauris, Feryal Ozel, Ewan Barr, David J. Champion, and Paulo C. C. Freire, *The millisecond pulsar mass distribution: Evidence for bimodality and constraints on the maximum neutron star mass*, [`1605.01665`].

[99] Justin Alsing, Hector O. Silva, and Emanuele Berti, *Evidence for a maximum mass cut-off in the neutron star mass distribution and constraints on the equation of state*, *Mon. Not. Roy. Astron. Soc.* **478** (2018) 1377 [`1709.07889`].

[100] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *GW190425: Observation of a Compact Binary Coalescence with Total Mass* $\sim 3.4 M_{\odot}$, *Astrophys. J. Lett.* **892** (2020) L3 [`2001.01761`].

[101] Simon Stevenson, Alejandro Vigna-Gómez, Ilya Mandel, Jim W. Barrett, Coenraad J. Neijssel, David Perkins, and Selma E. de Mink, *Formation of the first three gravitational-wave observations through isolated binary evolution*, [`1704.01352`].

[102] Krzystof Belczynski, Vassiliki Kalogera, Frederic A. Rasio, Ronald E. Taam, Andreas Zezas, Tomasz Bulik, Thomas J. Maccarone, and Natalia Ivanova, *Compact object modeling with the startrack population synthesis code*, *Astrophys. J. Suppl.* **174** (2008) 223 [`astro-ph/0511811`].

[103] Jason W. T. Hessels, Scott M. Ransom, Ingrid H. Stairs, Paulo Cesar Carvalho Freire, Victoria M. Kaspi, and Fernando Camilo, *A radio pulsar spinning at 716-hz*, *Science* **311** (2006) 1901 [`astro-ph/0601337`].

[104] Piero Madau and Mark Dickinson, *Cosmic Star Formation History*, *Ann. Rev. Astron. Astrophys.* **52** (2014) 415 [`1403.0007`].

[105] Mohammadtaher Safarzadeh and Edo Berger, *Measuring the delay time distribution of binary neutron stars. I. Through Scaling Relations of the Host Galaxies of Gravitational Wave Events*, *Astrophys. J. Lett.* **878** (2019) L12 [`1904.08436`].

[106] Alejandro Vigna-Gómez, Coenraad J. Neijssel, Simon Stevenson, Jim W. Barrett, Krzysztof Belczynski, Stephen Justham, Selma E. de Mink, Bernhard Müller, Philipp Podsiadlowski, Mathieu Renzo, Dorottya Szécsi, and Ilya Mandel, *On the formation history of Galactic double neutron stars*, *Mon. Not. Roy. Astron. Soc.* **481** (2018) 4009 [`1805.07974`].

[107] K. Belczynski, T. Bulik, A. Olejak, M. Chruslinska, N. Singh, N. Pol, L. Zdunik, R. O'Shaughnessy, M. McLaughlin, D. Lorimer, O. Korobkin, E. P. J. van den Heuvel, M. B. Davies, and D. E. Holz, *Binary neutron star formation and the origin of GW170817*, [`1812.10065`].

[108] Zheng Zheng and Enrico Ramirez-Ruiz, *Deducing the lifetime of short gamma-ray burst progenitors from host galaxy demography*, *Astrophys. J.* **665** (2007) 1220 [`astro-ph/0601622`].

[109] Carl L. Rodriguez, Sourav Chatterjee, and Frederic A. Rasio, *Binary Black Hole Mergers from Globular Clusters: Masses, Merger Rates, and the Impact of Stellar Evolution*, *Phys. Rev.* **D93** (2016) 084029 [`1602.02444`].

[110] K. Belczynski, T. Ryu, R. Perna, E. Berti, T. L. Tanaka, and T. Bulik, *On the likelihood of detecting gravitational waves from Population III compact object binaries*, *Mon. Not. Roy. Astron. Soc.* **471** (2017) 4702 [`1612.01524`].

[111] Ataru Tanikawa, Hajime Susa, Takashi Yoshida, Alessandro A. Trani, and Tomoya Kinugawa, *Merger rate density of Population III binary black holes below, above, and in the pair-instability mass gap*, [2008.01890].

[112] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J. P. Bernard, M. Bersanelli, P. Bielewicz, J. J. Bock, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, M. Bucher, C. Burigana, R. C. Butler, E. Calabrese, J. F. Cardoso, J. Carron, A. Challinor, H. C. Chiang, J. Chluba, L. P. L. Colombo, C. Combet, D. Contreras, B. P. Crill, F. Cuttaia, P. de Bernardis, G. de Zotti, J. Delabrouille, J. M. Delouis, E. Di Valentino, J. M. Diego, O. Doré, M. Douspis, A. Ducout, X. Dupac, S. Dusini, G. Efstathiou, F. Elsner, T. A. Enßlin, H. K. Eriksen, Y. Fantaye, M. Farhang, J. Fergusson, R. Fernandez-Cobos, F. Finelli, F. Forastieri, M. Frailis, A. A. Fraisse, E. Franceschi, A. Frolov, S. Galeotta, S. Galli, K. Ganga, R. T. Génova-Santos, M. Gerbino, T. Ghosh, J. González-Nuevo, K. M. Górski, S. Gratton, A. Gruppuso, J. E. Gudmundsson, J. Hamann, W. Handley, F. K. Hansen, D. Herranz, S. R. Hildebrandt, E. Hivon, Z. Huang, A. H. Jaffe, W. C. Jones, A. Karakci, E. Keihänen, R. Keskitalo, K. Kiiveri, J. Kim, T. S. Kisner, L. Knox, N. Krachmalnicoff, M. Kunz, H. Kurki-Suonio, G. Lagache, J. M. Lamarre, A. Lasenby, M. Lattanzi, C. R. Lawrence, M. Le Jeune, P. Lemos, J. Lesgourgues, F. Levrier, A. Lewis, M. Liguori, P. B. Lilje, M. Lilley, V. Lindholm, M. López-Caniego, P. M. Lubin, Y. Z. Ma, J. F. Macías-Pérez, G. Maggio, D. Maino, N. Mandolesi, A. Mangilli, A. Marcos-Caballero, M. Maris, P. G. Martin, M. Martinelli, E. Martínez-González, S. Matarrese, N. Mauri, J. D. McEwen, P. R. Meinhold, A. Melchiorri, A. Mennella, M. Migliaccio, M. Millea, S. Mitra, M. A. Miville-Deschênes, D. Molinari, L. Montier, G. Morgante, A. Moss, P. Natoli, H. U. Nørgaard-Nielsen, L. Pagano, D. Paoletti, B. Partridge, G. Patanchon, H. V. Peiris, F. Perrotta, V. Pettorino, F. Piacentini, L. Polastri, G. Polenta, J. L. Puget, J. P. Rachen, M. Reinecke, M. Remazeilles, A. Renzi, G. Rocha, C. Rosset, G. Roudier, J. A. Rubiño-Martín, B. Ruiz-Granados, L. Salvati, M. Sandri, M. Savelainen, D. Scott, E. P. S. Shellard, C. Sirignano, G. Sirri, L. D. Spencer, R. Sunyaev, A. S. Suur-Uski, J. A. Tauber, D. Tavagnacco, M. Tenti, L. Toffolatti, M. Tomasi, T. Trombetti, L. Valenziano, J. Valiviita, B. Van Tent, L. Vibert, P. Vielva, F. Villa, N. Vittorio, B. D. Wand elt, I. K. Wehus, M. White, S. D. M. White, A. Zacchei, and A. Zonca, PLANCK COLLABORATION , *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [1807.06209].

[113] R. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog*, [2010.14533].

[114] LIGO SCIENTIFIC, VIRGO, KAGRA SCIENTIFIC , *The population of merging compact binaries inferred using gravitational waves through GWTC-3*, [2111.03634].

[115] Michele Vallisneri, Jonah Kanner, Roy Williams, Alan Weinstein, and Branson Stephens, *The LIGO Open Science Center*, *J. Phys. Conf. Ser.* **610** (2015) 012021 [1410.4839].

[116] Derek Weitzel, Brian Bockelman, Duncan A. Brown, Peter Couvares, Frank Würthwein, and Edgar Fajardo Hernandez, *Data access for LIGO on the OSG*, *CoRR* **abs/1705.06202** (2017) [1705.06202].

[117] PyCBC can be downloaded from: `https://pycbc.org/`.

[118] GstLAL can be downloaded from: `https://lscsoft.docs.ligo.org/gstlal/`.

[119] LALSuite can be downloaded from: `https://git.ligo.org/lscsoft/lalsuite`.

[120] J. Veitch, V. Raymond, B. Farr, W. Farr, P. Graff, S. Vitale, B. Aylott, K. Blackburn, N. Christensen, M. Coughlin, W. Del Pozzo, F. Feroz, J. Gair, C. J. Haster, V. Kalogera, T. Littenberg, I. Mandel, R. O'Shaughnessy, M. Pitkin, C. Rodriguez, C. Röver, T. Sidery, R. Smith, M. Van Der Sluys, A. Vecchio, W. Vousden, and L. Wade, *Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library*, *Phys. Rev.* **D91** (2015) 042003 [`1409.7215`].

[121] Duncan Meacher, Eric Thrane, and Tania Regimbau, *Statistical properties of astrophysical gravitational-wave backgrounds*, *Phys. Rev.* **D89** (2014) 084063 [`1402.6231`].

[122] Rory Smith and Eric Thrane, *Optimal Search for an Astrophysical Gravitational-Wave Background*, *Phys. Rev.* **X8** (2018) 021019 [`1712.00688`].

[123] Simon Stevenson, Frank Ohme, and Stephen Fairhurst, *Distinguishing compact binary population synthesis models using gravitational-wave observations of coalescing binary black holes*, *Astrophys. J.* **810** (2015) 58 [`1504.07802`].

[124] C. Van Den Broeck, *Astrophysics, cosmology, and fundamental physics with compact binary coalescence and the Einstein Telescope*, *J. Phys. Conf. Ser.* **484** (2014) 012008 [`1303.7393`].

[125] Surabhi Sachdev, Ryan Magee, Chad Hanna, Kipp Cannon, Leo Singer, Javed Rana SK, Debnandini Mukherjee, Sarah Caudill, Chiwai Chan, Jolien D. E. Creighton, Becca Ewing, Heather Fong, Patrick Godwin, Rachael Huxford, Shasvath Kapadia, Alvin K. Y. Li, Rico Ka Lok Lo, Duncan Meacher, Cody Messick, Siddharth R. Mohite, Atsushi Nishizawa, Hiroaki Ohta, Alexander Pace, Amit Reza, B. S. Sathyaprakash, Minori Shikauchi, Divya Singh, Leo Tsukada, Daichi Tsuna, Takuya Tsutsui, and Koh Ueno, *An early warning system for electromagnetic follow-up of gravitational-wave events*, [`2008.04288`].

[126] Kipp Cannon, Romain Cariou, Adrian Chapman, Mireia Crispin-Ortuzar, Nickolas Fotopoulos, Melissa Frei, Chad Hanna, Erin Kara, Drew Keppel, Laura Liao, Stephen Privitera, Antony Searle, Leo Singer, and Alan Weinstein, *Toward Early-Warning Detection of Gravitational Waves from Compact Binary Coalescence*, *Astrophys. J.* **748** (2012) 136 [`1107.2665`].

[127] Man Leong Chan, Chris Messenger, Ik Siong Heng, and Martin Hendry, *Binary Neutron Star Mergers and Third Generation Detectors: Localization and Early Warning*, *Phys. Rev. D* **97** (2018) 123014 [`1803.09680`].

[128] Pratika Dayal, Elena M. Rossi, Banafsheh Shiralilou, Olmo Piana, Tirthankar Roy Choudhury, and Marta Volonteri, *The hierarchical assembly of galaxies and black holes in the first billion years: predictions for the era of gravitational wave astronomy*, *Mon. Not. Roy. Astron. Soc.* **486** (2019) 2336 [`1810.11033`].

[129] Marta Volonteri, Francesco Haardt, and Piero Madau, *The Assembly and merging history of supermassive black holes in hierarchical models of galaxy formation*, *Astrophys. J.* **582** (2003) 559 [`astro-ph/0207276`].

[130] Jeff Crowder and Neil J. Cornish, *LISA source confusion*, *Phys. Rev.* **D70** (2004) 082004 [`gr-qc/0404129`].

[131] Tyson Littenberg, Neil Cornish, Kristen Lackeos, and Travis Robson, *Global Analysis of the Gravitational Wave Signal from Galactic Binaries*, *Phys. Rev.* **D101** (2020) 123021 [2004.08464].

[132] Bernard F. Schutz, *Determining the Hubble Constant from Gravitational Wave Observations*, *Nature* **323** (1986) 310.

[133] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *A gravitational-wave measurement of the Hubble constant following the second observing run of Advanced LIGO and Virgo*, [1908.06060].

[134] Walter Del Pozzo, *Inference of the cosmological parameters from gravitational waves: application to second generation interferometers*, *Phys. Rev. D* **86** (2012) 043011 [1108.1317].

[135] M. Soares-Santos et al., DES, LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *First Measurement of the Hubble Constant from a Dark Standard Siren using the Dark Energy Survey Galaxies and the LIGO/Virgo Binary–Black-hole Merger GW170814*, *Astrophys. J. Lett.* **876** (2019) L7 [1901.01540].

[136] M. Fishbach, R. Gray, I. Magaña Hernandez, H. Qi, A. Sur, F. Acernese, L. Aiello, A. Allocca, M. A. Aloy, A. Amato, S. Antier, M. Arène, N. Arnaud, S. Ascenzi, P. Astone, F. Aubin, S. Babak, P. Bacon, F. Badaracco, M. K. M. Bader, F. Baldaccini, G. Ballardin, F. Barone, M. Barsuglia, D. Barta, A. Basti, M. Bawaj, M. Bazzan, M. Bejger, I. Belahcene, S. Bernuzzi, D. Bersanetti, A. Bertolini, M. Bitossi, M. A. Bizouard, C. D. Blair, S. Bloemen, M. Boer, G. Bogaert, F. Bondu, R. Bonnand, B. A. Boom, V. Boschi, Y. Bouffanais, A. Bozzi, C. Bradaschia, P. R. Brady, M. Branchesi, T. Briant, F. Brighenti, A. Brillet, V. Brisson, T. Bulik, H. J. Bulten, D. Buskulic, C. Buy, G. Cagnoli, E. Calloni, M. Canepa, E. Capocasa, F. Carbognani, G. Carullo, J. Casanueva Diaz, C. Casentini, S. Caudill, F. Cavalier, R. Cavalieri, G. Cella, P. Cerdá-Durán, G. Cerretani, E. Cesarini, O. Chaibi, E. Chassande-Mottin, K. Chatziioannou, H. Y. Chen, A. Chincarini, A. Chiummo, N. Christensen, S. Chua, G. Ciani, R. Ciolfi, F. Cipriano, A. Cirone, F. Cleva, E. Coccia, P. F. Cohadon, D. Cohen, L. Conti, I. Cordero-Carrión, S. Cortese, M. W. Coughlin, J. P. Coulon, M. Croquette, E. Cuoco, G. Dálya, S. D'Antonio, L. E. H. Datrier, V. Dattilo, M. Davier, J. Degallaix, M. De Laurentis, S. Deléglise, W. Del Pozzo, M. Denys, R. De Pietri, R. De Rosa, C. De Rossi, R. DeSalvo, T. Dietrich, L. Di Fiore, M. Di Giovanni, T. Di Girolamo, A. Di Lieto, S. Di Pace, I. Di Palma, F. Di Renzo, Z. Doctor, M. Drago, J. G. Ducoin, M. Eisenmann, R. C. Essick, D. Estevez, V. Fafone, S. Farinon, W. M. Farr, F. Feng, I. Ferrante, F. Ferrini, F. Fidecaro, I. Fiori, D. Fiorucci, R. Flaminio, J. A. Font, J. D. Fournier, S. Frasca, F. Frasconi, V. Frey, J. R. Gair, L. Gammaitoni, F. Garufi, G. Gemme, E. Genin, A. Gennai, D. George, V. Germain, A. Ghosh, B. Giacomazzo, A. Giazotto, G. Giordano, J. M. Gonzalez Castro, M. Gosselin, R. Gouaty, A. Grado, M. Granata, G. Greco, P. Groot, P. Gruning, G. M. Guidi, Y. Guo, O. Halim, J. Harms, C. J. Haster, A. Heidmann, H. Heitmann, P. Hello, G. Hemming, M. Hendry, T. Hinderer, D. Hoak, D. Hofman, D. E. Holz, A. Hreibi, D. Huet, B. Idzkowski, A. Iess, G. Intini, J. M. Isac, T. Jacqmin, P. Jaranowski, R. J. G. Jonker, S. Katsanevas, E. Katsavounidis, F. Kéfélian, I. Khan, G. Koekoek, S. Koley, I. Kowalska, A. Królak, A. Kutynia, J. Lange, A. Lartaux-Vollard, C. Lazzaro, P. Leaci, N. Letendre, T. G. F. Li, F. Linde, A. Longo, M. Lorenzini, V. Loriette, G. Losurdo, D. Lumaca, R. Macas, A. Macquet, E. Majorana, I. Maksimovic, N. Man, M. Mantovani, F. Marchesoni, C. Markakis, A. Marquina, F. Martelli, E. Massera, A. Masserot, S. Mastrogiovanni, J. Meidam, L. Mereni, M. Merzougui, C. Messenger, R. Metzdorff, C. Michel, L. Milano, A. Miller, O. Minazzoli, Y. Minenkov, M. Montani, S. Morisaki, B. Mours, A. Nagar,

I. Nardecchia, L. Naticchioni, G. Nelemans, D. Nichols, F. Nocera, M. Obergaulinger, G. Pagano, C. Palomba, F. Pannarale, F. Paoletti, A. Paoli, A. Pasqualetti, R. Passaquieti, D. Passuello, M. Patil, B. Patricelli, R. Pedurand, A. Perreca, O. J. Piccinni, M. Pichot, F. Piergiovanni, G. Pillant, L. Pinard, R. Poggiani, P. Popolizio, G. A. Prodi, M. Punturo, P. Puppo, N. Radulescu, P. Raffai, P. Rapagnani, V. Raymond, M. Razzano, T. Regimbau, L. Rei, F. Ricci, A. Rocchi, L. Rolland , M. Romanelli, R. Romano, D. Rosińska, P. Ruggi, L. Salconi, A. Samajdar, N. Sanchis-Gual, B. Sassolas, B. F. Schutz, D. Sentenac, V. Sequino, M. Sieniawska, N. Singh, A. Singhal, F. Sorrentino, C. Stachie, D. A. Steer, G. Stratta, B. L. Swinkels, M. Tacca, N. Tamanini, S. Tiwari, M. Tonelli, A. Torres-Forné, F. Travasso, M. C. Tringali, A. Trovato, L. Trozzo, K. W. Tsang, N. van Bakel, M. van Beuzekom, J. F. J. van den Brand, C. Van Den Broeck, L. van der Schaaf, J. V. van Heijningen, M. Vardaro, M. Vasúth, G. Vedovato, J. Veitch, D. Verkindt, F. Vetrano, A. Viceré, J. Y. Vinet, H. Vocca, R. Walet, G. Wang, Y. F. Wang, M. Was, A. R. Williamson, M. Yvert, A. Zadrożny, T. Zelenova, J. P. Zendri, and A. B. Zimmerman, *A Standard Siren Measurement of the Hubble Constant from GW170817 without the Electromagnetic Counterpart*, *Astrophys. J. Lett.* **871** (2019) L13 [`1807.05667`].

[137] Samaya Nissanke, Daniel E. Holz, Neal Dalal, Scott A. Hughes, Jonathan L. Sievers, and Christopher M. Hirata, *Determining the Hubble constant from gravitational wave observations of merging compact binaries*, [`1307.2638`].

[138] Salvatore Vitale and Hsin-Yu Chen, *Measuring the Hubble constant with neutron star black hole mergers*, *Phys. Rev. Lett.* **121** (2018) 021303 [`1804.07337`].

[139] Adam G. Riess, Lucas M. Macri, Samantha L. Hoffmann, Dan Scolnic, Stefano Casertano, Alexei V. Filippenko, Brad E. Tucker, Mark J. Reid, David O. Jones, Jeffrey M. Silverman, Ryan Chornock, Peter Challis, Wenlong Yuan, Peter J. Brown, and Ryan J. Foley, *A 2.4% Determination of the Local Value of the Hubble Constant*, *Astrophys. J.* **826** (2016) 56 [`1604.01424`].

[140] Rachel Gray, Ignacio Magaña Hernandez, Hong Qi, Ankan Sur, Patrick R. Brady, Hsin-Yu Chen, Will M. Farr, Maya Fishbach, Jonathan R. Gair, Archisman Ghosh, Daniel E. Holz, Simone Mastrogiovanni, Christopher Messenger, Danièle A. Steer, and John Veitch, *Cosmological inference using gravitational wave standard sirens: A mock data analysis*, *Phys. Rev.* **D101** (2020) 122001 [`1908.06050`].

[141] Hsin-Yu Chen, Maya Fishbach, and Daniel E. Holz, *A two per cent Hubble constant measurement from standard sirens within five years*, *Nature* **562** (2018) 545 [`1712.06531`].

[142] Hsin-Yu Chen, *Systematic uncertainty of standard sirens from the viewing angle of binary neutron star inspirals*, *Phys. Rev. Lett.* **125** (2020) 201301 [`2006.02779`].

[143] Zack Carson, Andrew W. Steiner, and Kent Yagi, *Constraining nuclear matter parameters with GW170817*, *Phys. Rev.* **D99** (2019) 043010 [`1812.08910`].

[144] Zack Carson, Andrew W. Steiner, and Kent Yagi, *Future Prospects for Constraining Nuclear Matter Parameters with Gravitational Waves*, *Phys. Rev.* **D100** (2019) 023012 [`1906.05978`].

[145] Michalis Agathos, Jeroen Meidam, Walter Del Pozzo, Tjonnie G. F. Li, Marco Tompitak, John Veitch, Salvatore Vitale, and Chris Van Den Broeck, *Constraining the neutron star equation of state with gravitational wave signals from coalescing binary neutron stars*, *Phys. Rev.* **D92** (2015) 023012 [`1503.05405`].

[146] T. Regimbau, M. Evans, N. Christensen, E. Katsavounidis, B. Sathyaprakash, and S. Vitale, *Digging deeper: Observing primordial gravitational waves below the binary black hole produced stochastic background*, *Phys. Rev. Lett.* **118** (2017) 151105 [`1611.08943`].

[147] Bruce Allen and Joseph D. Romano, *Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities*, *Phys. Rev.* **D59** (1999) 102001 [`gr-qc/9710117`].

[148] B. P. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *Search for the isotropic stochastic background using data from Advanced LIGO's second observing run*, *Phys. Rev.* **D100** (2019) 061101 [`1903.02886`].

[149] Sylvia Biscoveanu, Colm Talbot, Eric Thrane, and Rory Smith, *Measuring the primordial gravitational-wave background in the presence of astrophysical foregrounds*, *Phys. Rev. Lett.* **125** (2020) 241101 [`2009.04418`].

[150] Ik Siong Heng, *Rotating stellar core-collapse waveform decomposition: A principal component analysis approach*, *Class. Quant. Grav.* **26** (2009) 105005 [`0810.5707`].

[151] J. Logue, C. D. Ott, I. S. Heng, P. Kalmus, and J. H. C. Scargill, *Inferring Core-Collapse Supernova Physics with Gravitational Waves*, *Phys. Rev.* **D86** (2012) 044023 [`1202.3256`].

[152] Jade Powell, Sarah E. Gossan, Joshua Logue, and Ik Siong Heng, *Inferring the core-collapse supernova explosion mechanism with gravitational waves*, *Phys. Rev.* **D94** (2016) 123012 [`1610.05573`].

[153] Jade Powell, Marek Szczepanczyk, and Ik Siong Heng, *Inferring the core-collapse supernova explosion mechanism with three-dimensional gravitational-wave simulations*, *Phys. Rev.* **D96** (2017) 123013 [`1709.00955`].

[154] Vincent Roma, Jade Powell, Ik Siong Heng, and Ray Frey, *Astrophysics with core-collapse supernova gravitational wave signals in the next generation of gravitational wave detectors*, *Phys. Rev.* **D99** (2019) 063018 [`1901.08692`].

[155] Matthew C. Edwards, Renate Meyer, and Nelson Christensen, *Bayesian parameter estimation of core collapse supernovae using gravitational wave simulations*, *Inverse Prob.* **30** (2014) 114008 [`1407.7549`].

[156] Chaitanya Afle and Duncan A. Brown, *Inferring physical properties of stellar collapse by third-generation gravitational-wave detectors*, [`2010.00719`].

[157] Keith Riles, *Recent searches for continuous gravitational waves*, *Mod. Phys. Lett.* **A32** (2017) 1730035 [`1712.05897`].

[158] Shilpa Kastha, Anuradha Gupta, K. G. Arun, B. S. Sathyaprakash, and Chris Van Den Broeck, *Testing the multipole structure of compact binaries using gravitational wave observations*, *Phys. Rev.* **D98** (2018) 124033 [`1809.10465`].

[159] Salvatore Vitale, *Multiband Gravitational-Wave Astronomy: Parameter Estimation and Tests of General Relativity with Space- and Ground-Based Detectors*, *Phys. Rev. Lett.* **117** (2016) 051102 [`1605.01037`].

[160] J. Meidam, M. Agathos, C. Van Den Broeck, J. Veitch, and B. S. Sathyaprakash, *Testing the no-hair theorem with black hole ringdowns using TIGER*, *Phys. Rev.* **D90** (2014) 064009 [`1406.3201`].

[161] Emanuele Berti, Enrico Barausse, Vitor Cardoso, Leonardo Gualtieri, Paolo Pani, Ulrich Sperhake, Leo C. Stein, Norbert Wex, Kent Yagi, Tessa Baker, C. P. Burgess, Flávio S. Coelho, Daniela Doneva, Antonio De Felice, Pedro G. Ferreira, Paulo C. C. Freire, James Healy, Carlos Herdeiro, Michael Horbatsch, Burkhard Kleihaus, Antoine Klein, Kostas Kokkotas, Jutta Kunz, Pablo Laguna, Ryan N. Lang, Tjonnie G. F. Li, Tyson Littenberg, Andrew Matas, Saeed Mirshekari, Hirotada Okawa, Eugen Radu, Richard O'Shaughnessy, Bangalore S. Sathyaprakash, Chris Van Den Broeck, Hans A. Winther, Helvi Witek, Mir Emad Aghili, Justin Alsing, Brett Bolen, Luca Bombelli, Sarah Caudill, Liang Chen, Juan Carlos Degollado, Ryuichi Fujita, Caixia Gao, Davide Gerosa, Saeed Kamali, Hector O. Silva, João G. Rosa, Laleh Sadeghian, Marco Sampaio, Hajime Sotani, and Miguel Zilhao, *Testing General Relativity with Present and Future Astrophysical Observations*, *Class. Quant. Grav.* **32** (2015) 243001 [`1501.07274`].

[162] Zack Carson and Kent Yagi, *Multi-band gravitational wave tests of general relativity*, *Class. Quant. Grav.* **37** (2020) 02LT01 [`1905.13155`].

[163] Walter Del Pozzo, John Veitch, and Alberto Vecchio, *Testing General Relativity using Bayesian model selection: Applications to observations of gravitational waves from compact binary systems*, *Phys. Rev.* **D83** (2011) 082002 [`1101.1391`].

[164] Neil Cornish, Laura Sampson, Nicolas Yunes, and Frans Pretorius, *Gravitational Wave Tests of General Relativity with the Parameterized Post-Einsteinian Framework*, *Phys. Rev.* **D84** (2011) 062003 [`1105.2088`].

[165] Clifford M. Will, *The Confrontation between General Relativity and Experiment*, *Living Rev. Rel.* **17** (2014) 4 [`1403.7377`].

[166] R. Abbott et al., LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION , *Tests of General Relativity with Binary Black Holes from the second LIGO-Virgo Gravitational-Wave Transient Catalog*, [`2010.14529`].

[167] B. S. Sathyaprakash, B. F. Schutz, and C. Van Den Broeck, *Cosmography with the Einstein Telescope*, *Class. Quant. Grav.* **27** (2010) 215006 [`0906.4151`].

[168] B. S. Sathyaprakash and S. V. Dhurandhar, *Choice of filters for the detection of gravitational waves from coalescing binaries*, *Phys. Rev.* **D44** (1991) 3819.

[169] S. V. Dhurandhar and B. S. Sathyaprakash, *Choice of filters for the detection of gravitational waves from coalescing binaries. 2. Detection in colored noise*, *Phys. Rev.* **D49** (1994) 1707.

[170] R. Balasubramanian, B. S. Sathyaprakash, and S. V. Dhurandhar, *Gravitational waves from coalescing binaries: Detection strategies and Monte Carlo estimation of parameters*, *Phys. Rev.* **D53** (1996) 3033 [`gr-qc/9508011`].

[171] Benjamin J. Owen and B. S. Sathyaprakash, *Matched filtering of gravitational waves from inspiraling compact binaries: Computational cost and template placement*, *Phys. Rev.* **D60** (1999) 022002 [`gr-qc/9808076`].

[172] Ian W. Harry, Bruce Allen, and B. S. Sathyaprakash, *A Stochastic template placement algorithm for gravitational wave data analysis*, *Phys. Rev.* **D80** (2009) 104014 [`0908.2090`].

[173] Stanislav Babak, Mark Hannam, Sascha Husa, and Bernard F. Schutz, *Resolving Super Massive Black Holes with LISA*, [`0806.1591`].

[174] Surabhi Sachdev, Tania Regimbau, and B. S. Sathyaprakash, *Subtracting compact binary foreground sources to reveal primordial gravitational-wave backgrounds*, *Phys. Rev.* **D102** (2020) 024051 [`2002.05365`].

[175] Luc Blanchet and B. S. Sathyaprakash, *Detecting the tail effect in gravitational wave experiments*, *Phys. Rev. Lett.* **74** (1995) 1067.

[176] K. G. Arun, Bala R. Iyer, M. S. S. Qusailah, and B. S. Sathyaprakash, *Probing the non-linear structure of general relativity with black hole binaries*, *Phys. Rev.* **D74** (2006) 024006 [`gr-qc/0604067`].

[177] K. G. Arun, Bala R. Iyer, M. S. S. Qusailah, and B. S. Sathyaprakash, *Testing post-Newtonian theory with gravitational wave observations*, *Class. Quant. Grav.* **23** (2006) L37 [`gr-qc/0604018`].

[178] Chandra Kant Mishra, K. G. Arun, Bala R. Iyer, and B. S. Sathyaprakash, *Parametrized tests of post-Newtonian theory using Advanced LIGO and Einstein Telescope*, *Phys. Rev.* **D82** (2010) 064010 [`1005.0304`].

[179] Shilpa Kastha, Anuradha Gupta, K. G. Arun, B. S. Sathyaprakash, and Chris Van Den Broeck, *Testing the multipole structure and conservative dynamics of compact binaries using gravitational wave observations: The spinning case*, *Phys. Rev.* **D100** (2019) 044007 [`1905.07277`].

[180] Siddharth Dhanpal, Abhirup Ghosh, Ajit Kumar Mehta, Parameswaran Ajith, and B. S. Sathyaprakash, *A no-hair test for binary black holes*, *Phys. Rev.* **D99** (2019) 104056 [`1804.03297`].

[181] Tousif Islam, Ajit Kumar Mehta, Abhirup Ghosh, Vijay Varma, Parameswaran Ajith, and B. S. Sathyaprakash, *Testing the no-hair nature of binary black holes using the consistency of multipolar gravitational radiation*, *Phys. Rev.* **D101** (2020) 024032 [`1910.14259`].

[182] Sukanta Bose, Kabir Chakravarti, Luciano Rezzolla, B. S. Sathyaprakash, and Kentaro Takami, *Neutron-star Radius from a Population of Binary Neutron Star Mergers*, *Phys. Rev. Lett.* **120** (2018) 031102 [`1705.10850`].

[183] Salvatore Vitale, Ryan Lynch, John Veitch, Vivien Raymond, and Riccardo Sturani, *Measuring the spin of black holes in binary systems using gravitational waves*, *Phys. Rev. Lett.* **112** (2014) 251101 [`1403.0129`].

[184] Salvatore Vitale, Ryan Lynch, Vivien Raymond, Riccardo Sturani, John Veitch, and Philp Graff, *Parameter estimation for heavy binary-black holes with networks of second-generation gravitational-wave detectors*, *Phys. Rev.* **D95** (2017) 064053 [`1611.01122`].

[185] Ken K. Y. Ng, Salvatore Vitale, Aaron Zimmerman, Katerina Chatziioannou, Davide Gerosa, and Carl-Johan Haster, *Gravitational-wave astrophysics with effective-spin measurements: asymmetries and selection biases*, *Phys. Rev.* **D98** (2018) 083007 [`1805.03046`].

[186] Yiwen Huang, Hannah Middleton, Ken K. Y. Ng, Salvatore Vitale, and John Veitch, *Characterization of low-significance gravitational-wave compact binary sources*, *Phys. Rev.* **D98** (2018) 123021 [`1810.10035`].

[187] Salvatore Vitale, *Multiband Gravitational-Wave Astronomy: Parameter Estimation and Tests of General Relativity with Space- and Ground-Based Detectors*, Phys. Rev. Lett. **117** (2016) 051102 [`1605.01037`].

[188] Salvatore Vitale, *Three observational differences for binary black holes detections with second and third generation gravitational-wave detectors*, *Phys. Rev.* **D94** (2016) 121501 [`1610.06914`].

[189] Yiwen Huang, Carl-Johan Haster, Salvatore Vitale, Aaron Zimmerman, Javier Roulet, Tejaswi Venumadhav, Barak Zackay, Liang Dai, and Matias Zaldarriaga, *Source properties of the lowest signal-to-noise-ratio binary black hole detections*, [`2003.04513`].

[190] Yiwen Huang, Carl-Johan Haster, Salvatore Vitale, Vijay Varma, Francois Foucart, and Sylvia Biscoveanu, *Statistical and systematic uncertainties in extracting the source properties of neutron star - black hole binaries with gravitational waves*, [`2005.11850`].

[191] Salvatore Vitale, Ryan Lynch, Riccardo Sturani, and Philip Graff, *Use of gravitational waves to probe the formation channels of compact binaries*, *Class. Quant. Grav.* **34** (2017) 03LT01 [`1503.04307`].

[192] Davide Gerosa, Salvatore Vitale, and Emanuele Berti, *Astrophysical implications of GW190412 as a remnant of a previous black-hole merger*, *Phys. Rev. Lett.* **125** (2020) 101103 [`2005.04243`].

[193] Christopher P. L. Berry, Ilya Mandel, Hannah Middleton, Leo P. Singer, Alex L. Urban, Alberto Vecchio, Salvatore Vitale, Kipp Cannon, Ben Farr, Will M. Farr, Philip B. Graff, Chad Hanna, Carl-Johan Haster, Satya Mohapatra, Chris Pankow, Larry R. Price, Trevor Sidery, and John Veitch, *Parameter Estimation for Binary Neutron-star Coalescences with Realistic Noise during the Advanced LIGO Era*, ApJ **804** (2015) 114 [`1411.6934`].

[194] Ben Farr, Christopher P. L. Berry, Will M. Farr, Carl-Johan Haster, Hannah Middleton, Kipp Cannon, Philip B. Graff, Chad Hanna, Ilya Mandel, Chris Pankow, Larry R. Price, Trevor Sidery, Leo P. Singer, Alex L. Urban, Alberto Vecchio, John Veitch, and Salvatore Vitale, *Parameter estimation on gravitational waves from neutron-star binaries with spinning components*, *Astrophys. J.* **825** (2016) 116 [`1508.05336`].

[195] Hsin-Yu Chen, Salvatore Vitale, and Ramesh Narayan, *Viewing angle of binary neutron star mergers*, *Phys. Rev.* **X9** (2019) 031028 [`1807.05226`].

[196] Leo P. Singer, Larry R. Price, Ben Farr, Alex L. Urban, Chris Pankow, Salvatore Vitale, John Veitch, Will M. Farr, Chad Hanna, Kipp Cannon, Tom Downes, Philip Graff, Carl-Johan Haster, Ilya Mandel, Trevor Sidery, and Alberto Vecchio, *The First Two Years of Electromagnetic Follow-up with Advanced LIGO and Virgo*, ApJ **795** (2014) 105 [`1404.5623`].

[197] Leo P. Singer, Hsin-Yu Chen, Daniel E. Holz, Will M. Farr, Larry R. Price, Vivien Raymond, S. Bradley Cenko, Neil Gehrels, John Cannizzo, Mansi M. Kasliwal, Samaya Nissanke, Michael Coughlin, Ben Farr, Alex L. Urban, Salvatore Vitale, John Veitch, Philip Graff, Christopher P. L. Berry, Satya Mohapatra, and Ilya Mandel, *Going the Distance: Mapping Host Galaxies of LIGO and Virgo Sources in Three Dimensions Using Local Cosmography and Targeted Follow-up*, *Astrophys. J. Lett.* **829** (2016) L15 [`1603.07333`].

[198] Sylvia Biscoveanu, Eric Thrane, and Salvatore Vitale, *Constraining short gamma-ray burst jet properties with gravitational waves and gamma rays*, *Astrophys. J.* **893** (2020) 38 [`1911.01379`].

[199] Sylvia Biscoveanu, Salvatore Vitale, and Carl-Johan Haster, *The reliability of the low-latency estimation of binary neutron star chirp mass*, *Astrophys. J. Lett.* **884** (2019) L32 [`1908.03592`].

[200] Salvatore Vitale, Davide Gerosa, Carl-Johan Haster, Katerina Chatziioannou, and Aaron Zimmerman, *Impact of Bayesian Priors on the Characterization of Binary Black Hole Coalescences*, *Phys. Rev. Lett.* **119** (2017) 251103 [`1707.04637`].

[201] Michael Zevin, Christopher P. L. Berry, Scott Coughlin, Katerina Chatziioannou, and Salvatore Vitale, *You Can't Always Get What You Want: The Impact of Prior Assumptions on Interpreting GW190412*, *Astrophys. J. Lett.* **899** (2020) L17 [`2006.11293`].

[202] Hsin-Yu Chen, Daniel E. Holz, John Miller, Matthew Evans, Salvatore Vitale, and Jolien Creighton, *Distance measures in gravitational-wave astrophysics and cosmology*, [`1709.08079`].

[203] Ken K. Y. Ng, Otto A. Hannuksela, Salvatore Vitale, and Tjonnie G. F. Li, *Searching for ultralight bosons within spin measurements of a population of binary black hole mergers*, *Phys. Rev. D* **103** (2021) 063010 [`1908.02312`].

[204] Ken K. Y. Ng, Salvatore Vitale, Otto A. Hannuksela, and Tjonnie G. F. Li, *Constraints on Ultralight Scalar Bosons within Black Hole Spin Measurements from the LIGO-Virgo GWTC-2*, *Phys. Rev. Lett.* **126** (2021) 151102 [`2011.06010`].

[205] Reed Essick, Salvatore Vitale, and Nevin N. Weinberg, *Impact of the tidal p-g instability on the gravitational wave signal from coalescing binary neutron stars*, *Phys. Rev.* **D94** (2016) 103012 [`1609.06362`].

[206] Salvatore Vitale and Walter Del Pozzo, *How serious can the stealth bias be in gravitational wave parameter estimation?*, *Phys. Rev.* **D89** (2014) 022002 [`1311.2057`].

[207] Michalis Agathos, Walter Del Pozzo, Tjonnie G. F. Li, Chris Van Den Broeck, John Veitch, and Salvatore Vitale, *TIGER: A data analysis pipeline for testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries*, *Phys. Rev.* **D89** (2014) 082001 [`1311.0420`].

[208] Jeroen Meidam, Ka Wa Tsang, Janna Goldstein, Michalis Agathos, Archisman Ghosh, Carl-Johan Haster, Vivien Raymond, Anuradha Samajdar, Patricia Schmidt, Rory Smith, Kent Blackburn, Walter Del Pozzo, Scott E. Field, Tjonnie Li, Michael Pürrer, Chris Van Den Broeck, John Veitch, and Salvatore Vitale, *Parametrized tests of the strong-field dynamics of general relativity using gravitational wave signals from coalescing binary black holes: Fast likelihood calculations and sensitivity of the method*, *Phys. Rev.* **D97** (2018) 044033 [`1712.08772`].

[209] Nathan K. Johnson-Mcdaniel, Arunava Mukherjee, Rahul Kashyap, Parameswaran Ajith, Walter Del Pozzo, and Salvatore Vitale, *Constraining black hole mimickers with gravitational wave observations*, [`1804.08026`].

[210] Reed Essick, Salvatore Vitale, and Matthew Evans, *Frequency-dependent responses in third generation gravitational-wave detectors*, *Phys. Rev.* **D96** (2017) 084004 [`1708.06843`].

[211] Ken K. Y. Ng, Maximiliano Isi, Carl-Johan Haster, and Salvatore Vitale, *Multiband gravitational-wave searches for ultralight bosons*, *Phys. Rev.* **D102** (2020) 083020 [2007.12793].

[212] Mohammadtaher Safarzadeh, Edo Berger, Ken K. Y. Ng, Hsin-Yu Chen, Salvatore Vitale, Chris Whittle, and Evan Scannapieco, *Measuring the delay time distribution of binary neutron stars. II. Using the redshift distribution from third-generation gravitational wave detectors network*, *Astrophys. J. Lett.* **878** (2019) L13 [1904.10976].

[213] Salvatore Vitale and Chris Whittle, *Characterization of binary black holes by heterogeneous gravitational-wave networks*, *Phys. Rev.* **D98** (2018) 024029 [1804.07866].

[214] John Miller, Lisa Barsotti, Salvatore Vitale, Peter Fritschel, Matthew Evans, and Daniel Sigg, *Prospects for doubling the range of Advanced LIGO*, *Phys. Rev.* **D91** (2015) 062005 [1410.5882].

[215] Ryan Lynch, Salvatore Vitale, Lisa Barsotti, Sheila Dwyer, and Matthew Evans, *Effect of squeezing on parameter estimation of gravitational waves emitted by compact binary systems*, Phys. Rev. D **91** (2015) 044032 [1410.8503].

[216] C. Biwer, D. Barker, J. C. Batch, J. Betzwieser, R. P. Fisher, E. Goetz, S. Kandhasamy, S. Karki, J. S. Kissel, A. P. Lundgren, D. M. Macleod, A. Mullavey, K. Riles, J. G. Rollins, K. A. Thorne, E. Thrane, T. D. Abbott, B. Allen, D. A. Brown, P. Charlton, S. G. Crowder, P. Fritschel, J. B. Kanner, M. Landry, C. Lazzaro, M. Millhouse, M. Pitkin, R. L. Savage, P. Shawhan, D. H. Shoemaker, J. R. Smith, L. Sun, J. Veitch, S. Vitale, A. J. Weinstein, N. Cornish, R. C. Essick, M. Fays, E. Katsavounidis, J. Lange, T. B. Littenberg, R. Lynch, P. M. Meyers, F. Pannarale, R. Prix, R. O'Shaughnessy, and D. Sigg, *Validating gravitational-wave detections: The Advanced LIGO hardware injection system*, Phys. Rev. D **95** (2017) 062002 [1612.07864].

[217] Hang Yu, Denis Martynov, Salvatore Vitale, Matthew Evans, David Shoemaker, Bryan Barr, Giles Hammond, Stefan Hild, James Hough, Sabina Huttner, Sheila Rowan, Borja Sorazu, Ludovico Carbone, Andreas Freise, Conor Mow-Lowry, Katherine L. Dooley, Paul Fulda, Hartmut Grote, and Daniel Sigg, *Prospects for detecting gravitational waves at 5 Hz with ground-based detectors*, *Phys. Rev. Lett.* **120** (2018) 141102 [1712.05417].

[218] J. C. Driggers, S. Vitale, A. P. Lundgren, M. Evans, K. Kawabe, S. E. Dwyer, K. Izumi, R. M. S. Schofield, A. Effler, D. Sigg, P. Fritschel, M. Drago, A. Nitz, B. P. Abbott, R. Abbott, T. D. Abbott, C. Adams, R. X. Adhikari, V. B. Adya, A. Ananyeva, S. Appert, K. Arai, S. M. Aston, C. Austin, S. W. Ballmer, D. Barker, B. Barr, L. Barsotti, J. Bartlett, I. Bartos, J. C. Batch, A. S. Bell, J. Betzwieser, G. Billingsley, J. Birch, S. Biscans, C. D. Blair, R. M. Blair, R. Bork, A. F. Brooks, H. Cao, G. Ciani, F. Clara, S. J. Cooper, P. Corban, S. T. Countryman, P. B. Covas, M. J. Cowart, D. C. Coyne, A. Cumming, L. Cunningham, K. Danzmann, C. F. Da Silva Costa, E. J. Daw, D. DeBra, R. DeSalvo, K. L. Dooley, S. Doravari, T. B. Edo, T. Etzel, T. M. Evans, H. Fair, A. Fernandez-Galiana, E. C. Ferreira, R. P. Fisher, H. Fong, R. Frey, V. V. Frolov, P. Fulda, M. Fyffe, B. Gateley, J. A. Giaime, K. D. Giardina, E. Goetz, R. Goetz, S. Gras, C. Gray, H. Grote, K. E. Gushwa, E. K. Gustafson, R. Gustafson, E. D. Hall, G. Hammond, J. Hanks, J. Hanson, T. Hardwick, G. M. Harry, M. C. Heintze, A. W. Heptonstall, J. Hough, R. Jones, S. Kandhasamy, S. Karki, M. Kasprzack, S. Kaufer, R. Kennedy, N. Kijbunchoo, W. Kim, E. J. King, P. J. King, J. S. Kissel, W. Z. Korth, G. Kuehn, M. Landry, B. Lantz, M. Laxen, J. Liu, N. A. Lockerbie, M. Lormand, M. MacInnis, D. M. Macleod, S. Márka, Z. Márka, A. S. Markosyan, E. Maros,

P. Marsh, I. W. Martin, D. V. Martynov, K. Mason, T. J. Massinger, F. Matichard, N. Mavalvala, R. McCarthy, D. E. McClelland , S. McCormick, L. McCuller, J. McIver, D. J. McManus, T. McRae, G. Mendell, E. L. Merilh, P. M. Meyers, R. Mittleman, K. Mogushi, D. Moraru, G. Moreno, C. M. Mow-Lowry, G. Mueller, N. Mukund, A. Mullavey, J. Munch, T. J. N. Nelson, P. Nguyen, L. K. Nuttall, J. Oberling, M. Oliver, P. Oppermann, Richard J. Oram, B. O'Reilly, D. J. Ottaway, H. Overmier, J. R. Palamos, W. Parker, A. Pele, S. Penn, C. J. Perez, M. Phelps, V. Pierro, I. M. Pinto, M. Pirello, M. Principe, L. G. Prokhorov, O. Puncken, V. Quetschke, E. A. Quintero, H. Radkins, P. Raffai, K. E. Ramirez, S. Reid, D. H. Reitze, N. A. Robertson, J. G. Rollins, V. J. Roma, C. L. Romel, J. H. Romie, M. P. Ross, S. Rowan, K. Ryan, T. Sadecki, E. J. Sanchez, L. E. Sanchez, V. Sandberg, R. L. Savage, D. Sellers, D. A. Shaddock, T. J. Shaffer, B. Shapiro, D. H. Shoemaker, B. J. J. Slagmolen, B. Smith, J. R. Smith, B. Sorazu, A. P. Spencer, K. A. Strain, D. B. Tanner, R. Taylor, M. Thomas, P. Thomas, K. A. Thorne, E. Thrane, K. Toland, C. I. Torrie, G. Traylor, M. Tse, D. Tuyenbayev, G. Vajente, G. Valdes, A. A. van Veggel, S. Vass, A. Vecchio, P. J. Veitch, K. Venkateswara, G. Venugopalan, T. Vo, C. Vorvick, M. Walker, R. L. Ward, J. Warner, B. Weaver, R. Weiss, P. Weßels, B. Willke, C. C. Wipf, J. Worden, H. Yamamoto, C. C. Yancey, Hang Yu, Haocun Yu, L. Zhang, M. E. Zucker, and J" Zweizig, *Improving astrophysical parameter estimation via offline noise subtraction for Advanced LIGO*, *Phys. Rev.* **D99** (2019) 042001 [`1806.00532`].

[219] Gabriele Vajente, Yiwen Huang, Maximiliano Isi, Jenne C. Driggers, Jeffrey S. Kissel, Marek J. Szczepanczyk, and Salvatore Vitale, *Machine-learning nonstationary noise out of gravitational-wave detectors*, *Phys. Rev.* **D101** (2020) 042003 [`1911.09083`].

[220] Sylvia Biscoveanu, Carl-Johan Haster, Salvatore Vitale, and Jonathan Davies, *Quantifying the Effect of Power Spectral Density Uncertainty on Gravitational-Wave Parameter Estimation for Compact Binary Sources*, *Phys. Rev.* **D102** (2020) 023008 [`2004.05149`].

[221] Salvatore Vitale, Carl-Johan Haster, Ling Sun, Ben Farr, Evan Goetz, Jeff Kissel, and Craig Cahillane, *Physical approach to the marginalization of LIGO calibration uncertainties*, *Phys. Rev. D* **103** (2021) 063016 [`2009.10192`].

[222] Bruce Allen, Warren G. Anderson, Patrick R. Brady, Duncan A. Brown, and Jolien D. E. Creighton, *FINDCHIRP: An Algorithm for detection of gravitational waves from inspiraling compact binaries*, *Phys. Rev.* **D85** (2012) 122006 [`gr-qc/0509116`].

[223] Samantha A. Usman, Alexander H. Nitz, Ian W. Harry, Christopher M. Biwer, Duncan A. Brown, Miriam Cabero, Collin D. Capano, Tito Dal Canton, Thomas Dent, Stephen Fairhurst, Marcel S. Kehl, Drew Keppel, Badri Krishnan, Amber Lenon, Andrew Lundgren, Alex B. Nielsen, Larne P. Pekowsky, Harald P. Pfeiffer, Peter R. Saulson, Matthew West, and Joshua L. Willis, *The PyCBC search for gravitational waves from compact binary coalescence*, *Class. Quant. Grav.* **33** (2016) 215004 [`1508.02357`].

[224] Alexander H. Nitz, Thomas Dent, Tito Dal Canton, Stephen Fairhurst, and Duncan A. Brown, *Detecting binary compact-object mergers with gravitational waves: Understanding and Improving the sensitivity of the PyCBC search*, *Astrophys. J.* **849** (2017) 118 [`1705.01513`].

[225] C. Biwer, D. Barker, J. C. Batch, J. Betzwieser, R. P. Fisher, E. Goetz, S. Kandhasamy, S. Karki, J. S. Kissel, A. P. Lundgren, D. M. Macleod, A. Mullavey, K. Riles, J. G. Rollins, K. A. Thorne, E. Thrane, T. D. Abbott, B. Allen, D. A. Brown, P. Charlton, S. G. Crowder, P. Fritschel, J. B. Kanner, M. Landry, C. Lazzaro, M. Millhouse, M. Pitkin, R. L. Savage, P. Shawhan, D. H.

Shoemaker, J. R. Smith, L. Sun, J. Veitch, S. Vitale, A. J. Weinstein, N. Cornish, R. C. Essick, M. Fays, E. Katsavounidis, J. Lange, T. B. Littenberg, R. Lynch, P. M. Meyers, F. Pannarale, R. Prix, R. O'Shaughnessy, and D. Sigg, *Validating gravitational-wave detections: The Advanced LIGO hardware injection system*, *Phys. Rev.* **D95** (2017) 062002 [`1612.07864`].

[226] F Beauville, M-A Bizouard, L Blackburn, L Bosi, P Brady, L Brocco, D A Brown, D Buskulic, S Chatterji, N Christensen, A-C Clapson, S Fairhurst, D Grosjean, G Guidi, P Hello, E Katsavounidis, M Knight, A Lazzarini, F Marion, B Mours, F Ricci, A Viceré, and M Zanolin, *A First comparison between LIGO and Virgo inspiral search pipelines*, *Class. Quant. Grav.* **22** (2005) S1149 [`gr-qc/0504050`].

[227] B. P. Abbott et al., LIGO Scientific Collaboration , *Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914*, *Phys. Rev.* **D95** (2017) 062003 [`1602.03845`].

[228] A. D. Viets, M. Wade, A. L. Urban, S. Kandhasamy, J. Betzwieser, Duncan A. Brown, J. Burguet-Castell, C. Cahillane, E. Goetz, K. Izumi, S. Karki, J. S. Kissel, G. Mendell, R. L. Savage, X. Siemens, D. Tuyenbayev, and A. J. Weinstein, *Reconstructing the calibrated strain signal in the Advanced LIGO detectors*, *Class. Quant. Grav.* **35** (2018) 095015 [`1710.09973`].

[229] Duncan A. Brown, LIGO Scientific Collaboration , *Testing the LIGO inspiral analysis with hardware injections*, *Class. Quant. Grav.* **21** (2004) S797 [`gr-qc/0312031`].

[230] P. Ajith, Michael Boyle, Duncan A. Brown, Bernd Brügmann, Luisa T. Buchman, Laura Cadonati, Manuela Campanelli, Tony Chu, Zachariah B. Etienne, Stephen Fairhurst, Mark Hannam, James Healy, Ian Hinder, Sascha Husa, Lawrence E. Kidder, Badri Krishnan, Pablo Laguna, Yuk Tung Liu, Lionel London, Carlos O. Lousto, Geoffrey Lovelace, Ilana MacDonald, Pedro Marronetti, Satya Mohapatra, Philipp Mösta, Doreen Müller, Bruno C. Mundim, Hiroyuki Nakano, Frank Ohme, Vasileios Paschalidis, Larne Pekowsky, Denis Pollney, Harald P. Pfeiffer, Marcelo Ponce, Michael Pürrer, George Reifenberger, Christian Reisswig, Lucía Santamaría, Mark A. Scheel, Stuart L. Shapiro, Deirdre Shoemaker, Carlos F. Sopuerta, Ulrich Sperhake, Béla Szilágyi, Nicholas W. Taylor, Wolfgang Tichy, Petr Tsatsin, and Yosef Zlochower, *The NINJA-2 catalog of hybrid post-Newtonian/numerical-relativity waveforms for non-precessing black-hole binaries*, *Class. Quant. Grav.* **29** (2012) 124001 [`1201.5319`].

[231] J. Aasi et al., LIGO Scientific Collaboration, Virgo Collaboration, NINJA-2 , *The NINJA-2 project: Detecting and characterizing gravitational waveforms modelled using numerical binary black hole simulations*, *Class. Quant. Grav.* **31** (2014) 115004 [`1401.0939`].

[232] Ian Hinder, Alessandra Buonanno, Michael Boyle, Zachariah B. Etienne, James Healy, Nathan K. Johnson-McDaniel, Alessandro Nagar, Hiroyuki Nakano, Yi Pan, Harald P. Pfeiffer, Michael Pürrer, Christian Reisswig, Mark A. Scheel, Erik Schnetter, Ulrich Sperhake, Bela Szilágyi, Wolfgang Tichy, Barry Wardell, Anıl Zenginoğlu, Daniela Alic, Sebastiano Bernuzzi, Tanja Bode, Bernd Brügmann, Luisa T. Buchman, Manuela Campanelli, Tony Chu, Thibault Damour, Jason D. Grigsby, Mark Hannam, Roland Haas, Daniel A. Hemberger, Sascha Husa, Lawrence E. Kidder, Pablo Laguna, Lionel London, Geoffrey Lovelace, Carlos O. Lousto, Pedro Marronetti, Richard A. Matzner, Philipp Mösta, Abdul Mroué, Doreen Müller, Bruno C. Mundim, Andrea Nerozzi, Vasileios Paschalidis, Denis Pollney, George Reifenberger, Luciano Rezzolla, Stuart L. Shapiro, Deirdre Shoemaker, Andrea Taracchini, Nicholas W. Taylor, Saul A. Teukolsky, Marcus Thierfelder, Helvi Witek, and Yosef Zlochower, *Error-analysis and comparison to analytical*

models of numerical waveforms produced by the NRAR Collaboration, Class. Quant. Grav. **31** (2014) 025012 [1307.5307].

[233] Duncan A. Brown, Jeff Crowder, Curt Cutler, Ilya Mandel, and Michele Vallisneri, *A Three-stage search for supermassive black hole binaries in LISA data*, Class. Quant. Grav. **24** (2007) S595 [0704.2447].

[234] Stanislav Babak, John G. Baker, Matthew J. Benacquista, Neil J. Cornish, Jeff Crowder, Curt Cutler, Shane L. Larson, Tyson B. Littenberg, Edward K. Porter, Michele Vallisneri, Alberto Vecchio, the Mock LISA data challenge task force, Gerard Auger, Leor Barack, Arkadiusz Błaut, Ed Bloomer, Duncan A. Brown, Nelson Christensen, James Clark, Stephen Fairhurst, Jonathan R. Gair, Hubert Halloin, Martin Hendry, Arturo Jimenez, Andrzej Królak, Ilya Mand el, Chris Messenger, Renate Meyer, Soumya Mohanty, Rajesh Nayak, Antoine Petiteau, Matt Pitkin, Eric Plagnol, Reinhard Prix, Emma L. Robinson, Christian Roever, Pavlin Savov, Alexander Stroeer, Jennifer Toher, John Veitch, Jean-Yves Vinet, Linqing Wen, John T. Whelan, and Graham Woan, MOCK LISA DATA CHALLENGE TASK FORCE , *Report on the second Mock LISA Data Challenge*, Class. Quant. Grav. **25** (2008) 114037 [0711.2667].

[235] Brown, Duncan A. and Brady, Patrick R. and Dietz, Alexander and Cao, Junwei and Johnson, Ben and McNabb, John, *A case study on the use of workflow technologies for scientific analysis: Gravitational wave data analysis*, in *Workflows for e-Science*, Ian J. Taylor, Ewa Deelman, Dennis Gannon, and Matthew S. Shields, eds., pp. 41–61, Springer-Verlag, (2006).

[236] Gurmeet Singh, Karan Vahi, Arun Ramakrishnan, Gaurang Mehta, Ewa Deelman, Henan Zhao, Rizos Sakellariou, Kent Blackburn, Duncan Brown, Stephen Fairhurst, David Meyers, G. Bruce Berriman, John Good, and Daniel S. Katz, *Optimizing workflow data footprint*, *Scientific Programming* **15** (2007) 249.

[237] Alex Withers, Brian Bockelman, Derek Weitzel, Duncan Brown, Jeff Gaynor, Jim Basney, Todd Tannenbaum, and Zach Miller, *Scitokens: Capability-based secure access to remote scientific data*, in *Proceedings of the Practice and Experience on Advanced Research Computing*, PEARC '18, (New York, NY, USA), pp. 24:1–24:8, ACM, 2018, DOI.

[238] Karan Vahi, Mats Rynge, George Papadimitriou, Duncan A. Brown, Rajiv Mayani, Rafael Ferreira da Silva, Ewa Deelman, Anirban Mandal, Eric Lyons, and Michael Zink, *Custom Execution Environments with Containers in Pegasus-enabled Scientific Workflows*, [1905.08204].

[239] Ryan P. Fisher, Gary Hemming, Marie-Anne Bizouard, Duncan A. Brown, Peter F. Couvares, Florent Robinet, and Didier Verkindt, *DQSEGDB: A time-interval database for storing gravitational wave observatory metadata*, *arXiv e-prints* (2020) arXiv:2008.11316 [2008.11316].

[240] Dylan Chapp, Danny Rorabaugh, Duncan A. Brown, Ewa Deelman, Karan Vahi, Von Welch, and Michela Taufer, *Applicability study of the PRIMAD model to LIGO gravitational wave search workflows*, in *P-RECS '19: Proceedings of the 2Nd International Workshop on Practical Reproducible Evaluation of Computer Systems*, (New York, NY, USA), ACM, 2019, [1904.05211].

[241] Duncan A. Brown, Karan Vahi, Michela Taufer, Von Welch, and Ewa Deelman, *Reproducing GW150914: the first observation of gravitational waves from a binary black hole merger*, [2010.07244].

[242] Daniel Finstad, Soumi De, Duncan A. Brown, Edo Berger, and Christopher M. Biwer, *Measuring the viewing angle of GW170817 with electromagnetic and gravitational waves*, *Astrophys. J. Lett.* **860** (2018) L2 [1804.04179].

[243] Alex B. Nielsen, Alexander H. Nitz, Collin D. Capano, and Duncan A. Brown, *Investigating the noise residuals around the gravitational wave event GW150914*, *JCAP* **1902** (2019) 019 [1811.04071].

[244] Soumi De, Christopher M. Biwer, Collin D. Capano, Alexander H. Nitz, and Duncan A. Brown, *Posterior samples of the parameters of binary black holes from Advanced LIGO, Virgo's second observing run*, [1811.09232].

[245] Alexander H. Nitz, Amber Lenon, and Duncan A. Brown, *Search for Eccentric Binary Neutron Star Mergers in the first and second observing runs of Advanced LIGO*, *Astrophys. J.* **890** (2019) 1 [1912.05464].

[246] Steven Reyes and Duncan A. Brown, *Constraints on Nonlinear Tides due to $p-g$ Mode Coupling from the Neutron Star Merger GW170817*, *Astrophys. J.* **894** (2020) 41 [1808.07013].

[247] Amber K. Lenon, Alexander H. Nitz, and Duncan A. Brown, *Measuring the eccentricity of GW170817 and GW190425*, *Mon. Not. Roy. Astron. Soc.* **497** (2020) 1966 [2005.14146].

[248] Ssohrab Borhanian, *gwbench: a novel Fisher information package for gravitational-wave benchmarking*, [2010.15202].

[249] Gravitational-Wave Bench Marking Tool: `https://gitlab.com/sborhanian/gwbench`.

[250] Anuradha Gupta, Davide Gerosa, K. G. Arun, Emanuele Berti, Will M. Farr, and B. S. Sathyaprakash, *Black holes in the low mass gap: Implications for gravitational wave observations*, *Phys. Rev.* **D101** (2020) 103036 [1909.05804].

[251] Anuradha Gupta, Derek Fox, B. S. Sathyaprakash, and B. F. Schutz, *Calibrating the cosmic distance ladder using gravitational-wave observations*, [1907.09897].

[252] Anuradha Gupta, Sayantani Datta, Shilpa Kastha, Ssohrab Borhanian, K. G. Arun, and B. S. Sathyaprakash, *Multiparameter tests of general relativity using multiband gravitational-wave observations*, *Phys. Rev. Lett.* **125** (2020) 201101 [2005.09607].

[253] Sayantani Datta, Anuradha Gupta, Shilpa Kastha, K. G. Arun, and B. S. Sathyaprakash, *Tests of general relativity using multiband observations of intermediate mass binary black hole mergers*, [2006.12137].

[254] Snowmass21 webpage: `https://snowmass21.org/`.

[255] *Cosmic Probes of Fundamental Physics* topical group of Snowmass21: `https://snowmass21.org/cosmic/cosmic_probes`.

[256] Curt Cutler, Emanuele Berti, Kelly Holley-Bockelmann, Karan Jani, Ely D. Kovetz, Shane L. Larson, Tyson Littenberg, Sean T. McWilliams, Guido Mueller, Lisa Randall, Jeremy D. Schnittman, David H. Shoemaker, Michele Vallisneri, Salvatore Vitale, and Kaze W. K. Wong, *What we can learn from multi-band observations of black hole binaries*, [1903.04069].

[257] Sherwood Richers, Christian D. Ott, Ernazar Abdikamalov, Evan O'Connor, and Chris Sullivan, *Equation of State Effects on Gravitational Waves from Rotating Core Collapse*, *Phys. Rev.* **D95** (2017) 063019 [`1701.02752`].

[258] National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. The National Academies Press; Washington, DC, 2012.

[259] K–12 Computer Science Framework Steering Committee, "K–12 computer science framework." https://k12cs.org/wp-content/uploads/2016/09/K%E2%80%9312-Computer-Science-Framework.pdf,
2016.

[260] National Governors Association Center for Best Practices, Council of Chief State School Officers, *Common Core State Standards for Mathematics*. National Governors Association Center for Best Practices and the Council of Chief State School Officers; Washington, DC, 2010.

[261] Google Inc. & Gallup Inc., "Diversity Gaps in Computer Science: Exploring the Underrepresentation of Girls, Blacks and Hispanics." http://goo.gl/PG34aH, 2016.

[262] Google Inc. & Gallup Inc., "Trends in the State of Computer Science in U.S. K-12 Schools." http://goo.gl/j291E0, 2016.

[263] National Academies of Sciences, Engineering, and Medicine, *Science Teachers' Learning: Enhancing Opportunities, Creating Supportive Contexts*. The National Academies Press; Washington, DC, 2015.

[264] K. Roth, H. Garnier, C. Chen, M. Lemmens, K. Schwille, and N.I.Z. Wickler, *Videobased lesson analysis: Effective science pd for teacher and student learning*, *Journal of Research in Science Teaching* **48** (2011) 117.

[265] `http://uaap.mit.edu/research-exploration/urop`.

[266] `https://oge.mit.edu/graddiversity/msrp/`.

[267] `https://outreach.mit.edu/events/`.

[268] T. R. Guskey, *Evaluating professional development*. Corwin Press; Thousand Oaks, CA, 2000.