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## Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo

Rich Abbott, Thomas D. Abbott, Sheelu Abraham, Fausto Acernese, Kendall Ackley, Carl Adams, Rana X. Adhikari, Vaishali B. Adya, Christoph Affeldt, Michalis Agathos, et al.

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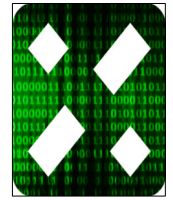
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## Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo



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## ABSTRACT

Advanced LIGO and Advanced Virgo are monitoring the sky and collecting gravitational-wave strain data with sufficient sensitivity to detect signals routinely. In this paper we describe the data recorded by these instruments during their first and second observing runs. The main data products are gravitational-wave strain time series sampled at 16384 Hz. The datasets that include this strain measurement can be freely accessed through the Gravitational Wave Open Science Center at <http://gw-openscience.org>, together with data-quality information essential for the analysis of LIGO and Virgo data, documentation, tutorials, and supporting software.

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## Code metadata

|   |   |
|---|---|
| Current data version  | O1 V1 and O2 R1   |
| Permanent link to code/repository used for this data version    | <a href="https://doi.org/10.7935/K57P8W9D">https://doi.org/10.7935/K57P8W9D</a> and <a href="https://doi.org/10.7935/CA75-FM95">https://doi.org/10.7935/CA75-FM95</a>   |
| Legal Code License  | Creative Commons Attribution International Public License 4.0   |
| Code versioning system used                                     | NA  |
| Software code languages, tools, and services used               | Python, Django  |
| Compilation requirements, operating environments & dependencies | Unix, Linux, Mac, Windows   |
| Link to documentation/manual                                    | <a href="https://www.gw-openscience.org/O1">https://www.gw-openscience.org/O1</a> and <a href="https://www.gw-openscience.org/O2">https://www.gw-openscience.org/O2</a> |
| Support email for questions                                     | <a href="mailto:gwosc@igwn.org">gwosc@igwn.org</a>  |

## 1. Motivation and significance

Gravitational waves (GWs) are transverse waves in the space-time metric that travel at the speed of light. They are generated by accelerated masses and more precisely, to lowest order, by time changes of the mass quadrupole [1], such as in the orbital motion of a binary system of compact stars. GWs were predicted in 1916 by Albert Einstein after the final formulation of the field equations of general relativity [2,3]. They were first observed directly in 2015 [4] by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [5] during its first observing run (O1), which took place from September 12, 2015 to January 19, 2016.

After an upgrade of the detectors, the second observing run (O2) took place from November 30, 2016 to August 25, 2017. Advanced Virgo [6] joined this observing run on August 1, 2017. On April 1, 2019, Advanced LIGO and Advanced Virgo initiated their third observing run (O3), lasting almost one year [7]. The analysis of O1 and O2 data produced 11 confident detections (10 binary black hole mergers [4,8–12] and 1 binary neutron star merger [13]) and 14 marginal triggers, collected and described in the Gravitational Wave Transient Catalog (GWTC-1) [14].

Notable events in this catalog are the first observed event GW150914 [4], the first three-detector event GW170814 [12] and the binary neutron star (BNS) coalescence GW170817 [13]. This latter event is the first case where gravitational and electromagnetic waves have been observed from a single source [15] offering a unique description of the physical processes at play during and after the merger of two neutron stars.

The main data product of the LIGO and Virgo detectors is a time series containing the measure of the strain, which will be described more in detail in the section 2. The LIGO Scientific Collaboration and the Virgo Collaboration (LVC) release their calibrated strain data to researchers outside the LVC and to a broader public that includes amateur scientists, students, etc. The roadmap for these data releases is described in the LIGO Data Management Plan [16] and in the Memorandum of Understanding between Virgo and LIGO [17] (Attachment A, Sec. 2.9). Two types of data release are foreseen. When GW events are discovered and published individually or in a catalog, the LVC releases short segments of GW strain data around the time of the GW events, as in the case of GWTC-1 [18]. In addition, a release of the strain recorded during the entire observation run occurs after a proprietary period of internal use, necessary also to validate and calibrate the data.

The cleaned, calibrated GW strain data related to both the O1 and O2 runs were released in January 2018 [19] and in February 2019 [20], respectively. The release of the strain data for the first block of six months of O3 is currently scheduled for April 2021, and November 2021 for the second 6-month block.

This article focuses on the already-released data from the O1 and O2 runs. Public access to these data along with extensive

documentation and usage instructions are provided through the Gravitational Wave Open Science Center (GWOSC) [21] at <http://gw-openscience.org>. GWOSC also provides online tools for finding and viewing data, usage guidelines and tutorials. We summarize this information, and include a comprehensive bibliography describing the detectors, the data collection and calibration, the noise characterization and software packages for data analysis.

To date more than 200 scientific articles have been written using the data from the GWOSC website. These analyses confirm, complement and extend the results published by the LVC, demonstrating the impact on the scientific community of the GW data releases. The covered topics span from alternative methods to search for gravitational wave events, some leading to new detections, e.g. [22–34], to reassessed estimations of the event parameters, e.g. [35–42], studies on matter effects for the binary neutron star, e.g. [43–46], GW polarization, e.g. [47,48], black-hole ringdown, e.g. [49,50], application of machine learning techniques to GW data analysis, e.g. [51,52], search for GW lensing effects, e.g. [53,54] and many other applications to astrophysics and cosmology, e.g. [55–59]. The list of projects goes beyond published scientific research and also includes student projects, academic courses, and art installations.<sup>1</sup>

This paper is organized as follows. The section 2 provides insights about how the data are collected and calibrated, about data quality and simulated signal injections. The GWOSC file format and content are described in the section 3, while the section 5 gives suggestions on the tools that can be used to guide the analysis of the GW data.

## 2. Methods

The Advanced LIGO [5] and Advanced Virgo [6] detectors are enhanced Michelson interferometers (see a simplified description of the experimental layout in Fig. 3 of [4] and Fig. 3 of [6]). Each detector has two orthogonal arms of equal length  $L_x = L_y = L$ , each with two mirrors acting as test masses and forming a Fabry–Perot optical cavity. The arm length is  $L = 4$  km for LIGO, and  $L = 3$  km for Virgo. Advanced LIGO consists of two essentially identical detectors at Hanford, Washington and Livingston, Louisiana, while the Advanced Virgo detector is located in Cascina near Pisa, Italy.

When GWs reach Earth, they alter the detector arm lengths, stretching or contracting each one according to the wave's direction, polarization and phase. This induces a time-dependent differential arm length change  $\Delta L = \delta L_x - \delta L_y = hL$ , proportional to the GW strain amplitude  $h$  projected onto the detector (see e.g., [1] chap. 9, p. 470). Photodiodes continuously sense the differential length variations by measuring the interference between

<sup>1</sup> See <http://gw-openscience.org/projects/> for the list of scientific papers and projects.

the two laser beams that return to the beam splitter from the detector arms.

While Advanced LIGO and Advanced Virgo follow a similar general scheme, each facility has a specific, though closely related, design. We refer the reader to the following references for details about the technical developments on the instrumentation and instrument controls that play a major part in reaching the sensitivities obtained during the O1 and O2 observing runs. For Advanced LIGO those include the light source (a pre-stabilized laser) [60,61], the main optics [62–69], the signal recycling mirror (used to optimize the GW signal extraction) [5,70,71], the optics suspension and seismic isolation systems [72–85], the sensing and control strategies [86–88], the automation system [89], and various techniques for the mitigation of optical contamination, stray light and thermal effects [90–93].

For Advanced Virgo [6,94] a similar list includes the high reflective coatings of the core optics [95,96], the locking, control and thermal compensation systems [97–99], and the mitigation of magnetic and seismic noises [100–103].

When the detectors are taking data in their nominal configuration, they are said to be in *observing mode* or *science mode*. This condition does not occur all the time for various technical reasons. For example, the Fabry–Perot cavities included in the detector arms have to be kept at resonance together with the power and signal recycling cavities [104]. There are periods when the control loops fail to maintain the instrument on this working point causing a non-observing period. Other possible reasons for non-observing include maintenance periods and environmental effects like earthquakes, wind and the microseismic ground motion arising from ocean storms [105,106].

The time percentage during which the detectors are in science mode is called *duty cycle* or *duty factor*. During O1 the LIGO detectors had individual duty factors of 64.6% for Hanford and 57.4% for Livingston, while in O2 it was 65.3% and 61.8%, respectively. Virgo operated with a duty factor of 85.1% during O2 (see table 1 of [7]).

If we define the *network duty factor* by the time percentage during which all the detectors in the network are in science mode simultaneously, we find 42.8% for the LIGO network during O1 and 46.1% during O2 [14]. For the LIGO–Virgo network it was 35%.

It is customary to quantify the detector sensitivity by the *range* [107,108], i.e., the distance to which sources can be observed. In Figs. 1 and 2, the *BNS range* is calculated assuming that the observed source is a coalescence of compact objects of masses of  $1.4 M_{\odot}$  each, the observation has a minimum threshold in signal-to-noise ratio (SNR) of 8, and the range is averaged over all possible sky locations and orientations of the source, following [107]. The figures contain also the equivalent cumulative time–volume [108] obtained by multiplying the amount of time spent observing by the observed astrophysical volume as defined by the range. The sharp drops in the *BNS range* are typically due to transient noise in the interferometer limiting its sensitivity, while the gaps are due to non-observing periods. In particular, during O2, there were two long breaks, one for end-of-year holidays and another to make improvements to the detectors. At the end of both runs there was a sensitivity drop in one of the LIGO detectors. For O1, a drop in sensitivity at LIGO Livingston was caused by electronics noise at one of the end stations while, for O2, a drop in sensitivity at LIGO Hanford was due to electrostatic charging of the test mass optics caused by an earthquake in Montana.

The plots in Figs. 1 and 2 are indicative of the performance of the individual detectors.<sup>2</sup> However, observations are performed

jointly by Advanced LIGO and Advanced Virgo as a network. Roughly speaking, the sensitivity of the global network is determined by that of the second most sensitive detector operating at any time. Despite the lower BNS range and cumulative time–volume for Virgo, its contribution has been important for astrophysical parameter estimation, especially in determining source localization and orientation [109]. For instance, GW170814 and GW170817 were localized by the three-detector network within a few tens of square degrees while the other events were localized by the two-detector network in sky areas ranging from a few hundreds to several thousands of square degrees.

Note that the sensitive distance depends strongly on the source mass, and can be much higher (up to gigaparsecs) for higher-mass BBH systems (see e.g. Fig. 1 of Ref. [110]).

The next sections provide details on the calibration, the detector noise characterization, the data quality and signal injections.

### 2.1. Calibration

The differential arm length read-out of the interferometer is recorded digitally through a data acquisition system [5,6,111]. The LIGO and Virgo data acquisition systems acquire data at sampling rates  $f_s = 16\,384$  Hz and 20 000 Hz, respectively. The Virgo data is digitally converted to the same sampling rate as LIGO prior to any analysis.

A calibration procedure [112–117] is applied to produce the dimensionless strain from the differential arm length read-out. For both the Advanced LIGO and Advanced Virgo detectors, the calibration procedure creates a digital time series,  $h(t)$ , from the detector control system channels. Details of the production and characterization of  $h(t)$  can be found in [118,119]. The calibration uncertainty estimation and residual systematic errors are discussed in [119–121]. The strain time series include both detector noise and any astrophysical signal that might be present.

Multiple versions of the calibrated data are produced as more precise measurements or instrument models become available. A first strain  $h(t)$  is initially produced online using calibration parameters measured just before the observing period starts. This data stream is analyzed within a few seconds to generate alerts when an event is detected thus allowing follow-up observations by other facilities [122]. Other offline versions of the calibration is produced later, offline, to include improvements to the calibration models or filters, to resolve dropouts in the initial online version or after applying noise cleaning procedures. This data stream is used in the production of the final search results, e.g., the final event catalog.

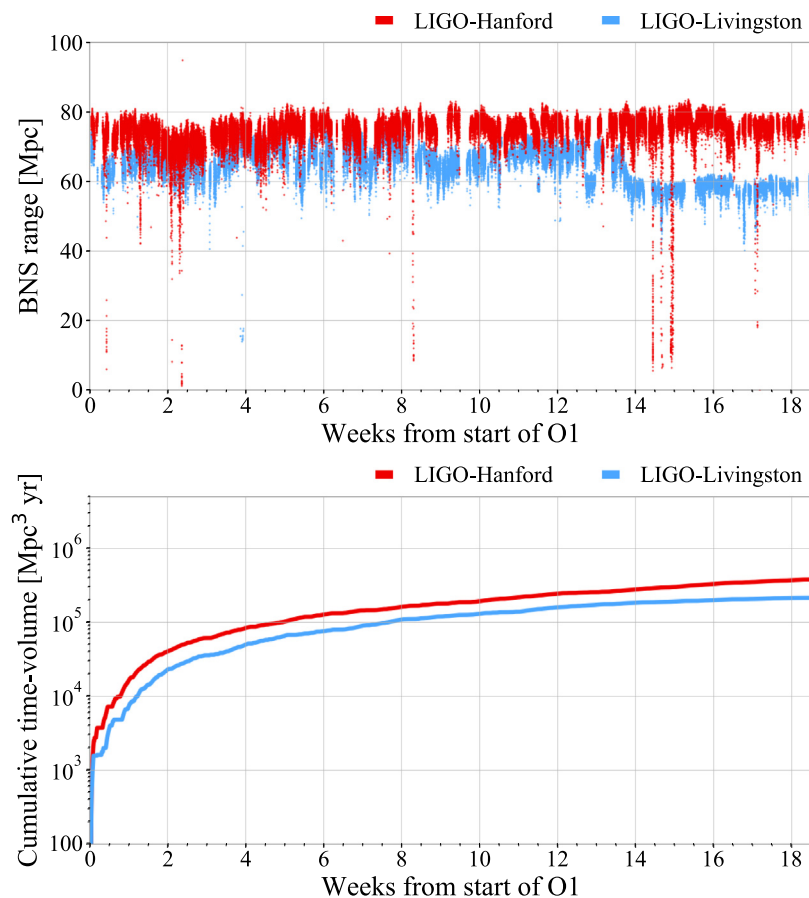
For the O1 and O2 science runs, we released the final offline version, that has the most precise uncertainties and after applying available noise cleaning procedures. The calibration versions differ for the single event data releases depending on whether they pertain to the initial publication of the event (early version) [123–129] or to the catalog GWTC-1 publication (final version) [18].

The detector strain  $h(t)$  is only calibrated between 10 Hz and 5000 Hz for Advanced LIGO [118,120] and 10 Hz and 8000 Hz for Advanced Virgo [119]. Any apparent signal outside this range cannot be trusted because it is not a faithful representation of the GW strain at those frequencies. This part of the spectrum where the data are not calibrated corresponds to the regions where the measurement noise increases rapidly, thus drastically reducing the chance for observing GWs.

### 2.2. Detector noise characterization and data quality

The strain measurement is impacted by multiple noise sources, such as quantum sensing noise, seismic noise, suspension thermal noise, mirror coating thermal noise, and local gravity gradient

<sup>2</sup> These figures are produced with data calibrated using the procedure described in the next section.



**Fig. 1.** Upper plot: O1 sensitivity of the Livingston and Hanford detectors to GWs as measured by the BNS range (in megaparsecs) to binary neutron-star mergers averaged over all sky positions and source orientations [107]. Lower plot: cumulative time–volume (assuming an Euclidean geometry appropriate for small redshifts) of the Livingston and Hanford detectors during O1, obtained by multiplying the observed astrophysical volume by the amount of time spent observing.

noise produced by seismic waves (called Newtonian noise) [5]. The noise budget plot for Advanced LIGO during O1 can be found in [70]. In Figs. 3 and 4 the noise budget for O2 is shown for Advanced LIGO and Advanced Virgo, respectively.

The plots show the measured noise spectrum and the contribution from various known noise sources.<sup>3</sup> The noise spectra indicate that the dominant noises rise steeply at high and low frequencies. This opens an observational window between tens of Hz and a few kHz. Data analysis pipelines that are used to search for gravitational-wave signals usually concentrate on frequency intervals smaller than the full calibrated bandwidth to avoid the high noise level at the extremes of this band.

The strain data are high-pass filtered at 8 Hz to avoid a number of digital signal processing problems related to spectral dynamic range and floating point precision limitation that may occur downstream when searching in the data.<sup>4</sup>

As shown in Figs. 3 and 4, the data contain spectral lines that can complicate searches for signals in those frequency bands [132]. These lines include calibration lines, power line harmonics, “violin” modes (resonant frequencies of mirror suspension fibers), other known instrumental lines, unknown lines and also evenly spaced combs of narrow lines, typically in exact multiples of some fundamental frequency. Further details on spectral lines during

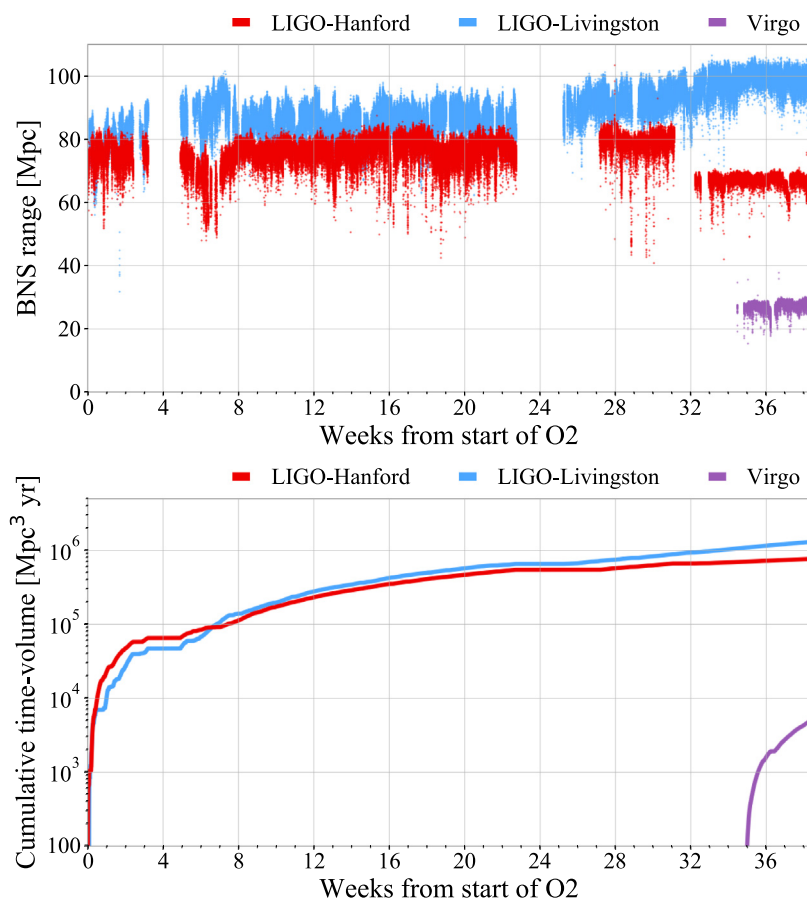
<sup>3</sup> Other useful references for the detector sensitivity are [130] for O1 and [14] for O2.

<sup>4</sup> See [https://www.gw-openscience.org/yellow\\_box/](https://www.gw-openscience.org/yellow_box/) and in particular the example showing the 8 Hz roll-off at [https://www.gw-openscience.org/static/images/ASDs\\_GW150914\\_1-Hz.png](https://www.gw-openscience.org/static/images/ASDs_GW150914_1-Hz.png).

O1 and O2 can be found in [133,134] as well as on the GWOSC web pages.<sup>5</sup>

The detector sites are equipped with a large number of sensors that monitor both the instrumental and environmental state (see [105,106,135] for details). The measurements performed by these sensors are recorded in *auxiliary channels* that are crucial for diagnosing instrument faults or for identifying environmental perturbations. Non-Gaussian transient noise artifacts, called *glitches*, can mask or mimic true astrophysical signals [105]. Auxiliary channels provide a useful source of information for the characterization of glitches, and their mitigation. Glitches are caused by anomalous behavior in instrumental or environmental channels that couple into the GW channel. The observation of coincident glitches between the GW and auxiliary channels provides a mechanism for rejecting a detected (potential) event in the former as not astrophysical in origin. The large volume of auxiliary data (hundreds of thousands of auxiliary channels) are inspected (see [105,106,135] for details) and distilled into *data quality vetoes* that allow identification of times that are unsuitable for analysis or are likely to produce false alarms. Veto conditions are determined using systematic studies to remove glitches with high efficiency and limited loss of observation time [105]. As an example, vetoes discard glitches from electronics faults, photodiode saturations, analog-to-digital converter (ADC) and digital-to-analog converter (DAC) overflows, elevated seismic noise and computer failures. The data quality vetoes are

<sup>5</sup> <http://gw-openscience.org/o1speclines> and <http://gw-openscience.org/o2speclines>.



**Fig. 2.** Upper plot: O2 sensitivity of the Livingston, Hanford and Virgo detectors to GWs as measured by the BNS range (in megaparsecs) to binary neutron-star mergers averaged over all sky positions and source orientations [107]. Lower plot: cumulative time-volume (assuming Euclidean geometry appropriate for small redshifts) of the Livingston, Hanford and Virgo detectors during O2, obtained by multiplying the observed astrophysical volume by the amount of time spent observing. Although Virgo has a lower BNS range and cumulative time-volume, its contribution is crucial for source localization and astrophysical parameter estimation.

used by the GW searches to reduce the noise background [105] (see Sec. 3.2 for search-related usage information).

Different categories of data quality are defined according to the severity level and degree of understanding of the noise artifact. Data flagged as invalid due to severe detector malfunctioning, calibration error, or data acquisition problems, as described in [136] are typically not used for data analysis and are replaced by NaNs in the GWOSC data releases. We elaborate further on the various data quality categories and their usage in the section 3.6

Auxiliary channels are also used to subtract post-facto some well identified instrumental noise from the GW strain data. A procedure based on a linear coupling model [137] computes the transfer function that couples the witness channels to  $h(t)$  and subtracts the contributing noise from the strain amplitude. This procedure was used during the second observing run in Advanced LIGO data. It achieved an increase of up to 30% of the detector sensitive volume to GWs for a broad range of compact binary systems and was most significant for the LIGO-Hanford detector [138]. In some cases data are available both before and after noise subtraction is applied (for example in the case of GW170817 [129]).

### 2.3. Signal injections

In addition to data quality, some metadata provide information about *hardware injections* [139] inserted into the detector

<sup>6</sup> See also [http://gw-openscience.org/o1\\_details](http://gw-openscience.org/o1_details) and [http://gw-openscience.org/o2\\_details](http://gw-openscience.org/o2_details).

data for testing and calibration. The detectors' test masses (interferometer mirrors) are physically displaced by an actuator in order to simulate the effects of a GW.<sup>7</sup> A simulated GW signal is introduced into the detector control system yielding a response which mimics that of a true GW. The analysis of a data segment that includes an injection allows an end-to-end test of the ability for the analysis procedure to detect and characterize the GW strain signal.

Hardware injections are also used for detector characterization to check that the auxiliary channels used for vetoes do not respond to gravitational-wave-like signals. This is a *safety* check since a channel that has no sensitivity to GWs is considered safe for use when constructing a veto. It is clearly important to keep a record of injections to avoid any confusion with real events. In the section 3 we describe how this bookkeeping is done.<sup>8</sup>

### 3. Data records

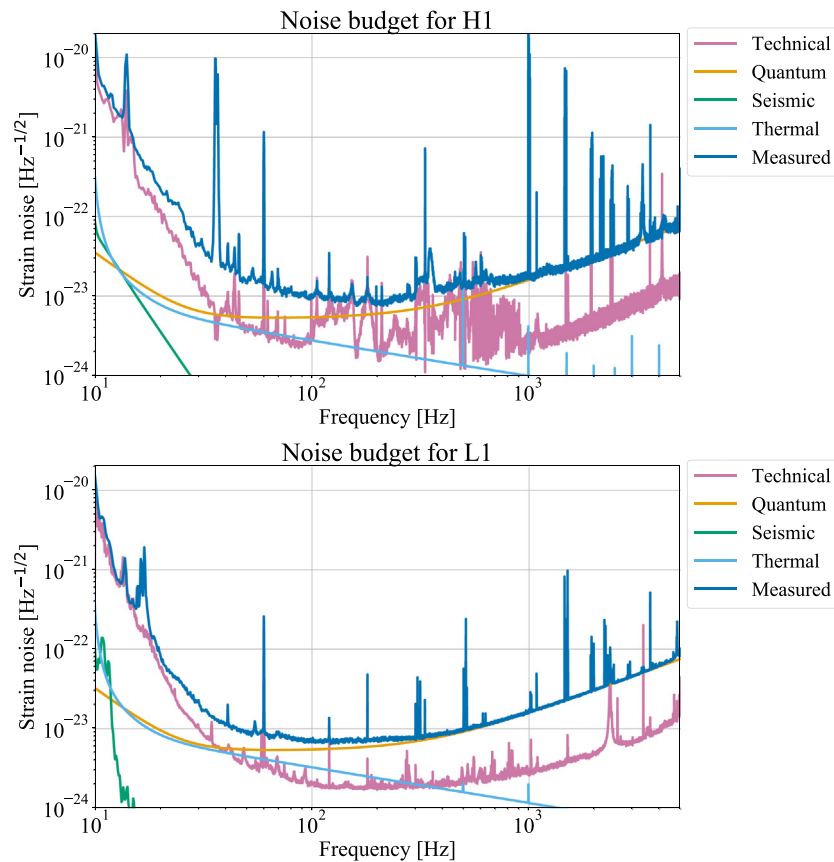
GW open data are distributed under the Creative Commons Attribution International Public License 4.0<sup>9</sup> through the GWOSC web pages.<sup>10</sup> The files can be directly downloaded one by one from this web page. However, to download large amounts of

<sup>7</sup> Calibration lines mentioned earlier are generated using the same process.

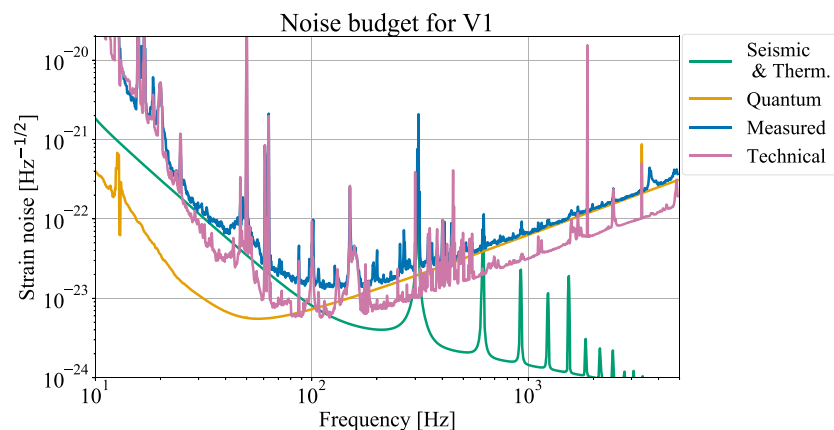
<sup>8</sup> See the GWOSC web page [http://gw-openscience.org/o1\\_inj](http://gw-openscience.org/o1_inj) and [http://gw-openscience.org/o2\\_inj](http://gw-openscience.org/o2_inj).

<sup>9</sup> <https://creativecommons.org/licenses/by/4.0/legalcode>

<sup>10</sup> <http://gw-openscience.org/data/>



**Fig. 3.** Sensitivities of the Advanced LIGO detectors during the second observation run (O2), expressed as the equivalent strain noise spectrum of each detector (the blue “Measured” curves). Also shown are the known contributors to the detector noise, which sum to the measured spectrum across much, but not all of the frequency band (i.e. the measured noise spectrum is not fully explained by all known sources of noise). The quantum noise includes both shot noise (dominant at higher frequencies) and radiation pressure noise (dominant at lower frequencies). Thermal noise includes contributions from the suspensions, the substrate and coatings of the test masses. Seismic noise is computed as the ground displacement attenuated through the seismic isolation system and the suspensions chain. The seismic curves differ for H1 and L1 as actual seismic data were used for L1 while the H1 curve is a model that also includes Newtonian noise. Technical noise includes angular and length sensing/control noise for degrees of freedom that are not related to the differential arm length measurement, and other sub-dominant noises such as laser frequency, intensity and beam jitter noise, sensor and actuation noise, and Rayleigh scattering by the residual gas. The strong line features are due to the violin modes of the suspension wires, other resonance modes of the suspensions, the AC power line and its harmonics, and the calibration lines. Examples of similar plots for other data taking runs can be found in [70,131]. These noise spectra do not include any of the post-data collection noise subtraction mentioned in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Sensitivity of the Advanced Virgo detector during the O2 observation run. The meaning of the noise source contributions is the same as in Fig. 3, except for the seismic and thermal noises that are combined in this case and for the Newtonian noise which is not included. These noise spectra do not include any of the post-data collection noise subtraction mentioned in the text.

data (such as an entire observing run) the use of the distributed filesystem CernVM-FS [140,141] is preferred.<sup>11</sup> Once installed,

<sup>11</sup> For installation instructions, see <http://gw-openscience.org/cvmfs/>

**Table 1**

The channel names and frame types listed in this table are unique identifiers in the LIGO and Virgo data archives that allow tracing the provenance of the strain data released on GWOSC. The attribute CLEAN in H1 and L1 for O2 indicates that the noise subtraction procedure mentioned previously and described in [137] was used. The attributes CO2, DCS, DCH and Repro2A refer to the calibration version.

| Run Det. | Channel name                      | Frame type          |
|----------|-----------------------------------|---------------------|
| O1 H1    | H1:DCS-CALIB_STRAIN_CO2           | H1_HOFT_CO2         |
| O1 L1    | L1:DCS-CALIB_STRAIN_CO2           | L1_HOFT_CO2         |
| O2 H1    | H1:DCH-CLEAN_STRAIN_CO2           | H1_CLEANED_HOFT_CO2 |
| O2 L1    | L1:DCH-CLEAN_STRAIN_CO2           | L1_CLEANED_HOFT_CO2 |
| O2 V1    | V1:Hrec_hoft_V102Repro2A_16384_Hz | V102Repro2A         |

this filesystem allows access to GWOSC data as files in a directory tree mounted locally on the user's computer.

The calibrated strain data of O1 [19] and O2 [20] described in this paper are conveniently divided into files of 4096 s. Short segments of 32 s and 4096 s duration for each GW event are also released.<sup>12</sup> The description of the data records that follows is valid both for single event release and for bulk data release.

The strain data are repackaged and resampled by GWOSC to make it more accessible to users both within the LVC and outside. Along with the native 16384 Hz sampling rate, the data on GWOSC are also made available at 4096 Hz.<sup>13</sup> The down-sampling is performed using the standard decimation technique implemented in `scipy.signal.decimate`<sup>14</sup> from the Python package `scipy` [143]. From the Nyquist-Shannon sampling theorem [144–146], the largest accessible frequency is the Nyquist frequency equal to half of the sampling rate  $f_s$ . This should be kept in mind when choosing the sampling rate to download from GWOSC, and in general when analyzing these files; in particular, because of the anti-aliasing filter's roll-off, the data sampled at 4 kHz are valid only up to frequencies of about 1700 Hz.

The publicly released data are generated from data streams in the LIGO and Virgo data archives uniquely identified by a channel name and a frame type (an internal label that specifies the content of the files). For completeness, we give the provenance of the GWOSC data in Table 1 and list the channel names and frame types used to generate the O1 and O2 dataset discussed in this article. In this table and in the following, H1 and L1 indicate the two LIGO detectors (Hanford and Livingston respectively) while V1 refers to Virgo. Downsampling (for the 4 kHz dataset) and replacement with NaNs of bad quality or absent data are the only modifications of the original data.

### 3.1. Gwosc file formats

The GW open data are delivered in two different file formats: `hdf` and `gwf`. The Hierarchical Data Format `hdf` [147] is a portable data format readable by many programming languages. The Frame format `gwf` [148] is used internally by the GW community. In addition, the data associated with GW events are also released as plain text files containing two columns with the GPS time and the corresponding strain values.

There are some differences in the structure of the file names between O1 and O2 due to the evolution of GWOSC itself. For O1 the name of the files has the structure: `obs-ifo_LOSC_s_Vn-GPSstart-duration.extension`, where `obs` is the observatory, i.e. the

<sup>12</sup> <http://gw-openscience.org/eventapi/>

<sup>13</sup> In the rest of the paper the sampling rates will be indicated in kHz and rounded to the closest integer, i.e. 4 and 16 kHz means 4096 and 16384 Hz, respectively

<sup>14</sup> This method applies an anti-aliasing filter based on an order-8 Chebyshev type I infinite impulse response (IIR) filter [142] before decimation.

**Table 2**

Channel names of the GWOSC frame (`gwf`) files. In the name, `ifo` is a place holder for the interferometer name, i.e. H1, L1 or V1, and `s` the sampling rate in kHz. The R1 substring represents the revision number of the channel name so it will become R2 in case there is a second (revised) release, and so on.

|                   | O1 (4 kHz sampling)           | O1 (16 kHz sampling) and O2            |
|-------------------|-------------------------------|--|
| Strain            | <code>ifo:LOSC-STRAIN</code>  | <code>ifo:GWOSC-sKHZ_R1_STRAIN</code>  |
| Data quality mask | <code>ifo:LOSC-DQMASK</code>  | <code>ifo:GWOSC-sKHZ_R1_DQMASK</code>  |
| Injections mask   | <code>ifo:LOSC-INJMASK</code> | <code>ifo:GWOSC-sKHZ_R1-INJMASK</code> |

site, so can have values L or H; `ifo` is the interferometer and can have values H1 or L1; `LOSC` is the previous name of GWOSC, (the L in `LOSC` stands for LIGO); `s` is the sampling rate in kHz with possible values 4 or 16; `n` is the version number of the file (until now we have only one version, so only V1); `GPSstart` is the starting time in GPS of the data contained in the file; `duration` is the duration in seconds of this segment of data, which value is always 4096 in this case; the `extension` can be `gwf` or `hdf`. The file names in O2 are instead of the type `obs-ifo_GWOSC_ObservationRun_sKHZ_Rn-GPSstart-duration.extension`, with the same meaning of the italic letters, but in this case `obs` and `ifo` can have also the values V and V1, respectively, for Virgo data and we added the run name in the file names, so in this case `ObservationRun` is O2.

The folders (or groups) included in the `hdf` files are:

- `meta`: metadata of the file containing the following fields:
  - `Description`, e.g. “Strain data time series from LIGO”,
  - `DescriptionURL`: URL of the GWOSC website,
  - `Detector`, e.g. L1, and `Observatory`, e.g. L,<sup>15</sup>
  - `Duration`, `GPSstart`, `UTCstart`: duration and starting time (in GPS and UTC, respectively) of the segment of data contained in the file.

In the O2 files it was decided to add also the `StrainChannel` and `FrameType` of the original files internally used by the LVC (i.e. the content of Table 1).

- `strain`: array of  $h(t)$ , sampled at 4 or 16 kHz depending on the file. For the times when the detector is not in science mode or the data does not meet the minimum required data quality conditions (see next section), the strain values are set to NaNs. The strain  $h(t)$  is a function of time, so it is accompanied by the attributes `Xstart` and `Xspacing` defining the starting GPS time of the data contained in the array and the corresponding distance in time between the points of the array.
- `quality`: this folder contains two sub-folders, one for data quality and the other for injections, each including a bitmask to indicate at each second the status of the data quality or the injections and the description of each bit of the mask, i.e. the content of Tables 3 and 4 (see section 3.2 for details).

The `gwf` files have a similar content but with a different structure. They contain 3 channels, one for the strain data, one for the data quality and one for the injections. The channel names differ slightly in O1 and O2 as described in Table 2. Note that the original files produced internally, whose channel names are listed in Table 1, contain only the strain channel, while the GWOSC files include also the data quality and injection information in the same file.

<sup>15</sup> The observatory refer to the site and it is indicated by one letter, like L for Livingston. The addition of a number after the letter to indicate the detector, e.g. L1, could be useful if multiple detectors are installed in the same site, as it was at the beginning of LIGO.



### 3.2. Data quality and injections in gwosc files

Several types of searches are performed on the LIGO and Virgo data. Those searches are divided into four families named after the type of signals they target: Compact binary coalescences (CBC), GW bursts (BURST), continuous waves (CW) and stochastic backgrounds (STOCH).

CBC analyses (see e.g., [8,14,110,149–153]) seek signals from merging neutron stars and black holes by filtering the data with waveform templates. BURST analyses (see e.g., [154–158]) search for generic GW transients with minimal assumption on the source or signal morphology by identifying excess power in the time–frequency representation of the GW strain data. CW searches (see e.g., [159–162]) look for long-duration, continuous, periodic GW signals from asymmetries of rapidly spinning neutron stars. STOCH searches (see e.g., [163,164]) target the stochastic GW background signal which is formed by the superposition of a wide variety of independent and unresolved sources from different stages of the evolution of the Universe.

Due to the fundamental differences among these searches, some types of noise are problematic only for one or two types of search. For this reason, the data quality related to transient noises depends on the search type. It is provided inside the GWOSC files for the two GW transient searches CBC and BURST, that are most sensitive to this type of noise. The data quality information most relevant for CW and STOCH searches is in the frequency domain and it is provided as lists of instrumental lines in separate files [165–169].

Data quality and signal injection information for a given GPS second is indicated by bitmasks with a 1-Hz sampling rate. The bit meanings are given in Tables 3 and 4 for the data quality and injections, respectively. To describe data quality, different categories are defined. For each category, the corresponding bit in the bitmask shown in Table 3 has value 1 (good data) if in that second of time the requirements of the category are fulfilled, otherwise 0 (bad data).

The meaning of each category is the following:

**DATA** Failing this level indicates that LIGO and Virgo data are not available in GWOSC data because the instruments were not operating in nominal conditions. For O1 and O2, this is equivalent to failing Category 1 criteria, defined below. For these seconds of bad or absent data, NaNs have been inserted.

**CAT1** (Category 1) Failing a data quality check at this category indicates a critical issue with a key detector component not operating in its nominal configuration. Since these times indicate a major known problem they are identical for each data analysis group. However, while CBC\_CAT1 and BURST\_CAT1 flag the same data, they exist separately in the dataset. GWOSC data during times that fail CAT1 criteria are replaced by NaN values in the strain time series. The time lost due to these critical quality issues (*dead time*) is: 1.683% (H1) and 1.039% (L1) of the run during O1; and 0.001% (H1), 0.003% (L1) and 0.053% (V1) of the run during O2 (all the percentages have been calculated with respect to the periods of science mode).

**CAT2** (Category 2) Failing a data quality check at this category indicates times when there is a known, understood physical coupling between a sensor/auxiliary channel that monitors excess noise, and the strain channel [170]. The dead times corresponding to this veto for the CBC analysis are: 0.890% (H1) and 0.007% (L1) of the run during O1; 0.157% (H1) and 0.090% (L1) of the run during O2. The dead times corresponding to this veto for the BURST analysis are:

**Table 3**

Data quality bitmasks description. Data that are *not* present are replaced by NaN values in the strain time series. CBC\_CAT1 and BURST\_CAT1 are equivalent (see the definition of CAT1 in the text).

| Bit | Short name | Description   |
|-----|------------|---|
| 0   | DATA       | Data present  |
| 1   | CBC_CAT1   | Pass CAT1 test                                      |
| 2   | CBC_CAT2   | Pass CAT1 and CAT2 test for CBC searches            |
| 3   | CBC_CAT3   | Pass CAT1 and CAT2 and CAT3 test for CBC searches   |
| 4   | BURST_CAT1 | Pass CAT1 test                                      |
| 5   | BURST_CAT2 | Pass CAT1 and CAT2 test for BURST searches          |
| 6   | BURST_CAT3 | Pass CAT1 and CAT2 and CAT3 test for BURST searches |

**Table 4**

Meaning of the injection bits.

| Bit | Short name        | Description                             |
|-----|-------------------|---|
| 0   | NO_CBC_HW_INJ     | No CBC injections                       |
| 1   | NO_BURST_HW_INJ   | No burst injections                     |
| 2   | NO_DETCHAR_HW_INJ | No detector characterization injections |
| 3   | NO_CW_HW_INJ      | No continuous wave injections           |
| 4   | NO_STOCH_HW_INJ   | No stochastic injections                |

0.624% (H1) and 0.021% (L1) of the run during O1; 0.212% (H1) and 0.151% (L1) of the run during O2. CAT2 was not used for Virgo in O2.

**CAT3** (Category 3) Failing a data quality check at this category indicates times when there is statistical coupling between a sensor/auxiliary channel and the strain channel which is not fully understood. This category was not used in O1 and O2 LVC searches, but it is still in the file format for historical reasons.

As an example, [170] gives the list of all sensors/auxiliary channels used to define the CAT1 and CAT2 flags for BURST and CBC around the event GW150914.

Data quality categories are cascading: a time which fails a given category automatically fails all higher categories. Since CAT3 is not used in this specific case and only data passing CAT1 are provided, there is only the possibility that the data pass or not CAT2. However, the different analysis groups qualify the data independently: failing BURST\_CAT2 does not necessarily imply failing CBC\_CAT2.

The injection bitmask marks the injection-free times. Five different types of injections are usually performed: injections simulating signals searched for by CBC, BURST, CW and STOCH LVC pipelines, and injections used for detector characterization, labeled DETCHAR. For each injection type, the bit of the bitmask, whose meaning is described in Table 4, has value 1 if the injection is not present, otherwise 0.

Virgo did not perform hardware injections during O2, therefore all the bits of the injection bitmask have value 1.

## 4. Technical validation

The data repackaged for public use are validated by another independent internal team. In particular, this review team checks that:

- the strain vectors in the GWOSC hdf and gwf files are identical to machine precision to the corresponding strain vectors of the LVC main archives;
- the data quality and injection information given to the user correspond to what is included in the original LVC data quality database. The user can get this information in two ways: the bitmask included in the GWOSC files and the *Timeline* tool described in detail in the section 5. The output of both methods is checked against the database;

- the documentation web pages and the content of the present article contain correct and comprehensive information.

The data files, the *Timeline* and the web pages are released to the public once all those checks have been passed.

## 5. Usage notes

GW detectors are complex instruments, and their data reflect this complexity. For this reason, caution should be taken when searching for GW signals in the detector strain data, taking into account all the details about the usable frequency range, noise artifacts, data quality and injections discussed in this paper and in the references. In particular, the application of all data quality flags described in the previous section does *not* imply that the remaining data are free of transient noise artifacts. The user can find guidance to analyze the GW data in the tutorials and tools collected in the GWOSC website and discussed in the next subsections. The data analysis techniques used to detect GW signals and infer the source properties are described in [132] where good practices and advices to avoid common errors are also provided. The GWOSC website also contains basic information about the geographical position<sup>16</sup> and the current status<sup>17</sup> of the detectors.

### 5.1. Timeline

The LIGO and Virgo detectors are not always in observing mode and, even when they are, it is possible that data quality does not meet the requirements of a given analysis. For these reasons it is necessary to restrict analysis to valid *segments* of data characterized by data quality information that indicates the data is acceptable for the desired analysis. *Timeline*<sup>18</sup> is a tool to provide a visual representation of available valid data segments over a time interval, together with the related information about data quality and presence of injected signals (see Fig. 5 for an example with the O2 dataset). If the requested interval is short enough, this is shown at the time scale of seconds. For longer intervals, *Timeline* shows the average value of the selected data-quality bit over nonoverlapping  $2^n$ -second subintervals.

Besides the visual representation, this tool allows the user to download the list of start and stop of the segments for a specific data quality category or injection type, and also the corresponding data.

### 5.2. Courses, software packages and tutorials for gw data analysis

On-line courses that provide an introduction to GW data analysis ranging from the basics to more advanced topics with hands-on exercises are available from the GWOSC website.<sup>19</sup> Those courses have been recorded during the GW Open Data Workshops. They include lectures on various aspects of GW science and are supported by many tutorials that can be used to understand how to read and analyze the data. The tutorials on the GWOSC website<sup>20</sup> are in the form of Jupyter notebooks [171]. They explain how to access the data, produce time–frequency spectrograms, carry out matched-filtering searches, infer astrophysical parameters, and manipulate GW localization information. A few tutorials start from first principles and use generic and broadly used analysis software such as *scipy* [143], but most are based on the specialized software packages and libraries that the LVC

developed to produce observational results and other scientific products.

A list of those packages is available on the GWOSC website<sup>21</sup> and includes:

- the light-weight application *readligo* to access data;
- general purpose application software, such as the LSC Algorithm Library Suite (LALSuite) [172] and the Python package *gwp* [173];
- search-oriented software such as *pycbc* [149,150], *Gst-LAL* [174] and Coherent Waveburst (*cWB*) [154];
- post-processing software for e.g., parameter estimation such as *bilby* [175], *LALInference* [176] and *Bayeswave* [177, 178].

All these packages are open source and freely distributed.

### 5.3. Summary and additional information

The LVC is committed to providing strain data from the LIGO and Virgo detectors to the public, according to the schedule outlined in the LIGO Data Management Plan [16], via the Gravitational Wave Open Science Center (GWOSC) [179]. They are also committed to providing a broad range of data analysis products to facilitate reproducing the results presented in their observational papers. Many of these data products are available through the LIGO Document Control Center (DCC); for example, data products associated with the GWTC-1 event catalog [14] can be found in [18] and [180]. Many more data offerings are planned for the future. This includes the catalog of observed events and the bulk strain data from the LIGO/Virgo O3 run. More GWOSC Open Data Workshops are also planned.

All users of these data are welcome to sign up with the GWOSC User's Group at <https://www.gw-openscience.org/join/>. Anyone who uses these data in publications and other public data products are requested to acknowledge GWOSC by following the guidance in [181]. Publications that acknowledge GWOSC will be listed in <https://www.gw-openscience.org/projects/>; email [gwosc@igwn.org](mailto:gwosc@igwn.org) to make sure your publication(s) are included.

The Collaborations, and the GWOSC team, welcome comments and suggestions for improving these data releases and products, and their presentation on the GWOSC website [179], via email to [gwosc@igwn.org](mailto:gwosc@igwn.org). Questions about the use of these data products may also be sent to that email, and will be entered into our help ticket system. More general questions about LIGO, Virgo, and GW science should go to [questions@ligo.org](mailto:questions@ligo.org).

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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<sup>16</sup> <http://gw-openscience.org/static/param/position.txt>

<sup>17</sup> [http://gw-openscience.org/detector\\_status/](http://gw-openscience.org/detector_status/)

<sup>18</sup> <http://gw-openscience.org/timeline/>

<sup>19</sup> <http://gw-openscience.org/workshops/>

<sup>20</sup> <http://gw-openscience.org/tutorials/>

<sup>21</sup> <http://gw-openscience.org/software/>



**Fig. 5.** The GWOSC offers immediate access to duty cycle information for data quality and injection bits through the *Timeline* (<http://gw-openscience.org/timeline/>). By default, the time resolution is chosen to display the entire dataset. From there, one can zoom in to smaller timescales by clicking on the display.

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## References

- [1] Maggiore M. Gravitational waves, volume 1: theory and experiments. Oxford University Press; 2008.
- [2] Einstein A. Approximative integration of the field equations of gravitation. Sitzungsber Preuss Akad Wiss Berlin (Math Phys) 1916;1916:688–96.
- [3] Einstein A. Über Gravitationswellen. Sitzungsber Preuss Akad Wiss Berlin (Math Phys) 1918;1918:154–67.
- [4] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Observation of gravitational waves from a binary black hole merger. Phys Rev Lett 2016;116:061102.
- [5] Aasi J, et al., LIGO Scientific Collaboration. Advanced LIGO. Classical Quantum Gravity 2015;32:074001.
- [6] Acernese F, et al., Virgo Collaboration. Advanced Virgo: a second-generation interferometric gravitational wave detector. Classical Quantum Gravity 2015;32:024001.
- [7] KAGRA Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration. Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. 2019, Preprint at <https://arxiv.org/abs/1304.0670>.
- [8] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW150914: First results from the search for binary black hole coalescence with Advanced LIGO. Phys Rev D 2016;93:122003.
- [9] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence. Phys Rev Lett 2016;116:241103.
- [10] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Binary black hole mergers in the first Advanced LIGO observing run. Phys Rev X 2016;6:041015.
- [11] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW170104: Observation of a 50-solar-mass binary black hole coalescence at Redshift 0.2. Phys Rev Lett 2017;118:221101.
- [12] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW170814: A three-detector observation of gravitational waves from a binary black hole coalescence. Phys Rev Lett 2017;119:141101.

- [13] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys Rev Lett* 2017;119:161101.
- [14] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and virgo during the first and second observing runs. *Phys Rev X* 2019;9:031040, arXiv:1811.12907.
- [15] Abbott BP, et al. Multi-messenger observations of a binary neutron star merger. *Astrophys J* 2017;848:L12.
- [16] Anderson S, Williams R. LIGO data management plan. 2017, URL <https://dcc.ligo.org/LIGO-M1000066/public>.
- [17] LIGO Scientific Collaboration and Virgo Collaboration. Memorandum of understanding between Virgo and LIGO. LIGO-M060038, VIR-0091A, 2019, <https://dcc.ligo.org/LIGO-M060038/public>.
- [18] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo GWTC-1 data release. 2018, URL <https://www.gw-openscience.org/GWTC-1/>.
- [19] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo O1 data release. 2018, URL <https://www.gw-openscience.org/O1/>.
- [20] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo O2 data release. 2019, URL <https://www.gw-openscience.org/O2/>.
- [21] Vallisneri M, Kanner J, Williams R, Weinstein A, Stephens B. The LIGO open science center. *J Phys Conf Ser* 2015;610:012021, arXiv:1410.4839.
- [22] Green MA, Moffat JW. Extraction of black hole coalescence waveforms from noisy data. *Phys Lett B* 2018;784:312, arXiv:1711.00347.
- [23] Nielsen AB, Nitz AH, Capano CD, Brown DA. Investigating the noise residuals around the gravitational wave event GW150914. *J Cosmol Astropart Phys* 2019;1902:019, arXiv:1811.04071.
- [24] Nitz AH, et al. 1-OGC: The first open gravitational-wave catalog of binary mergers from analysis of public Advanced LIGO data. *Astrophys J* 2019;872:195, arXiv:1811.01921.
- [25] Zackay B, Venumadhav T, Dai L, Roulet J, Zaldarriaga M. A highly spinning and aligned binary black hole merger in the Advanced LIGO first observing run. *Phys Rev D* 2019;100:023007, arXiv:1902.10331.
- [26] Venumadhav T, Zackay B, Roulet J, Dai L, Zaldarriaga M. New binary black hole mergers in the second observing run of Advanced LIGO and Advanced Virgo. *Phys Rev D* 2020;101:083030, arXiv:1904.07214.
- [27] Nitz AH, et al. 2-OGC: Open gravitational-wave catalog of binary mergers from analysis of public Advanced LIGO and Virgo data, 891. 2020, p. 123, Preprint at <https://arxiv.org/abs/1910.05331>.
- [28] Zackay B, Dai L, Venumadhav T, Roulet J, Zaldarriaga M. Detecting gravitational waves with disparate detector responses: Two new binary black hole mergers. 2019, Preprint at <https://arxiv.org/abs/1910.09528>.
- [29] Kanner JB, et al. Leveraging waveform complexity for confident detection of gravitational waves. *Phys Rev D* 2016;93:022002, URL <https://link.aps.org/doi/10.1103/PhysRevD.93.022002>.
- [30] Yamamoto T, Hayama K, Mano S, Itoh Y, Kanda N. Characterization of non-gaussianity in gravitational wave detector noise. *Phys Rev D* 2016;93:082005, URL <https://link.aps.org/doi/10.1103/PhysRevD.93.082005>.
- [31] Green MA, Moffat J. Extraction of black hole coalescence waveforms from noisy data. *Phys Lett B* 2018;784:312–23, URL <http://www.sciencedirect.com/science/article/pii/S0370269318306129>.
- [32] Gayathri V, et al. Astrophysical signal consistency test adapted for gravitational-wave transient searches. *Phys Rev D* 2019;100:124022, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.124022>.
- [33] Yanagisawa K, et al. A time-frequency analysis of gravitational wave signals with non-harmonic analysis. *Prog Theor Exp Phys* 2019;2019:063F01. <http://dx.doi.org/10.1093/ptep/ptz043>, <https://academic.oup.com/ptep/article-pdf/2019/6/063F01/28788035/ptz043.pdf>.
- [34] Gadre B, Mitra S, Dhurandhar S. Hierarchical search strategy for the efficient detection of gravitational waves from nonprecessing coalescing compact binaries with aligned-spins. *Phys Rev D* 2019;99:124035, URL <https://link.aps.org/doi/10.1103/PhysRevD.99.124035>.
- [35] Dai L, Venumadhav T, Zackay B. Parameter estimation for GW170817 using relative binning. 2018, Preprint at <https://arxiv.org/abs/1806.08793>.
- [36] De S, Capano CD, Biwer CM, Nitz AH, Brown DA. Posterior samples of the parameters of binary black holes from Advanced LIGO, Virgo's second observing run. *Sci Data* 2019;6:81, arXiv:1811.09232.
- [37] Gerosa D, Vitale S, Haster C-J, Chatziioannou K, Zimmerman A. Reanalysis of ligo black-hole coalescences with alternative prior assumptions. *Proc Int Astron Union* 2017;13:22–8.
- [38] Chatziioannou K, et al. Noise spectral estimation methods and their impact on gravitational wave measurement of compact binary mergers. *Phys Rev D* 2019;100:104004, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.104004>.
- [39] Kumar P, et al. Constraining the parameters of gw150914 and gw170104 with numerical relativity surrogates. *Phys Rev D* 2019;99:124005, URL <https://link.aps.org/doi/10.1103/PhysRevD.99.124005>.
- [40] Chatziioannou K, et al. On the properties of the massive binary black hole merger gw170729. *Phys Rev D* 2019;100:104015, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.104015>.
- [41] Kalaghatgi C, Hannam M, Raymond V. Parameter estimation with a spinning multimode waveform model. *Phys Rev D* 2020;101:103004, URL <https://link.aps.org/doi/10.1103/PhysRevD.101.103004>.
- [42] Buscicchio R, Roebber E, Goldstein JM, Moore CJ. Label switching problem in bayesian analysis for gravitational wave astronomy. *Phys Rev D* 2019;100:084041, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.084041>.
- [43] De S, et al. Tidal deformabilities and radii of neutron stars from the observation of GW170817. *Phys Rev Lett* 2018;121:091102, arXiv:1804.08583.
- [44] Carson Z, Chatziioannou K, Haster C-J, Yagi K, Yunes N. Equation-of-state insensitive relations after gw170817. *Phys Rev D* 2019;99:083016, URL <https://link.aps.org/doi/10.1103/PhysRevD.99.083016>.
- [45] Reyes S, Brown DA. Constraints on nonlinear tides due to  $p$ - $g$  mode coupling from the neutron-star merger GW170817. *Astrophys J* 2020;894:41, 1808.07013.
- [46] Pratten G, Schmidt P, Hinderer T. Gravitational-wave asteroseismology with fundamental modes from compact binary inspirals. *Nature Commun* 2020;11:2553.
- [47] Hagiwara Y, Era N, Iikawa D, Nishizawa A, Asada H. Constraining extra gravitational wave polarizations with advanced ligo, advanced virgo, and kagra and upper bounds from gw170817. *Phys Rev D* 2019;100:064010, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.064010>.
- [48] Isi M, Weinstein AJ, Mead C, Pitkin M. Detecting beyond-einstein polarizations of continuous gravitational waves. *Phys Rev D* 2015;91:082002, URL <https://link.aps.org/doi/10.1103/PhysRevD.91.082002>.
- [49] Carullo G, Del Pozzo W, Veitch J. Observational black hole spectroscopy: A time-domain multimode analysis of gw150914. *Phys Rev D* 2019;99:123029, URL <https://link.aps.org/doi/10.1103/PhysRevD.99.123029>.
- [50] Isi M, Giesler M, Farr WM, Scheel MA, Teukolsky SA. Testing the no-hair theorem with gw150914. *Phys Rev Lett* 2019;123:111102, URL <https://link.aps.org/doi/10.1103/PhysRevLett.123.111102>.
- [51] Gebhard TD, Kilbertus N, Harry I, Schölkopf B. Convolutional neural networks: A magic bullet for gravitational-wave detection? *Phys Rev D* 2019;100:063015, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.063015>.
- [52] Wang H, Wu S, Cao Z, Liu X, Zhu J-Y. Gravitational-wave signal recognition of ligo data by deep learning. *Phys Rev D* 2020;101:104003, URL <https://link.aps.org/doi/10.1103/PhysRevD.101.104003>.
- [53] Hannuksela OA, et al. Search for gravitational lensing signatures in LIGO-virgo binary black hole events. *Astrophys J* 2019;874:L2. <http://dx.doi.org/10.3847/2041-8213/ab0c0f>.
- [54] Broadhurst T, M. Diego J, F. Smoot G. Twin ligo/virgo detections of a viable gravitationally-lensed black hole merger. 2019, Preprint at <https://arxiv.org/abs/1901.03190>.
- [55] Radice D, Dai L. Multimessenger parameter estimation of GW170817. *Eur Phys J A* 2019;55:50, arXiv:1810.12917.
- [56] Lousto CO, Healy J. Kicking gravitational wave detectors with recoiling black holes. *Phys Rev D* 2019;100:104039, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.104039>.
- [57] Finstad D, De S, Brown DA, Berger E, Biwer CM. Measuring the viewing angle of GW170817 with electromagnetic and gravitational waves. *Astrophys J* 2018;860:L2.
- [58] Nicolaou C, Lahav O, Lemos P, Hartley W, Braden J. The impact of peculiar velocities on the estimation of the hubble constant from gravitational wave standard sirens. *Mon Not R Astron Soc* 2020;495:90–7, <https://academic.oup.com/mnras/article-pdf/495/1/90/33216608/staa1120.pdf>.
- [59] Chen Z-C, Huang Q-G. Distinguishing primordial black holes from astrophysical black holes by einstein telescope and cosmic explorer. *J Cosmol Astropart Phys* 2020;2020. 039–039.
- [60] Kwee P, et al. Stabilized high-power laser system for the gravitational wave detector Advanced LIGO. *Opt Express* 2012;20:10617–34. <http://dx.doi.org/10.1364/OE.20.010617>.
- [61] Winkelmann L, et al. Injection-locked single-frequency laser with an output power of 220 W. *Appl Phys B* 2011;102:529–38. <http://dx.doi.org/10.1007/s00340-011-4411-9>.
- [62] Liu Z, et al. Feedback control of optical beam spatial profiles using thermal lensing. *Appl Opt* 2013;52:6452–7. <http://dx.doi.org/10.1364/AO.52.006452>.
- [63] Palashov OV, et al. High-vacuum-compatible high-power faraday isolators for gravitational-wave interferometers. *J Opt Soc Amer B* 2012;29:1784–92. <http://dx.doi.org/10.1364/JOSAB.29.001784>.
- [64] Dooley KL, et al. Thermal effects in the input optics of the enhanced laser interferometer gravitational-wave observatory interferometers. *Rev Sci Instrum* 2012;83. <http://dx.doi.org/10.1063/1.3695405>.
- [65] Arain MA, Mueller G. Design of the Advanced LIGO recycling cavities. *Opt Express* 2008;16:10018–32, URL <http://www.opticsexpress.org/abstract.cfm?URI=oe-16-14-10018>.

- [66] Mueller CL, et al. The Advanced LIGO input optics. *Rev Sci Instrum* 2016;87:014502, URL <http://scitation.aip.org/content/aip/journal/rsi/87/1/10.1063/1.4936974>.
- [67] Harry GM, et al. Titania-doped tantala/silica coatings for gravitational-wave detection. *Classical Quantum Gravity* 2007;24:405, URL <http://stacks.iop.org/0264-9381/24/i=2/a=008>.
- [68] Granata M, et al. Mechanical loss in state-of-the-art amorphous optical coatings. *Phys Rev D* 2016;93:012007. <http://dx.doi.org/10.1103/PhysRevD.93.012007>.
- [69] Pinard L, et al. Mirrors used in the LIGO interferometers for first detection of gravitational waves. *Appl Opt* 2017;56:C11. <http://dx.doi.org/10.1364/AO.56.000C11>.
- [70] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. GW150914: The Advanced LIGO detectors in the era of first discoveries. *Phys Rev Lett* 2016;116:131103, URL <http://link.aps.org/doi/10.1103/PhysRevLett.116.131103>.
- [71] Buonanno A, Chen Y. Signal recycled laser-interferometer gravitational-wave detectors as optical springs. *Phys Rev D* 2002;65:042001, URL <https://link.aps.org/doi/10.1103/PhysRevD.65.042001>.
- [72] Heptonstall A, et al. Enhanced characteristics of fused silica fibers using laser polishing. *Classical Quantum Gravity* 2014;31:105006, URL <http://stacks.iop.org/0264-9381/31/i=10/a=105006>.
- [73] Bell CJ, et al. Experimental results for nulling the effective thermal expansion coefficient of fused silica fibres under a static stress. *Classical Quantum Gravity* 2014;31:065010, URL <http://stacks.iop.org/0264-9381/31/i=6/a=065010>.
- [74] Tokmakov K, et al. A study of the fracture mechanisms in pristine silica fibres utilising high speed imaging techniques. *J Non Cryst Solids* 2012;358:1699-709, URL <http://www.sciencedirect.com/science/article/pii/S0022309312002554>.
- [75] Hammond GD, et al. Reducing the suspension thermal noise of advanced gravitational wave detectors. *Classical Quantum Gravity* 2012;29:124009, URL <http://stacks.iop.org/0264-9381/29/i=12/a=124009>.
- [76] Aston SM, et al. Update on quadruple suspension design for Advanced LIGO. *Classical Quantum Gravity* 2012;29:235004, URL <http://stacks.iop.org/0264-9381/29/i=23/a=235004>.
- [77] Carbone L, et al. Sensors and actuators for the Advanced LIGO mirror suspensions. *Classical Quantum Gravity* 2012;29:115005, URL <http://stacks.iop.org/0264-9381/29/i=11/a=115005>.
- [78] Cumming AV, et al. Design and development of the Advanced LIGO monolithic fused silica suspension. *Classical Quantum Gravity* 2012;29:035003, URL <http://stacks.iop.org/0264-9381/29/i=3/a=035003>.
- [79] Heptonstall A, et al. Invited article: CO<sub>2</sub> laser production of fused silica fibers for use in interferometric gravitational wave detector mirror suspensions. *Rev Sci Instrum* 2011;82, URL <http://scitation.aip.org/content/aip/journal/rsi/82/1/10.1063/1.3532770>.
- [80] Shapiro BN, et al. Noise and control decoupling of Advanced LIGO suspensions. *Classical Quantum Gravity* 2015;32:015004, URL <http://stacks.iop.org/0264-9381/32/i=1/a=015004>.
- [81] Matichard F, et al. Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. part 1: Design and production overview. *Precis Eng* 2015;40:273-86, URL <http://www.sciencedirect.com/science/article/pii/S0141635914001561>.
- [82] Matichard F, et al. Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. part 2: Experimental investigation and tests results. *Precis Eng* 2015;40:287-97, URL <http://www.sciencedirect.com/science/article/pii/S0141635914002098>.
- [83] Matichard F, et al. Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance. *Classical Quantum Gravity* 2015;32:185003, URL <http://stacks.iop.org/0264-9381/32/i=18/a=185003>.
- [84] Wen S, et al. Hydraulic external pre-isolator system for LIGO. *Classical Quantum Gravity* 2014;31:235001, URL <http://stacks.iop.org/0264-9381/31/i=23/a=235001>.
- [85] Daw EJ, Giaime JA, Lormand D, Lubinski M, Zweizig J. Long-term study of the seismic environment at LIGO. *Classical Quantum Gravity* 2004;21:2255, URL <http://stacks.iop.org/0264-9381/21/i=9/a=003>.
- [86] Barsotti L, Evans M, Fritschel P. Alignment sensing and control in Advanced LIGO. *Classical Quantum Gravity* 2010;27:084026, URL <http://stacks.iop.org/0264-9381/27/i=8/a=084026>.
- [87] Staley A, et al. High precision optical cavity length and width measurements using double modulation. *Opt Express* 2015;23:19417-31, URL <http://www.opticsexpress.org/abstract.cfm?URI=oe-23-15-19417>.
- [88] Evans M, et al. Observation of parametric instability in Advanced LIGO. *Phys Rev Lett* 2015;114:161102, URL <http://link.aps.org/doi/10.1103/PhysRevLett.114.161102>.
- [89] Rollins JG. Distributed state machine supervision for long-baseline gravitational-wave detectors. *Rev Sci Instrum* 2016;87, URL <http://scitation.aip.org/content/aip/journal/rsi/87/9/10.1063/1.4961665>.
- [90] Phelps MH, Gushwa KE, Torrie CI. Optical contamination control in the Advanced LIGO ultra-high vacuum system. *Proc SPIE* 2013;8885:88852E. <http://dx.doi.org/10.1117/12.2047327>.
- [91] Smith MR. Scattered light control in Advanced LIGO. World Scientific Publishing Company; 2012, URL [http://www.worldscientific.com/doi/abs/10.1142/9789814374552\\_0312](http://www.worldscientific.com/doi/abs/10.1142/9789814374552_0312).
- [92] Brooks AF, et al. Direct measurement of absorption-induced wavefront distortion in high optical power systems. *Appl Opt* 2009;48:355-64, URL <http://ao.osa.org/abstract.cfm?URI=ao-48-2-355>.
- [93] Lawrence R, Zucker M, Fritschel P, Marfuta P, Shoemaker D. Adaptive thermal compensation of test masses in Advanced LIGO. *Classical Quantum Gravity* 2002;19:1803, URL <http://stacks.iop.org/0264-9381/19/i=7/a=377>.
- [94] Heitmann H, on behalf of the Virgo Collaboration. Status of the Advanced Virgo gravitational wave detector. *Proc SPIE* 2018;10700:1070017. <http://dx.doi.org/10.1117/12.2312572>.
- [95] Granata M, et al. Amorphous optical coatings of present gravitational-wave interferometers. 2019, Preprint at <https://arxiv.org/abs/1909.03737>.
- [96] Amato A, et al. Optical properties of high-quality oxide coating materials used in gravitational-wave advanced detectors. *J Phys Mater* 2019;2:035004.
- [97] Bersanetti D, et al. New algorithm for the guided lock technique for a high-finesse optical cavity. *Astropart Phys* 2020;117:102405, URL <https://doi.org/10.1016/j.astropartphys.2019.102405>.
- [98] Acernese F, et al., Virgo Collaboration. The advanced Virgo longitudinal control system for the O2 observing run. *Astropart Phys* 2020;116:102386, URL <https://doi.org/10.1016/j.astropartphys.2019.07.005>.
- [99] Aiello L, et al. Thermal compensation system in advanced and third generation gravitational wave interferometric detectors. *J Phys Conf Ser* 2019;1226:012019.
- [100] Cirone A, et al. Investigation of magnetic noise in Advanced Virgo. *Classical Quantum Gravity* 2019;36:225004, Preprint at <https://arxiv.org/abs/1908.11174>.
- [101] Cirone A, et al. Magnetic coupling to the Advanced Virgo payloads and its impact on the low frequency sensitivity. *Rev Sci Instrum* 2018;89:114501. <http://dx.doi.org/10.1063/1.5045397>.
- [102] Tringali MC, et al. Seismic array measurements at Virgo's west end building for the configuration of a Newtonian-noise cancellation system. *Classical Quantum Gravity* 2019, URL <http://iopscience.iop.org/10.1088/1361-6382/ab5c43>.
- [103] van Heijningen JV, et al. A multistage vibration isolation system for Advanced Virgo suspended optical benches. *Classical Quantum Gravity* 2019;36:075007.
- [104] Staley A, et al. Achieving resonance in the advanced LIGO gravitational-wave interferometer. *Classical Quantum Gravity* 2014;31:245010. <http://dx.doi.org/10.1088/0264-9381/31/24/245010>.
- [105] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914. *Classical Quantum Gravity* 2016;33:134001, arXiv:1602.03844.
- [106] Effler A, et al. Environmental influences on the LIGO gravitational wave detectors during the 6th science run. *Classical Quantum Gravity* 2015;32:035017.
- [107] Finn LS, Chernoff DF. Observing binary inspiral in gravitational radiation: One interferometer. *Phys Rev D* 1993;47:2198-219, arXiv:gr-qc/9301003.
- [108] Chen H-Y, et al. Distance measures in gravitational-wave astrophysics and cosmology. 2017, arXiv:1709.08079.
- [109] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Low-latency gravitational-wave alerts for multimessenger astronomy during the second Advanced LIGO and virgo observing run. *Astrophys J* 2019;875:161.
- [110] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Search for intermediate mass black hole binaries in the first and second observing runs of the Advanced LIGO and virgo network. *Phys Rev D* 2019;100:064064.
- [111] Bartos I, et al. The Advanced LIGO timing system. *Classical Quantum Gravity* 2010;27:084025, URL <http://stacks.iop.org/0264-9381/27/i=8/a=084025>.
- [112] Goetz E, Savage RL. Calibration of the LIGO displacement actuators via laser frequency modulation. *Classical Quantum Gravity* 2010;27:215001. <http://dx.doi.org/10.1088/0264-9381/27/21/215001>.
- [113] Goetz E, et al. Accurate calibration of test mass displacement in the LIGO interferometers. *Classical Quantum Gravity* 2010;27:084024, URL <http://stacks.iop.org/0264-9381/27/i=8/a=084024>.
- [114] Goetz E, et al. Precise calibration of LIGO test mass actuators using photon radiation pressure. *Classical Quantum Gravity* 2009;26:245011, URL <http://stacks.iop.org/0264-9381/26/i=24/a=245011>.
- [115] Abadie J, et al., LIGO Scientific Collaboration. Calibration of the LIGO gravitational wave detectors in the fifth science run. *Nucl Instrum Methods Phys Res A* 2010;624:223-40, URL <http://www.sciencedirect.com/science/article/pii/S0168900210017031>.

- [116] Accadia T, et al., Virgo Collaboration. Reconstruction of the gravitational wave signal  $h(t)$  during the Virgo science runs and independent validation with a photon calibrator. *Classical Quantum Gravity* 2014;31:165013.
- [117] Accadia T, et al., Virgo Collaboration. Calibration and sensitivity of the virgo detector during its second science run. *Classical Quantum Gravity* 2010;28:025005.
- [118] Viets AD, et al. Reconstructing the calibrated strain signal in the Advanced LIGO detectors. *Classical Quantum Gravity* 2018;35:095015, [arXiv:1710.09973](https://arxiv.org/abs/1710.09973).
- [119] Acernese F, et al., Virgo Collaboration. Calibration of Advanced Virgo and reconstruction of the gravitational wave signal  $h(t)$  during the observing run O2. *Classical Quantum Gravity* 2018;35:205004.
- [120] Cahillane C, et al. Calibration uncertainty for Advanced LIGO's first and second observing runs. *Phys Rev D* 2017;96:102001, [arXiv:1708.03023](https://arxiv.org/abs/1708.03023).
- [121] Abbott BP, et al., LIGO Scientific Collaboration. Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914. *Phys Rev D* 2017;95:062003, URL <https://link.aps.org/doi/10.1103/PhysRevD.95.062003>.
- [122] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo public alerts user guide. 2018, URL <https://emfollow.docs.ligo.org/userguide/>.
- [123] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW150914. 2016, URL <https://www.gw-openscience.org/events/GW150914/>.
- [124] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event LVT151012. 2016, URL <https://www.gw-openscience.org/events/LVT151012/>.
- [125] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW151226. 2016, URL <https://www.gw-openscience.org/events/GW151226/>.
- [126] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW170104. 2017, URL <https://www.gw-openscience.org/events/GW170104/>.
- [127] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW170608. 2017, URL <https://www.gw-openscience.org/events/GW170608/>.
- [128] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW170814. 2017, URL <https://www.gw-openscience.org/events/GW170814/>.
- [129] LIGO Scientific Collaboration and Virgo Collaboration. Data release for event GW170817. 2017, URL <https://www.gw-openscience.org/events/GW170817/>.
- [130] Martynov DV, et al. Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy. *Phys Rev D* 2016;93:112004, URL <https://link.aps.org/doi/10.1103/PhysRevD.93.112004>.
- [131] Adhikari R. Sensitivity and noise analysis of 4 km laser interferometric gravitational wave antennae [Ph.D. thesis], Massachusetts Institute of Technology; 2004.
- [132] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. A guide to LIGO-virgo detector noise and extraction of transient gravitational-wave signals. 2019, Preprint at <https://arxiv.org/abs/1908.11170>.
- [133] Covas PB, et al. Identification and mitigation of narrow spectral artifacts that degrade searches for persistent gravitational waves in the first two observing runs of Advanced LIGO. *Phys Rev D* 2018;97:082002, [arXiv:1801.07204](https://arxiv.org/abs/1801.07204).
- [134] Fiori I. O2 lines summary. 2017, URL <https://logbook.virgo-gw.eu/virgo/?r=40306>.
- [135] Aasi J, et al. The characterization of virgo data and its impact on gravitational-wave searches. *Classical Quantum Gravity* 2012;29:155002, 1203.5613.
- [136] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Effects of data quality vetoes on a search for compact binary coalescences in Advanced LIGO's first observing run. *Classical Quantum Gravity* 2018;35:065010, [arXiv:1710.02185](https://arxiv.org/abs/1710.02185).
- [137] Davis D, et al. Improving the sensitivity of Advanced LIGO using noise subtraction. *Classical Quantum Gravity* 2019;36:055011, [arXiv:1809.05348](https://arxiv.org/abs/1809.05348).
- [138] Pankow C, et al. Mitigation of the instrumental noise transient in gravitational-wave data surrounding GW170817. *Phys Rev D* 2018;98:084016, URL <https://link.aps.org/doi/10.1103/PhysRevD.98.084016>.
- [139] Biwer C, et al. Validating gravitational-wave detections: The Advanced LIGO hardware injection system. *Phys Rev D* 2017;95:062002, [arXiv:1612.07864](https://arxiv.org/abs/1612.07864).
- [140] URL <https://cernvm.cern.ch/fs/>.
- [141] Weitzel D, et al. Data access for LIGO on the OSG. In: Proceedings of the practice and experience in advanced research computing 2017 on sustainability, success and impact; 2017.
- [142] Ellis G. *Control system design guide*. 4th ed. Butterworth-Heinemann; 2012.
- [143] Jones E, et al. SciPy: Open source scientific tools for Python. 2001, URL <http://www.scipy.org/>.
- [144] Nyquist H. Certain factors affecting telegraph speed. *Bell Syst Tech J* 1924;3:324-46.
- [145] Nyquist H. Certain topics in telegraph transmission theory. *Trans AIEE* 1928;47:617-44.
- [146] Shannon CE. Communication in the presence of noise. *Proc IRE* 1949;37:10-21.
- [147] Koziol Q, Robinson D. HDF5. 2018, <http://dx.doi.org/10.11578/dc.20180330.1>.
- [148] LIGO Scientific Collaboration and Virgo Collaboration. Specification of a common data frame format for interferometric gravitational wave detectors. Tech. rep. VIR-067A-08, 2009, URL <https://dcc.ligo.org/LIGO-T970130/public>.
- [149] Nitz AH, et al. PyCBC software. GitHub repository; 2017, URL <https://github.com/ligo-cbc/pycbc>.
- [150] Usman SA, et al. The PyCBC search for gravitational waves from compact binary coalescence. *Classical Quantum Gravity* 2016;33:215004, [arXiv:1508.02357](https://arxiv.org/abs/1508.02357).
- [151] Sachdev S, et al. The GstLAL search analysis methods for compact binary mergers in Advanced LIGO's second and Advanced Virgo's first observing runs. *Phys Rev D* 2019 [submitted for publication]. Preprint at <https://arxiv.org/abs/1901.08580>.
- [152] Cody M, et al. Analysis framework for the prompt discovery of compact binary mergers in gravitational-wave data. *Phys Rev D* 2017;95:042001, [arXiv:1604.04324](https://arxiv.org/abs/1604.04324).
- [153] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Search for subsolar mass ultracompact binaries in Advanced LIGO's second observing run. *Phys Rev Lett* 2019;123:161102.
- [154] Klimentenko S, et al. Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors. *Phys Rev D* 2016;93:042004, [arXiv:1511.05999](https://arxiv.org/abs/1511.05999).
- [155] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. All-sky search for short gravitational-wave bursts in the second Advanced LIGO and Advanced Virgo run. *Phys Rev D* 2019;100:024017.
- [156] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. An optically targeted search for gravitational waves emitted by core-collapse Supernovae during the first and second observing runs of Advanced LIGO and Advanced Virgo. 2019, Preprint at <https://arxiv.org/abs/1908.03584>.
- [157] Lynch R, Vitale S, Essick R, Katsavounidis E, Robinet F. Information-theoretic approach to the gravitational-wave burst detection problem. *Phys Rev D* 2017;95:104046.
- [158] Littenberg TB, Kanner JB, Cornish NJ, Millhouse M. Enabling high confidence detections of gravitational-wave bursts. *Phys Rev D* 2016;94:044050.
- [159] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data. *Phys Rev D* 2019;100:061101, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.024004>.
- [160] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Narrow-band search for gravitational waves from known pulsars using the second LIGO observing run. *Phys Rev D* 2019;99:122002, URL <https://link.aps.org/doi/10.1103/PhysRevD.99.122002>.
- [161] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Searches for gravitational waves from known pulsars at two harmonics in 2015-2017 LIGO data. *Astrophys J* 2015;879:10.
- [162] Search for gravitational waves from scorpius X-1 in the first Advanced LIGO observing run with a hidden Markov model. *Phys Rev D* 2017;95:122003.
- [163] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Upper limits on the stochastic gravitational-wave background from Advanced LIGO's first observing run. *Phys Rev Lett* 2017;118:121101, URL <https://link.aps.org/doi/10.1103/PhysRevLett.118.121101>.
- [164] Abbott BP, et al., LIGO Scientific Collaboration, Virgo Collaboration. Search for the isotropic stochastic background using data from Advanced LIGO's second observing run. *Phys Rev D* 2019;100:061101, URL <https://link.aps.org/doi/10.1103/PhysRevD.100.061101>.
- [165] LIGO Scientific Collaboration and Virgo Collaboration. H1 lines cleaning file for O1 - version 3. 2015, URL [https://www.gw-openscience.org/static/specines/o1/O1LinesToBeCleaned\\_H1\\_v3.txt](https://www.gw-openscience.org/static/specines/o1/O1LinesToBeCleaned_H1_v3.txt).
- [166] LIGO Scientific Collaboration and Virgo Collaboration. L1 lines cleaning file for O1 - version 3. 2015, URL [https://www.gw-openscience.org/static/specines/o1/O1LinesToBeCleaned\\_L1\\_v3.txt](https://www.gw-openscience.org/static/specines/o1/O1LinesToBeCleaned_L1_v3.txt).
- [167] LIGO Scientific Collaboration and Virgo Collaboration. H1 lines cleaning file for O2 - version 2. 2019, URL [https://www.gw-openscience.org/static/specines/o2/O2LinesToBeCleaned\\_H1\\_v2.txt](https://www.gw-openscience.org/static/specines/o2/O2LinesToBeCleaned_H1_v2.txt).
- [168] LIGO Scientific Collaboration and Virgo Collaboration. L1 lines cleaning file for O2 - version 2. 2019, URL [https://www.gw-openscience.org/static/specines/o2/O2LinesToBeCleaned\\_L1\\_v2.txt](https://www.gw-openscience.org/static/specines/o2/O2LinesToBeCleaned_L1_v2.txt).

- [169] LIGO Scientific Collaboration and Virgo Collaboration. List of lines for Virgo V1 during O2 - 20190209, version 1. 2019, URL [https://www.gwopenscience.org/static/speclines/o2/O2\\_lines\\_Virgo\\_V1.txt](https://www.gwopenscience.org/static/speclines/o2/O2_lines_Virgo_V1.txt).
- [170] LIGO Scientific Collaboration and Virgo Collaboration. Data quality vetoes applied to the analysis of GW150914. 2016, <https://dcc.ligo.org/public/0123/T1600011/003/DQdoc.pdf>.
- [171] Kluyver T, et al. Jupyter notebooks – a publishing format for reproducible computational workflows. In: Positioning and power in academic publishing: Players, agents and agendas. IOS Press; 2016, p. 87–90.
- [172] LIGO Scientific Collaboration. Source code for: LIGO algorithm library - LALSuite. 2018, <http://dx.doi.org/10.7935/GT1W-FZ16>.
- [173] Macleod D, et al. Source code for: GWpy software. 2019, <http://dx.doi.org/10.5281/zenodo.2603187>.
- [174] Home page for: GstLAL – <https://wiki.ligo.org/Computing/DASWG/GstLAL>.
- [175] Ashton G, et al. BILBY: A user-friendly Bayesian inference library for gravitational-wave astronomy. *Astrophys J Suppl Ser* 2019;241:27. <http://dx.doi.org/10.5281/zenodo.2602178>.
- [176] Veitch J, et al. Parameter estimation for compact binaries with ground-based gravitational-wave observations using the lalinference software library. *Phys Rev D* 2015;91:042003.
- [177] J. Cornish N, Littenberg TB. Bayeswave: Bayesian inference for gravitational wave bursts and instrument glitches. *Classical Quantum Gravity* 2015;32:135012, [arXiv:1410.3835](https://arxiv.org/abs/1410.3835).
- [178] Littenberg TB, Cornish NJ. Bayesian inference for spectral estimation of gravitational wave detector noise. *Phys Rev D* 2015;91:084034.
- [179] Gravitational wave open science center (GWOSC). <http://www.gwopenscience.org>.
- [180] GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs. 2018, <http://dx.doi.org/10.7935/82H3-HH23>, URL <https://dcc.ligo.org/LIGO-P1800307/public>.
- [181] How to acknowledge use of LIGO/Virgo data through GWOSC. <https://www.gwopenscience.org/acknowledgement/>.