PHYSICAL REVIEW D **96,** 022001 (2017)

Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 14 April 2017; published 11 July 2017)

During their first observational run, the two Advanced LIGO detectors attained an unprecedented sensitivity, resulting in the first direct detections of gravitational-wave signals produced by stellar-mass binary black hole systems. This paper reports on an all-sky search for gravitational waves (GWs) from merging intermediate mass black hole binaries (IMBHBs). The combined results from two independent search techniques were used in this study: the first employs a matched-filter algorithm that uses a bank of filters covering the GW signal parameter space, while the second is a generic search for GW transients (bursts). No GWs from IMBHBs were detected; therefore, we constrain the rate of several classes of IMBHB mergers. The most stringent limit is obtained for black holes of individual mass 100 $M_\odot$, with spins aligned with the binary orbital angular momentum. For such systems, the merger rate is constrained to be less than 0.93 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ in comoving units at the 90% confidence level, an improvement of nearly 2 orders of magnitude over previous upper limits.

DOI: 10.1103/PhysRevD.96.022001

I. INTRODUCTION

The first observing run (O1) of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors [1] took place from September 12, 2015 to January 19, 2016. During this period, there were a total of 51.5 days of coincident analysis time between the two detectors, located in Hanford, Washington (H1), and Livingston, Louisiana (L1). This resulted in the detection of gravitational-wave (GW) signals from the coalescence of two binary black hole (BBH) systems with high statistical significance, GW150914 [2] and GW151226 [3], and a third lower-significance candidate, LVT151012 [4], which is also likely to be a BBH coalescence [5].

In all three cases, the estimated premerger individual source-frame masses, $(36.2^{+5.2}_{-3.8}, 29.1^{+3.7}_{-4.4})\,M_\odot$, $(14.2^{+8.3}_{-3.7}, 7.5^{+2.3}_{-2.3})\,M_\odot$, and $(23^{+18}_{-6}, 13^{+4}_{-5})\,M_\odot$, respectively [5,6], are consistent with stellar evolutionary scenarios [7].[1] These systems were observed at relatively low redshifts, $z = 0.09^{+0.03}_{-0.04}$, $0.09^{+0.03}_{-0.04}$, and $0.20^{+0.09}_{-0.09}$, respectively. If relatively heavy black hole remnants, similar to those already observed by Advanced LIGO, exist within dense globular cluster (GCs), further hierarchical merging of these objects could be a natural formation mechanism for intermediate mass black holes (IMBHs) [9]. IMBHs are normally defined as black holes with masses in the range $10^2 \le M_\bullet/M_\odot \le 10^5$; in this paper, we consider any BBH with a total mass above $10^2\,M_\odot$ and mass ratio of $0.1 \le q \le 1$ to be an IMBH binary (IMBHB).

It is possible that there will be numerous BBH detections in the next few years of GW astronomy [5,10,11]. In the near future, we should be able to place stringent astrophysical constraints on the formation and evolution of stellar-mass black holes. In addition to surveying stellar-mass black holes, we will also be able to investigate the astrophysics of IMBHs.

If they are found to exist, IMBHB mergers would be the LIGO-Virgo sources that emit the most gravitational-wave energy. Given an estimate of the power spectral density of a detector [12], and assuming a matched-filter single-detector signal-to-noise ratio (SNR) threshold of 8, in Fig. 1 we plot the horizon distance (the distance to which we can detect an optimally located and oriented source) as a function of source-frame total mass. As Fig. 1 displays, the O1 sensitivity for IMBHBs constitutes a factor of ≈6 improvement in peak horizon distance (≈200 in search volume) as compared to the sensitivity achieved between 2009 and 2010, during the sixth and final science run (S6) of initial LIGO [13]. However, the matched-filter SNR is only an optimal detection statistic in stationary, Gaussian noise. Since LIGO data are known to contain nonstationary noise [14], this figure is useful primarily as an approximate upper bound on the reach of a modeled search for IMBHBs.

In this paper, we report on the search for IMBHBs during O1. In previous IMBHB searches using LIGO-Virgo data taken in 2005–2010 [13,16], an unmodeled transient search and a modeled matched-filter search using only the ringdown part of the waveform were separately employed to set distinct upper limits on the merger rates of IMBHBs. For this study, two distinct search pipelines were also used: a

[*]The full author list can be found at the end of the article.
[1]Since GWs undergo a cosmological redshift between source and detector, we relate the observed detector-frame mass m_{det} and the physical source-frame mass m_{source} via $m_{\mathrm{det}} = (1+z)m_{\mathrm{source}}$, where z is the redshift of the source assuming standard cosmology [8].

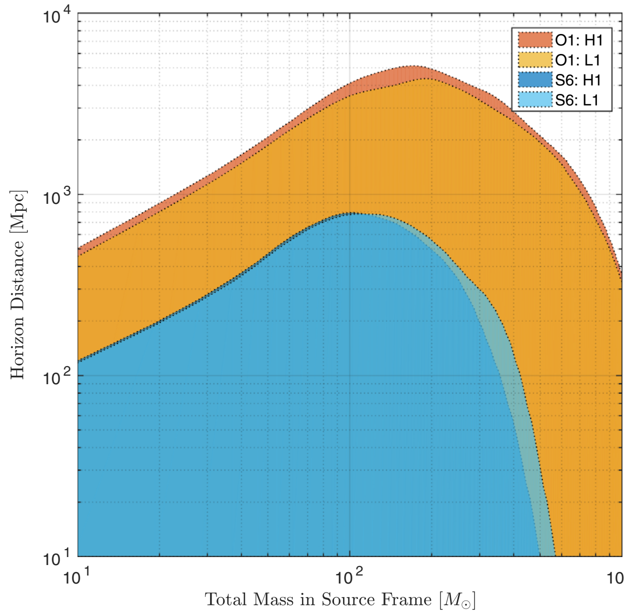

FIG. 1. Horizon distance for equal-mass, nonspinning binary black hole systems with a single-detector SNR threshold of 8 in the first observing run (O1) of the Advanced LIGO detectors [12]. Comparison curves are also given for the previous sixth science run (S6) of the initial LIGO detectors [15].

matched-filter search algorithm, GstLAL [17–19], that uses inspiral–merger–ringdown waveform templates [4,5] which are cross-correlated with the data, and an unmodeled transient search algorithm, coherent WaveBurst (cWB) [20–22], which looks for excess power which is coherent across the network of GW detectors. Instead of setting distinct upper limits, however, the results presented in this paper are the combined statistics from both independent search techniques. No IMBHBs were detected in this combined search in O1; based on this, we set a 90% confidence level limit on the rate of mergers (see Table I below).

TABLE I. Results of our analysis for IMBHB systems with (source-frame) component masses $m_{1,2}$ and spins $\chi_{1,2}$ parallel to the orbital angular momentum. For each set of parameters, we report the 90% confidence combined upper limit on the rate density $R_{90\%}$ and the combined- and single-pipeline sensitive distance $D_{\langle VT \rangle}$. Uncertainty in the detectors' amplitude calibration introduces an $\approx$18% uncertainty in the rates and an $\approx$6% uncertainty in the sensitive distance.

m_1 $[M_\odot]$	m_2 $[M_\odot]$	$\chi_{1,2}$	$R_{90\%}$ [Gpc^{-3} yr^{-1}]	[GC^{-1} Gyr^{-1}]	$D_{\langle VT \rangle}{}^{\mathrm{GstLAL}}_{\mathrm{cWB}}$ [Gpc]
100	100	0.8	0.93	0.3	$1.6^{1.7}_{1.3}$
100	100	0	2.0	0.7	$1.3^{1.3}_{1.0}$
100	100	−0.8	3.5	1	$1.1^{1.1}_{0.89}$
100	20	0	13	4	$0.68^{0.69}_{0.46}$
100	50	0	3.3	1	$1.1^{1.1}_{0.78}$
200	50	0	9.8	3	$0.75^{0.76}_{0.66}$
200	100	0	4.6	2	$0.97^{0.98}_{0.84}$
200	200	0	5.0	2	$0.94^{0.95}_{0.78}$
300	50	0	45	20	$0.45^{0.46}_{0.37}$
300	100	0	16	5	$0.63^{0.64}_{0.52}$
300	200	0	12	4	$0.69^{0.70}_{0.58}$
300	300	0	20	7	$0.59^{0.60}_{0.45}$

The paper is organized as follows: Section II summarizes our search techniques and how they are combined for the current analysis. Section III describes how upper limits on rates are calculated and includes Table I and Fig. 2 as main results. Section IV discusses the astrophysical implications inferred from this analysis, and Sec. V presents our conclusions. We use the "TT + lowP + lensing + ext" parameters from Table 4 of the Planck 2015 results [8] for cosmological calculations.

II. SEARCH TECHNIQUE

For O1, a new search was inaugurated, in which both modeled and unmodeled analyses, specifically tuned to search for IMBHBs, were combined to form a single search. The modeled analysis employs a matched filter, which yields the optimal detection efficiency for signals of known form in stationary, Gaussian noise [23] and thus requires a sufficiently accurate signal waveform model for use as a template. The unmodeled transient analysis, by contrast, can identify burstlike signals which do not correspond to any currently available waveform model. IMBHB signals, as a consequence of their sources' high mass, have relatively few cycles in the LIGO frequency band; therefore, the IMBHB search benefits from the combination of the two complementary analysis techniques.

A. Modeled analysis

The GstLAL pipeline, which is a matched-filter search algorithm for GWs from compact binary coalescences [17–19], was used in its offline mode to analyze the entirety of O1 [4,5]. The GstLAL IMBHB analysis is based on a discrete bank of GW templates constructed over a total mass between 50 $M_\odot$ and 600 $M_\odot$ in the detector frame, with mass ratios less extreme than 1∶10, and with dimensionless spin $\chi_{1,2}$ between −0.99 and 0.99, where positive values are aligned with the orbital angular momentum of the system and negative values are antialigned. The templates used in this search are a reduced-order model of a double aligned-spin effective-one-body waveform [24,25]. As a consequence of the noise characteristics at low frequencies [12], GstLAL began its analysis at a frequency of 15 Hz.

In this analysis, the data are filtered through a singular-value decomposition of the template bank, and the matched-filter SNR time series for each template in the bank is reconstructed from the filtered output of the basis templates [19]. Maxima in the SNR, called triggers, are

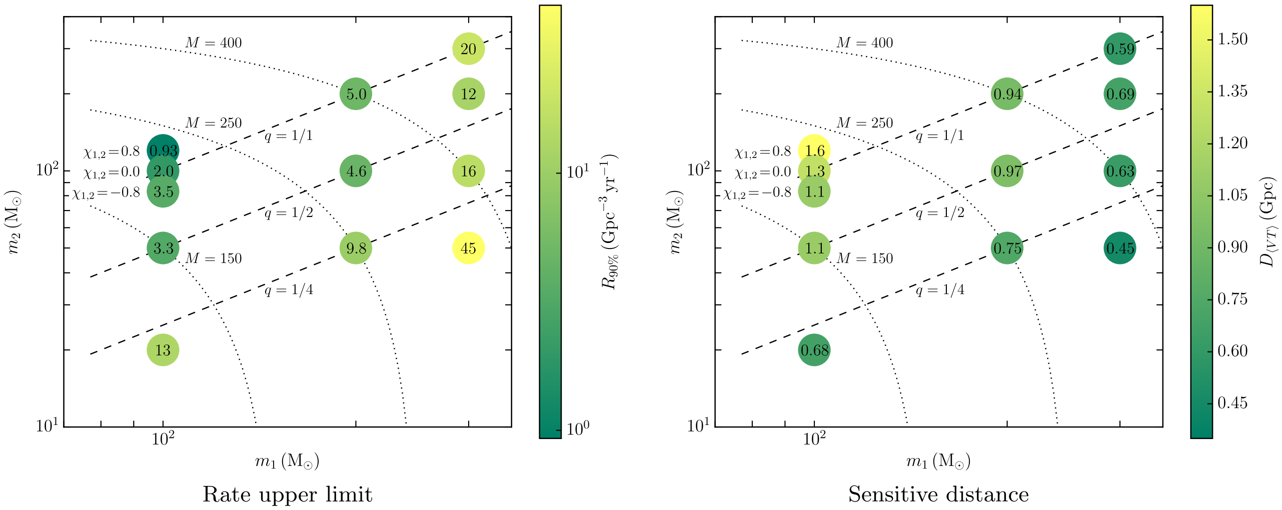

FIG. 2. 90% confidence rate upper limit in $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (left) and sensitive distance in Gpc (right) achieved by this search for IMBHB mergers in Advanced LIGO's first observing run. Each circle represents a set of simulated IMBHB signals, with circles centered on the component masses (m_1, m_2). All except two sets have nonspinning binary components. For masses $m_1 = m_2 = 100\ M_\odot$, additional simulations were performed with spins aligned ($\chi_1 = \chi_2 = 0.8$) or antialigned ($\chi_1 = \chi_2 = -0.8$) with the orbital angular momentum; these are shown as displaced circles. The straight dashed lines represent contours of constant mass ratio $q = m_2/m_1$; the curved dotted lines are those of constant total mass $M = m_1 + m_2$. All reported quantities are calculated in the source frame.

identified, and corresponding values of a signal consistency test, which is a comparison of the SNR time series for the data to the SNR time series expected from a real signal, are computed. Triggers found in one detector that are not coincident with triggers in another detector are assumed to be nonastrophysical and are used to estimate the probability distribution of noise events in each detector. Coincident triggers are considered GW candidates and are ranked against each other via a likelihood ratio, which compares the probability that each is a signal to the probability that each is noise [19]. Finally, a coincident trigger is assigned a p-value [19], which is the probability of finding a noise fluctuation with such likelihood ratio or higher under the hypothesis that the data contain no GW signals.[2]

For validation, another independent matched-filter search algorithm, PyCBC [27,28], was also run over the same GW parameter space using a spin-aligned frequency-domain phenomenological waveform model [29,30] as templates. PyCBC uses a different SNR-based ranking statistic [4,27,28,31]. These two independent matched-filter algorithms find consistent results over the IMBH parameter space, which increases our confidence in their reliability and robustness.

The three most significant events from the GstLAL matched-filter analysis correspond to GW150914, LVT151012, and GW151226, which have already been reported [2–6]. Since parameter-estimation studies have placed these events outside of the IMBH mass range [4–6,32], we have removed these triggers from our analysis. We discuss the production of our overall IMBHB results in Sec. II C.

The bank of waveform templates used by the GstLAL IMBHB analysis notably overlaps with the O1 stellar-mass BBH search [4,5] between $M = 50\ M_\odot$ and $100\ M_\odot$. It was therefore expected that this new analysis would find GW150914 and LVT151012 as two of its most significant events, since the masses of these two signals have posterior support in this range [4–6]. Additionally, GW151226 being the third most significant event in this analysis demonstrates the robustness of modeled analyses to identify signals even outside of their covered parameter spaces.

This is the first modeled analysis that includes the inspiral, merger, and ringdown portions of the compact binary coalescence waveform to extend above $M = 100\ M_\odot$ and into the IMBHB parameter space. Even though IMBHB mergers potentially have large values of SNR, detecting them with this analysis can be difficult. Signal consistency checks are often inefficient at distinguishing true signals from background events. This problem is caused primarily by the short duration of signals produced by high-mass systems, especially those with antialigned spin configurations. Continuing to pursue improvements in IMBHB search methods will undoubtedly improve the sensitivity of the analysis.

B. Unmodeled analysis

The unmodeled analysis was conducted with cWB, the data-analysis algorithm used for previous LIGO-Virgo unmodeled IMBHB searches [13,33]. More recently, this algorithm has been used extensively on O1 data [22].

[2] See Ref. [26] for a study of the properties of different methods to estimate the p-value in a coincident search for transient GW signals.

cWB performs a coherent analysis on data from multiple detectors [21]; for the O1 analysis, just the H1 and L1 detectors were available. After decomposing the data into a time-frequency representation, the algorithm identifies coherent triggers from regions in the time-frequency domain with excess power relative to the noise level. GW candidate events are subsequently reconstructed in the framework of a constrained maximum-likelihood analysis.

As this reconstruction of signal is agnostic to the waveform modeling of the specific astrophysical source, this algorithm can be used in a variety of searches, including eccentric BBH mergers [34]. Past simulation studies have shown that the cWB unmodeled analysis is sensitive to BBH mergers over large regions of the binary parameter space accessible with initial GW detectors [35]; analogous conclusions were reached for the case of advanced detectors [36].

For this analysis, we applied a further, weak constraint to favor the reconstruction of chirality-polarized waveforms [21]. Moreover, with respect to the generic burst search reported in [22], frequency-dependent postproduction selection cuts were tuned in order to minimize the impact of such cuts on IMBHB mergers: the low-frequency part of the spectrum of GW data is often polluted by various environmental and instrumental noises that effectively mimic the expected waveforms for massive binary mergers. The cWB analysis began at a frequency of 16 Hz.

The significance of any GW candidate event is estimated by comparing it with the noise background distribution in order to calculate its p-value. The background set was empirically produced by analyzing $\simeq$9000 independent time-shifted O1 data sets.[3] Approximately 1100 yr of effective background livetime was accumulated with this procedure. Additional time lags would have been analyzed had loud IMBHB candidates been identified and a more precise estimate of the background tails been required. The only GW signal found in the O1 data by cWB was GW150914, which is louder than all background events. Similarly to the aforementioned matched-filter searches, GW150914 was then removed from the unmodeled analysis.

C. Combining analyses

After running on the data collected by the detectors, each search algorithm produces a trigger list with times and associated p-values $\mathcal{P}$. We combine the two lists together to form a single list of triggers ranked by their p-value. To avoid double counting of events, we remove triggers within 100 ms of a more significant trigger found by the other search algorithm. To account for the use of two search algorithms, we apply a trials factor of 2 to produce the final p-value of our search,

$$\bar{\mathcal{P}} = 1 - (1 - \mathcal{P})^2. \tag{1}$$

This assumes that the triggers produced by the two algorithms are independent; a correlation in the two lists of triggers from the pipelines would reduce the effective trials factor, making 2 a conservative choice. Of the top 150 triggers output by the two pipelines, only GW150914 is common between the lists, indicating that the noise triggers are independent here. We consider $\bar{\mathcal{P}}$ as the ranking statistic for the combined search algorithm. Excluding GW150914, LVT151012, and GW151226, the most significant trigger has $\bar{\mathcal{P}} \simeq 0.26$, well below the significance needed to be considered as a detection candidate.

III. UPPER LIMITS ON RATES

Since no IMBHB coalescences were detected during O1, we can calculate upper limits on the astrophysical rate (density) of such events. With the loudest-event method [37], if the most significant IMBHB trigger is consistent with noise, the 90% confidence upper limit is given by

$$R_{90\%} = -\frac{\ln(0.1)}{\langle VT \rangle} = \frac{2.303}{\langle VT \rangle}, \tag{2}$$

where $\langle VT \rangle$ is the averaged spacetime volume to which our search is sensitive at the loudest-event threshold. We compute $\langle VT \rangle$ by injecting a large number of simulated waveforms into the O1 data, then analyzing the data with both pipelines (GstLAL and cWB) to produce a list of combined p-values $\bar{\mathcal{P}}$. A simulated signal is considered to be detected by the search if $\bar{\mathcal{P}}$ is smaller than the p-value of the loudest event, 0.26. The sensitive $\langle VT \rangle$ is then given by

$$\langle VT \rangle = T_0 \int \mathrm{d}z \mathrm{d}\theta \frac{\mathrm{d}V_\mathrm{c}}{\mathrm{d}z} \frac{1}{1+z} s(\theta) f(z, \theta), \tag{3}$$

where T_0 is the total time covered by the injections (in the detector frame), $V_\mathrm{c}(z)$ is the comoving volume contained within a sphere out to redshift z [38], $s(\theta)$ is the injected distribution of binary parameters θ (e.g., masses, spins, orientation angles, distance), and $0 \leq f(z, \theta) \leq 1$ is the selection function indicating the fraction of injections with redshift z and parameters θ that are detected by our search. We evaluate the integral (3) using a Monte Carlo technique.

The injected waveforms are generated using a spin-aligned effective-one-body model [24], which is the waveform model used as a base for the reduced-order model [25] that the GstLAL search pipeline used for its template bank. Precession and higher-order modes are possibly important for IMBHB detection [39–45], particularly for sources with

[3]Since the noise sources are uncorrelated between H1 and L1, introducing relative time delays larger than the GW travel time ($\lesssim$10 ms) is an effective way to generate an empirical noise distribution.

more extreme mass ratios; however, we neglect both effects due to current limitations in the waveform models.

Since the true population of IMBHBs, and thus the true function $s(\theta)$, is unknown, we focus on placing limits on 12 specific locations in the IMBHB parameter space. We choose 10 specific combinations of masses (see Table I). For 9 of these mass combinations, we consider only nonspinning black holes. In the case $m_1 = m_2 = 100 M_\odot$, we consider nonspinning black holes and two spinning cases. In both spinning cases, we choose dimensionless spins $\chi_{1,2}$ of magnitude 0.8 which are aligned with each other. In one case, the spins are also aligned with the orbital angular momentum of the system ($\chi_1 = \chi_2 = 0.8$); in the other, they are antialigned ($\chi_1 = \chi_2 = -0.8$). Angular parameters (i.e., binary orientation and sky location) are chosen from a uniform distribution on a sphere.

The luminosity distances of the sources are chosen approximately uniformly in comoving volume out to a maximum redshift $z = 1$.[4] The sources are distributed uniformly in the O1 observation time ($T_0 \simeq 130$ days), with a correction factor to account for time dilation. In the detector frame, the injections are spaced by 100 s on average. The total number of injections in each set is $N_{\mathrm{total}} \simeq 112000$, with some slight variation between sets due to the random nature of assigning injection times. Each set includes times during which the detectors were not taking coincident data; the procedure is insensitive to their inclusion in the total. The total spacetime volume covered by the injection sets is $\langle VT \rangle_{\mathrm{total}} \simeq 35\ \mathrm{Gpc}^3\ \mathrm{yr}$. With these choices, expression (3) for the sensitive $\langle VT \rangle$ reduces to the form

$$\langle VT \rangle = \frac{N_{\text{below cutoff}}}{N_{\text{total}}} \langle VT \rangle_{\text{total}}, \tag{4}$$

where $N_{\text{below cutoff}}$ is the number of injections assigned a p-value lower than 0.26.

The results are given in Table I. The table shows the 90% confidence rate upper limit for each of the 12 injection sets. Amplitude and phase errors arising from detector calibration [46] have not been included in the analysis; we expect uncertainty in $R_{90\%}$ to be ≈18% because of the ≈6% uncertainty in the detectors' amplitude calibration [5]. The tightest bound is placed on the merger of two $100\ M_\odot$ black holes whose spins are aligned with their orbital angular momentum: the rate of these mergers is constrained to be less than $0.93\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$. Since IMBHB merger rates are commonly expressed in events per GC per Gyr, we convert our results into these units by assuming, for the sake of simplicity, a redshift-independent GC density of $3\ \mathrm{GC\,Mpc}^{-3}$ [47],[5] yielding a minimal $R_{90\%} \approx 0.3\ \mathrm{GC}^{-1}\,\mathrm{Gyr}^{-1}$.

We also report a sensitive distance,

$$D_{\langle VT \rangle} = \left(\frac{3 \langle VT \rangle}{4\pi T_{\mathrm{a}}} \right)^{1/3}, \tag{5}$$

where $T_{\mathrm{a}} < T_0$ is the total time analyzed by the search. The sensitive distance is analogous to the sense-monitor range [48], except that (5) includes cosmological effects. It is given in Table I for the combined $\langle VT \rangle$, used to generate $R_{90\%}$, as well as for the GstLAL and cWB search algorithms individually. The searches are most sensitive to binaries with $m_1 = m_2 = 100\ M_\odot$ and aligned spins. Figure 2 also reports $R_{90\%}$ and $D_{\langle VT \rangle}$ for the combined search with lines of constant mass ratio $q = m_2/m_1$ and total mass $M = m_1 + m_2$ to guide the eye.

IV. ASTROPHYSICAL IMPLICATIONS

There are currently few good candidates for IMBHs, but if one extrapolates the observed relation between supermassive black holes and the masses of their host galaxies to lower-mass systems, it is plausible to infer the existence of IMBHs [49–56]. While the formation channel of IMBHs is unknown, there are a small number of proposed scenarios: (i) the direct collapse of massive first-generation, low-metallicity Population III stars [57–60], (ii) runaway mergers of massive main sequence stars in dense stellar clusters [61–65], (iii) the accretion of residual gas onto stellar-mass black holes [66], and (iv) chemically homogeneous evolution [67].[6]

It has been suggested that the most likely locations to find IMBHs are at the centers of GCs [68–80]. It follows that these are also the most likely places to find IMBHBs. Again, while the formation mechanisms are unknown, it is postulated that an IMBHB can be formed in a GC with a fraction of binary stars higher than ≈10% [81] or as a result of a merger of two clusters, each of which contains an IMBH [82,83]. While no direct observational evidence of IMBHBs exists, this hypothesis is supported by recent simulations of dense stellar systems [84]. Measurements of an IMBHB's components would allow us to not only constrain IMBH formation channels, but also make statements on the link between IMBHs and both ultraluminous [85] and hyperluminous [86–88] x-ray systems.

[4] A flat cosmology with an incorrect value of $\Omega_{\mathrm{m}} = 0.3156$ (instead of 0.3065) was used to generate the injection sets. We find that the error has no significant effect on our results, introducing an error of less than 1%.

[5] This density encompasses GCs with a range of masses and central concentrations; we make the further simplifying assumption that all GCs have the potential to form IMBHs with the masses we consider.

[6] Since IMBHs are potentially formed via different channels than stellar-mass black holes, we do not attempt to extrapolate the BBH mass distribution to IMBHBs. The O1 BBH merger rate and mass distribution reported in [5,10] were calculated assuming that the total mass is less than $100\,M_\odot$.

As stated in Table I, the minimal $R_{90\%}$ is found to be $\approx 0.3\ \mathrm{GC}^{-1}\,\mathrm{Gyr}^{-1}$. The improvement in detector sensitivity since the S6 run means that this result is nearly 2 orders of magnitude lower than the lowest upper limit set using previous LIGO-Virgo data [13,16]. This number is within a factor of a few of $0.1\ \mathrm{GC}^{-1}\,\mathrm{Gyr}^{-1}$, the IMBHB merger rate corresponding to one event occurring in each GC within the lifetime of the cluster (assumed equal to 10 Gyr), although it only refers to a single point in the IMBHB mass-spin parameter space and not to the full physical distribution of IMBHBs. The bounds are compatible with rate predictions coming from astrophysical models of IMBHB formation [83,89,90]. To make a full comparison of the upper limits with predictions, or with the BBH merger rate (9–240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ [5,10]), it would be necessary to assume a mass, spin, and redshift distribution for IMBHB mergers; this distribution is currently uncertain, so we defer a comparison to future studies.

Further improvements to the detector sensitivity in the next observing runs will allow us to increasingly improve the IMBHB merger-rate estimation and provide relevant constraints on the merger rate in the local Universe. A single GW detection of an IMBHB merger could provide the first conclusive proof of the existence of IMBHs in the Universe [91–93]. Multiple detections, where astrophysically important parameters, such as mass and spin, are measured, would allow us to make statements not only on the formation and evolutionary channels of IMBHs but also on their link with other observed phenomena.

V. CONCLUSION

This paper describes a search for intermediate mass black hole binaries during the first observing run of the Advanced LIGO detectors. Due to improvement in detector sensitivity, this run had an increase in search horizon of a factor of ≈ 6 compared to the previous science run. The search uses the combined information from a modeled matched-filter pipeline and an unmodeled transient burst pipeline. While no IMBHBs were found, 90% confidence limits were placed on the merger rates of IMBHBs in the local Universe. The minimum merger rate of $\approx 0.3\ \mathrm{GC}^{-1}\,\mathrm{Gyr}^{-1}$ constitutes an improvement of almost 2 orders of magnitude over the previous search results. The results presented here are based on nonprecessing and, in most cases, nonspinning waveforms, that also omit higher modes. It is believed that these higher-order physical effects may be important for IMBHBs, but they should be less important for the near equal-mass systems where we can set best upper limits. We plan to include these effects in future analyses. It is also believed that continued improvements in the detector performance during future observing runs [94] will allow us to further tighten these bounds and may lead to the first detections of IMBHs.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Ministerio de Economía y Competitividad, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the National Science Centre of Poland, the European Commission, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources.

This is LIGO document LIGO-P1600273.

[1] J. Aasi *et al.* (LIGO Scientific Collaboration), Classical Quantum Gravity **32**, 074001 (2015).
[2] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 061102 (2016).
[3] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 241103 (2016).
[4] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **93**, 122003 (2016).
[5] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. X **6**, 041015 (2016).
[6] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 241102 (2016).
[7] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Astrophys. J. **818**, L22 (2016).
[8] P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett *et al.*, Astron. Astrophys. **594**, A13 (2016).
[9] M. C. Miller and E. J. M. Colbert, Int. J. Mod. Phys. **D13**, 1 (2004).
[10] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Astrophys. J. **833**, L1 (2016).
[11] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Astrophys. J. **832**, L21 (2016).
[12] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 131103 (2016).
[13] J. Aasi *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **89**, 122003 (2014).
[14] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Classical Quantum Gravity **33**, 134001 (2016).
[15] B. P. Abbott *et al.* (LIGO Scientific Collaboration), Rep. Prog. Phys. **72**, 076901 (2009).
[16] J. Aasi *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **89**, 102006 (2014).
[17] K. Cannon *et al.*, Astrophys. J. **748**, 136 (2012).
[18] S. Privitera, S. R. P. Mohapatra, P. Ajith, K. Cannon, N. Fotopoulos, M. A. Frei, C. Hanna, A. J. Weinstein, and J. T. Whelan, Phys. Rev. D **89**, 024003 (2014).
[19] C. Messick *et al.*, Phys. Rev. D **95**, 042001 (2017).
[20] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **93**, 122004 (2016).
[21] S. Klimenko *et al.*, Phys. Rev. D **93**, 042004 (2016).
[22] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **95**, 042003 (2017).
[23] N. Wiener, *Extrapolation, Interpolation, and Smoothing of Stationary Time Series* (Wiley, New York, 1949).
[24] A. Taracchini *et al.*, Phys. Rev. D **89**, 061502 (2014).
[25] M. Pürrer, Phys. Rev. D **93**, 064041 (2016).
[26] C. Capano, T. Dent, Y.-M. Hu, M. Hendry, C. Messenger, and J. Veitch, arXiv:1601.00130.
[27] T. Dal Canton *et al.*, Phys. Rev. D **90**, 082004 (2014).
[28] S. A. Usman *et al.*, Classical Quantum Gravity **33**, 215004 (2016).
[29] S. Husa, S. Khan, M. Hannam, M. Pürrer, F. Ohme, X. Jiménez Forteza, and A. Bohé, Phys. Rev. D **93**, 044006 (2016).
[30] S. Khan, S. Husa, M. Hannam, F. Ohme, M. Pürrer, X. Jiménez Forteza, and A. Bohé, Phys. Rev. D **93**, 044007 (2016).
[31] S. Babak *et al.*, Phys. Rev. D **87**, 024033 (2013).
[32] B. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. X **6**, 041014 (2016).
[33] J. Abadie *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **85**, 102004 (2012).
[34] V. Tiwari *et al.*, Phys. Rev. D **93**, 043007 (2016).
[35] S. Mohapatra, L. Cadonati, S. Caudill, J. Clark, C. Hanna, S. Klimenko, C. Pankow, R. Vaulin, G. Vedovato, and S. Vitale, Phys. Rev. D **90**, 022001 (2014).
[36] G. Mazzolo *et al.*, Phys. Rev. D **90**, 063002 (2014).
[37] R. Biswas, P. R. Brady, J. D. E. Creighton, and S. Fairhurst, Classical Quantum Gravity **26**, 175009 (2009); **30**, 079502 (E) (2013).
[38] D. W. Hogg, arXiv:astro-ph/9905116.
[39] R. O'Shaughnessy, L. London, J. Healy, and D. Shoemaker, Phys. Rev. D **87**, 044038 (2013).
[40] P. Schmidt, F. Ohme, and M. Hannam, Phys. Rev. D **91**, 024043 (2015).
[41] C. Capano, Y. Pan, and A. Buonanno, Phys. Rev. D **89**, 102003 (2014).
[42] V. Varma, P. Ajith, S. Husa, J. C. Bustillo, M. Hannam, and M. Pürrer, Phys. Rev. D **90**, 124004 (2014).
[43] I. Harry, S. Privitera, A. Bohé, and A. Buonanno, Phys. Rev. D **94**, 024012 (2016).
[44] J. Calderón Bustillo, S. Husa, A. M. Sintes, and M. Pürrer, Phys. Rev. D **93**, 084019 (2016).
[45] J. Calderón Bustillo, P. Laguna, and D. Shoemaker, arXiv:1612.02340.
[46] B. P. Abbott *et al.* (LIGO Scientific Collaboration), Phys. Rev. D **95**, 062003 (2017).
[47] S. F. Portegies Zwart and S. McMillan, Astrophys. J. **528**, L17 (2000).
[48] B. Allen, W. G. Anderson, P. R. Brady, D. A. Brown, and J. D. E. Creighton, Phys. Rev. D **85**, 122006 (2012).
[49] L. Ferrarese and D. Merritt, Astrophys. J. **539**, L9 (2000).
[50] K. Gebhardt *et al.*, Astrophys. J. **539**, L13 (2000).
[51] K. Gültekin, E. M. Cackett, J. M. Miller, T. Di Matteo, S. Markoff, and D. O. Richstone, Astrophys. J. **706**, 404 (2009).
[52] A. W. Graham, C. A. Onken, E. Athanassoula, and F. Combes, Mon. Not. R. Astron. Soc. **412**, 2211 (2011).
[53] N. J. McConnell and C.-P. Ma, Astrophys. J. **764**, 184 (2013).
[54] J. Kormendy, in *Galactic Bulges, IAU Symposium*, edited by H. Dejonghe and H. J. Habing (Kluwer, Dordrecht, 1993), Vol. 153, p. 209.
[55] A. Marconi and L. K. Hunt, Astrophys. J. **589**, L21 (2003).
[56] A. W. Graham and N. Scott, Astrophys. J. **764**, 151 (2013).
[57] P. Madau and M. J. Rees, Astrophys. J. **551**, L27 (2001).
[58] R. Schneider, A. Ferrara, P. Natarajan, and K. Omukai, Astrophys. J. **571**, 30 (2002).
[59] T. Ryu, T. L. Tanaka, R. Perna, and Z. Haiman, Mon. Not. R. Astron. Soc. **460**, 4122 (2016).
[60] T. Kinugawa, K. Inayoshi, K. Hotokezaka, D. Nakauchi, and T. Nakamura, Mon. Not. R. Astron. Soc. **442**, 2963 (2014).
[61] M. C. Miller and D. P. Hamilton, Mon. Not. R. Astron. Soc. **330**, 232 (2002).
[62] S. F. Portegies Zwart, H. Baumgardt, P. Hut, J. Makino, and S. L. W. McMillan, Nature (London) **428**, 724 (2004).
[63] S. F. Portegies Zwart and S. L. W. McMillan, Astrophys. J. **576**, 899 (2002).

[64] M. Atakan Gurkan, M. Freitag, and F. A. Rasio, Astrophys. J. **604**, 632 (2004).
[65] M. Mapelli, Mon. Not. R. Astron. Soc. **459**, 3432 (2016).
[66] N. Leigh, A. Sills, and T. Böker, Mon. Not. R. Astron. Soc. **433**, 1958 (2013).
[67] P. Marchant, N. Langer, P. Podsiadlowski, T. M. Tauris, and T. J. Moriya, Astron. Astrophys. **588**, A50 (2016).
[68] O. Godet, D. Barret, N. A. Webb, S. A. Farrell, and N. Gehrels, Astrophys. J. **705**, L109 (2009).
[69] A. Askar, P. Bianchini, R. de Vita, M. Giersz, A. Hypki, and S. Kamann, Mon. Not. R. Astron. Soc. **464**, 3090 (2017).
[70] B. Lanzoni, E. Dalessandro, F. R. Ferraro, P. Miocchi, E. Valenti, and R. T. Rood, Astrophys. J. Lett. **668**, L139 (2007).
[71] B. Jalali, M. Kissler-Patig, K. Gebhardt, E. Noyola, and N. Neumayer, in *American Institute of Physics Conference Series*, edited by V. P. Debattista and C. C. Popescu (2010), Vol. 1240, pp. 245–246.
[72] E. Noyola, K. Gebhardt, and M. Bergmann, Astrophys. J. **676**, 1008 (2008).
[73] J. Anderson and R. P. van der Marel, Astrophys. J. **710**, 1032 (2010).
[74] D. R. Pasham, T. E. Strohmayer, and R. F. Mushotzky, Nature (London) **513**, 74 (2015).
[75] M. Brightman *et al.*, Astrophys. J. **829**, 28 (2016).
[76] D. Cseh *et al.*, Mon. Not. R. Astron. Soc. **446**, 3268 (2015).
[77] M. Mezcua, T. P. Roberts, A. P. Lobanov, and A. D. Sutton, Mon. Not. R. Astron. Soc. **448**, 1893 (2015).
[78] N. Lützgendorf, M. Kissler-Patig, N. Neumayer, H. Baumgardt, E. Noyola, P. T. de Zeeuw, K. Gebhardt, B. Jalali, and A. Feldmeier, Astron. Astrophys. **555**, A26 (2013).
[79] F. Koliopanos, B. C. Ciambur, A. W. Graham, N. A. Webb, M. Coriat, B. Mutlu-Pakdil, B. L. Davis, O. Godet, D. Barret, and M. S. Seigar, Astron. Astrophys. **601**, A20 (2017).
[80] B. Kızıltan, H. Baumgardt, and A. Loeb, Nature (London) **542**, 203 (2017).
[81] M. A. Gurkan, J. M. Fregeau, and F. A. Rasio, Astrophys. J. **640**, L39 (2006).
[82] P. Amaro-Seoane and M. Freitag, Astrophys. J. **653**, L53 (2006).
[83] J. M. Fregeau, S. L. Larson, M. C. Miller, R. W. O'Shaughnessy, and F. A. Rasio, Astrophys. J. **646**, L135 (2006).
[84] M. Giersz, N. Leigh, A. Hypki, N. Lützgendorf, and A. Askar, Mon. Not. R. Astron. Soc. **454**, 3150 (2015).
[85] M. Mezcua, T. P. Roberts, A. D. Sutton, and A. P. Lobanov, Mon. Not. R. Astron. Soc. **436**, 3128 (2013).
[86] Y. Gao, Q. D. Wang, P. N. Appleton, and R. A. Lucas, Astrophys. J. **596**, L171 (2003).
[87] S. A. Farrell, N. A. Webb, D. Barret, O. Godet, and J. M. Rodrigues, Nature (London) **460**, 73 (2009).
[88] A. D. Sutton, T. P. Roberts, D. J. Walton, J. C. Gladstone, and A. E. Scott, Mon. Not. R. Astron. Soc. **423**, 1154 (2012).
[89] M. Giersz, N. Leigh, A. Hypki, A. Askar, and N. Lützgendorf, Mem. Soc. Astron. Ital. **87**, 555 (2016).
[90] C. L. Rodriguez, S. Chatterjee, and F. A. Rasio, Phys. Rev. D **93**, 084029 (2016).
[91] J. Veitch, M. Pürrer, and I. Mandel, Phys. Rev. Lett. **115**, 141101 (2015).
[92] P. B. Graff, A. Buonanno, and B. S. Sathyaprakash, Phys. Rev. D **92**, 022002 (2015).
[93] C.-J. Haster, Z. Wang, C. P. L. Berry, S. Stevenson, J. Veitch, and I. Mandel, Mon. Not. R. Astron. Soc. **457**, 4499 (2016).
[94] J. Aasi *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Living Rev. Relativ. **19**, 1 (2016).

B. P. Abbott,[1] R. Abbott,[1] T. D. Abbott,[2] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] T. Adams,[7] P. Addesso,[8] R. X. Adhikari,[1] V. B. Adya,[9] C. Affeldt,[9] M. Afrough,[10] B. Agarwal,[11] K. Agatsuma,[12] N. Aggarwal,[13] O. D. Aguiar,[14] L. Aiello,[15,16] A. Ain,[17] B. Allen,[9,18,19] G. Allen,[11] A. Allocca,[20,21] H. Almoubayyed,[22] P. A. Altin,[23] A. Amato,[24] A. Ananyeva,[1] S. B. Anderson,[1] W. G. Anderson,[18] S. Antier,[25] S. Appert,[1] K. Arai,[1] M. C. Araya,[1] J. S. Areeda,[26] N. Arnaud,[25,27] K. G. Arun,[28] S. Ascenzi,[29,16] G. Ashton,[9] M. Ast,[30] S. M. Aston,[6] P. Astone,[31] P. Aufmuth,[19] C. Aulbert,[9] K. AultONeal,[32] A. Avila-Alvarez,[26] S. Babak,[33] P. Bacon,[34] M. K. M. Bader,[12] S. Bae,[35] P. T. Baker,[36,37] F. Baldaccini,[38,39] G. Ballardin,[27] S. W. Ballmer,[40] S. Banagiri,[41] J. C. Barayoga,[1] S. E. Barclay,[22] B. C. Barish,[1] D. Barker,[42] F. Barone,[3,4] B. Barr,[22] L. Barsotti,[13] M. Barsuglia,[34] D. Barta,[43] J. Bartlett,[42] I. Bartos,[44] R. Bassiri,[45] A. Basti,[20,21] J. C. Batch,[42] C. Baune,[9] M. Bawaj,[46,39] M. Bazzan,[47,48] B. Bécsy,[49] C. Beer,[9] M. Bejger,[50] I. Belahcene,[25] A. S. Bell,[22] B. K. Berger,[1] G. Bergmann,[9] C. P. L. Berry,[51] D. Bersanetti,[52,53] A. Bertolini,[12] J. Betzwieser,[6] S. Bhagwat,[40] R. Bhandare,[54] I. A. Bilenko,[55] G. Billingsley,[1] C. R. Billman,[5] J. Birch,[6] R. Birney,[56] O. Birnholtz,[9] S. Biscans,[13] A. Bisht,[19] M. Bitossi,[27,21] C. Biwer,[40] M. A. Bizouard,[25] J. K. Blackburn,[1] J. Blackman,[57] C. D. Blair,[58] D. G. Blair,[58] R. M. Blair,[42] S. Bloemen,[59] O. Bock,[9] N. Bode,[9] M. Boer,[60] G. Bogaert,[60] A. Bohe,[33] F. Bondu,[61] R. Bonnand,[7] B. A. Boom,[12] R. Bork,[1] V. Boschi,[20,21] S. Bose,[62,17] Y. Bouffanais,[34] A. Bozzi,[27] C. Bradaschia,[21] P. R. Brady,[18] V. B. Braginsky,[55,†] M. Branchesi,[63,64] J. E. Brau,[65] T. Briant,[66] A. Brillet,[60] M. Brinkmann,[9] V. Brisson,[25] P. Brockill,[18] J. E. Broida,[67] A. F. Brooks,[1] D. A. Brown,[40] D. D. Brown,[51] N. M. Brown,[13] S. Brunett,[1] C. C. Buchanan,[2] A. Buikema,[13] T. Bulik,[68] H. J. Bulten,[69,12] A. Buonanno,[33,70] D. Buskulic,[7] C. Buy,[34] R. L. Byer,[45] M. Cabero,[9] L. Cadonati,[71] G. Cagnoli,[24,72] C. Cahillane,[1] J. Calderón Bustillo,[71]

T. A. Callister,[1] E. Calloni,[73,4] J. B. Camp,[74] M. Canepa,[52,53] P. Canizares,[59] K. C. Cannon,[75] H. Cao,[76] J. Cao,[77] C. D. Capano,[9] E. Capocasa,[34] F. Carbognani,[27] S. Caride,[78] M. F. Carney,[79] J. Casanueva Diaz,[25] C. Casentini,[29,16] S. Caudill,[18] M. Cavaglià,[10] F. Cavalier,[25] R. Cavalieri,[27] G. Cella,[21] C. B. Cepeda,[1] L. Cerboni Baiardi,[63,64] G. Cerretani,[20,21] E. Cesarini,[29,16] S. J. Chamberlin,[80] M. Chan,[22] S. Chao,[81] P. Charlton,[82] E. Chassande-Mottin,[34] D. Chatterjee,[18] B. D. Cheeseboro,[36,37] H. Y. Chen,[83] Y. Chen,[57] H.-P. Cheng,[5] A. Chincarini,[53] A. Chiummo,[27] T. Chmiel,[79] H. S. Cho,[84] M. Cho,[70] J. H. Chow,[23] N. Christensen,[67,60] Q. Chu,[58] A. J. K. Chua,[85] S. Chua,[66] A. K. W. Chung,[86] S. Chung,[58] G. Ciani,[5] R. Ciolfi,[87,88] C. E. Cirelli,[45] A. Cirone,[52,53] F. Clara,[42] J. A. Clark,[71] F. Cleva,[60] C. Cocchieri,[10] E. Coccia,[15,16] P.-F. Cohadon,[66] A. Colla,[89,31] C. G. Collette,[90] L. R. Cominsky,[91] M. Constancio Jr.,[14] L. Conti,[48] S. J. Cooper,[51] P. Corban,[6] T. R. Corbitt,[2] K. R. Corley,[44] N. Cornish,[92] A. Corsi,[78] S. Cortese,[27] C. A. Costa,[14] M. W. Coughlin,[67] S. B. Coughlin,[93,94] J.-P. Coulon,[60] S. T. Countryman,[44] P. Couvares,[1] P. B. Covas,[95] E. E. Cowan,[71] D. M. Coward,[58] M. J. Cowart,[6] D. C. Coyne,[1] R. Coyne,[78] J. D. E. Creighton,[18] T. D. Creighton,[96] J. Cripe,[2] S. G. Crowder,[97] T. J. Cullen,[26] A. Cumming,[22] L. Cunningham,[22] E. Cuoco,[27] T. Dal Canton,[74] S. L. Danilishin,[19,9] S. D'Antonio,[16] K. Danzmann,[19,9] A. Dasgupta,[98] C. F. Da Silva Costa,[5] V. Dattilo,[27] I. Dave,[54] M. Davier,[25] G. S. Davies,[22] D. Davis,[40] E. J. Daw,[99] B. Day,[71] S. De,[40] D. DeBra,[45] E. Deelman,[100] J. Degallaix,[24] M. De Laurentis,[73,4] S. Deléglise,[66] W. Del Pozzo,[51,20,21] T. Denker,[9] T. Dent,[9] V. Dergachev,[33] R. De Rosa,[73,4] R. T. DeRosa,[6] R. DeSalvo,[101] J. Devenson,[56] R. C. Devine,[36,37] S. Dhurandhar,[17] M. C. Díaz,[96] L. Di Fiore,[4] M. Di Giovanni,[102,88] T. Di Girolamo,[73,4,44] A. Di Lieto,[20,21] S. Di Pace,[89,31] I. Di Palma,[89,31] F. Di Renzo,[20,21] Z. Doctor,[83] V. Dolique,[24] F. Donovan,[13] K. L. Dooley,[10] S. Doravari,[9] I. Dorrington,[94] R. Douglas,[22] M. Dovale Álvarez,[51] T. P. Downes,[18] M. Drago,[9] R. W. P. Drever,[1,†] J. C. Driggers,[42] Z. Du,[77] M. Ducrot,[7] J. Duncan,[93] S. E. Dwyer,[42] T. B. Edo,[99] M. C. Edwards,[67] A. Effler,[6] H.-B. Eggenstein,[9] P. Ehrens,[1] J. Eichholz,[1] S. S. Eikenberry,[5] R. A. Eisenstein,[13] R. C. Essick,[13] Z. B. Etienne,[36,37] T. Etzel,[1] M. Evans,[13] T. M. Evans,[6] M. Factourovich,[44] V. Fafone,[29,16,15] H. Fair,[40] S. Fairhurst,[94] X. Fan,[77] S. Farinon,[53] B. Farr,[83] W. M. Farr,[51] E. J. Fauchon-Jones,[94] M. Favata,[103] M. Fays,[94] H. Fehrmann,[9] J. Feicht,[1] M. M. Fejer,[45] A. Fernandez-Galiana,[13] I. Ferrante,[20,21] E. C. Ferreira,[14] F. Ferrini,[27] F. Fidecaro,[20,21] I. Fiori,[27] D. Fiorucci,[34] R. P. Fisher,[40] R. Flaminio,[24,104] M. Fletcher,[22] H. Fong,[105] P. W. F. Forsyth,[23] S. S. Forsyth,[71] J.-D. Fournier,[60] S. Frasca,[89,31] F. Frasconi,[21] Z. Frei,[49] A. Freise,[51] R. Frey,[65] V. Frey,[25] E. M. Fries,[1] P. Fritschel,[13] V. V. Frolov,[6] P. Fulda,[5,74] M. Fyffe,[6] H. Gabbard,[9] M. Gabel,[106] B. U. Gadre,[17] S. M. Gaebel,[51] J. R. Gair,[107] L. Gammaitoni,[38] M. R. Ganija,[76] S. G. Gaonkar,[17] F. Garufi,[73,4] S. Gaudio,[32] G. Gaur,[108] V. Gayathri,[109] N. Gehrels,[74,†] G. Gemme,[53] E. Genin,[27] A. Gennai,[21] D. George,[11] J. George,[54] L. Gergely,[110] V. Germain,[7] S. Ghonge,[71] Abhirup Ghosh,[111] Archisman Ghosh,[111,12] S. Ghosh,[59,12] J. A. Giaime,[2,6] K. D. Giardina,[6] A. Giazotto,[21] K. Gill,[32] L. Glover,[101] E. Goetz,[9] R. Goetz,[5] S. Gomes,[94] G. González,[2] J. M. Gonzalez Castro,[20,21] A. Gopakumar,[112] M. L. Gorodetsky,[55] S. E. Gossan,[1] M. Gosselin,[27] R. Gouaty,[7] A. Grado,[113,4] C. Graef,[22] M. Granata,[24] A. Grant,[22] S. Gras,[13] C. Gray,[42] G. Greco,[63,64] A. C. Green,[51] P. Groot,[59] H. Grote,[9] S. Grunewald,[33] P. Gruning,[25] G. M. Guidi,[63,64] X. Guo,[77] A. Gupta,[80] M. K. Gupta,[98] K. E. Gushwa,[1] E. K. Gustafson,[1] R. Gustafson,[114] B. R. Hall,[62] E. D. Hall,[1] G. Hammond,[22] M. Haney,[112] M. M. Hanke,[9] J. Hanks,[42] C. Hanna,[80] M. D. Hannam,[94] O. A. Hannuksela,[86] J. Hanson,[6] T. Hardwick,[2] J. Harms,[63,64] G. M. Harry,[115] I. W. Harry,[33] M. J. Hart,[22] C.-J. Haster,[105] K. Haughian,[22] J. Healy,[116] A. Heidmann,[66] M. C. Heintze,[6] H. Heitmann,[60] P. Hello,[25] G. Hemming,[27] M. Hendry,[22] I. S. Heng,[22] J. Hennig,[22] J. Henry,[116] A. W. Heptonstall,[1] M. Heurs,[9,19] S. Hild,[22] D. Hoak,[27] D. Hofman,[24] K. Holt,[6] D. E. Holz,[83] P. Hopkins,[94] C. Horst,[18] J. Hough,[22] E. A. Houston,[22] E. J. Howell,[58] Y. M. Hu,[9] E. A. Huerta,[11] D. Huet,[25] B. Hughey,[32] S. Husa,[95] S. H. Huttner,[22] T. Huynh-Dinh,[6] N. Indik,[9] D. R. Ingram,[42] R. Inta,[78] G. Intini,[89,31] H. N. Isa,[22] J.-M. Isac,[66] M. Isi,[1] B. R. Iyer,[111] K. Izumi,[42] T. Jacqmin,[66] K. Jani,[71] P. Jaranowski,[117] S. Jawahar,[118] F. Jiménez-Forteza,[95] W. W. Johnson,[2] D. I. Jones,[119] R. Jones,[22] R. J. G. Jonker,[12] L. Ju,[58] J. Junker,[9] C. V. Kalaghatgi,[94] V. Kalogera,[93] S. Kandhasamy,[6] G. Kang,[35] J. B. Kanner,[1] S. Karki,[65] K. S. Karvinen,[9] M. Kasprzack,[2] M. Katolik,[11] E. Katsavounidis,[13] W. Katzman,[6] S. Kaufer,[19] K. Kawabe,[42] F. Kéfélian,[60] D. Keitel,[22] A. J. Kemball,[11] R. Kennedy,[99] C. Kent,[94] J. S. Key,[120] F. Y. Khalili,[55] I. Khan,[15,16] S. Khan,[9] Z. Khan,[98] E. A. Khazanov,[121] N. Kijbunchoo,[42] Chunglee Kim,[122] J. C. Kim,[123] W. Kim,[76] W. S. Kim,[124] Y.-M. Kim,[84,122] S. J. Kimbrell,[71] E. J. King,[76] P. J. King,[42] R. Kirchhoff,[9] J. S. Kissel,[42] L. Kleybolte,[30] S. Klimenko,[5] P. Koch,[9] S. M. Koehlenbeck,[9] S. Koley,[12] V. Kondrashov,[1] A. Kontos,[13] M. Korobko,[30] W. Z. Korth,[1] I. Kowalska,[68] D. B. Kozak,[1] C. Krämer,[9] V. Kringel,[9] B. Krishnan,[9] A. Królak,[125,126] G. Kuehn,[9] P. Kumar,[105] R. Kumar,[98] S. Kumar,[111] L. Kuo,[81] A. Kutynia,[125] S. Kwang,[18] B. D. Lackey,[33] K. H. Lai,[86] M. Landry,[42] R. N. Lang,[18] J. Lange,[116] B. Lantz,[45] R. K. Lanza,[13] A. Lartaux-Vollard,[25] P. D. Lasky,[127] M. Laxen,[6] A. Lazzarini,[1] C. Lazzaro,[48] P. Leaci,[89,31] S. Leavey,[22] C. H. Lee,[84] H. K. Lee,[128] H. M. Lee,[122] H. W. Lee,[123] K. Lee,[22] J. Lehmann,[9] A. Lenon,[36,37]

M. Leonardi,[102,88] N. Leroy,[25] N. Letendre,[7] Y. Levin,[127] T. G. F. Li,[86] A. Libson,[13] T. B. Littenberg,[129] J. Liu,[58] N. A. Lockerbie,[118] L. T. London,[94] J. E. Lord,[40] M. Lorenzini,[15,16] V. Loriette,[130] M. Lormand,[6] G. Losurdo,[21] J. D. Lough,[9,19] C. O. Lousto,[116] G. Lovelace,[26] H. Lück,[19,9] D. Lumaca,[29,16] A. P. Lundgren,[9] R. Lynch,[13] Y. Ma,[57] S. Macfoy,[56] B. Machenschalk,[9] M. MacInnis,[13] D. M. Macleod,[2] I. Magaña Hernandez,[86] F. Magaña-Sandoval,[40] L. Magaña Zertuche,[40] R. M. Magee,[80] E. Majorana,[31] I. Maksimovic,[130] N. Man,[60] V. Mandic,[41] V. Mangano,[22] G. L. Mansell,[23] M. Manske,[18] M. Mantovani,[27] F. Marchesoni,[46,39] F. Marion,[7] S. Márka,[44] Z. Márka,[44] C. Markakis,[11] A. S. Markosyan,[45] E. Maros,[1] F. Martelli,[63,64] L. Martellini,[60] I. W. Martin,[22] D. V. Martynov,[13] J. N. Marx,[1] K. Mason,[13] A. Masserot,[7] T. J. Massinger,[1] M. Masso-Reid,[22] S. Mastrogiovanni,[89,31] A. Matas,[41] F. Matichard,[13] L. Matone,[44] N. Mavalvala,[13] R. Mayani,[100] N. Mazumder,[62] R. McCarthy,[42] D. E. McClelland,[23] S. McCormick,[6] L. McCuller,[13] S. C. McGuire,[131] G. McIntyre,[1] J. McIver,[1] D. J. McManus,[23] T. McRae,[23] S. T. McWilliams,[36,37] D. Meacher,[80] G. D. Meadors,[33,9] J. Meidam,[12] E. Mejuto-Villa,[8] A. Melatos,[132] G. Mendell,[42] R. A. Mercer,[18] E. L. Merilh,[42] M. Merzougui,[60] S. Meshkov,[1] C. Messenger,[22] C. Messick,[80] R. Metzdorff,[66] P. M. Meyers,[41] F. Mezzani,[31,89] H. Miao,[51] C. Michel,[24] H. Middleton,[51] E. E. Mikhailov,[133] L. Milano,[73,4] A. L. Miller,[5] A. Miller,[89,31] B. B. Miller,[93] J. Miller,[13] M. Millhouse,[92] O. Minazzoli,[60] Y. Minenkov,[16] J. Ming,[33] C. Mishra,[134] S. Mitra,[17] V. P. Mitrofanov,[55] G. Mitselmakher,[5] R. Mittleman,[13] A. Moggi,[21] M. Mohan,[27] S. R. P. Mohapatra,[13] M. Montani,[63,64] B. C. Moore,[103] C. J. Moore,[85] D. Moraru,[42] G. Moreno,[42] S. R. Morriss,[96] B. Mours,[7] C. M. Mow-Lowry,[51] G. Mueller,[5] A. W. Muir,[94] Arunava Mukherjee,[9] D. Mukherjee,[18] S. Mukherjee,[96] N. Mukund,[17] A. Mullavey,[6] J. Munch,[76] E. A. M. Muniz,[40] P. G. Murray,[22] K. Napier,[71] I. Nardecchia,[29,16] L. Naticchioni,[89,31] R. K. Nayak,[135] G. Nelemans,[59,12] T. J. N. Nelson,[6] M. Neri,[52,53] M. Nery,[9] A. Neunzert,[114] J. M. Newport,[115] G. Newton,[22,†] K. K. Y. Ng,[86] T. T. Nguyen,[23] D. Nichols,[59] A. B. Nielsen,[9] S. Nissanke,[59,12] A. Noack,[9] F. Nocera,[27] D. Nolting,[6] M. E. N. Normandin,[96] L. K. Nuttall,[40] J. Oberling,[42] E. Ochsner,[18] E. Oelker,[13] G. H. Ogin,[106] J. J. Oh,[124] S. H. Oh,[124] F. Ohme,[9] M. Oliver,[95] P. Oppermann,[9] Richard J. Oram,[6] B. O'Reilly,[6] R. Ormiston,[41] L. F. Ortega,[5] R. O'Shaughnessy,[116] D. J. Ottaway,[76] H. Overmier,[6] B. J. Owen,[78] A. E. Pace,[80] J. Page,[129] M. A. Page,[58] A. Pai,[109] S. A. Pai,[54] J. R. Palamos,[65] O. Palashov,[121] C. Palomba,[31] A. Pal-Singh,[30] H. Pan,[81] B. Pang,[57] P. T. H. Pang,[86] C. Pankow,[93] F. Pannarale,[94] B. C. Pant,[54] F. Paoletti,[21] A. Paoli,[27] M. A. Papa,[33,18,9] H. R. Paris,[45] W. Parker,[6] D. Pascucci,[22] A. Pasqualetti,[27] R. Passaquieti,[20,21] D. Passuello,[21] B. Patricelli,[136,21] B. L. Pearlstone,[22] M. Pedraza,[1] R. Pedurand,[24,137] L. Pekowsky,[40] A. Pele,[6] S. Penn,[138] C. J. Perez,[42] A. Perreca,[1,102,88] L. M. Perri,[93] H. P. Pfeiffer,[105] M. Phelps,[22] O. J. Piccinni,[89,31] M. Pichot,[60] F. Piergiovanni,[63,64] V. Pierro,[8] G. Pillant,[27] L. Pinard,[24] I. M. Pinto,[8] M. Pitkin,[22] R. Poggiani,[20,21] P. Popolizio,[27] E. K. Porter,[34] A. Post,[9] J. Powell,[22] J. Prasad,[17] J. W. W. Pratt,[32] V. Predoi,[94] T. Prestegard,[18] M. Prijatelj,[9] M. Principe,[8] S. Privitera,[33] G. A. Prodi,[102,88] L. G. Prokhorov,[55] O. Puncken,[9] M. Punturo,[39] P. Puppo,[31] M. Pürrer,[33] H. Qi,[18] J. Qin,[58] S. Qiu,[127] V. Quetschke,[96] E. A. Quintero,[1] R. Quitzow-James,[65] F. J. Raab,[42] D. S. Rabeling,[23] H. Radkins,[42] P. Raffai,[49] S. Raja,[54] C. Rajan,[54] M. Rakhmanov,[96] K. E. Ramirez,[96] P. Rapagnani,[89,31] V. Raymond,[33] M. Razzano,[20,21] J. Read,[26] T. Regimbau,[60] L. Rei,[53] S. Reid,[56] D. H. Reitze,[1,5] H. Rew,[133] S. D. Reyes,[40] F. Ricci,[89,31] P. M. Ricker,[11] S. Rieger,[9] K. Riles,[114] M. Rizzo,[116] N. A. Robertson,[1,22] R. Robie,[22] F. Robinet,[25] A. Rocchi,[16] L. Rolland,[7] J. G. Rollins,[1] V. J. Roma,[65] R. Romano,[3,4] C. L. Romel,[42] J. H. Romie,[6] D. Rosińska,[139,50] M. P. Ross,[140] S. Rowan,[22] A. Rüdiger,[9] P. Ruggi,[27] K. Ryan,[42] M. Rynge,[100] S. Sachdev,[1] T. Sadecki,[42] L. Sadeghian,[18] M. Sakellariadou,[141] L. Salconi,[27] M. Saleem,[109] F. Salemi,[9] A. Samajdar,[135] L. Sammut,[127] L. M. Sampson,[93] E. J. Sanchez,[1] V. Sandberg,[42] B. Sandeen,[93] J. R. Sanders,[40] B. Sassolas,[24] B. S. Sathyaprakash,[80,94] P. R. Saulson,[40] O. Sauter,[114] R. L. Savage,[42] A. Sawadsky,[19] P. Schale,[65] J. Scheuer,[93] E. Schmidt,[32] J. Schmidt,[9] P. Schmidt,[1,59] R. Schnabel,[30] R. M. S. Schofield,[65] A. Schönbeck,[30] E. Schreiber,[9] D. Schuette,[9,19] B. W. Schulte,[9] B. F. Schutz,[94,9] S. G. Schwalbe,[32] J. Scott,[22] S. M. Scott,[23] E. Seidel,[11] D. Sellers,[6] A. S. Sengupta,[142] D. Sentenac,[27] V. Sequino,[29,16] A. Sergeev,[121] D. A. Shaddock,[23] T. J. Shaffer,[42] A. A. Shah,[129] M. S. Shahriar,[93] L. Shao,[33] B. Shapiro,[45] P. Shawhan,[70] A. Sheperd,[18] D. H. Shoemaker,[13] D. M. Shoemaker,[71] K. Siellez,[71] X. Siemens,[18] M. Sieniawska,[50] D. Sigg,[42] A. D. Silva,[14] A. Singer,[1] L. P. Singer,[74] A. Singh,[33,9,19] R. Singh,[2] A. Singhal,[15,31] A. M. Sintes,[95] B. J. J. Slagmolen,[23] B. Smith,[6] J. R. Smith,[26] R. J. E. Smith,[1] E. J. Son,[124] J. A. Sonnenberg,[18] B. Sorazu,[22] F. Sorrentino,[53] T. Souradeep,[17] A. P. Spencer,[22] A. K. Srivastava,[98] A. Staley,[44] M. Steinke,[9] J. Steinlechner,[22,30] S. Steinlechner,[30] D. Steinmeyer,[9,19] B. C. Stephens,[18] R. Stone,[96] K. A. Strain,[22] G. Stratta,[63,64] S. E. Strigin,[55] R. Sturani,[143] A. L. Stuver,[6] T. Z. Summerscales,[144] L. Sun,[132] S. Sunil,[98] P. J. Sutton,[94] B. L. Swinkels,[27] M. J. Szczepańczyk,[32] M. Tacca,[34] D. Talukder,[65] D. B. Tanner,[5] M. Tápai,[110] A. Taracchini,[33] J. A. Taylor,[129] R. Taylor,[1] T. Theeg,[9] E. G. Thomas,[51] M. Thomas,[6] P. Thomas,[42] K. A. Thorne,[6] K. S. Thorne,[57] E. Thrane,[127] S. Tiwari,[15,88] V. Tiwari,[94] K. V. Tokmakov,[118]

K. Toland,[22] M. Tonelli,[20,21] Z. Tornasi,[22] C. I. Torrie,[1] D. Töyrä,[51] F. Travasso,[27,39] G. Traylor,[6] D. Trifirò,[10] J. Trinastic,[5] M. C. Tringali,[102,88] L. Trozzo,[145,21] K. W. Tsang,[12] M. Tse,[13] R. Tso,[1] D. Tuyenbayev,[96] K. Ueno,[18] D. Ugolini,[146] C. S. Unnikrishnan,[112] A. L. Urban,[1] S. A. Usman,[94] K. Vahi,[100] H. Vahlbruch,[19] G. Vajente,[1] G. Valdes,[96] N. van Bakel,[12] M. van Beuzekom,[12] J. F. J. van den Brand,[69,12] C. Van Den Broeck,[12] D. C. Vander-Hyde,[40] L. van der Schaaf,[12] J. V. van Heijningen,[12] A. A. van Veggel,[22] M. Vardaro,[47,48] V. Varma,[57] S. Vass,[1] M. Vasúth,[43] A. Vecchio,[51] G. Vedovato,[48] J. Veitch,[51] P. J. Veitch,[76] K. Venkateswara,[140] G. Venugopalan,[1] D. Verkindt,[7] F. Vetrano,[63,64] A. Viceré,[63,64] A. D. Viets,[18] S. Vinciguerra,[51] D. J. Vine,[56] J.-Y. Vinet,[60] S. Vitale,[13] T. Vo,[40] H. Vocca,[38,39] C. Vorvick,[42] D. V. Voss,[5] W. D. Vousden,[51] S. P. Vyatchanin,[55] A. R. Wade,[1] L. E. Wade,[79] M. Wade,[79] R. Walet,[12] M. Walker,[2] L. Wallace,[1] S. Walsh,[18] G. Wang,[15,64] H. Wang,[51] J. Z. Wang,[80] M. Wang,[51] Y.-F. Wang,[86] Y. Wang,[58] R. L. Ward,[23] J. Warner,[42] M. Was,[7] J. Watchi,[90] B. Weaver,[42] L.-W. Wei,[9,19] M. Weinert,[9] A. J. Weinstein,[1] R. Weiss,[13] L. Wen,[58] E. K. Wessel,[11] P. Weßels,[9] T. Westphal,[9] K. Wette,[9] J. T. Whelan,[116] B. F. Whiting,[5] C. Whittle,[127] D. Williams,[22] R. D. Williams,[1] A. R. Williamson,[116] J. L. Willis,[147] B. Willke,[19,9] M. H. Wimmer,[9,19] W. Winkler,[9] C. C. Wipf,[1] H. Wittel,[9,19] G. Woan,[22] J. Woehler,[9] J. Wofford,[116] K. W. K. Wong,[86] J. Worden,[42] J. L. Wright,[22] D. S. Wu,[9] G. Wu,[6] W. Yam,[13] H. Yamamoto,[1] C. C. Yancey,[70] M. J. Yap,[23] Hang Yu,[13] Haocun Yu,[13] M. Yvert,[7] A. Zadrożny,[125] M. Zanolin,[32] T. Zelenova,[27] J.-P. Zendri,[48] M. Zevin,[93] L. Zhang,[1] M. Zhang,[133] T. Zhang,[22] Y.-H. Zhang,[116] C. Zhao,[58] M. Zhou,[93] Z. Zhou,[93] X. J. Zhu,[58] M. E. Zucker,[1,13] and J. Zweizig[1]

(LIGO Scientific Collaboration and Virgo Collaboration)

[1]*LIGO, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[3]*Università di Salerno, Fisciano, I-84084 Salerno, Italy*
[4]*INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy*
[5]*University of Florida, Gainesville, Florida 32611, USA*
[6]*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
[7]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France*
[8]*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
[9]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[10]*The University of Mississippi, University, Mississippi 38677, USA*
[11]*NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[12]*Nikhef, Science Park, 1098 XG Amsterdam, Netherlands*
[13]*LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[14]*Instituto Nacional de Pesquisas Espaciais, 12227-010S ao José dos Campos, São Paulo, Brazil*
[15]*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[16]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[17]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[18]*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*
[19]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[20]*Università di Pisa, I-56127 Pisa, Italy*
[21]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[22]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[23]*Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[24]*Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France*
[25]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France*
[26]*California State University Fullerton, Fullerton, California 92831, USA*
[27]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[28]*Chennai Mathematical Institute, Chennai 603103, India*
[29]*Università di Roma Tor Vergata, I-00133 Roma, Italy*
[30]*Universität Hamburg, D-22761 Hamburg, Germany*
[31]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[32]*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
[33]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*
[34]*APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France*

[35]Korea Institute of Science and Technology Information, Daejeon 34141, Korea
[36]West Virginia University, Morgantown, West Virginia 26506, USA
[37]Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, West Virginia 26505, USA
[38]Università di Perugia, I-06123 Perugia, Italy
[39]INFN, Sezione di Perugia, I-06123 Perugia, Italy
[40]Syracuse University, Syracuse, New York 13244, USA
[41]University of Minnesota, Minneapolis, Minnesota 55455, USA
[42]LIGO Hanford Observatory, Richland, Washington 99352, USA
[43]Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
[44]Columbia University, New York, New York 10027, USA
[45]Stanford University, Stanford, California 94305, USA
[46]Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
[47]Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
[48]INFN, Sezione di Padova, I-35131 Padova, Italy
[49]MTA Eötvös University, "Lendulet" Astrophysics Research Group, Budapest 1117, Hungary
[50]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716 Warsaw, Poland
[51]University of Birmingham, Birmingham B15 2TT, United Kingdom
[52]Università degli Studi di Genova, I-16146 Genova, Italy
[53]INFN, Sezione di Genova, I-16146 Genova, Italy
[54]RRCAT, Indore, Madhya Pradesh 452013, India
[55]Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
[56]SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom
[57]Caltech CaRT, Pasadena, California 91125, USA
[58]University of Western Australia, Crawley, Western Australia 6009, Australia
[59]Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands
[60]Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
[61]Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France
[62]Washington State University, Pullman, Washington 99164, USA
[63]Università degli Studi di Urbino 'Carlo Bo', I-61029 Urbino, Italy
[64]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
[65]University of Oregon, Eugene, Oregon 97403, USA
[66]Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France
[67]Carleton College, Northfield, Minnesota 55057, USA
[68]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
[69]VU University Amsterdam, 1081 HV Amsterdam, Netherlands
[70]University of Maryland, College Park, Maryland 20742, USA
[71]Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
[72]Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
[73]Università di Napoli 'Federico II', Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
[74]NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
[75]RESCEU, University of Tokyo, Tokyo, 113-0033, Japan
[76]University of Adelaide, Adelaide, South Australia 5005, Australia
[77]Tsinghua University, Beijing 100084, China
[78]Texas Tech University, Lubbock, Texas 79409, USA
[79]Kenyon College, Gambier, Ohio 43022, USA
[80]The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[81]National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
[82]Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
[83]University of Chicago, Chicago, Illinois 60637, USA
[84]Pusan National University, Busan 46241, Korea
[85]University of Cambridge, Cambridge CB2 1TN, United Kingdom
[86]The Chinese University of Hong Kong, Shatin, NT, Hong Kong
[87]INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[88]INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
[89]Università di Roma 'La Sapienza', I-00185 Roma, Italy

[90]*Université Libre de Bruxelles, Brussels 1050, Belgium*
[91]*Sonoma State University, Rohnert Park, California 94928, USA*
[92]*Montana State University, Bozeman, Montana 59717, USA*
[93]*Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, Illinois 60208, USA*
[94]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[95]*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
[96]*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
[97]*Bellevue College, Bellevue, Washington 98007, USA*
[98]*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
[99]*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
[100]*University of Southern California Information Sciences Institute, Marina Del Rey, California 90292, USA*
[101]*California State University, Los Angeles, 5151 State University Dr, Los Angeles, California 90032, USA*
[102]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[103]*Montclair State University, Montclair, New Jersey 07043, USA*
[104]*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[105]*Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada*
[106]*Whitman College, 345 Boyer Avenue, Walla Walla, Washington 99362 USA*
[107]*School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
[108]*University and Institute of Advanced Research, Gandhinagar Gujarat 382007, India*
[109]*IISER-TVM, CET Campus, Trivandrum Kerala 695016, India*
[110]*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
[111]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[112]*Tata Institute of Fundamental Research, Mumbai 400005, India*
[113]*INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy*
[114]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[115]*American University, Washington, D.C. 20016, USA*
[116]*Rochester Institute of Technology, Rochester, New York 14623, USA*
[117]*University of Biał ystok, 15-424 Biał ystok, Poland*
[118]*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[119]*University of Southampton, Southampton SO17 1BJ, United Kingdom*
[120]*University of Washington Bothell, 18115 Campus Way NE, Bothell, Washington 98011, USA*
[121]*Institute of Applied Physics, Nizhny Novgorod 603950, Russia*
[122]*Seoul National University, Seoul 08826, Korea*
[123]*Inje University Gimhae, South Gyeongsang 50834, Korea*
[124]*National Institute for Mathematical Sciences, Daejeon 34047, Korea*
[125]*NCBJ, 05-400 Świerk-Otwock, Poland*
[126]*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[127]*The School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[128]*Hanyang University, Seoul 04763, Korea*
[129]*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
[130]*ESPCI, CNRS, F-75005 Paris, France*
[131]*Southern University and A&M College, Baton Rouge, Louisiana 70813, USA*
[132]*The University of Melbourne, Parkville, Victoria 3010, Australia*
[133]*College of William and Mary, Williamsburg, Virginia 23187, USA*
[134]*Indian Institute of Technology Madras, Chennai 600036, India*
[135]*IISER-Kolkata, Mohanpur, West Bengal 741252, India*
[136]*Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy*
[137]*Université de Lyon, F-69361 Lyon, France*
[138]*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
[139]*Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland*
[140]*University of Washington, Seattle, Washington 98195, USA*
[141]*King's College London, University of London, London WC2R 2LS, United Kingdom*
[142]*Indian Institute of Technology, Gandhinagar Ahmedabad, Gujarat 382424, India*

[143]*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
[144]*Andrews University, Berrien Springs, Michigan 49104, USA*
[145]*Università di Siena, I-53100 Siena, Italy*
[146]*Trinity University, San Antonio, Texas 78212, USA*
[147]*Abilene Christian University, Abilene, Texas 79699, USA*

[†]Deceased.