



HAL
open science

Search for subsolar-mass ultracompact binaries in advanced LIGO's first observing run

B.P. Abbott, R. Abbott, T.D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R.X. Adhikari, V.B. Adya, et al.

► **To cite this version:**

B.P. Abbott, R. Abbott, T.D. Abbott, F. Acernese, K. Ackley, et al.. Search for subsolar-mass ultracompact binaries in advanced LIGO's first observing run. *Phys.Rev.Lett.*, 2018, 121 (23), pp.231103. 10.1103/PhysRevLett.121.231103 . hal-01863138

HAL Id: hal-01863138

<https://hal.science/hal-01863138>

Submitted on 10 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



CHORUS

This is the accepted manuscript made available via CHORUS. The article has been published as:

Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. **121**, 231103 — Published 7 December 2018

DOI: [10.1103/PhysRevLett.121.231103](https://doi.org/10.1103/PhysRevLett.121.231103)

Search for sub-solar mass ultracompact binaries in Advanced LIGO’s first observing run

The LIGO Scientific Collaboration and The Virgo Collaboration
(Dated: September 13, 2018)

We present the first Advanced LIGO and Advanced Virgo search for ultracompact binary systems with component masses between $0.2 M_{\odot} - 1.0 M_{\odot}$ using data taken between September 12, 2015 and January 19, 2016. We find no viable gravitational wave candidates. Our null result constrains the coalescence rate of monochromatic (delta function) distributions of non-spinning ($0.2 M_{\odot}$, $0.2 M_{\odot}$) ultracompact binaries to be less than $1.0 \times 10^6 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and the coalescence rate of a similar distribution of ($1.0 M_{\odot}$, $1.0 M_{\odot}$) ultracompact binaries to be less than $1.9 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (at 90% confidence). Neither black holes nor neutron stars are expected to form below $\sim 1 M_{\odot}$ through conventional stellar evolution, though it has been proposed that similarly low mass black holes could be formed primordially through density fluctuations in the early universe and contribute to the dark matter density. The interpretation of our constraints in the primordial black hole dark matter paradigm is highly model dependent, however, under a particular primordial black hole binary formation scenario we constrain monochromatic primordial black hole populations of $0.2 M_{\odot}$ to be less than 33% of the total dark matter density and monochromatic populations of $1.0 M_{\odot}$ to be less than 5% of the dark matter density. The latter strengthens the presently placed bounds from micro-lensing surveys of MAssive Compact Halo Objects (MACHOs) provided by the MACHO and EROS collaborations.

INTRODUCTION

The era of gravitational wave astronomy began with the observation of the binary black hole merger GW150914 [1]. Since then, four additional binary black hole mergers [2–5] and one binary neutron star merger [6] have been announced as of November 2017. Thus far, Advanced LIGO and Advanced Virgo searches have targeted binary systems with total masses from 2–600 M_{\odot} [7, 8], but the LIGO and Virgo detectors are also sensitive to ultracompact binaries with components below $1 M_{\odot}$ if the compactness (mass to radius ratio) is close to that of a black hole. White dwarf binaries, while often formed with components below one solar mass, are not sufficiently compact to be a LIGO/Virgo gravitational wave source. Neutron stars or black holes are sufficiently compact as would be other exotic compact objects. Previous gravitational wave searches for sub-solar mass ultracompact binaries used data from initial LIGO observations from Feb 14, 2003 – March 24, 2005 [9, 10]. Advanced LIGO [11] presently surveys a volume of space approximately 1000 times larger than the previous search for sub-solar mass ultracompact objects therefore improving the chances of detecting such a binary 1000-fold.

In conventional stellar evolution models, the lightest ultracompact objects are formed when stellar remnants exceed $\sim 1.4 M_{\odot}$, the Chandrasekhar mass limit [12, 13]. Beyond the Chandrasekhar mass limit, electron degeneracy pressure can no longer prevent the gravitational collapse of a white dwarf. The lightest remnants that exceed the Chandrasekhar mass limit form neutron stars [14]. When even the neutron degeneracy pressure cannot prevent collapse, heavier stellar remnants will collapse to black holes. Some equations of state predict that neutron

stars remain stable down to $\sim 0.1 M_{\odot}$ [15]; there is no widely accepted model for forming neutron stars below $\sim 1 M_{\odot}$, though a recent measurement does not exclude the possibility of $0.92 M_{\odot}$ neutron star [16]. This result may be due to the low inclination of the system. The lowest precisely measured neutron star mass is $1.174 M_{\odot}$ [17]. Observationally, black holes appear to have a minimum mass of $\sim 5 M_{\odot}$ with a gap between the heaviest observed neutron star ($\sim 2 M_{\odot}$) and black hole masses [18–21]. Detecting ultracompact objects below one solar mass could challenge our ideas about stellar evolution or possibly hint at new, unconventional formation scenarios.

Beyond conventional stellar evolution, one of the most prolific black hole formation models posits that primordial black holes (PBHs) could have formed in the early universe through the collapse of highly over-dense regions [22–26]. It has been suggested that PBHs could constitute a fraction of the missing dark matter [23, 26], though this scenario has been constrained [27]. LIGO’s detections have revived interest in black hole formation mechanisms and, in particular, the formation of primordial black holes (PBHs) [28–30]. Though there are proposals on how to distinguish a primordial black hole distribution from an astrophysical one [31–36], disentangling them is challenging when the populations overlap in mass. Hence, detection of sub-solar mass ultracompact objects would provide the cleanest signature for determining primordial formation. Still, recent proposals for non-baryonic dark matter models can produce sub-solar mass black holes either by allowing a lower Chandrasekhar mass in the dark sector [37], or by triggering neutron stars to collapse into $\sim 1 M_{\odot}$ black holes [38].

This letter describes a gravitational wave search for ultracompact binary systems with component masses between $0.2 M_{\odot}$ and $1.0 M_{\odot}$ using data from Advanced

LIGO’s first observing run. No viable gravitational wave candidates were identified. We briefly describe the data analyzed and the anticipated sensitivity to sub-solar mass ultracompact objects, as well as the search that was conducted, which led to the null result. We then describe how the null result constrains the merger rate of sub-solar mass binaries in the nearby universe. We consider the merger rate constraints in the context of binary merger rate estimates most recently given by Sasaki et al [29] thereby constraining the fraction of dark matter density made up of PBHs between $0.2 M_{\odot}$ and $1.0 M_{\odot}$. Finally, we conclude with a discussion of future work.

SEARCH

We report on data analyzed from Advanced LIGO’s first observing run, taken from September 12, 2015 – January 19, 2016 at the LIGO Hanford and LIGO Livingston detectors. After taking into account data quality cuts [39] and detector downtime, we analyzed a total of 48.16 days of Hanford-Livingston coincident data. The data selection process was identical to that used in previous searches [40].

During Advanced LIGO’s first observing run, each LIGO instrument was sensitive to sub-solar mass ultracompact binaries at extra-galactic distances. Figure 1 shows the maximum distance to which an equal-mass compact binary merger with given component masses would be visible at a signal-to-noise ratio of 8 in either LIGO Hanford or LIGO Livingston.

The search was conducted using standard gravitational wave analysis software [41–46]. Our search consisted of a matched-filter stage that filtered a discrete bank of templates against the LIGO data. The peak SNR for each template for each second was identified and recorded as a trigger. Subsequently, a chi-squared test was performed that checked the consistency of the trigger with a signal [42]. The triggers from each LIGO detector and gravitational wave template were combined and searched for coincidences within 20 ms. Candidates that pass coincidence were assigned a likelihood ratio, \mathcal{L} , that accounts for the relative probability that the candidates are signal versus noise as a function of SNR, chi-squared, and time delay and phase offset between detectors. Larger values of \mathcal{L} were deemed to be more signal-like. The rate at which noise produced candidates with a given value of \mathcal{L} was computed via a Monte Carlo integral of the noise derived from non-coincident triggers, which we define as the false alarm rate of candidate signals.

Our discrete bank of 500 332 template waveforms [47] conformed to the gravitational wave emission expected from general relativity [48, 49]. We use the 3.5 post-Newtonian order TaylorF2 waveform to model the inspiral portion of the binary evolution, which is constructed under the stationary phase approximation [49]. The Tay-

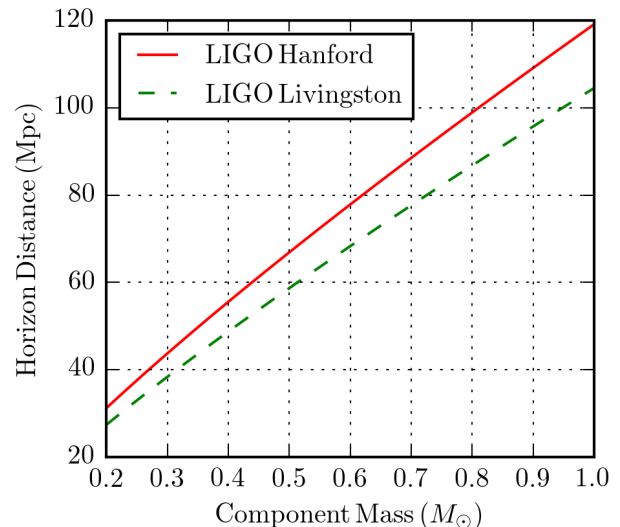


FIG. 1. Distance to which an optimally oriented and aligned equal-mass ultracompact binary merger would produce at least SNR 8 in each of the LIGO Livingston and LIGO Hanford detectors as a function of component mass, based on the median sensitivity obtained from our analyzed data.

lorF2 waveform has been used in previous low-mass Advanced LIGO and Advanced Virgo searches. The bank covered component masses in the detector frame between $0.19 - 2.0 M_{\odot}$ with 97% fidelity. While we restrict our analysis of the search results to the sub-solar region, we have allowed for the possibility of high mass ratio systems. Our template bank assumed that each binary component has negligible spin. Relaxing that assumption is a direction for future work, but is a computationally challenging problem requiring resources well beyond those used for this and previous LIGO analyses. We integrated the template waveforms between 45–1024 Hz, with the longest waveform lasting about 470 seconds. Advanced LIGO is sensitive down to ~ 15 Hz, but integrating from that frequency would have been too computationally burdensome. Our choice to integrate from 45 Hz to 1024 Hz recovered 93.0% of the total possible SNR that integration over the full band would have provided. Additional details are described in [47].

No viable gravitational wave candidates were found. Our loudest gravitational wave candidate was consistent with noise and had a false alarm rate of 6.19 per year.

CONSTRAINT ON BINARY MERGER RATE

We constrained the binary merger rate in this mass region by considering nine monochromatic mass distributions with equal component masses and negligible spin. We constructed sets of simulated signals with component

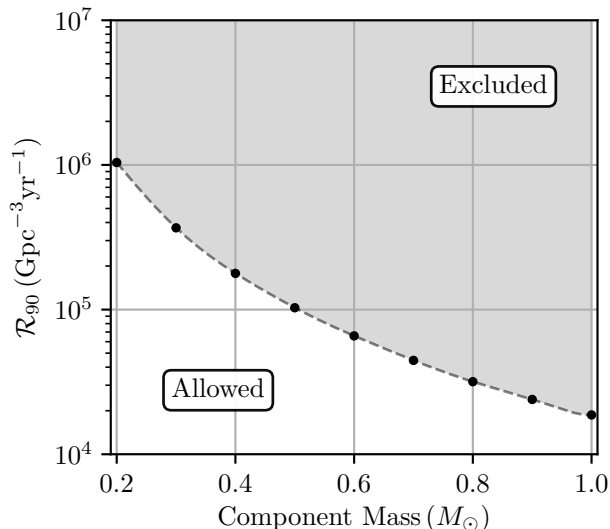


FIG. 2. Constraints on the merger rate of equal-mass ultracompact binaries at the 9 masses considered. The gray region represents an exclusion at 90% confidence on the binary merger rate in units of $\text{Gpc}^{-3} \text{yr}^{-1}$. These limits are found using the loudest event statistic formalism, as described in section III and [50]. The bounds presented here are ~ 3 orders of magnitude stricter than those found in initial LIGO’s search for sub-solar mass ultracompact objects [9, 10].

masses $m_i \in \{0.2, 0.3, \dots, 1.0\}M_\odot$ distributed uniformly in distance and uniformly on the sky. We injected 374 480 simulated signals into the LIGO data and conducted a gravitational wave search with the same parameters as described in section . We then calculated our detection efficiency as a function of distance, $\epsilon_i(r)$. This allowed us to compute the volume-time, $\langle VT \rangle$, that was accessible for our search via,

$$\langle VT \rangle_i = T \int 4\pi r^2 \epsilon_i(r) dr, \quad (1)$$

where T is 48.16 days. We then used the loudest event statistic formalism [50] to compute an upper limit on the binary merger rate in each mass bin to 90% confidence,

$$\mathcal{R}_{90,i} = \frac{2.3}{\langle VT \rangle_i}. \quad (2)$$

We report the upper limits on the binary merger rate in Fig. 2. Several factors in our analysis could lead to uncertainty in \mathcal{R}_{90} at the 25% level, including LIGO calibration errors and Monte Carlo errors. However, these errors are far smaller than potential systematic errors in the models we will be considering in the next section, so we do not attempt to further quantify them in this work.

CONSTRAINT ON PRIMORDIAL BLACK HOLES AS DARK MATTER

For an assumed model of PBH binary formation, the constraint on the binary merger rate places bounds on the total fraction of dark matter made of primordial black holes, f . These bounds are derived from the expected event rate for a uniform distribution of monochromatic PBHs with mass m_i as considered above. The limits on f are sensitive to the model of binary formation. Motivated by previous LIGO searches [9] we follow a method originally proposed by [51, 52] and recently used to constrain $\sim 30M_\odot$ PBH mergers by [29].

We assume an initial, early-universe, monochromatic distribution of PBHs. As the universe expands, the energy density of a pair of black holes not too widely separated becomes larger than the background energy density. The pair decouples from the cosmic expansion and can be prevented from prompt merger by the local tidal field, determined primarily by a third black hole nearest the pair. The initial separation of the pair and the relative location of the primary perturber determine the parameters of the initial binary. From those, the coalescence time can be determined. Assuming a spatially uniform initial distribution of black holes, the distribution of coalescence times for those black holes that form binaries is

$$dP = \begin{cases} \frac{3f^{\frac{37}{8}}}{58} \left[f^{-\frac{29}{8}} \left(\frac{t}{t_c} \right)^{\frac{3}{37}} - \left(\frac{t}{t_c} \right)^{\frac{3}{8}} \right] \frac{dt}{t}, & t < t_c \\ \frac{3f^{\frac{37}{8}}}{58} \left[f^{-\frac{29}{8}} \left(\frac{t}{t_c} \right)^{-\frac{1}{7}} - \left(\frac{t}{t_c} \right)^{\frac{3}{8}} \right] \frac{dt}{t}, & t \geq t_c \end{cases} \quad (3)$$

where t_c is a function of the mass of the PBHs and the fraction of the dark matter they comprise:

$$t_c = \frac{3}{170} \frac{c^5}{(Gm_i)^{5/3}} \frac{f^7}{(1+z_{\text{eq}})^4} \left(\frac{8\pi}{3H_0^2 \Omega_{\text{DM}}} \right)^{4/3} \quad (4)$$

This expression is evaluated at the time today, t_0 , then multiplied by n_{BH} , the current average number density of PBHs, to get the model event rate [29]:

$$\mathcal{R}_{\text{model}} = n_{\text{BH}} \left. \frac{dP}{dt} \right|_{t=t_0}. \quad (5)$$

Given the measured event rate, $\mathcal{R}_{90,i}$, and a particular mass, the above expression can be inverted to find a constraint on the fraction of dark matter in PBHs at that mass. The results of this calculation using the measured upper limits on the merger rate are shown in Fig. 3. A discussion on how some assumptions of this model may affect the constraints on f shown in Fig. 3, are discussed in [47]. The non-detection of a stochastic background in

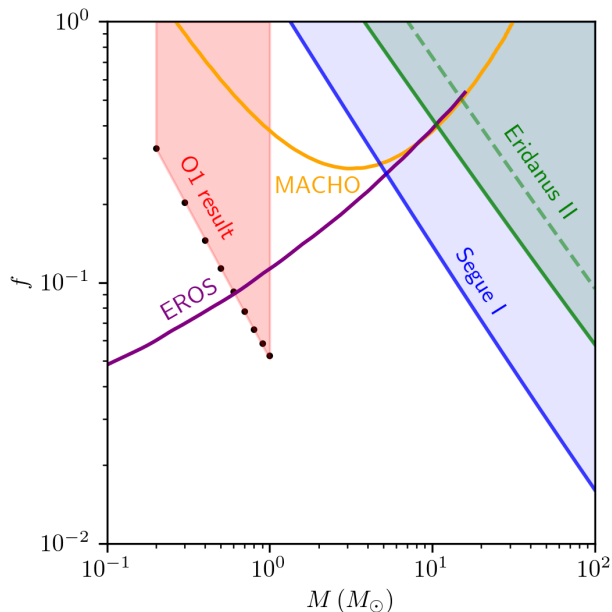


FIG. 3. Constraints on the fraction of dark matter composed of primordial black holes for monochromatic distributions ($f = \Omega_{\text{PBH}}/\Omega_{\text{DM}}$). Shown in black are the results for the nine mass bins considered in this search. For this model of primordial black hole formation, LIGO finds constraints tighter than those of the MACHO collaboration [62] for all mass bins considered and tighter than the EROS collaboration [63] for $m_i \in (0.7, 1.0)M_{\odot}$. The limits presented here also improve upon other constraints at this mass [64]. The curves shown in this figure are digitizations of the original results from [62, 63, 65, 66]. We use the Planck “TT,TE,EE+lowP+lensing+ext” cosmology [67].

the first observing run of Advanced LIGO [53] also implies an upper limit on the merger rate and therefore the PBH abundance. In particular, it is shown that the non-detection of a stochastic background yields constraints that are about a factor of two weaker than the targeted search [54–57].

These results are sensitive to the model of binary formation as well as the mass distribution of PBHs. The effects of initial clustering of PBHs is a current area of research, though it appears that for the expected narrow mass distributions of PBHs this effect is small in the mass range we consider [58–60]. While the results presented here do not take into account other effects on the binary parameters [61], they provide a conservative estimate of the bounds.

CONCLUSION

We presented the first Advanced LIGO and Advanced Virgo search for ultracompact binary mergers with components below $1 M_{\odot}$. No viable gravitational wave can-

didates were found. Therefore, we were able to constrain the binary merger rate for monochromatic mass functions spanning from $0.2 - 1.0 M_{\odot}$. Using a well-studied model from the literature [29, 51, 52], we constrained the abundance of primordial black holes as a fraction of the total dark matter for each of our nine monochromatic mass functions considered.

This work was only the first step in constraints by LIGO on new physics involving sub-solar mass ultracompact objects. The constraints presented in Fig. 2 (and consequently those that arise from the model of binary formation we consider shown in Fig. 3) may not apply if the ultracompact binary components have non-negligible spin since the waveforms used for signal recovery were generated only for non-spinning binaries. Future work may either quantify the extent to which the present search could detect spinning components, or expand the template bank to include systems with spin. Third, we should consider more general distributions of primordial black hole masses; extended mass functions allow for the possibility of unequal mass binaries, and the effect of this imbalance on the predicted merger rate has not been quantified. We also stress that our present results do not rule out an extended mass function that peaks below $0.2 M_{\odot}$ and extends all the way to LIGO’s currently detected systems at or above $30 M_{\odot}$. Each model would have to be explicitly checked by producing an expected binary merger rate density that could be integrated against Advanced LIGO and Advanced Virgo search results. **Extensions to more general distributions have already been considered in the literature [68].**

The first two areas of future work are computational challenges. Lowering the minimum mass and including spin effects in the waveform models could easily increase the computational cost of searching for sub-solar mass ultracompact objects by an order of magnitude each, which would be beyond the capabilities of present LIGO data grid resources.

Advanced LIGO and Advanced Virgo have not reached their final design sensitivities. The distance to which Advanced LIGO will be sensitive to the mergers of ultracompact binaries in this mass range should increase by a factor of three over the next several years [69]. Furthermore, at least a factor of ten more data will be available than what was analyzed in this work. These two facts combined imply that the merger rate constraint should improve by $\gtrsim 2$ orders of magnitude in the coming years.

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 King-

dom, 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, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the Conselleria d'Educació, Investigació, Cultura i Esport de la Generalitat Valenciana, the National Science Centre of Poland, the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), 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 Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFI), 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, the Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the 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. Funding for this project was provided by the Charles E. Kaufman Foundation of The Pittsburgh Foundation. Computing resources and personnel for this project were provided by the Pennsylvania State University. This article has been assigned the document number LIGO-P1800158-v13.

-
- [1] B. P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116(6):061102, 2016.
 - [2] B. P. Abbott et al. GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 116(24):241103, 2016.
 - [3] Benjamin P. Abbott et al. GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.*, 118(22):221101, 2017.
 - [4] B. P. Abbott et al. GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence. *Astrophys. J.*, 851(2):L35, 2017.
 - [5] B. P. Abbott et al. GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 119(14):141101, 2017.
 - [6] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, 2017.
 - [7] B. P. Abbott et al. Binary Black Hole Mergers in the first Advanced LIGO Observing Run. *Phys. Rev.*, X6(4):041015, 2016.
 - [8] Benjamin P. Abbott et al. Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO. *Phys. Rev.*, D96(2):022001, 2017.
 - [9] B. Abbott et al. Search for gravitational waves from primordial black hole binary coalescences in the galactic halo. *Phys. Rev.*, D72:082002, 2005.
 - [10] B. Abbott et al. Search for gravitational waves from binary inspirals in S3 and S4 LIGO data. *Phys. Rev.*, D77:062002, 2008.
 - [11] J. Aasi et al. Advanced LIGO. *Class. Quant. Grav.*, 32:074001, 2015.
 - [12] S. Chandrasekhar. The highly collapsed configurations of a stellar mass (Second paper). *Mon. Not. Roy. Astron. Soc.*, 95:207–225, 1935.
 - [13] Subrahmanyan Chandrasekhar. The maximum mass of ideal white dwarfs. *Astrophys. J.*, 74:81–82, 1931.
 - [14] Norman K Glendenning. *Compact stars: Nuclear physics, particle physics and general relativity*. Springer Science & Business Media, 2012.
 - [15] A. Y. Potekhin, A. F. Fantina, N. Chamel, J. M. Pearson, and S. Goriely. Analytical representations of unified equations of state for neutron-star matter. *Astron. Astrophys.*, 560:A48, 2013.
 - [16] J. G. Martinez, K. Stovall, P. C. C. Freire, J. S. Deneva, T. M. Tauris, A. Ridolfi, N. Wex, F. A. Jenet, M. A. McLaughlin, and M. Bagchi. Pulsar J1411+2551: A Low-mass Double Neutron Star System. *Astrophys. J.*, 851(2):L29, 2017.
 - [17] J. G. Martinez, K. Stovall, P. C. C. Freire, J. S. Deneva, F. A. Jenet, M. A. McLaughlin, M. Bagchi, S. D. Bates, and A. Ridolfi. Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry. *Astrophys. J.*, 812(2):143, 2015.
 - [18] James M. Lattimer. The nuclear equation of state and neutron star masses. *Annual Review of Nuclear and Particle Science*, 62(1):485–515, 2012.
 - [19] F. Özel, D. Psaltis, R. Narayan, and J. E. McClintock. The Black Hole Mass Distribution in the Galaxy. *Astrophys. J.*, 725:1918–1927, 2010.

- [20] W. M. Farr, N. Sravan, A. Cantrell, L. Kreidberg, C. D. Bailyn, I. Mandel, and V. Kalogera. The Mass Distribution of Stellar-mass Black Holes. *Astrophys. J.*, 741:103, 2011.
- [21] L. Kreidberg, C. D. Bailyn, W. M. Farr, and V. Kalogera. Mass Measurements of Black Holes in X-Ray Transients: Is There a Mass Gap? *Astrophys. J.*, 757:36, 2012.
- [22] Y. B. Zeldovich and I. D. Novikov. The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model. *Soviet Astronomy*, 10(4):602–603, 1967.
- [23] S. Hawking. Gravitationally Collapsed Objects of Very Low Mass. *Monthly Notices of the Royal Astronomical Society*, 152(1):75–78, 1971.
- [24] B. J. Carr and S. W. Hawking. Black Holes in the Early Universe. *Monthly Notices of the Royal Astronomical Society*, 168(2):399–415, 1974.
- [25] P. Mészáros. The behaviour of point masses in an expanding cosmological substratum. *Astronomy and Astrophysics*, 37:225–228, 1974.
- [26] George F. Chapline. Cosmological effects of primordial black holes. *Nature*, 253(5489):251–252, 1975.
- [27] Bernard Carr, Florian Kühnel, and Marit Sandstad. Primordial black holes as dark matter. *Physical Review D*, 94(8):083504, 2016.
- [28] Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess. Did LIGO detect dark matter? *Phys. Rev. Lett.*, 116(20):201301, 2016.
- [29] Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama. Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914. *Phys. Rev. Lett.*, 117(6):061101, 2016.
- [30] Sebastien Clesse and Juan García-Bellido. The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO. *Phys. Dark Univ.*, 15:142–147, 2017.
- [31] Ely D. Kovetz, Ilias Cholis, Patrick C. Breysse, and Marc Kamionkowski. Black hole mass function from gravitational wave measurements. *Phys. Rev.*, D95(10):103010, 2017.
- [32] Alvise Raccanelli, Ely D. Kovetz, Simeon Bird, Ilias Cholis, and Julian B. Munoz. Determining the progenitors of merging black-hole binaries. *Phys. Rev.*, D94(2):023516, 2016.
- [33] Ilias Cholis, Ely D. Kovetz, Yacine Ali-Haïmoud, Simeon Bird, Marc Kamionkowski, Julian B. Muñoz, and Alvise Raccanelli. Orbital eccentricities in primordial black hole binaries. *Phys. Rev.*, D94(8):084013, 2016.
- [34] Alvise Raccanelli. Gravitational wave astronomy with radio galaxy surveys. *Mon. Not. Roy. Astron. Soc.*, 469(1):656–670, 2017.
- [35] Savvas M. Koushiappas and Abraham Loeb. Maximum redshift of gravitational wave merger events. *Phys. Rev. Lett.*, 119(22):221104, 2017.
- [36] Hiroya Nishikawa, Ely D. Kovetz, Marc Kamionkowski, and Joseph Silk. Primordial-black-hole mergers in dark-matter spikes. 2017.
- [37] Sarah Shandera, Donghui Jeong, and Henry S. Grasshorn Gebhardt. Gravitational Waves from Binary Mergers of Sub-solar Mass Dark Black Holes. 2018.
- [38] Chris Kouvaris, Peter Tinyakov, and Michel H. G. Tytgat. Non-Primordial Solar Mass Black Holes. 2018.
- [39] B P Abbott et al. Effects of data quality vetoes on a search for compact binary coalescences in Advanced LIGO’s first observing run. *Class. Quant. Grav.*, 35(6):065010, 2018.
- [40] BP Abbott, R Abbott, TD Abbott, MR Abernathy, F Acernese, K Ackley, C Adams, T Adams, P Addesso, RX Adhikari, et al. Binary black hole mergers in the first advanced ligo observing run. *Physical Review X*, 6(4):041015, 2016.
- [41] Kipp Cannon et al. Toward Early-Warning Detection of Gravitational Waves from Compact Binary Coalescence. *Astrophys. J.*, 748:136, 2012.
- [42] Cody Messick et al. Analysis Framework for the Prompt Discovery of Compact Binary Mergers in Gravitational-wave Data. *Phys. Rev.*, D95(4):042001, 2017.
- [43] GstLAL software: git.ligo.org/lscsoft/gstlal.
- [44] Lal software: [git.ligo.org/lalsuite](http://git.ligo.org/lscsoft/lalsuite).
- [45] P. Ajith, N. Fotopoulos, S. Privitera, A. Neunzert, and A. J. Weinstein. Effectual template bank for the detection of gravitational waves from inspiralling compact binaries with generic spins. *Phys. Rev.*, D89(8):084041, 2014.
- [46] Collin Capano, Ian Harry, Stephen Privitera, and Alessandra Buonanno. Implementing a search for gravitational waves from binary black holes with nonprecessing spin. *Phys. Rev.*, D93(12):124007, 2016.
- [47] Ryan Magee, Anne-Sylvie Deutsch, Phoebe McClincy, Chad Hanna, Christian Horst, Duncan Meacher, Cody Messick, Sarah Shandera, and Madeline Wade. Methods for the detection of gravitational waves from sub-solar mass ultracompact binaries, 2018. arXiv:1808.04772.
- [48] Luc Blanchet, Thibault Damour, Bala R. Iyer, Clifford M. Will, and Alan G. Wiseman. Gravitational-radiation damping of compact binary systems to second post-newtonian order. *Phys. Rev. Lett.*, 74:3515–3518, 1995.
- [49] Alessandra Buonanno, Bala R Iyer, Evan Ochsner, Yi Pan, and Bangalore Suryanarayana Sathyaprakash. Comparison of post-newtonian templates for compact binary inspiral signals in gravitational-wave detectors. *Physical Review D*, 80(8):084043, 2009.
- [50] Rahul Biswas, Patrick R. Brady, Jolien D. E. Creighton, and Stephen Fairhurst. The Loudest event statistic: General formulation, properties and applications. *Class. Quant. Grav.*, 26:175009, 2009. [Erratum: *Class. Quant. Grav.* 30,079502(2013)].
- [51] Takashi Nakamura, Misao Sasaki, Takahiro Tanaka, and Kip S. Thorne. Gravitational waves from coalescing black hole MACHO binaries. *Astrophys. J.*, 487:L139–L142, 1997.
- [52] Kunihito Ioka, Takeshi Chiba, Takahiro Tanaka, and Takashi Nakamura. Black Hole Binary Formation in the Expanding Universe : Three Body Problem Approximation. *Physical Review D*, 58(6):063003, 1998.
- [53] Benjamin P. Abbott et al. Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO’s First Observing Run. *Phys. Rev. Lett.*, 118(12):121101, 2017. [Erratum: *Phys. Rev. Lett.* 119, no. 2, 029901(2017)].
- [54] V. Mandic, S. Bird, and I. Cholis. Stochastic Gravitational-Wave Background due to Primordial Binary Black Hole Mergers. *Physical Review Letters*, 117(20):201102, 2016.
- [55] Sai Wang, Yi-Fan Wang, Qing-Guo Huang, and Tjonnie G. F. Li. Constraints on the Primordial Black Hole Abundance from the First Advanced LIGO Observation Run Using the Stochastic Gravitational-Wave Background.

- Phys. Rev. Lett.*, 120(19):191102, 2018.
- [56] I. Cholis. On the gravitational wave background from black hole binaries after the first LIGO detections. *J. Cosmology Astropart. Phys.*, 6:037, 2017.
- [57] M. Raidal, V. Vaskonen, and H. Veermäe. Gravitational waves from primordial black hole mergers. *J. Cosmology Astropart. Phys.*, 9:037, 2017.
- [58] Vincent Desjacques and Antonio Riotto. The Spatial Clustering of Primordial Black Holes. 2018.
- [59] Guillermo Ballesteros, Pasquale D. Serpico, and Marco Taoso. On the merger rate of primordial black holes: effects of nearest neighbours distribution and clustering. 2018.
- [60] Yacine Ali-Haïmoud. Correlation Function of High-Threshold Regions and Application to the Initial Small-Scale Clustering of Primordial Black Holes. *Phys. Rev. Lett.*, 121(8):081304, 2018.
- [61] Yacine Ali-Haïmoud, Ely D. Kovetz, and Marc Kamionkowski. Merger rate of primordial black-hole binaries. *Phys. Rev.*, D96(12):123523, 2017.
- [62] R. A. Allsman et al. MACHO project limits on black hole dark matter in the 1-30 solar mass range. *Astrophys. J.*, 550:L169, 2001.
- [63] P. Tisserand et al. Limits on the Macho Content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds. *Astron. Astrophys.*, 469:387–404, 2007.
- [64] Miguel Zumalacarregui and Uros Seljak. Limits on stellar-mass compact objects as dark matter from gravitational lensing of type Ia supernovae. 2017.
- [65] Savvas M. Koushiappas and Abraham Loeb. Dynamics of Dwarf Galaxies Disfavor Stellar-Mass Black Holes as Dark Matter. *Phys. Rev. Lett.*, 119(4):041102, 2017.
- [66] Timothy D. Brandt. Constraints on MACHO Dark Matter from Compact Stellar Systems in Ultra-Faint Dwarf Galaxies. *Astrophys. J.*, 824(2):L31, 2016.
- [67] P. A. R. Ade et al. Planck 2015 results. XIII. Cosmological parameters. *Astron. Astrophys.*, 594:A13, 2016.
- [68] Nicola Bellomo, José Luis Bernal, Alvise Raccanelli, and Licia Verde. Primordial Black Holes as Dark Matter: Converting Constraints from Monochromatic to Extended Mass Distributions. *JCAP*, 1801(01):004, 2018.
- [69] Benjamin P. Abbott et al. Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev. Rel.*, 21:3, 2018. [Living Rev. Rel.19,1(2016)].

Authors

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,^{9,10} C. Affeldt,^{9,10} B. Agarwal,¹¹ M. Agathos,¹² K. Agatsuma,¹³ N. Aggarwal,¹⁴ O. D. Aguiar,¹⁵ L. Aiello,^{16,17} A. Ain,¹⁸ P. Ajith,¹⁹ B. Allen,^{9,20,10} G. Allen,¹¹ A. Allocca,^{21,22} M. A. Aloy,²³ P. A. Altin,²⁴ A. Amato,²⁵ A. Ananyeva,¹ S. B. Anderson,¹ W. G. Anderson,²⁰ S. V. Angelova,²⁶ S. Antier,²⁷ S. Appert,¹ K. Arai,¹ M. C. Araya,¹ J. S. Areeda,²⁸ M. Arène,²⁹ N. Arnaud,^{27,30} K. G. Arun,³¹ S. Ascenzi,^{32,33} G. Ashton,⁵ M. Ast,³⁴ S. M. Aston,⁶ P. Astone,³⁵ D. V. Atallah,³⁶ F. Aubin,⁷ P. Aufmuth,¹⁰ C. Aulbert,⁹ K. AultO'Neal,³⁷ C. Austin,² A. Avila-Alvarez,²⁸ S. Babak,^{38,29} P. Bacon,²⁹ F. Badaracco,^{16,17} M. K. M. Bader,¹³ S. Bae,³⁹ P. T. Baker,⁴⁰ F. Baldaccini,^{41,42} G. Ballardín,³⁰ S. W. Ballmer,⁴³ S. Banagiri,⁴⁴ J. C. Barayoga,¹ S. E. Barclay,⁴⁵ B. C. Barish,¹ D. Barker,⁴⁶ K. Barkett,⁴⁷ S. Barnum,¹⁴ F. Barone,^{3,4} B. Barr,⁴⁵ L. Barsotti,¹⁴ M. Barsuglia,²⁹ D. Barta,⁴⁸ J. Bartlett,⁴⁶ I. Bartos,⁴⁹ R. Bassiri,⁵⁰ A. Basti,^{21,22} J. C. Batch,⁴⁶ M. Bawaj,^{51,42} J. C. Bayley,⁴⁵ M. Bazzan,^{52,53} B. Bécsy,⁵⁴ C. Beer,⁹ M. Bejger,⁵⁵ I. Belahcene,²⁷ A. S. Bell,⁴⁵ D. Beniwal,⁵⁶ M. Bensch,^{9,10} B. K. Berger,¹ G. Bergmann,^{9,10} S. Bernuzzi,^{57,58} J. J. Bero,⁵⁹ C. P. L. Berry,⁶⁰ D. Bersanetti,⁶¹ A. Bertolini,¹³ J. Betzwieser,⁶ R. Bhandare,⁶² I. A. Bilenko,⁶³ S. A. Bilgili,⁴⁰ G. Billingsley,¹ C. R. Billman,⁴⁹ J. Birch,⁶ R. Birney,²⁶ O. Birnholtz,⁵⁹ S. Biscans,^{1,14} S. Biscoveanu,⁵ A. Bisht,^{9,10} M. Bitossi,^{30,22} M. A. Bizouard,²⁷ J. K. Blackburn,¹ J. Blackman,⁴⁷ C. D. Blair,⁶ D. G. Blair,⁶⁴ R. M. Blair,⁴⁶ S. Bloemen,⁶⁵ O. Bock,⁹ N. Bode,^{9,10} M. Boer,⁶⁶ Y. Boetzel,⁶⁷ G. Bogaert,⁶⁶ A. Bohe,³⁸ F. Bondu,⁶⁸ E. Bonilla,⁵⁰ R. Bonnand,⁷ P. Booker,^{9,10} B. A. Boom,¹³ C. D. Booth,³⁶ R. Bork,¹ V. Boschi,³⁰ S. Bose,^{69,18} K. Bossie,⁶ V. Bossilkov,⁶⁴ J. Bosveld,⁶⁴ Y. Bouffanais,²⁹ A. Bozzi,³⁰ C. Bradaschia,²² P. R. Brady,²⁰ A. Bramley,⁶ M. Branchesi,^{16,17} J. E. Brau,⁷⁰ T. Briant,⁷¹ F. Brighenti,^{72,73} A. Brillet,⁶⁶ M. Brinkmann,^{9,10} V. Brisson,^{27,*} P. Brockill,²⁰ A. F. Brooks,¹ D. D. Brown,⁵⁶ S. Brunett,¹ C. C. Buchanan,² A. Buikema,¹⁴ T. Bulik,⁷⁴ H. J. Bulten,^{75,13} A. Buonanno,^{38,76} D. Buskulic,⁷ C. Buy,²⁹ R. L. Byer,⁵⁰ M. Cabero,⁹ L. Cadonati,⁷⁷ G. Cagnoli,^{25,78} C. Cahillane,¹ J. Calderón Bustillo,⁷⁷ T. A. Callister,¹ E. Calloni,^{79,4} J. B. Camp,⁸⁰ M. Canepa,^{81,61} P. Canizares,⁶⁵ K. C. Cannon,⁸² H. Cao,⁵⁶ J. Cao,⁸³ C. D. Capano,⁹ E. Capocasa,²⁹ F. Carbognani,³⁰ S. Caride,⁸⁴ M. F. Carney,⁸⁵ J. Casanueva Diaz,²² C. Casentini,^{32,33} S. Caudill,^{13,20} M. Cavaglià,⁸⁶ F. Cavalier,²⁷ R. Cavalieri,³⁰ G. Cella,²² C. B. Cepeda,¹ P. Cerdá-Durán,²³ G. Cerretani,^{21,22} E. Cesarini,^{87,33} O. Chaibi,⁶⁶ S. J. Chamberlin,⁸⁸ M. Chan,⁴⁵ S. Chao,⁸⁹ P. Charlton,⁹⁰ E. Chase,⁹¹ E. Chassande-Mottin,²⁹ D. Chatterjee,²⁰ B. D. Cheeseboro,⁴⁰ H. Y. Chen,⁹² X. Chen,⁶⁴ Y. Chen,⁴⁷ H.-P. Cheng,⁴⁹ H. Y. Chia,⁴⁹ A. Chincarini,⁶¹ A. Chiummo,³⁰ T. Chmiel,⁸⁵ H. S. Cho,⁹³ M. Cho,⁷⁶ J. H. Chow,²⁴ N. Christensen,^{94,66} Q. Chu,⁶⁴ A. J. K. Chua,⁴⁷ S. Chua,⁷¹ K. W. Chung,⁹⁵ S. Chung,⁶⁴ G. Ciani,^{52,53,49} A. A. Ciobanu,⁵⁶ R. Ciolfi,^{96,97} F. Cipriano,⁶⁶ C. E. Cirelli,⁵⁰ A. Cirone,^{81,61} F. Clara,⁴⁶ J. A. Clark,⁷⁷ P. Clearwater,⁹⁸ F. Cleva,⁶⁶ C. Cocchieri,⁸⁶

- E. Coccia,^{16,17} P.-F. Cohadon,⁷¹ D. Cohen,²⁷ A. Colla,^{99,35} C. G. Collette,¹⁰⁰ C. Collins,⁶⁰ L. R. Cominsky,¹⁰¹
M. Constancio Jr.,¹⁵ L. Conti,⁵³ S. J. Cooper,⁶⁰ P. Corban,⁶ T. R. Corbitt,² I. Cordero-Carrión,¹⁰²
K. R. Corley,¹⁰³ N. Cornish,¹⁰⁴ A. Corsi,⁸⁴ S. Cortese,³⁰ C. A. Costa,¹⁵ R. Cotesta,³⁸ M. W. Coughlin,¹
S. B. Coughlin,^{36,91} J.-P. Coulon,⁶⁶ S. T. Countryman,¹⁰³ P. Couvares,¹ P. B. Covas,¹⁰⁵ E. E. Cowan,⁷⁷
D. M. Coward,⁶⁴ M. J. Cowart,⁶ D. C. Coyne,¹ R. Coyne,¹⁰⁶ J. D. E. Creighton,²⁰ T. D. Creighton,¹⁰⁷ J. Cripe,²
S. G. Crowder,¹⁰⁸ T. J. Cullen,² A. Cumming,⁴⁵ L. Cunningham,⁴⁵ E. Cuoco,³⁰ T. Dal Canton,⁸⁰ G. Dálya,⁵⁴
S. L. Danilishin,^{10,9} S. D'Antonio,³³ K. Danzmann,^{9,10} A. Dasgupta,¹⁰⁹ C. F. Da Silva Costa,⁴⁹ V. Dattilo,³⁰
I. Dave,⁶² M. Davier,²⁷ D. Davis,⁴³ E. J. Daw,¹¹⁰ B. Day,⁷⁷ D. DeBra,⁵⁰ M. Deenadayalan,¹⁸ J. Degallaix,²⁵
M. De Laurentis,^{79,4} S. Deléglise,⁷¹ W. Del Pozzo,^{21,22} N. Demos,¹⁴ T. Denker,^{9,10} T. Dent,⁹ R. De Pietri,^{57,58}
J. Derby,²⁸ V. Dergachev,⁹ R. De Rosa,^{79,4} C. De Rossi,^{25,30} R. DeSalvo,¹¹¹ A. S. Deutsch,⁸⁸ O. de Varona,^{9,10}
S. Dhurandhar,¹⁸ M. C. Díaz,¹⁰⁷ L. Di Fiore,⁴ M. Di Giovanni,^{112,97} T. Di Girolamo,^{79,4} A. Di Lieto,^{21,22}
B. Ding,¹⁰⁰ S. Di Pace,^{99,35} I. Di Palma,^{99,35} F. Di Renzo,^{21,22} A. Dmitriev,⁶⁰ Z. Doctor,⁹² V. Dolique,²⁵
F. Donovan,¹⁴ K. L. Dooley,^{36,86} S. Doravari,^{9,10} I. Dorrington,³⁶ M. Dovale Álvarez,⁶⁰ T. P. Downes,²⁰
M. Drago,^{9,16,17} C. Dreissigacker,^{9,10} J. C. Driggers,⁴⁶ Z. Du,⁸³ P. Dupej,⁴⁵ S. E. Dwyer,⁴⁶ P. J. Easter,⁵
T. B. Edo,¹¹⁰ M. C. Edwards,⁹⁴ A. Effler,⁶ H.-B. Eggenstein,^{9,10} P. Ehrens,¹ J. Eichholz,¹ S. S. Eikenberry,⁴⁹
M. Eisenmann,⁷ R. A. Eisenstein,¹⁴ R. C. Essick,⁹² H. Estelles,¹⁰⁵ D. Estevez,⁷ Z. B. Etienne,⁴⁰ T. Etzel,¹
M. Evans,¹⁴ T. M. Evans,⁶ V. Fafone,^{32,33,16} H. Fair,⁴³ S. Fairhurst,³⁶ X. Fan,⁸³ S. Farinon,⁶¹ B. Farr,⁷⁰
W. M. Farr,⁶⁰ E. J. Fauchon-Jones,³⁶ M. Favata,¹¹³ M. Fays,³⁶ C. Fee,⁸⁵ H. Fehrmann,⁹ J. Feicht,¹ M. M. Fejer,⁵⁰
F. Feng,²⁹ A. Fernandez-Galiana,¹⁴ I. Ferrante,^{21,22} E. C. Ferreira,¹⁵ F. Ferrini,³⁰ F. Fidecaro,^{21,22} I. Fiori,³⁰
D. Fiorucci,²⁹ M. Fishbach,⁹² R. P. Fisher,⁴³ J. M. Fishner,¹⁴ M. Fitz-Axen,⁴⁴ R. Flamini,^{7,114} M. Fletcher,⁴⁵
H. Fong,¹¹⁵ J. A. Font,^{23,116} P. W. F. Forsyth,²⁴ S. S. Forsyth,⁷⁷ J.-D. Fournier,⁶⁶ S. Frasca,^{99,35} F. Frasconi,²²
Z. Frei,⁵⁴ A. Freise,⁶⁰ R. Frey,⁷⁰ V. Frey,²⁷ P. Fritschel,¹⁴ V. V. Frolov,⁶ P. Fulda,⁴⁹ M. Fyffe,⁶ H. A. Gabbard,⁴⁵
B. U. Gadre,¹⁸ S. M. Gaebel,⁶⁰ J. R. Gair,¹¹⁷ L. Gammaitoni,⁴¹ M. R. Ganija,⁵⁶ S. G. Gaonkar,¹⁸ A. Garcia,²⁸
C. García-Quirós,¹⁰⁵ F. Garufi,^{79,4} B. Gateley,⁴⁶ S. Gaudio,³⁷ G. Gaur,¹¹⁸ V. Gayathri,¹¹⁹ G. Gemme,⁶¹
E. Genin,³⁰ A. Gennai,²² D. George,¹¹ J. George,⁶² L. Gergely,¹²⁰ V. Germain,⁷ S. Ghonge,⁷⁷ Abhirup Ghosh,¹⁹
Archisman Ghosh,¹³ S. Ghosh,²⁰ B. Giacomazzo,^{112,97} J. A. Giaime,^{2,6} K. D. Giardino,⁶ A. Giazotto,^{22,†} K. Gill,³⁷
G. Giordano,^{3,4} L. Glover,¹¹¹ E. Goetz,⁴⁶ R. Goetz,⁴⁹ B. Goncharov,⁵ G. González,² J. M. Gonzalez Castro,^{21,22}
A. Gopakumar,¹²¹ M. L. Gorodetsky,⁶³ S. E. Gossan,¹ M. Gosselin,³⁰ R. Gouaty,⁷ A. Grado,^{122,4} C. Graef,⁴⁵
M. Granata,²⁵ A. Grant,⁴⁵ S. Gras,¹⁴ C. Gray,⁴⁶ G. Greco,^{72,73} A. C. Green,⁶⁰ R. Green,³⁶ E. M. Gretarsson,³⁷
P. Groot,⁶⁵ H. Grote,³⁶ S. Grunewald,³⁸ P. Gruning,²⁷ G. M. Guidi,^{72,73} H. K. Gulati,¹⁰⁹ X. Guo,⁸³ A. Gupta,⁸⁸
M. K. Gupta,¹⁰⁹ K. E. Gushwa,¹ E. K. Gustafson,¹ R. Gustafson,¹²³ O. Halim,^{17,16} B. R. Hall,⁶⁹ E. D. Hall,¹⁴
E. Z. Hamilton,³⁶ H. F. Hamilton,¹²⁴ G. Hammond,⁴⁵ M. Haney,⁶⁷ M. M. Hanke,^{9,10} J. Hanks,⁴⁶ C. Hanna,⁸⁸
O. A. Hannuksela,⁹⁵ J. Hanson,⁶ T. Hardwick,² J. Harms,^{16,17} G. M. Harry,¹²⁵ I. W. Harry,³⁸ M. J. Hart,⁴⁵
C.-J. Haster,¹¹⁵ K. Haughian,⁴⁵ J. Healy,⁵⁹ A. Heidmann,⁷¹ M. C. Heintze,⁶ H. Heitmann,⁶⁶ P. Hello,²⁷
G. Hemming,³⁰ M. Hendry,⁴⁵ I. S. Heng,⁴⁵ J. Hennig,⁴⁵ A. W. Heptonstall,¹ F. J. Hernandez,⁵ M. Heurs,^{9,10}
S. Hild,⁴⁵ T. Hinderer,⁶⁵ D. Hoak,³⁰ S. Hochheim,^{9,10} D. Hofman,²⁵ N. A. Holland,²⁴ K. Holt,⁶ D. E. Holz,⁹²
P. Hopkins,³⁶ C. Horst,²⁰ J. Hough,⁴⁵ E. A. Houston,⁴⁵ E. J. Howell,⁶⁴ A. Hreibi,⁶⁶ E. A. Huerta,¹¹ D. Huet,²⁷
B. Hughey,³⁷ M. Hulko,¹ S. Husa,¹⁰⁵ S. H. Huttner,⁴⁵ T. Huynh-Dinh,⁶ A. Iess,^{32,33} N. Indik,⁹ C. Ingram,⁵⁶
R. Inta,⁸⁴ G. Intini,^{99,35} H. N. Isa,⁴⁵ J.-M. Isac,⁷¹ M. Isi,¹ B. R. Iyer,¹⁹ K. Izumi,⁴⁶ T. Jacqmin,⁷¹ K. Jani,⁷⁷
P. Jaranowski,¹²⁶ D. S. Johnson,¹¹ W. W. Johnson,² D. I. Jones,¹²⁷ R. Jones,⁴⁵ R. J. G. Jonker,¹³ L. Ju,⁶⁴
J. Junker,^{9,10} C. V. Kalaghatgi,³⁶ V. Kalogera,⁹¹ B. Kamai,¹ S. Kandhasamy,⁶ G. Kang,³⁹ J. B. Kanner,¹
S. J. Kapadia,²⁰ S. Karki,⁷⁰ K. S. Karvinen,^{9,10} M. Kasprzack,² M. Katolik,¹¹ S. Katsanevas,³⁰ E. Katsavounidis,¹⁴
W. Katzman,⁶ S. Kaufer,^{9,10} K. Kawabe,⁴⁶ N. V. Keerthana,¹⁸ F. Kéfélian,⁶⁶ D. Keitel,⁴⁵ A. J. Kambhampati,¹¹
R. Kennedy,¹¹⁰ J. S. Key,¹²⁸ F. Y. Khalili,⁶³ B. Khamesra,⁷⁷ H. Khan,²⁸ I. Khan,^{16,33} S. Khan,⁹ Z. Khan,¹⁰⁹
E. A. Khazanov,¹²⁹ N. Kijbunchoo,²⁴ Chunglee Kim,¹³⁰ J. C. Kim,¹³¹ K. Kim,⁹⁵ W. Kim,⁵⁶ W. S. Kim,¹³²
Y.-M. Kim,¹³³ E. J. King,⁵⁶ P. J. King,⁴⁶ M. Kinley-Hanlon,¹²⁵ R. Kirchhoff,^{9,10} J. S. Kissel,⁴⁶ L. Kleybolte,³⁴
S. Klimenko,⁴⁹ T. D. Knowles,⁴⁰ P. Koch,^{9,10} S. M. Koehlenbeck,^{9,10} S. Koley,¹³ V. Kondrashov,¹ A. Kontos,¹⁴
M. Korobko,³⁴ W. Z. Korth,¹ I. Kowalska,⁷⁴ D. B. Kozak,¹ C. Krämer,⁹ V. Kringel,^{9,10} A. Królak,^{134,135}
G. Kuehn,^{9,10} P. Kumar,¹³⁶ R. Kumar,¹⁰⁹ S. Kumar,¹⁹ L. Kuo,⁸⁹ A. Kutynia,¹³⁴ S. Kwang,²⁰ B. D. Lackey,³⁸
K. H. Lai,⁹⁵ M. Landry,⁴⁶ R. N. Lang,¹³⁷ J. Lange,⁵⁹ B. Lantz,⁵⁰ R. K. Lanza,¹⁴ A. Lartaux-Vollard,²⁷
P. D. Lasky,⁵ M. Laxen,⁶ A. Lazzarini,¹ C. Lazzaro,⁵³ P. Leaci,^{99,35} S. Leavey,^{9,10} C. H. Lee,⁹³ H. K. Lee,¹³⁸

H. M. Lee,¹³⁰ H. W. Lee,¹³¹ K. Lee,⁴⁵ J. Lehmann,^{9,10} A. Lenon,⁴⁰ M. Leonardi,^{9,10,114} N. Leroy,²⁷ N. Letendre,⁷ Y. Levin,⁵ J. Li,⁸³ T. G. F. Li,⁹⁵ X. Li,⁴⁷ S. D. Linker,¹¹¹ T. B. Littenberg,¹³⁹ J. Liu,⁶⁴ X. Liu,²⁰ R. K. L. Lo,⁹⁵ N. A. Lockerbie,²⁶ L. T. London,³⁶ A. Longo,^{140,141} M. Lorenzini,^{16,17} V. Loriette,¹⁴² M. Lormand,⁶ G. Losurdo,²² J. D. Lough,^{9,10} G. Lovelace,²⁸ H. Lück,^{9,10} D. Lumaca,^{32,33} A. P. Lundgren,⁹ R. Lynch,¹⁴ Y. Ma,⁴⁷ R. Macas,³⁶ S. Macfoy,²⁶ B. Machenschalk,⁹ M. MacInnis,¹⁴ D. M. Macleod,³⁶ I. Magaña Hernandez,²⁰ F. Magaña-Sandoval,⁴³ L. Magaña Zertuche,⁸⁶ R. M. Magee,⁸⁸ E. Majorana,³⁵ I. Maksimovic,¹⁴² N. Man,⁶⁶ V. Mandic,⁴⁴ V. Mangano,⁴⁵ G. L. Mansell,²⁴ M. Manske,^{20,24} M. Mantovani,³⁰ F. Marchesoni,^{51,42} F. Marion,⁷ S. Márka,¹⁰³ Z. Márka,¹⁰³ C. Markakis,¹¹ A. S. Markosyan,⁵⁰ A. Markowitz,¹ E. Maros,¹ A. Marquina,¹⁰² F. Martelli,^{72,73} L. Martellini,⁶⁶ I. W. Martin,⁴⁵ R. M. Martin,¹¹³ D. V. Martynov,¹⁴ K. Mason,¹⁴ E. Massera,¹¹⁰ A. Masserot,⁷ T. J. Massinger,¹ M. Masso-Reid,⁴⁵ S. Mastrogiovanni,^{99,35} A. Matas,⁴⁴ F. Matichard,^{1,14} L. Matone,¹⁰³ N. Mavalvala,¹⁴ N. Mazumder,⁶⁹ J. J. McCann,⁶⁴ R. McCarthy,⁴⁶ D. E. McClelland,²⁴ S. McCormick,⁶ L. McCuller,¹⁴ S. C. McGuire,¹⁴³ J. McIver,¹ D. J. McManus,²⁴ T. McRae,²⁴ S. T. McWilliams,⁴⁰ D. Meacher,⁸⁸ G. D. Meadors,⁵ M. Mehmet,^{9,10} J. Meidam,¹³ E. Mejuto-Villa,⁸ A. Melatos,⁹⁸ G. Mendell,⁴⁶ D. Mendoza-Gandara,^{9,10} R. A. Mercer,²⁰ L. Mereni,²⁵ E. L. Merilh,⁴⁶ M. Merzougui,⁶⁶ S. Meshkov,¹ C. Messenger,⁴⁵ C. Messick,⁸⁸ R. Metzdorff,⁷¹ P. M. Meyers,⁴⁴ H. Miao,⁶⁰ C. Michel,²⁵ H. Middleton,⁹⁸ E. E. Mikhailov,¹⁴⁴ L. Milano,^{79,4} A. L. Miller,⁴⁹ A. Miller,^{99,35} B. B. Miller,⁹¹ J. Miller,¹⁴ M. Millhouse,¹⁰⁴ J. Mills,³⁶ M. C. Milovich-Goff,¹¹¹ O. Minazzoli,^{66,145} Y. Minenkov,³³ J. Ming,^{9,10} C. Mishra,¹⁴⁶ S. Mitra,¹⁸ V. P. Mitrofanov,⁶³ G. Mitselmakher,⁴⁹ R. Mittleman,¹⁴ D. Moffa,⁸⁵ K. Mogushi,⁸⁶ M. Mohan,³⁰ S. R. P. Mohapatra,¹⁴ M. Montani,^{72,73} C. J. Moore,¹² D. Moraru,⁴⁶ G. Moreno,⁴⁶ S. Morisaki,⁸² B. Mours,⁷ C. M. Mow-Lowry,⁶⁰ G. Mueller,⁴⁹ A. W. Muir,³⁶ Arunava Mukherjee,^{9,10} D. Mukherjee,²⁰ S. Mukherjee,¹⁰⁷ N. Mukund,¹⁸ A. Mullavey,⁶ J. Munch,⁵⁶ E. A. Muñoz,⁴³ M. Muratore,³⁷ P. G. Murray,⁴⁵ A. Nagar,^{87,147,148} K. Napier,⁷⁷ I. Nardecchia,^{32,33} L. Naticchioni,^{99,35} R. K. Nayak,¹⁴⁹ J. Neilson,¹¹¹ G. Nelemans,^{65,13} T. J. N. Nelson,⁶ M. Nery,^{9,10} A. Neunzert,¹²³ L. Nevin,¹ J. M. Newport,¹²⁵ K. Y. Ng,¹⁴ S. Ng,⁵⁶ P. Nguyen,⁷⁰ T. T. Nguyen,²⁴ D. Nichols,⁶⁵ A. B. Nielsen,⁹ S. Nissanke,^{65,13} A. Nitz,⁹ F. Nocera,³⁰ D. Nolting,⁶ C. North,³⁶ L. K. Nuttall,³⁶ M. Obergaulinger,²³ J. Oberling,⁴⁶ B. D. O'Brien,⁴⁹ G. D. O'Dea,¹¹¹ G. H. Ogini,¹⁵⁰ J. J. Oh,¹³² S. H. Oh,¹³² F. Ohme,⁹ H. Ohta,⁸² M. A. Okada,¹⁵ M. Oliver,¹⁰⁵ P. Oppermann,^{9,10} Richard J. Oram,⁶ B. O'Reilly,⁶ R. Ormiston,⁴⁴ L. F. Ortega,⁴⁹ R. O'Shaughnessy,⁵⁹ S. Ossokine,³⁸ D. J. Ottaway,⁵⁶ H. Overmier,⁶ B. J. Owen,⁸⁴ A. E. Pace,⁸⁸ G. Pagano,^{21,22} J. Page,¹³⁹ M. A. Page,⁶⁴ A. Pai,¹¹⁹ S. A. Pai,⁶² J. R. Palamos,⁷⁰ O. Palashov,¹²⁹ C. Palomba,³⁵ A. Pal-Singh,³⁴ Howard Pan,⁸⁹ Huang-Wei Pan,⁸⁹ B. Pang,⁴⁷ P. T. H. Pang,⁹⁵ C. Pankow,⁹¹ F. Pannarale,³⁶ B. C. Pant,⁶² F. Paoletti,²² A. Paoli,³⁰ M. A. Papa,^{9,20,10} A. Parida,¹⁸ W. Parker,⁶ D. Pascucci,⁴⁵ A. Pasqualetti,³⁰ R. Passaquieti,^{21,22} D. Passuello,²² M. Patil,¹³⁵ B. Patricelli,^{151,22} B. L. Pearlstone,⁴⁵ C. Pedersen,³⁶ M. Pedraza,¹ R. Pedurand,^{25,152} L. Pekowsky,⁴³ A. Pele,⁶ S. Penn,¹⁵³ C. J. Perez,⁴⁶ A. Perreca,^{112,97} L. M. Perri,⁹¹ H. P. Pfeiffer,^{115,38} M. Phelps,⁴⁵ K. S. Phukon,¹⁸ O. J. Piccinni,^{99,35} M. Pichot,⁶⁶ F. Piergiovanni,^{72,73} V. Pierro,⁸ G. Pillant,³⁰ L. Pinard,²⁵ I. M. Pinto,⁸ M. Pirello,⁴⁶ M. Pitkin,⁴⁵ R. Poggiani,^{21,22} P. Popolizio,³⁰ E. K. Porter,²⁹ L. Possenti,^{154,73} A. Post,⁹ J. Powell,¹⁵⁵ J. Prasad,¹⁸ J. W. W. Pratt,³⁷ G. Pratten,¹⁰⁵ V. Predoi,³⁶ T. Prestegard,²⁰ M. Principe,⁸ S. Privitera,³⁸ G. A. Prodi,^{112,97} L. G. Prokhorov,⁶³ O. Puncken,^{9,10} M. Punturo,⁴² P. Puppo,³⁵ M. Pürerer,³⁸ H. Qi,²⁰ V. Quetschke,¹⁰⁷ E. A. Quintero,¹ R. Quitzow-James,⁷⁰ F. J. Raab,⁴⁶ D. S. Rabeling,²⁴ H. Radkins,⁴⁶ P. Raffai,⁵⁴ S. Raja,⁶² C. Rajan,⁶² B. Rajbhandari,⁸⁴ M. Rakhmanov,¹⁰⁷ K. E. Ramirez,¹⁰⁷ A. Ramos-Buades,¹⁰⁵ Javed Rana,¹⁸ P. Rapagnani,^{99,35} V. Raymond,³⁶ M. Razzano,^{21,22} J. Read,²⁸ T. Regimbau,^{66,7} L. Rei,⁶¹ S. Reid,²⁶ D. H. Reitze,^{1,49} W. Ren,¹¹ F. Ricci,^{99,35} P. M. Ricker,¹¹ K. Riles,¹²³ M. Rizzo,⁵⁹ N. A. Robertson,^{1,45} R. Robie,⁴⁵ F. Robinet,²⁷ T. Robson,¹⁰⁴ A. Rocchi,³³ L. Rolland,⁷ J. G. Rollins,¹ V. J. Roma,⁷⁰ R. Romano,^{3,4} C. L. Romel,⁴⁶ J. H. Romie,⁶ D. Rosińska,^{156,55} M. P. Ross,¹⁵⁷ S. Rowan,⁴⁵ A. Rüdiger,^{9,10} P. Ruggi,³⁰ G. Rutins,¹⁵⁸ K. Ryan,⁴⁶ S. Sachdev,¹ T. Sadecki,⁴⁶ M. Sakellariadou,¹⁵⁹ L. Salconi,³⁰ M. Saleem,¹¹⁹ F. Salemi,⁹ A. Samajdar,^{149,13} L. Sammut,⁵ L. M. Sampson,⁹¹ E. J. Sanchez,¹ L. E. Sanchez,¹ N. Sanchis-Gual,²³ V. Sandberg,⁴⁶ J. R. Sanders,⁴³ N. Sarin,⁵ B. Sassolas,²⁵ B. S. Sathyaprakash,^{88,36} P. R. Saulson,⁴³ O. Sauter,¹²³ R. L. Savage,⁴⁶ A. Sawadsky,³⁴ P. Schale,⁷⁰ M. Scheel,⁴⁷ J. Scheuer,⁹¹ P. Schmidt,⁶⁵ R. Schnabel,³⁴ R. M. S. Schofield,⁷⁰ A. Schönbeck,³⁴ E. Schreiber,^{9,10} D. Schuette,^{9,10} B. W. Schulte,^{9,10} B. F. Schutz,^{36,9} S. G. Schwalbe,³⁷ J. Scott,⁴⁵ S. M. Scott,²⁴ E. Seidel,¹¹ D. Sellers,⁶ A. S. Sengupta,¹⁶⁰ D. Sentenac,³⁰ V. Sequino,^{32,33,16} A. Sergeev,¹²⁹ Y. Setyawati,⁹ D. A. Shaddock,²⁴ T. J. Shaffer,⁴⁶ A. A. Shah,¹³⁹ M. S. Shahriar,⁹¹ M. B. Shaner,¹¹¹ L. Shao,³⁸ B. Shapiro,⁵⁰ P. Shawhan,⁷⁶ H. Shen,¹¹ D. H. Shoemaker,¹⁴ D. M. Shoemaker,⁷⁷ K. Siellez,⁷⁷ X. Siemens,²⁰ M. Sieniawska,⁵⁵ D. Sigg,⁴⁶ A. D. Silva,¹⁵ L. P. Singer,⁸⁰ A. Singh,^{9,10} A. Singhal,^{16,35} A. M. Sintes,¹⁰⁵ B. J. J. Slagmolen,²⁴

T. J. Slaven-Blair,⁶⁴ B. Smith,⁶ J. R. Smith,²⁸ R. J. E. Smith,⁵ S. Somala,¹⁶¹ E. J. Son,¹³² B. Sorazu,⁴⁵ F. Sorrentino,⁶¹ T. Souradeep,¹⁸ A. P. Spencer,⁴⁵ A. K. Srivastava,¹⁰⁹ K. Staats,³⁷ M. Steinke,^{9,10} J. Steinlechner,^{34,45} S. Steinlechner,³⁴ D. Steinmeyer,^{9,10} B. Steltner,^{9,10} S. P. Stevenson,¹⁵⁵ D. Stocks,⁵⁰ R. Stone,¹⁰⁷ D. J. Stops,⁶⁰ K. A. Strain,⁴⁵ G. Stratta,^{72,73} S. E. Strigin,⁶³ A. Strunk,⁴⁶ R. Sturani,¹⁶² A. L. Stuver,¹⁶³ T. Z. Summerscales,¹⁶⁴ L. Sun,⁹⁸ S. Sunil,¹⁰⁹ J. Suresh,¹⁸ P. J. Sutton,³⁶ B. L. Swinkels,¹³ M. J. Szczepańczyk,³⁷ M. Tacca,¹³ S. C. Tait,⁴⁵ C. Talbot,⁵ D. Talukder,⁷⁰ D. B. Tanner,⁴⁹ M. Tápai,¹²⁰ A. Taracchini,³⁸ J. D. Tasson,⁹⁴ J. A. Taylor,¹³⁹ R. Taylor,¹ S. V. Tewari,¹⁵³ T. Theeg,^{9,10} F. Thies,^{9,10} E. G. Thomas,⁶⁰ M. Thomas,⁶ P. Thomas,⁴⁶ K. A. Thorne,⁶ E. Thrane,⁵ S. Tiwari,^{16,97} V. Tiwari,³⁶ K. V. Tokmakov,²⁶ K. Toland,⁴⁵ M. Tonelli,^{21,22} Z. Tornasi,⁴⁵ A. Torres-Forné,²³ C. I. Torrie,¹ D. Töyrä,⁶⁰ F. Travasso,^{30,42} G. Traylor,⁶ J. Trinastic,⁴⁹ M. C. Tringali,^{112,97} L. Trozzo,^{165,22} K. W. Tsang,¹³ M. Tse,¹⁴ R. Tso,⁴⁷ D. Tsuna,⁸² L. Tsukada,⁸² D. Tuyenbayev,¹⁰⁷ K. Ueno,²⁰ D. Ugolini,¹⁶⁶ A. L. Urban,¹ S. A. Usman,³⁶ H. Vahlbruch,^{9,10} G. Vajente,¹ G. Valdes,² N. van Bakel,¹³ M. van Beuzekom,¹³ J. F. J. van den Brand,^{75,13} C. Van Den Broeck,^{13,167} D. C. Vander-Hyde,⁴³ L. van der Schaaf,¹³ J. V. van Heijningen,¹³ A. A. van Veggel,⁴⁵ M. Vardaro,^{52,53} V. Varma,⁴⁷ S. Vass,¹ M. Vasúth,⁴⁸ A. Vecchio,⁶⁰ G. Vedovato,⁵³ J. Veitch,⁴⁵ P. J. Veitch,⁵⁶ K. Venkateswara,¹⁵⁷ G. Venugopalan,¹ D. Verkindt,⁷ F. Vetrano,^{72,73} A. Viceré,^{72,73} A. D. Viets,²⁰ S. Vinciguerra,⁶⁰ D. J. Vine,¹⁵⁸ J.-Y. Vinet,⁶⁶ S. Vitale,¹⁴ T. Vo,⁴³ H. Vocca,^{41,42} C. Vorvick,⁴⁶ S. P. Vyatchanin,⁶³ A. R. Wade,¹ L. E. Wade,⁸⁵ M. Wade,⁸⁵ R. Walet,¹³ M. Walker,²⁸ L. Wallace,¹ S. Walsh,^{20,9} G. Wang,^{16,22} H. Wang,⁶⁰ J. Z. Wang,¹²³ W. H. Wang,¹⁰⁷ Y. F. Wang,⁹⁵ R. L. Ward,²⁴ J. Warner,⁴⁶ M. Was,⁷ J. Watchi,¹⁰⁰ B. Weaver,⁴⁶ L.-W. Wei,^{9,10} M. Weinert,^{9,10} A. J. Weinstein,¹ R. Weiss,¹⁴ F. Wellmann,^{9,10} L. Wen,⁶⁴ E. K. Wessel,¹¹ P. Weßels,^{9,10} J. Westerweck,⁹ K. Wette,²⁴ J. T. Whelan,⁵⁹ B. F. Whiting,⁴⁹ C. Whittle,¹⁴ D. Wilken,^{9,10} D. Williams,⁴⁵ R. D. Williams,¹ A. R. Williamson,^{59,65} J. L. Willis,^{1,124} B. Willke,^{9,10} M. H. Wimmer,^{9,10} W. Winkler,^{9,10} C. C. Wipf,¹ H. Wittel,^{9,10} G. Woan,⁴⁵ J. Woehler,^{9,10} J. K. Wofford,⁵⁹ W. K. Wong,⁹⁵ J. Worden,⁴⁶ J. L. Wright,⁴⁵ D. S. Wu,^{9,10} D. M. Wysocki,⁵⁹ S. Xiao,¹ W. Yam,¹⁴ H. Yamamoto,¹ C. C. Yancey,⁷⁶ L. Yang,¹⁶⁸ M. J. Yap,²⁴ M. Yazback,⁴⁹ Hang Yu,¹⁴ Haocun Yu,¹⁴ M. Yvert,⁷ A. Zadrożny,¹³⁴ M. Zanolin,³⁷ T. Zelenova,³⁰ J.-P. Zendri,⁵³ M. Zevin,⁹¹ J. Zhang,⁶⁴ L. Zhang,¹ M. Zhang,¹⁴⁴ T. Zhang,⁴⁵ Y.-H. Zhang,^{9,10} C. Zhao,⁶⁴ M. Zhou,⁹¹ Z. Zhou,⁹¹ S. J. Zhu,^{9,10} X. J. Zhu,⁵ M. E. Zucker,^{1,14} and J. Zweigig¹

(The LIGO Scientific Collaboration and the Virgo Collaboration)

S. Shandera⁸⁸

¹LIGO, California Institute of Technology, Pasadena, CA 91125, USA

²Louisiana State University, Baton Rouge, LA 70803, USA

³Università di Salerno, Fisciano, I-84084 Salerno, Italy

⁴INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

⁵OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia

⁶LIGO Livingston Observatory, Livingston, LA 70754, USA

⁷Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France

⁸University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy

⁹Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

¹⁰Leibniz Universität Hannover, D-30167 Hannover, Germany

¹¹NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

¹²University of Cambridge, Cambridge CB2 1TN, United Kingdom

¹³Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

¹⁴LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

¹⁵Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil

¹⁶Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

¹⁷INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy

¹⁸Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

¹⁹International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India

²⁰University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

²¹Università di Pisa, I-56127 Pisa, Italy

²²INFN, Sezione di Pisa, I-56127 Pisa, Italy

²³Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain

²⁴OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

²⁵Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France

²⁶SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom

- ²⁷LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France
- ²⁸California State University Fullerton, Fullerton, CA 92831, USA
- ²⁹APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
- ³⁰European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- ³¹Chennai Mathematical Institute, Chennai 603103, India
- ³²Università di Roma Tor Vergata, I-00133 Roma, Italy
- ³³INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ³⁴Universität Hamburg, D-22761 Hamburg, Germany
- ³⁵INFN, Sezione di Roma, I-00185 Roma, Italy
- ³⁶Cardiff University, Cardiff CF24 3AA, United Kingdom
- ³⁷Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
- ³⁸Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
- ³⁹Korea Institute of Science and Technology Information, Daejeon 34141, Korea
- ⁴⁰West Virginia University, Morgantown, WV 26506, USA
- ⁴¹Università di Perugia, I-06123 Perugia, Italy
- ⁴²INFN, Sezione di Perugia, I-06123 Perugia, Italy
- ⁴³Syracuse University, Syracuse, NY 13244, USA
- ⁴⁴University of Minnesota, Minneapolis, MN 55455, USA
- ⁴⁵SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom
- ⁴⁶LIGO Hanford Observatory, Richland, WA 99352, USA
- ⁴⁷Caltech CaRT, Pasadena, CA 91125, USA
- ⁴⁸Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
- ⁴⁹University of Florida, Gainesville, FL 32611, USA
- ⁵⁰Stanford University, Stanford, CA 94305, USA
- ⁵¹Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
- ⁵²Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁵³INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁵⁴MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary
- ⁵⁵Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- ⁵⁶OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ⁵⁷Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- ⁵⁸INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ⁵⁹Rochester Institute of Technology, Rochester, NY 14623, USA
- ⁶⁰University of Birmingham, Birmingham B15 2TT, United Kingdom
- ⁶¹INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁶²RRCAT, Indore, Madhya Pradesh 452013, India
- ⁶³Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- ⁶⁴OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
- ⁶⁵Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
- ⁶⁶Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
- ⁶⁷Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ⁶⁸Univ Rennes, CNRS, Institut FOTON - UMR6082, F-3500 Rennes, France
- ⁶⁹Washington State University, Pullman, WA 99164, USA
- ⁷⁰University of Oregon, Eugene, OR 97403, USA
- ⁷¹Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- ⁷²Università degli Studi di Urbino 'Carlo Bo,' I-61029 Urbino, Italy
- ⁷³INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁷⁴Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ⁷⁵VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
- ⁷⁶University of Maryland, College Park, MD 20742, USA
- ⁷⁷School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
- ⁷⁸Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
- ⁷⁹Università di Napoli 'Federico II,' Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁸⁰NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ⁸¹Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ⁸²RESCEU, University of Tokyo, Tokyo, 113-0033, Japan.
- ⁸³Tsinghua University, Beijing 100084, China
- ⁸⁴Texas Tech University, Lubbock, TX 79409, USA
- ⁸⁵Kenyon College, Gambier, OH 43022, USA

- ⁸⁶*The University of Mississippi, University, MS 38677, USA*
- ⁸⁷*Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi",
I-00184 Roma, Italyrico Fermi, I-00184 Roma, Italy*
- ⁸⁸*The Pennsylvania State University, University Park, PA 16802, USA*
- ⁸⁹*National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China*
- ⁹⁰*Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
- ⁹¹*Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA),
Northwestern University, Evanston, IL 60208, USA*
- ⁹²*University of Chicago, Chicago, IL 60637, USA*
- ⁹³*Pusan National University, Busan 46241, Korea*
- ⁹⁴*Carleton College, Northfield, MN 55057, USA*
- ⁹⁵*The Chinese University of Hong Kong, Shatin, NT, Hong Kong*
- ⁹⁶*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
- ⁹⁷*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
- ⁹⁸*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
- ⁹⁹*Università di Roma 'La Sapienza,' I-00185 Roma, Italy*
- ¹⁰⁰*Université Libre de Bruxelles, Brussels 1050, Belgium*
- ¹⁰¹*Sonoma State University, Rohnert Park, CA 94928, USA*
- ¹⁰²*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹⁰³*Columbia University, New York, NY 10027, USA*
- ¹⁰⁴*Montana State University, Bozeman, MT 59717, USA*
- ¹⁰⁵*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
- ¹⁰⁶*University of Rhode Island*
- ¹⁰⁷*The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA*
- ¹⁰⁸*Bellevue College, Bellevue, WA 98007, USA*
- ¹⁰⁹*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
- ¹¹⁰*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
- ¹¹¹*California State University, Los Angeles, 5151 State University Dr, Los Angeles, CA 90032, USA*
- ¹¹²*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
- ¹¹³*Montclair State University, Montclair, NJ 07043, USA*
- ¹¹⁴*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
- ¹¹⁵*Canadian Institute for Theoretical Astrophysics,
University of Toronto, Toronto, Ontario M5S 3H8, Canada*
- ¹¹⁶*Osservatori Astronomic, Universitat de València, E-46980 Paterna, València, Spain*
- ¹¹⁷*School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
- ¹¹⁸*University and Institute of Advanced Research,
Koba Institutional Area, Gandhinagar Gujarat 382007, India*
- ¹¹⁹*Indian Institute of Technology Bombay*
- ¹²⁰*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
- ¹²¹*Tata Institute of Fundamental Research, Mumbai 400005, India*
- ¹²²*INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy*
- ¹²³*University of Michigan, Ann Arbor, MI 48109, USA*
- ¹²⁴*Abilene Christian University, Abilene, TX 79699, USA*
- ¹²⁵*American University, Washington, D.C. 20016, USA*
- ¹²⁶*University of Białystok, 15-424 Białystok, Poland*
- ¹²⁷*University of Southampton, Southampton SO17 1BJ, United Kingdom*
- ¹²⁸*University of Washington Bothell, 18115 Campus Way NE, Bothell, WA 98011, USA*
- ¹²⁹*Institute of Applied Physics, Nizhny Novgorod, 603950, Russia*
- ¹³⁰*Korea Astronomy and Space Science Institute, Daejeon 34055, Korea*
- ¹³¹*Inje University Gimhae, South Gyeongsang 50834, Korea*
- ¹³²*National Institute for Mathematical Sciences, Daejeon 34047, Korea*
- ¹³³*Ulsan National Institute of Science and Technology*
- ¹³⁴*NCBJ, 05-400 Świerk-Otwock, Poland*
- ¹³⁵*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ¹³⁶*Cornell University*
- ¹³⁷*Hillsdale College, Hillsdale, MI 49242, USA*
- ¹³⁸*Hanyang University, Seoul 04763, Korea*
- ¹³⁹*NASA Marshall Space Flight Center, Huntsville, AL 35811, USA*
- ¹⁴⁰*Dipartimento di Fisica, Università degli Studi Roma Tre, I-00154 Roma, Italy*
- ¹⁴¹*INFN, Sezione di Roma Tre, I-00154 Roma, Italy*
- ¹⁴²*ESPCI, CNRS, F-75005 Paris, France*
- ¹⁴³*Southern University and A&M College, Baton Rouge, LA 70813, USA*
- ¹⁴⁴*College of William and Mary, Williamsburg, VA 23187, USA*
- ¹⁴⁵*Centre Scientifique de Monaco, 8 quai Antoine 1er, MC-98000, Monaco*

- ¹⁴⁶ *Indian Institute of Technology Madras, Chennai 600036, India*
- ¹⁴⁷ *INFN Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*
- ¹⁴⁸ *Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
- ¹⁴⁹ *IISER-Kolkata, Mohanpur, West Bengal 741252, India*
- ¹⁵⁰ *Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA*
- ¹⁵¹ *Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy*
- ¹⁵² *Université de Lyon, F-69361 Lyon, France*
- ¹⁵³ *Hobart and William Smith Colleges, Geneva, NY 14456, USA*
- ¹⁵⁴ *Università degli Studi di Firenze, I-50121 Firenze, Italy*
- ¹⁵⁵ *OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
- ¹⁵⁶ *Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland*
- ¹⁵⁷ *University of Washington, Seattle, WA 98195, USA*
- ¹⁵⁸ *SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
- ¹⁵⁹ *King's College London, University of London, London WC2R 2LS, United Kingdom*
- ¹⁶⁰ *Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India*
- ¹⁶¹ *Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
- ¹⁶² *International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
- ¹⁶³ *Villanova University, 800 Lancaster Ave, Villanova, PA 19085, USA*
- ¹⁶⁴ *Andrews University, Berrien Springs, MI 49104, USA*
- ¹⁶⁵ *Università di Siena, I-53100 Siena, Italy*
- ¹⁶⁶ *Trinity University, San Antonio, TX 78212, USA*
- ¹⁶⁷ *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*
- ¹⁶⁸ *Colorado State University, Fort Collins, CO 80523, USA*