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B. P. Abbott

Marco Cavaglia
Missouri University of Science and Technology, cavagliam@mst.edu

For full list of authors, see publisher's website.

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

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
and S. Shandera

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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 nonspinning (0.2 $M_\odot$, 0.2 $M_\odot$) ultracompact binaries to be less than 1.0×10^6 Gpc^{-3} 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 1.9×10^4 Gpc^{-3} yr^{-1} (at 90% confidence). Neither black holes nor neutron stars are expected to form below ~ 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 microlensing surveys of massive compact halo objects (MACHOs) provided by the MACHO and EROS Collaborations.

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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 February 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 ~ 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 ~ 0.1 $M_\odot$ [15]; there is no widely accepted model for forming neutron stars below ~ 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 ~ 5 $M_\odot$ with a gap between the heaviest observed neutron star (~ 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 overdense regions

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[*] Full author list given at end of the Letter.

[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 nonbaryonic 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 ∼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 noncoincident triggers, which we define as the false alarm rate of candidate signals.

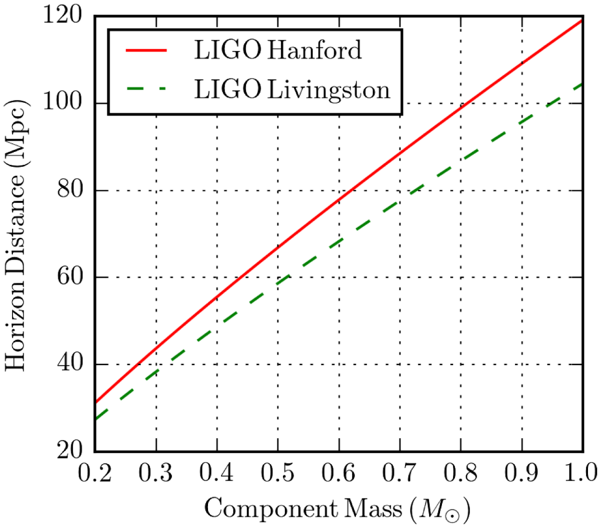

FIG. 1. Distance to which an optimally oriented and aligned equal-mass ultracompact binary merger would produce at least SNR 8 in each of the LIGO Livingston and LIGO Hanford detectors as a function of component mass, based on the median sensitivity obtained from our analyzed data.

Our discrete bank of 500332 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 TaylorF2 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 subsolar 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 to 1024 Hz recovered 93.0% of the total possible SNR that integration

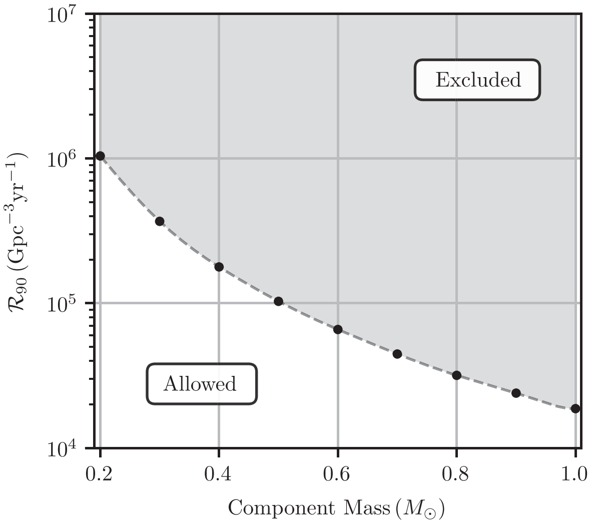

FIG. 2. Constraints on the merger rate of equal-mass ultracompact binaries at the 9 masses considered. The gray region represents an exclusion at 90% confidence on the binary merger rate in units of $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$. These limits are found using the loudest event statistic formalism,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

over the full band would have provided. Additional details are described in Ref. [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 masses $m_i \in \{0.2, 0.3, \ldots, 1.0\} M_\odot$ distributed uniformly in distance and uniformly on the sky. We injected 374480 simulated signals into the LIGO data and conducted a gravitational wave search with the same parameters as described earlier. 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

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

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,

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

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 Refs. [51,52] and recently used to constrain ~30 $M_\odot$ PBH mergers by Ref. [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

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

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

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

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]:

$$\mathcal{R}_{\mathrm{model}} = n_{\mathrm{BH}} \frac{dP}{dt}\bigg|_{t=t_0}. \tag{5}$$

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

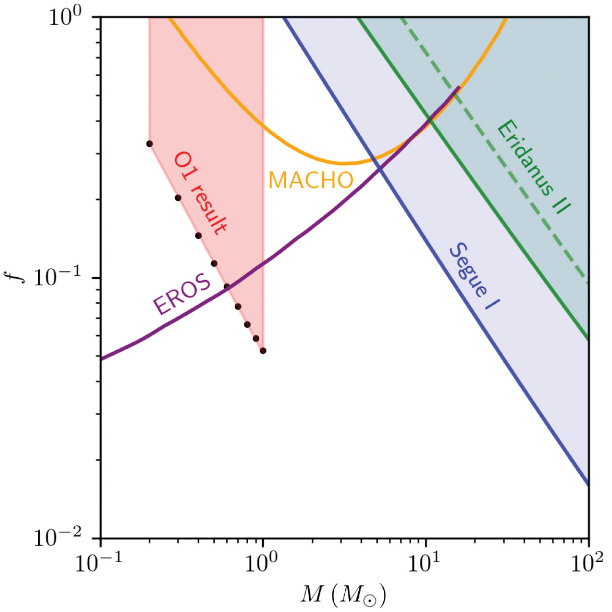

FIG. 3. Constraints on the fraction of dark matter composed of primordial black holes for monochromatic distributions ($f = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$). Shown in black are the results for the nine mass bins considered in this search. For this model of primordial black hole formation, LIGO finds constraints tighter than those of the MACHO Collaboration [58] for all mass bins considered and tighter than the EROS Collaboration [59] for $m_i \in (0.7, 1.0) M_\odot$. The limits presented here also improve upon other constraints at this mass [60]. The curves shown in this figure are digitizations of the original results from Refs. [58,59,61,62]. We use the Planck "TT, TE, EE + lowP + lensing + ext" cosmology [63].

Ref. [47]. The nondetection of a stochastic background in 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 nondetection of a stochastic background yields constraints that are about a factor of 2 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 [64–66]. While the results presented here to not take into account other effects on the binary parameters [67], 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 candidates were found. Therefore, we were able to constrain the binary merger rate for monochromatic mass functions spanning from 0.2 $M_\odot$–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 nonspinning 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 3 over the next several years [69]. Furthermore, at least a factor of 10 more data will be available than what were 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.

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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. Flaminio,[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. Giardina,[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. Kemball,[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. Muñiz,[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. Ogin,[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. Pürrer,[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. Zweizig[1]

(LIGO Scientific Collaboration and Virgo Collaboration)

S. Shandera[169]

[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]*OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[6]*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
[7]*Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, 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]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
[10]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[11]*NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[12]*University of Cambridge, Cambridge CB2 1TN, United Kingdom*
[13]*Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
[14]*LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[15]*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
[16]*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[17]*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[18]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[19]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[20]*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*
[21]*Università di Pisa, I-56127 Pisa, Italy*
[22]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[23]*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
[24]*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[25]*Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France*
[26]*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[27]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France*
[28]*California State University Fullerton, Fullerton, California 92831, USA*
[29]*APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France*
[30]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[31]*Chennai Mathematical Institute, Chennai 603103, India*
[32]*Università di Roma Tor Vergata, I-00133 Roma, Italy*
[33]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[34]*Universität Hamburg, D-22761 Hamburg, Germany*
[35]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[36]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[37]*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
[38]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany*
[39]*Korea Institute of Science and Technology Information, Daejeon 34141, Korea*

[40]*West Virginia University, Morgantown, West Virginia 26506, USA*
[41]*Università di Perugia, I-06123 Perugia, Italy*
[42]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[43]*Syracuse University, Syracuse, New York 13244, USA*
[44]*University of Minnesota, Minneapolis, Minnesota 55455, USA*
[45]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[46]*LIGO Hanford Observatory, Richland, Washington 99352, USA*
[47]*Caltech CaRT, Pasadena, California 91125, USA*
[48]*Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary*
[49]*University of Florida, Gainesville, Florida 32611, USA*
[50]*Stanford University, Stanford, California 94305, USA*
[51]*Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
[52]*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
[53]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[54]*MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary*
[55]*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
[56]*OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
[57]*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
[58]*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
[59]*Rochester Institute of Technology, Rochester, New York 14623, USA*
[60]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[61]*INFN, Sezione di Genova, I-16146 Genova, Italy*
[62]*RRCAT, Indore, Madhya Pradesh 452013, India*
[63]*Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[64]*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
[65]*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands*
[66]*Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France*
[67]*Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[68]*Univ Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France*
[69]*Washington State University, Pullman, Washington 99164, USA*
[70]*University of Oregon, Eugene, Oregon 97403, USA*
[71]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France*
[72]*Università degli Studi di Urbino 'Carlo Bo,' I-61029 Urbino, Italy*
[73]*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
[74]*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
[75]*VU University Amsterdam, 1081 HV Amsterdam, Netherlands*
[76]*University of Maryland, College Park, Maryland 20742, USA*
[77]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
[78]*Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*
[79]*Università di Napoli 'Federico II,' Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy*
[80]*NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[81]*Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy*
[82]*RESCEU, University of Tokyo, Tokyo, 113-0033, Japan*
[83]*Tsinghua University, Beijing 100084, China*
[84]*Texas Tech University, Lubbock, Texas 79409, USA*
[85]*Kenyon College, Gambier, Ohio 43022, USA*
[86]*The University of Mississippi, University, Mississippi 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, Pennsylvania 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, Illinois 60208, USA*
[92]*University of Chicago, Chicago, Illinois 60637, USA*
[93]*Pusan National University, Busan 46241, Korea*
[94]*Carleton College, Northfield, Minnesota 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, California 94928, USA*
[102]*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
[103]*Columbia University, New York, New York 10027, USA*
[104]*Montana State University, Bozeman, Montana 59717, USA*
[105]*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
[106]*University of Rhode Island, Kingston, Rhode Island 02881, USA*
[107]*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
[108]*Bellevue College, Bellevue, Washington 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, California 90032, USA*
[112]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[113]*Montclair State University, Montclair, New Jersey 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]*Observatori Astronòmic, 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, Michigan 48109, USA*
[124]*Abilene Christian University, Abilene, Texas 79699, USA*
[125]*American University, Washington, DC 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, Washington 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 Universtiy, Ithaca, New York 14850, USA*
[137]*Hillsdale College, Hillsdale, Michigan 49242, USA*
[138]*Hanyang University, Seoul 04763, Korea*
[139]*NASA Marshall Space Flight Center, Huntsville, Alabama 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, Louisiana 70813, USA*
[144]*College of William and Mary, Williamsburg, Virginia 23187, USA*
[145]*Centre Scientifique de Monaco, 8 quai Antoine Ier, 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, Washington 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, New York 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, Washington 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, Pennsylvania 19085, USA*
[164]*Andrews University, Berrien Springs, Michigan 49104, USA*
[165]*Università di Siena, I-53100 Siena, Italy*
[166]*Trinity University, San Antonio, Texas 78212, USA*
[167]*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands*
[168]*Colorado State University, Fort Collins, Colorado 80523, USA*
[169]*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

[†] Deceased.

[‡] Corresponding author.lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it