Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO’s Second Observing Run

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

Phys. Rev. Lett. **123**, 161102 — Published 18 October 2019

DOI: 10.1103/PhysRevLett.123.161102

Search for sub-solar mass ultracompact binaries in Advanced LIGO's second observing run

The LIGO Scientific Collaboration and The Virgo Collaboration

(Dated: August 7, 2019)

We present a search for sub-solar mass ultracompact objects in data obtained during Advanced LIGO's second observing run. In contrast to a previous search of Advanced LIGO data from the first observing run, this search includes the effects of component spin on the gravitational waveform. We identify no viable gravitational wave candidates consistent with sub-solar mass ultracompact binaries with at least one component between $0.2 - 1.0\,M_\odot$. We use the null result to constrain the binary merger rate of $(0.2\,M_\odot,\,0.2\,M_\odot)$ binaries to be less than 3.7×10^5 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ and the binary merger rate of $(1.0\,M_\odot,\,1.0\,M_\odot)$ binaries to be less than 5.2×10^3 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. Sub-solar mass ultracompact objects are not expected to form via known stellar evolution channels, though it has been suggested that primordial density fluctuations or particle dark matter with cooling mechanisms and/or nuclear interactions could form black holes with sub-solar masses. Assuming a particular primordial black hole formation model, we constrain a population of merging $0.2\,M_\odot$ black holes to account for less than 16% of the dark matter density and a population of merging $1.0\,M_\odot$ black holes to account for less than 2% of the dark matter density. We discuss how constraints on the merger rate and dark matter fraction may be extended to arbitrary black hole population models that predict sub-solar mass binaries.

INTRODUCTION

Gravitational wave and multi-messenger astronomy progressed remarkably in Advanced LIGO [1] and Advanced Virgo's [2] second observing run, which included the first observation of gravitational waves from a binary neutron star merger [3] and seven of the ten observed binary black hole mergers [4–7]. These detections, as well as the candidates presented in the gravitational wave transient catalog (GWTC-1) [7], have led to a better understanding of the populations of compact binaries detectable by ground based interferometers [8]. These observations, however, represent just a portion of the parameter space that Advanced LIGO and Advanced Virgo currently search [9, 10] and are sensitive to [11]. We report on an extension of the searched parameter space in data obtained during O2 to compact binaries with component masses $< 1\,M_\odot$. To distinguish between other astrophysical compact objects (e.g. white dwarfs) that are not compact enough to form binaries that merge within LIGO's sensitive frequency band, we label our target population as *ultracompact.* This is the second search for sub-solar mass ultracompact objects in Advanced LIGO data and the fourth since initial LIGO [12–14], as well as the first search to incorporate spin effects in the modeling of the gravitational wave emission.

There is no widely accepted mechanism for the formation of ultracompact objects with masses well below a solar mass within the standard model of particle physics and the standard ΛCDM model of cosmology. Neutron stars are expected to have masses greater than the minimum Chandrasekhar mass [15] minus the gravitational binding energy. Calculations by [16] and more recently [17] found the minimum mass of a neutron star to be $1.15\,M_\odot$ and $1.17\,M_\odot$, respectively. These predictions closely agree with the lowest currently measured neutron star mass of $1.17\,M_\odot$ [18]. Similarly, black holes formed via established astrophysical collapse mechanisms are not expected to have masses below the maximum mass of a non-rotating neutron star, which recent pulsar timing observations [19] suggest is $\sim 2\,M_\odot$. We note that there is one model that predicts that rapidly rotating collapsing cores could fission and produce a neutron star binary [20, 21], though this is not a favored astrophysical mechanism for the production of binary systems.

A detection of a sub-solar mass object in a merger would therefore be a clear signal of new physics. Indeed, there are several proposals that link sub-solar mass compact objects to proposals for the nature of dark matter, which makes up nearly 85% of the matter in the Universe. One possibility is that black holes with masses accessible to ground based interferometers could have formed deep in the radiation era from the prompt collapse of large primordial over-densities on the scale of the early time Hubble volume [22, 23]. The size and abundance of any such primordial black holes depends on the spectrum of primordial perturbations and on the equation of state of the early universe [24–27]. An alternative inflationary mechanism proposes that vacuum bubbles nucleated during inflation may result in black holes (with masses that can be around a solar mass) after inflation ends [28].

A different class of possibilities, explored more recently, is motivated by ideas for the particle nature of dark matter. For example, dark matter may have a sufficiently complex particle spectrum to support cooling mechanisms that allow dense regions to collapse into black holes at late times, in processes analogous to known astrophysical processes [29]. Alternatively, dark matter may have interactions with nuclear matter that allow it to collect inside of neutron stars and trigger their collapse to black holes [30–36]. The details of when dark matter can collapse a neutron star to form a black hole or other exotic compact object are still under investigation [37], but the postulated black holes will have masses comparable to the progenitor neutron star mass, or perhaps smaller if some matter can be expelled by rapid rotation of the star during collapse.

A detection of a sub-solar mass black hole would have far-reaching implications. In the primordial black hole scenario, the mass and abundance of the black holes would constrain a combination of the spectrum of initial density perturbations on very small scales and the equation of state of the Universe at a time when the typical mass inside a Hubble volume was of the order of the black hole mass. For particle dark matter scenarios, the abundance of sub-solar mass black holes would provide a direct estimate of the cooling rate for dark matter. The black hole mass would constrain the masses of cosmologically abundant dark matter particles through, for example, the Chandrasekhar relation for fermions [29] or analogous relations for non-interacting bosons [38, 39]. In the case that all black holes are observed to be near but not below the mass of neutron stars, the abundance of such objects would constrain the dark matter-nucleon interaction strength, as well as the dark matter self-interaction strength and mass(es) [36].

This letter reports the results of a search for gravitational waves from sub-solar mass ultracompact binaries using data from Advanced LIGO's second observing run. No significant candidates consistent with a sub-solar mass binary were identified. The null result places the tightest constraints to date on the merger rate and abundance of sub-solar mass ultracompact binaries. We describe an extension of our merger rate constraints to arbitrary populations and models under the assumption that the horizon distance controls the sensitivity of the search. We once more consider the merger rate constraints in the context of merging primordial black hole populations contributing to the dark matter [14]. We describe how to extend the dark matter fraction parameterization to other models by separating LIGO observables from model dependent quantities. Finally, we conclude with a discussion of the implications of this search.

SEARCH

We analyze data obtained from November 30, 2016 to August 25, 2017 during Advanced LIGO's second observing run (O2).[1] Noise artifacts are linearly subtracted from the data; this includes strong sinusoidal features in both detectors due to injected calibration frequencies and the AC power grid, as well as laser beam jitter in the LIGO-Hanford detector data [40]. 117.53 days of coincident data remain after the application of data quality cuts [41–45]. The Advanced Virgo interferometer completed commissioning and joined Advanced LIGO in August 2017 for 15 days of triple coincident observation [7], however, we only report on the analysis of data obtained by the LIGO Hanford and LIGO Livingston interferometers.

The search was conducted using publicly available gravitational-wave analysis software [46–52]. The initial stage of the search performed a matched-filter analysis using a discrete bank of template waveforms generated using the TaylorF2 frequency-domain, post-Newtonian inspiral approximant. This waveform was chosen since negligible power is deposited in the merger and ringdown portion of the waveform for low-mass systems [53]. The template bank used for this search was designed to recover binaries with component masses of $0.19 - 2.0\,M_\odot$ and total masses of $0.4 - 4.0\,M_\odot$ in the detector frame with 97% fidelity, as in [14]. The search presented here, however, additionally includes spin effects in the modeling of the gravitational waveform. The bank is constructed to recover gravitational waves originating from binaries with component spins purely aligned or anti-aligned with the orbital angular momentum, and with dimensionless spin magnitudes of 0.1 or less. The inclusion of spin effects required denser placement of the waveforms in the template bank; the resulting bank had 992 461 templates, which is nearly twice as large as the non-spinning bank used in [14].

In order to reduce the computational burden, matched filtering was only performed for a subset of Advanced LIGO's full sensitive band [11]. The choice to only analyze the 45–1024 Hz band led to a detector averaged signal-to-noise ratio (SNR) loss of 8% when compared to the full $\sim 10 - 2048$Hz frequency band. This estimated SNR loss is a property of Advanced LIGO's noise curves and is independent of the templates used in the search; the discrete nature of the template bank causes an additional $\lesssim 3\%$ loss in SNR.

Gravitational-wave candidates that were found coincident in both the Hanford and Livingston detectors were ranked using the logarithm of the likelihood-ratio , $\mathcal{L}$ [46–48]. For a candidate with a likelihood-ratio of $\mathcal{L}^*$, we assign a false-alarm-rate of

$$\mathrm{FAR}(\log \mathcal{L}^*) = \frac{N}{T} P\left(\log \mathcal{L} \geq \log \mathcal{L}^* | \mathrm{noise}\right), \qquad (1)$$

where N is the number of observed candidates, T is the total live time of the experiment, and $P\left(\log \mathcal{L} \geq \log \mathcal{L}^* | \mathrm{noise}\right)$ describes the probability that noise produces a candidate with a ranking statistic at least as high as the candidate's.

---

[1] Data from Advanced LIGO's second observing run is available from the Gravitational Wave Open Science Center with and without noise sources linearly subtracted: `https://www.gw-openscience.org`

The search recovered the previously detected signal GW170817 [3], which was observed along with an electromagnetic counterpart [54]. This signal is consistent with a binary neutron star. No other viable gravitational wave candidates were identified. The next loudest candidate was identified by a template waveform with a chirp mass of $0.23\,M_\odot$ and a SNR of 9.5. The candidate was consistent with noise and assigned a FAR of 3.25 per year.

CONSTRAINT ON BINARY MERGER RATE

As in [14], we consider nine populations of equal mass, non-spinning binaries that are delta-function distributed in mass, i.e. $m_i \in \{0.2, 0.3, \ldots, 1.0\}$. We injected 913 931 fake signals into our data; the injections were randomly oriented and spaced uniformly in distance and isotropically across the sky. The recovered signals provide an estimate of the pipeline's detection efficiency as a function of source distance for each equal mass population. This in turn allows us to estimate the sensitive volume-time accumulated for each mass bin. We once more use the loudest event statistic formalism [55] to estimate the upper limit on the binary merger rate to 90% confidence,

$$\mathcal{R}_i = \frac{2.3}{\langle VT \rangle_i} \tag{2}$$

These upper limits are shown for equal mass binaries and as a function of chirp mass in Fig. 1. Although our template bank includes systems with total mass up to $4\,M_\odot$, we only place bounds on the merger rate of systems where both components are $\leq 1\,M_\odot$. We estimate that detector calibration uncertainties [7, 56, 57] and Monte Carlo errors lead to an uncertainty in our rate constraint of no more than 20%.

Advanced LIGO and Virgo's horizon distance scales as:

$$D_{\text{horizon}} \propto \mathcal{M}^{5/6} \sqrt{\int_{f_{\min}}^{f_{\max}} \frac{f^{-7/3}}{S_n(f)}\, df} \tag{3}$$

where $S_n(f)$ is the noise spectra of the detector and $f_{\min}$ and $f_{\max}$ are 45 Hz and 1024 Hz, respectively.[2] For a null result, we therefore expect $\mathcal{R}(\mathcal{M}) \propto \mathcal{M}^{-15/6}$ provided the horizon distance controls the sensitivity of the search. The observed power law dependence of the rate constraint on the chirp mass is within $\sim 4\%$ of the expected $\mathcal{M}^{-15/6}$ dependence; this is well within the error bound on the rate upper limit and is strong evidence that the chirp mass is the primary parameter that dictates the sensitivity of the search. Therefore our upper limits from equal mass systems also apply to unequal mass systems within the range of mass ratios we have searched over. For verification, we performed a small injection campaign over five days of coincident data with injected component masses distributed between $0.19\,M_\odot$ and $2.0\,M_\odot$ with at least one component $< 1.0\,M_\odot$. The search sensitivity remained a function of the chirp mass; this implies that the rate constraints found from the equal mass injection sets can therefore be applied to systems with arbitrary mass ratios provided that both component masses lie within $0.20\,M_\odot$ and $1.0\,M_\odot$ where our injection sets were performed.

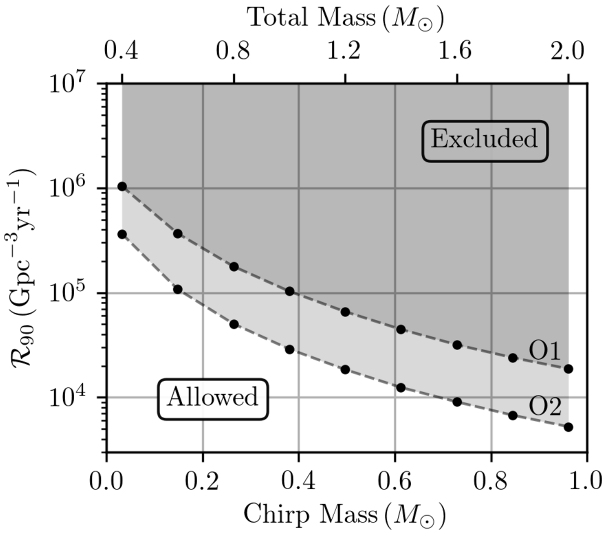

FIG. 1. The constraint on the merger rate density for equal mass binaries as a function of total mass (top) and chirp mass (bottom). The two sets of lines show the constraints for the O1 search [14] and the O2 search presented here. The null result from O2 places bounds that are ~ 3 times tighter than the O1 results. The majority of this improvement is due to the increased coincident observing time in Advanced LIGO's second observing run ($\sim$ 118 days vs. $\sim$ 48 days), though the improved sensitivity of the detectors led to an observed physical volume up to $\sim 50\%$ larger than in O1 for sub-solar mass ultracompact binaries.

The Advanced LIGO and Virgo rate upper limit can be expanded as:

$$\mathcal{R}(\mathcal{M}_1, \mathcal{M}_2) = \int_{\mathcal{M}_1}^{\mathcal{M}_2} \mathcal{R}(\mathcal{M}) \times \psi(\mathcal{M})\, \mathrm{d}\mathcal{M} \tag{4}$$

where $\mathcal{R}$ is the rate density as a function of chirp mass and $\psi(\mathcal{M})$ denotes the black hole population distribution in chirp mass. We ignore the effects of redshift due to the small detector range for sub-solar mass binaries. Setting $\psi(\mathcal{M}) = \delta(\mathcal{M})$ then reveals the form of the LIGO

---

[2] The waveform model used to generate our template bank, TaylorF2, truncates the waveform at an upper frequency f_{ISCO}, which corresponds to radiation from the innermost stable circular orbit of a black hole binary with mass M_{total}. This frequency is above $f_{\max}$ for all non-spinning waveforms in our template bank and so does not impact D_{horizon}.

constraining rate density, $\mathcal{R}(\mathcal{M})$, which is shown in Figure 1. For a given model, $\psi(\mathcal{M})$, $\mathcal{R}(\mathcal{M}_1, \mathcal{M}_2)$ provides the LIGO rate constraint on that model for chirp masses between $\mathcal{M}_1$ and $\mathcal{M}_2$. The resulting rate constraints allow direct comparison of sub-solar mass ultracompact object models with LIGO observations.

GENERAL CONSTRAINTS ON SUB-SOLAR MASS BLACK HOLE DARK MATTER

We convert our limits on the merger rate of sub-solar mass ultracompact objects into a constraint on the abundance of primordial black holes using our fiducial formation model [58] first developed in [23, 59] and used previously in LIGO analyses [12, 14]. We consider a population of equal mass primordial black holes that is created deep in the radiation era. We model the binary formation via three-body interactions, though others have considered the full field of tidal interactions [60]. By equating the model's predicted merger rate with the merger rate upper limit provided by Advanced LIGO and Virgo, we can numerically solve for the upper limit on the PBH abundance. These constraints are shown in Figure 2.[3]

This interpretation is highly model dependent; the mass distribution, binary fraction, and binary formation mechanisms all have a large effect on the expected present day merger rate and consequently the bounds on the primordial black hole composition of the dark matter. The Advanced LIGO and Virgo observables can be separated from the model dependent terms:

$$f_{\mathrm{CO}} = \frac{\rho_{\mathrm{lim}}}{\rho_{\mathrm{CDM}}} \times \frac{1}{f_{\mathrm{obs}}} = \frac{\mathcal{R}(M_{\mathrm{tot}})\, T_{\mathrm{obs}}\, M_{\mathrm{tot}}}{\rho_{\mathrm{CDM}}} \times \frac{1}{f_{\mathrm{obs}}}. \quad (5)$$

where T_{obs} is the duration of the observation (in the analysis presented here, 117.53 days). Here we use f_{CO} to refer to the dark matter fraction in ultracompact objects instead of f_{PBH} to emphasize that this is generally applicable to other compact object models that could contribute to the dark matter [29], and not just PBHs. The first term, $\rho_{\mathrm{lim}}/\rho_{\mathrm{CDM}}$, represents the upper limit on the fraction of the dark matter contained in presently merging sub-solar mass ultracompact binaries. In the second term, f_{obs} describes the fraction of sub-solar mass ultracompact objects that are observable by Advanced LIGO and Virgo for a particular model. This is set by the binary fraction and the probability density of binaries merging at present day. Note that the merger rate density must be converted from a function of chirp mass to total mass; this can be done by mapping to total mass for each mass ratio on an equal chirp mass curve.

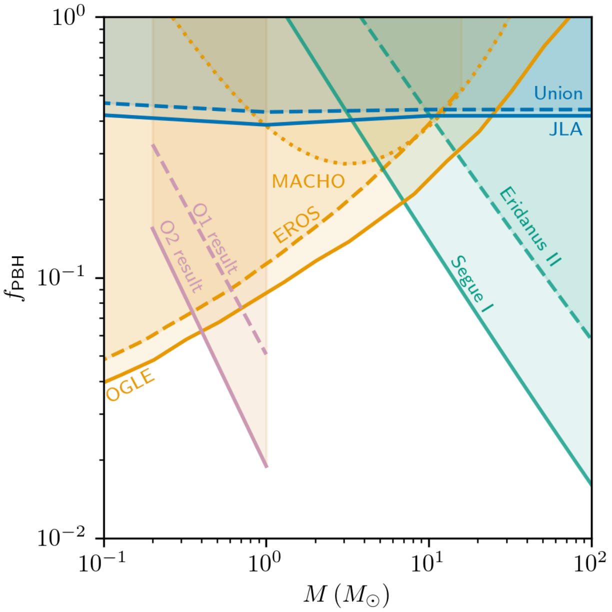

FIG. 2. Constraints on the fraction of dark matter comprised of delta-function distributions of primordial black holes ($f_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$). Shown here are (pink) Advanced LIGO constraints from the O1 (dashed) and O2 ultracompact binary search presented here (solid), (orange) microlensing constraints provided by the OGLE (solid), EROS (dashed) [61], and MACHO (dotted) collaborations [62], (cyan) dynamical constraints from observations of Segue I (solid) [63] and Eridanus II (dashed) [64] dwarf galaxies, and (blue) supernova lensing constraints from the Joint Light-curve Analysis (solid) and Union 2.1 (dashed) datasets [65]. There is an inherent population model dependency in each of these constraints. Advanced LIGO and Advanced Virgo results carry an additional dependence on the binary fraction of the black hole population. Advanced LIGO and Advanced Virgo results use the Planck "TT,TE,EE+lowP+lensing+ext" cosmology [66].

Equation (5) applies to any dark matter model that predicts the formation of dark compact objects. The abundance of those dark compact objects can then be expressed as a fraction of the dark matter density.

CONCLUSION

We have presented the second Advanced LIGO and Advanced Virgo search for sub-solar mass ultracompact objects. No unambiguous sub-solar mass gravitational wave candidates were identified. The null result allows us to place tight constraints on the abundance of sub-solar mass ultracompact binaries.

This work represents an expansion of previous initial and Advanced LIGO and Advanced Virgo sub-solar mass

---

[3] The normalization of the PBH distribution used in our fiducial model [58] differs by a factor of 2 from the normalization in [23]. As such, our fiducial model (used here and in [14]) predicts a more conservative PBH merger rate and leads to less constraining limits on f_{PBH} than would be attained using the model of [23].

searches. First, we have broadened the searched parameter space to increase sensitivity to systems with non-negligible component spins. Second, we have presented a method to extend our constraints on the binary merger rate to arbitrarily distributed populations that contain sub-solar mass ultracompact objects. Combined with the existing rate limits, this may already be enough to begin constraining collapsed particulate dark matter models [29] or the cross section of nuclear interactions [30–34, 36]. Finally, we have provided a method to separate Advanced LIGO and Advanced Virgo observables from model dependent terms in our interpretation of the limits on primordial black hole dark matter.

Ground based interferometer searches for sub-solar mass ultracompact objects will continue to inform cosmological and particle physics scenarios. Advanced LIGO and Advanced Virgo have begun a year long observing run in early 2019, with improved sensitivities [67]. Advanced Virgo will have more coincident time with the Advanced LIGO detectors over its next observing run, which will improve network sensitivity and aid in further constraining the above scenarios.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, 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. Computing resources and personnel for this project were provided by the Pennsylvania State University. This article has been assigned the document number LIGO-P1900037.

[1] J. Aasi et al. Advanced LIGO. *Class. Quant. Grav.*, 32:074001, 2015.

[2] F. Acernese et al. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Class. Quant. Grav.*, 32(2):024001, 2015.

[3] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, 2017.

[4] 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.

[5] B.. P.. Abbott et al. GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence. *Astrophys. J.*, 851(2):L35, 2017.

[6] 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.

[7] B. P. Abbott et al. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Preprint: arXiv 1811.12907*, 2018.

[8] B. P. Abbott et al. Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo. 2018.

[9] Tito Dal Canton and Ian W. Harry. Designing a template bank to observe compact binary coalescences in Advanced LIGO's second observing run. *Preprint: arXiv 1705.01845*, 2017.

[10] Debnandini Mukherjee, Sarah Caudill, Ryan Magee, Cody Messick, Stephen Privitera, Surabhi Sachdev, Kent Blackburn, Patrick Brady, Patrick Brockill, Kipp Cannon, Sydney J. Chamberlin, Deep Chatterjee, Jolien D. E. Creighton, Heather Fong, Patrick Godwin, Chad Hanna, Shasvath Kapadia, Ryan N. Lang, Tjonnie G. F. Li, Rico K. L. Lo, Duncan Meacher, Alex Pace, Laleh Sadeghian, Leo Tsukada, Leslie Wade, Madeline Wade, Alan Weinstein, and Liting Xiao. The GstLAL template bank for spinning compact binary mergers in the second observation run of Advanced LIGO and Virgo. *Preprint: arXiv 1812.05121*, Dec 2018.

[11] 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 subsolar mass ultracompact binaries. *Phys. Rev.*, D98(10):103024, 2018.

[12] B. Abbott et al. Search for gravitational waves from primordial black hole binary coalescences in the galactic halo. *Phys. Rev.*, D72:082002, 2005.

[13] B. Abbott et al. Search for gravitational waves from binary inspirals in S3 and S4 LIGO data. *Phys. Rev.*, D77:062002, 2008.

[14] B. P. Abbott et al. Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 121(23):231103, 2018.

[15] Subrahmanyan Chandrasekhar. The maximum mass of ideal white dwarfs. *Astrophys. J.*, 74:81–82, 1931.

[16] F. X. Timmes, S. E. Woosley, and Thomas A. Weaver. The Neutron star and black hole initial mass function. *Astrophys. J.*, 457:834, 1996.

[17] Yudai Suwa, Takashi Yoshida, Masaru Shibata, Hideyuki Umeda, and Koh Takahashi. On the minimum mass of neutron stars. *Mon. Not. Roy. Astron. Soc.*, 481(3):3305–3312, 2018.

[18] 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.

[19] John Antoniadis, Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, and David G. Whelan. A massive pulsar in a compact relativistic binary. *Science*, 340(6131), 2013.

[20] V. S. Imshennik. A possible scenario of a supernova explosion as a result of the gravitational collapse of a massive stellar core. *Soviet Astronomy Letters*, 18:194, June 1992.

[21] Melvyn B. Davies, Andrew King, Stephan Rosswog, and Graham Wynn. Gamma-ray bursts, supernova kicks, and gravitational radiation. *Astrophys. J.*, 579:L63–L66, 2002.

[22] Bernard J. Carr. The Primordial black hole mass spectrum. *Astrophys. J.*, 201:1–19, 1975.

[23] Takashi Nakamura, Misao Sasaki, Takahiro Tanaka, and Kip S Thorne. Gravitational waves from coalescing black hole macho binaries. *The Astrophysical Journal Letters*, 487(2):L139, 1997.

[24] Karsten Jedamzik. Primordial black hole formation during the QCD epoch. *Phys. Rev.*, D55:5871–5875, 1997.

[25] Peter Widerin and Christoph Schmid. Primordial black holes from the QCD transition? *Preprint: arXiv astro-ph/9808142*, 1998.

[26] Julian Georg and Scott Watson. A Preferred Mass Range for Primordial Black Hole Formation and Black Holes as Dark Matter Revisited. *JHEP*, 09:138, 2017.

[27] Christian T. Byrnes, Mark Hindmarsh, Sam Young, and Michael R. S. Hawkins. Primordial black holes with an accurate QCD equation of state. *JCAP*, 1808(08):041, 2018.

[28] Heling Deng and Alexander Vilenkin. Primordial black hole formation by vacuum bubbles. *JCAP*, 1712(12):044, 2017.

[29] Sarah Shandera, Donghui Jeong, and Henry S. Grasshorn Gebhardt. Gravitational Waves from Binary Mergers of Subsolar Mass Dark Black Holes. *Phys. Rev. Lett.*, 120(24):241102, 2018.

[30] Chris Kouvaris and Peter Tinyakov. Constraining Asymmetric Dark Matter through observations of compact stars. *Phys. Rev.*, D83:083512, 2011.

[31] Arnaud de Lavallaz and Malcolm Fairbairn. Neutron Stars as Dark Matter Probes. *Phys. Rev.*, D81:123521, 2010.

[32] Itzhak Goldman and Shmuel Nussinov. Weakly interacting massive particles and neutron stars. *Phys. Rev. D*, 40:3221–3230, Nov 1989.

[33] Joseph Bramante and Fatemeh Elahi. Higgs portals to pulsar collapse. *Phys. Rev.*, D91(11):115001, 2015.

[34] Joseph Bramante and Tim Linden. Detecting Dark Matter with Imploding Pulsars in the Galactic Center. *Phys. Rev. Lett.*, 113(19):191301, 2014.

[35] Joseph Bramante, Tim Linden, and Yu-Dai Tsai. Searching for dark matter with neutron star mergers and quiet kilonovae. *Phys. Rev.*, D97(5):055016, 2018.

[36] Chris Kouvaris, Peter Tinyakov, and Michel H. G. Tytgat. NonPrimordial Solar Mass Black Holes. *Phys. Rev. Lett.*, 121(22):221102, 2018.

[37] Moira I. Gresham and Kathryn M. Zurek. Asymmetric Dark Stars and Neutron Star Stability. *Phys. Rev.*, D99(8):083008, 2019.

[38] J. D. Breit, S. Gupta, and A. Zaks. Cold Bose stars. *Physics Letters B*, 140:329–332, June 1984.

[39] L. A. Urena-Lopez, T. Matos, and R. Becerril. Inside oscillatons. *Class. Quant. Grav.*, 19:6259–6277, 2002.

[40] D. Davis, T.J. Massinger, et al. Improving the Sensitivity of Advanced LIGO Using Noise Subtraction. *Preprint: arXiv 1809.05348*, 2018.

[41] 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.

[42] B. P. Abbott et al. Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914. *Class. Quant. Grav.*, 33(13), 2016.

[43] 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.

[44] L.K. Nuttall. Characterizing transient noise in the LIGO detectors. *Royal Society Proceedings A*, 376(2120), 2018.

[45] B.K. Berger. Identification and mitigation of Advanced LIGO noise sources. *J. Phys.: Conf. Ser.*, 957(012004), 2018.

[46] Kipp Cannon et al. Toward Early-Warning Detection of Gravitational Waves from Compact Binary Coalescence. *Astrophys. J.*, 748:136, 2012.

[47] Cody Messick et al. Analysis Framework for the Prompt Discovery of Compact Binary Mergers in Gravitational-wave Data. *Phys. Rev.*, D95(4):042001, 2017.

[48] Surabhi Sachdev et al. The GstLAL Search Analysis Methods for Compact Binary Mergers in Advanced LIGO's Second and Advanced Virgo's First Observing Runs. *Preprint: arXiv 1901.08580*, 2019.

[49] GstLAL software: git.ligo.org/lscsoft/gstlal.

[50] LAL software: git.ligo.org/lscsoft/lalsuite.

[51] 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.

[52] 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.

[53] Alessandra Buonanno, Bala R. Iyer, Evan Ochsner, Yi Pan, and B. S. Sathyaprakash. Comparison of post-Newtonian templates for compact binary inspiral signals in gravitational-wave detectors. *Phys. Rev. D*, 80:084043, October 2009.

[54] B. P. Abbott et al. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophys. J.*, 848(2):L12, 2017.

[55] 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)].

[56] Craig Cahillane, Joe Betzwieser, Duncan A. Brown, Evan Goetz, Evan D. Hall, Kiwamu Izumi, Shivaraj Kand hasamy, Sudarshan Karki, Jeff S. Kissel, Greg Mendell, Richard L. Savage, Darkhan Tuyenbayev, Alex Urban, Aaron Viets, Madeline Wade, and Alan J. Weinstein. Calibration uncertainty for Advanced LIGO's first and second observing runs. *Phys. Rev. D*, 96:102001, Nov 2017.

[57] Aaron Viets et al. Reconstructing the calibrated strain signal in the Advanced LIGO detectors. *Class. Quant. Grav.*, 35(9):095015, 2018.

[58] 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.

[59] 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.

[60] Yacine Ali-Haïmoud, Ely D. Kovetz, and Marc Kamionkowski. Merger rate of primordial black-hole binaries. *Phys. Rev.*, D96(12):123523, 2017.

[61] 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.

[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] 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.

[64] Timothy D. Brandt. Constraints on MACHO Dark Matter from Compact Stellar Systems in Ultra-Faint Dwarf Galaxies. *Astrophys. J.*, 824(2):L31, 2016.

[65] Miguel Zumalacarregui and Uros Seljak. Limits on stellar-mass compact objects as dark matter from gravitational lensing of type Ia supernovae. *Phys. Rev. Lett.*, 121(14):141101, 2018.

[66] P. A. R. Ade et al. Planck 2015 results. XIII. Cosmological parameters. *Astron. Astrophys.*, 594:A13, 2016.

[67] 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] S. Abraham,[3] F. Acernese,[4,5] K. Ackley,[6] C. Adams,[7] R. X. Adhikari,[1] V. B. Adya,[8] C. Affeldt,[9,10] M. Agathos,[11,12] K. Agatsuma,[13] N. Aggarwal,[14] O. D. Aguiar,[15] L. Aiello,[16,17] A. Ain,[3] P. Ajith,[18] G. Allen,[19] A. Allocca,[20,21] M. A. Aloy,[22] P. A. Altin,[8] A. Amato,[23] S. Anand,[1] A. Ananyeva,[1] S. B. Anderson,[1] W. G. Anderson,[24] S. V. Angelova,[25] S. Antier,[26] S. Appert,[1] K. Arai,[1] M. C. Araya,[1] J. S. Areeda,[27] M. Arène,[26] N. Arnaud,[28,29] S. M. Aronson,[30] K. G. Arun,[31] S. Ascenzi,[16,32] G. Ashton,[6] S. M. Aston,[7] P. Astone,[33] F. Aubin,[34] P. Aufmuth,[10] K. AultONeal,[35] C. Austin,[2] V. Avendano,[36] A. Avila-Alvarez,[27] S. Babak,[26] P. Bacon,[26] F. Badaracco,[16,17] M. K. M. Bader,[37] S. Bae,[38] J. Baird,[26] P. T. Baker,[39] F. Baldaccini,[40,41] G. Ballardin,[29] S. W. Ballmer,[42] A. Bals,[35] S. Banagiri,[43] J. C. Barayoga,[1] C. Barbieri,[44,45] S. E. Barclay,[46] B. C. Barish,[1] D. Barker,[47] K. Barkett,[48] S. Barnum,[14] F. Barone,[49,5] B. Barr,[46] L. Barsotti,[14] M. Barsuglia,[26] D. Barta,[50] J. Bartlett,[47] I. Bartos,[30] R. Bassiri,[51] A. Basti,[20,21] M. Bawaj,[52,41] J. C. Bayley,[46] M. Bazzan,[53,54] B. Bécsy,[55] M. Bejger,[26,56] I. Belahcene,[28] A. S. Bell,[46] D. Beniwal,[57] M. G. Benjamin,[35] B. K. Berger,[51] G. Bergmann,[9,10] S. Bernuzzi,[11] C. P. L. Berry,[58] D. Bersanetti,[59] A. Bertolini,[37] J. Betzwieser,[7] R. Bhandare,[60] J. Bidler,[27] E. Biggs,[24] I. A. Bilenko,[61] S. A. Bilgili,[39] G. Billingsley,[1] R. Birney,[25] O. Birnholtz,[62] S. Biscans,[1,14] M. Bischi,[63,64] S. Biscoveanu,[14] A. Bisht,[10] M. Bitossi,[29,21] M. A. Bizouard,[65] J. K. Blackburn,[1] J. Blackman,[48] C. D. Blair,[7] D. G. Blair,[66] R. M. Blair,[47] S. Bloemen,[67] F. Bobba,[68,69] N. Bode,[9,10] M. Boer,[65] Y. Boetzel,[70] G. Bogaert,[65] F. Bondu,[71] R. Bonnand,[34] P. Booker,[9,10] B. A. Boom,[37] R. Bork,[1] V. Boschi,[29] S. Bose,[3] V. Bossilkov,[66] J. Bosveld,[66] Y. Bouffanais,[53,54] A. Bozzi,[29] C. Bradaschia,[21] P. R. Brady,[24] A. Bramley,[7] M. Branchesi,[16,17] J. E. Brau,[72] M. Breschi,[11] T. Briant,[73] J. H. Briggs,[46] F. Brighenti,[63,64] A. Brillet,[65] M. Brinkmann,[9,10] P. Brockill,[24] A. F. Brooks,[1] J. Brooks,[29] D. D. Brown,[57] S. Brunett,[1] A. Buikema,[14] T. Bulik,[74] H. J. Bulten,[75,37] A. Buonanno,[76,77] D. Buskulic,[34] C. Buy,[26] R. L. Byer,[51] M. Cabero,[9,10] L. Cadonati,[78] G. Cagnoli,[79] C. Cahillane,[1] J. Calderón Bustillo,[6] T. A. Callister,[1] E. Calloni,[80,5] J. B. Camp,[81] W. A. Campbell,[6,59] K. C. Cannon,[82] H. Cao,[57] J. Cao,[83] G. Carapella,[68,69] F. Carbognani,[29] S. Caride,[84] M. F. Carney,[58] G. Carullo,[20,21] J. Casanueva Diaz,[21] C. Casentini,[85,32] S. Caudill,[37] M. Cavaglià,[86,87] F. Cavalier,[28] R. Cavalieri,[29] G. Cella,[21] P. Cerdá-Durán,[22] E. Cesarini,[88,32] O. Chaibi,[65] K. Chakravarti,[3] S. J. Chamberlin,[89] M. Chan,[46] S. Chao,[90] P. Charlton,[91] E. A. Chase,[58] E. Chassande-Mottin,[26] D. Chatterjee,[24] M. Chaturvedi,[60] K. Chatziioannou,[92] B. D. Cheeseboro,[39] H. Y. Chen,[93] X. Chen,[66] Y. Chen,[48] H.-P. Cheng,[30] C. K. Cheong,[94] H. Y. Chia,[30] F. Chiadini,[95,69] A. Chincarini,[59] A. Chiummo,[29] G. Cho,[96] H. S. Cho,[97] M. Cho,[77] N. Christensen,[98,65] Q. Chu,[66] S. Chua,[73] K. W. Chung,[94] S. Chung,[66] G. Ciani,[53,54] M. Cieślar,[56] A. A. Ciobanu,[57] R. Ciolfi,[99,54] F. Cipriano,[65] A. Cirone,[100,59] F. Clara,[47] J. A. Clark,[78] P. Clearwater,[101] F. Cleva,[65] E. Coccia,[16,17] P.-F. Cohadon,[73] D. Cohen,[28] M. Colleoni,[102] C. G. Collette,[103] C. Collins,[13] M. Colpi,[44,45] L. R. Cominsky,[104] M. Constancio Jr.,[15] L. Conti,[54] S. J. Cooper,[13] P. Corban,[7] T. R. Corbitt,[2] I. Cordero-Carrión,[105] S. Corezzi,[40,41] K. R. Corley,[106] N. Cornish,[55] D. Corre,[28] A. Corsi,[84] S. Cortese,[29] C. A. Costa,[15] R. Cotesta,[76] M. W. Coughlin,[1] S. B. Coughlin,[107,58] J.-P. Coulon,[65] S. T. Countryman,[106] P. Couvares,[1] P. B. Covas,[102] E. E. Cowan,[78] D. M. Coward,[66] M. J. Cowart,[7] D. C. Coyne,[1] R. Coyne,[108] J. D. E. Creighton,[24] T. D. Creighton,[109] J. Cripe,[2] M. Croquette,[73] S. G. Crowder,[110] T. J. Cullen,[2] A. Cumming,[46] L. Cunningham,[46] E. Cuoco,[29] T. Dal Canton,[81] G. Dálya,[111] B. D'Angelo,[100,59] S. L. Danilishin,[9,10] S. D'Antonio,[32] K. Danzmann,[10,9] A. Dasgupta,[112] C. F. Da Silva Costa,[30] L. E. H. Datrier,[46] V. Dattilo,[29] I. Dave,[60] M. Davier,[28] D. Davis,[42] E. J. Daw,[113] D. DeBra,[51] M. Deenadayalan,[3] J. Degallaix,[23] M. De Laurentis,[80,5] S. Deléglise,[73] W. Del Pozzo,[20,21] L. M. DeMarchi,[58] N. Demos,[14] T. Dent,[114] R. De Pietri,[115,116] R. De Rosa,[80,5] C. De Rossi,[23,29] R. DeSalvo,[117] O. de Varona,[9,10] S. Dhurandhar,[3] M. C. Díaz,[109] T. Dietrich,[37] L. Di Fiore,[5] C. DiFronzo,[13] C. Di Giorgio,[68,69] F. Di Giovanni,[22] M. Di Giovanni,[118,119] T. Di Girolamo,[80,5] A. Di Lieto,[20,21] B. Ding,[103] S. Di Pace,[120,33] I. Di Palma,[120,33] F. Di Renzo,[20,21] A. K. Divakarla,[30] A. Dmitriev,[13] Z. Doctor,[93] F. Donovan,[14] K. L. Dooley,[107,86] S. Doravari,[3] I. Dorrington,[107] T. P. Downes,[24] M. Drago,[16,17] J. C. Driggers,[47] Z. Du,[83] J.-G. Ducoin,[28] P. Dupej,[46] O. Durante,[68,69] S. E. Dwyer,[47] P. J. Easter,[6] G. Eddolls,[46] T. B. Edo,[113] A. Effler,[7] P. Ehrens,[1] J. Eichholz,[8] S. S. Eikenberry,[30] M. Eisenmann,[34] R. A. Eisenstein,[14] L. Errico,[80,5] R. C. Essick,[93] H. Estelles,[102] D. Estevez,[34] Z. B. Etienne,[39] T. Etzel,[1] M. Evans,[14] T. M. Evans,[7] V. Fafone,[85,32,16] S. Fairhurst,[107] X. Fan,[83] S. Farinon,[59] B. Farr,[72] W. M. Farr,[13] E. J. Fauchon-Jones,[107] M. Favata,[36] M. Fays,[113] M. Fazio,[121] C. Fee,[122] J. Feicht,[1] M. M. Fejer,[51] F. Feng,[26] A. Fernandez-Galiana,[14] I. Ferrante,[20,21] E. C. Ferreira,[15] T. A. Ferreira,[15] F. Fidecaro,[20,21] I. Fiori,[29] D. Fiorucci,[16,17] M. Fishbach,[93] R. P. Fisher,[123] J. M. Fishner,[14] R. Fittipaldi,[124,69] M. Fitz-Axen,[43] V. Fiumara,[125,69] R. Flaminio,[34,126] M. Fletcher,[46] E. Floden,[43] E. Flynn,[27]

H. Fong,[82] J. A. Font,[22,127] P. W. F. Forsyth,[8] J.-D. Fournier,[65] Francisco Hernandez Vivanco,[6] S. Frasca,[120,33]
F. Frasconi,[21] Z. Frei,[111] A. Freise,[13] R. Frey,[72] V. Frey,[28] P. Fritschel,[14] V. V. Frolov,[7] G. Fronzè,[128] P. Fulda,[30]
M. Fyffe,[7] H. A. Gabbard,[46] B. U. Gadre,[76] S. M. Gaebel,[13] J. R. Gair,[129] L. Gammaitoni,[40] S. G. Gaonkar,[3]
C. García-Quirós,[102] F. Garufi,[80,5] B. Gateley,[47] S. Gaudio,[35] G. Gaur,[130] V. Gayathri,[131] G. Gemme,[59] E. Genin,[29]
A. Gennai,[21] D. George,[19] J. George,[60] L. Gergely,[132] S. Ghonge,[78] Abhirup Ghosh,[76] Archisman Ghosh,[37]
S. Ghosh,[24] B. Giacomazzo,[118,119] J. A. Giaime,[2,7] K. D. Giardina,[7] D. R. Gibson,[133] K. Gill,[106] L. Glover,[134]
J. Gniesmer,[135] P. Godwin,[89] E. Goetz,[47] R. Goetz,[30] B. Goncharov,[6] G. González,[2] J. M. Gonzalez Castro,[20,21]
A. Gopakumar,[136] S. E. Gossan,[1] M. Gosselin,[29,20,21] R. Gouaty,[34] B. Grace,[8] A. Grado,[137,5] M. Granata,[23]
A. Grant,[46] S. Gras,[14] P. Grassia,[1] C. Gray,[47] R. Gray,[46] G. Greco,[63,64] A. C. Green,[30] R. Green,[107]
E. M. Gretarsson,[35] A. Grimaldi,[118,119] S. J. Grimm,[16,17] P. Groot,[67] H. Grote,[107] S. Grunewald,[76] P. Gruning,[28]
G. M. Guidi,[63,64] H. K. Gulati,[112] Y. Guo,[37] A. Gupta,[89] Anchal Gupta,[1] P. Gupta,[37] E. K. Gustafson,[1]
R. Gustafson,[138] L. Haegel,[102] O. Halim,[17,16] B. R. Hall,[139] E. D. Hall,[14] E. Z. Hamilton,[107] G. Hammond,[46]
M. Haney,[70] M. M. Hanke,[9,10] J. Hanks,[47] C. Hanna,[89] M. D. Hannam,[107] O. A. Hannuksela,[94] T. J. Hansen,[35]
J. Hanson,[7] T. Harder,[65] T. Hardwick,[2] K. Haris,[18] J. Harms,[16,17] G. M. Harry,[140] I. W. Harry,[141] R. K. Hasskew,[7]
C. J. Haster,[14] K. Haughian,[46] F. J. Hayes,[46] J. Healy,[62] A. Heidmann,[73] M. C. Heintze,[7] H. Heitmann,[65]
F. Hellman,[142] P. Hello,[28] G. Hemming,[29] M. Hendry,[46] I. S. Heng,[46] J. Hennig,[9,10] M. Heurs,[9,10] S. Hild,[46]
T. Hinderer,[143,37,144] S. Hochheim,[9,10] D. Hofman,[23] A. M. Holgado,[19] N. A. Holland,[8] K. Holt,[7] D. E. Holz,[93]
P. Hopkins,[107] C. Horst,[24] J. Hough,[46] E. J. Howell,[66] C. G. Hoy,[107] Y. Huang,[14] M. T. Hübner,[6] E. A. Huerta,[19]
D. Huet,[28] B. Hughey,[35] V. Hui,[34] S. Husa,[102] S. H. Huttner,[46] T. Huynh-Dinh,[7] B. Idzkowski,[74] A. Iess,[85,32]
H. Inchauspe,[30] C. Ingram,[57] R. Inta,[84] G. Intini,[120,33] B. Irwin,[122] H. N. Isa,[46] J.-M. Isac,[73] M. Isi,[14] B. R. Iyer,[18]
T. Jacqmin,[73] S. J. Jadhav,[145] K. Jani,[78] N. N. Janthalur,[145] P. Jaranowski,[146] D. Jariwala,[30] A. C. Jenkins,[147]
J. Jiang,[30] D. S. Johnson,[19] A. W. Jones,[13] D. I. Jones,[148] J. D. Jones,[47] R. Jones,[46] R. J. G. Jonker,[37] L. Ju,[66]
J. Junker,[9,10] C. V. Kalaghatgi,[107] V. Kalogera,[58] B. Kamai,[1] S. Kandhasamy,[3] G. Kang,[38] J. B. Kanner,[1]
S. J. Kapadia,[24] S. Karki,[72] R. Kashyap,[18] M. Kasprzack,[1] S. Katsanevas,[29] E. Katsavounidis,[14] W. Katzman,[7]
S. Kaufer,[10] K. Kawabe,[47] N. V. Keerthana,[3] F. Kéfélian,[65] D. Keitel,[141] R. Kennedy,[113] J. S. Key,[149]
F. Y. Khalili,[61] I. Khan,[16,32] S. Khan,[9,10] E. A. Khazanov,[150] N. Khetan,[16,17] M. Khursheed,[60] N. Kijbunchoo,[8]
Chunglee Kim,[151] J. C. Kim,[152] K. Kim,[94] W. Kim,[57] W. S. Kim,[153] Y.-M. Kim,[154] C. Kimball,[58] P. J. King,[47]
M. Kinley-Hanlon,[46] R. Kirchhoff,[9,10] J. S. Kissel,[47] L. Kleybolte,[135] J. H. Klika,[24] S. Klimenko,[30] T. D. Knowles,[39]
P. Koch,[9,10] S. M. Koehlenbeck,[9,10] G. Koekoek,[37,155] S. Koley,[37] V. Kondrashov,[1] A. Kontos,[156] N. Koper,[9,10]
M. Korobko,[135] W. Z. Korth,[1] M. Kovalam,[66] D. B. Kozak,[1] C. Krämer,[9,10] V. Kringel,[9,10] N. Krishnendu,[31]
A. Królak,[157,158] N. Krupinski,[24] G. Kuehn,[9,10] A. Kumar,[145] P. Kumar,[159] Rahul Kumar,[47] Rakesh Kumar,[112]
L. Kuo,[90] A. Kutynia,[157] S. Kwang,[24] B. D. Lackey,[76] D. Laghi,[20,21] K. H. Lai,[94] T. L. Lam,[94] M. Landry,[47]
B. B. Lane,[14] R. N. Lang,[160] J. Lange,[62] B. Lantz,[51] R. K. Lanza,[14] A. Lartaux-Vollard,[28] P. D. Lasky,[6] M. Laxen,[7]
A. Lazzarini,[1] C. Lazzaro,[54] P. Leaci,[120,33] S. Leavey,[9,10] Y. K. Lecoeuche,[47] C. H. Lee,[97] H. K. Lee,[161]
H. M. Lee,[162] H. W. Lee,[152] J. Lee,[96] K. Lee,[46] J. Lehmann,[9,10] A. K. Lenon,[39] N. Leroy,[28] N. Letendre,[34]
Y. Levin,[6] A. Li,[94] J. Li,[83] K. J. L. Li,[94] T. G. F. Li,[94] X. Li,[48] F. Lin,[6] F. Linde,[163,37] S. D. Linker,[134]
T. B. Littenberg,[164] J. Liu,[66] X. Liu,[24] M. Llorens-Monteagudo,[22] R. K. L. Lo,[94,1] L. T. London,[14] A. Longo,[165,166]
M. Lorenzini,[16,17] V. Loriette,[167] M. Lormand,[7] G. Losurdo,[21] J. D. Lough,[9,10] C. O. Lousto,[62] G. Lovelace,[27]
M. E. Lower,[168] H. Lück,[10,9] D. Lumaca,[85,32] A. P. Lundgren,[141] R. Lynch,[14] Y. Ma,[48] R. Macas,[107] S. Macfoy,[25]
M. MacInnis,[14] D. M. Macleod,[107] A. Macquet,[65] I. Magaña Hernandez,[24] F. Magaña-Sandoval,[30] R. M. Magee,[89]
E. Majorana,[33] I. Maksimovic,[167] A. Malik,[60] N. Man,[65] V. Mandic,[43] V. Mangano,[46,120,33] G. L. Mansell,[47,14]
M. Manske,[24] M. Mantovani,[29] M. Mapelli,[53,54] F. Marchesoni,[52,41] F. Marion,[34] S. Márka,[106] Z. Márka,[106]
C. Markakis,[19] A. S. Markosyan,[51] A. Markowitz,[1] E. Maros,[1] A. Marquina,[105] S. Marsat,[26] F. Martelli,[63,64]
I. W. Martin,[46] R. M. Martin,[36] V. Martinez,[79] D. V. Martynov,[13] H. Masalehdan,[135] K. Mason,[14] E. Massera,[113]
A. Masserot,[34] T. J. Massinger,[1] M. Masso-Reid,[46] S. Mastrogiovanni,[26] A. Matas,[76] F. Matichard,[1,14]
L. Matone,[106] N. Mavalvala,[14] J. J. McCann,[66] R. McCarthy,[47] D. E. McClelland,[8] P. McClincy,[89] S. McCormick,[7]
L. McCuller,[14] S. C. McGuire,[169] C. McIsaac,[141] J. McIver,[1] D. J. McManus,[8] T. McRae,[8] S. T. McWilliams,[39]
D. Meacher,[24] G. D. Meadors,[6] M. Mehmet,[9,10] A. K. Mehta,[18] J. Meidam,[37] E. Mejuto Villa,[117,69] A. Melatos,[101]
G. Mendell,[47] R. A. Mercer,[24] L. Mereni,[23] K. Merfeld,[72] E. L. Merilh,[47] M. Merzougui,[65] S. Meshkov,[1]
C. Messenger,[46] C. Messick,[89] F. Messina,[44,45] R. Metzdorff,[73] P. M. Meyers,[101] F. Meylahn,[9,10] A. Miani,[118,119]
H. Miao,[13] C. Michel,[23] H. Middleton,[101] L. Milano,[80,5] A. L. Miller,[30,120,33] M. Millhouse,[101] J. C. Mills,[107]

M. C. Milovich-Goff,[134] O. Minazzoli,[65,170] Y. Minenkov,[32] A. Mishkin,[30] C. Mishra,[171] T. Mistry,[113] S. Mitra,[3]
V. P. Mitrofanov,[61] G. Mitselmakher,[30] R. Mittleman,[14] G. Mo,[98] D. Moffa,[122] K. Mogushi,[86] S. R. P. Mohapatra,[14]
M. Molina-Ruiz,[142] M. Mondin,[134] M. Montani,[63,64] C. J. Moore,[13] D. Moraru,[47] F. Morawski,[56] G. Moreno,[47]
S. Morisaki,[82] B. Mours,[34] C. M. Mow-Lowry,[13] F. Muciaccia,[120,33] Arunava Mukherjee,[9,10] D. Mukherjee,[24]
S. Mukherjee,[109] Subroto Mukherjee,[112] N. Mukund,[9,10,3] A. Mullavey,[7] J. Munch,[57] E. A. Muñiz,[42] M. Muratore,[35]
P. G. Murray,[46,128,172] I. Nardecchia,[85,32] L. Naticchioni,[120,33] R. K. Nayak,[173] B. F. Neil,[66] J. Neilson,[117,69]
G. Nelemans,[67,37] T. J. N. Nelson,[7] M. Nery,[9,10] A. Neunzert,[138] L. Nevin,[1] K. Y. Ng,[14] S. Ng,[57] C. Nguyen,[26]
P. Nguyen,[72] D. Nichols,[143,37] S. A. Nichols,[2] S. Nissanke,[143,37] F. Nocera,[29] C. North,[107] L. K. Nuttall,[141]
M. Obergaulinger,[22,174] J. Oberling,[47] B. D. O'Brien,[30] G. Oganesyan,[16,17] G. H. Ogin,[175] J. J. Oh,[153] S. H. Oh,[153]
F. Ohme,[9,10] H. Ohta,[82] M. A. Okada,[15] M. Oliver,[102] P. Oppermann,[9,10] Richard J. Oram,[7] B. O'Reilly,[7]
R. G. Ormiston,[43] L. F. Ortega,[30] R. O'Shaughnessy,[62] S. Ossokine,[76] D. J. Ottaway,[57] H. Overmier,[7] B. J. Owen,[84]
A. E. Pace,[89] G. Pagano,[20,21] M. A. Page,[66] G. Pagliaroli,[16,17] A. Pai,[131] S. A. Pai,[60] J. R. Palamos,[72]
O. Palashov,[150] C. Palomba,[33] H. Pan,[90] P. K. Panda,[145] P. T. H. Pang,[94,37] C. Pankow,[58] F. Pannarale,[120,33]
B. C. Pant,[60] F. Paoletti,[21] A. Paoli,[29] A. Parida,[3] W. Parker,[7,169] D. Pascucci,[46,37] A. Pasqualetti,[29]
R. Passaquieti,[20,21] D. Passuello,[21] M. Patil,[158] B. Patricelli,[20,21] E. Payne,[6] B. L. Pearlstone,[46] T. C. Pechsiri,[30]
A. J. Pedersen,[42] M. Pedraza,[1] R. Pedurand,[23,176] A. Pele,[7] S. Penn,[177] A. Perego,[118,119] C. J. Perez,[47]
C. Périgois,[34] A. Perreca,[118,119] J. Petermann,[135] H. P. Pfeiffer,[76] M. Phelps,[9,10] K. S. Phukon,[3] O. J. Piccinni,[120,33]
M. Pichot,[65] F. Piergiovanni,[63,64] V. Pierro,[117,69] G. Pillant,[29] L. Pinard,[23] I. M. Pinto,[117,69,88] M. Pirello,[47]
M. Pitkin,[46] W. Plastino,[165,166] R. Poggiani,[20,21] D. Y. T. Pong,[94] S. Ponrathnam,[3] P. Popolizio,[29] E. K. Porter,[26]
J. Powell,[168] A. K. Prajapati,[112] J. Prasad,[3] K. Prasai,[51] R. Prasanna,[145] G. Pratten,[102] T. Prestegard,[24]
M. Principe,[117,88,69] G. A. Prodi,[118,119] L. Prokhorov,[13] M. Punturo,[41] P. Puppo,[33] M. Pürrer,[76] H. Qi,[107]
V. Quetschke,[109] P. J. Quinonez,[35] F. J. Raab,[47] G. Raaijmakers,[143,37] H. Radkins,[47] N. Radulesco,[65] P. Raffai,[111]
S. Raja,[60] C. Rajan,[60] B. Rajbhandari,[84] M. Rakhmanov,[109] K. E. Ramirez,[109] A. Ramos-Buades,[102] Javed Rana,[3]
K. Rao,[58] P. Rapagnani,[120,33] V. Raymond,[107] M. Razzano,[20,21] J. Read,[27] T. Regimbau,[34] L. Rei,[59] S. Reid,[25]
D. H. Reitze,[1,30] P. Rettegno,[128,178] F. Ricci,[120,33] C. J. Richardson,[35] J. W. Richardson,[1] P. M. Ricker,[19]
G. Riemenschneider,[178,128] K. Riles,[138] M. Rizzo,[58] N. A. Robertson,[1,46] F. Robinet,[28] A. Rocchi,[32] L. Rolland,[34]
J. G. Rollins,[1] V. J. Roma,[72] M. Romanelli,[71] R. Romano,[4,5] C. L. Romel,[47] J. H. Romie,[7] C. A. Rose,[24] D. Rose,[27]
K. Rose,[122] D. Rosińska,[74] S. G. Rosofsky,[19] M. P. Ross,[179] S. Rowan,[46] A. Rüdiger,[9,10,*] P. Ruggi,[29] G. Rutins,[133]
K. Ryan,[47] S. Sachdev,[89] T. Sadecki,[47] M. Sakellariadou,[147] O. S. Salafia,[180,44,45] L. Salconi,[29] M. Saleem,[31]
A. Samajdar,[37] L. Sammut,[6] E. J. Sanchez,[1] L. E. Sanchez,[1] N. Sanchis-Gual,[181] J. R. Sanders,[182] K. A. Santiago,[36]
E. Santos,[65] N. Sarin,[6] B. Sassolas,[23] B. S. Sathyaprakash,[89,107] O. Sauter,[138,34] R. L. Savage,[47] P. Schale,[72]
M. Scheel,[48] J. Scheuer,[58] P. Schmidt,[13,67] R. Schnabel,[135] R. M. S. Schofield,[72] A. Schönbeck,[135] E. Schreiber,[9,10]
B. W. Schulte,[9,10] B. F. Schutz,[107] J. Scott,[46] S. M. Scott,[8] E. Seidel,[19] D. Sellers,[7] A. S. Sengupta,[183]
N. Sennett,[76] D. Sentenac,[29] V. Sequino,[59] A. Sergeev,[150] Y. Setyawati,[9,10] D. A. Shaddock,[8] T. Shaffer,[47]
M. S. Shahriar,[58] M. B. Shaner,[134] A. Sharma,[16,17] P. Sharma,[60] P. Shawhan,[77] H. Shen,[19] R. Shink,[184]
D. H. Shoemaker,[14] D. M. Shoemaker,[78] K. Shukla,[142] S. ShyamSundar,[60] K. Siellez,[78] M. Sieniawska,[56] D. Sigg,[47]
L. P. Singer,[81] D. Singh,[89] N. Singh,[74] A. Singhal,[16,33] A. M. Sintes,[102] S. Sitmukhambetov,[109] V. Skliris,[107]
B. J. J. Slagmolen,[8] T. J. Slaven-Blair,[66] J. R. Smith,[27] R. J. E. Smith,[6] S. Somala,[185] E. J. Son,[153] S. Soni,[2]
B. Sorazu,[46] F. Sorrentino,[59] T. Souradeep,[3] E. Sowell,[84] A. P. Spencer,[46] M. Spera,[53,54] A. K. Srivastava,[112]
V. Srivastava,[42] K. Staats,[58] C. Stachie,[65] M. Standke,[9,10] D. A. Steer,[26] M. Steinke,[9,10] J. Steinlechner,[135,46]
S. Steinlechner,[135] D. Steinmeyer,[9,10] S. P. Stevenson,[168] D. Stocks,[51] R. Stone,[109] D. J. Stops,[13] K. A. Strain,[46]
G. Stratta,[186,64] S. E. Strigin,[61] A. Strunk,[47] R. Sturani,[187] A. L. Stuver,[188] V. Sudhir,[14] T. Z. Summerscales,[189]
L. Sun,[1] S. Sunil,[112] A. Sur,[56] J. Suresh,[82] P. J. Sutton,[107] B. L. Swinkels,[37] M. J. Szczepańczyk,[35] M. Tacca,[37]
S. C. Tait,[46] C. Talbot,[6] D. B. Tanner,[30] D. Tao,[1] M. Tápai,[132] A. Tapia,[27] J. D. Tasson,[98] R. Taylor,[1]
R. Tenorio,[102] L. Terkowski,[135] M. Thomas,[7] P. Thomas,[47] S. R. Thondapu,[60] K. A. Thorne,[7] E. Thrane,[6]
Shubhanshu Tiwari,[118,119] Srishti Tiwari,[136] V. Tiwari,[107] K. Toland,[46] M. Tonelli,[20,21] Z. Tornasi,[46]
A. Torres-Forné,[190] C. I. Torrie,[1] D. Töyrä,[13] F. Travasso,[29,41] G. Traylor,[7] M. C. Tringali,[74] A. Tripathee,[138]
A. Trovato,[26] L. Trozzo,[191,21] K. W. Tsang,[37] M. Tse,[14] R. Tso,[48] L. Tsukada,[82] D. Tsuna,[82] T. Tsutsui,[82]
D. Tuyenbayev,[109] K. Ueno,[82] D. Ugolini,[192] C. S. Unnikrishnan,[136] A. L. Urban,[2] S. A. Usman,[93] H. Vahlbruch,[10]
G. Vajente,[1] G. Valdes,[2] M. Valentini,[118,119] N. van Bakel,[37] M. van Beuzekom,[37] J. F. J. van den Brand,[75,37]
C. Van Den Broeck,[37,193] D. C. Vander-Hyde,[42] L. van der Schaaf,[37] J. V. VanHeijningen,[66] A. A. van Veggel,[46]

M. Vardaro,[53,54] V. Varma,[48] S. Vass,[1] M. Vasúth,[50] A. Vecchio,[13] G. Vedovato,[54] J. Veitch,[46] P. J. Veitch,[57]
K. Venkateswara,[179] G. Venugopalan,[1] D. Verkindt,[34] F. Vetrano,[63,64] A. Viceré,[63,64] A. D. Viets,[24]
S. Vinciguerra,[13] D. J. Vine,[133] J.-Y. Vinet,[65] S. Vitale,[14] T. Vo,[42] H. Vocca,[40,41] C. Vorvick,[47] S. P. Vyatchanin,[61]
A. R. Wade,[1] L. E. Wade,[122] M. Wade,[122] R. Walet,[37] M. Walker,[27] L. Wallace,[1] S. Walsh,[24] H. Wang,[13]
J. Z. Wang,[138] S. Wang,[19] W. H. Wang,[109] Y. F. Wang,[94] R. L. Ward,[8] Z. A. Warden,[35] J. Warner,[47] M. Was,[34]
J. Watchi,[103] B. Weaver,[47] L.-W. Wei,[9,10] M. Weinert,[9,10] A. J. Weinstein,[1] R. Weiss,[14] F. Wellmann,[9,10] L. Wen,[66]
E. K. Wessel,[19] P. Weßels,[9,10] J. W. Westhouse,[35] K. Wette,[8] J. T. Whelan,[62] B. F. Whiting,[30] C. Whittle,[14]
D. M. Wilken,[9,10] D. Williams,[46] A. R. Williamson,[143,37] J. L. Willis,[1] B. Willke,[10,9] W. Winkler,[9,10] C. C. Wipf,[1]
H. Wittel,[9,10] G. Woan,[46] J. Woehler,[9,10] J. K. Wofford,[62] J. L. Wright,[46] D. S. Wu,[9,10] D. M. Wysocki,[62]
S. Xiao,[1] R. Xu,[110] H. Yamamoto,[1] C. C. Yancey,[77] L. Yang,[121] Y. Yang,[30] Z. Yang,[43] M. J. Yap,[8]
M. Yazback,[30] D. W. Yeeles,[107] Hang Yu,[14] Haocun Yu,[14] S. H. R. Yuen,[94] A. K. Zadrożny,[109] A. Zadrożny,[157]
M. Zanolin,[35] T. Zelenova,[29] J.-P. Zendri,[54] M. Zevin,[58] J. Zhang,[66] L. Zhang,[1] T. Zhang,[46] C. Zhao,[66]
G. Zhao,[103] M. Zhou,[58] Z. Zhou,[58] X. J. Zhu,[6] A. B. Zimmerman,[194] M. E. Zucker,[1,14] and J. Zweizig[1]
(The LIGO Scientific Collaboration and the Virgo Collaboration)

S. Shandera[89]

[1]*LIGO, California Institute of Technology, Pasadena, CA 91125, USA*
[2]*Louisiana State University, Baton Rouge, LA 70803, USA*
[3]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[4]*Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[5]*INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy*
[6]*OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[7]*LIGO Livingston Observatory, Livingston, LA 70754, USA*
[8]*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[9]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
[10]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[11]*Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*
[12]*University of Cambridge, Cambridge CB2 1TN, United Kingdom*
[13]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[14]*LIGO, Massachusetts Institute of Technology, Cambridge, MA 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]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[19]*NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[20]*Università di Pisa, I-56127 Pisa, Italy*
[21]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[22]*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
[23]*Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France*
[24]*University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA*
[25]*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[26]*APC, AstroParticule et Cosmologie, Université Paris Diderot,*
CNRS/IN2P3, CEA/Irfu, Observatoire de Paris,
Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
[27]*California State University Fullerton, Fullerton, CA 92831, USA*
[28]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France*
[29]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[30]*University of Florida, Gainesville, FL 32611, USA*
[31]*Chennai Mathematical Institute, Chennai 603103, India*
[32]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[33]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[34]*Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes,*
Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
[35]*Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA*
[36]*Montclair State University, Montclair, NJ 07043, USA*
[37]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[38]*Korea Institute of Science and Technology Information, Daejeon 34141, South Korea*
[39]*West Virginia University, Morgantown, WV 26506, USA*
[40]*Università di Perugia, I-06123 Perugia, Italy*
[41]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*

[42]Syracuse University, Syracuse, NY 13244, USA
[43]University of Minnesota, Minneapolis, MN 55455, USA
[44]Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
[45]INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
[46]SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[47]LIGO Hanford Observatory, Richland, WA 99352, USA
[48]Caltech CaRT, Pasadena, CA 91125, USA
[49]Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,
” Università di Salerno, I-84081 Baronissi, Salerno, Italy
[50]Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
[51]Stanford University, Stanford, CA 94305, USA
[52]Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
[53]Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
[54]INFN, Sezione di Padova, I-35131 Padova, Italy
[55]Montana State University, Bozeman, MT 59717, USA
[56]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
[57]OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
[58]Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA),
Northwestern University, Evanston, IL 60208, USA
[59]INFN, Sezione di Genova, I-16146 Genova, Italy
[60]RRCAT, Indore, Madhya Pradesh 452013, India
[61]Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
[62]Rochester Institute of Technology, Rochester, NY 14623, USA
[63]Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy
[64]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
[65]Artemis, Université Côte d’Azur, Observatoire Côte d’Azur,
CNRS, CS 34229, F-06304 Nice Cedex 4, France
[66]OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
[67]Department of Astrophysics/IMAPP, Radboud University Nijmegen,
P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
[68]Dipartimento di Fisica “E.R. Caianiello,” Università di Salerno, I-84084 Fisciano, Salerno, Italy
[69]INFN, Sezione di Napoli, Gruppo Collegato di Salerno,
Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
[70]Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[71]Univ Rennes, CNRS, Institut FOTON - UMR6082, F-3500 Rennes, France
[72]University of Oregon, Eugene, OR 97403, USA
[73]Laboratoire Kastler Brossel, Sorbonne Université, CNRS,
ENS-Université PSL, Collège de France, F-75005 Paris, France
[74]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
[75]VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
[76]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
[77]University of Maryland, College Park, MD 20742, USA
[78]School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[79]Université de Lyon, Université Claude Bernard Lyon 1,
CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
[80]Università di Napoli “Federico II,” Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
[81]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[82]RESCEU, University of Tokyo, Tokyo, 113-0033, Japan.
[83]Tsinghua University, Beijing 100084, China
[84]Texas Tech University, Lubbock, TX 79409, USA
[85]Università di Roma Tor Vergata, I-00133 Roma, Italy
[86]The University of Mississippi, University, MS 38677, USA
[87]Missouri University of Science and Technology, Rolla, MO 65409, USA
[88]Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy
[89]The Pennsylvania State University, University Park, PA 16802, USA
[90]National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
[91]Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
[92]Canadian Institute for Theoretical Astrophysics,
University of Toronto, Toronto, Ontario M5S 3H8, Canada
[93]University of Chicago, Chicago, IL 60637, USA
[94]The Chinese University of Hong Kong, Shatin, NT, Hong Kong
[95]Dipartimento di Ingegneria Industriale (DIIN),
Università di Salerno, I-84084 Fisciano, Salerno, Italy
[96]Seoul National University, Seoul 08826, South Korea

[97]*Pusan National University, Busan 46241, South Korea*
[98]*Carleton College, Northfield, MN 55057, USA*
[99]*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
[100]*Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy*
[101]*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
[102]*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
[103]*Université Libre de Bruxelles, Brussels 1050, Belgium*
[104]*Sonoma State University, Rohnert Park, CA 94928, USA*
[105]*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
[106]*Columbia University, New York, NY 10027, USA*
[107]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[108]*University of Rhode Island, Kingston, RI 02881, USA*
[109]*The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA*
[110]*Bellevue College, Bellevue, WA 98007, USA*
[111]*MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary*
[112]*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
[113]*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
[114]*IGFAE, Campus Sur, Universidade de Santiago de Compostela, 15782 Spain*
[115]*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
[116]*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
[117]*Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy*
[118]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[119]*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
[120]*Università di Roma "La Sapienza," I-00185 Roma, Italy*
[121]*Colorado State University, Fort Collins, CO 80523, USA*
[122]*Kenyon College, Gambier, OH 43022, USA*
[123]*Christopher Newport University, Newport News, VA 23606, USA*
[124]*CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[125]*Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy*
[126]*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[127]*Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain*
[128]*INFN Sezione di Torino, I-10125 Torino, Italy*
[129]*School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
[130]*Institute Of Advanced Research, Gandhinagar 382426, India*
[131]*Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
[132]*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
[133]*SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[134]*California State University, Los Angeles, 5151 State University Dr, Los Angeles, CA 90032, USA*
[135]*Universität Hamburg, D-22761 Hamburg, Germany*
[136]*Tata Institute of Fundamental Research, Mumbai 400005, India*
[137]*INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy*
[138]*University of Michigan, Ann Arbor, MI 48109, USA*
[139]*Washington State University, Pullman, WA 99164, USA*
[140]*American University, Washington, D.C. 20016, USA*
[141]*University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
[142]*University of California, Berkeley, CA 94720, USA*
[143]*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics,*
University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
[144]*Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, The Netherlands*
[145]*Directorate of Construction, Services & Estate Management, Mumbai 400094 India*
[146]*University of Białystok, 15-424 Białystok, Poland*
[147]*King's College London, University of London, London WC2R 2LS, United Kingdom*
[148]*University of Southampton, Southampton SO17 1BJ, United Kingdom*
[149]*University of Washington Bothell, Bothell, WA 98011, USA*
[150]*Institute of Applied Physics, Nizhny Novgorod, 603950, Russia*
[151]*Ewha Womans University, Seoul 03760, South Korea*
[152]*Inje University Gimhae, South Gyeongsang 50834, South Korea*
[153]*National Institute for Mathematical Sciences, Daejeon 34047, South Korea*
[154]*Ulsan National Institute of Science and Technology, Ulsan 44919, South Korea*
[155]*Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands*
[156]*Bard College, 30 Campus Rd, Annandale-On-Hudson, NY 12504, USA*
[157]*NCBJ, 05-400 Świerk-Otwock, Poland*
[158]*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[159]*Cornell University, Ithaca, NY 14850, USA*

[160]*Hillsdale College, Hillsdale, MI 49242, USA*
[161]*Hanyang University, Seoul 04763, South Korea*
[162]*Korea Astronomy and Space Science Institute, Daejeon 34055, South Korea*
[163]*Institute for High-Energy Physics, University of Amsterdam,*
Science Park 904, 1098 XH Amsterdam, The Netherlands
[164]*NASA Marshall Space Flight Center, Huntsville, AL 35811, USA*
[165]*Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
[166]*INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
[167]*ESPCI, CNRS, F-75005 Paris, France*
[168]*OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
[169]*Southern University and A&M College, Baton Rouge, LA 70813, USA*
[170]*Centre Scientifique de Monaco, 8 quai Antoine Ier, MC-98000, Monaco*
[171]*Indian Institute of Technology Madras, Chennai 600036, India*
[172]*Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
[173]*IISER-Kolkata, Mohanpur, West Bengal 741252, India*
[174]*Institut für Kernphysik, Theoriezentrum, 64289 Darmstadt, Germany*
[175]*Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA*
[176]*Université de Lyon, F-69361 Lyon, France*
[177]*Hobart and William Smith Colleges, Geneva, NY 14456, USA*
[178]*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
[179]*University of Washington, Seattle, WA 98195, USA*
[180]*INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
[181]*Centro de Astrofísica e Gravitação (CENTRA),*
Departamento de Física, Instituto Superior Técnico,
Universidade de Lisboa, 1049-001 Lisboa, Portugal
[182]*Marquette University, 11420 W. Clybourn St., Milwaukee, WI 53233, USA*
[183]*Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India*
[184]*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
[185]*Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
[186]*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
[187]*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
[188]*Villanova University, 800 Lancaster Ave, Villanova, PA 19085, USA*
[189]*Andrews University, Berrien Springs, MI 49104, USA*
[190]*Max Planck Institute for Gravitationalphysik (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany*
[191]*Università di Siena, I-53100 Siena, Italy*
[192]*Trinity University, San Antonio, TX 78212, USA*
[193]*Van Swinderen Institute for Particle Physics and Gravity,*
University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
[194]*Department of Physics, University of Texas, Austin, TX 78712, USA*