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)

(Received 25 May 2019; published 18 October 2019)

We present a search for subsolar 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 subsolar mass ultracompact binaries with at least one component between $0.2\ M_{\odot}$–$1.0\ M_{\odot}$. 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 $3.7\times10^{5}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ and the binary merger rate of $(1.0\ M_{\odot}, 1.0\ M_{\odot})$ binaries to be less than $5.2\times10^{3}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Subsolar 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 subsolar masses. Assuming a particular primordial black hole (PBH) 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 subsolar mass binaries.

DOI: 10.1103/PhysRevLett.123.161102

Introduction.—Gravitational-wave and multimessenger 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 [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 subsolar 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 into 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 Λ cold dark matter (ΛCDM) model of cosmology. Neutron stars are expected to have masses greater than the minimum Chandrasekhar mass [15] minus the gravitational binding energy. Calculations in Ref. [16] and more recently in Ref. [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 nonrotating 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 subsolar mass object in a merger would therefore be a clear signal of new physics. Indeed, there are several proposals that link subsolar 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 overdensities on the scale of the early time Hubble volume [22,23]. The size and abundance of any such PBHs depends on the spectrum of primordial perturbations and on the equation of

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

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 another 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 subsolar mass black hole would have far-reaching implications. In the PBH 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 subsolar 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 noninteracting bosons [38,39]. In the case in which 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 on the results of a search for gravitational waves from subsolar mass ultracompact binaries using data from Advanced LIGO's second observing run. No significant candidates consistent with a subsolar mass binary were identified. The null result places the tightest constraints to date on the merger rate and the abundance of subsolar 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 PBH populations contributing to the dark matter [14]. We describe how to extend the dark matter fraction parametrization 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) [40]. 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 [41]. We find that 117.53 days of coincident data remain after the application of data quality cuts [42–46]. The Advanced Virgo interferometer completed commissioning and joined Advanced LIGO in August 2017 for 15 days of triple coincident observations [7]; however, we report only 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 [47–53]. 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 [54]. The template bank used for this search was designed to recover binaries with component masses of 0.19 $M_\odot$–2.0 $M_\odot$ and total masses of 0.4 $M_\odot$–4.0 $M_\odot$ in the detector frame with 97% fidelity, as in Ref. [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 antialigned 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 nonspinning bank used in Ref. [14].

In order to reduce the computational burden, matched filtering was performed only 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 ~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, $\mathcal{L}$ [47–49]. For a candidate with a likelihood ratio of $\mathcal{L}^*$, we assign a false-alarm rate (FAR) of

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

where N is the number of observed candidates, T is the total live time of the experiment, and $P(\log \mathcal{L} \geq \log \mathcal{L}^* | \mathrm{noise})$

describes the probability that noise produces a candidate with a ranking statistic at least as high as the candidate's.

The search recovered the previously detected signal GW170817 [3], which was observed along with an electromagnetic counterpart [55]. 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 Ref. [14], we consider nine populations of equal mass, nonspinning binaries that are δ-function distributed in mass, i.e., $m_i \in \{0.2, 0.3, \ldots, 1.0\}$. We injected 913931 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 [56] 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 a total mass of up to 4 $M_\odot$, we place bounds on the merger rate of systems only where both components are ≤ 1 $M_\odot$. We estimate that detector calibration uncertainties [7,57,58] 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

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

where $S_n(f)$ is the noise spectra of the detector and f_{min} and f_{max} are 45 and 1024 Hz, respectively [59]. For a null result, we therefore expect $\mathcal{R}(\mathcal{M}) \propto \mathcal{M}^{-15/6}$ provided that the horizon distance controls the sensitivity of the search. The observed power law dependence of the rate constraint on the chirp mass is within ~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.

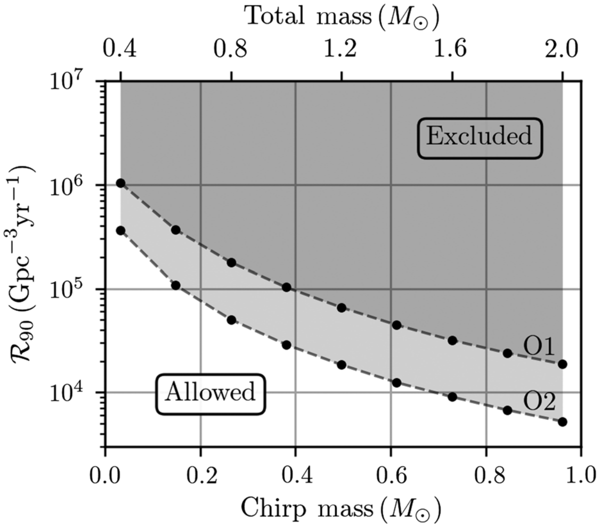

FIG. 1. The constraint on the merger rate density for equal mass binaries as a function of total mass (top) and chirp mass (bottom). The two sets of lines show the constraints for the O1 search [14] and the O2 search presented here. The null result from O2 places bounds that are ~3 times tighter than the O1 results. The majority of this improvement is due to the increased coincident observing time in Advanced LIGO's second observing run (~118 days vs ~48 days), though the improved sensitivity of the detectors led to an observed physical volume up to ~50% larger than in O1 for subsolar 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 subsolar mass binaries. Setting $\psi(\mathcal{M}) = \delta(\mathcal{M})$ then reveals the form of the LIGO constraining rate density, $\mathcal{R}(\mathcal{M})$, which is shown in Fig. 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 subsolar mass ultracompact object models with LIGO observations.

General constraints on subsolar mass black hole dark matter.—We convert our limits on the merger rate of subsolar mass ultracompact objects into a constraint on the abundance of PBHs using our fiducial formation model [60] first developed in Refs. [23,61] and used previously in

LIGO analyses [12,14]. We consider a population of equal mass PBHs 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 [62]. 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 Fig. 2 [63].

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 PBH composition of the dark matter. The Advanced LIGO and Virgo observables can be separated from the model dependent terms:

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

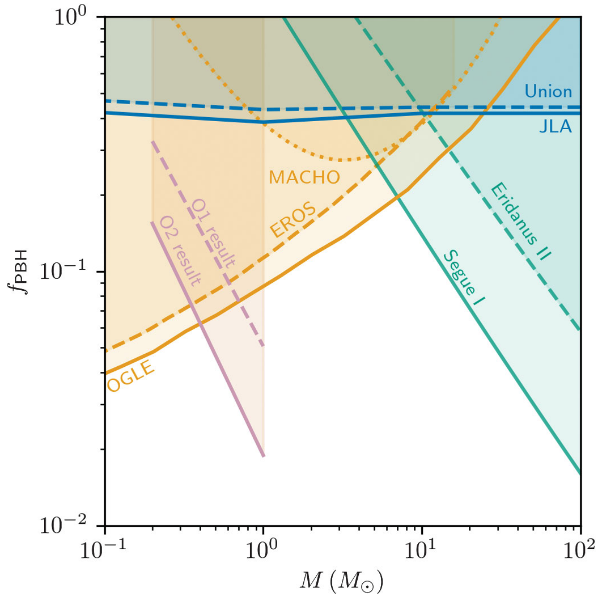

FIG. 2. Constraints on the fraction of dark matter comprising δ-function distributions of PBHs ($f_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$). Shown here are (pink lines) Advanced LIGO constraints from the O1 (dashed lines) and O2 ultracompact binary search presented here (solid lines), (orange lines) microlensing constraints provided by the OGLE (solid line), EROS (dashed line) [64], and MACHO (dotted line) collaborations [65], (cyan lines) dynamical constraints from observations of Segue I (solid line) [66] and Eridanus II (dashed line) [67] dwarf galaxies, and (blue) supernova lensing constraints from the Joint Light-curve Analysis (solid) and Union 2.1 (dashed) datasets [68]. 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 [69].

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 subsolar mass ultracompact binaries. In the second term, f_{obs} describes the fraction of subsolar 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.

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

This work represents an expansion of previous initial and Advanced LIGO and Advanced Virgo subsolar mass searches. First, we broadened the searched parameter space to increase sensitivity to systems with non-negligible component spins. Second, we presented a method to extend our constraints on the binary merger rate to arbitrarily distributed populations that contain subsolar 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 provided a method to separate Advanced LIGO and Advanced Virgo observables from model dependent terms in our interpretation of the limits on PBH dark matter.

Ground based interferometer searches for subsolar mass ultracompact objects will continue to inform cosmological and particle physics scenarios. Advanced LIGO and Advanced Virgo began a yearlong observing run in early 2019, with improved sensitivities [70]. 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.

The authors gratefully acknowledge the support of the U.S. 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 and 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.

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[1] J. Aasi *et al.*, Advanced LIGO, Classical Quantum Gravity **32**, 074001 (2015).

[2] F. Acernese *et al.*, Advanced Virgo: A second-generation interferometric gravitational wave detector, Classical Quantum Gravity **32**, 024001 (2015).

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

[4] B. P. Abbott *et al.*, GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2, Phys. Rev. Lett. **118**, 221101 (2017).

[5] B. P. Abbott *et al.*, GW170608: Observation of a 19-solar-mass binary black hole coalescence, Astrophys. J. **851**, 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**, 141101 (2017).

[7] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo During the First and Second Observing Runs, Phys. Rev. X **9**, 031040 (2019).

[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, Astrophys. J. Lett. **882**, L24 (2019)

[9] T. Dal Canton and I. W. Harry, Designing a template bank to observe compact binary coalescences in Advanced LIGO's second observing run, arXiv:1705.01845.

[10] D. Mukherjee *et al.*, The GstLAL template bank for spinning compact binary mergers in the second observation run of Advanced LIGO and Virgo, arXiv:1812.05121.

[11] R. Magee, A.-S. Deutsch, P. McClincy, C. Hanna, C. Horst, D. Meacher, C. Messick, S. Shandera, and M. Wade, Methods for the detection of gravitational waves from subsolar mass ultracompact binaries, Phys. Rev. D **98**, 103024 (2018).

[12] B. Abbott *et al.*, Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D **72**, 082002 (2005).

[13] B. Abbott *et al.*, Search for gravitational waves from binary inspirals in S3 and S4 LIGO data, Phys. Rev. D **77**, 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**, 231103 (2018).

[15] S. Chandrasekhar, The maximum mass of ideal white dwarfs, Astrophys. J. **74**, 81 (1931).

[16] F. X. Timmes, S. E. Woosley, and T. A. Weaver, The neutron star and black hole initial mass function, Astrophys. J. **457**, 834 (1996).

[17] Y. Suwa, T. Yoshida, M. Shibata, H. Umeda, and K. Takahashi, On the minimum mass of neutron stars, Mon. Not. R. Astron. Soc. **481**, 3305 (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**, 143 (2015).

[19] J. Antoniadis *et al.*, A massive pulsar in a compact relativistic binary, Science **340**, 1233232 (2013).

[20] V. S. Imshennik, A possible scenario of a supernova explosion as a result of the gravitational collapse of a massive stellar core, Sov. Astron. Lett. **18**, 194 (1992).

[21] M. B. Davies, A. King, S. Rosswog, and G. Wynn, Gamma-ray bursts, supernova kicks, and gravitational radiation, Astrophys. J. **579**, L63 (2002).

[22] B. J. Carr, The primordial black hole mass spectrum, Astrophys. J. **201**, 1 (1975).

[23] T. Nakamura, M. Sasaki, T. Tanaka, and K. S. Thorne, Gravitational waves from coalescing black hole macho binaries, Astrophys. J. Lett. **487**, L139 (1997).

[24] K. Jedamzik, Primordial black hole formation during the QCD epoch, Phys. Rev. D **55**, R5871 (1997).

[25] P. Widerin and C. Schmid, Primordial black holes from the QCD transition?, arXiv:astro-ph/9808142.

[26] J. Georg and S. Watson, A preferred mass range for primordial black hole formation and black holes as dark matter revisited, J. High Energy Phys. 09 (2017) 138.

[27] C. T. Byrnes, M. Hindmarsh, S. Young, and M. R. S. Hawkins, Primordial black holes with an accurate QCD equation of state, J. Cosmol. Astropart. Phys. 08 (2018) 041.

[28] H. Deng and A. Vilenkin, Primordial black hole formation by vacuum bubbles, J. Cosmol. Astropart. Phys. 12 (2017) 044.

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

[30] C. Kouvaris and P. Tinyakov, Constraining asymmetric dark matter through observations of compact stars, Phys. Rev. D **83**, 083512 (2011).

[31] A. de Lavallaz and M. Fairbairn, Neutron stars as dark matter probes, Phys. Rev. D **81**, 123521 (2010).

[32] I. Goldman and S. Nussinov, Weakly interacting massive particles and neutron stars, Phys. Rev. D **40**, 3221 (1989).

[33] J. Bramante and F. Elahi, Higgs portals to pulsar collapse, Phys. Rev. D **91**, 115001 (2015).

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

[35] J. Bramante, T. Linden, and Y.-D. Tsai, Searching for dark matter with neutron star mergers and quiet kilonovae, Phys. Rev. D **97**, 055016 (2018).

[36] C. Kouvaris, P. Tinyakov, and M. H. G. Tytgat, Non-Primordial Solar Mass Black Holes, Phys. Rev. Lett. **121**, 221102 (2018).

[37] M. I. Gresham and K. M. Zurek, Asymmetric dark stars and neutron star stability, Phys. Rev. D **99**, 083008 (2019).

[38] J. D. Breit, S. Gupta, and A. Zaks, Cold Bose stars, Phys. Lett. **140B**, 329 (1984).

[39] L. A. Urena-Lopez, T. Matos, and R. Becerril, Inside oscillations, Classical Quantum Gravity **19**, 6259 (2002).

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

[41] D. Davis, T. Massinger, A. Lundgren, J. C. Driggers, A. L. Urban, and L. Nuttall, Improving the sensitivity of Advanced LIGO using noise subtraction, Classical Quantum Gravity **36**, 055011 (2019).

[42] B. P. Abbott *et al.*, Effects of data quality vetoes on a search for compact binary coalescences in Advanced LIGO's first observing run, Classical Quantum Gravity **35**, 065010 (2018).

[43] B. P. Abbott *et al.*, Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914, Classical Quantum Gravity **33**, 134001 (2016).

[44] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari *et al.*, Binary Black Hole Mergers in the First Advanced LIGO Observing Run, Phys. Rev. X **6**, 041015 (2016).

[45] L. K. Nuttall, Characterizing transient noise in the LIGO detectors, Phil. Trans. R. Soc. A **376**, 20170286 (2018).

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

[47] K. Cannon *et al.*, Toward early-warning detection of gravitational waves from compact binary coalescence, Astrophys. J. **748**, 136 (2012).

[48] C. Messick *et al.*, Analysis framework for the prompt discovery of compact binary mergers in gravitational-wave data, Phys. Rev. D **95**, 042001 (2017).

[49] S. Sachdev *et al.*, The GstLAL search analysis methods for compact binary mergers in Advanced LIGO's Second and Advanced Virgo's First Observing Runs, arXiv:1901.08580.

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

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

[52] 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. D **89**, 084041 (2014).

[53] C. Capano, I. Harry, S. Privitera, and A. Buonanno, Implementing a search for gravitational waves from binary black holes with nonprecessing spin, Phys. Rev. D **93**, 124007 (2016).

[54] A. Buonanno, B. R. Iyer, E. Ochsner, Y. Pan, and B. S. Sathyaprakash, Comparison of post-Newtonian templates for compact binary inspiral signals in gravitational-wave detectors, Phys. Rev. D **80**, 084043 (2009).

[55] B. P. Abbott *et al.*, Multi-messenger observations of a binary neutron star merger, Astrophys. J. **848**, L12 (2017).

[56] R. Biswas, P. R. Brady, J. D. E. Creighton, and S. Fairhurst, The loudest event statistic: General formulation, properties and applications, Classical Quantum Gravity **26**, 175009 (2009); Erratum, Classical Quantum Gravity **30**, 079502(E) (2013).

[57] C. Cahillane, J. Betzwieser, D. A. Brown, E. Goetz, E. D. Hall, K. Izumi, S. Kandhasamy, S. Karki, J. S. Kissel, G. Mendell, R. L. Savage, D. Tuyenbayev, A. Urban, A. Viets, M. Wade, and A. J. Weinstein, Calibration uncertainty for Advanced LIGO's first and second observing runs, Phys. Rev. D **96**, 102001 (2017).

[58] A. Viets *et al.*, Reconstructing the calibrated strain signal in the Advanced LIGO detectors, Classical Quantum Gravity **35**, 095015 (2018).

[59] 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 nonspinning waveforms in our template bank and thus does not impact D_{horizon}.

[60] M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama, Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914, Phys. Rev. Lett. **117**, 061101 (2016).

[61] K. Ioka, T. Chiba, T. Tanaka, and T. Nakamura, Black hole binary formation in the expanding Universe: Three body problem approximation, Phys. Rev. D **58**, 063003 (1998).

[62] Y. Ali-Haïmoud, E. D. Kovetz, and M. Kamionkowski, Merger rate of primordial black-hole binaries, Phys. Rev. D **96**, 123523 (2017).

[63] The normalization of the PBH distribution used in our fiducial model [60] differs by a factor of 2 from the normalization in Ref. [23]. As such, our fiducial model (used here and in Ref. [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 Ref. [23].

[64] 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 (2007).

[65] 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).

[66] S. M. Koushiappas and Abraham Loeb, Dynamics of Dwarf Galaxies Disfavor Stellar-Mass Black Holes as Dark Matter, Phys. Rev. Lett. **119**, 041102 (2017).

[67] T. D. Brandt, Constraints on MACHO dark matter from compact stellar systems in ultra-faint dwarf galaxies, Astrophys. J. **824**, L31 (2016).

[68] M. Zumalacarregui and U. Seljak, Limits on Stellar-Mass Compact Objects as Dark Matter from Gravitational Lensing of Type Ia Supernovae, Phys. Rev. Lett. **121**, 141101 (2018).

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

[70] B. P. Abbott *et al.*, Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Rev. Relativity **19**, 1 (2016); **21**, 3 (2018).

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]
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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,a] 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]

(LIGO Scientific Collaboration and the Virgo Collaboration)

S. Shandera[89]

[1]*LIGO, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Louisiana State University, Baton Rouge, Louisiana 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 Sant'Angelo, I-80126 Napoli, Italy*
[6]*OzGrav, School of Physics and Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[7]*LIGO Livingston Observatory, Livingston, Louisiana 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, 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]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[19]*NCSA, University of Illinois at Urbana–Champaign, Urbana, Illinois 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, Wisconsin 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, California 92831, USA*
[28]*LAL, Université 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, Florida 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), Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France*
[35]*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
[36]*Montclair State University, Montclair, New Jersey 07043, USA*
[37]*Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
[38]*Korea Institute of Science and Technology Information, Daejeon 34141, Korea*
[39]*West Virginia University, Morgantown, West Virginia 26506, USA*
[40]*Università di Perugia, I-06123 Perugia, Italy*
[41]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[42]*Syracuse University, Syracuse, New York 13244, USA*
[43]*University of Minnesota, Minneapolis, Minnesota 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, Washington 99352, USA*
[48]*Caltech CaRT, Pasadena, California 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, California 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, Montana 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 and Research in Astrophysics (CIERA), Northwestern University, Evanston, Illinois 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, New York 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, 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 Sant'Angelo, I-80126 Napoli, Italy*
[70]*Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[71]*Université Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France*
[72]*University of Oregon, Eugene, Oregon 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, Netherlands*
[76]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany*
[77]*University of Maryland, College Park, Maryland 20742, USA*
[78]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 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 Sant'Angelo, I-80126 Napoli, Italy*
[81]*NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[82]*RESCEU, University of Tokyo, Tokyo 113-0033, Japan*
[83]*Tsinghua University, Beijing 100084, China*
[84]*Texas Tech University, Lubbock, Texas 79409, USA*
[85]*Università di Roma Tor Vergata, I-00133 Roma, Italy*

[86]*The University of Mississippi, University, Mississippi 38677, USA*
[87]*Missouri University of Science and Technology, Rolla, Missouri 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, Pennsylvania 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, Illinois 60637, USA*
[94]*The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong*
[95]*Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[96]*Seoul National University, Seoul 08826, Korea*
[97]*Pusan National University, Busan 46241, Korea*
[98]*Carleton College, Northfield, Minnesota 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, California 94928, USA*
[105]*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
[106]*Columbia University, New York, New York 10027, USA*
[107]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[108]*University of Rhode Island, Kingston, Rhode Island 02881, USA*
[109]*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
[110]*Bellevue College, Bellevue, Washington 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, 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, Colorado 80523, USA*
[122]*Kenyon College, Gambier, Ohio 43022, USA*
[123]*Christopher Newport University, Newport News, Virginia 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 Drive, Los Angeles, California 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, Michigan 48109, USA*
[139]*Washington State University, Pullman, Washington 99164, USA*
[140]*American University, Washington, D.C. 20016, USA*
[141]*University of Portsmouth, Portsmouth PO1 3FX, United Kingdom*
[142]*University of California, Berkeley, California 94720, USA*
[143]*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[144]*Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, Netherlands*

[145]*Directorate of Construction, Services and 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, Washington 98011, USA*
[150]*Institute of Applied Physics, Nizhny Novgorod 603950, Russia*
[151]*Ewha Womans University, Seoul 03760, Korea*
[152]*Inje University Gimhae, South Gyeongsang 50834, Korea*
[153]*National Institute for Mathematical Sciences, Daejeon 34047, Korea*
[154]*Ulsan National Institute of Science and Technology, Ulsan 44919, Korea*
[155]*Maastricht University, P.O. Box 616, 6200 MD Maastricht, Netherlands*
[156]*Bard College, 30 Campus Road, Annandale-On-Hudson, New York 12504, USA*
[157]*NCBJ, 05-400 Świerk-Otwock, Poland*
[158]*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[159]*Cornell University, Ithaca, New York 14850, USA*
[160]*Hillsdale College, Hillsdale, Michigan 49242, USA*
[161]*Hanyang University, Seoul 04763, Korea*
[162]*Korea Astronomy and Space Science Institute, Daejeon 34055, Korea*
[163]*Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[164]*NASA Marshall Space Flight Center, Huntsville, Alabama 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, Victoria 3122, Australia*
[169]*Southern University and A&M College, Baton Rouge, Louisiana 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, Washington 99362, USA*
[176]*Université de Lyon, F-69361 Lyon, France*
[177]*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
[178]*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
[179]*University of Washington, Seattle, Washington 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 West Clybourn Street, Milwaukee, Wisconsin 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 Avenue, Villanova, Pennsylvania 19085, USA*
[189]*Andrews University, Berrien Springs, Michigan 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, Texas 78212, USA*
[193]*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands*
[194]*Department of Physics, University of Texas, Austin, Texas 78712, USA*

[a] Deceased.