



Publication Year	2017
Acceptance in OA @INAF	2023-05-30T14:40:45Z
Title	Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube
Authors	Albert, A.; André, M.; Anghinolfi, M.; Anton, G.; Ardid, M.; et al.
DOI	10.1103/PhysRevD.96.022005
Handle	http://hdl.handle.net/20.500.12386/34227
Journal	PHYSICAL REVIEW D
Number	96

Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube

A. Albert *et al.**

(ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration)

(Received 1 April 2017; published 12 July 2017)

The Advanced LIGO observatories detected gravitational waves from two binary black hole mergers during their first observation run (O1). We present a high-energy neutrino follow-up search for the second gravitational wave event, GW151226, as well as for gravitational wave candidate LVT151012. We find two and four neutrino candidates detected by IceCube, and one and zero detected by ANTARES, within ± 500 s around the respective gravitational wave signals, consistent with the expected background rate. None of these neutrino candidates are found to be directionally coincident with GW151226 or LVT151012. We use nondetection to constrain isotropic-equivalent high-energy neutrino emission from GW151226, adopting the GW event's 3D localization, to less than $2 \times 10^{51} - 2 \times 10^{54}$ erg.

DOI: 10.1103/PhysRevD.96.022005

I. INTRODUCTION

Gravitational wave (GW) astronomy began with the observation of a binary black hole (BBH) merger by Advanced LIGO on September 14th, 2015 [1]. Following this first discovery, LIGO recorded an additional BBH merger, GW151226 [2]. Another possible signal, named LVT151012, has also been identified with 87% probability that it was of astrophysical origin [3]. These events provide information on the formation mechanism, environment and rate of BBH mergers. They also enable sensitive tests of gravity in the strong field regime [3].

The GW signals were followed up by a broad multi-messenger observation campaign, covering the full electromagnetic spectrum [4] as well as neutrinos [5–7]. Data from the Gamma-ray Burst Monitor on the Fermi satellite [8] indicate a signal that could be associated with the first merger observed, GW150914, although this signal is in tension with nondetection by INTEGRAL [9]. BBH mergers may produce electromagnetic or neutrino emission if a sufficient amount of circumbinary matter is available for accretion. Most BBH systems likely lack such an environment; however, some binaries residing in active galactic nuclei [10,11], or those with gas remaining from their stellar progenitors [12,13], may produce a detectable counterpart [14,15].

Accreting black holes can drive relativistic outflows [16]. Dissipation within outflows with a hadronic component can produce nonthermal, high-energy neutrinos [17,18].

High-energy neutrinos of astrophysical origin have recently been discovered by the IceCube detector [19–22]; however, the source of these neutrinos is currently unknown.

In this paper we report the results of high-energy neutrino follow-up searches of GW event GW151226 and GW candidate LVT151012 using the IceCube Neutrino Observatory, a cubic-kilometer facility at the South Pole [23–25], and the ANTARES neutrino telescope in the Mediterranean sea [26–28]. We briefly discuss the detectors and search procedure in Sec. II and present the results in Sec. III. We summarize our results and conclude in Sec. IV.

II. ANALYSIS

On December 26, 2015 at 03:38:53 UTC, the Advanced LIGO detectors observed the coalescence of two black holes, an event named GW151226, with estimated masses of $14.2_{-3.7}^{+8.3} M_{\odot}$ and $7.5_{-2.3}^{+2.3} M_{\odot}$, at a luminosity distance of 440_{-190}^{+180} Mpc, corresponding to a redshift of $0.09_{-0.04}^{+0.03}$ [3]. Subsequently, the significance of the event was established to be greater than 5σ by offline analyses. The source of the GW was confined to within 850 deg^2 of the sky at 90% credible level (hereafter skymap) [3].

Beyond GW151226 (and the first observed GW event GW150914 [29]), LIGO also detected a GW event candidate, LVT151012, on October 12, 2015 at 09:54:43 UTC [3]. While this candidate was not sufficiently significant to claim discovery, it is probably of astrophysical origin. If LVT151012 is indeed a GW signal, it is consistent with a BBH merger at luminosity distance 1000_{-500}^{+500} Mpc, or redshift of $0.20_{-0.09}^{+0.09}$, with black hole masses of $23_{-6}^{+18} M_{\odot}$ and $13_{-5}^{+4} M_{\odot}$. The source direction was confined to a 1600 deg^2 skymap [3]. Since this event candidate is probably astrophysical, we include it in this analysis.

We searched for neutrinos coincident with GW151226 and LVT151012 using a time window of ± 500 s around the

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

TABLE I. Parameters for neutrino candidates detected by IceCube within ± 500 s around GW151226 and LVT151012. ΔT is the time of arrival of the neutrino candidates relative to that of the GW event. E_{μ}^{rec} is the reconstructed muon energy. $\sigma_{\mu}^{\text{rec}}$ is the (50% for IceCube, 1σ for ANTARES) angular uncertainty of the reconstructed track direction [37,38].

Event	No.	Detector	ΔT [s]	RA [h]	Dec [°]	$\sigma_{\mu}^{\text{rec}}$ [°]	E_{μ}^{rec} [TeV]
GW151226	1	ANTARES	-387.3	16.7	-28.0	0.7	9
GW151226	2	IceCube	-290.9	21.7	-15.1	0.1	158
GW151226	3	IceCube	-22.5	5.9	14.9	0.7	6.3
LVT151012	1	IceCube	-423.3	24.0	28.7	3.5	0.38
LVT151012	2	IceCube	-410.0	0.5	32.0	1.1	0.45
LVT151012	3	IceCube	-89.8	7.7	-14.0	0.6	13.7
LVT151012	4	IceCube	147.0	0.6	12.3	0.3	0.35

GW transients. This is our standard search window adopted for joint GW-neutrino searches [30]. Within the ± 500 s, we do not further weigh the temporal difference between GWs and neutrinos. This time difference, nevertheless, may be indicative of the underlying emission mechanism [31–33].

For IceCube, we adopted the detector’s online event stream, which is used in IceCube’s online analyses [34,35]. This event selection was adopted to ensure compatibility with low-latency GW + neutrino searches. The online event stream uses an event selection similar to that of point source searches [36], but is optimized for near-real-time analysis at the South Pole. This event selection consists primarily of cosmic-ray-induced background events, with an expectation of 2.2 events in the northern sky (atmospheric neutrinos) and 2.2 events in the southern sky (high-energy atmospheric muons) per 1000 seconds. In the search window of ± 500 s centered on the GW alert times, two and four neutrino candidates were found by IceCube in correspondence of GW151226 and LVT151012, respectively. This result is consistent with the expected background. The properties of these events are listed in Table I. The listed muon energies are reconstructed assuming a single muon is producing the event. The sky location of the neutrino candidates are shown in Fig. 1. The significantly greater reconstructed energy for the neutrino candidates on the southern hemisphere is consistent with our expectations due to the different selection criteria on the two hemispheres, allowed by the Earth’s filtering effect of atmospheric muons.

We performed an additional search for high-energy starting events detected by IceCube (that is, events with tracks starting within the detector). A significant fraction of high-energy starting events are likely of astrophysical origin given the low background rate at the considered high energies. The corresponding IceCube event selection is described in [19]. No high-energy starting events were found in coincidence with GW151226 or LVT151012.

The IceCube detector is also sensitive to outbursts of MeV neutrinos via a sudden increase in the photo-multiplier counting rates. Galactic core-collapse supernovae, e.g., will be detected with high significance [39].

This global counting rate is monitored continuously, the influence of cosmic-ray muons is removed and low-level triggers are formed when deviations from the nominal rate exceed predefined levels. An IceCube MeV neutrino trigger was issued on October 12th, 2015, 09:56:36 UTC. The probability of a trigger with the recorded excess counting rate to occur during the ± 500 s time window around the GW candidate is 12%. This is not sufficiently significant to require further consideration. To account for the possible time delay of \sim MeV neutrinos traveling from the

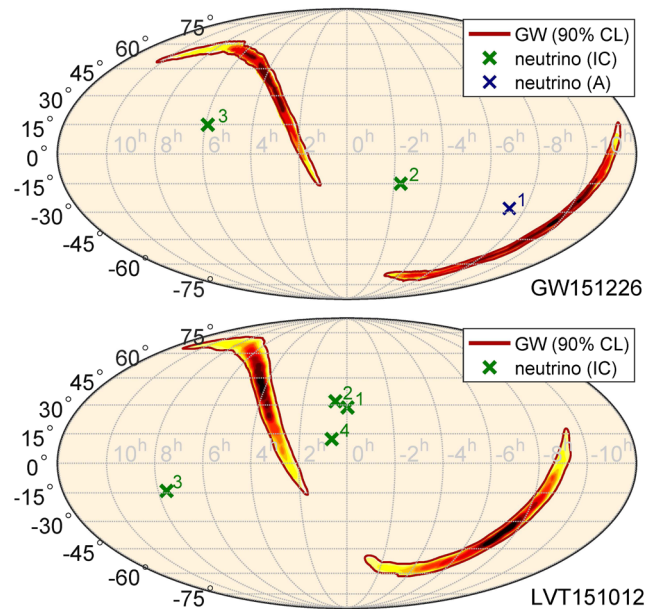


FIG. 1. GW skymap for GW151226 (top) and LVT151012 (bottom), and the reconstructed directions for high-energy neutrino candidates detected by IceCube (green crosses) and ANTARES (blue cross) within ± 500 s around the GW signals. The maps are in equatorial coordinates. The GW skymap shows the reconstructed probability density contours of the GW event 90% C.L. GW shading indicates the reconstructed probability density of the GW event, darker regions corresponding to higher probability. The neutrino directional uncertainties are below 1° for most of the candidates, and in any case too small to be shown. Neutrino event numbers refer to the first column of Table I.

reconstructed distances of GW151226 and LVT151012, we also considered an extended time window of ± 1 h. For LVT151012, the same trigger remained the most significant even within this extended window. For GW151226, the trigger with the highest excess counting rate within ± 1 h was recorded +51 min after the GW event. Events with at least the measured excess counting rate occur at a rate of $\sim 0.3 \text{ h}^{-1}$; therefore, we do not consider it to be of astrophysical origin.

We searched for coincident neutrinos within ANTARES data by selecting up-going events. The search was performed with the most recent official offline data set, produced incorporating dedicated calibrations, in terms of positioning [40], timing [41] and efficiency [27]. This sample is dominated by background events from misreconstructed down-going atmospheric muons. It was optimized for each GW event individually so that one event that passes the search criteria and is located within the 90% GW probability contour would lead to a detection with a significance level of 3σ . For GW151226, a total of 1.4×10^{-2} atmospheric neutrino candidates are expected in the field of view within ± 500 s, while the number of misreconstructed down-going muons amounts to 8×10^{-2} events in the same time window. We found one event that is temporally coincident with GW151226, located outside the 90% GW probability contour. The Poissonian probability of detecting at least one such background event when 9.4×10^{-2} are expected is $\sim 9\%$. Thus, this detection is consistent with the expected background muon rate and we conclude that this event is likely a misreconstructed down-going muon. The properties of this event are listed in Table I. In particular, the estimated deposited energy [42] is 9 TeV, in agreement with what is expected from a misreconstructed down-going muon. The sky location of the event is shown in Fig. 1.

For LVT151210, the atmospheric neutrino candidate rate expected from the southern sky within ± 500 s is equal to 1.8×10^{-2} while the number of misreconstructed down-going muons amounts to 4×10^{-2} . These are somewhat different from the values obtained for GW151226 as the sensitivity of ANTARES varies with time. No neutrino candidates temporally coincident with LVT151012 were found with ANTARES.

III. RESULTS

A. Constraints on neutrino emission

We found that of the temporally coincident neutrino candidates, none were directionally coincident with the GW signals at the 90% credible level, as shown in Fig. 1.

We use the nondetection of joint GW and neutrino events to constrain neutrino emission from the GW source. Since the sensitivity of neutrino detectors is highly dependent on source direction, we calculate upper limits as a function of source direction for the whole sky.

Upper limits on the neutrino emission for IceCube from a point source within the ± 500 s second interval are calculated in a similar way to the procedure in [43], using a Monte Carlo simulation to determine the mean fluence required to produce a neutrino signal in 90% of simulated trials that is above the observed one in the data. For ANTARES, we computed upper limits (90% confidence level) using a full Monte Carlo simulation, with the standard ANTARES chain [44–46], of the detector’s response at the time for the GW signal.

For a given direction, we adopt the upper limit from IceCube or ANTARES, whichever is more constraining. Fig. 2 shows this neutrino spectral fluence upper limit for GW151226 as a function of source direction. We calculate upper limits on the spectral fluence ϕ_0 for two different neutrino spectral models: $dN/dE = \phi_0 E^{-2}$ typically expected for Fermi acceleration [17], and $dN/dE = \phi_0 E^{-2} \exp[-(E/100 \text{ TeV})^{1/2}]$, in order to characterize sensitivity to a source that emits only at lower energies (e.g., [32]). We show the same upper limits for LVT151012 in Fig. 3. These limits are similar to those obtained for GW event GW150914 [5].

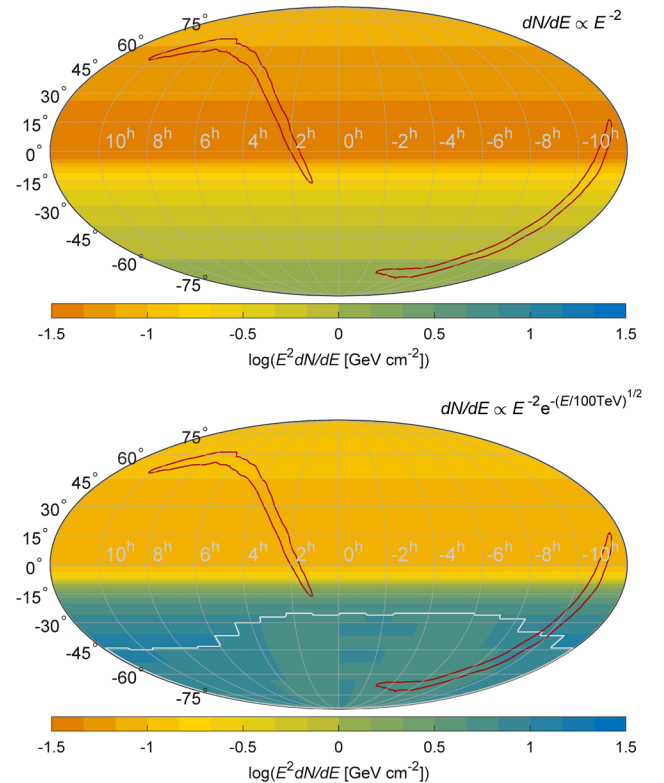


FIG. 2. Upper limit for high-energy neutrino spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) as a function of source direction corresponding to GW151226, assuming $dN/dE \propto E^{-2}$ (top) and $dN/dE \propto E^{-2} \exp[-(E/100 \text{ TeV})^{1/2}]$ (bottom) neutrino spectra. The region surrounded by a white line shows the part of the sky in which ANTARES is more sensitive (lowest declinations), while in the rest of the sky, IceCube is more sensitive. For comparison, the 90% credible-level contour for the GW skymap is also shown.

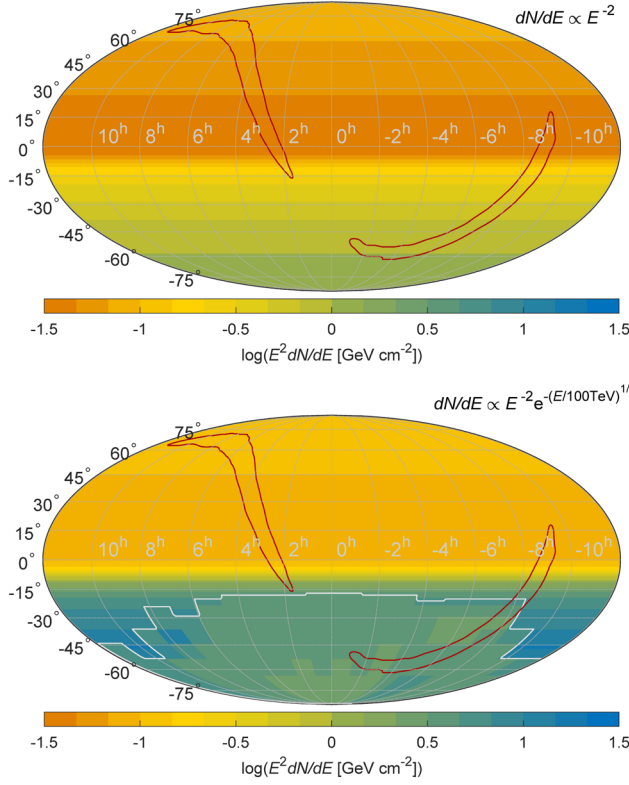


FIG. 3. Same as Fig. 2, but for LVT151012.

B. Constraints from 3D gravitational wave localization

The GW signal of a binary merger contains information not only on the source direction, but also on its distance, which can be reconstructed [47]. The source position can therefore be constrained to within a 3D volume [48]. The GW detectors' direction-dependent sensitivity and the detector noise make such a 3D sky volume skewed towards some directions. Reconstructing a 3D source constraint is useful for identifying possible host galaxies for follow-up observations [49–53]. It can also be used for deriving direction-dependent multimessenger source constraints.

We adopt the reconstructed sky volume for GW151226 to constrain neutrino emission as a function of source direction [54]. We take the lower limit $D_{\text{low}}^{95\%}(\vec{x})$ on the source distance for a given direction \vec{x} such that the source is located within this distance at 95% credible level. We then use $D_{\text{low}}^{95\%}(\vec{x})$ to calculate the upper limit on the total isotropic-equivalent energy emitted in neutrinos by the source as follows:

$$E_{\nu, \text{iso}}^{\text{ul}}(\vec{x}) = 4\pi [D_{\text{low}}^{95\%}(\vec{x})]^2 \int \frac{dN}{dE} E dE. \quad (1)$$

We obtain upper limits for both $dN/dE \propto E^{-2}$ and $dN/dE \propto E^{-2} \exp[-(E/100 \text{ TeV})^{1/2}]$ neutrino spectral models. We integrate the spectrum over the interval [100 GeV, 100 PeV] for both spectral models. The resulting limits as a function of the position on the sky are shown in

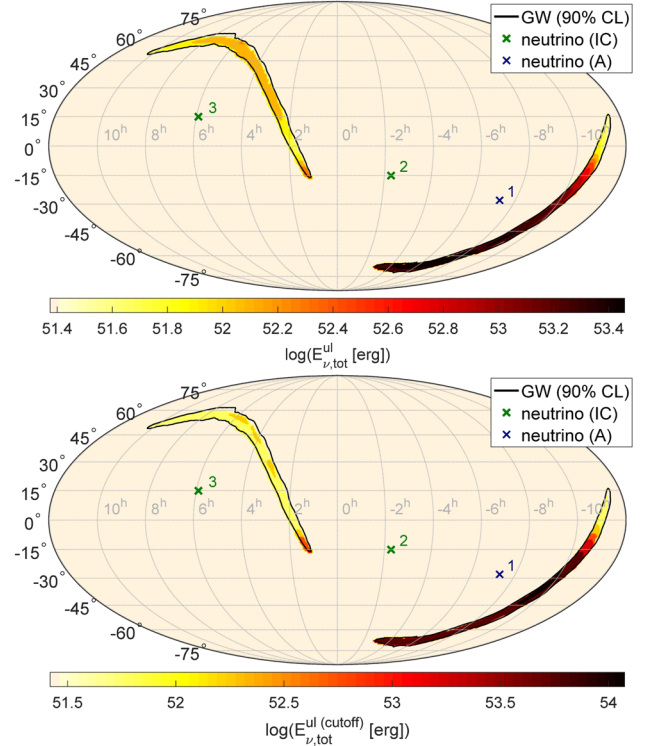


FIG. 4. Upper limit on the total energy radiated in high-energy neutrinos by the progenitor of GW151226 as a function of source direction, assuming $dN/dE \propto E^{-2}$ (top) and $dN/dE \propto E^{-2} \exp[-(E/100 \text{ TeV})^{1/2}]$ (bottom) neutrino spectra. The direction-dependent constraint is derived from the direction-dependent neutrino spectral fluence upper limit (see Fig. 2) as well as the reconstructed 3D GW localization.

Fig. 4. We see that for either spectral model, there is over two orders of magnitude variation in the total neutrino emission upper limit over the GW skymap. To quantify the range of the upper limits over the skymap, we calculate the minimum and maximum upper limit values over the whole GW skymap, separately for the two spectral models. We obtain the following ranges:

$$E_{\nu, \text{iso}}^{\text{ul}} = (2 \times 10^{51} - 3 \times 10^{53}) \text{ erg}, \quad (2)$$

$$E_{\nu, \text{iso}}^{\text{ul}(\text{cutoff})} = (3 \times 10^{51} - 2 \times 10^{54}) \text{ erg}. \quad (3)$$

For comparison, the total energy emitted from GW151226 in GWs is $\approx 1.8 \times 10^{54}$ erg. Constraints for LVT151012 are about a factor of four weaker as its expected distance is about twice that of GW151226 [3], while both their skymaps similarly lie over a large declination range, corresponding to similar neutrino detector sensitivities.

IV. CONCLUSION

Searching in data recorded by the IceCube Neutrino Observatory and the ANTARES Neutrino Telescope, we detected no neutrino emission associated with the second

binary black hole merger, GW151226, discovered by Advanced LIGO. We similarly found no coincident neutrino emission for GW event candidate LVT151012. We used the nondetection to constrain the total neutrino emission from GW151226 to $\sim 2 \times 10^{51} - 2 \times 10^{54}$ erg, allowing for different possible neutrino spectra. For these constraints, we also adopted 3D GW localizations and found significant directional dependence in the neutrino emission upper limit. This is due to the fact that the sensitivity of both neutrino and GW detectors is direction dependent.

The observational constraints on total neutrino emission for GW151226 presented here are overall about a factor of two better than the range $5.4 \times 10^{51} - 3.7 \times 10^{54}$ erg previously reported for GW event GW150914 [5]; however, this previous work has not incorporated 3D localization for GWs. Without this change, the range of observational constraints for GW150914 and GW151226 would be essentially identical, since (i) the sensitivities of the neutrino observatories are very similar for the two cases, (ii) the luminosity distance of the two GW events is also similar, and (iii) both GW events have sky localizations consistent with both a northern and southern origin, for which neutrino sensitivities are very different. Nevertheless, the source direction for GW151226 has higher probability of originating from the northern hemisphere, for which the upper limits are significantly more constraining.

High-energy neutrino emission induced by a binary black hole system would require significant gas accretion, as well as for an energetic outflow driven by the accretion disk to be beamed towards the Earth. These conditions are not satisfied for most binary black hole mergers. Nevertheless, with the expected high rate of observations by the Advanced LIGO-Virgo network, neutrino searches can probe even small subpopulations of mergers, testing binary evolution channels in gaseous environments. With the all-sky sensitivity of neutrino detectors, these searches represent a promising way in comprehensively probing high-energy emission also for sources outside of the field of view of electromagnetic telescopes, and even for emission prior to the detection of the GW event.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the funding agencies: Centre National de la Recherche Scientifique (CNRS), Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Commission Européenne (FEDER fund and Marie Curie Program), Institut Universitaire de France (IUF), IdEx program and UnivEarthS Labex program at Sorbonne Paris Cité (Grants No. ANR-10-LABX-0023 and No. ANR-11-IDEX-0005-02), Labex OCEVU (Grant No. ANR-11-LABX-0060) and the A*MIDEX project (Grant No. ANR-11-IDEX-0001-02), Région Île-de-France (DIM-ACAV), Région Alsace (contrat CPER), Région Provence-Alpes-Côte d'Azur,

Département du Var and Ville de La Seyne-sur-Mer, France; Bundesministerium für Bildung und Forschung (BMBF), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Stichting voor Fundamenteel Onderzoek der Materie (FOM), Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; Council of the President of the Russian Federation for young scientists and leading scientific schools supporting grants, Russia; National Authority for Scientific Research (ANCS), Romania; Ministerio de Economía y Competitividad (MINECO): Plan Estatal de Investigación [Grants No. FPA2015-65150-C3-1-P, No. -2-P and No. -3-P, (MINECO/FEDER)], Severo Ochoa Centre of Excellence and MultiDark Consolider (MINECO), and Prometeo and Grisolia programs (Generalitat Valenciana), Spain; Ministry of Higher Education, Scientific Research and Professional Training, Morocco. We also acknowledge the technical support of Ifremer, AIM and Foselev Marine for the sea operation and the CC-IN2P3 for the computing facilities. We acknowledge the support from the following agencies: U.S. National Science Foundation—Office of Polar Programs, U.S. National Science Foundation—Physics Division, University of Wisconsin Alumni Research Foundation, the Grid Laboratory Of Wisconsin (GLOW) grid infrastructure at the University of Wisconsin—Madison, the Open Science Grid (OSG) grid infrastructure; U.S. Department of Energy, and National Energy Research Scientific Computing Center, the Louisiana Optical Network Initiative (LONI) grid computing resources; Natural Sciences and Engineering Research Council of Canada, WestGrid and Compute/Calcul Canada; Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Research Department of Plasmas with Complex Interactions (Bochum), Germany; Fund for Scientific Research (FNRS-FWO), FWO Odysseus programme, Flanders Institute to encourage scientific and technological research in industry (IWT), Belgian Federal Science Policy Office (Belspo); University of Oxford, United Kingdom; Marsden Fund, New Zealand; Australian Research Council; Japan Society for Promotion of Science (JSPS); the Swiss National Science Foundation (SNSF), Switzerland; National Research Foundation of Korea (NRF); Villum Fonden, Danish National Research Foundation (DNRF), Denmark. 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 European Gravitational Observatory (EGO) consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board, India; Ministry of Human Resource Development, India; the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia i Competitivitat and Conselleria

d'Educació, Cultura i Universitats of the Govern de les Illes Balears; the National Science Centre of Poland; the European Commission; the Royal Society; the Scottish Funding Council; the Scottish Universities Physics Alliance; the Hungarian Scientific Research Fund; the Lyon Institute of Origins; the National Research Foundation of Korea; Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation; the Natural Science and Engineering Research Council Canada; Canadian Institute for Advanced Research; the Brazilian Ministry of Science, Technology, and Innovation, Fundao de Amparo à Pesquisa do Estado de So Paulo (FAPESP); Russian Foundation for Basic Research; the Leverhulme Trust; the Research Corporation; Ministry of Science and Technology, 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 the provision of computational resources.

-
- [1] B. Abbott *et al.*, *Phys. Rev. Lett.* **116**, 061102 (2016).
 [2] B. Abbott *et al.*, *Phys. Rev. Lett.* **116**, 241103 (2016).
 [3] B.P. Abbott (LIGO Scientific Collaboration and Virgo Collaboration), *Phys. Rev. X* **6**, 041015 (2016).
 [4] B. Abbott *et al.*, *Astrophys. J. Lett.* **826**, L13 (2016).
 [5] S. Adrián-Martínez *et al.*, *Phys. Rev. D* **93**, 122010 (2016).
 [6] A. Aab (Pierre Auger Collaboration), *Phys. Rev. D* **94**, 122007 (2016).
 [7] K. Abe (Super-Kamiokande Collaboration), *Astrophys. J. Lett.* **830**, L11 (2016).
 [8] V. Connaughton *et al.*, *Astrophys. J. Lett.* **826**, L6 (2016).
 [9] V. Savchenko *et al.*, *Astrophys. J. Lett.* **820**, L36 (2016).
 [10] I. Bartos, B. Kocsis, Z. Haiman, and S. Márka, *Astrophys. J.* **835**, 165 (2017).
 [11] N. Stone, B. Metzger, and Z. Haiman, *Mon. Not. R. Astron. Soc.* **464**, 946 (2017).
 [12] R. Perna, D. Lazzati, and B. Giacomazzo, *Astrophys. J. Lett.* **821**, L18 (2016).
 [13] A. Loeb, *Astrophys. J. Lett.* **819**, L21 (2016).
 [14] K. Murase, K. Kashiyama, P. Mészáros, I. Shoemaker, and N. Senno, *Astrophys. J. Lett.* **822**, L9 (2016).
 [15] X. Li, F.-W. Zhang, Q. Yuan, Z.-P. Jin, Y.-Z. Fan, S.-M. Liu, and D.-M. Wei, *Astrophys. J. Lett.* **827**, L16 (2016).
 [16] P. Mészáros, *Rep. Prog. Phys.* **69**, 2259 (2006).
 [17] E. Waxman and J. Bahcall, *Phys. Rev. Lett.* **78**, 2292 (1997).
 [18] A. Beloborodov, *Mon. Not. R. Astron. Soc.* **407**, 1033 (2010).
 [19] M. Aartsen *et al.*, *Phys. Rev. Lett.* **113**, 101101 (2014).
 [20] M. Aartsen *et al.*, *Phys. Rev. Lett.* **115**, 081102 (2015).
 [21] M. Aartsen *et al.*, *Phys. Rev. D* **91**, 022001 (2015).
 [22] M. Aartsen *et al.*, *Astrophys. J.* **809**, 98 (2015).
 [23] A. Achterberg *et al.*, *Astropart. Phys.* **26**, 155 (2006).
 [24] R. Abbasi *et al.*, *Nucl. Instrum. Methods Res., Sect. A* **601**, 294 (2009).
 [25] R. Abbasi *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **618**, 139 (2010).
 [26] M. Ageron *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **656**, 11 (2011).
 [27] J. Aguilar *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **570**, 107 (2007).
 [28] J. Aguilar *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **555**, 132 (2005).
 [29] B. Abbott *et al.*, *Phys. Rev. Lett.* **116**, 061102 (2016).
 [30] B. Baret *et al.*, *Astropart. Phys.* **35**, 1 (2011).
 [31] S. Razzaque, P. Mészáros, and E. Waxman, *Phys. Rev. D* **68**, 083001 (2003).
 [32] I. Bartos, B. Dasgupta, and S. Márka, *Phys. Rev. D* **86**, 083007 (2012).
 [33] I. Bartos and S. Márka, *Phys. Rev. D* **90**, 101301 (2014).
 [34] T. Kintscher and IceCube Collaboration, *J. Phys. Conf. Ser.* **718**, 062029 (2016).
 [35] M.G. Aartsen *et al.* (IceCube Collaboration), arXiv: 1612.06028.
 [36] M. Aartsen *et al.*, *Astrophys. J.* **796**, 109 (2014).
 [37] M. Aartsen *et al.*, *Phys. Rev. D* **89**, 102004 (2014).
 [38] S. Adrián-Martínez *et al.*, *Astrophys. J. Lett.* **786**, L5 (2014).
 [39] R. Abbasi *et al.*, *Astron. Astrophys.* **535**, A109 (2011).
 [40] S. Adrián-Martínez *et al.*, *J. Instrum.* **7**, T08002 (2012).
 [41] J.A. Aguilar (ANTARES Collaboration), *Astropart. Phys.* **34**, 539 (2011).
 [42] S. Adrián-Martínez *et al.*, *Eur. Phys. J. C* **73**, 2606 (2013).
 [43] M. Aartsen *et al.*, *Astrophys. J.* **807**, 46 (2015).
 [44] J. Brunner, VLVnT Workshop **100**, 109 (2003).

- [45] A. Margiotta and the ANTARES Collaboration, *Nucl. Instrum. Methods Res., Sect. A* **725**, 98 (2013).
- [46] L. Fusco and A. Margiotta, *Eur. Phys. J. Web Conf.* **116**, 02002 (2016).
- [47] B. P. Abbott *et al.*, *Phys. Rev. Lett.* **116**, 241102 (2016).
- [48] S. Nissanke, M. Kasliwal, and A. Georgieva, *Astrophys. J.* **767**, 124 (2013).
- [49] I. Bartos, A. Crotts, and S. Márka, *Astrophys. J. Lett.* **801**, L1 (2015).
- [50] I. Bartos, T. Huard, and S. Márka, *Astrophys. J.* **816**, 61 (2016).
- [51] C. Hanna, I. Mandel, and W. Vousden, *Astrophys. J.* **784**, 8 (2014).
- [52] X. Fan, C. Messenger, and I. Heng, *Astrophys. J.* **795**, 43 (2014).
- [53] L. Blackburn, M. S. Briggs, J. Camp, N. Christensen, V. Connaughton, P. Jenke, R. A. Remillard, and J. Veitch, *Astrophys. J. Suppl. Ser.* **217**, 8 (2015).
- [54] L. Singer *et al.*, *Astrophys. J. Lett.* **829**, L15 (2016).

A. Albert,¹ M. André,² M. Anghinolfi,³ G. Anton,⁴ M. Ardid,⁵ J.-J. Aubert,⁶ T. Avgitas,⁷ B. Baret,⁷ J. Barrios-Martí,⁸ S. Basa,⁹ V. Bertin,⁶ S. Biagi,¹⁰ R. Bormuth,^{11,12} S. Bourret,⁷ M. C. Bouwhuis,¹¹ R. Bruijn,^{11,13} J. Brunner,⁶ J. Busto,⁶ A. Capone,^{14,15} L. Caramete,¹⁶ J. Carr,⁶ S. Celli,^{14,15,17} T. Chiarusi,¹⁸ M. Circella,¹⁹ J. A. B. Coelho,⁷ A. Coleiro,⁷ R. Coniglione,¹⁰ H. Costantini,⁶ P. Coyle,⁶ A. Creusot,⁷ A. Deschamps,²⁰ G. De Bonis,^{14,15} C. Distefano,¹⁰ I. Di Palma,^{14,15} C. Donzaud,^{7,21} D. Dornic,⁶ D. Drouhin,¹ T. Eberl,⁴ I. El Bojaddaini,²² D. Elsässer,²³ A. Enzenhöfer,⁶ I. Felis,⁵ L. A. Fusco,^{18,24} S. Galatà,⁷ P. Gay,^{25,7} V. Giordano,²⁶ H. Glotin,^{27,28} T. Grégoire,⁷ R. Gracia Ruiz,⁷ K. Graf,⁴ S. Hallmann,⁴ H. van Haren,²⁹ A. J. Heijboer,¹¹ Y. Hello,²⁰ J. J. Hernández-Rey,⁸ J. Hößl,⁴ J. Hofestädt,⁴ C. Hugon,^{3,30} G. Illuminati,^{8,14,15} C. W. James,⁴ M. de Jong,^{11,12} M. Jongen,¹¹ M. Kadler,²³ O. Kalekin,⁴ U. Katz,⁴ D. Kießling,⁴ A. Kouchner,^{7,28} M. Kreter,²³ I. Kreykenbohm,³¹ V. Kulikovskiy,^{6,32} C. Lachaud,⁷ R. Lahmann,⁴ D. Lefèvre,³³ E. Leonora,^{26,34} M. Lotze,⁸ S. Loucatos,^{35,7} M. Marcelin,⁹ A. Margiotta,^{18,24} A. Marinelli,^{36,37} J. A. Martínez-Mora,⁵ A. Mathieu,⁶ R. Mele,^{38,39} K. Melis,^{11,13} T. Michael,¹¹ P. Migliozzi,³⁸ A. Moussa,²² E. Nezri,⁹ G. E. Pávālas,¹⁶ C. Pellegrino,^{18,24} C. Perrina,^{14,15} P. Piattelli,¹⁰ V. Popa,¹⁶ T. Pradier,⁴⁰ L. Quinn,⁶ C. Racca,¹ G. Riccobene,¹⁰ A. Sánchez-Losa,¹⁹ M. Saldaña,⁵ I. Salvadori,⁶ D. F. E. Samtleben,^{11,12} M. Sanguineti,^{3,30} P. Sapienza,¹⁰ F. Schüssler,³⁵ C. Sieger,⁴ M. Spurio,^{18,24} Th. Stolarczyk,³⁵ M. Taiuti,^{3,30} Y. Tayalati,⁴¹ A. Trovato,¹⁰ D. Turpin,⁶ C. Tönnis,⁸ B. Vallage,^{35,7} C. Vallée,⁶ V. Van Elewyck,^{7,28} F. Versari,^{18,24} D. Vivolo,^{38,39} A. Vizzoca,^{14,15} J. Wilms,³¹ J. D. Zornoza,⁸ and J. Zúñiga⁸
(ANTARES Collaboration)

M. G. Aartsen,⁴² M. Ackermann,⁴³ J. Adams,⁴⁴ J. A. Aguilar,⁴⁵ M. Ahlers,⁴⁶ M. Ahrens,⁴⁷ I. Al Samarai,⁴⁸ D. Altmann,⁴ K. Andeen,⁴⁹ T. Anderson,⁵⁰ I. Anseau,⁴⁵ G. Anton,⁴ M. Archinger,⁵¹ C. Argüelles,⁵² J. Auffenberg,⁵³ S. Axani,⁵² H. Bagherpour,⁴⁴ X. Bai,⁵⁴ S. W. Barwick,⁵⁵ V. Baum,⁵¹ R. Bay,⁵⁶ J. J. Beatty,^{57,58} J. Becker Tjus,⁵⁹ K.-H. Becker,⁶⁰ S. BenZvi,⁶¹ D. Berley,⁶² E. Bernardini,⁴³ D. Z. Besson,⁶³ G. Binder,^{64,56} D. Bindig,⁶⁰ E. Blaufuss,⁶² S. Blot,⁴³ C. Bohm,⁴⁷ M. Börner,⁶⁵ F. Bos,⁵⁹ D. Bose,⁶⁶ S. Böser,⁵¹ O. Botner,⁶⁷ F. Bradascio,⁴³ J. Braun,⁴⁶ L. Brayeur,⁶⁸ H.-P. Bretz,⁴³ S. Bron,⁴⁸ A. Burgman,⁶⁷ T. Carver,⁴⁸ M. Casier,⁶⁸ E. Cheung,⁶² D. Chirkin,⁴⁶ A. Christov,⁴⁸ K. Clark,⁶⁹ L. Classen,⁷⁰ S. Coenders,⁷¹ G. H. Collin,⁵² J. M. Conrad,⁵² D. F. Cowen,^{50,72} R. Cross,⁶¹ M. Day,⁴⁶ J. P. A. M. de André,⁷³ C. De Clercq,⁶⁸ E. del Pino Rosendo,⁵¹ H. Dembinski,⁷⁴ S. De Ridder,⁷⁵ P. Desiati,⁴⁶ K. D. de Vries,⁶⁸ G. de Wasseige,⁶⁸ M. de With,⁷⁶ T. DeYoung,⁷³ J. C. Díaz-Vélez,⁴⁶ V. di Lorenzo,⁵¹ H. Dujmovic,⁶⁶ J. P. Dumm,⁴⁷ M. Dunkman,⁵⁰ B. Eberhardt,⁵¹ T. Ehrhardt,⁵¹ B. Eichmann,⁵⁹ P. Eller,⁵⁰ S. Euler,⁶⁷ P. A. Evenson,⁷⁴ S. Fahey,⁴⁶ A. R. Fazely,⁷⁷ J. Feintzeig,⁴⁶ J. Felde,⁶² K. Filimonov,⁵⁶ C. Finley,⁴⁷ S. Flis,⁴⁷ C.-C. Fösig,⁵¹ A. Franckowiak,⁴³ E. Friedman,⁶² T. Fuchs,⁶⁵ T. K. Gaisser,⁷⁴ J. Gallagher,⁷⁸ L. Gerhardt,^{64,56} K. Ghorbani,⁴⁶ W. Giang,⁷⁹ L. Gladstone,⁴⁶ T. Glauch,⁵³ T. Glüsenkamp,⁴ A. Goldschmidt,⁶⁴ J. G. Gonzalez,⁷⁴ D. Grant,⁷⁹ Z. Griffith,⁴⁶ C. Haack,⁵³ A. Hallgren,⁶⁷ F. Halzen,⁴⁶ E. Hansen,⁸⁰ T. Hansmann,⁵³ K. Hanson,⁴⁶ D. Hebecker,⁷⁶ D. Heereman,⁴⁵ K. Helbing,⁶⁰ R. Hellauer,⁶² S. Hickford,⁶⁰ J. Hignight,⁷³ G. C. Hill,⁴² K. D. Hoffman,⁶² R. Hoffmann,⁶⁰ K. Hoshina,^{46,235} F. Huang,⁵⁰ M. Huber,⁷¹ K. Hultqvist,⁴⁷ S. In,⁶⁶ A. Ishihara,⁸¹ E. Jacobi,⁴³ G. S. Japaridze,⁸² M. Jeong,⁶⁶ K. Jero,⁴⁶ B. J. P. Jones,⁵² W. Kang,⁶⁶ A. Kappes,⁷⁰ T. Karg,⁴³ A. Karle,⁴⁶ U. Katz,⁴ M. Kauer,⁴⁶ A. Keivani,⁵⁰ J. L. Kelley,⁴⁶ A. Kheirandish,⁴⁶ J. Kim,⁶⁶ M. Kim,⁶⁶ T. Kintscher,⁴³ J. Kiryluk,⁸³ T. Kittler,⁴ S. R. Klein,^{64,56} G. Kohlen,⁸⁴ R. Koirala,⁷⁴ H. Kolanoski,⁷⁶ R. Konietz,⁵³ L. Köpke,⁵¹ C. Kopper,⁷⁹ S. Kopper,⁶⁰ D. J. Koskinen,⁸⁰ M. Kowalski,^{76,43} K. Krings,⁷¹ M. Kroll,⁵⁹ G. Krückl,⁵¹ C. Krüger,⁴⁶ J. Kunnen,⁶⁸ S. Kunwar,⁴³ N. Kurahashi,⁸⁵ T. Kuwabara,⁸¹ A. Kyriacou,⁴² M. Labare,⁷⁵ J. L. Lanfranchi,⁵⁰ M. J. Larson,⁸⁰ F. Lauber,⁶⁰ D. Lennarz,⁷³ M. Lesiak-Bzdak,⁸³ M. Leuermann,⁵³ L. Lu,⁸¹ J. Lünemann,⁶⁸ J. Madsen,⁸⁶ G. Maggi,⁶⁸ K. B. M. Mahn,⁷³ S. Mancina,⁴⁶

R. Maruyama,⁸⁷ K. Mase,⁸¹ R. Maunu,⁶² F. McNally,⁴⁶ K. Meagher,⁴⁵ M. Medici,⁸⁰ M. Meier,⁶⁵ T. Menne,⁶⁵ G. Merino,⁴⁶ T. Meures,⁴⁵ S. Miarcecki,^{64,56} J. Micallef,⁷³ G. Momenté,⁵¹ T. Montaruli,⁴⁸ M. Moulai,⁵² R. Nahnauer,⁴³ U. Naumann,⁶⁰ G. Neer,⁷³ H. Niederhausen,⁸³ S. C. Nowicki,⁷⁹ D. R. Nygren,⁶⁴ A. Obertacke Pollmann,⁶⁰ A. Olivas,⁶² A. O’Murchadha,⁴⁵ T. Palczewski,^{64,56} H. Pandya,⁷⁴ D. V. Pankova,⁵⁰ P. Peiffer,⁵¹ Ö. Penek,⁵³ J. A. Pepper,⁸⁸ C. Pérez de los Heros,⁶⁷ D. Pieloth,⁶⁵ E. Pinat,⁴⁵ P. B. Price,⁵⁶ G. T. Przybylski,⁶⁴ M. Quinnan,⁵⁰ C. Raab,⁴⁵ L. Rädcl,⁵³ M. Rameez,⁸⁰ K. Rawlins,⁸⁹ R. Reimann,⁵³ B. Relethford,⁸⁵ M. Relich,⁸¹ E. Resconi,⁷¹ W. Rhode,⁶⁵ M. Richman,⁸⁵ B. Riedel,⁷⁹ S. Robertson,⁴² M. Rongen,⁵³ C. Rott,⁶⁶ T. Ruhe,⁶⁵ D. Ryckbosch,⁷⁵ D. Rysewyk,⁷³ L. Sabbatini,⁴⁶ S. E. Sanchez Herrera,⁷⁹ A. Sandrock,⁶⁵ J. Sandroos,⁵¹ S. Sarkar,^{80,90} K. Satalecka,⁴³ P. Schlunder,⁶⁵ T. Schmidt,⁶² S. Schoenen,⁵³ S. Schöneberg,⁵⁹ L. Schumacher,⁵³ D. Seckel,⁷⁴ S. Seunarine,⁸⁶ D. Soldin,⁶⁰ M. Song,⁶² G. M. Spiczak,⁸⁶ C. Spiering,⁴³ J. Stachurska,⁴³ T. Stanev,⁷⁴ A. Stasik,⁴³ J. Stettner,⁵³ A. Steuer,⁵¹ T. Stezelberger,⁶⁴ R. G. Stokstad,⁶⁴ A. Stöbl,⁸¹ R. Ström,⁶⁷ N. L. Strotjohann,⁴³ G. W. Sullivan,⁶² M. Sutherland,⁵⁷ H. Taavola,⁶⁷ I. Taboada,⁹¹ J. Tatar,^{64,56} F. Tenholt,⁵⁹ S. Ter-Antonyan,⁷⁷ A. Terliuk,⁴³ G. Tešić,⁵⁰ S. Tilav,⁷⁴ P. A. Toale,⁸⁸ M. N. Tobin,⁴⁶ S. Toscano,⁶⁸ D. Tosi,⁴⁶ M. Tselengidou,⁴ C. F. Tung,⁹¹ A. Turcati,⁷¹ E. Unger,⁶⁷ M. Usner,⁴³ J. Vandenbroucke,⁴⁶ N. van Eijndhoven,⁶⁸ S. Vanheule,⁷⁵ M. van Rossem,⁴⁶ J. van Santen,⁴³ M. Vehring,⁵³ M. Voge,⁹² E. Vogel,⁵³ M. Vraeghe,⁷⁵ C. Walck,⁴⁷ A. Wallace,⁴² M. Wallraff,⁵³ N. Wandkowsky,⁴⁶ A. Waza,⁵³ Ch. Weaver,⁷⁹ M. J. Weiss,⁵⁰ C. Wendt,⁴⁶ S. Westerhoff,⁴⁶ B. J. Whelan,⁴² S. Wickmann,⁵³ K. Wiebe,⁵¹ C. H. Wiebusch,⁵³ L. Wille,⁴⁶ D. R. Williams,⁸⁸ L. Wills,⁸⁵ M. Wolf,⁴⁷ T. R. Wood,⁷⁹ E. Woolsey,⁷⁹ K. Woschnagg,⁵⁶ D. L. Xu,⁴⁶ X. W. Xu,⁷⁷ Y. Xu,⁸³ J. P. Yanez,⁷⁹ G. Yodh,⁵⁵ S. Yoshida,⁸¹ and M. Zoll⁴⁷

(IceCube Collaboration)

B. P. Abbott,⁹³ R. Abbott,⁹³ T. D. Abbott,⁹⁴ M. R. Abernathy,⁹⁵ F. Acernese,^{96,97} K. Ackley,⁹⁸ C. Adams,⁹⁹ T. Adams,¹⁰⁰ P. Addesso,¹⁰¹ R. X. Adhikari,⁹³ V. B. Adya,¹⁰² C. Affeldt,¹⁰² M. Agathos,¹⁰³ K. Agatsuma,¹⁰³ N. Aggarwal,¹⁰⁴ O. D. Aguiar,¹⁰⁵ L. Aiello,^{106,107} A. Ain,¹⁰⁸ P. Ajith,¹⁰⁹ B. Allen,^{102,110,111} A. Allocca,^{112,113} P. A. Altin,¹¹⁴ A. Ananyeva,⁹³ S. B. Anderson,⁹³ W. G. Anderson,¹¹⁰ S. Appert,⁹³ K. Arai,⁹³ M. C. Araya,⁹³ J. S. Areeda,¹¹⁵ N. Arnaud,¹¹⁶ K. G. Arun,¹¹⁷ S. Ascenzi,^{118,107} G. Ashton,¹⁰² M. Ast,¹¹⁹ S. M. Aston,⁹⁹ P. Astone,¹²⁰ P. Aufmuth,¹¹¹ C. Aulbert,¹⁰² A. Avila-Alvarez,¹¹⁵ S. Babak,¹²¹ P. Bacon,⁷ M. K. M. Bader,¹⁰³ P. T. Baker,^{122,123} F. Baldaccini,^{124,125} G. Ballardini,¹²⁶ S. W. Ballmer,¹²⁷ J. C. Barayoga,⁹³ S. E. Barclay,¹²⁸ B. C. Barish,⁹³ D. Barker,¹²⁹ F. Barone,^{96,97} B. Barr,¹²⁸ L. Barsotti,¹⁰⁴ M. Barsuglia,⁷ D. Barta,¹³⁰ J. Bartlett,¹²⁹ I. Bartos,¹³¹ R. Bassiri,¹³² A. Basti,^{112,113} J. C. Batch,¹²⁹ C. Baune,¹⁰² V. Bavigadda,¹²⁶ M. Bazzan,^{133,134} C. Beer,¹⁰² M. Bejger,¹³⁵ I. Belahcene,¹¹⁶ M. Belgin,¹³⁶ A. S. Bell,¹²⁸ B. K. Berger,⁹³ G. Bergmann,¹⁰² C. P. L. Berry,¹³⁷ D. Bersanetti,^{138,139} A. Bertolini,¹⁰³ J. Betzwieser,⁹⁹ S. Bhagwat,¹²⁷ R. Bhandare,¹⁴⁰ I. A. Bilenko,¹⁴¹ G. Billingsley,⁹³ C. R. Billman,⁹⁸ J. Birch,⁹⁹ R. Birney,¹⁴² O. Birnholtz,¹⁰² S. Biscans,^{104,93} A. Bisht,¹¹¹ M. Bitossi,¹²⁶ C. Biwer,¹²⁷ M. A. Bizouard,¹¹⁶ J. K. Blackburn,⁹³ J. Blackman,¹⁴³ C. D. Blair,¹⁴⁴ D. G. Blair,¹⁴⁴ R. M. Blair,¹²⁹ S. Bloemen,¹⁴⁵ O. Bock,¹⁰² M. Boer,¹⁴⁶ G. Bogaert,¹⁴⁶ A. Bohe,¹²¹ F. Bondu,¹⁴⁷ R. Bonnand,¹⁰⁰ B. A. Boom,¹⁰³ R. Bork,⁹³ V. Boschi,^{112,113} S. Bose,^{148,108} Y. Bouffanais,⁷ A. Bozzi,¹²⁶ C. Bradaschia,¹¹³ P. R. Brady,¹¹⁰ V. B. Braginsky,^{141,235} M. Branchesi,^{149,150} J. E. Brau,¹⁵¹ T. Briant,¹⁵² A. Brillet,¹⁴⁶ M. Brinkmann,¹⁰² V. Brisson,¹¹⁶ P. Brockill,¹¹⁰ J. E. Broida,¹⁵³ A. F. Brooks,⁹³ D. A. Brown,¹²⁷ D. D. Brown,¹³⁷ N. M. Brown,¹⁰⁴ S. Brunett,⁹³ C. C. Buchanan,⁹⁴ A. Buikema,¹⁰⁴ T. Bulik,¹⁵⁴ H. J. Bulten,^{155,103} A. Buonanno,^{121,156} D. Buskulic,¹⁰⁰ C. Buy,⁷ R. L. Byer,¹³² M. Cabero,¹⁰² L. Cadonati,¹³⁶ G. Cagnoli,^{157,158} C. Cahillane,⁹³ J. Calderón Bustillo,¹³⁶ T. A. Callister,⁹³ E. Calloni,^{159,97} J. B. Camp,¹⁶⁰ M. Canepa,^{138,139} K. C. Cannon,¹⁶¹ H. Cao,¹⁶² J. Cao,¹⁶³ C. D. Capano,¹⁰² E. Capocasa,⁷ F. Carbognani,¹²⁶ S. Caride,¹⁶⁴ J. Casanueva Diaz,¹¹⁶ C. Casentini,^{118,107} S. Caudill,¹¹⁰ M. Cavaglia,¹⁶⁵ F. Cavalier,¹¹⁶ R. Cavalieri,¹²⁶ G. Cella,¹¹³ C. B. Cepeda,⁹³ L. Cerboni Baiardi,^{149,150} G. Cerretani,^{112,113} E. Cesarini,^{118,107} S. J. Chamberlin,¹⁶⁶ M. Chan,¹²⁸ S. Chao,¹⁶⁷ P. Charlton,¹⁶⁸ E. Chassande-Mottin,⁷ B. D. Cheeseboro,^{122,123} H. Y. Chen,¹⁶⁹ Y. Chen,¹⁴³ H.-P. Cheng,⁹⁸ A. Chincarini,¹³⁹ A. Chiummo,¹²⁶ T. Chmiel,¹⁷⁰ H. S. Cho,¹⁷¹ M. Cho,¹⁵⁶ J. H. Chow,¹¹⁴ N. Christensen,¹⁵³ Q. Chu,¹⁴⁴ A. J. K. Chua,¹⁷² S. Chua,¹⁵² S. Chung,¹⁴⁴ G. Ciani,⁹⁸ F. Clara,¹²⁹ J. A. Clark,¹³⁶ F. Cleva,¹⁴⁶ C. Cocchieri,¹⁶⁵ E. Coccia,^{106,107} P.-F. Cohadon,¹⁵² A. Colla,^{173,120} C. G. Collette,¹⁷⁴ L. Cominsky,¹⁷⁵ M. Constancio Jr.,¹⁰⁵ L. Conti,¹³⁴ S. J. Cooper,¹³⁷ T. R. Corbitt,⁹⁴ N. Cornish,¹⁷⁶ A. Corsi,¹⁶⁴ S. Cortese,¹²⁶ C. A. Costa,¹⁰⁵ M. W. Coughlin,¹⁵³ S. B. Coughlin,¹⁷⁷ J.-P. Coulon,¹⁴⁶ S. T. Countryman,¹³¹ P. Couvares,⁹³ P. B. Covas,¹⁷⁸ E. E. Cowan,¹³⁶ D. M. Coward,¹⁴⁴ M. J. Cowart,⁹⁹ D. C. Coyne,⁹³ R. Coyne,¹⁶⁴ J. D. E. Creighton,¹¹⁰ T. D. Creighton,¹⁷⁹ J. Cripe,⁹⁴ S. G. Crowder,¹⁸⁰ T. J. Cullen,¹¹⁵ A. Cumming,¹²⁸ L. Cunningham,¹²⁸ E. Cuoco,¹²⁶ T. Dal Canton,¹⁶⁰ S. L. Danilishin,¹²⁸ S. D’Antonio,¹⁰⁷ K. Danzmann,^{111,102} A. Dasgupta,¹⁸¹ C. F. Da Silva Costa,⁹⁸ V. Dattilo,¹²⁶ I. Dave,¹⁴⁰ M. Davier,¹¹⁶ G. S. Davies,¹²⁸ D. Davis,¹²⁷ E. J. Daw,¹⁸² B. Day,¹³⁶

R. Day,¹²⁶ S. De,¹²⁷ D. DeBra,¹³² G. Debreczeni,¹³⁰ J. Degallaix,¹⁵⁷ M. De Laurentis,^{159,97} S. Deléglise,¹⁵² W. Del Pozzo,¹³⁷ T. Denker,¹⁰² T. Dent,¹⁰² V. Dergachev,¹²¹ R. De Rosa,^{159,97} R. T. DeRosa,⁹⁹ R. DeSalvo,¹⁸³ R. C. Devine,^{122,123} S. Dhurandhar,¹⁰⁸ M. C. Díaz,¹⁷⁹ L. Di Fiore,⁹⁷ M. Di Giovanni,^{184,185} T. Di Girolamo,^{159,97} A. Di Lieto,^{112,113} S. Di Pace,^{173,120} I. Di Palma,^{121,173,120} A. Di Virgilio,¹¹³ Z. Doctor,¹⁶⁹ V. Dolique,¹⁵⁷ F. Donovan,¹⁰⁴ K. L. Dooley,¹⁶⁵ S. Doravari,¹⁰² I. Dorrington,¹⁸⁶ R. Douglas,¹²⁸ M. Dovalé Álvarez,¹³⁷ T. P. Downes,¹¹⁰ M. Drago,¹⁰² R. W. P. Drever,⁹³ J. C. Driggers,¹²⁹ Z. Du,¹⁶³ M. Ducrot,¹⁰⁰ S. E. Dwyer,¹²⁹ T. B. Edo,¹⁸² M. C. Edwards,¹⁵³ A. Effler,⁹⁹ H.-B. Eggenstein,¹⁰² P. Ehrens,⁹³ J. Eichholz,⁹³ S. S. Eikenberry,⁹⁸ R. A. Eisenstein,¹⁰⁴ R. C. Essick,¹⁰⁴ Z. Etienne,^{122,123} T. Etzel,⁹³ M. Evans,¹⁰⁴ T. M. Evans,⁹⁹ R. Everett,¹⁶⁶ M. Factourovich,¹³¹ V. Fafone,^{118,107,106} H. Fair,¹²⁷ S. Fairhurst,¹⁸⁶ X. Fan,¹⁶³ S. Farinon,¹³⁹ B. Farr,¹⁶⁹ W. M. Farr,¹³⁷ E. J. Fauchon-Jones,¹⁸⁶ M. Favata,¹⁸⁷ M. Fays,¹⁸⁶ H. Fehrmann,¹⁰² M. M. Fejer,¹³² A. Fernández Galiana,¹⁰⁴ I. Ferrante,^{112,113} E. C. Ferreira,¹⁰⁵ F. Ferrini,¹²⁶ F. Fidecaro,^{112,113} I. Fiori,¹²⁶ D. Fiorucci,⁷ R. P. Fisher,¹²⁷ R. Flaminio,^{157,188} M. Fletcher,¹²⁸ H. Fong,¹⁸⁹ S. S. Forsyth,¹³⁶ J.-D. Fournier,¹⁴⁶ S. Frasca,^{173,120} F. Frasconi,¹¹³ Z. Frei,¹⁹⁰ A. Freise,¹³⁷ R. Frey,¹⁵¹ V. Frey,¹¹⁶ E. M. Fries,⁹³ P. Fritschel,¹⁰⁴ V. V. Frolov,⁹⁹ P. Fulda,^{98,160} M. Fyffe,⁹⁹ H. Gabbard,¹⁰² B. U. Gadre,¹⁰⁸ S. M. Gaebel,¹³⁷ J. R. Gair,¹⁹¹ L. Gammaitoni,¹²⁴ S. G. Gaonkar,¹⁰⁸ F. Garufi,^{159,97} G. Gaur,¹⁹² V. Gayathri,¹⁹³ N. Gehrels,¹⁶⁰ G. Gemme,¹³⁹ E. Genin,¹²⁶ A. Gennai,¹¹³ J. George,¹⁴⁰ L. Gergely,¹⁹⁴ V. Germain,¹⁰⁰ S. Ghonge,¹⁰⁹ Abhirup Ghosh,¹⁰⁹ Archisman Ghosh,^{103,109} S. Ghosh,^{145,103} J. A. Giaime,^{94,99} K. D. Giardino,⁹⁹ A. Giazotto,¹¹³ K. Gill,¹⁹⁵ A. Glaefke,¹²⁸ E. Goetz,¹⁰² R. Goetz,⁹⁸ L. Gondan,¹⁹⁰ G. González,⁹⁴ J. M. Gonzalez Castro,^{112,113} A. Gopakumar,¹⁹⁶ M. L. Gorodetsky,¹⁴¹ S. E. Gossan,⁹³ M. Gosselin,¹²⁶ R. Gouaty,¹⁰⁰ A. Grado,^{197,97} C. Graef,¹²⁸ M. Granata,¹⁵⁷ A. Grant,¹²⁸ S. Gras,¹⁰⁴ C. Gray,¹²⁹ G. Greco,^{149,150} A. C. Green,¹³⁷ P. Groot,¹⁴⁵ H. Grote,¹⁰² S. Grunewald,¹²¹ G. M. Guidi,^{149,150} X. Guo,¹⁶³ A. Gupta,¹⁰⁸ M. K. Gupta,¹⁸¹ K. E. Gushwa,⁹³ E. K. Gustafson,⁹³ R. Gustafson,¹⁹⁸ J. J. Hacker,¹¹⁵ B. R. Hall,¹⁴⁸ E. D. Hall,⁹³ G. Hammond,¹²⁸ M. Haney,¹⁹⁶ M. M. Hanke,¹⁰² J. Hanks,¹²⁹ C. Hanna,¹⁶⁶ M. D. Hannam,¹⁸⁶ J. Hanson,⁹⁹ T. Hardwick,⁹⁴ J. Harms,^{149,150} G. M. Harry,⁹⁵ I. W. Harry,¹²¹ M. J. Hart,¹²⁸ M. T. Hartman,⁹⁸ C.-J. Haster,^{137,189} K. Haughian,¹²⁸ J. Healy,¹⁹⁹ A. Heidmann,¹⁵² M. C. Heintze,⁹⁹ H. Heitmann,¹⁴⁶ P. Hello,¹¹⁶ G. Hemming,¹²⁶ M. Hendry,¹²⁸ I. S. Heng,¹²⁸ J. Hennig,¹²⁸ J. Henry,¹⁹⁹ A. W. Heptonstall,⁹³ M. Heurs,^{102,111} S. Hild,¹²⁸ D. Hoak,¹²⁶ D. Hofman,¹⁵⁷ K. Holt,⁹⁹ D. E. Holz,¹⁶⁹ P. Hopkins,¹⁸⁶ J. Hough,¹²⁸ E. A. Houston,¹²⁸ E. J. Howell,¹⁴⁴ Y. M. Hu,¹⁰² E. A. Huerta,²⁰⁰ D. Huet,¹¹⁶ B. Hughey,¹⁹⁵ S. Husa,¹⁷⁸ S. H. Huttner,¹²⁸ T. Huynh-Dinh,⁹⁹ N. Indik,¹⁰² D. R. Ingram,¹²⁹ R. Inta,¹⁶⁴ H. N. Isa,¹²⁸ J.-M. Isac,¹⁵² M. Isi,⁹³ T. Isogai,¹⁰⁴ B. R. Iyer,¹⁰⁹ K. Izumi,¹²⁹ T. Jacqmin,¹⁵² K. Jani,¹³⁶ P. Jaranowski,²⁰¹ S. Jawahar,²⁰² F. Jiménez-Forteza,¹⁷⁸ W. W. Johnson,⁹⁴ D. I. Jones,²⁰³ R. Jones,¹²⁸ R. J. G. Jonker,¹⁰³ L. Ju,¹⁴⁴ J. Junker,¹⁰² C. V. Kalaghatgi,¹⁸⁶ V. Kalogera,¹⁷⁷ S. Kandhasamy,¹⁶⁵ G. Kang,¹⁷¹ J. B. Kanner,⁹³ S. Karki,¹⁵¹ K. S. Karvinen,¹⁰² M. Kasprzack,⁹⁴ E. Katsavounidis,¹⁰⁴ W. Katzman,⁹⁹ S. Kaufer,¹¹¹ T. Kaur,¹⁴⁴ K. Kawabe,¹²⁹ F. Kéfélian,¹⁴⁶ D. Keitel,¹⁷⁸ D. B. Kelley,¹²⁷ R. Kennedy,¹⁸² J. S. Key,²⁰⁴ F. Y. Khalili,¹⁴¹ I. Khan,¹⁰⁶ S. Khan,¹⁸⁶ Z. Khan,¹⁸¹ E. A. Khazanov,²⁰⁵ N. Kijbunchoo,¹²⁹ Chunglee Kim,²⁰⁶ J. C. Kim,²⁰⁷ Whansun Kim,²⁰⁸ W. Kim,¹⁶² Y.-M. Kim,^{209,206} S. J. Kimbrell,¹³⁶ E. J. King,¹⁶² P. J. King,¹²⁹ R. Kirchoff,¹⁰² J. S. Kissel,¹²⁹ B. Klein,¹⁷⁷ L. Kleybolte,¹¹⁹ S. Klimenko,⁹⁸ P. Koch,¹⁰² S. M. Koehlenbeck,¹⁰² S. Koley,¹⁰³ V. Kondrashov,⁹³ A. Kontos,¹⁰⁴ M. Korobko,¹¹⁹ W. Z. Korth,⁹³ I. Kowalska,¹⁵⁴ D. B. Kozak,⁹³ C. Krämer,¹⁰² V. Kringel,¹⁰² A. Królak,^{210,211} G. Kuehn,¹⁰² P. Kumar,¹⁸⁹ R. Kumar,¹⁸¹ L. Kuo,¹⁶⁷ A. Kutynia,²¹⁰ B. D. Lackey,^{121,127} M. Landry,¹²⁹ R. N. Lang,¹¹⁰ J. Lange,¹⁹⁹ B. Lantz,¹³² R. K. Lanza,¹⁰⁴ A. Lartaux-Vollard,¹¹⁶ P. D. Lasky,²¹² M. Laxen,⁹⁹ A. Lazzarini,⁹³ C. Lazzaro,¹³⁴ P. Leaci,^{173,120} S. Leavey,¹²⁸ E. O. Lebigot,⁷ C. H. Lee,²⁰⁹ H. K. Lee,²¹³ H. M. Lee,²⁰⁶ K. Lee,¹²⁸ J. Lehmann,¹⁰² A. Lenon,^{122,123} M. Leonardi,^{184,185} J. R. Leong,¹⁰² N. Leroy,¹¹⁶ N. Letendre,¹⁰⁰ Y. Levin,²¹² T. G. F. Li,²¹⁴ A. Libson,¹⁰⁴ T. B. Littenberg,²¹⁵ J. Liu,¹⁴⁴ N. A. Lockerbie,²⁰² A. L. Lombardi,¹³⁶ L. T. London,¹⁸⁶ J. E. Lord,¹²⁷ M. Lorenzini,^{106,107} V. Loriette,²¹⁶ M. Lormand,⁹⁹ G. Losurdo,¹¹³ J. D. Lough,^{102,111} G. Lovelace,¹¹⁵ H. Lück,^{111,102} A. P. Lundgren,¹⁰² R. Lynch,¹⁰⁴ Y. Ma,¹⁴³ S. Macfoy,¹⁴² B. Machenschalk,¹⁰² M. MacInnis,¹⁰⁴ D. M. Macleod,⁹⁴ F. Magaña-Sandoval,¹²⁷ E. Majorana,¹²⁰ I. Maksimovic,²¹⁶ V. Malvezzi,^{118,107} N. Man,¹⁴⁶ V. Mandic,²¹⁷ V. Mangano,¹²⁸ G. L. Mansell,¹¹⁴ M. Manske,¹¹⁰ M. Mantovani,¹²⁶ F. Marchesoni,^{218,125} F. Marion,¹⁰⁰ S. Márka,¹³¹ Z. Márka,¹³¹ A. S. Markosyan,¹³² E. Maros,⁹³ F. Martelli,^{149,150} L. Martellini,¹⁴⁶ I. W. Martin,¹²⁸ D. V. Martynov,¹⁰⁴ K. Mason,¹⁰⁴ A. Masserot,¹⁰⁰ T. J. Massinger,⁹³ M. Masso-Reid,¹²⁸ S. Mastrogiovanni,^{173,120} F. Matchard,^{104,93} L. Matone,¹³¹ N. Mavalvala,¹⁰⁴ N. Mazumder,¹⁴⁸ R. McCarthy,¹²⁹ D. E. McClelland,¹¹⁴ S. McCormick,⁹⁹ C. McGrath,¹¹⁰ S. C. McGuire,²¹⁹ G. McIntyre,⁹³ J. McIver,⁹³ D. J. McManus,¹¹⁴ T. McRae,¹¹⁴ S. T. McWilliams,^{122,123} D. Meacher,^{146,166} G. D. Meadors,^{121,102} J. Meidam,¹⁰³ A. Melatos,²²⁰ G. Mendell,¹²⁹ D. Mendoza-Gandara,¹⁰² R. A. Mercer,¹¹⁰ E. L. Merilh,¹²⁹ M. Merzougui,¹⁴⁶ S. Meshkov,⁹³ C. Messenger,¹²⁸ C. Messick,¹⁶⁶ R. Metzdrorff,¹⁵² P. M. Meyers,²¹⁷ F. Mezzani,^{120,173} H. Miao,¹³⁷ C. Michel,¹⁵⁷

H. Middleton,¹³⁷ E. E. Mikhailov,²²¹ L. Milano,^{159,97} A. L. Miller,^{98,173,120} A. Miller,¹⁷⁷ B. B. Miller,¹⁷⁷ J. Miller,¹⁰⁴
 M. Millhouse,¹⁷⁶ Y. Minenkov,¹⁰⁷ J. Ming,¹²¹ S. Mirshekari,²²² C. Mishra,¹⁰⁹ S. Mitra,¹⁰⁸ V. P. Mitrofanov,¹⁴¹
 G. Mitselmakher,⁹⁸ R. Mittleman,¹⁰⁴ A. Moggi,¹¹³ M. Mohan,¹²⁶ S. R. P. Mohapatra,¹⁰⁴ M. Montani,^{149,150} B. C. Moore,¹⁸⁷
 C. J. Moore,¹⁷² D. Moraru,¹²⁹ G. Moreno,¹²⁹ S. R. Morriss,¹⁷⁹ B. Mours,¹⁰⁰ C. M. Mow-Lowry,¹³⁷ G. Mueller,⁹⁸
 A. W. Muir,¹⁸⁶ Arunava Mukherjee,¹⁰⁹ D. Mukherjee,¹¹⁰ S. Mukherjee,¹⁷⁹ N. Mukund,¹⁰⁸ A. Mullavey,⁹⁹ J. Munch,¹⁶²
 E. A. M. Muniz,¹¹⁵ P. G. Murray,¹²⁸ A. Mytidis,⁹⁸ K. Napier,¹³⁶ I. Nardecchia,^{118,107} L. Naticchioni,^{173,120}
 G. Nelemans,^{145,103} T. J. N. Nelson,⁹⁹ M. Neri,^{138,139} M. Nery,¹⁰² A. Neunzert,¹⁹⁸ J. M. Newport,⁹⁵ G. Newton,¹²⁸
 T. T. Nguyen,¹¹⁴ A. B. Nielsen,¹⁰² S. Nissanke,^{145,103} A. Nitz,¹⁰² A. Noack,¹⁰² F. Nocera,¹²⁶ D. Nolting,⁹⁹
 M. E. N. Normandin,¹⁷⁹ L. K. Nuttall,¹²⁷ J. Oberling,¹²⁹ E. Ochsner,¹¹⁰ E. Oelker,¹⁰⁴ G. H. Ogin,²²³ J. J. Oh,²⁰⁸ S. H. Oh,²⁰⁸
 F. Ohme,^{186,102} M. Oliver,¹⁷⁸ P. Oppermann,¹⁰² Richard J. Oram,⁹⁹ B. O'Reilly,⁹⁹ R. O'Shaughnessy,¹⁹⁹ D. J. Ottaway,¹⁶²
 H. Overmier,⁹⁹ B. J. Owen,¹⁶⁴ A. E. Pace,¹⁶⁶ J. Page,²¹⁵ A. Pai,¹⁹³ S. A. Pai,¹⁴⁰ J. R. Palamos,¹⁵¹ O. Palashov,²⁰⁵
 C. Palomba,¹²⁰ A. Pal-Singh,¹¹⁹ H. Pan,¹⁶⁷ C. Pankow,¹⁷⁷ F. Pannarale,¹⁸⁶ B. C. Pant,¹⁴⁰ F. Paoletti,^{126,113} A. Paoli,¹²⁶
 M. A. Papa,^{121,110,102} H. R. Paris,¹³² W. Parker,⁹⁹ D. Pascucci,¹²⁸ A. Pasqualetti,¹²⁶ R. Passaquieti,^{112,113} D. Passuello,¹¹³
 B. Patricelli,^{112,113} B. L. Pearlstone,¹²⁸ M. Pedraza,⁹³ R. Pedurand,^{157,224} L. Pekowsky,¹²⁷ A. Pele,⁹⁹ S. Penn,²²⁵
 C. J. Perez,¹²⁹ A. Perreca,⁹³ L. M. Perri,¹⁷⁷ H. P. Pfeiffer,¹⁸⁹ M. Phelps,¹²⁸ O. J. Piccinni,^{173,120} M. Pichot,¹⁴⁶
 F. Piergiovanni,^{149,150} V. Pierro,¹⁰¹ G. Pillant,¹²⁶ L. Pinard,¹⁵⁷ I. M. Pinto,¹⁰¹ M. Pitkin,¹²⁸ M. Poe,¹¹⁰ R. Poggiani,^{112,113}
 P. Popolizio,¹²⁶ A. Post,¹⁰² J. Powell,¹²⁸ J. Prasad,¹⁰⁸ J. W. W. Pratt,¹⁹⁵ V. Predoi,¹⁸⁶ T. Prestegard,^{217,110} M. Prijatelj,^{102,126}
 M. Principe,¹⁰¹ S. Privitera,¹²¹ G. A. Prodi,^{184,185} L. G. Prokhorov,¹⁴¹ O. Puncken,¹⁰² M. Punturo,¹²⁵ P. Puppo,¹²⁰
 M. Pürner,¹²¹ H. Qi,¹¹⁰ J. Qin,¹⁴⁴ S. Qiu,²¹² V. Quetschke,¹⁷⁹ E. A. Quintero,⁹³ R. Quitzow-James,¹⁵¹ F. J. Raab,¹²⁹
 D. S. Rabeling,¹¹⁴ H. Radkins,¹²⁹ P. Raffai,¹⁹⁰ S. Raja,¹⁴⁰ C. Rajan,¹⁴⁰ M. Rakhmanov,¹⁷⁹ P. Rapagnani,^{173,120}
 V. Raymond,¹²¹ M. Razzano,^{112,113} V. Re,¹¹⁸ J. Read,¹¹⁵ T. Regimbau,¹⁴⁶ L. Rei,¹³⁹ S. Reid,¹⁴² D. H. Reitze,^{93,98} H. Rew,²²¹
 S. D. Reyes,¹²⁷ E. Rhoades,¹⁹⁵ F. Ricci,^{173,120} K. Riles,¹⁹⁸ M. Rizzo,¹⁹⁹ N. A. Robertson,^{93,128} R. Robie,¹²⁸ F. Robinet,¹¹⁶
 A. Rocchi,¹⁰⁷ L. Rolland,¹⁰⁰ J. G. Rollins,⁹³ V. J. Roma,¹⁵¹ R. Romano,^{96,97} J. H. Romie,⁹⁹ D. Rosińska,^{226,135} S. Rowan,¹²⁸
 A. Rüdiger,¹⁰² P. Ruggi,¹²⁶ K. Ryan,¹²⁹ S. Sachdev,⁹³ T. Sadecki,¹²⁹ L. Sadeghian,¹¹⁰ M. Sakellariadou,²²⁷ L. Salconi,¹²⁶
 M. Saleem,¹⁹³ F. Salemi,¹⁰² A. Samajdar,²²⁸ L. Sammut,²¹² L. M. Sampson,¹⁷⁷ E. J. Sanchez,⁹³ V. Sandberg,¹²⁹
 J. R. Sanders,¹²⁷ B. Sassolas,¹⁵⁷ B. S. Sathyaprakash,^{166,186} P. R. Saulson,¹²⁷ O. Sauter,¹⁹⁸ R. L. Savage,¹²⁹ A. Sawadsky,¹¹¹
 P. Schale,¹⁵¹ J. Scheuer,¹⁷⁷ E. Schmidt,¹⁹⁵ J. Schmidt,¹⁰² P. Schmidt,^{93,143} R. Schnabel,¹¹⁹ R. M. S. Schofield,¹⁵¹
 A. Schönbeck,¹¹⁹ E. Schreiber,¹⁰² D. Schuette,^{102,111} B. F. Schutz,^{186,121} S. G. Schwalbe,¹⁹⁵ J. Scott,¹²⁸ S. M. Scott,¹¹⁴
 D. Sellers,⁹⁹ A. S. Sengupta,²²⁹ D. Sentenac,¹²⁶ V. Sequino,^{118,107} A. Sergeev,²⁰⁵ Y. Setyawati,^{145,103} D. A. Shaddock,¹¹⁴
 T. J. Shaffer,¹²⁹ M. S. Shahriar,¹⁷⁷ B. Shapiro,¹³² P. Shawhan,¹⁵⁶ A. Sheperd,¹¹⁰ D. H. Shoemaker,¹⁰⁴ D. M. Shoemaker,¹³⁶
 K. Siellez,¹³⁶ X. Siemens,¹¹⁰ M. Sieniawska,¹³⁵ D. Sigg,¹²⁹ A. D. Silva,¹⁰⁵ A. Singer,⁹³ L. P. Singer,¹⁶⁰ A. Singh,^{121,102,111}
 R. Singh,⁹⁴ A. Singhal,¹⁰⁶ A. M. Sintès,¹⁷⁸ B. J. J. Slagmolen,¹¹⁴ B. Smith,⁹⁹ J. R. Smith,¹¹⁵ R. J. E. Smith,⁹³ E. J. Son,²⁰⁸
 B. Sorazu,¹²⁸ F. Sorrentino,¹³⁹ T. Souradeep,¹⁰⁸ A. P. Spencer,¹²⁸ A. K. Srivastava,¹⁸¹ A. Staley,¹³¹ M. Steinke,¹⁰²
 J. Steinlechner,¹²⁸ S. Steinlechner,^{119,128} D. Steinmeyer,^{102,111} B. C. Stephens,¹¹⁰ S. P. Stevenson,¹³⁷ R. Stone,¹⁷⁹
 K. A. Strain,¹²⁸ N. Straniero,¹⁵⁷ G. Stratta,^{149,150} S. E. Strigin,¹⁴¹ R. Sturani,²²² A. L. Stuver,⁹⁹ T. Z. Summerscales,²³⁰
 L. Sun,²²⁰ S. Sunil,¹⁸¹ P. J. Sutton,¹⁸⁶ B. L. Swinkels,¹²⁶ M. J. Szczepańczyk,¹⁹⁵ M. Tacca,⁷ D. Talukder,¹⁵¹ D. B. Tanner,⁹⁸
 M. Tápai,¹⁹⁴ A. Taracchini,¹²¹ R. Taylor,⁹³ T. Theeg,¹⁰² E. G. Thomas,¹³⁷ M. Thomas,⁹⁹ P. Thomas,¹²⁹ K. A. Thorne,⁹⁹
 E. Thrane,²¹² T. Tippens,¹³⁶ S. Tiwari,^{106,185} V. Tiwari,¹⁸⁶ K. V. Tokmakov,²⁰² K. Toland,¹²⁸ C. Tomlinson,¹⁸²
 M. Tonelli,^{112,113} Z. Tornasi,¹²⁸ C. I. Torrie,⁹³ D. Töyrä,¹³⁷ F. Travasso,^{124,125} G. Traylor,⁹⁹ D. Trifirò,¹⁶⁵ J. Trinastic,⁹⁸
 M. C. Tringali,^{184,185} L. Trozzo,^{231,113} M. Tse,¹⁰⁴ R. Tso,⁹³ M. Turconi,¹⁴⁶ D. Tuyenbayev,¹⁷⁹ D. Ugolini,²³²
 C. S. Unnikrishnan,¹⁹⁶ A. L. Urban,⁹³ S. A. Usman,¹⁸⁶ H. Vahlbruch,¹¹¹ G. Vajente,⁹³ G. Valdes,¹⁷⁹ N. van Bakel,¹⁰³
 M. van Beuzekom,¹⁰³ J. F. J. van den Brand,^{155,103} C. Van Den Broeck,¹⁰³ D. C. Vander-Hyde,¹²⁷ L. van der Schaaf,¹⁰³
 J. V. van Heijningen,¹⁰³ A. A. van Veggel,¹²⁸ M. Vardaro,^{133,134} V. Varma,¹⁴³ S. Vass,⁹³ M. Vasúth,¹³⁰ A. Vecchio,¹³⁷
 G. Vedovato,¹³⁴ J. Veitch,¹³⁷ P. J. Veitch,¹⁶² K. Venkateswara,²³³ G. Venugopalan,⁹³ D. Verkindt,¹⁰⁰ F. Vetrano,^{149,150}
 A. Viceré,^{149,150} A. D. Viets,¹¹⁰ S. Vinciguerra,¹³⁷ D. J. Vine,¹⁴² J.-Y. Vinet,¹⁴⁶ S. Vitale,¹⁰⁴ T. Vo,¹²⁷ H. Vocca,^{124,125}
 C. Vorvick,¹²⁹ D. V. Voss,⁹⁸ W. D. Voudsen,¹³⁷ S. P. Vyatchanin,¹⁴¹ A. R. Wade,⁹³ L. E. Wade,¹⁷⁰ M. Wade,¹⁷⁰ M. Walker,⁹⁴
 L. Wallace,⁹³ S. Walsh,^{121,102} G. Wang,^{106,150} H. Wang,¹³⁷ M. Wang,¹³⁷ Y. Wang,¹⁴⁴ R. L. Ward,¹¹⁴ J. Warner,¹²⁹ M. Was,¹⁰²
 J. Watchi,¹⁷⁴ B. Weaver,¹²⁹ L.-W. Wei,¹⁴⁶ M. Weinert,¹⁰² A. J. Weinstein,⁹³ R. Weiss,¹⁰⁴ L. Wen,¹⁴⁴ P. Weßels,¹⁰²
 T. Westphal,¹⁰² K. Wette,¹⁰² J. T. Whelan,¹⁹⁹ B. F. Whiting,⁹⁸ C. Whittle,²¹² D. Williams,¹²⁸ R. D. Williams,⁹³

A. R. Williamson,¹⁸⁶ J. L. Willis,²³⁴ B. Willke,^{111,102} M. H. Wimmer,^{102,111} W. Winkler,¹⁰² C. C. Wipf,⁹³ H. Wittel,^{102,111} G. Woan,¹²⁸ J. Woehler,¹⁰² J. Worden,¹²⁹ J. L. Wright,¹²⁸ D. S. Wu,¹⁰² G. Wu,⁹⁹ W. Yam,¹⁰⁴ H. Yamamoto,⁹³ C. C. Yancey,¹⁵⁶ M. J. Yap,¹¹⁴ Hang Yu,¹⁰⁴ Haocun Yu,¹⁰⁴ M. Yvert,¹⁰⁰ A. Zdrozny,²¹⁰ L. Zangrando,¹³⁴ M. Zanolin,¹⁹⁵ J.-P. Zendri,¹³⁴ M. Zevin,¹⁷⁷ L. Zhang,⁹³ M. Zhang,²²¹ T. Zhang,¹²⁸ Y. Zhang,¹⁹⁹ C. Zhao,¹⁴⁴ M. Zhou,¹⁷⁷ Z. Zhou,¹⁷⁷ S. J. Zhu,^{121,102} X. J. Zhu,¹⁴⁴ M. E. Zucker,^{93,104} and J. Zweizig⁹³
(LIGO Scientific Collaboration and Virgo Collaboration)

- ¹*GRPHE, Institut universitaire de technologie de Colmar, Université de Haute Alsace, 34 rue du Grillenbreit BP 50568, 68008 Colmar, France*
- ²*Laboratory of Applied Bioacoustics, Technical University of Catalonia, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain*
- ³*INFN, Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy*
- ⁴*Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany*
- ⁵*Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC), Universitat Politècnica de València, c/ Paranimf 1, 46730 Gandia, Spain*
- ⁶*Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France*
- ⁷*AstroParticule et Cosmologie (APC), Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France*
- ⁸*Instituto de Física Corpuscular (IFIC), CSIC, Universitat de València, c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain*
- ⁹*Laboratoire d'Astrophysique de Marseille (LAM), Pôle de l'Étoile Site de Château-Gombert, rue Frédéric Joliot-Curie 38, 13388 Marseille Cedex 13, France*
- ¹⁰*INFN, Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy*
- ¹¹*Nikhef, Science Park, Amsterdam, The Netherlands*
- ¹²*Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands*
- ¹³*Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands*
- ¹⁴*INFN, Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy*
- ¹⁵*Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy*
- ¹⁶*Institute for Space Science, RO-077125 Bucharest, Măgurele, Romania*
- ¹⁷*Gran Sasso Science Institute, Viale Francesco Crispi 7, 00167 L'Aquila, Italy*
- ¹⁸*INFN, Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy*
- ¹⁹*INFN, Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy*
- ²⁰*Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France*
- ²¹*Université Paris-Sud, 91405 Orsay Cedex, France*
- ²²*Laboratory of Physics of Matter and Radiations, University Mohammed I, B.P.717, Oujda 6000, Morocco*
- ²³*Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany*
- ²⁴*Dipartimento di Fisica e Astronomia dell'Università, Viale Berti Pichat 6/2, 40127 Bologna, Italy*
- ²⁵*Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France*
- ²⁶*INFN, Sezione di Catania, Viale Andrea Doria 6, 95125 Catania, Italy*
- ²⁷*LSIS, Aix Marseille Université CNRS ENSAM LSIS UMR 7296 13397 Marseille, France; Université de Toulon CNRS LSIS UMR 7296 83957 La Garde, France*
- ²⁸*Institut Universitaire de France, 75005 Paris, France*
- ²⁹*Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ 't Horntje (Texel), The Netherlands*
- ³⁰*Dipartimento di Fisica dell'Università, Via Dodecaneso 33, 16146 Genova, Italy*
- ³¹*Dr. Remeis-Sternwarte and Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany*
- ³²*Moscow State University, Skobeltsyn Institute of Nuclear Physics, Leninskie gory, 119991 Moscow, Russia*
- ³³*Mediterranean Institute of Oceanography (MIO), CNRS-INSU/IRD UM 110, Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, 83957, La Garde Cedex, France*
- ³⁴*Dipartimento di Fisica ed Astronomia dell'Università, Viale Andrea Doria 6, 95125 Catania, Italy*

- ³⁵*Direction des Sciences de la Matière, Institut de recherche sur les lois fondamentales de l'Univers, Service de Physique des Particules, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France*
- ³⁶*INFN, Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy*
- ³⁷*Dipartimento di Fisica dell'Università, Largo B. Pontecorvo 3, 56127 Pisa, Italy*
- ³⁸*INFN, Sezione di Napoli, Via Cintia 80126 Napoli, Italy*
- ³⁹*Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia 80126, Napoli, Italy*
- ⁴⁰*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
- ⁴¹*Faculty of Sciences, University Mohammed V in Rabat, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco*
- ⁴²*Department of Physics, University of Adelaide, Adelaide, 5005, Australia*
- ⁴³*DESY, D-15735 Zeuthen, Germany*
- ⁴⁴*Department of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
- ⁴⁵*Science Faculty CP230, Université Libre de Bruxelles, B-1050 Brussels, Belgium*
- ⁴⁶*Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, Wisconsin 53706, USA*
- ⁴⁷*Oskar Klein Centre and Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden*
- ⁴⁸*Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland*
- ⁴⁹*Department of Physics, Marquette University, Milwaukee, Wisconsin, 53201, USA*
- ⁵⁰*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*
- ⁵¹*Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany*
- ⁵²*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- ⁵³*III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany*
- ⁵⁴*Physics Department, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, USA*
- ⁵⁵*Department of Physics and Astronomy, University of California, Irvine, California 92697, USA*
- ⁵⁶*Department of Physics, University of California, Berkeley, California 94720, USA*
- ⁵⁷*Department of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, Ohio 43210, USA*
- ⁵⁸*Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*
- ⁵⁹*Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
- ⁶⁰*Department of Physics, University of Wuppertal, D-42119 Wuppertal, Germany*
- ⁶¹*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
- ⁶²*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
- ⁶³*Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045, USA*
- ⁶⁴*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
- ⁶⁵*Department of Physics, TU Dortmund University, D-44221 Dortmund, Germany*
- ⁶⁶*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
- ⁶⁷*Department of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden*
- ⁶⁸*Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium*
- ⁶⁹*Department of Physics, University of Toronto, Toronto, Ontario, Canada, M5S 1A7*
- ⁷⁰*Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany*
- ⁷¹*Physik-department, Technische Universität München, D-85748 Garching, Germany*
- ⁷²*Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*
- ⁷³*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
- ⁷⁴*Bartol Research Institute and Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*
- ⁷⁵*Department of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium*
- ⁷⁶*Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*
- ⁷⁷*Department of Physics, Southern University, Baton Rouge, Louisiana 70813, USA*
- ⁷⁸*Department of Astronomy, University of Wisconsin, Madison, Wisconsin 53706, USA*
- ⁷⁹*Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1*
- ⁸⁰*Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark*
- ⁸¹*Department of Physics and Institute for Global Prominent Research, Chiba University, Chiba 263-8522, Japan*
- ⁸²*CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA*
- ⁸³*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*

- ⁸⁴*Université de Mons, 7000 Mons, Belgium*
- ⁸⁵*Department of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, Pennsylvania 19104, USA*
- ⁸⁶*Department of Physics, University of Wisconsin, River Falls, Wisconsin 54022, USA*
- ⁸⁷*Department of Physics, Yale University, New Haven, Connecticut 06520, USA*
- ⁸⁸*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*
- ⁸⁹*Department of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, Alaska 99508, USA*
- ⁹⁰*Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
- ⁹¹*School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
- ⁹²*Physikalisches Institut, Universität Bonn, Nussallee 12, D-53115 Bonn, Germany*
- ⁹³*LIGO, California Institute of Technology, Pasadena, California 91125, USA*
- ⁹⁴*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
- ⁹⁵*American University, Washington, D.C. 20016, USA*
- ⁹⁶*Università di Salerno, Fisciano, I-84084 Salerno, Italy*
- ⁹⁷*INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
- ⁹⁸*University of Florida, Gainesville, Florida 32611, USA*
- ⁹⁹*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
- ¹⁰⁰*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France*
- ¹⁰¹*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
- ¹⁰²*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
- ¹⁰³*Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands*
- ¹⁰⁴*LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- ¹⁰⁵*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
- ¹⁰⁶*INFN, Gran Sasso Science Institute, I-67100 L'Aquila, Italy*
- ¹⁰⁷*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹⁰⁸*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
- ¹⁰⁹*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
- ¹¹⁰*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*
- ¹¹¹*Leibniz Universität Hannover, D-30167 Hannover, Germany*
- ¹¹²*Università di Pisa, I-56127 Pisa, Italy*
- ¹¹³*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
- ¹¹⁴*Australian National University, Canberra, Australian Capital Territory 0200, Australia*
- ¹¹⁵*California State University Fullerton, Fullerton, California 92831, USA*
- ¹¹⁶*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France*
- ¹¹⁷*Chennai Mathematical Institute, Chennai 603103, India*
- ¹¹⁸*Università di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹¹⁹*Universität Hamburg, D-22761 Hamburg, Germany*
- ¹²⁰*INFN, Sezione di Roma, I-00185 Roma, Italy*
- ¹²¹*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*
- ¹²²*West Virginia University, Morgantown, West Virginia 26506, USA*
- ¹²³*Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, West Virginia 26505, USA*
- ¹²⁴*Università di Perugia, I-06123 Perugia, Italy*
- ¹²⁵*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
- ¹²⁶*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
- ¹²⁷*Syracuse University, Syracuse, New York 13244, USA*
- ¹²⁸*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
- ¹²⁹*LIGO Hanford Observatory, Richland, Washington 99352, USA*
- ¹³⁰*Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary*
- ¹³¹*Columbia University, New York, New York 10027, USA*
- ¹³²*Stanford University, Stanford, California 94305, USA*
- ¹³³*Dipartimento di Fisica e Astronomia, Università di Padova, I-35131 Padova, Italy*
- ¹³⁴*INFN, Sezione di Padova, I-35131 Padova, Italy*
- ¹³⁵*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*

- ¹³⁶*Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
- ¹³⁷*University of Birmingham, Birmingham B15 2TT, United Kingdom*
- ¹³⁸*Università degli Studi di Genova, I-16146 Genova, Italy*
- ¹³⁹*INFN, Sezione di Genova, I-16146 Genova, Italy*
- ¹⁴⁰*RRCAT, Indore MP 452013, India*
- ¹⁴¹*Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
- ¹⁴²*SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
- ¹⁴³*Caltech CaRT, Pasadena, California 91125, USA*
- ¹⁴⁴*University of Western Australia, Crawley, Western Australia 6009, Australia*
- ¹⁴⁵*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
- ¹⁴⁶*Artemis, CNRS, Observatoire Côte d'Azur, Université Côte d'Azur, CS 34229, F-06304 Nice Cedex 4, France*
- ¹⁴⁷*Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France*
- ¹⁴⁸*Washington State University, Pullman, Washington 99164, USA*
- ¹⁴⁹*Università degli Studi di Urbino "Carlo Bo," I-61029 Urbino, Italy*
- ¹⁵⁰*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
- ¹⁵¹*University of Oregon, Eugene, Oregon 97403, USA*
- ¹⁵²*Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France*
- ¹⁵³*Carleton College, Northfield, Minnesota 55057, USA*
- ¹⁵⁴*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
- ¹⁵⁵*VU University Amsterdam, 1081 HV Amsterdam, The Netherlands*
- ¹⁵⁶*University of Maryland, College Park, Maryland 20742, USA*
- ¹⁵⁷*Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France*
- ¹⁵⁸*Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*
- ¹⁵⁹*Università di Napoli "Federico II," Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
- ¹⁶⁰*NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
- ¹⁶¹*RESCEU, University of Tokyo, Tokyo, 113-0033, Japan*
- ¹⁶²*University of Adelaide, Adelaide, South Australia 5005, Australia*
- ¹⁶³*Tsinghua University, Beijing 100084, China*
- ¹⁶⁴*Texas Tech University, Lubbock, Texas 79409, USA*
- ¹⁶⁵*University of Mississippi, University, Mississippi 38677, USA*
- ¹⁶⁶*Pennsylvania State University, University Park, Pennsylvania 16802, USA*
- ¹⁶⁷*National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China*
- ¹⁶⁸*Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
- ¹⁶⁹*University of Chicago, Chicago, Illinois 60637, USA*
- ¹⁷⁰*Kenyon College, Gambier, Ohio 43022, USA*
- ¹⁷¹*Korea Institute of Science and Technology Information, Daejeon 305-806, Korea*
- ¹⁷²*University of Cambridge, Cambridge CB2 1TN, United Kingdom*
- ¹⁷³*Università di Roma "La Sapienza," I-00185 Roma, Italy*
- ¹⁷⁴*Université Libre de Bruxelles, Brussels 1050, Belgium*
- ¹⁷⁵*Sonoma State University, Rohnert Park, California 94928, USA*
- ¹⁷⁶*Montana State University, Bozeman, Montana 59717, USA*
- ¹⁷⁷*Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, Illinois 60208, USA*
- ¹⁷⁸*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
- ¹⁷⁹*University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
- ¹⁸⁰*Bellevue College, Bellevue, Washington 98007, USA*
- ¹⁸¹*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
- ¹⁸²*University of Sheffield, Sheffield S10 2TN, United Kingdom*
- ¹⁸³*California State University, Los Angeles, 5154 State University Drive, Los Angeles, California 90032, USA*
- ¹⁸⁴*Dipartimento di Fisica, Università di Trento, I-38123 Povo, Trento, Italy*
- ¹⁸⁵*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
- ¹⁸⁶*Cardiff University, Cardiff CF24 3AA, United Kingdom*
- ¹⁸⁷*Montclair State University, Montclair, New Jersey 07043, USA*
- ¹⁸⁸*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*

- ¹⁸⁹Canadian Institute for Theoretical Astrophysics, University of Toronto,
Toronto, Ontario M5S 3H8, Canada
- ¹⁹⁰“Lendulet” Astrophysics Research Group, MTA Eötvös University, Budapest 1117, Hungary
- ¹⁹¹School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
- ¹⁹²University and Institute of Advanced Research, Gandhinagar, Gujarat 382007, India
- ¹⁹³IISER-TVM, CET Campus, Trivandrum Kerala 695016, India
- ¹⁹⁴University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ¹⁹⁵Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA
- ¹⁹⁶Tata Institute of Fundamental Research, Mumbai 400005, India
- ¹⁹⁷INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy
- ¹⁹⁸University of Michigan, Ann Arbor, Michigan 48109, USA
- ¹⁹⁹Rochester Institute of Technology, Rochester, New York 14623, USA
- ²⁰⁰NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
- ²⁰¹University of Białystok, 15-424 Białystok, Poland
- ²⁰²SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
- ²⁰³University of Southampton, Southampton SO17 1BJ, United Kingdom
- ²⁰⁴University of Washington Bothell, 18115 Campus Way NE, Bothell, Washington 98011, USA
- ²⁰⁵Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
- ²⁰⁶Seoul National University, Seoul 151-742, Korea
- ²⁰⁷Inje University Gimhae, 621-749 South Gyeongsang, Korea
- ²⁰⁸National Institute for Mathematical Sciences, Daejeon 305-390, Korea
- ²⁰⁹Pusan National University, Busan 609-735, Korea
- ²¹⁰NCBJ, 05-400 Świerk-Otwock, Poland
- ²¹¹Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
- ²¹²The School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia
- ²¹³Hanyang University, Seoul 133-791, Korea
- ²¹⁴The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- ²¹⁵University of Alabama in Huntsville, Huntsville, Alabama 35899, USA
- ²¹⁶ESPCI, CNRS, F-75005 Paris, France
- ²¹⁷University of Minnesota, Minneapolis, Minnesota 55455, USA
- ²¹⁸Dipartimento di Fisica, Università di Camerino, I-62032 Camerino, Italy
- ²¹⁹Southern University and A&M College, Baton Rouge, Louisiana 70813, USA
- ²²⁰University of Melbourne, Parkville, Victoria 3010, Australia
- ²²¹College of William and Mary, Williamsburg, Virginia 23187, USA
- ²²²Instituto de Física Teórica, University Estadual Paulista/ICTP
South American Institute for Fundamental Research, São Paulo SP 01140-070, Brazil
- ²²³Whitman College, 345 Boyer Avenue, Walla Walla, Washington 99362 USA
- ²²⁴Université de Lyon, F-69361 Lyon, France
- ²²⁵Hobart and William Smith Colleges, Geneva, New York 14456, USA
- ²²⁶Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland
- ²²⁷King’s College London, University of London, London WC2R 2LS, United Kingdom
- ²²⁸IISER-Kolkata, Mohanpur, West Bengal 741252, India
- ²²⁹Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India
- ²³⁰Andrews University, Berrien Springs, Michigan 49104, USA
- ²³¹Università di Siena, I-53100 Siena, Italy
- ²³²Trinity University, San Antonio, Texas 78212, USA
- ²³³University of Washington, Seattle, Washington 98195, USA
- ²³⁴Abilene Christian University, Abilene, Texas 79699, USA
- ²³⁵Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan