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Citation for published version (APA):

KAGRA Collaboration, LIGO Scientific Collaboration, & Virgo Collaboration (2021). All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run. *Physical Review D*, 104(10), Article 102001. <https://doi.org/10.1103/PhysRevD.104.102001>

Document status and date:

Published: 11/11/2021

DOI:

[10.1103/PhysRevD.104.102001](https://doi.org/10.1103/PhysRevD.104.102001)

Document Version:

Publisher's PDF, also known as Version of record

Document license:

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All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run

R. Abbott *et al.**

(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

 (Received 30 July 2021; accepted 4 October 2021; published 11 November 2021)

After the detection of gravitational waves from compact binary coalescences, the search for transient gravitational-wave signals with less well-defined waveforms for which matched filtering is not well suited is one of the frontiers for gravitational-wave astronomy. Broadly classified into “short” $\lesssim 1$ s and “long” $\gtrsim 1$ s duration signals, these signals are expected from a variety of astrophysical processes, including non-axisymmetric deformations in magnetars or eccentric binary black hole coalescences. In this work, we present a search for long-duration gravitational-wave transients from Advanced LIGO and Advanced Virgo’s third observing run from April 2019 to March 2020. For this search, we use minimal assumptions for the sky location, event time, waveform morphology, and duration of the source. The search covers the range of 2–500 s in duration and a frequency band of 24–2048 Hz. We find no significant triggers within this parameter space; we report sensitivity limits on the signal strength of gravitational waves characterized by the root-sum-square amplitude h_{rss} as a function of waveform morphology. These h_{rss} limits improve upon the results from the second observing run by an average factor of 1.8.

DOI: [10.1103/PhysRevD.104.102001](https://doi.org/10.1103/PhysRevD.104.102001)

I. INTRODUCTION

The third observing run of the Advanced LIGO [1] and Advanced Virgo [2] detectors has revealed a large number of new gravitational-wave (GW) signals from the collision of compact objects. Many binary black hole systems [3] have been identified. These include GW190521 [4] with the largest progenitor masses discovered so far, and GW190814, a merger containing an object in the “mass-gap” between neutron stars and black holes [5]. A second binary neutron star (BNS) system was also discovered, GW190425 [6], following the first BNS system GW170817 [7], which also produced GRB 170817A [8] and an optical transient, AT 2017gfo [9]. In addition, two neutron star–black hole binary coalescences (GW200105_162426 and GW200115_042309) have also been detected [10].

Searches for “long” $\gtrsim 1$ s duration signals cover a variety of astrophysical phenomena [11]. While well-modeled compact binary coalescences can have similar durations in the sensitive band of the interferometers and the methods employed in this paper are also sensitive to them, this search is not aimed at these systems as matched filtering is much more sensitive. However, there are less well-defined waveforms for which matched filtering is not well-suited. Plausible processes include fallback accretion onto a rapidly rotating black hole [12] or in newborn neutron stars [13–15]. They also include nonaxisymmetric

deformations in magnetars [16] or accretion disk instabilities and fragmentation of material spiraling into a black hole [17–19] and in the central engine of superluminous supernovae [20,21]. Figure 1 shows several different realizations of the corresponding waveform morphologies.

In this paper, we present the results of unmodeled long-duration transient searches from the third observing run, updating the results from the first two observing runs [24,25]. As in previous analyses [24–27], three pipelines are used; their different assumptions and data handling techniques yield complementary coverage of the signal models.

The paper is organized as follows. The data used in the analysis is described in Sec. II. The algorithms used to analyze the data are outlined in Sec. III. The results of the analysis and their implications are discussed in Sec. IV.

II. DATA

The third observing run (O3) of Advanced LIGO and Advanced Virgo spanned April 1, 2019–March 27, 2020. O3 was broken up into two segments, with O3a running April 1, 2019–Oct 1, 2019 and O3b running November 1, 2019–March 27, 2020; together, these correspond to 330 days. It is customary to assess detector sensitivities in terms of a binary neutron star inspiral range (BNS range), which is the average distance to which these signals could be detected [28,29]. Detector upgrades to the LIGO detectors in Hanford, WA, and Livingston, LA, yielded binary neutron star ranges of ~ 115 and 133 Mpc, respectively, amounting to improvements of $\sim 50\%$ with respect to

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

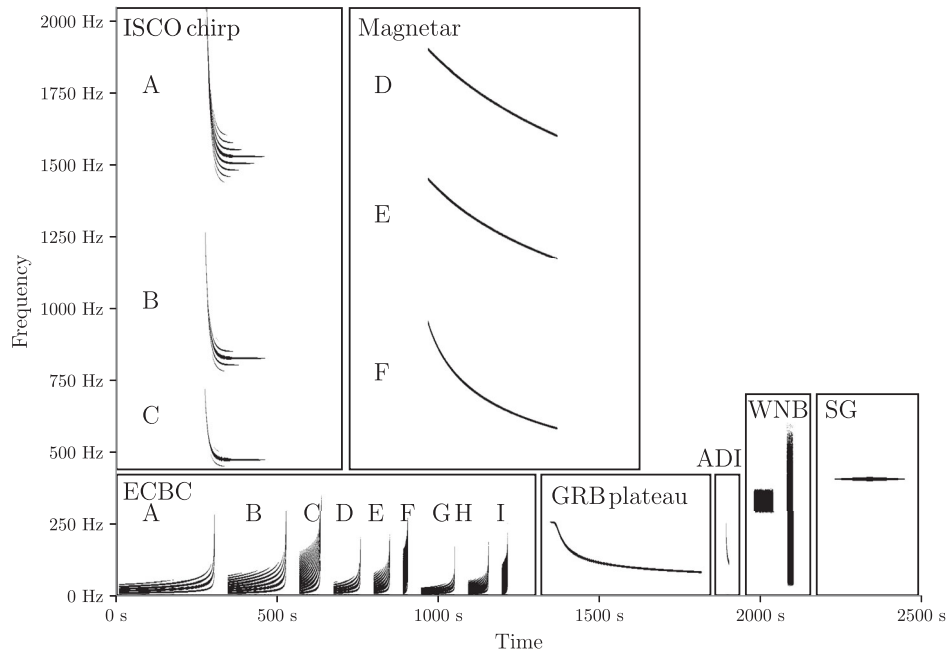


FIG. 1. Time-frequency spectrogram of the reference waveforms used in this search. We show examples of astrophysical waveforms such as postmerger magnetars (Magnetar) [22], black hole accretion disk instabilities (ADI) [18], newly formed magnetar powering a gamma-ray burst plateau (GRB plateau) [16], eccentric inspiral-merger-ringdown compact binary coalescence waveforms (ECBC) [23], broadband chirps from innermost stable circular orbit waves around rotating black holes (ISCO chirp) [12], and “*ad hoc*” waveforms, band-limited white noise burst (WNB) and sine-Gaussian bursts (SG). The ISCO chirp waveforms have been shifted up in frequency by 50 Hz for readability. Durations range from 6 (ADI-B) to 470 s (GRB plateau).

O2. Similarly, Advanced Virgo reached a binary neutron star range of ~ 50 Mpc, a $\sim 100\%$ improvement. In the following, the algorithms employed require at least two detectors to be available to process the data; therefore, only data where both LIGO detectors are simultaneously available are used. Due to the significant difference in detector alignment and sensitivities, the Virgo data in the analysis would not improve the coincidence selection when the other two detectors are active, while the high rate of non-Gaussian noise would increase the overall false-alarm rate. We plan to include Virgo in the analysis of the next observing run.

A major challenge in searches for gravitational-wave transients is non-Gaussian noise. Known sources of noise, including nonlinear sources such as time-varying spectral lines, from, e.g., machinery on site, sidebands from the 60 Hz power lines, can be witnessed and subtracted using both linear Wiener filters [30] and machine learning techniques [31,32]. The analyses that follow use data for which some of the identified sources of noise that couple in linearly to the detector have been subtracted. Beyond spectral features, there are transient noise triggers known as *glitches*, which have a variety of origins [33], such as the light reflected from surfaces such as the chamber walls and scattered back into the main beam [34]. Glitch rejection procedures rely on correlations with auxiliary channels [35,36] such as seismometers and magnetometers; yet, noise transients not witnessed by auxiliary sensors remain

and reduce sensitivity of the searches [37,38]. Each pipeline, described in the next section, implements different strategies to reduce the impact from glitches. Altogether, during the third observing run, coincident data of sufficient quality to be analyzed totaled 204.4 days. Since some time segments are too short to be processed by search pipelines, a small fraction ($< 2\%$) of this coincident data is not analyzed.

III. SEARCHES

Long-duration unmodeled searches are now briefly reviewed, and we refer the reader to previous publications for further detail [24,25]. Most unmodeled searches use time-frequency spectrograms with statistics derived from Fourier transforms or wavelet analysis performed on consecutive time segments. Pattern-recognition algorithms then are employed to search for gravitational waves in these spectrograms. These algorithms can be classified as “seed-based” [39,40], for which pixels above predetermined thresholds are clustered, and “seedless” [41,42], for which sequences of pixels are derived from generic models, such as Bézier curves [41–45]. Seedless clustering algorithms are sensitive to narrowband signals at the price of sensitivity to broadband sources, while seed-based algorithms are generally more sensitive to more generic waveform morphologies. These algorithms identify candidate gravitational-wave events known as *triggers*. To estimate

the background, all pipelines use “time slides,” [46,47], where detector data is shifted by nonphysical time delays and reanalyzed; this procedure is repeated a sufficient number of times such that at least 50 years of coincident live time is analyzed, allowing for a false alarm rate of 1 per 50 years to be estimated.

Three pipelines are deployed in the analysis: two different versions of the Stochastic Transient Analysis Multi-detector Pipeline-all sky (STAMP-AS) pipeline [11,40,45] and the long-duration configuration of coherent WaveBurst (cWB) [48]. The cWB pipeline is seed based while the two STAMP-AS algorithms, Zebragard and Lonetrack, use seed-based and seedless clustering algorithms, respectively. Altogether, the analyses are sensitive to transients lasting 2–500 s and covering a frequency band of 24–2048 Hz. Due to the short duration of binary black hole signals and the weakness of the coalescences containing neutron stars observed during O3 [6], we are not sensitive to and therefore do not excise any time around known compact binary coalescences. All false alarm rates reported are per pipeline, with no combination of searches made outside of reporting the most sensitive limit across the parameter space below.

A. STAMP-AS

Spectrograms, with duration 500 s and frequency band 24–2048 Hz and a pixel size of 1 s \times 1 Hz, are derived with cross-power SNR as the statistic computed in the maps. Nonstationary, high-amplitude spectral features are masked to limit their effect on the search. Zebragard uses cuts on the fraction of SNR per time bin (summing all pixels of the same time index) and the ratio in SNR between detectors to remove data transients [24]; Lonetrack does not require this cut due to the narrowband assumption. During a short period of time, a time segment veto that flags periods of instabilities in the high-power laser at Hanford is applied on Zebragard triggers [38].

B. CWB

The algorithm used by cWB [48] is based on a maximum likelihood approach applied to the multiresolution time-frequency representation of the time series of the detectors’ data. Candidate triggers are identified as a cluster if there is a coherent excess power in the time-frequency pixel representation over the network data. The search is performed in the frequency range 24–2048 Hz. Selection criteria are applied on the duration and on the coherence of the trigger; the coherence coefficient, measuring the degree of correlation between the detectors, must be larger than 0.6 [48]. Moreover, the trigger energy-weighted duration, defined as

$$d = \sqrt{\frac{\sum w_i (t - t^*)^2}{\sum w_i}},$$

where t is the central time of the pixel, w the energy of the pixel, t^* the mean time and the sum is computed over the selected pixels of the event in all the resolutions, is required to be greater than 1.5 s. Since observed glitch excess in the 16–48 Hz band, associated with elevated anthropogenic noise, is different between the first and second part of the run, the acceptance criteria in the latter one have been slightly modified. The triggers have an energy-weighted duration larger than 0.5 s and a total duration greater than 5 s, this to ensure increased acceptance for the eccentric compact binary waveforms family discussed in the next section.

IV. RESULTS AND FUTURE PROSPECTS

The detection threshold is defined to be a false alarm rate lower than 1/50 years (equivalent to 6.3×10^{-10} Hz). None of the pipelines found triggers consistent with such a false alarm rate; the most significant triggers, nonoverlapping between the different pipelines and consistent with the background, are listed in Table I. The most significant event reported by the cWB algorithm (statistical significance $\sim 1.7\sigma$, p value 0.088) shows a time-frequency map composed of two separated excess power cluster pixels, respectively, at 838 and 861 Hz mean frequency. This trigger appears to be associated with a random (time) coincidence of pixels belonging to two different nonstationary spectral lines of unknown origin, at 838 Hz (present in H1 and L1) and 861 Hz (present in H1). The STAMP-AS Zebragard and Lonetrack pipeline triggers are consistent with typical events identified in the background.

To place these results in context, upper limits are derived on the gravitational-wave strain amplitude using a set of simulated waveforms added coherently into detector data. Waveforms that span the parameter space in both frequency and time, as well as a sampling of potential astrophysical models, are used. For the astrophysical models, postmerger magnetars (Magnetar) [22], black hole ADI [18], newly formed magnetar powering a GRB plateau [16], ECBC waveforms [23], and broadband chirps from ISCO waves around rotating black holes [12] are used (see Ref. [49] for further developments). To include signal morphologies

TABLE I. Properties of the most significant coincident triggers found by each of the long-duration transient search pipelines during the third observing run. FAR stands for false alarm rate, while the p value is the probability of observing at least 1 noise trigger at higher significance than the most significant coincident trigger.

Pipeline	FAR [Hz]	p value	Frequency [Hz]	Duration [s]	Time [GPS]
cWB	1.0×10^{-8}	0.088	838–861	16	1252808855
Zebragard	5.6×10^{-8}	0.40	1650–1769	21	1244819393
Lonetrack	1.7×10^{-8}	0.14	1510–1937	417	1253105020

otherwise not addressed by the astrophysical models, “*ad hoc*” waveforms, band-limited white noise burst and sine-Gaussian bursts are also used. Their time-frequency spectrograms are shown in Fig. 1.

The upper limits on the gravitational-wave strain amplitude are typically reported for unmodeled searches using the root-sum-square gravitational-wave amplitude at the Earth, h_{rss} ,

$$h_{\text{rss}} = \sqrt{\int_{-\infty}^{\infty} (h_+^2(t) + h_\times^2(t)) dt}, \quad (1)$$

where h_+ and h_\times are the two signal polarizations. Simulations are varied with h_{rss} and injected uniformly in time, sky location, polarization angle, and the cosine of the inclination angle of the assumed source.

Upper limits on gravitational-wave strain versus mean frequency for sources detected with 50% efficiency and a false alarm rate of 1 event in 50 years are shown in Fig. 2. The strongest bounds obtained from the three pipelines are shown on the plot. Because each pipeline uses a different clustering algorithm, their relative sensitivities vary with waveform morphology. Lonetrack, which uses seedless clustering, performs best on magnetar signals (Magnetar and GRB plateau) but is not sensitive to white noise bursts. Zebragard and coherent WaveBurst give the most constraining values with similar sensitivities for most of the remaining waveforms. On average, for all waveforms considered in this paper, the h_{rss} sensitivity improved

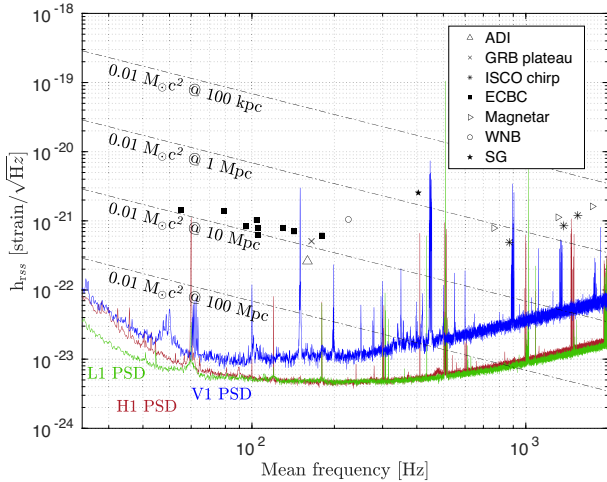


FIG. 2. The GW root-sum-square strain amplitude versus mean frequency at 50% detection efficiency and a FAR of 1/50 years. The red, green, and blue curves are the averaged amplitude spectral noise densities for Hanford, Livingston, and Virgo detectors to show that the search results follow the detectors’ sensitivity frequency. We also show in dashed-dotted lines the gravitational-wave amplitudes corresponding to the energy of $0.01 M_\odot c^2$ at various distances, with examples at 100 kpc, 1, 10, and 100 Mpc shown.

by a factor of 1.8 upon the analysis from the second observing run [25].

For the eccentric binary waveforms, we determine 90% confidence level limits on the rate of events. We do this using the “loudest event statistic” method, which uses the candidate with the largest value to estimate rate constraints [50]. Taking as an example the eccentric binary waveforms, the 90% upper limits on the event rates as a function of distance are highlighted in Fig. 3. In addition, Table II gives the upper limits $\mathcal{R}_{90\%}$ at 90% confidence on the rate of eccentric binary coalescences per unit volume. Following [51], and assuming an isotropic and uniform distribution of sources, $\mathcal{R}_{90\%}$ is given by

$$\mathcal{R}_{90\%} = \frac{2.3}{4\pi T \int_0^{r_{\text{max}}} dr r^2 \epsilon(r)}, \quad (2)$$

where $\epsilon(r)$ is the detection efficiency as a function of distance, computed as the fraction of transients detectable at a given distance [51], r_{max} is the maximum detectable distance, and $T = 204.4$ days is the total observing time. For 1.4–1.4 solar masses eccentric binaries, rate upper limits are ~ 1.5 – 2 lower than the ones computed in Ref. [52] for O2 data. Such improvement can be explained by both the increased sensitivity of the search and the increased livetime between O2 and O3. For comparison, estimated merger rates from the second LIGO-Virgo GW transient catalog [53] are $23.9_{-8.6}^{+14.3} \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $340_{-240}^{+490} \text{ Gpc}^{-3} \text{ yr}^{-1}$ for binary black holes and binary neutron stars, respectively. With eccentric systems expected to be only a small fraction of the total binary systems, the upper limits derived are compatible with an absence of detection of such systems in this search; for this reason, we do not constrain the fraction of

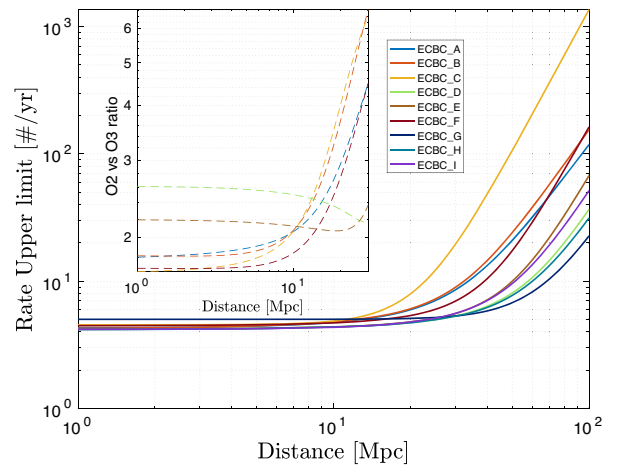


FIG. 3. Upper limits at 90% confidence level on the rate of eccentric compact binary coalescences as a function of the distance. Only the best result is shown for each waveform. The inset shows the ratio of the rates with respect to O2 results [25] for ECBC_A to ECBC_F (see Table II for parameters).

TABLE II. Rate upper limits per unit volume at 90% confidence level on eccentric compact binary coalescences with various masses and eccentricity e , computed with Eq. (2).

Waveform	$M_1[M_\odot]$	$M_2[M_\odot]$	e	$\mathcal{R}_{90\%}$ [$\text{Gpc}^{-3} \text{yr}^{-1}$]
ECBC_A	1.4	1.4	0.2	9.97×10^2
ECBC_B	1.4	1.4	0.4	8.09×10^2
ECBC_C	1.4	1.4	0.6	3.21×10^3
ECBC_D	3.0	3.0	0.2	3.99×10^2
ECBC_E	3.0	3.0	0.4	8.89×10^2
ECBC_F	3.0	3.0	0.6	2.43×10^3
ECBC_G	5.0	5.0	0.2	1.50×10^3
ECBC_H	5.0	5.0	0.4	5.10×10^2
ECBC_I	5.0	5.0	0.6	6.98×10^2

eccentric binary systems, but this may become possible in the future with more sensitive detector data.

It is expected that continued improvements both to the gravitational-wave detectors and to the search algorithms, e.g., [49,54,55], will lead to either detections or improved limits on this portion of parameter space. Going forward, increasing the parameter space searched, such as for longer signals, is a high priority; these signals may include long-lived remnants of binary neutron star mergers, whose detection in gravitational waves may constrain the nature of the remnant [12,27]. In addition, integration of Advanced Virgo into the analyses will be important, especially in case of a genuine signal for characterization. With range improvements of $\sim 50\%$ expected for the fourth observing run and more than a factor of 2 expected by the fifth observing run [28], significant gains in detection possibilities can be expected.

ACKNOWLEDGMENTS

This material is based upon work supported by NSF's LIGO Laboratory, which is a major facility fully funded by the National Science Foundation. The authors also gratefully acknowledge the support of 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 Netherlands Organization for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering

Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the Conselleria d'Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the National Science Centre of Poland and the Foundation for Polish Science (FNP), 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 French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek—Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, 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, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN and CNRS for provision of computational resources. This work was supported by MEXT, JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, JSPS Grant-in-Aid for Scientific Research on Innovative Areas 2905: Grants No. JP17H06358, No. JP17H06361, and No. JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grant-in-Aid for Scientific Research (S) Grants No. 17H06133 and No. 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 20A203: Grant No. JP20H05854, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, National Research Foundation (NRF) and Computing Infrastructure Project of KISTI-GSDC in Korea, Academia Sinica (AS), AS Grid Center (ASGC) and the Ministry of Science and Technology (MoST) in Taiwan under grants including Grant No. AS-CDA-105-M06, Advanced Technology Center (ATC) of NAOJ, Mechanical Engineering Center of KEK.

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Ballardín,⁴⁰ S. W. Ballmer,⁵⁸ A. Balsamo,⁵⁴ G. Baltus,⁵⁹ S. Banagiri,⁶⁰ D. Bankar,¹¹ J. C. Barayoga,¹ C. Barbieri,^{61,62,63} B. C. Barish,¹ D. Barker,⁶⁴ P. Barneo,²⁷ F. Barone,^{65,4} B. Barr,⁶⁶ L. Barsotti,⁶⁷ M. Barsuglia,³⁴ D. Barta,⁶⁸ J. Bartlett,⁶⁴ M. A. Barton,^{66,20} I. Bartos,⁶⁹ R. Bassiri,⁷⁰ A. Basti,^{71,18} M. Bawaj,^{72,73} J. C. Bayley,⁶⁶ A. C. Baylor,⁷ M. Bazzan,^{74,75} B. Bécsy,⁷⁶ V. M. Bedakihale,⁷⁷ M. Bejger,⁷⁸ I. Belahcene,³⁹ V. Benedetto,⁷⁹ D. Beniwal,⁸⁰ T. F. Bennett,⁸¹ J. D. Bentley,¹⁴ M. BenYaala,³⁰ F. Bergamin,^{9,10} B. K. Berger,⁷⁰ S. Bernuzzi,¹³ D. Bersanetti,⁸² A. Bertolini,⁵⁰ J. Betzwieser,⁶ D. Beveridge,⁸³ R. Bhandare,⁸⁴ U. Bhardwaj,^{85,50} D. Bhattacharjee,⁸⁶ S. Bhaumik,⁶⁹ I. A. Bilenko,⁸⁷ G. Billingsley,¹ S. Bini,^{88,89} R. Birney,⁹⁰ O. Birnholtz,⁹¹ S. Biscans,^{1,67} M. Bischì,^{46,47} S. Biscoveanu,⁶⁷ A. Bisht,^{9,10} B. Biswas,¹¹ M. Bitossi,^{40,18} M.-A. Bizouard,⁹² J. K. Blackburn,¹ C. D. Blair,^{83,6} D. G. Blair,⁸³ R. M. Blair,⁶⁴ F. Bobba,^{93,94} N. Bode,^{9,10} M. Boer,⁹² G. Bogaert,⁹² M. Boldrini,^{95,48} L. D. Bonavena,⁷⁴ F. Bondu,⁹⁶ E. Bonilla,⁷⁰ R. Bonnand,²⁸ P. Booker,^{9,10} B. A. Boom,⁵⁰ R. Bork,¹ V. Boschi,¹⁸ N. Bose,⁹⁷ S. Bose,¹¹ V. Bossilkov,⁸³ V. Boudart,⁵⁹ Y. Bouffanais,^{74,75} A. Bozzi,⁴⁰ C. Bradaschia,¹⁸ P. R. Brady,⁷ A. Bramley,⁶ A. Branch,⁶ M. Branchesi,^{29,98} J. E. Brau,⁵⁷ M. Breschi,¹³ T. Briant,⁹⁹ J. H. Briggs,⁶⁶ A. Brilliet,⁹² M. Brinkmann,^{9,10} P. Brockill,⁷ A. F. Brooks,¹ J. Brooks,⁴⁰ D. D. Brown,⁸⁰ S. Brunett,¹ G. Bruno,⁴⁹ R. Bruntz,⁵⁴ J. Bryant,¹⁴ T. Bulik,¹⁰⁰ H. J. Bulten,⁵⁰ A. Buonanno,^{101,102} R. Buscicchio,¹⁴ D. Buskulic,²⁸ C. Buy,¹⁰³ R. L. Byer,⁷⁰ L. Cadonati,¹⁰⁴ G. Cagnoli,²⁴ C. Cahillane,⁶⁴ J. Calderón Bustillo,^{105,106} J. D. Callaghan,⁶⁶ T. A. Callister,^{107,108} E. Calloni,^{23,4} J. Cameron,⁸³ J. B. Camp,¹⁰⁹ M. Canepa,^{110,82} S. Canevarolo,¹¹¹ M. Cannavacciuolo,⁹³ K. C. Cannon,¹¹² H. Cao,⁸⁰ Z. Cao,¹¹³ E. Capocasa,²⁰ E. Capote,⁵⁸ G. Carapella,^{93,94} F. Carbognani,⁴⁰ J. B. Carlin,¹¹⁴ M. F. Carney,¹⁵ M. Carpinelli,^{115,116,40} G. Carrillo,⁵⁷ G. Carullo,^{71,18} T. L. Carver,¹⁷ J. Casanueva Diaz,⁴⁰ C. Casentini,^{117,118} G. Castaldi,¹¹⁹ S. Caudill,^{50,111} M. Cavaglia,⁸⁶ F. Cavalier,³⁹ R. Cavalieri,⁴⁰ M. Ceasar,¹²⁰ G. Cella,¹⁸ P. Cerdá-Durán,¹²¹ E. Cesarini,¹¹⁸ W. Chaibi,⁹² K. Chakravarti,¹¹ S. Chalathadka Subrahmanya,¹²² E. Champion,¹²³ C.-H. Chan,¹²⁴ C. Chan,¹¹² C. L. Chan,¹⁰⁶ K. Chan,¹⁰⁶ M. Chan,¹²⁵ K. Chandra,⁹⁷ P. Chanial,⁴⁰ S. Chao,¹²⁴ P. Charlton,¹²⁶ E. A. Chase,¹⁵ E. Chassande-Mottin,³⁴ C. Chatterjee,⁸³ Debarati Chatterjee,¹¹ Deep Chatterjee,⁷ M. Chaturvedi,⁸⁴ S. Chaty,³⁴ C. Chen,^{127,128} H. Y. Chen,⁶⁷ J. Chen,¹²⁴ K. Chen,¹²⁹ X. Chen,⁸³ Y.-B. Chen,¹³⁰ Y.-R. Chen,¹³¹ Z. Chen,¹⁷ H. Cheng,⁶⁹ C. K. Cheong,¹⁰⁶ H. Y. Cheung,¹⁰⁶ H. Y. Chia,⁶⁹ F. Chiadini,^{132,94} C.-Y. Chiang,¹³³ G. Chiarini,⁷⁵ R. Chierici,¹³⁴ A. Chincarini,⁸² M. L. Chiofalo,^{71,18} A. Chiummo,⁴⁰ G. Cho,¹³⁵ H. S. Cho,¹³⁶ R. K. Choudhary,⁸³ S. Choudhary,¹¹ N. Christensen,⁹² H. Chu,¹²⁹ Q. Chu,⁸³ Y.-K. Chu,¹³³ S. Chua,⁸ K. W. Chung,⁵¹ G. Ciani,^{74,75} P. Cielciag,⁷⁸ M. Cieřlar,⁷⁸ M. Cifaldi,^{117,118} A. A. Ciobanu,⁸⁰ R. Ciolfi,^{137,75} F. Cipriano,⁹² A. Cirone,^{110,82} F. Clara,⁶⁴ E. N. Clark,¹³⁸ J. A. Clark,^{1,104} L. Clarke,¹³⁹ P. Clearwater,¹⁴⁰ S. Clesse,¹⁴¹ F. Cleva,⁹² E. Coccia,^{29,98} E. Codazzo,²⁹ P.-F. Cohadon,⁹⁹ D. E. Cohen,³⁹ L. Cohen,² M. Colleoni,¹⁴² C. G. Collette,¹⁴³ A. Colombo,⁶¹ M. Colpi,^{61,62} C. M. Compton,⁶⁴ M. Constancio Jr.,¹⁶ L. Conti,⁷⁵ S. J. Cooper,¹⁴ P. Corban,⁶ T. R. Corbitt,² I. Cordero-Carrión,¹⁴⁴ S. Corezzi,^{73,72} K. R. Corley,⁴³ N. Cornish,⁷⁶ D. Corre,³⁹ A. Corsi,¹⁴⁵ S. Cortese,⁴⁰ C. A. Costa,¹⁶ R. Cotesta,¹⁰² M. W. Coughlin,⁶⁰ J.-P. Coulon,⁹² S. T. Countryman,⁴³ B. Cousins,¹⁴⁶ P. Couvares,¹ D. M. Coward,⁸³ M. J. Cowart,⁶ D. C. Coyne,¹ R. Coyne,¹⁴⁷ J. D. E. Creighton,⁷ T. D. Creighton,¹⁴⁸ A. W. Criswell,⁶⁰ M. Croquette,⁹⁹ S. G. Crowder,¹⁴⁹ J. R. Cudell,⁵⁹ T. J. Cullen,² A. Cumming,⁶⁶ R. Cummings,⁶⁶ L. 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Di Pace,^{95,48} I. Di Palma,^{95,48} F. Di Renzo,^{71,18} A. K. Divakarla,⁶⁹ A. Dmitriev,¹⁴ Z. Doctor,⁵⁷ L. D’Onofrio,^{23,4}

F. Donovan,⁶⁷ K. L. Dooley,¹⁷ S. Doravari,¹¹ I. Dorrington,¹⁷ M. Drago,^{95,48} J. C. Driggers,⁶⁴ Y. Drori,¹ J.-G. Ducoin,³⁹ P. Dupej,⁶⁶ O. Durante,^{93,94} D. D'Urso,^{115,116} P.-A. Duverne,³⁹ S. E. Dwyer,⁶⁴ C. Eassa,⁶⁴ P. J. Easter,⁵ M. Ebersold,¹⁵⁸ T. Eckhardt,¹²² G. Eddolls,⁶⁶ B. Edelman,⁵⁷ T. B. Edo,¹ O. Edy,¹⁵³ A. Effler,⁶ S. Eguchi,¹²⁵ J. Eichholz,⁸ S. S. Eikenberry,⁶⁹ M. Eisenmann,²⁸ R. A. Eisenstein,⁶⁷ A. Ejlli,¹⁷ E. Engelby,³⁸ Y. Enomoto,²⁵ L. Errico,^{23,4} R. C. Essick,¹⁵⁹ H. Estellés,¹⁴² D. Estevez,¹⁶⁰ Z. Etienne,¹⁶¹ T. Etzel,¹ M. Evans,⁶⁷ T. M. Evans,⁶ B. E. Ewing,¹⁴⁶ V. Fafone,^{117,118,29} H. Fair,⁵⁸ S. Fairhurst,¹⁷ A. M. Farah,¹⁵⁹ S. Farinon,⁸² B. Farr,⁵⁷ W. M. Farr,^{107,108} N. W. Farrow,⁵ E. J. Fauchon-Jones,¹⁷ G. Favaro,⁷⁴ M. Favata,¹⁶² M. Fays,⁵⁹ M. Fazio,¹⁶³ J. Feicht,¹ M. M. Fejer,⁷⁰ E. Fenyvesi,^{68,164} D. L. Ferguson,¹⁶⁵ A. Fernandez-Galiana,⁶⁷ I. Ferrante,^{71,18} T. A. Ferreira,¹⁶ F. Fidecaro,^{71,18} P. Figura,¹⁰⁰ I. Fiori,⁴⁰ M. Fishbach,¹⁵ R. P. 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Hansen,³³ J. Hanson,⁶ T. Harder,⁹² T. Hardwick,² K. Haris,^{50,111} J. Harms,^{29,98} G. M. Harry,¹⁸⁸ I. W. Harry,¹⁵³ D. Hartwig,¹²² K. Hasegawa,³⁵ B. Haskell,⁷⁸ R. K. Hasske,⁶ C.-J. Haster,⁶⁷ K. Hattori,¹⁸⁹ K. Haughian,⁶⁶ H. Hayakawa,¹⁹⁰ K. Hayama,¹²⁵ F. J. Hayes,⁶⁶ J. Healy,¹²³ A. Heidmann,⁹⁹ A. Heidt,^{9,10} M. C. Heintze,⁶ J. Heinze,^{9,10} J. Heinzl,¹⁹¹ H. Heitmann,⁹² F. Hellman,¹⁹² P. Hello,³⁹ A. F. Helmling-Cornell,⁵⁷ G. Hemming,⁴⁰ M. Hendry,⁶⁶ I. S. Heng,⁶⁶ E. Hennes,⁵⁰ J. Hennig,¹⁹³ M. H. Hennig,¹⁹³ A. G. Hernandez,⁸¹ F. Hernandez Vivanco,⁵ M. Heurs,^{9,10} S. Hild,^{152,50} P. Hill,³⁰ Y. Himemoto,¹⁹⁴ A. S. Hines,¹⁸³ Y. Hiranuma,¹⁹⁵ N. Hirata,²⁰ E. Hirose,³⁵ S. Hochheim,^{9,10} D. Hofman,¹⁵⁵ J. N. Hohmann,¹²² D. G. Holcomb,¹²⁰ N. A. Holland,⁸ I. J. Hollows,¹⁵⁴ Z. J. Holmes,⁸⁰ K. Holt,⁶ D. E. Holz,¹⁵⁹ Z. Hong,¹⁹⁶ P. Hopkins,¹⁷ J. Hough,⁶⁶ S. Hourihane,¹³⁰ E. J. Howell,⁸³ C. G. Hoy,¹⁷ D. Hoyland,¹⁴ A. Hreibi,^{9,10} B.-H. Hsieh,³⁵ Y. Hsu,¹²⁴ G.-Z. Huang,¹⁹⁶ H.-Y. Huang,¹³³ P. Huang,¹⁷⁴ Y.-C. Huang,¹³¹ Y.-J. Huang,¹³³ Y. Huang,⁶⁷ M. T. Hübner,⁵ A. D. Huddart,¹³⁹ B. Hughey,³³ D. C. Y. Hui,¹⁹⁷ V. Hui,²⁸ S. Husa,¹⁴² S. H. Huttner,⁶⁶ R. Huxford,¹⁴⁶ T. Huynh-Dinh,⁶ S. Ide,¹⁹⁸ B. Idzkowski,¹⁰⁰ A. Iess,^{117,118} B. Ikenoue,²¹ S. Imam,¹⁹⁶ K. Inayoshi,¹⁹⁹ C. Ingram,⁸⁰ Y. Inoue,¹²⁹ K. Ioka,²⁰⁰ M. Isi,⁶⁷ K. Isleif,¹²² K. Ito,²⁰¹ Y. Itoh,^{202,203} B. R. Iyer,¹⁹ K. Izumi,²⁰⁴ V. JaberianHamedan,⁸³ T. Jacqmin,⁹⁹ S. J. Jadhav,²⁰⁵ S. P. Jadhav,¹¹ A. L. James,¹⁷ A. Z. Jan,¹²³ K. Jani,²⁰⁶ J. Janquart,^{111,50} K. Janssens,^{207,92} N. N. Janthalur,²⁰⁵ P. Jaranowski,²⁰⁸ D. Jariwala,⁶⁹ R. Jaume,¹⁴² A. C. Jenkins,⁵¹ K. Jenner,⁸⁰ C. Jeon,²⁰⁹ M. Jeunon,⁶⁰ W. Jia,⁶⁷ H.-B. Jin,^{210,211} G. R. Johns,⁵⁴ A. W. Jones,⁸³ D. I. Jones,²¹² J. D. Jones,⁶⁴ P. Jones,¹⁴ R. Jones,⁶⁶ R. J. G. Jonker,⁵⁰ L. Ju,⁸³ P. Jung,⁵³ K. Jung,¹⁸⁴ J. Junker,^{9,10} V. Juste,¹⁶⁰ K. Kaihotsu,²⁰¹ T. Kajita,²¹³ M. Kakizaki,¹⁸⁹ C. V. Kalaghatgi,^{17,111} V. Kalogera,¹⁵ B. Kamai,¹ M. Kamiizumi,¹⁹⁰ N. 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Martelli,^{46,47} I. W. Martin,⁶⁶ R. M. Martin,¹⁶² M. Martinez,²¹⁵ V. A. Martinez,⁶⁹ V. Martinez,²⁴ K. Martinovic,⁵¹ D. V. Martynov,¹⁴ E. J. Marx,⁶⁷ H. Masalehdan,¹²² K. Mason,⁶⁷ E. Massera,¹⁵⁴ A. Masserot,²⁸ T. J. Massinger,⁶⁷ M. Masso-Reid,⁶⁶ S. Mastrogiovanni,³⁴ A. Matas,¹⁰² M. Mateu-Lucena,¹⁴² F. Matichard,^{1,67} M. Matushechkina,^{9,10} N. Mavalvala,⁶⁷ J. J. McCann,⁸³ R. McCarthy,⁶⁴ D. E. McClelland,⁸ P. K. McClincy,¹⁴⁶ S. McCormick,⁶ L. McCuller,⁶⁷ G. I. McGhee,⁶⁶ S. C. McGuire,²⁴⁹ C. McIsaac,¹⁵³ J. McIver,¹⁷⁸ T. McRae,⁸ S. T. McWilliams,¹⁶¹ D. Meacher,⁷ M. Mehmet,^{9,10} A. K. Mehta,¹⁰² Q. Meijer,¹¹¹ A. Melatos,¹¹⁴ D. A. Melchor,³⁸ G. Mendell,⁶⁴ A. Menendez-Vazquez,²¹⁵ C. S. Menoni,¹⁶³ R. A. Mercer,⁷ L. Mereni,¹⁵⁵ K. Merfeld,⁵⁷ E. L. Merilh,⁶ J. D. Merritt,⁵⁷ M. Merzougui,⁹² S. Meshkov,^{1,†} C. Messenger,⁶⁶ C. Messick,¹⁶⁵ P. M. Meyers,¹¹⁴ F. Meylahn,^{9,10} A. Mhaske,¹¹ A. Miani,^{88,89} H. Miao,¹⁴ I. Michaloliakos,⁶⁹ C. Michel,¹⁵⁵ Y. Michimura,²⁵ H. Middleton,¹¹⁴ L. 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Nakamura,²⁰ H. Nakano,²⁵⁶ M. Nakano,³⁵ R. Nakashima,²¹⁶ Y. Nakayama,²⁰¹ V. Napolano,⁴⁰ I. Nardecchia,^{117,118} T. Narikawa,³⁵ L. Naticchioni,⁴⁸ B. Nayak,⁸¹ R. K. Nayak,²⁵⁷ R. Negishi,¹⁹⁵ B. F. Neil,⁸³ J. Neilson,^{79,94} G. Nelemans,²⁵⁸ T. J. N. Nelson,⁶ M. Nery,^{9,10} P. Neubauer,¹⁷⁰ A. Neunzert,²¹⁷ K. Y. Ng,⁶⁷ S. W. S. Ng,⁸⁰ C. Nguyen,³⁴ P. Nguyen,⁵⁷ T. Nguyen,⁶⁷ L. Nguyen Quynh,²⁵⁹ W.-T. Ni,^{210,174,131} S. A. Nichols,² A. Nishizawa,²⁶ S. Nissanke,^{85,50} E. Nitoglia,¹³⁴ F. Nocera,⁴⁰ M. Norman,¹⁷ C. North,¹⁷ S. Nozaki,¹⁸⁹ L. K. Nuttall,¹⁵³ J. Oberling,⁶⁴ B. D. O'Brien,⁶⁹ Y. Obuchi,²¹ J. O'Dell,¹³⁹ E. Oelker,⁶⁶ W. Ogaki,³⁵ G. Oganessian,^{29,98} J. J. Oh,²²³ K. Oh,¹⁹⁷ S. H. Oh,²²³ M. Ohashi,¹⁹⁰ N. Ohishi,⁴⁴ M. Ohkawa,¹⁷³ F. Ohme,^{9,10} H. Ohta,¹¹² M. A. Okada,¹⁶ Y. Okutani,¹⁹⁸ K. Okutomi,¹⁹⁰ C. Olivetto,⁴⁰ K. Oohara,¹⁹⁵ C. Ooi,²⁵ R. Oram,⁶ B. O'Reilly,⁶ R. G. Ormiston,⁶⁰ N. D. Ormsby,⁵⁴ L. F. Ortega,⁶⁹ R. O'Shaughnessy,¹²³ E. O'Shea,¹⁷⁷ S. Oshino,¹⁹⁰ S. Ossokine,¹⁰² C. Osthelder,¹ S. Otabe,²¹⁶ D. J. Ottaway,⁸⁰ H. Overmier,⁶ A. E. Pace,¹⁴⁶ G. Pagano,^{71,18} M. A. Page,⁸³ G. Pagliaroli,^{29,98} A. Pai,⁹⁷ S. A. Pai,⁸⁴ J. R. Palamos,⁵⁷ O. Palashov,²¹⁸ C. Palomba,⁴⁸ H. Pan,¹²⁴ K. Pan,^{131,227} P. K. Panda,²⁰⁵ H. Pang,¹²⁹ P. T. H. Pang,^{50,111} C. Pankow,¹⁵ F. Pannarale,^{95,48} B. C. Pant,⁸⁴ F. H. Panther,⁸³ F. Paoletti,¹⁸ A. Paoli,⁴⁰ A. Paolone,^{48,260} A. Parisi,¹²⁷ H. Park,⁷ J. Park,²⁶¹ W. Parker,^{6,249} D. Pascucci,⁵⁰ A. Pasqualetti,⁴⁰ R. Passaquieti,^{71,18} D. Passuello,¹⁸ M. Patel,⁵⁴ M. Pathak,⁸⁰ B. Patricelli,^{40,18} A. S. Patron,² S. Patrone,^{95,48} S. Paul,⁵⁷ E. Payne,⁵ M. Pedraza,¹ M. Pegoraro,⁷⁵ A. Pele,⁶ F. E. Peña Arellano,¹⁹⁰ S. Penn,²⁶² A. Perego,^{88,89} A. Pereira,²⁴ T. Pereira,²⁶³ C. J. Perez,⁶⁴ C. Périgois,²⁸ C. C. Perkins,⁶⁹ A. Perreca,^{88,89} S. Perriès,¹³⁴ J. Petermann,¹²² D. Petterson,¹ H. P. Pfeiffer,¹⁰² K. A. Pham,⁶⁰

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 S. Ponrathnam,¹¹ P. Popolizio,⁴⁰ E. K. Porter,³⁴ R. Poulton,⁴⁰ J. Powell,¹⁴⁰ M. Pracchia,²⁸ T. Pradier,¹⁶⁰ A. K. Prajapati,⁷⁷
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 M. Sakellariadou,⁵¹ Y. Sakuno,¹²⁵ O. S. Salafia,^{63,62,61} L. Salconi,⁴⁰ M. Saleem,⁶⁰ F. Salemi,^{88,89} A. Samajdar,^{50,111}
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 R. Shimizu,²¹ T. Shimoda,²⁵ K. Shimode,¹⁹⁰ H. Shinkai,²⁷⁶ T. Shishido,⁴⁵ A. Shoda,²⁰ D. H. Shoemaker,⁶⁷
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 A. Singha,^{152,50} A. M. Sintes,¹⁴² V. Sipala,^{115,116} V. Skliris,¹⁷ B. J. J. Slagmolen,⁸ T. J. Slaven-Blair,⁸³ J. Smetana,¹⁴
 J. R. Smith,³⁸ R. J. E. Smith,⁵ J. Soldateschi,^{277,278,47} S. N. Somala,²⁷⁹ K. Somiya,²¹⁶ E. J. Son,²²³ K. Soni,¹¹ S. Soni,²
 V. Sordini,¹³⁴ F. Sorrentino,⁸² N. Sorrentino,^{71,18} H. Sotani,²⁸⁰ R. Soulard,⁹² T. Souradeep,^{267,11} E. Sowell,¹⁴⁵
 V. Spagnuolo,^{152,50} A. P. Spencer,⁶⁶ M. Spera,^{74,75} R. Srinivasan,⁹² A. K. Srivastava,⁷⁷ V. Srivastava,⁵⁸ K. Staats,¹⁵
 C. Stachie,⁹² D. A. Steer,³⁴ J. Steinlechner,^{152,50} S. Steinlechner,^{152,50} D. J. Stops,¹⁴ M. Stover,¹⁷⁰ K. A. Strain,⁶⁶
 L. C. Strang,¹¹⁴ G. Stratta,^{281,47} A. Strunk,⁶⁴ R. Sturani,²⁶³ A. L. Stuver,¹²⁰ S. Sudhagar,¹¹ V. Sudhir,⁶⁷ R. Sugimoto,^{282,204}
 H. G. Suh,⁷ T. Z. Summerscales,²⁸³ H. Sun,⁸³ L. Sun,⁸ S. Sunil,⁷⁷ A. Sur,⁷⁸ J. Suresh,^{112,35} P. J. Sutton,¹⁷ Takamasa Suzuki,¹⁷³
 Toshikazu Suzuki,³⁵ B. L. Swinkels,⁵⁰ M. J. Szczepańczyk,⁶⁹ P. Szewczyk,¹⁰⁰ M. Tacca,⁵⁰ H. Tagoshi,³⁵ S. C. Tait,⁶⁶
 H. Takahashi,²⁸⁴ R. Takahashi,²⁰ A. Takamori,³⁷ S. Takano,²⁵ H. Takeda,²⁵ M. Takeda,²⁰² C. J. Talbot,³⁰ C. Talbot,¹
 H. Tanaka,²⁸⁵ Kazuyuki Tanaka,²⁰² Kenta Tanaka,²⁸⁵ Taiki Tanaka,³⁵ Takahiro Tanaka,²⁷⁰ A. J. Tanasijczuk,⁴⁹
 S. Tanioka,^{20,45} D. B. Tanner,⁶⁹ D. Tao,¹ L. Tao,⁶⁹ E. N. Tapia San Martín,^{50,20} C. Taranto,¹¹⁷ J. D. Tasson,¹⁹¹ S. Telada,²⁸⁶
 R. Tenorio,¹⁴² J. E. Terhune,¹²⁰ L. Terkowski,¹²² M. P. Thirugnanasambandam,¹¹ M. Thomas,⁶ P. Thomas,⁶⁴
 J. E. Thompson,¹⁷ S. R. Thondapu,⁸⁴ K. A. Thorne,⁶ E. Thrane,⁵ Shubhanshu Tiwari,¹⁵⁸ Srishti Tiwari,¹¹ V. Tiwari,¹⁷
 A. M. Toivonen,⁶⁰ K. Toland,⁶⁶ A. E. Tolley,¹⁵³ T. Tomaru,²⁰ Y. Tomigami,²⁰² T. Tomura,¹⁹⁰ M. Tonelli,^{71,18}
 A. Torres-Forné,¹²¹ C. I. Torrie,¹ I. Tosta e Melo,^{115,116} D. Töyrä,⁸ A. Trapananti,^{247,72} F. Travasso,^{72,247} G. Traylor,⁶
 M. Trevor,¹⁰¹ M. C. Tringali,⁴⁰ A. Tripathy,¹⁸² L. Troiano,^{287,94} A. Trovato,³⁴ L. Trozzo,^{4,190} R. J. Trudeau,¹ D. S. Tsai,¹²⁴
 D. Tsai,¹²⁴ K. W. Tsang,^{50,288,111} T. Tsang,²⁸⁹ J-S. Tsao,¹⁹⁶ M. Tse,⁶⁷ R. Tso,¹³⁰ K. Tsubono,²⁵ S. Tsuchida,²⁰² L. Tsukada,¹¹²
 D. Tsuna,¹¹² T. Tsutsui,¹¹² T. Tsuzuki,²¹ K. Turbang,^{290,207} M. Turconi,⁹² D. Tuyenbayev,²⁰² A. S. Ubhi,¹⁴ N. Uchikata,³⁵
 T. Uchiyama,¹⁹⁰ R. P. Udall,¹ A. Ueda,¹⁸⁵ T. Uehara,^{291,292} K. Ueno,¹¹² G. Ueshima,²⁹³ C. S. Unnikrishnan,¹⁷⁹ F. Uraguchi,²¹
 A. L. Urban,² T. Ushiba,¹⁹⁰ A. Utina,^{152,50} H. Vahlbruch,^{9,10} G. Vajente,¹ A. Vajpeyi,⁵ G. Valdes,¹⁸³ M. Valentini,^{88,89}
 V. Valsan,⁷ N. van Bakel,⁵⁰ M. van Beuzekom,⁵⁰ J. F. J. van den Brand,^{152,294,50} C. Van Den Broeck,^{111,50}
 D. C. Vander-Hyde,⁵⁸ L. van der Schaaf,⁵⁰ J. V. van Heijningen,⁴⁹ J. Vanosky,¹ M. H. P. M. van Putten,²⁹⁵
 N. van Remortel,²⁰⁷ M. Vardaro,^{240,50} A. F. Vargas,¹¹⁴ V. Varma,¹⁷⁷ M. Vasúth,⁶⁸ A. Vecchio,¹⁴ G. Vedovato,⁷⁵ J. Veitch,⁶⁶
 P. J. Veitch,⁸⁰ J. Venneberg,^{9,10} G. Venugopalan,¹ D. Verkindt,²⁸ P. Verma,²³⁰ Y. Verma,⁸⁴ D. Veske,⁴³ F. Vetrano,⁴⁶

A. Viceré,^{46,47} S. Vidyant,⁵⁸ A. D. Viets,²⁴⁶ A. Vijaykumar,¹⁹ V. Villa-Ortega,¹⁰⁵ J.-Y. Vinet,⁹² A. Virtuoso,^{186,32} S. Vitale,⁶⁷ T. Vo,⁵⁸ H. Vocca,^{73,72} E. R. G. von Reis,⁶⁴ J. S. A. von Wrangel,^{9,10} C. Vorvick,⁶⁴ S. P. Vyatchanin,⁸⁷ L. E. Wade,¹⁷⁰ M. Wade,¹⁷⁰ K. J. Wagner,¹²³ R. C. Walet,⁵⁰ M. Walker,⁵⁴ G. S. Wallace,³⁰ L. Wallace,¹ S. Walsh,⁷ J. Wang,¹⁷⁴ J. Z. Wang,¹⁸² W. H. Wang,¹⁴⁸ R. L. Ward,⁸ J. Warner,⁶⁴ M. Was,²⁸ T. Washimi,²⁰ N. Y. Washington,¹ J. Watchi,¹⁴³ B. Weaver,⁶⁴ S. A. Webster,⁶⁶ M. Weinert,^{9,10} A. J. Weinstein,¹ R. Weiss,⁶⁷ C. M. Weller,²⁴² F. Wellmann,^{9,10} L. Wen,⁸³ P. Weßels,^{9,10} K. Wette,⁸ J. T. Whelan,¹²³ D. D. White,³⁸ B. F. Whiting,⁶⁹ C. Whittle,⁶⁷ D. Wilken,^{9,10} D. Williams,⁶⁶ M. J. Williams,⁶⁶ A. R. Williamson,¹⁵³ J. L. Willis,¹ B. Willke,^{9,10} D. J. Wilson,¹³⁸ W. Winkler,^{9,10} C. C. Wipf,¹ T. Wlodarczyk,¹⁰² G. Woan,⁶⁶ J. Woehler,^{9,10} J. K. Wofford,¹²³ I. C. F. Wong,¹⁰⁶ C. Wu,¹³¹ D. S. Wu,^{9,10} H. Wu,¹³¹ S. Wu,¹³¹ D. M. Wysocki,⁷ L. Xiao,¹ W.-R. Xu,¹⁹⁶ T. Yamada,²⁸⁵ H. Yamamoto,¹ Kazuhiro Yamamoto,¹⁸⁹ Kohei Yamamoto,²⁸⁵ T. Yamamoto,¹⁹⁰ K. Yamashita,²⁰¹ R. Yamazaki,¹⁹⁸ F. W. Yang,¹⁶⁹ L. Yang,¹⁶³ Y. Yang,²⁹⁶ Yang Yang,⁶⁹ Z. Yang,⁶⁰ M. J. Yap,⁸ D. W. Yeeles,¹⁷ A. B. Yelikar,¹²³ M. Ying,¹²⁴ K. Yokogawa,²⁰¹ J. Yokoyama,^{26,25} T. Yokozawa,¹⁹⁰ J. Yoo,¹⁷⁷ T. Yoshioka,²⁰¹ Hang Yu,¹³⁰ Haocun Yu,⁶⁷ H. Yuzurihara,³⁵ A. Zadrożny,²³⁰ M. Zanolin,³³ S. Zeidler,²⁹⁷ T. Zelenova,⁴⁰ J.-P. Zendri,⁷⁵ M. Zevin,¹⁵⁹ M. Zhan,¹⁷⁴ H. Zhang,¹⁹⁶ J. Zhang,⁸³ L. Zhang,¹ T. Zhang,¹⁴ Y. Zhang,¹⁸³ C. Zhao,⁸³ G. Zhao,¹⁴³ Y. Zhao,²⁰ Yue Zhao,¹⁶⁹ R. Zhou,¹⁹² Z. Zhou,¹⁵ X. J. Zhu,⁵ Z.-H. Zhu,¹¹³ A. B. Zimmerman,¹⁶⁵ M. E. Zucker,^{1,67} and J. Zweizig¹

(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

¹*LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

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

³*Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*

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

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

⁶*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*

⁷*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, 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*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*

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

¹³*Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*

¹⁴*University of Birmingham, Birmingham B15 2TT, United Kingdom*

¹⁵*Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, Illinois 60208, USA*

¹⁶*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*

¹⁷*Gravity Exploration Institute, Cardiff University, Cardiff CF24 3AA, United Kingdom*

¹⁸*INFN, Sezione di Pisa, I-56127 Pisa, Italy*

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

²⁰*Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*

²¹*Advanced Technology Center, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*

²²*INFN Sezione di Torino, I-10125 Torino, Italy*

²³*Università di Napoli “Federico II,” Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

²⁴*Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France*

²⁵*Department of Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

²⁶*Research Center for the Early Universe (RESCEU), The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

²⁷*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, C/ Martí i Franquès 1, Barcelona 08028, Spain*

²⁸*Laboratoire d’Annecy de Physique des Particules (LAPP), Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France*

²⁹*Gran Sasso Science Institute (GSSI), I-67100 L’Aquila, Italy*

³⁰*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*

³¹*Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy*

- ³²INFN, Sezione di Trieste, I-34127 Trieste, Italy
- ³³Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA
- ³⁴Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France
- ³⁵Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- ³⁶Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan
- ³⁷Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan
- ³⁸California State University Fullerton, Fullerton, California 92831, USA
- ³⁹Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
- ⁴⁰European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- ⁴¹Chennai Mathematical Institute, Chennai 603103, India
- ⁴²Department of Mathematics and Physics, Gravitational Wave Science Project, Hirosaki University, Hirosaki City, Aomori 036-8561, Japan
- ⁴³Columbia University, New York, New York 10027, USA
- ⁴⁴Kamioka Branch, National Astronomical Observatory of Japan (NAOJ), Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ⁴⁵The Graduate University for Advanced Studies (SOKENDAI), Mitaka City, Tokyo 181-8588, Japan
- ⁴⁶Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy
- ⁴⁷INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁴⁸INFN, Sezione di Roma, I-00185 Roma, Italy
- ⁴⁹Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
- ⁵⁰Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands
- ⁵¹King’s College London, University of London, London WC2R 2LS, United Kingdom
- ⁵²Korea Institute of Science and Technology Information (KISTI), Yuseong-gu, Daejeon 34141, Korea
- ⁵³National Institute for Mathematical Sciences, Yuseong-gu, Daejeon 34047, Korea
- ⁵⁴Christopher Newport University, Newport News, Virginia 23606, USA
- ⁵⁵International College, Osaka University, Toyonaka City, Osaka 560-0043, Japan
- ⁵⁶School of High Energy Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba City, Ibaraki 305-0801, Japan
- ⁵⁷University of Oregon, Eugene, Oregon 97403, USA
- ⁵⁸Syracuse University, Syracuse, New York 13244, USA
- ⁵⁹Université de Liège, B-4000 Liège, Belgium
- ⁶⁰University of Minnesota, Minneapolis, Minnesota 55455, USA
- ⁶¹Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- ⁶²INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
- ⁶³INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
- ⁶⁴LIGO Hanford Observatory, Richland, Washington 99352, USA
- ⁶⁵Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,” Università di Salerno, I-84081 Baronissi, Salerno, Italy
- ⁶⁶SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom
- ⁶⁷LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
- ⁶⁸Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
- ⁶⁹University of Florida, Gainesville, Florida 32611, USA
- ⁷⁰Stanford University, Stanford, California 94305, USA
- ⁷¹Università di Pisa, I-56127 Pisa, Italy
- ⁷²INFN, Sezione di Perugia, I-06123 Perugia, Italy
- ⁷³Università di Perugia, I-06123 Perugia, Italy
- ⁷⁴Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁷⁵INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁷⁶Montana State University, Bozeman, Montana 59717, USA
- ⁷⁷Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ⁷⁸Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716 Warsaw, Poland
- ⁷⁹Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- ⁸⁰OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ⁸¹California State University, Los Angeles, 5151 State University Drive, Los Angeles, California 90032, USA
- ⁸²INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁸³OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
- ⁸⁴RRCAT, Indore, Madhya Pradesh 452013, India

- ⁸⁵GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
- ⁸⁶Missouri University of Science and Technology, Rolla, Missouri 65409, USA
- ⁸⁷Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- ⁸⁸Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- ⁸⁹INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- ⁹⁰SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom
- ⁹¹Bar-Ilan University, Ramat Gan 5290002, Israel
- ⁹²Artemis, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, F-06304 Nice, France
- ⁹³Dipartimento di Fisica "E.R. Caianiello," Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁹⁴INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁹⁵Università di Roma "La Sapienza," I-00185 Roma, Italy
- ⁹⁶Université Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France
- ⁹⁷Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- ⁹⁸INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
- ⁹⁹Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- ¹⁰⁰Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ¹⁰¹University of Maryland, College Park, Maryland 20742, USA
- ¹⁰²Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany
- ¹⁰³L2IT, Laboratoire des 2 Infinis—Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
- ¹⁰⁴School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
- ¹⁰⁵IGFAE, Campus Sur, Universidade de Santiago de Compostela, 15782 Spain
- ¹⁰⁶The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- ¹⁰⁷Stony Brook University, Stony Brook, New York 11794, USA
- ¹⁰⁸Center for Computational Astrophysics, Flatiron Institute, New York, New York 10010, USA
- ¹⁰⁹NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
- ¹¹⁰Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ¹¹¹Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, Netherlands
- ¹¹²RESCEU, University of Tokyo, Tokyo 113-0033, Japan
- ¹¹³Department of Astronomy, Beijing Normal University, Beijing 100875, China
- ¹¹⁴OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
- ¹¹⁵Università degli Studi di Sassari, I-07100 Sassari, Italy
- ¹¹⁶INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
- ¹¹⁷Università di Roma Tor Vergata, I-00133 Roma, Italy
- ¹¹⁸INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ¹¹⁹University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- ¹²⁰Villanova University, 800 Lancaster Ave, Villanova, Pennsylvania 19085, USA
- ¹²¹Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
- ¹²²Universität Hamburg, D-22761 Hamburg, Germany
- ¹²³Rochester Institute of Technology, Rochester, New York 14623, USA
- ¹²⁴National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
- ¹²⁵Department of Applied Physics, Fukuoka University, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
- ¹²⁶OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ¹²⁷Department of Physics, Tamkang University, Danshui Dist., New Taipei City 25137, Taiwan
- ¹²⁸Department of Physics and Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan
- ¹²⁹Department of Physics, Center for High Energy and High Field Physics, National Central University, Zhongli District, Taoyuan City 32001, Taiwan
- ¹³⁰CaRT, California Institute of Technology, Pasadena, California 91125, USA
- ¹³¹Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
- ¹³²Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹³³Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan
- ¹³⁴Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon/IN2P3, UMR 5822, F-69622 Villeurbanne, France

- ¹³⁵Seoul National University, Seoul 08826, South Korea
- ¹³⁶Pusan National University, Busan 46241, South Korea
- ¹³⁷INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- ¹³⁸University of Arizona, Tucson, Arizona 85721, USA
- ¹³⁹Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom
- ¹⁴⁰OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- ¹⁴¹Université libre de Bruxelles, Avenue Franklin Roosevelt 50–1050 Bruxelles, Belgium
- ¹⁴²Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
- ¹⁴³Université Libre de Bruxelles, Brussels 1050, Belgium
- ¹⁴⁴Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- ¹⁴⁵Texas Tech University, Lubbock, Texas 79409, USA
- ¹⁴⁶The Pennsylvania State University, University Park, Pennsylvania 16802, USA
- ¹⁴⁷University of Rhode Island, Kingston, Rhode Island 02881, USA
- ¹⁴⁸The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA
- ¹⁴⁹Bellevue College, Bellevue, Washington 98007, USA
- ¹⁵⁰Scuola Normale Superiore, Piazza dei Cavalieri, 7–56126 Pisa, Italy
- ¹⁵¹MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary
- ¹⁵²Maastricht University, P.O. Box 616, 6200 Maryland Maastricht, Netherlands
- ¹⁵³University of Portsmouth, Portsmouth PO1 3FX, United Kingdom
- ¹⁵⁴The University of Sheffield, Sheffield S10 2TN, United Kingdom
- ¹⁵⁵Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon/IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹⁵⁶Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- ¹⁵⁷INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ¹⁵⁸Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ¹⁵⁹University of Chicago, Chicago, Illinois 60637, USA
- ¹⁶⁰Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
- ¹⁶¹West Virginia University, Morgantown, West Virginia 26506, USA
- ¹⁶²Montclair State University, Montclair, New Jersey 07043, USA
- ¹⁶³Colorado State University, Fort Collins, Colorado 80523, USA
- ¹⁶⁴Institute for Nuclear Research, Hungarian Academy of Sciences, Bem tér 18/c, H-4026 Debrecen, Hungary
- ¹⁶⁵Department of Physics, University of Texas, Austin, Texas 78712, USA
- ¹⁶⁶CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹⁶⁷Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- ¹⁶⁸Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- ¹⁶⁹The University of Utah, Salt Lake City, Utah 84112, USA
- ¹⁷⁰Kenyon College, Gambier, Ohio 43022, USA
- ¹⁷¹Vrije Universiteit Amsterdam, 1081 HV, Amsterdam, Netherlands
- ¹⁷²Department of Astronomy, The University of Tokyo, Mitaka City, Tokyo 181-8588, Japan
- ¹⁷³Faculty of Engineering, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- ¹⁷⁴State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Innovation Academy for Precision Measurement Science and Technology (APM), Chinese Academy of Sciences, Xiao Hong Shan, Wuhan 430071, China
- ¹⁷⁵University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ¹⁷⁶Universiteit Gent, B-9000 Gent, Belgium
- ¹⁷⁷Cornell University, Ithaca, New York 14850, USA
- ¹⁷⁸University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
- ¹⁷⁹Tata Institute of Fundamental Research, Mumbai 400005, India
- ¹⁸⁰INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- ¹⁸¹University of Mississippi, University, Mississippi 38677, USA
- ¹⁸²University of Michigan, Ann Arbor, Michigan 48109, USA
- ¹⁸³Texas A&M University, College Station, Texas 77843, USA
- ¹⁸⁴Department of Physics, Ulsan National Institute of Science and Technology (UNIST), Ulsu-gun, Ulsan 44919, Korea
- ¹⁸⁵Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan
- ¹⁸⁶Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy

- ¹⁸⁷*Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China*
- ¹⁸⁸*American University, Washington, D.C. 20016, USA*
- ¹⁸⁹*Faculty of Science, University of Toyama, Toyama City, Toyama 930-8555, Japan*
- ¹⁹⁰*Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ¹⁹¹*Carleton College, Northfield, Minnesota 55057, USA*
- ¹⁹²*University of California, Berkeley, California 94720, USA*
- ¹⁹³*Maastricht University, 6200 Maryland, Maastricht, Netherlands*
- ¹⁹⁴*College of Industrial Technology, Nihon University, Narashino City, Chiba 275-8575, Japan*
- ¹⁹⁵*Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
- ¹⁹⁶*Department of Physics, National Taiwan Normal University, sec. 4, Taipei 116, Taiwan*
- ¹⁹⁷*Astronomy and Space Science, Chungnam National University, Yuseong-gu, Daejeon 34134, Korea, Korea*
- ¹⁹⁸*Department of Physics and Mathematics, Aoyama Gakuin University, Sagami-hara City, Kanagawa 252-5258, Japan*
- ¹⁹⁹*Kavli Institute for Astronomy and Astrophysics, Peking University, Haidian District, Beijing 100871, China*
- ²⁰⁰*Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Sakyo-ku, Kyoto City, Kyoto 606-8502, Japan*
- ²⁰¹*Graduate School of Science and Engineering, University of Toyama, Toyama City, Toyama 930-8555, Japan*
- ²⁰²*Department of Physics, Graduate School of Science, Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan*
- ²⁰³*Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan*
- ²⁰⁴*Institute of Space and Astronautical Science (JAXA), Chuo-ku, Sagami-hara City, Kanagawa 252-0222, Japan*
- ²⁰⁵*Directorate of Construction, Services and Estate Management, Mumbai 400094, India*
- ²⁰⁶*Vanderbilt University, Nashville, Tennessee 37235, USA*
- ²⁰⁷*Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium*
- ²⁰⁸*University of Bialystok, 15-424 Bialystok, Poland*
- ²⁰⁹*Department of Physics, Ewha Womans University, Seodaemun-gu, Seoul 03760, Korea*
- ²¹⁰*National Astronomical Observatories, Chinese Academic of Sciences, Chaoyang District, Beijing 100101211, China*
- ²¹¹*School of Astronomy and Space Science, University of Chinese Academy of Sciences, Chaoyang District, Beijing 100101237, China*
- ²¹²*University of Southampton, Southampton SO17 1BJ, United Kingdom*
- ²¹³*Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
- ²¹⁴*Chung-Ang University, Seoul 06974, South Korea*
- ²¹⁵*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain*
- ²¹⁶*Graduate School of Science, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan*
- ²¹⁷*University of Washington Bothell, Bothell, Washington 98011, USA*
- ²¹⁸*Institute of Applied Physics, Nizhny Novgorod 603950, Russia*
- ²¹⁹*Ewha Womans University, Seoul 03760, South Korea*
- ²²⁰*Inje University Gimhae, South Gyeongsang 50834, South Korea*
- ²²¹*Department of Physics, Myongji University, Yongin 17058, Korea*
- ²²²*Korea Astronomy and Space Science Institute, Daejeon 34055, South Korea*
- ²²³*National Institute for Mathematical Sciences, Daejeon 34047, South Korea*
- ²²⁴*Ulsan National Institute of Science and Technology, Ulsan 44919, South Korea*
- ²²⁵*Department of Physical Science, Hiroshima University, Higashihiroshima City, Hiroshima 903-0213, Japan*
- ²²⁶*School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, United Kingdom*
- ²²⁷*Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*
- ²²⁸*Bard College, 30 Campus Rd, Annandale-On-Hudson, New York 12504, USA*
- ²²⁹*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ²³⁰*National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
- ²³¹*Instituto de Física Teórica, 28049 Madrid, Spain*

- ²³²*Department of Physics, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8602, Japan*
- ²³³*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
- ²³⁴*Laboratoire Lagrange, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, F-06304 Nice, France*
- ²³⁵*Department of Physics, Hanyang University, Seoul 04763, Korea*
- ²³⁶*Sungkyunkwan University, Seoul 03063, South Korea*
- ²³⁷*NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée 77420296, France*
- ²³⁸*Department of Physics, National Cheng Kung University, Tainan City 701, Taiwan*
- ²³⁹*National Center for High-performance computing, National Applied Research Laboratories, Hsinchu Science Park, Hsinchu City 30076, Taiwan*
- ²⁴⁰*Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
- ²⁴¹*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
- ²⁴²*University of Washington, Seattle, Washington 98195, USA*
- ²⁴³*Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
- ²⁴⁴*INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
- ²⁴⁵*ESPCI, CNRS, F-75005 Paris, France*
- ²⁴⁶*Concordia University Wisconsin, Mequon, Wisconsin 53097, USA*
- ²⁴⁷*Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
- ²⁴⁸*School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
- ²⁴⁹*Southern University and A&M College, Baton Rouge, Louisiana 70813, USA*
- ²⁵⁰*Centre Scientifique de Monaco, 8 quai Antoine 1er, MC-98000, Monaco*
- ²⁵¹*Institute for Photon Science and Technology, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*
- ²⁵²*Indian Institute of Technology Madras, Chennai 600036, India*
- ²⁵³*Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India*
- ²⁵⁴*The Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology (NICT), Koganei City, Tokyo 184-8795, Japan*
- ²⁵⁵*Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
- ²⁵⁶*Faculty of Law, Ryukoku University, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
- ²⁵⁷*Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
- ²⁵⁸*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands*
- ²⁵⁹*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
- ²⁶⁰*Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
- ²⁶¹*Korea Astronomy and Space Science Institute (KASI), Yuseong-gu, Daejeon 34055, Korea*
- ²⁶²*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
- ²⁶³*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
- ²⁶⁴*Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy*
- ²⁶⁵*Lancaster University, Lancaster LA1 4YW, United Kingdom*
- ²⁶⁶*Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy*
- ²⁶⁷*Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India*
- ²⁶⁸*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
- ²⁶⁹*Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
- ²⁷⁰*Department of Physics, Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ²⁷¹*Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, Nagaoka City, Niigata 940-8532, Japan*
- ²⁷²*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, Campus de Santiago, 3810-183 Aveiro, Portugal*
- ²⁷³*Marquette University, 11420 W. Clybourn Street, Milwaukee, Wisconsin 53233, USA*
- ²⁷⁴*Graduate School of Science and Engineering, Hosei University, Koganei City, Tokyo 184-8584, Japan*
- ²⁷⁵*Faculty of Science, Toho University, Funabashi City, Chiba 274-8510, Japan*
- ²⁷⁶*Faculty of Information Science and Technology, Osaka Institute of Technology, Hirakata City, Osaka 573-0196, Japan*
- ²⁷⁷*Università di Firenze, Sesto Fiorentino I-50019, Italy*
- ²⁷⁸*INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy*
- ²⁷⁹*Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*

- ²⁸⁰*iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program),
The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan*
- ²⁸¹*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
- ²⁸²*Department of Space and Astronautical Science, The Graduate University for Advanced Studies
(SOKENDAI), Sagamihara City, Kanagawa 252-5210, Japan*
- ²⁸³*Andrews University, Berrien Springs, Michigan 49104, USA*
- ²⁸⁴*Research Center for Space Science, Advanced Research Laboratories, Tokyo City University,
Setagaya, Tokyo 158-0082, Japan*
- ²⁸⁵*Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN),
The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
- ²⁸⁶*National Metrology Institute of Japan, National Institute of Advanced Industrial Science and
Technology, Tsukuba City, Ibaraki 305-8568, Japan*
- ²⁸⁷*Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS),
Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ²⁸⁸*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen,
Nijenborgh 4, 9747 AG Groningen, Netherlands*
- ²⁸⁹*Faculty of Science, Department of Physics, The Chinese University of Hong Kong,
Shatin, NT, Hong Kong*
- ²⁹⁰*Vrije Universiteit Brussel, Boulevard de la Plaine 2, 1050 Ixelles, Belgium*
- ²⁹¹*Department of Communications Engineering, National Defense Academy of Japan,
Yokosuka City, Kanagawa 239-8686, Japan*
- ²⁹²*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
- ²⁹³*Department of Information and Management Systems Engineering, Nagaoka University of Technology,
Nagaoka City, Niigata 940-2188, Japan*
- ²⁹⁴*Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
- ²⁹⁵*Department of Physics and Astronomy, Sejong University, Gwangjin-gu, Seoul 143-747, Korea*
- ²⁹⁶*Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan*
- ²⁹⁷*Department of Physics, Rikkyo University, Toshima-ku, Tokyo 171-8501, Japan*

[†]Deceased.