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R. Abbott, T.D. Abbott, S. Abraham, F. Acernese, K. Ackley, A. Adams, C. Adams, R.X. Adhikari, V.B. Adya, C. Affeldt, et al.

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Constraints on Cosmic Strings Using Data from the Third Advanced LIGO–Virgo Observing Run

R. Abbott *et al.**

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

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We search for gravitational-wave signals produced by cosmic strings in the Advanced LIGO and Virgo full O3 dataset. Search results are presented for gravitational waves produced by cosmic string loop features such as cusps, kinks, and, for the first time, kink-kink collisions. A template-based search for short-duration transient signals does not yield a detection. We also use the stochastic gravitational-wave background energy density upper limits derived from the O3 data to constrain the cosmic string tension $G\mu$ as a function of the number of kinks, or the number of cusps, for two cosmic string loop distribution models. Additionally, we develop and test a third model that interpolates between these two models. Our results improve upon the previous LIGO–Virgo constraints on $G\mu$ by 1 to 2 orders of magnitude depending on the model that is tested. In particular, for the one-loop distribution model, we set the most competitive constraints to date: $G\mu \lesssim 4 \times 10^{-15}$. In the case of cosmic strings formed at the end of inflation in the context of grand unified theories, these results challenge simple inflationary models.

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Introduction.—The Advanced LIGO [1] and Advanced Virgo [2] detectors have opened a new channel to observe the Universe through the detection of gravitational waves. In their first three observing runs (O1, O2, and the first half of O3), the LIGO Scientific Collaboration and the Virgo Collaboration have reported the detection of 50 candidate gravitational-wave events from compact binary coalescences [3]. These detections have yielded important information on the population properties of these compact binary sources [4]. In the future, ground-based detectors may discover new sources of gravitational waves [5], some of which could probe the physics of the early Universe. Cosmic strings [6] belong to this category of sources. The third observing run (O3) started on April 1, 2019, and ended on March 27, 2020, and we use the data from the LIGO-Hanford (H1), LIGO-Livingston (L1), and Virgo (V1) interferometers to place constraints on cosmic strings. These constraints are reported in this Letter.

Cosmic strings are linelike topological defects—analogs of vortices in different condensed matter systems—that are formed from spontaneous symmetry breaking phase transitions (with the additional condition that the vacuum manifold has noncontractible closed curves [6–9]). In cosmology, such phase transitions may have occurred at grand unifications [10] corresponding to an energy scale of about 10^{16} GeV and more generally at lower energy scales. Thus, cosmic strings, through their different observational predictions, offer a tool to probe particle physics beyond the standard model at energy scales much above the ones

reached by accelerators. In particular, the production of gravitational waves by cosmic strings [11,12] is one of the most promising observational signatures accessible by ground-based detectors.

The width of the string, of the order of the energy scale of the transition, is generally negligible compared to the cosmological scales over which it extends. This limit is well described by the Nambu-Goto action. Nambu-Goto strings [7] are parameterized by a dimensionless quantity: the string tension $G\mu$ related to the string formation energy scale η , $G\mu \sim (\eta/M_{\text{Pl}})^2$, where G is Newton's constant, M_{Pl} is the Planck mass, and μ denotes the string linear mass density [13]. We set the speed of light at $c = 1$. In an expanding background, such as a radiation or dominated era, a cosmic string network relaxes toward a scaling solution—a self-similar, attractor solution in which all typical loop lengths are proportional to cosmic time, or equivalently they scale with the Hubble radius. Superhorizon (also called infinite) strings reach this scaling solution [16–18], being stretched by the expansion of the Universe and by losing energy through the formation of subhorizon (loop) strings, which consequently lead to a cascade of smaller loops eventually decaying through the emission of gravitational waves [12,19,20]. In this Letter, we focus on the gravitational waves emitted by the network of loops. The length distribution of loops will therefore be crucial in determining the gravitational-wave signatures. We consider different loop distribution models that have been studied in the literature; they differ in the way they model the production and cascade of loops from the infinite string network.

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

Cosmic string loops oscillate periodically in time, emitting gravitational waves with power [11] $P_{\text{gw}} = \Gamma_d G\mu^2$ and decay in a lifetime ℓ/γ_d , where Γ_d is a numerical factor ($\Gamma_d \sim 50$ [21]), ℓ is the invariant loop length, and $\gamma_d = \Gamma_d G\mu$ is the gravitational-wave length scale measured in units of time [22]. The high-frequency ($f\ell \gg 1$, where f denotes frequency) gravitational-wave spectrum of an oscillating loop is dominated by bursts emitted by string features called cusps and kinks [25–27]. Cusps [28] are points on the string that briefly travel at the speed of light; they are generic features for smooth loops. Kinks are discontinuities in the tangent vector of the string that propagate at the speed of light. They appear in pairs as the result of collisions between two cosmic strings and are chopped off when a loop forms; hence, a loop can contain any integer number of kinks. Numerical simulations of Nambu-Goto strings have shown that kinks accumulate over the cosmological evolution [16–18], while the number of cusps per loop is yet undetermined.

Cusps are short-lived and produce beamed gravitational waves in the forward direction of the cusp, while left-moving (right-moving) kinks propagate around the string, creating gravitational waves with a fanlike emission (like a lighthouse) in the directions generated by right-moving (left-moving) waves. Additionally, the collision of two kinks is expected to radiate gravitational waves isotropically. We report here searches for gravitational waves produced by cusps, kinks, and kink-kink collisions using O3 LIGO–Virgo data. In addition to distinct individual bursts, the incoherent superposition of weaker gravitational-wave bursts from cosmic strings produced over the history of the Universe would create a stochastic gravitational-wave background [27,30].

Cosmic strings emit gravitational waves with a wide range of frequencies that can be searched by other means, including the cosmic microwave background [31], Big Bang nucleosynthesis [32], and pulsar timing arrays [33–35]; see also, e.g., [36–38].

The gravitational-wave emission from cosmic string loops is introduced in the next section. We consider two simulation-based models [39,40] (labeled **A** and **B**) for the loop distribution. We further develop a third model (labeled **C**) that interpolates between the other two models. We also derive the burst rates and the dimensionless energy density in that section. Individual gravitational-wave bursts are searched in O3 data with a dedicated analysis presented in the “Burst search” section. The incoherent superposition of bursts from cusps, kinks, and kink-kink collisions produces a stationary and nearly Gaussian stochastic background of gravitational waves. We search O3 data for this background, and the results, detailed in [41], are summarized in the “Stochastic search” section. Both the burst and stochastic background searches yield no detections. Combining their sensitivities, we constrain two cosmic string parameters in the “Constraints” section: the string

tension $G\mu$ and the number of kinks per loop. We provide a table listing the meanings of symbols used in this study in the Supplemental Material [42].

Gravitational waves from cosmic string loops.—Gravitational waves are produced by cusps, kinks, and kink-kink collisions on cosmic string loops. The strain waveforms are linearly polarized and have been calculated in [25–27]. For a loop of length ℓ at redshift z , they are power-law functions in the frequency domain for the strain in [44]

$$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i}, \quad (1)$$

where $i = \{c, k, kk\}$ identifies the cusp, kink, and kink-kink collision cases. The power-law indices are $q_c = 4/3$, $q_k = 5/3$, and $q_{kk} = 2$, and the amplitude A_i is [26]

$$A_i(\ell, z) = g_{1,i} \frac{G\mu\ell^{2-q_i}}{(1+z)^{q_i-1} r(z)}, \quad (2)$$

where $r(z)$ is the comoving distance to the loop. We adopt the cosmological model used in [44]; it is encoded in three functions: $\varphi_r(z)$, $\varphi_V(z)$, and $\varphi_t(z)$ (see Appendix A of [44]). The proper distance, the proper volume element, and the proper time are $r(z) = \varphi_r(z)/H_0$, $dV(z) = \varphi_V(z)/H_0^3 dz$, and $t(z) = \varphi_t(z)/H_0$, respectively, where $H_0 = 67.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [45]. The prefactor $g_{1,i}$ is [46] $g_{1,c} = 8/\Gamma^2(1/3) \times (2/3)^{2/3} \approx 0.85$, $g_{1,k} = 2\sqrt{2}/\pi/\Gamma(1/3) \times (2/3)^{2/3} \approx 0.29$, and $g_{1,kk} = 1/\pi^2 \approx 0.10$, where Γ is the Gamma function [47].

Cusps and kinks emit gravitational waves in highly concentrated beams. Cusps are transient and produce a beam along a single direction, while kinks propagate around the loop, beaming over a fanlike range of directions. The beam opening angle is

$$\theta_m = [g_2 f (1+z)\ell]^{-1/3}, \quad (3)$$

where $g_2 = \sqrt{3}/4$ [46]. To guarantee self-consistency (validity of the waveform), we require that $\theta_m < 1$ rad, which is equivalent to setting a lower limit on the frequency for a fixed loop length. For kink-kink collisions, the gravitational-wave emission is isotropic [48].

The burst rate of type i per unit loop size and per unit volume can be decomposed into four factors:

$$\frac{dR_i}{d\ell dV} = \frac{2}{\ell} N_i \times n(\ell, t) \times \Delta_i \times (1+z)^{-1}. \quad (4)$$

The first factor accounts for an average of N_i gravitational-wave burst events of type i produced per loop oscillation time periodicity $\ell/2$. The second factor stands for the number of loops per unit loop size and per unit volume at cosmic time t :

$$n(\ell, t) = \frac{d^2 \mathcal{N}}{d\ell dV}(\ell, t). \quad (5)$$

The third factor, Δ_i , reflects that only a fraction of burst events can be effectively detected due to the beamed emission of gravitational waves with respect to the 4π solid angle. The gravitational-wave emission within a cone for cusps, a fanlike range of directions for kinks, and all directions for kink-kink collisions can be conveniently absorbed into a single beaming fraction expression: $\Delta_i = (\theta_m/2)^{3(2-q_i)}$. Finally, the last factor shows that the burst emission rate is redshifted by $(1+z)^{-1}$.

The burst rate at redshift z is then obtained by integrating over all loop sizes:

$$\frac{dR_i}{dz} = \frac{\varphi_V(z)}{H_0^3(1+z)} \int_{\ell_{\min}}^{\ell_{\max}} d\ell \frac{2N_i}{\ell} n(\ell, t) \Delta_i. \quad (6)$$

Introducing the dimensionless loop size parameter $\gamma \equiv \ell/t$, Eq. (6) reads

$$\frac{dR_i}{dz}(z, f) = \frac{\phi_V(z)}{H_0^3(1+z)} \int_{\gamma_{\min}(z, f)}^{\gamma_{\max}(z)} d\gamma \frac{2N_i}{\gamma} n(\gamma, z) \Delta_i(\gamma, z, f). \quad (7)$$

The upper bound of the integral $\gamma_{\max}(z)$ is derived by requiring the loop size to be smaller than the horizon size, i.e., $\gamma_{\max} = 2$ and 3 for radiation and matter dominated universes, respectively [44]. The lower bound γ_{\min} corresponds to the fundamental frequency of a loop, i.e., $2/\ell$, leading to $\gamma_{\min}(z, f) = 2/[f(1+z)\varphi_t(z)/H_0]$.

We consider two analytical models, labeled **A** [39] and **B** [40], to describe the distribution of cosmic string loops $n(\gamma, z)$ in a scaling regime within a Friedmann-Lemaître-Robertson-Walker metric. These models were respectively dubbed $M = 2$ and $M = 3$ in [44]. In model **A**, the number of long-lived non-self-intersecting loops of invariant length ℓ per unit volume per unit time formed at cosmic time t is directly inferred from Nambu-Goto simulations of cosmic string networks in the radiation and matter eras. Model **B** is based on a different Nambu-Goto string simulation [49]. In this model, the distribution of non-self-intersecting scaling loops is the extracted quantity. Within model **B**, loops are formed at all sizes following a power law specified by a parameter taking different values in the radiation and matter eras, while the scaling loop distribution is cut off on small scales by the gravitational backreaction scale. There is a qualitative difference between these two models since in the latter, tiny loops are produced in a much larger amount than in the former. In addition, we will use a new model, based on [50] and labeled **C**, that extends and encompasses both models **A** and **B**. Like model **B**, model **C** assumes that the scaling loop distribution is a power law but leaves its slope unspecified. Given the wide parameter space opened by model **C**, we will select two samples: models **C-1**

and **C-2**. Model **C-1** (respectively, **C-2**) reproduces qualitatively the loop production function of model **A** (**B**) in the radiation era and the loop production of model **B** (**A**) in the matter era. We expect the addition of these two models to showcase intermediate situations in between the two simulation-inferred models **A** and **B**. The loop distribution functions $n(\gamma, z)$ for the three models are given in the Supplemental Material [42].

For models **A**, **B**, and **C**, the contributions from cusps, kinks, and kink-kink collisions to the gravitational-wave emission must be considered all together. Indeed, the dimensionless decay constant Γ_d of a cosmic string, driving the loop size evolution, can be decomposed into three contributions:

$$\Gamma_d \equiv \frac{P_{\text{gw}}}{G\mu^2} = \sum_i \frac{P_{\text{gw},i}}{G\mu^2} = N_c \frac{3\pi^2 g_{1,c}^2}{(2\delta)^{1/3} g_2^{2/3}} + N_k \frac{3\pi^2 g_{1,k}^2}{(2\delta)^{2/3} g_2^{1/3}} + N_{kk} 2\pi^2 g_{1,kk}^2, \quad (8)$$

where $\delta = \max[1, 1/(2g_2)]$ since the gravitational-wave frequency cannot be smaller than the fundamental frequency of the loop $2/\ell$, while the condition $\theta_m < 1$ for cusps and kinks imposes $f > 1/(\ell g_2)$. Parameters N_c , N_k are, respectively, the average number of cusps and kinks per oscillation. The number of kink-kink collisions per oscillation N_{kk} is $N_{kk} \approx N_k^2/4$ for large N_k . While this equation is only an approximation when N_k is order unity, the kink-kink contribution is very small in this case and the error would hardly affect our results. On the other hand, it is clear that the kink-kink collision quickly dominates the gravitational-wave production when the number of kinks increases, as was also shown in [51]. Here we fix N_c to be 1 and comment later on the effects of increasing N_c . The only free parameter is N_k ; we consider $N_k = 1, \dots, 200$, with the upper limit motivated by numerical simulations of string loops that favor $\Gamma_d \sim 50$ [21].

The incoherent superposition of bursts from loops with all possible sizes through the history of the Universe produces a stochastic gravitational wave background (SGWB) [52]; its normalized energy density is defined as

$$\Omega_{\text{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df}, \quad (9)$$

where $\rho_c = 3H_0^2 c^2 / (8\pi G)$. The spectrum of the SGWB is [53]

$$\Omega_{\text{GW}}(f) = \frac{4\pi^2}{3H_0^2} f^3 \sum_i \int dz \int d\ell h_i^2 \times \frac{d^2 R_i}{dz d\ell}. \quad (10)$$

The integration range is restricted by two requirements. First, the size of a loop is limited to a fraction of the Hubble radius, or equivalently of the cosmic time $\ell < at(z)$.

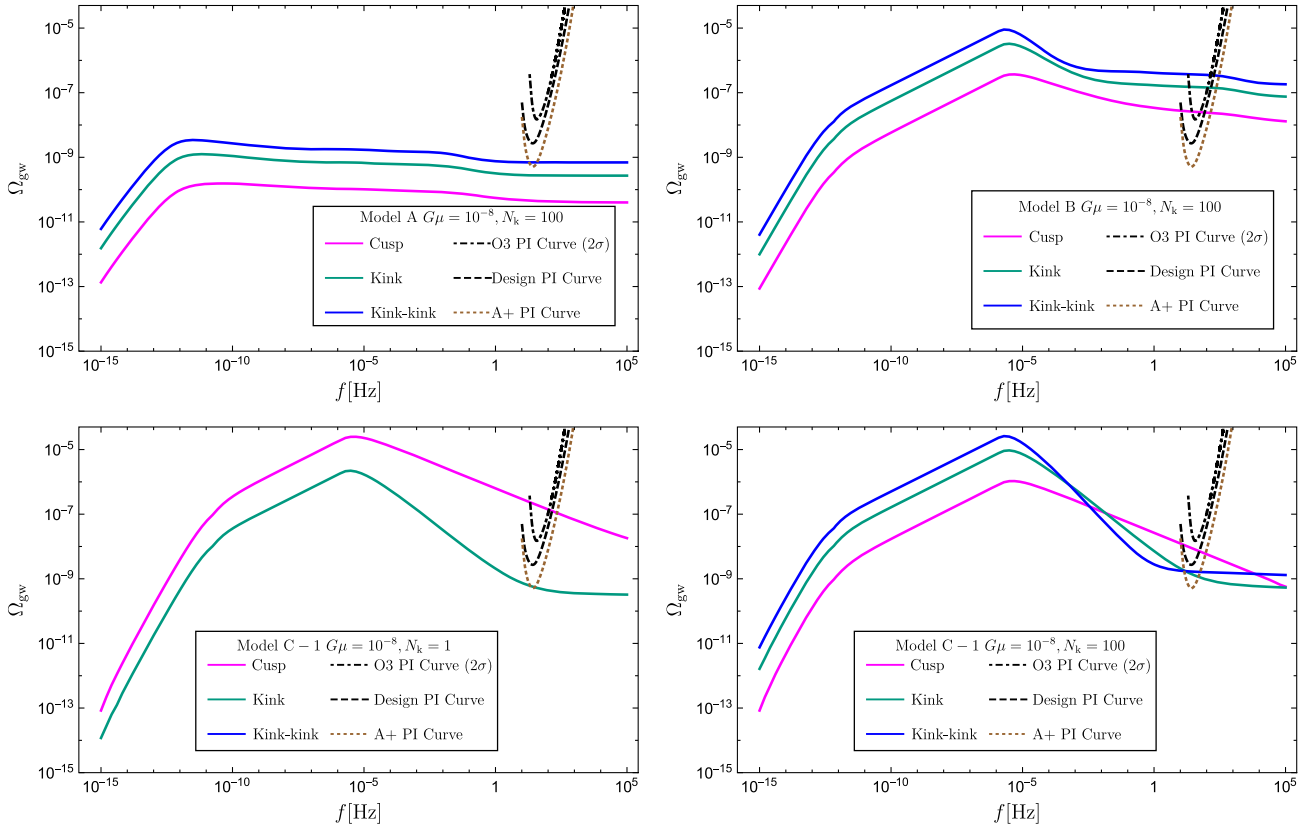


FIG. 1. Predictions of the gravitational-wave energy density spectra using different models for the loop distribution function $n(\gamma, z)$ and for two values of the number of kinks per loop oscillation N_k : 1 and 100. The string tension $G\mu$ is fixed to 10^{-8} . Top left: model **A**, $N_k = 100$. Top right: model **B**, $N_k = 100$. Bottom left: model **C-1**, $N_k = 1$. Bottom right: model **C-1**, $N_k = 100$. For model **C-1**, we use the following model parameters (see the Supplemental Material [42]): $\chi_{\text{rad}} = 0.45$, $\chi_{\text{mat}} = 0.295$, $c_{\text{rad}} = 0.15$, $c_{\text{mat}} = 0.019$; the subscripts refer to the radiation and matter eras, respectively. We also show the energy density spectra of the three different components and 2- σ power-law integrated (PI) curves [55] for the O3 isotropic stochastic search [41], and projections for the Hanford, Livingston, and Virgo network at design sensitivity, and the A + detectors [56].

Second, the frequency has to be larger than the low-frequency cutoff $f\ell(1+z) > \delta$. In Fig. 1, we show examples of gravitational-wave spectra calculated with Eq. (10). The two plots at the top are derived from models **A** and **B** with $N_k \gg 1$. The dominant contribution comes from kink-kink collisions. The lower plots show gravitational-wave spectra taking $N_k = 1$ (left) and $N_k = 100$ (right) and are derived from model **C** with a given set of parameters (see the Supplemental Material [42]), i.e., $\chi_{\text{rad}} = 0.45$, $\chi_{\text{mat}} = 0.295$, $c_{\text{rad}} = 0.15$, and $c_{\text{mat}} = 0.019$; the subscripts refer to matter and radiation eras, respectively. When N_k is large, the dominant contribution depends on the frequency band, which is a unique feature in this model. In this study, we ignore the suppression of the gravitational waves from cusps due to the primordial black hole production as pointed out in [54]. Including such an effect leads to lower spectrum amplitudes for small N_k , thus reducing the sensitivity to cosmic string signals. In Fig. 1, we also show the 2 σ power-law integrated (PI) curves [55] indicating the integrated sensitivity of the O3 search [41], along with projections for two years of the Advanced

LIGO–Virgo network at design sensitivity, and the envisioned upgrade of Advanced LIGO, A+ [56], sensitivity after two years, assuming a 50% duty cycle.

Burst search.—The O3 dataset is analyzed with a dedicated burst search algorithm previously used to produce LIGO–Virgo results [44,57,58]. The burst analysis pipeline, as well as its O3 configuration, is described in the Supplemental Material [42]. The search can be summarized into three analysis steps. First, we carry out a matched-filter search using the cosmic string waveform in Eq. (1). Then, resulting candidates are filtered to retain only those detected in more than one detector within a time window accounting for the difference in the gravitational-wave arrival time between detectors. Finally, double- and triple-coincident events are ranked using an approximated likelihood ratio $\Lambda(x)$, where x is a set of parameters used to discriminate true cosmic string signals from noise [59]. The burst search is performed separately for cusps, kinks, and kink-kink collision waveforms, integrating $T_{\text{obs}} = 273.5$ days of data when at least two detectors are operating simultaneously.

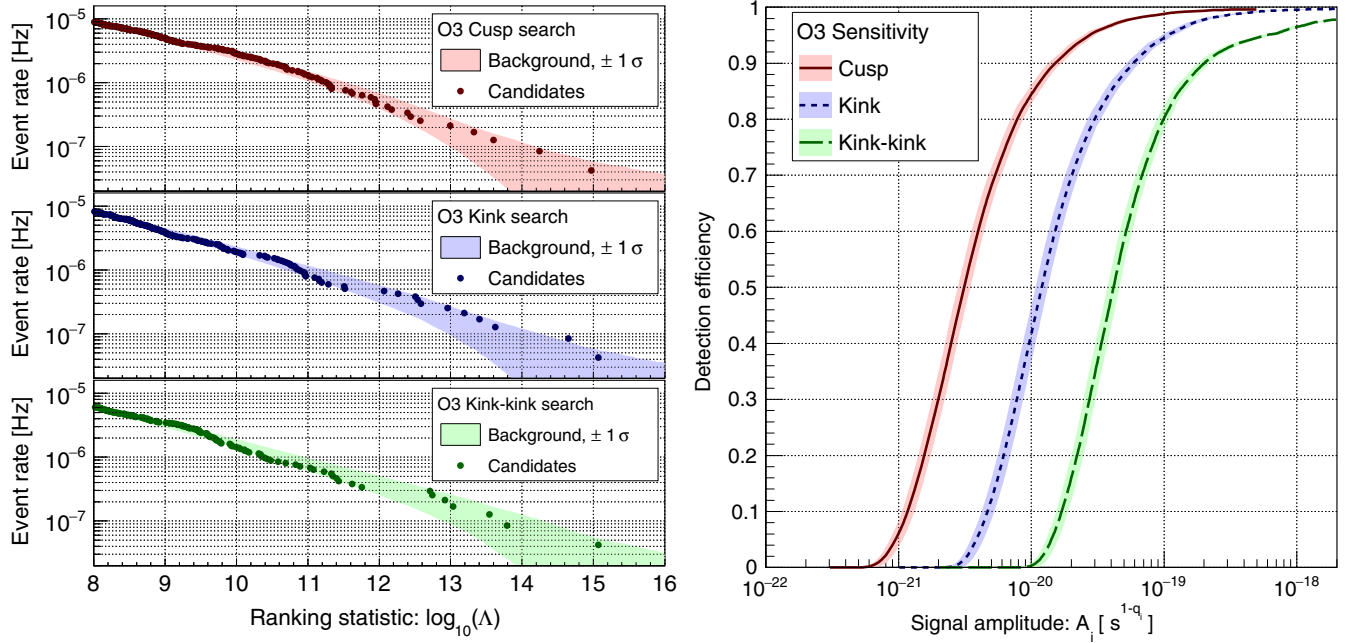


FIG. 2. Left panel: cumulative distribution of cosmic string burst candidate events produced by cusps (top), kinks (middle), and kink-kink collisions (bottom). The expected distributions from background noise are represented by $\pm 1\sigma$ shaded areas. Right panel: the detection efficiency is measured using simulated signals as a function of the signal amplitude for cusps, kinks, and kink-kink collisions. Note that the horizontal axis measures different amplitude quantities A_i for the three types of signals, parameterized by the waveform frequency power law q_i .

The left panel of Fig. 2 presents the cumulative distribution of coincident O3 burst events as a function of the likelihood ratio Λ for the cusp, kink, and kink-kink collision searches. To estimate the background noise associated with each search, time shifts are applied to each detector strain data such that no real gravitational-wave event can be found in coincidence. For this study, we use 300 time shifts, totaling $T_{\text{bkg}} = 225$ years of data containing only noise coincident events, the distribution of which is represented in the left panel of Fig. 2 with a $\pm 1\sigma$ shaded band. The candidate events, obtained with no time shift, are all compatible with the noise distribution within $\pm 2\sigma$. The cusp, kink, and kink-kink collision waveforms are very similar, resulting in the loudest events being the same for the three searches. The ten loudest events were carefully scrutinized. They all originate from a well-known category of transient noise affecting all detectors that are broadband and very short-duration noise events of unknown instrumental origin [60,61].

From the nondetection result, we measure our search sensitivity to cosmic string signals by performing the burst search analysis over O3 data with injections of simulated cusp, kink, and kink-kink collision waveforms. The amplitudes of injected signals comfortably cover the range where none to almost all the signals are detected. Other parameters (sky location, polarization angle, high-frequency cutoff) are randomly distributed. To recover injected signals, we use the loudest-event method described in [62],

where the detection threshold is set to the level of the highest-ranked event found in the search: $\log_{10}(\Lambda) \simeq 15.0, 15.1, 15.1$ for cusps, kinks, and kink-kink collisions, respectively. The resulting efficiencies $\varepsilon_i(A_i)$ as a function of the signal amplitude are presented in the right panel of Fig. 2. Cusp events directed at Earth with $A_c > 2 \times 10^{-20} \text{ s}^{-1/3}$ would have produced a result more significant than any of the ones obtained by our search with $\sim 90\%$ confidence. In terms of loop proper lengths, this corresponds, for example, to loops larger than $1.7 \times 10^6 (G\mu/10^{-10})^{-3/2}$ light years at redshift 100. The expected detection burst rate is calculated from the detection efficiency

$$R_i = \int \frac{dR_i}{dA_i}(A_i, f_*; G\mu, N_k) \varepsilon_i(A_i) dA_i. \quad (11)$$

The detectable burst rate dR_i/dA_i is obtained from Eq. (7), which can be expressed in terms of amplitude using Eq. (2) and calculated for the lowest value of the high-frequency cutoff f_* that can be most abundantly observed (see the Supplemental Material [42] for details).

We assume that the occurrence of a detectable burst of gravitational waves follows a Poisson distribution with mean given by the estimated detection rate. For a set of parameters $(G\mu, N_k)$, models that predict a detection rate larger than $2.996/T_{\text{obs}}$ are excluded at 95%, i.e., we

exclude models that predict a $> 95\%$ confidence level detection.

Stochastic search.—A search for a stochastic gravitational wave background [52] is carried out using the LIGO and Virgo O3 data [41] in which a correlated background in different interferometer pairs is sought. These results are combined with those from the previous two observing runs: O1 and O2 [44,63,64]. The results reported in [41] assume the normalized energy density of the stochastic background, Eq. (9), is a power law α of the frequency

$$\Omega_{\text{GW}}(f) = \Omega_{\text{ref}} \left(\frac{f}{f_{\text{ref}}} \right)^\alpha, \quad (12)$$

where f_{ref} denotes a reference frequency fixed to 25 Hz, a convenient choice in the sensitive part of the frequency band. The search reported in [41] does not detect a stochastic background and so sets upper limits depending on the value of α . The stochastic background from cosmic strings in the LIGO–Virgo frequency band is predicted to be approximately flat, setting the upper bound $\Omega_{\text{GW}} \leq 5.8 \times 10^{-9}$ at the 95% credible level for a flat $\alpha = 0$ background and using a log-uniform prior in Ω_{GW} ; the 20–76.6 Hz band is responsible for 99% of this sensitivity.

Here, we perform a Bayesian analysis taking into account the precise shape of the background (see Fig. 1) instead of a power law and use it to derive upper limits on the cosmic string parameters. We first calculate the log-likelihood function assuming a Gaussian distributed noise, which up to a constant is

$$\ln \mathcal{L}(\hat{C}_a^{IJ} | G\mu, N_k) = -\frac{1}{2} \sum_{IJ,a} \frac{[\hat{C}_a^{IJ} - \Omega_{\text{GW}}^{(M)}(f_a; G\mu, N_k)]^2}{\sigma_{IJ}^2(f_a)}. \quad (13)$$

Here, $\hat{C}_a^{IJ} \equiv \hat{C}^{IJ}(f_a)$ with IJ as the detector pairs L1-H1, L1-V1, and H1-V1. $\hat{C}^{IJ}(f_a)$ and $\sigma^2(f_a)$ are, respectively, a cross-correlation estimator for the pair IJ and its variance at f_a [65]. Following the same approach as in the O1 stochastic analysis, we use the frequency bins from 20 to 86 Hz [44]; higher frequencies do not contribute to the sensitivity. The spectrum, $\Omega_{\text{GW}}^{(M)}(f_a; G\mu, N_k)$ at f_a is predicted by the model $M = \{\mathbf{A}, \mathbf{B}, \mathbf{C}\}$ through Eq. (10).

We specify priors for the parameters in the cosmic string model, i.e., $p(G\mu | I_{G\mu})$ and $p(N_k | I_{N_k})$. The variables $I_{G\mu}$ and I_{N_k} denote the information on the distributions of $G\mu$ and N_k , which are determined by theory predictions. For $p(G\mu | I_{G\mu})$, we choose a log-uniform prior for $10^{-18} \leq G\mu \leq 10^{-6}$. The upper bound is set by the cosmic microwave background measurements [66–69]. The lower bound is arbitrary, chosen for consistency with the study in [70]; we note that our results remain almost unchanged if we choose a smaller value for the lower bound on $G\mu$.

For $p(N_k | I_{N_k})$, we constrain $G\mu$ for each choice of N_k . Therefore, the prior $p(N_k | I_{N_k})$ is taken to be a δ function for each value of N_k . The number of kinks per loop oscillation N_k being fixed, the posterior for $G\mu$ is calculated from Bayes' theorem:

$$p(G\mu | N_k) \propto \mathcal{L}(\hat{C}_a^{IJ} | G\mu, N_k) p(G\mu | I_{G\mu}) p(N_k | I_{N_k}). \quad (14)$$

We calculate 95% credible intervals for $G\mu$.

Constraints.—We show in Fig. 3 the region of the $G\mu$ and N_k parameter space excluded at the 95% confidence level by the burst and stochastic searches where $N_c = 1$. For the stochastic search, we present constraints from the combined O1 + O2 + O3 data; for the burst search, we derive constraints from the nondetection result using O3 data for models **A**, **B**, and **C**. For model **C**, we choose two sets of benchmark numbers: **C-1**, where $(\chi_{\text{rad}}, \chi_{\text{mat}}) = (0.45, 0.295)$, and **C-2**, where $(\chi_{\text{rad}}, \chi_{\text{mat}}) = (0.2, 0.45)$ (see the Supplemental Material [42]).

For model **A**, the gravitational-wave signal is much weaker than the other models, leading to weaker constraints. Model **C-2** mimics the loop production function of model **A** in the matter era and of model **B** in the radiation era. In the frequency band of LIGO–Virgo, the stochastic background is dominated by the contribution from loops in the radiation era, hence models **B** and **C-2** give similar results. Conversely, the spectrum from model **C-1**, which mimics the loop production function of model **A** in the radiation era and of model **B** in the matter era, presents more subtle features. Larger values of $G\mu$ do not necessarily produce larger signals, creating structures in this figure. For an analytical understanding of these findings, see [71]. For a better understanding of the loop visibility domain in terms of redshift; see Fig. 2 of [51].

From the stochastic analysis, the following regions, depending on N_k , are excluded: $G\mu \gtrsim (9.6 \times 10^{-9} - 10^{-6})$ for model **A**, $G\mu \gtrsim (4.0 - 6.3) \times 10^{-15}$ for model **B**, and $G\mu \gtrsim (2.1 - 4.5) \times 10^{-15}$ aside from a small region where $N_k \gtrsim 180$ for model **C-1** and $G\mu \gtrsim (4.2 - 7.0) \times 10^{-15}$ for model **C-2**.

The burst search upper limits are not as stringent as those from the stochastic search. The constraints on $G\mu$ for model **A** are too weak to be represented in the figure. The only case where the burst analysis leads to tighter constraints is for model **C-1** and for $N_k > 70$.

Here N_c has been set to 1. It was shown that N_c scales with the number of harmonics on the loop [72]. For large N_c , the decay constant Γ_d is enhanced, leading to a reduced lifetime of the loop. Consequently, a large N_c gives qualitatively the same result as increasing N_k : for model **A**, the constraints are weakened, whereas for models **B** and **C**, the bounds are insensitive to N_c ; this has been confirmed by our numerical study.

One can also compare these results with limits obtained from pulsar timing array measurements, indirect limits

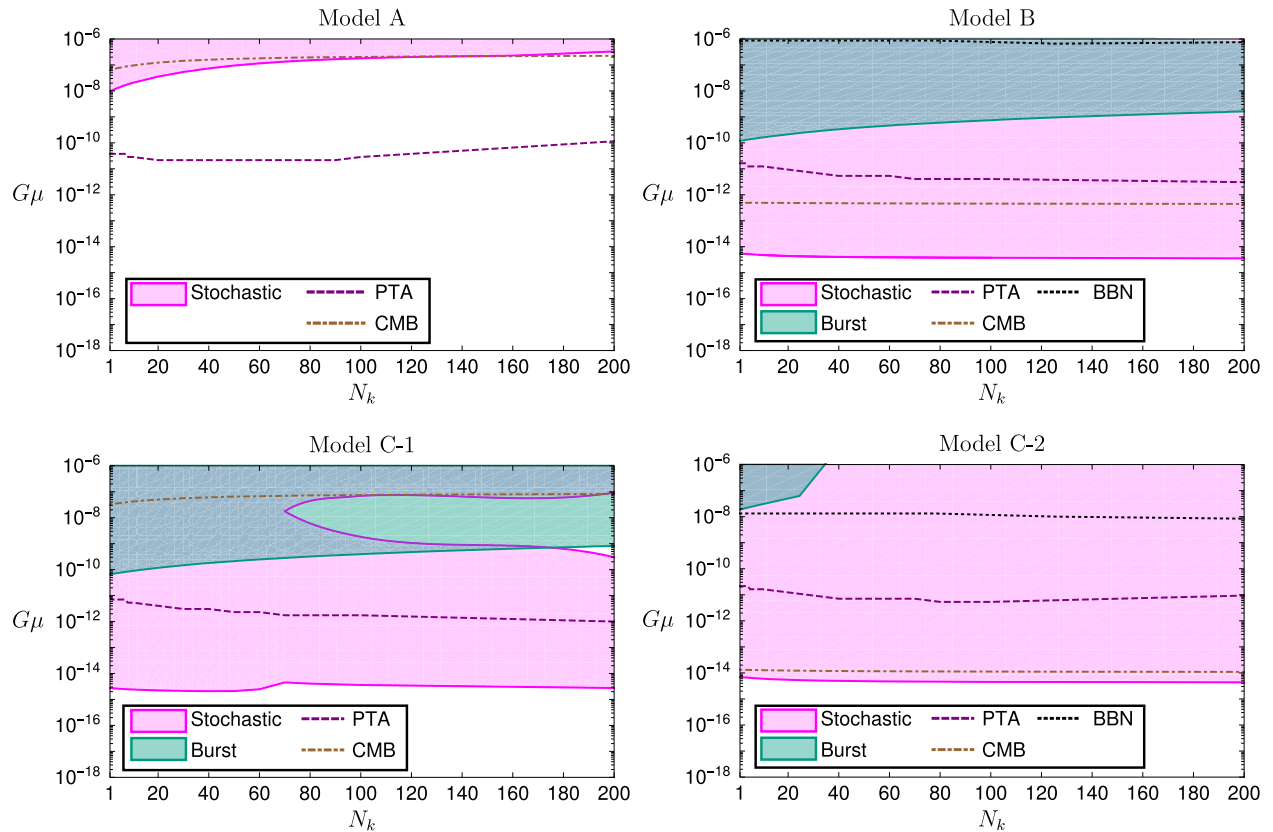


FIG. 3. Exclusion regions at 95% C.L. on the cosmic string parameter space ($N_k, G\mu$) derived from the stochastic search (pink) and the burst search (turquoise). Four models are considered to describe the distribution of cosmic string loops: model **A** (top left), model **B** (top right), model **C-1** (bottom left), and model **C-2** (bottom right). Note that the stochastic result combines the data of O1, O2, and O3, while the burst search only includes O3 data. We also report limits from other experiments: pulsar timing arrays (PTA) [33,34], cosmic microwave background (CMB) [31], and Big Bang nucleosynthesis [32]. The notch in the SGWB constraint for model **C-1** is explained in the Supplemental Material [42].

from Big Bang nucleosynthesis, and cosmic microwave background data [33]. Note: here, we do not investigate nonstandard thermal history; see, however, e.g., [73,74]. Repeating the analysis done in [44] with N_k up to 200, we find that for model **A**, the strongest limit comes from pulsar timing measurements, with $G\mu \gtrsim 10^{-10}$ excluded. For models **B**, **C-1**, and **C-2**, the strongest upper limits are derived from this search.

Conclusions.—Using data from the third observing run of Advanced LIGO and Virgo, we have performed a burst and a stochastic gravitational-wave background search to constrain the tension of Nambu-Goto strings, as a function of the number of kinks per oscillation, for four loop distributions. We have tested models **A** and **B**, already considered in the O1 and O2 analyses [64]. The current constraints on $G\mu$ are stronger by 2 orders of magnitude for model **A** and 1 order of magnitude for model **B** when fixing $N_k = 1$. In addition, we have used two variants of a new model, dubbed model **C**, that interpolates between models **A** and **B**. For the first time, we have studied the effect of kink-kink collision interactions, which is relevant for large numbers of kinks, and investigated the effect of a large

number of cusps, as both effects are favored by cosmic string simulations. In the context of cosmic strings formed at the end of an inflationary era, these results raise questions about the validity of simple inflationary models (which occurred between 10^{16} and 10^{11} GeV) in the context of grand unified theories [10], unless one invokes extra fields in order to avoid cosmic string formation [75].

Given the current experimental results, it would seem important to intensify numerical and theoretical studies on cosmic strings. From a numerical point of view, the number of kinks and cusps should be determined. Concerning phenomenological aspects, new models, like model **C** that interpolates between models **A** and **B**, should be further explored, as well as models including particle physics leading to cosmic string formation in the early Universe. On the experimental side, the sensitivity of Advanced LIGO and Virgo detectors will continue to improve [56], and a fourth interferometer, KAGRA [76], will join the network.

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Carbognani,⁴¹ J. B. Carlin,¹¹⁰ M. F. Carney,¹⁵ M. Carpinelli,^{111,112} G. Carullo,^{21,20} T. L. Carver,¹⁷ J. Casanueva Diaz,⁴¹ C. Casentini,^{113,114} G. Castaldi,¹¹⁵ S. Caudill,^{49,116} M. Cavaglià,⁸¹ F. Cavalier,⁴⁰ R. Cavalieri,⁴¹ G. Cella,²⁰ P. Cerdá-Durán,¹¹⁷ E. Cesarini,¹¹⁴ W. Chaibi,⁸⁷ K. Chakravarti,³ B. Champion,¹¹⁸ C.-H. Chan,¹¹⁹ C. Chan,³¹ C. L. Chan,¹⁰³ M. Chan,¹²⁰ K. Chandra,⁹⁴ P. Chanial,⁴¹ S. Chao,¹¹⁹ P. Charlton,¹²¹ E. A. Chase,¹⁵ E. Chassande-Mottin,³⁶ D. Chatterjee,²⁹ M. Chaturvedi,⁸⁰ K. Chatziioannou,^{1,104,105} A. Chen,¹⁰³ C. Chen,^{122,123} H. Y. Chen,¹²⁴ J. Chen,¹¹⁹ K. Chen,¹²⁵ X. Chen,⁸⁹ Y.-B. Chen,⁸⁸ Y.-R. Chen,¹²³ Z. Chen,¹⁷ H. Cheng,⁴² C. K. Cheong,¹⁰³ H. Y. Cheung,¹⁰³ H. Y. Chia,⁴² F. Chiadini,^{126,91} C.-Y. Chiang,¹²⁷ R. Chierici,¹²⁸ A. Chincarini,⁷⁹ M. L. Chiofalo,^{21,20} A. Chiummo,⁴¹ G. Cho,¹²⁹ H. S. Cho,¹³⁰ S. Choate,¹⁰² R. K. Choudhary,⁸⁹ S. Choudhary,³ N. Christensen,⁸⁷ H. Chu,¹²⁵ Q. Chu,⁸⁹ Y.-K. Chu,¹²⁷ S. Chua,⁹⁵ K. W. Chung,¹³¹ G. Ciani,^{71,72} P. Ciecielag,⁷⁵ M. Cieřlar,⁷⁵ M. Cifaldi,^{113,114} A. A. Ciobanu,⁷⁷ R. Ciolfi,^{132,72} F. Cipriano,⁸⁷ A. Cirone,^{107,79} F. Clara,⁶² E. N. Clark,¹³³ J. A. Clark,¹⁰¹ L. Clarke,¹³⁴ P. Clearwater,¹¹⁰ S. Clesse,¹³⁵ F. Cleva,⁸⁷ E. Coccia,^{18,19} P.-F. Cohadon,⁹⁵ D. E. Cohen,⁴⁰ L. Cohen,² M. Colleoni,¹³⁶ C. G. Collette,¹³⁷ M. Colpi,^{59,60} C. M. Compton,⁶² M. Constancio Jr.,¹⁶ L. Conti,⁷² S. J. Cooper,¹⁴ P. Corban,⁸ T. R. Corbitt,² I. Cordero-Carrión,¹³⁸ S. Corezzi,^{70,69} K. R. Corley,⁴⁴ N. Cornish,⁷³ D. Corre,⁴⁰ A. Corsi,¹³⁹ S. Cortese,⁴¹ C. A. Costa,¹⁶ R. Cotesta,¹⁰⁰ M. W. Coughlin,⁵⁸ S. B. Coughlin,^{15,17} J.-P. Coulon,⁸⁷ S. T. Countryman,⁴⁴ B. Cousins,¹⁴⁰ P. Couvares,¹ P. B. Covas,¹³⁶ D. M. Coward,⁸⁹ M. J. Cowart,⁸ D. C. Coyne,¹ R. Coyne,¹⁴¹ J. D. E. Creighton,²⁹ T. D. Creighton,¹⁴² A. W. Criswell,⁵⁸ M. Croquette,⁹⁵ S. G. Crowder,¹⁴³ J. R. Cudell,⁵⁷ T. J. Cullen,² A. Cumming,⁶⁶ R. Cummings,⁶⁶ E. Cuoco,^{41,144,20} M. Curyło,⁹⁷ T. Dal Canton,^{100,40} G. 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Y.-W. Huang,⁶⁴ M. T. Hübner,⁶ A. D. Huddart,¹³⁴ E. A. Huerta,²⁶ B. Hughey,³⁵ D. C. Y. Hui,¹⁹⁰ V. Hui,⁴⁸ S. Husa,¹³⁶
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K. Inayoshi,¹⁹² H. Inchauspe,⁴² C. Ingram,⁷⁷ Y. Inoue,¹²⁵ G. Intini,^{92,47} K. Ioka,¹⁹³ M. Isi,⁶⁴ K. Isleif,¹⁴⁷ K. Ito,¹⁹⁴
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M. Kakizaki,¹⁸³ C. V. Kalaghatgi,¹⁷ V. Kalogera,¹⁵ B. Kamai,¹ M. Kamiizumi,¹⁸⁴ N. Kanda,^{195,196} S. Kandhasamy,³
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I. Khan,^{18,114} S. Khan,¹⁷ E. A. Khazanov,²⁰⁹ N. Khetan,^{18,19} M. Khursheed,⁸⁰ N. Kijbunchoo,⁹ C. Kim,^{210,201} J. C. Kim,²¹¹
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E. Knyazev,⁶⁴ P. Koch,^{10,11} G. Koekoek,^{49,146} Y. Kojima,²¹⁴ K. Kokeyama,¹⁸⁴ S. Koley,⁴⁹ P. Kolitsidou,¹⁷ M. Kolstein,²⁰⁶
K. Komori,^{64,30} V. Kondrashov,¹ A. K. H. Kong,¹²³ A. Kontos,²¹⁵ N. Koper,^{10,11} M. Korobko,¹⁴⁷ K. Kotake,¹²⁰
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G. Kuehn,^{10,11} F. Kuei,¹¹⁹ A. Kumar,¹⁹⁸ P. Kumar,²¹⁹ Rahul Kumar,⁶² Rakesh Kumar,⁷⁴ J. Kume,³¹ K. Kuns,⁶⁴ C. Kuo,¹²⁵

H-S. Kuo,¹⁸⁹ Y. Kuromiya,¹⁹⁴ S. Kuroyanagi,²²⁰ K. Kusayanagi,²⁰⁷ K. Kwak,¹⁷⁸ S. Kwang,²⁹ D. Laghi,^{21,20} E. Lalande,²²¹
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 C. Markakis,¹² A. S. Markosyan,⁶⁸ A. Markowitz,¹ E. Maros,¹ A. Marquina,¹³⁸ S. Marsat,³⁶ F. Martelli,^{85,86} I. W. Martin,⁶⁶
 R. M. Martin,¹⁵⁷ M. Martinez,²⁰⁶ V. Martinez,²⁸ K. Martinovic,¹³¹ D. V. Martynov,¹⁴ E. J. Marx,⁶⁴ H. Masalehdan,¹⁴⁷
 K. Mason,⁶⁴ E. Massera,¹⁵⁰ A. Masserot,⁴⁸ T. J. Massinger,⁶⁴ M. Masso-Reid,⁶⁶ S. Mastrogiovanni,³⁶ A. Matas,¹⁰⁰
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 D. E. McClelland,⁹ P. McClincy,¹⁴⁰ S. McCormick,⁸ L. McCuller,⁶⁴ G. I. McGhee,⁶⁶ S. C. McGuire,²³⁵ C. McIsaac,¹⁴⁹
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 K. Merfeld,⁵⁵ E. L. Merilh,⁶² J. D. Merritt,⁵⁵ M. Merzougui,⁸⁷ S. Meshkov,^{1,†} C. Messenger,⁶⁶ C. Messick,²²³
 P. M. Meyers,¹¹⁰ F. Meylahn,^{10,11} A. Mhaske,³ A. Miani,^{174,175} H. Miao,¹⁴ I. Michaloliakos,⁴² C. Michel,¹⁵¹ Y. Michimura,³⁰
 H. Middleton,¹¹⁰ L. Milano,²⁷ A. L. Miller,^{96,42} M. Millhouse,¹¹⁰ J. C. Mills,¹⁷ E. Milotti,^{180,34} M. C. Milovich-Goff,⁷⁸
 O. Minazzoli,^{87,236} Y. Minenkov,¹¹⁴ N. Mio,²³⁷ L. M. Mir,²⁰⁶ A. Mishkin,⁴² C. Mishra,²³⁸ T. Mishra,⁴² T. Mistry,¹⁵⁰
 S. Mitra,³ V. P. Mitrofanov,⁸² G. Mitselmakher,⁴² R. Mittleman,⁶⁴ O. Miyakawa,¹⁸⁴ A. Miyamoto,¹⁹⁵ Y. Miyazaki,³⁰
 K. Miyo,¹⁸⁴ S. Miyoki,¹⁸⁴ Geoffrey Mo,⁶⁴ K. Mogushi,⁸¹ S. R. P. Mohapatra,⁶⁴ S. R. Mohite,²⁹ I. Molina,²⁵
 M. Molina-Ruiz,¹⁸⁶ M. Mondin,⁷⁸ M. Montani,^{85,86} C. J. Moore,¹⁴ D. Moraru,⁶² F. Morawski,⁷⁵ A. More,³ C. Moreno,³⁵
 G. Moreno,⁶² Y. Mori,¹⁹⁴ S. Morisaki,^{31,37} Y. Moriwaki,¹⁸³ B. Mours,¹⁵⁵ C. M. Mow-Lowry,¹⁴ S. Mozzon,¹⁴⁹
 F. Muciaccia,^{92,47} Arunava Mukherjee,^{239,66} D. Mukherjee,¹⁴⁰ Soma Mukherjee,¹⁴² Subroto Mukherjee,⁷⁴ N. Mukund,^{10,11}
 A. Mullavey,⁸ J. Munch,⁷⁷ E. A. Muñoz,⁵⁶ P. G. Murray,⁶⁶ R. Musenich,^{79,107} S. L. Nadji,^{10,11} K. Nagano,¹⁹⁷ S. Nagano,²⁴⁰
 K. Nakamura,²³ H. Nakano,²⁴¹ M. Nakano,³⁷ R. Nakashima,²⁰⁷ Y. Nakayama,¹⁸³ I. Nardecchia,^{113,114} T. Narikawa,³⁷
 L. Naticchioni,⁴⁷ B. Nayak,⁷⁸ R. K. Nayak,²⁴² R. Negishi,¹⁸⁸ B. F. Neil,⁸⁹ J. Neilson,^{76,91} G. Nelemans,²⁴³ T. J. N. Nelson,⁸
 M. Nery,^{10,11} A. Neunzert,²⁰⁸ K. Y. Ng,⁶⁴ S. W. S. Ng,⁷⁷ C. Nguyen,³⁶ P. Nguyen,⁵⁵ T. Nguyen,⁶⁴ L. Nguyen Quynh,²⁴⁴
 W.-T. Ni,^{202,168,245} S. A. Nichols,² A. Nishizawa,³¹ S. Nissanke,^{246,49} F. Nocera,⁴¹ M. Noh,¹⁷¹ M. Norman,¹⁷ C. North,¹⁷
 S. Nozaki,¹⁸³ L. K. Nuttall,¹⁴⁹ J. Oberling,⁶² B. D. O'Brien,⁴² Y. Obuchi,²⁴ J. O'Dell,¹³⁴ W. Ogaki,³⁷ G. Oganessian,^{18,19}
 J. J. Oh,⁵¹ K. Oh,¹⁹⁰ S. H. Oh,⁵¹ M. Ohashi,¹⁸⁴ N. Ohishi,⁴⁵ M. Ohkawa,¹⁶⁷ F. Ohme,^{10,11} H. Ohta,³¹ M. A. Okada,¹⁶
 Y. Okutani,¹⁹¹ K. Okutomi,¹⁸⁴ C. Olivetto,⁴¹ K. Oohara,¹⁸⁸ C. Ooi,³⁰ R. Oram,⁸ B. O'Reilly,⁸ R. G. Ormiston,⁵⁸
 N. D. Ormsby,⁷ L. F. Ortega,⁴² R. O'Shaughnessy,¹¹⁸ E. O'Shea,²¹⁹ S. Oshino,¹⁸⁴ S. Ossokine,¹⁰⁰ C. Osthelder,¹ S. Otabe,²⁰⁷
 D. J. Ottaway,⁷⁷ H. Overmier,⁸ A. E. Pace,¹⁴⁰ G. Pagano,^{21,20} M. A. Page,⁸⁹ G. Pagliaroli,^{18,19} A. Pai,⁹⁴ S. A. Pai,⁸⁰
 J. R. Palamos,⁵⁵ O. Palashov,²⁰⁹ C. Palomba,⁴⁷ K. Pan,¹²³ P. K. Panda,¹⁹⁸ H. Pang,¹²⁵ P. T. H. Pang,^{49,116} C. Pankow,¹⁵
 F. Pannarale,^{92,47} B. C. Pant,⁸⁰ F. Paoletti,²⁰ A. Paoli,⁴¹ A. Paolone,^{47,247} A. Parisi,¹²² J. Park,²¹³ W. Parker,^{8,235} D. Pascucci,⁴⁹
 A. Pasqualetti,⁴¹ R. Passaquietti,^{21,20} D. Passuello,²⁰ M. Patel,⁷ B. Patricelli,^{41,20} E. Payne,⁶ T. C. Pechsiri,⁴² M. Pedraza,¹
 M. Pegoraro,⁷² A. Pele,⁸ F. E. Peña Arellano,¹⁸⁴ S. Penn,²⁴⁸ A. Perego,^{174,175} A. Pereira,²⁸ T. Pereira,²⁴⁹ C. J. Perez,⁶²
 C. Péroigois,⁴⁸ A. Perreca,^{174,175} S. Perriès,¹²⁸ J. Petermann,¹⁴⁷ D. Petterson,¹ H. P. Pfeiffer,¹⁰⁰ K. A. Pham,⁵⁸
 K. S. Phukon,^{49,227,3} O. J. Piccinni,⁴⁷ M. Pichot,⁸⁷ M. Piendibene,^{21,20} F. Piergiorganni,^{85,86} L. Pierini,^{92,47} V. Pierro,^{76,91}
 G. Pillant,⁴¹ F. Pilo,²⁰ L. Pinard,¹⁵¹ I. M. Pinto,^{76,91,250,251} B. J. Piotrkowski,²⁹ K. Piotrkowski,⁹⁶ M. Pirello,⁶² M. Pitkin,²⁵²
 E. Placidi,^{92,47} W. Plastino,^{230,231} C. Pluchar,¹³³ R. Poggiani,^{21,20} E. Polini,⁴⁸ D. Y. T. Pong,¹⁰³ S. Ponrathnam,³
 P. Popolizio,⁴¹ E. K. Porter,³⁶ J. Powell,²⁵³ M. Pracchia,⁴⁸ T. Pradier,¹⁵⁵ A. K. Prajapati,⁷⁴ K. Prasai,⁶⁸ R. Prasanna,¹⁹⁸
 G. Pratten,¹⁴ T. Prestegard,²⁹ M. Principe,^{76,250,91} G. A. Prodi,^{254,175} L. Prokhorov,¹⁴ P. Proposito,^{113,114} L. Prudenzi,¹⁰⁰

A. Puecher,^{49,116} M. Punturo,⁶⁹ F. Puosi,^{20,21} P. Puppo,⁴⁷ M. Pürner,¹⁰⁰ H. Qi,¹⁷ V. Quetschke,¹⁴² P. J. Quinonez,³⁵
 R. Quitzow-James,⁸¹ F. J. Raab,⁶² G. Raaijmakers,^{246,49} H. Radkins,⁶² N. Radulesco,⁸⁷ P. Raffai,¹⁴⁵ S. X. Rail,²²¹ S. Raja,⁸⁰
 C. Rajan,⁸⁰ K. E. Ramirez,¹⁴² T. D. Ramirez,²⁵ A. Ramos-Buades,¹⁰⁰ J. Rana,¹⁴⁰ P. Rapagnani,^{92,47} U. D. Rapol,²⁵⁵
 B. Ratto,³⁵ V. Raymond,¹⁷ N. Raza,¹⁷¹ M. Razzano,^{21,20} J. Read,²⁵ L. A. Rees,¹⁸² T. Regimbau,⁴⁸ L. Rei,⁷⁹ S. Reid,³²
 D. H. Reitze,^{1,42} P. Relton,¹⁷ P. Rettegno,^{256,52} F. Ricci,^{92,47} C. J. Richardson,³⁵ J. W. Richardson,¹ L. Richardson,¹³³
 P. M. Ricker,²⁶ G. Riemenschneider,^{256,52} K. Riles,¹⁷⁷ M. Rizzo,¹⁵ N. A. Robertson,^{1,66} R. Robie,¹ F. Robinet,⁴⁰
 A. Rocchi,¹¹⁴ J. A. Rocha,²⁵ S. Rodriguez,²⁵ R. D. Rodriguez-Soto,³⁵ L. Rolland,⁴⁸ J. G. Rollins,¹ V. J. Roma,⁵⁵
 M. Romanelli,⁹³ R. Romano,^{4,5} C. L. Romel,⁶² A. Romero,²⁰⁶ I. M. Romero-Shaw,⁶ J. H. Romie,⁸ C. A. Rose,²⁹
 D. Rosińska,⁹⁷ S. G. Rosofsky,²⁶ M. P. Ross,²²⁹ S. Rowan,⁶⁶ S. J. Rowlinson,¹⁴ Santosh Roy,³ Soumen Roy,²⁵⁷
 D. Rozza,^{111,112} P. Ruggi,⁴¹ K. Ryan,⁶² S. Sachdev,¹⁴⁰ T. Sadecki,⁶² J. Sadiq,¹⁴⁸ N. Sago,²⁵⁸ S. Saito,²⁴ Y. Saito,¹⁸⁴
 K. Sakai,²⁵⁹ Y. Sakai,¹⁸⁸ M. Sakellariadou,¹³¹ Y. Sakuno,¹²⁰ O. S. Salafia,^{61,60,59} L. Salconi,⁴¹ M. Saleem,²⁶⁰ F. Salemi,^{174,175}
 A. Samajdar,^{49,116} E. J. Sanchez,¹ J. H. Sanchez,²⁵ L. E. Sanchez,¹ N. Sanchis-Gual,²⁶¹ J. R. Sanders,²⁶² A. Sanuy,⁶³
 T. R. Saravanan,³ N. Sarin,⁶ B. Sassolas,¹⁵¹ H. Satari,⁸⁹ S. Sato,²⁶³ T. Sato,¹⁶⁷ O. Sauter,^{42,48} R. L. Savage,⁶² V. Savant,³
 T. Sawada,¹⁹⁵ D. Sawant,⁹⁴ H. L. Sawant,³ S. Sayah,¹⁵¹ D. Schaetzl,¹ M. Scheel,⁸⁸ J. Scheuer,¹⁵ A. Schindler-Tyka,⁴²
 P. Schmidt,¹⁴ R. Schnabel,¹⁴⁷ M. Schneewind,^{10,11} R. M. S. Schofield,⁵⁵ A. Schönbeck,¹⁴⁷ B. W. Schulte,^{10,11}
 B. F. Schutz,^{17,10} E. Schwartz,¹⁷ J. Scott,⁶⁶ S. M. Scott,⁹ M. Seglar-Arroyo,⁴⁸ E. Seidel,²⁶ T. Sekiguchi,³¹ Y. Sekiguchi,²⁶⁴
 D. Sellers,⁸ A. S. Sengupta,²⁵⁷ N. Sennett,¹⁰⁰ D. Sentenac,⁴¹ E. G. Seo,¹⁰³ V. Sequino,^{27,5} Y. Setyawati,^{10,11} T. Shaffer,⁶²
 M. S. Shahriar,¹⁵ B. Shams,¹⁶³ L. Shao,¹⁹² S. Sharifi,² A. Sharma,^{18,19} P. Sharma,⁸⁰ P. Shawhan,⁹⁹ N. S. Shcheblanov,²²⁵
 H. Shen,²⁶ S. Shibagaki,¹²⁰ M. Shikauchi,³¹ R. Shimizu,²⁴ T. Shimoda,³⁰ K. Shimode,¹⁸⁴ R. Shink,²²¹ H. Shinkai,²⁶⁵
 T. Shishido,⁴⁶ A. Shoda,²³ D. H. Shoemaker,⁶⁴ D. M. Shoemaker,²²³ K. Shukla,¹⁸⁶ S. ShyamSundar,⁸⁰ M. Sieniawska,⁹⁷
 D. Sigg,⁶² L. P. Singer,¹⁰⁶ D. Singh,¹⁴⁰ N. Singh,⁹⁷ A. Singha,^{146,49} A. M. Sintes,¹³⁶ V. Sipala,^{111,112} V. Skliris,¹⁷
 B. J. J. Slagmolen,⁹ T. J. Slaven-Blair,⁸⁹ J. Smetana,¹⁴ J. R. Smith,²⁵ R. J. E. Smith,⁶ S. N. Somala,²⁶⁶ K. Somiya,²⁰⁷
 E. J. Son,⁵¹ K. Soni,³ S. Soni,² B. Sorazu,⁶⁶ V. Sordini,¹²⁸ F. Sorrentino,⁷⁹ N. Sorrentino,^{21,20} H. Sotani,²⁶⁷ R. Souldar,⁸⁷
 T. Souradeep,^{255,3} E. Sowell,¹³⁹ V. Spagnuolo,^{146,49} A. P. Spencer,⁶⁶ M. Spera,^{71,72} A. K. Srivastava,⁷⁴ V. Srivastava,⁵⁶
 K. Staats,¹⁵ C. Stachie,⁸⁷ D. A. Steer,³⁶ J. Steinlechner,^{146,49} S. Steinlechner,^{146,49} D. J. Stops,¹⁴ M. Stover,¹⁶⁴ K. A. Strain,⁶⁶
 L. C. Strang,¹¹⁰ G. Stratta,^{268,86} A. Strunk,⁶² R. Sturani,²⁴⁹ A. L. Stuver,¹⁰² J. Südbeck,¹⁴⁷ S. Sudhagar,³ V. Sudhir,⁶⁴
 R. Sugimoto,^{269,197} H. G. Suh,²⁹ T. Z. Summerscales,²⁷⁰ H. Sun,⁸⁹ L. Sun,^{9,1} S. Sunil,⁷⁴ A. Sur,⁷⁵ J. Suresh,^{31,37} P. J. Sutton,¹⁷
 Takamasa Suzuki,¹⁶⁷ Toshikazu Suzuki,³⁷ B. L. Swinkels,⁴⁹ M. J. Szczepańczyk,⁴² P. Szewczyk,⁹⁷ M. Tacca,⁴⁹ H. Tagoshi,³⁷
 S. C. Tait,⁶⁶ H. Takahashi,²⁷¹ R. Takahashi,²³ A. Takamori,³⁹ S. Takano,³⁰ H. Takeda,³⁰ M. Takeda,¹⁹⁵ C. Talbot,¹
 H. Tanaka,²⁷² Kazuyuki Tanaka,¹⁹⁵ Kenta Tanaka,²⁷² Taiki Tanaka,³⁷ Takahiro Tanaka,²⁵⁸ A. J. Tanasijczuk,⁹⁶
 S. Tanioka,^{23,46} D. B. Tanner,⁴² D. Tao,¹ A. Tapia,²⁵ E. N. Tapia San Martin,²³ E. N. Tapia San Martin,⁴⁹ J. D. Tasson,¹⁸⁵
 S. Telada,²⁷³ R. Tenorio,¹³⁶ L. Terkowski,¹⁴⁷ M. Test,²⁹ M. P. Thirugnanasambandam,³ M. Thomas,⁸ P. Thomas,⁶²
 J. E. Thompson,¹⁷ S. R. Thondapu,⁸⁰ K. A. Thorne,⁸ E. Thrane,⁶ Shubhanshu Tiwari,¹⁵⁴ Srishti Tiwari,¹⁷² V. Tiwari,¹⁷
 K. Toland,⁶⁶ A. E. Tolley,¹⁴⁹ T. Tomaru,²³ Y. Tomigami,¹⁹⁵ T. Tomura,¹⁸⁴ M. Tonelli,^{21,20} A. Torres-Forné,¹¹⁷ C. I. Torrie,¹
 I. Tosta e Melo,^{111,112} D. Töyrä,⁹ A. Trapananti,^{234,69} F. Travasso,^{69,234} G. Traylor,⁸ M. C. Tringali,⁴¹ A. Tripathy,¹⁷⁷
 L. Troiano,^{274,91} A. Trovato,³⁶ L. Trozzo,¹⁸⁴ R. J. Trudeau,¹ D. S. Tsai,¹¹⁹ D. Tsai,¹¹⁹ K. W. Tsang,^{49,275,116} T. Tsang,¹⁰³
 J.-S. Tsao,¹⁸⁹ M. Tse,⁶⁴ R. Tso,⁸⁸ K. Tsubono,³⁰ S. Tsuchida,¹⁹⁵ L. Tsukada,³¹ D. Tsuna,³¹ T. Tsutsui,³¹ T. Tsuzuki,²⁴
 M. Turconi,⁸⁷ D. Tuyenbayev,¹²⁷ A. S. Ubhi,¹⁴ N. Uchikata,³⁷ T. Uchiyama,¹⁸⁴ R. P. Udall,^{101,1} A. Ueda,¹⁷⁹ T. Uehara,^{276,277}
 K. Ueno,³¹ G. Ueshima,²⁷¹ D. Ugolini,²⁷⁸ C. S. Unnikrishnan,¹⁷² F. Uraguchi,²⁴ A. L. Urban,² T. Ushiba,³⁷ S. A. Usman,¹²⁴
 A. C. Utina,^{146,49} H. Vahlbruch,^{10,11} G. Vajente,¹ A. Vajpeyi,⁶ G. Valdes,² M. Valentini,^{174,175} V. Valsan,²⁹ N. van Bakel,⁴⁹
 M. van Beuzekom,⁴⁹ J. F. J. van den Brand,^{146,98,49} C. Van Den Broeck,^{116,49} D. C. Vander-Hyde,⁵⁶ L. van der Schaaf,⁴⁹
 J. V. van Heijningen,^{89,96} M. H. P. M. van Putten,²⁷⁹ N. van Remortel,¹⁹⁹ M. Vardaro,^{227,49} A. F. Vargas,¹¹⁰ V. Varma,⁸⁸
 M. Vasúth,⁶⁷ A. Vecchio,¹⁴ G. Vedovato,⁷² J. Veitch,⁶⁶ P. J. Veitch,⁷⁷ K. Venkateswara,²²⁹ J. Venneberg,^{10,11}
 G. Venugopalan,¹ D. Verkindt,⁴⁸ Y. Verma,⁸⁰ D. Veske,⁴⁴ F. Vetrano,⁸⁵ A. Viceré,^{85,86} A. D. Viets,²³³ V. Villa-Ortega,¹⁴⁸
 J.-Y. Vinet,⁸⁷ S. Vitale,⁶⁴ T. Vo,⁵⁶ H. Vocca,^{70,69} E. R. G. von Reis,⁶² C. Vorvick,⁶² S. P. Vyatchanin,⁸² L. E. Wade,¹⁶⁴
 M. Wade,¹⁶⁴ K. J. Wagner,¹¹⁸ R. C. Walet,⁴⁹ M. Walker,⁷ G. S. Wallace,³² L. Wallace,¹ S. Walsh,²⁹ J. Wang,¹⁶⁸ J. Z. Wang,¹⁷⁷
 W. H. Wang,¹⁴² R. L. Ward,⁹ J. Warner,⁶² M. Was,⁴⁸ T. Washimi,²³ N. Y. Washington,¹ J. Watchi,¹³⁷ B. Weaver,⁶² L. Wei,^{10,11}
 M. Weinert,^{10,11} A. J. Weinstein,¹ R. Weiss,⁶⁴ C. M. Weller,²²⁹ F. Wellmann,^{10,11} L. Wen,⁸⁹ P. Weßels,^{10,11} J. W. Westhouse,³⁵
 K. Wette,⁹ J. T. Whelan,¹¹⁸ D. D. White,²⁵ B. F. Whiting,⁴² C. Whittle,⁶⁴ D. Wilken,^{10,11} D. Williams,⁶⁶ M. J. Williams,⁶⁶

A. R. Williamson,¹⁴⁹ J. L. Willis,¹ B. Willke,^{10,11} D. J. Wilson,¹³³ W. Winkler,^{10,11} C. C. Wipf,¹ T. Wlodarczyk,¹⁰⁰ G. Woan,⁶⁶ J. Woehler,^{10,11} J. K. Wofford,¹¹⁸ I. C. F. Wong,¹⁰³ J. Wrangel,^{10,11} C. Wu,¹²³ D. S. Wu,^{10,11} H. Wu,¹²³ S. Wu,¹²³ D. M. Wysocki,^{29,118} L. Xiao,¹ W.-R. Xu,¹⁸⁹ T. Yamada,²⁷² H. Yamamoto,¹ Kazuhiro Yamamoto,¹⁸³ Kohei Yamamoto,²⁷² T. Yamamoto,¹⁸⁴ K. Yamashita,¹⁸³ R. Yamazaki,¹⁹¹ F. W. Yang,¹⁶³ L. Yang,¹⁵⁸ Yang Yang,⁴² Yi Yang,²⁸⁰ Z. Yang,⁵⁸ M. J. Yap,⁹ D. W. Yeeles,¹⁷ A. B. Yelikar,¹¹⁸ M. Ying,¹¹⁹ K. Yokogawa,¹⁹⁴ J. Yokoyama,^{31,30} T. Yokozawa,¹⁸⁴ A. Yoon,⁷ T. Yoshioka,¹⁹⁴ Hang Yu,⁸⁸ Haocun Yu,⁶⁴ H. Yuzurihara,³⁷ A. Zadrożny,²¹⁸ M. Zanolin,³⁵ S. Zeidler,²⁸¹ T. Zelenova,⁴¹ J.-P. Zendri,⁷² M. Zevin,¹⁵ M. Zhan,¹⁶⁸ H. Zhang,¹⁸⁹ J. Zhang,⁸⁹ L. Zhang,¹ R. Zhang,⁴² T. Zhang,¹⁴ C. Zhao,⁸⁹ G. Zhao,¹³⁷ Yue Zhao,¹⁶³ Yuhang Zhao,²³ Z. Zhou,¹⁵ X. J. Zhu,⁶ Z.-H. Zhu,¹⁰⁹ M. E. Zucker,^{1,64} 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*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*

⁴*Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*

⁵*INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

⁶*OzGrav, School of Physics and Astronomy, Monash University, Clayton 3800, Victoria, Australia*

⁷*Christopher Newport University, Newport News, Virginia 23606, USA*

⁸*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*

⁹*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*

¹⁰*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*

¹¹*Leibniz Universität Hannover, D-30167 Hannover, Germany*

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 and 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*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*

¹⁹*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*

²⁰*INFN, Sezione di Pisa, I-56127 Pisa, Italy*

²¹*Università di Pisa, I-56127 Pisa, Italy*

²²*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*

²³*Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*

²⁴*Advanced Technology Center, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*

²⁵*California State University Fullerton, Fullerton, California 92831, USA*

²⁶*NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

²⁷*Università di Napoli "Federico II", Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

²⁸*Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France*

²⁹*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*

³⁰*Department of Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

³¹*Research Center for the Early Universe (RESCEU), The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

³²*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*

³³*Dipartimento di Matematica e Informatica, Università di Udine, I-33100 Udine, Italy*

³⁴*INFN, Sezione di Trieste, I-34127 Trieste, Italy*

³⁵*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*

³⁶*Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France*

³⁷*Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*

³⁸*Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*

³⁹*Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan*

⁴⁰*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

⁴¹*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*

⁴²*University of Florida, Gainesville, Florida 32611, USA*

⁴³*Department of Mathematics and Physics, Hirosaki University, Hirosaki City, Aomori 036-8561, Japan*

- ⁴⁴Columbia University, New York, New York 10027, USA
- ⁴⁵Kamioka Branch, National Astronomical Observatory of Japan (NAOJ), Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ⁴⁶The Graduate University for Advanced Studies (SOKENDAI), Mitaka City, Tokyo 181-8588, Japan
- ⁴⁷INFN, Sezione di Roma, I-00185 Roma, Italy
- ⁴⁸Univ. Grenoble Alpes, Laboratoire d'Annecy de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
- ⁴⁹Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands
- ⁵⁰Korea Institute of Science and Technology Information (KISTI), Yuseong-gu, Daejeon 34141, Korea
- ⁵¹National Institute for Mathematical Sciences, Daejeon 34047, South Korea
- ⁵²INFN Sezione di Torino, I-10125 Torino, Italy
- ⁵³International College, Osaka University, Toyonaka City, Osaka 560-0043, Japan
- ⁵⁴School of High Energy Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba City, Ibaraki 305-0801, Japan
- ⁵⁵University of Oregon, Eugene, Oregon 97403, USA
- ⁵⁶Syracuse University, Syracuse, New York 13244, USA
- ⁵⁷Université de Liège, B-4000 Liège, Belgium
- ⁵⁸University of Minnesota, Minneapolis, Minnesota 55455, USA
- ⁵⁹Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- ⁶⁰INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
- ⁶¹INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
- ⁶²LIGO Hanford Observatory, Richland, Washington 99352, USA
- ⁶³Institut de Ciències del Cosmos, Universitat de Barcelona, C/ Martí i Franquès 1, Barcelona, 08028, Spain
- ⁶⁴LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, 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
- ⁶⁷Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
- ⁶⁸Stanford University, Stanford, California 94305, USA
- ⁶⁹INFN, Sezione di Perugia, I-06123 Perugia, Italy
- ⁷⁰Università di Perugia, I-06123 Perugia, Italy
- ⁷¹Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁷²INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁷³Montana State University, Bozeman, Montana 59717, USA
- ⁷⁴Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ⁷⁵Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- ⁷⁶Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- ⁷⁷OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ⁷⁸California State University, Los Angeles, 5151 State University Drive, Los Angeles, California 90032, USA
- ⁷⁹INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁸⁰RRCAT, Indore, Madhya Pradesh 452013, India
- ⁸¹Missouri University of Science and Technology, Rolla, Missouri 65409, USA
- ⁸²Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- ⁸³SUPA, University of the West of Scotland, Paisley Pennsylvania 1 2BE, United Kingdom
- ⁸⁴Bar-Ilan University, Ramat Gan, 5290002, Israel
- ⁸⁵Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy
- ⁸⁶INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁸⁷Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, F-06304 Nice, France
- ⁸⁸CaRT, California Institute of Technology, Pasadena, California 91125, USA
- ⁸⁹OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
- ⁹⁰Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁹¹INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁹²Università di Roma "La Sapienza", I-00185 Roma, Italy
- ⁹³Univ Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France
- ⁹⁴Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- ⁹⁵Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- ⁹⁶Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
- ⁹⁷Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ⁹⁸VU University Amsterdam, 1081 HV Amsterdam, Netherlands
- ⁹⁹University of Maryland, College Park, Maryland 20742, USA
- ¹⁰⁰Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany

- ¹⁰¹*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
- ¹⁰²*Villanova University, 800 Lancaster Avenue, Villanova, Pennsylvania 19085, USA*
- ¹⁰³*Faculty of Science, Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
- ¹⁰⁴*Stony Brook University, Stony Brook, New York 11794, USA*
- ¹⁰⁵*Center for Computational Astrophysics, Flatiron Institute, New York, New York 10010, USA*
- ¹⁰⁶*NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
- ¹⁰⁷*Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy*
- ¹⁰⁸*Tsinghua University, Beijing 100084, China*
- ¹⁰⁹*Department of Astronomy, Beijing Normal University, Beijing 100875, China*
- ¹¹⁰*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
- ¹¹¹*Università degli Studi di Sassari, I-07100 Sassari, Italy*
- ¹¹²*INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy*
- ¹¹³*Università di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹¹⁴*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹¹⁵*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
- ¹¹⁶*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, Netherlands*
- ¹¹⁷*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹¹⁸*Rochester Institute of Technology, Rochester, New York 14623, USA*
- ¹¹⁹*National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China*
- ¹²⁰*Department of Applied Physics, Fukuoka University, Jonan, Fukuoka City, Fukuoka 814-0180, Japan*
- ¹²¹*OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
- ¹²²*Department of Physics, Tamkang University, Danshui Dist., New Taipei City 25137, Taiwan*
- ¹²³*Department of Physics and Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*
- ¹²⁴*University of Chicago, Chicago, Illinois 60637, USA*
- ¹²⁵*Department of Physics, Center for High Energy and High Field Physics, National Central University, Zhongli District, Taoyuan City 32001, Taiwan*
- ¹²⁶*Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ¹²⁷*Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan*
- ¹²⁸*Institut de Physique des 2 Infinis de Lyon (IP2I), CNRS/IN2P3, Université de Lyon, Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*
- ¹²⁹*Seoul National University, Seoul 08826, South Korea*
- ¹³⁰*Pusan National University, Busan 46241, South Korea*
- ¹³¹*King's College London, University of London, London WC2R 2LS, United Kingdom*
- ¹³²*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
- ¹³³*University of Arizona, Tucson, Arizona 85721, USA*
- ¹³⁴*Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom*
- ¹³⁵*Université libre de Bruxelles, Avenue Franklin Roosevelt 50—1050 Bruxelles, Belgium*
- ¹³⁶*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
- ¹³⁷*Université Libre de Bruxelles, Brussels 1050, Belgium*
- ¹³⁸*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹³⁹*Texas Tech University, Lubbock, Texas 79409, USA*
- ¹⁴⁰*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
- ¹⁴¹*University of Rhode Island, Kingston, Rhode Island 02881, USA*
- ¹⁴²*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
- ¹⁴³*Bellevue College, Bellevue, Washington 98007, USA*
- ¹⁴⁴*Scuola Normale Superiore, Piazza dei Cavalieri, 7—56126 Pisa, Italy*
- ¹⁴⁵*MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary*
- ¹⁴⁶*Maastricht University, 6200 Maryland, Maastricht, Netherlands*
- ¹⁴⁷*Universität Hamburg, D-22761 Hamburg, Germany*
- ¹⁴⁸*IGFAE, Campus Sur, Universidade de Santiago de Compostela, 15782 Spain*
- ¹⁴⁹*University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
- ¹⁵⁰*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
- ¹⁵¹*Laboratoire des Matériaux Avancés (LMA), Institut de Physique des 2 Infinis (IP2I) de Lyon, CNRS/IN2P3, Université de Lyon, Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*
- ¹⁵²*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
- ¹⁵³*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
- ¹⁵⁴*Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
- ¹⁵⁵*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
- ¹⁵⁶*West Virginia University, Morgantown, West Virginia 26506, USA*

- ¹⁵⁷Montclair State University, Montclair, New Jersey 07043, USA
¹⁵⁸Colorado State University, Fort Collins, Colorado 80523, USA
¹⁵⁹Institute for Nuclear Research, Hungarian Academy of Sciences, Bem t'er 18/c, H-4026 Debrecen, Hungary
¹⁶⁰CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
¹⁶¹Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
¹⁶²Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
¹⁶³The University of Utah, Salt Lake City, Utah 84112, USA
¹⁶⁴Kenyon College, Gambier, Ohio 43022, USA
¹⁶⁵Vrije Universiteit Amsterdam, 1081 HV, Amsterdam, Netherlands
¹⁶⁶Department of Astronomy, The University of Tokyo, Mitaka City, Tokyo 181-8588, Japan
¹⁶⁷Faculty of Engineering, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
¹⁶⁸State 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
¹⁶⁹University of Szeged, Dóm tér 9, Szeged 6720, Hungary
¹⁷⁰Universiteit Gent, B-9000 Gent, Belgium
¹⁷¹University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
¹⁷²Tata Institute of Fundamental Research, Mumbai 400005, India
¹⁷³INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
¹⁷⁴Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
¹⁷⁵INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
¹⁷⁶The University of Mississippi, University, Mississippi 38677, USA
¹⁷⁷University of Michigan, Ann Arbor, Michigan 48109, USA
¹⁷⁸Department of Physics, School of Natural Science, Ulsan National Institute of Science and Technology (UNIST), Ulsu-gun, Ulsan 44919, Korea
¹⁷⁹Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan
¹⁸⁰Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
¹⁸¹Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
¹⁸²American University, Washington, D.C. 20016, USA
¹⁸³Faculty of Science, University of Toyama, Toyama City, Toyama 930-8555, Japan
¹⁸⁴Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kamioka-cho, Hida City, Gifu 506-1205, Japan
¹⁸⁵Carleton College, Northfield, Minnesota 55057, USA
¹⁸⁶University of California, Berkeley, California 94720, USA
¹⁸⁷College of Industrial Technology, Nihon University, Narashino City, Chiba 275-8575, Japan
¹⁸⁸Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
¹⁸⁹Department of Physics, National Taiwan Normal University, sec. IV, Taipei 116, Taiwan
¹⁹⁰Astronomy and Space Science, Chungnam National University, Yuseong-gu, Daejeon 34134, Korea, Korea
¹⁹¹Department of Physics and Mathematics, Aoyama Gakuin University, Sagami-hara City, Kanagawa 252-5258, Japan
¹⁹²Kavli Institute for Astronomy and Astrophysics, Peking University, Haidian District, Beijing 100871, China
¹⁹³Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Sakyo-ku, Kyoto City, Kyoto 606-8502, Japan
¹⁹⁴Graduate School of Science and Engineering, University of Toyama, Toyama City, Toyama 930-8555, Japan
¹⁹⁵Department of Physics, Graduate School of Science, Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
¹⁹⁶Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
¹⁹⁷Institute of Space and Astronautical Science (JAXA), Chuo-ku, Sagami-hara City, Kanagawa 252-0222, Japan
¹⁹⁸Directorate of Construction, Services and Estate Management, Mumbai 400094 India
¹⁹⁹Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium
²⁰⁰University of Białystok, 15-424 Białystok, Poland
²⁰¹Department of Physics, Ewha Womans University, Seodaemun-gu, Seoul 03760, Korea
²⁰²National Astronomical Observatories, Chinese Academic of Sciences, Chaoyang District, Beijing, China
²⁰³School of Astronomy and Space Science, University of Chinese Academy of Sciences, Chaoyang District, Beijing, China
²⁰⁴University of Southampton, Southampton SO17 1BJ, United Kingdom
²⁰⁵Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
²⁰⁶Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain
²⁰⁷Graduate School of Science and Technology, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan
²⁰⁸University of Washington Bothell, Bothell, Washington 98011, USA
²⁰⁹Institute of Applied Physics, Nizhny Novgorod, 603950, Russia

- ²¹⁰*Ewha Womans University, Seoul 03760, South Korea*
- ²¹¹*Inje University Gimhae, South Gyeongsang 50834, South Korea*
- ²¹²*Department of Physics, Myongji University, Yongin 17058, Korea*
- ²¹³*Korea Astronomy and Space Science Institute (KASI), Yuseong-gu, Daejeon 34055, Korea*
- ²¹⁴*Department of Physical Science, Hiroshima University, Higashihiroshima City, Hiroshima 903-0213, Japan*
- ²¹⁵*Bard College, 30 Campus Rd, Annandale-On-Hudson, New York 12504, USA*
- ²¹⁶*Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN), The University of Tokyo, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ²¹⁷*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ²¹⁸*National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
- ²¹⁹*Cornell University, Ithaca, New York 14850, USA*
- ²²⁰*Institute for Advanced Research, Nagoya University, Furocho, Chikusa-ku, Nagoya City, Aichi 464-8602, Japan*
- ²²¹*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
- ²²²*Laboratoire Lagrange, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, F-06304 Nice, France*
- ²²³*Department of Physics, University of Texas, Austin, Texas 78712, USA*
- ²²⁴*Department of Physics, Hanyang University, Seoul 04763, Korea*
- ²²⁵*NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France*
- ²²⁶*National Center for High-performance computing, National Applied Research Laboratories, Hsinchu Science Park, Hsinchu City 30076, Taiwan*
- ²²⁷*Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
- ²²⁸*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
- ²²⁹*University of Washington, Seattle, Washington 98195, USA*
- ²³⁰*Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
- ²³¹*INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
- ²³²*ESPCI, CNRS, F-75005 Paris, France*
- ²³³*Concordia University Wisconsin, Mequon, Wisconsin 53097, USA*
- ²³⁴*Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
- ²³⁵*Southern University and AandM College, Baton Rouge, Louisiana 70813, USA*
- ²³⁶*Centre Scientifique de Monaco, 8 quai Antoine 1er, MC-98000, Monaco*
- ²³⁷*Institute for Photon Science and Technology, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*
- ²³⁸*Indian Institute of Technology Madras, Chennai 600036, India*
- ²³⁹*Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India*
- ²⁴⁰*The Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology (NICT), Koganei City, Tokyo 184-8795, Japan*
- ²⁴¹*Faculty of Law, Ryukoku University, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
- ²⁴²*Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
- ²⁴³*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands*
- ²⁴⁴*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
- ²⁴⁵*Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan*
- ²⁴⁶*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
- ²⁴⁷*Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
- ²⁴⁸*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
- ²⁴⁹*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
- ²⁵⁰*Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, I-00184 Roma, Italy*
- ²⁵¹*Department of Engineering, University of Sannio, Benevento 82100, Italy*
- ²⁵²*Lancaster University, Lancaster LA1 4YW, United Kingdom*
- ²⁵³*OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
- ²⁵⁴*Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy*
- ²⁵⁵*Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India*
- ²⁵⁶*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
- ²⁵⁷*Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
- ²⁵⁸*Department of Physics, Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ²⁵⁹*Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, Nagaoka City, Niigata 940-8532, Japan*
- ²⁶⁰*Chennai Mathematical Institute, Chennai 603103, India*
- ²⁶¹*Centro de Astrofísica e Gravitação (CENTRA), Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
- ²⁶²*Marquette University, 11420 W. Clybourn Street, Milwaukee, Wisconsin 53233, USA*
- ²⁶³*Graduate School of Science and Engineering, Hosei University, Koganei City, Tokyo 184-8584, Japan*

- ²⁶⁴*Faculty of Science, Toho University, Funabashi City, Chiba 274-8510, Japan*
- ²⁶⁵*Faculty of Information Science and Technology, Osaka Institute of Technology, Hirakata City, Osaka 573-0196, Japan*
- ²⁶⁶*Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
- ²⁶⁷*iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program), The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan*
- ²⁶⁸*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
- ²⁶⁹*Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), Sagamihara, Kanagawa 252-5210, Japan*
- ²⁷⁰*Andrews University, Berrien Springs, Michigan 49104, USA*
- ²⁷¹*Department of Information and Management Systems Engineering, Nagaoka University of Technology, Nagaoka City, Niigata 940-2188, Japan*
- ²⁷²*Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
- ²⁷³*National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba City, Ibaraki 305-8568, Japan*
- ²⁷⁴*Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ²⁷⁵*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands*
- ²⁷⁶*Department of Communications Engineering, National Defense Academy of Japan, Yokosuka City, Kanagawa 239-8686, Japan*
- ²⁷⁷*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
- ²⁷⁸*Trinity University, San Antonio, Texas 78212, USA*
- ²⁷⁹*Department of Physics and Astronomy, Sejong University, Gwangjin-gu, Seoul 143-747, Korea*
- ²⁸⁰*Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan*
- ²⁸¹*Department of Physics, Rikkyo University, Toshima-ku, Tokyo 171-8501, Japan*

[†]Deceased, August 2020.