

Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

R. Abbott *et al.**

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



(Received 27 May 2021; accepted 8 March 2022; published 31 March 2022)

We present a search for dark photon dark matter that could couple to gravitational-wave interferometers using data from Advanced LIGO and Virgo's third observing run. To perform this analysis, we use two methods, one based on cross-correlation of the strain channels in the two nearly aligned LIGO detectors, and one that looks for excess power in the strain channels of the LIGO and Virgo detectors. The excess power method optimizes the Fourier transform coherence time as a function of frequency, to account for the expected signal width due to Doppler modulations. We do not find any evidence of dark photon dark matter with a mass between $m_A \sim 10^{-14}$ – 10^{-11} eV/ c^2 , which corresponds to frequencies between 10–2000 Hz, and therefore provide upper limits on the square of the minimum coupling of dark photons to baryons, i.e., $U(1)_B$ dark matter. For the cross-correlation method, the best median constraint on the squared coupling is $\sim 1.31 \times 10^{-47}$ at $m_A \sim 4.2 \times 10^{-13}$ eV/ c^2 ; for the other analysis, the best constraint is $\sim 2.4 \times 10^{-47}$ at $m_A \sim 5.7 \times 10^{-13}$ eV/ c^2 . These limits improve upon those obtained in direct dark matter detection experiments by a factor of ~ 100 for $m_A \sim [2\text{--}4] \times 10^{-13}$ eV/ c^2 , and are, in absolute terms, the most stringent constraint so far in a large mass range $m_A \sim 2 \times 10^{-13}$ – 8×10^{-12} eV/ c^2 .

DOI: [10.1103/PhysRevD.105.063030](https://doi.org/10.1103/PhysRevD.105.063030)

I. INTRODUCTION

Dark matter has been known to exist for decades [1], yet its physical nature has remained elusive. Depending on the theory, dark matter could consist of particles with masses as low as 10^{-22} eV/ c^2 [2], or as high as (sub-) solar-mass primordial black holes [3–6]. Furthermore, dark matter clouds could form around black holes that deplete over time and emit gravitational waves [7,8]. Here, we focus on a subset of the “ultralight” dark matter regime, i.e., masses of $\mathcal{O}(10^{-14}\text{--}10^{-11})$ eV/ c^2 [9], in which a variety of dark matter candidates may interact with gravitational-wave interferometers. Scalar, dilaton dark matter could change the mass of the electron and other physical constants, causing oscillations in the Bohr radius of atoms in various components of the interferometer [10]; axions [11] could alter the phase velocities of circularly polarized photons in the laser beams traveling down each arm of the detector [12]; dark photons could couple to baryons in the mirrors, causing an oscillatory force on the detector [13]; tensor bosons could also interact with the interferometer in an analogous way as gravitational waves [14]. Here, we focus on dark photon dark matter whose relic abundance could be induced by the misalignment mechanism [15–17], the tachyonic instability of a scalar field [18–21], or cosmic string network decays [22]. Cosmic strings, in particular, also offer a promising way to probe physics beyond the

standard model with gravitational-wave detectors at energies much larger than those attainable by particle accelerators [23], which complements the kind of direct dark matter search we perform here. Independently of the formation mechanism, analyses of gravitational-wave data could make a statement on the existence of dark photons.

A search for dark photons using data from Advanced LIGO/Virgo's first observing run [13,24] has already been performed, resulting in competitive constraints on the coupling of dark photons to baryons. Furthermore, scalar, dilaton dark matter was searched for recently using data from GEO600 [25], and upper limits were placed on the degree to which scalar dark matter could have altered the electron mass or fine-structure constant [26].

Other experiments that have probed the ultralight dark matter regime include the Eöt-Wash experiment, which aims to find a violation to the equivalence principle of general relativity resulting from a new force acting on test masses in a dark matter field, by looking for a difference in the horizontal accelerations of two different materials using a continuously rotating torsion balance [27,28]; the MICROSCOPE satellite [29], which measures the accelerations of two freely-floating objects in space made of different materials to look for a violation of the equivalence principle and hence a new force [30]; the Axion Dark Matter Experiment (ADMX), which searches for $\mathcal{O}(\mu\text{eV}/c^2)$ dark matter by trying to induce an axion-to-photon conversion in the presence of a strong magnetic field in a resonant cavity [31]; and the Any Light Particle

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

Search (ALPS), which looks for particles with masses less than $\mathcal{O}(\text{meV}/c^2)$ (that could compose dark matter) by subjecting photons to strong magnetic fields in two cavities, separated by an opaque barrier, to cause a transition to an axion and then back to a photon [32]. Ultralight dark matter has also been constrained by observing gravitational waves from depleting boson clouds around black holes [8,33–38], and by analyzing binary mergers, e.g., GW190521, which is consistent with the merger of complex vector boson stars [39].

Compared to the analysis on data from LIGO/Virgo's first observing run [24], we use two methods, one based on cross-correlation [13], and another that judiciously varies the Fourier Transform coherence time [40,41], to search for dark photons in Advanced LIGO and Virgo data from the third observing run (O3). Additionally, we include the signal induced by the common motion of the mirrors [42]—see Sec. II. Although we do not find any evidence for a dark photon signal, we place stringent upper limits on the degree to which dark photons could have coupled to the baryons in the interferometer.

II. DARK MATTER INTERACTION MODEL

Ultralight dark photon dark matter is expected to cause time-dependent oscillations in the mirrors of the LIGO/Virgo interferometers, which would lead to a differential strain on the detector. We formulate dark photons in an analogous way to ordinary photons: as having a vector potential with an associated dark electric field that causes a quasisinusoidal force on the mirrors in the interferometers. The Lagrangian $\mathcal{L}$ that characterizes the dark photon coupling to a number current density J^μ of baryons or baryons minus leptons is

$$\mathcal{L} = -\frac{1}{4\mu_0} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2\mu_0} \left(\frac{m_A c}{\hbar} \right)^2 A^\mu A_\mu - \epsilon e J^\mu A_\mu, \quad (1)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor, $\hbar$ is the reduced Planck's constant, c is the speed of light, μ_0 is the magnetic permeability in vacuum, m_A is the dark photon mass, A_μ is the four-vector potential of the dark photon, e is the electric charge, and ϵ is the strength of the particle/dark photon coupling normalized by the electromagnetic coupling constant.¹

If the analysis observation time exceeds the signal coherence time, given by Eq. (3) [41], we can write the acceleration of the identical LIGO/Virgo mirrors in the dark photon field as [24]:

$$\vec{a}(t, \vec{x}) \simeq \epsilon e \frac{q}{M} \omega \vec{A} \cos(\omega t - \vec{k} \cdot \vec{x} + \phi), \quad (2)$$

¹We note that the dark photon in our scenario is a different from the one which couples to the standard model via kinetic mixing.

where ω , $\vec{k}$, and $\vec{A}$ are the angular frequency, propagation vector, and polarization vector of the dark photon field, $\vec{x}$ is the position of a mirror, ϕ is a random phase, and q and M are the charge and the mass of the mirror, respectively. If the dark photon couples to the baryon number, q is the number of protons and neutrons in each mirror. If it couples to the difference between the baryon and lepton numbers, q is the number of neutrons in each mirror. For a fused Silica mirror, $q/M = 5.61 \times 10^{26}$ charges/kg for baryon coupling and $q/M = 2.80 \times 10^{26}$ charges/kg for baryon-lepton coupling. Practically, we cannot distinguish between the two types of coupling, though the baryon-lepton coupling would lead to half the acceleration relative to that of the baryon coupling.

Because we observe for almost one year, significantly longer than the assumed dark photon coherence time, and the dark photons travel with nonrelativistic velocities, we model the signal as a superposition of many plane waves, each with a velocity drawn from a Maxwell-Boltzmann distribution [43]. The superposition of dark photon plane waves with different velocities leads to a frequency variation of the signal [13,41]:

$$\Delta f = \frac{1}{2} \left(\frac{v_0}{c} \right)^2 f_0 \approx 2.94 \times 10^{-7} f_0, \quad (3)$$

where $v_0 \simeq 220$ km/s is the velocity at which dark matter orbits the center of our galaxy, i.e., the virial velocity [44], and the frequency f_0 is

$$f_0 = \frac{m_A c^2}{2\pi\hbar}. \quad (4)$$

Dark photons cause small motions of an interferometer's mirrors, and lead to an observable effect in two ways. First, the mirrors are well-separated from each other and hence experience slightly different dark photon dark matter phases. Such a phase difference leads to a differential change of the arm length, suppressed by v_0/c . A simple relation between dark photon parameters and the effective strain h_D can be written as [13]:

$$\begin{aligned} \sqrt{\langle h_D^2 \rangle} &= C \frac{q}{M} \frac{v_0}{2\pi c^2} \sqrt{\frac{2\rho_{\text{DM}} e\epsilon}{\epsilon_0 f_0}} \\ &\simeq 6.56 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}} \right) \left(\frac{100 \text{ Hz}}{f_0} \right), \end{aligned} \quad (5)$$

where ϵ_0 is the permittivity of free space, and $C = \sqrt{2}/3$ is a geometrical factor obtained by averaging over all possible dark photon propagation and polarization directions. Equation (5) can be derived by integrating Eq. (2) twice over time, dividing by the arm length of the interferometer, and performing the averages over time and the dark photon polarization and propagation directions.

Second, the common motion of the interferometer mirrors, induced by the dark photon dark matter background, can lead to an observable signal because of the finite travel time of the laser light in the interferometer arms. The light will hit the mirrors at different times during their common motions, and although the common motions do not change the instantaneous arm length, they can lead to a longer roundtrip travel time for the light, equivalent to arm lengthening, and therefore an apparent differential strain [42]. Instead of being suppressed by v_0/c as shown in Eq. (5), such an effect suffers from a suppression factor of $(f_0 L/c)$, where L is the arm length of the interferometers. Similarly to Eq. (5), the common motion induces an observable signal with an effective strain h_C as:

$$\begin{aligned} \sqrt{\langle h_C^2 \rangle} &= \frac{\sqrt{3}}{2} \sqrt{\langle h_D^2 \rangle} \frac{2\pi f_0 L}{v_0}, \\ &\simeq 6.58 \times 10^{-26} \left(\frac{\epsilon}{10^{-23}} \right). \end{aligned} \quad (6)$$

h_D maps to h_2 in [42], and h_C is the result of a Taylor expansion of h_1 in [42]. The interference between the two contributions to the strain averages to zero over time, which indicates that the total effective strain can be written as $\langle h_{\text{total}}^2 \rangle = \langle h_D^2 \rangle + \langle h_C^2 \rangle$.

III. SEARCH METHOD

A. Cross-correlation

Cross-correlation has been widely used in gravitational-wave searches [45–47], but is employed differently here. Because we are interested in ultralight dark matter, the coherence length of a dark photon signal, given by Eq. (2) in [41], is always much larger than the separation between earth-based detectors [19]. Therefore, the interferometers should experience almost the same dark photon dark matter field, and the signals at any two detectors are highly correlated [19].

Because the dark photon signal is quasimonochromatic, we analyze the frequency domain by discrete Fourier transforming the strain time series. Given a total coincident observation time, T_{obs} , for two detectors, we divide the time series into N_{FFT} smaller segments, with durations T_{FFT} , i.e., $T_{\text{obs}} = N_{\text{FFT}} T_{\text{FFT}}$. For the i th time segment, j th frequency bin, and interferometer k (1 or 2), we label the complex discrete Fourier transform coefficients as $z_{k,ij}$. The one-sided power spectral densities (PSDs) of interferometer 1(2) can be estimated by taking a (bias-corrected) running median of the raw noise powers $P_{k,ij}$ from 50 neighboring frequency bins: $\text{PSD}_{k,ij} = 2P_{k,ij}/T_{\text{FFT}}$.

The cross-correlated signal strength is

$$S_j = \frac{1}{N_{\text{FFT}}} \sum_{i=1}^{N_{\text{FFT}}} \frac{z_{1,ij} z_{2,ij}^*}{P_{1,ij} P_{2,ij}}, \quad (7)$$

where “*” is the complex conjugate, and the variance is

$$\sigma_j^2 = \frac{1}{N_{\text{FFT}}} \left\langle \frac{1}{2P_{1,ij} P_{2,ij}} \right\rangle_{N_{\text{FFT}}}, \quad (8)$$

where $\langle \dots \rangle_{N_{\text{FFT}}}$ is the average over N_{FFT} time segments. Therefore, the signal-to-noise ratio (SNR) is

$$\text{SNR}_j = \frac{S_j}{\sigma_j}. \quad (9)$$

In Gaussian noise without a signal, SNR_j has zero mean and unit variance. The presence of a signal would lead to a nonzero offset in the mean SNR proportional to ϵ^2 [see Eqs. (5)–(6)]. We note that we will include the overlap reduction function (ORF) in our upper limit calculation, which accounts for the relative orientation and overlap of two detectors and the responses of the detectors to a signal. As indicated in [13], the ORF is constant (~ -0.9) for the LIGO Hanford (H1) and LIGO Livingston (L1) detectors because the dark photon coherence length always exceeds the detector separation.

Here, we analyze only time segments satisfying standard data quality requirements used in gravitational-wave searches (see Sec. IV), and further restrict to contiguous, coincident intervals of good data spanning the fast Fourier transform coherence time. As in the analysis performed using data from the first observing run (O1) [24], we set $T_{\text{FFT}} = 1800$ s, a pragmatic compromise between recovering signal power at high frequencies with shorter-than-optimal coherence times, and reducing noise contamination at low frequencies for longer-than-optimal coherence times. An important constraint at low frequencies is that requiring longer (contiguous) coherence times necessarily reduces total available livetime, especially given the need for coincident H1 and L1 data. In total, we analyze 7539 pairs of 1800-second coincident time segments from H1 and L1.

B. BSD analysis

In addition to cross-correlation, we employ an independent method [41] to search for dark photon dark matter. The method relies on band sampled data (BSD) structures, which store the detector’s downsampled strain data as a reduced analytic signal [40] in 10-Hz/1-month chunks. In each 10-Hz band, we change the fast Fourier transform coherence time [40] based on the expected Maxwell-Boltzmann frequency spread of dark photons, Eq. (3). Although this frequency spread is given as a function of v_0 , we instead use the escape velocity from the galaxy, $v_{\text{esc}} \simeq 540$ km/s [44], to determine the maximum allowed T_{FFT} , $T_{\text{FFT,max}}$, by requiring that the frequency spread be contained in one frequency bin in $T_{\text{FFT,max}}$:

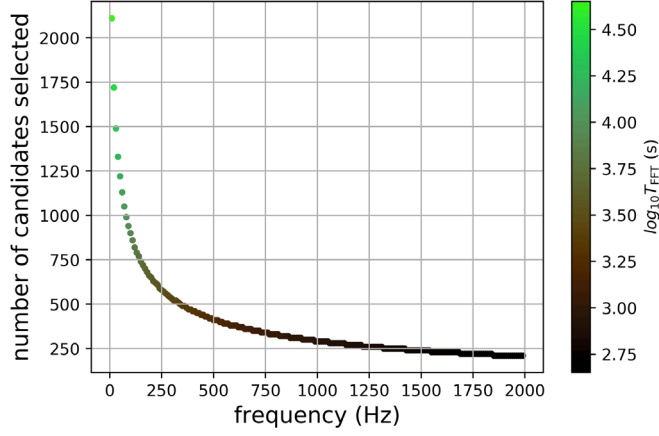


FIG. 1. Number of candidates selected as a function of frequency in the BSD analysis, with $\log_{10} T_{\text{FFT}}$ colored. We select enough candidates in each 1-Hz band such that one coincident candidate between two detectors would occur in Gaussian noise. The changing number of candidates as a function of frequency ensures that we select uniformly in frequency. See Supplemental Material [50].

$$T_{\text{FFT,max}} \lesssim \frac{2}{f_0} \frac{c^2}{v_{\text{esc}}^2} \simeq \frac{6 \times 10^5}{f_0} \text{ s}. \quad (10)$$

Based on simulations [41], we found that the sensitivity of the search improves when taking $T_{\text{FFT}} = 1.5T_{\text{FFT,max}}$, because the power lost due to over-resolving in frequency is less than that gained by increasing T_{FFT} .

After selecting T_{FFT} , we create time/frequency “peak-maps” [48,49], which are collections of ones and zeros that represent when the power in particular frequency bins has exceeded a threshold in the equalized spectrum. Because we choose T_{FFT} to confine a signal’s power to one frequency bin, we project the peakmap onto the frequency axis and look for frequency bins with large numbers of peaks, which we call the “number count”.

We should uniformly select candidates in the frequency domain. In Fig. 1 shows how many candidates to select in each 10-Hz frequency band such that we would obtain, on average, one coincident candidate every one Hz in Gaussian noise. We also show in color how $\log_{10} T_{\text{FFT}}$ changes with frequency [Eq. (10)].

Our detection statistic is the critical ratio CR:

$$\text{CR} = \frac{y - \mu}{\sigma}, \quad (11)$$

where y is the number count in a particular frequency bin, and μ and σ are the mean and standard deviations of the number counts across all frequency bins in the band. The CR has a normal distribution with an expectation value of 0 and unit variance in Gaussian noise, and a normalized noncentral χ^2 distribution with two degrees of freedom when a signal is present.

IV. DATA

We use data from the third observing run (O3) of the Advanced LIGO [51] and Virgo [52] gravitational-wave detectors between 10–2000 Hz. O3 lasted from 2019 April 1 to 2020 March 27, with a one-month pause in data collection in October 2019. The three detectors’ datasets, H1, L1, and Virgo (V1), had duty factors of $\sim 76\%$, $\sim 77\%$, and $\sim 76\%$, respectively, during O3.

In the event of a detection, calibration uncertainties would limit our ability to provide robust estimates of the coupling of dark matter to the interferometers. Even without a detection, these uncertainties affect the estimated instruments’ sensitivities and inferred upper limits. The uncertainties vary over the course of a run but do not change by large values, so we do not consider time-dependent calibration uncertainties here [53].

For the LIGO O3 data set, the analyses use the “C01” calibration, which has estimated maximum amplitude and phase uncertainties of $\sim 7\%$ and $\sim 4^\circ$, respectively [53]. Because of the presence of a large number of noise artifacts, *gating* [54,55] has also been applied to LIGO data. This procedure applies an inverse Tukey window to LIGO data at times when the root-mean-square value of the whitened strain channel in the 25–50 Hz band or 70–110 Hz band exceeds a certain threshold. The improvements from gating are significant, as seen in stochastic and continuous gravitational-wave analyses in O3 [46]. For the Virgo O3 dataset, we use the “V0” calibration with estimated maximum amplitude and phase uncertainties of 5% and 2 deg, respectively.

V. RESULTS

A. Cross-correlation

The output of the cross-correlation analysis is a value of the SNR in every frequency bin analyzed. At this point, we remove frequency bins with noise artifacts, i.e., bins within 0.056 Hz of known noise lines [56]. To further estimate the non-Gaussian background from artifacts, control samples are constructed using frequency lags, i.e., examining the correlations among a set of offset bins. We apply ten lags of the frequency bin offsets, i.e., $(-50, -40, \dots, -10, +10, \dots, +50)$. If any frequency bin in the control sample has a $|\text{Re}(\text{SNR})|$ or $|\text{Im}(\text{SNR})|$ larger than 4.0 within 0.1 Hz of the outlier, the outlier is vetoed as contaminated by spectral leakage from a nearby non-Gaussian artifact. We choose a band of 0.1 Hz because within that band, spectral leakage causes non-physical correlated amplitudes and phases. Furthermore, ten lags allows us to compare frequency bins that are not too far from each other to construct an estimation of the noise in the chosen frequency bin.

After removing these instrumental artifacts, we look for frequency bins with $\text{Re}(\text{SNR}) < -5.8$, which corresponds to an overall $\sim 1\%$ false alarm probability after including the trial factor in Gaussian noise, and is negative because

TABLE I. Four sub-threshold outliers returned by the cross correlation analysis of the HL baseline. We report the (complex) signal-to-noise ratio (SNR) for each outlier and the associated background (Bkg) SNR. For the background SNR, we include the range of the real part (Re) and imaginary part (Im) among ten lagged results. These four events are consistent with the Gaussian noise expectation over all of the clean bands in the analysis.

Frequency (Hz)	SNR	SNR(Bkg)
483.872	$0.53 + 5.03i$	Re: $[-3.62, 3.62]$ Im: $[-3.52, 3.51]$
853.389	$-0.18 + 5.02i$	Re: $[-3.85, 3.85]$ Im: $[-3.55, 3.90]$
1139.590	$-5.21 + 0.67i$	Re: $[-3.54, 3.39]$ Im: $[-3.61, 3.58]$
1686.598	$5.01 + 1.63i$	Re: $[-3.50, 3.70]$ Im: $[-3.65, 3.89]$

H1 and L1 are rotated 90 deg with respect to each other. We find no outliers that pass this threshold.

Finally, as a cross-check, between $[5.0, 5.8]$ for $|\text{Re}(\text{SNR})|$ or $|\text{Im}(\text{SNR})|$, we find four nonvetoed outliers, which are shown in Table I. The number of outliers is consistent with the Gaussian noise expectation of 4.1. We consider the absolute value of the real and imaginary components of the SNR because we are checking consistency with the expected number of outliers in Gaussian noise, which does not depend on the sign of the SNR. We show the distribution of the real and imaginary parts of the SNR in the Appendix.

B. BSD analysis

Before selecting candidates, we remove any frequencies that fall within one frequency bin of known noise lines from each detector's data [56]. We subsequently require coincident candidates between two or more detectors to be within one frequency bin of each other. At this stage, our analyses of the Hanford-Livingston (HL), Hanford-Virgo (HV), and the Livingston-Virgo (LV) baselines return 5801, 5628, and 5592 candidates, respectively.

In all baselines, we veto coincident candidates if one of the candidates' critical ratios is less than five or one of the candidates' frequencies is too close, i.e., within 5 bins, to the edges of the 10 Hz-band analyzed. The latter veto is necessary because the construction of the BSDs introduces artifacts in some bands at the edges. For the HL baseline, we remove candidates whose critical ratios differ by more than a factor of two because the sensitivity of each interferometer is comparable, so we do not expect a dark photon signal to appear with vastly different critical ratios in each detector. In the HV and LV baselines, we reject candidates whose critical ratios in V1 are higher than those in L1 or H1 because Virgo is less sensitive than LIGO [57]. We show distributions of CR in the Hanford and Livingston detectors across all frequencies in the Appendix, Figs. 5 and 6, respectively, as well as the CR distribution of the number of coincident candidates in Fig. 7.

We are then left with eleven surviving candidates across the three baselines, given in Table II, that are all due to instrumental noise or artifacts in the peakmap. Peakmap artifacts occur because when there are strong lines at

particular frequencies, we tend to select peaks that correspond to those lines. This causes a “depletion” of peaks nearby, and thus, a candidate could result because the level of the noise in the projected peakmap is lower on one side than on the other. No candidate has been found to be coincident in all three interferometers. These surviving candidates do not overlap with the list of known lines used in this search [56], although line artifacts or/and combs regions are clearly visible when using a different resolution to construct the spectra. In Fig. 2, we show an example of the disturbances near an outlier at 1498.76 Hz, where a family of combs is present in both the H1 and L1 detectors.

C. Upper limits

Finding no evidence of a signal, in Fig. 3 we place 95% confidence-level upper limits on the square of the minimum detectable dark photon/baryon coupling, $U(1)_B$, using the HL baseline. The cross-correlation limits are

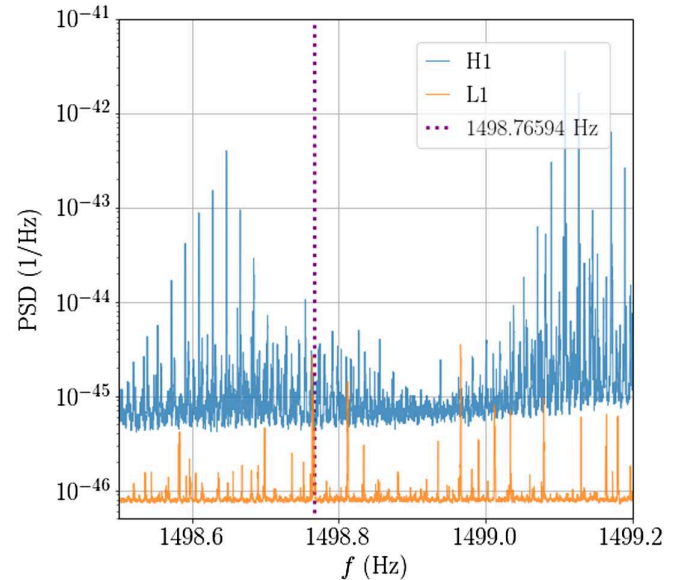


FIG. 2. We discarded all surviving outliers because they were due to instrumental noise or artifacts. In this figure, we can see the comb affecting the power spectral density (PSD) of H1 and the line in L1 responsible for the production of an outlier near 1498.8 Hz. Frequency resolution: $\delta f = 3.47 \times 10^{-5}$ Hz.

TABLE II. Outliers returned by the BSD analysis. The frequency resolution of each outlier is $1/T_{\text{FFT}}$. We have determined the origin of all outliers to be from instrumental lines or peakmap artifacts. No outlier was found to be in triple coincidence. A list of unidentified lines can be found in [58].

Frequency (Hz)	Average CR	T_{FFT} (s)	Baseline	Source
15.9000	5.29	44762	HL	Unknown line in L
17.8000	28.93	44762	LV	Unidentified line in L (17.8 Hz)
36.2000	8.90	22382	HV	Unidentified line in H (36.2 Hz)
599.324	12.38	1492	HV	Peakmap artifact; no significant candidate in L
599.325	12.33	1492	HV	Peakmap artifact; no significant candidate in L
1478.75	6.47	604	HL	Noisy spectra in H
1496.26	7.12	596	HL	Noisy violin resonance regions
1498.77	8.73	596	HL	Noisy violin resonance regions
1799.63	7.40	498	HV	Unidentified line in H (1799.63904 Hz)
1936.88	7.96	462	HL	Noisy violin resonance regions
1982.91	6.34	450	HL	Noisy violin resonance regions

shown in red for every 0.556-mHz bin, while the BSD limits are given in black with cyan 1σ shading in frequency bins in which coincident candidates were found. To calculate these limits, we employ the Feldman-Cousins [59] approach, in which we assume that both CR and SNR follow Gaussian distributions, and map the measured detection statistics to “inferred” positive-definite statistics based on the upper value of Table 10 of [59] at 95% confidence. As shown in [5], this approach produces consistent limits with respect to those that would be obtained by injecting simulated signals. With our estimates of the noise power spectral density and T_{FFT} , we can translate the inferred SNR and CR at each frequency to the

corresponding signal amplitude using Eq. (9) in [13] and Eq. (30) in [41], respectively. This amplitude is then converted to a coupling strength using Eq. (5), and adjusted for the common mode motion effect [42].

The limits from the cross-correlation analysis are more stringent than those from the BSD method because the former employs the phase information of the signal, while the latter only looks at power. Furthermore, though the choice of T_{FFT} is “optimal” in the BSD method, it is still shorter than that used by cross correlation by as much as a factor of six above ~ 330 Hz, and the definition of optimal depends on whether we consider the escape or virial velocity of dark matter as responsible for the frequency

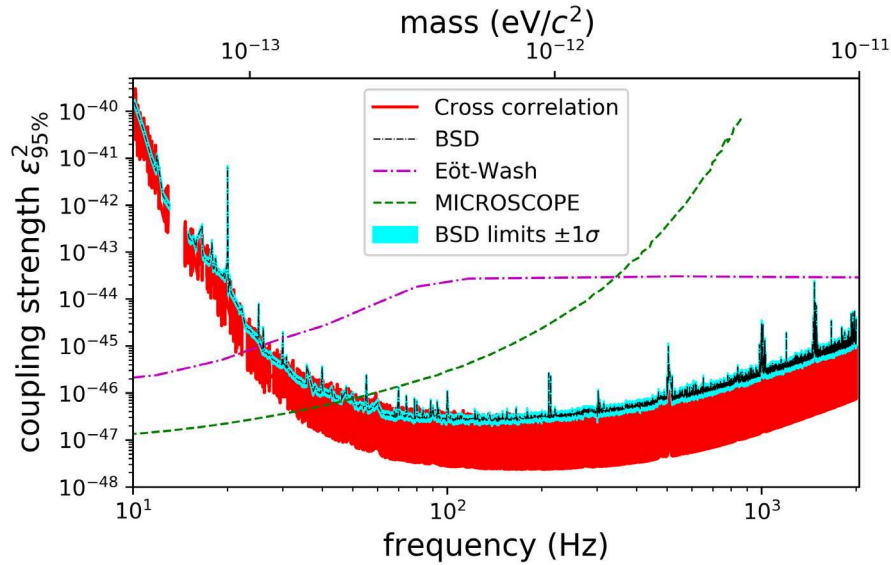


FIG. 3. Upper limits derived using a Feldman-Cousins approach for both searches on dark photon/baryon coupling, $U(1)_B$. The limits from each method are comparable, noting that the BSD-based analysis takes an optimally chosen T_{FFT} and can observe for twice as long as the cross-correlation method can. We plot for comparison upper limits from MICROSCOPE given in [30], though other weaker limits exist [60–62], that have been converted from the coupling constant to gravity, α , to e^2 , using the equation below Fig. 3 in [63], and from the Eöt-Wash torsion balance experiment [28]. To produce limits on dark photon/baryon-lepton coupling, $U(1)_{B-L}$, our limits should be multiplied by four. See Supplemental Material [50].

variation. Additionally, cross-correlation of two data streams can achieve better sensitivity than coincidence analysis of the same streams (for the same livetime) because coincidence analysis is limited by the less sensitive of the two detectors at a given frequency.

VI. CONCLUSIONS

We have presented strong constraints on the coupling strength of dark photon dark matter to baryons by using data from LIGO's and Virgo's third observing run. In the mass range $m_A \sim [2-4] \times 10^{-13} \text{ eV}/c^2$, we improve upon previous limits derived using data from the first observing run of LIGO [24] by a factor of ~ 100 in the square of the coupling strength of dark photons to baryons. This improvement is due to more sensitive detectors and to accounting for the finite light travel time [42]. Additionally, our limits surpass those of existing dark matter experiments, such as the Eöt-Wash torsion balance and MICROSCOPE, by orders of magnitude in certain frequency bands, and support new ways to use gravitational-wave detectors as direct probes of the existence of ultralight dark matter. As the sensitivities of current ground-based gravitational-wave detectors improve, and third generation detectors, such as Cosmic Explorer [64] and Einstein Telescope [65], come online, we will dig even more deeply into the noise. Furthermore, once future-generation space-based detectors, such as DECIGO [66], LISA [67], and TianQin [68], are operational, we will probe dark photon couplings at masses as low as $m_A \sim 10^{-18} \text{ eV}/c^2$.

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: No. JP17H06358, No. JP17H06361 and No. JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grant-in-Aid for Scientific Research (S) No. 17H06133, 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 AS-CDA-105-M06, Advanced Technology Center (ATC) of NAOJ, and Mechanical Engineering Center of KEK.

APPENDIX: DISTRIBUTION OF DETECTION STATISTICS

We provide here more details on our detection statistics for both methods. When we calculate upper limits, we assume that these statistics follow Gaussian distributions,

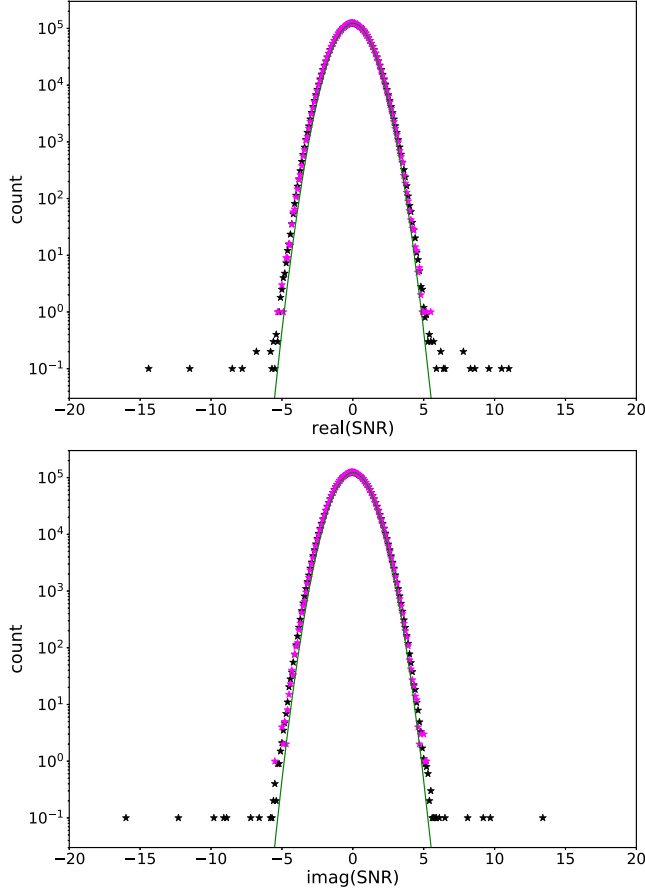


FIG. 4. Distribution of the real (top) and imaginary (bottom) parts of the SNR in the cross-correlation search, with those corresponding to on-source (with zero lag) results in magenta, background (with frequency lags) in black and the ideal Gaussian distribution in green.

which is actually true only in clean bands. But, because we showed the Feldman-Cousins approach to be robust toward noise disturbances in [41], we are confident that the limits are reflective of what we would have obtained if we performed software injections.

For the cross-correlation search, the distributions of the real and imaginary parts of the SNR are shown in Fig. 4 after vetoing frequency bins within 0.056 Hz of the known noise lines [56] and after vetoing the instrumental artifacts as described in the main text above.

We show the distributions of the CR in Hanford (Fig. 5) and Livingston (Fig. 6), over all frequency bins between 10–2000 Hz. We also overlay a Gaussian on the plot to show the extent to which the distributions differs from a Gaussian distribution. In both detectors, the number of frequency bins whose CRs deviate from Gaussianity is of $\mathcal{O}(10^2)$, which is a small fraction of the total number of bins analyzed.

We also include a plot to characterize the *coincident* candidates between Hanford and Livingston that are

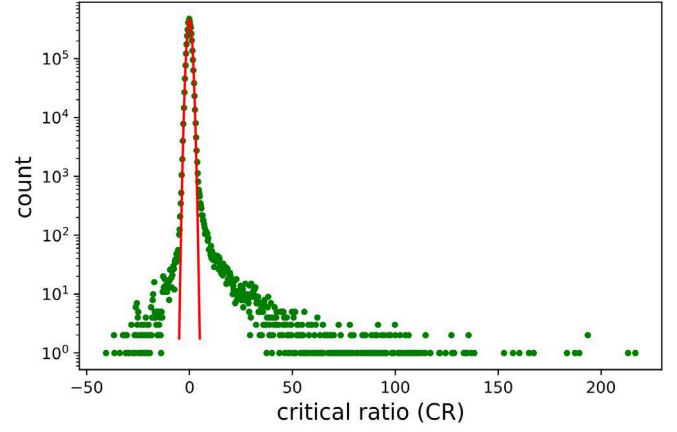


FIG. 5. Histogram of critical ratios in all frequency bins in the Hanford detector, with a Gaussian (in red) overlaid.

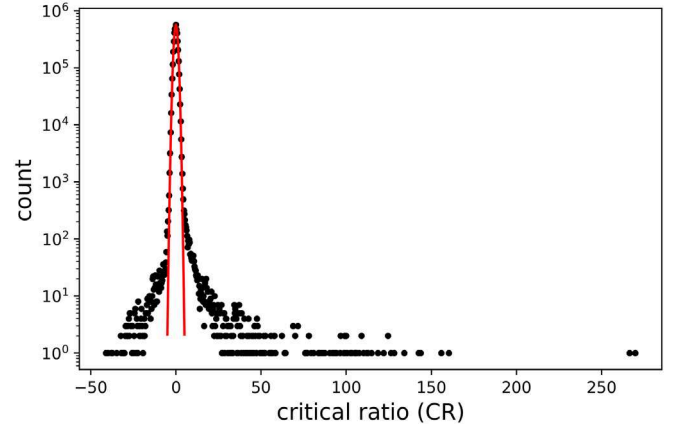


FIG. 6. Histogram of critical ratios in all frequency bins in the Livingston detector, with a Gaussian (in red) overlaid.

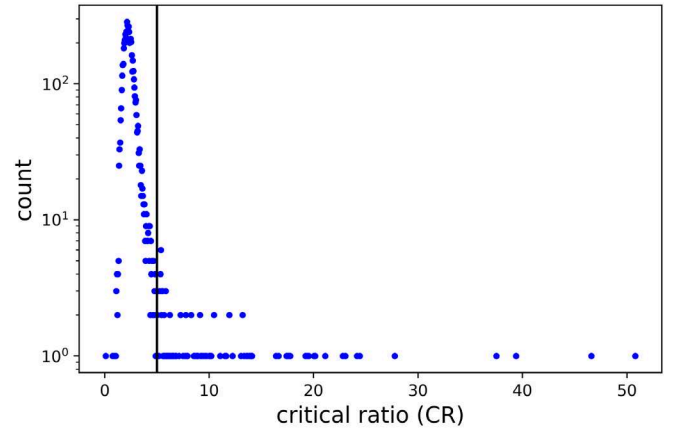


FIG. 7. Histogram of coincident critical ratios, after our selection of candidates in each 10-Hz frequency band. We performed the coincidences between the candidates returned after analyzing Hanford and Livingston data.

selected in our search. Figure 7 shows a histogram of all the coincident candidates' critical ratios that we select, as well as a black line that indicates the threshold on the critical ratio that we impose, equal to 5. We can see that very few

candidates are coincident relative to the number of candidates plotted in Figs. 5 and 6, and that the total number of coincident candidates that are subject to further study is of $\mathcal{O}(1000)$.

-
- [1] G. Bertone and D. Hooper, *Rev. Mod. Phys.* **90**, 045002 (2018).
 - [2] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, *Phys. Rev. D* **95**, 043541 (2017).
 - [3] S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess, *Phys. Rev. Lett.* **116**, 201301 (2016).
 - [4] S. Clesse and J. García-Bellido, *Phys. Dark Universe* **22**, 137 (2018).
 - [5] A. L. Miller, S. Clesse, F. De Lillo, G. Bruno, A. Depasse, and A. Tanasijczuk, *Phys. Dark Universe* **32**, 100836 (2021).
 - [6] A. L. Miller, N. Aggarwal, S. Clesse, and F. De Lillo, *arXiv:2110.06188*.
 - [7] R. Brito, V. Cardoso, and P. Pani, *Lect. Notes Phys.* **906**, 1 (2015).
 - [8] M. Isi, L. Sun, R. Brito, and A. Melatos, *Phys. Rev. D* **99**, 084042 (2019).
 - [9] G. Bertone, D. Croon, M. A. Amin, K. K. Boddy, B. J. Kavanagh, K. J. Mack, P. Natarajan, T. Opferkuch, K. Schutz, V. Takhistov *et al.*, *SciPost Phys. Core* **3**, 007 (2020).
 - [10] H. Grote and Y. Stadnik, *Phys. Rev. Research* **1**, 033187 (2019).
 - [11] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
 - [12] K. Nagano, T. Fujita, Y. Michimura, and I. Obata, *Phys. Rev. Lett.* **123**, 111301 (2019).
 - [13] A. Pierce, K. Riles, and Y. Zhao, *Phys. Rev. Lett.* **121**, 061102 (2018).
 - [14] J. M. Armaleo, D. L. Nacir, and F. R. Urban, *J. Cosmol. Astropart. Phys.* **04** (2021) 053.
 - [15] A. E. Nelson and J. Scholtz, *Phys. Rev. D* **84**, 103501 (2011).
 - [16] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, *J. Cosmol. Astropart. Phys.* **06** (2012) 013.
 - [17] P. W. Graham, J. Mardon, and S. Rajendran, *Phys. Rev. D* **93**, 103520 (2016).
 - [18] P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, and F. Takahashi, *Phys. Lett. B* **801**, 135136 (2020).
 - [19] R. T. Co, A. Pierce, Z. Zhang, Y. Zhao *et al.*, *Phys. Rev. D* **99**, 075002 (2019).
 - [20] M. Bastero-Gil, J. Santiago, L. Ubaldi, and R. Vega-Morales, *J. Cosmol. Astropart. Phys.* **04** (2019) 015.
 - [21] J. A. Dror, K. Harigaya, and V. Narayan, *Phys. Rev. D* **99**, 035036 (2019).
 - [22] A. J. Long and L.-T. Wang, *Phys. Rev. D* **99**, 063529 (2019).
 - [23] R. Abbott *et al.* (LIGO Scientific, Virgo, KAGRA Collaborations), *Phys. Rev. Lett.* **126**, 241102 (2021).
 - [24] H.-K. Guo, K. Riles, F.-W. Yang, and Y. Zhao, *Commun. Phys.* **2**, 155 (2019).
 - [25] K. L. Dooley *et al.*, *Classical Quantum Gravity* **33**, 075009 (2016).
 - [26] S. M. Vermeulen *et al.*, *Nature (London)* **600**, 424 (2021).
 - [27] Y. Su, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, M. Harris, G. L. Smith, and H. E. Swanson, *Phys. Rev. D* **50**, 3614 (1994).
 - [28] S. Schlamminger, K. Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger, *Phys. Rev. Lett.* **100**, 041101 (2008).
 - [29] P. Touboul, G. Metris, V. Lebat, and A. Robert, *Classical Quantum Gravity* **29**, 184010 (2012).
 - [30] J. Bergé, P. Brax, G. Métris, M. Pernot-Borràs, P. Touboul, and J.-P. Uzan, *Phys. Rev. Lett.* **120**, 141101 (2018).
 - [31] N. Du *et al.* (ADMX Collaboration), *Phys. Rev. Lett.* **120**, 151301 (2018).
 - [32] M. D. Ortiz *et al.*, *Phys. Dark Universe* **35**, 100968 (2022).
 - [33] C. Palomba, S. D'Antonio, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. L. Miller, F. Muciaccia *et al.*, *Phys. Rev. Lett.* **123**, 171101 (2019).
 - [34] L. Sun, R. Brito, and M. Isi, *Phys. Rev. D* **101**, 063020 (2020); **102**, 089902(E) (2020).
 - [35] S. D'Antonio, C. Palomba, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. Miller, F. Muciaccia *et al.*, *Phys. Rev. D* **98**, 103017 (2018).
 - [36] K. K. Y. Ng, S. Vitale, O. A. Hannuksela, and T. G. F. Li, *Phys. Rev. Lett.* **126**, 151102 (2021).
 - [37] S. J. Zhu, M. Baryakhtar, M. A. Papa, D. Tsuna, N. Kawanaka, and H.-B. Eggenstein, *Phys. Rev. D* **102**, 063020 (2020).
 - [38] L. Tsukada, T. Callister, A. Matas, and P. Meyers, *Phys. Rev. D* **99**, 103015 (2019).
 - [39] J. C. Bustillo, N. Sanchis-Gual, A. Torres-Forné, J. A. Font, A. Vajpeyi, R. Smith, C. Herdeiro, E. Radu, and S. H. W. Leong, *Phys. Rev. Lett.* **126**, 081101 (2021).
 - [40] O. Piccinni, P. Astone, S. D'Antonio, S. Frasca, G. Intini, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, and A. Singhal, *Classical Quantum Gravity* **36**, 015008 (2019).
 - [41] A. L. Miller *et al.*, *Phys. Rev. D* **103**, 103002 (2021).
 - [42] S. Morisaki, T. Fujita, Y. Michimura, H. Nakatsuka, and I. Obata, *Phys. Rev. D* **103**, L051702 (2021).
 - [43] D. Carney, A. Hook, Z. Liu, J. M. Taylor, and Y. Zhao, *New J. Phys.* **23**, 023041 (2021).
 - [44] M. C. Smith, G. R. Ruchti, A. Helmi, R. F. Wyse, J. P. Fulbright, K. C. Freeman, J. F. Navarro, G. M. Seabroke, M. Steinmetz, M. Williams *et al.*, *Mon. Not. R. Astron. Soc.* **379**, 755 (2007).

- [45] J. D. Romano and N. J. Cornish, *Living Rev. Relativity* **20**, 2 (2017).
- [46] R. Abbott *et al.* (KAGRA, Virgo, LIGO Scientific Collaborations), *Phys. Rev. D* **104**, 022004 (2021).
- [47] R. Abbott *et al.* (KAGRA, Virgo, LIGO Scientific Collaborations), *Phys. Rev. D* **104**, 022005 (2021).
- [48] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba, *Phys. Rev. D* **90**, 042002 (2014).
- [49] P. Astone, S. Frasca, and C. Palomba, *Classical Quantum Gravity* **22**, S1197 (2005).
- [50] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevD.105.063030> for the data used in Figs. 1 and 3.
- [51] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, K. Ackley, C. Adams, T. Adams, P. Addesso *et al.*, *Classical Quantum Gravity* **32**, 115012 (2015).
- [52] F. Acernese, M. Agathos, K. Agatsuma, D. Aisa, N. Allemandou, A. Allocca, J. Amarni, P. Astone, G. Balestri, G. Ballardin *et al.*, *Classical Quantum Gravity* **32**, 024001 (2015).
- [53] L. Sun *et al.*, *Classical Quantum Gravity* **37**, 225008 (2020).
- [54] <https://dcc.ligo.org/T2000384/>.
- [55] <https://dcc.ligo.org/LIGO-P2000546/public>.
- [56] <https://dcc.ligo.org/LIGO-T2100200-v1>.
- [57] B. P. Abbott *et al.* (KAGRA, LIGO Scientific, Virgo Collaborations), *Living Rev. Relativity* **23**, 3 (2020).
- [58] <https://dcc.ligo.org/LIGO-T2100201-v1>.
- [59] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).
- [60] P. Touboul *et al.*, *Phys. Rev. Lett.* **119**, 231101 (2017).
- [61] P. Fayet, *Phys. Rev. D* **97**, 055039 (2018).
- [62] P. Fayet, *Phys. Rev. D* **99**, 055043 (2019).
- [63] Y. Michimura, T. Fujita, S. Morisaki, H. Nakatsuka, and I. Obata, *Phys. Rev. D* **102**, 102001 (2020).
- [64] D. Reitze *et al.*, *Bull. Am. Astron. Soc.* **51**, 035 (2019).
- [65] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker *et al.*, *Classical Quantum Gravity* **27**, 194002 (2010).
- [66] S. Kawamura *et al.*, *Prog. Theor. Exp. Phys.* **2021**, 05A105 (2021).
- [67] S. Babak, J. Gair, A. Sesana, E. Barausse, C. F. Sopuerta, C. P. L. Berry, E. Berti, P. Amaro-Seoane, A. Petiteau, and A. Klein, *Phys. Rev. D* **95**, 103012 (2017).
- [68] J. Luo *et al.* (TianQin Collaboration), *Classical Quantum Gravity* **33**, 035010 (2016).

R. Abbott,¹ T. D. Abbott,² F. Acernese,^{3,4} K. Ackley,⁵ C. Adams,⁶ N. Adhikari,⁷ R. X. Adhikari,¹ V. B. Adya,⁸ C. Affeldt,^{9,10} D. Agarwal,¹¹ M. Agathos,^{12,13} K. Agatsuma,¹⁴ N. Aggarwal,¹⁵ O. D. Aguiar,¹⁶ L. Aiello,¹⁷ A. Ain,¹⁸ P. Ajith,¹⁹ T. Akutsu,^{20,21} S. Albanesi,²² A. Allocca,^{23,4} P. A. Altin,⁸ A. Amato,²⁴ C. Anand,⁵ S. Anand,¹ A. Ananyeva,¹ S. B. Anderson,¹ W. G. Anderson,⁷ M. Ando,^{25,26} T. Andrade,²⁷ N. Andres,²⁸ T. Andrić,²⁹ S. V. Angelova,³⁰ S. Ansoldi,^{31,32} J. M. Antelis,³³ S. Antier,³⁴ S. Appert,¹ Koji Arai,¹ Koya Arai,³⁵ Y. Arai,³⁵ S. Araki,³⁶ A. Araya,³⁷ M. C. Araya,¹ J. S. Areeda,³⁸ M. Arène,³⁴ N. Aritomi,²⁵ N. Arnaud,^{39,40} S. M. Aronson,² K. G. Arun,⁴¹ H. Asada,⁴² Y. Asali,⁴³ G. Ashton,⁵ Y. Aso,^{44,45} M. Assiduo,^{46,47} S. M. Aston,⁶ P. Astone,⁴⁸ F. Aubin,²⁸ C. Austin,² S. Babak,³⁴ F. Badaracco,⁴⁹ M. K. M. Bader,⁵⁰ C. Badger,⁵¹ S. Bae,⁵² Y. Bae,⁵³ A. M. Baer,⁵⁴ S. Bagnasco,²² Y. Bai,¹ L. Baiotti,⁵⁵ J. Baird,³⁴ R. Bajpai,⁵⁶ M. Ball,⁵⁷ G. Ballardin,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. Brillet,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. Cavaglià,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. Ciecielag,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. Cunningham,⁶⁶ E. Cuoco,^{40,150,18} M. Curyło,¹⁰⁰ P. Dabadie,²⁴ T. Dal Canton,³⁹ S. Dall'Osso,²⁹ G. Dály, ¹⁵¹ A. Dana,⁷⁰ L. M. DaneshgaranBajastani,⁸¹ B. D'Angelo,^{110,82} S. Danilishin,^{152,50} S. D'Antonio,¹¹⁸ K. Danzmann,^{9,10} C. Darsow-Fromm,¹²² A. Dasgupta,⁷⁷ L. E. H. Datrier,⁶⁶ S. Datta,¹¹ V. Dattilo,⁴⁰ I. Dave,⁸⁴ M. Davies,¹⁵³ D. Davis,¹ M. C. Davis,¹²⁰ E. J. Daw,¹⁵⁴ R. Dean,¹²⁰ D. DeBra,⁷⁰ M. Deenadayalan,¹¹ J. Degallaix,¹⁵⁵ M. De Laurentis,^{23,4} S. Deléglise,⁹⁹ V. Del Favero,¹²³ F. De Lillo,⁴⁹ N. De Lillo,⁶⁶ W. Del Pozzo,^{71,18} L. M. DeMarchi,¹⁵ F. De Matteis,^{117,118} V. D'Emilio,¹⁷ N. Demos,⁶⁷ T. Dent,¹⁰⁵ A. Depasse,⁴⁹ R. De Pietri,^{156,157} R. De Rosa,^{23,4} C. De Rossi,⁴⁰ R. DeSalvo,¹¹⁹ R. De Simone,¹³² S. Dhurandhar,¹¹ M. C. Díaz,¹⁴⁸ M. Diaz-Ortiz Jr.,⁶⁹ N. A. Didio,⁵⁸ T. Dietrich,^{102,50} L. Di Fiore,⁴ C. Di Fronzo,¹⁴ C. Di Giorgio,^{93,94} F. Di Giovanni,¹²¹ M. Di Giovanni,²⁹ T. Di Girolamo,^{23,4} A. Di Lieto,^{71,18} B. Ding,¹⁴³ S. 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. Fisher,⁵⁴ R. Fittipaldi,^{166,94} V. Fiumara,^{167,94} R. Flaminio,^{28,20} E. Floden,⁶⁰ H. Fong,¹¹² J. A. Font,^{121,168} B. Fornal,¹⁶⁹ P. W. F. Forsyth,⁸ A. Franke,¹²² S. Frasca,^{95,48} F. Frasconi,¹⁸ C. Frederick,¹⁷⁰ J. P. Freed,³³ Z. Frei,¹⁵¹ A. Freise,¹⁷¹ R. Frey,⁵⁷ P. Fritschel,⁶⁷ V. V. Frolov,⁶ G. G. Fronzé,²² Y. Fujii,¹⁷² Y. Fujikawa,¹⁷³ M. Fukunaga,³⁵ M. Fukushima,²¹ P. Fulda,⁶⁹ M. Fyffe,⁶ H. A. Gabbard,⁶⁶ B. U. Gadre,¹⁰² J. R. Gair,¹⁰² J. Gais,¹⁰⁶ S. Galaudage,⁵ R. Gamba,¹³ D. Ganapathy,⁶⁷ A. Ganguly,¹⁹ D. Gao,¹⁷⁴ S. G. Gaonkar,¹¹ B. Garaventa,^{82,110} C. García-Núñez,⁹⁰ C. García-Quirós,¹⁴² F. Garufi,^{23,4} B. Gateley,⁶⁴ S. Gaudio,³³ V. Gayathri,⁶⁹ G.-G. Ge,¹⁷⁴ G. Gemme,⁸² A. Gennai,¹⁸ J. George,⁸⁴ O. Gerberding,¹²² L. Gergely,¹⁷⁵ P. Gewecke,¹²² S. Ghonge,¹⁰⁴ Abhirup Ghosh,¹⁰² Archisman Ghosh,¹⁷⁶ Shaon Ghosh,^{7,162} Shrobana Ghosh,¹⁷ B. Giacomazzo,^{61,62,63} L. Giacoppo,^{95,48} J. A. Giaime,^{2,6} K. D. Giardina,⁶ D. R. Gibson,⁹⁰ C. Gier,³⁰ M. Giesler,¹⁷⁷ P. Giri,^{18,71} F. Gissi,⁷⁹ J. Glanzer,² A. E. Gleckl,³⁸ P. Godwin,¹⁴⁶ E. Goetz,¹⁷⁸ R. Goetz,⁶⁹ N. Gohlke,^{9,10} B. Goncharov,^{5,29} G. González,² A. Gopakumar,¹⁷⁹ M. Gosselin,⁴⁰ R. Gouaty,²⁸ D. W. Gould,⁸ B. Grace,⁸ A. Grado,^{180,4} M. Granata,¹⁵⁵ V. Granata,⁹³ A. Grant,⁶⁶ S. Gras,⁶⁷ P. Grassia,¹ C. Gray,⁶⁴ R. Gray,⁶⁶ G. Greco,⁷² A. C. Green,⁶⁹ R. Green,¹⁷ A. M. Gretarsson,³³ E. M. Gretarsson,³³ D. Griffith,¹ W. Griffiths,¹⁷ H. L. Griggs,¹⁰⁴ G. Grignani,^{73,72} A. Grimaldi,^{88,89} S. J. Grimm,^{29,98} H. Grote,¹⁷ S. Grunewald,¹⁰² P. Gruning,³⁹ D. Guerra,¹²¹ G. M. Guidi,^{46,47} A. R. Guimaraes,² G. Guixé,²⁷ H. K. Gulati,⁷⁷ H.-K. Guo,¹⁶⁹ Y. Guo,⁵⁰ Anchal Gupta,¹ Anuradha Gupta,¹⁸¹ P. Gupta,^{50,111} E. K. Gustafson,¹ R. Gustafson,¹⁸² F. Guzman,¹⁸³ S. Ha,¹⁸⁴ L. Haegel,³⁴ A. Hagiwara,^{35,185} S. Haino,¹³³ O. Halim,^{32,186} E. D. Hall,⁶⁷ E. Z. Hamilton,¹⁵⁸ G. Hammond,⁶⁶ W.-B. Han,¹⁸⁷ M. Haney,¹⁵⁸ J. Hanks,⁶⁴ C. Hanna,¹⁴⁶ M. D. Hannam,¹⁷ O. Hannuksela,^{111,50} H. Hansen,⁶⁴ T. J. 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. Hasskew,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. Kanda,^{202,203} S. Kandhasamy,¹¹ G. Kang,²¹⁴ J. B. Kanner,¹ Y. Kao,¹²⁴ S. J. Kapadia,¹⁹ D. P. Kapasi,⁸ S. Karat,¹ C. Karathanasis,²¹⁵ S. Karki,⁸⁶ R. Kashyap,¹⁴⁶ M. Kasprzack,¹ W. Kastaun,^{9,10} S. Katsanevas,⁴⁰ E. Katsavounidis,⁶⁷ W. Katzman,⁶ T. Kaur,⁸³ K. Kawabe,⁶⁴ K. Kawaguchi,³⁵ N. Kawai,²¹⁶ T. Kawasaki,²⁵ F. Kéfélian,⁹² D. Keitel,¹⁴² J. S. Key,²¹⁷ S. Khadka,⁷⁰ F. Y. Khalili,⁸⁷ S. Khan,¹⁷ E. A. Khazanov,²¹⁸ N. Khetan,^{29,98} M. Khursheed,⁸⁴ N. Kijbunchoo,⁸ C. Kim,²¹⁹ J. C. Kim,²²⁰ J. Kim,²²¹ K. Kim,²²² W. S. Kim,²²³ Y.-M. Kim,²²⁴ C. Kimball,¹⁵ N. Kimura,¹⁸⁵ M. Kinley-Hanlon,⁶⁶ R. Kirchhoff,^{9,10} J. S. Kissel,⁶⁴ N. Kita,²⁵ H. Kitazawa,²⁰¹ L. Kleybolte,¹²² S. Klimenko,⁶⁹ A. M. Knee,¹⁷⁸ T. D. Knowles,¹⁶¹ E. Knyazev,⁶⁷ P. Koch,^{9,10} G. Koekoek,^{50,152} Y. Kojima,²²⁵ K. Kokeyama,²²⁶ S. Koley,²⁹ P. Kolitsidou,¹⁷ M. Kolstein,²¹⁵ K. Komori,^{67,25} V. Kondrashov,¹ A. K. H. Kong,²²⁷ A. Kontos,²²⁸ N. Koper,^{9,10} M. Korobko,¹²² K. Kotake,¹²⁵ M. Kovalam,⁸³ D. B. Kozak,¹ C. Kozakai,⁴⁴ R. Kozu,¹⁹⁰ V. Kringel,^{9,10} N. V. Krishnendu,^{9,10} A. Królak,^{229,230} G. Kuehn,^{9,10} F. Kuei,¹²⁴ P. Kuijter,⁵⁰ A. Kumar,²⁰⁵ P. Kumar,¹⁷⁷ Rahul Kumar,⁶⁴ Rakesh Kumar,⁷⁷ J. Kume,²⁶ K. Kuns,⁶⁷ C. Kuo,¹²⁹ H.-S. Kuo,¹⁹⁶ Y. Kuromiya,²⁰¹ S. Kuroyanagi,^{231,232} K. Kusayanagi,²¹⁶ S. Kuwahara,¹¹² K. Kwak,¹⁸⁴ P. Lagabbe,²⁸ D. Laghi,^{71,18} E. Lalande,²³³ T. L. Lam,¹⁰⁶ A. Lamberts,^{92,234} M. Landry,⁶⁴ B. B. Lane,⁶⁷ R. N. Lang,⁶⁷ J. Lange,¹⁶⁵ B. Lantz,⁷⁰ I. La Rosa,²⁸ A. Lartaux-Vollard,³⁹ P. D. Lasky,⁵ M. Laxen,⁶ A. Lazzarini,¹ C. Lazzaro,^{74,75} P. Leaci,^{95,48} S. Leavey,^{9,10} Y. K. Lecoeuche,¹⁷⁸ H. K. Lee,²³⁵ H. M. Lee,¹³⁵ H. W. Lee,²²⁰ J. Lee,¹³⁵ K. Lee,²³⁶ R. Lee,¹³¹ J. Lehmann,^{9,10} A. Lemaître,²³⁷ M. Leonardi,²⁰ N. Leroy,³⁹ N. Letendre,²⁸ C. Levesque,²³³ Y. Levin,⁵ J. N. Leviton,¹⁸² K. Leyde,³⁴ A. K. Y. Li,¹ B. Li,¹²⁴ J. Li,¹⁵ K. L. Li,²³⁸ T. G. F. Li,¹⁰⁶ X. Li,¹³⁰ C.-Y. Lin,²³⁹ F.-K. Lin,¹³³ F.-L. Lin,¹⁹⁶ H. L. Lin,¹²⁹ L. C.-C. Lin,¹⁸⁴ F. Linde,^{240,50} S. D. Linker,⁸¹ J. N. Linley,⁶⁶ T. B. Littenberg,²⁴¹ G. C. Liu,¹²⁷ J. Liu,^{9,10} K. Liu,¹²⁴ X. Liu,⁷ F. Llamas,¹⁴⁸ M. Llorens-Monteagudo,¹²¹ R. K. L. Lo,¹ A. Lockwood,²⁴² L. T. London,⁶⁷ A. Longo,^{243,244} D. Lopez,¹⁵⁸ M. Lopez Portilla,¹¹¹ M. Lorenzini,^{117,118} V. Lorette,²⁴⁵ M. Lormand,⁶ G. Losurdo,¹⁸ T. P. Lott,¹⁰⁴ J. D. Lough,^{9,10} C. O. Lousto,¹²³ G. Lovelace,³⁸ J. F. Lucaccioni,¹⁷⁰ H. Lück,^{9,10} D. Lumaca,^{117,118} A. P. Lundgren,¹⁵³ L.-W. Luo,¹³³ J. E. Lynam,⁵⁴ R. Macas,¹⁵³ M. MacInnis,⁶⁷ D. M. Macleod,¹⁷ I. A. O. MacMillan,¹ A. Macquet,⁹² I. Magaña Hernandez,⁷ C. Magazzù,¹⁸ R. M. Magee,¹ R. Maggiore,¹⁴ M. Magnozzi,^{82,110} S. Mahesh,¹⁶¹ E. Majorana,^{95,48} C. Makarem,¹ I. Maksimovic,²⁴⁵ S. Maliakal,¹ A. Malik,⁸⁴ N. Man,⁹² V. Mandic,⁶⁰ V. Mangano,^{95,48} J. L. Mango,²⁴⁶ G. L. Mansell,^{64,67} M. Manske,⁷ M. Mantovani,⁴⁰ M. Mapelli,^{74,75} F. Marchesoni,^{247,72,248} M. Marchio,²⁰ F. Marion,²⁸ Z. Mark,¹³⁰ S. Márka,⁴³ Z. Márka,⁴³ C. Markakis,¹² A. S. Markosyan,⁷⁰ A. Markowitz,¹ E. Maros,¹ A. Marquina,¹⁴⁴ S. Marsat,³⁴ F. 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. Matiushechkina,^{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. Merilä,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. Milano,²³ A. L. Miller,⁴⁹ A. Miller,⁸¹ B. Miller,^{85,50} M. Millhouse,¹¹⁴ J. C. Mills,¹⁷ E. Milotti,^{186,32} O. Minazzoli,^{92,250} Y. Minenkov,¹¹⁸ N. Mio,²⁵¹ L. M. Mir,²¹⁵ M. Miravet-Tenés,¹²¹ C. Mishra,²⁵² T. Mishra,⁶⁹ T. Mistry,¹⁵⁴ S. Mitra,¹¹ V. P. Mitrofanov,⁸⁷ G. Mitselmakher,⁶⁹ R. Mittleman,⁶⁷ O. Miyakawa,¹⁹⁰

A. Miyamoto,²⁰² Y. Miyazaki,²⁵ K. Miyo,¹⁹⁰ S. Miyoki,¹⁹⁰ Geoffrey Mo,⁶⁷ E. Moguel,¹⁷⁰ K. Mogushi,⁸⁶
 S. R. P. Mohapatra,⁶⁷ S. R. Mohite,⁷ I. Molina,³⁸ M. Molina-Ruiz,¹⁹² M. Mondin,⁸¹ M. Montani,^{46,47} C. J. Moore,¹⁴
 D. Moraru,⁶⁴ F. Morawski,⁷⁸ A. More,¹¹ C. Moreno,³³ G. Moreno,⁶⁴ Y. Mori,²⁰¹ S. Morisaki,⁷ Y. Moriwaki,¹⁸⁹ B. Mours,¹⁶⁰
 C. M. Mow-Lowry,^{14,171} S. Mozzon,¹⁵³ F. Muciaccia,^{95,48} Arunava Mukherjee,²⁵³ D. Mukherjee,¹⁴⁶ Soma Mukherjee,¹⁴⁸
 Subroto Mukherjee,⁷⁷ Suvodip Mukherjee,⁸⁵ N. Mukund,^{9,10} A. Mullavey,⁶ J. Munch,⁸⁰ E. A. Muñoz,⁵⁸ P. G. Murray,⁶⁶
 R. Musenich,^{82,110} S. Muusse,⁸⁰ S. L. Nadj,^{9,10} K. Nagano,²⁰⁴ S. Nagano,²⁵⁴ A. Nagar,^{22,255} K. 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. Passaquietti,^{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. Pettersson,¹ H. P. Pfeiffer,¹⁰² K. A. Pham,⁶⁰
 K. S. Phukon,^{50,240} O. J. Piccinni,⁴⁸ M. Pichot,⁹² M. Piendibene,^{71,18} F. Piergiovanni,^{46,47} L. Pierini,^{95,48} V. Pierro,^{79,94}
 G. Pillant,⁴⁰ M. Pillas,³⁹ F. Pilo,¹⁸ L. Pinard,¹⁵⁵ I. M. Pinto,^{79,94,264} M. Pinto,⁴⁰ K. Piotrkowski,⁴⁹ M. Pirello,⁶⁴
 M. D. Pitkin,²⁶⁵ E. Placidi,^{95,48} L. Planas,¹⁴² W. Plastino,^{243,244} C. Pluchar,¹³⁸ R. Poggiani,^{71,18} E. Polini,²⁸ D. Y. T. Pong,¹⁰⁶
 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
 K. Prasai,⁷⁰ R. Prasanna,²⁰⁵ G. Pratten,¹⁴ M. Principe,^{79,264,94} G. A. Prodi,^{266,89} L. Prokhorov,¹⁴ P. Prospero,^{117,118}
 L. Prudenzi,¹⁰² A. Puecher,^{50,111} M. Punturo,⁷² F. Puosi,^{18,71} P. Puppo,⁴⁸ M. Pürer,¹⁰² H. Qi,¹⁷ V. Quetschke,¹⁴⁸
 R. Quitzow-James,⁸⁶ F. J. Raab,⁶⁴ G. Raaijmakers,^{85,50} H. Radkins,⁶⁴ N. Radulesco,⁹² P. Raffai,¹⁵¹ S. X. Rail,²³³ S. Raja,⁸⁴
 C. Rajan,⁸⁴ K. E. Ramirez,⁶ T. D. Ramirez,³⁸ A. Ramos-Buades,¹⁰² J. Rana,¹⁴⁶ P. Rapagnani,^{95,48} U. D. Rapol,²⁶⁷ A. Ray,⁷
 V. Raymond,¹⁷ N. Raza,¹⁷⁸ M. Razzano,^{71,18} J. Read,³⁸ L. A. Rees,¹⁸⁸ T. Regimbau,²⁸ L. Rei,⁸² S. Reid,³⁰ S. W. Reid,⁵⁴
 D. H. Reitze,^{1,69} P. Relton,¹⁷ A. Renzini,¹ P. Rettegno,^{268,22} M. Rezac,³⁸ F. Ricci,^{95,48} D. Richards,¹³⁹ J. W. Richardson,¹
 L. Richardson,¹⁸³ G. Riemschneider,^{268,22} K. Riles,¹⁸² S. Rinaldi,^{18,71} K. Rink,¹⁷⁸ M. Rizzo,¹⁵ N. A. Robertson,^{1,66}
 R. Robie,¹ F. Robinet,³⁹ A. Rocchi,¹¹⁸ S. Rodriguez,³⁸ L. Rolland,²⁸ J. G. Rollins,¹ M. Romanelli,⁹⁶ R. Romano,^{3,4}
 C. L. Romel,⁶⁴ A. Romero-Rodríguez,²¹⁵ I. M. Romero-Shaw,⁵ J. H. Romie,⁶ S. Ronchini,^{29,98} L. Rosa,^{4,23} C. A. Rose,⁷
 D. Rosińska,¹⁰⁰ M. P. Ross,²⁴² S. Rowan,⁶⁶ S. J. Rowlinson,¹⁴ S. Roy,¹¹¹ Santosh Roy,¹¹ Soumen Roy,²⁶⁹ D. Rozza,^{115,116}
 P. Ruggi,⁴⁰ K. Ryan,⁶⁴ S. Sachdev,¹⁴⁶ T. Sadecki,⁶⁴ J. Sadiq,¹⁰⁵ N. Sago,²⁷⁰ S. Saito,²¹ Y. Saito,¹⁹⁰ K. Sakai,²⁷¹ Y. Sakai,¹⁹⁵
 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}
 E. J. Sanchez,¹ J. H. Sanchez,³⁸ L. E. Sanchez,¹ N. Sanchis-Gual,²⁷² J. R. Sanders,²⁷³ A. Sanuy,²⁷ T. R. Saravanan,¹¹
 N. Sarin,⁵ B. Sassolas,¹⁵⁵ H. Satari,⁸³ B. S. Sathyaprakash,^{146,17} S. Sato,²⁷⁴ T. Sato,¹⁷³ O. Sauter,⁶⁹ R. L. Savage,⁶⁴
 T. Sawada,²⁰² D. Sawant,⁹⁷ H. L. Sawant,¹¹ S. Sayah,¹⁵⁵ D. Schaetzl,¹ M. Scheel,¹³⁰ J. Scheuer,¹⁵ M. Schiowski,⁸⁰
 P. Schmidt,¹⁴ S. Schmidt,¹¹¹ R. Schnabel,¹²² M. Schneewind,^{9,10} R. M. S. Schofield,⁵⁷ A. Schönbeck,¹²² B. W. Schulte,^{9,10}
 B. F. Schutz,^{17,9,10} E. Schwartz,¹⁷ J. Scott,⁶⁶ S. M. Scott,⁸ M. Seglar-Arroyo,²⁸ T. Sekiguchi,²⁶ Y. Sekiguchi,²⁷⁵ D. Sellers,⁶
 A. S. Sengupta,²⁶⁹ D. Sentenac,⁴⁰ E. G. Seo,¹⁰⁶ V. Sequino,^{23,4} A. Sergeev,²¹⁸ Y. Setyawati,¹¹¹ T. Shaffer,⁶⁴ M. S. Shahriar,¹⁵
 B. Shams,¹⁶⁹ L. Shao,¹⁹⁹ A. Sharma,^{29,98} P. Sharma,⁸⁴ P. Shawhan,¹⁰¹ N. S. Shcheblanov,²³⁷ S. Shibagaki,¹²⁵
 M. Shikauchi,¹¹² R. Shimizu,²¹ T. Shimoda,²⁵ K. Shimode,¹⁹⁰ H. Shinkai,²⁷⁶ T. Shishido,⁴⁵ A. Shoda,²⁰ D. H. Shoemaker,⁶⁷
 D. M. Shoemaker,¹⁶⁵ S. ShyamSundar,⁸⁴ M. Sieniawska,¹⁰⁰ D. Sigg,⁶⁴ L. P. Singer,¹⁰⁹ D. Singh,¹⁴⁶ N. Singh,¹⁰⁰
 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,²⁰ E. N. Tapia San Martín,⁵⁰ 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 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 M. E. Zucker,^{1,67} and J. Zweizig¹

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

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

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

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

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

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

⁶LIGO Livingston Observatory, Livingston, Louisiana 70754, USA

⁷University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA

⁸OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

⁹Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

¹⁰Leibniz Universität Hannover, D-30167 Hannover, Germany

¹¹Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

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

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

¹⁴University 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*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*
- ³²*INFN, Sezione di Trieste, I-34127 Trieste, Italy*
- ³³*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
- ³⁴*Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France*
- ³⁵*Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
- ³⁶*Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*
- ³⁷*Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan*
- ³⁸*California State University Fullerton, Fullerton, California 92831, USA*
- ³⁹*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
- ⁴⁰*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
- ⁴¹*Chennai Mathematical Institute, Chennai 603103, India*
- ⁴²*Department of Mathematics and Physics, Gravitational Wave Science Project, Hirosaki University, Hirosaki City, Aomori 036-8561, Japan*
- ⁴³*Columbia University, New York, New York 10027, USA*
- ⁴⁴*Kamioka Branch, National Astronomical Observatory of Japan (NAOJ), Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ⁴⁵*The Graduate University for Advanced Studies (SOKENDAI), Mitaka City, Tokyo 181-8588, Japan*
- ⁴⁶*Università degli Studi di Urbino “Carlo Bo”, I-61029 Urbino, Italy*
- ⁴⁷*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
- ⁴⁸*INFN, Sezione di Roma, I-00185 Roma, Italy*
- ⁴⁹*Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
- ⁵⁰*Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
- ⁵¹*King’s College London, University of London, London WC2R 2LS, United Kingdom*
- ⁵²*Korea Institute of Science and Technology Information (KISTI), Yuseong-gu, Daejeon 34141, Korea*
- ⁵³*National Institute for Mathematical Sciences, Yuseong-gu, Daejeon 34047, Korea*
- ⁵⁴*Christopher Newport University, Newport News, Virginia 23606, USA*
- ⁵⁵*International College, Osaka University, Toyonaka City, Osaka 560-0043, Japan*
- ⁵⁶*School of High Energy Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba City, Ibaraki 305-0801, Japan*
- ⁵⁷*University of Oregon, Eugene, Oregon 97403, USA*
- ⁵⁸*Syracuse University, Syracuse, New York 13244, USA*
- ⁵⁹*Université de Liège, B-4000 Liège, Belgium*
- ⁶⁰*University of Minnesota, Minneapolis, Minnesota 55455, USA*
- ⁶¹*Università 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 State 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 Dr, 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
- ⁹⁶Univ 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, Universidad de Santiago de Compostela, 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

- ¹¹⁶*INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy*
- ¹¹⁷*Università di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹¹⁸*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
- ¹¹⁹*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
- ¹²⁰*Villanova University, 800 Lancaster Ave, Villanova, Pennsylvania 19085, USA*
- ¹²¹*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹²²*Universität Hamburg, D-22761 Hamburg, Germany*
- ¹²³*Rochester Institute of Technology, Rochester, New York 14623, USA*
- ¹²⁴*National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China*
- ¹²⁵*Department of Applied Physics, Fukuoka University, Jonan, Fukuoka City, Fukuoka 814-0180, Japan*
- ¹²⁶*OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
- ¹²⁷*Department of Physics, Tamkang University, Danshui District, New Taipei City 25137, Taiwan*
- ¹²⁸*Department of Physics and Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*
- ¹²⁹*Department of Physics, Center for High Energy and High Field Physics, National Central University, Zhongli District, Taoyuan City 32001, Taiwan*
- ¹³⁰*CaRT, California Institute of Technology, Pasadena, California 91125, USA*
- ¹³¹*Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan*
- ¹³²*Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ¹³³*Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan*
- ¹³⁴*Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
- ¹³⁵*Seoul National University, Seoul 08826, South Korea*
- ¹³⁶*Pusan National University, Busan 46241, South Korea*
- ¹³⁷*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
- ¹³⁸*University of Arizona, Tucson, Arizona 85721, USA*
- ¹³⁹*Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom*
- ¹⁴⁰*OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
- ¹⁴¹*Université libre de Bruxelles, Avenue Franklin Roosevelt 50–1050 Bruxelles, Belgium*
- ¹⁴²*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
- ¹⁴³*Université Libre de Bruxelles, Brussels 1050, Belgium*
- ¹⁴⁴*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹⁴⁵*Texas Tech University, Lubbock, Texas 79409, USA*
- ¹⁴⁶*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
- ¹⁴⁷*University of Rhode Island, Kingston, Rhode Island 02881, USA*
- ¹⁴⁸*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
- ¹⁴⁹*Bellevue College, Bellevue, Washington State 98007, USA*
- ¹⁵⁰*Scuola Normale Superiore, Piazza dei Cavalieri, 7 - 56126 Pisa, Italy*
- ¹⁵¹*MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary*
- ¹⁵²*Maastricht University, P.O. Box 616, 6200 MD Maastricht, Netherlands*
- ¹⁵³*University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
- ¹⁵⁴*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
- ¹⁵⁵*Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
- ¹⁵⁶*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
- ¹⁵⁷*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
- ¹⁵⁸*Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
- ¹⁵⁹*University of Chicago, Chicago, Illinois 60637, USA*
- ¹⁶⁰*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
- ¹⁶¹*West Virginia University, Morgantown, West Virginia 26506, USA*
- ¹⁶²*Montclair State University, Montclair, New Jersey 07043, USA*
- ¹⁶³*Colorado State University, Fort Collins, Colorado 80523, USA*
- ¹⁶⁴*Institute for Nuclear Research, Hungarian Academy of Sciences, Bem t'er 18/c, H-4026 Debrecen, Hungary*
- ¹⁶⁵*Department of Physics, University of Texas, Austin, Texas 78712, USA*
- ¹⁶⁶*CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy*

- ¹⁶⁷*Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy*
- ¹⁶⁸*Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain*
- ¹⁶⁹*The University of Utah, Salt Lake City, Utah 84112, USA*
- ¹⁷⁰*Kenyon College, Gambier, Ohio 43022, USA*
- ¹⁷¹*Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
- ¹⁷²*Department of Astronomy, The University of Tokyo, Mitaka City, Tokyo 181-8588, Japan*
- ¹⁷³*Faculty of Engineering, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
- ¹⁷⁴*State 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*
- ¹⁷⁵*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
- ¹⁷⁶*Universiteit Gent, B-9000 Gent, Belgium*
- ¹⁷⁷*Cornell University, Ithaca, New York 14850, USA*
- ¹⁷⁸*University of British Columbia, Vancouver BC V6T 1Z4, Canada*
- ¹⁷⁹*Tata Institute of Fundamental Research, Mumbai 400005, India*
- ¹⁸⁰*INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy*
- ¹⁸¹*The University of Mississippi, University, Mississippi 38677, USA*
- ¹⁸²*University of Michigan, Ann Arbor, Michigan 48109, USA*
- ¹⁸³*Texas A&M University, College Station, Texas 77843, USA*
- ¹⁸⁴*Department of Physics, Ulsan National Institute of Science and Technology (UNIST), Ulsu-gun, Ulsan 44919, Korea*
- ¹⁸⁵*Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*
- ¹⁸⁶*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
- ¹⁸⁷*Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China*
- ¹⁸⁸*American University, Washington DC 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, Gifu City, Gifu 506-1205, Japan*
- ¹⁹¹*Carleton College, Northfield, Minnesota 55057, USA*
- ¹⁹²*University of California, Berkeley, California 94720, USA*
- ¹⁹³*Maastricht University, 6200 MD, 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 Białystok, 15-424 Białystok, Poland*
- ²⁰⁹*Department of Physics, Ewha Womans University, Seodaemun-gu, Seoul 03760, Korea*
- ²¹⁰*National Astronomical Observatories, Chinese Academic of Sciences, Chaoyang District, Beijing 100107, China*

- ²¹¹*School of Astronomy and Space Science, University of Chinese Academy of Sciences, Chaoyang District, Beijing 100864, 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 State 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 77313, 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 State 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*

- ²⁶⁰Consiglio Nazionale delle Ricerche - Istituto dei Sistemi Complessi,
Piazzale Aldo Moro 5, I-00185 Roma, Italy
- ²⁶¹Korea Astronomy and Space Science Institute (KASI), Yuseong-gu, Daejeon 34055, Korea
- ²⁶²Hobart and William Smith Colleges, Geneva, New York 14456, USA
- ²⁶³International Institute of Physics, Universidade Federal do Rio Grande do Norte,
Natal RN 59078-970, Brazil
- ²⁶⁴Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, I-00184 Roma, Italy
- ²⁶⁵Lancaster University, Lancaster LA1 4YW, United Kingdom
- ²⁶⁶Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy
- ²⁶⁷Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India
- ²⁶⁸Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy
- ²⁶⁹Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India
- ²⁷⁰Department of Physics, Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- ²⁷¹Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College,
Nagaoka City, Niigata 940-8532, Japan
- ²⁷²Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in
Mathematics and Applications, Campus de Santiago, 3810-183 Aveiro, Portugal
- ²⁷³Marquette University, 11420 W. Clybourn Street, Milwaukee, Wisconsin 53233, USA
- ²⁷⁴Graduate School of Science and Engineering, Hosei University, Koganei City, Tokyo 184-8584, Japan
- ²⁷⁵Faculty of Science, Toho University, Funabashi City, Chiba 274-8510, Japan
- ²⁷⁶Faculty of Information Science and Technology, Osaka Institute of Technology,
Hirakata City, Osaka 573-0196, Japan
- ²⁷⁷Università di Firenze, Sesto Fiorentino I-50019, Italy
- ²⁷⁸INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
- ²⁷⁹Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India
- ²⁸⁰iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program), The Institute of Physical
and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
- ²⁸¹INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy
- ²⁸²Department of Space and Astronautical Science, The Graduate University for Advanced Studies
(SOKENDAI), Sagamihara City, Kanagawa 252-5210, Japan
- ²⁸³Andrews University, Berrien Springs, Michigan 49104, USA
- ²⁸⁴Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, Setagaya,
Tokyo 158-0082, Japan
- ²⁸⁵Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN),
The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- ²⁸⁶National Metrology Institute of Japan, National Institute of Advanced Industrial Science and
Technology, Tsukuba City, Ibaraki 305-8568, Japan
- ²⁸⁷Dipartimento di Scienze Aziendali - Management and Innovation Systems (DISA-MIS), Università di
Salerno, I-84084 Fisciano Salerno, Italy
- ²⁸⁸Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747
AG Groningen, Netherlands
- ²⁸⁹Faculty of Science, Department of Physics, The Chinese University of Hong Kong,
Shatin, N.T., Hong Kong
- ²⁹⁰Vrije Universiteit Brussel, Boulevard de la Plaine 2, 1050 Ixelles, Belgium
- ²⁹¹Department of Communications Engineering, National Defense Academy of Japan, Yokosuka City,
Kanagawa 239-8686, Japan
- ²⁹²Department of Physics, University of Florida, Gainesville, Florida 32611, USA
- ²⁹³Department of Information and Management Systems Engineering, Nagaoka University of Technology,
Nagaoka City, Niigata 940-2188, Japan
- ²⁹⁴Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands
- ²⁹⁵Department of Physics and Astronomy, Sejong University, Gwangjin-gu, Seoul 143-747, Korea
- ²⁹⁶Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan
- ²⁹⁷Department of Physics, Rikkyo University, Toshima-ku, Tokyo 171-8501, Japan

[†]Deceased.