

Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data

R. Abbott *et al.**

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



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Results are presented for a semicoherent search for continuous gravitational waves from the low-mass x-ray binary Scorpius X-1, using a hidden Markov model (HMM) to allow for spin wandering. This search improves on previous HMM-based searches of Laser Interferometer Gravitational-Wave Observatory data by including the orbital period in the search template grid, and by analyzing data from the latest (third) observing run. In the frequency range searched, from 60 to 500 Hz, we find no evidence of gravitational radiation. This is the most sensitive search for Scorpius X-1 using a HMM to date. For the most sensitive subband, starting at 256.06 Hz, we report an upper limit on gravitational wave strain (at 95% confidence) of $h_0^{95\%} = 6.16 \times 10^{-26}$, assuming the orbital inclination angle takes its electromagnetically restricted value $\iota = 44^\circ$. The upper limits on gravitational wave strain reported here are on average a factor of ~ 3 lower than in the second observing run HMM search. This is the first Scorpius X-1 HMM search with upper limits that reach below the indirect torque-balance limit for certain subbands, assuming $\iota = 44^\circ$.

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I. INTRODUCTION

Rotating neutron stars are promising candidates for continuous-wave searches with terrestrial gravitational wave (GW) detectors such as the second-generation Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [1–5], Advanced Virgo [4], and the Kamioka Gravitational-Wave Detector [6]. Continuous GWs from neutron stars are emitted by an oscillating quadrupole moment, which can be produced in various ways, including elastic strain [7,8], magnetic gradients [9–11], r -modes [12–14], or nonaxisymmetric circulation of the superfluid interior [15–18]. These mechanisms emit GWs at specific multiples of the spin frequency $f_\star$ [1]. Low-mass x-ray binaries (LMXBs) have been targeted by previous LIGO searches, [19–24] because they may emit GWs relatively strongly while existing in a state of rotational equilibrium, in which the accretion torque balances the GW torque [25–27]. Under torque-balance conditions, the characteristic GW strain h_0 is proportional to the square root of the x-ray flux, implying that the brightest LMXB, Scorpius X-1 (Sco X-1), is also a strong GW emitter [1,27].

Continuous-wave searches directed at Sco X-1 have been performed with data from the first (O1) and second (O2) observing runs of LIGO [19–21,23,28–31]. No signal has been detected to date, but astrophysically interesting upper limits have been obtained. For O1, a hidden Markov model (HMM) pipeline [29] obtained an upper limit at 95% confidence level of $h_0^{95\%} = 8.3 \times 10^{-25}$ in the 100–200 Hz

frequency range, while a cross-correlation (CrossCorr) pipeline [28,32] achieved $h_0^{95\%} = 2.3 \times 10^{-25}$ in the same frequency range. For O2, the HMM pipeline [21] obtained $h_0^{95\%} = 3.47 \times 10^{-25}$, in the 100–200 Hz frequency range, while CrossCorr [23] improved on its O1 results by a factor of ≈ 1.8 . All of these upper limits on $h_0^{95\%}$ are marginalized over the neutron star spin inclination ι , assuming an isotropic prior. If instead one assumes an electromagnetically informed prior, $\iota = 44^\circ \pm 6^\circ$ [33], the O2 upper limits obtained by CrossCorr reduce to $\sim 10^{-26}$ [23]. As with any observation the upper limits are conditional on the signal model. CrossCorr and the HMM assume different phase evolution, so the foregoing $h_0^{95\%}$ values cannot be compared directly (see Sec. V B), although they are broadly indicative of course. Now, the third observation run (O3), which is longer and more sensitive than O1 and O2, offers an opportunity to repeat the O1 and O2 searches with improved sensitivity. The improved HMM search is the subject of this paper.

Searching for LMXBs presents two challenges. First, $f_\star$ (and hence the GW frequency) wanders stochastically in objects where it is measured electromagnetically, due to fluctuations in the hydromagnetic accretion torque [34–37]. Second, in some LMXBs including Sco X-1, which do not exhibit x-ray pulsations, $f_\star$ is not measured electromagnetically [1,37]. Hence a GW search must cover a wide band (width ~ 1 kHz) looking for an unknown, wandering, quasimonochromatic tone [38,39]. HMM tracking is a tried and tested method for searches of the above sort, with a long history of practical use in telecommunications [40]

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

and remote sensing [41]. HMM tracking has been used in numerous searches for GWs, e.g. for Sco X-1 in O1 [29] and O2 [21], young supernova remnants in O3 [42], accreting millisecond x-ray pulsars in O2 [22] and O3 [24], all sky searches [43], and long-duration transients [44].

The $\mathcal{J}$ -statistic [45], a frequency domain matched filter, is used in tandem with the HMM described in Refs. [21,29,45,46]. The outline of the rest of the paper is as follows. Section II explains briefly the HMM formulation used and the $\mathcal{J}$ -statistic. In Sec. III, the search pipeline and parameter space are described. In Secs. IV and V, we present the search results and upper limits, respectively. We conclude in Sec. VI.

II. HMM ALGORITHM

In Sec. II A we review the HMM formalism used to track the wandering GW emission frequency from one time step to the next, according to a user-selected set of transition probabilities. For each time step we calculate the likelihood of a signal being present given the data, via a maximum likelihood matched filter called the $\mathcal{J}$ -statistic, which is reviewed in Sec. II B.

A. Hidden state structure and automaton

A HMM is a probabilistic finite state automaton characterized by a hidden state variable $q(t)$, which takes the discrete values $\{q_1, \dots, q_{N_Q}\}$, and an observable state variable $o(t)$, which takes the discrete values $\{o_1, \dots, o_{N_O}\}$. The automaton jumps between states at discrete time epochs $\{t_1, \dots, t_{N_T}\}$. The probability of being in hidden state $q(t_{n+1})$ at time t_{n+1} depends only upon the state at the previous time step t_n . This is known as a Markov process.

To complete the model, two matrices are defined. First, the transition probability matrix $A_{q(t_{n+1})q(t_n)}$, which relates the probability of a state $q(t_n)$ to jump to $q(t_{n+1})$, takes the form

$$A_{q(t_{n+1})q(t_n)} = \frac{1}{3} [\delta_{[q(t_{n+1})][q(t_n)-\Delta q]} + \delta_{[q(t_{n+1})][q(t_n)]} + \delta_{[q(t_{n+1})][q(t_n)+\Delta q]}], \quad (1)$$

where δ_{ij} is the Kronecker delta, with i and j given by the terms in square brackets, respectively. Equation (1) defines the signal model as a piecewise constant function that jumps by -1 , 0 , or 1 frequency bin Δq at each discrete transition time. See Sec. III A for the details on the search frequency bin size. The other matrix is the emission probability matrix $L_{o(t_n)q(t_n)}$ that relates the likelihood of observing $o(t_n)$ if the hidden state variable is $q(t_n)$. $L_{o(t_n)q(t_n)}$ is constructed from the matched-filter $\mathcal{J}$ -statistic, which we review in Sec. II B. In our GW application, $f_\star(t)$ maps onto $q(t)$, noting that $f_\star(t)$ is hidden because it cannot be measured electromagnetically for Sco X-1.

The data, specifically the Fourier transform of the time series output by the detector, map onto $o(t)$. The total observation time T_{obs} is divided into N_T segments of duration T_{drift} rounded down to the nearest integer, i.e. $N_T = \lfloor T_{\text{obs}}/T_{\text{drift}} \rfloor$. T_{drift} is chosen to prevent $f_\star(t)$ from wandering by more than one frequency bin per time step. The rate of spin wandering is unknown *a priori* in Sco X-1, as $f_\star(t)$ cannot be measured electromagnetically. The observed x-ray flux variability can be used to estimate the stochastic variation in $f_\star(t)$ [38,47], and from this we make an informed choice of T_{drift} , as in previous searches.

The probability that the hidden state follows some path $Q = \{q(t_1), \dots, q_{t_{N_T}}\}$ given some observed data $O = \{o(t_0), \dots, o_{t_{N_T}}\}$ is then given by the product of the transition and emission probabilities for each step, viz.

$$P(Q|O) = L_{o(t_{N_T})q(t_{N_T})} A_{q(t_{N_T})q(t_{N_T-1})} \cdots \times L_{o(t_1)q(t_1)} A_{q(t_1)q(t_0)} \Pi_{q(t_0)}, \quad (2)$$

where we define the prior probability of being in some initial state $q(t_0)$ at time t_0 as $\Pi_{q(t_0)}$. In this paper we assign equal probability to all initial states, with $\Pi_{q(t_0)} = 1/N_Q$.

We seek the path Q^* that maximizes $P(Q|O)$ in Eq. (2). But it is computationally inefficient to consider all the $N_Q^{N_T+1}$ possible paths. A robust and computationally efficient way to find Q^* is the Viterbi algorithm [48]. This recursive algorithm exploits the principle of optimality to find Q^* given O . A comprehensive description of the algorithm can be found in Appendix A of Ref. [29].

In this paper we use as detection statistic the log-likelihood of the most likely path $\mathcal{L} = \ln P(Q^*|O)$.

B. $\mathcal{J}$ -statistic

The emission probability $L_{o(t_n)q(t_n)}$ relates the observed data $o(t_n)$, collected in the interval $t_n \leq t \leq t_n + T_{\text{drift}}$ to the hidden states $q(t_n)$. In this paper, we express $L_{o(t_n)q(t_n)}$ in terms of the $\mathcal{J}$ -statistic [21,45]. The $\mathcal{J}$ -statistic is a maximum likelihood, frequency domain, matched-filter which tracks the orbital phase of the neutron star in its binary system. It is an extension of the traditional $\mathcal{F}$ -statistic [49], which is a matched filter for a biaxial rotor [50]. The Doppler shift due to the binary motion disperses the $\mathcal{F}$ -statistic power into orbital sidebands of the GW carrier frequency. Although the $\mathcal{F}$ -statistic can be used to produce matched filters to account for the Doppler shift due to the binary motion, the $\mathcal{J}$ -statistic is used for computational efficiency. Section III in Ref. [45] presents the detailed derivation of the $\mathcal{J}$ -statistic.

In general, to account for the dispersed power, the $\mathcal{J}$ -statistic is constructed from matched filters of the suggestive form

$$G(f) = \mathcal{F}(f) \otimes B(f), \quad (3)$$

with

$$B(f) = \sum_{s=-m}^m J_s(2\pi f_0 a_0) \exp(-i s \phi_a) \delta\left(f - \frac{s}{P}\right), \quad (4)$$

where $\otimes$ denotes convolution, $J_s(x)$ is the Bessel function of the first kind of order s , $m = \text{ceil}(2\pi f_0 a_0)$, and f_0 is the central frequency of the subband (see Sec. III A for details). Equation (4) assumes the GW signal is produced by a biaxial rotor in a circular Keplerian orbit and requires three binary orbital parameters: the projected semimajor axis a_0 , the orbital phase at a reference time ϕ_a , and P is the binary orbital period.

III. SEARCH IMPLEMENTATION

In this section we discuss the practical details of the search. Sections III A and III B define the parameter domain and grid, respectively. Section III C sets out the workflow. Section III D justifies the selection of the false alarm probability in terms of the number of search templates. Section III E specifies the primary and secondary data products ingested by the search.

A. Sco X-1 parameters

The $\mathcal{J}$ -statistic depends on the location of the source, described by the right ascension α and declination δ . It also depends on the three binary orbital elements: P , a_0 , and ϕ_a . The time of passage through the ascending node T_{asc} is linked to ϕ_a via $\phi_a = 2\pi T_{\text{asc}}/P \pmod{2\pi}$. Henceforth we use T_{asc} instead of ϕ_a . Some of these parameters have been measured electromagnetically for Sco X-1. Their values and uncertainties are summarized in Table I.

The last electromagnetic measurements [51] for the time of ascension $T_{\text{asc,ref}} = 974\,416\,624$ Global Positioning System (GPS) time are dated November 22 04:00:15 Greenwich Mean Time 2010, here denoted T_0 . We forward

propagate $T_{\text{asc,ref}}$ to the start of O3, $T_{\text{O3},0} = 1238166483$ GPS time, viz.

$$T_{\text{asc},0} = T_{\text{asc,ref}} + N_{\text{orb}} P_0, \quad (5)$$

where $P_0 = 68023.86048$ s is the central value of the orbital period in Table I, and $N_{\text{orb}} = \lceil \frac{T_{\text{O3},0} - T_0}{P_0} \rceil$ is the number of full orbits between the reference time T_0 and $T_{\text{O3},0}$. The original uncertainties for $T_{\text{asc,ref}}$ and P are also propagated using Eq. (5). This is illustrated in Fig. 1. The propagation maps the original uncertainty ellipses of $T_{\text{asc,ref}} - P$ (upper panel in Fig. 1) to the present uncertainty ellipses $T_{\text{asc}} - P$ (lower panel in Fig. 1). Propagating the original uncertainties via Eq. (5) creates correlations between the uncertainties of T_{asc} and P .

The propagated priors on T_{asc} and P change throughout the search duration as their correlation grows with time. The lower panel of Fig. 1 shows the change from the start of O3 marked as solid color lines, to its end, $T_{\text{O3end}} = 1269361423$ GPS time, shown as dotted lines. The search has been designed to cover the whole 3σ region of the propagated $T_{\text{asc}} - P$ space, from start to end of O3.

For a_0 , we cover the range $1.45 \leq a_0/(1\text{s}) \leq 3.25$, following the electromagnetic measurements presented in [51]. We can write this range equivalently as $\bar{a}_0 \pm 3\sigma_{a_0}$, with $\bar{a}_0 = 2.35$ and $\sigma_{a_0} = 0.3$ s.

The coherence time is set to $T_{\text{drift}} = 10$ d. The latter choice is justified astrophysically: it is the characteristic timescale of the random walk in $f_\star$ inferred from accretion-driven fluctuations in the x-ray flux of Sco X-1 [19,38,47]. It also matches the value used in previous published searches for Sco X-1, enabling direct comparison with historical results [19,21,28,29]. The resolution in frequency space Δf_{drift} , i.e. the size of the frequency bins, is set by the coherence time as $\Delta f_{\text{drift}} = 1/(2T_{\text{drift}}) = 5.787037 \times 10^{-7}$ Hz.

TABLE I. Search parameters and their range. The column headed “EM data” records the availability of electromagnetic measurements in the references in the last column. All parameter ranges include the central value together with $\pm 1\sigma$ uncertainties; values without uncertainties are treated as constants. In the text generally the central values are denoted with the subscript 0, e.g. P_0 . The time of ascension T_{asc} stands for the value in [51] propagated up to the start of O3, as described in Sec. III A. As written here T_{asc} and P , plus their uncertainties, define a rectangular parameter domain. We only search over the grid points that have support from the propagated priors, defined by all the ellipses in the lower panel of Fig. 1; see Sec. III B for details.

Parameter	Symbol	Search range	EM data	Reference
Right ascension	α	16 h 19 m 55.0850 s	Y	[52]
Declination	δ	$-15^\circ 38' 24.9''$	Y	[52]
Orbital inclination angle	i	$44 \pm 6^\circ$	Y	[33]
Projected semimajor axis	a_0	2.35 ± 0.3 s	Y	[51]
Orbital period	P	$68\,023.86048 \pm 0.0432$ s	Y	[51]
GPS time of ascension	T_{asc}	$1\,238\,149\,477.03488 \pm 200$ s	Y	[51]
Frequency	f	60–500 Hz	N	...

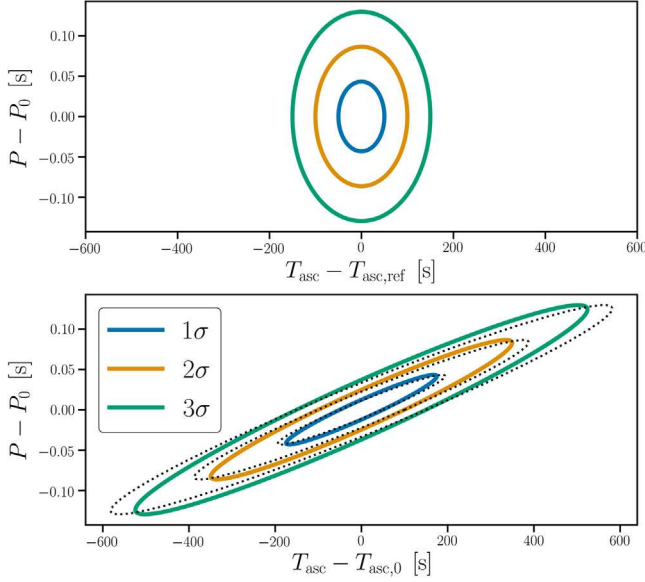


FIG. 1. Uncertainty ellipses corresponding to 1σ (blue line), 2σ (yellow line), and 3σ (green line), for T_{asc} and P . Top: the curves at the reference time T_0 , when $T_{\text{asc,ref}}$ is uncorrelated with P_0 or its uncertainties. Bottom: the effect of propagating $T_{\text{asc,ref}}$ and P_0 , with their respective uncertainties, to the start of O3 ($T_{\text{O3},0} = 1238166483$ GPS time) (solid lines) or the end of O3 ($T_{\text{O3end}} = 1269361423$ GPS time) (black dots). $T_{\text{asc},0}$ represents the central value of $T_{\text{asc,ref}}$ propagated to the start or end of O3; that is, $T_{\text{asc},0}$ is different for the solid and dotted lines. In both panels we have $P_0 = 68023.86048$ s.

The range of frequencies to be searched, 60–500 Hz, covers the region where LIGO is most sensitive. This frequency range is divided into subbands. This eases the manipulation of the data and allows one to approximate f_0 in Eq. (4) by the midpoint frequency $\bar{f}$ in each subband, accelerating the process of creating each matched filter via Eq. (4) [45]. The subbands are designed to contain a number of frequency bins N_f that is a power of 2, in order to accelerate the fast Fourier transform involved in calculating the convolution in Eq. (4). For this search we use $N_f = 2^{20}$, setting the subband width to $\Delta f_{\text{sub}} = N_f \Delta f_{\text{drift}} = 0.6068148$ Hz. As such the total number of subbands to consider in our search is $N_{\text{sub}} = \lceil (500-60) \text{ Hz} / \Delta f_{\text{sub}} \rceil = 725$. As the $\mathcal{J}$ -statistic is less sensitive farther away from $\bar{f}$, we create subbands with an overlap of $\Delta f_{\text{sub}}/4$. This way the area with less sensitivity in a subband is covered with greater sensitivity in the neighboring subband. All of the parameters discussed in this section are summarized in Table I.

B. Number and placing of orbital templates

In this subsection we describe the procedure to calculate and place the orbital templates needed to cover the search parameter domain per subband.

As explained in Sec. III A, the forward propagation of the reference $T_{\text{asc,ref}}$ increases its uncertainty as a function

of N_{orb} . To be conservative, we choose to propagate the uncertainties on $T_{\text{asc,ref}}$ to the end of O3 with

$$\sigma_{T_{\text{asc}}} = \sqrt{\sigma_{T_{\text{asc,ref}}}^2 + (N_{\text{orb,end}} \sigma_P)^2}, \quad (6)$$

where one has $N_{\text{orb,end}} = \lceil \frac{T_{\text{O3end}} - T_0}{P_0} \rceil$, and $\sigma_{T_{\text{asc,ref}}} = 50$ and $\sigma_P = 0.0432$ s are the uncertainties for $T_{\text{asc,ref}}$ and P , respectively, the result $\sigma_{T_{\text{asc}}} = 200$ s is included in Table I. Although the uncertainties are propagated to the end of O3, the central value for the time of ascension is only propagated to the start of O3, $T_{\text{asc},0} = 1238149477.03488$ s, as shown in Sec. III A.

We cover the parameter space by using a rectangular grid defined by the limits $(\bar{a}_0 \pm 3\sigma_{a_0}, T_{\text{asc}} \pm 3\sigma_{T_{\text{asc}}}, P_0 \pm 3\sigma_P)$. We set the spacing of the grid points by selecting an acceptable maximum mismatch μ_{max} , following [53]. This mismatch represents the fractional loss in signal-to-noise ratio between the search with the true parameters and the nearest grid point. For the search we use $\mu_{\text{max}} = 0.1$. The number of grid points needed to cover the (a_0, T_{asc}, P) space, for a given μ_{max} , are calculated using Eq. (71) of Ref. [53], namely

$$N_{a_0} = \lceil 3\sqrt{2}\mu_{\text{max}}^{-1/2} f \sigma_{a_0} \rceil, \quad (7)$$

$$N_{T_{\text{asc}}} = \lceil 6\pi^2 \sqrt{2}\mu_{\text{max}}^{-1/2} f a_0 P^{-1} \sigma_{T_{\text{asc}}} \rceil, \quad (8)$$

$$N_P = \lceil \pi^2 \sqrt{6}\mu_{\text{max}}^{-1/2} f a_0 T_{\text{drift}} N_T P^{-2} \sigma_P \rceil. \quad (9)$$

For O3 the number of contiguous semicoherent segments is $N_T = 36$. To be conservative when applying Eqs. (7)–(9), we use the highest frequency in each subband for f , the highest $a_0 = \bar{a}_0 + 3\sigma_{a_0}$, and the lowest $P = P_0 - 3\sigma_P$. Table II lists the number of grid points in selected subbands. For T_{asc} and P we search only the points defined by Eqs. (7)–(9) that lie within the start (color lines) and end (dotted lines) ellipses in the bottom panel of Fig. 1.

C. Workflow

The workflow for the search is illustrated in Fig. 2, as a flowchart.

TABLE II. Selected subbands and corresponding N_{a_0} , $N_{T_{\text{asc}}}$, N_P values, using $\mu_{\text{max}} = 0.1$. The table serves to illustrate how the number of orbital templates varies across the full frequency band.

Subband (Hz)	N_{a_0}	$N_{T_{\text{asc}}}$	N_P
60	767	149	5
160	2031	394	12
260	3296	640	19
360	4560	885	27
460	6331	1228	37

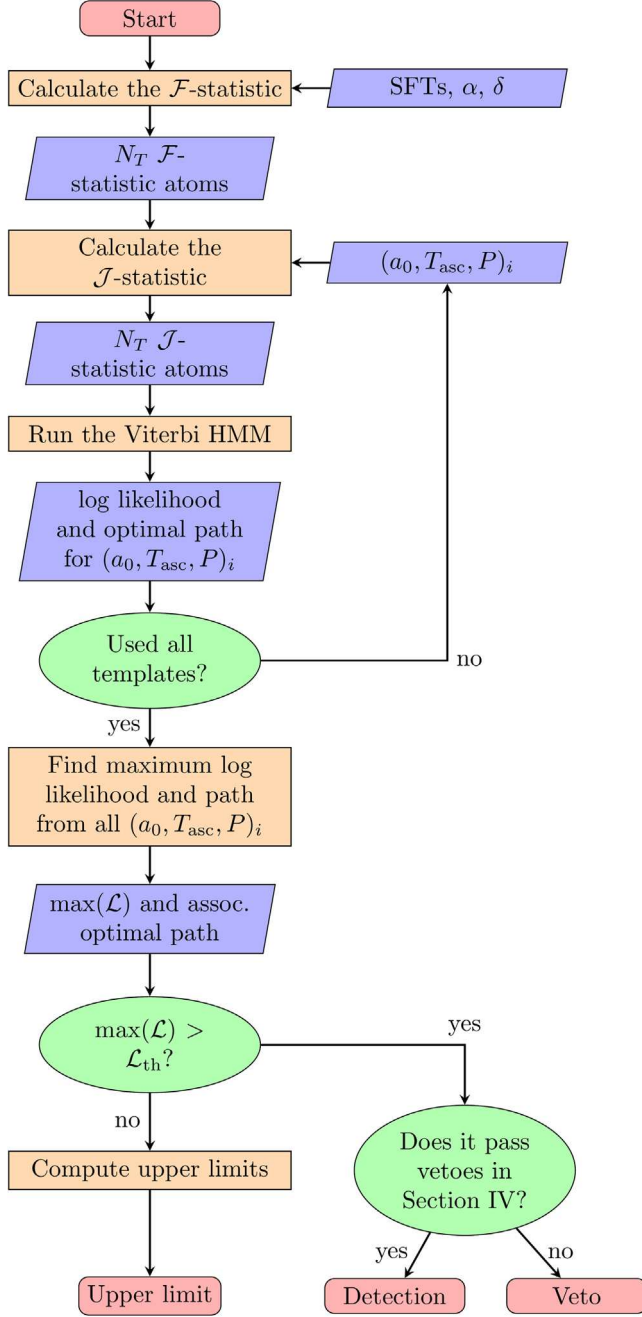


FIG. 2. Flowchart of the search pipeline for a subband. The light red octagons are the start and end points, the orange rectangles are processes, the blue parallelograms are input or output data, and the green ovals stand for decision points. The full search repeats the steps in the flowchart for 725 subbands from 60 to 500 Hz.

At the outset, the time series from the detector is converted into short Fourier transforms (SFTs) lasting $T_{\text{SFT}} = 1800$ s. The corresponding data, for each frequency subband, are divided into N_T blocks of duration $T_{\text{drift}} = 10$ d. All of the SFTs in a single block are used to calculate an $\mathcal{F}$ -statistic *atom* [54] with the fixed parameters

α and δ in Table I. The process is repeated for all the blocks, generating N_T atoms. The $\mathcal{F}$ -statistic atoms do not depend on the orbital parameters so they are stored in a look-up table. The steps in this paragraph conclude in the blue parallelogram denoted “ $N_T \mathcal{F}$ -statistic atoms” in Fig. 2.

In every subband, each $\mathcal{F}$ -statistic atom is fed into the $\mathcal{J}$ -statistic in Eq. (4) for a triad of orbital parameters (a_0, T_{asc}, P) . The Viterbi algorithm (see [48] or Sec. II B of Ref. [45]) finds the optimal frequency path connecting the $\mathcal{J}$ -statistic blocks and its associated log-likelihood. In Fig. 2, the latter steps extend from the orange rectangle “Calculate the $\mathcal{J}$ -statistic” up to the blue parallelogram marked “log-likelihood and optimal path for $(a_0, T_{\text{asc}}, P)_i$.”

For a subband centered on the frequency $\bar{f}$, the search scans over all binary templates $(a_0, T_{\text{asc}}, P)_i$ with $1 \leq i \leq N_{a_0}(\bar{f})N_{T_{\text{asc}}}(\bar{f})N_P(\bar{f})$, calculated using Eqs. (7)–(9). This step is illustrated as the green oval denoted “Used all templates?” in Fig. 2. For each $(a_0, T_{\text{asc}}, P)_i$ an optimal path and its associated log-likelihood are recorded.

Following the loop over all binary templates, the optimal path with highest log-likelihood, denoted $\max(\mathcal{L})$, is selected in the blue parallelogram marked “ $\max(\mathcal{L})$ and assoc. optimal path” in Fig. 2. If $\max(\mathcal{L})$ is higher than the detection threshold (see Sec. III D), then the subband is recorded as a candidate and passed through a hierarchy of vetoes (see Sec. IV B), via the “yes” output of the upper green oval.

Subbands with $\max(\mathcal{L})$ below the detection threshold are used to calculate GW strain upper limits via the “no” output of the upper green oval. Vetoes subbands are not used to calculate GW upper limits.

D. False alarm probability and detection threshold

A subband is registered as a candidate, when $\max(\mathcal{L})$ exceeds a threshold $\mathcal{L}_{\text{th}}$, corresponding to a user-selected false alarm probability. As the distribution of $\max(\mathcal{L})$ in pure noise is unknown, we rely on Monte Carlo simulations to determine $\mathcal{L}_{\text{th}}$ in each subband of the search. To estimate the distribution of $\max(\mathcal{L})$ in pure noise, we generate synthetic Gaussian data using the `lalapp_Makefakedata_v5` program in the LIGO Scientific Collaboration Algorithm Library [55]. The synthetic data are generated for a subband centered on the frequency $\bar{f}$, with α and δ copied from Table I. Then the search workflow described in Sec. III C is applied. To avoid needless computation, we limit the grid to $N_{a_0} = 322$, $N_{T_{\text{asc}}} = 35$, and $N_P = 5$ in every subband, independent of $\bar{f}$.

In general, $\mathcal{L}_{\text{th}}$ depends on the number of generated log-likelihoods per subband, i.e. $N_{\text{tot}} = N_f N_{a_0} N_{T_{\text{asc}}} N_P$. We describe the false alarm probability $\alpha_{N_{\text{tot}}}$ of a subband with N_{tot} log-likelihoods in terms of the probability of a false alarm in a single terminating frequency bin per orbital template α as

$$\alpha_{N_{\text{tot}}} = 1 - (1 - \alpha)^{N_{\text{tot}}}. \quad (10)$$

The probability density function of the log-likelihood per subband $p(\mathcal{L})$ for the most likely path given an orbital template is observed to follow an exponential tail, $p(\mathcal{L}) = A \exp[-\lambda(\mathcal{L} - \mathcal{L}_{\text{tail}})]$ in noise. The cutoff $\mathcal{L}_{\text{tail}}$ and the λ -parameter are obtained empirically. From our synthetic Gaussian trials we obtain $\lambda = 0.23$ across all subbands. The normalization $A = N_{\text{tail}}/N_{\text{tot}}$, where N_{tail} is the number of log-likelihoods above $\mathcal{L}_{\text{tail}}$, is calculated from the N_{tot} samples used to generate $p(\mathcal{L})$. The probability α in Eq. (10) is given by

$$\alpha = \int_{\mathcal{L}_{\text{th}}}^{\infty} p(\mathcal{L}) d\mathcal{L}. \quad (11)$$

Combining $p(\mathcal{L})$, Eq. (10), and Eq. (11) yields for $\mathcal{L}_{\text{th}}$

$$\mathcal{L}_{\text{th}} = \mathcal{L}_{\text{tail}} - \frac{1}{\lambda} \log\left(\frac{\alpha_{N_{\text{tot}}}}{N_{\text{tail}}}\right), \quad (12)$$

provided Eq. (10) is Taylor expanded to first order, given $N_{\text{tot}} \gg 1$. Note that $\mathcal{L}_{\text{th}}$ is an implicit function of the subband frequency through N_{tail} .

Historically HMM Sco X-1 searches [21,29] use $\alpha_{N_{\text{tot}}} = 0.01$, a choice we adopt here to avoid excessive follow-up of candidates and ease the comparison with previous HMM Sco X-1 searches. A false alarm probability of 1% per subband applied to a total of 725 subbands

implies we should expect ~ 7 false alarms from the search. Searches with electromagnetically constrained $f_{\star}$ such as Refs. [22,24] allow for $\alpha_{N_{\text{tot}}} = 0.3$, given the reduced search space. Appendix A in Ref. [24] presents the detailed procedure to set thresholds using Monte Carlo simulations.

E. O3 data

The search uses all the O3 dataset, starting April 1, 2019, 15:00 UTC and finishing March 27, 2020, 17:00 UTC. The dataset is divided in two. The first part (O3a) spans April 1, 2019 to October 1, 2019 followed by a month-long commissioning break. The second part (O3b) was intended to span November 1, 2019 to April 30, 2020 but was suspended in March 2020 due to the COVID-19 coronavirus pandemic. SFTs are generated from the “C01 calibrated self-gated” dataset, specifically designed to remove loud glitches from the strain data, following the procedure in Ref. [56].

Due to the month-long commissioning break between O3a and O3b, two out of N_T segments have no SFTs. The two segments are dated October 8, 2019, 15:00 UTC and October 15, 2019, 15:00 UTC, respectively. We replace them by segments with uniform log-likelihood across all frequency bins, to allow the HMM to connect data from O3a with data from O3b while accommodating spin wandering. Every time atoms are created, such as in Secs. III D, IV B 2, and IV B, the relevant missing atoms are replaced with uniform log-likelihood atoms.

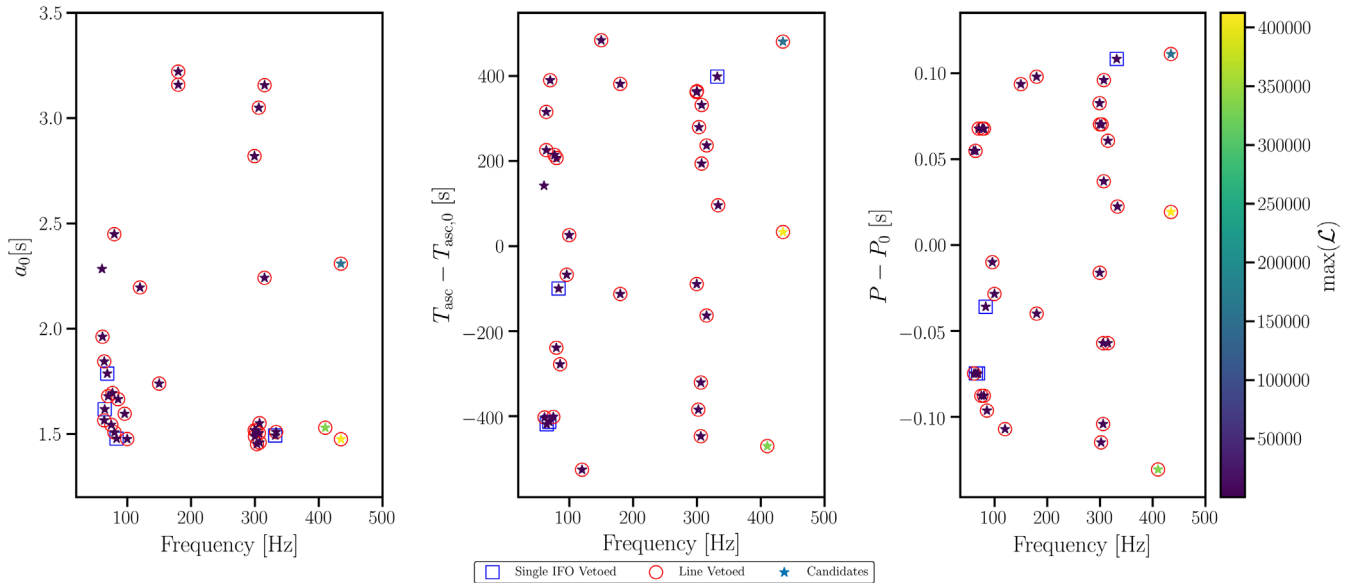


FIG. 3. Candidates plotted as a function of their terminating frequency bin $q^*(t_{N_T})$ (horizontal axis, units in hertz) and the orbital parameters a_0 (vertical axis in left panel, units in seconds), offset from the central time of ascension $T_{\text{asc}} - T_{\text{asc},0}$ (vertical axis in central panel; units in seconds) and offset from the central period $P - P_0$ (vertical axis in right panel; units in seconds). The color scale indicates the $\max(\mathcal{L})$ obtained for the candidate. Candidates marked with purple squares are eliminated by the single IFO veto, while red circles mark the ones eliminated by the known lines veto. The candidate with no marking survives both the single IFO and known lines vetoes, but is eliminated by its absence when using noise-subtracted data (see Sec. IV A).

IV. O3 ANALYSIS

A. Candidates

The results of the search are plotted in Fig. 3. On the horizontal axis we show the terminating frequency bin of the optimal path, i.e. $q^*(t_{N_T})$ per subband, that satisfies $\max(\mathcal{L}) > \mathcal{L}_{\text{th}}$, defining preliminary signal candidates. On the vertical axes we graph the orbital parameters a_0 (left panel), T_{asc} (middle panel), and P (right panel).

Figure 3 contains 35 candidates with $\max(\mathcal{L}) > \mathcal{L}_{\text{th}}$. To eliminate false alarms we use the hierarchy of vetoes employed in Ref. [21]. The vetoes discard candidates that (i) lie near an instrumental noise line (known line veto) or (ii) appear in one interferometer (IFO) but not the other (single IFO veto). In previous searches, other vetoes, e.g. candidates that appear in half of the observation time ($T_{\text{obs}}/2$ veto), have been used in addition to (i) and (ii) [21,22,24,29,42]. Additional vetoes are unnecessary in this paper; all but one of the candidates are vetoed by (i) and (ii), and the survivor is eliminated by other means, as discussed below. The outcomes of the vetoes in the 35 subbands containing outliers are recorded in Table III.

The sole candidate that passes vetoes (i) and (ii), contained in the subband starting at 60.05 Hz, is suspiciously close to the known 60 Hz noise line due to the United States of America power grid [57]. Additionally, several other candidates appear near harmonics of 60.05 Hz, for instance 119.52 and 179.60 Hz. When we search the subband using the C01 calibrated self-gated 60 Hz subtracted dataset, which uses the algorithm described in Ref. [58] to subtract the 60 Hz noise line, the candidate disappears.

B. Vetoes

1. Known lines

Narrow band noise features in the IFO are caused by a plethora of reasons, such as the suspension system or the electricity grid [59,60]. As noise lines artificially increase the output of the $\mathcal{F}$ -statistic, subbands that contain them tend to be flagged as candidates. In response, we veto any candidate whose optimal frequency path $f(t_i)$ satisfies

$$|f(t_i) - f_{\text{line}}| < \frac{2\pi a_0 f_{\text{line}}}{P}, \quad (13)$$

for any epoch t_i in the search. Here f_{line} is the frequency of the noise line. We refer to the vetted known lines list in Ref. [61]. This test vetoes 30 out of the 35 candidates. We note that the number of remaining candidates, after eliminating those caused by noise lines, is consistent with our original number of expected candidates.

TABLE III. Candidates for the O3 search. The first column corresponds to the minimum frequency in the subband that contains the candidate. The second column is the log-likelihood of the candidate. The other columns record the outcome of the two vetoes used in Secs. IV B 1 and IV B 2. A candidate that passes or fails a veto is marked with a ✓ or X, respectively. H and L are the Hanford-only and Livingston-only $\max(\mathcal{L})$ values. The remaining candidate, contained in the 60.05 Hz subband, is eliminated when using the C01 calibrated self-gated 60 Hz subtracted dataset.

Subband (Hz)	$\max(\mathcal{L})/10^3$	Known lines veto	Single IFO veto
60.05	0.45	✓	✓; H:398.58, L:427.97
60.66	0.40	X	...
63.09	1.73	X	...
63.70	1.39	X	...
64.30	0.39	✓	X
67.94	0.37	✓	X
69.76	0.60	X	...
74.62	4.33	X	...
76.44	0.35	X	...
78.87	0.35	X	...
79.47	0.46	X	...
82.51	0.53	✓	X
84.93	0.41	X	...
95.25	0.56	X	...
99.50	1.35	X	...
119.52	0.64	X	...
149.26	0.47	X	...
178.99	0.43	X	...
179.60	0.59	X	...
298.53	1.18	X	...
299.14	2.81	X	...
299.75	0.38	X	...
301.57	3.75	X	...
302.78	4.26	X	...
305.21	2.34	X	...
305.81	4.79	X	...
306.42	0.59	X	...
307.03	5.21	X	...
314.31	3.00	X	...
314.92	1.50	X	...
331.30	6.40	✓	X
332.51	0.45	X	...
409.58	332.67	X	...
433.85	155.83	X	...
434.46	412.41	X	...
Total: 35			

2. Single IFO

A plausible astrophysical signal that has escaped detection in prior searches would likely be weak enough to need data from both IFOs to be detectable, or strong enough to be seen in both, given their comparable sensitivities in most frequency bands. In contrast, instrumental artifacts are unlikely to appear simultaneously in both IFOs. Let $\max(\mathcal{L})_a$ and $\max(\mathcal{L})_b > \max(\mathcal{L})_a$ denote the

log-likelihoods in each IFO, and let $\max(\mathcal{L})_{\cup}$ denote the log-likelihood of the original candidate. There are four possible outcomes:

- (1) If one finds $\max(\mathcal{L})_a < \mathcal{L}_{\text{th}}$ and $\max(\mathcal{L})_b > \max(\mathcal{L})_{\cup}$, and the optimal path $f_b(t_i)$, associated with $\max(\mathcal{L})_b$, satisfies

$$|f_{\cup}(t_i) - f_b(t_i)| < \frac{2\pi a_0 f_{\cup}}{P} \quad (14)$$

for any epoch t_i in the search, where $f_{\cup}(t_i)$ is the optimal path associated with $\max(\mathcal{L})_{\cup}$ then the candidate is consistent with an instrumental artifact in detector b . It is vetoed.

- (2) If one finds $\max(\mathcal{L})_a < \mathcal{L}_{\text{th}}$ and $\max(\mathcal{L})_b > \max(\mathcal{L})_{\cup}$ but the candidate does not satisfy Eq. (14), then it is saved for further postprocessing. Such a candidate could be a faint astrophysical signal which needs both IFOs to be detected.
- (3) If one finds $\max(\mathcal{L})_a > \mathcal{L}_{\text{th}}$ and $\max(\mathcal{L})_b > \mathcal{L}_{\text{th}}$, then the candidate could be a strong astrophysical signal. It could also imply a common noise source in both detectors. The candidate is flagged for postprocessing.
- (4) If one finds $\max(\mathcal{L})_a < \mathcal{L}_{\text{th}}$ and $\max(\mathcal{L})_b < \max(\mathcal{L})_{\cup}$, the candidate could be a weak astrophysical signal that needs both detectors to appear above threshold. This candidate is also saved for postprocessing.

This test vetoes four out of the remaining five candidates, with the last candidate eliminated by its nonappearance in noise-subtracted data, as discussed in Sec. IV A.

V. FREQUENTIST UPPER LIMITS

A. Procedure

Subbands without candidates are used to place upper limits on the gravitational wave strain detectable at a 95% confidence level $h_0^{95\%}$. We use the approach in the historical HMM Sco X-1 searches [21,29] to set frequentist upper limits. This is done to facilitate comparison with previous upper limits.

To capture the variation of the wave strain as a function of the inclination angle ι , we define the effective strain [47]

$$h_0^{\text{eff}} = h_0 2^{-1/2} \{[(1 + \cos^2 \iota)/2]^2 + \cos^2 \iota\}^{1/2}. \quad (15)$$

We note that Eq. (15) allows us to rescale $h_0^{95\%}$ for the circularly polarized case, $|\cos \iota| = 1$, to any other inclination angle ι . For example, if we assume the electromagnetically measured inclination of Sco X-1 orbit as $\iota = 44^\circ$ then Eq. (15) yields $h_0^{\text{eff},95\%} = 1.35 h_0^{95\%}$.

To set frequentist upper limits in a subband with central frequency $\bar{f}$, we start by generating 100 copies of the O3 data for this subband. A Sco X-1-like signal, i.e. using the astrophysical parameters in Table I, is injected into each copy of the subband. The parameters $\{\psi, a_0, T_{\text{asc}}, P\}_{\text{inj}}$ used

to create the injected signal are drawn from uniform distributions within the range given by their respective 3σ error bars. We make sure the injected $T_{\text{asc},\text{inj}}$ and P_{inj} values lie inside the propagated priors shown in Fig. 1, second panel. The injected frequency f_{inj} is uniformly selected from the interval $\bar{f} \pm \delta f$ with $\delta f = 0.05$ Hz. The interval $\bar{f} \pm \delta f$ is chosen for simplicity. The initial value of h_0 is chosen such that there is at least one frequency path with $\max(\mathcal{L}) > \mathcal{L}_{\text{th}}$. We progressively reduce h_0 , holding $\{\psi, a_0, T_{\text{asc}}, P\}_{\text{inj}}$ constant, until the signal is no longer detectable. We record the last detectable amplitude as $h_{0 \text{ min } i}$. The procedure is repeated for all copies of the subband, choosing a new set of injection parameters $\{\psi, a_0, T_{\text{asc}}, P\}_{\text{inj}}$ per copy. Finally $\{h_{0 \text{ min } 1}, \dots, h_{0 \text{ min } 100}\}$ are sorted in ascending order and the 95th becomes $h_0^{95\%}$. The injections have $|\cos \iota| = 1$, so we use Eq. (15) to convert $h_0^{95\%}$ to other polarizations.

B. Upper limits

The limits on $h_0^{95\%}$ are plotted in Fig. 4. We present three cases, as in Ref. [21]: circular polarization $\iota = 0$ (blue dots in Fig. 4), $\iota = 44^\circ$ (following the electromagnetic measurements in Ref. [51]; denoted by green dots in Fig. 4), and unknown polarization (orange dots in Fig. 4). In the latter context, unknown polarization means we marginalize over all possible polarizations assuming a uniform distribution in $\cos \iota$ from -1 to 1 .

The upper limits from the O3 search are on average ~ 3 times lower than those from the O2 HMM search [21]. For the subband starting at 256.06 Hz we obtain the lowest $h_0^{95\%}$, given by 4.56×10^{-26} , 6.16×10^{-26} , and 9.41×10^{-26} for circular, electromagnetically restricted ($\iota = 44^\circ$), and unknown polarizations, respectively. Compared to the most sensitive subbands in previous HMM Sco X-1 searches, the lowest $h_0^{95\%}$ is a factor of ~ 13 lower than in O1 data [29] and ~ 3 lower than in O2 data [21].

It is tempting to compare the results presented in this section with the results of searches with other pipelines, such as CrossCorr O1 [28] and O2 [23]. Such comparisons can be broadly indicative, if done informally. However, the $h_0^{95\%}$ values output by different pipelines cannot be compared directly, when the pipelines assume different phase models, as foreshadowed in Sec. I. The phase evolution assumed by CrossCorr is given by Eq. (4.15) in Ref. [20], viz. $\Phi_K = \Phi_0 + 2\pi f_0 \{t_K - d_K - a_0 \sin[2\pi(t_K - t_{\text{asc}})/P]\}$, where K indexes jointly the detector and the selected time interval, with t_K the midpoint of the latter, and d_K is the projected distance from the solar system barycenter to the detector. In previously published CrossCorr implementations [20,23,28,32], it is assumed that f_0 stays constant throughout the total observation time T_{obs} . Section VA of Ref. [20] explores how the foregoing phase evolution can be generalized in future CrossCorr implementations. On the other hand, the HMM executes an unbiased random walk in $f(t)$, which is piecewise constant in the coherent blocks

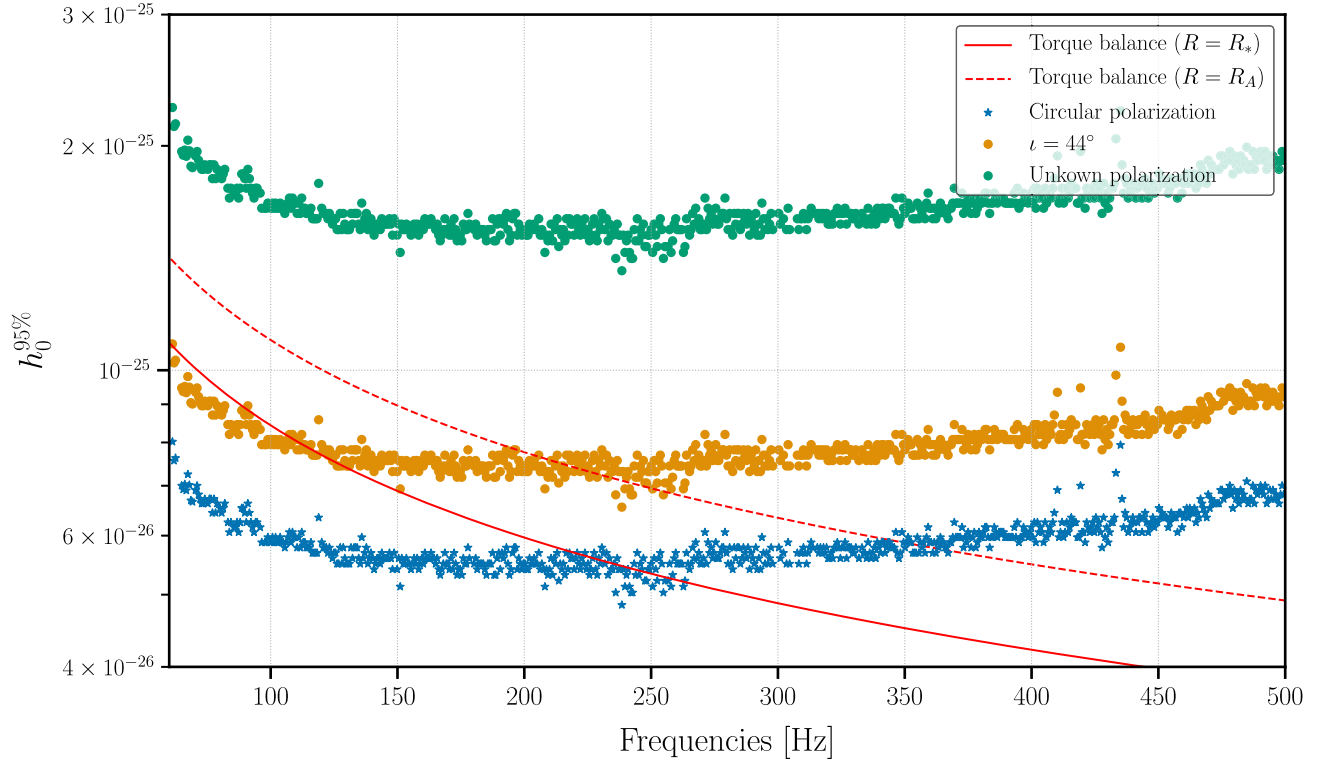


FIG. 4. Frequentist effective wave strain upper limits at 95% confidence as a function of subband frequency, for three scenarios: circular polarization with $\iota = 0$ (blue stars), $\iota \approx 44^\circ$ based on the electromagnetic measurements (see Ref. [51]; orange dots), and a flat prior on $\cos \iota$ (green dots). Indirect torque-balance upper limits (see Sec. V C) for two torque lever arms are also shown: the stellar radius (red solid line) and the Alfvén radius (dashed red line).

$t_n \leq t \leq t_n + T_{\text{drift}}$, as presented in Sec. II A. The different phase evolution for CrossCorr and the HMM translates into upper limits that are specific to the two different sets of phase paths.

C. Torque-balance upper limit

Torque balance assumes the spin-down torque due to gravitational wave emission balances the accretion spin-up torque. From this assumption theoretical upper limits on gravitational wave strain can be estimated from x-ray observations. Following Eq. (4) in Ref. [23], the amplitude of the GW signal produced in torque equilibrium h_0^{eq} is

$$h_0^{\text{eq}} = 3.4 \times 10^{-26} \left(\frac{R}{10 \text{ km}} \right)^{1/2} \left(\frac{1.4 M_\odot}{M} \right)^{1/4} \left(\frac{r_m}{10 \text{ km}} \right)^{1/4} \times \left(\frac{F_X}{3.9 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left(\frac{600 \text{ Hz}}{f_{\text{GW}}} \right)^{1/2}. \quad (16)$$

In Eq. (16), F_X is the x-ray flux, M is the fiducial neutron star mass, r_m is the lever arm, R is the neutron star radius, and f_{GW} is the GW frequency. Equation (16) assumes the maximum accretion luminosity is completely radiated as x rays, i.e. $X = 1$ in Eq. (4) of Ref. [23]. To calculate Eq. (16), we use $r_m = R = 10 \text{ km}$, plotted as a solid red line in Fig. 4, or $r_m = R_A$, where R_A is the Alfvén radius,

which corresponds approximately to the inner edge of the accretion disk [29,36]. This is given by

$$R_A = 35 \left(\frac{B_\star}{10^9 \text{ G}} \right)^{1/4} \left(\frac{R}{10 \text{ km}} \right)^{12/7} \times \left(\frac{1.4 M_\odot}{M} \right)^{1/7} \left(\frac{10^{-8} M_\odot \text{ yr}^{-1}}{\dot{M}} \right)^{2/7} \text{ km}, \quad (17)$$

where $B_\star$ is the polar magnetic field strength at the stellar surface, G is Newton’s gravitational constant, and $\dot{M}$ is the accretion rate set to the Eddington limit $2 \times 10^{-8} M_\odot \text{ yr}^{-1}$, for a fiducial neutron star with mass $M = 1.4 M_\odot$ and radius $R = 10 \text{ km}$ [62,63]. This limit is plotted in Fig. 4 as the dashed red line.

The electromagnetic inclination $\iota = 44^\circ$ produces upper limits that dip under the theoretical torque-balance limits (red lines in Fig. 4) for the first time in the HMM Sco X-1 search history. The CrossCorr search pipeline achieved this milestone in the O2 search; see Fig. 1 in Ref. [23]. Again, the reader is reminded that different pipelines assume different signal models, and upper limits conditional on different signal models cannot be compared directly.

VI. CONCLUSIONS

In this paper we search the LIGO O3 data for continuous GWs from the LMXB Sco X-1, using a hidden Markov model, combined with the maximum-likelihood $\mathcal{J}$ -statistic and a binary template grid that includes the projected semimajor axis a_0 , time of ascension T_{asc} , and orbital period P . The binary orbital elements are constrained via electromagnetic observations, but the spin frequency is unknown. Monte Carlo simulations are used to establish a detection threshold $\mathcal{L}_{\text{th}}$, with a false alarm probability $\alpha_{N_{\text{tot}}} = 0.01$, per subband. The search is conducted in the range 60–500 Hz, partitioned into subbands of width $\Delta f_{\text{sub}} = 0.606$ Hz. The subbands with an optimal path satisfying $\max(\mathcal{L}) > \mathcal{L}_{\text{th}}$ are passed through a hierarchy of vetoes. One candidate survives the vetoes, but this candidate is eliminated when using the C01 calibrated self-gated 60 Hz subtracted dataset.

The most sensitive subband, starting at 256.06 Hz, yields $h_0^{95\%} = 4.56 \times 10^{-26}$, 6.16×10^{-26} , and 9.41×10^{-26} for circular, electromagnetically restricted ($\iota = 44^\circ$), and unknown polarizations, respectively.

The above results improve on the two previous HMM Sco X-1 searches [21,29] by using data from O3 and including the orbital period P in the searched template grid. For comparison, the most sensitive subband in the O2 HMM search, 194.6 Hz, obtained $h_0^{95\%} = 1.42 \times 10^{-25}$ for $\iota = 0$ [21], while for the same subband and polarization the present search obtains $h_0^{95\%} = 5.40 \times 10^{-26}$. On average our upper limits are a factor of ~ 3 below the O2 HMM results. The present search sets the lowest upper limits for the HMM searches, beating for first time the torque-balance limit for the electromagnetically restricted $\iota = 44^\circ$ case.

Other LMXBs are not as bright in x rays as Sco X-1, but they are important targets too. Some LMXBs emit x-ray pulsations, so that $f_\star$ is measured to high precision electromagnetically, an important advantage. However, the gravitational wave frequency emitted by such objects may be displaced from $f_\star$ and wander randomly with respect to it. A HMM-based search is well placed to track such wandering. Searches for LMXBs with electromagnetically constrained rotation frequencies have been performed in O2 [22] and O3 [24] data. Reference [24] reported strain upper limits in the range $5.1 \times 10^{-26} \leq h_0^{95\%} \leq 1.1 \times 10^{-25}$ for its 20 candidates. Such searches offer considerable promise in future observing runs.

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Di Girolamo,^{25,4} A. Di Lieto,^{78,18} A. Di Michele,⁷⁹ B. Ding,¹⁴⁵ S. Di Pace,^{104,57} I. Di Palma,^{104,57} F. Di Renzo,^{78,18} A. K. Divakarla,⁷⁶ A. Dmitriev,¹⁴ Z. Doctor,¹⁵ L. Donahue,¹⁶¹ L. D'Onofrio,^{25,4} F. Donovan,⁷⁴ K. L. Dooley,¹⁷ S. Doravari,¹¹ M. Drago,^{104,57} J. C. Driggers,⁷² Y. Drori,¹ J.-G. Ducoin,⁴⁶ P. Dupej,²⁴ U. Dupletsa,³² O. Durante,^{102,103} D. D'Urso,^{121,122} P.-A. Duverne,⁴⁶ S. E. Dwyer,⁷² C. Eassa,⁷² P. J. Easter,⁵ M. Ebersold,¹⁶² T. Eckhardt,¹²⁷ G. Eddolls,²⁴ B. Edelman,⁶⁶ T. B. Edo,¹ O. Edy,⁵¹ A. Effler,⁵⁶ S. Eguchi,¹³¹ J. Eichholz,⁸ S. S. Eikenberry,⁷⁶ M. Eisenmann,^{30,20} R. A. Eisenstein,⁷⁴ A. Ejlli,¹⁷ E. Engelby,⁴⁴ Y. Enomoto,²⁷ L. Errico,^{25,4} R. C. Essick,¹⁶³ H. Estellés,¹⁴⁴ D. Estevez,¹⁶⁴ Z. Etienne,¹⁶⁵ T. Etzel,¹ M. Evans,⁷⁴ T. M. Evans,⁵⁶ T. Evstafyeva,¹² B. E. Ewing,¹⁴⁹ F. Fabrizi,^{54,55} F. Faedi,⁵⁵ V. Fafone,^{123,124,32} H. Fair,⁶⁷ S. Fairhurst,¹⁷ P. C. Fan,¹⁶¹ A. M. Farah,¹⁶⁶ S. Farinon,⁹² B. Farr,⁶⁶ W. M. Farr,^{115,116} E. J. Fauchon-Jones,¹⁷ G. Favaro,⁸⁰ M. Favata,¹⁶⁷ M. Fays,⁶⁸ M. Fazio,¹⁶⁸ J. Feicht,¹ M. M. Fejer,⁷⁷ E. Fenyvesi,^{75,169} D. L. Ferguson,¹⁷⁰ A. Fernandez-Galiana,⁷⁴ I. Ferrante,^{78,18} T. A. Ferreira,¹⁶ F. Fidecaro,^{78,18} P. Figura,¹⁰⁹ A. Fiori,^{18,78} I. Fiori,⁴⁷ M. Fishbach,¹⁵ R. P. Fisher,⁶³ R. Fittipaldi,^{171,103} V. Fiumara,^{172,103} R. Flaminio,^{30,20} E. Floden,¹⁴⁸ H. K. Fong,²⁸ J. A. Font,^{126,173} B. Fornal,¹⁶⁰ P. W. F. Forsyth,⁸ A. Franke,¹²⁷ S. Frasca,^{104,57} F. Frasconi,¹⁸ J. P. Freed,³⁶ Z. Frei,¹⁵³ A. Freise,^{59,96} O. Freitas,¹⁷⁴ R. Frey,⁶⁶ P. Fritschel,⁷⁴ V. V. Frolov,⁵⁶ G. G. Fronzè,²³ Y. Fujii,¹⁷⁵ Y. Fujikawa,¹⁷⁶ Y. Fujimoto,¹⁷⁷ P. Fulda,⁷⁶ M. Fyffe,⁵⁶ H. A. Gabbard,²⁴ B. U. Gadre,¹¹¹ J. R. Gair,¹¹¹ J. Gais,¹³⁰ S. Galaudage,⁵ R. Gamba,¹³ D. Ganapathy,⁷⁴ A. Ganguly,¹¹ D. Gao,¹⁷⁸ S. G. Gaonkar,¹¹ B. Garaventa,^{92,118} C. García Núñez,¹⁰⁰ C. García-Quirós,¹⁴⁴ F. Garufi,^{25,4} B. Gateley,⁷² V. Gayathri,⁷⁶ G.-G. Ge,¹⁷⁸ G. Gemme,⁹² A. Gennai,¹⁸ J. George,⁹⁴ O. Gerberding,¹²⁷ L. Gergely,¹⁷⁹ P. Gewecke,¹²⁷ S. Ghonge,⁴⁸ Abhirup Ghosh,¹¹¹ Archisman Ghosh,⁸⁵ Shaon Ghosh,¹⁶⁷ Shrobona Ghosh,¹⁷ Tathagata Ghosh,¹¹ B. Giacomazzo,^{69,70,71} L. Giaccoppo,^{104,57} J. A. Giaime,^{7,56} K. D. Giardina,⁵⁶ D. R. Gibson,¹⁰⁰ C. Gier,³³ M. Giesler,¹⁸⁰ P. Giri,^{18,78} F. Gissi,⁸⁷ S. Gkaitatzis,^{18,78} J. Glanzer,⁷ A. E. Gleckl,⁴⁴ P. Godwin,¹⁴⁹ E. Goetz,¹⁸¹ R. Goetz,⁷⁶ N. Gohlke,^{9,10} J. Golomb,¹ B. Goncharov,³² G. González,⁷ M. Gosselin,⁴⁷ R. Gouaty,³⁰ D. W. Gould,⁸ S. Goyal,¹⁹ B. Grace,⁸ A. Grado,^{182,4} V. Graham,²⁴ M. Granata,¹⁵⁷ V. Granata,¹⁰² A. Grant,²⁴ S. Gras,⁷⁴ P. Grassia,¹ C. Gray,⁷² R. Gray,²⁴ G. Greco,⁴⁰ A. C. Green,⁷⁶ R. Green,¹⁷ A. M. Gretarsson,³⁶ E. M. Gretarsson,³⁶ D. Griffith,¹ W. L. Griffiths,¹⁷ H. L. Griggs,⁴⁸ G. Grignani,^{79,40} A. Grimaldi,^{98,99} E. Grimes,³⁶ S. J. Grimm,^{32,107} H. Grote,¹⁷ S. Grunewald,¹¹¹ P. Gruning,⁴⁶ A. S. Gruson,⁴⁴ D. Guerra,¹²⁶ G. M. Guidi,^{54,55} A. R. Guimaraes,⁷ G. Guixé,²⁹ H. K. Gulati,⁸⁴ A. M. Gunny,⁷⁴ H.-K. Guo,¹⁶⁰ Y. Guo,⁵⁹ Anchal Gupta,¹ Anuradha Gupta,¹⁸³ I. M. Gupta,¹⁴⁹ P. Gupta,^{59,65} S. K. Gupta,¹⁰⁶ R. Gustafson,¹⁸⁴ F. Guzman,¹⁸⁵ S. Ha,¹⁸⁶ I. P. W. Hadiputrawan,¹³⁵ L. Haegel,⁴⁵ S. Haino,¹³⁹ O. Halim,³⁵ E. D. Hall,⁷⁴ E. Z. Hamilton,¹⁶² G. Hammond,²⁴ W.-B. Han,¹⁸⁷ M. Haney,¹⁶² J. Hanks,⁷² C. Hanna,¹⁴⁹ M. D. Hannam,¹⁷ O. Hannuksela,^{65,59} H. Hansen,⁷² T. J. Hansen,³⁶ J. Hanson,⁵⁶ T. Harder,³⁷ K. Haris,^{59,65} J. Harms,^{32,107} G. M. Harry,⁴² I. W. Harry,⁵¹ D. Hartwig,¹²⁷ K. Hasegawa,¹⁸⁸ B. Haskell,⁸⁶ C.-J. Haster,⁷⁴ J. S. Hathaway,¹²⁸ K. Hattori,¹⁸⁹ K. Haughian,²⁴ H. Hayakawa,¹⁹⁰ K. Hayama,¹³¹ F. J. Hayes,²⁴ J. Healy,¹²⁸ A. Heidmann,¹⁰⁸ A. Heidt,^{9,10} M. C. Heintze,⁵⁶ J. Heinze,^{9,10} J. Heinzl,⁷⁴ H. Heitmann,³⁷ F. Hellman,¹⁹¹ P. Hello,⁴⁶ A. F. Helmling-Cornell,⁶⁶ G. Hemming,⁴⁷ M. Hendry,²⁴ I. S. Heng,²⁴ E. Hennes,⁵⁹ J. Hennig,¹⁹² M. H. Hennig,¹⁹² C. Henshaw,⁴⁸ A. G. Hernandez,⁹⁰ F. Hernandez Vivanco,⁵ M. Heurs,^{9,10} A. L. Hewitt,¹⁹³ S. Higginbotham,¹⁷ S. Hild,^{154,59} P. Hill,³³ Y. Himemoto,¹⁹⁴ A. S. Hines,¹⁸⁵ N. Hirata,²⁰ C. Hirose,¹⁷⁶ T.-C. Ho,¹³⁵ S. Hochheim,^{9,10} D. Hofman,¹⁵⁷

- J. N. Hohmann,¹²⁷ D. G. Holcomb,¹¹³ N. A. Holland,⁸ I. J. Hollows,¹⁵⁶ Z. J. Holmes,⁸⁸ K. Holt,⁵⁶ D. E. Holz,¹⁶⁶ Q. Hong,¹²⁹ J. Hough,²⁴ S. Hourihane,¹ E. J. Howell,⁹³ C. G. Hoy,¹⁷ D. Hoyland,¹⁴ A. Hreibi,^{9,10} B.-H. Hsieh,¹⁸⁸ H.-F. Hsieh,¹⁹⁵ C. Hsiung,¹³³ Y. Hsu,¹²⁹ H.-Y. Huang,¹³⁹ P. Huang,¹⁷⁸ Y.-C. Huang,¹³⁷ Y.-J. Huang,¹³⁹ Yiting Huang,¹⁵¹ Yiwen Huang,⁷⁴ M. T. Hübner,⁵ A. D. Huddart,¹⁹⁶ B. Hughey,³⁶ D. C. Y. Hui,¹⁹⁷ V. Hui,³⁰ S. Husa,¹⁴⁴ S. H. Huttner,²⁴ R. Huxford,¹⁴⁹ T. Huynh-Dinh,⁵⁶ S. Ide,¹⁹⁸ B. Idzkowski,¹⁰⁹ A. Iess,^{123,124} K. Inayoshi,¹⁹⁹ Y. Inoue,¹³⁵ P. Iosif,²⁰⁰ M. Isi,⁷⁴ K. Isleif,¹²⁷ K. Ito,²⁰¹ Y. Itoh,^{177,202} B. R. Iyer,¹⁹ V. JaberianHamedan,⁹³ T. Jacqmin,¹⁰⁸ P.-E. Jacquet,¹⁰⁸ S. J. Jadhav,²⁰³ S. P. Jadhav,¹¹ T. Jain,¹² A. L. James,¹⁷ A. Z. Jan,¹⁷⁰ K. Jani,²⁰⁴ J. Janquart,^{65,59} K. Janssens,^{205,37} N. N. Janthapur,²⁰³ P. Jaranowski,²⁰⁶ D. Jariwala,⁷⁶ R. Jaume,¹⁴⁴ A. C. Jenkins,⁶⁰ K. Jenner,⁸⁸ C. Jeon,²⁰⁷ W. Jia,⁷⁴ J. Jiang,⁷⁶ H.-B. Jin,^{208,209} G. R. Johns,⁶³ R. Johnston,²⁴ A. W. Jones,⁹³ D. I. Jones,²¹⁰ P. Jones,¹⁴ R. Jones,²⁴ P. Joshi,¹⁴⁹ L. Ju,⁹³ A. Jue,¹⁶⁰ P. Jung,⁶² K. Jung,¹⁸⁶ J. Junker,^{9,10} V. Juste,¹⁶⁴ K. Kaihotsu,²⁰¹ T. Kajita,²¹¹ M. Kakizaki,¹⁸⁹ C. V. Kalaghatgi,^{17,65,59,212} V. Kalogera,¹⁵ B. Kamai,¹ M. Kamiizumi,¹⁹⁰ N. Kanda,^{177,202} S. Kandhasamy,¹¹ G. Kang,²¹³ J. B. Kanner,¹ Y. Kao,¹²⁹ S. J. Kapadia,¹⁹ D. P. Kapasi,⁸ C. Karathanasis,³¹ S. Karki,⁹⁵ R. Kashyap,¹⁴⁹ M. Kasprzak,¹ W. Kastaun,^{9,10} T. Kato,¹⁸⁸ S. Katsanevas,⁴⁷ E. Katsavounidis,⁷⁴ W. Katzman,⁵⁶ T. Kaur,⁹³ K. Kawabe,⁷² K. Kawaguchi,¹⁸⁸ F. Kéfélian,³⁷ D. Keitel,¹⁴⁴ J. S. Key,²¹⁴ S. Khadka,⁷⁷ F. Y. Khalili,⁹⁷ S. Khan,¹⁷ T. Khanam,¹⁴⁷ E. A. Khazanov,²¹⁵ N. Khetan,^{32,107} M. Khursheed,⁹⁴ N. Kijbunchoo,⁸ A. Kim,¹⁵ C. Kim,²⁰⁷ J. C. Kim,²¹⁶ J. Kim,²¹⁷ K. Kim,²⁰⁷ W. S. Kim,⁶² Y.-M. Kim,¹⁸⁶ C. Kimball,¹⁵ N. Kimura,¹⁹⁰ M. Kinley-Hanlon,²⁴ R. Kirchhoff,^{9,10} J. S. Kissel,⁷² S. Klimenko,⁷⁶ T. Klinger,¹² A. M. Knee,¹⁸¹ T. D. Knowles,¹⁶⁵ N. Knust,^{9,10} E. Knyazev,⁷⁴ Y. Kobayashi,¹⁷⁷ P. Koch,^{9,10} G. Koekoek,^{59,154} K. Kohri,²¹⁸ K. Kokeyama,²¹⁹ S. Koley,³² P. Kolitsidou,¹⁷ M. Kolstein,³¹ K. Komori,⁷⁴ V. Kondrashov,¹ A. K. H. Kong,¹⁹⁵ A. Kontos,⁸² N. Koper,^{9,10} M. Korobko,¹²⁷ M. Kovalam,⁹³ N. Koyama,¹⁷⁶ D. B. Kozak,¹ C. Kozakai,⁵² V. Kringel,^{9,10} N. V. Krishnendu,^{9,10} A. Królak,^{220,221} G. Kuehn,^{9,10} F. Kuei,¹²⁹ P. Kuijper,⁵⁹ S. Kulkarni,¹⁸³ A. Kumar,²⁰³ Prayush Kumar,¹⁹ Rahul Kumar,⁷² Rakesh Kumar,⁸⁴ J. Kume,²⁸ K. Kuns,⁷⁴ Y. Kuromiya,²⁰¹ S. Kuroyanagi,^{222,223} K. Kwak,¹⁸⁶ G. Lacaille,²⁴ P. Lagabbe,³⁰ D. Laghi,¹¹² E. Lalande,²²⁴ M. Lalleman,²⁰⁵ T. L. Lam,¹³⁰ A. Lamberts,^{37,225} M. Landry,⁷² B. B. Lane,⁷⁴ R. N. Lang,⁷⁴ J. Lange,¹⁷⁰ B. Lantz,⁷⁷ I. La Rosa,³⁰ A. Lartaux-Vollard,⁴⁶ P. D. Lasky,⁵ M. Laxen,⁵⁶ A. Lazzarini,¹ C. Lazzaro,^{80,81} P. Leaci,^{104,57} S. Leavey,^{9,10} S. LeBohec,¹⁶⁰ Y. K. Lecoeuche,¹⁸¹ E. Lee,¹⁸⁸ H. M. Lee,²²⁶ H. W. Lee,²¹⁶ K. Lee,²²⁷ R. Lee,¹³⁷ I. N. Legred,¹ J. Lehmann,^{9,10} A. Lemaître,²²⁸ M. Lenti,^{55,229} M. Leonardi,²⁰ E. Leonova,³⁸ N. Leroy,⁴⁶ N. Letendre,³⁰ C. Levesque,²²⁴ Y. Levin,⁵ J. N. Leviton,¹⁸⁴ K. Leyde,⁴⁵ A. K. Y. Li,¹ B. Li,¹²⁹ J. Li,¹⁵ K. L. Li,²³⁰ P. Li,²³¹ T. G. F. Li,¹³⁰ X. Li,¹³⁶ C.-Y. Lin,²³² E. T. Lin,¹⁹⁵ F.-K. Lin,¹³⁹ F.-L. Lin,²³³ H. L. Lin,¹³⁵ L. C.-C. Lin,²³⁰ F. Linde,^{212,59} S. D. Linker,^{125,90} J. N. Linley,²⁴ T. B. Littenberg,²³⁴ G. C. Liu,¹³³ J. Liu,⁹³ K. Liu,¹²⁹ X. Liu,⁶ F. Llamas,⁸⁹ R. K. L. Lo,¹ T. Lo,¹²⁹ L. T. London,^{38,74} A. Longo,²³⁵ D. Lopez,¹⁶² M. Lopez Portilla,⁶⁵ M. Lorenzini,^{123,124} V. Lorette,²³⁶ M. Lormand,⁵⁶ G. Losurdo,¹⁸ T. P. Lott,⁴⁸ J. D. Lough,^{9,10} C. O. Lousto,¹²⁸ G. Lovelace,⁴⁴ J. F. Lucaccioni,²³⁷ H. Lück,^{9,10} D. Lumaca,^{123,124} A. P. Lundgren,⁵¹ L.-W. Luo,¹³⁹ J. E. Lynam,⁶³ M. Ma'arif,¹³⁵ R. Macas,⁵¹ J. B. Machtinger,¹⁵ M. MacInnis,⁷⁴ D. M. Macleod,¹⁷ I. A. O. MacMillan,¹ A. Macquet,³⁷ I. Magaña Hernandez,⁶ C. Magazzù,¹⁸ R. M. Magee,¹ R. Maggiore,¹⁴ M. Magnozzi,^{92,118} S. Mahesh,¹⁶⁵ E. Majorana,^{104,57} I. Maksimovic,²³⁶ S. Maliakal,¹ A. Malik,⁹⁴ N. Man,³⁷ V. Mandic,¹⁴⁸ V. Mangano,^{104,57} G. L. Mansell,^{72,74} M. Manske,⁶ M. Mantovani,⁴⁷ M. Mapelli,^{80,81} F. Marchesoni,^{41,40,238} D. Marín Pina,²⁹ F. Marion,³⁰ Z. Mark,¹³⁶ S. Márka,⁵⁰ Z. Márka,⁵⁰ C. Markakis,¹² A. S. Markosyan,⁷⁷ A. Markowitz,¹ E. Maros,¹ A. Marquina,¹⁴⁶ S. Marsat,⁴⁵ F. Martelli,^{54,55} I. W. Martin,²⁴ R. M. Martin,¹⁶⁷ M. Martinez,³¹ V. A. Martinez,⁷⁶ V. Martinez,²⁶ K. Martinovic,⁶⁰ D. V. Martynov,¹⁴ E. J. Marx,⁷⁴ H. Masalehdan,¹²⁷ K. Mason,⁷⁴ E. Massera,¹⁵⁶ A. Masserot,³⁰ M. Masso-Reid,²⁴ S. Mastrogiorganni,⁴⁵ A. Matas,¹¹¹ M. Mateu-Lucena,¹⁴⁴ F. Matichard,^{1,74} M. Matushechkin,^{9,10} N. Mavalvala,⁷⁴ J. J. McCann,⁹³ R. McCarthy,⁷² D. E. McClelland,⁸ P. K. McClincy,¹⁴⁹ S. McCormick,⁵⁶ L. McCuller,⁷⁴ G. I. McGhee,²⁴ S. C. McGuire,⁵⁶ C. McIsaac,⁵¹ J. McIver,¹⁸¹ T. McRae,⁸ S. T. McWilliams,¹⁶⁵ D. Meacher,⁶ M. Mehmet,^{9,10} A. K. Mehta,¹¹¹ Q. Meijer,⁶⁵ A. Melatos,¹²⁰ D. A. Melchor,⁴⁴ G. Mendell,⁷² A. Menendez-Vazquez,³¹ C. S. Menoni,¹⁶⁸ R. A. Mercer,⁶ L. Mereni,¹⁵⁷ K. Merfeld,⁶⁶ E. L. Merill,⁵⁶ J. D. Merritt,⁶⁶ M. Merzougui,³⁷ S. Meshkov,^{1,a} C. Messenger,²⁴ C. Messick,⁷⁴ P. M. Meyers,¹²⁰ F. Meylahn,^{9,10} A. Mhaske,¹¹ A. Miani,^{98,99} H. Miao,¹⁴ I. Michaloliakos,⁷⁶ C. Michel,¹⁵⁷ Y. Michimura,²⁷ H. Middleton,¹²⁰ D. P. Mihaylov,¹¹¹ L. Milano,^{25,b} A. L. Miller,⁵⁸ A. Miller,⁹⁰ B. Miller,^{38,59} M. Millhouse,¹²⁰ J. C. Mills,¹⁷ E. Milotti,^{239,35} Y. Minenkov,¹²⁴ N. Mio,²⁴⁰ L. M. Mir,³¹ M. Miravet-Tenés,¹²⁶ A. Mishkin,⁷⁶ C. Mishra,²⁴¹ T. Mishra,⁷⁶ T. Mistry,¹⁵⁶ S. Mitra,¹¹ V. P. Mitrofanov,⁹⁷ G. Mitselmakher,⁷⁶ R. Mittleman,⁷⁴ O. Miyakawa,¹⁹⁰ K. Miyo,¹⁹⁰ S. Miyoki,¹⁹⁰ Geoffrey Mo,⁷⁴ L. M. Modafferi,¹⁴⁴ E. Moguel,²³⁷ K. Mogushi,⁹⁵ S. R. P. Mohapatra,⁷⁴ S. R. Mohite,⁶ I. Molina,⁴⁴ M. Molina-Ruiz,¹⁹¹ M. Mondin,⁹⁰ M. Montani,^{54,55} C. J. Moore,¹⁴ J. Moragues,¹⁴⁴ D. Moraru,⁷² F. Morawski,⁸⁶ A. More,¹¹ C. Moreno,³⁶ G. Moreno,⁷² Y. Mori,²⁰¹ S. Morisaki,⁶ N. Morisue,¹⁷⁷ Y. Moriwaki,¹⁸⁹

- B. Mours,¹⁶⁴ C. M. Mow-Lowry,^{59,96} S. Mozzon,⁵¹ F. Muciaccia,^{104,57} Arunava Mukherjee,²⁴² D. Mukherjee,¹⁴⁹ Soma Mukherjee,⁸⁹ Subroto Mukherjee,⁸⁴ Suvodip Mukherjee,^{163,38} N. Mukund,^{9,10} A. Mullavey,⁵⁶ J. Munch,⁸⁸ E. A. Muñiz,⁶⁷ P. G. Murray,²⁴ R. Musenich,^{92,118} S. Muusse,⁸⁸ S. L. Nadji,^{9,10} K. Nagano,²⁴³ A. Nagar,^{23,244} K. Nakamura,²⁰ H. Nakano,²⁴⁵ M. Nakano,¹⁸⁸ Y. Nakayama,²⁰¹ V. Napolano,⁴⁷ I. Nardecchia,^{123,124} T. Narikawa,¹⁸⁸ H. Narola,⁶⁵ L. Naticchioni,⁵⁷ B. Nayak,⁹⁰ R. K. Nayak,²⁴⁶ B. F. Neil,⁹³ J. Neilson,^{87,103} A. Nelson,¹⁸⁵ T. J. N. Nelson,⁵⁶ M. Nery,^{9,10} P. Neubauer,²³⁷ A. Neunzert,²¹⁴ K. Y. Ng,⁷⁴ S. W. S. Ng,⁸⁸ C. Nguyen,⁴⁵ P. Nguyen,⁶⁶ T. Nguyen,⁷⁴ L. Nguyen Quynh,²⁴⁷ J. Ni,¹⁴⁸ W.-T. Ni,^{208,178,137} S. A. Nichols,⁷ T. Nishimoto,¹⁸⁸ A. Nishizawa,²⁸ S. Nissanke,^{38,59} E. Nitoglia,¹⁴⁰ F. Nocera,⁴⁷ M. Norman,¹⁷ C. North,¹⁷ S. Nozaki,¹⁸⁹ G. Nurbek,⁸⁹ L. K. Nuttall,⁵¹ Y. Obayashi,¹⁸⁸ J. Oberling,⁷² B. D. O'Brien,⁷⁶ J. O'Dell,¹⁹⁶ E. Oelker,²⁴ W. Ogaki,¹⁸⁸ G. Oganesyan,^{32,107} J. J. Oh,⁶² K. Oh,¹⁹⁷ S. H. Oh,⁶² M. Ohashi,¹⁹⁰ T. Ohashi,¹⁷⁷ M. Ohkawa,¹⁷⁶ F. Ohme,^{9,10} H. Ohta,²⁸ M. A. Okada,¹⁶ Y. Okutani,¹⁹⁸ C. Olivetto,⁴⁷ K. Oohara,^{188,248} R. Oram,⁵⁶ B. O'Reilly,⁵⁶ R. G. Ormiston,¹⁴⁸ N. D. Ormsby,⁶³ R. O'Shaughnessy,¹²⁸ E. O'Shea,¹⁸⁰ S. Oshino,¹⁹⁰ S. Ossokine,¹¹¹ C. Osthelder,¹ S. Otake,² D. J. Ottaway,⁸⁸ H. Overmier,⁵⁶ A. E. Pace,¹⁴⁹ G. Pagano,^{78,18} R. Pagano,⁷ M. A. Page,⁹³ G. Pagliaroli,^{32,107} A. Pai,¹⁰⁶ S. A. Pai,⁹⁴ S. Pal,²⁴⁶ J. R. Palamos,⁶⁶ O. Palashov,²¹⁵ C. Palomba,⁵⁷ H. Pan,¹²⁹ K.-C. Pan,^{137,195} P. K. Panda,²⁰³ P. T. H. Pang,^{59,65} C. Pankow,¹⁵ F. Pannarale,^{104,57} B. C. Pant,⁹⁴ F. H. Panther,⁹³ F. Paoletti,¹⁸ A. Paoli,⁴⁷ A. Paolone,^{57,249} G. Pappas,²⁰⁰ A. Parisi,¹³³ H. Park,⁶ J. Park,²⁵⁰ W. Parker,⁵⁶ D. Pascucci,^{59,85} A. Pasqualetti,⁴⁷ R. Passaquieti,^{78,18} D. Passuello,¹⁸ M. Patel,⁶³ M. Pathak,⁸⁸ B. Patricelli,^{47,18} A. S. Patron,⁷ S. Paul,⁶⁶ E. Payne,⁵ M. Pedraza,¹ R. Pedurand,¹⁰³ M. Pegoraro,⁸¹ A. Pele,⁵⁶ F. E. Peña Arellano,¹⁹⁰ S. Penano,⁷⁷ S. Penn,²⁵¹ A. Perego,^{98,99} A. Pereira,²⁶ T. Pereira,²⁵² C. J. Perez,⁷² C. Périgois,³⁰ C. C. Perkins,⁷⁶ A. Perreca,^{98,99} S. Perriès,¹⁴⁰ D. Pesios,²⁰⁰ J. Petermann,¹²⁷ D. Petterson,¹ H. P. Pfeiffer,¹¹¹ H. Pham,⁵⁶ K. A. Pham,¹⁴⁸ K. S. Phukon,^{59,212} H. Phurailatpam,¹³⁰ O. J. Piccinni,⁵⁷ M. Pichot,³⁷ M. Piendibene,^{78,18} F. Piergiovanni,^{54,55} L. Pierini,^{104,57} V. Pierro,^{87,103} G. Pillant,⁴⁷ M. Pillas,⁴⁶ F. Pilo,¹⁸ L. Pinard,¹⁵⁷ C. Pineda-Bosque,⁹⁰ I. M. Pinto,^{87,103,253} M. Pinto,⁴⁷ B. J. Piotrkowski,⁶ K. Piotrkowski,⁵⁸ M. Pirello,⁷² M. D. Pitkin,¹⁹³ A. Placidi,^{40,79} E. Placidi,^{104,57} M. L. Planas,¹⁴⁴ W. Plastino,^{254,235} C. Pluchar,²⁵⁵ R. Poggiani,^{78,18} E. Polini,³⁰ D. Y. T. Pong,¹³⁰ S. Ponrathnam,¹¹ E. K. Porter,⁴⁵ R. Poulton,⁴⁷ A. Poverman,⁸² J. Powell,¹⁴² M. Pracchia,³⁰ T. Pradier,¹⁶⁴ A. K. Prajapati,⁸⁴ K. Prasai,⁷⁷ R. Prasanna,²⁰³ G. Pratten,¹⁴ M. Principe,^{87,253,103} G. A. Prodi,^{256,99} L. Prokhorov,¹⁴ P. Prosperito,^{123,124} L. Prudenzi,¹¹¹ A. Puecher,^{59,65} M. Punturo,⁴⁰ F. Puosi,^{18,78} P. Puppo,⁵⁷ M. Pürer,¹¹¹ H. Qi,¹⁷ N. Quartey,⁶³ V. Quetschke,⁸⁹ P. J. Quinonez,³⁶ R. Quitzow-James,⁹⁵ F. J. Raab,⁷² G. Raaijmakers,^{38,59} H. Radkins,⁷² N. Radulesco,³⁷ P. Raffai,¹⁵³ S. X. Rail,²²⁴ S. Raja,⁹⁴ C. Rajan,⁹⁴ K. E. Ramirez,⁵⁶ T. D. Ramirez,⁴⁴ A. Ramos-Buades,¹¹¹ J. Rana,¹⁴⁹ P. Rapagnani,^{104,57} A. Ray,⁶ V. Raymond,¹⁷ N. Raza,¹⁸¹ M. Razzano,^{78,18} J. Read,⁴⁴ L. A. Rees,⁴² T. Regimbau,³⁰ L. Rei,⁹² S. Reid,³³ S. W. Reid,⁶³ D. H. Reitze,^{1,76} P. Relton,¹⁷ A. Renzini,¹ P. Rettengo,^{22,23} B. Revenu,⁴⁵ A. Reza,⁵⁹ M. Rezac,⁴⁴ F. Ricci,^{104,57} D. Richards,¹⁹⁶ J. W. Richardson,²⁵⁷ L. Richardson,¹⁸⁵ G. Riemenschneider,^{22,23} K. Riles,¹⁸⁴ S. Rinaldi,^{78,18} K. Rink,¹⁸¹ N. A. Robertson,¹ R. Robie,¹ F. Robinet,⁴⁶ A. Rocchi,¹²⁴ S. Rodriguez,⁴⁴ L. Rolland,³⁰ J. G. Rollins,¹ M. Romanelli,¹⁰⁵ R. Romano,^{3,4} C. L. Romel,⁷² A. Romero,³¹ I. M. Romero-Shaw,⁵ J. H. Romie,⁵⁶ S. Ronchini,^{32,107} L. Rosa,^{4,25} C. A. Rose,⁶ D. Rosińska,¹⁰⁹ M. P. Ross,²⁵⁸ S. Rowan,²⁴ S. J. Rowlinson,¹⁴ S. Roy,⁶⁵ Santosh Roy,¹¹ Soumen Roy,²⁵⁹ D. Rozza,^{121,122} P. Ruggi,⁴⁷ K. Ruiz-Rocha,²⁰⁴ K. Ryan,⁷² S. Sachdev,¹⁴⁹ T. Sadecki,⁷² J. Sadiq,¹¹⁴ S. Saha,¹⁹⁵ Y. Saito,¹⁹⁰ K. Sakai,²⁶⁰ M. Sakellariadou,⁶⁰ S. Sakon,¹⁴⁹ O. S. Salafia,^{71,70,69} F. Salces-Carcoba,¹ L. Salconi,⁴⁷ M. Saleem,¹⁴⁸ F. Salemi,^{98,99} A. Samajdar,⁷⁰ E. J. Sanchez,¹ J. H. Sanchez,⁴⁴ L. E. Sanchez,¹ N. Sanchis-Gual,²⁶¹ J. R. Sanders,²⁶² A. Sanuy,²⁹ T. R. Saravanan,¹¹ N. Sarin,⁵ B. Sassolas,¹⁵⁷ H. Satari,⁹³ B. S. Sathyaprakash,^{149,17} O. Sauter,⁷⁶ R. L. Savage,⁷² V. Savant,¹¹ T. Sawada,¹⁷⁷ H. L. Sawant,¹¹ S. Sayah,¹⁵⁷ D. Schaetzl,¹ M. Scheel,¹³⁶ J. Scheuer,¹⁵ M. G. Schiowski,⁸⁸ P. Schmidt,¹⁴ S. Schmidt,⁶⁵ R. Schnabel,¹²⁷ M. Schneewind,^{9,10} R. M. S. Schofield,⁶⁶ A. Schönbeck,¹²⁷ B. W. Schulte,^{9,10} B. F. Schutz,^{17,9,10} E. Schwartz,¹⁷ J. Scott,²⁴ S. M. Scott,⁸ M. Seglar-Arroyo,³⁰ Y. Sekiguchi,²⁶³ D. Sellers,⁵⁶ A. S. Sengupta,²⁵⁹ D. Sentenac,⁴⁷ E. G. Seo,¹³⁰ V. Sequino,^{25,4} A. Sergeev,²¹⁵ Y. Setyawati,^{9,10,65} T. Shaffer,⁷² M. S. Shahriar,¹⁵ M. A. Shaikh,¹⁹ B. Shams,¹⁶⁰ L. Shao,¹⁹⁹ A. Sharma,^{32,107} P. Sharma,⁹⁴ P. Shawhan,¹¹⁰ N. S. Shcheblanov,²²⁸ A. Sheela,²⁴¹ Y. Shikano,^{264,265} M. Shikauchi,²⁸ H. Shimizu,²⁶⁶ K. Shimode,¹⁹⁰ H. Shinkai,²⁶⁷ T. Shishido,⁵³ A. Shoda,²⁰ D. H. Shoemaker,⁷⁴ D. M. Shoemaker,¹⁷⁰ S. ShyamSundar,⁹⁴ M. Sieniawska,⁵⁸ D. Sigg,⁷² L. Silenzi,^{40,41} L. P. Singer,¹¹⁷ D. Singh,¹⁴⁹ M. K. Singh,¹⁹ N. Singh,¹⁰⁹ A. Singha,^{154,59} A. M. Sintes,¹⁴⁴ V. Sipala,^{121,122} V. Skliris,¹⁷ B. J. J. Slagmolen,⁸ T. J. Slaven-Blair,⁹³ J. Smetana,¹⁴ J. R. Smith,⁴⁴ L. Smith,²⁴ R. J. E. Smith,⁵ J. Soldateschi,^{229,268,55} S. N. Somala,²⁶⁹ K. Somiya,² I. Song,¹⁹⁵ K. Soni,¹¹ V. Sordini,¹⁴⁰ F. Sorrentino,⁹² N. Sorrentino,^{78,18} R. Soulard,³⁷ T. Souradeep,^{270,11} E. Sowell,¹⁴⁷ V. Spagnuolo,^{154,59} A. P. Spencer,²⁴ M. Spera,^{80,81} P. Spinicelli,⁴⁷ A. K. Srivastava,⁸⁴ V. Srivastava,⁶⁷ K. Staats,¹⁵ C. Stachie,³⁷ F. Stachurski,²⁴ D. A. Steer,⁴⁵

J. Steinlechner,^{154,59} S. Steinlechner,^{154,59} N. Stergioulas,²⁰⁰ D. J. Stops,¹⁴ M. Stover,²³⁷ K. A. Strain,²⁴ L. C. Strang,¹²⁰ G. Stratta,^{271,57} M. D. Strong,⁷ A. Strunk,⁷² R. Sturani,²⁵² A. L. Stuver,¹¹³ M. Suchenek,⁸⁶ S. Sudhagar,¹¹ V. Sudhir,⁷⁴ R. Sugimoto,^{272,243} H. G. Suh,⁶ A. G. Sullivan,⁵⁰ T. Z. Summerscales,²⁷³ L. Sun,⁸ S. Sunil,⁸⁴ A. Sur,⁸⁶ J. Suresh,²⁸ P. J. Sutton,¹⁷ Takamasa Suzuki,¹⁷⁶ Takanori Suzuki,² Toshikazu Suzuki,¹⁸⁸ B. L. Swinkels,⁵⁹ M. J. Szczepańczyk,⁷⁶ P. Szewczyk,¹⁰⁹ M. Tacca,⁵⁹ H. Tagoshi,¹⁸⁸ S. C. Tait,²⁴ H. Takahashi,²⁷⁴ R. Takahashi,²⁰ S. Takano,²⁷ H. Takeda,²⁷ M. Takeda,¹⁷⁷ C. J. Talbot,³³ C. Talbot,¹ K. Tanaka,²⁷⁵ Taiki Tanaka,¹⁸⁸ Takahiro Tanaka,²⁷⁶ A. J. Tanasijczuk,⁵⁸ S. Tanioka,¹⁹⁰ D. B. Tanner,⁷⁶ D. Tao,¹ L. Tao,⁷⁶ R. D. Tapia,¹⁴⁹ E. N. Tapia San Martín,⁵⁹ C. Taranto,¹²³ A. Taruya,²⁷⁷ J. D. Tasson,¹⁶¹ R. Tenorio,¹⁴⁴ J. E. S. Terhune,¹¹³ L. Terkowski,¹²⁷ M. P. Thirugnanasambandam,¹¹ M. Thomas,⁵⁶ P. Thomas,⁷² E. E. Thompson,⁴⁸ J. E. Thompson,¹⁷ S. R. Thondapu,⁹⁴ K. A. Thorne,⁵⁶ E. Thrane,⁵ Shubhanshu Tiwari,¹⁶² Srishti Tiwari,¹¹ V. Tiwari,¹⁷ A. M. Toivonen,¹⁴⁸ A. E. Tolley,⁵¹ T. Tomaru,²⁰ T. Tomura,¹⁹⁰ M. Tonelli,^{78,18} Z. Tornasi,²⁴ A. Torres-Forné,¹²⁶ C. I. Torrie,¹ I. Tosta e Melo,¹²² D. Töyrä,⁸ A. Trapananti,^{41,40} F. Travasso,^{40,41} G. Traylor,⁵⁶ M. Trevor,¹¹⁰ M. C. Tringali,⁴⁷ A. Tripathy,¹⁸⁴ L. Troiano,^{278,103} A. Trovato,⁴⁵ L. Trozzo,^{4,190} R. J. Trudeau,¹ D. Tsai,¹²⁹ K. W. Tsang,^{59,279,65} T. Tsang,²⁸⁰ J.-S. Tsao,²³³ M. Tse,⁷⁴ R. Tso,¹³⁶ S. Tsuchida,¹⁷⁷ L. Tsukada,¹⁴⁹ D. Tsuna,²⁸ T. Tsutsui,²⁸ K. Turbang,^{281,205} M. Turconi,³⁷ D. Tuyenbayev,¹⁷⁷ A. S. Ubhi,¹⁴ N. Uchikata,¹⁸⁸ T. Uchiyama,¹⁹⁰ R. P. Udall,¹ A. Ueda,²⁸² T. Uehara,^{283,284} K. Ueno,²⁸ G. Ueshima,²⁸⁵ C. S. Unnikrishnan,²⁸⁶ A. L. Urban,⁷ T. Ushiba,¹⁹⁰ A. Utina,^{154,59} G. Vajente,¹ A. Vajpeyi,⁵ G. Valdes,¹⁸⁵ M. Valentini,^{183,98,99} V. Valsan,⁶ N. van Bakel,⁵⁹ M. van Beuzekom,⁵⁹ M. van Dael,^{59,287} J. F. J. van den Brand,^{154,96,59} C. Van Den Broeck,^{65,59} D. C. Vander-Hyde,⁶⁷ H. van Haevermaet,²⁰⁵ J. V. van Heijningen,⁵⁸ M. H. P. M. van Putten,²⁸⁸ N. van Remortel,²⁰⁵ M. Vardaro,^{212,59} A. F. Vargas,¹²⁰ V. Varma,¹¹¹ M. Vasúth,⁷⁵ A. Vecchio,¹⁴ G. Vedovato,⁸¹ J. Veitch,²⁴ P. J. Veitch,⁸⁸ J. Venneberg,^{9,10} G. Venugopalan,¹ D. Verkindt,³⁰ P. Verma,²²¹ Y. Verma,⁹⁴ S. M. Vermeulen,¹⁷ D. Veske,⁵⁰ F. Vetrano,⁵⁴ A. Viceré,^{54,55} S. Vidyant,⁶⁷ A. D. Viets,²⁸⁹ A. Vijaykumar,¹⁹ V. Villa-Ortega,¹¹⁴ J.-Y. Vinet,³⁷ A. Virtuoso,^{239,35} S. Vitale,⁷⁴ H. Vocca,^{79,40} E. R. G. von Reis,⁷² J. S. A. von Wrangel,^{9,10} C. Vorvick,⁷² S. P. Vyatchanin,⁹⁷ L. E. Wade,²³⁷ M. Wade,²³⁷ K. J. Wagner,¹²⁸ R. C. Walet,⁵⁹ M. Walker,⁶³ G. S. Wallace,³³ L. Wallace,¹ J. Wang,¹⁷⁸ J. Z. Wang,¹⁸⁴ W. H. Wang,⁸⁹ R. L. Ward,⁸ J. Warner,⁷² M. Was,³⁰ T. Washimi,²⁰ N. Y. Washington,¹ J. Watchi,¹⁴⁵ B. Weaver,⁷² C. R. Weaving,⁵¹ S. A. Webster,²⁴ M. Weinert,^{9,10} A. J. Weinstein,¹ R. Weiss,⁷⁴ C. M. Weller,²⁵⁸ R. A. Weller,²⁰⁴ F. Wellmann,^{9,10} L. Wen,⁹³ P. Weßels,^{9,10} K. Wette,⁸ J. T. Whelan,¹²⁸ D. D. White,⁴⁴ B. F. Whiting,⁷⁶ C. Whittle,⁷⁴ D. Wilken,^{9,10} D. Williams,²⁴ M. J. Williams,²⁴ A. R. Williamson,⁵¹ J. L. Willis,¹ B. Willke,^{9,10} D. J. Wilson,²⁵⁵ C. C. Wipf,¹ T. Wlodarczyk,¹¹¹ G. Woan,²⁴ J. Woehler,^{9,10} J. K. Wofford,¹²⁸ D. Wong,¹⁸¹ I. C. F. Wong,¹³⁰ M. Wright,²⁴ C. Wu,¹³⁷ D. S. Wu,^{9,10} H. Wu,¹³⁷ D. M. Wysocki,⁶ L. Xiao,¹ T. Yamada,²⁶⁶ H. Yamamoto,¹ K. Yamamoto,¹⁸⁹ T. Yamamoto,¹⁹⁰ K. Yamashita,²⁰¹ R. Yamazaki,¹⁹⁸ F. W. Yang,¹⁶⁰ K. Z. Yang,¹⁴⁸ L. Yang,¹⁶⁸ Y.-C. Yang,¹²⁹ Y. Yang,²⁹⁰ Yang Yang,⁷⁶ M. J. Yap,⁸ D. W. Yeeles,¹⁷ S.-W. Yeh,¹³⁷ A. B. Yelkar,¹²⁸ M. Ying,¹²⁹ J. Yokoyama,^{28,27} T. Yokozawa,¹⁹⁰ J. Yoo,¹⁸⁰ T. Yoshioka,²⁰¹ Hang Yu,¹³⁶ Haocun Yu,⁷⁴ H. Yuzurihara,¹⁸⁸ A. Zadrożny,²²¹ M. Zanolin,³⁶ S. Zeidler,²⁹¹ T. Zelenova,⁴⁷ J.-P. Zendri,⁸¹ M. Zevin,¹⁶⁶ M. Zhan,¹⁷⁸ H. Zhang,²³³ J. Zhang,⁹³ L. Zhang,¹ R. Zhang,⁷⁶ T. Zhang,¹⁴ Y. Zhang,¹⁸⁵ C. Zhao,⁹³ G. Zhao,¹⁴⁵ Y. Zhao,^{188,20} Yue Zhao,¹⁶⁰ R. Zhou,¹⁹¹ Z. Zhou,¹⁵ X. J. Zhu,⁵ Z.-H. Zhu,^{119,231} A. B. Zimmerman,¹⁷⁰ M. E. Zucker,^{1,74} and J. Zweizig¹

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

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

²*Graduate School of Science, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan*

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

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

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

⁶*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*

⁷*Louisiana State University, Baton Rouge, Louisiana 70803, USA*

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

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

¹⁰*Leibniz Universität Hannover, D-30167 Hannover, Germany*

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

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

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

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

¹⁵*Northwestern University, Evanston, Illinois 60208, USA*

- ¹⁶*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
- ¹⁷*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*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
- ²³*INFN Sezione di Torino, I-10125 Torino, Italy*
- ²⁴*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
- ²⁵*Università di Napoli “Federico II,” Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
- ²⁶*Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France*
- ²⁷*Department of Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
- ²⁸*Research Center for the Early Universe (RESCEU), The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
- ²⁹*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, C/ Martí i Franquès 1, Barcelona 08028, Spain*
- ³⁰*Université Savoie Mont Blanc, CNRS, Laboratoire d’Annecy de Physique des Particules—IN2P3, F-74000 Annecy, France*
- ³¹*Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain*
- ³²*Gran Sasso Science Institute (GSSI), I-67100 L’Aquila, Italy*
- ³³*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
- ³⁴*Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy*
- ³⁵*INFN, Sezione di Trieste, I-34127 Trieste, Italy*
- ³⁶*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
- ³⁷*Artemis, Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, F-06304 Nice, France*
- ³⁸*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
- ³⁹*National and Kapodistrian University of Athens, School of Science Building, 2nd floor, Panepistimiopolis, 15771 Ilissia, Greece*
- ⁴⁰*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
- ⁴¹*Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
- ⁴²*American University, Washington, DC 20016, USA*
- ⁴³*Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan*
- ⁴⁴*California State University Fullerton, Fullerton, California 92831, USA*
- ⁴⁵*Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France*
- ⁴⁶*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
- ⁴⁷*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
- ⁴⁸*Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
- ⁴⁹*Department of Mathematics and Physics, Gravitational Wave Science Project, Hirosaki University, Hirosaki City, Aomori 036-8561, Japan*
- ⁵⁰*Columbia University, New York, New York 10027, USA*
- ⁵¹*University of Portsmouth, Portsmouth PO1 3FX, United Kingdom*
- ⁵²*Kamioka Branch, National Astronomical Observatory of Japan (NAOJ), Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ⁵³*The Graduate University for Advanced Studies (SOKENDAI), Mitaka City, Tokyo 181-8588, Japan*
- ⁵⁴*Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy*
- ⁵⁵*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
- ⁵⁶*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
- ⁵⁷*INFN, Sezione di Roma, I-00185 Roma, Italy*
- ⁵⁸*Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
- ⁵⁹*Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
- ⁶⁰*King’s College London, University of London, London WC2R 2LS, United Kingdom*
- ⁶¹*Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea*
- ⁶²*National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea*
- ⁶³*Christopher Newport University, Newport News, Virginia 23606, USA*

- ⁶⁴*School of High Energy Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba City, Ibaraki 305-0801, Japan*
- ⁶⁵*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, Netherlands*
- ⁶⁶*University of Oregon, Eugene, Oregon 97403, USA*
- ⁶⁷*Syracuse University, Syracuse, New York 13244, USA*
- ⁶⁸*Université de Liège, B-4000 Liège, Belgium*
- ⁶⁹*Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy*
- ⁷⁰*INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*
- ⁷¹*INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
- ⁷²*LIGO Hanford Observatory, Richland, Washington 99352, USA*
- ⁷³*Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,” Università di Salerno, I-84081 Baronissi, Salerno, Italy*
- ⁷⁴*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- ⁷⁵*Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary*
- ⁷⁶*University of Florida, Gainesville, Florida 32611, USA*
- ⁷⁷*Stanford University, Stanford, California 94305, USA*
- ⁷⁸*Università di Pisa, I-56127 Pisa, Italy*
- ⁷⁹*Università di Perugia, I-06123 Perugia, Italy*
- ⁸⁰*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
- ⁸¹*INFN, Sezione di Padova, I-35131 Padova, Italy*
- ⁸²*Bard College, Annandale-on-Hudson, New York 12504, USA*
- ⁸³*Montana State University, Bozeman, Montana 59717, USA*
- ⁸⁴*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
- ⁸⁵*Universiteit Gent, B-9000 Gent, Belgium*
- ⁸⁶*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716 Warsaw, Poland*
- ⁸⁷*Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy*
- ⁸⁸*OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
- ⁸⁹*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
- ⁹⁰*California State University, Los Angeles, Los Angeles, California 90032, USA*
- ⁹¹*Departamento de Matemáticas, Universitat Autònoma de Barcelona, Edificio C Facultad de Ciencias 08193 Bellaterra (Barcelona), Spain*
- ⁹²*INFN, Sezione di Genova, I-16146 Genova, Italy*
- ⁹³*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
- ⁹⁴*RRCAT, Indore, Madhya Pradesh 452013, India*
- ⁹⁵*Missouri University of Science and Technology, Rolla, Missouri 65409, USA*
- ⁹⁶*Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
- ⁹⁷*Lomonosov Moscow State University, Moscow 119991, Russia*
- ⁹⁸*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
- ⁹⁹*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
- ¹⁰⁰*SUPA, University of the West of Scotland, Paisley PN1 2BE, United Kingdom*
- ¹⁰¹*Bar-Ilan University, Ramat Gan 5290002, Israel*
- ¹⁰²*Dipartimento di Fisica “E.R. Caianiello,” Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ¹⁰³*INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
- ¹⁰⁴*Università di Roma “La Sapienza,” I-00185 Roma, Italy*
- ¹⁰⁵*Université Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France*
- ¹⁰⁶*Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
- ¹⁰⁷*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
- ¹⁰⁸*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France*
- ¹⁰⁹*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
- ¹¹⁰*University of Maryland, College Park, Maryland 20742, USA*
- ¹¹¹*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany*
- ¹¹²*L2IT, Laboratoire des 2 Infinis—Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France*
- ¹¹³*Villanova University, Villanova, Pennsylvania 19085, USA*
- ¹¹⁴*IGFAE, Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*
- ¹¹⁵*Stony Brook University, Stony Brook, New York 11794, USA*
- ¹¹⁶*Center for Computational Astrophysics, Flatiron Institute, New York, New York 10010, USA*

- ¹¹⁷NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
- ¹¹⁸Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ¹¹⁹Department of Astronomy, Beijing Normal University, Beijing 100875, China
- ¹²⁰OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
- ¹²¹Università degli Studi di Sassari, I-07100 Sassari, Italy
- ¹²²INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
- ¹²³Università di Roma Tor Vergata, I-00133 Roma, Italy
- ¹²⁴INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ¹²⁵University of Sannio at Benevento, I-82100 Benevento, Italy
and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- ¹²⁶Departamento de Astronomía y Astrofísica, Universitat de València,
E-46100 Burjassot, València, Spain
- ¹²⁷Universität Hamburg, D-22761 Hamburg, Germany
- ¹²⁸Rochester Institute of Technology, Rochester, New York 14623, USA
- ¹²⁹National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
- ¹³⁰The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong
- ¹³¹Department of Applied Physics, Fukuoka University, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
- ¹³²OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ¹³³Department of Physics, Tamkang University, Danshui District, New Taipei City 25137, Taiwan
- ¹³⁴Department of Physics and Institute of Astronomy, National Tsing Hua University,
Hsinchu 30013, Taiwan
- ¹³⁵Department of Physics, Center for High Energy and High Field Physics, National Central University,
Zhongli District, Taoyuan City 32001, Taiwan
- ¹³⁶CaRT, California Institute of Technology, Pasadena, California 91125, USA
- ¹³⁷Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
- ¹³⁸Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹³⁹Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan
- ¹⁴⁰Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3,
UMR 5822, F-69622 Villeurbanne, France
- ¹⁴¹INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- ¹⁴²OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- ¹⁴³Université libre de Bruxelles, Avenue Franklin Roosevelt 50–1050 Bruxelles, Belgium
- ¹⁴⁴IAC3–IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
- ¹⁴⁵Université Libre de Bruxelles, Brussels 1050, Belgium
- ¹⁴⁶Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- ¹⁴⁷Texas Tech University, Lubbock, Texas 79409, USA
- ¹⁴⁸University of Minnesota, Minneapolis, Minnesota 55455, USA
- ¹⁴⁹The Pennsylvania State University, University Park, Pennsylvania 16802, USA
- ¹⁵⁰University of Rhode Island, Kingston, Rhode Island 02881, USA
- ¹⁵¹Bellevue College, Bellevue, Washington 98007, USA
- ¹⁵²Scuola Normale Superiore, Piazza dei Cavalieri, 7–56126 Pisa, Italy
- ¹⁵³Eötvös University, Budapest 1117, Hungary
- ¹⁵⁴Maastricht University, P.O. Box 616, 6200 MD Maastricht, Netherlands
- ¹⁵⁵Chennai Mathematical Institute, Chennai 603103, India
- ¹⁵⁶The University of Sheffield, Sheffield S10 2TN, United Kingdom
- ¹⁵⁷Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA),
IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹⁵⁸Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma,
I-43124 Parma, Italy
- ¹⁵⁹INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ¹⁶⁰The University of Utah, Salt Lake City, Utah 84112, USA
- ¹⁶¹Carleton College, Northfield, Minnesota 55057, USA
- ¹⁶²University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ¹⁶³Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada
- ¹⁶⁴Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
- ¹⁶⁵West Virginia University, Morgantown, West Virginia 26506, USA
- ¹⁶⁶University of Chicago, Chicago, Illinois 60637, USA
- ¹⁶⁷Montclair State University, Montclair, New Jersey 07043, USA
- ¹⁶⁸Colorado State University, Fort Collins, Colorado 80523, USA
- ¹⁶⁹Institute for Nuclear Research, Bem t'er 18/c, H-4026 Debrecen, Hungary

- ¹⁷⁰University of Texas, Austin, Texas 78712, USA
- ¹⁷¹CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹⁷²Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- ¹⁷³Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- ¹⁷⁴Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, Campus de Gualtar, PT-4710-057 Braga, Portugal
- ¹⁷⁵Department of Astronomy, The University of Tokyo, Mitaka City, Tokyo 181-8588, Japan
- ¹⁷⁶Faculty of Engineering, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- ¹⁷⁷Department of Physics, Graduate School of Science, Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- ¹⁷⁸State 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
- ¹⁷⁹University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ¹⁸⁰Cornell University, Ithaca, New York 14850, USA
- ¹⁸¹University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
- ¹⁸²INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- ¹⁸³The University of Mississippi, University, Mississippi 38677, USA
- ¹⁸⁴University of Michigan, Ann Arbor, Michigan 48109, USA
- ¹⁸⁵Texas A&M University, College Station, Texas 77843, USA
- ¹⁸⁶Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
- ¹⁸⁷Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
- ¹⁸⁸Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- ¹⁸⁹Faculty of Science, University of Toyama, Toyama City, Toyama 930-8555, Japan
- ¹⁹⁰Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ¹⁹¹University of California, Berkeley, California 94720, USA
- ¹⁹²Maastricht University, 6200 MD Maastricht, Netherlands
- ¹⁹³Lancaster University, Lancaster LA1 4YW, United Kingdom
- ¹⁹⁴College of Industrial Technology, Nihon University, Narashino City, Chiba 275-8575, Japan
- ¹⁹⁵Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan
- ¹⁹⁶Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom
- ¹⁹⁷Department of Astronomy and Space Science, Chungnam National University, Yuseong-gu, Daejeon 34134, Republic of Korea
- ¹⁹⁸Department of Physical Sciences, Aoyama Gakuin University, Sagami-hara City, Kanagawa 252-5258, Japan
- ¹⁹⁹Kavli Institute for Astronomy and Astrophysics, Peking University, Haidian District, Beijing 100871, China
- ²⁰⁰Aristotle University of Thessaloniki, University Campus, 54124 Thessaloniki, Greece
- ²⁰¹Graduate School of Science and Engineering, University of Toyama, Toyama City, Toyama 930-8555, Japan
- ²⁰²Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- ²⁰³Directorate of Construction, Services and Estate Management, Mumbai 400094, India
- ²⁰⁴Vanderbilt University, Nashville, Tennessee 37235, USA
- ²⁰⁵Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium
- ²⁰⁶University of Białystok, 15-424 Białystok, Poland
- ²⁰⁷Ewha Womans University, Seoul 03760, Republic of Korea
- ²⁰⁸National Astronomical Observatories, Chinese Academic of Sciences, Chaoyang District, Beijing, China
- ²⁰⁹School of Astronomy and Space Science, University of Chinese Academy of Sciences, Chaoyang District, Beijing, China
- ²¹⁰University of Southampton, Southampton SO17 1BJ, United Kingdom
- ²¹¹Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- ²¹²Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
- ²¹³Chung-Ang University, Seoul 06974, Republic of Korea
- ²¹⁴University of Washington Bothell, Bothell, Washington 98011, USA

- ²¹⁵*Institute of Applied Physics, Nizhny Novgorod 603950, Russia*
- ²¹⁶*Inje University Gimhae, South Gyeongsang 50834, Republic of Korea*
- ²¹⁷*Department of Physics, Myongji University, Yongin 17058, Republic of Korea*
- ²¹⁸*Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*
- ²¹⁹*School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, United Kingdom*
- ²²⁰*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ²²¹*National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
- ²²²*Instituto de Física Teórica, 28049 Madrid, Spain*
- ²²³*Department of Physics, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8602, Japan*
- ²²⁴*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
- ²²⁵*Laboratoire Lagrange, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, F-06304 Nice, France*
- ²²⁶*Seoul National University, Seoul 08826, Republic of Korea*
- ²²⁷*Sungkyunkwan University, Seoul 03063, Republic of Korea*
- ²²⁸*NAVIER, École des Ponts, Université Gustave Eiffel, CNRS, Marne-la-Vallée, France*
- ²²⁹*Università di Firenze, Sesto Fiorentino I-50019, Italy*
- ²³⁰*Department of Physics, National Cheng Kung University, Tainan City 701, Taiwan*
- ²³¹*School of Physics and Technology, Wuhan University, Wuhan, Hubei 430072, China*
- ²³²*National Center for High-Performance Computing, National Applied Research Laboratories, Hsinchu Science Park, Hsinchu City 30076, Taiwan*
- ²³³*Department of Physics, National Taiwan Normal University, Sec. 4, Taipei 116, Taiwan*
- ²³⁴*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
- ²³⁵*INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
- ²³⁶*ESPCI, CNRS, F-75005 Paris, France*
- ²³⁷*Kenyon College, Gambier, Ohio 43022, USA*
- ²³⁸*School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
- ²³⁹*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
- ²⁴⁰*Institute for Photon Science and Technology, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*
- ²⁴¹*Indian Institute of Technology Madras, Chennai 600036, India*
- ²⁴²*Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India*
- ²⁴³*Institute of Space and Astronautical Science (JAXA), Chuo-ku, Sagami-hara City, Kanagawa 252-0222, Japan*
- ²⁴⁴*Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
- ²⁴⁵*Faculty of Law, Ryukoku University, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
- ²⁴⁶*Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
- ²⁴⁷*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
- ²⁴⁸*Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
- ²⁴⁹*Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
- ²⁵⁰*Korea Astronomy and Space Science Institute (KASI), Yuseong-gu, Daejeon 34055, Republic of Korea*
- ²⁵¹*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
- ²⁵²*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
- ²⁵³*Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy*
- ²⁵⁴*Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
- ²⁵⁵*University of Arizona, Tucson, Arizona 85721, USA*
- ²⁵⁶*Università di Trento, Dipartimento di Matematica, I-38123 Povo Trento, Italy*
- ²⁵⁷*University of California, Riverside, Riverside, California 92521, USA*
- ²⁵⁸*University of Washington, Seattle, Washington 98195, USA*
- ²⁵⁹*Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
- ²⁶⁰*Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, Nagaoka City, Niigata 940-8532, Japan*
- ²⁶¹*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, Campus de Santiago, 3810-183 Aveiro, Portugal*
- ²⁶²*Marquette University, Milwaukee, Wisconsin 53233, USA*
- ²⁶³*Faculty of Science, Toho University, Funabashi City, Chiba 274-8510, Japan*
- ²⁶⁴*Graduate School of Science and Technology, Gunma University, Maebashi, Gunma 371-8510, Japan*

- ²⁶⁵*Institute for Quantum Studies, Chapman University, Orange, California 92866, USA*
- ²⁶⁶*Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*
- ²⁶⁷*Faculty of Information Science and Technology, Osaka Institute of Technology, Hirakata City, Osaka 573-0196, Japan*
- ²⁶⁸*INAF, Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy*
- ²⁶⁹*Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
- ²⁷⁰*Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India*
- ²⁷¹*Istituto di Astrofisica e Planetologia Spaziali di Roma, Via del Fosso del Cavaliere, 100, 00133 Roma RM, Italy*
- ²⁷²*Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), Sagamihara City, Kanagawa 252-5210, Japan*
- ²⁷³*Andrews University, Berrien Springs, Michigan 49104, USA*
- ²⁷⁴*Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, Setagaya, Tokyo 158-0082, Japan*
- ²⁷⁵*Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
- ²⁷⁶*Department of Physics, Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ²⁷⁷*Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ²⁷⁸*Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ²⁷⁹*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands*
- ²⁸⁰*Faculty of Science, Department of Physics, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong*
- ²⁸¹*Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium*
- ²⁸²*Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan*
- ²⁸³*Department of Communications Engineering, National Defense Academy of Japan, Yokosuka City, Kanagawa 239-8686, Japan*
- ²⁸⁴*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
- ²⁸⁵*Department of Information and Management Systems Engineering, Nagaoka University of Technology, Nagaoka City, Niigata 940-2188, Japan*
- ²⁸⁶*Tata Institute of Fundamental Research, Mumbai 400005, India*
- ²⁸⁷*Eindhoven University of Technology, Postbus 513, 5600 MB Eindhoven, Netherlands*
- ²⁸⁸*Department of Physics and Astronomy, Sejong University, Gwangjin-gu, Seoul 143-747, Republic of Korea*
- ²⁸⁹*Concordia University Wisconsin, Mequon, Wisconsin 53097, USA*
- ²⁹⁰*Department of Electrophysics, National Yang Ming Chiao Tung University, Hsinchu, Taiwan*
- ²⁹¹*Department of Physics, Rikkyo University, Toshima-ku, Tokyo 171-8501, Japan*

^aDeceased, August 2020.

^bDeceased, April 2021.