

First Search for Nontensorial Gravitational Waves from Known Pulsars

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First Search for Nontensorial Gravitational Waves from Known PulsarsB. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)



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We present results from the first directed search for nontensorial gravitational waves. While general relativity allows for tensorial (plus and cross) modes only, a generic metric theory may, in principle, predict waves with up to six different polarizations. This analysis is sensitive to continuous signals of scalar, vector, or tensor polarizations, and does not rely on any specific theory of gravity. After searching data from the first observation run of the advanced LIGO detectors for signals at twice the rotational frequency of 200 known pulsars, we find no evidence of gravitational waves of any polarization. We report the first upper limits for scalar and vector strains, finding values comparable in magnitude to previously published limits for tensor strain. Our results may be translated into constraints on specific alternative theories of gravity.

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Introduction.—The first gravitational waves detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) and Virgo have already been used to place some of the most stringent constraints on deviations from the general theory of relativity (GR) in the highly dynamical and strong-field regimes of gravity [1–4]. However, even though some partial progress has been made with the observation of GW170814 [5,6] and in spite of the wealth of new information provided by GW170817 [7,8], it has not yet been possible to unambiguously confirm GR’s prediction that the associated metric perturbations are of a tensor nature (helicity ± 2), rather than vector (helicity ± 1), or scalar (helicity 0) [9]. This is unfortunate, since the presence of nontensorial modes is a key prediction of many extensions to GR [10–14]. Most importantly, the detection of a scalar or vector component, no matter how small, would automatically point to physics beyond Einstein’s theory [12,13].

In order to experimentally study gravitational-wave polarizations directly, one needs a local measurement of their geometric effect (i.e., which directions are stretched and squeezed) that breaks degeneracies between the five distinguishable (to differential-arm instruments) modes supported by a generic metric theory of gravity [10,11]. For transient waves like those detected so far, this cannot be fully achieved with the LIGO-Virgo network, as at least five non-co-oriented differential-arm antennas are required to break *all* such degeneracies [13,15]. Constraints on the magnitude of non-GR polarizations inferred from indirect measurements, like the rate of orbital decay of binary pulsars, are only meaningful in the context of specific theories (see, e.g., Refs. [16,17] or Refs. [18,19] for reviews).

Theory-independent polarization measurements could instead be carried out with current detectors in the presence of signals sufficiently long to probe the detector antenna patterns, which are themselves polarization sensitive [20–23]. Such is the case, for instance, for the continuous, almost-monochromatic waves expected from spinning neutron stars with an asymmetric moment of inertia [24]. Known galactic pulsars are one of the main candidates for searches for such signals in data from ground-based detectors, and analyses targeting them have already achieved sensitivities that are comparable to, or even surpass, their canonical spin-down limit (i.e., the strain that would be produced if the observed slowdown in the pulsar’s rotation was completely due to gravitational radiation) [25].

However, all previous targeted searches have been, by design, restricted to tensorial gravitational polarizations *only*. This leaves open the possibility that, due to a departure from GR, the neutron stars targeted in previous searches may indeed be emitting strong continuous waves with nontensorial content, in spite of the null results of standard searches.

In this Letter, we present results from a search for continuous gravitational waves in aLIGO data that makes no assumptions about how the gravitational field transforms under local spatial rotations, and is thus sensitive to any of the five measurable polarizations allowed by a generic metric theory of gravity. We targeted 200 known pulsars using data from aLIGO’s first observation run (O1), and assuming emission at twice the rotational frequency of the source.

Our data provide no evidence for the emission of gravitational signals of tensorial or nontensorial polarization from any of the pulsars targeted. For sources in the most sensitive band of our detectors, we constrain the strain of the scalar and vector modes to be below 1.5×10^{-26} at 95% credibility. These are the first direct upper limits for

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

scalar and vector strain, and may in principle be used to constrain beyond-GR theories of gravity.

Analysis.—We search aLIGO O1 data from the Hanford (H1) and Livingston (L1) detectors for continuous waves of any polarization (tensor, scalar, or vector) by applying the Bayesian time-domain method of Ref. [26], generalized to non-GR modes as described in Ref. [21] and summarized below. Our analysis follows closely that of Ref. [25], and uses the exact same interferometric data.

Calibrated detector data are heterodyned and filtered using the timing solutions obtained from electromagnetic observations for each pulsar. The maximum calibration uncertainties estimated over the whole run give a limit on the combined H1 and L1 amplitude uncertainties of 14%—this is the conservative level of uncertainty on the strain upper limits [25,27].

The data streams start on 2015 Sep 11 at 01:25:03 UTC for H1 and 18:29:03 UTC for L1, and finish on 2016 Jan 19 at 17:07:59 UTC at both sites. The pulsar timing solutions used are also the same as in Ref. [25] and were obtained from the 42-ft telescope and Lovell telescope at Jodrell Bank (UK), the 26-m telescope at Hartebeesthoek (South Africa), the Parkes radio telescope (Australia), the Nancay Decimetric Radio Telescope (France), the Arecibo Observatory (Puerto Rico), and the *Fermi* Large Area Telescope (LAT).

As described in detail in Ref. [21], we construct a Bayesian hypothesis that captures signals of any polarization content (our *any-signal* hypothesis, \mathcal{H}_S) by combining the sub-hypotheses corresponding to the signal being composed of tensor, vector, scalar modes, or any combination thereof. Each of these sub-hypotheses corresponds to a different signal model; in particular, the least restrictive template includes contributions from all polarizations and can be written as

$$h(t) = \sum_p F_p(t; \alpha, \delta, \psi) h_p(t), \quad (1)$$

where the sum is over the five independent polarizations: plus (+), cross (\times), vector x (x), vector y (y), and scalar (s) [11]. The two scalar modes in the most common basis, breathing and longitudinal, are degenerate for networks of quadrupolar antennas [13], so we do not make a distinction between them.

Each term in Eq. (1) is the product of an antenna pattern function F_p and an intrinsic strain function h_p . We define the different polarizations in a wave frame such that the z axis points in the direction of propagation, x lies in the plane of the sky along the line of nodes (here defined to be the intersection of the equatorial plane of the source with the plane of the sky), and y completes the right-handed system, such that the polarization angle ψ is the angle between the y axis and the projection of the celestial North onto the plane of the sky (see, e.g., Ref. [28]). We can thus write the F_p 's as implicit functions of the source's right

ascension α , declination δ , and polarization ψ . (For the sources targeted here, α and δ are always known to high accuracy, while ψ is usually unknown.) The antenna patterns acquire their time dependence from the sidereal rotation of Earth; explicit expressions for the F_p 's are given in Refs. [20–22,29,30].

For a continuous wave, the polarizations take the simple form

$$h_p(t) = a_p \cos[\phi(t) + \phi_p], \quad (2)$$

where a_p is a time-independent strain amplitude, $\phi(t)$ is the intrinsic phase evolution, and ϕ_p a phase offset for each polarization. The nature of these three quantities depends on the specifics of the underlying theory of gravity and the associated emission mechanism (for different emission mechanisms within GR, see, e.g., Refs. [31–33]). While we treat a_p and ϕ_p as free parameters, we take $\phi(t)$ to be the same as in the traditional GR analysis [25]:

$$\phi(t) = 2\pi \sum_{j=0}^N \frac{\partial_t^{(j)} f_{\text{GW},0}}{(j+1)!} [t - T_0 + \delta t(t)]^{(j+1)}, \quad (3)$$

where $\partial_t^{(j)} f_{\text{GW},0}$ is the j th time derivative of $f_{\text{GW},0}$, the emission frequency measured at the fiducial time T_0 ; $\delta t(t)$ is the time delay from the observatory to the solar system barycenter (including the known Rømer, Shapiro and Einstein delays), and can also include binary system corrections to transform the time coordinate to a frame approximately inertial with respect to the source; N is the order of the series expansion (1 or 2 for most sources).

The gravitational-wave frequency f_{GW} is related to the rotational frequency of the source f_{rot} , which is in turn known from electromagnetic observations. Although arbitrary theories of gravity and emission mechanisms may predict gravitational emission at any multiple of the rotational frequency, here we assume $f_{\text{GW}} = 2f_{\text{rot}}$, in accordance with the most favored emission model in GR [24]. This restriction arises from practical considerations affecting our specific implementation, and will be relaxed in future studies.

For convenience, we define *effective strain amplitudes* for tensor, vector, and scalar modes, respectively, by

$$h_t \equiv \sqrt{a_+^2 + a_\times^2}, \quad (4)$$

$$h_v \equiv \sqrt{a_x^2 + a_y^2}, \quad (5)$$

$$h_s \equiv a_s, \quad (6)$$

in terms of the intrinsic a_p amplitudes of Eq. (2). These quantities may serve as proxy for the total power in each polarization group.

One may recover the GR hypothesis considered in previous analyses by setting

$$a_+ = h_0(1 + \cos^2\iota)/2, \quad \phi_+ = \phi_0, \quad (7)$$

$$a_\times = h_0 \cos \iota, \quad \phi_\times = \phi_0 - \pi/2, \quad (8)$$

$$a_x = a_y = a_s = 0, \quad (9)$$

where ι is the inclination (angle between the line of sight and the spin axis of the source), and h_0 , ϕ_0 are free parameters. (As with ψ , ι is unknown for most pulsars.) This corresponds to the standard triaxial-star emission mechanism (see, e.g., Ref. [34]). We use this parameterization only when we wish to incorporate known orientation information as explained below; otherwise, we parametrize the tensor polarizations directly in terms of a_+ , a_\times , ϕ_+ and ϕ_\times .

Templates of the form of Eq. (1), together with appropriate priors, allow us to compute Bayes factors (marginalized-likelihood ratios) for the presence of signals in the data vs Gaussian noise. We do this using an extension of the nested sampling implementation presented in Ref. [35] (see Ref. [21] for details specific to non-GR polarizations). The Bayes factors corresponding to each signal model may be combined into the odds \mathcal{O}_N^S that the data contain a continuous signal of any polarization vs Gaussian noise:

$$\mathcal{O}_N^S = P(\mathcal{H}_S|\mathbf{B})/P(\mathcal{H}_N|\mathbf{B}), \quad (10)$$

i.e., the ratio of the posterior probabilities that the data \mathbf{B} contain a signal of any polarizations (\mathcal{H}_S) vs just Gaussian noise (\mathcal{H}_N). We compute these odds by setting model priors such that $P(\mathcal{H}_S) = P(\mathcal{H}_N)$; then, by Bayes' theorem, $\mathcal{O}_N^S = \mathcal{B}_N^S$, with the Bayes factor

$$\mathcal{B}_N^S \equiv P(\mathbf{B}|\mathcal{H}_S)/P(\mathbf{B}|\mathcal{H}_N). \quad (11)$$

Built into the astrophysical signal hypothesis, \mathcal{H}_S , is the requirement of coherence across detectors, which must be satisfied by a real gravitational wave. In order to make the analysis more robust against non-Gaussian instrumental features in the data, we also define an *instrumental feature* hypothesis, \mathcal{H}_I , that identifies non-Gaussian noise artifacts by their lack of coherence across detectors [25,36]. In particular, we define \mathcal{H}_I to capture Gaussian noise *or* a detector-incoherent signal (i.e., a feature that mimics an astrophysical signal in a single instrument, but is not recovered consistently across the network) in each detector [21]. We may then compare this to \mathcal{H}_S by means of the odds \mathcal{O}_I^S . For D detectors, this is given by

$$\log \mathcal{O}_I^S = \log \mathcal{B}_N^S - \sum_{d=1}^D \log (\mathcal{B}_{N_d}^{S_d} + 1), \quad (12)$$

where $\mathcal{B}_{N_d}^{S_d}$ is the signal vs noise Bayes factor computed only from data from the d th detector. This choice implicitly assigns prior weight to the models such that $P(\mathcal{H}_S) = P(\mathcal{H}_I) \times 0.5^D$ [21]. For an in depth analysis of the behavior of the different Bayesian hypotheses considered here, in

TABLE I. Existing orientation information for pulsars in our band, obtained from observations of the pulsar wind nebulae (see Table 3 in Ref. [42], and Refs. [43,44] for measurement details).

	ι	ψ
J0534 + 2200	$62^\circ 2 \pm 1^\circ 9$	$35^\circ 2 \pm 1^\circ 5$
J0537–6910	$92^\circ 8 \pm 0^\circ 9$	$41^\circ 0 \pm 2^\circ 2$
J0835–4510	$63^\circ 6 \pm 0^\circ 6$	$40^\circ 6 \pm 0^\circ 1$
J1833–1034	$85^\circ 4 \pm 0^\circ 3$	$45^\circ \pm 1^\circ$
J1952 + 3252		$-11^\circ 5 \pm 8^\circ 6$

the presence and absence of simulated signals of all polarizations, we again refer the reader to the methods paper [21].

We compute likelihoods by taking source location, frequency, and frequency derivatives as known quantities. In computing Bayes factors, we employ priors uniform in the logarithm of amplitude parameters (h_0 or a_p 's), since these are the least informative priors for scaling coefficients [37]; we bound these amplitudes to the $10^{-28} - 10^{-24}$ range [38]. On the other hand, flat amplitude priors are used to compute upper limits, to facilitate comparison with published GR results in Ref. [25]. In all cases, flat priors are placed over all phase offsets (ϕ_0 and all the ϕ_p 's).

For those few cases in which some orientation information exists (see Table I), we analyze the data a second time using the triaxial parametrization of tensor modes, Eqs. (7) and (8), taking that information into account by marginalizing over ranges of $\cos \iota$ and ψ in agreement with measurement uncertainties. Following previous work [25], we only consider orientation constraints obtained from pulsar wind nebulae. However, pulsar orientations can also be inferred from other measurements, especially if the object is in a binary (e.g., Refs. [39–41]). We will consider incorporating such constraints in future searches.

Results.—We find no evidence of continuous-wave signals of any polarization, tensorial or otherwise, from any of the 200 pulsars analyzed. The main quantity of interest is $\log_{10} \mathcal{O}_I^S$, defined in Eq. (12), since it encodes the probability that the data contain a signal vs just instrumental noise (Gaussian or otherwise). This quantity, together with the $\log(\text{odds})$ for signal vs Gaussian noise, is presented as a function of assumed emission frequency for each pulsar in Fig. 1, and histogrammed in Fig. 2. Importantly, the outliers in Fig. 1 lose significance once $\log_{10} \mathcal{O}_I^S$ is taken into account; indeed, Figs. 1 and 2 reveal the usefulness of $\log_{10} \mathcal{O}_I^S$ in increasing the robustness of the search against non-Gaussian instrumental artifacts.

Based on the intrinsic probabilistic meaning of $\log_{10} \mathcal{O}_I^S$ in terms of betting odds, it is standard to demand at least $\log_{10} \mathcal{O}_I^S > 1$ to conclude that the signal model is favored (see, e.g., the table in Sec. 3.2 of Ref. [46], or Jeffrey's original criteria in Ref. [47] or [48]). Since none of the odds obtained meet this criterion, we conclude that there is no evidence for signals from any of the pulsars targeted.

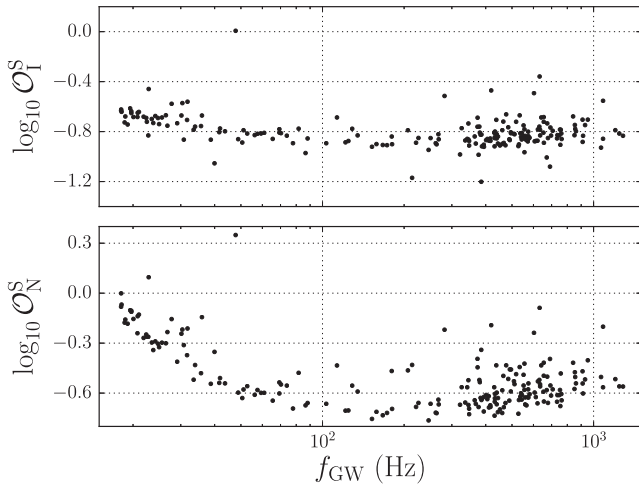


FIG. 1. Log(odds) vs emission frequency. Log(odds) comparing the any-signal hypothesis to the instrumental (top) and Gaussian noise (bottom) hypotheses, as a function of assumed gravitational-wave frequency, $f_{\text{GW}} = 2f_{\text{rot}}$, for each pulsar. Looking at the top plot for $\log_{10} \mathcal{O}_I^S$, notice that the instrumental noise hypothesis is clearly favored for all pulsars except one, for which the analysis is inconclusive. (This is J1932 + 17, the same nonsignificant outlier identified in Ref. [25].) These results were obtained without incorporating any information on the source orientation, and are tabulated in Table II in the Supplemental Material [45]. Expressions for both odds are given in Eq. (10) and Eq. (12).

In most cases, $\log_{10} \mathcal{O}_I^S < 0$ and the noise model is clearly favored; the single exception is J1932 + 17, for which $\log_{10} \mathcal{O}_I^S \sim 0$, so that we can make no conclusive statement about which hypothesis is preferred. (The presence of this nonsignificant outlier is to be expected, as it was already identified in Ref. [25].)

The distribution of the odds corresponding to the subhypotheses making up \mathcal{H}_S are summarized in the box plots of Fig. 3. These correspond to tensor-only (t), scalar-only (s), vector-only (v), scalar-vector (sv), scalar-tensor (st), vector-tensor (vt), and scalar-vector-tensor (stv) models. The mean of these distributions decreases with the number of degrees of freedom in the model, which is to be expected from the associated Occam penalties [21]. The rightmost panel in Fig. 3 shows the distribution of $\log_{10} \mathcal{O}_N^S$, which results from the combination of all the other odds; this is the same quantity histogrammed on the abscissa of Fig. 2.

In the absence of any discernible signals, we produce upper limits for the magnitude of scalar, vector, and tensor polarizations, with a 95% credibility. As usual in Bayesian analyses, upper limits are obtained by integrating posterior probability distributions for the relevant parameters up to the desired credibility (see, e.g., Ref. [21]). Using the effective amplitude definitions of Eqs. (4)–(6), these quantities are presented in Fig. 4 as a function of assumed emission frequency, and the Supplemental Material [45].

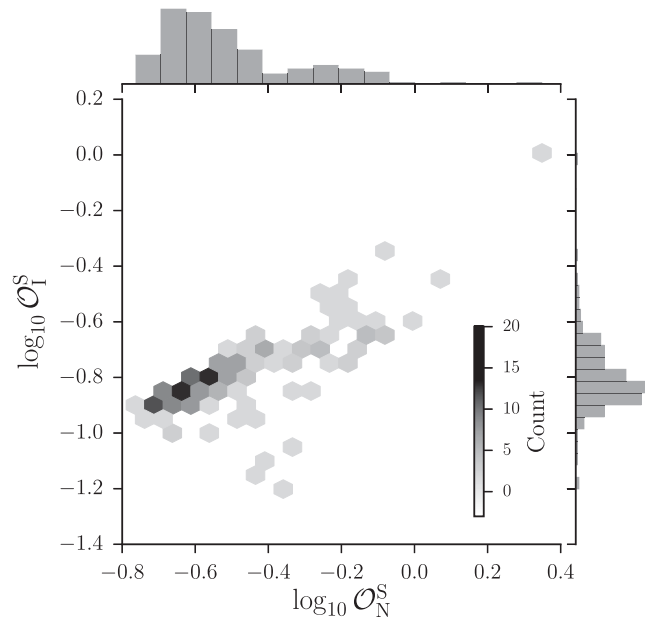


FIG. 2. Log(odds) distributions. Distributions of log(odds) comparing the any-signal hypothesis to the instrumental (ordinate axis, right) and Gaussian noise (abscissa axis, top) hypotheses for all pulsars. This plot contains the same information as Fig. 1 and displays the same nonsignificant outlier. These results were obtained without incorporating any information on the source orientation, and are tabulated in Table II in the Supplemental Material [45]. Expressions for both odds in this plot are given in Eq. (10) and Eq. (12). We underscore that, although this plot looks similar to Fig. 2 in Ref. [25], the signal hypothesis here incorporates scalar, vector, and tensor modes, in all possible combinations.

The plotted upper limits are computed under the assumption of a signal model that includes all five independent polarizations (\mathcal{H}_{svt}); limits obtained assuming other signal models may be found online in Ref. [45]. Previous work has demonstrated that the presence or absence of a GR component does not affect the non-GR upper limits (Fig. 13 in Ref. [21]).

As expected, the upper limits presented here are comparable in magnitude to the upper limits on the GR strain obtained by the traditional searches [25]. However, constraints on the scalar amplitude are, on average, around 20% less stringent than those on the vector or tensor amplitudes. This is a consequence of the fact that, for most source locations in the sky, the LIGO detectors are intrinsically less sensitive to continuous waves of scalar (breathing or longitudinal) polarization [21].

Technically, traditional all-sky searches for continuous gravitational waves are also sensitive to nontensorial modes, because they are generally designed to look for any signal of sidereal and half-sidereal periodicities in the data, without assuming knowledge of phase evolution or source sky location [49–53]. However, as can be seen by comparing the magnitude of all-sky upper limits

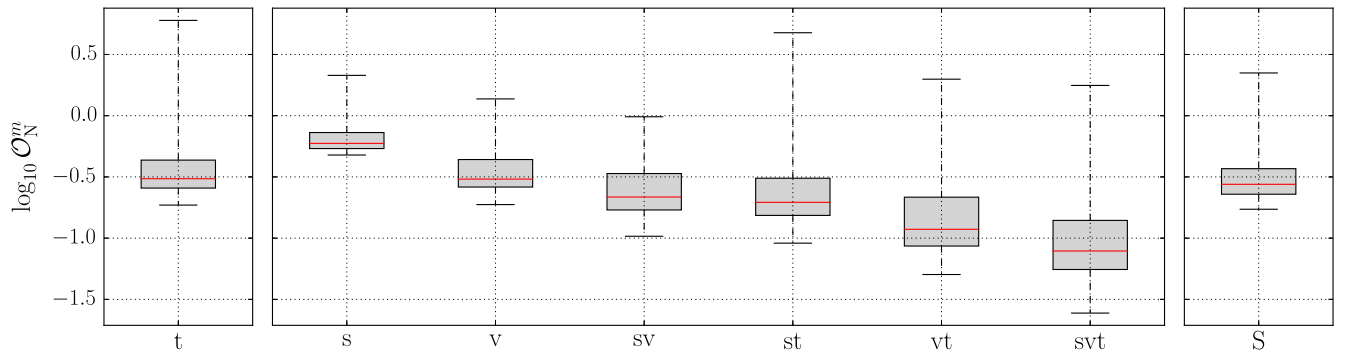


FIG. 3. Sub-hypothesis odds. Box plots for the distribution of the signal vs noise log(odds) for each of the sub-hypotheses considered, for all of the pulsars analyzed. The sub-hypotheses are (st) , vector-tensor (tv) , scalar-vector-tensor tensor-only (t) , scalar-only (s) , vector-only (v) , scalar-vector (sv) , scalar-tensor (st) , vector-tensor (vt) , and scalar-vector-tensor (stv) ; these are all combined into the signal hypothesis (S) . The quantity represented is $\log_{10} \mathcal{B}_N^m$, which is the same as $\log_{10} \mathcal{O}_N^m$ if neither \mathcal{H}_m nor \mathcal{H}_N are favored *a priori* (hence, the label on the ordinate axis). The horizontal red line marks the median of the distribution, while each gray box extends from the lower to upper quartile, and the whiskers mark the full range of the distribution of $\log_{10} \mathcal{O}_N^m$ for the 200 pulsars analyzed. These results were produced without incorporating any information on the source orientation, and are tabulated in Table II in the Supplemental Material [45].

(e.g., Fig. 9 in Ref. [49]) to those shown here in Fig. 4, the sensitivity of these searches would be substantially poorer than that of a targeted search like this one—if only because they are not targeted to a specific source. This is especially true if the search is optimized for a given signal polarization (e.g., circular combination of plus and cross).

Odds and 95%-credible upper limits are summarized in the Supplemental Material: Table I, for pulsars with measured orientations (using the triaxial parameterization of tensor modes), and Table II, for all pulsars without incorporating any orientation information (using the unconstrained parameterization of tensor modes) [45]. Odds values are reported with an error of 5% at 90% confidence; errors on the upper limits due to the use of finite samples in estimating posterior probability distributions are at most 10% at 90% confidence, which is slightly less than the 15% error expected from calibration uncertainties.

Conclusion.—We have presented the results of the first direct search for nontensorial gravitational waves. This is also the first search targeted at known pulsars that is sensitive to any of the five measurable polarizations of the gravitational perturbation allowed by a generic metric theory of gravity. From the analysis of O1 data from both aLIGO observatories, we have found no evidence of signals from any of the 200 pulsars targeted.

In the absence of a clear signal, we have produced the first direct upper limits for scalar and vector strains (Fig. 4, and tables in the Supplemental Material [45]). The values of the 95%-credible upper limits are comparable in magnitude to previously published GR constraints, reaching $h \sim 1.5 \times 10^{-26}$ for pulsars whose frequency is in the most sensitive band of our instruments. This means that, to 95% credibility, none of the pulsars in our set is emitting gravitational waves (tensorial or otherwise) at the frequencies analyzed with enough power for them to reach Earth with amplitudes larger than our upper limits.

Our results have been obtained in a theory-independent fashion. However, our upper limits on nontensorial strain can be translated into model-dependent constraints on beyond-GR theories by picking a specific alternative theory and emission mechanism. To do so, one should use the upper limits produced under the assumption of a signal model that incorporates the same polarizations allowed by the theory one wishes to constrain; these may not necessarily be those in Fig. 4 (e.g., for limits on a scalar-tensor theory, one needs upper limits from \mathcal{H}_{st}). However, this also requires nontrivial knowledge of the dynamics of spinning neutron stars under the theory of interest.

While it is conventional to compare the sensitivity of continuous wave searches to the canonical spin-down limit for each pulsar, it is not possible to do so here without committing to a specific theory of gravity. This is because doing so would require specific knowledge of how each polarization contributes to the effective gravitational-wave stress energy, how matter couples to the gravitational field, how the waves propagate (dispersion and dissipation), and what the angular dependence of the emission pattern is. However, analogs of the canonical spin-down limit for specific theories may be obtained from the results presented here by using the strain upper limits obtained assuming the sub-hypotheses with polarizations corresponding to that theory, as mentioned above.

We have demonstrated the robustness of searches for generalized polarization states (tensor, vector, or scalar) in gravitational waves from spinning neutron stars. Furthermore, even in the absence of a detection, we were able to obtain novel constraints on the strain amplitude of nontensorial polarizations. In the future, once a signal is detected, similar methods will allow us to characterize the gravitational polarization content and, in so doing, perform novel tests of general relativity. Although this search assumed an emission frequency of twice the rotational

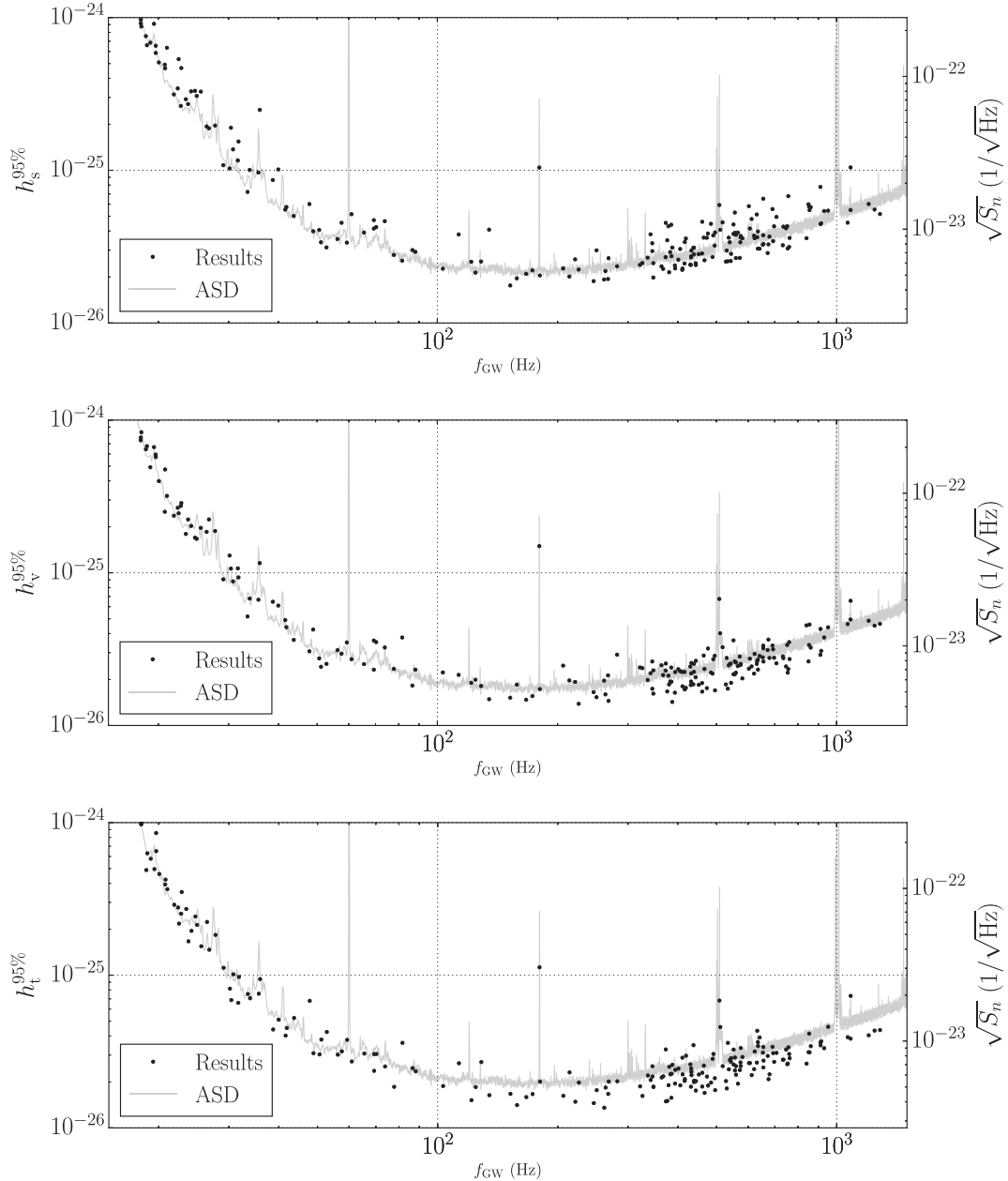


FIG. 4. Non-GR upper limits vs emission frequency. Circles mark the 95%-credible upper limit on the scalar, $h_s^{95\%}$ (top), and the effective vector, $h_v^{95\%}$ (middle), and tensor $h_t^{95\%}$ (bottom) strain amplitudes as a function of assumed gravitational-wave frequency for each of the 200 pulsars in our set. The upper limits are obtained assuming a signal model including all five independent polarizations (\mathcal{H}_{stv}), and incorporating no information on the orientation of the source (Table II in the Supplemental Material [45]). The effective amplitude spectral density (ASD) of the detector noise is also displayed for reference; this is the harmonic mean of the H1 and L1 spectra; the scaling is obtained from linear regression to the upper limits.

frequency of the source, this restriction will be relaxed in future analyses.

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B. P. Abbott,¹ R. Abbott,¹ T. D. Abbott,² F. Acernese,^{3,4} K. Ackley,⁵ C. Adams,⁶ T. Adams,⁷ P. Addesso,⁸ R. X. Adhikari,¹ V. B. Adya,⁹ C. Affeldt,⁹ M. Afrough,¹⁰ B. Agarwal,¹¹ M. Agathos,¹² K. Agatsuma,¹³ N. Aggarwal,¹⁴ O. D. Aguiar,¹⁵ L. Aiello,^{16,17} A. Ain,¹⁸ P. Ajith,¹⁹ G. Allen,¹¹ A. Allocca,^{20,21} P. A. Altin,²² A. Amato,²³ A. Ananyeva,¹ S. B. Anderson,¹ W. G. Anderson,²⁴ S. Antier,²⁵ S. Appert,¹ K. Arai,¹ M. C. Araya,¹ J. S. Areeda,²⁶ N. Arnaud,^{25,27} K. G. Arun,²⁸ S. Ascenzi,^{29,17} G. Ashton,⁹ M. Ast,³⁰ S. M. Aston,⁶ P. Astone,³¹ P. Aufmuth,³² C. Aulbert,⁹ K. AultONeal,³³ A. Avila-Alvarez,²⁶ S. Babak,³⁴ P. Bacon,³⁵ M. K. M. Bader,¹³ S. Bae,³⁶ P. T. Baker,^{37,38} F. Baldaccini,^{39,40} G. Ballardini,²⁷ S. W. Ballmer,⁴¹ S. Banagiri,⁴² J. C. Barayoga,¹ S. E. Barclay,⁴³ B. C. Barish,¹ D. Barker,⁴⁴ F. Barone,^{3,4} B. Barr,⁴³ L. Barsotti,¹⁴ M. Barsuglia,³⁵ D. Barta,⁴⁵ J. Bartlett,⁴⁴ I. Bartos,⁴⁶ R. Bassiri,⁴⁷ A. Basti,^{20,21} J. C. Batch,⁴⁴ C. Baune,⁹ M. Bawaj,^{48,40} M. Bazzan,^{49,50} B. Bécsy,⁵¹ C. Beer,⁹ M. Bejger,⁵² I. Belahcene,²⁵ A. S. Bell,⁴³ B. K. Berger,¹ G. Bergmann,⁹ C. P. L. Berry,⁵³ D. Bersanetti,^{54,55} A. Bertolini,¹³ J. Betzwieser,⁶ S. Bhagwat,⁴¹ R. Bhandare,⁵⁶ I. A. Bilenko,⁵⁷ G. Billingsley,¹ C. R. Billman,⁵ J. Birch,⁶ R. Birney,⁵⁸ O. Birnholtz,⁹ S. Biscans,¹⁴ A. Bisht,³² M. Bitossi,^{27,21} C. Biwer,⁴¹ M. A. Bizouard,²⁵ J. K. Blackburn,¹ J. Blackman,⁵⁹ C. D. Blair,⁶⁰ D. G. Blair,⁶⁰ R. M. Blair,⁴⁴ S. Bloemen,⁶¹ O. Bock,⁹ N. Bode,⁹ M. Boer,⁶² G. Bogaert,⁶² A. Bohe,³⁴ F. Bondu,⁶³ R. Bonnand,⁷ B. A. Boom,¹³ R. Bork,¹ V. Boschi,^{20,21} S. Bose,^{64,18} Y. Bouffanais,³⁵ A. Bozzi,²⁷ C. Bradaschia,²¹ P. R. Brady,²⁴ V. B. Braginsky,^{57,†} M. Branchesi,^{65,66} J. E. Brau,⁶⁷ T. Briant,⁶⁸ A. Brillet,⁶² M. Brinkmann,⁹ V. Brisson,²⁵ P. Brockill,²⁴ J. E. Broida,⁶⁹ A. F. Brooks,¹ D. A. Brown,⁴¹ D. D. Brown,⁵³ N. M. Brown,¹⁴ S. Brunett,¹ C. C. Buchanan,² A. Buikema,¹⁴ T. Bulik,⁷⁰ H. J. Bulten,^{71,13} A. Buonanno,^{34,72} D. Buskulic,⁷ C. Buy,³⁵ R. L. Byer,⁴⁷ M. Cabero,⁹ L. Cadonati,⁷³ G. Cagnoli,^{23,74} C. Cahillane,¹ J. Calderón Bustillo,⁷³ T. A. Callister,¹ E. Calloni,^{75,4} J. B. Camp,⁷⁶ M. Canepa,^{54,55} P. Canizares,⁶¹ K. C. Cannon,⁷⁷ H. Cao,⁷⁸ J. Cao,⁷⁹ C. D. Capano,⁹ E. Capocasa,³⁵ F. Carbognani,²⁷ S. Caride,⁸⁰ M. F. Carney,⁸¹ J. Casanueva Diaz,²⁵ C. Casentini,^{29,17} S. Caudill,²⁴ M. Cavaglia,¹⁰ F. Cavalier,²⁵ R. Cavalieri,²⁷ G. Cella,²¹ C. B. Cepeda,¹ L. Cerboni Baiardi,^{65,66} G. Cerretani,^{20,21} E. Cesarini,^{29,17} S. J. Chamberlin,⁸² M. Chan,⁴³ S. Chao,⁸³ P. Charlton,⁸⁴ E. Chassande-Mottin,³⁵ D. Chatterjee,²⁴ B. D. Cheeseboro,^{37,38} H. Y. Chen,⁸⁵ Y. Chen,⁵⁹ H.-P. Cheng,⁵ A. Chincarini,⁵⁵ A. Chiummo,²⁷ T. Chmiel,⁸¹ H. S. Cho,⁸⁶ M. Cho,⁷² J. H. Chow,²² N. Christensen,^{69,62} Q. Chu,⁶⁰ A. J. K. Chua,¹² S. Chua,⁶⁸ A. K. W. Chung,⁸⁷ S. Chung,⁶⁰ G. Ciani,⁵ R. Ciolfi,^{88,89} C. E. Cirelli,⁴⁷ A. Cirone,^{54,55} F. Clara,⁴⁴ J. A. Clark,⁷³ F. Cleva,⁶² C. Cocchiari,¹⁰ E. Coccia,^{16,17} P.-F. Cohadon,⁶⁸ A. Colla,^{90,31} C. G. Collette,⁹¹ L. R. Cominsky,⁹² M. Constanancio Jr.,¹⁵ L. Conti,⁵⁰ S. J. Cooper,⁵³ P. Corban,⁶ T. R. Corbitt,² K. R. Corley,⁴⁶ N. Cornish,⁹³ A. Corsi,⁸⁰ S. Cortese,²⁷ C. A. Costa,¹⁵ M. W. Coughlin,⁶⁹ S. B. Coughlin,^{94,95} J.-P. Coulon,⁶² S. T. Countryman,⁴⁶ P. Couvares,¹ P. B. Covas,⁹⁶ E. E. Cowan,⁷³ D. M. Coward,⁶⁰ M. J. Cowart,⁶ D. C. Coyne,¹ R. Coyne,⁸⁰ J. D. E. Creighton,²⁴ T. D. Creighton,⁹⁷ J. Cripe,² S. G. Crowder,⁹⁸ T. J. Cullen,²⁶ A. Cumming,⁴³ L. Cunningham,⁴³ E. Cuoco,²⁷ T. Dal Canton,⁷⁶ S. L. Danilishin,^{32,9} S. D'Antonio,¹⁷ K. Danzmann,^{32,9} A. Dasgupta,⁹⁹ C. F. Da Silva Costa,⁵ V. Dattilo,²⁷ I. Dave,⁵⁶ M. Davier,²⁵ D. Davis,⁴¹

E. J. Daw,¹⁰⁰ B. Day,⁷³ S. De,⁴¹ D. DeBra,⁴⁷ J. Degallaix,²³ M. De Laurentis,^{75,4} S. Deléglise,⁶⁸ W. Del Pozzo,^{53,20,21}
 T. Denker,⁹ T. Dent,⁹ V. Dergachev,³⁴ R. De Rosa,^{75,4} R. T. DeRosa,⁶ R. DeSalvo,¹⁰¹ J. Devenson,⁵⁸ R. C. Devine,^{37,38}
 S. Dhurandhar,¹⁸ M. C. Díaz,⁹⁷ L. Di Fiore,⁴ M. Di Giovanni,^{102,89} T. Di Girolamo,^{75,4,46} A. Di Lieto,^{20,21} S. Di Pace,^{90,31}
 I. Di Palma,^{90,31} F. Di Renzo,^{20,21} Z. Doctor,⁸⁵ V. Dolique,²³ F. Donovan,¹⁴ K. L. Dooley,¹⁰ S. Doravari,⁹ I. Dorrington,⁹⁵
 R. Douglas,⁴³ M. Dovale Álvarez,⁵³ T. P. Downes,²⁴ M. Drago,⁹ R. W. P. Drever,^{1,†} J. C. Driggers,⁴⁴ Z. Du,⁷⁹ M. Ducrot,⁷
 J. Duncan,⁹⁴ S. E. Dwyer,⁴⁴ T. B. Edo,¹⁰⁰ M. C. Edwards,⁶⁹ A. Effler,⁶ H.-B. Eggenstein,⁹ P. Ehrens,¹ J. Eichholz,¹
 S. S. Eikenberry,⁵ R. A. Eisenstein,¹⁴ R. C. Essick,¹⁴ Z. B. Etienne,^{37,38} T. Etzel,¹ M. Evans,¹⁴ T. M. Evans,⁶
 M. Factourovich,⁴⁶ V. Fafone,^{29,17,16} H. Fair,⁴¹ S. Fairhurst,⁹⁵ X. Fan,⁷⁹ S. Farinon,⁵⁵ B. Farr,⁸⁵ W. M. Farr,⁵³
 E. J. Fauchon-Jones,⁹⁵ M. Favata,¹⁰³ M. Fays,⁹⁵ H. Fehrmann,⁹ J. Feicht,¹ M. M. Fejer,⁴⁷ A. Fernandez-Galiana,¹⁴
 I. Ferrante,^{20,21} E. C. Ferreira,¹⁵ F. Ferrini,²⁷ F. Fidecaro,^{20,21} I. Fiori,²⁷ D. Fiorucci,³⁵ R. P. Fisher,⁴¹ R. Flaminio,^{23,104}
 M. Fletcher,⁴³ H. Fong,¹⁰⁵ P. W. F. Forsyth,²² S. S. Forsyth,⁷³ J.-D. Fournier,⁶² S. Frasca,^{90,31} F. Frasconi,²¹ Z. Frei,⁵¹
 A. Freise,⁵³ R. Frey,⁶⁷ V. Frey,²⁵ E. M. Fries,¹ P. Fritschel,¹⁴ V. V. Frolov,⁶ P. Fulda,^{5,76} M. Fyffe,⁶ H. Gabbard,⁹ M. Gabel,¹⁰⁶
 B. U. Gadre,¹⁸ S. M. Gaebel,⁵³ J. R. Gair,¹⁰⁷ L. Gammaitoni,³⁹ M. R. Ganija,⁷⁸ S. G. Gaonkar,¹⁸ F. Garufi,^{75,4} S. Gaudio,³³
 G. Gaur,¹⁰⁸ V. Gayathri,¹⁰⁹ N. Gehrels,^{76,†} G. Gemme,⁵⁵ E. Genin,²⁷ A. Gennai,²¹ D. George,¹¹ J. George,⁵⁶ L. Gergely,¹¹⁰
 V. Germain,⁷ S. Ghonge,⁷³ Abhirup Ghosh,¹⁹ Archisman Ghosh,^{19,13} S. Ghosh,^{61,13} J. A. Giaime,^{2,6} K. D. Giardina,⁶
 A. Giazotto,²¹ K. Gill,³³ L. Glover,¹⁰¹ E. Goetz,⁹ R. Goetz,⁵ S. Gomes,⁹⁵ G. González,² J. M. Gonzalez Castro,^{20,21}
 A. Gopakumar,¹¹¹ M. L. Gorodetsky,⁵⁷ S. E. Gossan,¹ M. Gosselin,²⁷ R. Gouaty,⁷ A. Grado,^{112,4} C. Graef,⁴³ M. Granata,²³
 A. Grant,⁴³ S. Gras,¹⁴ C. Gray,⁴⁴ G. Greco,^{65,66} A. C. Green,⁵³ P. Groot,⁶¹ H. Grote,⁹ S. Grunewald,³⁴ P. Gruning,²⁵
 G. M. Guidi,^{65,66} X. Guo,⁷⁹ A. Gupta,⁸² M. K. Gupta,⁹⁹ K. E. Gushwa,¹ E. K. Gustafson,¹ R. Gustafson,¹¹³ B. R. Hall,⁶⁴
 E. D. Hall,¹ G. Hammond,⁴³ M. Haney,¹¹¹ M. M. Hanke,⁹ J. Hanks,⁴⁴ C. Hanna,⁸² O. A. Hannuksela,⁸⁷ J. Hanson,⁶
 T. Hardwick,² J. Harms,^{65,66} G. M. Harry,¹¹⁴ I. W. Harry,³⁴ M. J. Hart,⁴³ C.-J. Haster,¹⁰⁵ K. Haughian,⁴³ J. Healy,¹¹⁵
 A. Heidmann,⁶⁸ M. C. Heintze,⁶ H. Heitmann,⁶² P. Hello,²⁵ G. Hemming,²⁷ M. Hendry,⁴³ I. S. Heng,⁴³ J. Hennig,⁴³
 J. Henry,¹¹⁵ A. W. Heptonstall,¹ M. Heurs,^{9,32} S. Hild,⁴³ D. Hoak,²⁷ D. Hofman,²³ K. Holt,⁶ D. E. Holz,⁸⁵ P. Hopkins,⁹⁵
 C. Horst,²⁴ J. Hough,⁴³ E. A. Houston,⁴³ E. J. Howell,⁶⁰ Y. M. Hu,⁹ E. A. Huerta,¹¹ D. Huet,²⁵ B. Hughey,³³ S. Husa,⁹⁶
 S. H. Huttner,⁴³ T. Huynh-Dinh,⁶ N. Indik,⁹ D. R. Ingram,⁴⁴ R. Inta,⁸⁰ G. Intini,^{90,31} H. N. Isa,⁴³ J.-M. Isac,⁶⁸ M. Isi,¹
 B. R. Iyer,¹⁹ K. Izumi,⁴⁴ T. Jacqmin,⁶⁸ K. Jani,⁷³ P. Jaranowski,¹¹⁶ S. Jawahar,¹¹⁷ F. Jiménez-Forteza,⁹⁶ W. W. Johnson,²
 D. I. Jones,¹¹⁸ R. Jones,⁴³ R. J. G. Jonker,¹³ L. Ju,⁶⁰ J. Junker,⁹ C. V. Kalaghatgi,⁹⁵ V. Kalogera,⁹⁴ S. Kandhasamy,⁶
 G. Kang,³⁶ J. B. Kanner,¹ S. Karki,⁶⁷ K. S. Karvinen,⁹ M. Kasprzack,² M. Katolik,¹¹ E. Katsavounidis,¹⁴ W. Katzman,⁶
 S. Kaufer,³² K. Kawabe,⁴⁴ F. Kéfélian,⁶² D. Keitel,⁴³ A. J. Kamball,¹¹ R. Kennedy,¹⁰⁰ C. Kent,⁹⁵ J. S. Key,¹¹⁹ F. Y. Khalili,⁵⁷
 I. Khan,^{16,17} S. Khan,⁹ Z. Khan,⁹⁹ E. A. Khazanov,¹²⁰ N. Kijbunchoo,⁴⁴ Chunglee Kim,¹²¹ J. C. Kim,¹²² W. Kim,⁷⁸
 W. S. Kim,¹²³ Y.-M. Kim,^{86,121} S. J. Kimbrell,⁷³ E. J. King,⁷⁸ P. J. King,⁴⁴ R. Kirchhoff,⁹ J. S. Kissel,⁴⁴ L. Kleybolte,³⁰
 S. Klimenko,⁵ P. Koch,⁹ S. M. Koehlenbeck,⁹ S. Koley,¹³ V. Kondrashov,¹ A. Kontos,¹⁴ M. Korobko,³⁰ W. Z. Korth,¹
 I. Kowalska,⁷⁰ D. B. Kozak,¹ C. Krämer,⁹ V. Kringel,⁹ B. Krishnan,⁹ A. Królak,^{124,125} G. Kuehn,⁹ P. Kumar,¹⁰⁵ R. Kumar,⁹⁹
 S. Kumar,¹⁹ L. Kuo,⁸³ A. Kutynia,¹²⁴ S. Kwang,²⁴ B. D. Lackey,³⁴ K. H. Lai,⁸⁷ M. Landry,⁴⁴ R. N. Lang,²⁴ J. Lange,¹¹⁵
 B. Lantz,⁴⁷ R. K. Lanza,¹⁴ A. Lartaux-Vollard,²⁵ P. D. Lasky,¹²⁶ M. Laxen,⁶ A. Lazzarini,¹ C. Lazzaro,⁵⁰ P. Leaci,^{90,31}
 S. Leavey,⁴³ C. H. Lee,⁸⁶ H. K. Lee,¹²⁷ H. M. Lee,¹²¹ H. W. Lee,¹²² K. Lee,⁴³ J. Lehmann,⁹ A. Lenon,^{37,38} M. Leonardi,^{102,89}
 N. Leroy,²⁵ N. Letendre,⁷ Y. Levin,¹²⁶ T. G. F. Li,⁸⁷ A. Libson,¹⁴ T. B. Littenberg,¹²⁸ J. Liu,⁶⁰ R. K. L. Lo,⁸⁷
 N. A. Lockerbie,¹¹⁷ L. T. London,⁹⁵ J. E. Lord,⁴¹ M. Lorenzini,^{16,17} V. Loriette,¹²⁹ M. Lormand,⁶ G. Losurdo,²¹
 J. D. Lough,^{9,32} C. O. Lousto,¹¹⁵ G. Lovelace,²⁶ H. Lück,^{32,9} D. Lumaca,^{29,17} A. P. Lundgren,⁹ R. Lynch,¹⁴ Y. Ma,⁵⁹
 S. Macfoy,⁵⁸ B. Machenschalk,⁹ M. MacInnis,¹⁴ D. M. Macleod,² I. Magaña Hernandez,⁸⁷ F. Magaña-Sandoval,⁴¹
 L. Magaña Zertuche,⁴¹ R. M. Magee,⁸² E. Majorana,³¹ I. Maksimovic,¹²⁹ N. Man,⁶² V. Mandic,⁴² V. Mangano,⁴³
 G. L. Mansell,²² M. Manske,²⁴ M. Mantovani,²⁷ F. Marchesoni,^{48,40} F. Marion,⁷ S. Márka,⁴⁶ Z. Márka,⁴⁶ C. Markakis,¹¹
 A. S. Markosyan,⁴⁷ E. Maros,¹ F. Martelli,^{65,66} L. Martellini,⁶² I. W. Martin,⁴³ D. V. Martynov,¹⁴ K. Mason,¹⁴ A. Masserot,⁷
 T. J. Massinger,¹ M. Masso-Reid,⁴³ S. Mastrogiovanni,^{90,31} A. Matas,⁴² F. Matichard,¹⁴ L. Matone,⁴⁶ N. Mavalvala,¹⁴
 N. Mazumder,⁶⁴ R. McCarthy,⁴⁴ D. E. McClelland,²² S. McCormick,⁶ L. McCuller,¹⁴ S. C. McGuire,¹³⁰ G. McIntyre,¹
 J. McIver,¹ D. J. McManus,²² T. McRae,²² S. T. McWilliams,^{37,38} D. Meacher,⁸² G. D. Meadors,^{34,9} J. Meidam,¹³
 E. Mejuto-Villa,⁸ A. Melatos,¹³¹ G. Mendell,⁴⁴ R. A. Mercer,²⁴ E. L. Merilh,⁴⁴ M. Merzougui,⁶² S. Meshkov,¹
 C. Messenger,⁴³ C. Messick,⁸² R. Metzдорff,⁶⁸ P. M. Meyers,⁴² F. Mezzani,^{31,90} H. Miao,⁵³ C. Michel,²³ H. Middleton,⁵³
 E. E. Mikhailov,¹³² L. Milano,^{75,4} A. L. Miller,⁵ A. Miller,^{90,31} B. B. Miller,⁹⁴ J. Miller,¹⁴ M. Millhouse,⁹³ O. Minazzoli,⁶²

Y. Minenkov,¹⁷ J. Ming,³⁴ C. Mishra,¹³³ S. Mitra,¹⁸ V. P. Mitrofanov,⁵⁷ G. Mitselmakher,⁵ R. Mittleman,¹⁴ A. Moggi,²¹
 M. Mohan,²⁷ S. R. P. Mohapatra,¹⁴ M. Montani,^{65,66} B. C. Moore,¹⁰³ C. J. Moore,¹² D. Moraru,⁴⁴ G. Moreno,⁴⁴
 S. R. Morriss,⁹⁷ B. Mours,⁷ C. M. Mow-Lowry,⁵³ G. Mueller,⁵ A. W. Muir,⁹⁵ Arunava Mukherjee,⁹ D. Mukherjee,²⁴
 S. Mukherjee,⁹⁷ N. Mukund,¹⁸ A. Mullavey,⁶ J. Munch,⁷⁸ E. A. M. Muniz,⁴¹ P. G. Murray,⁴³ K. Napier,⁷³ I. Nardecchia,^{29,17}
 L. Naticchioni,^{90,31} R. K. Nayak,¹³⁴ G. Nelemans,^{61,13} T. J. N. Nelson,⁶ M. Neri,^{54,55} M. Nery,⁹ A. Neunzert,¹¹³
 J. M. Newport,¹¹⁴ G. Newton,^{43,†} K. K. Y. Ng,⁸⁷ T. T. Nguyen,²² D. Nichols,⁶¹ A. B. Nielsen,⁹ S. Nissanke,^{61,13} A. Nitz,⁹
 A. Noack,⁹ F. Nocera,²⁷ D. Nolting,⁶ M. E. N. Normandin,⁹⁷ L. K. Nuttall,⁴¹ J. Oberling,⁴⁴ E. Ochsner,²⁴ E. Oelker,¹⁴
 G. H. Ogin,¹⁰⁶ J. J. Oh,¹²³ S. H. Oh,¹²³ F. Ohme,⁹ M. Oliver,⁹⁶ P. Oppermann,⁹ Richard J. Oram,⁶ B. O'Reilly,⁶
 R. Ormiston,⁴² L. F. Ortega,⁵ R. O'Shaughnessy,¹¹⁵ D. J. Ottaway,⁷⁸ H. Overmier,⁶ B. J. Owen,⁸⁰ A. E. Pace,⁸² J. Page,¹²⁸
 M. A. Page,⁶⁰ A. Pai,¹⁰⁹ S. A. Pai,⁵⁶ J. R. Palamos,⁶⁷ O. Palashov,¹²⁰ C. Palomba,³¹ A. Pal-Singh,³⁰ H. Pan,⁸³ B. Pang,⁵⁹
 P. T. H. Pang,⁸⁷ C. Pankow,⁹⁴ F. Pannarale,⁹⁵ B. C. Pant,⁵⁶ F. Paoletti,²¹ A. Paoli,²⁷ M. A. Papa,^{34,24,9} H. R. Paris,⁴⁷
 W. Parker,⁶ D. Pascucci,⁴³ A. Pasqualetti,²⁷ R. Passaquieti,^{20,21} D. Passuello,²¹ B. Patricelli,^{135,21} B. L. Pearlstone,⁴³
 M. Pedraza,¹ R. Pedurand,^{23,136} L. Pekowsky,⁴¹ A. Pele,⁶ S. Penn,¹³⁷ C. J. Perez,⁴⁴ A. Perreca,^{1,102,89} L. M. Perri,⁹⁴
 H. P. Pfeiffer,¹⁰⁵ M. Phelps,⁴³ O. J. Piccinni,^{90,31} M. Pichot,⁶² F. Piergiovanni,^{65,66} V. Pierro,⁸ G. Pillant,²⁷ L. Pinard,²³
 I. M. Pinto,⁸ M. Pitkin,⁴³ R. Poggiani,^{20,21} P. Popolizio,²⁷ E. K. Porter,³⁵ A. Post,⁹ J. Powell,⁴³ J. Prasad,¹⁸ J. W. W. Pratt,³³
 V. Predoi,⁹⁵ T. Prestegard,²⁴ M. Prijatelj,⁹ M. Principe,⁸ S. Privitera,³⁴ R. Prix,⁹ G. A. Prodi,^{102,89} L. G. Prokhorov,⁵⁷
 O. Puncken,⁹ M. Punturo,⁴⁰ P. Puppò,³¹ M. Pürner,³⁴ H. Qi,²⁴ J. Qin,⁶⁰ S. Qiu,¹²⁶ V. Quetschke,⁹⁷ E. A. Quintero,¹
 R. Quitzow-James,⁶⁷ F. J. Raab,⁴⁴ D. S. Rabeling,²² H. Radkins,⁴⁴ P. Raffai,⁵¹ S. Raja,⁵⁶ C. Rajan,⁵⁶ M. Rakhmanov,⁹⁷
 K. E. Ramirez,⁹⁷ P. Rapagnani,^{90,31} V. Raymond,³⁴ M. Razzano,^{20,21} J. Read,²⁶ T. Regimbau,⁶² L. Rei,⁵⁵ S. Reid,⁵⁸
 D. H. Reitze,^{1,5} H. Rew,¹³² S. D. Reyes,⁴¹ F. Ricci,^{90,31} P. M. Ricker,¹¹ S. Rieger,⁹ K. Riles,¹¹³ M. Rizzo,¹¹⁵
 N. A. Robertson,^{1,43} R. Robie,⁴³ F. Robinet,²⁵ A. Rocchi,¹⁷ L. Rolland,⁷ J. G. Rollins,¹ V. J. Roma,⁶⁷ R. Romano,^{3,4}
 C. L. Romel,⁴⁴ J. H. Romie,⁶ D. Rosińska,^{138,52} M. P. Ross,¹³⁹ S. Rowan,⁴³ A. Rüdiger,⁹ P. Ruggi,²⁷ K. Ryan,⁴⁴ S. Sachdev,¹
 T. Sadecki,⁴⁴ L. Sadeghian,²⁴ M. Sakellariadou,¹⁴⁰ L. Salconi,²⁷ M. Saleem,¹⁰⁹ F. Salemi,⁹ A. Samajdar,¹³⁴ L. Sammut,¹²⁶
 L. M. Sampson,⁹⁴ E. J. Sanchez,¹ V. Sandberg,⁴⁴ B. Sandeen,⁹⁴ J. R. Sanders,⁴¹ B. Sassolas,²³ B. S. Sathyaprakash,^{82,95}
 P. R. Saulson,⁴¹ O. Sauter,¹¹³ R. L. Savage,⁴⁴ A. Sawadsky,³² P. Schale,⁶⁷ J. Scheuer,⁹⁴ E. Schmidt,³³ J. Schmidt,⁹
 P. Schmidt,^{1,61} R. Schnabel,³⁰ R. M. S. Schofield,⁶⁷ A. Schönbeck,³⁰ E. Schreiber,⁹ D. Schuette,^{9,32} B. W. Schulte,⁹
 B. F. Schutz,^{95,9} S. G. Schwalbe,³³ J. Scott,⁴³ S. M. Scott,²² E. Seidel,¹¹ D. Sellers,⁶ A. S. Sengupta,¹⁴¹ D. Sentenac,²⁷
 V. Sequino,^{29,17} A. Sergeev,¹²⁰ D. A. Shaddock,²² T. J. Shaffer,⁴⁴ A. A. Shah,¹²⁸ M. S. Shahriar,⁹⁴ L. Shao,³⁴ B. Shapiro,⁴⁷
 P. Shawhan,⁷² A. Sheperd,²⁴ D. H. Shoemaker,¹⁴ D. M. Shoemaker,⁷³ K. Siellez,⁷³ X. Siemens,²⁴ M. Sieniawska,⁵²
 D. Sigg,⁴⁴ A. D. Silva,¹⁵ A. Singer,¹ L. P. Singer,⁷⁶ A. Singh,^{34,9,32} R. Singh,² A. Singhal,^{16,31} A. M. Sintes,⁹⁶
 B. J. J. Slagmolen,²² B. Smith,⁶ J. R. Smith,²⁶ R. J. E. Smith,¹ E. J. Son,¹²³ J. A. Sonnenberg,²⁴ B. Sorazu,⁴³ F. Sorrentino,⁵⁵
 T. Souradeep,¹⁸ A. P. Spencer,⁴³ A. K. Srivastava,⁹⁹ A. Staley,⁴⁶ M. Steinke,⁹ J. Steinlechner,^{43,30} S. Steinlechner,³⁰
 D. Steinmeyer,^{9,32} B. C. Stephens,²⁴ R. Stone,⁹⁷ K. A. Strain,⁴³ G. Stratta,^{65,66} S. E. Strigin,⁵⁷ R. Sturani,¹⁴² A. L. Stuver,⁶
 T. Z. Summerscales,¹⁴³ L. Sun,¹³¹ S. Sunil,⁹⁹ P. J. Sutton,⁹⁵ B. L. Swinkels,²⁷ M. J. Szczepańczyk,³³ M. Tacca,³⁵
 D. Talukder,⁶⁷ D. B. Tanner,⁵ M. Tápai,¹¹⁰ A. Taracchini,³⁴ J. A. Taylor,¹²⁸ R. Taylor,¹ T. Theeg,⁹ E. G. Thomas,⁵³
 M. Thomas,⁶ P. Thomas,⁴⁴ K. A. Thorne,⁶ K. S. Thorne,⁵⁹ E. Thrane,¹²⁶ S. Tiwari,^{16,89} V. Tiwari,⁹⁵ K. V. Tokmakov,¹¹⁷
 K. Toland,⁴³ M. Tonelli,^{20,21} Z. Tornasi,⁴³ C. I. Torrie,¹ D. Töyrä,⁵³ F. Travasso,^{27,40} G. Traylor,⁶ D. Trifirò,¹⁰ J. Trinastic,⁵
 M. C. Tringali,^{102,89} L. Trozzo,^{144,21} K. W. Tsang,¹³ M. Tse,¹⁴ R. Tso,¹ D. Tuyenbayev,⁹⁷ K. Ueno,²⁴ D. Ugolini,¹⁴⁵
 C. S. Unnikrishnan,¹¹¹ A. L. Urban,¹ S. A. Usman,⁹⁵ H. Vahlbruch,³² G. Vajente,¹ G. Valdes,⁹⁷ M. Vallisneri,⁵⁹
 N. van Bakel,¹³ M. van Beuzekom,¹³ J. F. J. van den Brand,^{71,13} C. Van Den Broeck,¹³ D. C. Vander-Hyde,⁴¹
 L. van der Schaaf,¹³ J. V. van Heijningen,¹³ A. A. van Veggel,⁴³ M. Vardaro,^{49,50} V. Varma,⁵⁹ S. Vass,¹ M. Vasúth,⁴⁵
 A. Vecchio,⁵³ G. Vedovato,⁵⁰ J. Veitch,⁵³ P. J. Veitch,⁷⁸ K. Venkateswara,¹³⁹ G. Venugopalan,¹ D. Verkindt,⁷ F. Vetrano,^{65,66}
 A. Viceré,^{65,66} A. D. Viets,²⁴ S. Vinciguerra,⁵³ D. J. Vine,⁵⁸ J.-Y. Vinet,⁶² S. Vitale,¹⁴ T. Vo,⁴¹ H. Vocca,^{39,40} C. Vorvick,⁴⁴
 D. V. Voss,⁵ W. D. Vousden,⁵³ S. P. Vyatchanin,⁵⁷ A. R. Wade,¹ L. E. Wade,⁸¹ M. Wade,⁸¹ R. Walet,¹³ M. Walker,²
 L. Wallace,¹ S. Walsh,²⁴ G. Wang,^{16,66} H. Wang,⁵³ J. Z. Wang,⁸² M. Wang,⁵³ Y.-F. Wang,⁸⁷ Y. Wang,⁶⁰ R. L. Ward,²²
 J. Warner,⁴⁴ M. Was,⁷ J. Watchi,⁹¹ B. Weaver,⁴⁴ L.-W. Wei,^{9,32} M. Weinert,⁹ A. J. Weinstein,¹ R. Weiss,¹⁴ L. Wen,⁶⁰
 E. K. Wessel,¹¹ P. Weßels,⁹ T. Westphal,⁹ K. Wette,⁹ J. T. Whelan,¹¹⁵ B. F. Whiting,⁵ C. Whittle,¹²⁶ D. Williams,⁴³
 R. D. Williams,¹ A. R. Williamson,¹¹⁵ J. L. Willis,¹⁴⁶ B. Willke,^{32,9} M. H. Wimmer,^{9,32} W. Winkler,⁹ C. C. Wipf,¹
 H. Wittel,^{9,32} G. Woan,⁴³ J. Woehler,⁹ J. Wofford,¹¹⁵ K. W. K. Wong,⁸⁷ J. Worden,⁴⁴ J. L. Wright,⁴³ D. S. Wu,⁹ G. Wu,⁶

W. Yam,¹⁴ H. Yamamoto,¹ C. C. Yancey,⁷² M. J. Yap,²² Hang Yu,¹⁴ Haocun Yu,¹⁴ M. Yvert,⁷ A. Zadrożny,¹²⁴ M. Zanolin,³³
 T. Zelenova,²⁷ J.-P. Zendri,⁵⁰ M. Zevin,⁹⁴ L. Zhang,¹ M. Zhang,¹³² T. Zhang,⁴³ Y.-H. Zhang,¹¹⁵ C. Zhao,⁶⁰ M. Zhou,⁹⁴
 Z. Zhou,⁹⁴ S. J. Zhu,^{34,9} X. J. Zhu,⁶⁰ M. E. Zucker,^{1,14} and J. Zweizig¹

(LIGO Scientific Collaboration and Virgo Collaboration)

S. Buchner,^{147,148} I. Cognard,^{149,150} A. Corongiu,¹⁵¹ P. C. C. Freire,¹⁵² L. Guillemot,^{149,150} G. B. Hobbs,¹⁵³ M. Kerr,¹⁵⁴
 A. G. Lyne,¹⁵⁵ A. Possenti,¹⁵¹ A. Ridolfi,¹⁵² R. M. Shannon,^{153,156} B. W. Stappers,¹⁵⁵ and P. Weltevrede¹⁵⁵

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

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

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

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

⁵University of Florida, Gainesville, Florida 32611, USA

⁶LIGO Livingston Observatory, Livingston, Louisiana 70754, USA

⁷Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France

⁸University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy

⁹Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany

¹⁰The University of Mississippi, University, Mississippi 38677, USA

¹¹NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

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

¹³Nikhef, Science Park, 1098 XG Amsterdam, Netherlands

¹⁴LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

¹⁵Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil

¹⁶Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

¹⁷INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy

¹⁸Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

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

²⁰Università di Pisa, I-56127 Pisa, Italy

²¹INFN, Sezione di Pisa, I-56127 Pisa, Italy

²²OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

²³Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France

²⁴University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA

²⁵LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France

²⁶California State University Fullerton, Fullerton, California 92831, USA

²⁷European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy

²⁸Chennai Mathematical Institute, Chennai 603103, India

²⁹Università di Roma Tor Vergata, I-00133 Roma, Italy

³⁰Universität Hamburg, D-22761 Hamburg, Germany

³¹INFN, Sezione di Roma, I-00185 Roma, Italy

³²Leibniz Universität Hannover, D-30167 Hannover, Germany

³³Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA

³⁴Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany

³⁵APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France

³⁶Korea Institute of Science and Technology Information, Daejeon 34141, Korea

³⁷West Virginia University, Morgantown, West Virginia 26506, USA

³⁸Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, West Virginia 26505, USA

³⁹Università di Perugia, I-06123 Perugia, Italy

⁴⁰INFN, Sezione di Perugia, I-06123 Perugia, Italy

⁴¹Syracuse University, Syracuse, New York 13244, USA

⁴²University of Minnesota, Minneapolis, Minnesota 55455, USA

⁴³SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom

⁴⁴LIGO Hanford Observatory, Richland, Washington 99352, USA

⁴⁵Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary

⁴⁶Columbia University, New York, New York 10027, USA

⁴⁷Stanford University, Stanford, California 94305, USA

⁴⁸Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy

- ⁴⁹*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
⁵⁰*INFN, Sezione di Padova, I-35131 Padova, Italy*
⁵¹*MTA Eötvös University, “Lendulet” Astrophysics Research Group, Budapest 1117, Hungary*
⁵²*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
⁵³*University of Birmingham, Birmingham B15 2TT, United Kingdom*
⁵⁴*Università degli Studi di Genova, I-16146 Genova, Italy*
⁵⁵*INFN, Sezione di Genova, I-16146 Genova, Italy*
⁵⁶*RRCAT, Indore, Madhya Pradesh 452013, India*
⁵⁷*Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
⁵⁸*SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
⁵⁹*Caltech CaRT, Pasadena, California 91125, USA*
⁶⁰*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
⁶¹*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands*
⁶²*Artemis, Université Côte d’Azur, Observatoire Côte d’Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France*
⁶³*Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France*
⁶⁴*Washington State University, Pullman, Washington 99164, USA*
⁶⁵*Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy*
⁶⁶*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
⁶⁷*University of Oregon, Eugene, Oregon 97403, USA*
⁶⁸*Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France*
⁶⁹*Carleton College, Northfield, Minnesota 55057, USA*
⁷⁰*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
⁷¹*VU University Amsterdam, 1081 HV Amsterdam, Netherlands*
⁷²*University of Maryland, College Park, Maryland 20742, USA*
⁷³*Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
⁷⁴*Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*
⁷⁵*Università di Napoli ‘Federico II’, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
⁷⁶*NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
⁷⁷*RESCEU, University of Tokyo, Tokyo, 113-0033, Japan*
⁷⁸*OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
⁷⁹*Tsinghua University, Beijing 100084, China*
⁸⁰*Texas Tech University, Lubbock, Texas 79409, USA*
⁸¹*Kenyon College, Gambier, Ohio 43022, USA*
⁸²*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
⁸³*National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China*
⁸⁴*Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
⁸⁵*University of Chicago, Chicago, Illinois 60637, USA*
⁸⁶*Pusan National University, Busan 46241, Korea*
⁸⁷*The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong*
⁸⁸*INAF, Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy*
⁸⁹*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
⁹⁰*Università di Roma “La Sapienza,” I-00185 Roma, Italy*
⁹¹*Université Libre de Bruxelles, Brussels 1050, Belgium*
⁹²*Sonoma State University, Rohnert Park, California 94928, USA*
⁹³*Montana State University, Bozeman, Montana 59717, USA*
⁹⁴*Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, Illinois 60208, USA*
⁹⁵*Cardiff University, Cardiff CF24 3AA, United Kingdom*
⁹⁶*Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain*
⁹⁷*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
⁹⁸*Bellevue College, Bellevue, Washington 98007, USA*
⁹⁹*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
¹⁰⁰*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
¹⁰¹*California State University, Los Angeles, 5151 State University Drive, Los Angeles, California 90032, USA*
¹⁰²*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
¹⁰³*Montclair State University, Montclair, New Jersey 07043, USA*
¹⁰⁴*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
¹⁰⁵*Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada*
¹⁰⁶*Whitman College, 345 Boyer Avenue, Walla Walla, Washington 99362, USA*

- ¹⁰⁷*School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
- ¹⁰⁸*University and Institute of Advanced Research, Gandhinagar Gujarat 382007, India*
- ¹⁰⁹*IISER-TVM, CET Campus, Trivandrum Kerala 695016, India*
- ¹¹⁰*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
- ¹¹¹*Tata Institute of Fundamental Research, Mumbai 400005, India*
- ¹¹²*INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy*
- ¹¹³*University of Michigan, Ann Arbor, Michigan 48109, USA*
- ¹¹⁴*American University, Washington, D.C. 20016, USA*
- ¹¹⁵*Rochester Institute of Technology, Rochester, New York 14623, USA*
- ¹¹⁶*University of Białystok, 15-424 Białystok, Poland*
- ¹¹⁷*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
- ¹¹⁸*University of Southampton, Southampton SO17 1BJ, United Kingdom*
- ¹¹⁹*University of Washington Bothell, 18115 Campus Way NE, Bothell, Washington 98011, USA*
- ¹²⁰*Institute of Applied Physics, Nizhny Novgorod, 603950, Russia*
- ¹²¹*Seoul National University, Seoul 08826, Korea*
- ¹²²*Inje University Gimhae, South Gyeongsang 50834, Korea*
- ¹²³*National Institute for Mathematical Sciences, Daejeon 34047, Korea*
- ¹²⁴*NCBJ, 05-400 Świerk-Otwock, Poland*
- ¹²⁵*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ¹²⁶*OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
- ¹²⁷*Hanyang University, Seoul 04763, Korea*
- ¹²⁸*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
- ¹²⁹*ESPCI, CNRS, F-75005 Paris, France*
- ¹³⁰*Southern University and A&M College, Baton Rouge, Louisiana 70813, USA*
- ¹³¹*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
- ¹³²*College of William and Mary, Williamsburg, Virginia 23187, USA*
- ¹³³*Indian Institute of Technology Madras, Chennai 600036, India*
- ¹³⁴*IISER-Kolkata, Mohanpur, West Bengal 741252, India*
- ¹³⁵*Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy*
- ¹³⁶*Université de Lyon, F-69361 Lyon, France*
- ¹³⁷*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
- ¹³⁸*Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland*
- ¹³⁹*University of Washington, Seattle, Washington 98195, USA*
- ¹⁴⁰*King's College London, University of London, London WC2R 2LS, United Kingdom*
- ¹⁴¹*Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India*
- ¹⁴²*International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal, Rio Grande do Norte, 59078-970, Brazil*
- ¹⁴³*Andrews University, Berrien Springs, Michigan 49104, USA*
- ¹⁴⁴*Università di Siena, I-53100 Siena, Italy*
- ¹⁴⁵*Trinity University, San Antonio, Texas 78212, USA*
- ¹⁴⁶*Abilene Christian University, Abilene, Texas 79699, USA*
- ¹⁴⁷*Square Kilometer Array South Africa, The Park, Park Road, Pinelands, Cape Town 7405, South Africa*
- ¹⁴⁸*Hartebeesthoek Radio Astronomy Observatory, PO Box 443, Krugersdorp, 1740, South Africa*
- ¹⁴⁹*Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, LPC2E, CNRS-Université d'Orléans, F-45071 Orléans, France*
- ¹⁵⁰*Station de Radioastronomie de Nançay, Observatoire de Paris, CNRS/INSU, F-18330 Nançay, France*
- ¹⁵¹*INAF—Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047 Selargius, Italy*
- ¹⁵²*Max-Planck-Institut für Radioastronomie MPIfR, Auf dem Hügel 69, D-53121 Bonn, Germany*
- ¹⁵³*CSIRO Astronomy and Space Science, Australia Telescope National Facility, Box 76 Epping, NSW, 1710, Australia*
- ¹⁵⁴*Space Science Division, Naval Research Laboratory, Washington, D.C. 20375-5352, USA*
- ¹⁵⁵*Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
- ¹⁵⁶*International Centre for Radio Astronomy Research, Curtin University, Bentley, Western Australia 6101, Australia*

[†]Deceased.