First search for nontensorial gravitational waves from known pulsars

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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.

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 streched 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 noncooriented 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. [16, 17], or [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 paper, 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 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 [26], generalized to non-GR modes as described in [21] and summarized below. Our analysis follows closely that of [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 [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 [21], we construct a Bayesian hypothesis that captures signals of any polarization content (our *any-signal* hypothesis, $\mathcal{H}_{\rm S}$) 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:

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

where the sum is over the five independent polarizations: plus (+), cross (×), 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. [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 the Earth; explicit expressions for the F_p's are given in [20–22, 29, 30].

For a continuous wave, the polarizations take the simple form:

$$h_p(t) = a_p \cos(\phi(t) + \phi_p), \tag{2}$$

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. [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]:

TABLE I. Existing orientation information for pulsars in our band, obtained from observations of the pulsar wind nebulae (see Table 3 in [34], and [35, 36] 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	N/A	$-11^\circ.5 \pm 8^\circ.6$

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

where $\partial_t^{(j)} f_{\rm GW,0}$ is the $j^{\rm th}$ time derivative of $f_{\rm GW,0}$, 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 $f_{\rm GW}$ is related to the rotational frequency of the source $f_{\rm rot}$, 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 $f_{\rm GW} = 2 f_{\rm rot}$, in accordance with the most favored emission model in GR [24]. This restriction arises from practical considerations affecting our specific implementation, and will be relaxd in future studies.

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

$$h_{\rm t} \equiv \sqrt{a_+^2 + a_\times^2}, \tag{4}$$

$$h_{\rm v} \equiv \sqrt{a_{\rm x}^2 + a_{\rm y}^2}, \tag{5}$$

$$h_{\rm s} \equiv a_{\rm s}, \tag{6}$$

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:

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

$$a_\times = h_0 \cos\iota \ , \ \phi_\times = \phi_0 - \pi/2, \tag{8}$$

$$a_{\rm x} = a_{\rm y} = a_{\rm s} = 0, \tag{9}$$

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. [37]). 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 $\phi_\times$.

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 [38] (see [21] for details specific to non-GR polarizations). The Bayes factors corresponding to each signal model may be combined into the odds $\mathcal{O}^{\rm S}_{\rm N}$ that the data contain a continuous signal of any polarization vs Gaussian noise:

$$\mathcal{O}^{\rm S}_{\rm N} = P(\mathcal{H}_{\rm S} \mid \mathbf{B}) / P(\mathcal{H}_{\rm N} \mid \mathbf{B}) \,, \tag{10}$$

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

$$\mathcal{B}^{\rm S}_{\rm N} \equiv P(\mathbf{B} \mid \mathcal{H}_{\rm S}) / P(\mathbf{B} \mid \mathcal{H}_{\rm N}) \,. \tag{11}$$

Built into the astrophysical signal hypothesis, $\mathcal{H}_{\rm S}$, 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, $\mathcal{H}_{\rm I}$, that identifies non-Gaussian noise artifacts by their lack of coherence across detectors [25, 39]. In particular, we define $\mathcal{H}_{\rm I}$ 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 $\mathcal{H}_{\rm S}$ by means of the odds $\mathcal{O}^{\rm S}_{\rm I}$. For D detectors, this is given by:

$$\log \mathcal{O}^{\rm S}_{\rm I} = \log \mathcal{B}^{\rm S}_{\rm N} - \sum_{d=1}^{D} \log\left(\mathcal{B}^{{\rm S}_d}_{{\rm N}_d} + 1\right), \tag{12}$$

where $\mathcal{B}^{{\rm S}_d}_{{\rm N}_d}$ is the signal vs noise Bayes factor computed only from data from the $d^{\rm th}$ detector. This choice implicitly assigns prior weight to the models such that $P(\mathcal{H}_{\rm S}) = P(\mathcal{H}_{\rm I}) \times 0.5^D$ [21]. For an in depth analysis of the behavior of the different Bayesian hypotheses considered here, in the presence and absence of simulated signals of all polarizations, we again refer the reader to the methods paper [21].

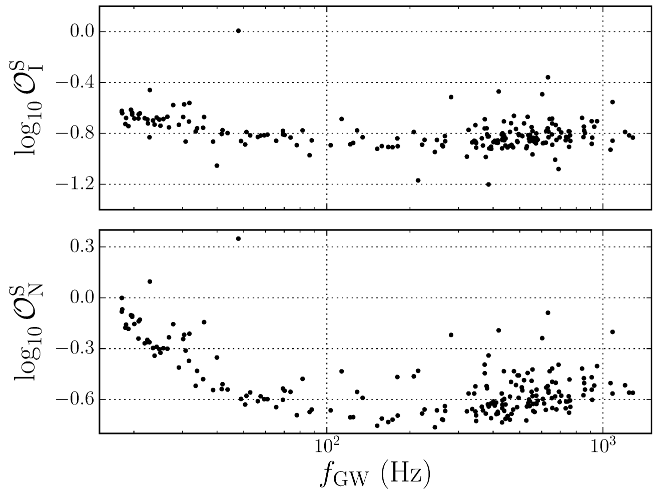

FIG. 1. *Log-odds vs emission frequency.* Log-odds comparing the any-signal hypothesis to the instrumental (top) and Gaussian noise (bottom) hypotheses, as a function of assumed gravitational-wave frequency, $f_{\rm GW} = 2f_{\rm rot}$, for each pulsar. Looking at the top plot for $\log_{10} \mathcal{O}^{\rm S}_{\rm I}$, 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 non-significant outlier identified in [25].) These results were obtained without incorporating any information on the source orientation, and are tabulated in Table II in the supplementary material [40]. Expressions for both odds are given in Eq. (10) and Eq. (12).

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 [41]; we bound these amplitudes to the 10^{-28}–10^{-24} range [42]. On the other hand, flat amplitude priors are used to compute upper limits, to facilitate comparison with published GR results in [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. [43–45]). 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 in-

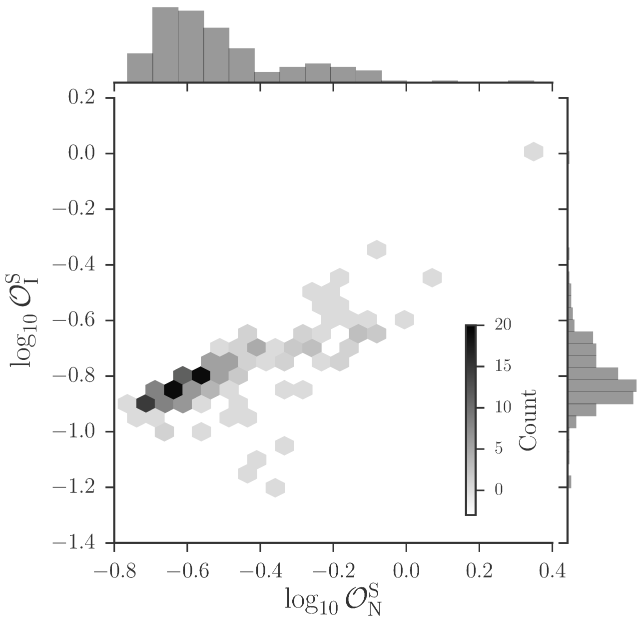

FIG. 2. *Log-odds distributions.* Distributions of log-odds comparing the any-signal hypothesis to the instrumental (ordinate axis, right) and Gaussian noise (abscissa axis, top) hypotheses for all pulsars. This plot contains the same information as Fig. 1 and displays the same non-significant outlier. These results were obtained without incorporating any information on the source orientation, and are tabulated in Table II in the supplementary material [40]. 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 [25], the signal hypothesis here incorporates scalar, vector and tensor modes, in all possible combinations.

terest is $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}}$, 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-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 $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}}$ is taken into account; indeed, Figs. 1 and 2 reveal the usefulness of $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}}$ in increasing the robustness of the search against non-Gaussian instrumental artifacts.

Based on the intrinsic probabilistic meaning of $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}}$ in terms of betting odds, it is standard to demand at least $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}} > 1$ to conclude that the signal model is favored (see e.g. the table in Sec. 3.2 of [46], or Jeffrey's original criteria in [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. In most cases, $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}} < 0$ and the noise model is clearly favored; the single exception is J1932+17, for which $\log_{10} \mathcal{O}_{\mathrm{I}}^{\mathrm{S}} \sim 0$, so that we can make no conclusive statement about which hypothesis is preferred. (The presence of this non-significant outlier is to be expected, as it was already identified in [25].)

The distribution of the odds corresponding to the sub-hypotheses making up $\mathcal{H}_{\mathrm{S}}$ 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 right-most panel in Fig. 3 shows the distribution of $\log_{10} \mathcal{O}_{\mathrm{N}}^{\mathrm{S}}$, 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. [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 supplementary material. The plotted upper limits are computed under the assumption of a signal model that includes all five independent polarizations ($\mathcal{H}_{\mathrm{svt}}$); limits obtained assuming other signal models may be found online in [40]. Previous work has demonstrated that the presence or absence of a GR component does not affect the non-GR upper limits (Fig. 13 in [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 (e.g. Fig. 9 in [49]) to those in 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 supplementary 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) [40]. Odds

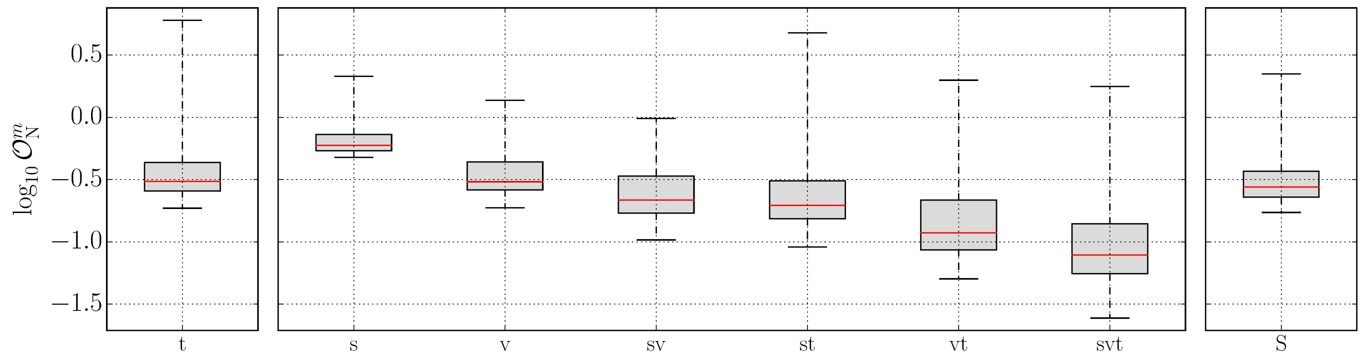

FIG. 3. *Sub-hypothesis odds.* Box plots for the distribution of the signal vs noise log-odds for each of the sub-hypotheses considered, for all of the pulsars analyzed. The sub-hypotheses are: (st), vector-tensor (tv), scalar-vector-tensor tensor-only (t), scalar-only (s), vector-only (v), scalar-vector (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 $\log_{10} \mathcal{B}_{\mathrm{N}}^{m}$, which is the same as $\log_{10} \mathcal{O}_{\mathrm{N}}^{m}$ if neither $\mathcal{H}_m$ nor $\mathcal{H}_{\mathrm{N}}$ 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 $\log_{10} \mathcal{O}_{\mathrm{N}}^{m}$ 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 supplementary material [40].

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 supplementary material). 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 $\mathcal{H}_{\mathrm{st}}$). 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, analogues 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 frequency of the source, this restriction will be relaxed in future analyses.

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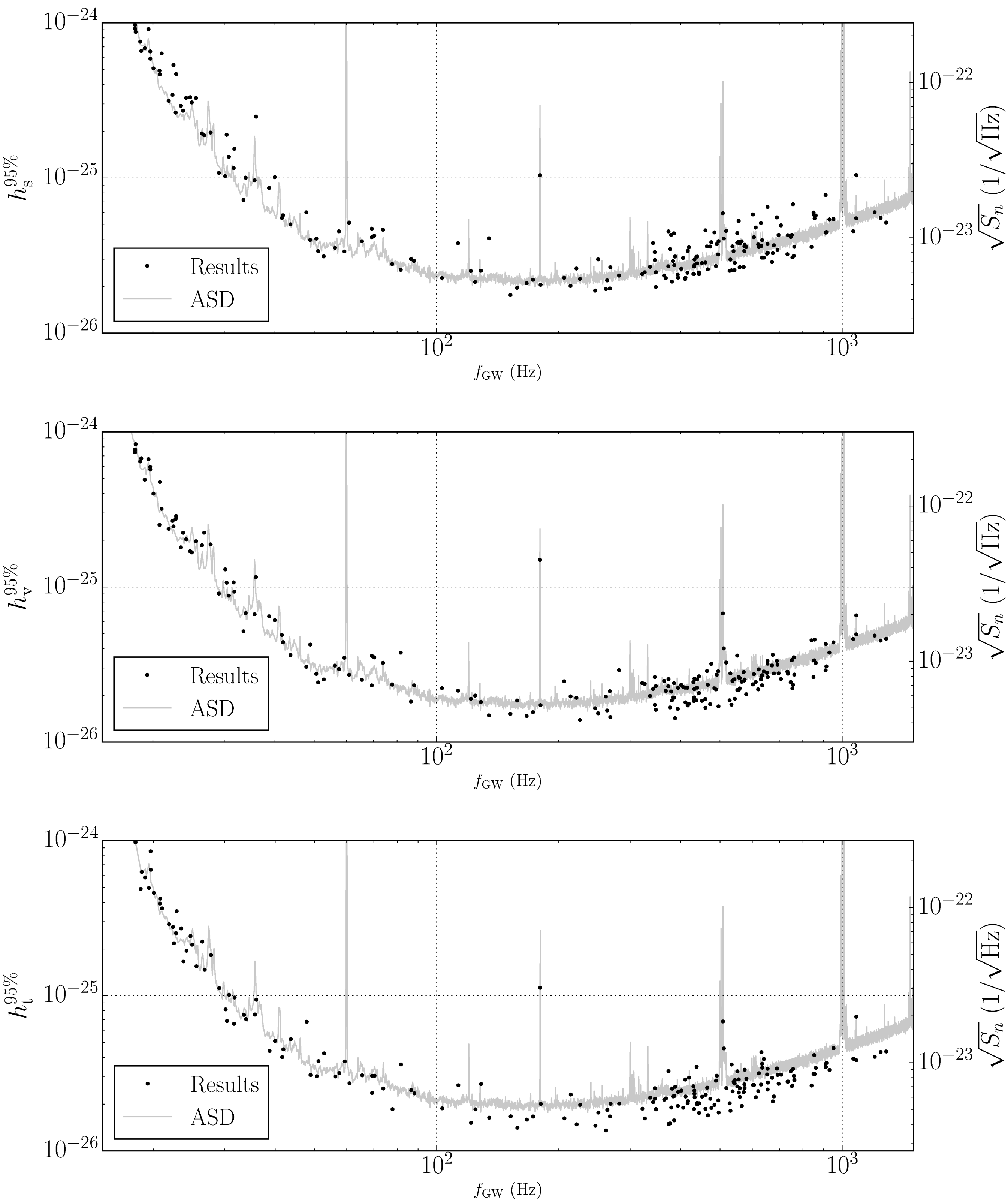

FIG. 4. *Non-GR upper limits vs emission frequency.* Circles mark the 95%-credible upper limit on the scalar, $h_{\rm s}^{95\%}$ (top), and the effective vector, $h_{\rm v}^{95\%}$ (middle), and tensor $h_{\rm t}^{95\%}$ (bottom) strain amplitudes as a function of assumed gravitational-wave frequency for each of the 200 pulsars in our set. The upper limits are obtained assuming a signal model including all five independent polarizations ($\mathcal{H}_{\rm stv}$), and incorporating no information on the orientation of the source (Table II in supplementary material [40]). 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.

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