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Narrowband Searches for Continuous Gravitational Waves from known Pulsars in the First Two Parts of the Fourth LIGO–Virgo–KAGRA Observing Run

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Abstract

Rotating nonaxisymmetric neutron stars (NSs) are promising sources for continuous gravitational waves (CWs). CWs may, if detected, inform us about the internal structure and equation of state of NSs. Here, we present a narrowband search for CWs from known pulsars, for which a matched-filter search can be applied. Narrowband searches are robust to mismatches between electromagnetic (EM) and gravitational emissions, in contrast to fully targeted searches where they are assumed to be phase-locked. In this work, we search for the CW counterparts emitted by 34 pulsars using data from the first and second parts of the fourth LIGO–Virgo–KAGRA observing run. We use the 5n-vector narrowband pipeline, which applies frequency-domain matched filtering. In previous searches, it covered a narrow range in the frequency—frequency time derivative (f—$\dot{f}$) space. Here, we also explore a range in the second time derivative of the frequency $\ddot{f}$ around the EM observations. Additionally, for the first time, we target sources in a binary system with this kind of search. We find no evidence for CWs and therefore set upper limits on the strain amplitude emitted by each pulsar. For 20 analyses, we report an upper limit below the theoretical spin-down limit. The tightest constraint is for pulsar PSR J0534+2200 (the Crab pulsar), for which our strain upper limit on the CW amplitude corresponds to $\leqslant 0.04\%$ of the spin-down power being radiated in the CW channel.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Pulsars (1306); Neutron stars (1108); Binary stars (154)

1. Introduction

Continuous gravitational waves (CWs) represent one of the most elusive and scientifically rich targets in gravitational wave (GW) astronomy. Unlike transient signals produced by cataclysmic events such as binary mergers of black holes and/or neutron stars (NSs), CWs are expected to be persistent and nearly monochromatic signals potentially emitted by rapidly rotating NSs with a nonsymmetric mass distribution with respect to the rotation axis (K. Riles 2023).

The mass-distribution asymmetries, such as "mountains" on the crust (F. Gittins 2024) or internal deformations supported by strong magnetic fields (S. Bonazzola & E. Gourgoulhon 1996; C. Cutler 2002) or exotic matter (B. J. Owen 2005), can cause the star to emit gravitational radiation steadily over timescales of months to years. In the literature (see B. Haskell & M. Bejger 2023; K. Riles 2023; K. Wette 2023), different emission models are generally considered; the single harmonic model predicts an emission at exactly twice the spin frequency, while the dual harmonic model has emission at both 1 and 2 times the spin frequency (D. I. Jones 2010). Additional mechanisms may also contribute to CW emission, such as free precession or internal fluid oscillation modes (e.g., r-modes) (N. Andersson 1998; J. L. Friedman & S. M. Morsink 1998). The search for CWs is motivated by their potential to unveil fundamental information about the structure and composition of NSs (B. Haskell & M. Bejger 2023; B. J. Owen 2026). A detection would provide direct evidence of nonaxisymmetric deformations, offer insight into the dense-matter physics of the

[355] Deceased, March 2026.
[356] Deceased, September 2024.
[357] Deceased, August 2025.

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NS interior (see, e.g., A. Idrisy et al. 2015; S. Ghosh et al. 2023; S. Ghosh 2023), and allow tests of gravitational theories in the strong-field regime (M. Isi et al. 2017; B. P. Abbott et al. 2019a).

However, CW signals are expected to be extremely weak and much weaker than the transient signals detected so far by the LIGO–Virgo–KAGRA (LVK) Collaboration (see A. G. Abac et al. (2026) for the latest catalog of GW detections, and J. Aasi et al. (2015), F. Acernese et al. (2015), and T. Akutsu et al. (2021) for more information on LVK detectors). This low amplitude necessitates long observation times and sensitive data analysis techniques capable of extracting faint, long-duration signals from detector noise. Searches for CWs must also account for intrinsic decrease in the NS's spin frequency (the so-called spin-down), and the Doppler modulation caused by Earth's motion and by the orbital motion for sources in binary systems.

To address these challenges, different types of CW search strategies have been developed (K. Riles 2023; K. Wette 2023), each optimized for different assumptions about the signal and the level of prior information available about the source. Known pulsars for which we have accurate measurements of their sky positions and rotation parameters from electromagnetic (EM) observations can be targeted using fully coherent searches. The most sensitive CW searches assume that the GW phase evolution is locked to the EM phase evolution and remains consistent throughout the entire observation time, performing fully coherent analyses with a single frequency evolution template per target.

Coherent narrowband searches, the focus of this paper, are also usually used for pulsars with known position, but when the signal frequency, while known, is uncertain or may have shifted from EM predictions (e.g., B. Abbott et al. 2008; J. Aasi et al. 2015; B. P. Abbott et al. 2017, 2019b; R. Abbott et al. 2022; A. Ashok et al. 2021; A. G. Abac et al. 2025a).[358] This could happen due to timing noise, glitches, or mismatches between gravitational and EM emission mechanisms (G. Ashton et al. 2017; M. Antonelli et al. 2025). Narrowband searches extend the targeted approach by scanning a small frequency band and a limited range of spin-down parameters, achieving improved robustness while maintaining relatively high sensitivity. Pulsars, NSs possessing powerful magnetic fields that emit beams of EM waves across different frequency bands (radio, X-rays, gamma rays), are the primary candidates for CW targeted and fully coherent narrowband searches.

In this work, we present a narrowband CW search using data from the recent LVK O4 observing run, considering the first two parts, namely, O4a and O4b data from the LIGO Livingston (L1) and LIGO Hanford detectors (H1). We study 34 pulsars, with ephemerides provided by a set of gamma-ray, radio, and X-ray observatories, representing the largest set of targets ever considered for a narrowband search. For the first time, we consider sources in binary systems and explore templates in the second-order spin-down ($\ddot{f}$) dimension, enlarging the science scope of this work.

The paper is organized as follows. Section 2 describes the EM and GW data used in the analysis. Section 3 outlines the astrophysical motivations and characteristics of the expected signals and describes the analysis method. The results are presented and discussed in Section 4. Our conclusions are given in Section 5.

[358] Broader searches, either for sources at known positions but with unknown frequencies or over the full sky, usually use semicoherent methods, see, e.g., K. Wette (2023) for an overview.

2. Datasets

2.1. EM Data

We used EM data to obtain pulsar timing solutions that were used as inputs for the GW search. A gamma-ray timing solution was obtained for one target from the Fermi Large Area Telescope (LAT; W. B. Atwood et al. 2009). Radio data for multiple pulsars were collected from the Nancay Radio Telescope (NRT; L. Guillemot et al. 2023), the 42 ft and Lovell telescopes at Jodrell Bank Observatory (JBO), the Argentine Institute of Radio astronomy (IAR; G. Gancio et al. 2020), the Canadian Hydrogen Intensity Mapping Experiment (CHIME; M. Amiri et al. 2021), the MeerKAT radio telescope (J. Jonas & MeerKAT Team 2018), and the Mount Pleasant Radio Observatory[359] (J. L. Palfreyman et al. 2011). The MeerKAT timing solutions were derived from observations over 6 yr, collected for the MeerKAT Pulsar Timing Array (MPTA). These data were processed following the methods used for the first two data releases of the MPTA (M. T. Miles et al. 2023, 2025). X-ray timing solutions were obtained from Chandra (M. C. Weisskopf et al. 2002) and the Neutron Star Interior Composition Explorer (NICER; K. C. Gendreau et al. 2016).

For processing the EM observations, we used PSRCHIVE (W. van Straten et al. 2012) or PRESTO (S. M. Ransom et al. 2002; S. Ransom 2011) packages, the Chandra Interactive Analysis of Observations (CIAO) package and Calibration Database (CALDB) (A. Fruscione et al. 2006), the NICER software in HEASoft (NASA High Energy Astrophysics Science Archive Research Center Heasarc 2014), and for the gamma-ray data, we used the procedures detailed in L. Kuiper & W. Hermsen (2009). We first cleaned the data for noise/radio frequency interference, when applicable. Next, we folded the observations and obtained the time of arrival (ToA) by cross-correlating the folded profiles with a template with a high signal-to-noise ratio. We selected the ToAs during the O4ab run and used TEMPO2 (R. T. Edwards et al. 2006; G. B. Hobbs et al. 2006; G. Hobbs et al. 2009) or PINT (J. Luo et al. 2019, 2021) to characterize the rotation of each pulsar by fitting the ToAs with a Taylor expansion of the rotational phase

$$\phi(t) = \phi_0 + 2\pi \left[f_{\rm rot}\,(t - t_0) + \frac{1}{2}\dot{f}_{\rm rot}\,(t - t_0)^2 + \frac{1}{6}\ddot{f}_{\rm rot}\,(t - t_0)^3 + ... \right]. \quad (1)$$

Here, $f_{\rm rot}$, $\dot{f}_{\rm rot}$, and $\ddot{f}_{\rm rot}$ are the rotation frequency of the pulsar, and its first and second derivatives, respectively. Their reference epoch is t_0, and ϕ_0 is the phase at t_0. Higher-order derivatives can be included if necessary.

2.1.1. Glitches

Pulsars are known for their extremely stable rotation; however, some of them present *glitches*. Glitches are abrupt changes in the rotational frequency of the pulsar, and they have

[359] Due to some mechanical issues in mid 2023, this observatory was not able to provide ephemerides entirely covering the O4ab run.

Table 1
Pulsar Glitches Incorporated in the O4ab Narrowband Search

PSR	t_g [MJD]
J0058−7218	60291
J0537−6910	60223, 60379, 60611
J0540−6919	60105, 60170
J0835−4510	60430
J1809−1917	60071
J1813−1246	60247
J2021+3651	60289
J2022+3842	60540
J2229+6114	60065

Note. Details of the two PSR J0540–6919 timing events are given in C. M. Espinoza et al. (2024). We truncated the analysis to MJD 60510 for PSR J2022+3842 due to a lack of observations to narrow down the post-glitch parameters. PSR J1809-1917 and PSR J2229+6114 glitched before the beginning of the run.

been observed in over 200 pulsars (C. M. Espinoza et al. 2011; M. Yu et al. 2013; A. Basu et al. 2022). Most glitches are likely a consequence of the interaction between the superfluid interiors of NSs and their solid crusts. However, their dynamics and the mechanisms that may trigger them are not well understood (S. Zhou et al. 2022; D. Antonopoulou et al. 2022).

The additional phase in pulsar rotation induced by glitches is included in the timing model as (P. M. McCulloch et al. 1987):

$$\phi_g(t) = \Delta\phi + 2\pi\,[\Delta f_{\rm rot}\,(t - t_g) + \frac{1}{2}\Delta\dot{f}_{\rm rot}\,(t - t_g)^2 + \frac{1}{6}\Delta\ddot{f}_{\rm rot}\,(t - t_g)^3 + \sum_i \left[1 - \exp\left(-\frac{t - t_g}{\tau^i_{\rm d}}\right)\right] \times \Delta f^{i,d}_{\rm rot}\,\tau^i_d], \quad (2)$$

where t_g is the glitch epoch, and $\Delta\phi$ is used to counteract its uncertainty. $\Delta f_{\rm rot}$, $\Delta\dot{f}_{\rm rot}$, and $\Delta\ddot{f}_{\rm rot}$ are the step changes in $f_{\rm rot}$, $\dot{f}_{\rm rot}$, and $\ddot{f}_{\rm rot}$ at t_g, respectively. Finally, $\Delta f^{d,i}_{\rm rot}$ represent temporary increases in frequency that recover in $\tau_{d,i}$ days. Detected timescales for well-monitored pulsars can range from minutes (R. G. Dodson et al. 2002; J. Palfreyman et al. 2018; G. Ashton et al. 2019; E. Zubieta et al. 2025) to ∼500 days (E. Zubieta et al. 2024).

For some pulsars, we consider data even before the beginning of the run to improve the parameter estimation. This results in the modeling of some pre-O4 glitches listed in Table 1, together with the others that occurred during the run. Details of glitching pulsar analyses will be provided in Section 3.

2.2. GW Data

We considered data from the first (O4a) and second (O4b) parts of the fourth observing run, known as O4ab, of the LIGO Livingston (L1) and LIGO Hanford (H1) detectors. The first part of the run (A. G. Abac et al. 2025b) took place between 2023 May 24, 15:00:00 UTC (MJD 60088) and ended 2024 January 16, 16:00:00 UTC (MJD 60325). The duty factors for L1 and H1 were 69.0% and 67.5%, respectively. Detectors resumed the observing mode for O4b on April 10, 2024, at 15:00 UTC (MJD 60410) and ended on 2025 January 28, at 17:00:00 UTC (MJD 60703). Here, the duty factors for L1 and H1 were 68.1% and 48.6%, respectively. As a result, we here consider ∼360 days (∼300 days) for L1 (H1) of effective observing time.

We use L1:GDS–CALIB_STRAIN_CLEAN_AR and H1:GDS–CALIB_STRAIN_CLEAN_AR frame channels with CAT1 vetoes (D. Davis et al. 2019) for L1 and H1, respectively, following E. Goetz & K. Riles (2024). For the PSR J0534+2200 search only, we substitute data from 2024 September 3 to November 11, with L1:DCS-CALIB_STRAIN_CLEAN_C01 and H1:DCS-CALIB_STRAIN_CLEAN_C01 channels since the 60 Hz line subtraction was not working well during this period in the online calibration, requiring an improved "C01" version (J. R. Merou et al. 2024).

A general description of the LIGO detectors' performance throughout O4ab is given in D. Ganapathy et al. (2023), W. Jia et al. (2024), E. Capote et al. (2025), and S. Soni et al. (2025). For the O4ab data used in this analysis, the worst 1σ calibration uncertainty is within $\lesssim$10% in amplitude and $\lesssim$10° in phase, over the range 10–2000 Hz (M. Wade et al. 2025). The uncertainty at specific frequencies or times can be significantly smaller. Two hours of H1 data with large calibration uncertainties ($\lesssim$25% in amplitude and $\lesssim$15° in phase, over the range 10–2000 Hz) (L. Dartez et al. 2024) were inadvertently included in the analysis. These data represent ∼0.03% of the effective observing time analyzed from the O4 run. We have confirmed, using spot checks of the hardware injections[360] (P. Baxi et al. 2026), that including these data has a <0.5% effect on our results.

During the proofs stage, it was realized that the dataset used in the analyses omitted ~20 days of data, between the official start of the O4b run on 2024 April 10 and the start date of the analyses on 2024 May 1. The omission of these data, which would have contributed ~2% to the search sensitivity, does not appreciably affect the results or conclusions presented in this paper.

The Virgo and KAGRA detectors have not been considered since they joined the O4 run, only in the second and third parts, respectively. For a description of the upgrades to the Advanced LIGO (E. Capote et al. 2025), Advanced Virgo (Virgo Collaboration 2025), and KAGRA detectors in preparation for the O4 run, we refer to Appendix A in A. G. Abac et al. (2024).

3. Signal Model and Search Method

In this section, we will briefly discuss the expected signal (K. Riles 2023) and the narrowband search method based on the five-vector formalism (P. Astone et al. 2010; S. Mastrogiovanni et al. 2017) as implemented in the Snag framework (S. Frasca et al. 2022). We will focus on the single harmonic emission model since the narrowband searches are performed around $f_{\rm gw} = 2f_{\rm rot}$, where $f_{\rm gw}$ is the GW frequency. For a triaxial star, the amplitude h_0 can be expressed as

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f^2_{\rm rot}}{d}, \quad (3)$$

[360] Simulated CW signals were injected through the detector hardware for testing purposes.

where d is the distance of the source, and ε the equatorial ellipticity defined as

$$\varepsilon \equiv \frac{|I_{xx} - I_{yy}|}{I_{zz}}, \tag{4}$$

where I_{xx}, I_{yy}, and I_{zz} are the source's principal moments of inertia, with the star rotating about the z-axis.

The spin-down limit $h_0^{\rm sd}$ quantifies the maximum CW amplitude assuming all the lost rotational energy is converted into GW emission. It is calculated as

$$h_0^{\rm sd} = \frac{1}{d}\left(\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}}\right)^{1/2}. \tag{5}$$

By constraining the CW emission, we can set upper bounds on the fraction of energy emitted through the gravitational channel.

The relative motion of Earth and the source modulates the signal received at the detector (K. Wette 2023). It depends on the source's sky location (Earth motion) and, where needed, on up to five Keplerian parameters for the binary orbit (source motion). After we correct the data for spin-down and Doppler effects (induced by the Earth's revolution and by the source binary motion), the expected CW signal is modulated in amplitude by the Earth's rotation and can be expressed as the real part of the following complex expression (P. Astone et al. 2010)

$$h(t) = H_0(H_+\boldsymbol{A}^+ + H_\times\boldsymbol{A}^\times)\cdot\boldsymbol{W}\, e^{i(\omega_{\rm gw}t+\phi)}, \tag{6}$$

where $\omega_{\rm gw} = 2\pi f_{\rm gw}$, and boldface symbols denote 5-vectors (arrays with five complex components). The $\boldsymbol{A}^{+/\times}$ represent the five vectors of the single-detector response to the two GW polarizations, and $\boldsymbol{W} = e^{ik\Theta}$ encodes sidereal modulation, with $k = \{0, \pm 1, \pm 2\}$ and Θ the local sidereal time (see Section 4 of P. Astone et al. 2010 for more information).

The amplitude H_0 is related to the standard GW amplitude h_0 (P. Jaranowski et al. 1998) as

$$H_0 = h_0\sqrt{\frac{1 + 6\cos^2\iota + \cos^4\iota}{4}}, \tag{7}$$

with ι being the angle between the rotation axis and line of sight. The polarization coefficients are given by

$$H_+ = \frac{\cos(2\psi) - i\eta\sin(2\psi)}{\sqrt{1+\eta^2}},$$
$$H_\times = \frac{\sin(2\psi) + i\eta\cos(2\psi)}{\sqrt{1+\eta^2}}, \tag{8}$$

being ψ the CW polarization angle, and

$$\eta = -\frac{2\cos\iota}{1+\cos^2\iota}. \tag{9}$$

The matched filters $\hat{H}_{+/\times}$ are computed in the frequency domain as

$$\hat{H}_{+/\times} = \frac{\boldsymbol{X}\cdot\boldsymbol{A}^{+/\times}}{|\boldsymbol{A}^{+/\times}|^2}, \tag{10}$$

where $\boldsymbol{X}$ is the data five-vector

$$\boldsymbol{X} = \int_{T_{\rm obs}} x(t)\, e^{-i\mathbf{k}\Theta}\, e^{-i\omega_{\rm gw}t}dt. \tag{11}$$

Finally, the detection statistic is

$$S = |\boldsymbol{A}^+|^4|\hat{H}_+|^2 + |\boldsymbol{A}^\times|^4|\hat{H}_\times|^2, \tag{12}$$

as defined in P. Astone et al. (2014). Note that recent works on the five-vector formalism (L. D'Onofrio et al. 2024; R. Prix 2025) have described the equivalence with the usual $\mathcal{F}$-statistic.

In this work, we focus on a narrowband approach where we search for CWs allowing for a small mismatch between the EM emission described by Equation (1) and the gravitational one. We use the 5n-vector narrowband pipeline, widely used in several CW searches (e.g., R. Abbott et al. 2022; B. P. Abbott et al. 2017, 2019b; J. Aasi et al. 2015; A. G. Abac et al. 2025a; L. Mirasola et al. 2025). We explore a narrow frequency and spin-down range around twice the best-fit values from the pulsar ephemeris, to allow for a small mismatch between the EM and CW emissions, namely,

$$f \in 2f_{\rm rot}[1-\delta,\ 1+\delta] \tag{13}$$

generally setting $\delta = 10^{-3}$ (R. Abbott et al. 2022), and a similar equation for $\dot{f}$ using the same value. As a novelty of this work, we explore a corresponding additional range of values in the $\ddot{f}$ space. During the implementation of this feature, we identified a bug in the spin-down correction of this pipeline used in A. G. Abac et al. (2025a). After rerunning the analyses in A. G. Abac et al. (2025a), we find no additional candidates, and upper limits (ULs) are unchanged. Moreover, the results of A. G. Abac et al. (2025a) are now superseded by those reported in Section 4.

The method makes use of the short Fourier data base (SFDB; P. Astone et al. 2005), which is a collection of short-duration (here we use 2048 s ones) fast Fourier transforms overlapped by half. For each pulsar, we then extract a narrow frequency band from the SFDBs around the region of interest that is then inverse-Fourier-transformed to the time domain.

For every target, data are Doppler-corrected in the time domain using a nonuniform resampling method that is independent of the CW frequency, and then they are subsampled at a rate of 1 Hz. For the first time, the pipeline can now target sources in binary systems, accounting for orbital modulation, following A. Singhal et al. (2019) and F. Amicucci et al. (2025).

At this point, the time series are Fourier-transformed and matched-filtered (using Equation (10)) to estimate the two CW polarizations using a template bank in the $f - \dot{f} - \ddot{f}$ space. The template grid consists of all the resolved parameter-space points within the region of interest, spaced by the corresponding resolution calculated as (P. Astone et al. 2014)

$$\delta f = \frac{1}{T_{\rm obs}},\quad \delta\dot{f} = \frac{1}{T_{\rm obs}^2},\quad \delta\ddot{f} = \frac{2}{T_{\rm obs}^3}, \tag{14}$$

with $T_{\rm obs}$ the data time span. Note that these resolutions neglect correlations among parameters, resulting in more templates than needed (K. Wette et al. 2008), though the overall impact on the computing cost is not significant. Higher-order spin-down terms, if provided in the ephemerides, are

fixed at twice the best-fit values to track the GW frequency evolution over time, without exploring any additional template (P. Astone et al. 2014). When we consider a glitching pulsar, we split the data into two segments that exclude from the analysis the period around [t_g–1 day, t_g+2 day], with t_g the glitch epoch. The segments are then analyzed independently. If the pulsar glitched more than once, this process is repeated until we cover the entire observing time.

The matched filter results from different detectors are coherently combined following S. Mastrogiovanni et al. (2017) to evaluate the detection statistic in Equation (12). Then, marginalization over the spin-downs is performed by sorting the detection statistic values along the frequency axis and selecting the maximum in every 10^{-4} Hz band. All templates with a detection statistic above a certain threshold, set by fixing the false-alarm probability (p_{fa}) at 1% after taking the number of explored grid points into account, are followed up on.[361] The noise-only distribution, used to set the threshold, is inferred with an exponential fit from the tail of the histogram of all statistic values which have not been selected as local maxima (A. Singhal et al. 2019).

If no CW-related outlier is found, we calculate the 95% confidence level (CL) ULs $h_0^{95\%}$ by injecting simulated signals in real data following the procedure detailed in Appendix A of B. P. Abbott et al. (2017), with the only difference being that we simulate signals with random $\ddot{f}$ within the explored range. A summary of the procedure is given here in the Appendix.

4. Search Details and Results

In this section, we present and discuss our results using LIGO O4ab data. We do not report a detection. The search identified a set of outliers for PSRs J0117+5914 and J1826–1334, for which we reject an astrophysical origin, as justified below. We first describe the target selection procedure and search setup in Section 4.1. Then, we detail our results in Section 4.2, which are then interpreted in terms of astrophysical constraints in Section 4.3.

4.1. Target Selection and Search Setup

The O4ab narrowband search selected all the targets from the set presented in Section 2.1. We focus on those pulsars with h_0^{sd} above or within a factor of 4 below the expected sensitivity calculated as (P. Astone et al. 2014; L. D'Onofrio et al. 2024)

$$h_0^{\rm sens} \approx \mathcal{C}\sqrt{\left(\sum_{i=1}^{n}\frac{\mu^i\, T^i_{\rm obs}}{S_i}\right)^{-1}}\,, \tag{15}$$

where μ^i and S_i are, respectively, the duty cycle and the harmonic average power spectral density (PSD) for the ith detector. The prefactor $\mathcal{C}$ in Equation 15 mildly depends on the number of explored templates $N_{\rm templ}$ for each target (P. Astone et al. 2014; L. D'Onofrio et al. 2024). In our plots, we consider $\mathcal{C} \in [20, 26.5]$ which roughly corresponds to $N_{\rm templ} \in [10^3, 10^9]$.

Of the 39 targets within this range, 7 isolated targets glitched within the O4ab period[362] (see Section 2.1.1), and 10 are in a binary system. Figure 1 shows the sky location of the pulsars targeted in this work.

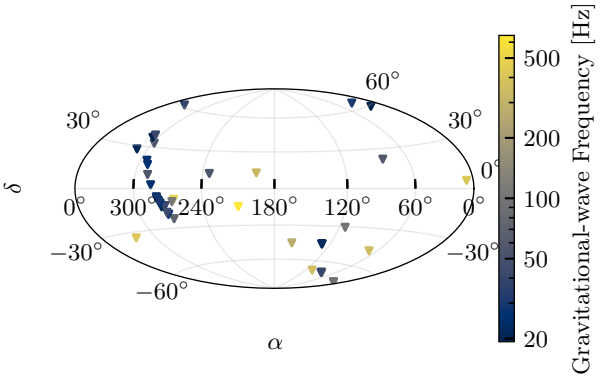

Figure 1. Sky location in equatorial coordinates of the selected targets. The color scale indicates the target's $f_{\rm gw}$.

For PSR J0540–6919, we analyzed data only after the second timing event, since both are very close to the beginning of the run (C. M. Espinoza et al. 2024).

Following L. Mirasola et al. (2024), we discard one pulsar, PSR J1231−1411, in a binary system for which the ephemeris does not provide all the Keplerian parameters needed to correct for the source's orbital motion. For each of the other targets in binary systems, we calculate the longest considerable time span ($T_{\rm obs}^{\rm max}$) within which a single fully coherent search can be applied without needing to account for uncertainties on orbital parameters (L. Mirasola et al. 2024). For four of the pulsars, PSRs J0437−4715, J1045−4509, J1737−0811, and J1745−0952, this calculation returns segments much shorter (1 day $\lesssim T_{\rm obs}^{\rm max} \lesssim$ 90 days) than $T_{\rm obs}^{\rm O4ab} \approx 610$ days. We exclude these four targets since the 5n-vector narrowband pipeline does not cover orbital uncertainties. On the other hand, we have split $T_{\rm obs}$ into three separate segments for pulsar J1400−1431, since $T_{\rm obs}^{\rm max} \sim 200$ days. We have not considered the second segment, as it includes the commissioning break, and the $\mu\, T_{\rm obs}$ would not be enough to perform the analysis. For the other pulsars in a binary system, we have analyzed the entire dataset coherently.

Due to storage limitations, we had to restrict the analysis to $\delta = 10^{-4}$ for PSRs J0534+2200 (Crab pulsar), J0540−6919, J0205+6449, and J2229+6114.

As a result, we present in the following section the search for CWs emitted by 34 selected targets.

4.2. Outliers and ULs

Only for two targets we report outliers (i.e., inferred p-value <1% after accounting for $N_{\rm templ}$): one for PSR J0117+5914 and eight for PSR J1826−1334. The two pulsars have a similar rotational frequency (∼19.7 Hz) that does not overlap with known line-like features reported in E. Goetz et al. (2026), though L1 data are affected by a known transient noise reported (T. Ohanlon & A. Effler 2023), which happens to cross the outliers' band. The noise is related to a ∼3.4 Hz line, which interacts with the ∼16.3 Hz calibration line. The interaction lost strength on 2023 August 3 (MJD 60159). This transient behavior, reported in T. Ohanlon & A. Effler (2023) is readily shown in Figure 2, where we display the spectrogram for the L1 detector along the run built with segments of 2048 s. For comparison, we superimpose the outliers' frequency tracks encompassing Doppler and spin-down effects

[361] Note that our trial factors do not account for the number of studied targets.

[362] Note that Table 1 reports nine glitching pulsars, but two glitched *before* the beginning of the run, therefore we do not have to perform separate pre- and post-glitch analyses.

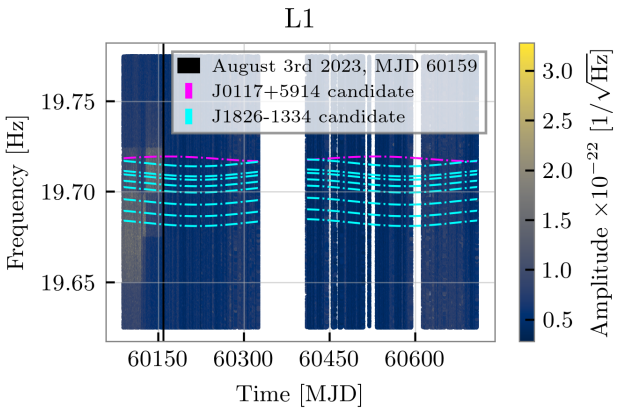

Figure 2. L1 spectrogram computed every 2048 s over the O4ab run. The PSRs J0117+5914 and J1826−1334 outlier tracks, calculated with Equation (16), are displayed in fuchsia and cyan, respectively. During the first part of the dataset, the spectrum is affected by a known noise transient reported in T. Ohanlon & A. Effler (2023), whose strength reduces after the MJD 60159 (vertical black line), see text for more details.

as (B. Krishnan et al. 2004)

$$f(t) = \left[f_0 + \dot{f}_0\,(t - t_0) + \tfrac{1}{2}\ddot{f}_0\,(t - t_0)^2 \right] \times \left(1 + \tfrac{\boldsymbol{v}_{\rm det}\cdot\boldsymbol{n}}{c}\right), \quad (16)$$

with the parameters f_0, $\dot{f}_0$, $\ddot{f}_0$ as those of the outliers, t the time at the detector, $\boldsymbol{v}_{\rm det}$ the detector's velocity in the solar system barycentre, and $\boldsymbol{n}$ the source sky location.

Since all the tracks are crossing the polluted band, their astrophysical origin is discarded.

As a result, we have calculated ULs at the 95% CL for each of the analyzed pulsars. In Table 2, we report the per-pulsar ULs, and in Figure 3, we compare $h_0^{95\%}$ with the expected sensitivity estimated through Equation (15).

For PSR J0835−4510 (the Vela pulsar), one of our most interesting targets, we performed an independent post-glitch cross-check analysis with a Mount Pleasant ephemeris covering $T_{\rm obs} \sim 117$ days of O4b. After correcting for the shorter $T_{\rm obs}$ compared with $T_{\rm obs} \sim 270$ days for the IAR ephemeris and the corresponding number of templates, the two results are in agreement. See Table 2 for numerical values. Constraints on GW emission from this target using O4 data have also been presented in A. G. Abac et al. (2025c), who searched for post-glitch transient signals. Results for signals lasting the full 120 days considered in that paper are in broad agreement with the Mount Pleasant ephemeris UL reported here. However, the two analyses considered different time evolution of the signal and different template banks, so there is no exact correspondence.

We also compare $h_0^{95\%}$ with the spin-down limit $h_0^{\rm sd}$ of each source using a moment of inertia $I_{zz} = 10^{38}$ kg m^2 in Equation (5). In this work, we have surpassed the spin-down limit in 20 analyses (counting pre- and post-glitch searches as separate analyses), with our most stringent constraint being a ratio of ∼2% between our UL and Crab's $h_0^{\rm sd}$.

From the ULs in Figure 3, we calculate the dimensionless sensitivity depth $\mathcal{D}$ (B. Behnke et al. 2015; C. Dreissigacker et al. 2018; K. Wette 2023) as

$$\mathcal{D} = \frac{\sqrt{S_h \cdot \mathrm{Hz}}}{h_0^{95\%}}, \quad (17)$$

where S_h is the power spectral density, harmonic-averaged over time and detectors. See B. Behnke et al. (2015) and C. Dreissigacker et al. (2018) for additional references on the sensitivity depth. In this work, we reached a median depth of $\mathcal{D} \approx 230$ (not including glitching pulsar analyses), in agreement with previous searches (K. Wette 2020). Note that the distribution of $\mathcal{D}$ in Figure 4, where we report the per-pulsar depths, can be tracked back to either $N_{\rm templ}$ or a glitching pulsar analysis (i.e., where we split the dataset into shorter segments).

In this work, we improve our previous constraints on the CW emission for all the considered nonglitching targets, as shown in Figure 5. If we compare with O4a (A. G. Abac et al. 2025a) and O3 (R. Abbott et al. 2022) analyses, which have a comparable sensitivity (A. G. Abac et al. 2025a), we see an improvement of about $\sim 1/\sqrt{2}$ related to the doubled $T_{\rm obs}$ (see Equation (15)). If we compare with O2 (B. P. Abbott et al. 2019b) and O1 (B. P. Abbott et al. 2017), the improvement is even larger thanks to the detectors' upgrades and a longer run.

4.3. Astrophysical Interpretation

In Figure 6, we recast our results as ULs on ellipticities, as defined in Equation (4); these are also reported in Table 2. In the figure, we also show lines of constant characteristic age $\tau = f/4|\dot{f}|$, as would be relevant if spin-down were driven entirely by GW emission from a constant mass quadrupole. This plot provides a natural place to interpret the astrophysical significance of our results. The ULs naturally divide into two subclasses.

For the younger pulsars, with $f \lesssim 100$ Hz, the ellipticity limits lie mainly in the range $10^{-3} \lesssim \varepsilon \lesssim 10^{-5}$, with a few ULs of a few times 10^{-6}. All of the pulsars for which we have beaten the energy-based spin-down limit belong to this class. The limit is surpassed by the greatest margin for the Crab pulsar (J0534+2200), for which we find $h_0^{95\%}/h_0^{\rm sd} \approx 0.02$, corresponding to no more than $0.02^2 \approx 0.04\%$ of its spin-down energy budget being radiated in the GW channel.

For the older millisecond pulsars, with $f \gtrsim 100$ Hz, our ULs on h_0 lead to upper bounds on ellipticity lying roughly in the range $10^{-8} \lesssim \varepsilon \lesssim 10^{-7}$. While smaller than the ellipticity constraints quoted above for the young pulsars, we do *not* beat the spin-down ULs for any of the millisecond pulsars, and thus their ellipticity constraints are not physically informative. The closest to the spin-down limit was PSR J0711−6830, for which we report $h_0^{95\%}/h_0^{\rm sd} \approx 1.15$. Note, however, our calculations of the spin-down limits assume a canonical moment of inertia $I_{zz} = 10^{38}$ kg m^2. For realistic NS masses and equations of state, values as large as $I_{zz} \approx 3 \times 10^{38}$ kg m^2 are possible (A. Worley et al. 2008). In this case, the spin-down limits in $h_0^{\rm sd}$ are decreased by a factor $\sqrt{\text{of } 3}$ (see Equation (5)), bringing this millisecond pulsar into the range of potential detectability, a significant achievement for a narrowband search.

To place our ULs in further context, theoretical estimates of maximum ellipticities supported by strains in NS crusts are around 10^{-6}, somewhat below our best ULs for young pulsars; see, e.g., M. Pitkin (2011), N. K. Johnson-McDaniel & B. J. Owen (2013), G. Ushomirsky et al. (2000), F. Gittins & N. Andersson (2021), and J. A. Morales & C. J. Horowitz (2022). Theoretical estimates of the ellipticities produced by magnetic fields depend upon the poorly constrained geometry and strength of the *internal* magnetic field $B_{\rm int}$, with an

Table 2
Results Table Obtained with the Method Described in Section 3

Pulsar Name J2000	$f_{\rm rot}$ (Hz)	$\dot{f}_{\rm rot}$ (Hz s^{-1})	$\ddot{f}_{\rm rot}$ (Hz s^{-2})	d kpc	$h_0^{95\%}$ $\times 10^{-26}$	$h_0^{95\%}/h_0^{sd}$	$\mathcal{D}$	$\varepsilon^{95\%}$	$N_{\rm trials}$ $\times 10^6$	Distance References
J0030+0451$^{\rho}$	205.53	-4.3×10^{-16}	⋯	0.32	1.52	4.21	233.8	2.7×10^{-8}	46	A. N. Lommen et al. (2000)
J0058−7218$^{\beta}$	45.94	-6.2×10^{-11}	6.6×10^{-21}	59.70	3.16	2.01	154.2	2.1×10^{-4}	701	C. Maitra et al. (2021)
J0058−7218 pg$^{\beta}$	45.94	-6.2×10^{-11}	4.9×10^{-21}	59.70	3.21	2.04	152.0	2.1×10^{-4}	6047	C. Maitra et al. (2021)
J0117+5914$^{\gamma}$	9.86	-5.7×10^{-13}	-8.4×10^{-24}	1.77	26.69	2.44	267.5	1.1×10^{-3}	55	J. M. Yao et al. (2017)
J0205+6449$^{*\gamma}$	15.19	-4.5×10^{-11}	1.7×10^{-20}	3.20	6.67	0.15	244.0	2.2×10^{-4}	50	S. S. Murray et al. (2002)
J0534+2200$^{*\gamma}$	29.57	-3.7×10^{-10}	1.8×10^{-20}	2.00	3.05	0.02	232.0	1.6×10^{-5}	753	A. R. Walker (2012)
J0537−6910$^{\beta}$	61.89	-2.0×10^{-10}	5.8×10^{-21}	49.70	3.63	1.25	121.5	1.1×10^{-4}	896	F. E. Marshall et al. (1998)
J0537−6910 pg1$^{\beta}$	61.89	-2.0×10^{-10}	5.8×10^{-21}	49.70	4.13	1.42	106.8	1.3×10^{-4}	1447	F. E. Marshall et al. (1998)
J0537−6910 pg2$^{\beta}$	61.89	-2.0×10^{-10}	1.4×10^{-20}	49.70	3.85	1.32	114.7	1.2×10^{-4}	4057	F. E. Marshall et al. (1998)
J0537−6910 pg3$^{\beta}$	61.89	-2.0×10^{-10}	9.0×10^{-21}	49.70	4.41	1.51	100.1	1.4×10^{-4}	252	F. E. Marshall et al. (1998)
J0540−6919$^{*\beta}$	19.64	-2.5×10^{-10}	4.7×10^{-21}	49.70	4.99	0.86	205.5	1.5×10^{-3}	226	M. Geyer et al. (2021)
J0711−6830$^{\nu}$	182.12	-4.9×10^{-16}	⋯	0.11	1.43	1.15	236.5	1.1×10^{-8}	83	J. M. Yao et al. (2017)
J0737–3039A$^{\dagger\gamma}$	44.05	-3.4×10^{-15}	⋯	1.10	2.00	3.09	250.2	2.7×10^{-6}	27	M. Burgay et al. (2003)
J0835−4510$^{\delta}$	11.18	-1.6×10^{-11}	2.0×10^{-22}	0.28	23.44	0.07	170.7	1.2×10^{-4}	213	J. P. W. Verbiest et al. (2012)
J0835−4510 pg$^{\delta}$	11.18	-1.6×10^{-11}	2.0×10^{-22}	0.28	24.58	0.07	162.8	1.3×10^{-4}	107	J. P. W. Verbiest et al. (2012)
J0835−4510 pgMt$^{\epsilon}$	11.18	-1.6×10^{-11}	-2.3×10^{-21}	0.28	39.02	0.11	102.6	2.1×10^{-4}	11	J. P. W. Verbiest et al. (2012)
J1300+1240$^{\dagger\alpha}$	160.81	-3.0×10^{-15}	⋯	0.71	1.98	4.06	176.2	1.3×10^{-7}	101	A. Wolszczan et al. (2000)
J1400−1431_1$^{\dagger\alpha}$	324.23	-7.6×10^{-16}	⋯	0.28	2.68	6.04	148.1	1.7×10^{-8}	48	R. Rosen et al. (2013)
J1400-1431_2$^{\dagger\alpha}$	324.23	-7.6×10^{-16}	⋯	0.28	3.10	6.96	128.4	1.9×10^{-8}	48	R. Rosen et al. (2013)
J1537+1155$^{\dagger\gamma}$	26.38	-1.7×10^{-15}	6.2×10^{-29}	0.93	3.15	4.57	231.3	1.0×10^{-5}	49	E. Fonseca et al. (2014)
J1756–2251$^{\dagger\gamma}$	35.14	-1.3×10^{-15}	3.0×10^{-27}	0.73	2.39	3.63	235.0	3.3×10^{-6}	22	A. J. Faulkner et al. (2004)
J1809−1917$^{\gamma}$	12.08	-3.7×10^{-12}	6.2×10^{-23}	3.27	12.91	0.94	240.4	6.8×10^{-4}	326	J. M. Yao et al. (2017)
J1811−1925$^{\beta}$	15.45	-1.1×10^{-11}	1.8×10^{-22}	5.00	6.75	0.50	227.9	3.3×10^{-4}	1175	K. Torii et al. (1997)
J1813−1246$^{\zeta}$	20.80	-7.6×10^{-12}	2.6×10^{-22}	2.63	7.49	0.40	124.2	1.1×10^{-4}	472	A. A. Abdo et al. (2009)
J1813−1246 pg$^{\zeta}$	20.80	-7.6×10^{-12}	2.6×10^{-22}	2.63	5.61	0.30	165.7	8.1×10^{-5}	472	A. A. Abdo et al. (2009)
J1813−1749$^{\eta}$	22.34	-6.3×10^{-11}	⋯	6.15	3.76	0.17	224.3	1.1×10^{-4}	3312	J. M. Yao et al. (2017)
J1826−1334$^{\gamma}$	9.85	-7.3×10^{-12}	2.1×10^{-22}	3.61	27.22	1.42	263.4	2.4×10^{-3}	513	J. M. Yao et al. (2017)
J1828−1101$^{\gamma}$	13.88	-2.8×10^{-12}	-3.9×10^{-23}	4.77	9.58	1.25	299.6	5.6×10^{-4}	95	J. M. Yao et al. (2017)
J1831−0952$^{\gamma}$	14.86	-1.8×10^{-12}	7.9×10^{-24}	3.68	7.04	0.92	256.6	2.8×10^{-4}	71	J. M. Yao et al. (2017)
J1833−0827$^{\gamma}$	11.72	-1.3×10^{-12}	-1.7×10^{-24}	4.50	13.75	2.34	240.9	1.1×10^{-3}	125	P. Esposito et al. (2011)
J1837−0604$^{\gamma}$	10.38	-4.9×10^{-12}	3.5×10^{-22}	4.78	20.16	1.74	264.2	2.1×10^{-3}	123	J. M. Yao et al. (2017)
J1838−0655$^{\beta}$	14.18	-1.0×10^{-11}	3.0×10^{-22}	6.60	8.48	0.83	248.1	6.6×10^{-4}	335	E. V. Gotthelf & J. P. Halpern (2008)
J1856+0245$^{\gamma}$	12.36	-9.5×10^{-12}	1.8×10^{-22}	6.32	12.63	1.13	242.3	1.2×10^{-3}	276	J. M. Yao et al. (2017)
J1913+1011$^{\gamma}$	27.85	-2.6×10^{-12}	-1.7×10^{-23}	4.61	2.77	0.51	241.1	3.9×10^{-5}	180	J. M. Yao et al. (2017)
J1925+1720$^{\gamma}$	13.22	-1.8×10^{-12}	1.8×10^{-23}	5.06	9.53	1.61	252.4	6.5×10^{-4}	63	J. M. Yao et al. (2017)
J1935+2025$^{\gamma}$	12.48	-9.5×10^{-12}	2.9×10^{-22}	4.59	12.22	0.80	236.9	8.5×10^{-4}	278	J. M. Yao et al. (2017)
J1952+3252$^{\gamma}$	25.29	-3.7×10^{-12}	9.2×10^{-22}	3.00	3.16	0.31	228.8	3.5×10^{-5}	684	B. R. Zeiger et al. (2008)
J2021+3651$^{\gamma}$	9.64	-8.9×10^{-12}	-2.5×10^{-22}	1.80	40.04	0.93	209.8	1.8×10^{-3}	25	M. S. E. Roberts et al. (2002)
J2021+3651 pg$^{\gamma}$	9.64	-8.9×10^{-12}	-2.5×10^{-22}	1.80	42.24	0.98	199.0	1.9×10^{-3}	190	M. S. E. Roberts et al. (2002)
J2022+3842$^{\beta}$	20.57	-3.7×10^{-11}	6.5×10^{-21}	10.00	5.44	0.51	175.5	3.0×10^{-4}	1757	Z. Arzoumanian et al. (2011)
J2043+2740$^{\gamma}$	10.40	-1.3×10^{-13}	3.1×10^{-23}	1.48	19.67	3.19	268.8	6.4×10^{-4}	6	J. M. Yao et al. (2017)
J2124−3358$^{\nu}$	202.79	-8.5×10^{-16}	⋯	0.41	1.53	3.80	225.1	3.6×10^{-8}	127	D. J. Reardon et al. (2016)
J2229+6114$^{*\gamma}$	19.35	-2.9×10^{-11}	2.7×10^{-21}	3.00	4.24	0.13	241.6	8.0×10^{-5}	41	J. P. Halpern et al. (2001)

Notes. The nomenclature "pg" identifies the post-glitch analyses, "pgMt" identifies the second post-glitch Vela analysis using the Mount Pleasant ephemeris; more information is given in the text. Starred pulsars have been analyzed using $\delta = 10^{-4}$. The marker † identifies pulsars in a binary system. Frequencies and spin-down parameters are referred to the starting day of the run. The following is a list of references for pulsar ephemeris data used in this analysis: Nancay: α, NICER: β, JBO: γ, IAR: δ, MeerKAT: ν, CHIME: ρ, Fermi-LAT: ζ, Chandra: η, Mount Pleasant: ϵ.
References. The last column lists references for pulsar distances, and they should be consulted for information on their associated uncertainty.

estimate of $\varepsilon \sim 10^{-8}(B_{\rm int}/10^{12}$ G) for a superconducting interior (see R. Abbott et al. (2020) for discussion and references). For such magnetic mountains to reach the level of our ULs for the young pulsars, the internal field strength would have to be several orders of magnitude greater than the external field strength $\sim 10^{12}$ G, typical of such pulsars (A. Lyne & F. Graham-Smith 2012).

However, mountains supported by less conventional matter phases, e.g., solid quark phases or the color-flavor-locked (CFL) phase, can be as large as $\sim 10^{-3}$; see, e.g., B. J. Owen (2005), K. Glampedakis et al. (2012). While exotic, such stars are potentially particularly relevant to narrowband searches, where a possible emission mechanism is from a nonaxisymmetric solid core, whose rotation is not perfectly coupled to that of the crust, allowing for a GW emission offset slightly from (twice) the radio pulsation frequency (B. Abbott et al. 2008). By this measure, all of our ULs that are tighter than the spin-down limits are of astrophysical interest, but not directly comparable with those set by targeted searches (e.g., A. G. Abac et al. 2025a) due to the intrinsic assumptions on the CW emission being mismatched (narrowband) or locked (targeted) to the EM emission.

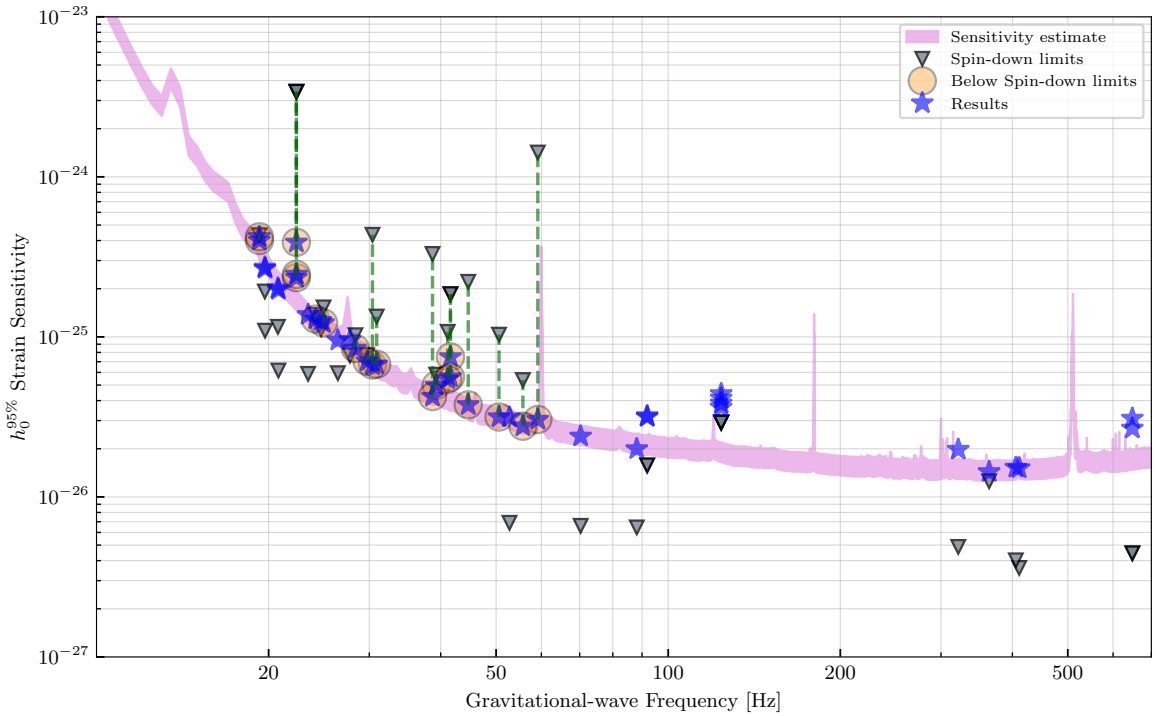

Figure 3. Expected sensitivity of the narrowband search using the O4ab (shaded pink region) dataset from the two LIGO detectors. The curve is compared with the spin-down limits (triangles) and the 95% CL ULs (stars) averaged over all the 10^{-4} Hz bands for each source. ULs below the spin-down limit are highlighted with orange circles. Superimposed blue stars correspond to the multiple analyses of glitching pulsars.

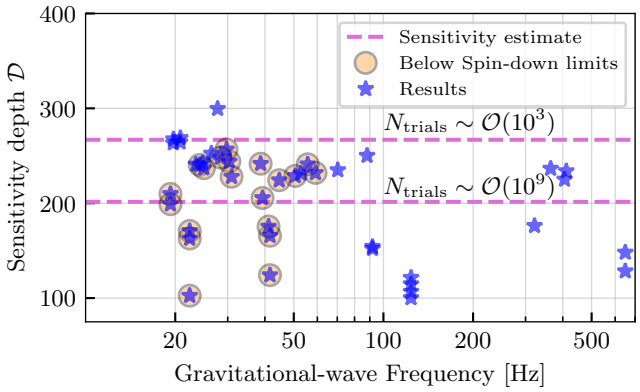

Figure 4. Sensitivity depths calculated with Equation (17) using the results in Figure 3. The two horizontal dotted lines highlight the theoretical sensitivity for the reported number of explored templates, calculated with Equations (15) and (17).

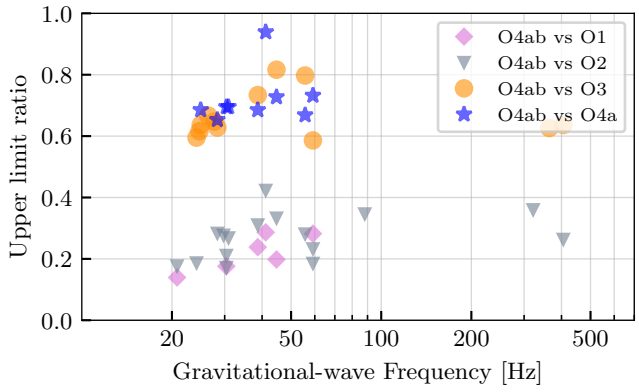

Figure 5. ULs in Figure 3 of nonglitching pulsars divided by our previous 5n-vector narrowband ULs. In particular, blue stars compare with the O4a-only analysis of A. G. Abac et al. (2025a), orange circles with O3 (R. Abbott et al. 2022), gray triangles with O2 (B. P. Abbott et al. 2019b), and O1 purple squares from B. P. Abbott et al. (2017). Note that multiple analyses might have targeted the same pulsar; we show all the comparisons to highlight the significant improvements from one observing run to the other.

5. Conclusions

In this work, we present a search for CW signals from a set of 34 known pulsars using O4ab data from the two LIGO detectors, allowing for a mismatch between the EM and GW emissions. This is the largest set of targets ever considered for a narrowband search.

We performed the CW search using the 5n-vector narrowband pipeline, based on matched filtering in the frequency domain. Narrowband searches allow a small mismatch between the EM and CW emissions, unlike targeted searches (e.g., A. G. Abac et al. 2025a). This implies that the results presented here are more robust in cases where the two signals are not phase-locked, e.g., for glitching pulsars, which are likely to have a superfluid interior flow.

For the first time, we study pulsars in binary systems in a narrowband search. Thanks to other improvements of the 5n-vector pipeline, it can now explore an additional range of values in the $\ddot{f}$ space.

We do not report a detection as all statistically significant outliers were associated with instrumental disturbances and vetoed. Therefore, we set ULs on the GW strain amplitude and ellipticity from each target. For 20 analyses, we report an UL below the theoretical spin-down limit. Overall, we improve our constraints on the CW emission from all the targets as shown in Figure 5. Our tightest constraint is for the Crab pulsar, for which our UL on the CW amplitude is $\lesssim$2% of its spin-down

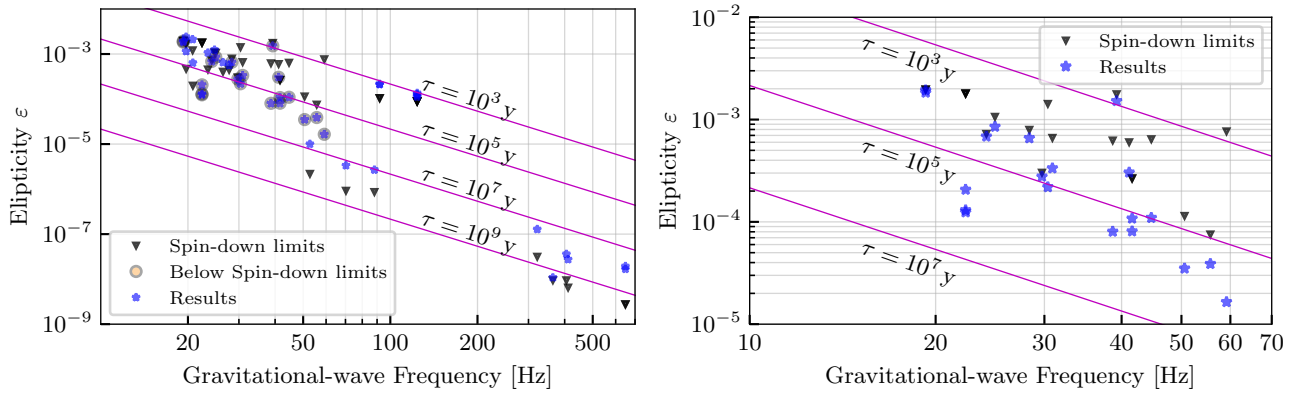

Figure 6. ULs on the star's ellipticity ε compared with the spin-down limits. While the left panel shows our results for all the pulsars, the right panel focuses only on those for which the observational UL is stricter than the spin-down limit (i.e., physically constraining the fraction of rotational energy emitted through the CW channel). The values are compared with contour lines of equal characteristic age $\tau = f/4|\dot{f}|$, assuming that GW emission alone is causing the spin-down.

limit, corresponding to no more than ∼0.04% of its spin-down energy budget being radiated in the GW channel.

Data products associated with this work are collected in the LIGO-DCC document T2600052.

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open access, the authors have applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising. We request that citations to this article use "A. G. Abac et al. (LIGO–Virgo–KAGRA Collaboration), ..." or similar phrasing, depending on journal convention.

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Software: The 5-vector method is based on the SFDB framework (P. Astone et al. 2005) and on the Virgo Rome Snag software (S. Frasca et al. 2022). Plots are produced using `matplotlib` (J. D. Hunter 2007). Many pulsar ephemerides are produced with `TEMPO` (D. Nice et al. 2015) and `TEMPO2` (G. B. Hobbs et al. 2006). The pulsar selection has been handled through `CWInPy` (M. Pitkin 2022) and `psrqpy` (M. Pitkin 2018).

Appendix
UL Calculation

We here summarize the UL procedure used to compute the results in Section 4. The methodology follows the frequentist approach described in Appendix A of B. P. Abbott et al. (2017). Relative to previous narrowband searches, the only methodological modification introduced in this analysis is the inclusion of random $\ddot{f}$ values within the explored parameter space during signal simulations.

ULs are computed independently in each 10^{-4} Hz band (following the search setup) using software injections. For each band, 100 unitary-amplitude simulated signals are generated in the time domain, including the same gaps as in real data, Doppler, and spin-down effects. After computing the pure-signal five vectors, we rescale them to different amplitudes (starting from $H_0 = 10^{-27}$, well below our theoretical sensitivity), allowing the same simulated signals to be reused efficiently when estimating the detection efficiency as a function of the strain amplitude H_0. The injections are combined with real data at the five-vector level in the frequency domain, and the detection statistic is evaluated. If the computed $\mathcal{S}$ is above the threshold corresponding to the 1% false-alarm probability (see Section 3), we identify the signal as detected. If less than 95% of the signals in a band are recovered, we increase the injected strain by 10^{-28} and recompute the detection statistic. When the fraction of recovered signals reaches the 95% CL at $H_0^{95\%}$, we compute the UL as

$$h_0^{95\%} \approx 1.31 \cdot H_0^{95\%}, \tag{A1}$$

where the factor 1.31 comes from averaging h_0 as a function of H_0 (i.e., inversion of Equation (7)) over a flat $\cos\iota$ distribution.

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