

From a Rumble to a Roar: The International Pulsar Timing Array's Third Data Release

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Abstract. Pulsar Timing Arrays (PTAs) use the remarkable rotational stability of millisecond pulsars (MSPs) to detect nanohertz-frequency gravitational waves (GWs). The International PTA (IPTA) combines datasets from six regional PTAs to form the most sensitive experiment to date, with the release of **IPTA Data Release 3 (IPTA-DR3)**. This dataset spans 130 pulsars, baselines up to 27 years, and frequency coverage from 30 to 5107 MHz, enabling precise characterisation of both the stochastic GW background (GWB) and potential continuous-wave (CGW) sources. We present an overview of IPTA-DR3 construction, including data combination pipelines, white and red noise modelling, and likelihood-based inference. We summarise current evidence for correlated GW signals and outline prospects for individual SMBHB detection, multi-messenger follow-up, and probing cosmological GW sources with next-generation PTAs.

1 Introduction

Rotating pulsars emit beams of radiation that, when sweeping across the Earth, appear as periodic pulses to radio telescopes. The photons in each crossing (or pulse) can be assigned precise times of arrival (TOAs). MSPs, which rotate at over 100 Hz, act as remarkably stable cosmic clocks, enabling TOA measurements with precisions down to tens of nanoseconds. Generating TOAs from observations requires folding thousands of rotations, dedispersing across wide frequency bands, and constructing high signal-to-noise (S/N) templates. Because individual pulsars are affected by intrinsic noise, PTAs monitor *arrays* of MSPs to extract spatially correlated deviations induced by GWs.

Major PTAs include the North American Nanohertz Observatory for GWs (NANOGrav), the European PTA (EPTA), the Indian PTA (InPTA), the Parkes PTA (PPTA) in Australia, the Chinese PTA (CPTA), and the MeerKAT PTA (MPTA) in South Africa. Together with the African Pulsar Timing (APT) collaboration, these regional PTAs coordinate under the International PTA (IPTA), combining global datasets to maximize sensitivity to nanohertz-frequency GWs.

PTAs search for correlated angular signatures predicted by the Hellings & Downs curve [1]; the characteristic quadrupolar-like pattern expected from an isotropic stochastic gravitational-wave background (GWB). While supermassive black hole binaries (SMBHBs) formed during galaxy mergers are expected to dominate the nanohertz GWB, other possible contributions include cosmic strings, early-universe phase transitions, and primordial black hole mergers. These scenarios predict distinct spectral slopes: circular SMBHB populations yield an ensemble-averaged strain spectrum $h_c(f) \propto f^{-2/3}$, whereas cosmic strings

produce flatter slopes and first-order phase transitions often generate peaked spectra. Precise measurements of the GWB's amplitude and spectral index therefore provide a pathway to distinguish between astrophysical and cosmological sources.

On 29 June 2023, four PTAs—the EPTA+InPTA collaboration, NANOGrav, PPTA, and CPTA [2–5]—jointly reported strong evidence for a common-spectrum process consistent with a GWB, with a significance of 2σ – 4.6σ , below the IPTA detection threshold [6]. The mean inferred amplitude and spectral index were $A \sim (2 - 3) \times 10^{-15}$, $\gamma \approx 3.5 \pm 2.5$, respectively consistent with expectations from a cosmological population of SMBHBs. The measured angular correlations matched Hellings & Downs predictions, marking the strongest hint yet of nanohertz GWs. Similar evidence was also presented by the MPTA in 2025 [7].

Regional PTAs differ in telescope counts, observing cadences, and frequency coverage, impacting achievable TOA precision and sensitivity to noise processes. Accurate modelling of red noise and dispersion measure (DM) variability requires both high-S/N TOAs and broad frequency coverage. Independent datasets remain essential for identifying instrumental biases, clock errors, and other systematics, ensuring robust global inference.

2 From Observations to Timing Residuals

Detecting nanohertz GWs requires long-term, high-precision monitoring of MSPs using large radio telescopes with sensitive electromagnetic *frontend receivers* and advanced data recording *backends*. In the EPTA, NANOGrav, and PPTA, for example, typical observations last 30–60 minutes and occur every few days to weeks. Data are initially recorded as short *sub-integrations*, folded over many pulsar rotations to boost S/N. The observations are taken at multiple radio frequencies in order to correct for frequency-dependent interstellar dispersion, quantified by the dispersion measure (DM), which traces the total column density of free electrons along the line of sight. Accurate DM estimation is critical for recovering the intrinsic pulse shape and achieving precise TOAs [8].

After sufficient observations are obtained, stable *templates* of the pulse profile are built and used in matched-filtering techniques to extract TOAs. These TOAs are compared against predictions from a comprehensive *pulsar timing model*, which incorporates spin, astrometry, binary motion, and propagation effects. The differences between observed and model-predicted TOAs are the *timing residuals*, the primary data products used by PTAs to search for correlated GW signatures.

3 Noise Modelling and Multi-Telescope Calibration

Combining data from multiple telescopes introduces systematics that must be carefully modelled. Constant *clock offsets* in local time references—detectable within individual PTAs or only apparent after merging datasets—are corrected alongside discrete *phase jumps* used to align TOAs from different receivers. Instrument-specific noise is addressed using empirical scaling parameters: *EFAC* rescales TOA uncertainties, *EQUAD* adds an extra white-noise variance term, and *ECORR* models short-timescale correlations between frequency channels within the same epoch. Accurate calibration of these *white noise* parameters is essential for producing consistent multi-telescope datasets.

However, white noise alone is insufficient: long-term stochastic processes introduce *red noise* into timing data, typically modelled as a power-law process:

$$P_{\text{RN}}(f) = \frac{A_{\text{RN}}^2}{12\pi^2} \left(\frac{f}{f_{\text{ref}}} \right)^{-\gamma_{\text{RN}}}, \quad (1)$$

where A_{RN} is the amplitude, γ_{RN} the spectral index, and $f_{\text{ref}} = 1 \text{ yr}^{-1}$. Red noise arises from irregularities in pulsar spin-down, magnetospheric torque fluctuations, or unmodelled propagation effects.

Additionally, turbulence in the ionised interstellar medium induces stochastic DM variations, producing frequency-dependent (chromatic) residuals that decorrelate across bands. These are modelled with a similar power-law spectrum but scaled by ν^{-2} , where ν is the observing frequency. Accurate modelling of both intrinsic red noise and DM variability is critical for unbiased GW searches.

4 Likelihood Framework for PTA Analysis

With calibrated TOAs and timing residuals, PTAs construct global timing solutions using a Gaussian likelihood over the concatenated vector $\delta\mathbf{t}$ of residuals [see e.g., 9, 10]:

$$P(\delta\mathbf{t} | \theta) = \frac{1}{\sqrt{(2\pi)^n \det \mathbf{C}}} \exp \left[-\frac{1}{2} (\delta\mathbf{t} - \mathbf{s})^T \mathbf{C}^{-1} (\delta\mathbf{t} - \mathbf{s}) \right], \quad (2)$$

where $\delta\mathbf{t}$ are the residuals, \mathbf{s} captures deterministic contributions (e.g., GWs from resolvable SMBHBs and corrections to the timing ephemeris), and \mathbf{C} is the total covariance matrix:

$$C_{\alpha i, \beta j} = C_{\text{WN}}\delta_{\alpha\beta}\delta_{ij} + C_{\text{RN}}^{ij}\delta_{\alpha\beta} + C_{\text{DM}}^{ij}\delta_{\alpha\beta} + C_{\text{GW}}^{ij}\delta_{\alpha\beta} + \dots \quad (3)$$

Here, i and j are indices for the MSPs and α and β identify their TOAs, while C_{WN} models white noise, C_{RN} red spin noise, C_{DM} DM variations, and C_{GW} a correlated GW background. Modelling this complete noise hierarchy is essential for maximizing PTA sensitivity and enabling robust astrophysical inference.

However, the statistical power of this framework depends critically on the size, quality, and diversity of the available dataset [11, 12]. Long baselines improve sensitivity to low-frequency signals, broad frequency coverage enhances modelling of chromatic DM variations, and high observing cadence strengthens constraints on pulsar-intrinsic red noise. Crucially, detecting a nanohertz GWB requires measuring spatial correlations across many pulsars, as predicted by the Hellings & Downs curve. The IPTA-DR3 provides the most comprehensive dataset to date, enabling robust joint constraints on these angular correlations.

5 IPTA-DR3 Dataset Overview

The IPTA-DR3 dataset integrates contributions from six regional PTAs: EPTA, NANOGrav, PPTA, InPTA, MPTA, and CPTA. Key statistics are shown in Table 1.

Table 1: Summary of IPTA-DR3 dataset properties.

Dataset	Pulsars	Tspan (yrs)	$f_{\text{GW,low}}$ (nHz)	Freq. Range (MHz)
EPTA-DR3	60	24.5	1.3	25–5107
NANOGrav 15-year	68	15.9	2.0	302–3988
PPTA-DR3	24	18.1	1.8	704–4032
MeerKAT DR2	83	4.5	7.0	856–1712
InPTA DR2	27	7.5	4.4	300–1460
CPTA DR1	57	2.3	13.8	1050–1450
IPTA DR3	130	~27	1.2	30–5107

IPTA-DR3 spans 130 pulsars, contributing over one million TOAs. Its ultra-wideband frequency coverage, combined with multi-decade baselines and diverse observing cadences, dramatically improves our ability to model intrinsic red noise and DM variations simultaneously. This precision is essential to isolate the common-spectrum GWB signature from pulsar-specific noise processes.

For example, PSR J0030+0451 contributes approximately 50,000 TOAs, includes 51 phase jumps in its timing solution, and achieves a precision of $\sim 7 \times 10^{-6}$ on $\Delta DM/DM$. Improvements of this kind enhance per-pulsar noise models, increasing the effective S/N of multi-pulsar searches and enabling IPTA-DR3 to approach the 5σ sensitivity threshold needed for a definitive detection of the nanohertz GWB.

The workflow for combining regional datasets into IPTA-DR3 employs three parallel pipelines: (i) **Tempo2** [14] + **TempoNest** [10], (ii) **Tempo2** + **Enterprise** [15], and (iii) **PINT** [16] + **Enterprise**. After *dataset gathering*, *flag unification* standardises metadata across PTAs. Initial pulsar timing models (*parfiles*) are produced using either **Tempo2** or **PINT**, followed by *jump fitting* to correct phase offsets between telescopes and backends. *Outlier analysis* removes problematic TOAs based on diagnostics such as χ^2 , RMS scatter, and fitted jump values. At present, advanced Bayesian outlier analyses such as those implemented for the NANOGrav dataset are not necessary given the TOAs provided to the IPTA are pre-assessed by each regional PTA. Cleaned datasets are then merged and fed into *single-pulsar noise analyses* using Bayesian inference. These models capture radiometer noise, jitter, intrinsic red noise, DM variations, scattering, and instrumental systematics. Cross-validation between pipelines ensures consistent timing solutions and robust noise estimates. Typically, for timing parameters this inspection is performed manually, using least squares fitting to check for unusual features in the residual plots, etc., while noise model posteriors are tested using distance measures. The final harmonised dataset will underpin the IPTA’s GW searches and enable precise modelling of correlated and uncorrelated noise across the array.

6 Future Prospects

Even for a purely SMBHB-driven GWB, simulations predict that a few nearby, *loud* binaries will produce continuous GW (CGW) signals atop a stochastic background from many fainter systems. Accurate

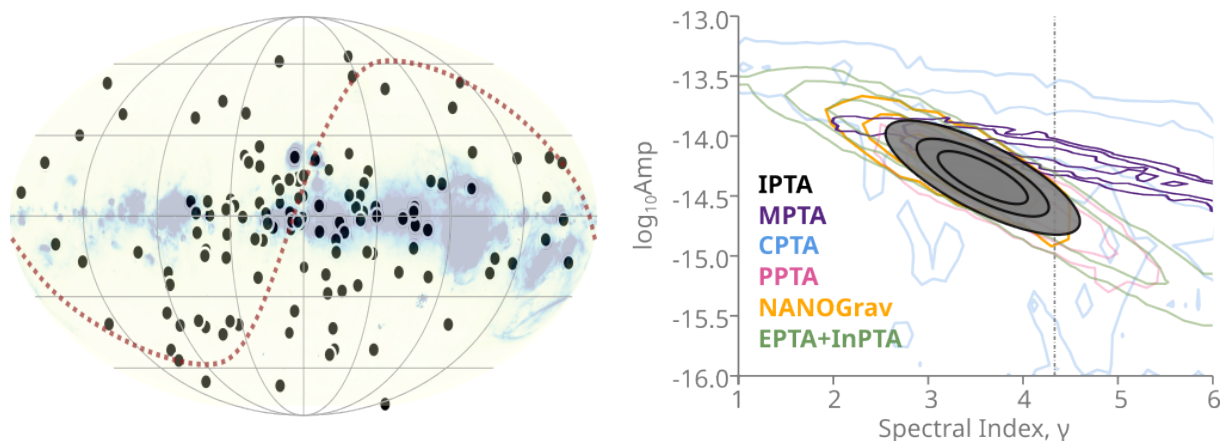


Figure 1: Sky coverage of the IPTA-DR3 MSPs, and expected minimal improvement to the parameter estimates for an HD-correlated signal, using a simplified simulation that mirrors the strategy used in [13].

characterization of the GW sky therefore requires **joint modelling** of the GWB and CGWs, enabling unbiased recovery of both stochastic and deterministic parameters [17] and investigating anisotropy from such loud CGW sources [18]. Improved sensitivity in IPTA-DR3 and future SKA-era PTAs will open access to higher GW frequencies, where individual SMBHBs are more resolvable, and allow precise GWB spectrum measurements to separate astrophysical and exotic contributions (e.g., cosmic strings or phase transitions). These advances will enable targeted multi-messenger searches linking GW detections to electromagnetic counterparts with facilities like LSST and next-generation X-ray surveys, marking the transition from statistical hints to precision nanohertz GW astronomy.

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The IPTA is a global collaboration of regional PTAs—including APT, EPTA, InPTA, NANOGrav, PPTA, MPTA, and CPTA—working together to detect nanohertz gravitational waves through precision pulsar timing. IPTA-DR3 is the result of decades of observations using the world's most powerful radio telescopes: the LOFAR observatory (Europe), NENUFAR radio telescope (France), Effelsberg 100-m Radio Telescope (Germany), Lovell Telescope at Jodrell Bank (UK), Nançay Radio Telescope (France), Westerbork Synthesis Radio Telescope (Netherlands), Sardinia Radio Telescope (Italy), Giant Metrewave Radio Telescope (India), Green Bank Telescope (USA), Arecibo Observatory (Puerto Rico), Very Large Array (USA), CHIME (Canada), FAST (China), Parkes/Murriyang Telescope (Australia) and MeerKAT (South Africa).

This work relies on the sustained contributions of hundreds of scientists, engineers, and students involved in timing observations, data calibration, software development, and theoretical modelling. The diverse global participation of IPTA members is essential for achieving the precision and sensitivity required to detect nanohertz gravitational waves. We acknowledge the generous support of national funding agencies, supercomputing facilities, and telescope operators who make this collaborative effort possible.

References

- [1] Hellings R W and Downs G S 1983 *ApJ* **265** L39–L42 ISSN 0004-637X
- [2] EPTA Collaboration, Antoniadis J, Babak S, Bak Nielsen A S, Bassa C G, Berthreau A, Bonetti M, Bortolas E, Brook P R, Burgay M, Caballero R N, Chalumeau A, Champion D J, Chanlaridis S, Chen S, Cognard I, Desvignes G, Falxa M, Ferdman R D, Franchini A, Gair J R, Goncharov B, Graikou E, Griesmeier J M, Guillemot L, Guo Y J, Hu H, Iraci F, Izquierdo-Villalba D, Jang J, Jawor J, Janssen G H, Jessner A, Karuppusamy R, Keane E F, Keith M J, Kramer M, Krishnakumar M A, Lackeos K, Lee K J, Liu K, Liu Y, Lyne A G, McKee J W, Main R A, Mickaliger M B, Nițu I C, Parthasarathy A, Perera B B P, Perrodin D, Petiteau A, Porayko N K, Possenti A, Quelquejay

- Leclere H, Samajdar A, Sanidas S A, Sesana A, Shaifullah G, Speri L, Spiewak R, Stappers B W, Susarla S C, Theureau G, Tiburzi C, van der Wateren E, Vecchio A, Venkatraman Krishnan V, Verbiest J P W, Wang J, Wang L and Wu Z 2023 *A&A* **678** A48 (*Preprint* 2306.16224)
- [3] Agazie G, Anumarlapudi A, Archibald A M, Arzoumanian Z, Baker P T, Bécsy B, Blecha L, Brazier A, Brook P R, Burke-Spolaor S, Burnette R, Case R, Charisi M, Chatterjee S, Chatziioannou K, Cheeseboro B D, Chen S, Cohen T, Cordes J M, Cornish N J, Crawford F, Cromartie H T, Crowter K, Cutler C J, Decesar M E, Degan D, Demorest P B, Deng H, Dolch T, Drachler B, Ellis J A, Ferrara E C, Fiore W, Fonseca E, Freedman G E, Garver-Daniels N, Gentile P A, Gersbach K A, Glaser J, Good D C, Gültekin K, Hazboun J S, Hourihane S, Islo K, Jennings R J, Johnson A D, Jones M L, Kaiser A R, Kaplan D L, Kelley L Z, Kerr M, Key J S, Klein T C, Laal N, Lam M T, Lamb W G, Lazio T J W, Lewandowska N, Littenberg T B, Liu T, Lommen A, Lorimer D R, Luo J, Lynch R S, Ma C P, Madison D R, Mattson M A, McEwen A, McKee J W, McLaughlin M A, McMann N, Meyers B W, Meyers P M, Mingarelli C M F, Mitridate A, Natarajan P, Ng C, Nice D J, Ocker S K, Olum K D, Pennucci T T, Perera B B P, Petrov P, Pol N S, Radovan H A, Ransom S M, Ray P S, Romano J D, Sardesai S C, Schmiedekamp A, Schmiedekamp C, Schmitz K, Schult L, Shapiro-Albert B J, Siemens X, Simon J, Siwek M S, Stairs I H, Stinebring D R, Stovall K, Sun J P, Susobhanan A, Swiggum J K, Taylor J, Taylor S R, Turner J E, Unal C, Vallisneri M, van Haasteren R, Vigeland S J, Wahl H M, Wang Q, Witt C A, Young O and Nanograv Collaboration 2023 *ApJL* **951** L8 (*Preprint* 2306.16213) URL <https://ui.adsabs.harvard.edu/abs/2023ApJ...951L...8A>
- [4] Reardon D J, Zic A, Shannon R M, Hobbs G B, Bailes M, Di Marco V, Kapur A, Rogers A F, Thrane E, Askew J, Bhat N D R, Cameron A, Curyło M, Coles W A, Dai S, Goncharov B, Kerr M, Kulkarni A, Levin Y, Lower M E, Manchester R N, Mandow R, Miles M T, Nathan R S, Osłowski S, Russell C J, Spiewak R, Zhang S and Zhu X J 2023 *ApJL* **951** L6 (*Preprint* 2306.16215) URL <https://ui.adsabs.harvard.edu/abs/2023ApJ...951L...6R>
- [5] Xu H, Chen S, Guo Y, Jiang J, Wang B, Xu J, Xue Z, Nicolas Caballero R, Yuan J, Xu Y, Wang J, Hao L, Luo J, Lee K, Han J, Jiang P, Shen Z, Wang M, Wang N, Xu R, Wu X, Manchester R, Qian L, Guan X, Huang M, Sun C and Zhu Y 2023 *Research in Astronomy and Astrophysics* **23** 075024 (*Preprint* 2306.16216) URL <https://ui.adsabs.harvard.edu/abs/2023RAA...23g5024X>
- [6] Allen B, Dhurandhar S, Gupta Y, McLaughlin M, Natarajan P, Shannon R M, Thrane E and Vecchio A 2023 *arXiv e-prints* arXiv:2304.04767 (*Preprint* 2304.04767)
- [7] Miles M T, Shannon R M, Reardon D J, Bailes M, Champion D J, Geyer M, Gitika P, Grunthal K, Keith M J, Kramer M, Kulkarni A D, Nathan R S, Parthasarathy A, Singha J, Theureau G, Thrane E, Abbate F, Buchner S, Cameron A D, Camilo F, Moreschi B E, Shaifullah G, Shamohammadi M, Possenti A and Krishnan V V 2025 *MNRAS* **536** 1489–1500 (*Preprint* 2412.01153)
- [8] Lorimer D R and Kramer M 2012 *Handbook of Pulsar Astronomy*
- [9] van Haasteren R, Levin Y, Janssen G H, Lazaridis K, Kramer M, Stappers B W, Desvignes G, Purver M B, Lyne A G, Ferdman R D, Jessner A, Cognard I, Theureau G, D'Amico N, Possenti A, Burgay M, Corongiu A, Hessels J W T, Smits R and Verbiest J P W 2011 *MNRAS* **414** 3117–3128 (*Preprint* 1103.0576) URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.414.3117V>
- [10] Lentati L, Alexander P, Hobson M P, Taylor S, Gair J, Balan S T and van Haasteren R 2013 *Phys.Rev.D* **87** 104021 (*Preprint* 1210.3578)
- [11] Verbiest J P W, Lentati L, Hobbs G, van Haasteren R, Demorest P B, Janssen G H, Wang J B, Desvignes G, Caballero R N, Keith M J, Champion D J, Arzoumanian Z, Babak S, Bassa C G, Bhat N D R, Brazier A, Brem P, Burgay M, Burke-Spolaor S, Chamberlin S J, Chatterjee S, Christy B, Cognard I, Cordes J M, Dai S, Dolch T, Ellis J A, Ferdman R D, Fonseca E, Gair J R, Garver-Daniels N E, Gentile P, Gonzalez M E, Graikou E, Guillemot L, Hessels J W T, Jones G, Karuppusamy R, Kerr M, Kramer M, Lam M T, Lasky P D, Lassus A, Lazarus P, Lazio T J W, Lee K J, Levin L, Liu K, Lynch R S, Lyne A G, McKee J, McLaughlin M A, McWilliams S T, Madison D R, Manchester R N, Mingarelli C M F, Nice D J, Osłowski S, Palliyaguru N T, Pennucci T T, Perera B B P, Perrodin D, Possenti A, Petiteau A, Ransom S M, Reardon D, Rosado P A, Sanidas S A, Sesana A, Shaifullah G, Shannon R M, Siemens X, Simon J, Smits R, Spiewak R, Stairs I H, Stappers B W, Stinebring D R, Stovall K, Swiggum J K, Taylor S R, Theureau G, Tiburzi C, Toomey L, Vallisneri M, van Straten W, Vecchio A, Wang Y, Wen L, You X P, Zhu W W and Zhu X J 2016 *MNRAS* **458** 1267–1288 (*Preprint* 1602.03640)

- [12] Siemens X, Ellis J, Jenet F and Romano J D 2013 *Classical and Quantum Gravity* **30** 224015 (*Preprint* 1305.3196) URL <https://ui.adsabs.harvard.edu/abs/2013CQGra...30v4015S>
- [13] Agazie G, Antoniadis J, Anumarlapudi A, Archibald A M, Arumugam P, Arumugam S, Arzoumanian Z, Askew J, Babak S, Bagchi M, Bailes M, Bak Nielsen A S, Baker P T, Bassa C G, Bathula A, Bécsy B, Berthereau A, Bhat N D R, Blecha L, Bonetti M, Bortolas E, Brazier A, Brook P R, Burgay M, Burke-Spolaor S, Burnette R, Caballero R N, Cameron A, Case R, Chalumeau A, Champion D J, Chanlaridis S, Charisi M, Chatterjee S, Chatziioannou K, Cheeseboro B D, Chen S, Chen Z C, Cognard I, Cohen T, Coles W A, Cordes J M, Cornish N J, Crawford F, Cromartie H T, Crowter K, Curyło M, Cutler C J, Dai S, Dandapat S, Deb D, DeCesar M E, DeGan D, Demorest P B, Deng H, Desai S, Desvignes G, Dey L, Dhanda-Batra N, Di Marco V, Dolch T, Drachler B, Dwivedi C, Ellis J A, Falxa M, Feng Y, Ferdman R D, Ferrara E C, Fiore W, Fonseca E, Franchini A, Freedman G E, Gair J R, Garver-Daniels N, Gentile P A, Gersbach K A, Glaser J, Good D C, Goncharov B, Gopakumar A, Graikou E, Griessmeier J M, Guillemot L, Gültekin K, Guo Y J, Gupta Y, Grunthal K, Hazboun J S, Hisano S, Hobbs G B, Hourihane S, Hu H, Iraci F, Islo K, Izquierdo-Villalba D, Jang J, Jawor J, Janssen G H, Jennings R J, Jessner A, Johnson A D, Jones M L, Joshi B C, Kaiser A R, Kaplan D L, Kapur A, Kareem F, Karuppusamy R, Keane E F, Keith M J, Kelley L Z, Kerr M, Key J S, Kharbanda D, Kikunaga T, Klein T C, Kolhe N, Kramer M, Krishnakumar M A, Kulkarni A, Laal N, Lackeos K, Lam M T, Lamb W G, Larsen B B, Lazio T J W, Lee K J, Levin Y, Lewandowska N, Littenberg T B, Liu K, Liu T, Liu Y, Lommen A, Lorimer D R, Lower M E, Luo J, Luo R, Lynch R S, Lyne A G, Ma C P, Maan Y, Madison D R, Main R A, Manchester R N, Mandow R, Mattson M A, McEwen A, McKee J W, McLaughlin M A, McMann N, Meyers B W, Meyers P M, Mickaliger M B, Miles M, Mingarelli C M F, Mitridate A, Natarajan P, Nathan R S, Ng C, Nice D J, Nițu I C, Nobleson K, Ocker S K, Olum K D, Osłowski S, Paladi A K, Parthasarathy A, Pennucci T T, Perera B B P, Perrodin D, Petiteau A, Petrov P, Pol N S, Porayko N K, Possenti A, Prabu T, Quelquejay Leclere H, Radovan H A, Rana P, Ransom S M, Ray P S, Reardon D J, Rogers A F, Romano J D, Russell C J, Samajdar A, Sanidas S A, Sardesai S C, Schmiedekamp A, Schmiedekamp C, Schmitz K, Schult L, Sesana A, Shaifullah G, Shannon R M, Shapiro-Albert B J, Siemens X, Simon J and Singha J 2024 *ApJ* **966** 105 (*Preprint* 2309.00693)
- [14] Hobbs G and Edwards R 2012 Tempo2: Pulsar Timing Package Astrophysics Source Code Library, record ascl:1210.015 (*Preprint* 1210.015)
- [15] Ellis J A, Vallisneri M, Taylor S R and Baker P T 2019 ENTERPRISE: Enhanced Numerical Toolbox Enabling a Robust Pulsar Inference Suite Astrophysics Source Code Library, record ascl:1912.015 (*Preprint* 1912.015)
- [16] Luo J, Ransom S, Demorest P, Ray P S, Archibald A, Kerr M, Jennings R J, Bachetti M, van Haasteren R, Champagne C A, Colen J, Phillips C, Zimmerman J, Stovall K, Lam M T and Jenet F A 2021 *ApJ* **911** 45 (*Preprint* 2012.00074)
- [17] Ferranti I, Shaifullah G, Chalumeau A and Sesana A 2025 *A&A* **694** A194 (*Preprint* 2407.21105)
- [18] Moreschi B E, Valtolina S, Sesana A, Shaifullah G, Falxa M, Speri L, Izquierdo-Villalba D and Chalumeau A 2025 *arXiv preprint arXiv:2506.14882* submitted to A&A (*Preprint* 2506.14882) URL <https://doi.org/10.48550/arXiv.2506.14882>