

## Second Data Release from the European Pulsar Timing Array: Challenging the Ultralight Dark Matter Paradigm

Clemente Smarra<sup>1,2,\*</sup>, Boris Goncharov,<sup>3,4</sup> Enrico Barausse,<sup>1,2</sup> J. Antoniadis,<sup>5,6</sup> S. Babak,<sup>7</sup> A.-S. Bak Nielsen,<sup>6,8</sup> C. G. Bassa,<sup>9</sup> A. Berthereau,<sup>10,11</sup> M. Bonetti,<sup>12,13,14</sup> E. Bortolas,<sup>12,13,14</sup> P. R. Brook,<sup>15</sup> M. Burgay,<sup>16</sup> R. N. Caballero,<sup>17</sup> A. Chalumeau,<sup>12</sup> D. J. Champion,<sup>6</sup> S. Chanlaridis,<sup>5</sup> S. Chen,<sup>18</sup> I. Cognard,<sup>10,11</sup> G. Desvignes,<sup>6</sup> M. Falxa,<sup>10,7</sup> R. D. Ferdman,<sup>19</sup> A. Franchini,<sup>12,13</sup> J. R. Gair,<sup>20</sup> E. Graikou,<sup>6</sup> J.-M. Grießmeier,<sup>10,11</sup> L. Guillemot,<sup>10,11</sup> Y. J. Guo,<sup>6</sup> H. Hu,<sup>6</sup> F. Iraci,<sup>16,21</sup> D. Izquierdo-Villalba,<sup>12,13</sup> J. Jang,<sup>6</sup> J. Jawor,<sup>6</sup> G. H. Janssen,<sup>9,22</sup> A. Jessner,<sup>6</sup> R. Karuppusamy,<sup>6</sup> E. F. Keane,<sup>23</sup> M. J. Keith,<sup>24</sup> M. Kramer,<sup>6,24</sup> M. A. Krishnakumar,<sup>6,8</sup> K. Lackeos,<sup>6</sup> K. J. Lee,<sup>5,6,11</sup> K. Liu,<sup>6</sup> Y. Liu,<sup>8,25</sup> A. G. Lyne,<sup>24</sup> J. W. McKee,<sup>26,27</sup> R. A. Main,<sup>6</sup> M. B. Mickaliger,<sup>24</sup> I. C. Nițu,<sup>24</sup> A. Parthasarathy,<sup>6</sup> B. B. P. Perera,<sup>28</sup> D. Perrodin,<sup>16</sup> A. Petiteau,<sup>29,7</sup> N. K. Porayko,<sup>6,12</sup> A. Possenti,<sup>16</sup> H. Quelquejay Leclere,<sup>7</sup> A. Samajdar,<sup>30</sup> S. A. Sanidas,<sup>24</sup> A. Sesana,<sup>12,13,14</sup> G. Shaifullah,<sup>12,13,16</sup> L. Speri,<sup>20</sup> R. Spiewak,<sup>24</sup> B. W. Stappers,<sup>24</sup> S. C. Susarla,<sup>31</sup> G. Theureau,<sup>10,11,32</sup> C. Tiburzi,<sup>16</sup> E. van der Wateren,<sup>22,9</sup> A. Vecchio,<sup>15</sup> V. Venkatraman Krishnan,<sup>6</sup> J. Wang,<sup>8,33,34</sup> L. Wang,<sup>24</sup> and Z. Wu<sup>25</sup>

(European Pulsar Timing Array)

<sup>1</sup>SISSA—International School for Advanced Studies, Via Bonomea 265, 34136, Trieste, Italy and INFN, Sezione di Trieste

<sup>2</sup>IFPU—Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy

<sup>3</sup>Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

<sup>4</sup>INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy

<sup>5</sup>Institute of Astrophysics, FORTH, Nikolaou Plastira 100, 70013, Heraklion, Greece

<sup>6</sup>Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

<sup>7</sup>Université Paris Cité CNRS, Astroparticule et Cosmologie, 75013 Paris, France

<sup>8</sup>Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany

<sup>9</sup>ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands

<sup>10</sup>Laboratoire de Physique et Chimie de l'Environnement et de l'Espace,

Université d'Orléans/CNRS, 45071 Orléans Cedex 02, France

<sup>11</sup>Observatoire Radioastronomique de Nançay, Observatoire de Paris,

Université PSL, Université d'Orléans, CNRS, 18330 Nançay, France

<sup>12</sup>Dipartimento di Fisica "G. Occhialini", Università degli Studi di Milano-Bicocca,

Piazza della Scienza 3, I-20126 Milano, Italy

<sup>13</sup>INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy

<sup>14</sup>INAF - Osservatorio Astronomico di Brera, via Brera 20, I-20121 Milano, Italy

<sup>15</sup>Institute for Gravitational Wave Astronomy and School of Physics and Astronomy,

University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

<sup>16</sup>INAF - Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047 Selargius (CA), Italy

<sup>17</sup>Hellenic Open University, School of Science and Technology, 26335 Patras, Greece

<sup>18</sup>Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People's Republic of China

<sup>19</sup>School of Physics, Faculty of Science, University of East Anglia, Norwich NR4 7TJ, United Kingdom

<sup>20</sup>Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, 14476 Potsdam, Germany

<sup>21</sup>Università di Cagliari, Dipartimento di Fisica, S.P. Monserrato-Sestu Km 0,700–09042 Monserrato (CA), Italy

<sup>22</sup>Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands

<sup>23</sup>School of Physics, Trinity College Dublin, College Green, Dublin 2, D02 PN40, Ireland

<sup>24</sup>Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy,

University of Manchester, Manchester M13 9PL, United Kingdom

<sup>25</sup>National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People's Republic of China

<sup>26</sup>E.A. Milne Centre for Astrophysics, University of Hull,

Cottingham Road, Kingston-upon-Hull, HU6 7RX, United Kingdom

<sup>27</sup>Centre of Excellence for Data Science, Artificial Intelligence and Modelling (DAIM),

University of Hull, Cottingham Road, Kingston-upon-Hull, HU6 7RX, United Kingdom

<sup>28</sup>Arecibo Observatory, HC3 Box 53995, Arecibo, Puerto Rico 00612

<sup>29</sup>IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France


<sup>30</sup>Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25, 14476, Potsdam, Germany

<sup>31</sup>Ollscoil na Gaillimhe—University of Galway, University Road, Galway H91 TK33, Ireland

<sup>32</sup>Laboratoire Univers et Théories LUTH, Observatoire de Paris,

Université PSL, CNRS, Université de Paris, 92190 Meudon, France

<sup>33</sup>Ruhr University Bochum, Faculty of Physics and Astronomy, Astronomical Institute (AIRUB), 44780 Bochum, Germany  
<sup>34</sup>Advanced Institute of Natural Sciences, Beijing Normal University, Zhuhai 519087, China

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Pulsar Timing Array experiments probe the presence of possible scalar or pseudoscalar ultralight dark matter particles through decade-long timing of an ensemble of galactic millisecond radio pulsars. With the second data release of the European Pulsar Timing Array, we focus on the most robust scenario, in which dark matter interacts only gravitationally with ordinary baryonic matter. Our results show that ultralight particles with masses  $10^{-24.0} \text{ eV} \lesssim m \lesssim 10^{-23.3} \text{ eV}$  cannot constitute 100% of the measured local dark matter density, but can have at most local density  $\rho \lesssim 0.3 \text{ GeV/cm}^3$ .

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*Introduction.*—The nature of dark matter (DM) is arguably one of the most fascinating and mysterious questions that we are struggling to answer. Galaxy rotation curves [1,2], the peculiar motion of clusters [3,4], the bullet cluster system [5], measurements of cosmological abundances from cosmic microwave background (CMB) and baryonic acoustic oscillation (BAO) observations [6,7] all point to the existence of a hitherto-unseen type of matter, constituting roughly 26% of the current energy density of the Universe and interacting mostly gravitationally with the standard model of particle physics. The standard cold dark matter (CDM) paradigm describes successfully many aspects of the large-scale structure of the Universe, but struggles to predict what we observe at scales smaller than the  $\sim \text{kpc}$ . For instance, observations favor a constant density profile in the inner part of galaxies, while CDM predicts a steep power-law-like behavior (*cuspy-core problem*) [8–10]. Furthermore, well-known issues are associated with the discrepancy between the observed and expected number of Milky Way (MW) satellites (*missing satellite problem*) [11,12] and with  $\Lambda\text{CDM}$  simulations showing that the most massive subhaloes of the MW would be too dense to host any of its bright satellites (*too-big-to-fail problem*) [13]. Moreover, recent anomalies in gravitationally lensed images [14] seem to disfavor the long-standing weakly interacting massive particles (WIMPs) hypothesis for CDM. While some of these issues might be alleviated by invoking baryonic feedback mechanisms [15], e.g., active galactic nuclei (AGN) [16] and/or supernova feedback [17–22], it is still unclear how the flat density profile of dwarf galaxies (e.g., Fornax [23]), with almost no baryonic activity in the center, can be explained without invoking a novel mechanism. An intriguing alternative is to consider the possibility that DM is fuzzy, i.e., an ultralight scalar field ( $m_\phi \sim 10^{-22} \text{ eV}$ ) or axionlike particle, whose wavelike nature suppresses structure formation on scales smaller than the de Broglie wavelength, while maintaining all the achievements of the CDM paradigm on large scales. Moreover, the existence of ultralight scalars can also be motivated on a more theoretical ground: in particular, axionlike particles generically arise in string theory

compactifications as Kaluza-Klein zero modes of antisymmetric tensor fields [24–26].

A wealth of studies have been carried out to probe the existence of ultralight dark matter (ULDM), ranging from CMB observables to Lyman- $\alpha$  and stellar kinematics. Specifically, the integrated Sachs-Wolfe effect on CMB anisotropies rules out masses  $m_\phi \lesssim 10^{-24} \text{ eV}$  [27], while Lyman- $\alpha$  gives a lower bound  $m_\phi \gtrsim 10^{-21} \text{ eV}$  for ultralight candidates constituting more than  $\sim 30\%$  of DM [28–33]. Stellar orbit kinematics in ultra-faint dwarf (UFD) galaxies might even be able to bound the scalar field mass to be  $m_\phi \gtrsim 10^{-19} \text{ eV}$ , although this is still under debate [34,35]. However, the sensitivity of non-CMB constraints to uncertainties in the modeling of small scale structure properties [36,37] makes it compelling to rely on complementary and independent probes. It was shown by Khmelnitsky and Rubakov [38] that the presence of ULDM induces an oscillating gravitational potential that affects the light travel time of radio pulses emitted by pulsars. Therefore, Pulsar Timing Arrays (PTAs) stand out as promising experiments to test the presence of ULDM particles in the MW. Previous PTA searches placed 95% upper limits on the local energy density of ULDM at  $3 \times 10^{-24} \text{ eV}$  to  $\lesssim 1 \text{ GeV/cm}^3$  [39–41].

In this Letter, which is complementary to the European Pulsar Timing Array (EPTA) interpretation effort [42], we focus on a specific range of ULDM masses and constrain the local ULDM density to values *below* the observed local DM density. We do so by analyzing the effect of ULDM on the times of arrival (TOAs) of pulsar radio beams. Therefore, if ULDM particles exist in the mass range that we consider, they cannot constitute all of the observed DM.

*Models.*—As we only have gravitational evidence of DM, we focus on an ultralight scalar field with negligible self-interactions and no couplings with the standard model. The action for this field can be written as

$$S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 \phi^2 \right]. \quad (1)$$

Because of its high occupation number and nonrelativistic nature, the ULDM scalar field can be thought as a classical wave [38]:

$$\phi(\vec{x}, t) = \frac{\sqrt{2\rho_\phi}}{m_\phi} \hat{\phi}(\vec{x}) \cos(m_\phi t + \gamma(\vec{x})), \quad (2)$$

where  $m_\phi$  is the mass of the scalar field,  $\gamma(\vec{x})$  is a space-dependent phase, and  $\hat{\phi}(\vec{x})$  accounts for the pattern of interference in the proximity of  $\vec{x}$  caused by the wavelike nature of ULDM. The scalar field density  $\rho_\phi$  is conveniently normalized to the local DM density  $\rho_{\text{DM}}$ , which can be determined, e.g., by fitting the MW rotation curve or, in a more refined way, by studying the vertical oscillations of disc stars [43–46]. In the following, we assume a fiducial value  $\rho_{\text{DM}} \approx 0.4 \text{ GeV/cm}^3$ . The oscillating nature of ULDM induces an oscillating gravitational potential leading to a periodic displacement  $\delta t_{\text{DM}}$  in the TOAs of radio pulses emitted by pulsars, which can be written as [38,40]

$$\delta t_{\text{DM}} = \frac{\Psi_c(\vec{x})}{2m_\phi} \left[ \hat{\phi}_E^2 \sin(2m_\phi + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi + \gamma_P) \right], \quad (3)$$

where

$$\frac{\Psi_c(\vec{x})}{10^{-18}} \approx 6.52 \left( \frac{10^{-22} \text{ eV}}{m_\phi} \right)^2 \left( \frac{\rho_\phi}{0.4 \text{ GeV/cm}^3} \right), \quad (4)$$

and  $\gamma_P \equiv 2\gamma(\vec{x}_P) - 2m_\phi d_p/c$  ( $\gamma_E \equiv 2\gamma(\vec{x}_E)$ ) are related to the phases of Eq. (2) evaluated at the pulsar (Earth) location, with  $d_p$  standing for the pulsar-Earth distance. The amplitude in Eq. (4) is computed assuming a constant DM density background and possible deviations caused by the wavelike nature of the ultralight scalar field are parametrized in terms of the pulsar (Earth) dependent phase factors  $\hat{\phi}^2(\vec{x}_P) \equiv \hat{\phi}_P^2$  ( $\hat{\phi}^2(\vec{x}_E) \equiv \hat{\phi}_E^2$ ). The approximation of constant DM density across pulsars is sufficient, as their distances from Earth are all  $\sim \text{kpc}$  and subject to large measurement uncertainties [40]. Notice that accurate measurements of pulsar-Earth distances might help to reduce the number of free parameters in the limit in which  $\gamma(\vec{x}_P) = \gamma(\vec{x}_E)$ . Moreover, precise determination of pulsar positions could provide us with more information about the dark matter density in its surroundings. On scales smaller than the de Broglie wavelength, the ULDM scalar field oscillates coherently, with the same amplitude  $\hat{\phi}$  [see Eq. (2)]. Since the typical ULDM velocity is expected to be  $v_\phi \sim 10^{-3}$ , the coherence length is approximately

$$l_c \approx \frac{2\pi}{m_\phi v_\phi} \approx 0.4 \text{ kpc} \left( \frac{10^{-22} \text{ eV}}{m_\phi} \right). \quad (5)$$

Therefore,  $\hat{\phi}_E^2$  and  $\hat{\phi}_P^2$  are (i) *uncorrelated* if the coherence length of ULDM is less than the average interpulsar and pulsar-Earth separation. In this case,  $\hat{\phi}_E^2$  and  $\hat{\phi}_P^2$  will thus be

separate parameters; (ii) *correlated* if the coherence length of ULDM is larger than the interpulsar and pulsar-Earth separations and encloses the typical Galacto-centric region tested by the most precise MW rotation curves measurements (roughly the inner  $\sim 20 \text{ kpc}$  [47]). In this case,  $\hat{\phi}_E^2 = \hat{\phi}_P^2$  for all the pulsars. Moreover, rotation curves also sample from the same coherence patch, and thus measure the local abundance  $\rho_{\text{DM}}$  of DM. Therefore, the stochastic parameter  $\hat{\phi}^2$  can be safely absorbed in a redefinition of  $\Psi_c$ . (iii) *pulsar correlated* if the coherence length of ULDM is larger than the interpulsar and pulsar-Earth separations, but smaller than the typical Galacto-centric radius sampled by rotation curves. In this case,  $\hat{\phi}_E^2 = \hat{\phi}_P^2$  for all the pulsars. However, DM density estimates from rotation curves average over different patches. We therefore keep  $\hat{\phi}^2$  as a free parameter and consistently marginalize over it. In this way, the limits on  $\rho_{\text{DM}}$  obtained from pulsars will constrain the same quantity measured by rotation curves. We perform the analysis in the three limits above, noting that the fully correlated limit has not been considered in the previous studies [48,49]. From Eq. (5), recalling that the pulsar-Earth distance is  $\mathcal{O}(\text{kpc})$  for the observed systems, it follows that the *correlated* regime is an excellent approximation for masses lower than  $m_\phi \sim 2 \times 10^{-24} \text{ eV}$ ; the *pulsar-correlated* regime holds for  $2 \times 10^{-24} \text{ eV} \lesssim m_\phi \lesssim 5 \times 10^{-23} \text{ eV}$ , and the *uncorrelated* regime is valid for  $m_\phi \gtrsim 5 \times 10^{-23} \text{ eV}$ .

*Dataset and methodology.*—The EPTA monitors 42 ms radio pulsars with five telescopes located in France, Germany, Italy, the Netherlands, and the United Kingdom. The second data release (DR2) of the EPTA contains 24.7 years of observations of pulse arrival times of 25 pulsars, surveyed with an approximate cadence of once every 3 weeks [50], which translates into a Nyquist frequency of approximately  $3 \times 10^{-7} \text{ Hz}$ . TOAs are measured at the position of the Solar System barycenter, and are primarily described by pulsar-specific deterministic timing models accounting for the position of each pulsar in the sky, spin down, proper motion, the presence of a binary companion, etc. The timing models are provided with the dataset. Deviations between the TOAs predicted by these models and the measured TOAs are referred to as the timing residuals,  $\delta t$ . The residuals contain contributions from various sources of noise, from variations in the dispersion measure to irregularities in pulsar rotation, but they may also contain signals of astrophysical interest. The sources of noise are identified as part of the noise analysis of the EPTA DR2 [51]. The DR2 dataset also hints at growing evidence for the stochastic gravitational-wave background, which manifests itself as a temporally correlated stochastic process with a hallmark interpulsar correlation signature of general relativity [52]. Our work is complementary to the EPTA-wide interpretation effort of the spatial and temporal correlations in DR2 [42].

We use Bayesian inference techniques to search for the ULDM signal while simultaneously fitting timing model parameters and all known sources of noise to the data, to correctly marginalize over the associated uncertainties. The likelihood of the timing residuals,  $\mathcal{L}(\delta t|\theta)$ , given the parameters of the models,  $\theta$ , is [53–57]

$$\ln \mathcal{L}(\delta t|\theta) \propto -\frac{1}{2}(\delta t - \mu)^T C^{-1}(\delta t - \mu). \quad (6)$$

This is a time-domain Gaussian likelihood, multivariate with respect to a number of observations, i.e.,  $\delta t$  has dimension equal to the number of observations. The contribution of ULDM from Eq. (3) is added to  $\mu$ , which also contains contributions from the timing model [50] and noise processes, according to the noise analysis of Ref. [51]. The diagonal part of the covariance matrix  $C$  contains TOA measurement uncertainties that include temporally uncorrelated “white” noise. Contributions from temporally correlated “red” noise may be added as off-diagonal elements in  $C$ . However, for computational efficiency, red noise contributions are modeled in  $\mu$  [54,55]. The priors  $\pi(\theta)$  are set based on Table I, see Ref. [48] for further details. To obtain a sufficient amount of posterior samples across the mass-frequency parameter space, the search is effectively performed across equally spaced segments of  $\pi(m_\phi)$ , which we refer to as bins. The measurements of parameters are obtained as posterior distributions,  $\mathcal{P}(\theta|d) \propto \mathcal{L}(\delta t|\theta)\pi(\theta)$ . The posteriors are evaluated using the parallel-tempering-Markov-chain Monte Carlo sampler [58] implemented in ENTERPRISE [56] and ENTERPRISE\_EXTENSIONS [57]. The conclusion about the presence or absence of the ULDM

signal in the data is based on the Bayesian odds ratio. In our case, that is equal to the Bayes factor, because we assume the prior odds of both scenarios to be equal. We evaluate Bayes factors,  $\mathcal{B}$ , using the Savage-Dickey density ratio [59]. In particular, finding  $\ln \mathcal{B} \gtrsim 5$  would indicate robust evidence for the ULDM signal.

There is strong evidence for a temporally correlated red signal in EPTA DR2, characterized by the same Fourier spectrum of  $\delta t$  in all pulsars [52]. This signal may contain contributions from the stochastic gravitational-wave background [60]. Because in the 24.7-yr dataset this signal does not show significant evidence for interpulsor correlations (unlike in the 10.3-yr dataset [42,50–52]), we model it as a spatially uncorrelated red noise process. Individual Fourier components of this broadband signal may contaminate frequencies at which the presence of ULDM is evaluated. Thus, this common red noise signal is included in the null hypothesis,  $\emptyset$ , along with the pulsar-intrinsic noise. The signal hypothesis is based on adding ULDM to the null hypothesis.

*Results.*—We carry out the search for ULDM in the correlated, pulsar-correlated, and uncorrelated limit for  $\hat{\phi}_E^2$  and  $\hat{\phi}_P^2$  with the parameters in Table I. The factors  $\hat{\phi}_E^2$  and  $\hat{\phi}_P^2$  are drawn from an exponential prior, to correctly model the stochastic nature of the ULDM field [61,62]. We find no evidence for a signal in the mass range  $m_\phi \sim [10^{-24} \text{ eV}, 10^{-22} \text{ eV}]$ . The largest  $\ln \mathcal{B}$  we find across frequency-mass bins is  $< 1$ , i.e., the null hypothesis is favored. Therefore, we calculate the 95% upper limits on the signal amplitude  $\Psi_c$  and, through Eq. (4), on the scalar field density  $\rho_\phi$ . The results are shown in Fig. 1.

TABLE I. Parameters employed for the search along with their respective priors. In the correlated limit, the parameters  $\hat{\phi}_E^2, \hat{\phi}_P^2$  are accounted for by a redefinition of  $\Psi_c$ , while in the pulsar-correlated regime  $\hat{\phi}_E^2 = \hat{\phi}_P^2 = \hat{\phi}^2$  is a free parameter.

Parameter	Description	Prior	Occurrence
White noise ( $\sigma = E_r^2 \sigma_{\text{TOA}}^2 + E_q^2$ )			
$E_r$	EFAC per receiver-backend system	Uniform [0, 10]	1 per pulsar
$E_q$	EQUAD per receiver-backend system	Log <sub>10</sub> -Uniform [−10, −5]	1 per pulsar
Red noise			
$A_{\text{red}}$	Red noise power-law amplitude	Log <sub>10</sub> -Uniform [−20, −6]	1 per pulsar
$\gamma_{\text{red}}$	Red noise power-law spectral index	Uniform [0, 10]	1 per pulsar
ULDM			
$\Psi_c$	ULDM signal amplitude	Log <sub>10</sub> -Uniform [−20, −12]	1 per PTA
$m_\phi$ [eV]	ULDM mass	Log <sub>10</sub> -Uniform [−24, −22]	1 per PTA
$\hat{\phi}_E^2$	Earth factor	$e^{-x}$	1 per PTA
$\hat{\phi}_P^2$	Pulsar factor	$e^{-x}$	1 per pulsar
$\gamma_E$	Earth signal phase	Uniform [0, $2\pi$ ]	1 per PTA
$\gamma_P$	Pulsar signal phase	Uniform [0, $2\pi$ ]	1 per pulsar
Common spatially uncorrelated red noise (CURN)			
$A_{\text{GWB}}$	Common process strain amplitude	Log <sub>10</sub> -Uniform [−20, −6]	1 per PTA

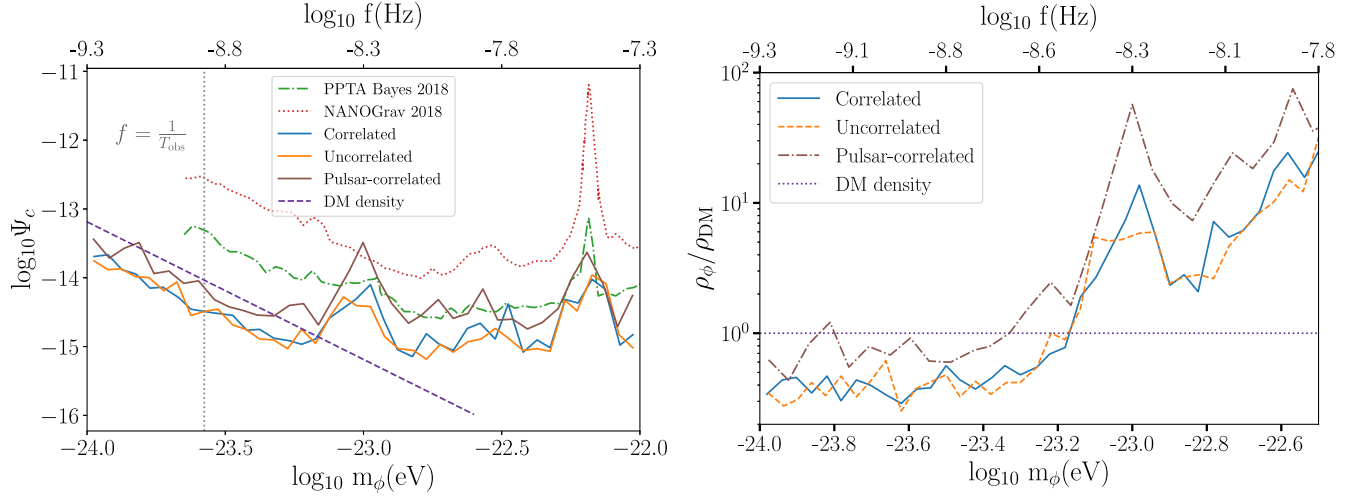


FIG. 1. Upper limits on ULDM, and, namely, on the dimensionless amplitude ( $\Psi_c$ , left panel) and the ULDM fraction of the local DM density  $\rho_{\text{DM}} = 0.4 \text{ GeV/cm}^3$  ( $\rho_\phi/\rho_{\text{DM}}$ , right panel), at 95% credibility. The bottom horizontal axes show the ULDM particle mass, whereas the top horizontal axes show the equivalent oscillation frequency of the scalar field. The upper limits from previous searches [39,40] are shown for comparison. As a reference, we highlight the frequency  $T_{\text{obs}}^{-1}$ . In the right panel, we zoom in on the excluded ULDM masses. The horizontal dotted line represents the value of  $\rho_\phi$  that would saturate the local DM density. Notice that based on our results ULDM particles with mass  $-24.0 < \log_{10}(m_\phi/\text{eV}) < -23.7$  can only make up at most 30%–40% of the total DM energy density, while particles with mass  $-23.7 < \log_{10}(m_\phi/\text{eV}) < -23.3$  can contribute at most up to  $\sim 70\%$ .

A highlight of our study is that not only does EPTA DR2 yield more stringent constraints than previous results [39,40], but it also rules out that particles with masses  $m_\phi \sim [10^{-24} \text{ eV}, 10^{-23.3} \text{ eV}]$  can be 100% of the observed local DM density. In particular, the scalar field density is  $\rho_\phi \lesssim 0.15 \text{ GeV/cm}^3$  in the mass range  $m_\phi \sim [10^{-24} \text{ eV}, 10^{-23.7} \text{ eV}]$ , while it is constrained to  $\rho_\phi \lesssim 0.30 \text{ GeV/cm}^3$  between  $m_\phi \sim [10^{-23.7} \text{ eV}, 10^{-23.4} \text{ eV}]$ . Furthermore, the correlated limit in Fig. 1 confirms Lyman- $\alpha$  bounds, which exclude ULDM in this mass range unless it constitutes less than 30% of DM [31]. It is worth noticing that the low-frequency end of Fig. 1 extends below the naïve expectation  $f = 1.3 \text{ nHz}$  corresponding to the inverse of the observation time  $T_{\text{obs}} = 24.7 \text{ yr}$ . In fact, while an ULDM candidate in this mass region does not complete an oscillation cycle during the observation timescale, the signal can still be approximated by a polynomial expansion in  $(m_\phi t)$  [48]. The sensitivity in this region is limited by the simultaneous fitting to pulsar spin frequency derivatives [63,64]. PTAs are only sensitive to the  $(m_\phi t)^3$  term, as the first terms in the expansion are degenerate with the timing model [65]. However, since the expected amplitude  $\Psi_c$  of an ULDM candidate increases as its mass decreases, we can still obtain competitive constraints at low frequency. While, in principle, our analysis could be pushed to even lower masses [66], we choose to focus on the region  $m_\phi \gtrsim 10^{-24} \text{ eV}$  to comply with the aforementioned CMB bounds. We find that the significant improvement in sensitivity to ULDM at low frequencies arises thanks to

the larger data span of EPTA DR2, in accordance with the theoretical sensitivity scaling proposed in Eq. (13) of Ref. [66]. In particular, because of the longer data span, we expect EPTA DR2 limits to be better than NANOGrav [67] ones by a factor of roughly  $\sim 3.6$ , which is in agreement with what observed. At high frequencies, we find that the advantage of the long timing baseline compared to NANOGrav diminishes, also in accordance with the scaling, as pulsar white noise levels become more important. We also performed an identical analysis of the 10-year subset of EPTA DR2 [50,52], as well as of the MeerTime data [68], which yield less stringent upper limits in agreement with the scaling. For comparison, the bounds in both the correlated and uncorrelated limit for the 10-year subset of the EPTA, shown in Fig. 22 in Ref. [42], appear at the level of the pulsar-correlated limit in Fig. 1 of this Letter.

In the following, we clarify some specific aspects of our results. First, we notice that a similar analysis has been done by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Collaboration [67]. There, the upper limits provided in the correlated and uncorrelated scenarios differ at low frequency. This can be understood by noticing that the correlated limit of NANOGrav corresponds to our pulsar-correlated limit. However, in the low mass limit of Fig. 1, the pulsars, the Earth and the stellar and gaseous tracers used for rotation curves estimates lie well within the area spanned by the coherence length; thus, one can only measure the combination  $\Psi_c^0 = \Psi_c \hat{\phi}^2$ , which represents the realization of DM in our Galaxy. Therefore, we remove the  $\hat{\phi}_{\text{E}}^2 = \hat{\phi}_{\text{p}}^2 \equiv \hat{\phi}^2$  parameter in the correlated limit, as it can be

accounted for by a redefinition of  $\Psi_c$ . Fitting for  $\Psi_c$  and  $\hat{\phi}^2$  separately, instead, introduces an additional uncertainty, which leads our pulsar-correlated analysis to produce a similar mismatch as the one found in Ref. [67], as shown in Fig. 1. Second, Fig. 1 hints at a steep increase in the upper limits at  $m_\phi \gtrsim 10^{-23.2}$  eV. In fact, we report the presence of excess signal power on top of the common red noise process, corresponding to a mass of  $m_\phi \simeq 10^{-23}$  eV and an amplitude of  $\Psi_c \simeq 6 \times 10^{-14}$  or, equivalently, a density of  $\rho_\phi = 90$  GeV/cm<sup>3</sup>. At face value, this excess is not compatible with an ULDM candidate, as the corresponding density is outside the local DM measurement uncertainties [43–46]. Moreover, such a mass would be in tension with astrophysical bounds, as extensively discussed in the introduction [27,29–35]. Anyway, the Bayesian odds ratio suggests that it is still consistent with noise ( $\ln \mathcal{B} \sim 0.1$ ). We find a similar excess in the analysis of 10-yr subset of the EPTA DR2 [42]. Moreover, the boson mass corresponding to the excess also matches the frequency of the continuous gravitational wave (CGW) candidate studied in [69]. This motivates further investigations as part of the International Pulsar Timing Array [70].

*Conclusions.*—ULDM is a theoretically motivated paradigm that may alleviate the *small-scale crisis* of structure formation. Here, we focused on the most robust scenario, in which ULDM features only gravitational interactions. These interactions produce a periodic oscillation in the TOAs of the radio beams emitted by pulsars, which can then be collected in PTA telescopes. PTAs stand out as excellent laboratories to test the effects of ULDM in the mass range  $m_\phi \sim [10^{-24}$  eV,  $10^{-22}$  eV]. In this work, we showed that PTAs constrain the presence of ULDM *below* a few tenths of the observed DM abundance in the mass range  $m_\phi \sim [10^{-24}$  eV,  $10^{-23.3}$  eV]. Therefore, in this range, ULDM cannot constitute 100% of the observed DM.

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\*csmarra@sissa.it

- [1] Vera C. Rubin and W. Kent Ford Jr., Rotation of the Andromeda Nebula from a spectroscopic survey of emission regions, *Astrophys. J.* **159**, 379 (1970).
- [2] V. C. Rubin, W. K. Ford Jr., and N. Thonnard, Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 ( $R = 4$  kpc) to UGC 2885 ( $R = 122$  kpc), *Astrophys. J.* **238**, 471 (1980).
- [3] F. Zwicky, Die Rotverschiebung von extragalaktischen Nebeln, *Helv. Phys. Acta* **6**, 110 (1933).
- [4] F. Zwicky, On the masses of nebulae and of clusters of nebulae, *Astrophys. J.* **86**, 217 (1937).
- [5] Douglas Clowe, Maruš a Bradač, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky, A direct empirical proof of the existence of dark matter, *Astrophys. J.* **648**, L109 (2006).
- [6] N. Aghanim, Y. Akrami, M. Ashdown *et al.*, Planck 2018 results, *Astron. Astrophys.* **641**, A6 (2020).
- [7] C. L. Bennett, D. Larson, J. L. Weiland *et al.*, Nine-year Wilkinson Microwave anisotropy probe (WMAP) observations: Final maps and results, *Astrophys. J. Suppl. Ser.* **208**, 20 (2013).
- [8] Ricardo A. Flores and Joel R. Primack, Observational and theoretical constraints on singular dark matter halos, *Astrophys. J.* **427**, L1 (1994).
- [9] Ben Moore, Evidence against dissipation-less dark matter from observations of galaxy haloes, *Nature (London)* **370**, 629 (1994).
- [10] E. V. Karukes, P. Salucci, and G. Gentile, The dark matter distribution in the spiral NGC 3198 out to  $0.22 R_{\text{vir}}$ , *Astron. Astrophys.* **578**, A13 (2015).
- [11] Anatoly Klypin, Andrey V. Kravtsov, Octavio Valenzuela, and Francisco Prada, Where are the missing galactic satellites?, *Astrophys. J.* **522**, 82 (1999).
- [12] Ben Moore, Sebastiano Ghigna, Fabio Governato, George Lake, Thomas Quinn, Joachim Stadel, and Paolo Tozzi, Dark matter substructure within galactic halos, *Astrophys. J.* **524**, L19 (1999).
- [13] Michael Boylan-Kolchin, James S. Bullock, and Manoj Kaplinghat, Too big to fail? The puzzling darkness of massive Milky Way subhaloes, *Mon. Not. R. Astron. Soc.* **415**, L40 (2011).
- [14] Alfred Amruth, Tom Broadhurst, Jeremy Lim *et al.*, Einstein rings modulated by wavelike dark matter from anomalies in gravitationally lensed images, *Nat. Astron.* **7**, 736 (2023).
- [15] Mariafelicia De Laurentis and Paolo Salucci, The accurate mass distribution of M87, the giant galaxy with imaged shadow of its supermassive black hole, as a portal to new physics, *Astrophys. J.* **929**, 17 (2022).
- [16] Raffaella Morganti, The many routes to AGN feedback, *Front. Astron. Space Sci.* **4**, 42 (2017).
- [17] J. F. Navarro, V. R. Eke, and C. S. Frenk, The cores of dwarf galaxy haloes, *Mon. Not. R. Astron. Soc.* **283**, L72 (1996).
- [18] F. Governato, A. Zolotov, A. Pontzen, C. Christensen, S. H. Oh, A. M. Brooks, T. Quinn, S. Shen, and J. Wadsley, Cuspy no more: How outflows affect the central dark matter and baryon distribution in  $\Lambda$  cold dark matter galaxies, *Mon. Not. R. Astron. Soc.* **422**, 1231 (2012).
- [19] Alyson M. Brooks, Michael Kuhlen, Adi Zolotov, and Dan Hooper, A baryonic solution to the missing satellites problem, *Astrophys. J.* **765**, 22 (2013).
- [20] T. K. Chan, D. Kereš, J. Oñorbe, P. F. Hopkins, A. L. Muratov, C.-A. Faucher-Giguère, and E. Quataert, The impact of baryonic physics on the structure of dark matter haloes: The view from the FIRE cosmological simulations, *Mon. Not. R. Astron. Soc.* **454**, 2981 (2015).
- [21] Jose Oñorbe, Michael Boylan-Kolchin, James S. Bullock, Philip F. Hopkins, Dušan Kereš, Claude-André Faucher-Giguère, Eliot Quataert, and Norman Murray, Forged in fire: Cusps, cores and baryons in low-mass dwarf galaxies, *Mon. Not. R. Astron. Soc.* **454**, 2092 (2015).
- [22] J. I. Read, O. Agertz, and M. L. M. Collins, Dark matter cores all the way down, *Mon. Not. R. Astron. Soc.* **459**, 2573 (2016).

- [23] John R. Jardel and Karl Gebhardt, The dark matter density profile of the fornax dwarf, *Astrophys. J.* **746**, 89 (2012).
- [24] Michael B. Green, J.H. Schwarz, and Edward Witten, *Superstring Theory. Vol. 1: Introduction*, Cambridge Monographs on Mathematical Physics (Cambridge University Press, Cambridge, 1988).
- [25] Peter Svrcek and Edward Witten, Axions in string theory, *J. High Energy Phys.* **06** (2006) 051.
- [26] Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, and John March-Russell, String axiverse, *Phys. Rev. D* **81**, 123530 (2010).
- [27] Renée Hlozek, Daniel Grin, David J.E. Marsh, and Pedro G. Ferreira, A search for ultralight axions using precision cosmological data, *Phys. Rev. D* **91**, 103512 (2015).
- [28] Notice, however, that the value of the fraction of ULDM compatible with Lyman- $\alpha$  is extrapolated for masses  $m_\phi \lesssim 10^{-22}$  eV.
- [29] Vid Iršič, Matteo Viel, Martin G. Haehnelt, James S. Bolton, and George D. Becker, First constraints on fuzzy dark matter from Lyman- $\alpha$  forest data and hydrodynamical simulations, *Phys. Rev. Lett.* **119**, 031302 (2017).
- [30] Eric Armengaud, Nathalie Palanque-Delabrouille, Christophe Yèche, David J.E. Marsh, and Julien Baur, Constraining the mass of light bosonic dark matter using SDSS Lyman- $\alpha$  forest, *Mon. Not. R. Astron. Soc.* **471**, 4606 (2017).
- [31] Takeshi Kobayashi, Riccardo Murgia, Andrea De Simone, Vid Iršič, and Matteo Viel, Lyman-alpha constraints on ultralight scalar dark matter: Implications for the early and late universe, *Phys. Rev. D* **96**, 123514 (2017).
- [32] Matteo Nori, Riccardo Murgia, Vid Iršič, Marco Baldi, and Matteo Viel, Lyman- $\alpha$  forest and non-linear structure characterization in Fuzzy dark matter cosmologies, *Mon. Not. R. Astron. Soc.* **482**, 3227 (2018).
- [33] Keir K. Rogers and Hiranya V. Peiris, Strong bound on canonical ultralight axion dark matter from the Lyman- $\alpha$  forest, *Phys. Rev. Lett.* **126**, 071302 (2021).
- [34] Kohei Hayashi, Elisa G.M. Ferreira, and Hei Yin Jowett Chan, Narrowing the mass range of fuzzy dark matter with ultrafaint dwarfs, *Astrophys. J. Lett.* **912**, L3 (2021).
- [35] Neal Dalal and Andrey Kravtsov, Excluding fuzzy dark matter with sizes and stellar kinematics of ultrafaint dwarf galaxies, *Phys. Rev. D* **106**, 063517 (2022).
- [36] Hsi-Yu Schive, Ming-Hsuan Liao, Tak-Pong Woo, Shing-Kwong Wong, Tzihong Chiueh, Tom Broadhurst, and W-Y. Pauchy Hwang, Understanding the core-halo relation of quantum wave dark matter from 3D simulations, *Phys. Rev. Lett.* **113**, 261302 (2014).
- [37] Jiajun Zhang, Hantao Liu, and Ming-Chung Chu, Cosmological simulation for fuzzy dark matter model, *Front. Astron. Space Sci.* **5**, 48 (2019).
- [38] Andrei Khmelnitsky and Valery Rubakov, Pulsar timing signal from ultralight scalar dark matter, *J. Cosmol. Astropart. Phys.* **02** (2014) 019.
- [39] N. K. Porayko and K. A. Postnov, Constraints on ultralight scalar dark matter from pulsar timing, *Phys. Rev. D* **90**, 062008 (2014).
- [40] Nataliya K. Porayko, Xingjiang Zhu, Yuri Levin *et al.*, Parkes pulsar timing array constraints on ultralight scalar-field dark matter, *Phys. Rev. D* **98**, 102002 (2018).
- [41] Zi-Qing Xia, Tian-Peng Tang, Xiaoyuan Huang, Qiang Yuan, and Yi-Zhong Fan, Constraining ultralight dark matter using the Fermi-LAT pulsar timing array, *Phys. Rev. D* **107**, L121302 (2023).
- [42] J. Antoniadis, P. Arumugam, S. Arumugam *et al.*, The second data release from the European pulsar timing array V. Implications for massive black holes, dark matter and the early universe, [arXiv:2306.16227](https://arxiv.org/abs/2306.16227).
- [43] Jo Bovy and Scott Tremaine, On the local dark matter density, *Astrophys. J.* **756**, 89 (2012).
- [44] J.I. Read, The local dark matter density, *J. Phys. G* **41**, 063101 (2014).
- [45] S. Sivertsson, H. Silverwood, J.I. Read, G. Bertone, and P. Steger, The local dark matter density from SDSS-SEGUE G-dwarfs, *Mon. Not. R. Astron. Soc.* **478**, 1677 (2018).
- [46] Pablo F. de Salas, Dark matter local density determination based on recent observations, *J. Phys. Conf. Ser.* **1468**, 012020 (2020).
- [47] Fabrizio Nesti and Paolo Salucci, The dark matter halo of the Milky Way, AD 2013, *J. Cosmol. Astropart. Phys.* **07** (2013) 016.
- [48] David E. Kaplan, Andrea Mitridate, and Tanner Trickle, Constraining fundamental constant variations from ultralight dark matter with pulsar timing arrays, *Phys. Rev. D* **106**, 035032 (2022).
- [49] Xiao Xue, Zi-Qing Xia, Xingjiang Zhu, Yue Zhao, Jing Shu *et al.*, High-precision search for dark photon dark matter with the Parkes pulsar timing array, *Phys. Rev. Res.* **4**, L012022 (2022).
- [50] J. Antoniadis, S. Babak, A.-S. Bak Nielsen, C. G. Bassa, A. Berthereau *et al.*, The second data release from the European pulsar timing array I. The dataset and timing analysis, *Astron. Astrophys.* (2023), [10.1051/0004-6361/202346841](https://doi.org/10.1051/0004-6361/202346841).
- [51] J. Antoniadis, P. Arumugam, S. Arumugam *et al.*, The second data release from the European pulsar timing array II. Customised pulsar noise models for spatially correlated gravitational waves, [arXiv:2306.16225](https://arxiv.org/abs/2306.16225).
- [52] J. Antoniadis, P. Arumugam, S. Arumugam *et al.*, The second data release from the European pulsar timing array III. Search for gravitational wave signals, [arXiv:2306.16214](https://arxiv.org/abs/2306.16214).
- [53] Rutger van Haasteren, Yuri Levin, Patrick McDonald, and Tingting Lu, On measuring the gravitational-wave background using Pulsar Timing Arrays, *Mon. Not. R. Astron. Soc.* **395**, 1005 (2009).
- [54] L. Lentati, P. Alexander, M. P. Hobson, F. Feroz, R. van Haasteren, K. J. Lee, and R. M. Shannon, TEMPONEST: A Bayesian approach to pulsar timing analysis, *Mon. Not. R. Astron. Soc.* **437**, 3004 (2014).
- [55] S. R. Taylor, L. Lentati, S. Babak, P. Brem, J. R. Gair, A. Sesana, and A. Vecchio, All correlations must die: Assessing the significance of a stochastic gravitational-wave background in pulsar timing arrays, *Phys. Rev. D* **95**, 042002 (2017).
- [56] Justin A. Ellis, Michele Vallisneri, Stephen R. Taylor, and Paul T. Baker, Enterprise: Enhanced numerical toolbox



- enabling a robust pulsar inference suite, Zenodo (2020), [10.5281/zenodo.4059815](https://zenodo.org/record/4059815).
- [57] Stephen R. Taylor, Paul T. Baker, Jeffrey S. Hazboun, Joseph Simon, and Sarah J. Vigeland, ENTERPRISE\_EXTENSIONS, v2.3.3 (2021), [https://github.com/nanograv/enterprise\\_extensions](https://github.com/nanograv/enterprise_extensions).
- [58] Justin Ellis and Rutger van Haasteren, jellis18/ptmcmcsampler: Official release (2017), [10.5281/zenodo.1037579](https://zenodo.org/record/1037579).
- [59] James M. Dickey, The weighted likelihood ratio, linear hypotheses on normal location parameters, *Ann. Math. Stat.* **42**, 204 (1971).
- [60] Boris Goncharov, Eric Thrane, Ryan M. Shannon *et al.*, Consistency of the Parkes pulsar timing array signal with a nanohertz gravitational-wave background, *Astrophys. J.* **932**, L22 (2022).
- [61] Joshua W. Foster, Nicholas L. Rodd, and Benjamin R. Safdi, Revealing the dark matter halo with axion direct detection, *Phys. Rev. D* **97**, 123006 (2018).
- [62] Gary P. Centers, John W. Blanchard, Jan Conrad *et al.*, Stochastic fluctuations of bosonic dark matter, *Nat. Commun.* **12**, 7321 (2021).
- [63] Jeffrey S. Hazboun, Joseph D. Romano, and Tristan L. Smith, Realistic sensitivity curves for pulsar timing arrays, *Phys. Rev. D* **100**, 104028 (2019).
- [64] R. Blandford, R. Narayan, and R. W. Romani, Arrival-time analysis for a millisecond pulsar, *J. Astrophys. Astron.* **5**, 369 (1984).
- [65] Harikrishnan Ramani, Tanner Trickle, and Kathryn M. Zurek, Observability of dark matter substructure with pulsar timing correlations, *J. Cosmol. Astropart. Phys.* **12** (2020) 033.
- [66] Caner Unal, Federico R. Urban, and Ely D. Kovetz, Probing ultralight scalar, vector and tensor dark matter with pulsar timing arrays, [arXiv:2209.02741](https://arxiv.org/abs/2209.02741).
- [67] Adeela Afzal, Gabriella Agazie, Akash Anumalapudi *et al.*, The nanograv 15 yr data set: Search for signals from new physics, *Astrophys. J. Lett.* **951**, L11 (2023).
- [68] M. T. Miles, R. M. Shannon, M. Bailes *et al.*, The MeerKAT pulsar timing array: First data release, *Mon. Not. R. Astron. Soc.* **519**, 3976 (2022).
- [69] J. Antoniadis, P. Arumugam, S. Arumugam *et al.*, The second data release from the european pulsar timing array IV. Search for continuous gravitational wave signals, [arXiv:2306.16226](https://arxiv.org/abs/2306.16226).
- [70] J. P. W. Verbiest, L. Lentati, G. Hobbs, R. van Haasteren, P. B. Demorest, G. H. Janssen, J. B. Wang, G. Desvignes, R. N. Caballero, M. J. Keith, D. J. Champion *et al.*, The International Pulsar Timing Array: First data release, *Mon. Not. R. Astron. Soc.* **458**, 1267 (2016).