

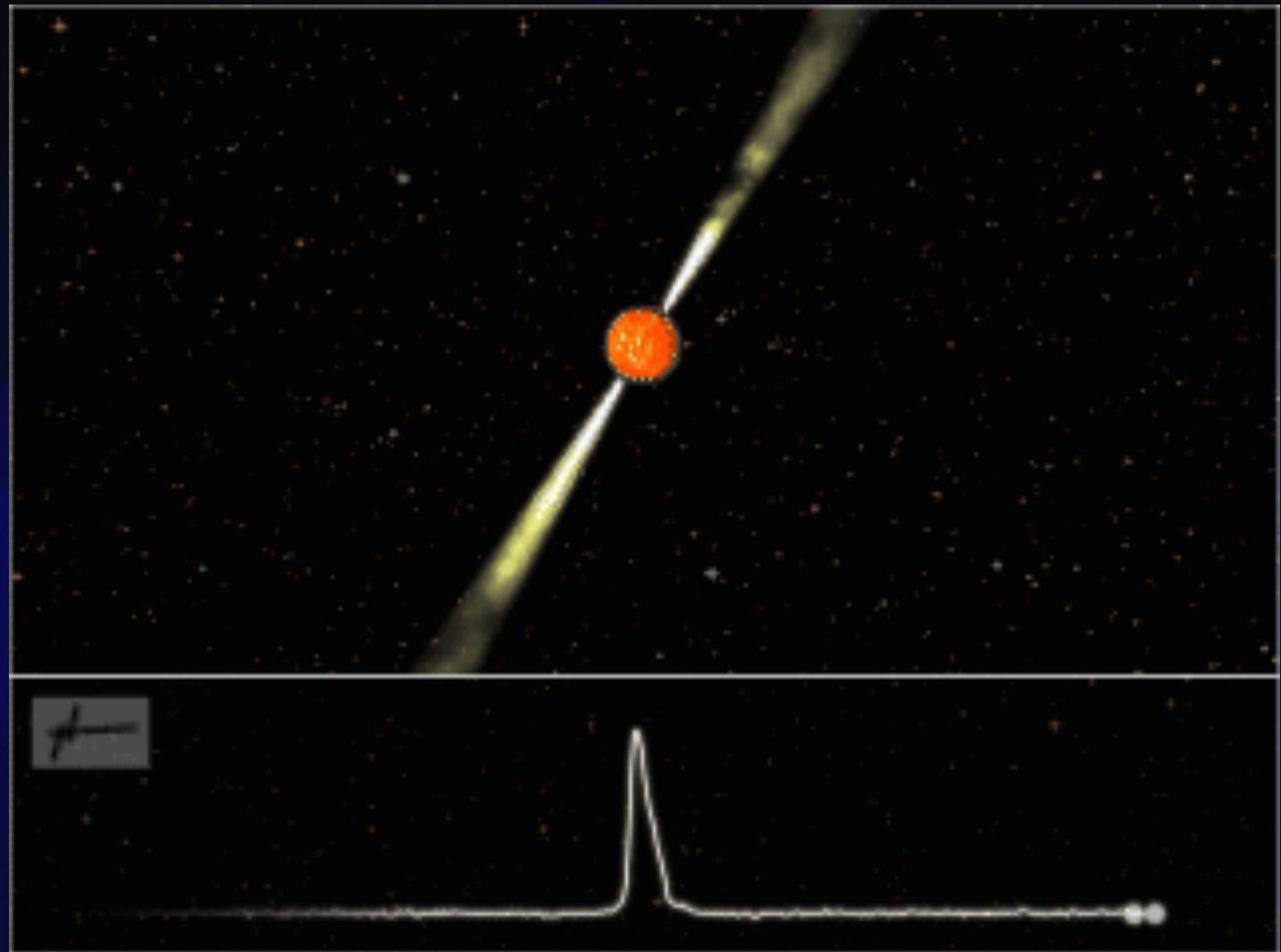


Pulsar timing with LOFAR: probing the interstellar medium

Francesco Iraci - Université Paris Cité, CNRS (FR)

Pulsar

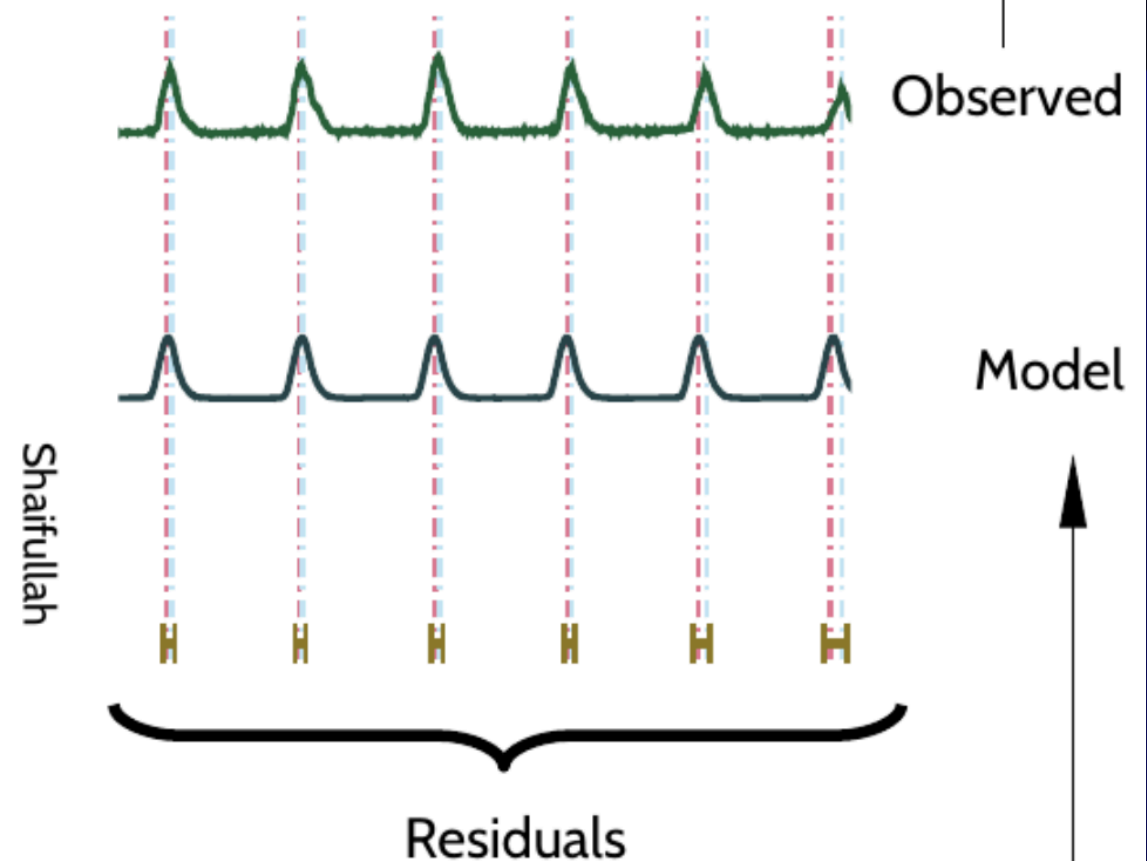
- Highly magnetised ($B \sim 10^{12} - 10^{14}$ G)
- Fast rotating ($T \sim 10^{-3} s$)
- Stable rotators
- Produce two radio beams of emission
- Lighthouse effect



Pulsar timing

It is possible to predict the arrival time of pulsar's radiation on Earth once that its ephemeris are known. Millisecond pulsars are characterised by the smallest “timing residuals” and, hence, are the most precise sources among pulsars.

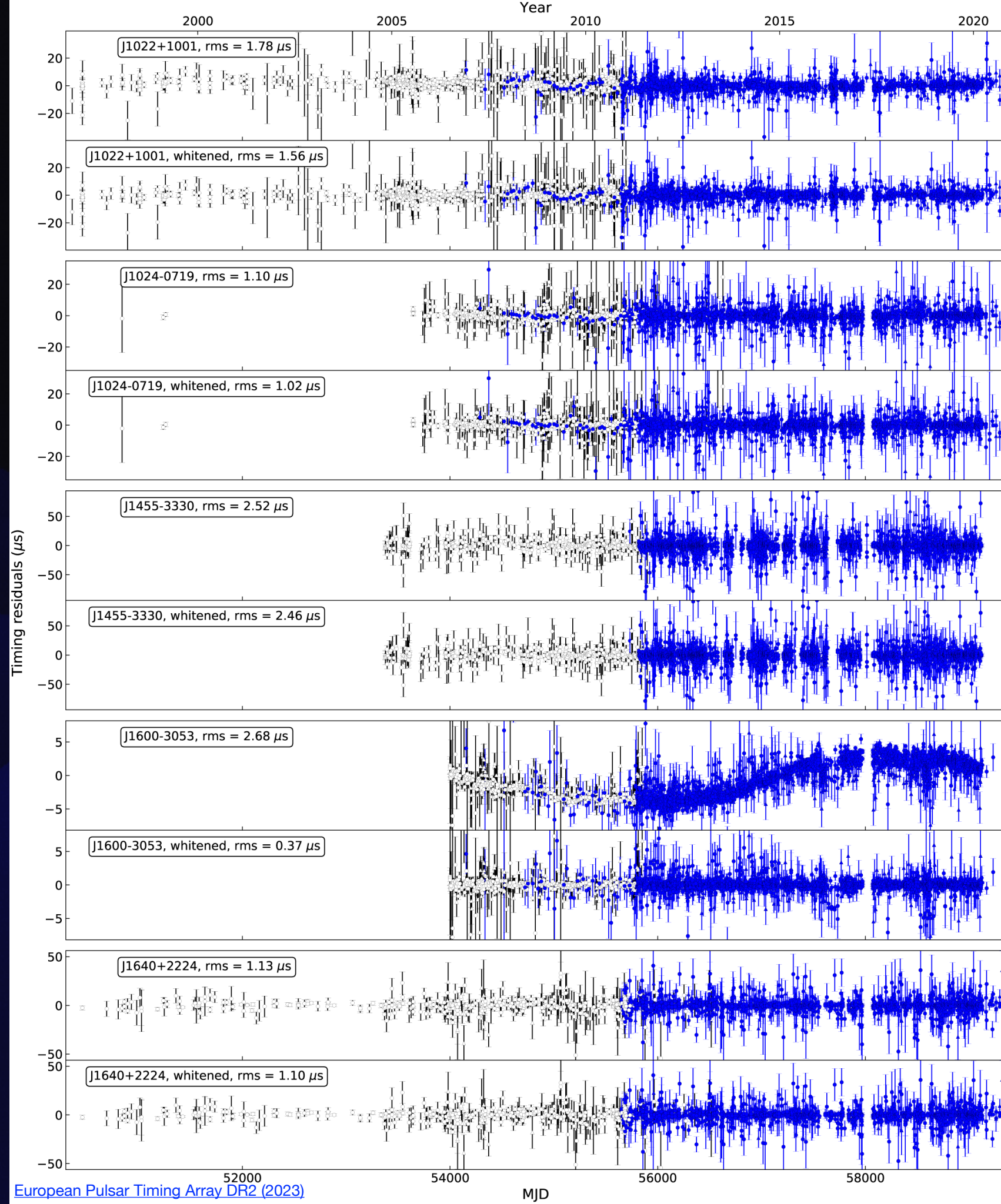
Pulsar	J1012+5307
Right Ascension	10:12:33.437521
Declination	+53:07:02.29999
DM	9.02314
Spin frequency	190.2678376220576
Spin freq. derivative	-6.20063E-16
Proper motion RA	2.609
Proper motion DEC	-25.482
BINARY	ELL1
Orbital period	0.604672722901
Rotation Measure	2.98
Solar Wind	Spherical, $n_0 = 4$
Companion mass	0.16
Clock reference	TT(BIPM2019)
SSE	DE440
[TBC]	



Timing residuals

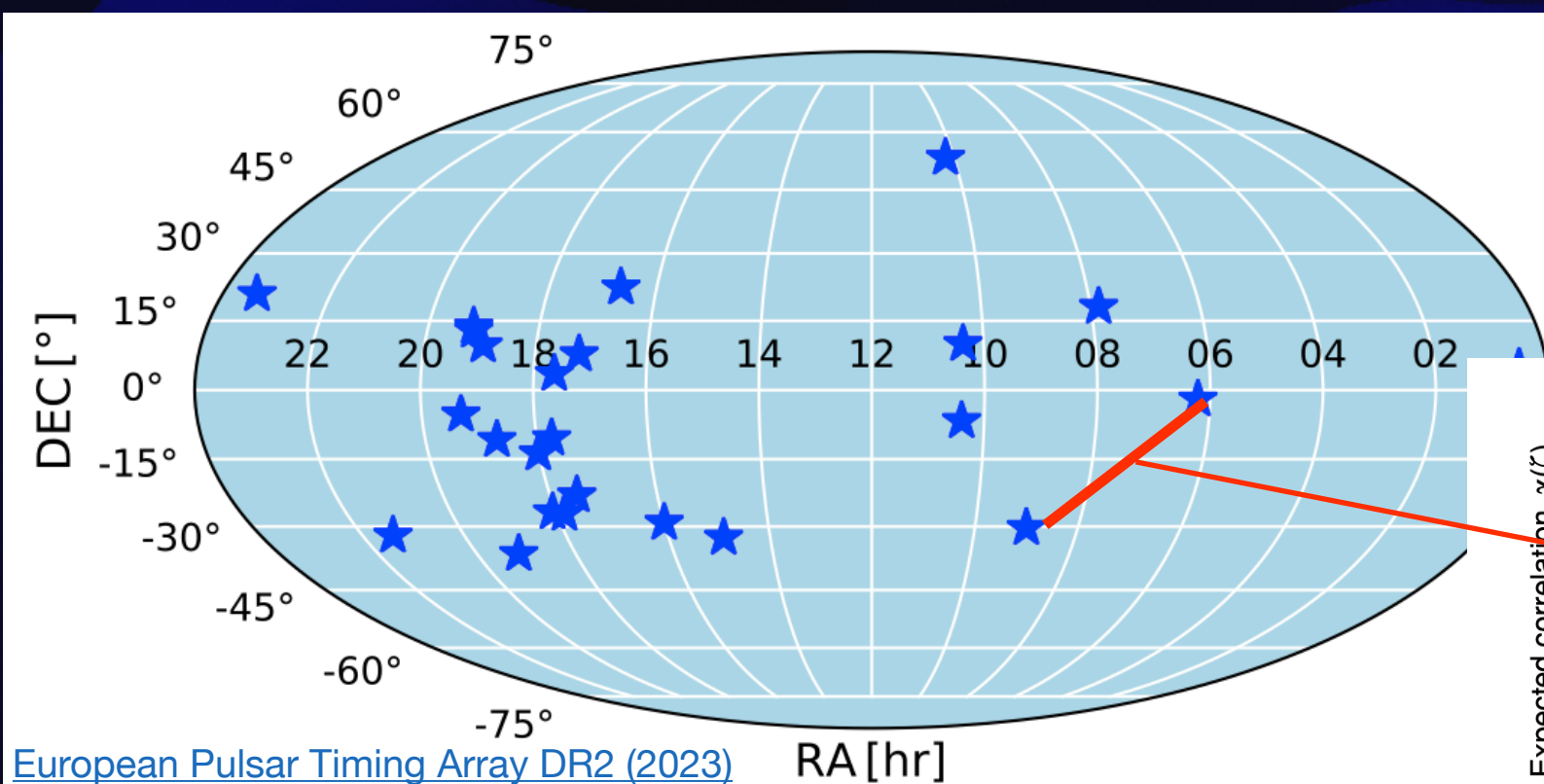
Long-term, un-modelled effects can perturb the ToAs and appear as ‘**red noise**’ in the timing residuals:

- turbulent ionised interstellar medium,
- spin noise,
- instrumentation issues,
- planetary ephemeris,
- **gravitational waves** or unknown effects



Pulsar Timing Array (PTA)

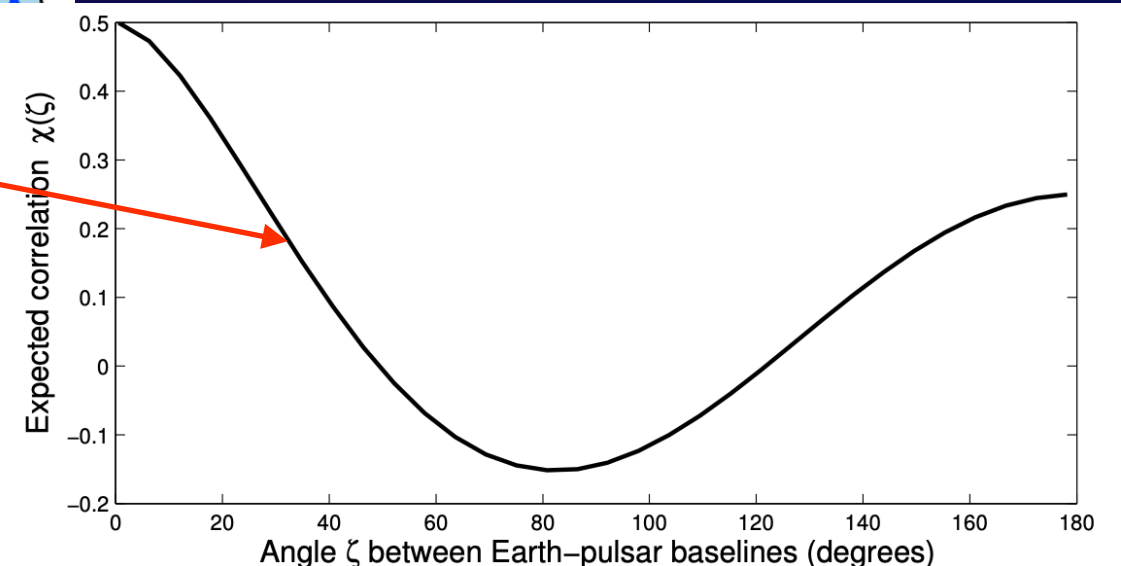
- Aim: detect extremely low-frequency GWs (nHz)
- Expected sources: ensemble of coalescing Supermassive Black Hole Binaries. Stochastic GW background.
- Array of stable millisecond pulsars



European Pulsar Timing Array DR2 (2023)

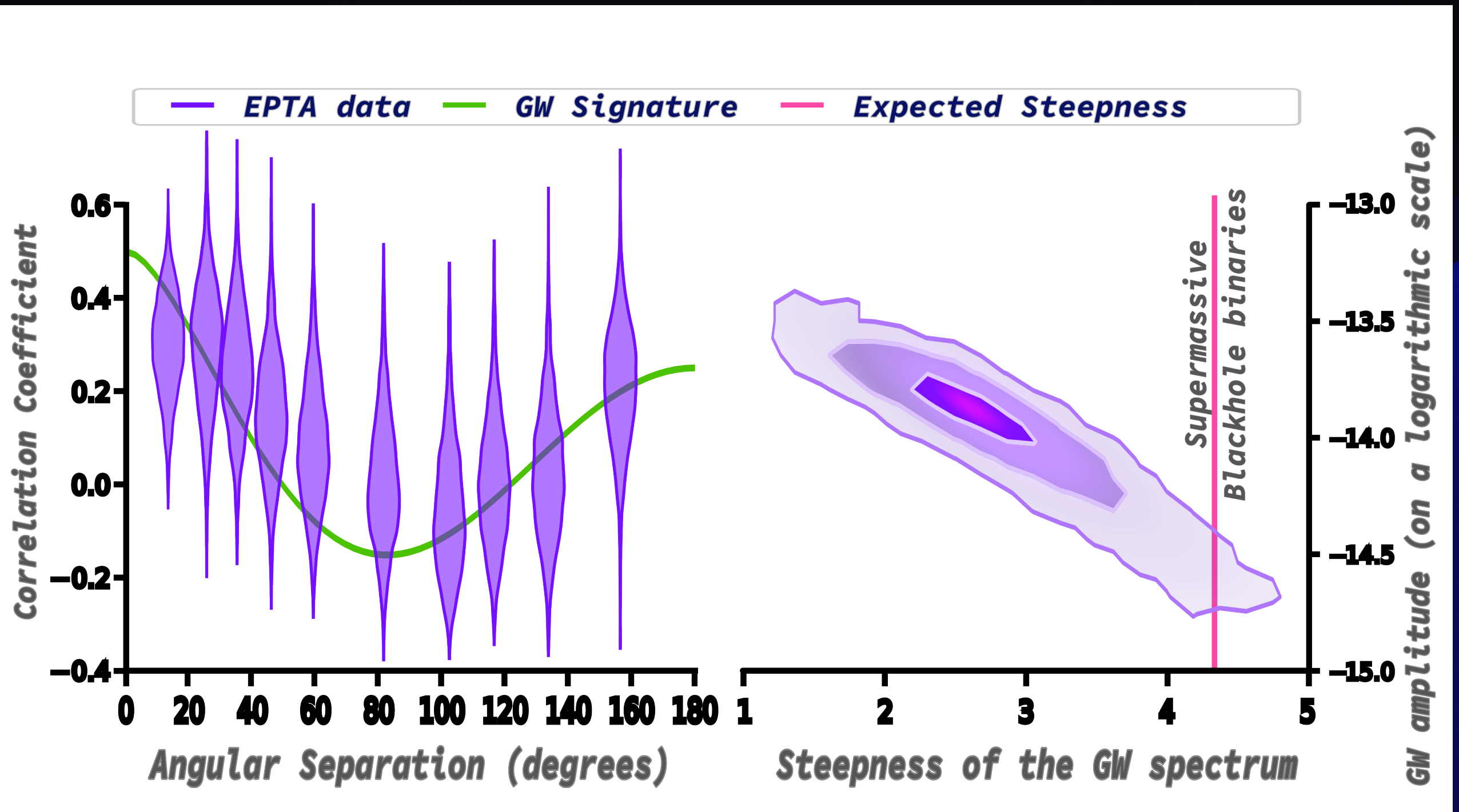
The correlation signature follows Hellings and Downs curve:

$$\chi(\zeta) = \frac{1}{2} - \frac{1}{4} \left(\frac{1 - \cos \zeta}{2} \right) + \frac{3}{2} \left(\frac{1 - \cos \zeta}{2} \right) \ln \left(\frac{1 - \cos \zeta}{2} \right)$$



Pulsar Timing Array

EPTA result: 3σ evidence for a stochastic GWB

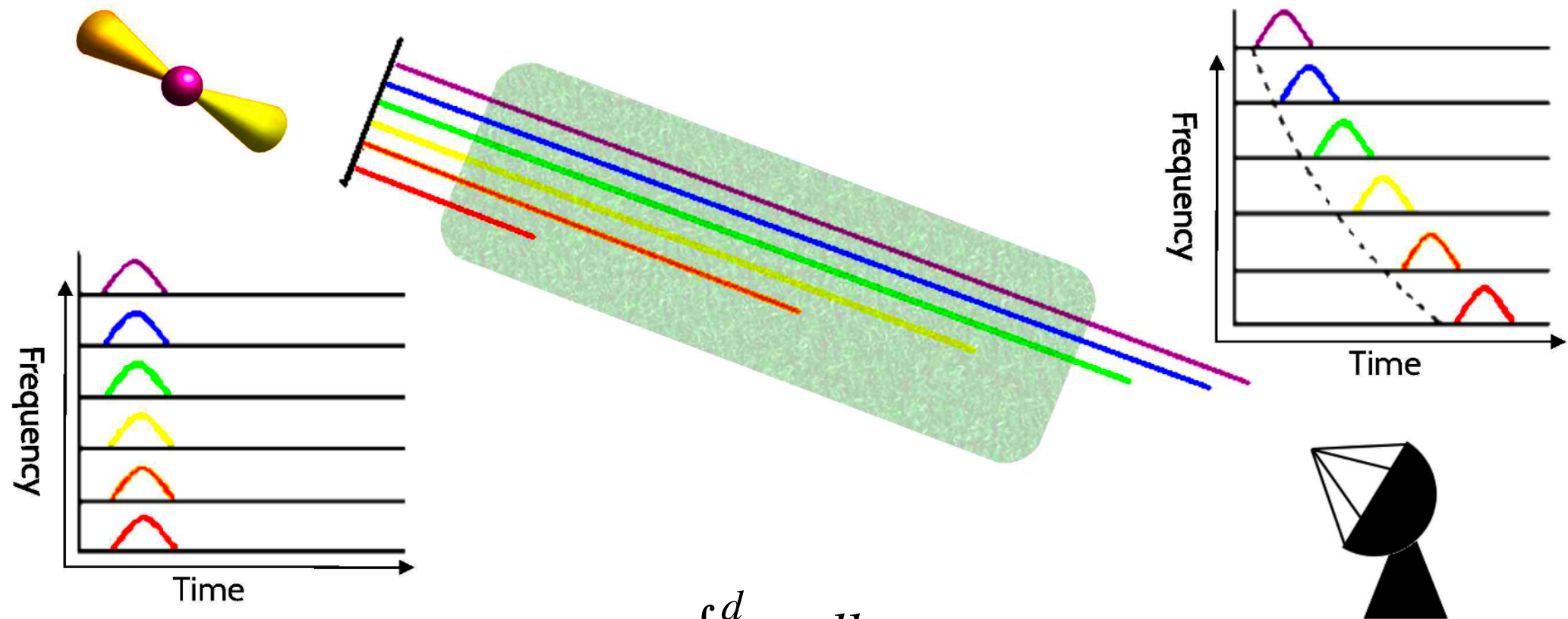


PTA collaborations



The IPTA

Dispersion

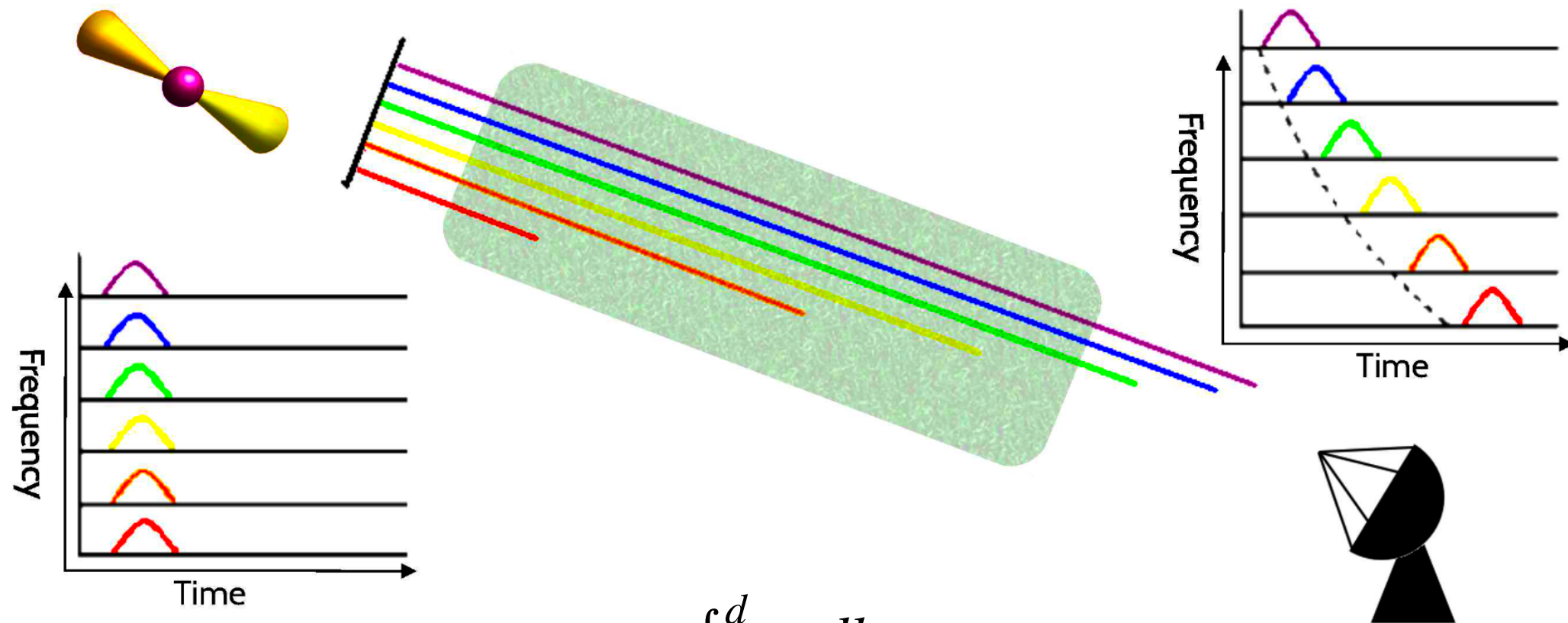


$$\Delta t = \frac{e^2}{2\pi m_e c^2} \frac{\int_0^d n_e dl}{\nu^2} \propto \frac{DM}{\nu^2}$$

$$DM = \int_0^d n_e dl$$

Credits: Caterina Tiburzi

Dispersion



$$\Delta t = \frac{e^2}{2\pi m_e c^2} \frac{\int_0^d n_e dl}{\nu^2} \propto \frac{DM}{\nu^2}$$

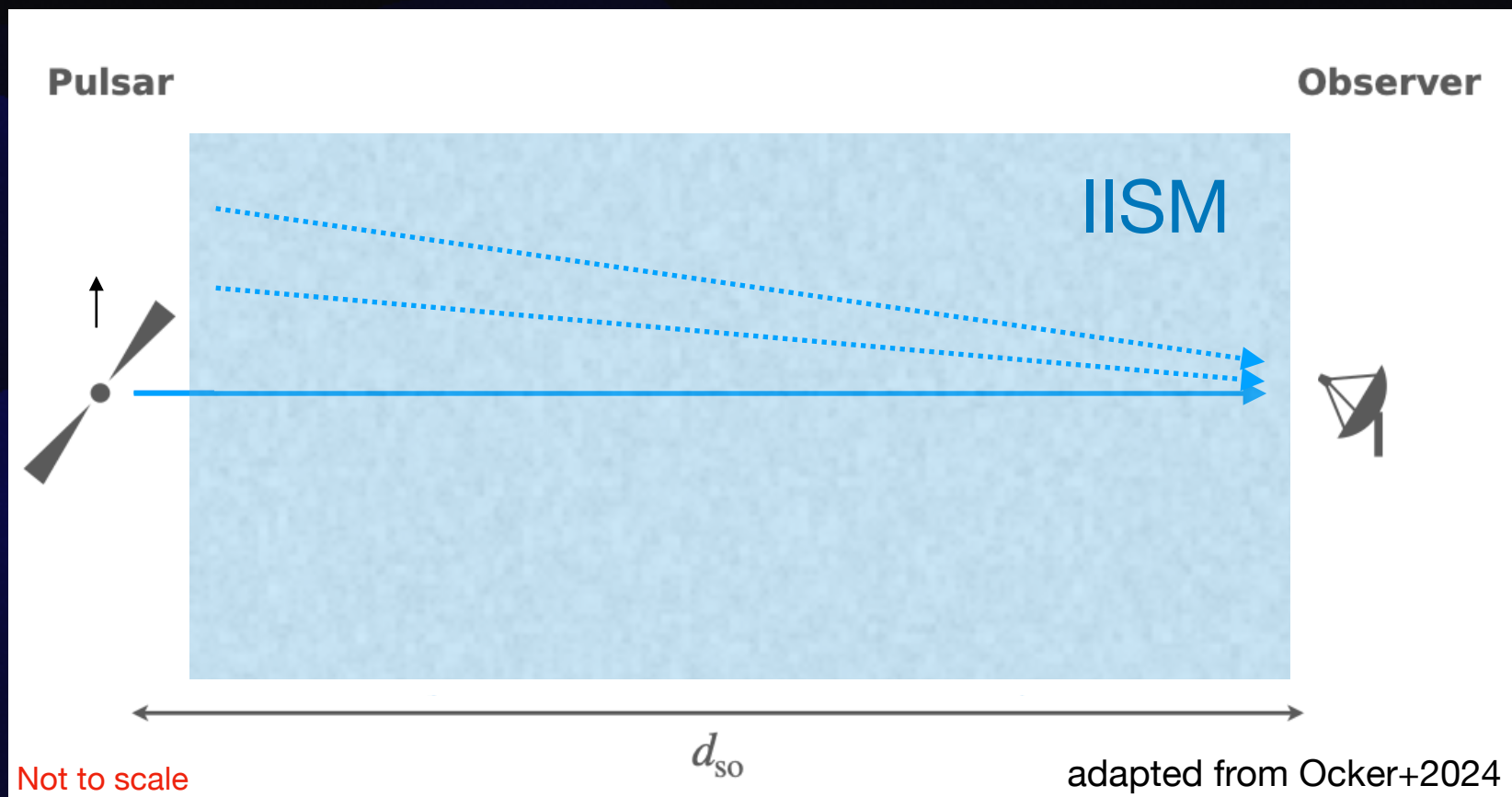
$$DM = \int_0^d n_e dl$$

$$\delta DM = 10^{-3} \text{ pc/cm}^3:$$

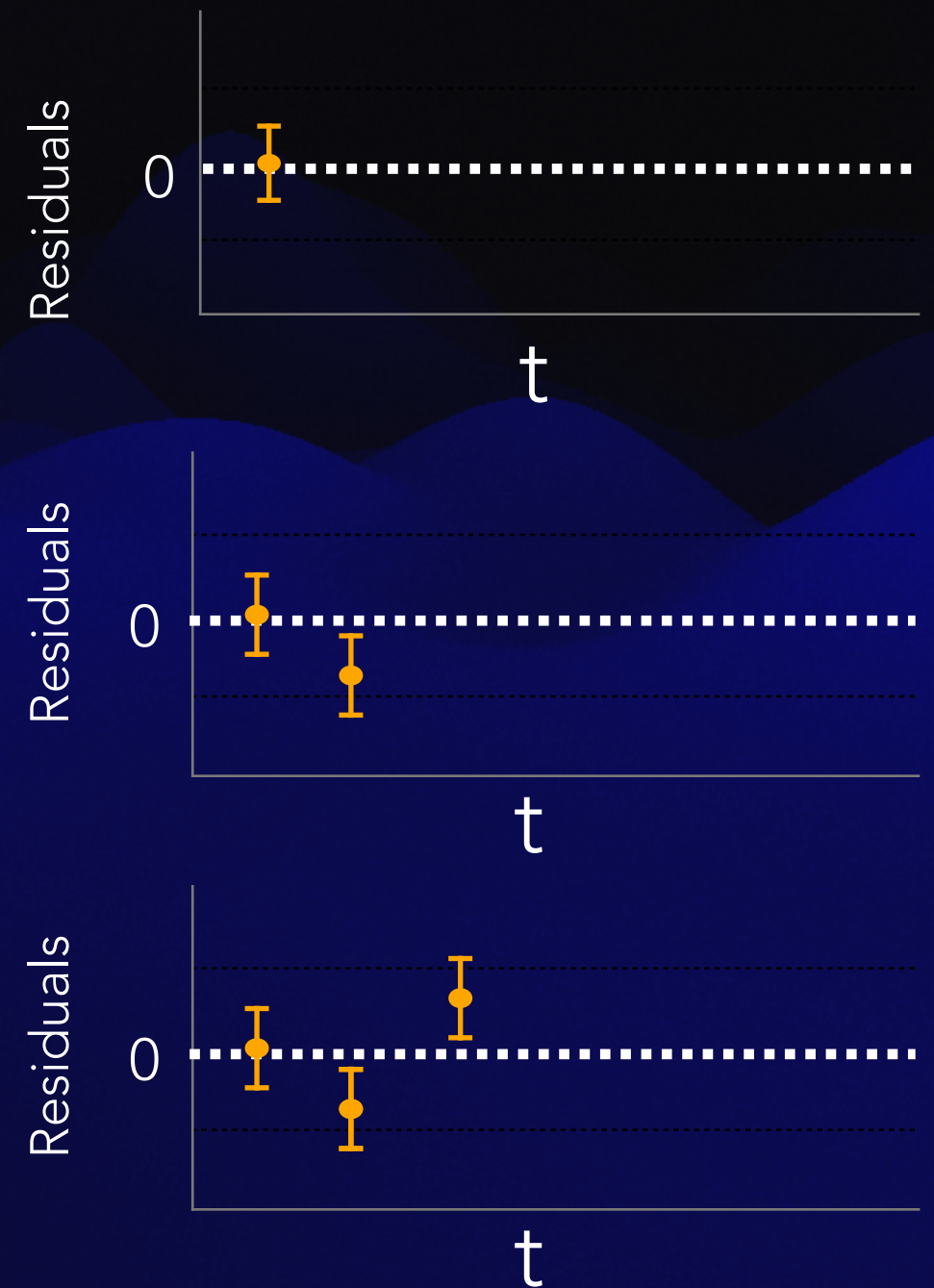
$$\rightarrow \delta t_{150 \text{ MHz}} \sim 0.2 \text{ ms}$$

$$\rightarrow \delta t_{1.4 \text{ GHz}} \sim 2 \mu\text{s}$$

Dispersion Measure variations



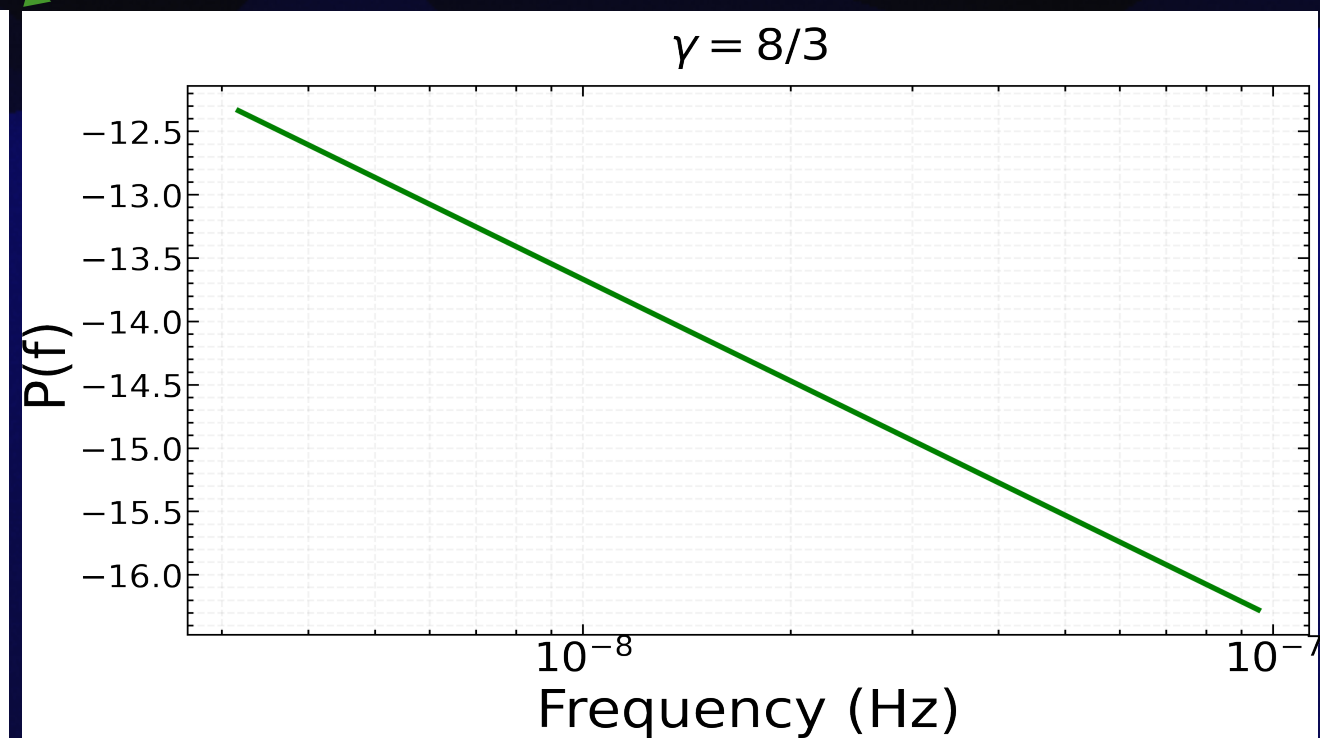
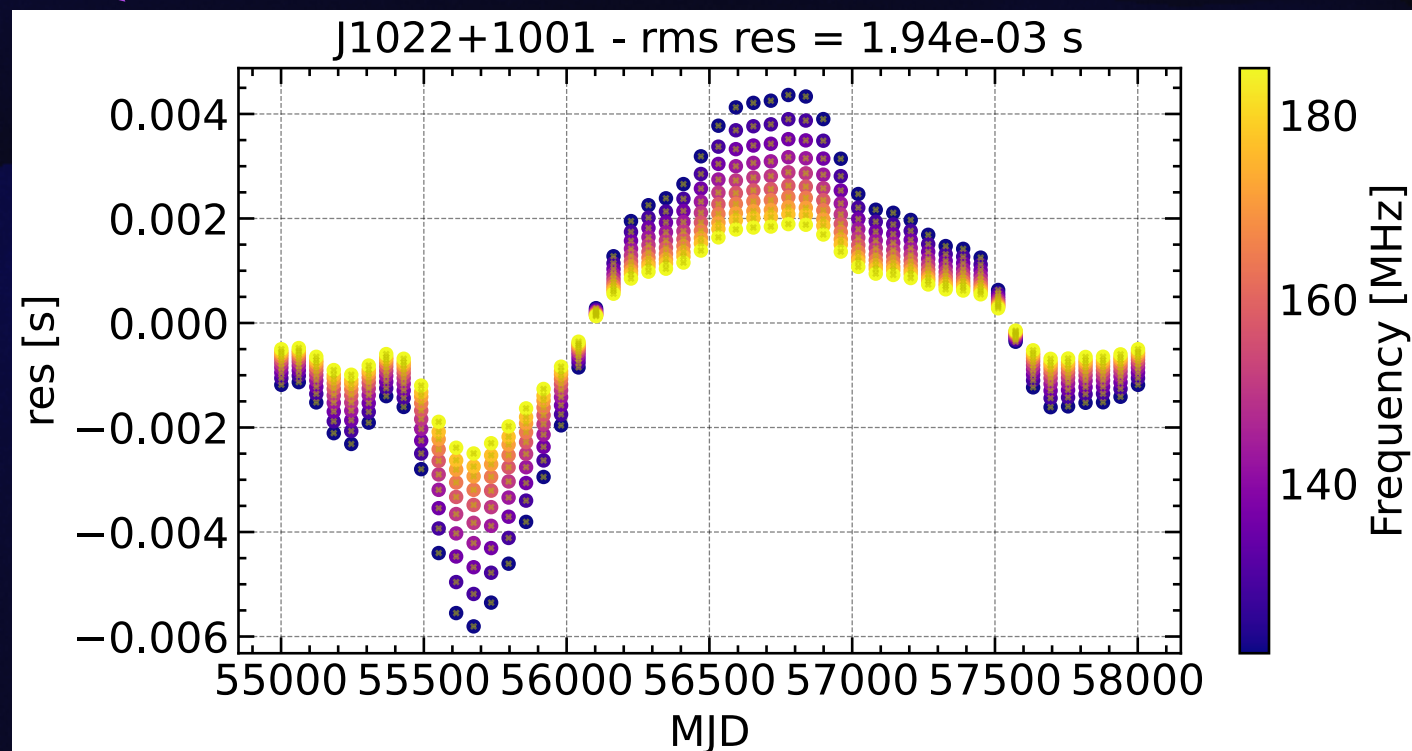
A different DM value per observation!



Dispersion Measure variations

Timing residuals example

Correlated structures in the timing residuals characterised by a steep red power spectrum. Competitor to the GWs red noise



EPTA DR2

- **25 millisecond pulsars** collected by the 5 largest telescopes in Europe (Effelsberg 100m radio telescope, Jodrell Bank Observatory, Nançay Radio Telescope, Westerbork Synthesis Radio Telescope, Sardinia Radio Telescope).
- Time spans ranging from 14 to ~25 years.
- Frequencies:
 - **EPTA**: > 1.4GHz
 - **InPTA**: 300-500 MHz, 1260-1460 MHz

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Astronomy
&
Astrophysics

The second data release from the European Pulsar Timing Array

I. The dataset and timing analysis

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ABSTRACT

Pulsar timing arrays offer a probe of the low-frequency gravitational wave spectrum (1–100 nHz), which is intimately connected to a number of markers that can uniquely trace the formation and evolution of the Universe. We present the dataset and the results of the timing analysis from the second data release of the European Pulsar Timing Array (EPTA). The dataset contains high-precision pulsar timing data from 25 millisecond pulsars collected with the five largest radio telescopes in Europe, as well as the Large European Array for Pulsars. The dataset forms the foundation for the search for gravitational waves by the EPTA, presented in associated papers. We describe the dataset and present the results of the frequentist and Bayesian pulsar timing analysis for individual millisecond pulsars that have been observed over the last ~25 yr. We discuss the improvements to the individual pulsar parameter estimates, as well as new measurements of the physical properties of these pulsars and their companions. This data release extends the dataset from EPTA Data Release 1 up to the beginning of 2021, with individual pulsar datasets with timespans ranging from 14 to 25 yr. These lead to improved constraints on annual parallaxes, secular variation of the orbital period, and Shapiro delay for a number of sources. Based on these results, we derived astrophysical parameters that include distances, transverse velocities, binary pulsar masses, and annual orbital parallaxes.

Key words. gravitational waves – pulsars: general – methods: observational – parallaxes – proper motions – ephemerides

1. Introduction

Pulsar timing arrays (PTAs; Sazhin 1978; Detweiler 1979) search for gravitational waves (GWs) at nanohertz (nHz) frequencies by observing a suite of stable, rapidly rotating millisecond pulsars (MSPs; Backer 1993) over decadal timescales (Foster & Backer 1990; Desvignes et al. 2016; Verbiest et al. 2016). These GWs may be produced by inspiralling supermassive black holes binaries (SMBHBs; see e.g. Sesana et al. 2004; Sesana 2013), cosmic strings (Damour & Vilenkin 2001; Grishchuk 2005; Boyle & Buonanno 2008), phase transitions in the early Universe (Schwaller 2015), quantum fluctuations in the primordial gravitational field (Grishchuk 2005; Lasky et al. 2016), or from a primordial magnetic field (see Caprini & Figueroa 2018, and references therein).

Several PTA experiments are currently operational: the European Pulsar Timing Array (EPTA; Desvignes et al. 2016),

the North American Nanohertz Observatory for Gravitational Waves (NANOGrav; McLaughlin 2013), the Parkes Pulsar Timing Array (PPTA; Manchester et al. 2013), the Indian Pulsar Timing Array (InPTA; Joshi et al. 2022), the MeerKAT Pulsar Timing Array (MPTA) based in South Africa (Miles et al. 2023), and the Chinese Pulsar Timing Array (CPTA; Lee 2016). These regional PTAs are also organised under the International Pulsar Timing Array (IPTA; Verbiest et al. 2016; Perera et al. 2019). Although individual GW sources remain an exciting prospect for detection with PTAs (see e.g. Babak et al. 2016; Falxa et al. 2023, and references therein) it is likely that the first signal detected by PTAs will be a stochastic GW background (GWB) arising from multiple overlapping sources (Rosado et al. 2015).

The recent detection of a common red noise process by EPTA, NANOGrav, PPTA and IPTA (Chen et al. 2021; Alam et al. 2021b; Goncharov et al. 2022; Antoniadis et al. 2022, respectively) suggests that the characteristic spatial quadrupole correlation of the GWB (Hellings & Downs 1983) can become detectable with a modest expansion of PTA datasets. In this article, we present the latest EPTA data release, henceforth

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- EPTA+InPTA (DR2new+):
 - EPTA: > 1.4GHz
 - InPTA: 300-500 MHz, 1260-1460 MHz
 - 25 millisecond pulsars
- LOFAR:
 - 100-200 MHz
 - **12 common pulsars**
- NenuFAR:
 - < 100 MHz
 - **2 common pulsars**

Combining the second data release of the European Pulsar Timing Array with low-frequency pulsar data

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(Affiliations can be found after the references)

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ABSTRACT

Context. Low radio frequency data are highly valuable for enhancing the sensitivity of pulsar timing arrays (PTAs) to propagation effects, such as dispersion measure (DM) variations. These low-frequency observations are particularly sensitive to DM fluctuations and can therefore significantly improve noise characterization in PTA datasets, which is essential for detecting the stochastic gravitational wave background (GWB).

Aims. For this work we incorporated for the first time low-frequency observations from LOFAR (100–200 MHz) and NenuFAR (30–90 MHz) into a PTA context by combining them with the most recent data release from the European and Indian PTAs (in particular, with the subsample labeled DR2new+, which includes only data from the new backends). This new combined dataset, labeled DR2low, consists of 12 pulsars observed over a time span of ~11 years, with radio frequencies spanning the range 30–2500 MHz. The expanded frequency coverage of DR2low enables us to update and refine the noise models of DR2new+, and this is crucial in order to increase the PTA sensitivity when searching for the stochastic gravitational wave background, which is the primary goal of PTA observations. This work is a milestone in the integration of low-frequency data into the upcoming third data release of the International PTA, which is posed to achieve the 5 σ detection of the GWB.

Methods. We used the pulsar timing software packages LIBSTEMPO and ENTERPRISE to perform a noise analysis of DR2low. At first, we applied a standard noise model including red noise (RN) and time-variable dispersion measure (DMv) as power laws, with Fourier components up to 30 and 100 frequencies, respectively. Next, we performed a fully Bayesian model selection to identify the favored noise model for each pulsar and compute the Bayes factors across all combinations of RN, DMv, and a noise term with a chromatic index of 4 (CN₄). Finally, we carried out a detailed analysis on the choice of the chromatic index for CN₄ and the contribution of the solar wind.

Results. The comparison between DR2low and DR2new+ using the standard noise model highlights the benefits of including low-frequency data. In particular, the additional frequency coverage improves the constraints on the DM variations and helps disentangle the DM and RN noise components in most pulsars. Through a Bayesian model selection, we found that the RN is required in the final model for 10 out of 12 pulsars, compared to only 5 in the DR2new+ dataset. The improved sensitivity to plasma effects provided by DR2low also favors the identification of significant CN₄ in eight pulsars, while none showed such evidence in DR2new+. The chromatic index of this process is consistent with four of the five pulsars, while two (PSRs J0030+0451 and J1022+1001) show significant deviations from such a value. We attribute this discrepancy to unmodeled contributions from the solar wind, especially because of the high DM sensitivity of LOFAR and NenuFAR and the high observing cadence provided by these datasets near solar conjunction. A dedicated analysis confirms that the current solar wind model fails to fully capture the observed delay, and residual power is absorbed into the DM component of the model.

Key words. gravitational waves – pulsars: general – ISM: general

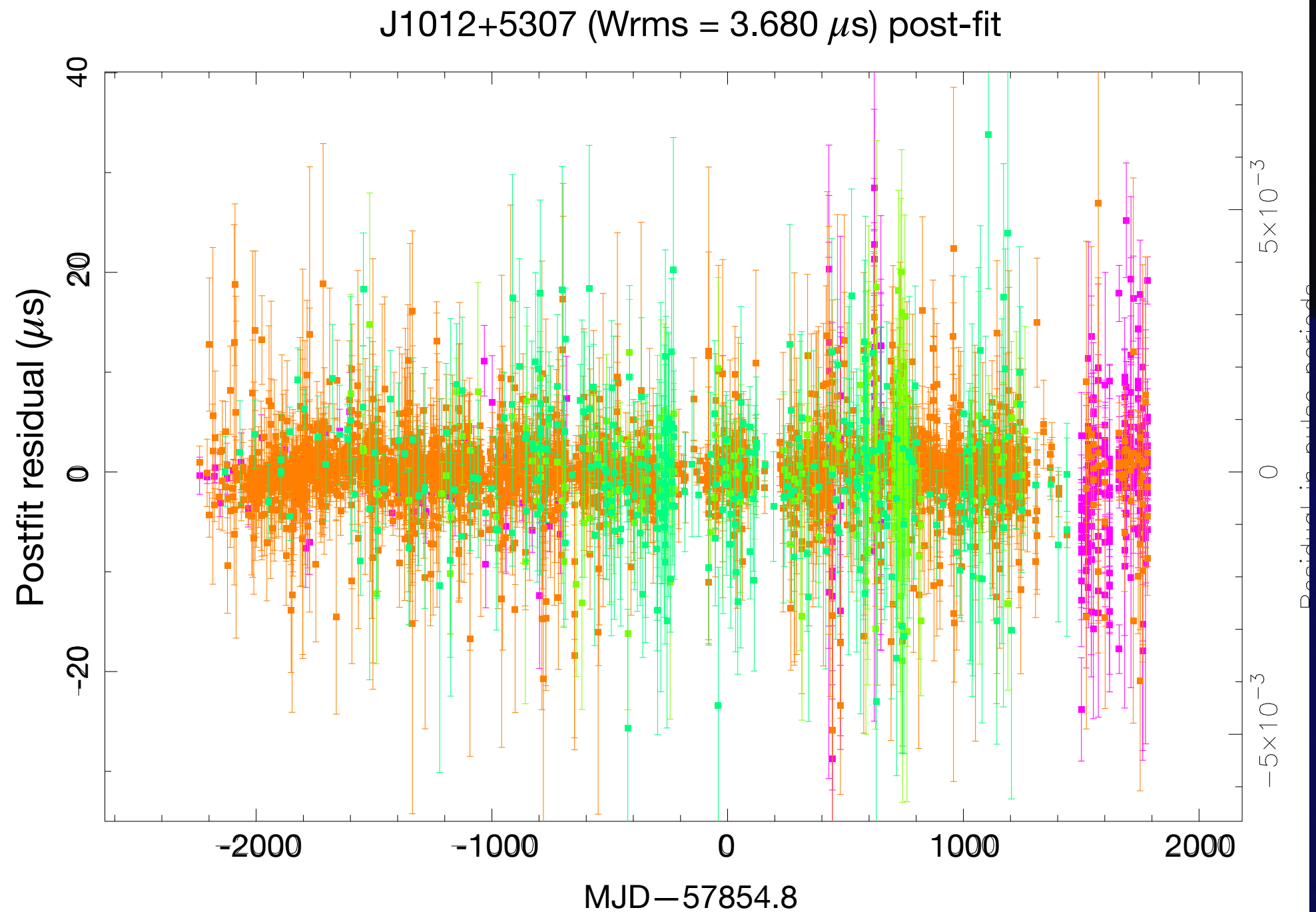
1. Introduction

Pulsar timing array (PTA) experiments exploit the clock-like precision of the periodic broadband radio emission received from pulsars to detect low-frequency (on the order of the nHz order) gravitational waves (GWs). Unpredicted fluctuations in such a precise series of radiation pulses reflect any kind of perturbation that the pulsar signal experiences, ranging from irregularities in the pulsar's rotation to the influence of Galactic plasma and GWs. A stochastic and isotropic gravitational wave background (GWB), generated by a population of supermassive black hole

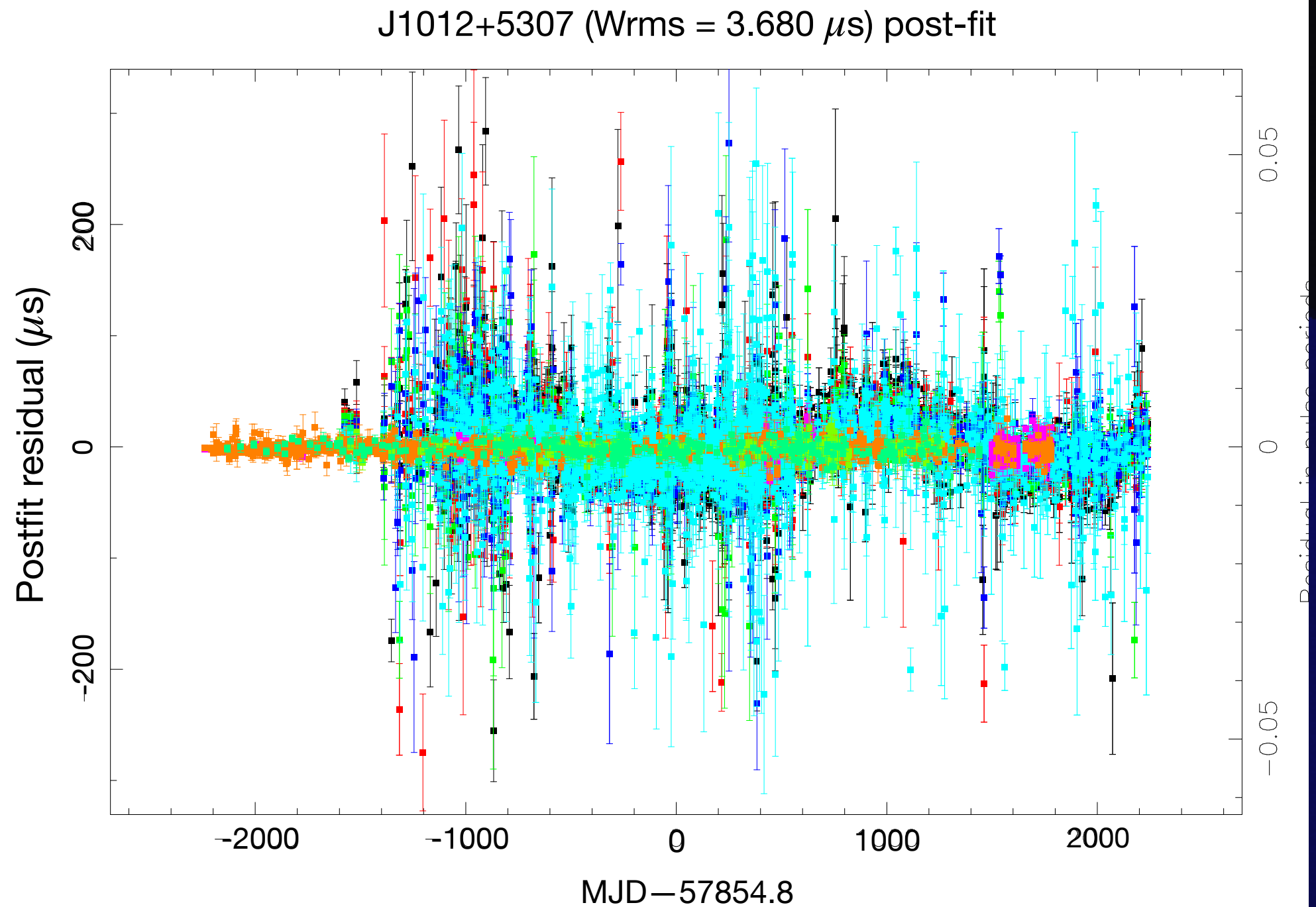
binaries (SMBHBs), introduces a temporally correlated noise in the time-of-arrival (ToA) fluctuations—also known as timing residuals—relative to the deterministic timing model (Sesana 2013). In the most simple case of circular SMBHBs, this noise has a red power spectrum, characterized by a steep spectral index of $-13/3$ (Phinney 2001). Moreover, these GW-induced fluctuations follow a spatial correlation among pulsars, referred to as the Hellings & Downs curve (Hellings & Downs 1983). To date, eight PTA collaborations exist in the world: the European PTA (EPTA Desvignes et al. 2016), the North-American Nanohertz Observatory for Gravitational waves (NANOGrav Ransom et al. 2019), the Parkes PTA (Manchester et al. 2013), the Indian PTA (InPTA Joshi et al. 2018), the Chinese PTA (CPTA Lee 2016), the MeerKAT PTA (MeerTIME Miles et al. 2023), the

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Data combination

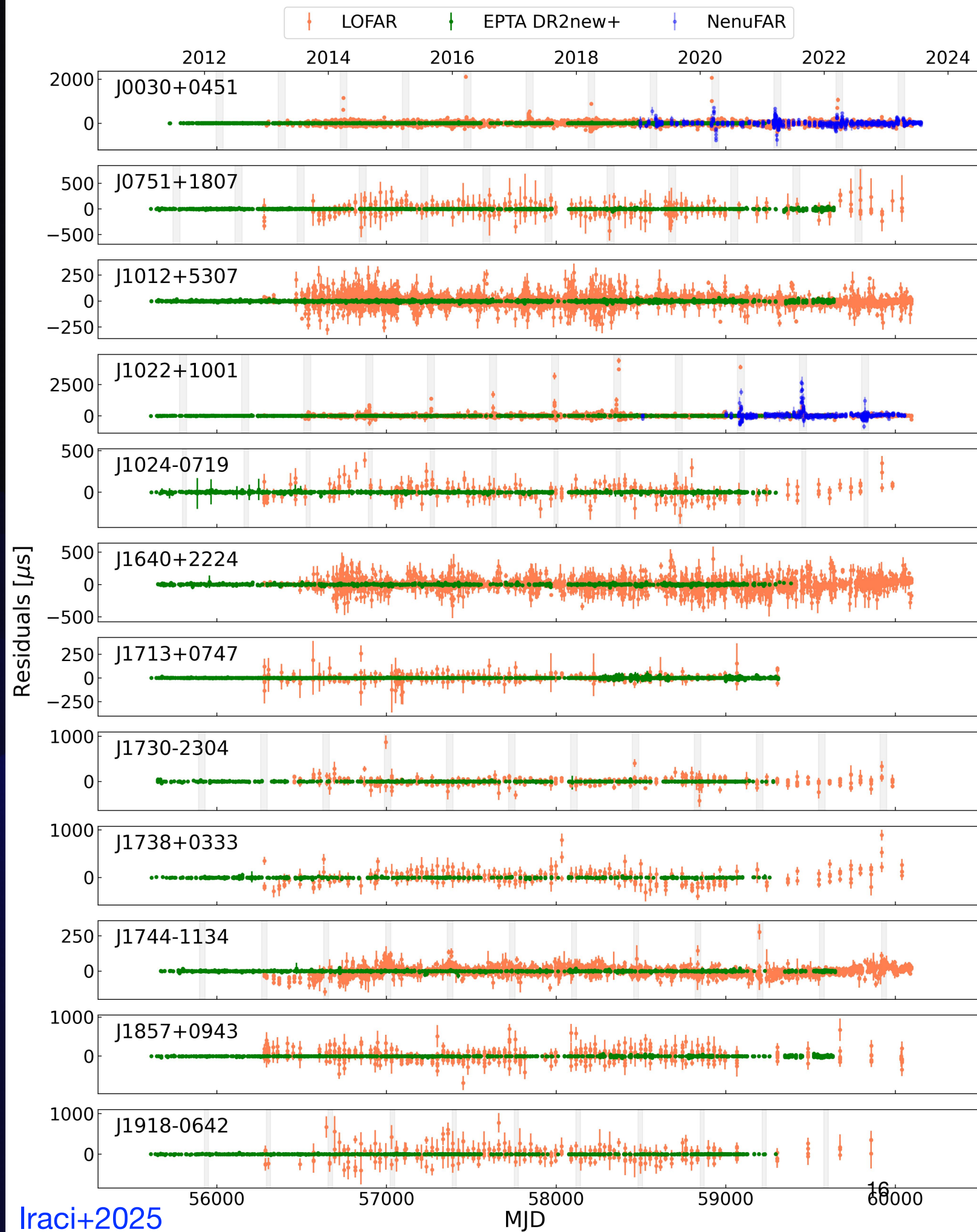


Data combination



DR2low

- EPTA+InPTA (DR2new+):
 - EPTA: $> 1.4\text{GHz}$
 - InPTA: 300-500 MHz, 1260-1460 MHz
 - 25 millisecond pulsars
- LOFAR:
 - 100-200 MHz
 - **12 common pulsars**
- NenuFAR:
 - $< 100\text{ MHz}$
 - **2 common pulsars**



Noise modelling

Power-law power spectrum

$$P(f) \propto A f^{-\gamma}$$

{ DM noise: A_{DM}, γ_{DM}
Achromatic noise - RN: A_{RN}, γ_{RN}

Need to choose the number of Fourier components

Vanilla red noise models: DM 100, RN 30

Vanilla noise runs

EPTA DR2

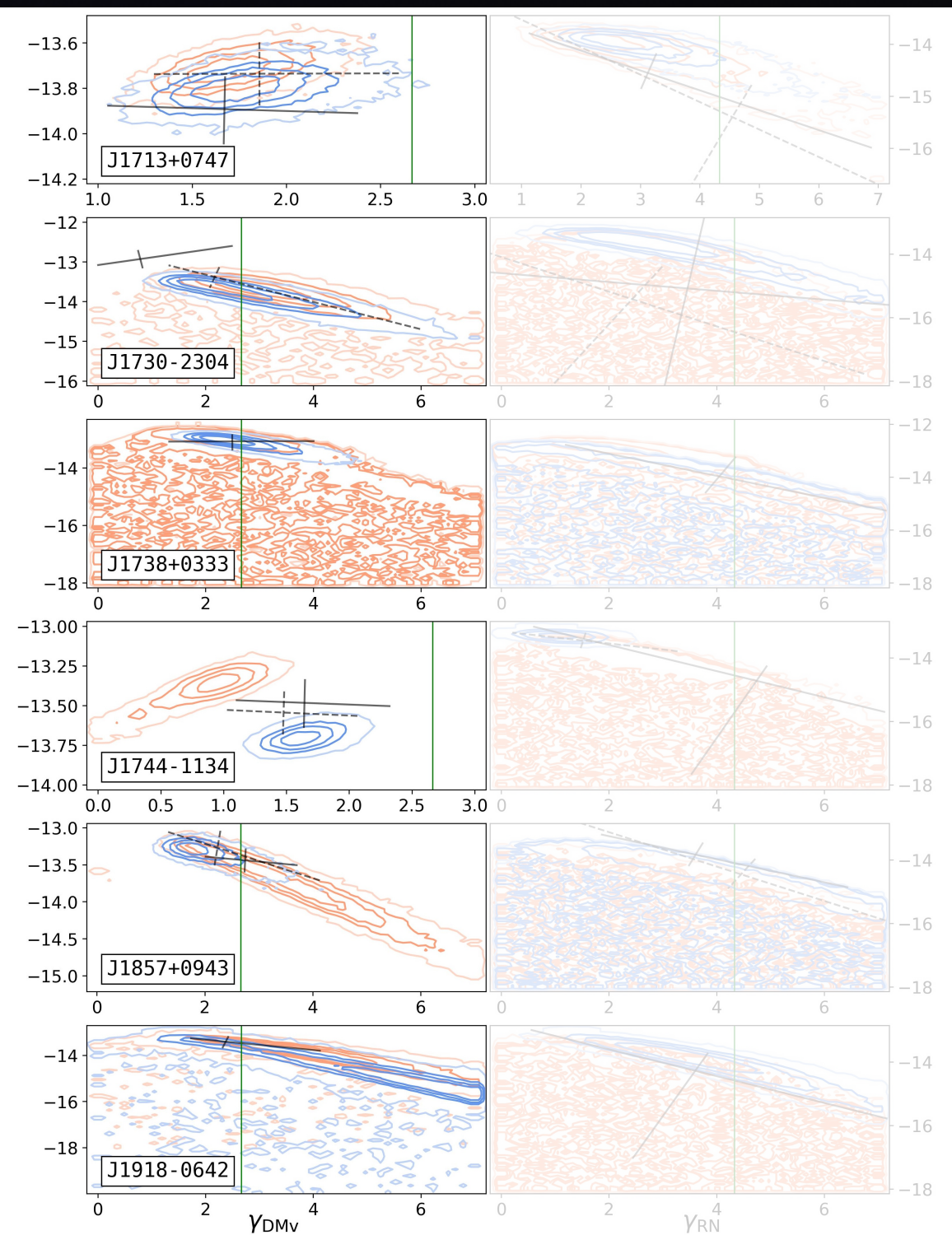
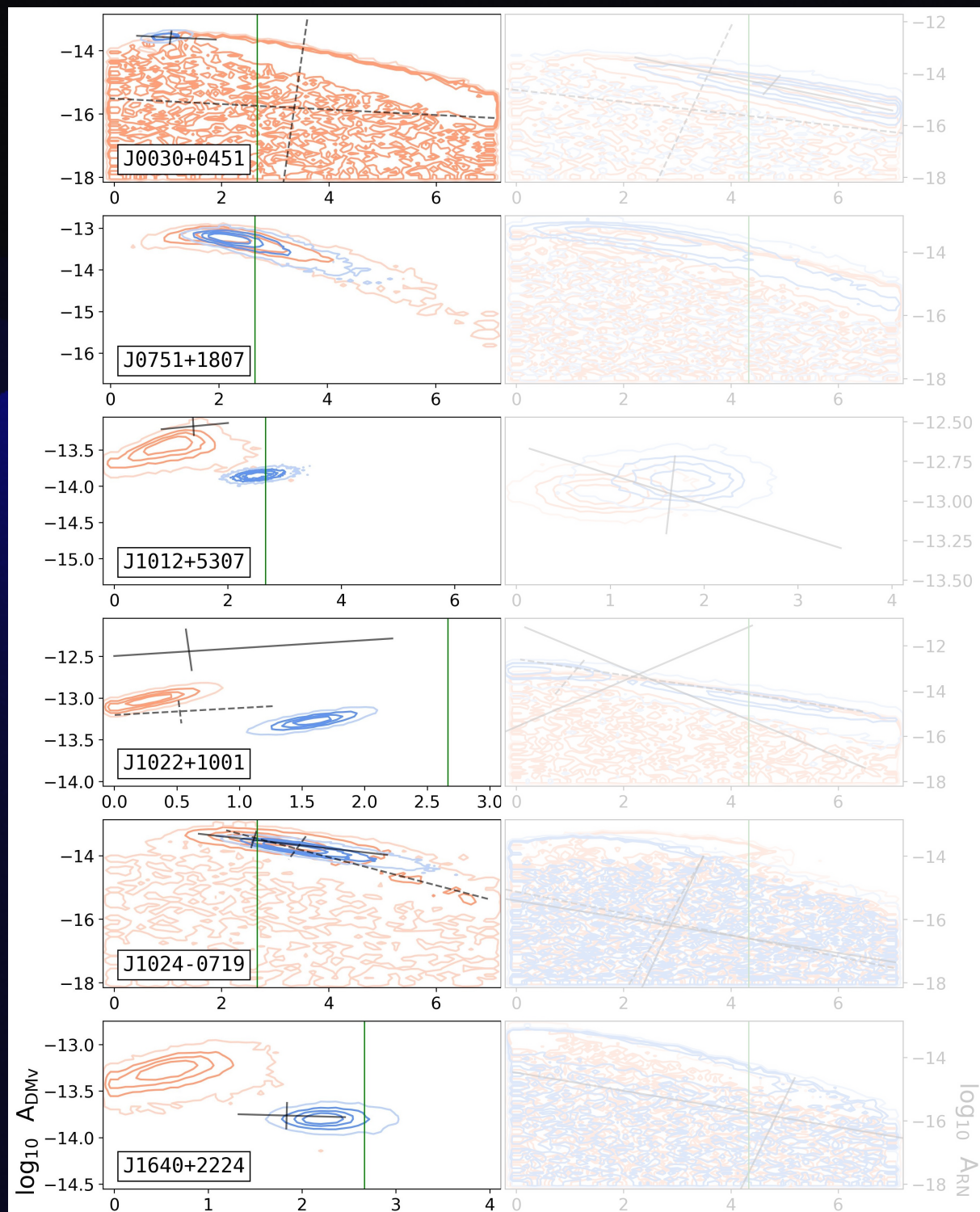
EPTA DR2low

DM (100 bins)

DM (100 bins)

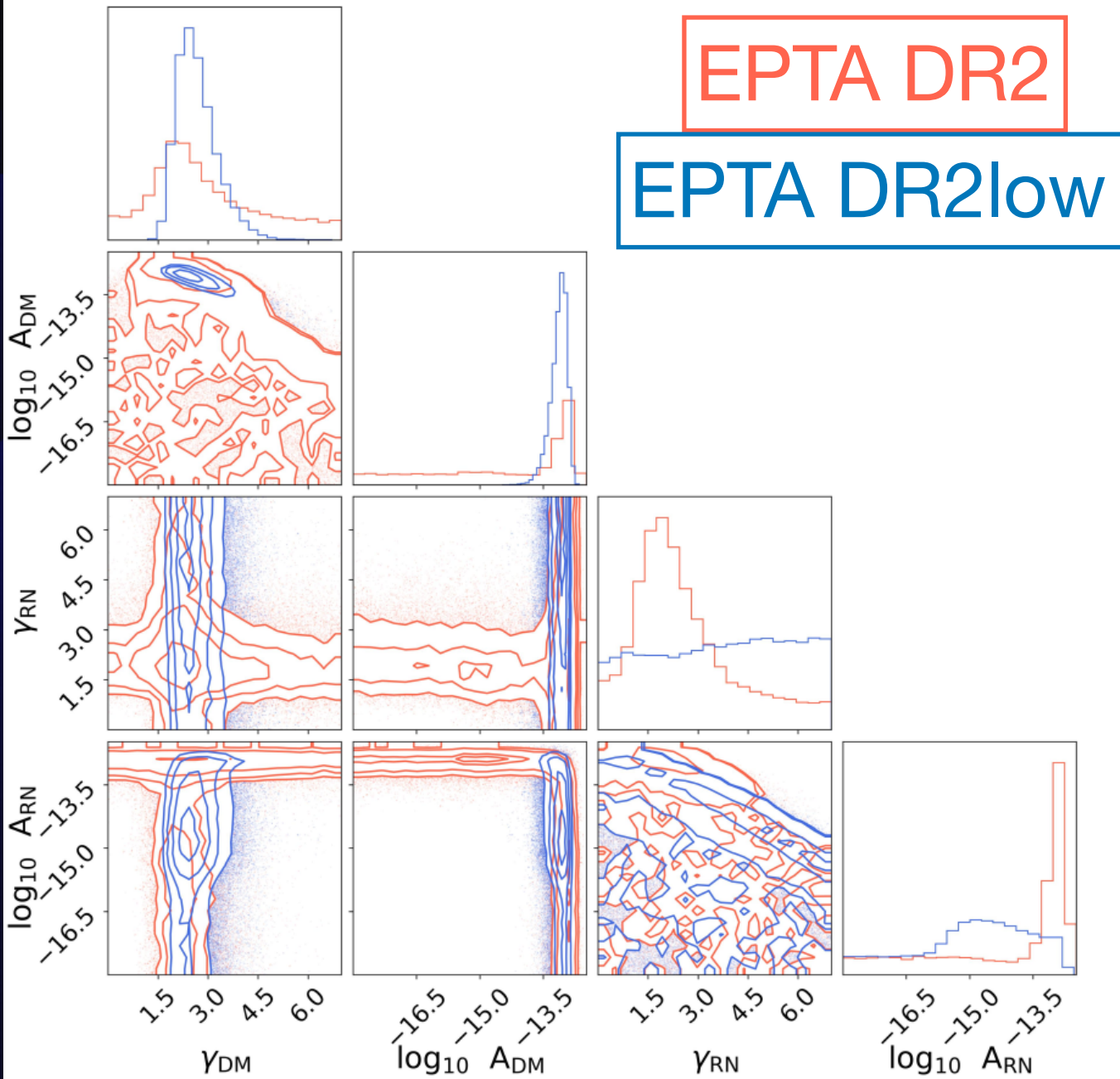
— NG15y
-- PPTA DR3

$\log_{10} A_{DM}$

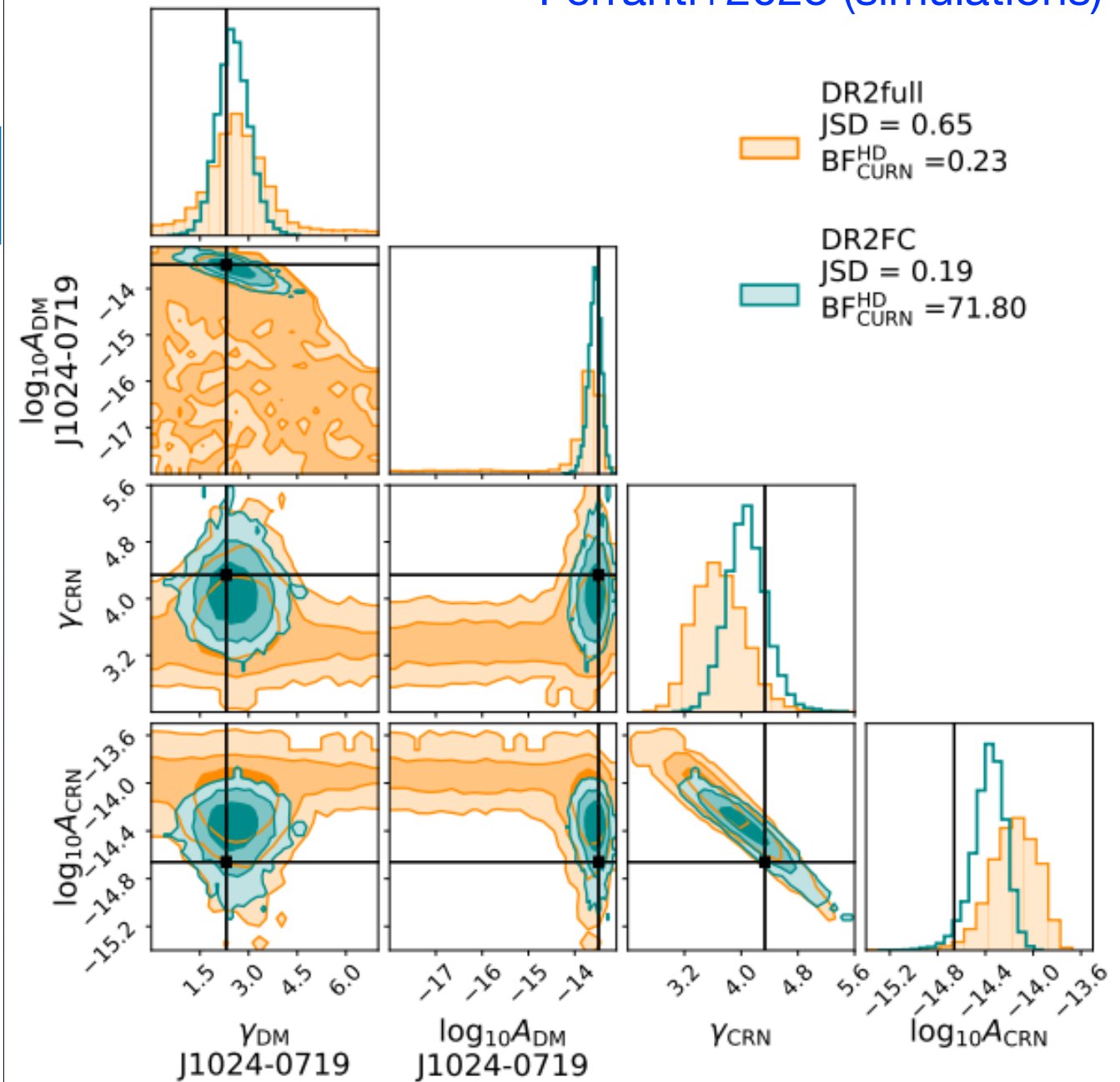


RN vs DM variations

PSR J1738+0333

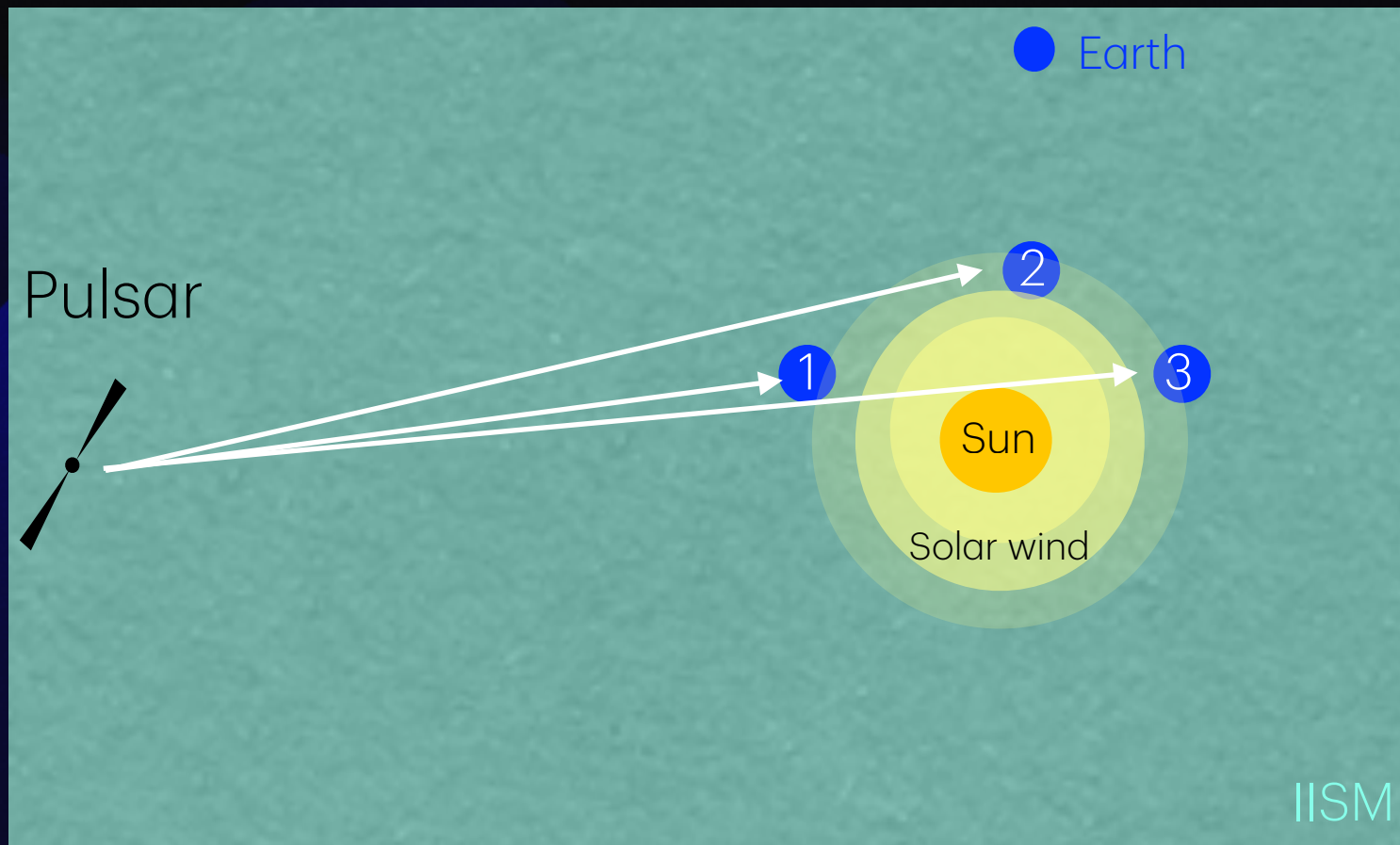


Ferranti+2025 (simulations)

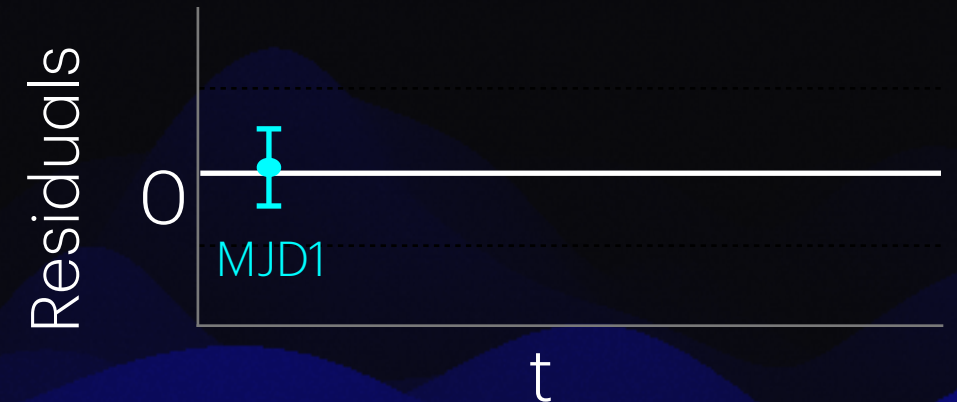


Solar wind in pulsar timing

is a flow of magnetised plasma that originates from the solar corona and continues outwards at constant velocity to a distance of ~ 100 au where it terminates.



Additional free-electron density content affects the ToA of pulsar radiation depending on the angular separation between the LoS and the Sun.



SW tracking

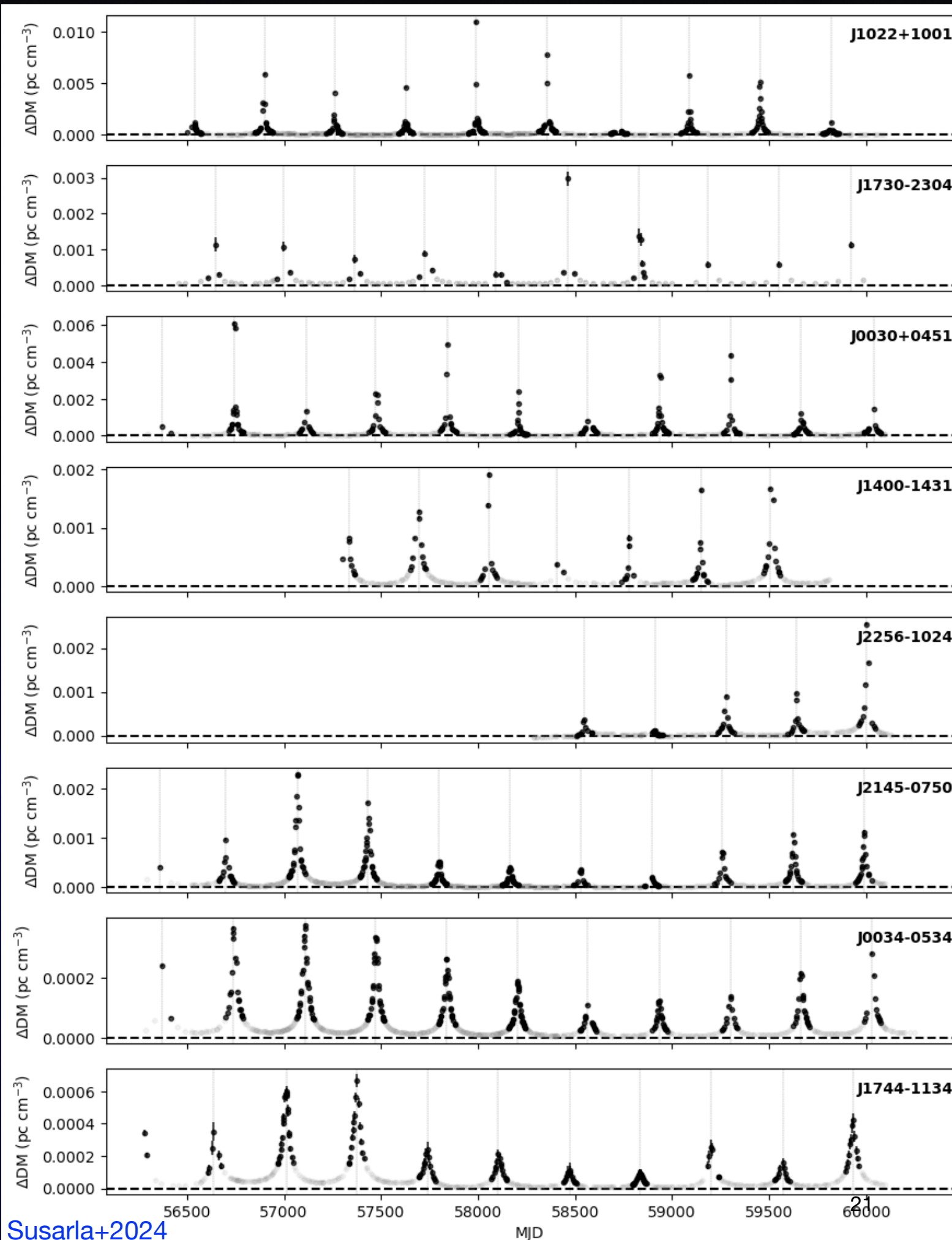
- long timespan
- High cadence especially around solar conjunction epochs

Spherical model:

$$DM_{SW} = n_e^{1 \text{ AU}} \frac{\rho}{r \sin \rho} [1 \text{ AU}]^2$$

PTA SW noise:

- deterministic (NE_SW)
- stochastic (SWGPs)

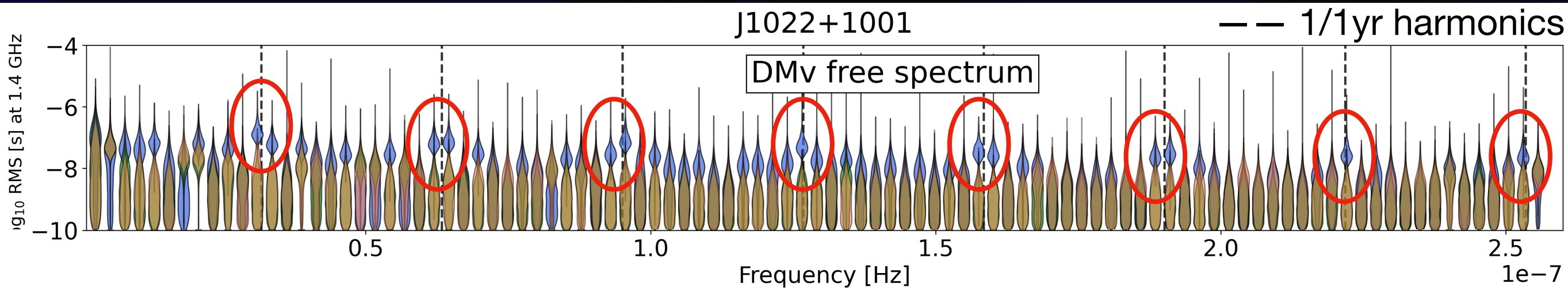


Solar wind in PTAs

DR2low

DR2low - 45 deg cut

DR2low - 75 deg cut



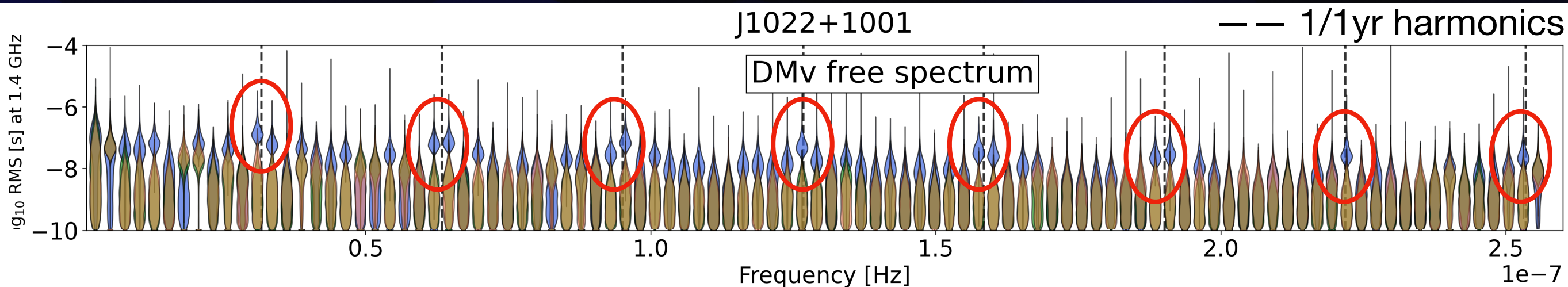
Unmodelled SW absorbed in the DM variations

Solar wind in PTAs

DR2low

DR2low - 45 deg cut

DR2low - 75 deg cut



Unmodelled SW absorbed in the DM variations

Low frequency data were crucial to identify the limits in the current SW model used within the PTA collaborations.

Current efforts

EPTA and IPTA

- LOFAR pulsars in EPTA DR3: 25/60
- LOFAR pulsars in IPTA DR3: 25/130

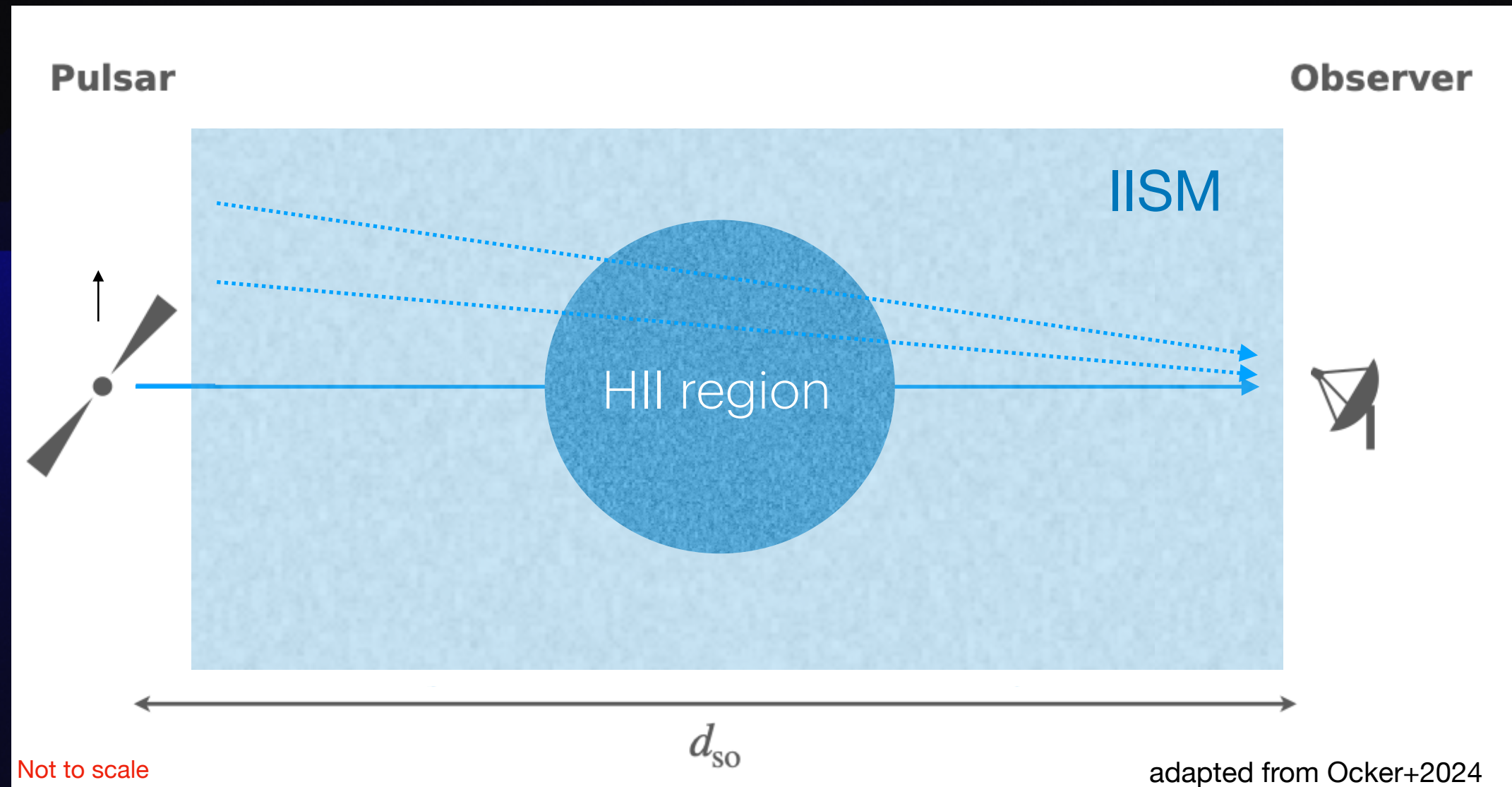
EPTA Meeting 2023 - Milan (Italy)



Credits: EPTA

Probing the IISM with LOFAR

$$t_{\text{delay}} \propto DM \nu^{-2} \quad DM = \int_{LoS} n_e dl \quad \delta_{LoS} \rightarrow \delta n_e \rightarrow \delta DM$$



Stochastic δn_e variations described by a power law wavenumber spectrum

$$P_{\delta n_e} = C_n^2 q^{-\beta}$$

Kolmogorov: $\beta = 11/3$

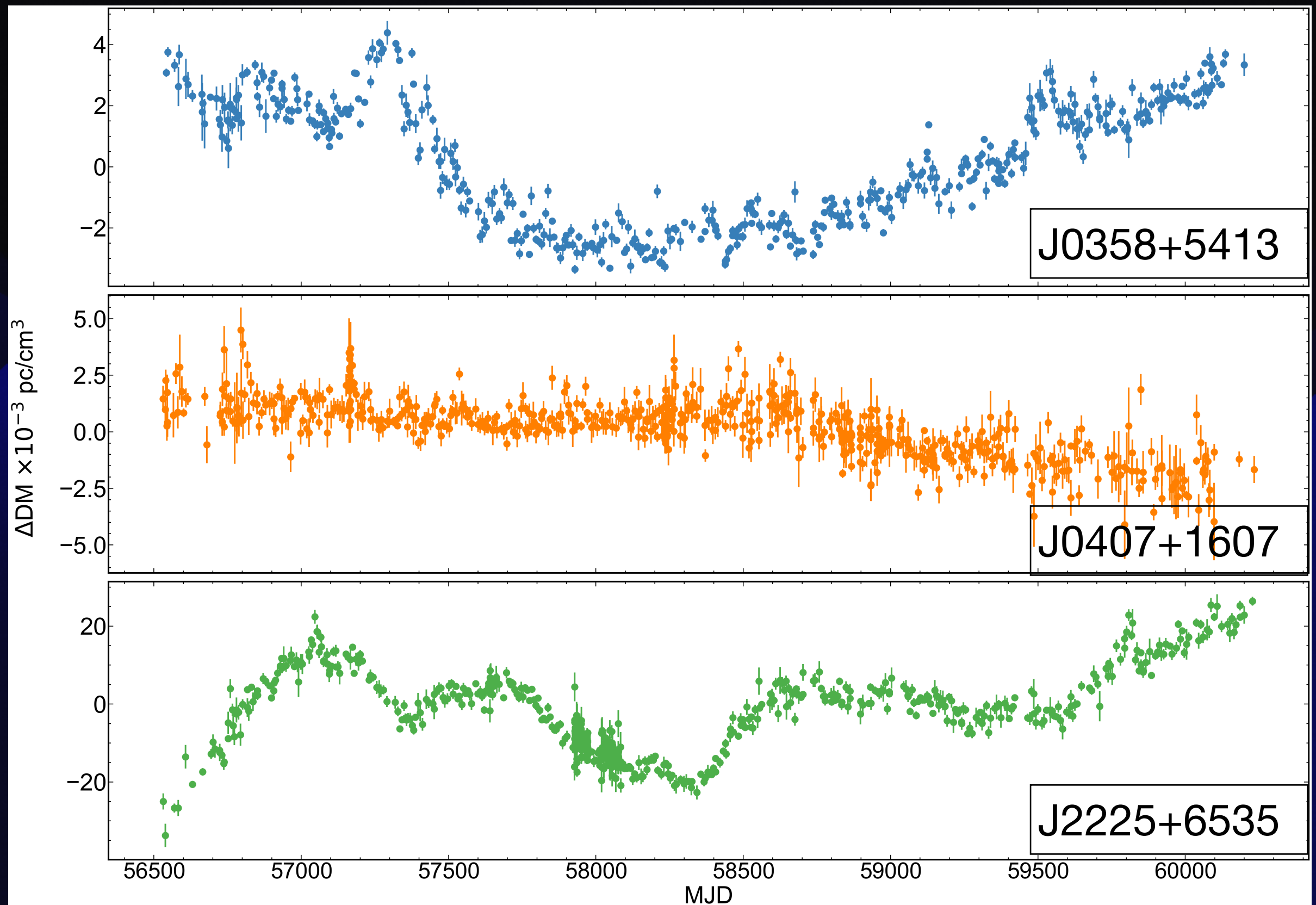
HII regions along the LoS

- Follow up of Ocker+2024 with LOFAR catalog
- 6 pulsar with HII region crossmatch:

J0358+5413
J0407+1607
~~J0609+2130~~
~~J0614+2224~~
~~J1955+2908~~
J2225+6535

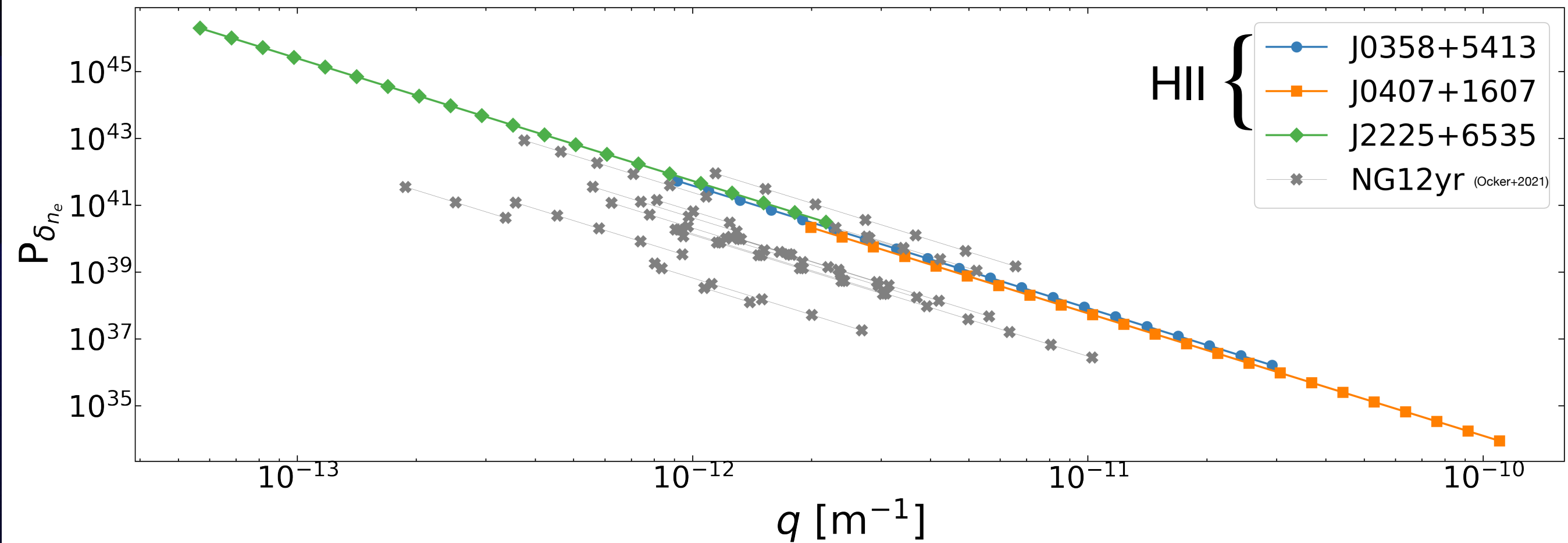
Pulsar					H II			
Name	l [deg]	b [deg]	d_{psr} [kpc]	$v_{\perp}$ [km/s]	l [deg]	b [deg]	d_{HII} [kpc]	r_{imp} [pc]
J0358+5413	148.19	0.81	1.10 ± 0.2	64^{+14}_{-9}	148.540	-0.240	0.850 ± 0.150	16.4
J0407+1607*	176.62	-25.66	2.2 ± 0.4	175^{+61}_{-52}	176.24	-20.88	0.150 ± 0.050	12.536
J2225+6535	108.6	6.8	$0.83^{+0.2}_{-0.1}$	763^{+138}_{-100}	107.92	5.78	0.764 ± 0.027	17.098
					108.86	6.15	0.764 ± 0.027	9.733

DM time series

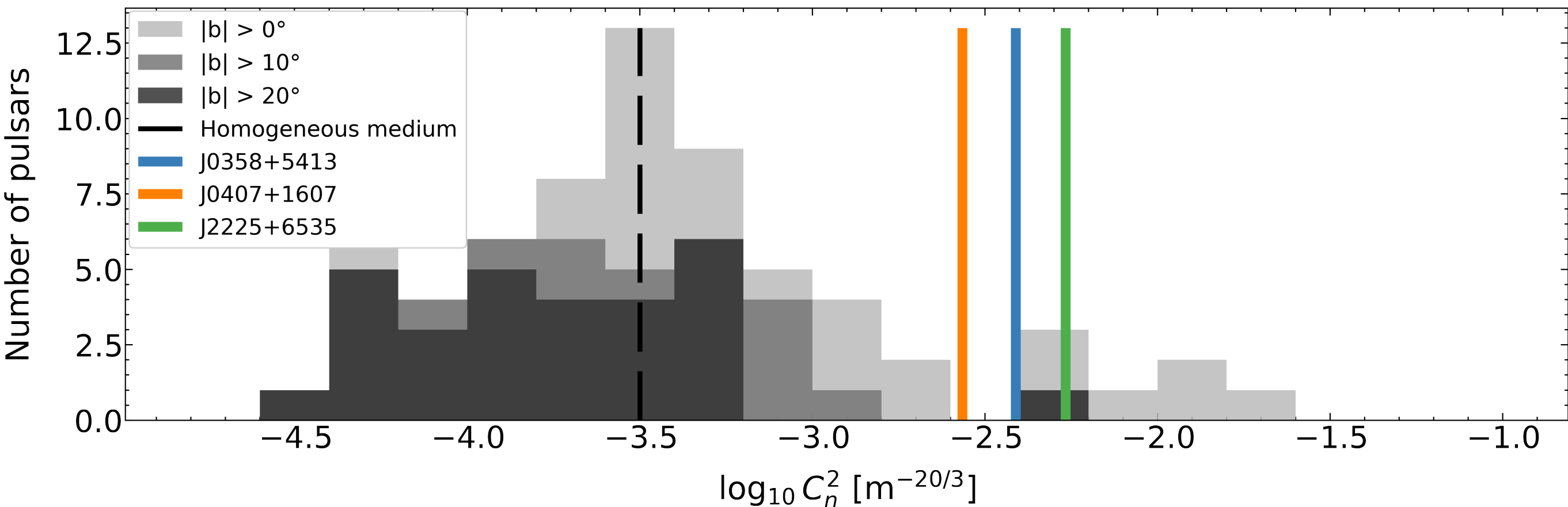


Power spectrum of density fluctuations

$$P_{\delta n_e} = C_n^2 q^{-\beta}$$



Control samples



EPTA DR3 pulsars with HII along the LoS: 4

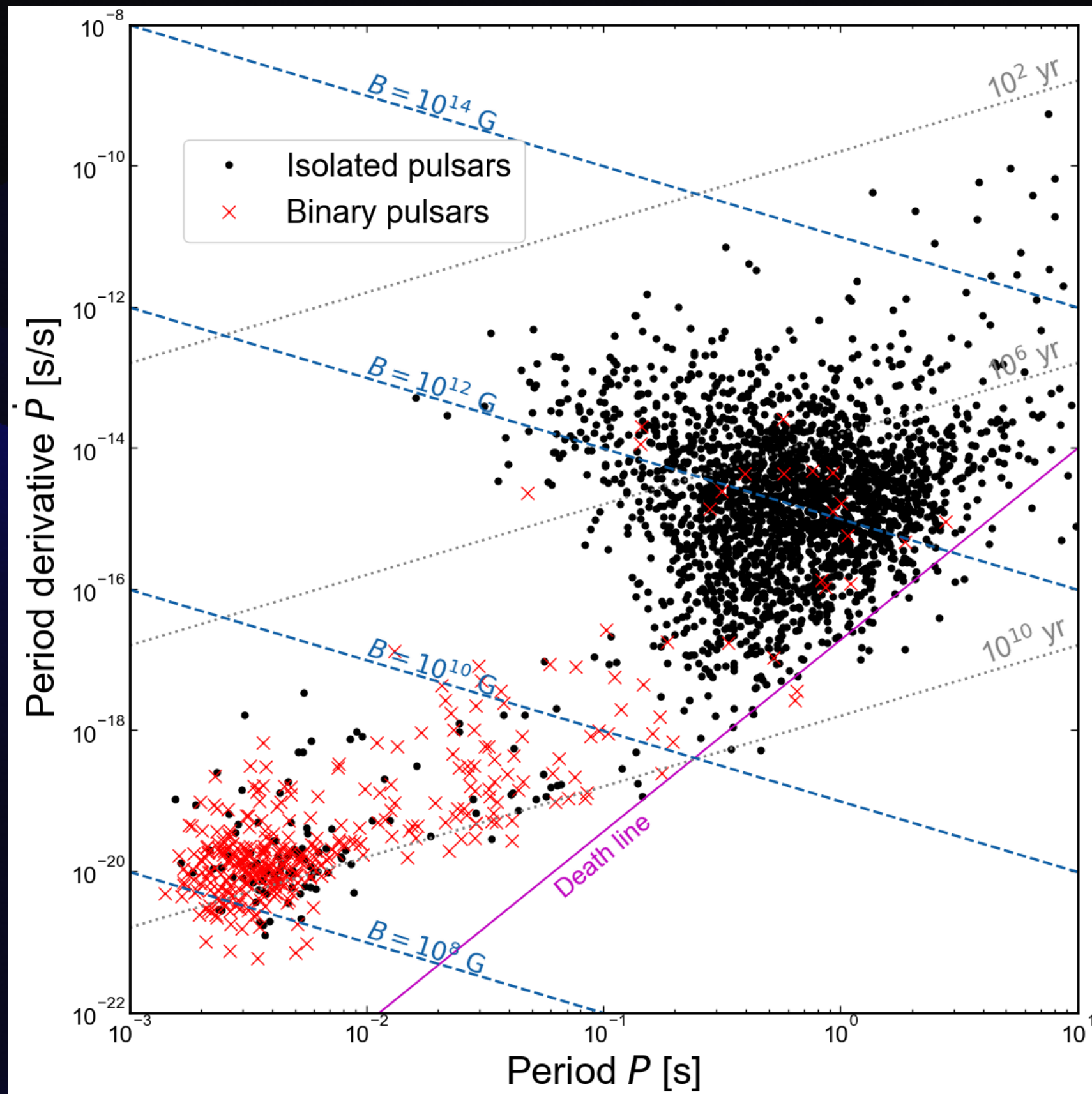
IPTA DR3 pulsars with HII along the LoS: 8

Summary

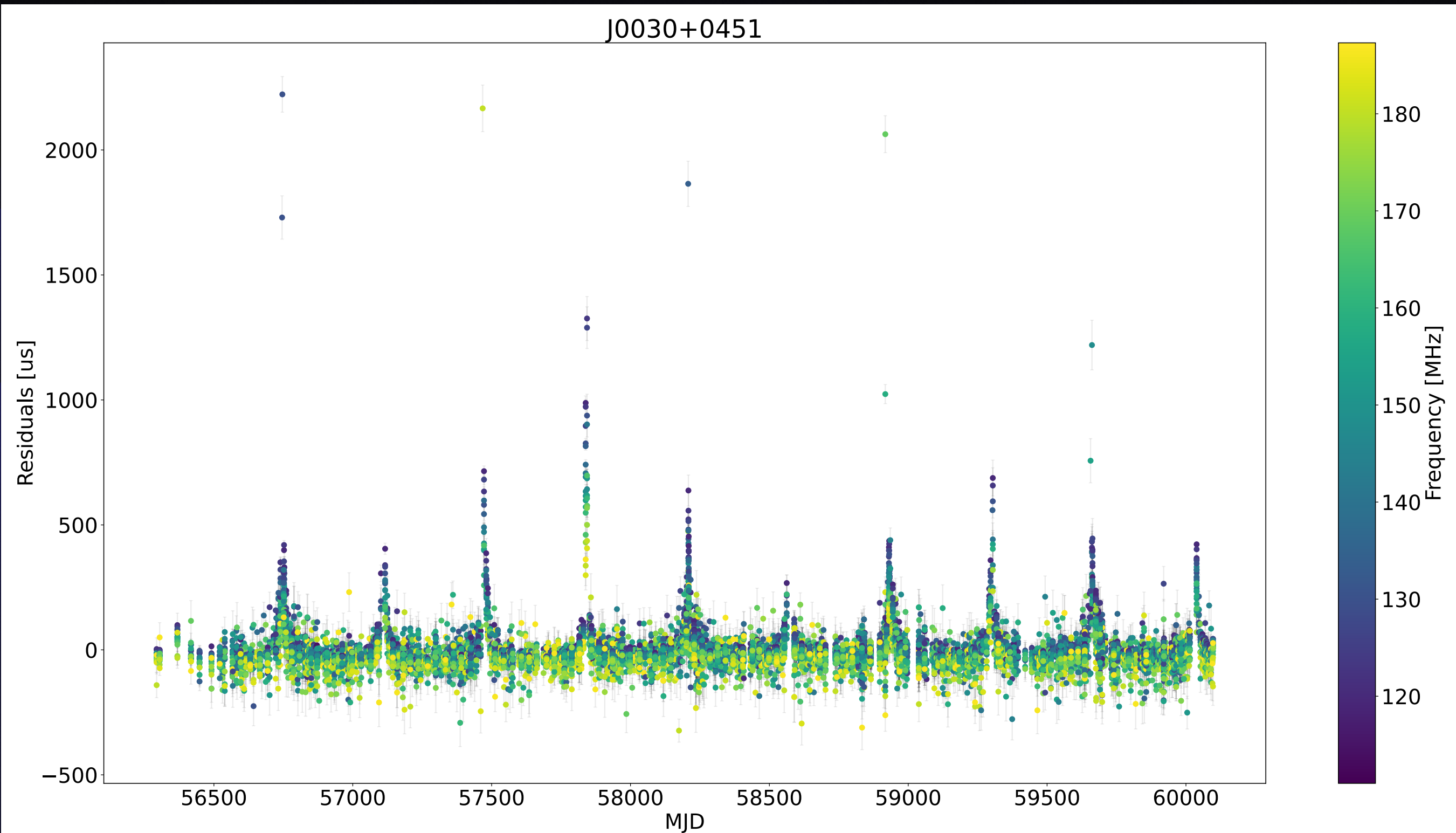
- LOFAR observations are very sensitive to IISM effects
- 12 LOFAR pulsar combined with EPTA DR2.
- Frequency coverage of LOFAR is essential for **disentangling the chromatic and achromatic processes**.
- LOFAR data highlighted the **limitations of the current chromatic noise models** used in PTA data analysis.
- 25 LOFAR pulsars will be part of EPTA DR3 and IPTA DR3
- Discrete IISM structures: HII regions along the LoS as scattering screens
- IISM turbulence and its connection to large-scales (See Pauline Noé's talk this afternoon!)

Backup

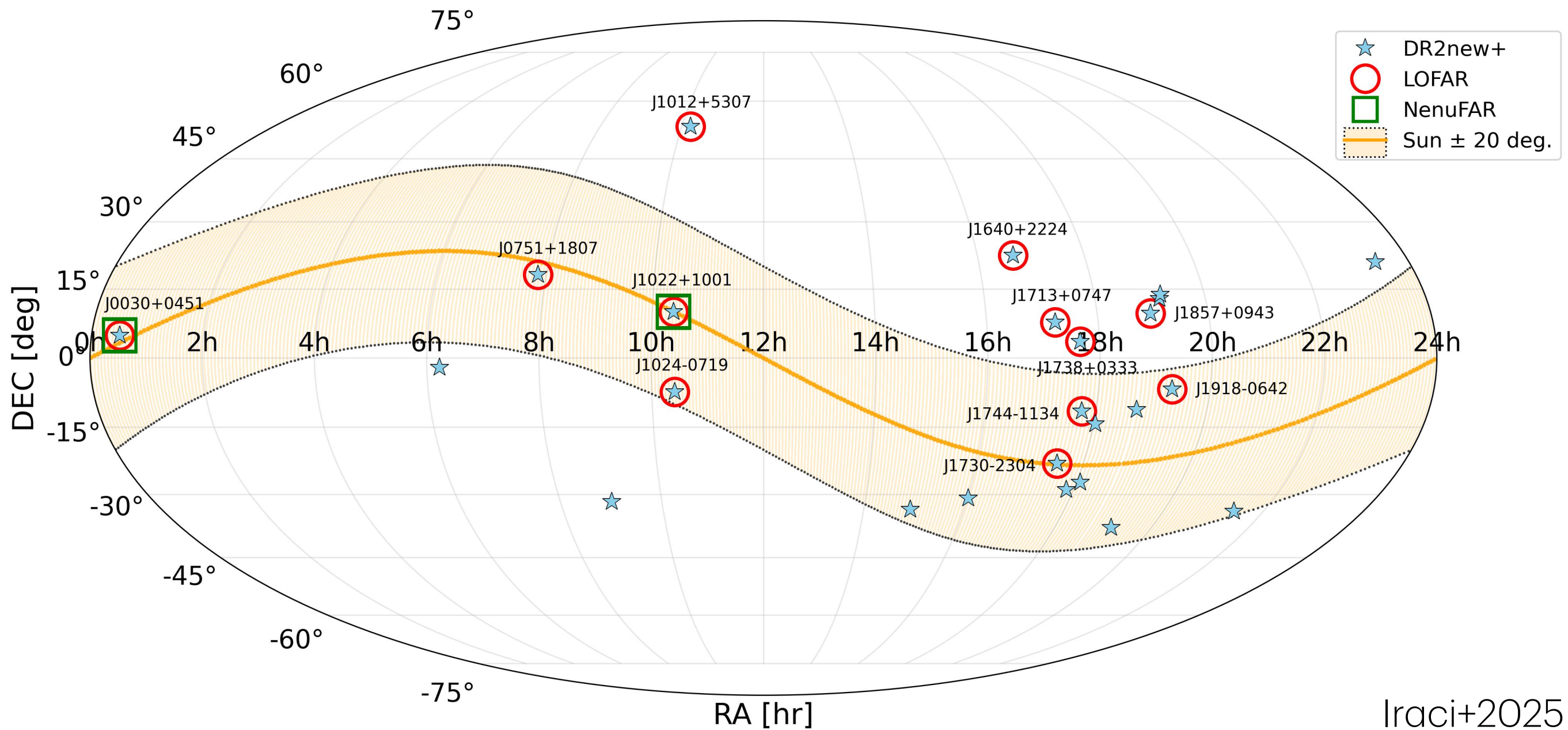
P- $\dot{P}$ diagram



Timing residuals affected by the SW



DR2low



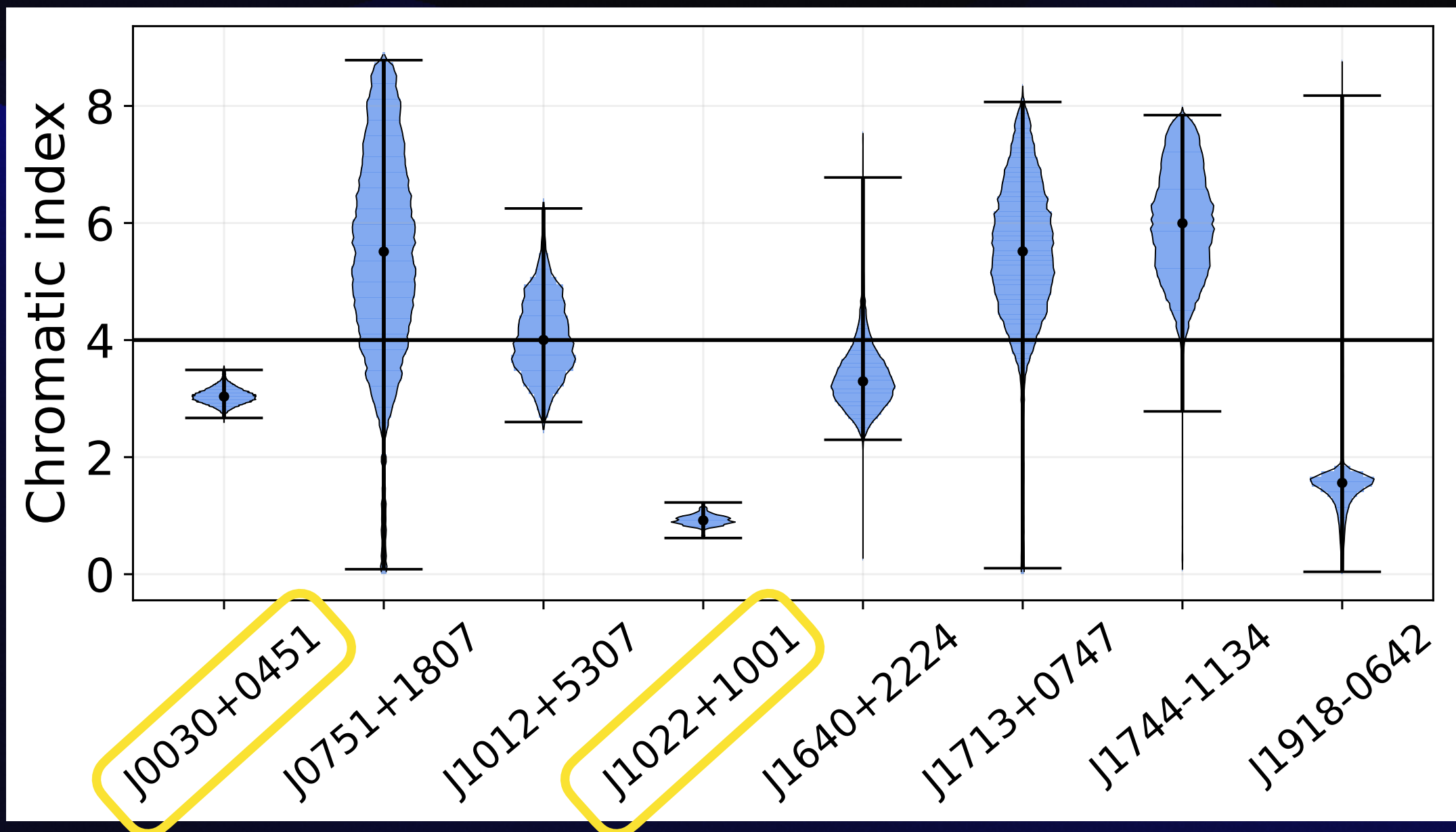
Advanced noise modelling

- Aim: identify the most favoured noise model for each pulsar
- Run multiple analysis with different noise models:
 - RN
 - DM
 - RN + DM
 - RN + DM + SV
 - DM + SV

PSR	Noise model	
	EPTA DR2low	EPTADR2new+
J0030+0451	RN13 DM100 SV77	RN10
J0751+1807	DM92 SV38	DM50
J1012+5307	RN87 DM20 SV100	RN100 DM47
J1022+1001	RN98 DM99 SV99	RN30 DM100
J1024-0719	DM18	DM15
J1640+2224	RN54 DM40 SV40	DM47
J1713+0747	RN73 DM74 SV12	RN73 DM72
J1730-2304	RN18 DM52	DM11
J1738+0333	RN29 DM28	DM24
J1744-1134	RN22 DM100 SV31	RN19 DM98
J1857+0943	RN87 DM99	DM92
J1918+0642	RN36 DM24 SV42	DM75

Chromatic index study

- Noise run with free chromatic index (only for pulsars with SV in the favoured model)

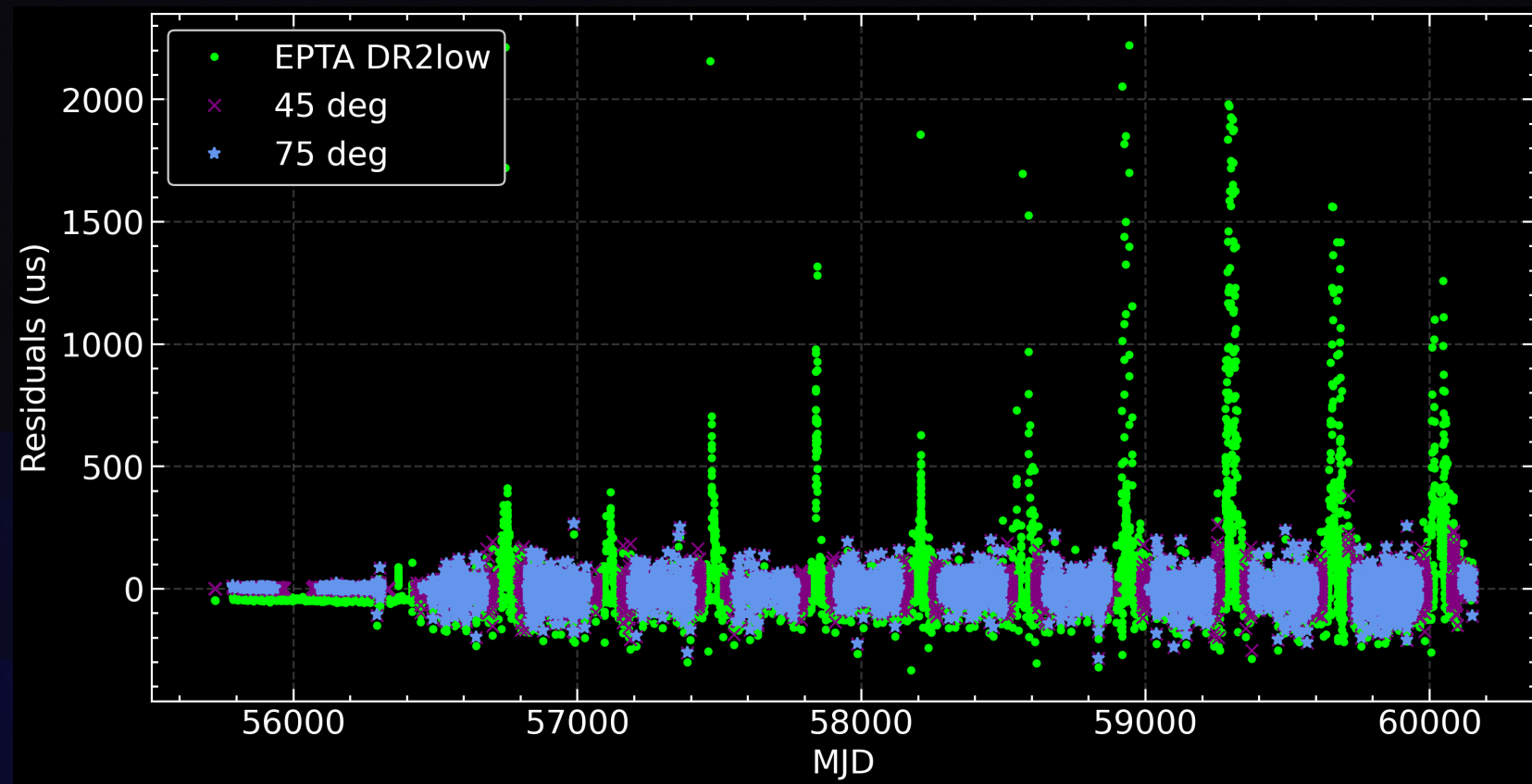


Solar wind

Remove data with solar angle:

$< 45^\circ$

$< 75^\circ$

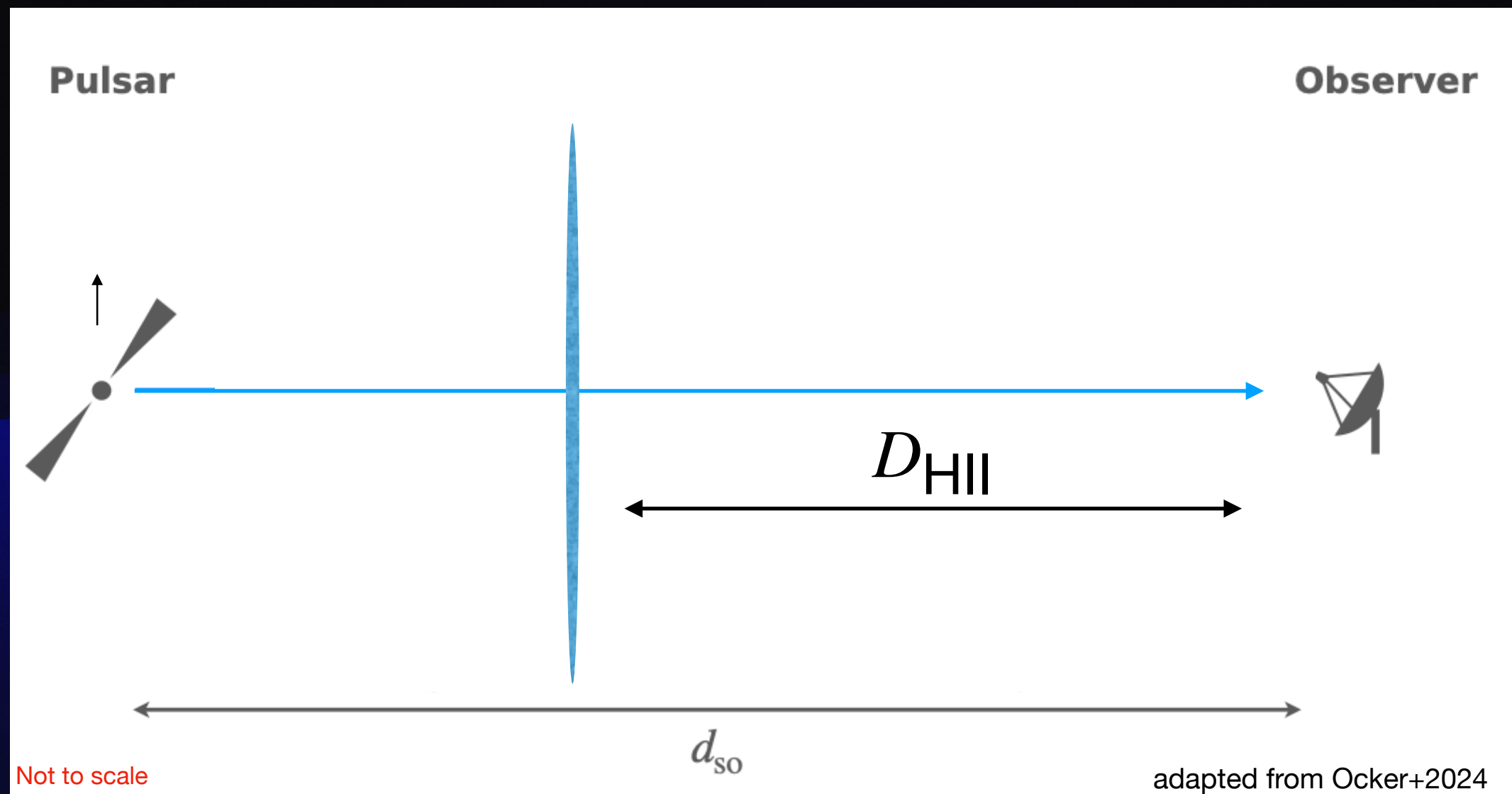


Analyse the data with the favoured noise model without SW

J0030+0451: RN13 DM100 SV77

J1022+1001: RN98 DM99 SV99

Characterising the turbulence of the HII



$$P_{\delta n_e} = C_n^2 q^{-\beta}$$

$$\hat{C}_n^2 = \frac{1}{K_{DM}(\beta)} \left[\frac{D_{DM}(\tau)}{d \left(v_{eff,\perp}(s) \tau \right)^{\beta-2}} \right]$$

Structure function of the DM time series

$$\hat{q} \approx \frac{2\pi}{v_{eff,\perp}(s) \tau}$$

Building a control sample

- 171 pulsar with parallax distance measurement (fractional uncertainty <20%. See Ocker+2026)

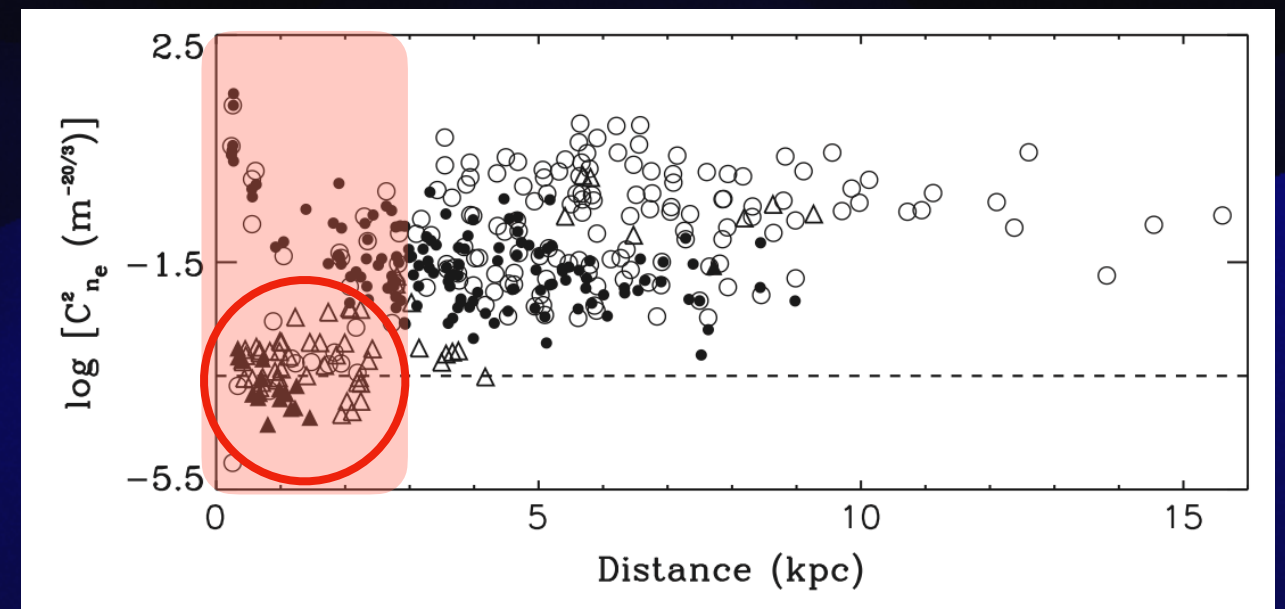
- Remove any pulsar with HII along the LoS

Krishnakumar+2015

- Distance threshold:

- $d_{psr} \leq 3 \text{ kpc}$ — — — — — >

- $\Delta d_{psr} \leq 0.5 \text{ kpc}$



- Compute C_n^2 for an extended uniform medium for all pulsars with scattering timescales measurements (88 out of 171)

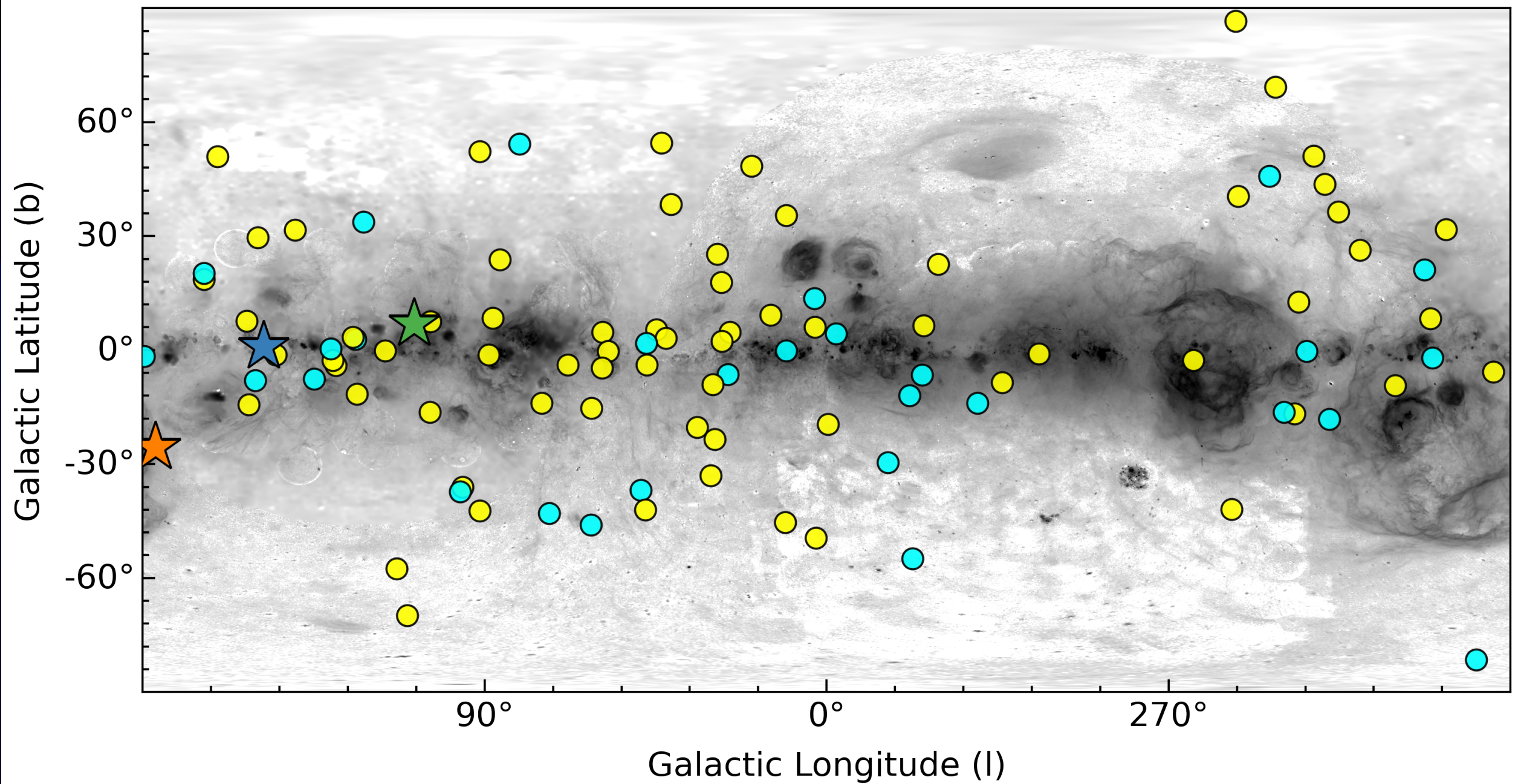
$$SM = 2.15 \nu_{\text{GHz}}^{11/3} D_{\text{kpc}}^{-5/6} \tau_{\text{ms}}^{5/6}$$

$$C_n^2 = \frac{SM}{D_{\text{kpc}}}$$

Krishnakumar+2015, Cordes+1986

Control sample ($d \leq 3$ kpc)

- | | |
|--------------|--|
| ★ J0358+5413 | ● Control sample (has $\tau_{1\text{GHz}}$) |
| ★ J0407+1607 | ● Control sample (no $\tau_{1\text{GHz}}$) |
| ★ J2225+6535 | |



J0358+5413 DM GP free spectrum

