Prospects with nanohertz GW astronomy arrays.

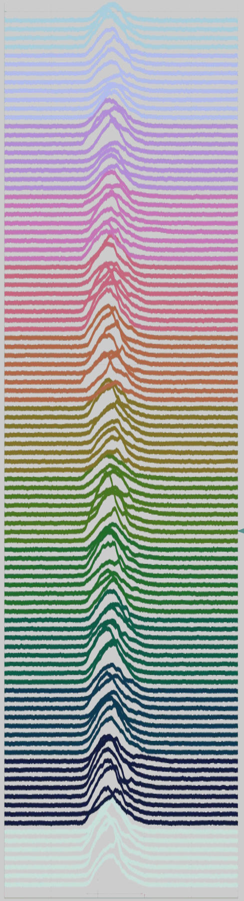
Golam Shaifullah

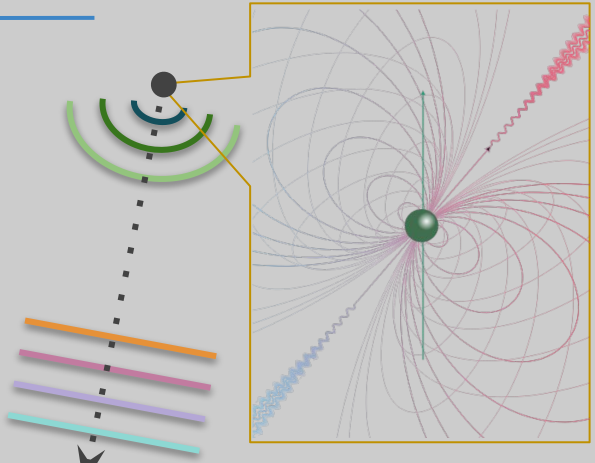
i do not know what it is about you that closes
and opens; only something in me understands
the voice of your eyes is deeper than all roses
-- E. E. Cummings

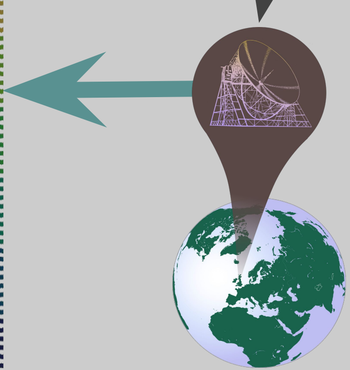
It’s not a bird, it’s not a plane, definitely not LGM

Pulsars are giant flywheels in space, their compact masses give rise to **incredibly stable rotation**.

On each rotation, the pulsar beam produces a ***‘pulse’*** at Earth, and the photons in that pulse can be assigned a **time-of-arrival (TOA)**.

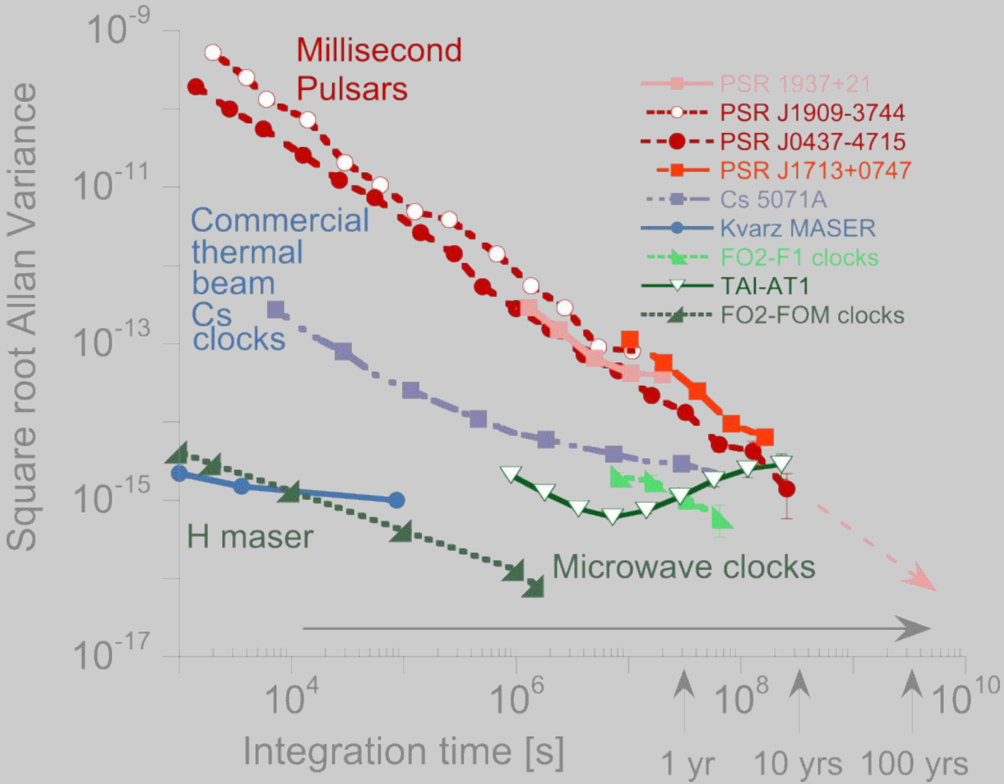




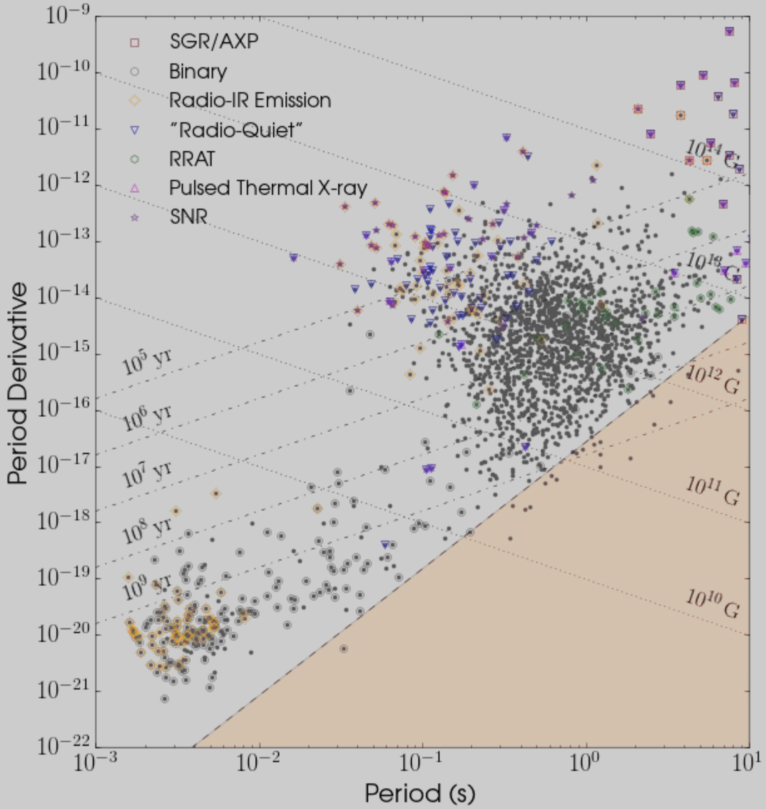


Discovered by Prof. Bell-Burnell

Millisecond pulsars as stable clocks



Adapted from Hartnett & Luiten, 2011



psrqpy, (Pitkin, 2011)

See Shannon et al (2016), Lam et al (2018) & others

Models, models, models

TOAs can be predicted using a model with the following (sets of) parameters:

- **astrometric**,
- **pulsar rotation** and
- **binary** (when applicable).

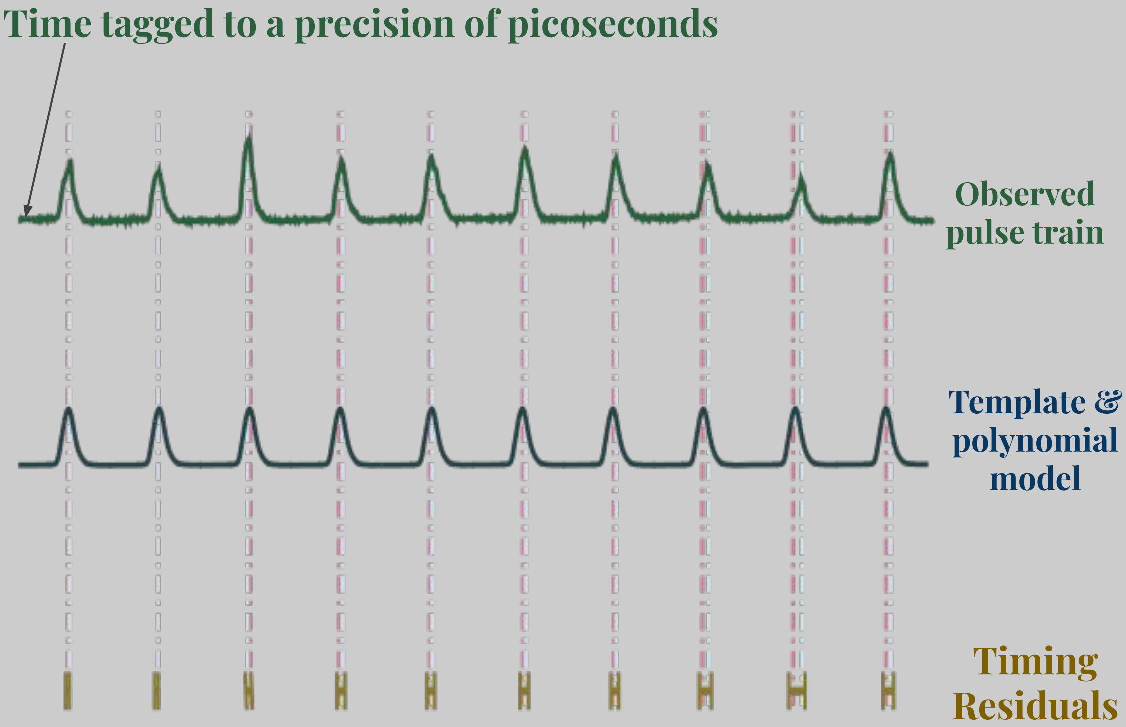
Apart from these pulsar emission is affected by:

- **Dispersive delays due to the intervening *ionised plasma***
- **Red noise (low frequency) processes**

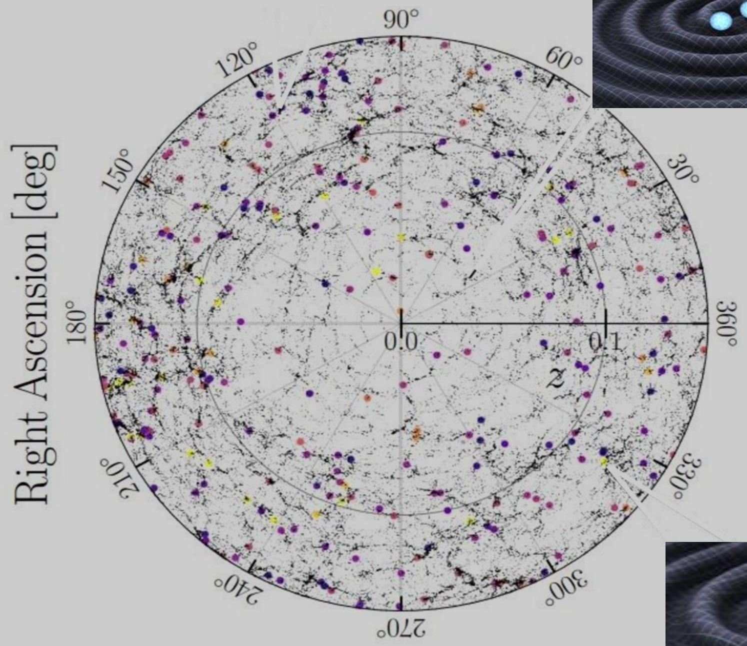
Pulsar timing

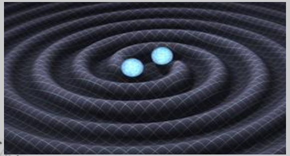
However, once we have estimates of those parameters, we can predict ***very precisely*** when the next pulse will arrive. Or the one after 20 million rotations.

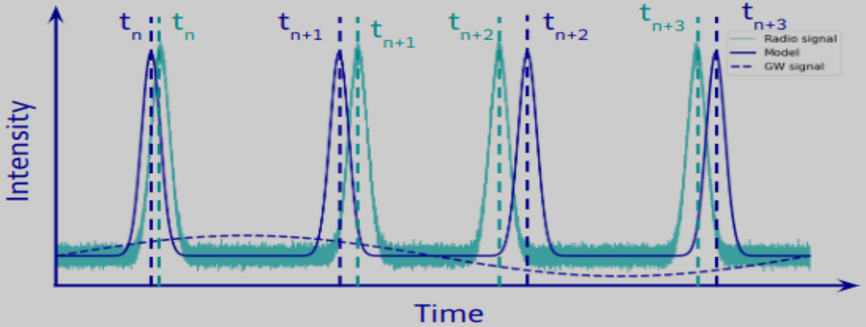
When pulses are averaged this precision quickly tends to tens of microseconds to hundreds of nanoseconds.



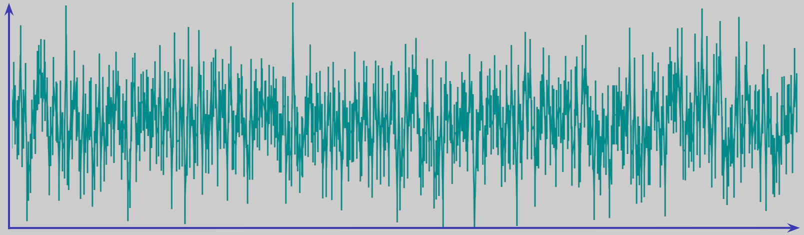
All of the light we can~~not~~ see

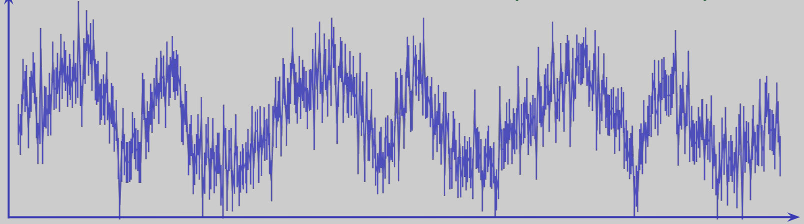






Manzini, MSc thesis, 2023



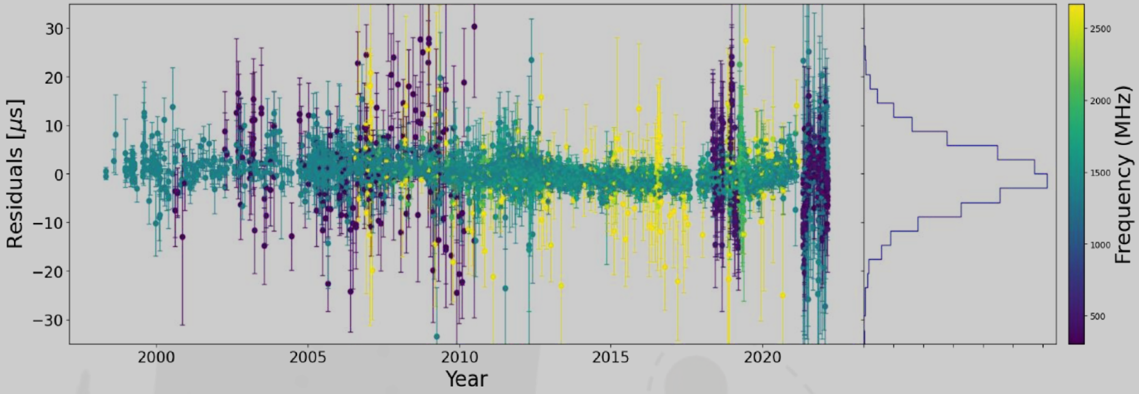


Izquierdo-Villalba et al (2024),
Curylo et al (2023), Bromm & Loeb 2003, Cole et al 2000, Benson (2012)

Pulsar timing arrays

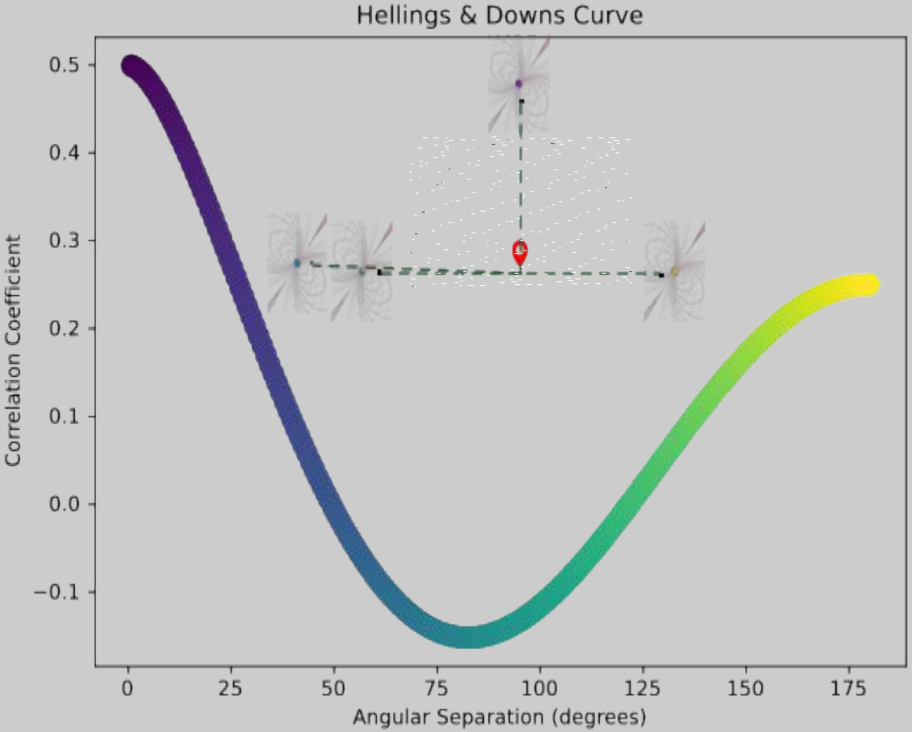
- GWs are expected to induce timing residuals on the order of a few tens of nanoseconds.
- TOA stability scales with number of rotations averaged - use **millisecond pulsars (MSPs)!**
- Single pulsars are 'jittery' and affected by noise, use an **array of MSPs**

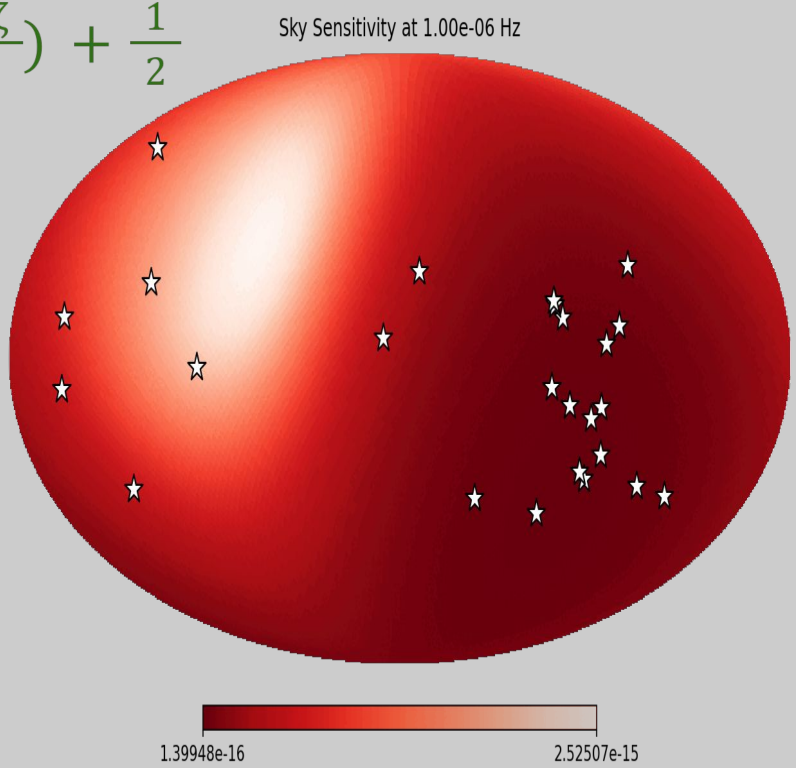
Ferranti, MSc thesis, 2023



What is the signal PTAs are looking for?

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



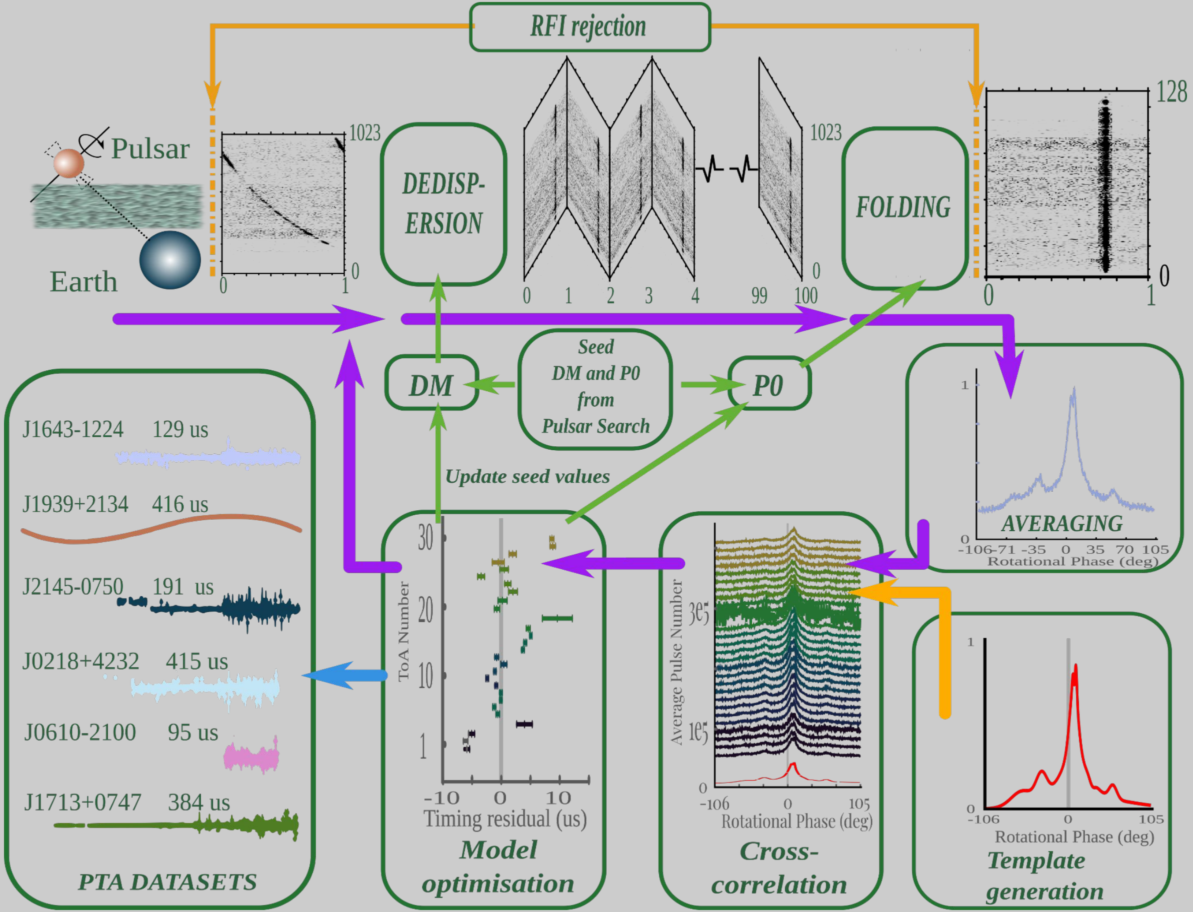


Hellings & Downs, 1983; Also see Romano & Allen, arxiv:2308.05847

FreqBayes™ pulsar timing:

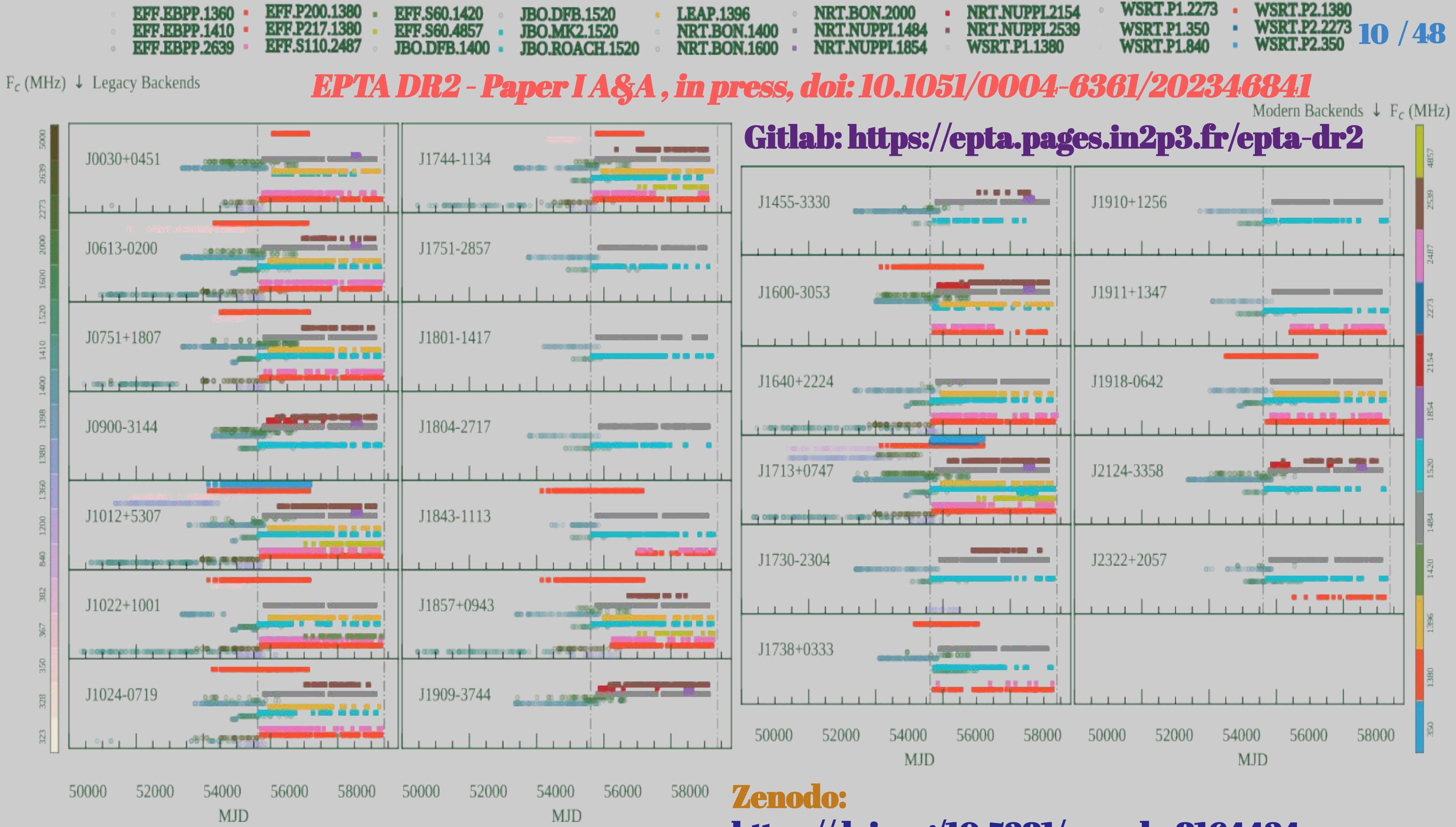
Figure from Verbiest & Shaifullah, 2018, CQG

- Observe a pulsar
- De-disperse
- Stack
- Average
- Make a template
- Cross-correlate
- Line up your TOAs
- Repeat for another 20 - 100 sources
- Sprinkle post-docs for flavour
- Bake for ~30 years, turning it over once or twice a decade.



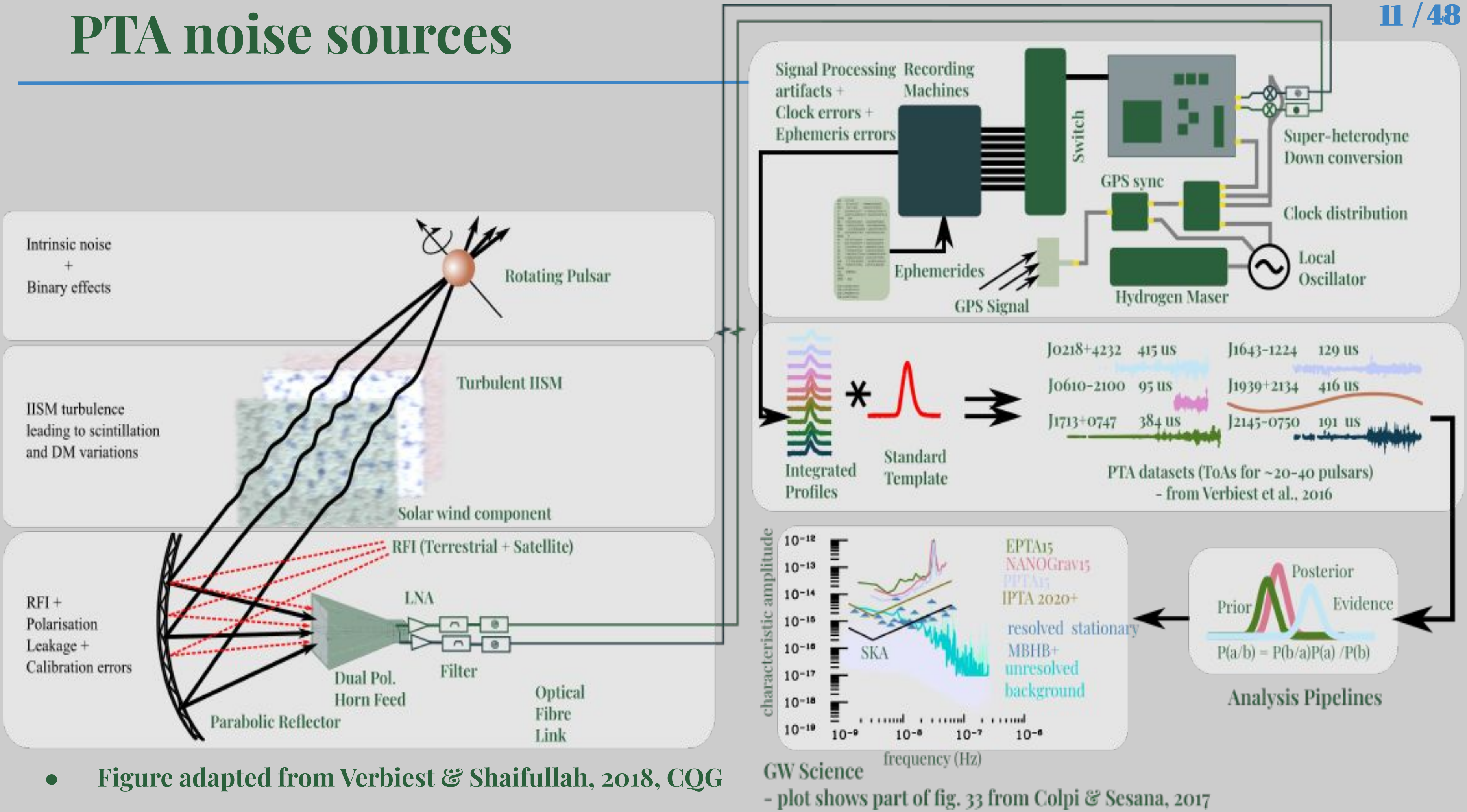
EPTA DR2 - Paper I A&A , in press, doi: 10.1051/0004-6361/202346841

Gitlab: https://epta.pages.in2p3.fr/epta-dr2



Zenodo:

PTA noise sources



- Figure adapted from Verbiest & Shaifullah, 2018, CQG

The detection statistic and search algorithm

- We assume that noise is Gaussian: the likelihood function (likelihood of the signal with given parameters) is

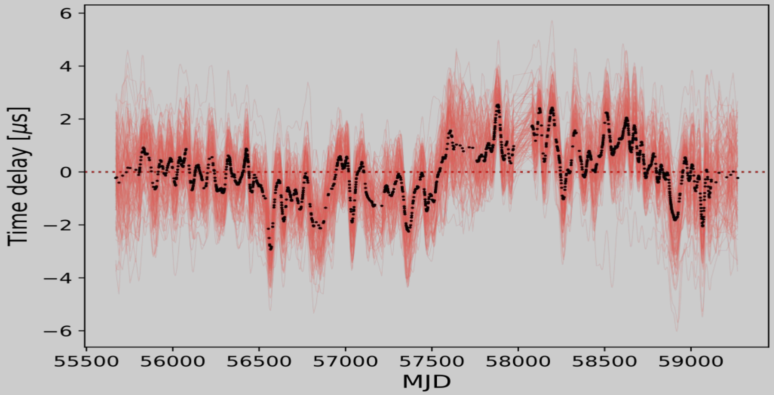
$$P(\vec{\delta t}, \vec{\theta}) = \{1/\sqrt{(2\pi)^n \det(C)}\} \exp(-½ (\vec{\delta t} - \vec{s})^T C^{-1} (\vec{\delta t} - \vec{s}))$$

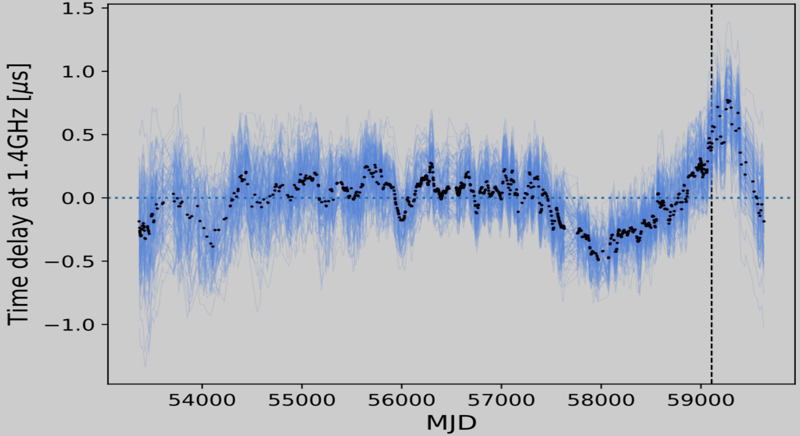
- δt - concatenated residuals from all pulsars in the array: total size n
- s - is a model of deterministic signals (e.g. - GW signals from individually resolvable SMBHBs)
- C is the noise variance-covariance matrix (size $n \times n$);

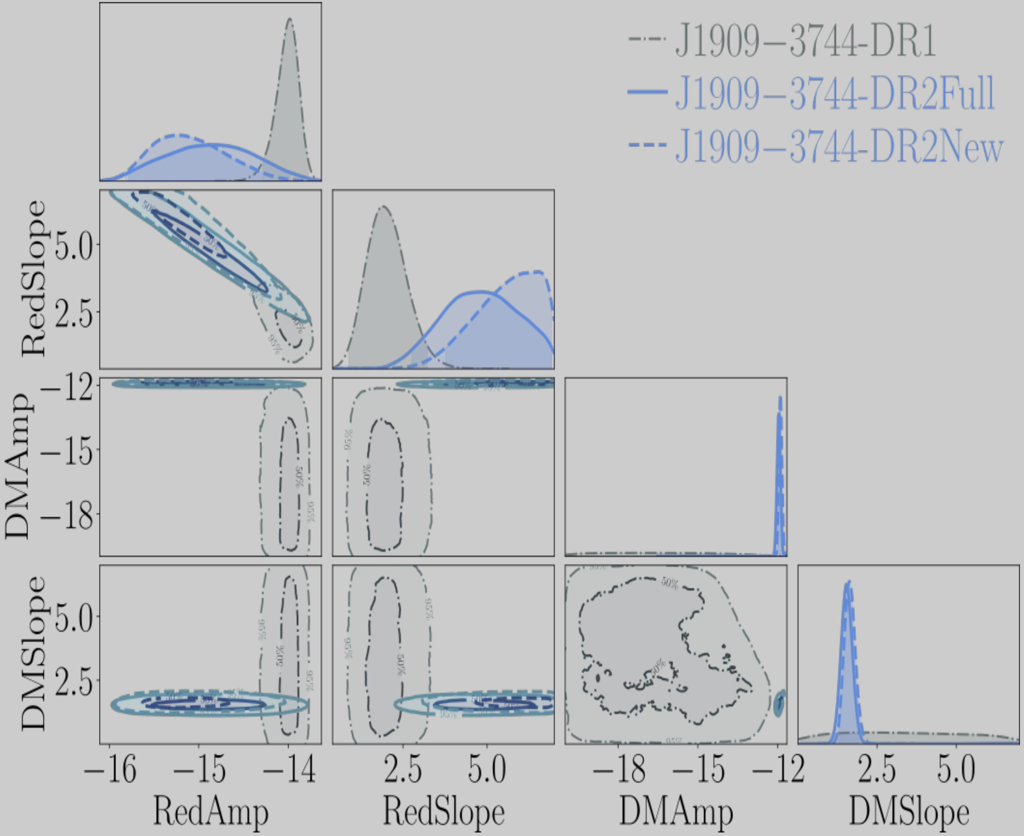
$$C_{\alpha i,\beta j} = C^{WN} \delta_{\alpha\beta} \delta_{ij} + C^{RN}{}_{ij} \delta_{\alpha\beta} + C^{DM}{}_{ij} \delta_{\alpha\beta} + C^{GW}{}_{ij} \delta_{\alpha\beta} + \ldots$$

white noise; pulsar index; red (spin) noise; toa index; dispersion noise; stochastic GW noise

Noise models & their validity







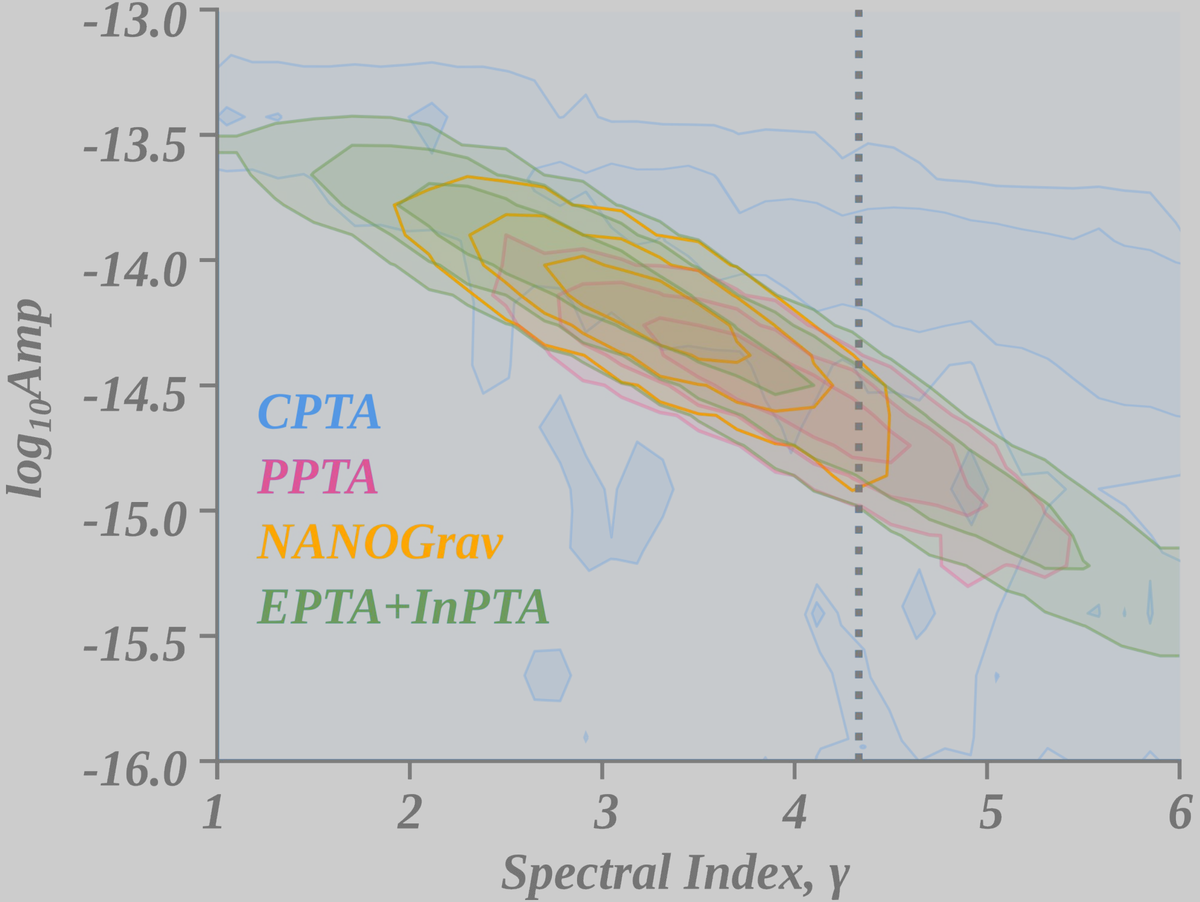
EPTA DR2 - Paper II A&A , 2023, doi: 10.1051/0004-6361/202346842

PTAs inching up to the GWB

On June 29, 2023 4 PTAs announced evidence for an HD correlated process in their data.

The significance ranges from **~2 to 4.6 σ**; below the **5σ** detection threshold.

Further this amplitude is **loud** (~2-3 x 10^{-15}) and the spectrum is **flat** (~3).



The International Pulsar Timing Array checklist for the detection of nanohertz gravitational waves

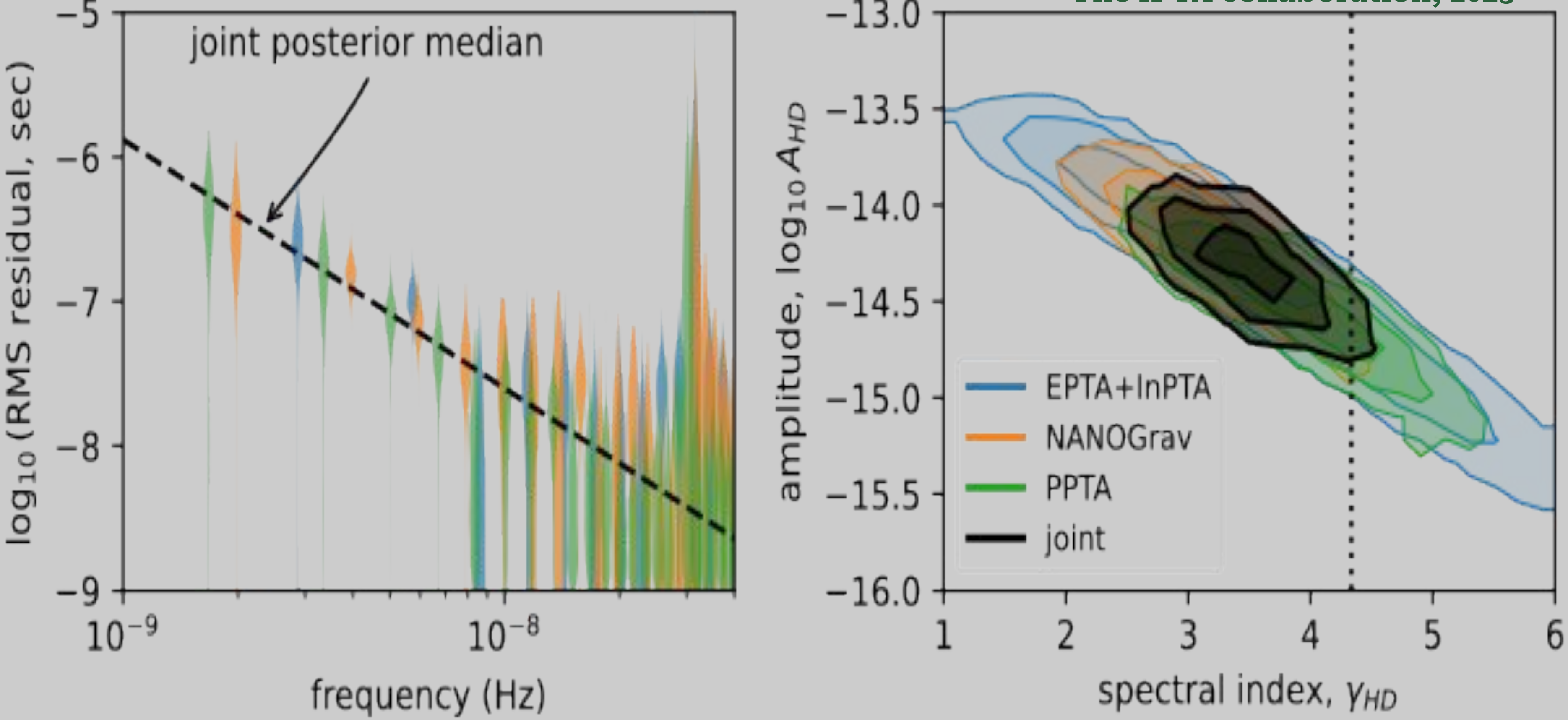
Bruce Allen,[1] Sanjeev Dhurandhar,[2] Yashwant Gupta,[3] Maura McLaughlin,[4] Priyamvada Natarajan,[5, 6] Ryan M. Shannon,[7, 8] Eric Thrane,[9, 10] and Alberto Vecchio[11]

1 Max Planck Institute for Gravitational Physics, Leibniz Universiẗat Hannover, Callinstrasse 38, D-30167 Hannover, Germany
2 Inter University Centre for Astronomy & Astrophysics, Ganeshkhind, Pune - 411 007, India
3 National Centre for Radio Astrophysics, Pune University Campus, Pune 411007, India
4 West Virginia University Department of Physics and Astronomy, Morgantown, WV, 26501, USA
5 Department of Astronomy, 52 Hillhouse Avenue, New Haven, CT 06511
6 Black Hole Initiative, 20 Garden Street, Cambridge, MA 02138
7 Centre for Astrophyics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC, 3122, Australia
8 OzGrav: The ARC Centre of Excellence for Gravitational Wave Discovery
9 School of Physics and Astronomy, Monash University, Clayton VIC 3800, Australia
10 OzGrav: The ARC Centre of Excellence for Gravitational Wave Discovery, Clayton VIC 3800, Australia
11 School of Physics and Astronomy & Institute for Gravitational Wave Astronomy, University of Birmingham, Birmingham, B15 2TT

“At the present time none of the PTAs have a detection claim.”

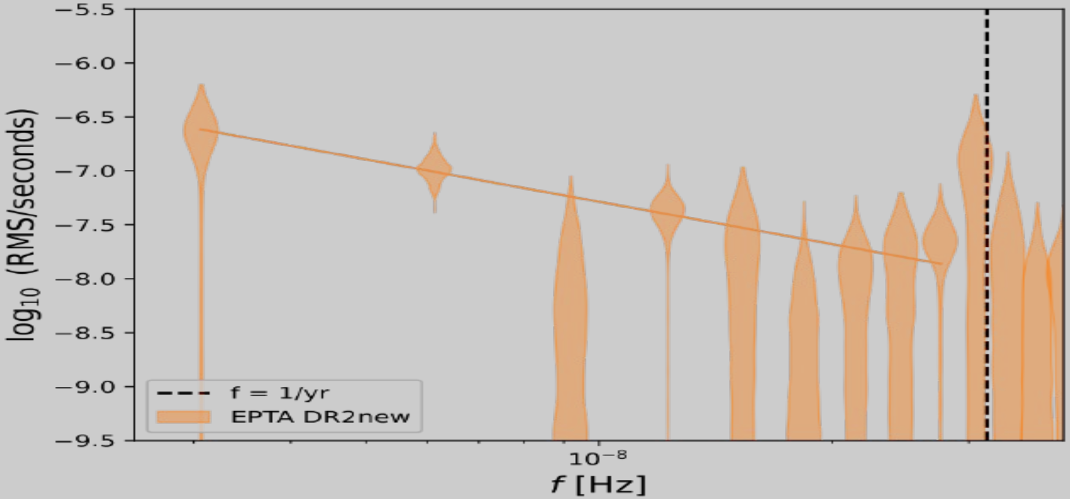
Do the PTAs agree?

The IPTA collaboration, 2023

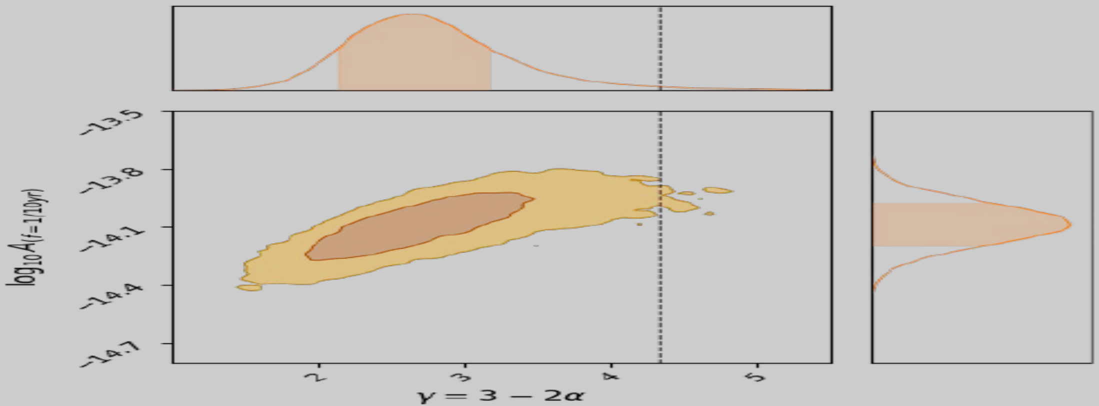


The astrophysical implications

- **The EPTA + InPTA result - a loud background**
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm

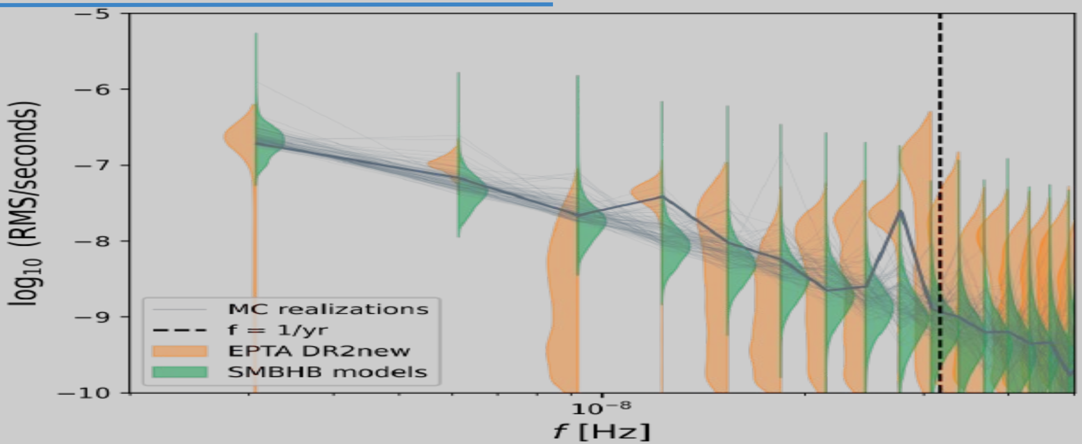


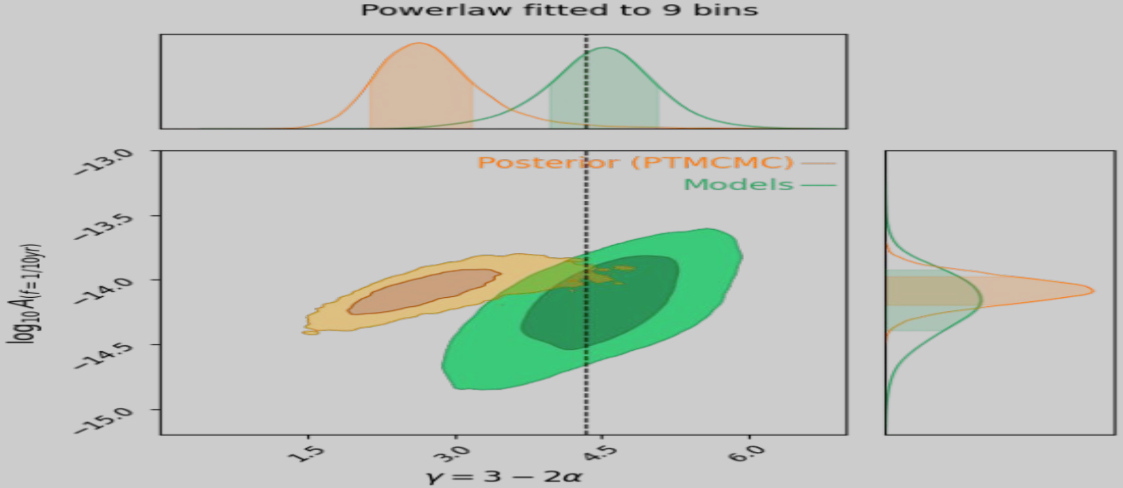
Powerlaw fitted to 9 bins



The astrophysical implications

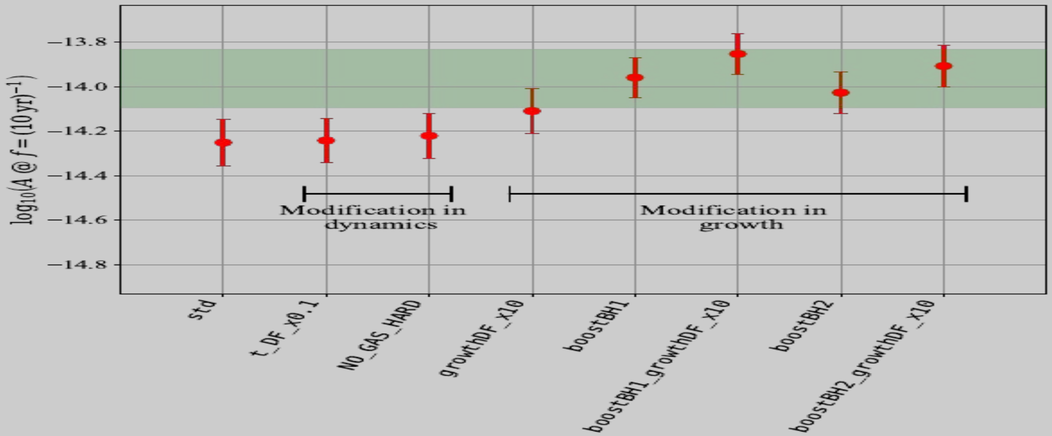
- The EPTA + InPTA result - a loud background
- **SMBHB generated backgrounds**
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm

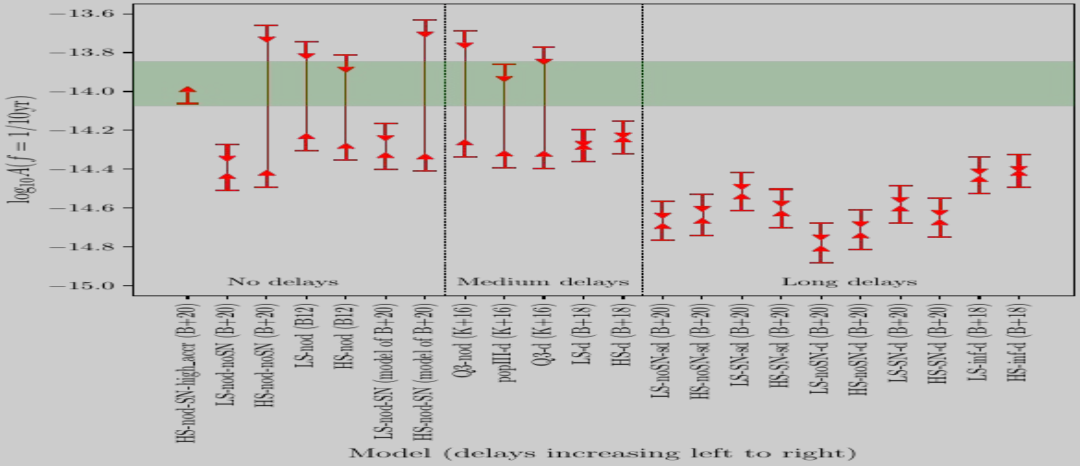




The astrophysical implications

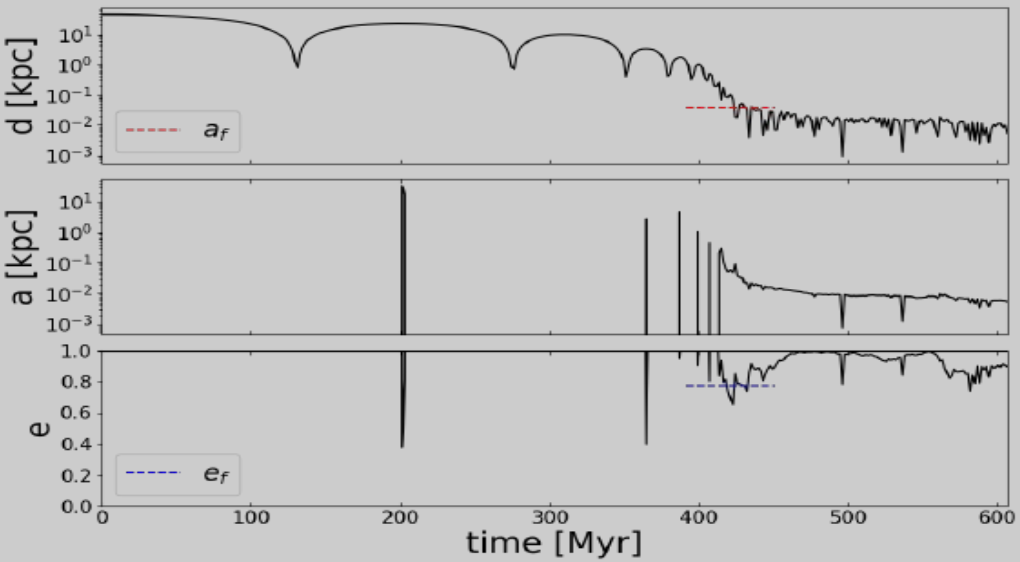
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- **Comparisons with Semi-Analytical Models**
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm





The astrophysical implications

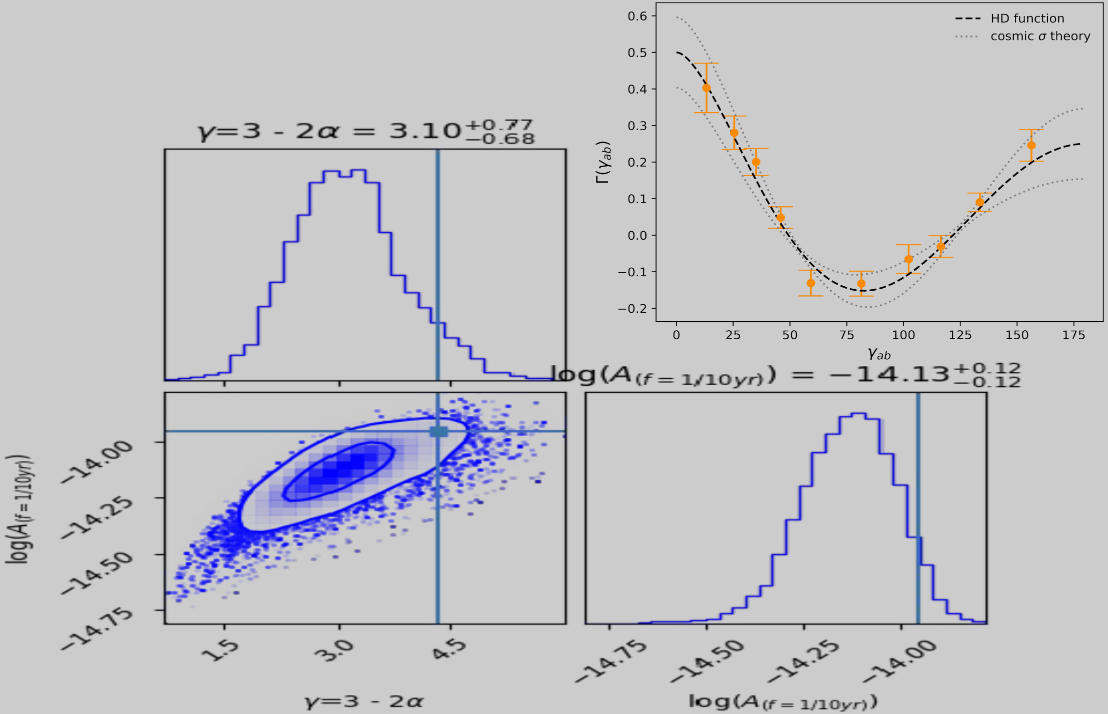
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- **Stellar hardening?**
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm



A GWB generated by stellar hardening-affected SMBHB does NOT explain the PTA result...

The astrophysical implications

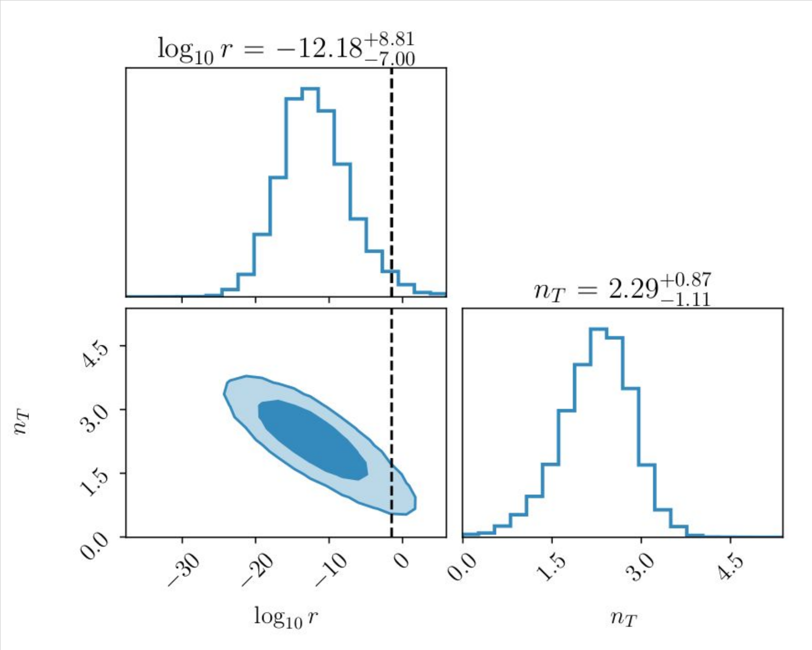
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- **Biased by cosmic variance?**
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm



... but a biased consideration of the uncertainties of the Hellings & Downs curve might.

The cosmological implications

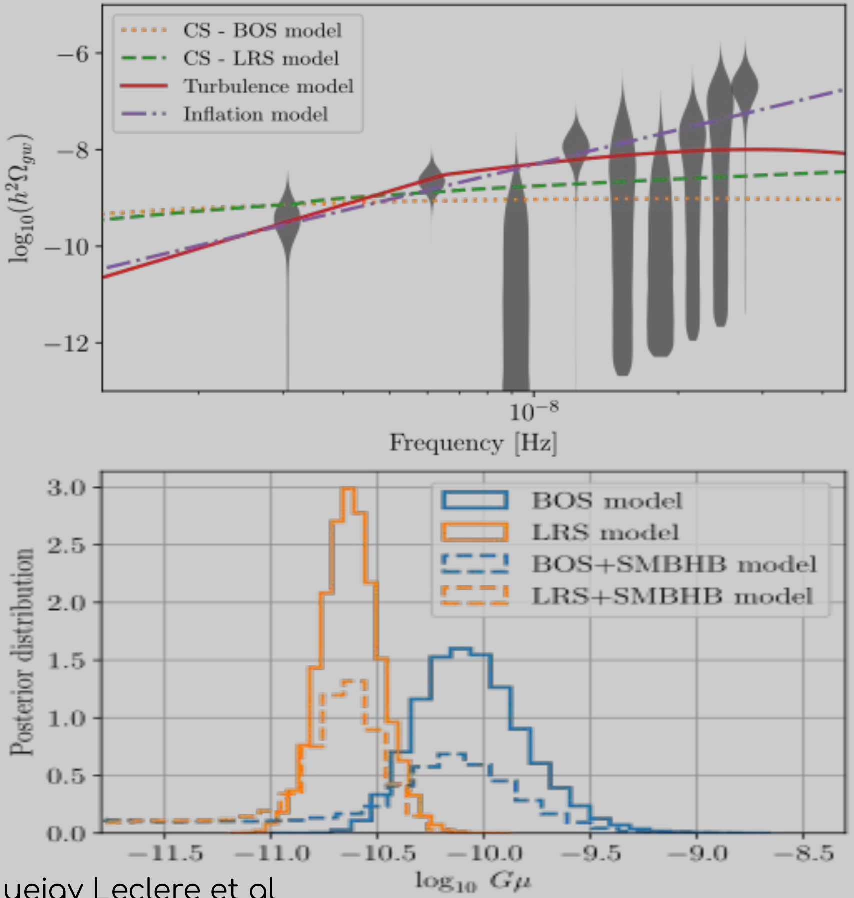
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- **Inflationary GWB**
- Cosmic Strings
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm



Quelquejay Leclere, Perrodin, Caprini et al

The cosmological implications

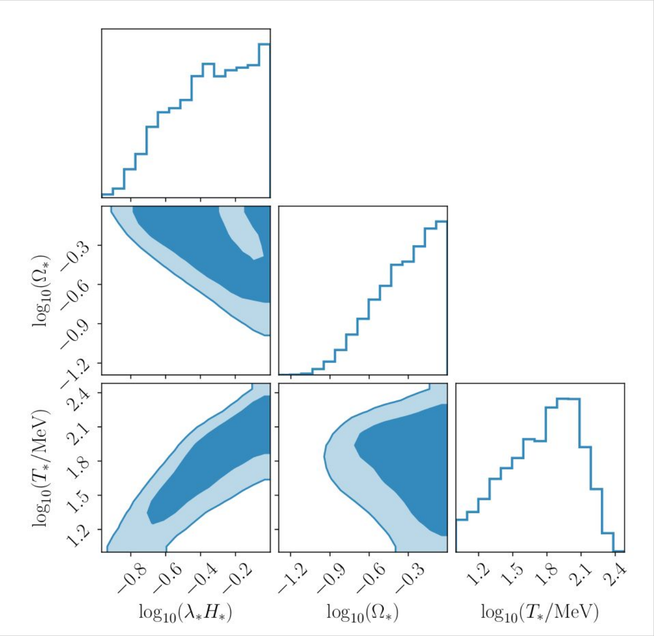
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- **Cosmic Strings**
- Cosmic turbulence
- Curvature perturbations
- Challenging the ultralight dark matter paradigm



arXiv: 2306.16227: Quelquejay Leclere et al

The cosmological implications

- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- **Cosmic turbulence**
- Curvature perturbations
- Challenging the ultralight dark matter paradigm

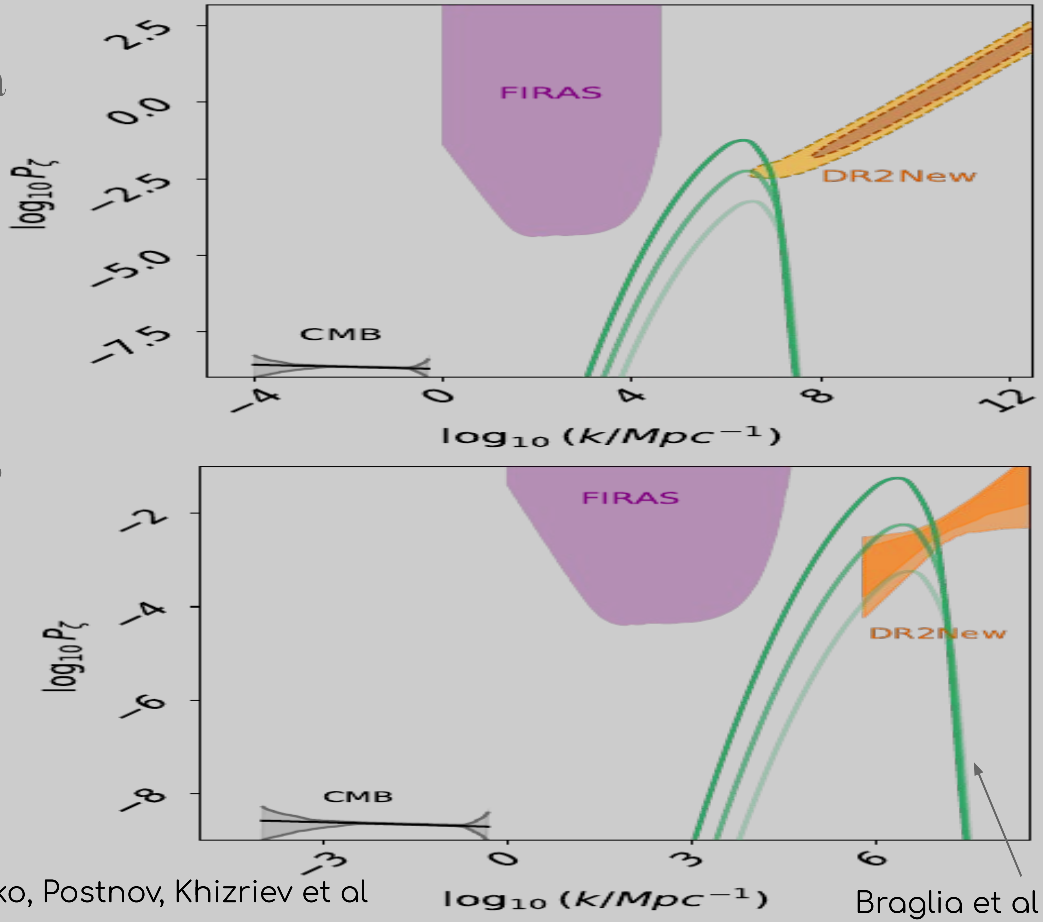


Quelquejay Leclere, Roper Pol et al

The cosmological implications

- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Inflationary GWB
- Cosmic Strings
- Cosmic turbulence
- **Curvature perturbations**
- Challenging the ultralight dark matter paradigm

2nd order scalar induced GWB



Porayko, Postnov, Khizriev et al

Braglia et al 2020

I. ULDM probes through timing data

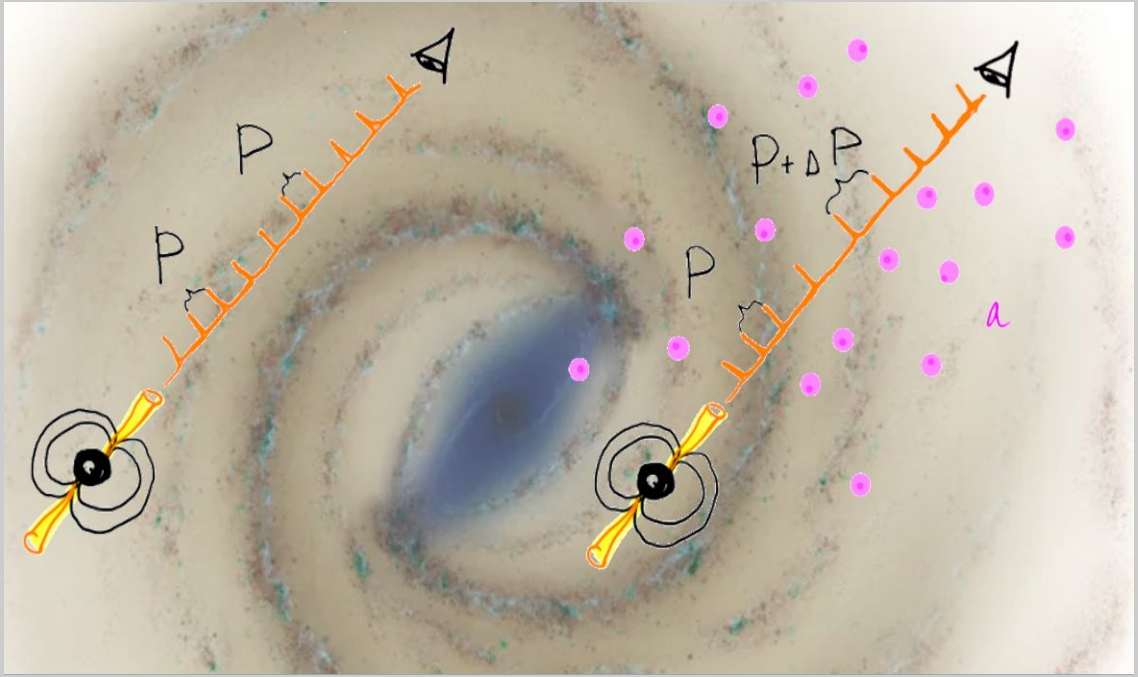
$$R(t) = r(x_E, t_E) - r(x_p, t_p), \quad r(x_E, t_E) = \frac{\Psi(x_E)}{2\pi f}\kappa(x_E)\sin(2\pi f t_E + \alpha(x_E))$$

Ultra-light axion dark matter:

1. **Very light axions** with masses ranging between 10^{-23} and 10^{-20} eV

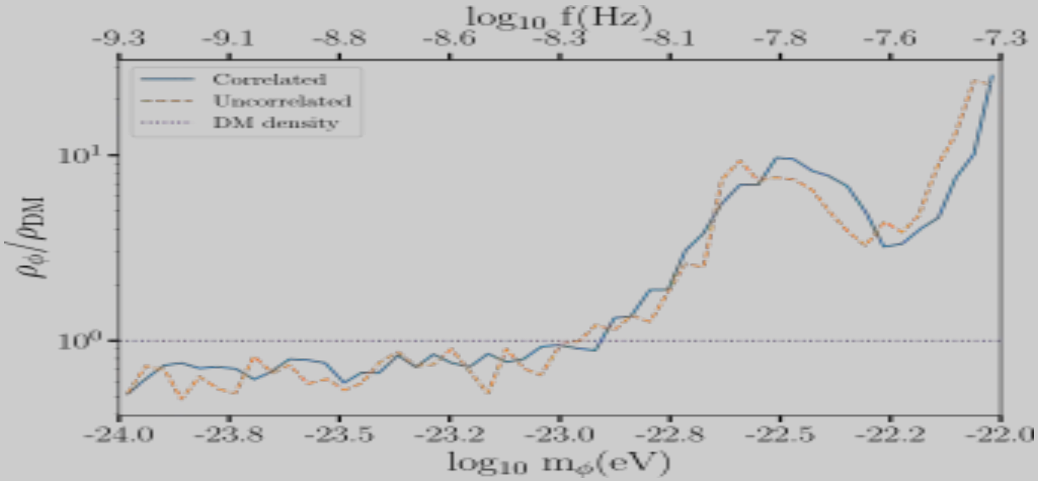
2. **Solve some of the issues of CDM** associated with overproduction of structures at galactic and sub-Galactic scales

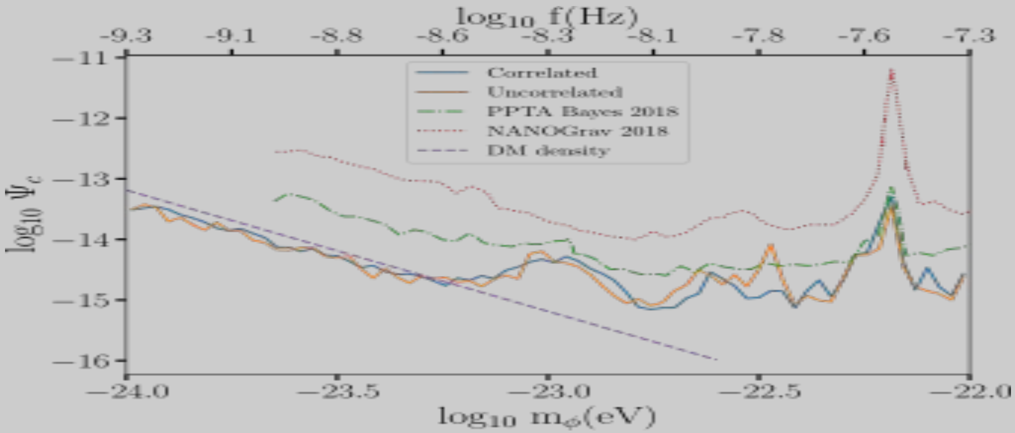
3. **Perturb the space-time**, so that the regular flow of pulses deviate from their regular flow



The astrophysical implications

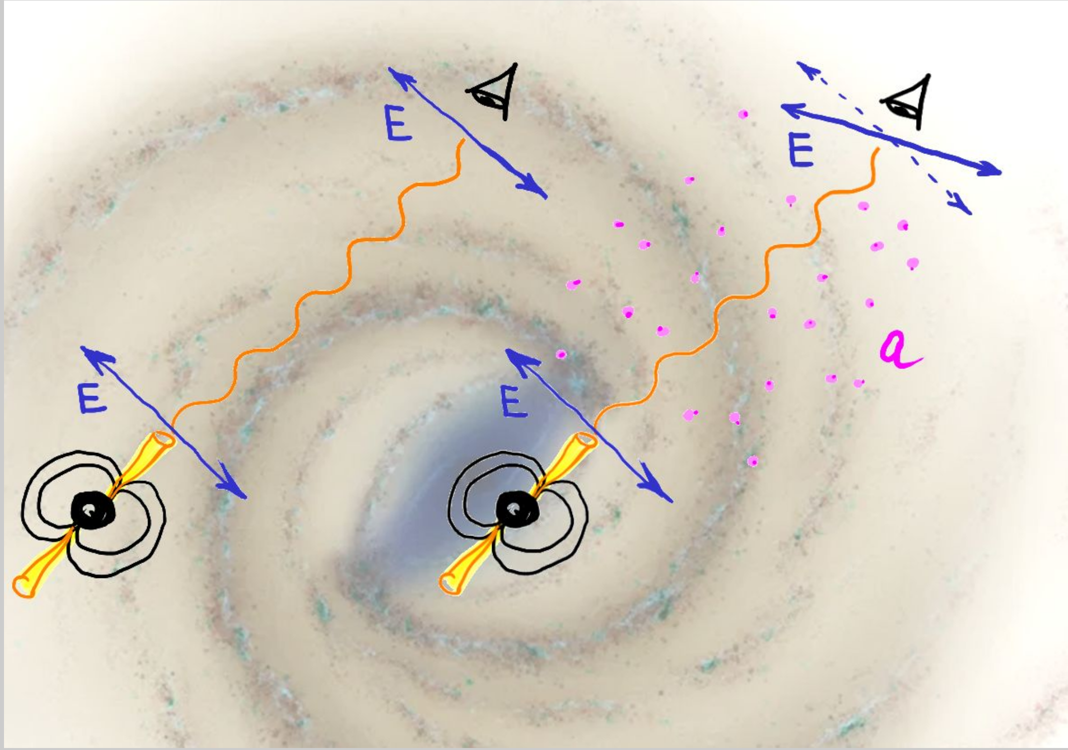
- The EPTA + InPTA result - a loud background
- SMBHB generated backgrounds
- Comparisons with Semi-Analytical Models
- Stellar hardening?
- Biased by cosmic variance?
- Cosmic Strings
- Curvature perturbations
- **Challenging the ultralight dark matter paradigm**





arXiv:2405.01633 : Smarra et al, PRD (2024)

II. ULDM with pulsar polarimetry



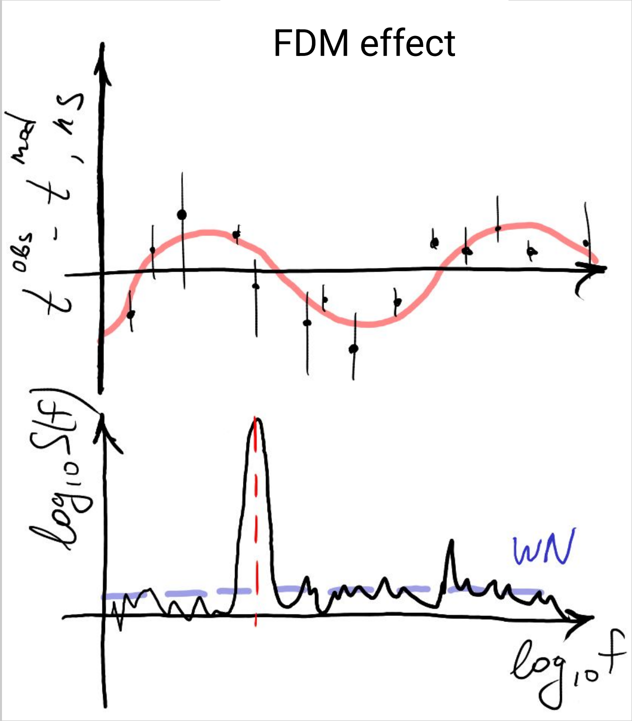
Credit:
NASA/JPL-Caltech

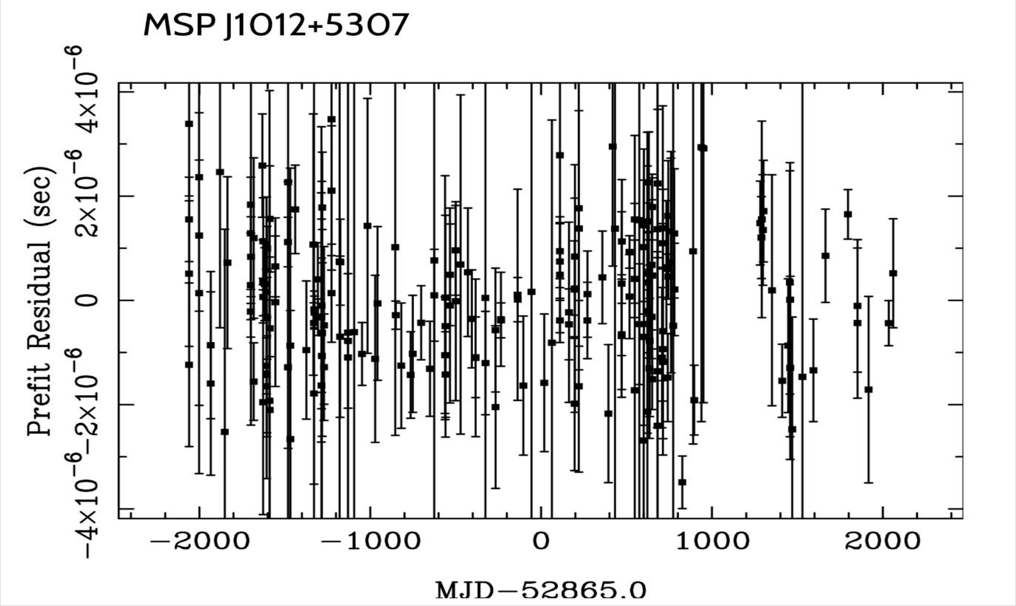
Ultra-light axions in the Milky Way:

1. **Very light axions** with masses ranging between 10^{-23} and 10^{-20} eV
2. When interacting weakly with photons, **rotate the plane** of linearly polarised pulsar light
3. Plane of linear polarisation **oscillates with periods of several years** due to varying pressure

I. ULDM probes through timing data

$$R(t) = r(x_E, t_E) - r(x_p, t_p), \quad r(x_E, t_E) = \frac{\Psi(x_E)}{2\pi f} \kappa(x_E) \sin(2\pi f t_E + \alpha(x_E))$$





II. ULDM with pulsar polarimetry

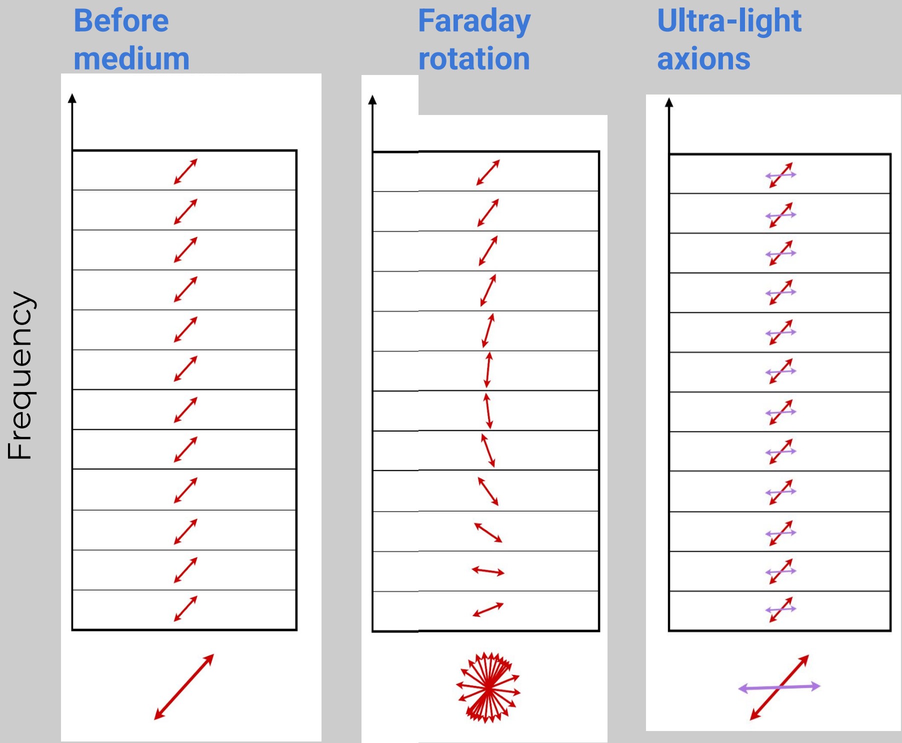
If we assume non-renormolizable interaction between fuzzy DM particles and photons:

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a\partial^\mu a - m_a^2 a^2\right)$$

$$(\Box + m_a^2)a + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} = 0$$

Polarization properties of light are altered

$$\omega_\pm = k\sqrt{1 \pm g_{a\gamma}\frac{\partial_0 a}{k}} \simeq k \pm \frac{1}{2}g_{a\gamma}\partial_0 a$$

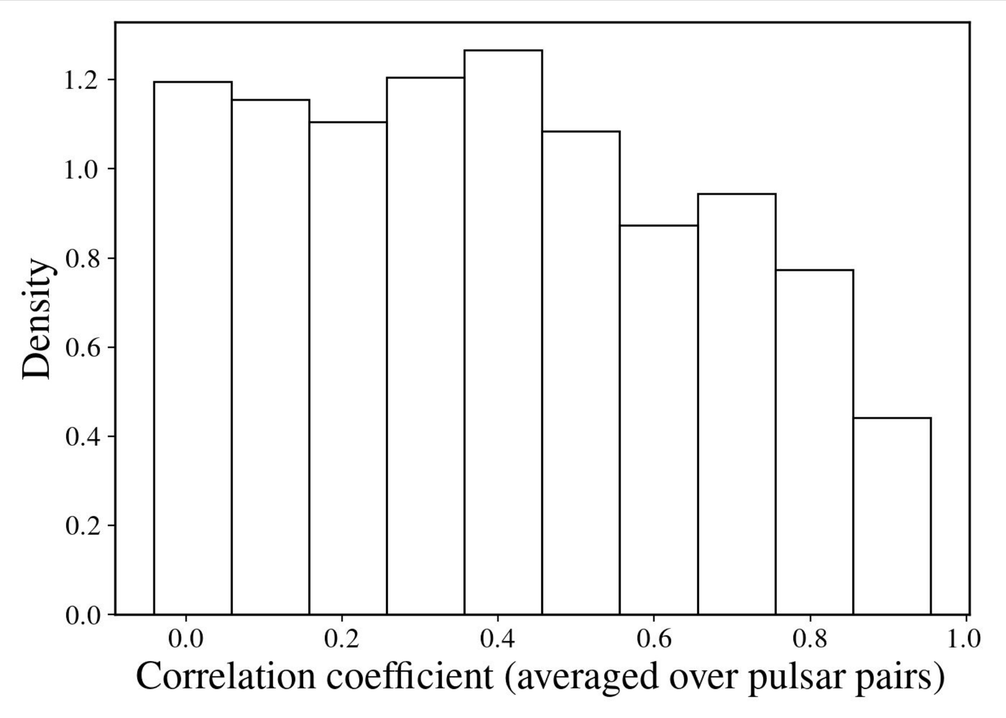


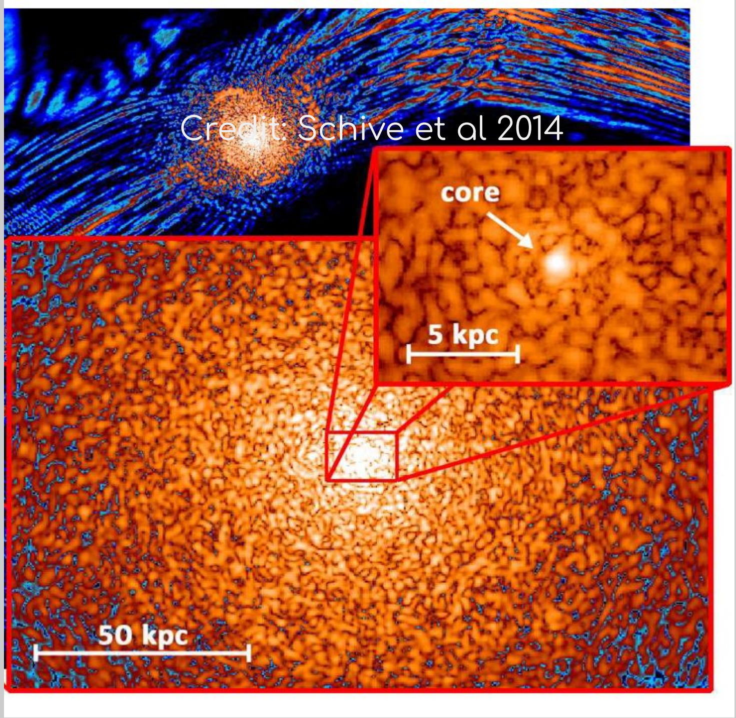
$$\Delta(\mathrm{PA}(t)) = \frac{g_{a\gamma}}{\sqrt{2}m}[\mathrm{p}(t_E, x_E) - \mathrm{p}(t_p, x_p)], \quad p(t_E, x_E) = \sqrt{\rho_{\mathrm{DM}}}\kappa_E \cos(mt + \phi(x_E))$$

See: Ivanov et al 2018, Castillo et al 2022

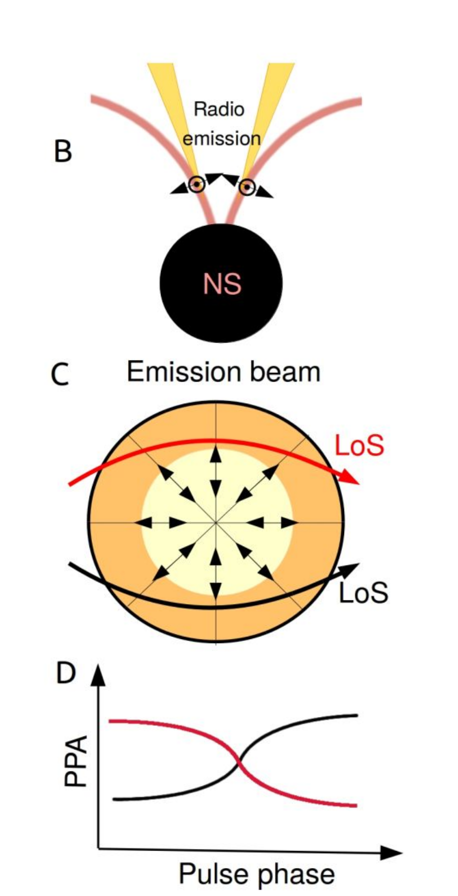
I. ULDM probes through timing data

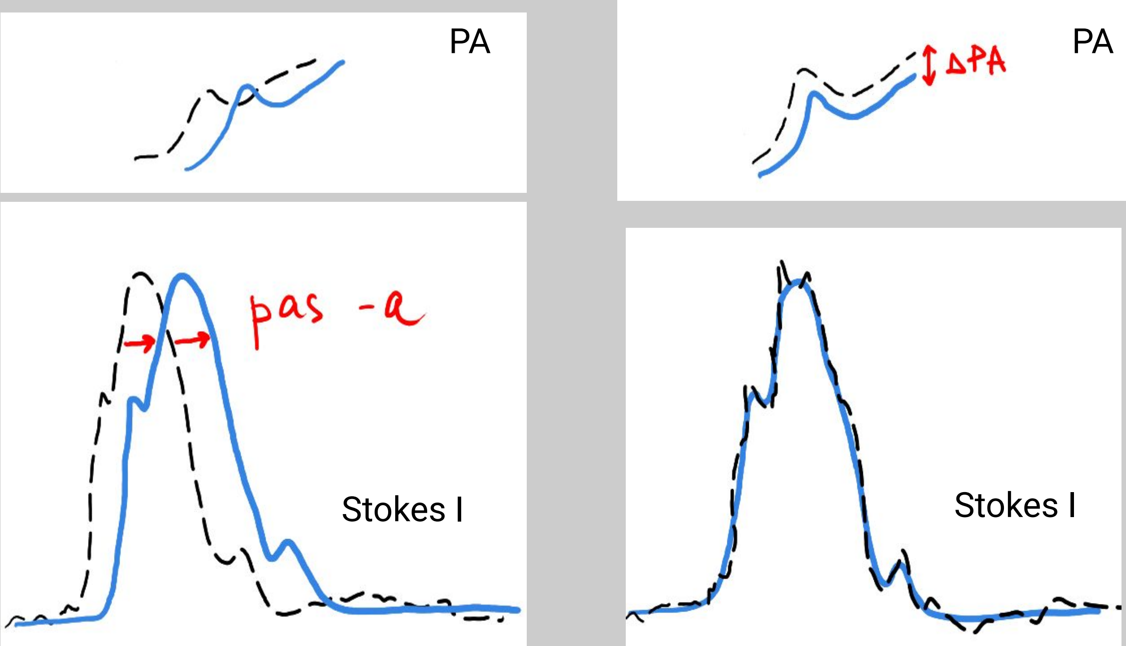
$$R(t) = r(x_E, t_E) - r(x_p, t_p), \quad r(x_E, t_E) = \frac{\Psi(x_E)}{2\pi f}\kappa(x_E)\sin(2\pi f t_E + \alpha(x_E))$$





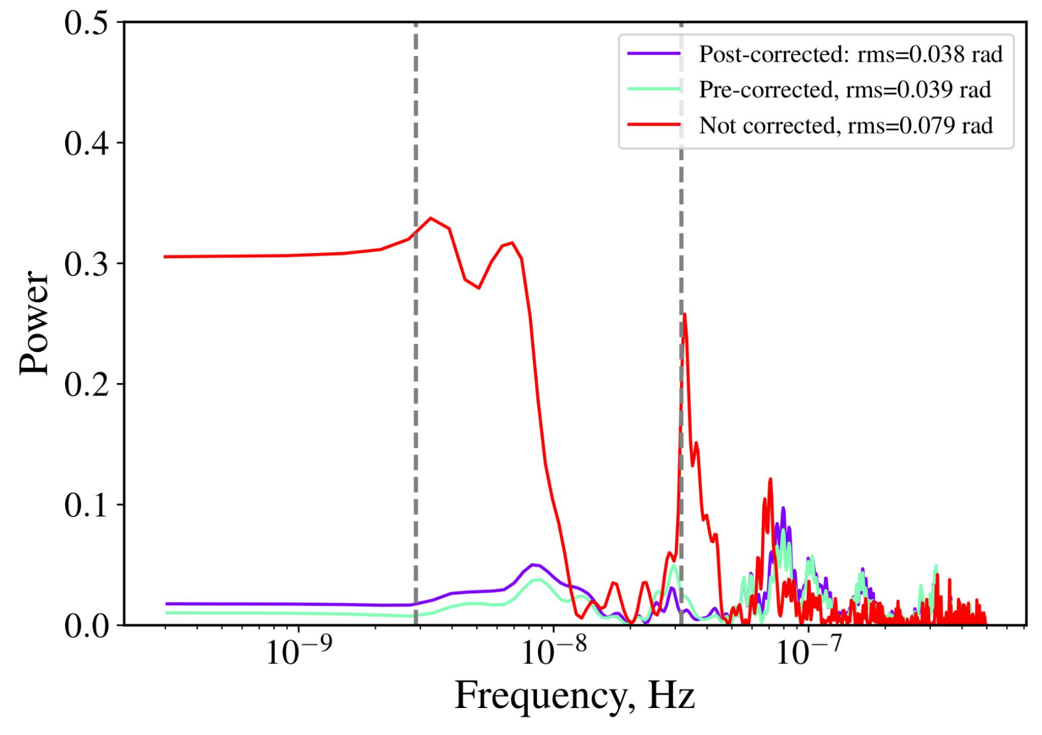
II. ULDM with pulsar polarimetry: data processing





$$\Delta\mathrm{PA} = \frac{1}{2}\arcsin\{(U^{\mathrm{obs}}Q^{\mathrm{tmpl}} - Q^{\mathrm{obs}}U^{\mathrm{tmpl}}\}$$

II. ULDM with pulsar polarimetry: systematics



RMextract from Maaijke Mevius: https://github.com/lofar-astron/RMextract /tree/master/RMextract

i) Ionospheric TEC maps (uqrg)

\+

ii) Geomagnetic field model (WMM)

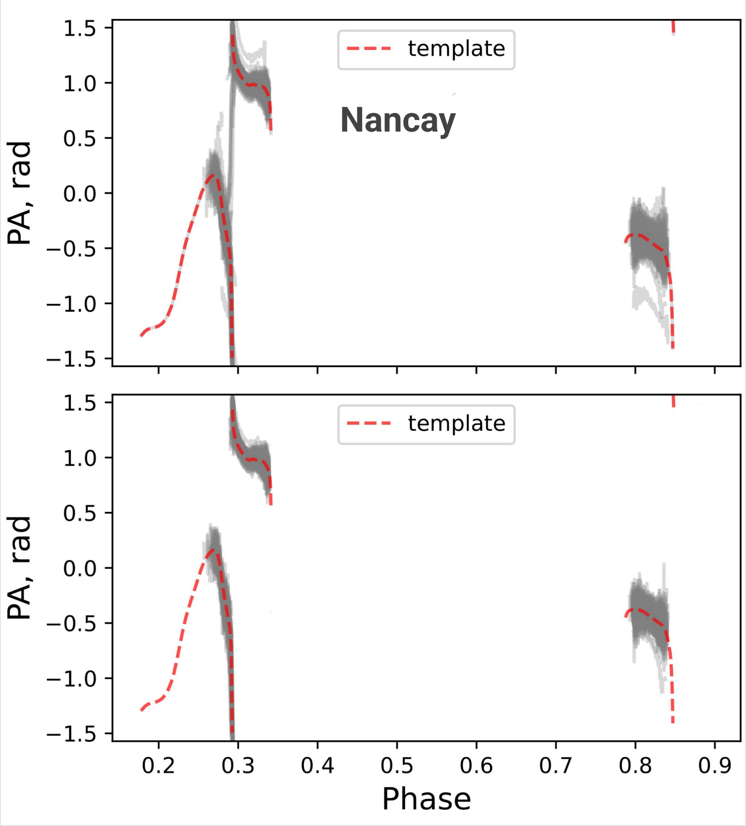
\+

iii)Thin screen approximation

$$\mathrm{RM}_{\mathrm{iono}} = \int n_e \mathbf{B}_{\mathrm{LOS}} \mathbf{dr}$$

$$\mathrm{RM}_{\mathrm{iono}} \sim \mathrm{STEC} \times \mathbf{B}_{\mathrm{IPP}}$$

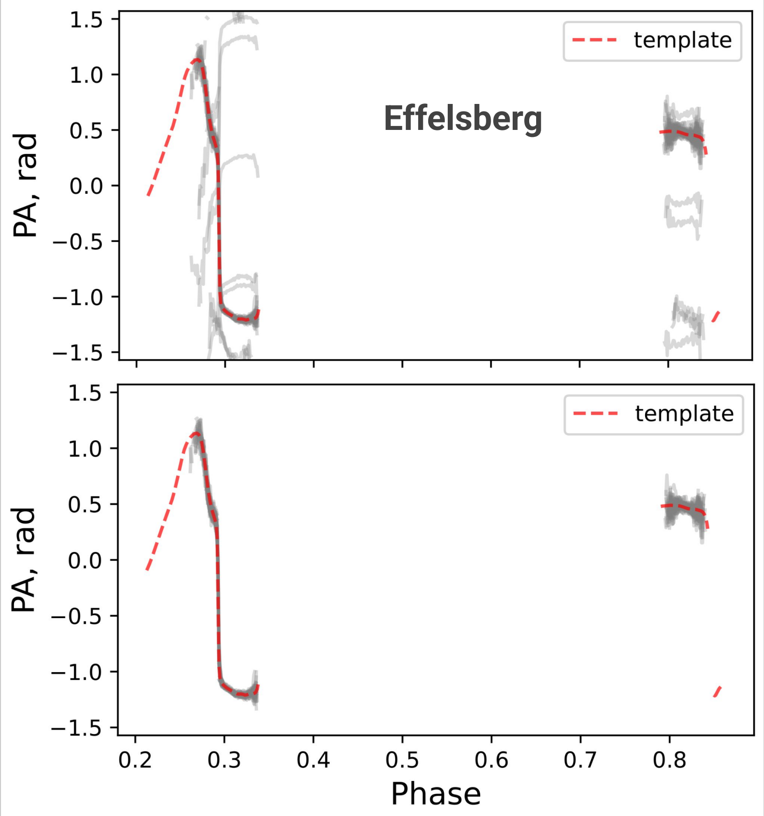
II. ULDM with pulsar polarimetry: challenges



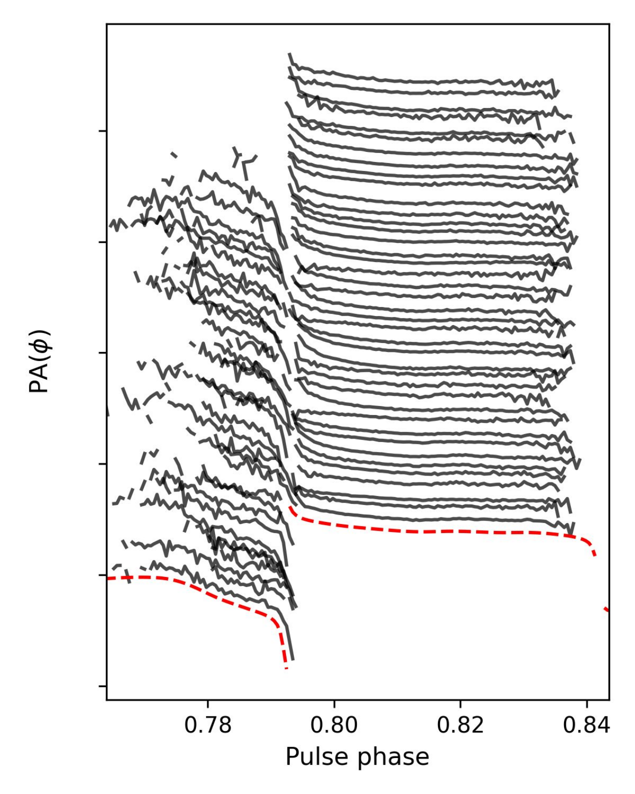
B1937+21

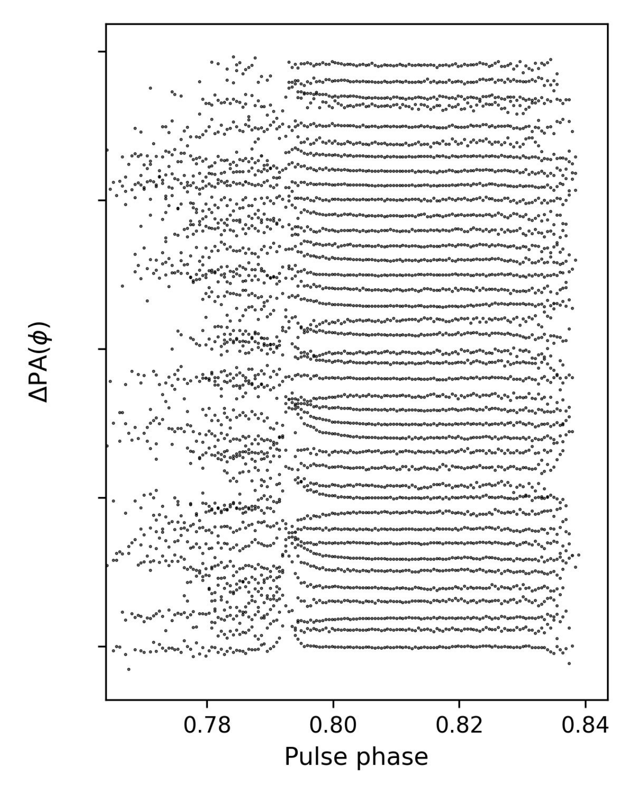
All PA profiles

Manually selected PA profiles

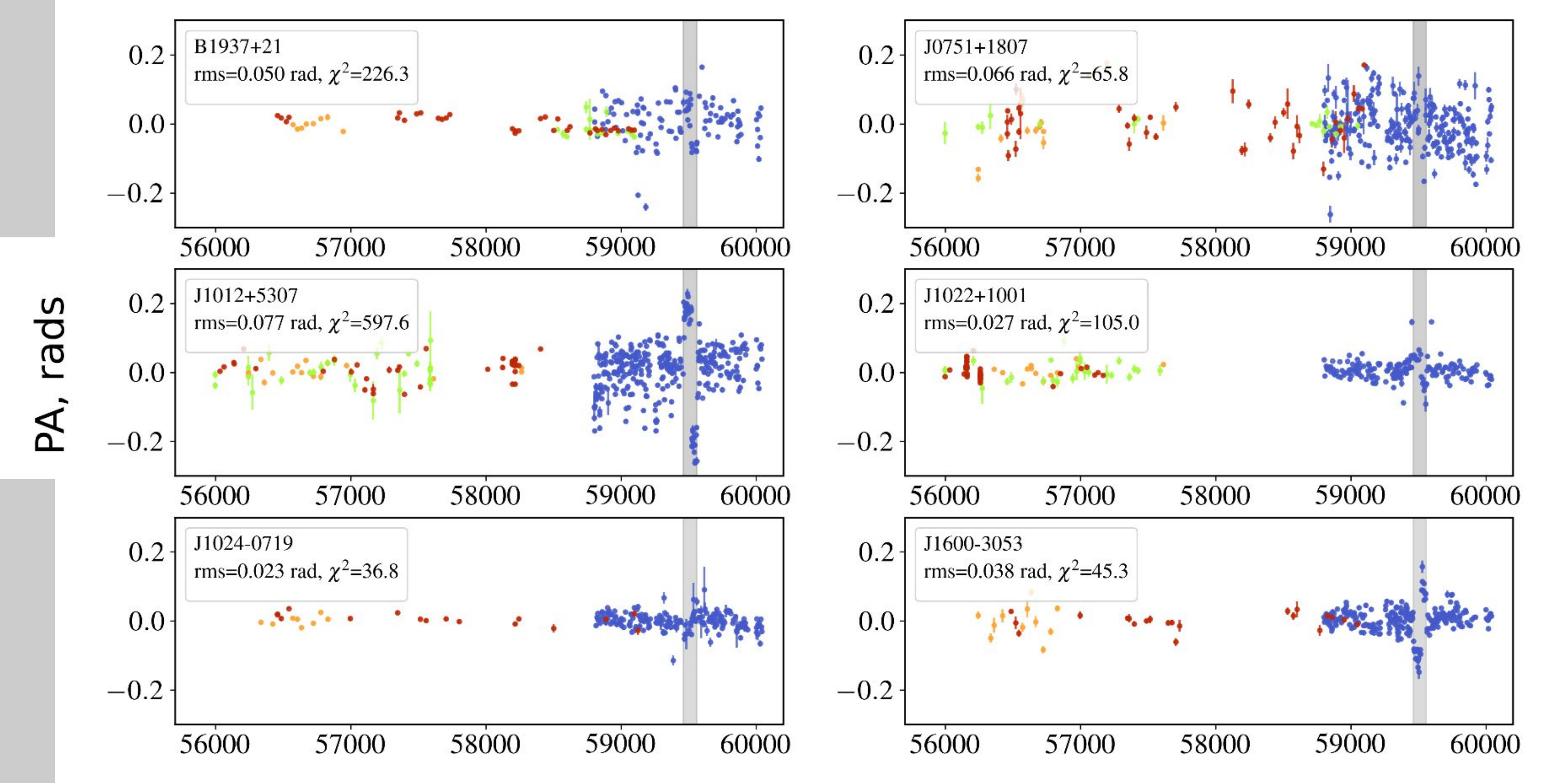


II. ULDM with pulsar polarimetry: challenges

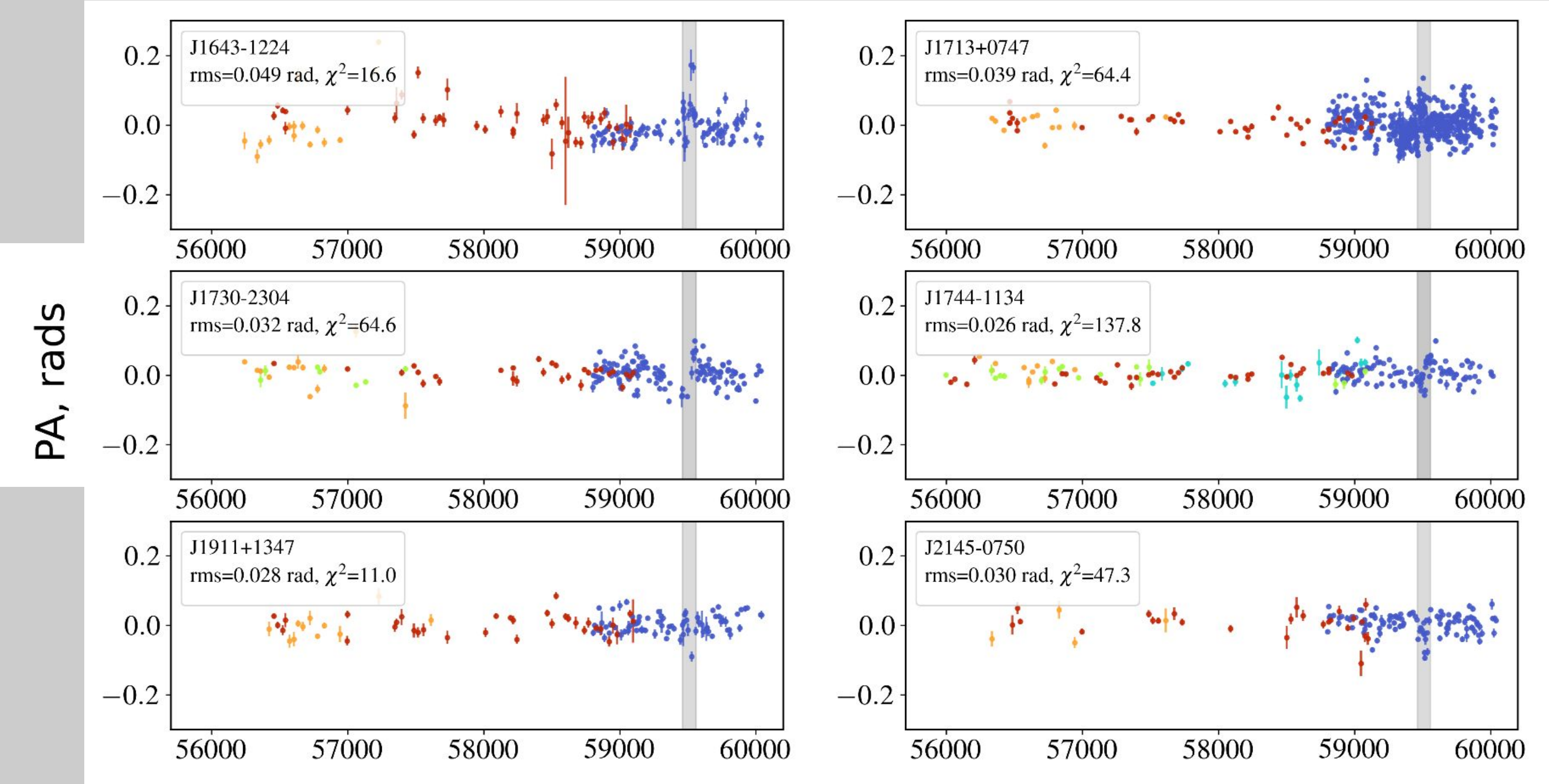




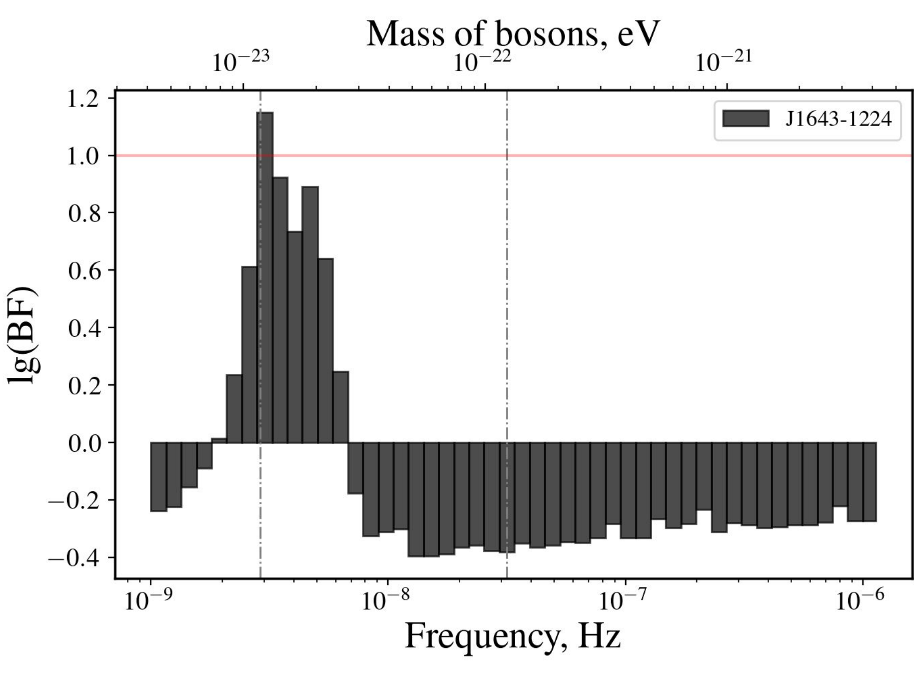
II. ULDM with pulsar polarimetry: dataset

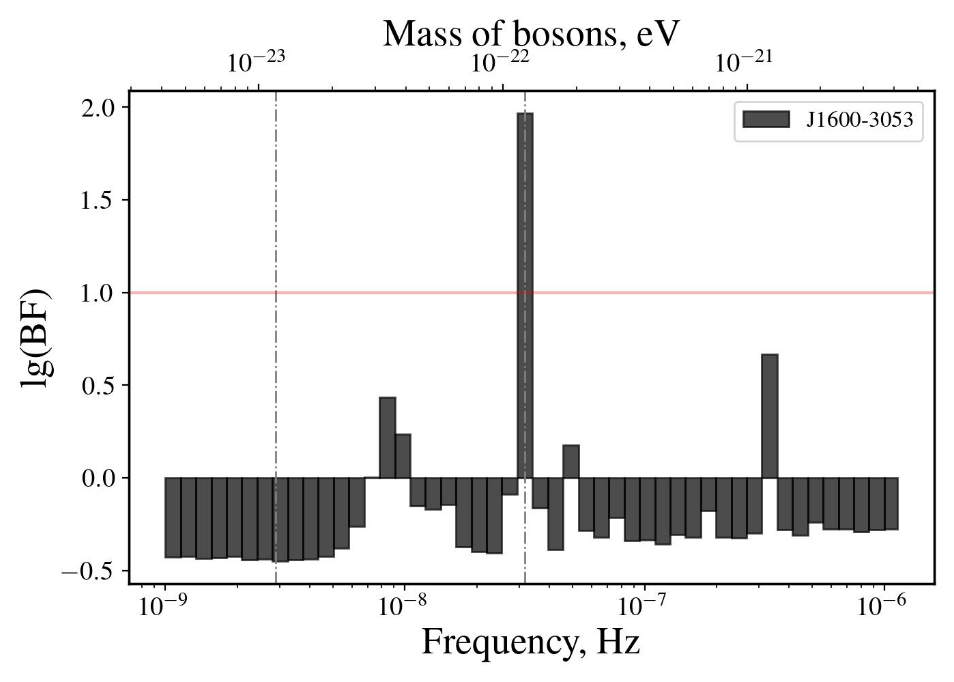


II. ULDM with pulsar polarimetry: dataset

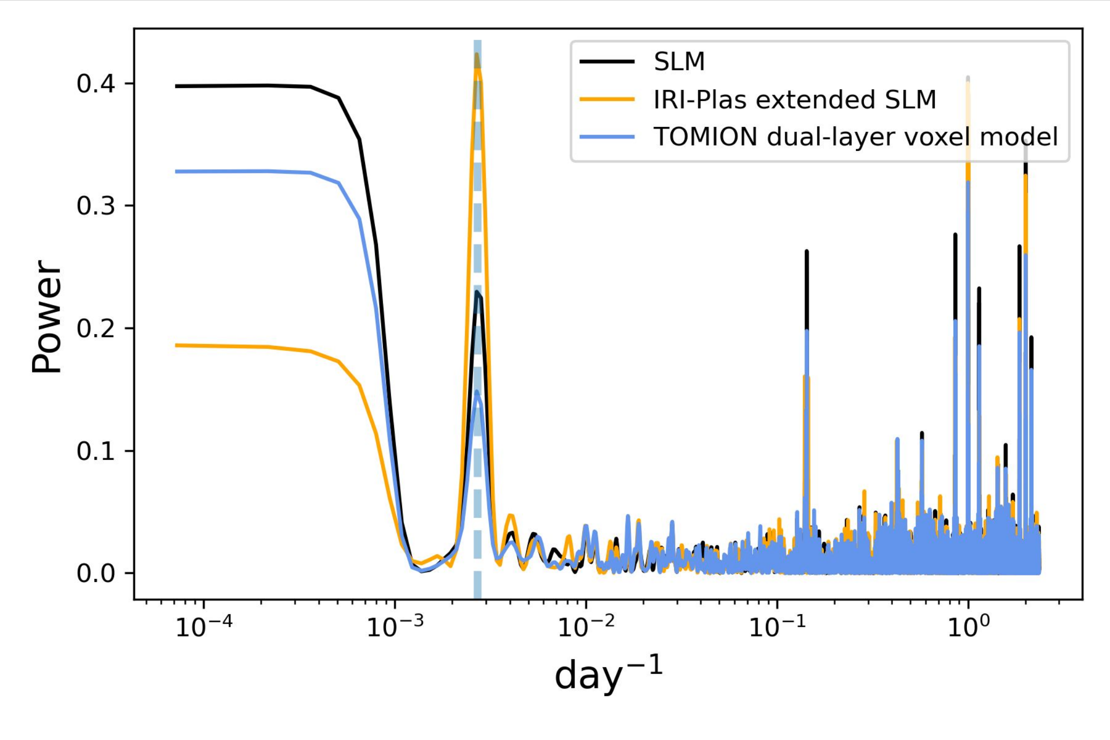


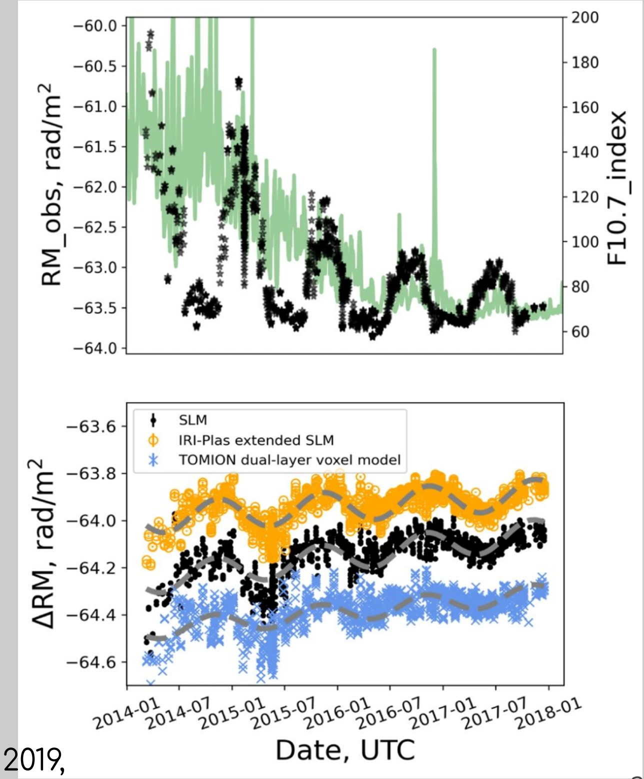
II. ULDM with pulsar polarimetry: back to the ionosphere





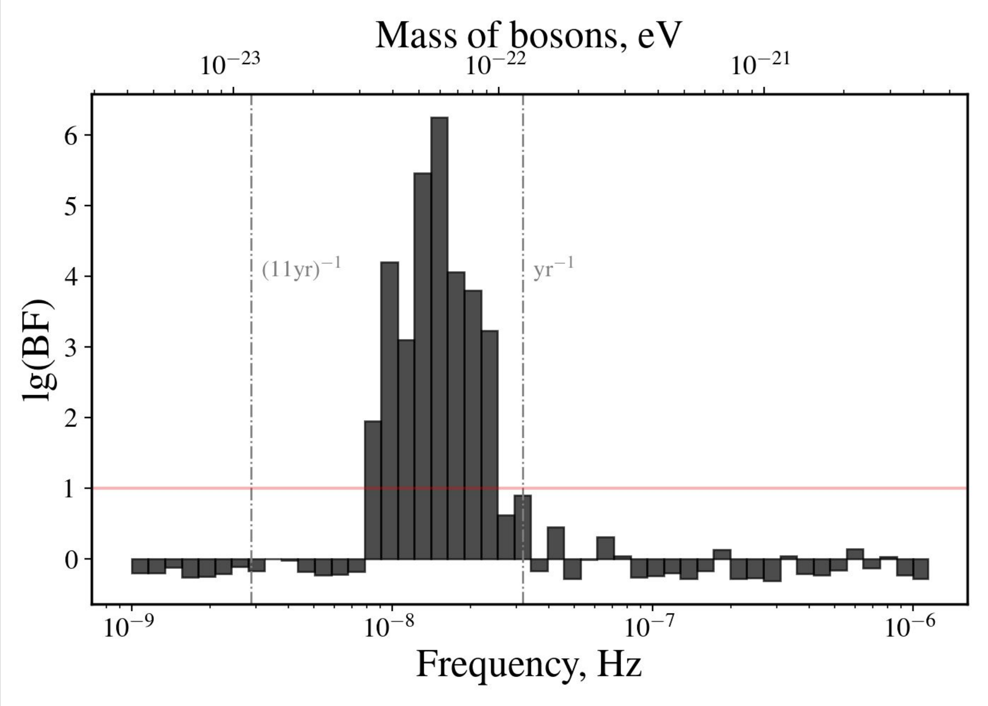
II. ULDM with pulsar polarimetry: back to the ionosphere

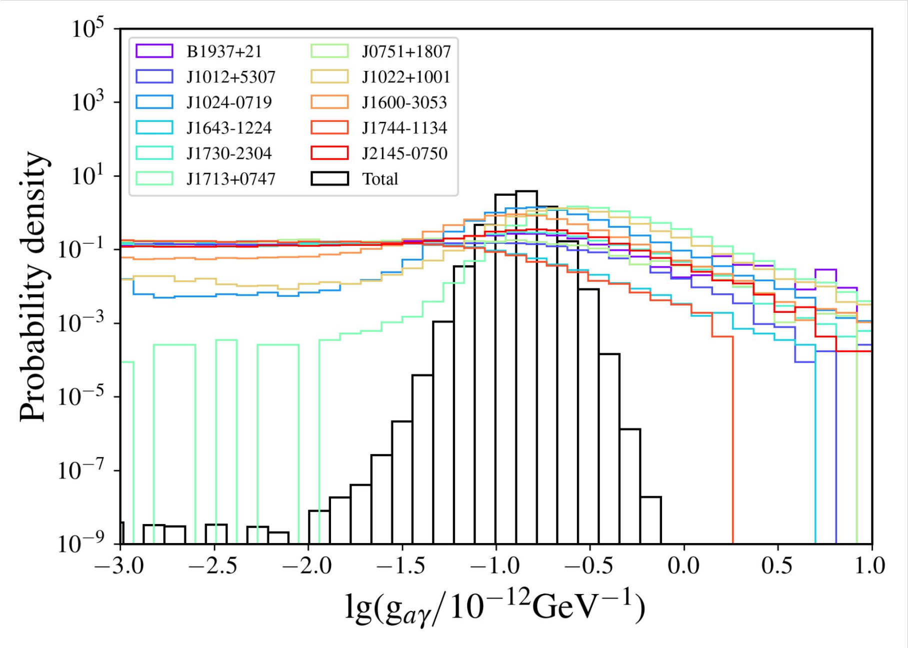




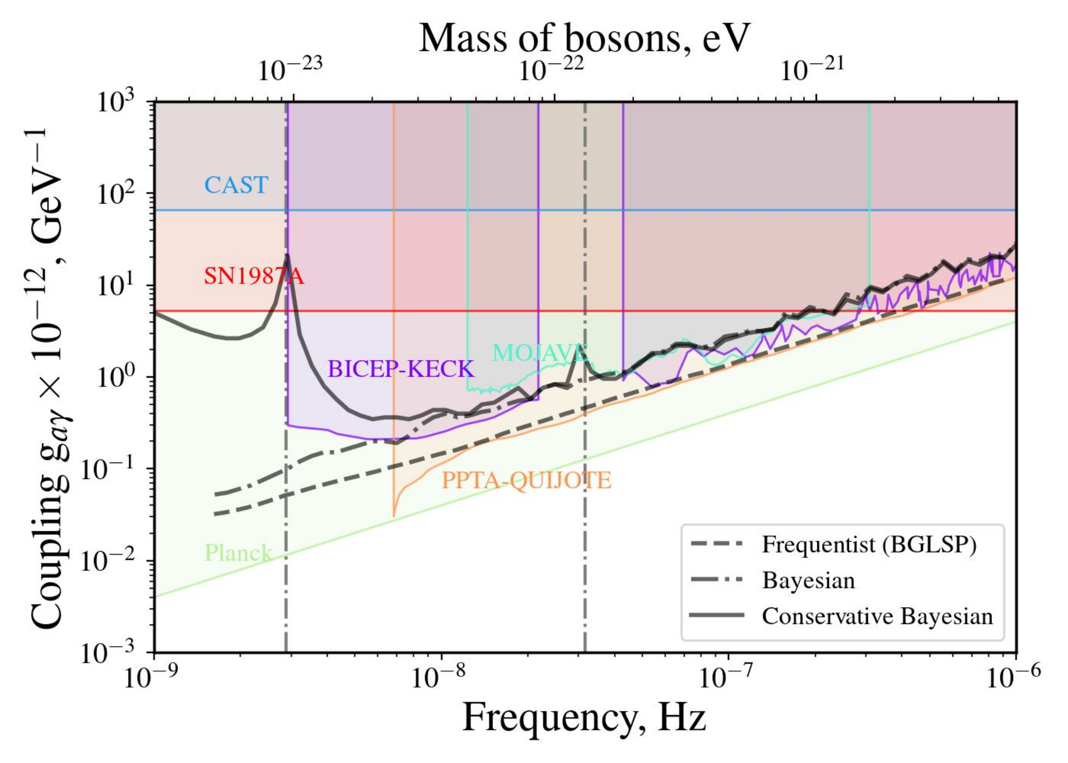
Porayko et al 2019,
Porayko et al 2023

Factorised upper limits and BFs





III. ULDM with pulsar polarimetry: first results



Ultra-light axions in the Milky Way:

3. The **effect is achromatic**, so can be distinguished from chromatic Faraday rotation

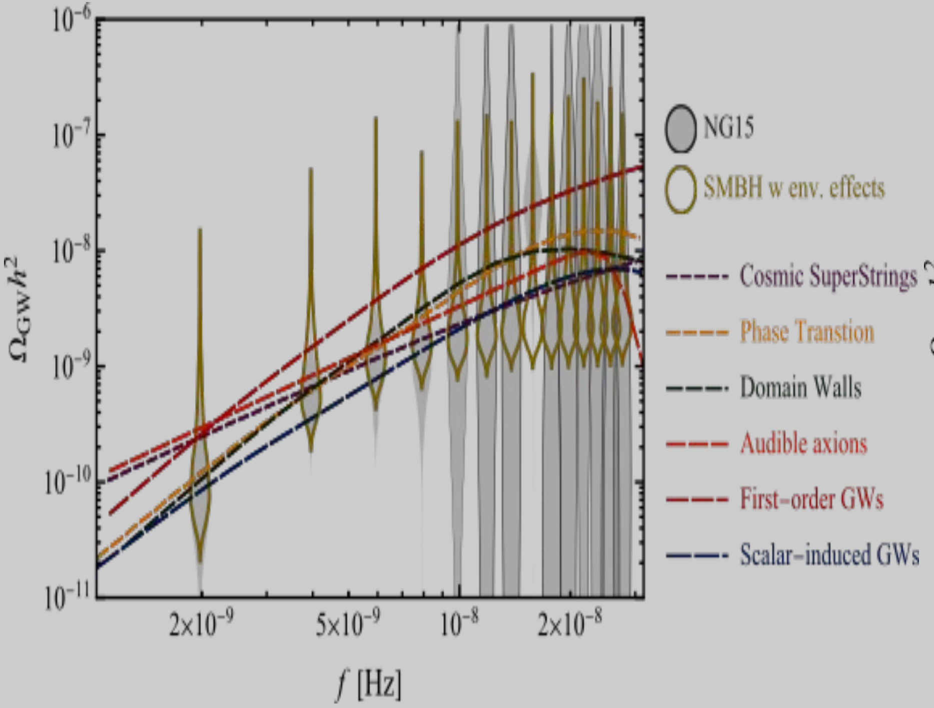
4. **Terrestrial ionosphere** is the main source of noise, when searching for ultra-light axions in pulsar polarimetry

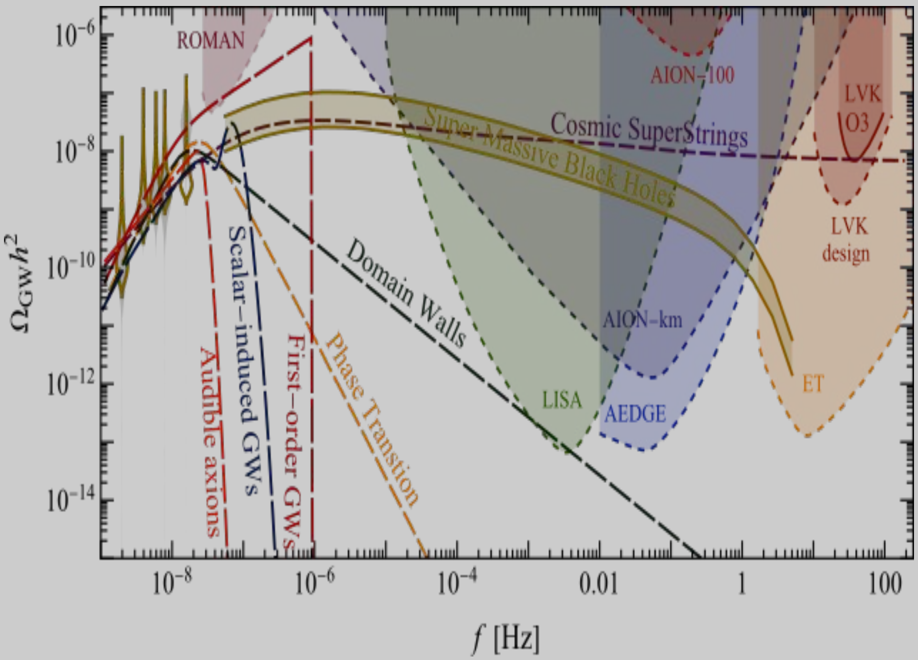
5. We plan to incorporate **low-frequency data** from LOFAR(2.0) to independently mitigate ionospheric Faraday rotation

Porayko et al. (submitted) : arxiv2412.02232

The true picture & a wider landscape

So we are tantalisingly close to *detecting* the GWB, but what is the true nature of this signal?





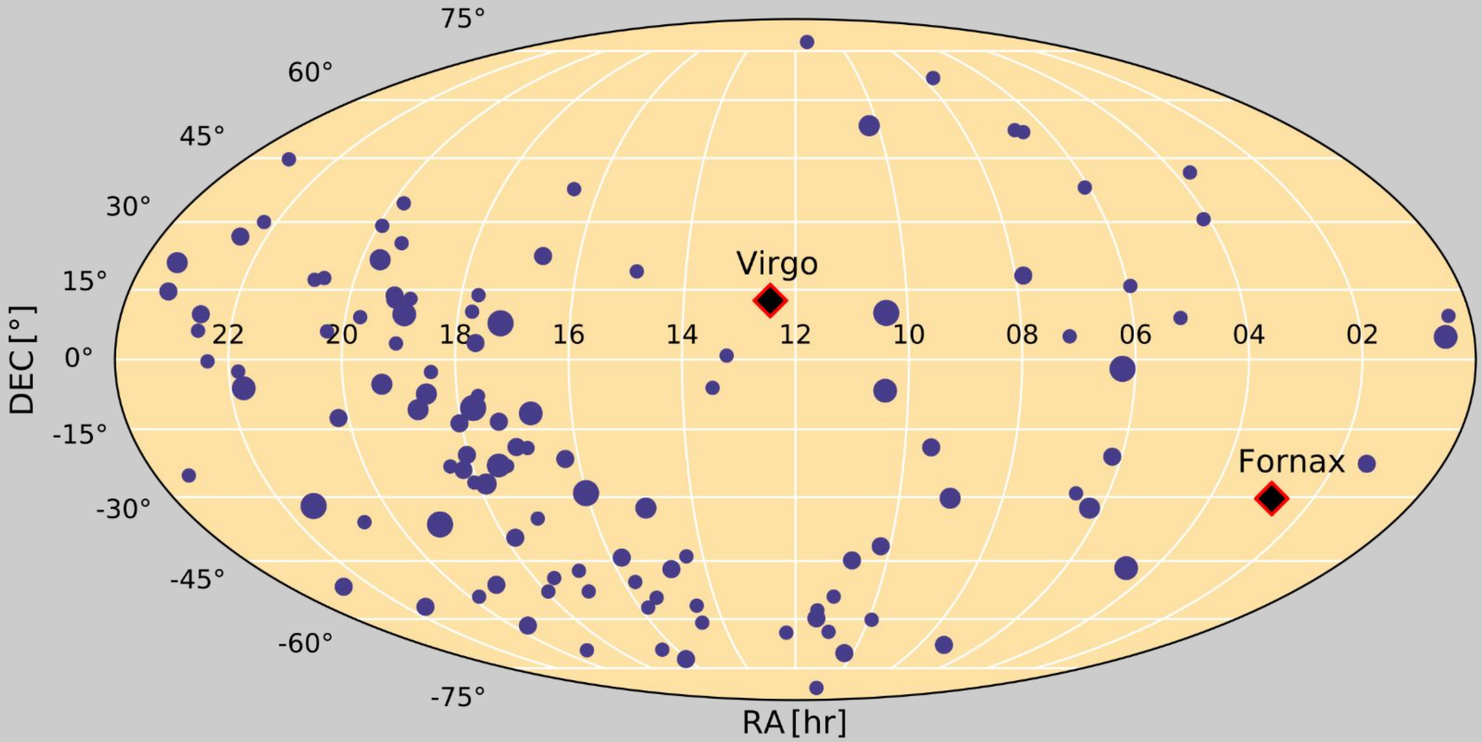
Ellis et al (2023; 2308.08546)

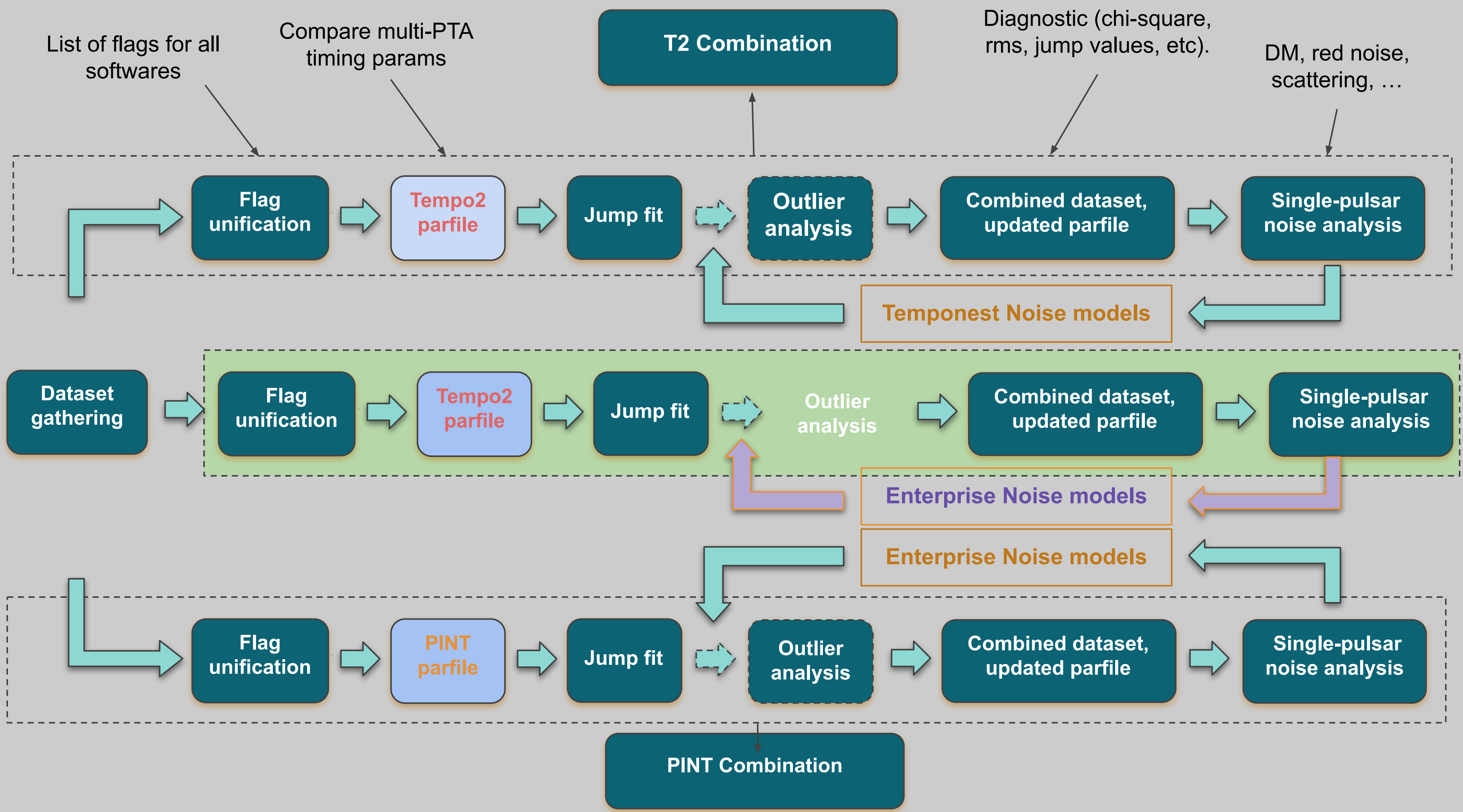
IPTA DR3 dimensions

PTA	Dataset	PSRs	Tspan (years)	$f_{GW,low}$ (nHz)	f_{radio} (MHz)
EPTA	DR2 / DR3	25 / +35	24.5	1.29	283 - 5107
	LOFAR + NENUFAR	17	9.6	-	30 - 190
NANOGrav	15-yr	68	15.9	1.99	302 - 3988
	CHIME	11	2.5		400 - 800
PPTA	DR3	24	18.1	1.75	704 - 4032
InPTA	DR1	14	3.5	9.05	300 - 1460
MeerKAT	DR2	88	4.5	7.04	856 - 1712
IPTA	**DR3**	**121**	**~25**/40	**1.29**/0.79	**30 - 5107**

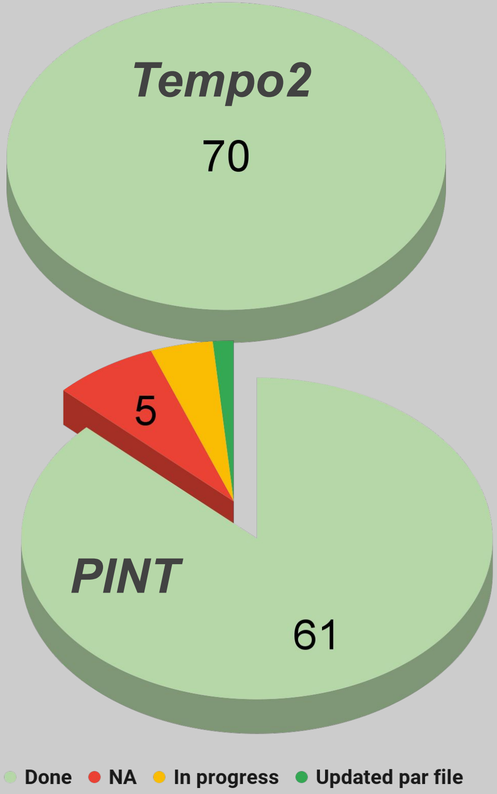
IPTA DR3 dimensions

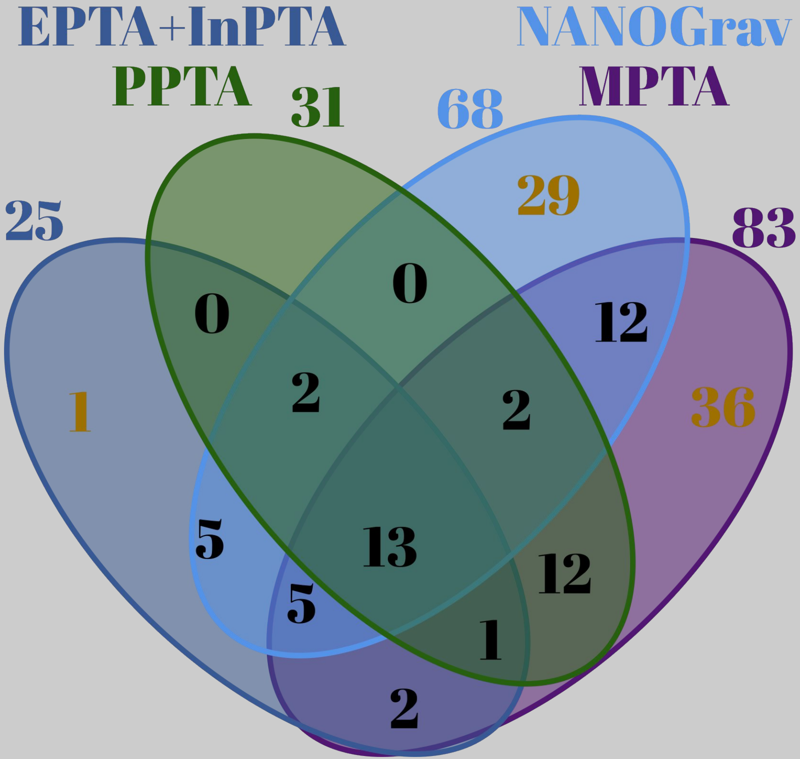
- In total **121** pulsars in full DR3;
  - The biggest / most sensitive PTA dataset ever made !!

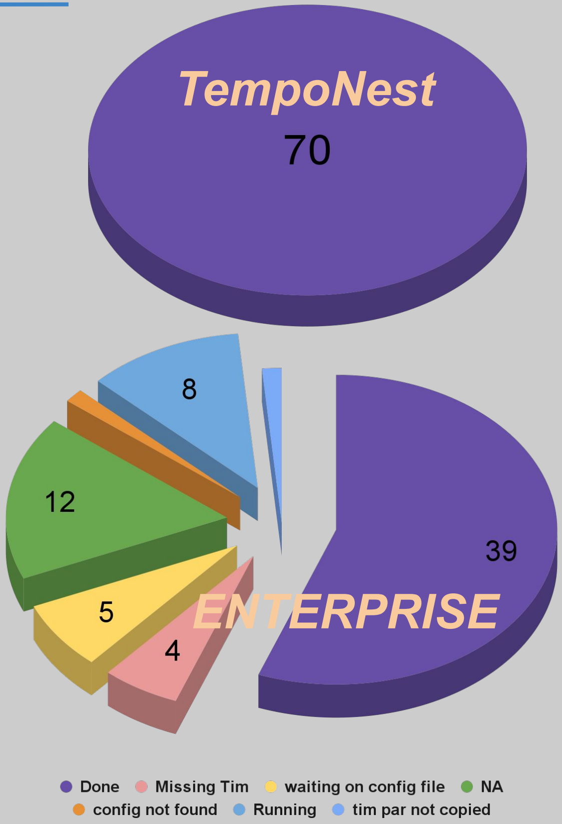



List of flags for all softwares
Compare multi-PTA timing params
T2 Combination
Diagnostic (chi-square, rms, jump values, etc).
DM, red noise, scattering, …
Flag unification
Tempo2 parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
Temponest Noise models
Dataset gathering
Flag unification
Tempo2 parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
Enterprise Noise models
Enterprise Noise models
Flag unification
PINT parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
PINT Combination

Current Status



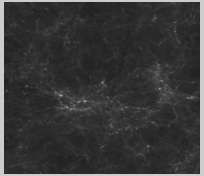




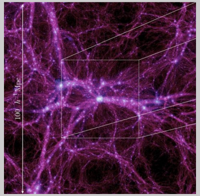
GALAXY FORMATION MODEL – MULTIMESSENGER

L - GALAXIES

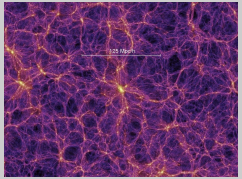
DARK MATTER MERGER TREES



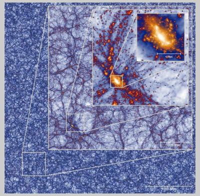
L_{box} = 30 Mpc / h
$M_{halo} \sim 10^6\ M_{sun}$



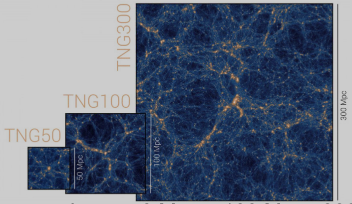
L_{box} = 100 Mpc / h
$M_{halo} \sim 10^8\ M_{sun}$



L_{box} = 500 Mpc / h
$M_{halo} \sim 10^{10}\ M_{sun}$



L_{box} = 3 Gpc / h
$M_{halo} \sim 10^{11}\ M_{sun}$



L_{box} = 50 Mpc , 100 Mpc , 300 Mpc
$M_{halo} \sim 10^7\ M_{sun}$, $10^8\ M_{sun}$, $10^{10}\ M_{sun}$

BARYONIC PHYSICS

Galaxy physics + Massive black hole physics

Galaxy merger — BH merger

Distance: ~ kpc — Galaxy nucleus → ~ pc — ~ 10^{-2} pc

PAIRING

$$t_{\rm dyn}^{\rm BH} = 19\, f(\varepsilon)\left(\frac{r_0}{4\,{\rm kpc}}\right)^2\left(\frac{\sigma}{200{\rm km/s}}\right)\left(\frac{10^8\,{\rm M}_\odot}{{\rm M}_{\rm BH}}\right)\frac{1}{\Lambda}\,[{\rm Gyr}]$$

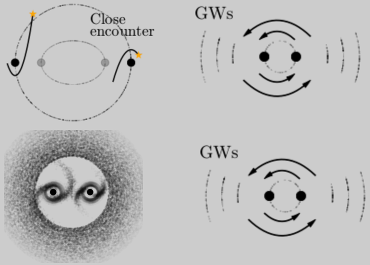
TRACK SELF-CONSISTENTLY VIA NUMERICAL INTEGRATION THE

- BINARY SEPARATION (a_{BH})
- BINARY ECCENTRICITY (e_{BH})

HARDENING

Gas poor

Gass rich



Triplets Bonetti et al. 2018

GRAVITATIONAL WAVE INSPIRAL

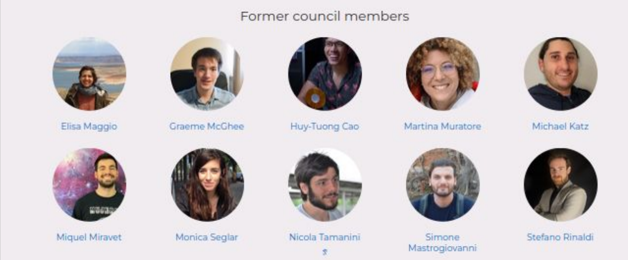
$$\frac{da_{\rm BH}}{dt} = \left(\frac{da_{\rm BH}}{dt}\right)_{\rm Hard} + \left(\frac{da_{\rm BH}}{dt}\right)_{\rm GW} = -\frac{GH\rho_{\rm inf}}{\sigma_{\rm inf}}a_{\rm BH}^2 - \frac{64G^3({\rm M}_{{\rm BH}_1}+{\rm M}_{{\rm BH}_2})^3F(e)}{5c^5(1+q)^2a_{\rm BH}^3}$$

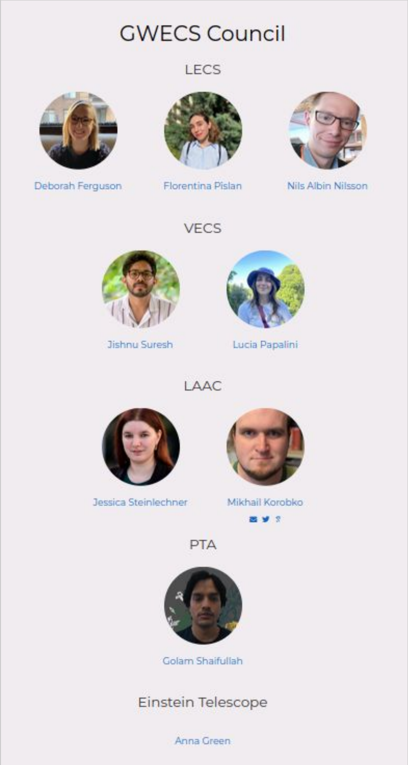
$$\frac{de}{dt} = a_{\rm BH}\frac{G\rho_{\rm inf}HK}{\sigma_{\rm inf}} - \frac{304}{15}\frac{G^3q(M_{{\rm BH}_1}+M_{{\rm BH}_2})^3}{c^5(1+q)^2a_{\rm BH}^4(1-e^2)^{5/2}}\left(e+\frac{121}{304}e^3\right)$$

$$\frac{da_{\rm BH}}{dt} = -\frac{2\dot{\rm M}}{\mu}\sqrt{\frac{\delta}{1-e^2}}\,a_{BH}$$

Gas accretion $\dot{M}_{{\rm BH}_1} = \dot{M}_{{\rm BH}_2}(0.1+0.9q)$

Gravitational-Wave Early Career Scientists





GWECS

https://gwecs.org/