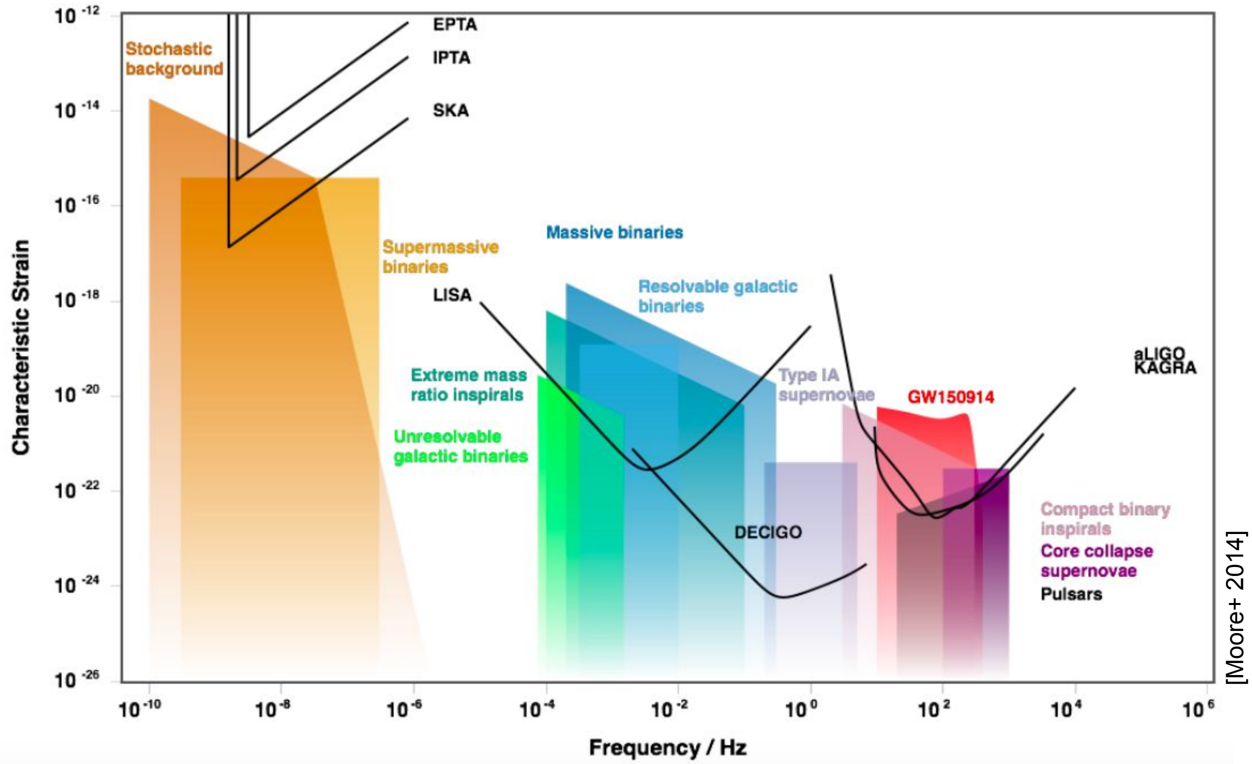
Results from the search for very-low frequency gravitational waves with the EPTA DR2 and InPTA DR1

Aurélien Chalumeau (UNIMIB)
aurelien.chalumeau@unimib.it

4th Italian Workshop on the SKA project
Catania - 30 Nov 2023

Pulsar Timing Arrays (PTAs)

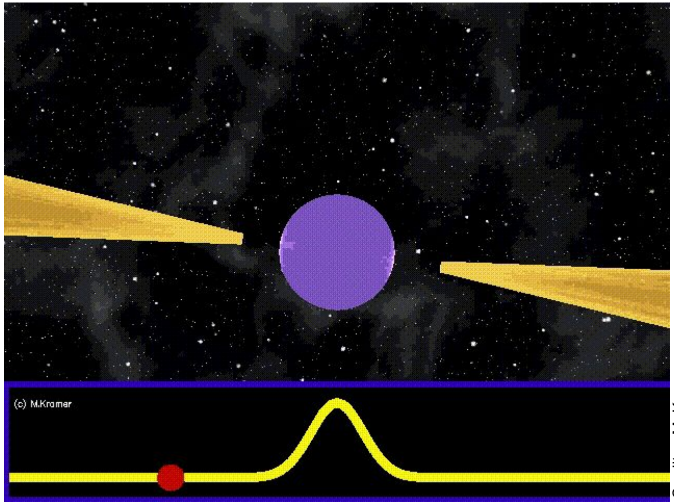
A **very-low frequency** gravitational wave detector



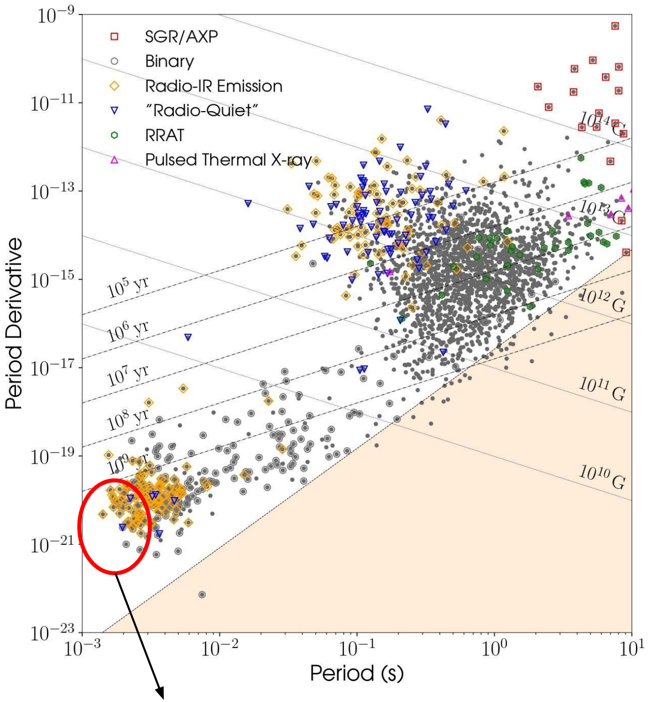
[Moore+ 2014]

Pulsars

Neutron stars with strong magnetic fields that **spin rapidly** and **emit radio beams** along their magnetic axes



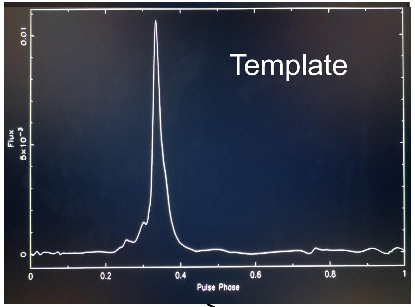
Credits : M. Kramer

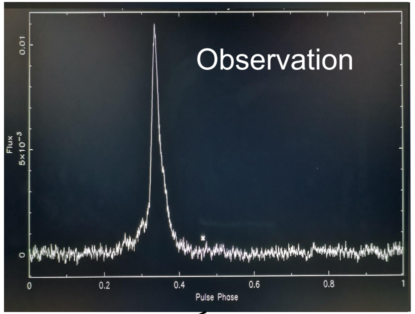


Millisecond pulsars → Highly stable clocks !

Pulsar timing

Observation





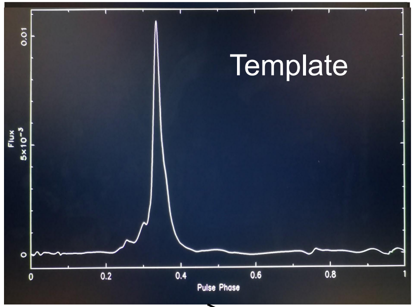
Template matching

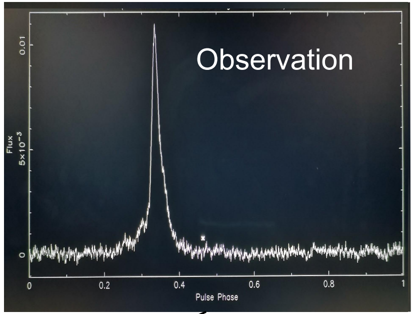
Time of Arrival
(ToA)

σ_{ToA} ~ 10 ns - 1 μs

Pulsar timing

Observation





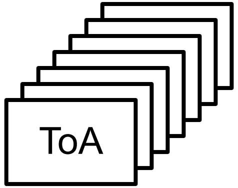
Template matching

Time of Arrival
(ToA)

σ_{ToA} ~ 10 ns - 1 μs

Data set (for 1 pulsar)

Data set

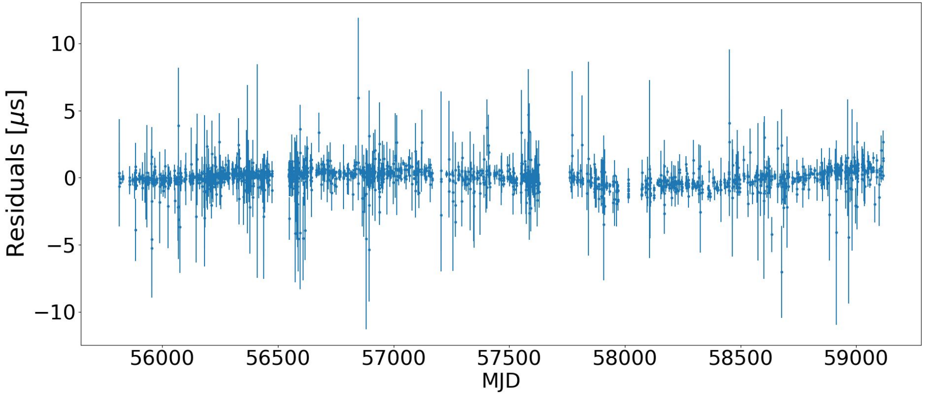


Timing model

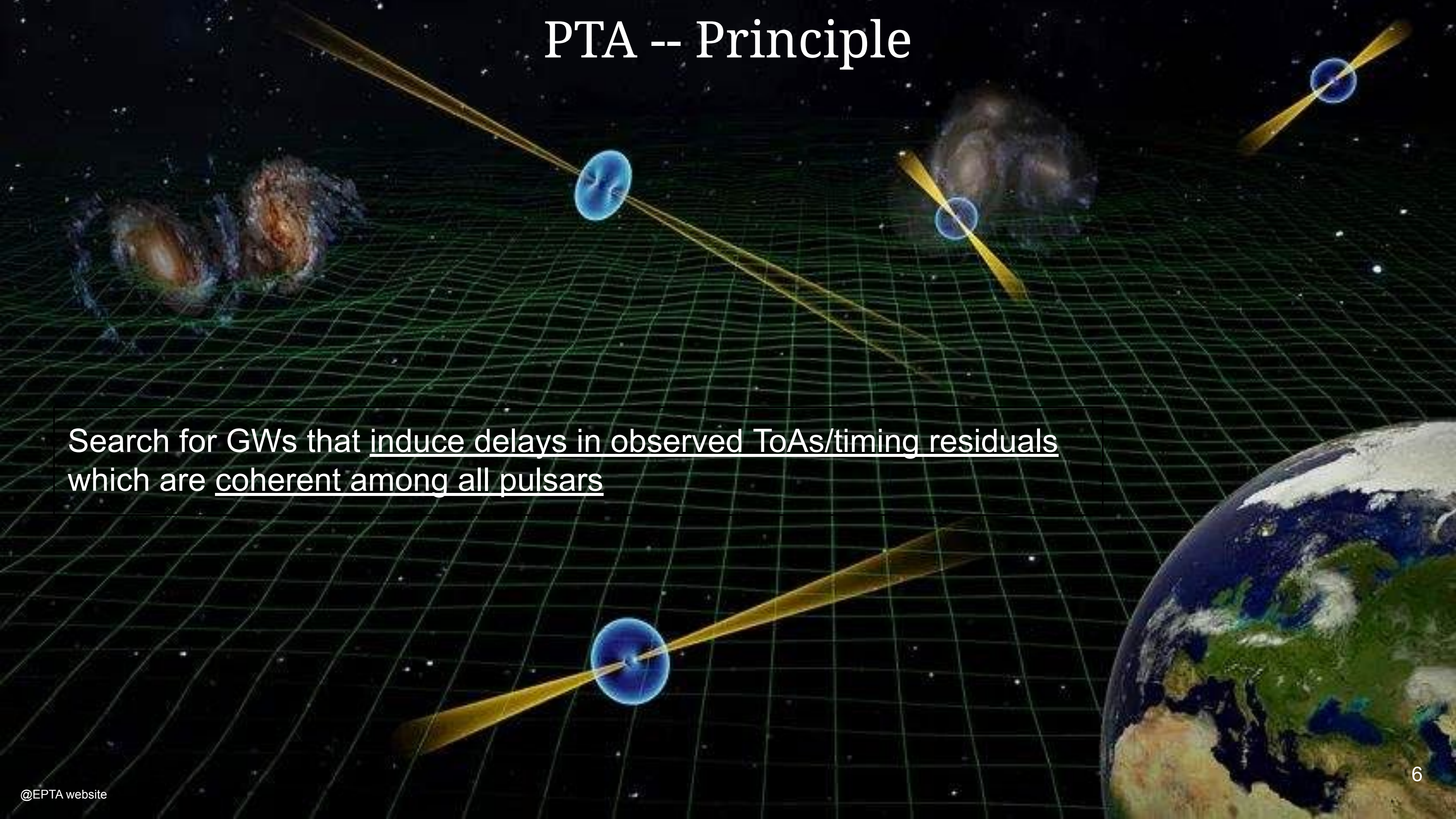
- Clock correction to the TT
- Transformation to the SSB
- Fit Rotational params
- Fit Astrometric params
- Fit DM params
- Fit Orbital params

Timing residuals = $ToA_{Observed}$ - $ToA_{Timing\ model}$

$wRMS_{res}$ ~ 100 ns - 5 μs



PTA -- Principle

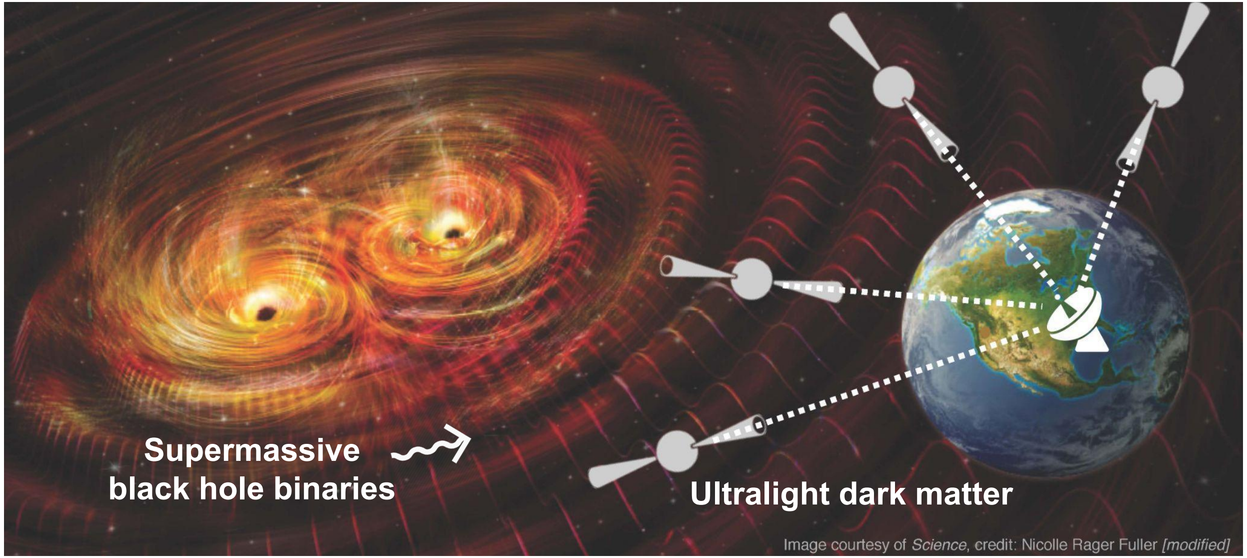


Search for GWs that induce delays in observed ToAs/timing residuals which are coherent among all pulsars

@EPTA website

PTA -- Sources

Credits : Nicole Rager Fuller



Early Universe processes

. Cosmic strings
. QCD phase transition
. Curvature perturbation
. Inflation
. …

Recent results from PTAs

On 29 June 2023, four series of papers by PTAs report
evidence for HD correlated GWB with differing significances

EPTA + InPTA	NANOGrav	PPTA	CPTA
$B^{HD/CURN}$ **~ 60, > 3σ**	$B^{HD/CURN}$ **~ 200, > 3.5σ**	$B^{HD/CURN}$ **~ 1.5, ~ 2σ**	**4.6σ**

EPTA + InPTA

Dataset
Antoniadis et al. 2023, A&A, 678, A48
Noise analysis
Antoniadis et al. 2023, A&A, 678, A49
GWB search
Antoniadis et al. 2023, A&A, 678, A50
Continuous GW search
Antoniadis et al. 2023, arXiv:2306.16226
Constraints on MBHBs, DM & Early Universe
Antoniadis et al. 2023, arXiv:2306.16227
ULDM search
Smarra et al. 2023, PRL, 131, 171001

NANOGrav

Dataset
Agazie et al. 2023, ApJL 951 L9
Noise analysis
Agazie et al. 2023, ApJL 951 L10
GWB search
Agazie et al. 2023, ApJL 951 L8
Continuous GW search
Agazie et al. 2023, ApJL 951 L50
Implications for potential sources
Afzal et al. 2023, ApJL 951 L11
Constraints on MBHBs
Agazie et al. 2023, ApJL 952 L37
Search for anisotropy in GWB
Agazie et al. 2023, ApJL 956 L3
Analysis pipeline
Johnson et al. 2023, arXiv:2306.16223

PPTA

Dataset
Zic et al. 2023, PASA, 40, E049
Noise analysis
Reardon et al. 2023, ApJL 951 L7
GWB search
Reardon et al. 2023, ApJL 951 L6

CPTA

GWB search
Xu et al. 2023, RAA. 23 075024

Focus on EPTA & InPTA

This talk

- Paper 1: The EPTA DR2 & timing analysis.
  DOI: 10.1051/0004-6361/202346841
- Paper 2: The noise analysis.
  DOI: 10.1051/0004-6361/202346842
- Paper 3: GWB search.
  DOI: 10.1051/0004-6361/202346844
- Paper 4: Continuous GW search.
  Submitted, arxiv:2306.16226

- Paper 5: Implication for SMBHB, DM and the early Universe. Submitted, arxiv:2306.16227
- Paper 6: Ultralight DM search.
  DOI: 10.1103/PhysRevLett.131.171001

See Golam's talk right after

The second data release from the European Pulsar Timing Array

III. Search for gravitational wave signals

J. Antoniadis, P. Arumugam, S. Arumugam, S. Babak, M. Bagchi, A.-S. Bak Nielsen, C. G. Bassa, A. Bathula, A. Berthereau, M. Bonetti, E. Bortolas, P. R. Brook, M. Burgay, R. N. Caballero, A. Chalumeau, D. J. Champion, S. Chanlaridis, S. Chen★, I. Cognard, S. Dandapat, D. Deb, S. Desai, G. Desvignes, N. Dhanda-Batra, C. Dwivedi, M. Falxa, R. D. Ferdman, A. Franchini, J. R. Gair, B. Goncharov, A. Gopakumar, E. Graikou, J.-M. Grießmeier, L. Guillemot, Y. J. Guo★★, Y. Gupta, S. Hisano, H. Hu, F. Iraci, D. Izquierdo-Villalba, J. Jang, J. Jawor, G. H. Janssen, A. Jessner, B. C. Joshi, F. Kareem, R. Karuppusamy, E. F. Keane, M. J. Keith, D. Kharbanda, T. Kikunaga, N. Kolhe, M. Kramer, M. A. Krishnakumar, K. Lackeos, K. J. Lee, K. Liu, Y. Liu, A. G. Lyne, J. W. McKee, Y. Maan, R. A. Main, M. B. Mickaliger, I. C. Niţu, K. Nobleson, A. K. Paladi, A. Parthasarathy, B. B. P. Perera, D. Perrodin, A. Petiteau, N. K. Porayko, A. Possenti, T. Prabu, H. Quelquejay Leclere, P. Rana, A. Samajdar, S. A. Sanidas, A. Sesana, G. Shaifullah, J. Singha, L. Speri, R. Spiewak, A. Srivastava, B. W. Stappers, M. Surnis, S. C. Susarla, A. Susobhanan, K. Takahashi, P. Tarafdar, G. Theureau, C. Tiburzi, E. van der Wateren, A. Vecchio, V. Venkatraman Krishnan, J. P. W. Verbiest, J. Wang, L. Wang and Z. Wu.

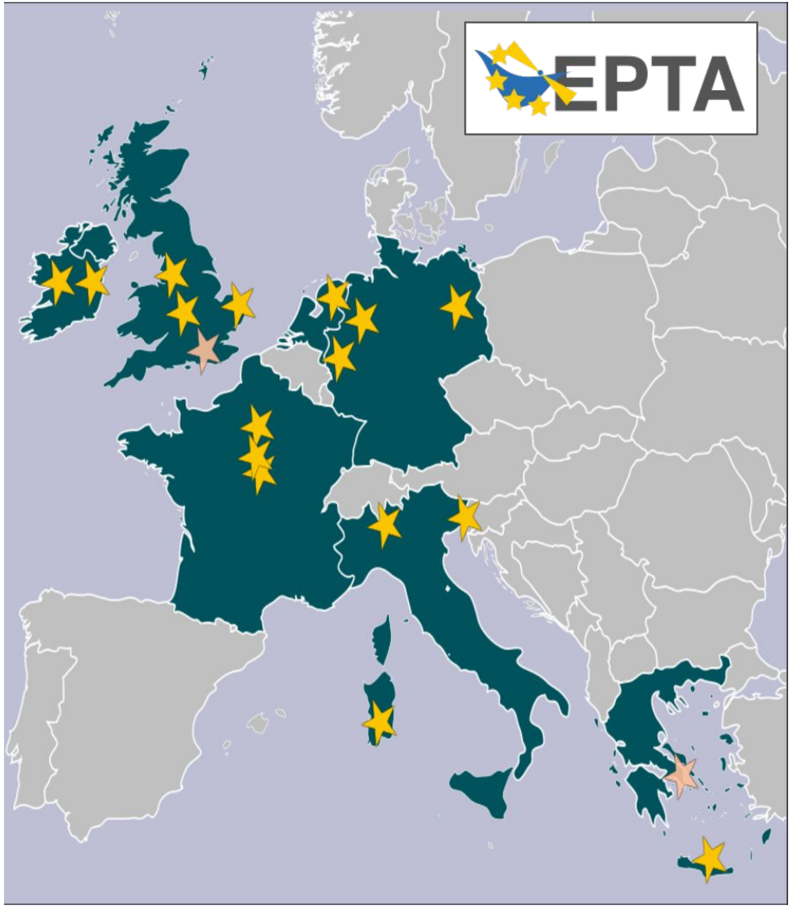
High contribution from Italy:

- Researchers from Cagliari Obs., Milano-Bicocca Univ., GSSI (L'Aquila), SISSA (Trieste)
- Data provided by Sardinia Radio Telescope (via LEAP)

The European PTA, member institutes & radiotelescopes

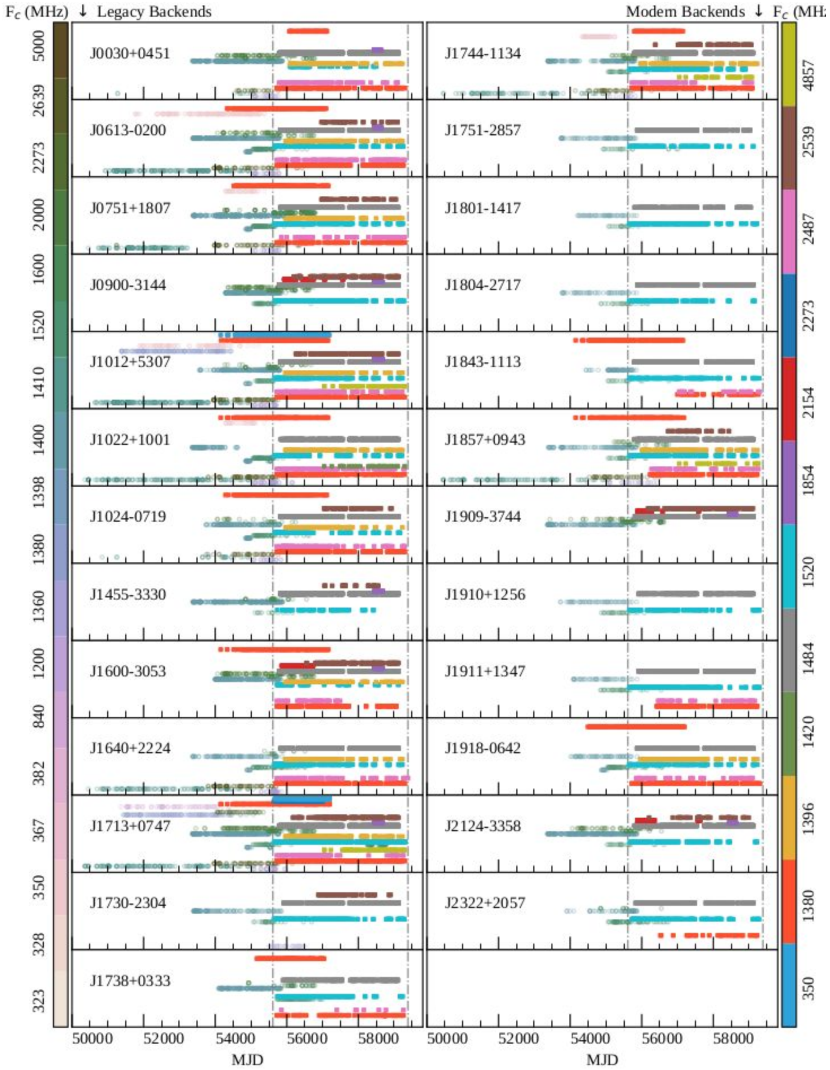
- France
  - APC (Paris)
  - LPC2E (Orléans)
  - Nançay(/Paris/Meudon) Observatory
- Germany
  - AEI (Potsdam-Golm)
  - Bielefeld University
  - MPI für Radioastronomie (Bonn)
- Greece
  - FORTH - Hellas (Heraklion)
  - Hellenic Open University (Patras)
- Ireland
  - Trinity College Dublin
  - University of Galway
- Italy
  - INAF/Osservatorio di Cagliari
  - Milano-Bicocca University
  - SISSA (Trieste)
  - GSSI (L'Aquila)
- Netherlands:
  - ASTRON (Dwingeloo)
- UK
  - Birmingham University
  - East Anglia University
  - Manchester University
  - Surrey University
- China
  - Peking University

\+ LEAP radiotelescope



EPTA DR2 data

Time
vs
Observing radio frequency



Data combination & Timing analysis - Outcomes

Precised timing models …

Parallax distance
- Measured in most pulsars
- Lutz-Kelker bias corrected
- Consistent with VLBI

Annual Orbital Parallax (varying apparent orbital geometry)
- Inclination angle+ascending nodes pos. angle constrained (KIN-KOM relation)

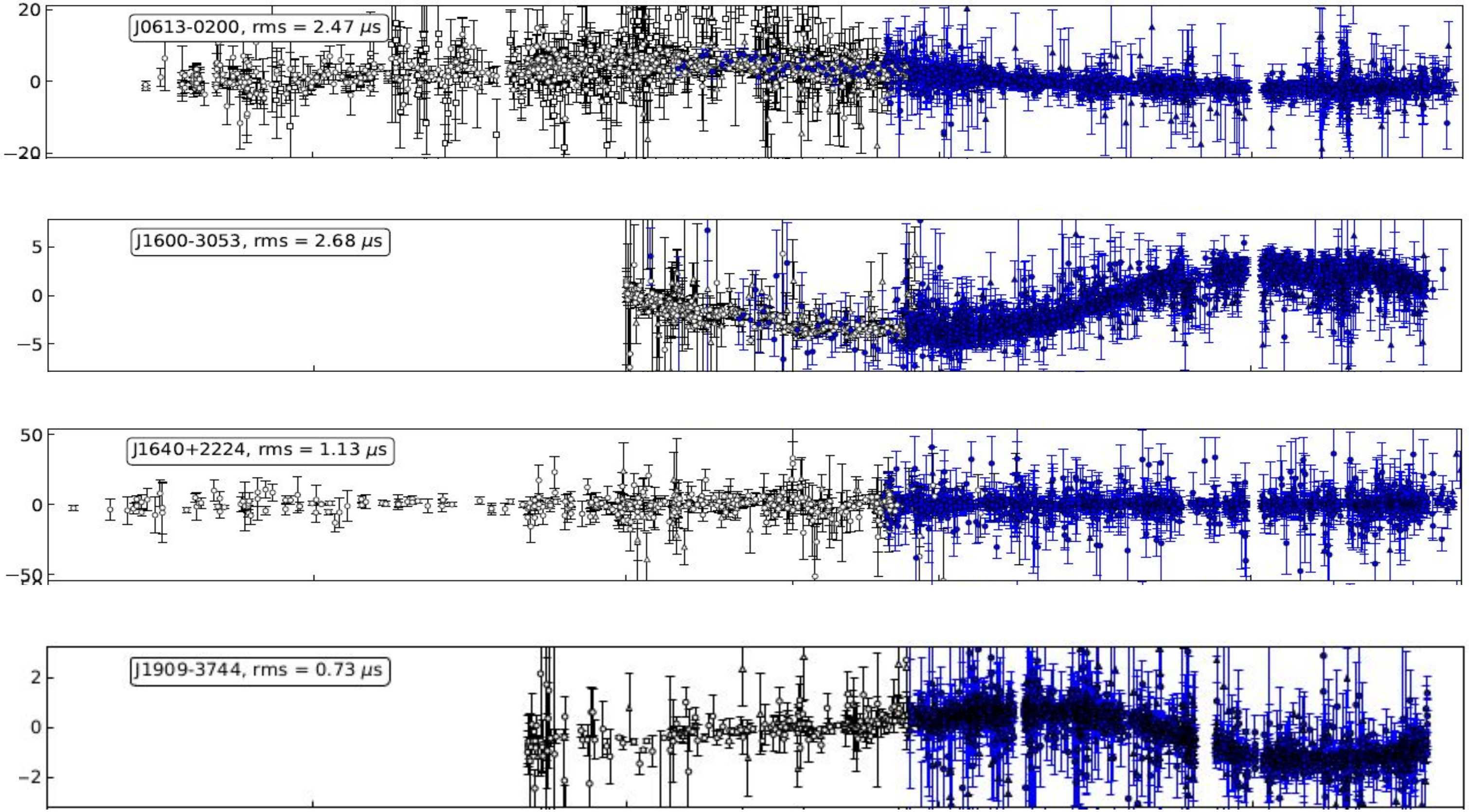
➔ improvements compare to DR1

Mass Measurement for 9 pulsars
- Post-Keplerian Parameters (Shapiro delay)

Binary Orbital Period Derivative measurements
- Caused by
  - intrinsic (GW emission)
  - extrinsic (proper motion & galactic acceleration)

- intrinsic factor was estimated and compared with theoretically calculated Pbdot (mostly consistent)
- kinematic distance broadly consistent with bias-corrected parallax distance

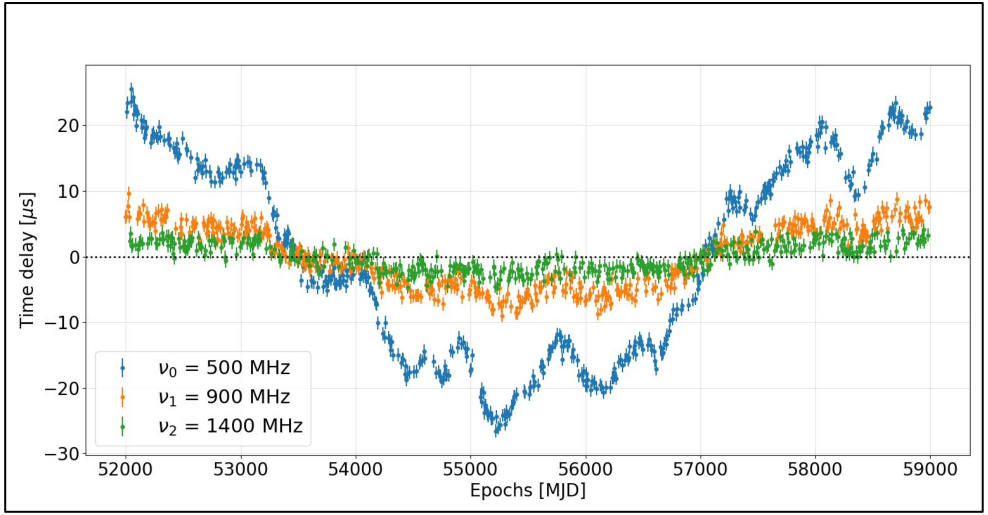
What remains in the data from the timing analysis ?



Noise + very-low frequency GWs !

- Time uncorrelated (white noise)
- Deterministic signals
  - Timing Model errors (marginalized over)
  - 'Exponential dips' in J1713+0747
- Time correlated noise ('red noise')
  - **'RN'** – Achromatic pulsar spin noise
  - **'DM'** – DM variations ($\delta t \propto \nu^{-2}$)
  - **'SV'** – Scattering variations ($\delta t \propto \nu^{-4}$)

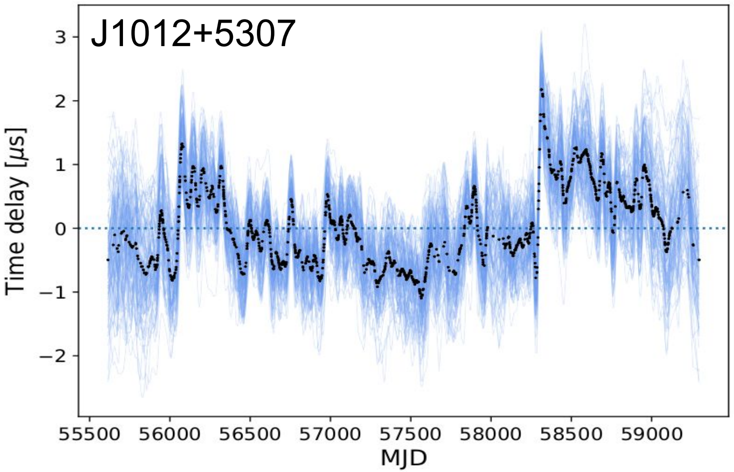
Example of DM variation signal

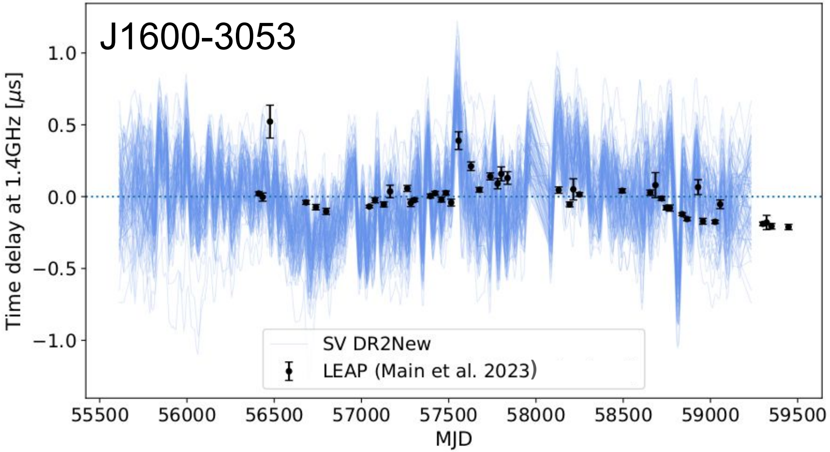


➔ To be well analyzed before GW searches !

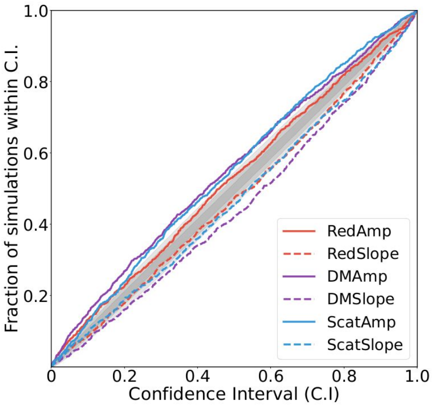
Noise analysis - General Outcomes

➔ **Customized noise models** obtained from Bayesian model selection





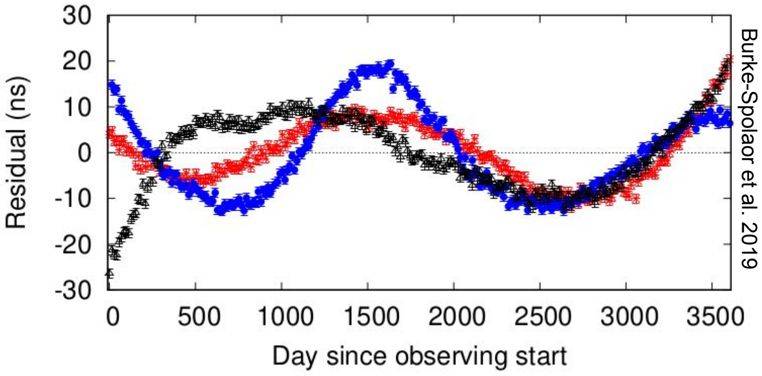
➔ Validation tests for robustness



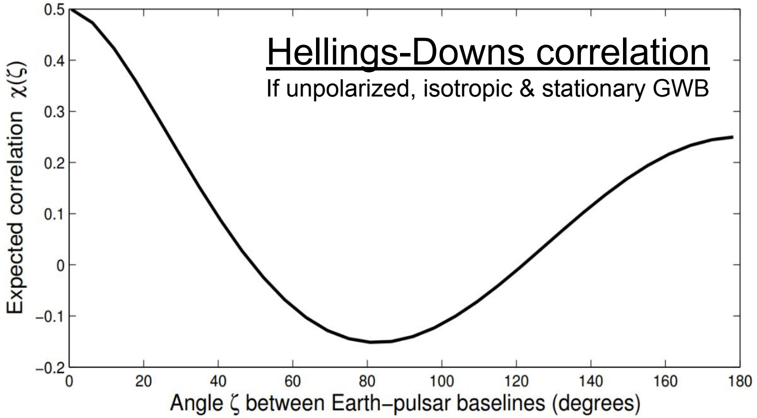
Noise + very-low frequency GWs !

Stochastic GW background (GWB)

Modeled with a power spectrum

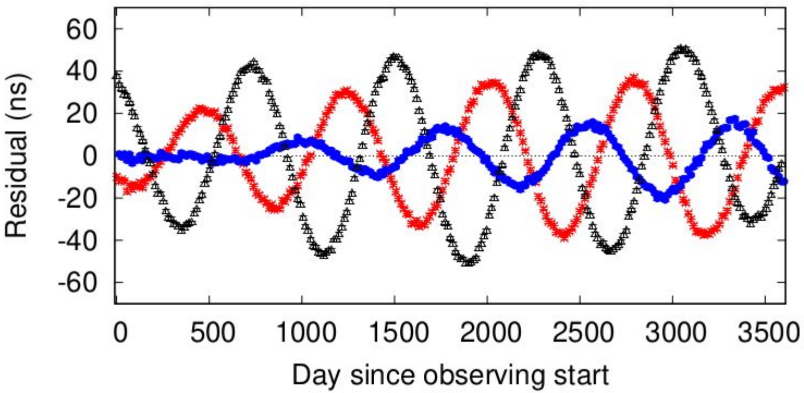


Burke-Spolaor et al. 2019



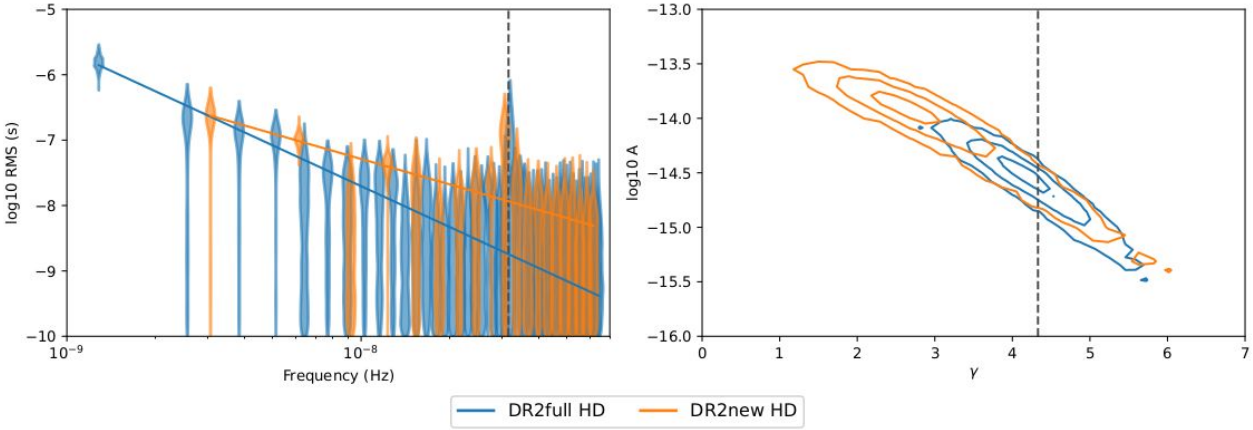
Deterministic signals

Modeled with a time-domain waveform

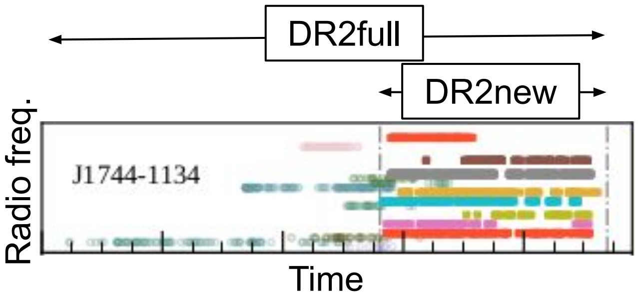


See Irene & Beatrice's talks for more details !

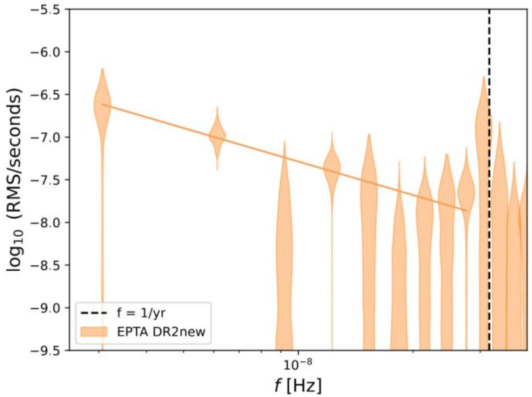
GWB analysis - Spectral properties



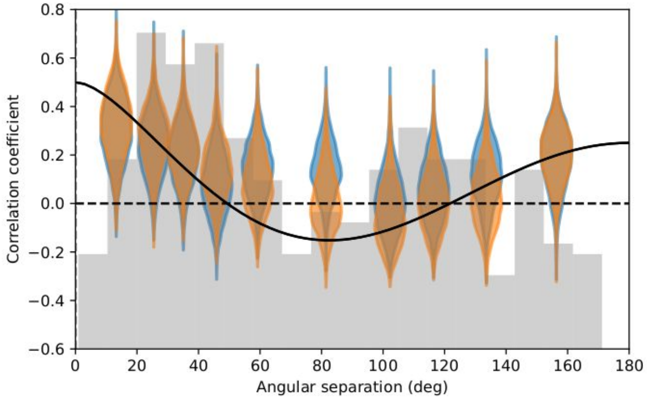
- Common “red” signal detected at high confidence
- DR2new power-law is shallower than DR2full
- HD correlation more evident on DR2new



- Only few bins are constrained at low frequencies



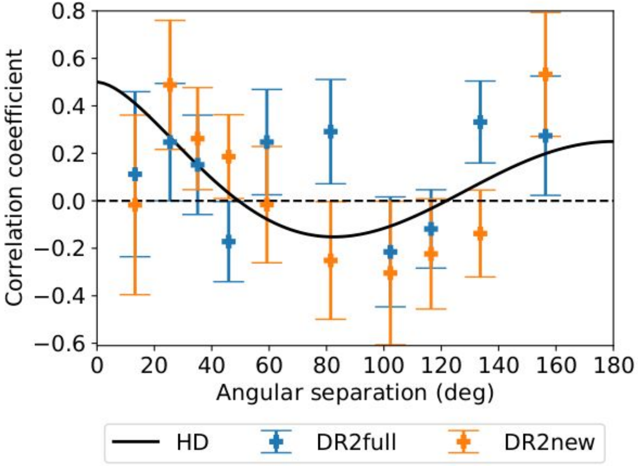
GWB analysis - Significance



Bayesian analysis

Bayes factors

Model	DR2full		DR2full+	DR2new		DR2new+
	ENTERPRISE	FORTYTWO	ENTERPRISE	ENTERPRISE	FORTYTWO	ENTERPRISE
PSRN + GWB	4	5	4	60	62	65
PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3



Frequentist analysis

S/N

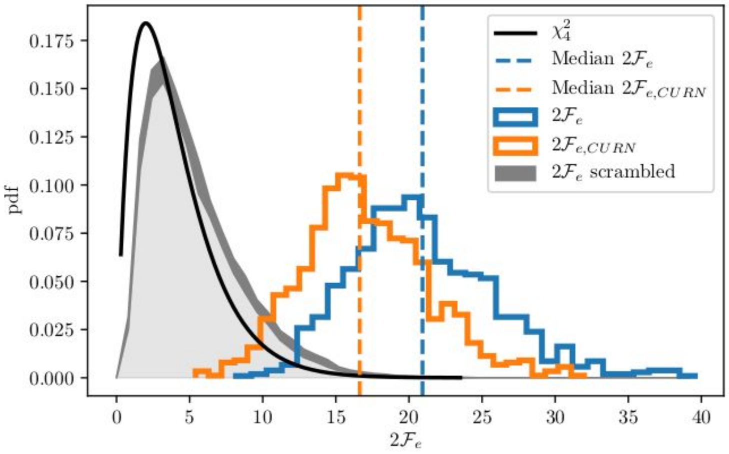
	DR2full	DR2full+	DR2new	DR2new+
S/N_{MP}	$1.1^{+1.1}_{-1.0}$	$1.0^{+1.1}_{-1.1}$	$0.3^{+1.4}_{-0.9}$	$0.8^{+1.7}_{-1.0}$
S/N_{DP}	$-0.4^{+0.9}_{-0.8}$	$-0.2^{+1.0}_{-0.9}$	$0.1^{+1.5}_{-0.9}$	$0.6^{+1.5}_{-0.9}$
S/N_{HD}	$1.3^{+1.3}_{-1.2}$	$1.4^{+1.2}_{-1.1}$	$3.5^{+2.4}_{-1.7}$	$4.1^{+2.7}_{-1.7}$

→ p-val < 0.0001 (≥ 3.5 σ)

Continuous GWs - Frequentist analysis

- Using the **Fe-statistics**, a **CGW candidate** is identified at **4.64 nHz**
- The inclusion of **CURN** in the model **absorbs a bit of power**
- We use **sky-scrambles** to evaluate the **p-value**, as well as the **theoretical null distribution** χ^2_4
- The **p-value** for this candidate is evaluated at **~3σ**

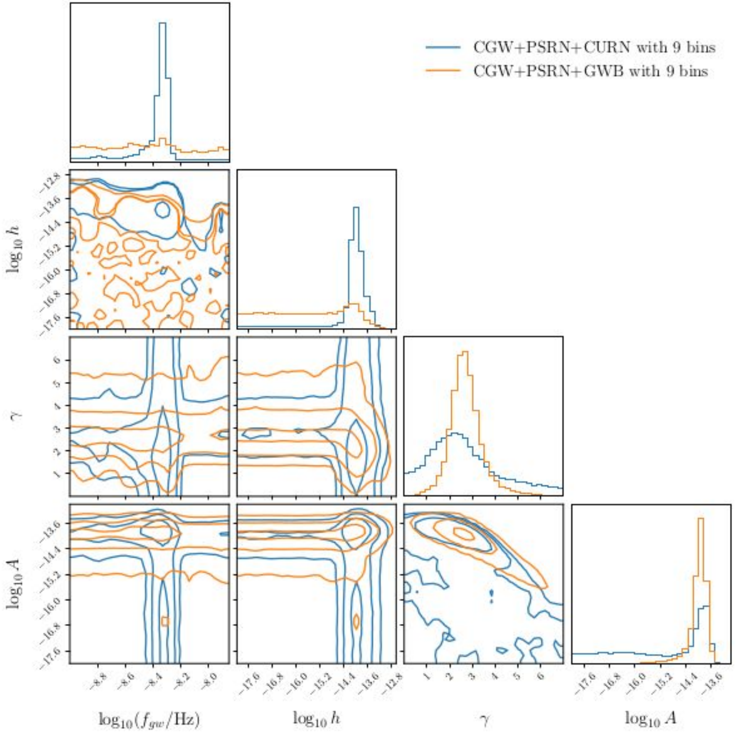
	$p(\mathcal{F}_e)$	$p(\mathcal{F}_{e,\mathrm{CURN}})$
χ^2_4	5×10^{-4}	1×10^{-3}
Sky scrambles	$(7 \pm 4) \times 10^{-4}$	$(6 \pm 1) \times 10^{-3}$



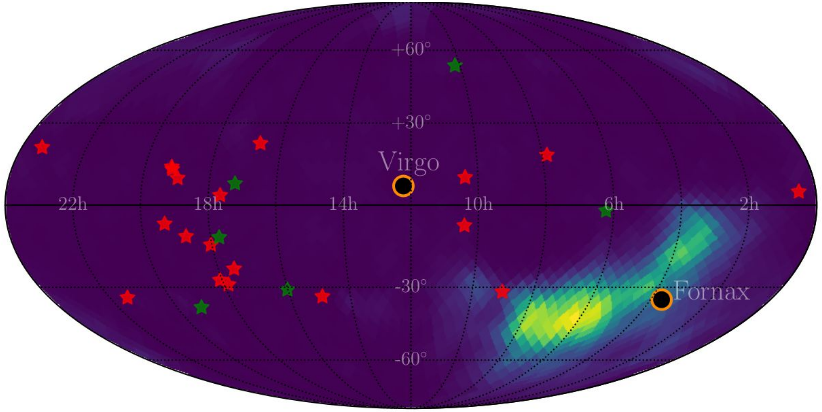
CURN: Common Uncorrelated Red Noise

Continuous GWs - Bayesian analysis

- **CGW candidate** found at **4.8 nHZ**



Model comparison	Bayes factor
CGW+PSRN vs PSRN	4000
CGW+PSRN+CURN vs PSRN+CURN, 3 bins	12
CGW+PSRN+CURN vs PSRN+CURN, 9 bins	4
CGW+PSRN+GWB vs PSRN+GWB, 3 bins	1
CGW+PSRN+GWB vs PSRN+GWB, 9 bins	0.7



- The inclusion of **HD GWB** in the model **absorbs the CGW candidate**
  - ➔ **GWB & CGWs hard to disentangle ! (cf. Irene's talk)**

Conclusions & perspectives

- Lots of results from pulsar timing analysis
- EPTA DR2 displays
  - evidence (BF~60, S/N~3.5) for Hellings-Downs correlations ($A=(2.5 \pm 0.7) \times 10^{-15}$)
  - And/or evidence for a signal from a single supermassive black hole binary ?
- *Let's hear now* about

  Further EPTA studies on signal properties (**Irene**) and implications (**Golam**)

  A search for continuous GWs with MeerKAT data (**Beatrice)**

- Consistency checks among results performed (Submitted, arXiv:2309.00693)
- Stay tuned: Current data combination @ International PTA level will lead to the best sensitivity available in the next few years ! -> IPTA DR3

Thank you !

EPTA Spring meeting 2023 @ Milano