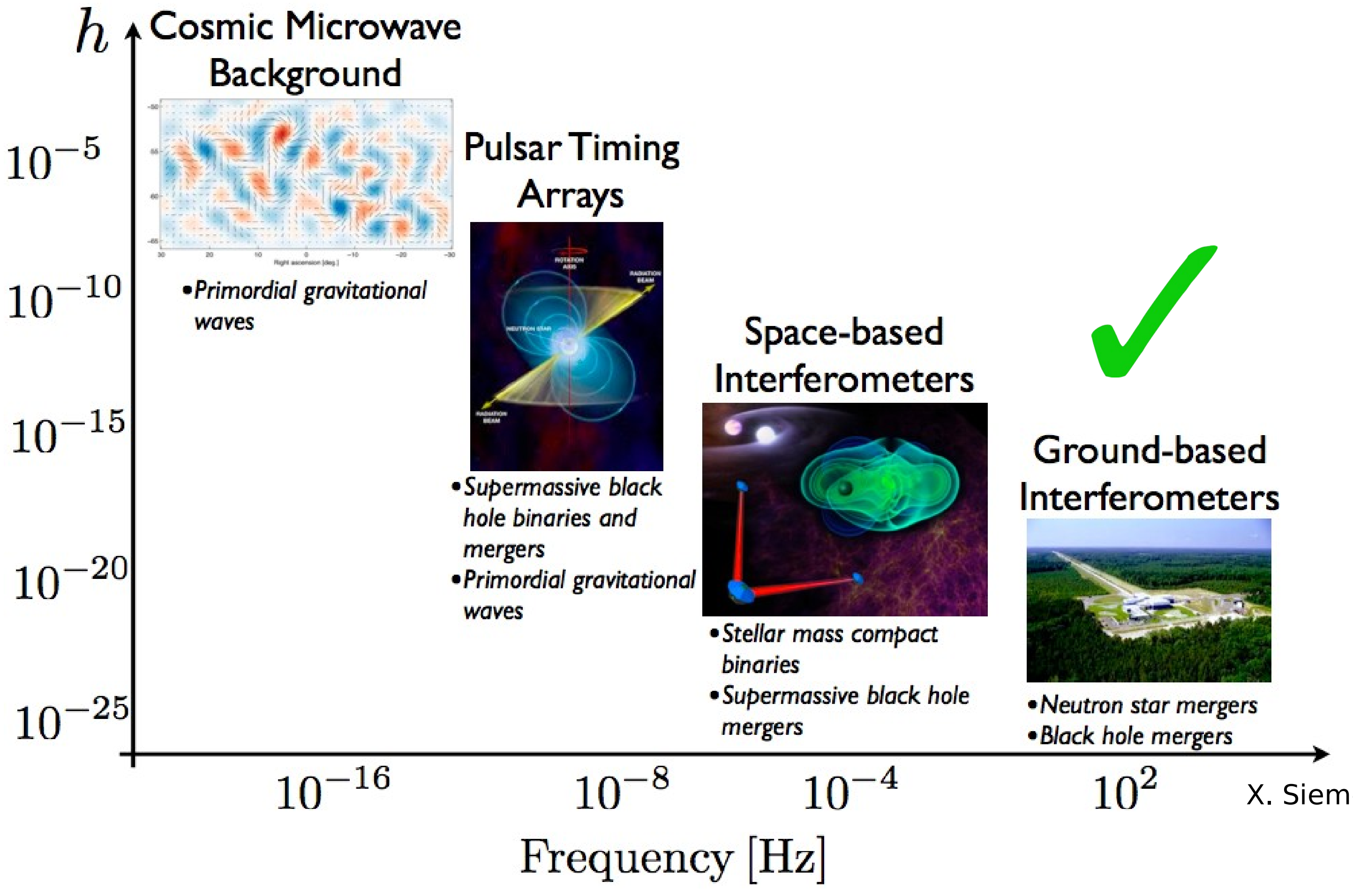
5th of June 2024, LOFAR Family Meeting

Pulsar Timing Arrays, the impact of LOFAR and NenuFAR

C. Tiburzi

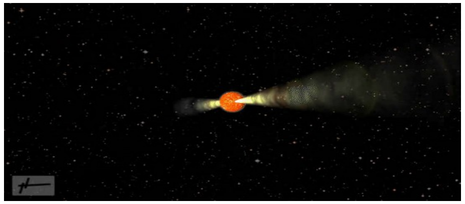
INAF-OAC

The Gravitational Wave spectrum

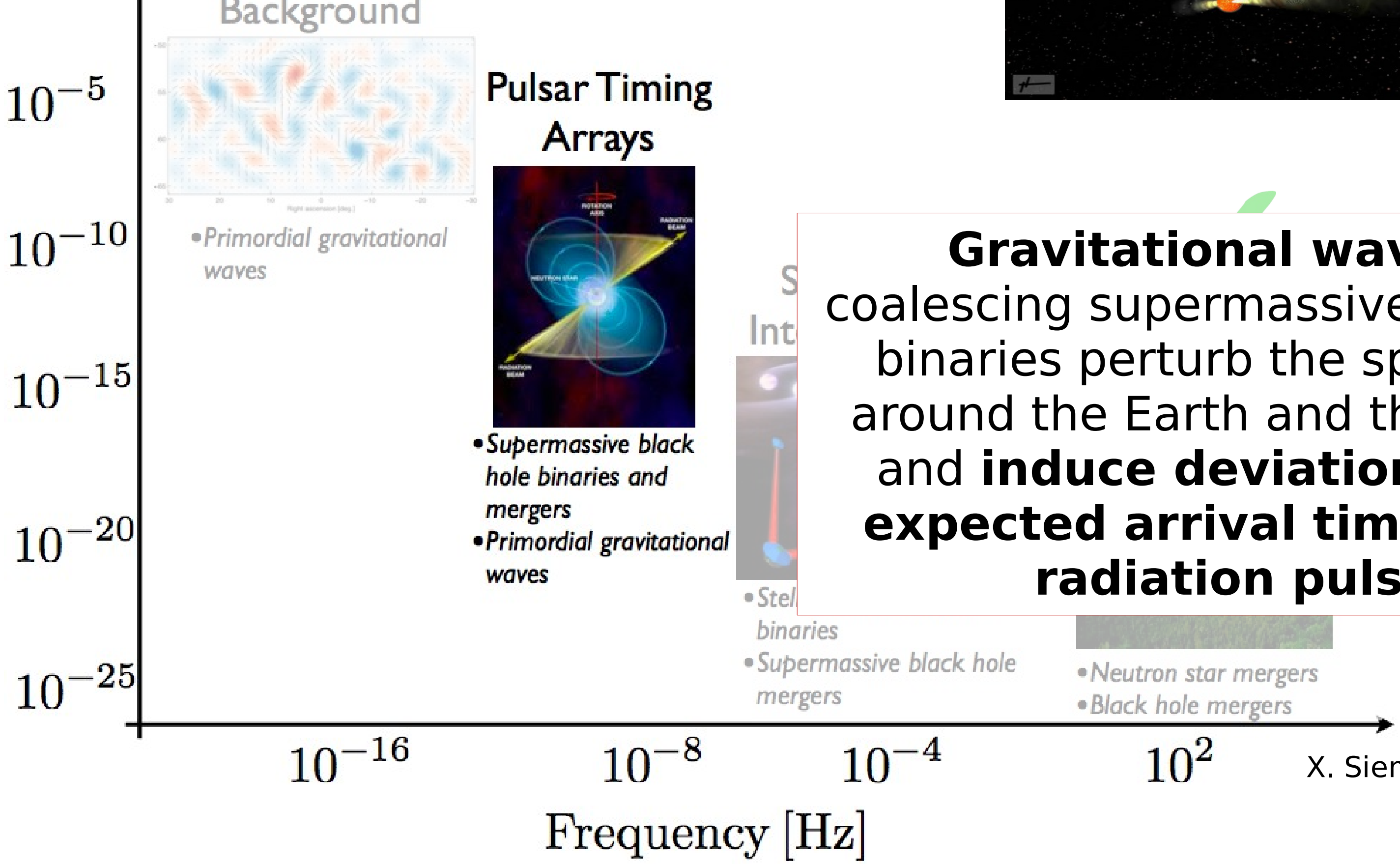


X. Siemens

The Gravitational Wave spectrum



J. van Leeuwen



X. Siemens

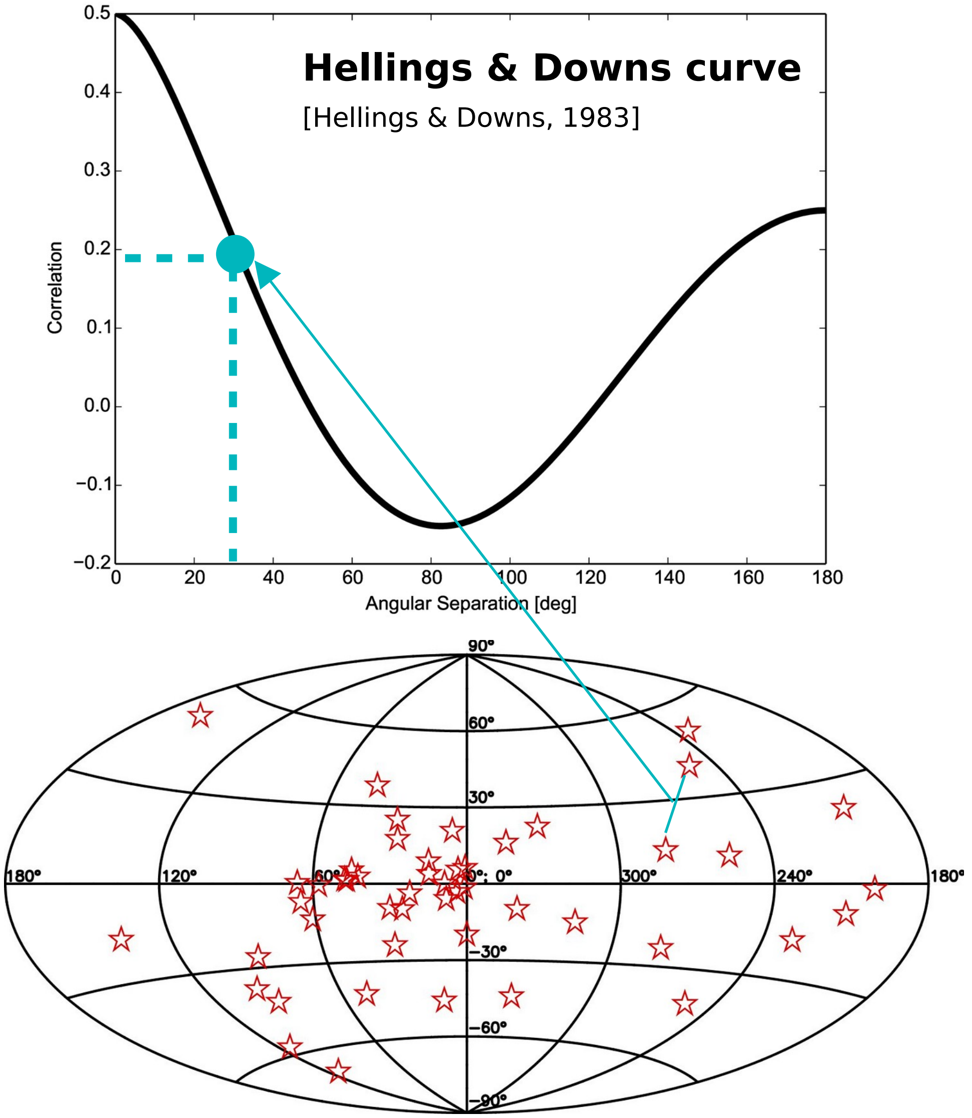
Gravitational waves by coalescing supermassive black-hole binaries perturb the space-time around the Earth and the pulsars, and **induce deviations in the expected arrival times of the radiation pulses**

PTAs: the nanoHertz window for gravitational waves

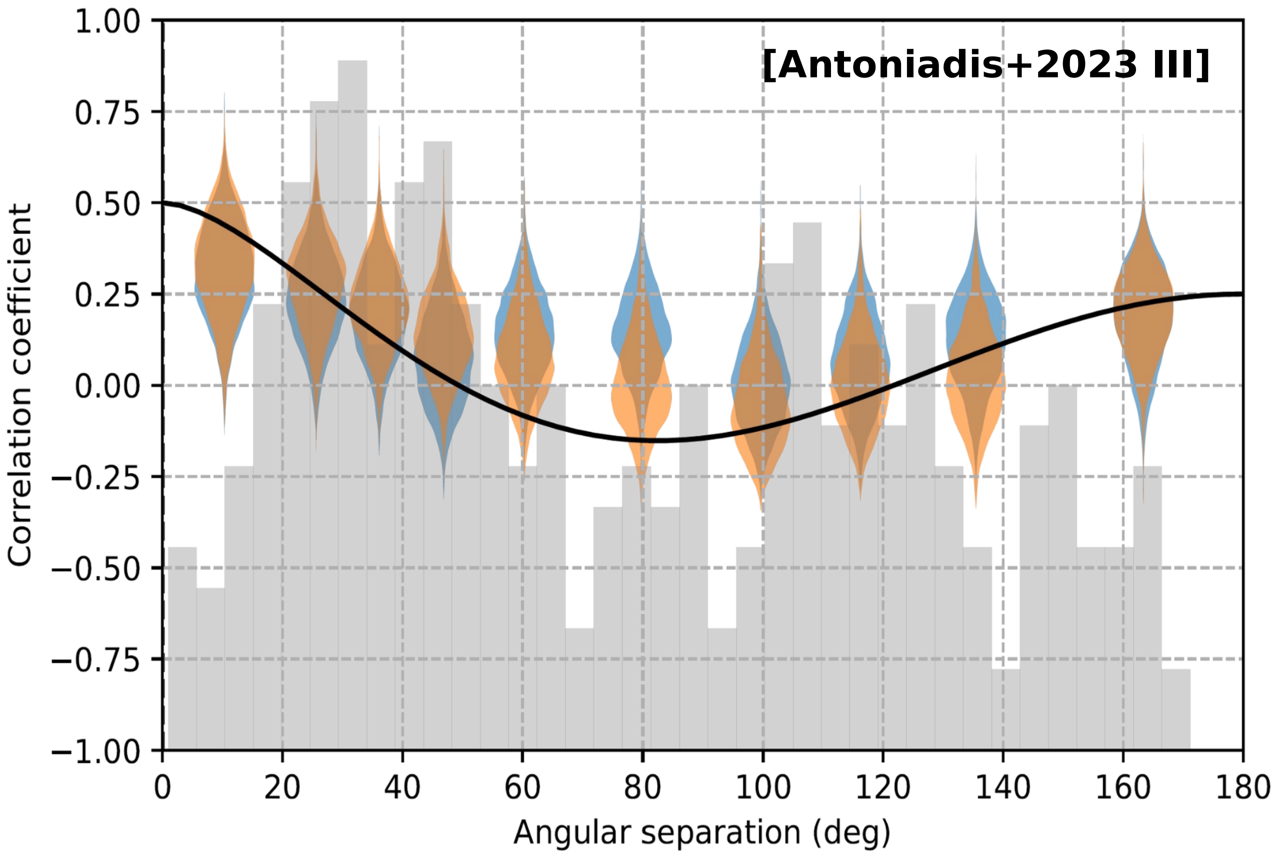
Pulsar timing arrays consist of an ensemble of very stable millisecond pulsars whose timing residuals are ***spatially correlated*** to detect GWs.

$$\begin{cases} \zeta(\theta_{ij}) = \frac{3}{2} x \log(x) - \frac{x}{4} + \frac{1}{2} \\ x = [1 - \cos(\theta_{ij})] \end{cases}$$

[Hellings & Downs, 1983]



First indication of a GWB signature in the EPTA data



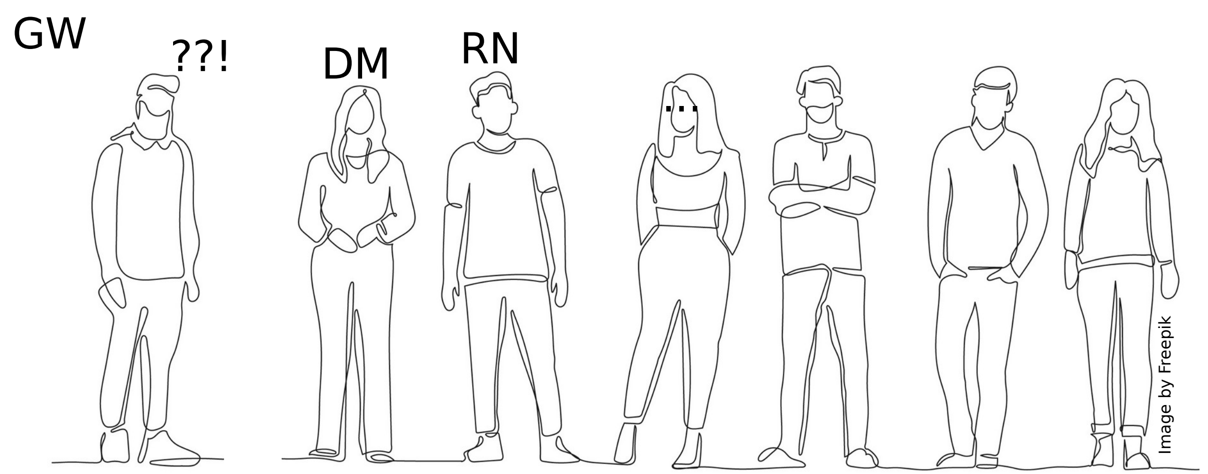
~3σ signal, lower than the targeted
5σ detection threshold

Get in line, Gravitational Waves

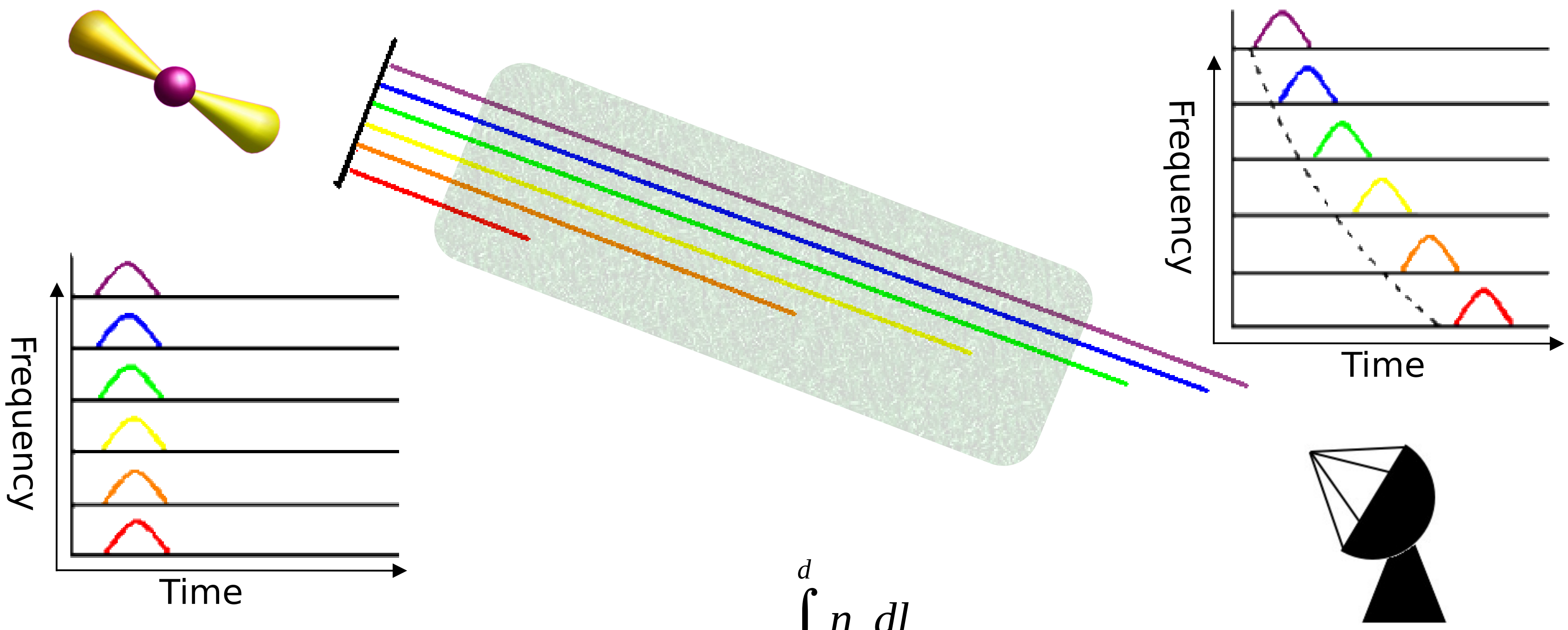
GWs are not the only phenomena that perturb the regular arrival of a pulsar’s radiation pulses.

The biggest competitors are:

- Intrinsic irregularities in the pulsar spin (‘Red noise’ tout-court, RN)
- Variations in the plasma density along the LoS (‘DM noise’)



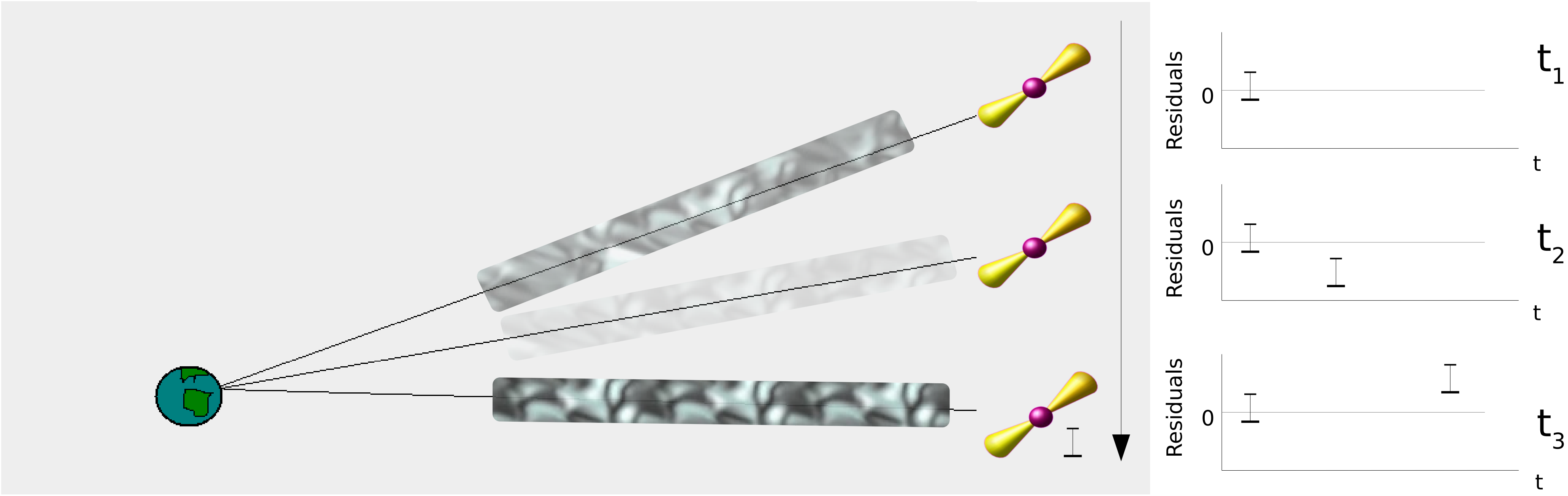
Dispersion



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

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

DM “noise”



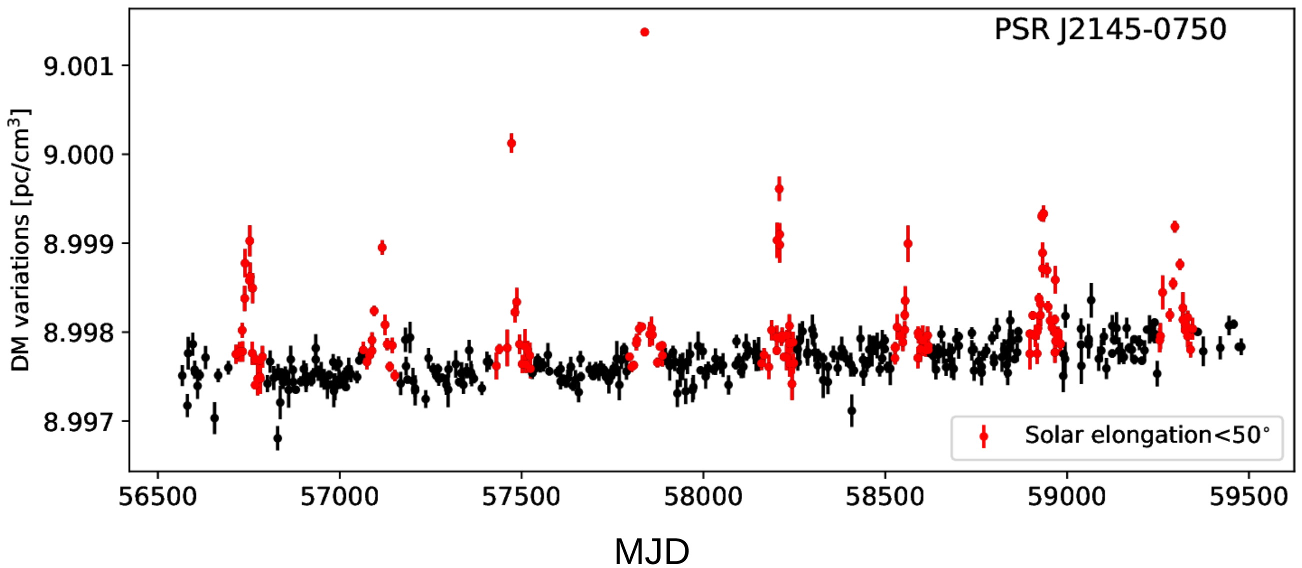
Neutralizing the DM noise

→ Spectral modeling

Bayesian-based software such *Enterprise* to model the power spectra of the various noise sources

However

The bulk of PTA data is obtained at L-Band (~1.4 GHz) where the **DM noise is present** but **cannot be precisely calculated** because its signature does not have sufficient magnitude ($\Delta t \propto DM/f^2$)



Integrating the low-frequency datasets in PTAs

Three main fronts of study:

PTA+LOFAR/NenuFAR data combination

[F. Iraci] Osservatorio Astronomico di Cagliari

[S. C. Susarla]

PTA+LOFAR/NenuFAR noise modeling

[F. Iraci] Osservatorio Astronomico di Cagliari

Testing of spectral models and priors

[S. C. Susarla]

[I. Niţu] The University of Manchester

Impact of LOFAR/NenuFAR on the EPTA noise modeling

[F. Iraci]

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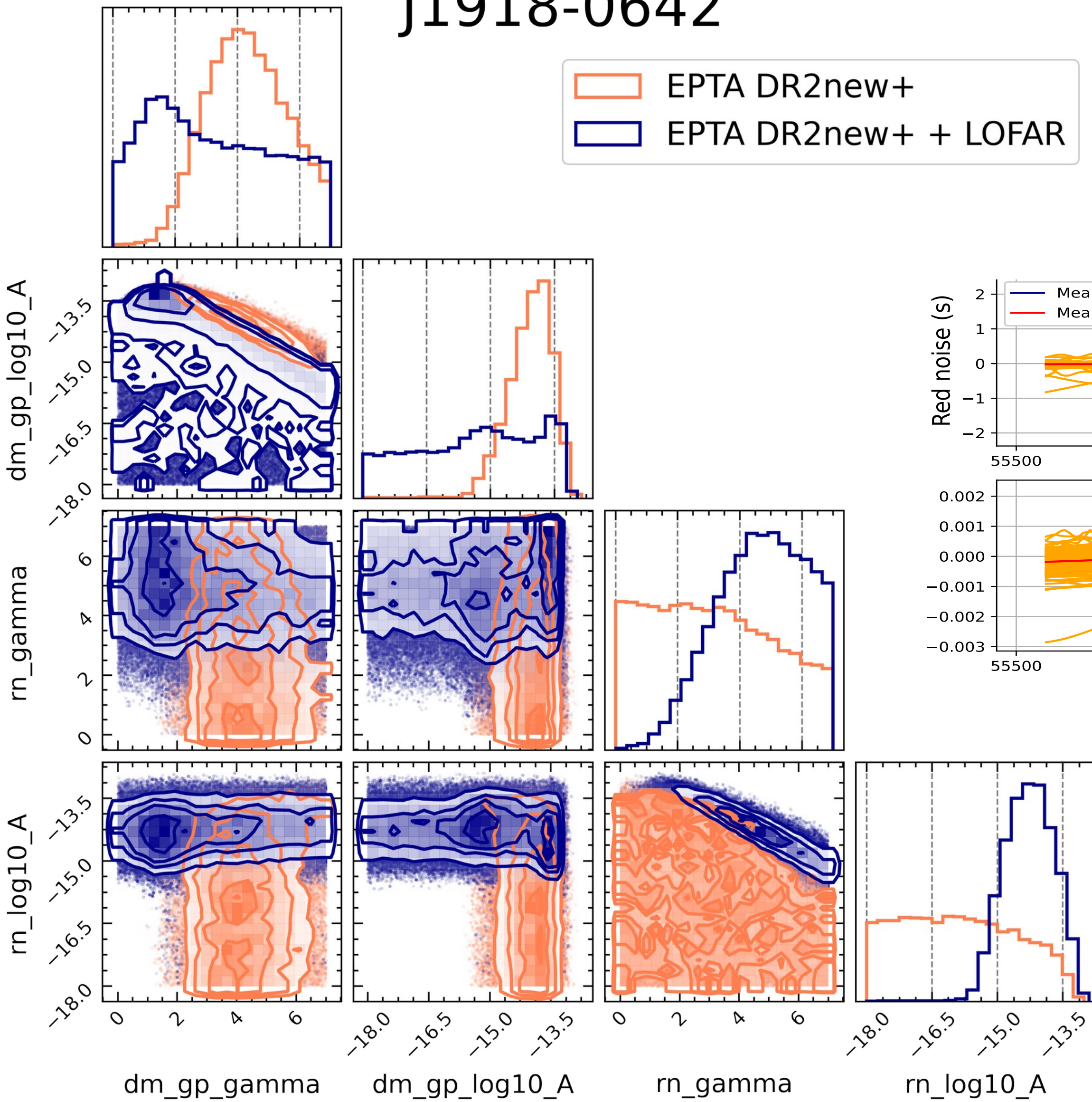
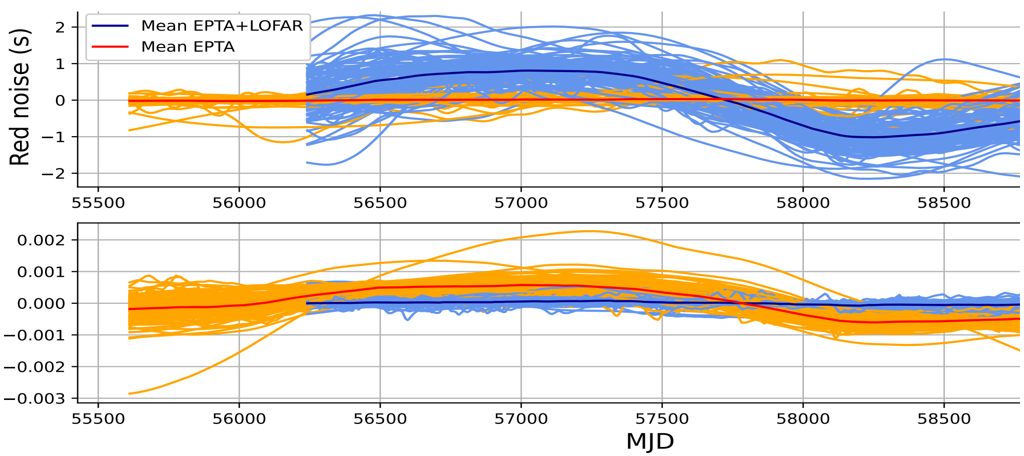
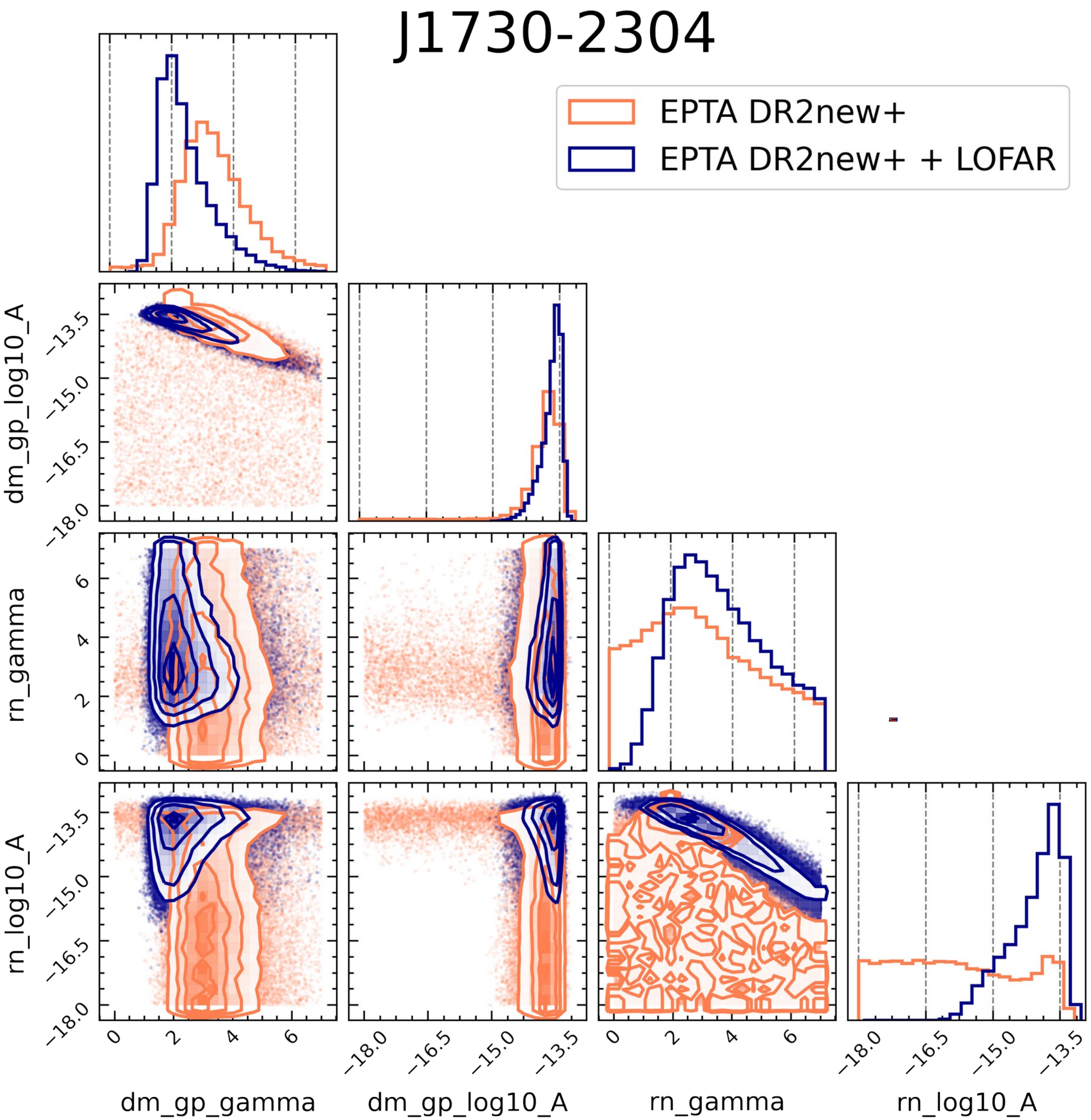




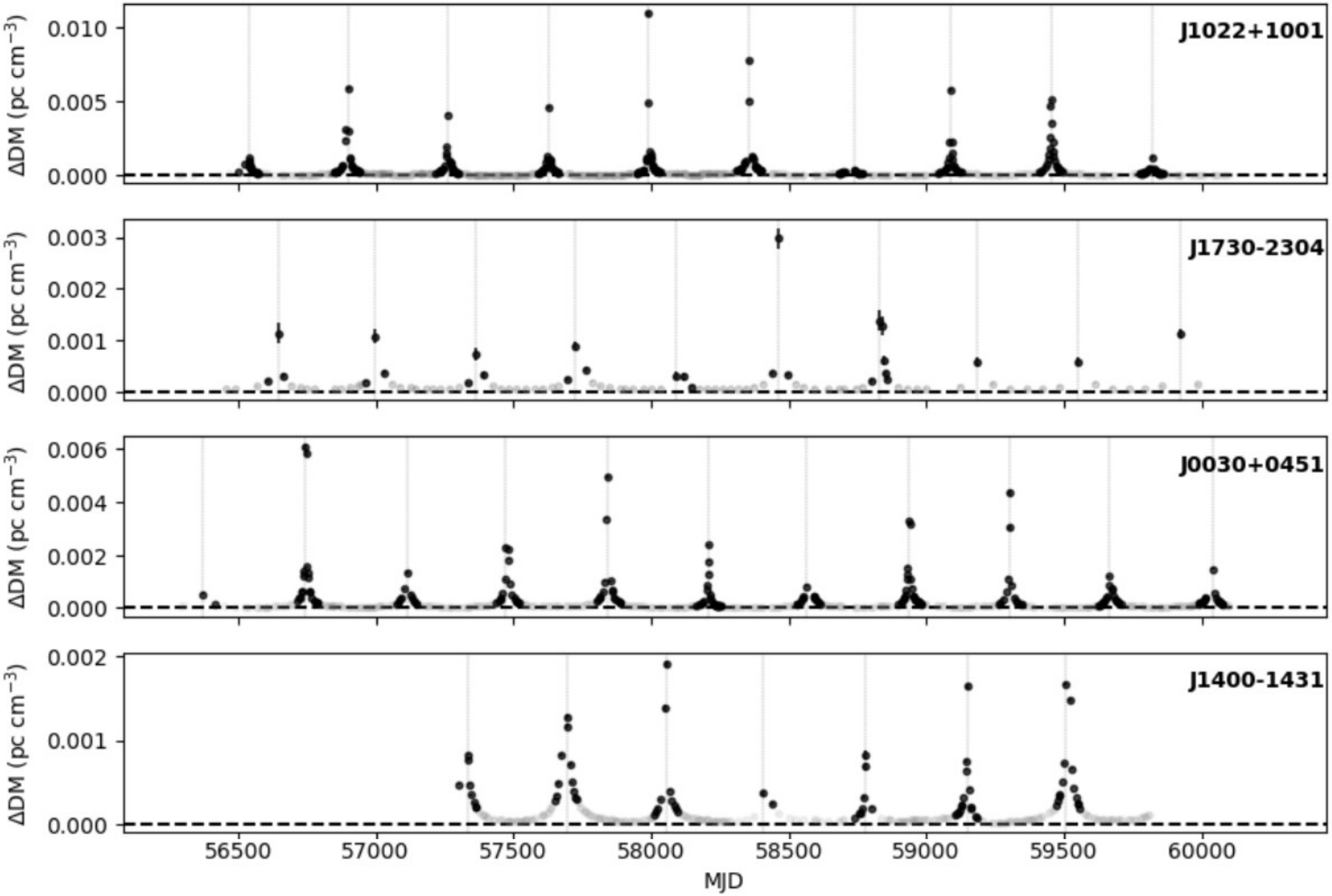
Impact of LOFAR/NenuFAR on the EPTA noise modeling

[F. Iraci]



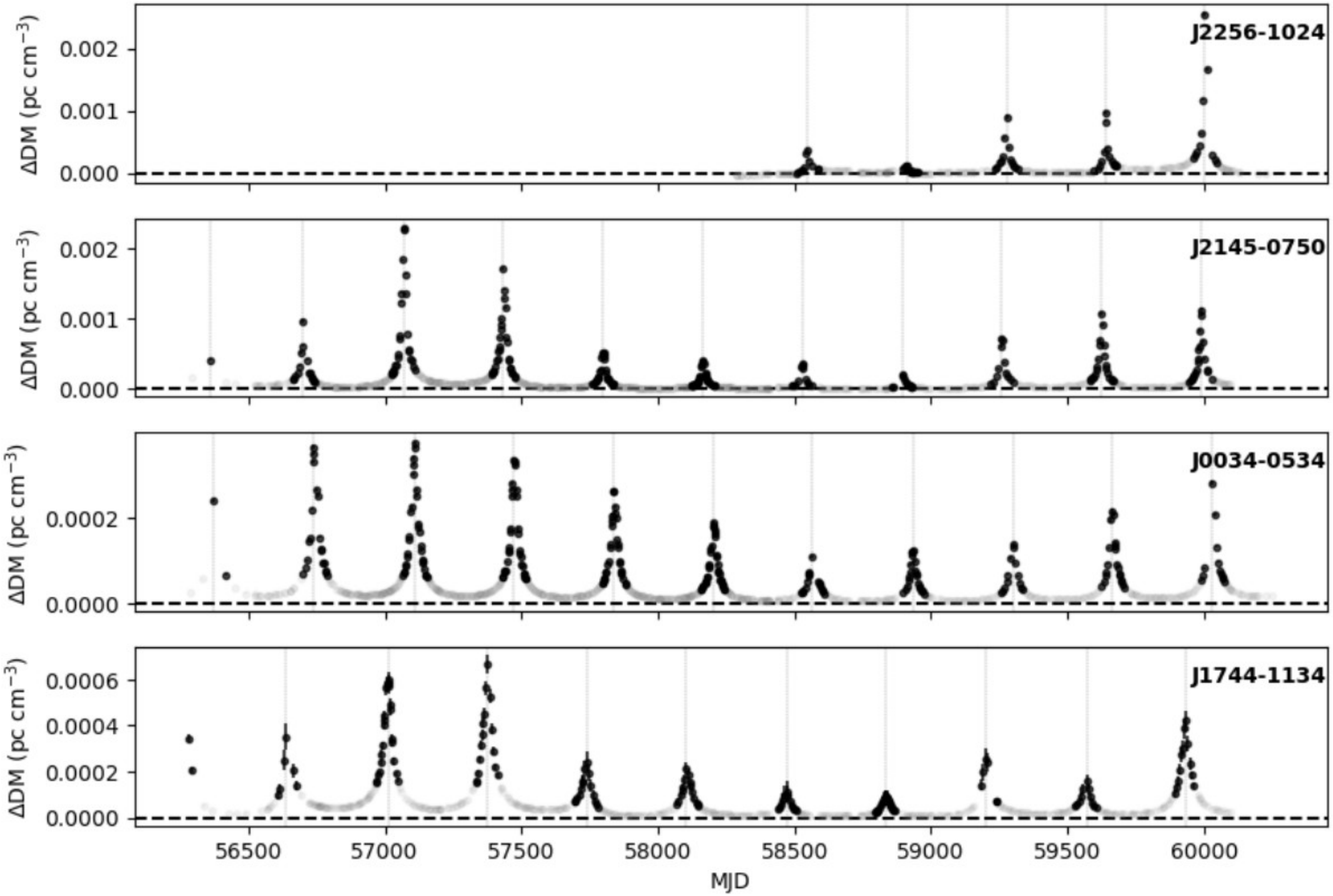
SW model testing, low-ecliptic pulsars

[S. C. Susarla]



SW model testing, medium-ecliptic pulsars

[S. C. Susarla]



SW model testing

[S. C. Susarla]

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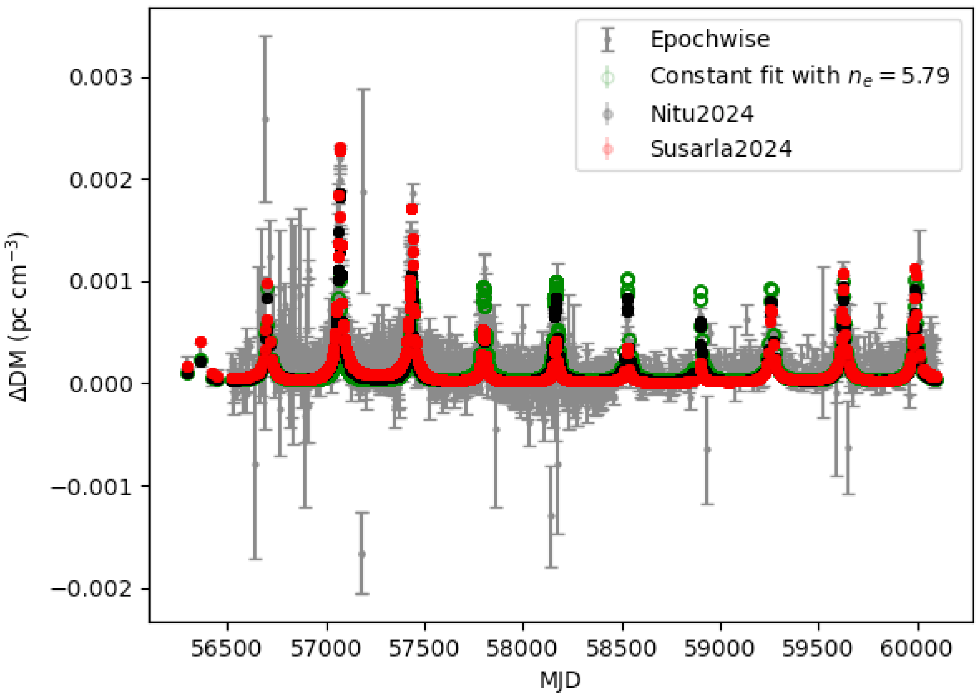
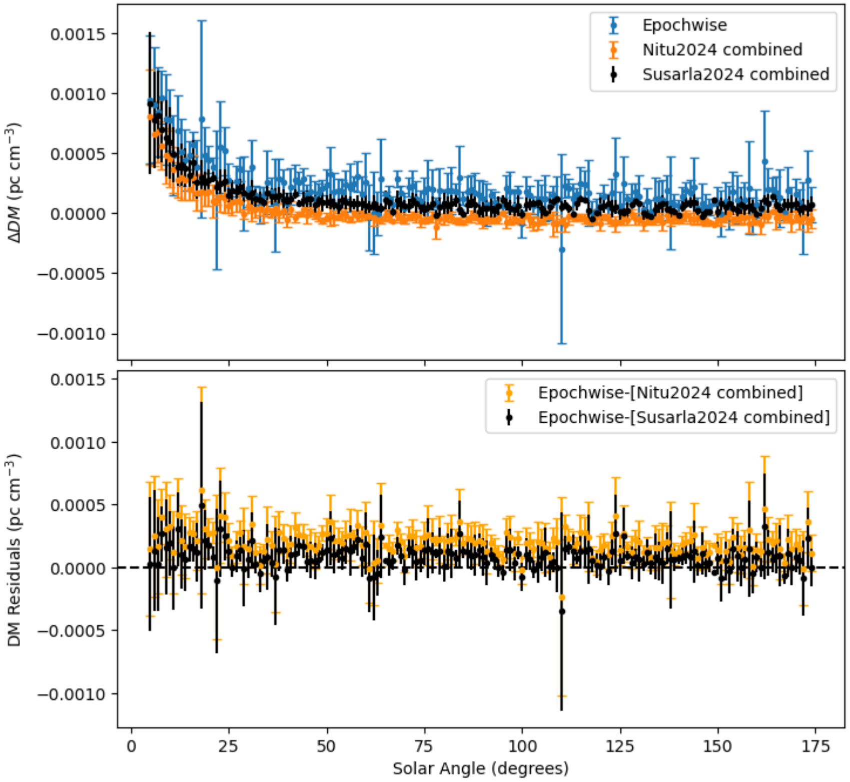




Pulsar monitoring with LOFAR2.0

- New hardware
- Higher angular resolution
- Increased sensitivity in the LBAs
- Simultaneous LBAs/HBAs observing
- Simultaneous LOFAR/NenuFAR observing
- Multibeaming

Our mascotte Luigi

Submission: LOFAR2.0 Large Programmes — Full proposal

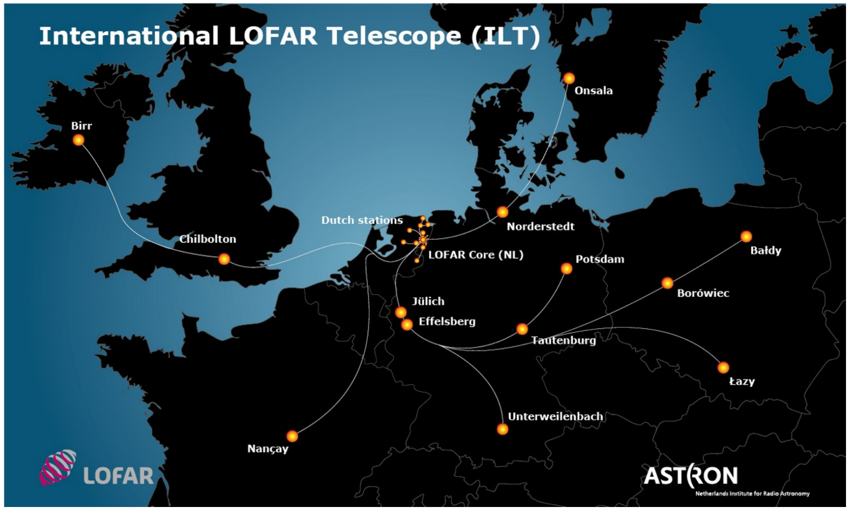
PURR – PUlsars and Repeaters Research, a Pulsar and Fast Transient Monitoring Project

C. Tiburzi[1], C. G. Bassa[2], J. W. T. Hessels[2,3], G. H. Janssen[2,4], E. F. Keane[5], M. A. Krishnakumar[6,7], L. S. Oswald[8,9], M. Pilia[1], C. Sobey[10,11], X. Song[2], M. Trudu[1], J. P. W. Verbiest[12], P. Weltevrede[13], F. Abbate[1,6], J. Antoniadis[14,6], A. Antonova[15], A. Basu[13], R. Basu[16], A. V. Bilous[17], C. Blanchard[18], L. Błaszkiewicz[19], M. Brionne[18], M. Burgay[1], M. Brüggen[20], J. A. Cázares[21], A. Chalumeau[22,23], B. Ciardi[24], A. Corongiu[1], P. Flisek[19], M. P. Gawroński[25], A. Golden[26], J.-M. Grießmeier[18,27], M. Hoeft[28], H. Hu[6], F. Iraci[1,29], F. Jankowski[18,13], O. A. Johnson[5], A. Karastergiou[8], M. R. Kennedy[30], J. Kijak[16], V. I. Kondratiev[2], K. Kozarev[15], M. Kramer[6,13], A. Krankowski[19], J. van Leeuwen[2], W. Lewandowski[16], G. A. Lowes[31,32], K. Liu[6], Y. Liu[33,34], R. A. Main[35,36], J. W. McKee[31,32], D. McKenna[5,2], R. Miteva[15], R. Nag[1,29], S. Osłowski[37], D. Perrodin[1], A. Parthasarathy[2,6], A. Possenti[1], N. K. Porayko[22,6], H. Qiu[38], A. Ridolfi[1,6], K. M. Rajwade[2], A. Rowlinson[2,3], K. Rozko[16], D. J. Schwarz[7], M. Serylak[38,39], G. M. Shaifullah[22,23,1], M. Soida[40], S. C. Susarla[26], B. W. Stappers[13], A. Szary[16], P. Tarafdar[41], G. Theureau[18,27,42], S. ter Veen[2], C. Vocks[43], E. van der Wateren[2,4], J. Wang[44,7], Z. Wu[33] and O. Wucknitz[6]

[1]*INAF - Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047 Selargius (CA), Italy*

Thank you for your attention

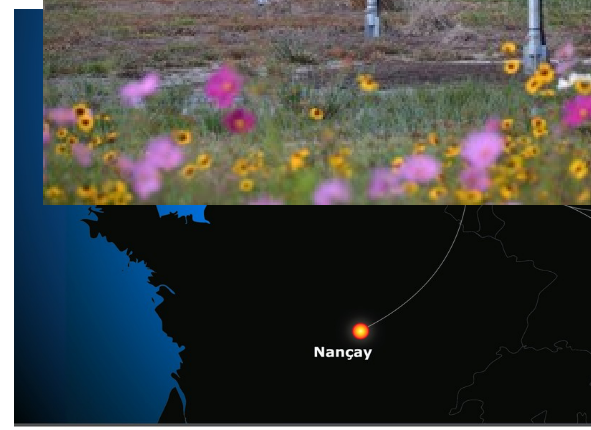
Observing pulsars with LOFAR



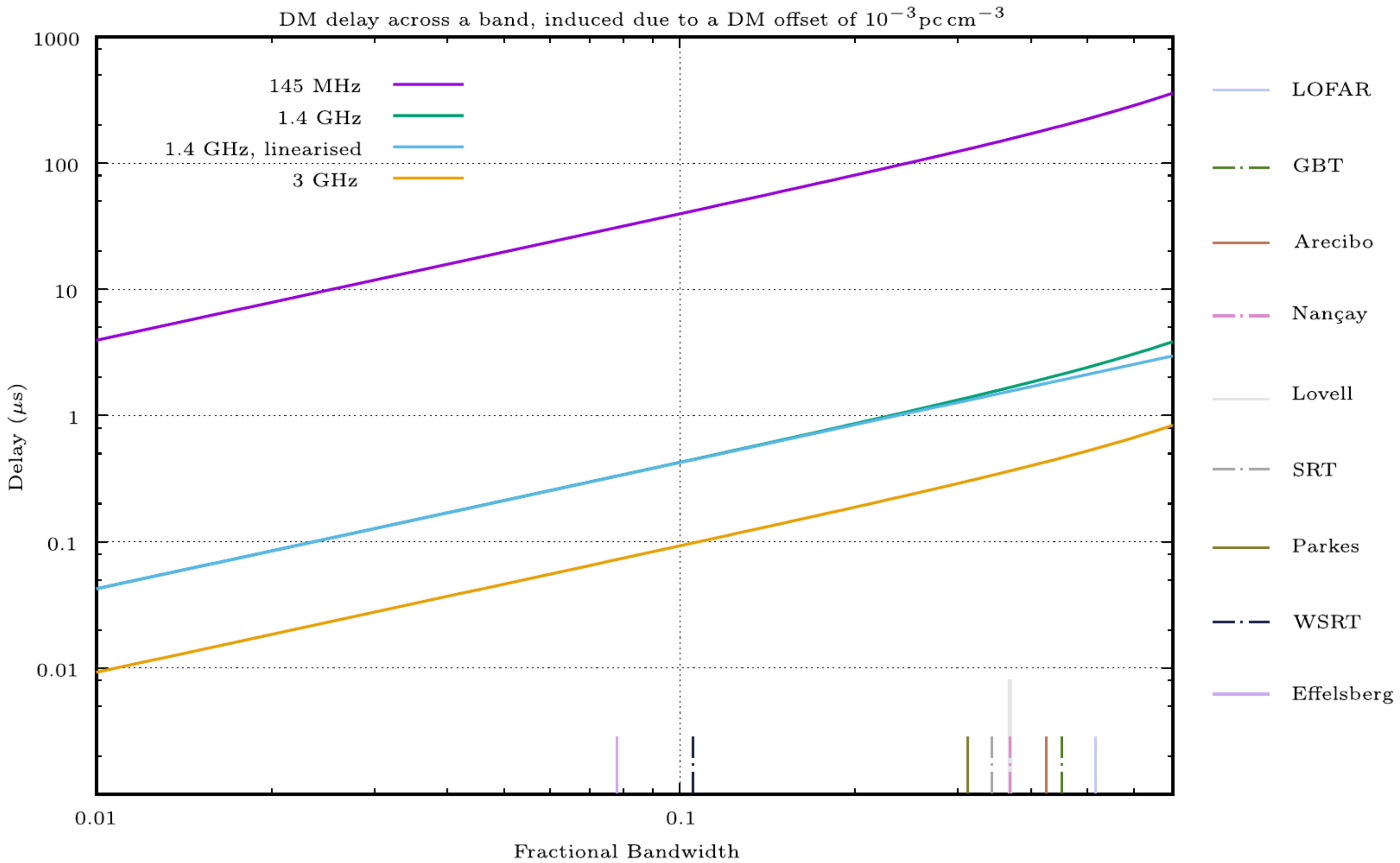
- Observations ongoing since 2013
- Core observations:
  - Bi-monthly cadence
  - 52 pulsars
- International stations used as stand-alone telescopes:
  - Weekly cadence
  - >100 pulsars
  - 6 German, 1 French, 1 Swedish stations
  - Part of data streamed to the Juelich Supercomputing Center (Germany)
- All data are then transferred to the University of Bielefeld, where they are preprocessed (i.e., RFI-cleaned and beam-calibrated) and made ready to use

Observing pulsars with NenuFAR

- NenuFAR covers the <100 MHz band with a much better *bandpass* than the LBAs
- In terms of sensitivity, it is equivalent to the core, but over almost the whole 10-90 MHz band
- Pulsar observations ongoing since 2019 under the **NenuFAR Pulsar KP**
- >40 monitored pulsars
- 4 millisecond pulsars
- Bi-weekly to monthly cadence
- Higher precision in the measure of DM and RM



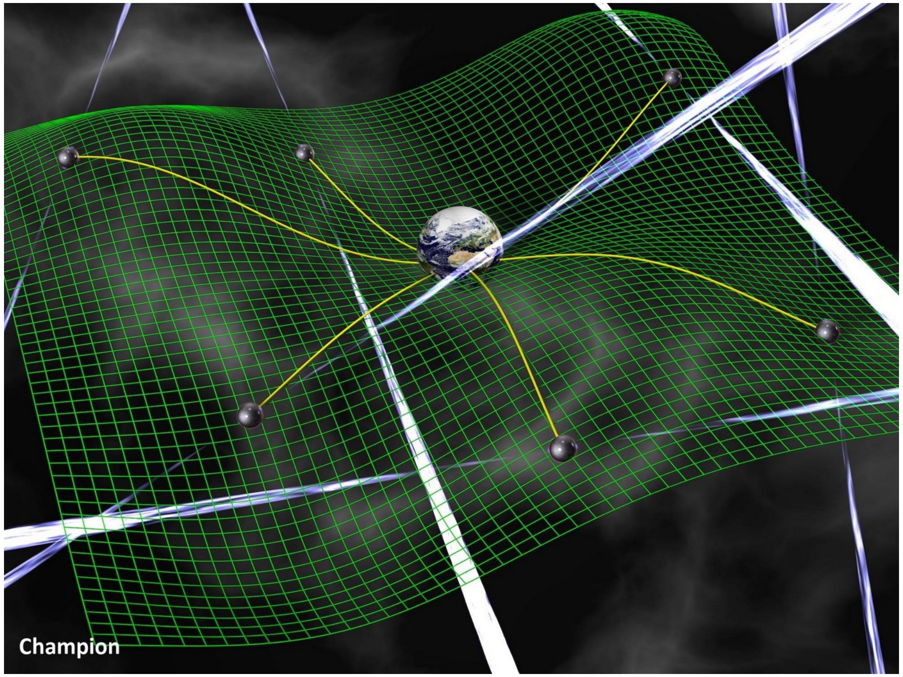
The upper leverage of low frequencies observations



[Verbiest & Shaifullah 2018]

PTAs: the nanoHertz window for gravitational waves

Gravitational waves by coalescing supermassive black-hole binaries perturb the space-time around the Earth and the pulsars, and **induce ‘red’ deviations in the expected arrival times of the radiation pulses**



$$P_{GWB}(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{yr^{-1}}\right)^{2\alpha-3=-13/3}$$

[Detweiler 1979, Jenet+2005/2006]