Congresso Nazionale Oggetti Compatti XII

The EPTA approach to the search for ultralong period GWs

on behalf of
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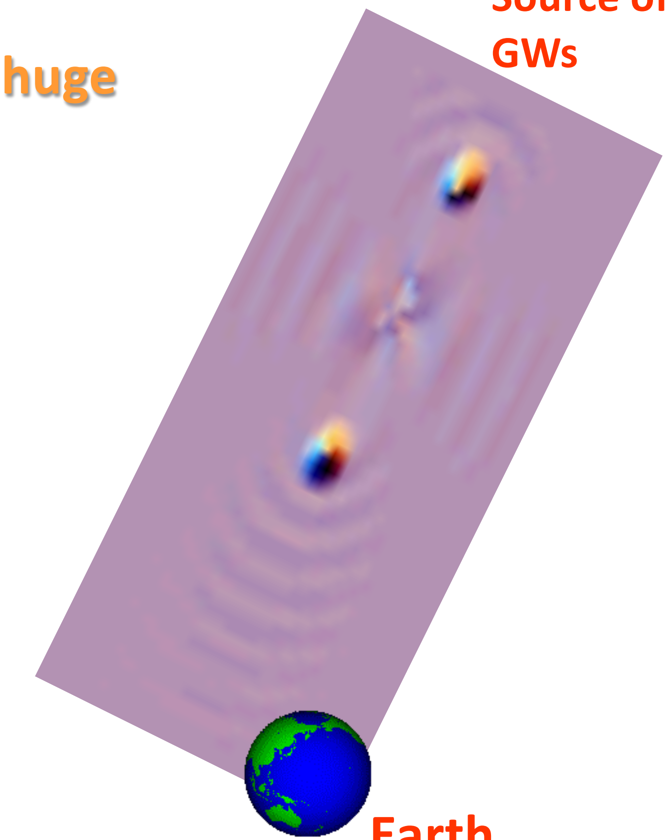
Pulsars as GW detectors

The Pulsar-Earth path can be used as the arm of a huge cosmic gravitational wave detector

Perturbation in space-time can be detected in timing residuals over a suitable long observation time span

Radio Pulsar



Sensitivity (rule of thumb):

$$h_c(f) \sim \frac{\sigma_{\mathrm{ToA}}}{T}$$

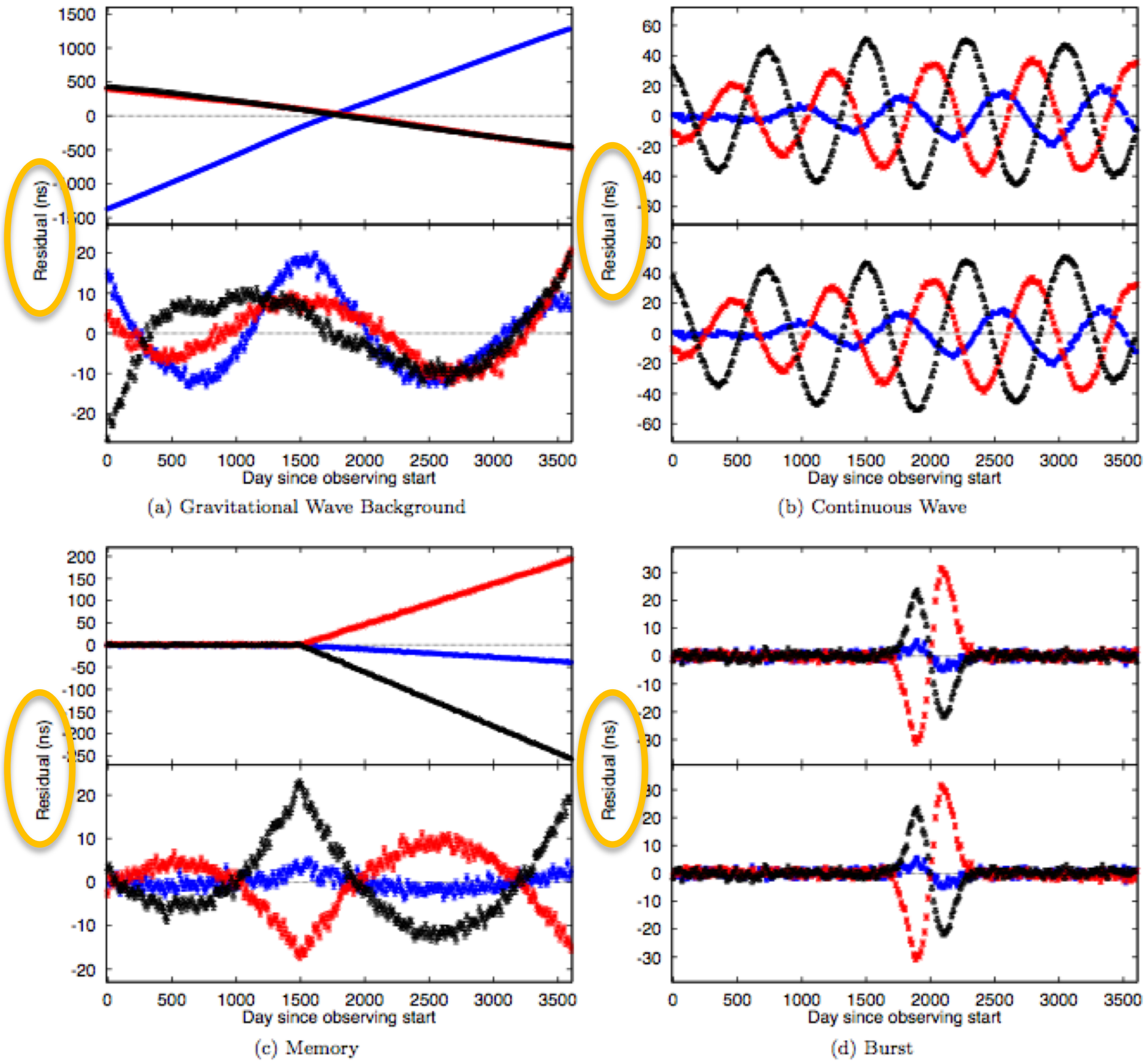
Where:

$h_c(f)$ is the dimensionless strain at GW frequency f

σ_{ToA} is the rms uncertainty in Time of Arrival of the pulses

T is the duration of the data span

The theoretical "clean" signals in the Residuals



(a) Gravitational Wave Background
(b) Continuous Wave
(c) Memory
(d) Burst

Upper panels: trends without fitting for P and dP/dt

Lower panels: trends after fitting for P and Pd/dt for 3 reference pulsars*:*

PSR J0437–4715,
PSR J1012+5307
PSR J1713+0747

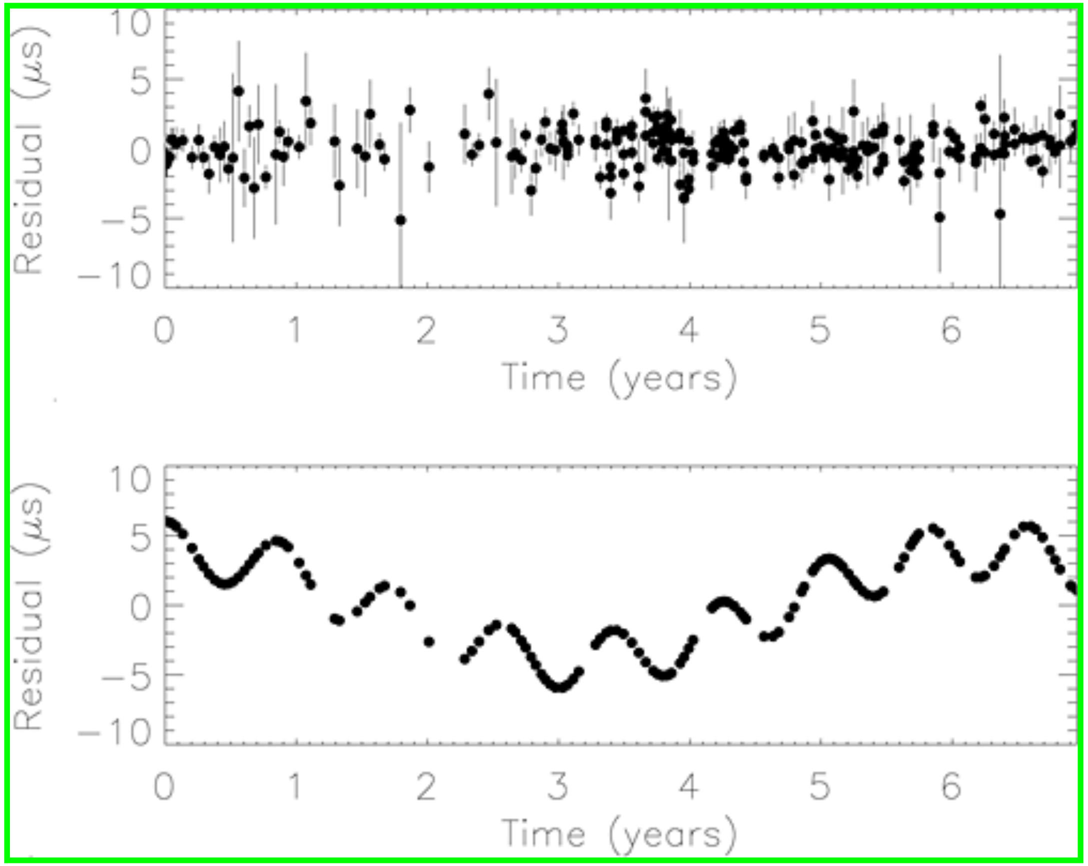
Effetti attesi ≈ 10-20 nanosec

[Burke-Spolaor 2016]

An instructive application (using 1 pulsar)

The radio galaxy 3C66 (at $z = 0.02$) was claimed to harbour a double SMBH with a total mass of $5.4 \cdot 10^{10}$ M_{sun} and an orbital period of order ~yr

[Sudou et al 2003]

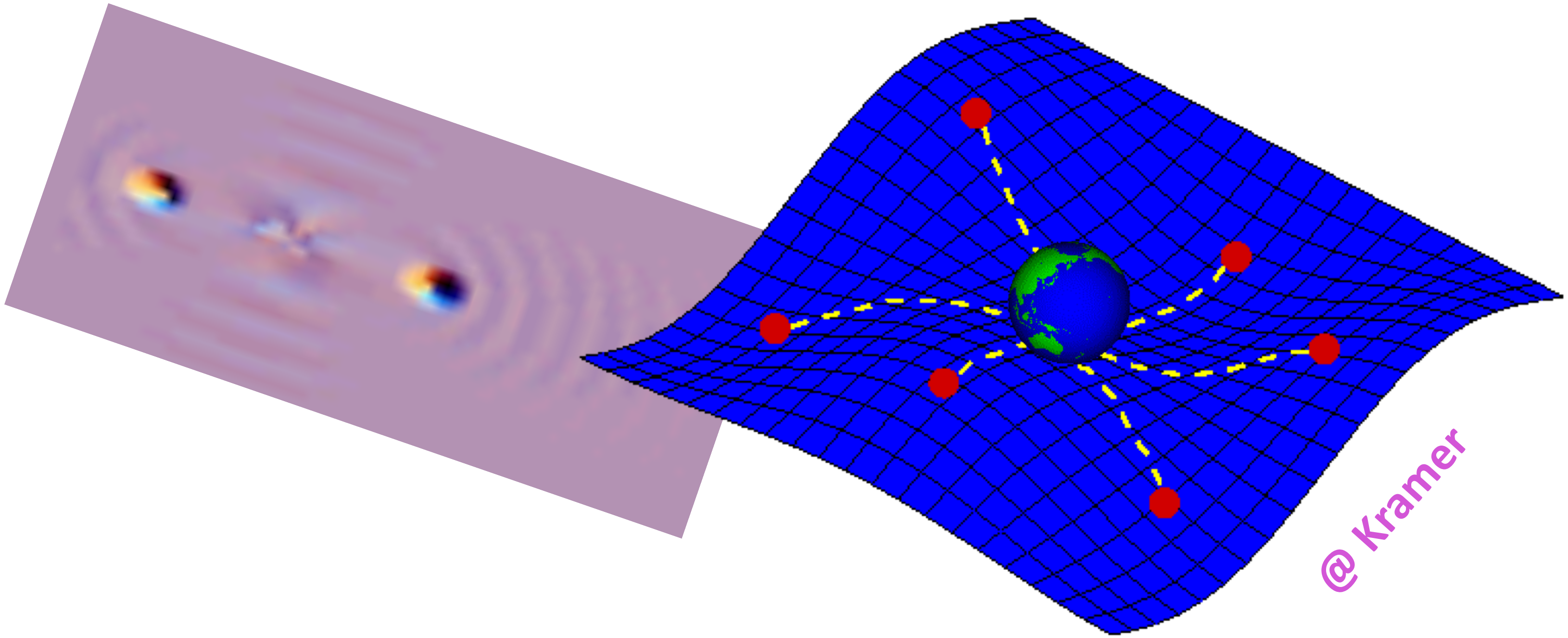


[Jenet et al 2004]

Timing residuals from PSR B1855+09 excluded such a massive double BH at 95 c.l.

A pulsar timing array (PTA)

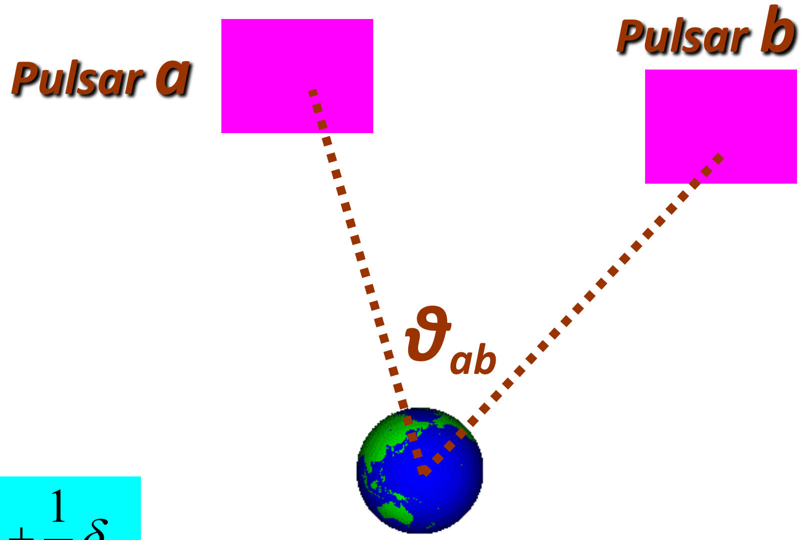
Using a number of pulsars distributed across the sky it is possible to separate the timing noise contribution from each pulsar from the signature of the GW background, which manifests as a local (at Earth) distortion in the times of arrival of the pulses which is common to the signal from all pulsars



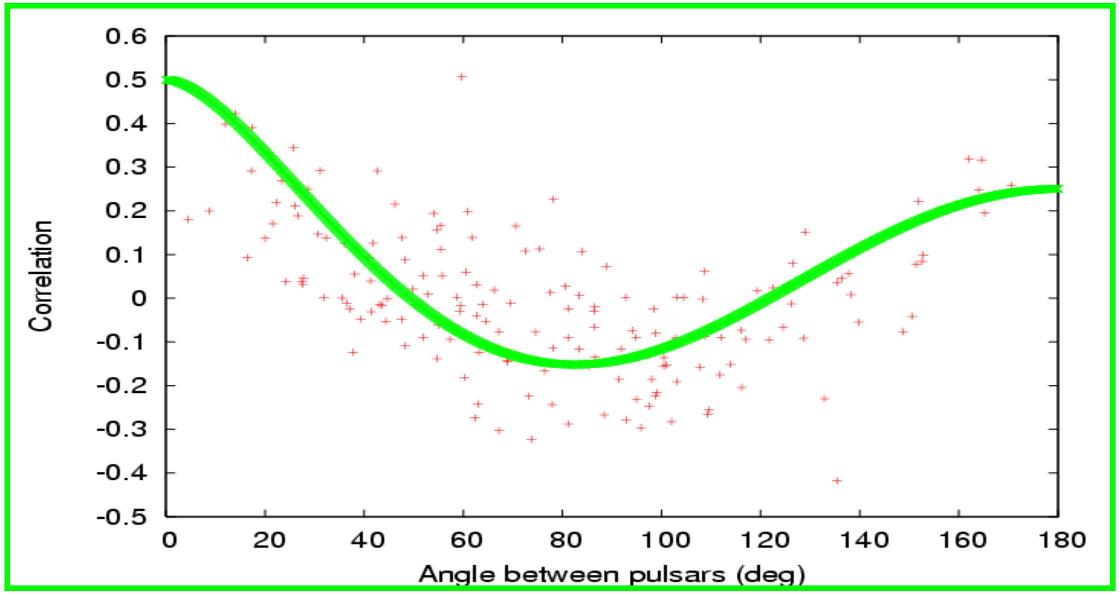
Searching for a GW background using 2+ pulsars

Idea first discussed by Romani [1989] and Foster & Backer [1990]

- **Clock errors**
  All pulsars have the same TOA variations:
  Monopole signature
- **Solar-System ephemeris errors**
  Dipole signature
- **Gravitational waves background**
  Quadrupole signature



$$\zeta(\theta_{ab}) = \frac{3}{2}\left(\frac{1-\cos\vartheta_{ab}}{2}\right)\log\left(\frac{1-\cos\vartheta_{ab}}{2}\right) - \frac{1}{4}\left(\frac{1-\cos\vartheta_{ab}}{2}\right) + \frac{1}{2} + \frac{1}{2}\delta_{ab}$$



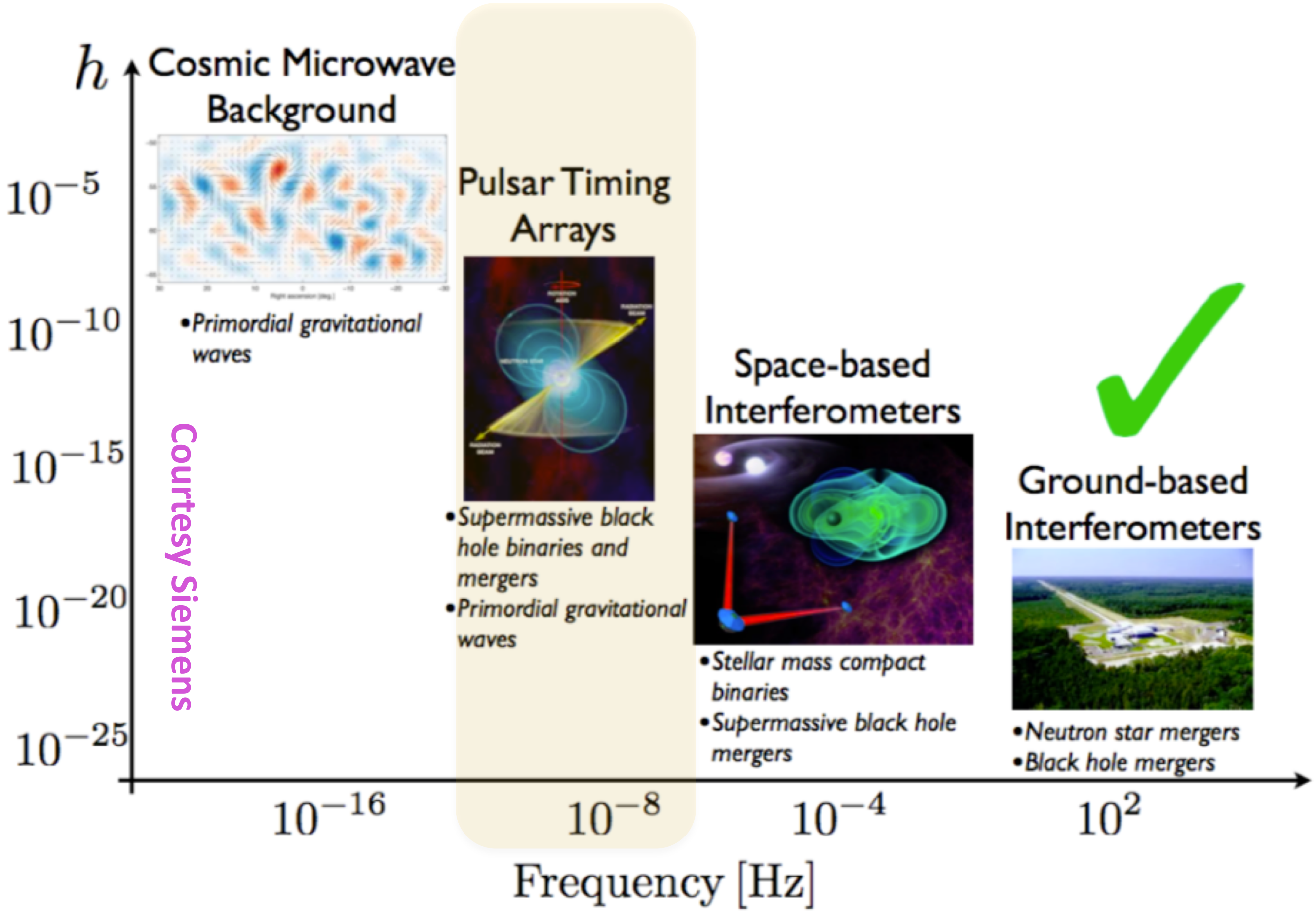
[slide adapted from Manchester 11]

Hellings & Downs [1983]: correlation that an isotropic and stochastic GWB leaves on the timing residuals of 2 pulsars *a* and *b* separated by an angle ϑ_{ab} in sky

Pulsar Timing Array(s): the frequency space

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like advLIGO, advVIRGO and eLISA

- **Expected sources**:
  - binary super-massive black holes in early Galaxy evolution
  - cosmic strings
  - cosmological sources
- **Types of signals**:
  - stochastic (multiple)
  - periodic (single)
  - burst (single)



The expected Power Spectrum of the GWB

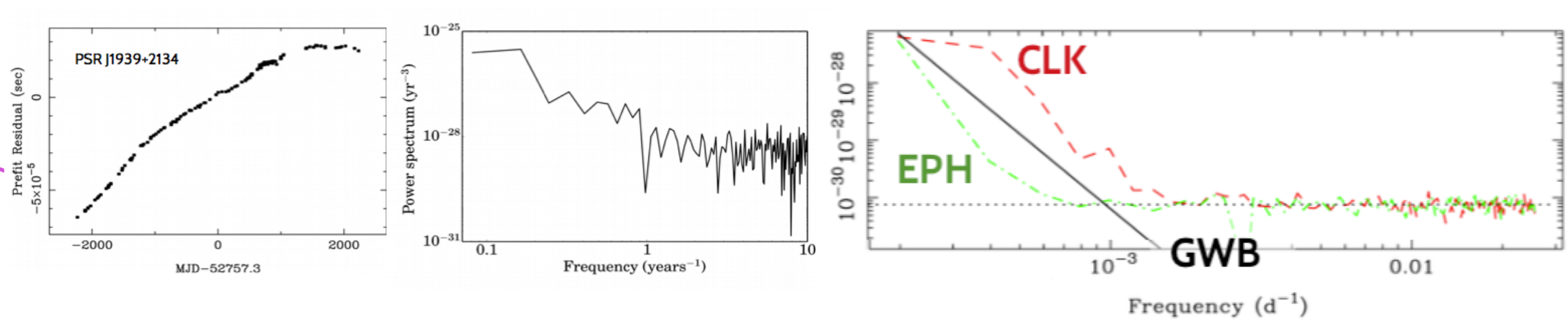
In the simplest picture, the corresponding Power Spectrum from the ensemble of these MBH binaries (supposed to be isotropic and stocastic) is

[e.g. Detweiler1979; Jenet et al. 2005, 2006]

$$P_{GWB}\,(f) \sim f^{-2\alpha-3} = f^{-13/3} \quad \text{for} \quad \alpha = 2/3$$

This is a very steep RED power spectrum for GWB

Courtesy Tiburzi 2019



[Tiburzi et al 2016]

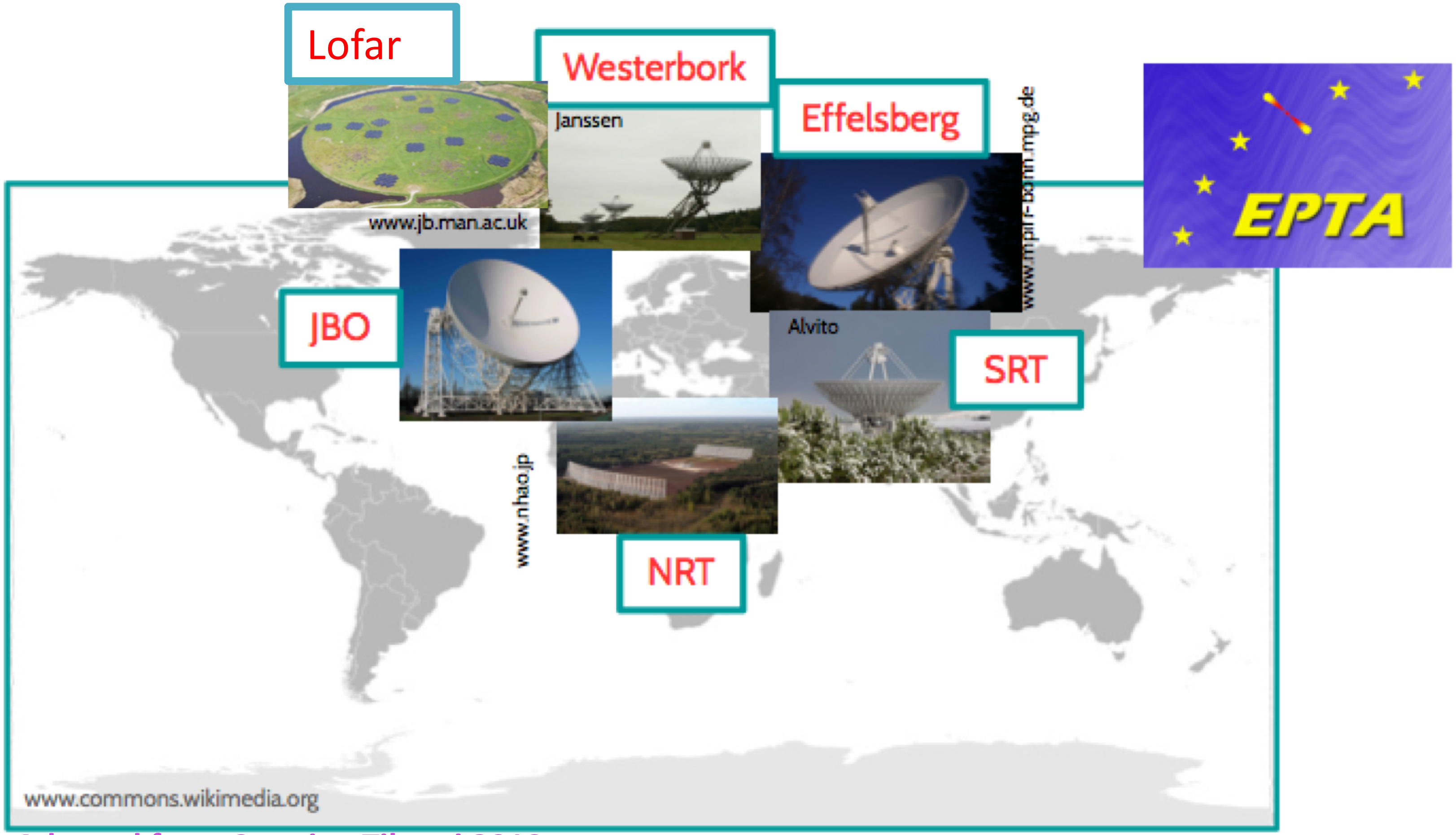
That must be disentangled from the RED noise affecting the Power Spectrum of the timing residuals of few recycled pulsars: that can be caused by turbulent ionised interstellar medium, spin noise, instrumentation issues, incorrect planetary ephemeris (EPH), incorrect time standards (CLK), gravitational waves (GW) or unknown effects

See [Chalumeau et al 2022] for a complete analysis of the noises in EPTA data

PPTA: Parkes Pulsar Timing Array

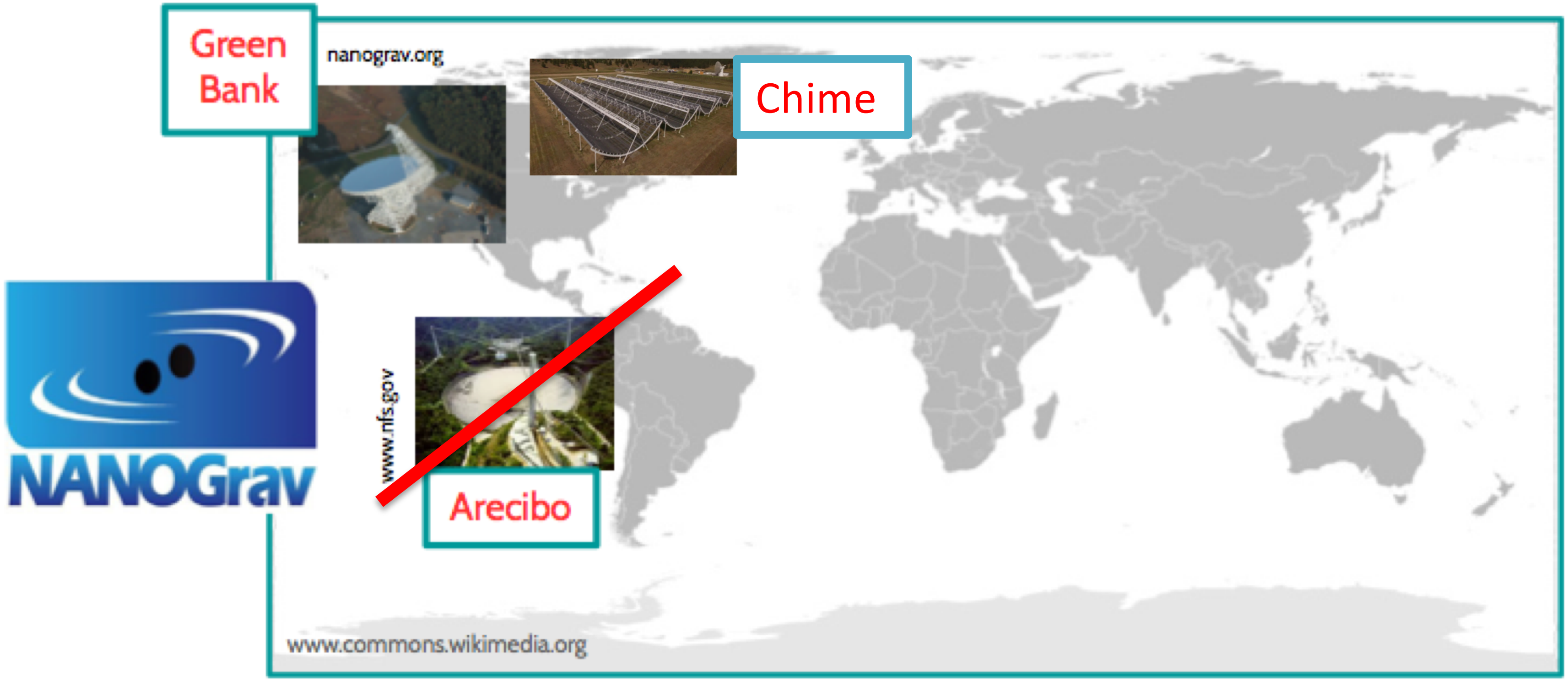
Adapted from Caterina Tiburzi 2019

EPTA: European Pulsar Timing Array



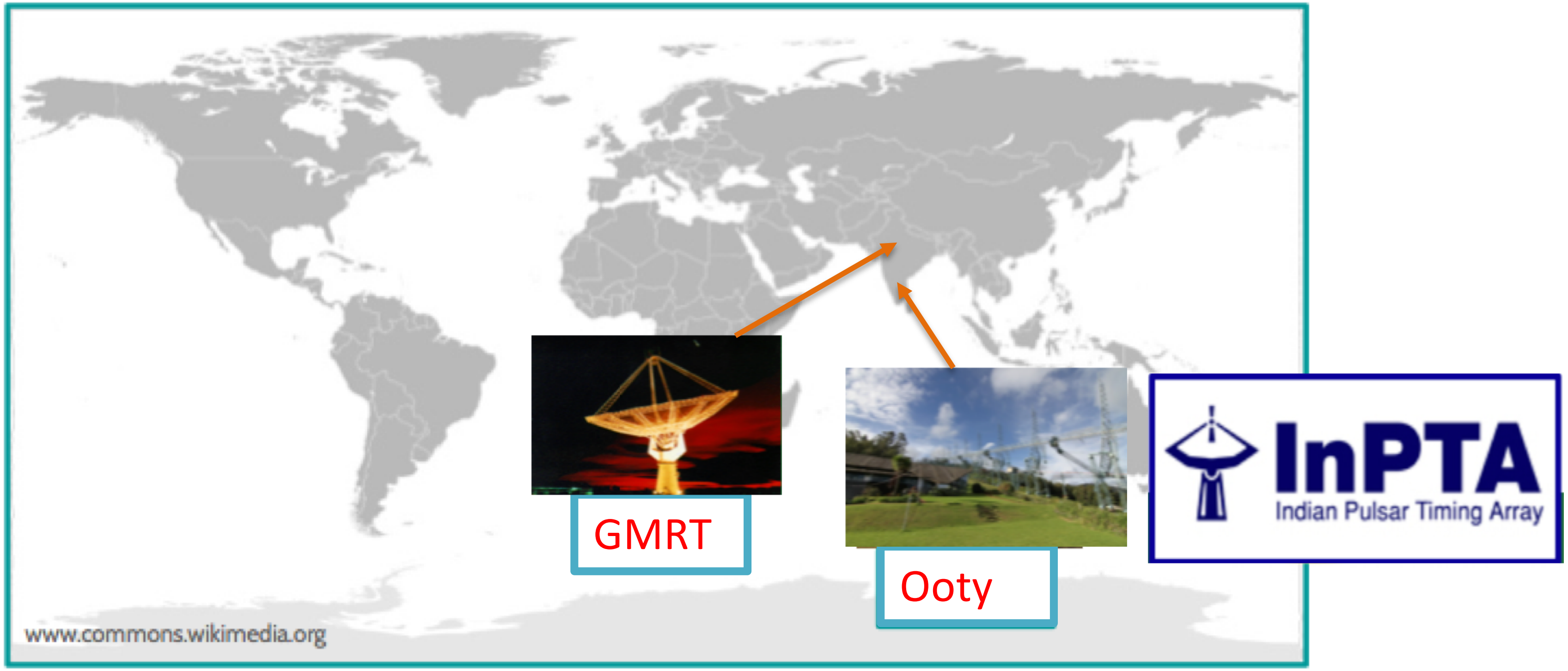
Adapted from Caterina Tiburzi 2019

NANOGrav: North American Array



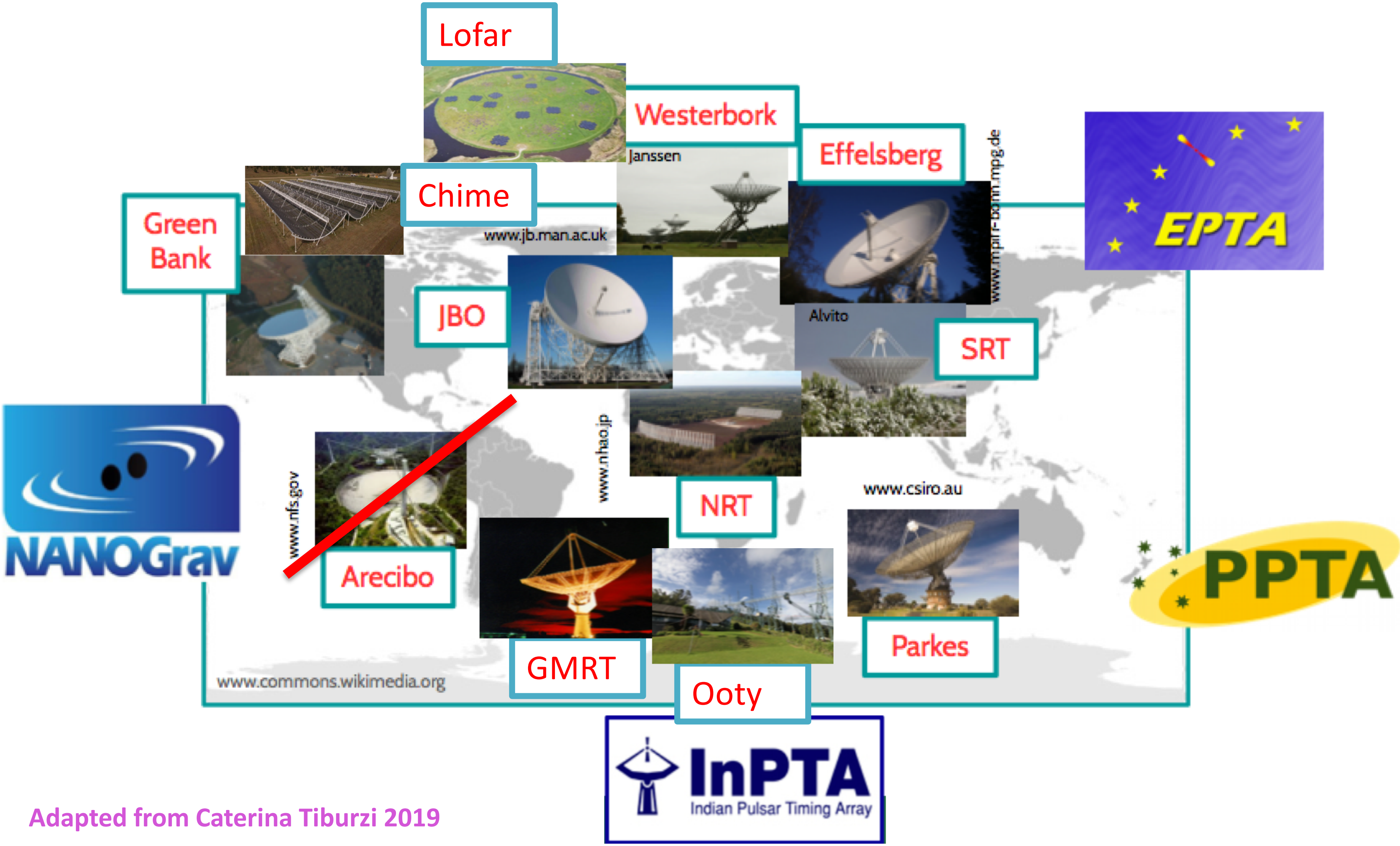
Adapted from Caterina Tiburzi 2019

InPTA: Indian Pulsar Timing Array



Adapted from Caterina Tiburzi 2019

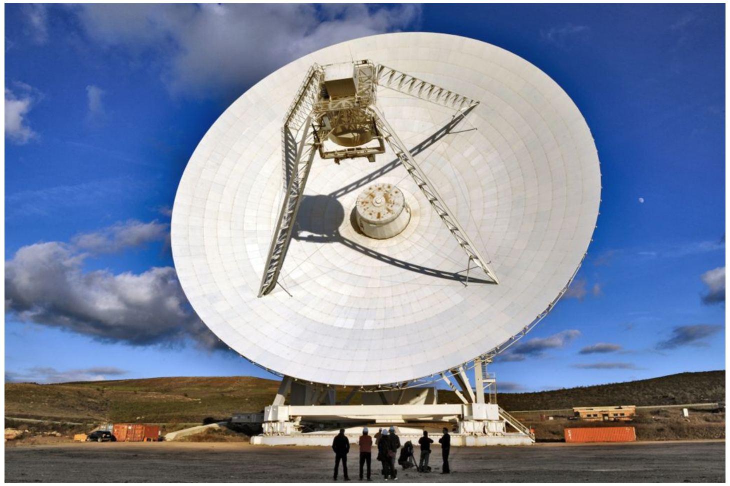
IPTA: International Pulsar Timing Array



Adapted from Caterina Tiburzi 2019

Italian Assets

Sardinia Radio Telescope: SRT



❖ Fully steerable, wheel-and-track radio telescope

➢ Frequency coverage: 0.3 - 115 GHz (almost continuously):

- ➢ **dual band 300-400 MHz 1300-1800 MHz receiver**
- ➢ 5.5-7.5 GHz receiver
- ➢ 7 beam 18-26 GHz receiver
- ➢ 19 beam 33-50 GHz receiver
- ➢ Tri-band for VLBI receiver
- ➢ 9 beam 75-116 GHz receiver
- ➢ 80-116 GHz bolometer

❖ Primary mirror : 64 m

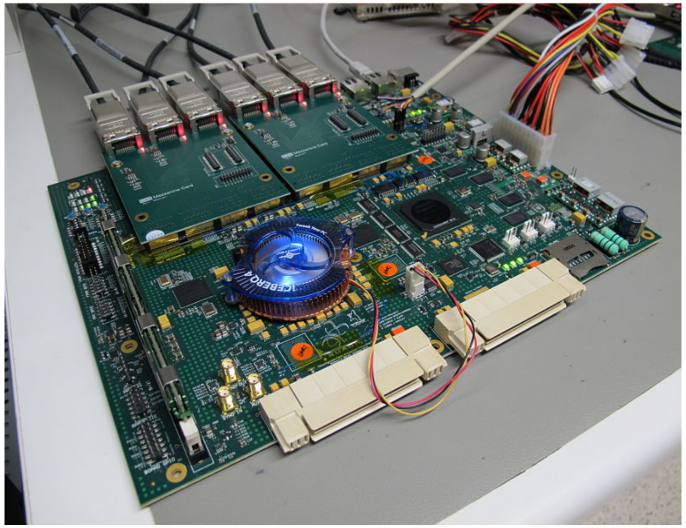
❖ *Quasi*-Gregorian system with shaped surfaces

❖ Active optics: 1116 actuators

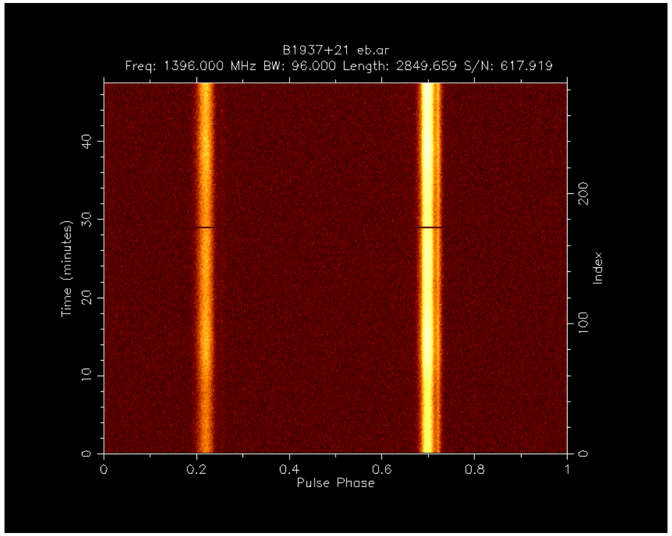
❖ 6 focal positions (up to 20 receivers): Primary, Gregorian, 4 Beam Wave Guide

❖ Frequency Agility

❖ **Coherently De-dispersing Back-end(s) operating in Baseband mode**

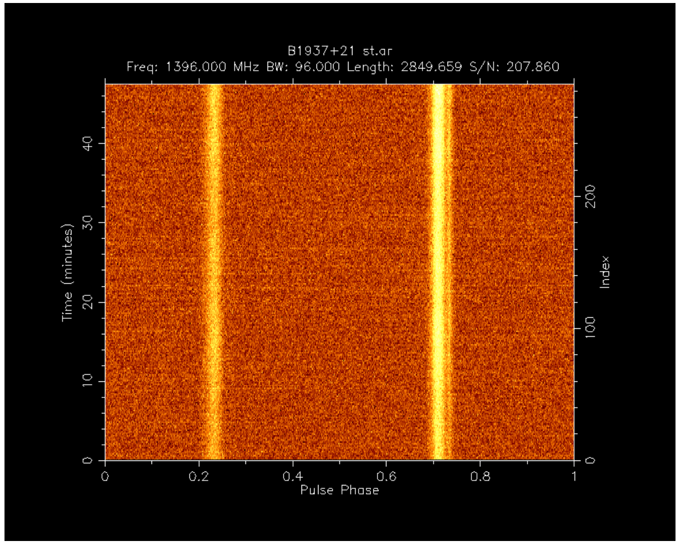


B1937+21 @ Effelsberg



[Courtesy Perrodin 2019]

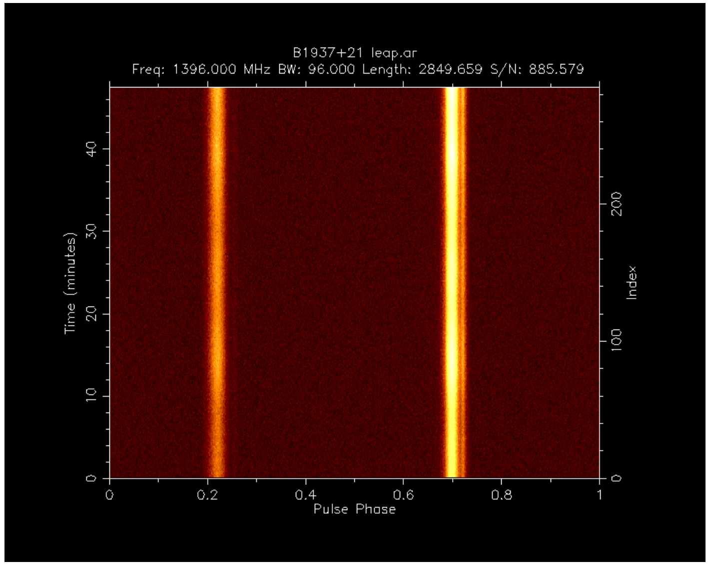
B1937+21 @ SRT



***LEAP**: Large European Array for Pulsars*

(originally funded by EU grant for 5 years)

B1937+21 @ SRT + Effelsberg



[Courtesy Perrodin 2019]

Combining "coherently" all the 5 major EPTA instruments, SRT is part of the best available telescope at 20cm-band for doing pulsar timing, before the SKA era...

Published best limits on amplitude of the GW background from SMBH binaries [with a GW spectral idx -2/3 at f_{GW}=2.8 nHz (i.e. P_{GW}=1 yr) for H_o = 73 km s^{-1} Mpc^{-1}]

NANOGrav: **Arzoumanian et al., 2015: A < 1.5 x 10^{-15}**

EPTA: **Lentati et al., 2015: A < 3 x 10^{-15}**

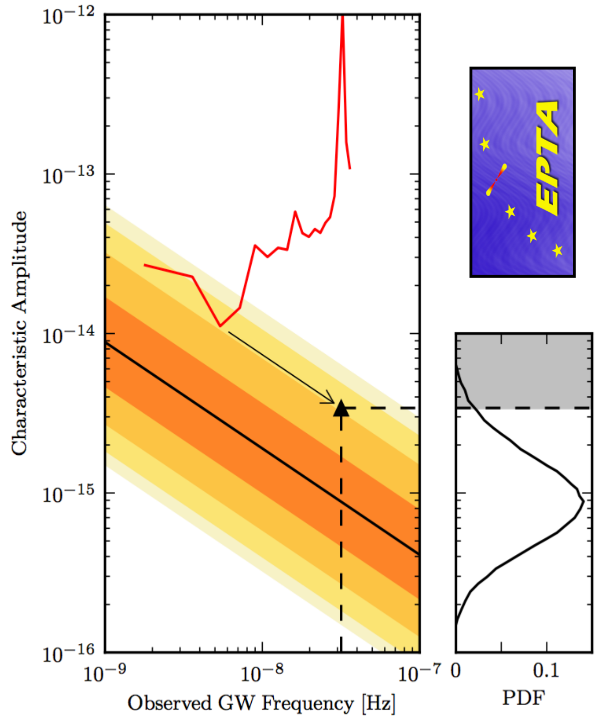
(very robust limit including all caveats)

PPTA: **Shannon et al., 2015:**

A < 1.0 x 10^{-15} [Ω_{GW} < 2.3 x 10^{-10}]

IPTA: **Verbiest et al., 2016: A < 1.7 x 10^{-15}**

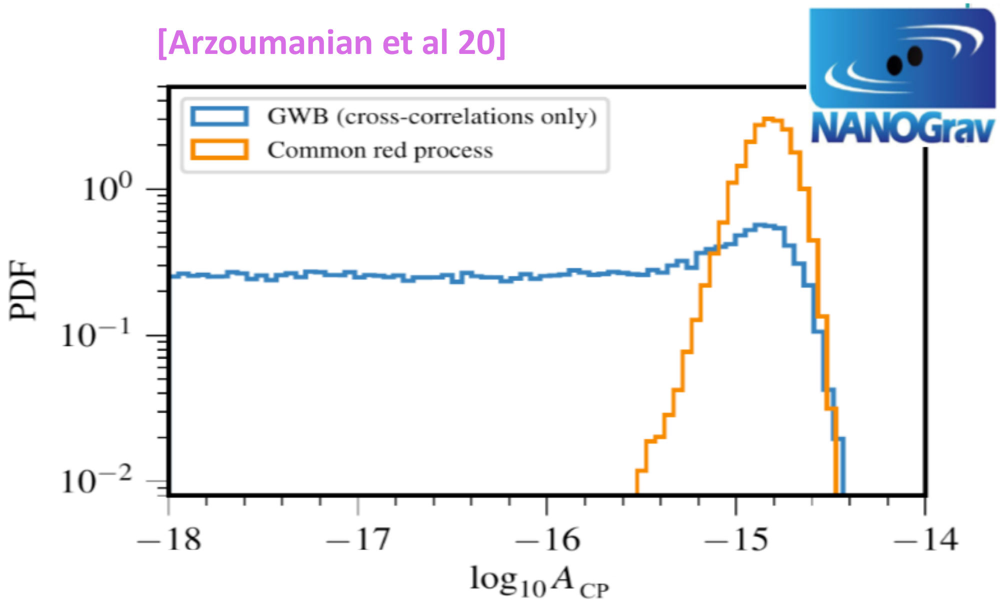
(based on relatively old data only)

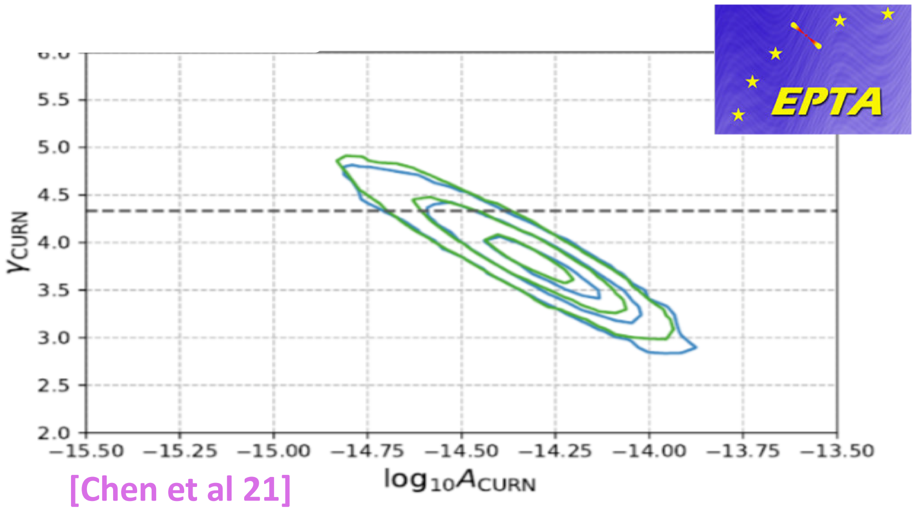


[Lentati et al 15]

Now detected a common uncorrelated red noise (CURN)

[Arzoumanian et al 20]





[Chen et al 21]

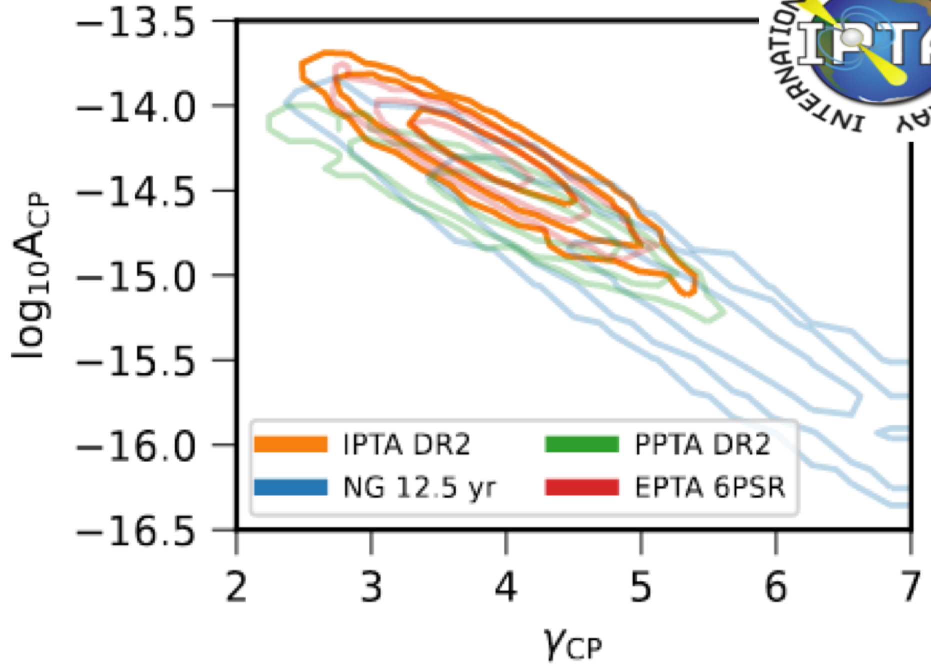
All the PTA collaborations are currently <u>separately</u> detecting a red noise process that seems to be common to all the millisecond pulsars in the arrays, although spatially uncorrelated

Need to work on larger datasets to address the interpretation of the CURN

Adapted from Tiburzi 2021

Detected a common uncorrelated red noise (CURN) by IPTA

[Antoniadis et al 22]



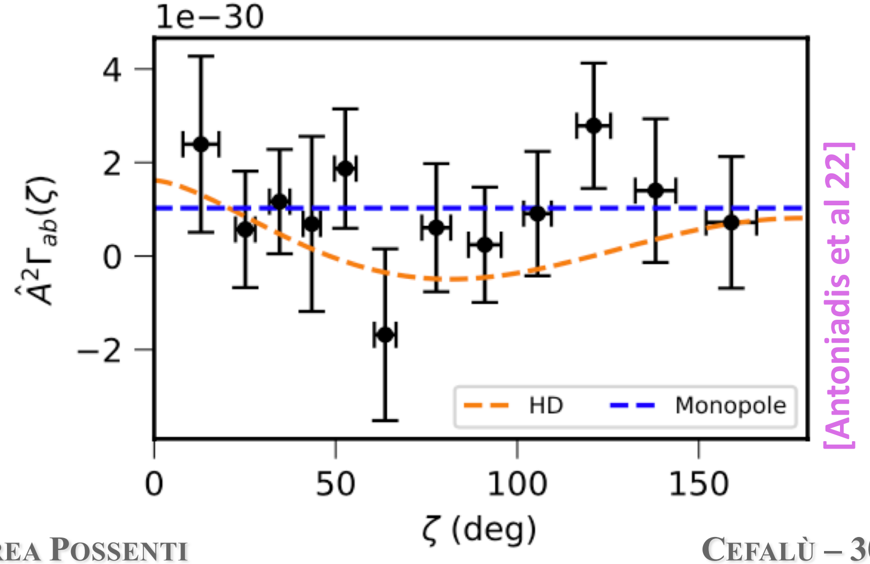
the combined international data set is more sensitive than individual PTA datasets

Parameters range:

$A_{CURN} = 3.8\,^{+6.3}_{-2.5} \times 10^{-15}$

$\gamma_{CURN} = 4 \pm 1$

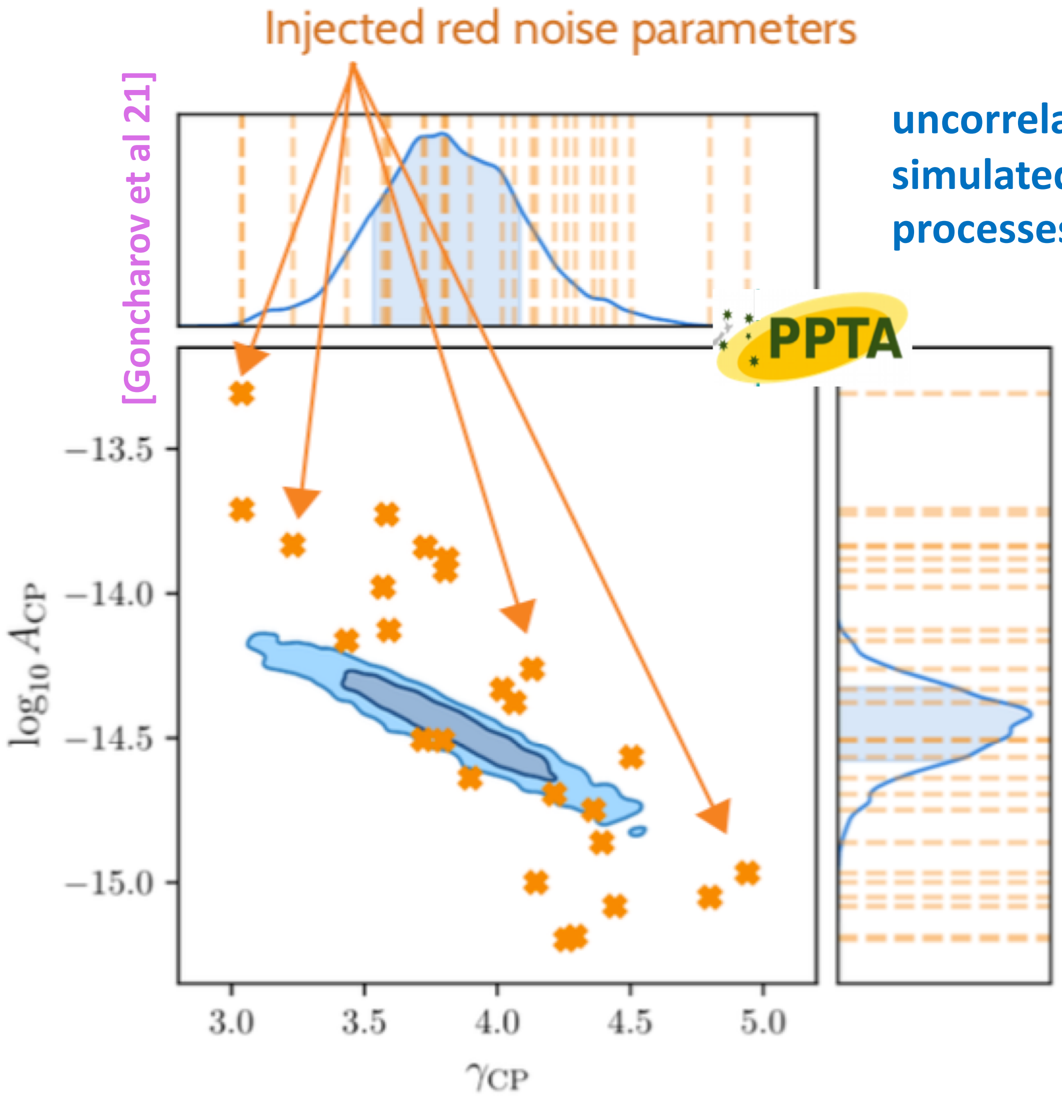
Fixing $\gamma_{CURN} = 13/3$, the best estimate is $A_{CURN} = 2.8\,^{+1.2}_{-0.8} \times 10^{-15}$



Still:

no hint of the H-D spatial correlation

Detected a common uncorrelated red noise (CURN): interpretations …



uncorrelated red noise is naturally favoured in simulated data containing non-common red noise processes

It is expected that a common, uncorrelated red noise process will show up before the GWB detection

However, there is no way yet to understand whether the currently detected signal is a

a) prelude to the GWB or
b) spin noise independently associated to each pulsar

Thanks