PULSAR TIMING ARRAYS AND THE DETECTION OF ULTRA-LONG PERIOD GRAVITATIONAL WAVES

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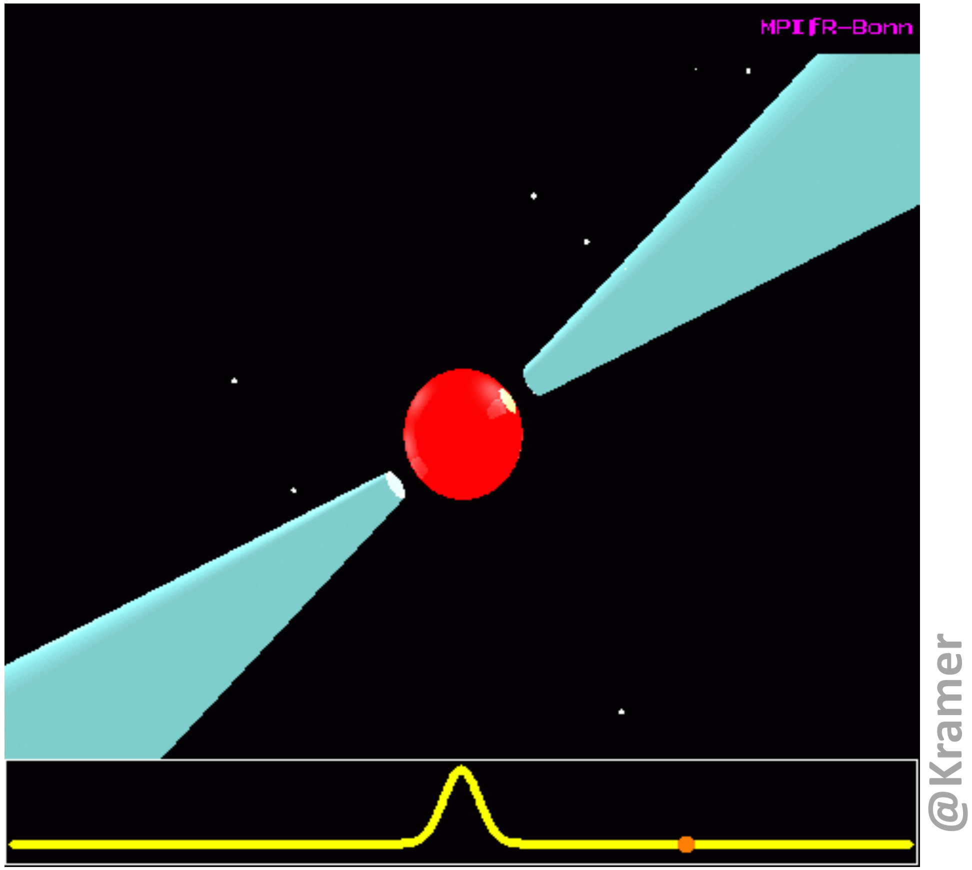
EPTA
IPTA – International Pulsar Timing Array

What is a pulsar

A PULSAR is a rapidly rotating and highly magnetized neutron star, emitting a pulsed radio signal as a consequence of a light-house effect

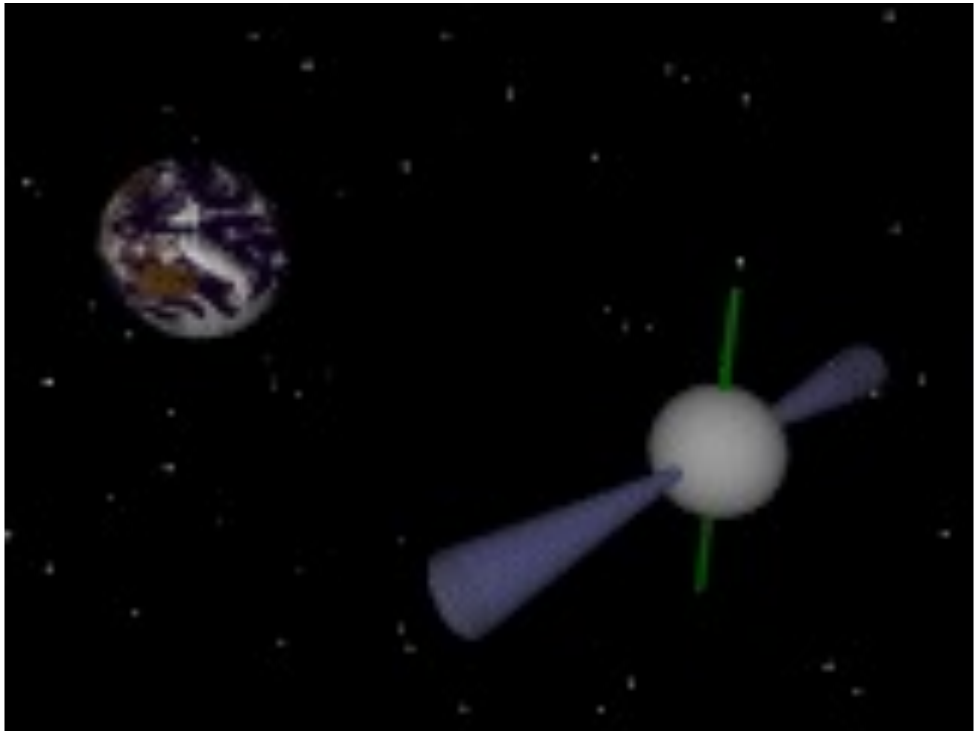


The procedure of "timing"

Performing repeated observations of the Times of Arrival (ToAs) at the telescope of the pulsations from <u>a given pulsar</u>

and

searching the ToAs for systematic trends on many different timescales, from minutes to decades



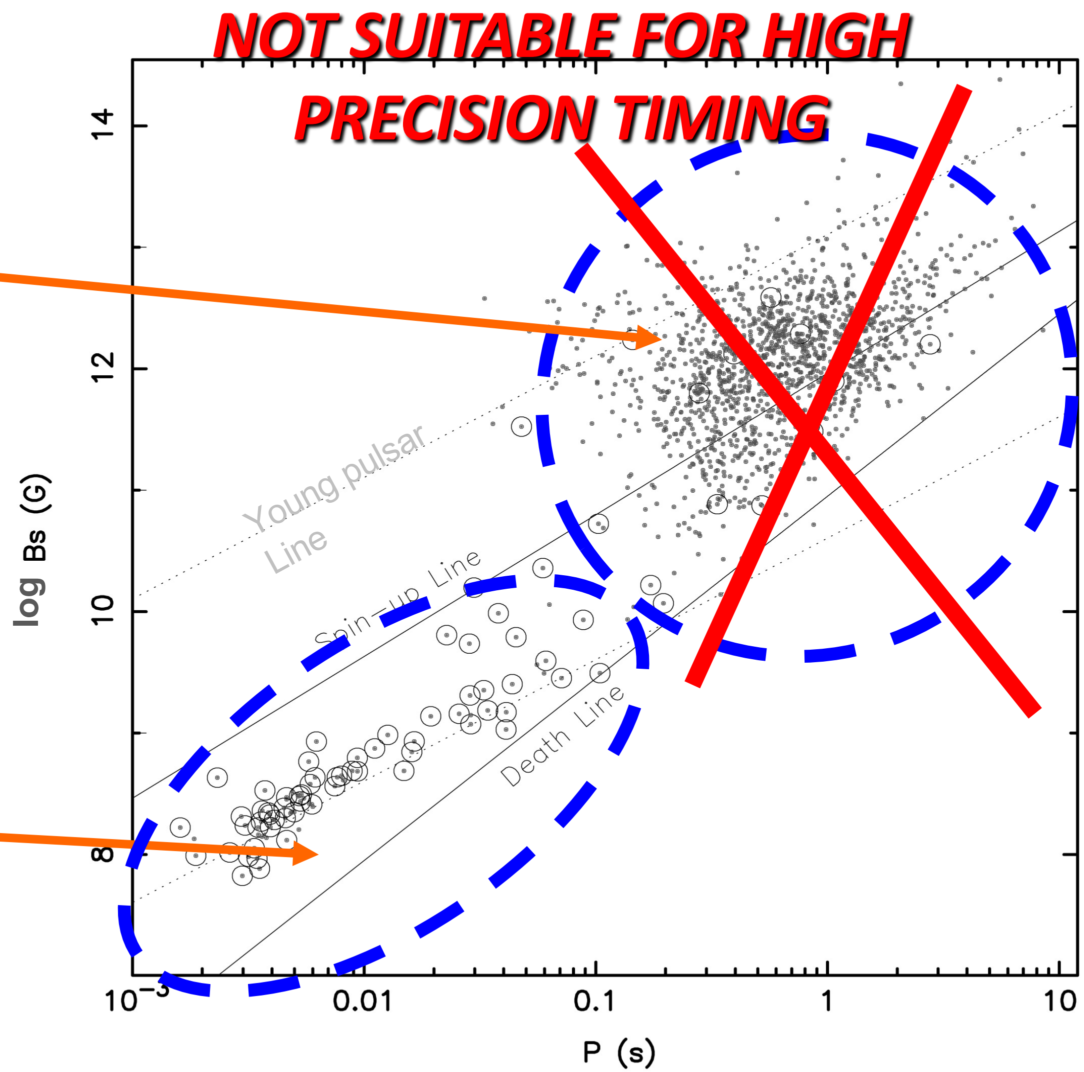
Which pulsars are suitable ?

Ordinary pulsars:
~ 3000 known objects;
NS_{age} < few 10^7 yr

relatively long pulses & rotational irregularities

Recycled pulsars:
~ 500 known objects;
NS_{age} > 10^8-10^9 yr

The most rapidly rotating are known as millisecond pulsars



ATNF Pulsar Catalogue Feb 2024

Why observing the “recycled” pulsars can be so effective ?

Pulsar periods can sometimes be measured with unrivalled precision

e.g. on Jan 16, 1999, PSR J0437-4715 had a period of

5.757451831072007 ± 0.000000000000008 ms

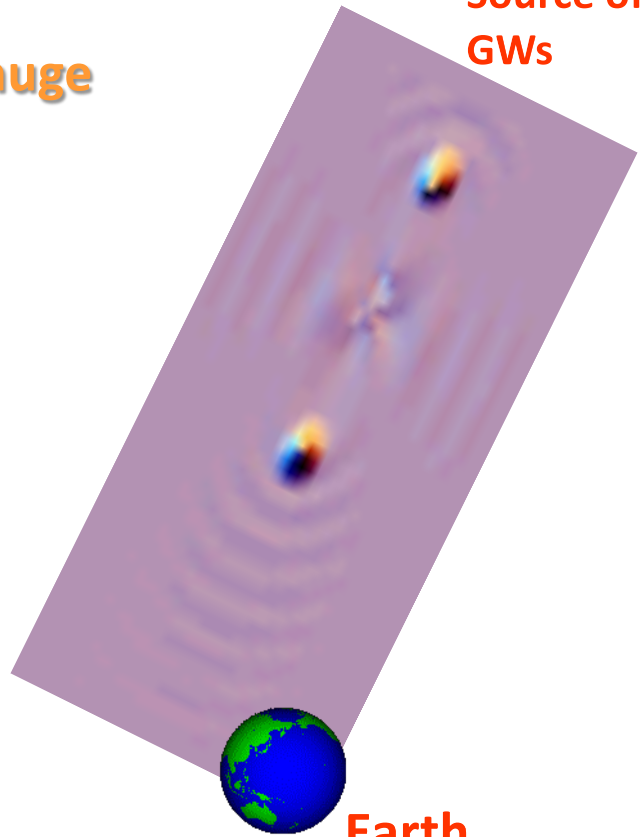
16 significant digits!

Several rapidly spinning pulsars can be used as clocks in the space-time

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):

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

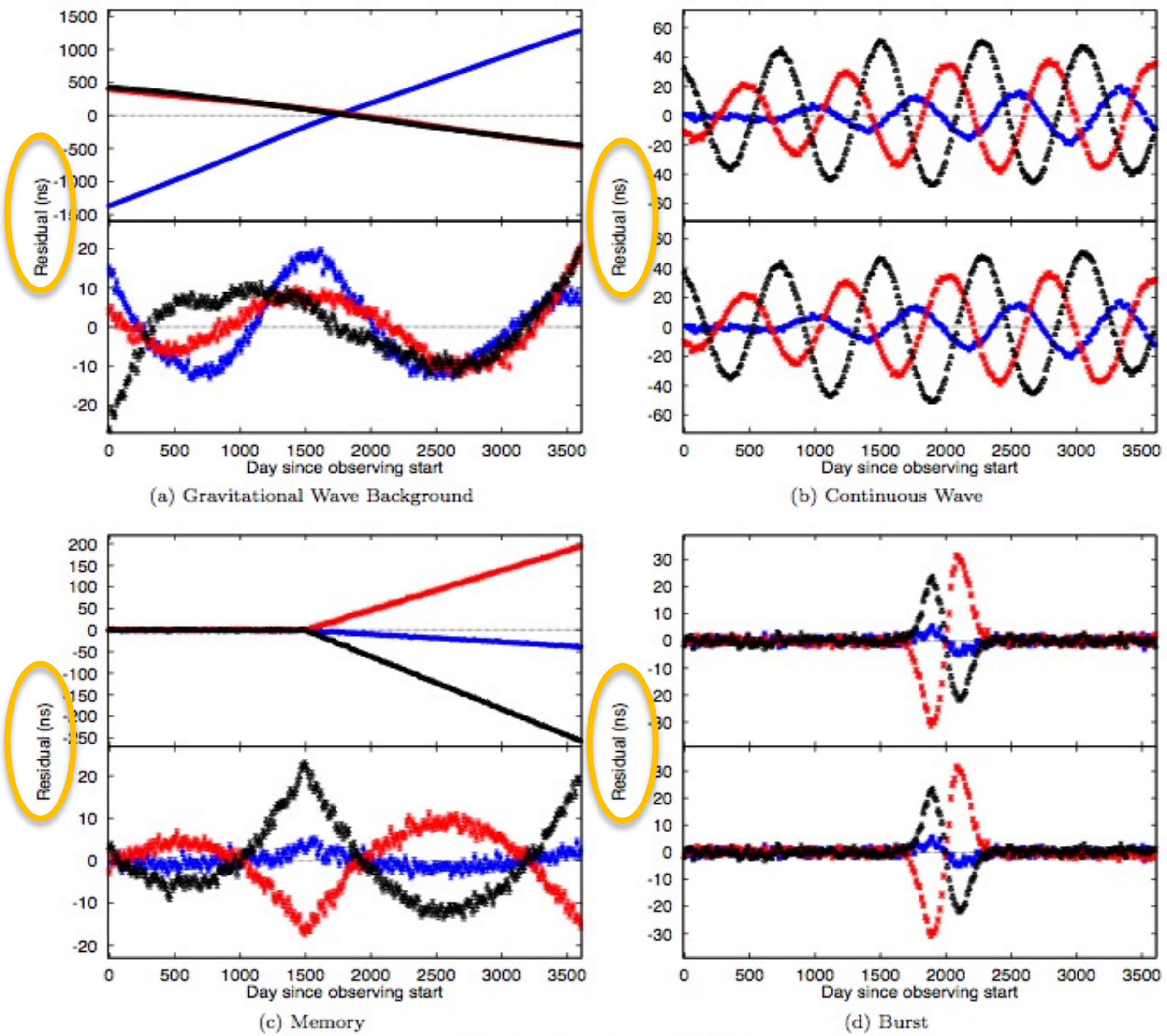
Where:

$h_c(f)$ 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 for various kinds of sources



[Burke-Spolaor 2016]

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

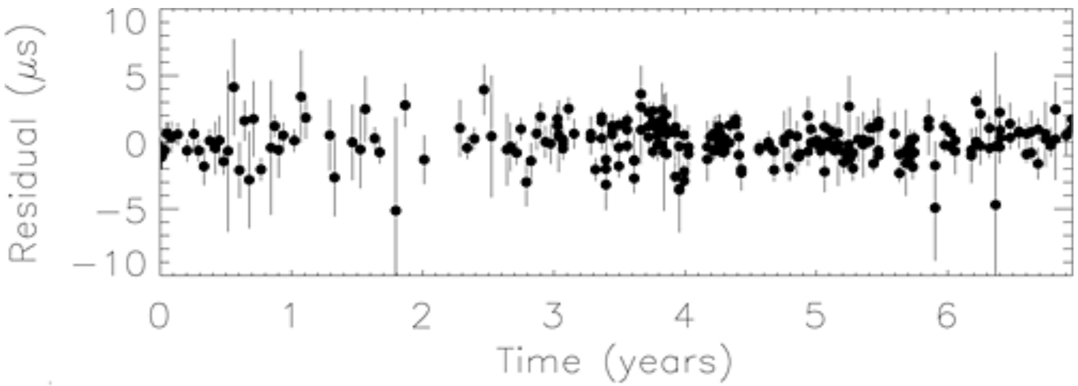
PSR J1713+0747

Expected effects ≈ 10-20 nanosec

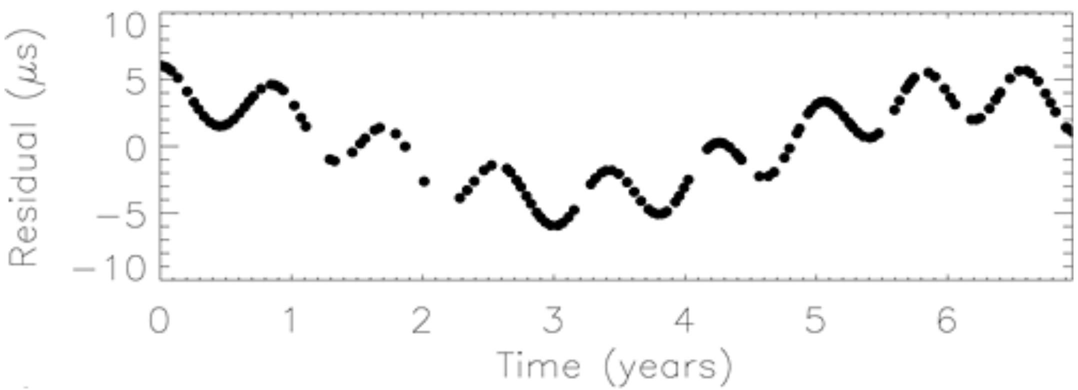
An instructive application (using 1 pulsar)

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]



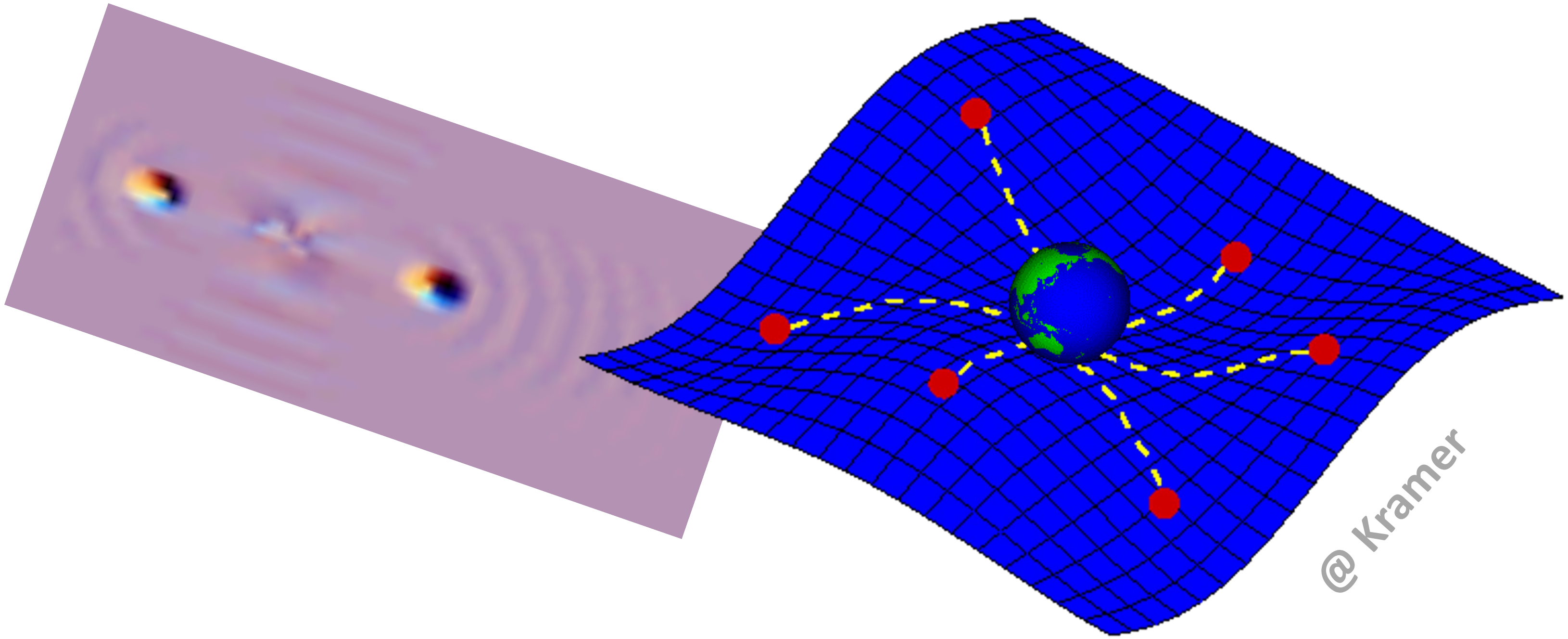
[Jenet et al 2004]



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

A pulsar timing array (PTA)

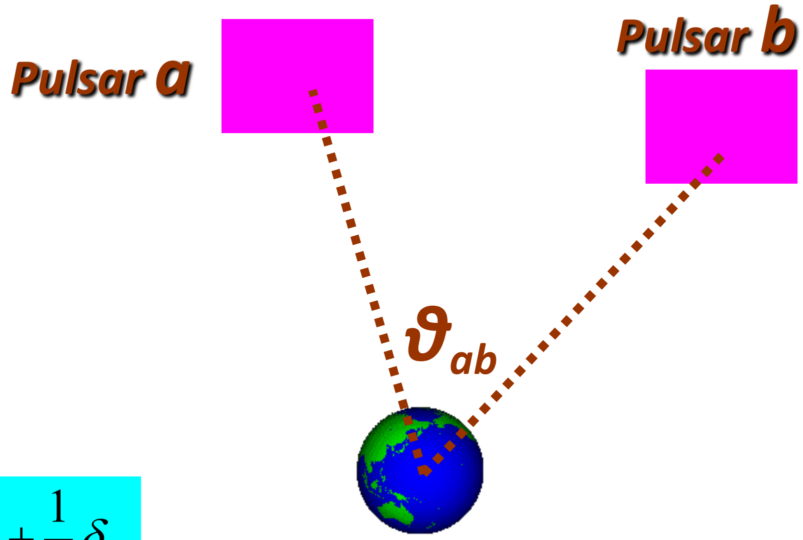
Using a number of pulsars distributed across the sky it is possible to separate the timing noise contribution from each pulsar from the signature of the GW background, which manifests as a local (at Earth) distortion in the times of arrival of the pulses which is common to the signal from all pulsars



Searching for a GW background using 2+ pulsars

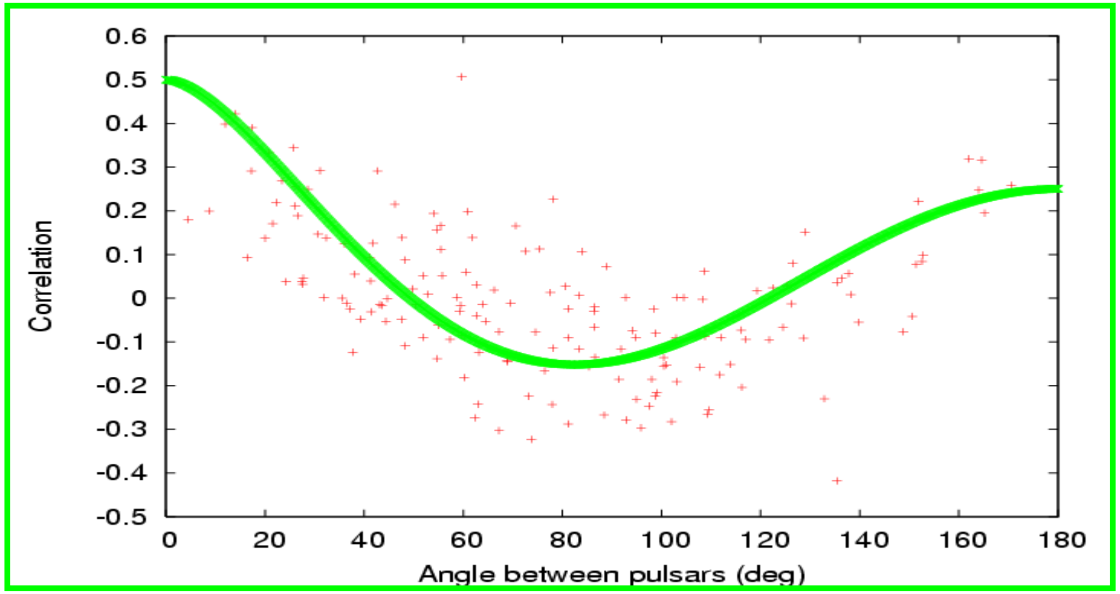
Idea first discussed by Romani [1989] **and** Foster & Backer [1990]

- **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]

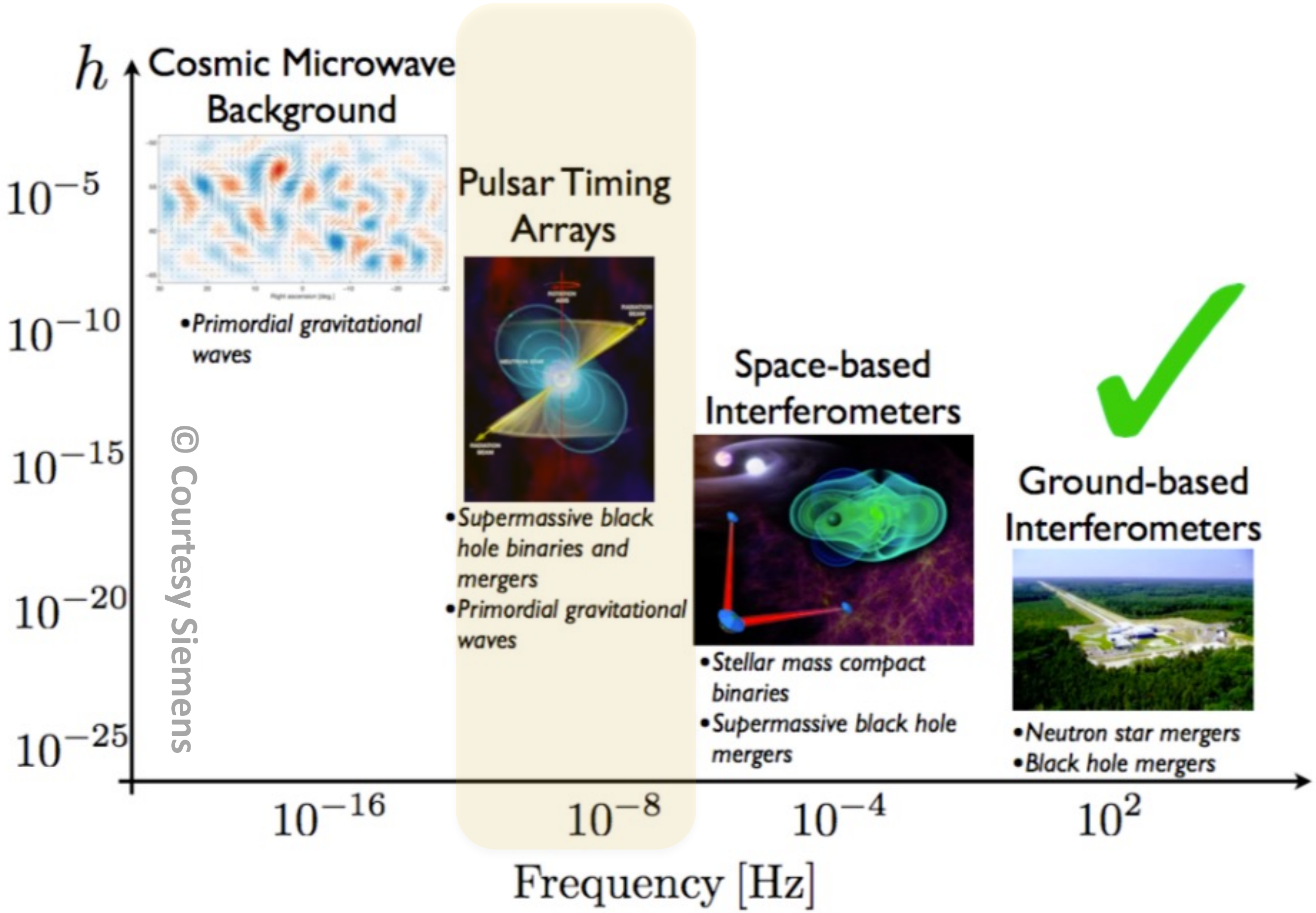


Hellings & Downs [1983]: correlation that an isotropic, stationary and stochastic GWB leaves on the timing residuals of pairs of pulsars *a* and *b* separated by angle ϑ_{ab} in sky

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 GW background due to Super Massive Black-Hole Binaries (SMBHBs)

It's well known that current paradigm is that [e.g. Ferrarese & Merrit 2000]
- mergers are an essential part in galaxy formation and evolution
- nuclei of most (all?) large galaxies host Massive BH(s) i.e. mass $M \gtrsim 10^6\ M_\odot$

When reaching orbital separation *a* of less than about 1 pc, GW emission at frequency *f* become the dominant term in energy loss, making the MBH binary to shrink faster and faster

$$f \sim 3\ \text{nHz} \left[\frac{M}{10^9\ M_\odot}\right]^{1/2} \left[\frac{a}{0{,}01\ \text{pc}}\right]^{-3/2}$$

The expected Power Spectrum of the GWB

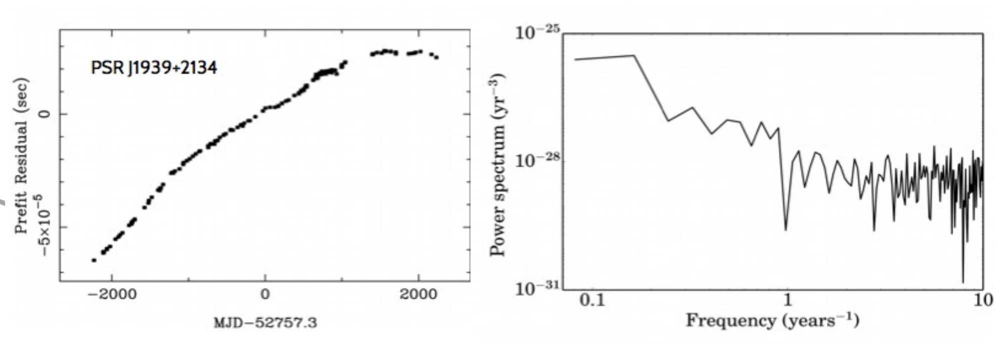
In the simplest picture, the corresponding Power Spectrum from the ensemble of these MBH binaries (supposed to be isotropic and stochastic) is

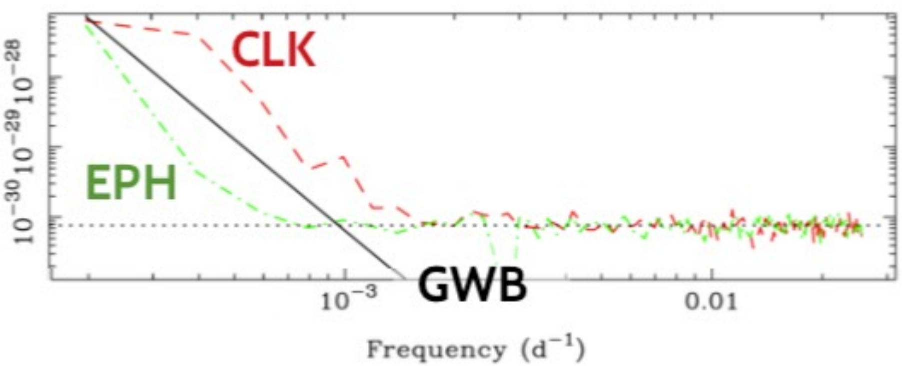
[e.g. Detweiler1979; Jenet et al. 2005, 2006]

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

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**

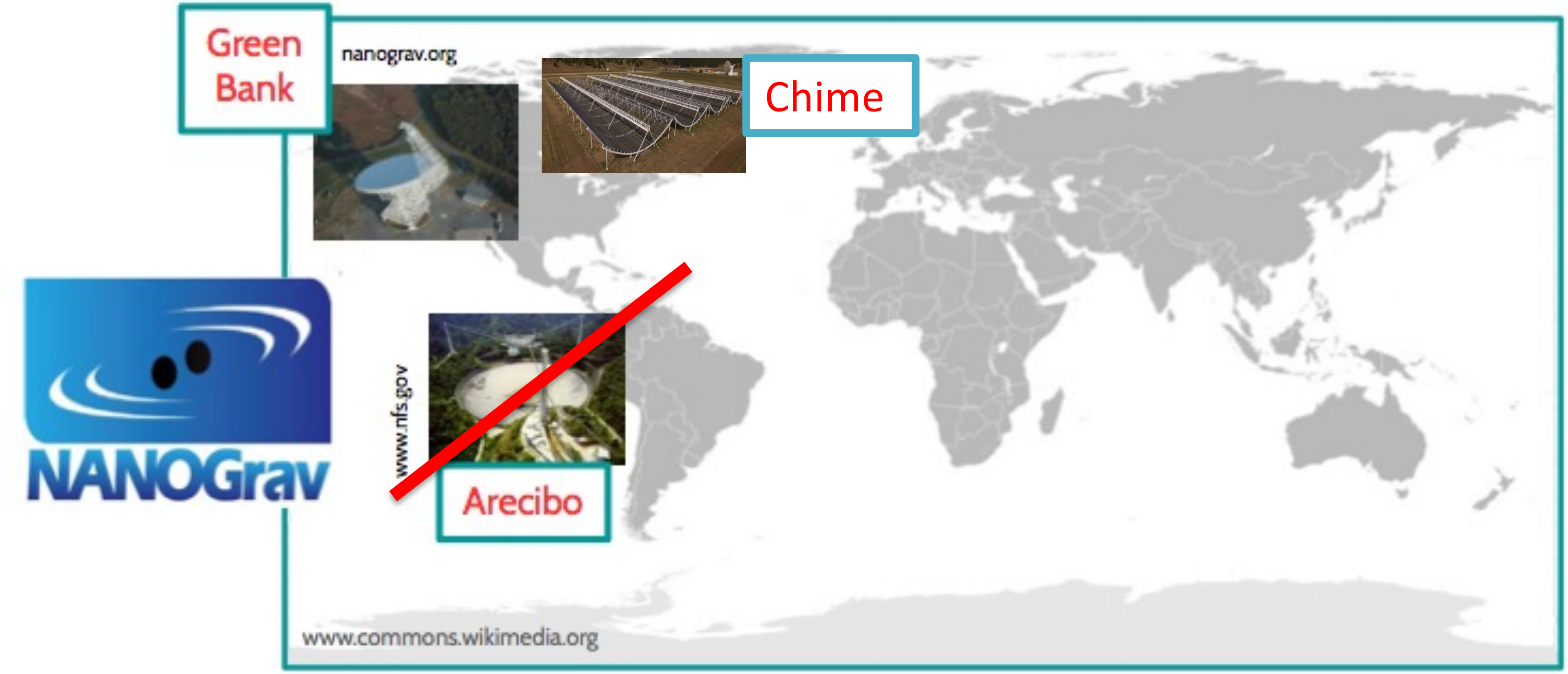
PTA experiments

PPTA: Parkes Pulsar Timing Array (since 2004)

Adapted from Caterina Tiburzi 2019

PTA experiments

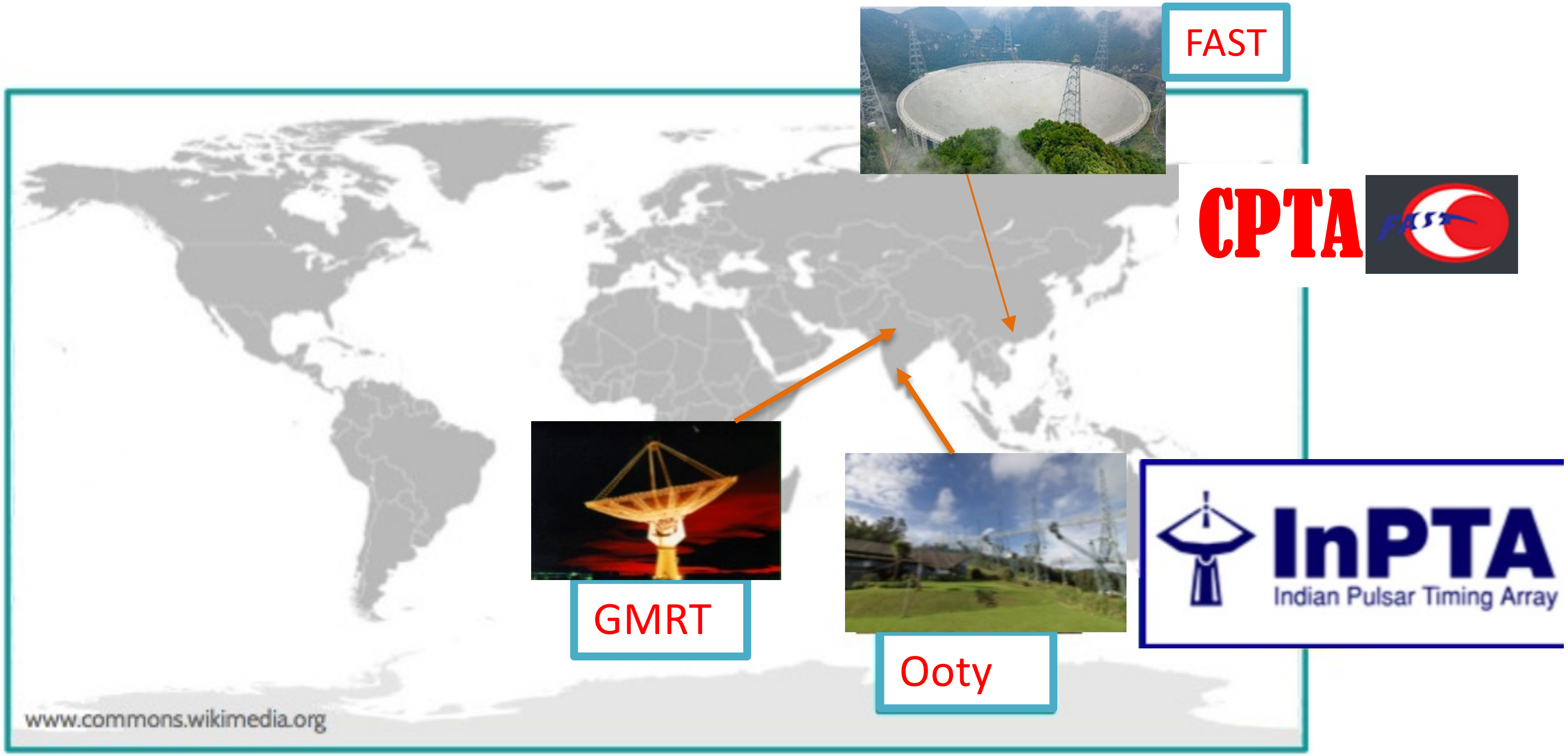
NANOGrav: North American Array (since ~2008)



Adapted from Caterina Tiburzi 2019

PTA experiments

InPTA: Indian Pulsar Timing Array (since 2016)
CPTA: Chinese Pulsar Timing Array (last ~5 years)

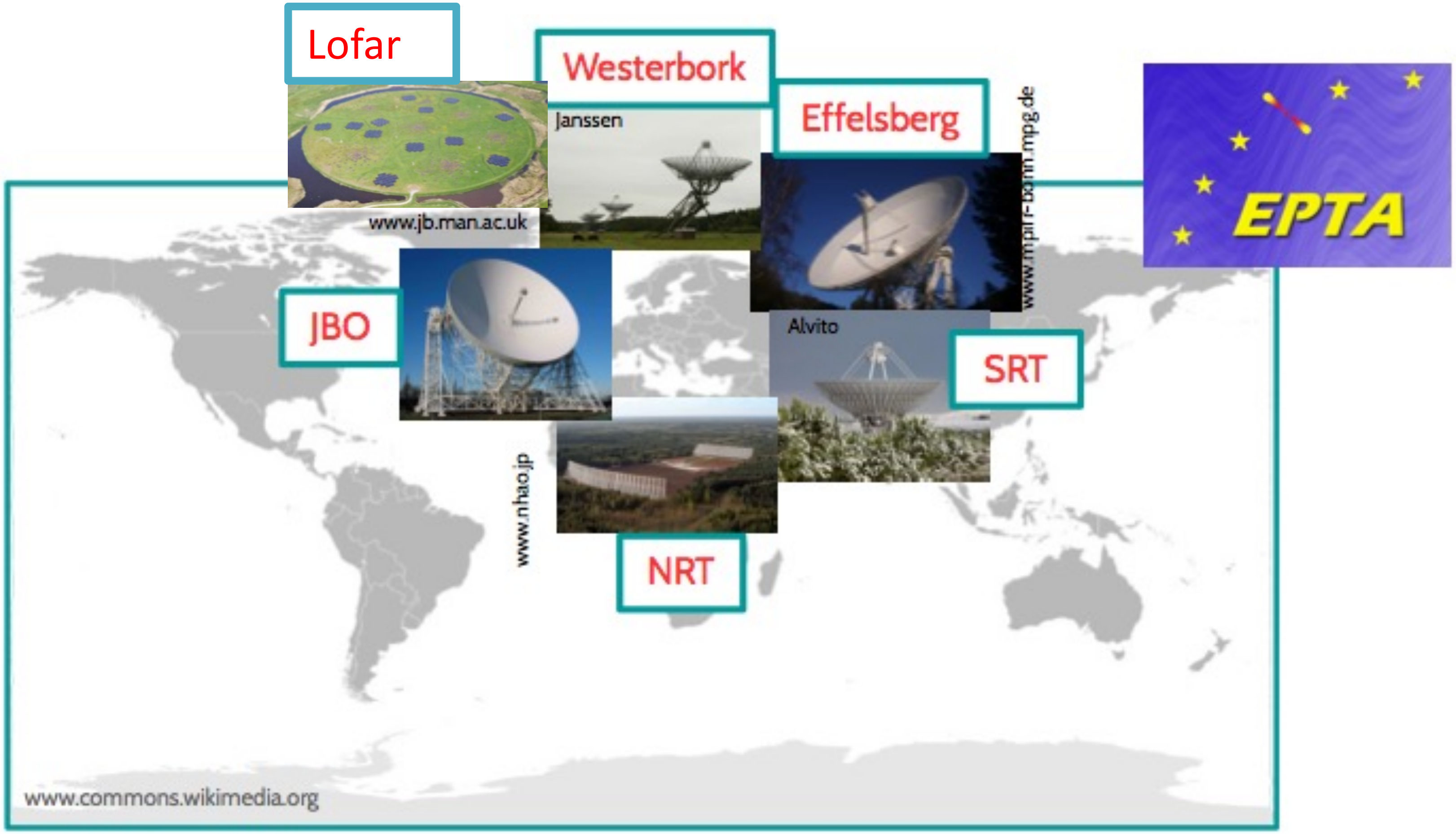


Adapted from Caterina Tiburzi 2019

PTA experiments

EPTA: European Pulsar Timing Array

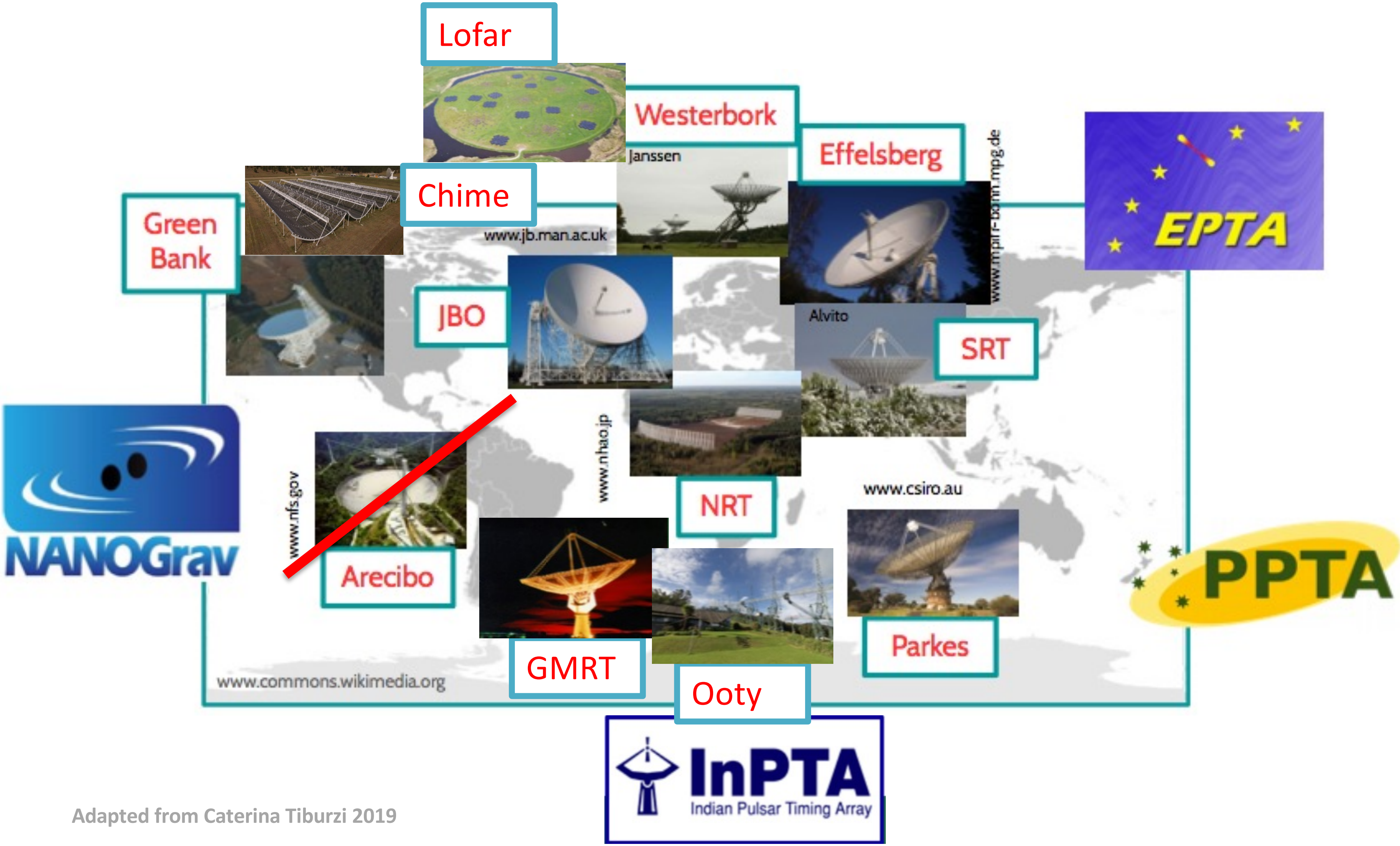
(formally since 2006, but data from 1998)



Adapted from Caterina Tiburzi 2019

PTA experiments

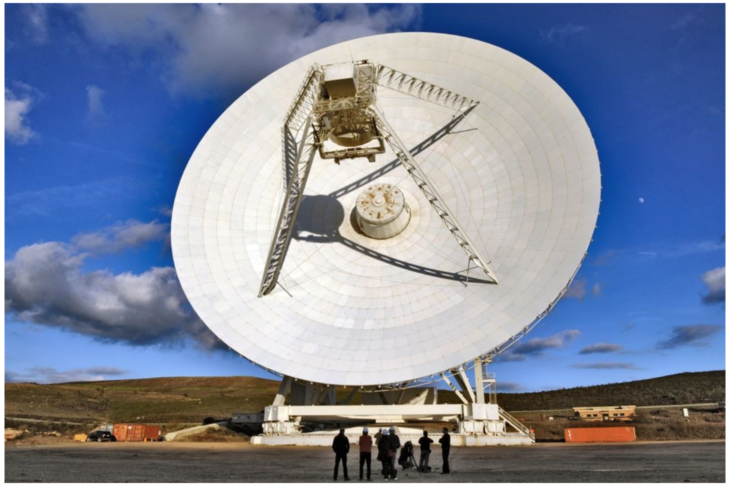
IPTA: International Pulsar Timing Array



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**

The earlier results (2015-16): upper limits only

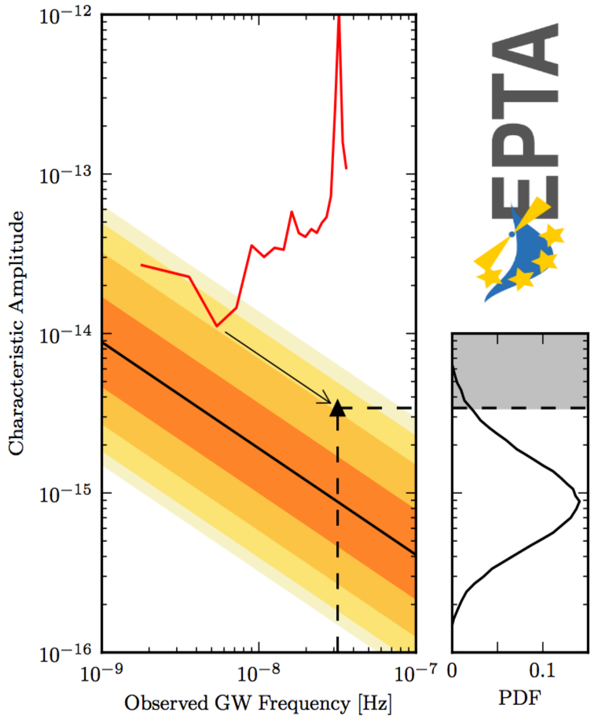
best limits on data until ≈2013 for the amplitude of the GW background from SMBH binaries [assuming a GWB spectral index α = -2/3 at f_{GW}=2.8 nHz (i.e. P_{GW}=1 yr) and for H_o = 73 km s^{-1} Mpc^{-1}]

NANOGrav — Arzoumanian et al., 2015: **$A < 1.5 \times 10^{-15}$**

EPTA — Lentati et al., 2015: **$A < 3 \times 10^{-15}$**
(very robust limit including all caveats)

PPTA — Shannon et al., 2015:
$A < 1.0 \times 10^{-15}$ [$\Omega_{GW} < 2.3 \times 10^{-10}$]

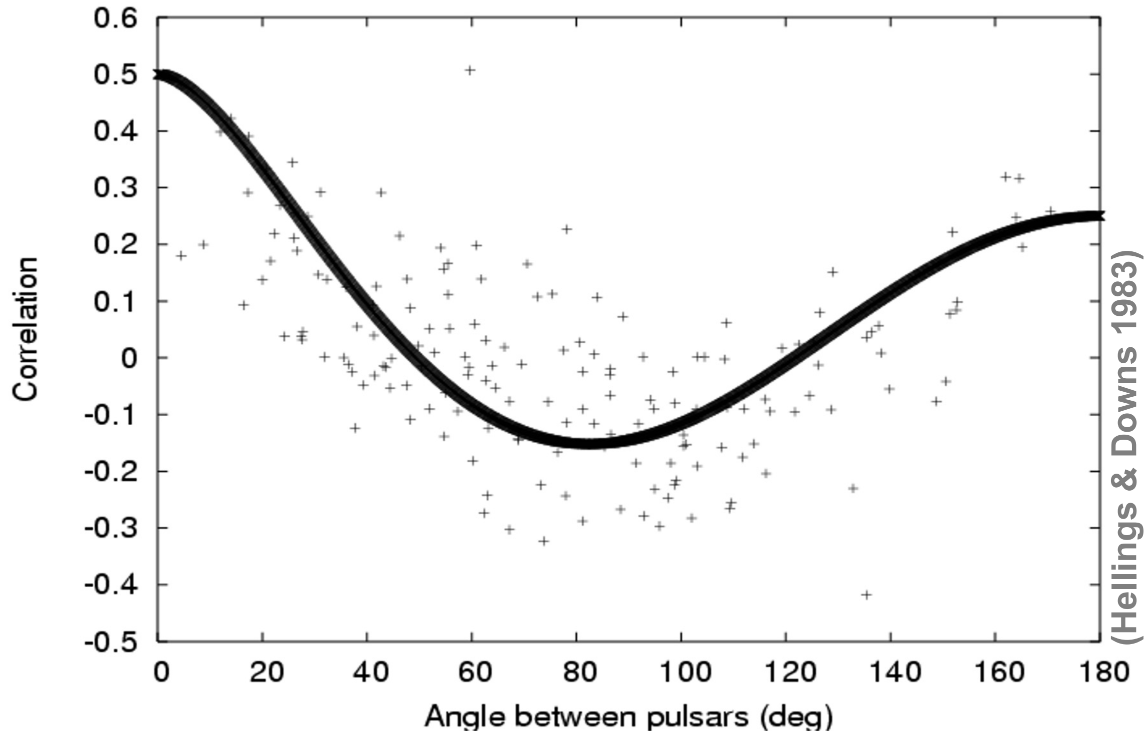
IPTA — Verbiest et al., 2016: **$A < 1.7 \times 10^{-15}$**
(based on relatively old data only)



[Lentati et al 15]

Last results (2023)

… the expected space quadrupolar correlation among pulsar-pairs residuals due to a stochastic, isotropic, unpolarized, stationary GW background …



(Hellings & Downs 1983)

Last results (2023)

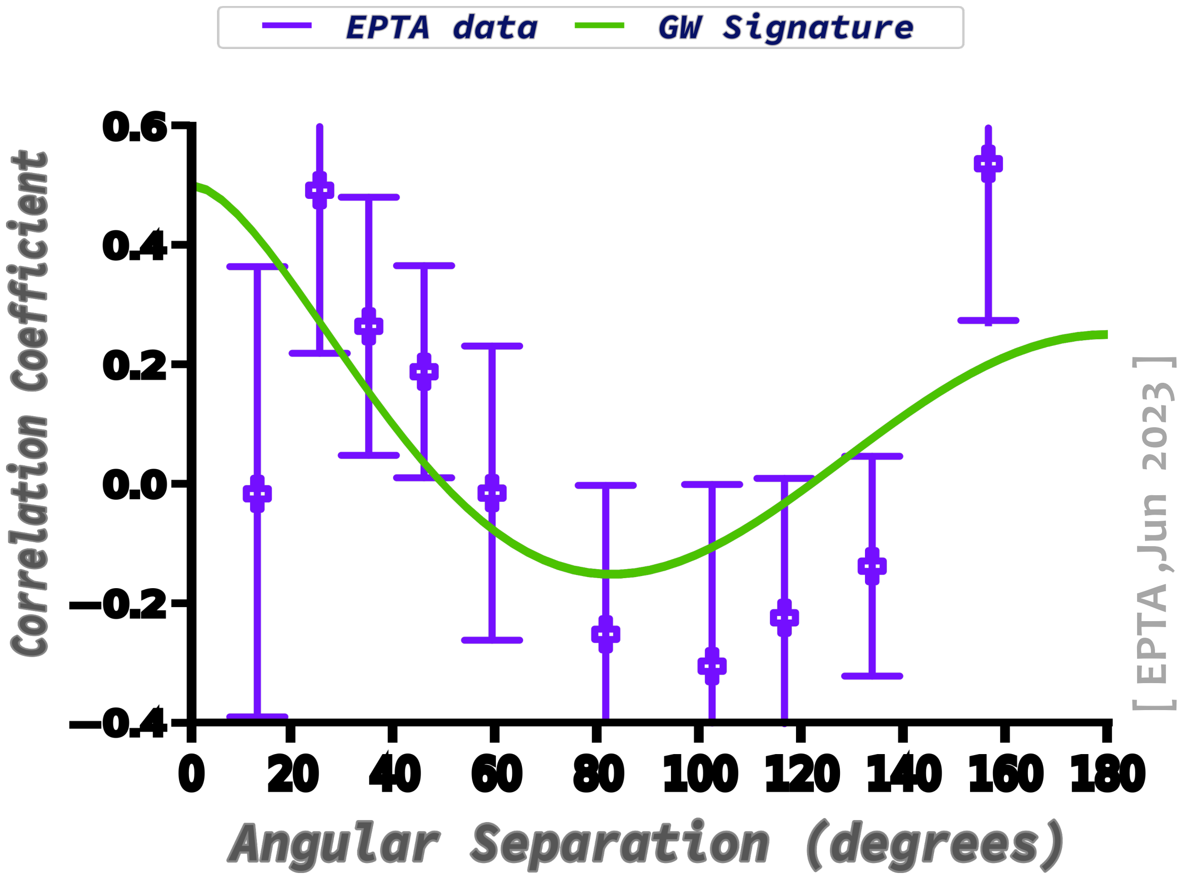
… what observed by EPTA with 10.3 or 24.7 years of data …

June 2023

EPTA

** For the last 10.3 yr of data, HD curve reproduced at 3 σ with a strain amplitude for the expected GWB spectrum at the GW freq of 1 yr $(2.5^{+0.7}_{-0.7}) \times 10^{-15}$ (90% c.l.)

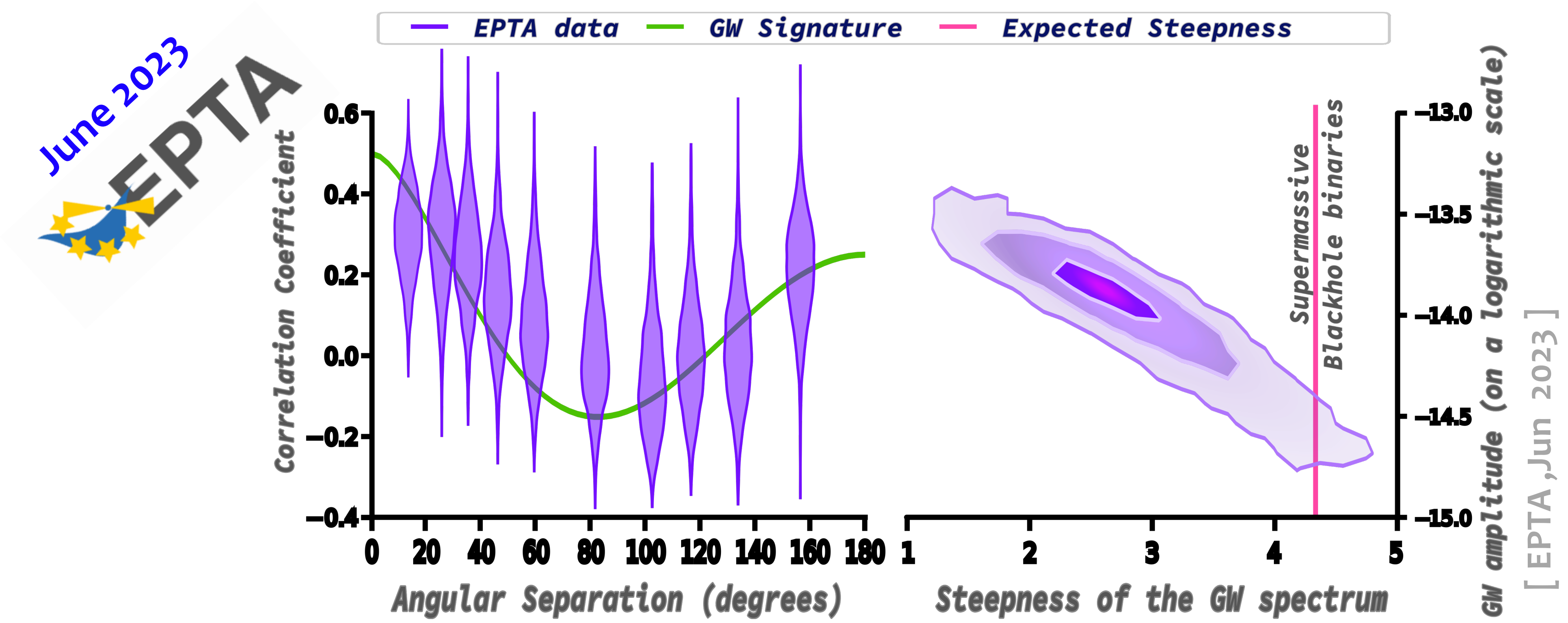
[Antoniadis+ Jun 2023]



** With the full data set, we find marginal evidence for a GWB, with a Bayes factor of 4 and a false alarm probability of 4%.

Last results (2023)

… what observed by EPTA with 10.3 or 24.7 years of data …



** for the last 10.3 yr of data, the index of the GW spectrum is compatible, but tendentially less steep then the expected 13/3=4.3 value for a GW Background due to SMBH binaries

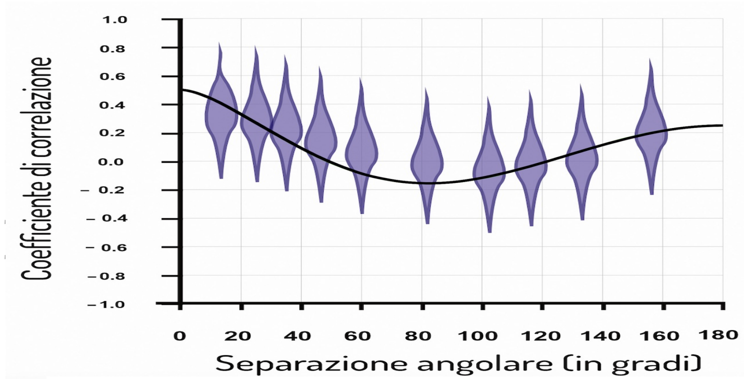
[Antoniadis+ Jun 2023]

Last results (2023)

… what also observed by the other experiments …

EPTA

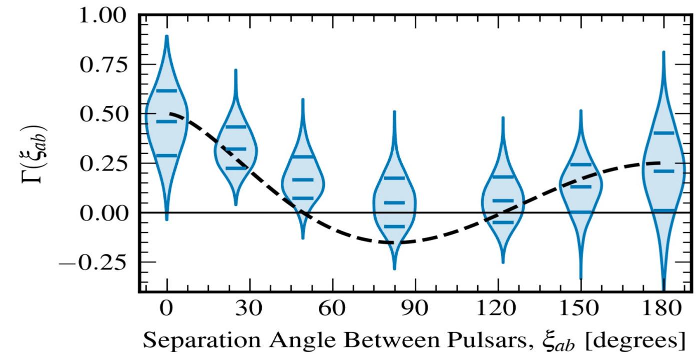
[Antoniadis+ Jun 2023]



HD curve at 3σ
with strain amplitude
at GW freq of 1 yr
$(2.5^{+0.7}_{-0.7}) \times 10^{-15}$
(90% c.l.)

NANOGrav

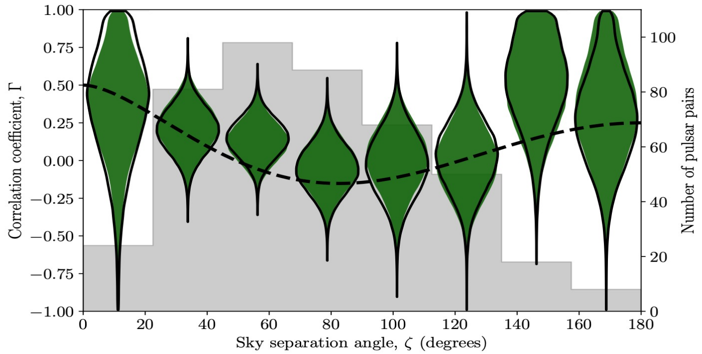
[Agazie+ Jun 2023]



HD curve at 3.5σ - 4σ
with strain amplitude
at GW freq of 1 yr
$(2.4^{+0.7}_{-0.6}) \times 10^{-15}$
(90% c.l.)

PPTA

[Reardon+ Jun 2023]



HD curve at 2σ
with strain amplitude
at GW freq of 1 yr
$(3.1^{+0.3}_{-0.9}) \times 10^{-15}$
(90% c.l.)

CPTA

[Xu+ Jun 2023]

HD curve compatible with data at 4.6 σ
with a <u>very poorly constrained</u> strain amplitude around
2.0×10^{-15}

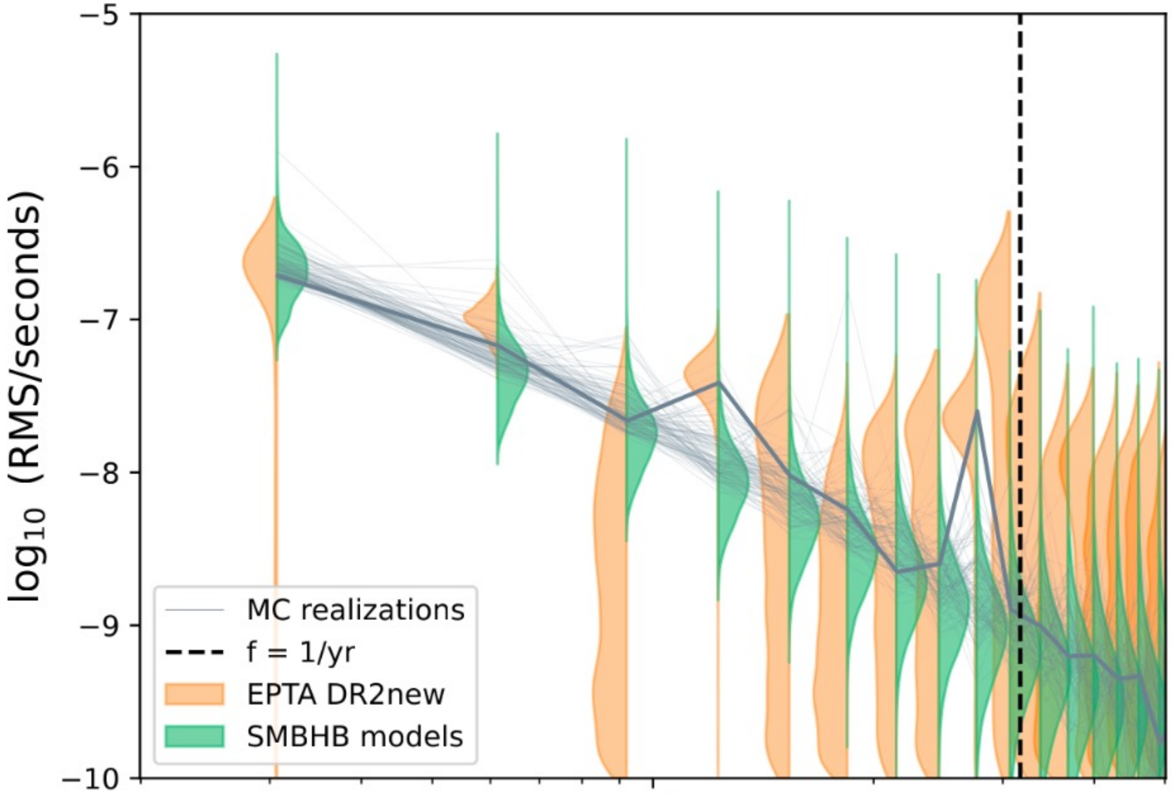
Implications

[Antoniadis+ Jun 2023-V]

The origin of the observed signal is still unassessed at the current stage:

1) a cosmic population of in-spiralling supermassive black hole binaries (SMBHBs)

strong indications that the signal is compatible with a cosmic population of SMBHBs coalescing in the aftermath of galaxy mergers. The relatively flat slope of the measured spectrum might be indicative of strong environmental coupling and high eccentricities



[e.g. Antoniadis et al 2024]

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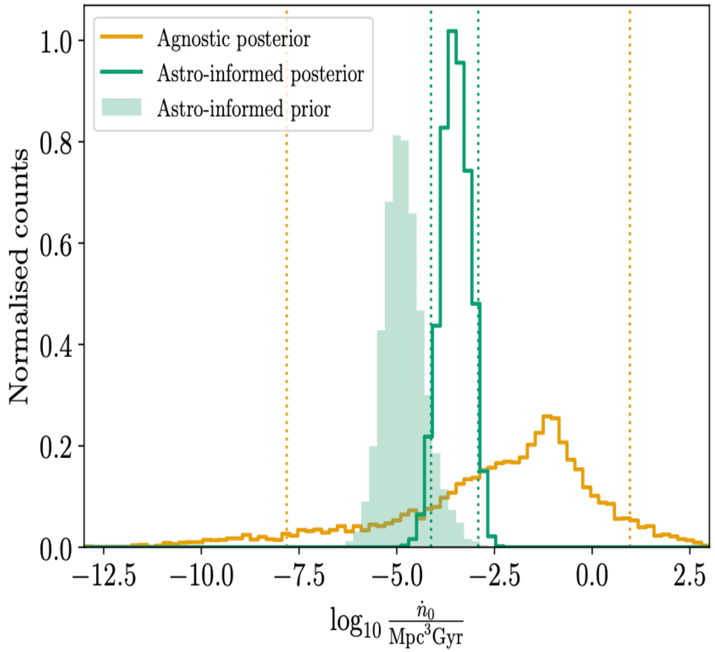


First nine spectral bins favours an inferred merger rate n_0 of SMBHBs at the upper bound of the Astro-informed priors

Implications

[Antoniadis+ Jun 2023-V]

The origin of the observed signal is still unassessed at the current stage:

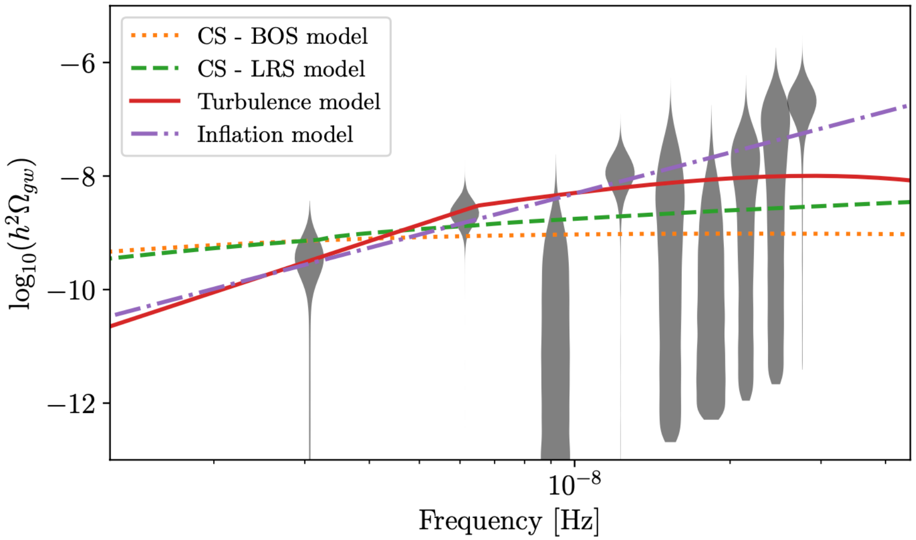
2) inflation, phase transitions, cosmic strings and tensor mode generation by non-linear evolution of scalar perturbations in the early Universe

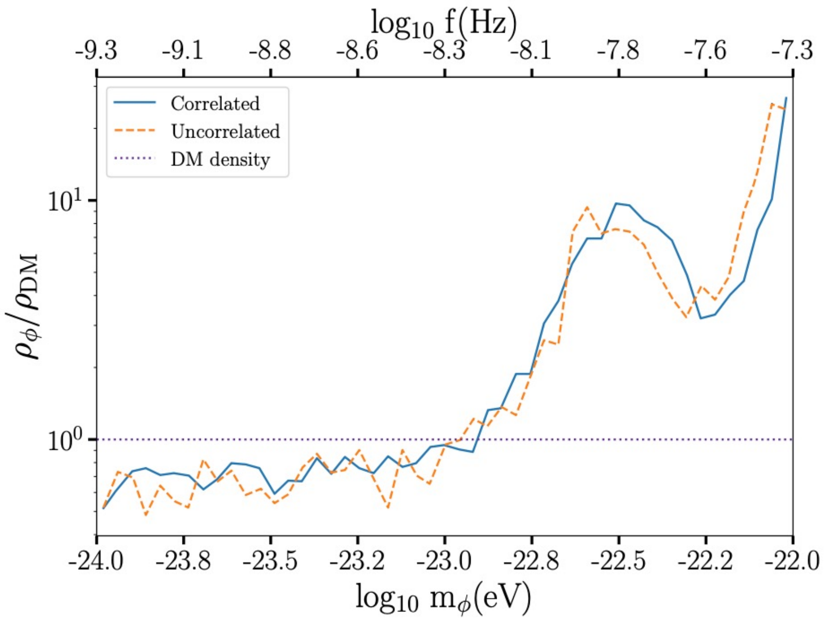
* inflationary origin of the GWB requires non-standard inflationary evolution leading to a blue-tilted spectrum

* string origin (BOS and LRS) would allow narrowing down the string tension to values **of $-11 \lesssim \log_{10}G\mu \lesssim -9.5$**

* GWB induced by MHD turbulence at the QCD energy scale requires either high turbulent energy densities or a turbulent scale close to the horizon at the QCD epoch

* evolution of scalar perturbations at second order only if an excess of their primordial spectrum is present at large wavenumbers





3) oscillations of the Galactic potential in the presence of ultra-light dark matter (ULDM)

if a joint ULDM+GWB search is performed, the data strongly prefer the presence of an HD correlation in the common power

* only about 80% of the DM density in the solar neighbourhood can be attributed to ULDM with $-24 < \log(m/\text{eV}) < -23$

[see also Smarra+ 2023]

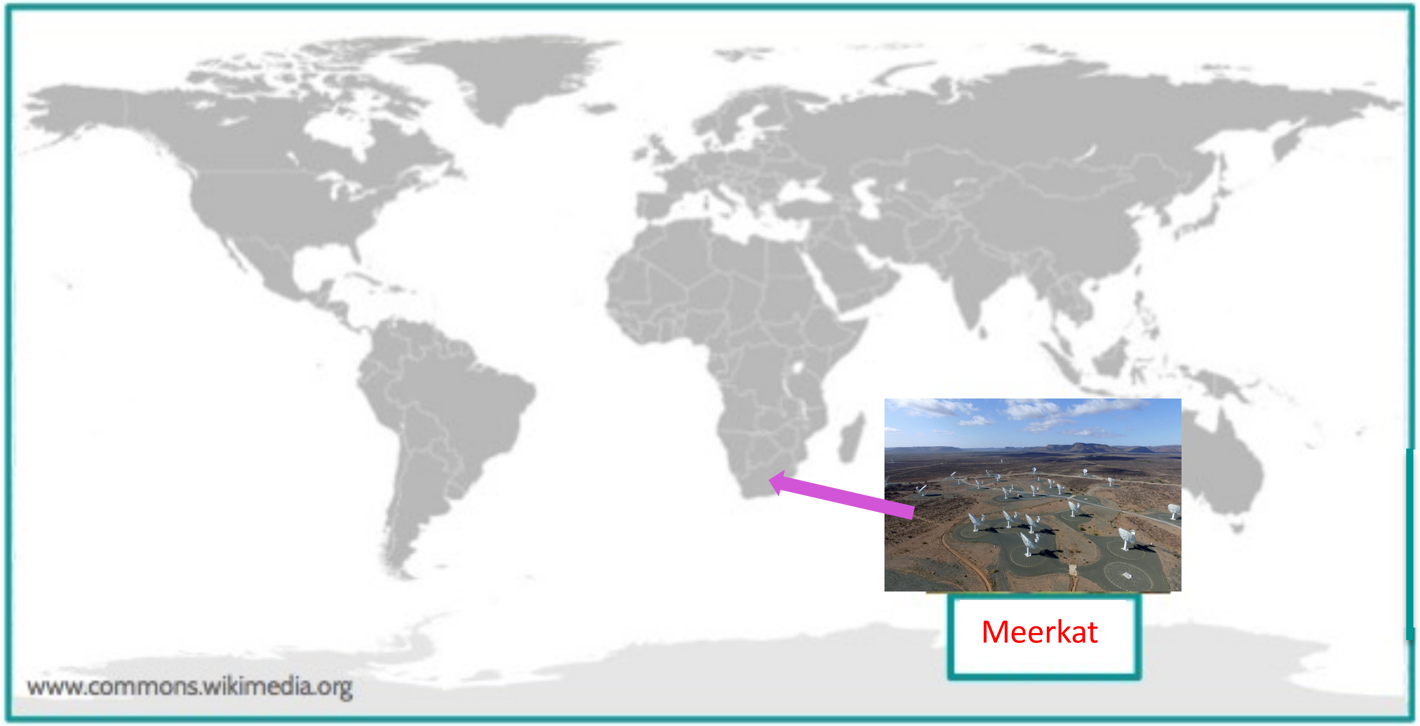
Additional PTA experiments

Meerkat

SKA
observatory

PTA experiments

MPTA: Meerkat Pulsar Timing Array (since 2018)

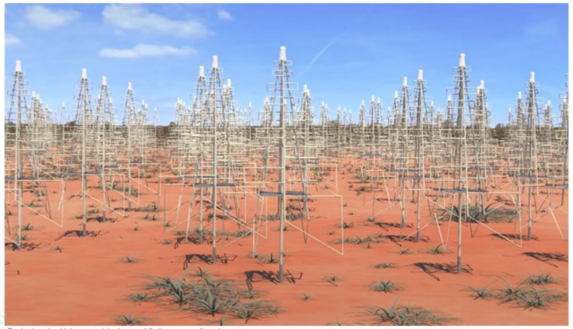


Adapted from Caterina Tiburzi 2019

The future pulsar science perspectives with SKAO

SKA1-LOW, Murchison, Australia:
130,000 dipoles (512 stations x 256 antennas); 50–350 MHz
~80km baselines; large areal concentration in core

[© R. Braun 2015]



[© SKA organization]

SKA1-MID, Karoo, South Africa:
133 SKA1 + 64 MeerKAT dishes. Max baseline ~150km
Bands: 2 (0.95–1.76 GHz), 5 (4.6–14(24) GHz), 1 (0.35–1.1 GHz)

[© R. Braun 2015]

[Keane et al 2015]

The post-SKA-searches pulsar population ≈ 12000 and in particular a population of Millisecond pulsars ≈ 1500

→ Leading to discover several exotic systems, including black-hole(s)

[Keane et al 2015; Shao et al 2015]

The SKA relativistic pulsar population ≈ 100-200 with a timing precision better by a factor ≈ 5-10 than available now

→ Transformational tests of gravity theories with neutron stars & BHs

[Shao et al 2015]

SKA will provide ≈ 100 MSPs with timing precision < 100 ns

→ Leading to start GW cosmology

Thanks