Looking for low frequency GWs with the Pulsar Timing Arrays

THE 2ND
PIETRO BARACCHI
CONFERENCE

Auditorium Fondazione Ente Cassa
di Risparmio di Firenze

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Andrea Possenti

INAF
OAC Osservatorio Astronomico di Cagliari

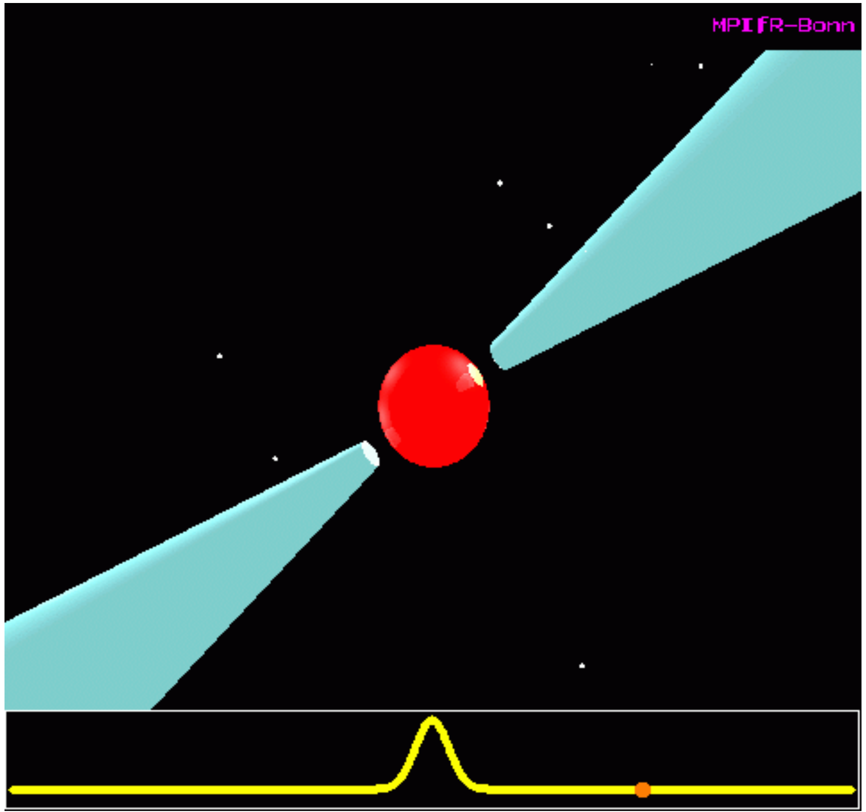
IPTA International Pulsar Timing Array

Summary

- Pulsar and Pulsar Timing rudiments
- Pulsars as GW detectors: a Pulsar Timing Array
- Running experiments
- Italian and Australian contributions & synergies
- Perspectives

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



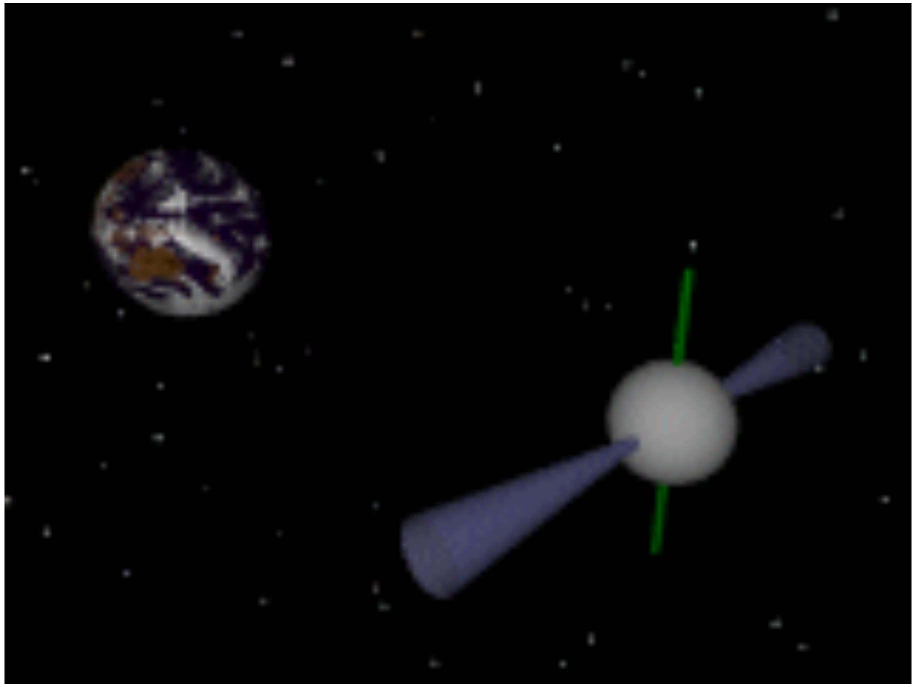
@Kramer

The procedure of "timing"

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

and

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



Which pulsars are suitable ?

Ordinary pulsars:

~ 2400 known objects;

NS_{age} < few 10^7 yr

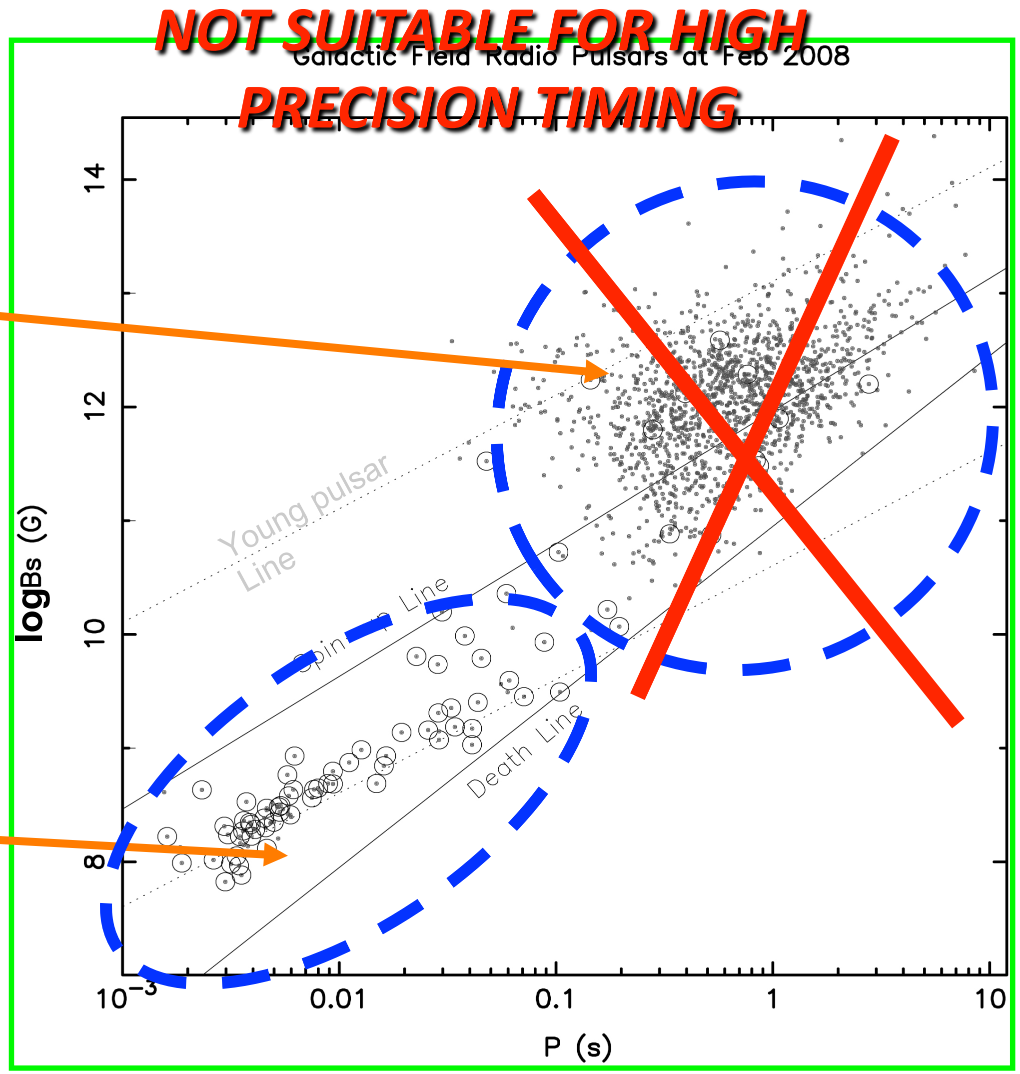
relatively long pulses & rotational irregularities

Recycled pulsars:

~ 300 known objects;

NS_{age} > 10^8-10^9 yr

The most rapidly rotating are known as millisecond pulsars



ATNF Pulsar Catalogue

Why recycled pulsar "timing" is 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!

The currently best target: Double Pulsar

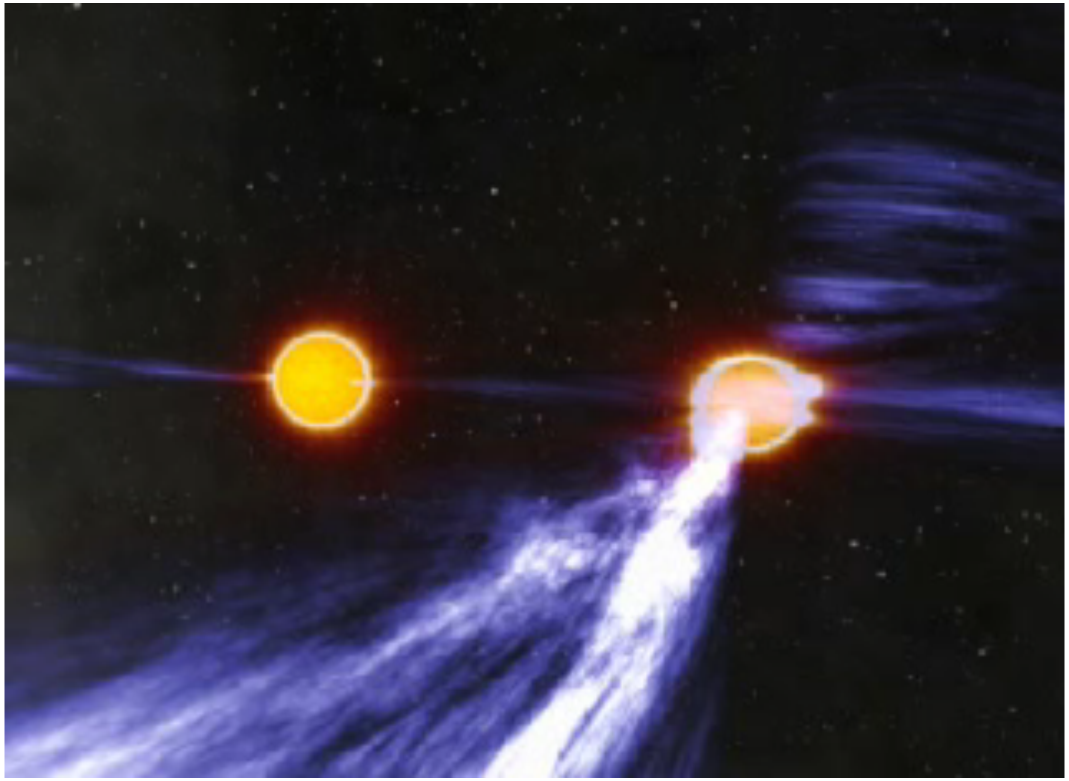
Old 23-ms pulsar in a 147-min orbit with young 2.77-s pulsar

[Burgay et al. 2003, Lyne et al. 2004]

Eclipsing binary in compact, slightly eccentric (e=0.088) and edge-on orbit

System showing the largest numbers of relativistic effects

[Kramer et al. 2006, Breton et al. 2008, Kramer et al. 2019 in prep., Wex et al. in prep, +….]



[Animation by Rowe - CASS_ATNF]

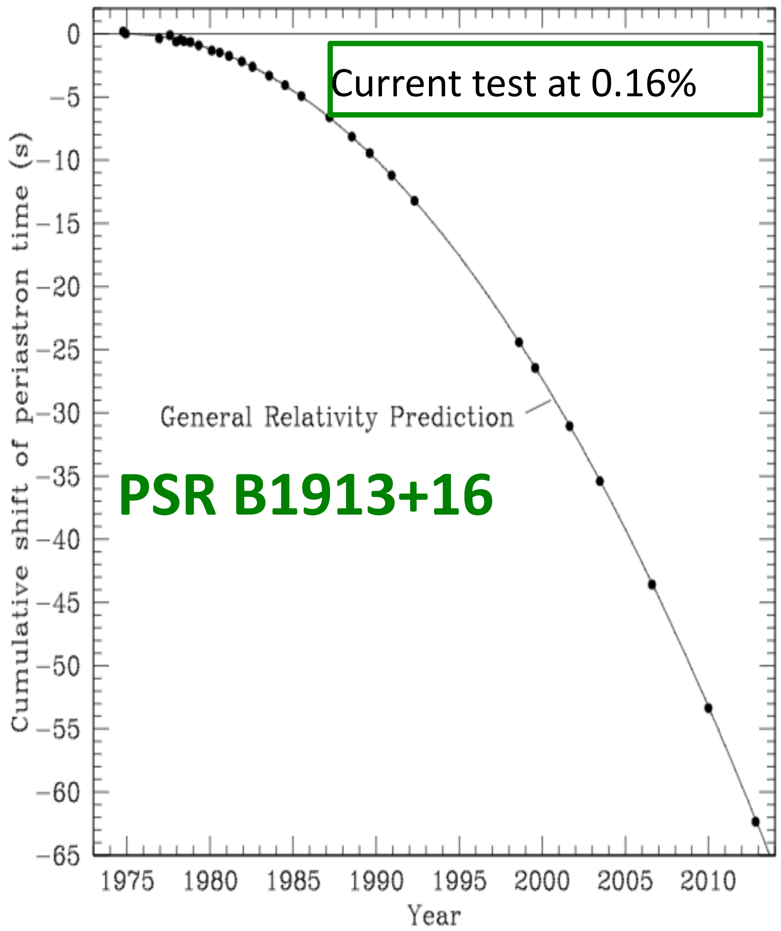
Collaborators (alphabetical):

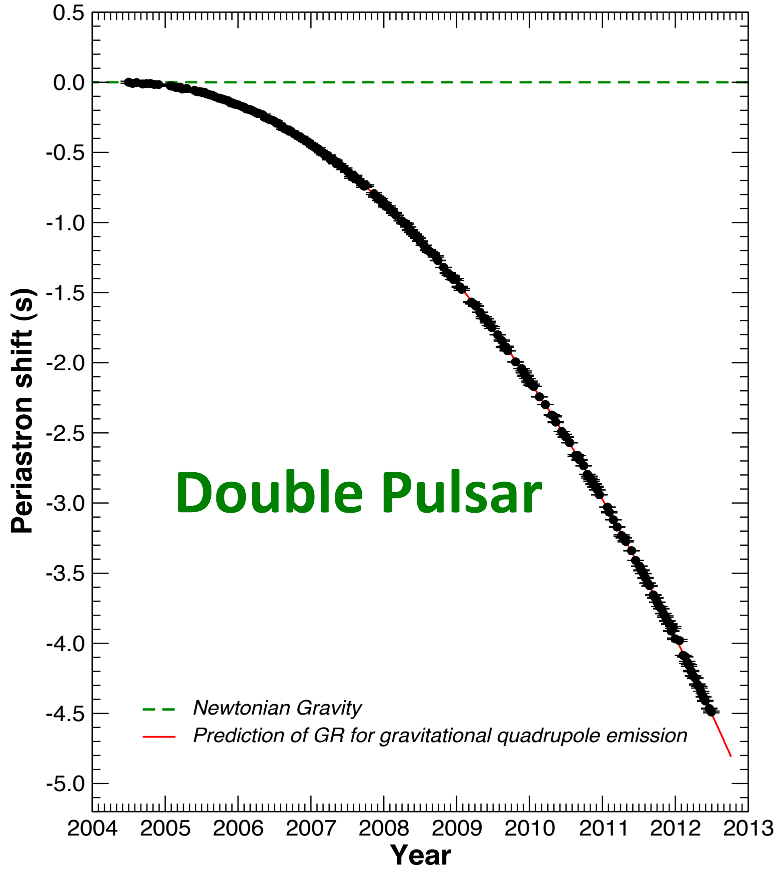
C. Bassa, R. Breton, M. Burgay, I. Cognard, N., G. Desvignes, R. Ferdman, P. Freire, L. Guillemot, G. Hobbs, G. Janssen, P. Lazarus, D. Lorimer, A. Lyne, R. Manchester, M. McLaughlin, A. Noutsos, B. Perera, A. Possenti, J. Reynolds, J. Sarkissian, I. Stairs, B. Stappers, G. Thereau, N. Wex .... and a few more

The famous orbital damping test:

from now on limited by Galactic potential

[Weisberg, Nice & Taylor 2010; Weisberg & Huang 2016]





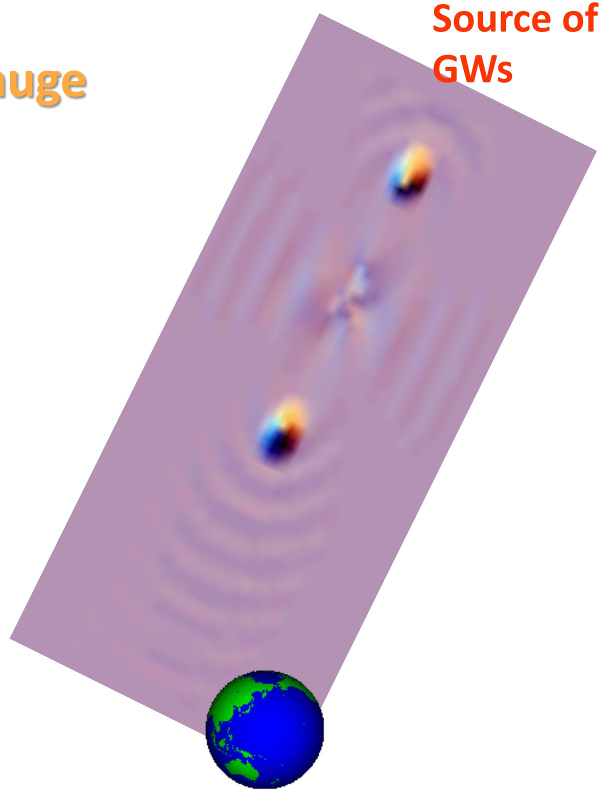
[Kramer et al 2019 in prep.)]

Testing the radiative predictions of GR with much improved precision wrt the Hulse-Taylor system...

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):

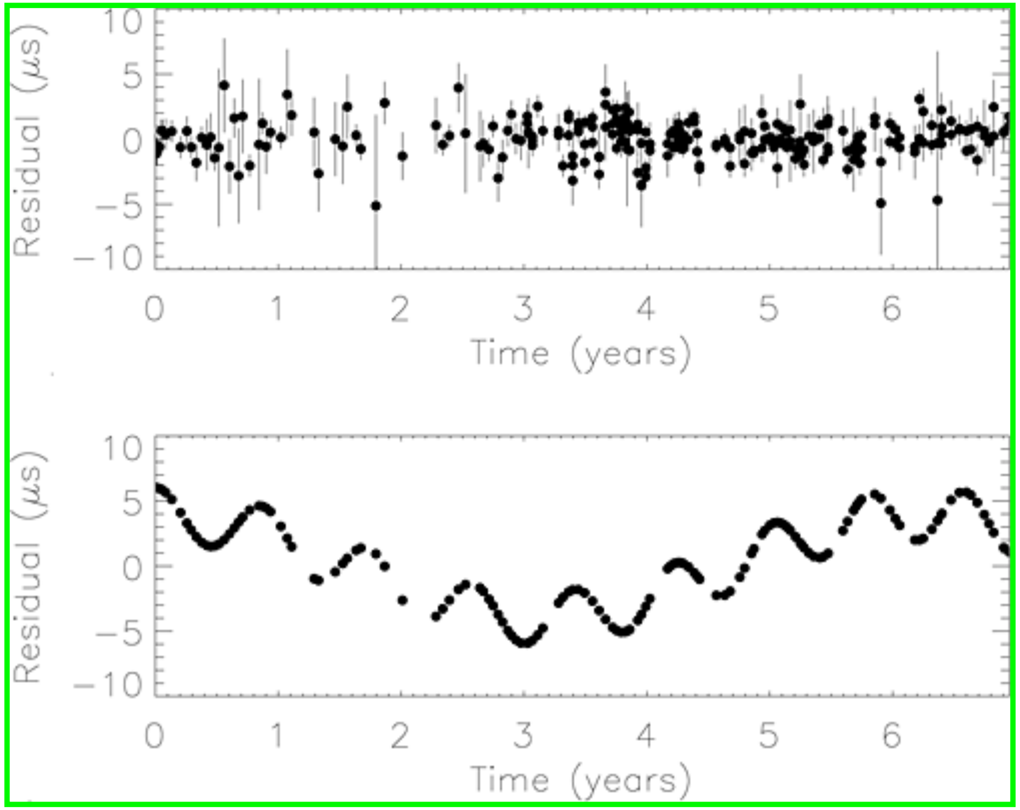
$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

where
$h_c(f)$ is the dimensionless strain at freq f
σ_{TOA} is the rms uncertainty in Time of Arrival
T is the duration of the dataspan

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

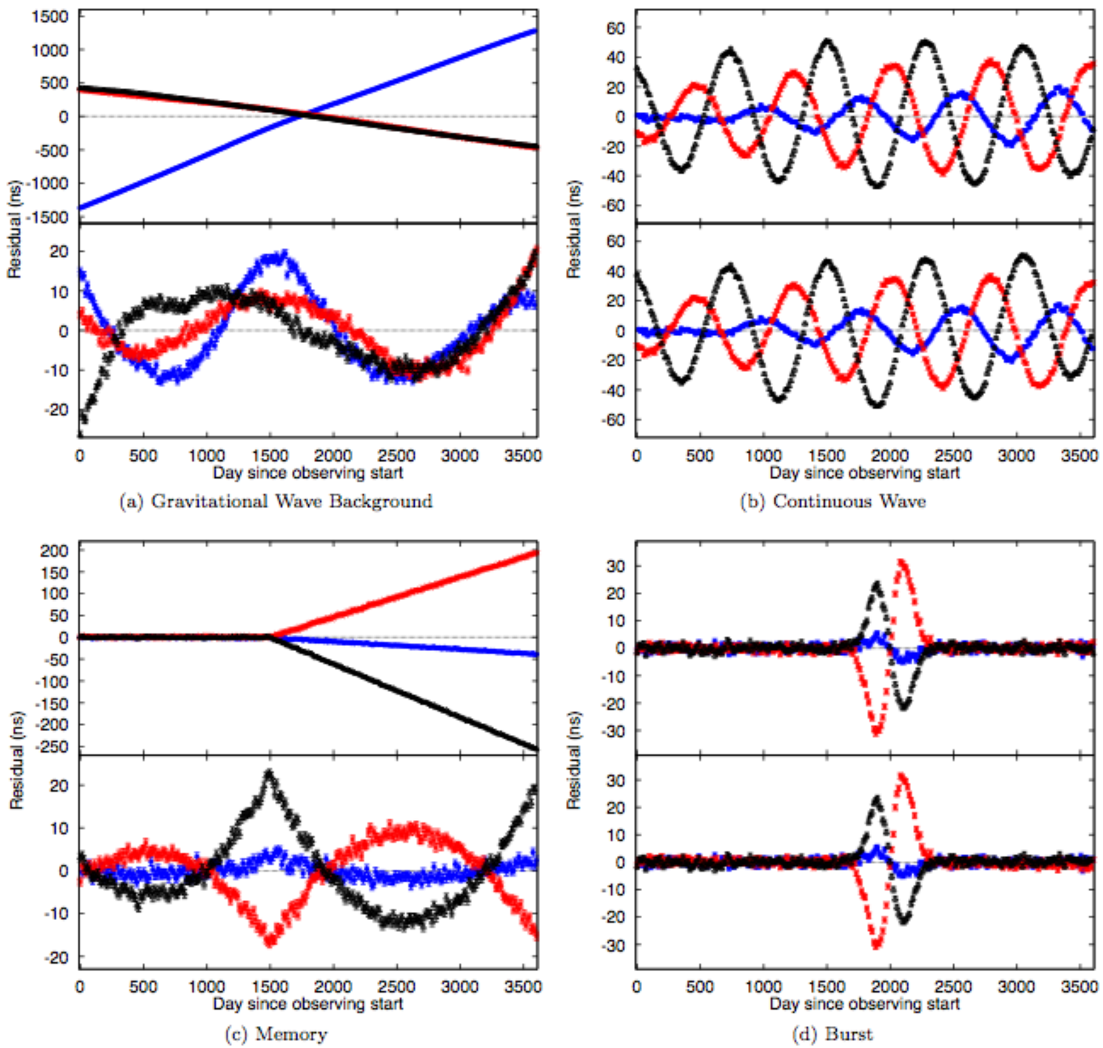
[Sudou et al 2003]



[Jenet et al 2004]

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

The theoretical "clean" signals in the residuals



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

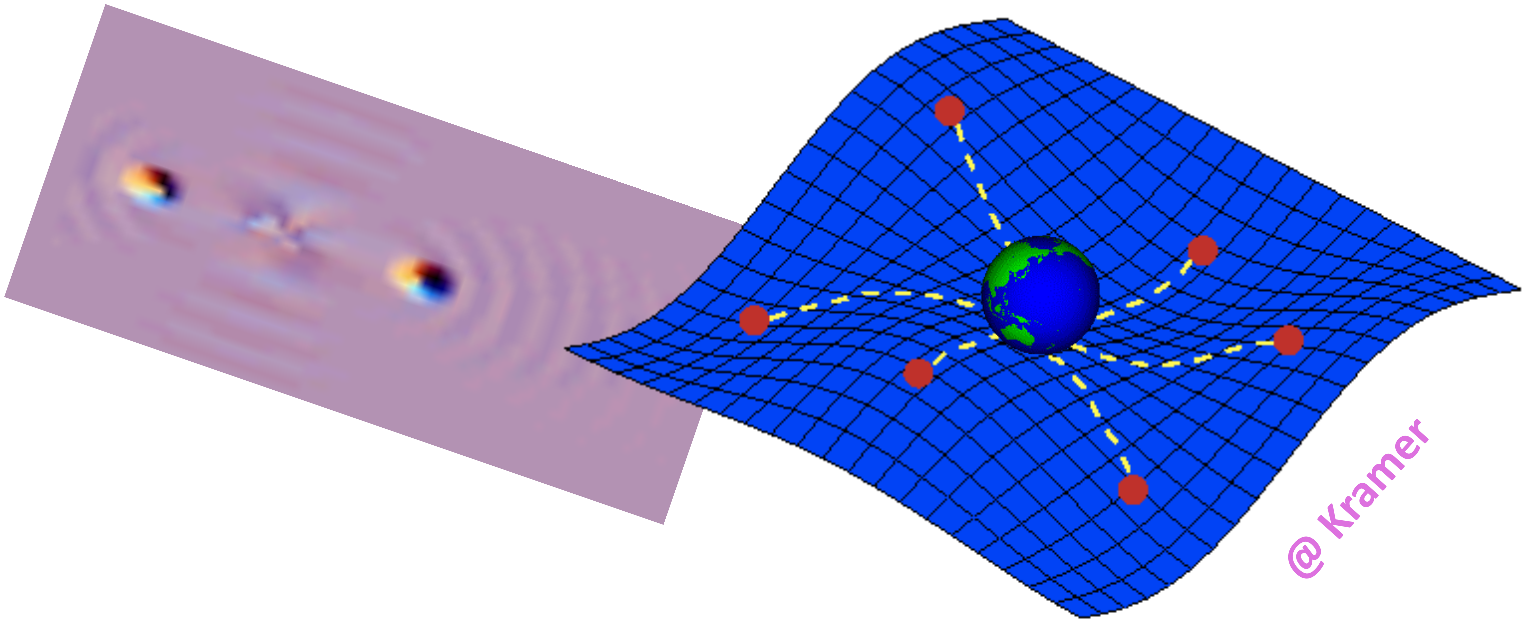
Lower panels: trends after fitting for P and Pd/dt for 3 reference pulsars*:*

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

[Burke-Spolaor 2016]

A pulsar timing array (PTA)

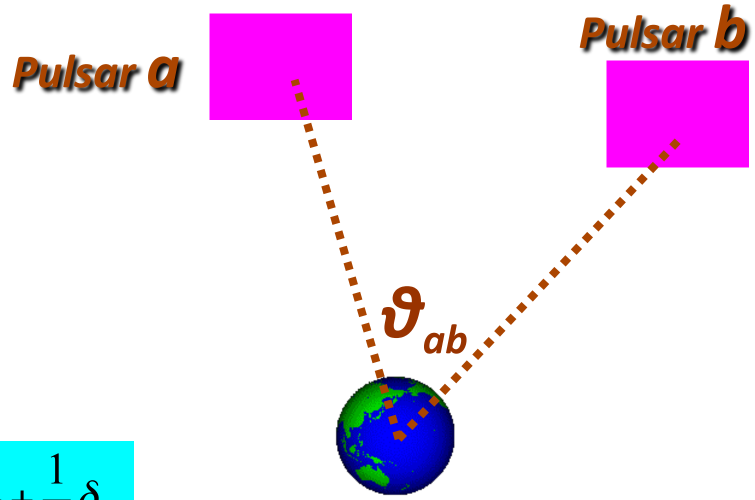
Using a number of pulsars distributed across the sky it is possible to separate the timing noise contribution from each pulsar from the signature of the GW background, which manifests as a local (at Earth) distortion in the times of arrival of the pulses which is common to the signal from all pulsars



Searching for a GW background using 2+ pulsars

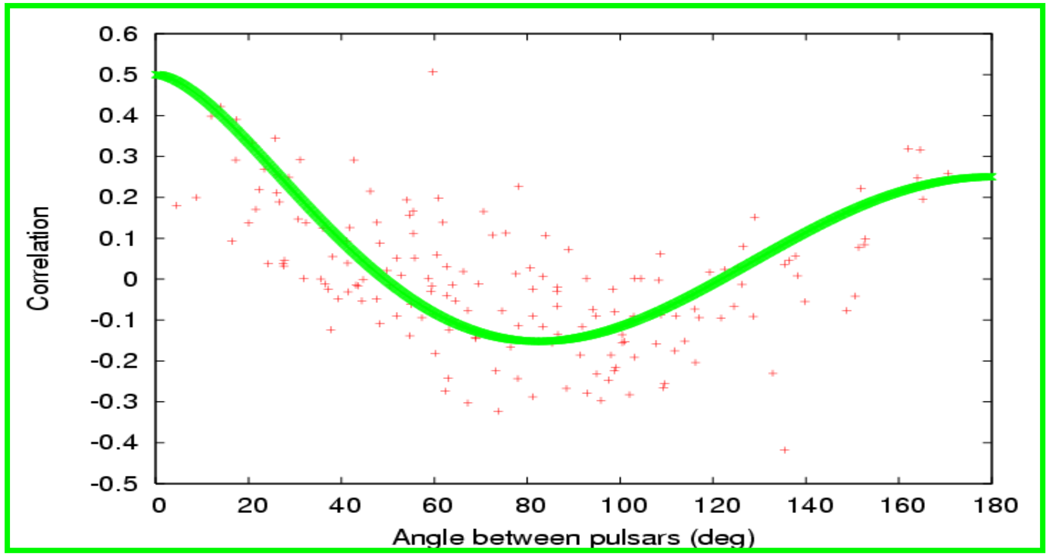
Idea first discussed by Romani [1989] and Foster & Backer [1990]

- **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]

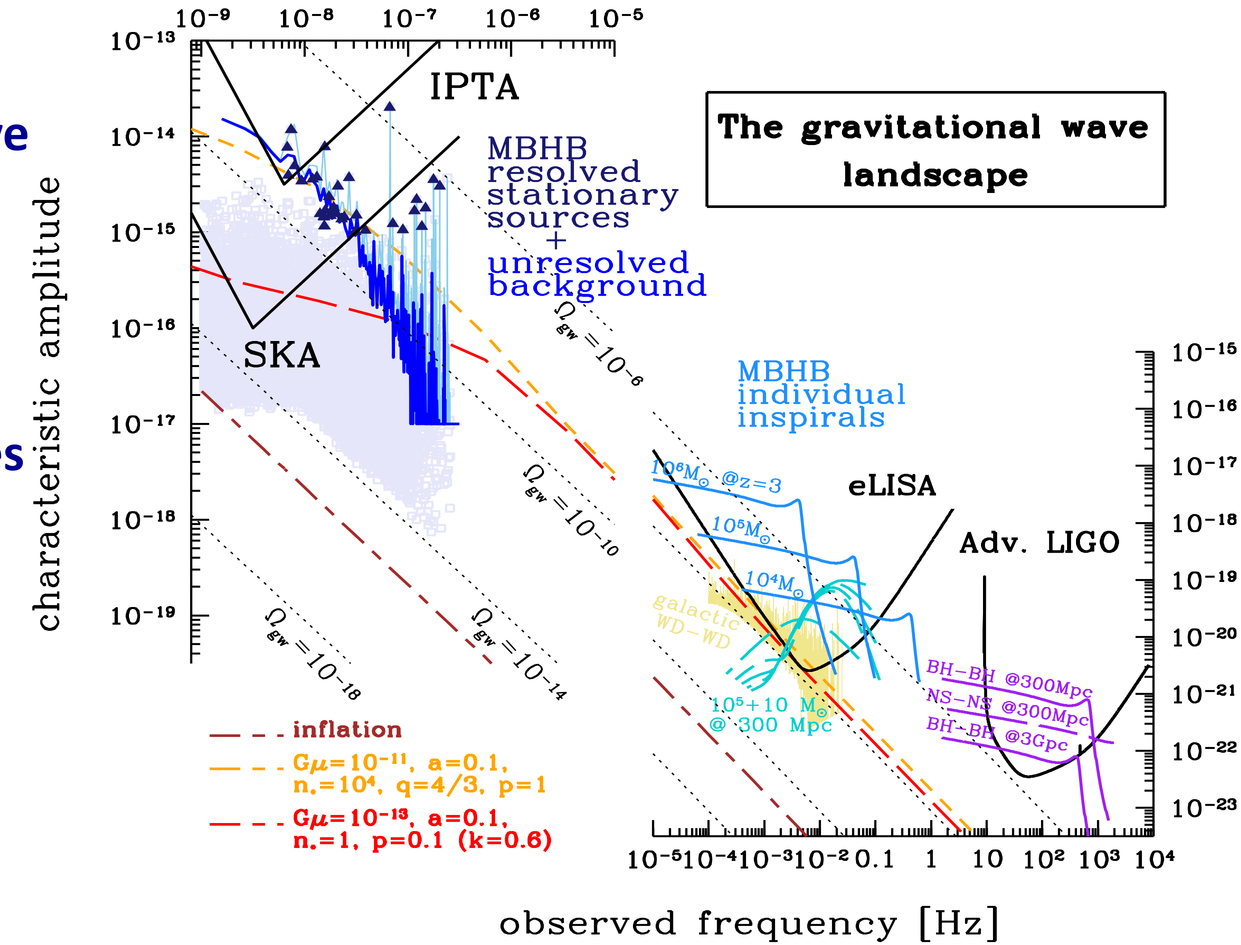


Hellings & Downs [1983]: correlation that an isotropic and stochastic GWB leaves on the timing residuals of 2 pulsars *a* and *b* separated by an angle ϑ_{ab} in sky

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)



Courtesy Janssen 2017

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

The 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 larger than 10^6 M_{sun}

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

$$f \sim 3\,\mathrm{nHz} \left[\frac{M}{10^9 M_{sun}}\right]^{1/2} \left[\frac{a}{0.01\mathrm{pc}}\right]^{-3/2}$$

The expected Strain Spectrum of the GWB

In the simplest picture, the expected amplitude spectrum from the ensemble of these MBH binaries (supposed to be isotropic and stochastic) is

[e.g. Phinney 2001; Jaffe & Backer 2003]

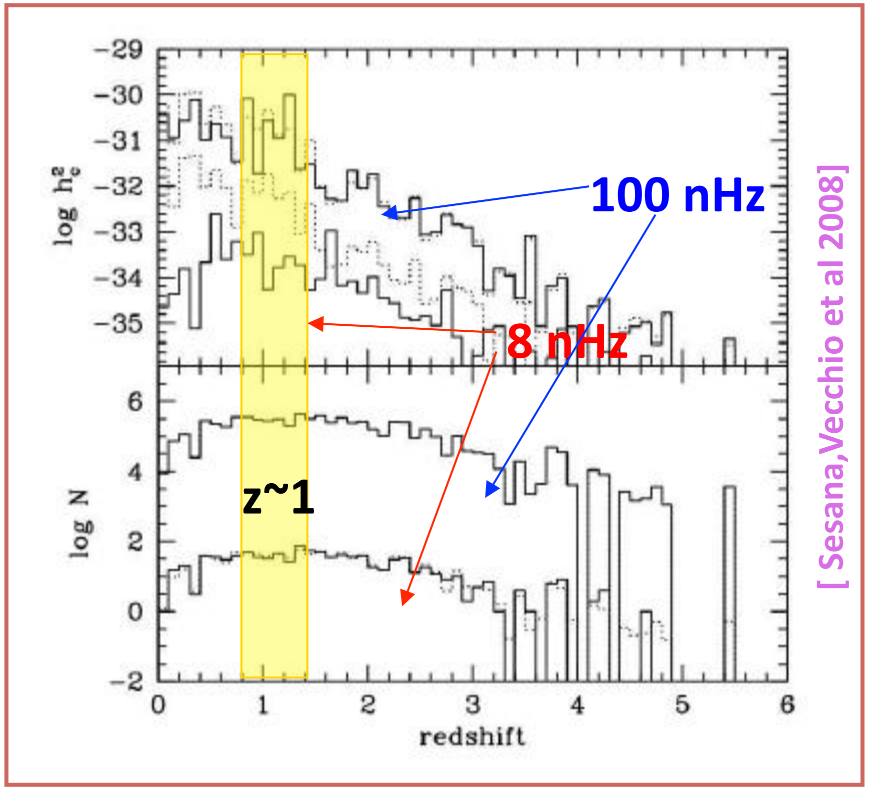
$$h_c(f) \sim f^{-\alpha}; \alpha = 2/3$$

with a strain amplitude now theoretically expected in the range [e.g. Jaffe & Backer 2003, Sesana et al 2016, Kelly et al 2017, Zhu et al 2019]

$h_c \approx 6 \bullet 10^{-17} \rightarrow 2 \bullet 10^{-15}$

around frequency $f_{GWB} = 1\ yr^{-1}$

Max contribution from BH binaries at $z \approx 1$



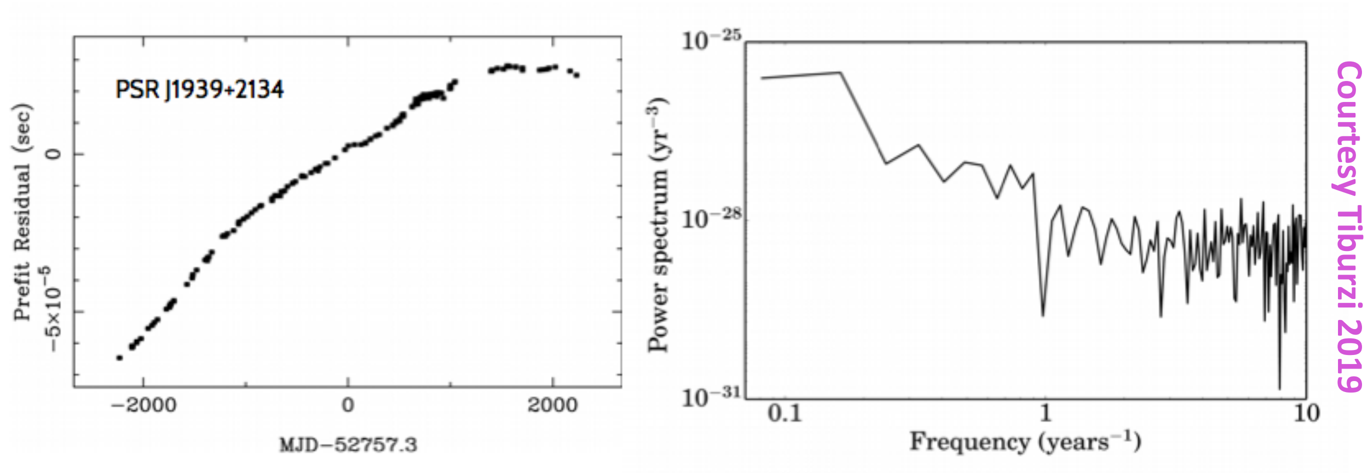
The expected Power Spectrum of the GWB

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]

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

This is a very steep RED spectrum for GWB



Courtesy Tiburzi 2019

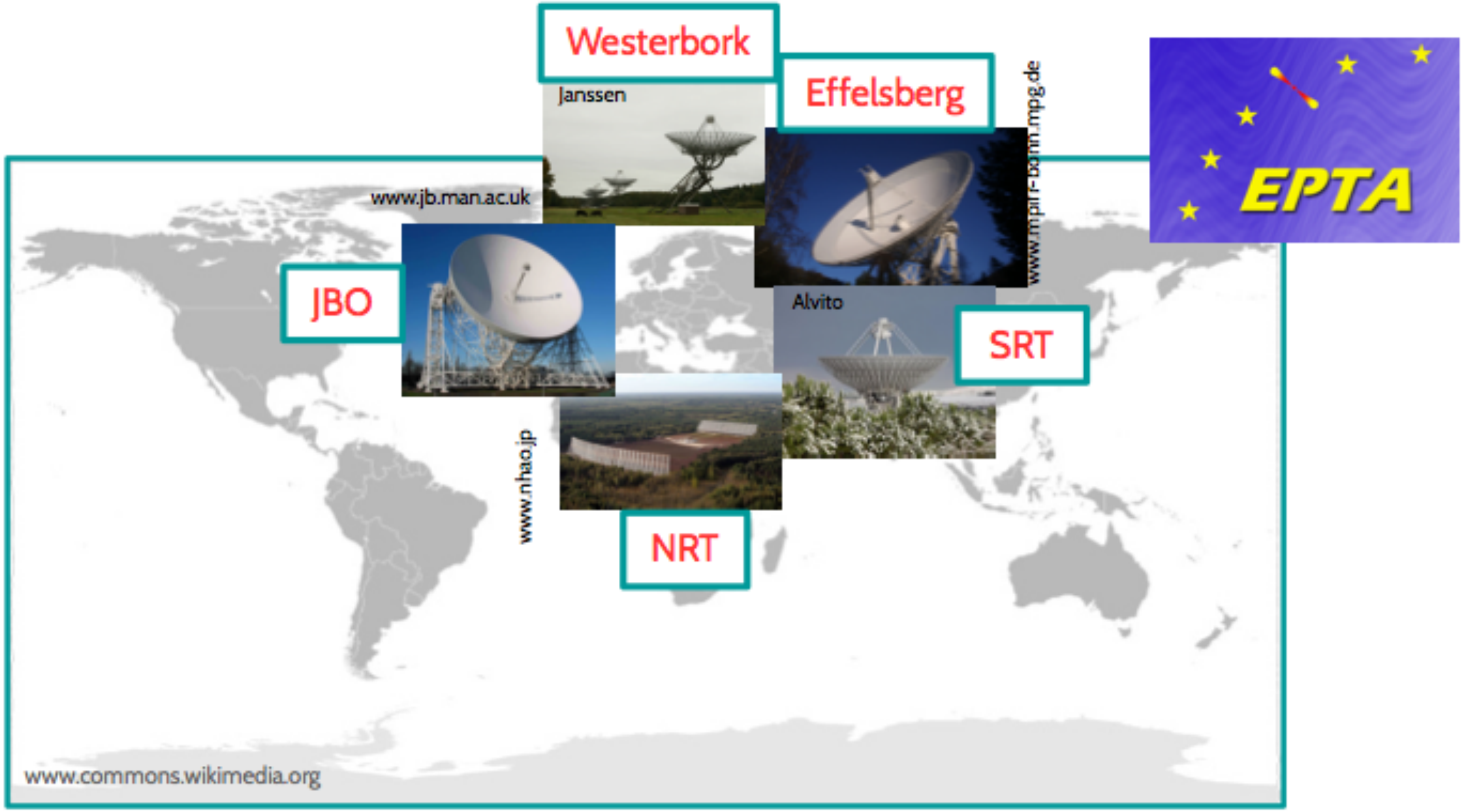
That must be disentangled from the RED noise affecting the Power Spectrum of the timing residuals of few recycled pulsars

PPTA: Parkes Pulsar Timing Array

PPTA

Courtesy Caterina Tiburzi 2019

EPTA: European Pulsar Timing Array

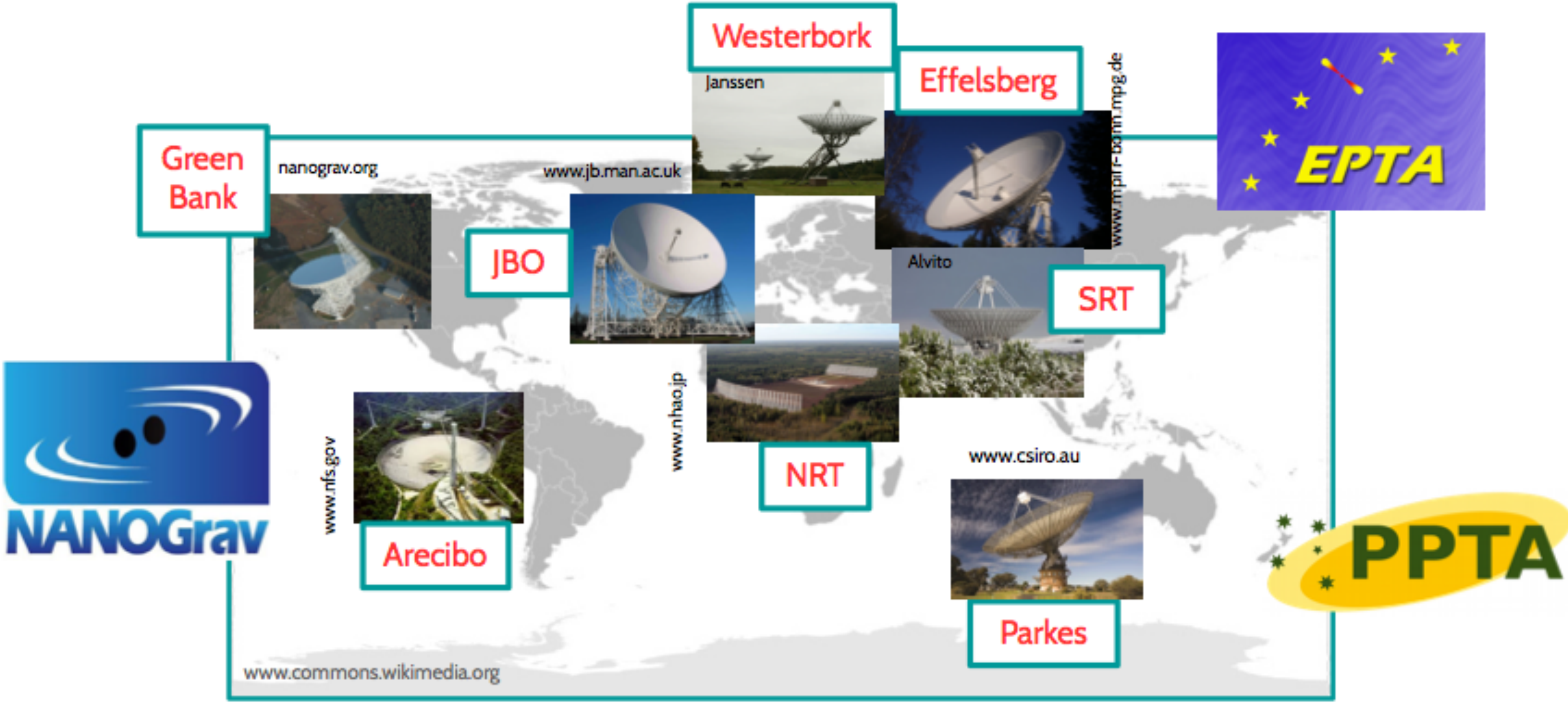


Courtesy Caterina Tiburzi 2019

NANOGrav: North American Array

Courtesy Caterina Tiburzi 2019

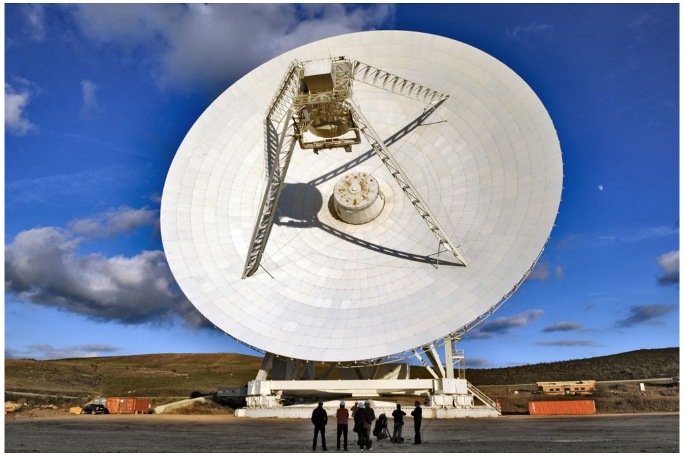
IPTA: International Pulsar Timing Array



Courtesy Caterina Tiburzi 2019

Italian Assets

Sardinia Radio Telescope: SRT



❖ Fully steerable, wheel-and-track radio telescope

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

- ➢ **dual band 300-400 MHz 1300-1800 MHz receiver**
- ➢ 5.5-7.5 GHz receiver
- ➢7 beam 18-26 GHz receiver

❖ Primary mirror : 64 m

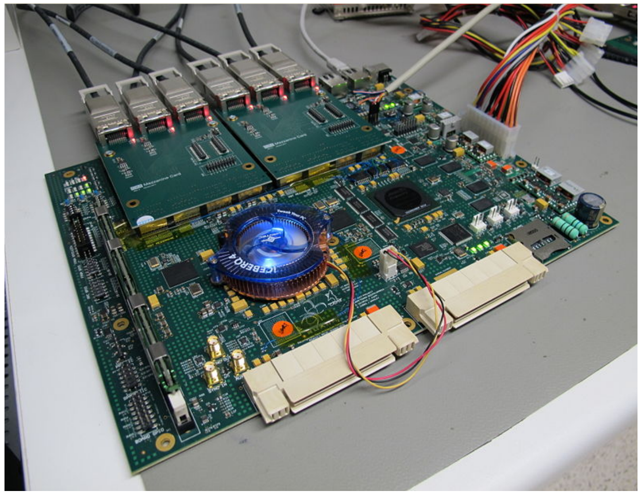
❖ *Quasi*-Gregorian system with shaped surfaces

❖ Active optics: 1116 actuators

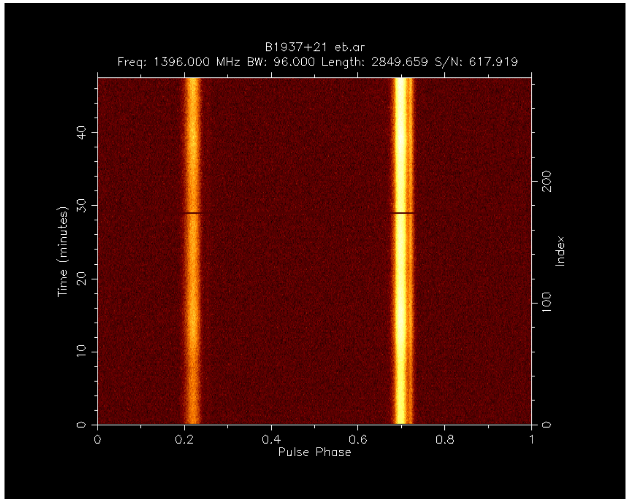
❖ 6 focal positions (up to 20 receivers): Primary, Gregorian, 4 Beam Wave Guide

❖ Frequency Agility

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

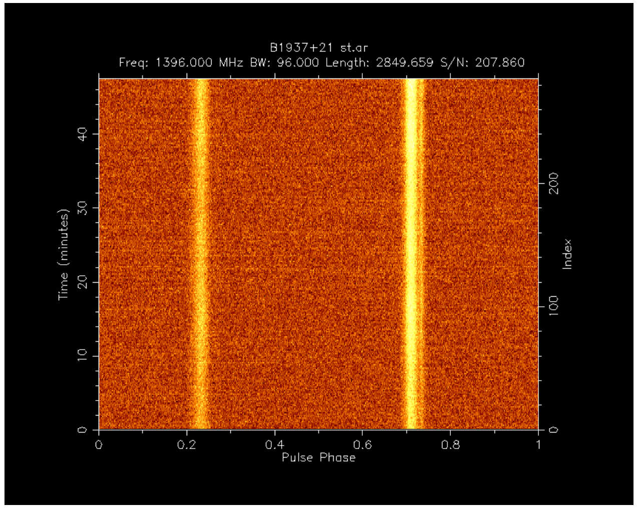


B1937+21 @ Effelsberg



[Courtesy Perrodin 2019]

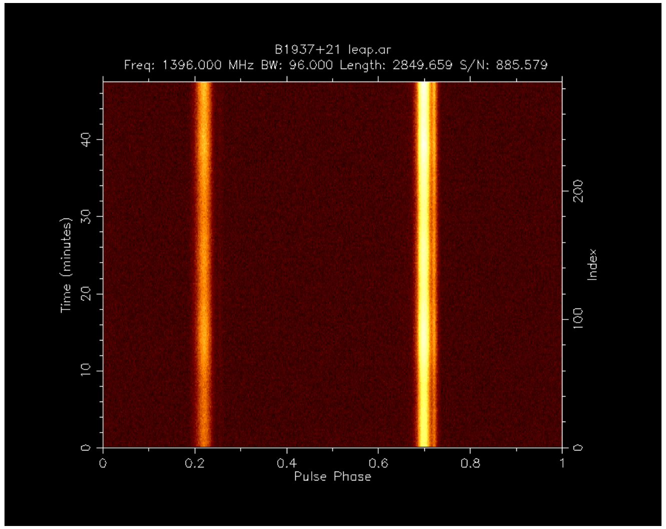
B1937+21 @ SRT



LEAP: Large European Array for Pulsars

(originally funded by EU grant for 5 years)

B1937+21 @ SRT + Effelsberg



[Courtesy Perrodin 2019]

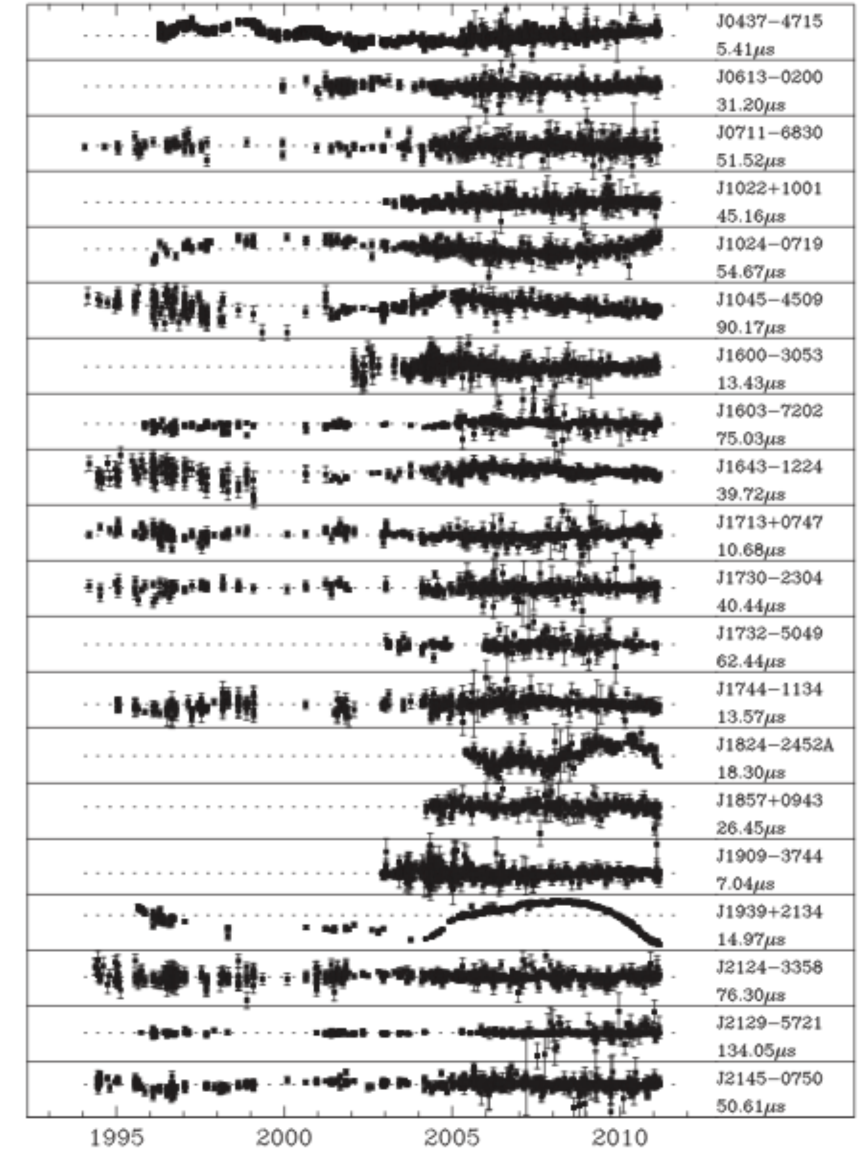
Combining “coherently” all the 5 major EPTA instruments, SRT is part of the best available telescope at 20cm-band for doing pulsar timing, before the SKA era…

Australian Assets

PPTA

Reardon et al. 2016:

20 years of timing of millisecond pulsars



Australian Assets

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

The Centre brings together the Australian pulsar and gravitational-wave communities in a focused national program.

Funded by a $31.3 million grant from the Australian Research Council

Director: Matthew Bailes
Deputy: David McClelland

Nodes: Swinburne University of Technology, Monash University, the Australian National University, the University of Melbourne, the University of Western Australia, and the University of Adelaide, plus collaborations with CSIRO, Anglo Australian Observatory (AAO), LIGO Observatory, Caltech, University of Florida, University of Glasgow, Max Planck Institutes of Gravitational Physics and Radio Astronomy, MIT, NASA, University of Warwick and Universita degli Studi di Urbino 'Carlo Bo'

Current 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: $A < 1.5 \times 10^{-15}$

EPTA — Lentati et al., 2015: $A < 3 \times 10^{-15}$

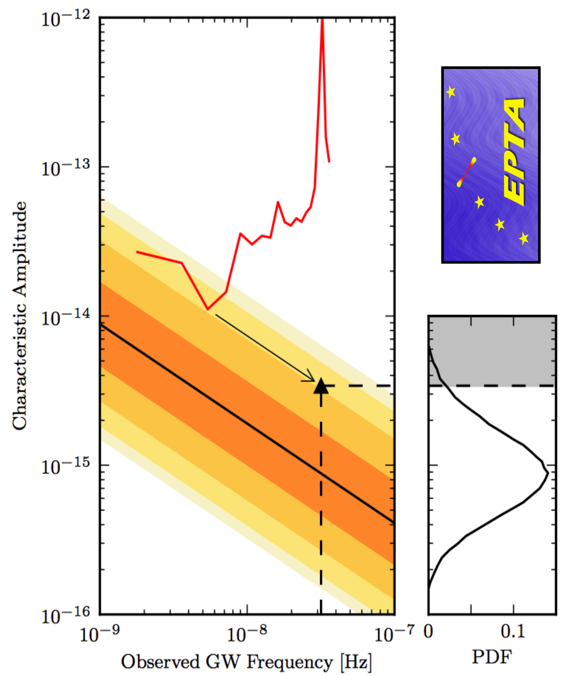
(robust limit including additional effects)

PPTA — Shannon et al., 2015:

$A < 1.0 \times 10^{-15}$ [$\Omega_{GW} < 2.3 \times 10^{-10}$]

IPTA — Verbiest et al., 2016: $A < 1.7 \times 10^{-15}$

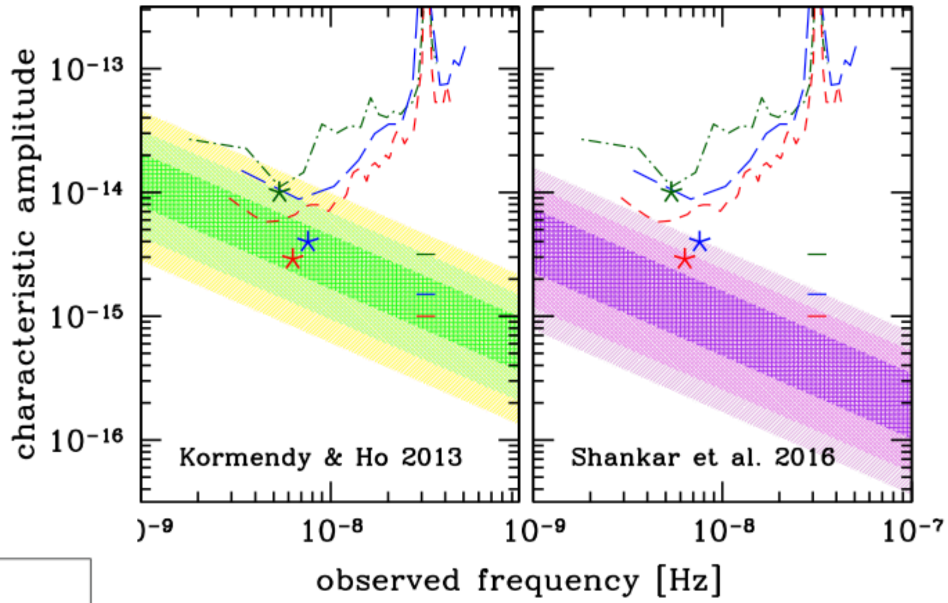
(based on relatively old data only)



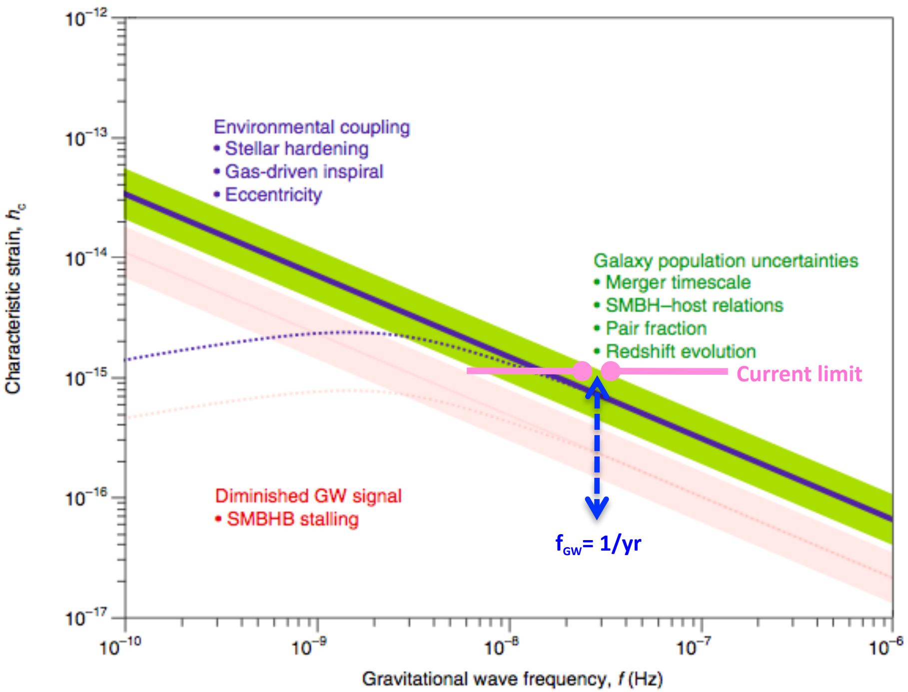
[Lentati et al. 15]

GWB amplitude predictions vs observations

- Already ruling out most generous theoretical models for stochastic GWB



[Sesana et al. 16, Kelly et al. 17]



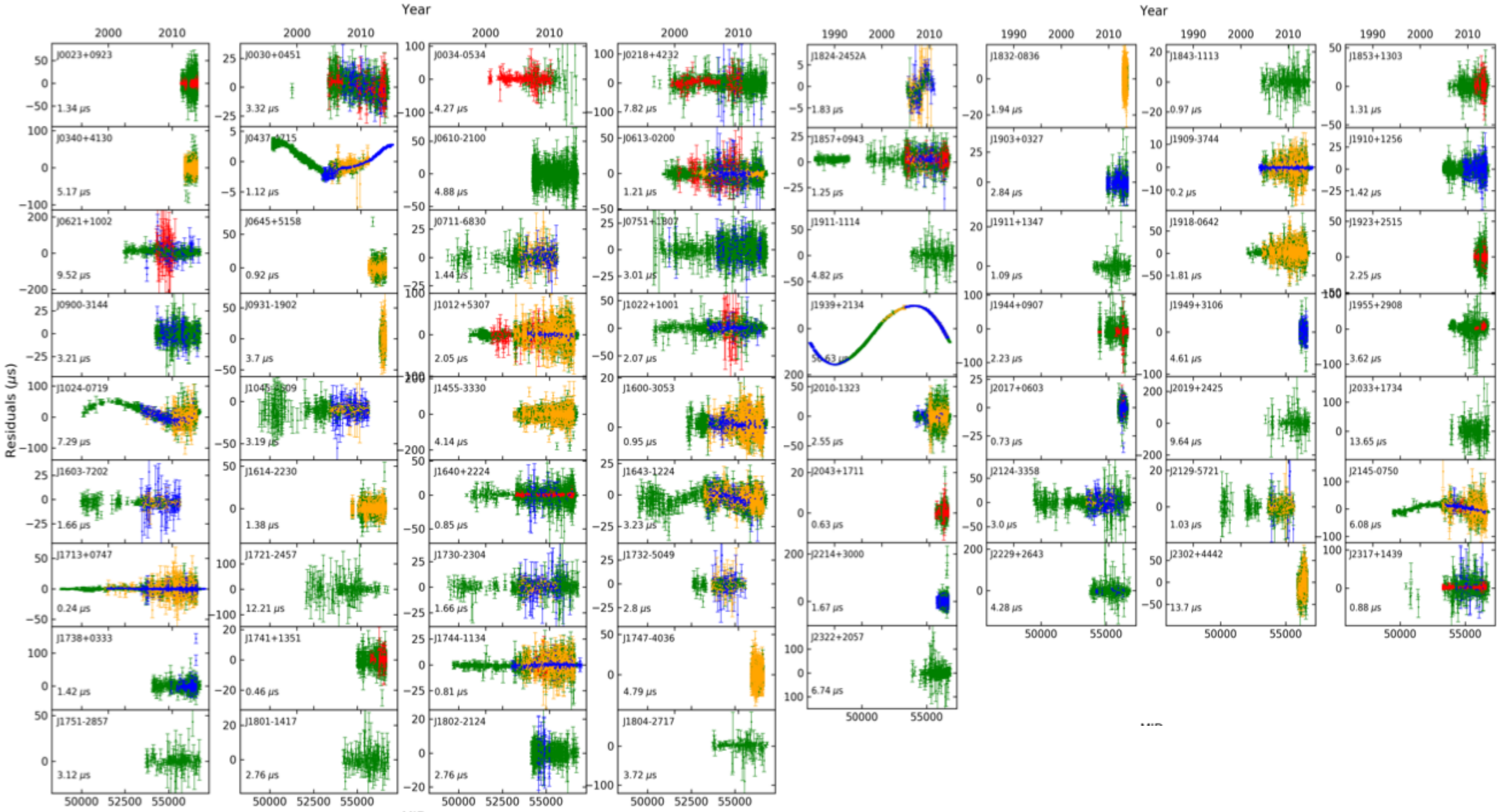
[@ Burke-Spolaor ; Mingarelli 19]

- Newer model predictions (including more physics, accounting for biases)
  - Expected GWB slightly lower
  - Still large range allowed

Ongoing work

Perera et al. 2019: IPTA Data Release 2: 65 pulsars.
Data are public for everyone to download

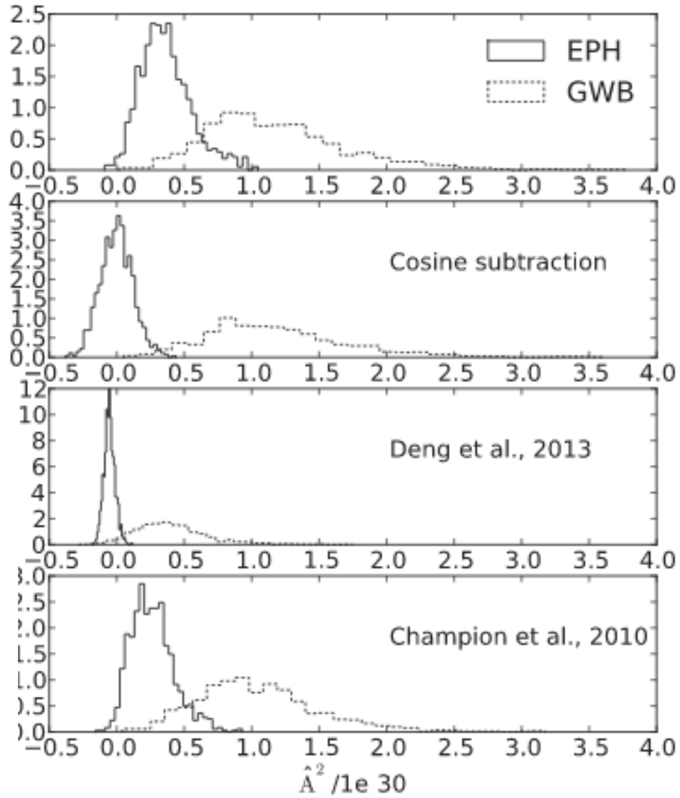
New results from IPTA analysis released early 2020

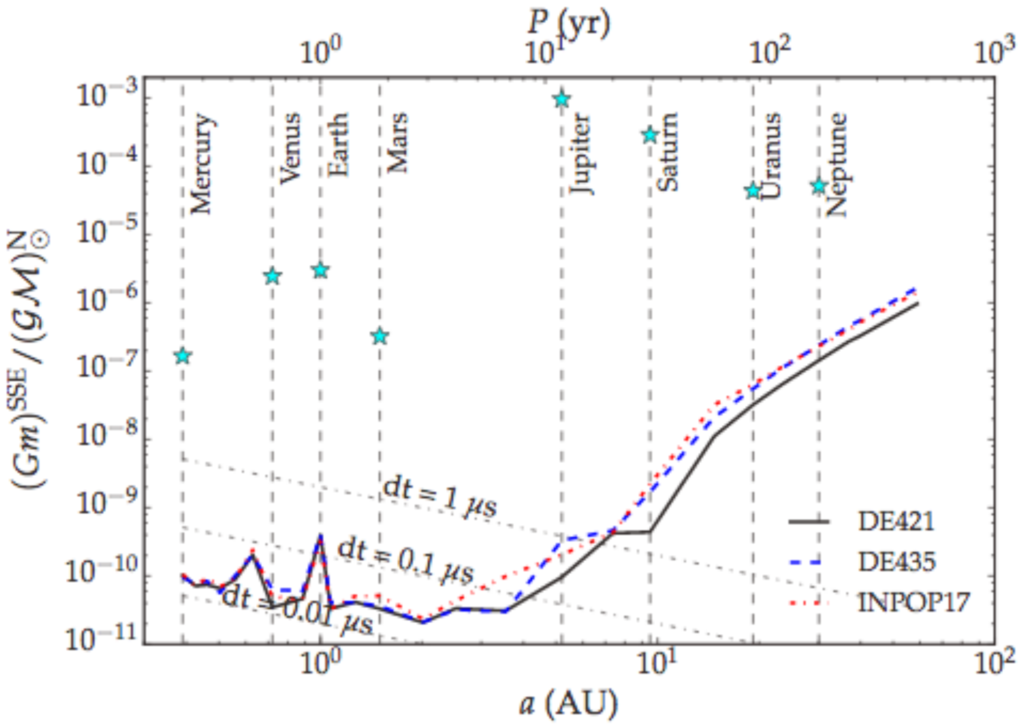


Examples of PPTA + (EPTA/Italy) collaboration

Tiburzi et al. 2016:

Highlighting the possible effects of inaccurate knowledge of Solar System ephemeris in mimicking a real GW background signal





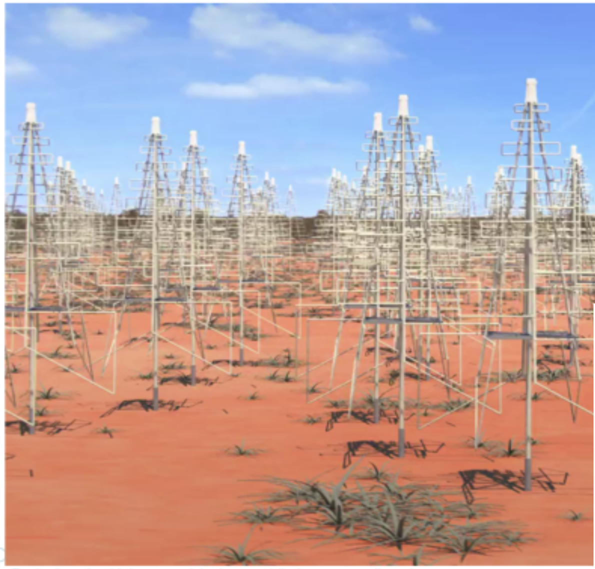
Caballero et al. 2018:

Constraining the presence of un-modelled minor bodies in the Solar System by using Pulsar Timing Array

The future: perspectives of SKA1

SKA1-LOW, Murchison, Australia:

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

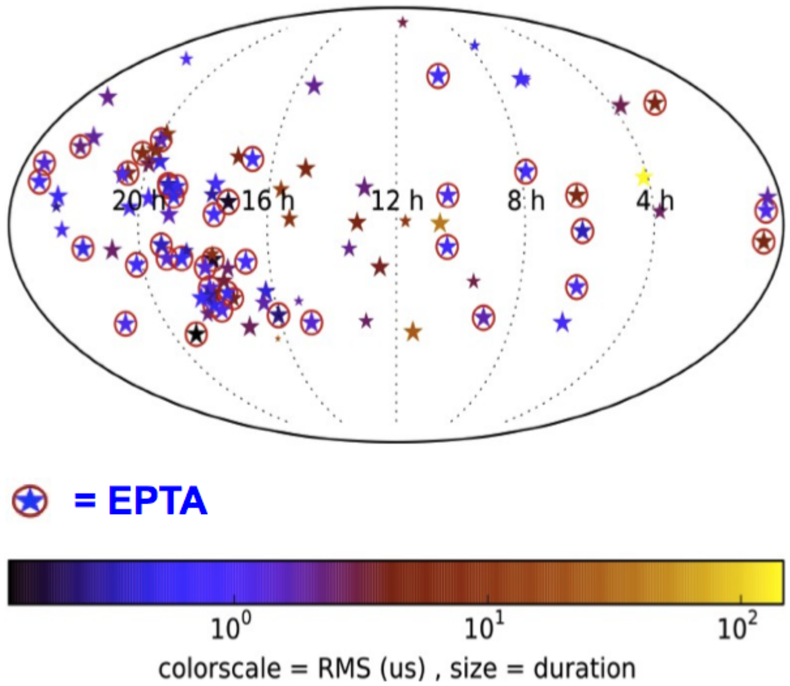


SKA1-MID, Karoo, South Africa:

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)

for a GW Background detection one needs a ...

large PTA of high precision pulsars



The current sample of MSP of IPTA ≈ 40, of which only a handful with precision < 100 ns

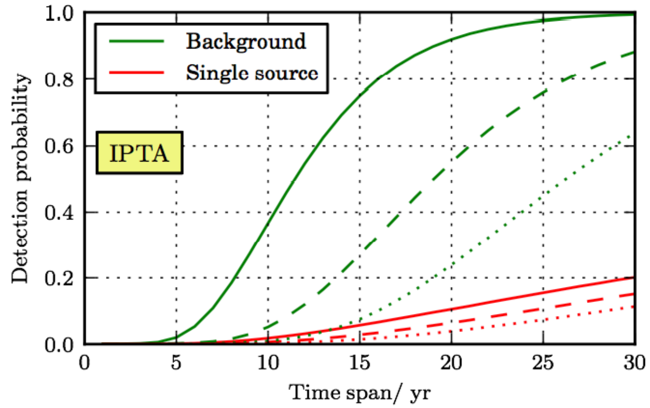
IPTA (International Pulsar Timing Array)

SKA1 will provide ≈ 100 MSPs with timing precision < 100 ns

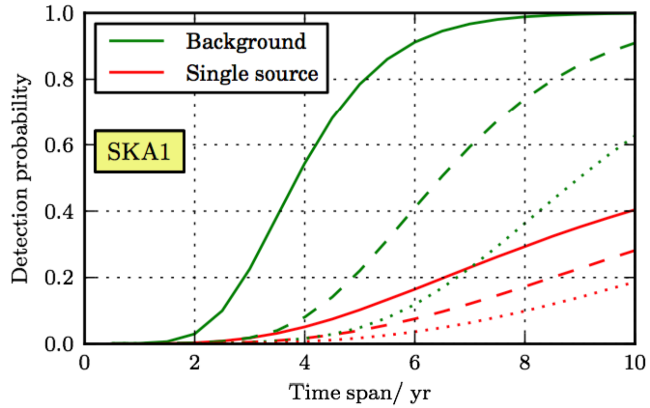
[Shao et al 2015]

Timing array(s): from limits to GWBs detection

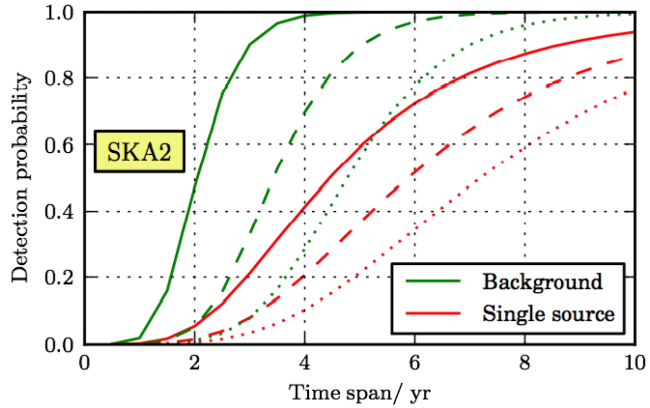
Current projects are evolving in pace with predictions. Then at least very significant limits (and hopefully a detection) should be achieved within few years by IPTA



Unless the galaxy assembling model has to be rewritten, the detection and a basic studies of the GWB [spectrum, anisotropy] and of many single sources is warranted with phase 1 of SKA

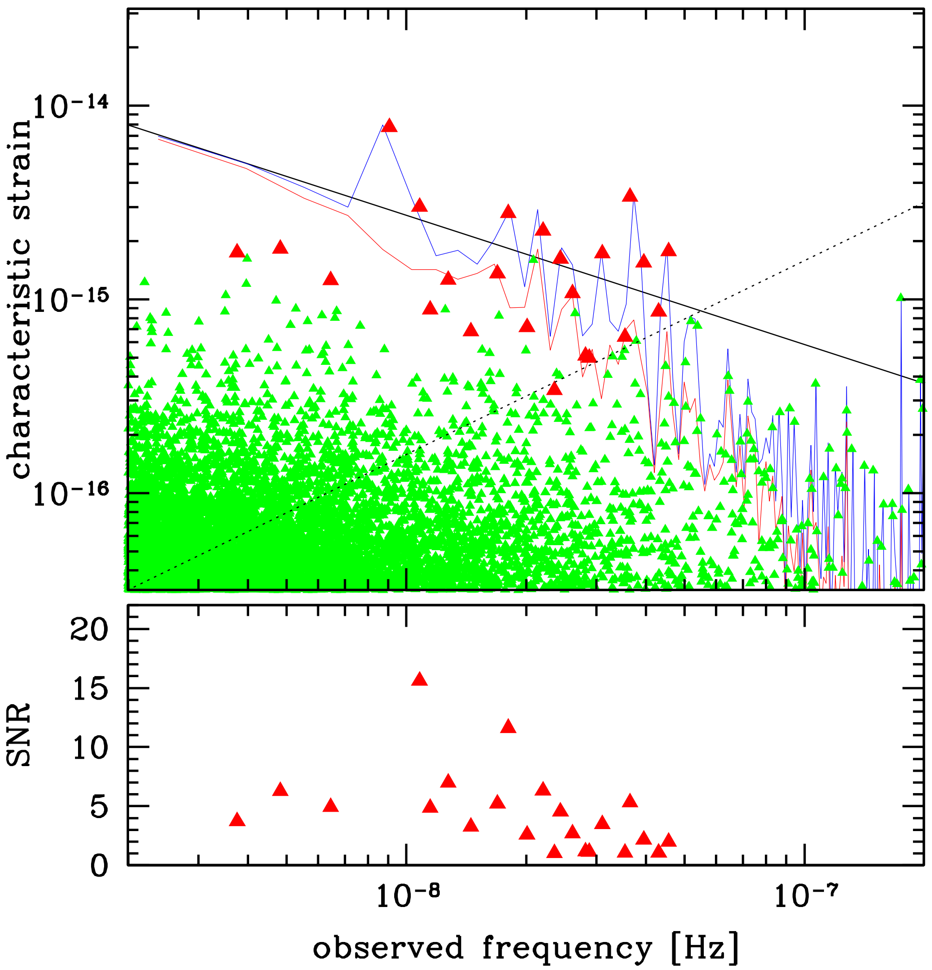


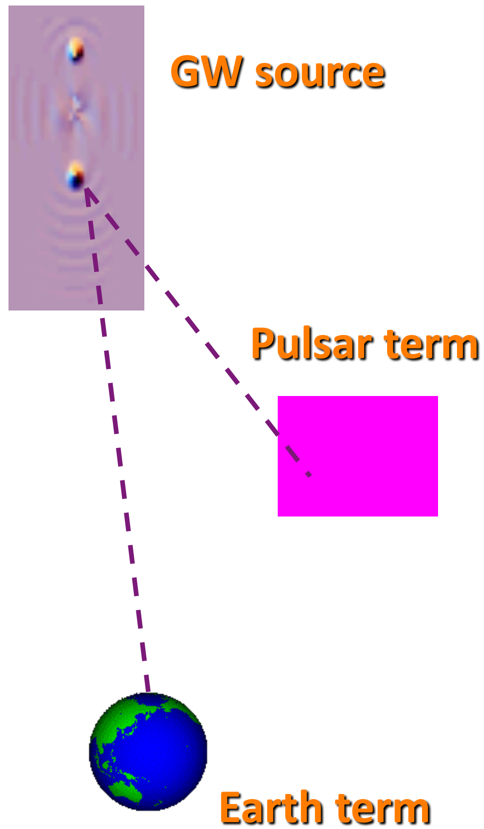
Full nanoHz-GW astronomy and implied fundamental physics tests will take place with phase 2 of SKA



[Rosado, Sesana & Gair 15]

Detection & localization of an in-spiral binary





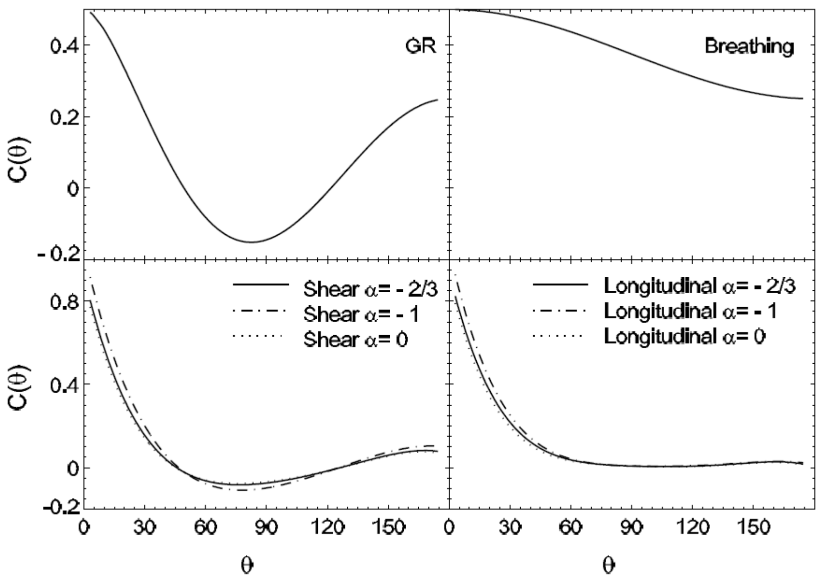
At least one SMBH+SMBH will induce timing residual of order 5-50 nanosec

[Sesana et al 2013]

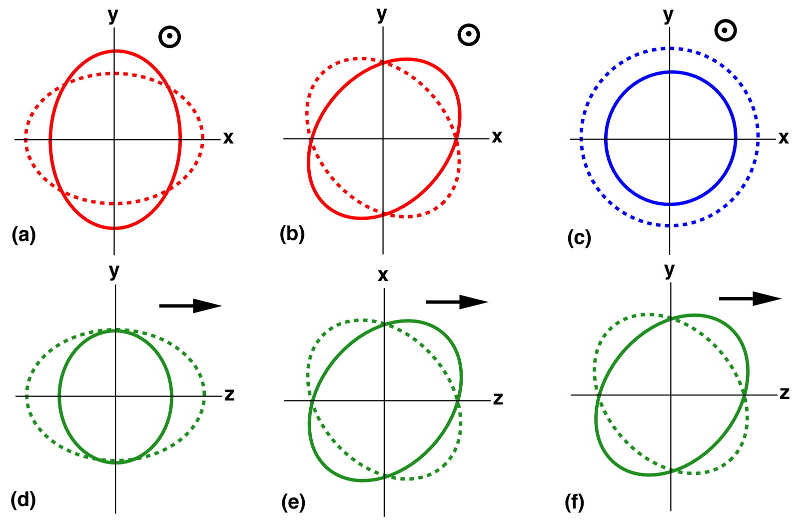
Signal contains information from two distinct epochs!

Fundamental physics tests

[Lee et al. 2009]



Tests of the polarization "modes" of the GWs

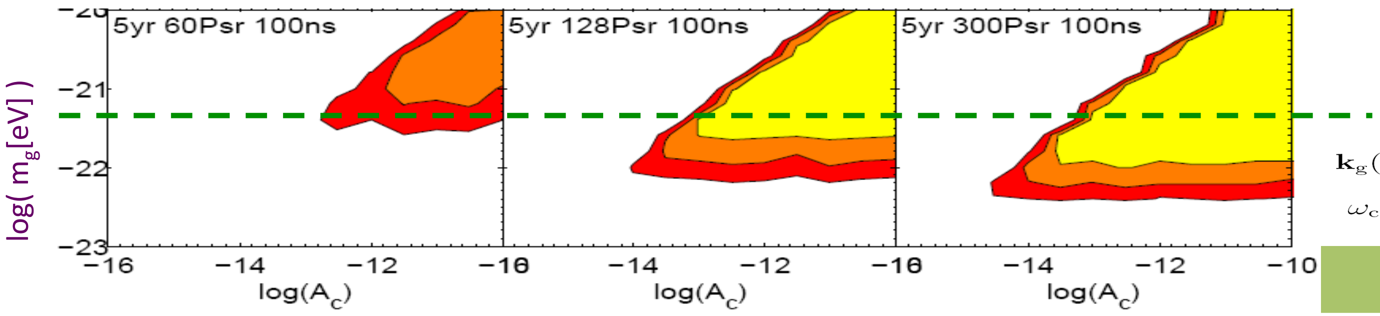


[Chamberlin & Siemens 2012]

Graviton mass

- - - - = present solar system limit

[Lee et al. 2010]



$$\mathbf{k}_g(\omega_g) = \frac{(\omega_g{}^2 - \omega_{cut}{}^2)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}$$

$$\omega_{cut} = m_g c^2/\hbar$$

Thanks