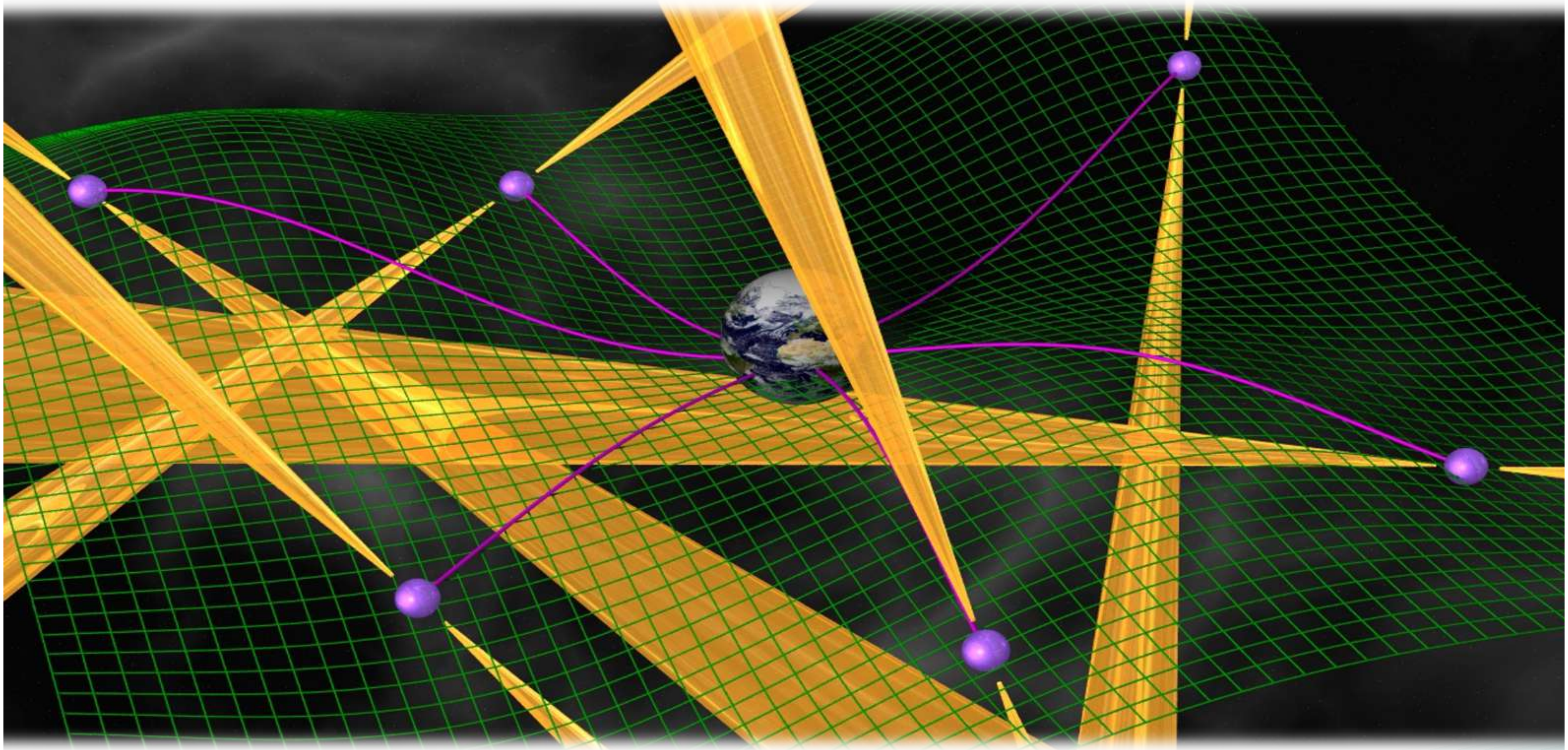
Prospect of detecting gravitational waves and probing gravity with pulsar timing arrays



Michael Kramer

Max-Planck-Institut für Radioastronomie, Bonn

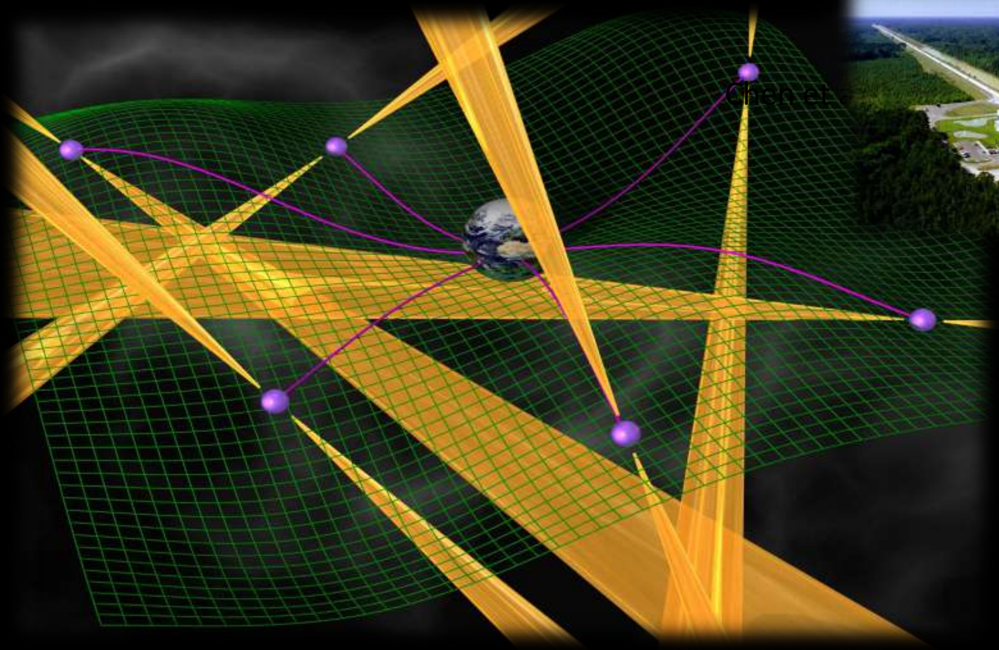
Jodrell Bank Centre for Astrophysics, University of Manchster

Pulsars as Gravitational Wave Detectors

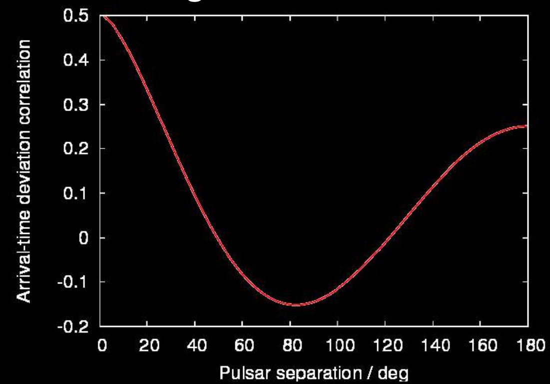
Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky

In a "Pulsar Timing Array" (PTA) pulsars act as the arms of a cosmic gravitational wave detector

A number of external noise sources which makes detection difficult – good progress is being made



Stochastic GWB signature:
Hellings-Downs Curve



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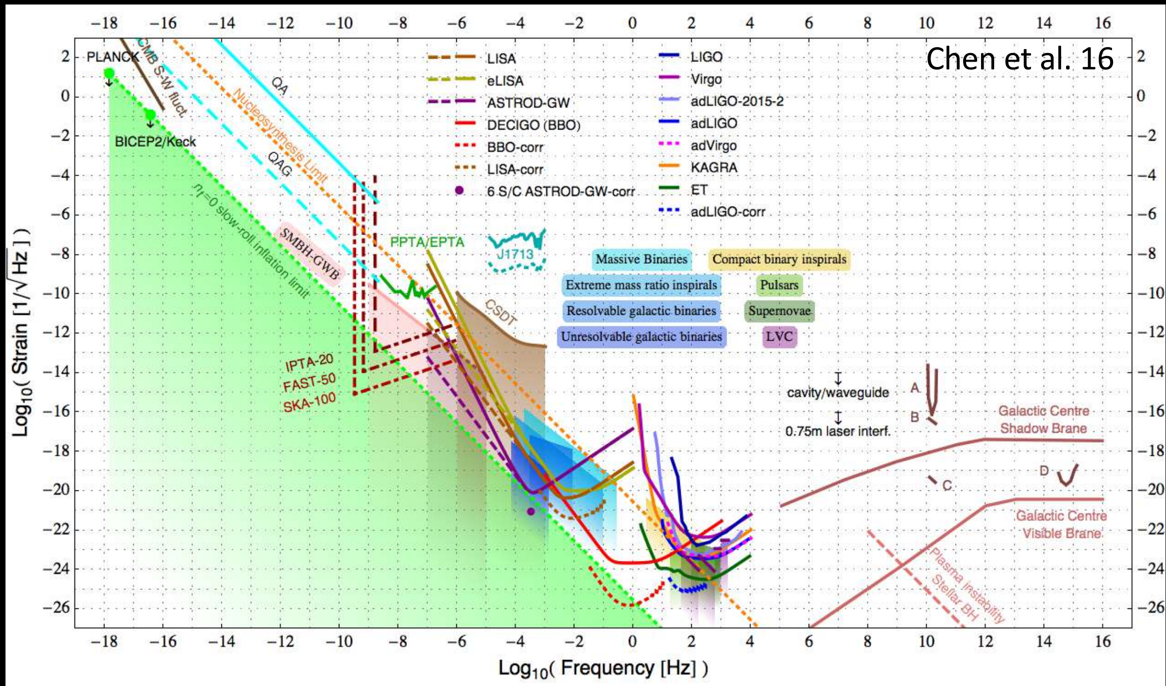
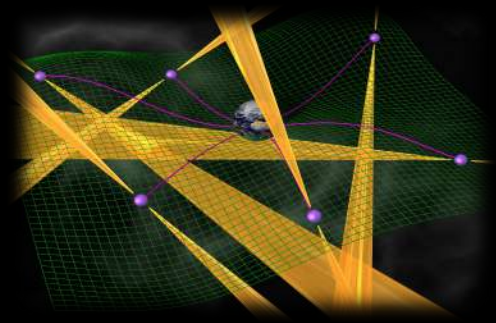
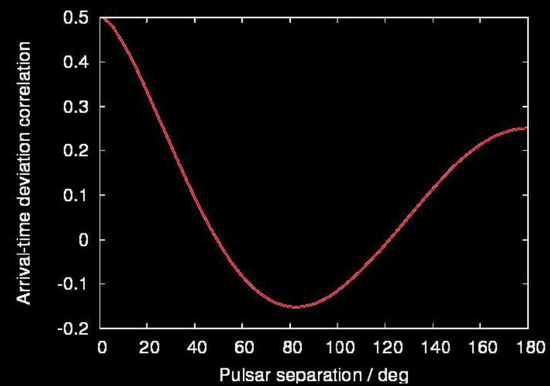


CMB PTA LISA LIGO





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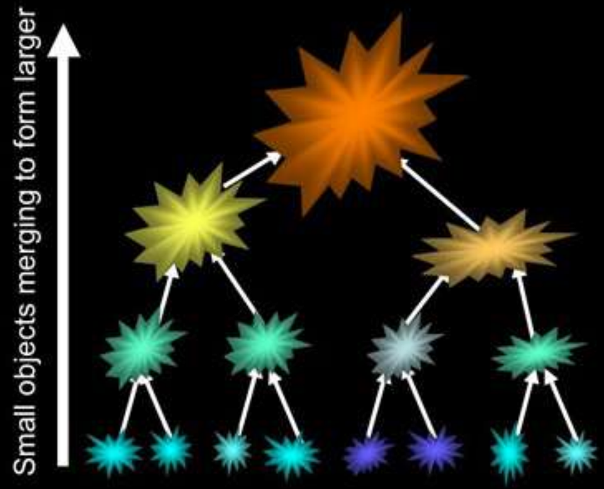
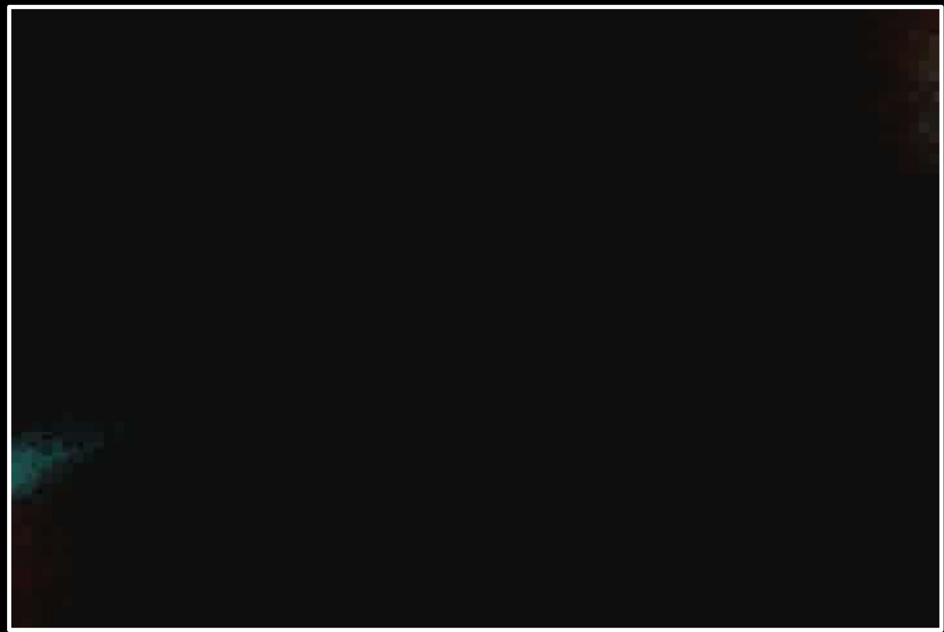
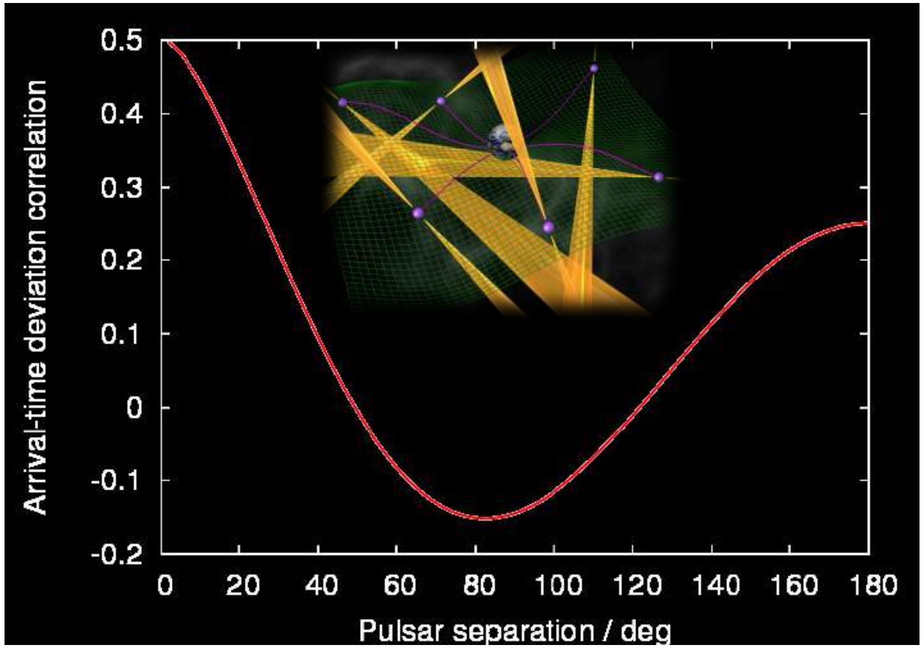




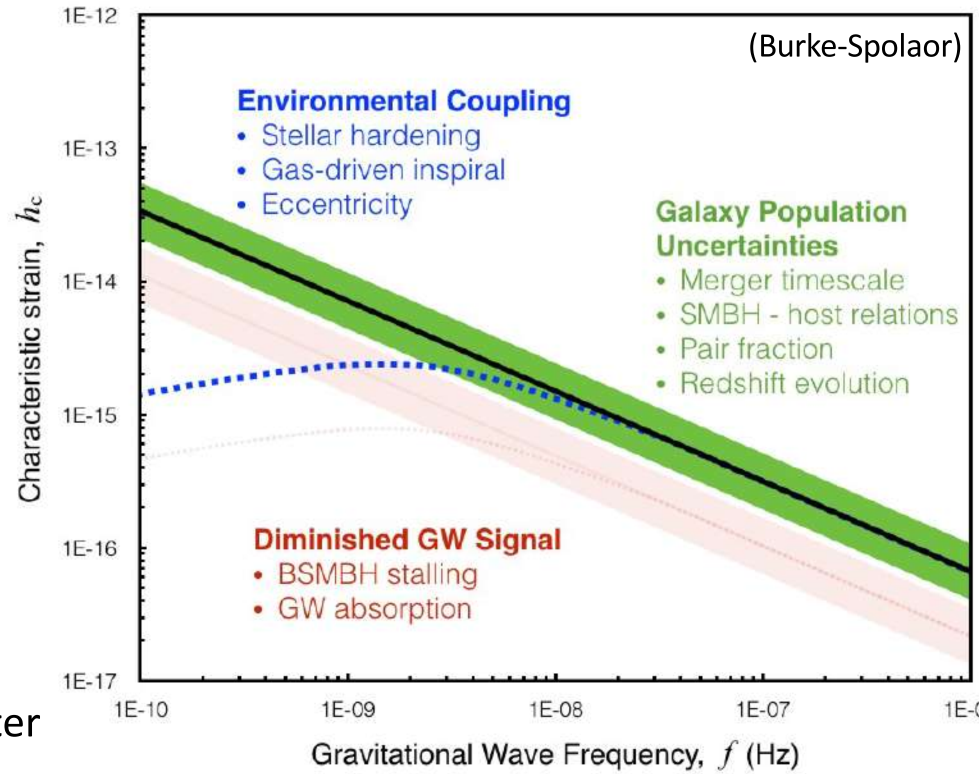
Hellings-Downs Curve

- Correlation between pairs of pulsars on the sky (Hellings & Downs 1983)
- Isotropic, stochastic GW background (GWB) signal should essentially have power law (with index **α** = -2/3)
- But, astrophysics modifies this

$$h_c = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$



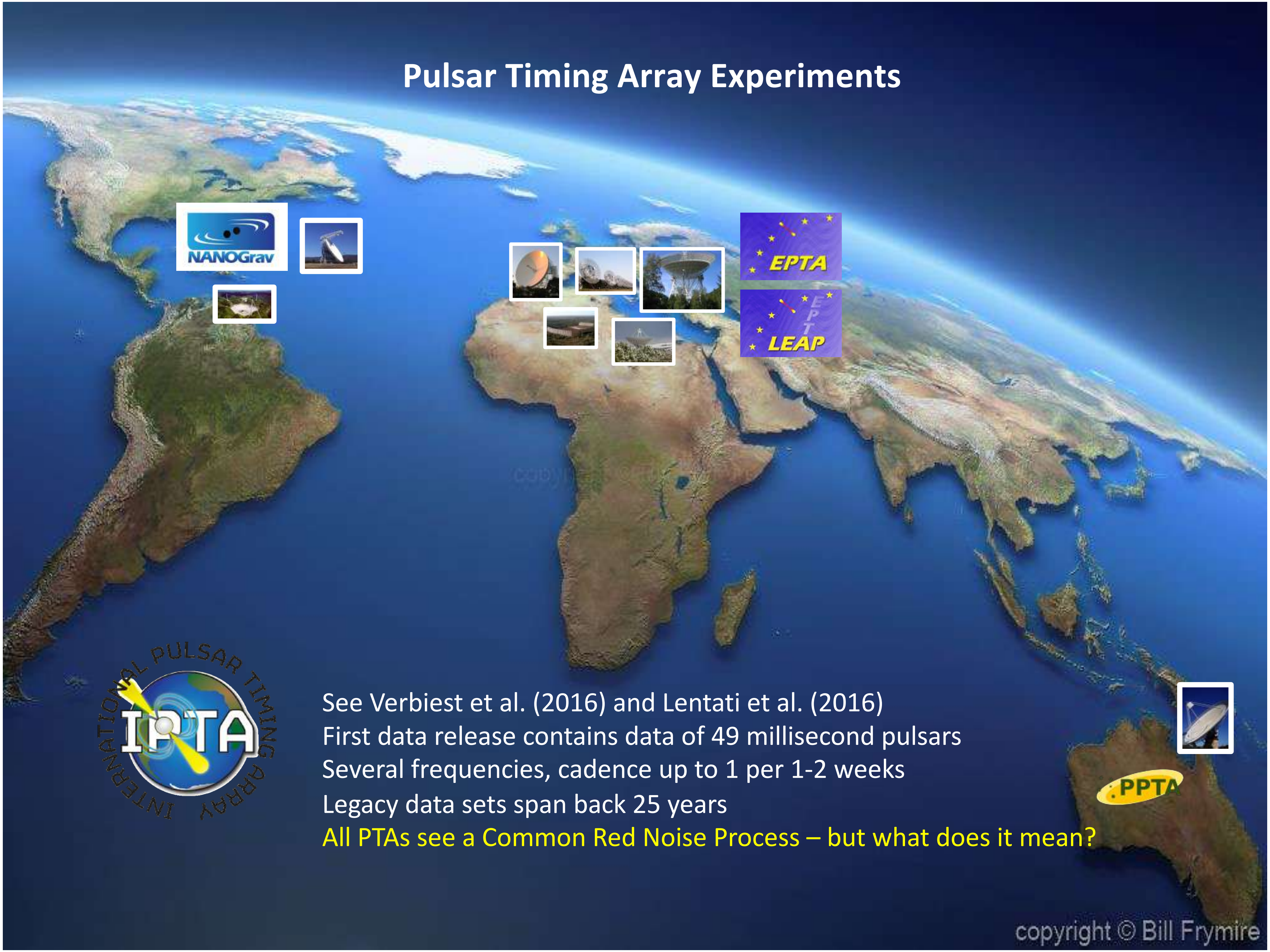
NB: Shape depends on graviton properties – see later



We may not observe in the optimal frequency window…! – See later

Pulsar Timing Array Experiments

Pulsar Timing Array Experiments



See Verbiest et al. (2016) and Lentati et al. (2016)
First data release contains data of 49 millisecond pulsars
Several frequencies, cadence up to 1 per 1-2 weeks
Legacy data sets span back 25 years
All PTAs see a Common Red Noise Process – but what does it mean?

Status

- There is no detection yet
- Data suggest a “common red noise process” seen by EPTA ,Nanograv and PPTA

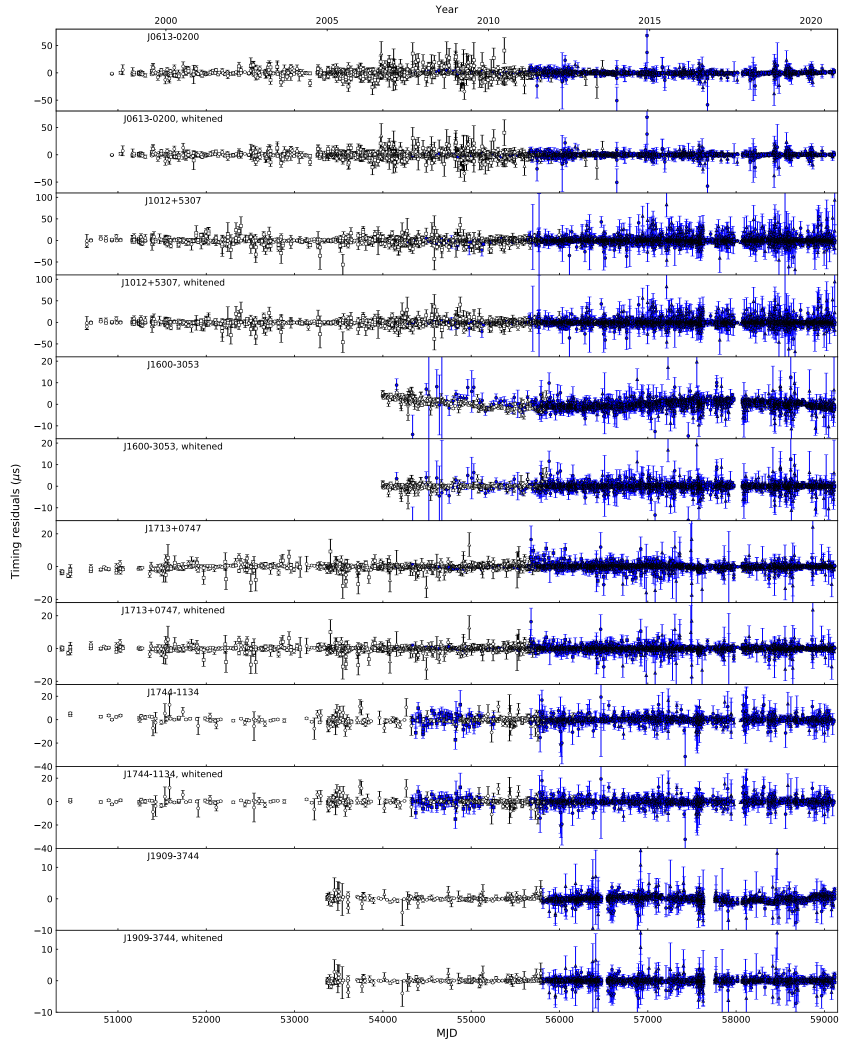
EPTA et al.

(to be submitted):

25 years of high precision data.

Here, 6 pulsars – publication with

25+ pulsars in prep.



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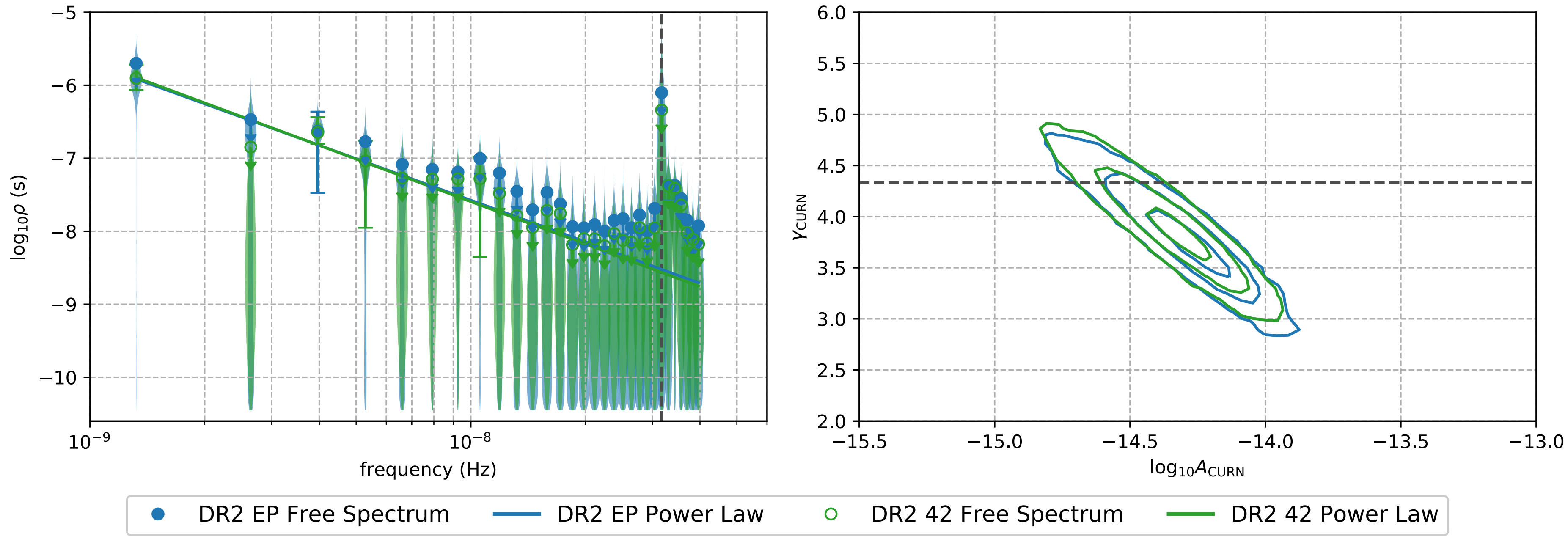
EPTA et al.



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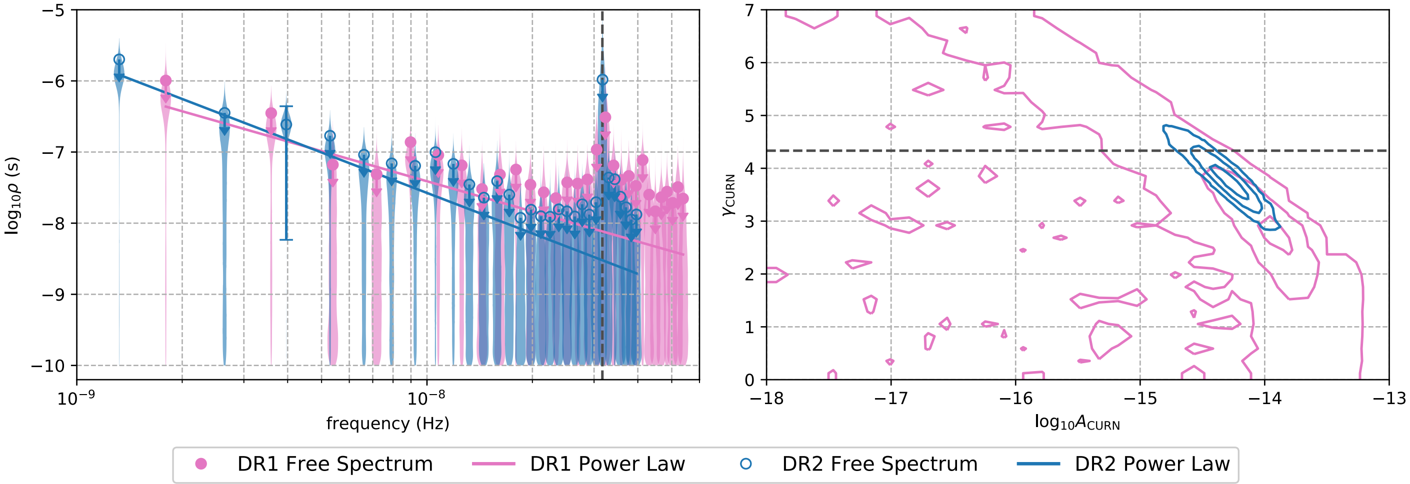
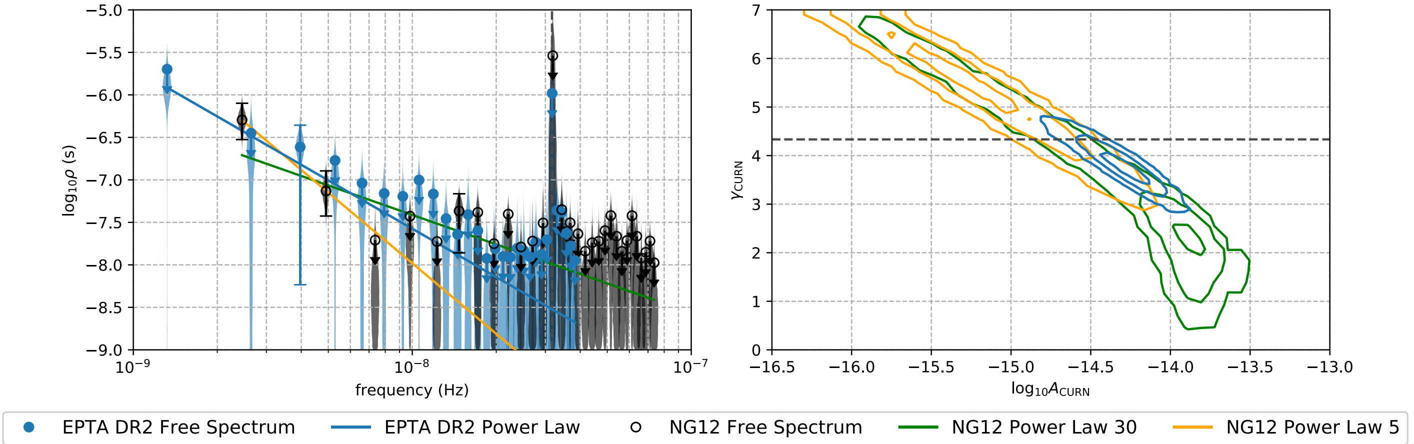
EPTA et al.

DR1 vs DR2



EPTA vs NG



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- It could be similar intrinsic noise in (some) pulsars
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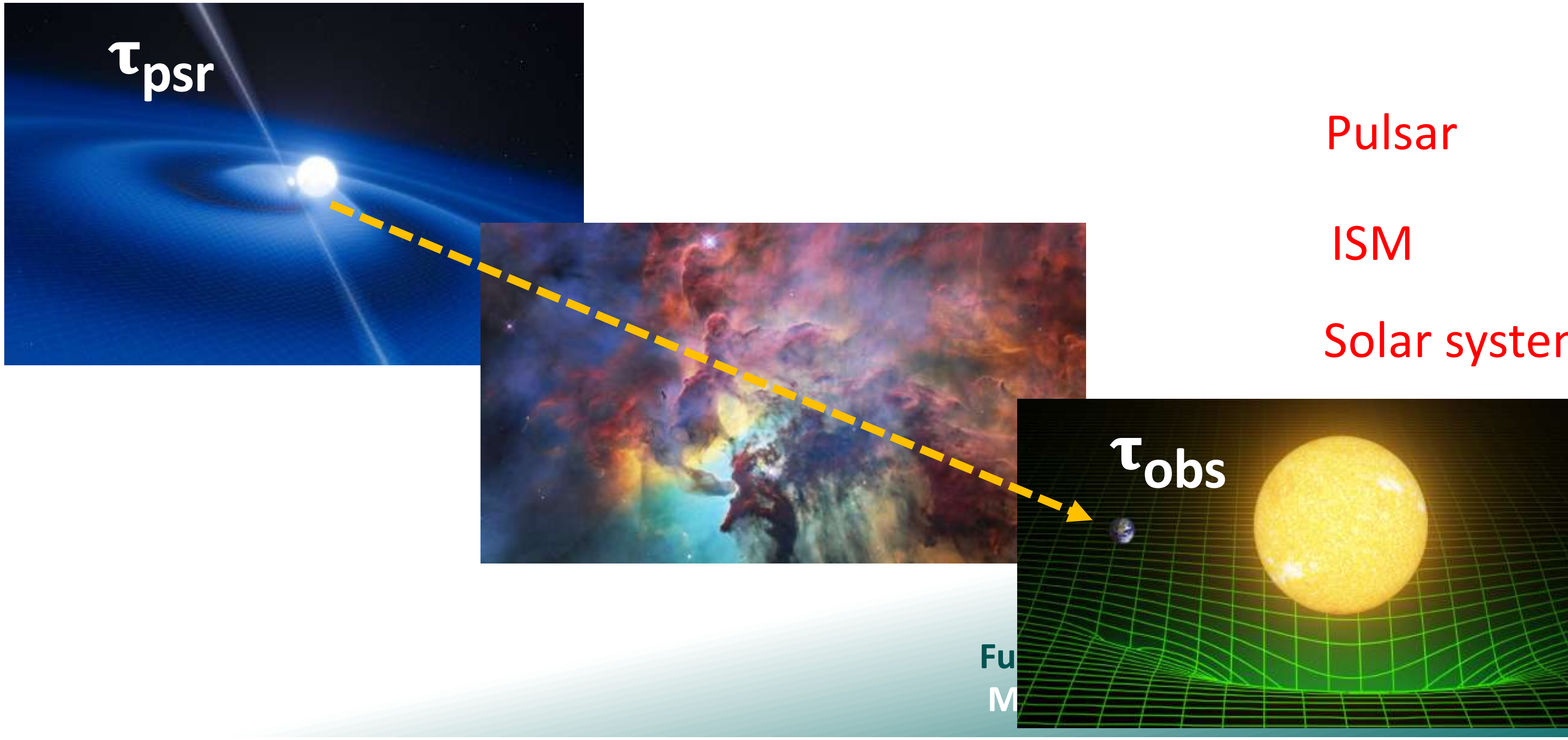

Pulsar

ISM

Solar system

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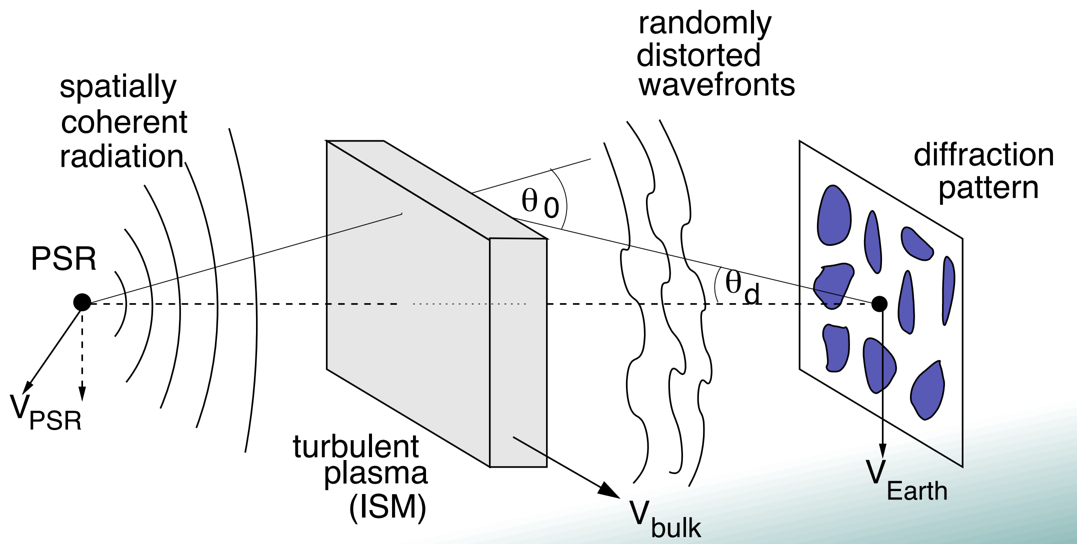
In addition to changing dispersion:

Scattering in ISM

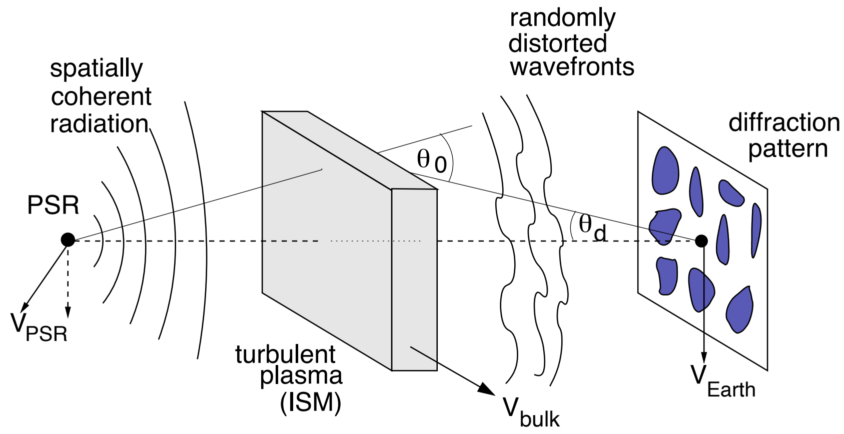


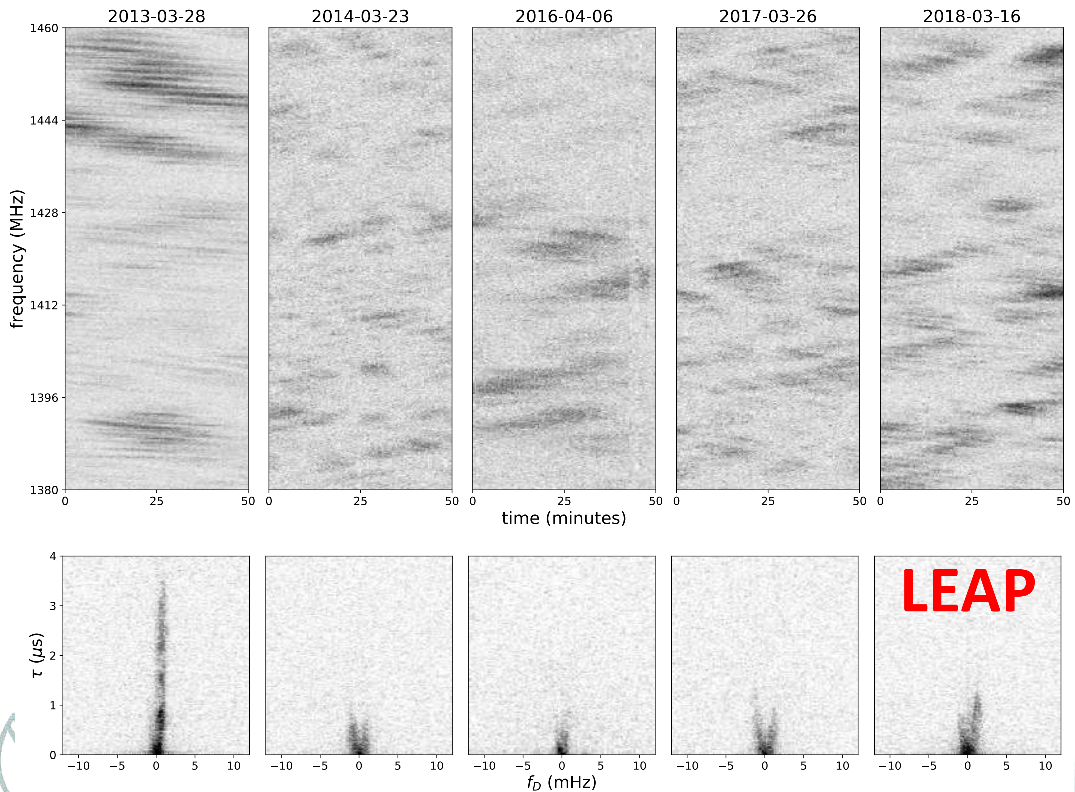
Interstellar scattering

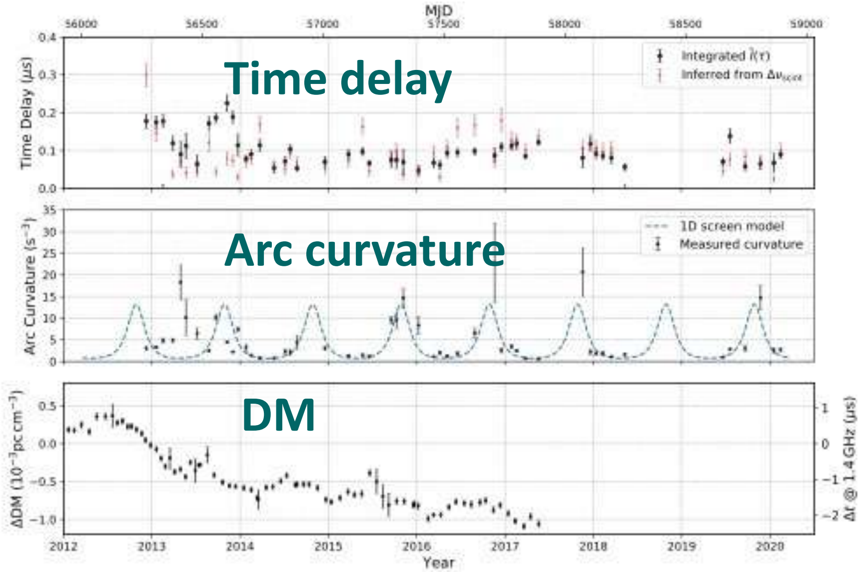
Changing also as a function of time:

Measuring Interstellar Delays of PSR J0613−0200 over 7 years, using the Large European Array for Pulsars

R. A. Main[1⋆], S. A. Sanidas[2,3], J. Antoniadis[1], C. Bassa[4], S. Chen[5,6,7], I. Cognard[7,5], M. Gaikwad[1], H. Hu[1], G. H. Janssen[4,8], R. Karuppusamy[1], M. Kramer[1,2], K. J. Lee[9], K. Liu[1], G. Mall[1], J. W. McKee[10], M. B. Mickaliger[2], D. Perrodin[11], B. W. Stappers[2], C. Tiburzi[4], O. Wucknitz[1], L. Wang[2,12], W. W. Zhu[12]







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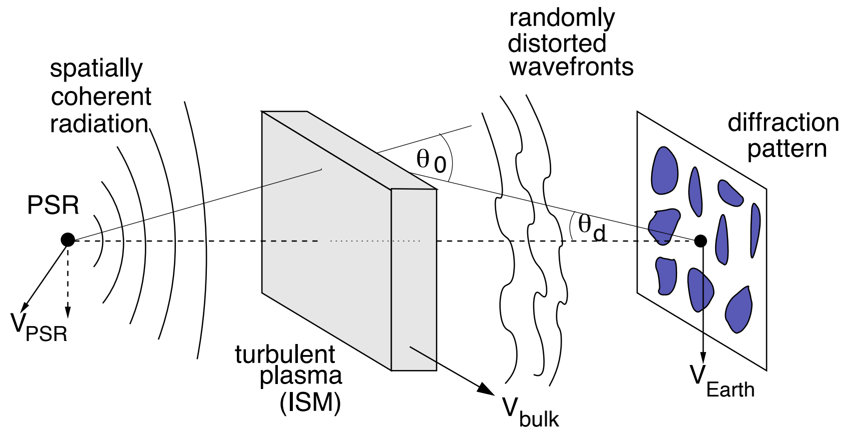
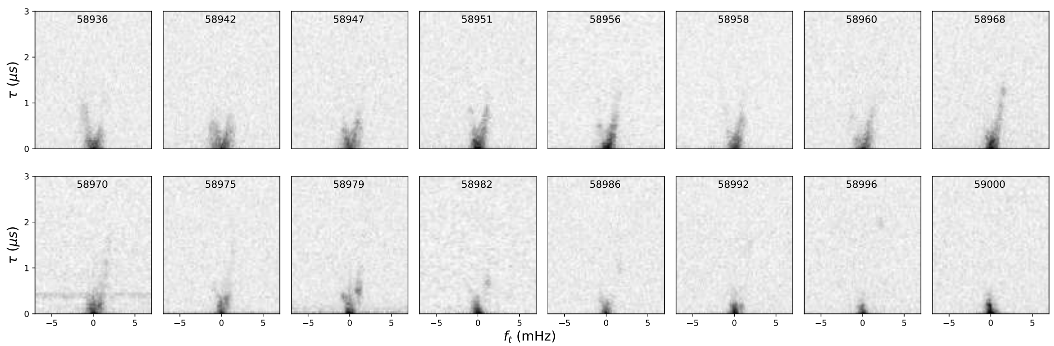
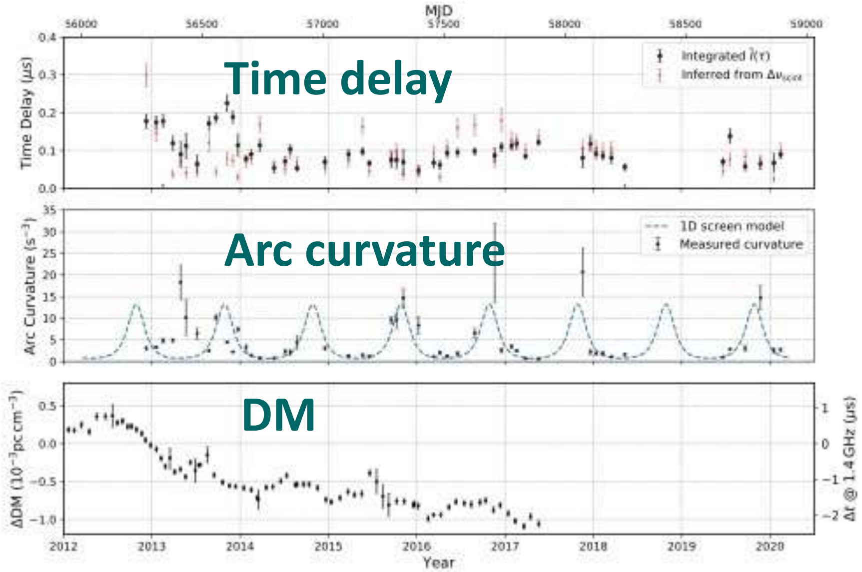
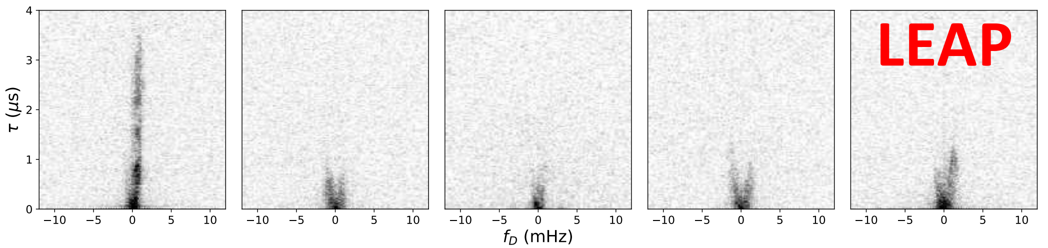


Effelsberg







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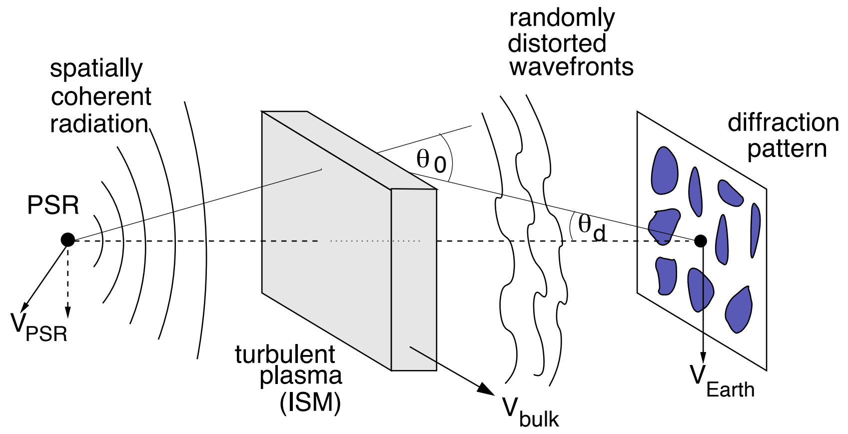

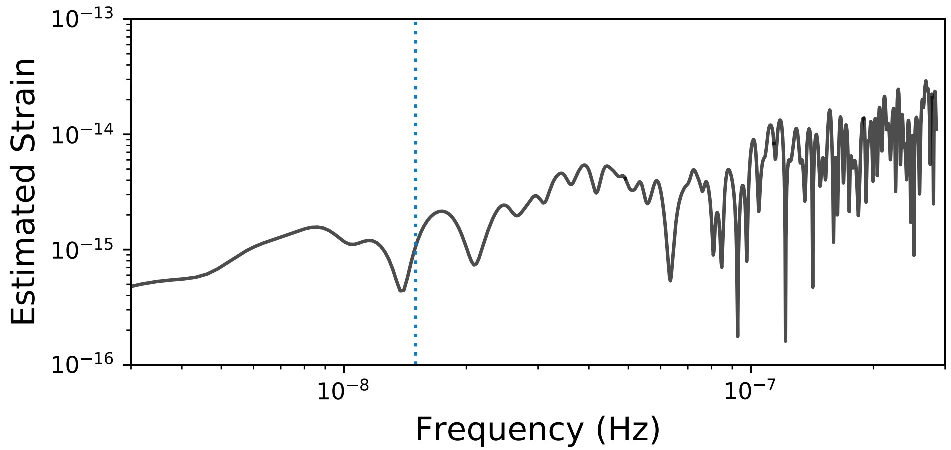

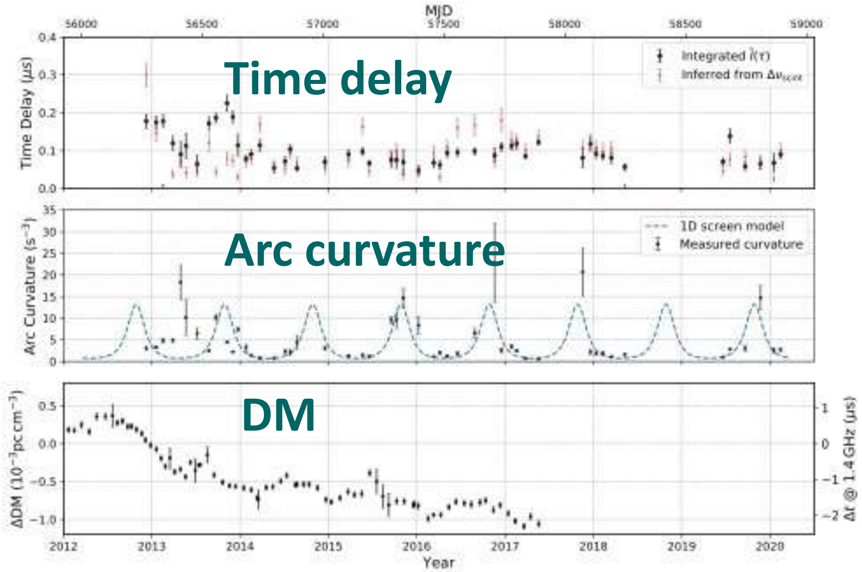

For most pulsars and instruments that is below the sensitivity threshold but it may manifest itself in common signals with the "right" timescales and amplitude…

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But what is it? – A hint of GWs?

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- It could be the extrinsic (non-GW) sources

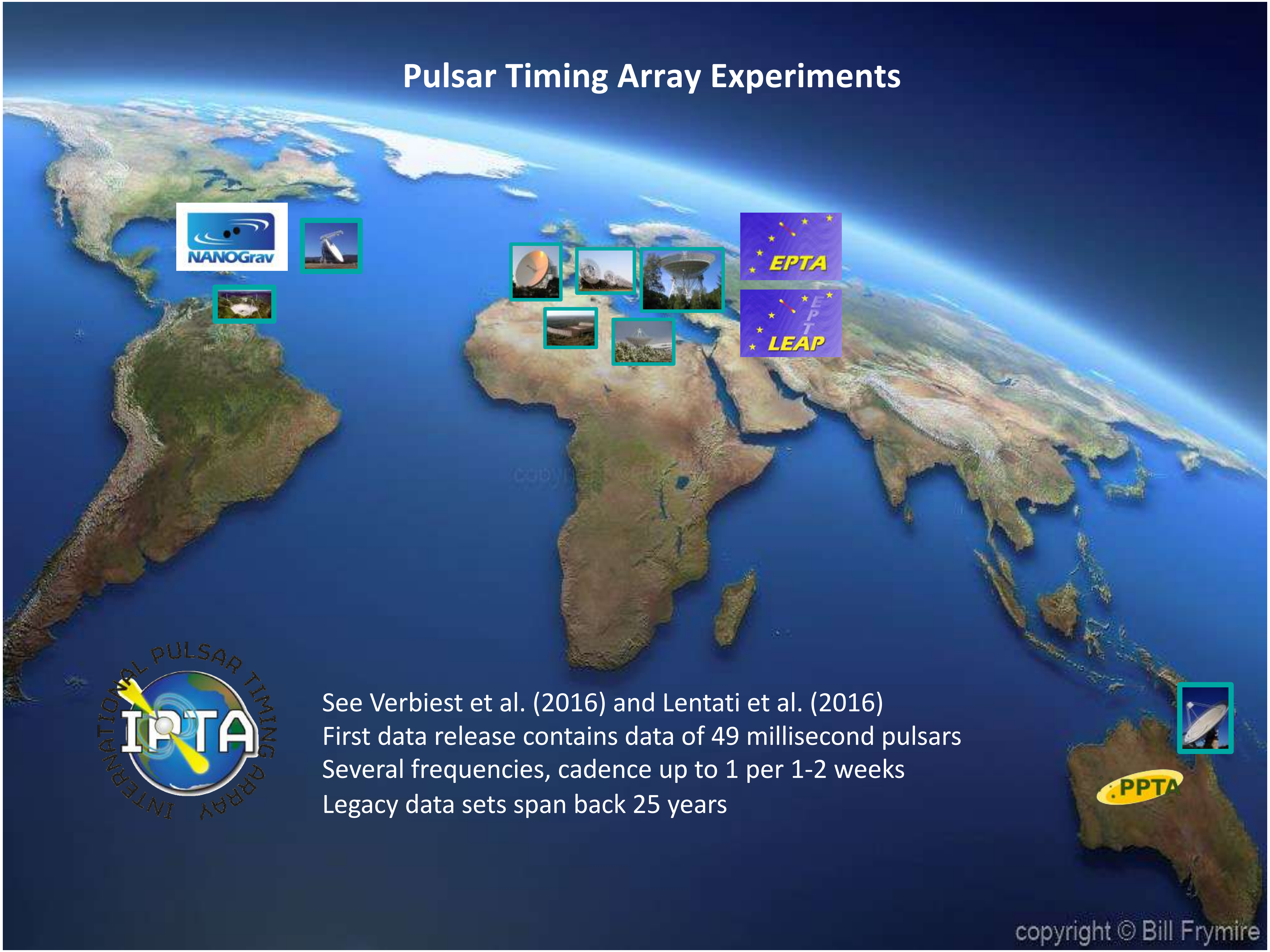
For a GW background, we need to see the HD-correlation.

Eventually, we want to see single sources.

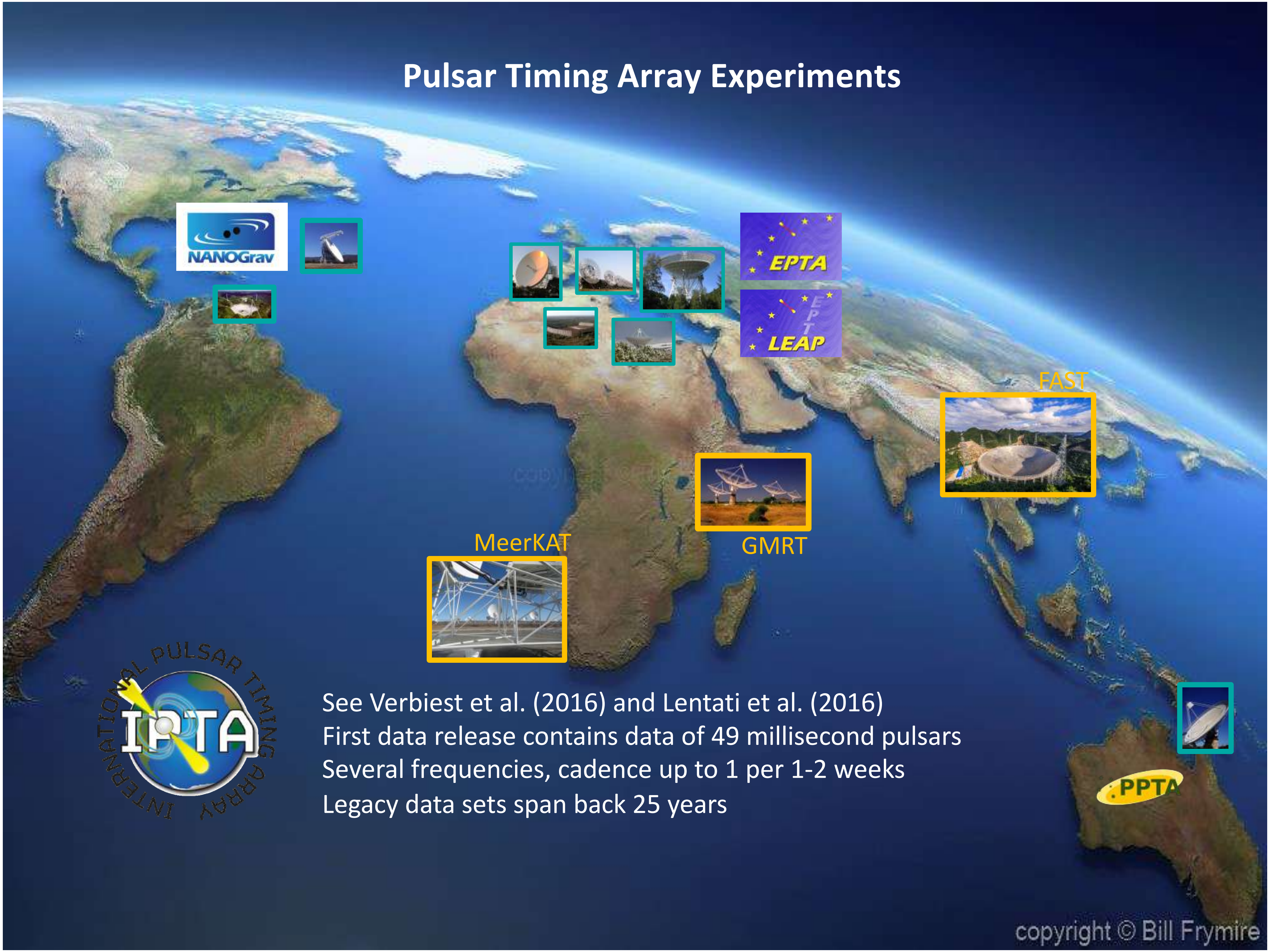
In both cases, we need more sensitivity and better data.

You can/must get sensitivity in two ways: bigger telescopes and more pulsars!

Pulsar Timing Array Experiments



See Verbiest et al. (2016) and Lentati et al. (2016)
First data release contains data of 49 millisecond pulsars
Several frequencies, cadence up to 1 per 1-2 weeks
Legacy data sets span back 25 years


Pulsar Timing Array Experiments
NANOGrav
EPTA
LEAP
FAST
GMRT
MeerKAT
INTERNATIONAL PULSAR TIMING ARRAY
IPTA
PPTA
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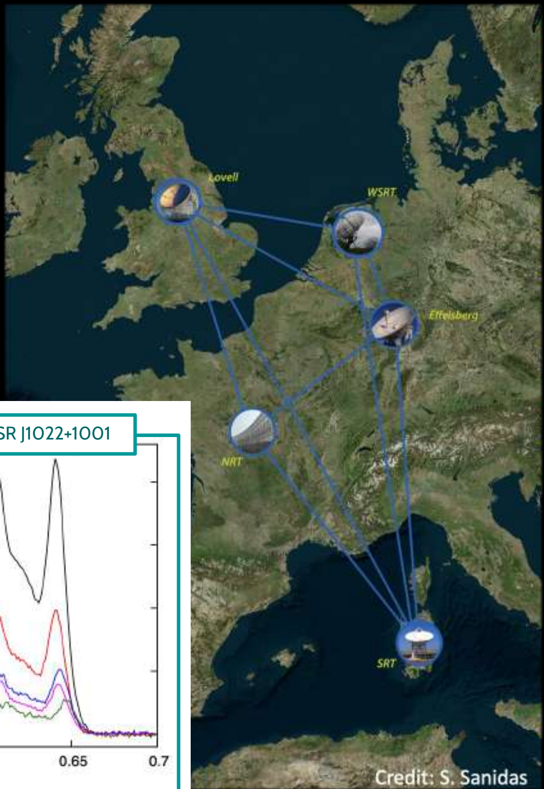
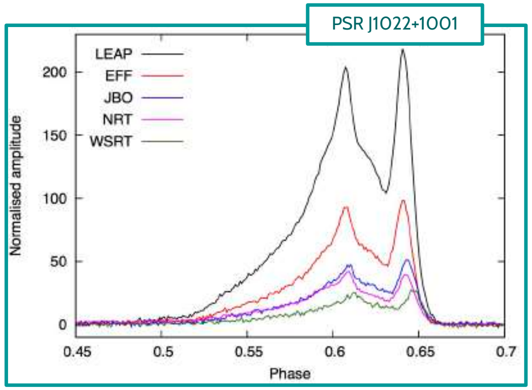
copyright © Bill Frymire

More sensitivity is available

LEAP: Combining EU telescopes to form equivalent 194-m dish





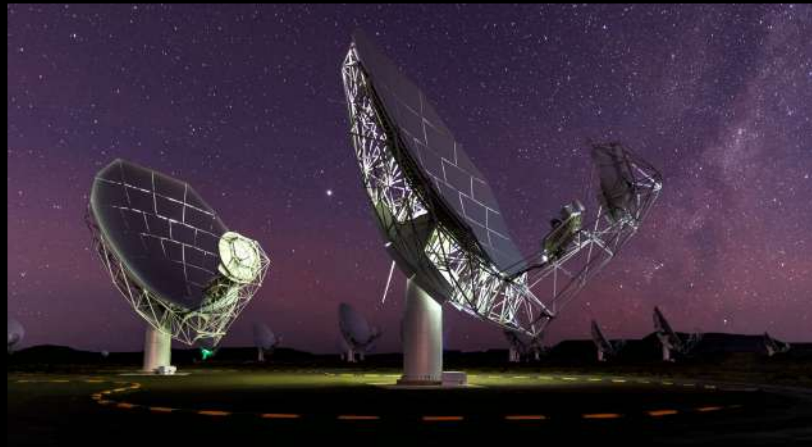
Bassa et al., 2016

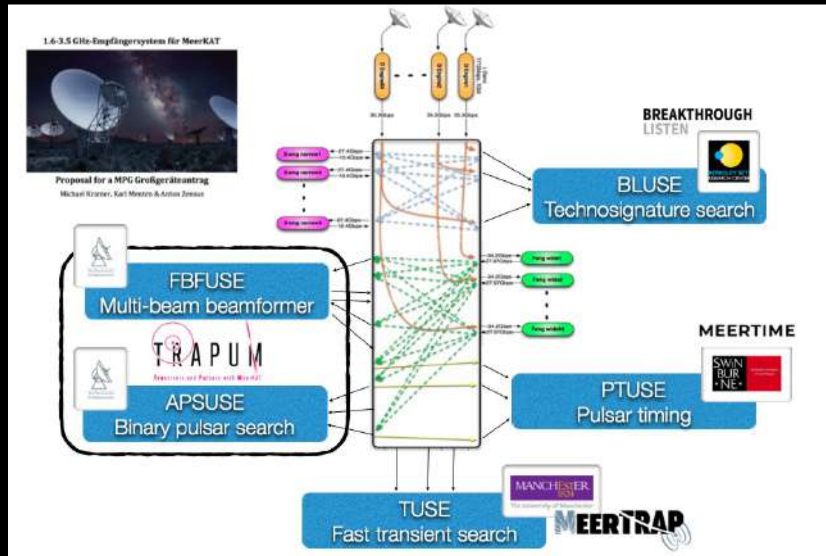
FAST: 2 x Arecibo

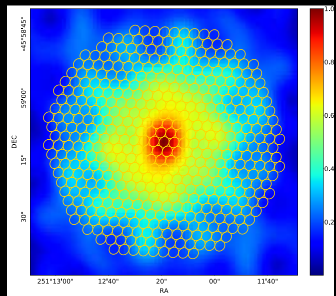
MeerKAT: SKA-precursor - 7 x Parkes

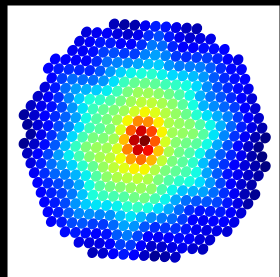
MPIfR systems for MeerKAT

- (64+2) x S-band receivers and digitisers
- Beamformer (~1,000 beams, dep on config.)
- HPC hardware and software for pulsars & transients
- Storage space (~3.5 PB)
- Close collaborating with South Africa
- 3000h of dedicated MPIfR time
- Transient and pulsars commensally with polarization imaging & spectroscopy









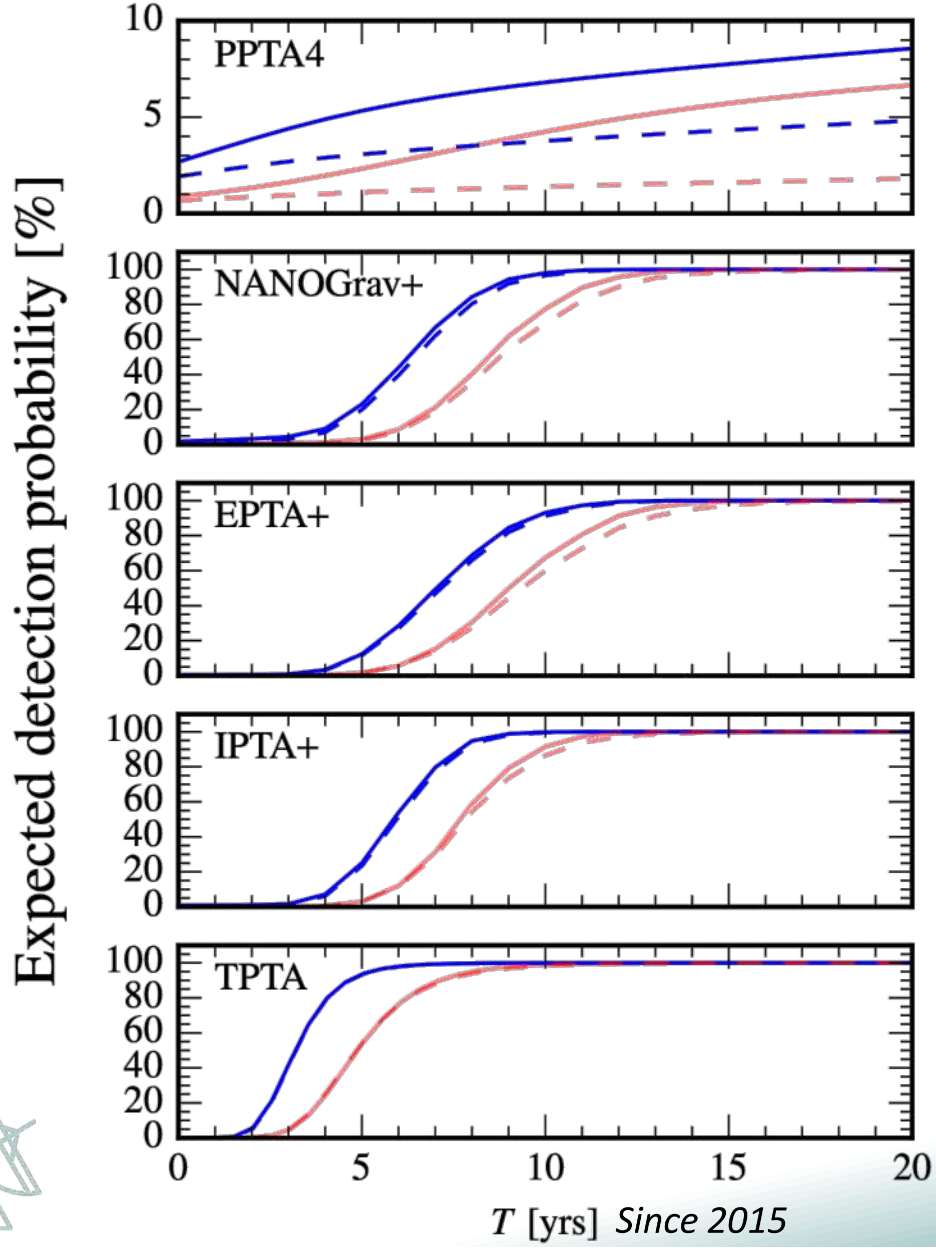
Chen et al. (submitted)

36 GB/s or 127 TB/h
or 3 PB/day.

S-Band receivers are ideal for high-precision timing to beat ISM effects!

When are we there?

(Taylor et al. 2016)



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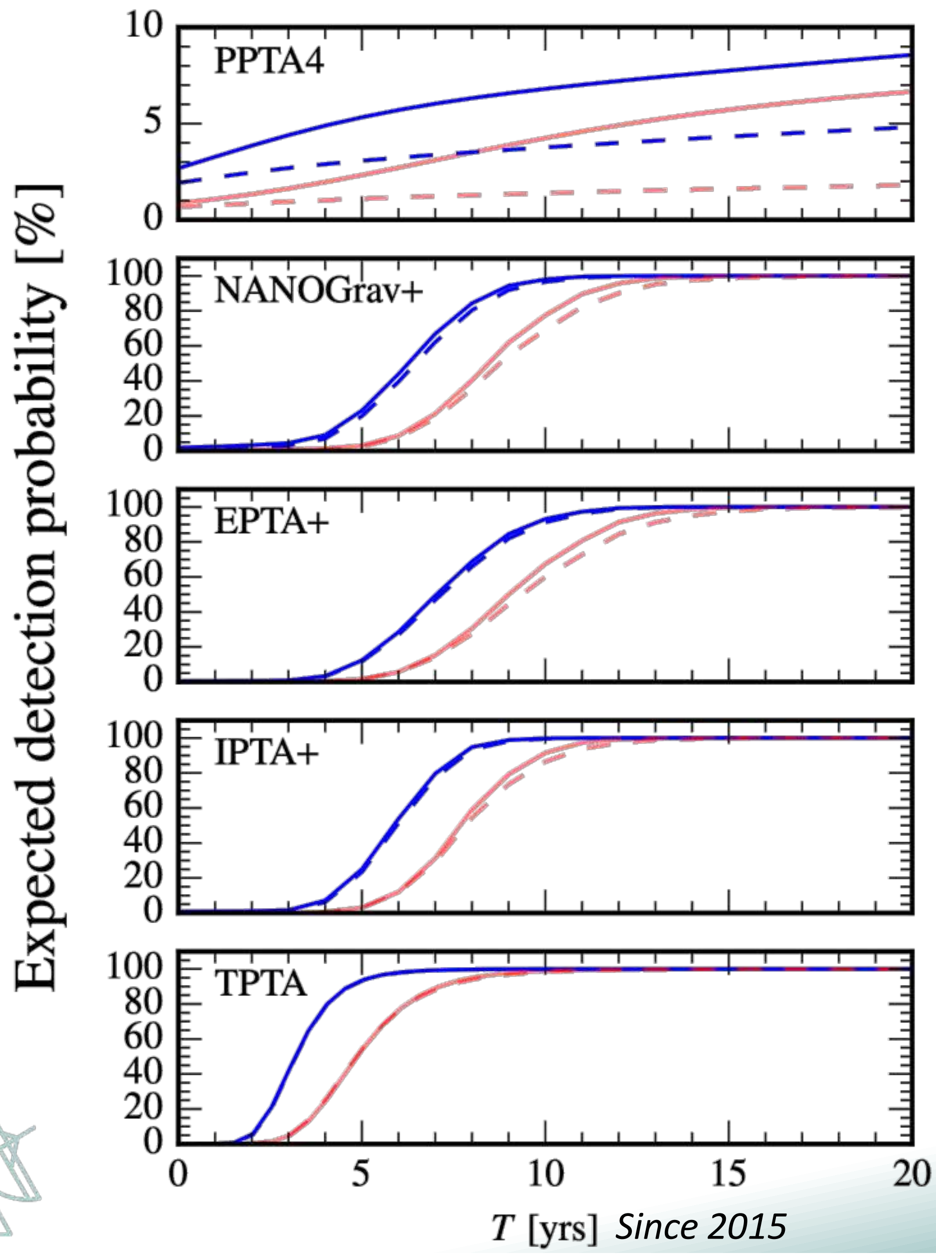
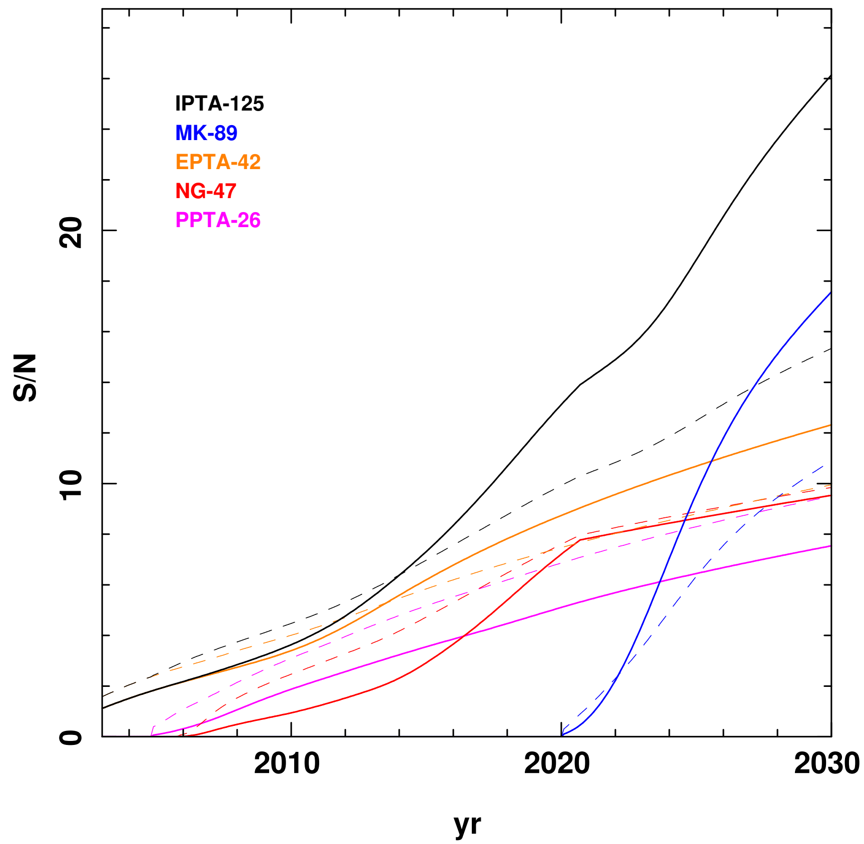
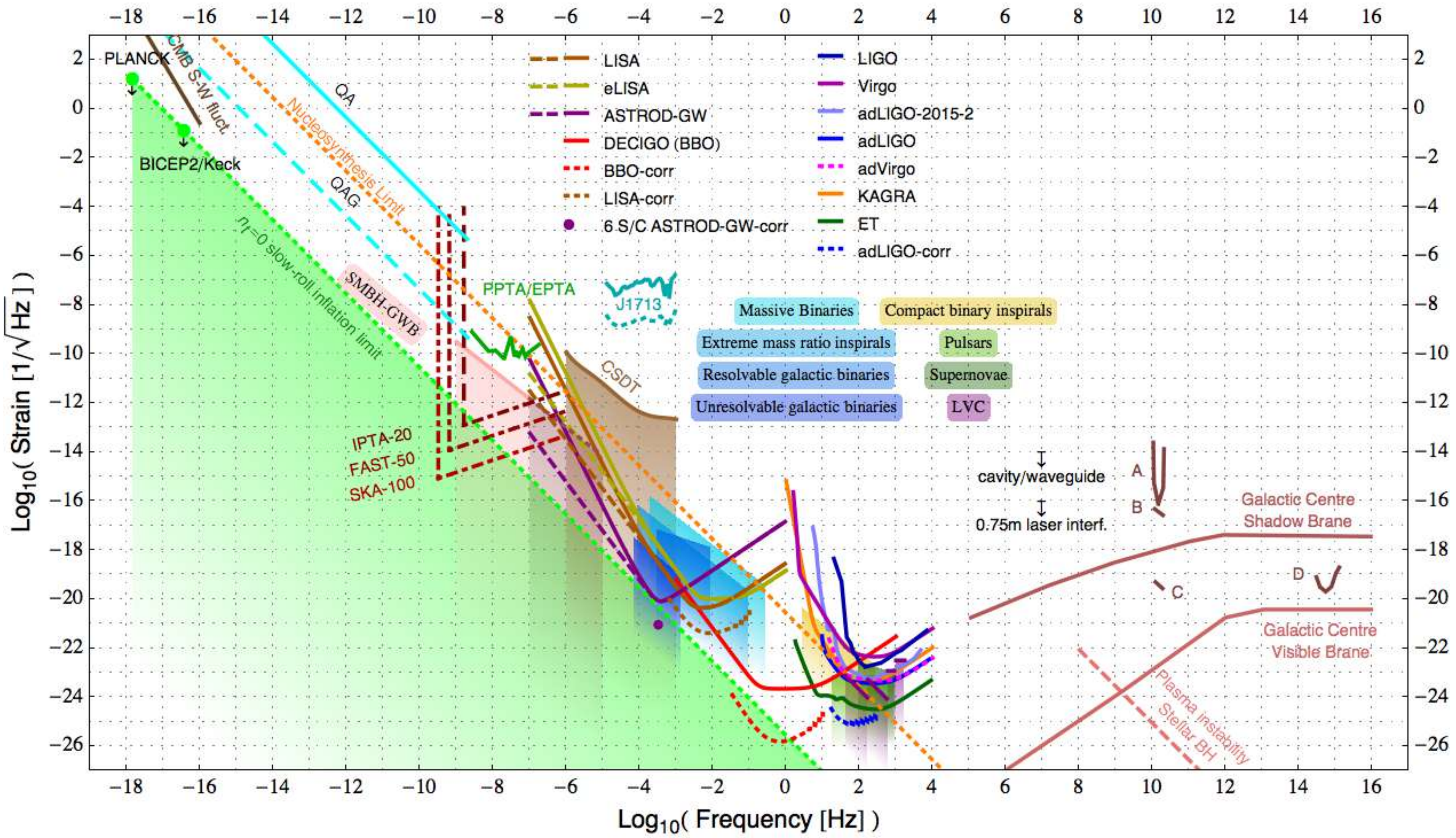


Spiewak et al. in prep



Frequency range of a Pulsar Timing Array (PTA)



Chen et al. 16

CMB PTA LISA LIGO

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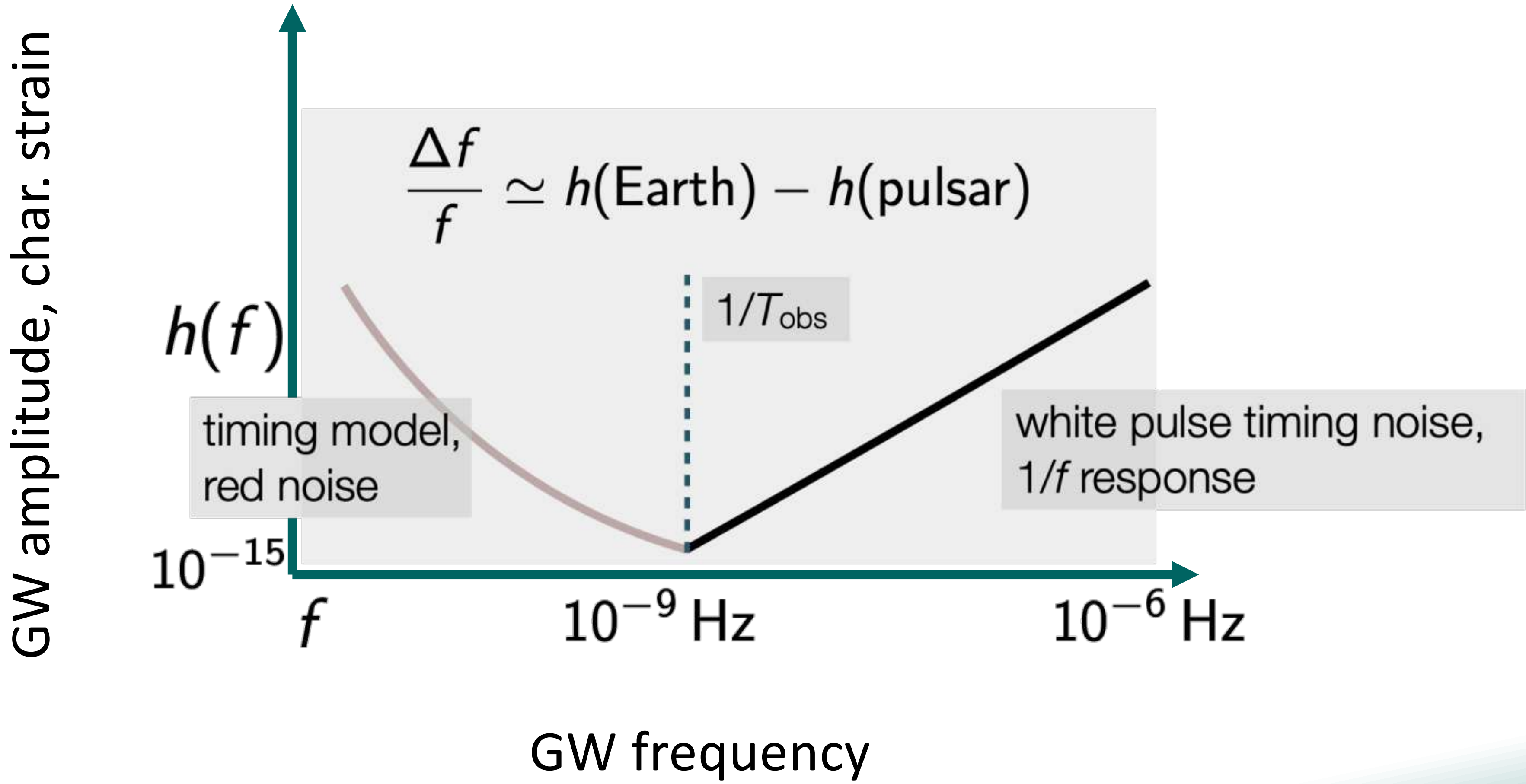
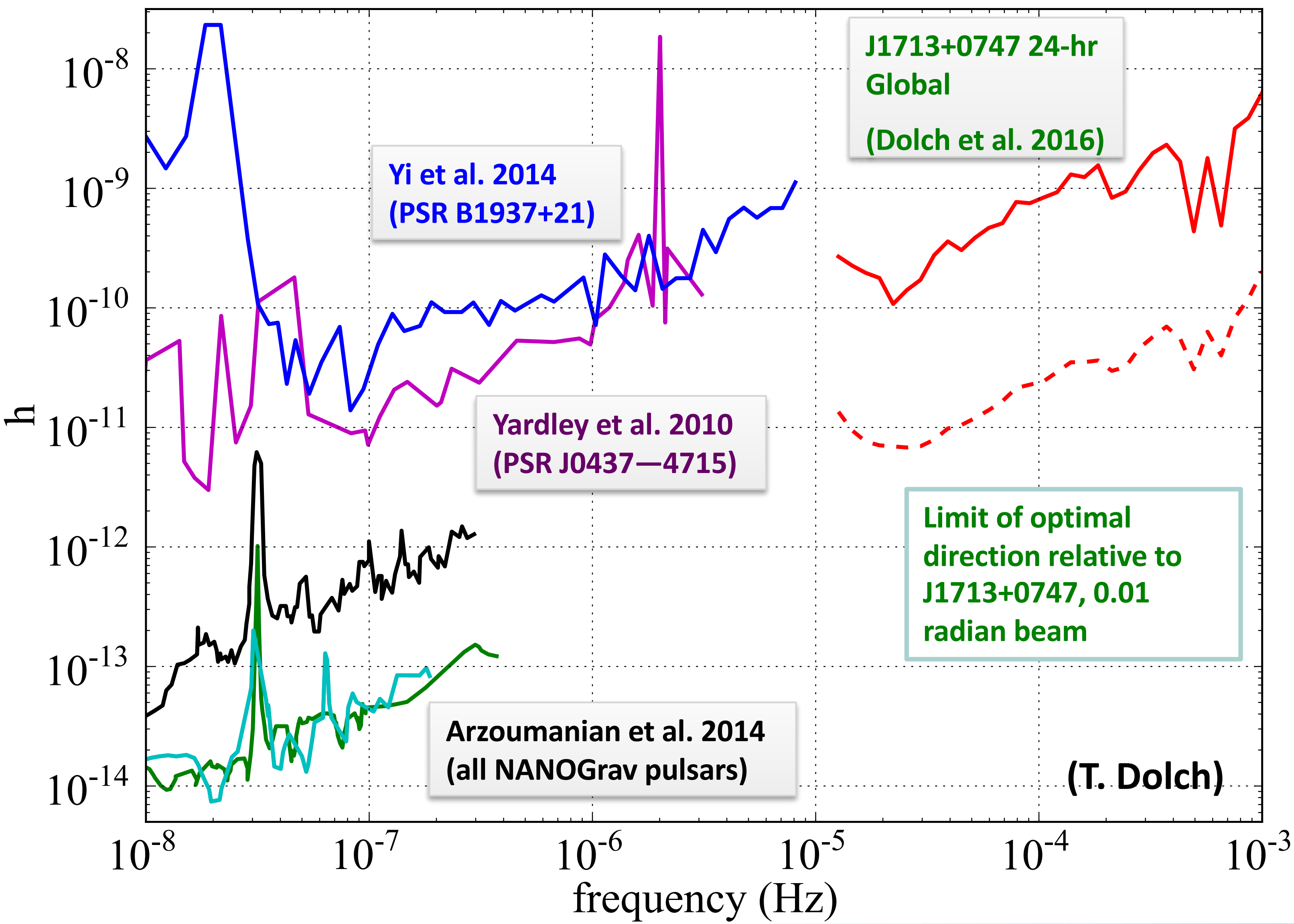


Highest frequency is given by cadence: ~1 per month => ~400 nHz

Lowest frequency is given by observing length: ~30 years => ~1 nHz

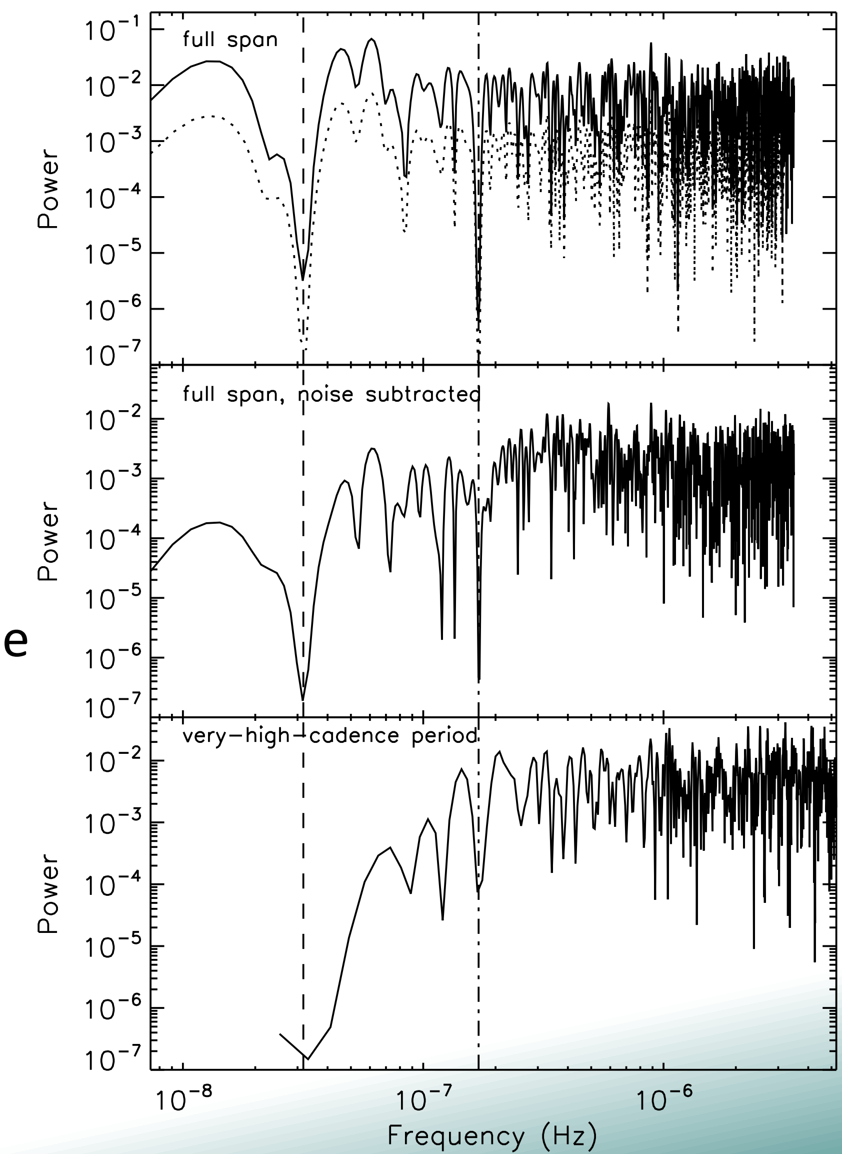
”High-Frequency Observations” via high cadence



”High-Frequency Observations” via high cadence

Improving timing sensitivity in the microhertz frequency regime: limits from PSR J1713+0747 on gravitational waves produced by super-massive black-hole binaries

B. B. P. Perera[1], B. W. Stappers[1], S. Babak[2,3], M. J. Keith[1], J. Antoniadis[4], C. G. Bassa[5], R. N. Caballero[4], D. J. Champion[4], I. Cognard[6,7], G. Desvignes[4], E. Graikou[4], L. Guillemot[6,7], G. H. Janssen[5,8], R. Karuppusamy[4], M. Kramer[4,1], P. Lazarus[4], L. Lentati[9], K. Liu[4], A. G. Lyne[1], J. W. McKee[1,4], S. Osłowski[10,4,11], D. Perrodin[12], S. A. Sanidas[13,1], A. Sesana[14], G. Shaifullah[11,4,5], G. Theureau[6,7,15], J. P. W. Verbiest[11,4], S. R. Taylor[16]



Perera et al. (2018):

- EPTA observations with average cadence of 1.6 days over four years
- Sensitive to 8 nHz to 5 μHz
- Limited direction and sensitivity
- But it shows what is possible!

We’ll get there. Let’s assume, we did…

We can make a detection with IPTA…

But to study the signal, we need more…

Strong-Field Tests of Gravity Using Pulsars and Black Holes

M. Kramer[a], *, D. C. Backer[b] †, J. M. Cordes[c] ‡, T. J. W. Lazio[d] § ¶, B. W. Stappers[e] ‖ S. Johnston[f] **

[a]University of Manchester, Jodrell Bank Observatory, Jodrell Bank, UK

[b]Department of Astronomy, Univsersity of California at Berkeley, Berkeley, CA, USA

[c]Department of Astronomy, Cornell University, Ithaca, NY, USA

[d]Naval Research Laboratory, Washington, DC, USA

[e]ASTRON, Dwingeloo, The Netherlands

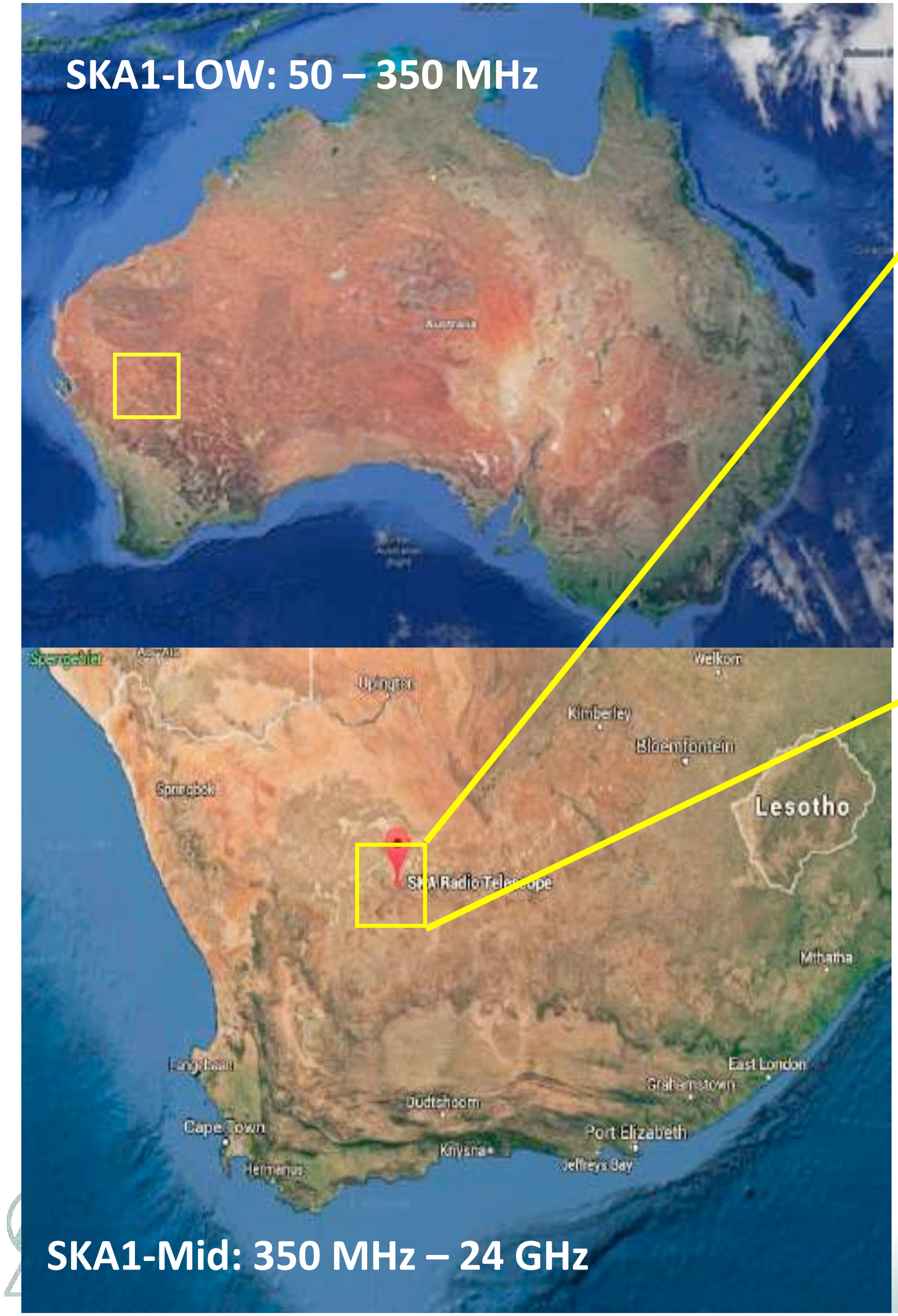
[f]University of Sydney, NSW 2006, Australia

The sensitivity of the SKA enables a number of tests of theories of gravity. A Galactic Census of pulsars will discover most of the active pulsars in the Galaxy beamed toward us. In this census will almost certainly be pulsar-black hole binaries as well as pulsars orbiting the super-massive black hole in the Galactic centre. These systems are unique in their capability to probe the ultra-strong field limit of relativistic gravity. These measurements can be used to test the Cosmic Censorship Conjecture and the No-Hair theorem.

The large number of millisecond pulsars discovered with the SKA will also provide a dense array of precision clocks on the sky. These clocks will act as the multiple arms of a huge gravitational wave detector, which can be used to detect and measure the stochastic cosmological gravitational wave background that is expected from a number of sources.

SKA-Key Science Case (2004)

A PTA with the SKA



especially SKA-Mid

With SKA we can do:

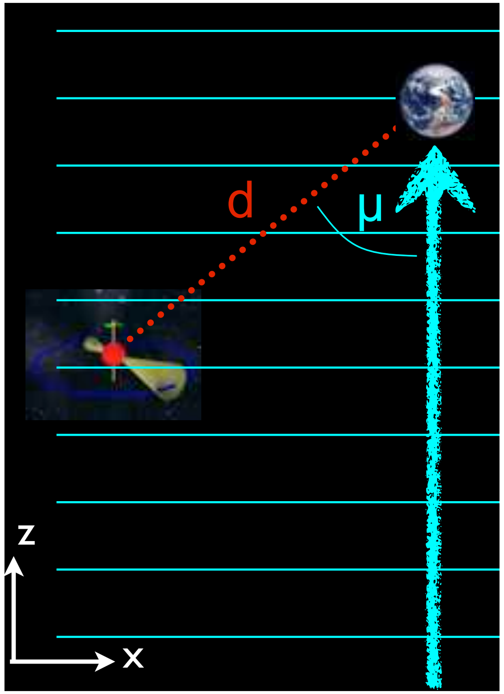
- pinpoint nHz-GW sources
- GW astronomy
- study properties of graviton
- ...

The power of the pulsar term

Remember Caterina's talk:

- The timing residual is the integral over these variation over the duration of the timing experiment:

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$



With Doppler shift given by

$$\frac{\delta\nu}{\nu} = H^{ij}(h^e_{ij} - h^p_{ij})$$

geometry Earth pulsar

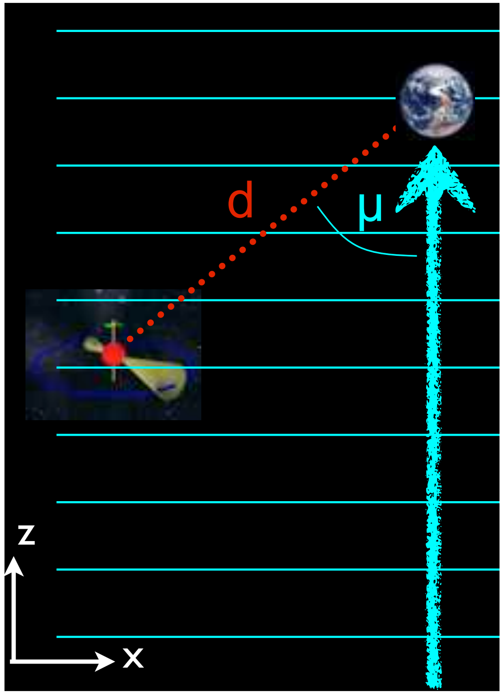
$cT_{\rm obs} \sim \lambda \ll d$ -> short wavelength approximation

The power of the pulsar term

Remember Caterina's talk:

- The timing residual is the integral over these variation over the duration of the timing experiment:

[Detweiler 1979, Jenet et al. 2004]



$$R(t) = \frac{1}{2}(1 + \cos\mu)[r_+(t)\cos(2\psi) + r_\times(t)\sin(2\psi)],$$

$$r_{+,\times}(t) = r^e_{+,\times}(t) - r^p_{+,\times}(t),$$

$$r^e_{+,\times}(t) = \int_0^t h^e_{+,\times}(\tau)\,d\tau,$$ "Earth term"

Retardation

$$r^p_{+,\times}(t) = \int_0^t h^p_{+,\times}\left[\tau - \frac{d}{c}(1 - \cos\mu)\right]d\tau,$$ "pulsar term"

Retardation & Source evolution

Like in binary pulsars, GW damping will cause the BH binary to shrink, leading to increase in GW frequency. For a circular orbit one has:

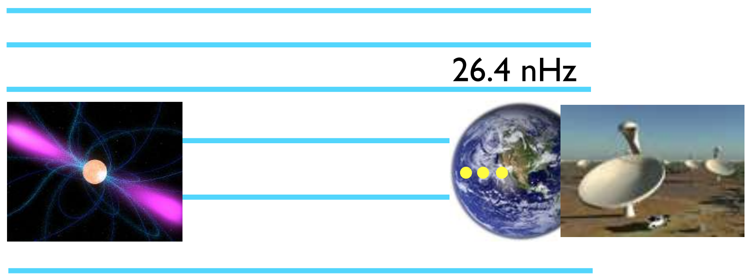
$$\frac{\dot{f}}{f} = \frac{96}{5}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3}(\pi f)^{8/3}$$

"chirp mass" $$\mathcal{M}_c \equiv \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

Frequency evolution during Tobs generally negligible, but some sources could have significant frequency evolution between pulsar term and Earth term.

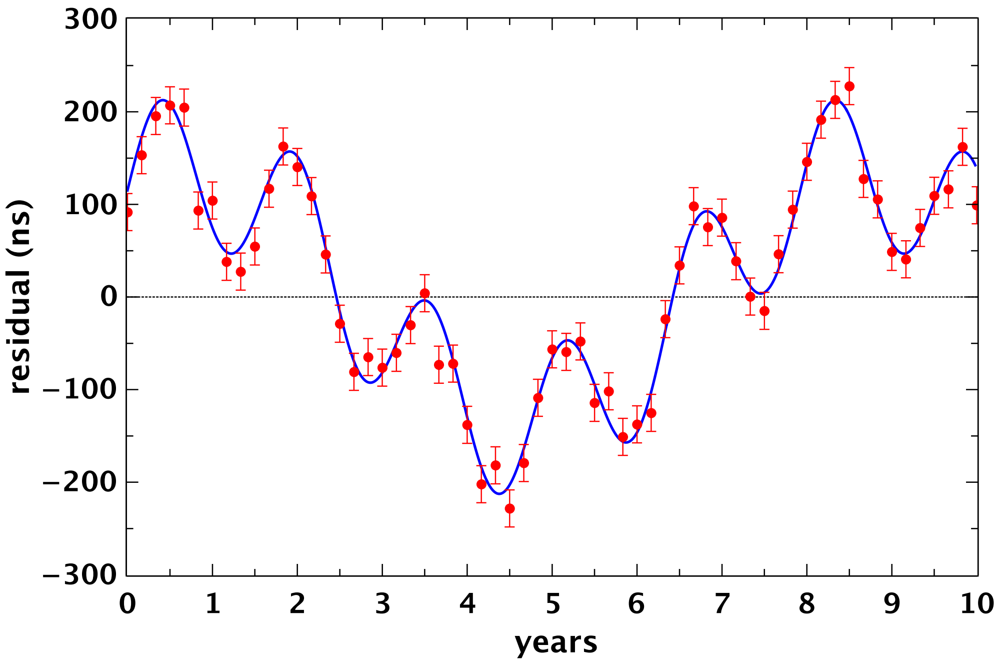
Example: pulsar at 1.4 kpc distance and a SMBH binary (m_1=m_2=$10^9 M_\odot$) in the Virgo cluster:

(Wex priv. comm.)

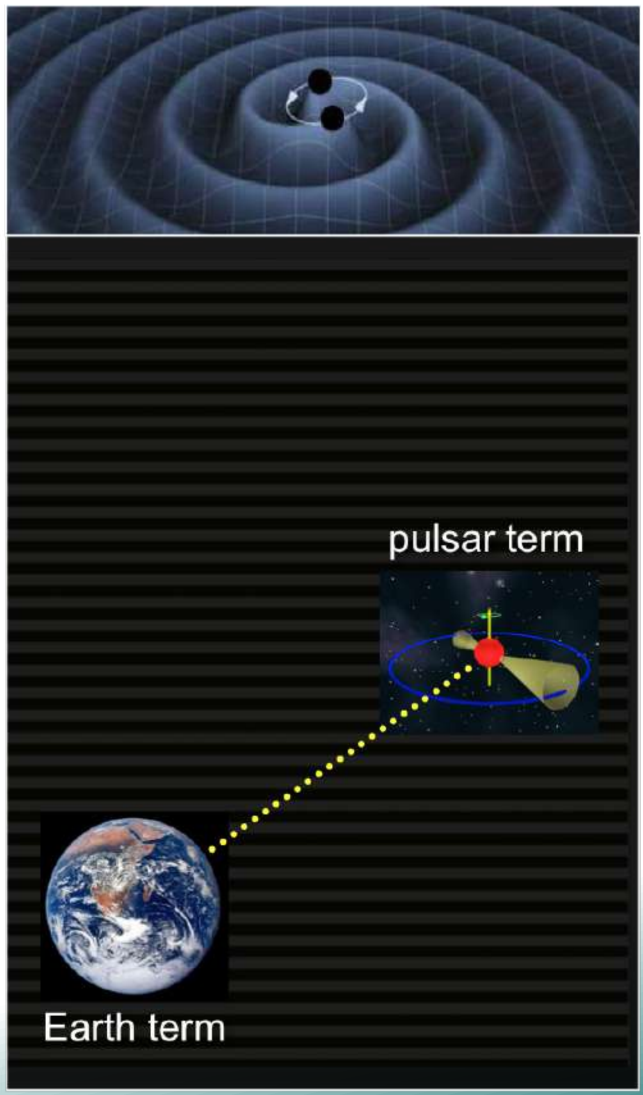


Pulsar-Earth as PTA "detector arm"

Single source affects both pulsar & Earth at different times (retardation):



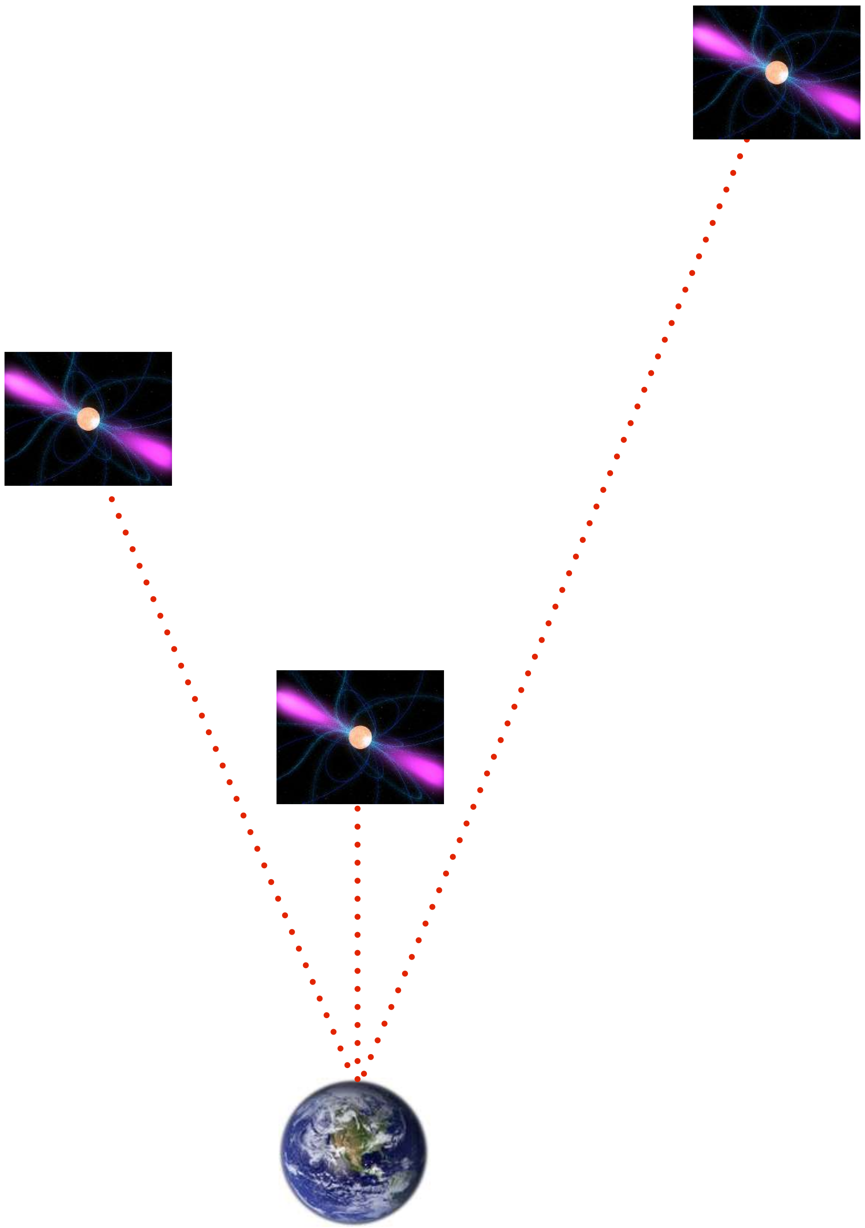
Wex

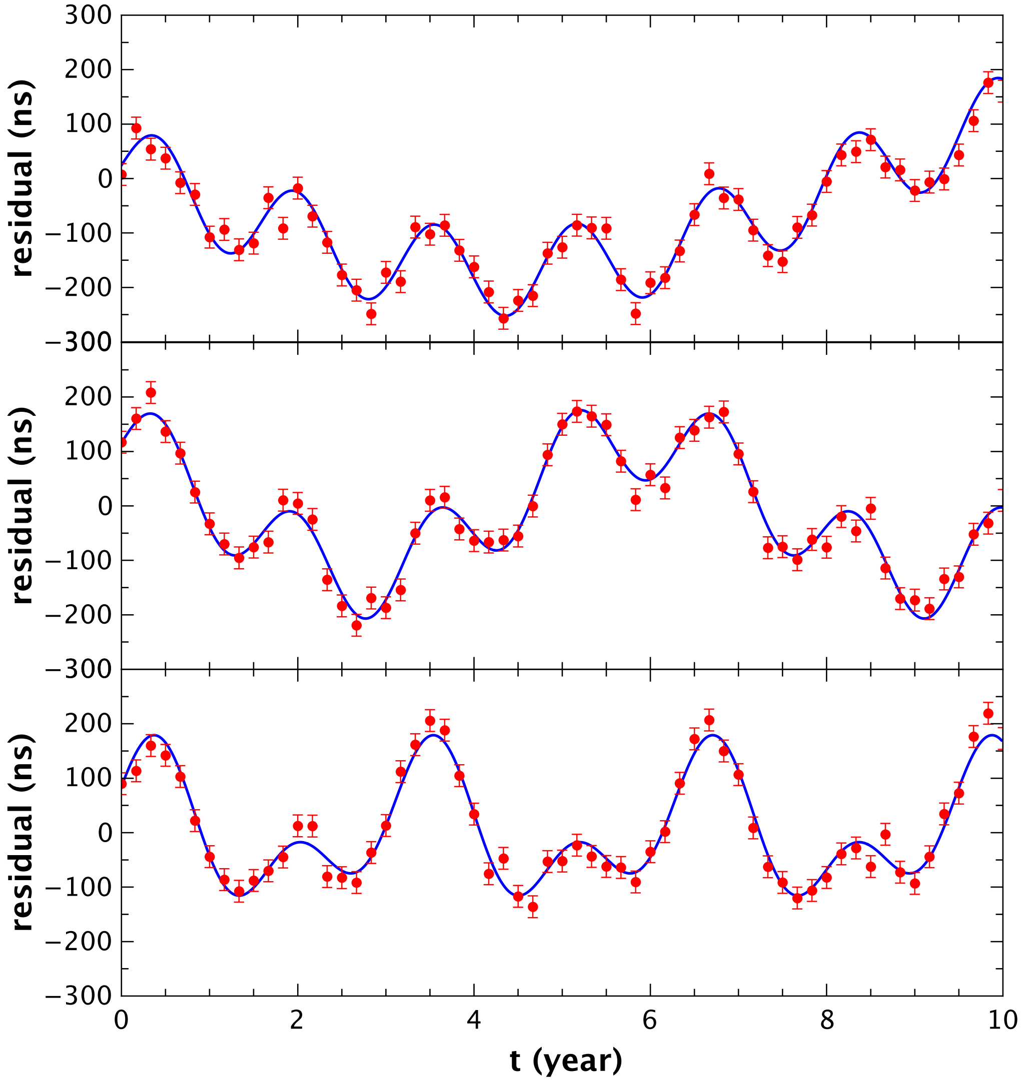


- Signal is superposition of two parts:
  - GW impacting on pulsar
  - GW impacting on Earth
- Different frequencies due to retardation

Retardation & Source evolution

In principle a tool to look at past evolution of source:



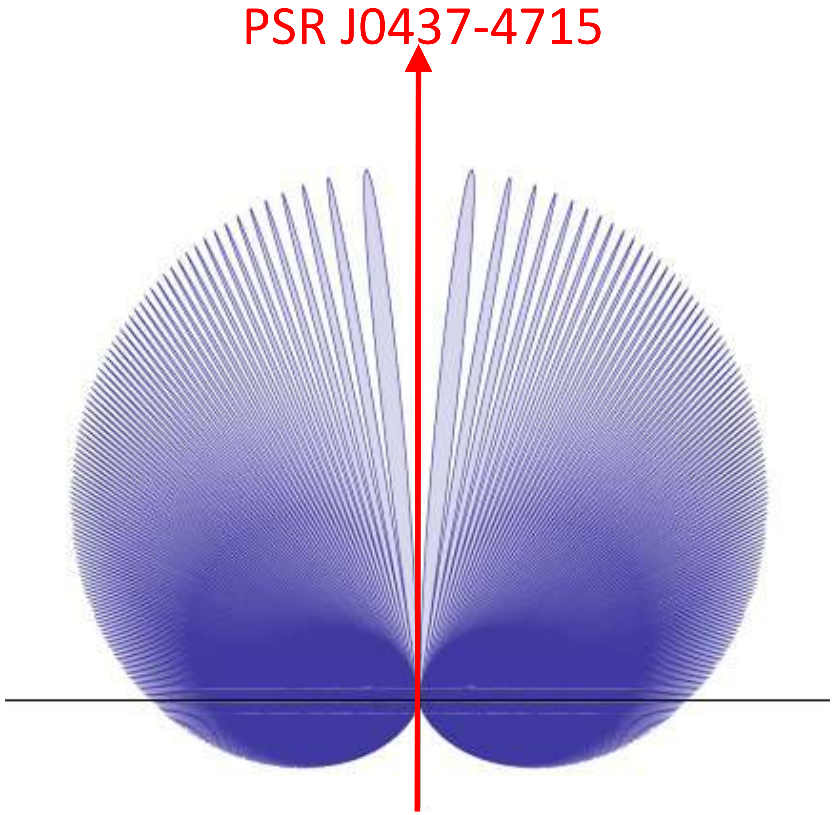


(Wex priv. comm.)

Locating a (non-evolving) single source with the SKA

Response pattern for PSR J0437-4715

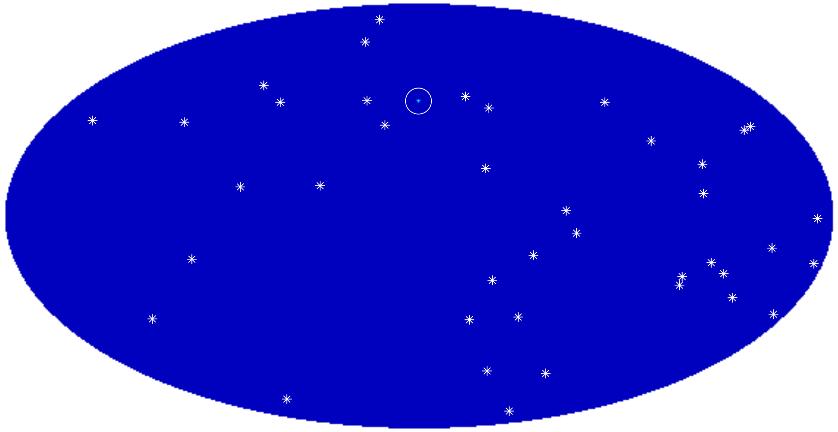
for a 6.3 nHz gravitational wave

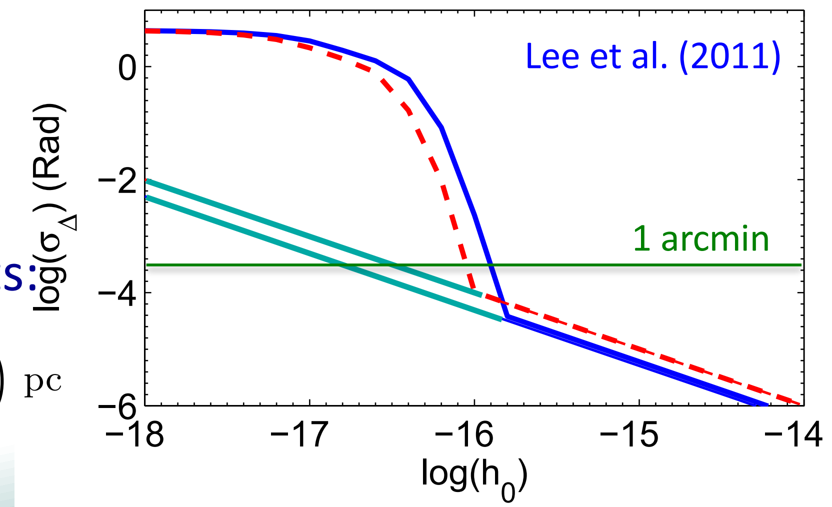


With a SKA-PTA, we can locate the binary SMBH in the sky:

40 millisecond pulsars at ~2 kpc distance

One 15 ns TOA every two weeks for 5 years





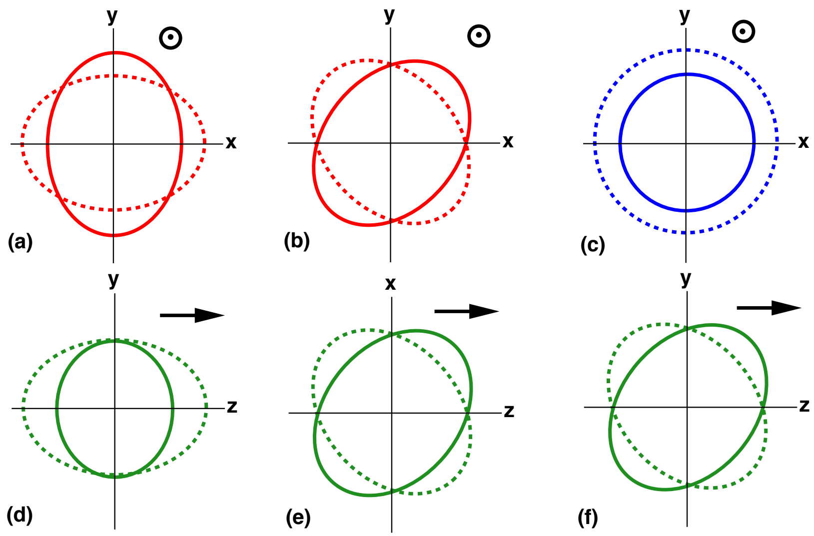
Enabling by spectacular SKA distance measurements:

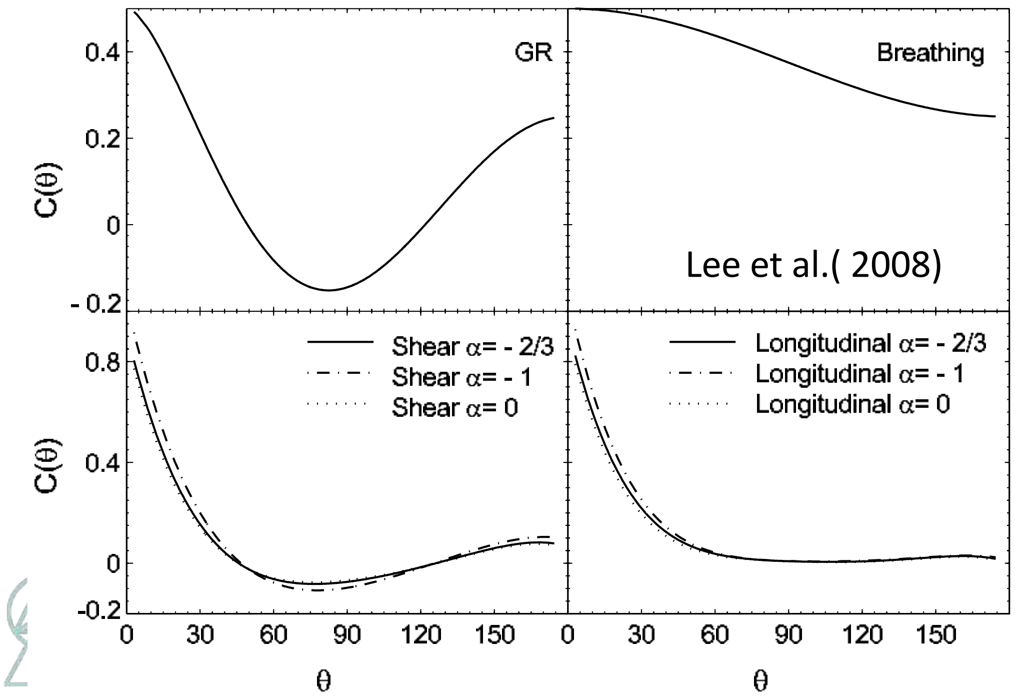
$$\sigma_{D_{\rm psr}} = \frac{4\sqrt{2}\,\sigma_{\rm n} D_{\rm psr}^2}{\sqrt{N_{\rm obs}}\, r_\oplus^2 \cos^2\beta_{\rm psr}} \simeq \frac{2.34}{\cos^2\beta_{\rm psr}} \left(\frac{N_{\rm obs}}{100}\right)^{-\frac{1}{2}} \left(\frac{D_{\rm psr}}{1\,{\rm kpc}}\right)^2 \left(\frac{\sigma_{\rm n}}{10\,{\rm ns}}\right)\ {\rm pc}$$

Allowing EM follow-up of GW sources!

Testing the properties of gravitons with the SKA

Polarization modes – Spin 2?

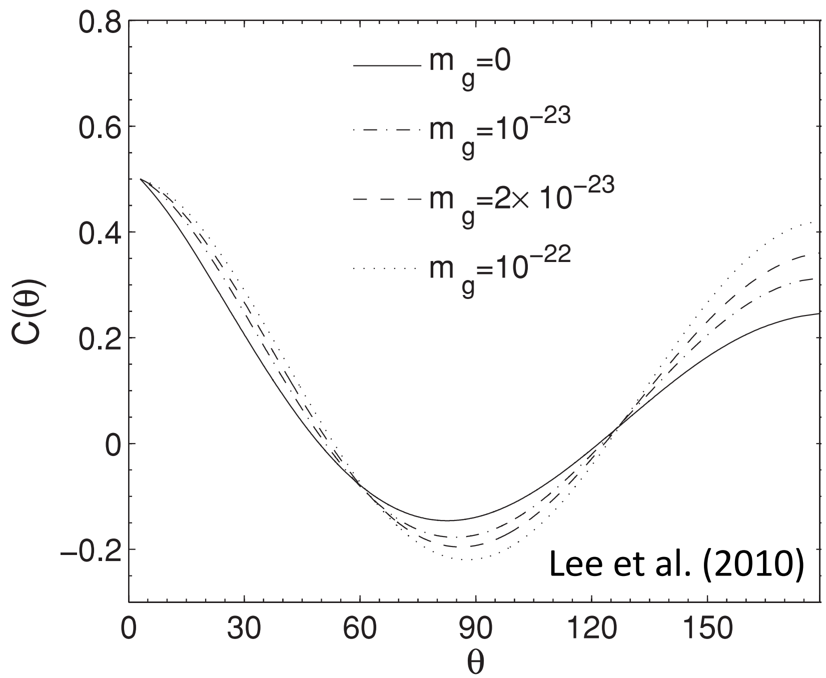




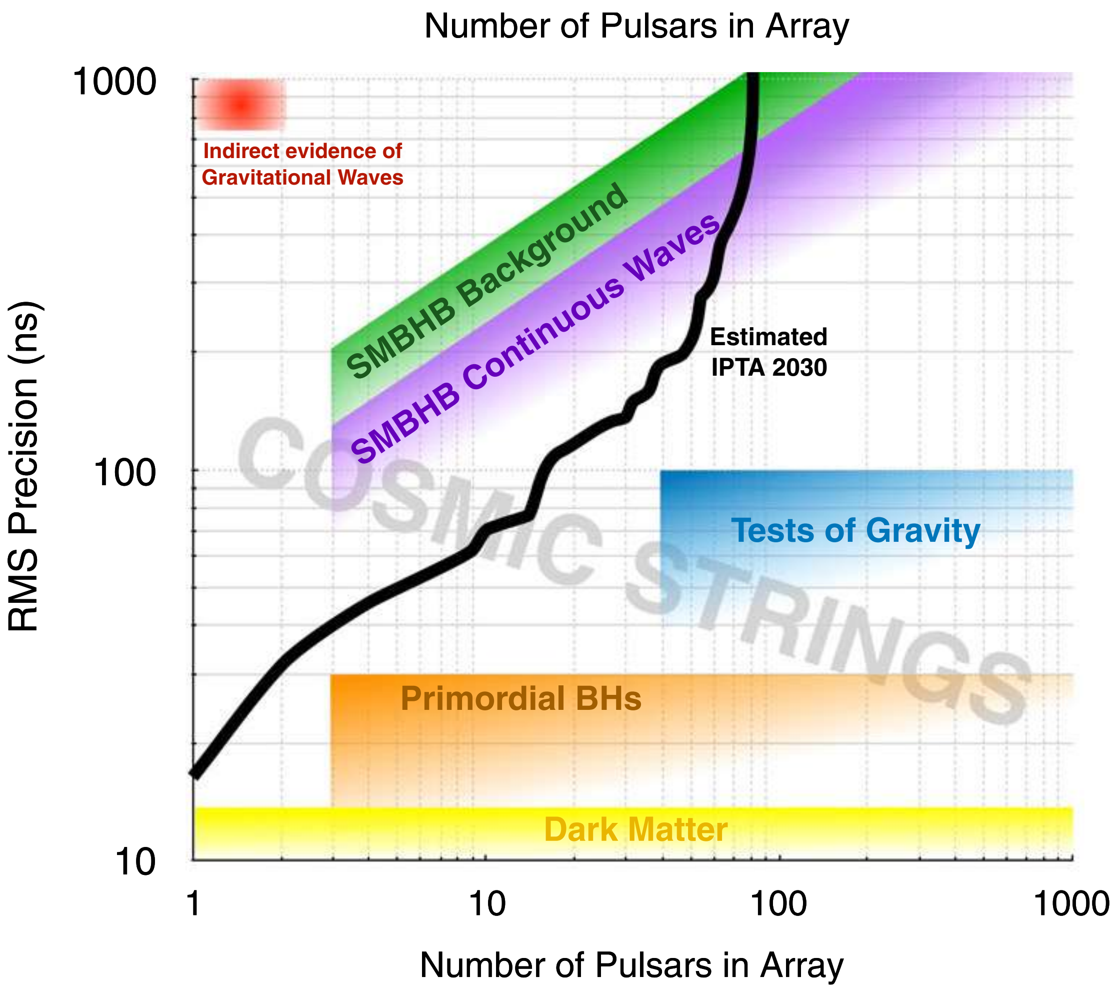
Dispersion relation: massive graviton?

$$\mathbf{k}_{\rm g}(\omega_{\rm g}) = \frac{\left(\omega_{\rm g}^2 - \omega_{\rm cut}^2\right)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}_z$$

$$\omega_{\rm cut} \equiv m_{\rm g} c^2/\hbar$$



There is more…

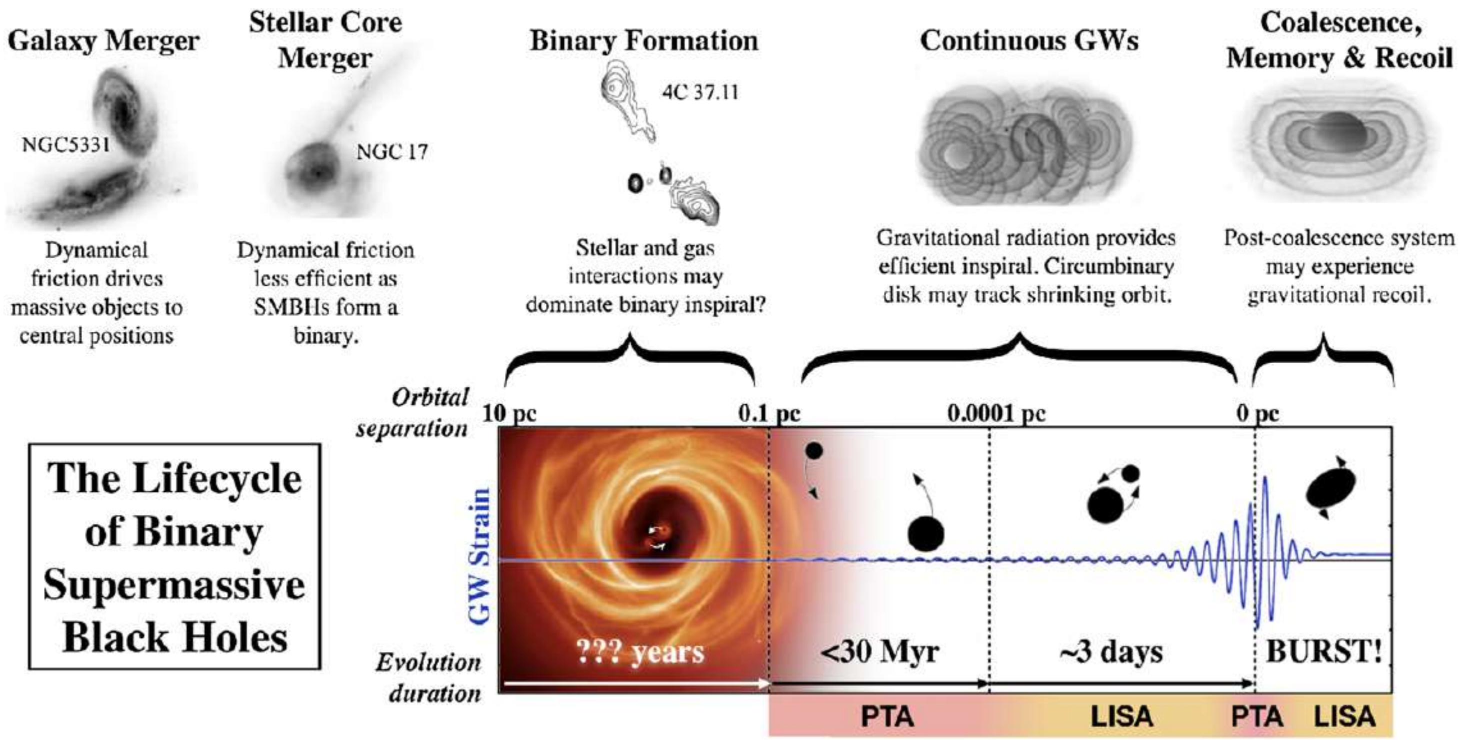


(Burke-Spolaor et al. 2019)

Strings, dark matter & axions etc., and…

...true complementarity

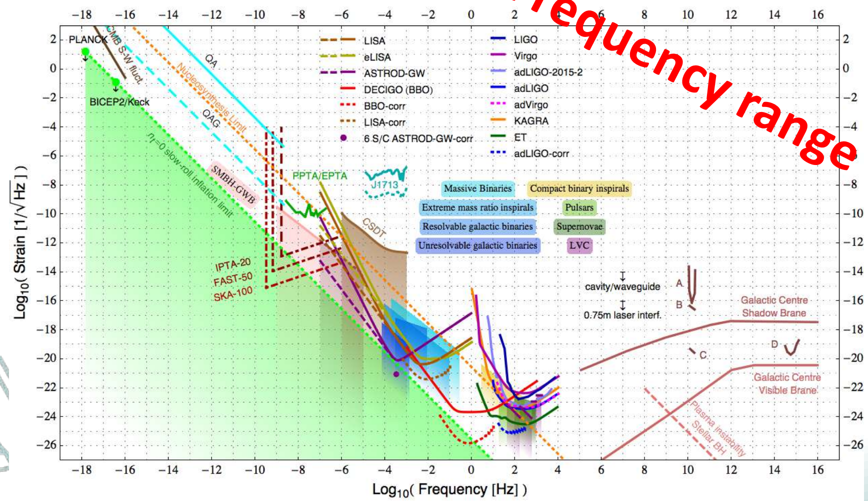
Source evolution



(Burke-Spolaor et al. 2019)

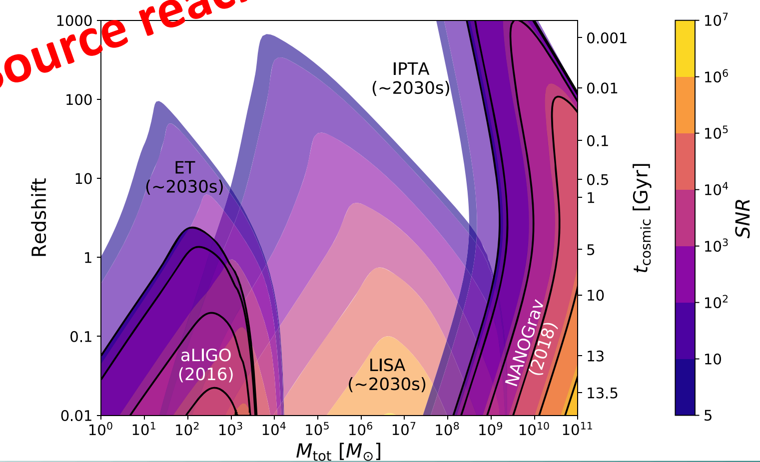
Chen et al. (2016)

Frequency range



Source reach

(Kaiser & McWilliams 2021)



Summary & Conclusions

- Current PTAs & IPTA may move towards a detection
- All PTAs see something – but what is it?
- We need control of systematic effects, independent data & analyses, cross-checks
- It requires the IPTA and different telescopes (EPTA as a mini-IPTA as example)
- A secure detection may require still further sensitivity
- New facilities are added (FAST, MeerKAT, GMRT)
- Future facilities (SKA, ngVLA or 6 x FAST!) will allow study of the signals
- Fundamental physics tests will become possible

About 50 years after pulsars provided the first evidence for gravitational waves,

they promise to be used as a GW telescope in their own right.