1° Congresso Nazionale della Scienza e della Tecnologia di SKA

La via italiana allo SKA

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MIUR - P.le Kennedy 20 - Roma

General Relativity Tests with Pulsars

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Timing concept

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

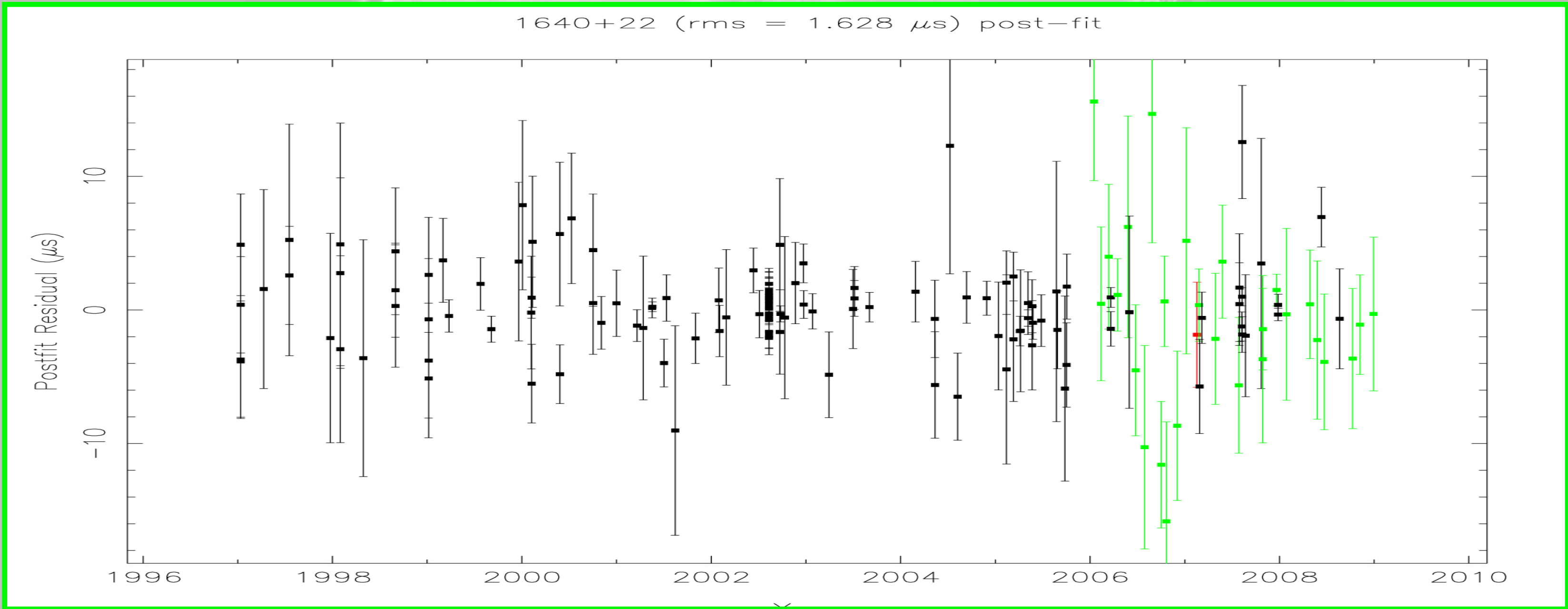
2. **Searching the ToAs for systematic trends** on many different timescales, from minutes to decades

If a physical model adequately describes the trends, it is applied with the smallest number of parameters

When a model finally describes accurately the observed ToAs, the values of the model's parameters shed light onto the physical properties of the pulsar and/or of its environment

Timing analysis quality: residuals

Quality factor in a timing point:
uncertainty σ_{TOA} in the TOA



(OBSERVED TOAs - MODEL TOAs) → residuals

Good timing solution → no evident trend in the residuals

Pulsars as clocks

For some pulsars the rotational periods can sometimes be measured with unrivalled precision

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

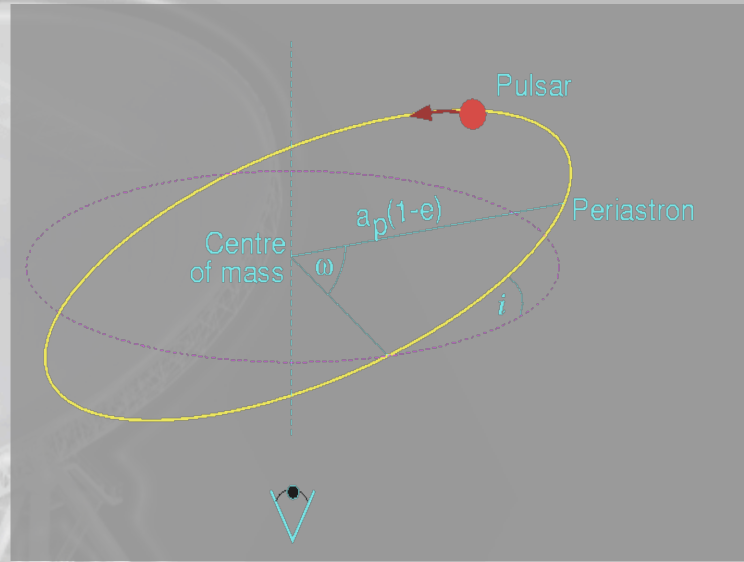
5.757451831072007 ± 0.000000000000008 ms

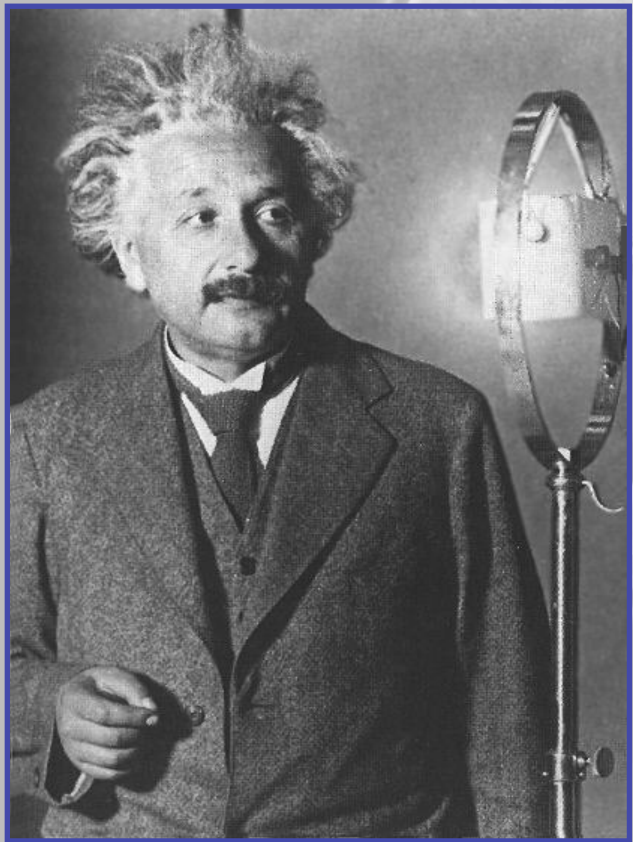
15 significant digits!

Pulsar Timing applied to binary pulsars

- By using repeated observations of the time of arrival of the pulses (Timing) one can measure 5 Keplerian parameters:

P_{orb}, a_p, e, ω, T_0





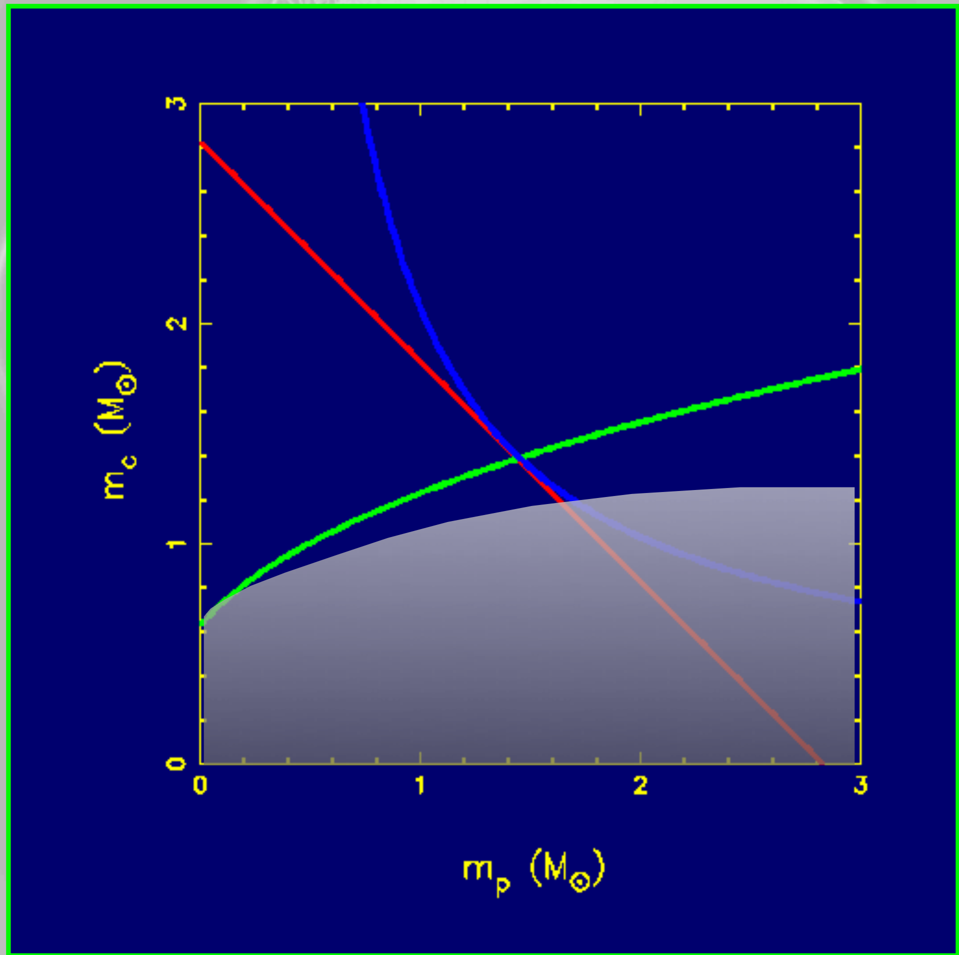
... and, in few cases, one or more post-Keplerian parameters:

$\dot{\omega}$, γ, $\dot{P}_{orb}$, s, r

plus additional GR effects:

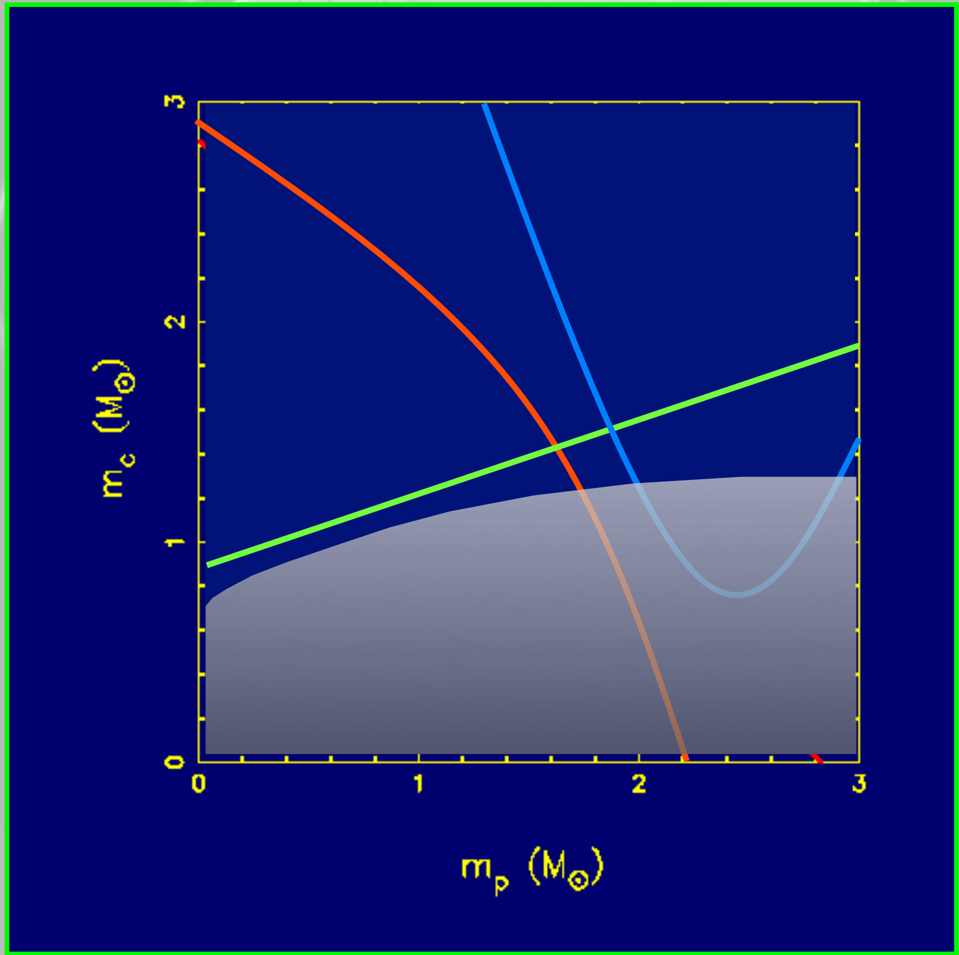
Ω_{prec}, ...

Each PK parameter corresponds to a strip in the MASS vs MASS diagram



Three PK parameters: in a correct theory the strips overlap !

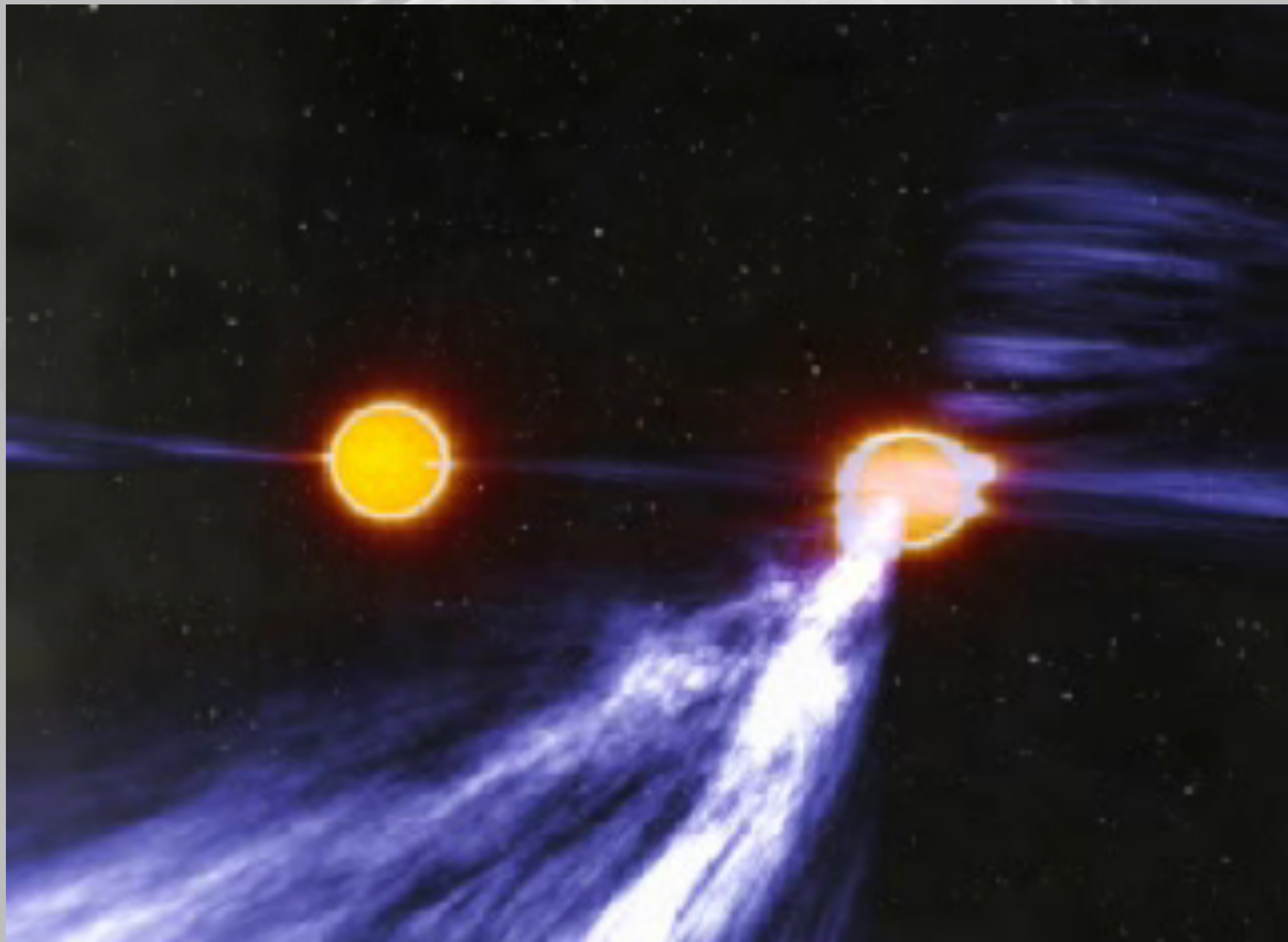
Each PK parameter corresponds to a strip in the MASS vs MASS diagram



But not in a wrong theory !

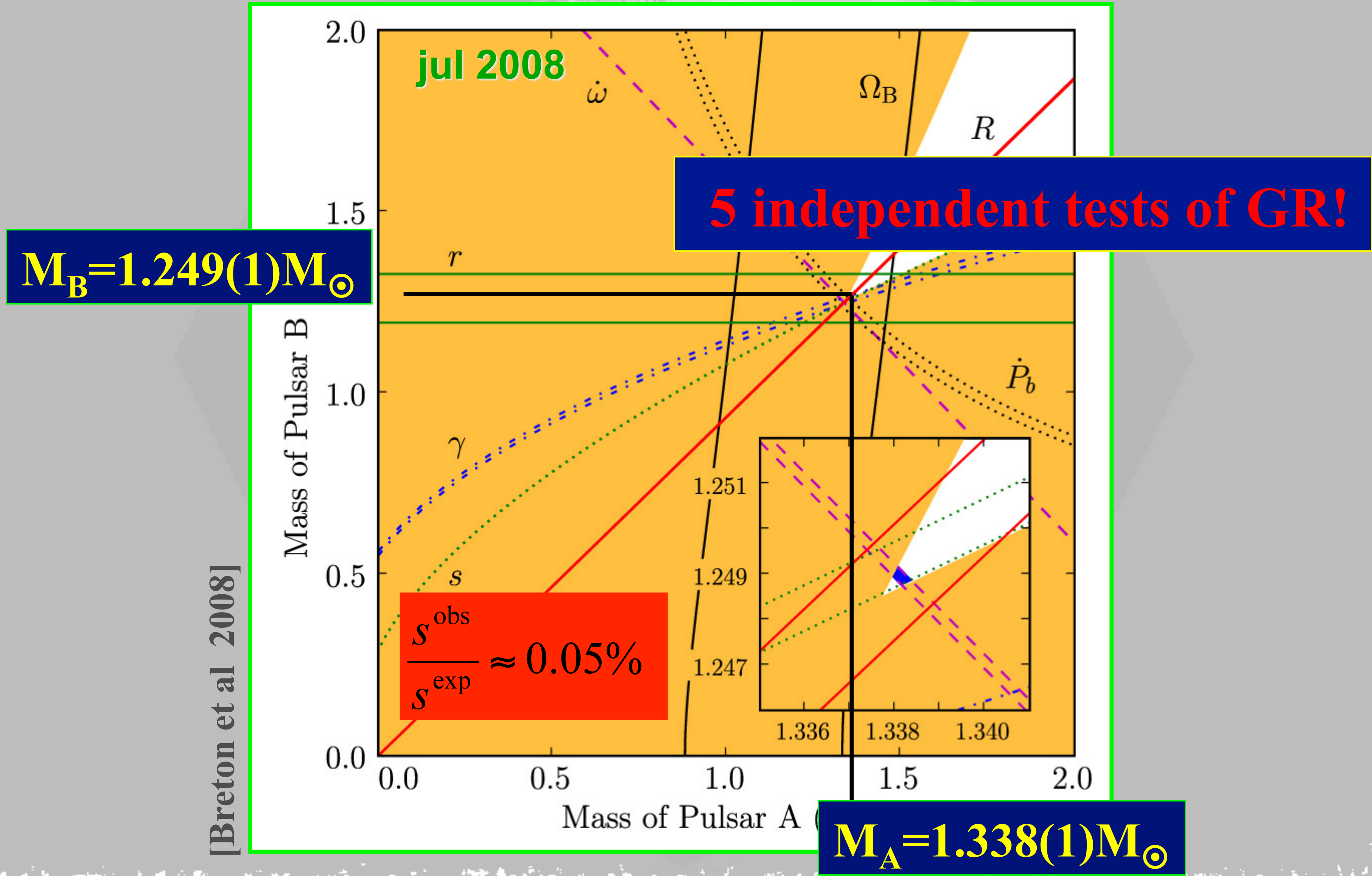
The best binary so far: J0737-3039A/B

[Burgay et al 2003, Lyne at al 2004]



[© Howe, ATNF]

The last published mass-mass diagram for the best binary: J0737-3039A/B



[Breton et al 2008]

The impact of SKA

Challenging Einstein:

tests of General Relativity and fundamental physics in pulsar binary systems

Search speed $\approx (T_{sys}/A_{eff})^2\ \Omega$

Timing quality $\sigma_{ToA} \approx T_{sys}/A_{eff}$

Multiplying a factor > 10 the known population

Timing the targets a factor > 10 better than now

How many targets?

TODAY
With SKA

Ordinary pulsars

~ 1850 known objects

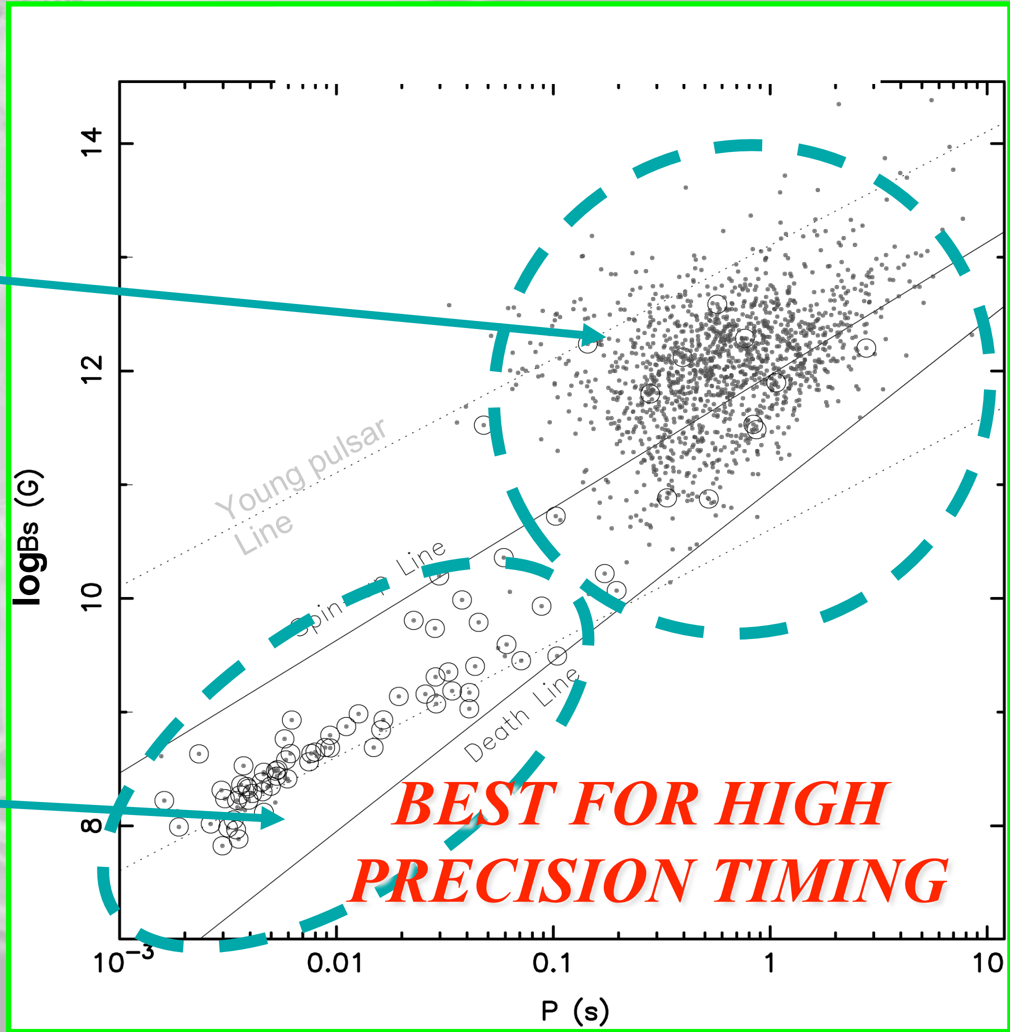
~ 30000 objects

Recycled pulsars

70% of them in binaries

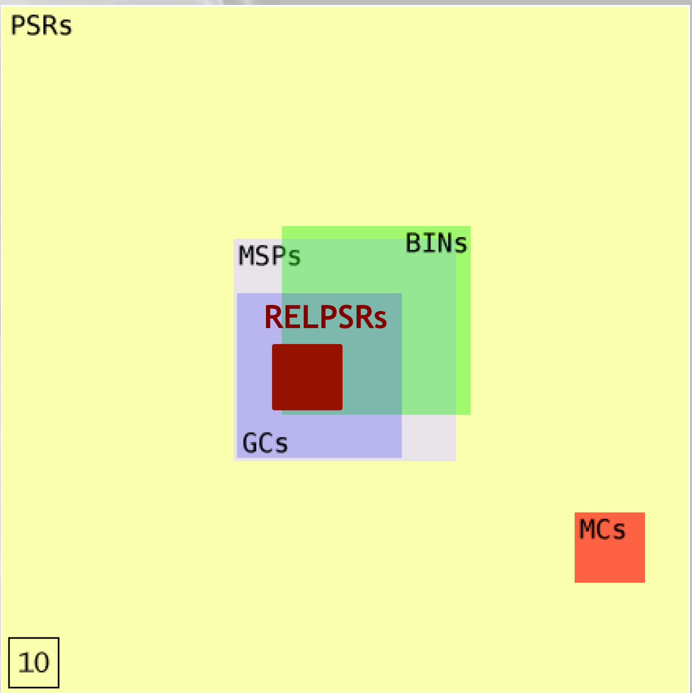
~ 150 known objects

~ 3000 objects



ATNF Pulsar Catalogue

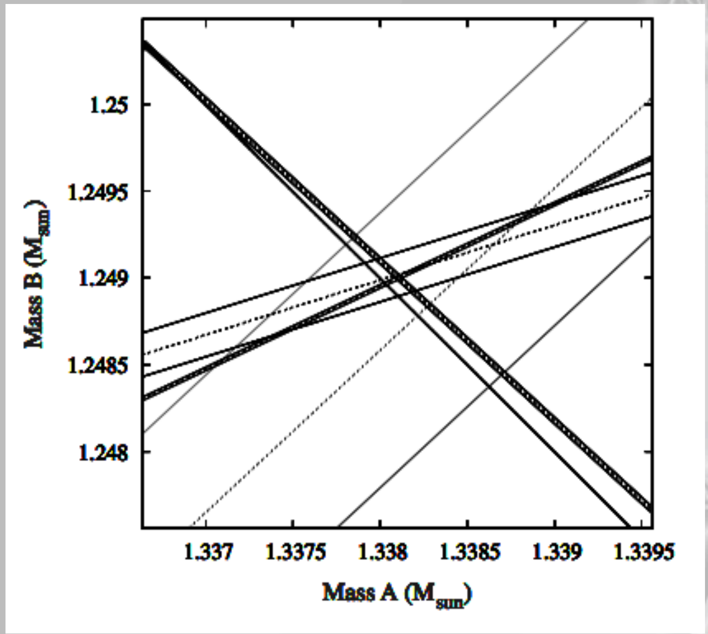
The most interesting binary relativistic pulsars are rare...



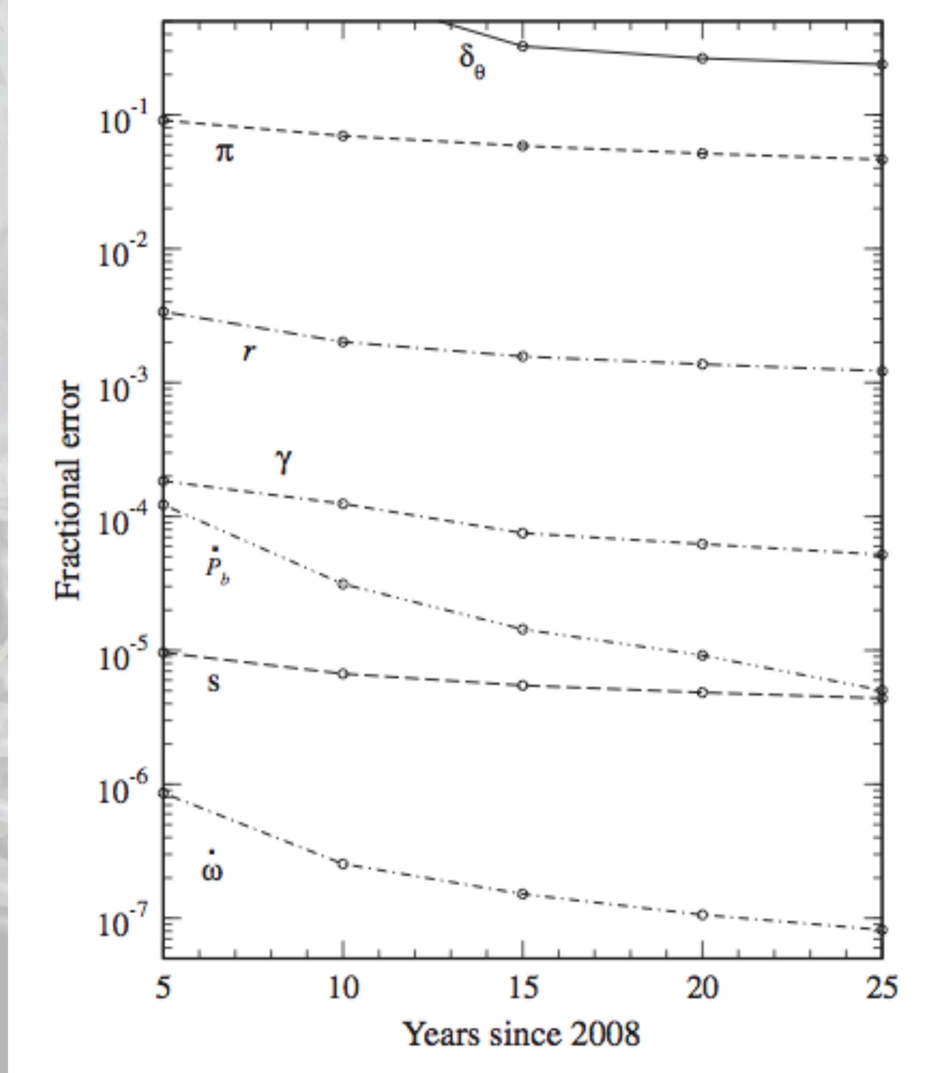
The current relativistic pulsars population ≈ 20

The SKA relativistic pulsars population ≈ 100-200

Improvements in timing the Double Pulsar



[Kramer & Wex 2009]



SKA will allow us having TOAs much better than the current ones

Why bother with further improving GR tests in strong field ?

Is GR still the best available theory for describing Nature also under extreme physical conditions?

This is NOT an ACADEMIC question:

e.g. extreme conditions are certainly those at which any long sought unified model for interactions applies [e.g. Antoniadis 2005]

Moreover, is enough to test alternative theories only in the weak-field limit?

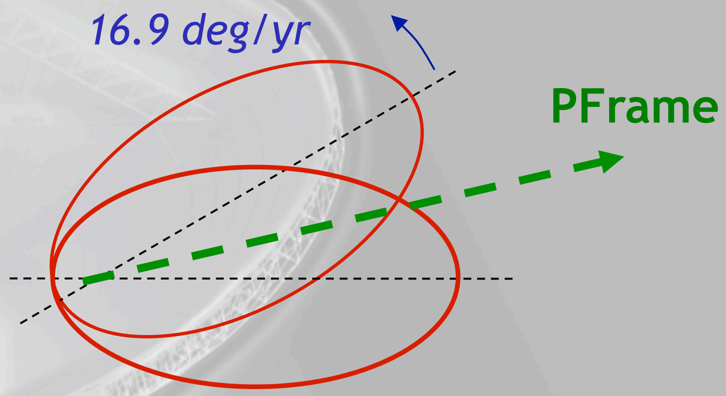
There exist alternative metric gravity theories (e.g. a subclass among the tensor-scalar theories) which would pass ALL Solar System (weak-field limit) tests, but would be violated as soon as extreme conditions (strong-field limit) are reached

[Damour & Esposito-Farese 1996]

What might be feasible to do: constraining existence of Preferred Frame

...If Lorentz-invariance is violated in strong gravitational fields a preferred frame would exist...

... and the orbital orientation relative to it would change due to orbital precession



time-varying orbital parameters should be seen, most notably in longitude of periastron (ω) and eccentricity (e)

$$\eta_1^{(\omega)}/\eta_1^{(e)} = 11.262$$

$$\eta_2^{(\omega)}/\eta_2^{(e)} = 5.642\ .$$

...for the Double Pulsar...

[Wex & Kramer 2007, 2010]

What might be feasible to measure:
Moment of Inertia of J0737-3039A

Total periastron advance to 2PN level: [Damour & Schaefer 1988]

$$k^{tot} = \frac{3\beta_0^2}{1-e_T}\left[1 + f_0\beta_0^2 - g_S{}^A \beta_0 \beta_S{}^A - g_S{}^B \beta_0 \beta_S{}^B\right]$$

1PN — 2PN — Spin A — Spin B

Neutron star dependent

Equation-of-State for the nuclear matter!!

$$\beta_S = \frac{2\pi c}{G}\frac{1}{P}\frac{I}{m^2}$$

A 10% accuracy on I would exclude most EoS

[Lattimer & Schutz 2004]
[Morrison et al. 2004]

The impact of SKA

Challenging Einstein:

Test basic principles of Black-Hole physics

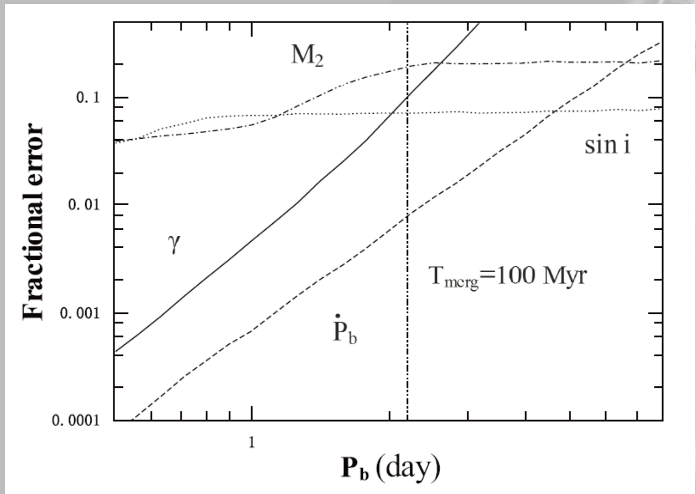
Open the parameter space for discovering the "expectedly very rare" PSR+BH binary

Giving the chance to discover a PSR orbiting Sgr A*

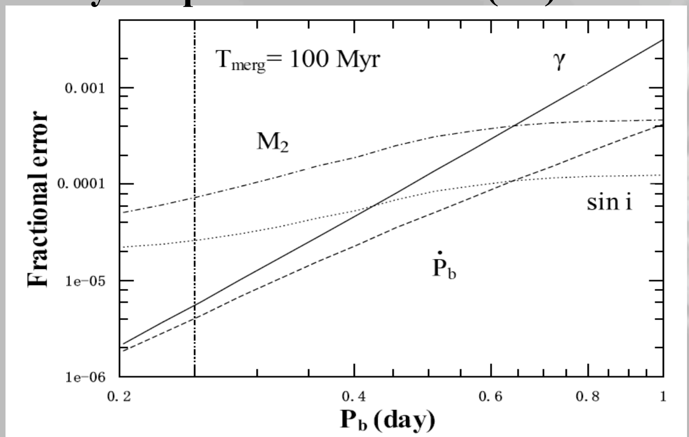
Measuring the mass & the spin of the BH

Mass from PK params assuming GR

Normal pulsar in highly eccentric (0.9) orbit



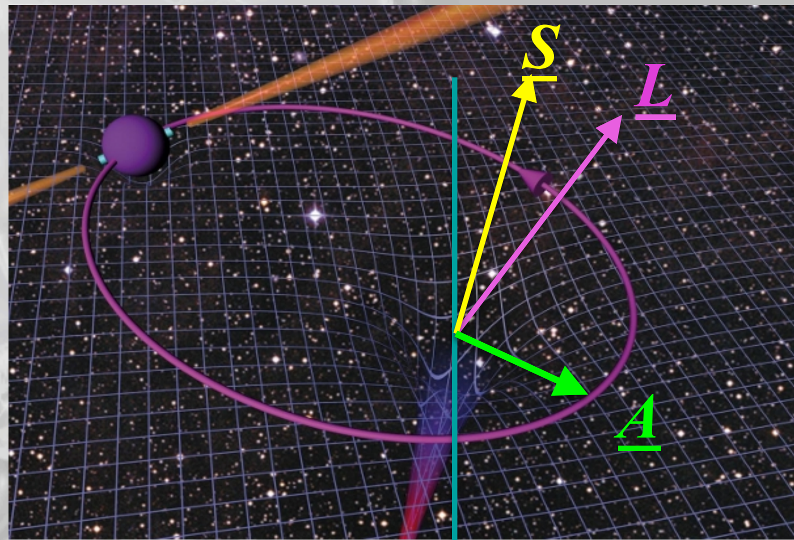
Recycled pulsar in eccentric (0.4) orbit



BH mass with precision < 0.1%

[Liu 2012, PhD thesis; Liu et al. in prep.]

Spin from measuring higher order derivatives of secular changes in semi-major axis and longitude of periastron



$$\dot{\boldsymbol{L}} = \boldsymbol{\Omega}_{\rm prec} \times \boldsymbol{L}\,, \quad \dot{\boldsymbol{A}} = \boldsymbol{\Omega}_{\rm prec} \times \boldsymbol{A}$$

$$\boldsymbol{\Omega}_{\rm prec} = \boldsymbol{\Omega}_{\rm PN} + \boldsymbol{\Omega}_{S}$$

Lense-Thirring (linear in S)

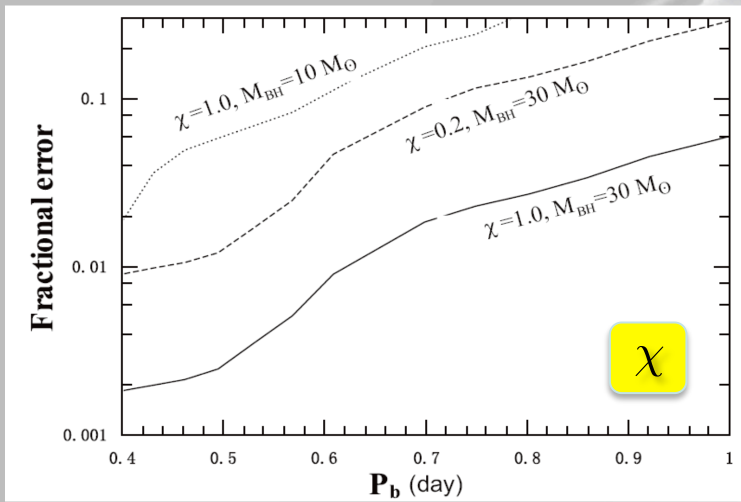
REQUIRES SKA!

BH spin with precision < 1%

What will be feasible to measure with SKA

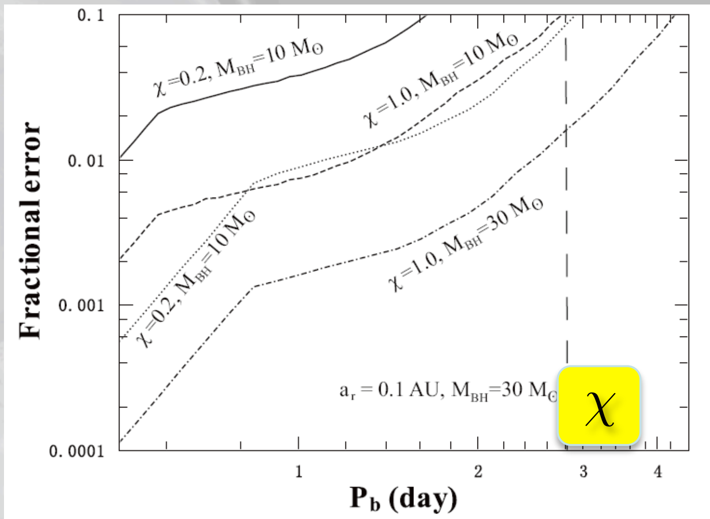
Cosmic Censorship Conjecture

Normal pulsar in highly eccentric (0.9) orbit



$$\chi \equiv \frac{c}{G}\frac{S}{M^2}$$

Recycled pulsar in eccentric (0.4) orbit



In GR, for Kerr-BH we expect: $\chi \leq 1$

test of "Cosmic Censorship Conjecture" *[Penrose 1969]*

All singularities are hidden within Event Horizon of BH!
i.e. no "Naked Singularities" allowed!

Testing alternate gravity theories

$g_{\mu\nu}$ = metric

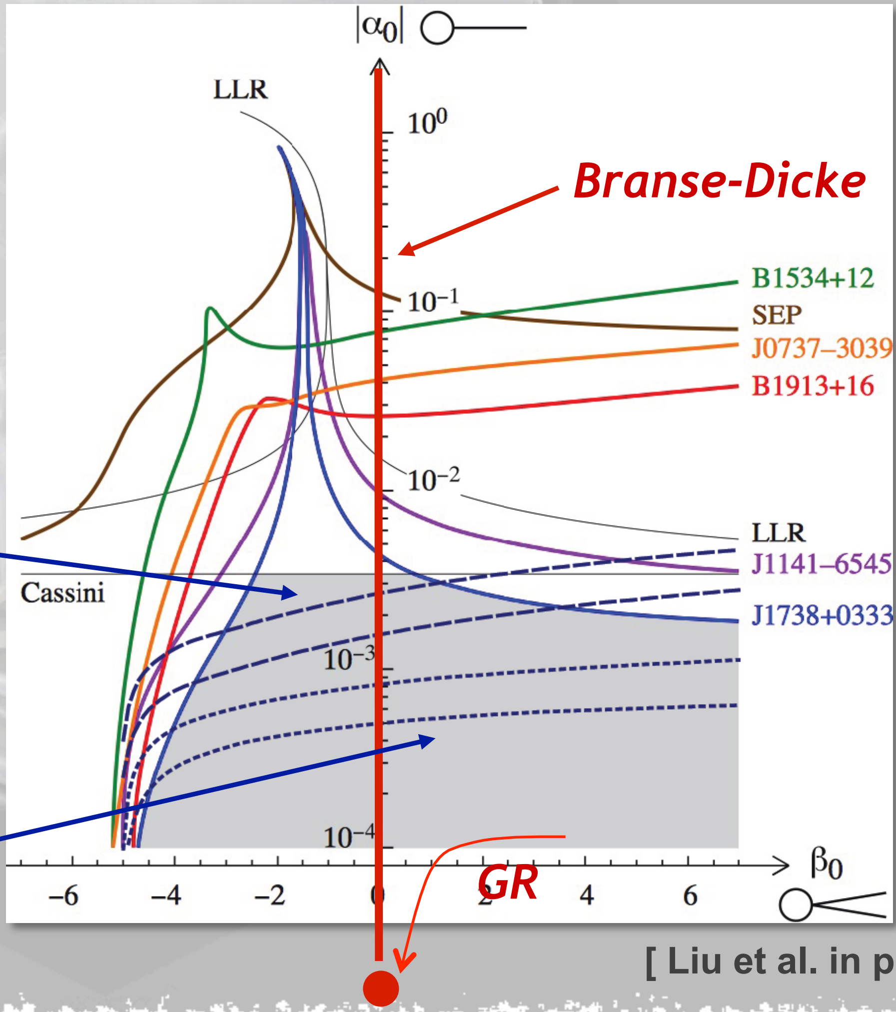
$$a(\varphi) = \alpha_0 \varphi + \frac{1}{2}\beta_0 \varphi^2$$

φ *scalar field*

$a(\varphi)$ *coupling field-matter*

α_0, β_0 *coupling parameters*

Even for gravity theories where BHs are the same as in GR (Kerr), PSR-BH systems would constitute superb gravity laboratories



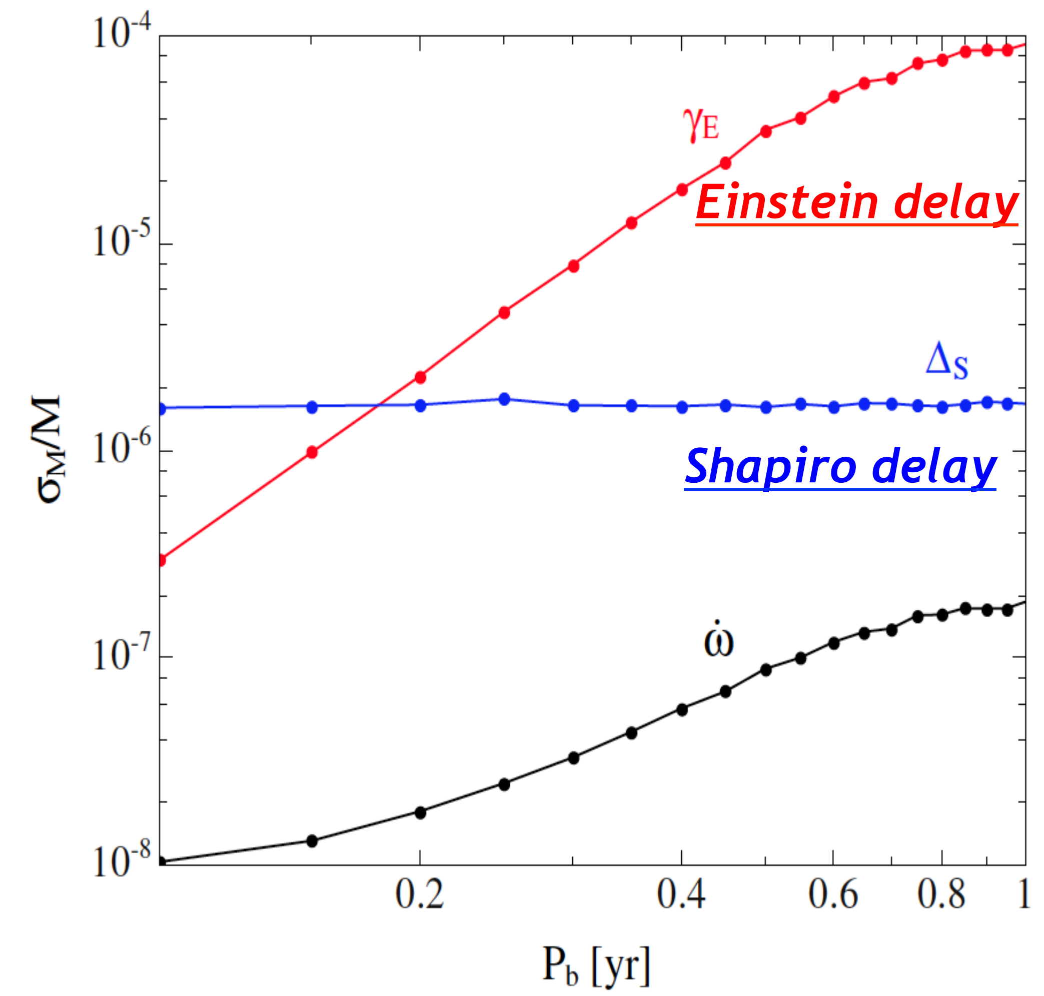
100m (10 yr): MSP + 10 $M_\odot$ BH
20 day orbit, e = 0.8
2 day orbit, e = 0.1

SKA (5 yr): MSP + 10 $M_\odot$ BH
20 day orbit, e = 0.8
2 day orbit, e = 0.1

[Liu et al. in prep.]

Measuring the mass of SGR A* [from Liu et al. 2012]

Mass measurement from relativistic effects using GR (one PK parameter is sufficient, since $M_{PSR} << M_{BH}$):



$$\simeq (2500\,\mathrm{s})\, e \left(\frac{P_b}{1\,\mathrm{yr}}\right)^{1/3} \left(\frac{M_{BH}}{4\times 10^6\, M_\odot}\right)^{2/3}$$

$$\simeq (39.4\,\mathrm{s}) \left(\frac{M_{BH}}{4\times 10^6\, M_\odot}\right) \ln\left(\frac{1+e\cos\varphi}{1-\sin i\,\sin(\omega+\varphi)}\right)$$

Precession of pericenter (possible "contamination" by frame dragging)

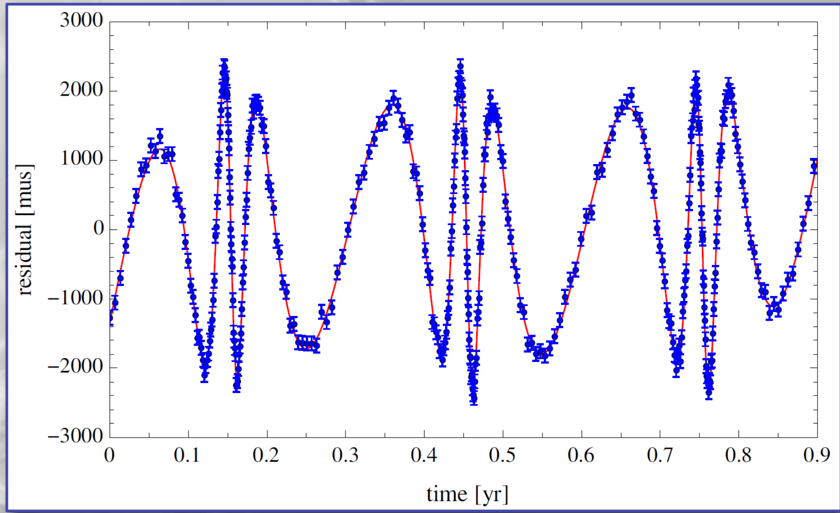
$$\simeq (0.269\,\mathrm{deg\,yr^{-1}}) \frac{1}{1-e^2} \left(\frac{P_b}{1\,\mathrm{yr}}\right)^{-5/3} \left(\frac{M_{BH}}{4\times 10^6\, M_\odot}\right)^{2/3}$$

BH mass with precision < 0.001%

What might be feasible to measure with SKA
Black-hole quadrupole moment

The oblateness of the spinning BH results in periodic (at the pace of the orbital period) transient signals appearing in timing residuals, which depend on the quadrupole moment Q of the BH

$$q \equiv \frac{c^4}{G^2}\frac{Q}{M^3}$$



BH quadrupole moment with precision ~ 1%

[Liu et al. 2012]

In GR, for Kerr-BH we expect: $q = -\chi^2$

test of "No Hair" theorem

An uncharged BH, is fully described by its mass and its spin !

The impact of SKA

Gravitational Wave Astrophysics in the nano-Hertz frequency band

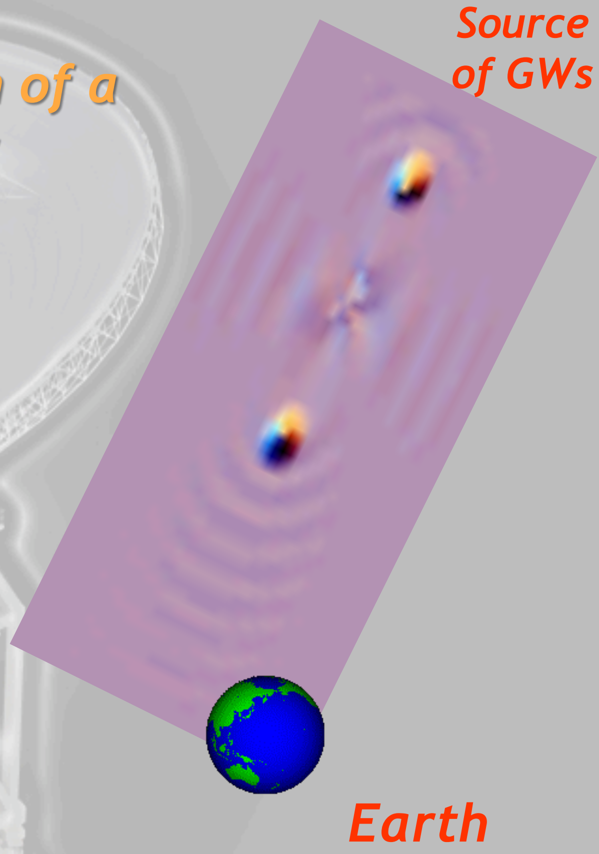
≈ 100 usable clocks to be timed with 100 ns accuracy

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

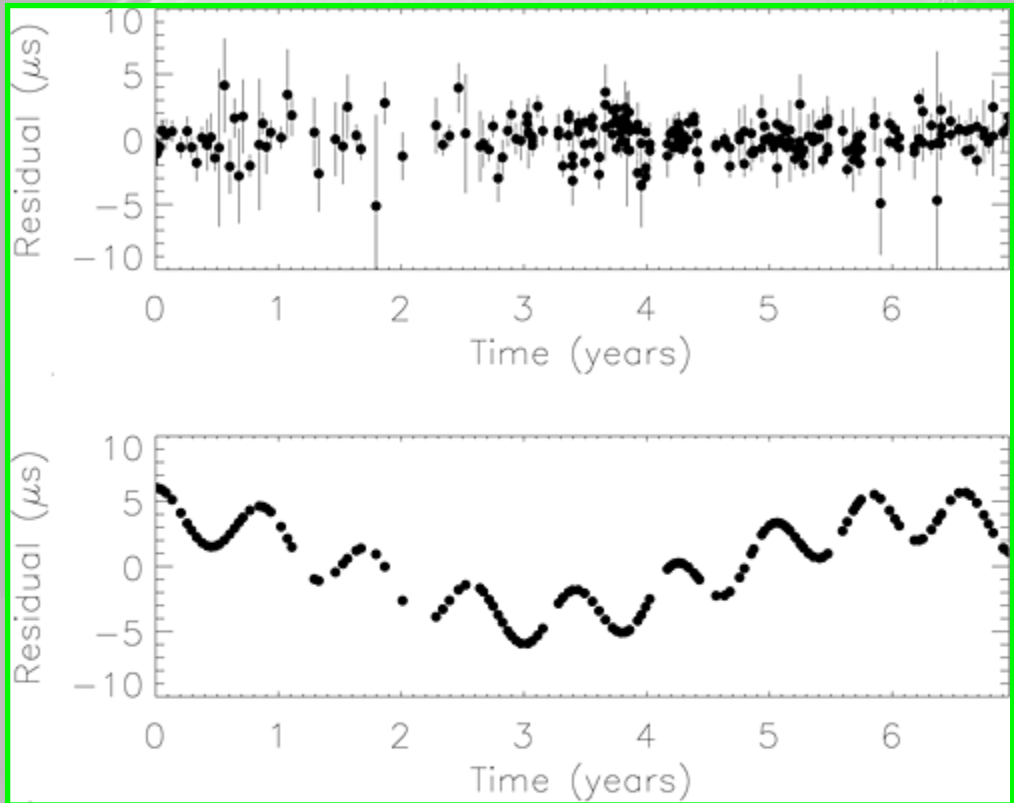
$h_c(f)$ is the dimensionless strain at freq f

σ_{TOA} is the rms uncertainty in Time of Arrival

T is the duration of the dataspan

An instructive application

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]

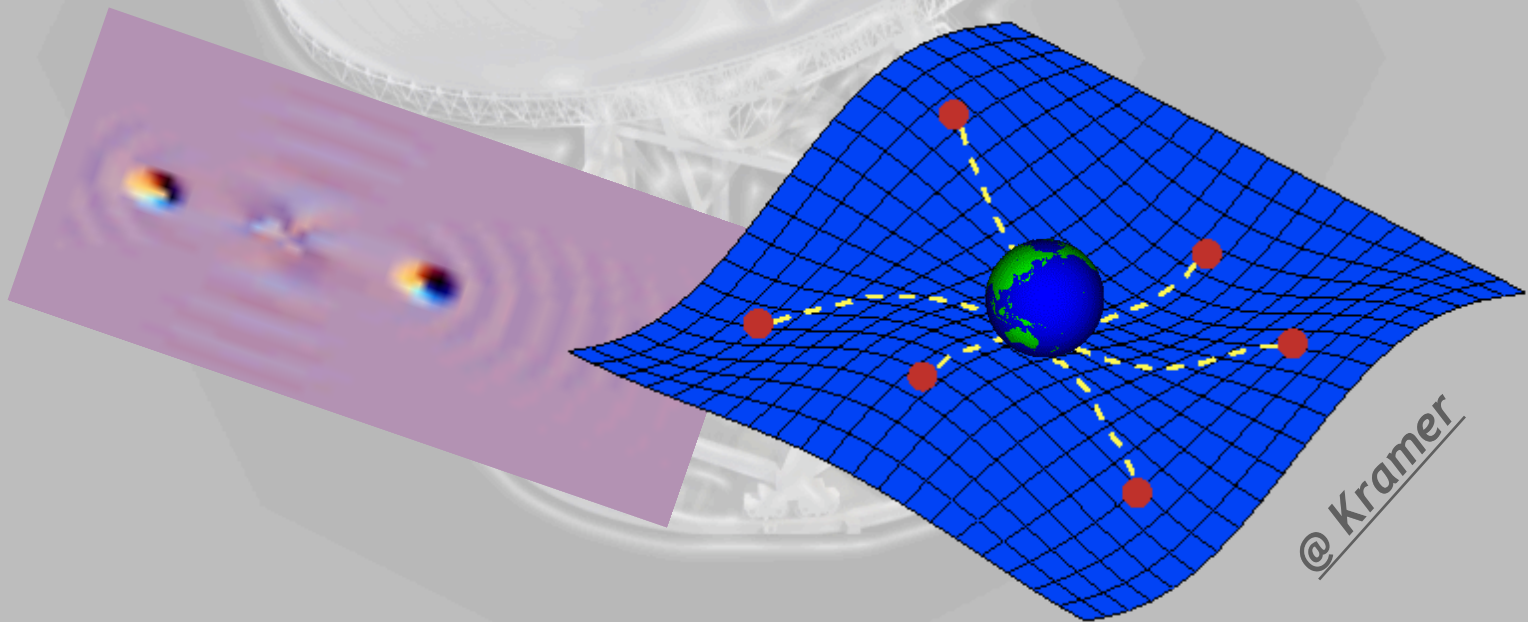


[Jenet et al 2004]

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

A pulsar timing array (PTA)

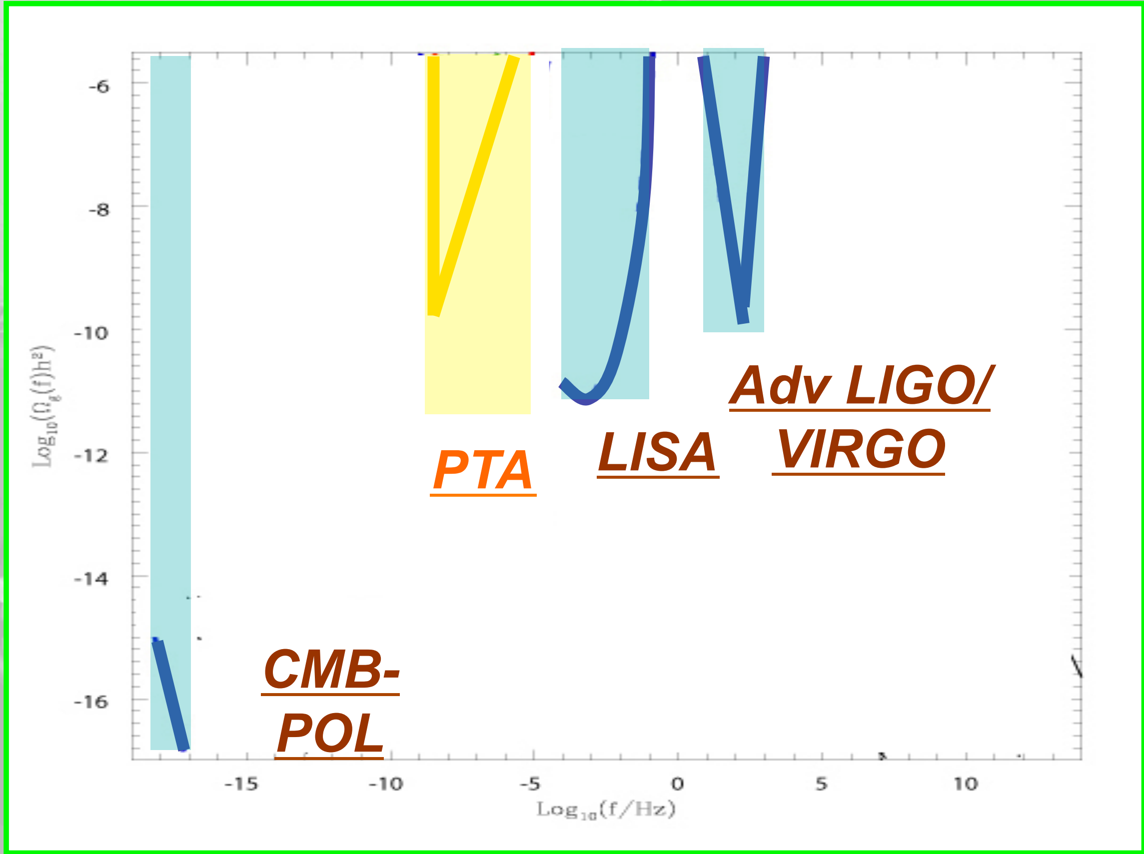
Using a number of pulsars distributed across the sky it is possible to separate the timing noise contribution from each pulsar from the signature of the GW background, which manifests as a local (at Earth) distortion in the times of arrival of the pulses which is common to the signal from all pulsars



Pulsar Timing array(s): the frequency space and the sources

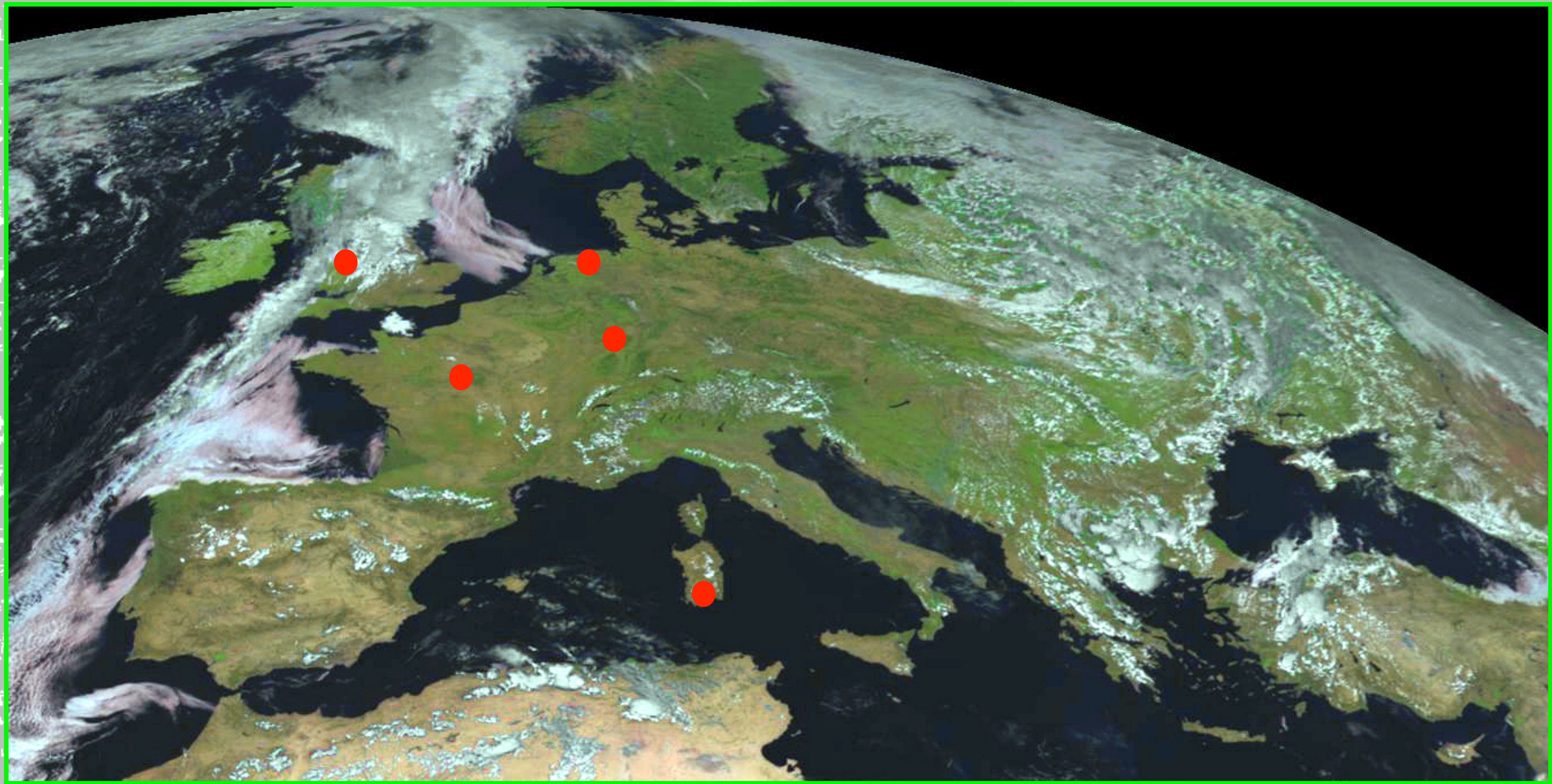
Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like LIGO, advLIGO, advVIRGO and LISA

- *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 PTA collaborations

EPTA: The partner institutions



University of Manchester, JBO, GB

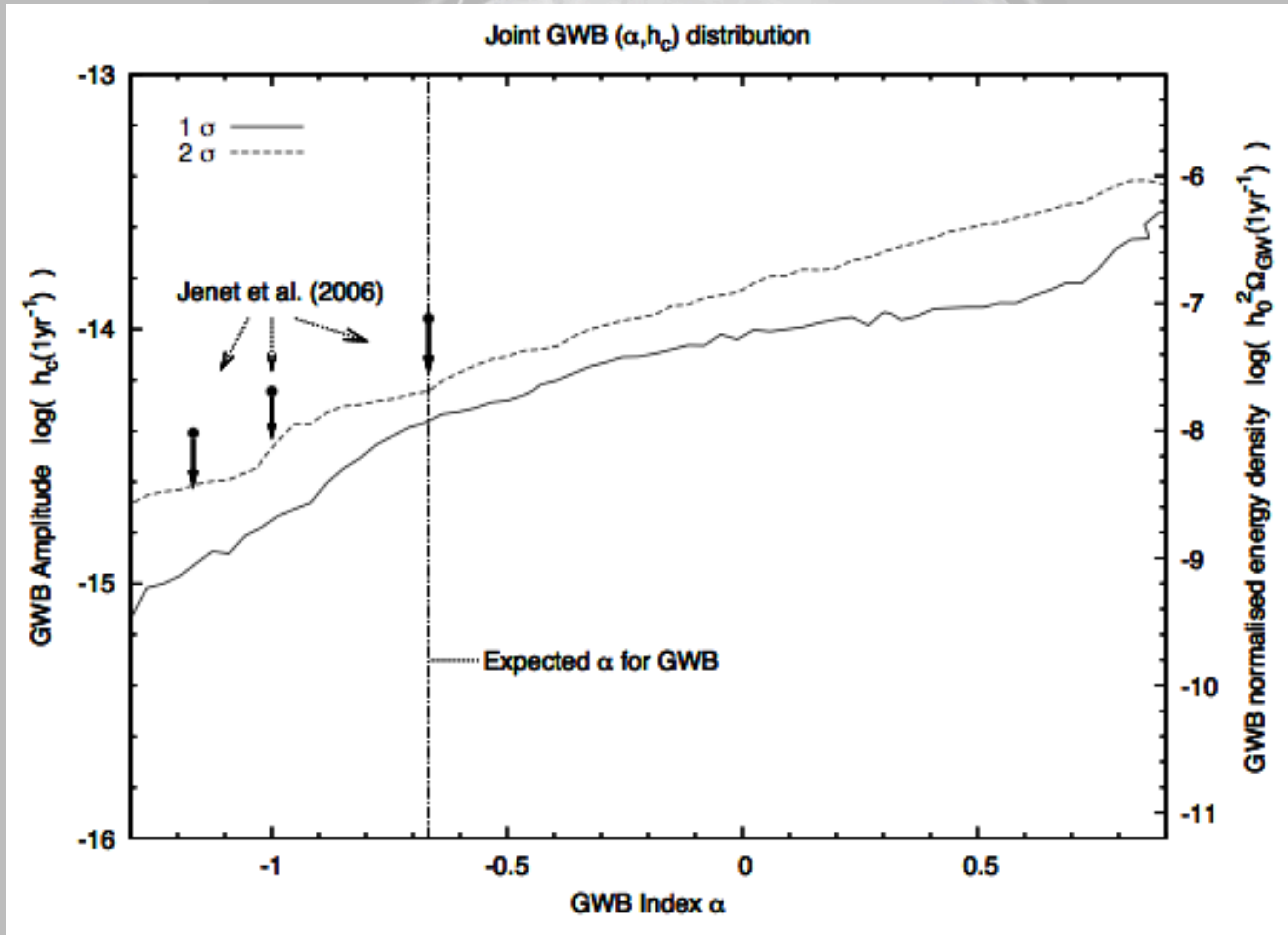
ASTRON,Un.Leiden,Un.Amsterdam NL

INAF Osservatorio Astronomico di Cagliari, ITA

Nancay Observatory, FR

Max-Planck Institut fur Radioastronomie, GER

Current best limits on GW background from EPTA

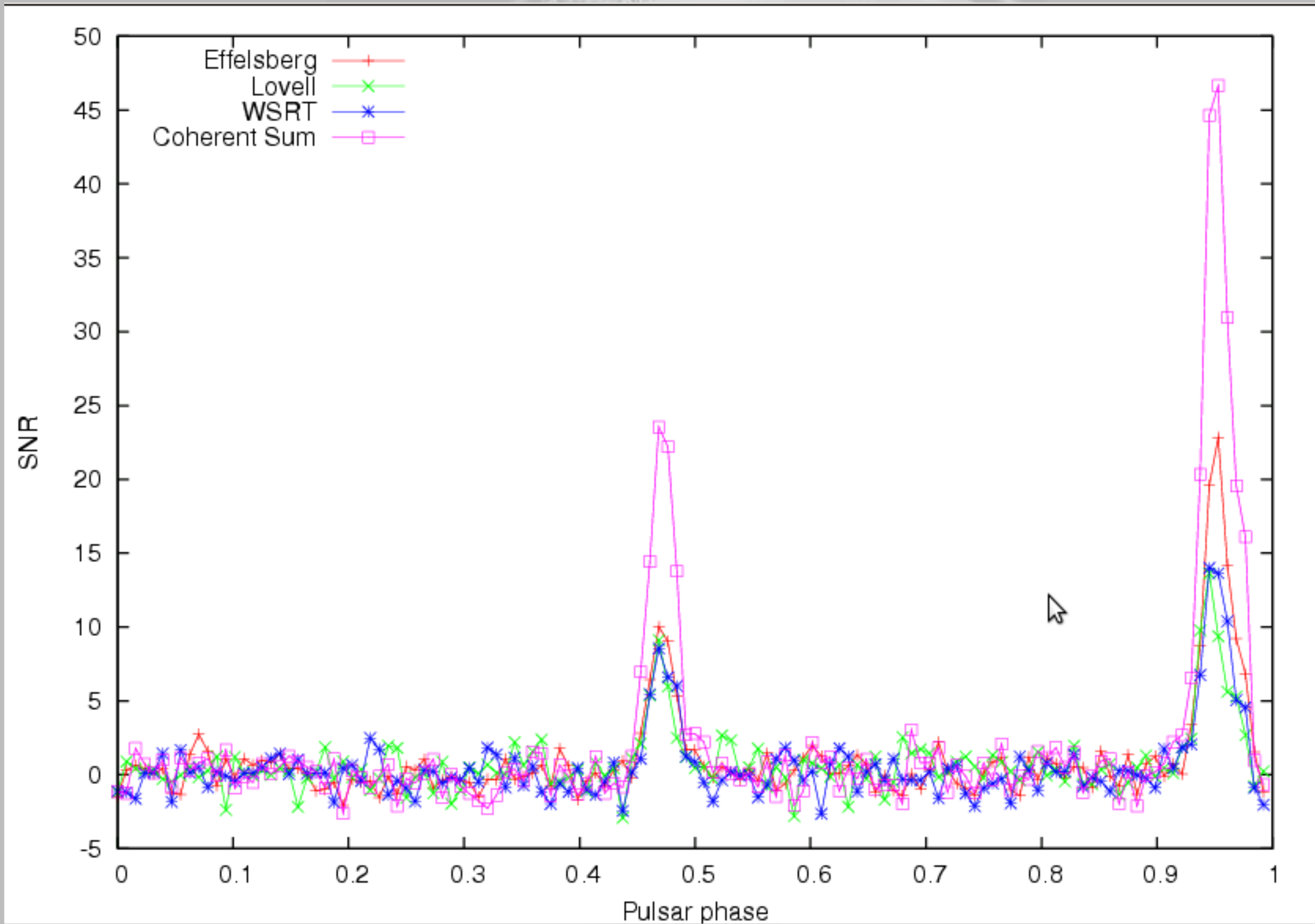


[van Haasteren et al. 2011]

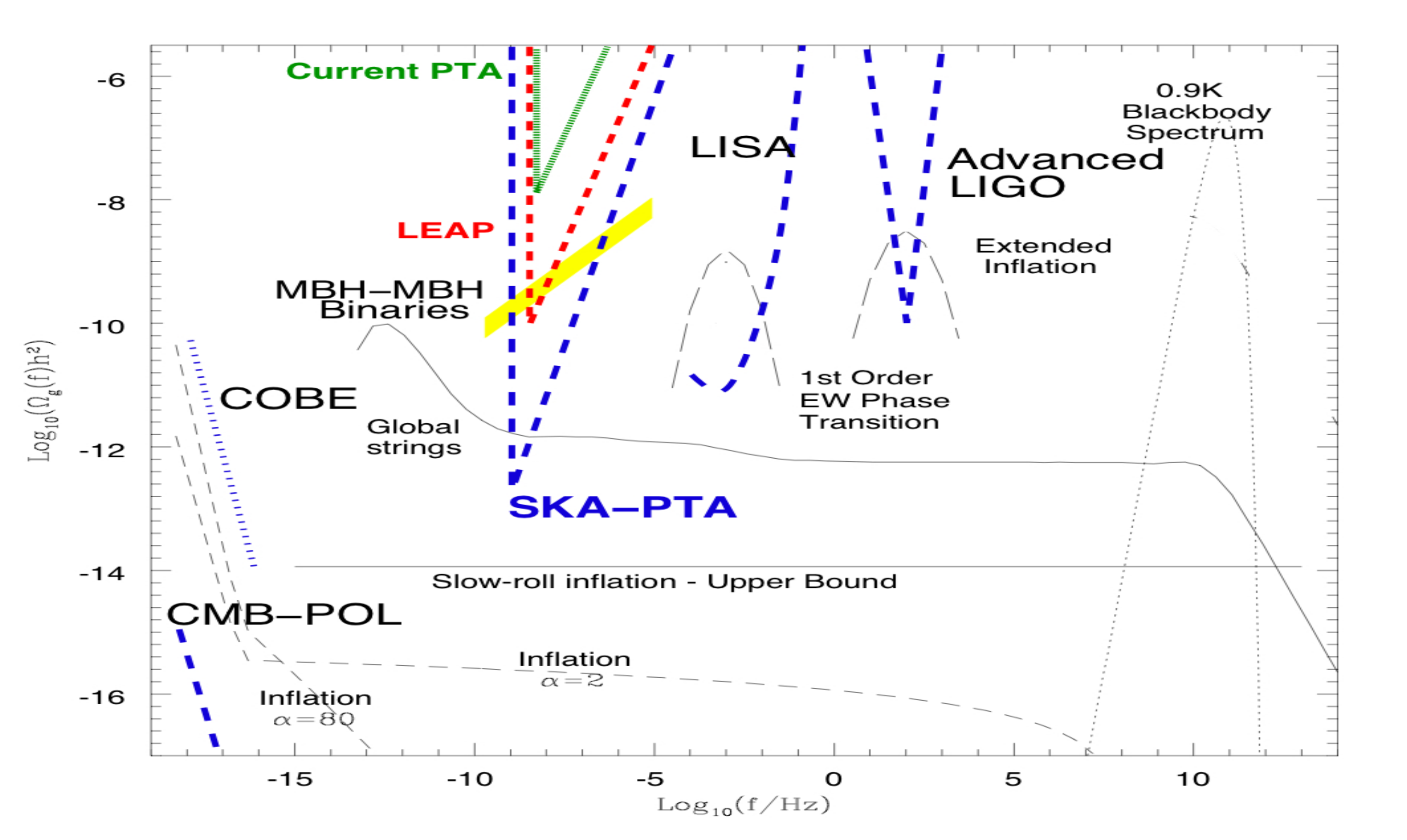
LEAP


Large European Array for Pulsars (LEAP)
• Coherent combination of 5 major European telescopes (at 20cm)
➡ 4% SKA

The (proto) LEAP results on PSR B1937+21



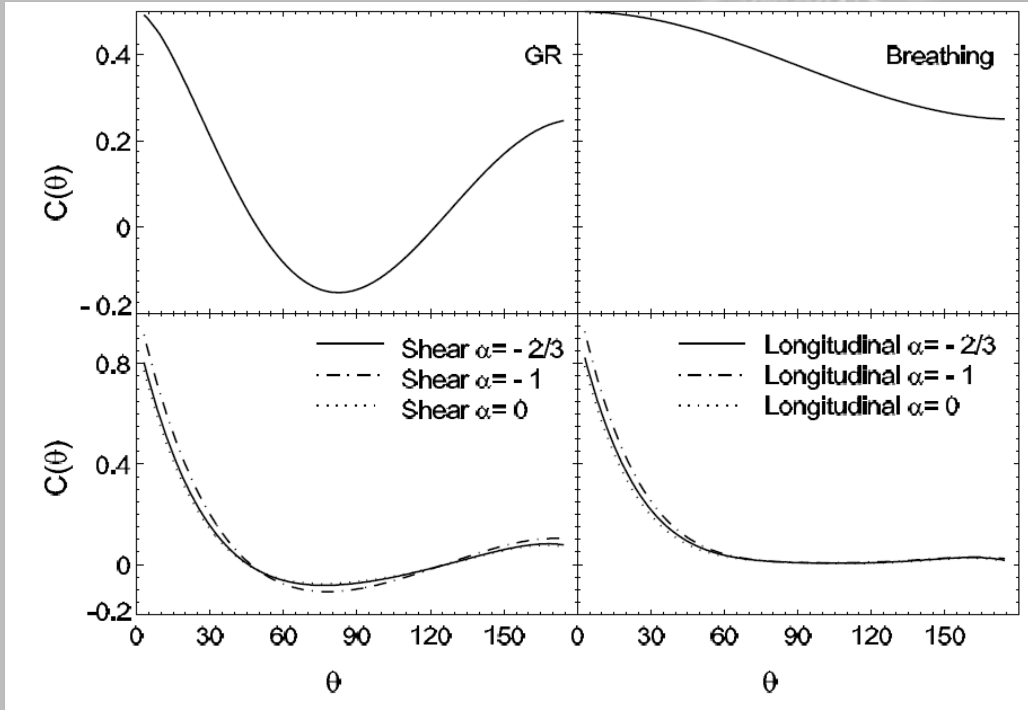
Current projects are evolving in pace with predictions. Then at least very significant limits on GWB (and hopefully a detection) will be achieved within 5-10 years



A detailed scientific investigation of the GWBackground is warranted with SKA

Graviton mass and polarization of the GWs

[Lee et al. 2009]



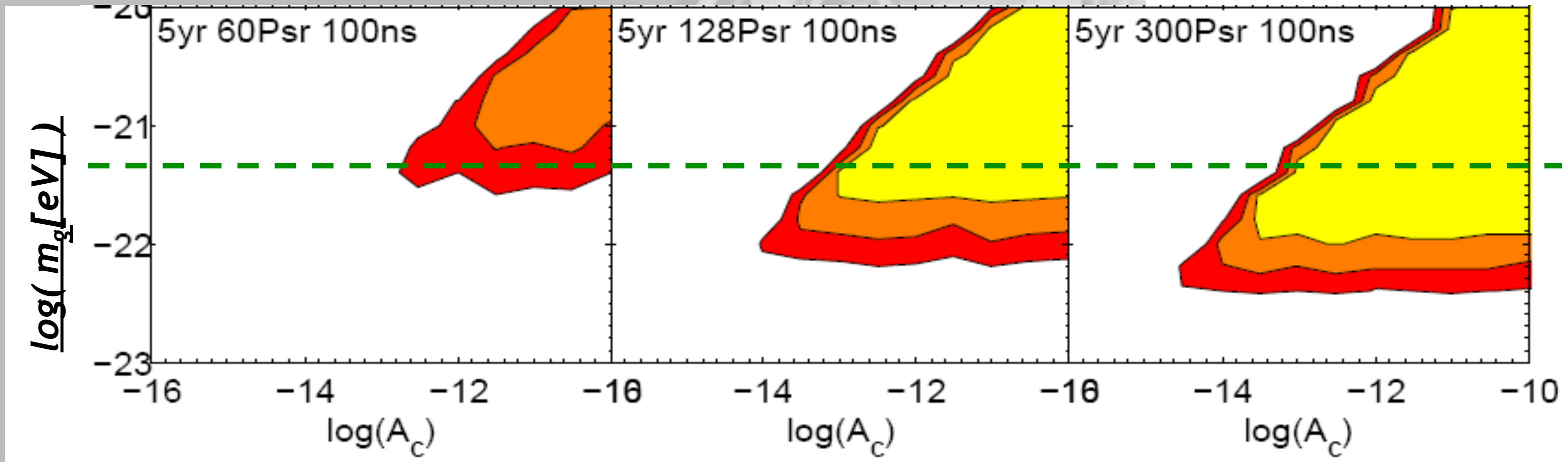
GW polarisation

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

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

Graviton mass

[Lee et al. 2010]

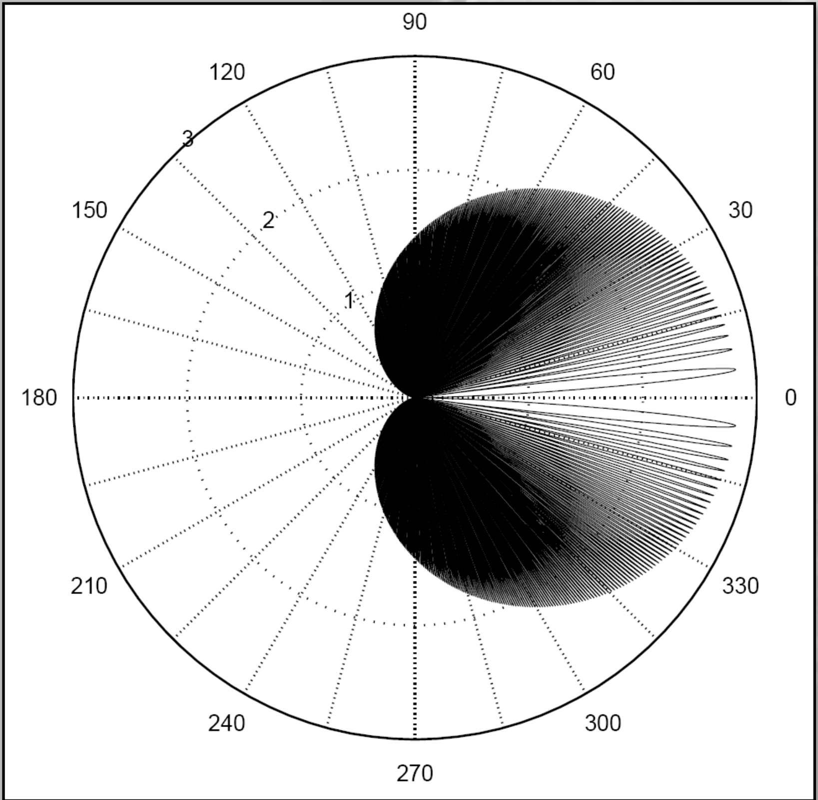


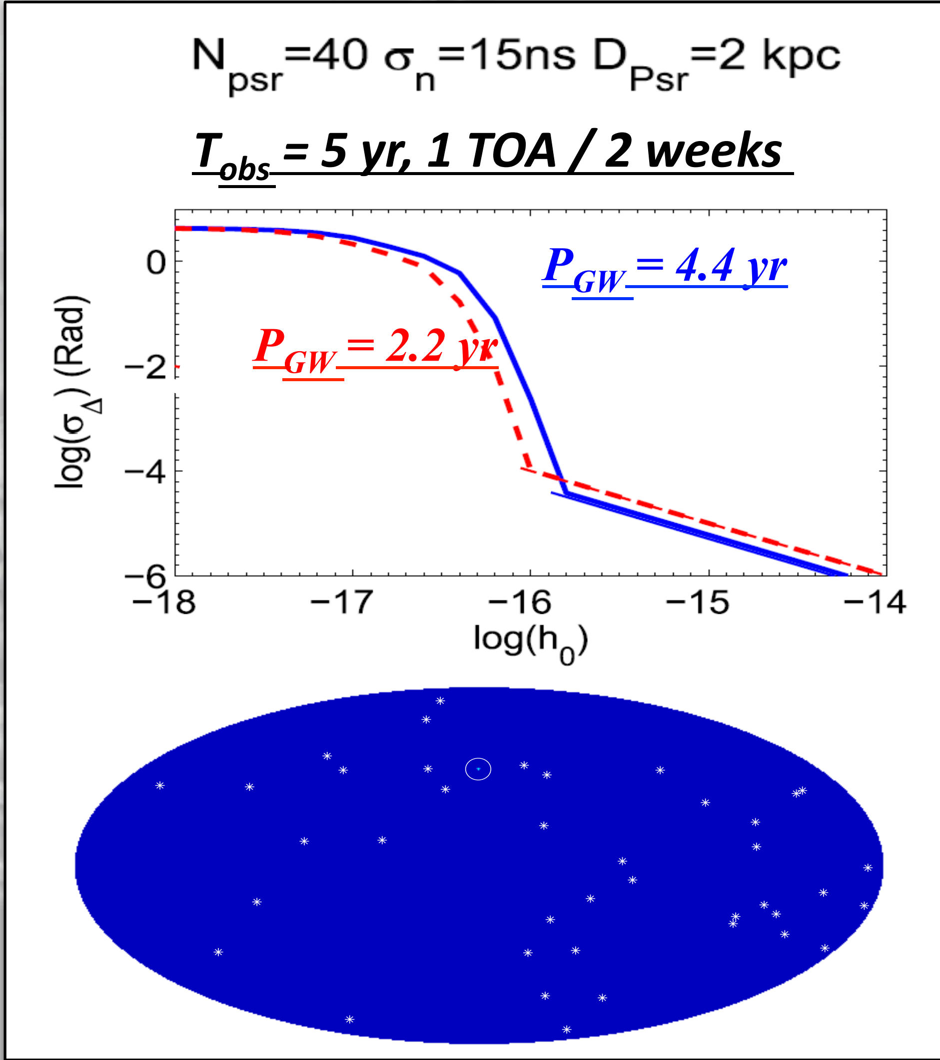
present solar system limit

Single source localization in the sky with a PTA

- Single binary super-massive black hole produces periodic signal
- Signal contains information from two distinct epochs: t and t-d/c

Response pattern of a single pulsar:





[Lee et al. 2011]

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Thank you !