Pulsar Timing Array

Benasque XLIII International Meeting
on Fundamental Physics

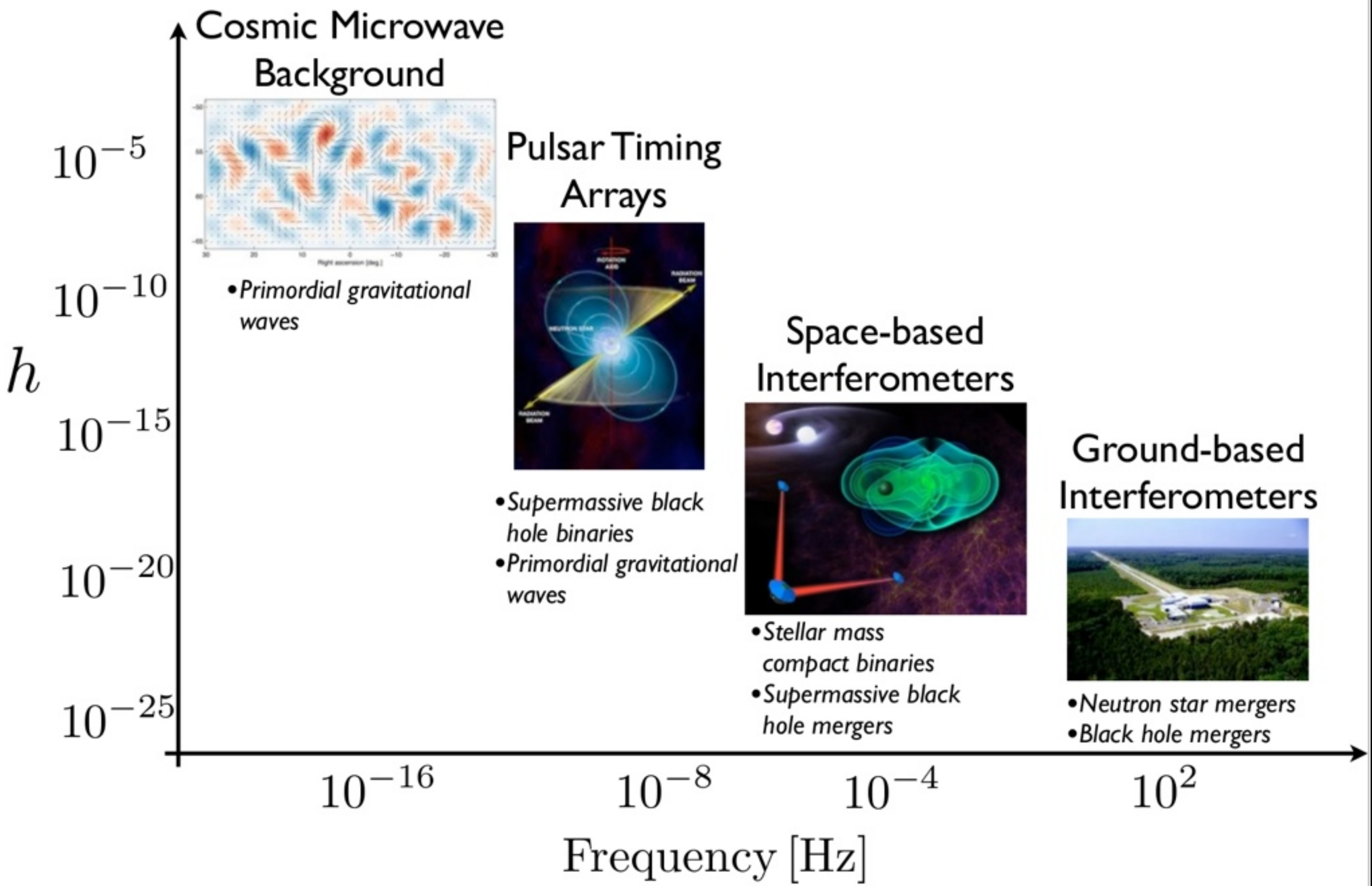
Antoine Lassus

Max-Planck-Institut
für
Radioastronomie

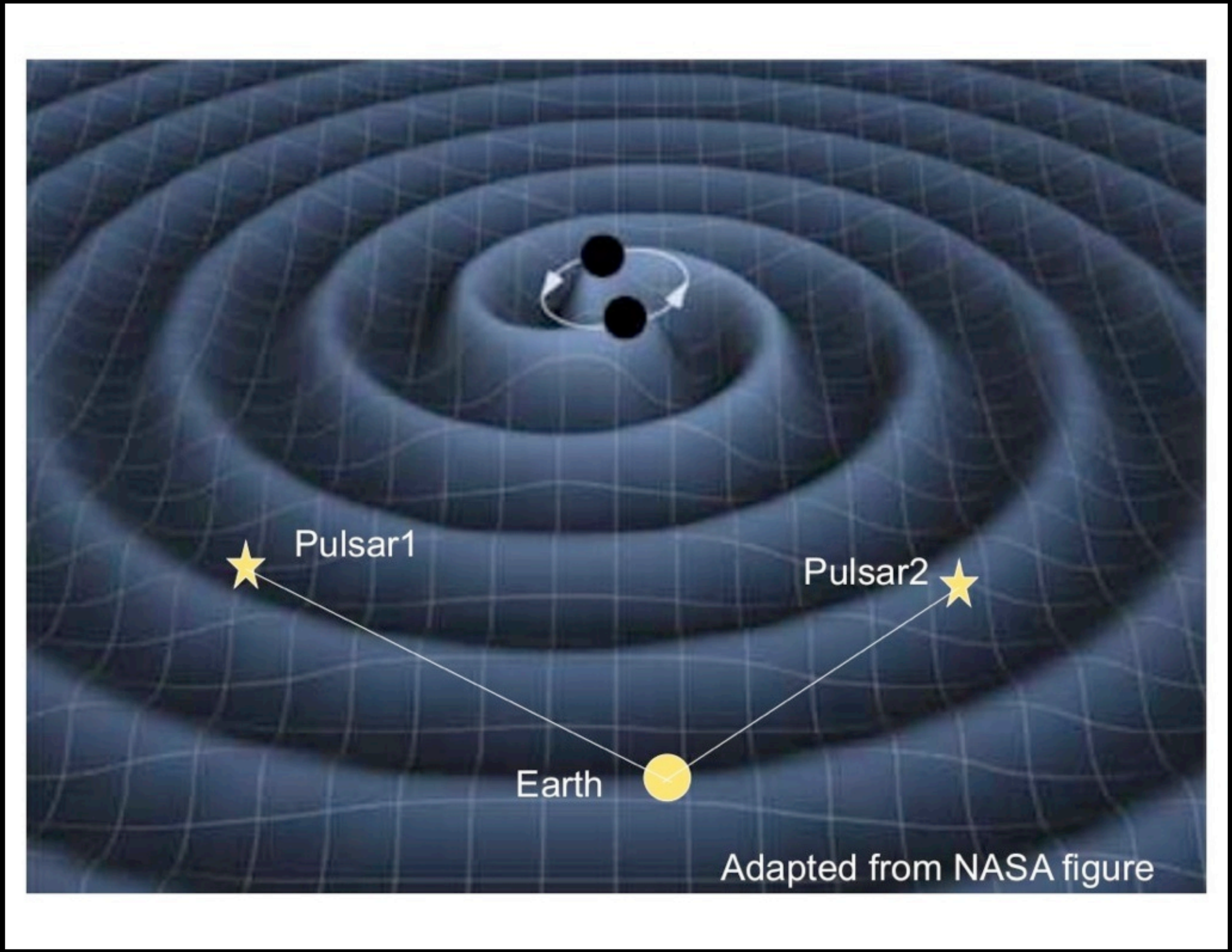
EPTA

- Introduction
- Pulsars and Timing
- Gravitational Waves Detection
- The Pulsar Timing Array Community
- Perspectives

The big picture of gravitational-wave astronomy



Concept : Using pulsars as galactic scale interferometer



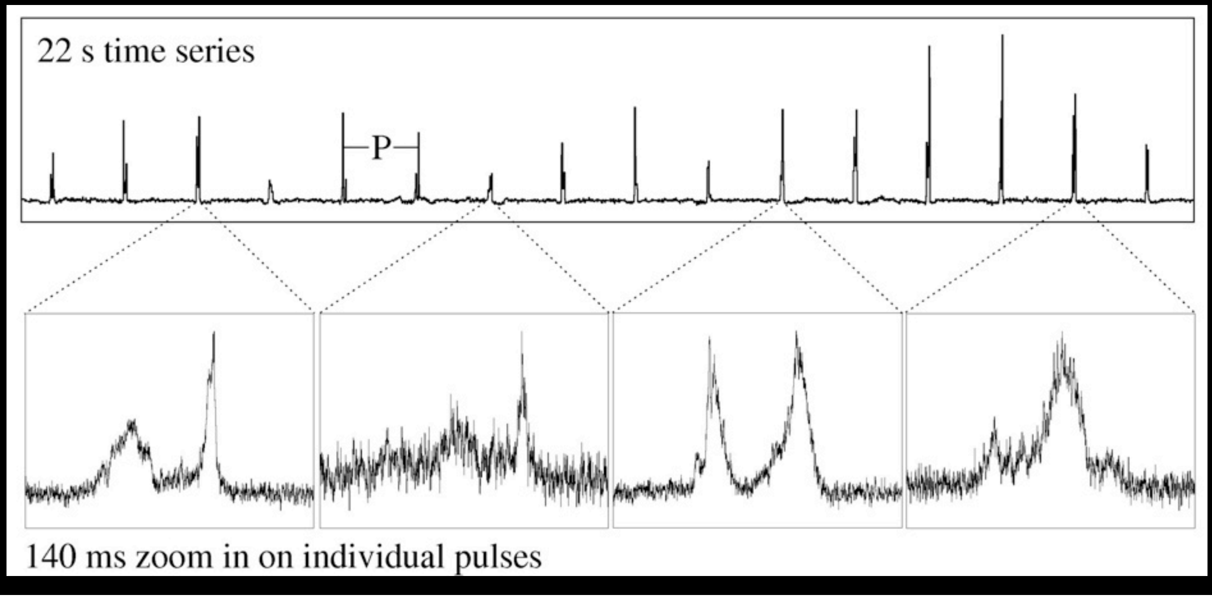
The pulsar is a magnetized neutron star

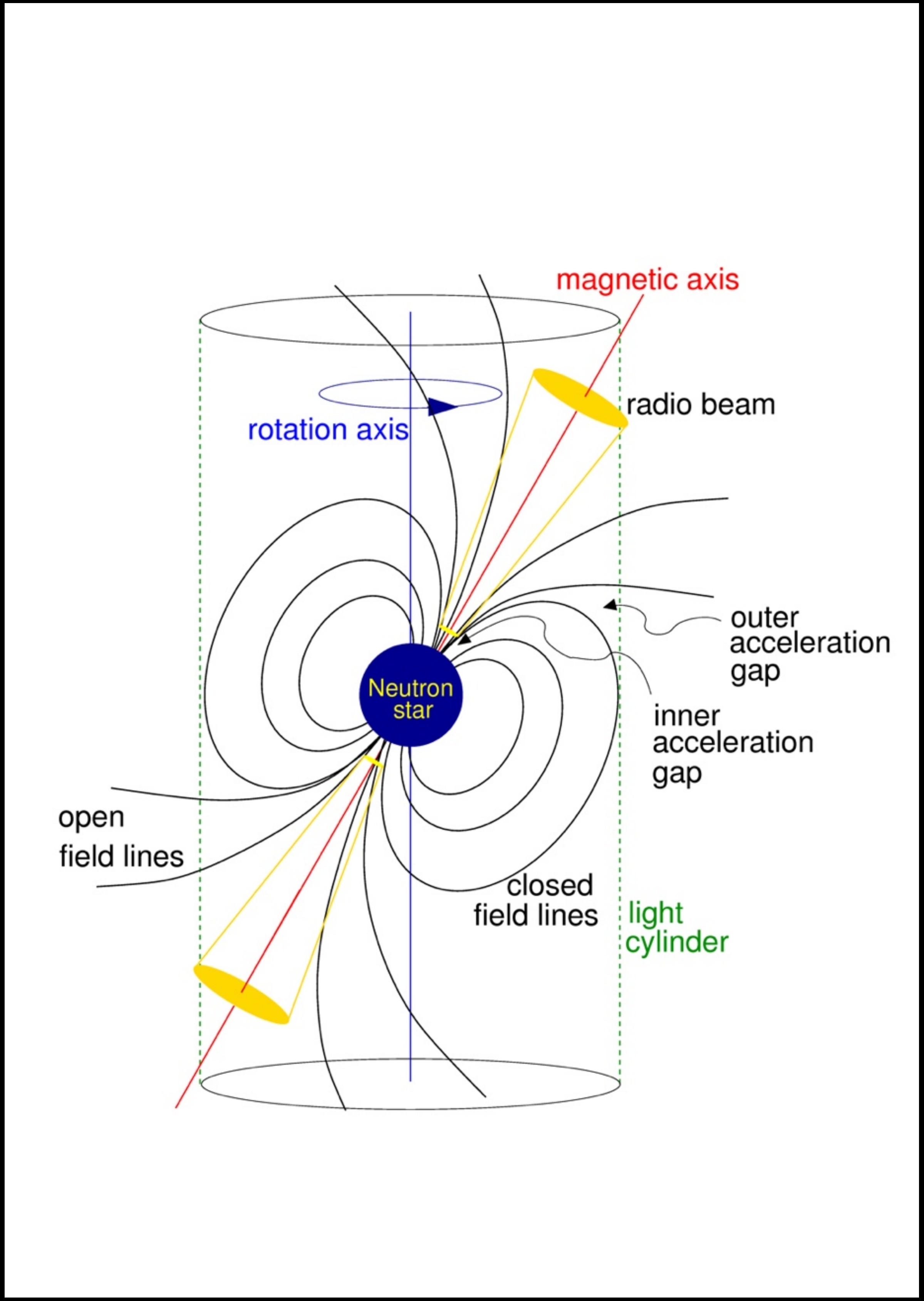
$$1.3\mathrm{M}_\odot < M < 2.1\mathrm{M}_\odot$$

$$1.4\mathrm{ms} < P < 12\mathrm{s}$$

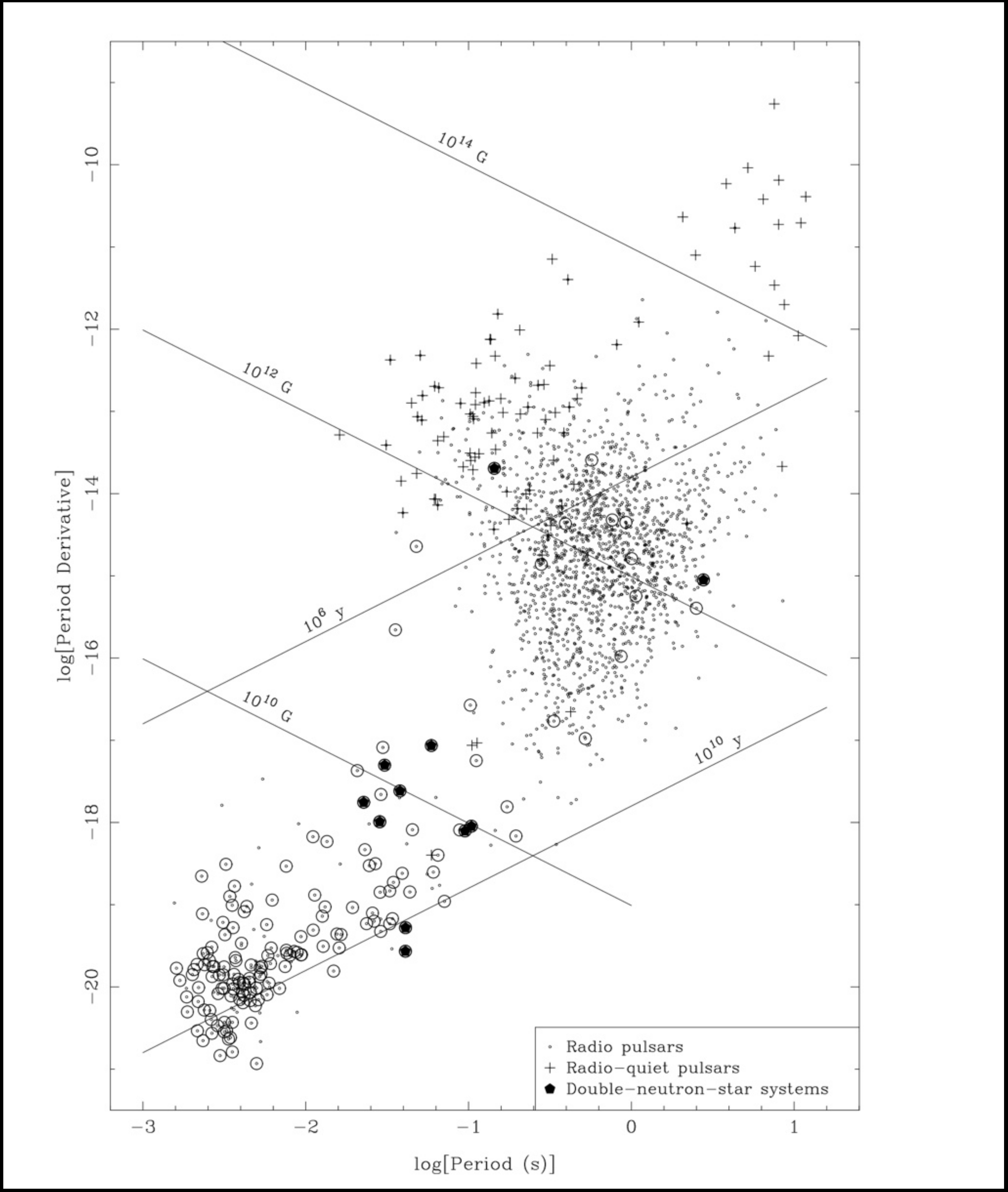
$$10^{10}\mathrm{G} < B < 10^{13}\mathrm{G}$$

«Lighthouse effect» : sweeping radio beams as the pulsar rotates





Pulsar Population
>2400 Pulsars



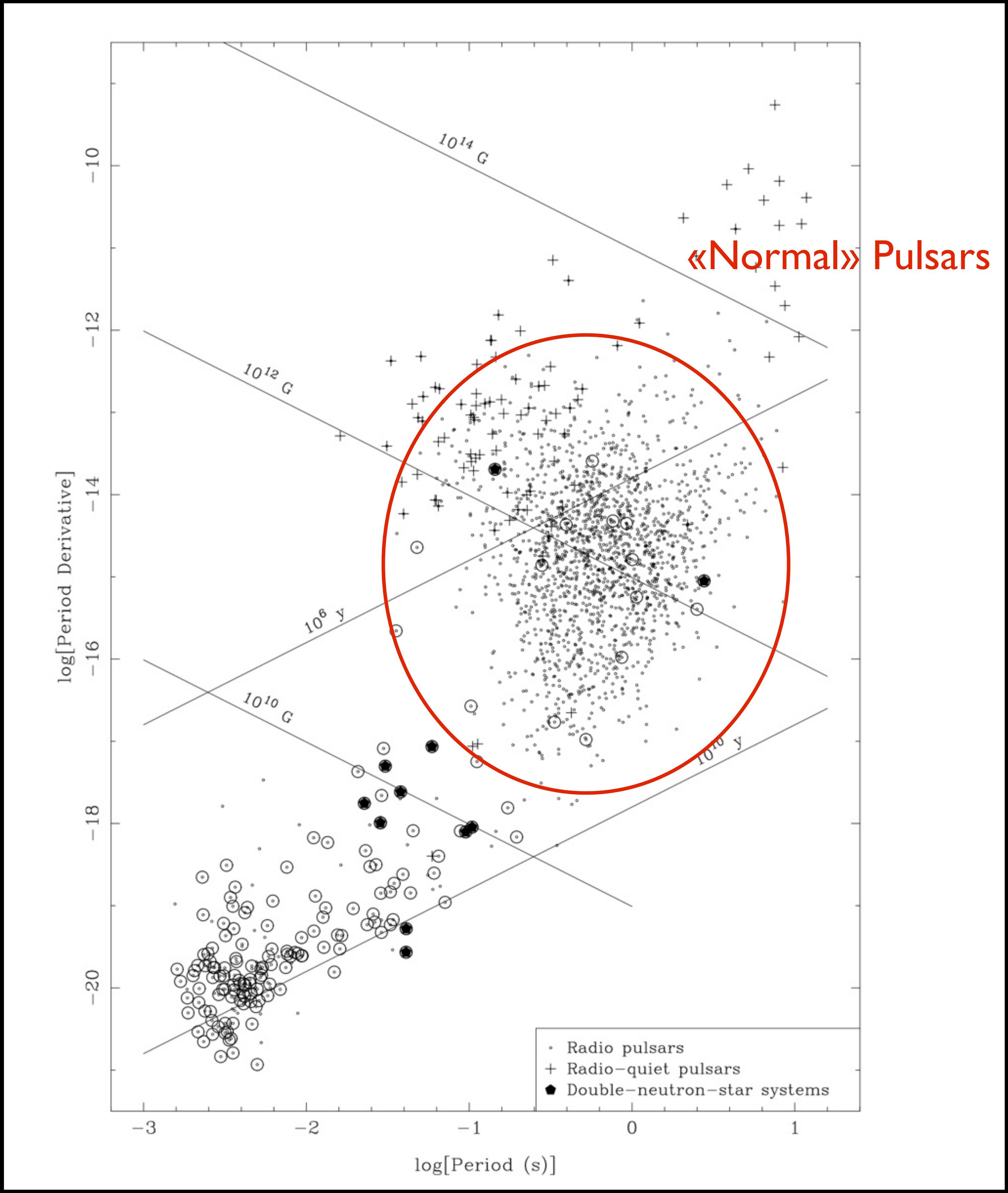
Pulsar Population
>2400 Pulsars

«Normal» Pulsars :

$$B > 10^{11}\mathrm{G}$$

$$30\mathrm{ms} < P < 12\mathrm{s}$$

$$\dot{P} \sim 10^{-15}\mathrm{s.s}^{-1}$$



Millisecond Pulsars (MSPs) :

Recycled Pulsar

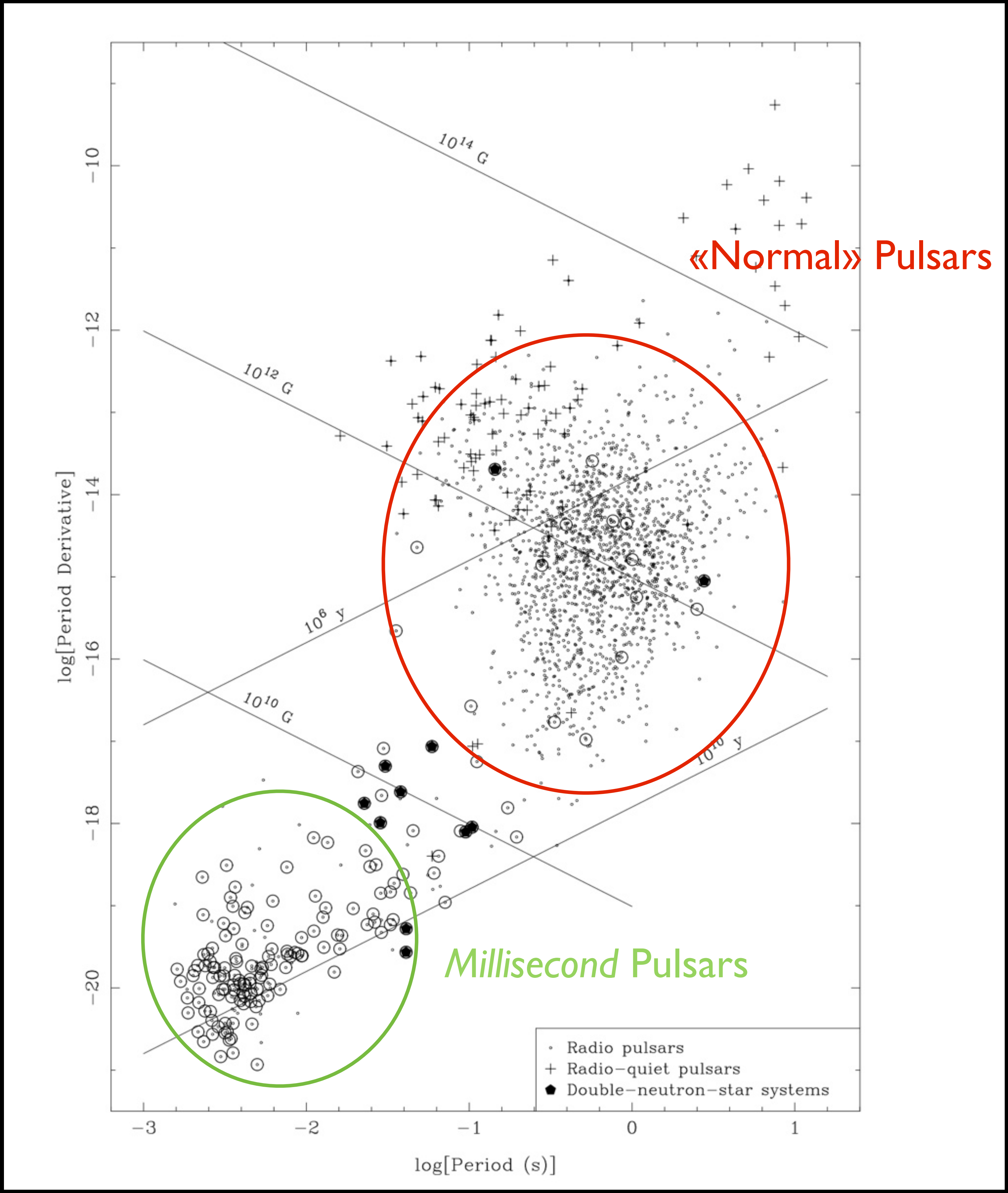
$$B \sim 10^8 \mathrm{G}$$

$$1.4\mathrm{ms} < P < 30\mathrm{ms}$$

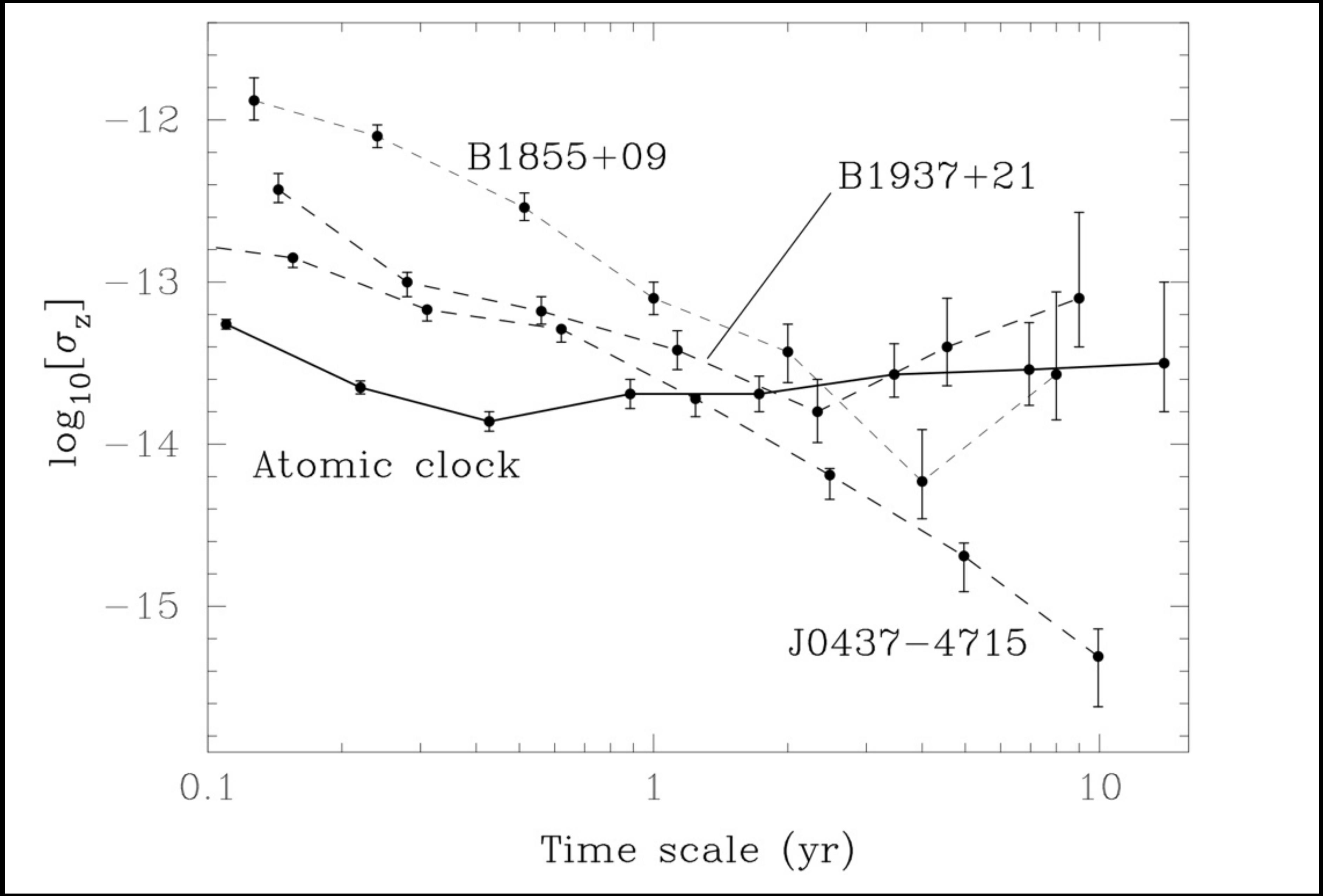
$$\dot{P} \sim 10^{-20} \mathrm{s.s}^{-1}$$

Highly stable object :

0.1 millisecond every 300 millions years !



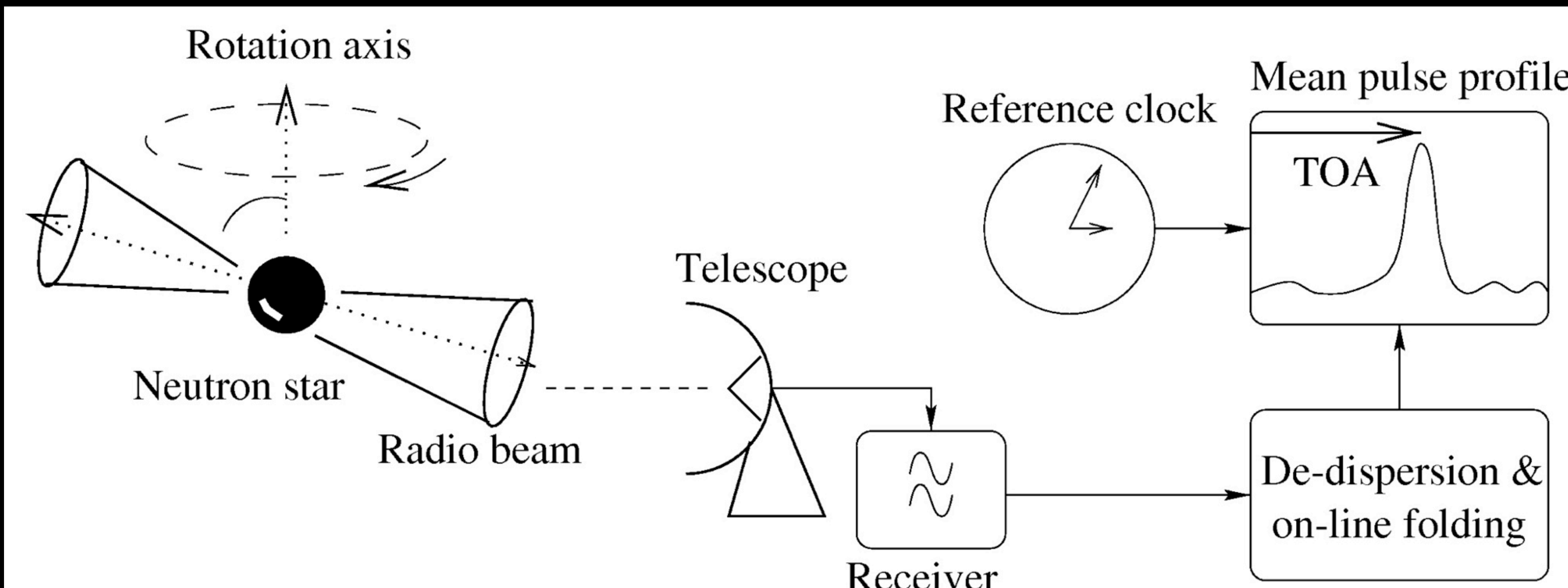
Comparision to atomic clock



Mesured Period for B1937+21 after 9 years (1988!) :

$$P = 1.5578064688197945 \pm 0.0000000000000004\text{ms}$$

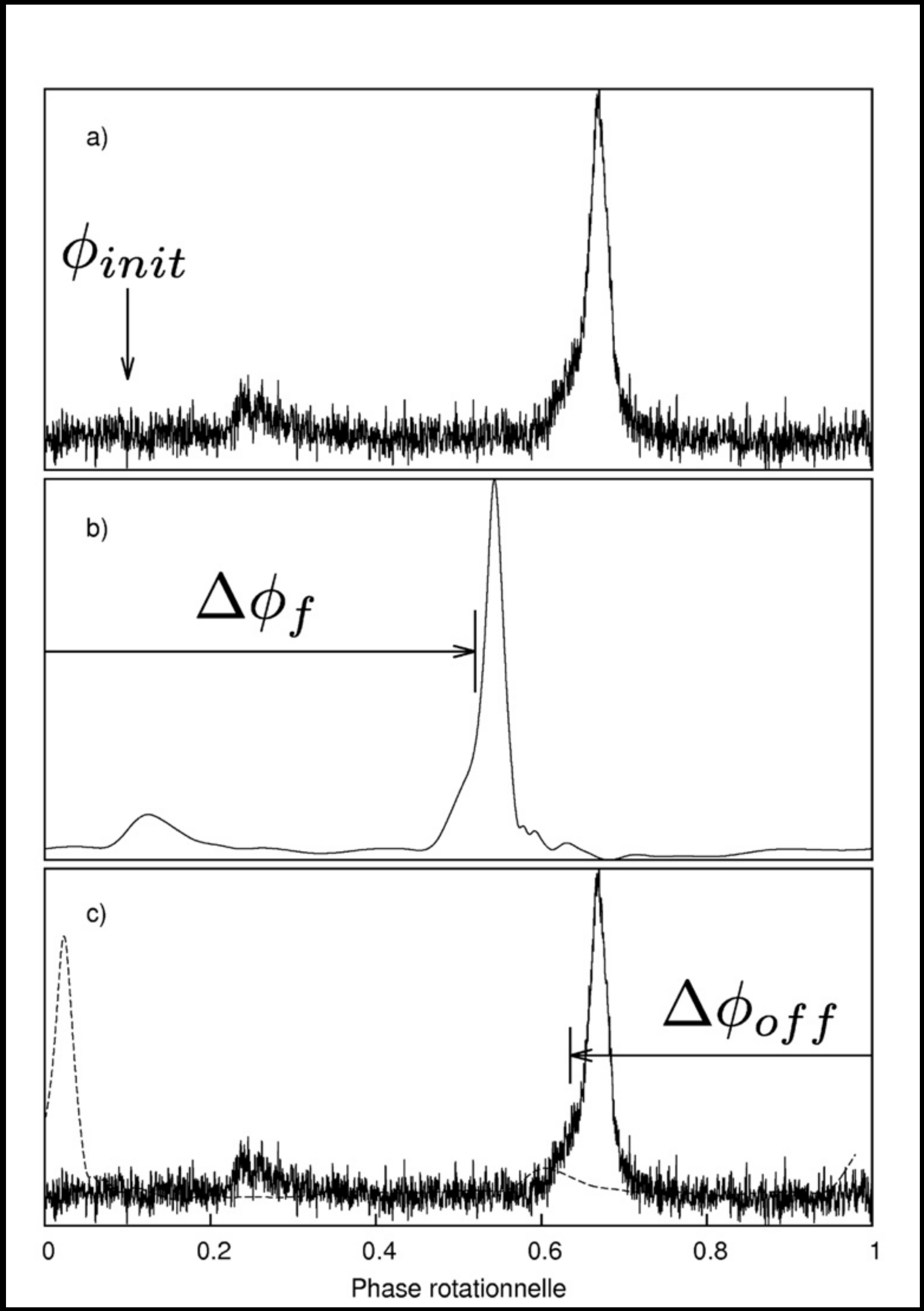
Pulsar Timing



Pulsar Timing

For each observation,
a mean profile is produced by
integrating individual pulses

which is cross-correlated with
a template profile providing
a time of arrival (TOA) with
precision as low as 30 ns



$$\sigma_{TOA} \sim \frac{w}{SNR} \propto \frac{w}{S_{PSR}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

$$TOA = t_{mid} + P \times (\Delta\phi_{off} - \phi_{init})$$

Pulsar Timing

TOA modelisation

Each TOA brought to the solar system barycenter (SSB) can be modeled by delays due to several effects :

$$t_{SSB} = t_{topo} + t_{corr} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{\pi} + \Delta_{S\odot} + \Delta_{E\odot}$$

Pulsar Timing

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Mesured TOA
at the
observatory

Pulsar Timing

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Clock Corrections

$$\text{Observatory Clock (maser)} \xrightarrow[\text{GPS}]{} \text{UTC} \xrightarrow[\text{BIPM}]{} \text{TAI} \longrightarrow \text{TT}$$

Pulsar Timing

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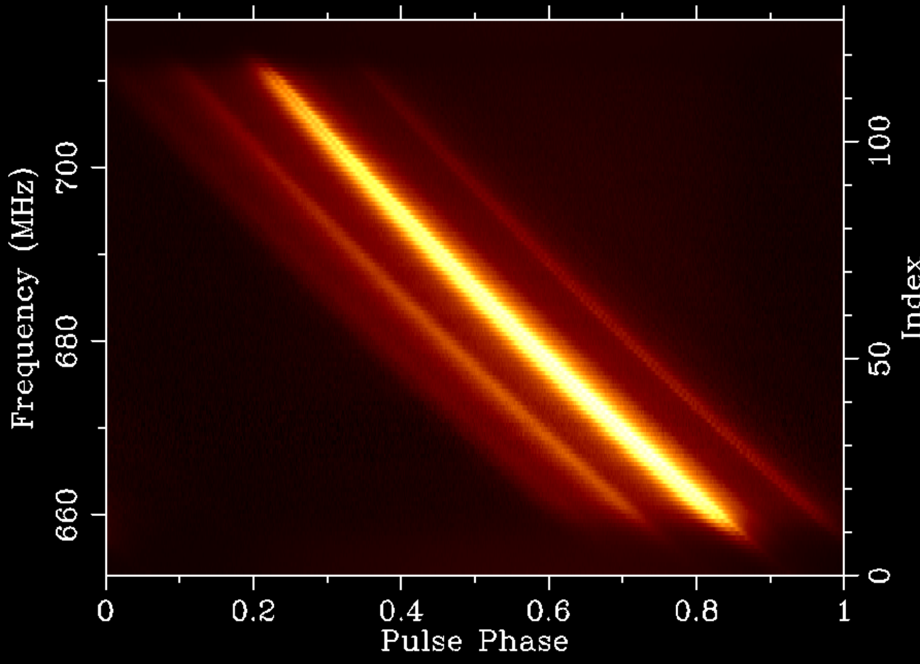
Dispersion in the InterSellar Medium (ISM)

$$\Delta D = k \times DM, k = \frac{e^2}{2\pi m_e c}$$

$$DM = \int_0^D n_e(l)dl$$



Pulsar Timing

TOA modelisation

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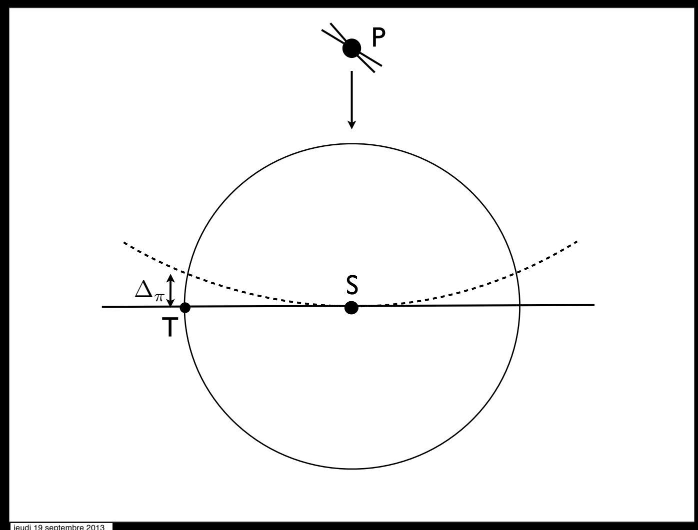
Römer Delay

Geometrical effect due to the Earth orbit

$$\frac{r \cdot n}{c}$$

Parallax

Delay due to the curvature of spherical wavefront



Pulsar Timing

TOA modelisation

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Shapiro Delay

Delay due to curved space-time close to massive solar system object

$$-2\sum_i \frac{GM_i}{c^3} \ln\left\{\frac{\hat{s}\cdot\hat{r}_i^E + r_i^E}{\hat{s}\cdot\hat{r}_i^P + r_i^P}\right\}$$

Einstein Delay

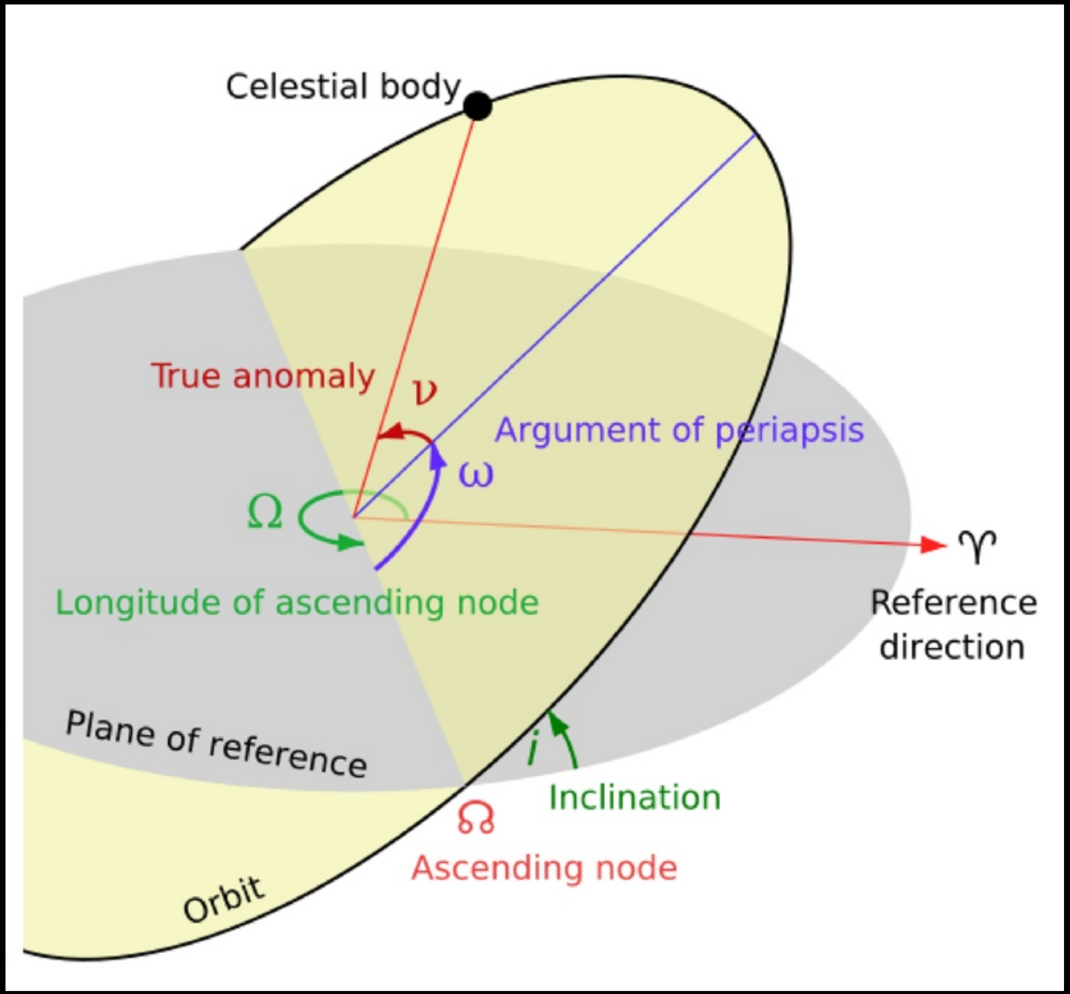
Due to time dilatation around massive solar system object and from earth motion around the Sun

Pulsar Timing

TOA modelisation

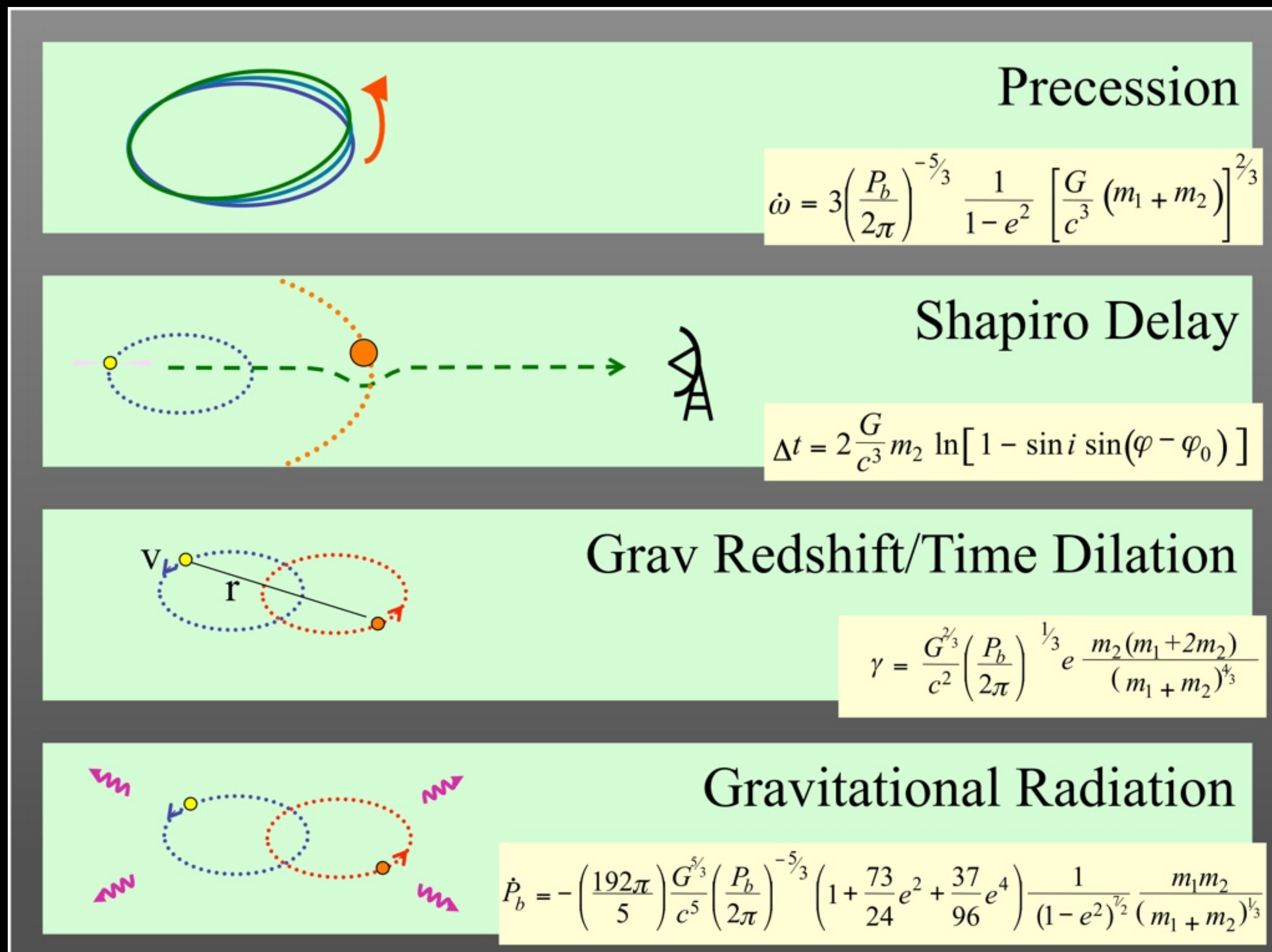
For Binary system, we have to extend the model to include the additional motion of the pulsar

5 Keplerian Parameters :
Orbital Period
Exentricity
Projected semi-major axis
Argument
epoch of periastron



Pulsar Timing

TOA modelisation
Post-Keplerian Parameters



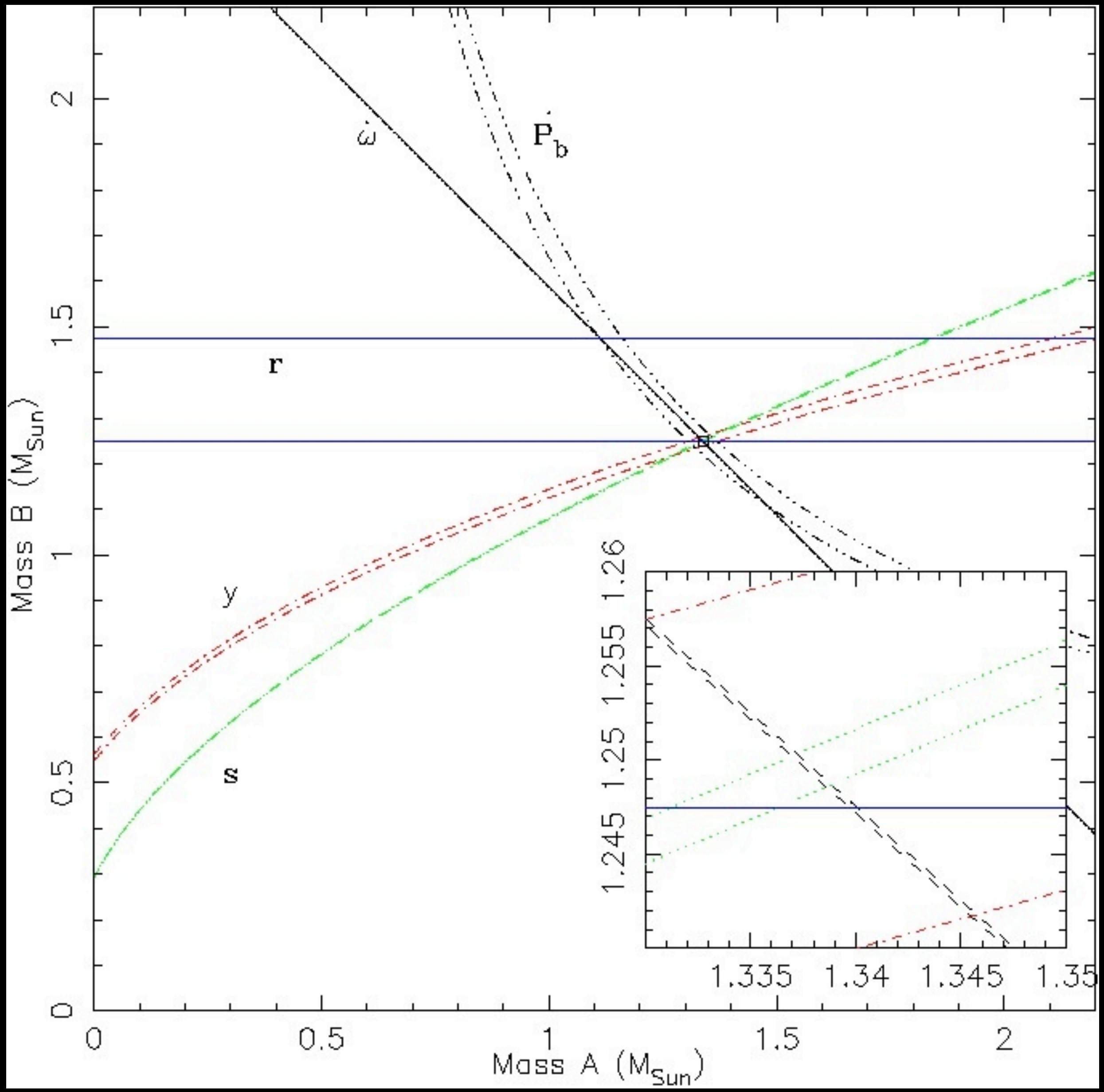
Pulsar Timing

TOA modelisation
Post-Keplerian Parameters

Double Pulsar J0737-3039A

«Agreement with General Relativity within an uncertainty of 0.05%»

Kramer et al., Science 314, 97 (2006)

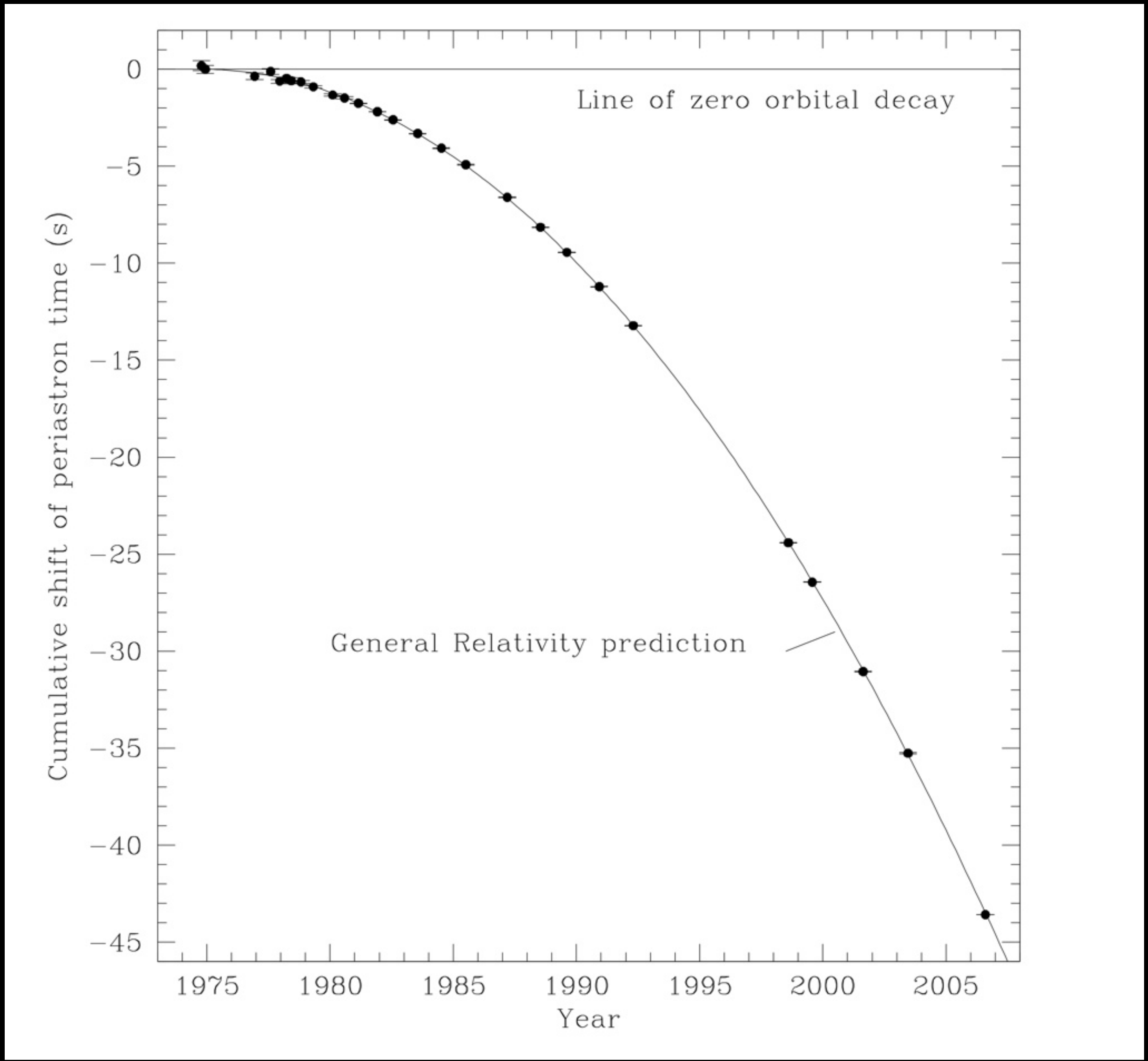


Pulsar Timing

TOA modelisation
«Indirect Detection»

Pulsar B1913+16
«Hulse-Taylor Pulsar»

Physics Nobel Prize
1993



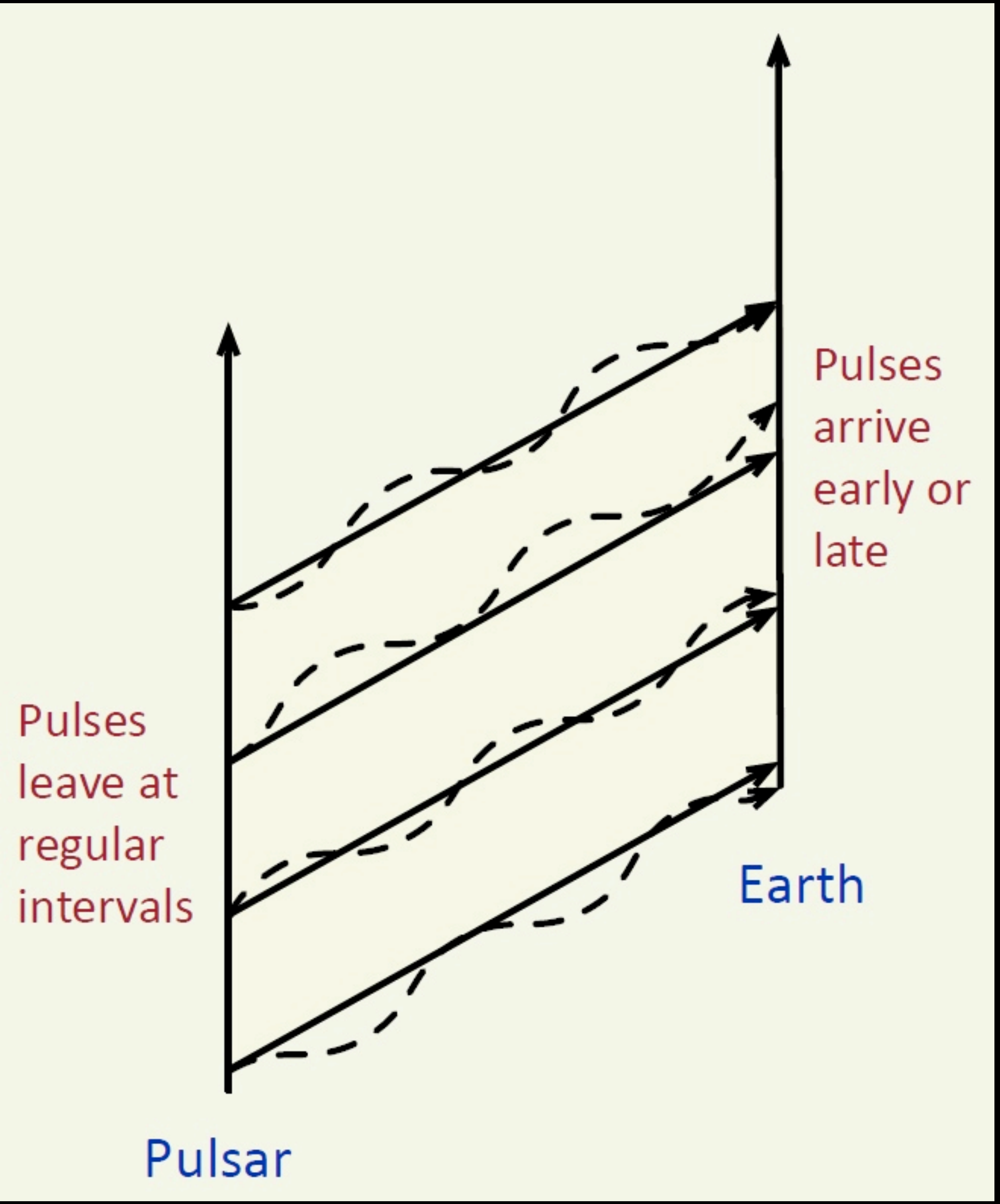
Gravitational Waves Detection

A GW modifies the path of the EM waves from the pulsar to the observatory

$$r(t) = \int_0^t \frac{\nu(t') - \nu_0}{\nu_0} dt'$$

$$\frac{\nu(t) - \nu_0}{\nu_0} = \frac{1}{2} \frac{\hat{n}^i_\alpha \hat{n}^j_\alpha}{1 + \hat{n}_\alpha \cdot \hat{k}} \Delta h_{ij}$$

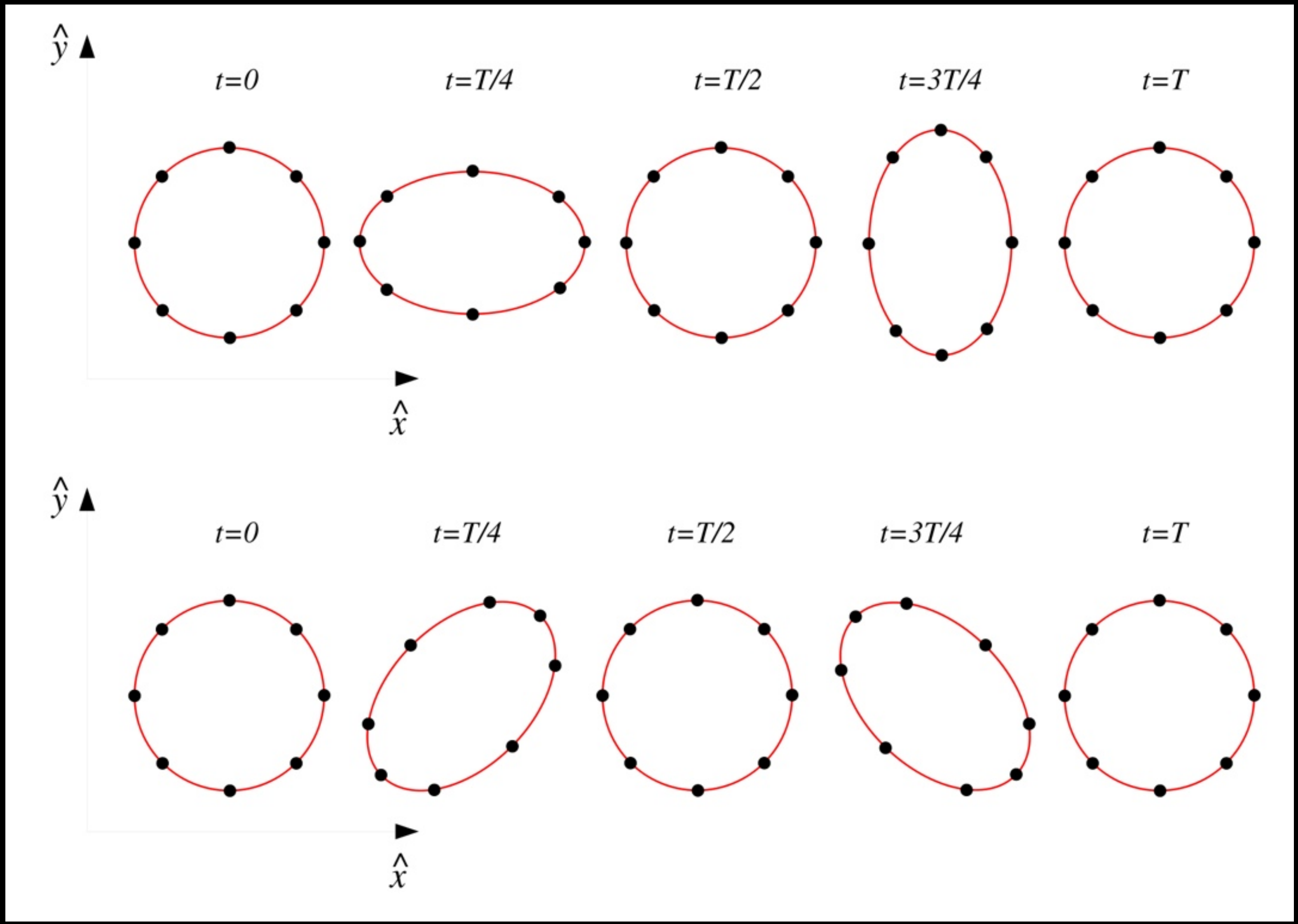
$$\Delta h_{ij} = h_{ij}(t_p) - h_{ij}(t)$$



Gravitational Waves Detection

h_+

$h_\times$



Two independant polarizations

Gravitational Waves Detection

For a single pulsar, the effect cannot be separated from intrinsic parameters

Need an array of pulsars to correlate the effect between them.

Observation of multiple pulsars over several years (10 yr)

Sensitive to nanoHertz band

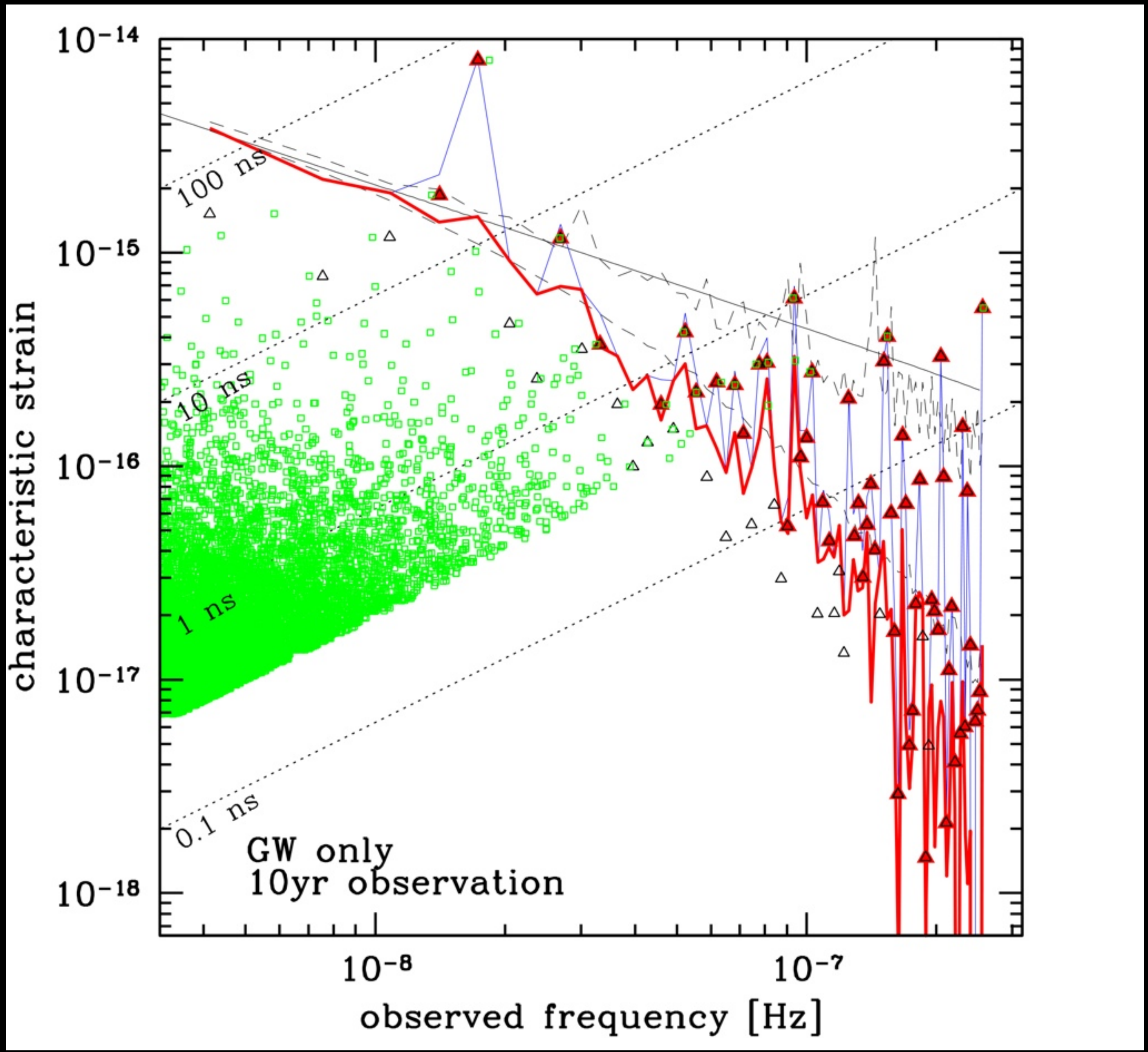
Gravitational Waves Detection

Super-Massive Black Holes Binaries (SMBHB) are expected to emit at those frequencies.

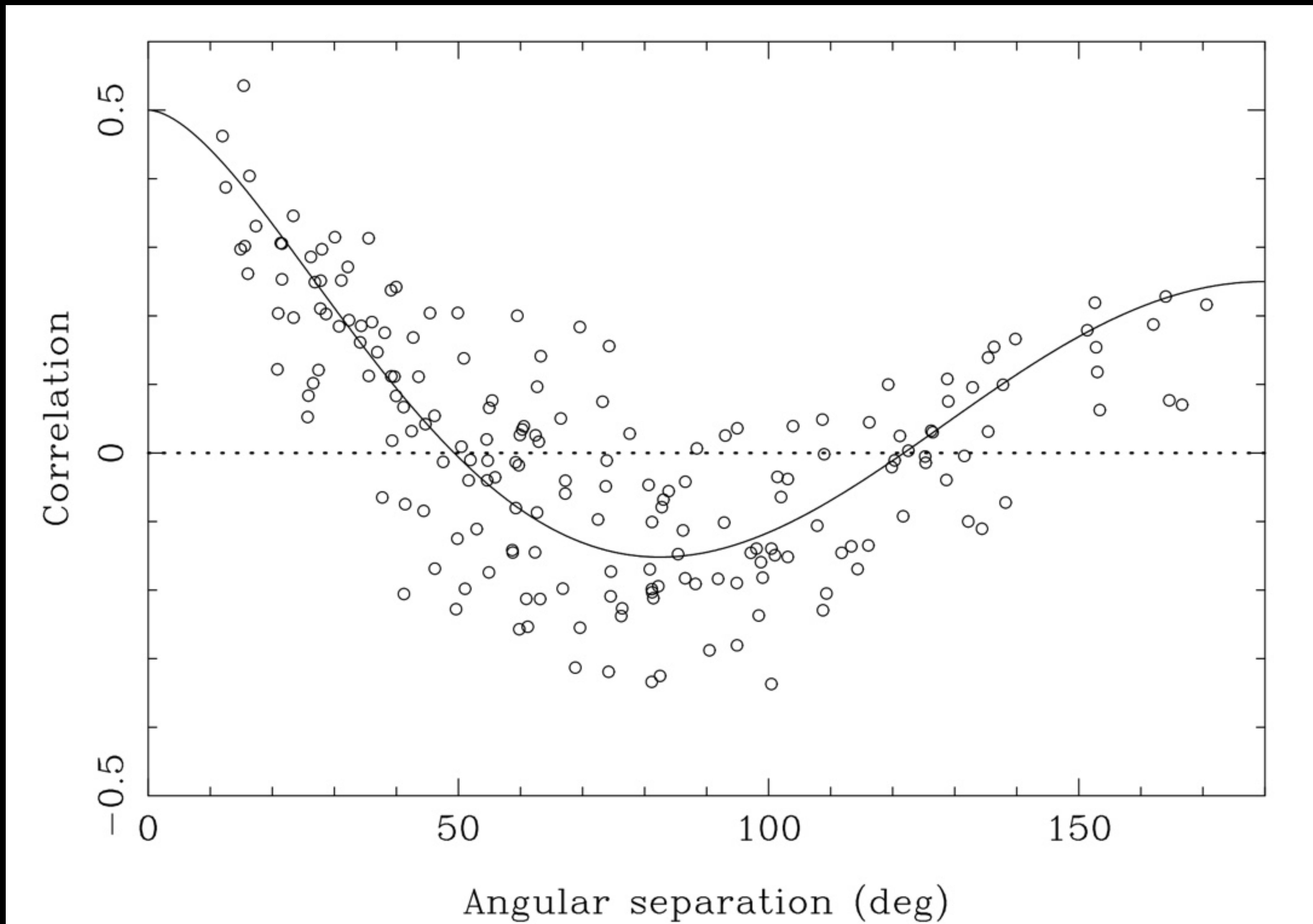
-Isotropic GW background

$$h_c(f) = A \left(\frac{f}{f_0} \right)^{-2/3}$$

-Single sources above the background

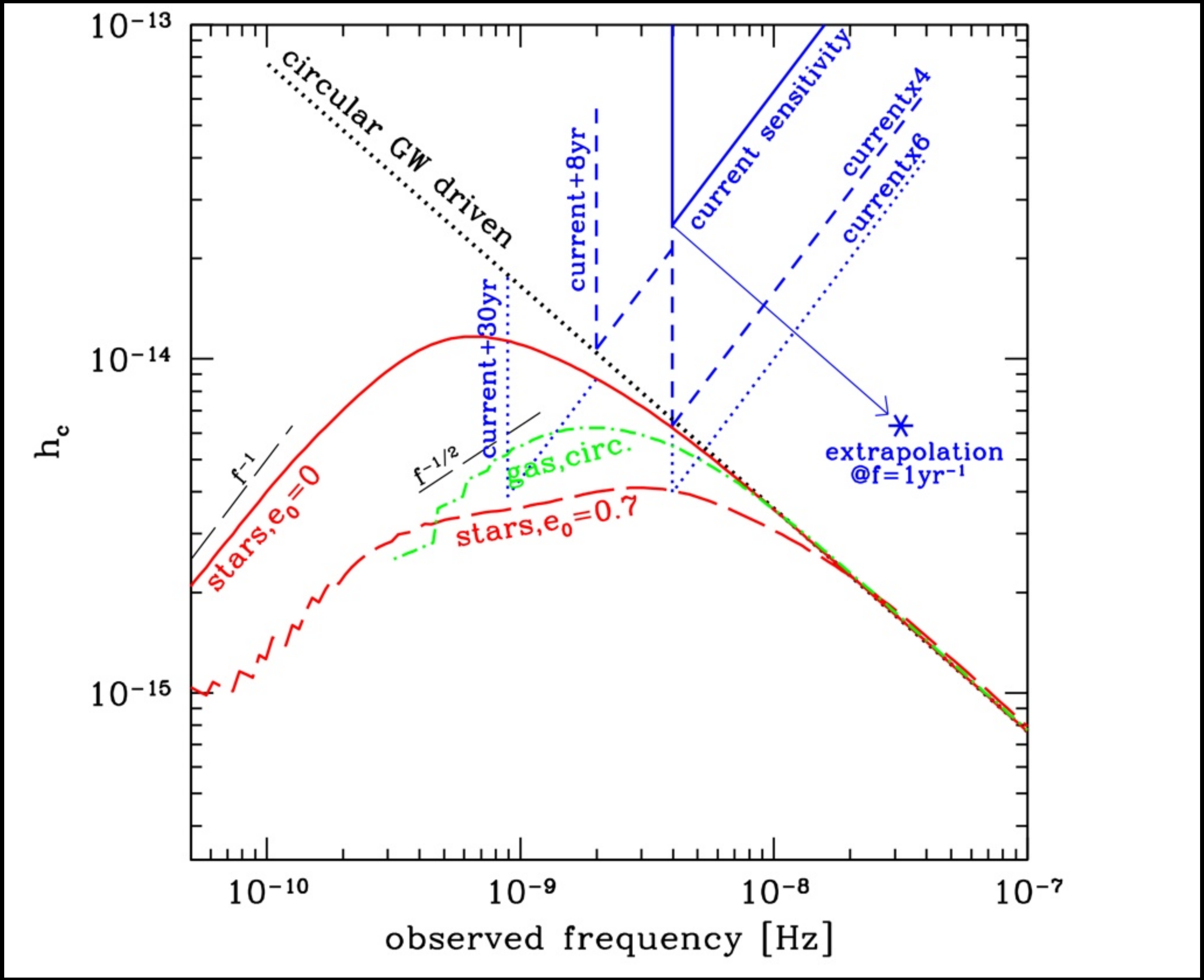


Gravitational Waves Detection



Correlated Red Noise between pulsars

Gravitational Waves Detection



Gravitational Waves Detection

Single Source

Evolution over the timespan of the observation negligeable

Presence of two monochromatic signals : Earth & Pulsar terms

$$\Delta h_{ij} = h_{ij}(t_p) - h_{ij}(t)$$

$$\begin{aligned} h_+(t) &= A(1+\cos^2 i)\cos(2\pi f t + \phi_0) \\ h_\times(t) &= -2A\cos i \sin(2\pi f t + \phi_0) \end{aligned}$$

$$A = \frac{2\mathcal{M}_c^{5/3}}{D_L}(\pi f)^{2/3} \qquad \mathcal{M}_c = \frac{(m_a m_b)^{3/5}}{m_{tot}^{1/3}}$$

Gravitational Waves Detection

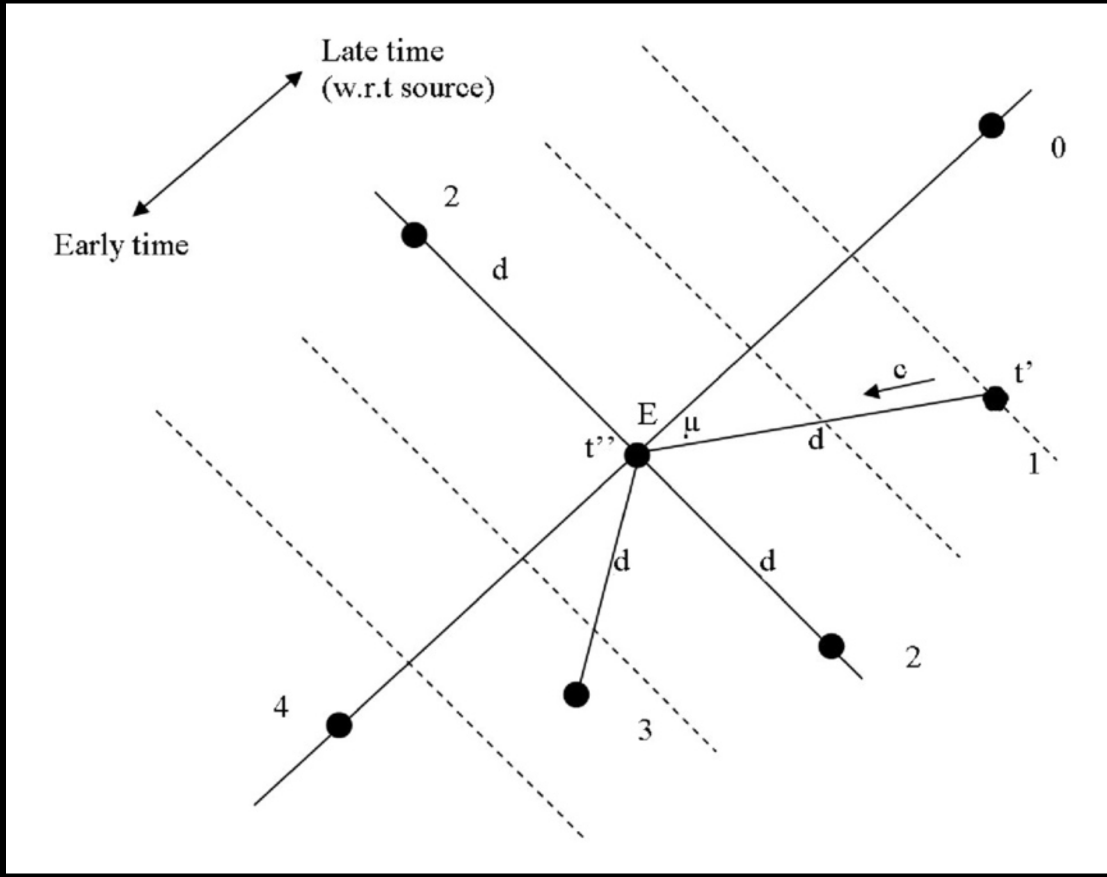
Single Source

Earth term is coherent between pulsars : epoch of the observation

Pulsar term incoherent : epoch of the pulse emission

$$\Delta f_\alpha \approx 15 \left(\frac{\mathcal{M}_c}{10^{8.5}\mathrm{M}_\odot}\right)^{5/3} \left(\frac{f}{50\mathrm{nHz}}\right)^{11/3} \tau_{\alpha,1} \quad \mathrm{nHz}$$

$$\tau_\alpha = 1.1 \times 10^{11} \left(\frac{L_\alpha}{1\mathrm{kpc}}\right)(1 + \hat{n}_\alpha \cdot \hat{k}) \quad \mathrm{s}$$



The Pulsar Timing Array Community

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European Pulsar Timing Array (EPTA)

Jodrell Bank (UK), 74m
Westerbork (Neartherland), 93m (eff)
Nançay (France), 94m (eff)
Effelsberg (Germany), 100m
SRT (Sardinia, Italy), 64m

60 MSPs observed every 2-3 weeks

LEAP : simulateous observations
from all observatories
194m equivalent dish

The Pulsar Timing Array Community

Parkes Pulsar Timing Array (PPTA)

Parkes RadioTelescope (Australia), 64m

20 MSPs every 2-3 weeks

The Pulsar Timing Array Community

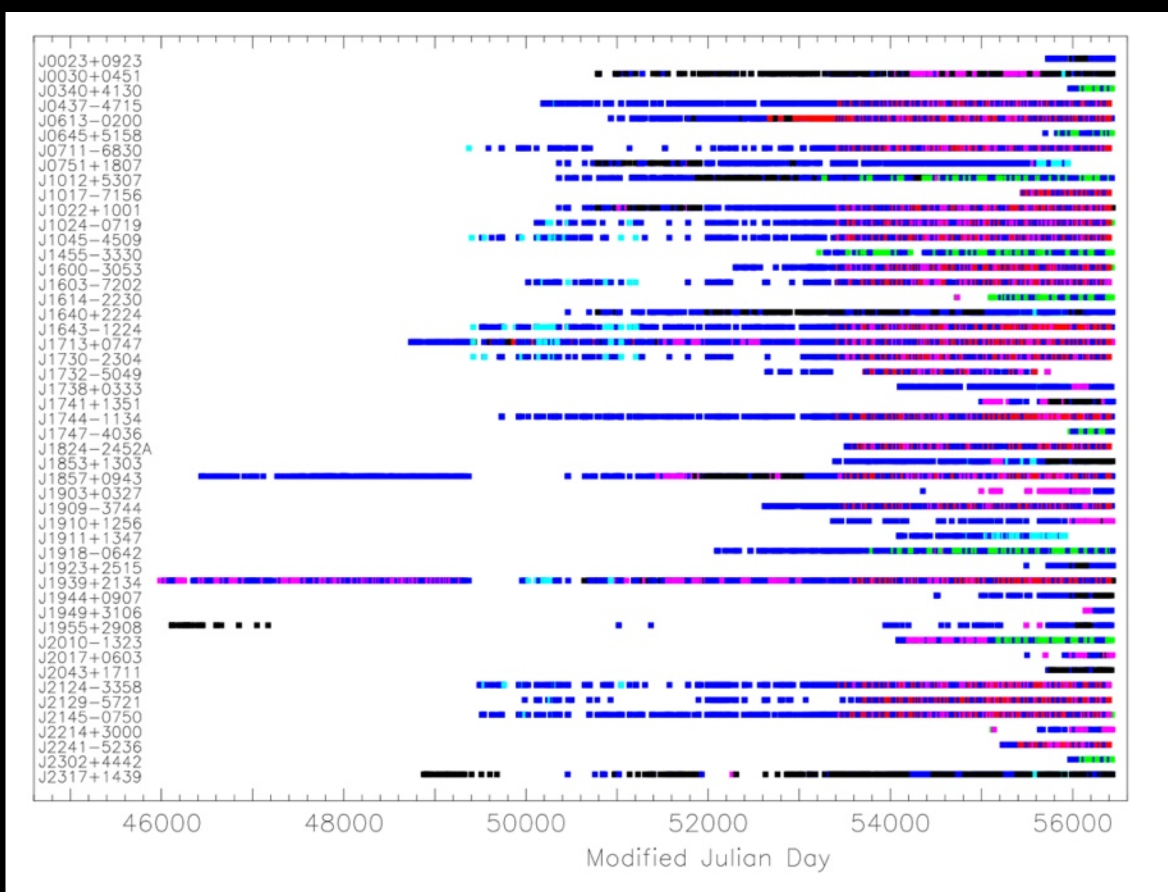
North American NanoHertz Observatory for GW (NANOGrav)

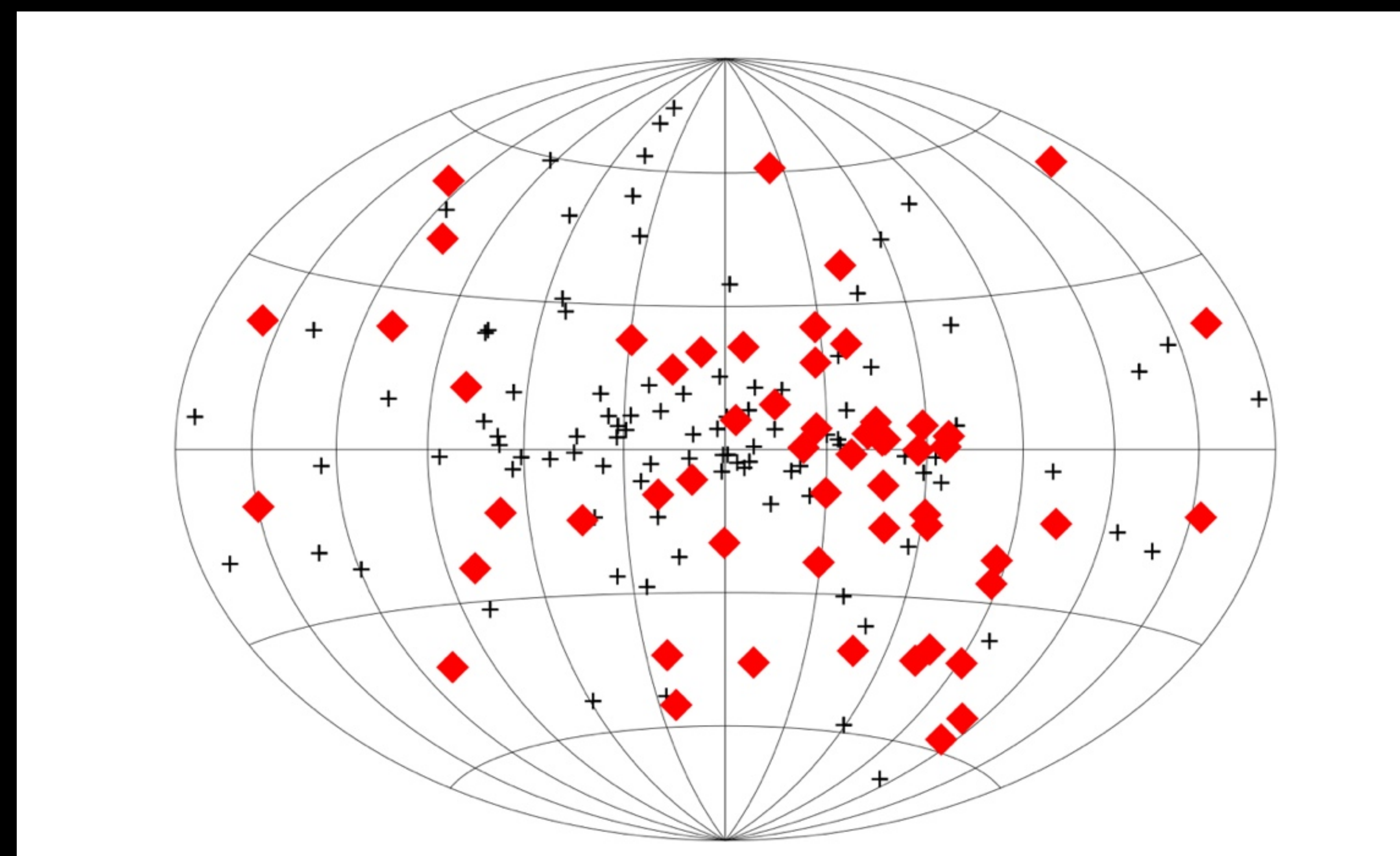
Green Bank (USA), 100m
Arecibo (Puerto Rico), 300m

43 MSPs every 3 weeks

The Pulsar Timing Array Community

All three form the International Pulsar Timing Array (IPTA)

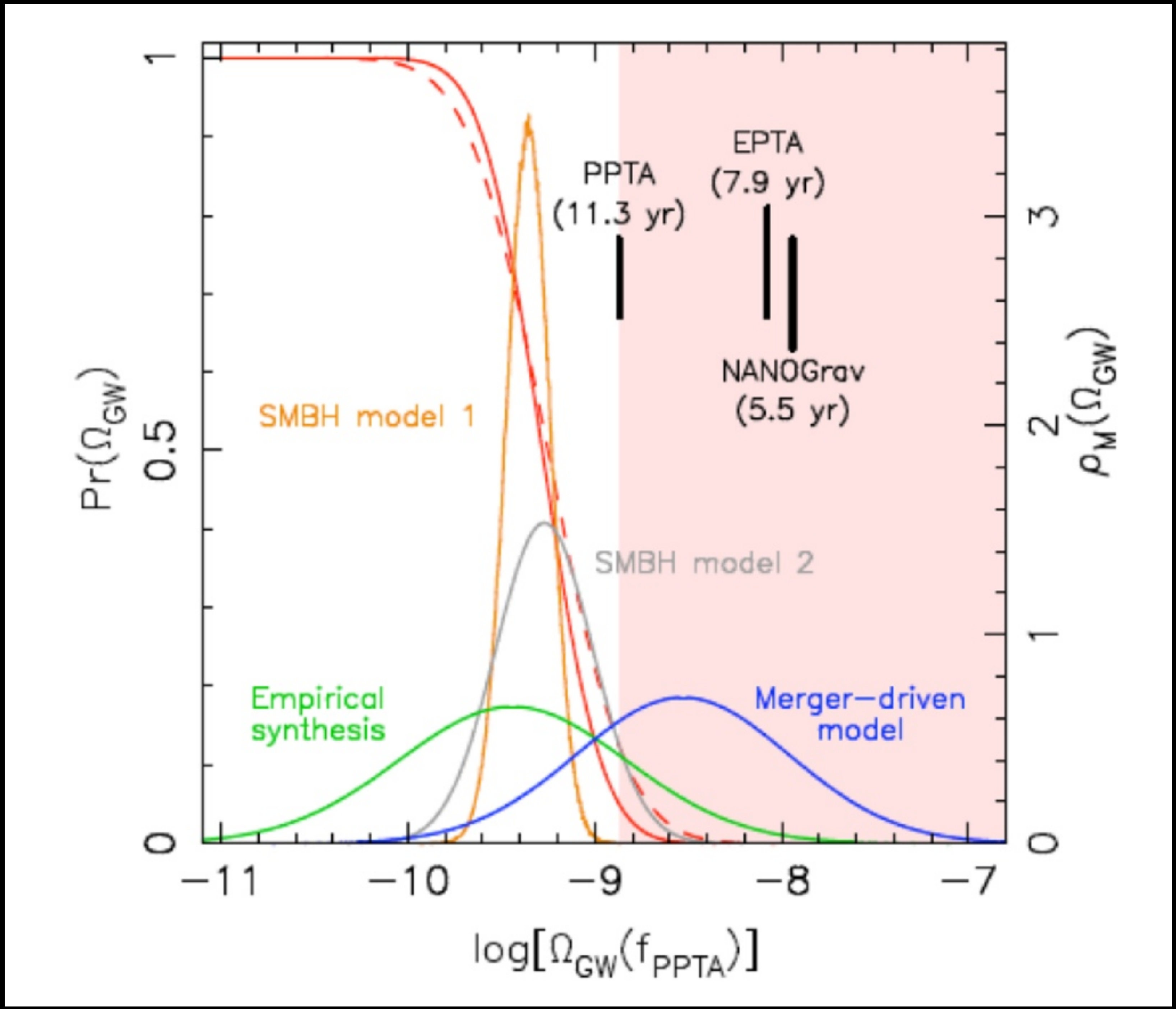




49 MSPs all over the sky

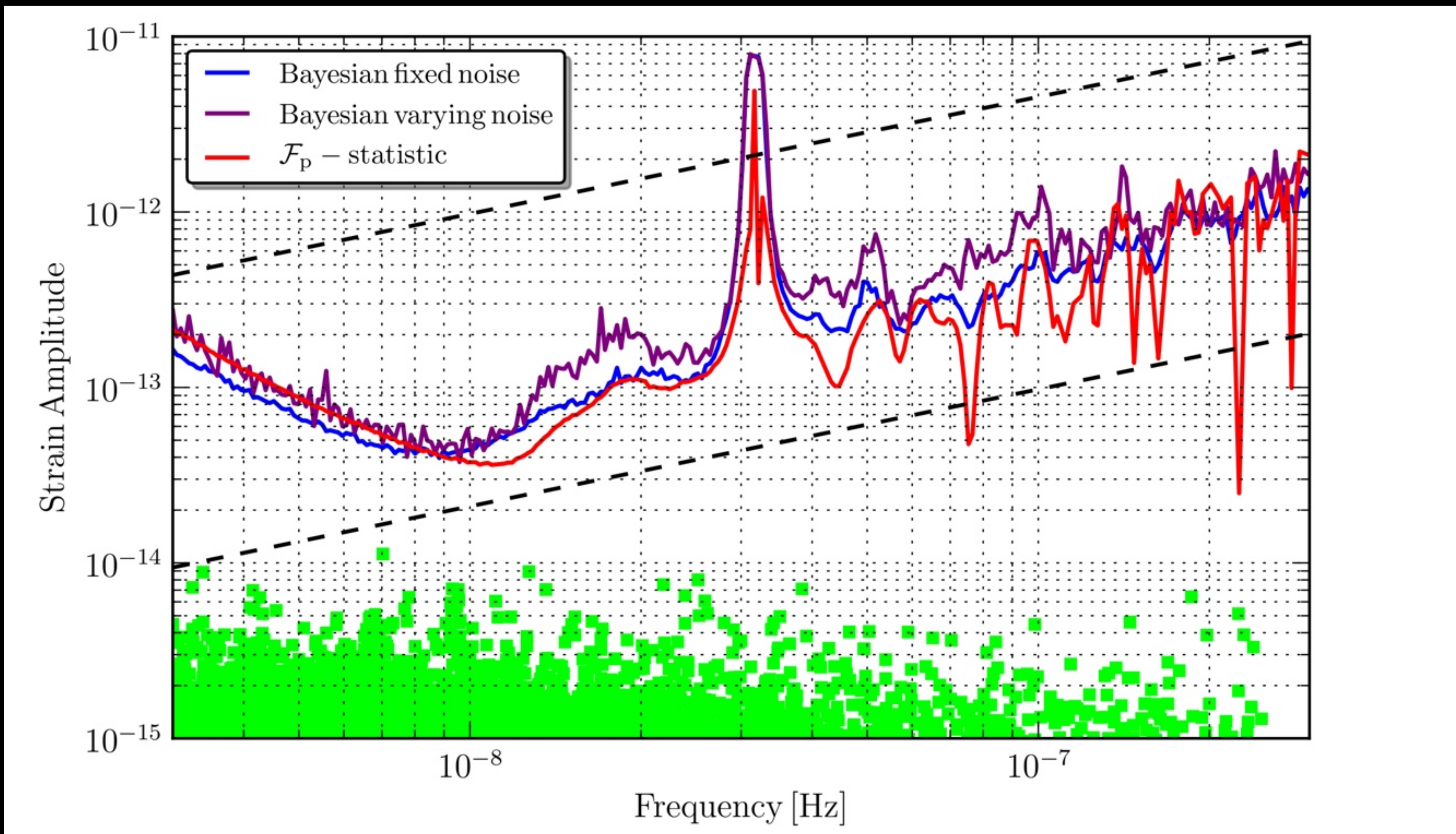
The Pulsar Timing Array Community

Current Limits on the isotropic GWB



The Pulsar Timing Array Community

Current Limits on continuous source (NANOGrav)



How to do better ?

$$h_{c,min} \propto \frac{\sigma_{rms}}{T\sqrt{N_{TOA}N_{PSR}}}$$

Increase timespan

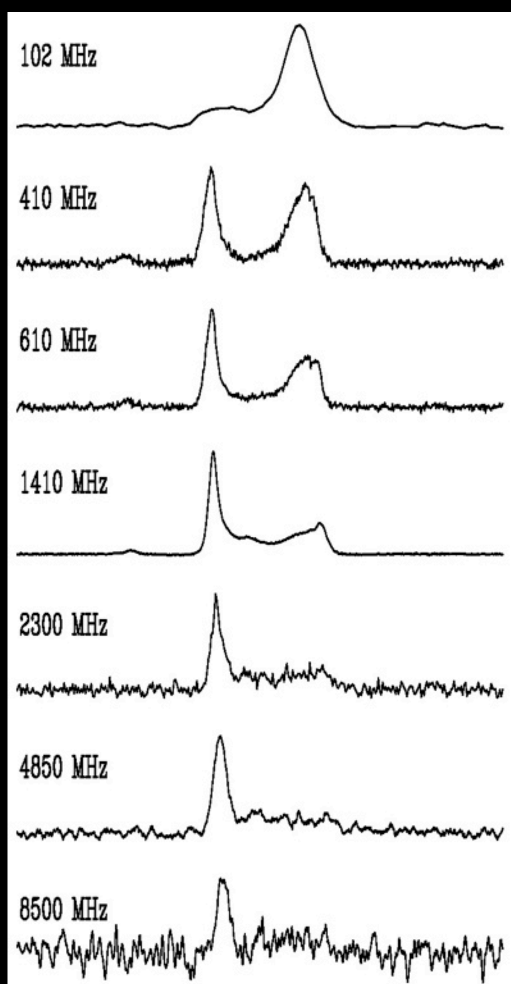
Increase cadence of observations

Increase number of pulsars in the array

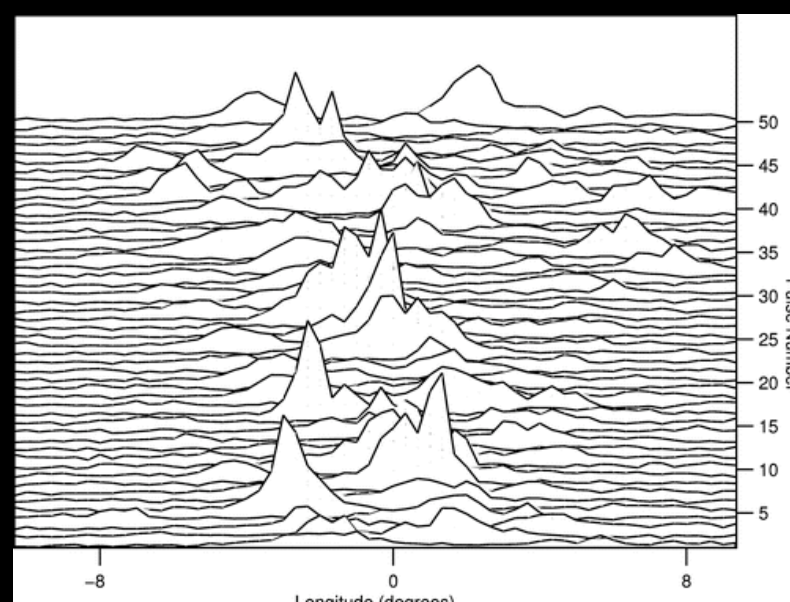
Better understanding of the intrinsic & extrinsic noises

How to do better ?

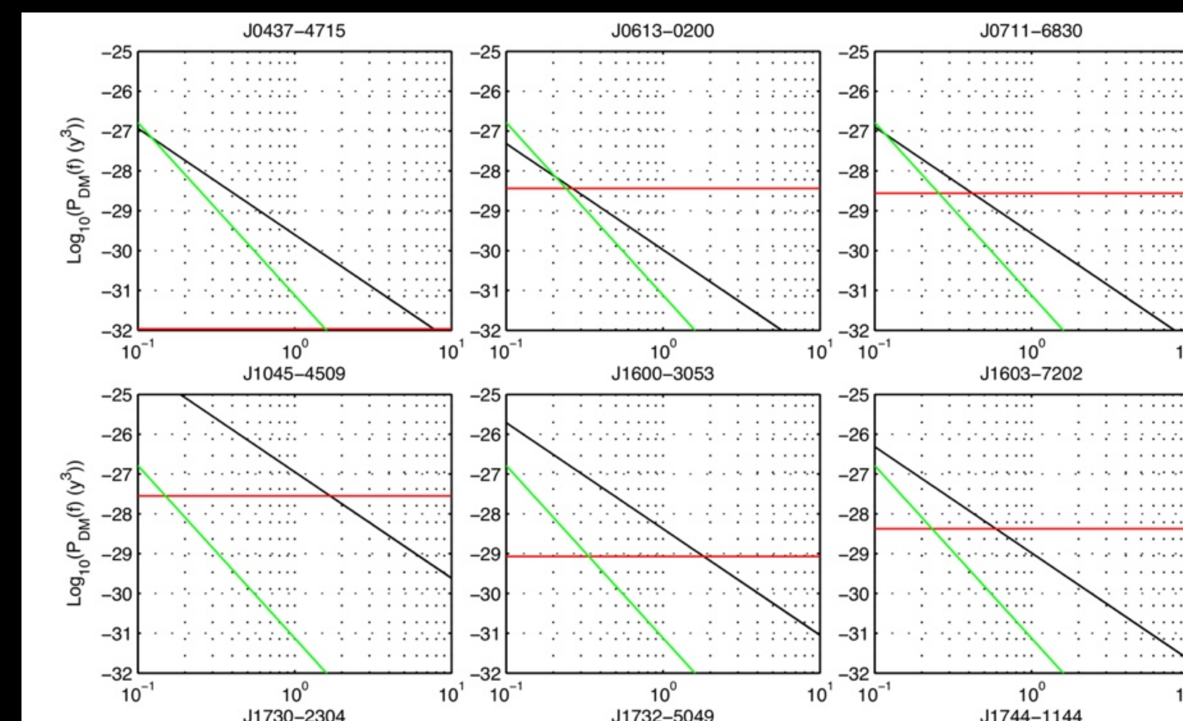
Better understanding of the intrinsic & extrinsic noises



Profile variation with frequency



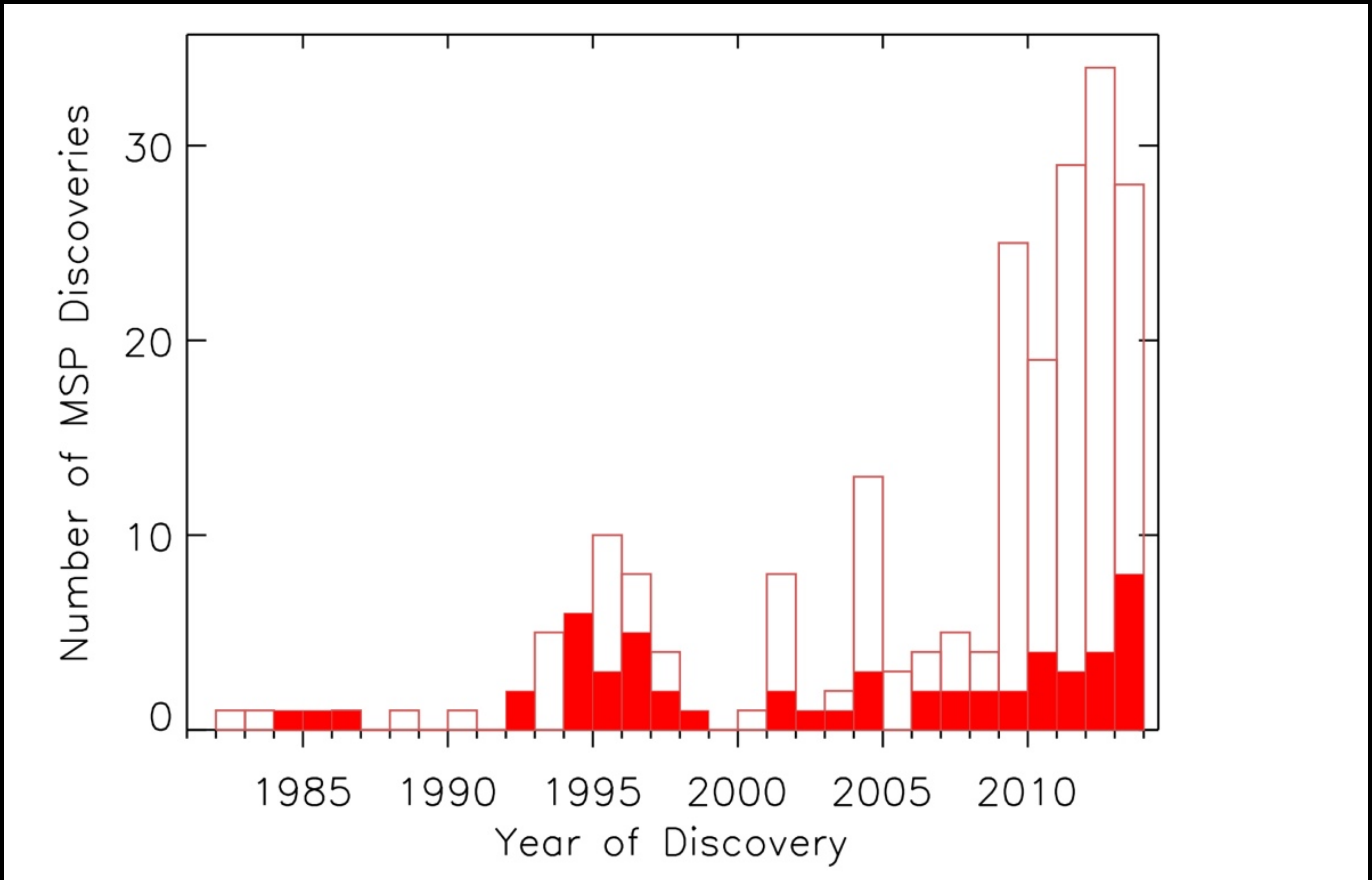
Scattering and profile variation with time



Presence of white and red noise
(DM variation, unknown intrinsic effects)

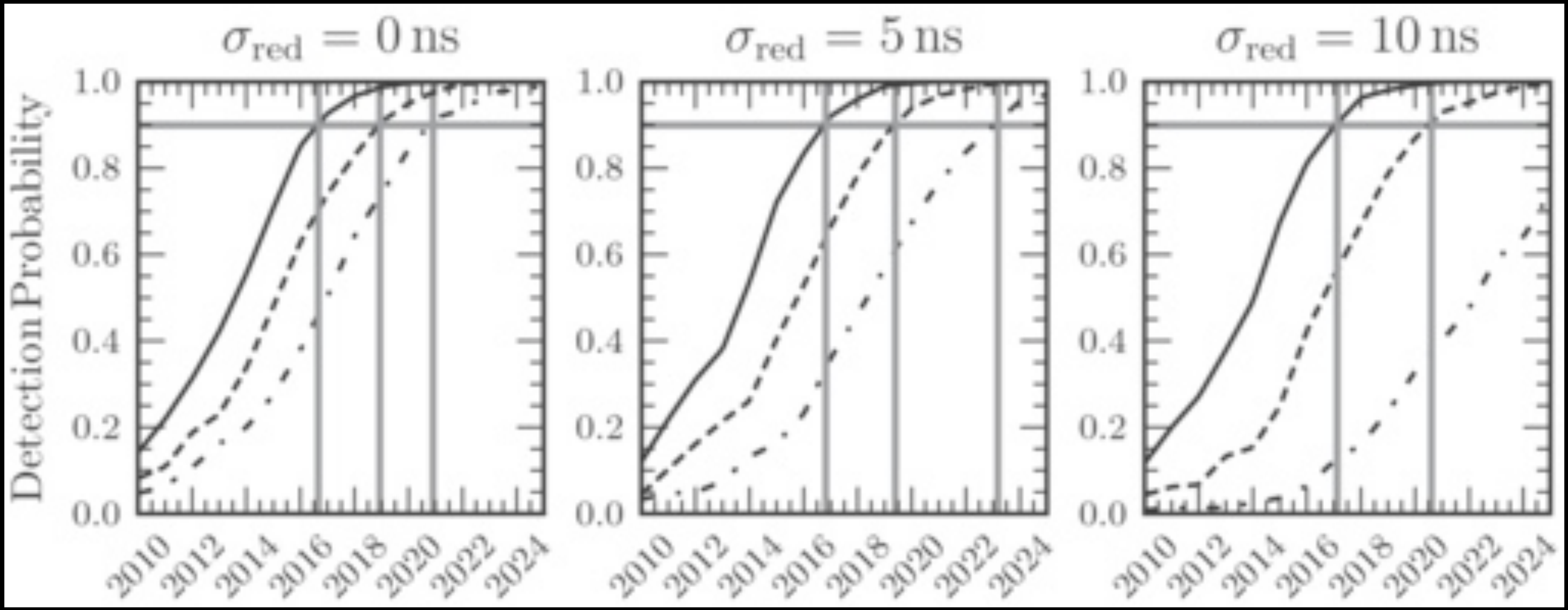
How to do better ?

Finding new pulsars

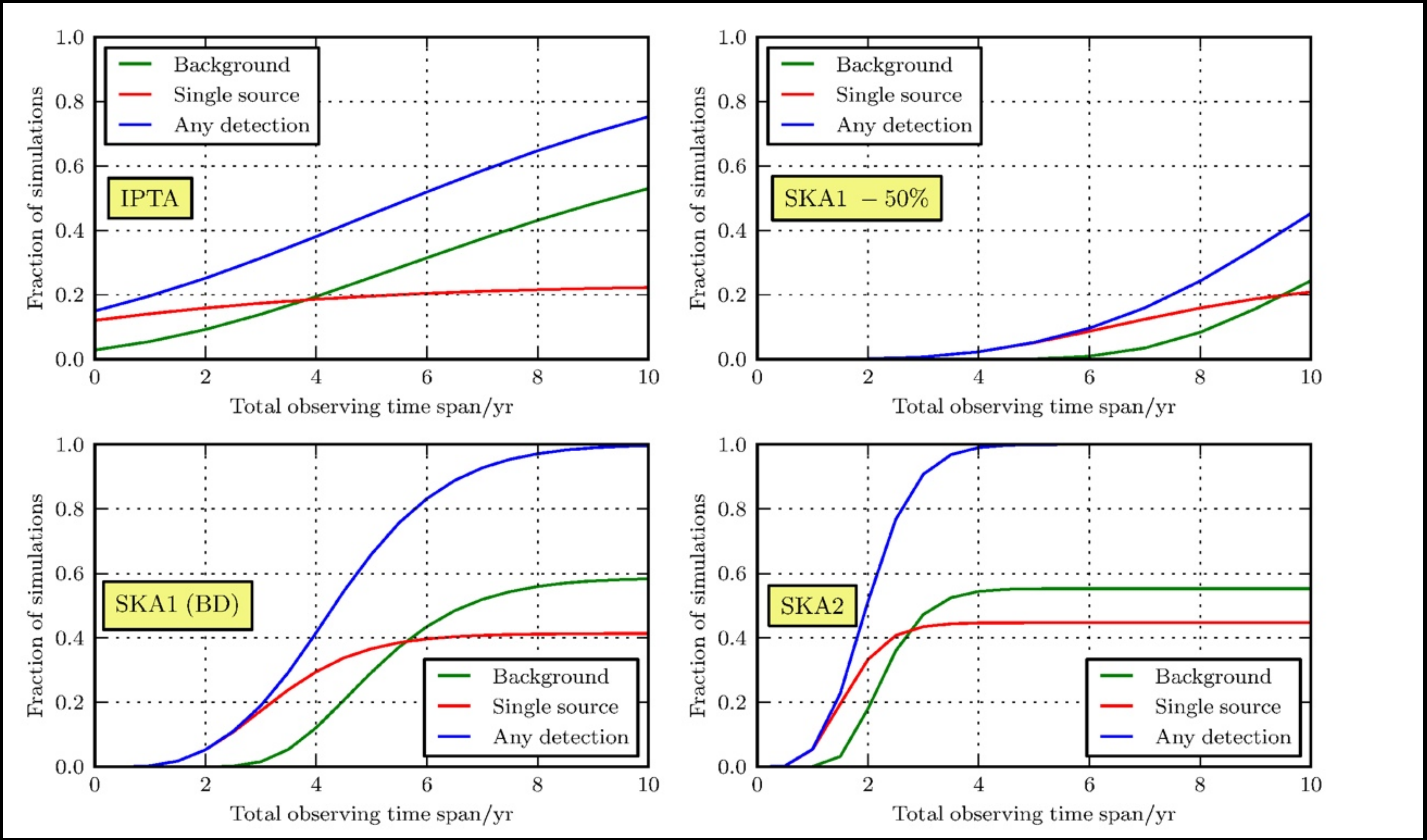


How to do better ?

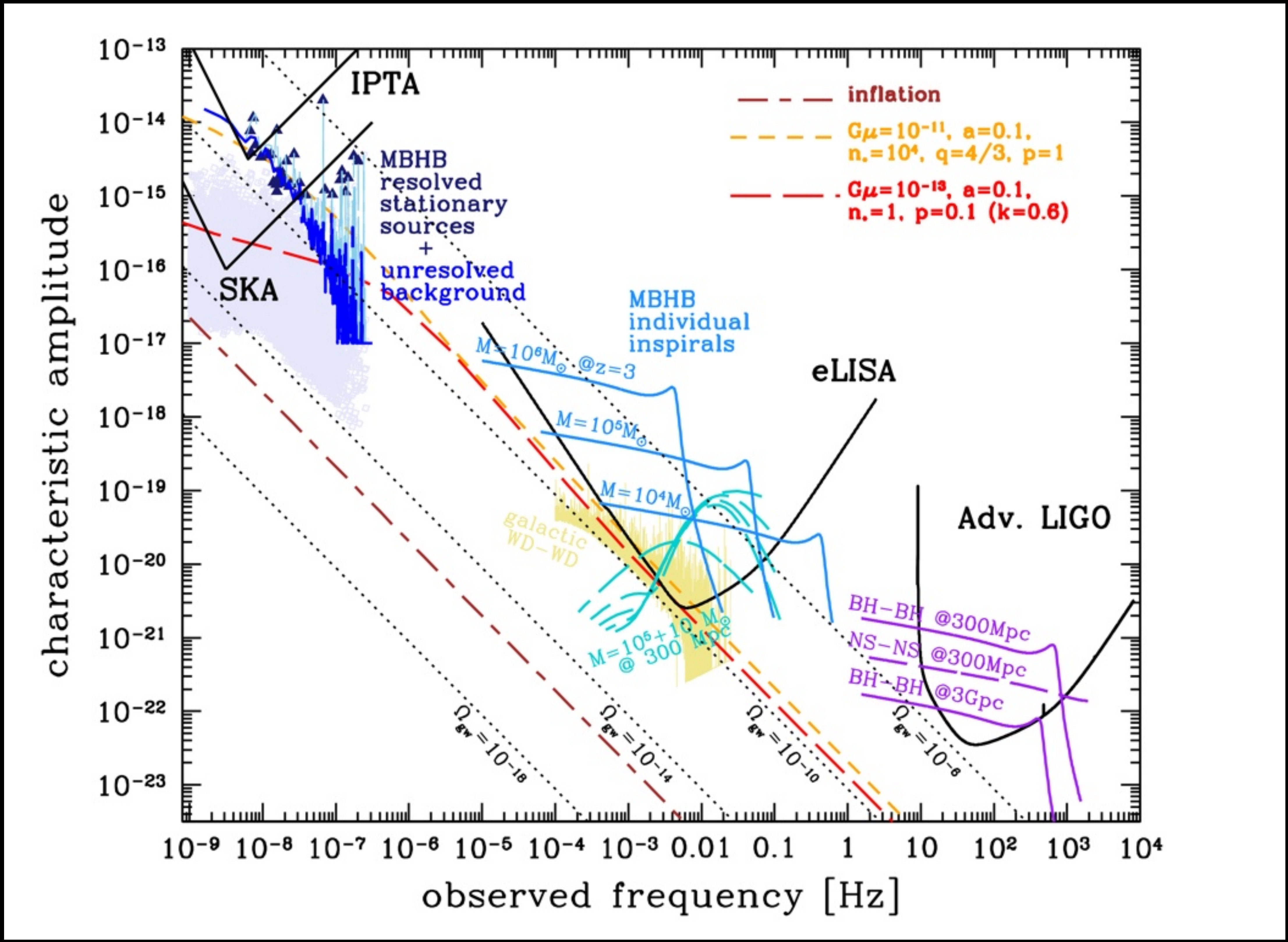
Finding new pulsars

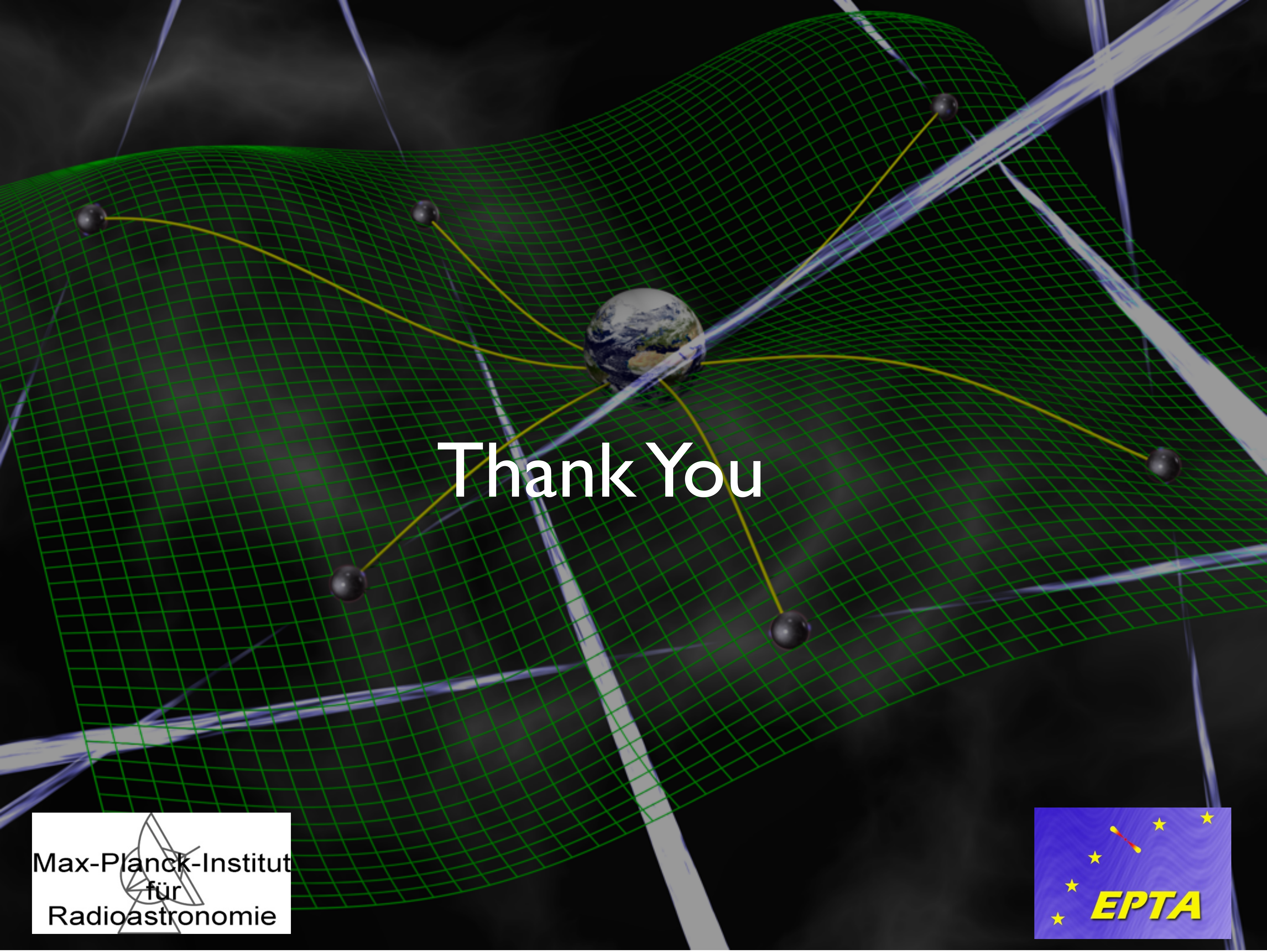


Perspectives



Perspectives




Thank You
Max-Planck-Institut
für
Radioastronomie
EPTA