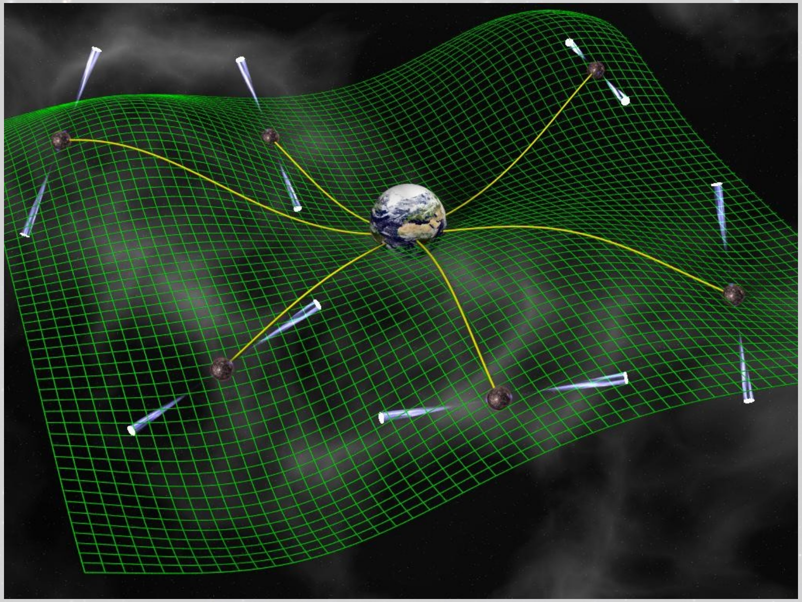
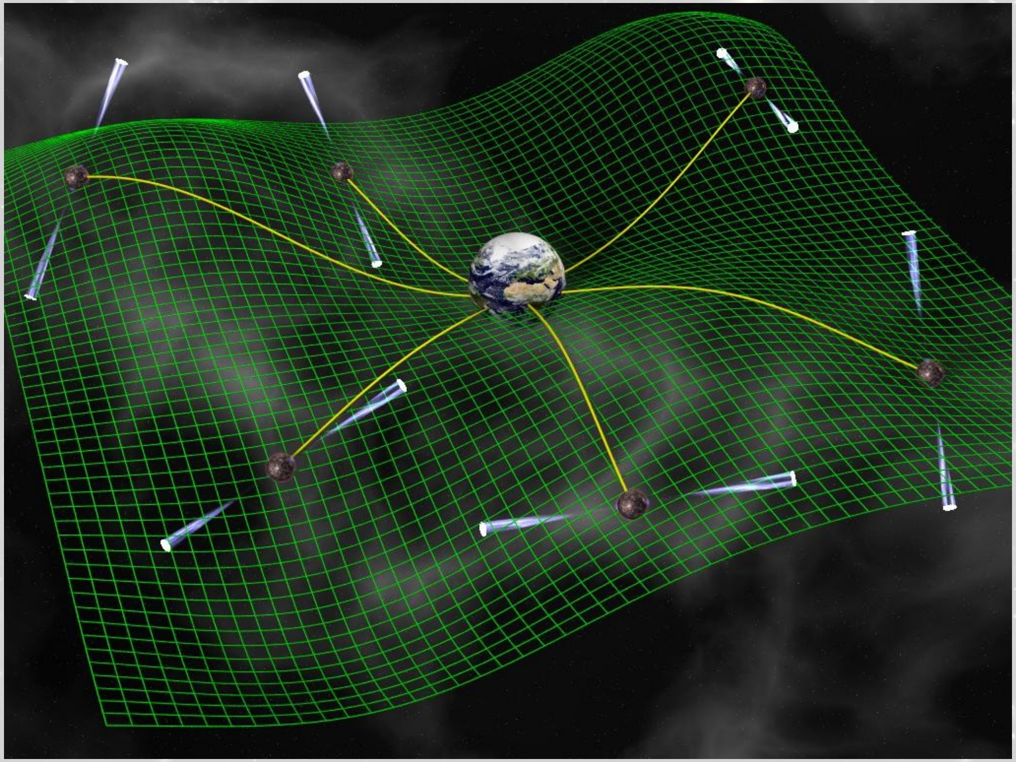
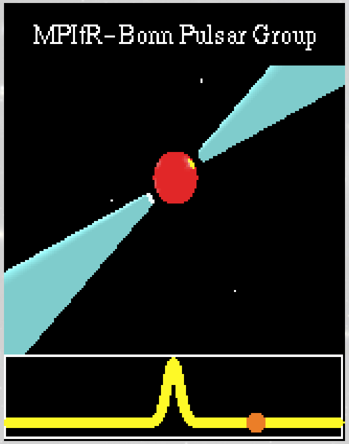
Pulsar Timing Arrays



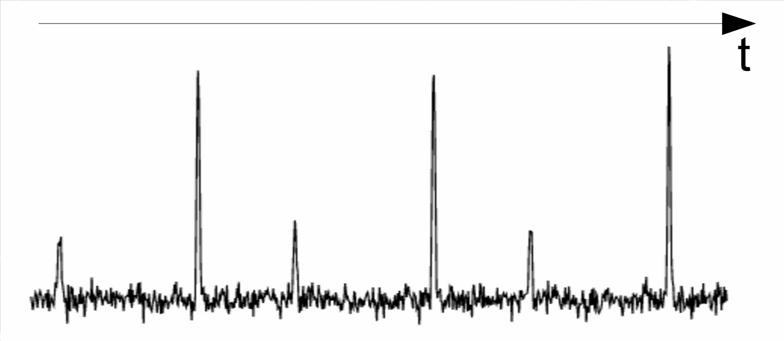
Gphys, May 2014, Observatoire de Paris
G.Theureau

Pulsar Timing Arrays : principles





Millisecond pulsars
Considered as quasi perfect clocks



Earth and distant PSR treated as free masses whose positions respond to changes in the local space time metric

→ *A passing GW perturbs the metric and produces fluctuations in the measured TOAs*

If uncertainty dt and length of data span T

→ *sensitive to amplitude dt/T and frequencies f ~ 1/T*

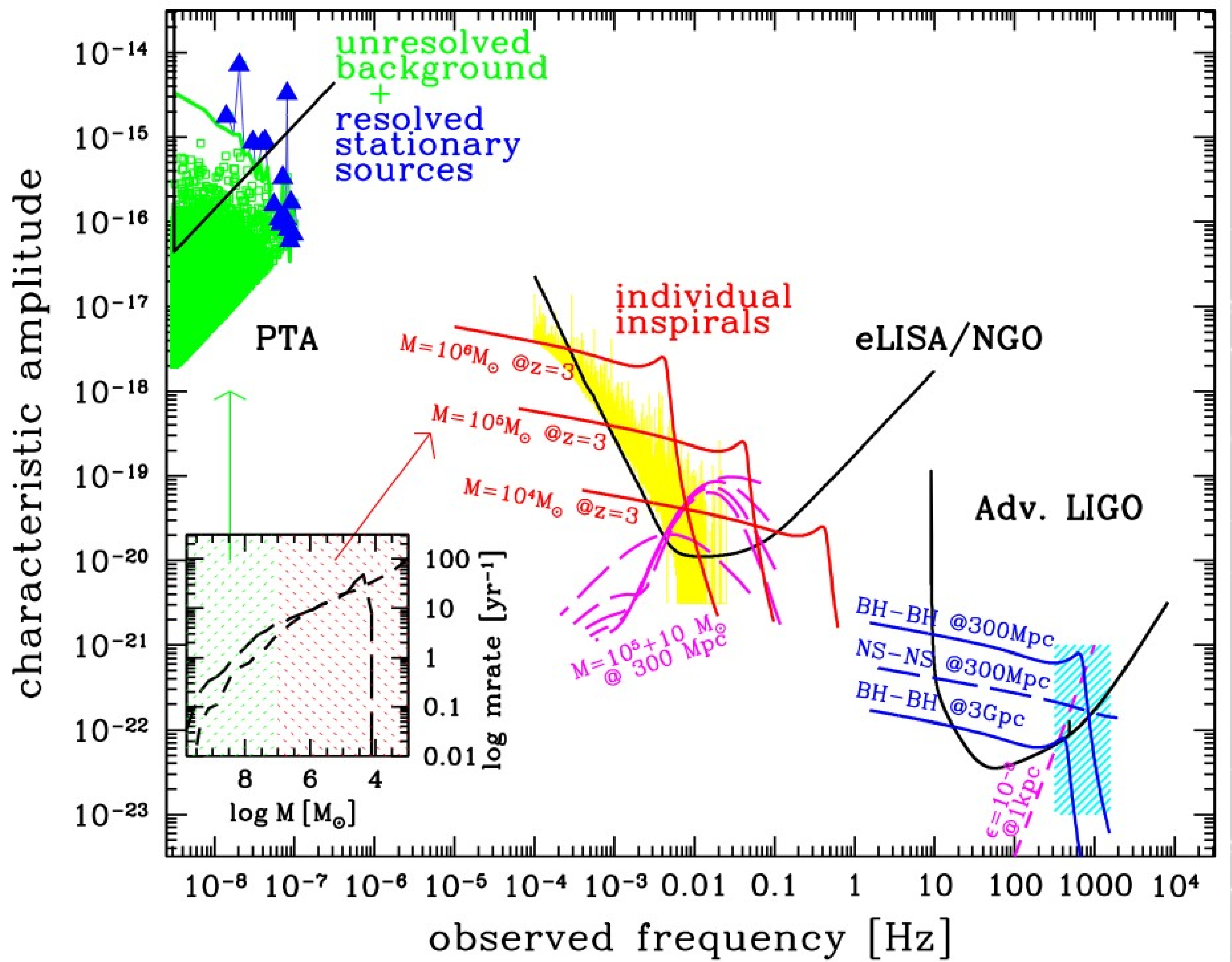
Frequency domain → 10^{-9} – 10^{-7} Hz

Gravitational waves background :

The nanoHertz regime

- Super massive binary black holes
- Cosmic string loops
- Relics of inflation

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



Model	A	α	References
Supermassive black holes	$10^{-15} - 10^{-14}$	$-2/3$	Jaffe & Backer (2003)
			Wyithe & Loeb (2003)
			Enoki et al. (2004)
Relic GWs	$10^{-17} - 10^{-15}$	$-1 - -0.8$	Grishchuk (2005)
Cosmic String	$10^{-16} - 10^{-14}$	$-7/6$	Maggiore (2000)

Super Massive Binary Black Holes

Population models

Binary formation

↓

monochromatic

↓

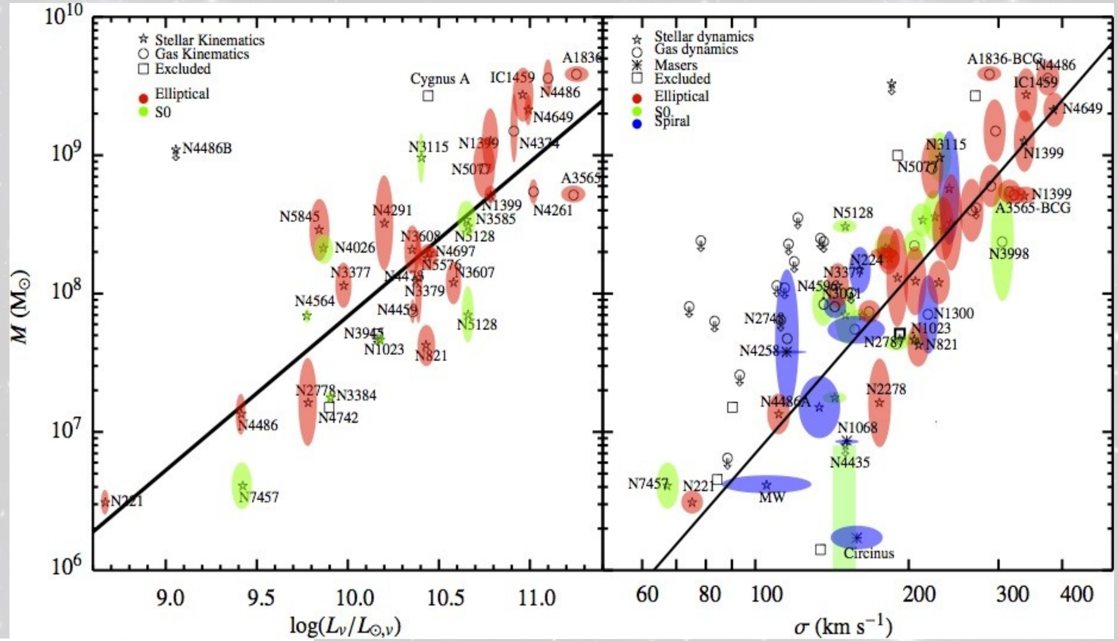
inspiralling

↓

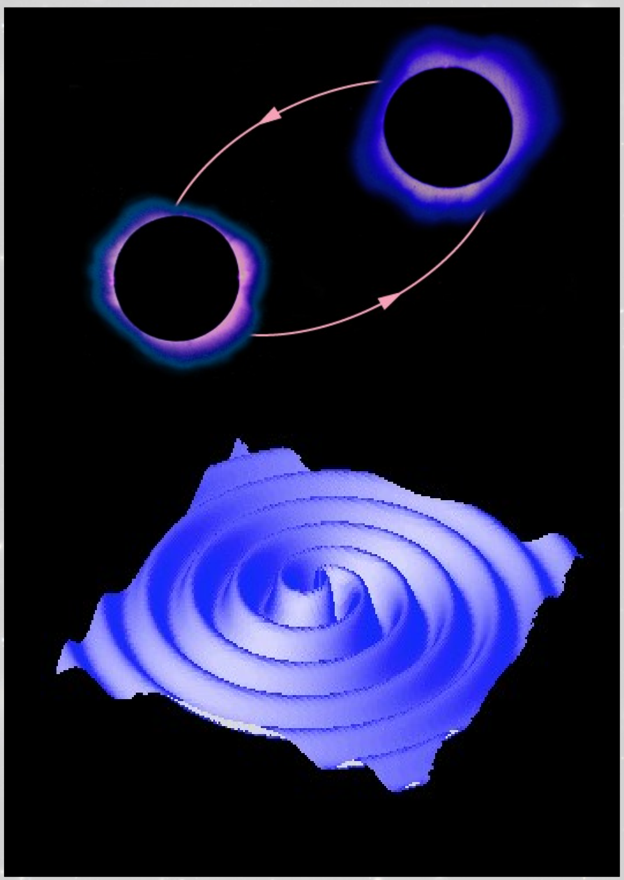
merging/burst

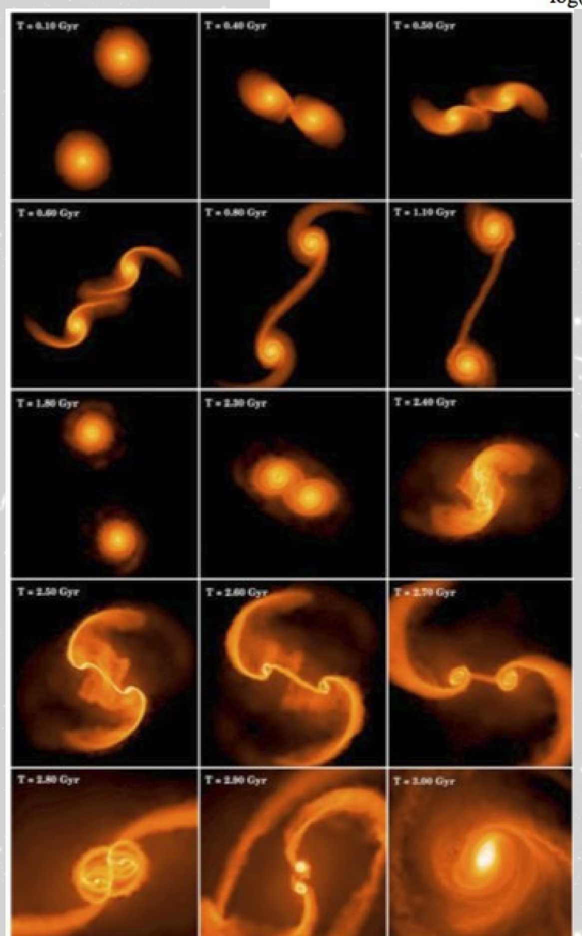
$M_{BH} > 10^7 M_\odot$

Distance z < 2



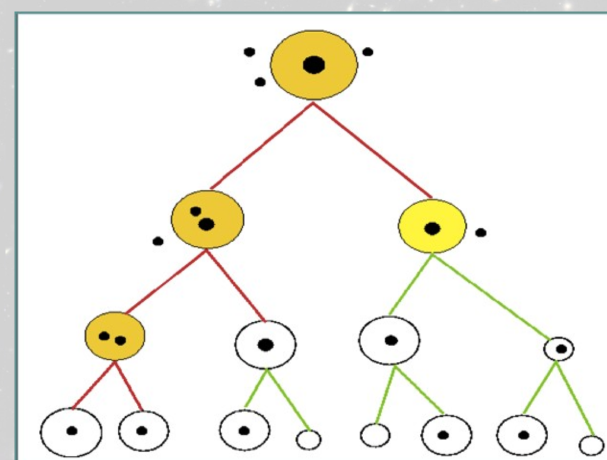
BH vs bulge mass
Gultekin 2009





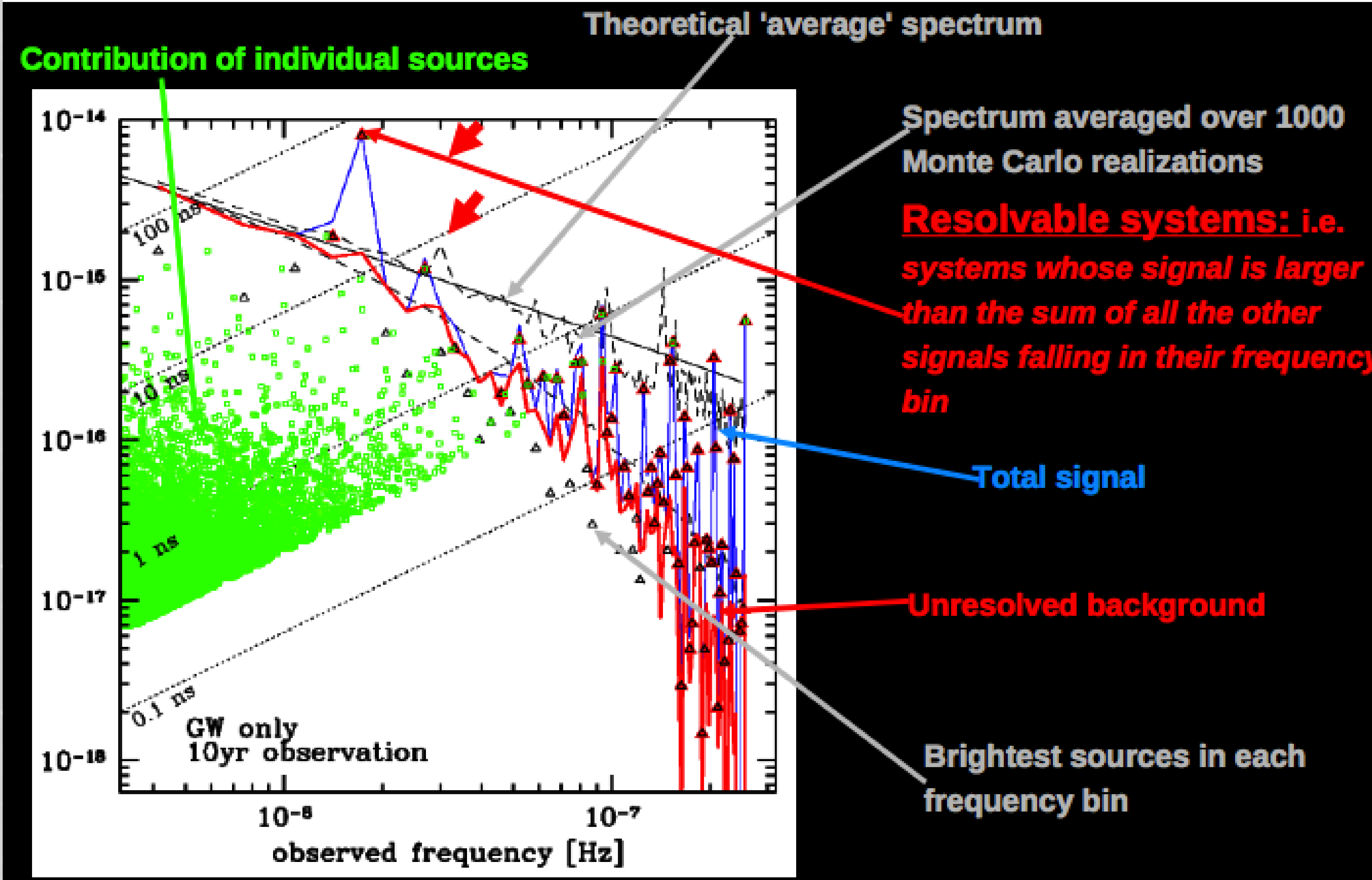
Colpi & Dotti (2009)

Hierarchical scenario of galaxies formation



Volonteri Haardt Madau 2003

SMBBH population : background contribution & single sources



Sesana (2013b)

Pessimistic Scenarii

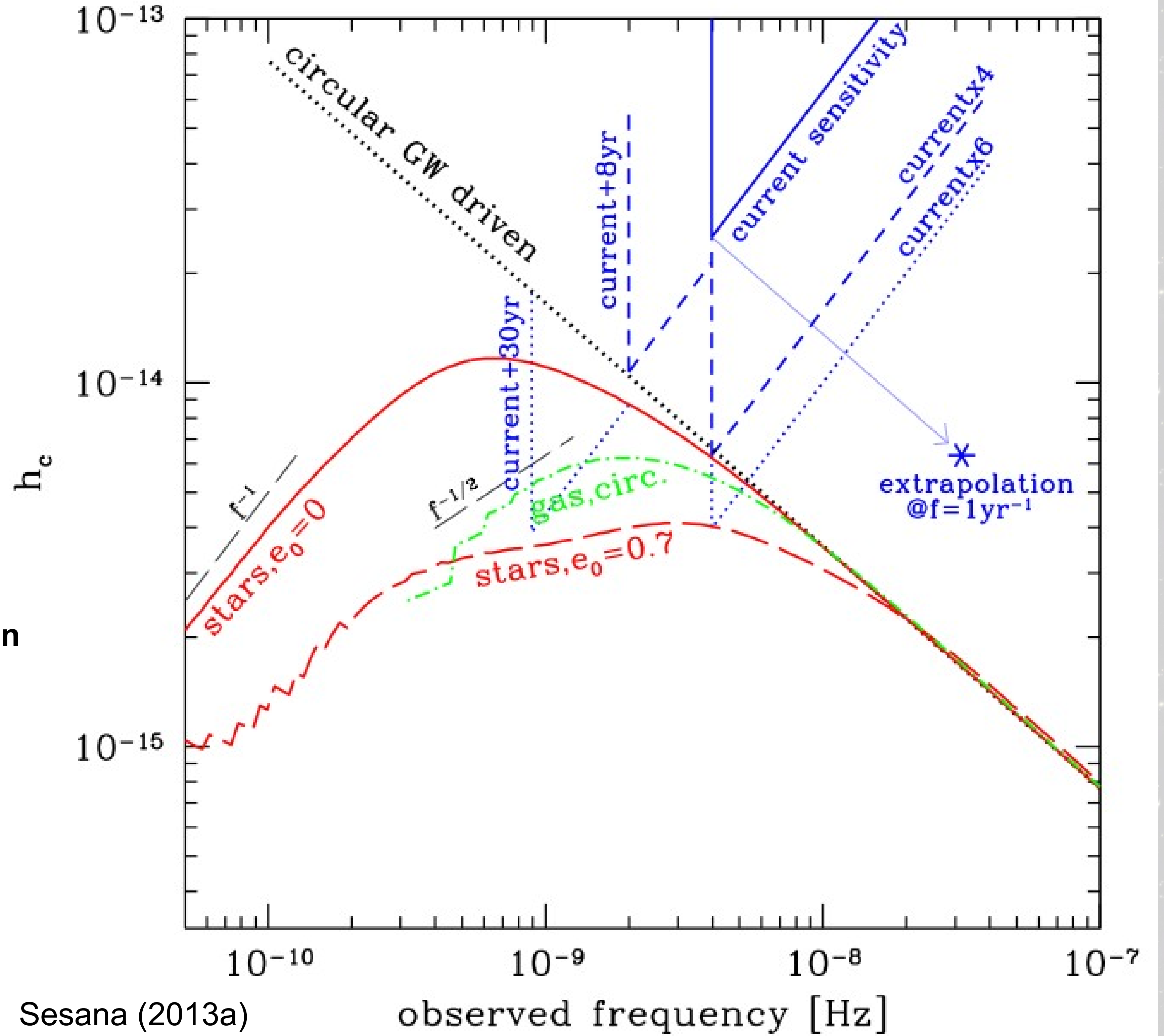
Contribution of accretion discs

+

Spin orientation

Excentricity

Which evolution time scales ?



Sesana (2013a)

Earth term & pulsar term

- n : direction of the pulsar
- L : distance Earth – pulsar
- k : direction of the GW propagation
- h_{ij} : GW strain

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

$$\frac{\delta\nu}{\nu}(t) = \frac{1}{2}\frac{\hat{n}^i\hat{n}^j}{1+\hat{n}.\hat{k}}\left(h_{ij}(t - L(1+\hat{k}.\hat{n})) - h_{ij}(t)\right)$$

Strain of GW at the pulsar

Strain of GW at the Earth

$$r^e_\alpha(t) = \frac{\mathcal{A}}{2\pi f}\{(1+\cos^2\iota)F^+_\alpha\left[\sin(\omega t+\Phi_0) - \sin\Phi_0\right] + 2\cos\iota F^\times_\alpha\left[\cos(\omega t+\Phi_0) - \cos\Phi_0\right]\},$$

$$r^p_\alpha(t) = \frac{\mathcal{A}_\alpha}{2\pi f_\alpha}\{(1+\cos^2\iota)F^+_\alpha\left[\sin(\omega_\alpha t+\Psi_\alpha+\Phi_0) - \sin(\Psi_\alpha+\Phi_0)\right] + 2\cos\iota F^\times_\alpha\left[\cos(\omega_\alpha t+\Psi_\alpha+\Phi_0) - \cos(\Psi_\alpha+\Phi_0)\right]\},$$

$$F^+_\alpha = \frac{1}{2}\frac{(\hat{n}^\alpha.\vec{p})^2 - (\hat{n}^\alpha.\vec{q})^2}{1+\hat{n}^\alpha.\hat{k}}$$

$$F^\times_\alpha = \frac{(\hat{n}^\alpha.\vec{p})(\hat{n}^\alpha.\vec{q})}{1+\hat{n}^\alpha.\hat{k}}$$

→ **4 x 2 x Nobs x Npsr + 2 x Npsr x NGW** **(Matrices 30,000 x 30,000)**

Noise analysis

White noise

EFAC, EQUAD

Red noise

Dispersion measure variations

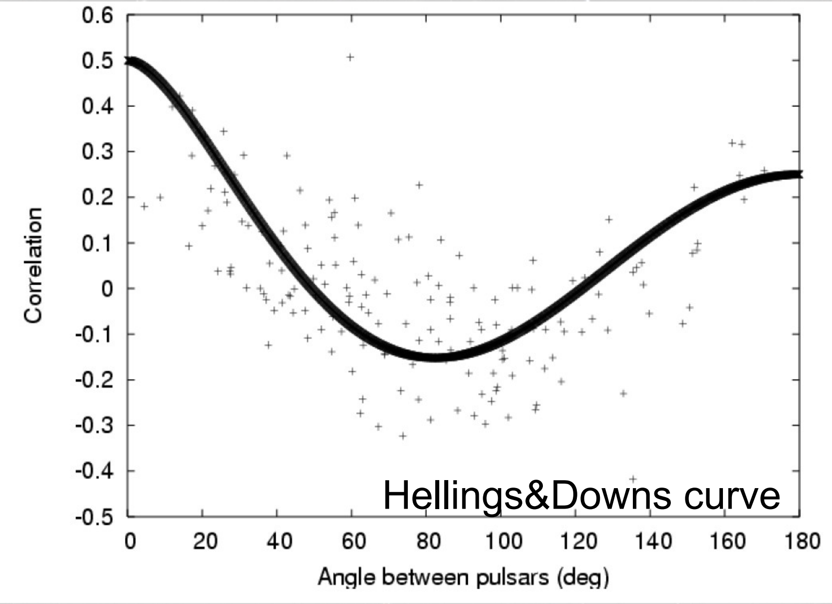
Pulse jitter, timing noise

Clock variations

Solar System ephemerides errors

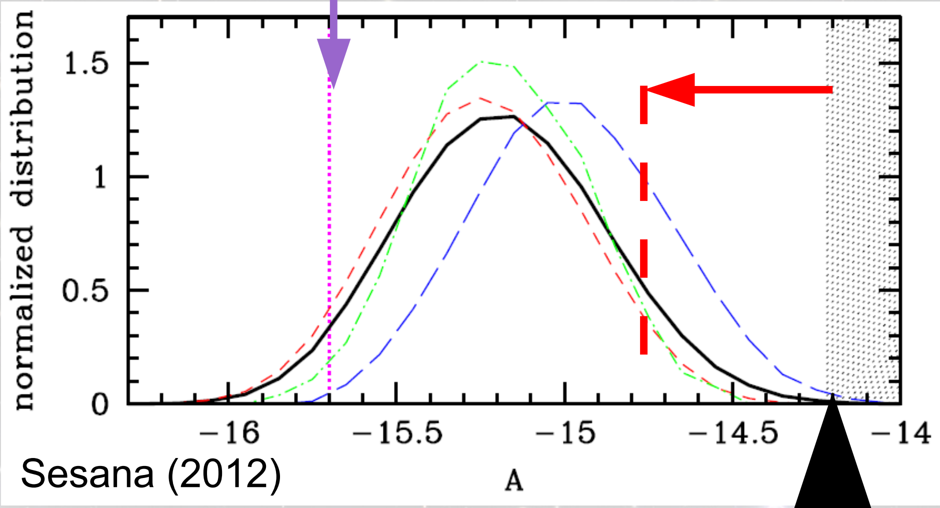
LSR

Gravitational Wave signature

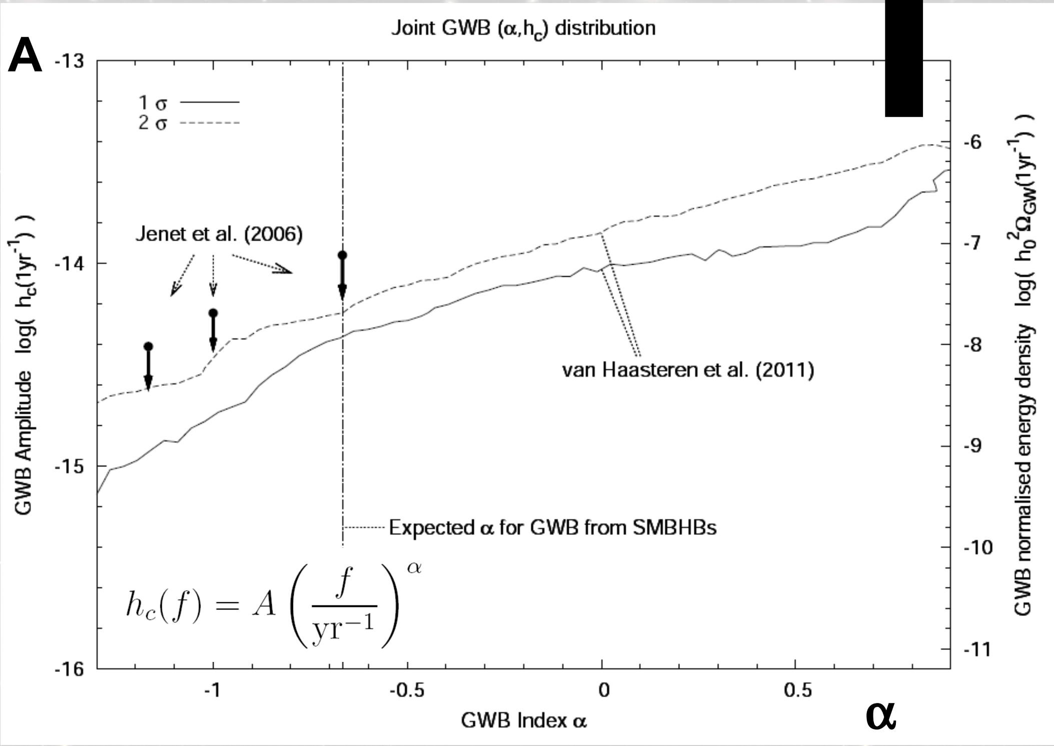


Ideal sample
20 pulsars @ 100 ns

42 pulsars
EPTA 2014 ?



5 pulsars
EPTA 2011



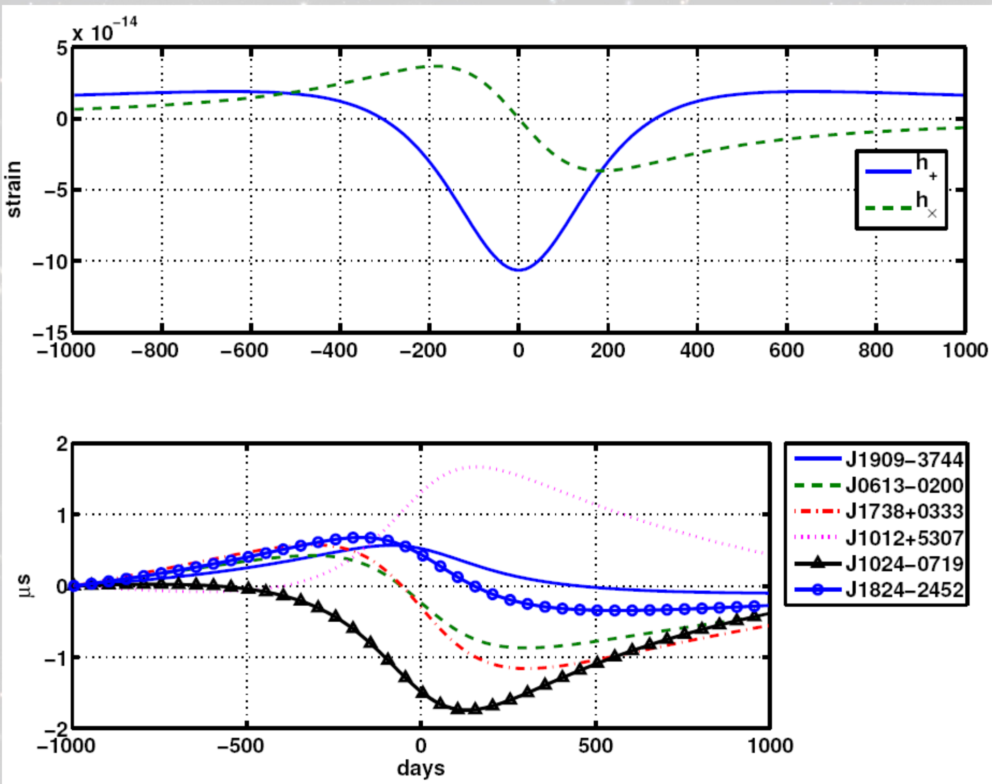
Van Haasteren et al (2011)

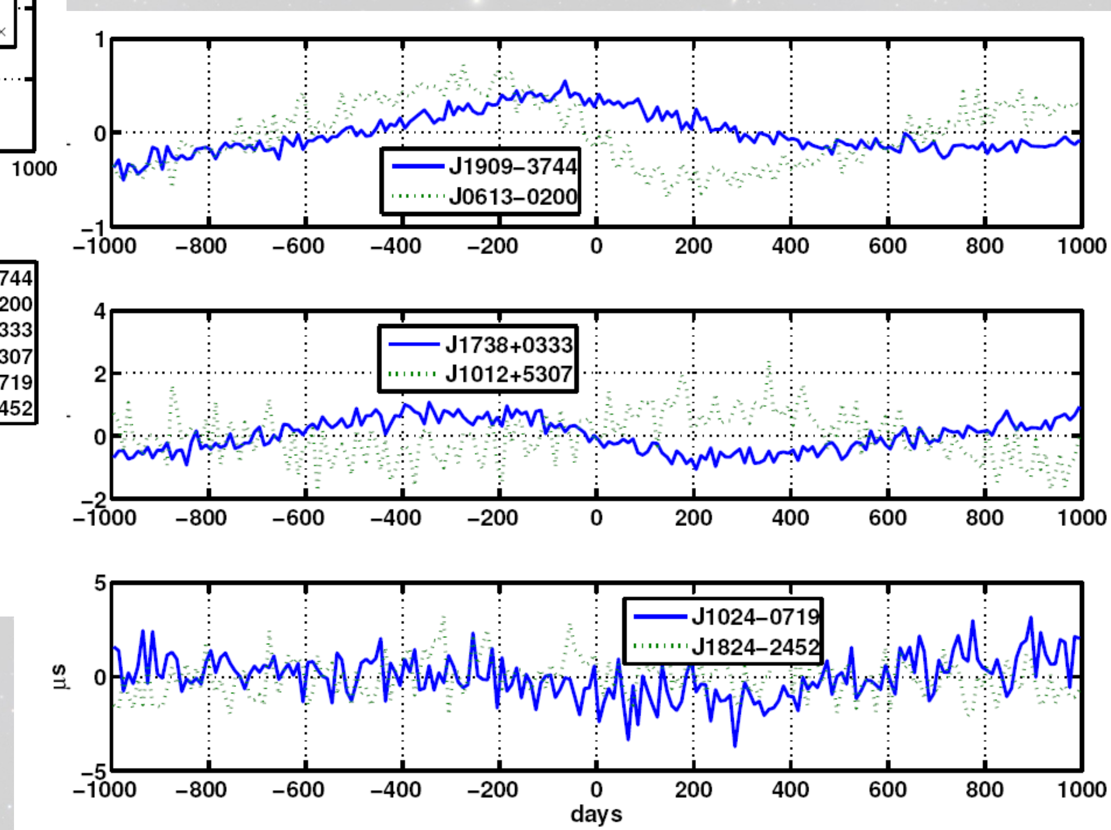
Single source search

Effect of a « burst » at the Virgo Cluster distance (15 Mpc)

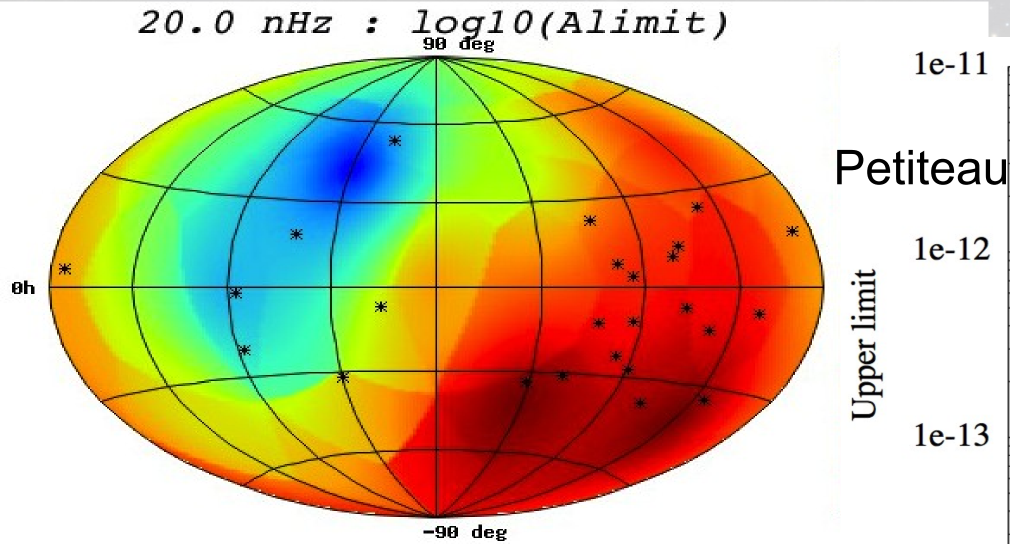
Parabolic encounter of two MBH of mass $10^9\ M_\odot$,
With a impact parameter of 0.02 pc

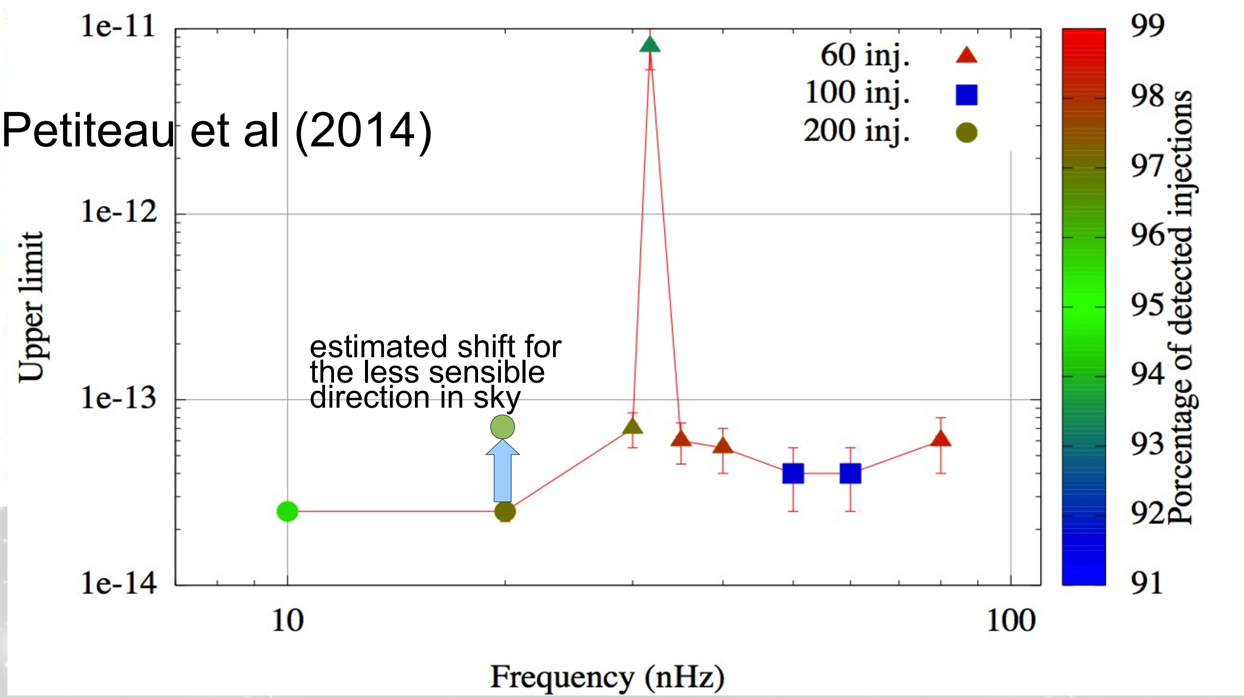
(Finn & Lommen 2010)





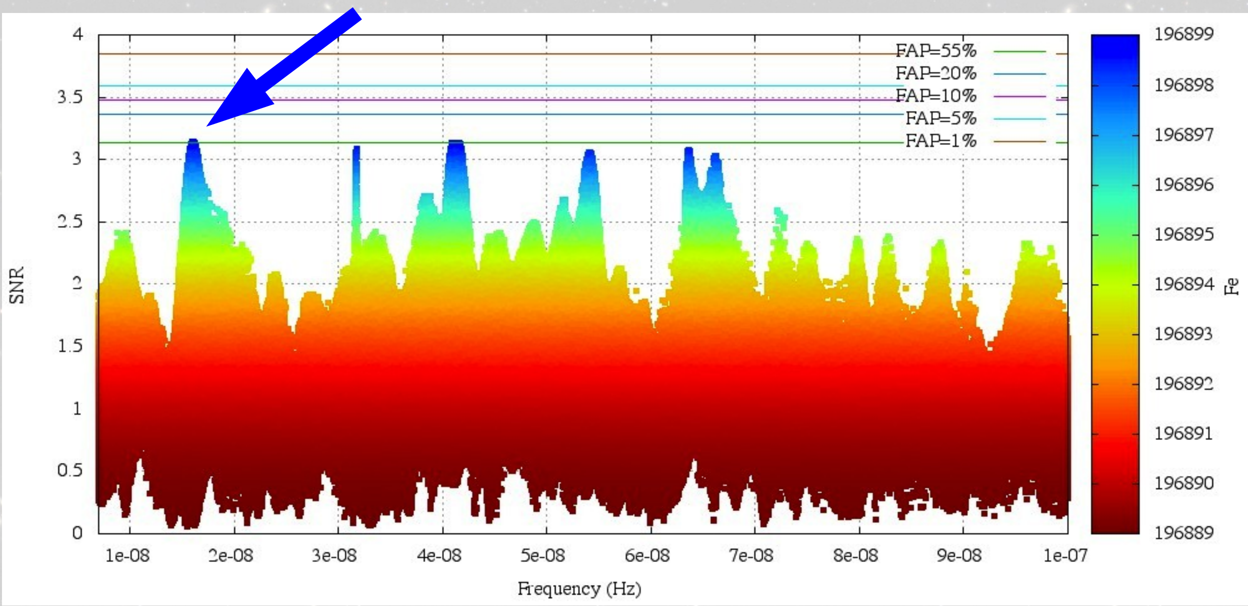
Single source search





Petiteau et al (2014)

Upper limit : 23 EPTA pulsars



Petiteau et al (2014)

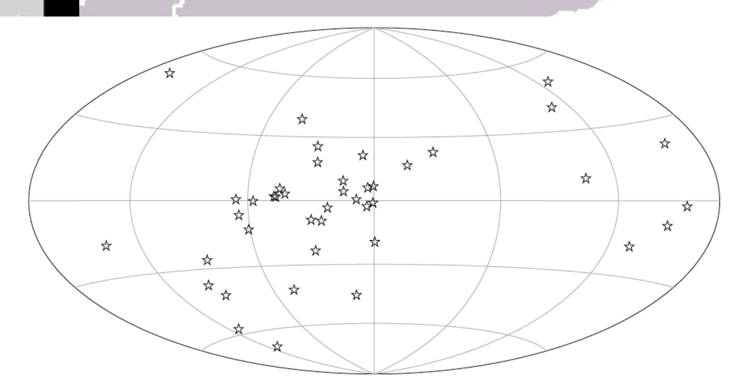
Detection algorithm

Data : 41 EPTA pulsars
(release 09/2013 : preliminary)

Estimator :
Fstatistic, Earth with term only

Best candidate : SNR=3.14
False Alarm Probability=55%

The European Pulsar Timing Array



Desvignes et al 2014

Observation des pulsars
Construction des TOAs

Détermination des paramètres des pulsars

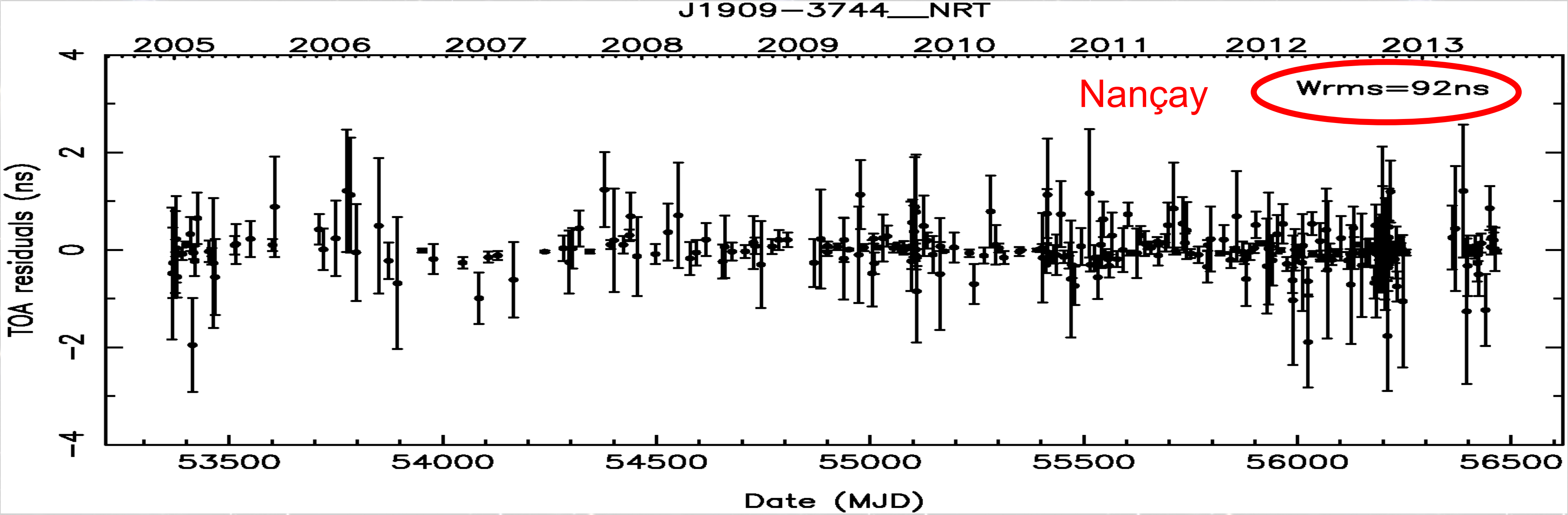
Evaluation des paramètres de bruits EFAC, EQUAD, Bruit Rouge

Recherche d'un fond d'onde
Recherche de sources individuelles

Timing group

Data Analysis Group

Cf thèse A.Lassus (2013)



TOA's

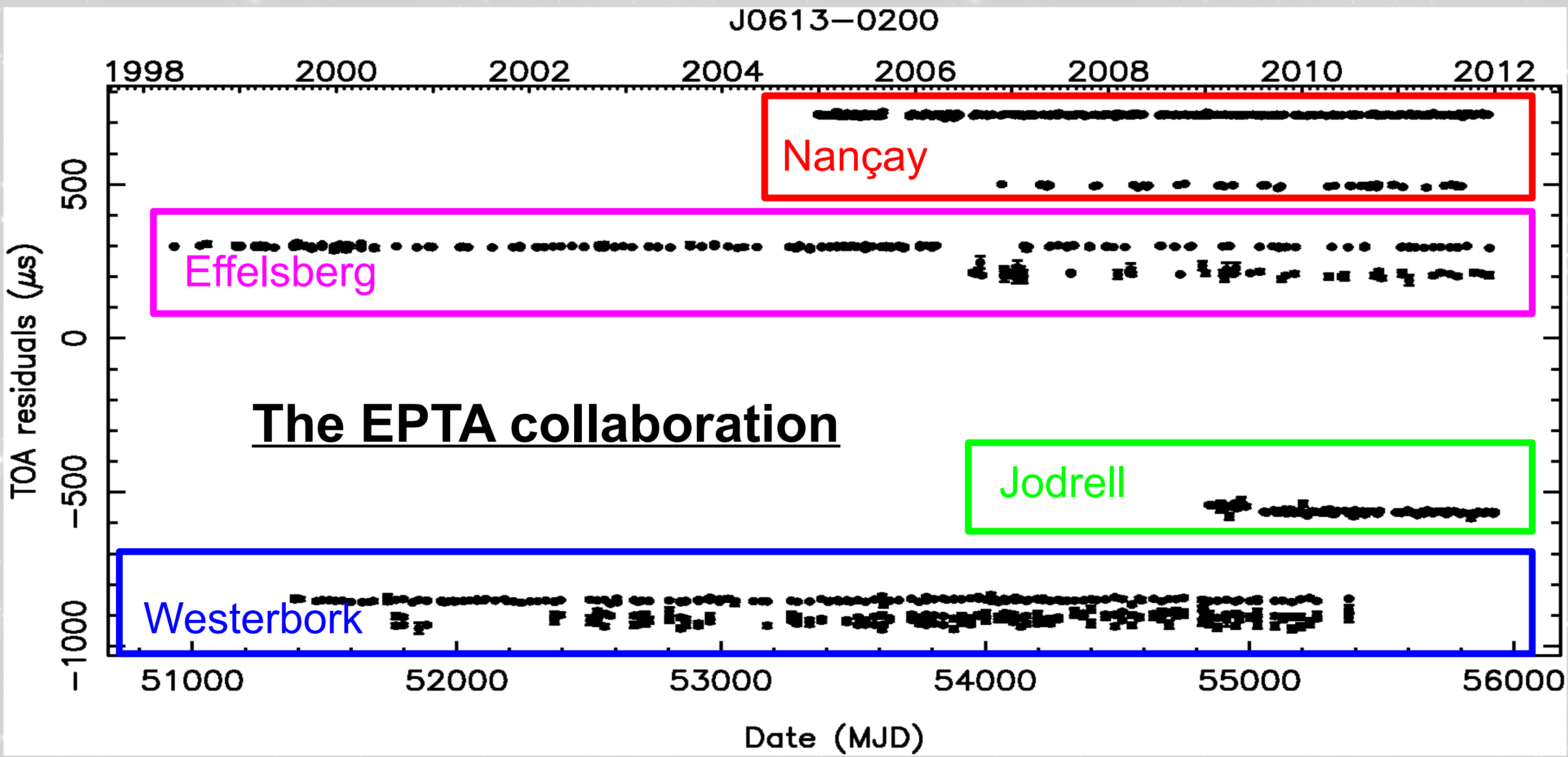
42 pulsars

Span 5-19 years

28 under 5 µs

4 under 1 µs

(15 with NUPPI since 2,5 years)



<u>EPTA, mai 2014 (Dwingeloo) :</u>

K.Liu, G.Theureau, A.Petiteau, I.Cognard, L.Guillemot, A.Lassus
+ G.Desvignes + PhD 2014 + ANR PTA-France ???