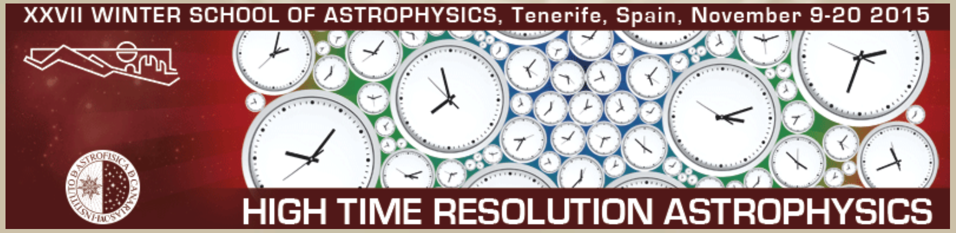
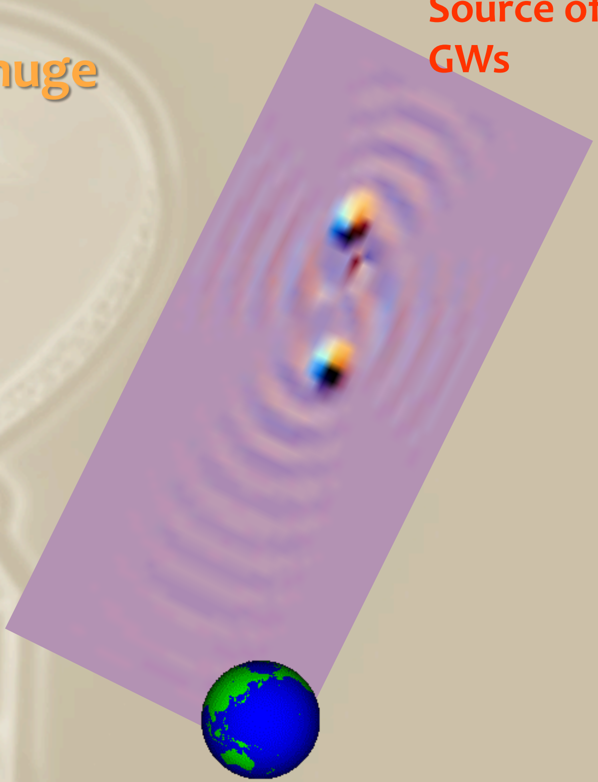
4.b

Detecting Gravitational Waves of ultra small frequencies


XXVII WINTER SCHOOL OF ASTROPHYSICS, Tenerife, Spain, November 9-20 2015

HIGH TIME RESOLUTION ASTROPHYSICS

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

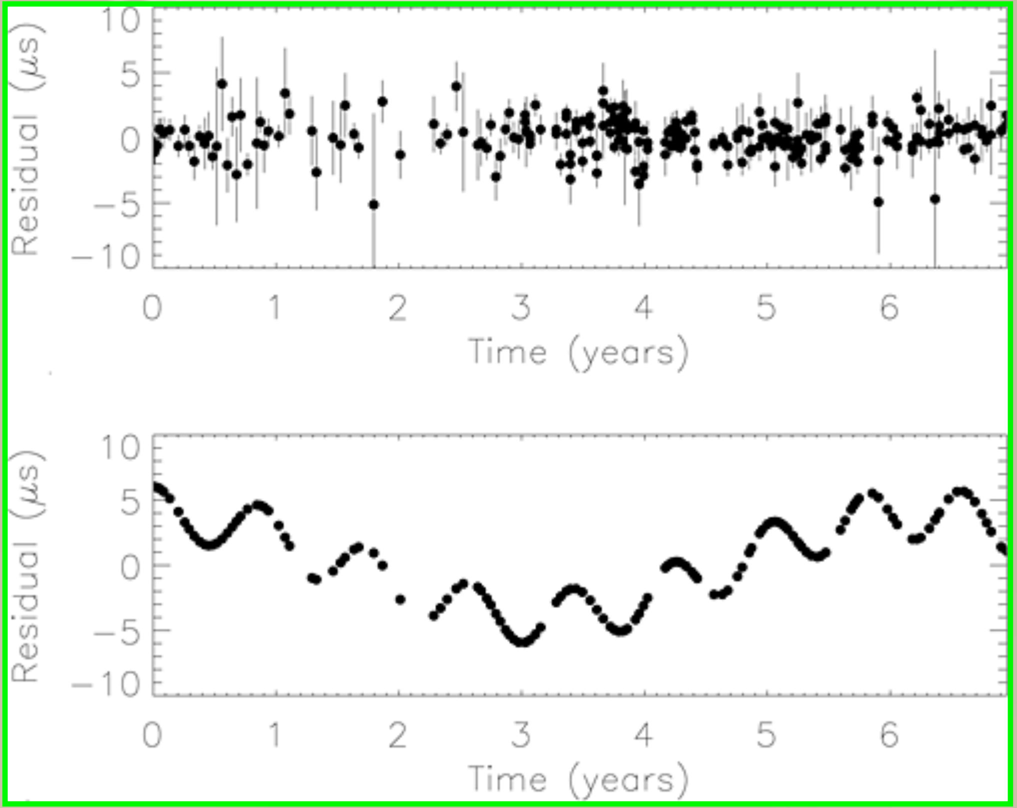
$h_c(f)$ is the dimensionless strain at freq f

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.

The GW background from Massive BH binaries

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) (MBH: i.e. mass larger than 10^6 M_{sun})

There should be plenty of SMBH binaries in the early universe, sinking to the their galaxy center (due to dynamical friction?)

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

The frequency of GW emitted by these systems is typically

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

© ATNF

The GW background from Massive BH binaries

The expected amplitude spectrum form the ensemble of these MBH binaries is [e.g. Phinney 2001; Jaffe & Backer 2003]

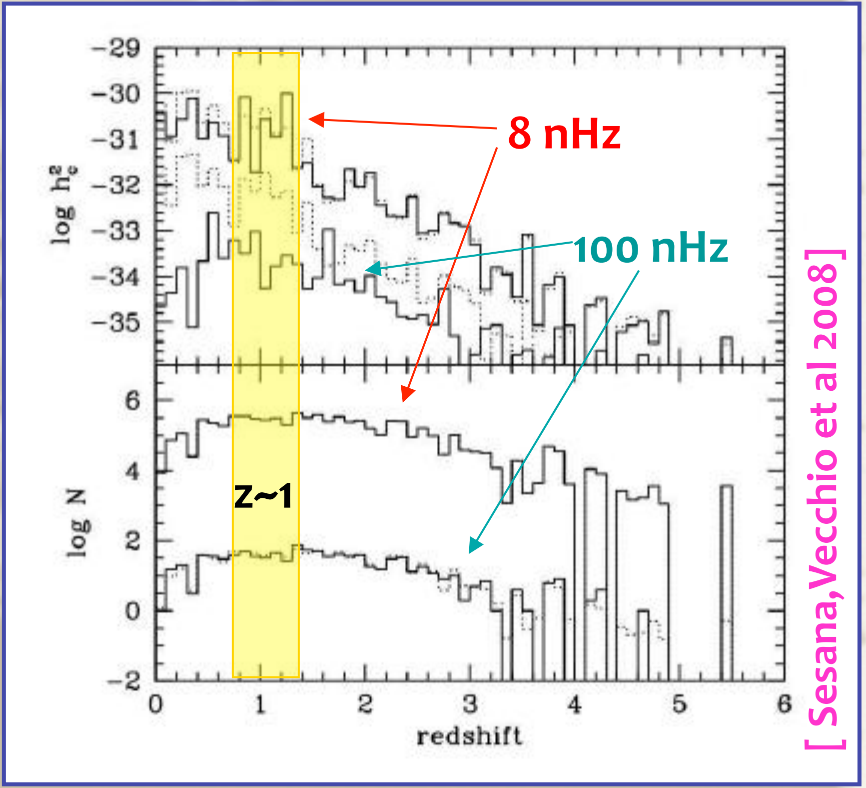
$$h_c(f) \sim f^{-\alpha}; \alpha = 2/3$$

with a strain amplitude theoretically expected in the range
[e.g. Jaffe & Backer 2003, Sesana,Vecchio et al 2008]

$$h_c \approx 10^{-16} \rightarrow 10^{-15}\ \text{(but...)}$$

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

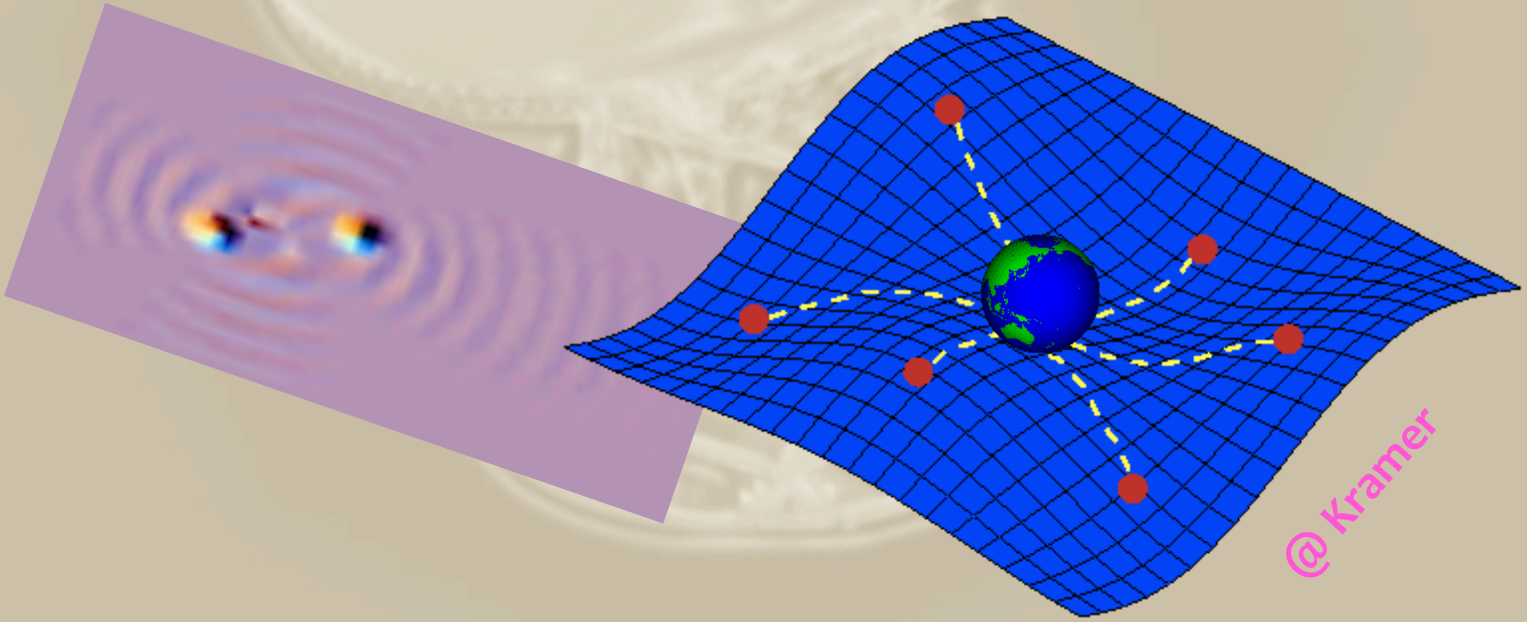
Max contribution from BH binaries at $z \approx 1$



[Sesana,Vecchio et al 2008]

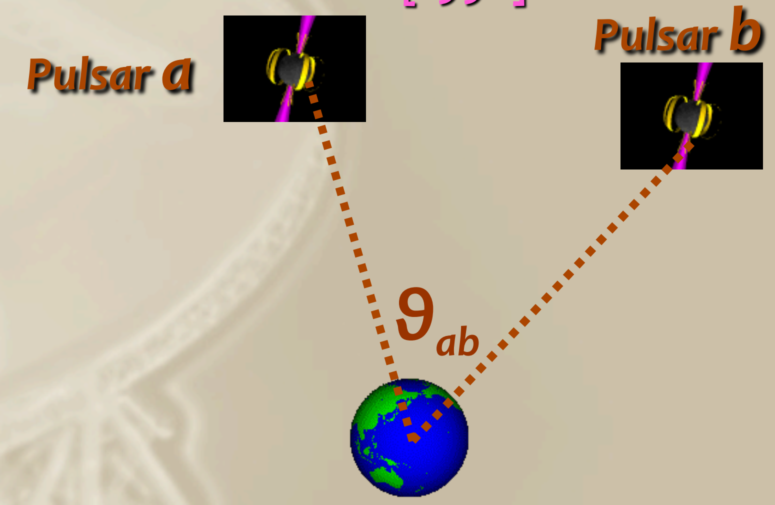
A pulsar timing array (PTA)

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



A pulsar timing array (PTA) for detecting a stocastic Background of GW (GWB)

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

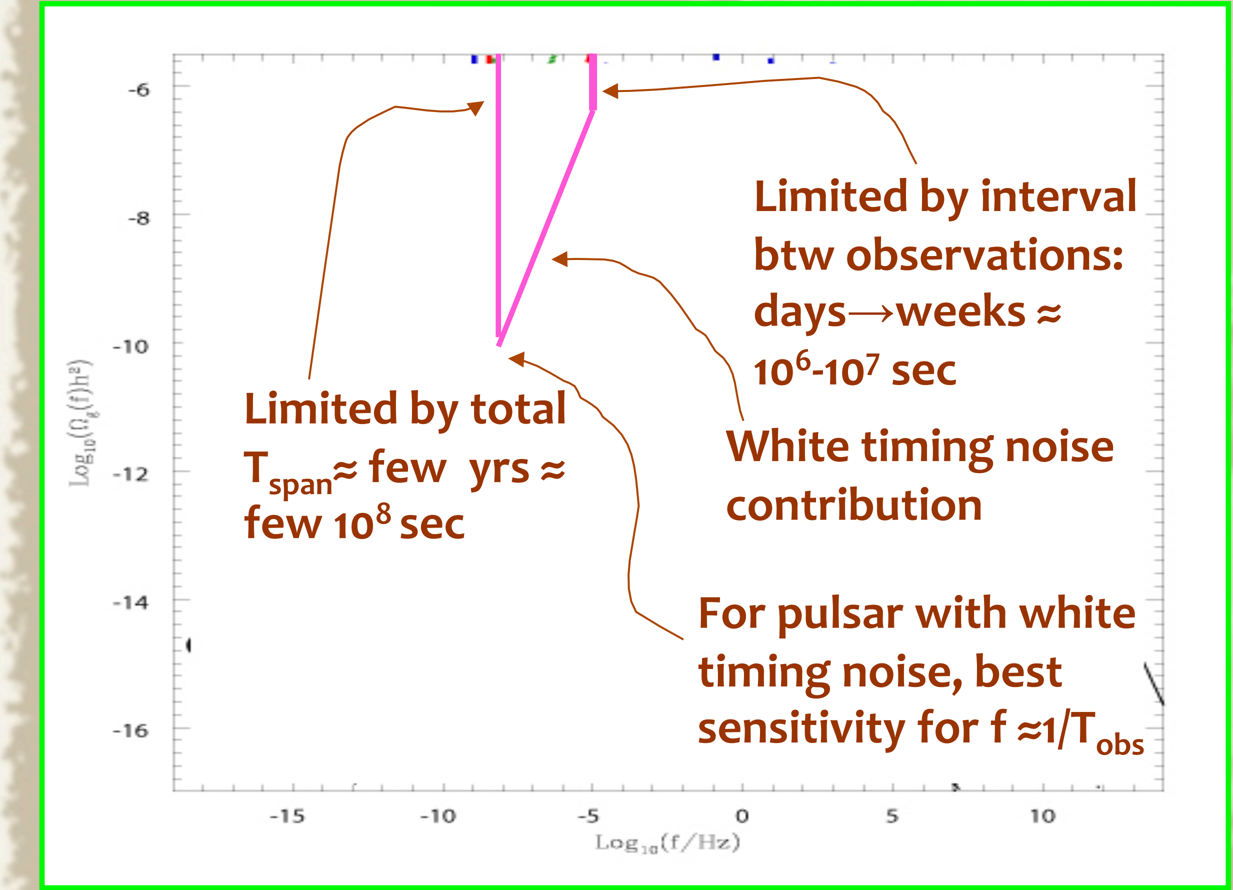
$$\zeta(\theta_{ab}) = \frac{3}{2}\left(\frac{1-\cos\vartheta_{ab}}{2}\right)\log\left(\frac{1-\cos\vartheta_{ab}}{2}\right) - \frac{1}{4}\left(\frac{1-\cos\vartheta_{ab}}{2}\right) + \frac{1}{2} + \frac{1}{2}\delta_{ab}$$

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

Can separate these effects provided there is a sufficient number of widely distributed pulsars

[adapted from Manchester]

Pulsar timing arrays for stocastic GWB: a typical sensitivity curve



Limited by interval btw observations: days→weeks ≈ 10^6-10^7 sec

White timing noise contribution

Limited by total $T_{span} \approx$ few yrs ≈ few 10^8 sec

For pulsar with white timing noise, best sensitivity for $f \approx 1/T_{obs}$

A too simple (interpretation of the) sensitivity curve...

Detailed simulations are required for more realistic sensitivity curves...

$$h_{c,GWB} \propto \frac{\sigma_{TOA}}{T_{span}^{5/3}\sqrt{N \bullet M(M-1)}}$$

for the GWB due to SMBH

N = number of epochs

M = number of pulsars

Data analysis for a stocastic GWB

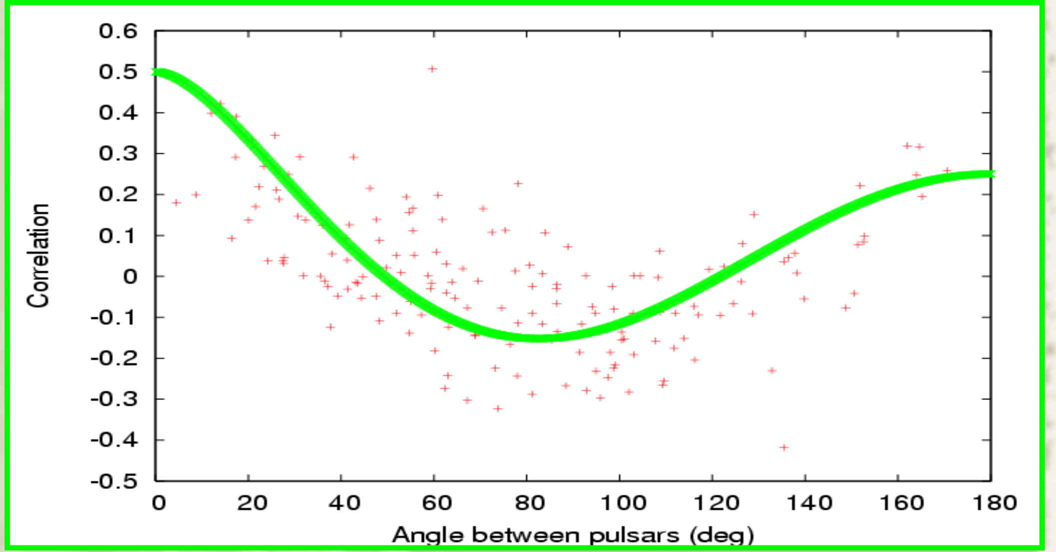
Spherical harmonic decomposition

[Burke 1975, Dettweiler 1979, Jaffe & Backer 2003, Demorest et al 2005]

Two point correlation

Correlating the time derivative of the residuals [Hellings & Downs 1983]

Directly correlating the time residuals [Jenet et al 2005]



Bayesian analysis

[van Haasteren, Levin, McDonald, Lu 2008]

Robust: deals easily with unevenly sampled data, variable number of tracked pulsars, etc.

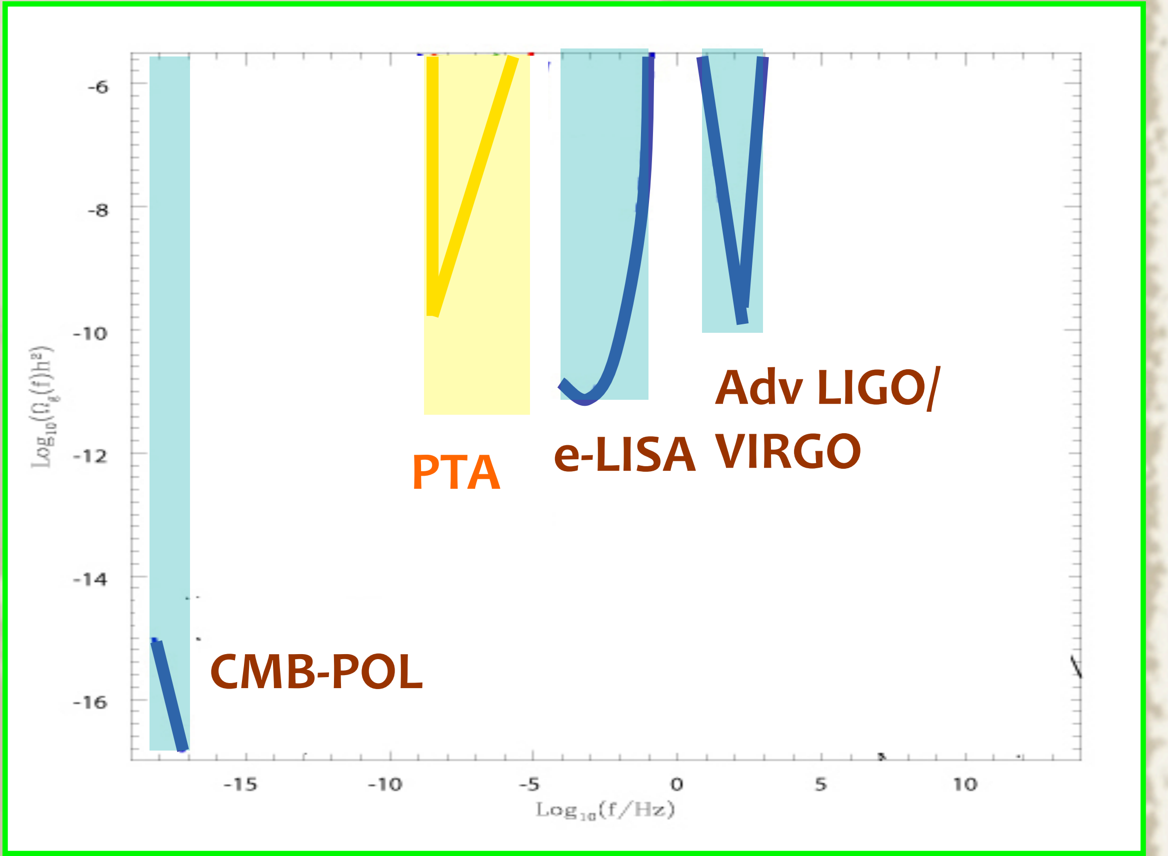
Marginalisation: deals easily with all systematics of known functional form, including the timing model

Capable to simultaneously measure the amplitude and the shape of the GWB

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 **advLIGO, advVIRGO and eLISA**

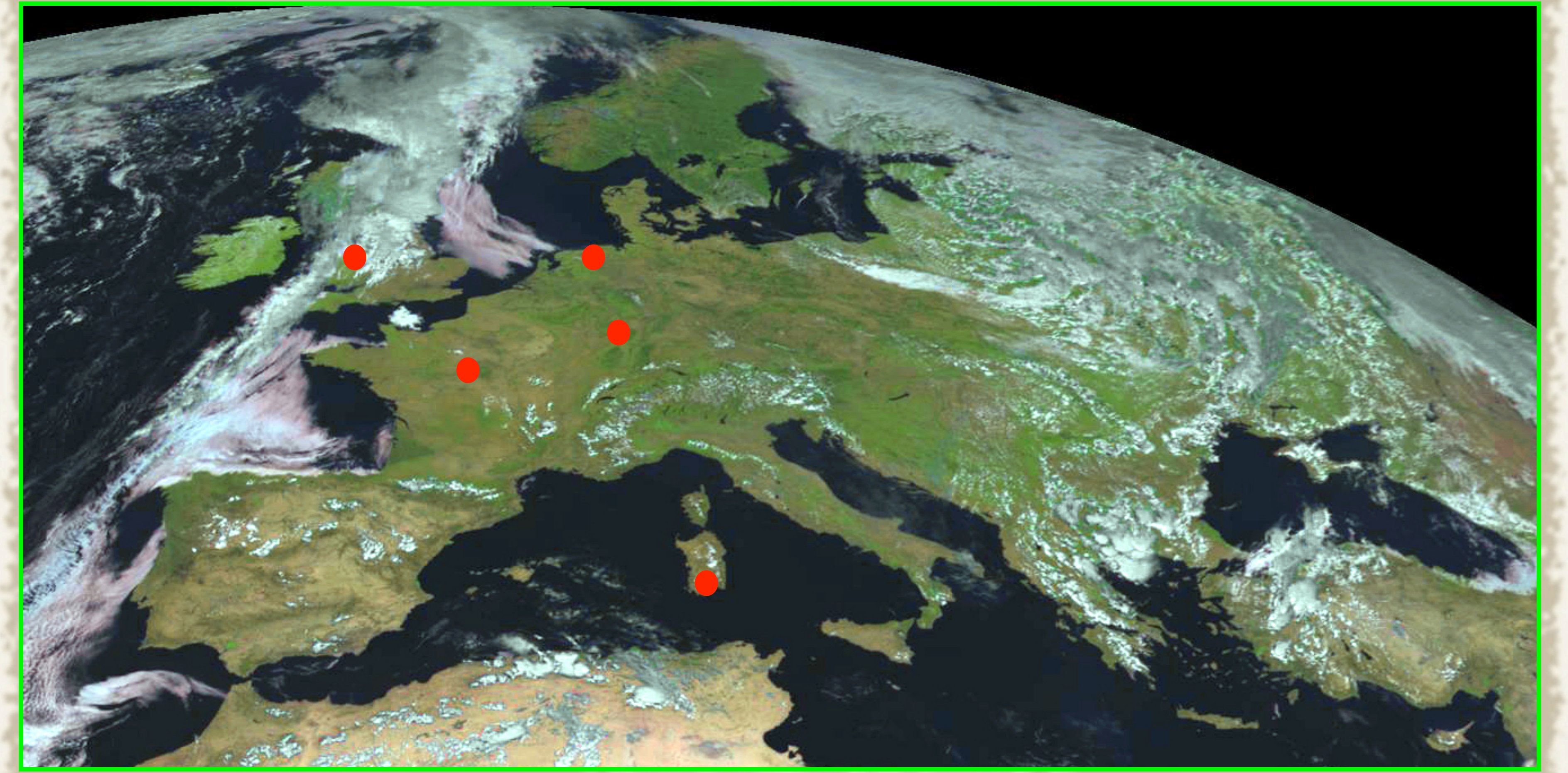
- Expected sources:
  - Binary super-massive black holes in early Galaxy evolution
  - Cosmic strings
  - Cosmological sources
- Types of signals:
  - Stochastic (multiple)
  - Periodic (single)
  - Burst (single)



The PTA collaborations

Figure courtesy of Brian Burt, Franklin & Marshall

EPTA: The partner institutions



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INAF Osservatorio Astronomico di Cagliari, ITA

Nancay Observatory, FR

Max-Planck Institut fur Radioastronomie, GER

Current best limits on GW background from SMBH binaries

(with a GW spectral index -2/3 at $f=1/(1\ \mathrm{yr})$ for $H_o = 73\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$)

NANOGrav *Demorest et al., 2015*: **$A < 1.5 \times 10^{-15}$**

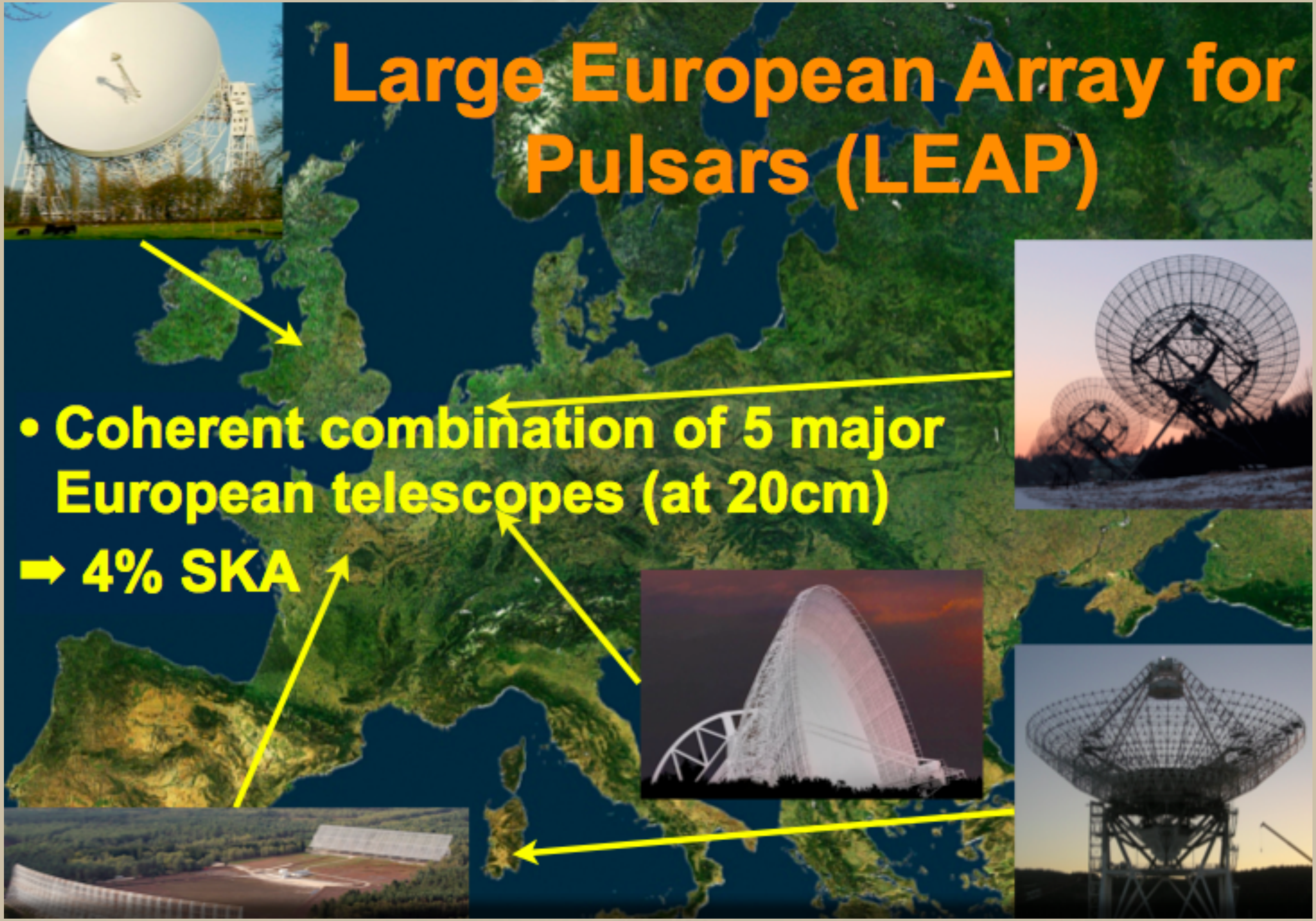
PPTA *Shannon et al., 2015:* **$A < 1.0 \times 10^{-15}$**

[$\Omega_{GW} < 2.6 \times 10^{-10}$ at f=/(0.2 yr)]

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

(robust limit including additional effects)

LEAP



Large European Array for Pulsars (LEAP)

- Coherent combination of 5 major European telescopes (at 20cm)

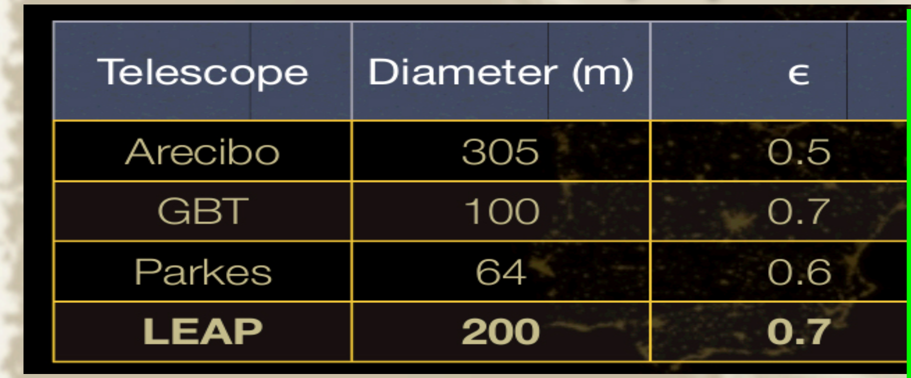
➡ 4% SKA

LEAP

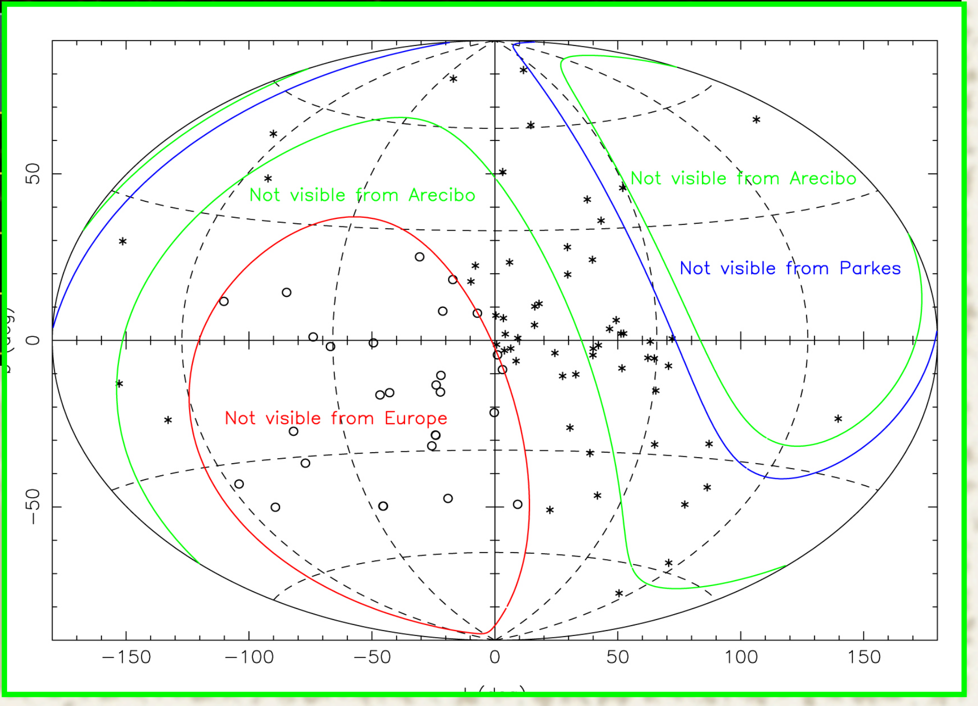
Phased array of the 5 major European telescopes

Funded by the EU Research Council: 2.5 M€
People involved: 2 staff, 2 senior postDoc and 2 junior postDoc
Duration: 5 years since mid 2009

Sensitivity equivalent to illuminated Arecibo



Telescope	Diameter (m)	ϵ
Arecibo	305	0.5
GBT	100	0.7
Parkes	64	0.6
LEAP	**200**	**0.7**



But able to see much more or the sky