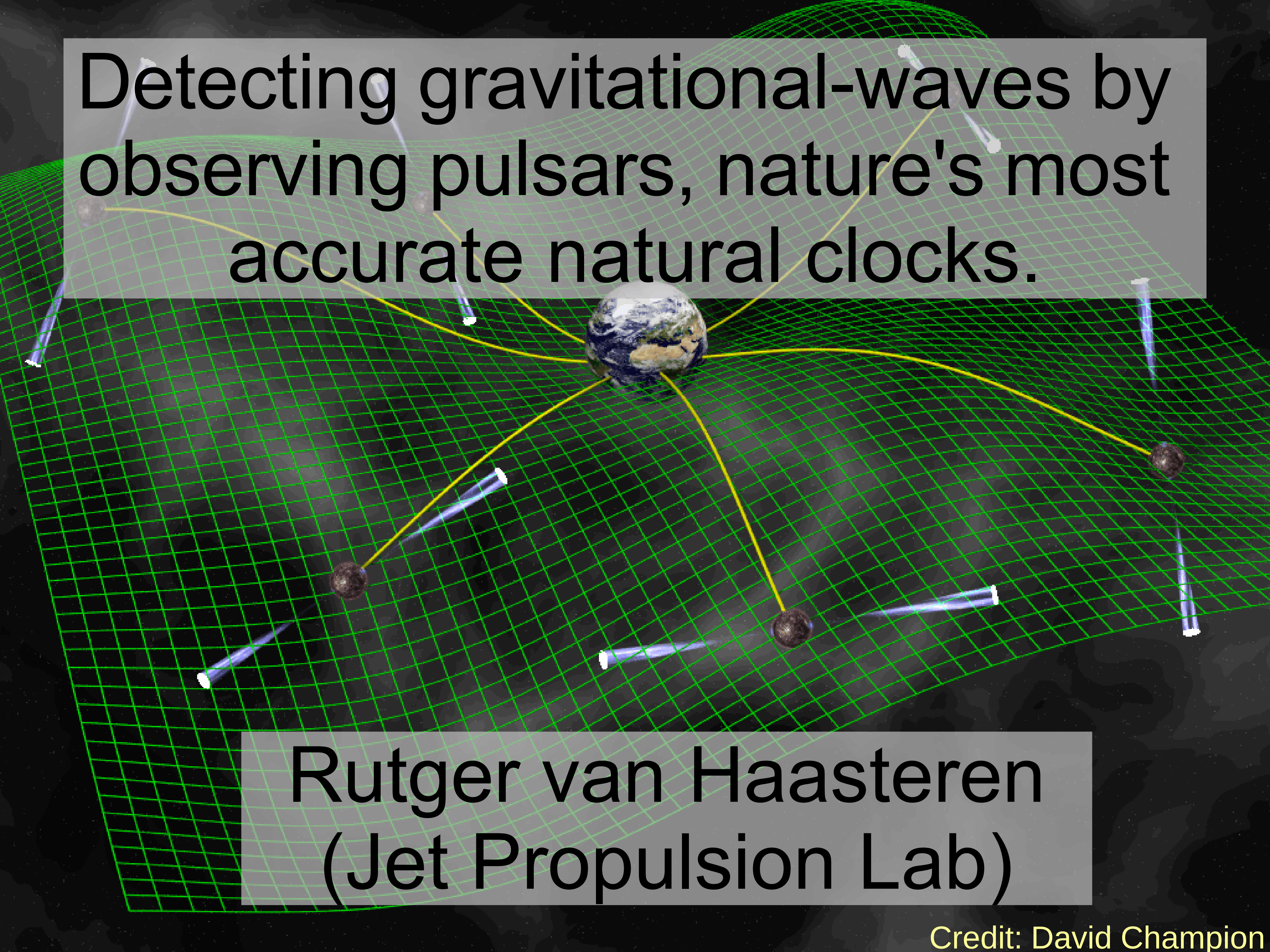
Detecting gravitational-waves by observing pulsars, nature's most accurate natural clocks.



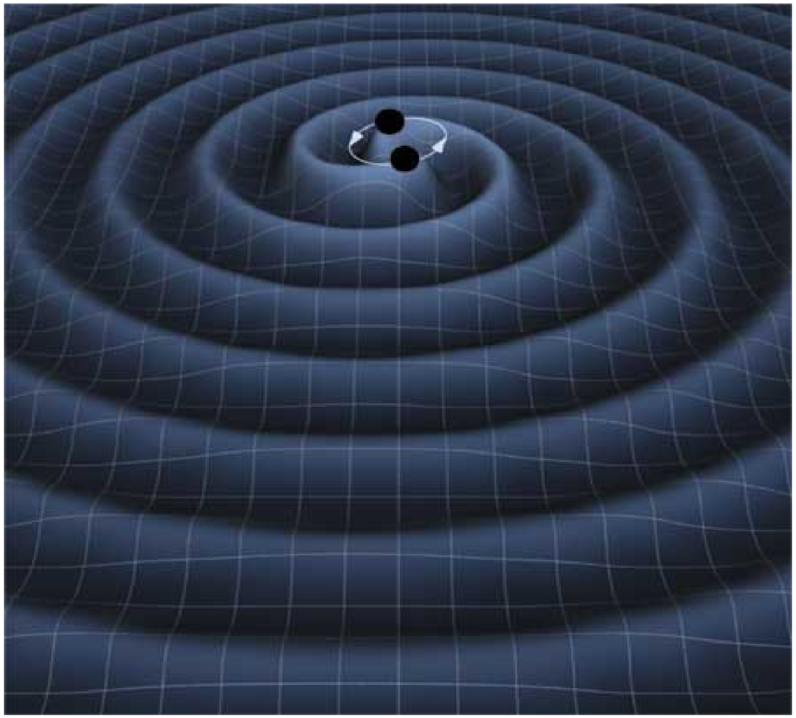
Rutger van Haasteren
(Jet Propulsion Lab)

Credit: David Champion

Outline

1. Gravitational-wave detector principles
2. Pulsars and pulsar timing
3. Examples of pulsar timing
4. Gravitational-waves sources
5. Pulsar timing arrays
6. Outlook and detection prospects

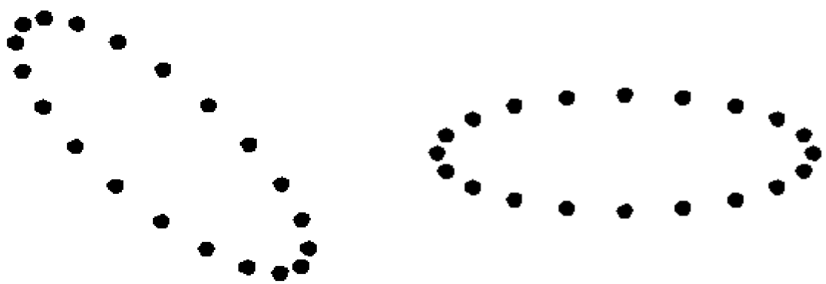
What is a GW?

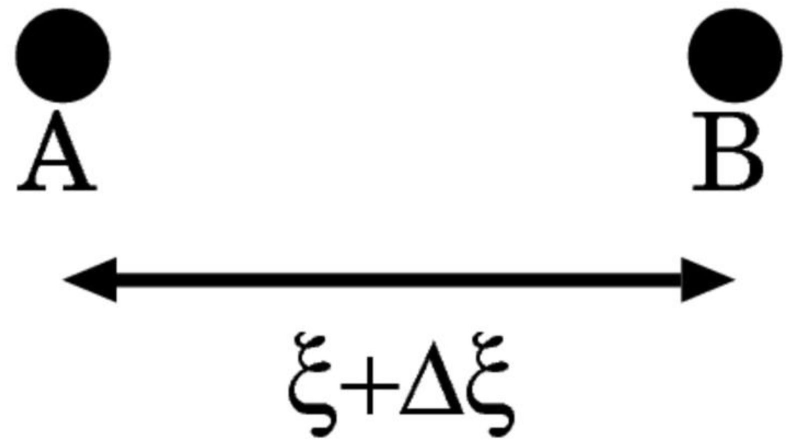


Gravitational wave: ripple in in the curvature of spacetime that propagates outward from the source as a wave.

Gravity wave: refer to one of Tokyo's local surfers

Effect and detectability of GWs





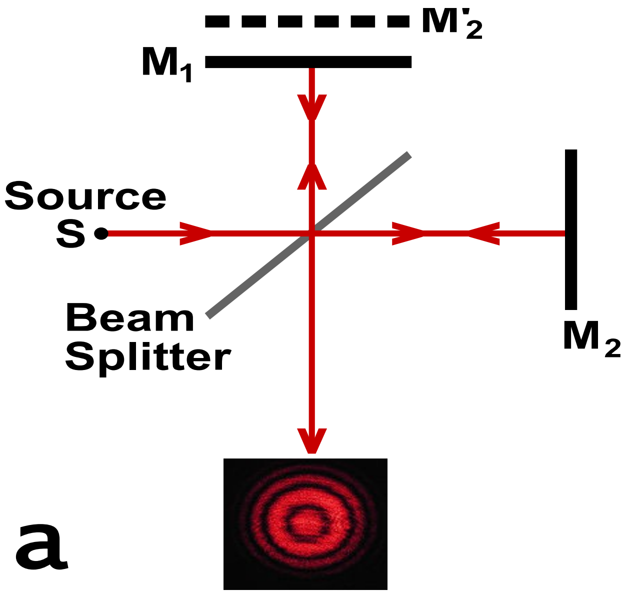
Effect of GWs is an oscillating Riemann curvature tensor, possible in two polarisations.
→ Measure propagation length!

Speed of light is constant.

Measure time, not distance.

Effect and detectability of GWs

Credit: Advanced Technology Center, NAOJ



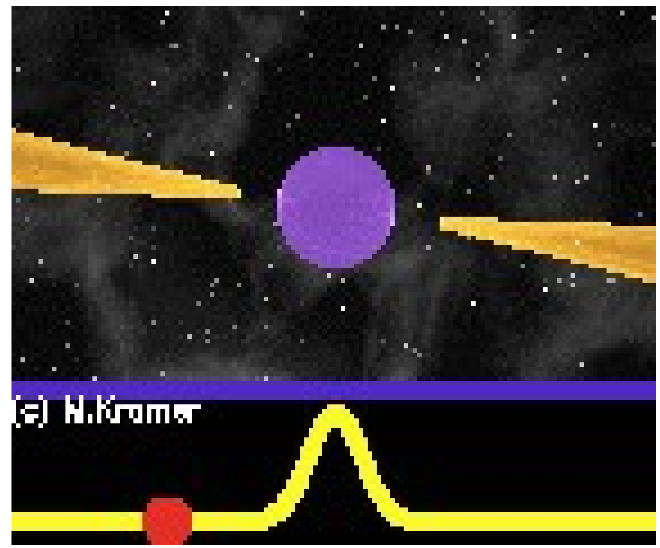
Emit light, and reflect back

Now it is truly a 'timing experiment'

LASER has precise frequency
→ equivalent to clock

Interferometry for detection

Need precise frequency/clock



Could say that KAGRA uses a LASER as an accurate frequency standard

What about pulsar's spin frequency?

Period of PSR B1937+21:
T = 0.0015578064487275 s

Strain sensitivity per frequency

Energy density function of wavelength

Electromagnetic waves: $\Omega \propto |E|^2 + |B|^2$

Gravitational waves: $\Omega \propto |\dot{h}|^2 = f^2 h(f)^2$

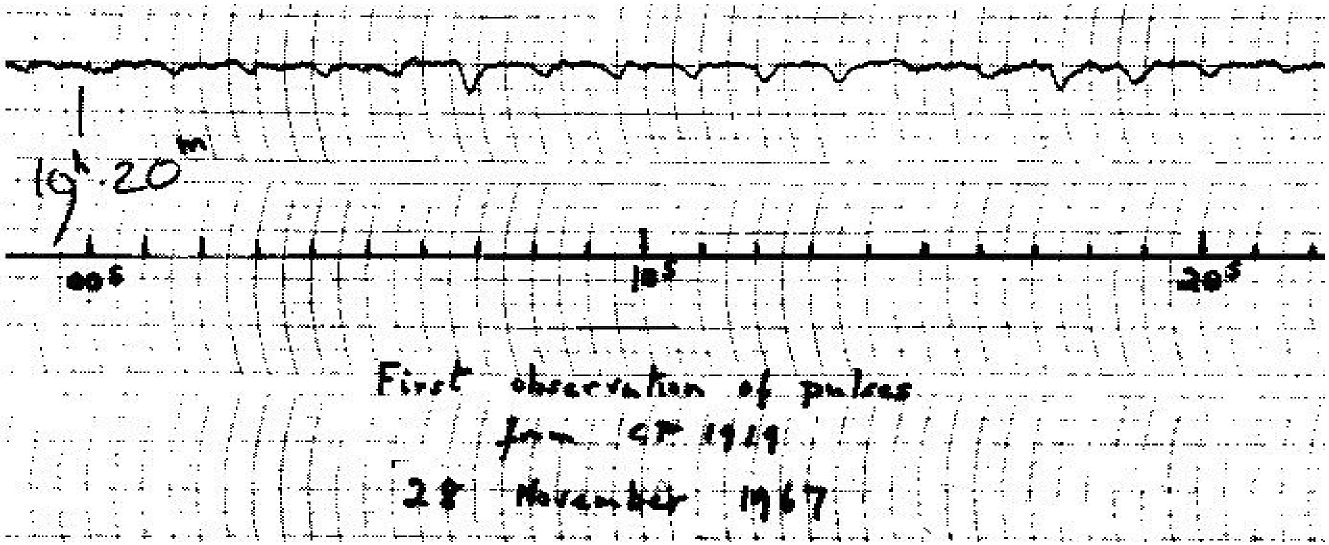
Atomic nucleus
is ~1e-15m

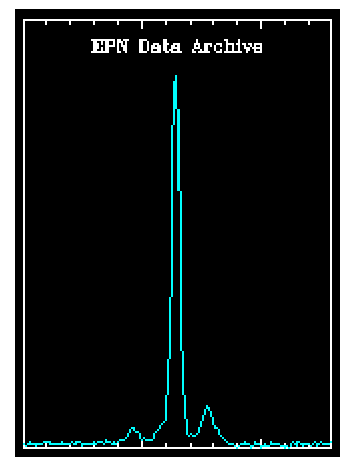
With 3km arm, reach sensitivity down to distance variations of ~1e-21m??
(zepto-meter)

Yardley et al. (2010)

Pulsars

Discovery: LGM1

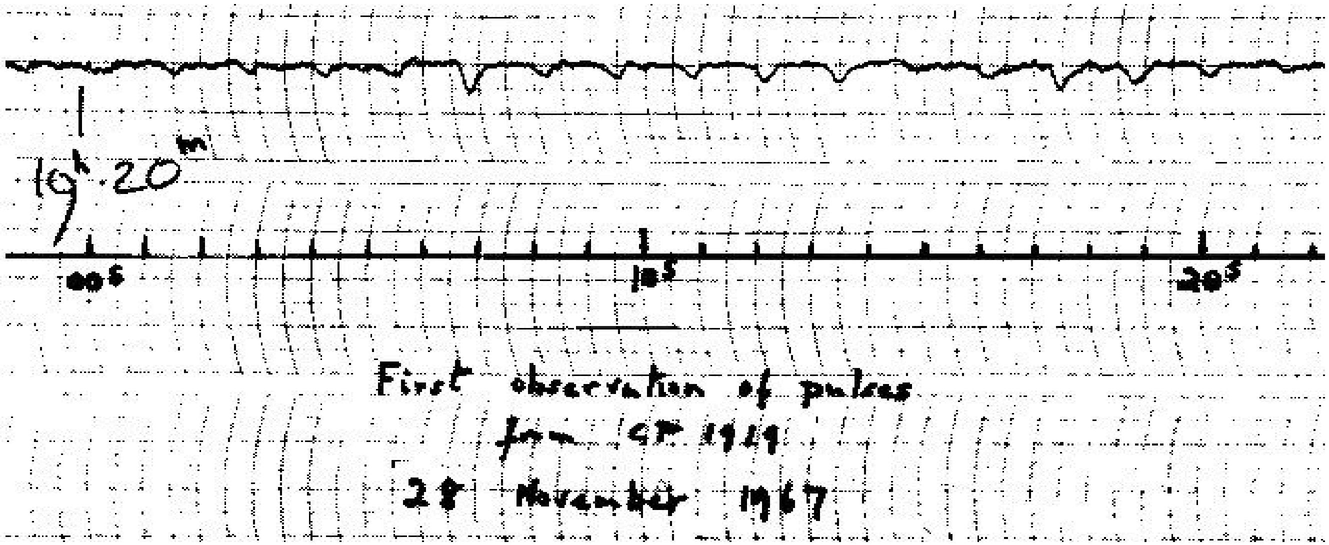




Pulsar discovery in 1967: LGM1
(= PSR B1919+21)

'Knocking sound'

Discovery: LGM1



Pulsar discovery in 1967: LGM1
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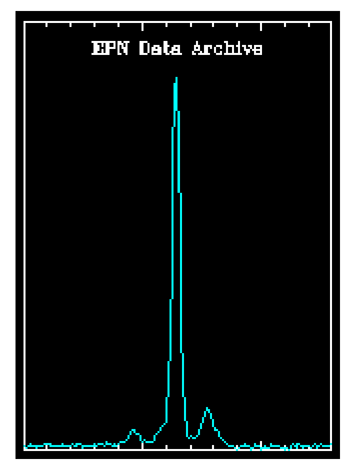
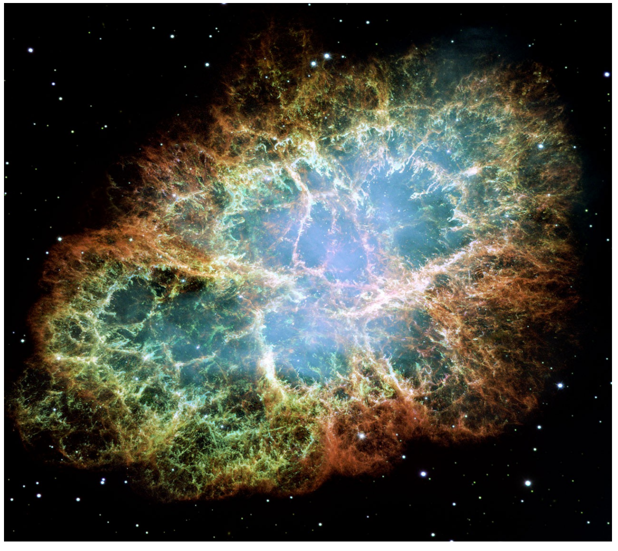
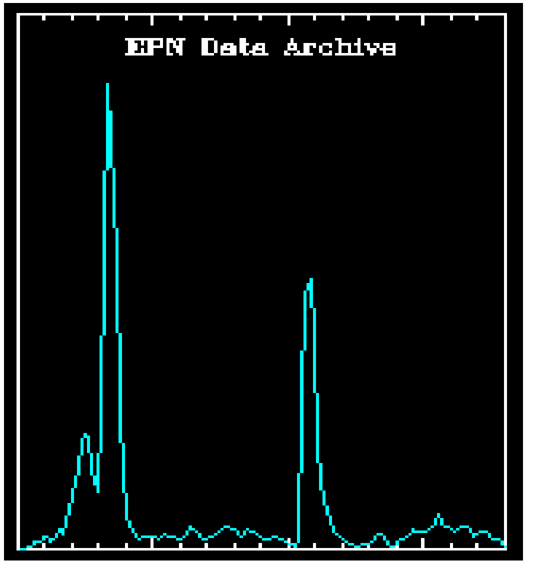


Explanation: neutron star

Baade & Zwicky in 1934: "With all reserve we advance the view that a supernova represents the transition of an ordinary star into a new form of star, the neutron star, which would be the end point of stellar evolution. Such a star may possess a very small radius and an extremely high density."



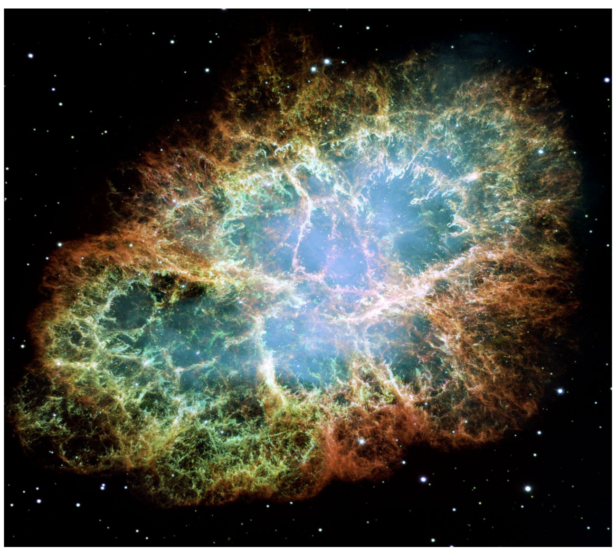
Crab Nebula. Remnant of 1054 AD supernova, seen by Chinese astronomers ('guest star').



Pulse profile of the Crab.

Associated supernova: the Crab

Baade & Zwicky in 1934: "With all reserve we advance the view that a supernova represents the transition of an ordinary star into a new form of star, the neutron star, which would be the end point of stellar evolution. Such a star may possess a very small radius and an extremely high density."



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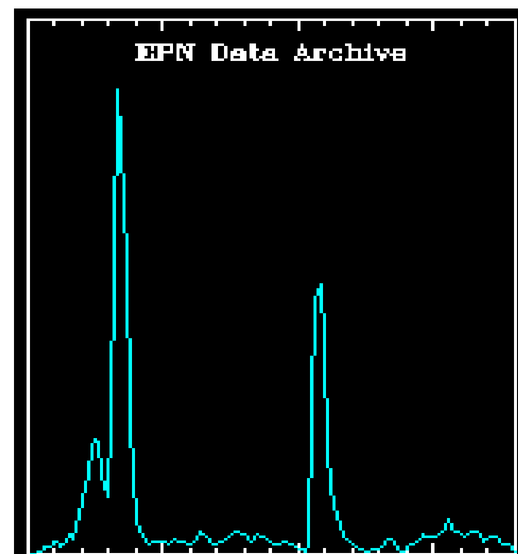
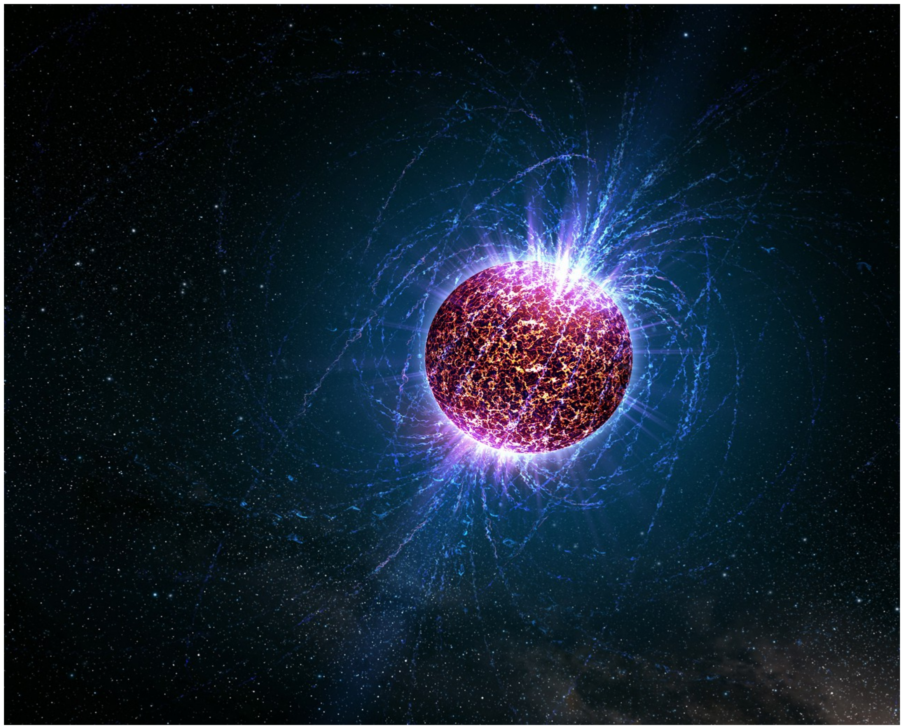
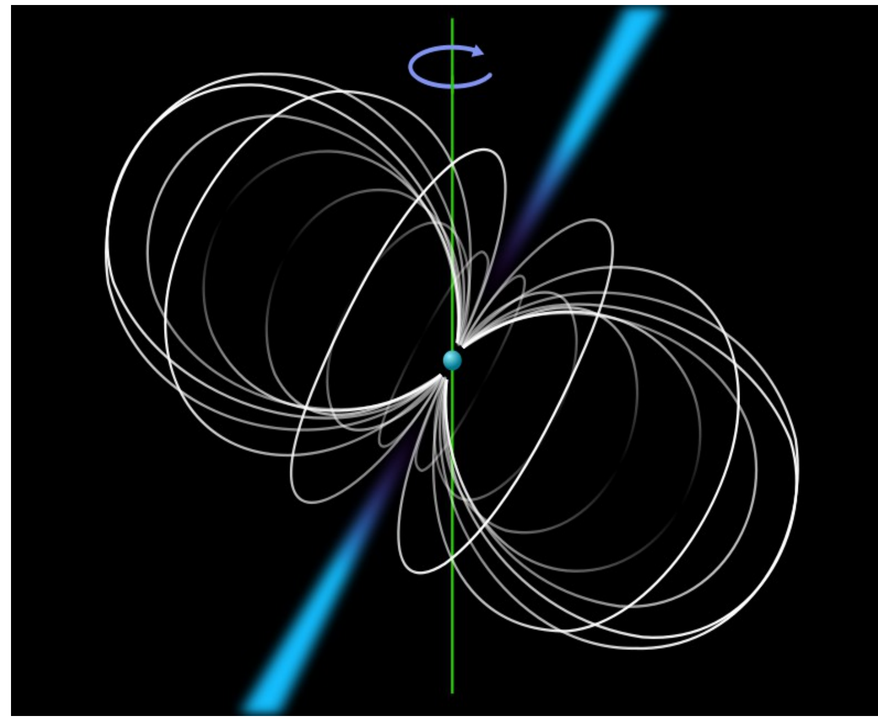


Pulse profile of the Crab.

Pulsars





Star dies → core pressure gone
Star collapses → compact object

Neutron star for heavy stars

Conserved from star:
- Angular momentum
- Magnetic field
→ Dynamo!

Period of 1.5 ms???

Don Backer et al. (1982), found a pulsar with a spin frequency of 716 Hz (P = 1.5 ms). This was the first millisecond pulsar. Can this still be a rotating neutron star?

Arecibo Observatory

Pulse profile of B1937

Period of 1.5 ms???

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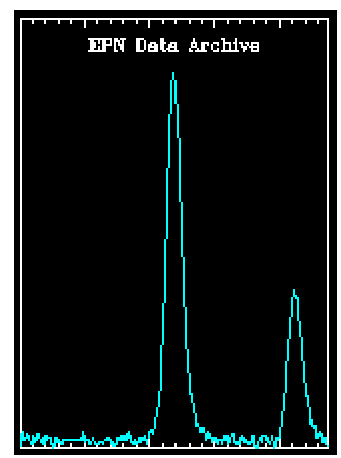
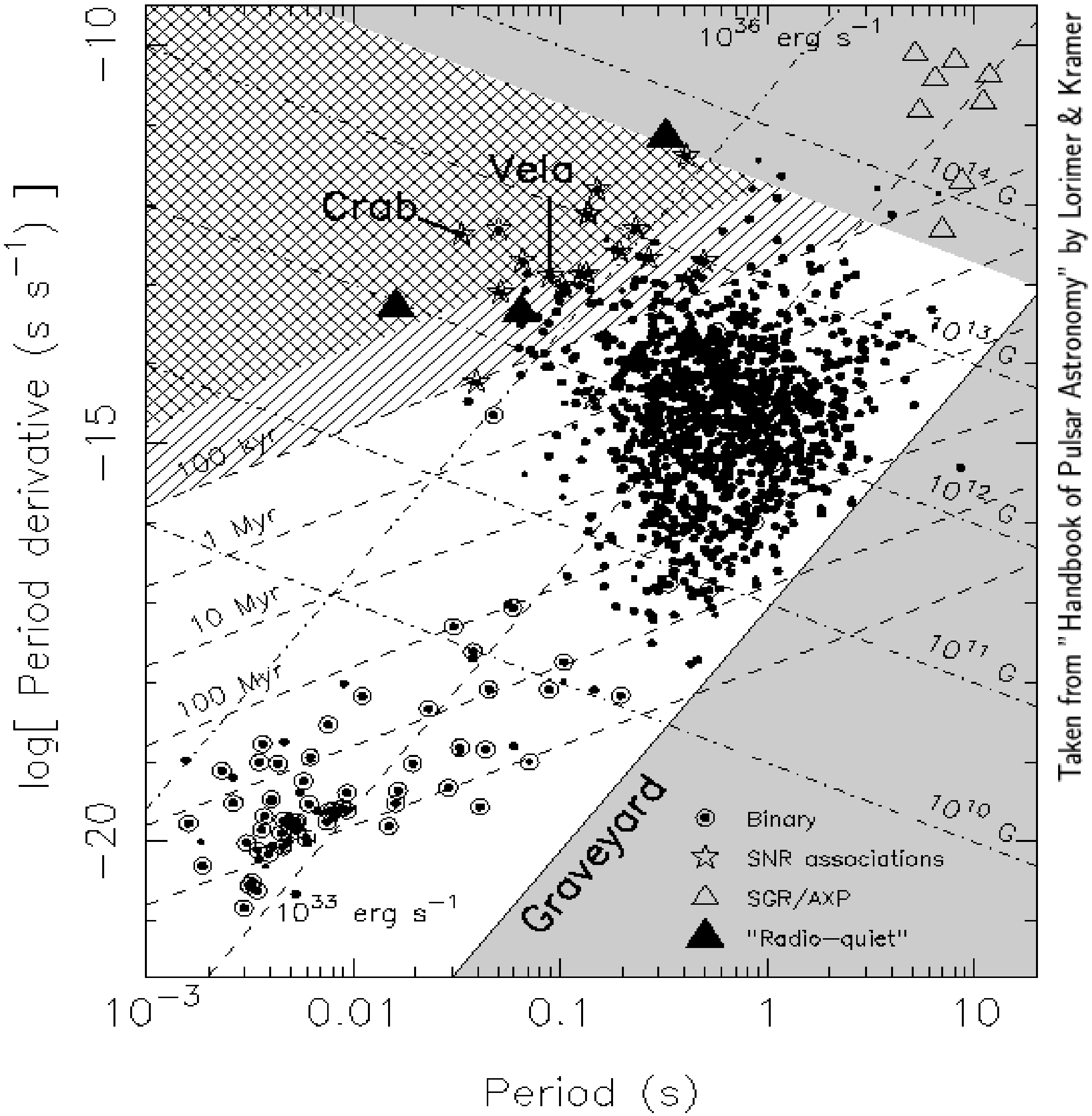
Arecibo Observatory



Pulse profile of B1937

Radius less than 16km. At equator, spin velocity > 70,000 km/s (= 24% speed of light)

P-Pdot diagram



Most stable 'clocks' are in the bottom left

Note: almost all binaries there

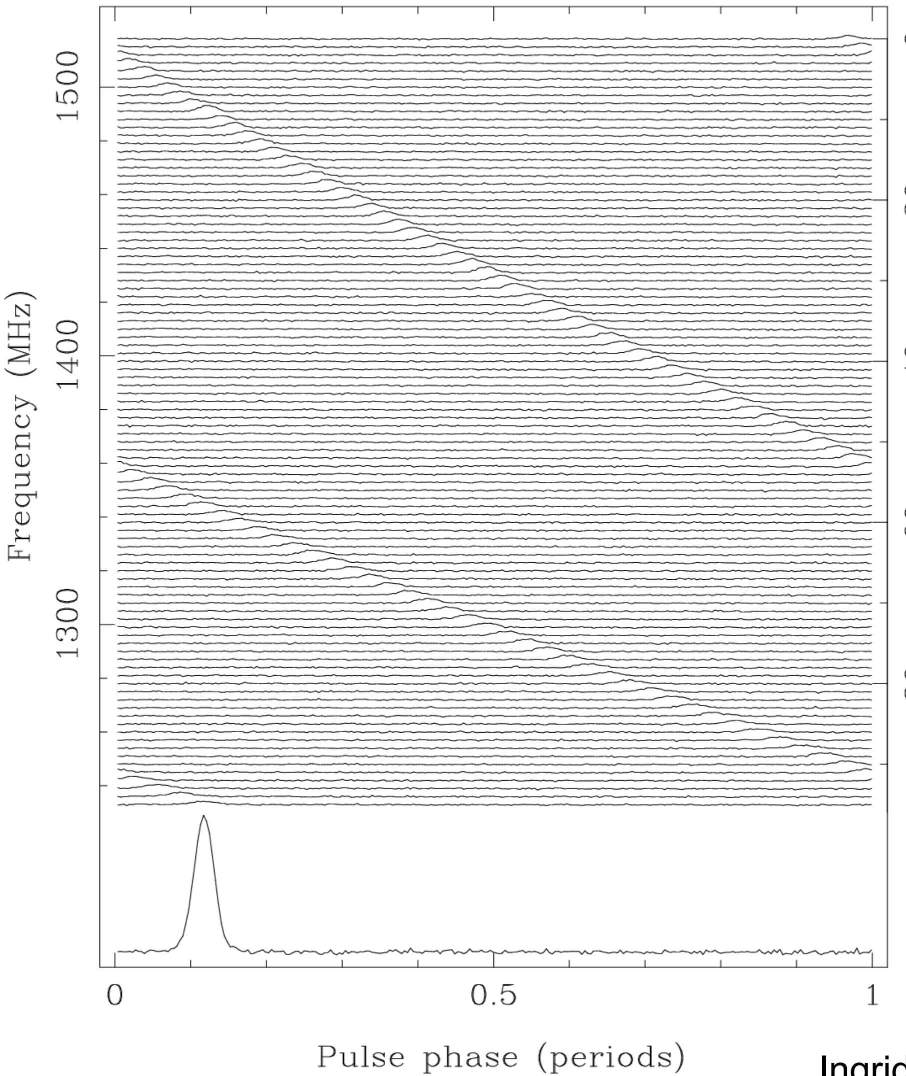
Millisecond pulsars

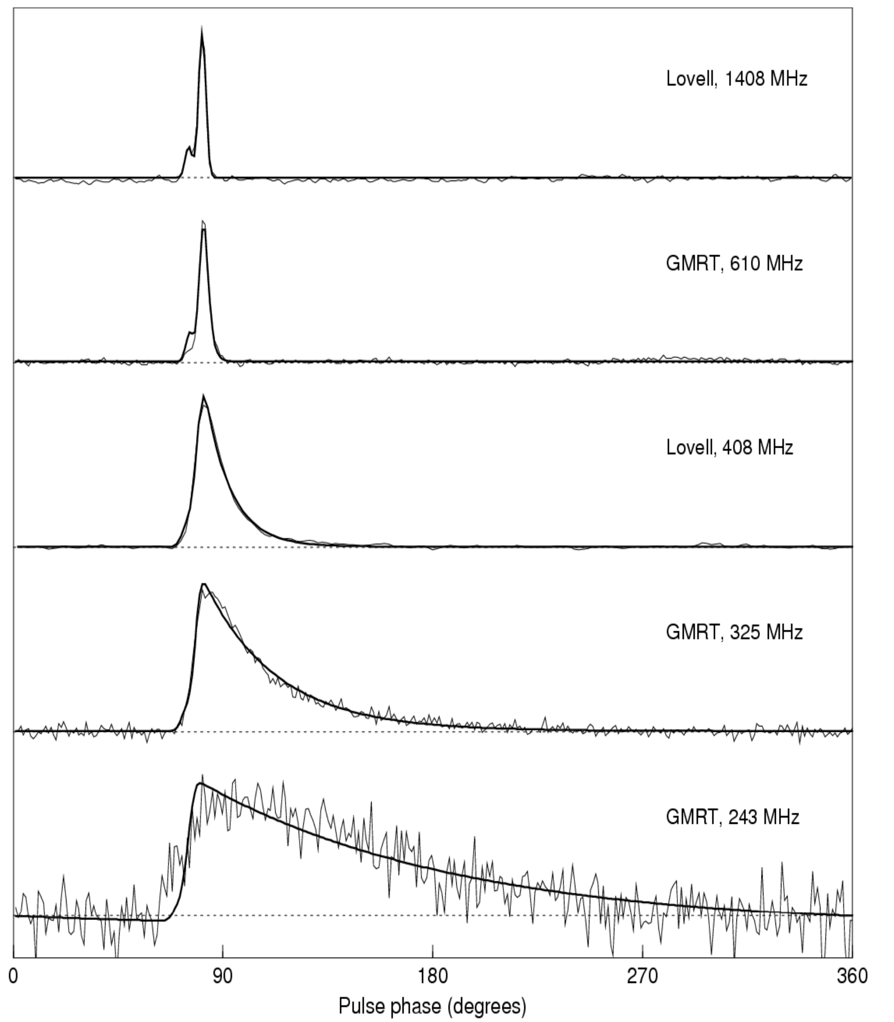
Credit: NASA animations

Pulsar Timing

Parkes Radio Telescope

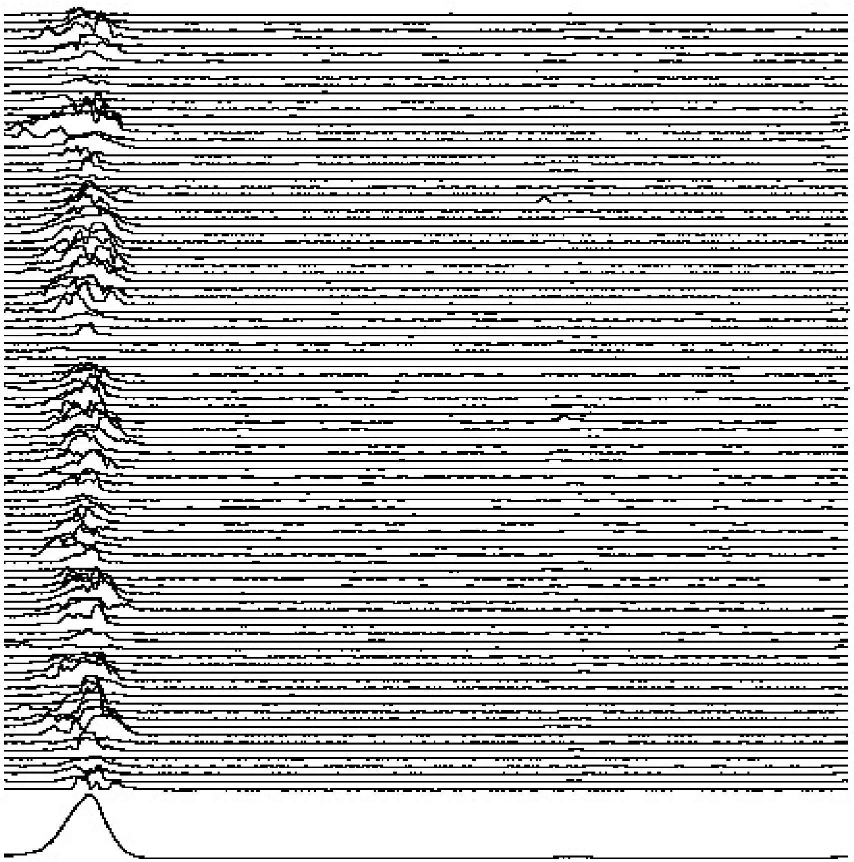
Dispersion $\Delta t \propto \frac{1}{f^2}$

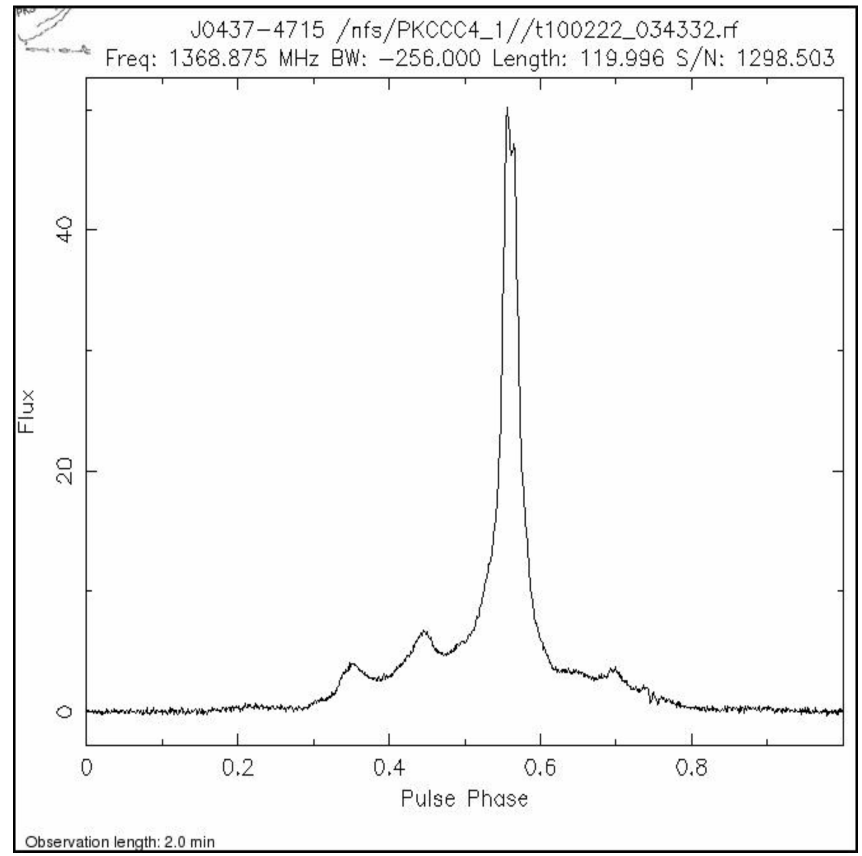




Ingrid Stairs (2001)

Pulse profiles





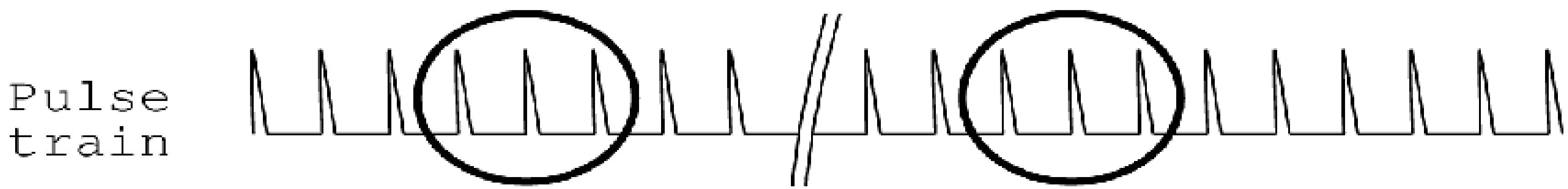
Ingrid Stairs (2001)

Timing residuals

Some typical numbers

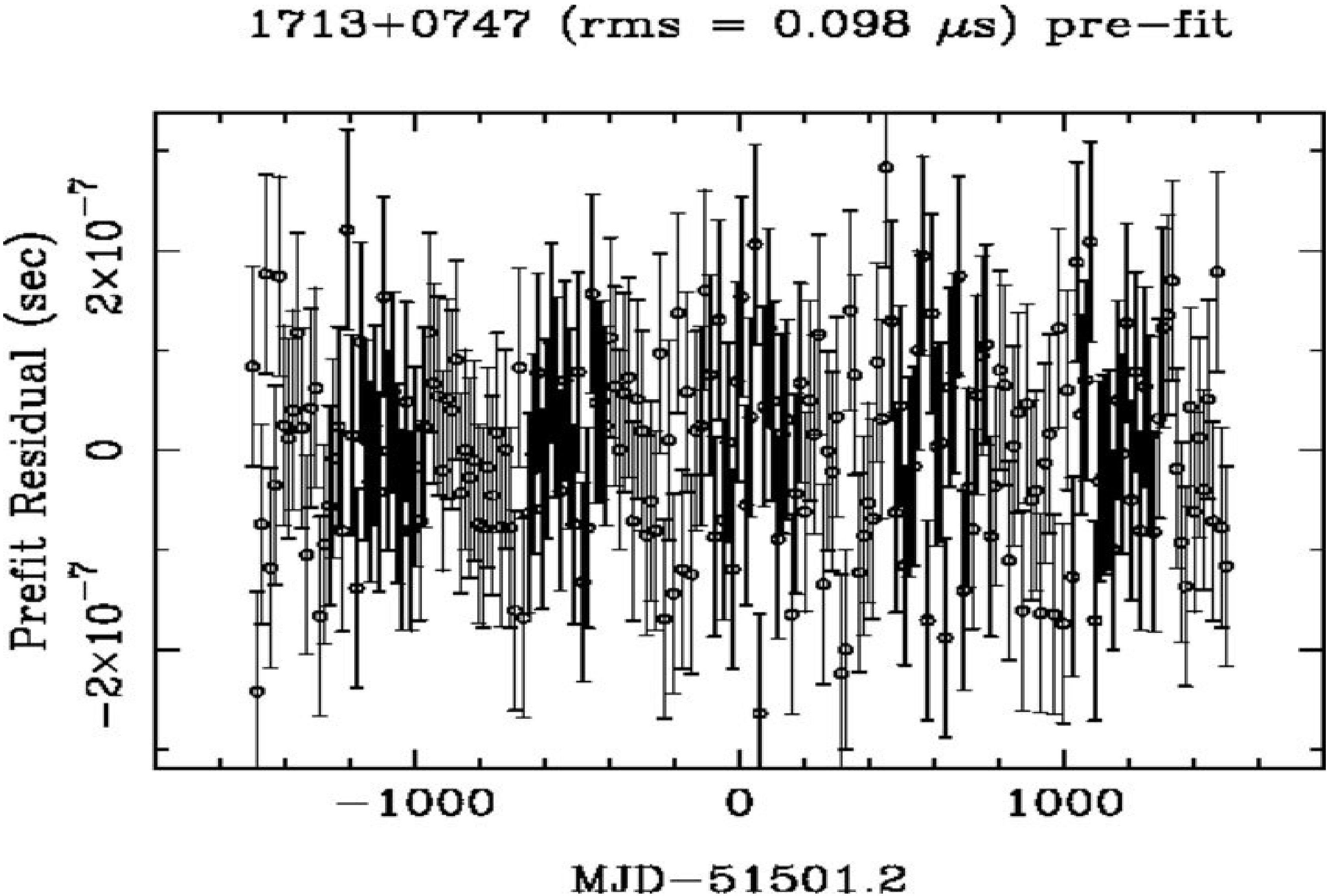
- **Pulse period:** 5 ms
- **Pulse width:** 0.5 ms (~10% of period)
- **Timing accuracy:** 100 ns
- **Pulsar distance:** several kpc (3 * 10^19 m)

→ sensitivity to distance variations of 30 m (< 1 part in 10^18)

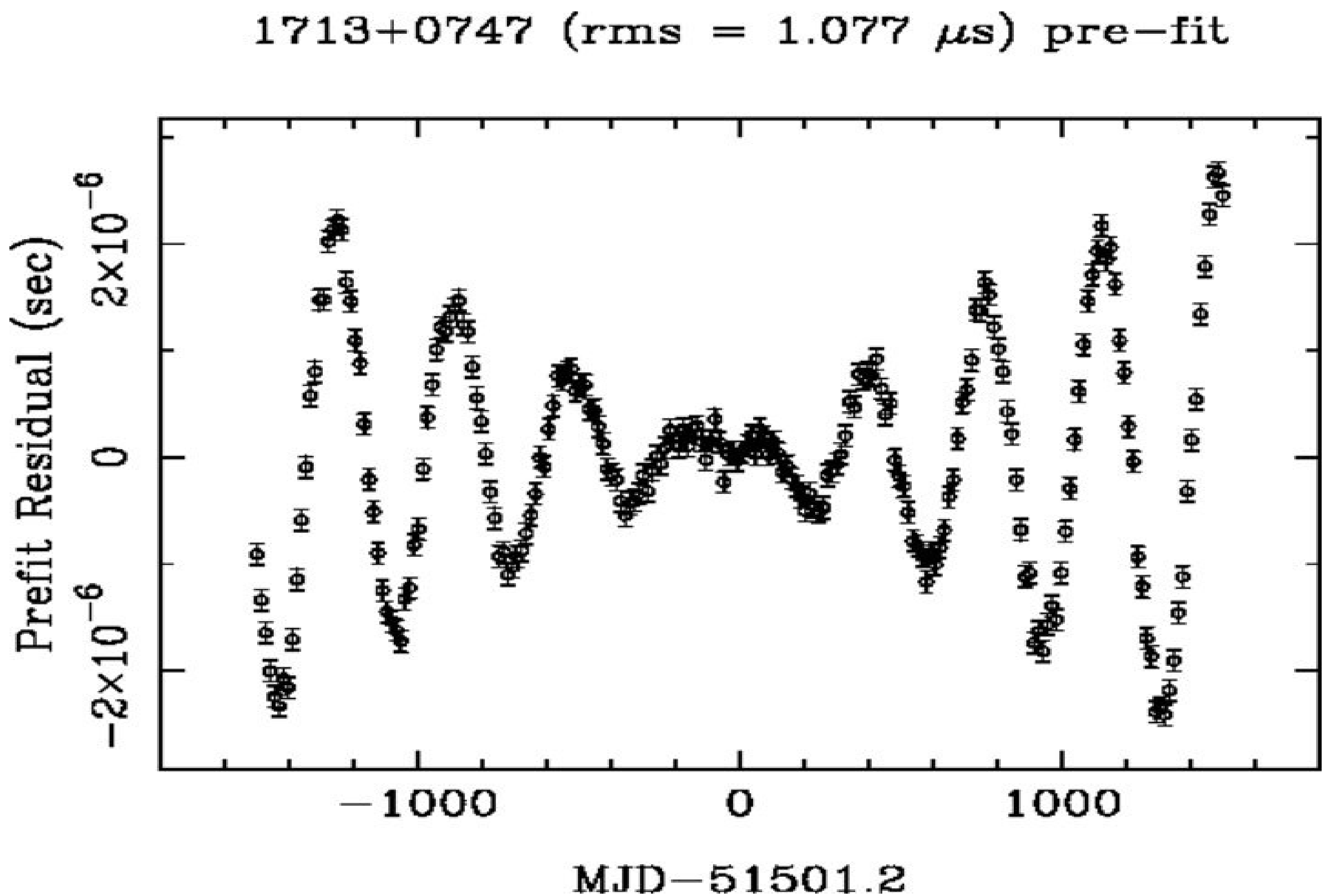


Can account for every not-observed rotation!

Timing residuals

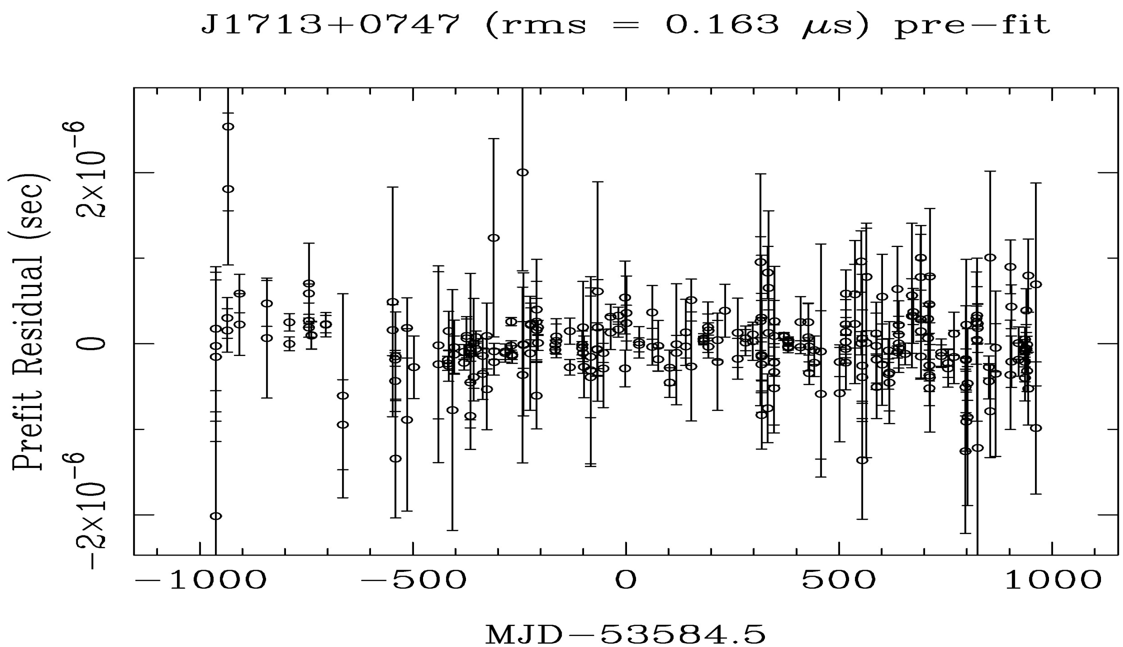


Wrong proper motion



'Standard' procedure

- Observe really often: get coherent solution
- Obtain longer time baseline: tune parameters
- Extend the timing model as much as possible
- Keep fitting until it looks ok

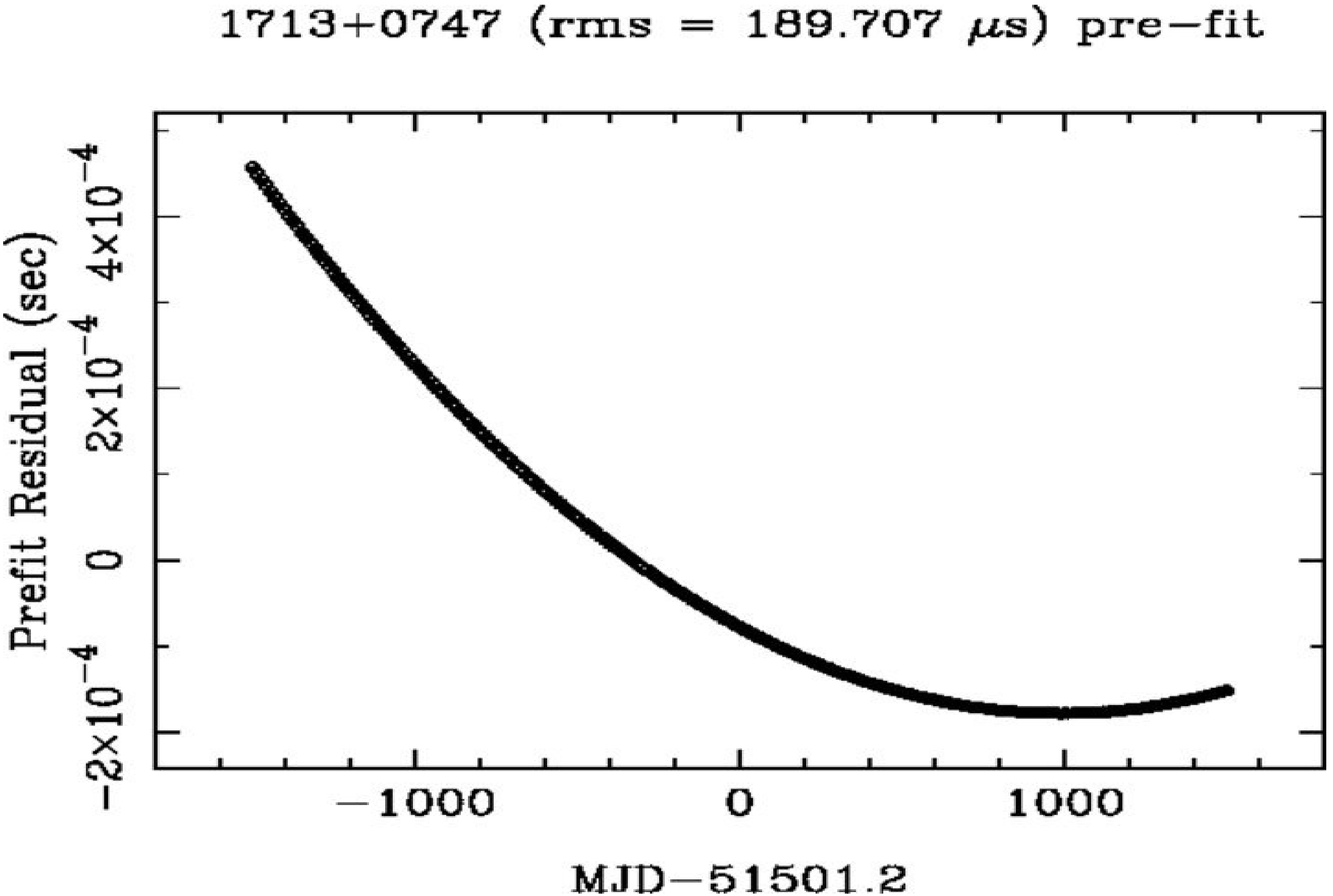


Not automated

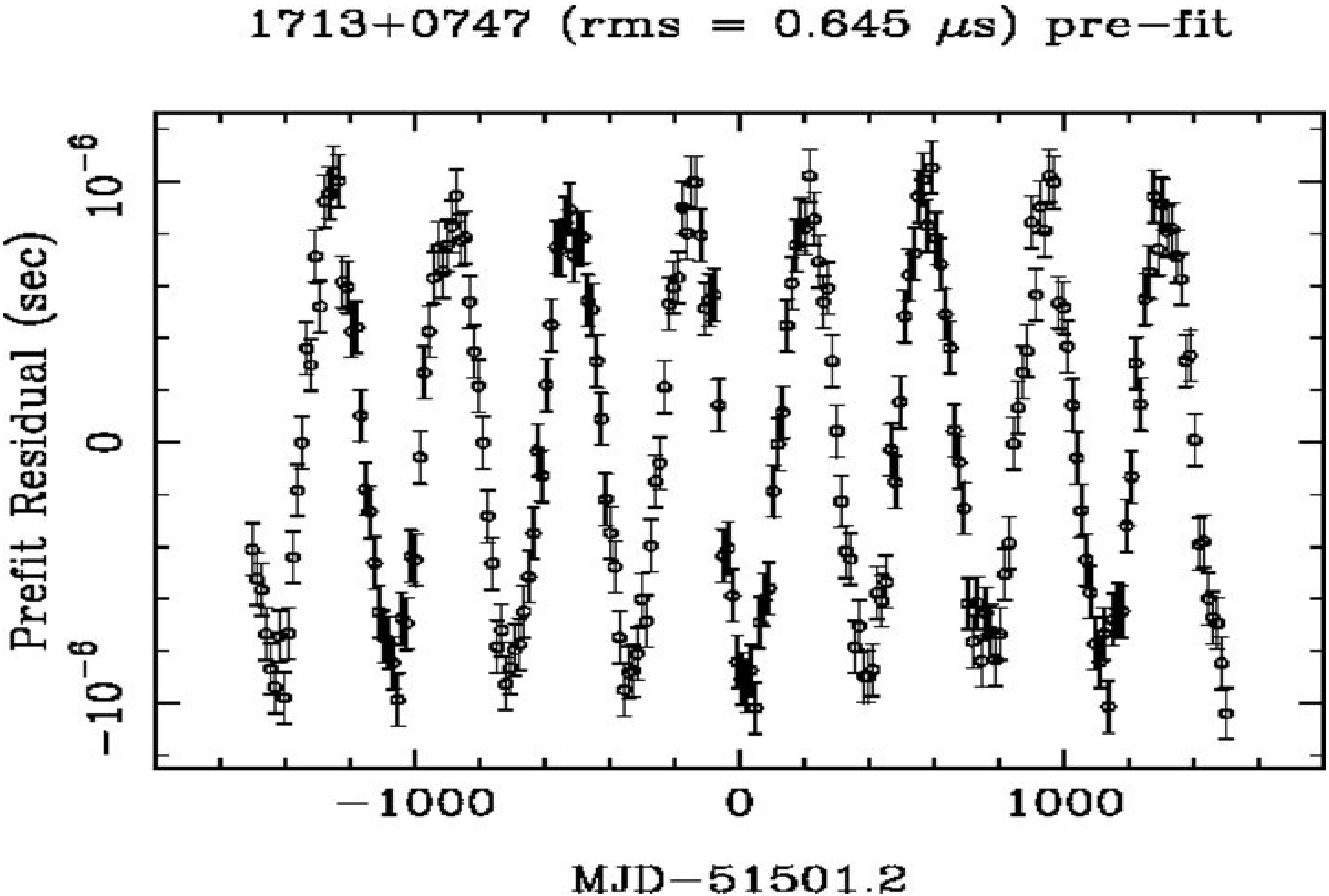
"Pulsar timing is an art"

– G.H. Hobbs

The timing model: spindown



The timing model: declination



Red spin noise / timing noise

Gravitational wave?

Timing noise?

Examples of pulsar timing

Pulsar timing basically uses pulsars as 'tools'. We do not fully understand pulsar emission, but they are very useful!

Let's look at some applications of pulsar timing...

The Hulse-Taylor binary

Hulse and Taylor found a binary pulsar in 1973. Nobel prize 1993.

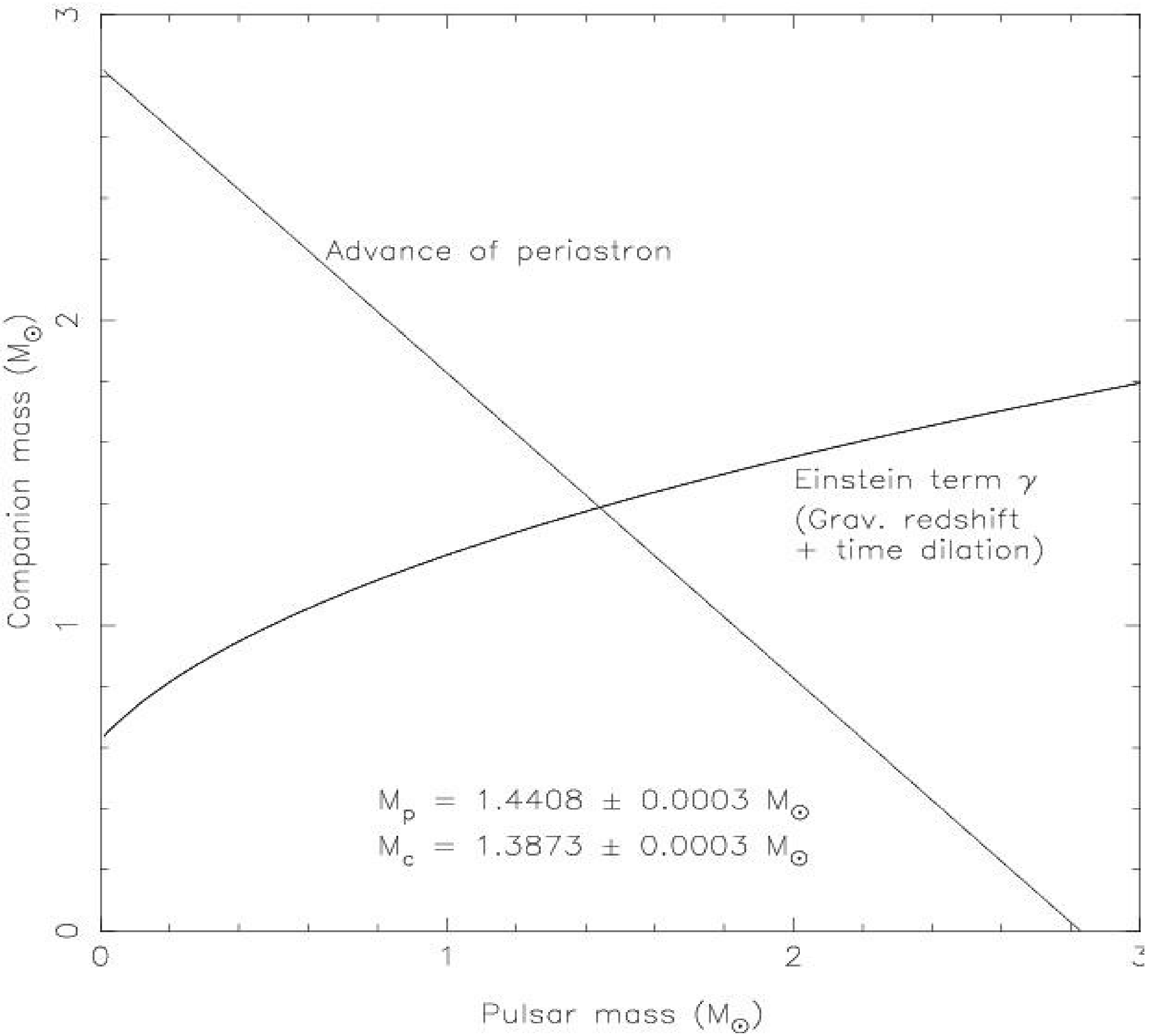
Parameter	Value
Orbital period P_b (d)	0.322997462727(5)
Projected semi-major axis x (s)	2.341774(1)
Eccentricity e	0.6171338(4)
Longitude of periastron ω (deg)	226.57518(4)
Epoch of periastron T_0 (MJD)	46443.99588317(3)
Advance of periastron $\dot{\omega}$ (deg yr^{-1})	4.226607(7)
Gravitational redshift γ (ms)	4.294(1)
Orbital period derivative $(\dot{P}_b)^{obs}$ (10^{-12})	$-2.4211(14)$

Table 2: *Orbital parameters for PSR B1913+16 in the DD framework, taken from [144].*

Post-keplerian parameters

The PK parameters are constructed such that only the two masses are unknown.

Thus: only two unknown parameters!



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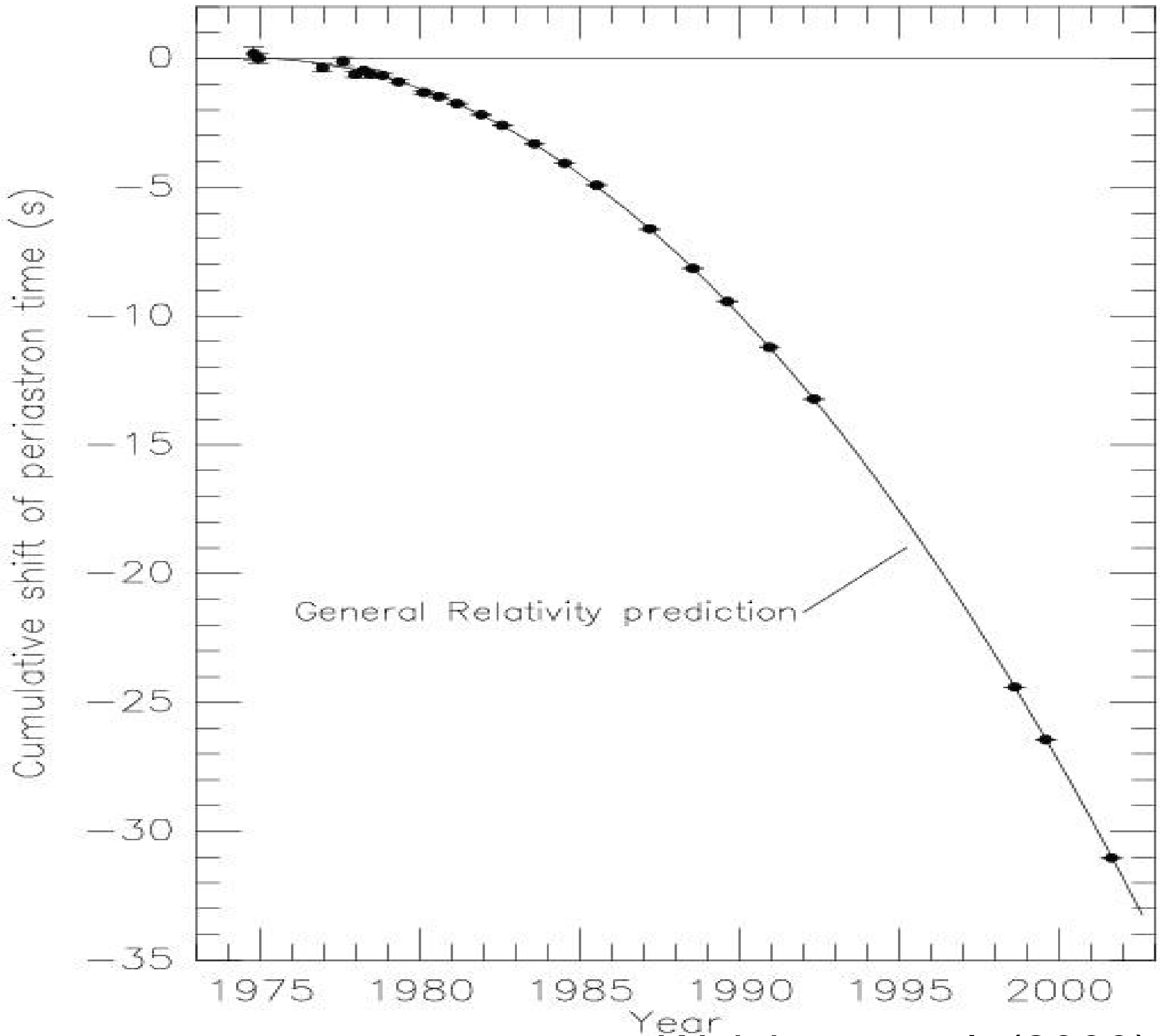
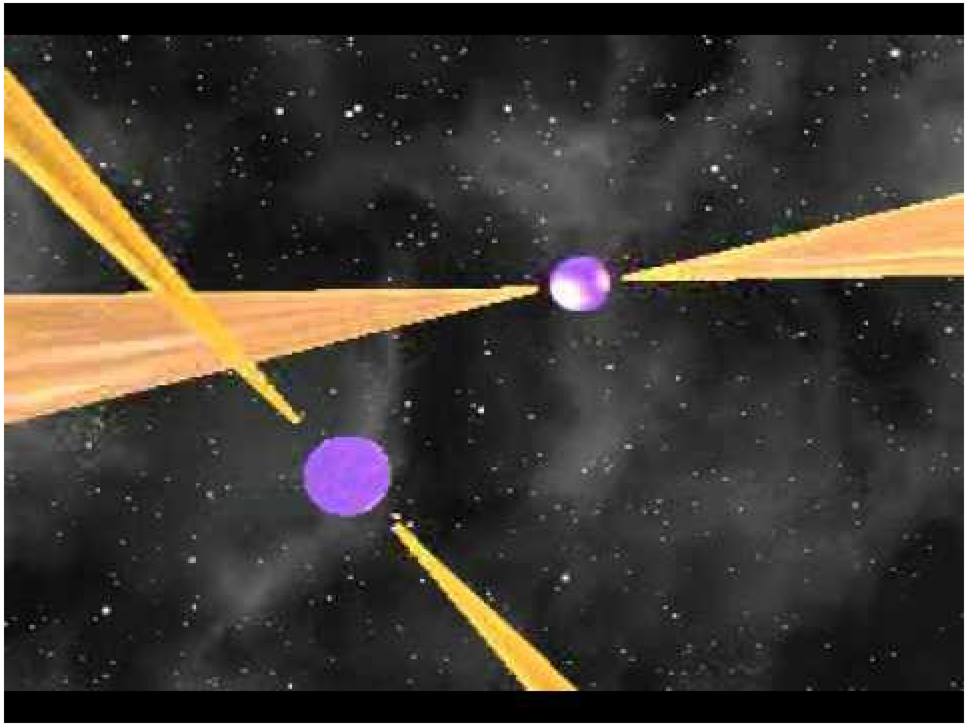


Weisberg et al. (2003)

Double pulsar

Discovered in the Parkes multibeam survey (Burgay et al. 2003). Incredibly lucky: edge-on system. Eclipses probe pulsar magnetosphere



Double pulsar GR tests

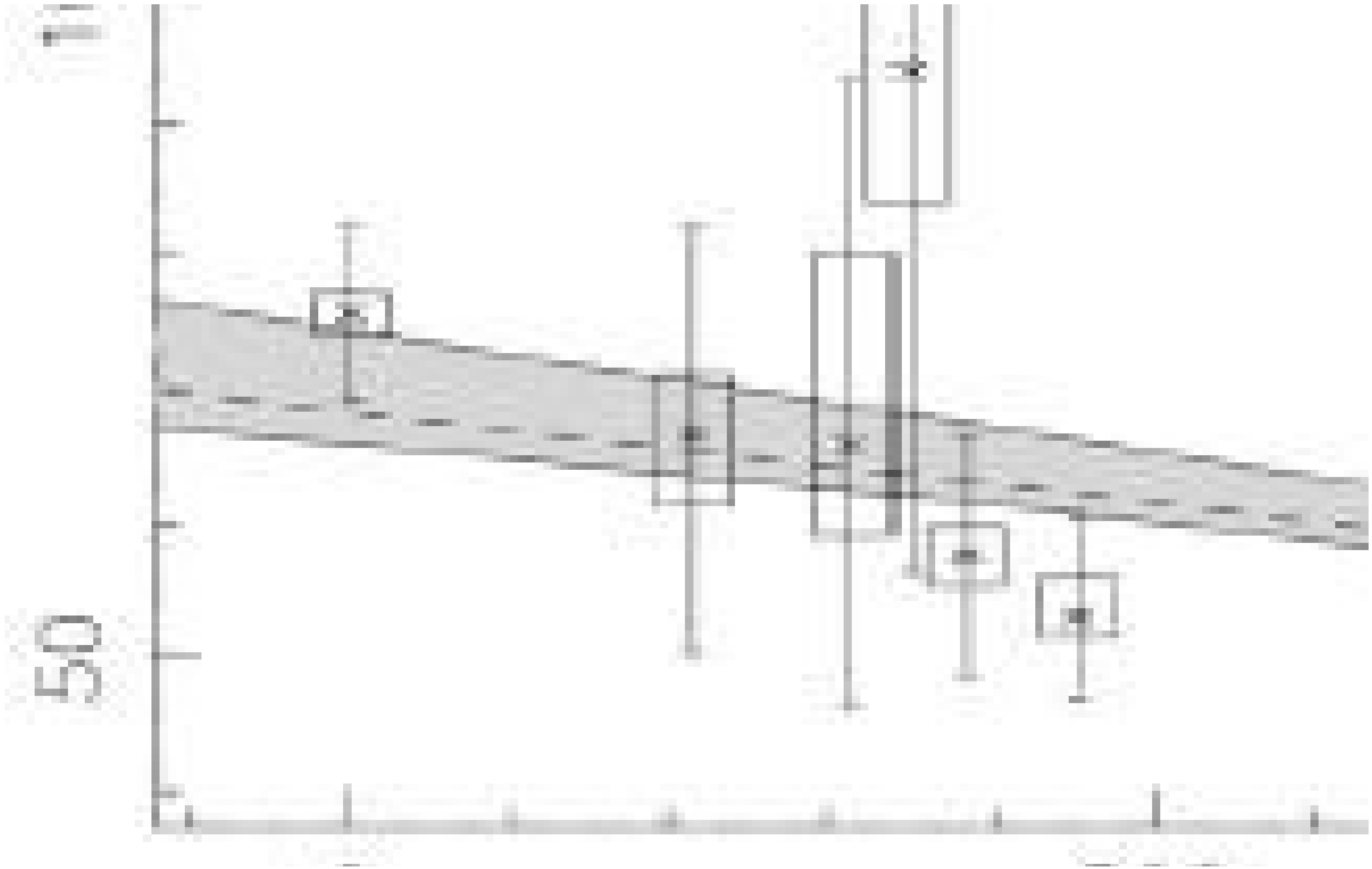
w: precession of periastron
g: time dilation gravitational redshift
r: Shapiro time delay (range)
S: Shapiro time delay (shape)
Pb: sec. change of the orbital period
R: mass ratio

Kramer et al. (2006)

Double pulsar magnetosphere

Breton et al. (2006)

Geodetic precession



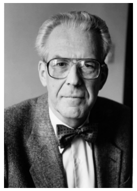
Breton et al. (science)   Only available for the double pulsar.

Constraining dipolar GWs

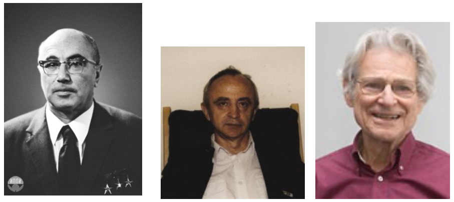
Freire et al. (2012): dipolar GW emission in pulsar-white dwarf systems are predictions of most alternate scalar-tensor theories of gravity, and tensor-vector-scalar (TeVeS) theories (relativistic MOND).

Pulsar Timing GWs: SMBHBs

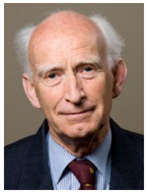
1917. Karl Schwarzschild finds an analytical solution for the Einstein field equations, predicting black holes



1962. Quasars discovered at billions of light years by Schmidt.



1964. Zeldovich & Novikov and Salpeter argue that Quasars are powered by the accretion of gas onto supermassive black holes



1969. Lynden-Bell argues that supermassive black holes should exist at the centers of many galaxies.

1996+. Hubble Telescope observations, analyzed using Martin Schwarzschild's method, establish that supermassive black holes exist in the large majority of galaxies with a central bulge.

Observations: ESO's 8.2 m Very Large Telescope (VLT)

Evolution of galaxies and their massive black holes

Question: how do black holes evolve?

Galaxy formation

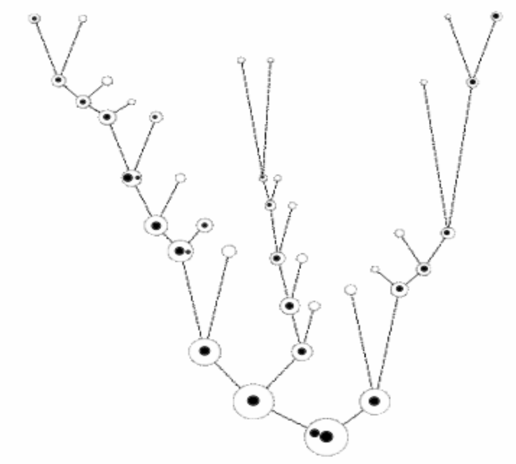
Universe becomes matter-dominated at z=10000. Gravitational instability becomes effective.

↓

Small halos collapse first, small galaxies form first

↓

Smaller galaxies merge to form large spirals and ellipticals.



Marta Volonteri (2003)

White & Rees 78

Supermassive BH binaries

Begelman, Blandford, &Rees 1982:

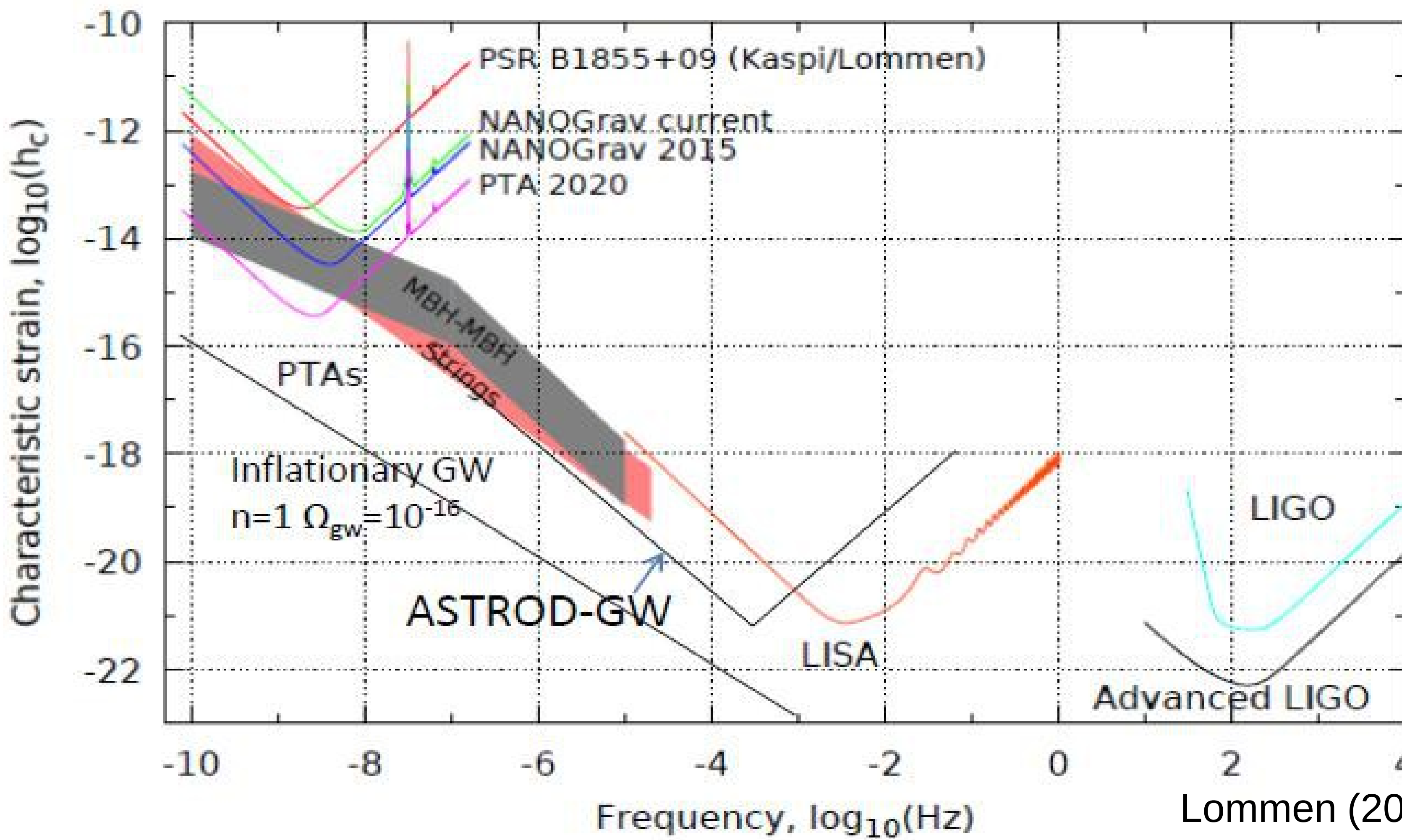
10 kpc → 2pc → 1pc → 0.01pc → merger

dynamical friction | scattering | wishful thinking | gravitational waves

wishful thinking →
- gas
- non-spherical potential
- another black hole

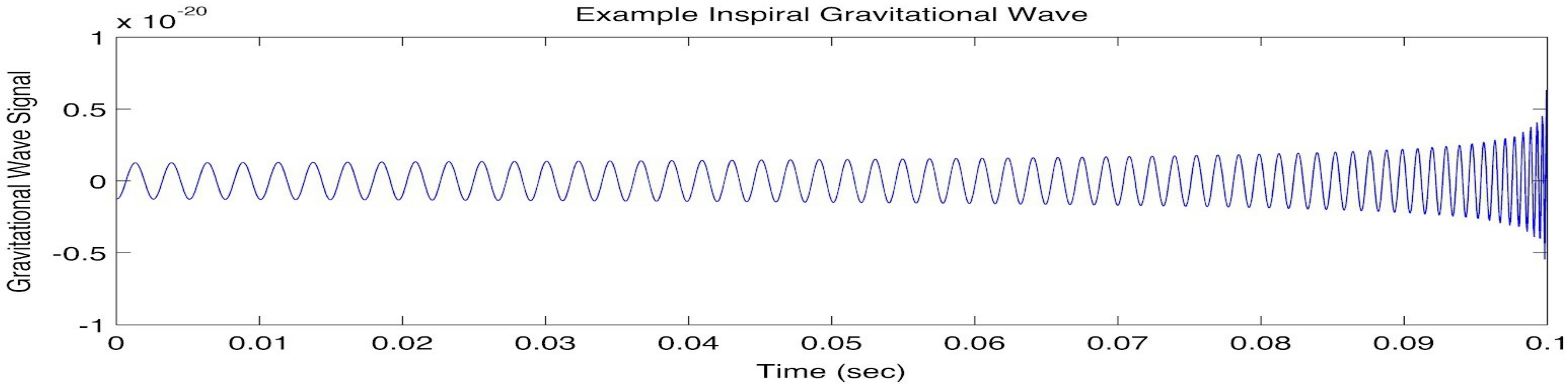
"last-parsec problem", considered mostly solved now

Frequency bands GW detectors



Lommen (2012)

Types of waveforms of interest



Inspiral – merger – ringdown

Inspiral: continuous wave
Merger: unresolvable.
Ringdown: unresolvable... but:

The memory effect is permanent!

Marc Favata (2010)

At low frequencies: background

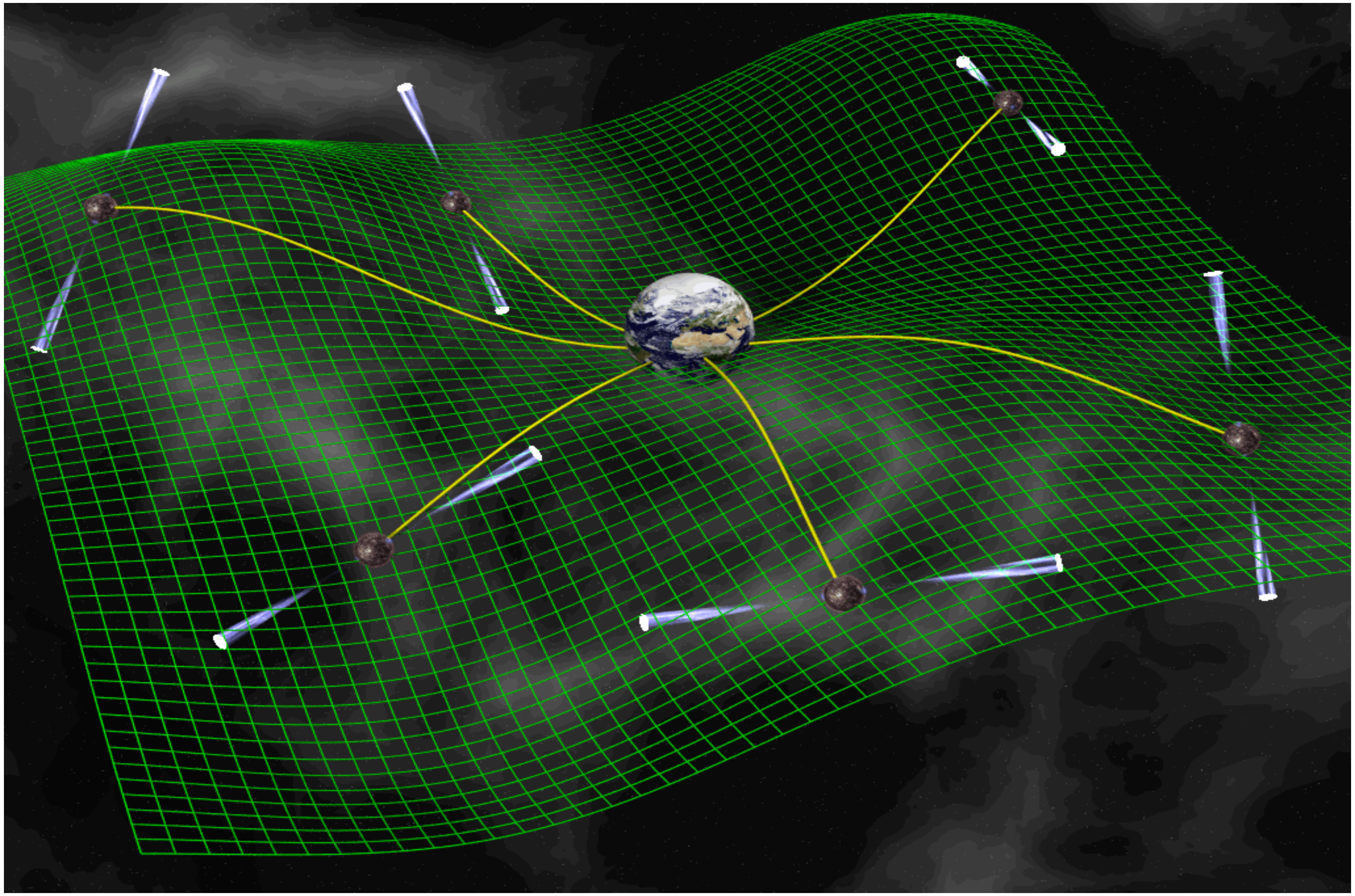
Phinney 01
Jaffe & Backer 03
Wyithe & Loeb 03
Sesana et al. 07, 09

General Relativity predicts:

$$\alpha = -2/3$$

$$h_c(f) = A \times (f/f_0)^\alpha$$

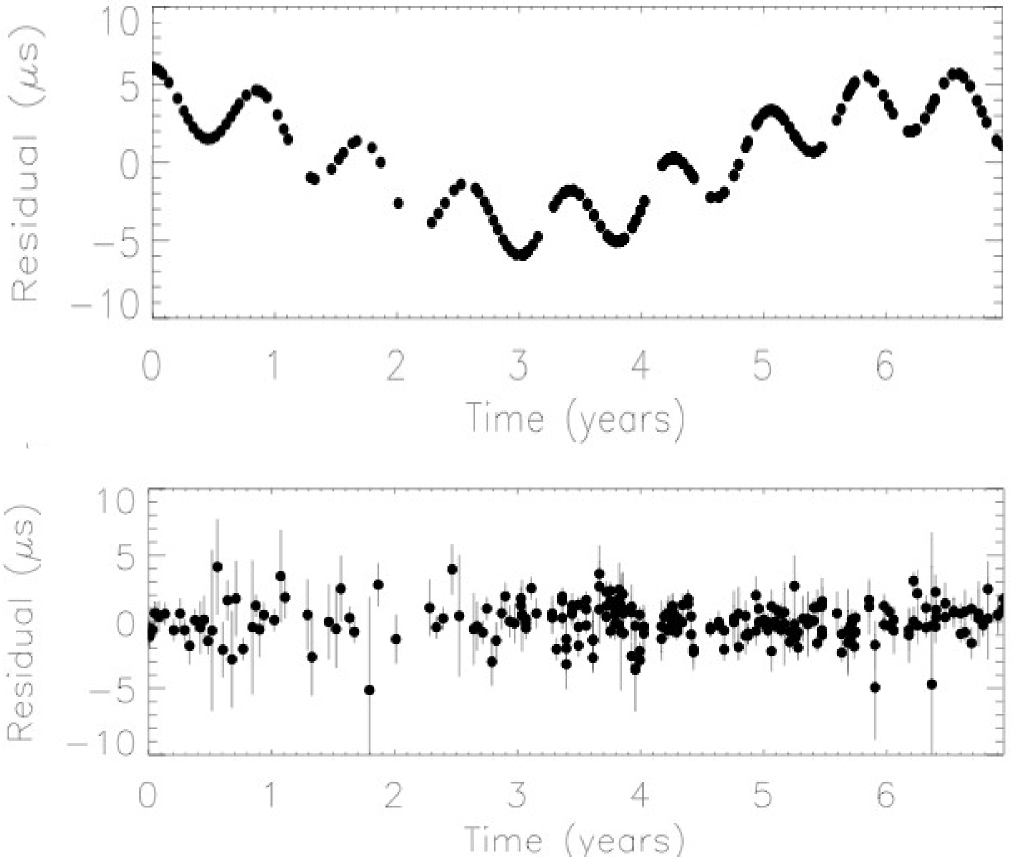
Pulsars and GW detection



Pulsars are nearly-perfect Einstein clocks. Very precise frequency standard. Can be used just like LASER in interferometers: phase-change due to propagation in GWs is observable.

Example: 3C66B

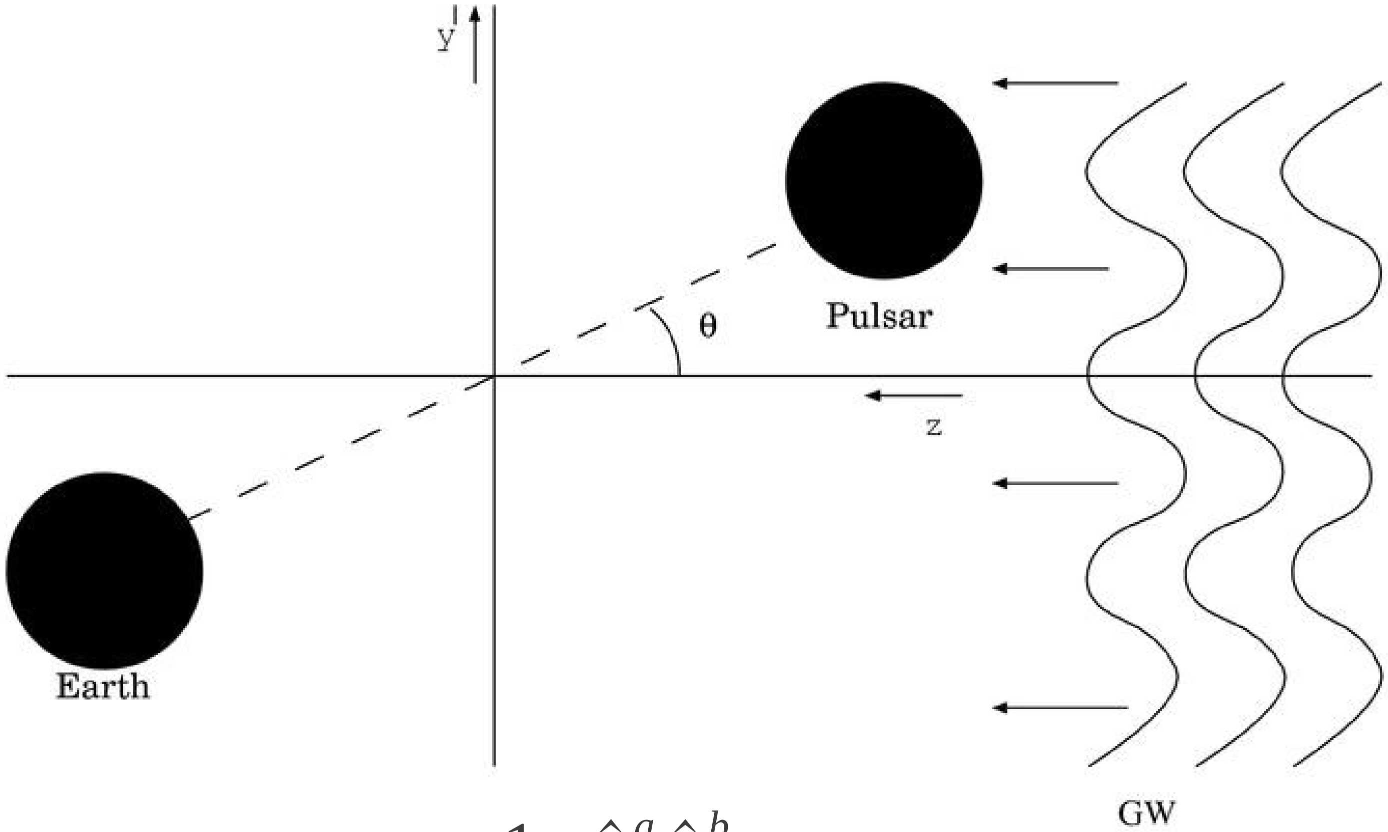
3C66B was a proposed supermassive binary black hole system. The emitted GWs should have been seen in B1855+09. System was ruled out



Jenet et al. (2004)

Data from Kaspi, Taylor, Ryba (1994) of pulsar PSR B1855+09

Earth term / Pulsar term

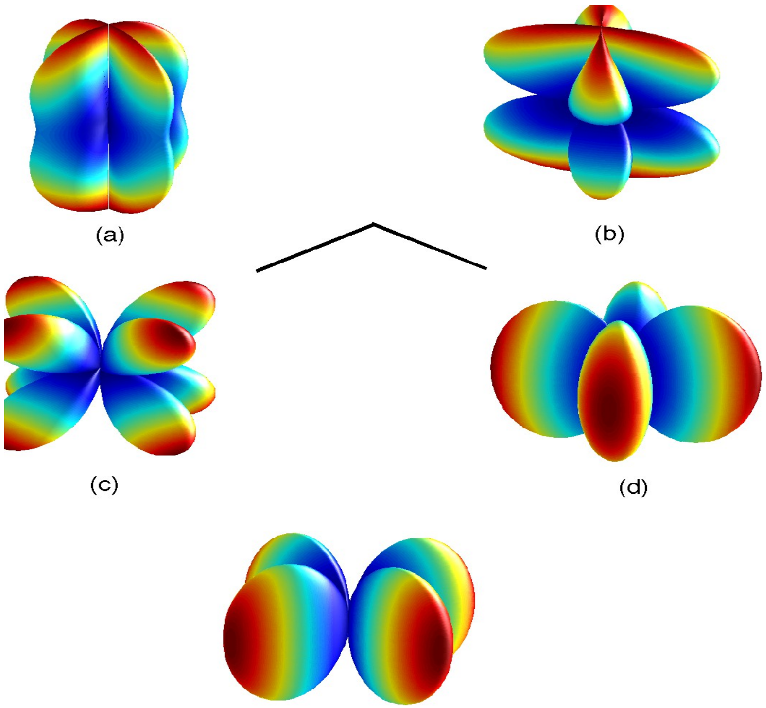


$$\frac{\delta\nu}{\nu} = e^{A}_{ab}(\hat{\Omega}) \frac{1}{2} \frac{\hat{p}^{a}\hat{p}^{b}}{1+\hat{\Omega}\cdot\hat{p}} \left(h_{e}(t_{e}) - h_{p}(t_{p}) \right)$$

Earth-term

Pulsar-term

Antenna pattern response



a,b: +,x polarisation
c,d: vector x,y modes
e: scalar mode

Most efforts focus on the usual +,x polarisations.

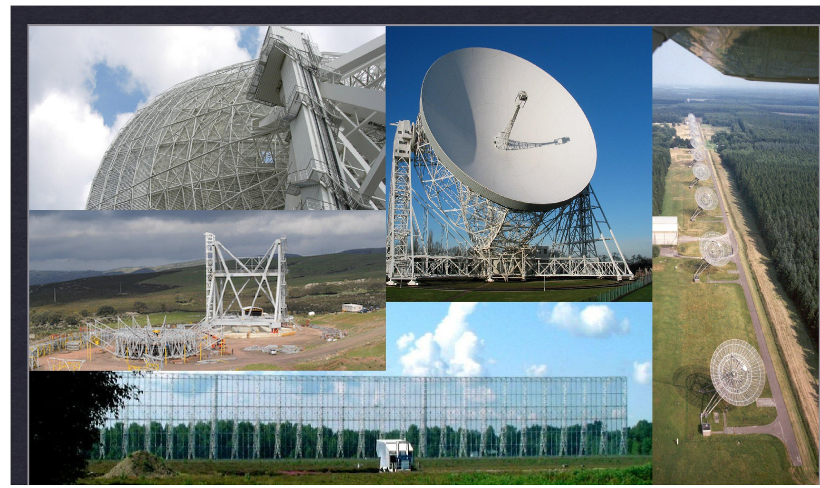
$$\frac{\delta\nu}{\nu} = e^{A}_{ab}(\hat{\Omega}) \frac{1}{2} \frac{\hat{p}^{a}\hat{p}^{b}}{1+\hat{\Omega}\cdot\hat{p}} \left(h_{e}(t_{e}) - h_{p}(t_{p})\right)$$

Earth-term

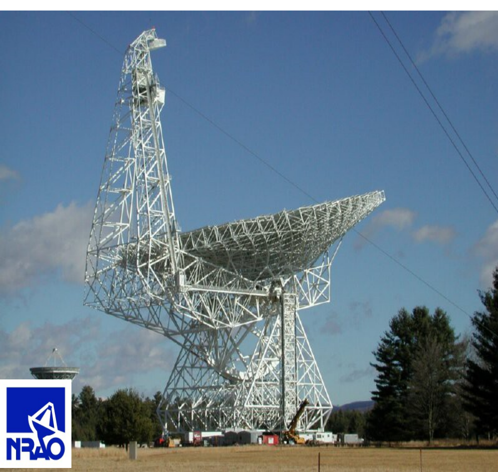
Pulsar-term

The Pulsar Timing Arrays

Parkes Pulsar Timing Array: Parkes radio telescope (64m). Oldest fully organised PTA effort. Best timing residuals to date. Southern Hemisphere



European Pulsar Timing Array: Effelsberg (100m), Westerbork synthesis (14x25m), Nancay (94m), Lovell (76m), Sardinia (64m). Most dishes.



NANOGrav: GreenBank (100m), Arecibo (300m). Biggest dishes.

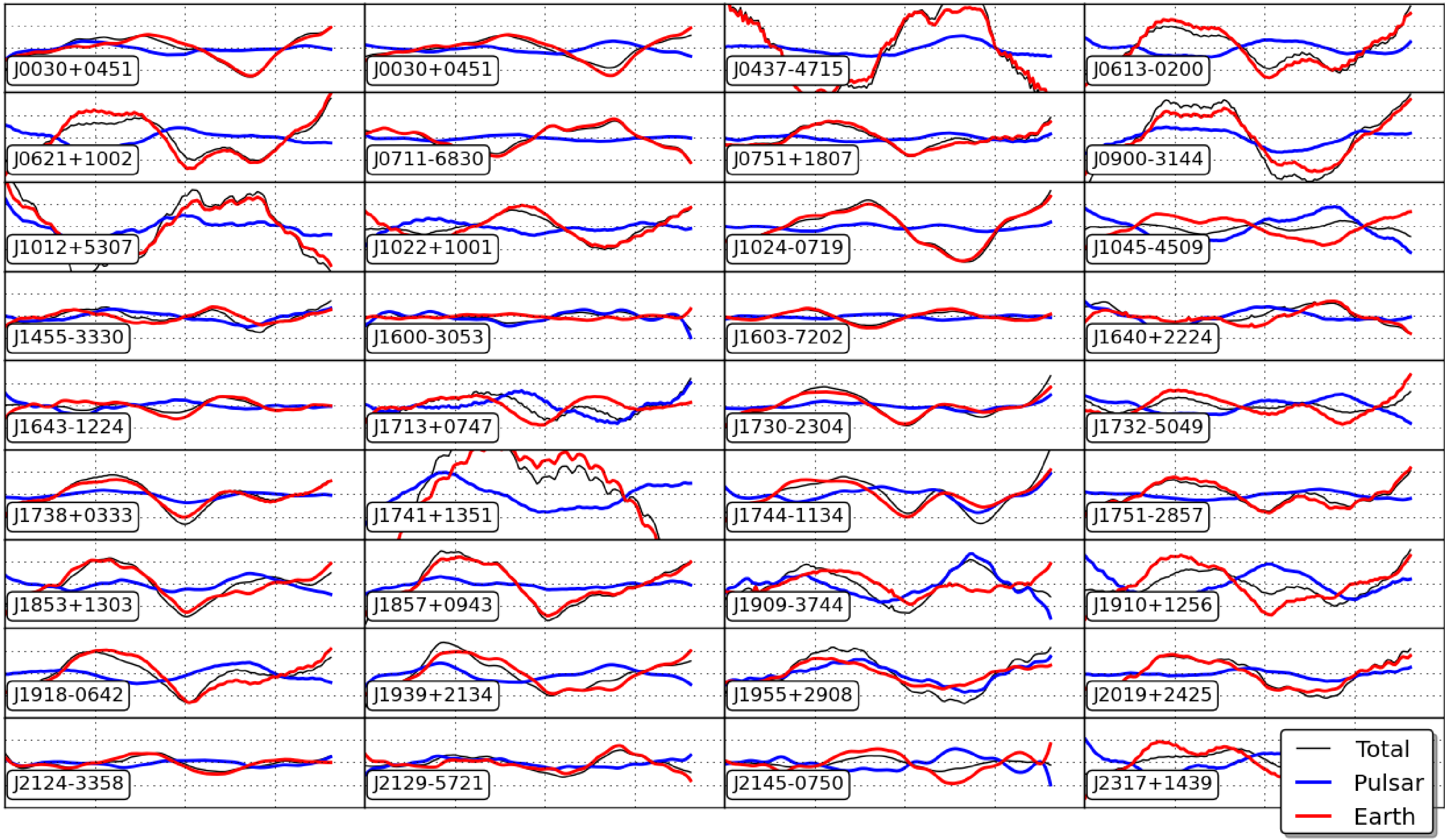
Typical signals in PTAs

Typical signals in PTAs

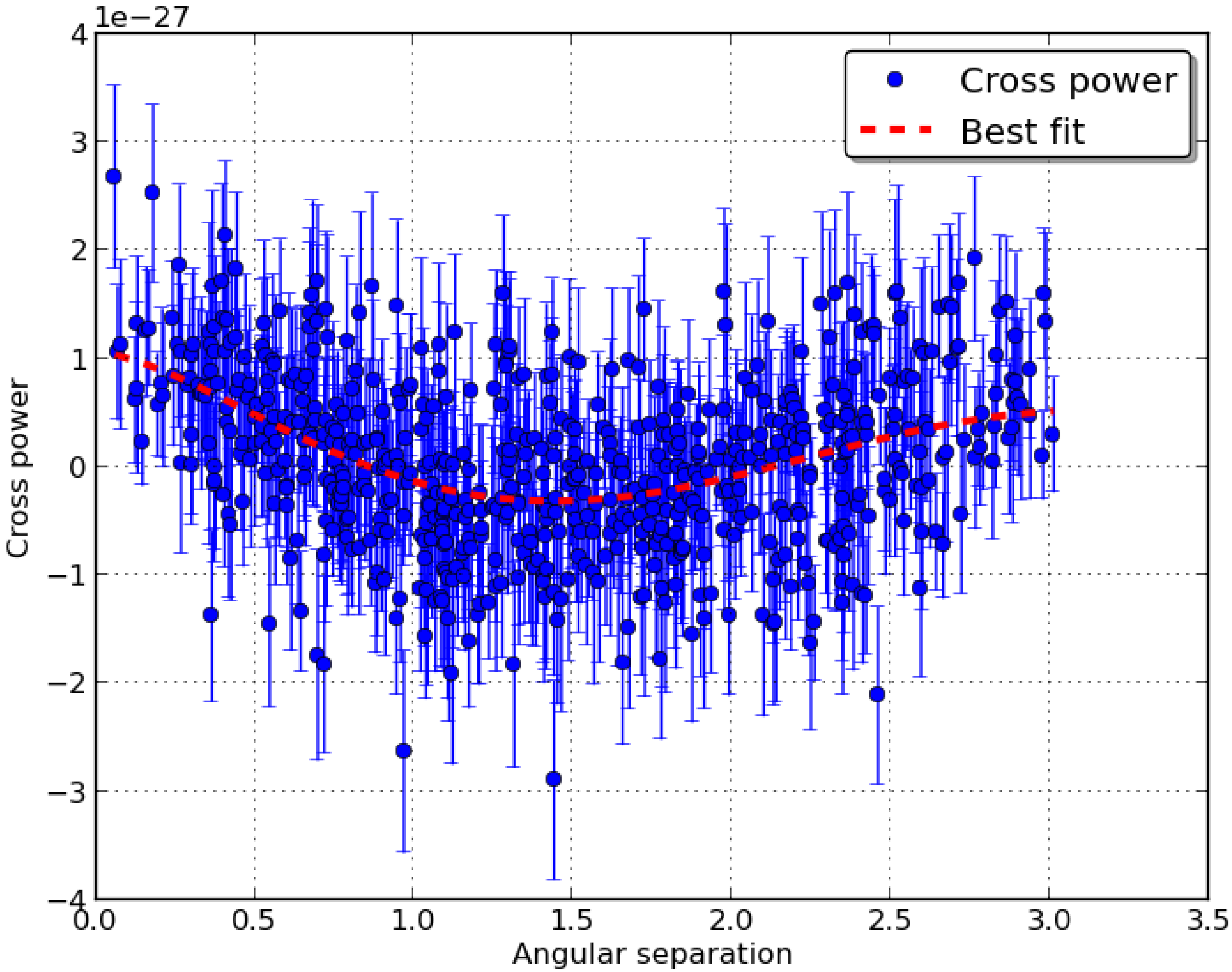
Stochastic isotropic signals are correlated between pulsars according to the overlap reduction function (Hellings & Downs curve). Due to quadrupolar nature of GWs.

Need many, many pulsars!!!

Stochastic GWB mock data

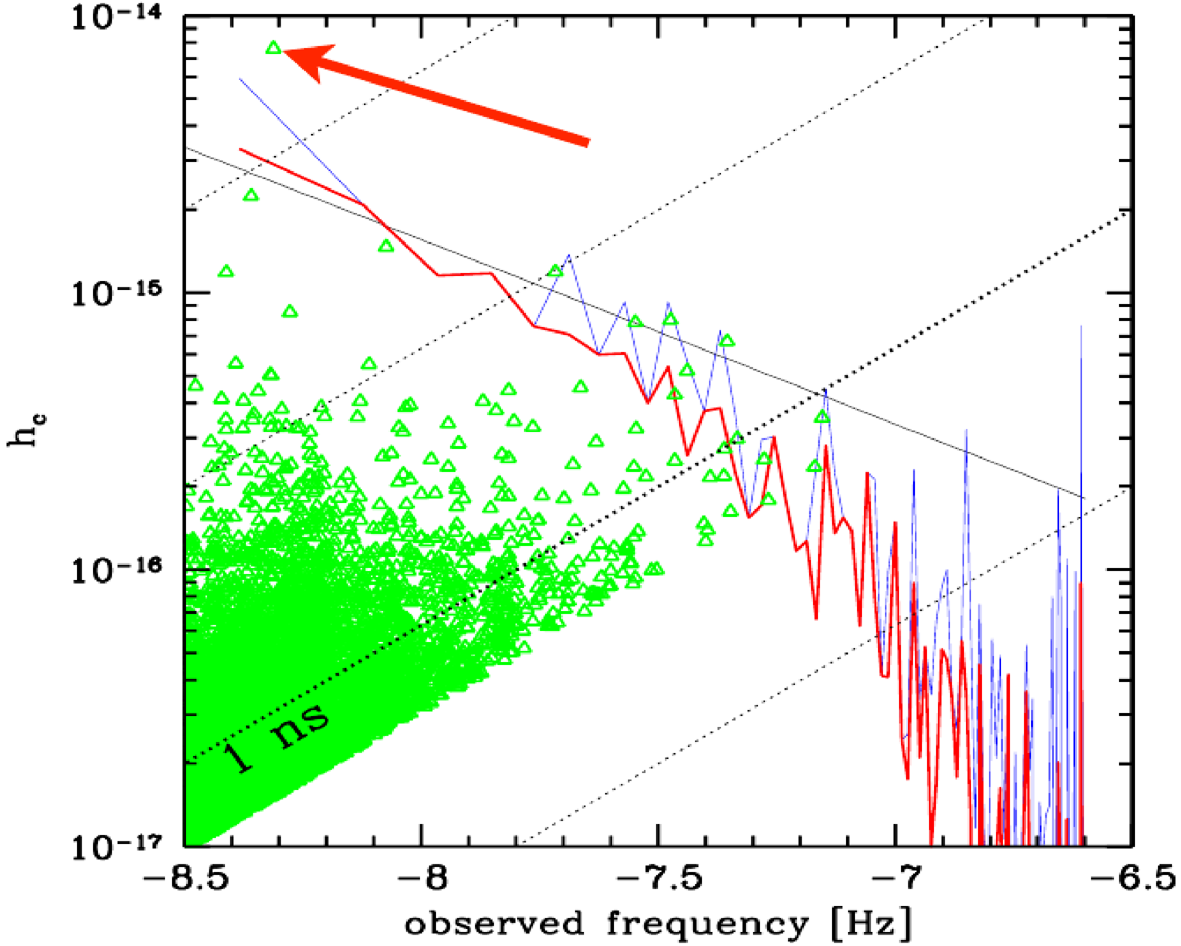


Searching for the H&D curve



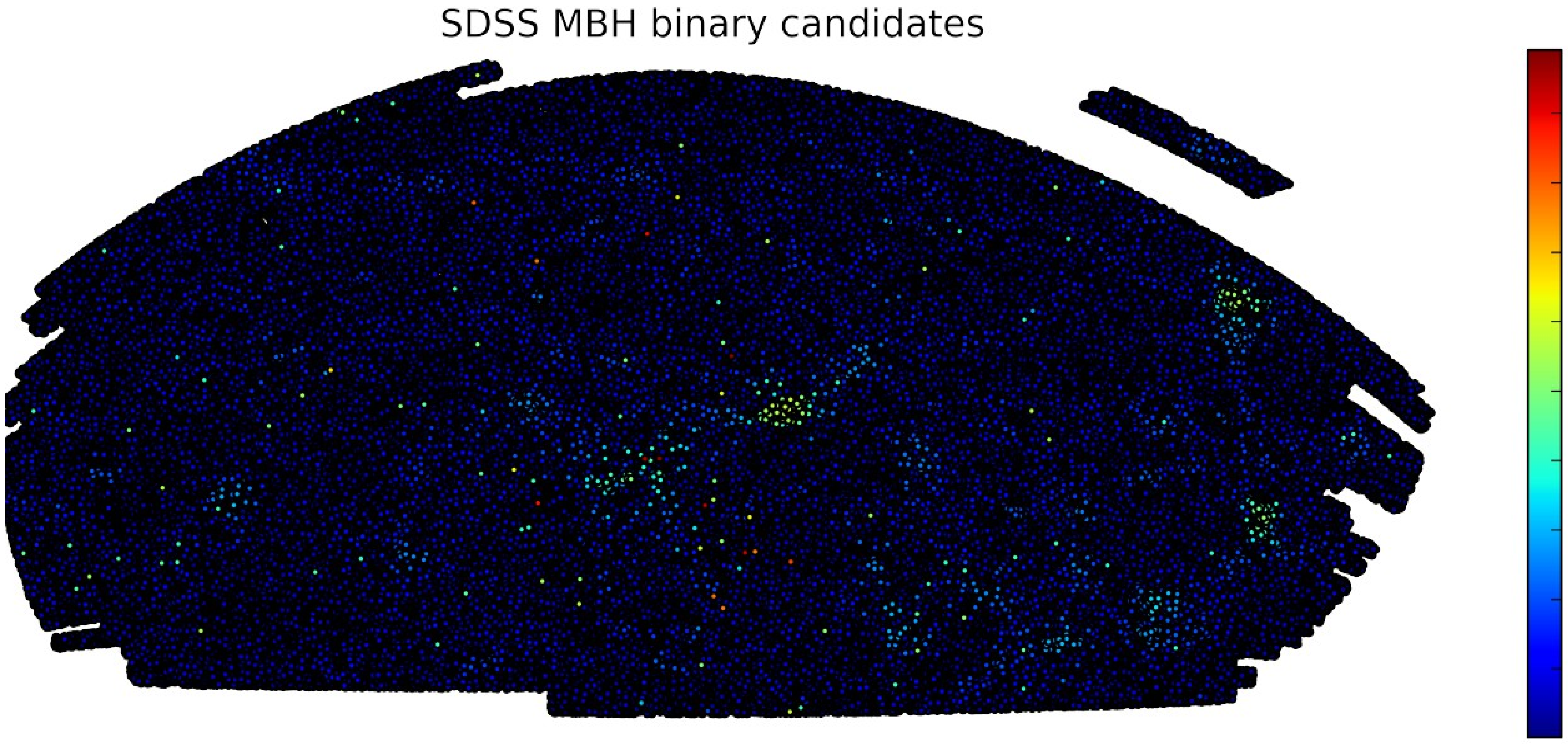
Jenet et al. (2005), Demorest et al. (2012), Lentati et al. (2013), Chamberlain (in prep.)

(An)Isotropy: millennium simulation



Sesana et al. (2008), Ravi et al. (2012): Theory and simulations suggest there is a non-zero probability that individual sources have SNR above the background.

Anisotropy: compare with SDSS



Pablo Rosado (AEI, preliminary): use SDSS to find candidates, predict statistics/GW hotspots. Test statistic based on Millennium simulation.

GW searches in PTA data

<u>Challenges in the analysis (compared to interferometers):</u>

- Irregularly sampled data with large gaps
- Unknown noise statistics
- Very low frequency signal (and noise)
- Various systematics that have to be mitigated (timing model, dispersion measure variations)

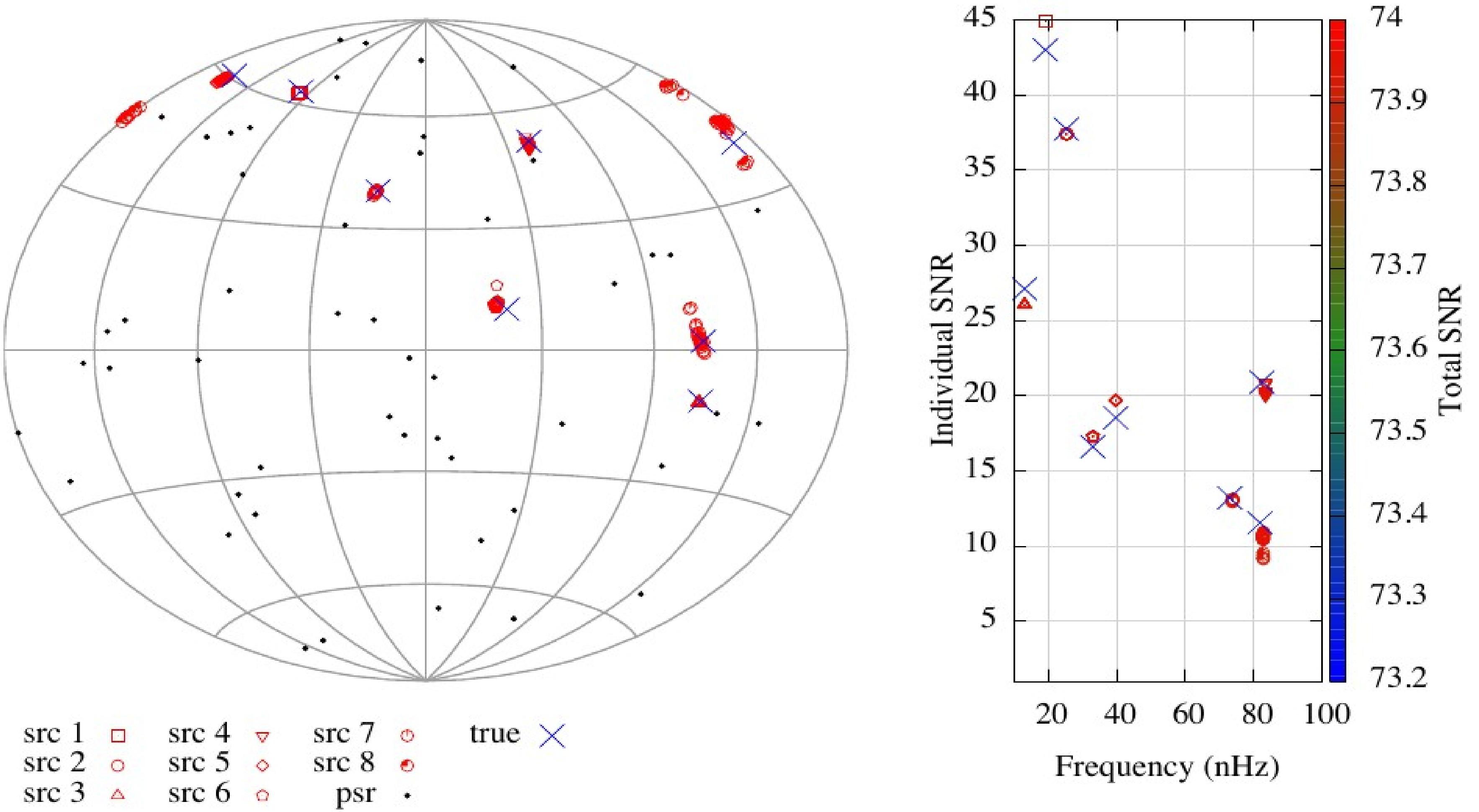
Our approach: Bayesian analysis (marginalisation, sampling, priors, …)

Likelihood a multivariate Gaussian:

$$P(\vec{x}|\vec{a}) = \frac{\exp\left[-(x - f(\vec{a}))C^{-1}(x - f(\vec{a}))/2\right]}{\sqrt{(2\pi)^n \det C}}$$

Practical difficulties... but we are getting there!

Continuous wave searches

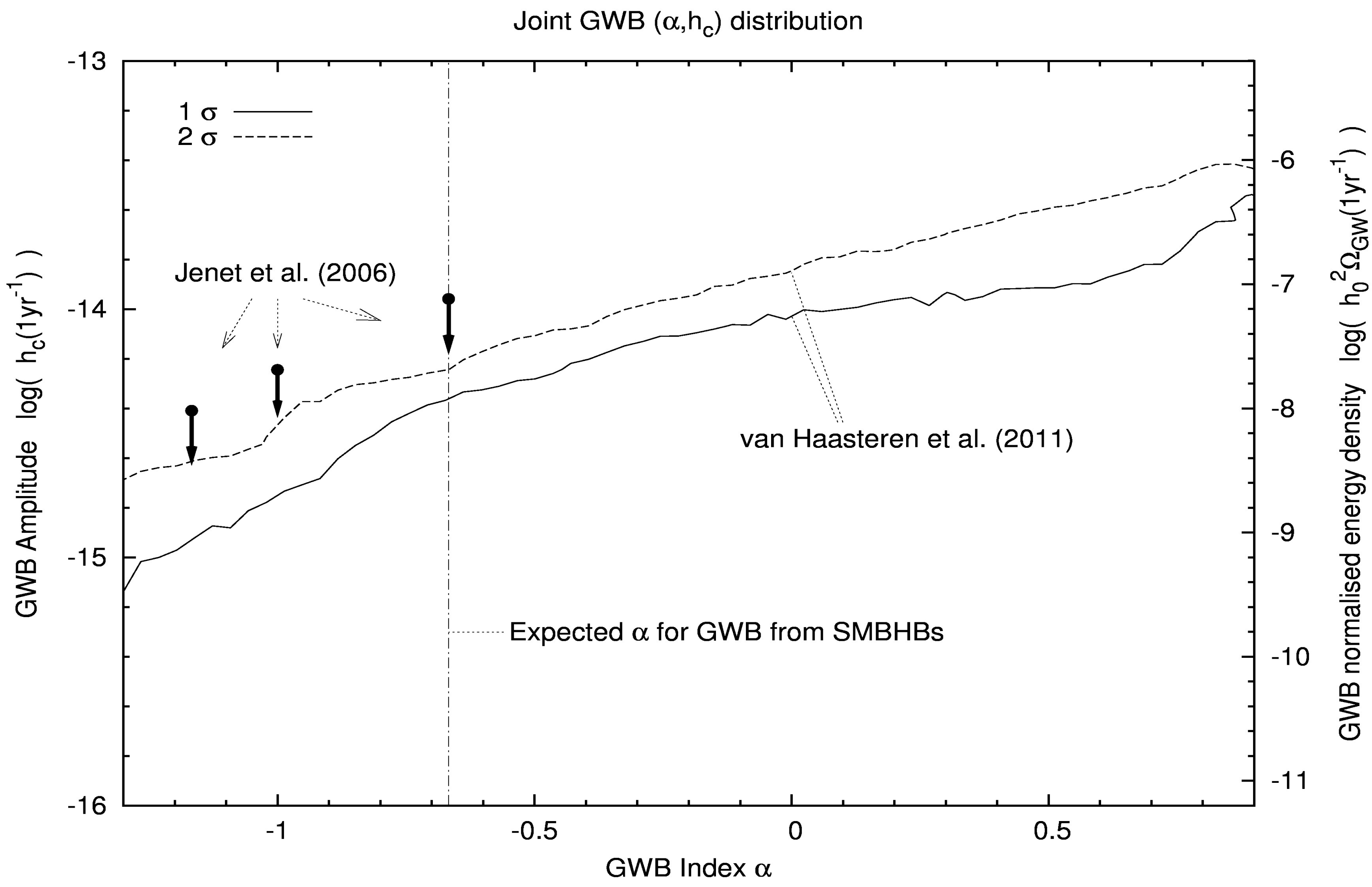


Babak, Petiteau et al. (2012): Parameter space of searches for continuous waves (single BH binaries) is quite large. Idea: use clever searches like genetic algorithm. Question: how many sources do we need?

Published upper limits: EPTA

Spectrum: $h_c(f) = Af^{-\alpha}$

Published upper limits: EPTA

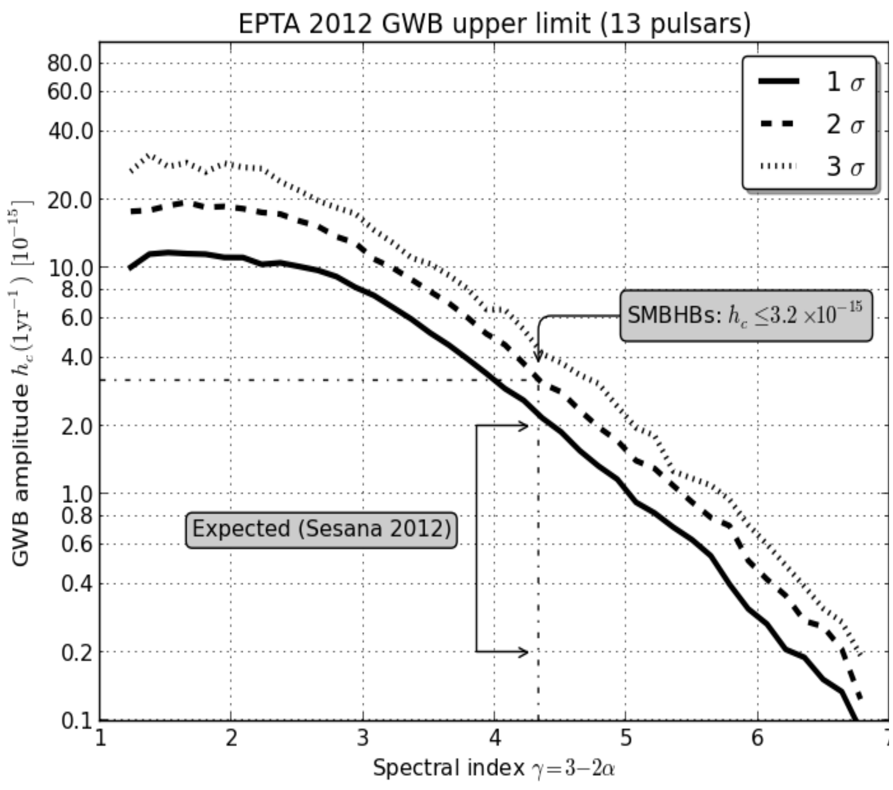


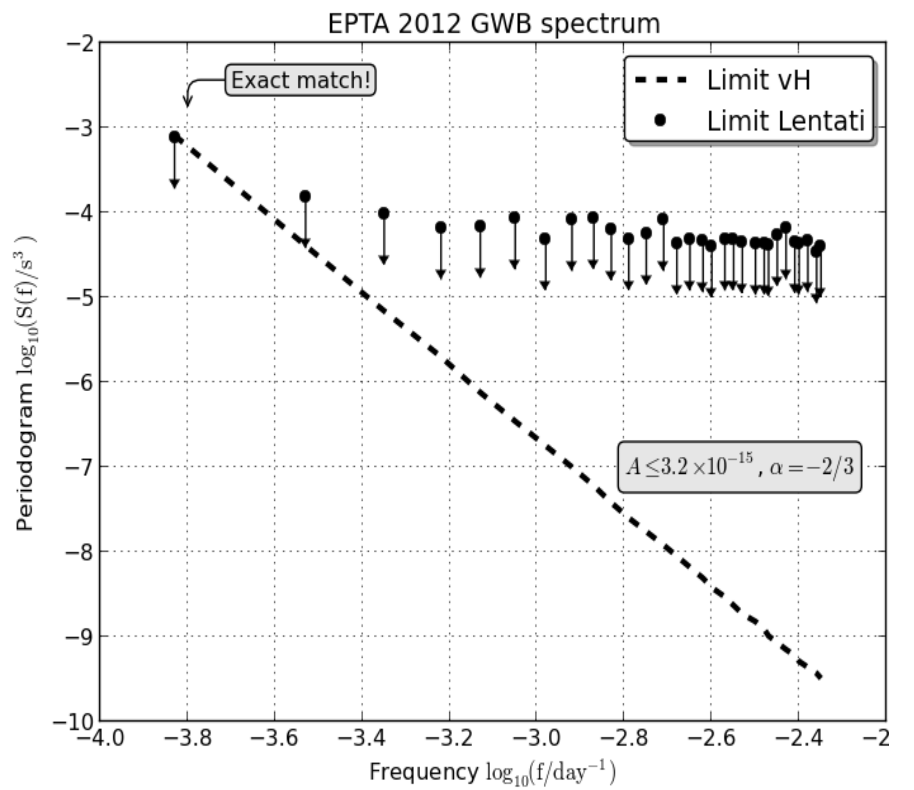
Spectrum: $h_c(f) = Af^{-\alpha}$ A < 6e-15

Published upper limits:NANOGrav

Demorest et al. (2012) $h_c(f) = Af^{-\alpha}$ A < 7e-15

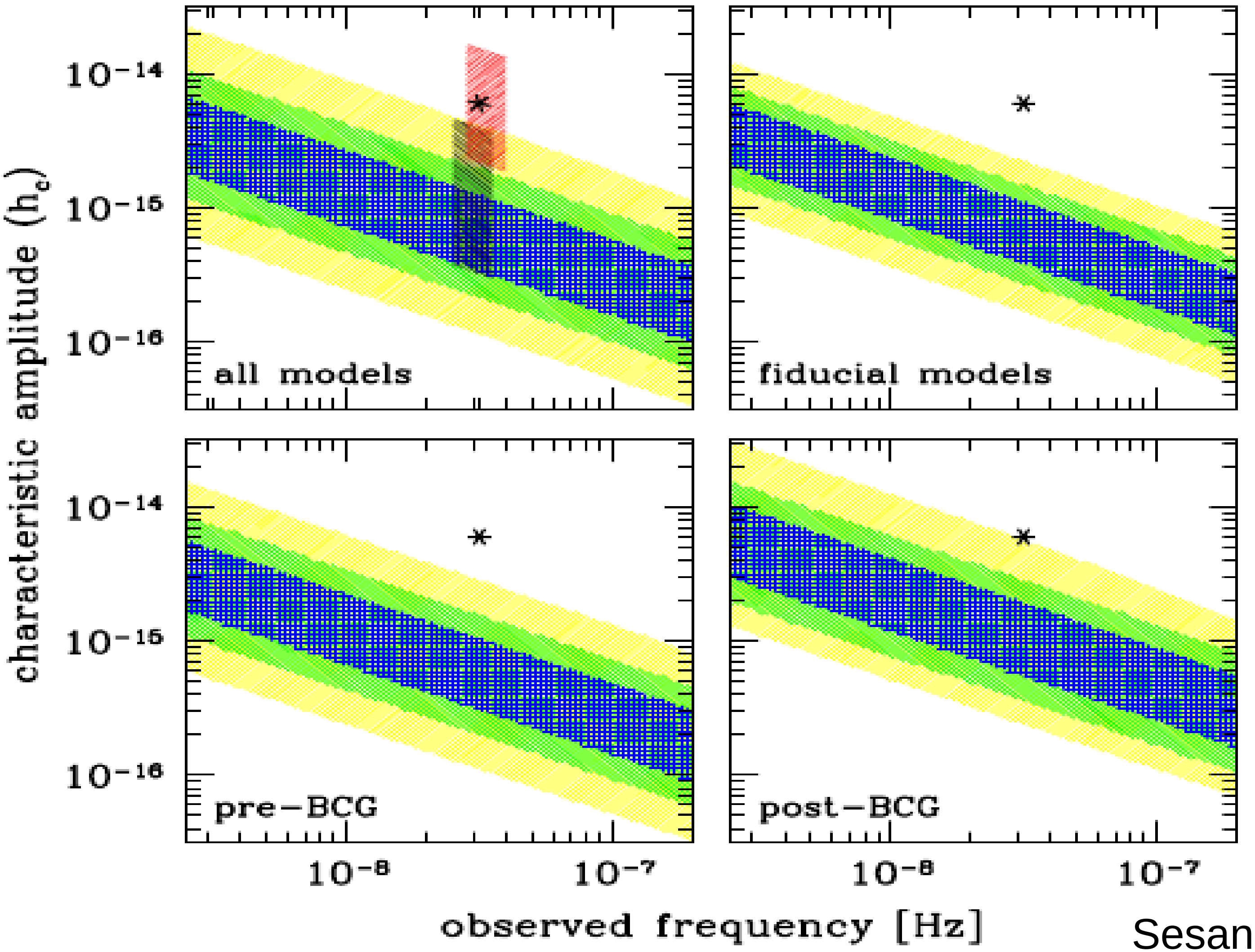
Current upper limit: EPTA





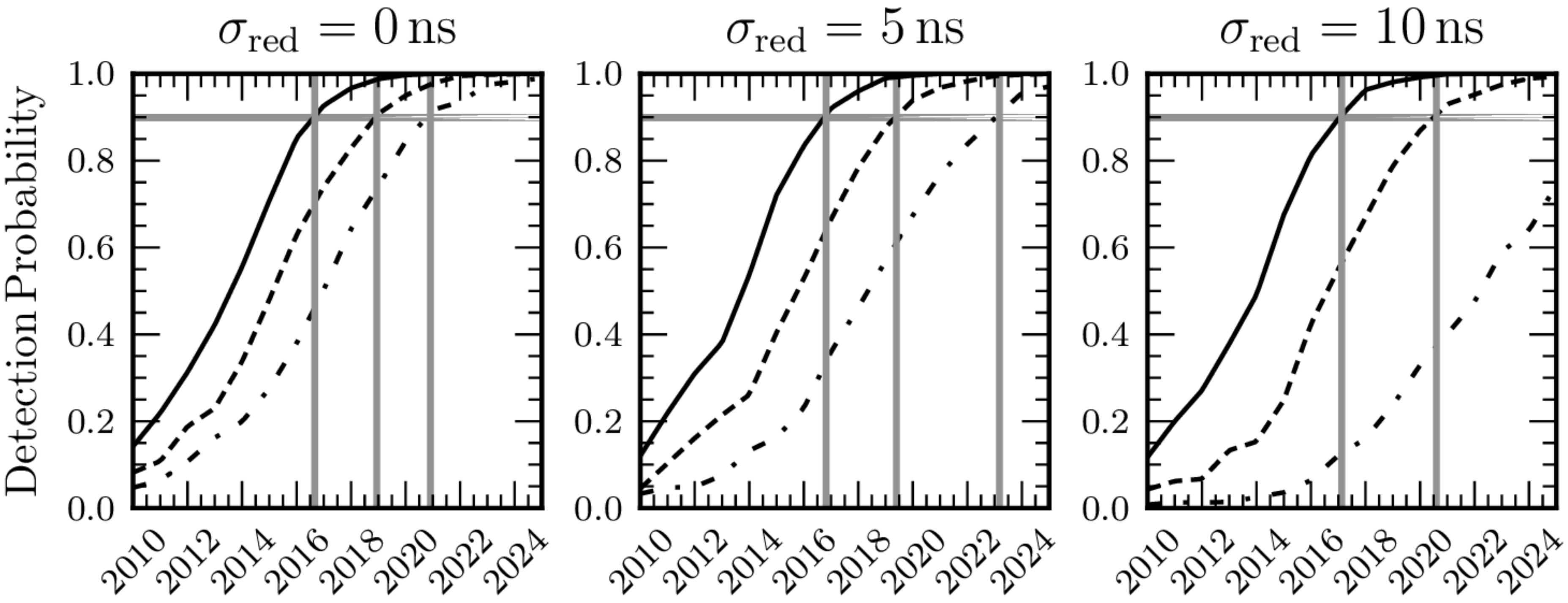
van Haasteren (in prep.) & Lentati (in prep.): A < 3e-15

Prospects for detection



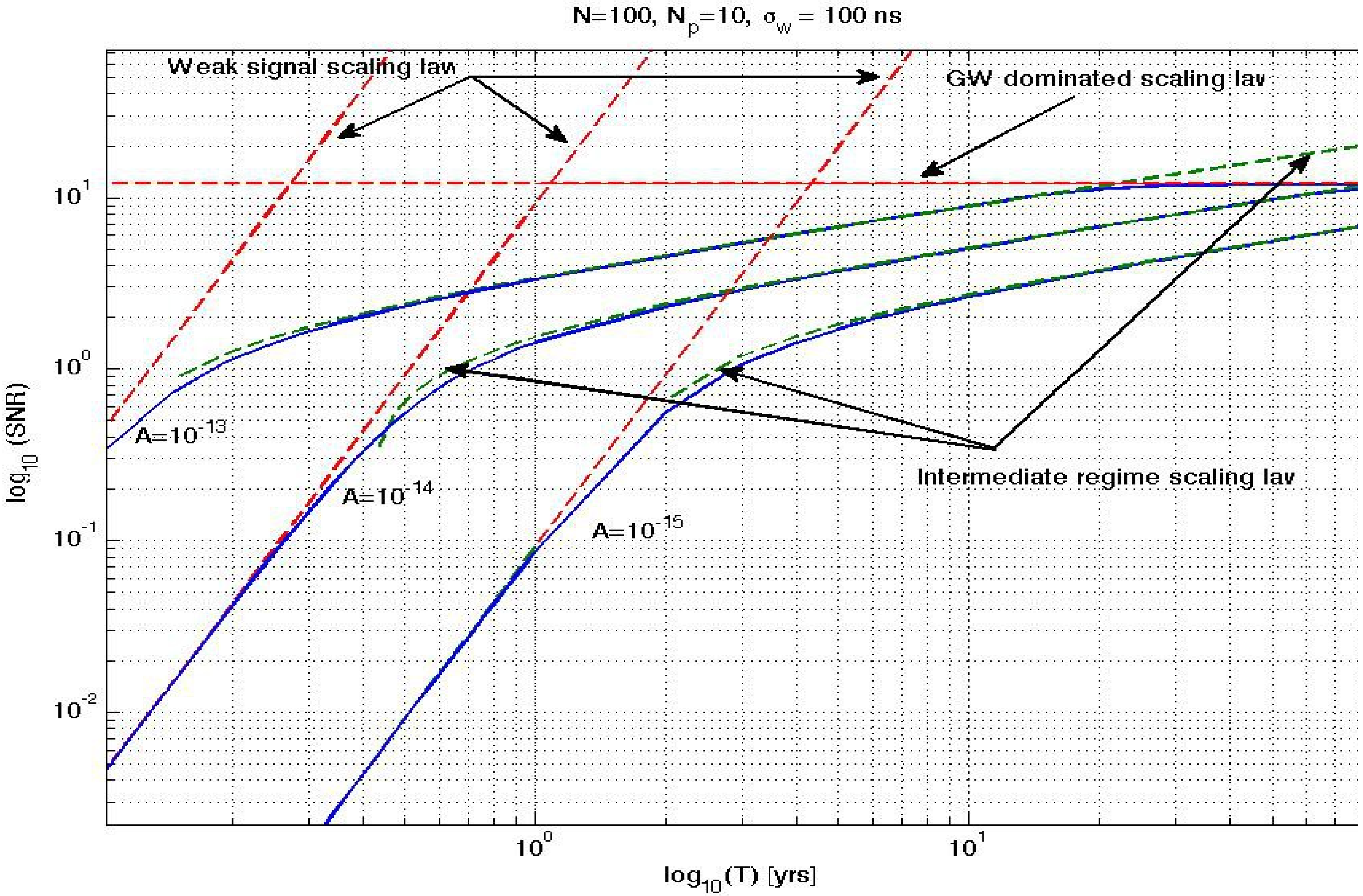
Sesana (2013)

Prospects for detection



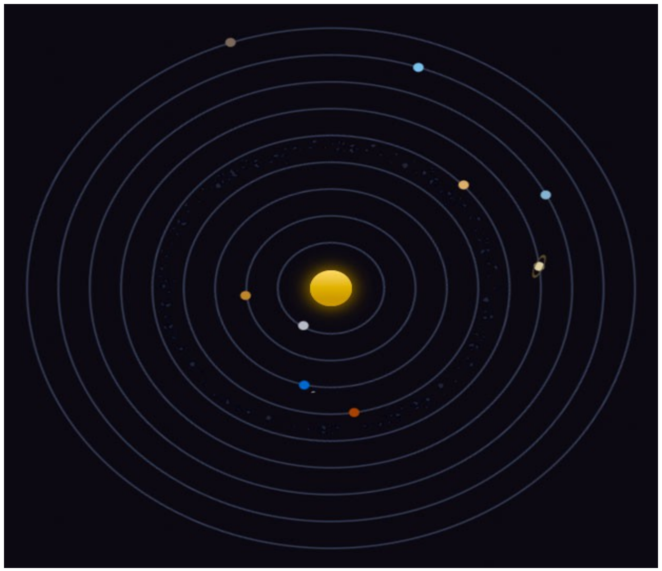
Siemens et al. (in prep.)

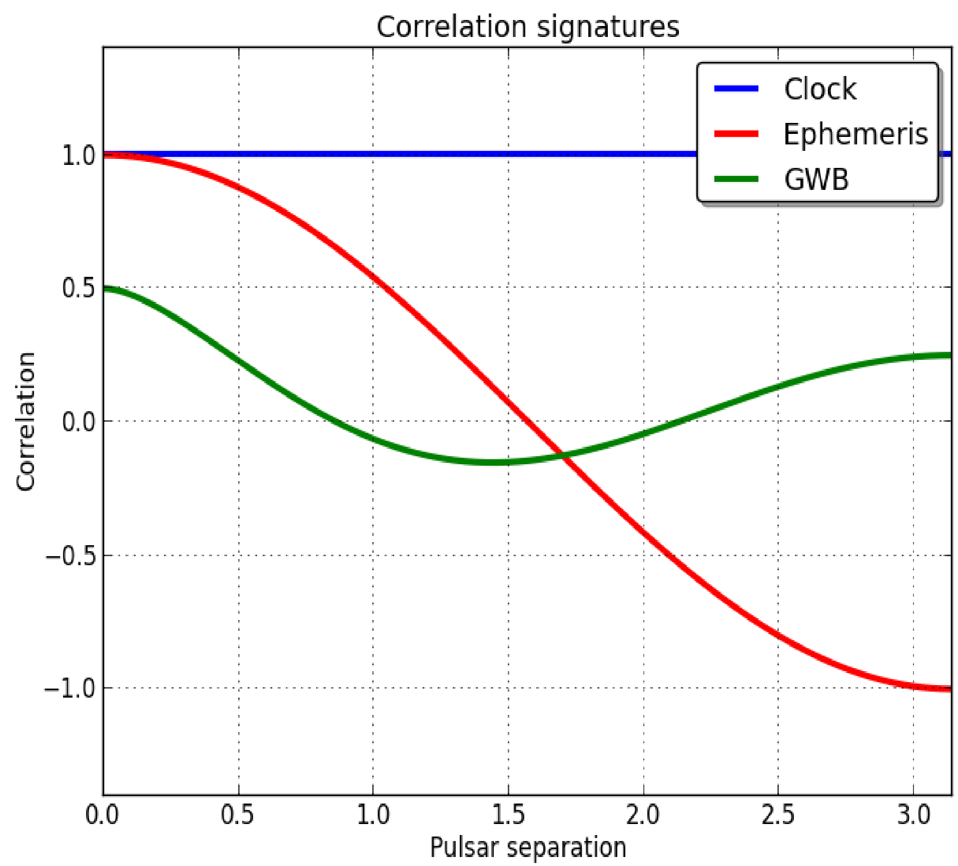
Scaling laws



Siemens et al. (in prep.)

Other applications





Other applications

Hobbs et al. (2012)

Pulsars can be used to construct a timescale, independent from atomic clocks

Other uses include: studying the solar system ephemeris (planet masses), cosmic strings, interstellar navigation, ...

Conclusions

•Pulsars can be used as sensitive instruments
•Lots of fundamental science done
•Ideal for testing gravitational theories
•Observing GWs in the near future with pulsar timing arrays (PTAs)

•**Unknown**: red spin noise millisecond pulsars
•**Unknown**: GW background amplitude
•Plenty of other uses for PTAs