Pulsars and Supernovae II

2. PULSARS AS ASTROPHYSICAL TOOLS

high precision time keeping and pulse profiles
astrometry
gravitational physics
super-dense matter
extreme plasmas
extrasolar planet detection
gravitational wave detection

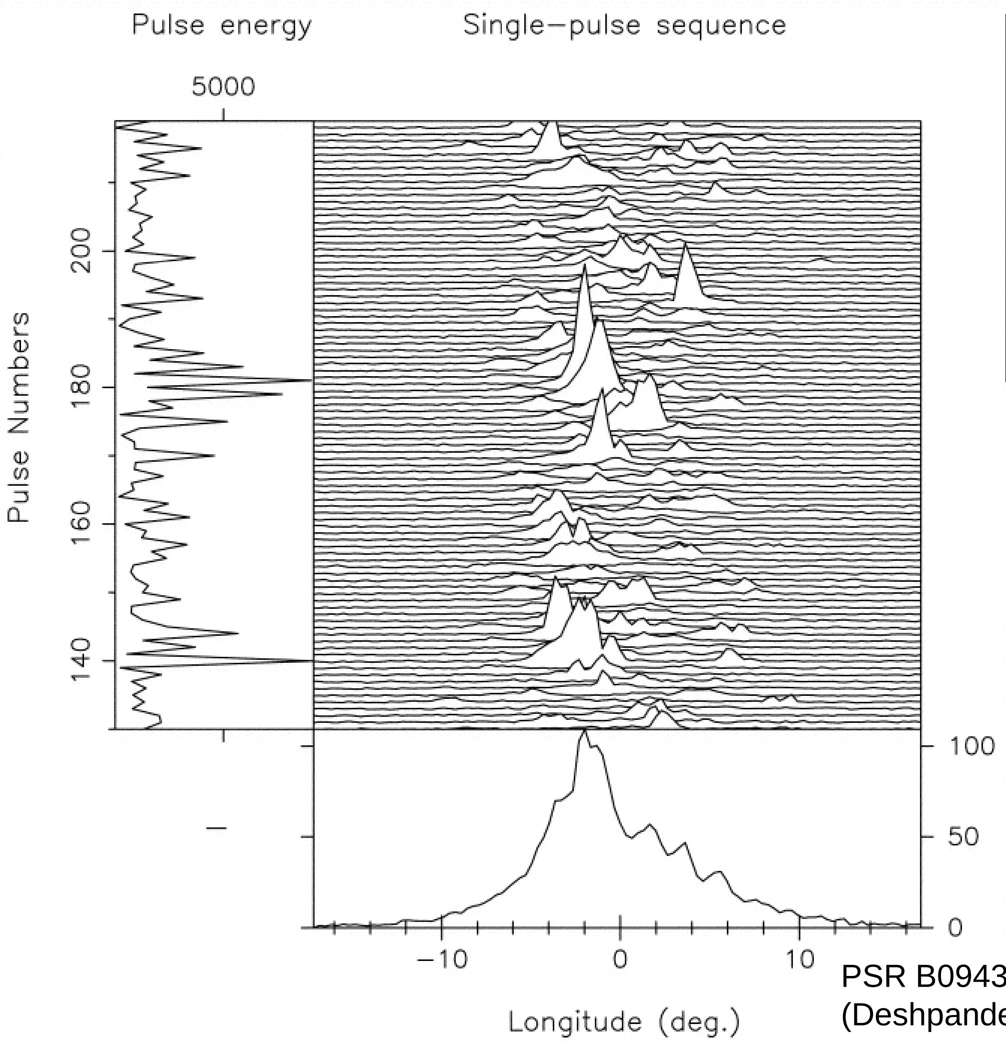
Pulsars as astrophysical tools

- Precise timing of pulsars, and the monitoring of pulse profiles over time, reveal detailed information on their motions, structure and environment.

- Most results rely on the use of pulsars as remarkably stable clocks.

- Note that there are strong pulse-to-pulse variations – only the mean pulse profile shows this high level of stability.

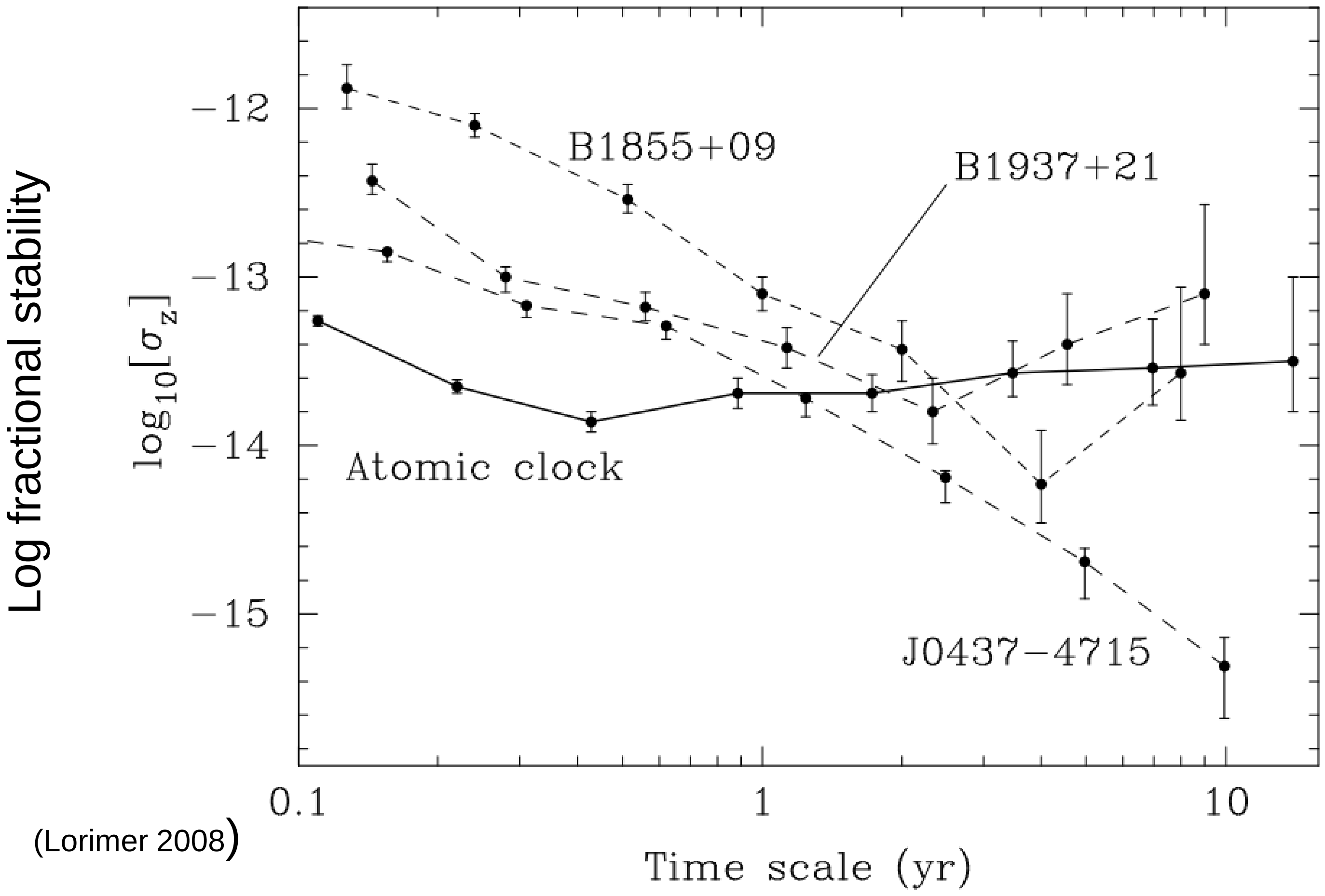
- Pulse profiles are usually measured over several minutes.



PSR B0943+10
(Deshpande & Rankin 1999)

Precision clocks

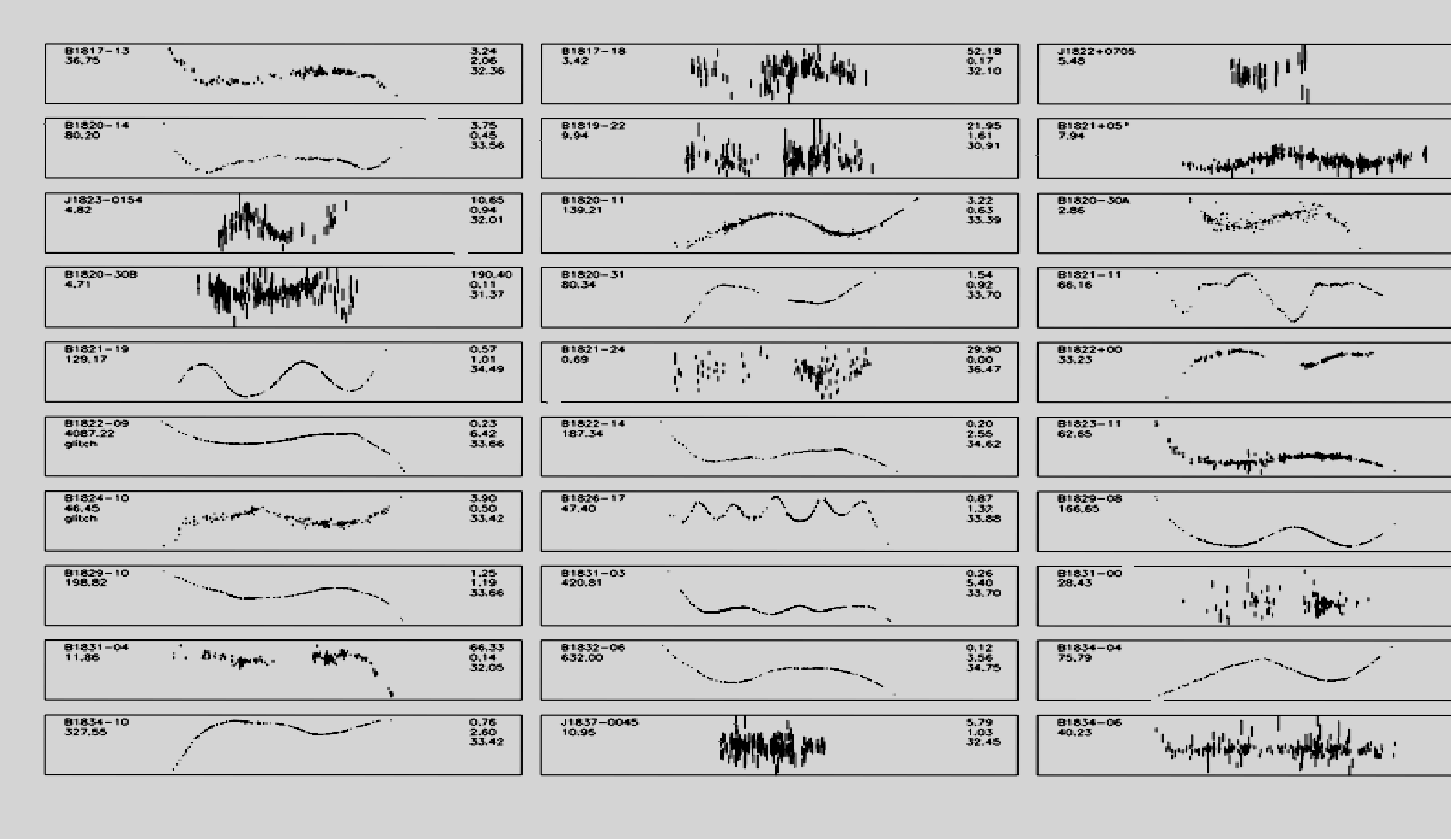
- Some pulsars have stabilities that rival atomic clocks on long (~1y) timescales, once our relative motion and a constant spin-down rate are taken into account.



(Lorimer 2008)

Timing noise

- At some level, all pulsars show timing noise that ultimately limits their usefulness as clocks. The origins of timing noise are not well understood, and some may be the result of gravitational waves on the propagation path (see later)



Timing residuals (i.e., the difference between observed and expected pulse arrival times) for a selection of pulsars over several years -- George Hobbs

Astrometry

- Pulsar timing observations need to be corrected for Earth motion, and the amount of correction needed is very sensitive to the pulsar's position on the sky.

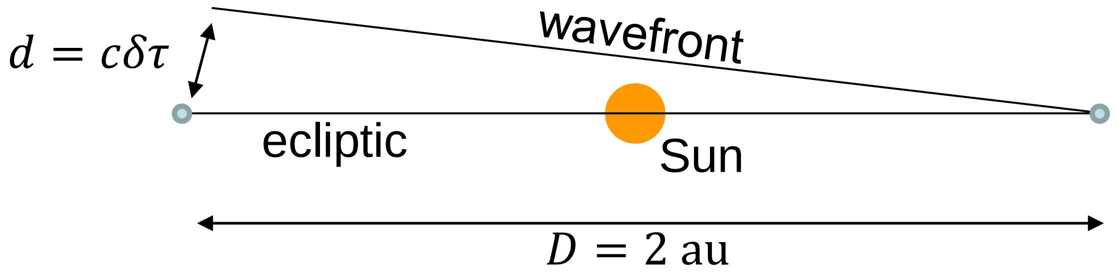
- The angular sensitivity of this timing is analogous to the angular resolution from an aperture of radius 1 au, observing 'waves' at the pulse frequency. [exercise for student: prove this!]

- So, in these terms, the astrometric precision for a pulsar of pulse frequency $\nu = 100\ \mathrm{Hz}$ at the ecliptic pole is approximately

$$\theta \simeq \frac{\lambda}{D} = \frac{\frac{c}{\nu}}{2\ \mathrm{au}} \simeq 2\ \mathrm{arcsec}.$$

Astrometry

- But pulsars can be timed to much better than one cycle:



- If we can time the arrival of a pulse to $\delta\tau$ seconds, then we can distinguish between pulse wavefronts that differ in angle by

$$\theta = \frac{d}{D} = \frac{c\,\delta\tau}{2\text{ au}}$$

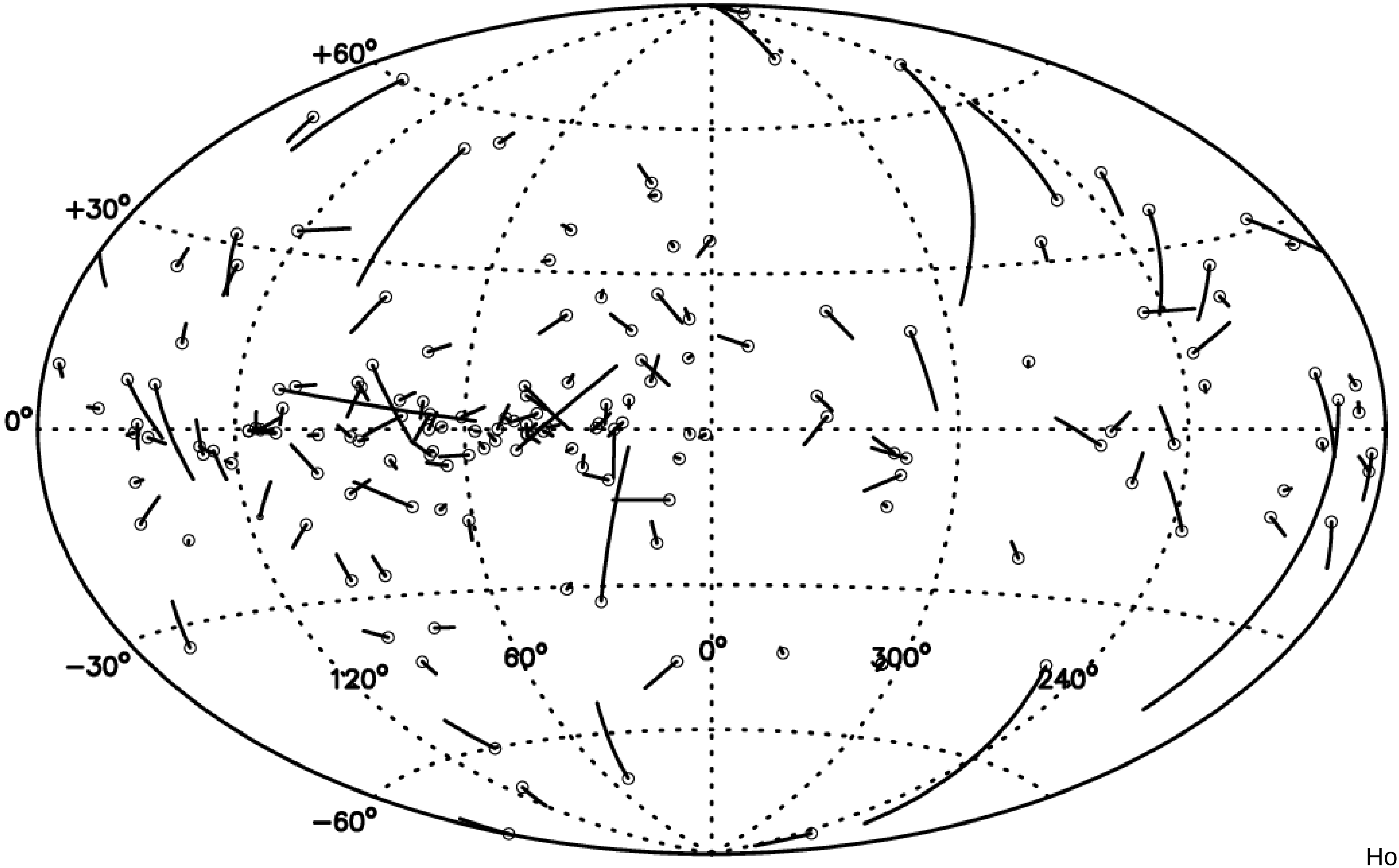
$$\simeq 0.001\,\delta\tau \quad \text{radians}$$

$$\simeq 206\,\delta\tau \quad \text{arcseconds}$$

- The best timing accuracies are ~ 50 ns, resulting in astrometric precisions of around 10 *micro*-arcseconds !

Astrometry

Inferred proper motions of a selection of pulsars over the last million years:



Hobbs & Lorimer 2005

Gravitational physics

- The first evidence for gravitational waves (pre-GW150914!) came from the orbital decay of the binary pulsar B1913+16. A binary neutron star system of separation a is a rotating mass quadrupole, and generates gravitational waves (according to GR) with a luminosity

$$L_{\mathrm{G}} = \frac{32}{5}\,\frac{G^4}{c^5}\,\frac{m_1^2 m_2^2 (m_1 + m_2)}{a^5}$$

  at twice the orbital frequency (i.e., 0.7 μHz), shrinking the orbit by about 1 cm per day.

- Agreement with GR is better than 0.5%.

- The double pulsar system PSR J0737-3039 constrains GR even further (see later!)

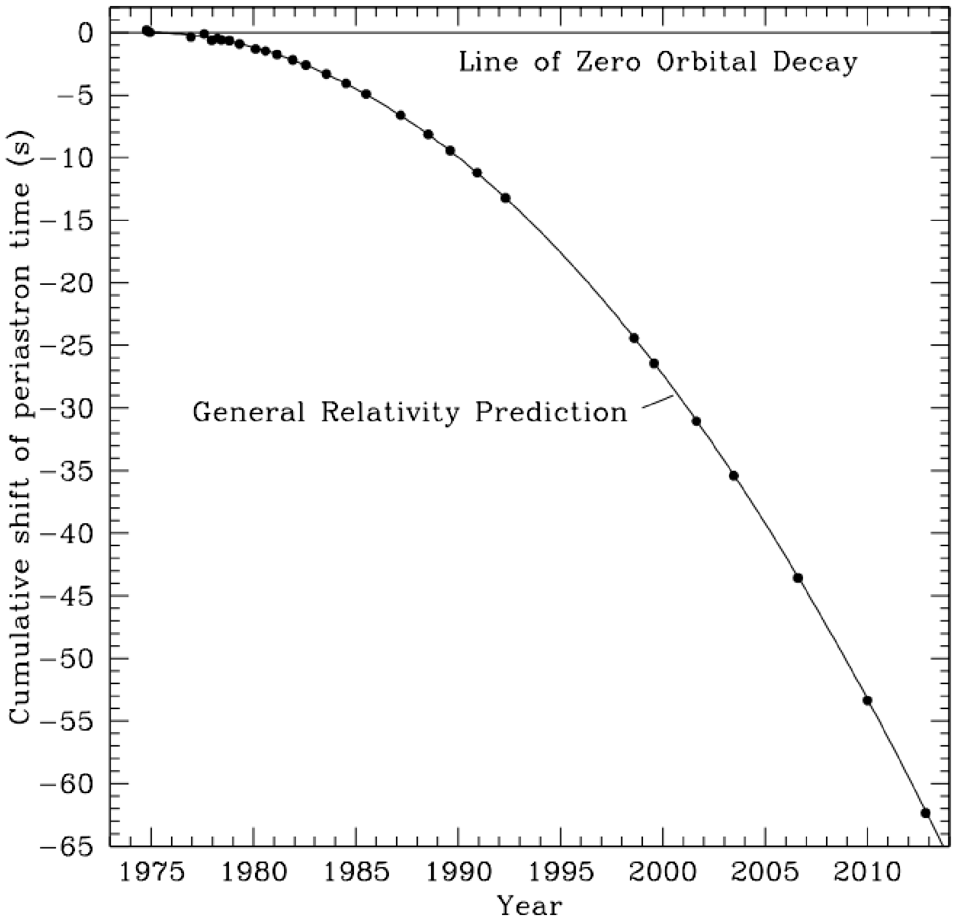
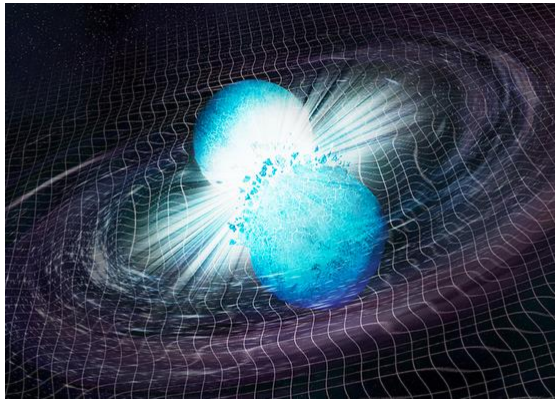


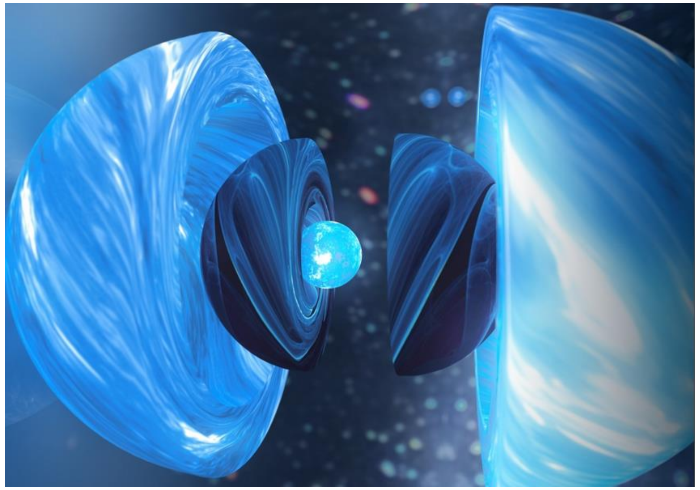
Figure 3. The orbital decay of PSR B1913+16 as a function of time. The curve represents the orbital phase shift expected from gravitational wave emission according to General Relativity. The points, with error bars too small to show, represent our measurements.

Weisberg & Huang 2016

In ~70 million years…



Super-dense matter



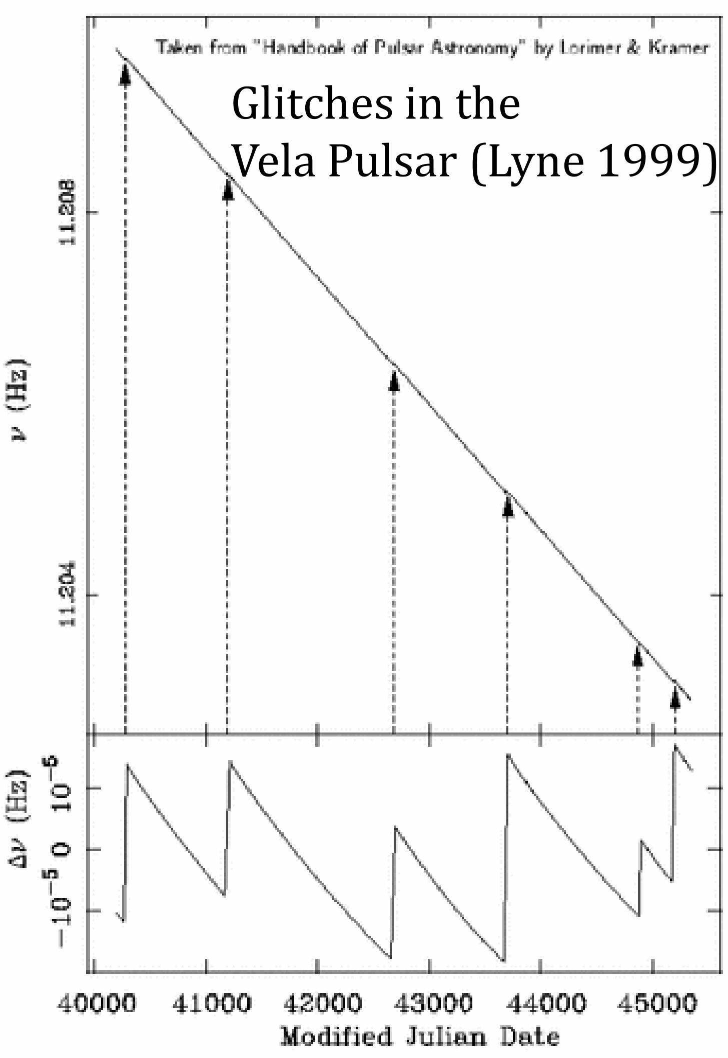
- Changes in the rotation of pulsars tells use something about the equation of state of a neutron star (i.e. the relationship between pressure and density, and therefore mass and radius).

- The density profile determines the relationship between moment of inertia, mass and radius:

$$I_{zz} = k\,MR^2, \qquad \text{with} \quad k = \frac{2}{5} \quad \text{for a uniform sphere.}$$

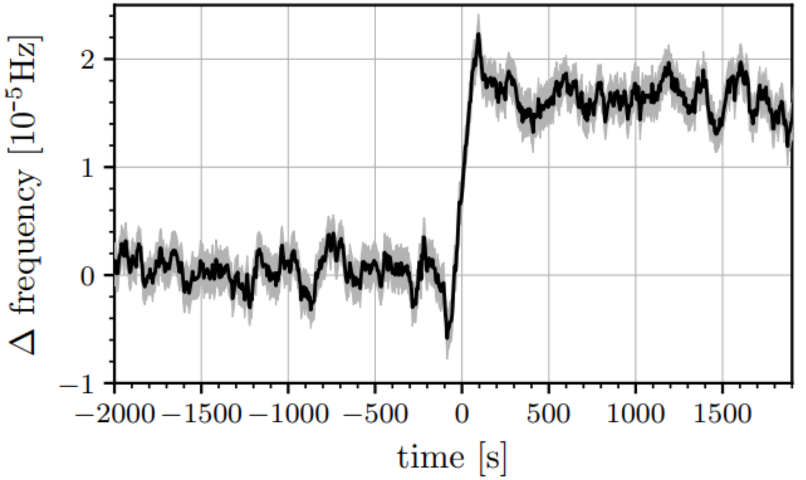
- Pulsar ‘glitches’ indicate how the superfluid internal structure of the neutron star couples to the crust (generating step-changes in rotation rate of 1 part in 10^6, seen in the Vela pulsar) and how the crust deforms (generating smaller glitches: 1 part in 10^8, seen in the Crab pulsar).

Pulsar glitches


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

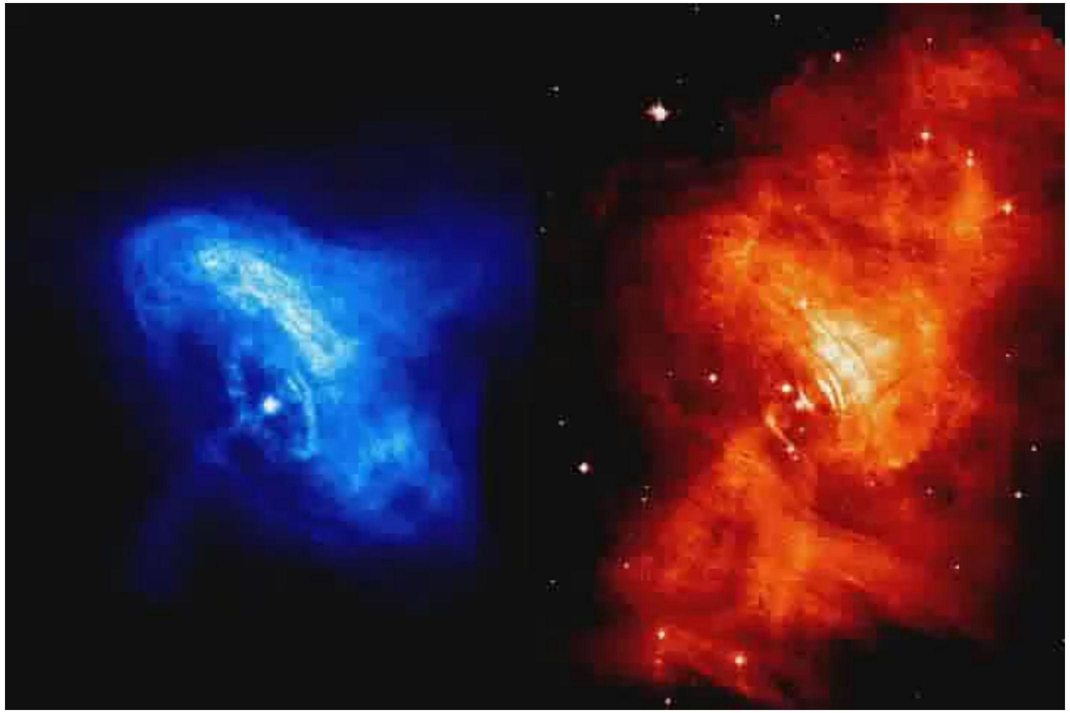
Glitches in the
Vela Pulsar (Lyne 1999)

The 2016 Vela glitch (Ashton et al 2019)



Extreme plasmas

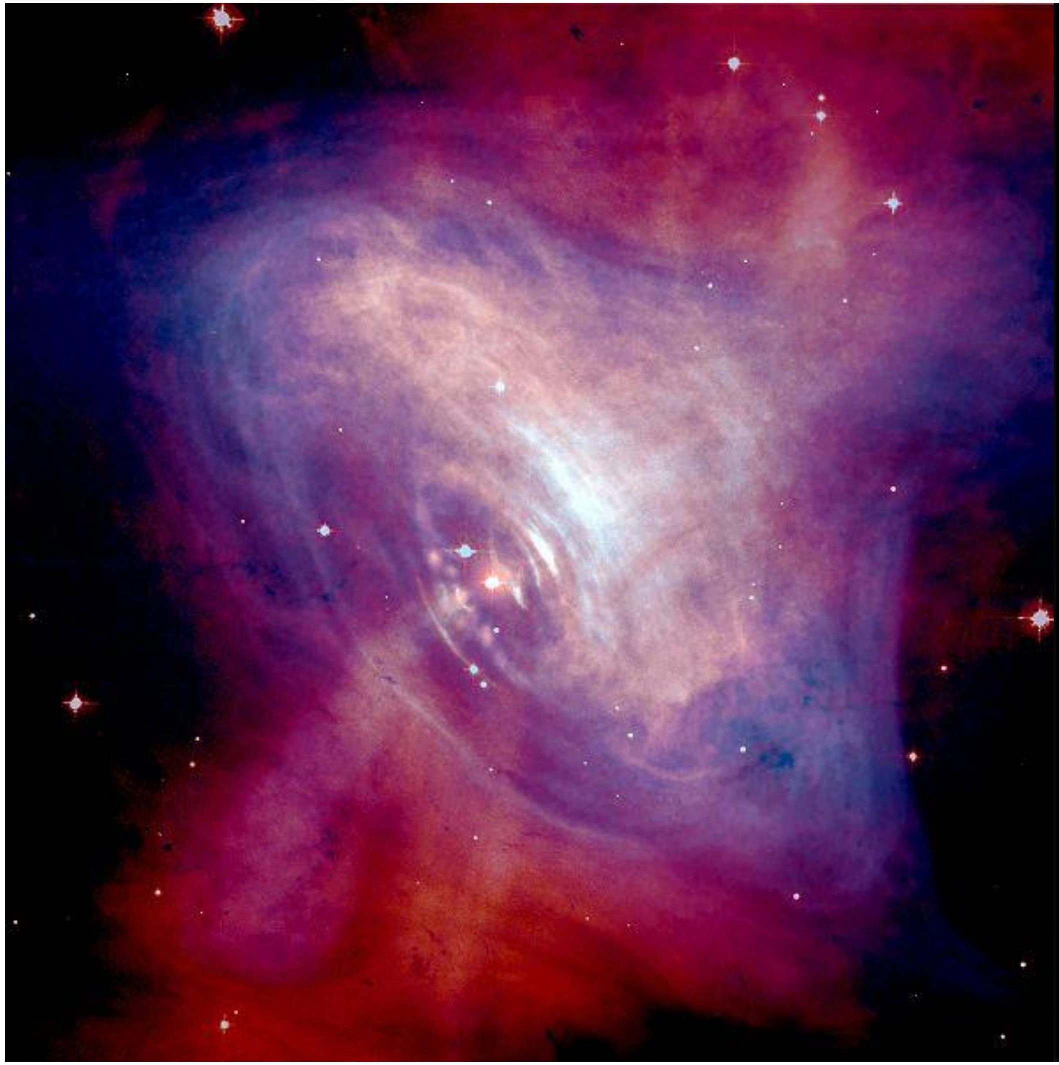
- Pulsars represent a complex problem in relativistic plasma physics, both in terms of the structure of their magnetospheres and in terms of their radiation mechanisms
  - Generally poorly understood
  - Pulsars give us some unique probes of these plasmas

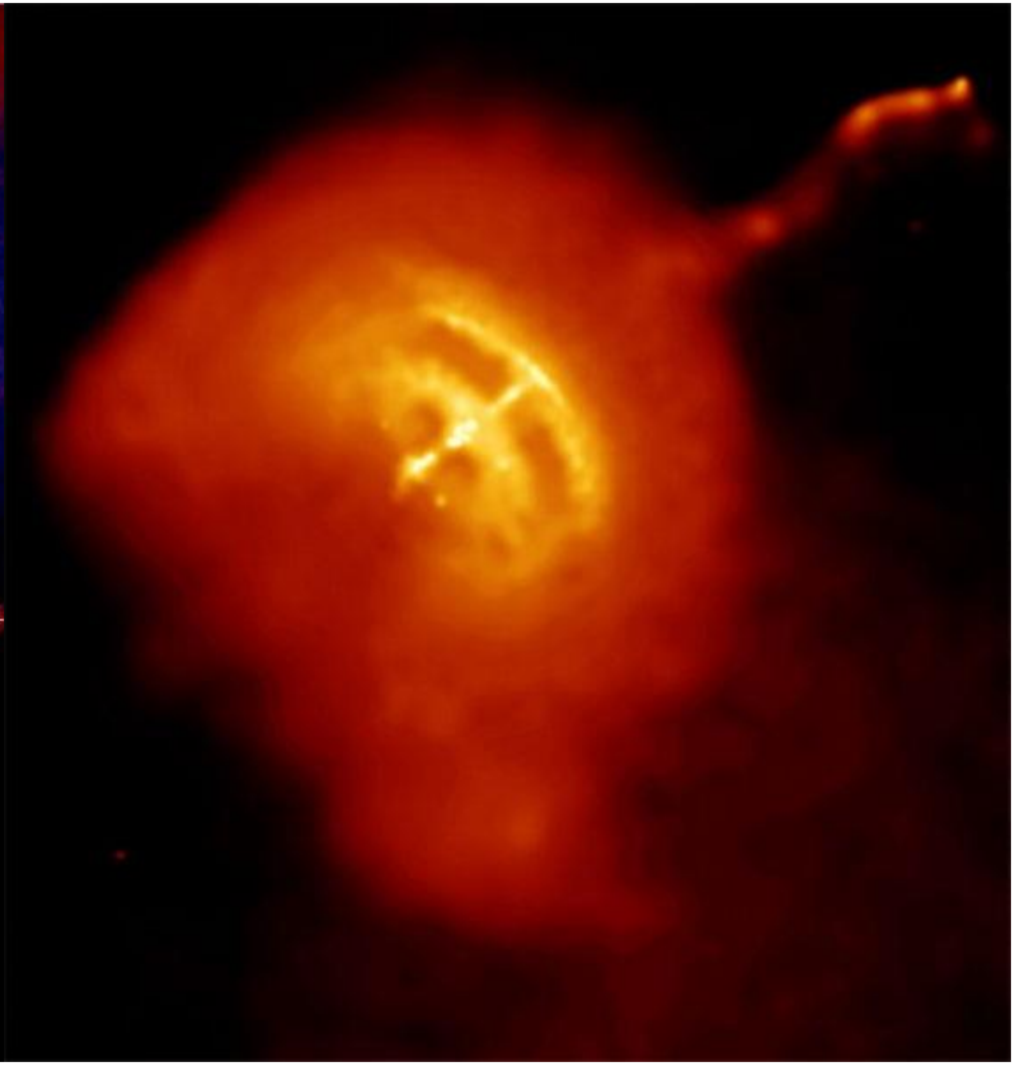


Crab X-ray
(Chandra)

Crab optical
(HST)

Crab and Vela wind nebulae





Extreme plasmas: the double pulsar system

- Fortunately, the double pulsar system PSR J0737-3039 gives us clues: the relativistic wind from one pulsar ('A') buffets the emission region of pulsar B. Also we see the system edge on, so that B eclipses A. More in the last lecture!

Extrasolar planet detection

- The first extrasolar planets were detected in 1992, using Arecibo pulsar timing measurements.
- PSR B1257+12 shows periodicities in its timing residuals consistent with three planets – still the lightest extrasolar planets seen.

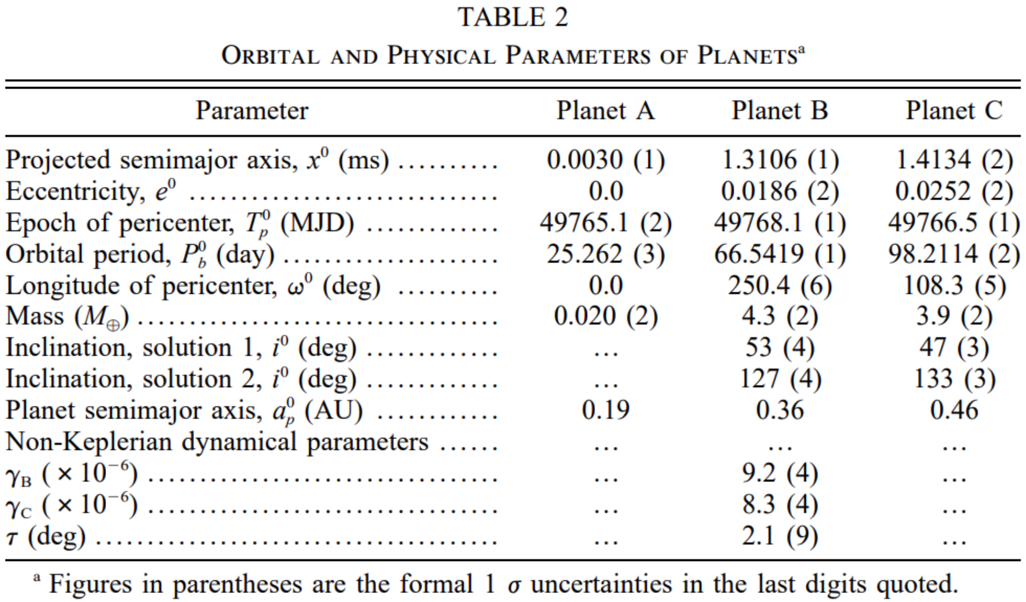


TABLE 2

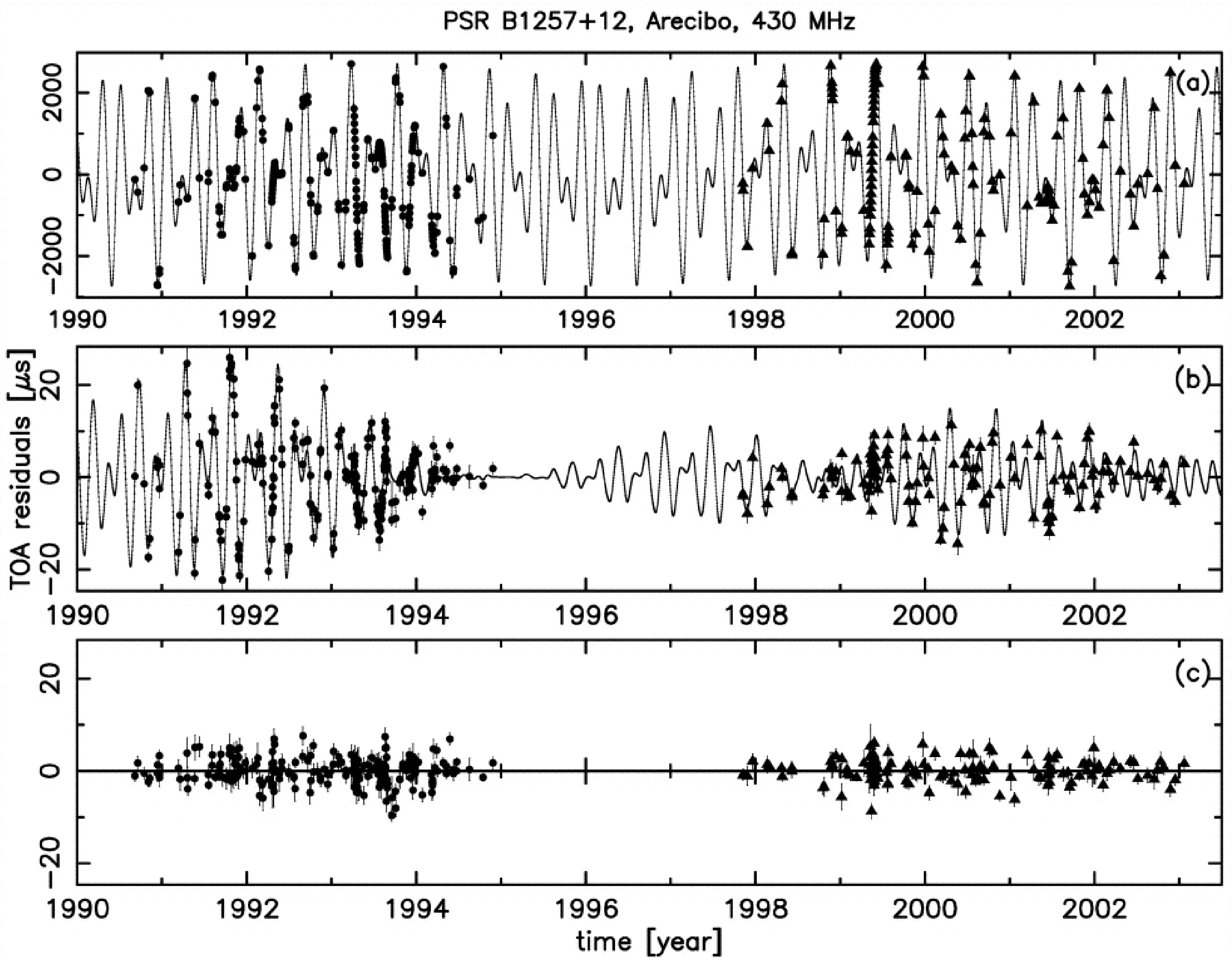
ORBITAL AND PHYSICAL PARAMETERS OF PLANETS[a]

Parameter	Planet A	Planet B	Planet C
Projected semimajor axis, x^0 (ms)	0.0030 (1)	1.3106 (1)	1.4134 (2)
Eccentricity, e^0	0.0	0.0186 (2)	0.0252 (2)
Epoch of pericenter, T_p^0 (MJD)	49765.1 (2)	49768.1 (1)	49766.5 (1)
Orbital period, P_b^0 (day)	25.262 (3)	66.5419 (1)	98.2114 (2)
Longitude of pericenter, ω^0 (deg)	0.0	250.4 (6)	108.3 (5)
Mass ($M_\oplus$)	0.020 (2)	4.3 (2)	3.9 (2)
Inclination, solution 1, i^0 (deg)	...	53 (4)	47 (3)
Inclination, solution 2, i^0 (deg)	...	127 (4)	133 (3)
Planet semimajor axis, a_p^0 (AU)	0.19	0.36	0.46
Non-Keplerian dynamical parameters	...	...	...
γ_B ($\times 10^{-6}$)	...	9.2 (4)	...
γ_C ($\times 10^{-6}$)	...	8.3 (4)	...
τ (deg)	...	2.1 (9)	...

[a] Figures in parentheses are the formal 1 σ uncertainties in the last digits quoted.

Konacki & Wolszczan 2003

Extrasolar planets: PSR B1257+12



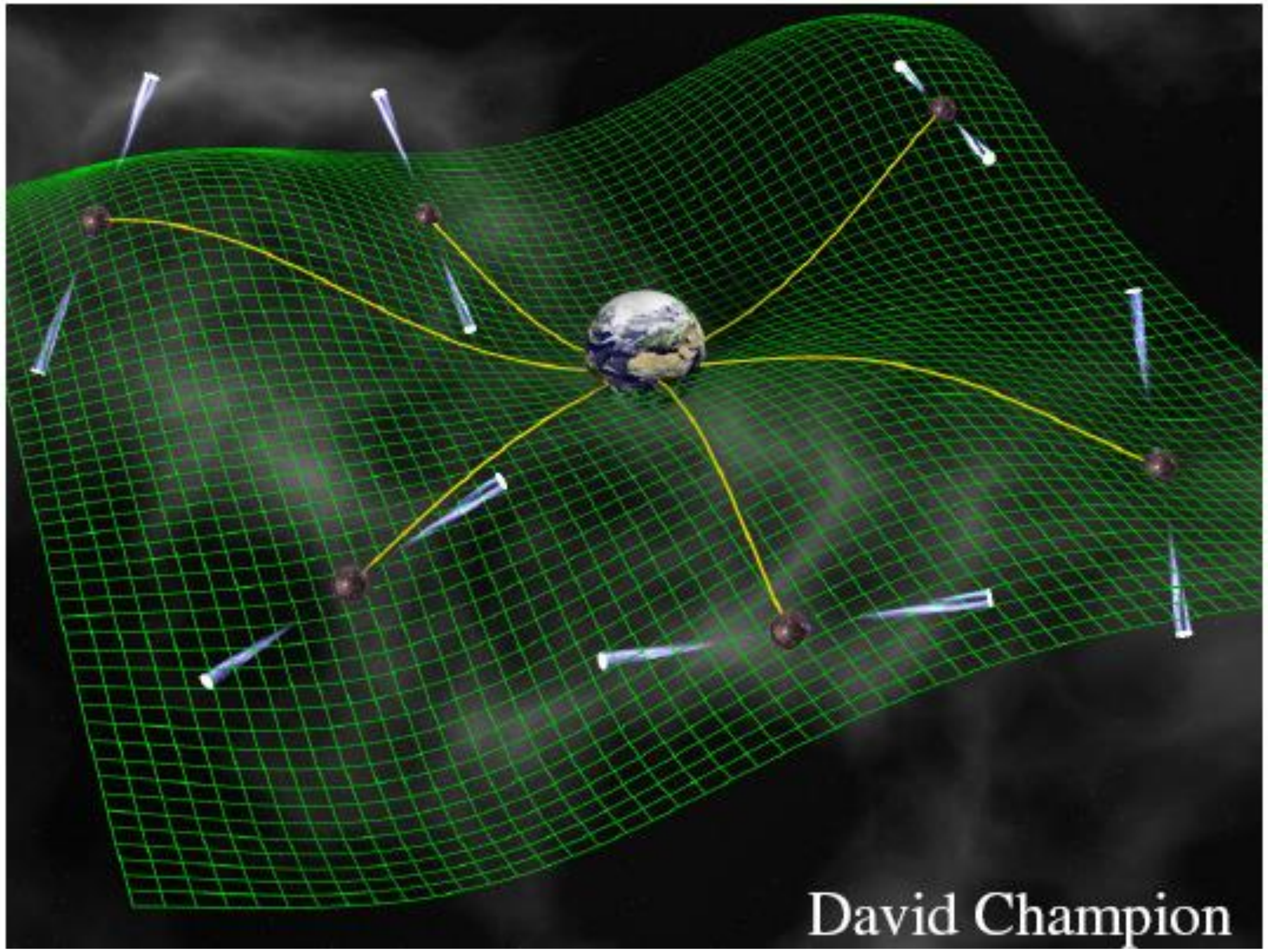
Raw time of arrival ‘residuals’ (solid line is model)

Three planets (A, B, C) fitted, no orbital interactions

... now taking orbital interactions into account

Konacki & Wolszczan 2003

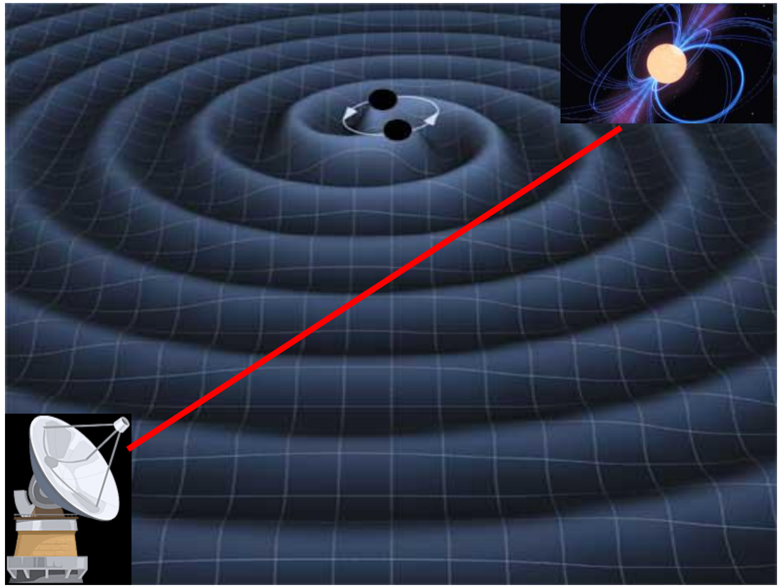
Gravitational wave detection using pulsars



David Champion

Gravitational wave detection

- Gravitational waves distort spacetime as they propagate. A periodic gravitational wave passing across the line-of-sight to a pulsar will produce a periodic variation in the time of arrival of pulses.



Pulses sent at (x_1, t_1)

Pulses received at (x_2, t_2)

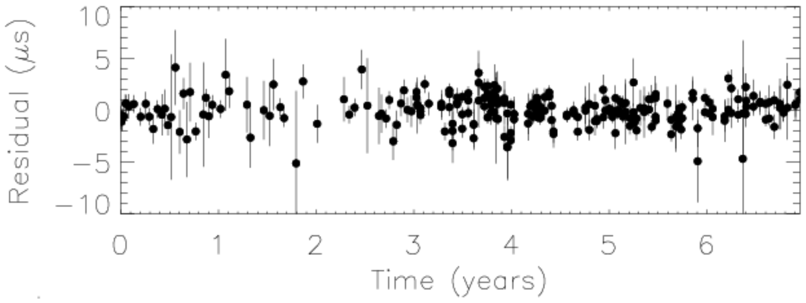
- If the strain along the line-of-sight is h, then the fractional change in the pulse arrival rate due to the gravitational wave just depends on the strain at emission and reception:

$$\frac{\delta\nu}{\nu} = h(x_1, t_1) - h(x_2, t_2).$$

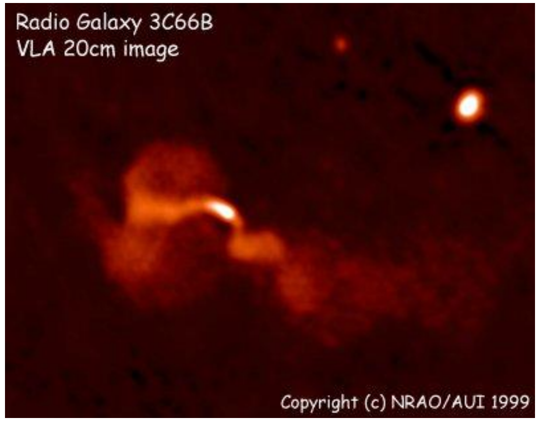
Gravitational wave detection

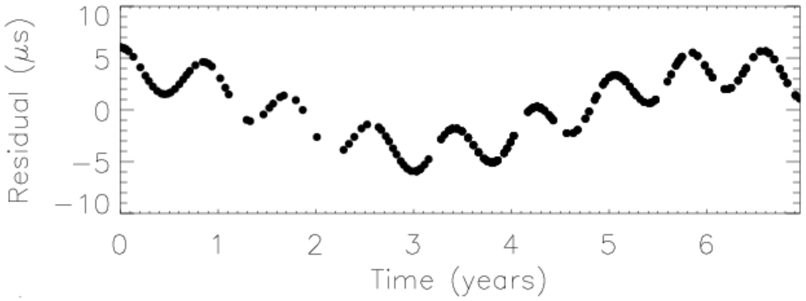
- The only way to detect very low frequency gravitational waves is in the timing residuals of pulsars (none seen yet!). The timing residual over some period t is

$$R(t) = -\int_0^t \frac{\delta\nu}{\nu}\,\mathrm{d}t\,.$$



Observed timing residuals for PSR B1855+09.





Simulated timing residuals
induced from a putative black hole binary
in 3C66B. (Jenet et al. 2004)