Detecting Gravitational Waves with Pulsars

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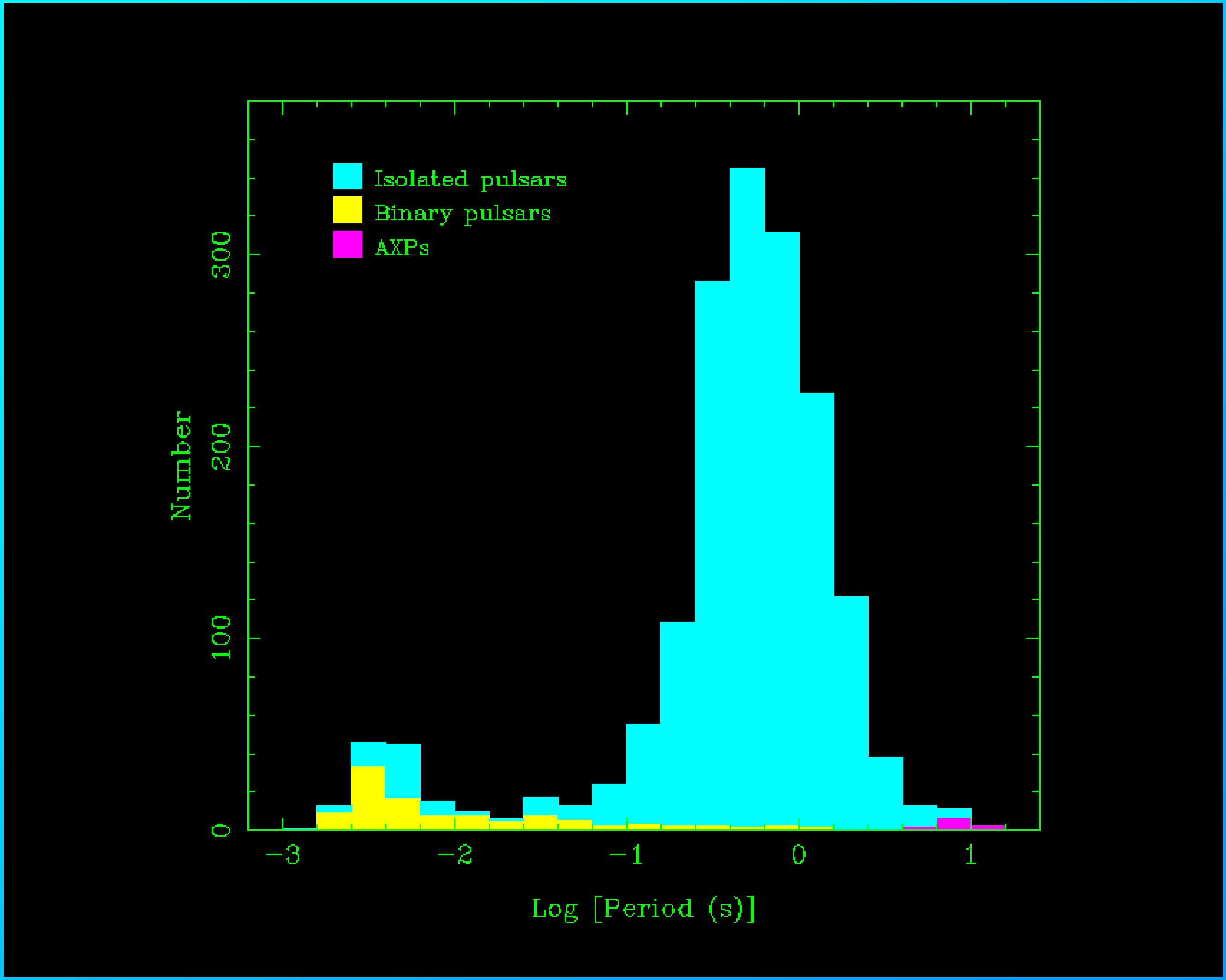
Summary

- Pulsars and pulsar timing
- Parkes pulsar surveys – the double pulsar
- The Parkes Pulsar Timing Array project

Spin-Powered Pulsars: A Census

- Number of known pulsars: 1740
- Number of millisecond pulsars: 175
- Number of binary pulsars: 130
- Number of AXPs: 11
- Number of pulsars in globular clusters: 98
- Number of extragalactic pulsars: 25

Includes unpublished data from Faulkner (Univ. Manchester thesis), Burgay (Univ. Bologna thesis) and Fan (Univ. HK thesis)



Data from ATNF Pulsar Catalogue (www.atnf.csiro.au/research/pulsar/psrcat)

Pulsars as clocks

- Pulsar periods are incredibly stable and can be measured precisely, e.g. on Jan 16, 1999, PSR J0437-4715 had a period of :

5.757451831072007 ± 0.000000000000008 ms

- Although pulsar periods are stable, they are not constant. Pulsars lose energy and slow down: dP/dt is typically 10^{-15} for normal pulsars and 10^{-20} for MSPs

- Young pulsars suffer period irregularities and glitches ($\Delta P/P$ <~ 10^{-6}) but these are weak or absent in MSPs

Sources of Pulsar Timing “Noise”

- Intrinsic noise
  - Period fluctuations, glitches
  - Pulse shape changes
- Perturbations of the pulsar’s motion
  - Gravitational wave background
  - Globular cluster accelerations
  - Orbital perturbations – planets, 1st order Doppler, relativistic effects
- Propagation effects
  - Wind from binary companion
  - Variations in interstellar dispersion
  - Scintillation effects
- Perturbations of the Earth’s motion
  - Gravitational wave background
  - Errors in the Solar-system ephemeris
- Clock errors
  - Timescale errors
  - Errors in time transfer
- Instrumental errors
  - Radio-frequency interference and receiver non-linearities
  - Digitisation artifacts or errors
  - Calibration errors and signal processing artifacts and errors
- Receiver noise

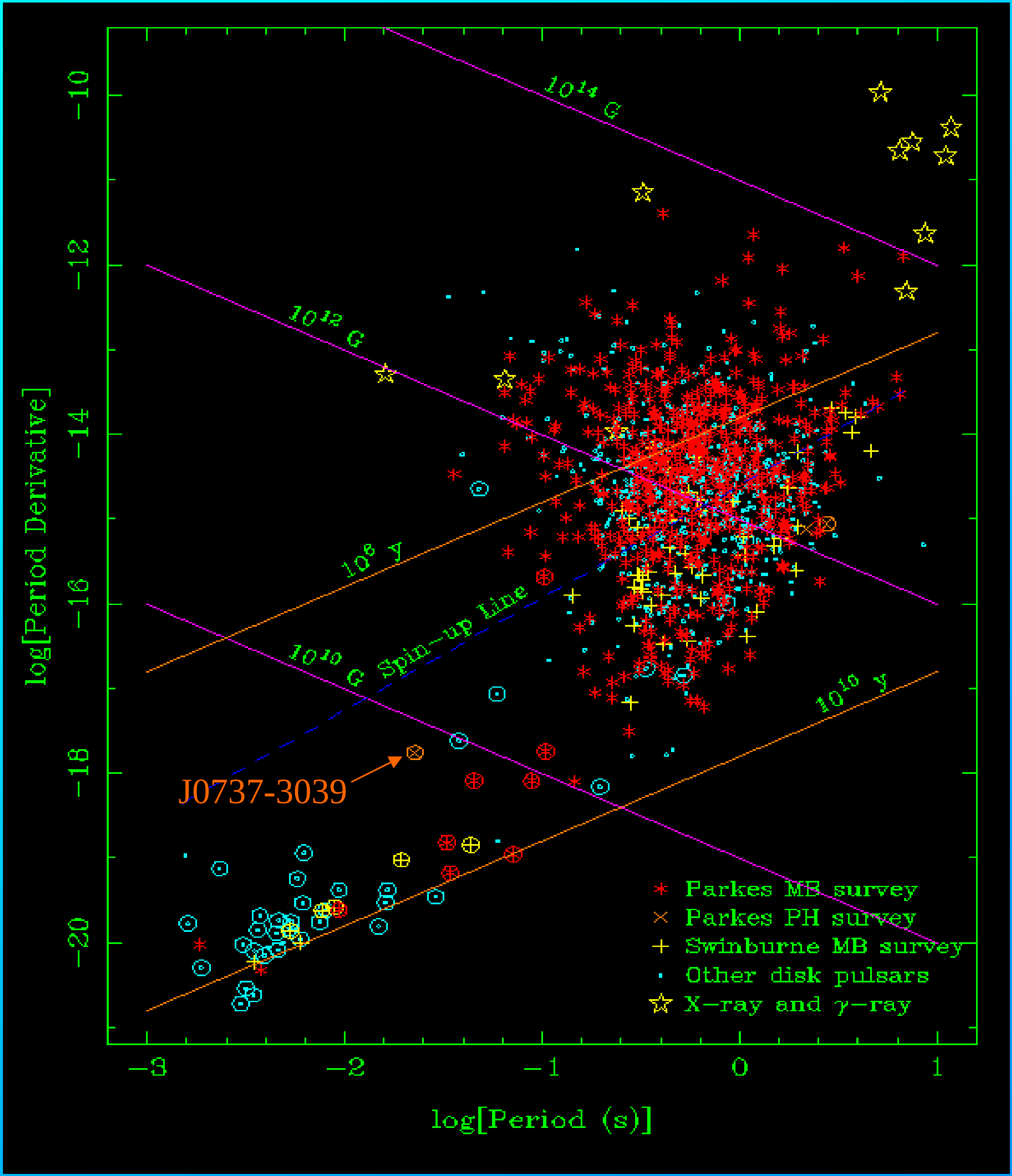
Parkes Multibeam Pulsar Surveys

- More than 850 pulsars discovered with multibeam system.
- The Parkes Multibeam Pulsar Survey (an international collaboration with UK, Italy, USA, Canada and Australia) has found more than 730 of these.
- High-latitude surveys have found about 120 pulsars including 15 MSPs

The Parkes radio telescope has found more than twice as many pulsars as the rest of the world's telescopes put together!

Parkes Multibeam Surveys: P vs $\dot{P}$

- New sample of young, high-B, long-period pulsars
- Large increase in sample of mildly recycled binary pulsars
- Three new double-neutron-star systems including one double pulsar!



J0737-3039

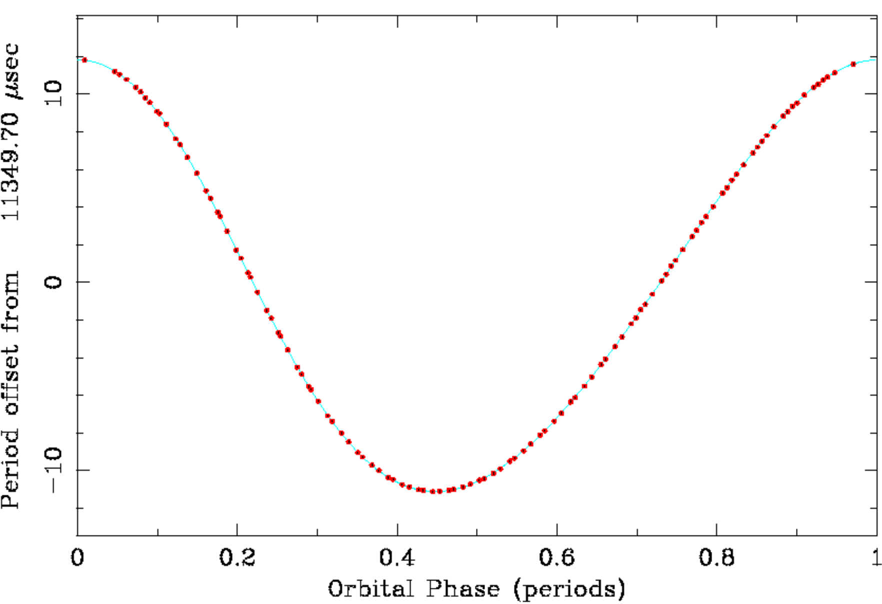
PSR J0737-3039A

- Discovered in the Parkes High-Latitude Survey
- P = 22 ms, P_b = 2.4 h, Ecc = 0.088 Min. M_c = 1.25 Msun
- Mean orbital velocity ~ 0.001 c
- Periastron advance = 16.90 deg/yr (Four times that for PSR B1913+16!)

➢ ***Double neutron-star system!***

➢ ***Many post-Keplerian parameters measurable!***

➢ ***Greatly increases expected rate of double neutron-star coalescences***



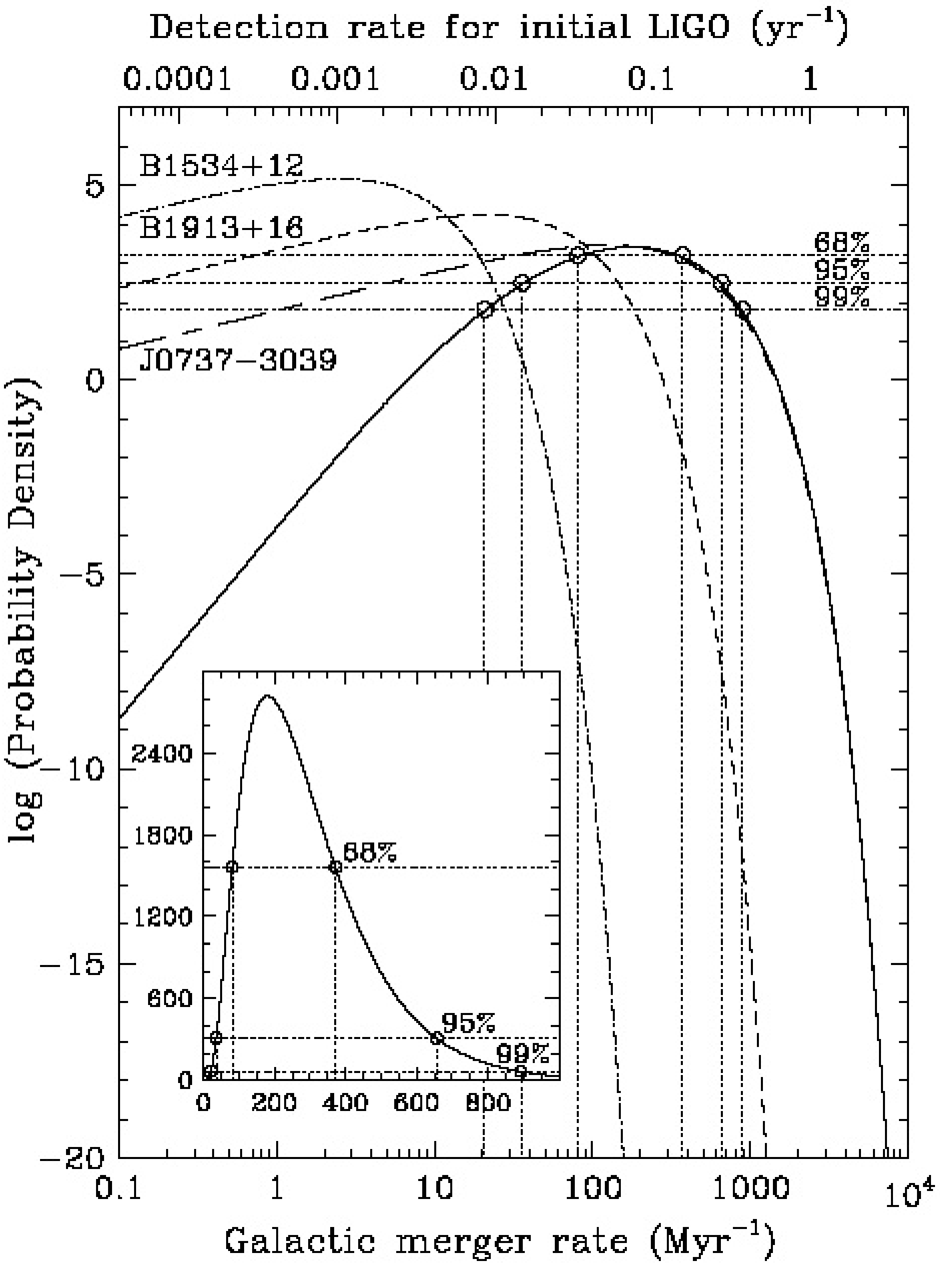
(Burgay et al., Nature, 426, 351, 2003)

Double-Neutron-Star Binary System Merger Rate

Dominated by the double pulsar!

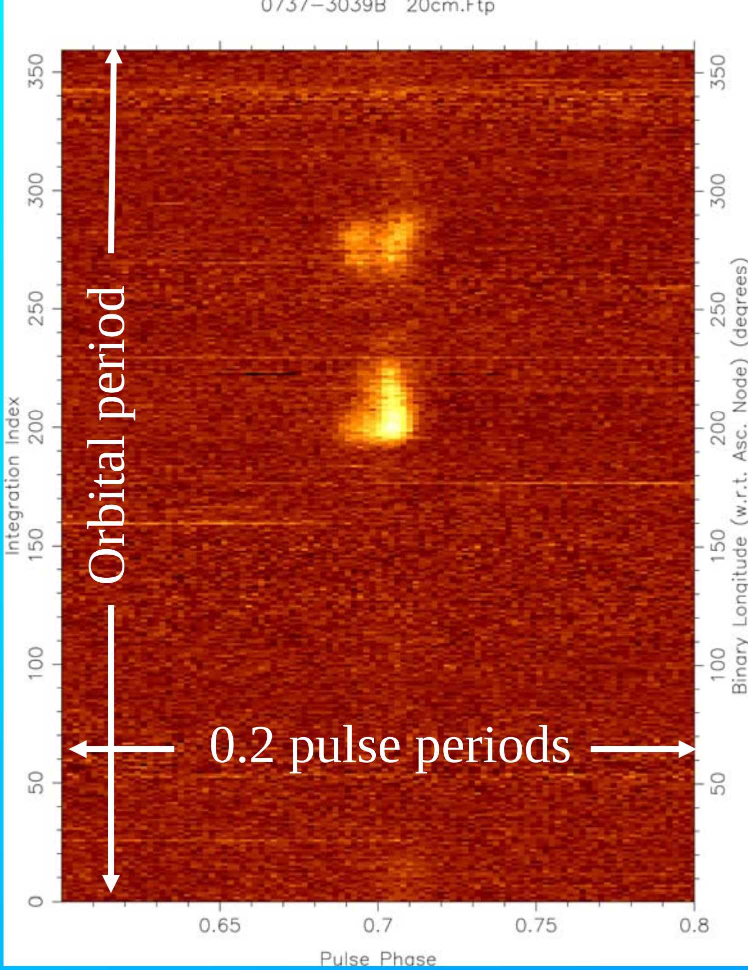
- Several hundred to several thousand systems similar to PSR J0737-3039A in Galaxy
- Galactic merger rate between 80 and 370 per Myr (1 σ)
- Detection rate for initial LIGO between one per 8 years and one per 35 years.
- Factor of seven increase over rates estimated from PSR B1913+16

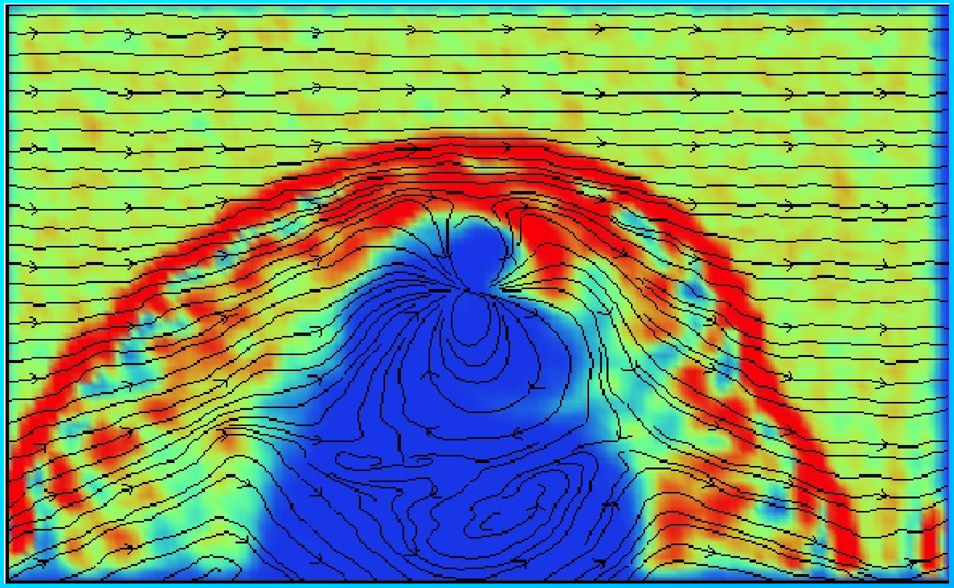
(Kalogera et al. 2004)



PSR J0737-3039B

- Second neutron star detected as a pulsar
  - ➢ ***First known double pulsar!***
- Pulse period = 2.7 seconds, τ_c = 55 Myr
- “Double-line binary” gives the mass ratio for the two stars – strong constraint on gravity theories (Lyne et al., Science, 303, 1153, 2004)





- MSP blows away most of B magnetosphere - dramatic effect on pulse emission

(Spitkovsky & Arons 2005)

Constraints on Gravitational Theories from PSR J0737-3039

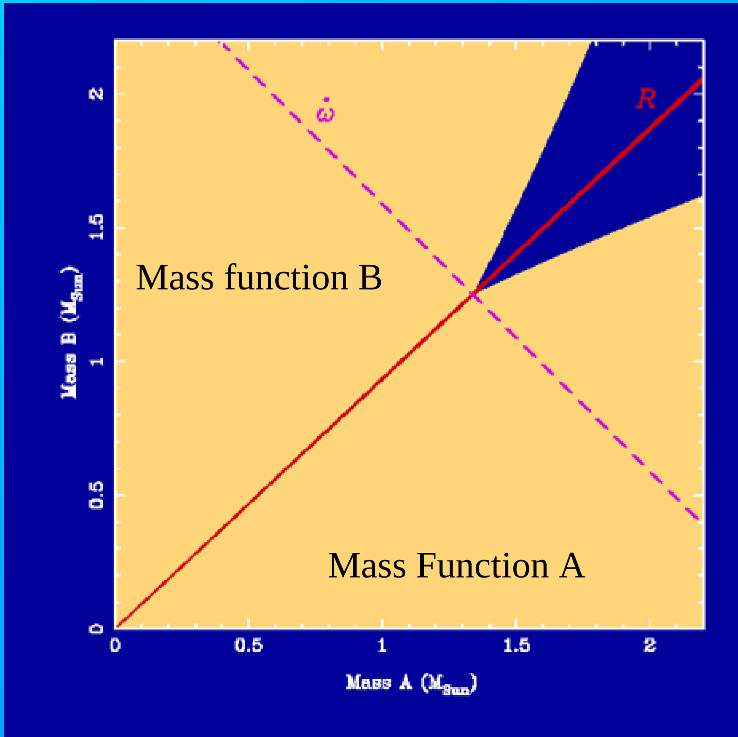
- Mass functions: sin *i* < 1 for A and B
- Mass ratio $R = M_A/M_B$ Measured value: 1.071 ± 0.001
    - ➢ Independent of theory to 1PN order. ***Strong constraint!***
- Periastron advance $\dot{\omega}$: 16.899 ± 0.001 deg/yr

Already gives masses of two stars (assuming GR):

$$M_A = 1.338 \pm 0.001\ M_{sun}$$

$$M_B = 1.249 \pm 0.001\ M_{sun}$$

Star B is a very low-mass NS!



Measured Post-Keplerian Parameters for PSR J0737-3039

	GR value	Measured value	Improves as
$\dot{\omega}$ Periast. adv. (deg/yr)	-	16.899 ± 0.001	$T^{1.5}$
γ Grav. Redshift (ms)	0.384	0.382 ± 0.005	$T^{1.5}$
$\dot{P}_b$ Orbit decay	-1.24×10^{-12}	$(-1.21 \pm 0.06) \times 10^{-12}$	$T^{2.5}$
r Shapiro range (μs)	6.2	6.2 ± 0.5	$T^{0.5}$
s Shapiro sin *i*	0.9997	0.9995 ± 0.0004	$T^{0.5}$

GR is OK! Already at the 0.1% level!

Non-radiative test - distinct from PSR B1913+16

(Kramer et al. 2005)

PSR J0737-3039 Post-Keplerian Effects

R: Mass ratio

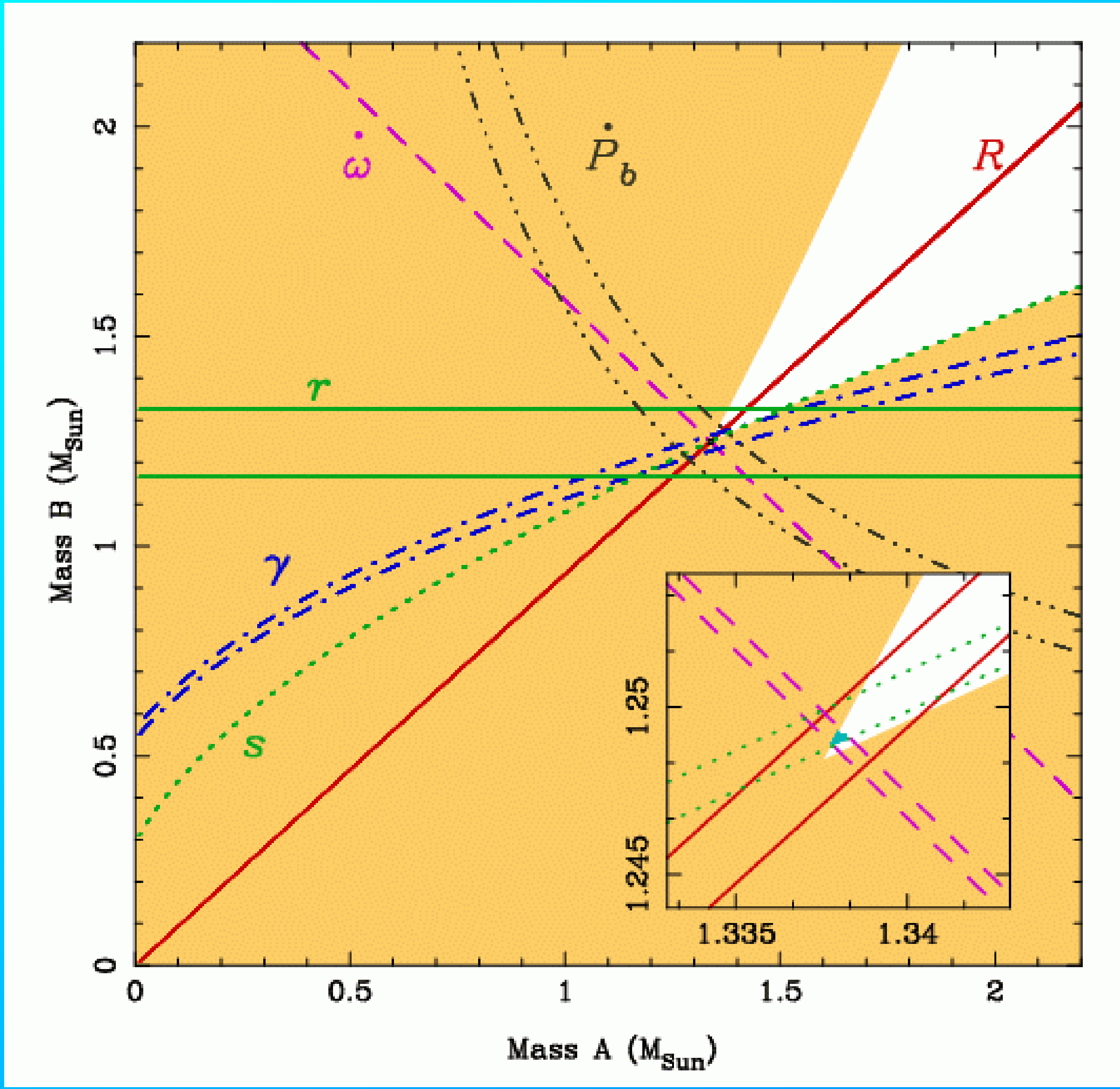
$\dot{\omega}$: periastron advance

γ: gravitational redshift

r & s: Shapiro delay

$\dot{P}_b$: orbit decay

- Six measured parameters – only two independent
- Fully consistent with general relativity (0.1%)



(Kramer et al. 2005)

Orbit Decay - PSR J0737-3039

- Measured $\dot{P}_b = (-1.21 \pm 0.06) \times 10^{-12}$ in 2 years
- Will improve at least as $T^{2.5}$
- Not limited by Galactic acceleration (unlike PSR B1913+16)
  - System is much closer to Sun - uncertainty in $\dot{P}_{b,Gal} \sim 10^{-16}$
- Main uncertainty is Shklovskii term due to uncertainty in proper motion and distance
  - Scintillation gives $V_{perp} = 66 \pm 15$ km s^{-1}
  - Timing gives ~15 km s^{-1}
  - VLBI measurements should be possible in 1-2 years

Will surpass PSR B1913+16 in ~5 years and improve rapidly!

PSR J0737-3039:
More Post-Keplerian Parameters!

- Relativistic orbit deformation: $e_r = e\,(1 + \delta_r)$

  $e_\theta = e\,(1 + \delta_\theta)$ $\sim T^{2.5}$

  Should be measurable in a few years

- Spin orbit coupling:
  - Geodetic precession - precession of spin axis about total angular momentum, period A: ~75 yrs, B: ~71 yrs

    Changes in pulse profile will give misalignment angle

  - Periastron precession - higher order terms

    Can give measurement of NS moment of inertia

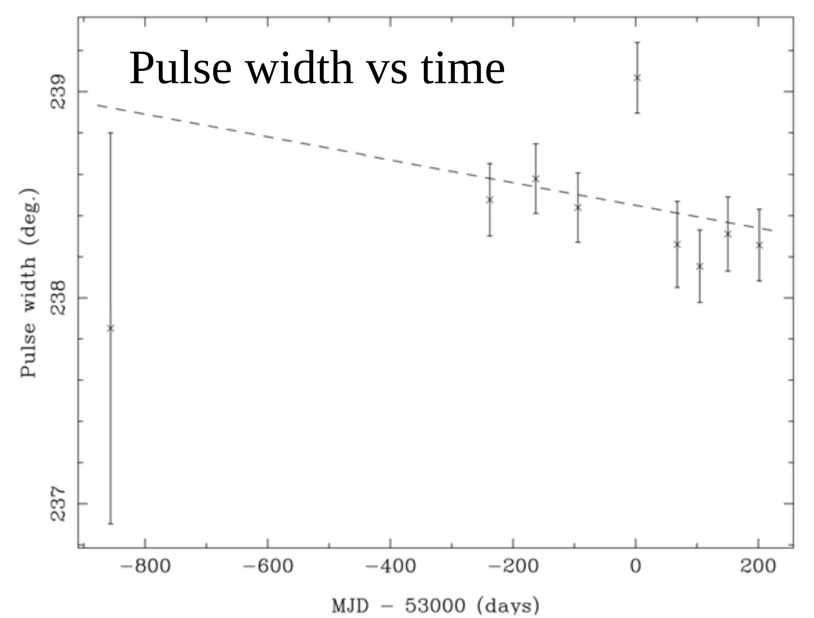
- Aberration: $x_{obs} = a_1 \sin i = (1 + \varepsilon_A) x_{int}$

  Will change due to geodetic precession

(Damour & Deruelle 1985)

Geodetic Precession

PSR J0737-3039A

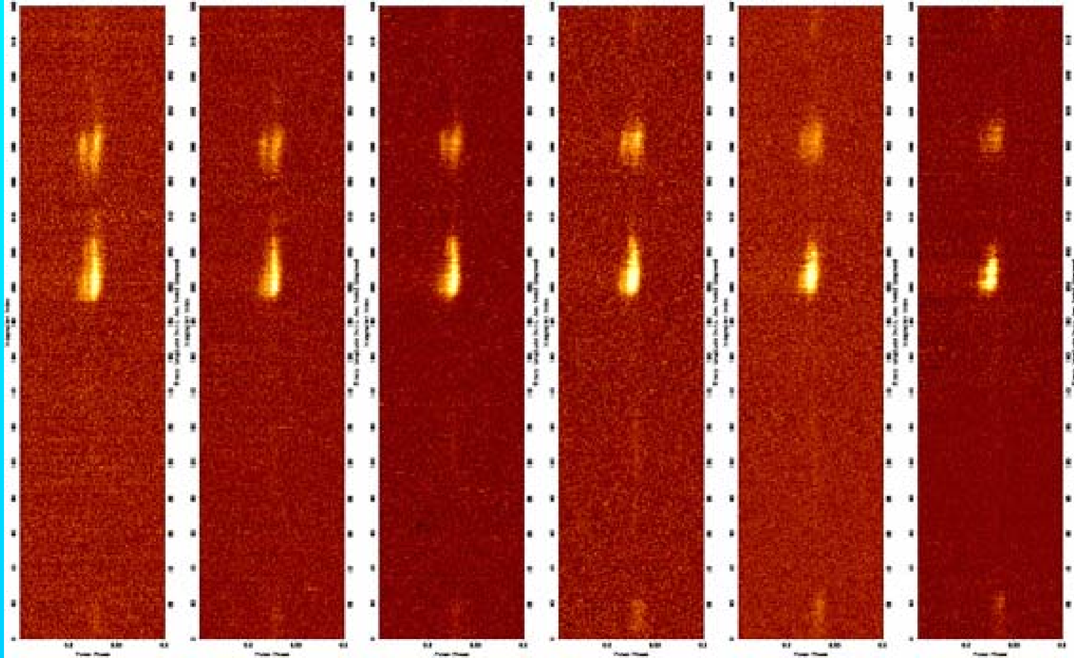


No significant change!

- ➢ Small misalignment angle?
- ➢ Light NS, low velocity, small eccentricity
- ➢ Small natal kick, different NS formation mechanism?

(Manchester et al. 2005)

PSR J0737-3039B

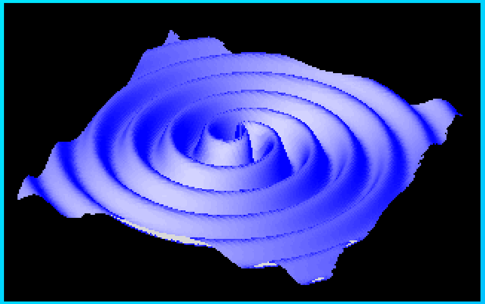


Secular changes are observed!

- ➢ Mechanism for orbital modulation not understood
- ➢ Can’t separate effects of periastron precession and geodetic precession

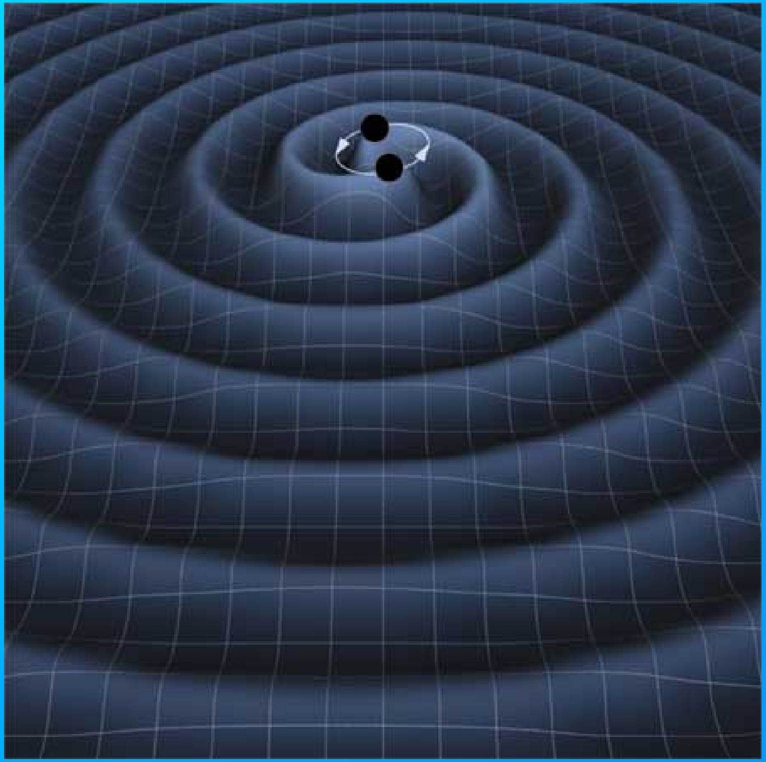
(Burgay et al. 2005)

Detection of Gravitational Waves



(NASA GSFC)

- Prediction of general relativity and other theories of gravity
- Generated by acceleration of massive object(s)
- Astrophysical sources:
  - ➢ Inflation era
  - ➢ Super-strings
  - ➢ Galaxy formation
  - ➢ Binary black holes in galaxies
  - ➢ Neutron-star formation in supernovae
  - ➢ Coalescing neutron-star binaries
  - ➢ Compact X-ray binaries

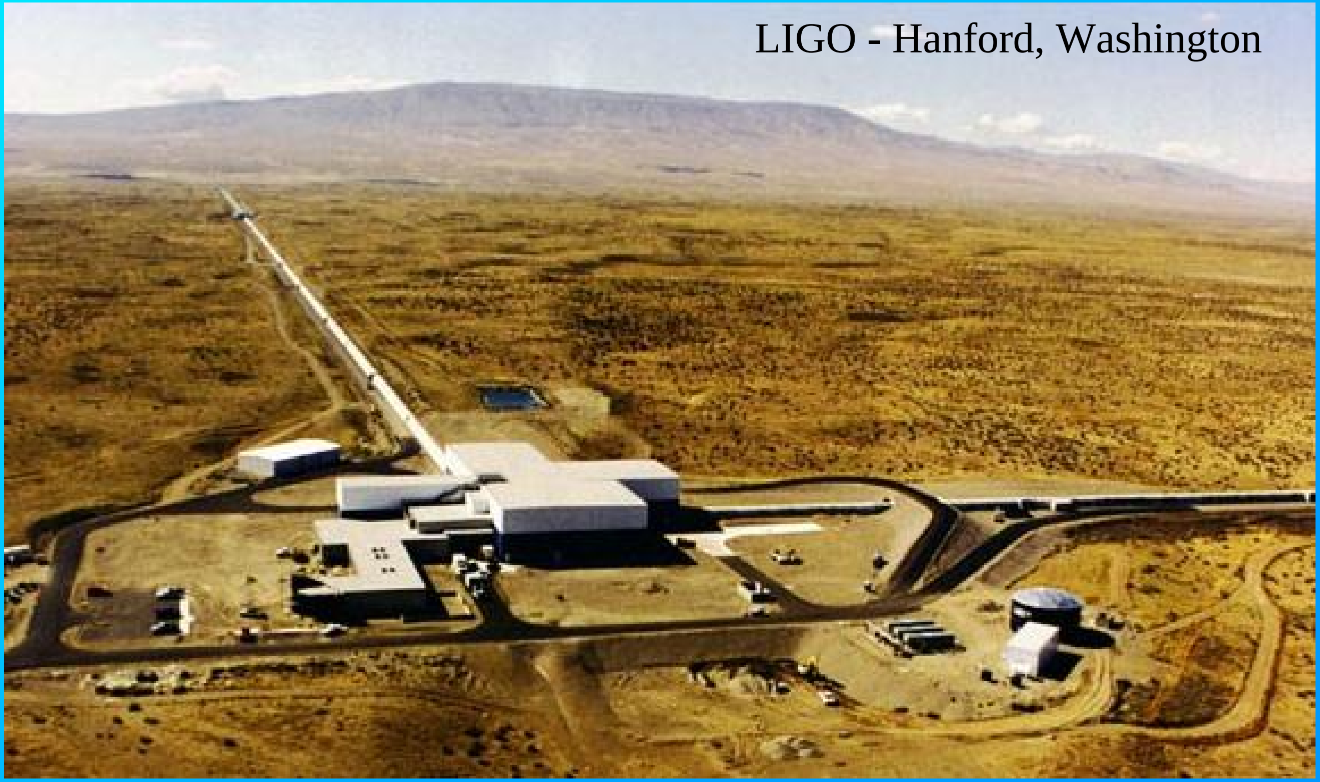


(K. Thorne, T. Carnahan, LISA Gallery)

Laser Interferometer Systems
e.g. LIGO, VIRGO

- LIGO - two sites in USA; VIRGO - European consortium
- 3-4 km vacuum arms, forming a laser interferometer
- Sensitive to GW signals in the 10 – 500 Hz range
- Both systems now commissioning, Advanced LIGO ~ 2011

Most probable astrophysical source: merger of double neutron-star binary systems

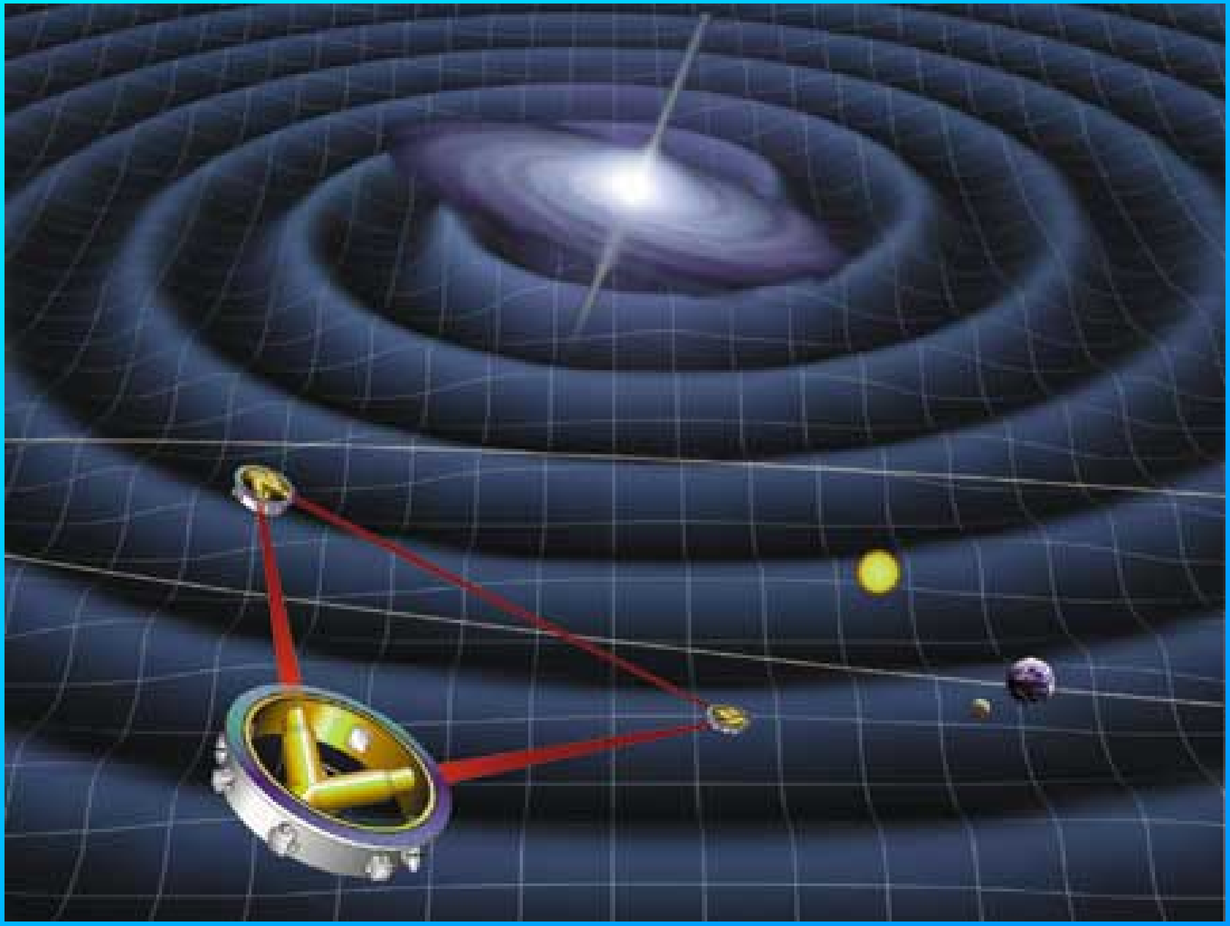


LIGO - Hanford, Washington

LISA: Laser Interferometer Space Antenna

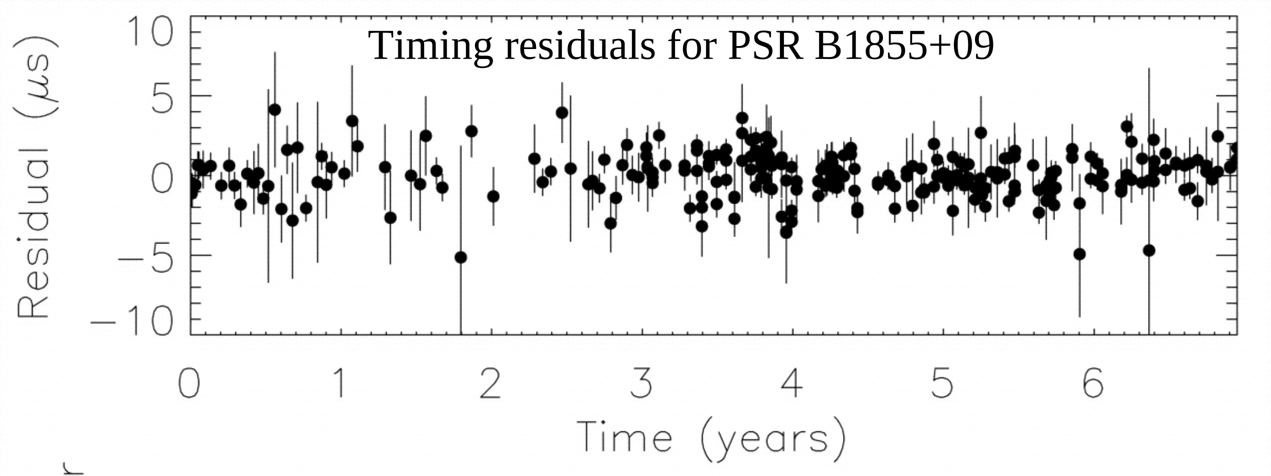
- ESA – NASA project
- Orbits Sun, 20° behind the Earth
- Three spacecraft in triangle, 5 million km each side
- Sensitive to GW signals in the range 10^{-4} – 10^{-1} Hz
- Planned launch ~2013

Most probable astrophysical source: merger of binary black holes in cores of galaxies



Detecting Gravity Waves with Pulsars

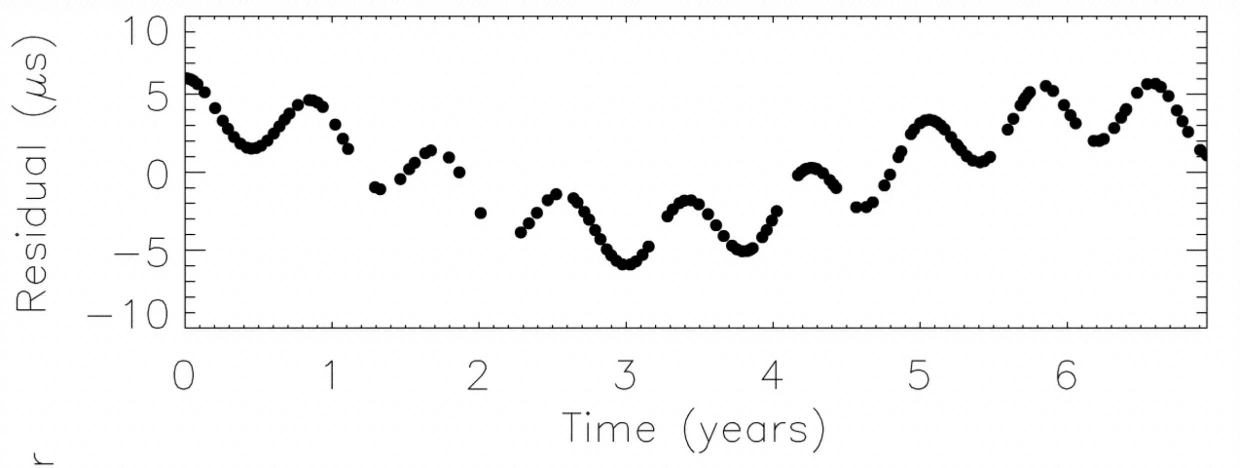
- Pulse arrival times are affected by motion of pulsar and motion of Earth.
- For stochastic GW background, motions of pulsar and Earth are uncorrelated
- With observations of one or two pulsars, can only put limit on strength of stochastic background
- Best limits are obtained for GW frequencies ~ 1/T where T is length of data span
- Analysis of 8-year sequence of Arecibo observations of PSR B1855+09 gives $\Omega_g = \rho_{GW}/\rho_c < 10^{-7}$ (Kaspi et al. 1994, McHugh et al.1996)
- Extended 17-year data set gives better limit, but non-uniformity makes quantitative analysis difficult – adopt $\Omega_g < 10^{-8}$ (Lommen 2001, Damour & Vilenkin 2004)



Individual Black-Hole Binary Systems

- Most (maybe all) galaxies have a black hole at their core
- Galaxy mergers are common, so binary black holes will exist in many galaxies
- Dissipative effects will result in spiral-in and eventual merger of BH pair
- For orbital periods of order years, can (in principle) detect binary signature in timing data
- Limits placed on binary mass ratio for six nearby galaxies containing central BH assuming orbital period ~2000 days from Arecibo observations of three pulsars (Lommen & Backer 2001)
- Based on VLBI measurements, proposed that there is a 10^{10} M_{sun} binary BH with 1-year period in 3C66B (z=0.02) (Sudou et al. 2003)
- Using PSR B1855+09 timing, existence ruled out at 98% confidence level (Jenet et al. 2004)

Expected timing signature for 3C66B binary BH



A Pulsar Timing Array

- With observations of many pulsars widely distributed on the sky can in principle ***detect*** a stochastic gravity wave background

- Gravity waves passing over Earth produce a correlated signal in TOA residuals for all pulsars

- Gravity waves passing over pulsars are uncorrelated

- Requires observations of ~20 MSPs over 5 – 10 years; could give ***first*** direct detection of gravity waves!

- A timing array can detect instabilities in terrestrial time standards – establish a ***pulsar timescale***

- Can improve knowledge of Solar system properties, e.g. masses and orbits of outer planets and asteroids

Idea first discussed by Foster & Backer (1990)

- **Clock errors**

  All pulsars have the same TOA variations: monopole signature

- **Solar-system ephemeris errors**

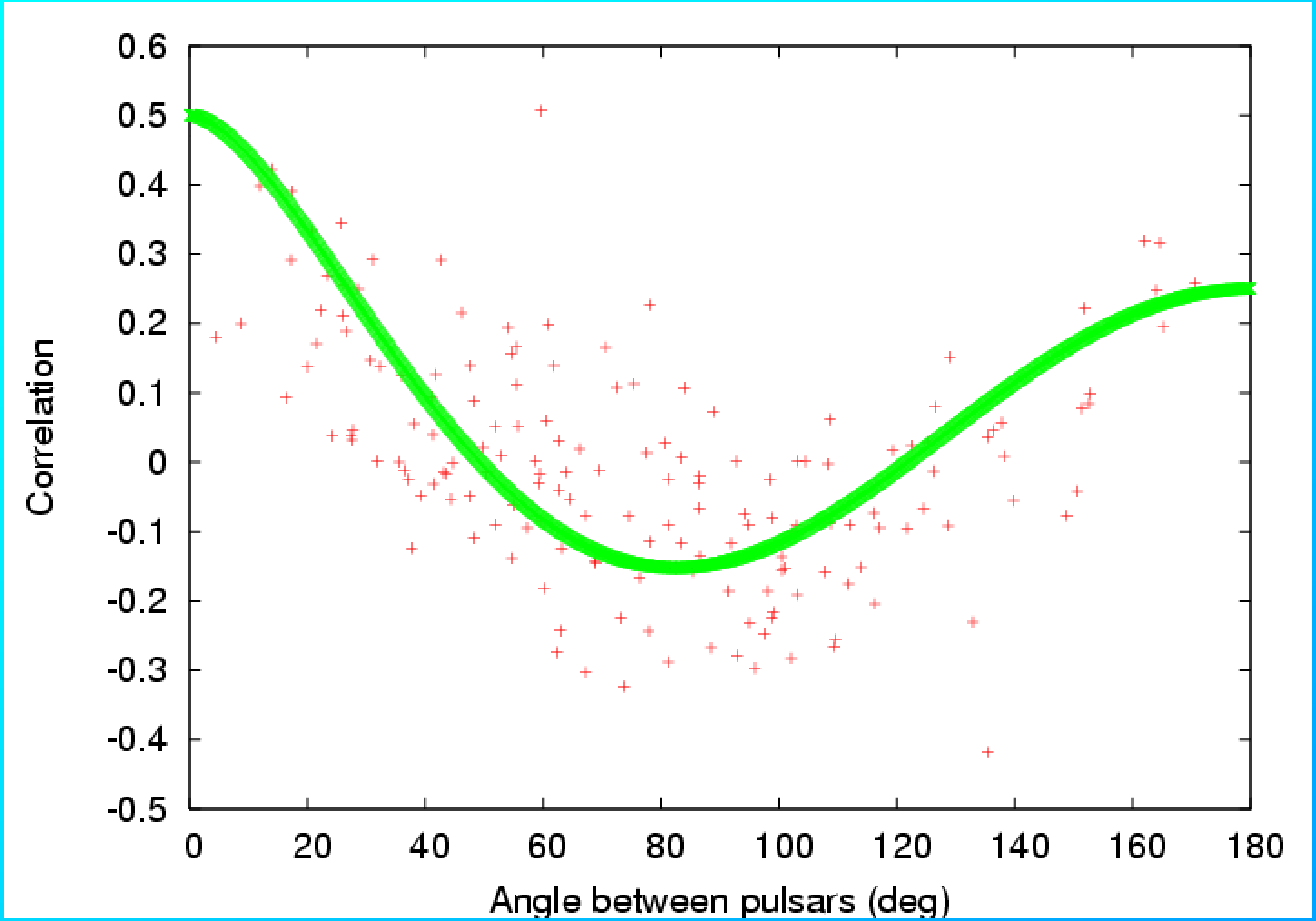
  Dipole signature

- **Gravity waves**

  Quadrupole signature

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

Detecting a Stochastic GW Background



Simulation using Parkes timing array pulsars with GW background from binary black holes in galaxies

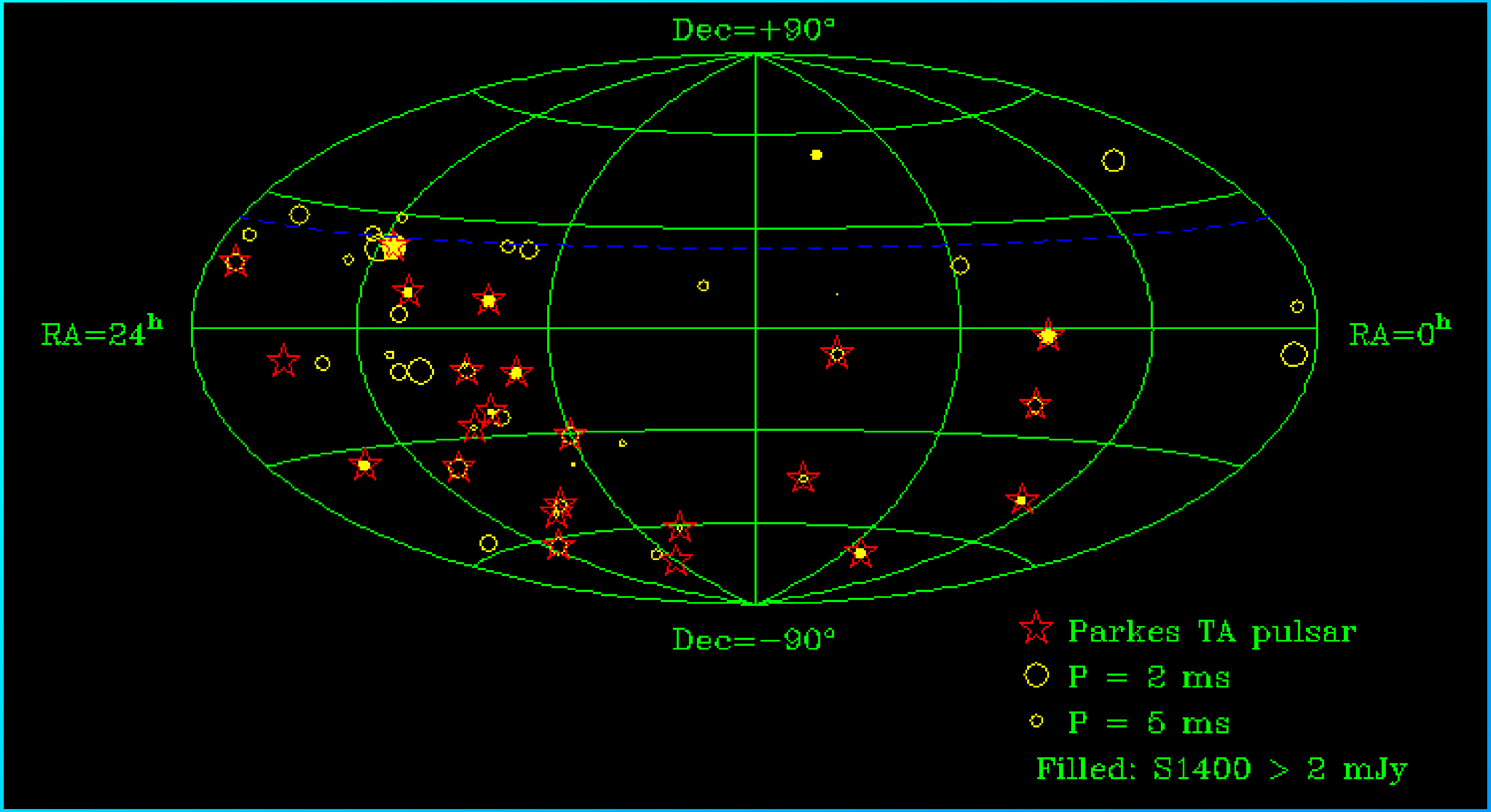
(Rick Jenet, George Hobbs)

Realisation of a Pulsar Timing Array

- Several groups around the world are embarking on timing array projects
- Parkes Pulsar Timing Array – a collaboration between groups at ATNF, Swinburne University and University of Texas
- Using Parkes 64-m telescope at three frequencies (680, 1400 and 3100 MHz)
- Wideband correlator, digital filterbank and CPSR2 baseband system
- Aim to get sub-microsecond precision on timing measurements for ~20 millisecond pulsars with observations at ~2 week intervals
- Will co-operate with northern-hemisphere observers to gain access to northern sky data

Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters



Detection Significance for PPTA of GW Stochastic Background

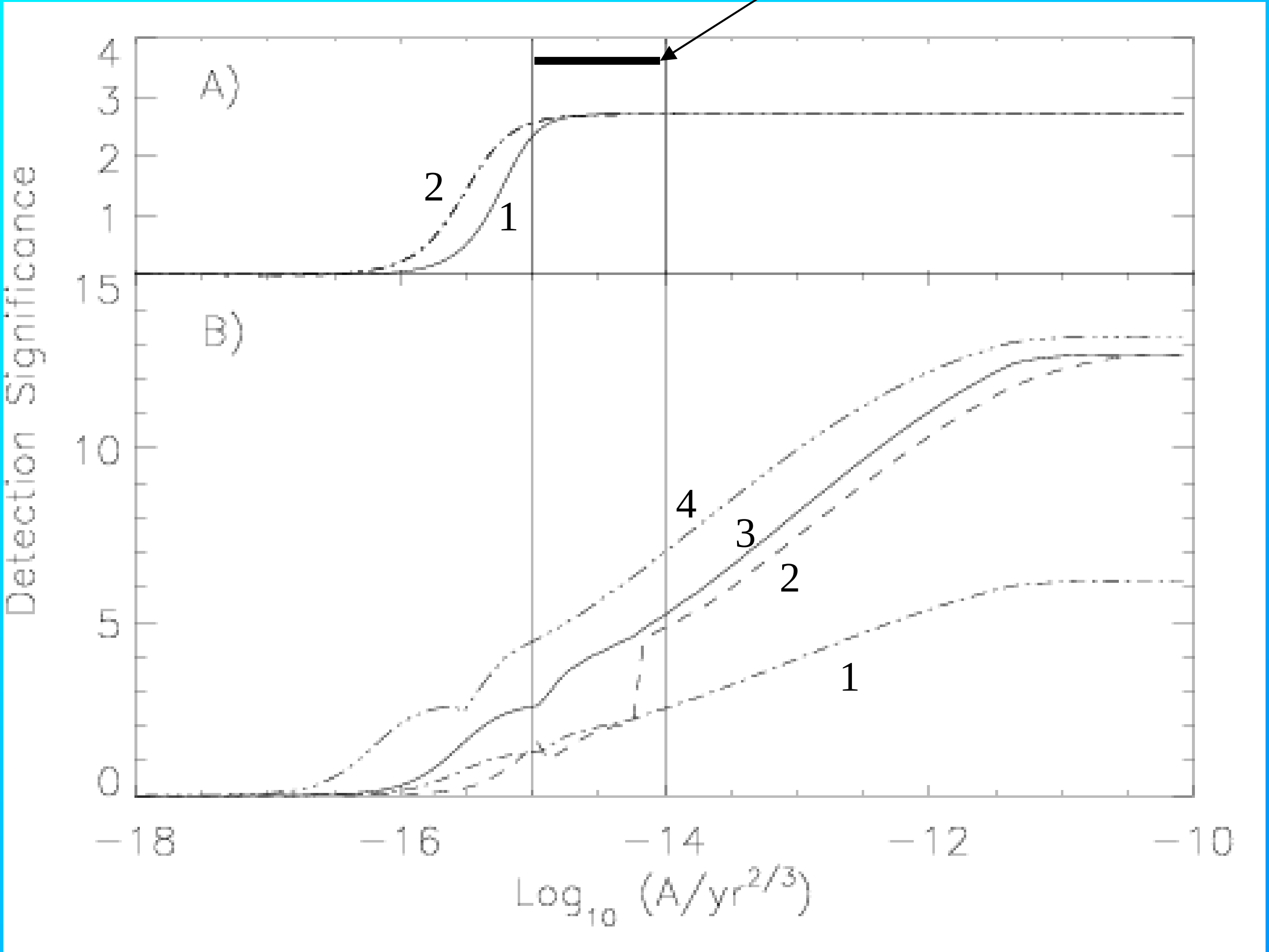
A: Simple correlation

1. 20 psrs, 250 obs, 5 yrs, 100 ns residuals
2. Low-pass filtered

B: Pre-whitened

1. 10 psrs, 250 obs, 5 yrs, 100 ns
2. 20 psrs, 10 @ 100ns, 10 @ 500 ns, 5 yrs
3. 250 obs, 5 yrs, 100 ns
4. 500 obs, 10 yrs, 100 ns

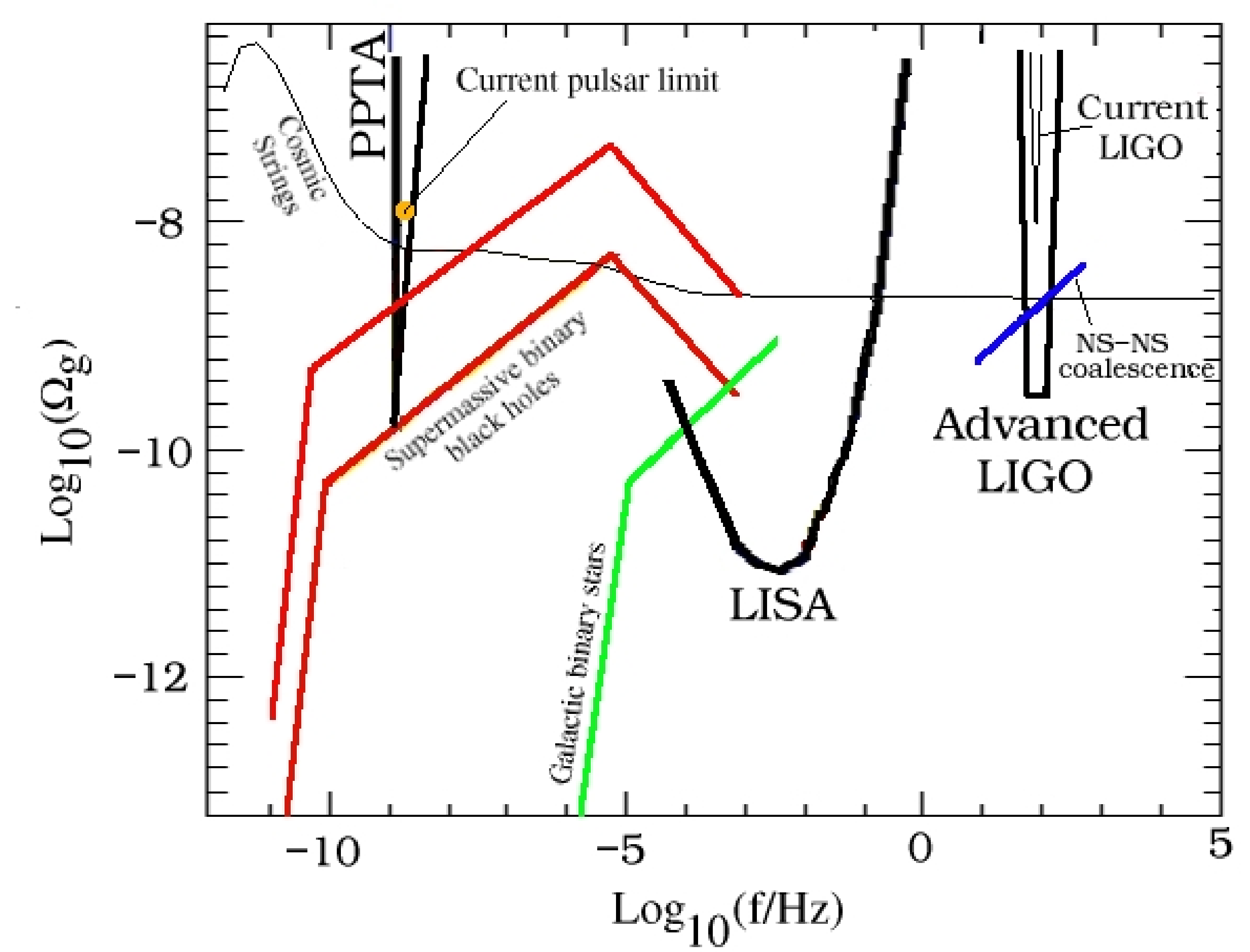
SKA
will do it easily!



Expected amplitude range for binary black-hole signal

(Jenet et al. 2005)

Gravity-Wave Spectrum



(After Maggiore, Phinney, Jenet, Hobbs)

Current Status of PPTA:

- Sample of 20 MSPs selected and ~2 weekly observations commenced

- Currently have ~12 with 1-hr TOA precision < 1 us, 3 or 4 with ~100 ns TOAs

- Best is PSR J1909-3744 with rms residual ~70 ns over 2 years (CPSR2 at 1.4 GHz)

- Developing wideband (1 GHz) digital filterbank and new baseband system – commissioning late 2005

- Interference mitigation is an important aspect

- Developing new data analysis methods – TEMPO2*

*See www.atnf.csiro.au/research/pulsar

Summary

- Pulsars are extraordinarily good clocks and provide highly sensitive probes of a range of gravitational effects
- Parkes multibeam pulsar surveys have been extremely successful, doubling the number of known pulsars
- First-known double-pulsar system detected! Makes possible several more independent tests of relativistic gravity
- Parkes Pulsar Timing Array (PPTA) has a chance of detecting gravity waves. It will require improvements in receiver technology and analysis techniques – and some luck
- PPTA will produce interesting science in MSP and interstellar medium properties, clock stabilities, RFI mitigation techniques
- SKA (Square Kilometre Array) will easily detect predicted GW signal

Thanks to: George Hobbs, Rick Jenet, Russell Edwards, John Sarkissian, John Reynolds, Matthew Bailes, Aidan Hotan, Steve Ord, Willem van Straten, Kejia Li, Mike Kesteven, Albert Teoh, Xiaopeng You and Jenny Zou.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Direct measurement of strong-field effects

- Most relevant for NS-NS systems
  - ➢ Eight now known
  - ➢ Five will coalesce in a Hubble time
- Many “Post-Keplerian” parameters measureable
  - ➢ Periastron precession, time dilation, orbit decay (all measured for Hulse-Taylor binary)
  - ➢ Shapiro delay (two parameters)
  - ➢ Geodetic precession
  - ➢ Relativistic orbit deformation
  - ➢ Aberration