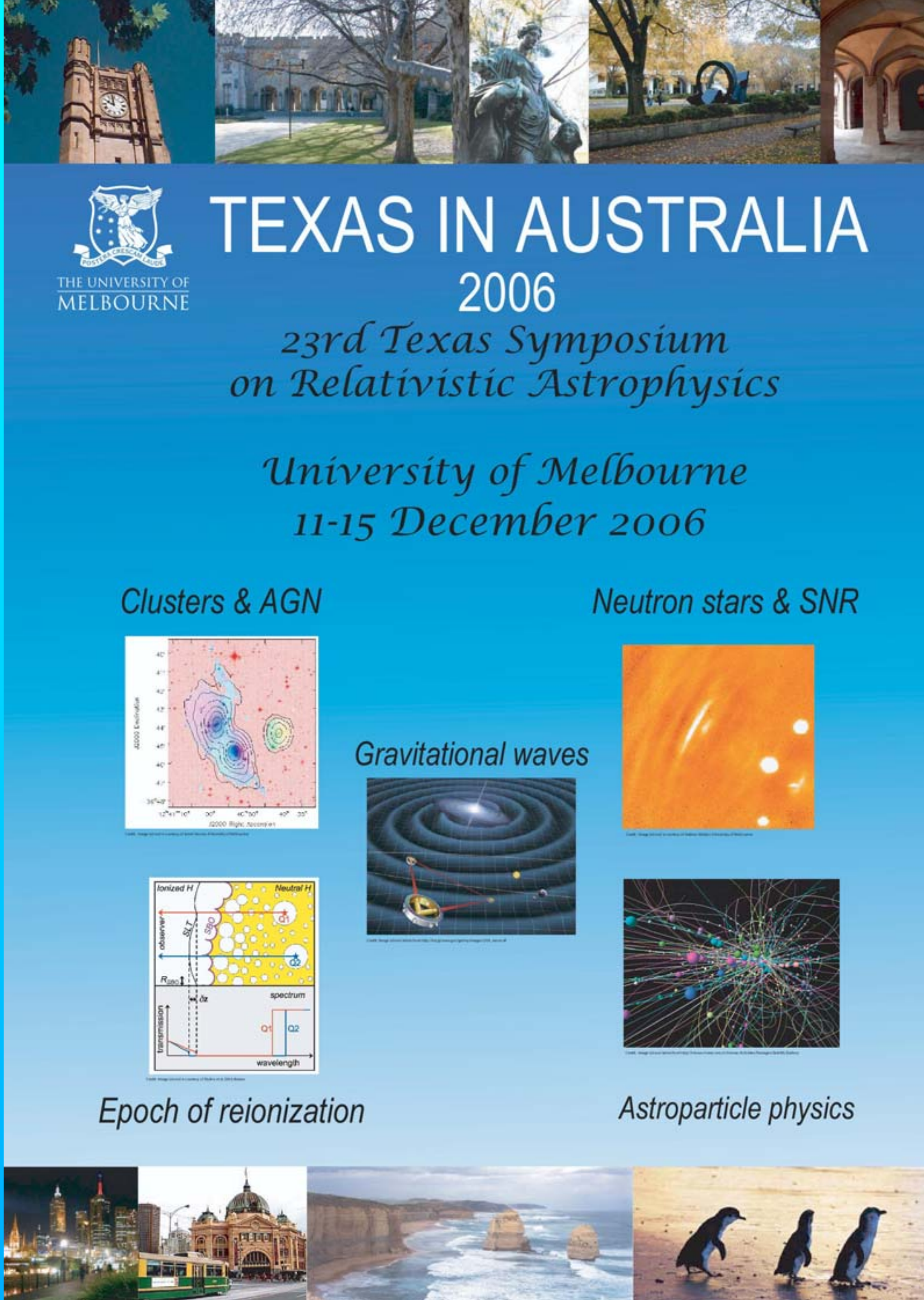
Next Texas Meeting December 2006

In Melbourne

It's warm in December!

- See kangaroos & koalas
- Swim at Barrier Reef
- Exciting science



Millisecond Pulsars and Gravity

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Australia

Summary

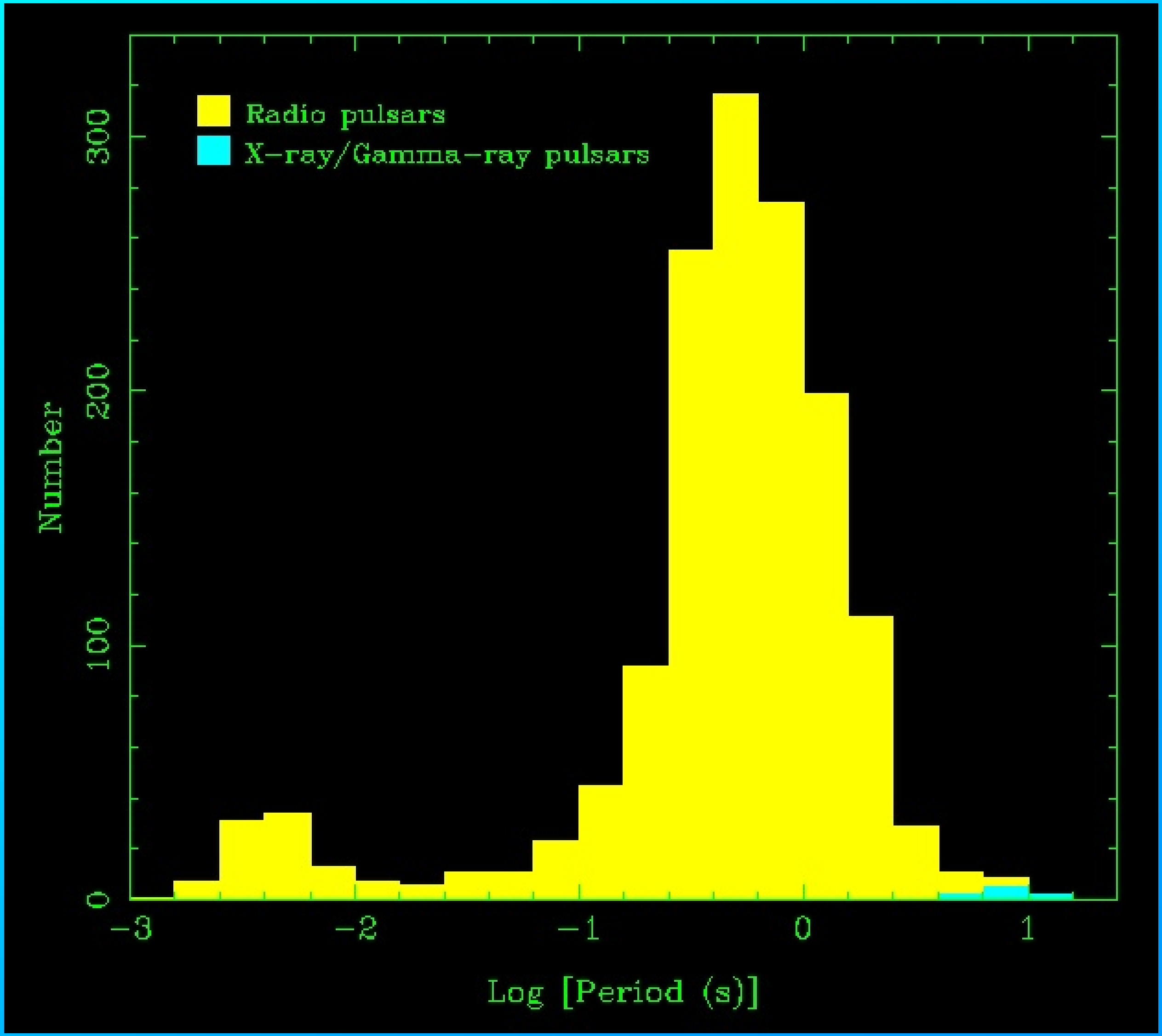
- Introduction to pulsar timing
- Parkes pulsar surveys – the double pulsar
- MSPs and gravity
- The Parkes Pulsar Timing Array project

Distribution of Pulsar Periods

• Total number known ~ 1600

• 'Normal' pulsars: 0.05 - 8.5 seconds

• 'Millisecond' pulsars: 1.5 - 30 ms. About 110 known.



Pulsar Origins

All pulsars are believed (by most people) to be rotating neutron stars

(ESO – VLT)

Normal Pulsars:

- Formed in supernova
- Relatively young (< 10^7 years)
- Mostly single (non-binary)

Millisecond Pulsars (MSPs):

- MSPs are very old (~10^9 years).
- Mostly binary
- They have been 'recycled' by accretion from an evolving binary companion.
- This accretion spins up the neutron star to millisecond periods.
- During the accretion phase the system may be detectable as an X-ray binary system.

Pulsars as clocks

• Pulsar periods are incredibly stable and can be measured to better than 1 part in 10^{15} in some cases

• Although they are stable, they are not constant: dP/dt is typically 10^{-15} for normal pulsars and 10^{-20} for MSPs

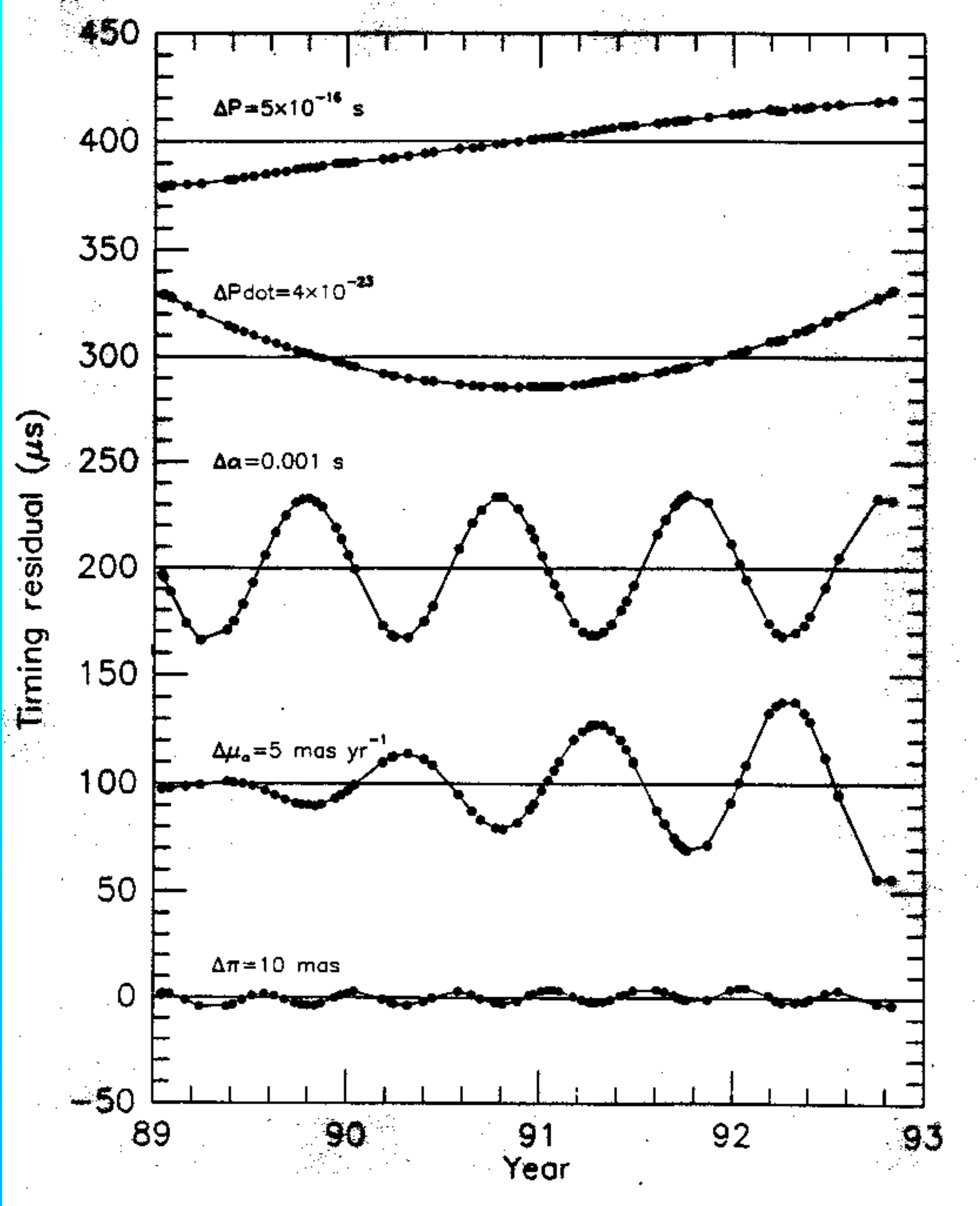
• Young pulsars suffer period irregularities and glitches ($\Delta P/P$ <~ 10^{-6}) but these are weak or absent in MSPs

Measurement of pulsar periods

- Start observation at known time and average 1000 or more pulses to get mean pulse profile.
- Cross-correlate this with a standard template to give the arrival time at the telescope of a fiducial point on profile, usually the pulse peak – the pulse time-of-arrival (TOA).
- Measure a series of TOAs over days – weeks – months – years.
- Compare observed TOAs with predicted values from a model for pulsar using TEMPO - differences are called timing residuals.
- Fit the observed residuals with functions representing errors in the model parameters (pulsar position, period, binary period etc.).
- Remaining residuals may be noise – or may be science!

Model timing residuals

- Period:
  $\Delta P = 5 \times 10^{-16}$ s
- Pdot:
  $\Delta \dot{P} = 4 \times 10^{-23}$
- Position:
  $\Delta\alpha = 1$ mas
- Proper motion:
  $\Delta\mu = 5$ mas/yr
- Parallax:
  $\Delta\pi = 10$ mas



Sources of Timing "Noise"

- Intrinsic noise
  - Period fluctuations, glitches
  - Pulse shape changes
- Perturbations of pulsar 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
- Receiver noise

The Binary Pulsar PSR B1913+16

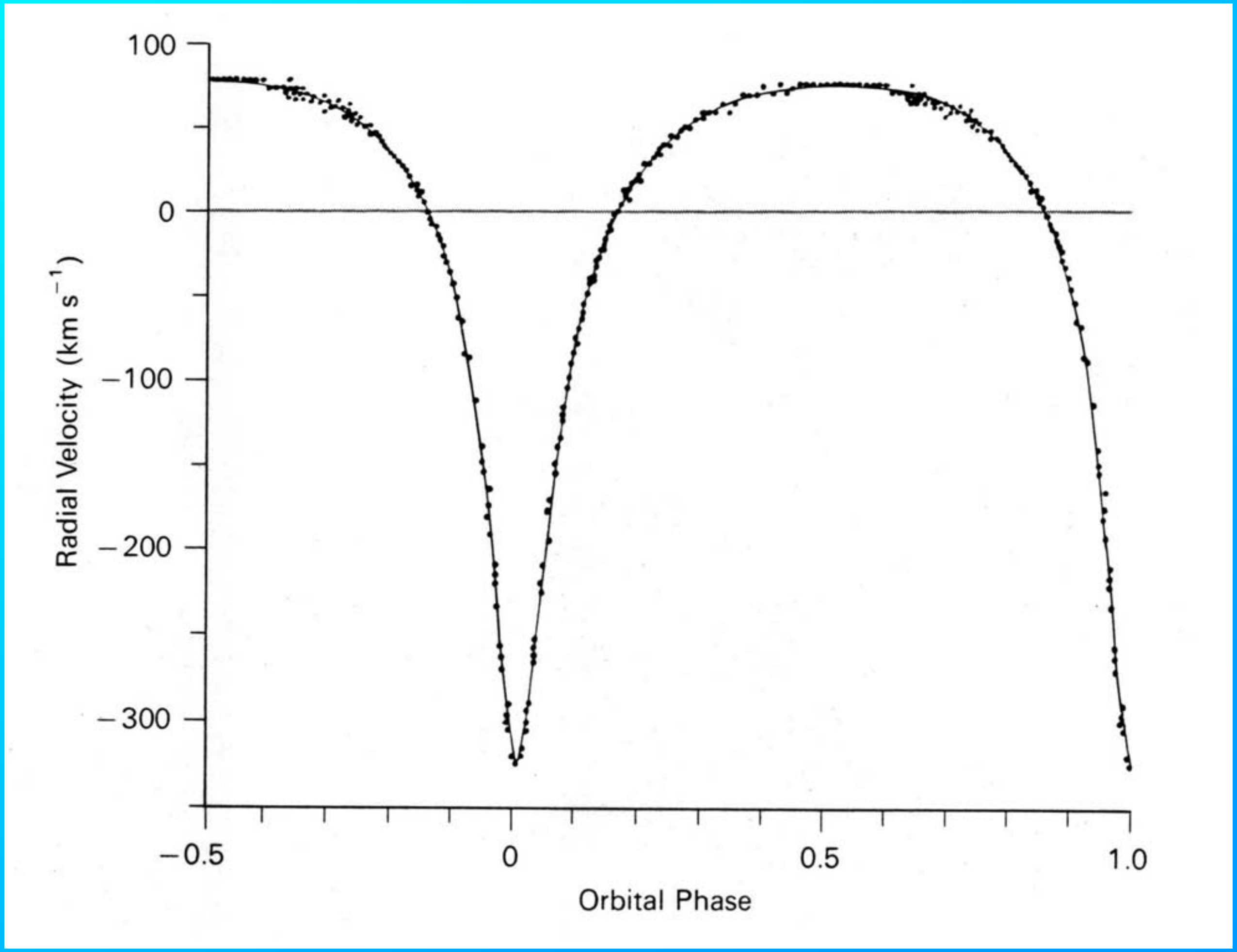
Discovered by Hulse & Taylor in 1975

Pulse period: 59 ms

Orbital Period:
7h 45m

Double neutron-star system

Velocity at periastron: ~ 0.001 of velocity of light



Post-Keplerian Parameters: PSR B1913+16

Given the Keplerian orbital parameters and assuming general relativity:

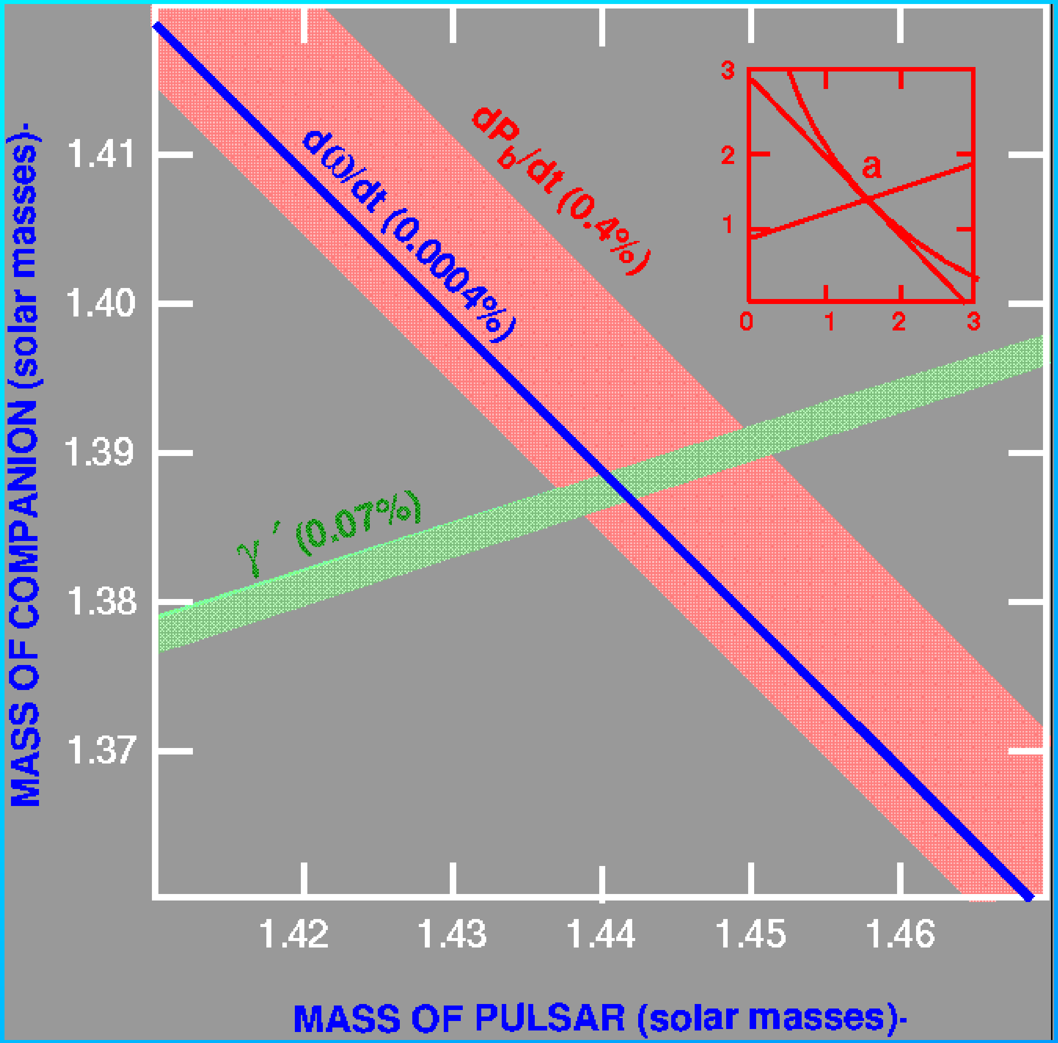
- Periastron advance: 4.226607(7) deg/year
  - ➢ $M = m_p + m_c$
- Gravitational redshift + Transverse Doppler: 4.294(1) ms
  - ➢ $m_c(m_p + 2m_c)M^{-4/3}$
- Orbital period decay: $-2.4211(14) \times 10^{-12}$
  - ➢ $m_p\, m_c\, M^{-1/3}$

First two measurements determine m_p and m_c. Third measurement checks consistency with adopted theory.

(Weisberg & Taylor 2003)

Neutron-star masses: PSR 1913+16

- Periastron advance
- Grav. Redshift
- Orbit decay



Mp = 1.4408 +/- 0.0003 M_{sun}

Mc = 1.3873 +/- 0.0003 M_{sun}

Both neutron stars!

(Weisberg & Taylor 2003)

(Diagram from C.M. Will, 2001)

PSR B1913+16 Orbit Decay

- Energy loss to gravitational radiation

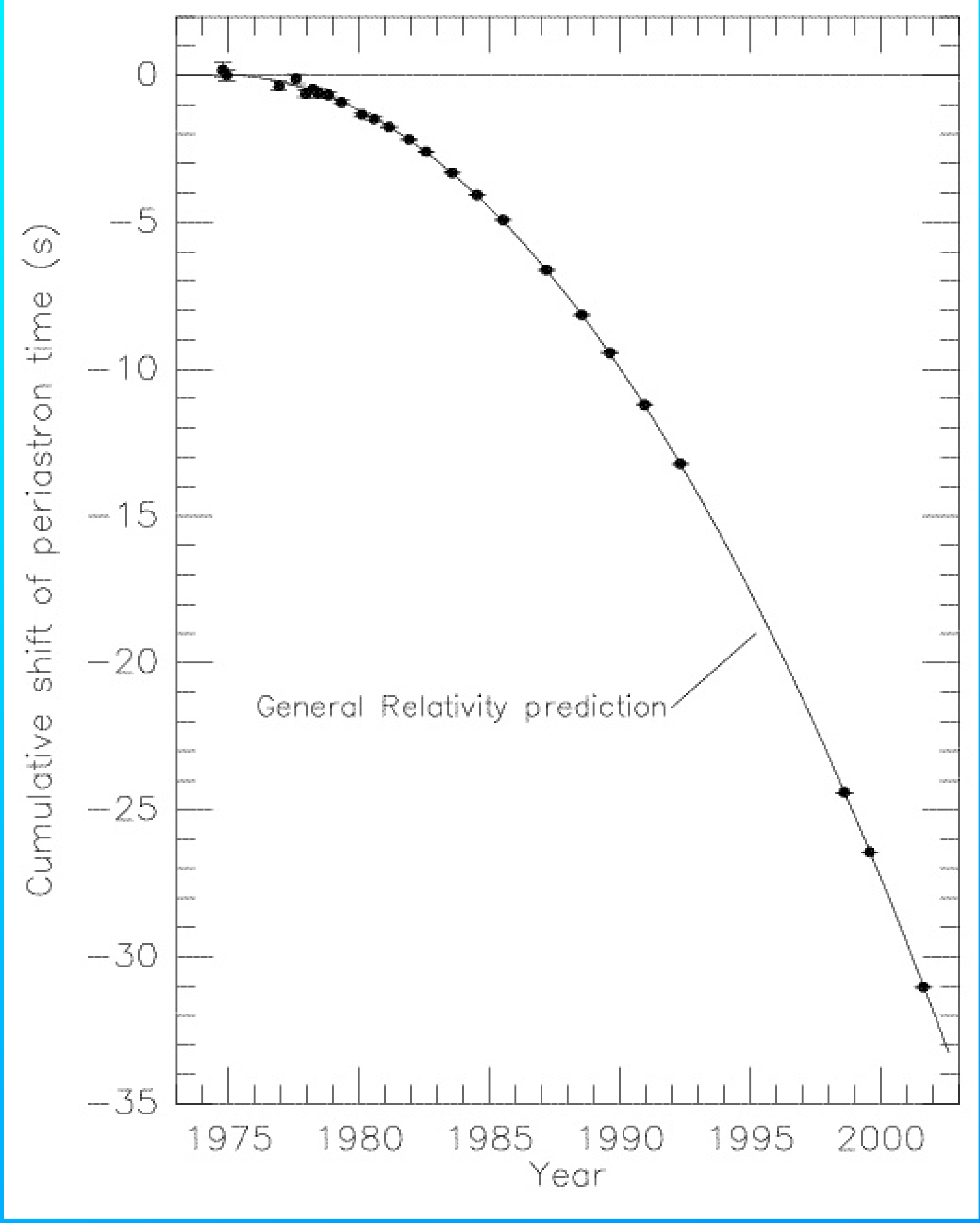
- Prediction based on measured Keplerian parameters and Einstein's general relativity

- Corrected for acceleration in gravitational field of Galaxy

- P_b(pred)/P_b(obs) = 1.0025 +/- 0.0021

First observational evidence for gravity waves!

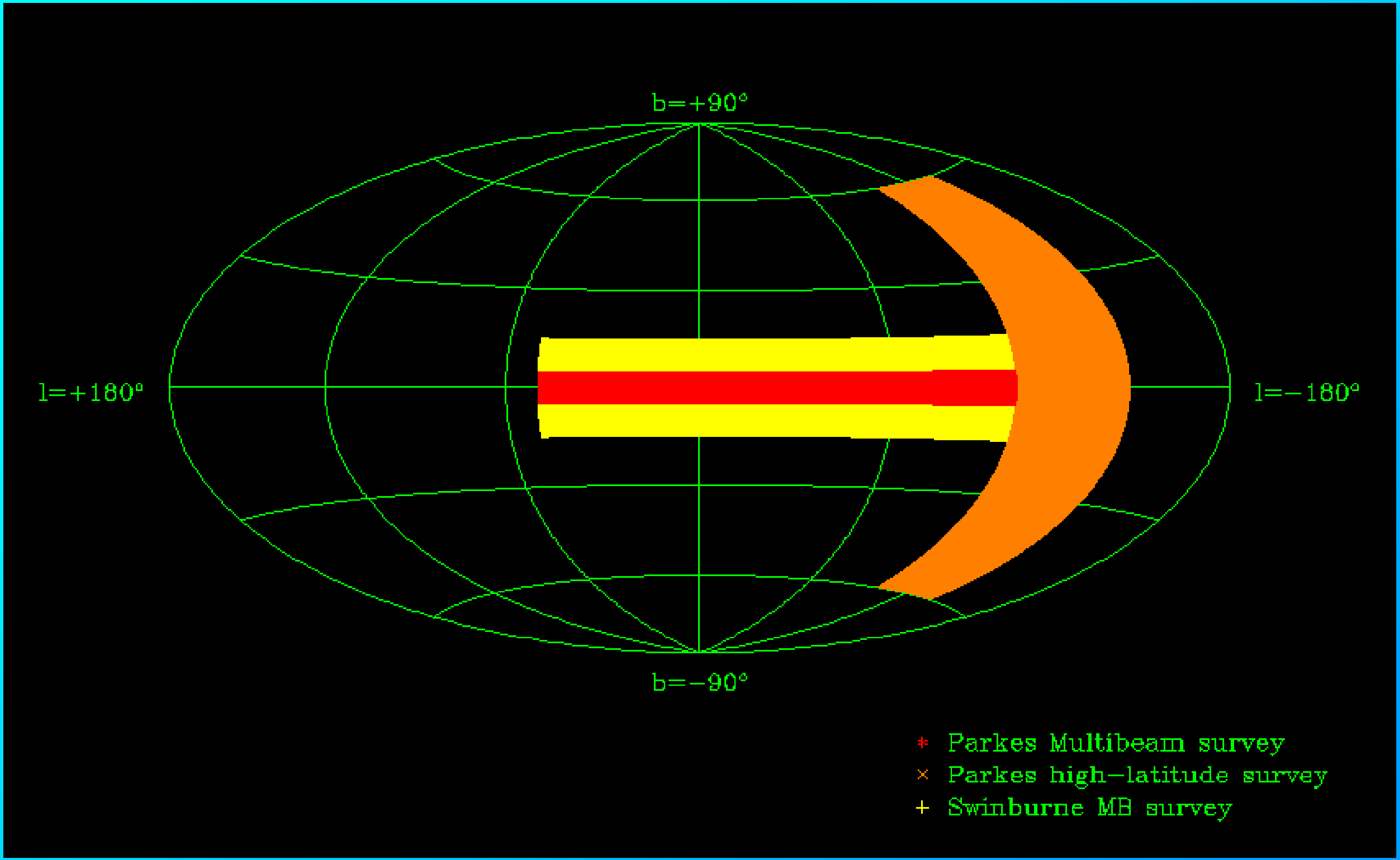
(Weisberg & Taylor 2003)



Parkes Multibeam Pulsar Surveys

- More than 800 pulsars discovered with multibeam system.
- The Parkes Multibeam Pulsar Survey (an international collaboration with UK, Italy, USA, Canada and Australia) has found more than 700 of these.
- High-latitude surveys have found about 120 pulsars including 15 MSPs
- Together with earlier surveys, more than 1000 pulsars have been discovered at Parkes: ~ two-thirds of total known.

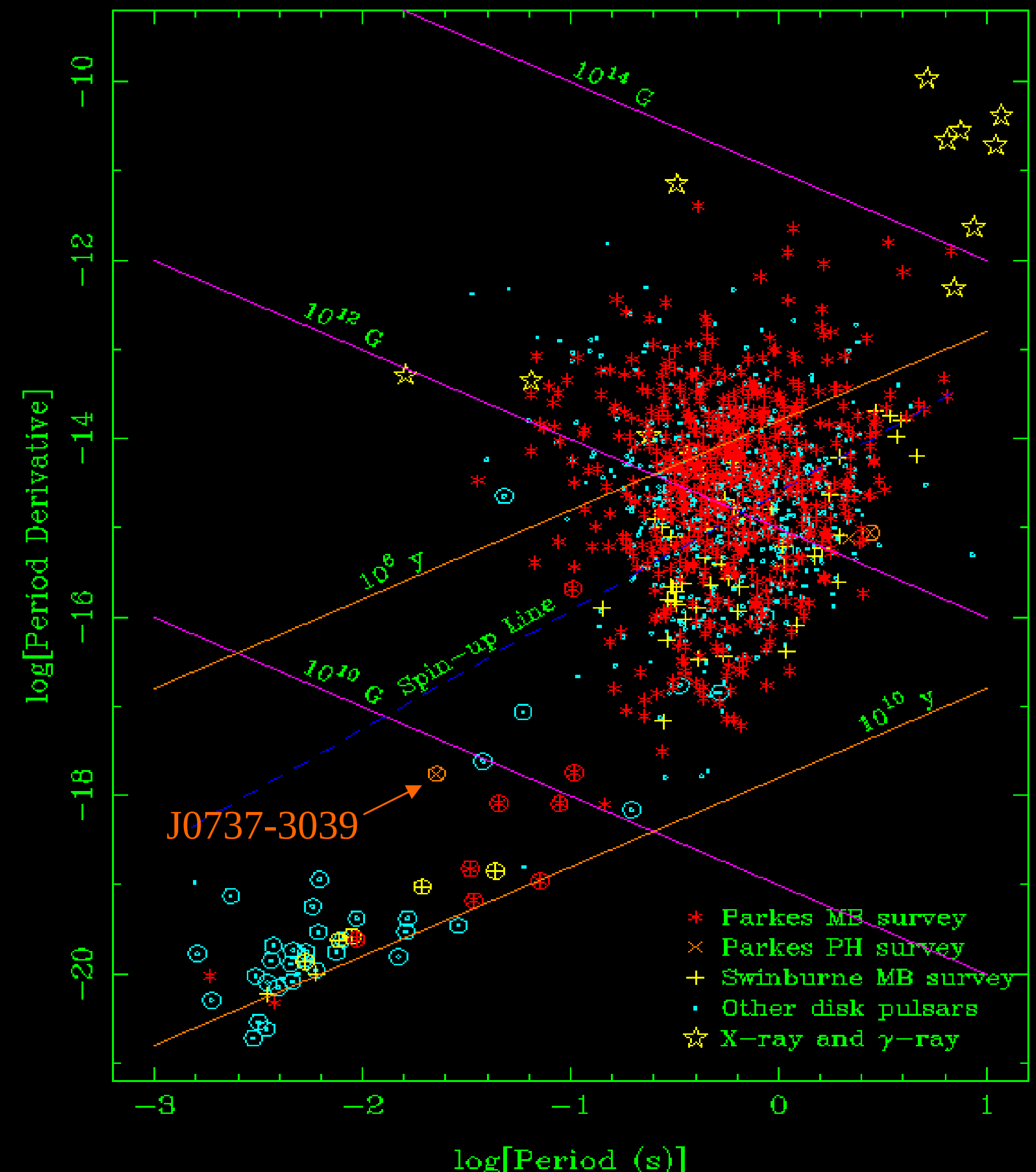
Parkes Multibeam Pulsar Surveys



PM and PH surveys collaborative with Jodrell Bank (UK), Bologna (Italy), Columbia (US), UBC and McGill (Canada)

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 and one double pulsar!



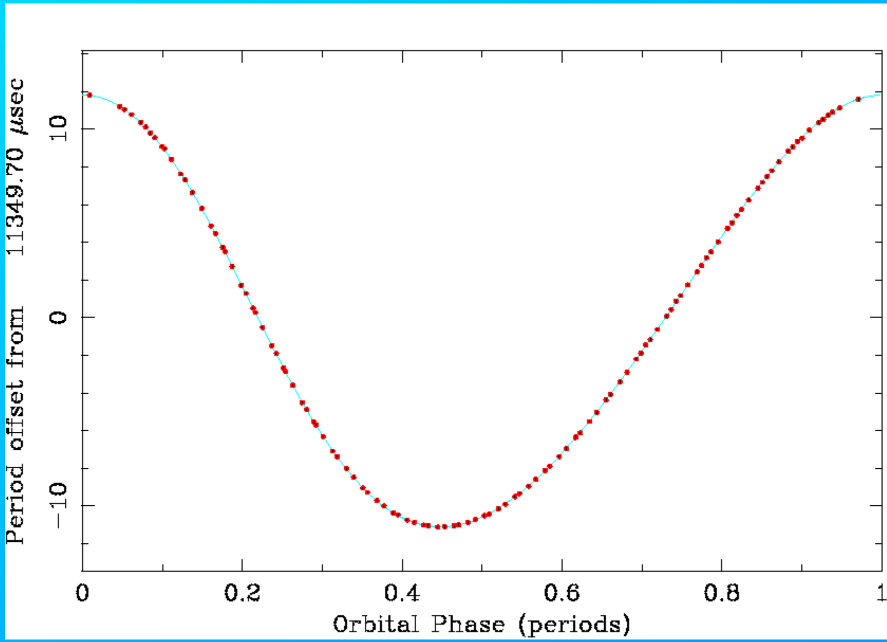
PSR J0737-3039A/B – The First Double Pulsar!

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!

Double neutron-star system!

- Many GR tests possible
- Large increase in predicted
NS-NS merger rate



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

PSR J0737-3039B

- Second neutron star detected as a pulsar

  ➢ ***First known double pulsar!***

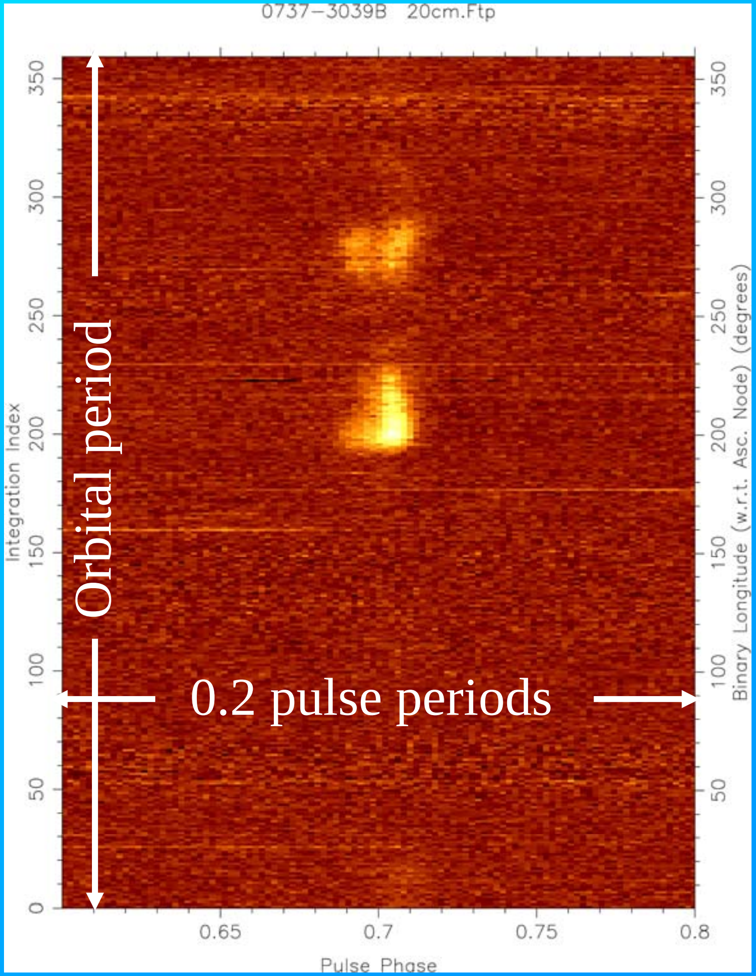
- Pulse period = 2.7 seconds, characteristic age = 55 Myr

- “Double-line binary” gives the mass ratio for the two stars – strong constraint on gravity theories

- MSP wind blows away most of B’s magnetosphere – dramatic effect on pulse emission

(Lyne et al., Science, 303, 1153, 2004)

➢ ***Talks by Michael Kramer and Thibault Damour***

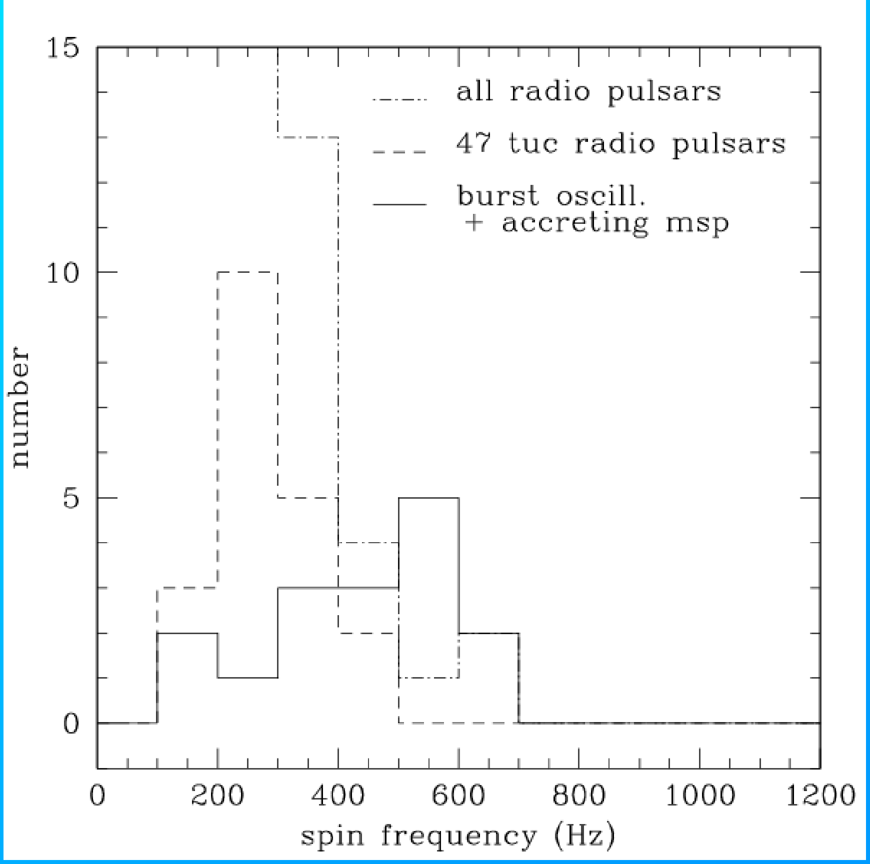


MSPs and Gravity: Maximum Spin Frequency

- In LMXB systems, long evolution time allows spin-up to > 1 kHz
- Most neutron-star EOSs allow spin at > 1 kHz
- X-ray observations and recent radio observations have little or no observational selection against sub-ms pulsars
- But, maximum observed spin frequency ~ 700 Hz

➢ Mass asymmetry due to accretion ($\Delta I/I \sim 10^{-7}$) results in GW emission (e.g., Bildsten 1998)

➢ r-mode instability in NS leads to viscous damping & GW emission (e.g., Ho & Lai 2000)



(Arras 2004)

Binary pulsars and gravity

Tests of Equivalence Principles

Limits on Parameterised Post-Newtonian (PPN) parameters

- Dipolar gravitational radiation – dP_b/dt
- Variation of gravitational constant G – dP/dt, dP_b/dt
- Orbit 'polarisation' due to external field – orbit circularity

Binary pulsars give limits comparable to or better than Solar-system tests, but in strong-field conditions ($GM/Rc^2 \sim 0.1$ compared to 10^{-5} for Solar-System tests)

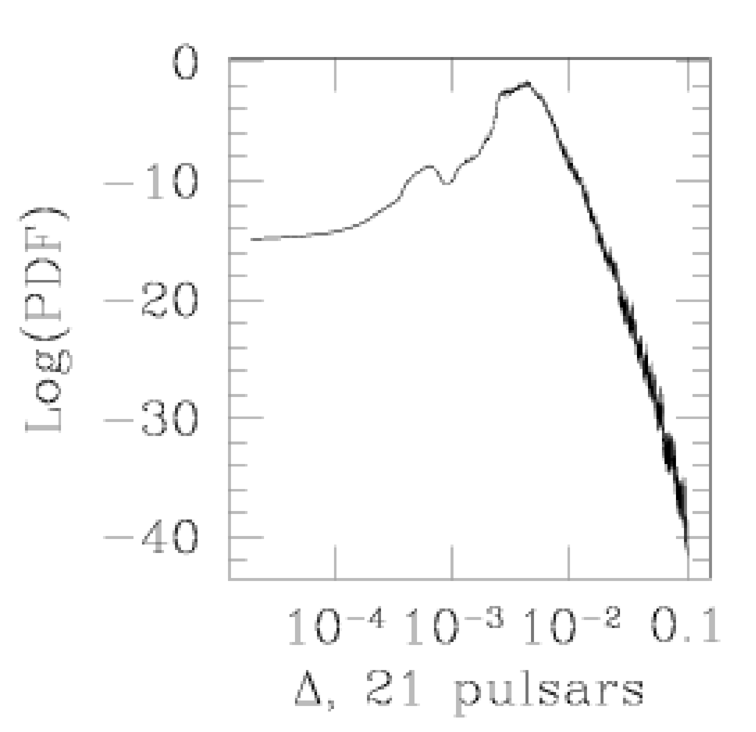
PSR J1853+1303 and Nordvedt Effect

- Long-period binary MSP discovered in Parkes Multibeam Survey
- $P = 4.09$ ms, $P_b = 115$ d, Ecc = 0.00002369(9), Min $M_{comp} = 0.24\ M_{sun}$
- White dwarf companion
- Test of Strong Equivalence Principle: Differential acceleration in Galactic gravitational field leads to "forced" eccentricity

(Damour & Schaefer 1991)

- Bayesian analysis with 20 other known low-mass wide binary pulsars
- $|\Delta| < 5 \times 10^{-3}$ (95% confidence) Comparable to LLR limit but in strong field limit.

(Stairs et al. 2005)



Binary Pulsars and Gravity

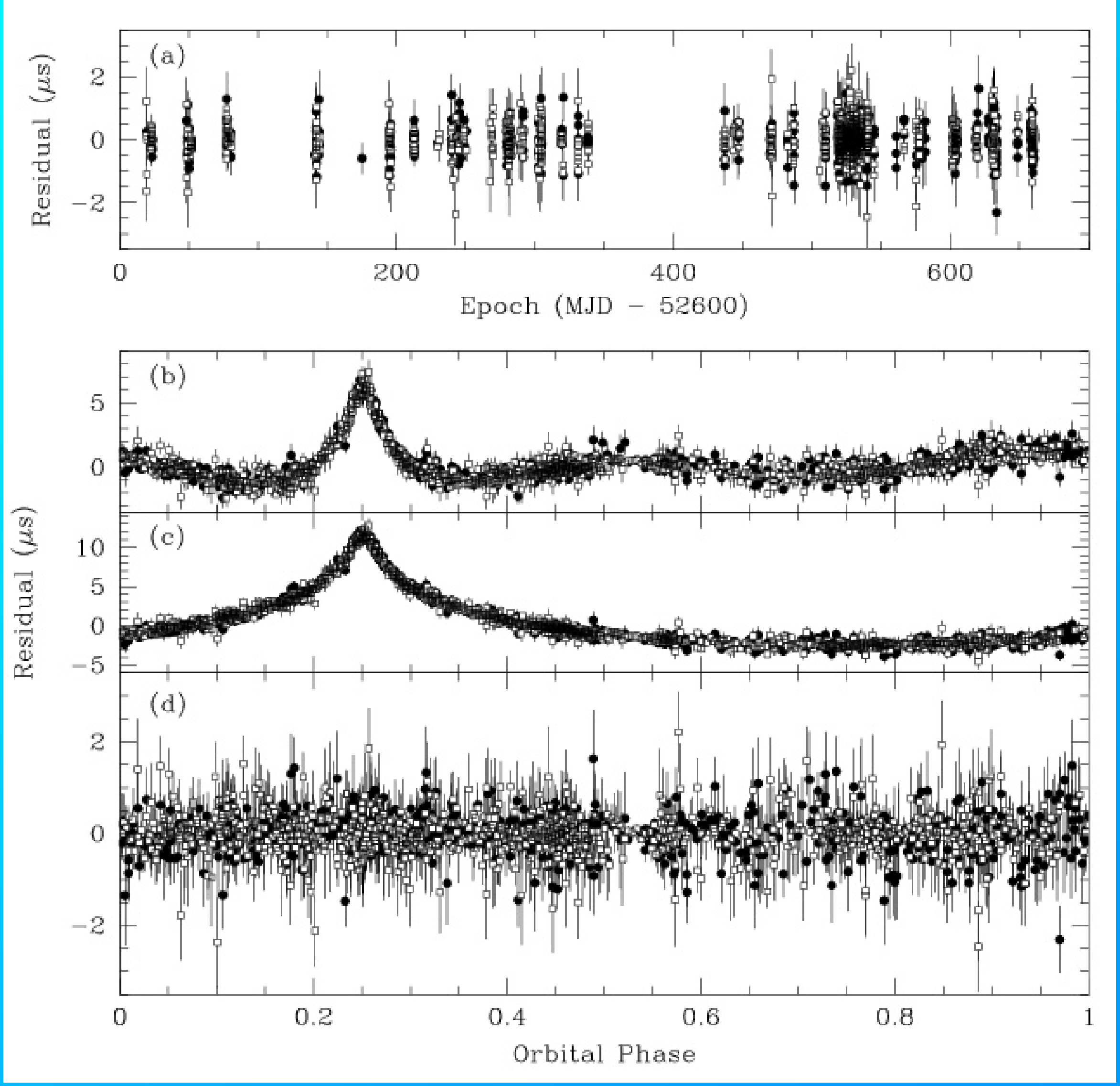
Direct measurement of strong-field effects

- Most relevant for NS-NS systems (plus one NS-WD system)
  - 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
  - Geodetic precession
  - Spin-orbit coupling etc.

More discussion in following talks!

PSR J1909-3744 – Shapiro Delay

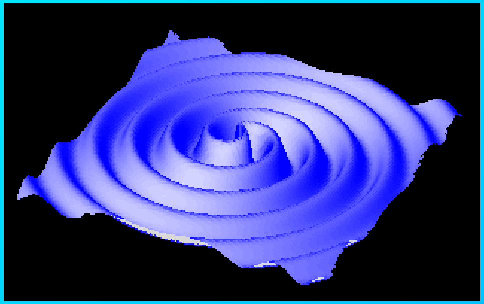
- Discovered in Swinburne – Caltech high-latitude survey at Parkes ($5^o < |b| < 30^o$)
- P = 2.9 ms, narrow pulse (Jacoby et al. 2003)
- Timing using CPSR2 baseband system – rms timing residual 227 ns for 10-min observations over 2 years
- Measurement of Shapiro delay: masses and orbit inclination



(Jacoby et al. 2005)

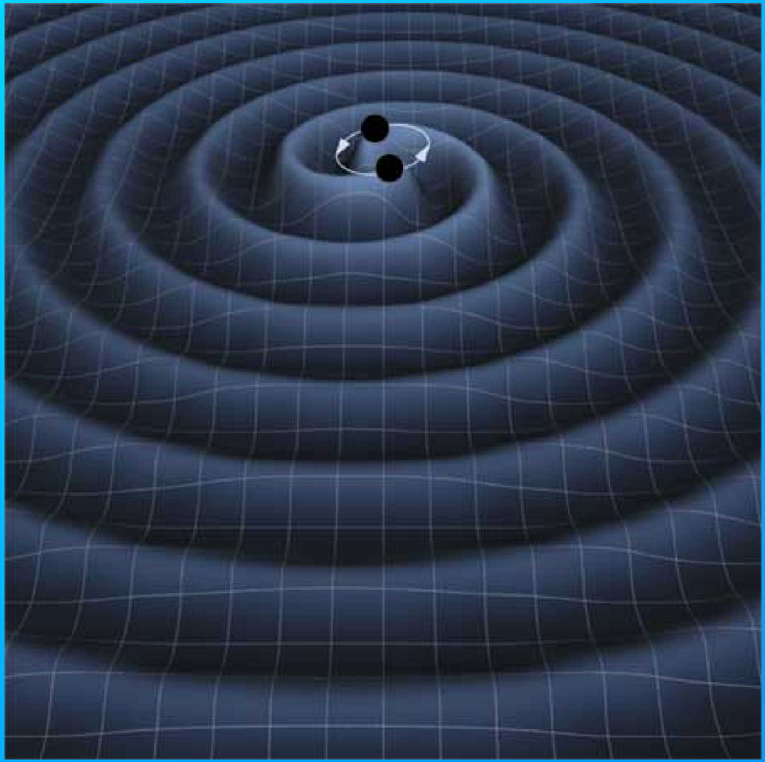
Gravitational Waves:

"Ripples in spacetime"



(NASA GSFC)

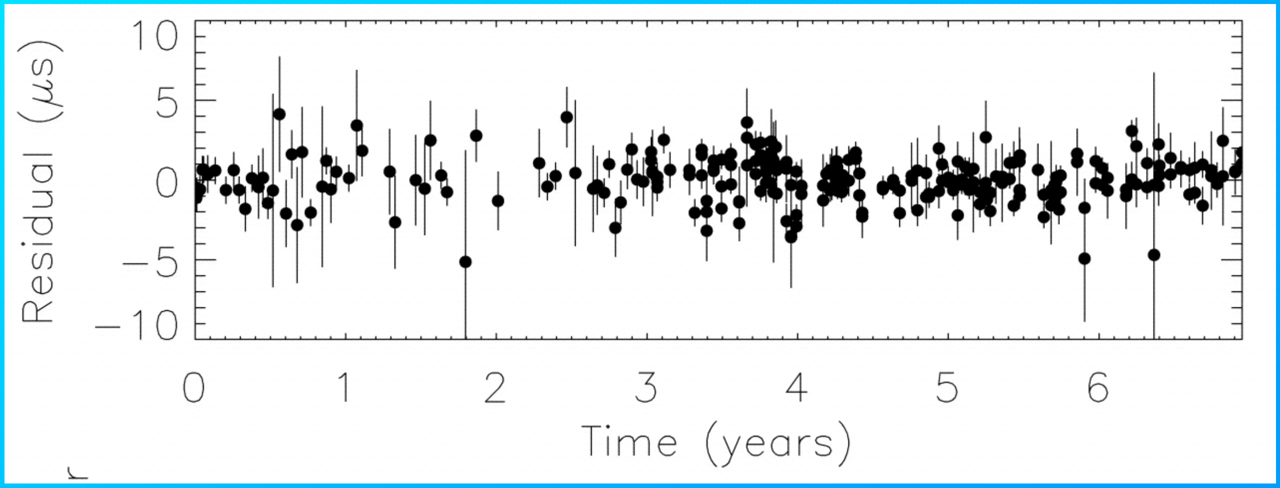
- Prediction of general relativity and other theories of gravity
- Generated by acceleration of massive object(s)
- Astrophysical sources:
  - Inflation era
  - Super-strings
  - Galaxy formation
  - Binary black holes in galaxies
  - Neutron-star formation in supernovae
  - Coalescing neutron-star binaries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



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

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

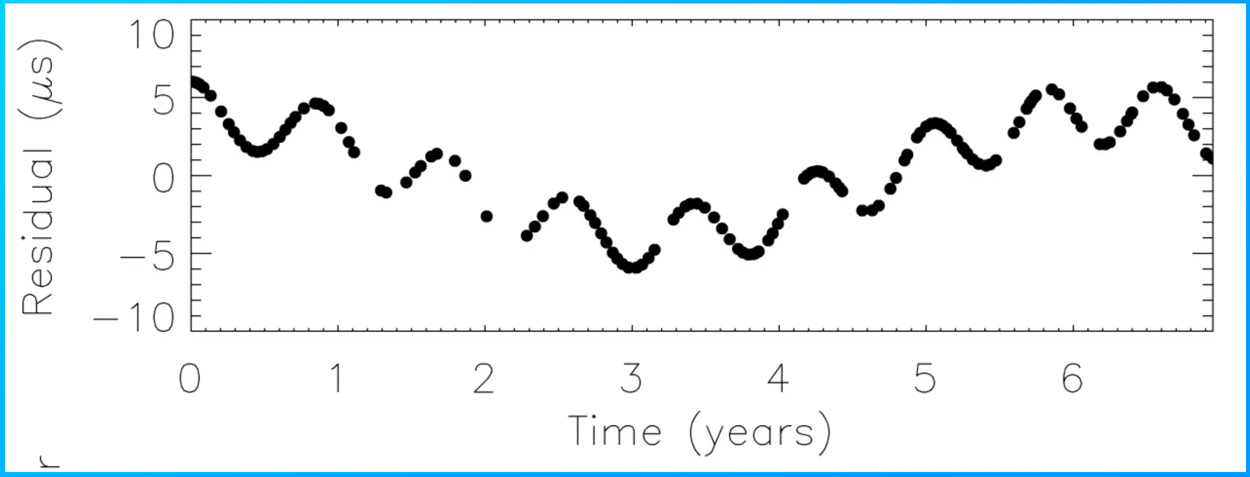
• For orbital periods of order years, can (in principle) detect binary signature in timing data

• 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:



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 15 – 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**

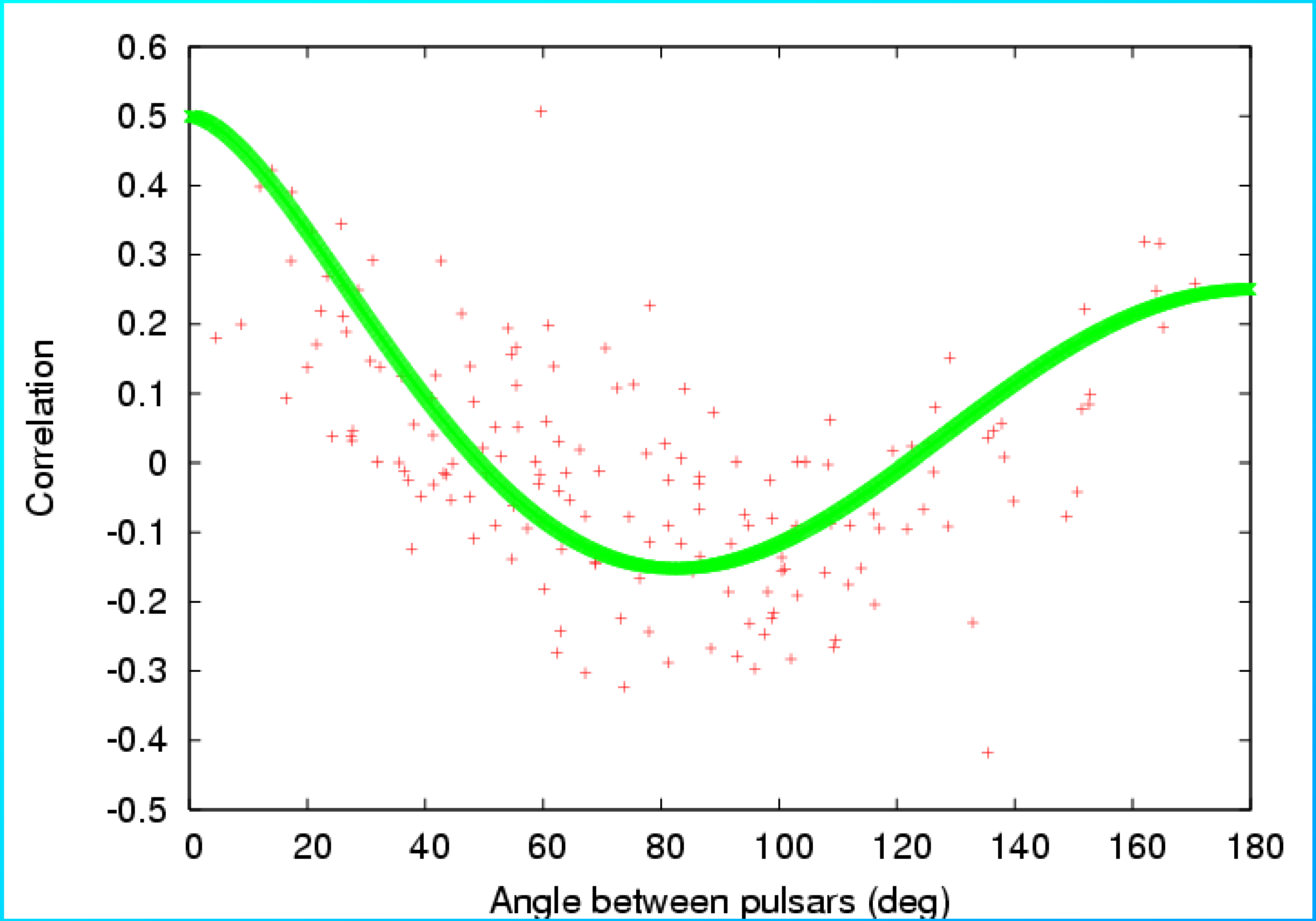
  Dipole signature

- **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

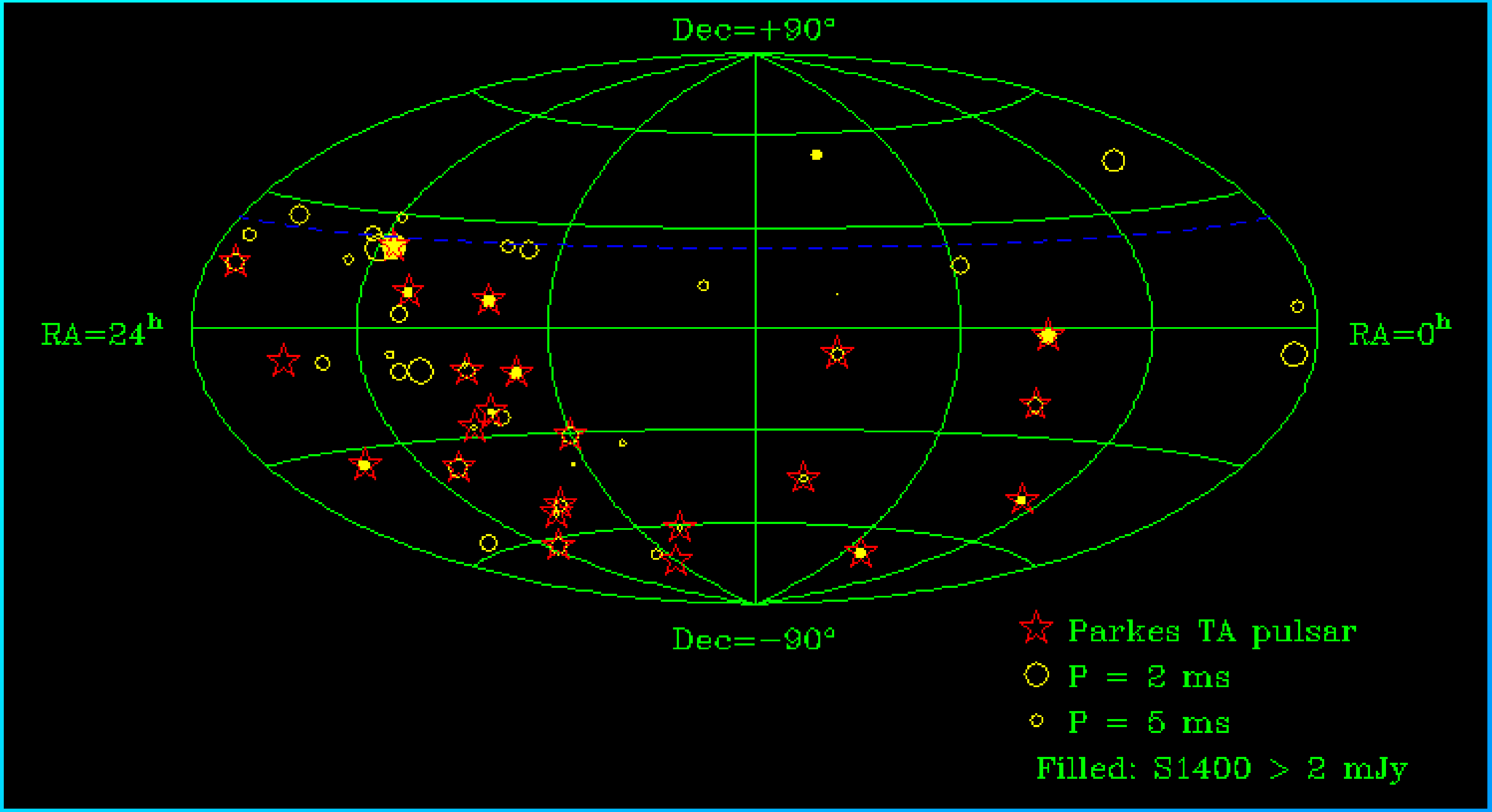
(Rick Jenet, George Hobbs)

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 and Swinburne University
- Using Parkes 64-m telescope at three frequencies (680, 1400 and 3100 MHz)
- Wideband correlator (digital filterbank system soon) and CPSR2 baseband system
- Aim to get sub-microsecond precision on timing measurements for 15 - 20 millisecond pulsars with observations at ~2 week intervals
- Will co-operate with northern-hemisphere observers to give access to northern sky data

Sky Distribution of Millisecond Pulsars

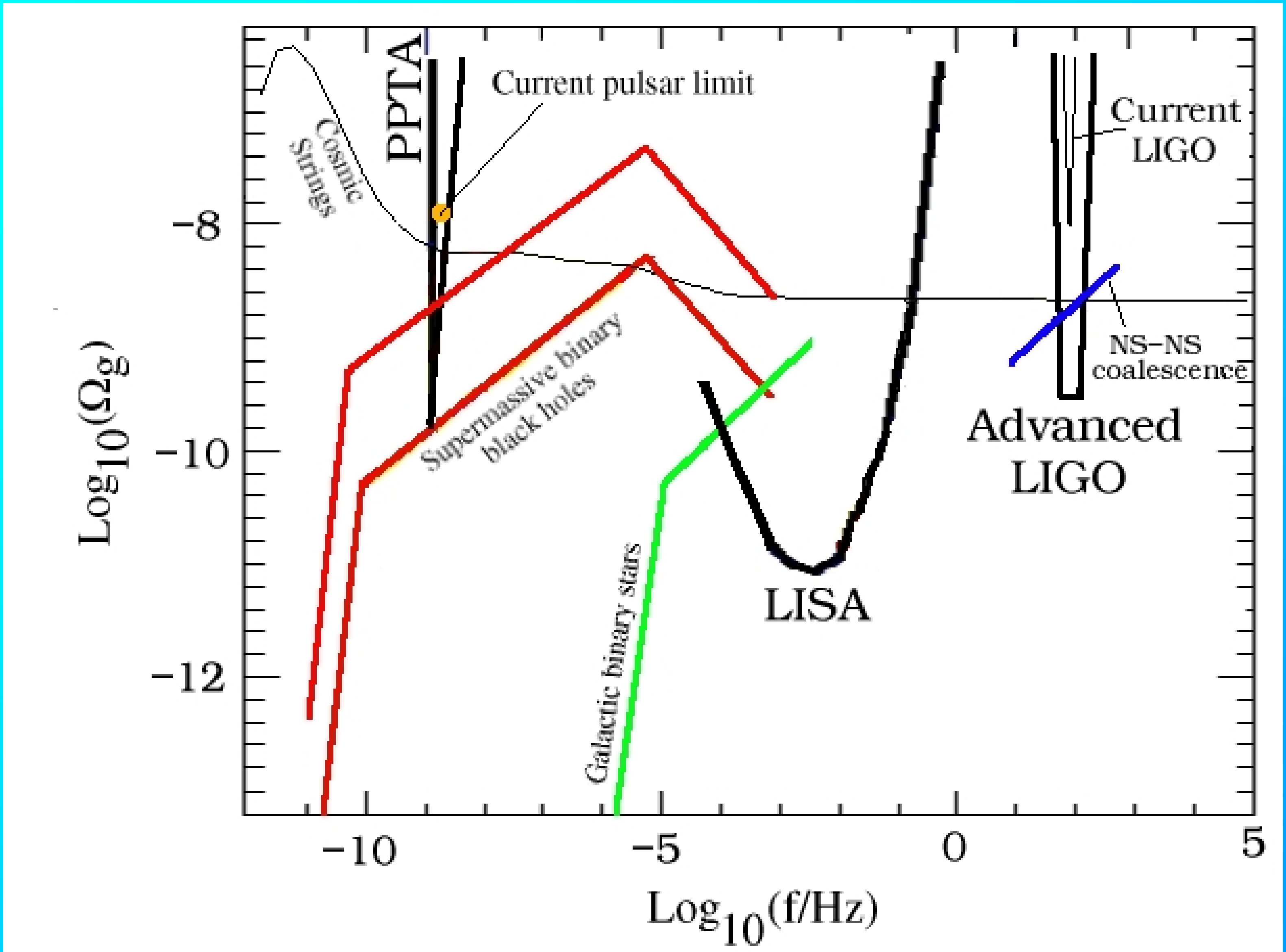
P < 20 ms and not in globular clusters



Current Status of PPTA:

- Sample of 20 MSPs selected and ~2 weekly observations commenced
- Currently have ~10 with 1-hr TOA precision < 1 us
- 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 programs – SuperTempo
- Collaboration with Rick Jenet (U Texas) on interpretation

Gravity-Wave Spectrum



(After Maggiore, Phinney, Jenet, Hobbs)

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

Thanks to: George Hobbs, Rick Jenet, Russell Edwards, Joel Weisberg, John Sarkissian, Matthew Bailes, Aidan Hotan, Steve Ord, Kejia Li, Mike Kesteven, Tejinder Uppal, Xiaopeng You and Jenny Zou.