The Parkes Pulsar Timing Array Project

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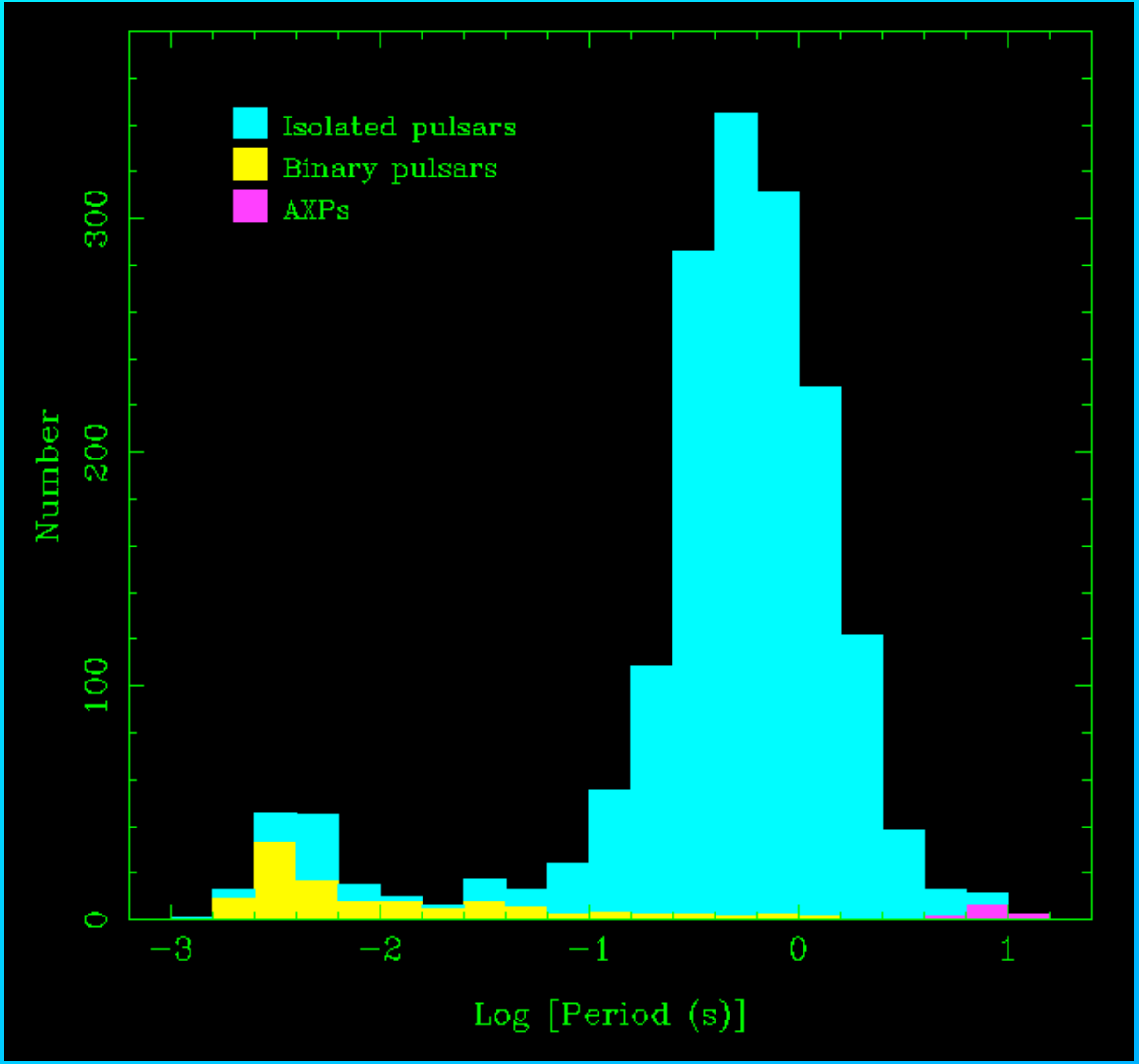
Summary

- A brief introduction to pulsar timing
- Testing gravity with binary pulsars
- The Parkes Pulsar Timing Array project

Spin-Powered Pulsars: A Census

- Number of known pulsars: 1791
- Number of millisecond pulsars: 181
- Number of binary pulsars: 139
- Number of AXPs: 13
- Number of pulsars in globular clusters: 107*
- Number of extragalactic pulsars: 20

* Total known: 137 in 25 clusters
(Paulo Freire's web page)



Data from ATNF Pulsar Catalogue, V1.33 (www.atnf.csiro.au /research/pulsar/psrcat; Manchester et al. 2005)

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

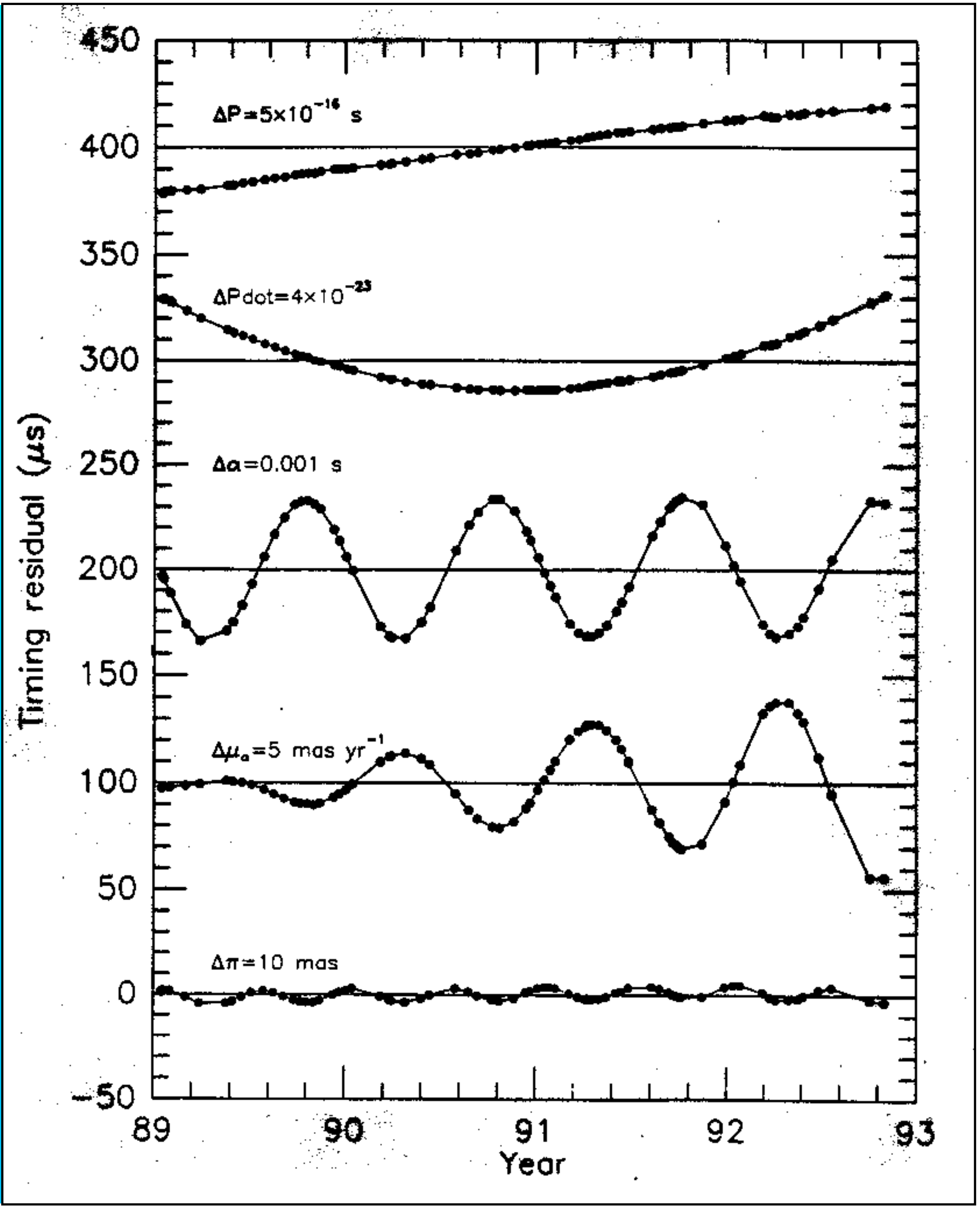
- Precise pulsar timing parameters are measured by comparing observed pulse ***times of arrival*** (TOAs) with predicted TOAs based on a model for the pulsar, then using the ***timing residuals*** - deviations from the model - to improve the model parameters and to search for unmodelled effects

Measurement of pulsar periods

- Start observation at a known time and average 10^3 - 10^5 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
- Transfer TOAs to an inertial frame - the Solar System barycentre
- Compare barycentric TOAs with predicted values from a model for pulsar - 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: $\Delta P = 5 \text{ x } 10^{-16}$ s
- dP/dt: $\Delta \dot{P} = 4 \text{ x } 10^{-23}$
- Position: $\Delta\alpha = 1$ mas
- Proper motion: $\Delta\mu = 5$ mas/yr
- Parallax: $\Delta\pi = 10$ mas



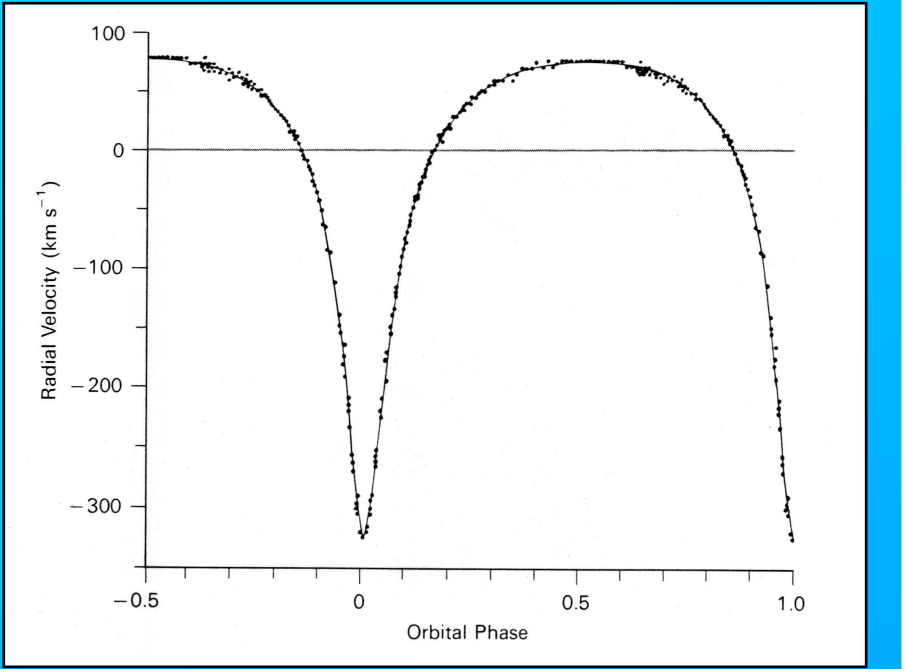
Sources of Pulsar Timing "Noise"

- 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

PSR B1913+16: The First Binary Pulsar

- Discovered at Arecibo Observatory by Russell Hulse & Joe Taylor in 1975
- Pulsar period 59 ms, a recycled pulsar
- Doppler shift in observed period due to orbital motion
- Orbital period only 7 hr 45 min
- Maximum orbital velocity 0.1% of velocity of light

Relativistic effects detectable!



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.

$M_p = 1.4408 \pm 0.0003\ M_{sun}$

$M_c = 1.3873 \pm 0.0003\ M_{sun}$

Both neutron stars!

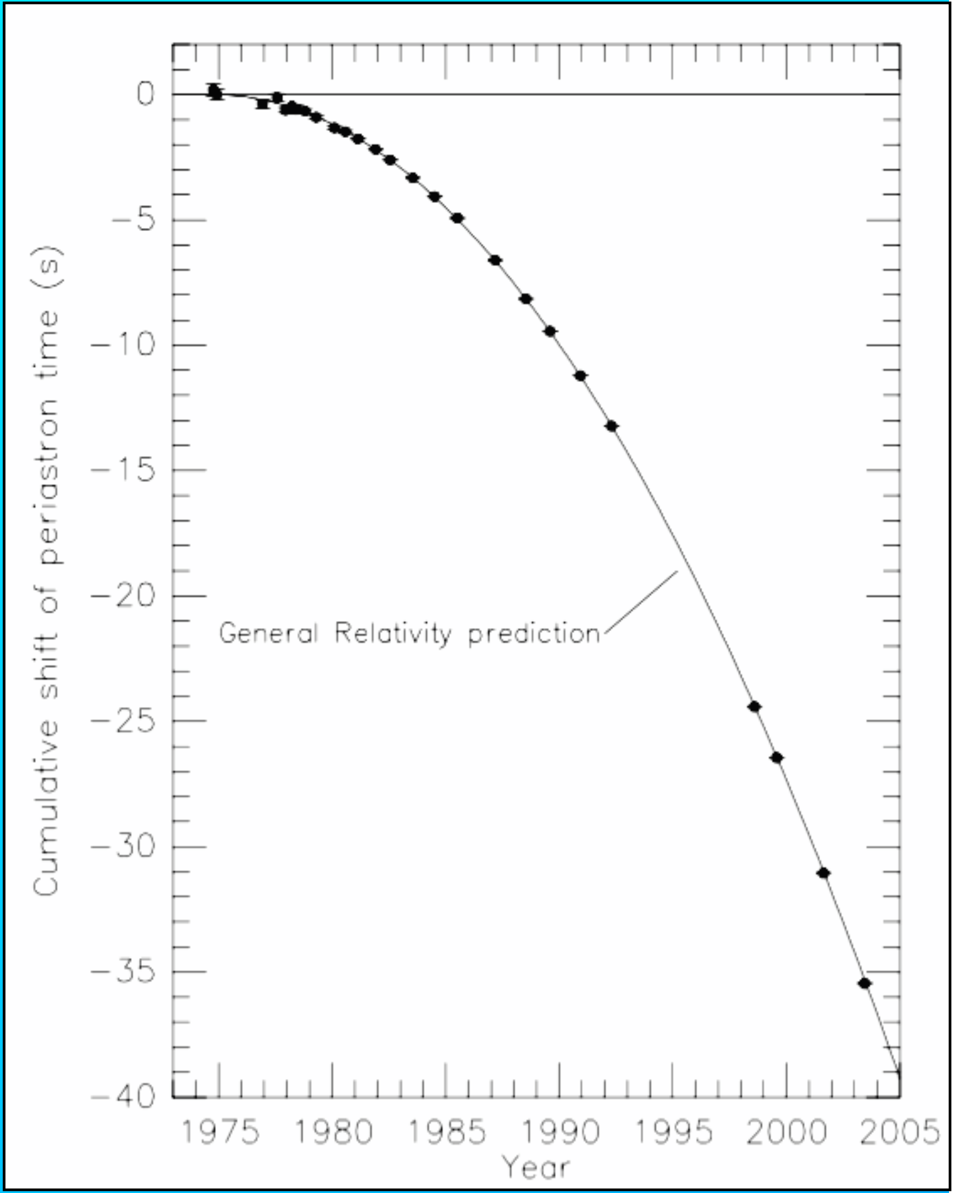
(Weisberg & Taylor 2005)

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
- $\dot{P}_b(\text{obs})/\dot{P}_b(\text{pred}) = 1.0013 \pm 0.0021$

First observational evidence for gravitational waves!

(Weisberg & Taylor 2005)



Parkes Multibeam Pulsar Survey

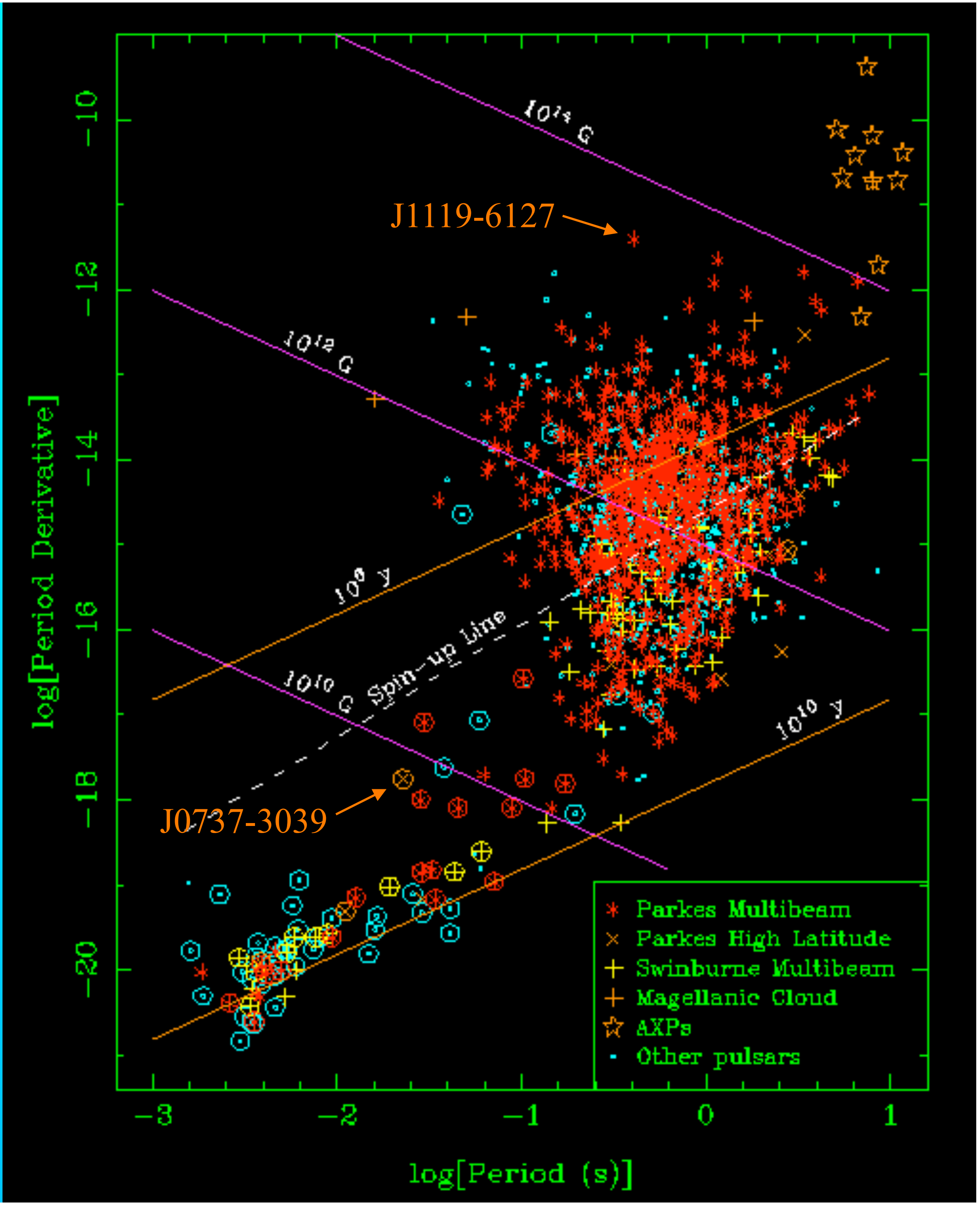
- Covers strip along Galactic plane, $-100^o < l < 50^o$, $|b| < 5^o$
- Central frequency 1374 MHz, bandwidth 288 MHz, 96 channels/poln/beam
- Sampling interval 250 μs, time/pointing 35 min, 3080 pointings
- Survey observations commenced 1997, completed 2003
- Processed on work-station clusters at ATNF, JBO and McGill
- 740 pulsars discovered, 1015 detected
- At least 18 months of timing data obtained for each pulsar

Principal papers:

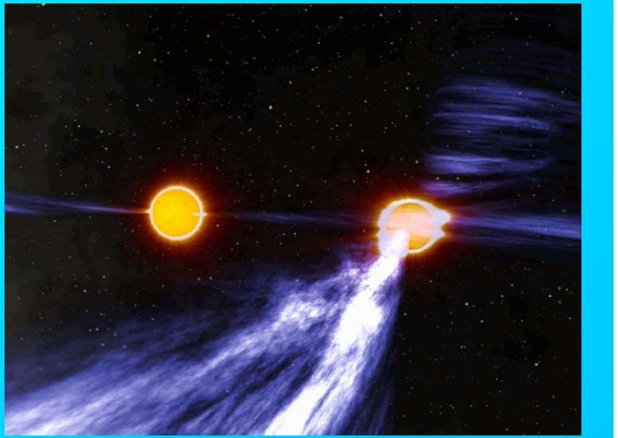
I: Manchester et al., MNRAS, 328, 17 (2001)
System and survey description, 100 pulsars
II: Morris et al., MNRAS, 335, 275 (2002)
120 pulsars, preliminary population statistics
III: Kramer et al., MNRAS, 342, 1299 (2003)
200 pulsars, young pulsars and γ-ray sources
IV: Hobbs et al., MNRAS, 352, 1439 (2004)
180 pulsars, 281 previously known pulsars
V: Faulkner et al., MNRAS, 355, 147 (2004)
Reprocessing methods, 17 binary/MSPs
VI: Lorimer et al., MNRAS, 372, 777 (2006)
142 pulsars, Galactic population and evolution

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 and one double pulsar!

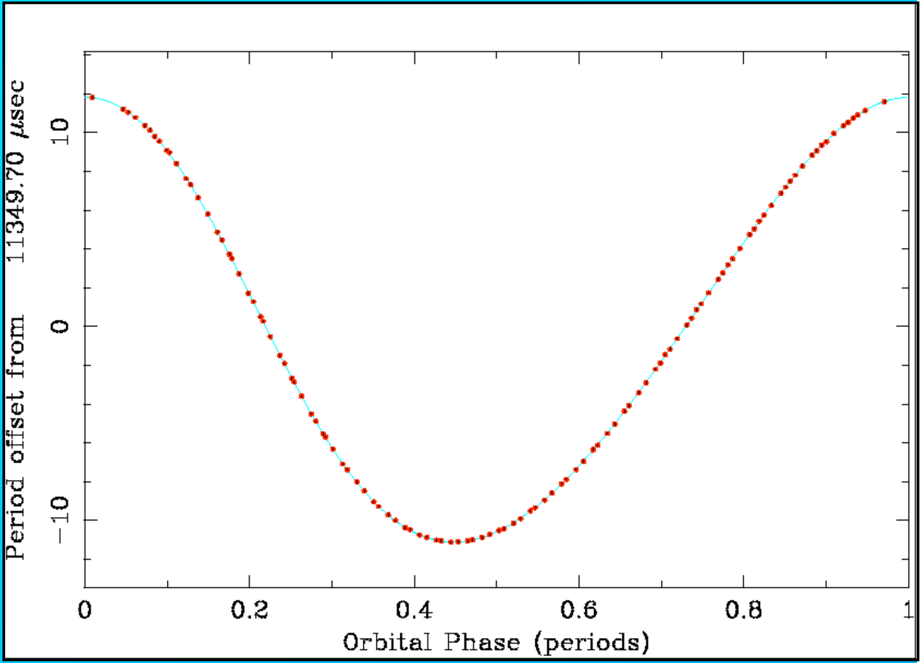


PSR J0730-3039A/B



The first double pulsar!

- Discovered at Parkes in 2003
- One of top ten science break-throughs of 2004 - Science
- $P_A = 22$ ms, $P_B = 2.7$ s
- Orbital period 2.4 hours!
- Periastron advance 16.9 deg/yr!



(Burgay et al., 2003; Lyne et al. 2004)

Highly relativistic binary system!

PSR J0737-3039A/B Post-Keplerian Effects

R: Mass ratio

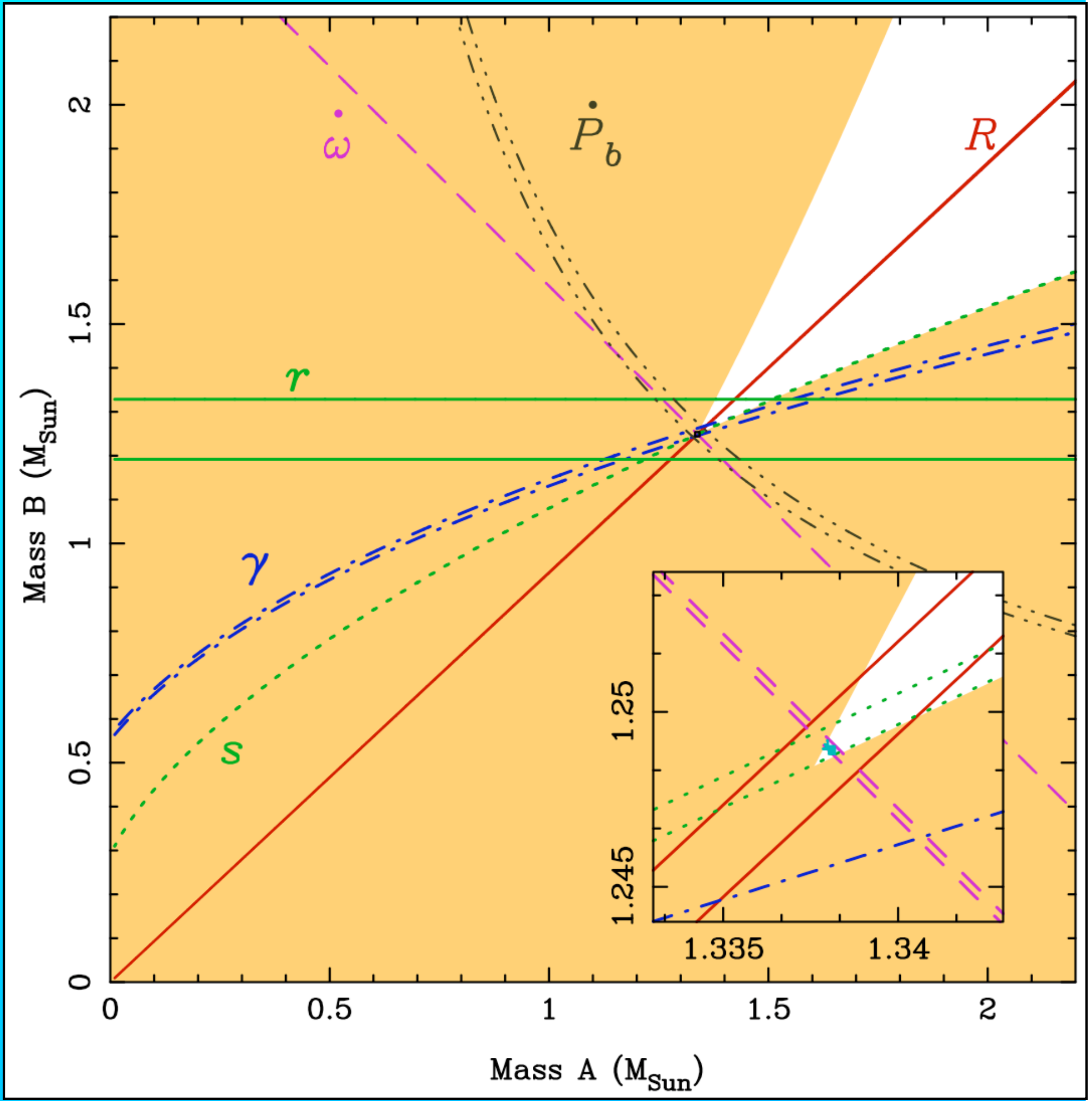
$\dot{\omega}$: periastron advance

γ: gravitational redshift

r & s: Shapiro delay

$\dot{P}_b$: orbit decay

- Six measured parameters
- Four independent tests
- Fully consistent with general relativity (0.05%)



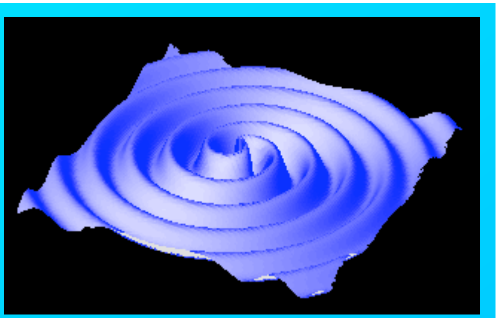
(Kramer et al. 2006)

Orbit Decay - PSR J0737-3039A/B

- Measured $\dot{P}_b = (-1.252 \pm 0.017) \times 10^{-12}$ in 2.5 years
- Will improve at least as $T^{2.5}$
- Not limited by Galactic acceleration!
    - ➢ System is much closer to Sun - uncertainty in $\dot{P}_{b,Gal} \sim 10^{-16}$
- Main uncertainty is in Shklovskii term due to uncertainty in transverse velocity and distance
    - ➢ Scintillation gives $V_{perp} = 66 \pm 15$ km s^{-1}
    - ➢ Timing gives $V_{perp} \sim 10$ km s^{-1} -- correction at 0.02% level
    - ➢ VLBI measurements should give improved distance

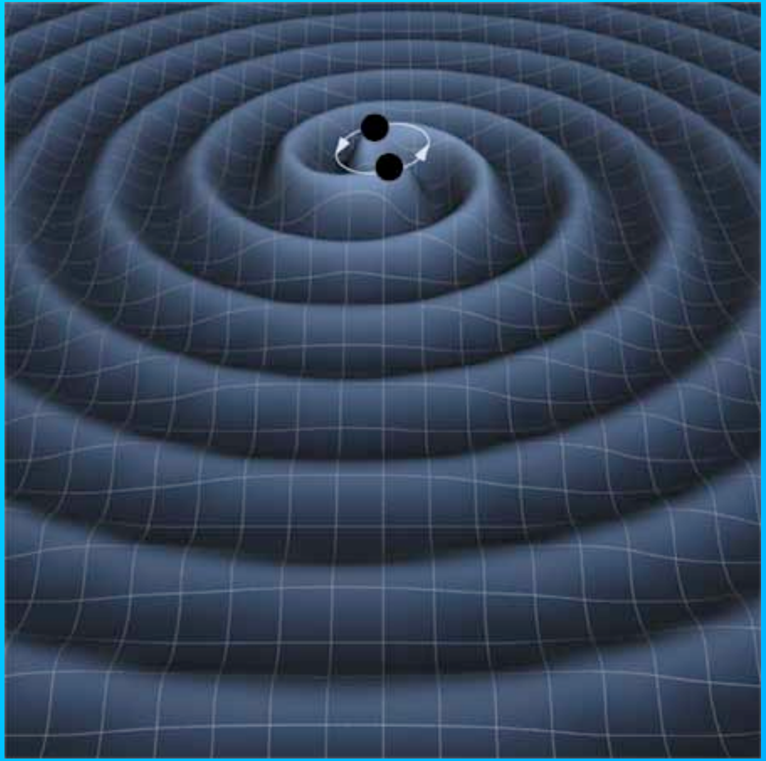
Will surpass PSR B1913+16 in ~5 years and improve rapidly!

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
  - ➢ Cosmic strings
  - ➢ SN, BH formation in early Universe
  - ➢ Binary black holes in galaxies
  - ➢ Coalescing neutron-star binaries
  - ➢ Compact X-ray binaries



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

Detection of Gravitational Waves

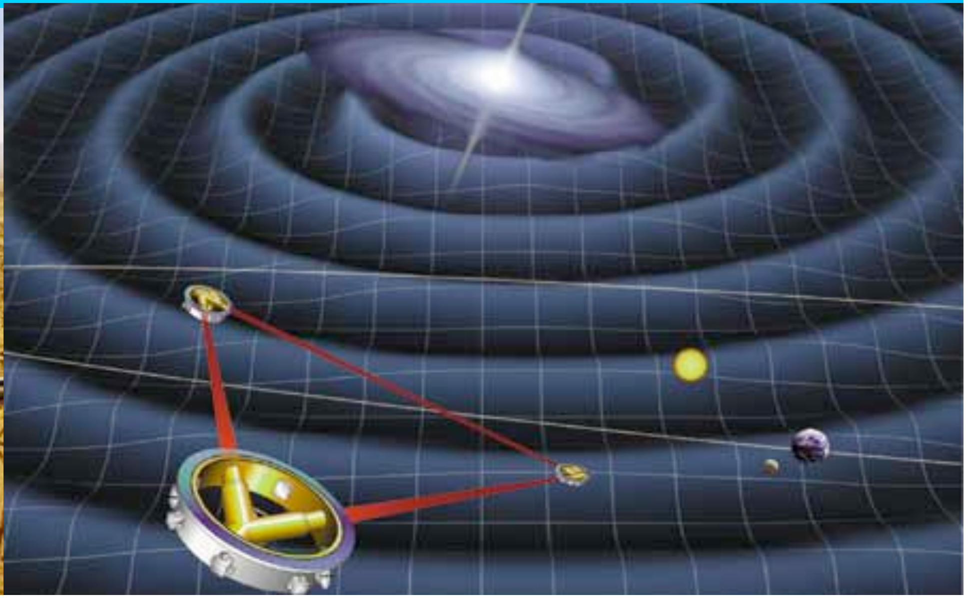
- Huge efforts over more than four decades to detect gravitational waves
- Initial efforts used bar detectors pioneered by Joseph Weber
- More recent efforts use laser interferometer systems, e.g., LIGO, VIRGO, LISA

LIGO

- Two sites in USA
- Perpendicular 4-km arms
- Spectral range 10 – 500 Hz
- Initial phase now operating
- Advanced LIGO ~ 2011

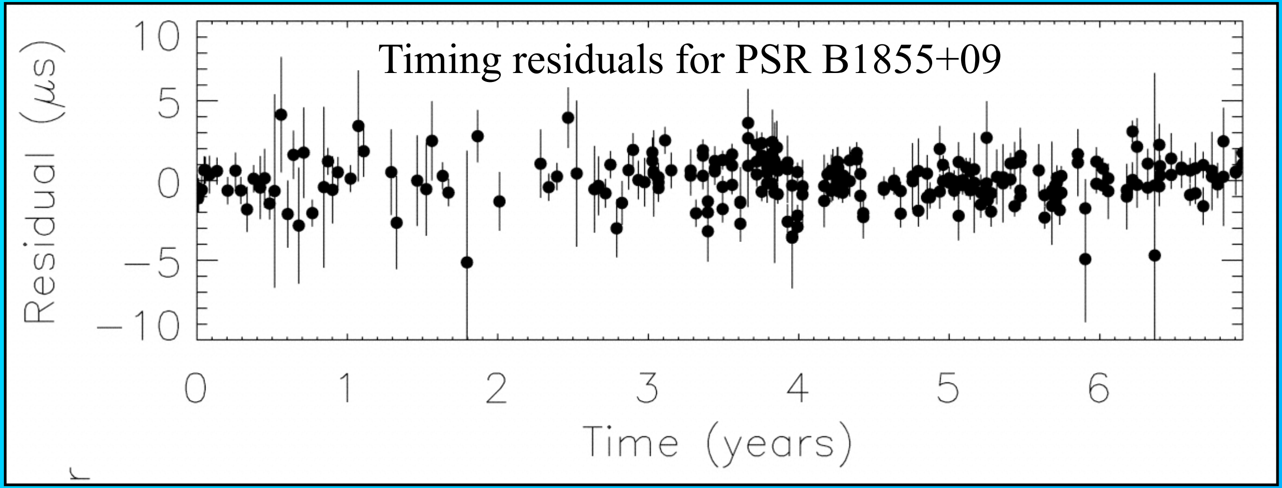
LISA

- Orbits Sun, 20° behind the Earth
- Three spacecraft in triangle
- Arm length 5 million km
- Spectral range $10^{-4} – 10^{-1}$ Hz
- Planned launch ~2018



Detecting Gravitational Waves with Pulsars

- Observed pulse periods affected by presence of gravitational waves in Galaxy
- With observations of <10 pulsars, can only put limit on the strength of the stochastic GW 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 (Lommen 2001, Damour & Vilenkin 2004)



A Pulsar Timing Array

- With observations of many pulsars widely distributed on the sky can in principle ***detect*** a stochastic gravitational wave background
- Gravitational waves passing over the pulsars are uncorrelated
- Gravitational waves passing over Earth produce a correlated signal in the TOA residuals for all pulsars
- Requires observations of ~20 MSPs over 5 – 10 years; could give the ***first*** direct detection of gravitational waves!
- A timing array can detect instabilities in terrestrial time standards – establish a ***pulsar timescale***
- Also can improve our knowledge of Solar system properties, e.g. masses and orbits of outer planets and asteroids

Idea first discussed by Hellings & Downs (1983),
Romani (1989) and Foster & Backer (1990)

- **Clock errors**

  All pulsars have the same TOA variations:
  monopole signature

- **Solar-System ephemeris errors**

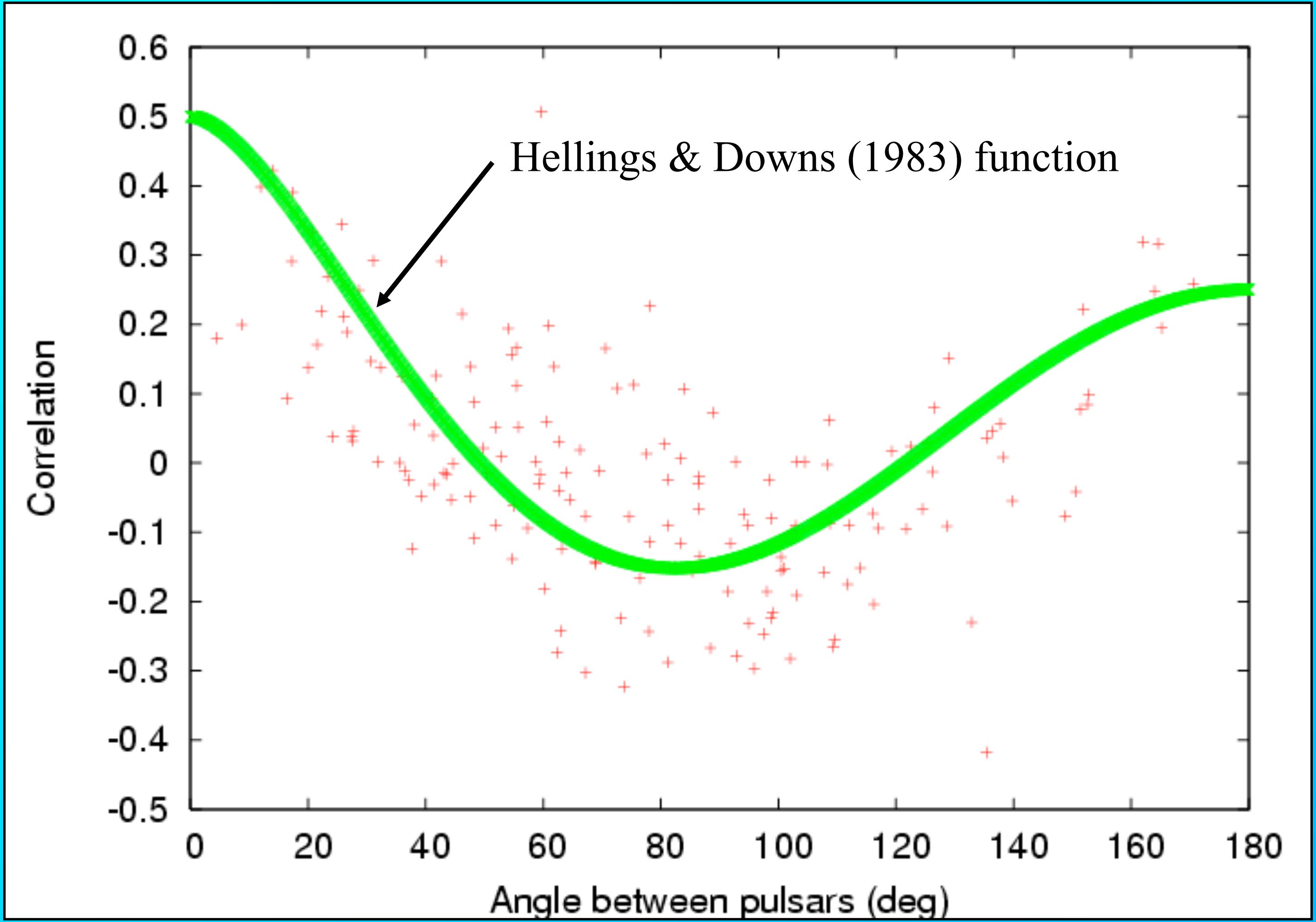
  Dipole signature

- **Gravitational waves**

  Quadrupole signature

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

Detecting a Stochastic GW Background



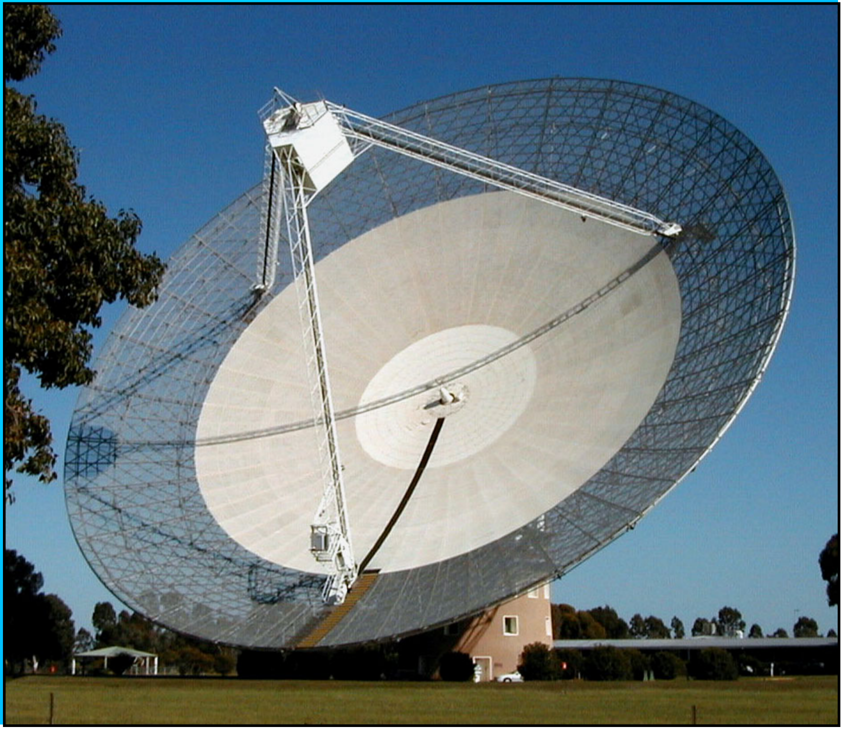
Simulation using Parkes Pulsar Timing Array (PPTA) pulsars with GW background from binary black holes in galaxies

(Hobbs et al., 2008)

The Parkes Pulsar Timing Array Project

Collaborators:

- Australia Telescope National Facility, CSIRO, Sydney
  - Dick Manchester, George Hobbs, David Champion, John Sarkissian, John Reynolds, Mike Kesteven, Warwick Wilson, Grant Hampson, Andrew Brown, David Smith, Jonathan Khoo, (Russell Edwards)
- Swinburne University of Technology, Melbourne
  - Matthew Bailes, Willem van Straten, Joris Verbiest, Ramesh Bhat, Sarah Burke, Andrew Jameson
- University of Texas, Brownsville
  - Rick Jenet
- University of California, San Diego
  - Bill Coles
- Franklin & Marshall College, Lancaster PA
  - Andrea Lommen
- University of Sydney, Sydney
  - Daniel Yardley
- National Observatories of China, Beijing
  - Johnny Wen
- Peking University, Beijing
  - Kejia Lee
- Southwest University, Chongqing
  - Xiaopeng You
- Curtin University, Perth
  - Aidan Hotan



The PPTA Project: Goals

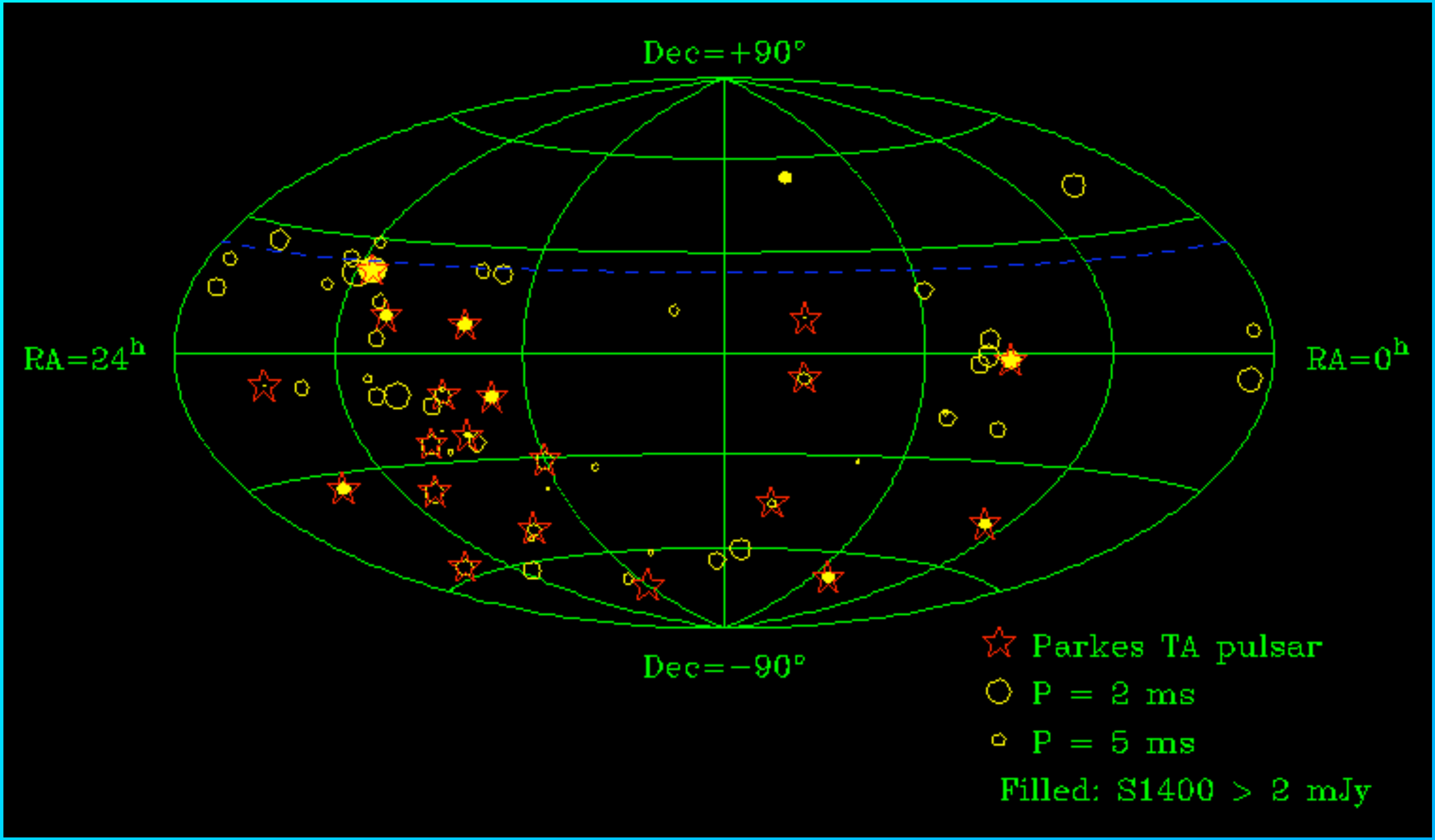
- ➢ To detect gravitational waves of astrophysical origin
- ➢ To establish a pulsar-based timescale and to investigate irregularities in terrestrial timescales
- ➢ To improve on the Solar System ephemeris used for barycentric correction

To achieve these goals we need ~weekly observations of ~20 MSPs over at least five years with TOA precisions of ~100 ns for ~10 pulsars and < 1 μs for rest

- Modelling and detection algorithms for GW signals
- Measurement and correction for interstellar and Solar System propagation effects
- Implementation of radio-frequency interference mitigation techniques

Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters

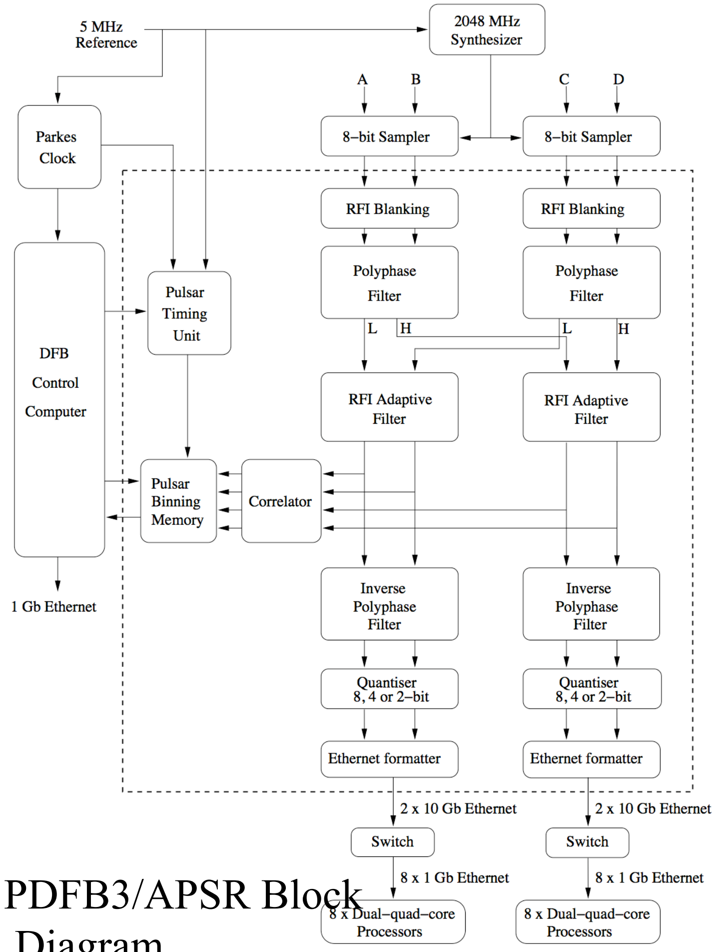


The PPTA Project

- Using the Parkes 64-m radio telescope at three frequencies, 685 MHz, 1400 MHz and 3100 MHz, to observe 20 MSPs
- Observations at 2 - 3 week intervals
- Using polyphase digitial filterbanks and baseband recording systems
- Regular observations commenced in mid-2004 using WBC, PDFB1 and CPSR2
- New digital filterbank systems with higher time and frequency resolution - PDFB2 commissioned in March 2007, PDFB3 in February 2008
- New baseband recorder system (APSR) currently being commissioned
- Improved pipeline processing and mySQL database
- GW simulations, detection algorithms and implications - TEMPO2, galaxy evolution studies
- International collaborations - EPTA, NANOGrav, CPTA(?)

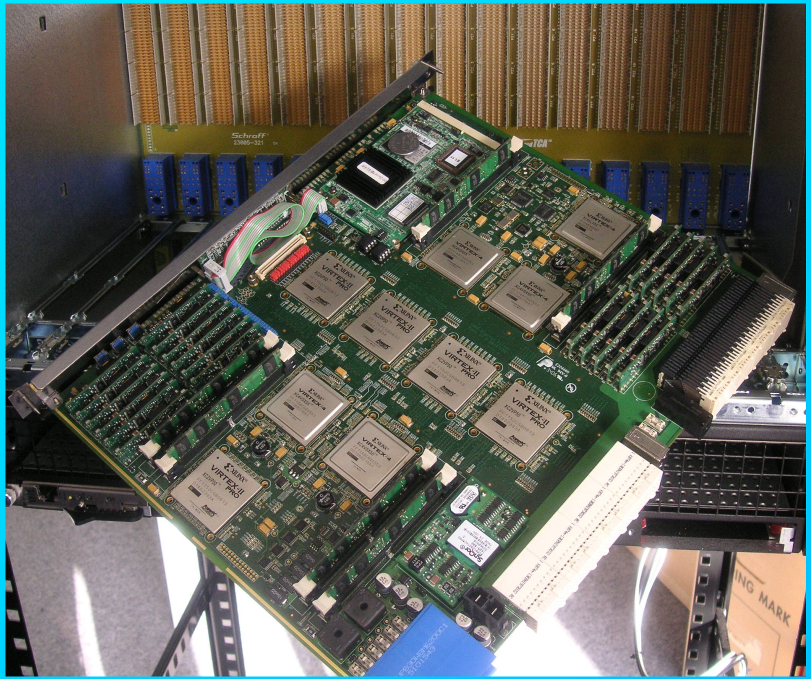
New Observing Systems

- PDFB2, PDFB3: Digital Polyphase Filterbank systems
- APSR: Baseband recording system



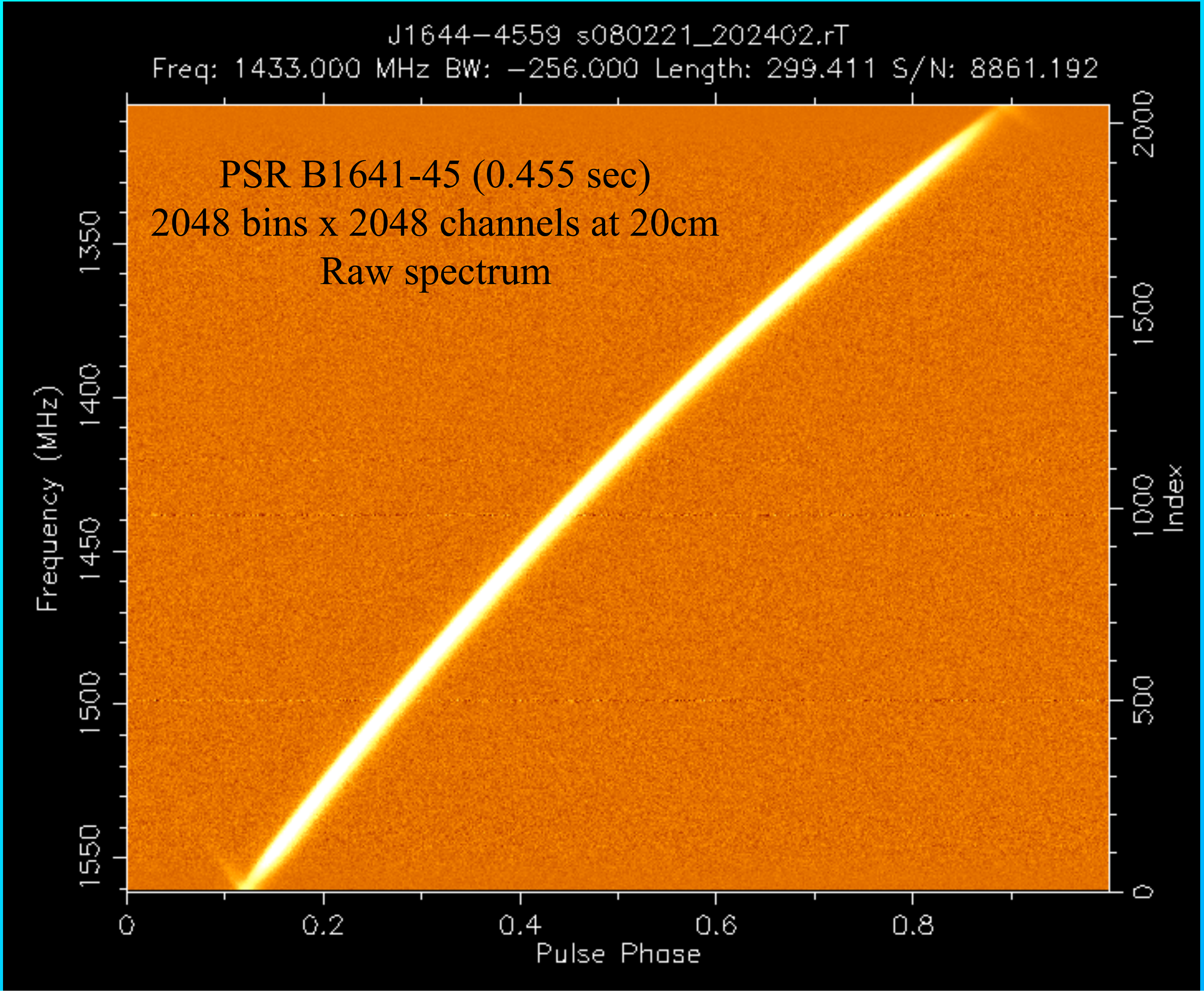
PDFB3/APSR Block Diagram

CABB Processor Board



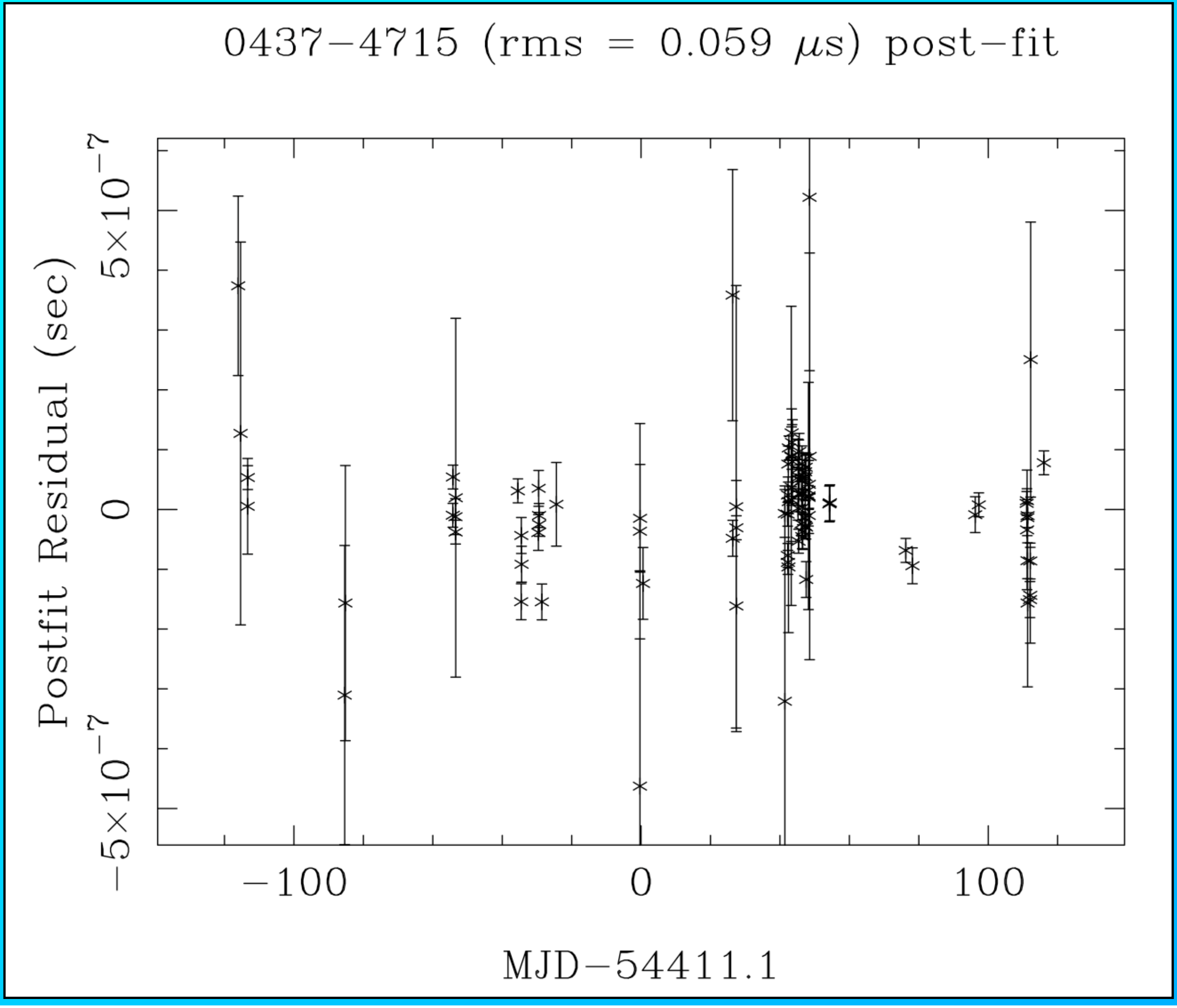
- Up to 1 GHz bandwidth
- On-line folding at pulsar period
- 2048 channels x 2048 phase bins for 4-ms pulsar
- Real-time RFI rejection
- Search mode - streamed data
- Front-end for APSR system

PDFB3 - Initial Results



PSR B1641-45 (0.455 sec)
2048 bins x 2048 channels at 20cm
Raw spectrum

Timing Residuals for PSR J0437-4715 PDFB2



PPTA Pulsars: Recent Results using PDFB2

- ~330 days of timing data at 2 -3 week intervals at 10cm and 20cm
- TOAs from 1-hour observations
- Uncorrected for DM variations
- Four pulsars with rms timing residuals < 200 ns, eleven < 1 μs
- Best results on J0437-4715 (59 ns) and J1909-3744 (130 ns)

Highest precision timing results ever obtained!

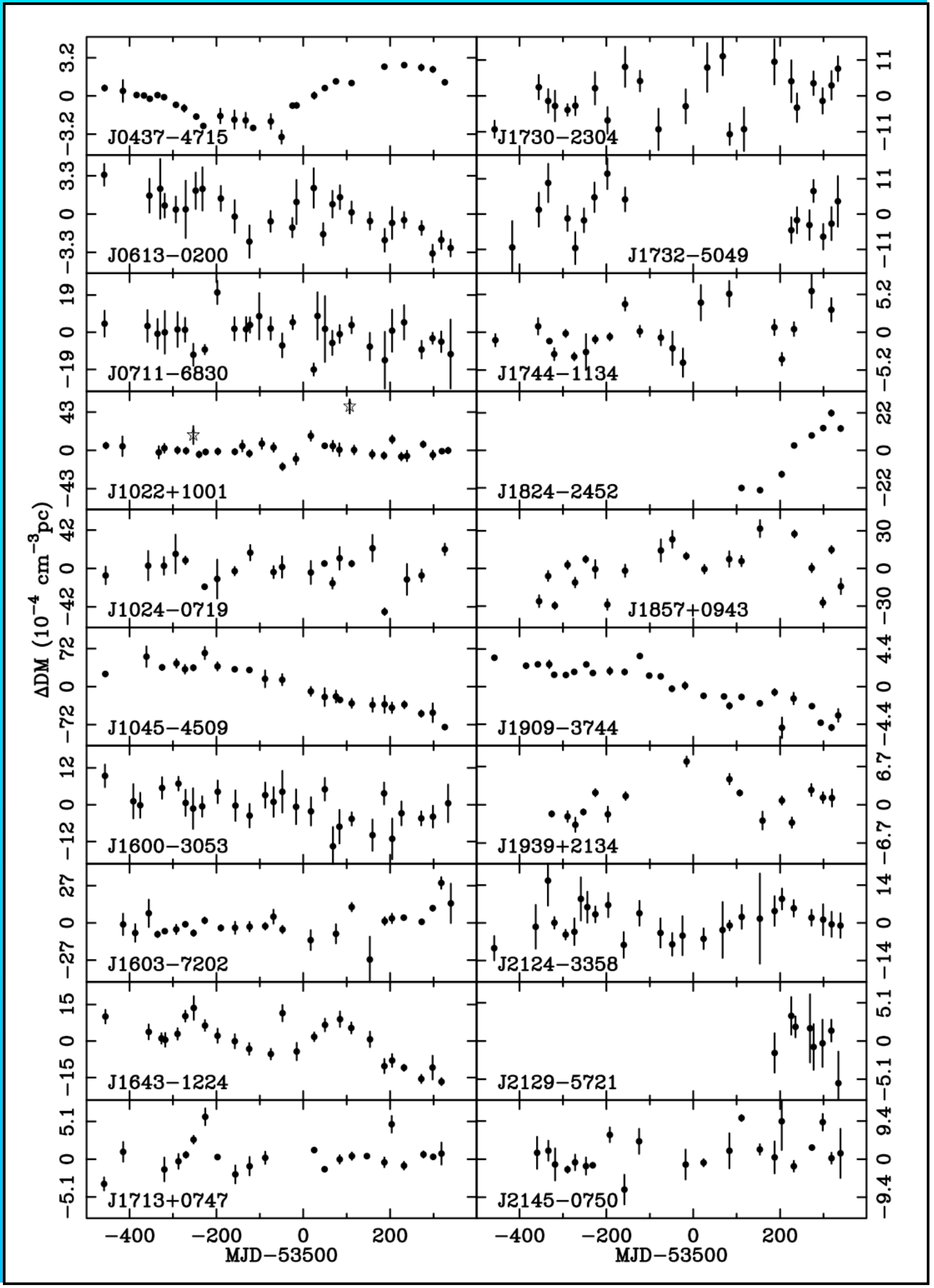
Still not quite good enough though!!

Name	Period (ms)	DM (cm^{-3} pc)	Orbital period (d)	Rms Residual (μs)
J0437-4715	5.757	2.65	5.74	0.06
J0613-0200	3.062	38.78	1.20	0.55
J0711-6830	5.491	18.41	-	1.29
J1022+1001	16.453	10.25	7.81	2.74
J1024-0719	5.162	6.49	-	0.92
J1045-4509	7.474	58.15	4.08	1.50
J1600-3053	3.598	52.19	14.34	0.33
J1603-7202	14.842	38.05	6.31	1.00
J1643-1224	4.622	62.41	147.02	0.66
J1713+0747	4.570	15.99	67.83	0.15
J1730-2304	8.123	9.61	-	1.20
J1732-5049	5.313	56.84	5.26	1.85
J1744-1134	4.075	3.14	-	0.33
J1824-2452	3.054	119.86	-	1.32
J1857+0943	5.362	13.31	12.33	0.77
J1909-3744	2.947	10.39	1.53	0.13
J1939+2134	1.558	71.04	-	0.16
J2124-3358	4.931	4.62	-	3.03
J2129-5721	3.726	31.85	6.63	1.47
J2145-0750	16.052	9.00	6.84	0.38

Dispersion Measure Variations

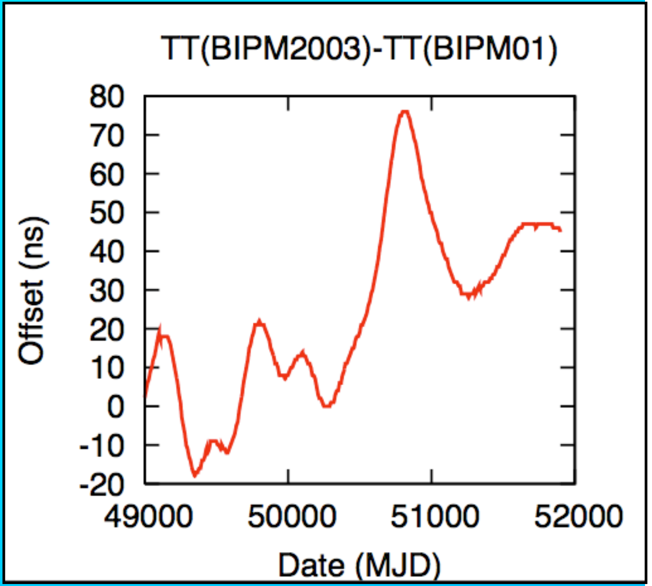
- ΔDM from 10/50cm or 20/50cm observation pairs
- Variations observed in most of PPTA pulsars
- ΔDM typically a few x 10^{-3} cm^{-3} pc
- Weak correlation of d(DM)/dt with DM, closer to linear rather than DM$^{1/2}$
- Effect of Solar wind observed in pulsars with low ecliptic latitude

(You et al., 2007)

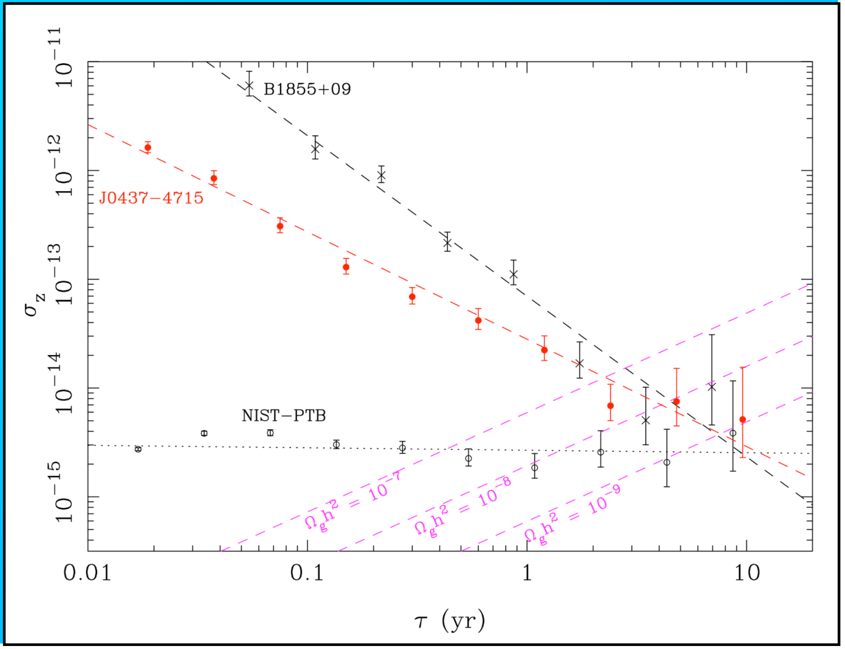


A Pulsar Timescale

- Terrestrial time defined by a weighted average of caesium clocks at time centres around the world
- Comparison of TAI with TT(BIPM03) shows variations of amplitude ~1 μs even after trend removed
- Revisions of TT(BIPM) show variations of ~50 ns
- Pulsar timescale is not absolute, but can reveal irregularities in TAI and other terrestrial timescales
- Current best pulsars give a 10-year stability (σ_z) comparable to TT(NIST) - TT(PTB)
- Full PPTA will define a pulsar timescale with precision of ~50 ns or better at 2-weekly intervals and model long-term trends to 5 ns or better

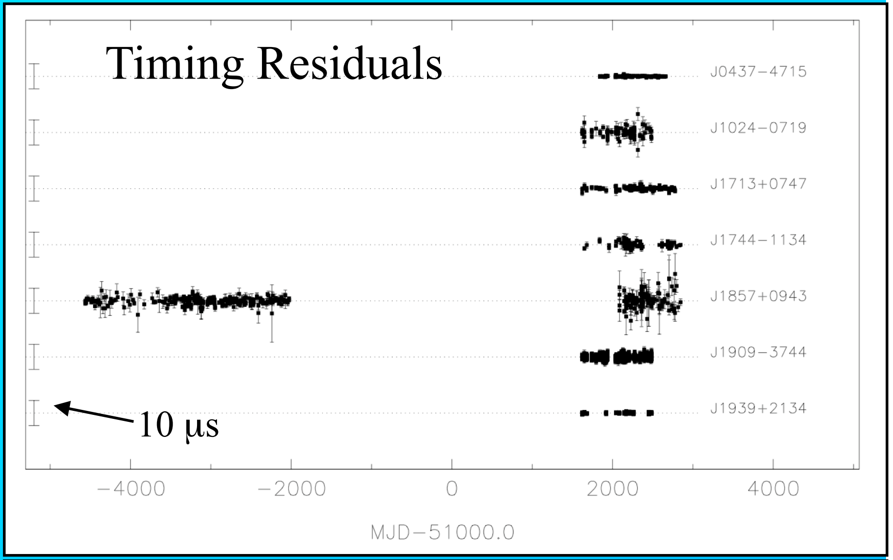


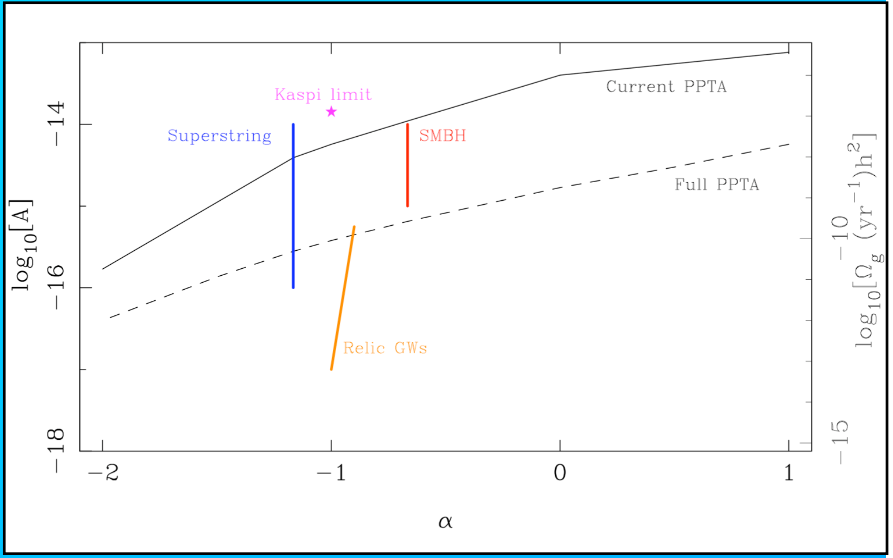
(Petit 2004)



Current and Future Limits on the Stochastic GW Background

- Arecibo data for PSR B1855+09 (Kaspi et al. 1994) and recent PPTA data
- Monte Carlo methods used to determine detection limit for stochastic background described by $h_c = A(f/1\,\mathrm{yr})^{\alpha}$ (where α = -2/3 for SMBH, ~ -1 for relic radiation, ~ -7/6 for cosmic strings)
- ➢ Current limit: $\Omega_{gw}(1/8\ \mathrm{yr}) \sim 2 \times 10^{-8}$
- ➢ For full PPTA (100ns, 5 yr): $\sim 10^{-10}$
- Currently consistent with all SMBH evolutionary models (e.g., Jaffe & Backer 2003; Wyithe & Loeb 2003, Enoki et al. 2004)
- If no detection with full PPTA, all current models ruled out
- Already limiting EOS of matter in epoch of inflation (w = p/ε > -1.3) and tension in cosmic strings (Grishchuk 2005; Damour & Vilenkin 2005)

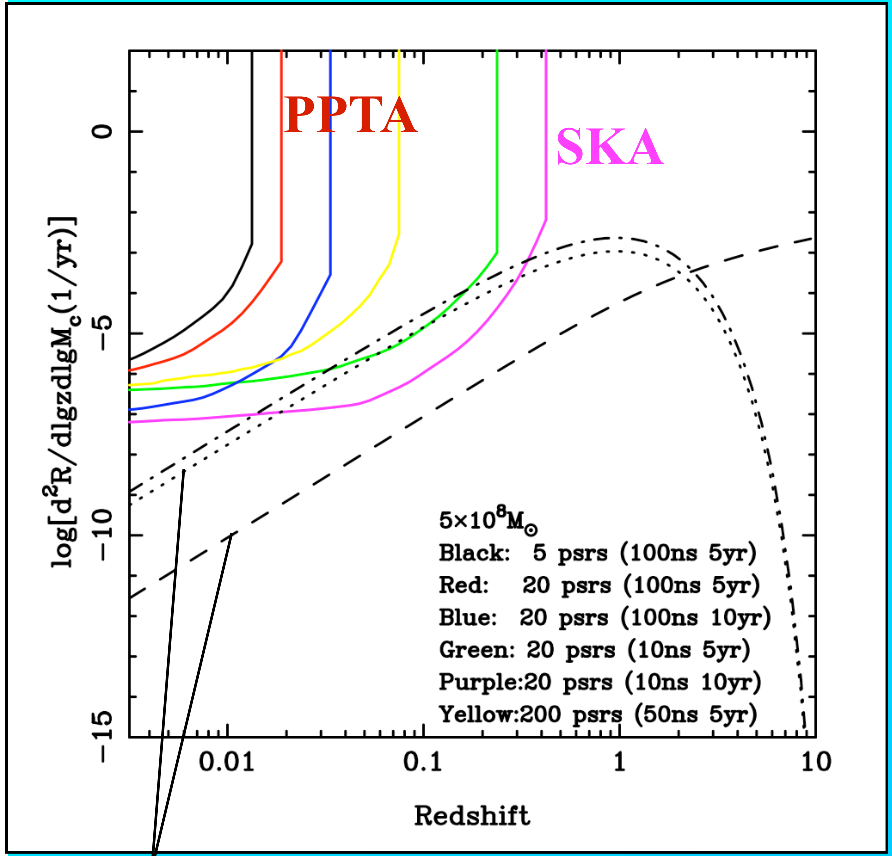




(Jenet et al. 2006)

Future Prospects

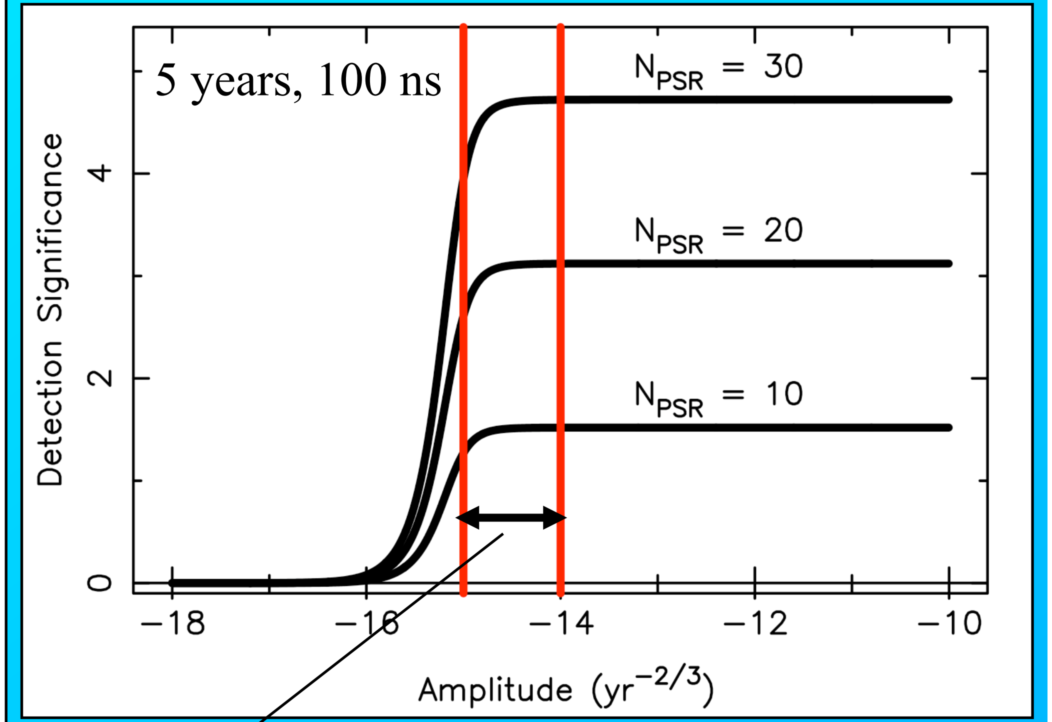
Single source detection



Predicted merger rates for 5 x 10^8 $M_\odot$ binaries (Wen & Jenet 2008)

PPTA can't detect individual binary systems - but SKA will!

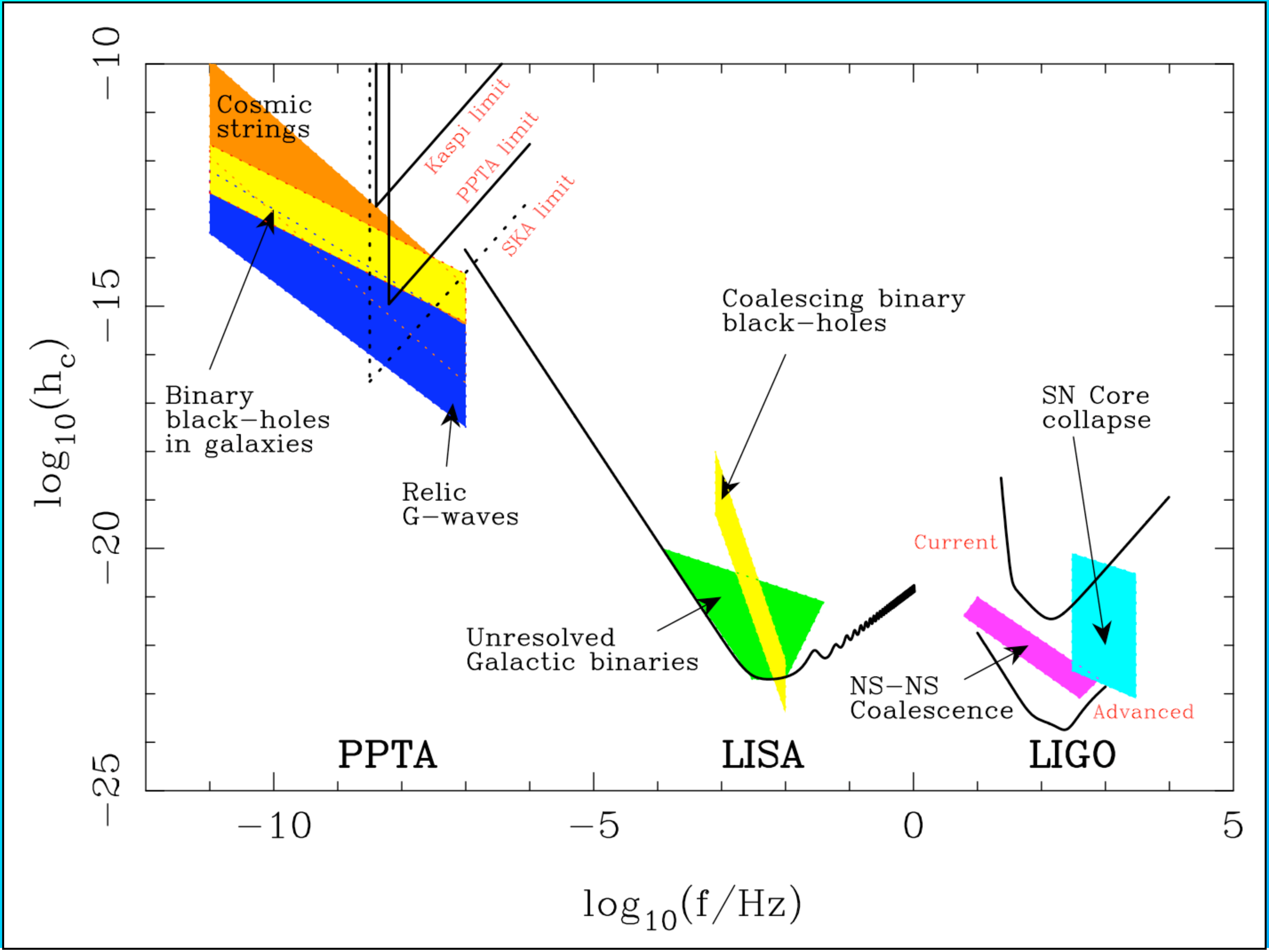
Stochastic GW Background



Range of predicted amplitudes (Jaffe & Backer 2003; Wyithe & Loeb 2003)

Difficult to get sufficient observations with PPTA alone - international collaborations important!

The Gravitational Wave Spectrum



Summary

- Pulsars are extraordinarily good clocks and provide highly sensitive probes of a range of gravitational effects
- Direct detection of gravitational waves (GW) is a major goal of current astrophysics - it will open a new window on the Universe
- A pulsar timing array can ***detect*** nanoHertz GW from astrophysical sources
- Parkes Pulsar Timing Array (PPTA) has been timing 20 MSPs since mid-2004. Goal is ~100 ns rms residuals on at least half of sample
- New instrumentation and signal processing methods have greatly improved our timing precision; currently have four pulsars with rms residuals < 200 ns and eleven less than 1 microsecond
- Within 5 - 10 years we will either detect GW or rule out all current models for generation of GW by SMBH binaries in galaxies
- A pulsar-based timescale will have better long-term stability than current best terrestrial timescales
- The SKA will herald a new era in the study of gravitation using pulsars!