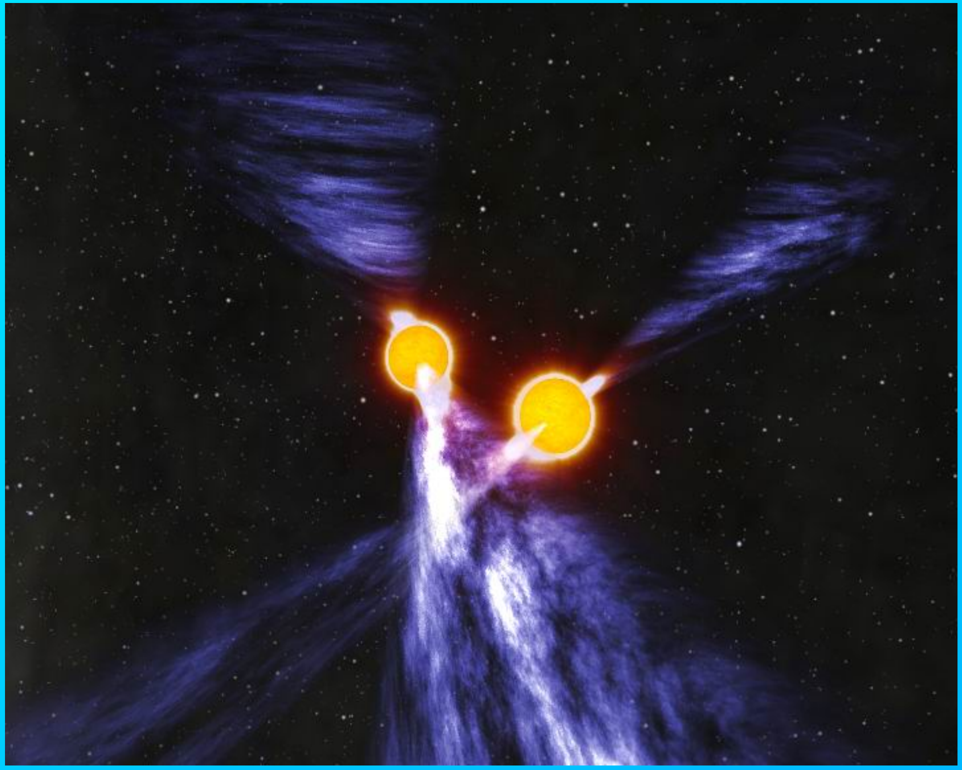
Highlights of Pulsar Research since (February) 1968

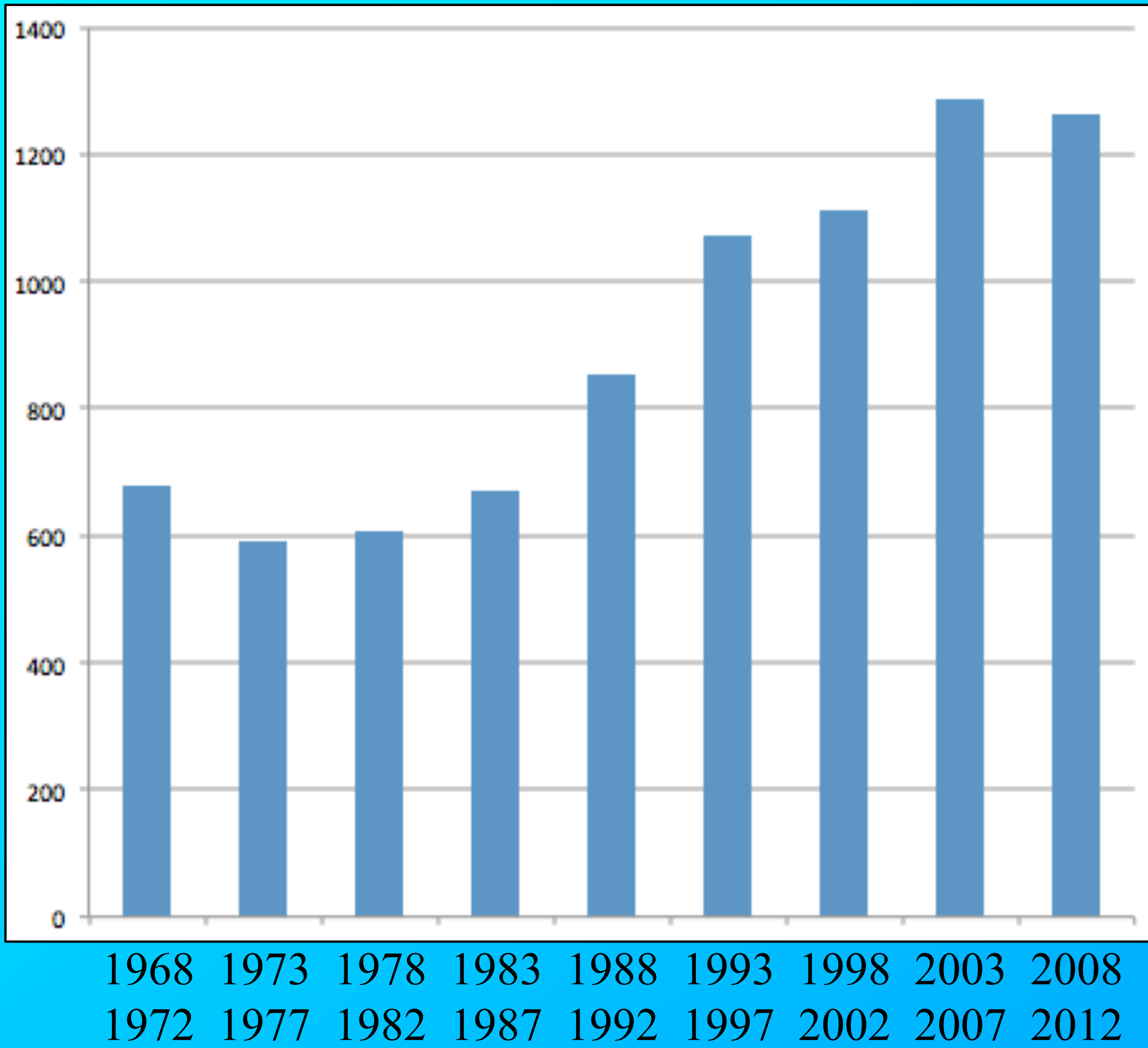
Dick Manchester

CSIRO Astronomy and Space Science
Sydney Australia



Pulsar Publications since 1968

- Searched ADS* for papers in refereed journals with "pulsar" in the title
- Five-year groups from 1968 to 2012
- These numbers are conservative since many pulsar papers do not have "pulsar" in the title
- Reasonably steady upward trend!



*Harvard-Smithsonian/NASA Astrophysics Data System

Most highly cited paper(s) in each 5-year group

1968-1972: Goldreich & Julian (1969) – Magnetospheric theory – 1413 cites

1973-1977: Ruderman & Sutherland (1975) – Magnetosph. theory – 1321 cites

1978-1982: Alpar et al. (1982) – Formation of MSPs – 473 cites

Backer et al. (1982) – Discovery of first MSP – 464 cites

1983-1987: Cheng et al. (1986) – Gamma-ray emission model – 662 cites

1988-1992: Bhattachacharya & van den Heuvel (1991) – MSP formation – 661

1993-1997: Taylor & Cordes (1993) – Pulsar distance model – 951 cites

Lyne & Lorimer (1994) – Pulsar velocities – 620 cites

1998-2002: Kouveliotou et al. (1998) – Discovery of first magnetar – 562 cites

2003-2007: Manchester et al. (2005) – ATNF Pulsar Catalogue – 626 cites

Lyne et al. (1994) – Discovery of Double Pulsar – 327 cites

2008-2012: Abdo et al. (2010) – First Fermi Source Catalogue – 282 cites

Hooper et al. (2009) – Psrs sources of cosmic-ray positrons – 282 ci

Theory

Observation (top)

Observation (2nd)

Catalogue or similar

Pulsar Highlights - My choice!
(Chronological order)

- Discovery of Crab & Vela pulsars – SNR associations & ident. of pulsars as rotating neutron-stars (1968)
- Pulse polarisation and rotating-vector model (1969)
- Discovery of the first binary pulsar (1975)
- Discovery of the first millisecond pulsar (MSP) (1982)
- The Parkes Multibeam Pulsar Survey (1997-2004)
- Discovery of first magnetar (1998)
- Discovery of the Double Pulsar (2003-2004)
- *Fermi* gamma-ray telescope MSP discoveries (2009)
- Pulsar Diversity (1969 on)

Discoveries are just the beginning!

Discovery of Crab & Vela Pulsars

- **Vela pulsar** discovered at Molonglo by Large, Vaughan & Mills, published Oct. 26, 1968 (received Oct. 17!)
- Located within Vela supernova remnant
- Pulse period only 89 ms

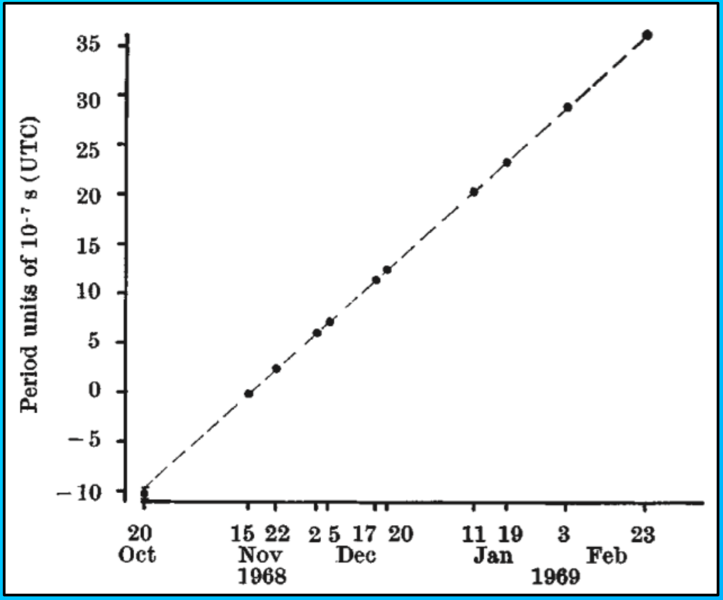

UKSTU

- **Crab pulsar** discovered at Green Bank using the 300-ft telescope by Staelin & Reifenstein, IAUC 2110, Nov. 6, 1968 (Science Dec 68)
- Intermittent giant pulses detected – no obvious periodicity
- 33 ms pulsations discovered at Arecibo by Lovelace, Sutton & Craft (IAUC 2113, Nov. 18, 1968)


ESO -VLT

Pulsars and Rotating Neutron Stars

- Very short period of Crab and Vela pulsars too fast for rotation or vibration of a white dwarf star (~ size of Earth)
- Neutron star only known more compact stable state (diam ~ 16 km) – can rotate or vibrate with periods in millisecond range
- NS rotation advocated by Gold (Nature, May 1968)
- Regular slow-down of Crab pulse period detected by Richards & Comella (1969) using Arecibo pulse timing observations – rate only ~0.04 μs/day
- Gold (1969) showed that rotational energy loss from NS could power the Crab Nebula – predicted by Pacini in 1967!



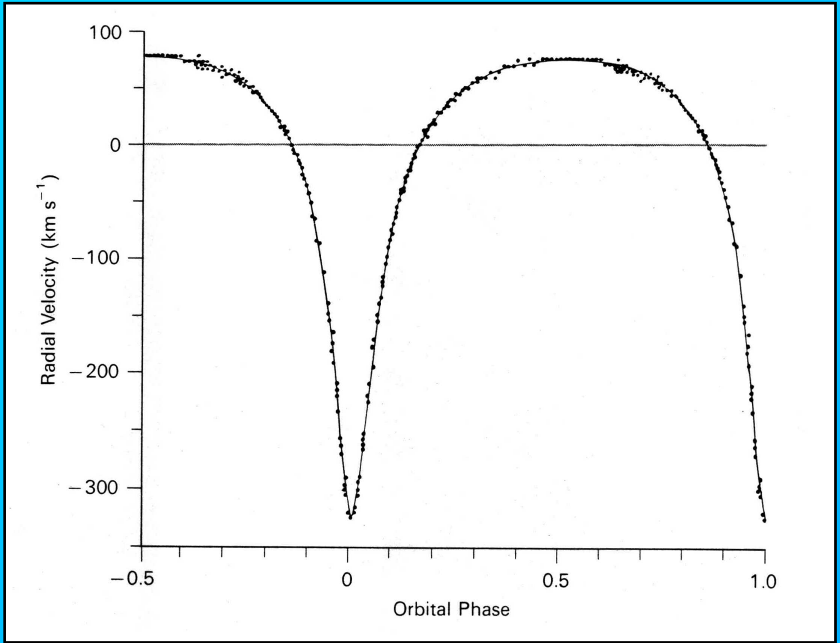
Pulsars are rotating neutron stars!

The First Binary Pulsar – PSR B1913+16

- 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
- Highly eccentric orbit
- Max orbital velocity ~300 km s^{-1}, ~0.1% of velocity of light

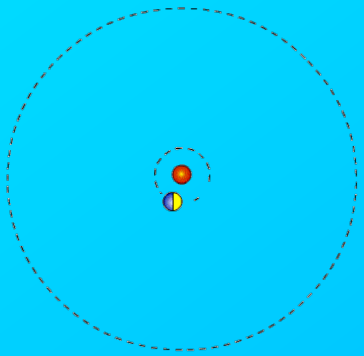
Relativistic effects detectable!

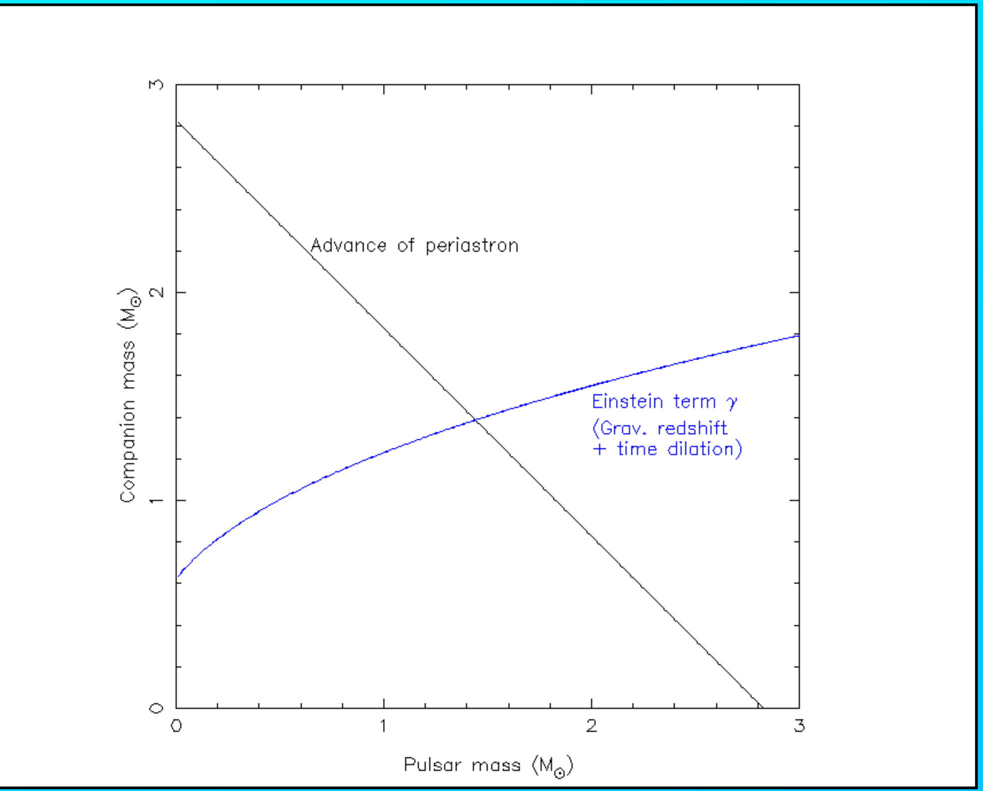
PSR B1913+16



Relativistic Effects in PSR B1913+16

- Periastron advance: 4.2 deg/yr (compared to 43 arcsec/century for Mercury perihelion advance!)
- Gravitational redshift and time dilation: 4.3 ms





In General Relativity, both effects depend on just the masses of the two stars:

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

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

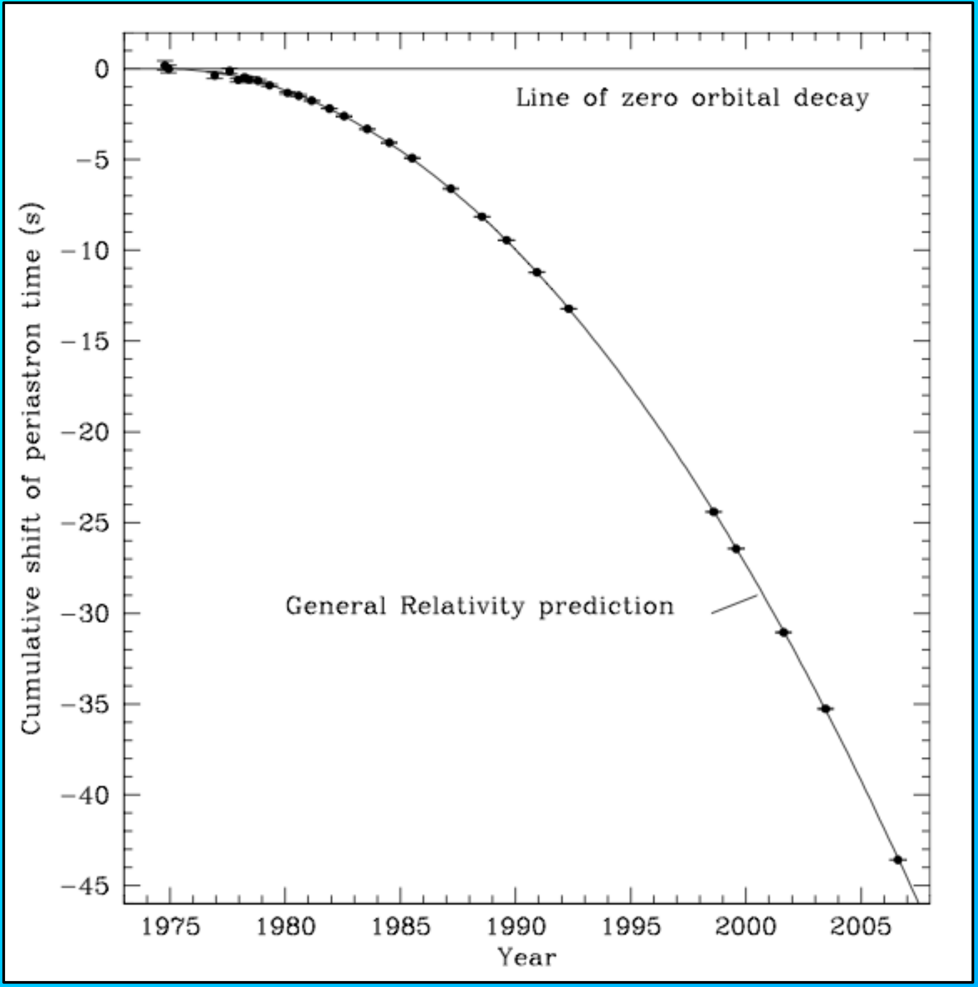
Both neutron stars!

PSR B1913+16 Orbit Decay

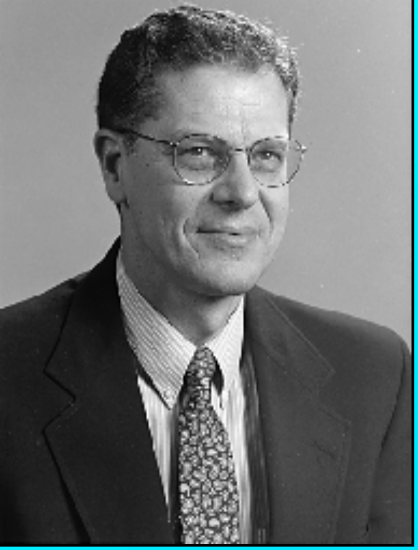
- Energy loss from orbital motion to gravitational radiation
- Prediction based on measured Keplerian parameters and Einstein's general relativity
- Corrected for acceleration in gravitational field of Galaxy

$\dot{P}_b(\mathrm{obs})/\dot{P}_b(\mathrm{pred}) = 0.997 \pm 0.002$

First observational evidence for gravitational waves!



(Weisberg, Nice & Taylor 2010)

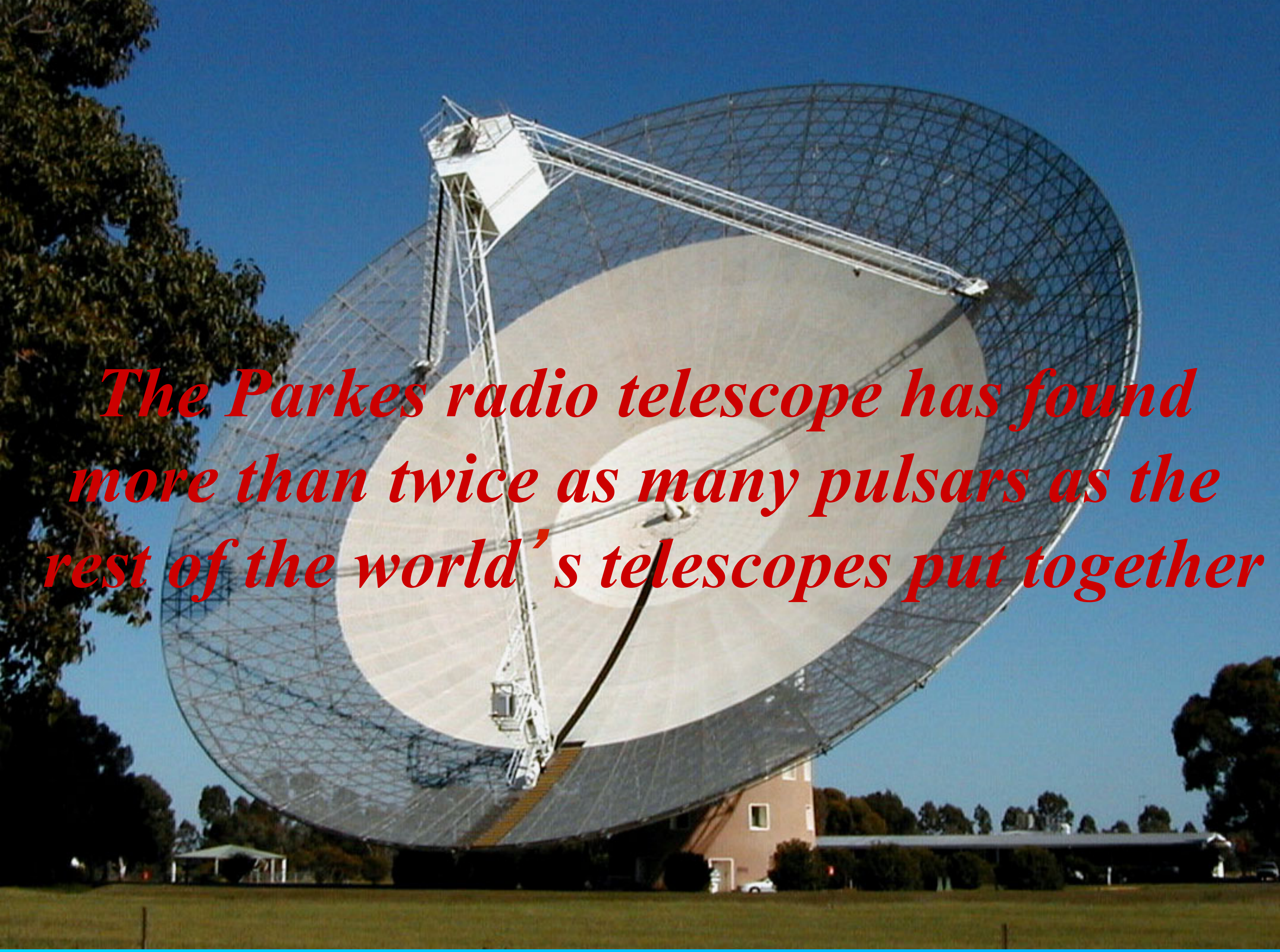


PSR B1913+16

The Hulse-Taylor Binary Pulsar

- First discovery of a binary pulsar
- First accurate determinations of neutron star masses
- First observational evidence for gravitational waves
- Confirmation of General Relativity as an accurate description of strong-field gravity

Nobel Prize for Taylor & Hulse in 1993


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

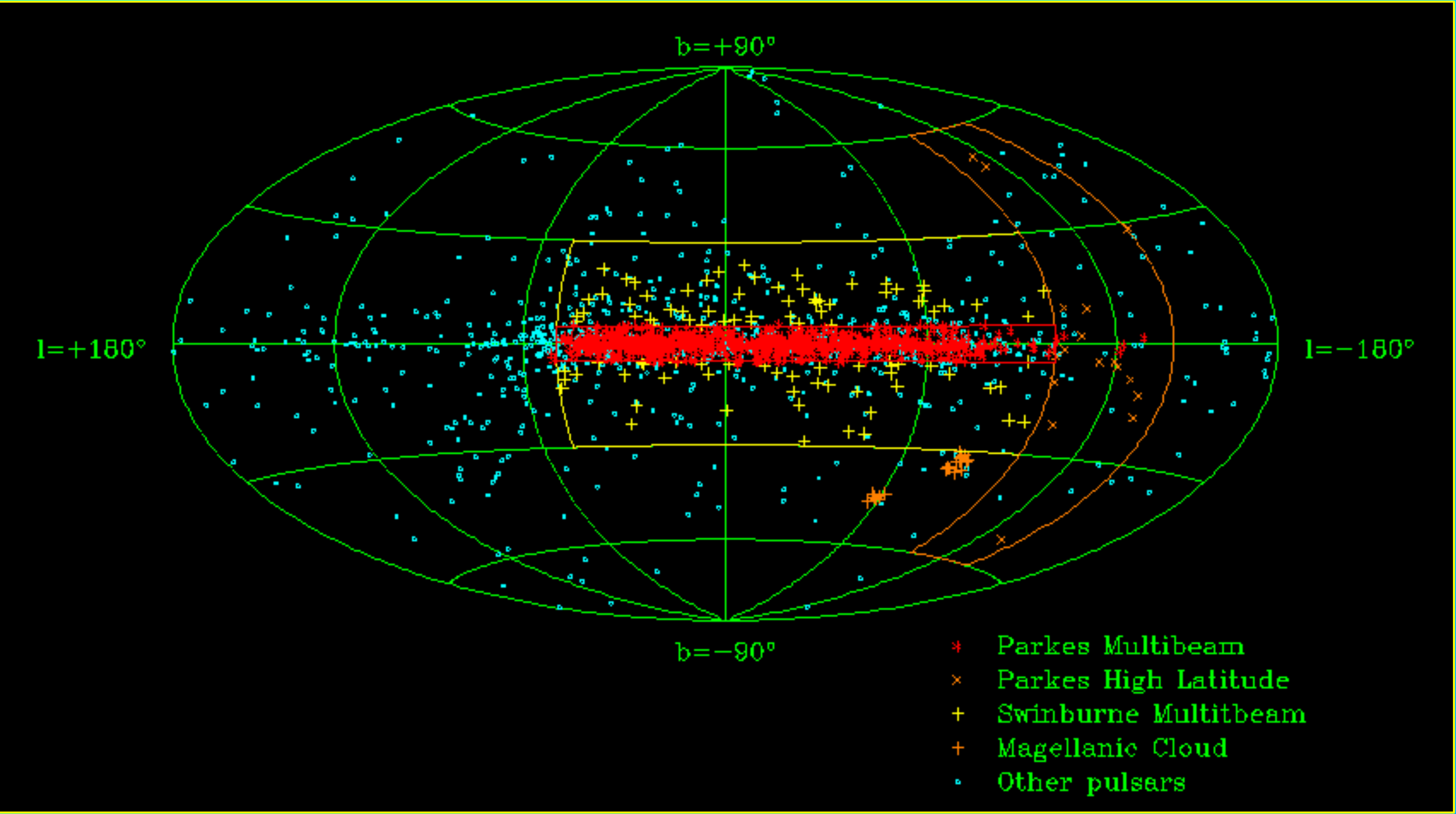
Parkes Multibeam Pulsar Survey

- Covers strip along Galactic plane, $-100^o < l < 50^o$, $|b| < 5^o$
- Uses 13-beam 20cm Multibeam receiver on the Parkes 64-m telescope
- 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
- **785 pulsars discovered, 1065 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

Galactic Distribution of Pulsars

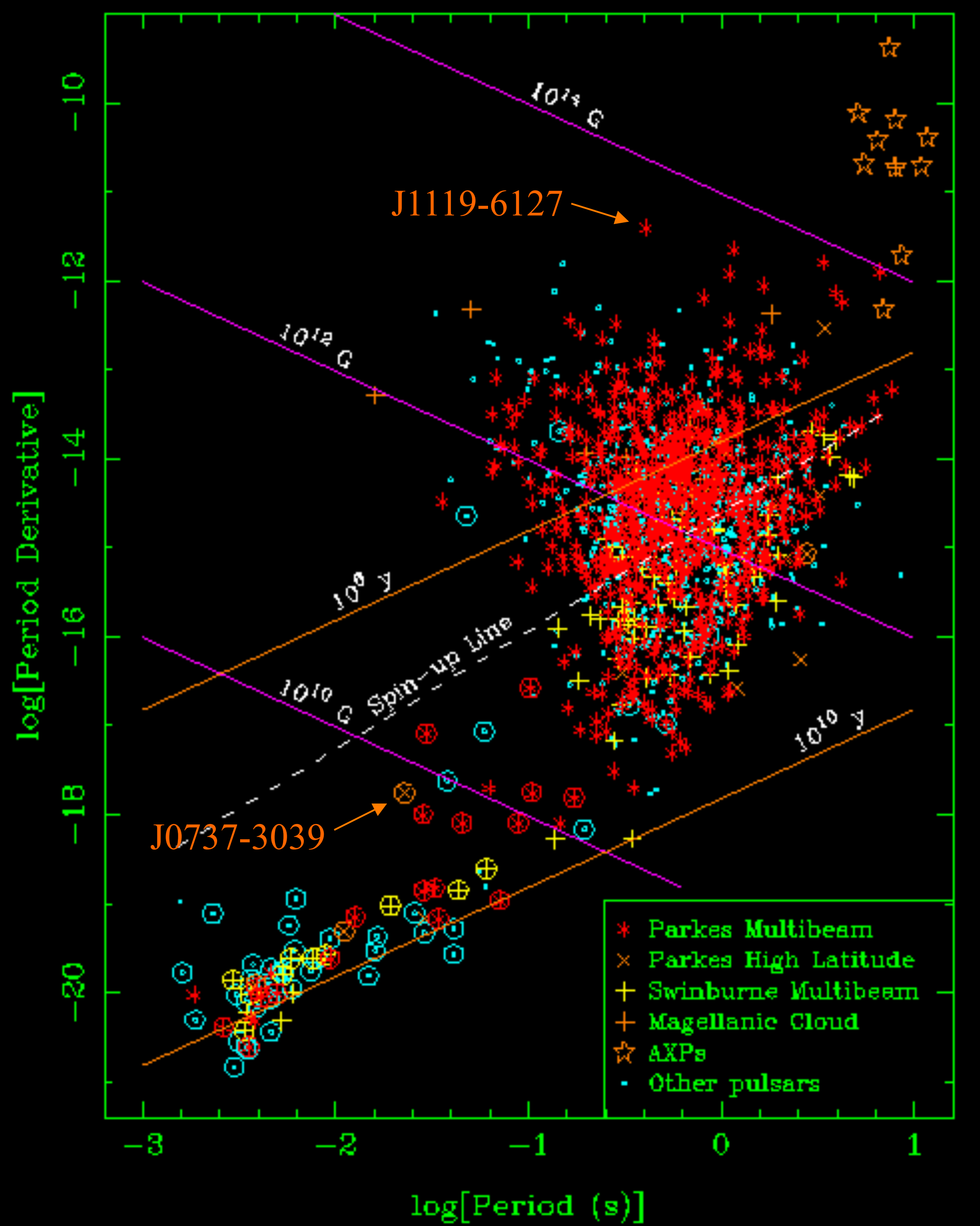


Parkes Multibeam Surveys: P vs $\dot{P}$

P =Pulsar period

$\dot{P}$ =dP/dt =slow-down rate

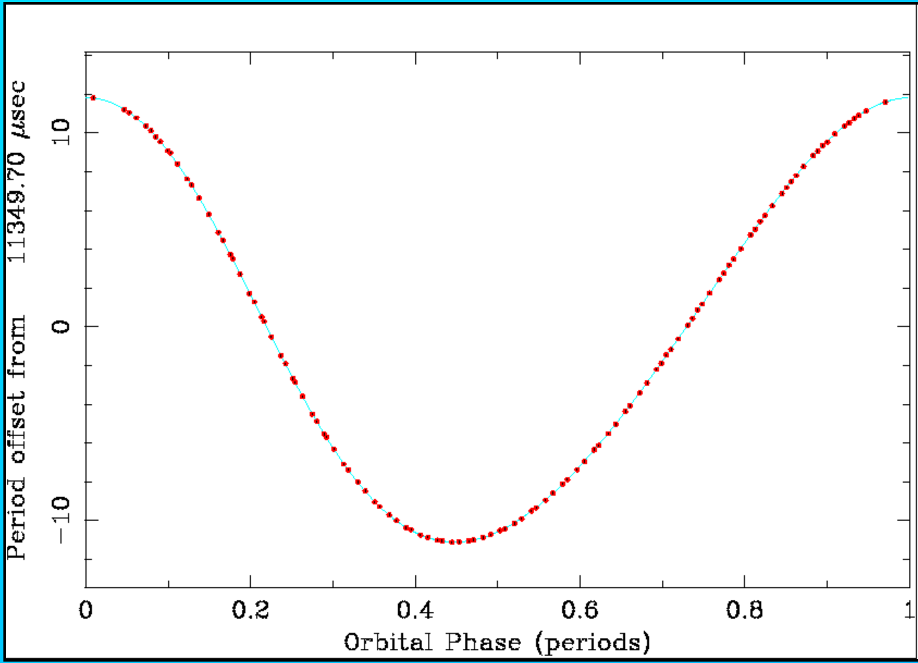
- New sample of young, high-B, long-period pulsars
- Large increase in sample of mildly recycled binary pulsars
- Three new double-neutron-star systems and one double pulsar!



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!



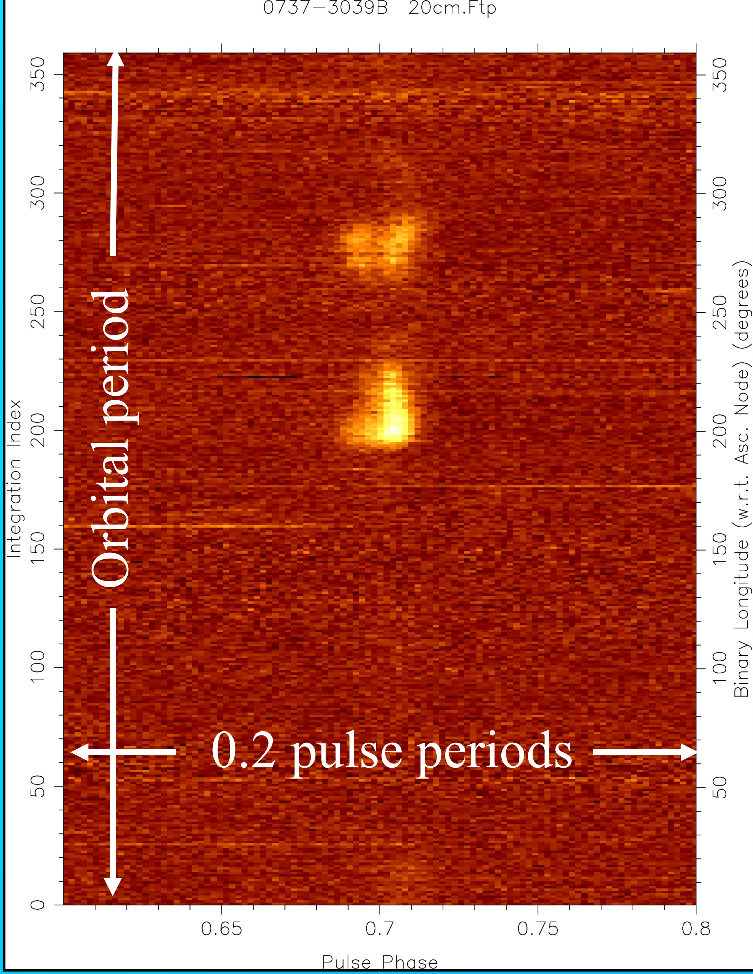
(Burgay et al., 2003; Lyne et al. 2004)

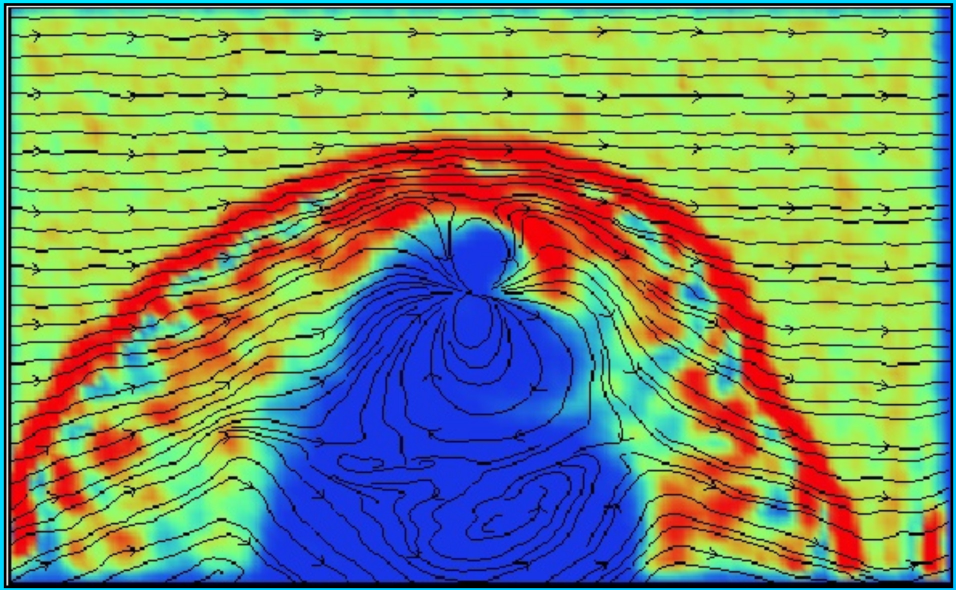
Highly relativistic binary system!

PSR J0737-3039B

- "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)

Measured Post-Keplerian Parameters for PSR J0737-3039A/B

	GR value	Measured value	Improves as
$\dot{\omega}$ Periast. adv. (deg/yr)	-	16.8995 ± 0.0007	$T^{1.5}$
γ Grav. Redshift (ms)	0.3842	0.386 ± 0.003	$T^{1.5}$
$\dot{P}_b$ Orbit decay	-1.248×10^{-12}	$(-1.252 \pm 0.017) \times 10^{-12}$	$T^{2.5}$
r Shapiro range (μs)	6.15	6.2 ± 0.3	$T^{0.5}$
s Shapiro sin *i*	0.99987	0.99974^{+16}_{-39}	$T^{0.5}$

GR is OK! Consistent at the 0.05% level!

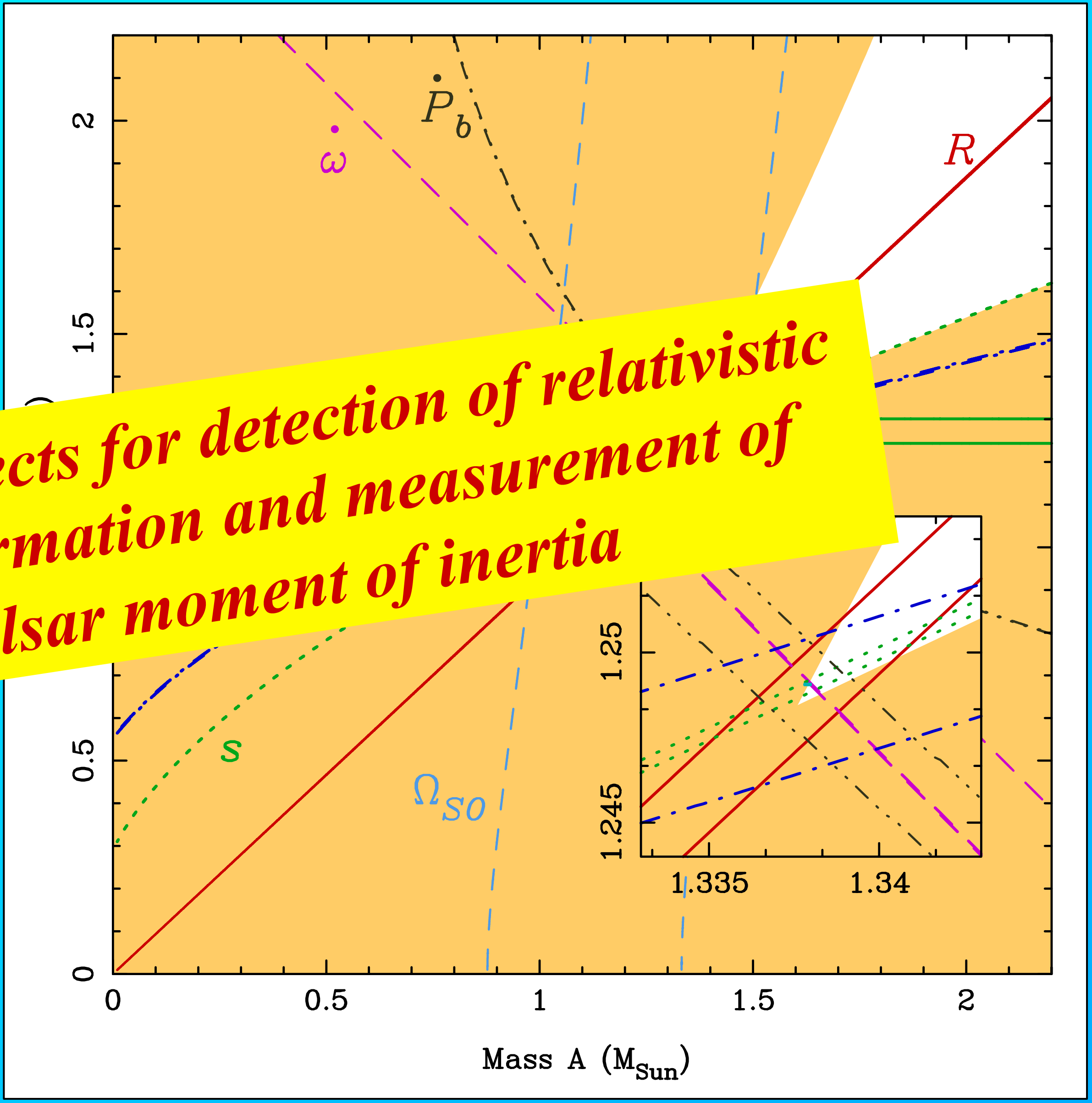
Non-radiative test - distinct from PSR B1913+16

(Kramer et al. 2006)

The Double Pulsar: Update

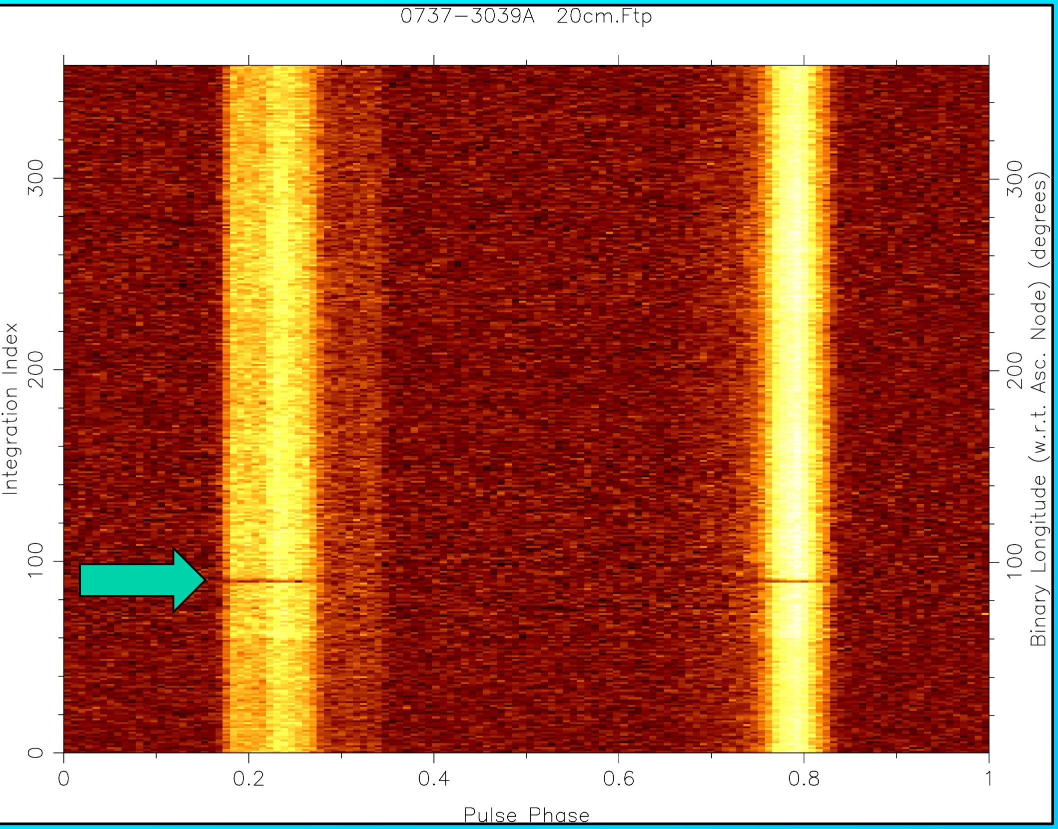
- PSR J0737-3039B has disappeared!
- Beam has moved away due to orbital precession
- Expected to return in 5 – 10 years
- Continue[d] ... Parkes an[d] ... refined rel[ativistic] ... parameters
- Now limits deviations from GR to 0.02%

(Kramer et al. 2013)

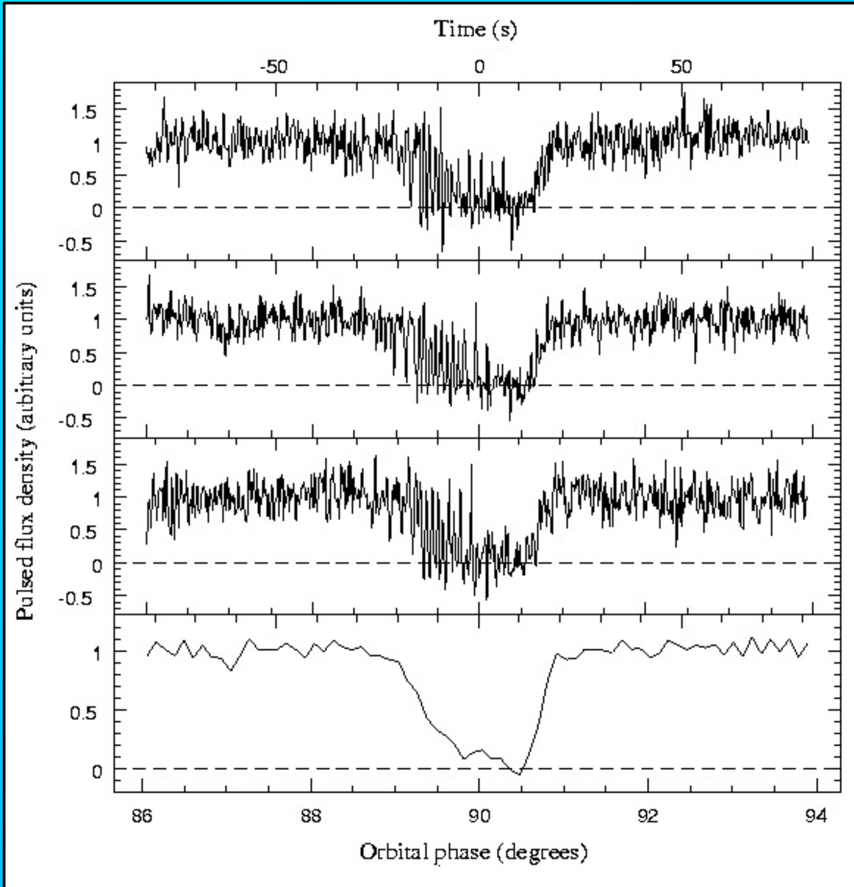


Good prospects for detection of relativistic orbit deformation and measurement of pulsar moment of inertia

PSR J0737-3039A Eclipses



- Pulses from A eclipsed for ~30 sec each orbit
- Eclipse by B magnetosphere – orbit seen nearly edge on



- High-resolution observations show modulation of eclipse at rotation period of B pulsar!

(McLaughlin et al., 2004)

PSR J0737-303A Eclipse

- Synchrotron absorption by high-density plasma in magnetospheric closed field-line region
- Fit to eclipse modulation determines:
  - Angle between B spin & orbit axes = 130.0^{o} +/- 0.4^{o}
  - Inclination angle of B magnetic axis relative to spin axis = 70.9^{o} +/- 0.4^{o}
  - Changes in eclipse profile over four years gives precession of B spin axis = 4.8^{o} +/- 0.7^{o} yr^{-1} – consistent with GR predictn

Relativistic Spin Precession in the Double Pulsar

See Breton et al. (Science, 2008)

Movie Description

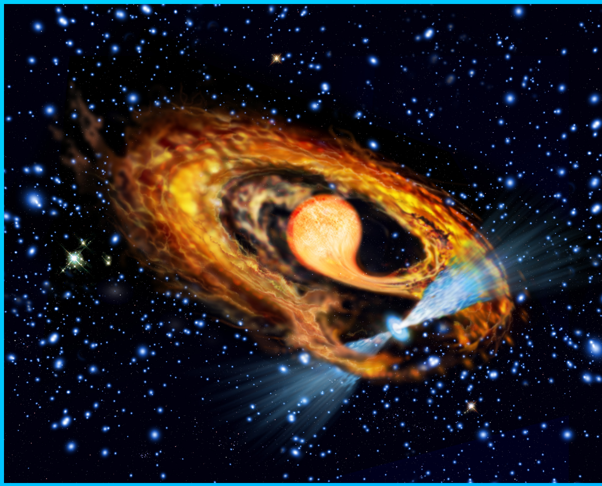
The eclipses in the double pulsar PSR J0737-3039A/B occur when pulsar A's projected orbital motion, represented by a gray circle moving on a black line, passes behind its companion, pulsar B. Radio emission from pulsar A is absorbed via synchrotron resonance with the plasma trapped in the closed field lines of the truncated dipolar magnetosphere of pulsar B, shown as a colored dipolar structure. Since pulsar B's magnetic dipole axis is misaligned with respect to its spin axis (represented by a diagonal rod), the optical depth along our sight line to pulsar A varies as a function of pulsar B's spin phase. The theoretical light curve resulting from the eclipse animated in the upper panel is drawn as a black curve in the bottom panel and real eclipse data, observed with the Green Bank Telescope in April 2007, are overlaid in red. The animation speed corresponds to real time and the audio track is the sound that one would hear if the radio signal detected from pulsar A by the radio telescope was noise-filtered and amplified into an audio device. While individual pulsations from pulsar A are too fast to be distinguished, we can hear a mixture of F musical tones harmonically related to 44 Hz (F1 tone), the spin frequency of the pulsar, which is modulated in intensity as a result of the eclipse.

(Breton et al. 2008)

Pulsar Diversity

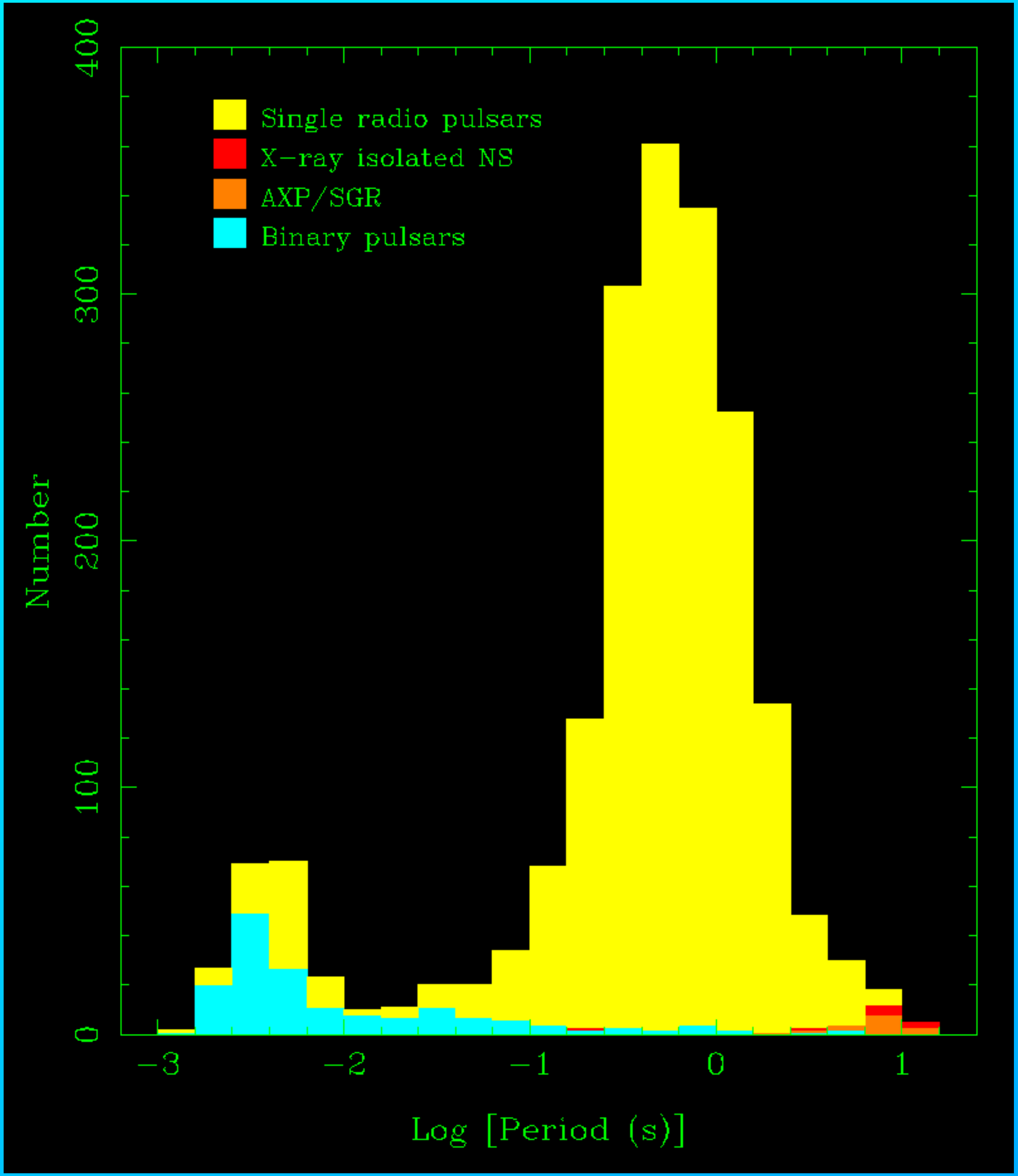
Right from the start, pulsars have continued to surprise (and delight) us with new and unexpected discoveries

- Jocelyn's 1967 discovery
- Fast pulsars in Crab and Vela – 1968
- Optical, X-ray & γ-ray pulses from the Crab pulsar – 1969
- The first binary pulsar – 1975
- The first millisecond pulsar (MSP) – 1982
- First extragalactic pulsar – 1986
- Pulsars in globular clusters – 1987
- X-ray isolated neutron stars – 1996
- Magnetars and High-B radio pulsars – 1998
- The Double Pulsar – 2004
- RRATs and intermittent pulsars – 2006
- Fermi γ-ray sources identified as MSPs – 2009



Pulsar Period Distribution

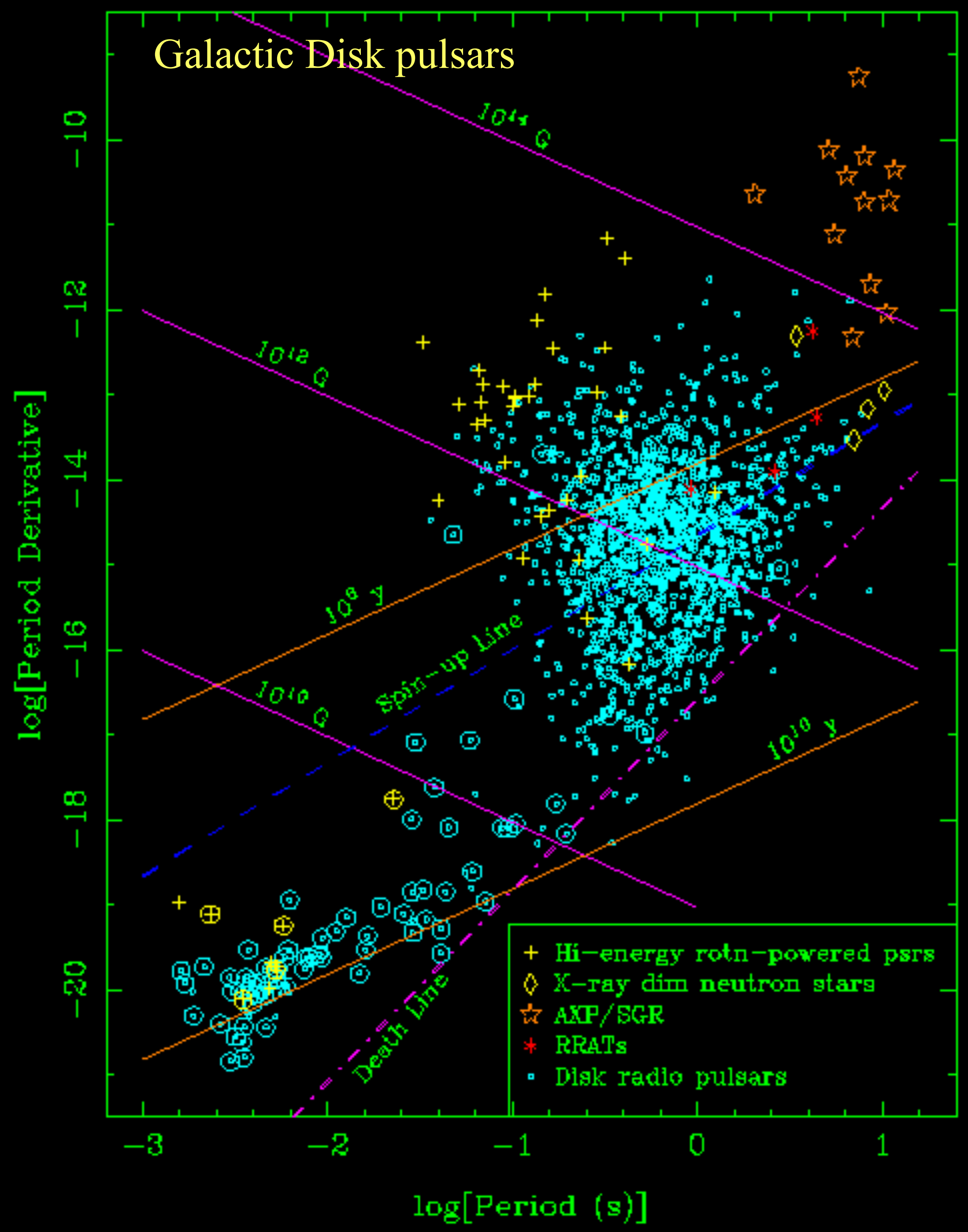
- Currently 2008 known (published) pulsars
- 1846 rotation-powered disk pulsars
- 186 in binary systems
- 252 millisecond pulsars
- 141 in globular clusters
- 8 X-ray isolated neutron stars
- 16 AXP/SGR – magnetars
- 20 extra-galactic pulsars



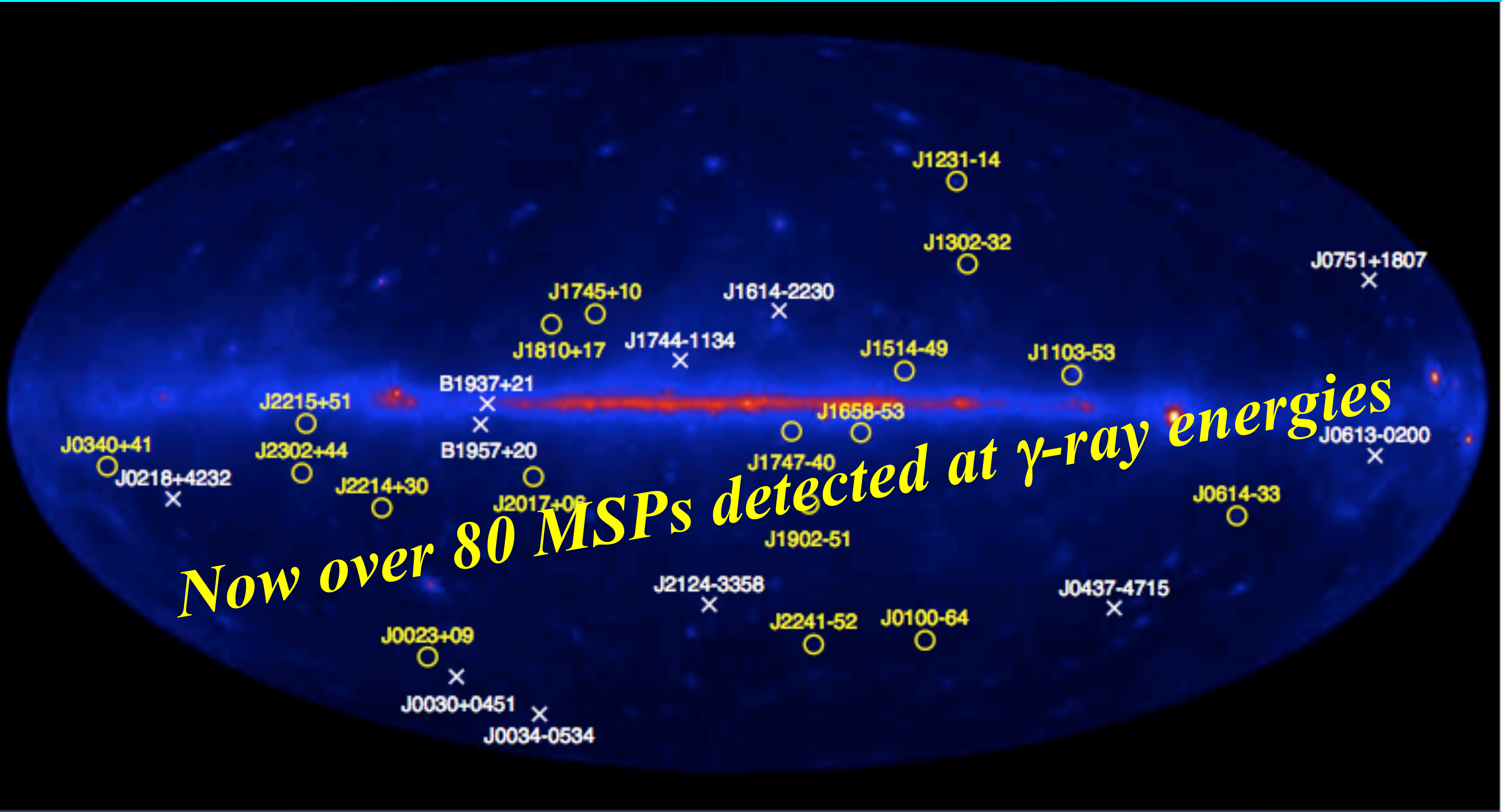
Data from ATNF Pulsar Catalogue, V1.44
(www.atnf.csiro.au/research/pulsar/psrcat)
(Manchester et al. 2005)

The P – Ṗ Diagram

- Different pulsar classes are nicely differentiated on the P – Ṗ diagram
- Binary and millisecond pulsars in lower-left
- Magnetars in top-right
- Young and high-energy emitters in top-left
- Double-neutron star systems between MSPs and normal pulsars
- RRATs and XINS between magnetars and normal pulsars



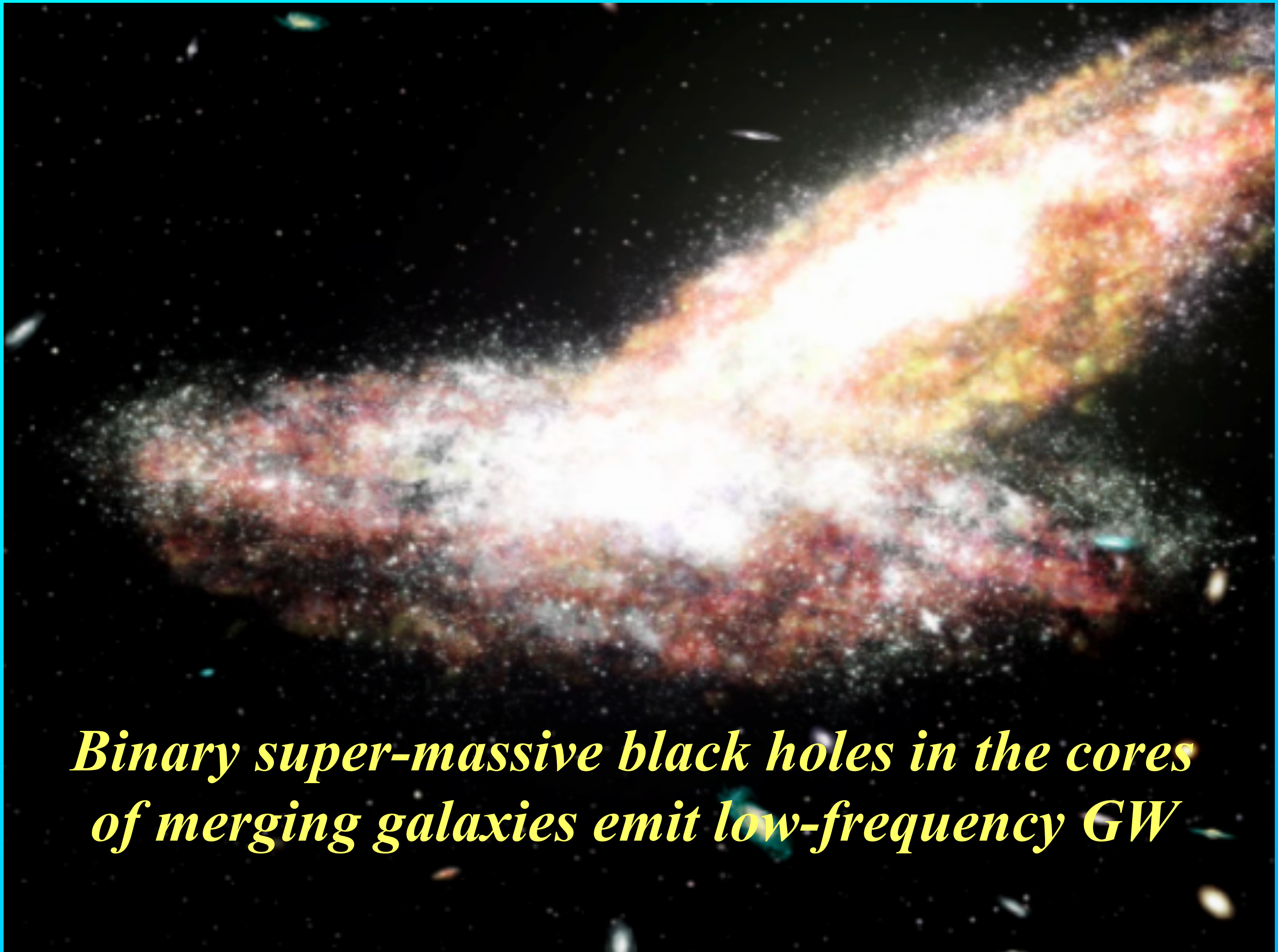
Fermi Gamma-ray Observatory MSP Discoveries

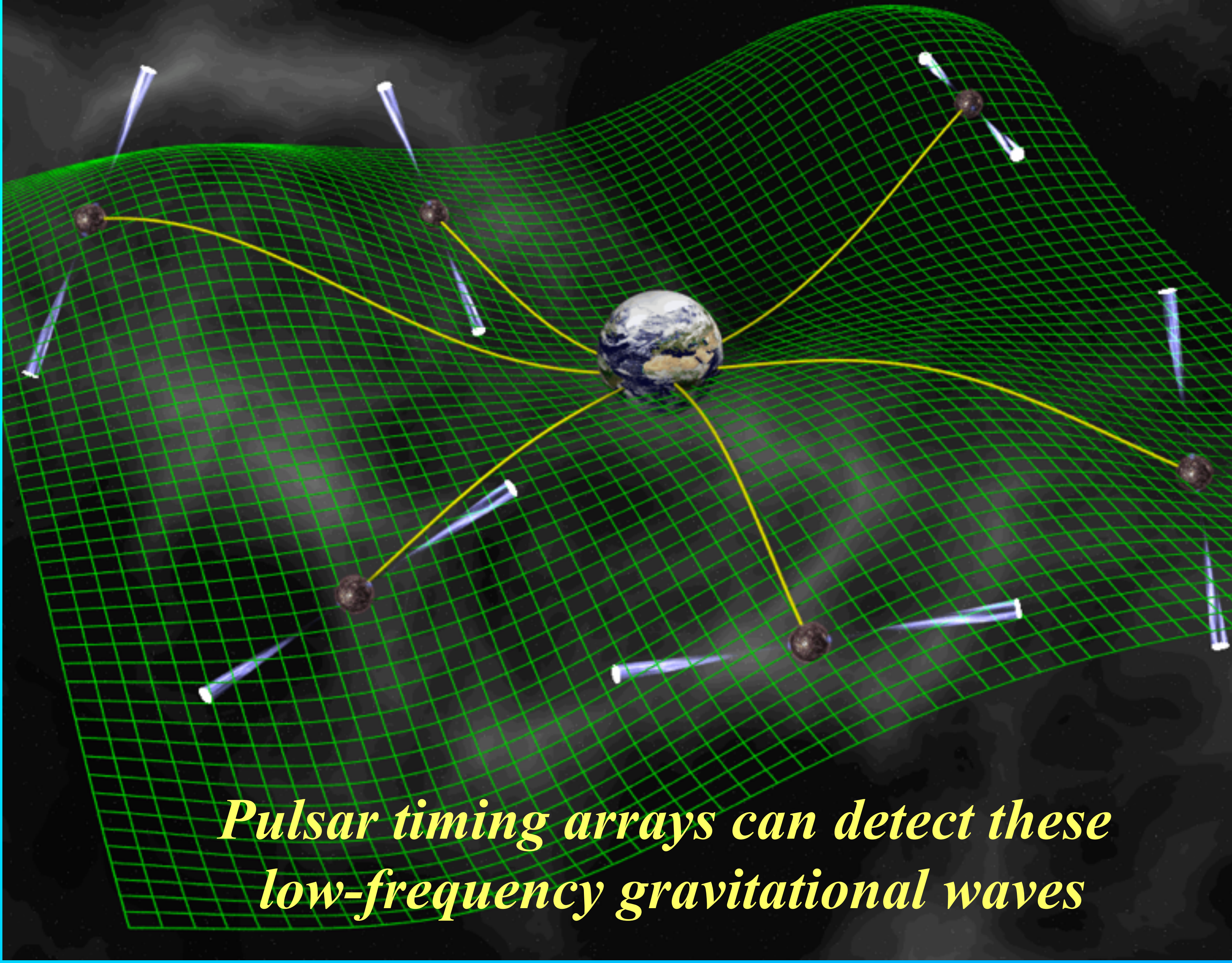


x: γ-ray detections of known radio MSPs
o: Radio MSPs found at location of un-ID γ-ray sources

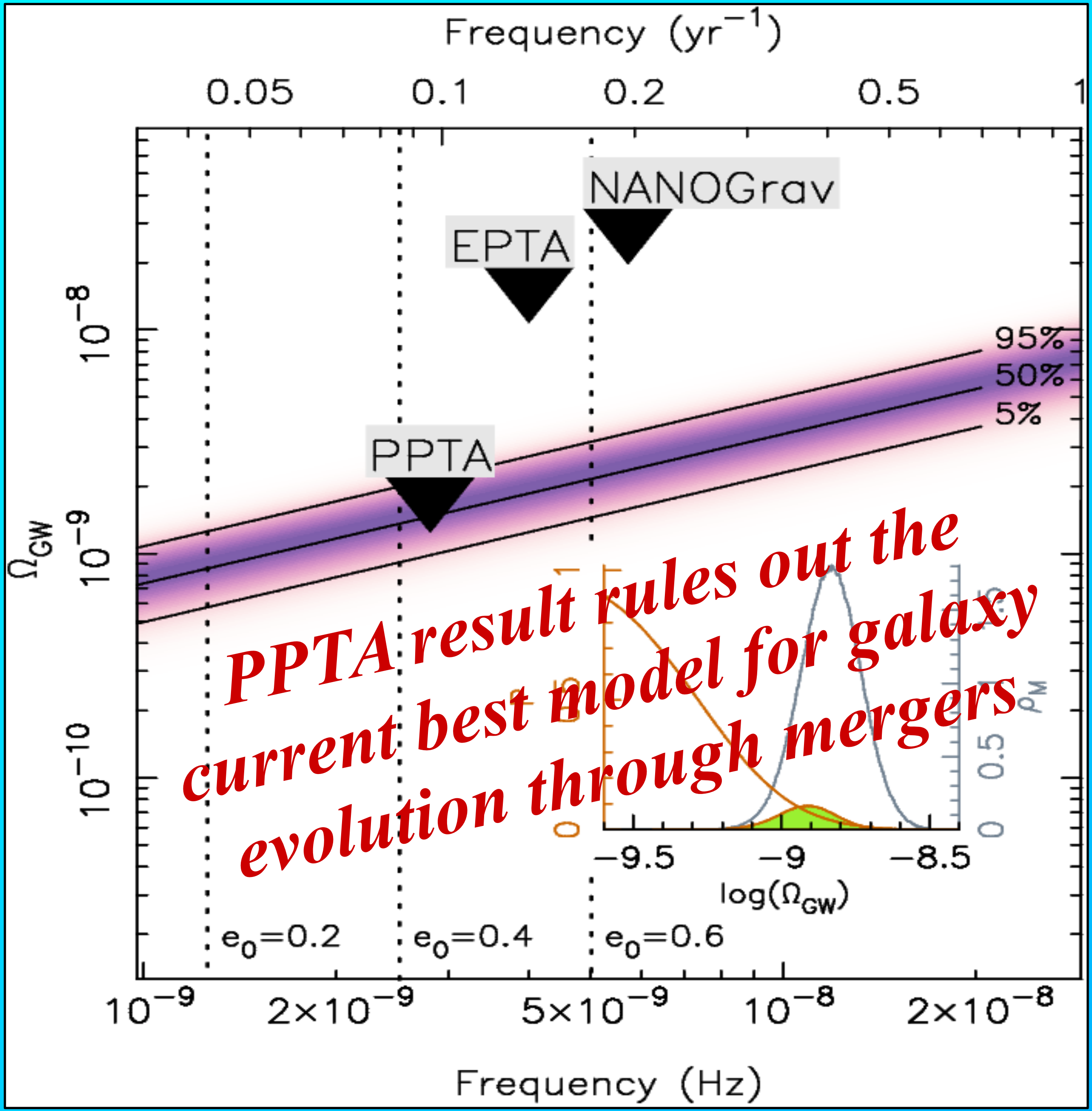
(Ray 2010)

Detection of Gravitational Waves using Pulsar Timing Arrays




Pulsar timing arrays can detect these
low-frequency gravitational waves

Parkes Pulsar Timing Array Limit



Pulsars are fantastic – thanks Jocelyn!