Pulsars are cool.... seriously

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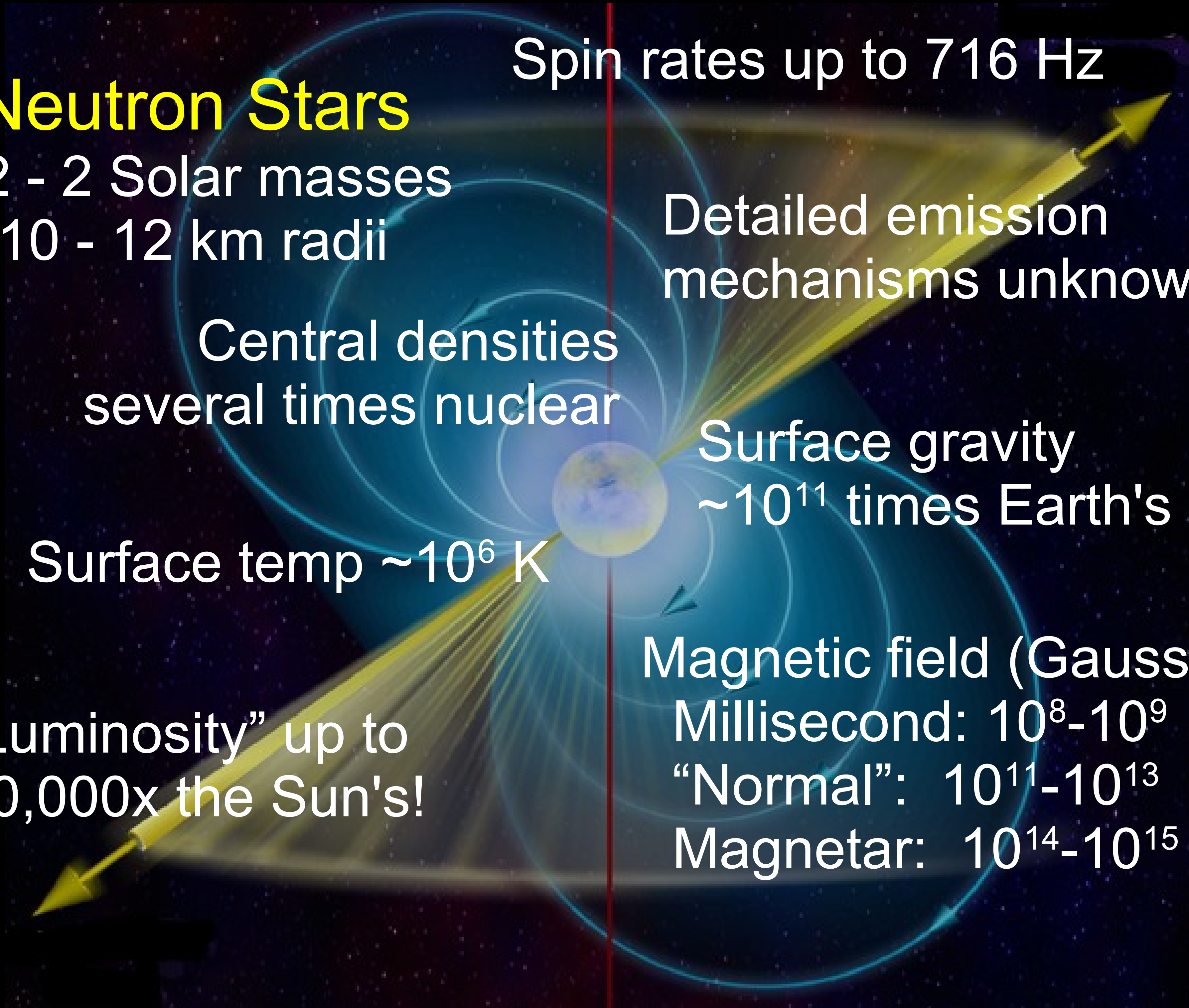

Neutron Stars
1.2 - 2 Solar masses
10 - 12 km radii
Spin rates up to 716 Hz
Detailed emission
mechanisms unknown
Central densities
several times nuclear
Surface gravity
~10^{11} times Earth's
Surface temp ~10^{6} K
Magnetic field (Gauss):
Millisecond: 10^{8}-10^{9}
"Normal": 10^{11}-10^{13}
Magnetar: 10^{14}-10^{15}
"Luminosity" up to
10,000x the Sun's!

Neutron Stars

1.2 - 2 Solar masses
10 - 12 km radii

Central densities

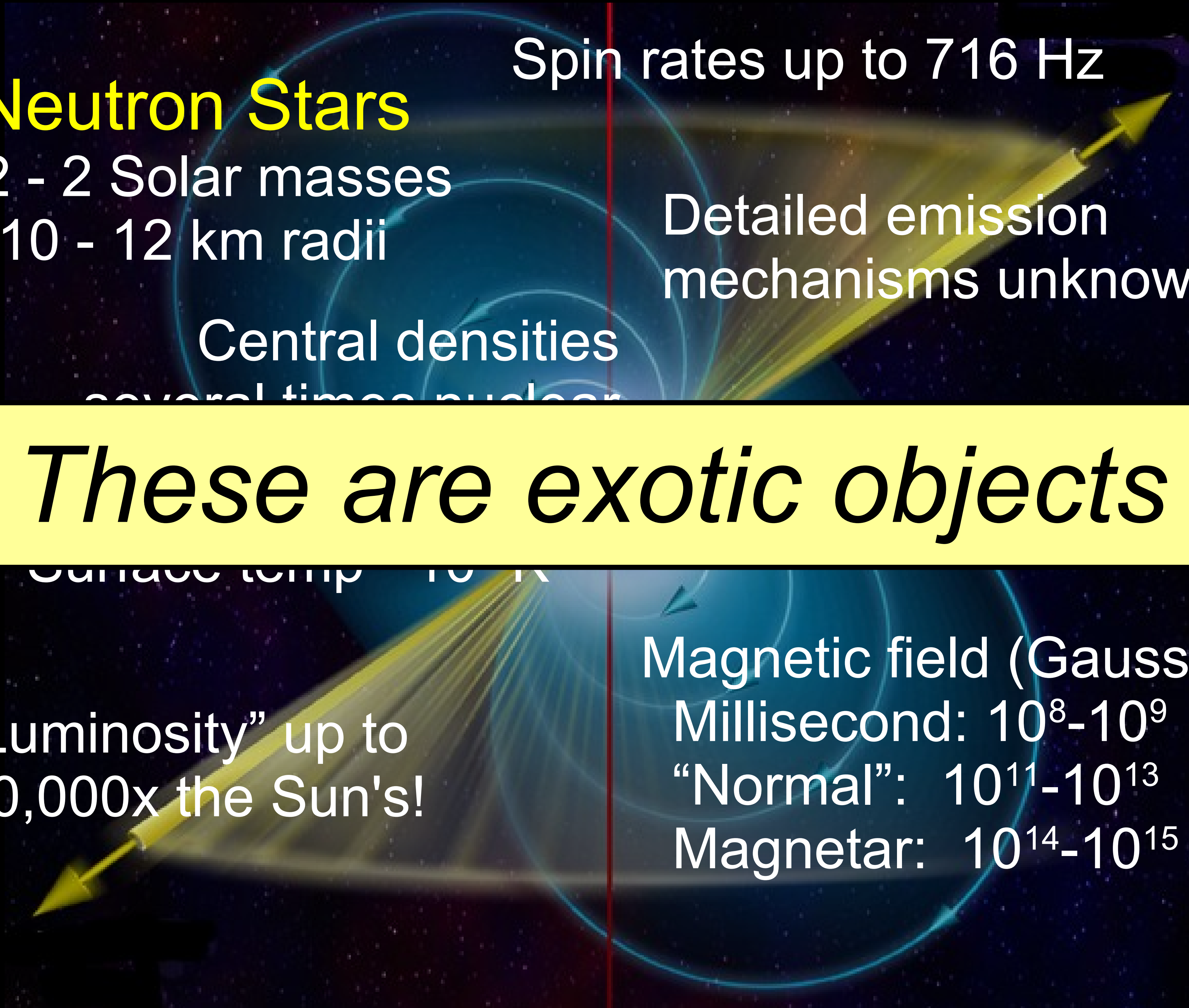
Spin rates up to 716 Hz

Detailed emission mechanisms unknown

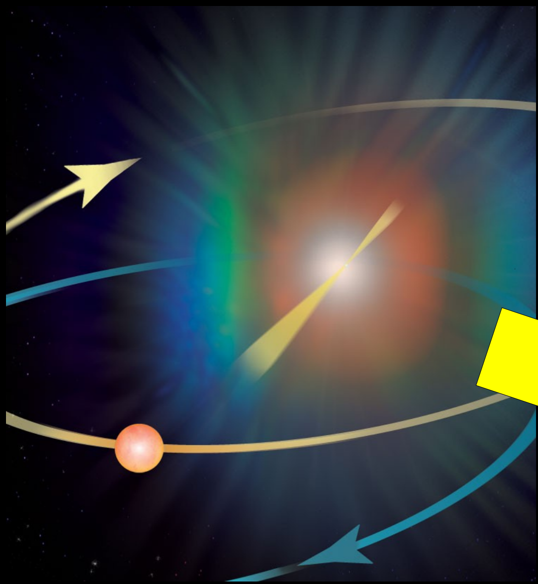
These are exotic objects

"Luminosity" up to 10,000x the Sun's!

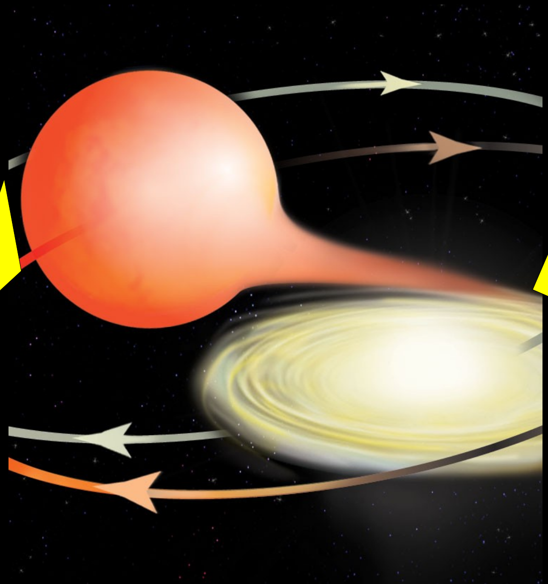
Magnetic field (Gauss):
Millisecond: 10^8-10^9
"Normal": 10^{11}-10^{13}
Magnetar: 10^{14}-10^{15}



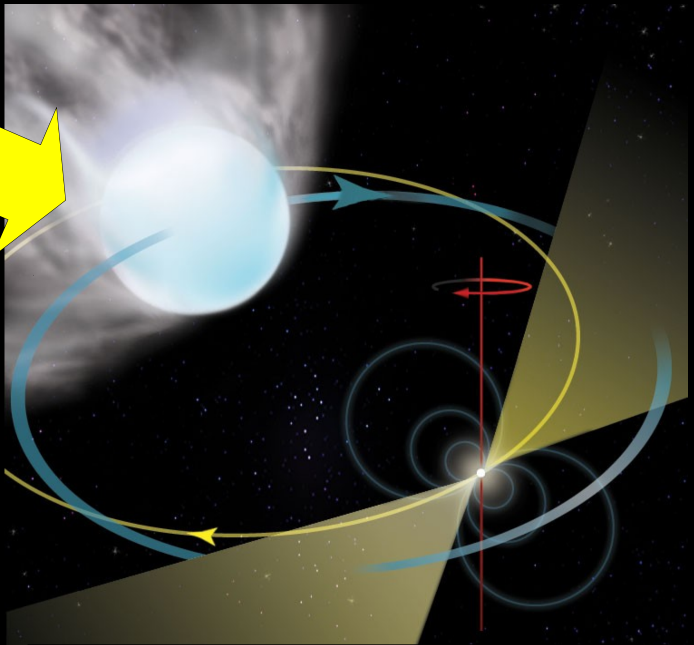
Millisecond Pulsars: via “Recycling”



Supernova produces a neutron star



Red Giant transfers matter to neutron star



Millisecond Pulsar emerges with a white dwarf companion

Alpar et al 1982
Radhakrishnan & Srinivasan 1984

Picture credits: Bill Saxton, NRAO/AUI/NSF

Pulsars are Precise Clocks

PSR J0437-4715

On Aug 23, 2012 at 08:40am CST :

P = 5.75745185566875 ms
+/- 0.000000000000001ms

The last digit changes by 1 every half hour!

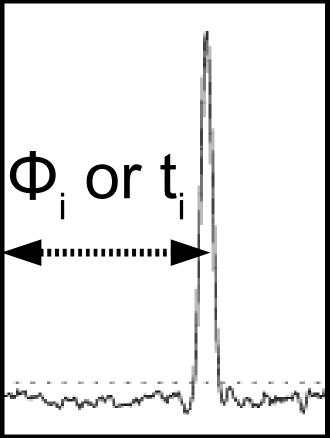
This digit changes by 1 every 500 years!

This extreme precision is what allows us to ***use pulsars as tools*** to do unique physics!

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years

All about the phase (Φ) ...



TOAs: Times of Arrival

For MSPs: TOA precision is <1μs *or* ΔΦ ~ 0.0001

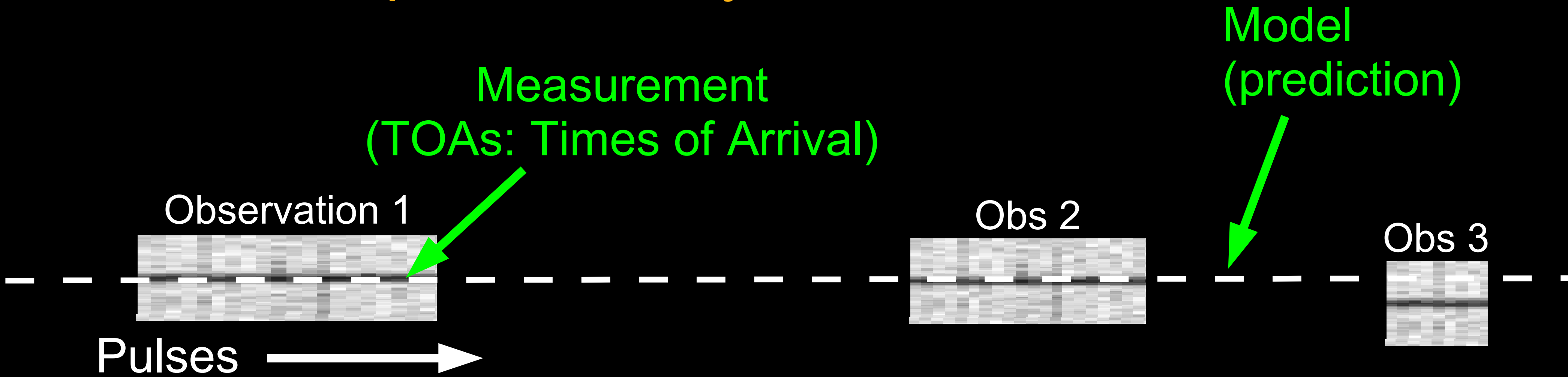
So for a 3 year set of observations....

$$\text{Frequency Error} \sim \frac{\Delta\phi}{\Delta T} \sim \frac{10^{-4}}{10^{8}\,\text{sec}} \sim 10^{-12}\,\text{Hz}$$

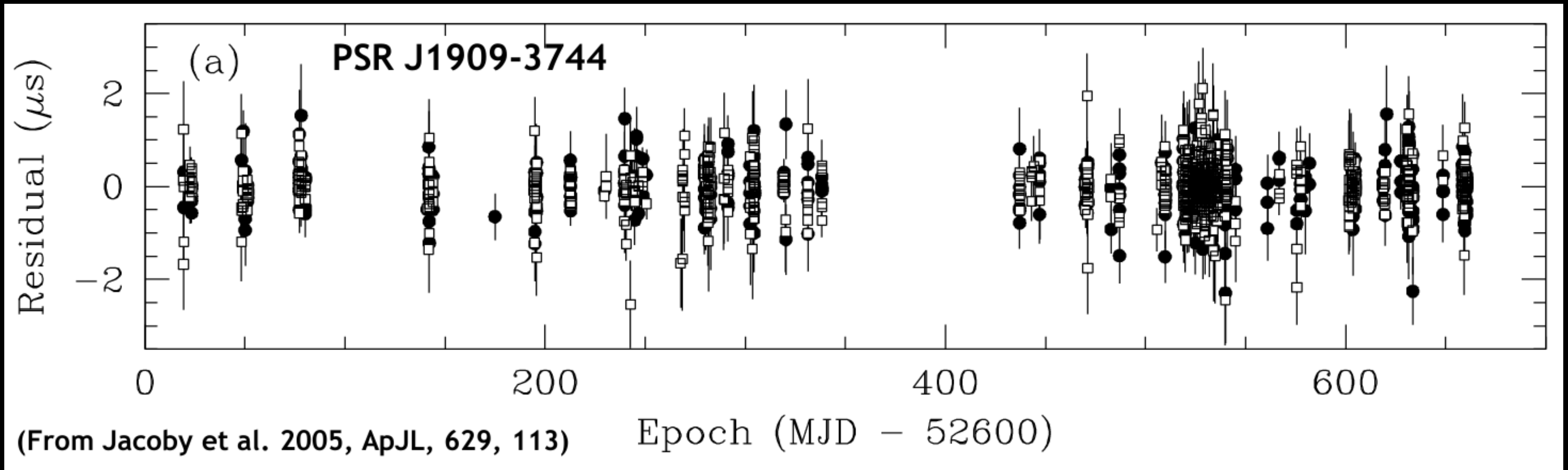
That is about 14 significant figures!

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



Measurement - Model = Timing Residuals



(From Jacoby et al. 2005, ApJL, 629, 113)

200ns RMS over 2 yrs

Precision Timing Example

- Isolated pulsars have 4 timing parameters:
  - RA, Dec, P_{spin}, $\dot{P}_{spin}$
- Extended timing can give:
  - Proper motion & parallax
- Binary pulsars add 5 Keplerian Orbital params
  - P_{orb}, asini/c, e, ω, T_0
- Some binaries give post-Keplerian params
  - $\dot{\omega}$, γ, $\dot{P}_{orb}$, r , s

Table 1 PSR J0437−4715 physical parameters

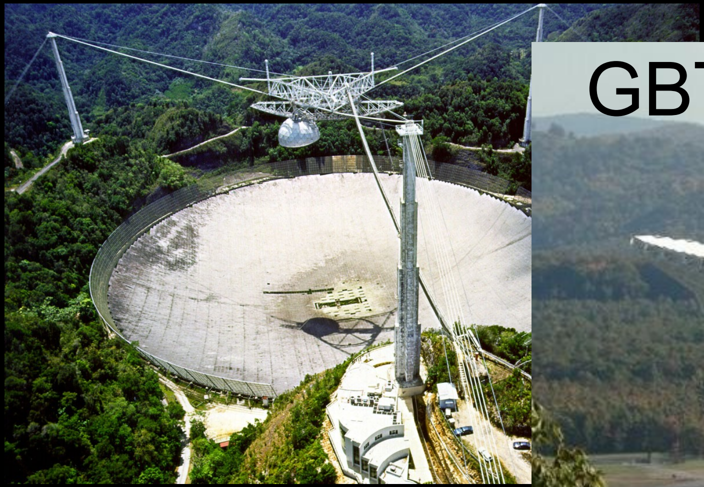
Right ascension, α (J2000) ...	$04^h37^m15^s.7865145(7)$
Declination, δ (J2000)	$-47°15'08''.461584(8)$
μ_α (mas yr^{-1})	121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_b (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_0 (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_2 ($M_\odot$) ...	0.236(17)
$\dot{P}_b$ (10^{-12})	3.64(20)
$\dot{\omega}$ (° yr^{-1})	0.016(10)

~100 ns RMS timing residuals over years!

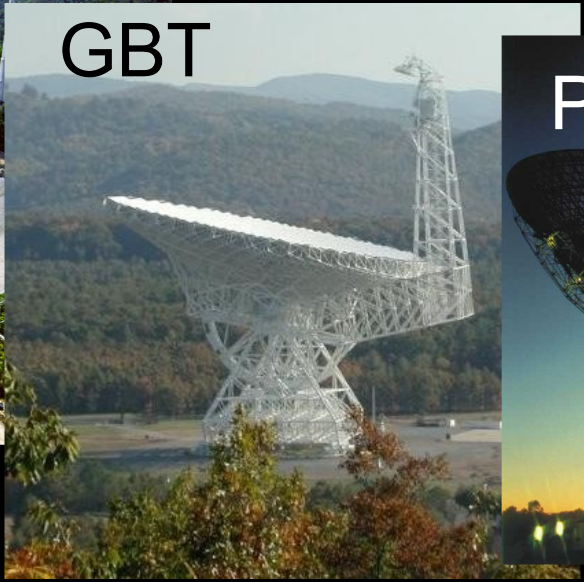
van Straten et al. 2001, Nature, 412, 158

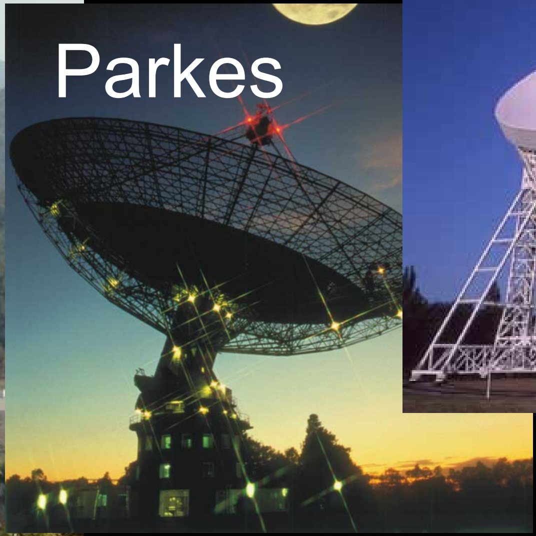
A Millisecond Pulsar Renaissance

- ***Until very recently:*** pulsar observations were severely limited by our instrumentation, not by our telescopes
- ***Now:*** digital signal processing and computing are finally allowing us to fully use our telescopes



Arecibo





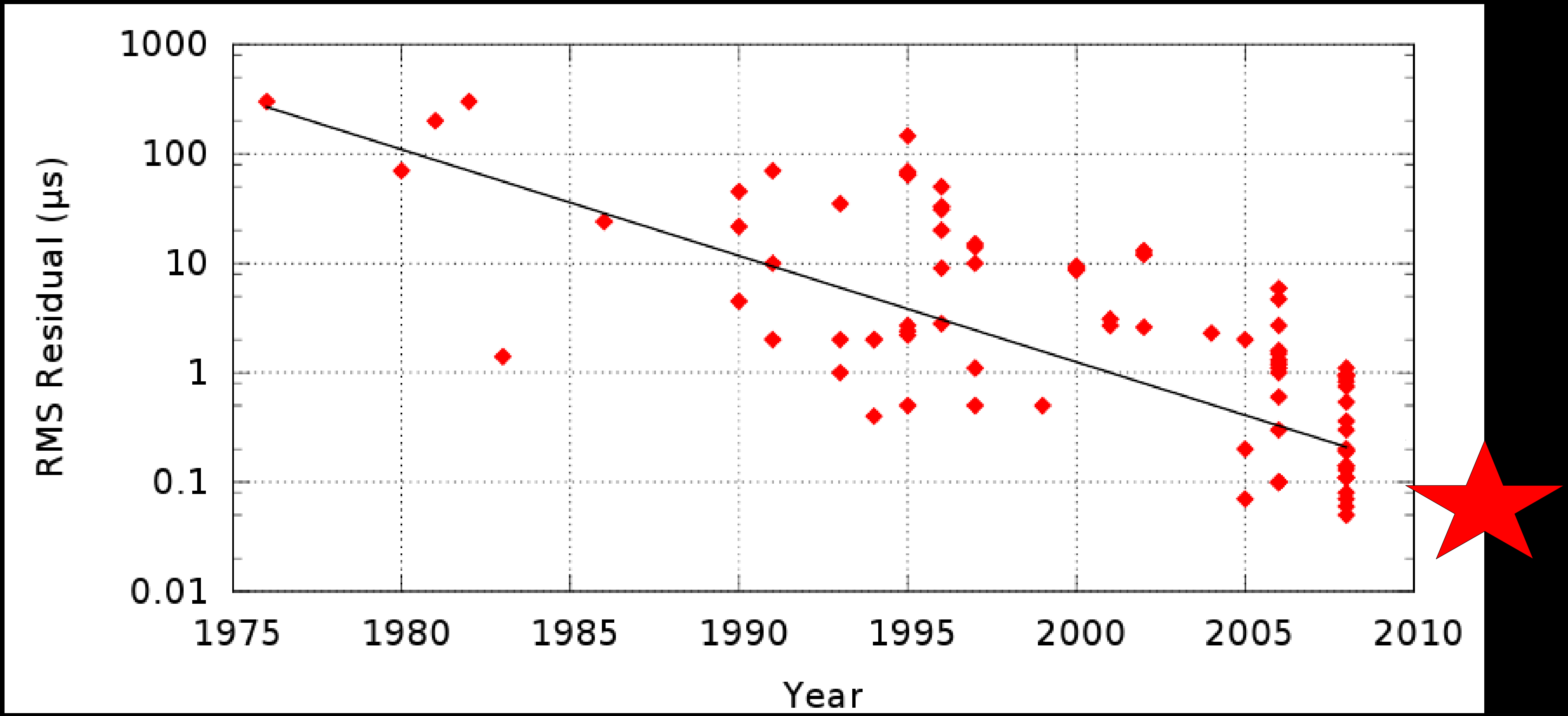
Jodrell Bank

Plus: Nancay, Effelsberg, GMRT, Westerbork, Urumqi...

A Millisecond Pulsar Renaissance

Timing precision improving roughly as Moore's Law

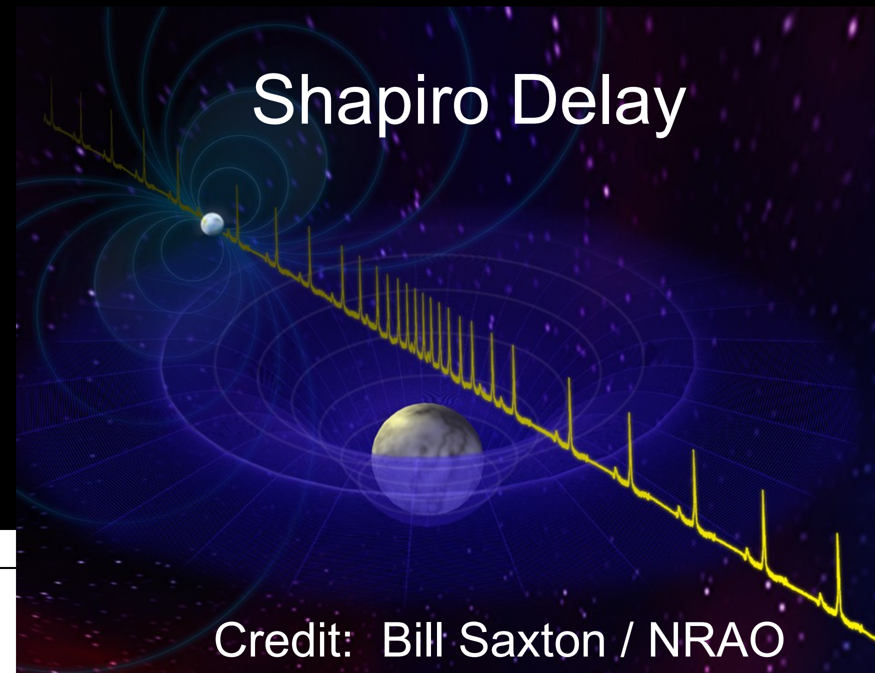
Currently have ~10 MSPs between 50-100 ns

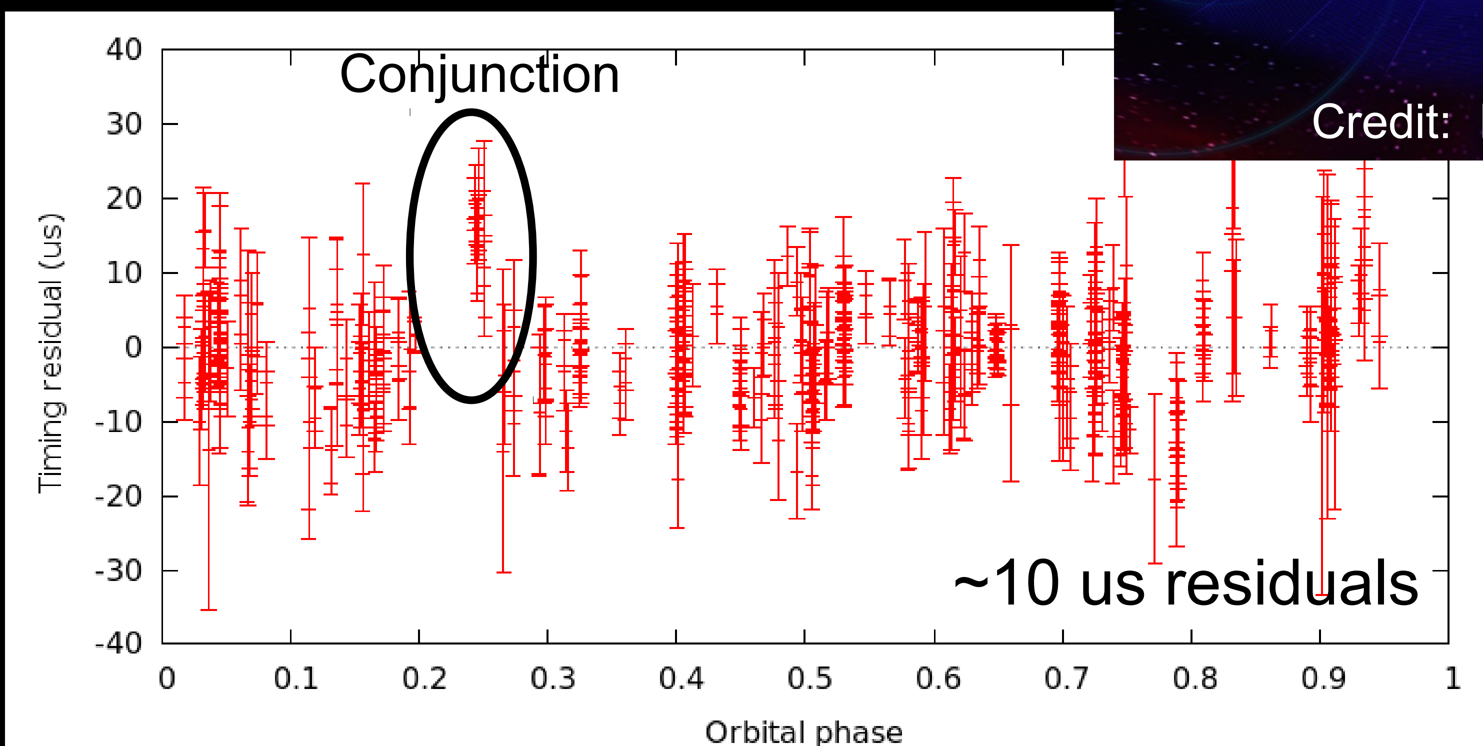


Courtesy R. Jenet and P. Demorest

Case in point: MSP J1614-2230

- 3.15 ms in 8.7 day binary
- >0.4 $M_\odot$ companion
- 2004-2009: Orbital timing systematics. Shapiro delay?
- 2010: GUPPI on GBT

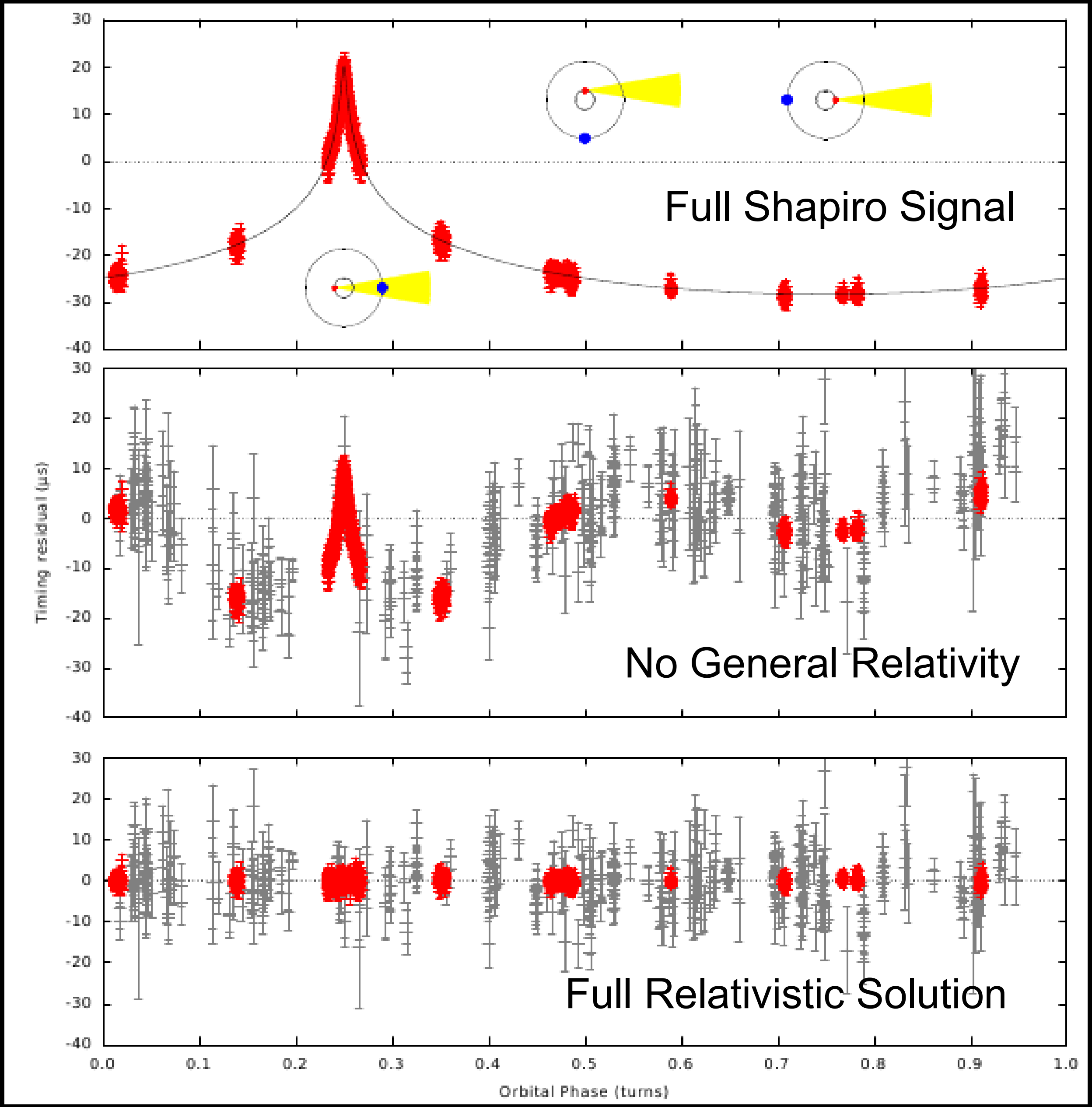




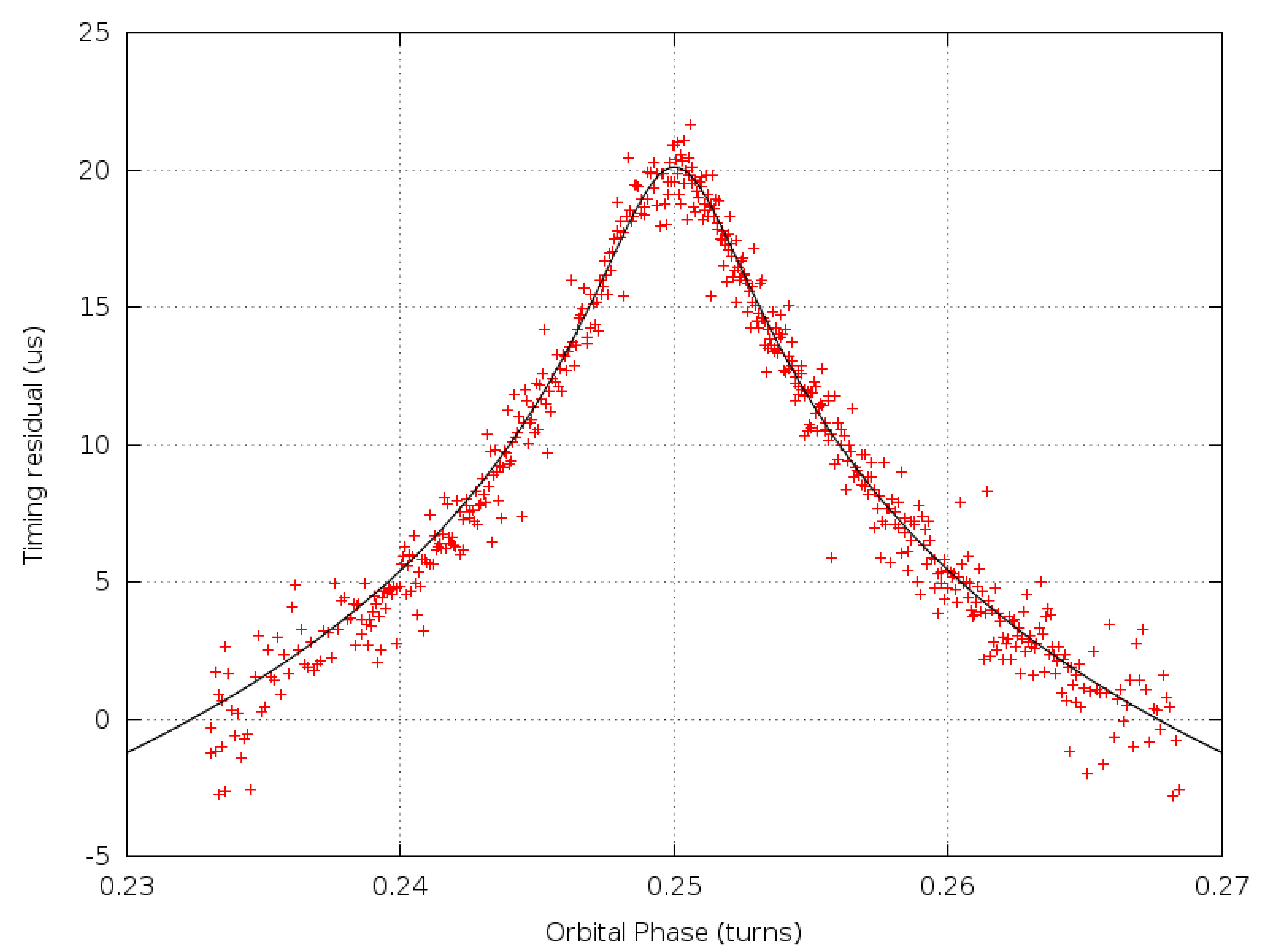
MSP J1614-2230
Incredible Shapiro Delay Signal

$M_{wd} = 0.500(6)\ M_{\odot}$
Inclination = 89.17(2) deg!

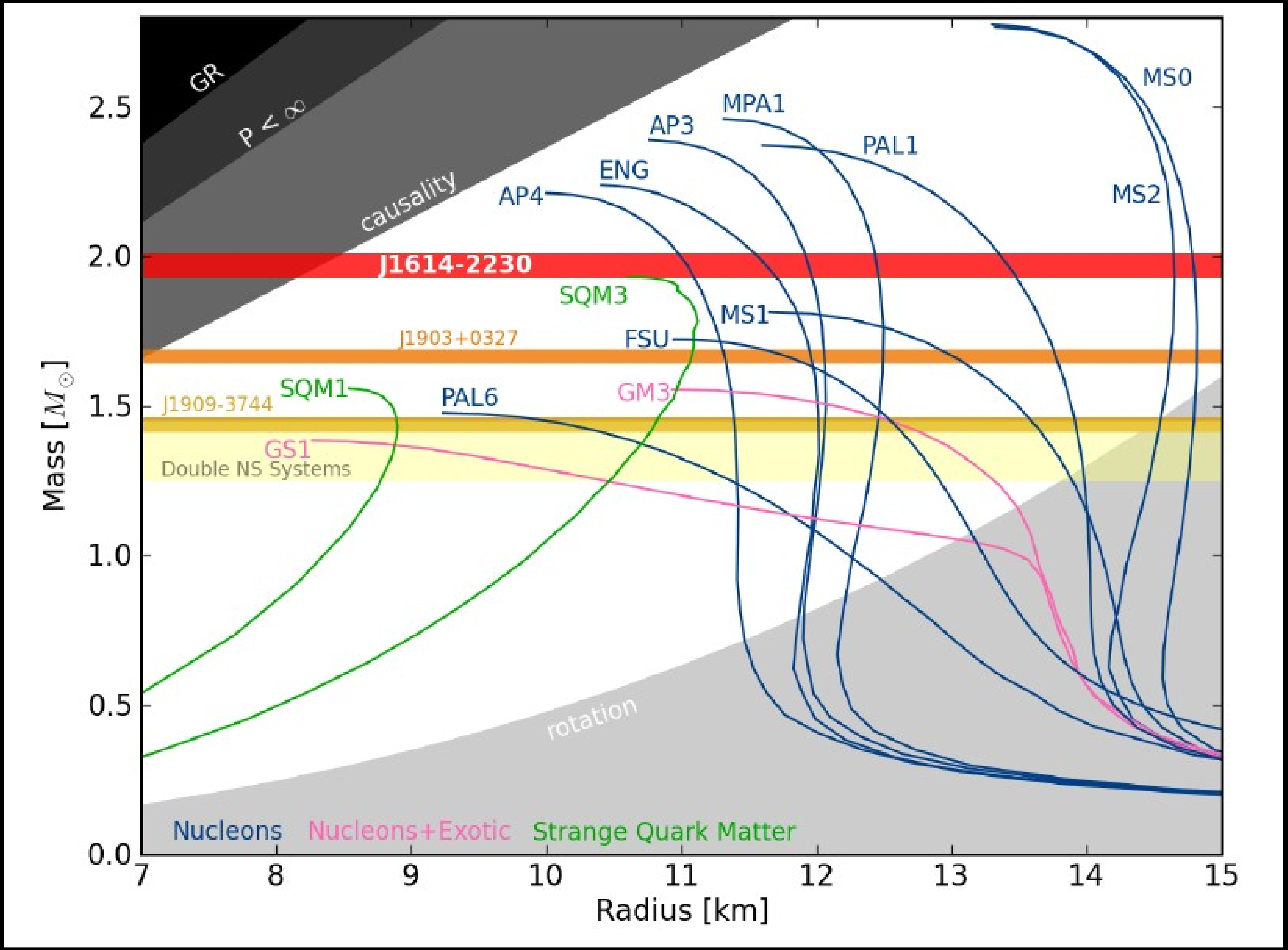
Mpsr = **1.97(4) $M_{\odot}$**!



Demorest et al. 2010, *Nature*, 467, 1081D
see Ozel et al. 2010, ApJL, 724, 1990


25
20
15
10
5
0
-5
0.23
0.24
0.25
0.26
0.27
Timing residual (us)
Orbital Phase (turns)

MSP J1614-2230: EOS Constraints



Demorest et al. 2010, *Nature*, 467, 1081D
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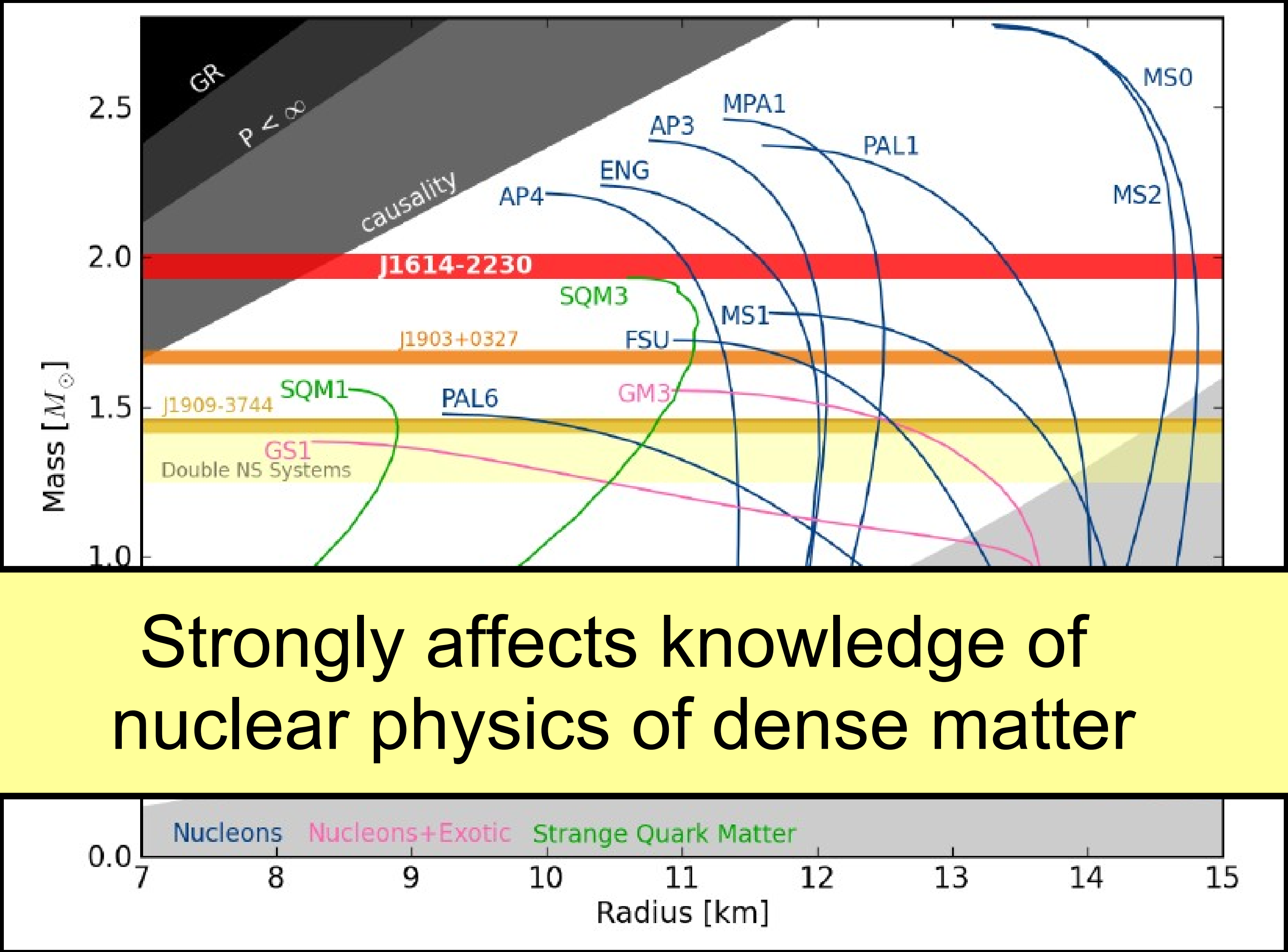
MSP J1614-2230: EOS Constraints

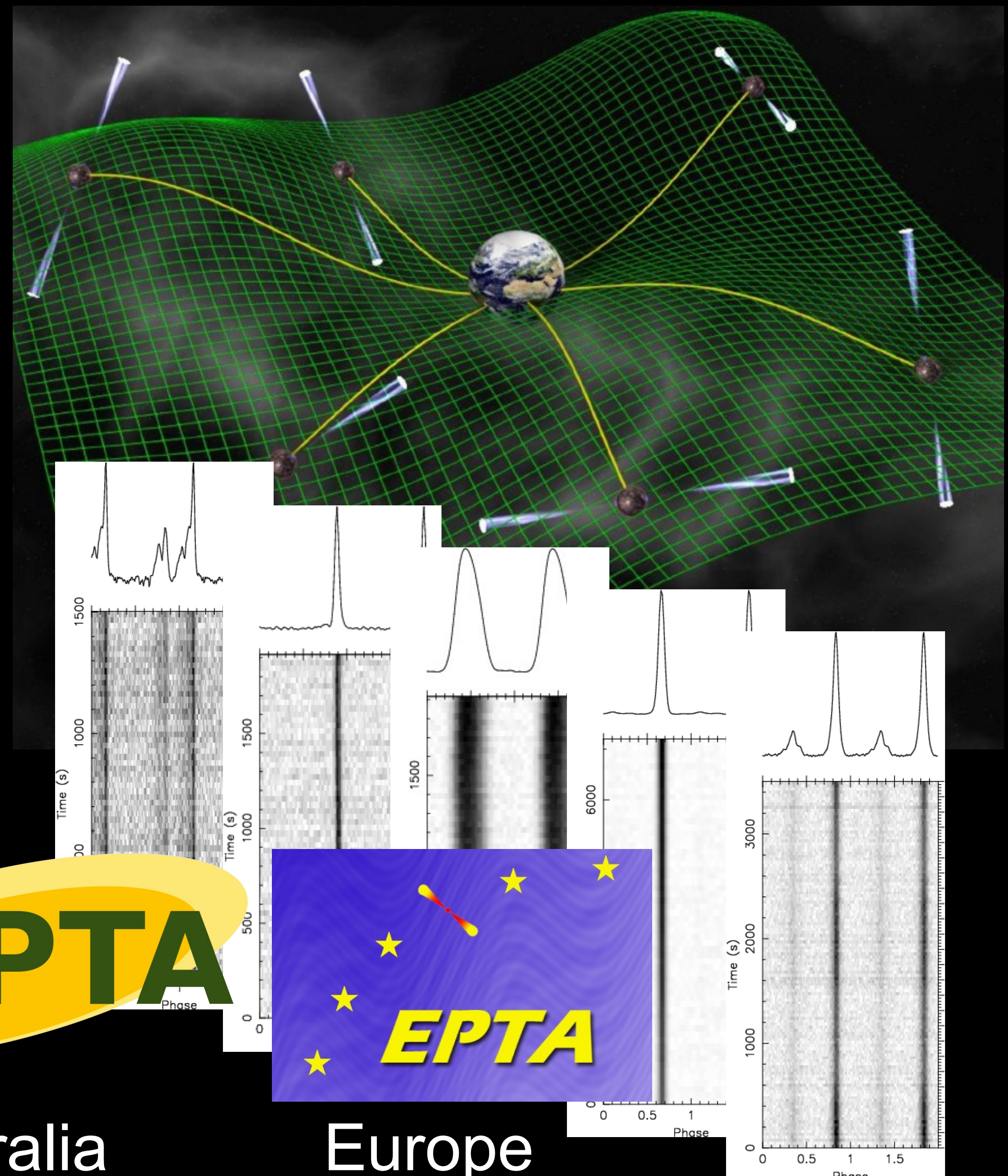


Strongly affects knowledge of nuclear physics of dense matter

Demorest et al. 2010, *Nature,* 467, 1081D
see Ozel et al. 2010, ApJL, 724, 1990

Gravitational Wave Detection with a Pulsar Timing Array

- Need good MSPs
- Significance scales directly with the number of MSPs being timed. Lack of good MSPs is currently the biggest limitation
- Must time the pulsars for 5-10 years at a precision of ~100 nano-seconds!



NANOGrav

PPTA

EPTA

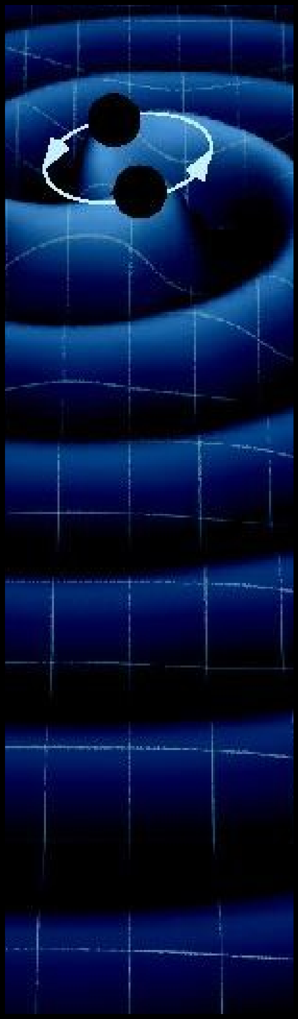
N. America

Australia

Europe

Where do these GWs come from?

Coalescing Super-Massive Black Holes



- Basically all galaxies have them
- Masses of $10^6 - 10^9\ M_\odot$
- Galaxy mergers lead to BH mergers
- When BHs within 1pc, GWs are main energy loss
- For total mass $M/(1+z)$, distance d_L, and SMBH orbital freq f, the induced timing residuals are:

$$\Delta\tau \sim 10\,\mathrm{ns}\left(\frac{1\,\mathrm{Gpc}}{\mathrm{d_L}}\right)\left(\frac{\mathrm{M}}{10^9\,\mathrm{M}_\odot}\right)^{5/3}\left(\frac{10^{-7}\,\mathrm{Hz}}{f}\right)^{1/3}$$

Potentially measurable with a single MSP!

A Pulsar Timing Array (PTA)

Timing residuals due to a GW have two components:

"Pulsar components" are uncorrelated between MSPs

"Earth components" are **correlated** between MSPs

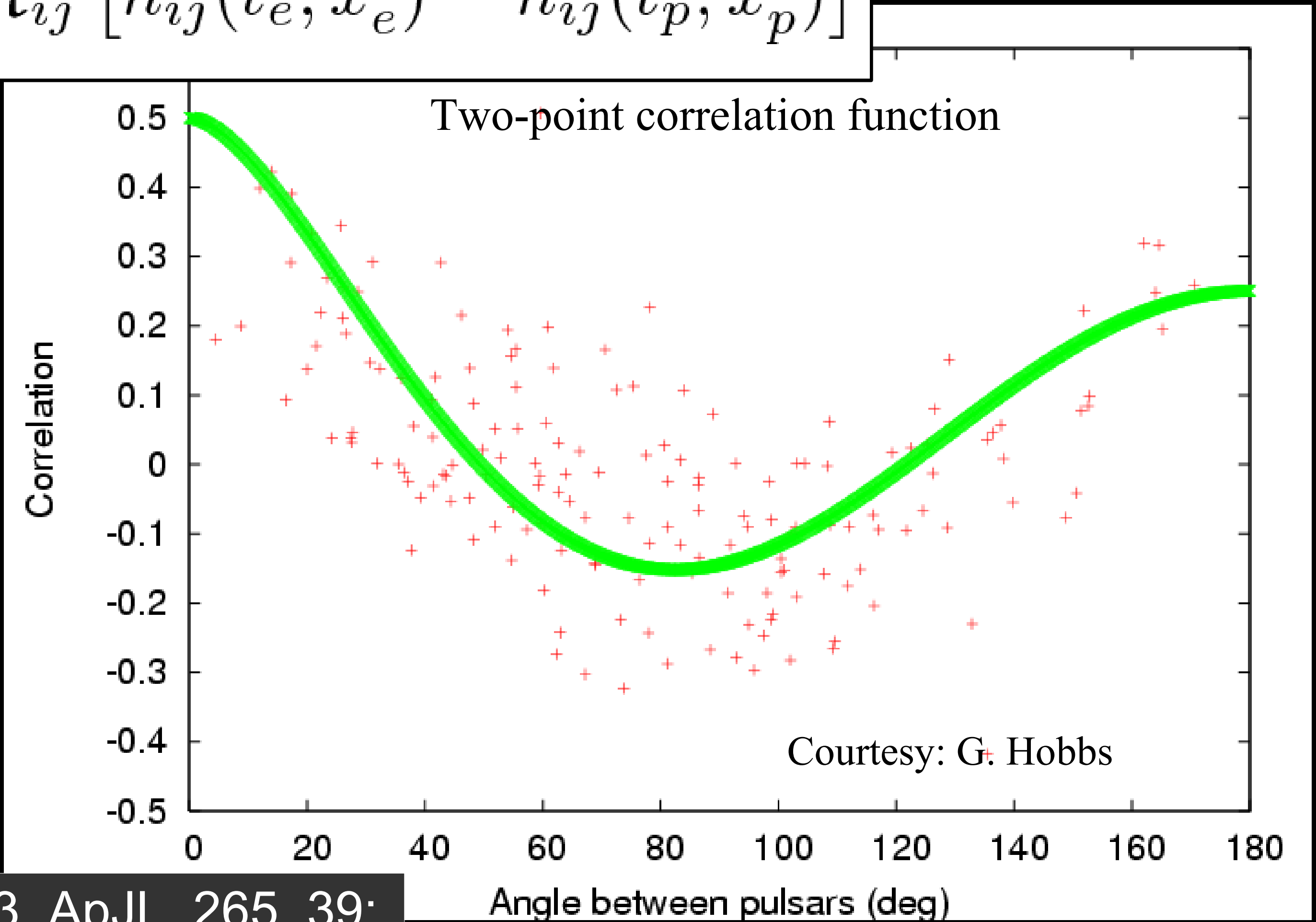
$$\frac{\delta\nu}{\nu} = -\mathcal{H}_{ij}\left[h_{ij}(t_e, x_e^i) - h_{ij}(t_p, x_p^i)\right]$$

Signal in Residuals

Clock errors:
- monopole

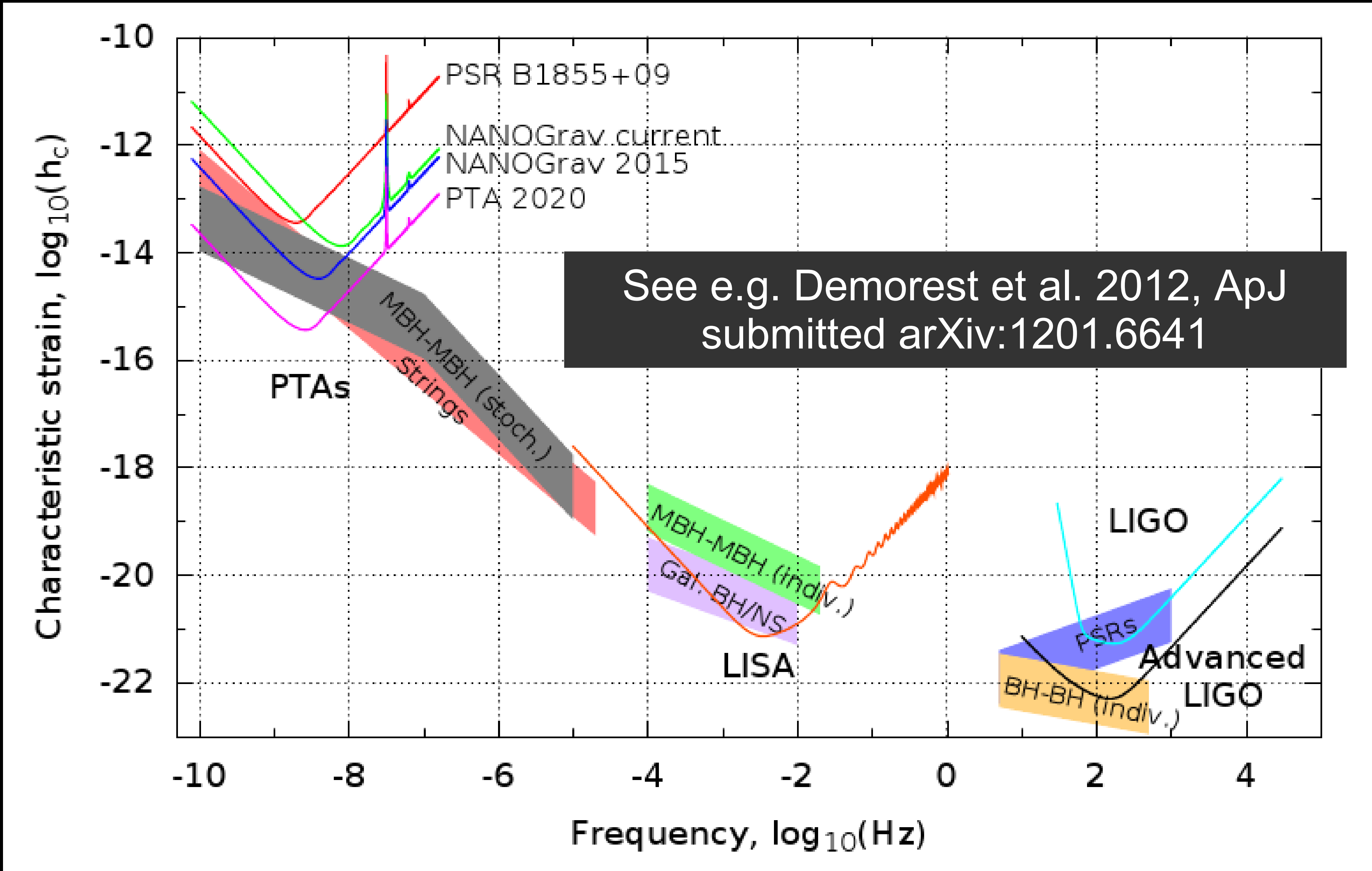
Ephemeris errors:
- dipole

GW signal:
- **quadrupole**

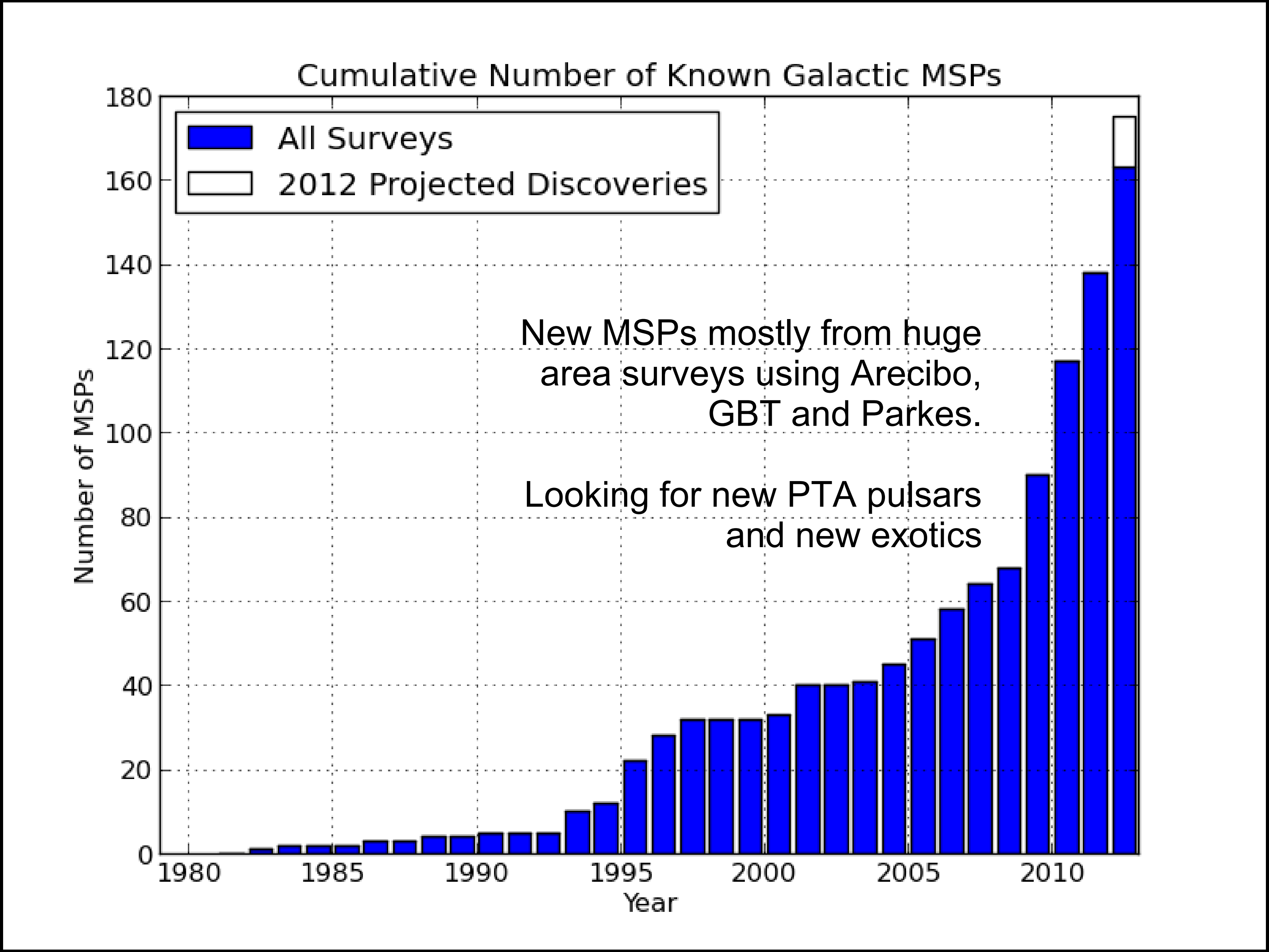


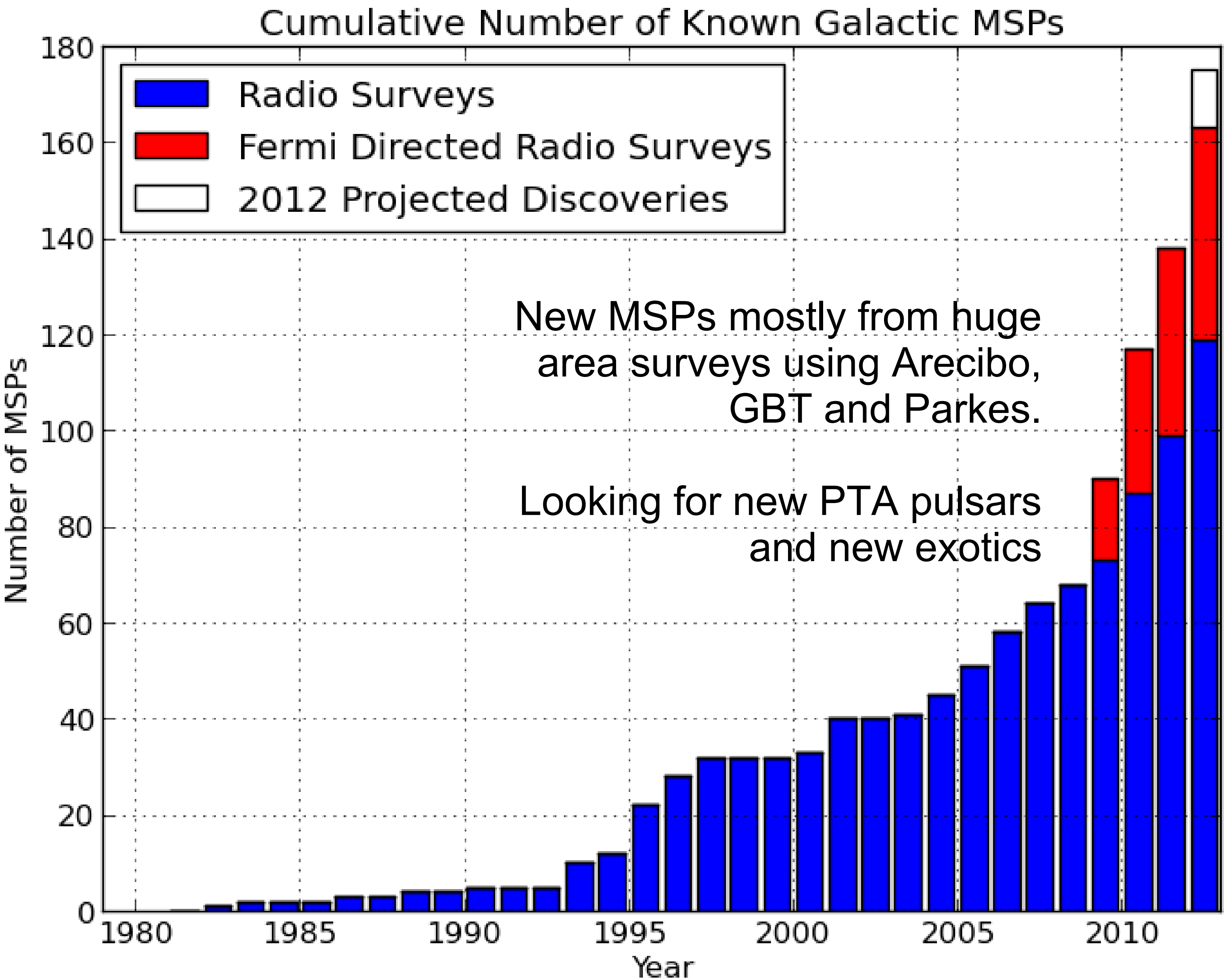
e.g. Hellings & Downs, 1983, ApJL, 265, 39; Jenet et al. 2005, ApJL, 625, 123

Timing array improvement with time



See e.g. Demorest et al. 2012, ApJ submitted arXiv:1201.6641


Cumulative Number of Known Galactic MSPs
All Surveys
2012 Projected Discoveries
New MSPs mostly from huge
area surveys using Arecibo,
GBT and Parkes.
Looking for new PTA pulsars
and new exotics
Number of MSPs
Year
0
20
40
60
80
100
120
140
160
180
1980
1985
1990
1995
2000
2005
2010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0
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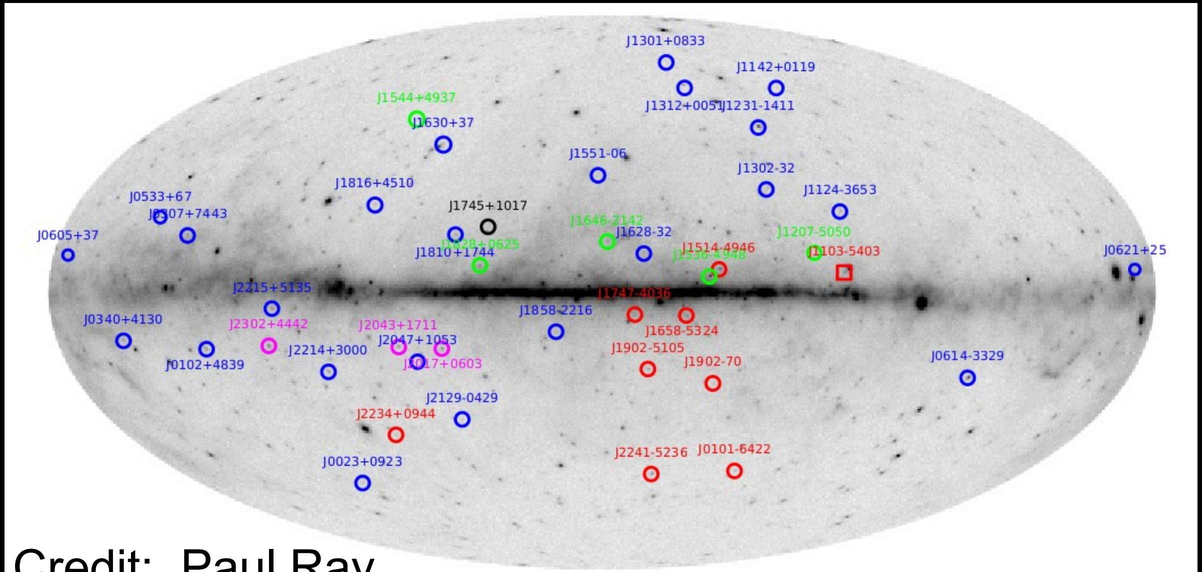
1980
1985
1990
1995
2000
2005
2010
Year

Fermi-directed Radio MSPs

Pulsar Search Consortium observes pulsar-like Fermi Unassociated Sources with radio telescopes



Credit: Paul Ray

43 and counting!

e.g. Ray et al. 2012, arXiv:1205.3089

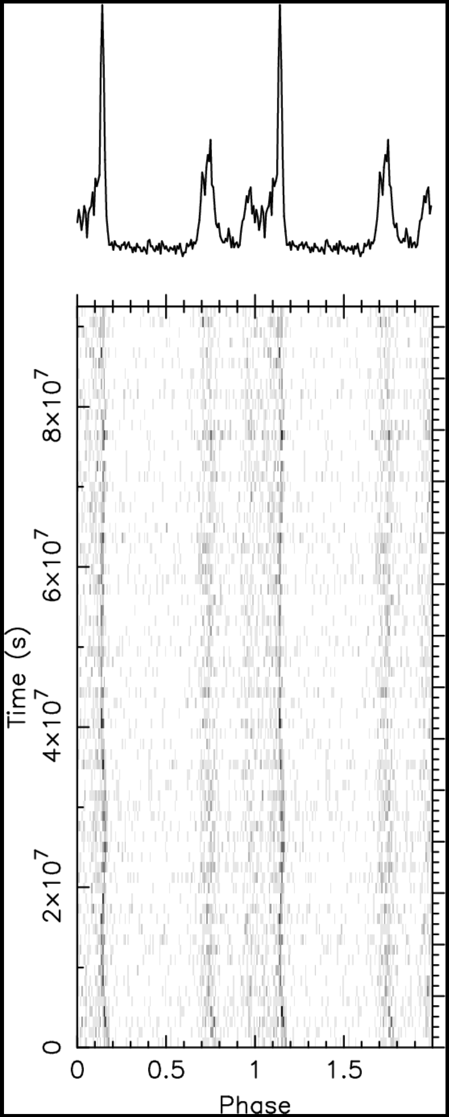
PSR J1231-1411

~3yrs of Fermi data

~3000 photons (~3/day)

~560 binary orbits

~24 billion rotations of MSP



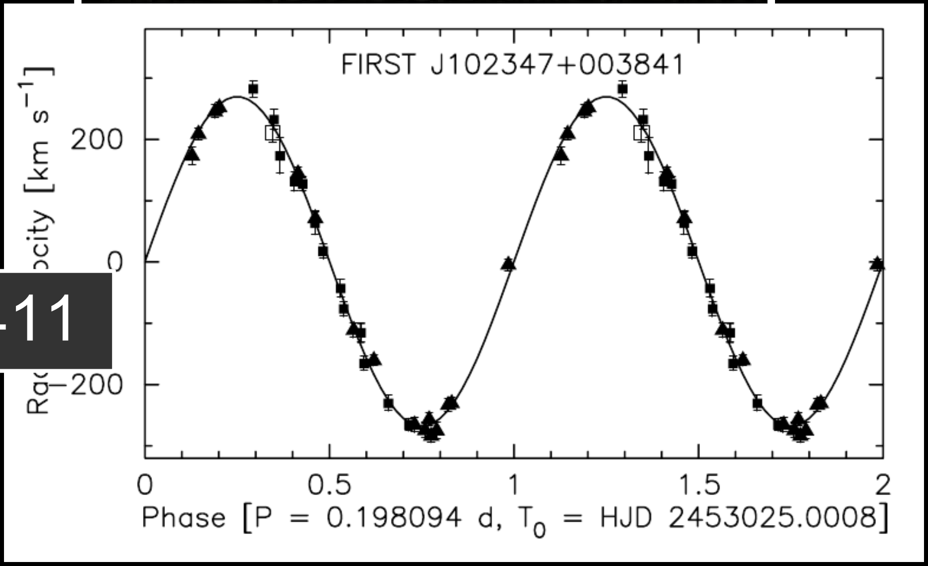
Recent exotics: "Missing Link"

J1023+0038: Previously (over last 10 yrs) detected in FIRST, optical images/ spectra, and X-rays and identified as a strange CV or a quiescent LMXB

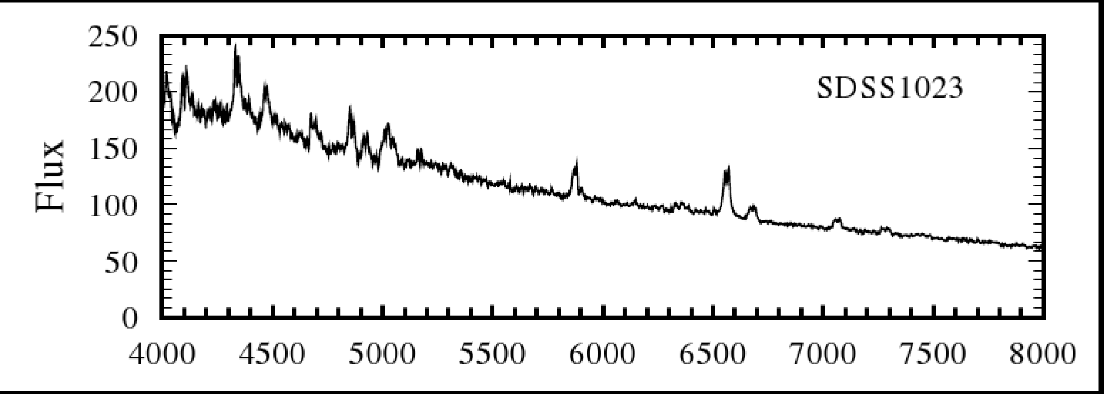
1.69 ms PSR in 4.75 hr binary

Evidence for accretion!

LMXB to MSP link!



Archibald et al, 2009, *Science*, 324, 1411



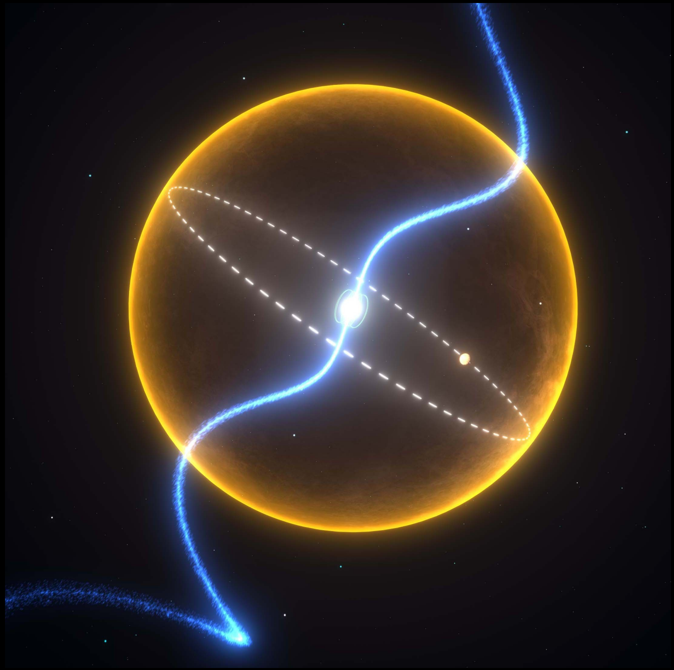
Bond et al. 2002, Szkody et al. 2003, Homer et al. 2006, **Thorstensen & Armstrong 2005**

Recent exotics: “Diamond” Planets

- PSR J1719-1438: MSP with a ~1 Jupiter mass companion found in Parkes HTRU survey
  - Compact orbit provides lower-limit on the companion density of >23g/cm3, approx CO WD-like
  - Companion is likely basically diamond!
  - Likely evolved from Ultra-Compact X-ray Binaries

Bailes et al. 2012, *Science*

- Within the last couple months, two new Jupiter-ish-mass companions found with HTRU and GBT GBNCC survey



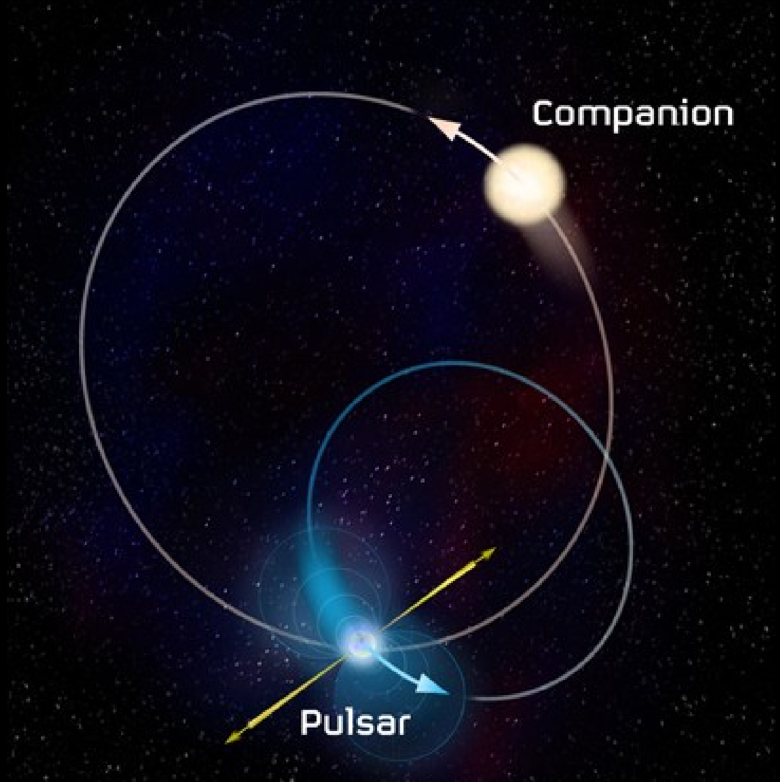
Recent exotics: Triple Systems(?)

- PSR J1903+0327: Arecibo PALFA survey found distant 2 ms pulsar in 95 day highly eccentric orbit around a main sequence star.
- High-precision relativistic mass measurement: 1.67+/-0.02 Msun PSR
- Binary now, but likely a triple *origin*

Champion et al. 2008, *Science*
Freire et al. 2011, ApJ

- Triple dynamics are complicated. Small number of true triples should exist.

Portegies-Zwart et al. 2011, ApJ

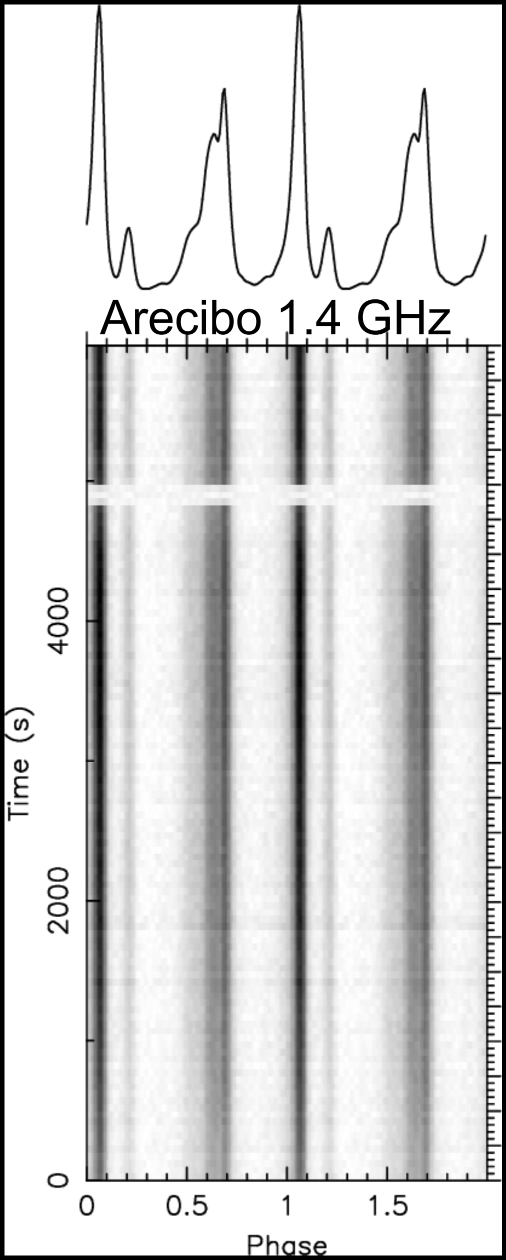


Credit: Bill Saxton / NRAO

Recent exotics: Triple Systems(?)

- PSR J0337+1715: Early this year, from the GBT Driftscan survey, a 2.7 ms PSR in a hierarchical triple system!
  - 1.6 day inner binary with hot WD
  - 327 day outer orbit with low-mass dwarf (white or red?)
  - Already showing strong secular orbital changes
  - Will be a beautiful testbed for non-Keplerian dynamics

Ransom et al. *in prep*

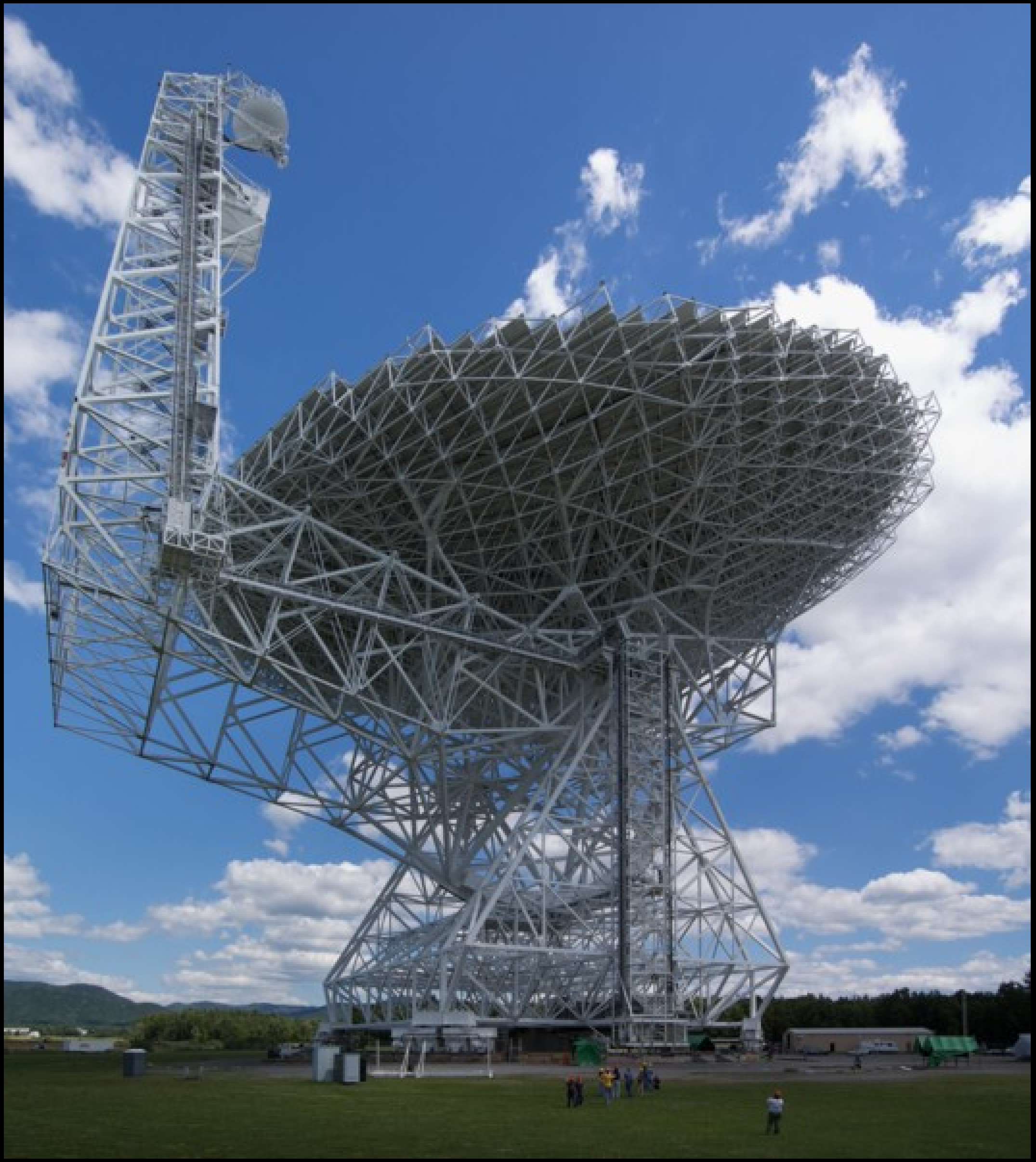


What about the future?

- Many surveys ongoing
  - Number of MSPs will continue to grow rapidly (~10000 still to discover)
  - Maybe new “Holy Grail” systems?
    - Sub-MSP, PSR-BH binary, SgrA* PSRs, MSP-MSP binary
- New telescopes coming soon will do great things for pulsars: MeerKAT, FAST, LOFAR...... SKA

NRAO's Green Bank Telescope: The GBT

- 100-m diam. (most sensitive besides Arecibo in PR)
- Can see ~85% of sky
- Unblocked optics
- Arguably the “best” pulsar telescope in the world and key for NANOGrav
- NSF Portfolio Review recommended “divestment” by mid 2016
- Loss would be *very* bad for pulsar research



Summary

Pulsars are cool.....

seriously

Post-Keplerian Orbital Params

Besides the normal 5 "Keplerian" parameters (P_{orb}, e, $a\sin(i)/c$, T_0, ω), General Relativity gives:

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}$$

(Orbital Precession)

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$

(Grav redshift + time dilation)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}$$

$$r = T_\odot m_2$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}$$

(Shapiro delay: "range" and "shape")

where: $T_\odot \equiv GM_\odot/c^3$ = 4.925490947 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2