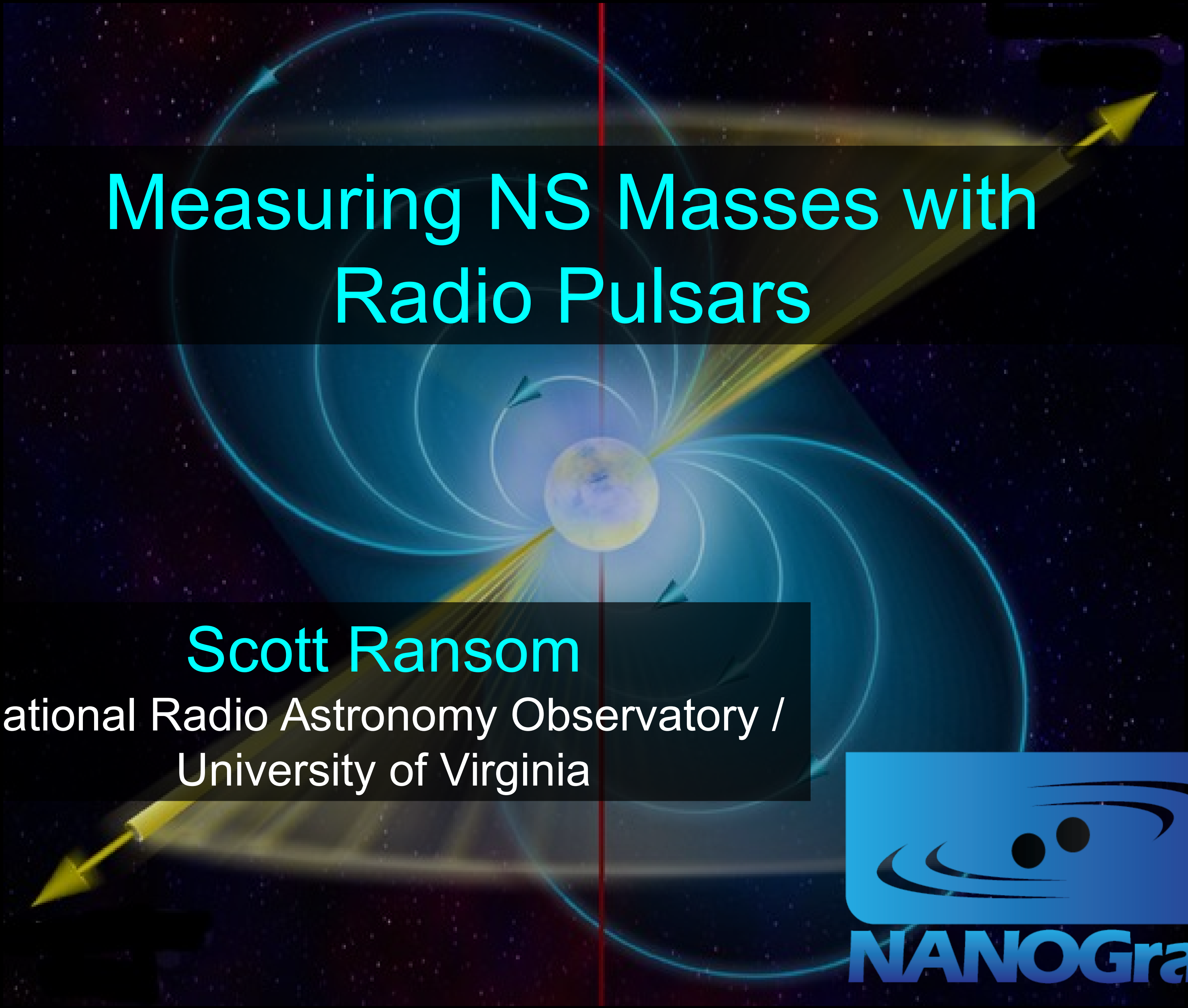


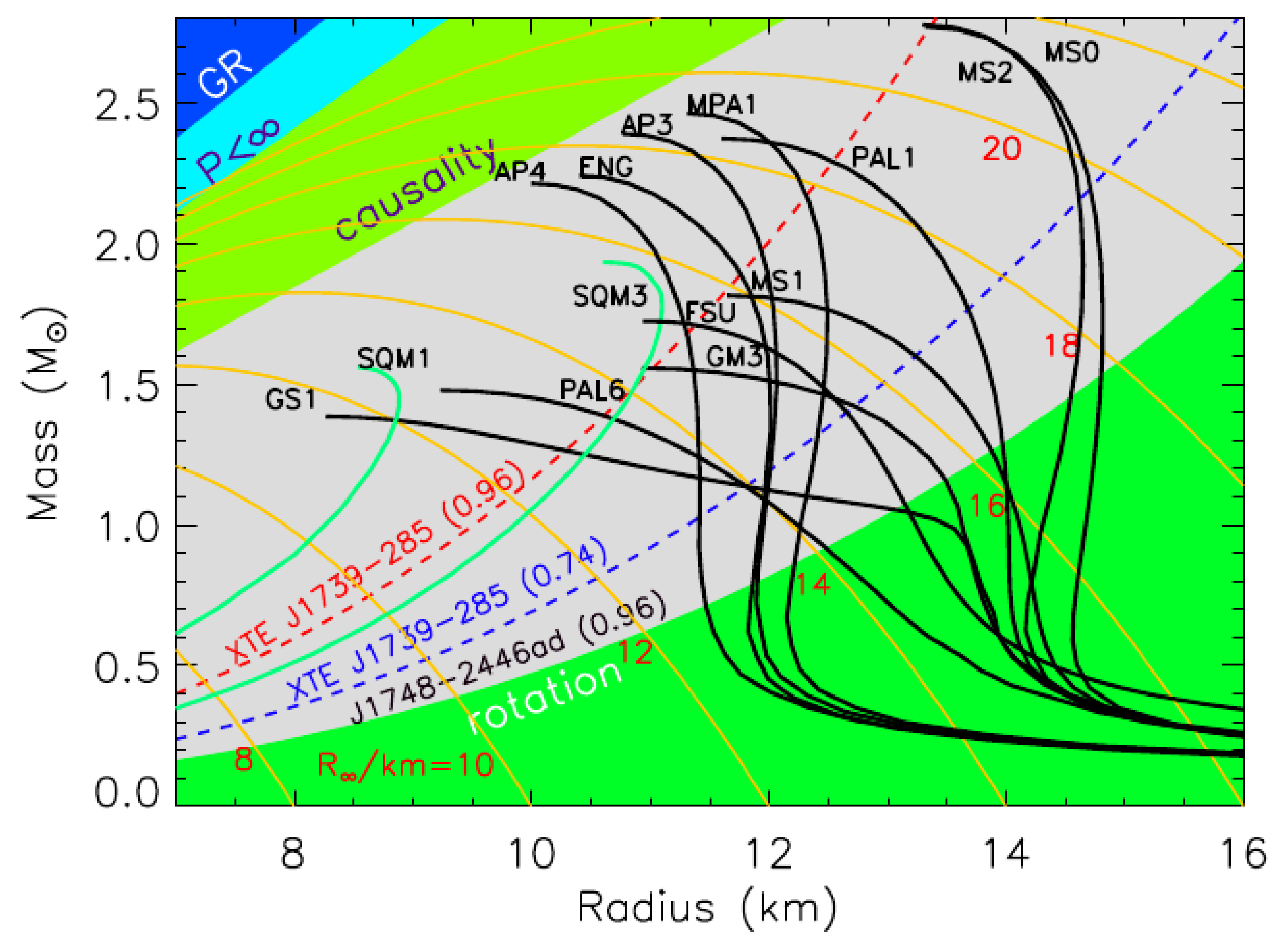
Measuring NS Masses with Radio Pulsars

Scott Ransom
National Radio Astronomy Observatory /
University of Virginia

NANOGrav

Why Measure NS Masses / Radii?

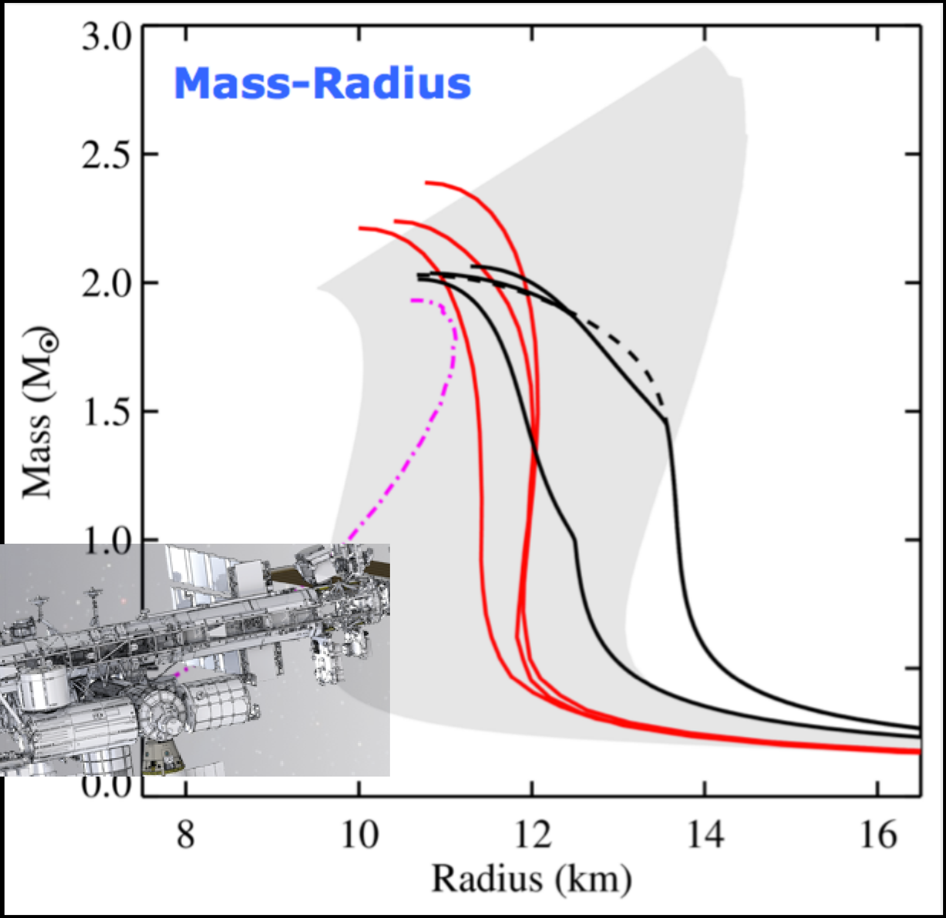
- The best observables to determine NS EOS
- Radio pulsars give masses, x-rays give radii



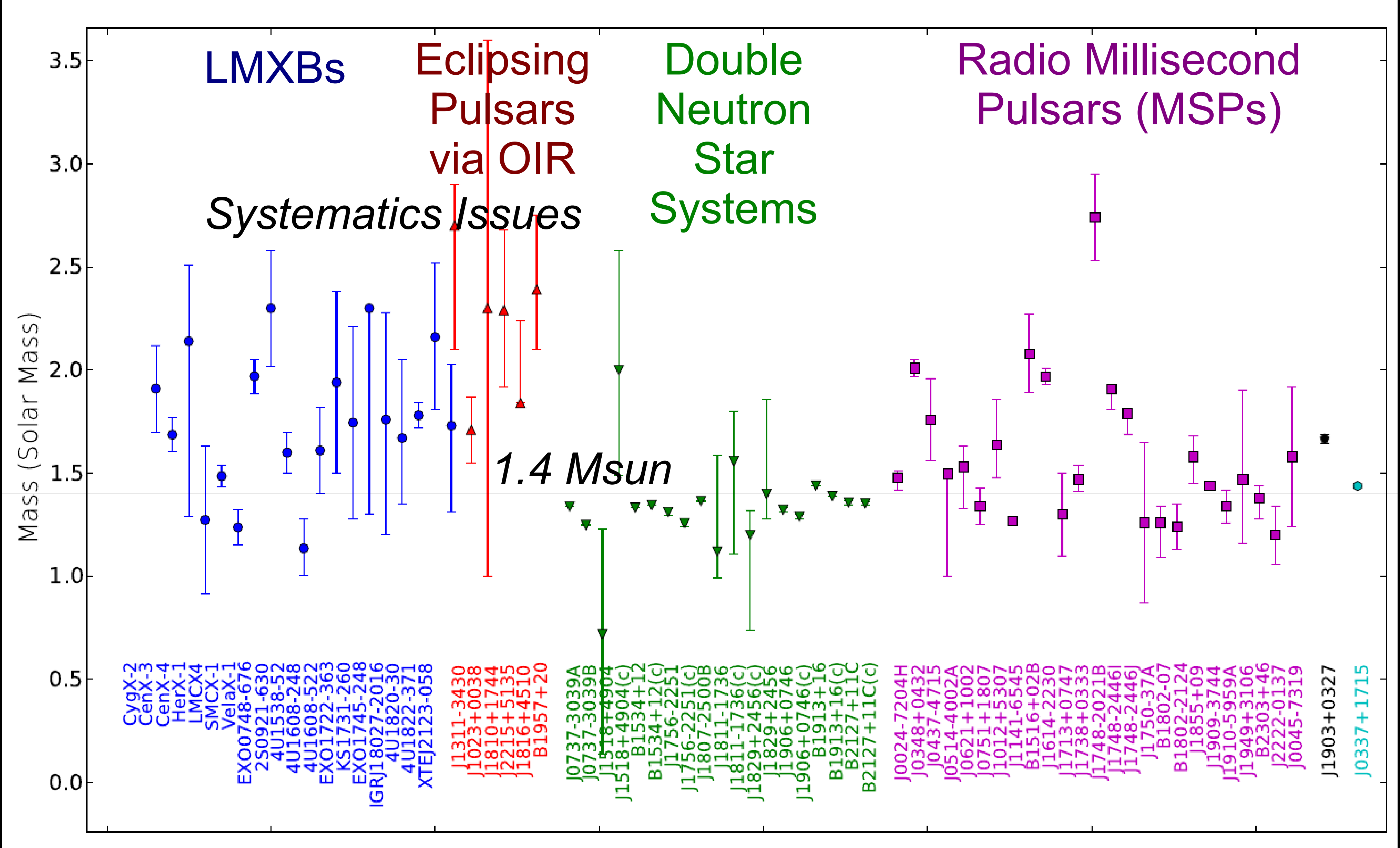
From Lattimer & Prakash 2007

How to determine the EOS?

- All neutron stars should live on the same EOS curve on the Mass-Radius diagram
- Optimally, measure M and R simultaneously
  - Can be done in x-rays, but many potential systematics, and may only give M/R
  - NASA's NICER (Neutron Star Composition Explorer) will fly on ISS in 2017

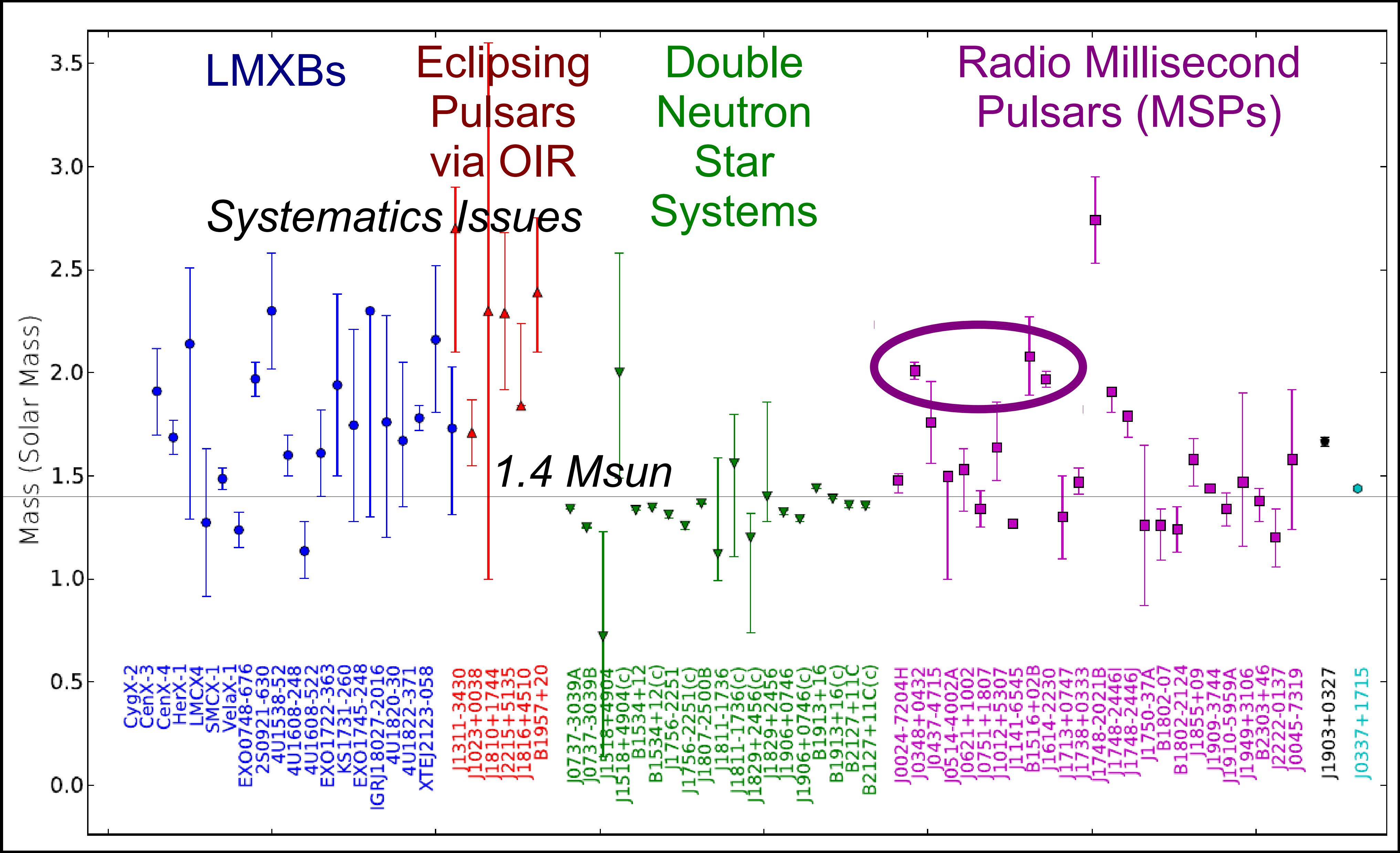


Pulsar Timing Can Give Precise Masses



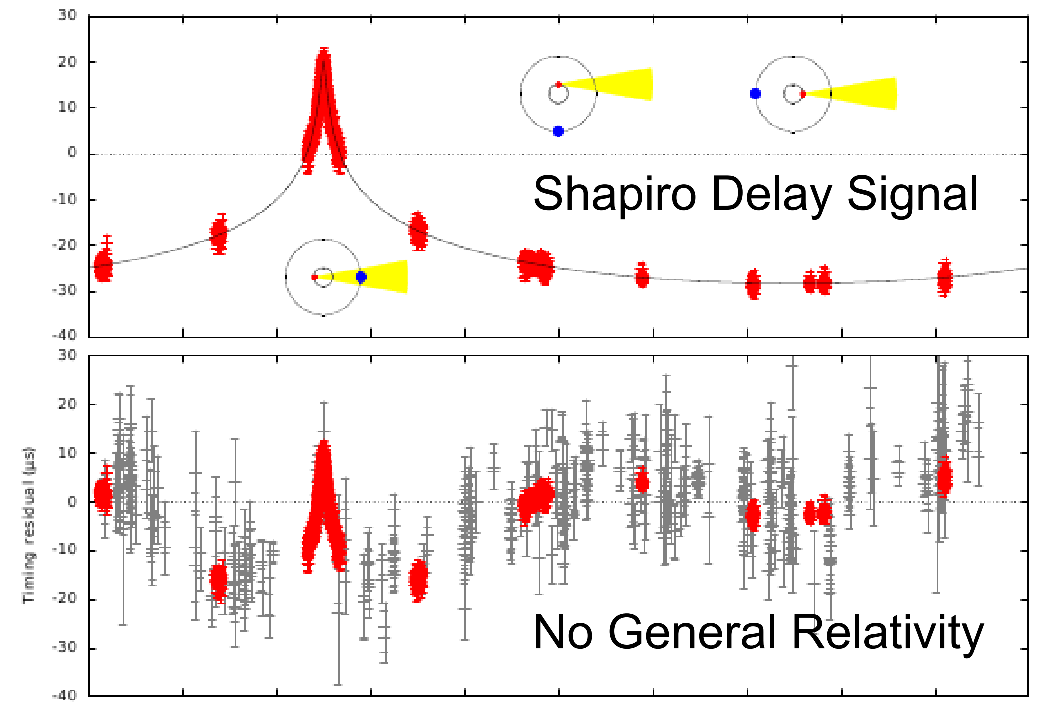
Watts et al. 2015

Pulsar Timing Can Give Precise Masses



Watts et al. 2015

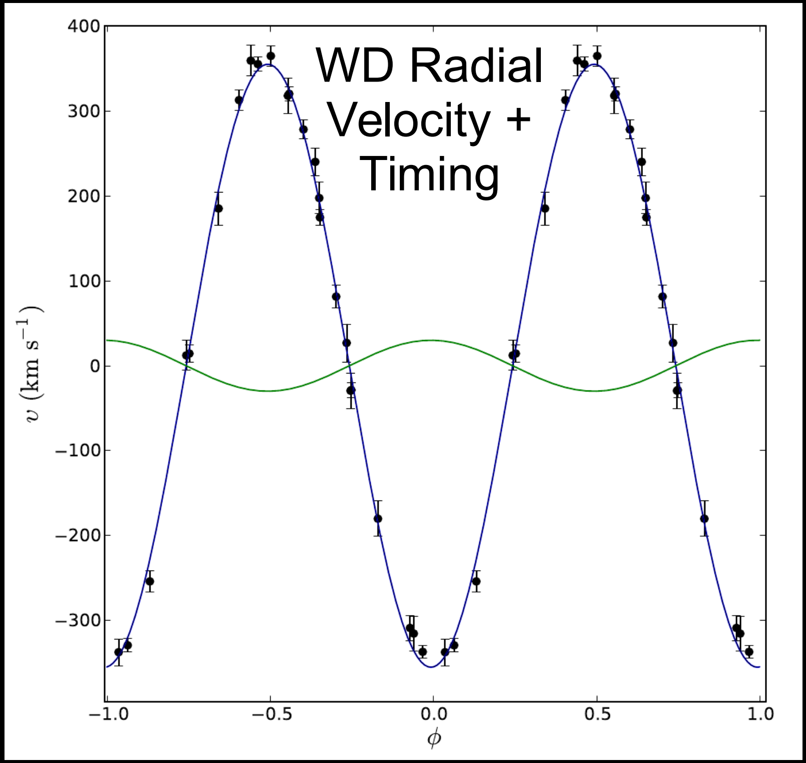
MSP J1614-2230



Mpsr = 1.97(4) M$_\odot$

Demorest et al. 2010,
Nature, 467, 1081D

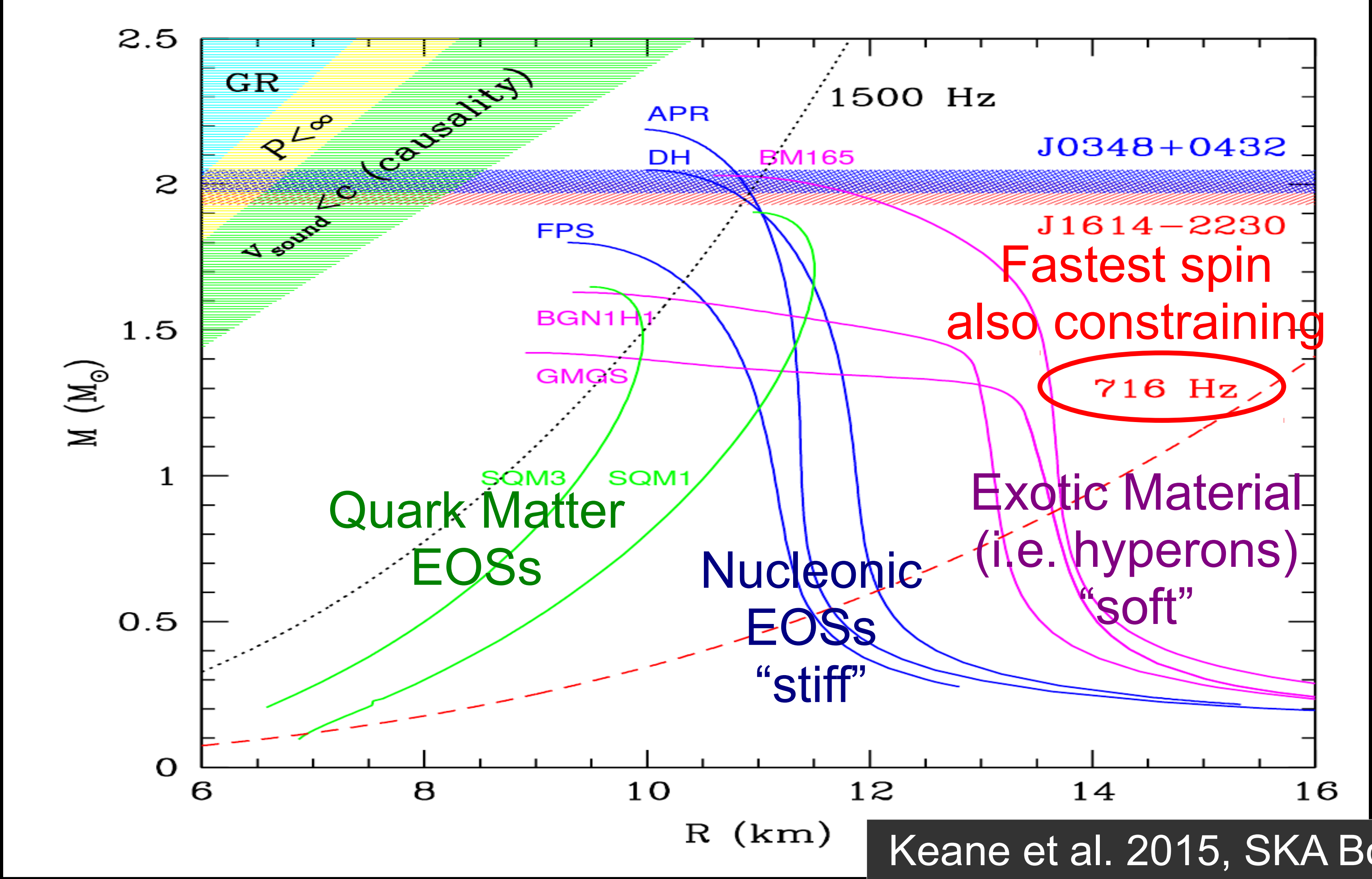
PSR J0348+0432



Mpsr = 2.01(4) M$_\odot$

Antoniadis et al 2013,
Science, 340, 448

- These 2 measurements are incredibly constraining since high-density nuclear physics becomes highly non-linear and uncertain as you go above 2 solar masses
- “hyperon puzzle” – exotics expected at these densities



Fastest spin also constraining

Quark Matter EOSs

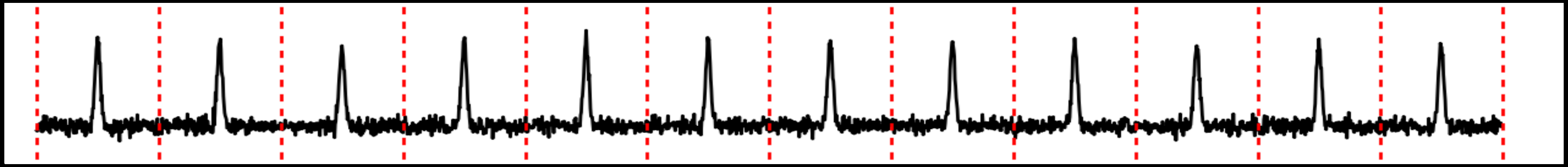
Nucleonic EOSs “stiff”

Exotic Material (i.e. hyperons) “soft”

Keane et al. 2015, SKA Book

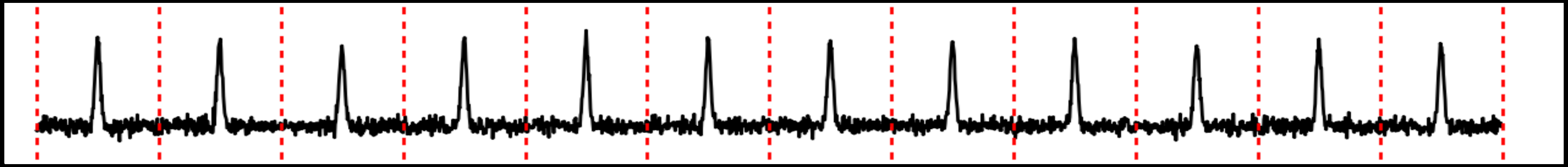
Pulsar Timing:

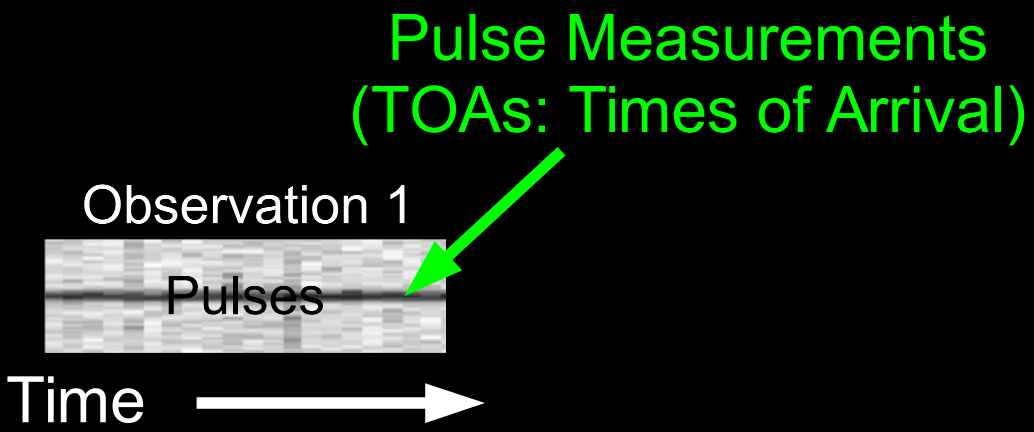
Unambiguously account for every rotation of a pulsar over years



Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years





Pulse Measurements
(TOAs: Times of Arrival)

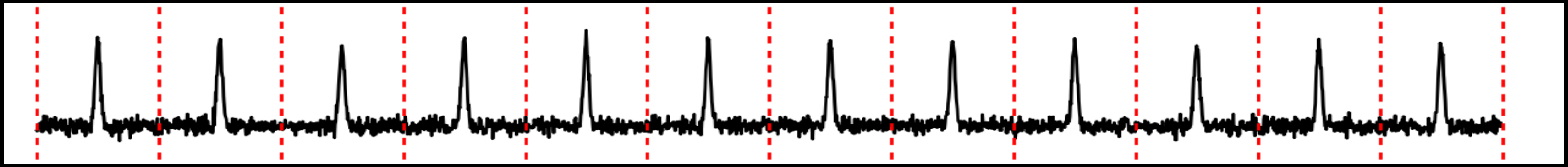
Observation 1

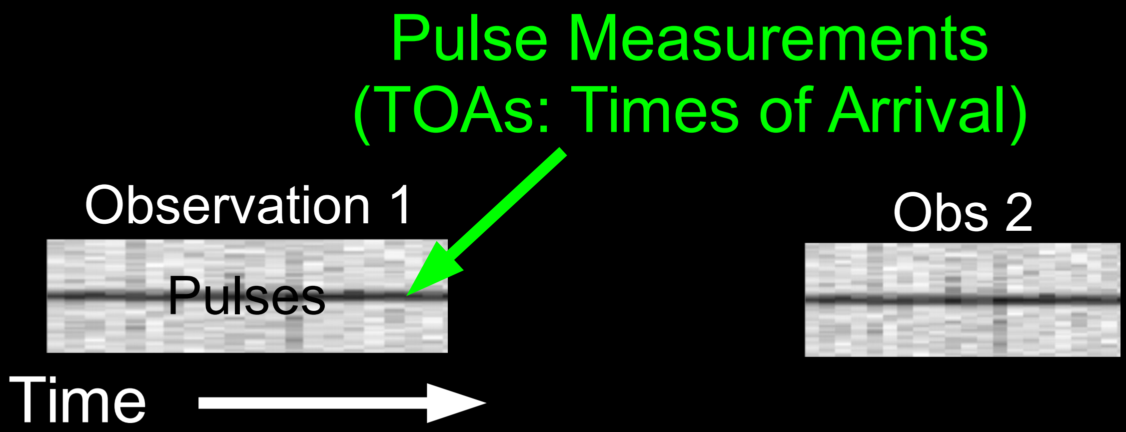
Pulses

Time

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years





Pulse Measurements
(TOAs: Times of Arrival)

Observation 1

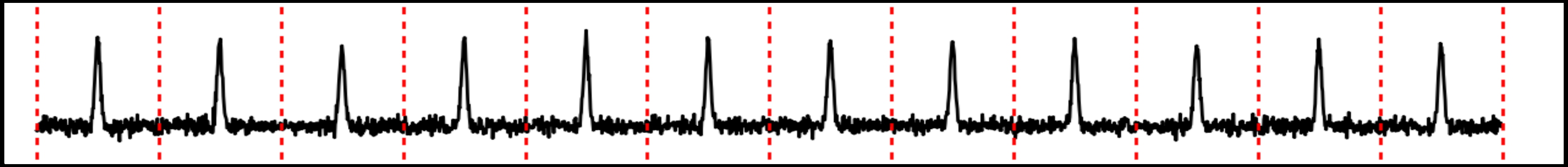
Pulses

Obs 2

Time

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



Pulse Measurements
(TOAs: Times of Arrival)

Observation 1

Pulses

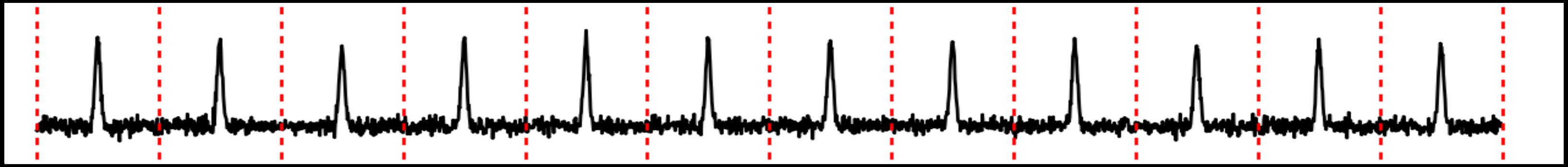
Obs 2

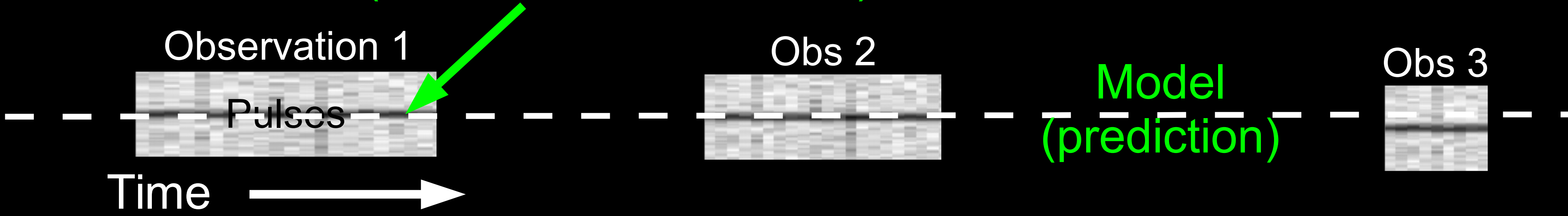
Model
(prediction)

Time

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years





Pulse Measurements
(TOAs: Times of Arrival)

Observation 1

Pulses

Obs 2

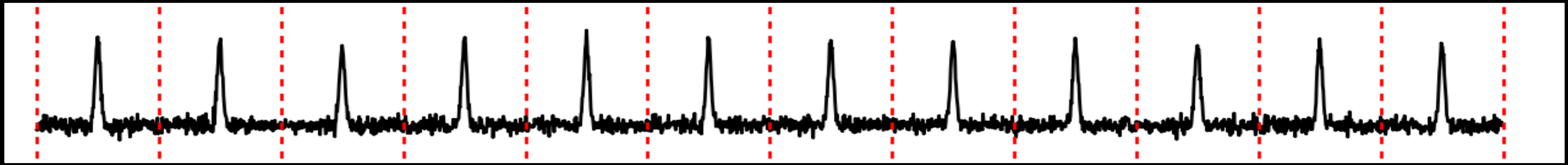
Model
(prediction)

Obs 3

Time

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



Pulse Measurements
(TOAs: Times of Arrival)

Observation 1

Pulses

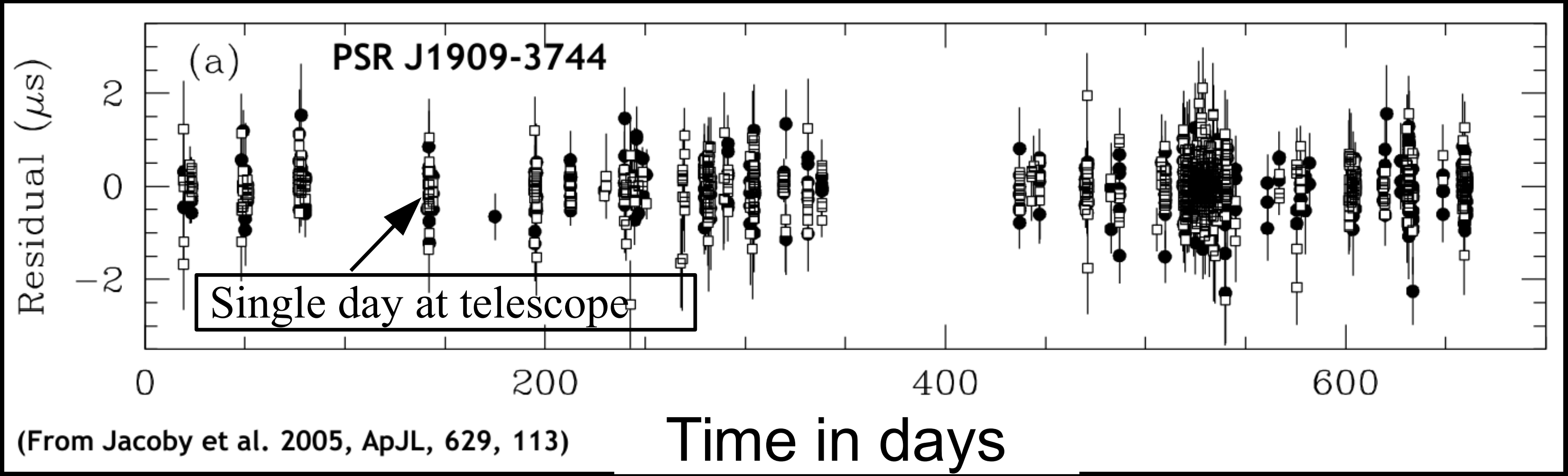
Obs 2

Model
(prediction)

Obs 3

Time

Measurement - Model = Timing Residuals



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

Predict each pulse to ~200 ns over 2 yrs!

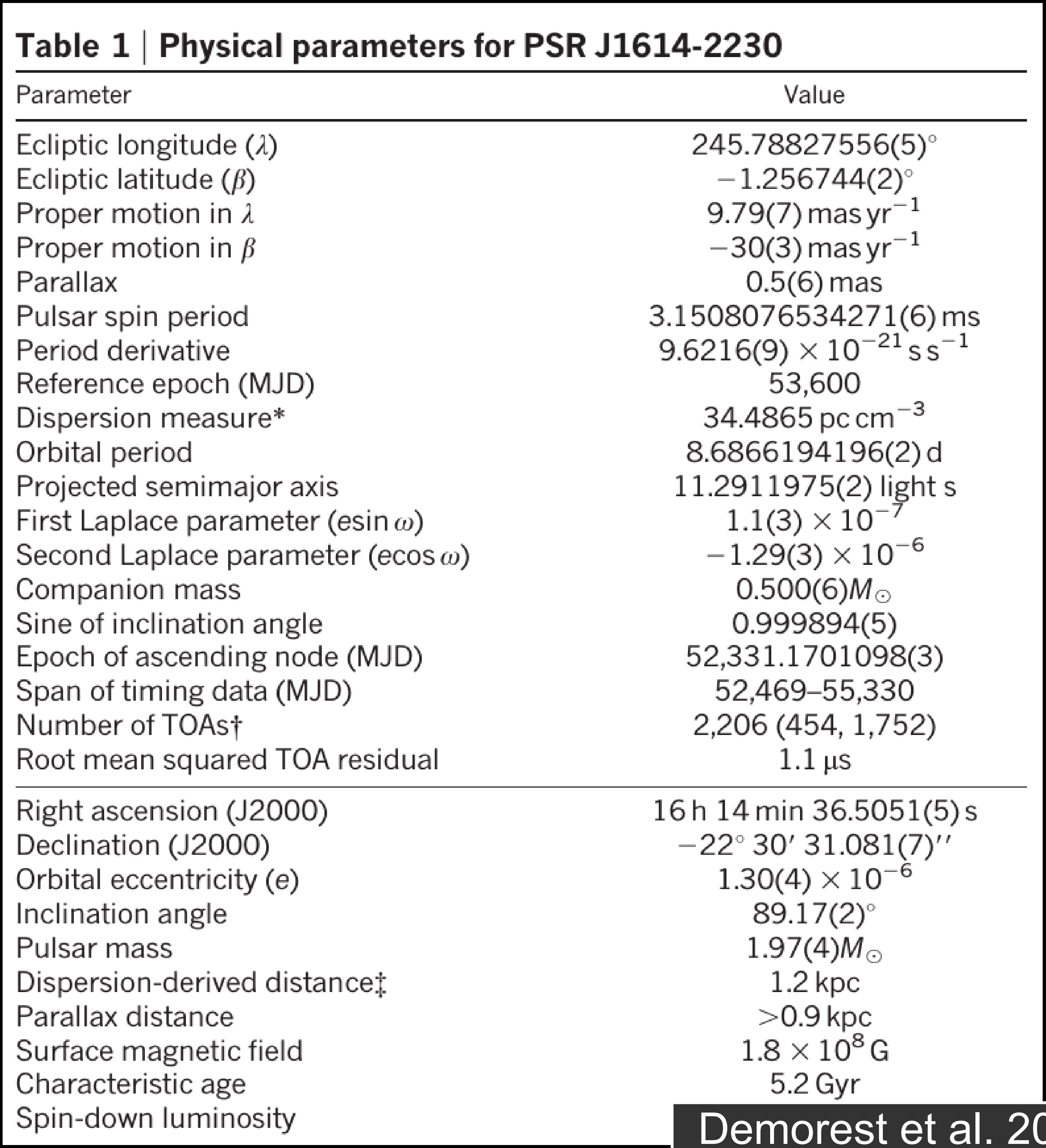


Table 1 | Physical parameters for PSR J1614-2230

Parameter	Value
Ecliptic longitude (λ)	245.78827556(5)°
Ecliptic latitude (β)	$-1.256744(2)^\circ$
Proper motion in λ	9.79(7) mas yr^{-1}
Proper motion in β	$-30(3)$ mas yr^{-1}
Parallax	0.5(6) mas
Pulsar spin period	3.1508076534271(6) ms
Period derivative	$9.6216(9) \times 10^{-21}\ \mathrm{s\,s}^{-1}$
Reference epoch (MJD)	53,600
Dispersion measure*	34.4865 pc cm^{-3}
Orbital period	8.6866194196(2) d
Projected semimajor axis	11.2911975(2) light s
First Laplace parameter ($e\sin\omega$)	$1.1(3) \times 10^{-7}$
Second Laplace parameter ($e\cos\omega$)	$-1.29(3) \times 10^{-6}$
Companion mass	$0.500(6) M_\odot$
Sine of inclination angle	0.999894(5)
Epoch of ascending node (MJD)	52,331.1701098(3)
Span of timing data (MJD)	52,469–55,330
Number of TOAs†	2,206 (454, 1,752)
Root mean squared TOA residual	1.1 μs
Right ascension (J2000)	16 h 14 min 36.5051(5) s
Declination (J2000)	$-22^\circ\ 30'\ 31.081(7)''$
Orbital eccentricity (e)	$1.30(4) \times 10^{-6}$
Inclination angle	89.17(2)°
Pulsar mass	$1.97(4) M_\odot$
Dispersion-derived distance‡	1.2 kpc
Parallax distance	>0.9 kpc
Surface magnetic field	1.8×10^8 G
Characteristic age	5.2 Gyr
Spin-down luminosity	

Demorest et al. 2010, *Nature*

Post-Keplerian Orbital Parameters

Besides the normal 5 “Keplerian” parameters (P_{orb}, e, *asin*(*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)

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

$$r = T_\odot m_2$$

(Shapiro delay: “range” and “shape”)

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

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

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Post-Keplerian Orbital Parameters

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

$\dot{\omega} =$ (Orbital Precession)

Need eccentric orbit and time for precession

$\gamma =$ (Grav redshift + time dilation)

$\dot{P}_b =$ Need compact orbit and a lot of patience

$r =$

$s =$

Need high precision, Inclination, and m_2

(Shapiro delay: “range” and “shape”)

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

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
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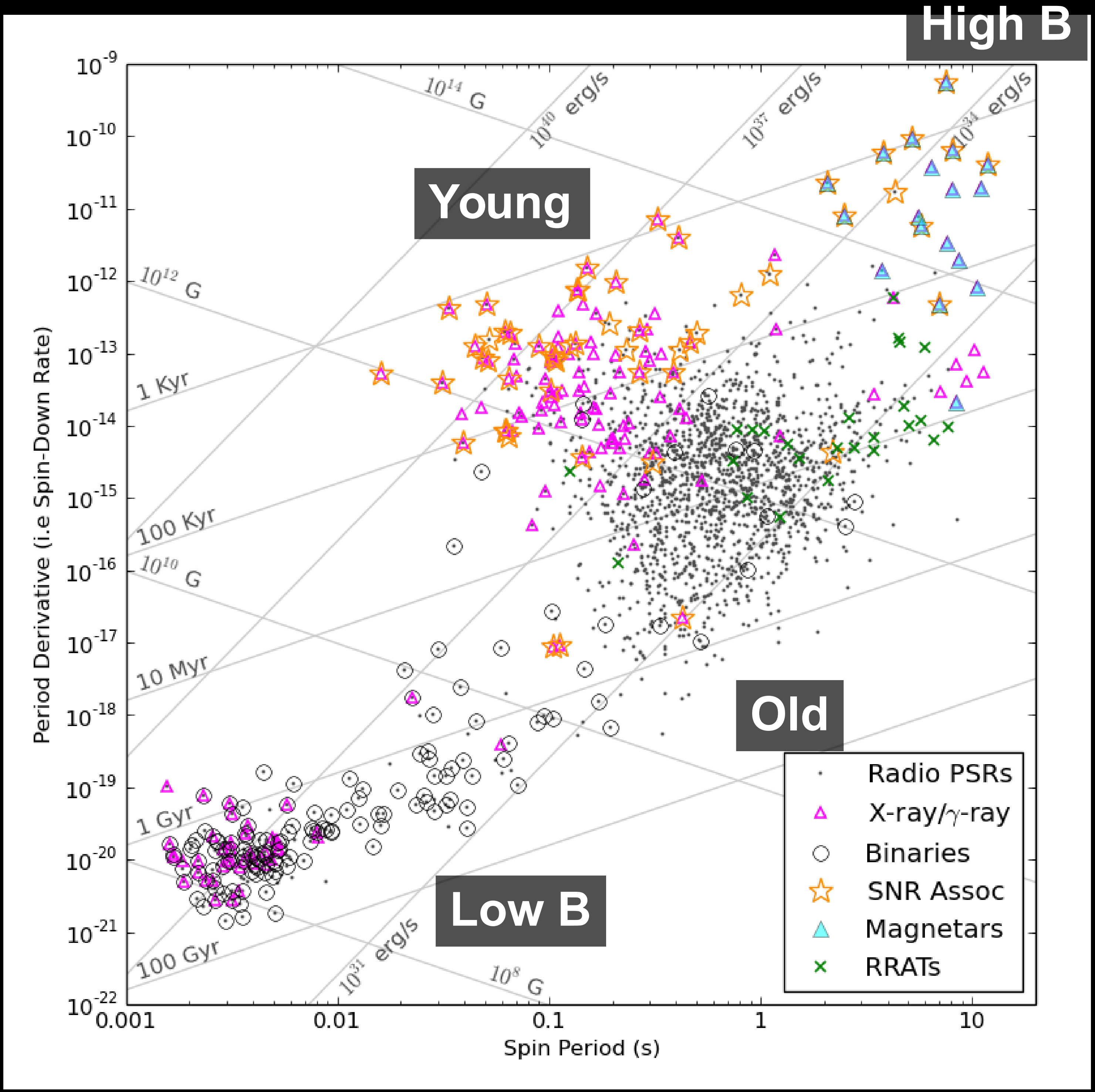
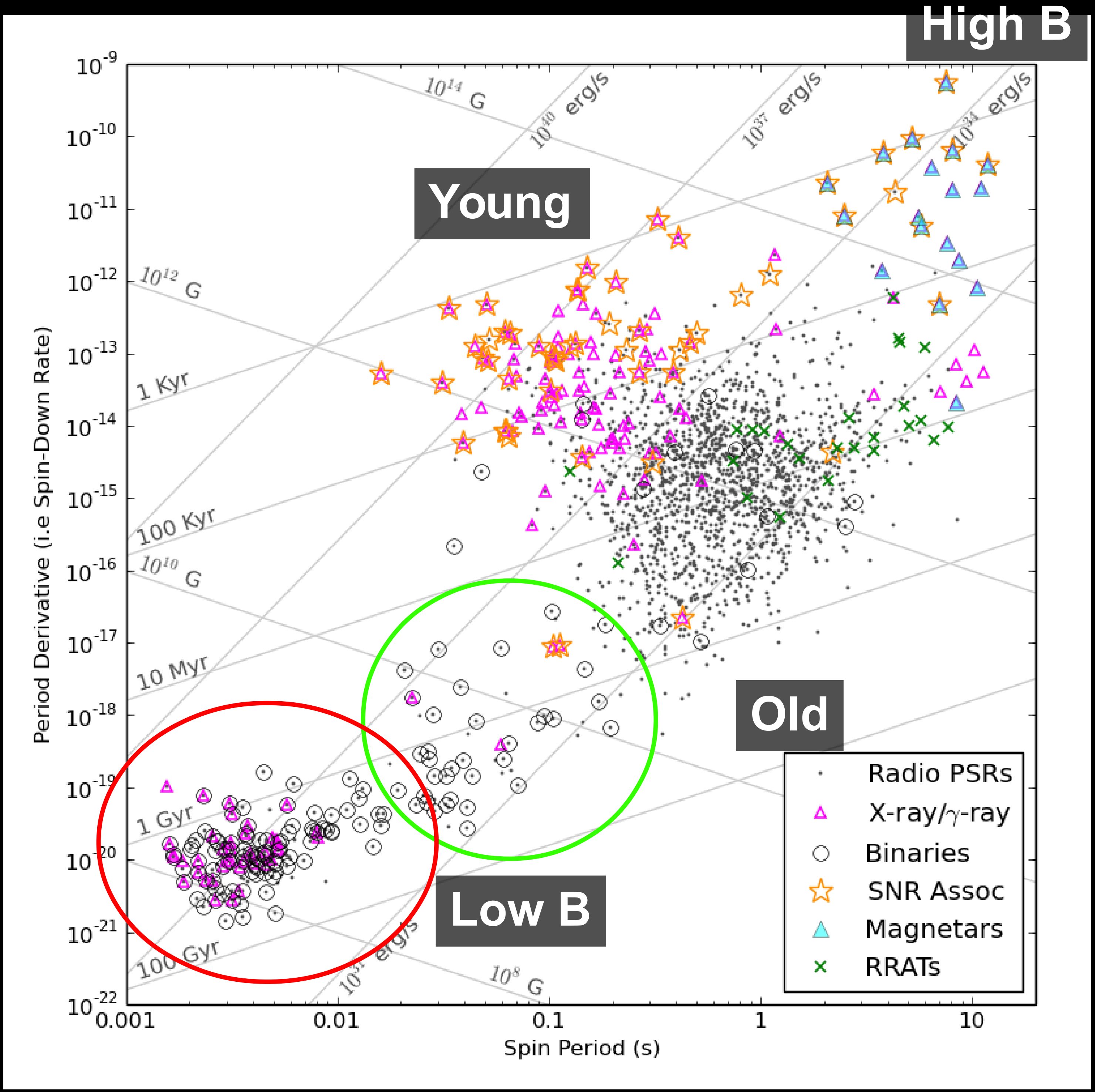
Pulsar Flavors



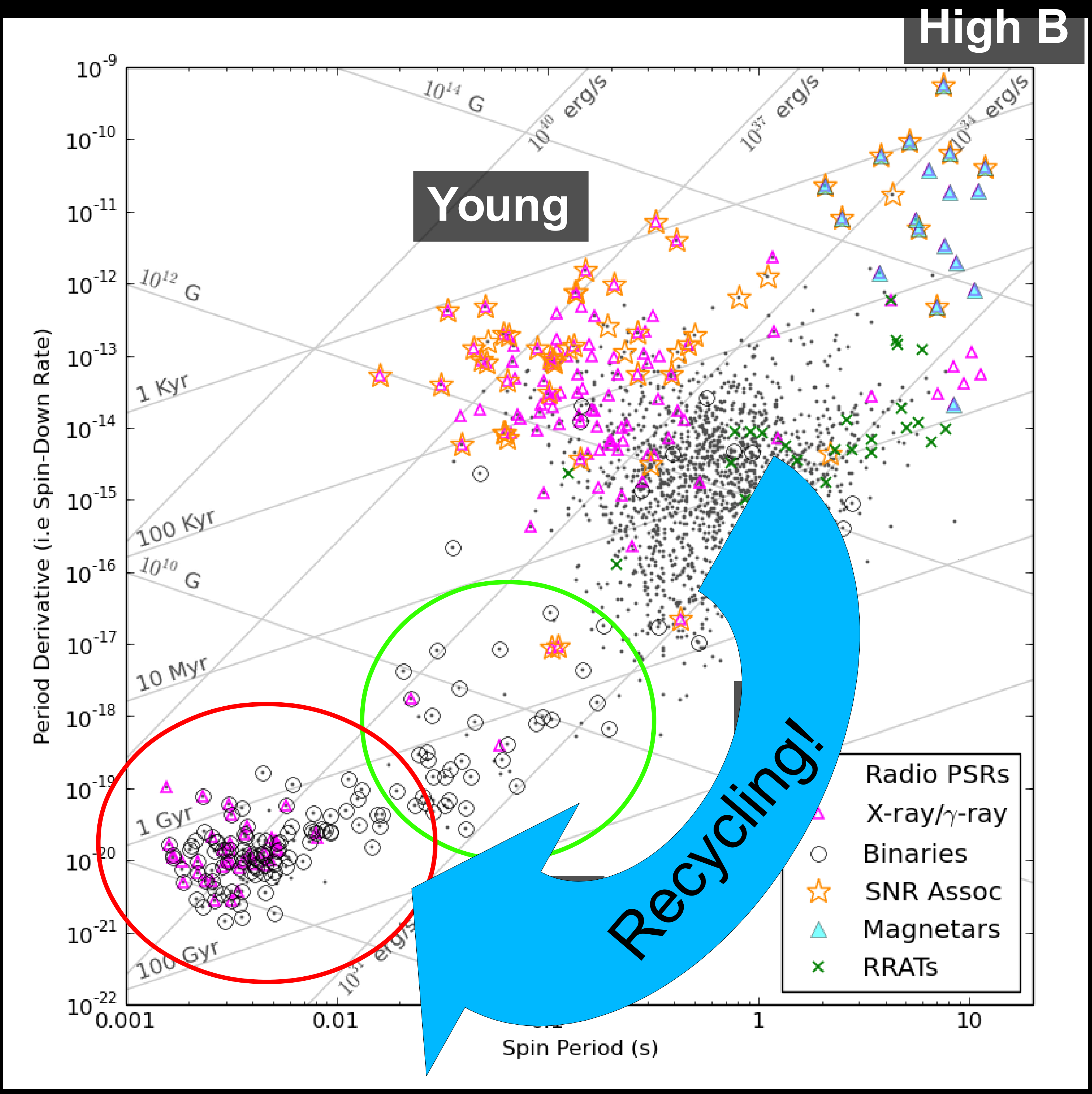
Pulsar Flavors



Double NSs
(mildly recycled, eccentric orbits)

Millisecond
(low B, very fast, very stable, WD companions, circular orbits)

Pulsar Flavors



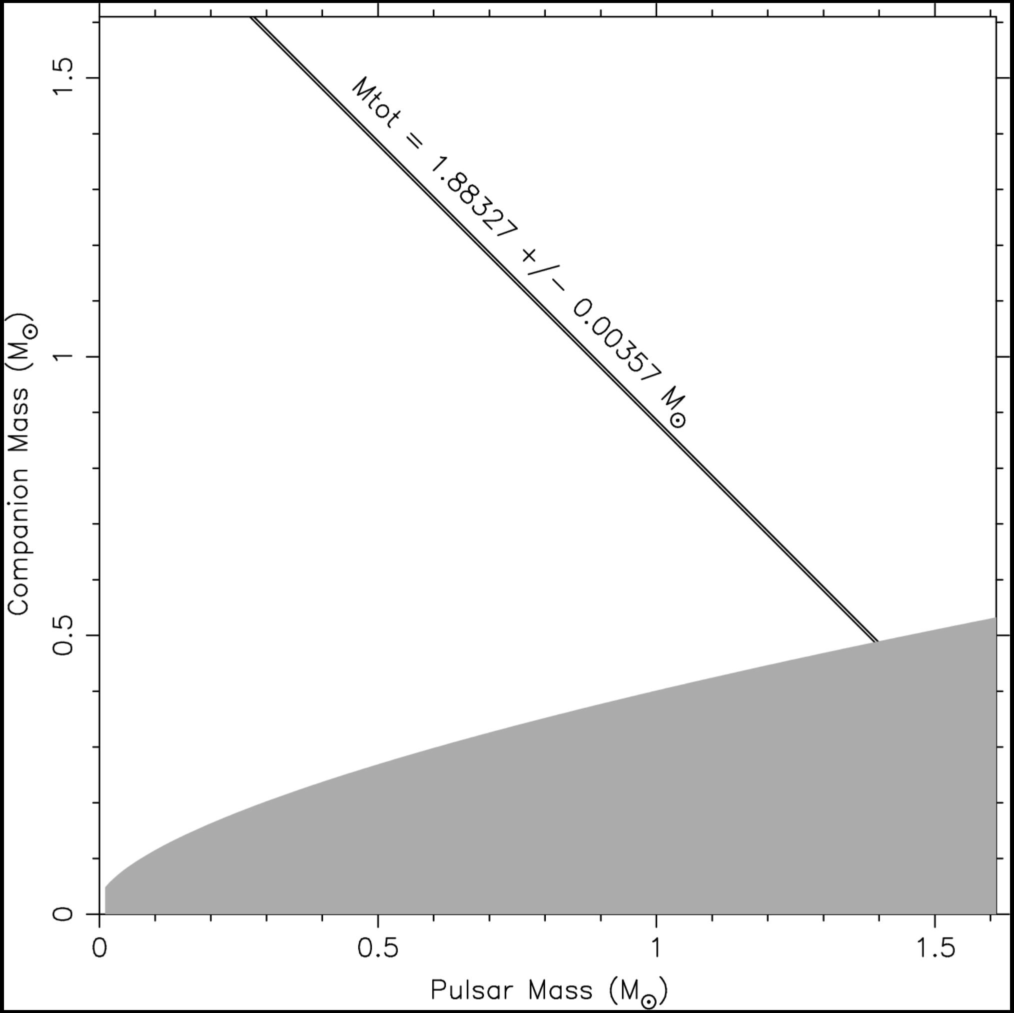
Double NSs
(mildly recycled, eccentric orbits)

Millisecond
(low B, very fast, very stable, WD companions, circular orbits)

Precession of Periastron

- Gives total system mass
- Mercury is 42”/century

  >16º/yr for double PSR
- DNS systems are deg/yr
- Need eccentric system
- “Easy” to measure
- *If* orbits are random, distribution is flat in cos(i)
- Possible (unlikely?) classical contributions (i.e. rotating WD, tidal effects)

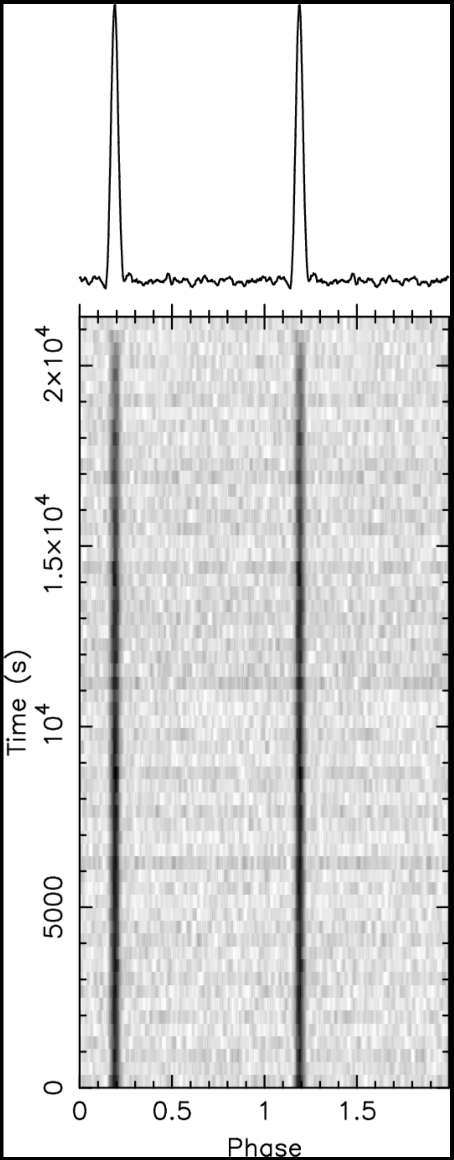


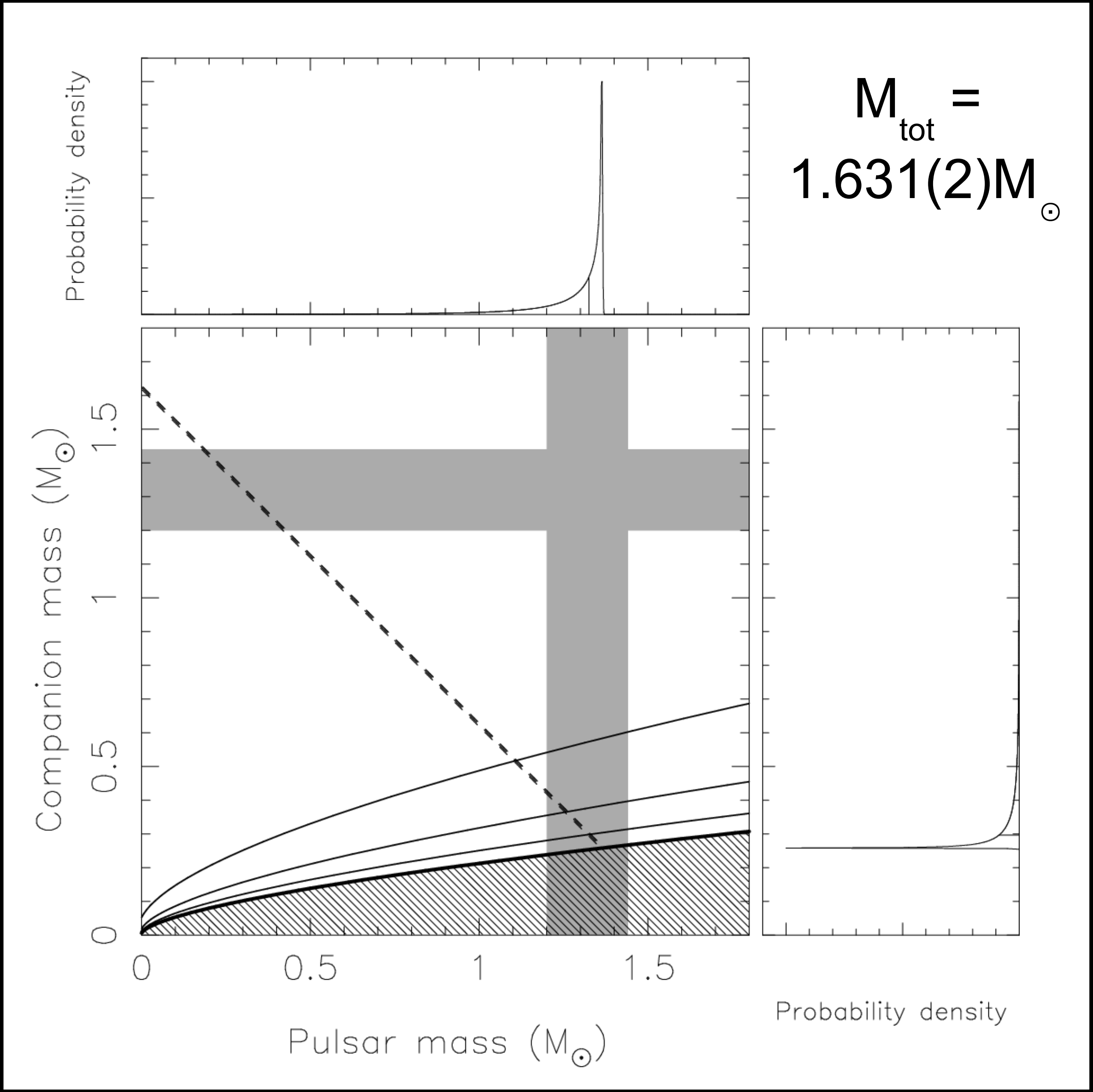
From new MSP Terzan5ai

Pulsars in Globular Clusters

- Clusters of ancient stars (9-12 billion years old) that orbit our galaxy
- Contain 10^5-10^6 stars, many of which have binary companions
- Very high central densities (100-10,000 stars/ly^3) result in stellar encounters and collisions!
- They are effectively millisecond pulsar factories (and strange ones at that!)
- Number known has quadrupled since 2000 (over 140 known now)

M28C





M_{tot} = $1.631(2) M_\odot$

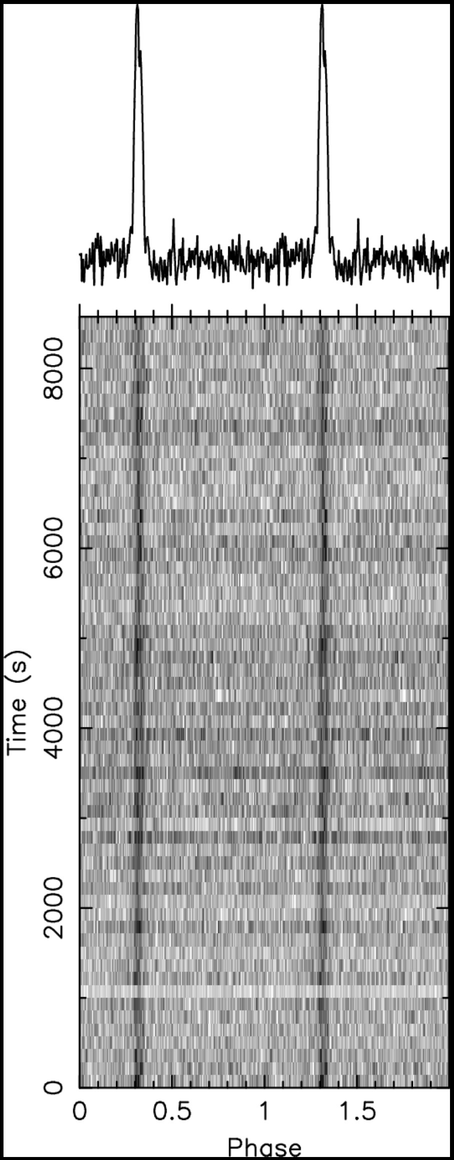
Highly eccentric (e=0.847)

P_{psr} ~ 4.158 ms

P_{orb} = 8.07 days

~5μs timing in ~5min

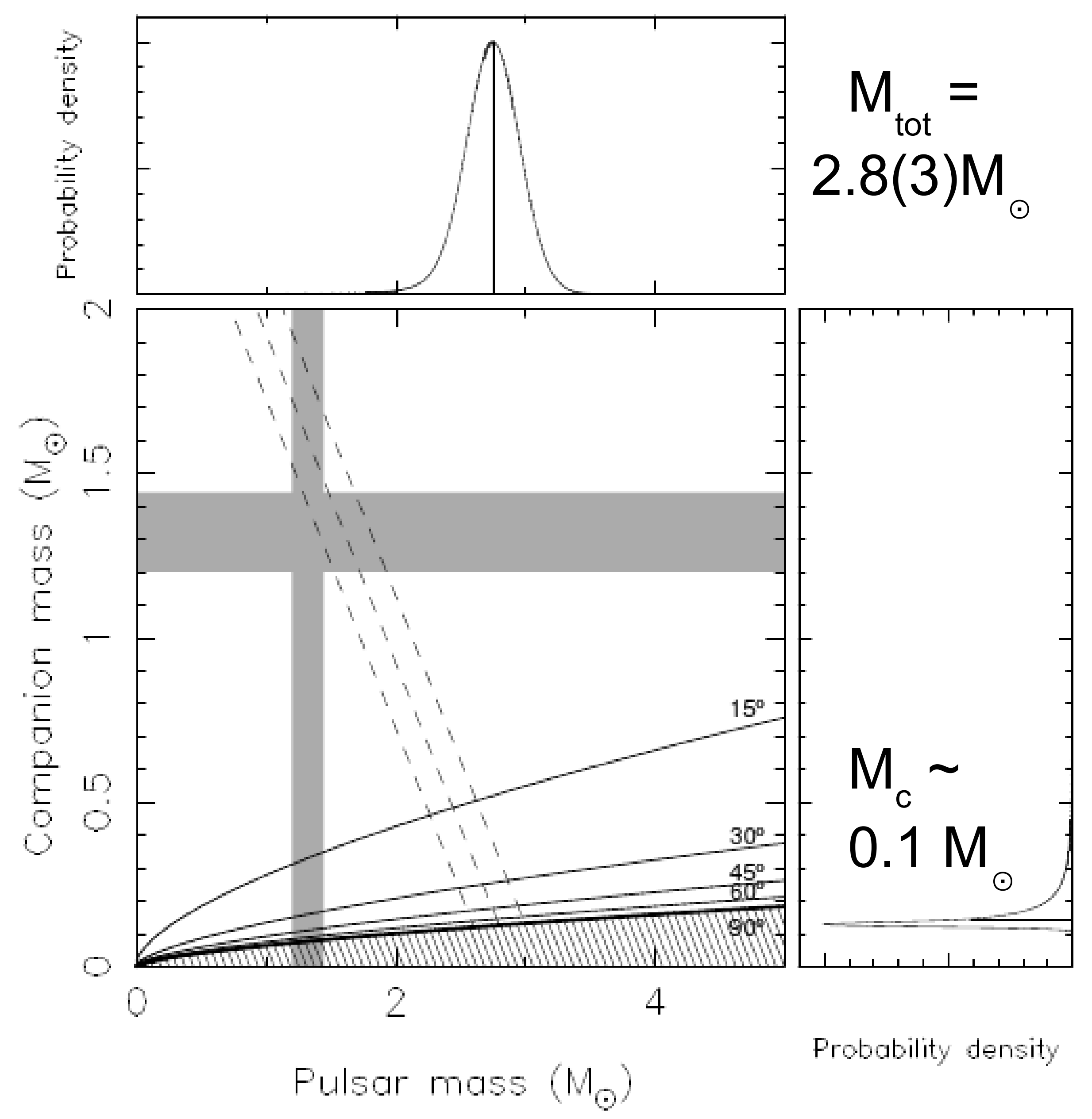
NGC6440B: A Massive PSR?



Highly eccentric (e=0.570)

P_{psr} ~ 16.76 ms

P_{orb} = 20.6 days



M_{tot} = 2.8(3)$M_\odot$

M_c ~ 0.1 $M_\odot$

Freire et al. 2008, ApJ, 675, 670

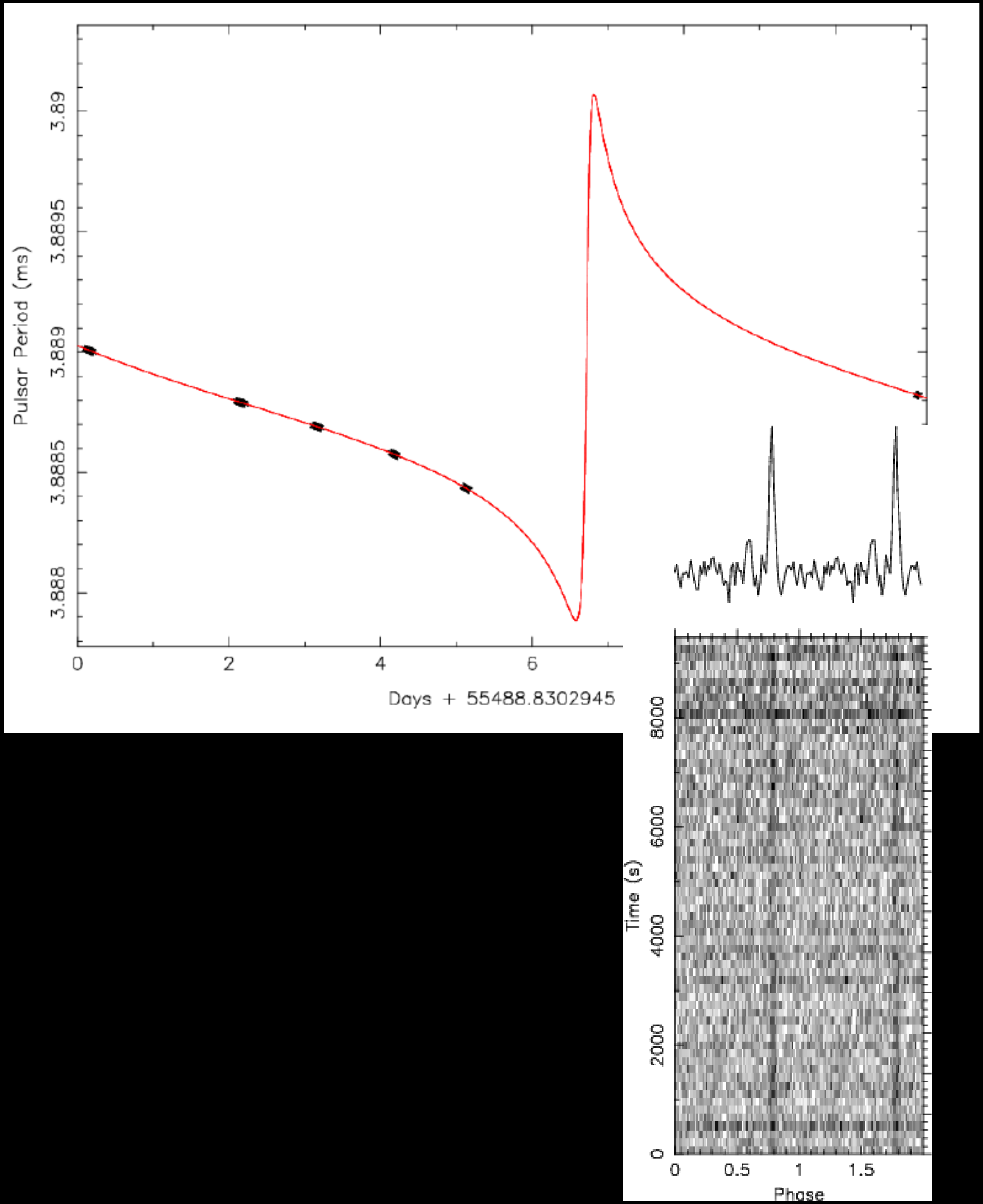
Precession in 15+ PSRs in Clusters

Name	P(ms)	Pb(d)	E	Mcmin	Mtot	Mpmed
Ter5ai	21.228	0.85	0.440	0.49	**1.887(1)**	**1.32**
Ter5J	80.338	1.10	0.350	0.34	**2.205(3)**	**1.74**
Ter5I	9.570	1.33	0.428	0.21	**2.1660(5)**	**1.87**
Ter5Z	2.463	3.49	0.761	0.22	**1.743(3)**	**1.48**
Ter5U	3.289	3.57	0.605	0.39	**2.246(2)**	**1.73**
Ter5W	4.205	4.88	0.016	0.25	**2.09(7)**	**1.69**
Ter5X	2.999	5.00	0.302	0.25	**1.92(1)**	**1.60**
M5B	7.947	6.85	0.138	0.13	**2.3(1)**	**2.12**
M28C	4.158	8.08	0.847	0.26	**1.631(1)**	**1.33**
NGC6544B	4.186	9.96	0.747	1.22	**2.567(2)**	**1.17**
NGC6441A	111.601	17.33	0.712	0.59	**2.0(2)**	**1.35**
NGC1851A	4.991	18.79	0.888	0.92	**2.44(5)**	**1.34**
NGC6440B	16.760	20.55	0.570	0.08	**2.8(3)**	**2.68**
Ter5Q	2.812	30.30	0.722	0.46	**2.422(9)**	**1.79**
M28D	79.835	30.41	0.776	0.38	**1.2(7)**	

SMR, PCCF, Freire et al 2007, 2008a+b, Lynch et al 2011

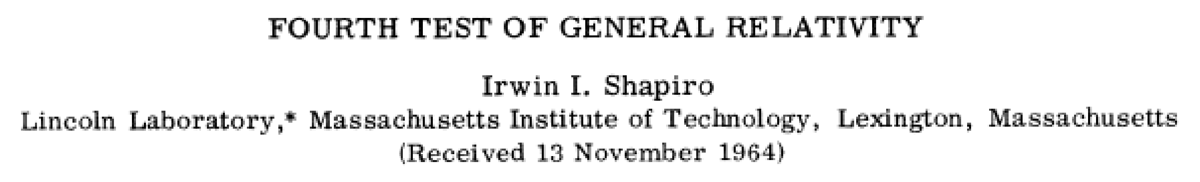
NGC6652A: new eccentric binary

- Cluster is a Fermi gamma-ray source: likely undetected MSPs
- Megan DeCesar (with Paul Ray and SMR) observed cluster with GBT
- Found 1 pulsar:
  - 3.89 ms
  - DM = 63 pc/cm^3 (low)
  - Unknown binary
- Initial timing solution shows eccen = 0.95!



Shapiro Delay

VOLUME 13, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1964

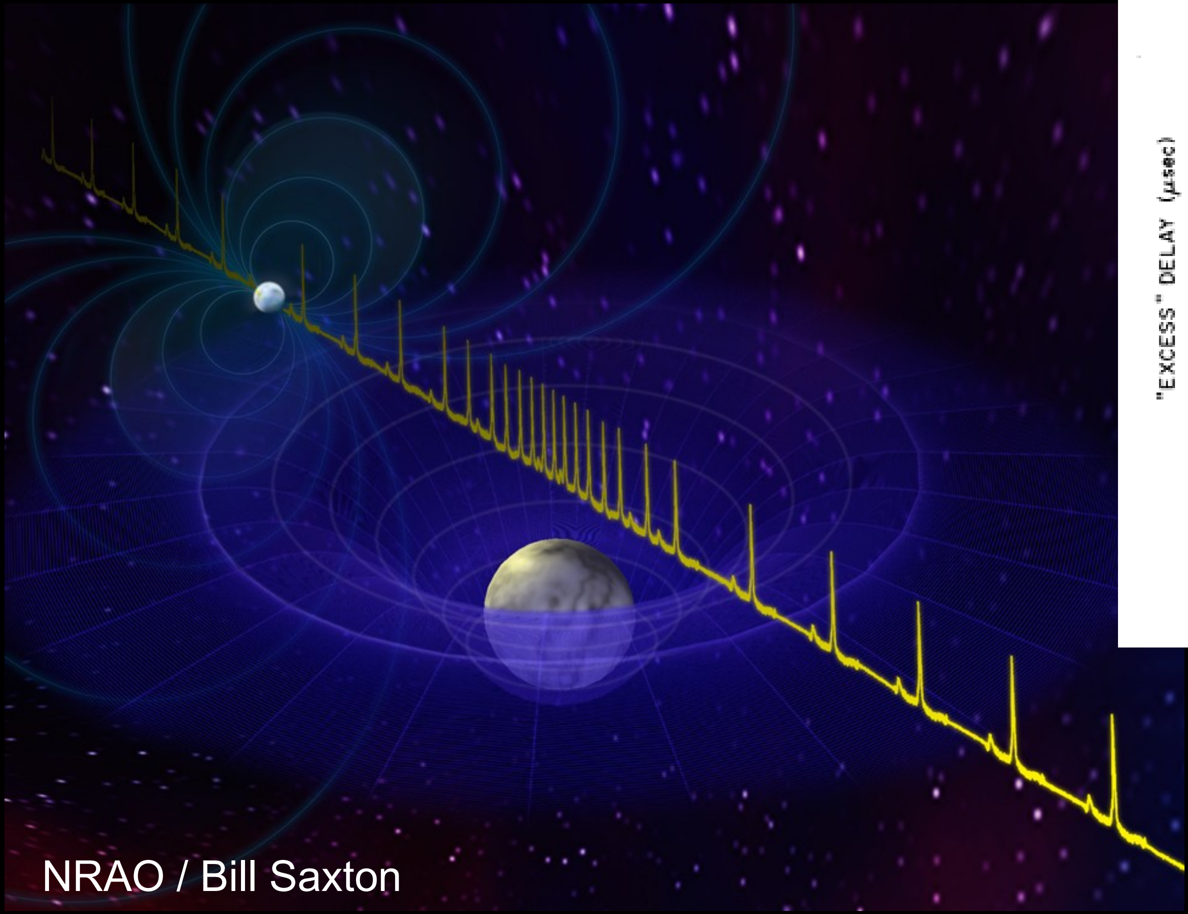


FOURTH TEST OF GENERAL RELATIVITY

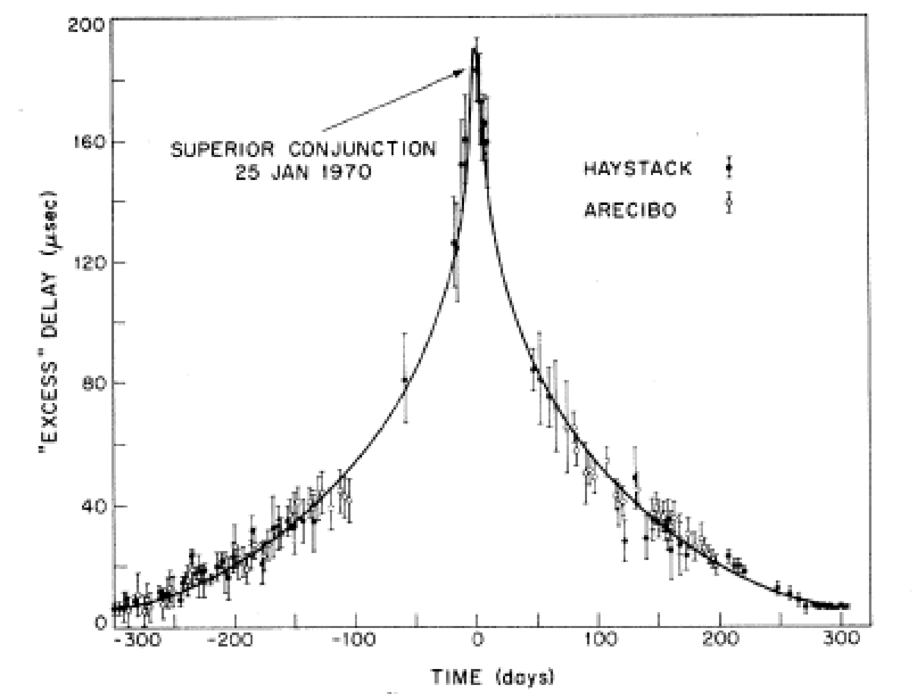
Irwin I. Shapiro

Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts

(Received 13 November 1964)



NRAO / Bill Saxton



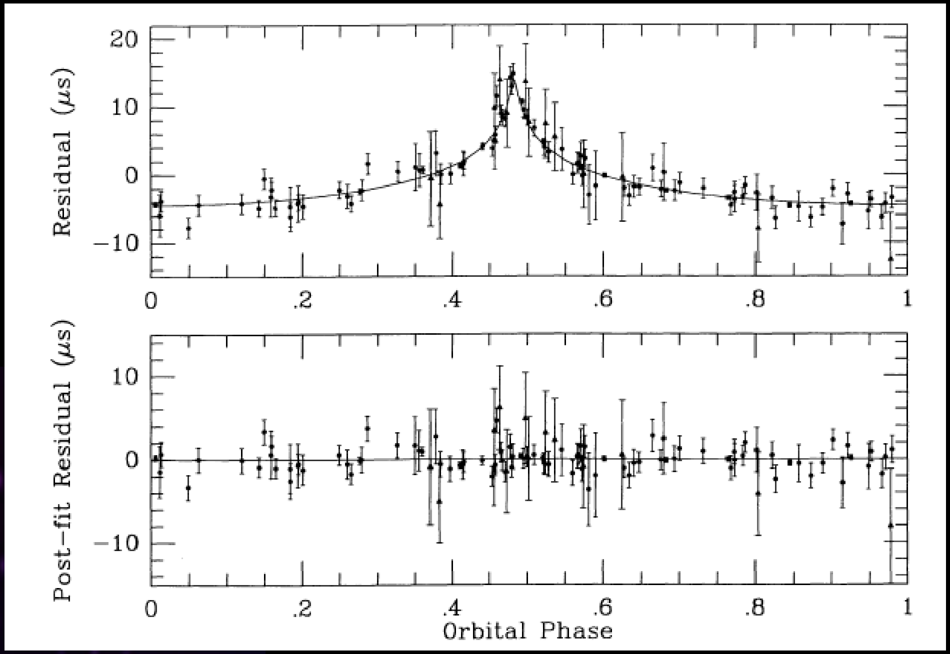
Irwin Shapiro 1964

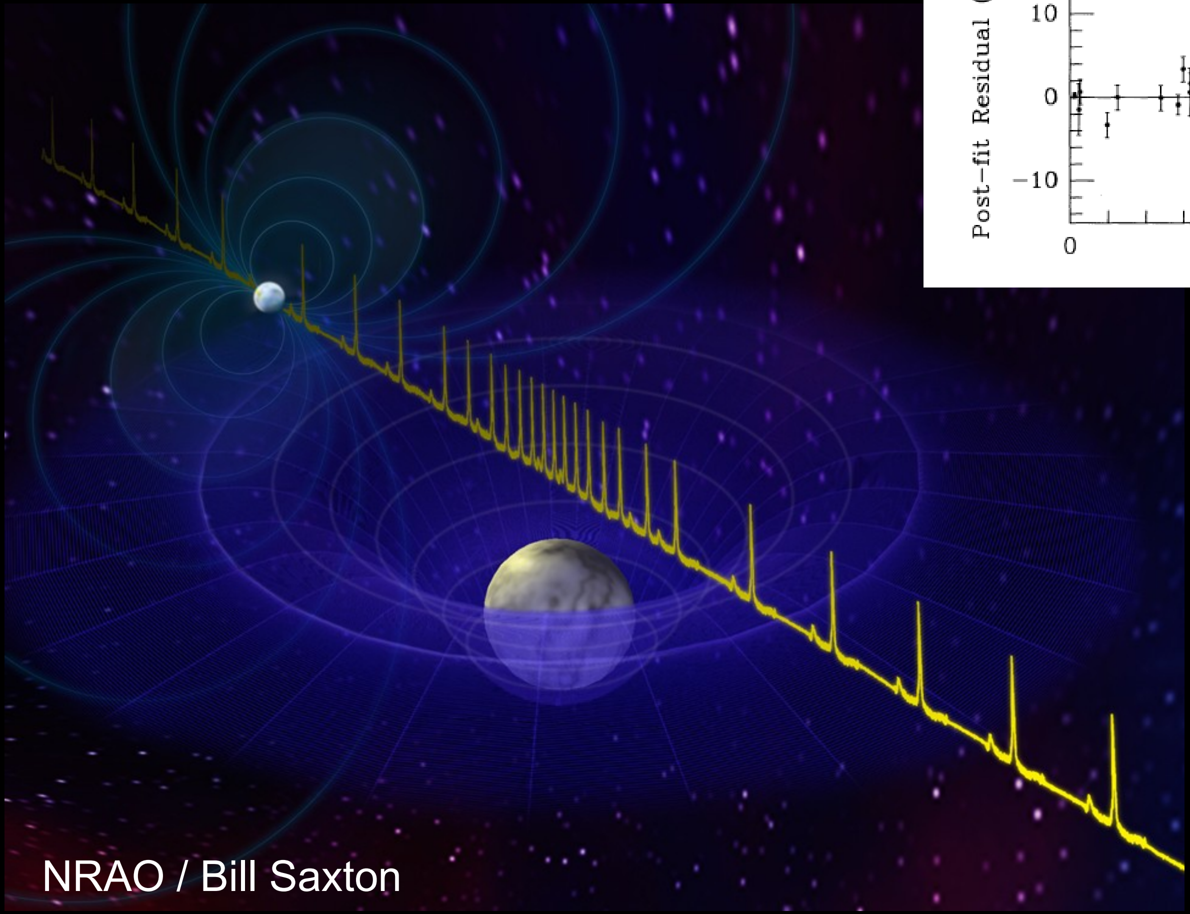
Shapiro et al. 1968, 1971

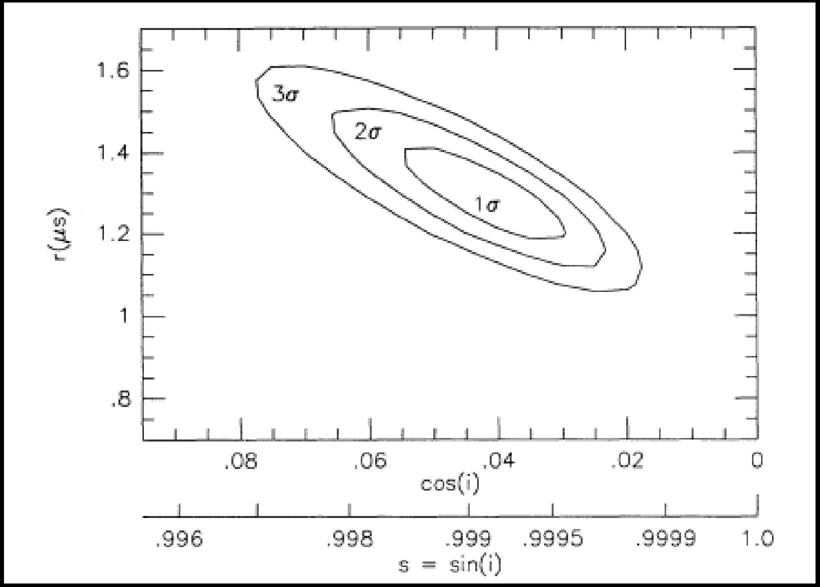
Shapiro Delay with a MSP

MSP B1855+09

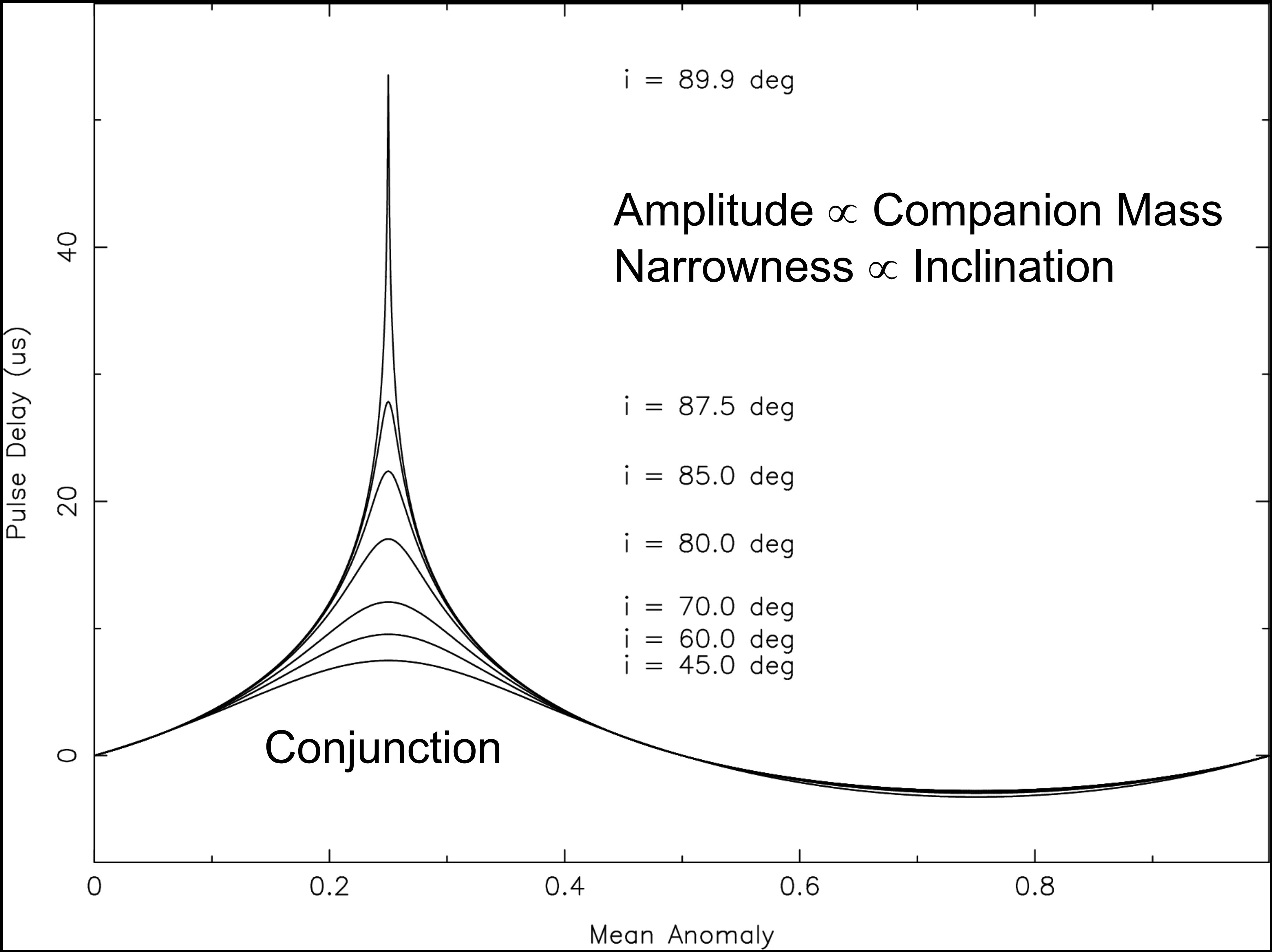
Ryba & Taylor 1991
Kaspi, Ryba & Taylor 1994




NRAO / Bill Saxton

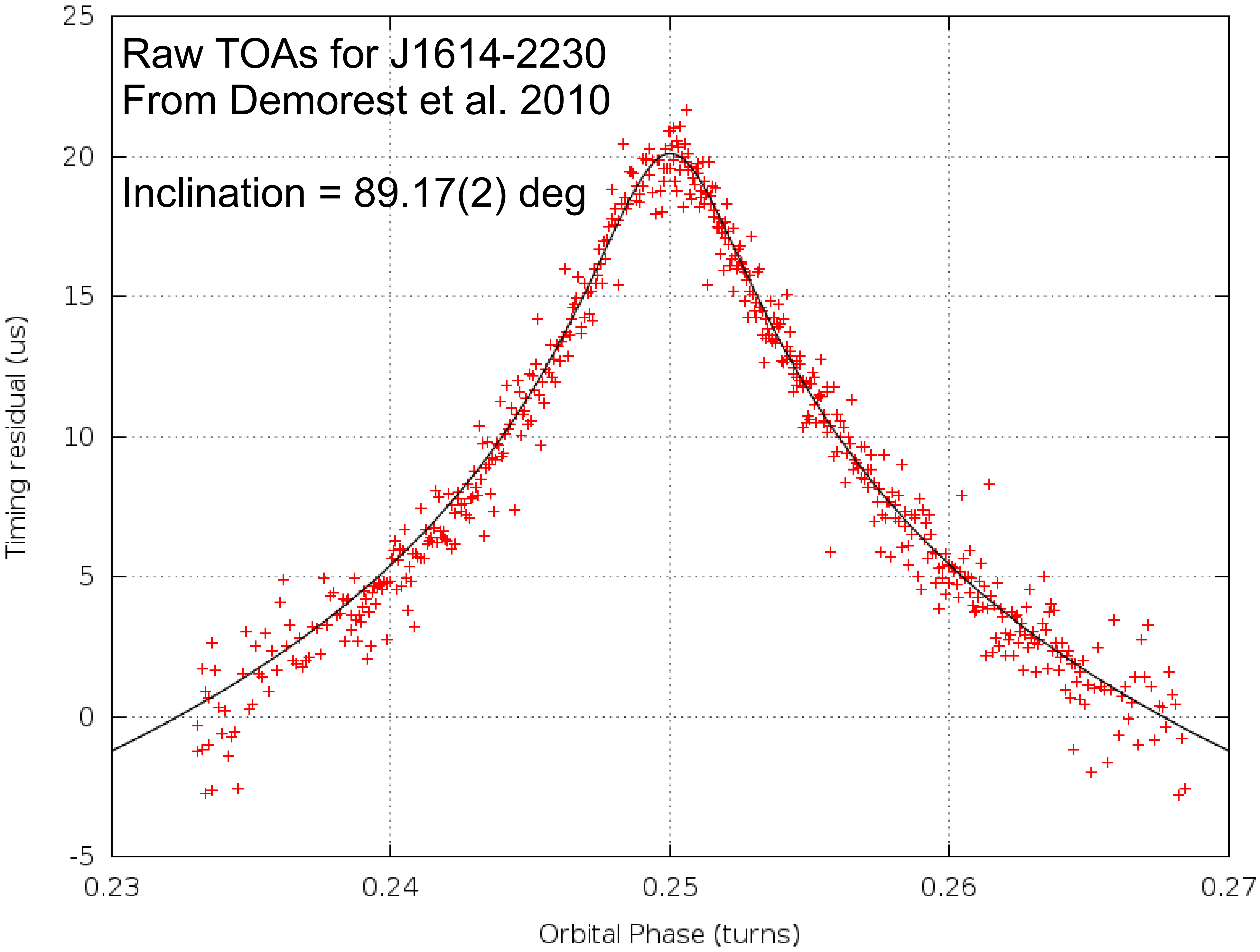


Shapiro Delay



Amplitude ∝ Companion Mass
Narrowness ∝ Inclination

Conjunction

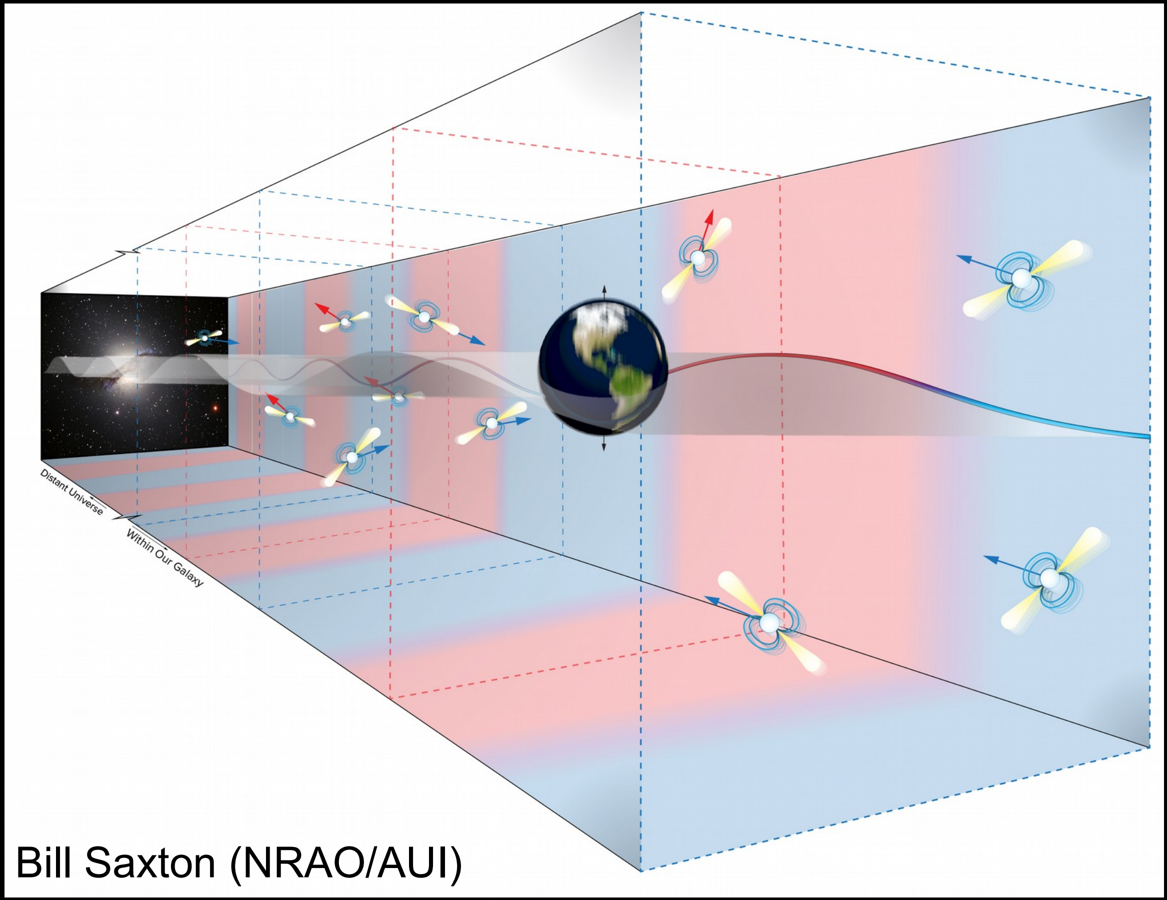


Raw TOAs for J1614-2230
From Demorest et al. 2010

Inclination = 89.17(2) deg

Gravitational Wave Detection with a Pulsar Timing Array

- Need very 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 10+ years at a precision of ~100 nano-seconds!



Bill Saxton (NRAO/AUI)

NANOGrav

N. America

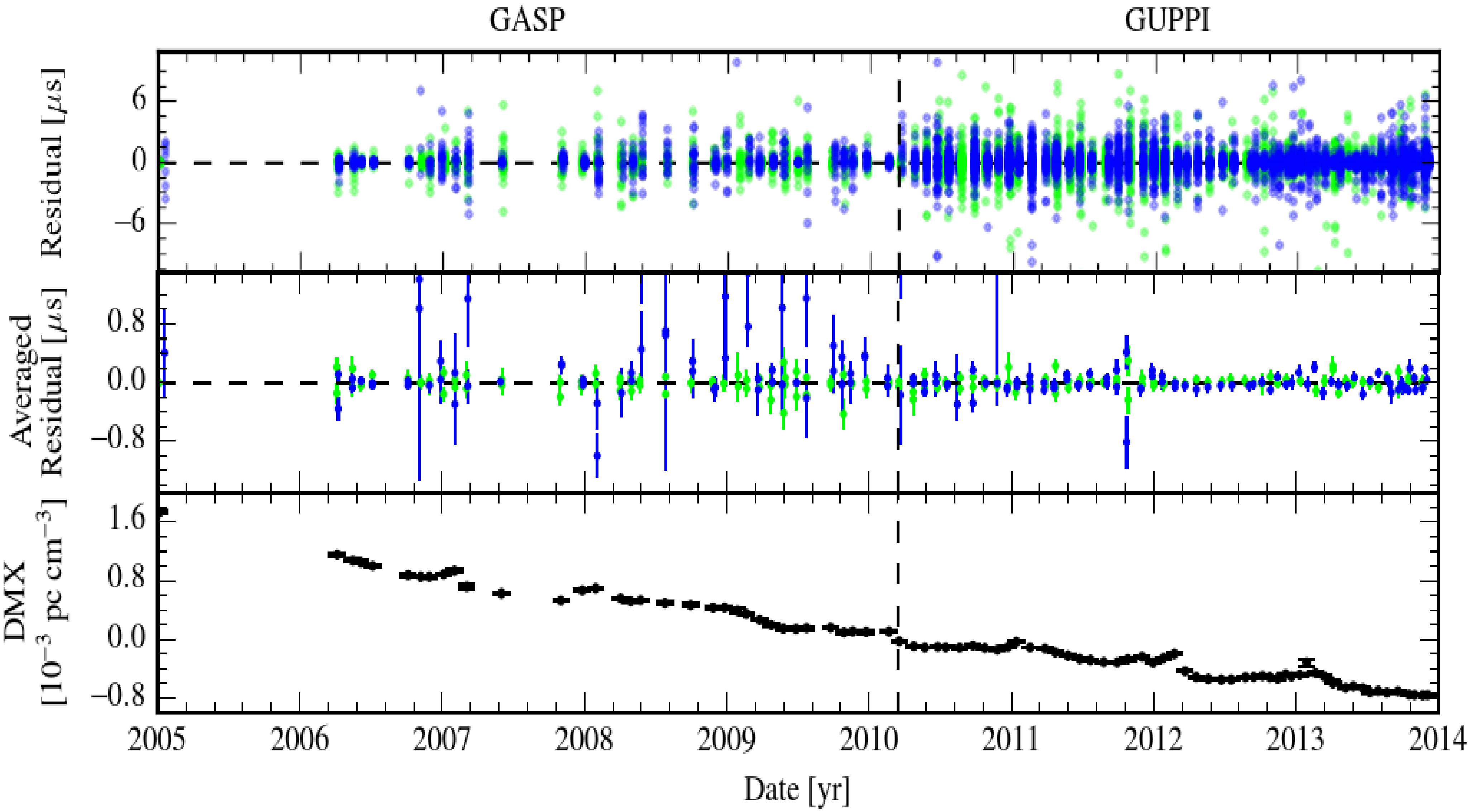
PPTA

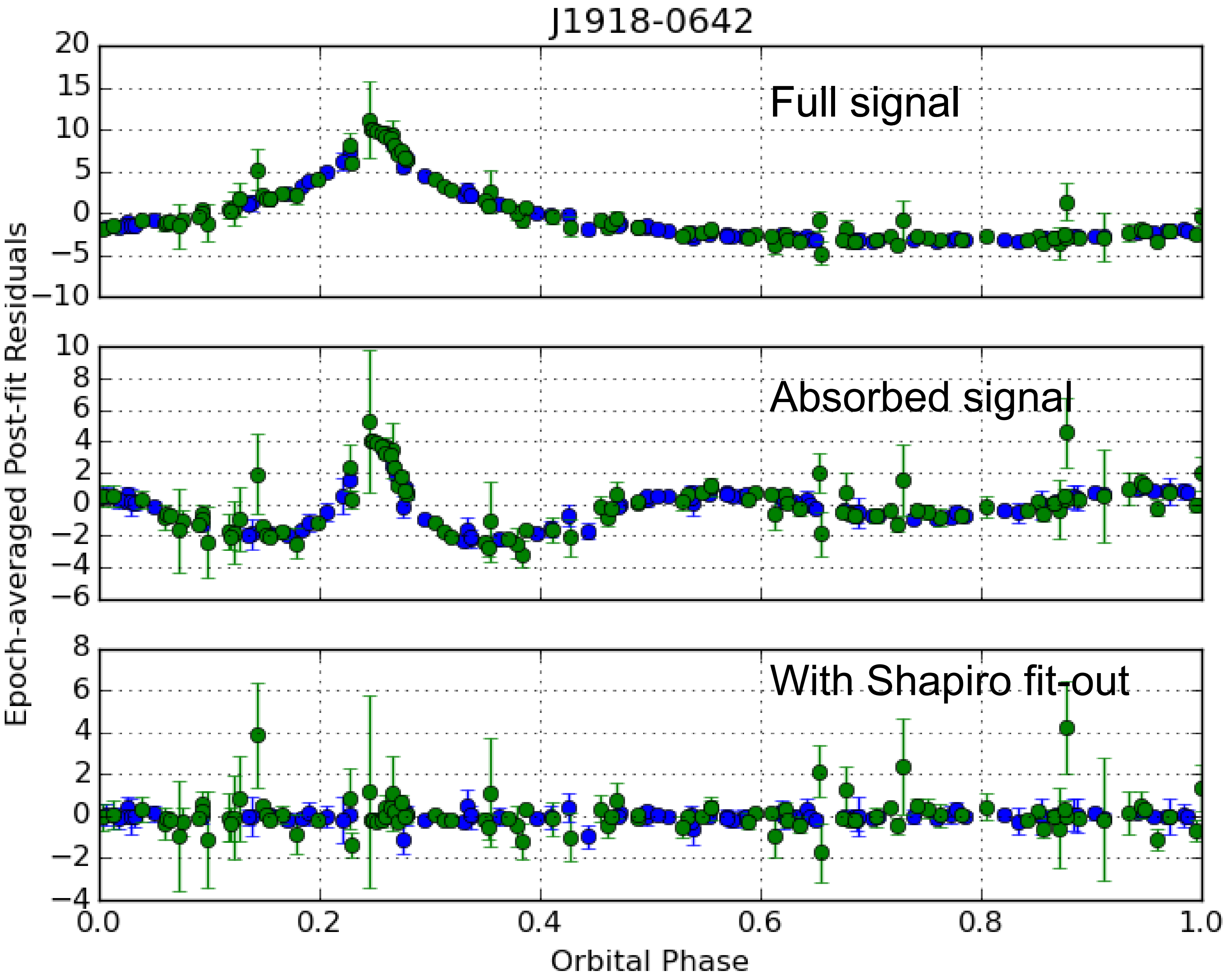
Australia

EPTA

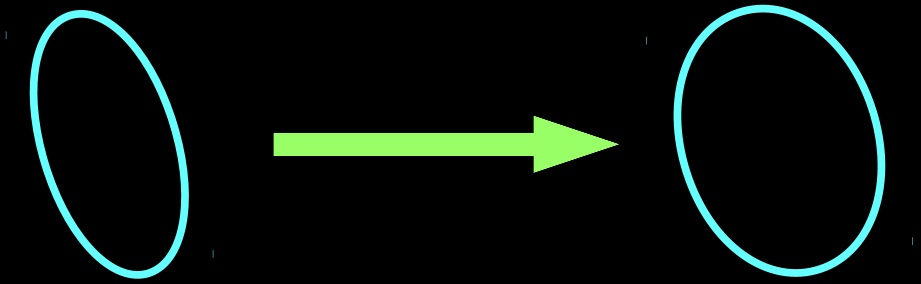
Europe

J1909−3744

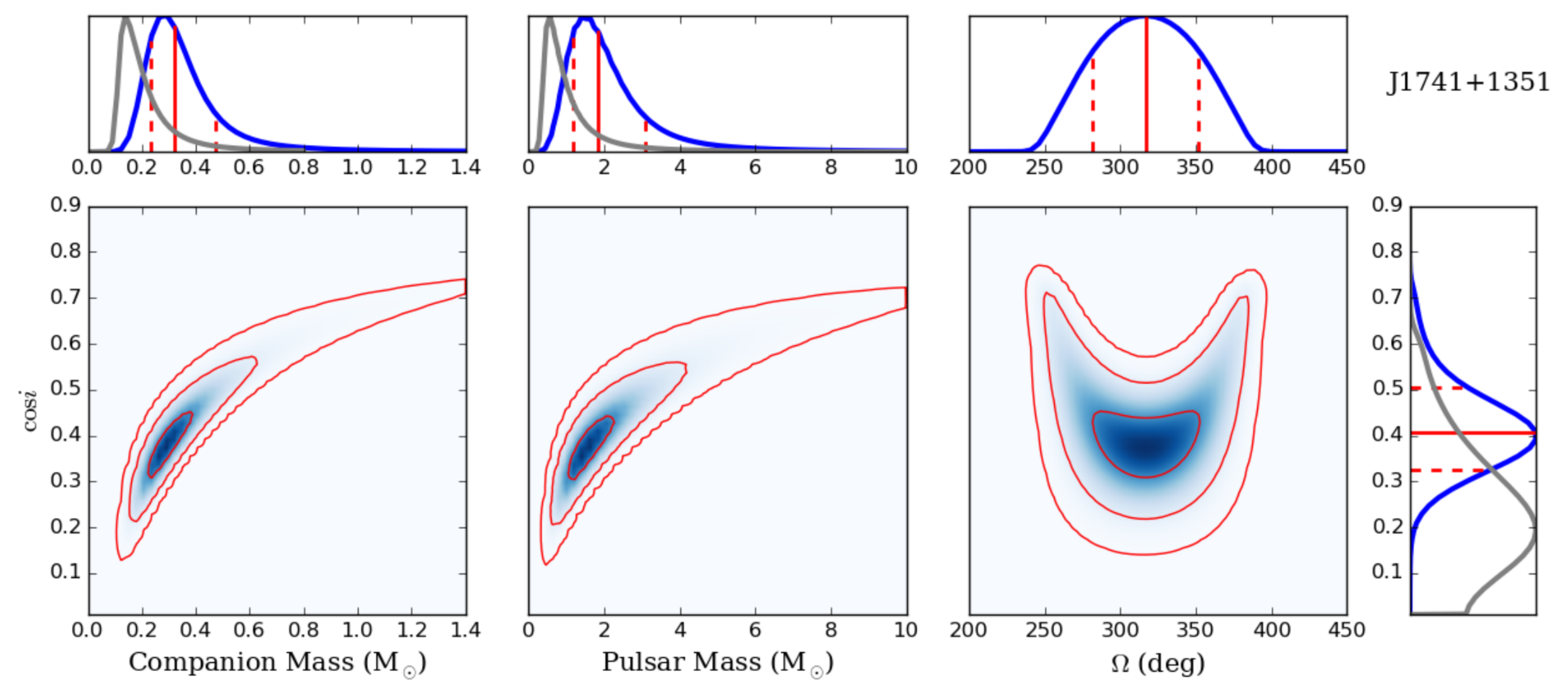

GASP
GUPPI
Residual [μs]
6
0
−6
Averaged Residual [μs]
0.8
0.0
−0.8
DMX [10^{-3} pc cm^{-3}]
1.6
0.8
0.0
−0.8
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Date [yr]


J1918-0642
Full signal
Absorbed signal
With Shapiro fit-out
Epoch-averaged Post-fit Residuals
Orbital Phase
20
15
10
5
0
−5
−10
10
8
6
4
2
0
−2
−4
−6
8
6
4
2
0
−2
−4
0.0
0.2
0.4
0.6
0.8
1.0

J1640+2224 and J1741+1351 require Kopeikin terms (i.e. XDOT)

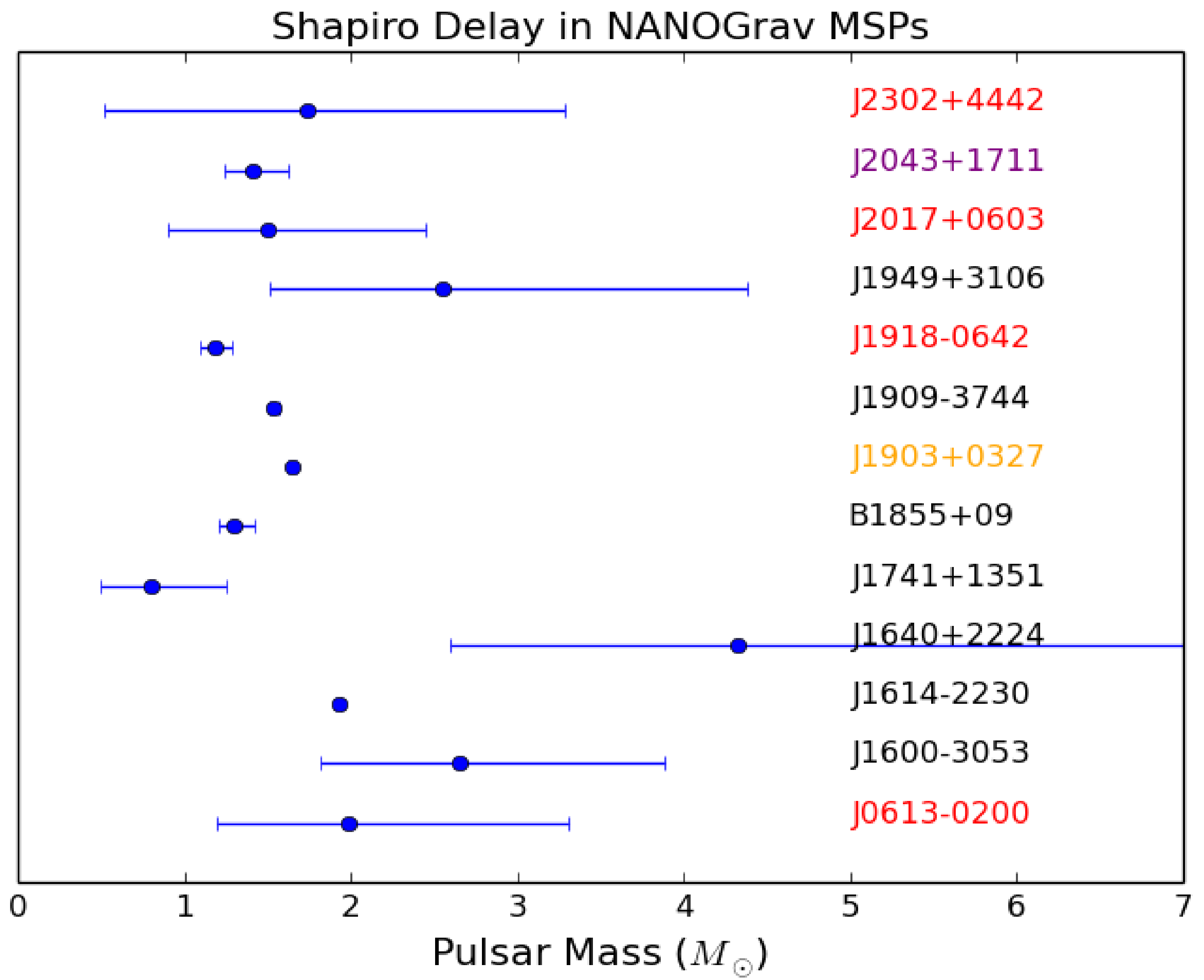


Apparent orbit size 'x = asini/c' changes as pulsar moves across sky



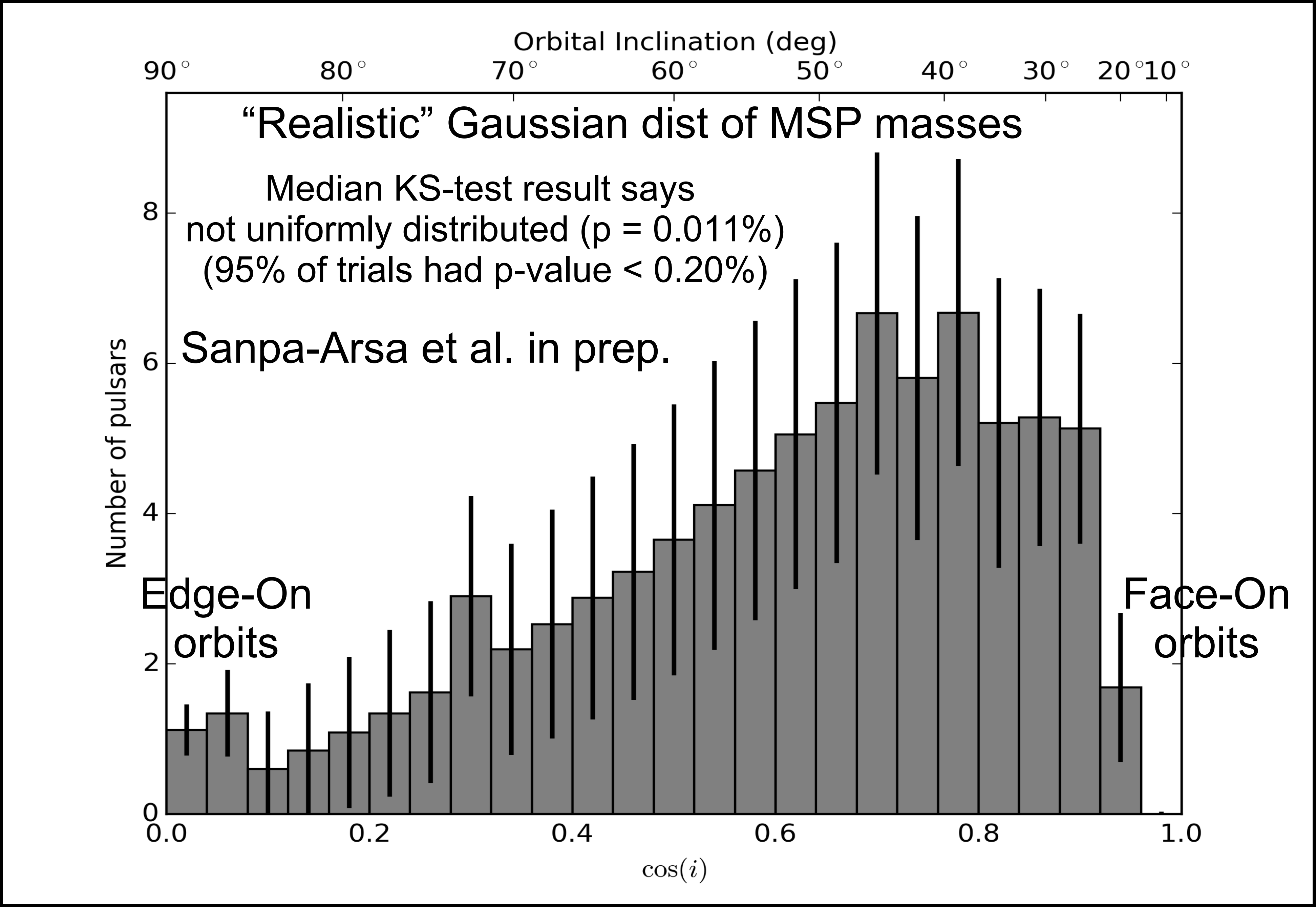
Fonseca et al. 2016 (submitted)

See also Desvignes et al. 2016 and Reardon et al. 2015 for EPTA and PPTA Results



Red = New Purple = Much Improved Orange = OMDOT as well

Distribution of cos(i) is not flat??


“Realistic” Gaussian dist of MSP masses

Median KS-test result says
not uniformly distributed (p = 0.011%)
(95% of trials had p-value < 0.20%)

Sanpa-Arsa et al. in prep.

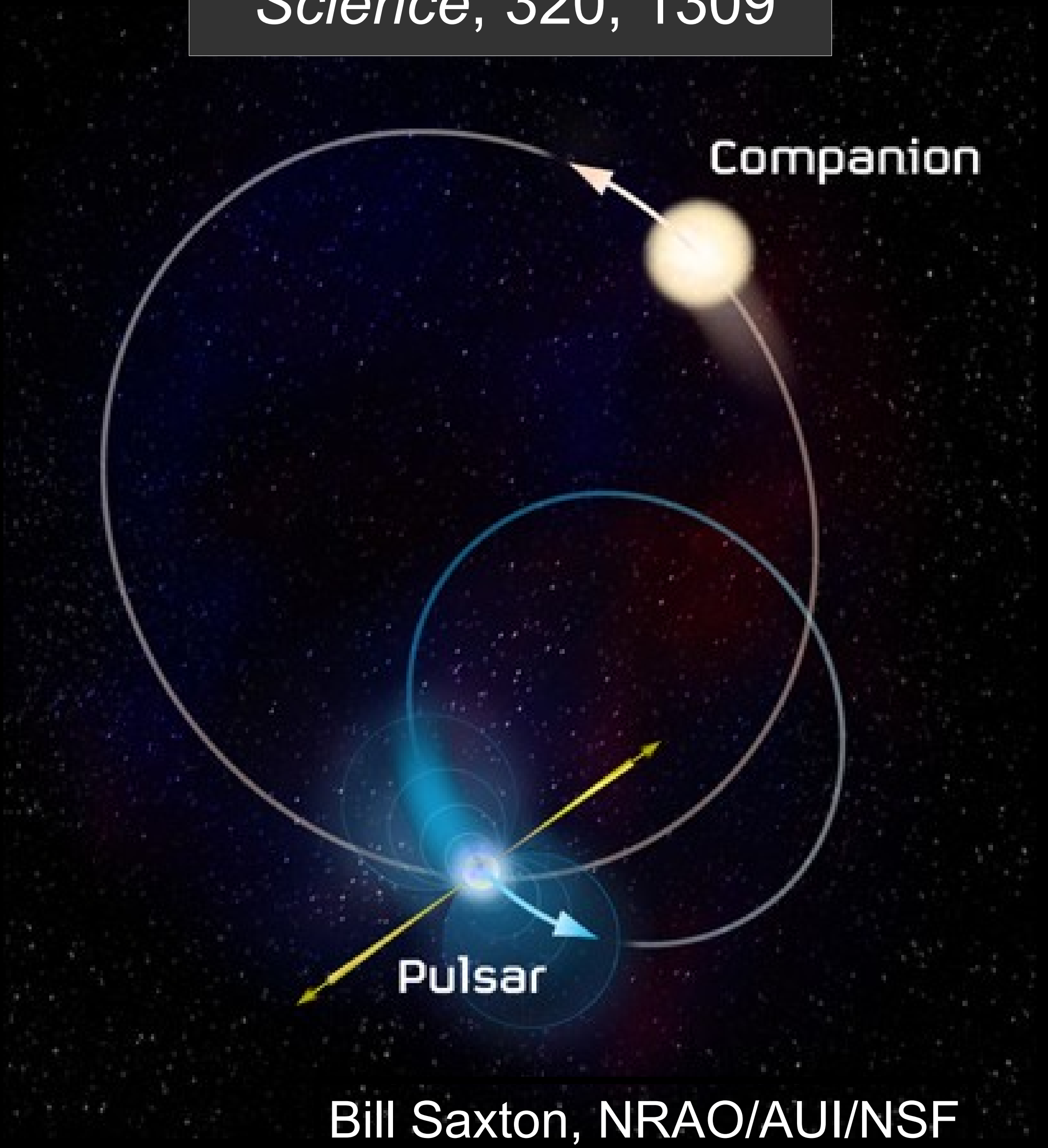
Edge-On
orbits

Face-On
orbits

PSR J1903+0327

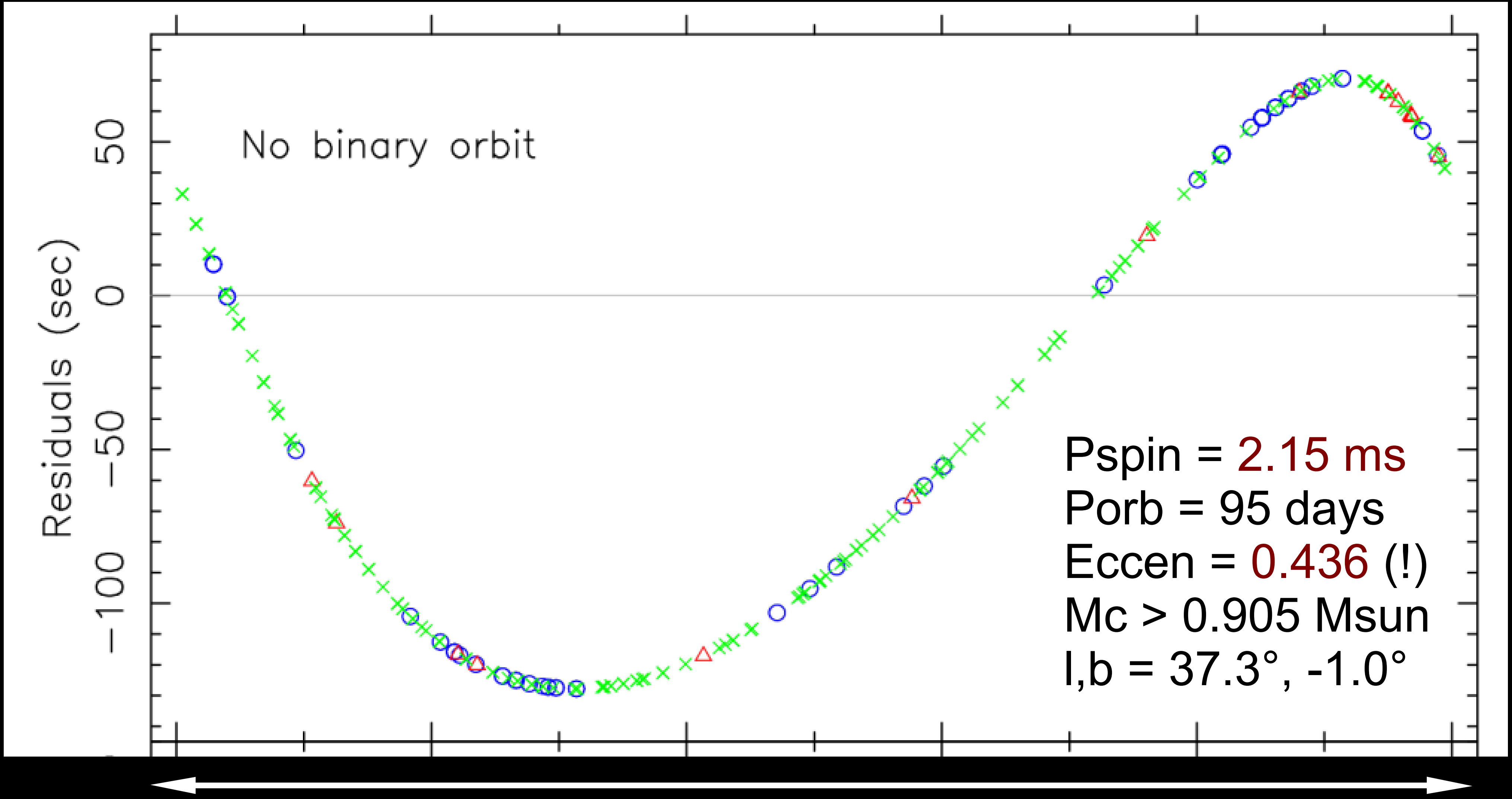
- Fully recycled PSR
- Highly eccentric orbit
- Massive main-sequence star companion
- High precision timing despite being distant and in Galactic plane

Champion et al. 2008, *Science*, 320, 1309



Bill Saxton, NRAO/AUI/NSF

J1903+0327 (Eccentric MSP) Timing

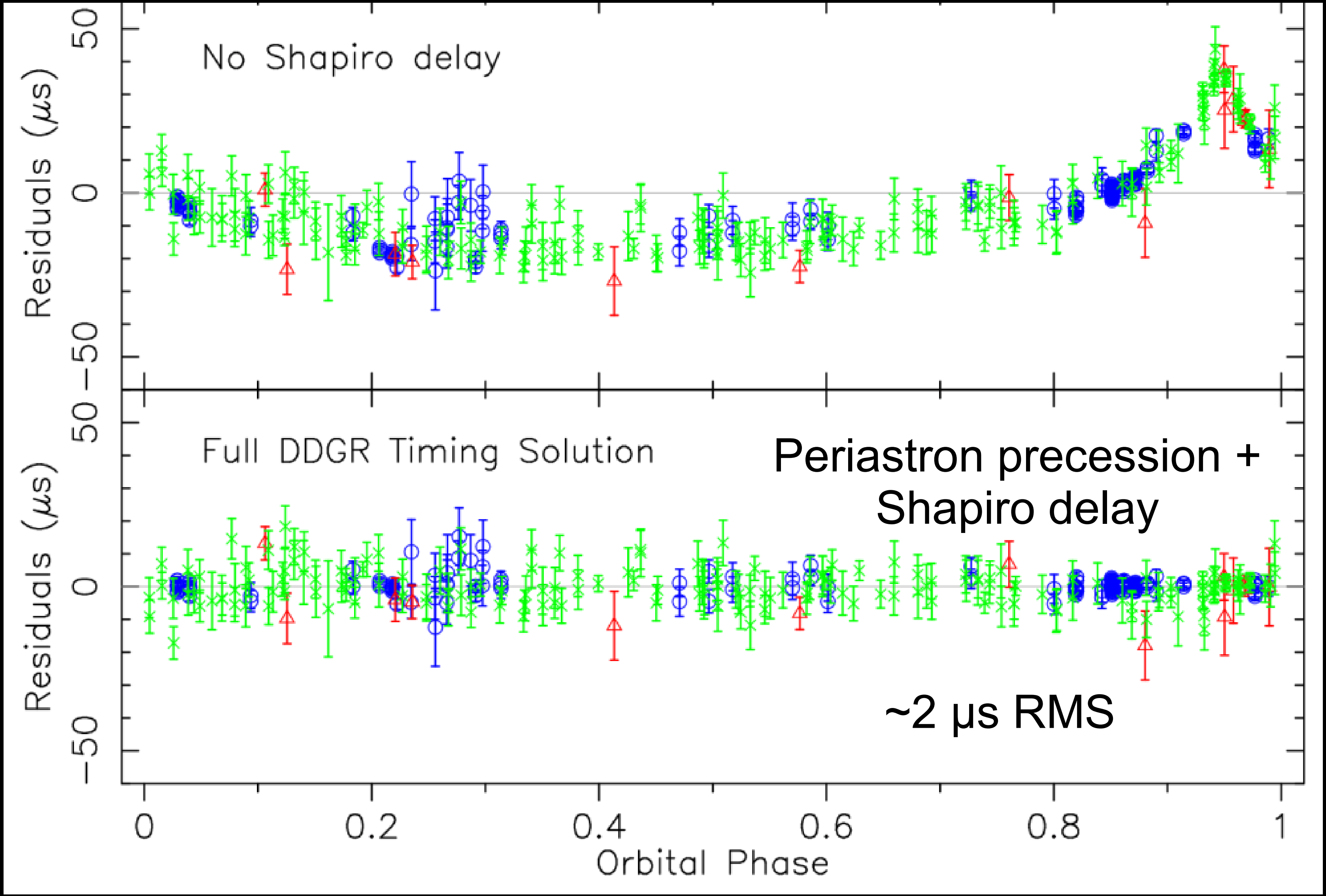


Pspin = 2.15 ms
Porb = 95 days
Eccen = 0.436 (!)
Mc > 0.905 Msun
l,b = 37.3°, -1.0°

One Orbit (Orbital Phase)

Champion et al. 2008, *Science*, 320, 1309

J1903+0327 (Eccentric MSP) Timing



Periastron precession + Shapiro delay

~2 μs RMS

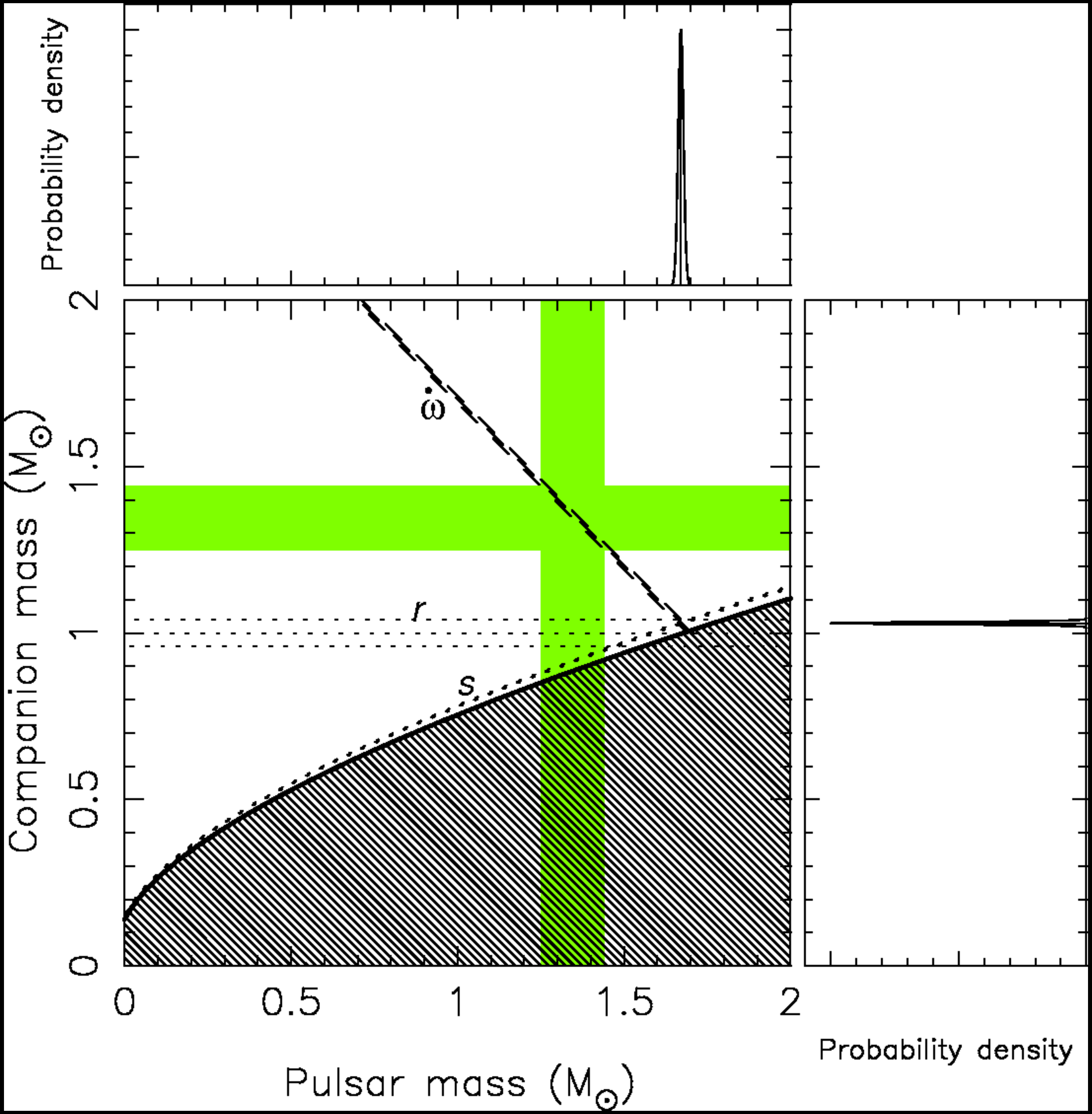
Champion et al. 2008, *Science*, 320, 1309

Additional Arecibo timing

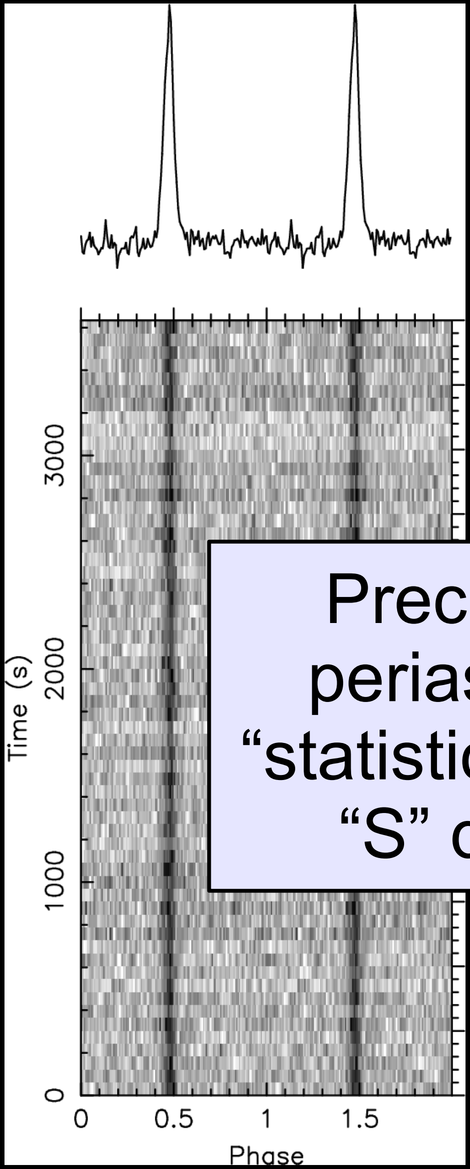
Much improved Shapiro delay
PSR = 1.67(2) $M_\odot$

Possibly formed in a triple system?

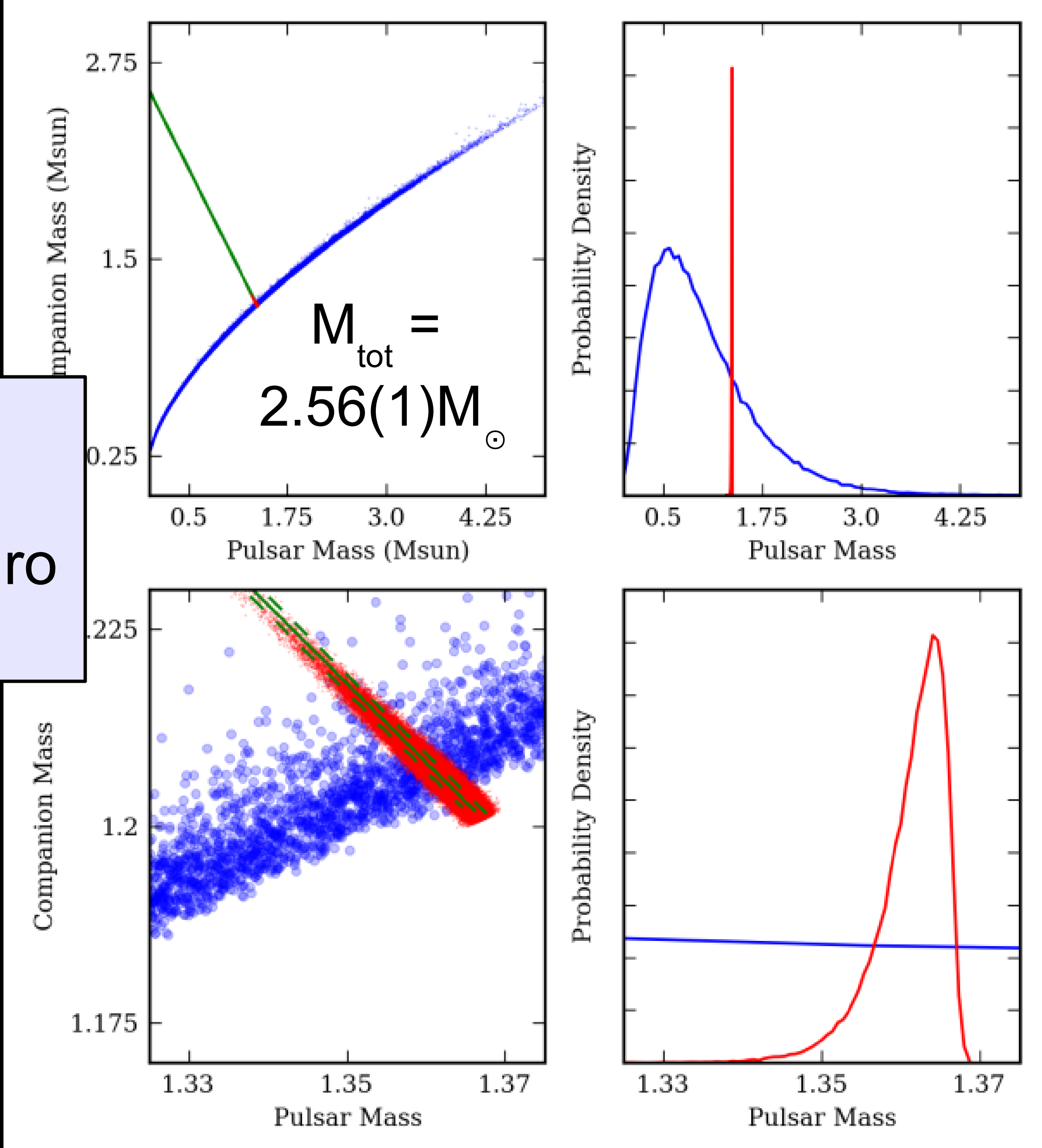
Freire et al. 2011, MNRAS, 412, 2763



NGC6544B



Precession of periastron plus “statistical” Shapiro “S” detection



M_{tot} = 2.56(1)$M_\odot$

Highly eccentric (e=0.747)

P_{psr} ~ 4.18 ms

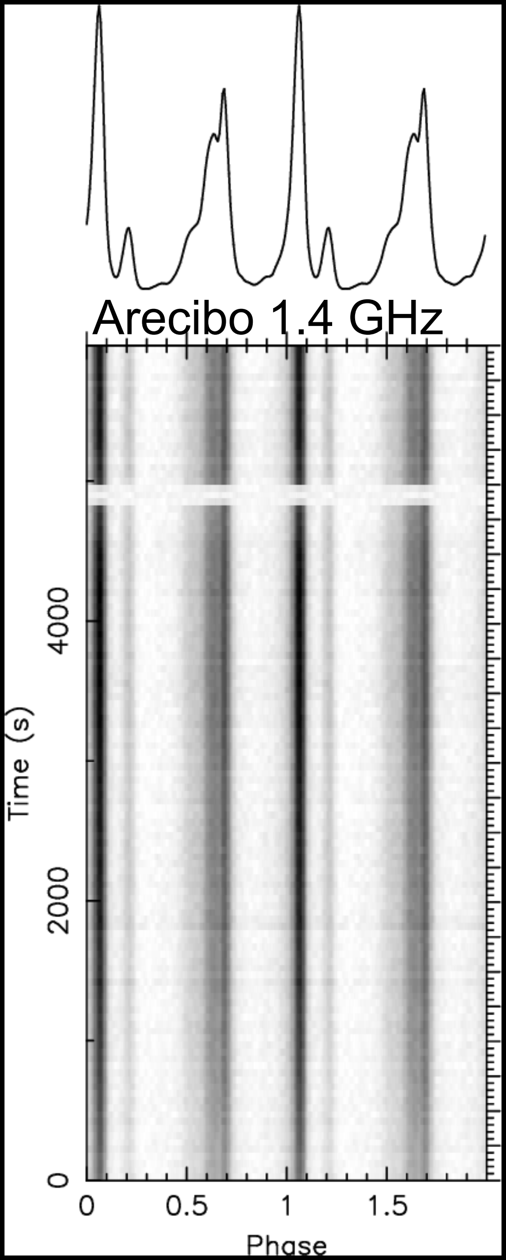
P_{orb} = 9.96 days

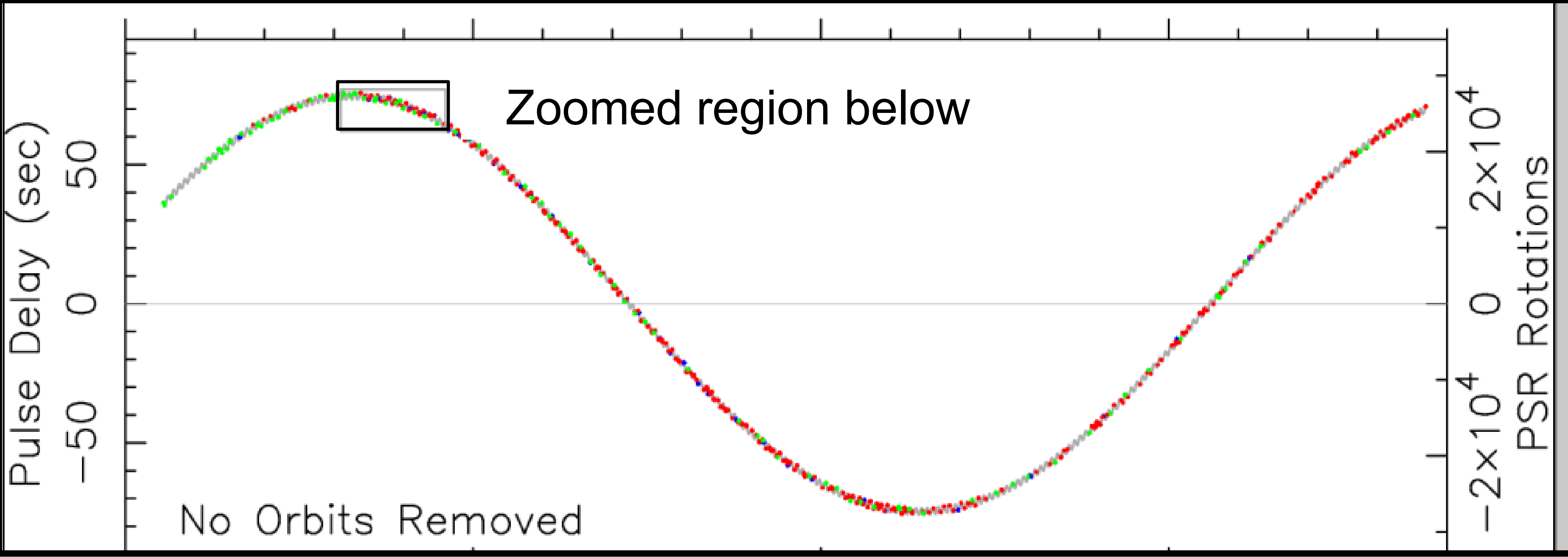
Lynch et al. 2012, ApJ, 745, 109L

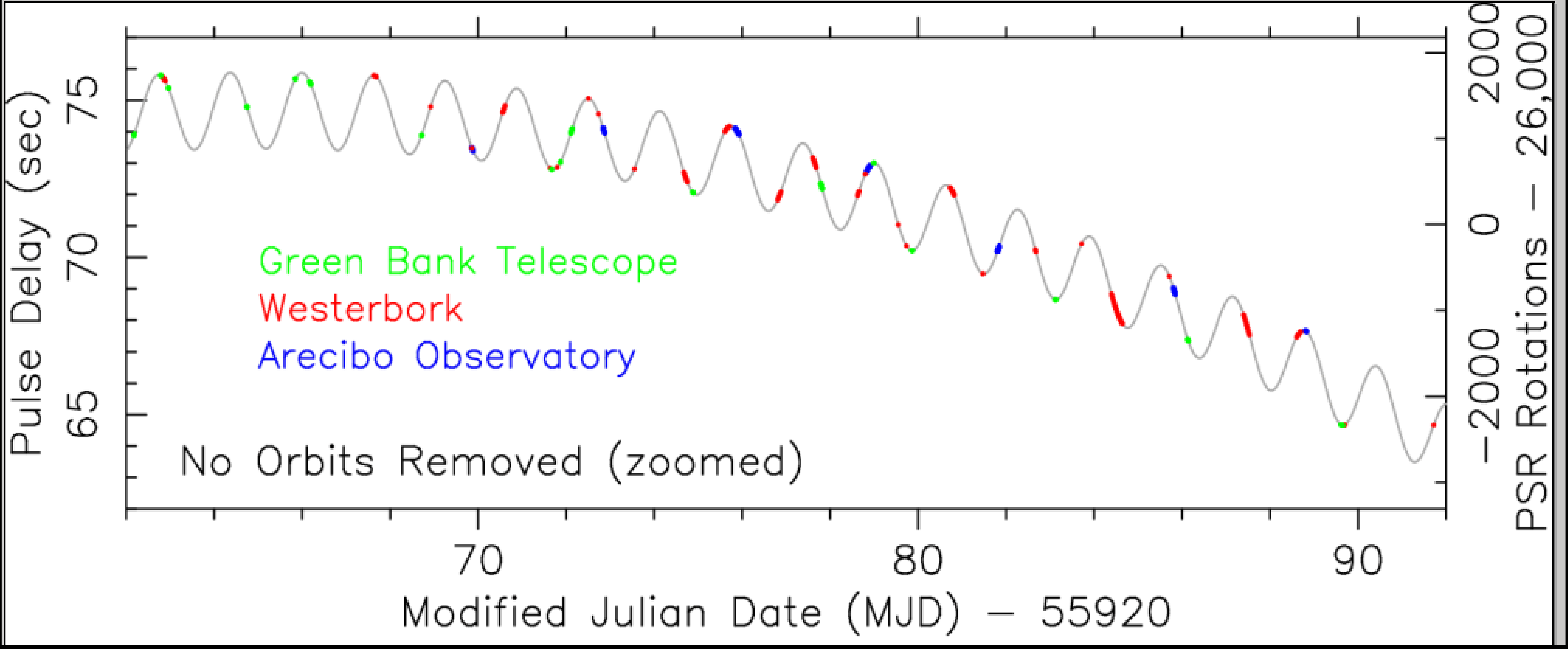
A MSP in a stellar triple system

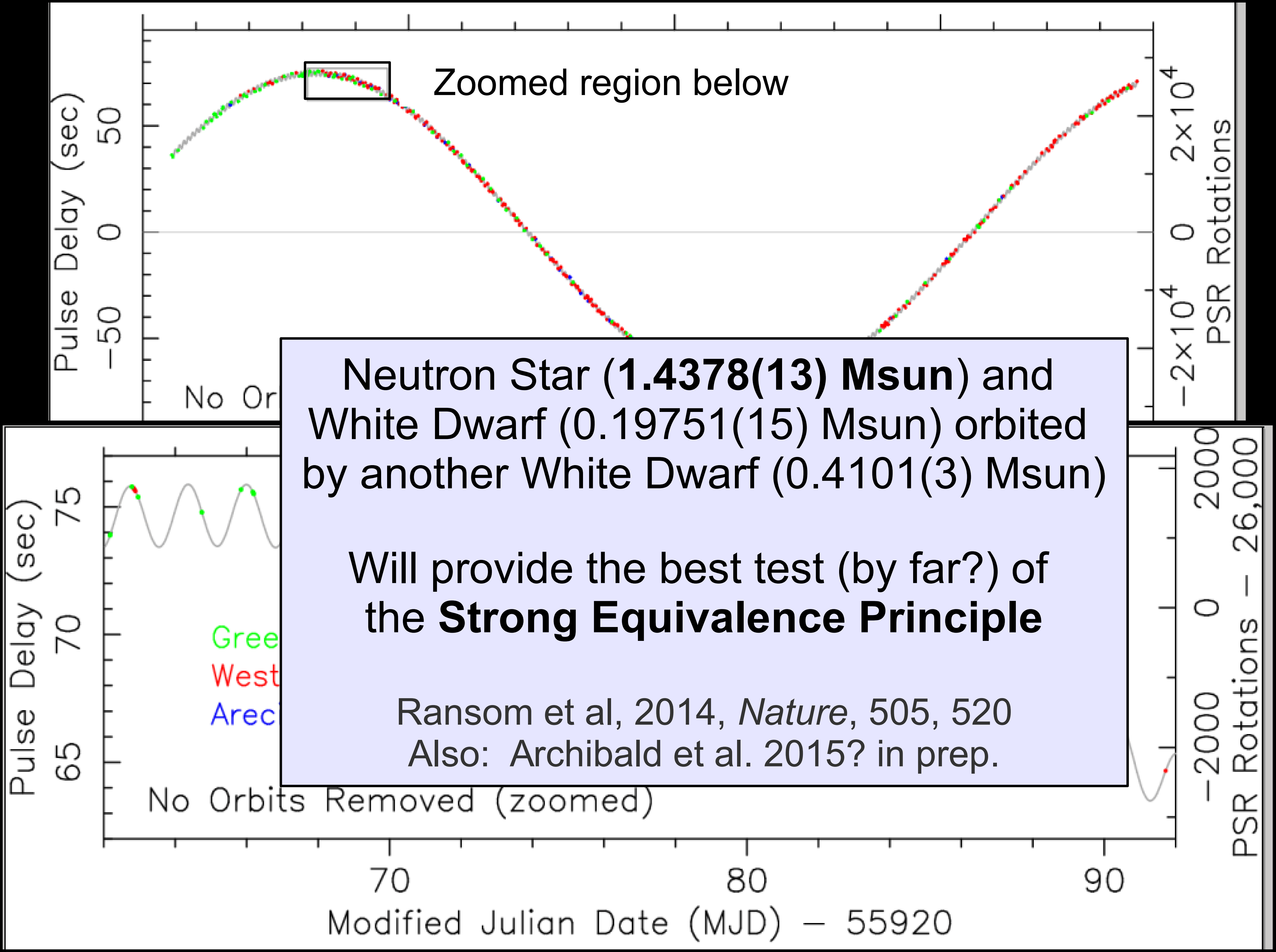
- PSR J0337+1715: In 2013, from the GBT Driftscan survey, a 2.7 ms PSR in a hierarchical triple system!
  - 1.6 day inner binary with hot WD
  - 327 day outer orbit with cool WD
  - Very strong 3-body effects...

Ransom et al. 2014, *Nature*, 505, 520




Zoomed region below
Pulse Delay (sec)
50
0
−50
PSR Rotations
2×10^4
0
−2×10^4
No Orbits Removed


Pulse Delay (sec)
75
70
65
PSR Rotations − 26,000
2000
0
−2000
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
70
80
90
Modified Julian Date (MJD) − 55920



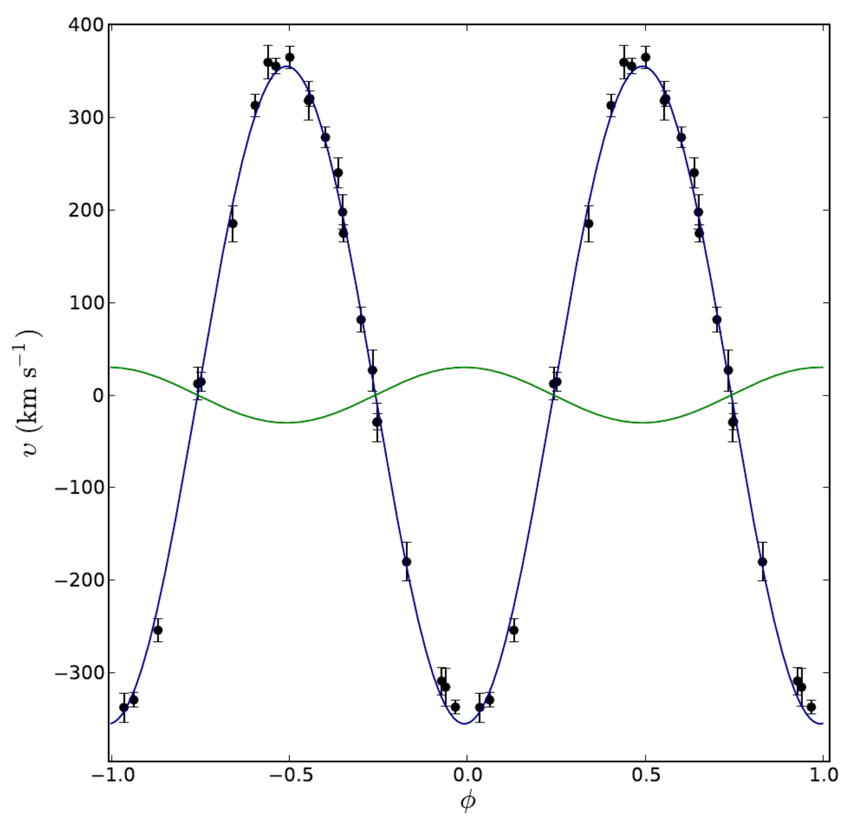
Neutron Star (**1.4378(13) Msun**) and White Dwarf (0.19751(15) Msun) orbited by another White Dwarf (0.4101(3) Msun)

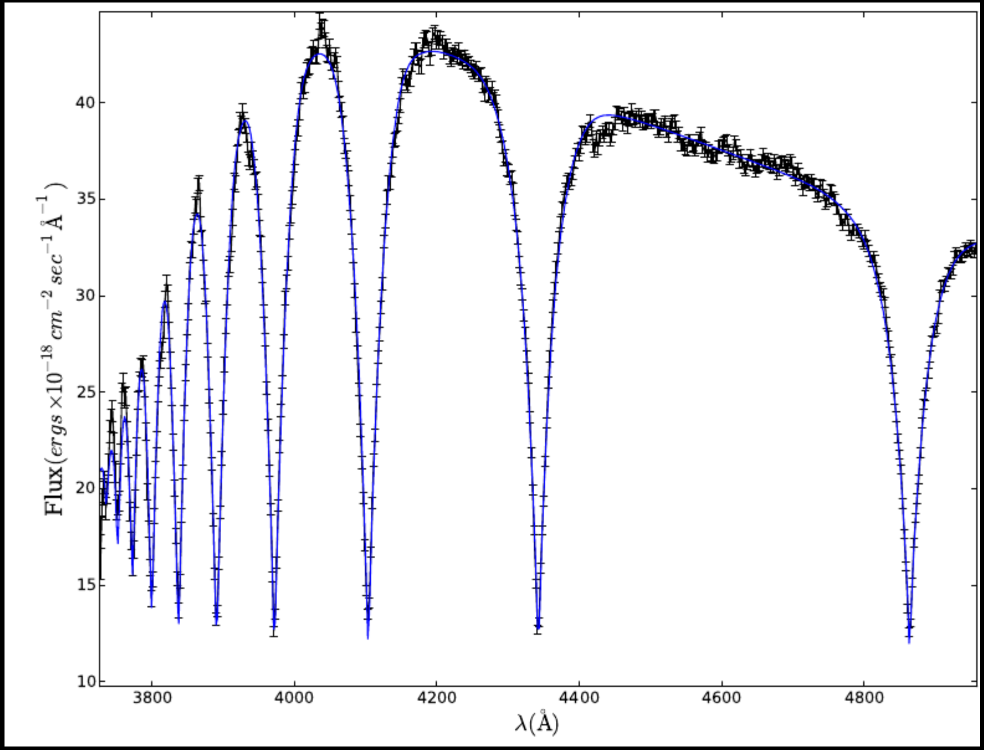
Will provide the best test (by far?) of the **Strong Equivalence Principle**

Ransom et al, 2014, *Nature*, 505, 520
Also: Archibald et al. 2015? in prep.

PSR J0348+0432

- 39.1 ms GBT Driftscan pulsar
- 2.4hr relativistic orbit with WD
- He WD is ~10,120K, log(g) ~6.0
- Mass ratio of 11.70 +/- 0.13!
- Orbital period decay coming...





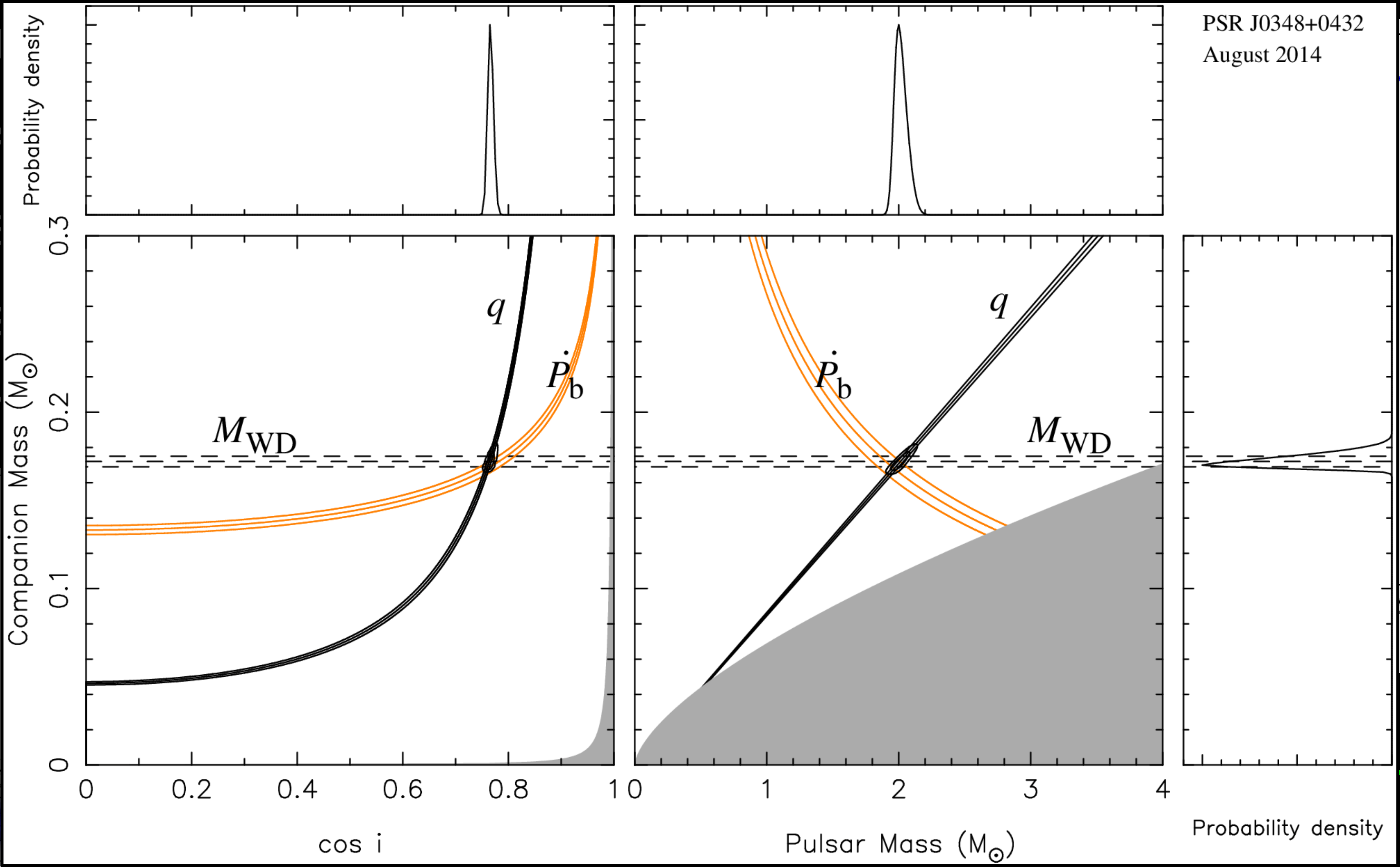
NS mass ~ 2.01(4) Msun!

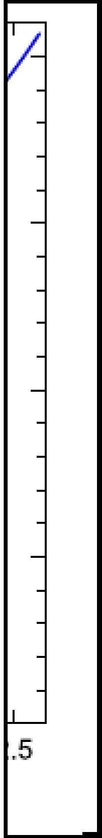
(interesting tests of GR)

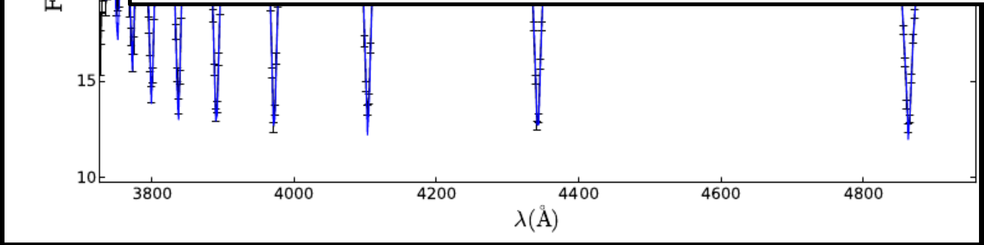
Antoniadis et al *Science*, 2013, 340, 448

PSR J0348+0432

- 39
- 2.4
- He
- Ma
- Or





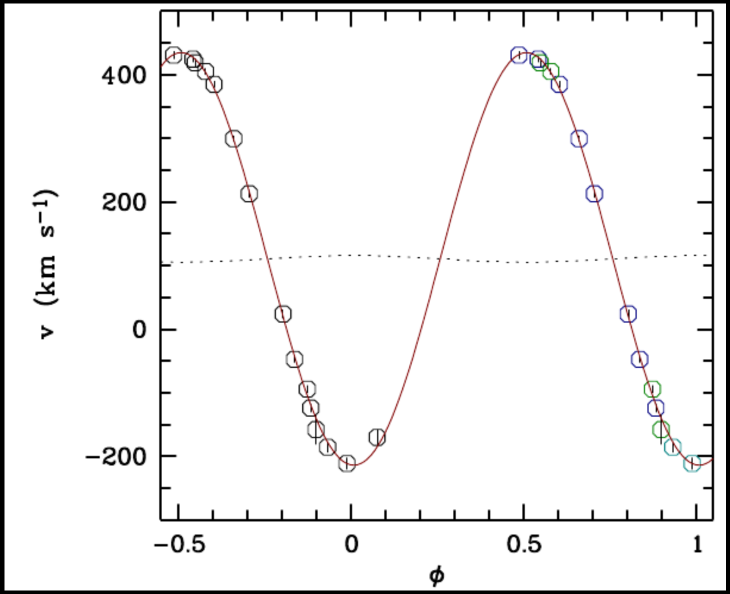


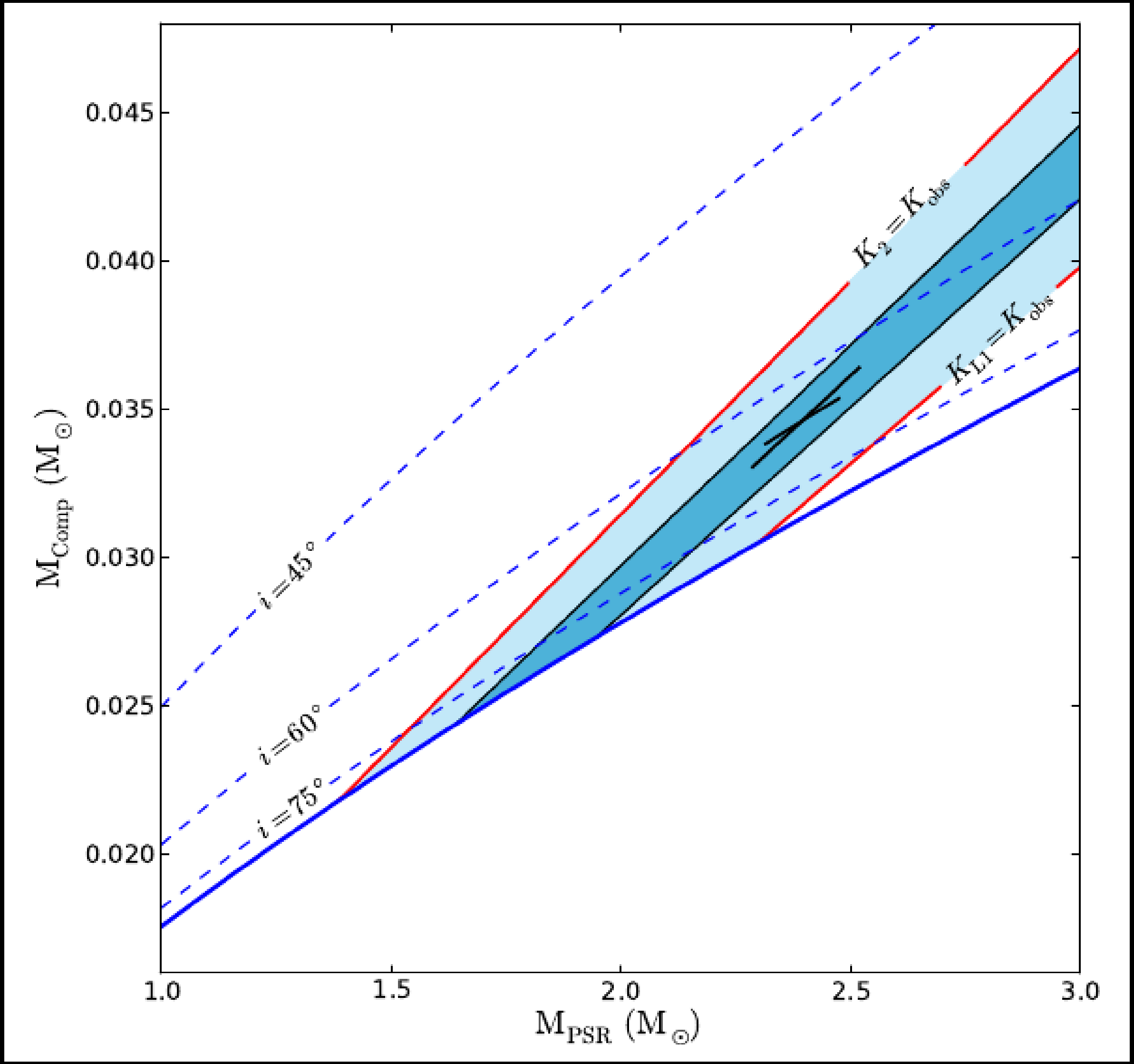
un!

Antoniadis et al *Science*, 2013, 340, 448

Original “Black Widow”: B1957+21

- New radial vel curve: 353(4) km/s amplitude (corr. for ctr-of-light)
- i=65(2)deg from lightcurve models
- Mp ~ 2.40+/-0.12Msun
- Mp > 1.66 Msun

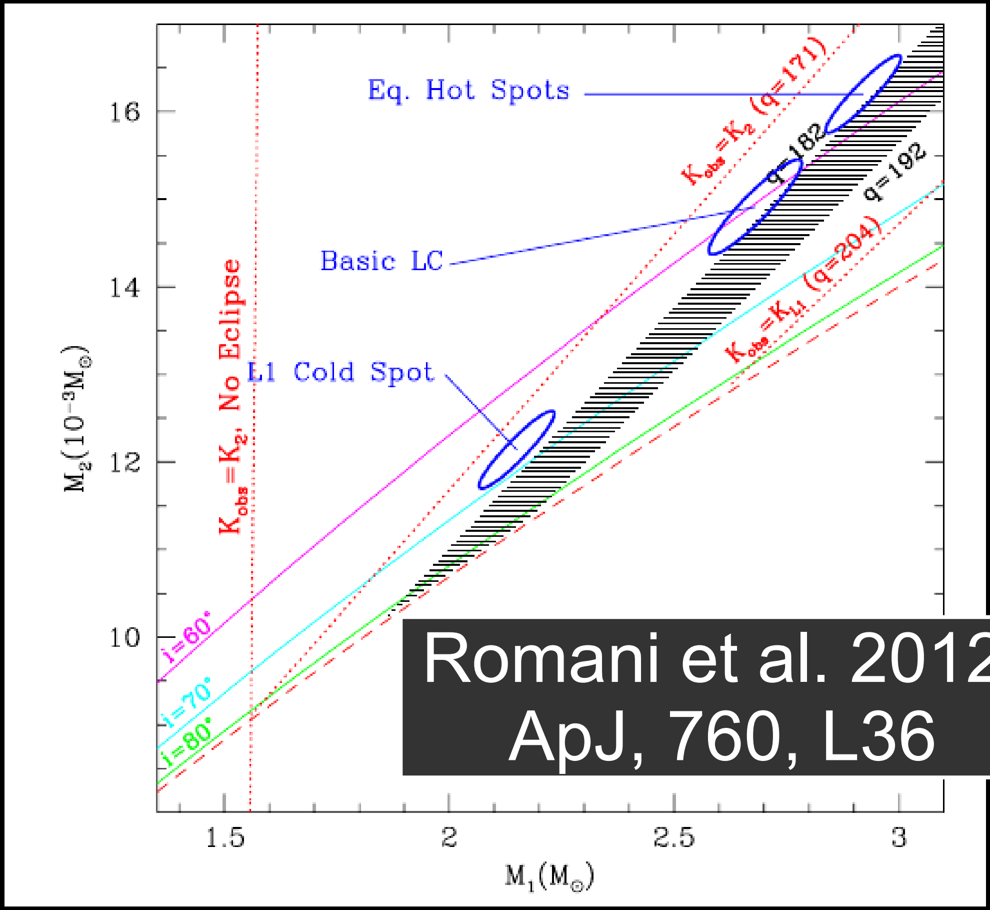




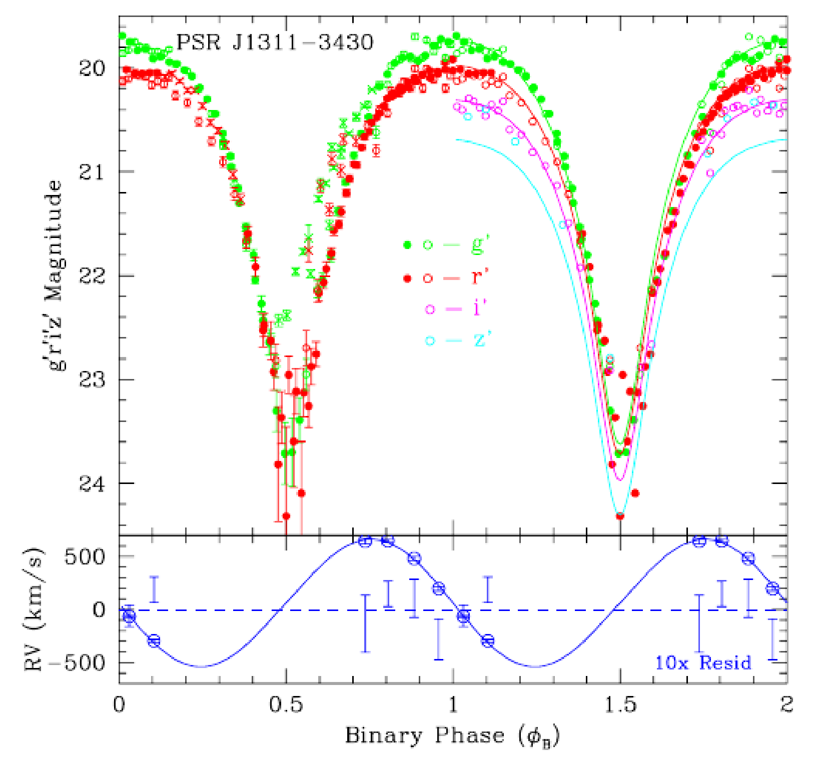
van Kerkwijk, Breton, & Kulkarni, 2011 ApJ, 728, 95

Black Widows: J1311-3430

- 94-min orbit gamma-ray MSP
- Similar analysis to B1957+21
- Radial vel curve: 609(8) km/s amplitude
- Mpsr > 2.1 Msun (!)



Romani et al. 2012, ApJ, 760, L36



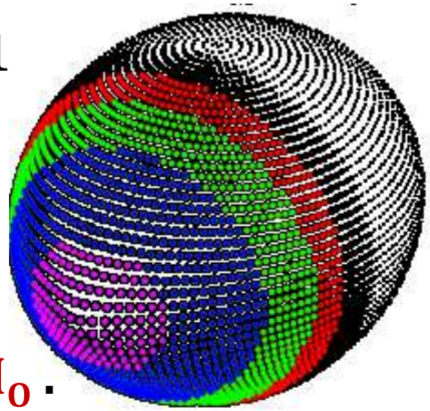
More to come?

15+ new Black Widows with *Fermi*

J2215+5135 also seems massive (Schroeder & Halpern 2014)

Caveats: Model Systematics

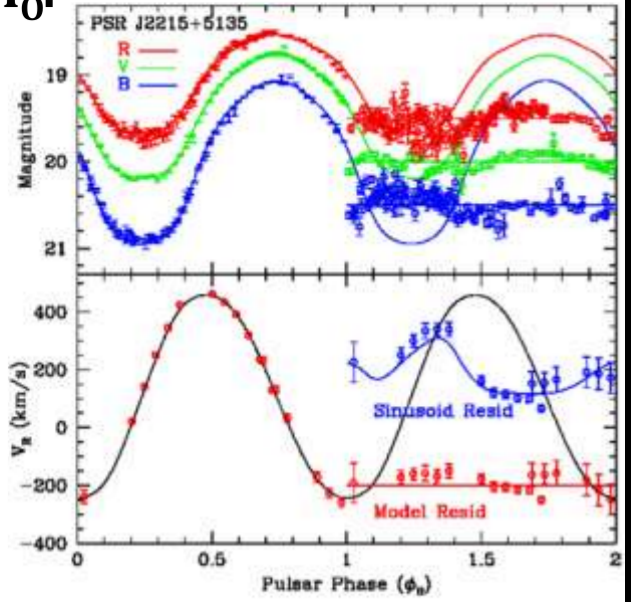
- **W/ good photometry and spectra direct heating fits poorly**
  - **Demands 'L_X' > L_{PSR} …**
  - **Asymmetry in several cases $\Delta\phi \sim 0.01$**
  - **bad minima ($\chi 2$/DoF ~3-10)**



RWR et al 2014

- **E.g. J1311-3430**
  - **Direct large L_X, low i: $2.68^{+}/{-0.14}\ M_O$.**
  - **Artificial cool spot at L_1 increases i, decreases M_{NS}. With arbitrary pattern allows M_{NS} ~1.9-2.9 M_O.**
  -

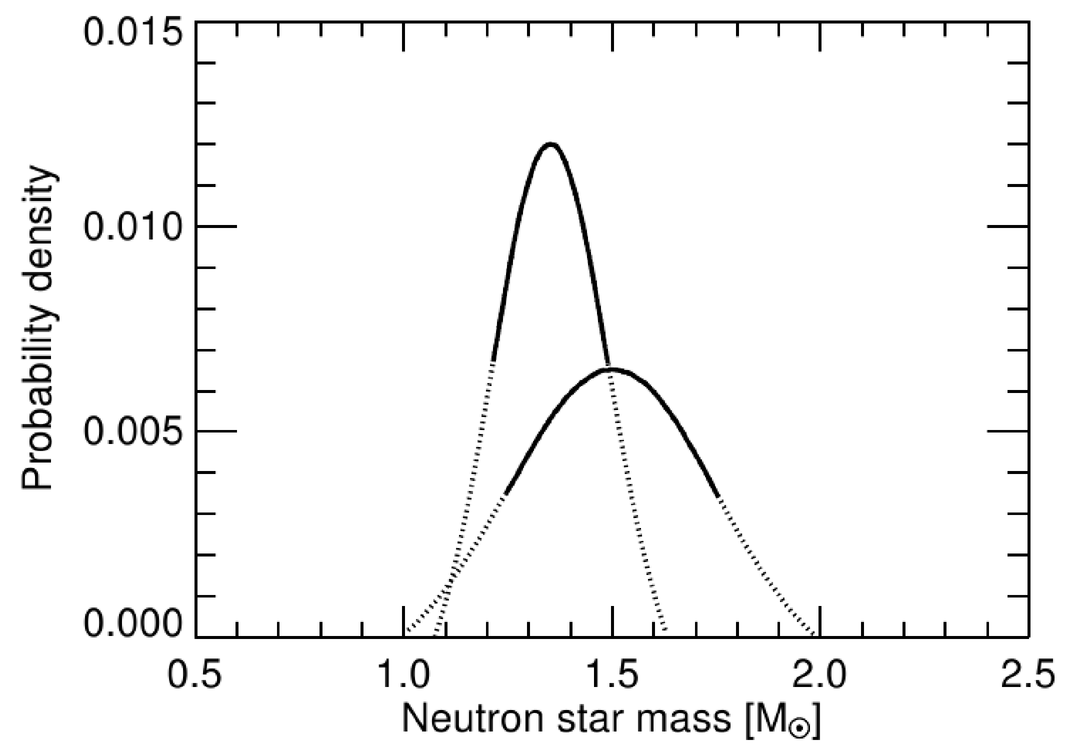
- **E.g. J2215+5135**
  - **Direct $M_{NS}=2.45^{+0.22}/_{-0.11}M_o$ …**
  - **Keck spectra to resolve T_{eff}, RV variation**
  - **New fit $M_P=1.60M_O/M_c=0.23M_O$**
  - **But unexplained phase shift, poor colors remain. Missing ingredient…**



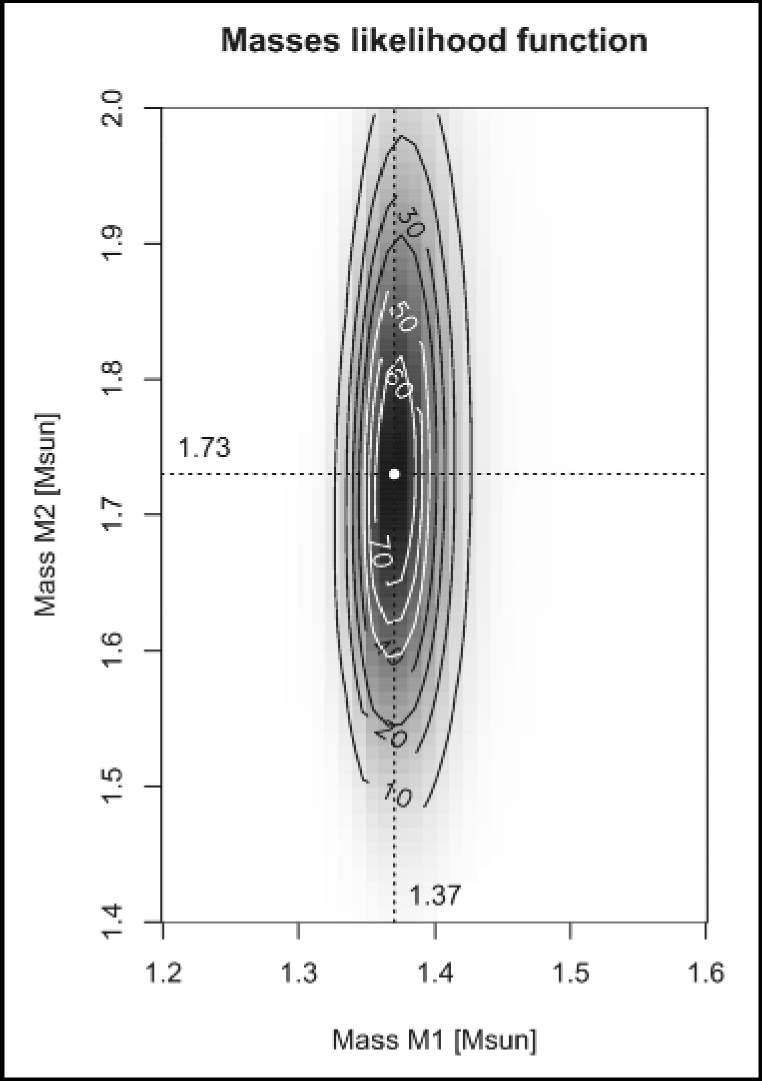
Slide from Roger Romani's JINA-CEE 2016 Talk at Ohio Univ

Two Mass Distributions?

- Bayesian Analyses suggest bi-modal mass distribution

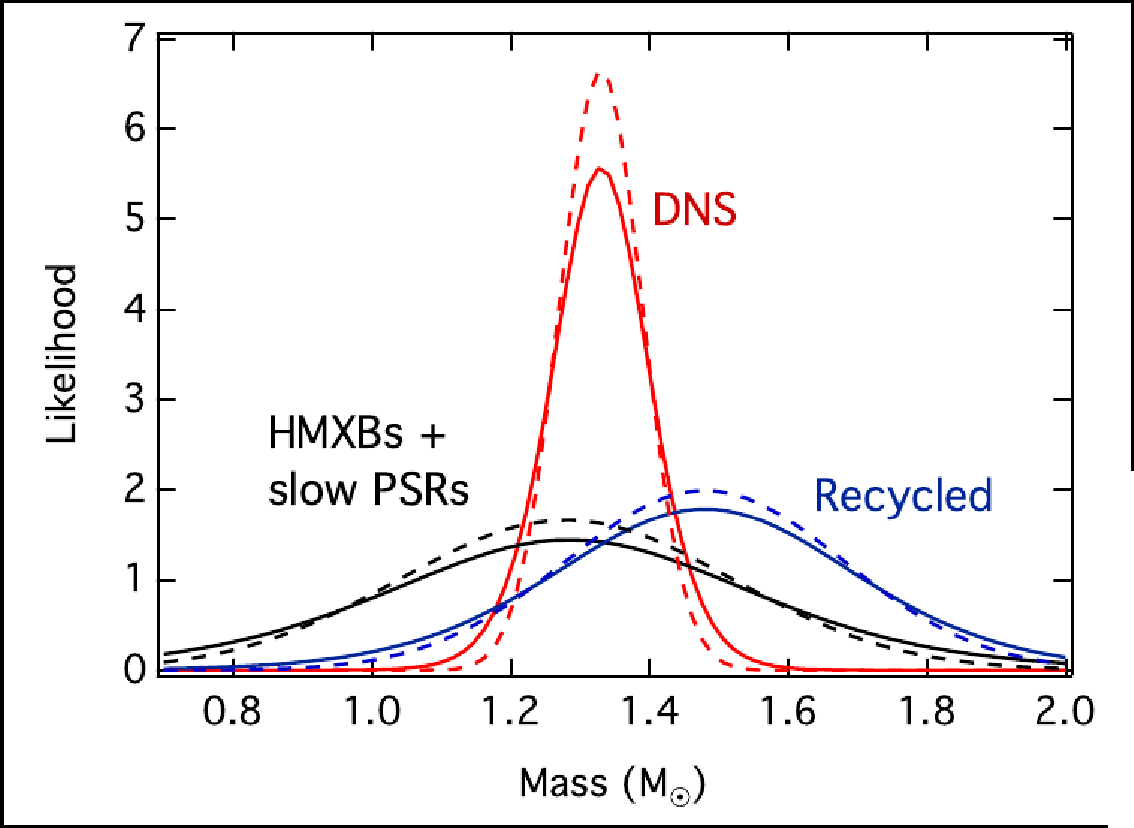


Kiziltan, Kottas & Thorsett (1011.4291)
See also
Zhang et al., 2011, A&A, 527, 83

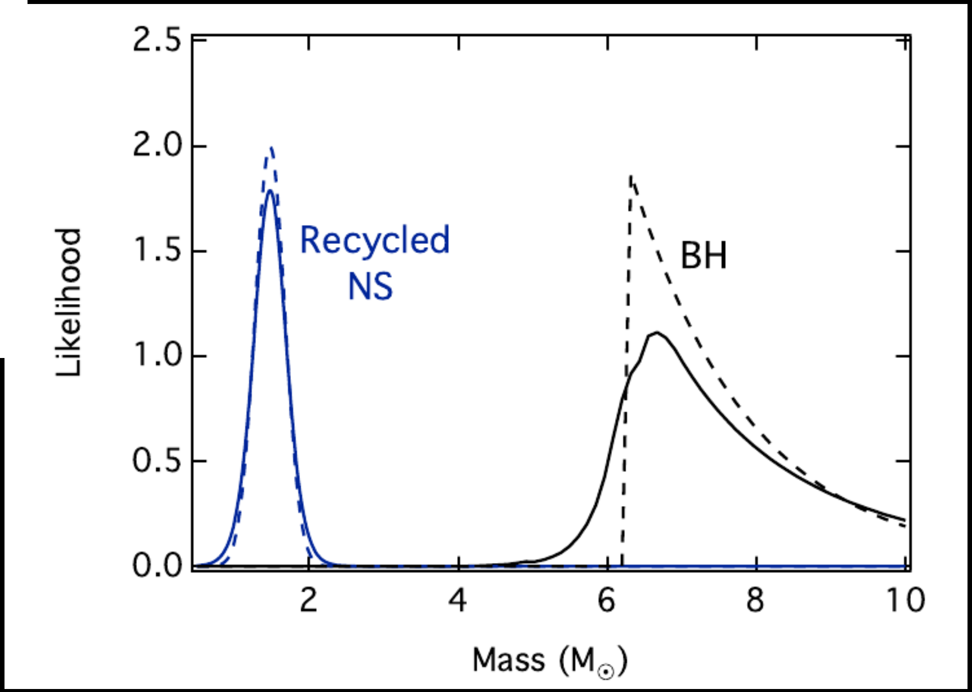


Valentim, Rangel & Horvath, 2011, MNRAS, 414, 1427

Two (or more) Mass Distributions?



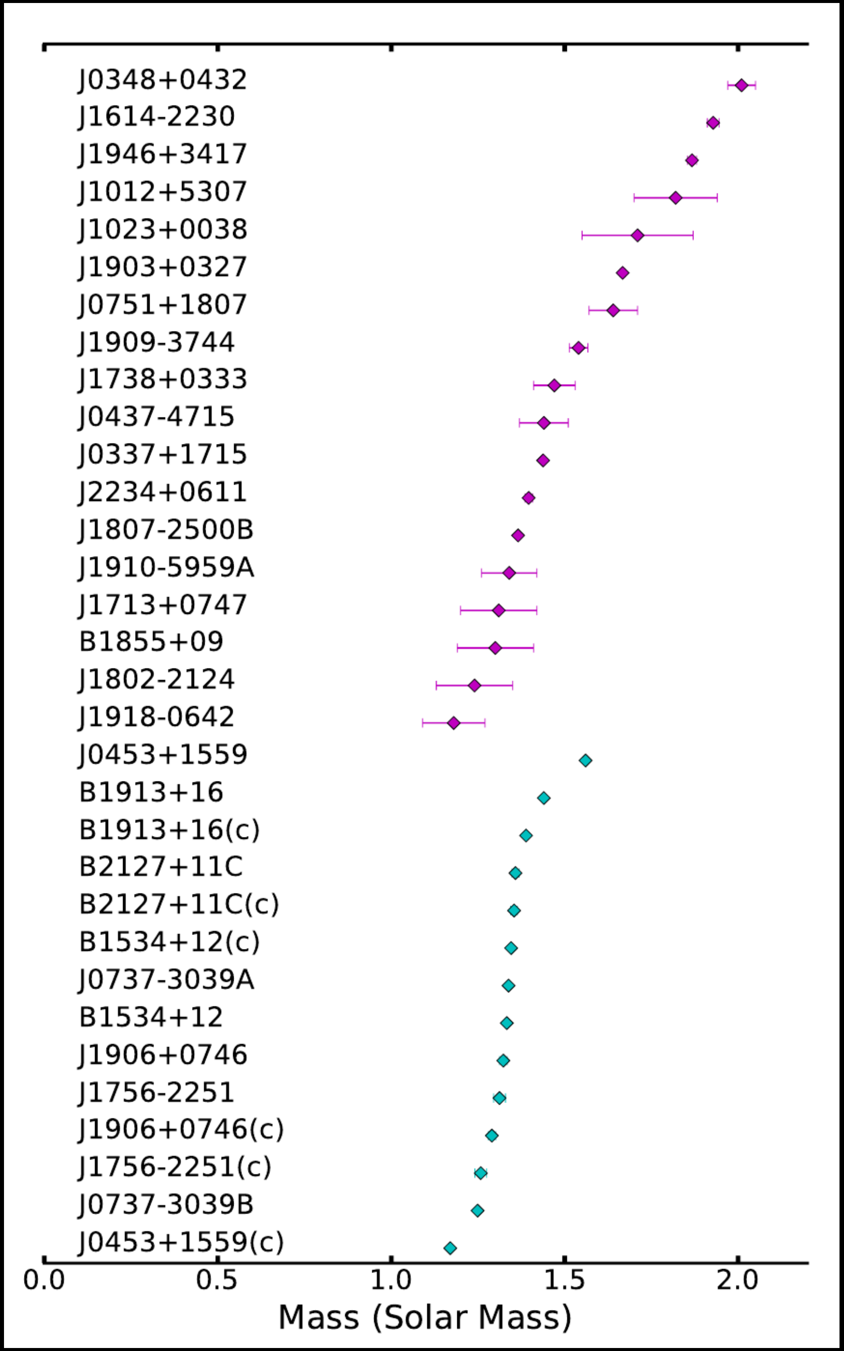
- Double neutron-star systems could be a special case
- NSs might not collapse to Black Holes



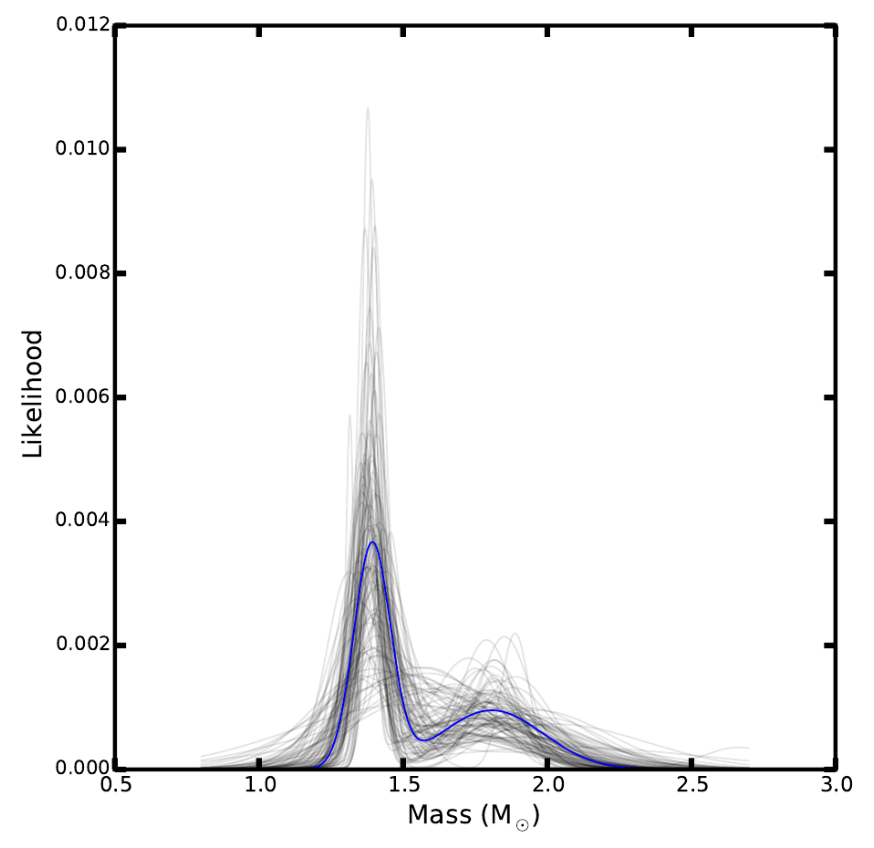
Ozel et al., 2012, ApJ, 757, 550

See also:
Kiziltan et al, arXiv:1309.6635

Bi-modal MSP Mass Distribution?



- Enough MSP masses now that distribution may be more complex

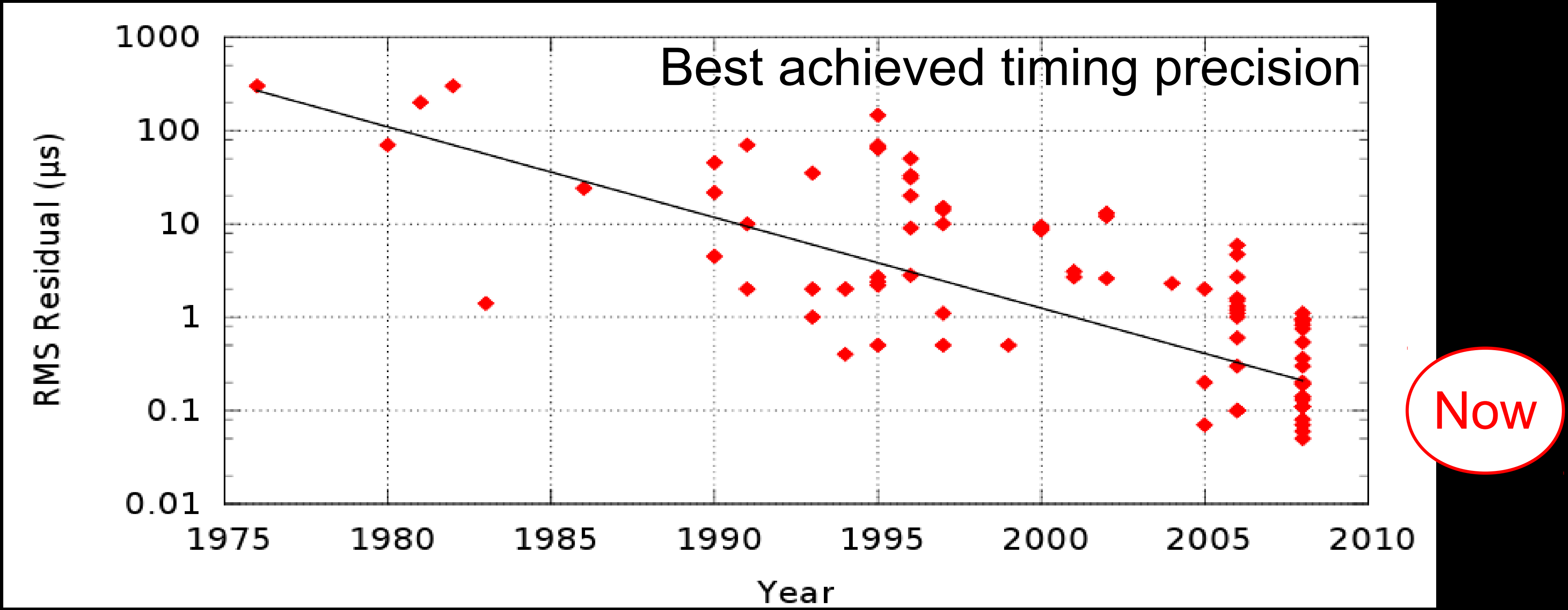


Antoniadis et al., 2016, ApJ submitted (arXiv:1605.01665)

How to do better?

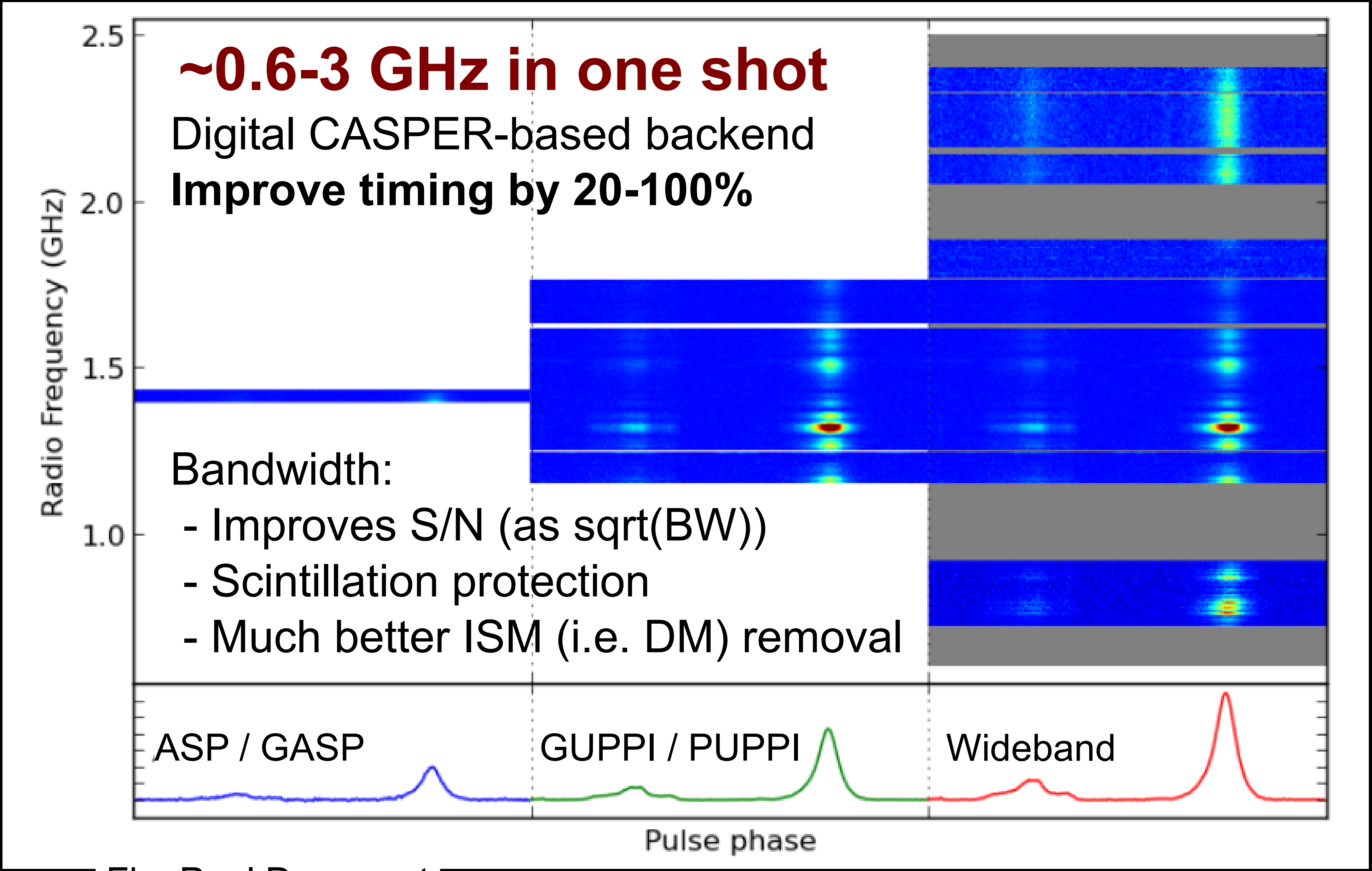
- Improved fidelity and systematics – instrumentation
- Better pulsars (right ones are rare) – searches
- PSRs are faint (sensitivity limited) – bigger telescopes

These improvements dramatically help all pulsar science!



R. Jenet & P. Demorest

Ultrawideband Receivers+Backends



~0.6-3 GHz in one shot

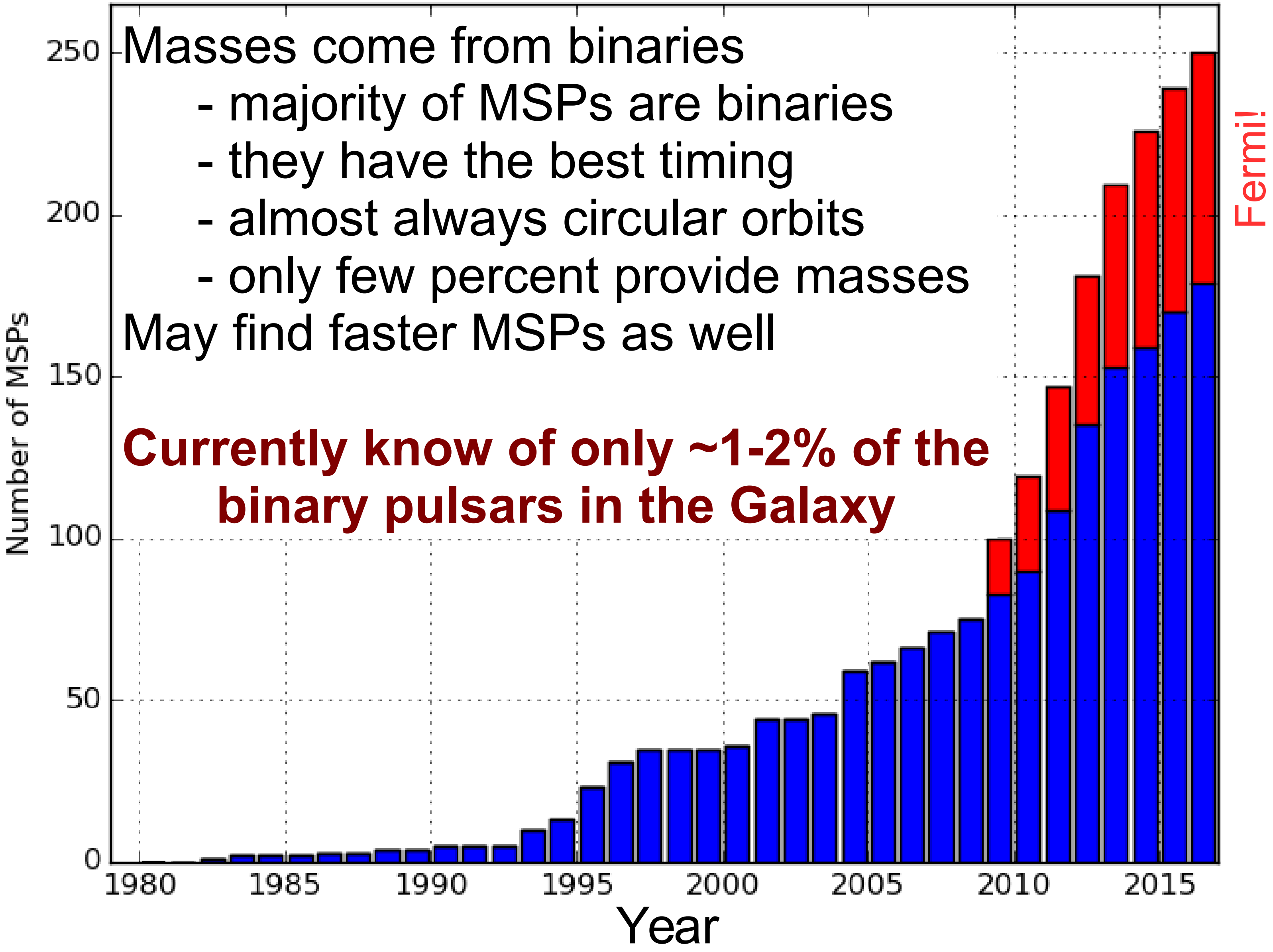
Digital CASPER-based backend

Improve timing by 20-100%

Bandwidth:
- Improves S/N (as sqrt(BW))
- Scintillation protection
- Much better ISM (i.e. DM) removal

Fig: Paul Demorest

Searches for Millisecond Pulsars



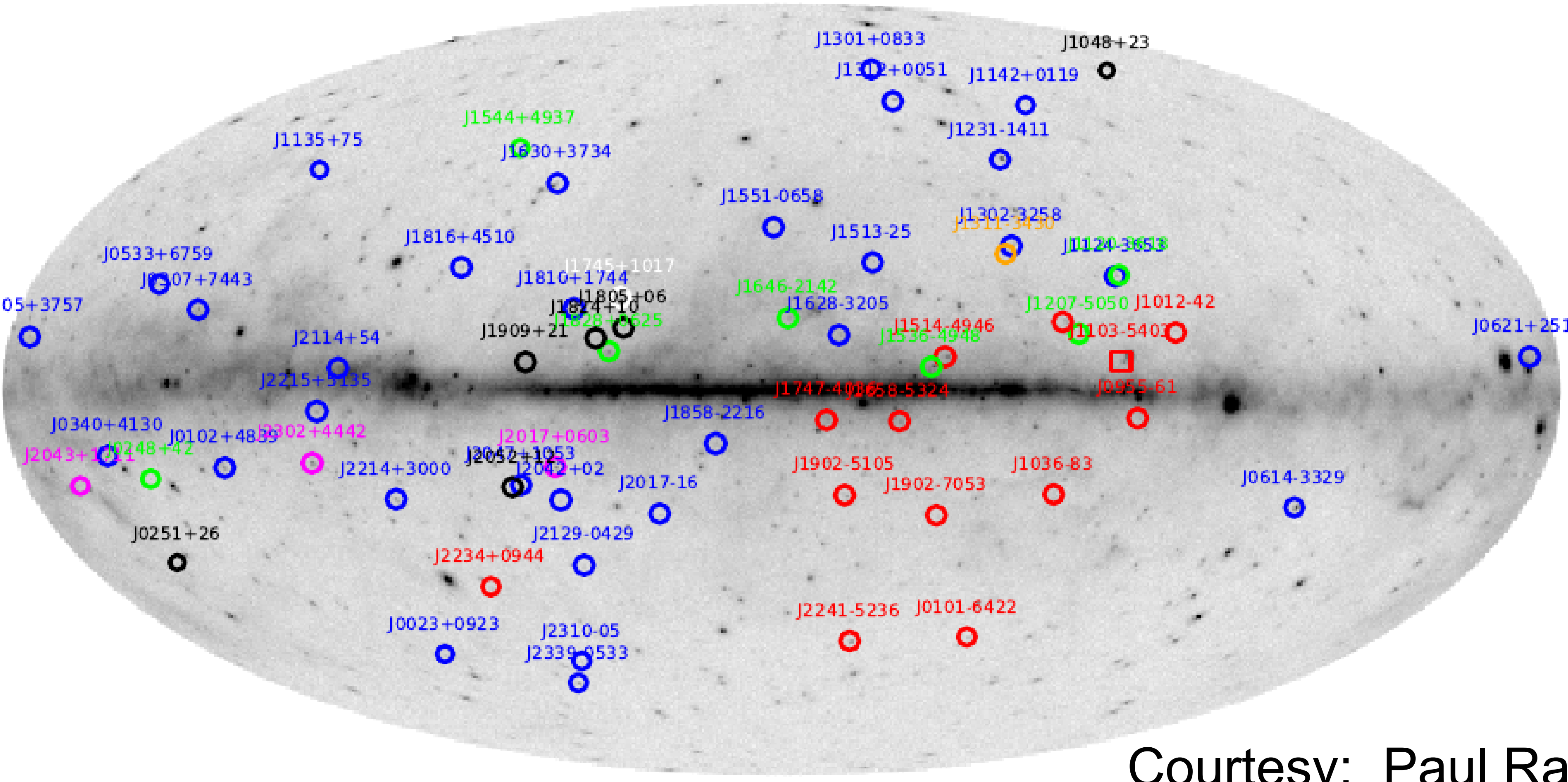
Masses come from binaries
- majority of MSPs are binaries
- they have the best timing
- almost always circular orbits
- only few percent provide masses

May find faster MSPs as well

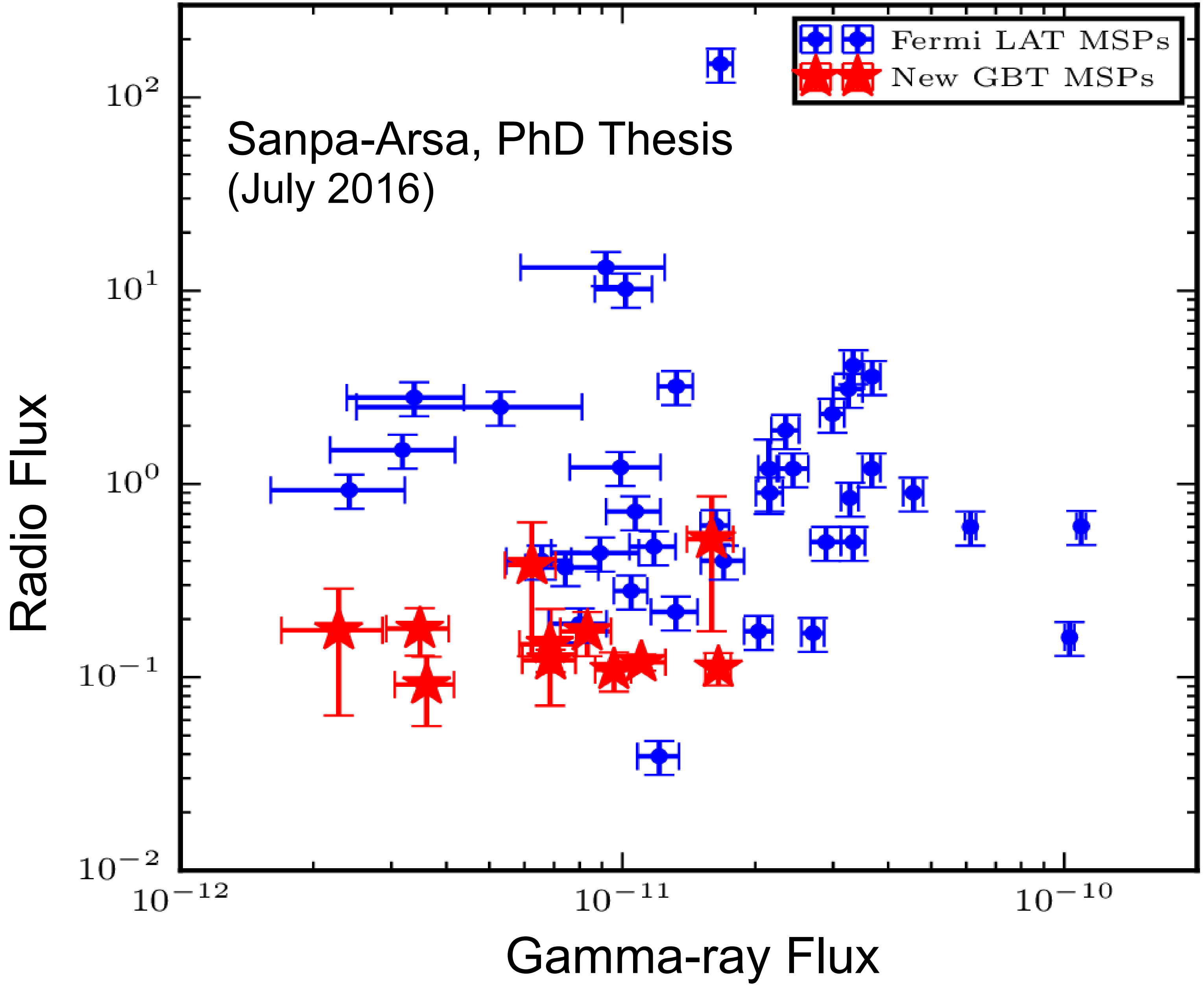
Currently know of only ~1-2% of the binary pulsars in the Galaxy

Currently ~70 new Radio/gamma-ray MSPs because of *Fermi*!

~10-20% of them look like they will be "good timers"
~30% are strange eclipsing systems: "Redbacks" and "Black-Widows"



Courtesy: Paul Ray



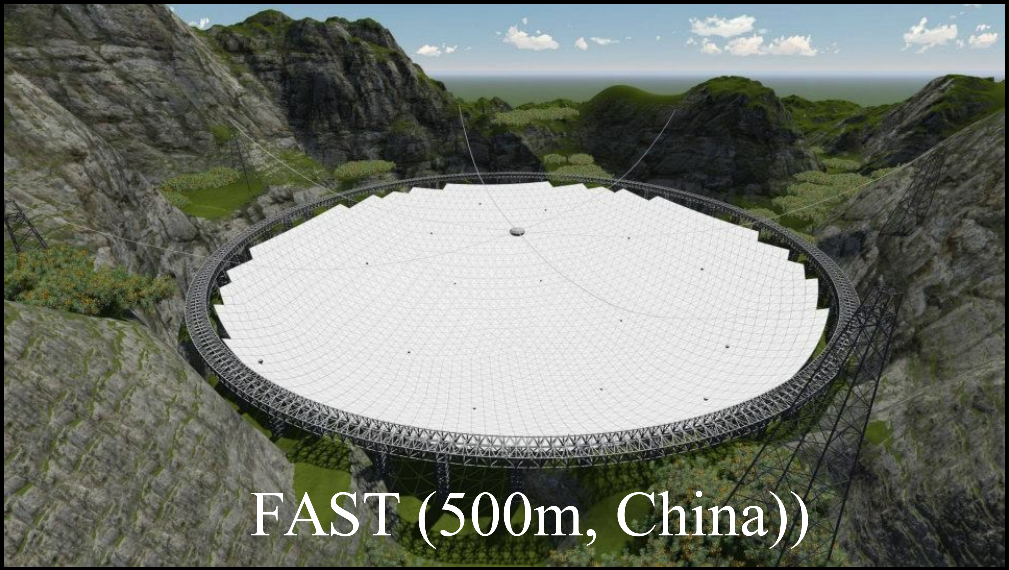
Sanpa-Arsa, PhD Thesis
(July 2016)

What about the future?

- We only know of about 2,000 out of ~50,000+ pulsars in the Galaxy!
  - Many of them will be “Holy Grails”
    - Sub-MSP, PSR-Black Hole systems, MSP-MSP binary
- Several new huge telescopes...

We need them because we are sensitivity limited!

MeerKAT (64 dishes, SA)

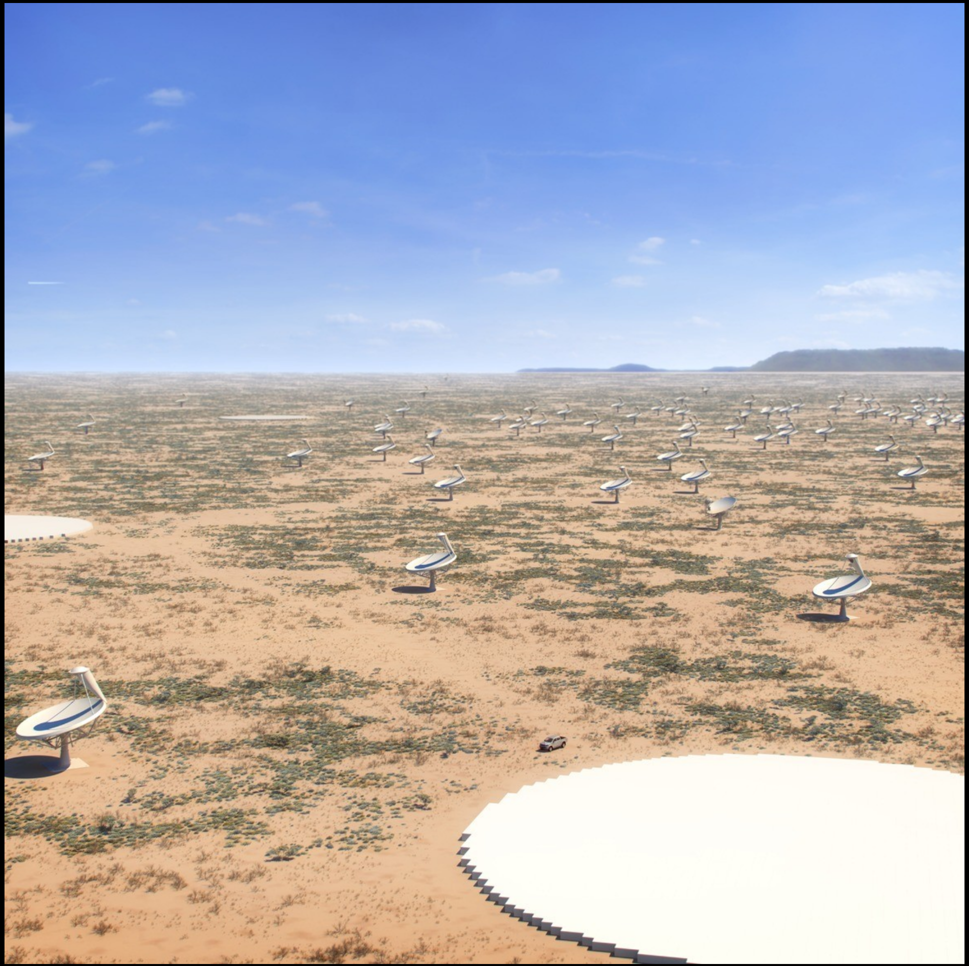


FAST (500m, China))


WWW.NEWS.CN

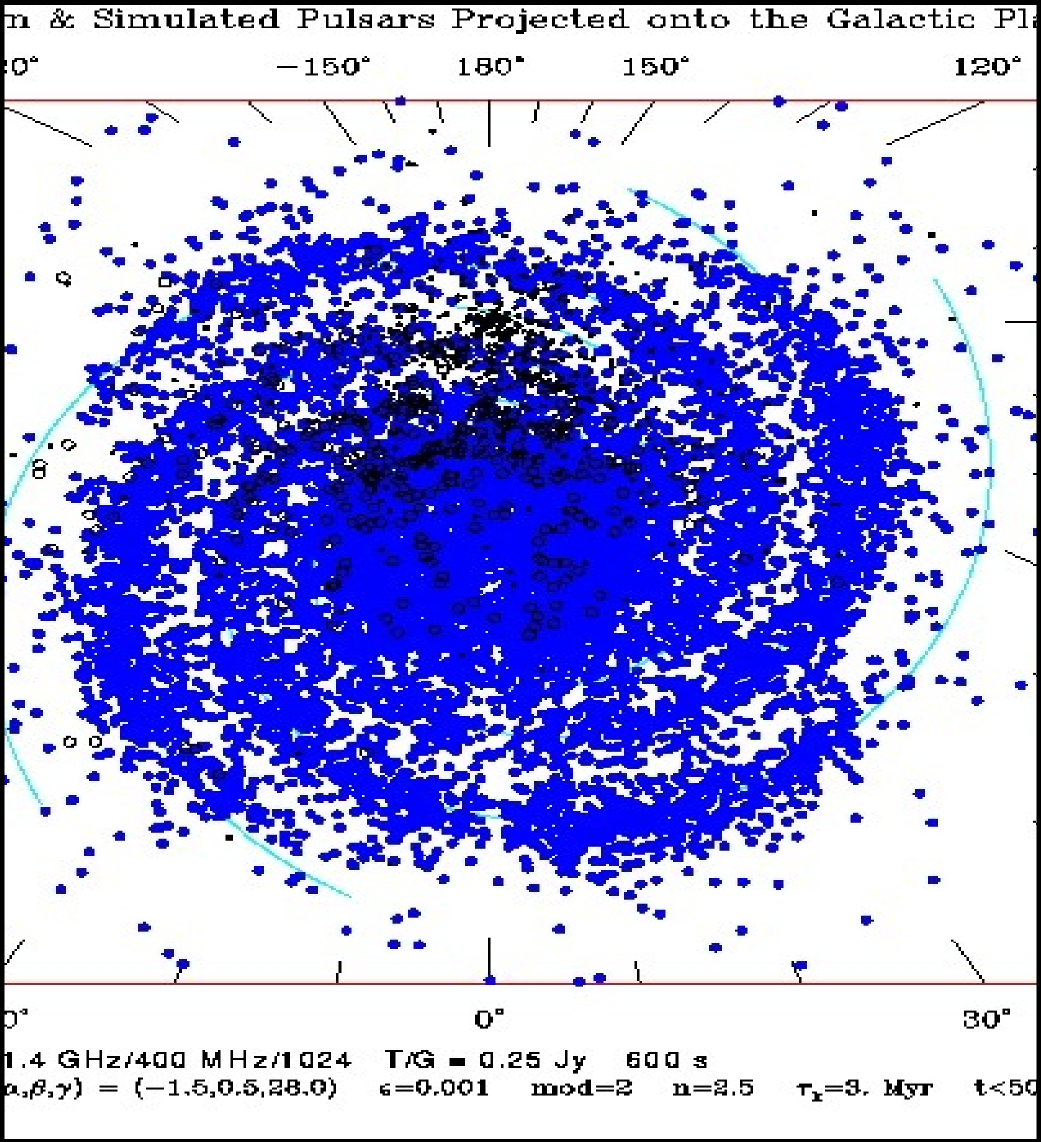
Square Kilometer Array

- SKA-1 (650 M€) 2020+, SKA-2 (3-5G€) 2025+
- 2 (or 3) arrays in S. Africa and W. Australia
- Should find most of the pulsars in the Galaxy
  - But will be incredibly difficult – can't record the data!



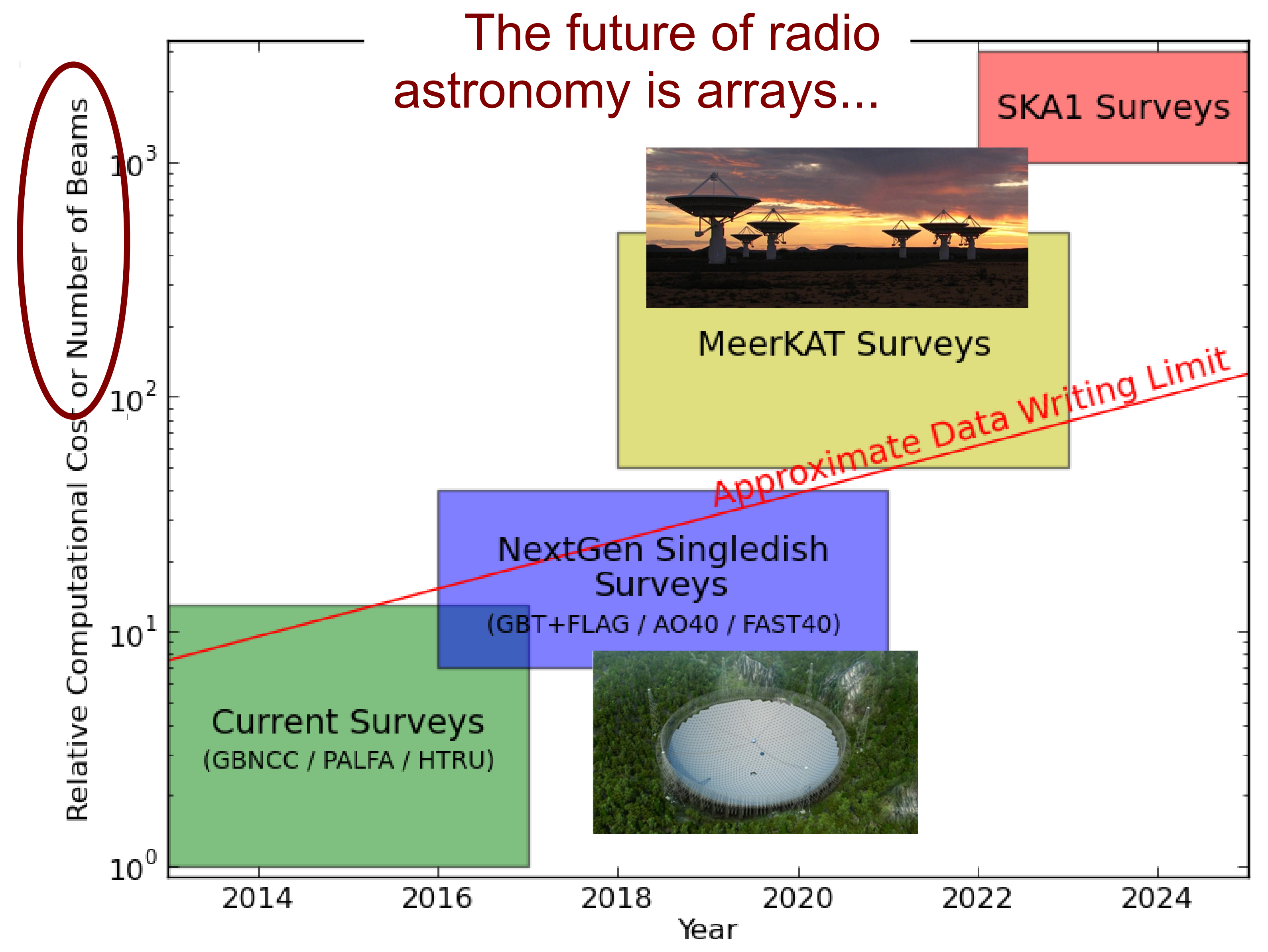
SKA Phase 1 Pulsar Searching

- See Smits et al. 2009
- ~20,000 each of potentially visible normal pulsars, RRATs, and MSPs
- SKA1 has the potential to find a large fraction (~50%?) of these pulsars
- Highly specialized computing
- Survey speed for Phase 1 with 15m dishes and fully sampled primary beam is: 42x Parkes MB, 140x GBT, 54x Arecibo, 23x FAST



Simulation by J. Cordes

Major PSR search problem: data rates



Summary

- Useful NS masses require luck and high-precision timing
- Moore's law caused a MSP revolution in the last ~5 years:
  - New broad-bandwidth instrumentation
  - New high-sensitivity searches
- We know of only a small percent of the pulsars in the Galaxy (productive searches)
- Only a small percent of the ones we know provide good masses (or other great science: new exotic pulsars)
- *Many* more high-precision NS masses (including high- and low-mass ones) will be measured with upcoming telescopes, such as MeerKAT, FAST, and the SKA