Measuring Radio Pulsar Masses

Paul Demorest, NRAO

Talk Outline:

1. Background, motivation for measuring NS masses.

2. How to measure NS masses from radio timing.

3. Eccentric binary MSPs.

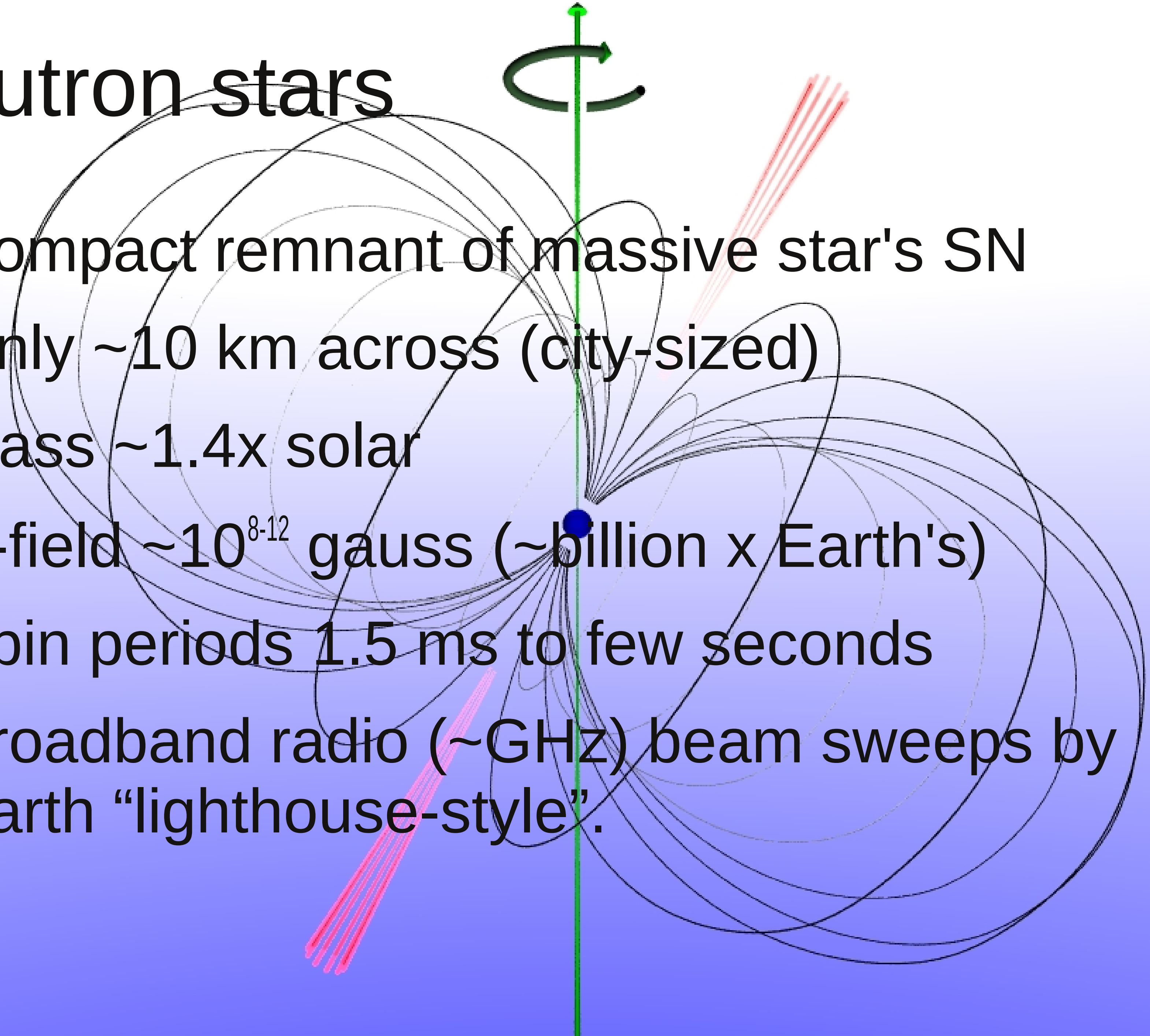
4. Shapiro delay and J1614-2230

5. Implications of J1614-2230 and future prospects.

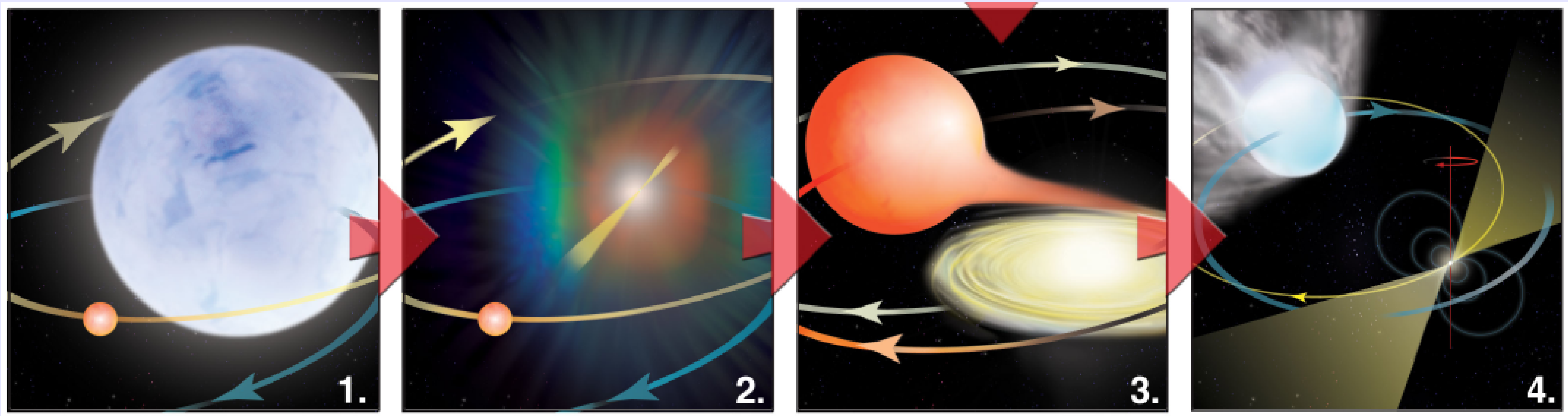
Thanks to Scott Ransom for several slides in this talk!

Neutron stars

- Compact remnant of massive star's SN
- Only ~10 km across (city-sized)
- Mass ~1.4x solar
- B-field $\sim 10^{8\text{-}12}$ gauss (~billion x Earth's)
- Spin periods 1.5 ms to few seconds
- Broadband radio (~GHz) beam sweeps by Earth “lighthouse-style”.

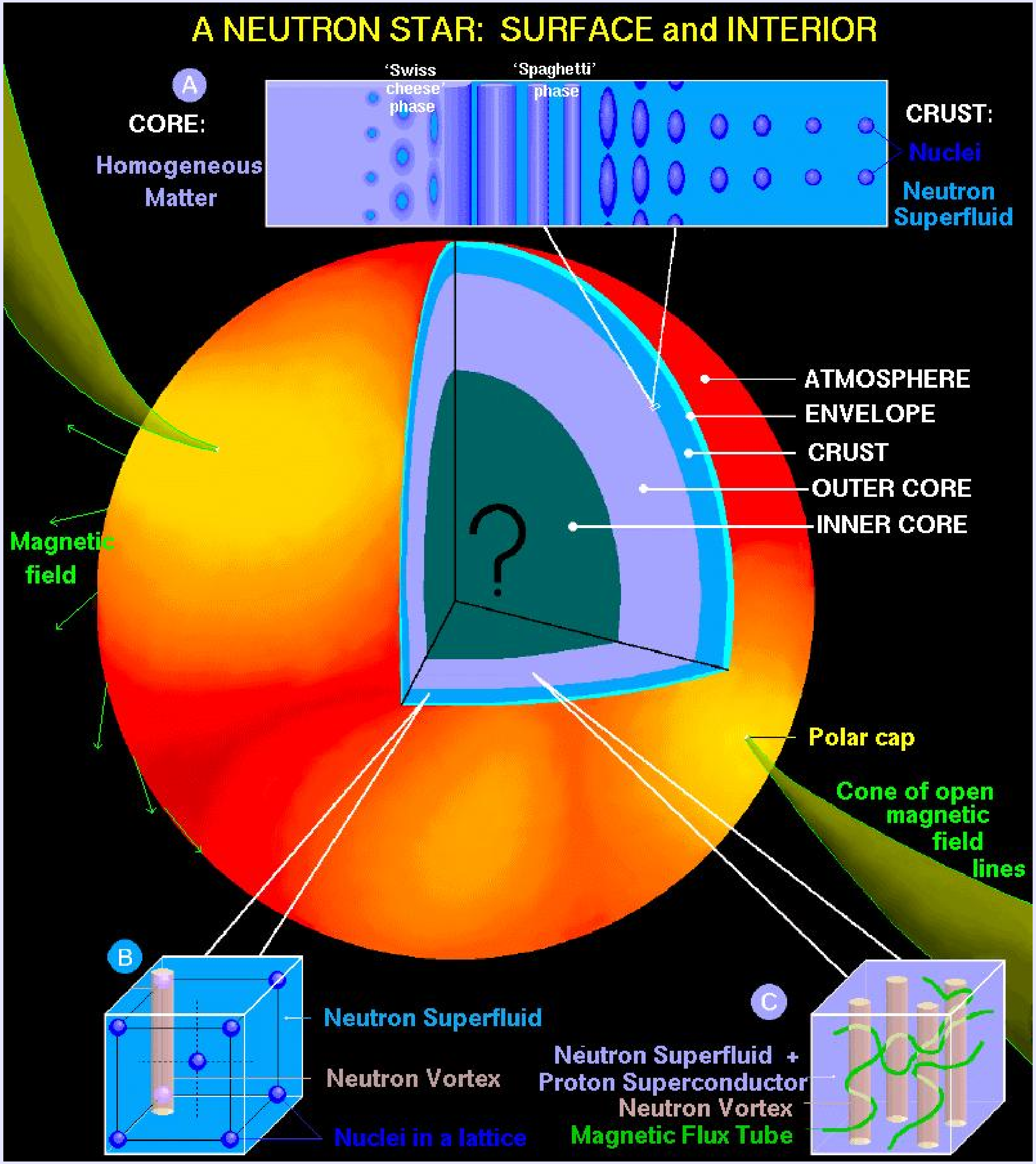


About 10% of observed radio pulsars are “recycled” millisecond pulsars (MSPs). These are spun up by accreting matter from a companion star:



(Image: B. Saxton, NRAO)

These rare objects are incredibly useful for exploring a variety of extreme physics and astrophysics!



Central density is several times that of an atomic nucleus.

So what is the "?" ....

… just neutrons?

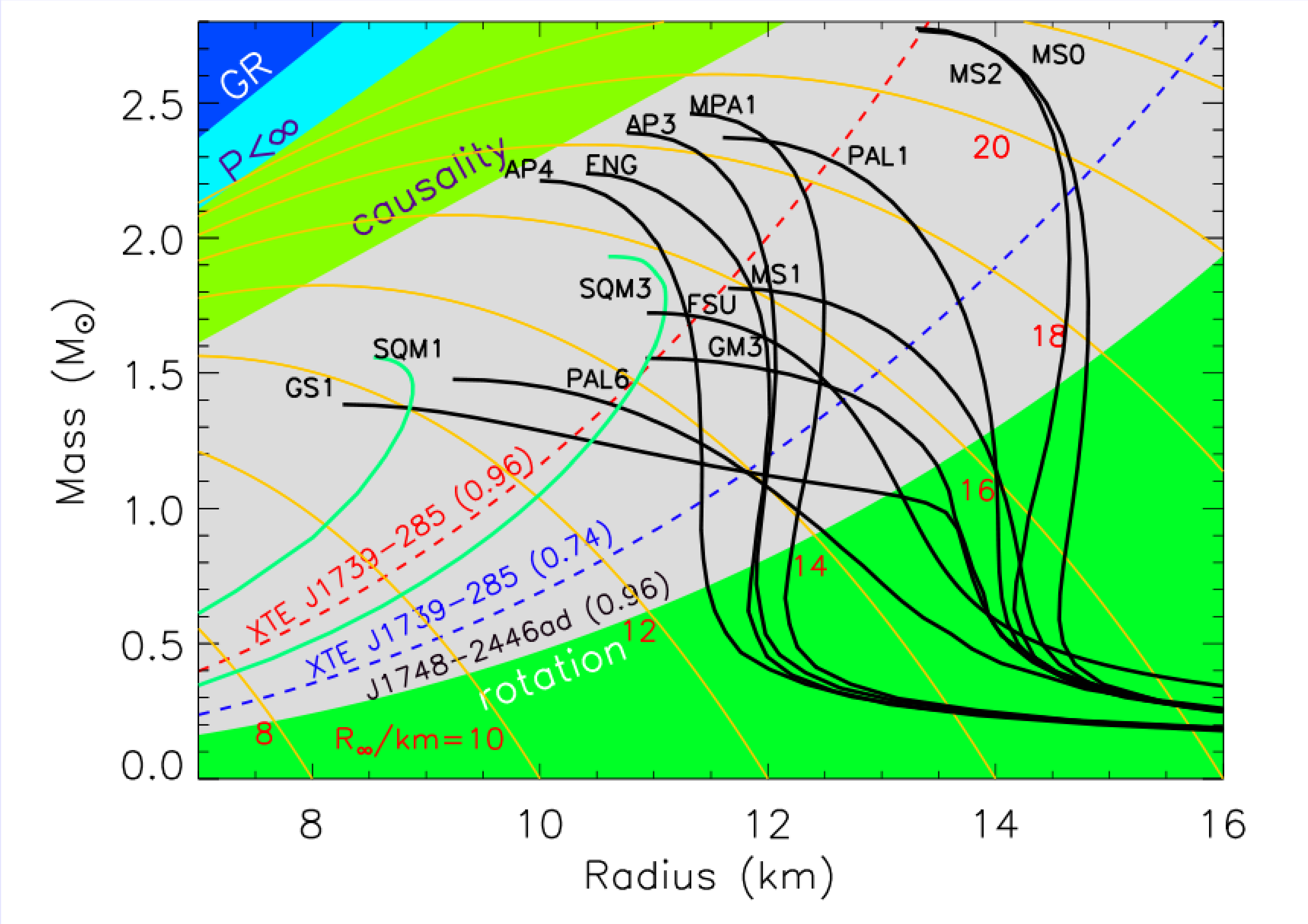
… hyperons?

… kaon condensate?

… free quarks?

Each makes a specific prediction for the NS equation of state.

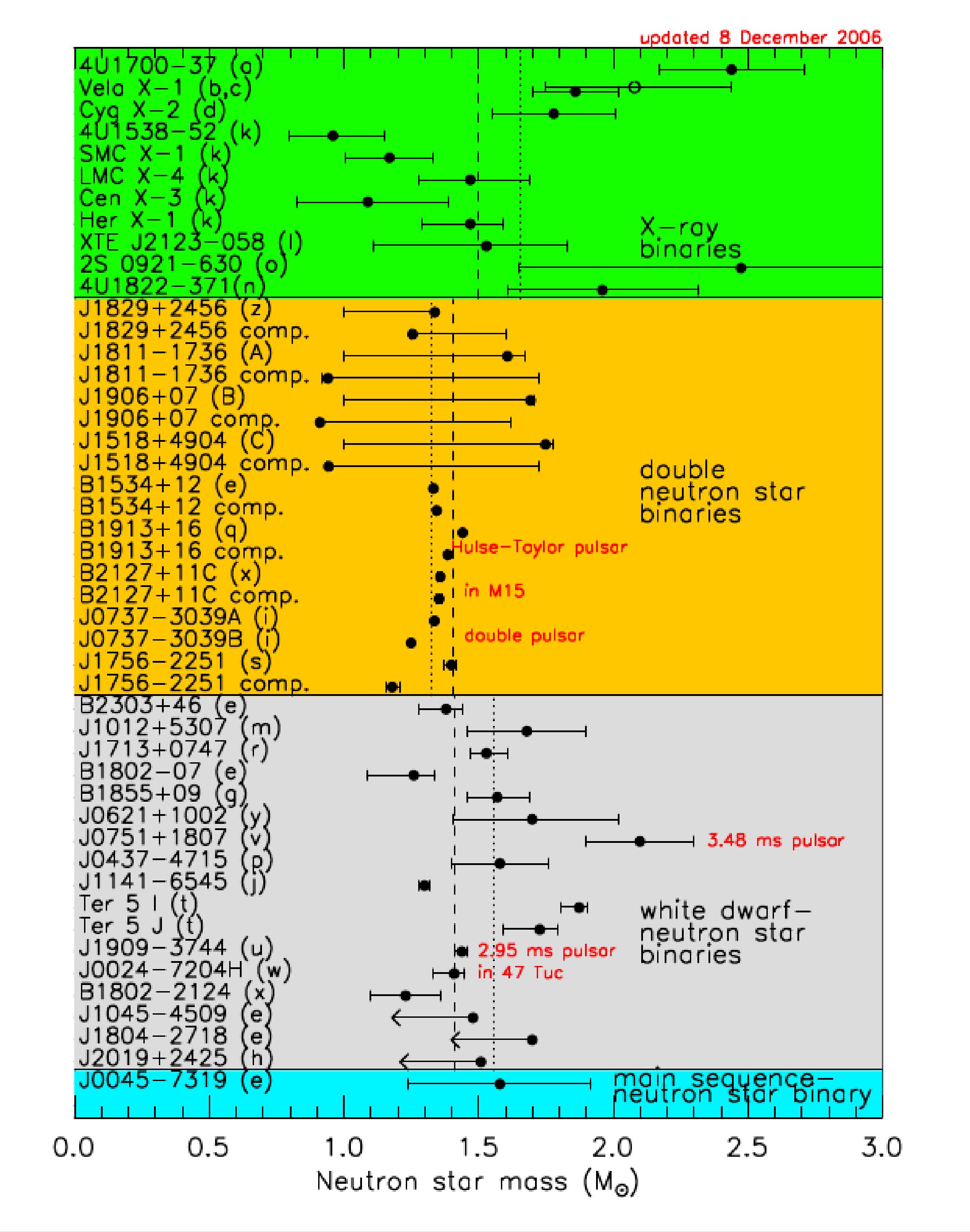
(see reviews by Lattimer & Prakash, 2004, 2007)



(Lattimer & Prakash, 2007)

Each EOS predicts a specific mass vs radius line.
Mass or radius measurements experimentally constrain the EOS.

The NS mass situation as of ~2007:



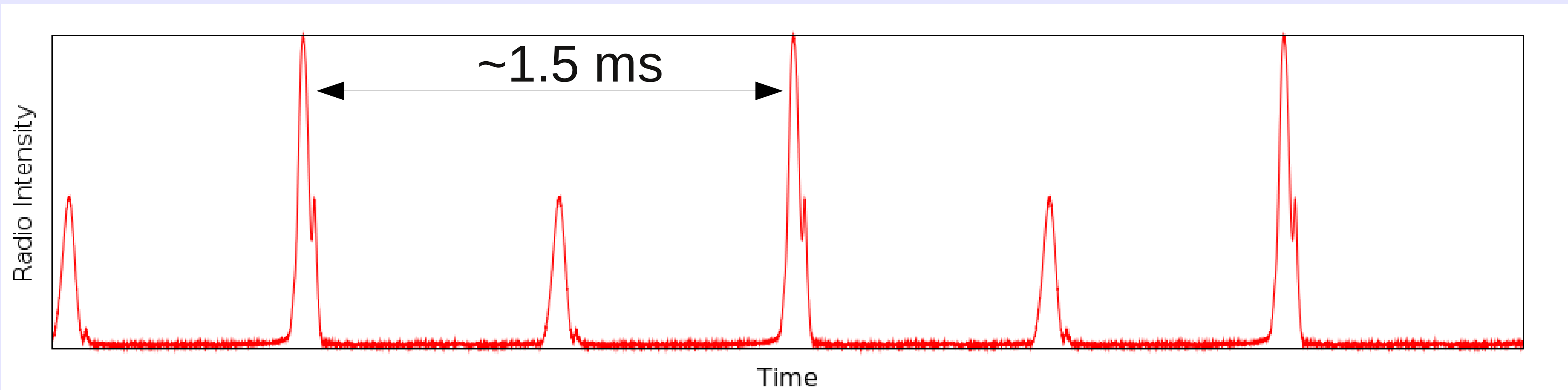
(Lattimer & Prakash, 2007)

X-ray binaries; large error bars; model dependence; radius info.

DNS binaries; mildly recycled; eccentric orbits; masses cluster at ~1.4.

True MSPs; circular orbits; hints of a wider mass range...

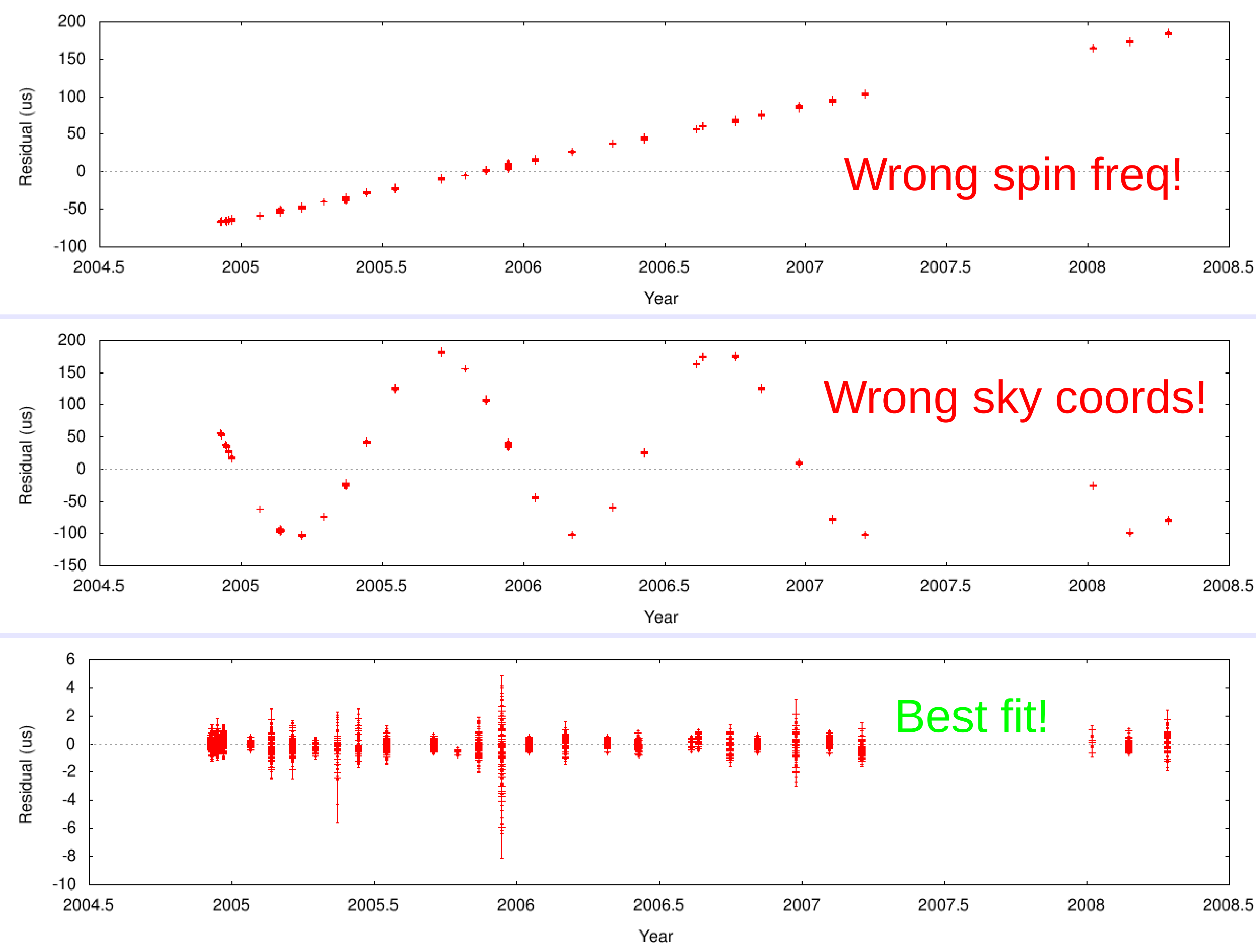
By measuring pulse arrival times at Earth, we can use MSPs as *extremely* precise astronomical clocks:



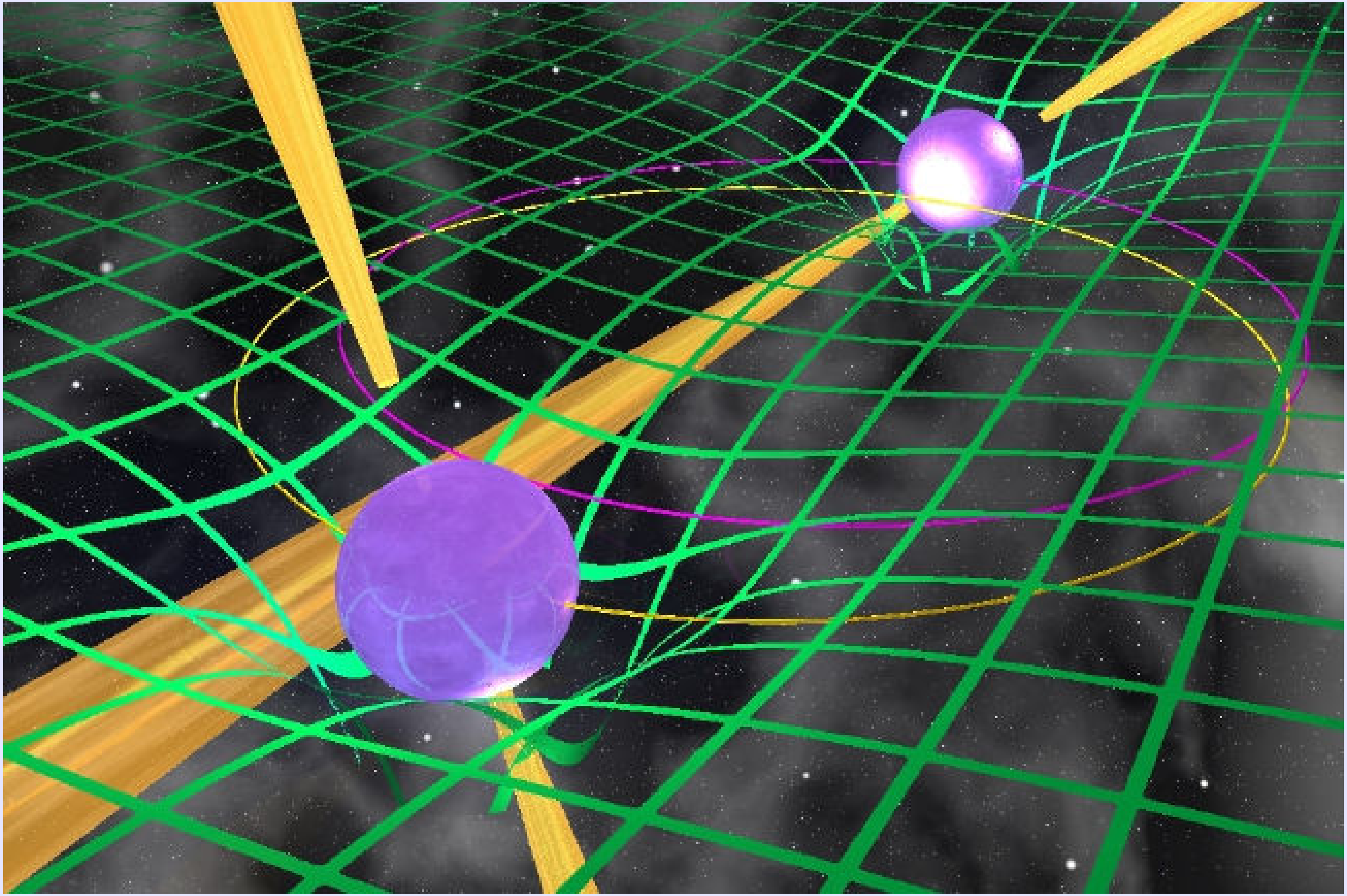
Phase-connected “timing model” accounts for every rotation of the star, giving impressive precision:

P = 1.5578064688197945 ms
+/- 0.0000000000000004 ms !

Timing residuals = Observed – model-predicted arrival times



Binary orbital parameters can be determined extremely accurately from timing.



Post-Keplerian Orbital Parameters

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

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

(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

Post-Keplerian Orbital Parameters

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

$\dot{\omega}$ =	Need eccentric orbit and time for precession	(Orbital Precession)
γ =		(Grav redshift + time dilation)
$\dot{P}_b$ =	Need compact orbit and a lot of patience	
r =	Need high precision, Inclination, and m_2	(Shapiro delay: “range” and “shape”)
s =		

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:

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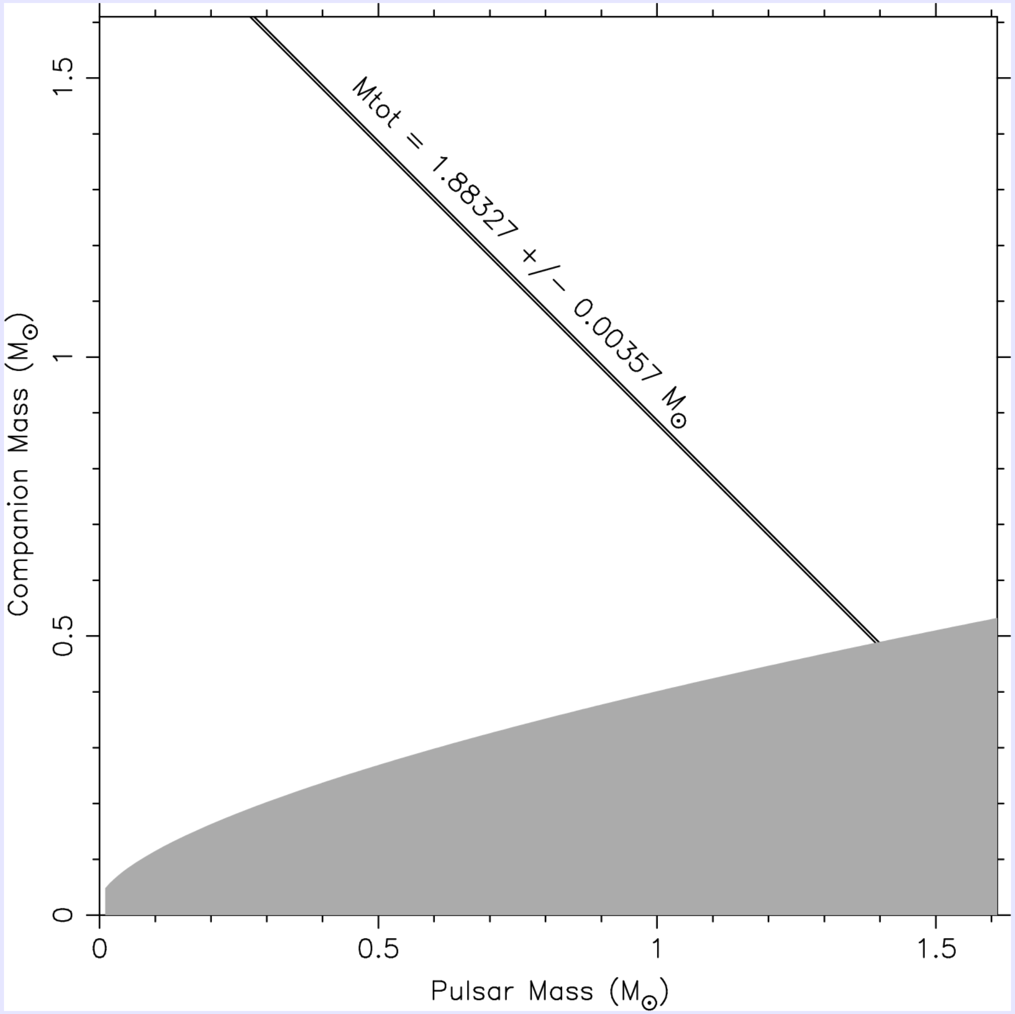
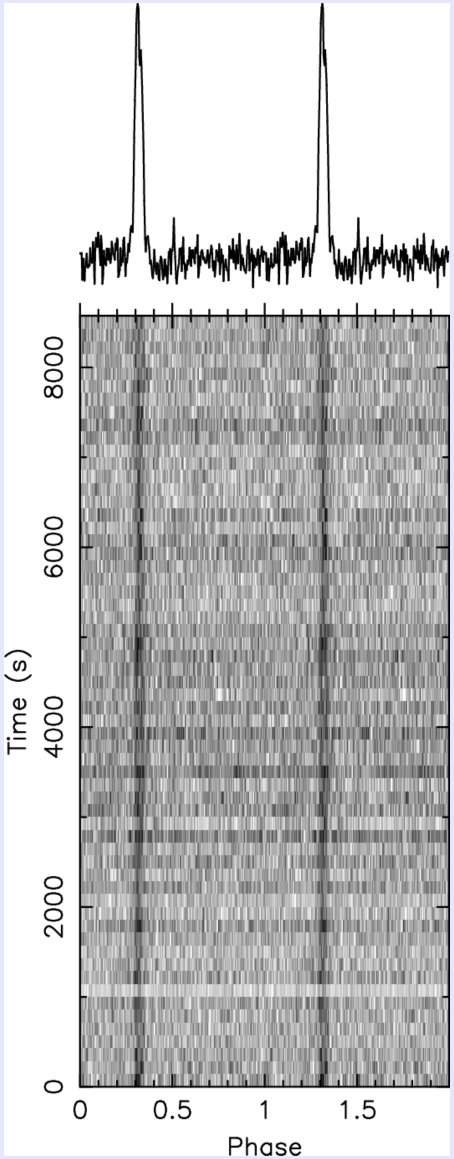
Precession of Periastron

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

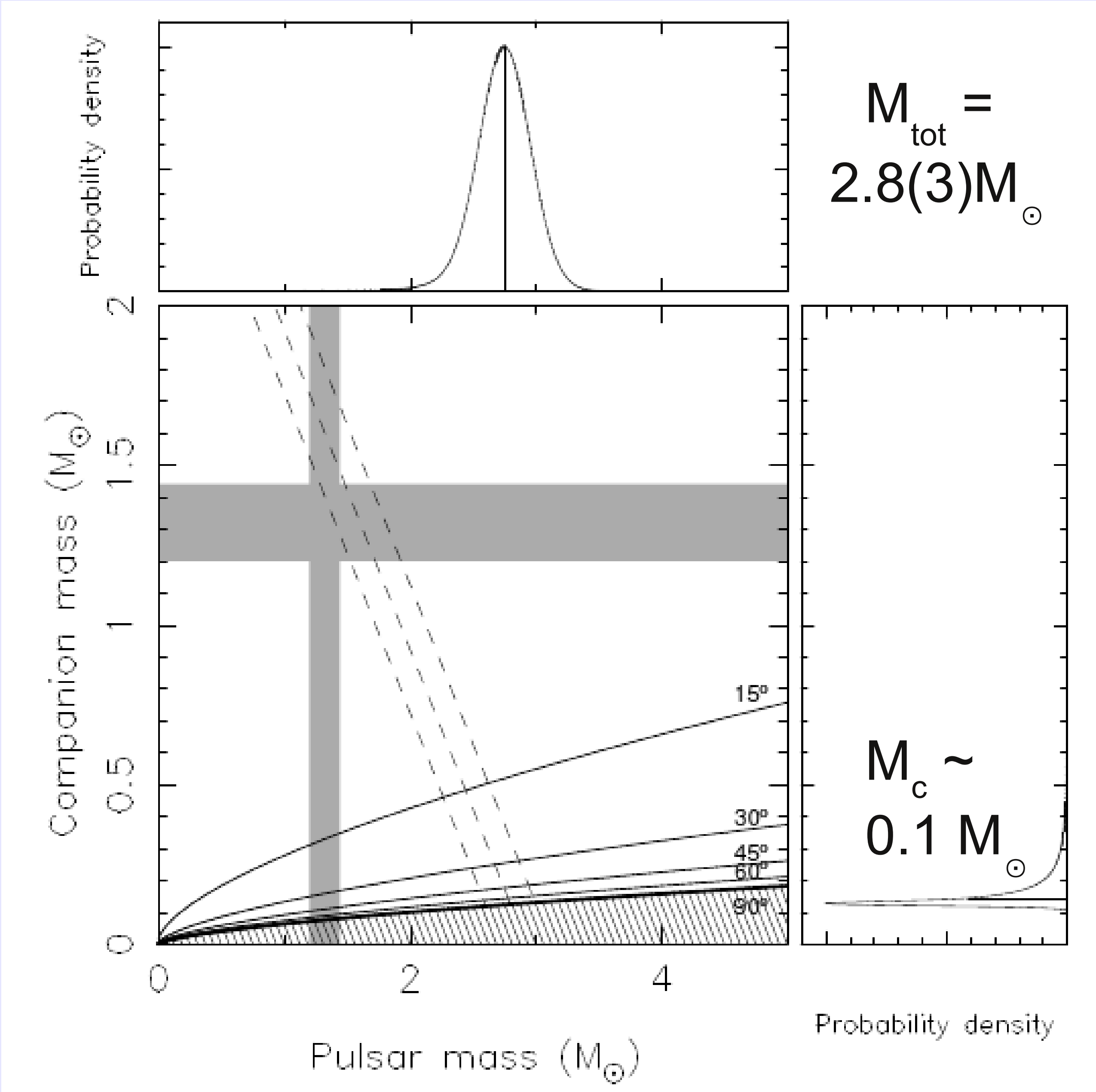
NGC6440B: A Massive PSR?



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

13 Eccentric (e>0.3) PSRs in Clusters

Name	P(ms)	Pb(d)	E	Mcmin	Mtot	Mpmed
Ter5ai	21.228	0.85	0.440	0.49	**1.883(4)**	**1.39**
Ter5J	80.338	1.10	0.350	0.34	**2.19(2)**	**1.73**
Ter5I	9.570	1.33	0.428	0.21	**2.171(3)**	**1.87**
Ter5Z	2.463	3.49	0.761	0.22	**1.79(1)**	**1.53**
Ter5U	3.289	3.57	0.605	0.39	**2.26(1)**	**1.73**
Ter5X	2.999	5.00	0.302	0.25	**1.91(5)**	**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**
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	**2.4(2)**	**1.79**
M28D	79.835	30.41	0.776	0.38	**1.2(7)**	

Table by Scott Ransom
M5B: Freire et al 2008, ApJ, 679, 1433

Multiple relativistic params

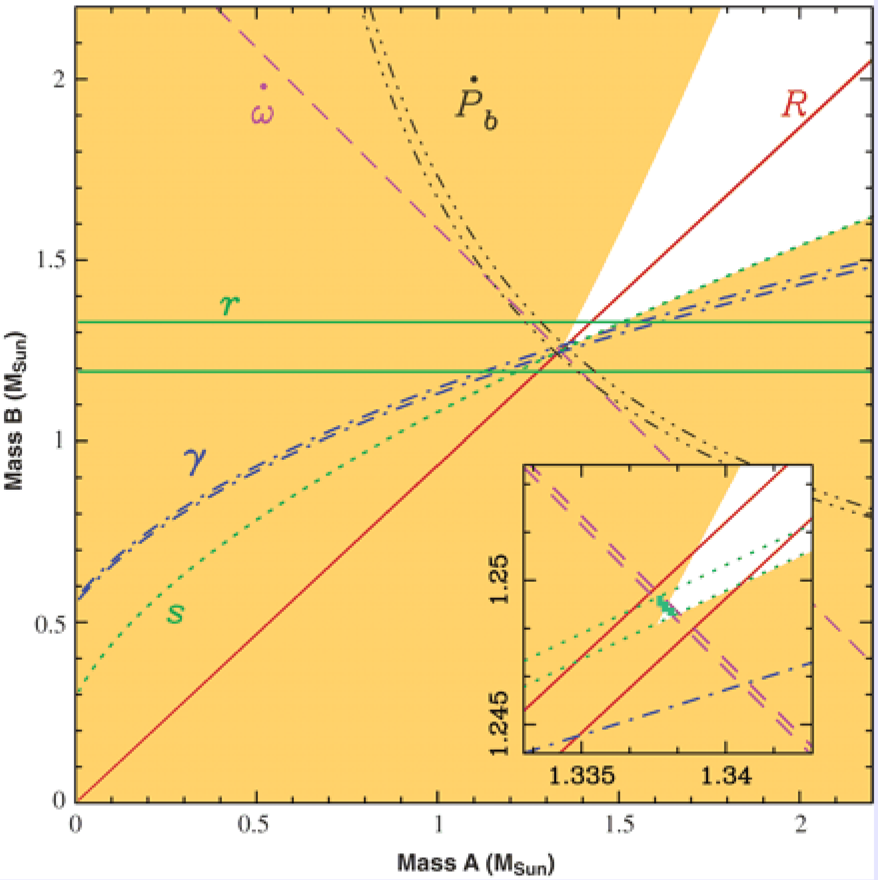
2 PK parameters → measurements of both masses without cos(i) assumptions.

3 or more → tests GR for consistency.

Commonly done in double-NS binaries (eccentric, compact orbits).

$$
\begin{aligned}
\dot{\omega} &= 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1} \\
\gamma &= e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} m_c(m_p+2m_c) \\
\dot{P}_b &= -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} f(e) T_\odot^{5/3} m_p m_c M^{-1/3} \\
r &= T_\odot m_c \\
s &= \sin i,
\end{aligned}
$$

"Post-Keplerian" orbital parameters, each provides a different constraint in mass-mass plane:



(J0737-3039; Kramer et al. 2006)

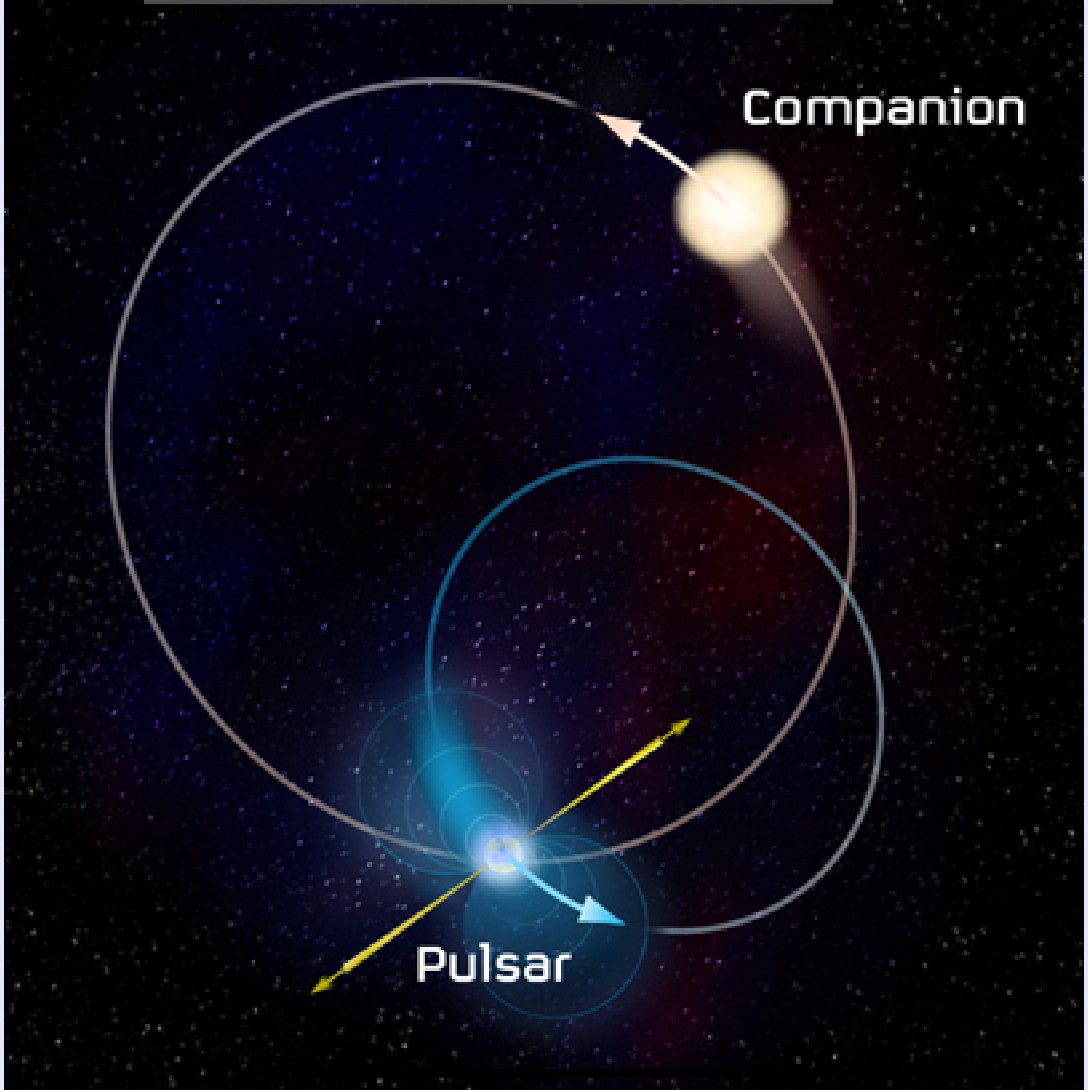
PSR J1903+0327 with Arecibo P-ALFA

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

This thing is weird.

- Fully recycled PSR
- Highly eccentric orbit
- Massive likely main-sequence star companion
- Massive NS (1.67(2) Msun)

  (Freire et al.2011)
- High precision timing despite being distant and in Galactic plane



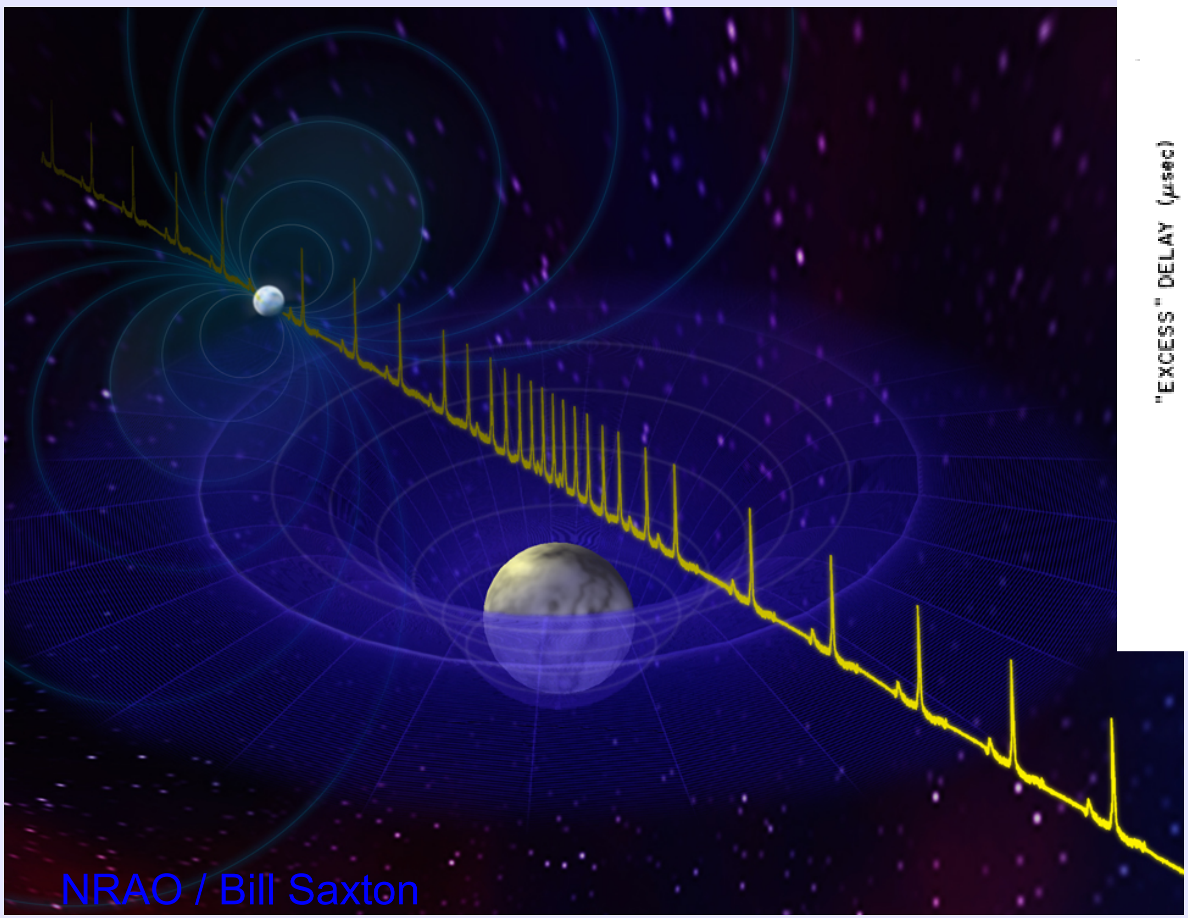
Bill Saxton, NRAO/AUI/NSF

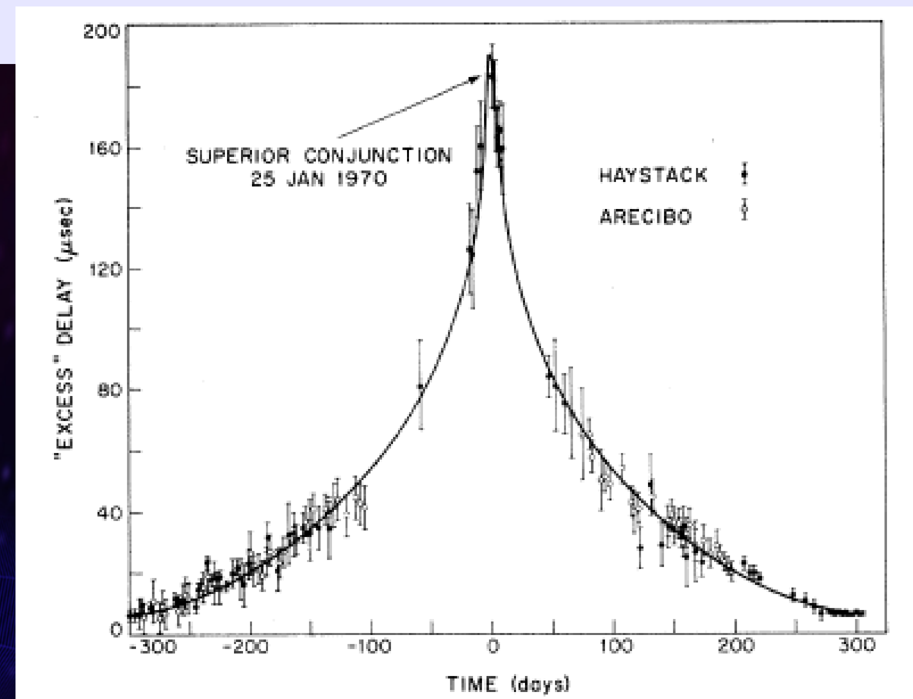
Shapiro Delay

VOLUME 13, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1964

FOURTH TEST OF GENERAL RELATIVITY

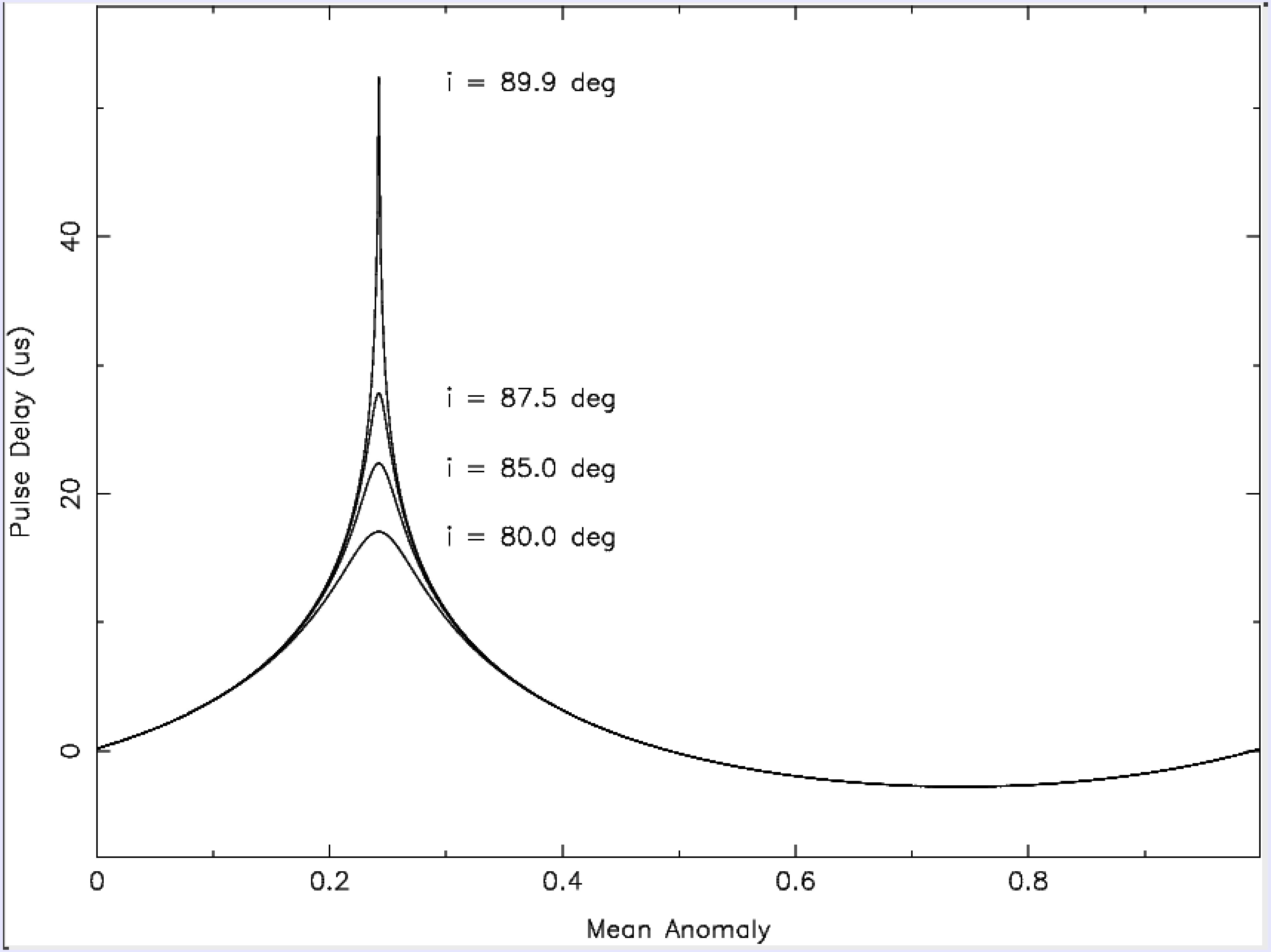
Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)





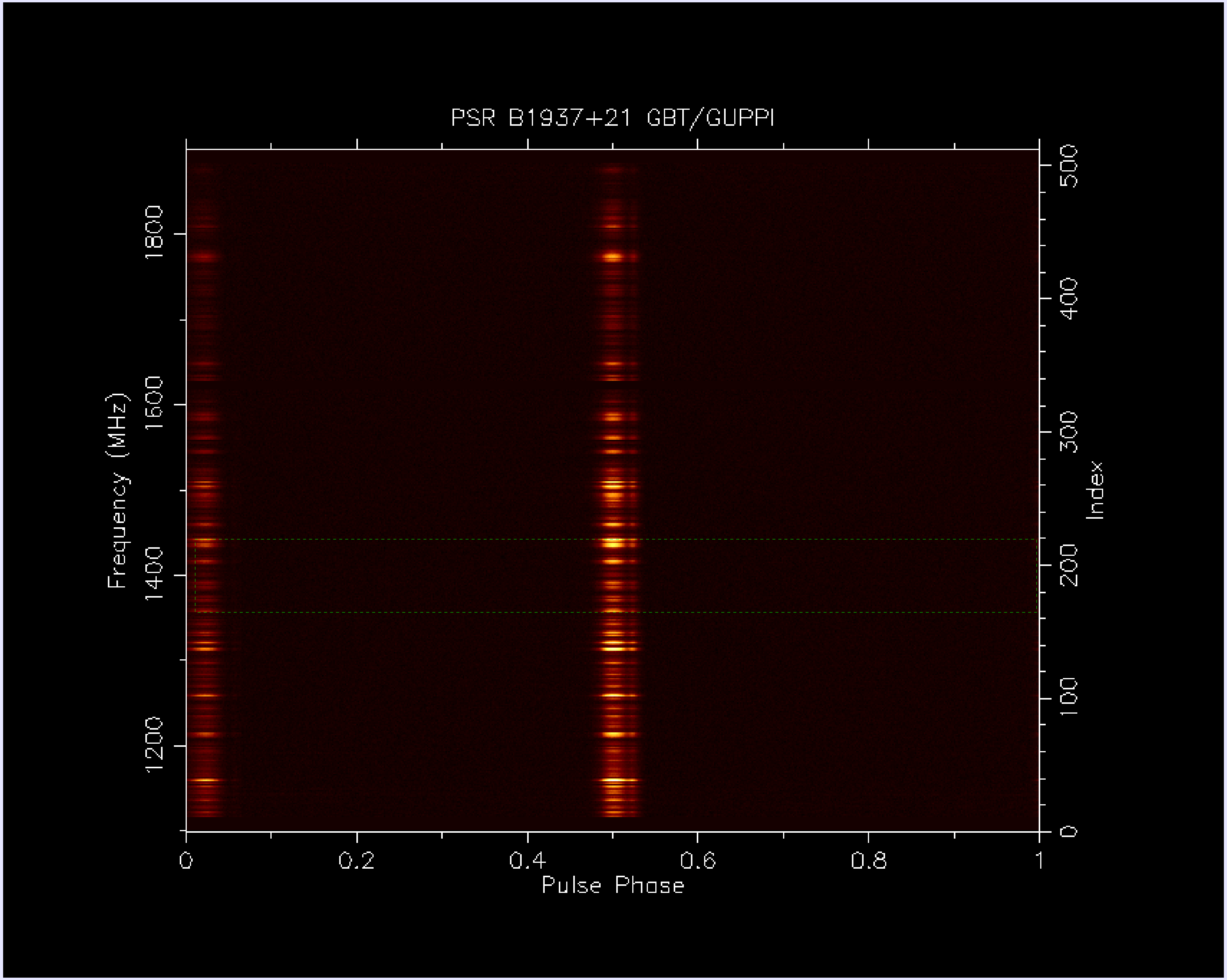
Irwin Shapiro 1964
Shapiro et al. 1968, 1971

Shapiro delay amplitude strongly dependent on geometry:



Green Bank Telescope: 100-m, fully steerable

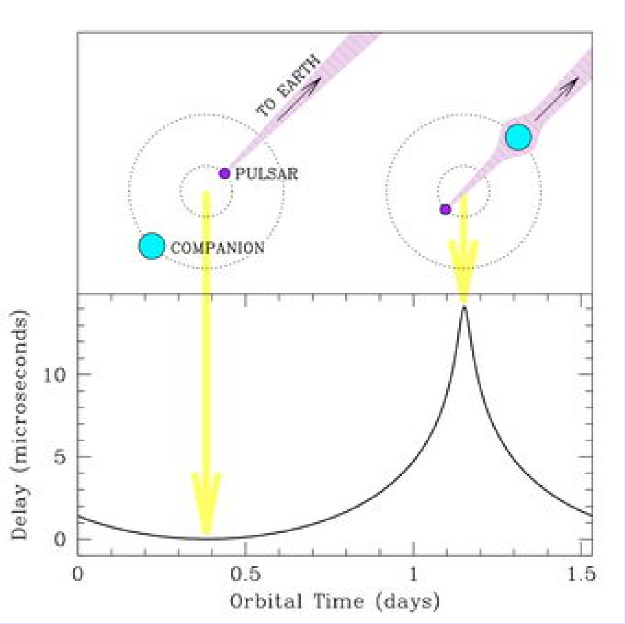
Coherent GUPPI first light
December 2009, PSR B1937+21, 1100--1900 MHz

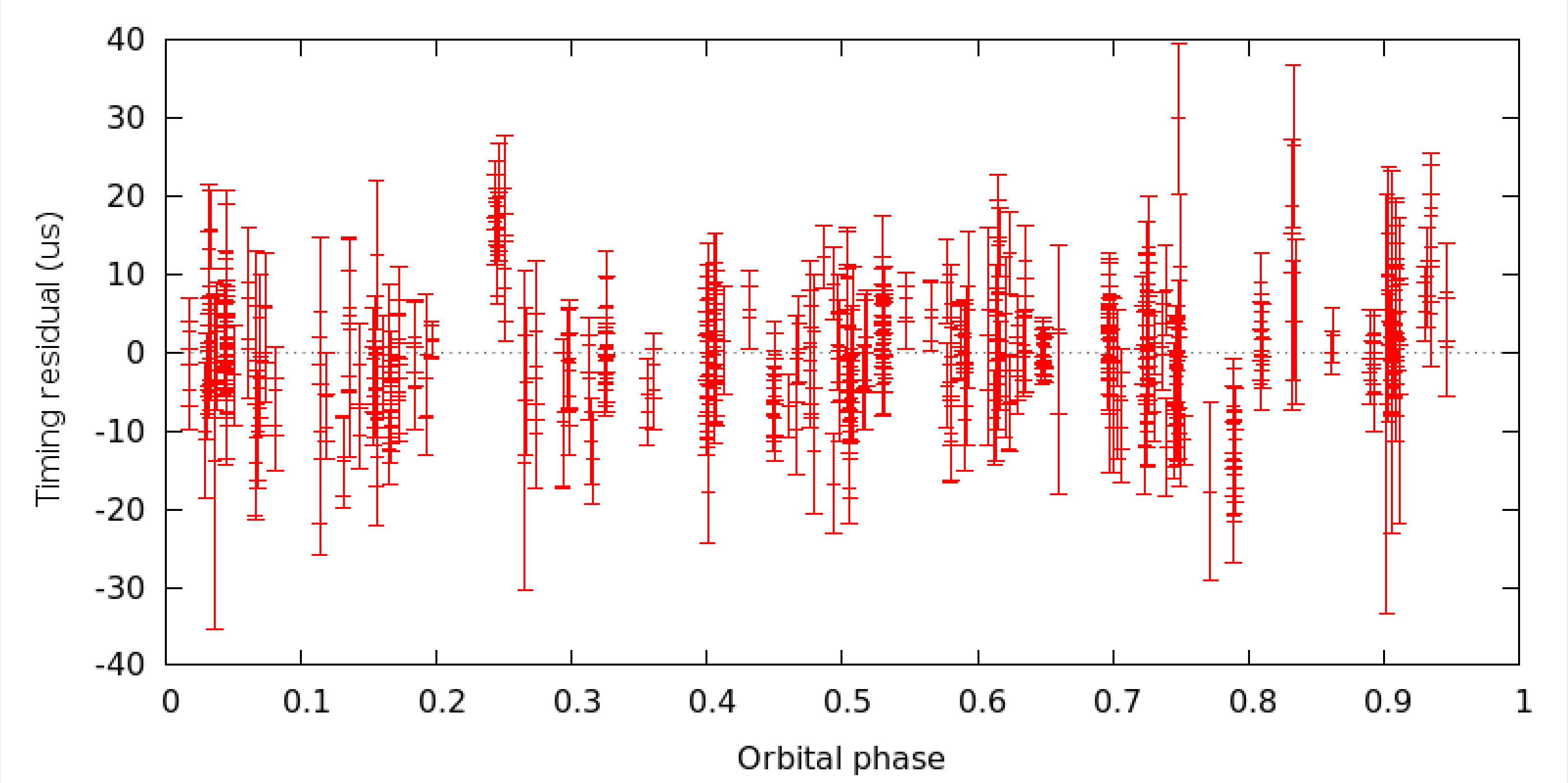


GASP
band

PSR J1614-2230 is a 3-ms pulsar in an 8.7-day orbit with a WD.

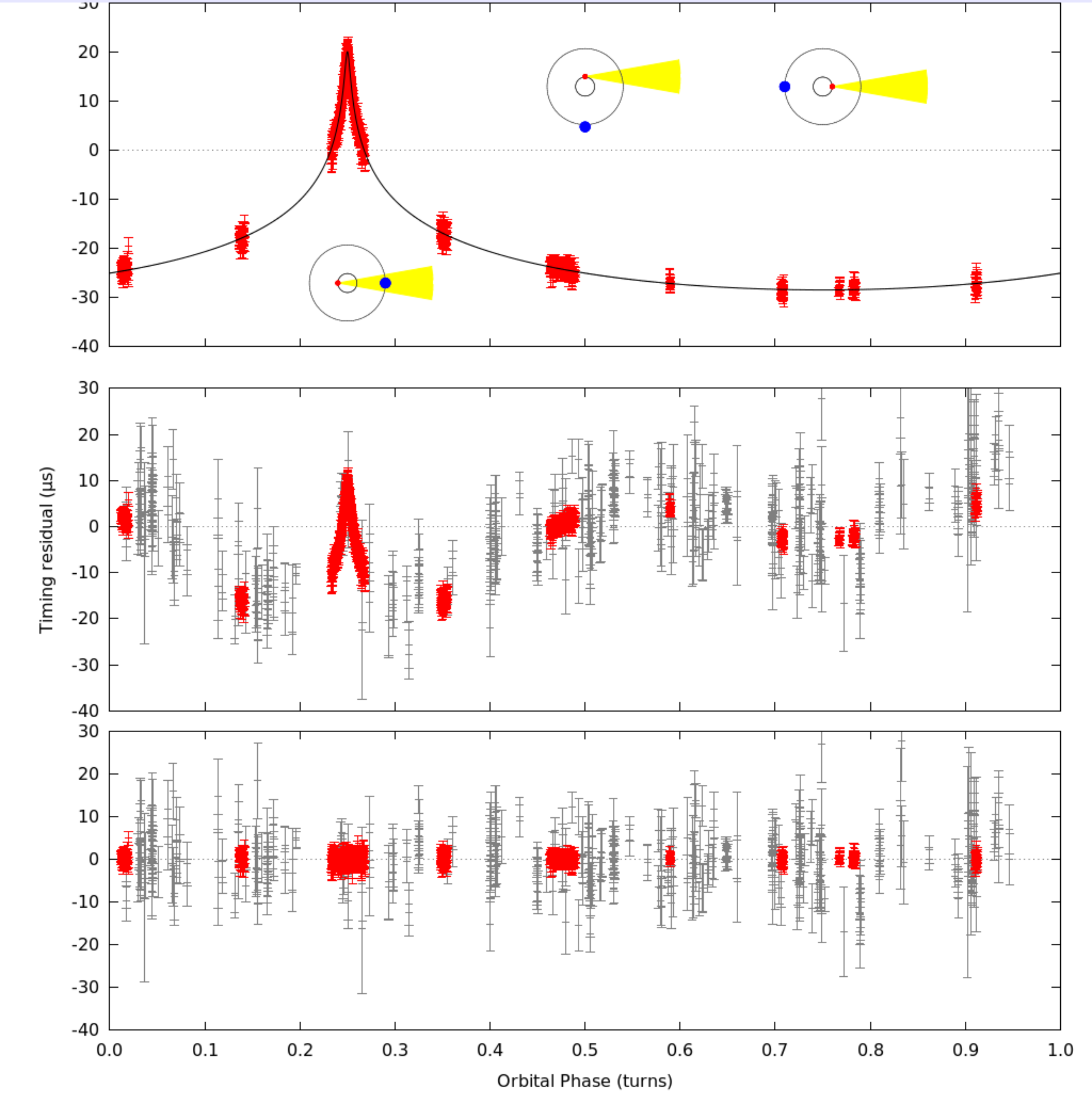
Marginal Shapiro delay after ~7 years of GBT timing with Spigot, BCPM, GUPPI-1, etc:





“Timing residuals” = Observed – predicted (model fit) pulse arrival times

… ~1 week of dense timing observations with coherent GUPPI:



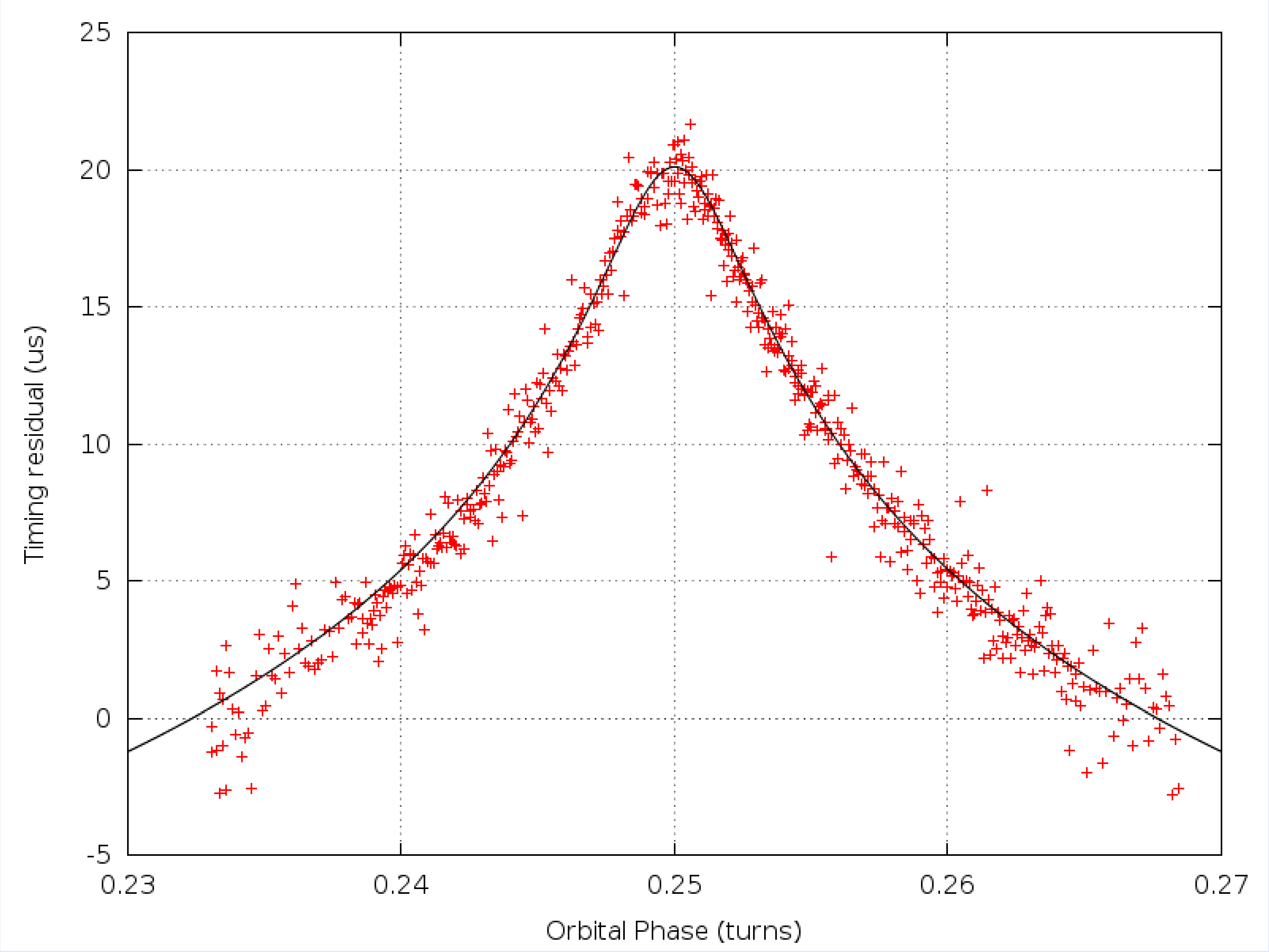
Orbital inclination = 89.17(2) deg!

Companion mass = 0.500(6) solar!

Pulsar mass = 1.97(4) solar!

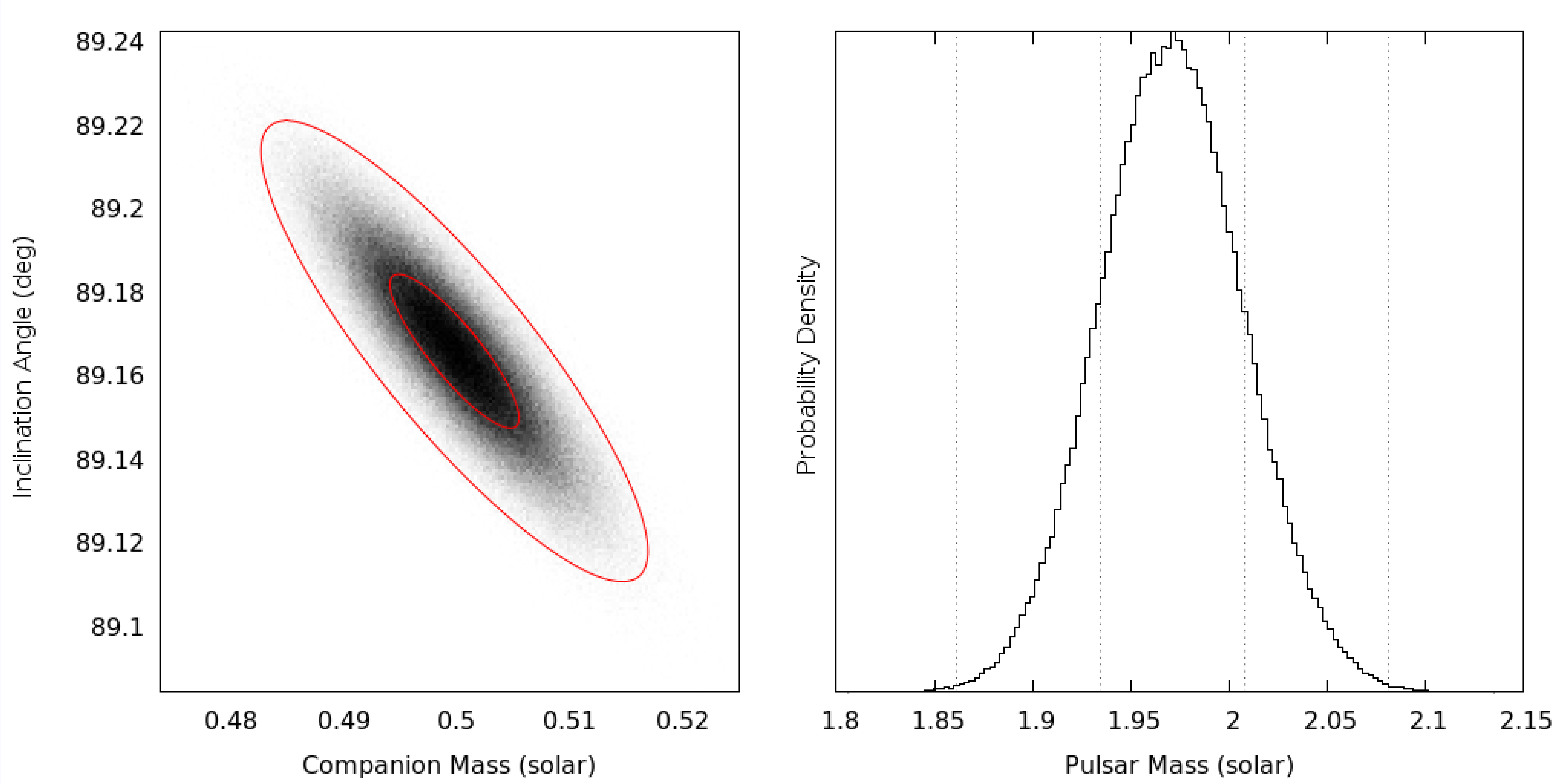
(Demorest, Pennucci, Ransom, Roberts, Hessels, *Nature,* 2010)

Closeup of orbital conjunction:



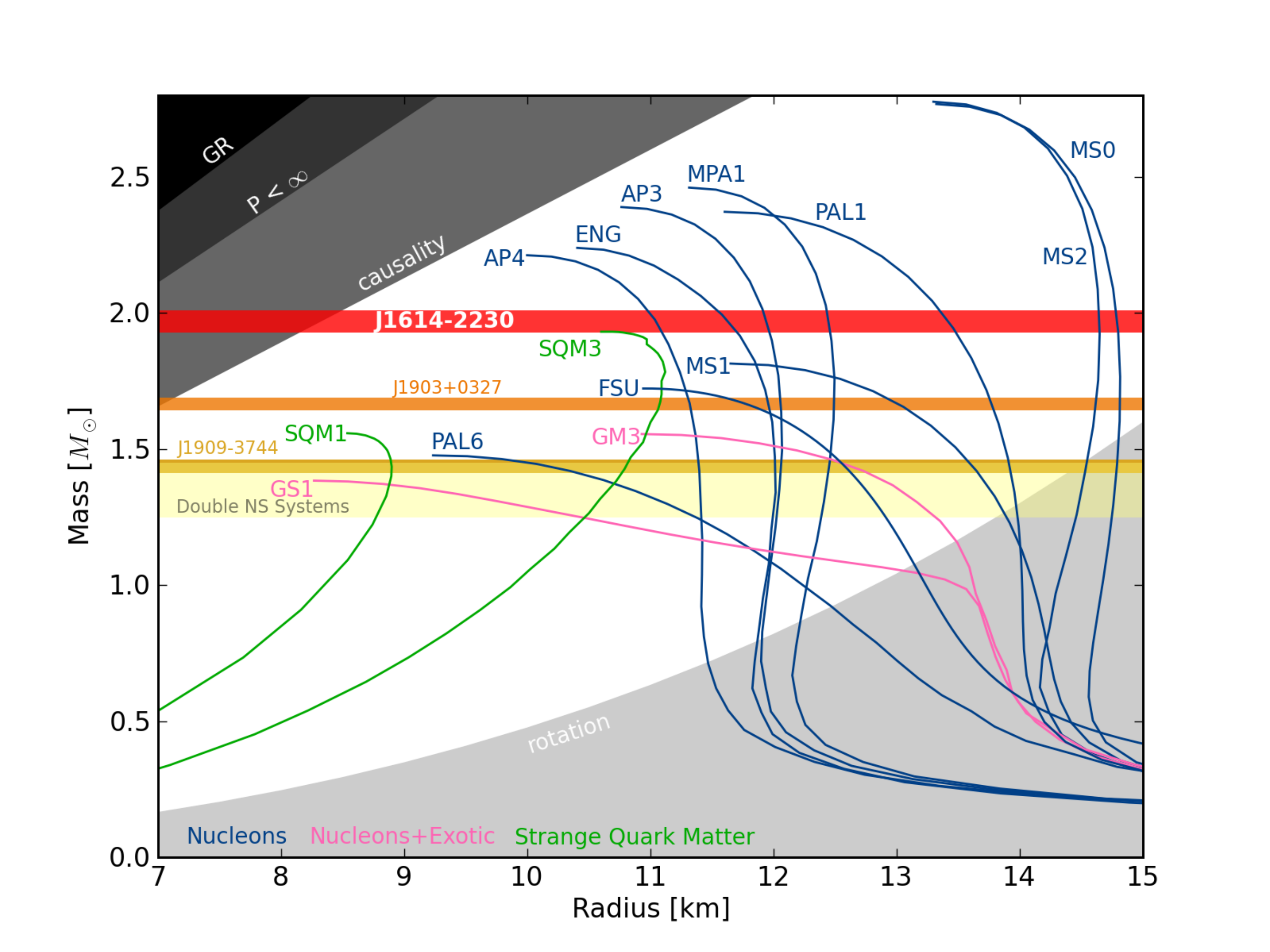
Time of arrival scatter is ~1us

Markov Chain Monte Carlo parameter estimation and error analysis:



Accounts for potential orbital DM variation, other parameter covariance.

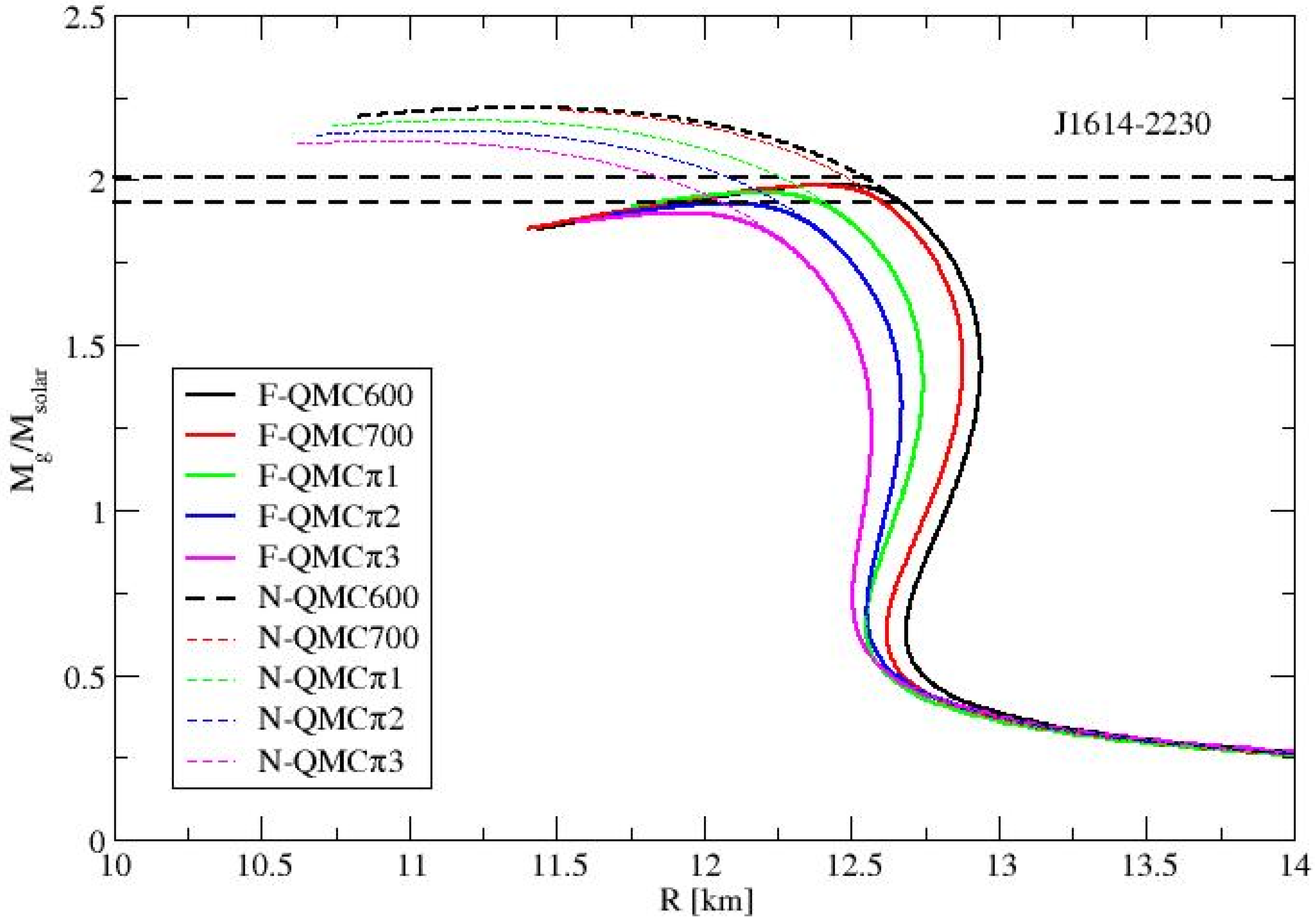
New EOS constraints:



(Demorest et al. 2010)

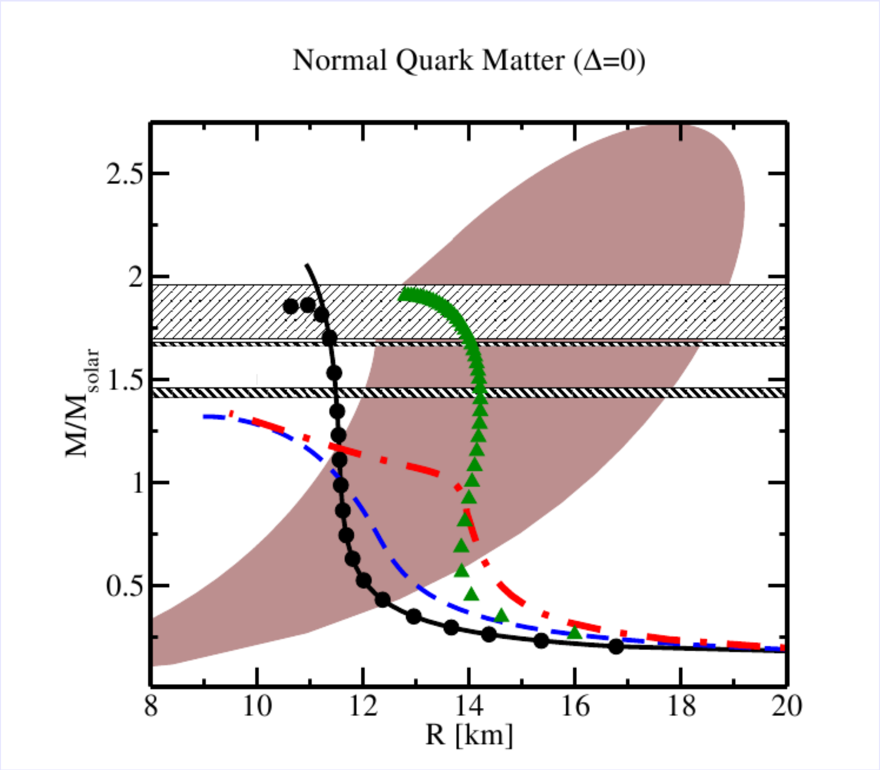
Rules out soft EOS including many “exotic” hyperon, kaon models.

Some hyperon models can just reach ~2.0 M_sun:



(Stone et al. 2010; see also Lackey et al. 2006)

Quark star models cover a wide parameter space:



(Kurkela et al. 2010)

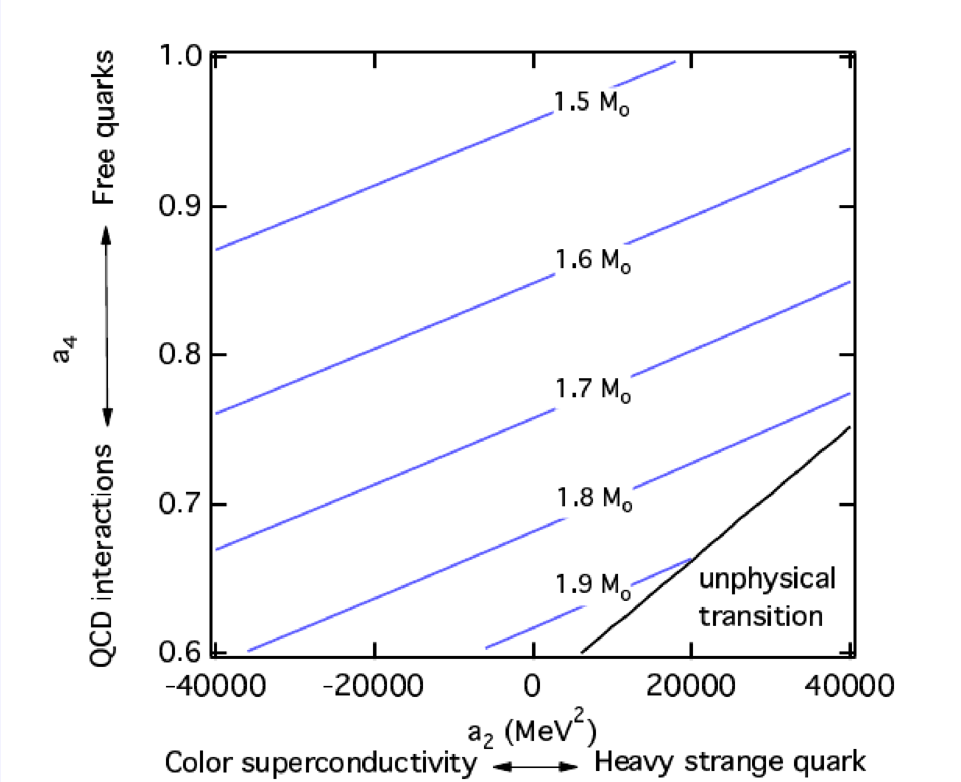
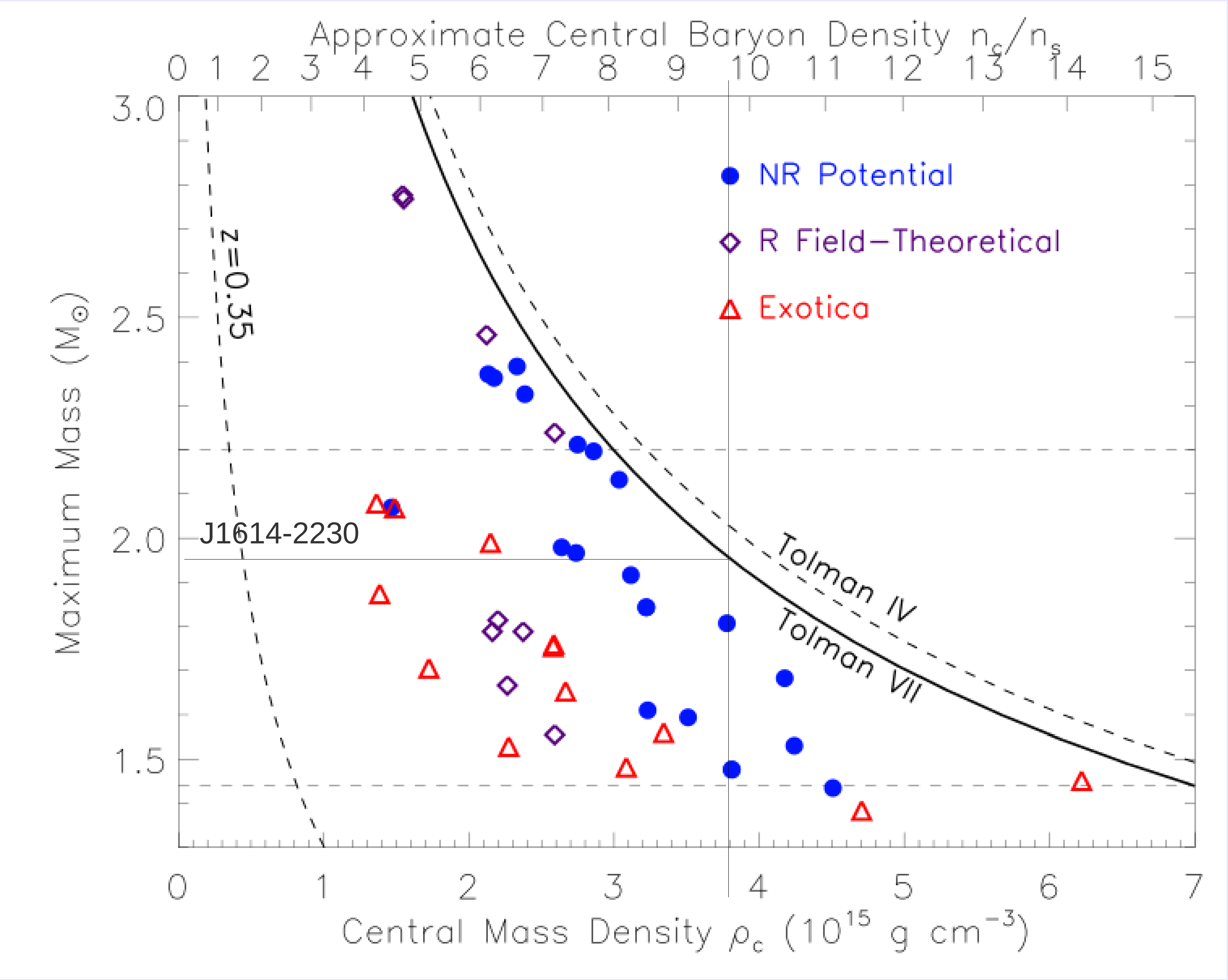


FIG. 1.— The maximum neutron star mass as a function of two parameters of quark matter when the density at which the transition from nucleonic to quark matter occurs is equal to 1.5 times the nuclear saturation density. The measurement of a pulsar mass of $\geq 1.93\ M_\odot$ from Shapiro delay observations indicates that, if the transition to quark matter occurs at densities that are relevant to neutron star interiors, such a massive star can be supported against collapse only if the quarks are strongly interacting ($a_4 \leq 0.63$).

(Ozel et al. 2010)

But our measurement places constraints on the quark interaction parameters; the quarks are not “free”.

EOS-independent mass density limit:



(Lattimer & Prakash, 2005)

How to improve the measurement?

1. Shapiro delay masses improve "only" as $T^{1/2}$. New instrumentation is required for substantial improvements:

- New pulsar timing optimized receiver and backend covering 0.5-3.0 GHz.
- Eventually, new telescopes (MeerKAT, FAST, SKA)

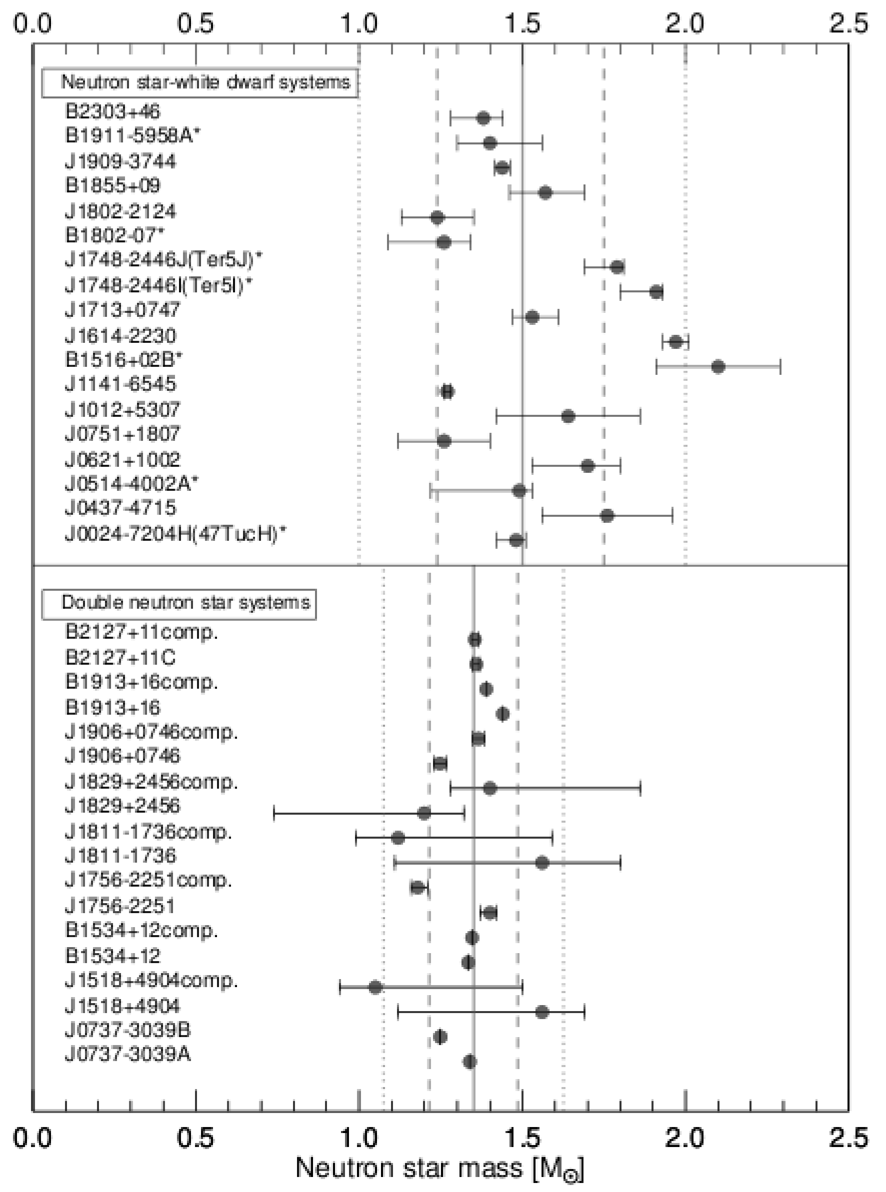
2. Find more pulsars!

- Ongoing PSR searches (Fermi, GBNCC, PALFA)
- Will improve population statistics as well as find new individual high-mass objects.

Both points apply equally to pulsar timing array gravitational wave detection (eg NANOGrav)!

Up-to-date NS mass compilation by Kiziltan et al (2010).

Explored statistics of DNS vs NS-WD systems.



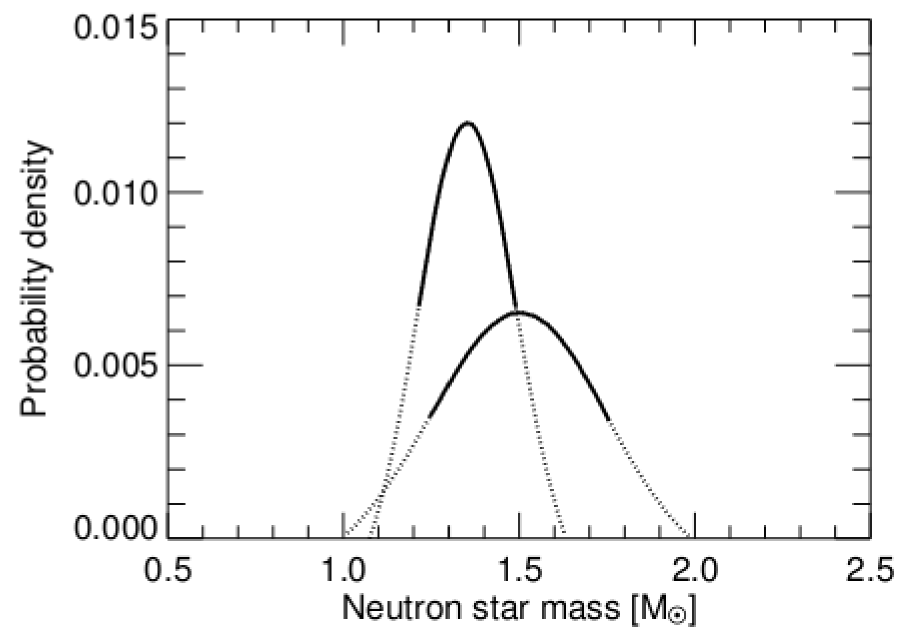


Figure 2. Posterior predictive density estimates for the neutron star mass distribution. DNS and NS-WD systems have respective peaks at 1.35 $M_\odot$ and 1.50 $M_\odot$. Probability densities are normalized to show the 95% posterior probability range. The solid parts of the curves show the central 68% probability range which correspond to 1.35 ± 0.13 $M_\odot$ and 1.50 ± 0.25 $M_\odot$ for the DNS and NS-WD system, respectively.

Binary evolution of J1614-2230

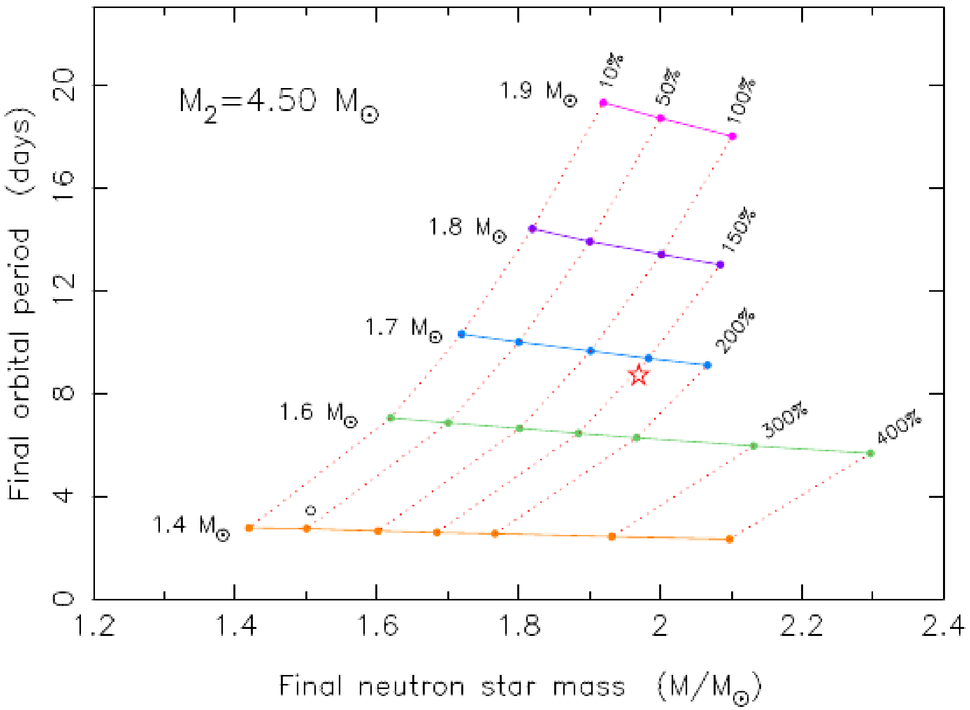


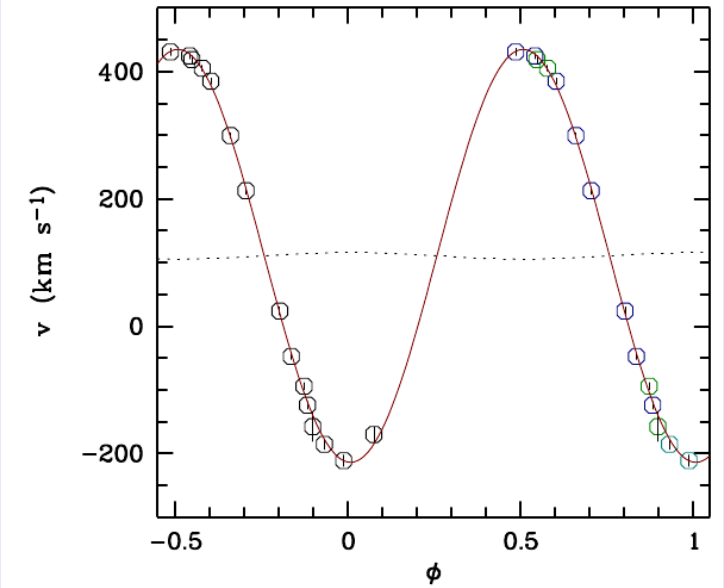
Figure 9. The final orbital period as a function of final neutron star mass for a grid of X-ray binaries evolving from a 4.5 $M_\odot$ donor star through Case A RLO. In all models the CO-WD is formed with a mass of about $0.51 \pm 0.01\, M_\odot$. The initial orbital period was in all cases about 2.2 days, corresponding to a core hydrogen content of $\sim 10\%$ at the time of RLO. The variables are the *initial* neutron star mass (solid lines) and the accretion efficiency (dotted lines). The observed values of PSR J1614−2230 are shown with a red star. Our calculations show that indeed PSR J1614−2230 could have evolved from a 4.5 $M_\odot$ donor star and a neutron star born with a mass of $\sim 1.7\, M_\odot$, accreting at an efficiency of 150% – see text.

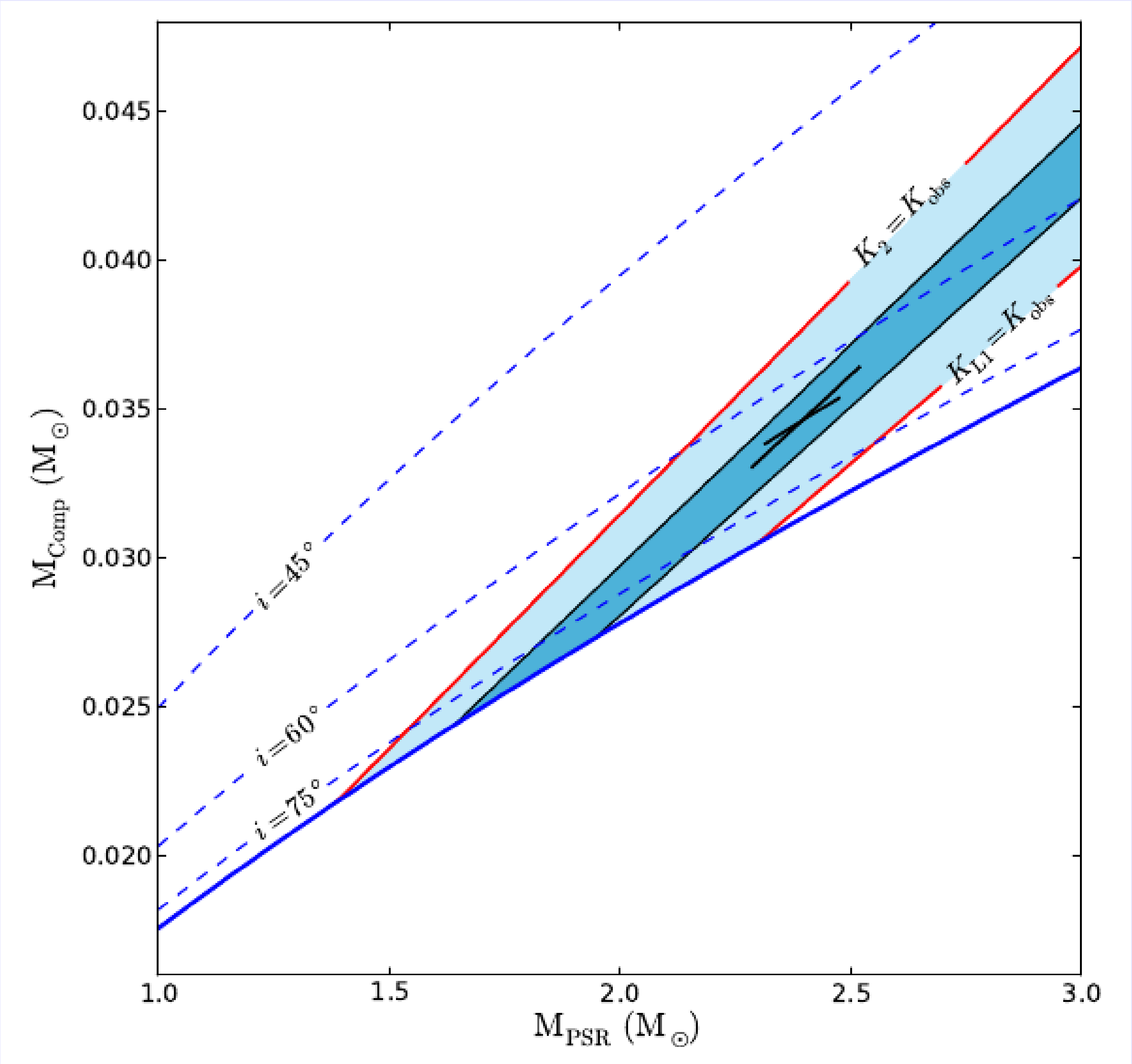
Tauris et al (2011) and Lin et al (2011) both find that J1614-2230 must have been born massive to achieve the observed current mass.

Minimum initial mass is ~1.6 to 1.7 M_{sun}.

Original “Black Widow”: B1957+21

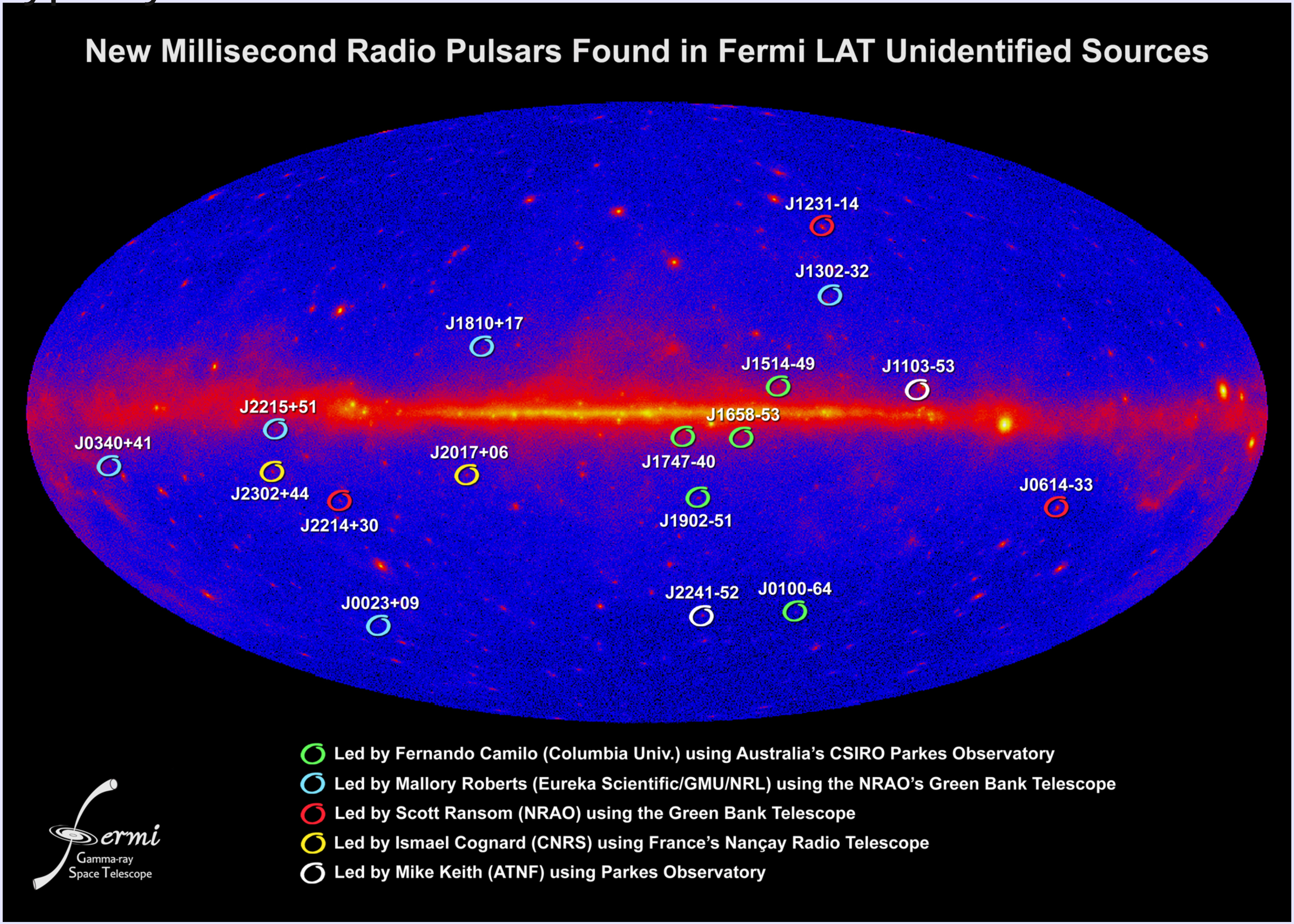
- New radial vel curve: 353(4) km/s amplitude (corr. for ctr-of-light)
- i=65(2)deg from lightcurve models
- Mp ~ 2.40+/-0.12Msun
- Mp > 1.66 Msun





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

~15 of the new Fermi MSPs appear to be "black widow" type systems …



Conclusions/Summary:

1. NS masses provide unique constraints on physics of high-density matter.

2. Requires high-precision timing (good instrumentation) and favorable orbits (highly inclined and/or eccentric).

3. Two recent precise MSP masses, 1.67(2) and 1.97(4) M_{sun}. Suggestions of even higher NS masses (cluster and BW results). Challenges “canonical 1.4 solar mass” NS.

4. Ongoing surveys and instrument development promise more mass results in the future!