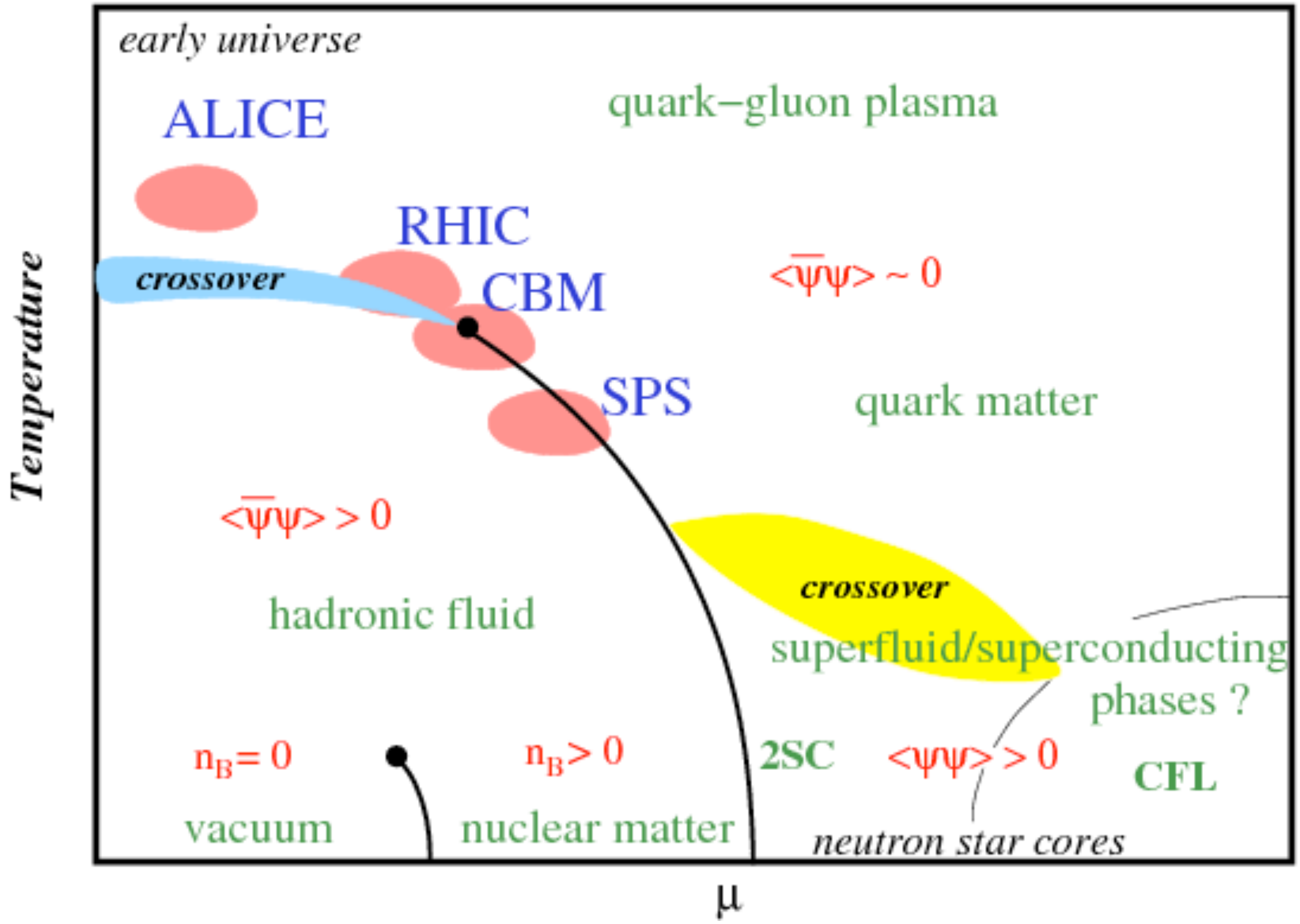
Neutron star mass measurements with binary radio pulsars

or: QCD matter: Dense and *COLD*

Paulo C. C. Freire
Max-Planck-Institut für Radioastronomie

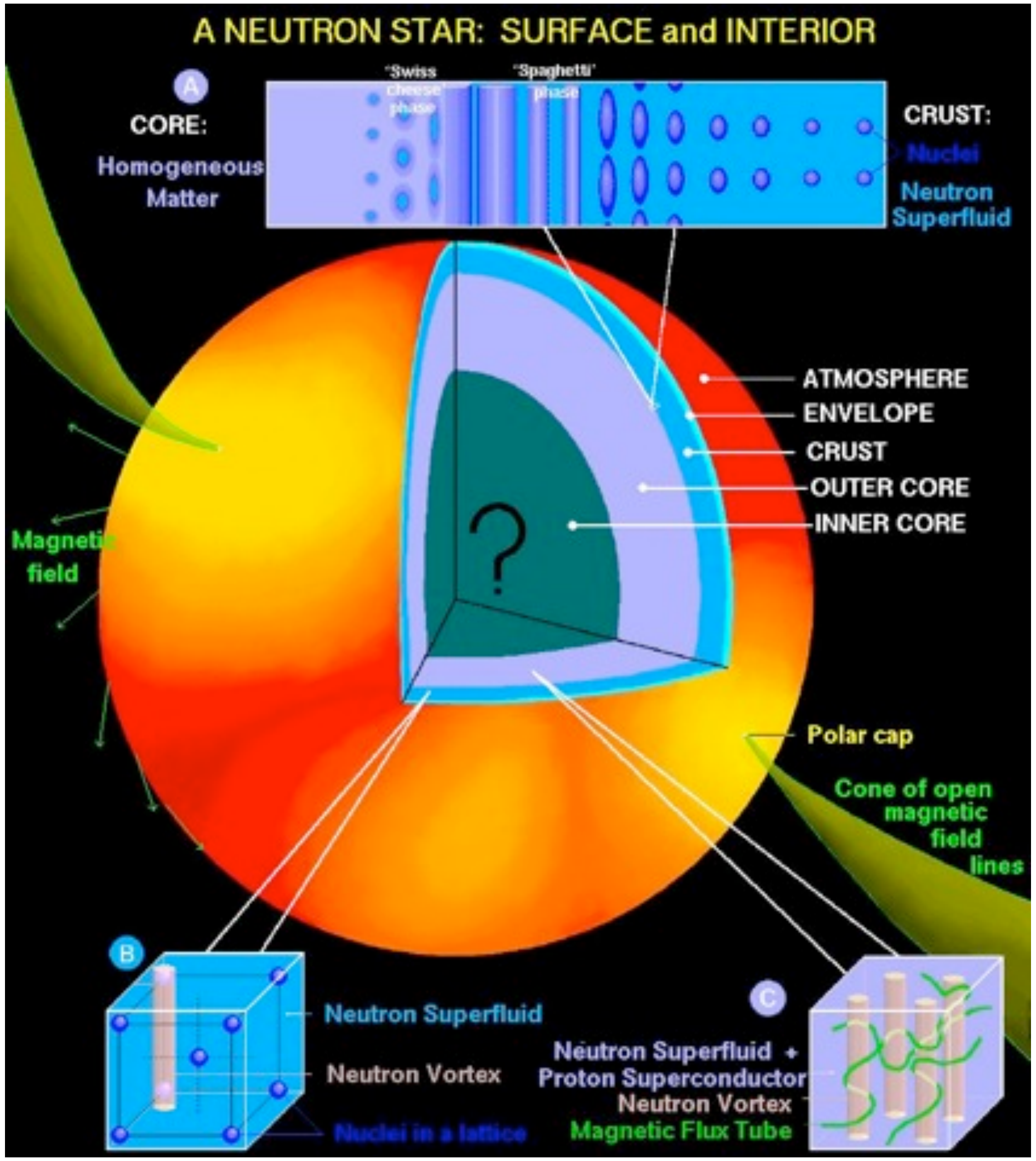
Why measure NS masses (and radii)?

- Neutron stars represent a location in the quark matter phase diagram that is not being probed by heavy ion collision experiments!
- Their macroscopic quantities, like mass and radius, depend on the microscopic behaviour of the very dense matter in their cores.



Picture in: Bernd-Jochen et al. Prog.Part.Nucl.Phys. 62 (2009) 381

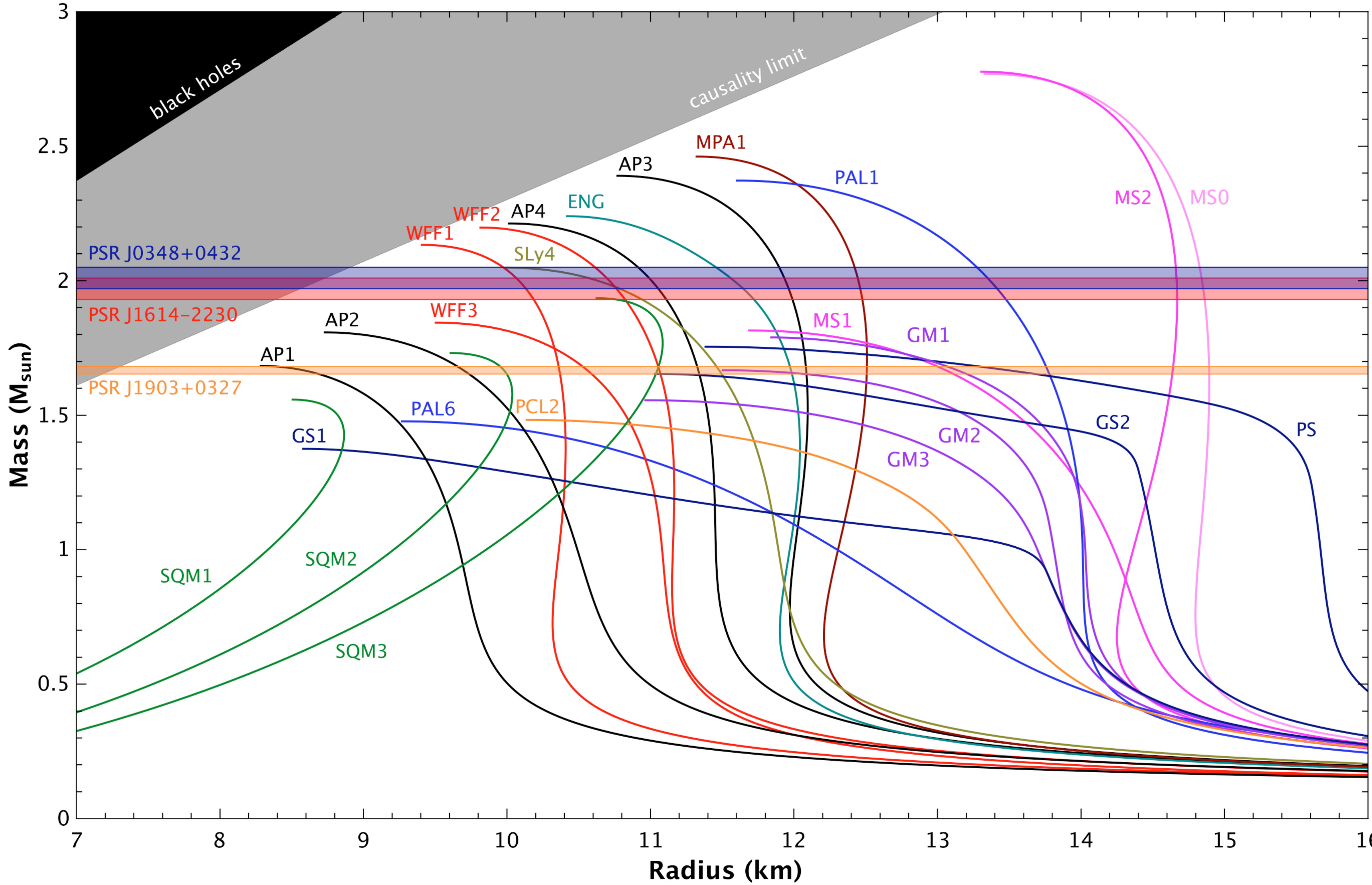
The Problem:



- No one knows in what form is matter in the core of a neutron stars!
- Many guesses being made, which lead to different relations for the mass and radius!

What these masses mean

Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

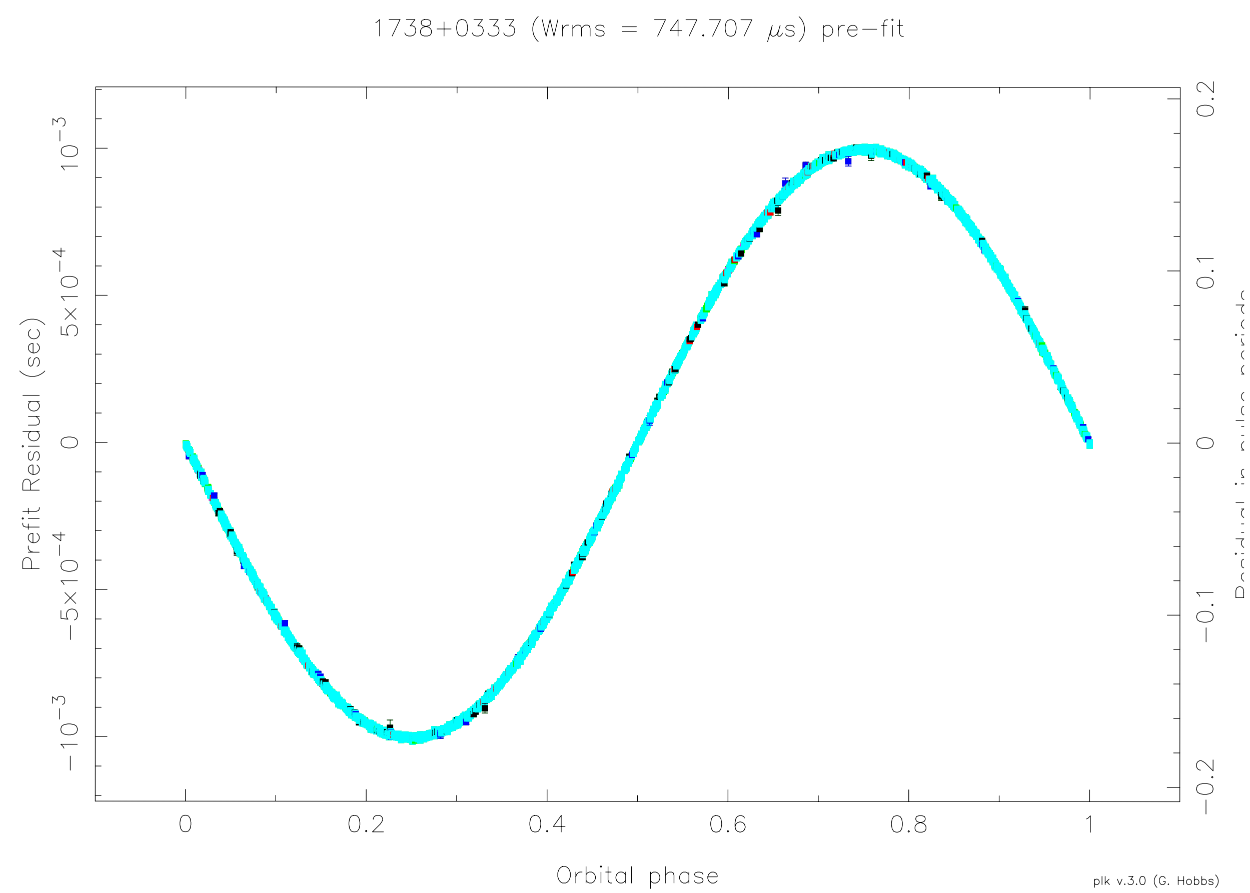


Contents

- Mass constraints on binary pulsars
- Mass measurements in DNS systems
- Mass measurements for Millisecond pulsars: Difficult!!!
    - Globular cluster pulsars
    - Shapiro delay measurements
    - Triples, disrupted triples and other monsters
    - Spectroscopic measurements of WD companions

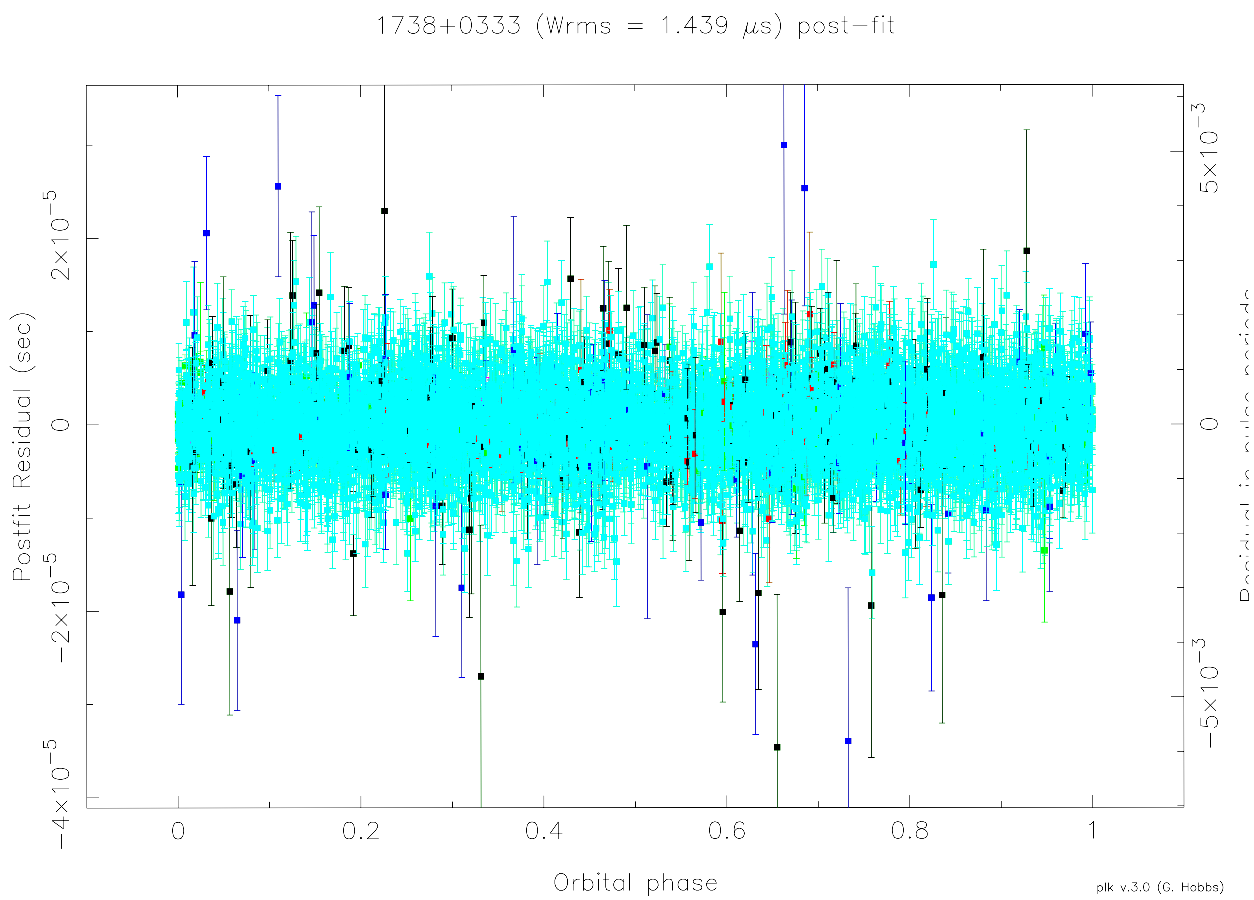
The Instrument...

Why are binary pulsars so exciting?



- In a binary pulsar, having a clock in the system allows us to measure the range relative to the center of mass of the binary.
- The 5 Keplerian orbital parameters derived from pulsar timing are thousands of times more precise than derived from Doppler measurements – with the same measurements!
- This feature is unique to pulsars, and is the fundamental reason why they are superior astrophysical tools.
- This is the reason why I am giving this talk here!
- Plus: two point masses! Clean system!!

Why are binary pulsars so exciting?



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Why are binary pulsars so exciting?

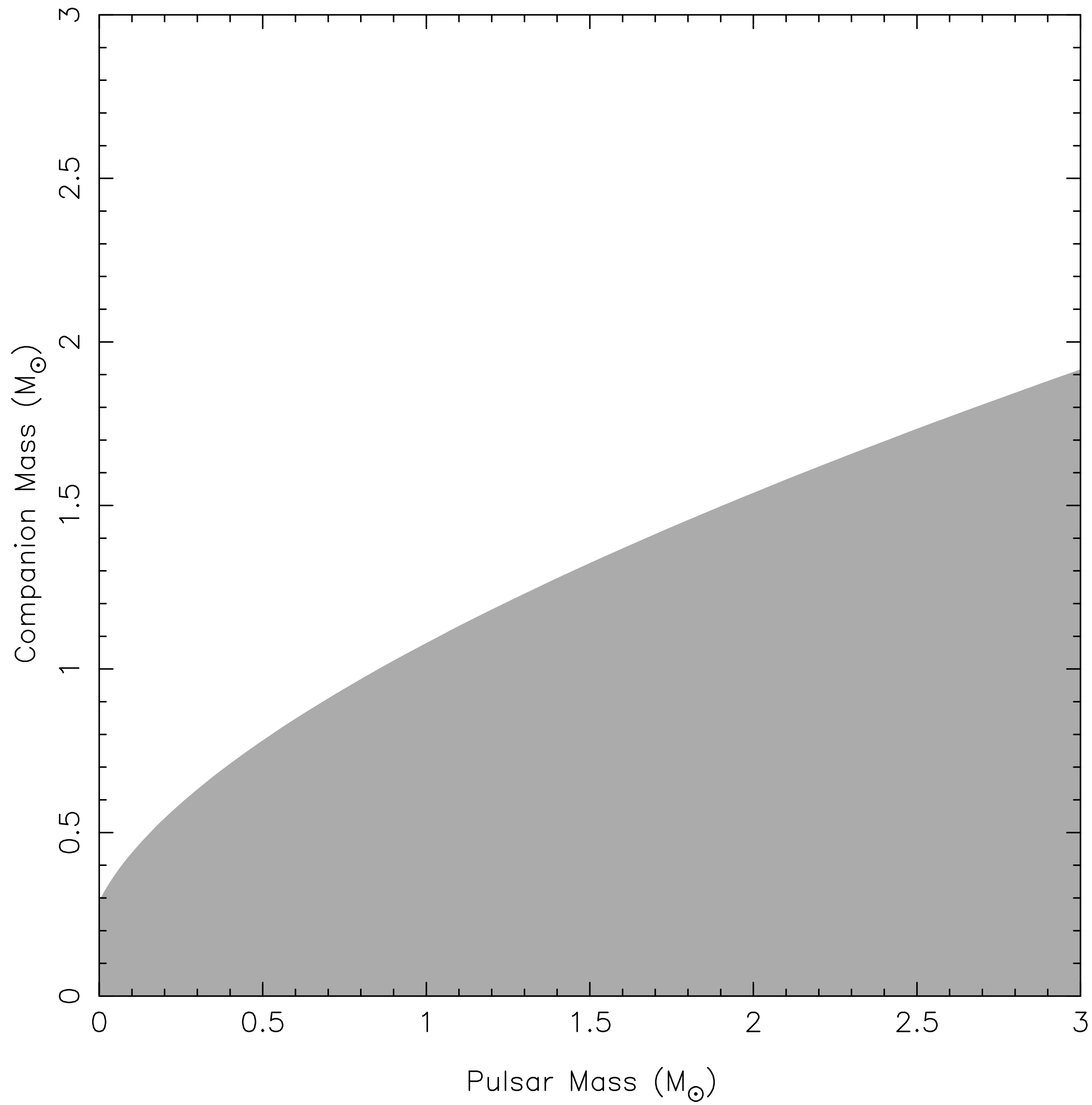
- Number of rotations between 52872.01692 and 55813.95899 (SSB): 43 449 485 656 ± 0.
- Spin period (today, MJD 57406, at 9:00): 0.005850095774916893 ± 0.000000000000000005 s
- Orbital period (P_b): $8^h\ 30^m$ 53.9199264 ± 0.0000003 s
- Semi-major axis of the pulsar's orbit, projected along the line of sight (x): 102957453 ± 6 m.
- Eccentricity (e): (3 ± 1) × 10^{-7}. This means that the orbit deviates from a circle by (5 ± 3) μm!
- Proper motion: 7.037 ± 0.005 mas yr^{-1}, 5.073 ± 0.012 mas yr^{-1}, parallax: 0.68 ± 0.05 mas.
- Orbital decay: −(25.9 ± 3.2) × 10^{-15} ss^{-1} (or 0.8 ± 0.1 μs yr^{-1}!) - See Freire et al. 2012, MNRAS, 423, 3328.

The mass function

- For most binary pulsars, all we have are the Keplerian parameters and all we can derive if the mass function:

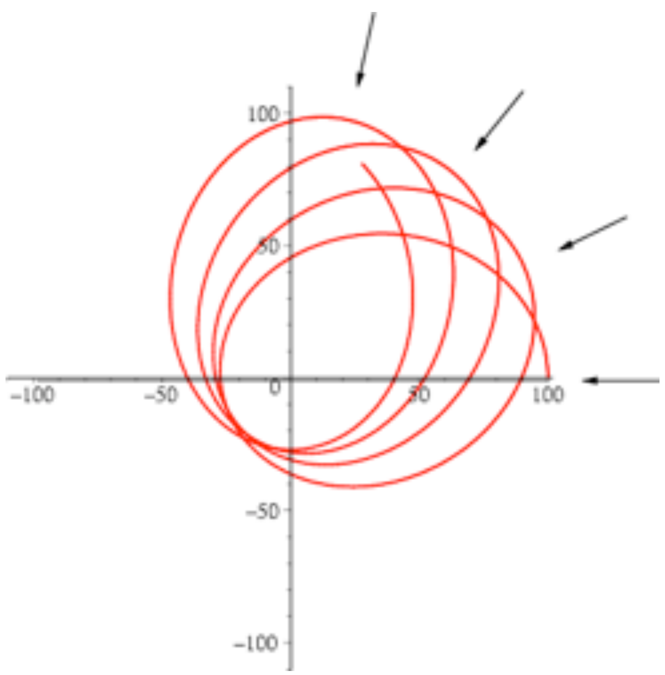
$$f(m_1, m_2, i)/\mathrm{M}_\odot \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$
$$= x^3 \left(\frac{2\pi}{P_b}\right)^2 \left(\frac{1}{T_\odot}\right)$$
$$T_\odot \equiv \frac{\mathrm{GM}_\odot}{c^3} = 4.925490947\ \mu s$$

- One equation, three (known) unknowns! :-(



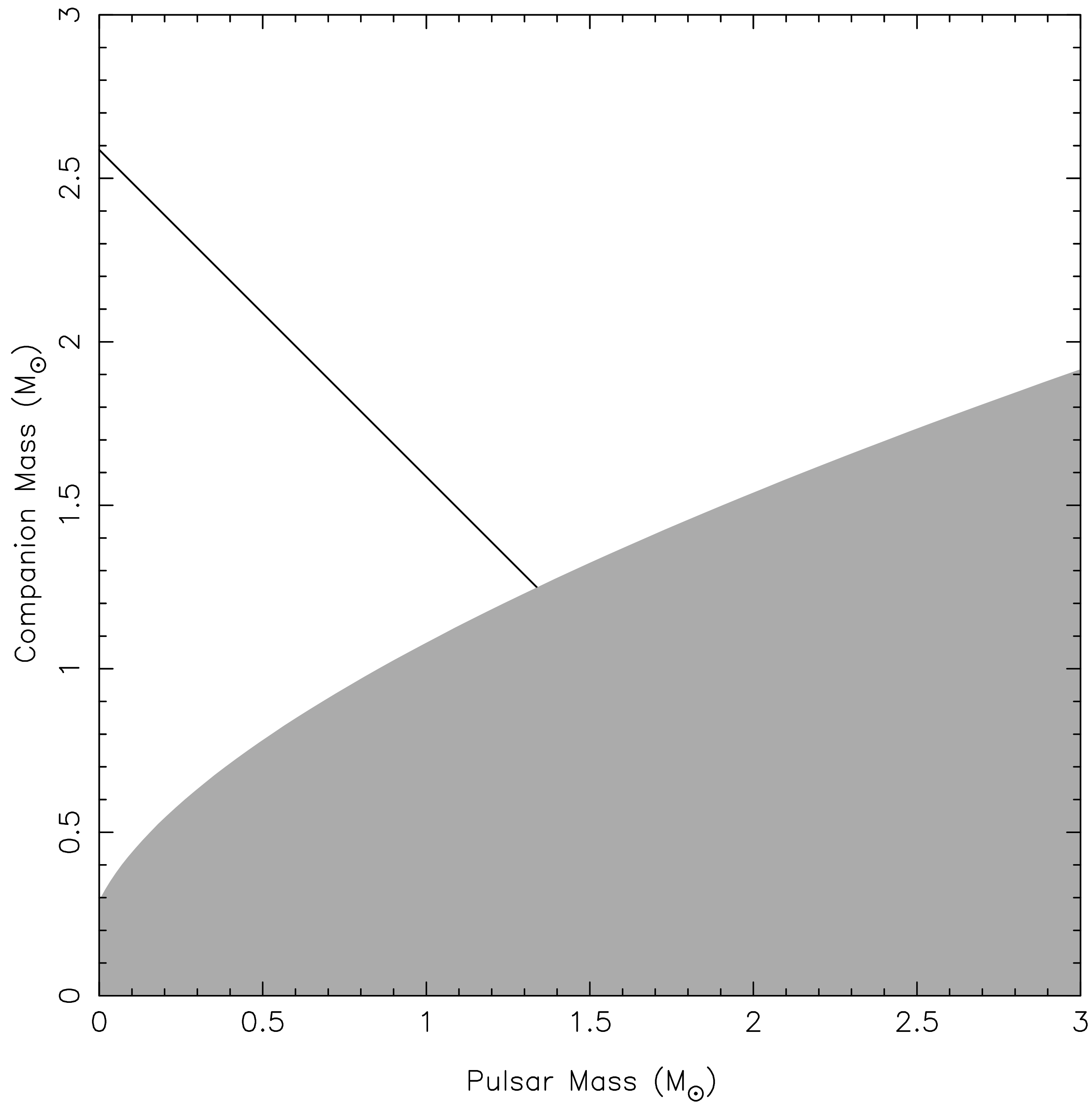
Precession of Periastron

- IF a binary pulsar is compact and eccentric – which the DNS J0737−3039 certainly is – the timing precision allows the measurement of several relativistic effects.



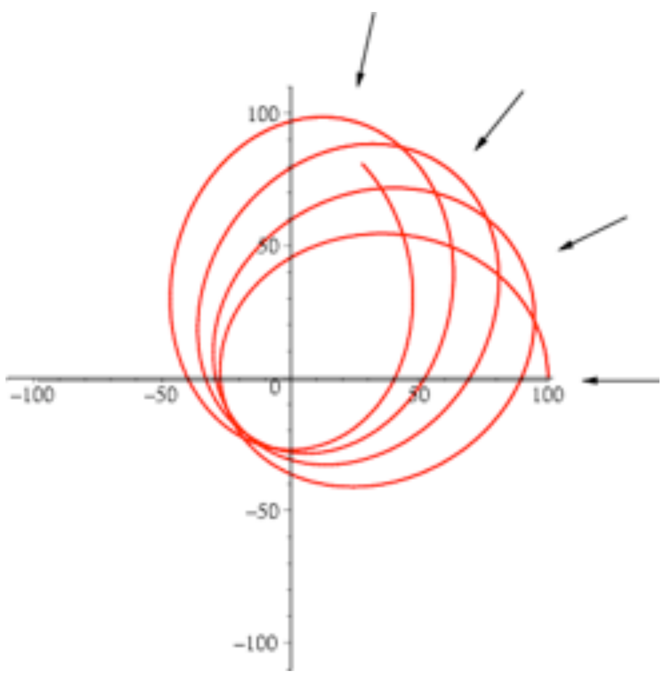
- The periastron of PSR J0737−3039 advances 16.89947 degrees/year.

$$M = m_1 + m_2\,,\; n_b = \frac{2\pi}{P_b}$$
$$\dot{\omega} = 3 n_b^{5/3} (M T_\odot)^{2/3} (1 - e^2)^{-1}$$
$$\gamma = n_b^{-1/3} e m_2 (2m_2 + m_1) M^{-4/3} T_\odot^{2/3}$$



The Einstein delay

- Einstein delay also measured: 0.3856 ms (from time running slower at periastron)
- *Enough for mass determination!*



- All assuming GR is the correct theory of gravity.

$$M = m_1 + m_2\,,\; n_b = \frac{2\pi}{P_b}$$
$$\dot{\omega} = 3 n_b^{5/3} (M T_\odot)^{2/3} (1 - e^2)^{-1}$$
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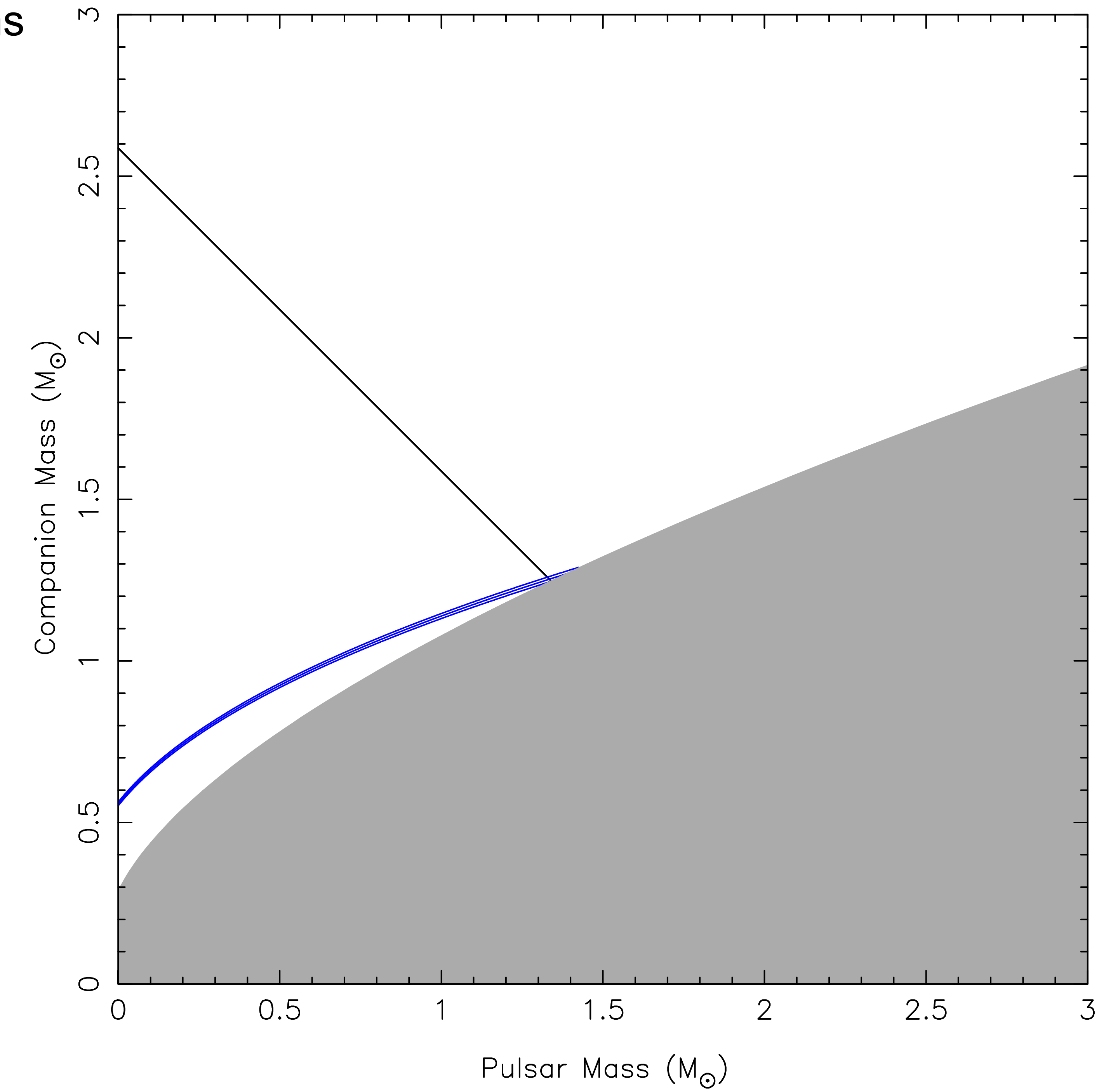
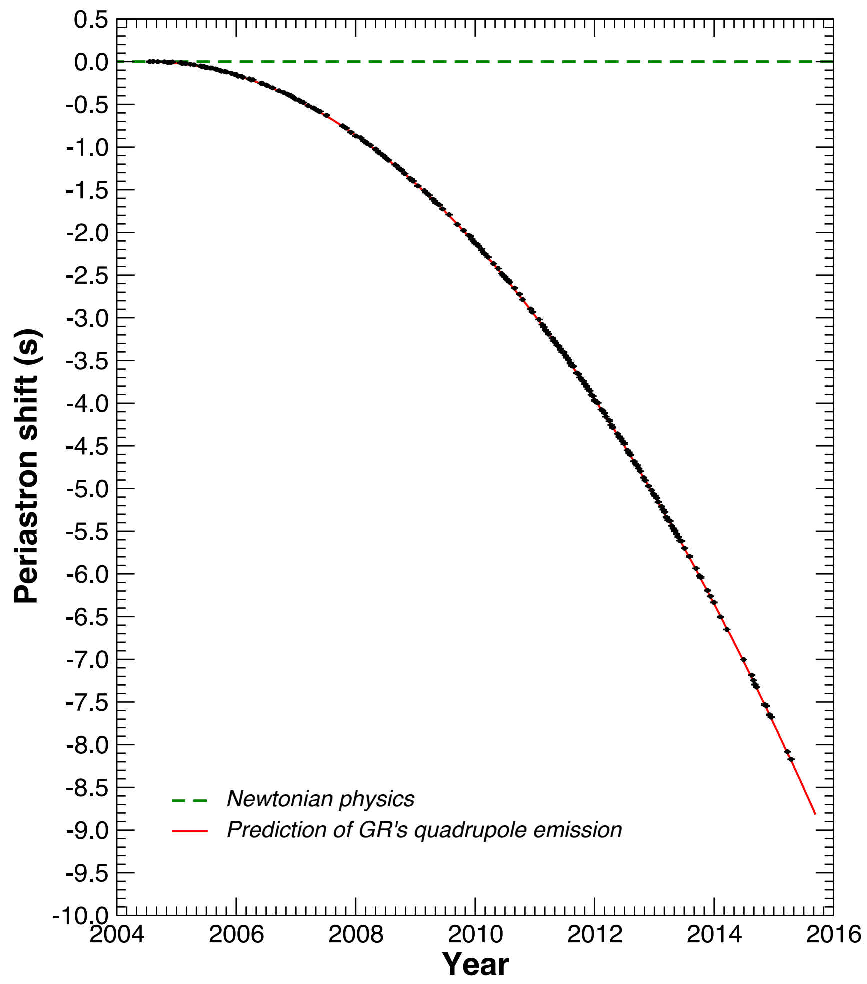


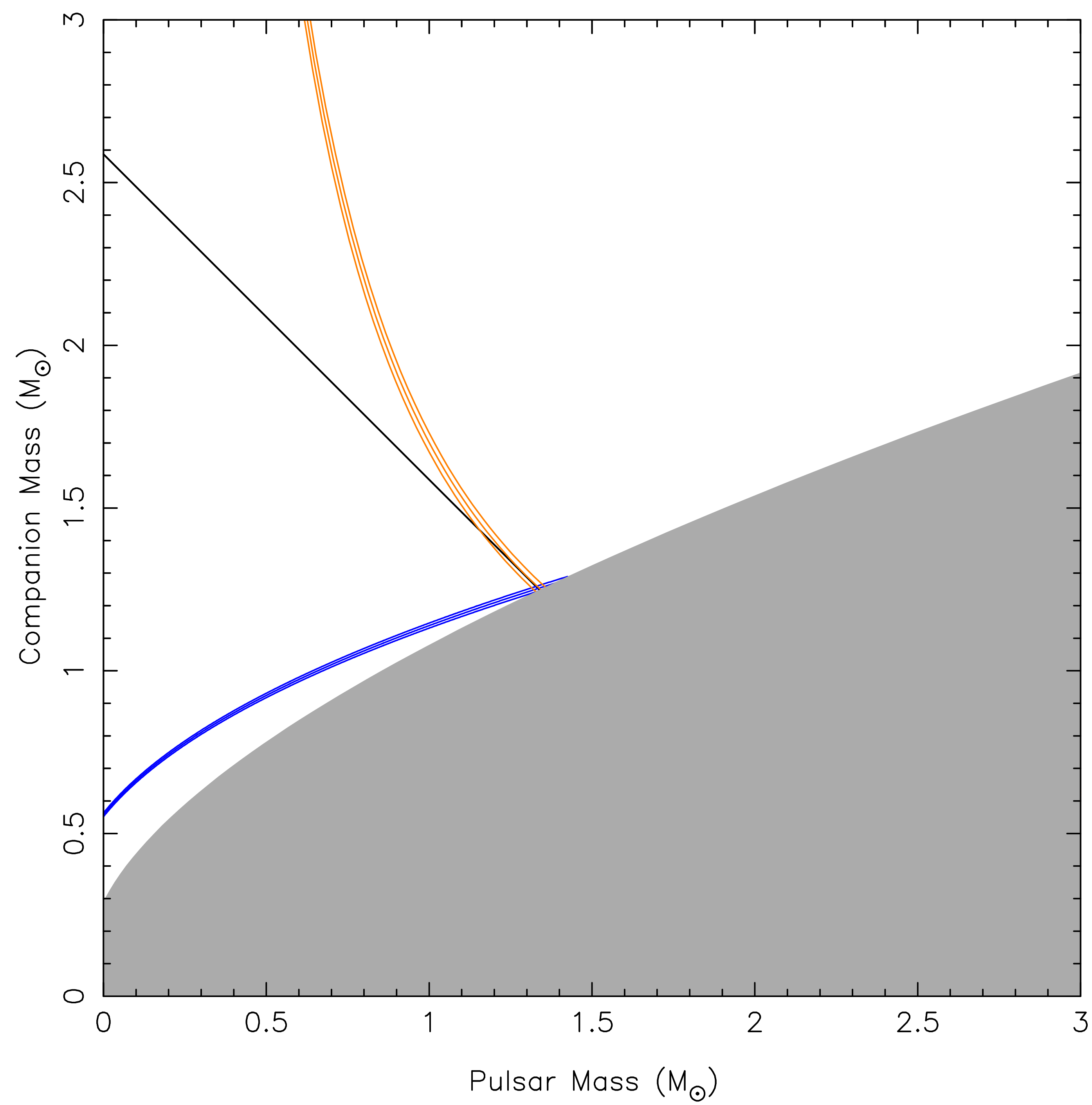
The orbital decay

- Orbital decay due to GW emission measured very precisely!



$$\dot{P}_b = -\frac{192}{5} n_b^{5/3} f_e m_1 m_2 M^{-1/3} T_\odot^{5/3}$$

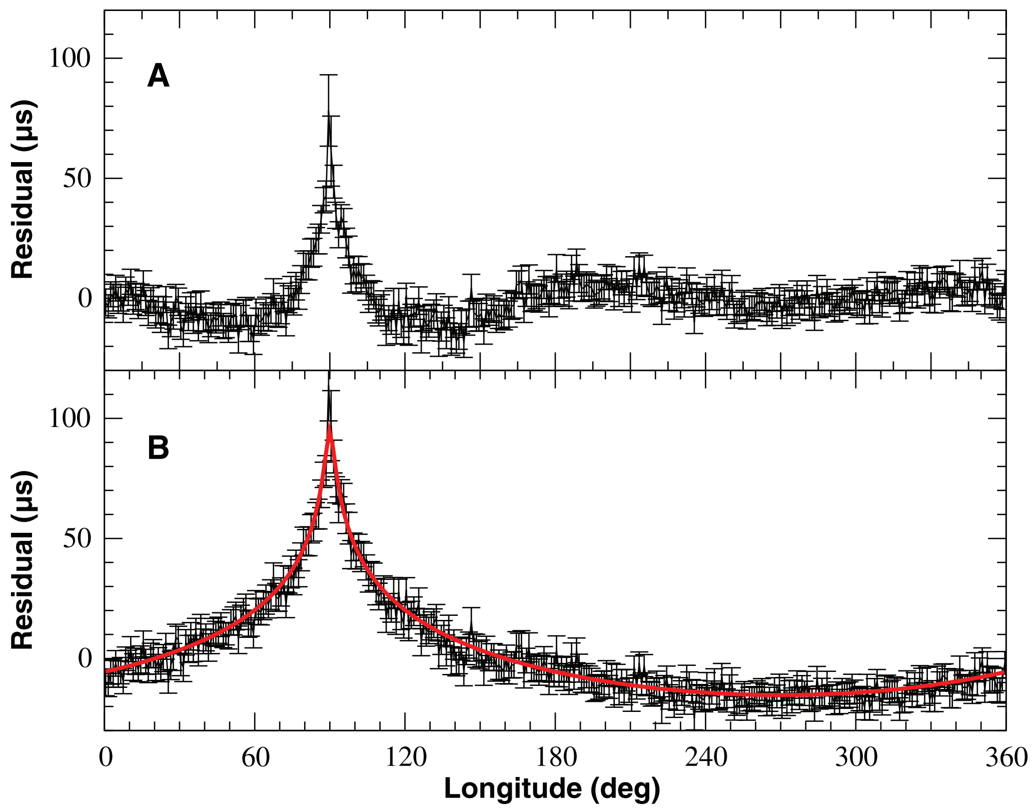
$$f_e = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1-e^2)^{-7/2}$$



- Test of GR!! Theory passes the test!!

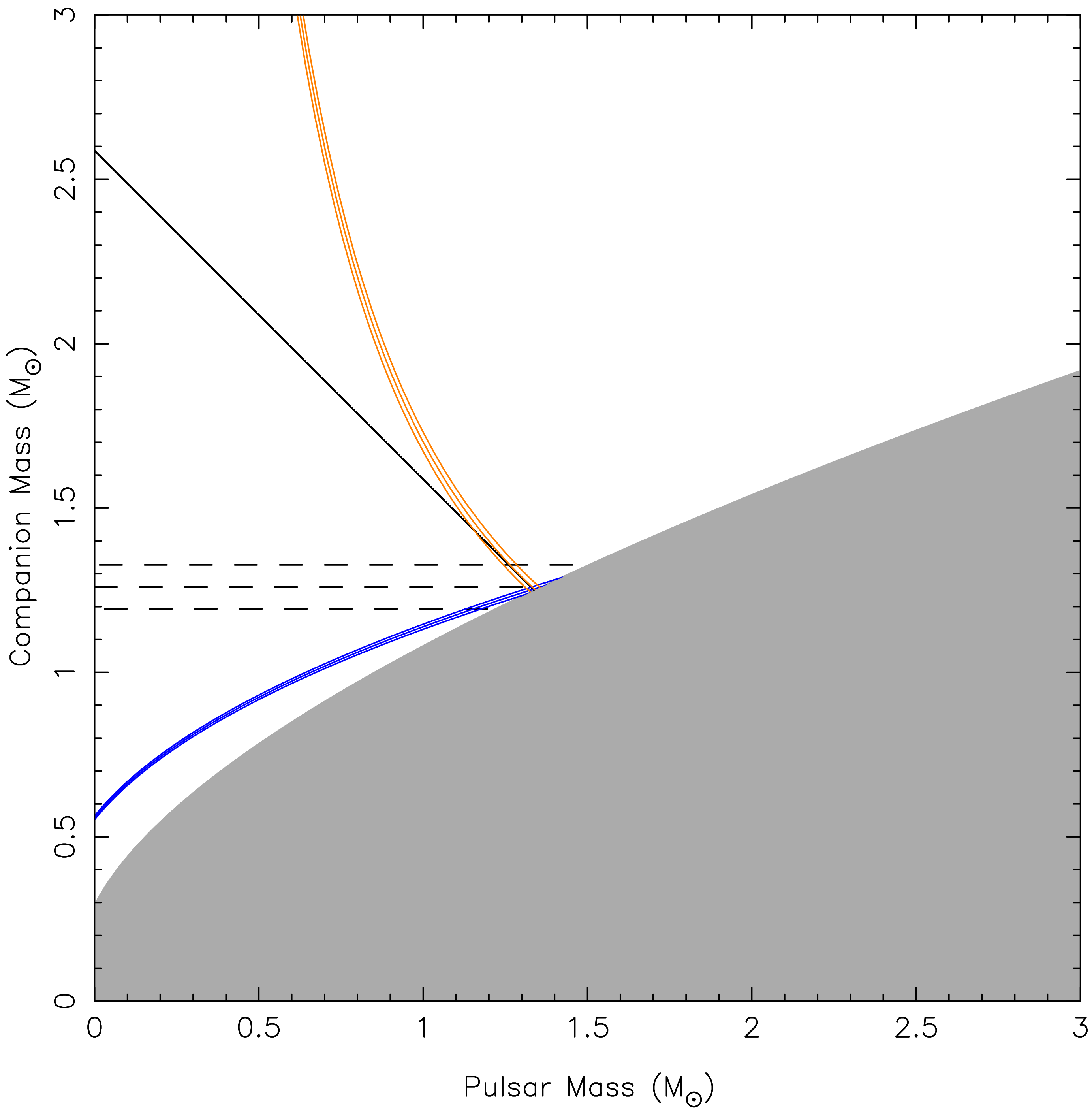
The Shapiro delay

- Orbit is edge-on!



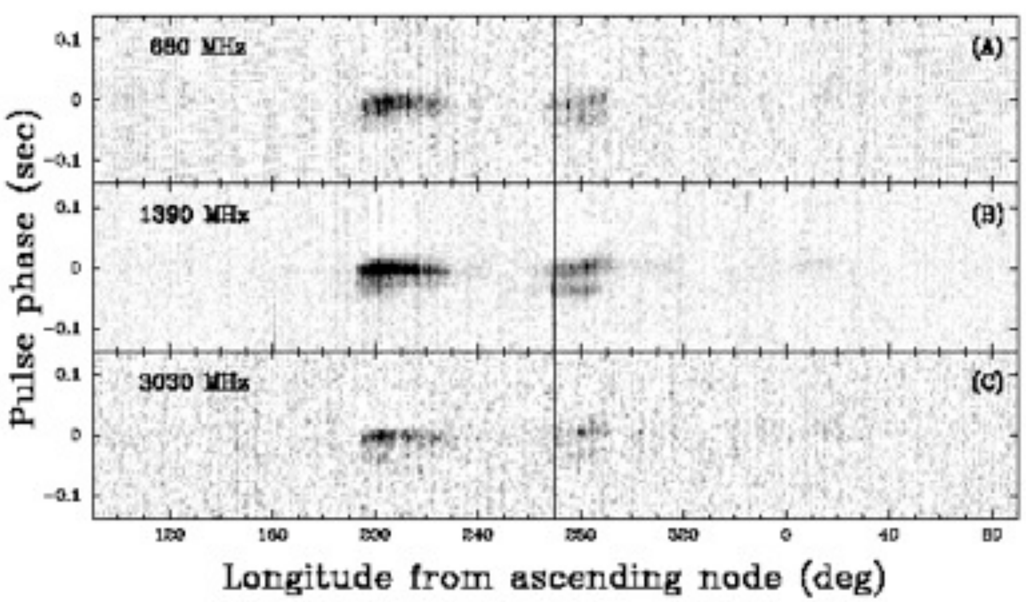
- Two more tests of GR (companion mass and sine of orbital inclination)!

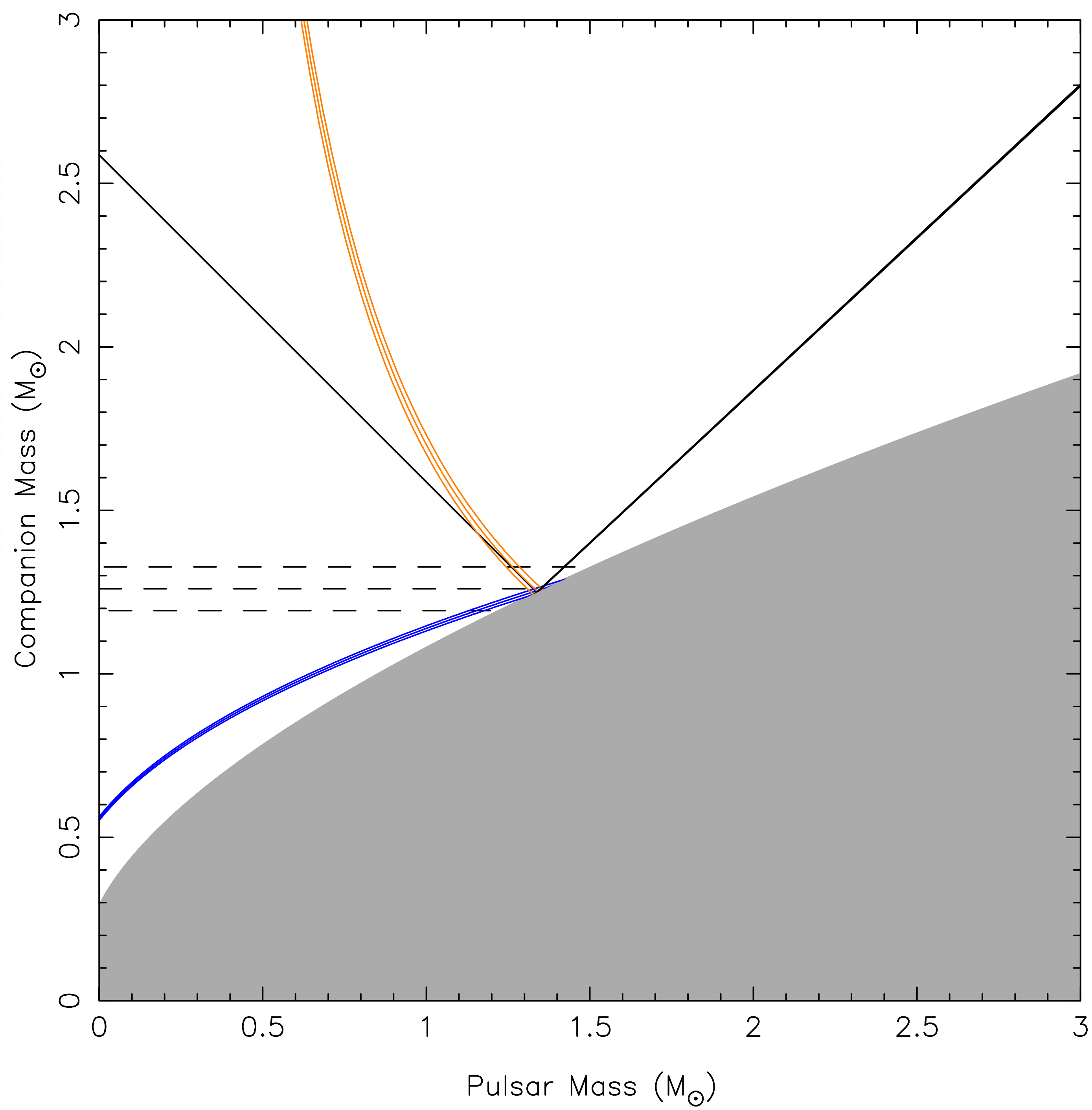
- Theory successful again!



The other pulsar

- The other neutron star is also visible as a pulsar (PSR J0737−3039B)!





- $R = m_A / m_B = x_B / x_A$

- Fourth test: GR still works!

Take away points

- In GR, *only the masses* enter as a parameters in the description of these effects, at least to leading PN order. To measure moment of inertia, we will need to go beyond LO (possible in the double pulsar).

- It is nice to have systems like the double pulsar to test GR / to cross-check the mass measurement techniques - they can really produce very precise (and consistent) results.

Double neutron star mass measurements

Table 1: Double neutron star systems known in the Galaxy

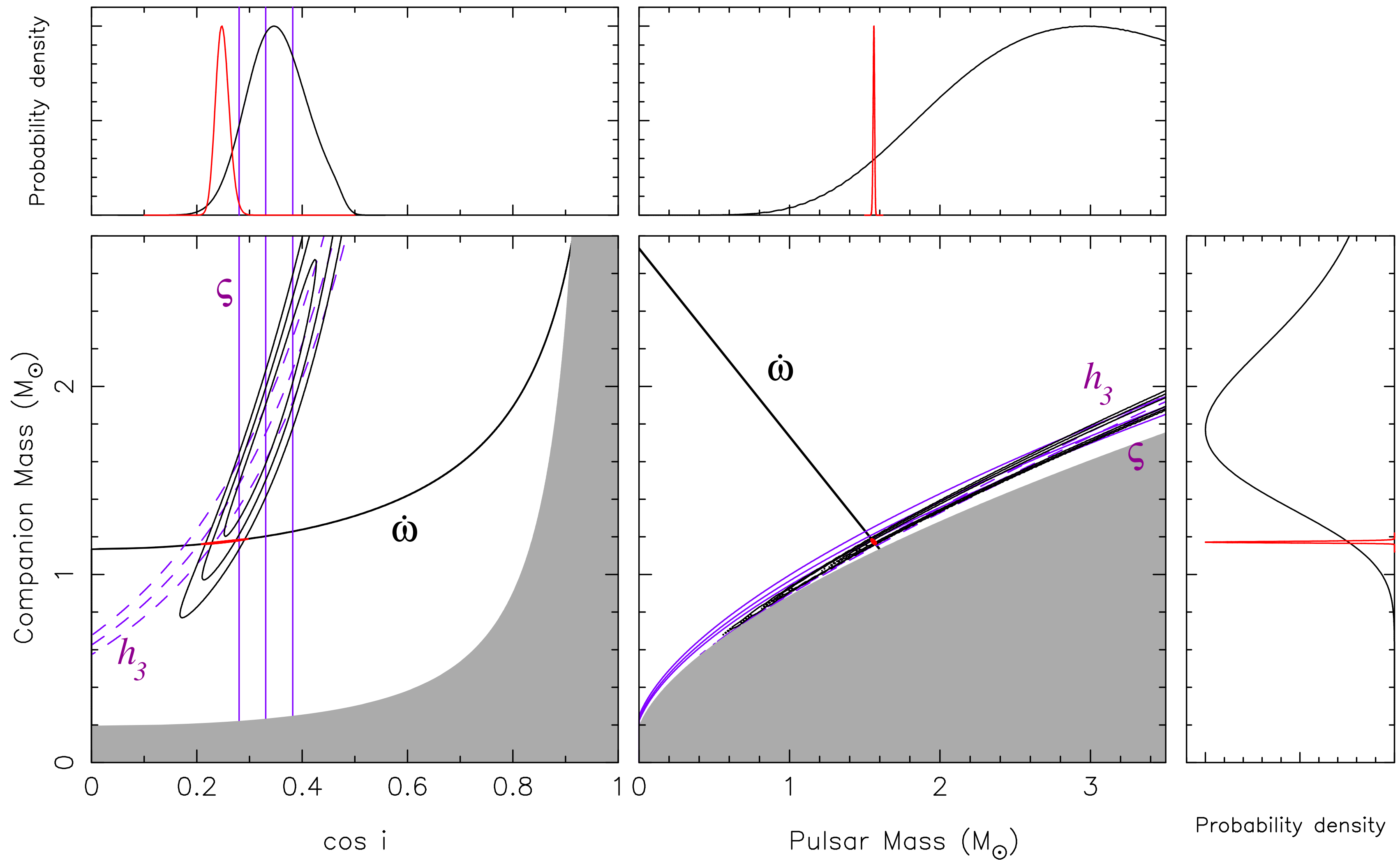
Pulsar	Period (ms)	$P_{\rm b}$ (days)	x (lt-sec)	e	M ($M_\odot$)	$M_{\rm p}$ ($M_\odot$)	$M_{\rm c}$ ($M_\odot$)	References
J0737−3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737−3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	3
J1753−2240	95.138	13.638	18.115	0.303582(10)	-	-	-	4
J1756−2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	5
J1811−1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	-	-	6
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	-	-	7
J1906+0746*	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	8
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	9
J1930−1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	-	-	10
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This Letter
Globular cluster systems								
J1807−2500B*	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	12
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	13

Note. — 1: Burgay et al. (2003) & Kramer et al. (2006), 2: Janssen et al. (2008), 3: Wolszczan (1991) & Fonseca et al. (2014), 4: Keith et al. (2009), 5: Faulkner et al. (2005) & Ferdman et al. (2014), 6: Corongiu et al. (2007), 7: Champion et al. (2004) & Champion et al. (2005), 8: Lorimer et al. (2006) & van Leeuwen et al. (2015), 9: Hulse & Taylor (1975) & Weisberg et al. (2010), 10: Swiggum et al. (2015), 12: Lynch et al. (2012), 13: Anderson et al. (1989) & Jacoby et al. (2006)

* Note: there is some uncertainty on whether these systems are DNSs.

New DNS mass measurement.

- PSR J0453+1559 (Martinez et al., ApJ. 812, 143, 2015)
- This is the first asymmetric DNS! $M_p = 1.559(5)\ M_\odot$, $M_c = 1.174(4)\ M_\odot$.
- If tighter systems like this are found, this has profound implications for the formation of heavy elements in the Universe!



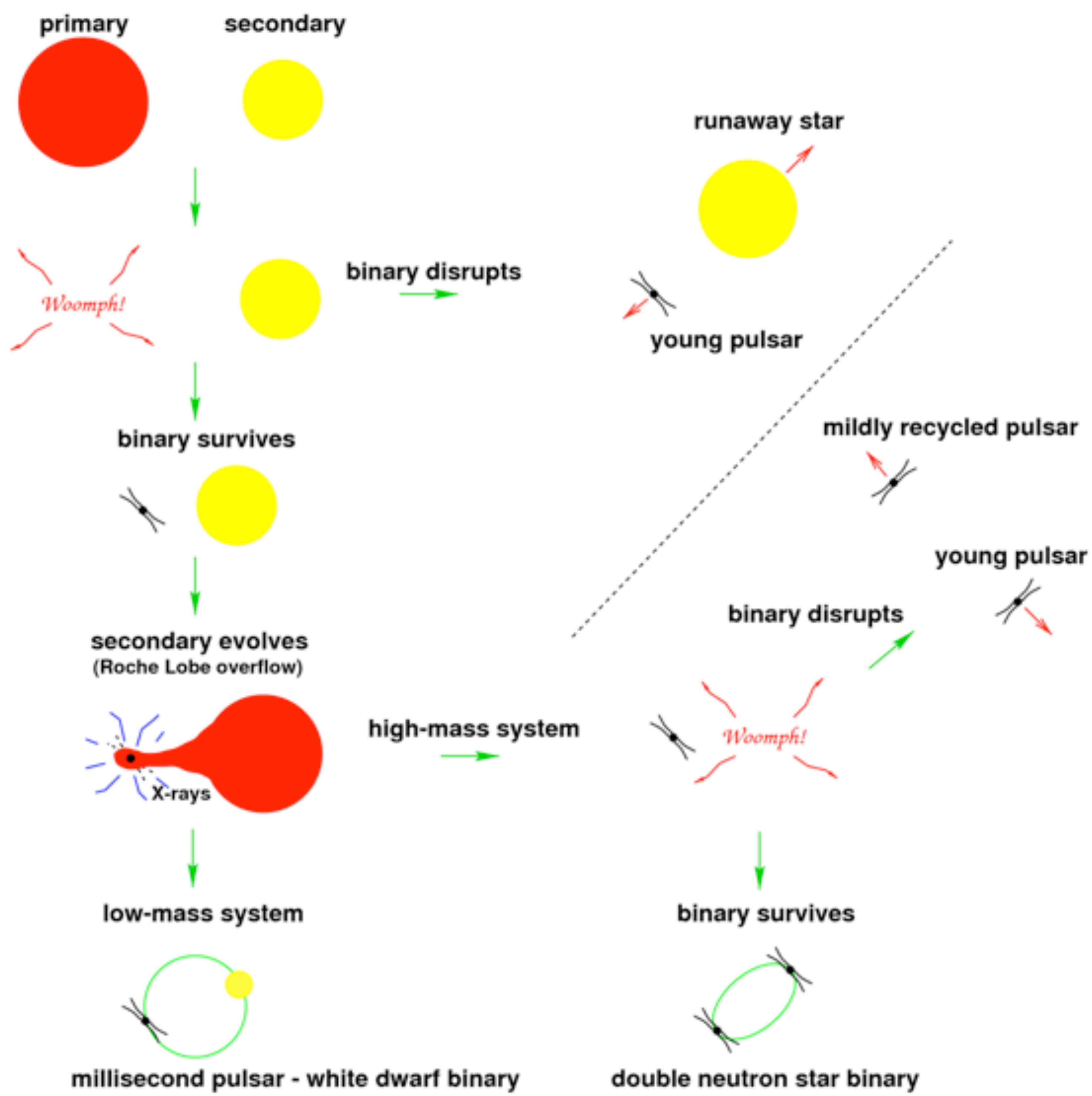
Old and new trends

- Total of 15 systems known might be DNSs, but three of these are doubtful. Outside globular clusters, there are now 13 systems, but two of them are doubtful.

- They can be born with a range of masses that is much wider than previously thought!

- Most DNSs discovered recently have low eccentricities, and many of the recently discovered NSs in them have relatively low masses.

DNSs and millisecond pulsars



- By millisecond pulsar we mean something that spins really fast - NOT the recycled pulsars in DNS systems, but the few ms pulsars in the circular pulsar-WD systems.

- It is thought that these could be more massive, given the much longer accretion episode! So, we REALLY WANT TO DO THIS

Measuring MSP masses: It’s hard!

- Timing precision is much higher, BUT

- Measuring masses much more difficult since generally orbits are so circular! This means that precession of periastron and Einstein delay (which provide precise mass measurements for most DNSs) are not available.

- Solutions: 1) Pulsars in globular clusters / 2) Measurements of Shapiro delay / 3) Find unusually eccentric systems / 4) do spectroscopy (see John Antoniadis’ talk).

Solution 1: Pulsars in globular clusters

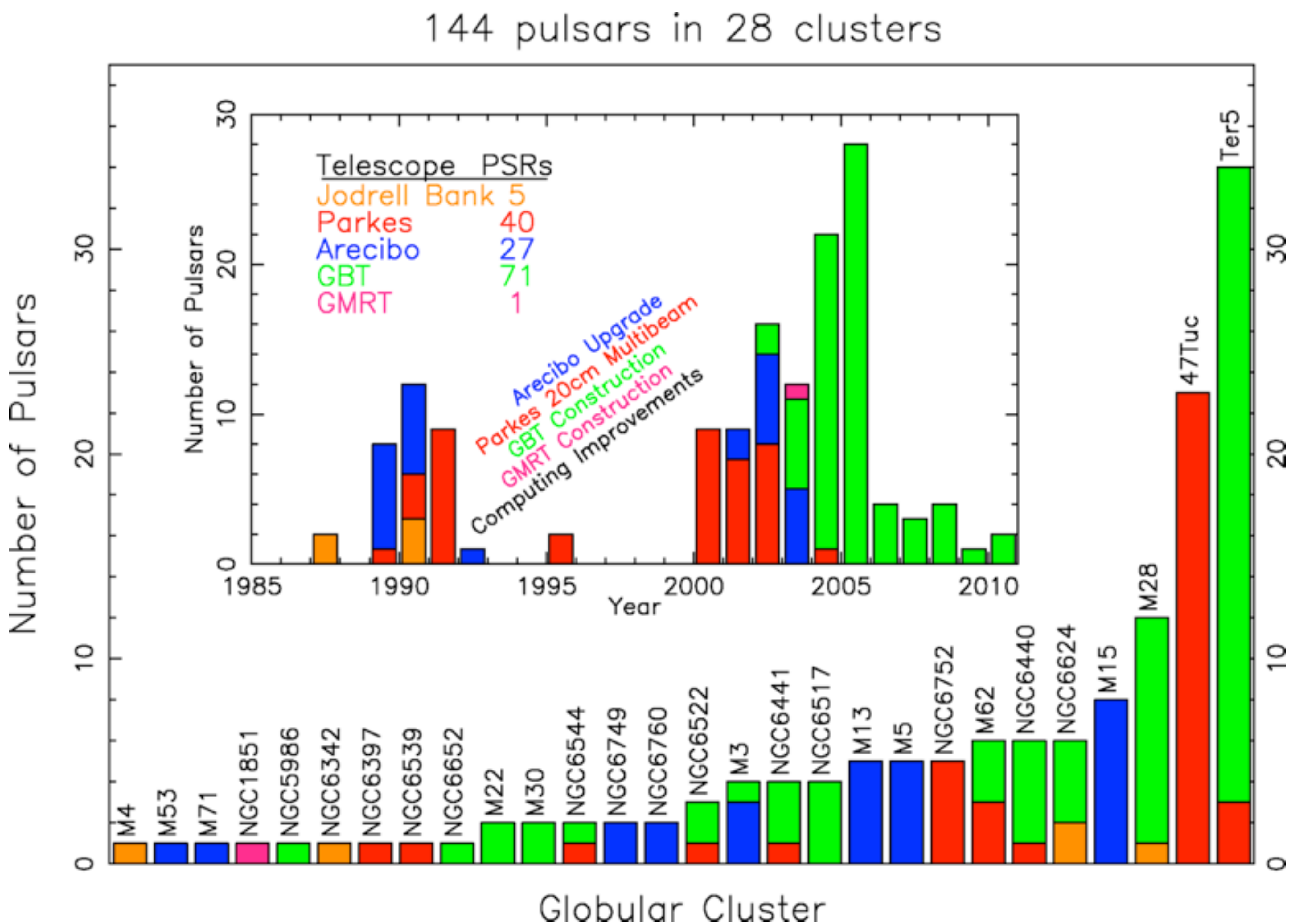


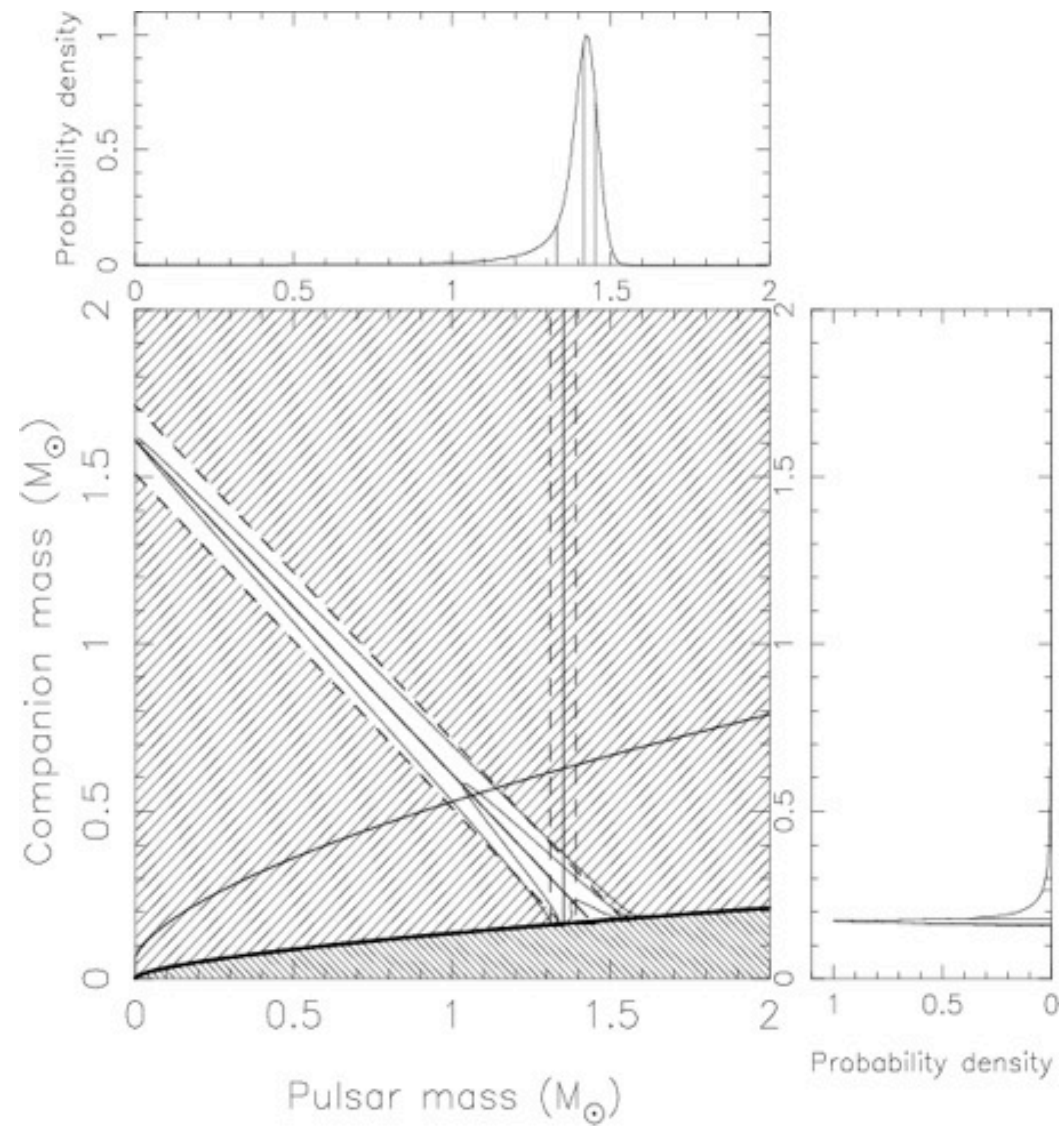
Image courtesy of Scott M. Ransom

Solution 1. Pulsars in Globular clusters

- Unlike Galaxy, pulsars in globular clusters are mostly MSPs in binary systems
- they have more eccentric orbits! This is due to the high stellar densities and the high probability of stellar encounters that change the shape of the orbit.
- These eccentric orbits allow the measurements of the precession of periastron - and perhaps something more.
- ... but not much. Wider orbits are the most affected, therefore other effects weaker.
- Shapiro delay difficult to measure: these pulsars are faint.

Timing of GC binaries. I. 47 Tuc H

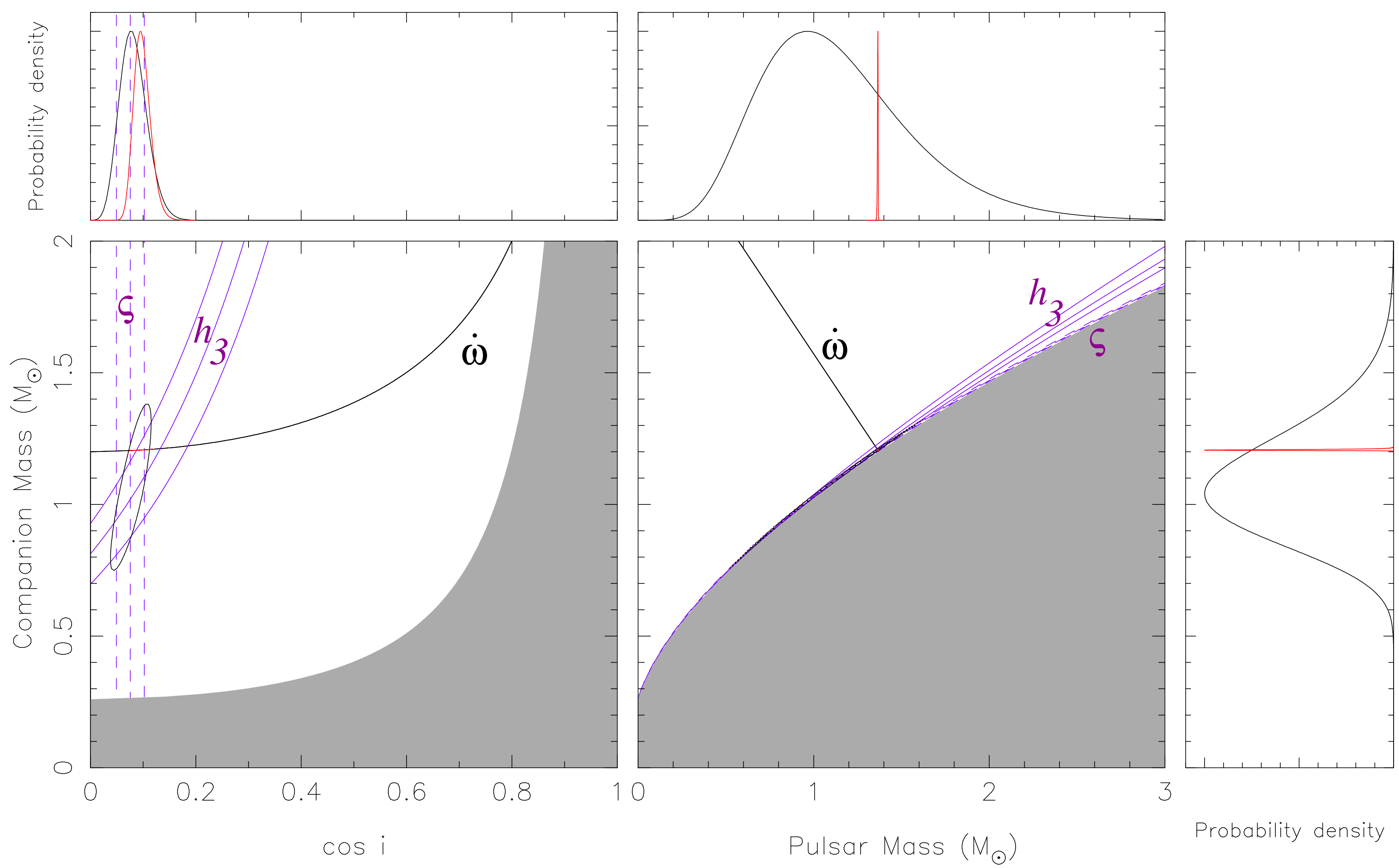
- The rate of advance of periastron allows an estimate of the total system mass for many GC binary MSPs.
- PSR J0024-7204H: (1.61±0.04) $M_\odot$ (Freire et al. 2003, MNRAS, 340, 1359).
- The pulsar mass can not be larger than 1.52 $M_\odot$, the companion has a mass larger than 0.16 $M_\odot$.
- This was the first measurement showing that the recycling of a MSP can be accomplished with ~0.1 $M_\odot$.



From: Freire et al., 2003, MNRAS. 340, 1359

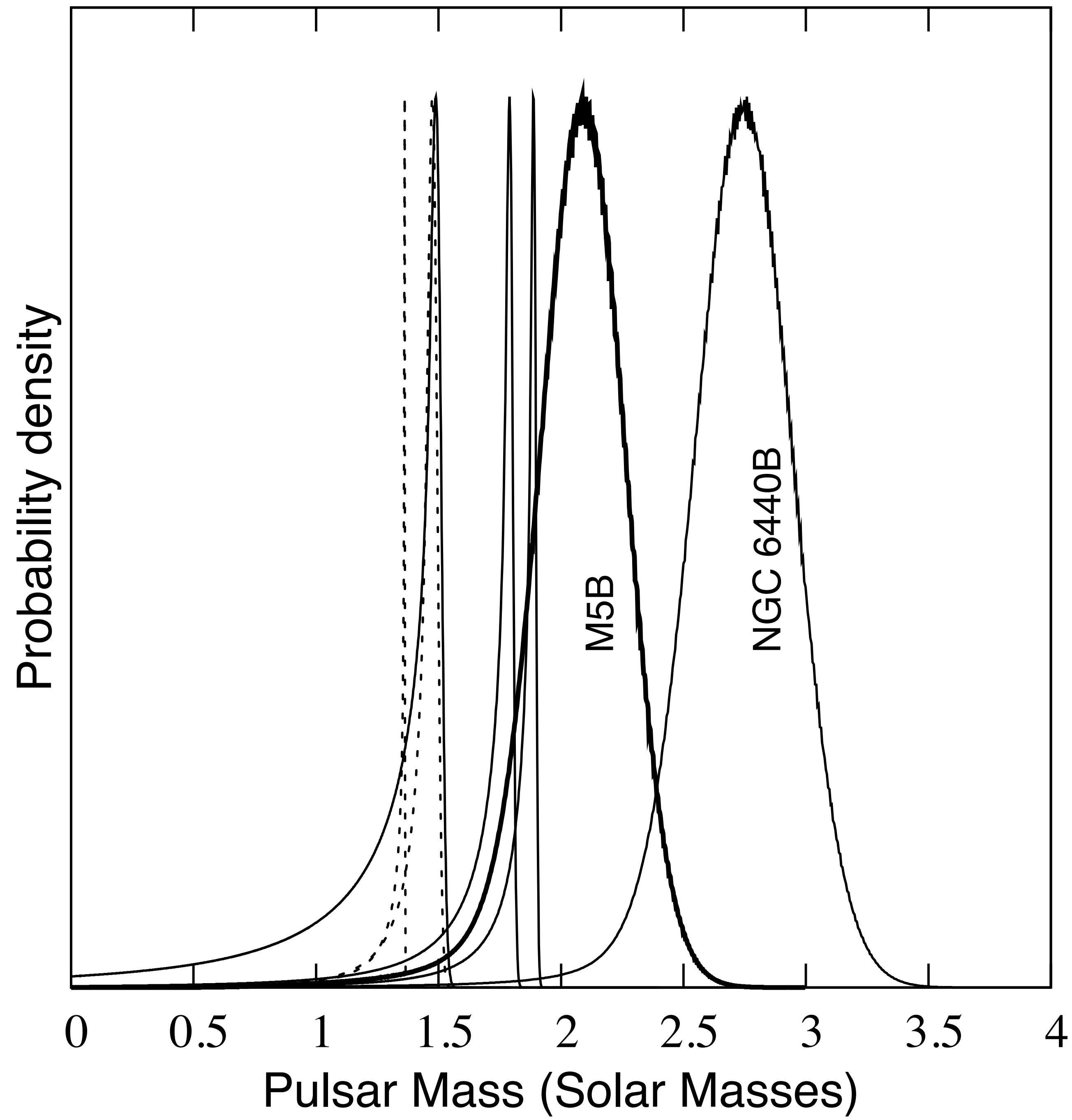
Timing of GC binaries.II. NGC 6544B

- PSR J1807-2500B is a MSP with a spin period of 4.18 ms.
- P_b = 9.95667 days, x = 28.9204 s, e = 0.74702.
- Precise masses derived from precession of periastron and Shapiro delay, as in the case of J0453+1559:
  $M_p = 1.3655(21)\,M_\odot$
  $M_c = 1.2064(20)\,M_\odot$
  (Lynch, Freire, Ransom & Jacoby 2012, ApJ, 745, 109)
- Possible DNS! Only one with a MSP, since it was formed in an exchange encounter.



MSP Ensemble

- Statistical evidence in 2008 was already suggesting that millisecond pulsars have a much broader mass range than previously thought - by a factor of two!
- Massive NSs are not rare!
- This is much wider than observed for the neutron stars in double neutron star systems, even now.
- The likely reason for this is the accretion of material into the neutron star that was needed to recycle it into a millisecond pulsar.



From: Freire et al. 2008b, ApJ, 679, 1433

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Confirmed!!!

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Confirmed!!!

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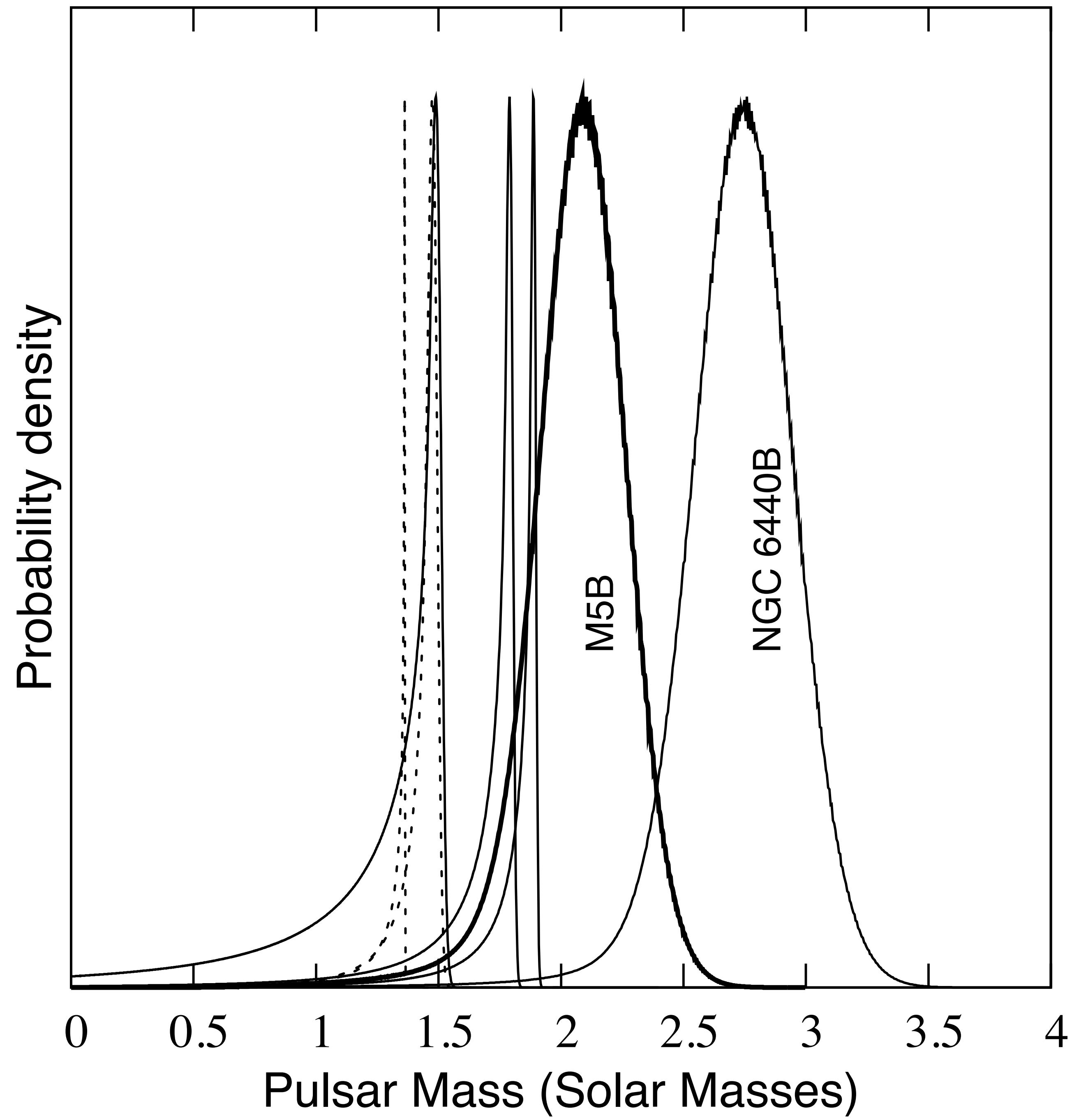
Not clear!



From: Freire et al. 2008b, ApJ, 679, 1433

Solution 2. Shapiro delay

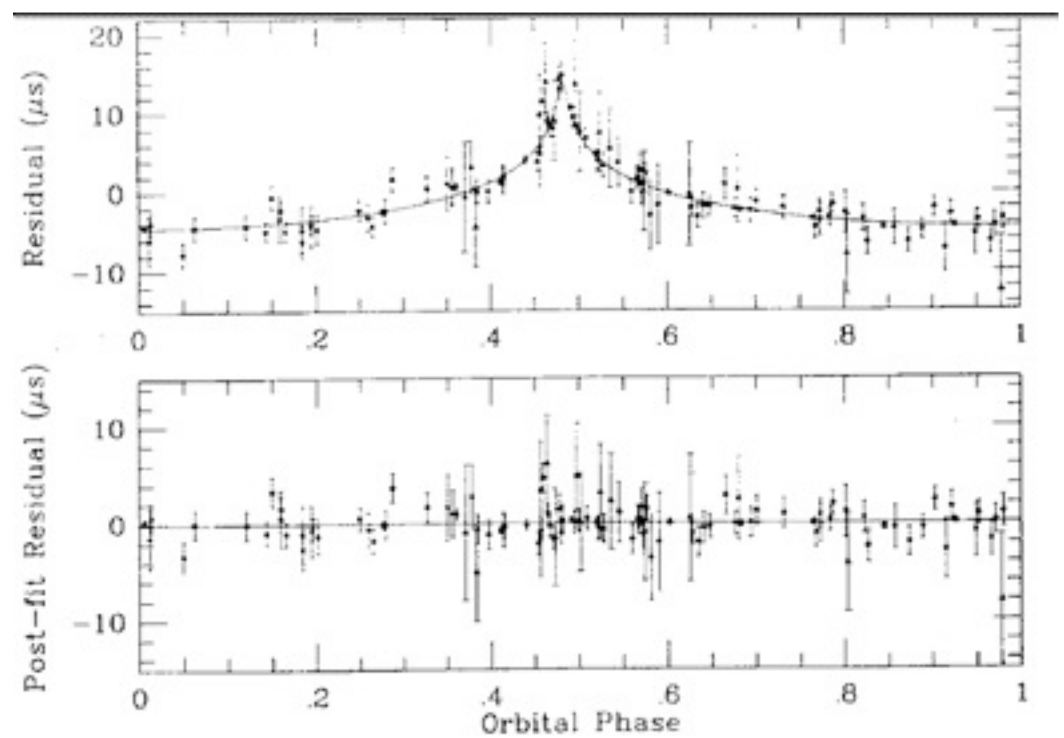
- Shapiro delay still measurable for circular orbits.

- Requires good timing precision and high inclination and preferably high companion masses - difficult for MSPs with He WD companions

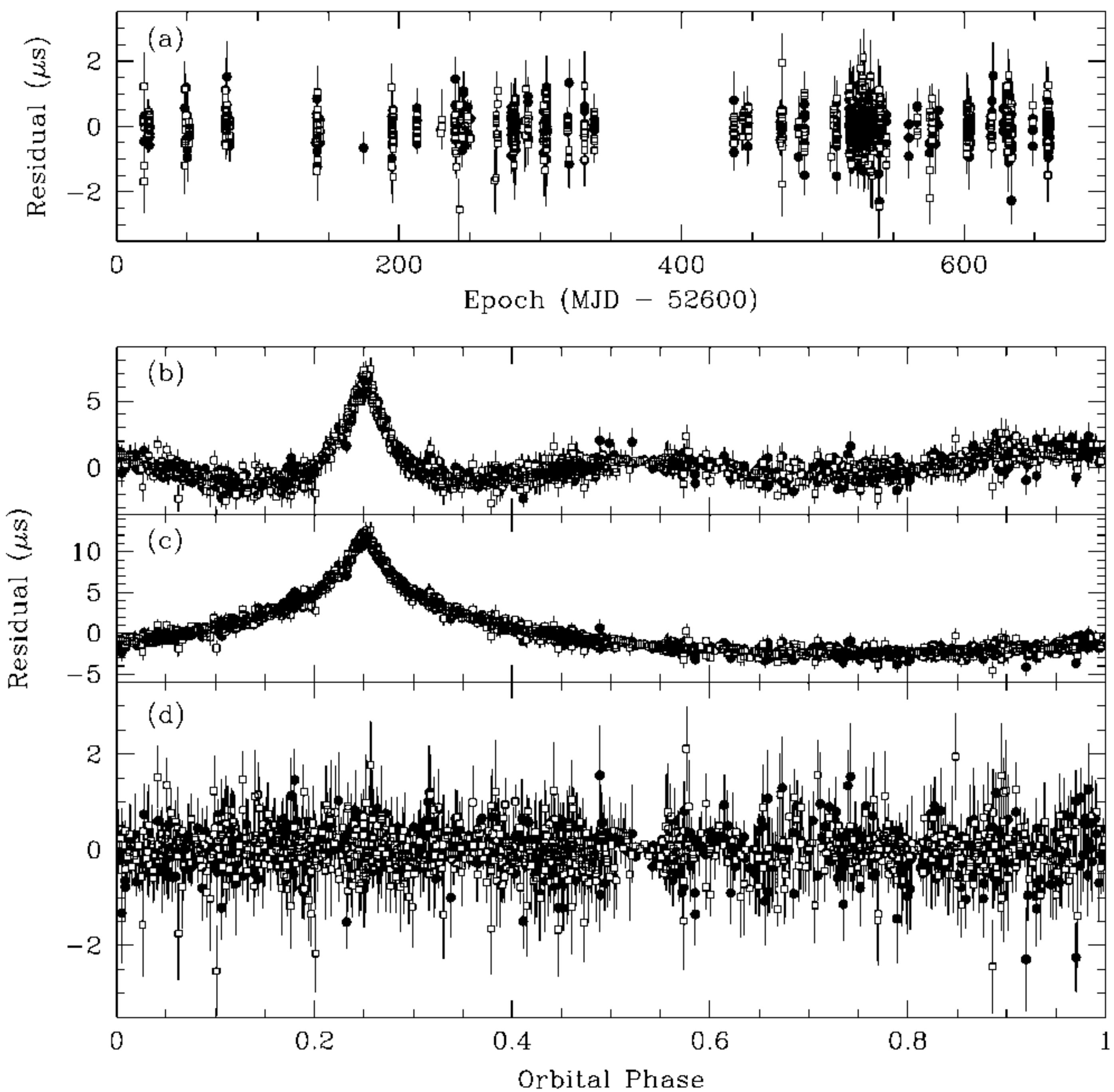
- First detection of Shapiro delay: PSR B1855+09

- No precise mass measurement: combination of timing accuracy and high inclination not there yet.

- Same for many of the early MSPs (like e.g., J1713+0747)

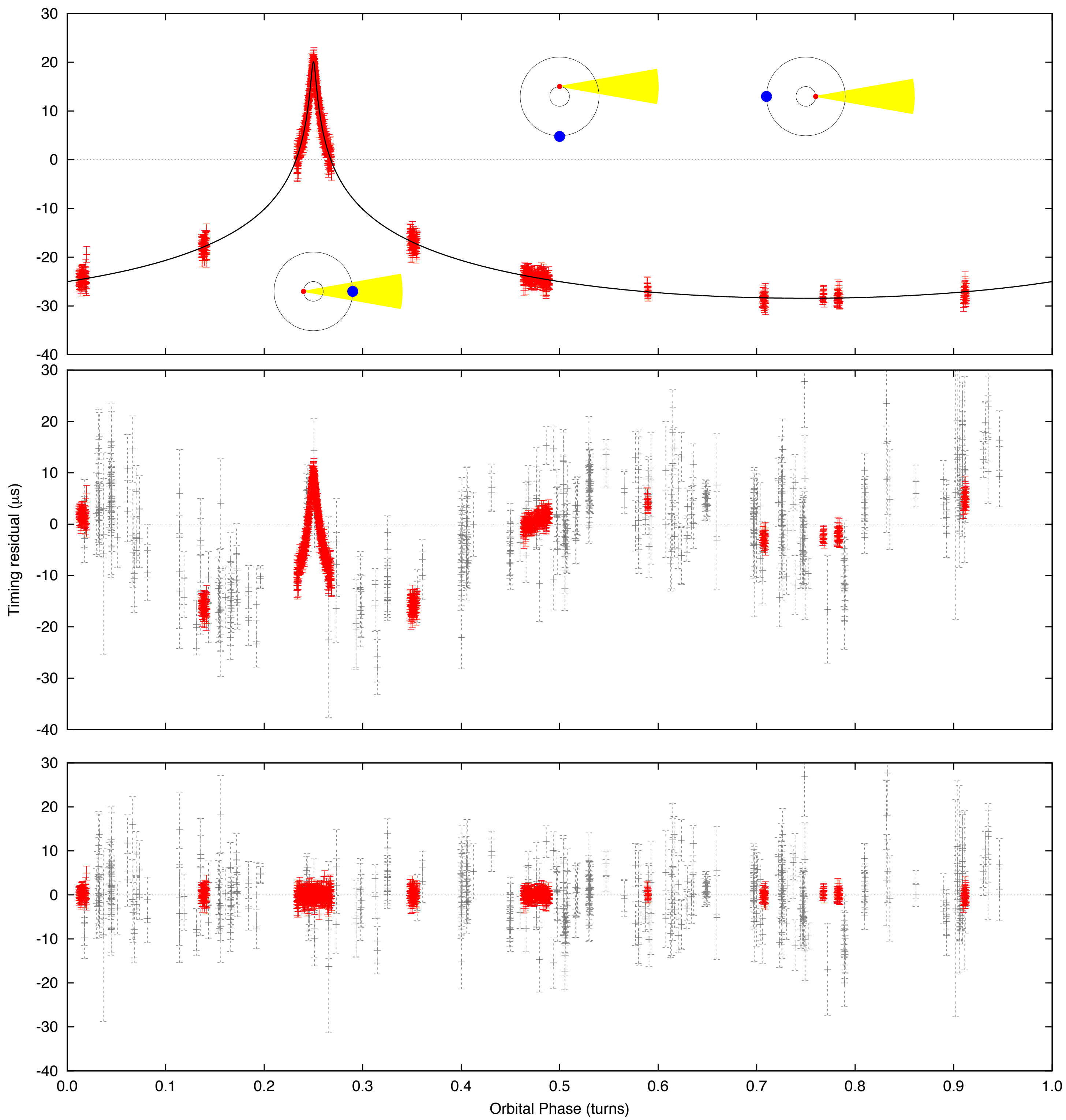


A precise MSP mass



- PSR J1909−3744 is a MSP with a spin period of 2.947 ms - and one of the most precise timers known.
- P_b = 1.533 d, e = 0.000000135(15)
- i = 86.58(11) degrees!
- Precise masses derived from Shapiro delay only:
  $M_p = 1.438(24)\ M_\odot$
  $M_c = 0.2038(23)\ M_\odot$
  (Jacoby et al. 2005, ApJL, 629, 113)

A precise *and large* MSP mass

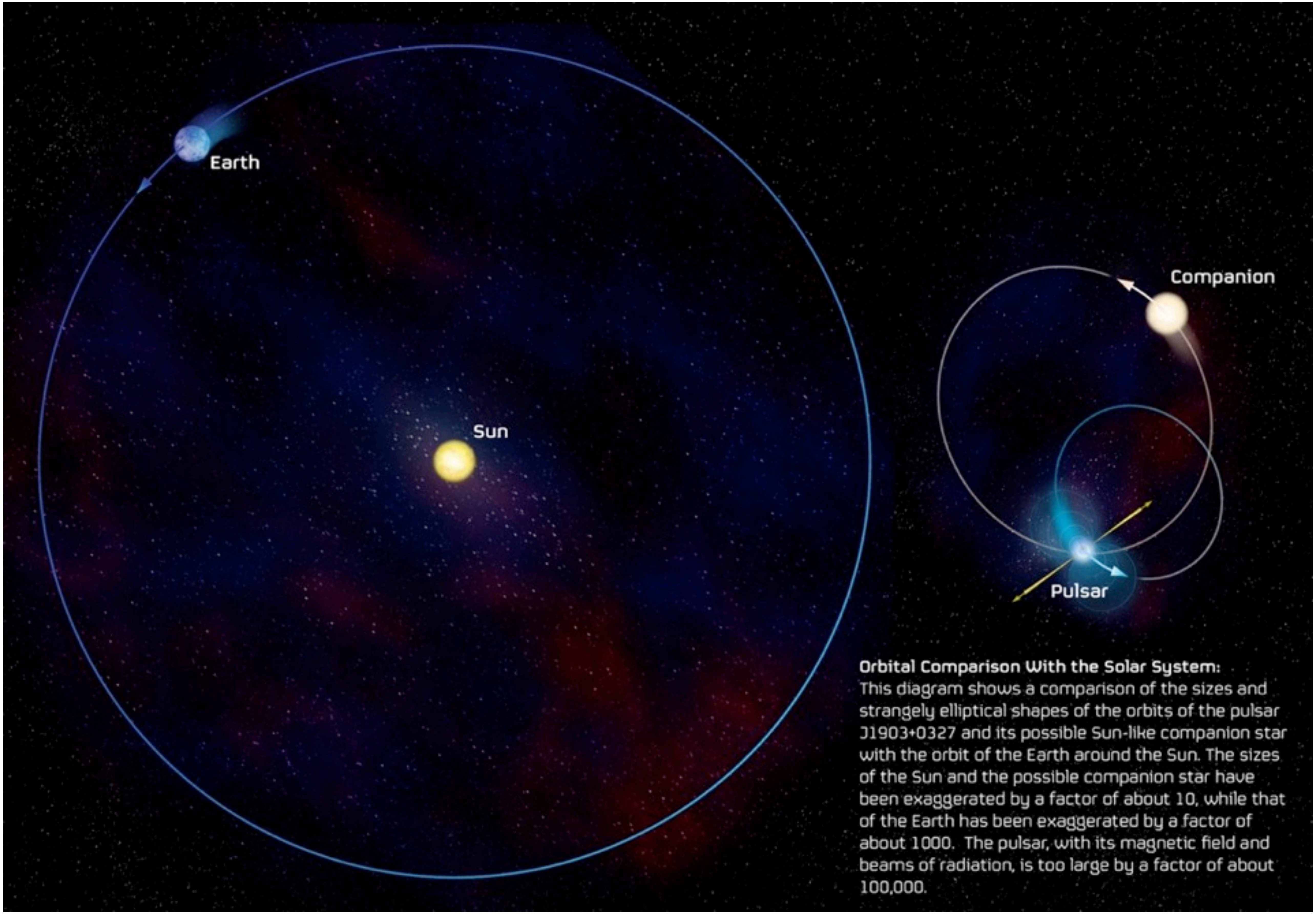


- PSR J1614–2230 is a MSP with a spin period of 3.15 ms.
- P_b = 8.68 d, e = 0.00000130(4)
- i = 89.17(2) degrees!
- Precise masses derived from Shapiro delay only:
  $M_p = 1.97(4)\ M_\odot$
  $M_c = 0.500(6)\ M_\odot$
  (Demorest et al. 2010, Nature)
- Update: $M_p = 1.928(17)\ M_\odot$
  (Fonseca et al., in preparation)

Solution 3: Triples, disrupted triples and other monsters

- These MSPs are eccentric, and can be quite strong - precise masses for most of them!

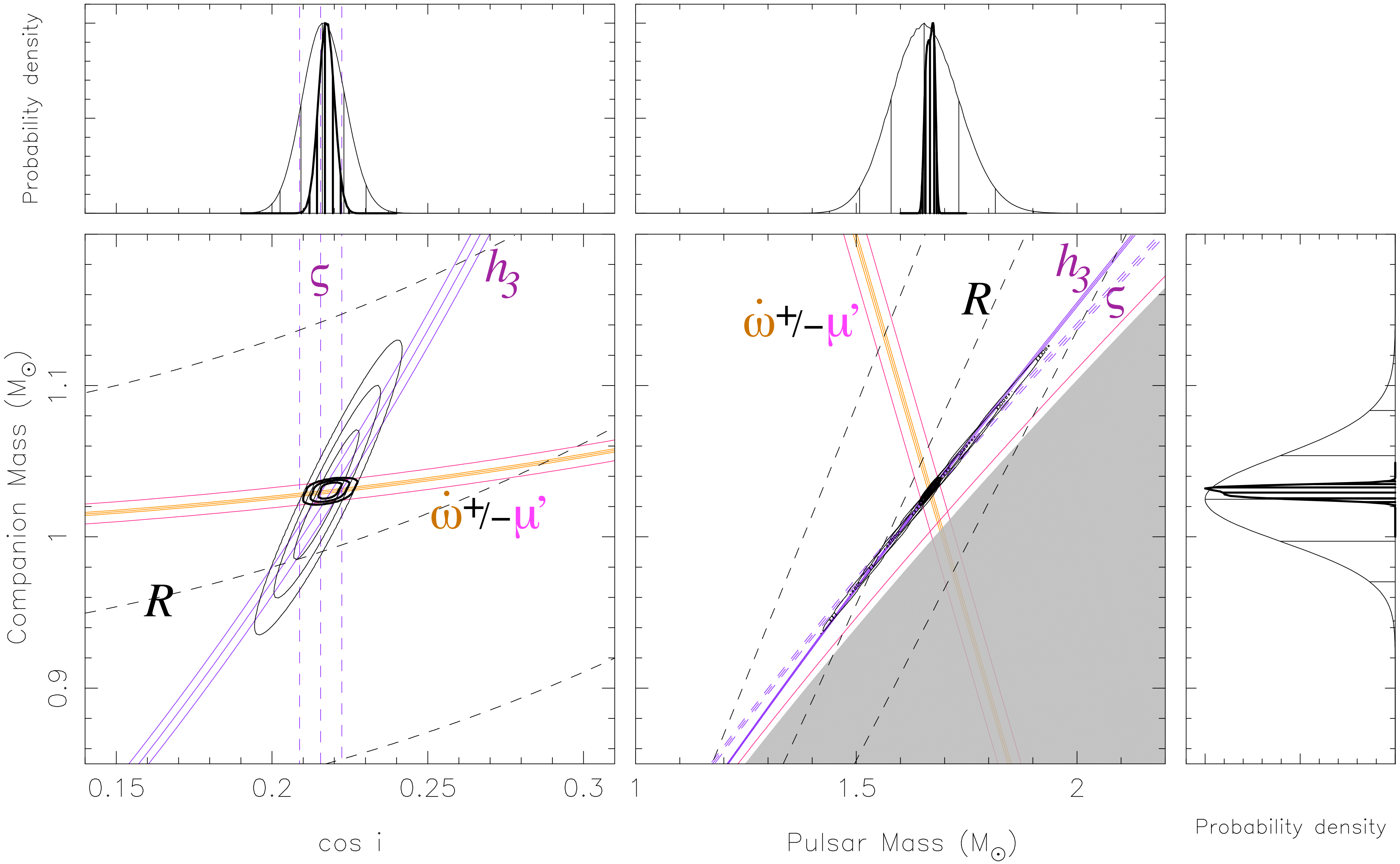
- Problem: rare



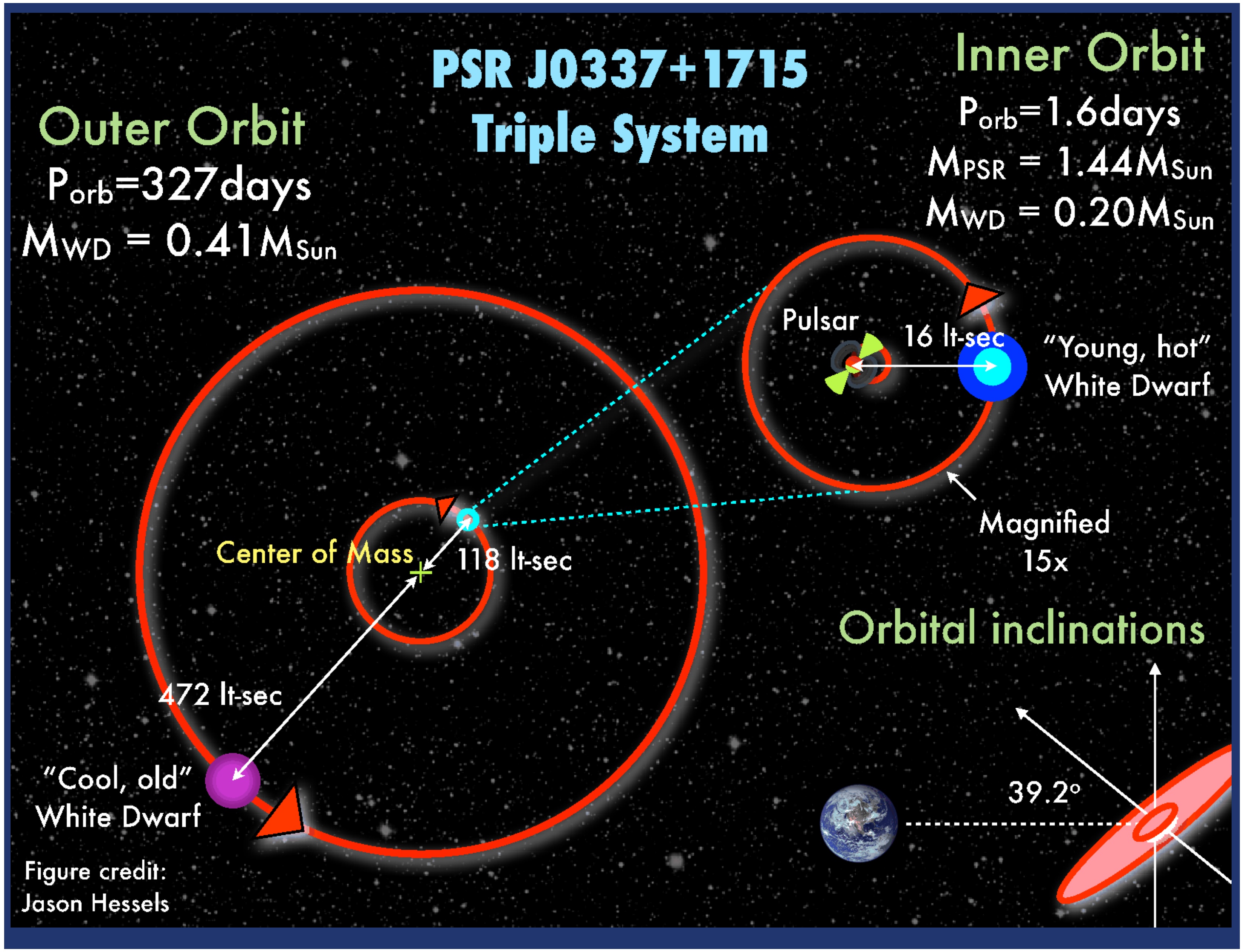
From: NRAO / Cornell University Press Release

Mass for PSR J1903+0327

- Precise MSP mass: 1.667 ± 0.021 $M_\odot$ (99.7% C. L.). See Freire et al., 2011, MNRAS,412, 2763.
  System formed by disruption of a triple system.



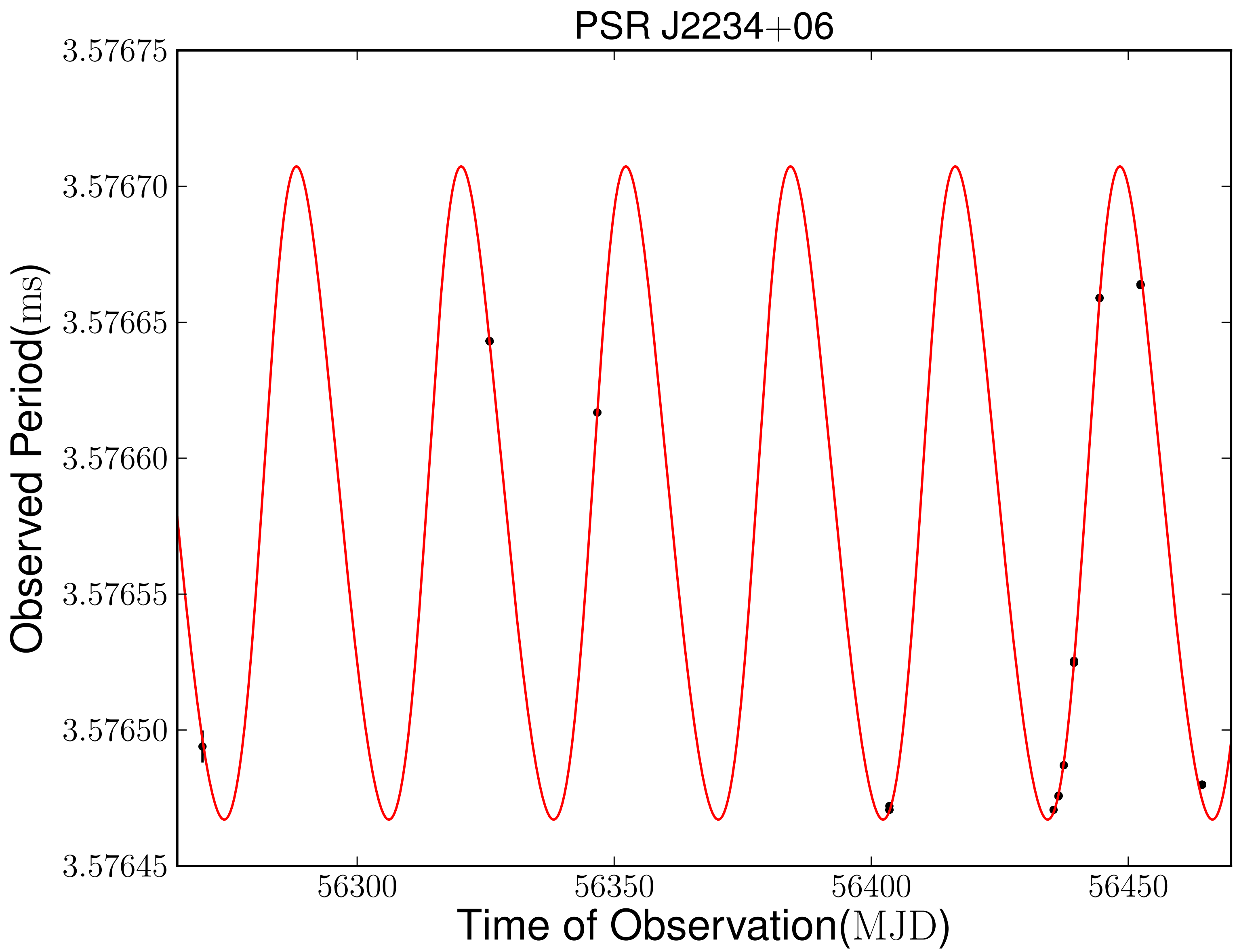
The triple system



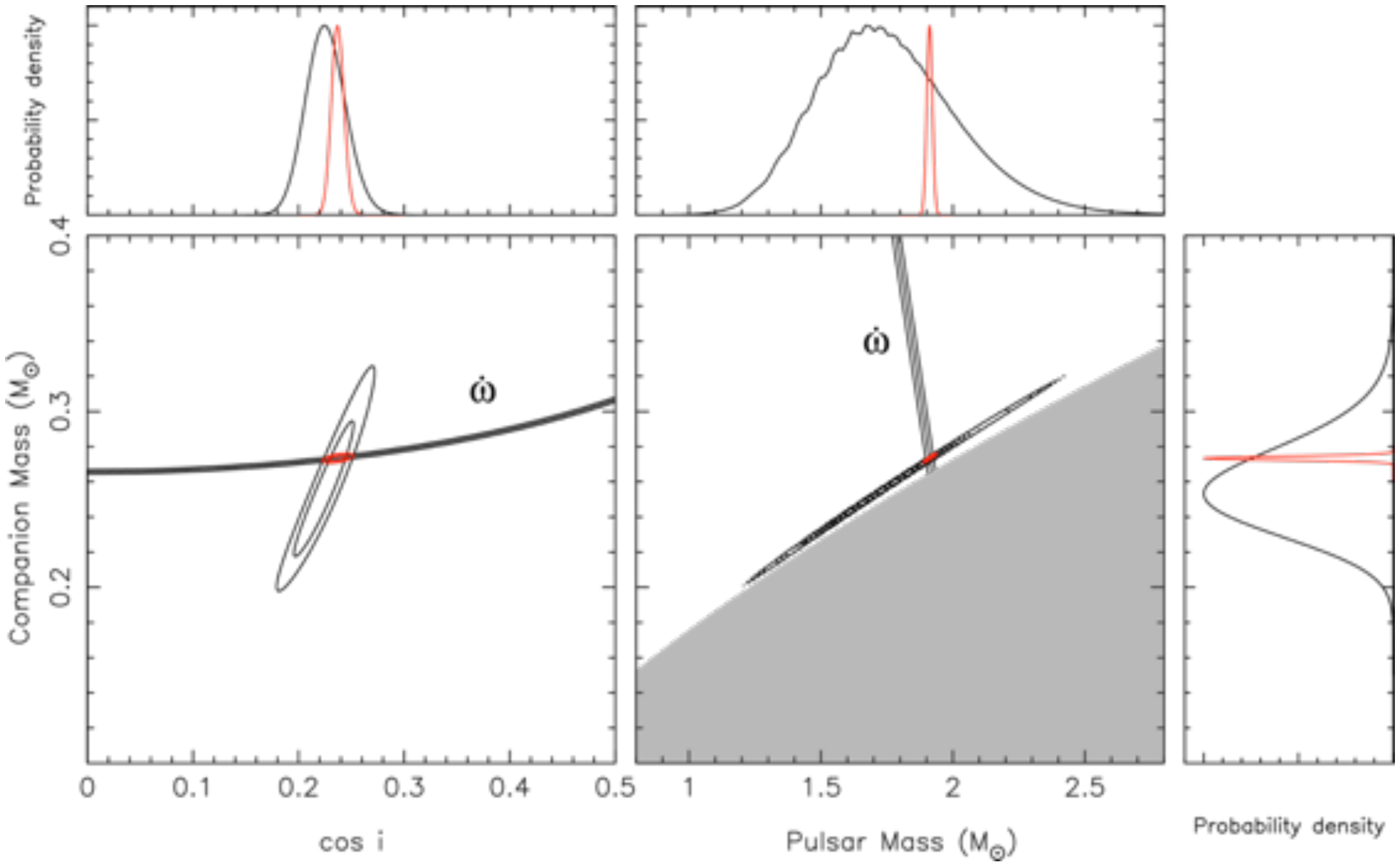
- The GBT 350-MHz drift-scan survey found a pulsar in a hierarchical triple, PSR J0337+1715! (Ransom et al., 2014, Nature, 505, 520)
- Precise mass measurements can be derived from the 3-body interaction.
- This system has enormous potential fof SEP tests (see Freire, Kramer & Wex, 2012, CQGra, 29, 184007)

A new class of binary MSPs

- There is a new class of binary MSPs with P = 2 - 5 ms, e ~ 0.1 and P_b = 22-32 days (4 so far)!
- Strong objects, with good timing...

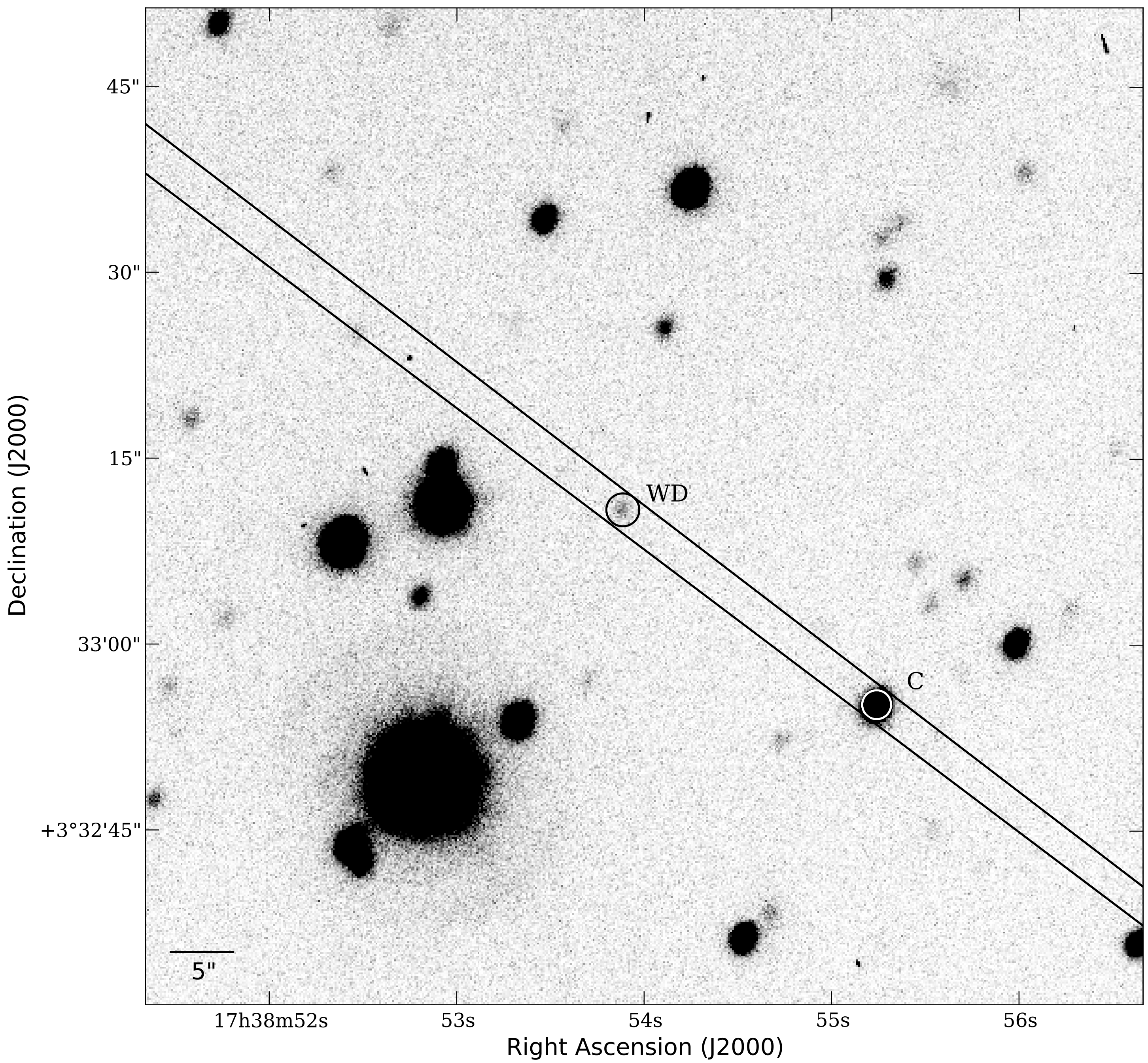


A new class of binary MSPs



- PSR J1946+3417 is a MSP with a spin period of 3.17 ms recentrly discovered with the Effelsberg telescope (Barr et al. 2013, MNRAS, 435, 2234).
- P_b = 27.02 d, e = 0.134
- Precise masses derived from Shapiro delay and precession of periastron:
  $M_p = 1.870(10)\ M_\odot$
  $M_c = 0.2733(11)\ M_\odot$
  (Barr et al., in preparation)
- Massive NSs are not rare!

Solution 4: spectroscopic mass measurements

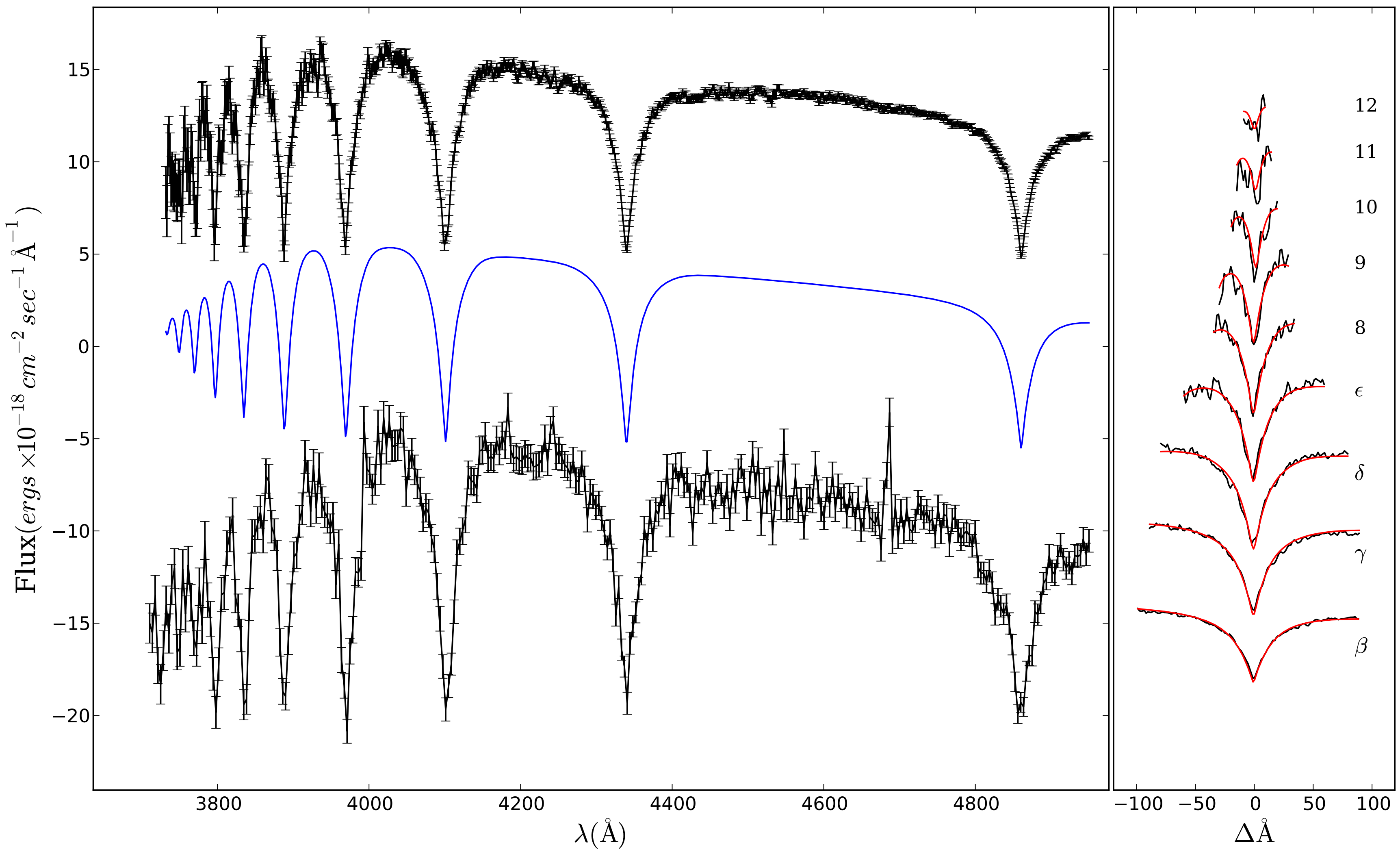


- PSR J1738+0333 is a 5.85-ms pulsar in a 8.5-hour, low eccentricity orbit. It was discovered in 2001 in a Parkes Multi-beam high-Galactic latitude survey (Jacoby 2005, Ph.D. Thesis, Caltech)

- Companion WD detected at optical wavelengths, and relatively bright!

All pictures in this section: Antoniadis et al. (2012), MNRAS, 423, 3316

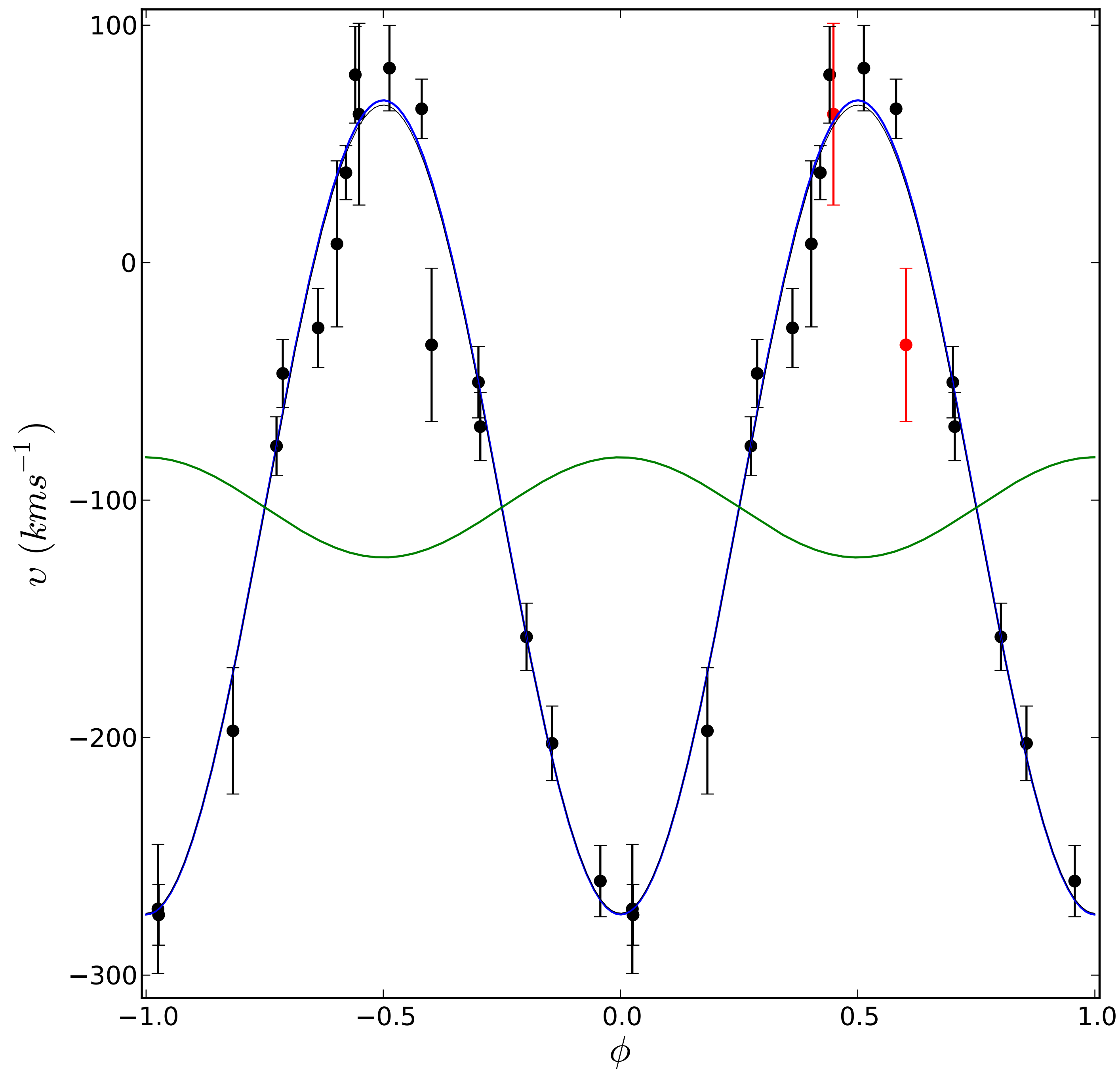
Solution 4: spectroscopic mass measurements



- The WD is bright enough for a study of the spectral lines!

- Together with WD models, these measurements allow an estimate of the WD mass: $0.181^{+0.007}_{-0.005}$ $M_{\odot}$.

Solution 4: spectroscopic mass measurements

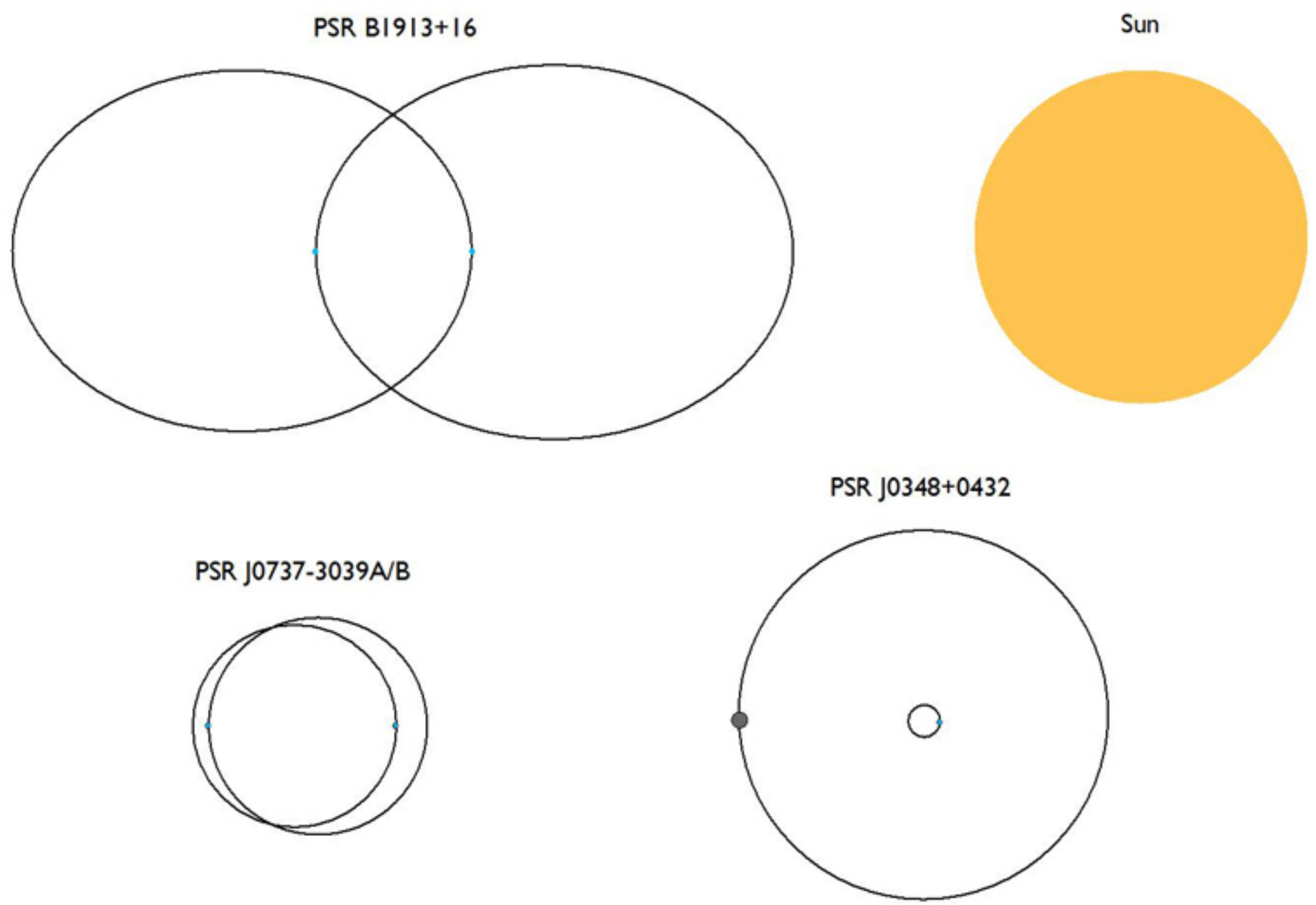


- Shift in the spectral lines allows an estimate of the mass ratio: q = 8.1 ± 0.2.
- This allows an estimate of the orbital inclination (32.6 ± 1.0°) and the mass of J1738+0333: $1.46^{+0.07}_{-0.06}$ $M_\odot$.
- Results in Antoniadis et al. 2012, MNRAS, 423, 3316.
- These mass measurements allowes the most stringent tests of alternative theories of gravity, like Scalar-Tensor theories - See Freire et al. 2012, MNRAS, 423, 3328.

The big one: PSR J0348+0432

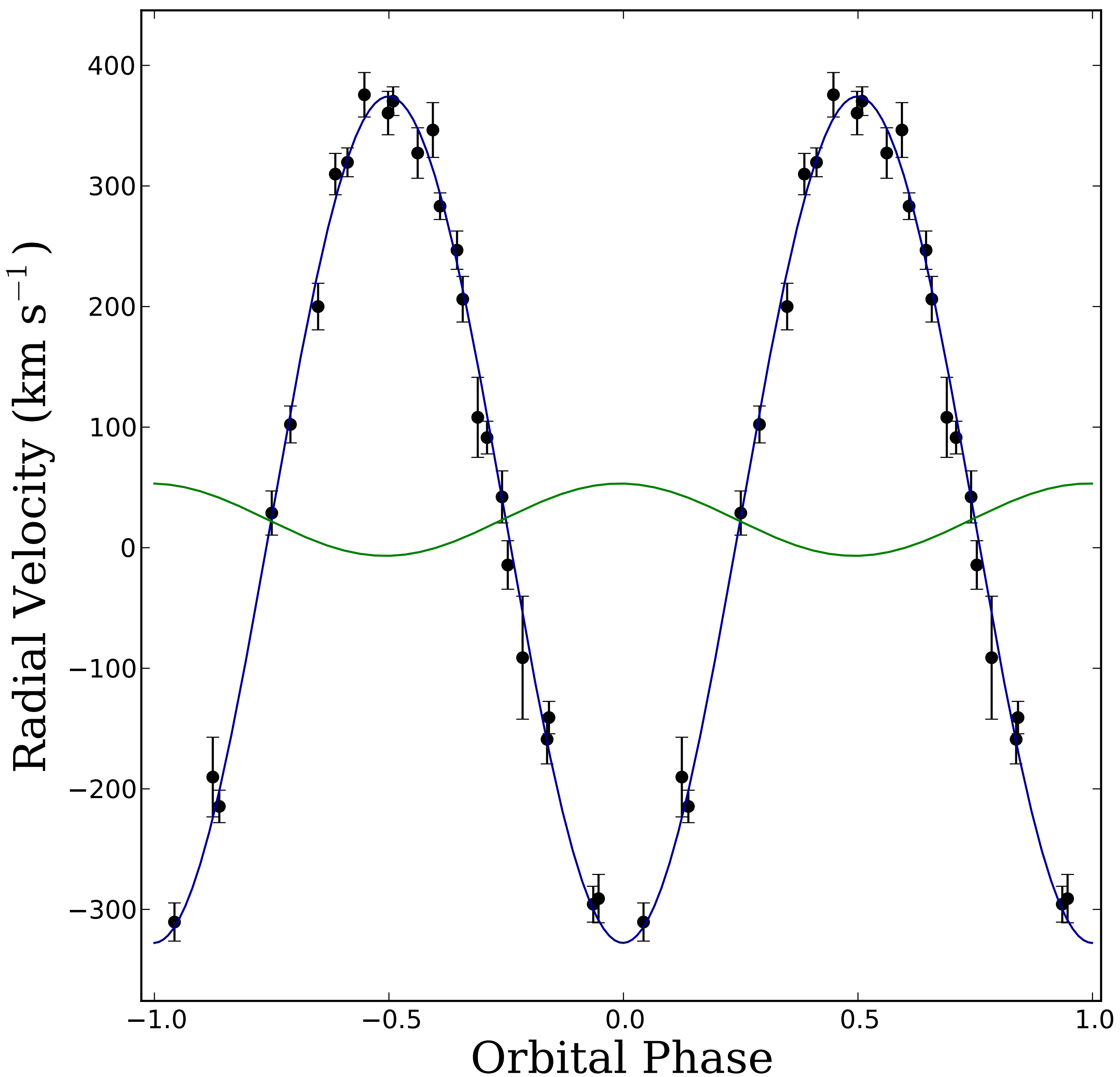
- This is a pulsar with a spin period of 39 ms discovered in a GBT 350-MHz drift-scan survey (Lynch et al. 2013, ApJ. 763, 81).

- It has a WD companion and (by far) the shortest orbital period for a pulsar-WD system: 2h 27 min.



Credit: Norbert Wex

PSR J0348+0432



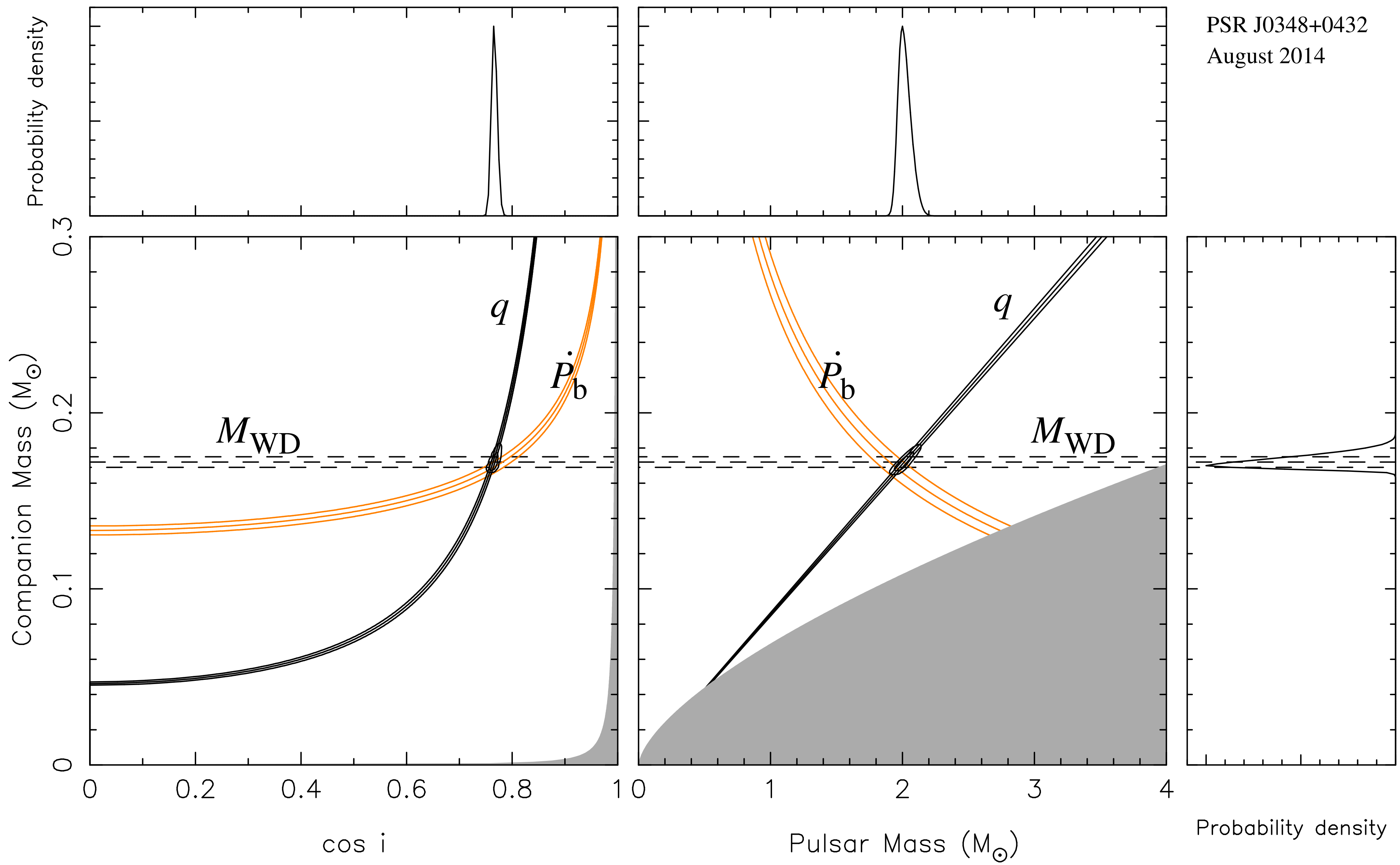
- Recent optical measurements at the VLT find a WD mass of 0.172 ± 0.003 M and **a pulsar mass of 2.01 ± 0.04 M** (Antoniadis et al. 2013, Science, 340, n. 6131).

- Most massive NS with a precise mass measurement.

- Confirms that such massive NSs exist using a different method than that used for J1614−2230. It also shows that these massive NSs are not rare.

- Allows, for the first time, tests of general relativity with such massive NSs! Prediction for orbital decay: −8.1 μs /year!

GR test / better mass measurement



- Already a test of GR: GW emission detected!

Conclusions

- NSs in DNSs are now showing a wider mass distribution
- Measuring masses for MSPs is much more difficult
- ...4 strategies employed, all with advantages and disadvantages,
    - GC pulsars, Shapiro delay measurements, eccentric Galactic binaries, spectroscopy
- ... which show that
    - MSP mass distribution is much wider in MSPs, with upper masses of about 2 $M_\odot$.
    - Massive NSs are not rare!
    - MSP mass distribution might be bimodal.

The Future:

- Within 2 years, the number of NS mass measurements will double.

- Within 10 years, we will have a ~10% measurement of the moment of inertia of PSR J0737−3039A (and possibly another system as well), which is interesting because we know the mass of that pulsar as well.

- We need the SKA!