Measurements of binary pulsar masses and a study on the nature of gravitational waves

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2 in 1 talk:

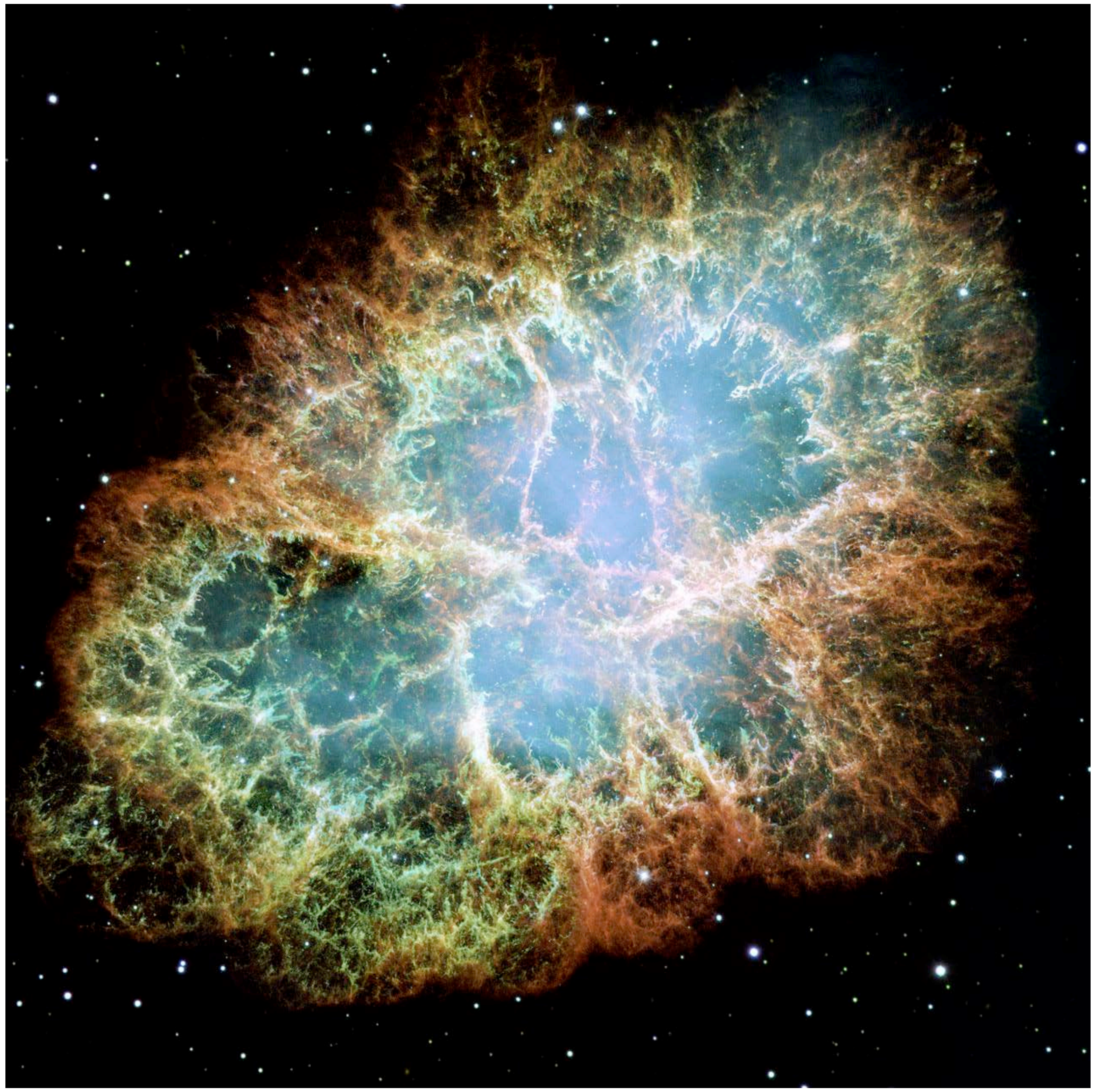
- Tests of gravity theories with binary pulsars

  … specifically, tests of the nature of gravitational waves

- Neutron star masses

- NOT in this talk: direct detection of gravitational waves with pulsar timing arrays (PTAs)

What are pulsars?



Neutron stars are the remnants of extremely massive stars. Towards the end of their lives they explode as Supernovae:

This stuff is so dense we don't know what it is.

POINT MASSES

Non-trivial grav. Prop.

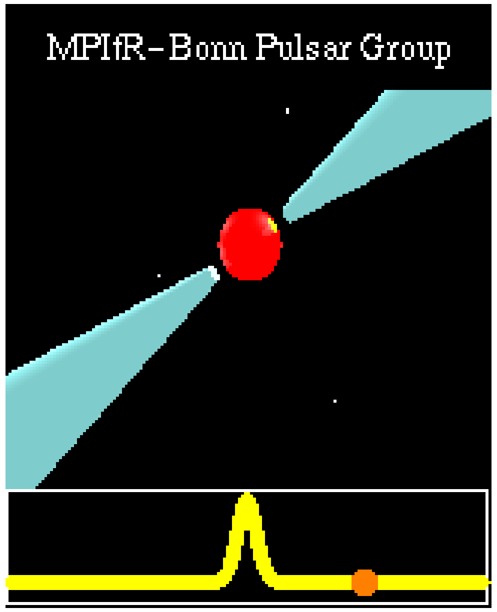
We can time the spin precisely!

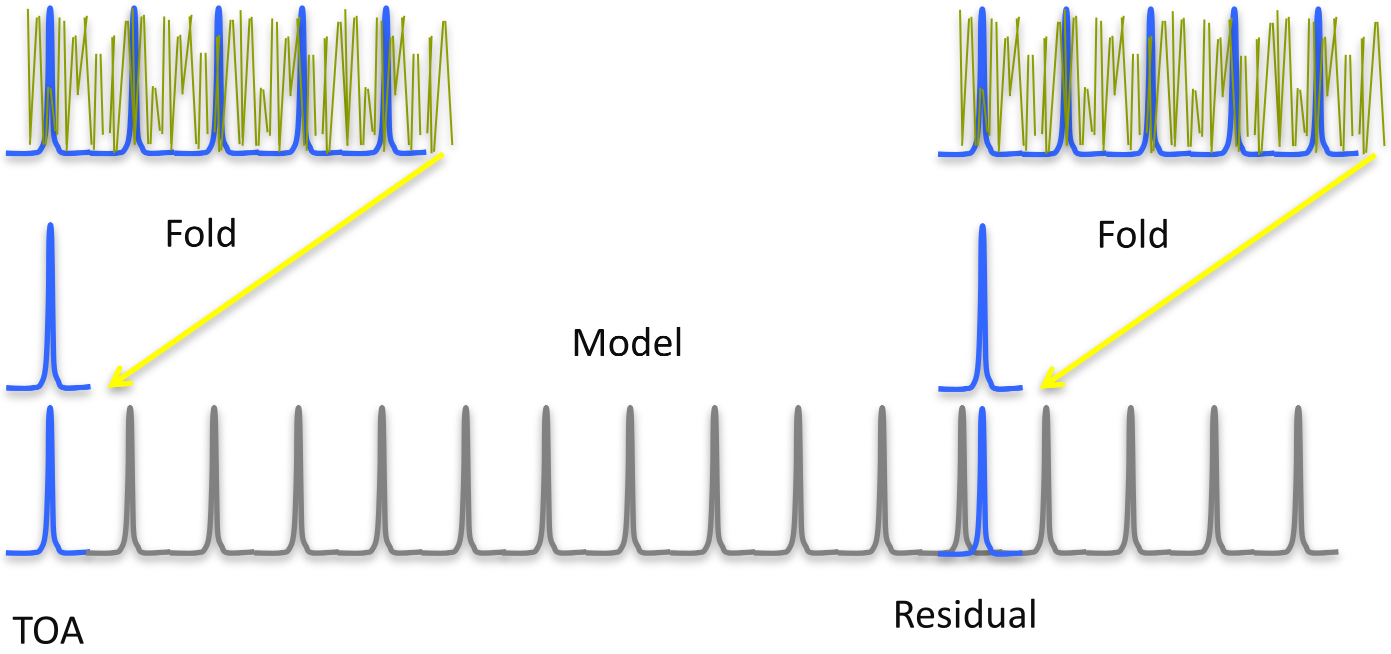
Pulsar timing

Once we find a pulsar, it is interesting to find out how regularly the pulses arrive at the Earth.

Pulsar timing measures pulsar arrival time at the telescope (TOA):

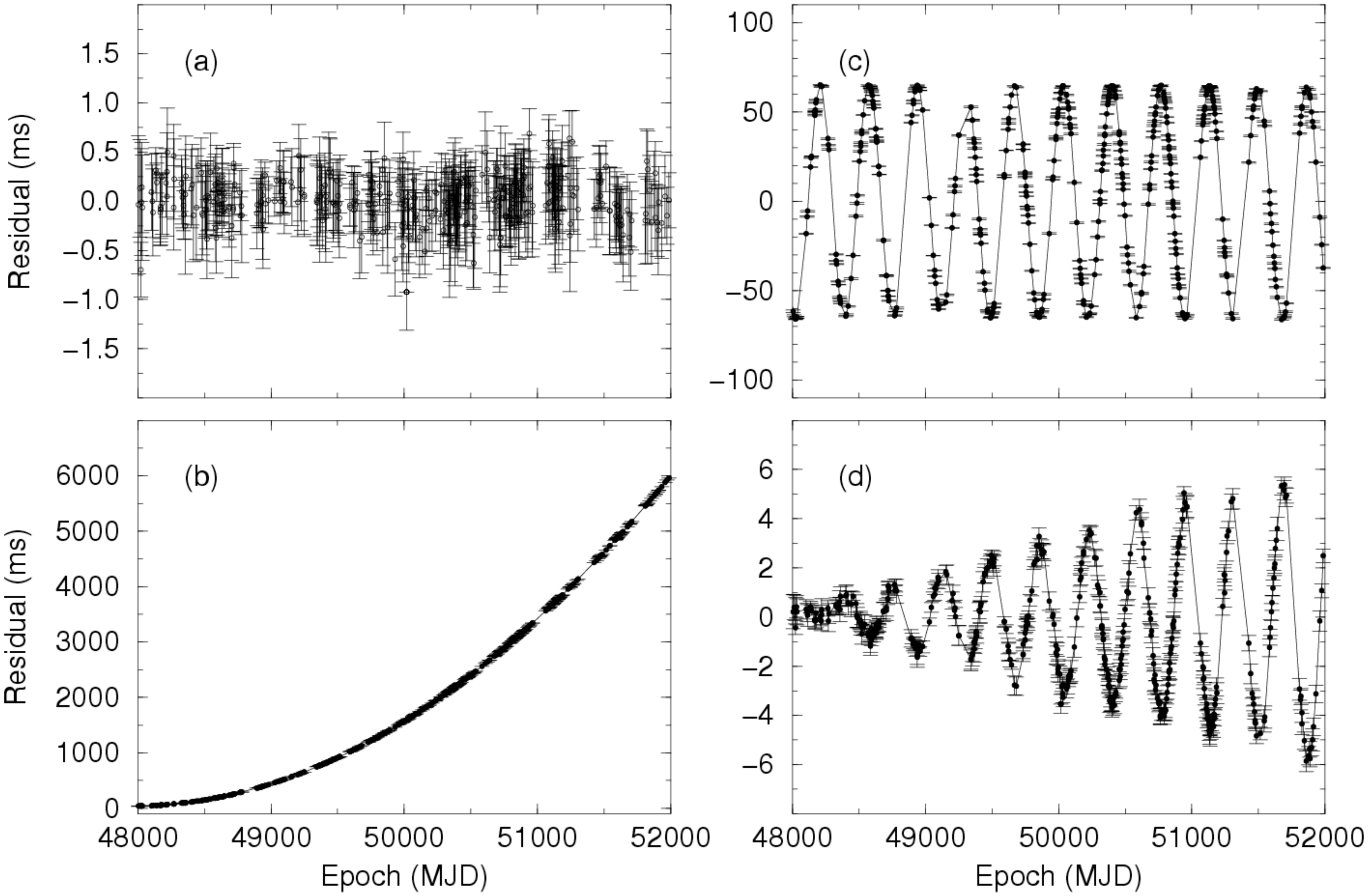
(Radio frequencies, normally 0.3 – 2.5 GHz)





Pulsar timing

The trends in the residuals will tell us what parameter(s) needs correction: generally, all of them!

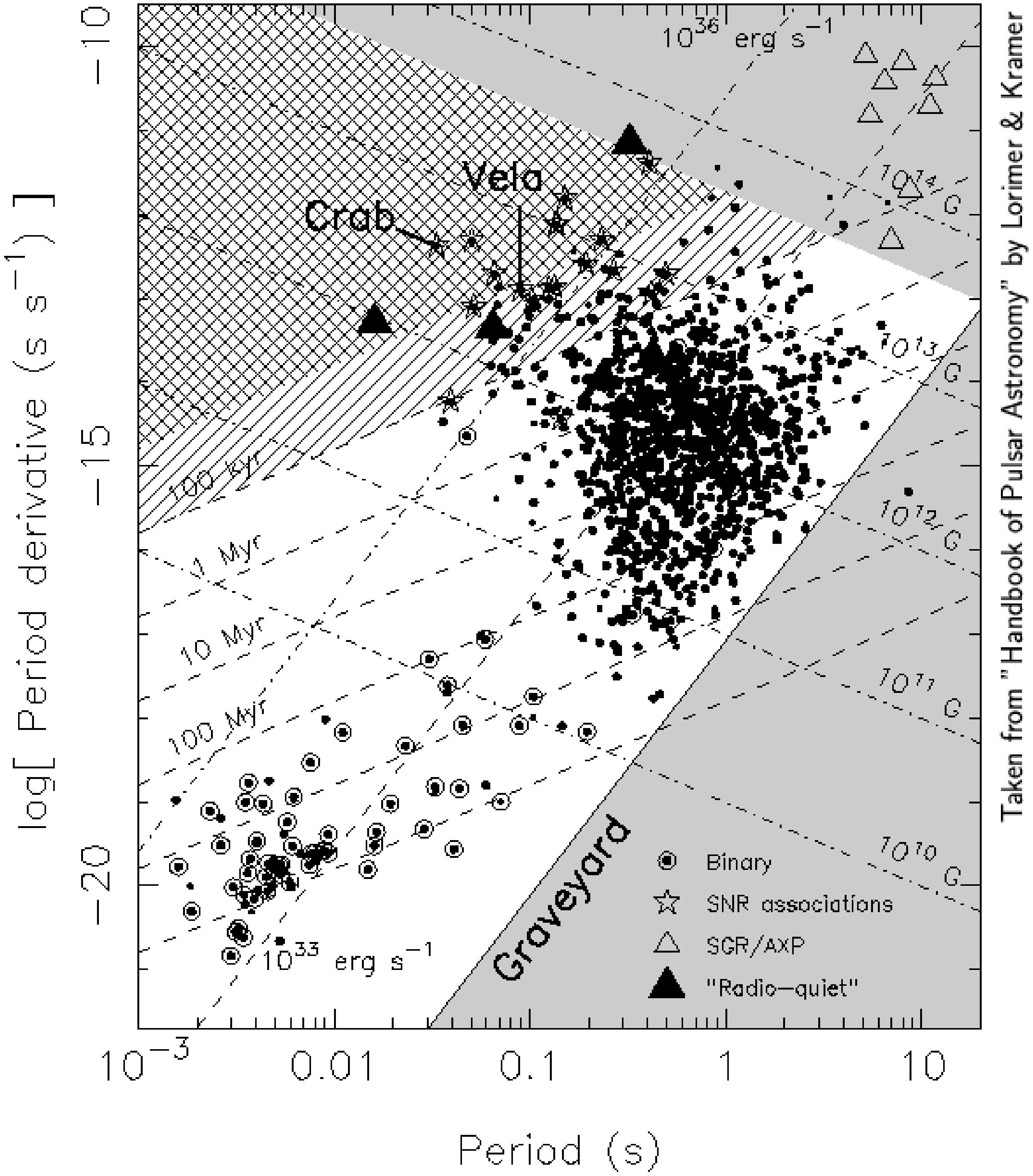


From: ``The Pulsar Handbook'', Lorimer & Kramer 2005

The P-Pdot diagram

- The spin period and the period derivative tell us a lot about the pulsar – its age, magnetic field, spin-down energy, etc.

- Many interesting trends appear in the *P- Pdot diagram*:
  - Like the Crab, youngest pulsars tend to be associated with SN
  - The fastest pulsars are *not* the youngest, but the oldest,
  - Most of these are in binary systems, where they have been *recycled*.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

pulsars

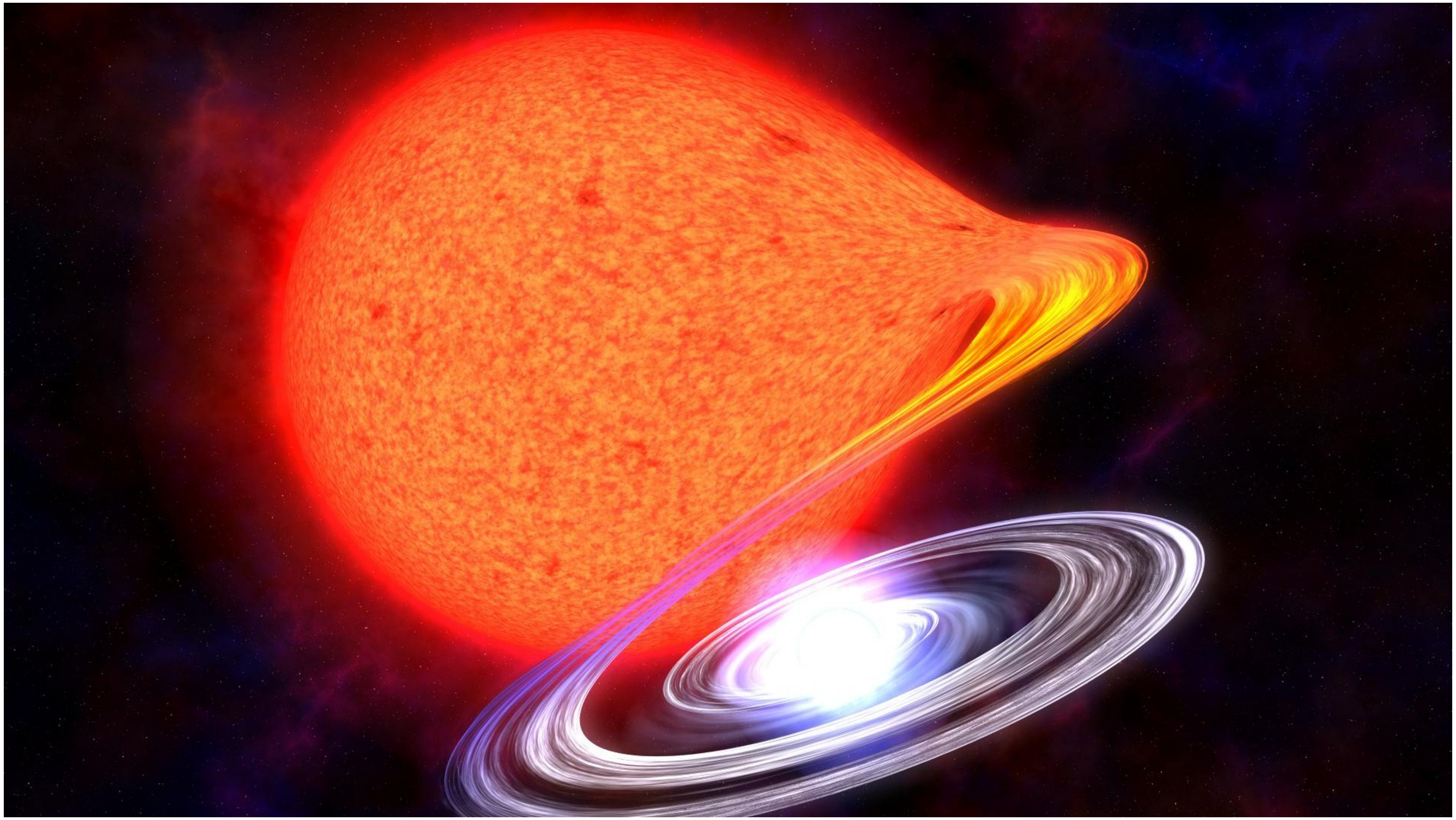


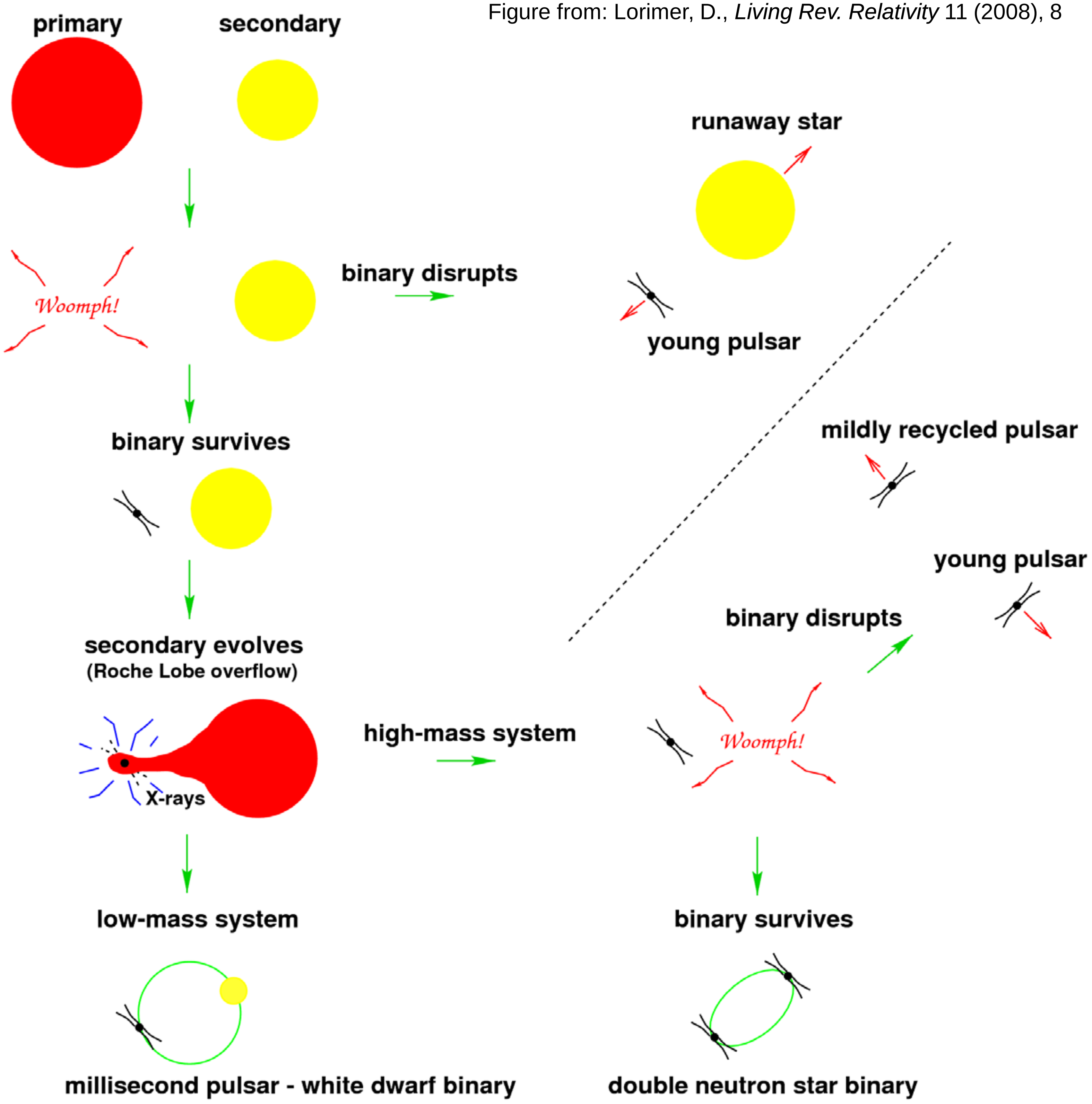
Figure: Alessandro Patruno

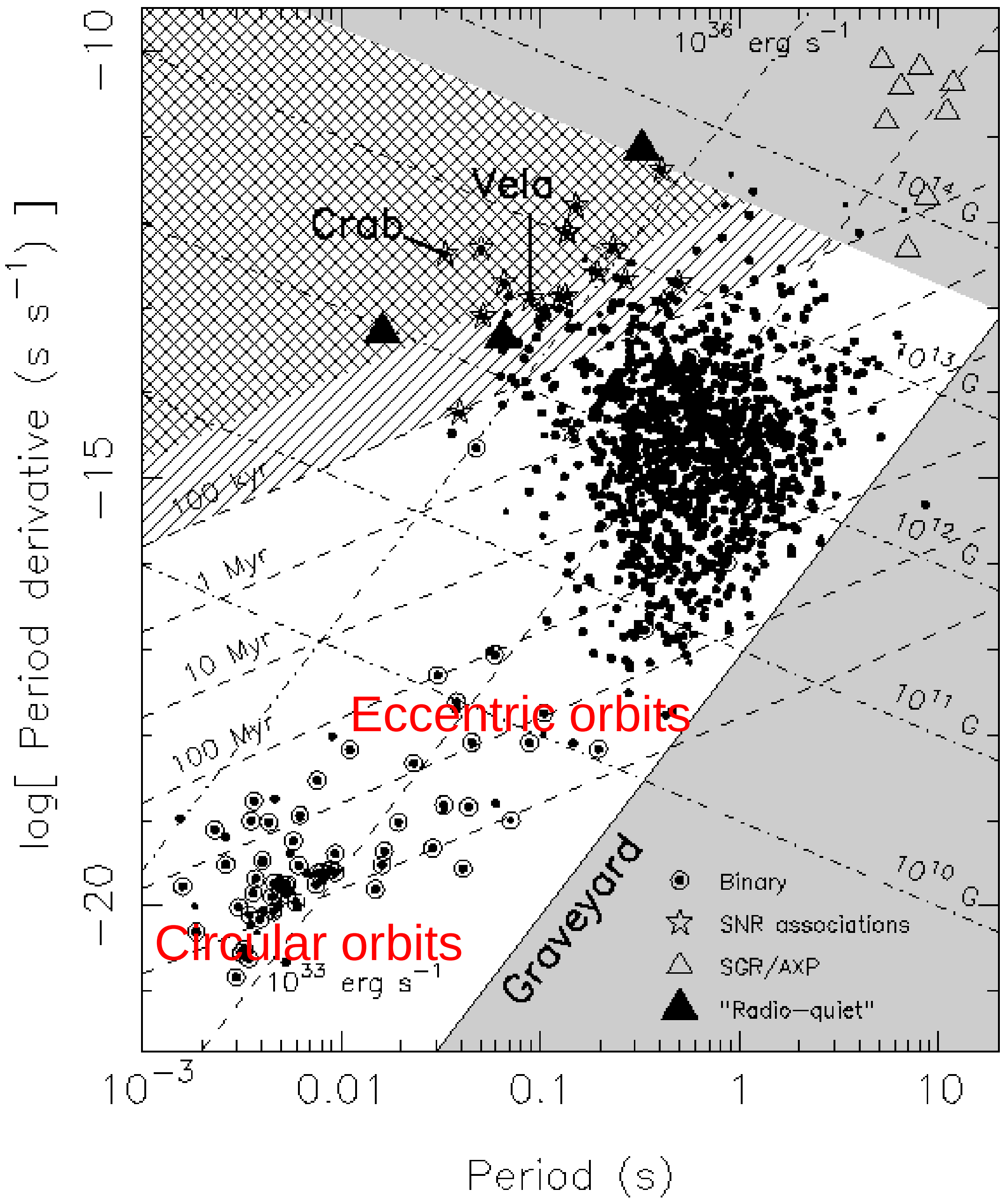
- Practically all massive stars (the type that go SN) is in binaries or multiple systems.

- If system survives first SN, then system will produce an *X-ray binary*.

How to recycle a pulsar

Figure from: Lorimer, D., *Living Rev. Relativity* 11 (2008), 8





Eccentric orbits

Circular orbits

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Why recycled pulsars are our friends:

1. The most stable and the most precisely timed pulsars are precisely those that tend to appear in the most interesting environments, like binary systems!

2. Most of these binary systems consist of two degenerate objects that behave *like point masses*.

Nature has been very generous to us!

Why is that exciting?

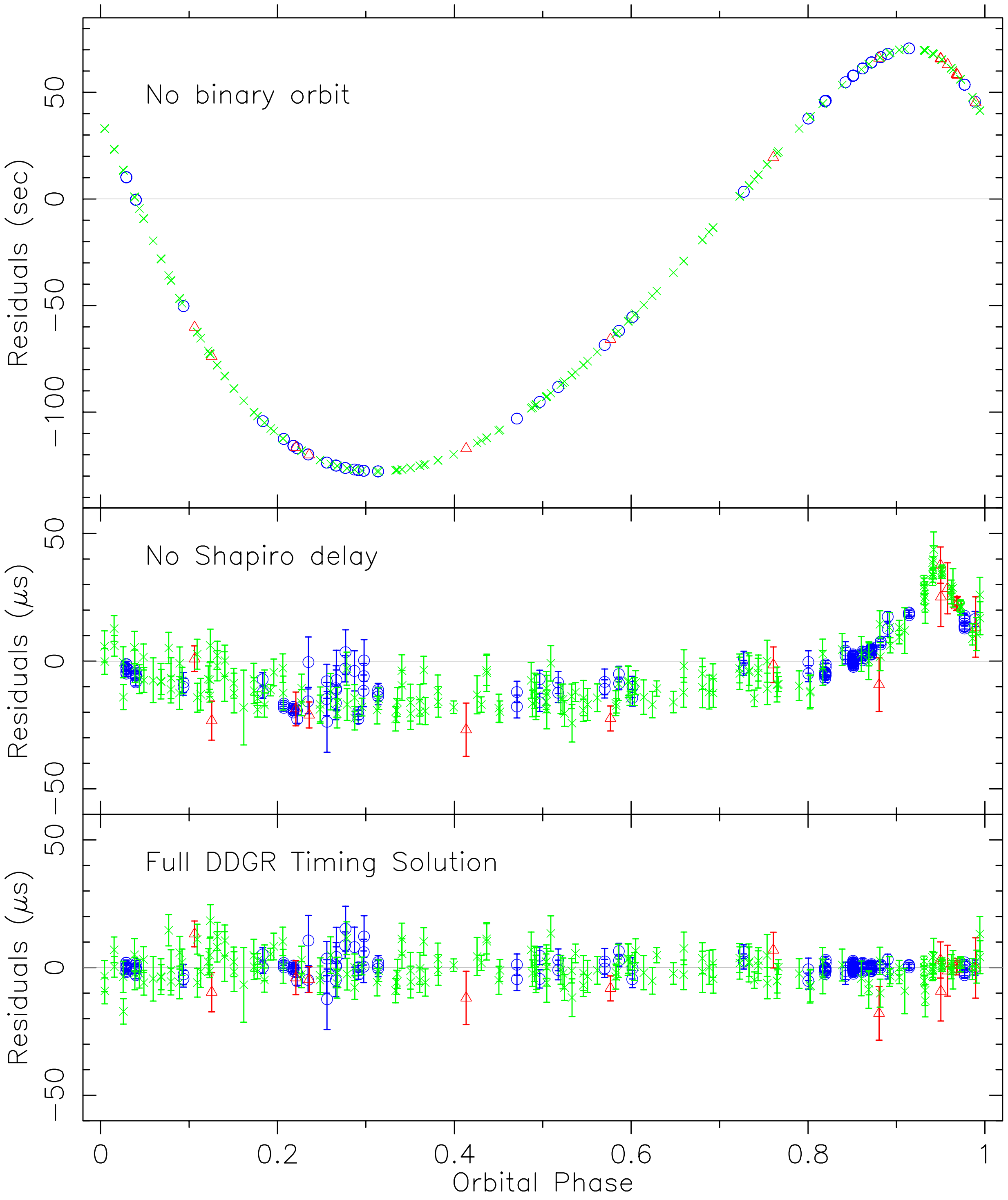
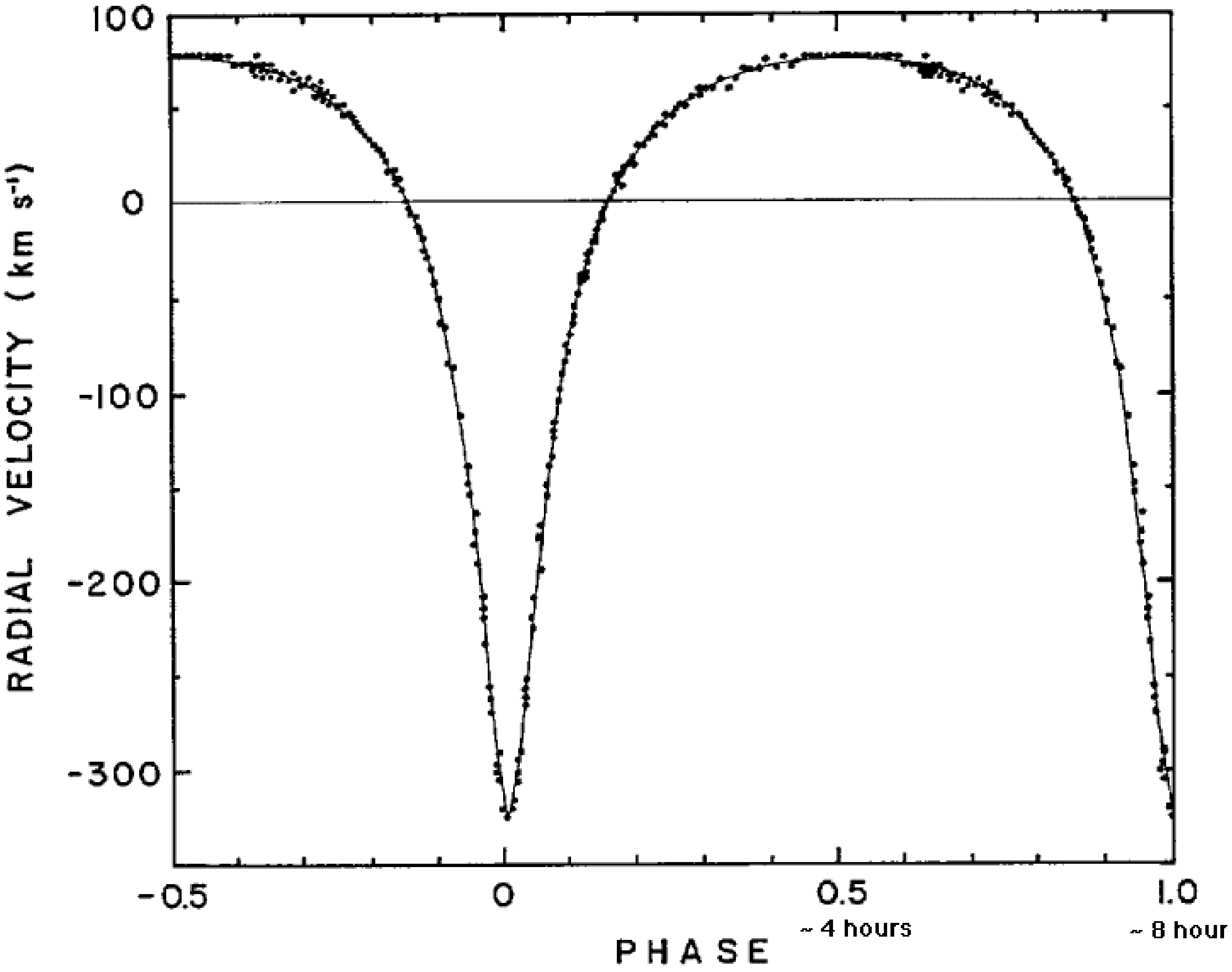


Figure: Scott Ransom

- 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 observational data*!
- 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: IT'S A CLEAN EXPERIMENT!

The first binary pulsar

The NSF funded the grant, and in 1974 Joe Taylor's student Russel Hulse discovered PSR B1913+16, a 59-ms pulsar in the constellation Aquila (the Eagle). *First binary pulsar*!



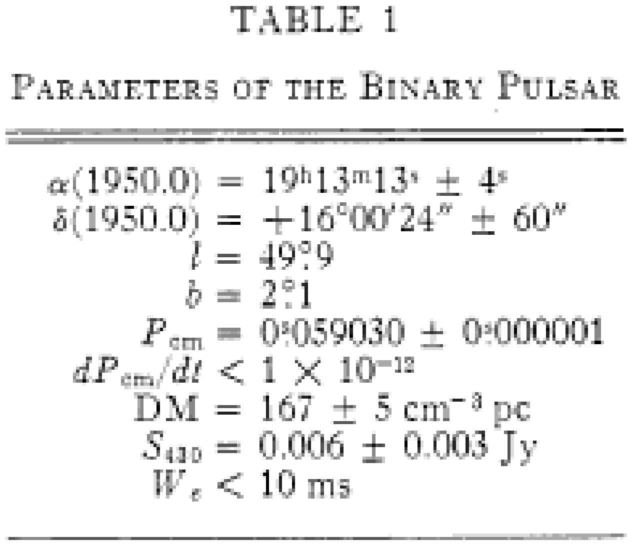


TABLE 1

PARAMETERS OF THE BINARY PULSAR

$\alpha(1950.0) = 19^h13^m13^s \pm 4^s$
$\delta(1950.0) = +16°00'24'' \pm 60''$
$l = 49.^\circ9$
$b = 2.^\circ1$
$P_{cm} = 0.^s059030 \pm 0.^s000001$
$dP_{cm}/dt < 1 \times 10^{-12}$
$\mathrm{DM} = 167 \pm 5\ \mathrm{cm}^{-3}\ \mathrm{pc}$
$S_{430} = 0.006 \pm 0.003\ \mathrm{Jy}$
$W_e < 10\ \mathrm{ms}$

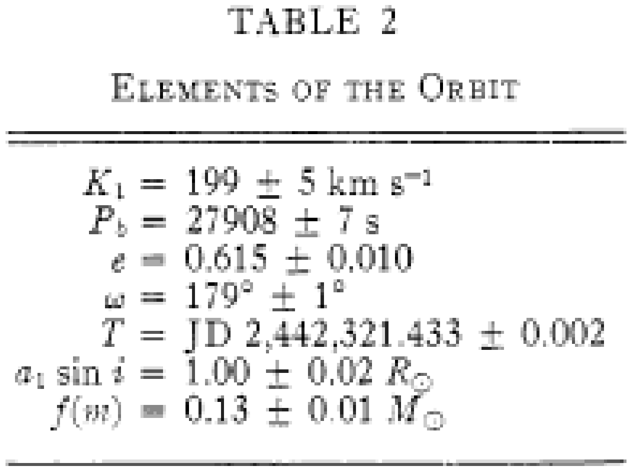


TABLE 2

ELEMENTS OF THE ORBIT

$K_1 = 199 \pm 5\ \mathrm{km\ s}^{-1}$
$P_b = 27908 \pm 7\ \mathrm{s}$
$e = 0.615 \pm 0.010$
$\omega = 179° \pm 1°$
$T = \mathrm{JD}\ 2{,}442{,}321.433 \pm 0.002$
$a_1 \sin i = 1.00 \pm 0.02\ R_\odot$
$f(m) = 0.13 \pm 0.01\ M_\odot$

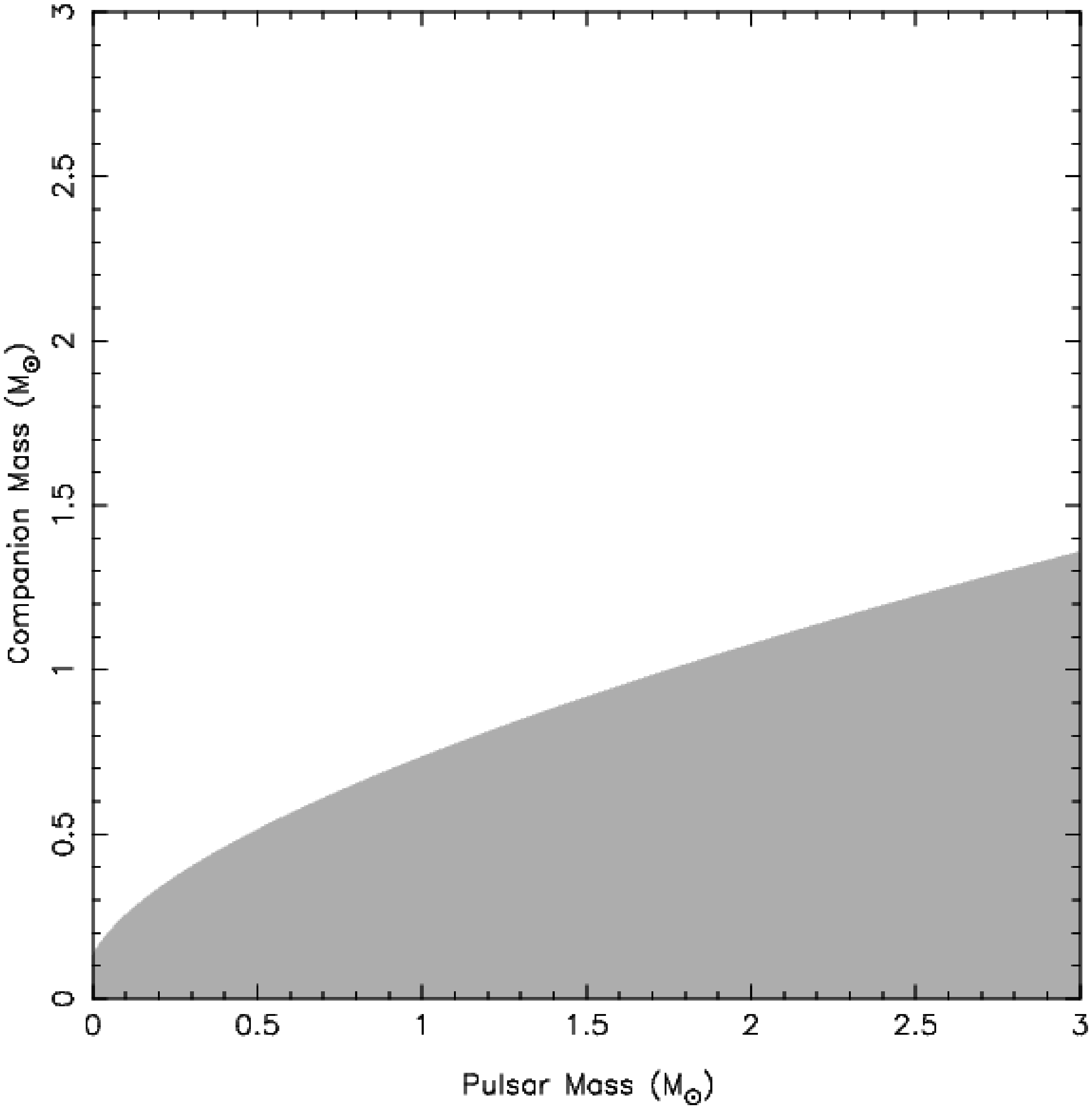
From: Hulse & Taylor, 1975, ApJ, 195, 51

PSR B1913+16

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

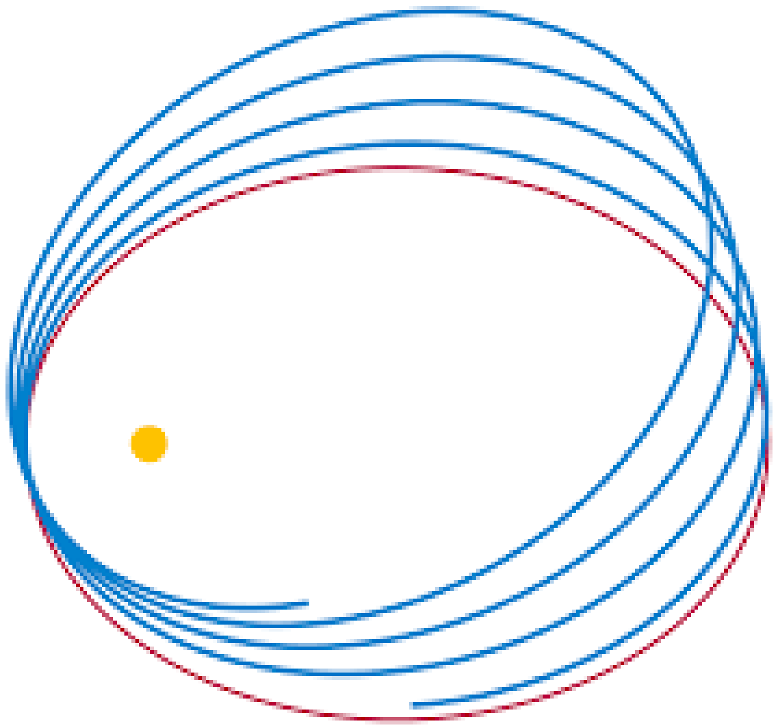
$$f(m_1, m_2, i)/\mathrm{M}_\odot \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$
$$= x^3 \left(\frac{2\pi}{P_b}\right)^2 \left(\frac{1}{T_\odot}\right)$$
$$T_\odot \equiv \frac{\mathrm{GM}_\odot}{c^3} = 4.925490947\,\mu s$$

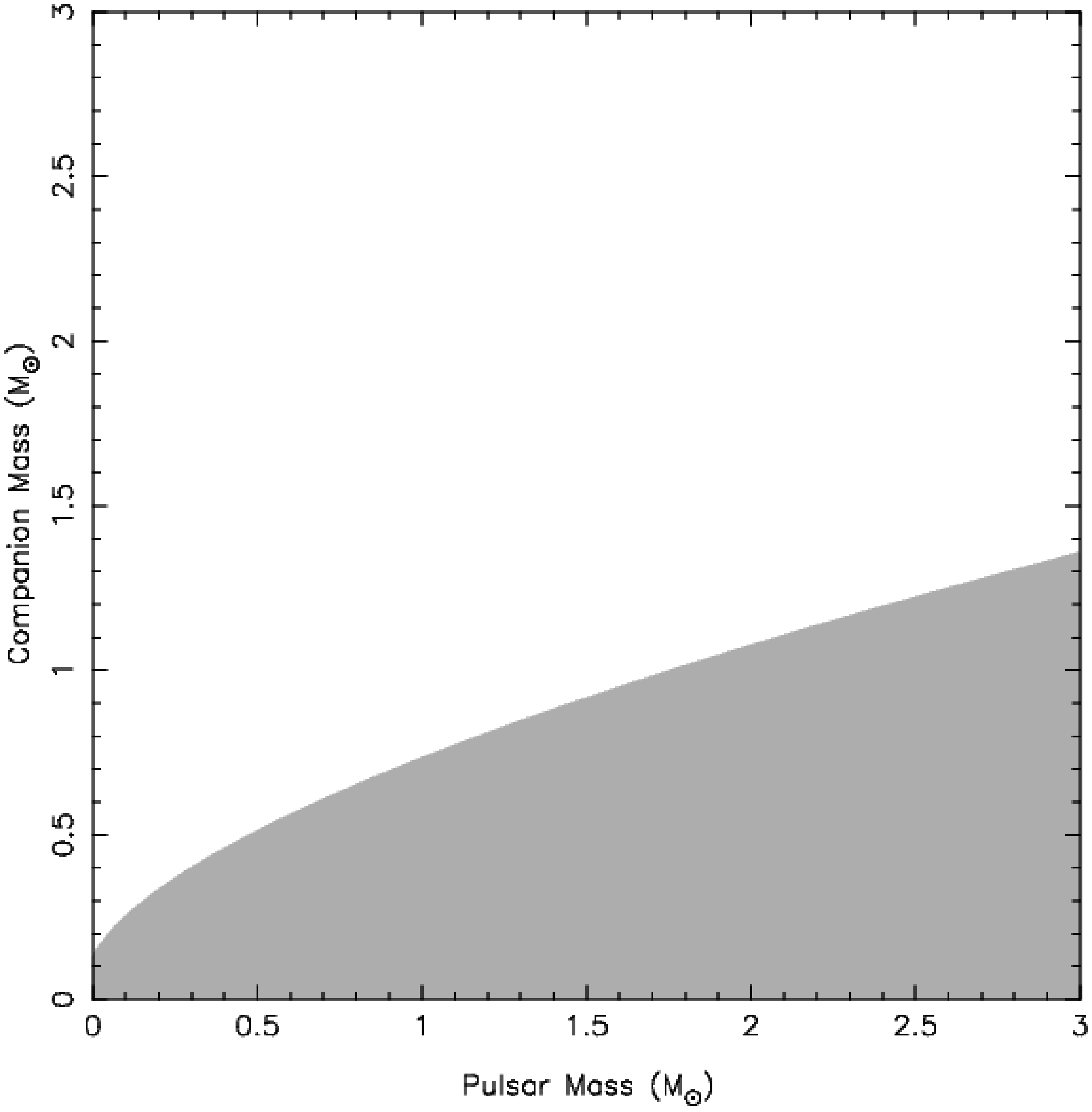
One equation, three (known) unknowns! ☹



PSR B1913+16

- **IF** a binary pulsar is compact and eccentric – which B1913+16 certainly is – the timing precision allows the measurement of several relativistic effects:
  - The advance of periastron.
  - The Einstein delay.



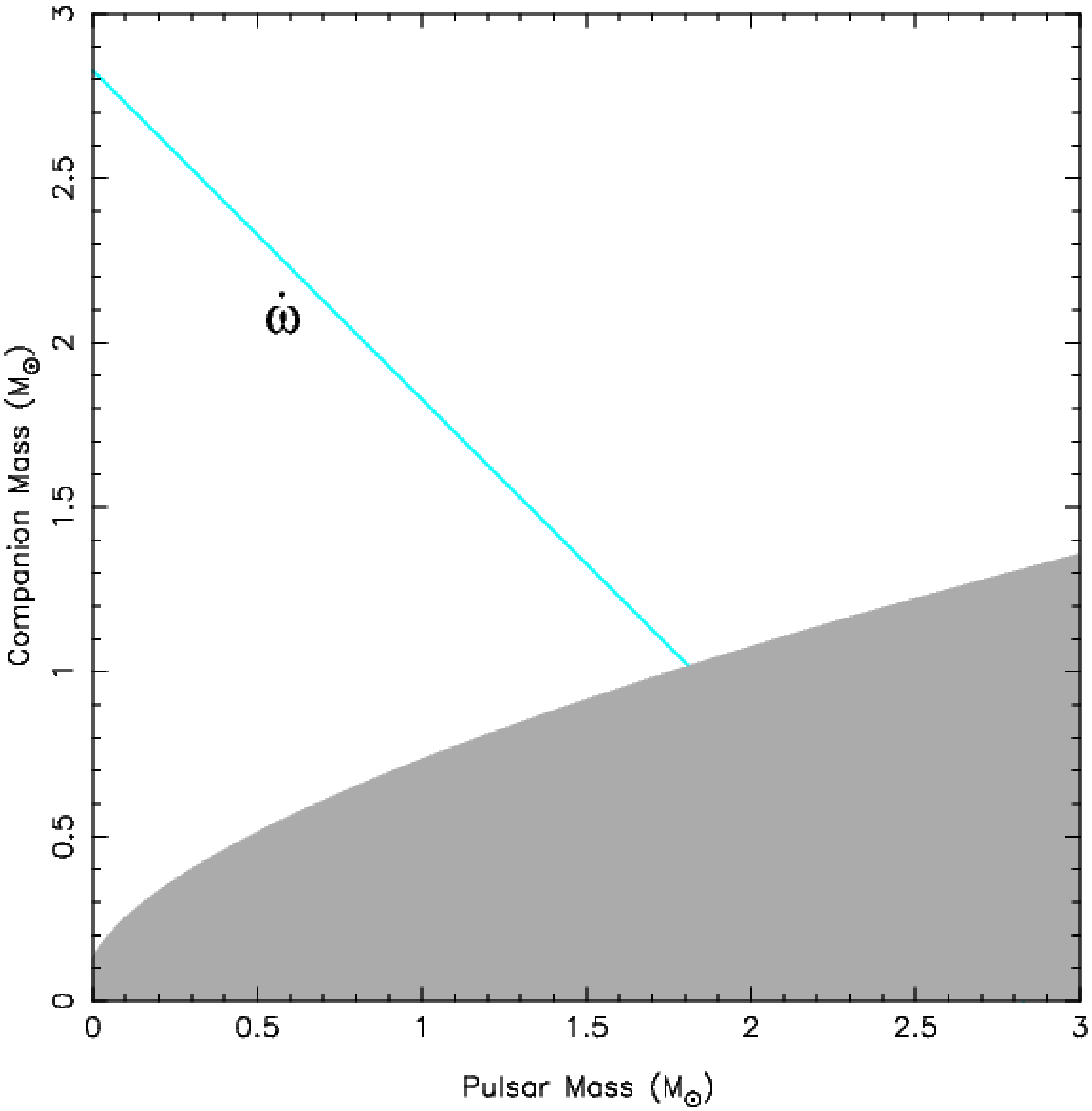


PSR B1913+16

- *Assuming* GR, 1 PN:

$$M = m_1 + m_2\,,\; n_b = \frac{2\pi}{P_b}$$

$$\dot{\omega} = 3n_b^{5/3}(MT_\odot)^{2/3}(1-e^2)^{-1}$$

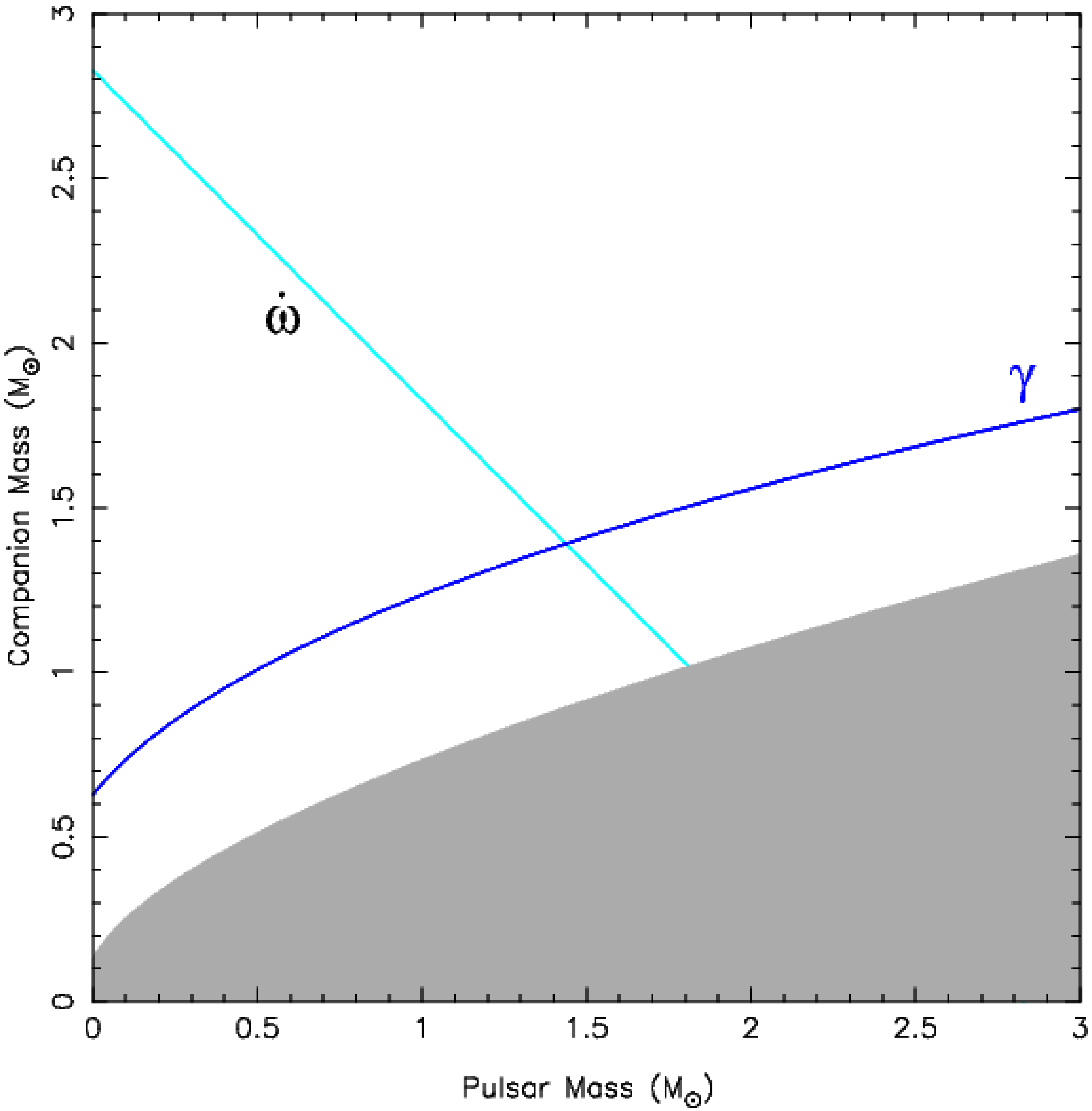


PSR B1913+16

- *Assuming* GR, 1 PN:

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

- 3 equations for 3 unknowns! Precise masses can be derived.
- This was at the time the most precise measurement of any mass outside the solar system.



PSR B1913+16

- *A third relativistic effect soon became measurable – the orbital decay due to GW emission!*

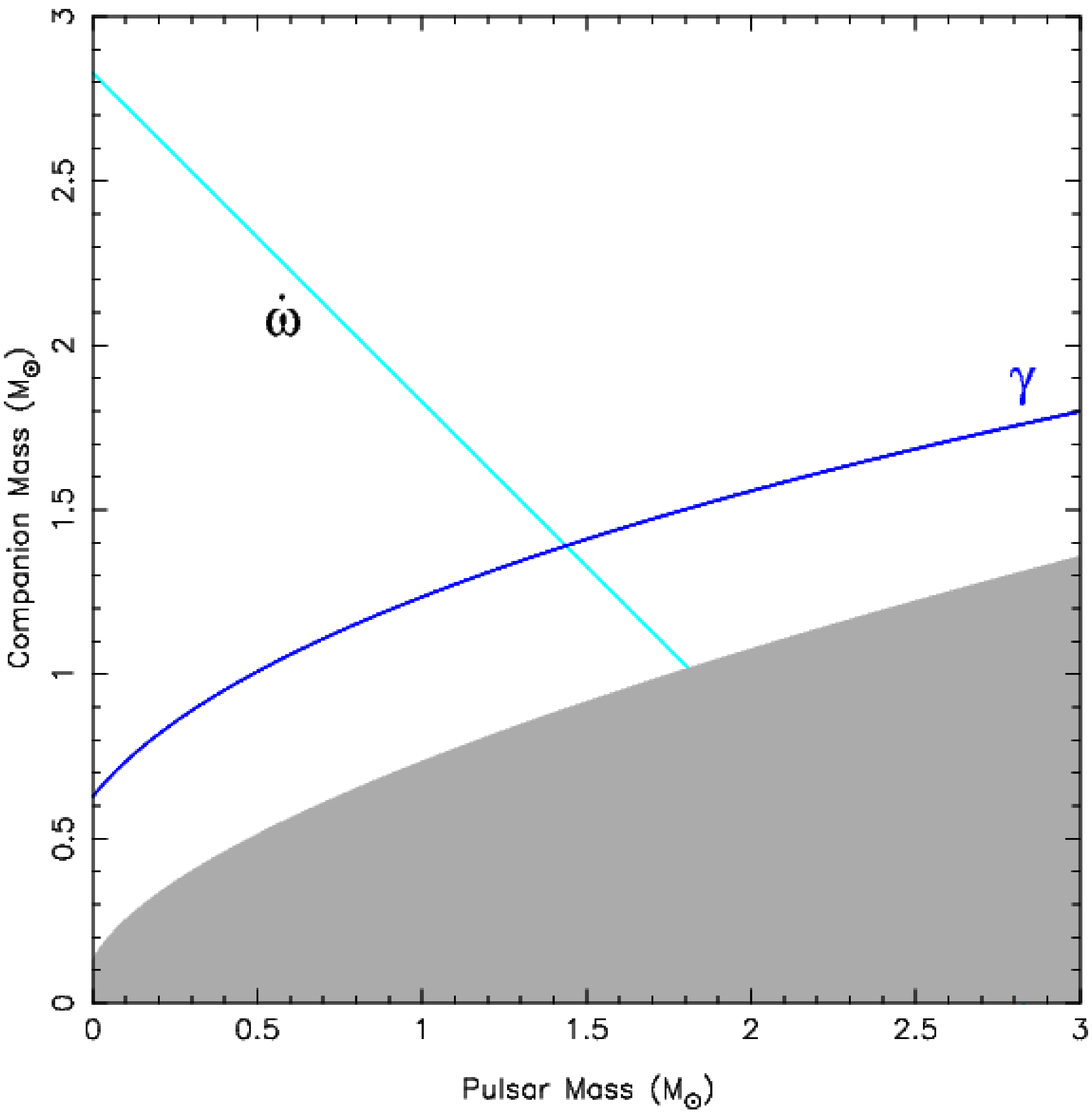
- *Assuming* GR, LO PN [(v/c)^5]:

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

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

- Prediction: the orbital period should decrease at a rate of –2.40247 × 10^{-12} s/s (or 75 μs per year!)

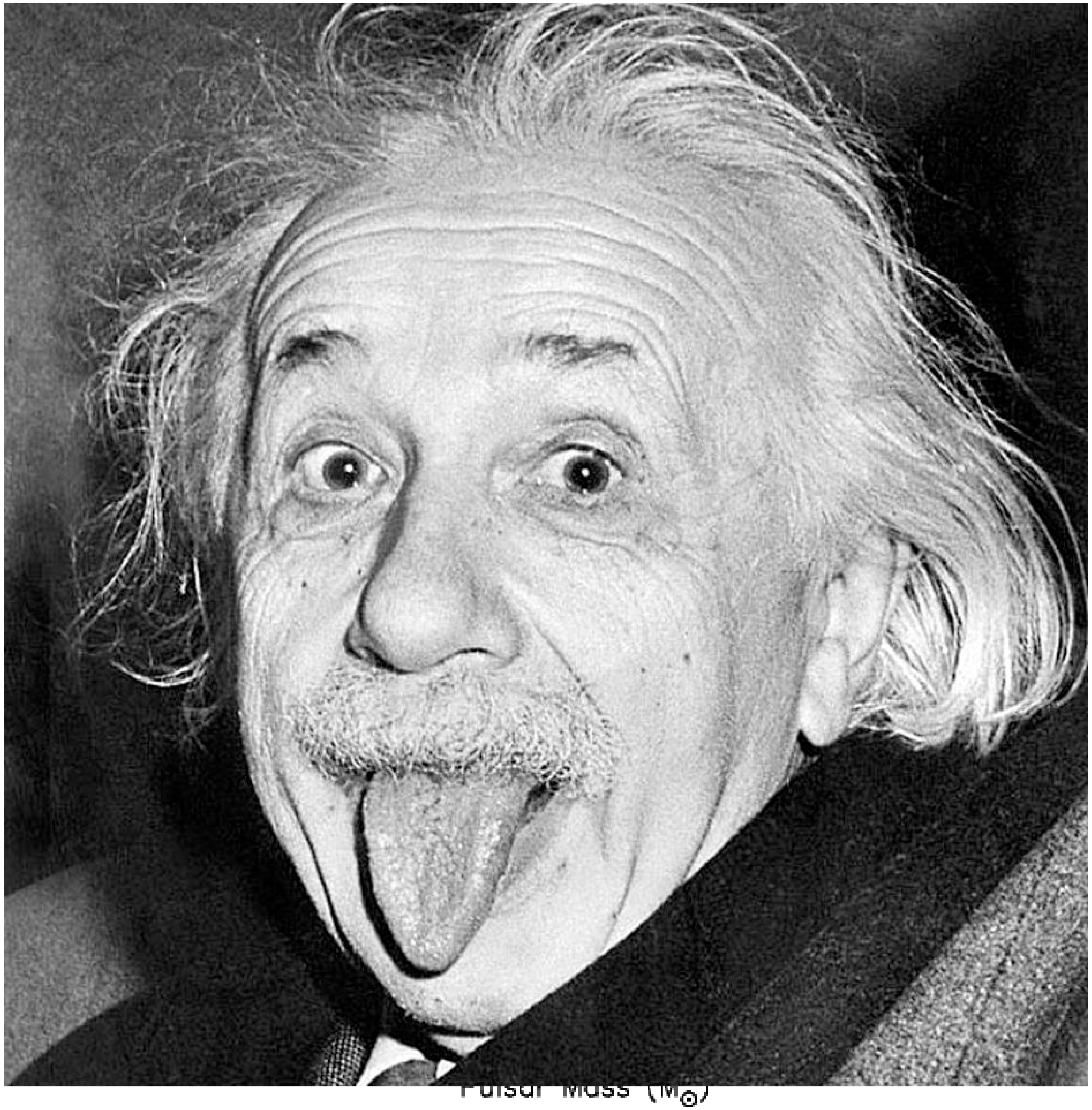
- Effect not detectable in Solar System.



PSR B1913+16

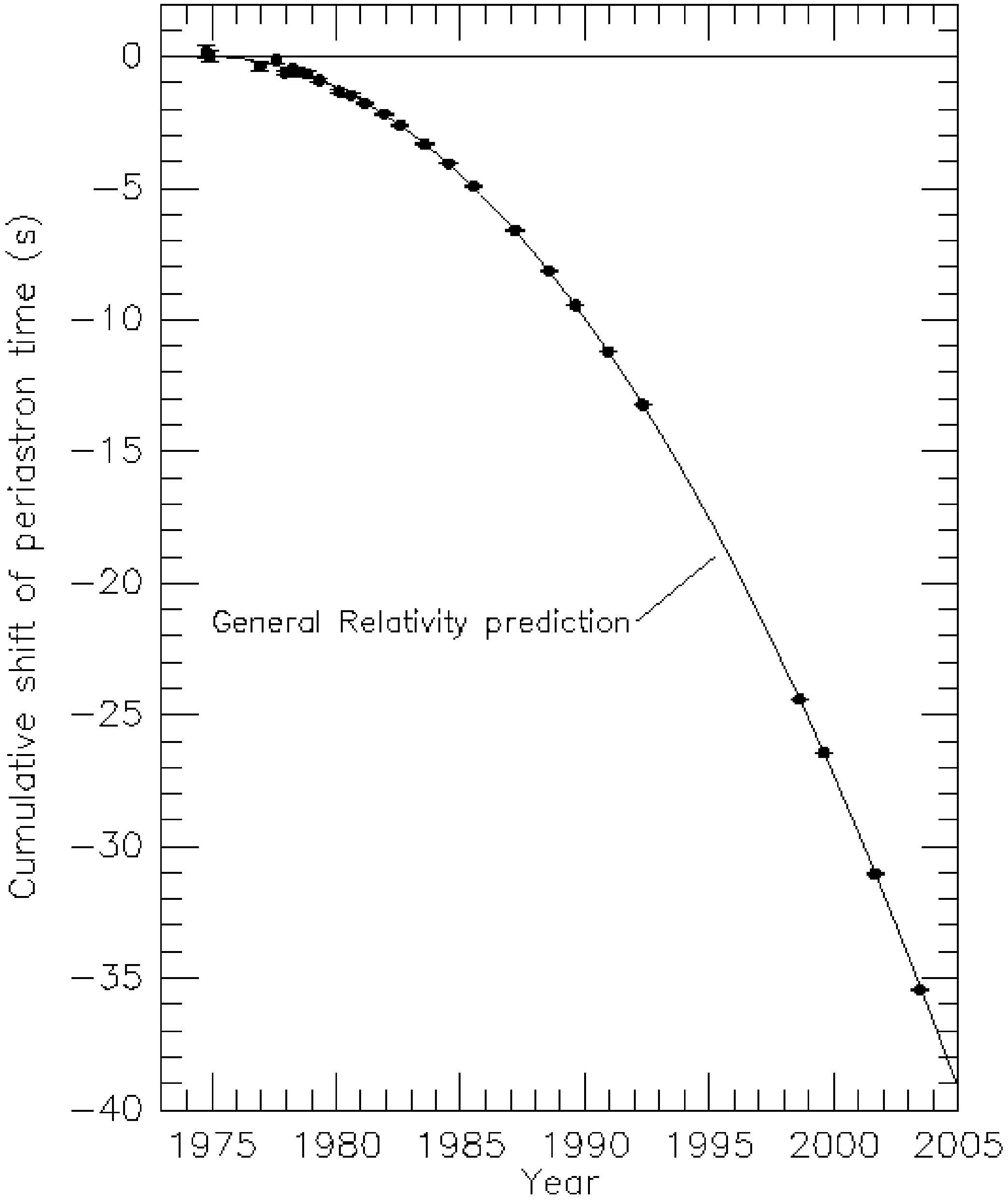
- Rate is –2.4085(52) x 10^{-12} s/s. Agreement with GR is perfect!

- GR gives a self-consistent estimate of the component masses!



Pulsar Mass ($M_\odot$)

PSR B1913+16



Gravitational waves exist!

Weisberg, J.M., and Taylor, J.H., “The Relativistic Binary Pulsar B1913+16”, in Bailes, M., Nice, D.J., and Thorsett, S.E., eds., Radio Pulsars: In Celebration of the Contributions of Andrew Lyne, Dick Manchester and Joe Taylor – A Festschrift Honoring their 60th Birthdays, Proceedings of a Meeting held at Mediterranean Agronomic Institute of Chania, Crete, Greece, 26 – 29 August 2002, ASP Conference Proceedings, vol. 302, (Astronomical Society of the Pacific, San Francisco, 2003).

Gravitational Waves Exist!

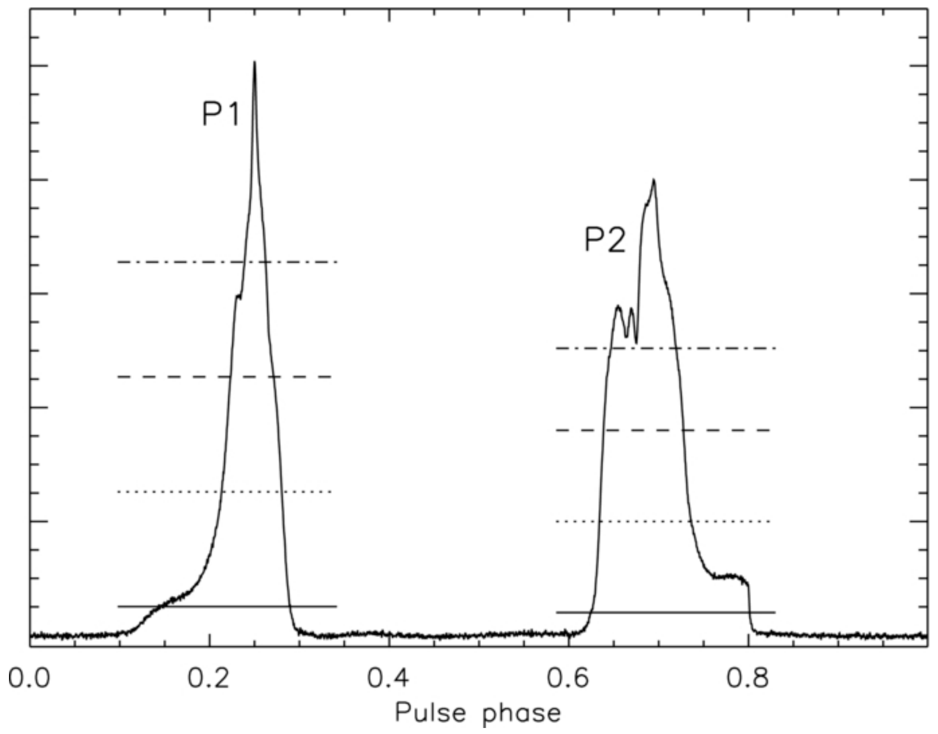
``(…) *the observation of the orbital decay in the TOAs of a binary pulsar is a direct effect of the retarded propagation (at the speed of light, and with a quadrupolar structure) of the gravitational interaction between the companion and the pulsar. In that sense, the Hulse-Taylor pulsar provides a direct observational proof that gravity propagates at the speed of light, and has a quadrupolar structure*.’’

Damour, 2014, arXiv:1411.3930v1. He adds:

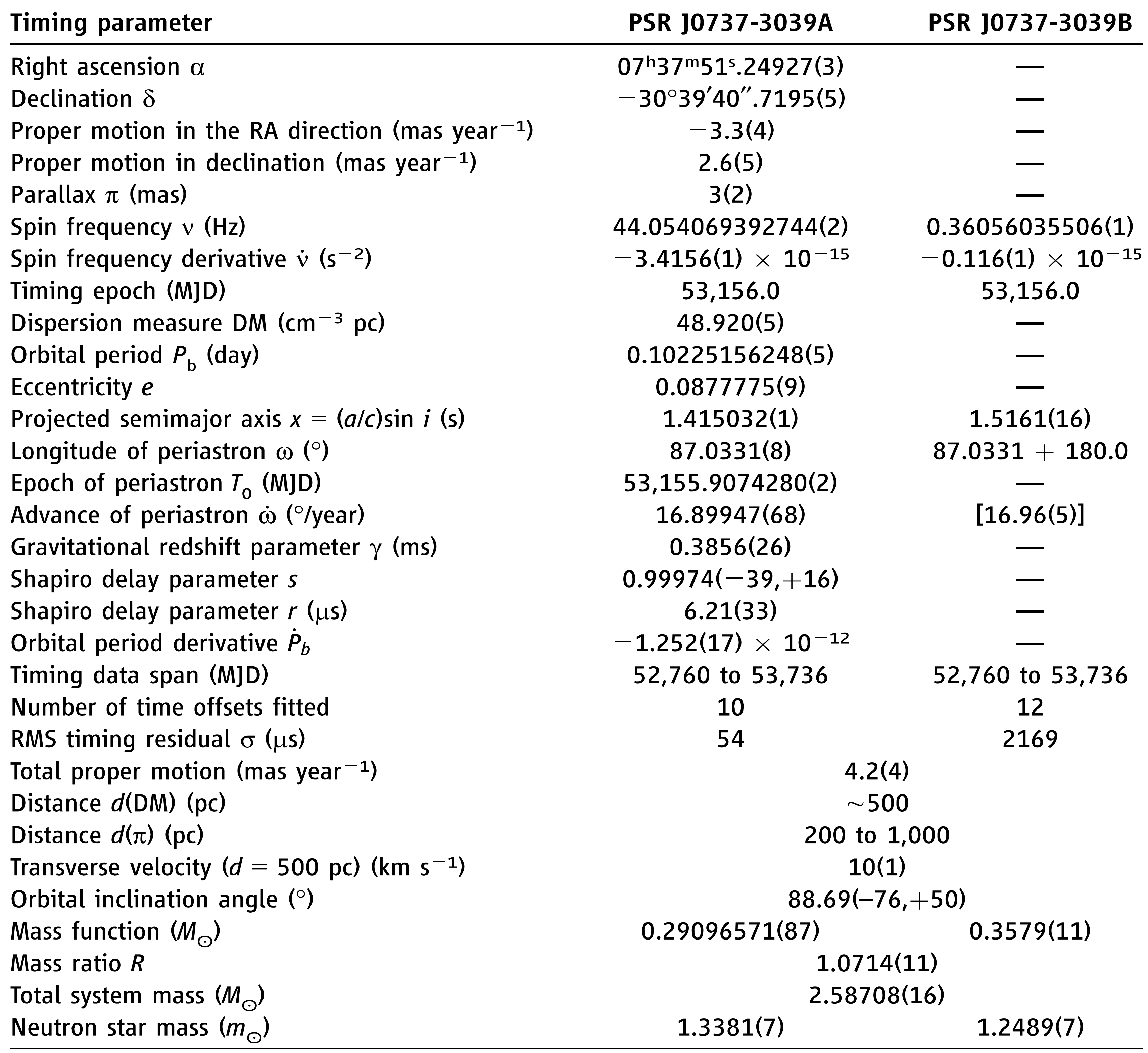
``*The latter point is confirmed by the theoretical computation of the orbital decay in alternative theories of gravity where the non purely quadrupolar (i.e. non purely spin 2) structure of the gravitational interaction generically induces drastic changes* (….)”

The ``Double Pulsar'': PSR J0737−3039

- Discovered in the Galactic anti-center survey with Parkes (Burgay et al. 2003, Nature, 426, 531)

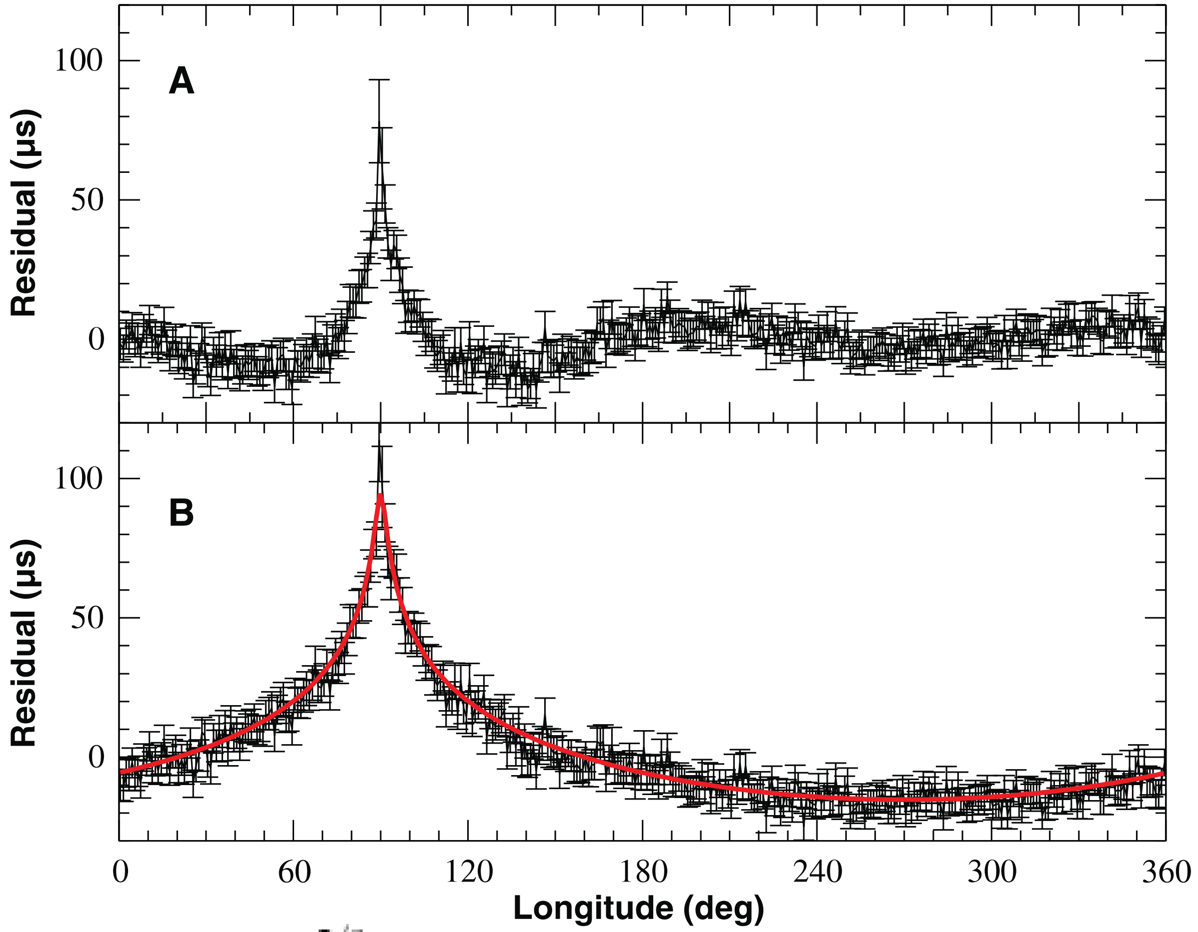


PSR J0737−3039: timing solution



Timing parameter	PSR J0737-3039A	PSR J0737-3039B
Right ascension α	$07^{h}37^{m}51^{s}.24927(3)$	—
Declination δ	$-30^{\circ}39'40''.7195(5)$	—
Proper motion in the RA direction (mas year^{-1})	−3.3(4)	—
Proper motion in declination (mas year^{-1})	2.6(5)	—
Parallax π (mas)	3(2)	—
Spin frequency ν (Hz)	44.054069392744(2)	0.36056035506(1)
Spin frequency derivative $\dot{\nu}$ (s^{-2})	$-3.4156(1) \times 10^{-15}$	$-0.116(1) \times 10^{-15}$
Timing epoch (MJD)	53,156.0	53,156.0
Dispersion measure DM (cm^{-3} pc)	48.920(5)	—
Orbital period P_b (day)	0.10225156248(5)	—
Eccentricity e	0.0877775(9)	—
Projected semimajor axis $x = (a/c)\sin i$ (s)	1.415032(1)	1.5161(16)
Longitude of periastron ω (°)	87.0331(8)	87.0331 + 180.0
Epoch of periastron T_0 (MJD)	53,155.9074280(2)	—
Advance of periastron $\dot{\omega}$ (°/year)	16.89947(68)	[16.96(5)]
Gravitational redshift parameter γ (ms)	0.3856(26)	—
Shapiro delay parameter s	0.99974(−39,+16)	—
Shapiro delay parameter r (μs)	6.21(33)	—
Orbital period derivative $\dot{P}_b$	$-1.252(17) \times 10^{-12}$	—
Timing data span (MJD)	52,760 to 53,736	52,760 to 53,736
Number of time offsets fitted	10	12
RMS timing residual σ (μs)	54	2169
Total proper motion (mas year^{-1})	4.2(4)	
Distance d(DM) (pc)	~500	
Distance $d(\pi)$ (pc)	200 to 1,000	
Transverse velocity (d = 500 pc) (km s^{-1})	10(1)	
Orbital inclination angle (°)	88.69(−76,+50)	
Mass function ($M_{\odot}$)	0.29096571(87)	0.3579(11)
Mass ratio R	1.0714(11)	
Total system mass ($M_{\odot}$)	2.58708(16)	
Neutron star mass ($m_{\odot}$)	1.3381(7)	1.2489(7)

The ``Double Pulsar”: PSR J0737−3039



Lucky bit #1:Orbital period of $2^h\ 27^m$, it is the most relativistic double neutron star system known!

Lucky bit #2: this super-relativistic system has a very high inclination. *Shapiro delay* is well measured, providing two extra mass constraints:

From: Kramer et al. 2006

$$\dot{\omega} = 3 \left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} \, (1 - e^2)^{-1}, \tag{31}$$

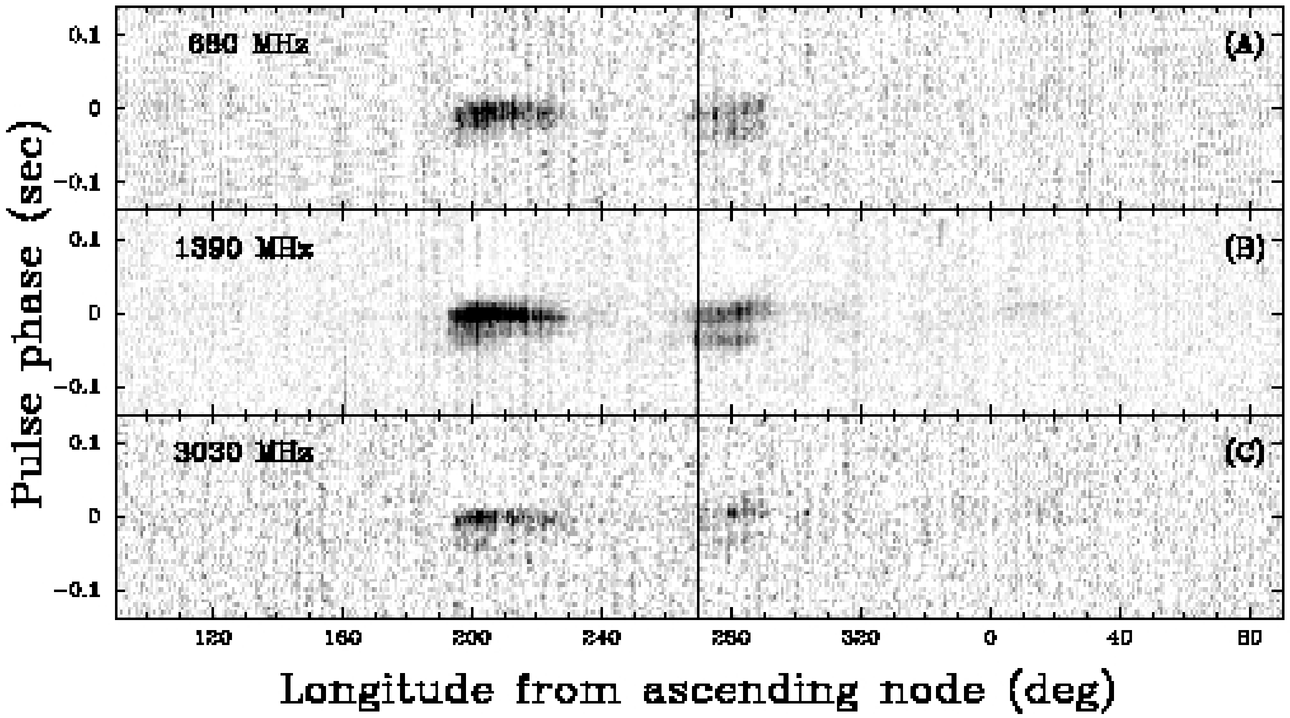
$$\gamma = e \left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} \, M^{-4/3} \, m_2(m_1 + 2m_2), \tag{32}$$

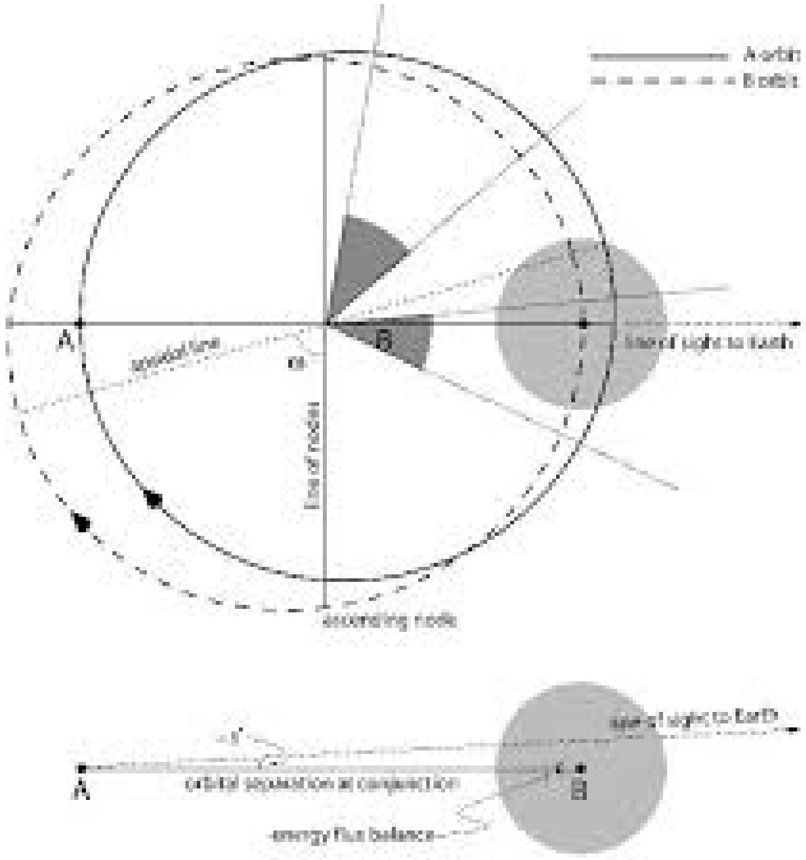
$$\dot{P}_b = -\frac{192\pi}{5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1 - e^2)^{-7/2} \, T_\odot^{5/3} \, m_1 m_2 \, M^{-1/3}, \tag{33}$$

$$\boxed{\begin{aligned} r &= T_\odot \, m_2, && (34) \\ s &= x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} \, M^{2/3} \, m_2^{-1}. && (35) \end{aligned}}$$

PSR J0737−3039

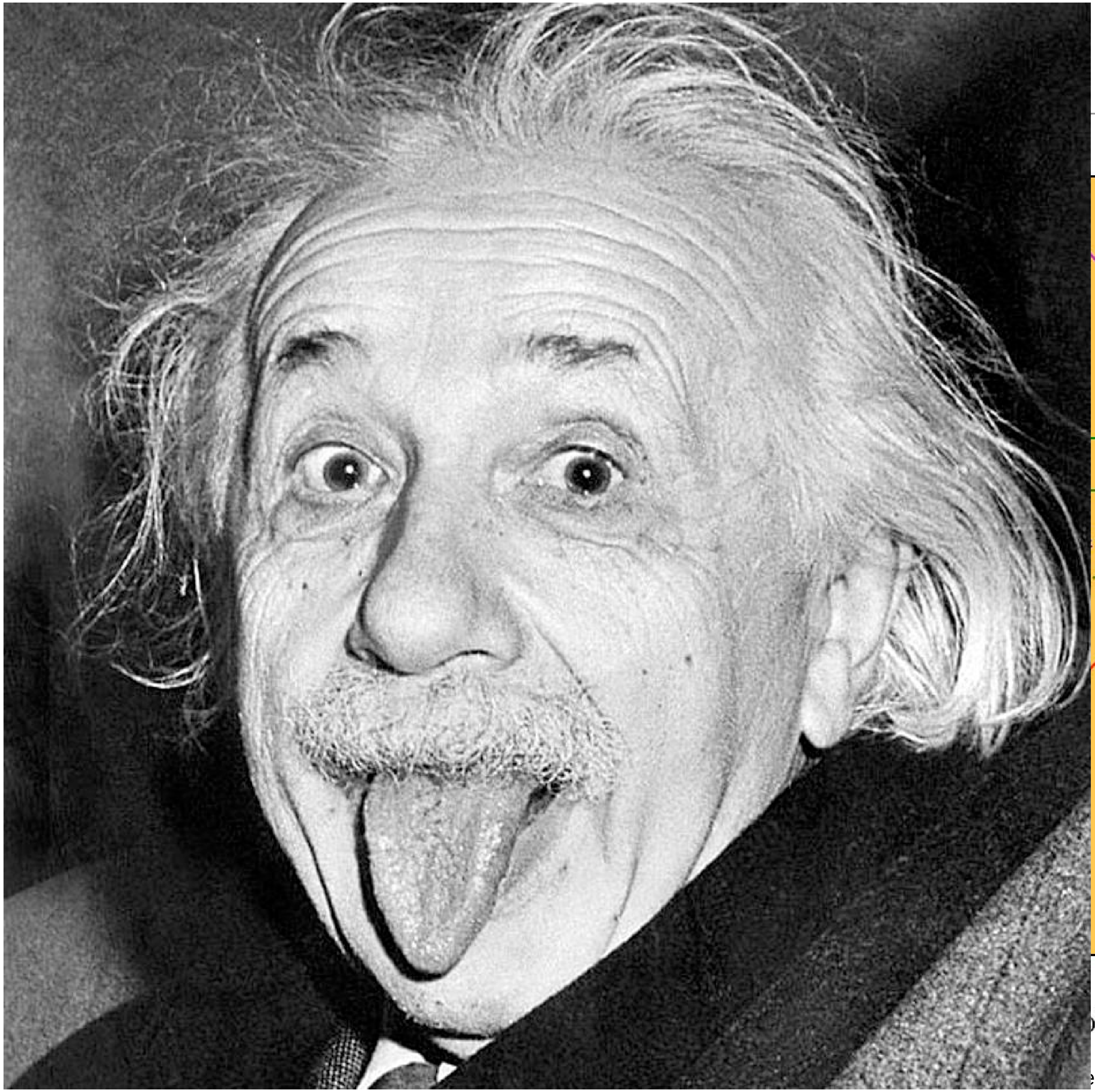
- **Lucky bit #3**: The second NS in the system (PSR J0737−3039B) is detectable as a radio

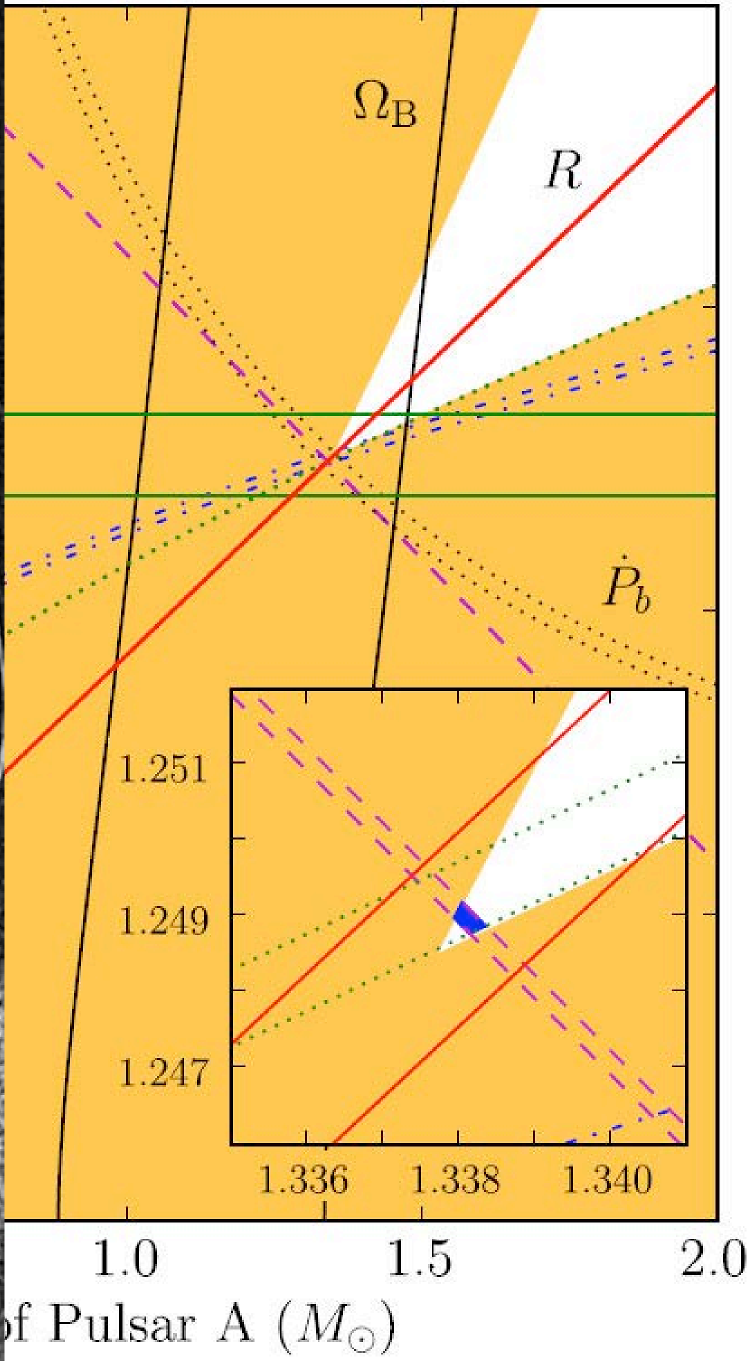




$$R = m_A / m_B = x_B / x_A$$

6 mass constraints for 2 unknowns! **4 independent tests of GR**!





et al. 2006, Science, 314, 97

PSR J0737−3039

Figure: Kramer et al., in prep.

PSR J0737−3039

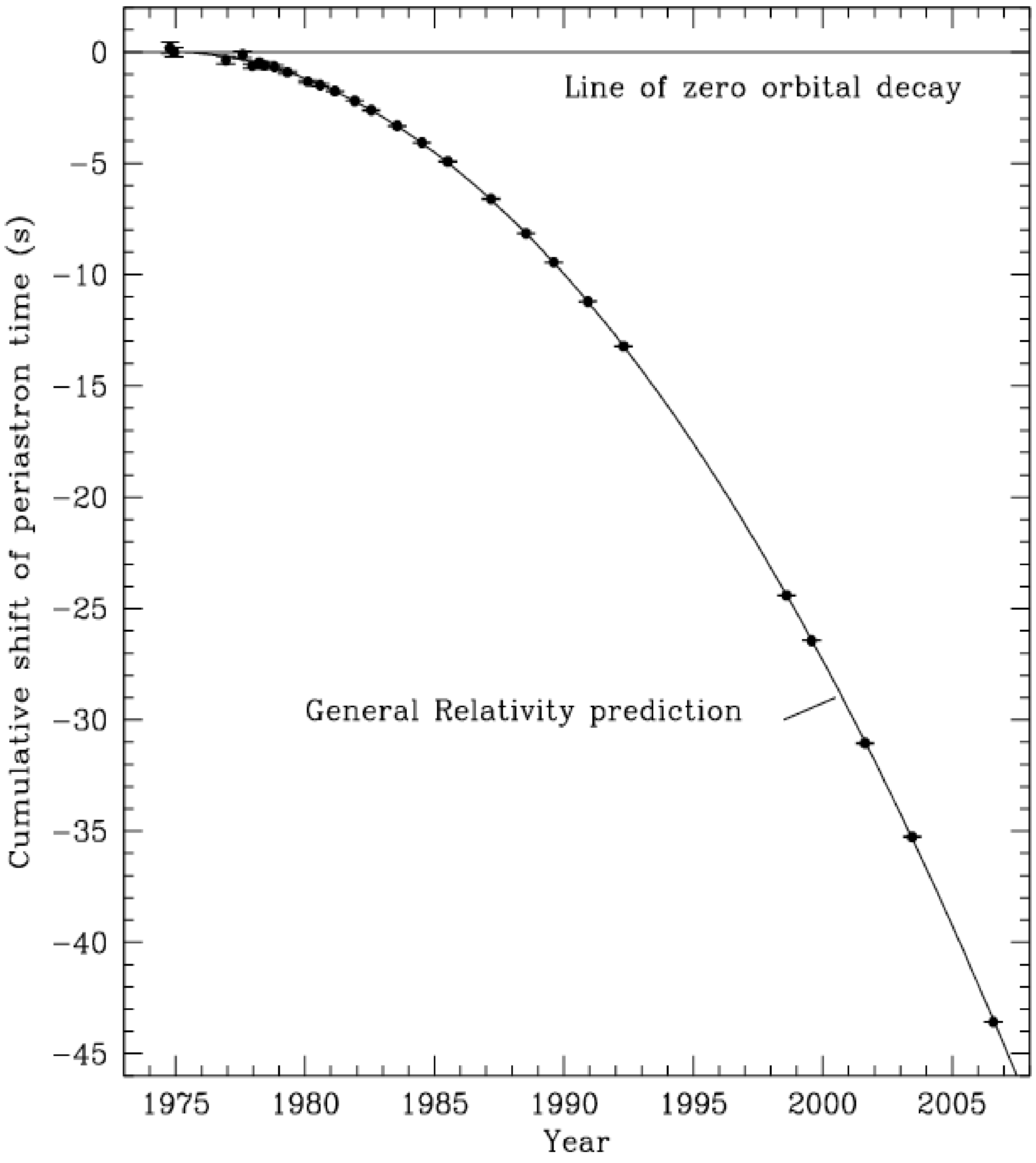
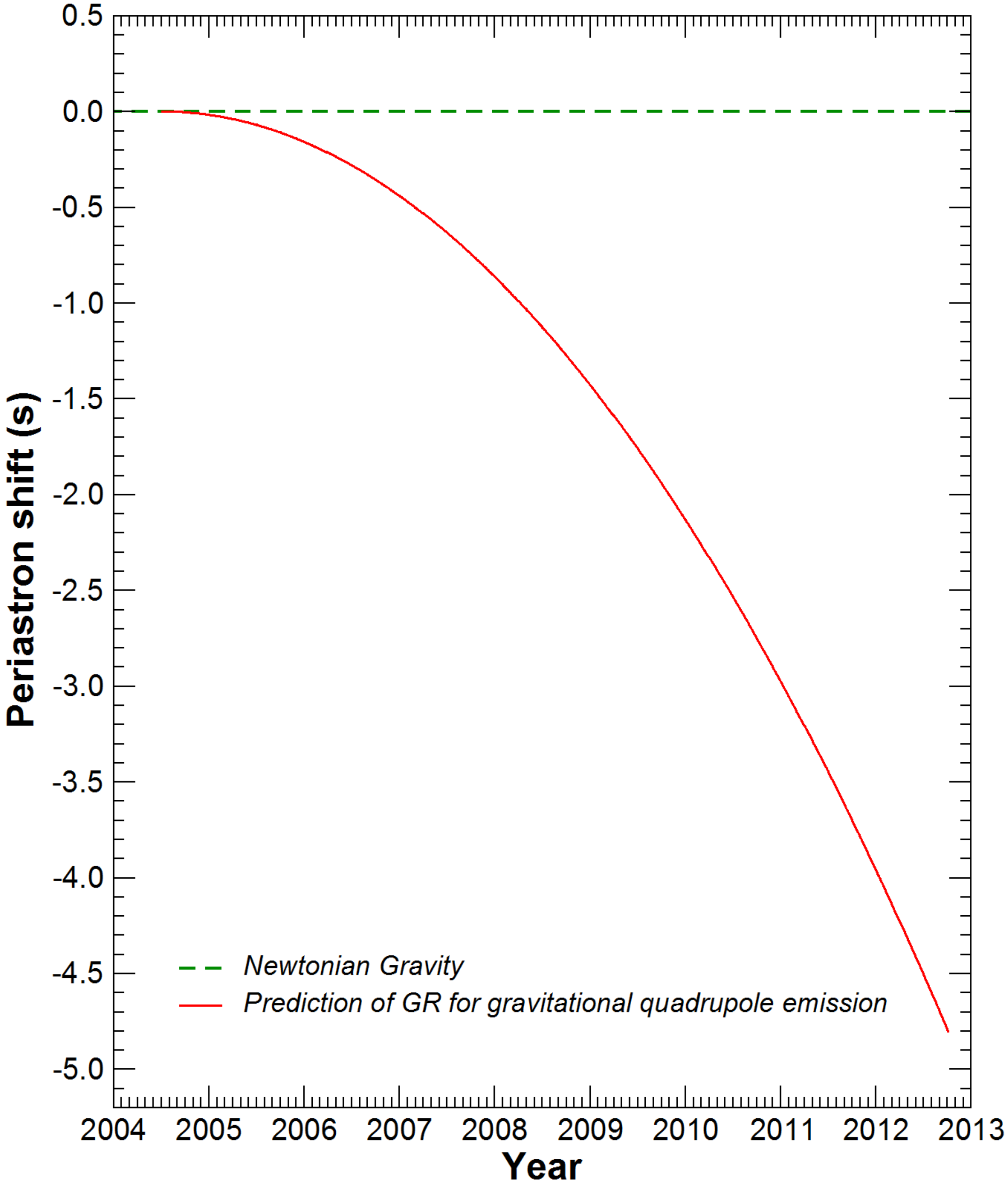


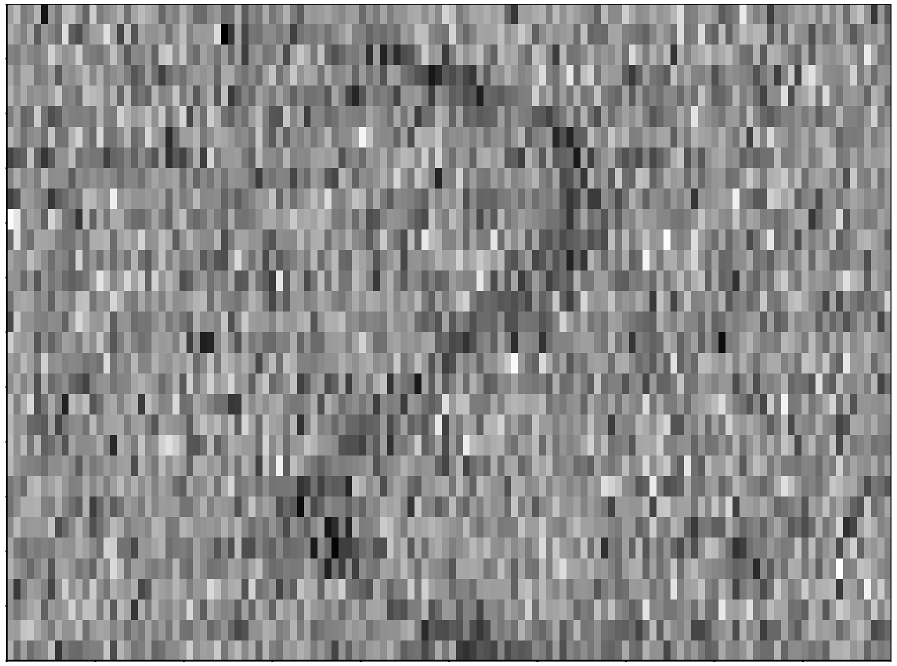
Figure: Kramer et al., in prep.

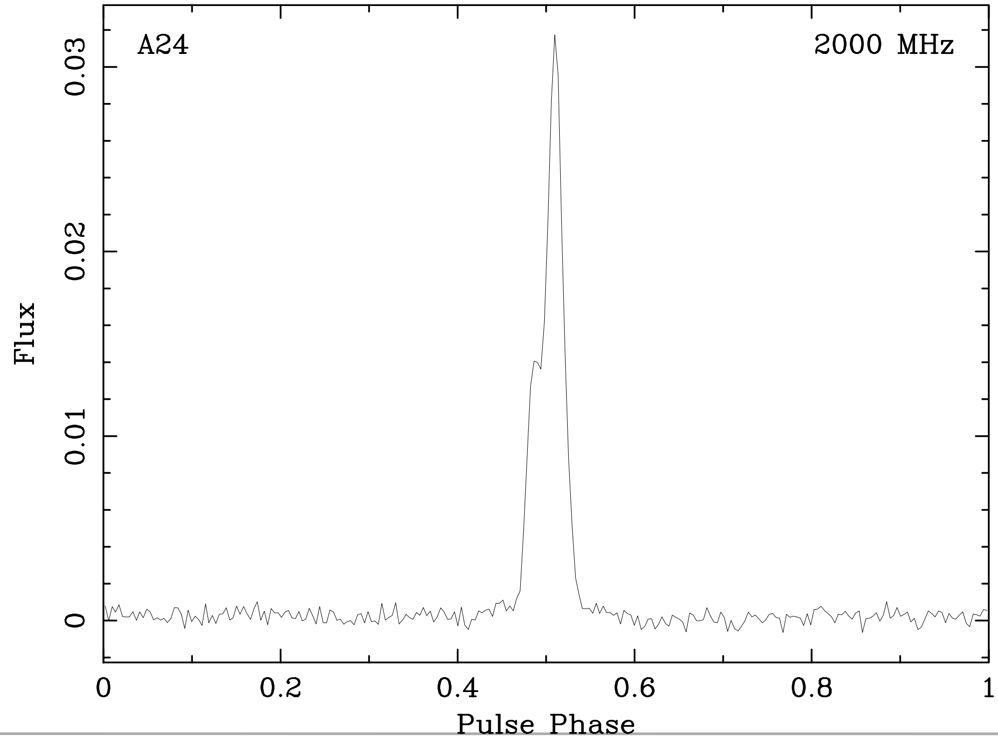


New! Even more relativistic DNS

New Discovery from Parkes Deep Galactic Survey (HTRU-S), to be published soon by A. Cameron (MPIfR), has even more extreme properties:

Spin frequency, ν (Hz)	46.51761744(6)
Spin period, P (ms)	21.49723169(2)
Timing epoch (MJD)	57553.5
Dispersion measure ($\mathrm{cm}^{-3}\,\mathrm{pc}$)	379(3)
DM derived distance, d (kpc)	~ 7.4
Orbital model	DD
Orbital period, P_b (days)	0.183537840(6)
Eccentricity, e	0.60581(2)
Projected semimajor axis, $x = a_p \sin i$ (lt-s)	2.23830(4)
Longitude of periastron, ω (deg)	275.274(2)
Epoch of periastron, T_0 (MJD)	57553.5448885(8)
Advance of periastron, $\dot{\omega}$ ($\mathrm{deg\,yr}^{-1}$)	10.37(2)





New! Even more relativistic DNS

- Most powerful GW emitter among DNSs (~20 % solar luminosity)

- Coalescence time: 75 Myr!

- Suggests LIGO detection of NS-NS mergers is not too far away…

Figure: Norbert Wex

NS mass measurements. 1 - DNSs

- In GR, *only the masses* enter as a parameters in the description of these effects to *leading PN order* (Moments of inertia need higher than LO)

- Radii need X-ray measurements – See review by Ozel & Freire (2016), ARAA, 54, 401

- It is very nice to have systems like the double pulsar to test GR / to cross-check the mass measurement techniques – the different combinations of PK parameters really produce very precise (and very consistent) results.

- But… what masses have been measured?

NS mass measurements. 1 – DNSs

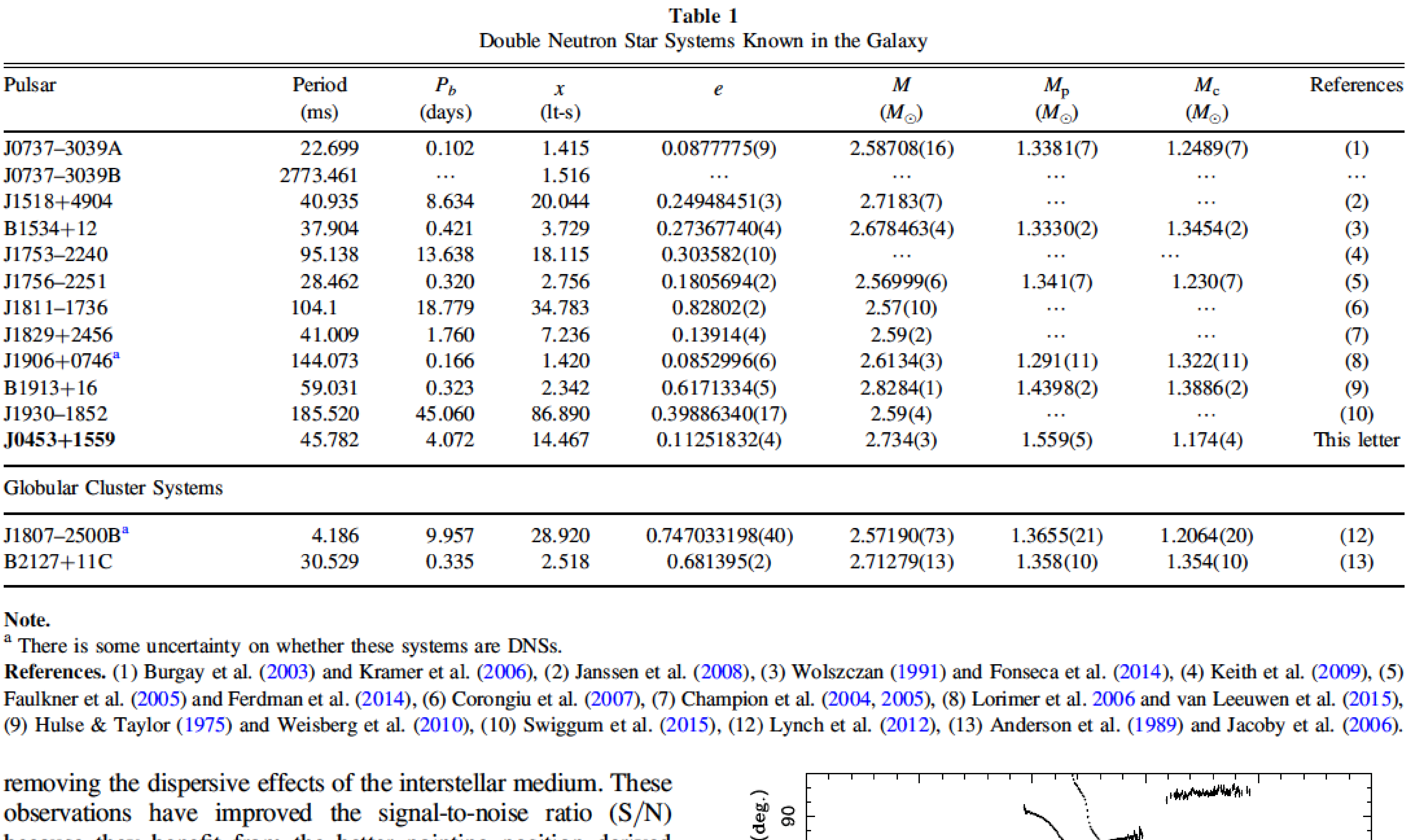


Table 1
Double Neutron Star Systems Known in the Galaxy

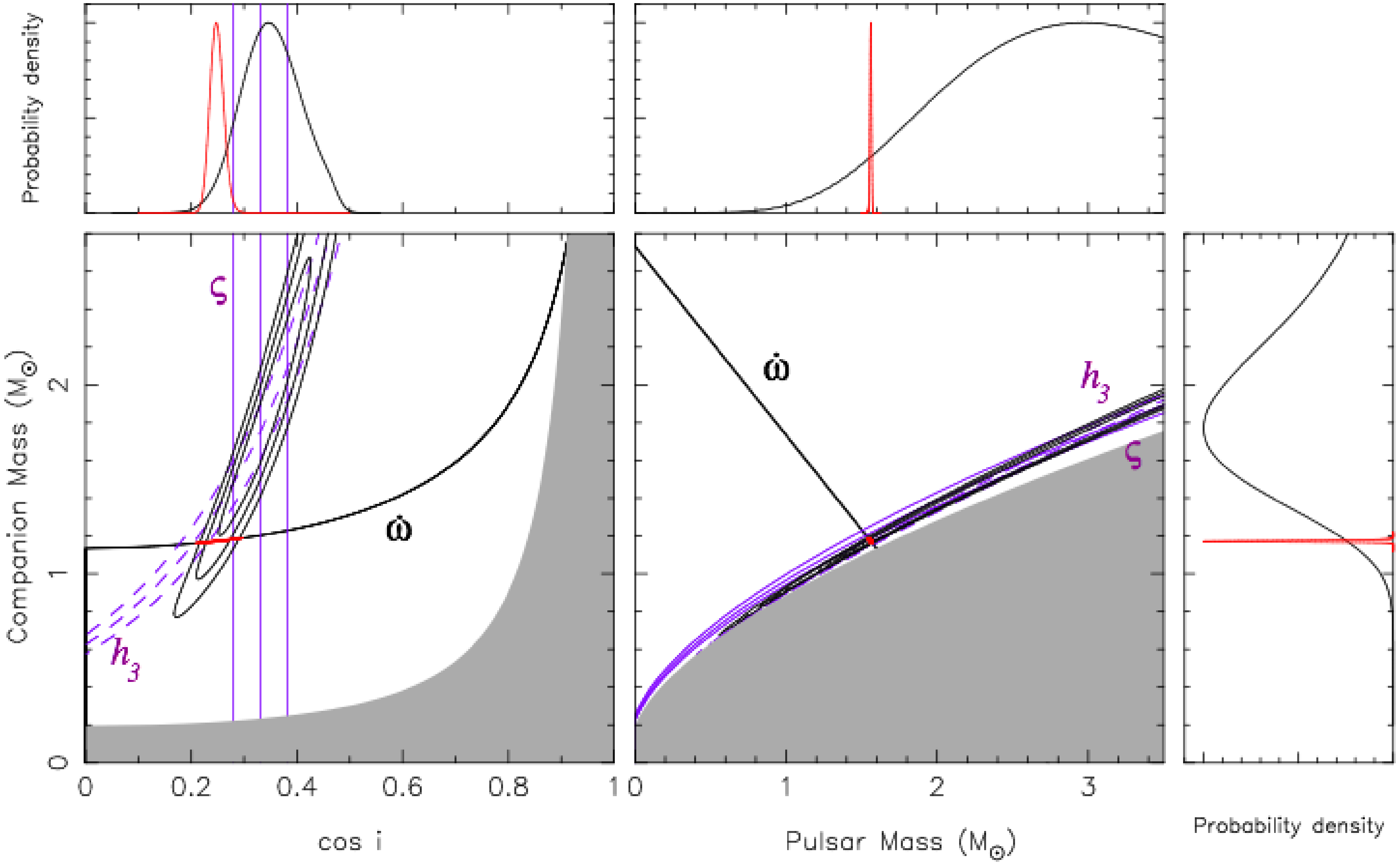
Pulsar	Period (ms)	P_b (days)	x (lt-s)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737–3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	(1)
J0737–3039B	2773.461	…	1.516	…	…	…	…	…
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	…	…	(2)
B1534+12	37.904	0.421	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[a]	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[a]	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.
[a] There is some uncertainty on whether these systems are DNSs.

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

removing the dispersive effects of the interstellar medium. These observations have improved the signal-to-noise ratio (S/N)

An asymmetric DNS!



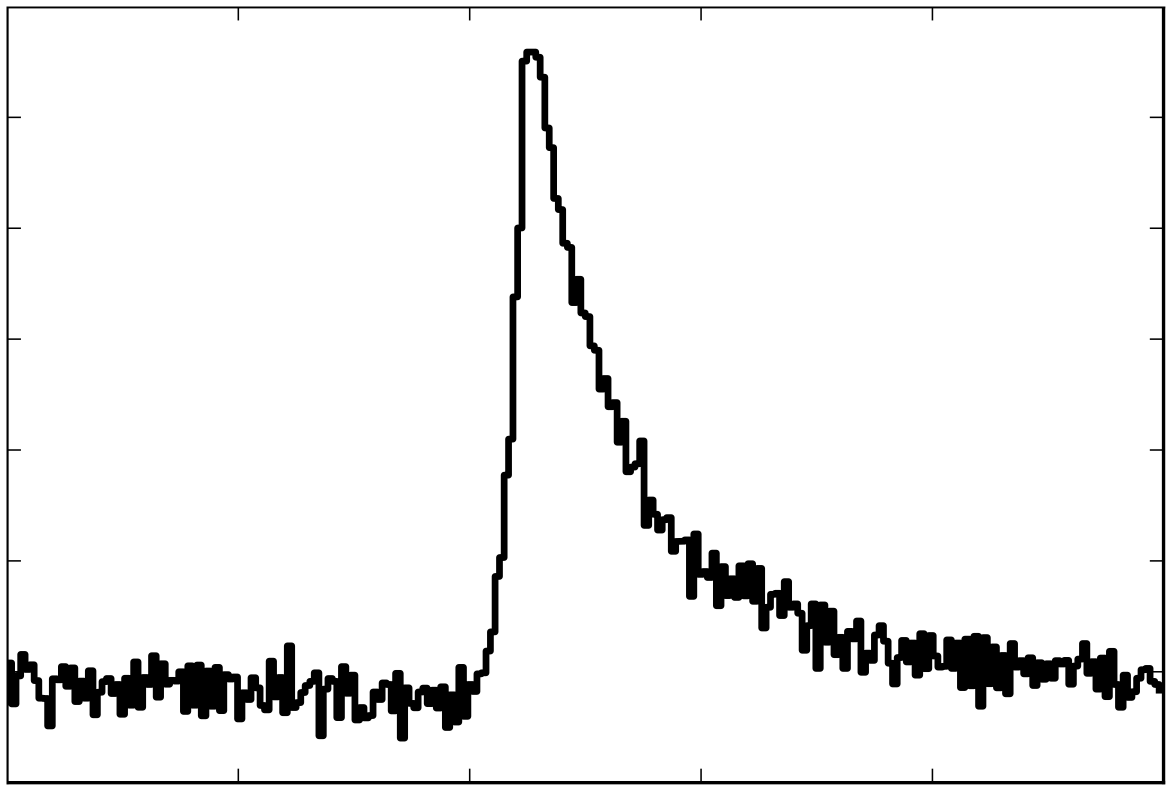
PSR J0453+1559 was discovered in the AO 327 MHz survey (Deneva et al. 2013, ApJ, 775, 51). It is the first asymmetric DNS! $M_p = 1.559(5)\ M_\odot$, $M_c = 1.174(4)\ M_\odot$, see Martinez, Stovall, Freire et al., (2015), ApJ, 812, 143.

Another asymmetric DNS – now with a tight orbit!

Such a system has just been discovered using the ALFA receiver at the Arecibo observatory – see Lazarus, Freire et al. (2016), ApJ, in press (arXiv:1608.08211).

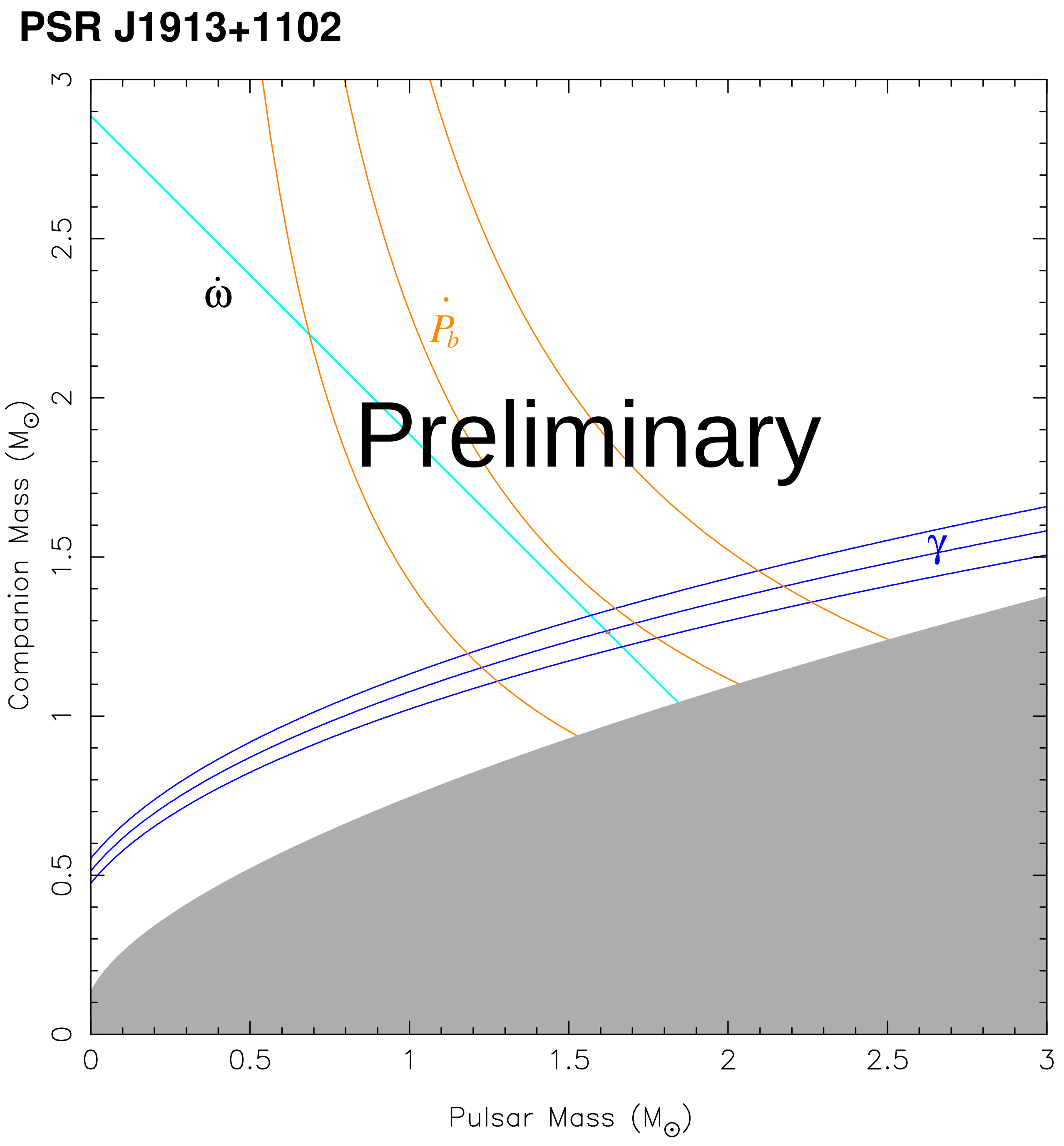
PSR J1913+1102

- P = 27 ms
- P_b = 4.95 hr
- e = 0.089
- Companion mass > 1 solar mass
- Double neutron star!



PSR J1913+1102

- Precession of periastron measured – most massive DNS ever (2.8854 ± 0.0012 $M_{\odot}$).
- Einstein delay measured! Companion mass is 1.25 ± 0.05 $M_{\odot}$., thus the mass of the pulsar is 1.64 ± 0.05 $M_{\odot}$.
- Orbital decay measured to 3-sigma significance – will improve fast during the next few years.
- Coalescence within 0.5 Gyr.
- Merger of systems like this important for: heavy element production, LIGO detection of matter affects, EM counterparts and tests of GR.



PSR J1913+1102

Old and new trends

- Total of 21 systems known might be DNSs, but three of these are doubtful. Outside globular clusters, there are now 19 systems, but two of them are doubtful.
- They can be born with a range of masses that is wider than previously thought.
- Two asymmetric systems have now been measured, one of them contain the least massive NS known.
- Emerging correlation: Low–e systems have low–mass second NS. This suggests a correlation between NS mass and SN kick.
- Are there any more massive NSs in DNSs? Why not?

Experiments* on the Nature of Gravitational Radiation

---

*These really are experiments: Nature changes the experimental setup, i.e., the orbit of the binary and the nature and masses of the components.
- our role is to make the measurements

Could Einstein still be wrong?

- Many alternative theories of gravity predict violation of the strong equivalence principle (SEP). Consequences:

1. **Dipolar gravitational wave (DGW) emission** (tight orbits, 1.5 PN, or 1/c^3):

$$\dot{P}_b^D = -2\pi n_b \frac{G_* M_c}{c^3} \frac{q}{q+1} \frac{1+e^2/2}{(1-e^2)^{5/2}} (\alpha_p - \alpha_c)^2,$$

2. **Orbital polarization** (Nordtvedt effect, for wide orbits AND PULSAR IN TRIPLE SYSTEM)

$$\Delta_{\rm p} - \Delta_{\rm c} \simeq \alpha_0(\alpha_{\rm p} - \alpha_{\rm c}) \simeq \alpha_0(\alpha_{\rm p} - \alpha_0)\ .$$

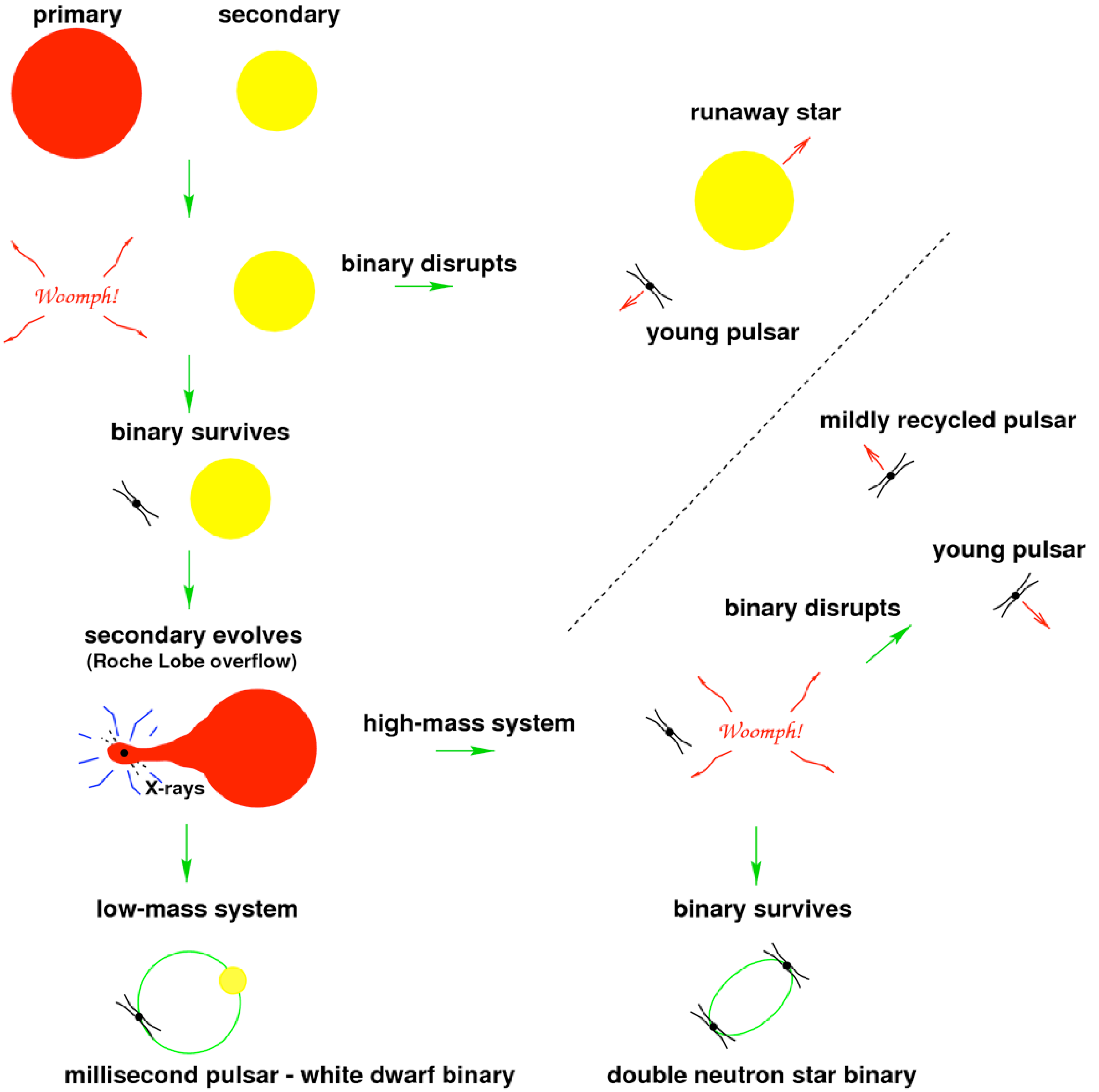
3. **Variation of Newton’s gravitational constant G.**

- **Detecting <u>any</u> of these effects would falsify GR**!

- The first two depend on *difference* of compactness between members of the binary. Therefore, pulsar – white dwarf systems might show these effects, even if they are not detectable in the double pulsar!

Pulsar – White dwarf systems

- For GR tests with these systems, mass measurements are *absolutely necessary*.
- Furthermore, it is thought that these could be more massive, given the much longer accretion episode!
- So, we REALLY WANT TO MEASURE THEIR MASSES!
- Measuring masses much more difficult since generally orbits are so circular! Precession of periastron and Einstein delay (which provide precise mass measurements for most DNSs) are not available.



Lorimer, D., *Living Rev. Relativity* 11 (2008), 8

Measuring MSP masses: It’s hard!

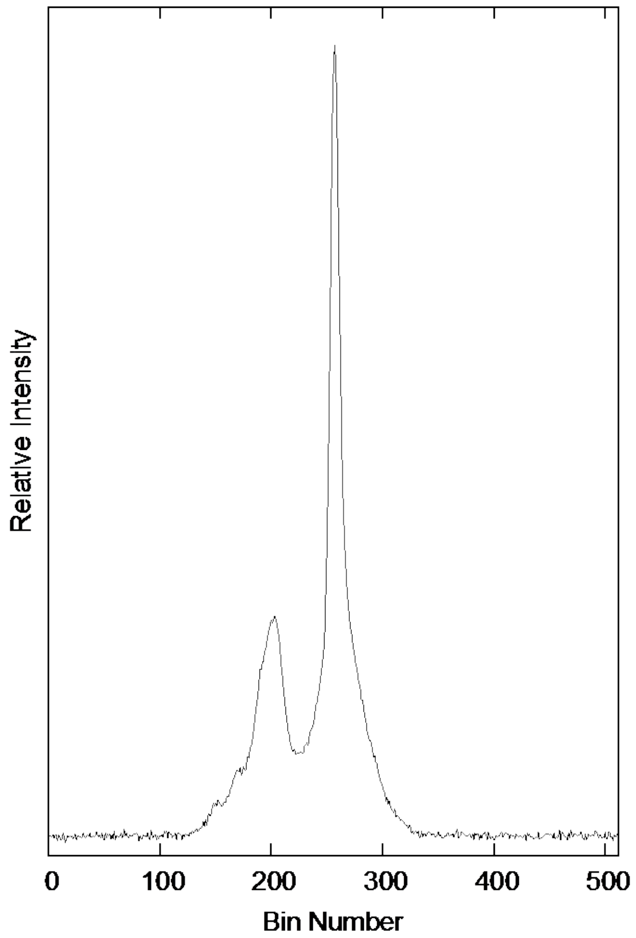
Solutions:

1) WD spectroscopy

2) Measurements of Shapiro delay

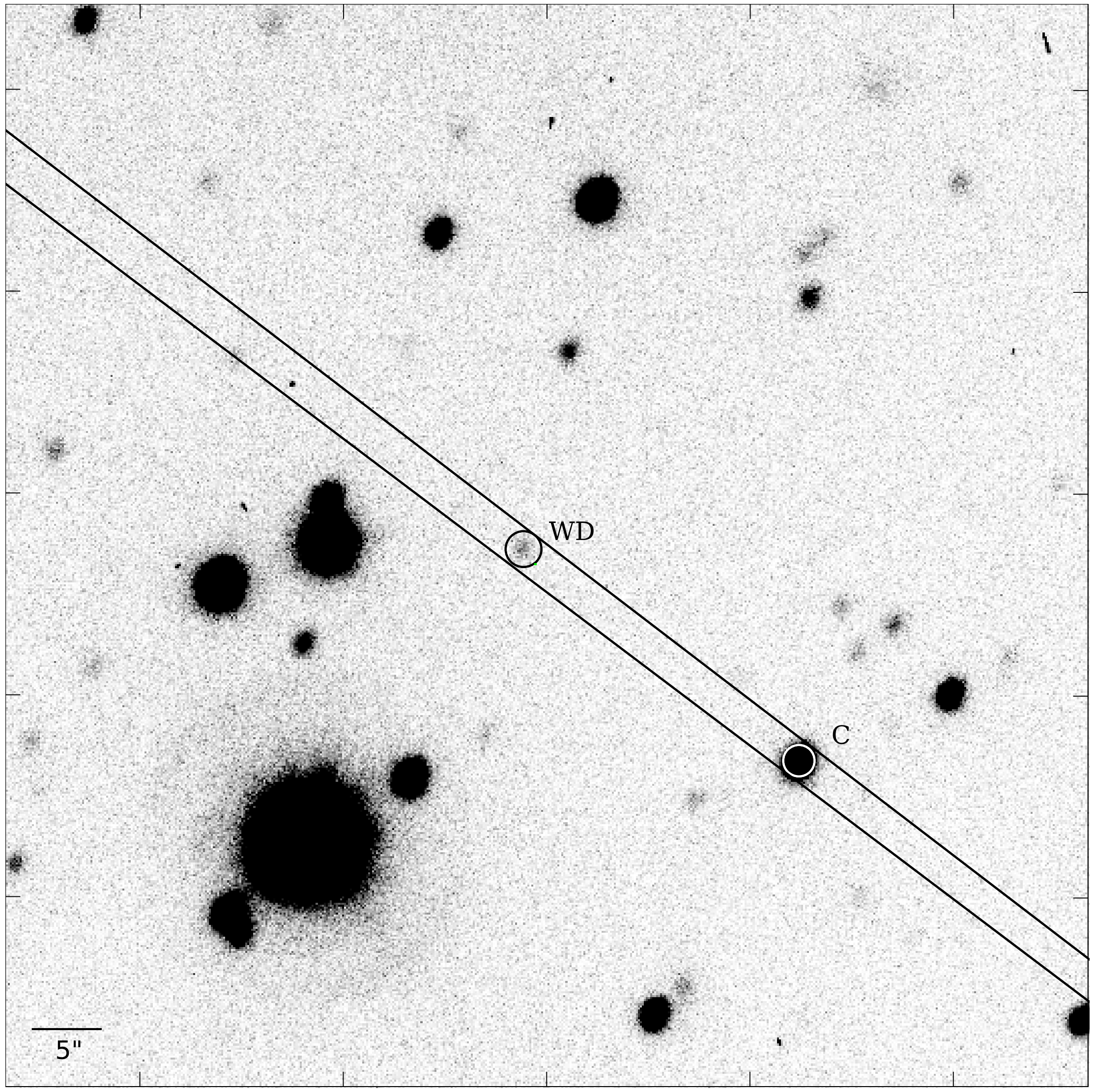
3) Find unusually eccentric systems

White dwarf spectroscopy: Sometimes we're lucky!



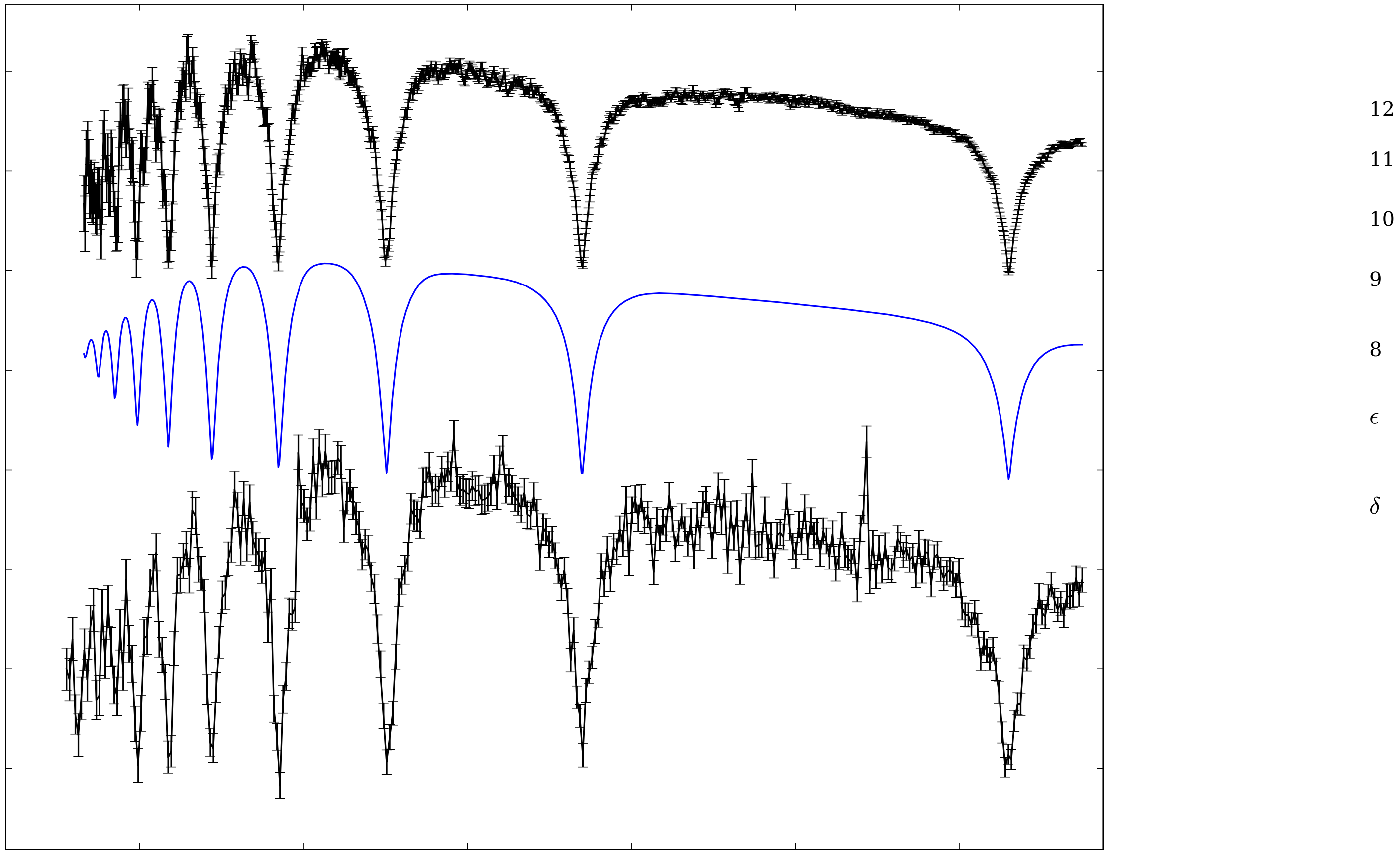
- PSR J1738+0333 is a 5.85-ms pulsar in 8.5-hour, low eccentricity orbit. It was discovered in 2001 in a Parkes Multi-bea high-Galactic latitude survey (Jacoby 2005, Ph.D. Thesis, Caltech).

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



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

Optical observations of PSR J1738+0333



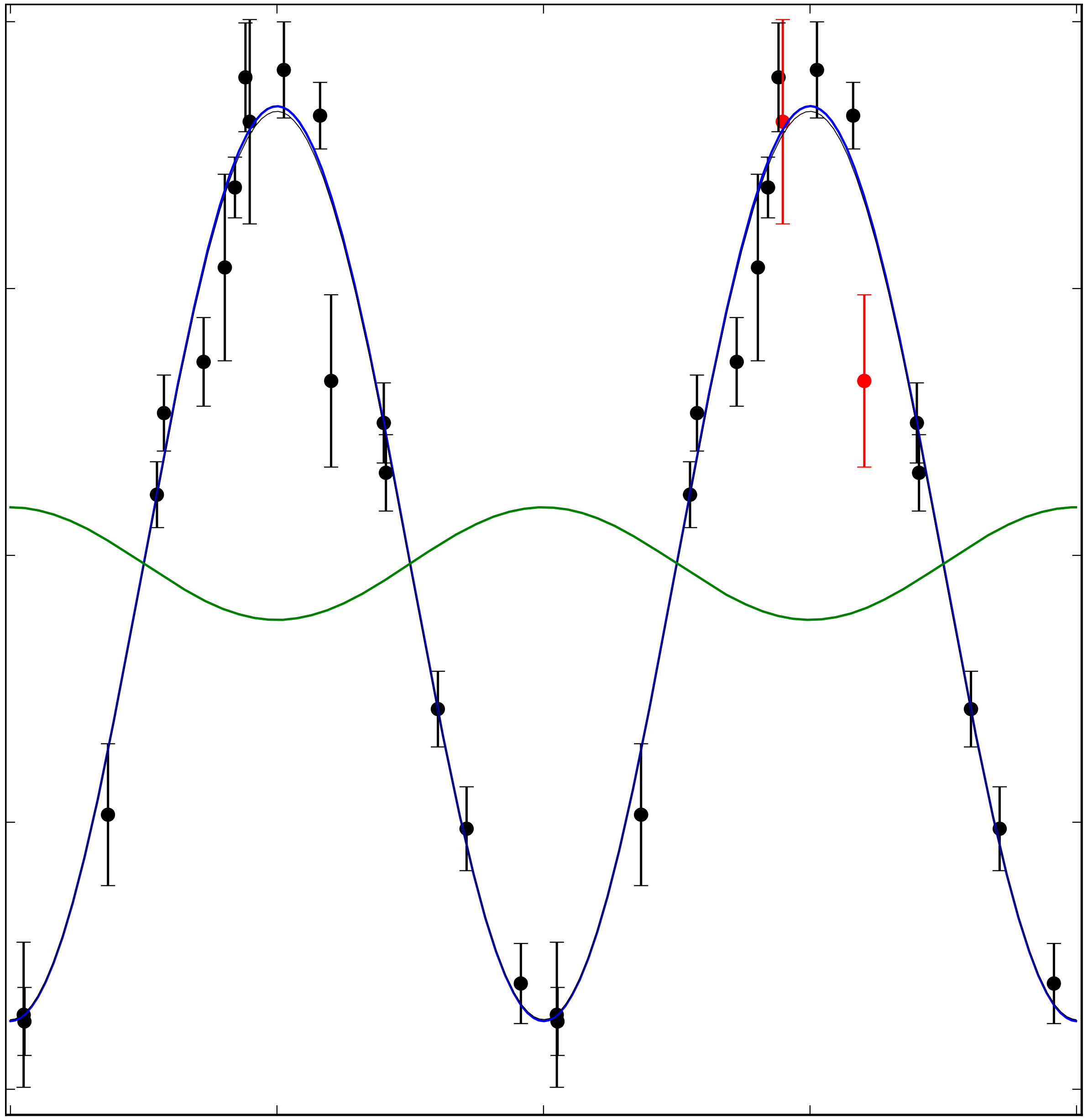
- The WD is bright enough for a study of the spectral lines!
- Together with WD models, these measurements allow an estimate of the WD mass: $0.181^{+0.007}_{-0.005}\ M_{\odot}$.

Optical observations of PSR J1738+0333

- 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 pulsar mass: $1.46^{+0.07}_{-0.06}\ M_{\odot}$.

- Results in Antoniadis et al. 2012, MNRAS, 423, 3316.



Prediction:

- Once the component masses are known, we can estimate the rate of orbital decay due to quadrupolar GW emission predicted by GR (2.5 PN):

$$\begin{aligned}\dot{P}_b^{\rm GR} &\simeq -\frac{192\,\pi}{5}\left(n_b \mathrm{T}_\odot\, m_c\right)^{5/3}\frac{q}{(q+1)^{1/3}}\\ &= -27.7^{+1.5}_{-1.9}\,\mathrm{fs\,s}^{-1},\end{aligned}$$

… which is a change on the orbital period of **−0.86 μs per year**!

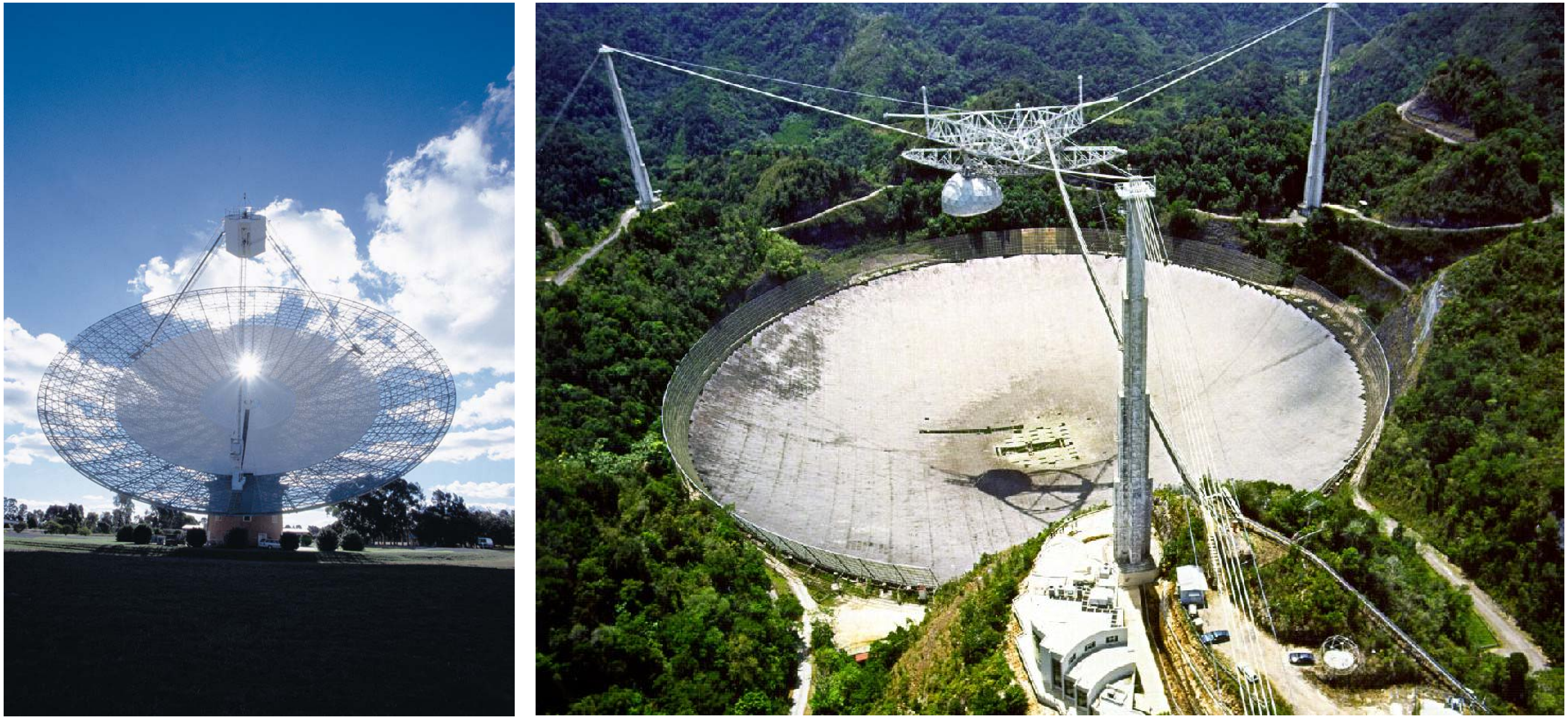
- In the presence of ***dipolar GW*** emission this quantity must be larger (in absolute value) - If α_p ~1, then orbital decay should be **~ −32000 μs per year**! It is a 1.5 PN effect.

$$\dot{P}_b^D = -2\pi n_b \frac{G_*\, M_c}{c^3}\,\frac{q}{q+1}\,\frac{1+e^2/2}{(1-e^2)^{5/2}}\,(\alpha_p-\alpha_c)^2,$$

- *Can such a small change in the orbital period be detected*?

Timing of PSR J1738+0333

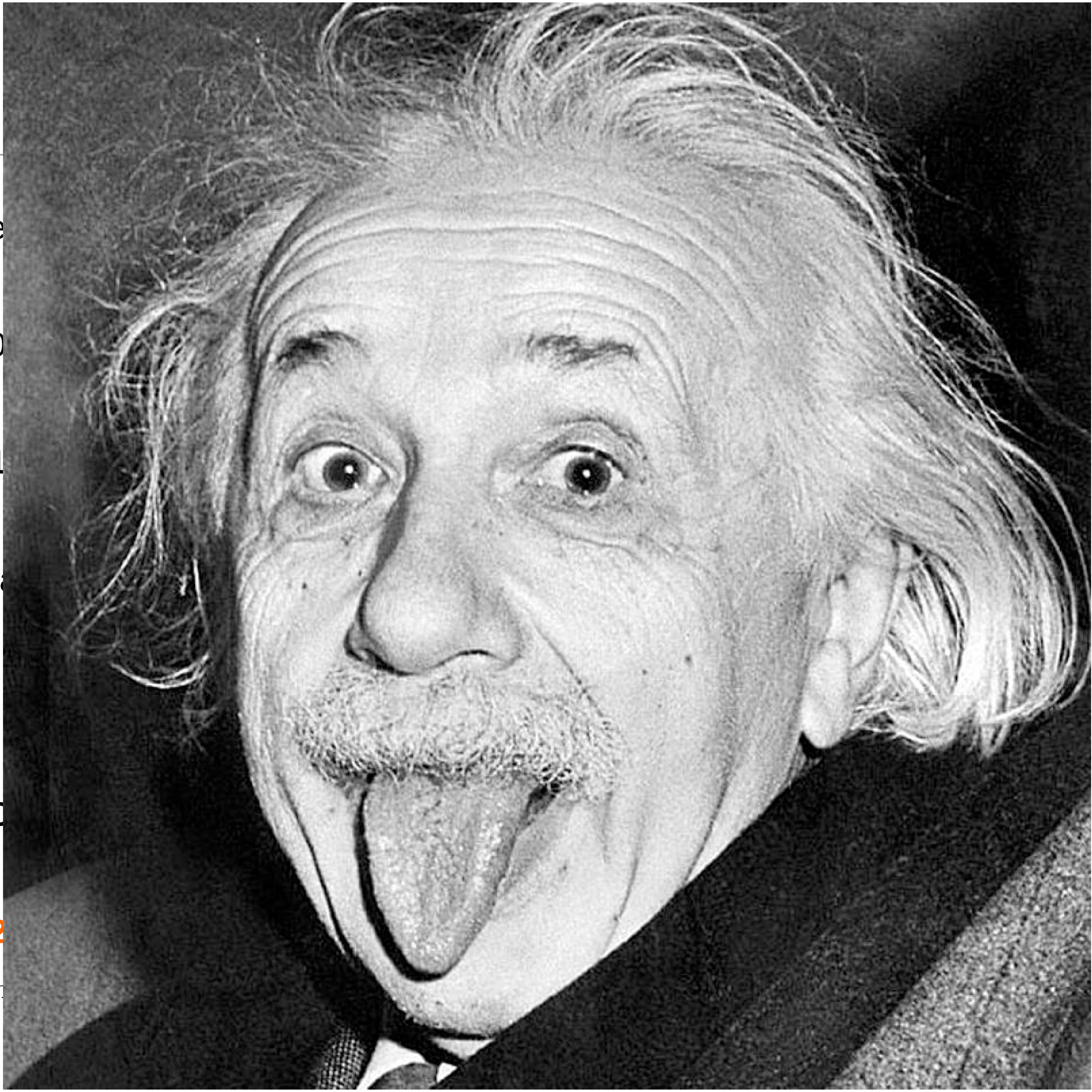
10 years of timing with Parkes and Arecibo were necessary to measure this number precisely!



The (awesome)

- Number of rotations betwee
- Spin period (today, at 14:00
- Orbital period: **8^h 30^m 53.91**
- Semi-major axis of the puls
- Eccentricity: **(3 ± 1) × 10^{-7}**.
- Proper motion: **7.037 ± 0.00**
- **Orbital decay: −(25.9 ± 3.2**

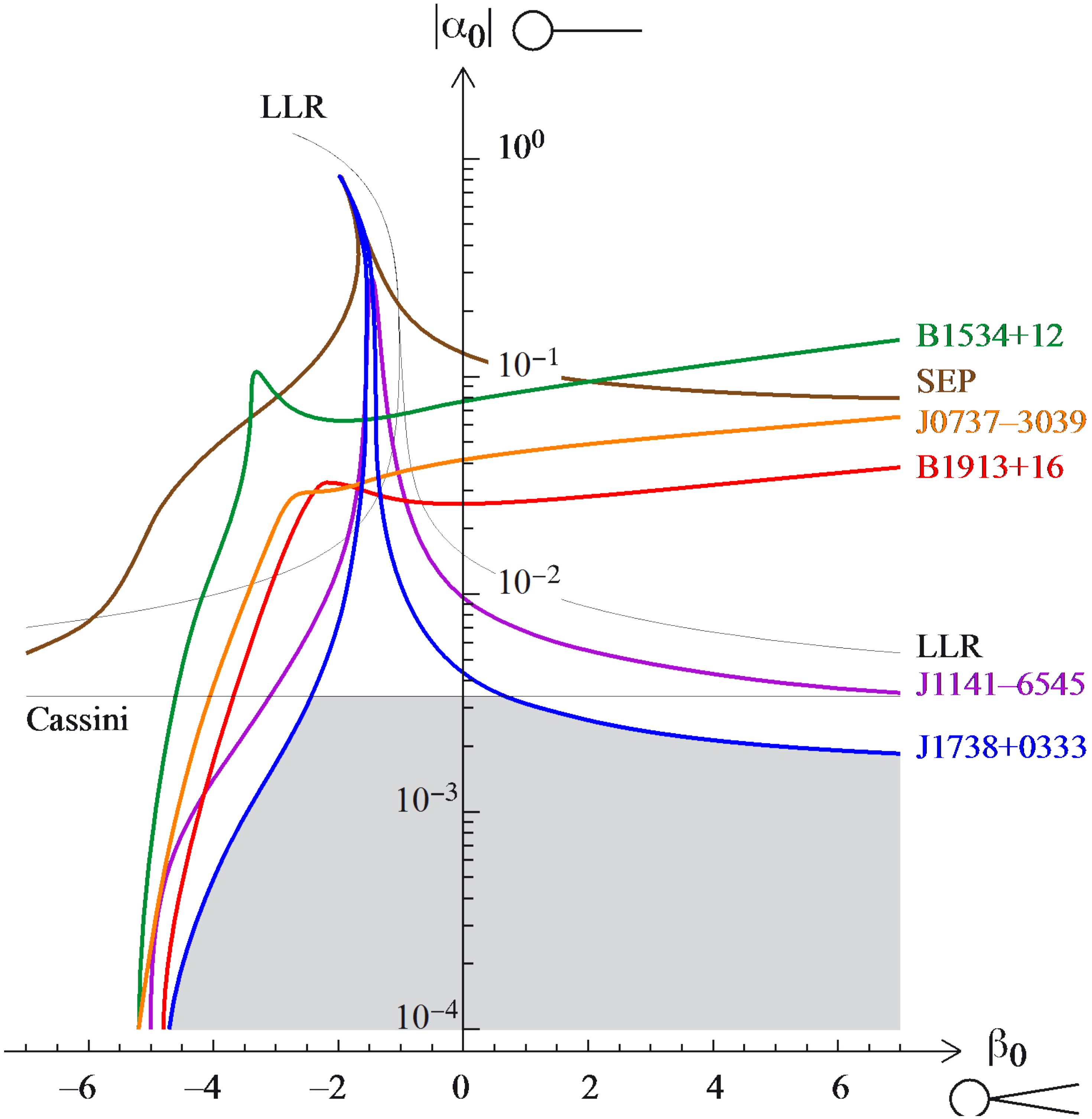
$$\dot{P}_b^{\mathrm{Int}} = \dot{P}_b - \dot{P}_b^{\mathrm{Acc}} - \dot{P}_b^{\mathrm{Sh}}$$



Limit on dipolar GW emission

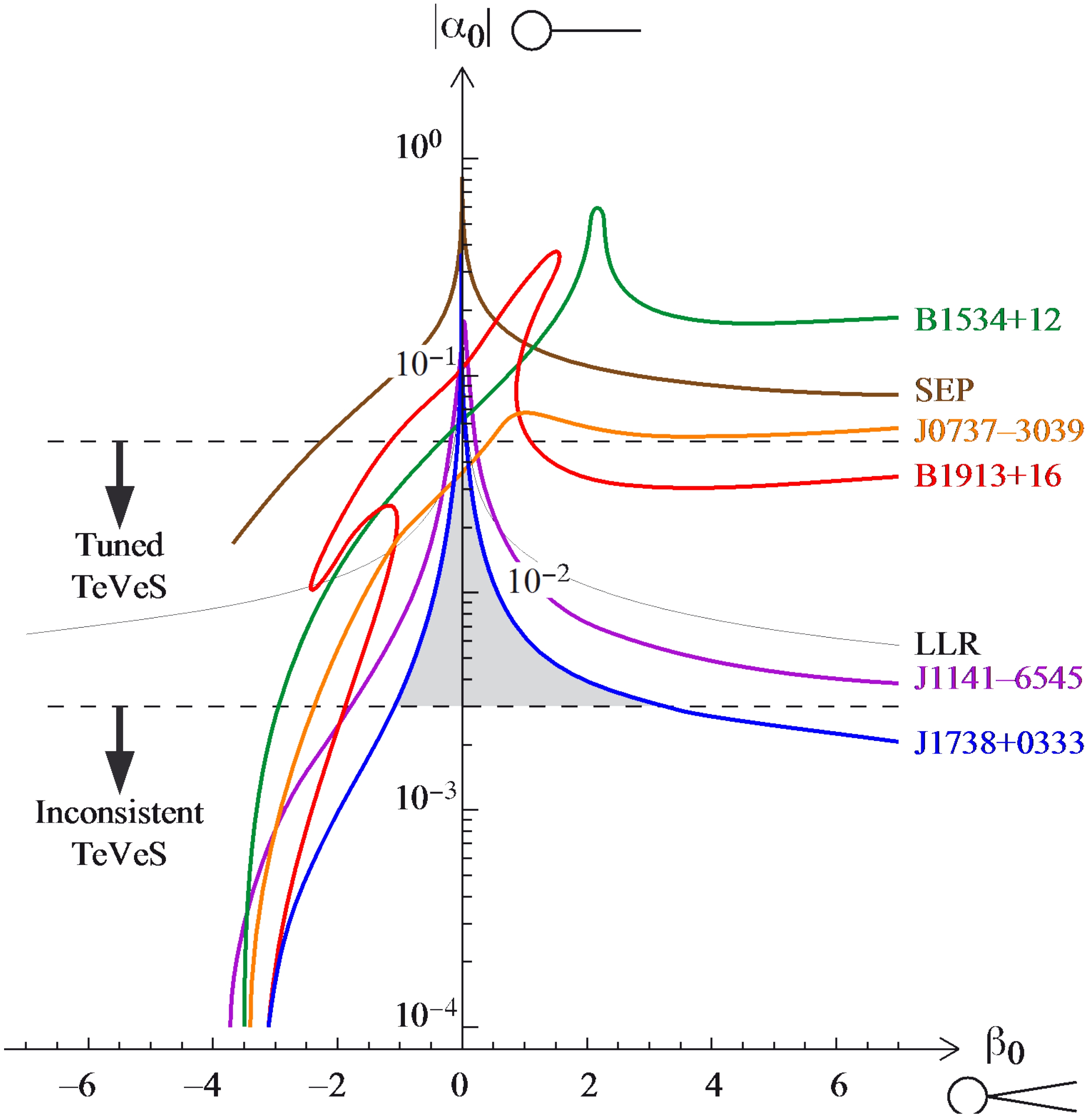
- Difference between orbital decay predicted by GR (quadrupolar) and observed is +0.06 ± 0.10 μs per year!
- This represents a very serious theoretical constraint: remember prediction of **−32000** μs per year! This implies that $(\alpha_p - \alpha_c)^2 < 3 \times 10^{-5}$.
- Gravitational waves in the Universe really are quadrupolar, as predicted by GR!
- This introduces stringent constraints on alternative theories of gravity that predict dipolar GW emission.

For Scalar-Tensor theories of gravity, this is the most constraining binary pulsar test ever!



See results in Freire, Wex, Esposito-Farèse et al. (2012), MNRAS, 423, 3328.

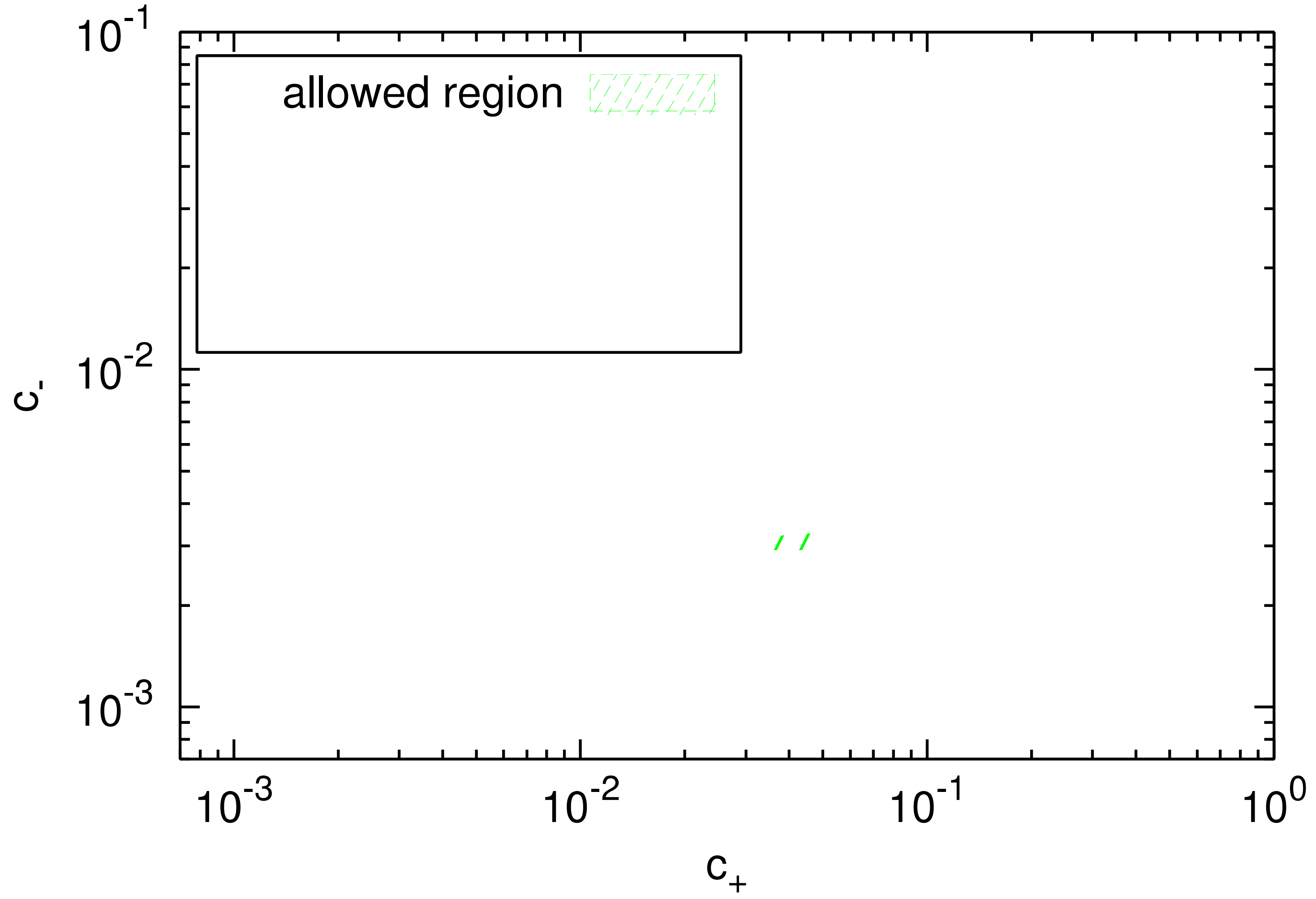
Also for TeVeS and friends!



- Tensor-Vector-Scalar theories (based on Bekenstein's 2004 TeVeS theory) can also be constrained, but in this case PSR J1738+0333 is not enough.
- Improvements in the timing precision of the double pulsar (PSR J0737−3039) will be essential to constrain regions near linear coupling. *To be published soon (Kramer et al)*.
- **TeVeS and all non-linear friends will soon be unnaturally fine-tuned theories**.

Also for many others!

See e.g., ``Constraints on Einstein-Æther theory and Hořava gravity from binary pulsar ovservations", Kent Yagi, Diego Blas, Enrico Barausse and Nicolás Yunes, (2013) Phys. Rev. D, 89, 084067.

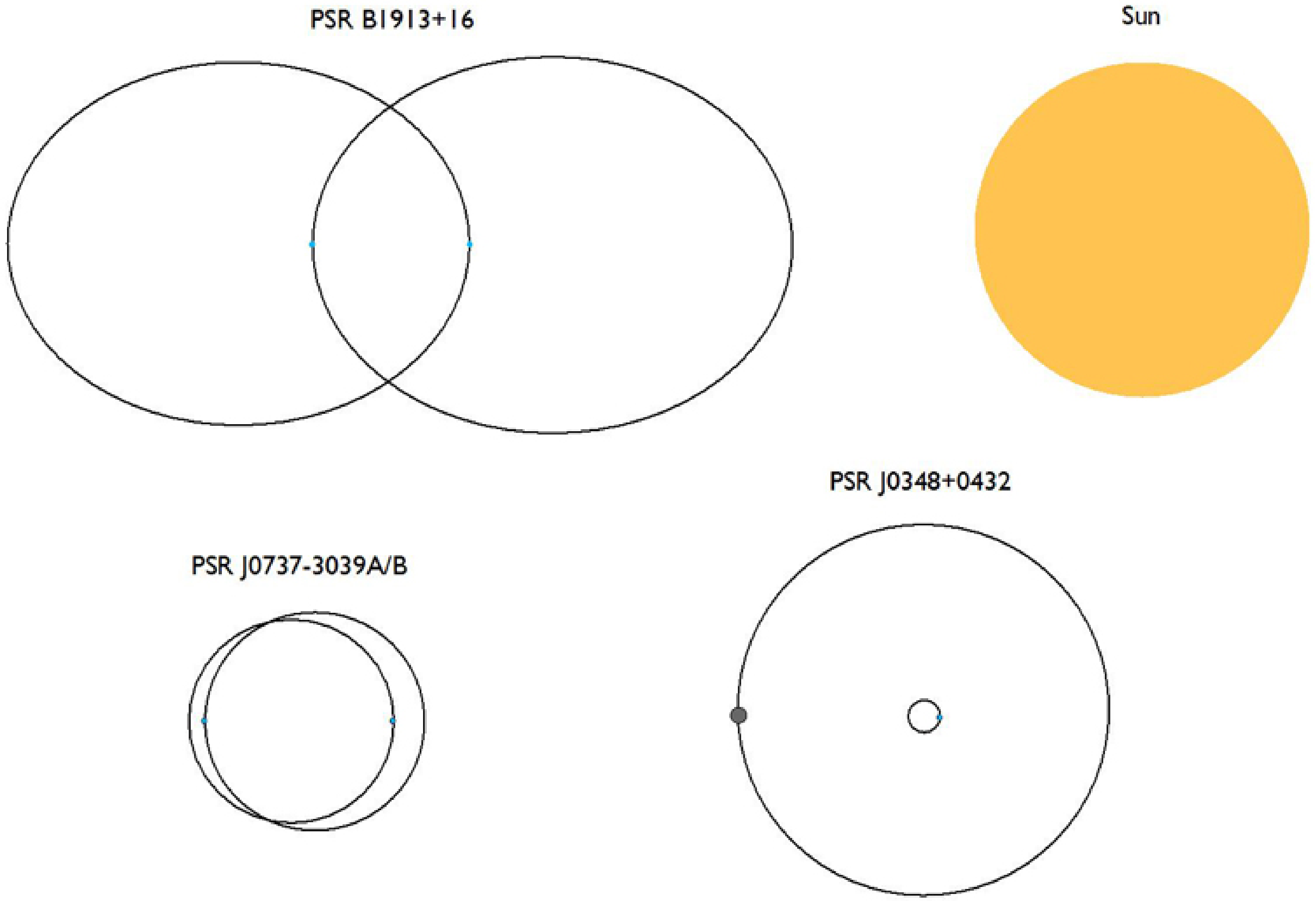


Constraints on Einstein-Æther theory from binary pulsar observations from the observed orbital decay of PSR J1738+0333.

Does GW emission change with NS mass?

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.

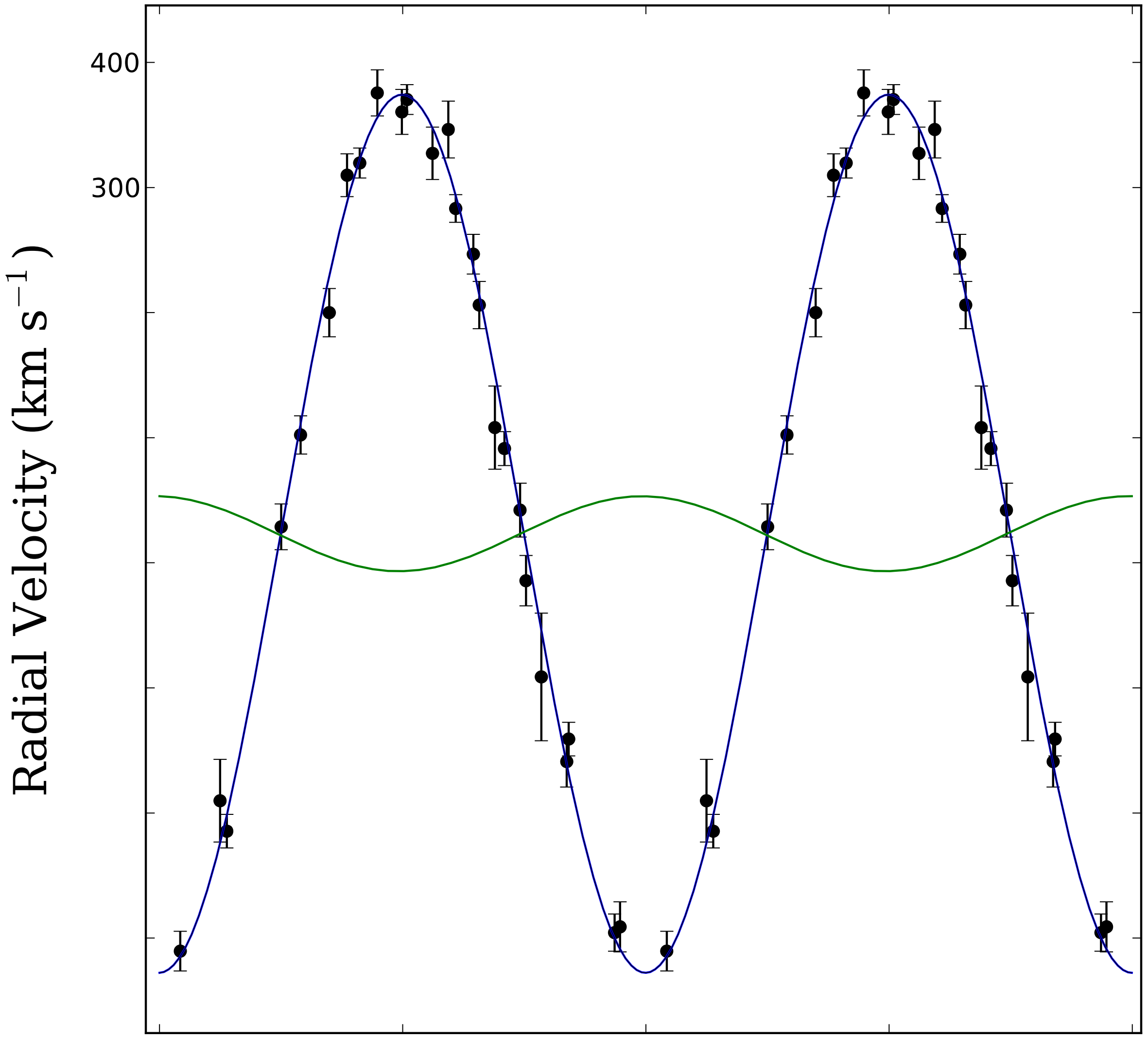


Credit: Norbert Wex

PSR J0348+0432

Optical measurements at the VLT find a WD mass of 0.172 ± 0.003 $M_{\odot}$ and **a pulsar mass of 2.01 ± 0.04 $M_{\odot}$** (Antoniadis, Freire, Wex, Tauris 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



Credit: Luis Calçada, ESO. See video at: http://www.eso.org/public/videos/eso1319a/

This is important – system is unique!

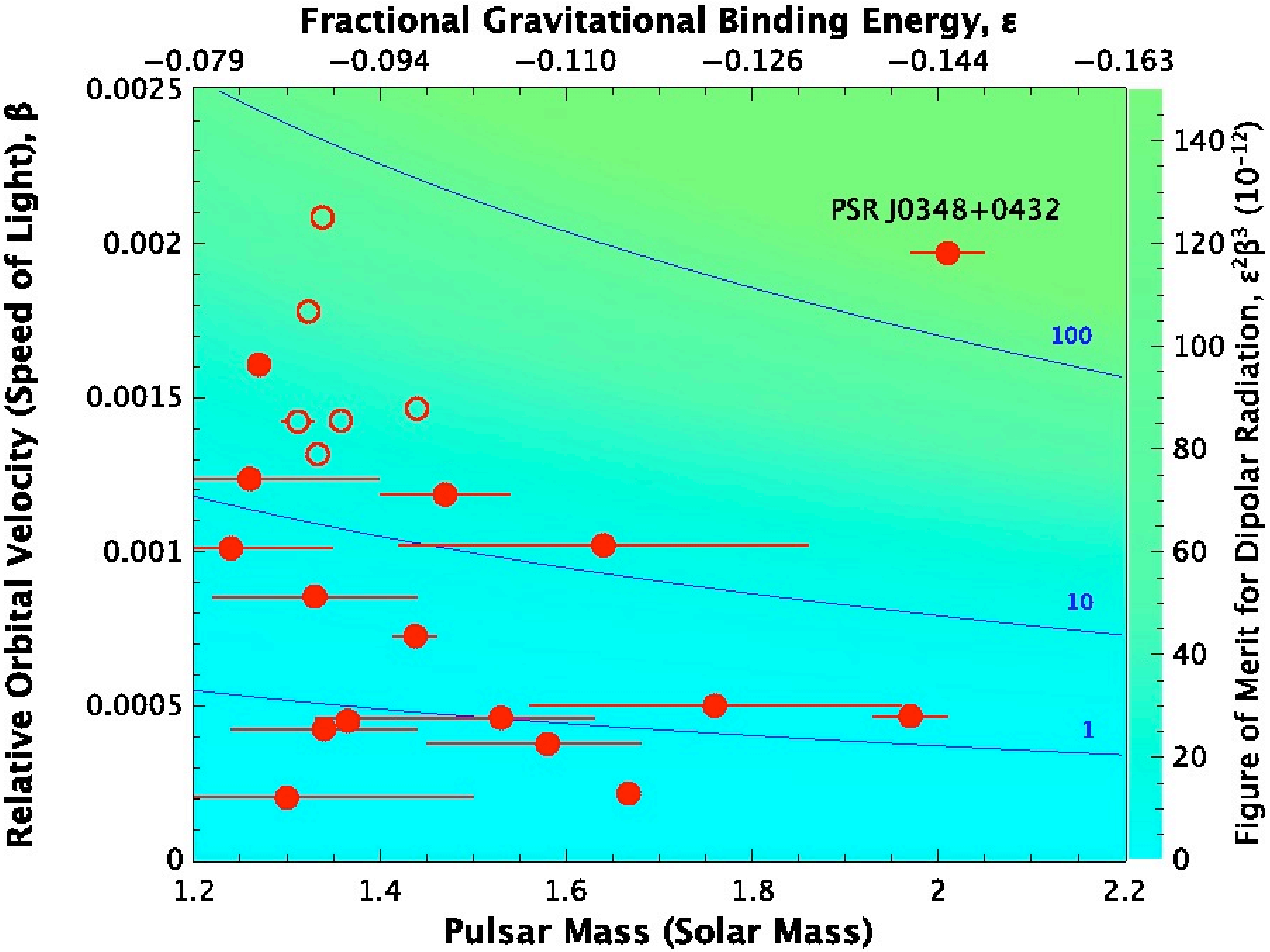
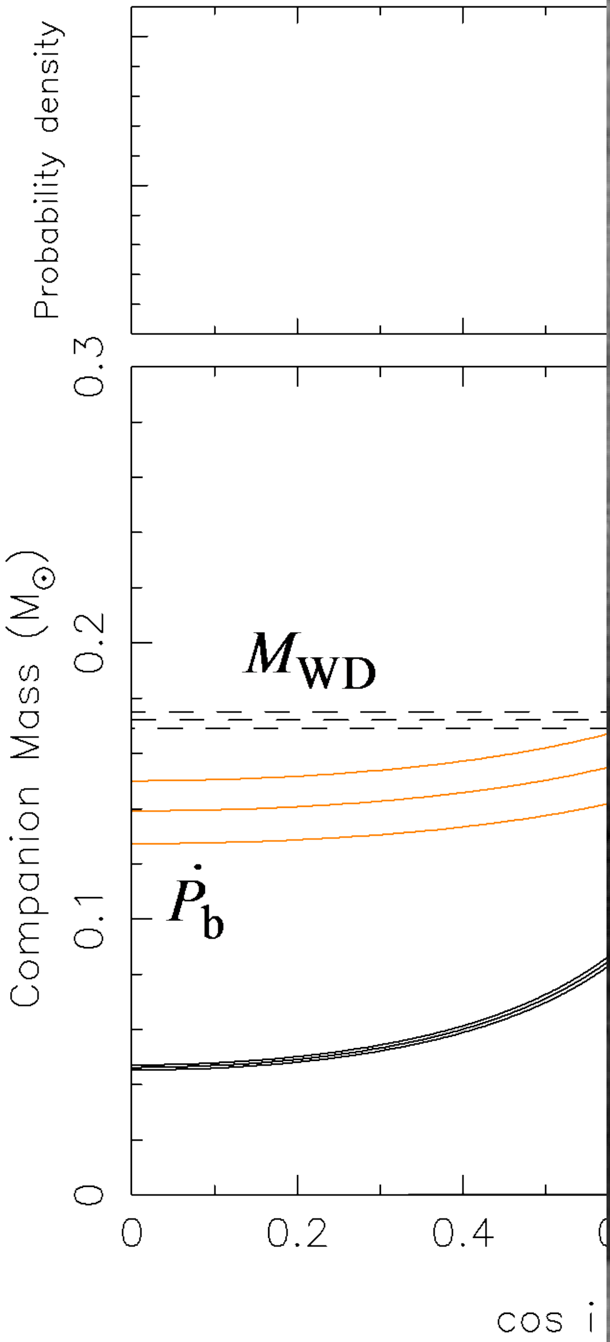
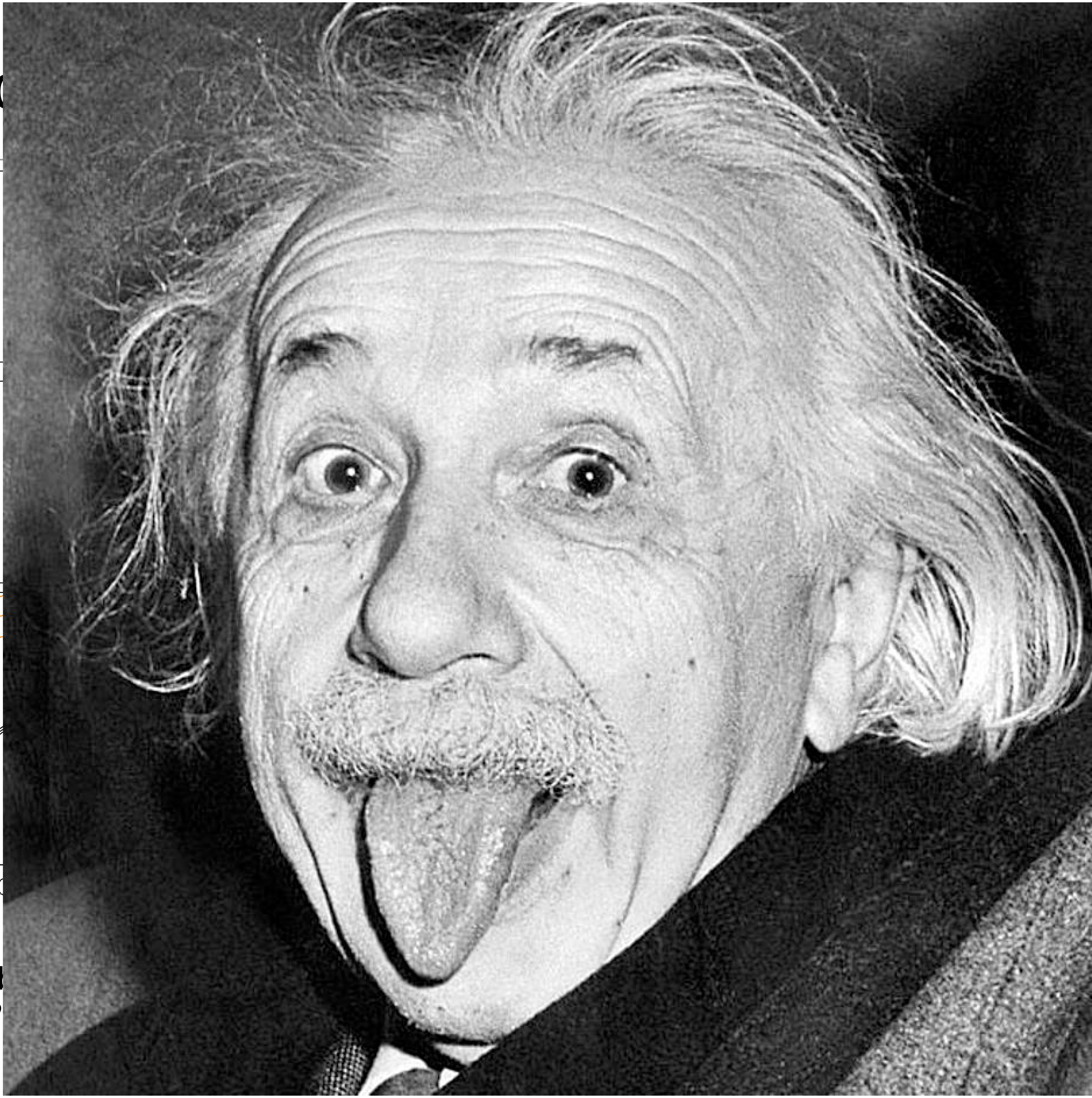


Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

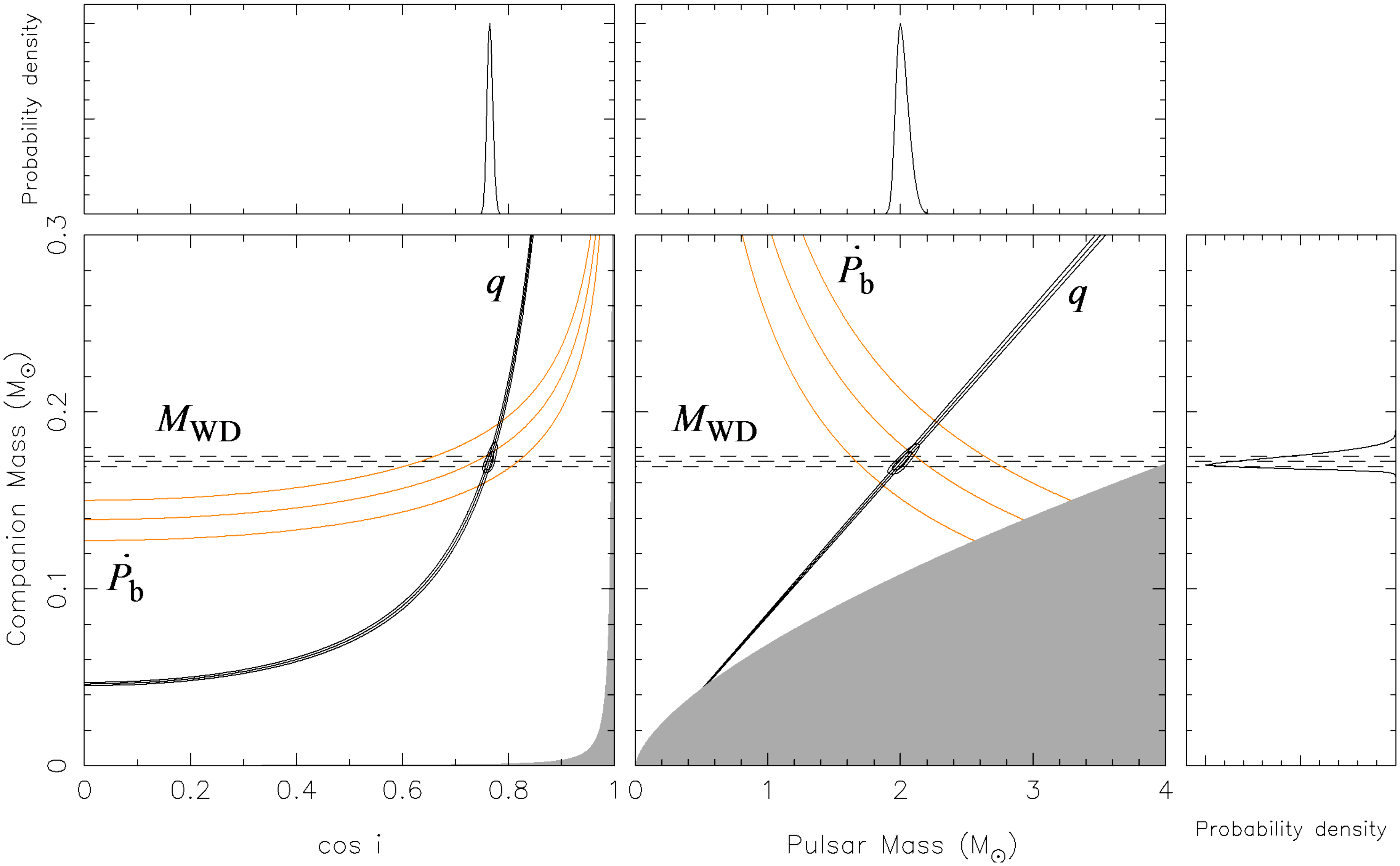
Measurement





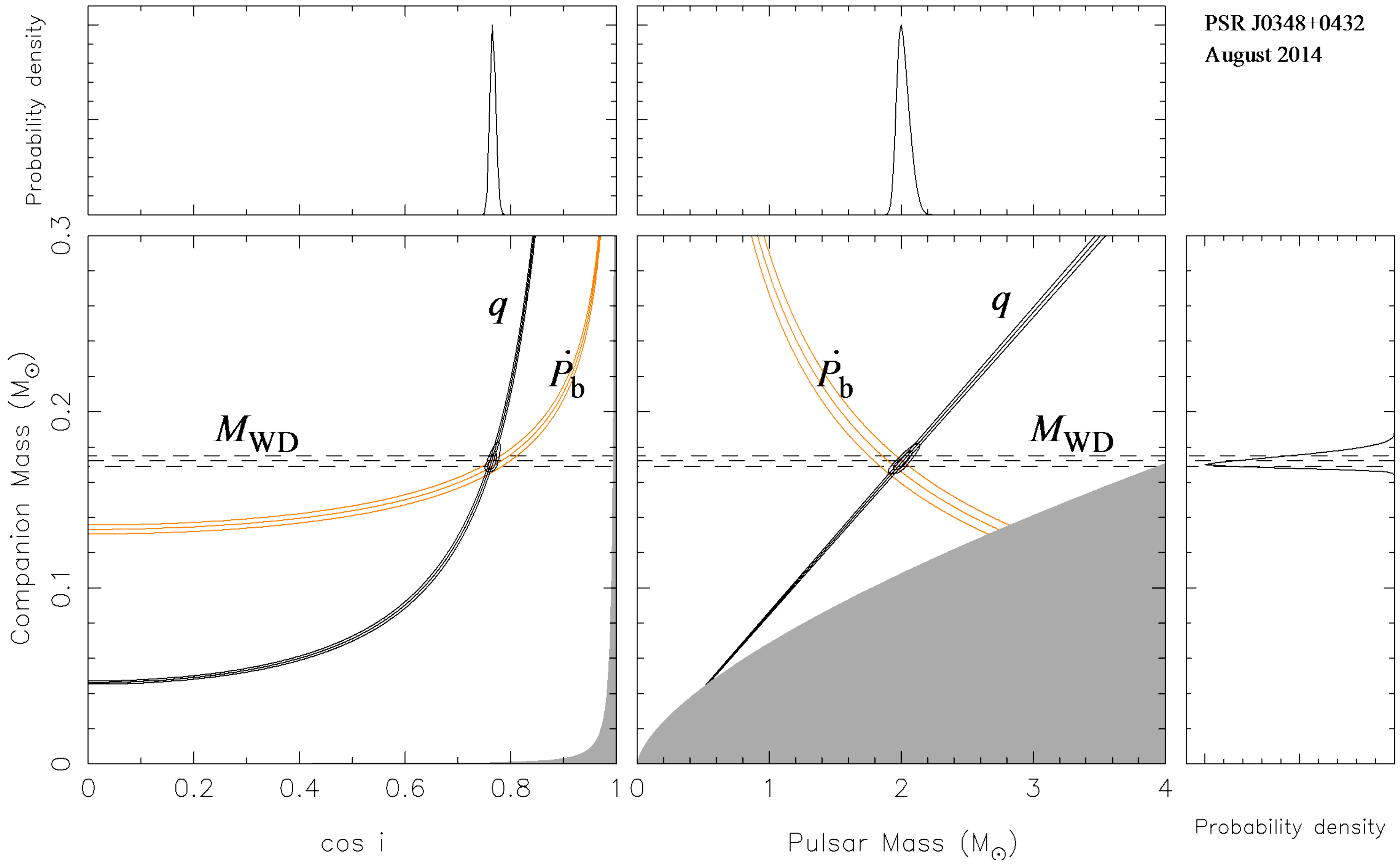
With Arecibo, GBT and Effels
Complete agreement with GR

Measurement of orbital decay



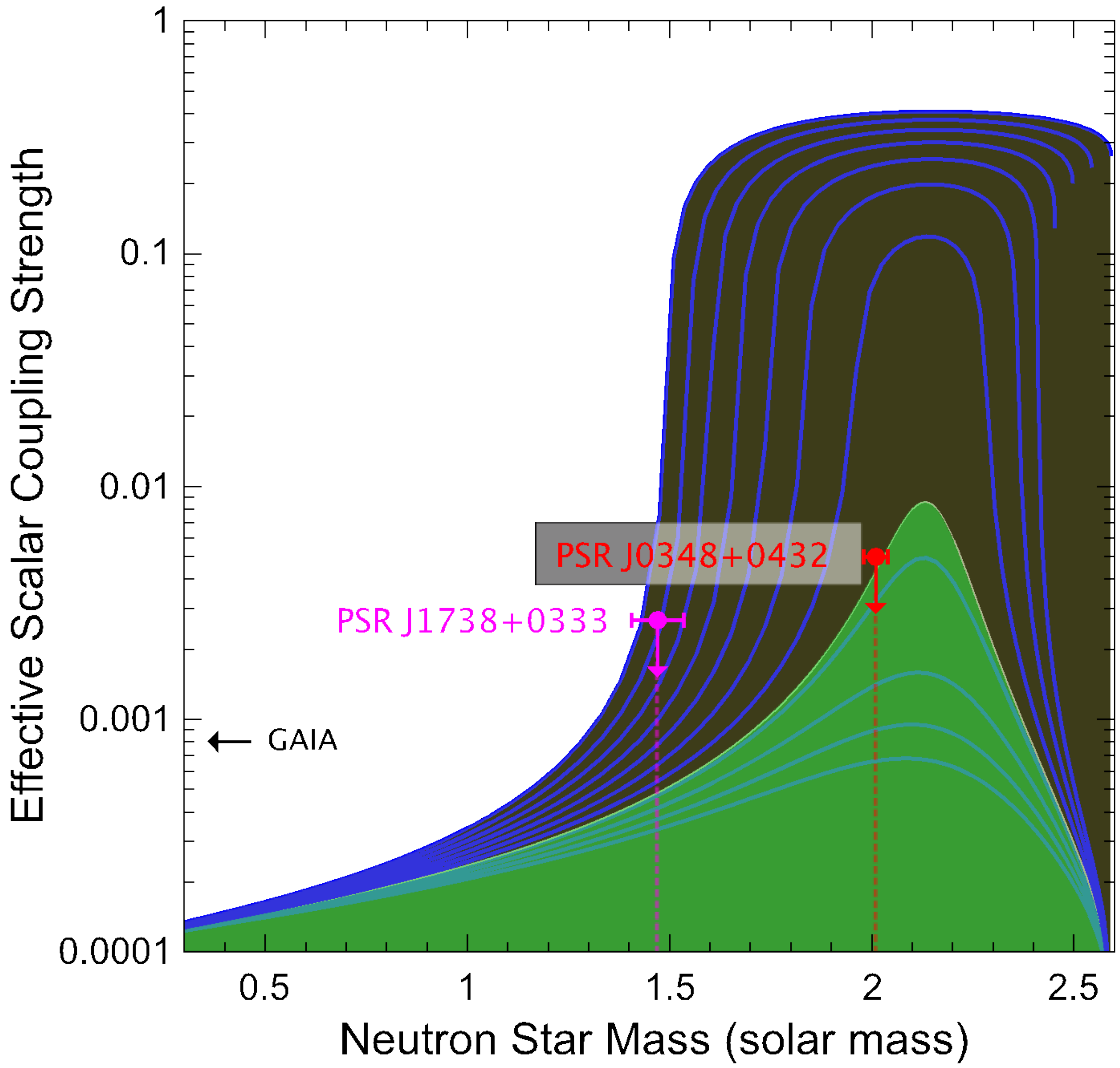
18 months after the Science publication, the orbital decay measurement had improved by a factor of 5 already! We will soon have a very precise mass measurement, *assuming* GR.

Measurement of orbital decay



18 months after the Science publication, the orbital decay measurement had improved by a factor of 5 already! We will soon have a very precise mass measurement, *assuming* GR.

Strong non-linear deviations from GR seriously constrained!



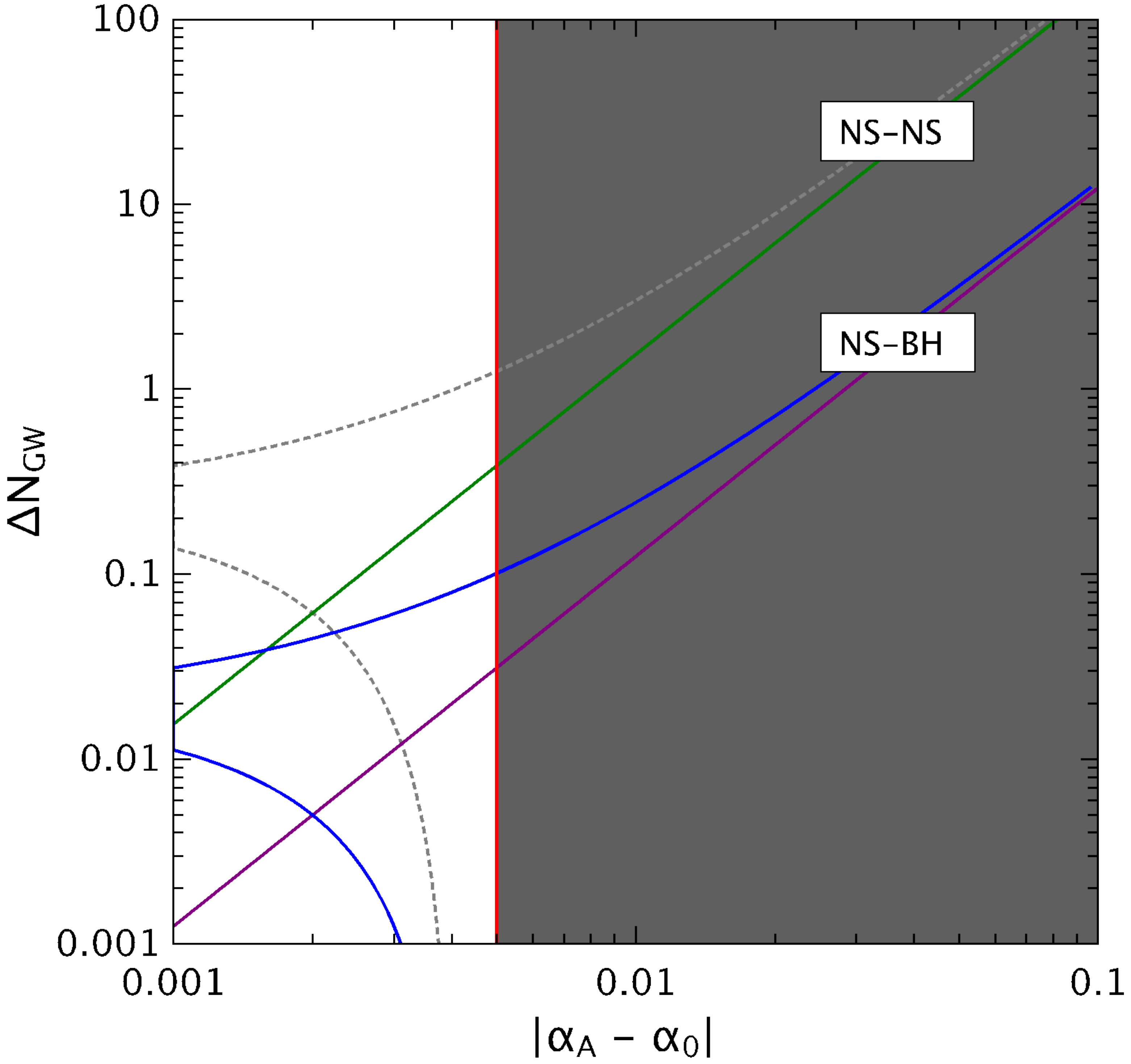
- This is the first time we do a GR test with such a massive NS: Previously, only 1.4 $M_\odot$ NSs had been used for such tests!

- This constrains the occurrence of strong non-linear deviations from GR, like *spontaneous scalarization* (e.g., Damour & Esposito-Farèse, 1996, Phys. Rev. D., 54,1474) – at least at large PSR-WD separations!

- Such phenomena simply just could not be probed before.

Implications for GW detection

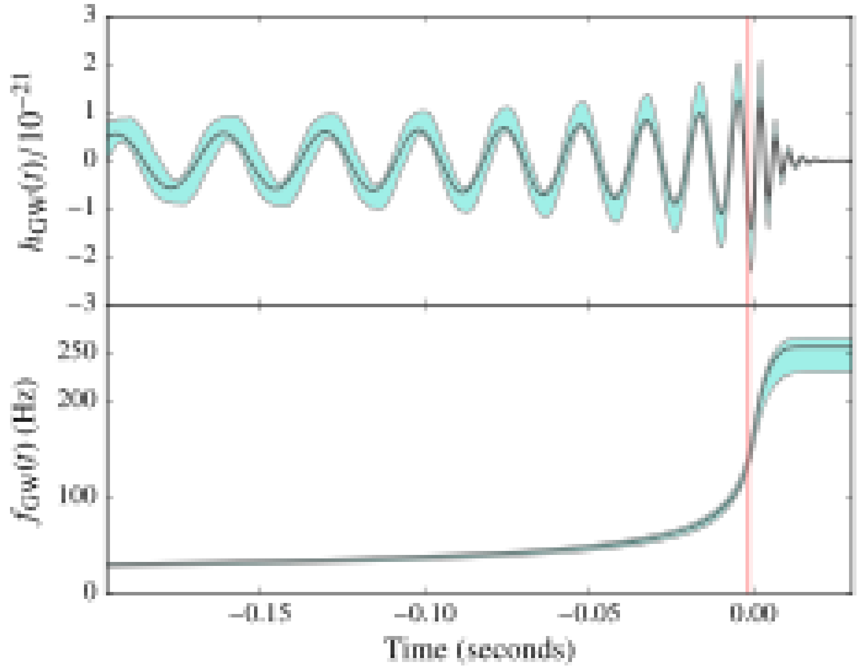
- For a NS-NS merger, only a small fraction of a cycle can be lost while it is in the LIGO/Virgo bands.
- … unless there are short-range, high frequency effects!



How do pulsars compare to LIGO?

GW 150914

GR violations are limited to less than 4 %
(for effects that cannot be absorbed in a
redefinition of parameters)



*90% credible regions for the waveform
and the GW frequency. From: LSC/ Virgo*

How do pulsars compare to LIGO?

Pulsar tests are complementary
to LIGO constraints!

Figure: LSC/Virgo 2016, Kramer et al. in prep.

■ GW150914 (v~0.4c)
◆ GW151226 (v~0.4c)
● combined

▼ Double Pulsar (v~0.002c)

(v^2/c^2 corrections)

Quadrupole formula

How do pulsars compare to LIGO?

- BH-BH mergers cannot test deviations from GR that appear only in the presence of matter, e.g., JFBD-type scalar-tensor theories.

- Certain alternatives to GR predict (significant) deviations only for BHs, e.g., decoupled dymamical Gauss-Bonnet (D2GB) gravity (see Yagi et al. 2016)

- For certain alternatives to GR, pulsars already provide better constraints than expected from LIGO/Virgo observations of NS-NS or NS-BH mergers.

- LIGO/Virgo observations of NS-NS mergers are essential to test short-range phenomena, like dynamical scalarization (Barausse et al. 2013)

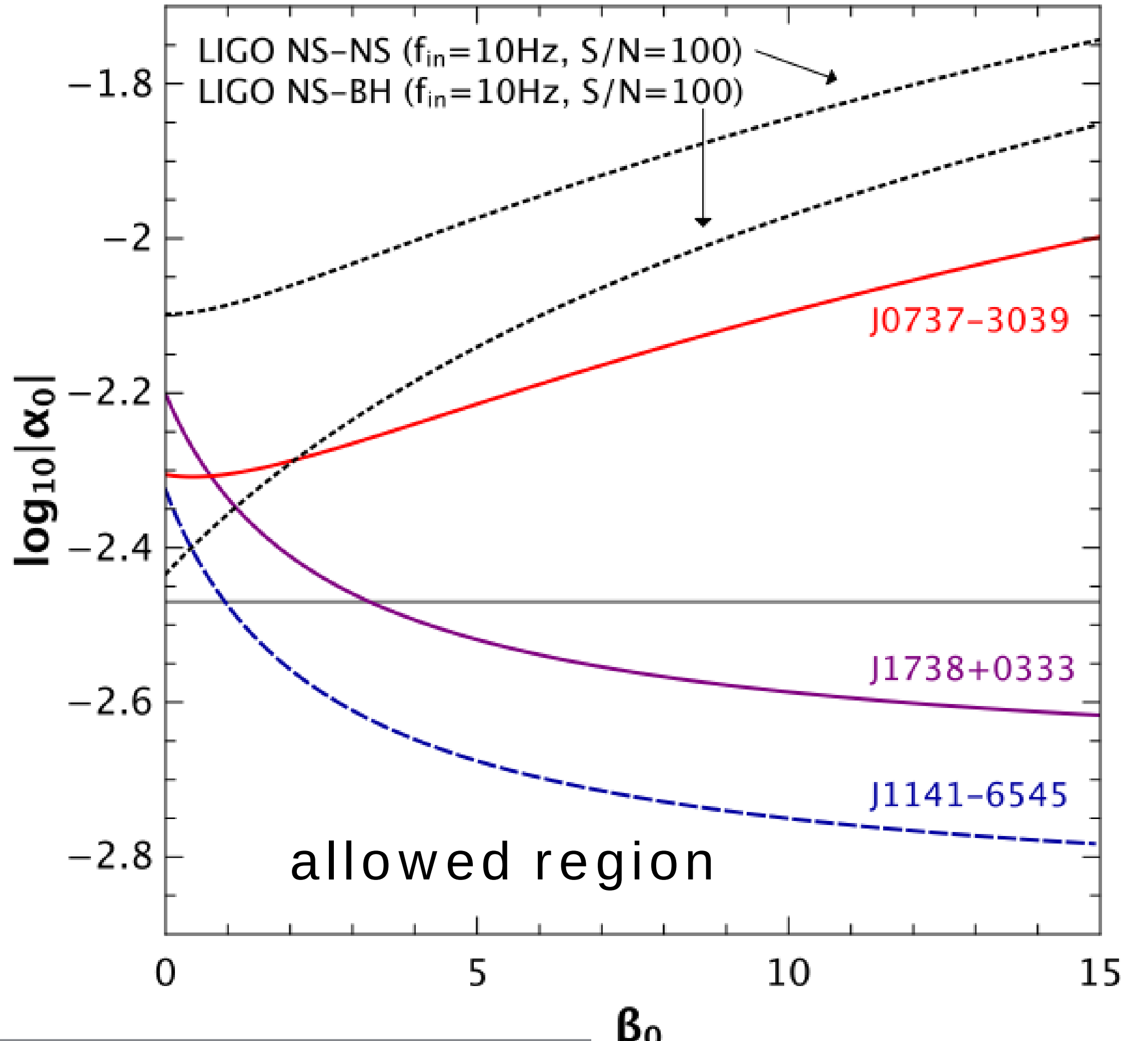


Figure: Wex, private Communication

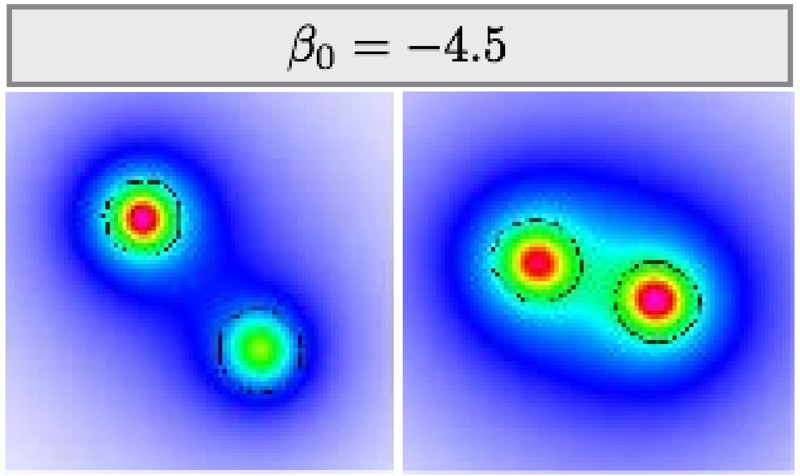


Figure: Barausse et al. (2013)

NS mass measurements. II - MSPs

Measuring MSP masses: It’s hard!

Solutions:

1) WD spectroscopy (already discussed)

2) Measurements of Shapiro delay

3) Find unusually eccentric systems

Solution 2: Shapiro delay

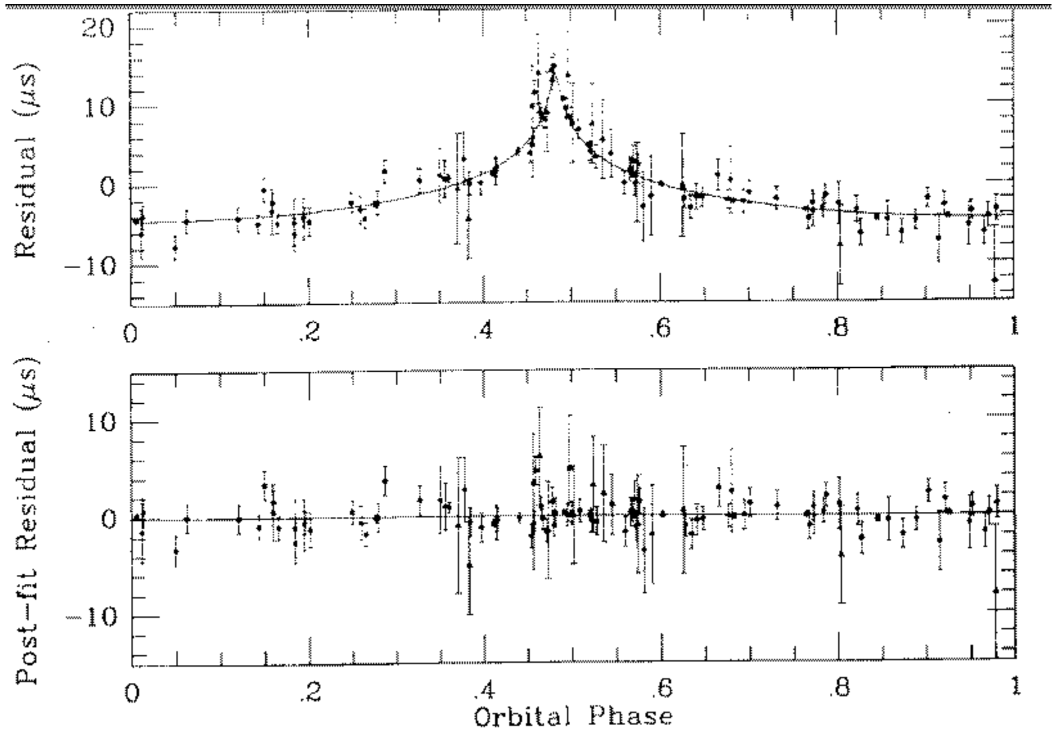
- Shapiro delay (described above for double pulsar) still measurable for circular orbits…

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

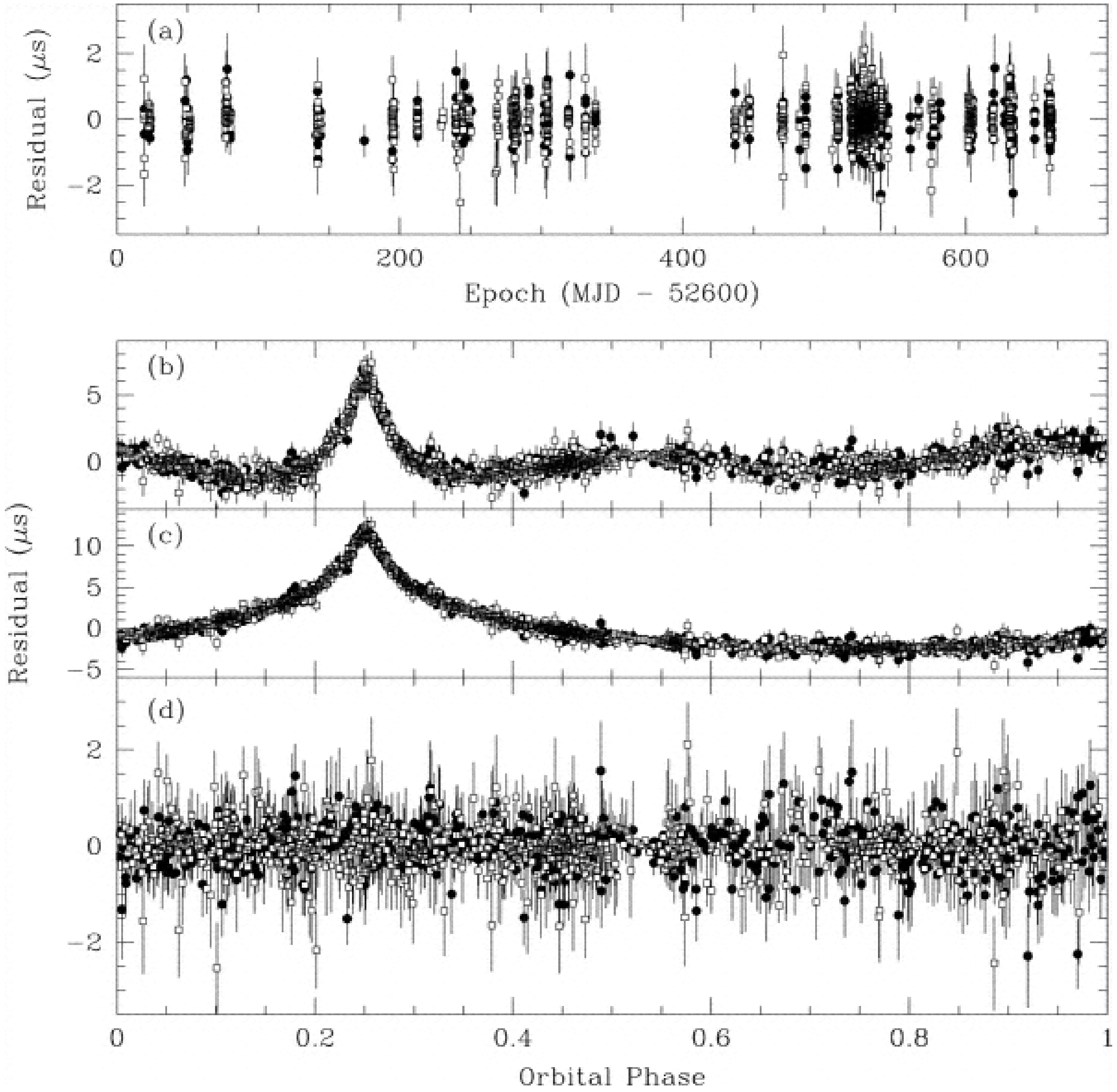
- Earlly detection of Shapiro delay in binary pulsars: PSR B1855+09 (Ryba, Taylor, 1991, ApJ, 371, 739)

- 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

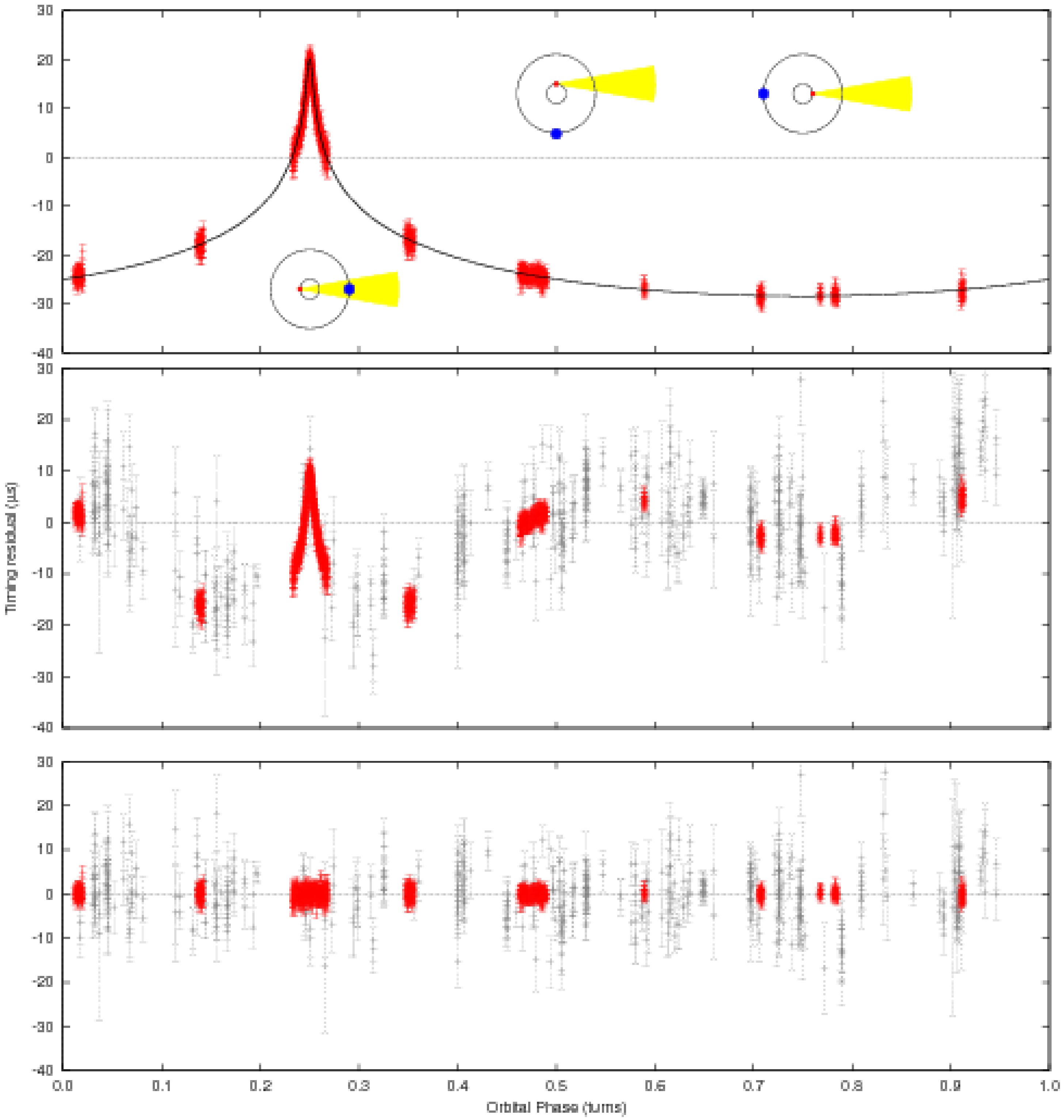


- PSR J1909−3744 is a MSP with a spin period of 2.947 ms - and one of the most precise timers known.
- P_b = 1.533 d, e = 0.000000135(15)
- i = 86.58(11) degrees!
- Precise masses derived from Shapiro delay only:
  M_p = 1.438(24) $M_\odot$
  M_c = 0.2038(23) $M_\odot$
  (Jacoby et al. 2005, ApJL, 629,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

- Update: Pulsar mass is 1.55(3) $M_\odot$ according to Fonseca et al. 2016, 1.54(3) $M_\odot$ according to Desvignes et al. (2015).

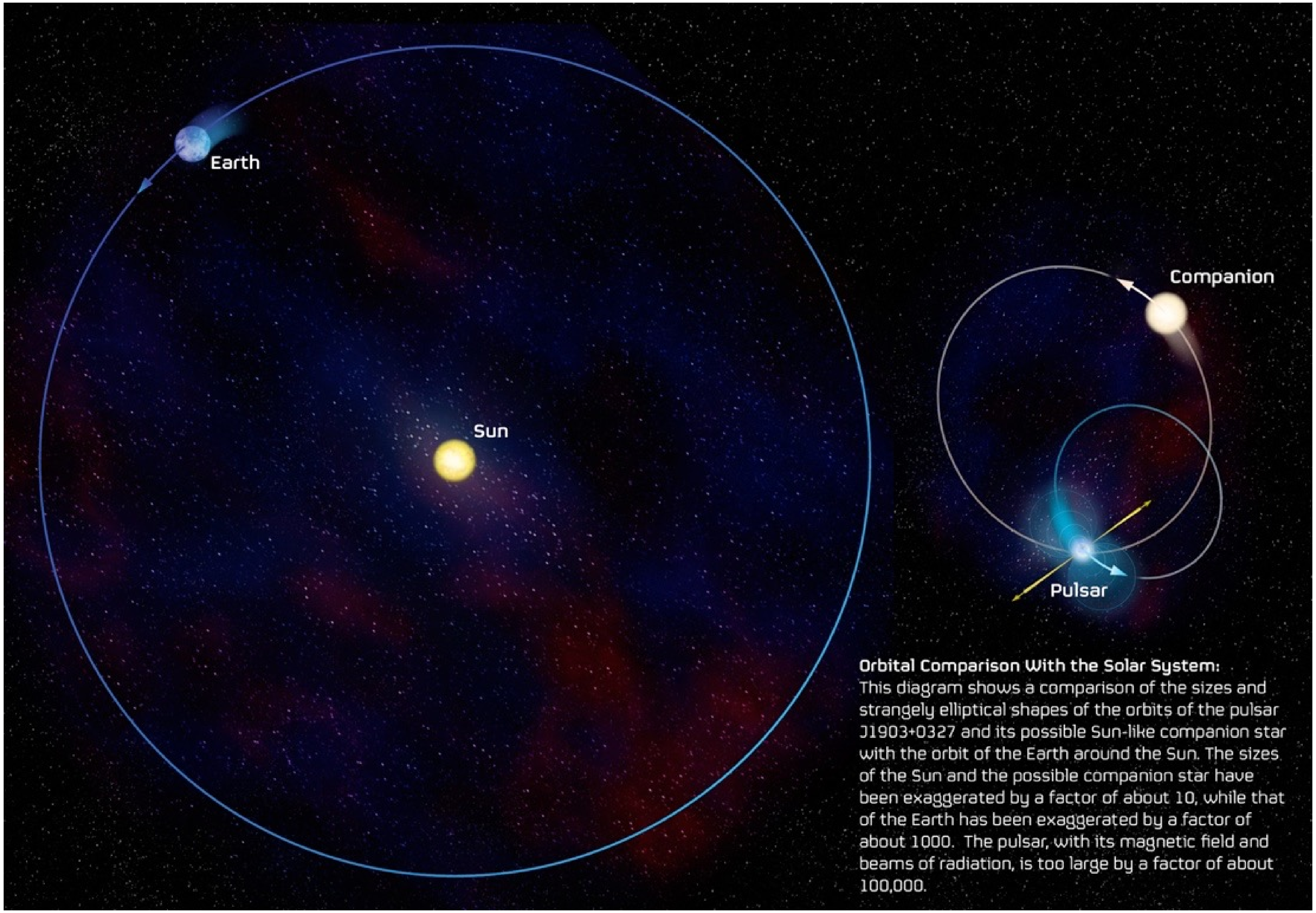
- *Shapiro delay is especially prone to systematic effects. Lots of TOAs needed…*

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., 2016, arXiv:1603.00545)

Solution 3: Triples, disrupted triples and other monsters

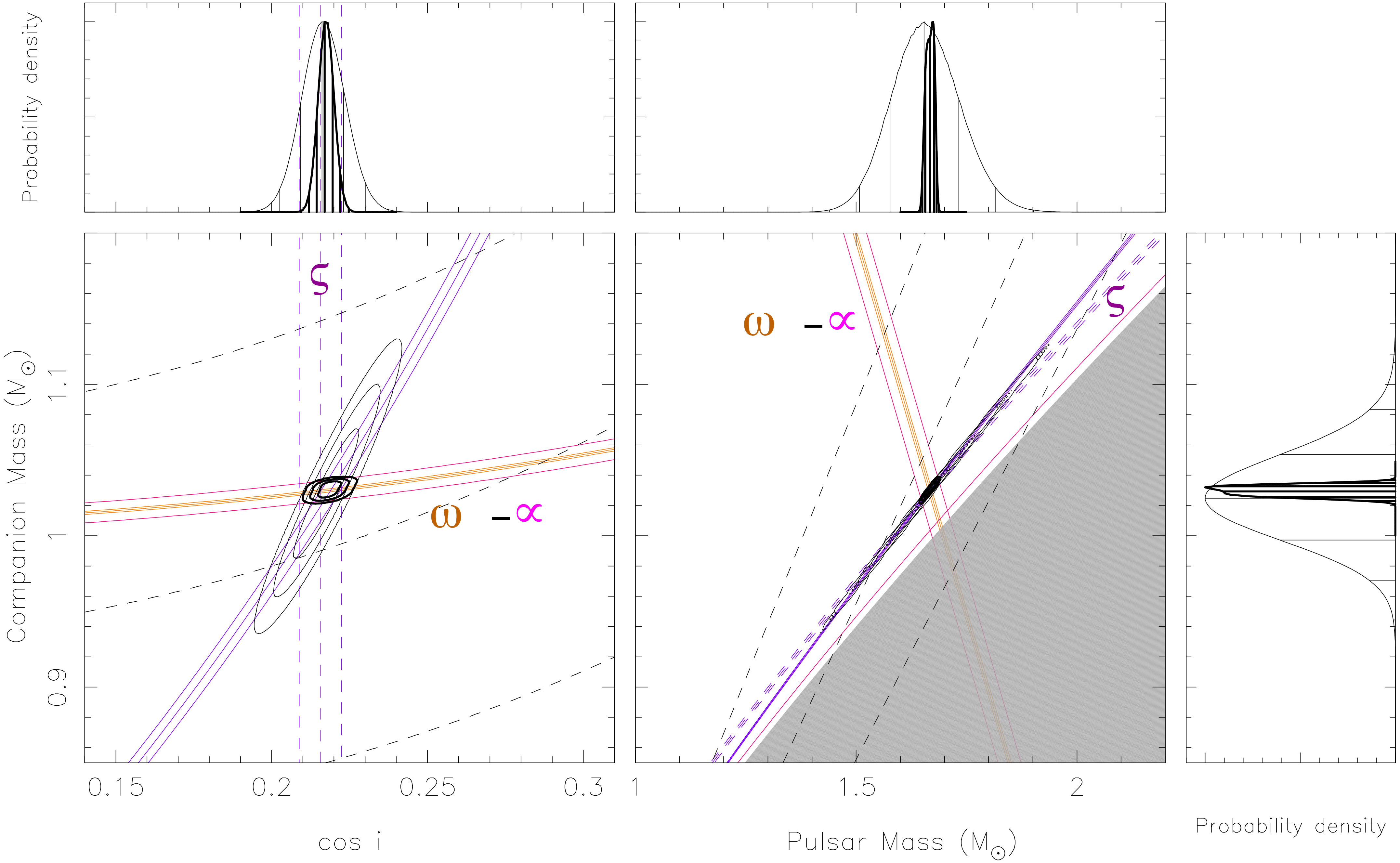


Orbital Comparison With the Solar System:
This diagram shows a comparison of the sizes and strangely elliptical shapes of the orbits of the pulsar J1903+0327 and its possible Sun-like companion star with the orbit of the Earth around the Sun. The sizes of the Sun and the possible companion star have been exaggerated by a factor of about 10, while that of the Earth has been exaggerated by a factor of about 1000. The pulsar, with its magnetic field and beams of radiation, is too large by a factor of about 100,000.

From: NRAO / Cornell University Press Release

Mass for PSR J1903+0327

Precise MSP mass: 1.667 ± 0.021 M⊙ (99.7% C. L.). See Freire et al., 2011, MNRAS,412, 2763, confirmed by Fonseca et al. (2016). System formed by disruption of a triple system.

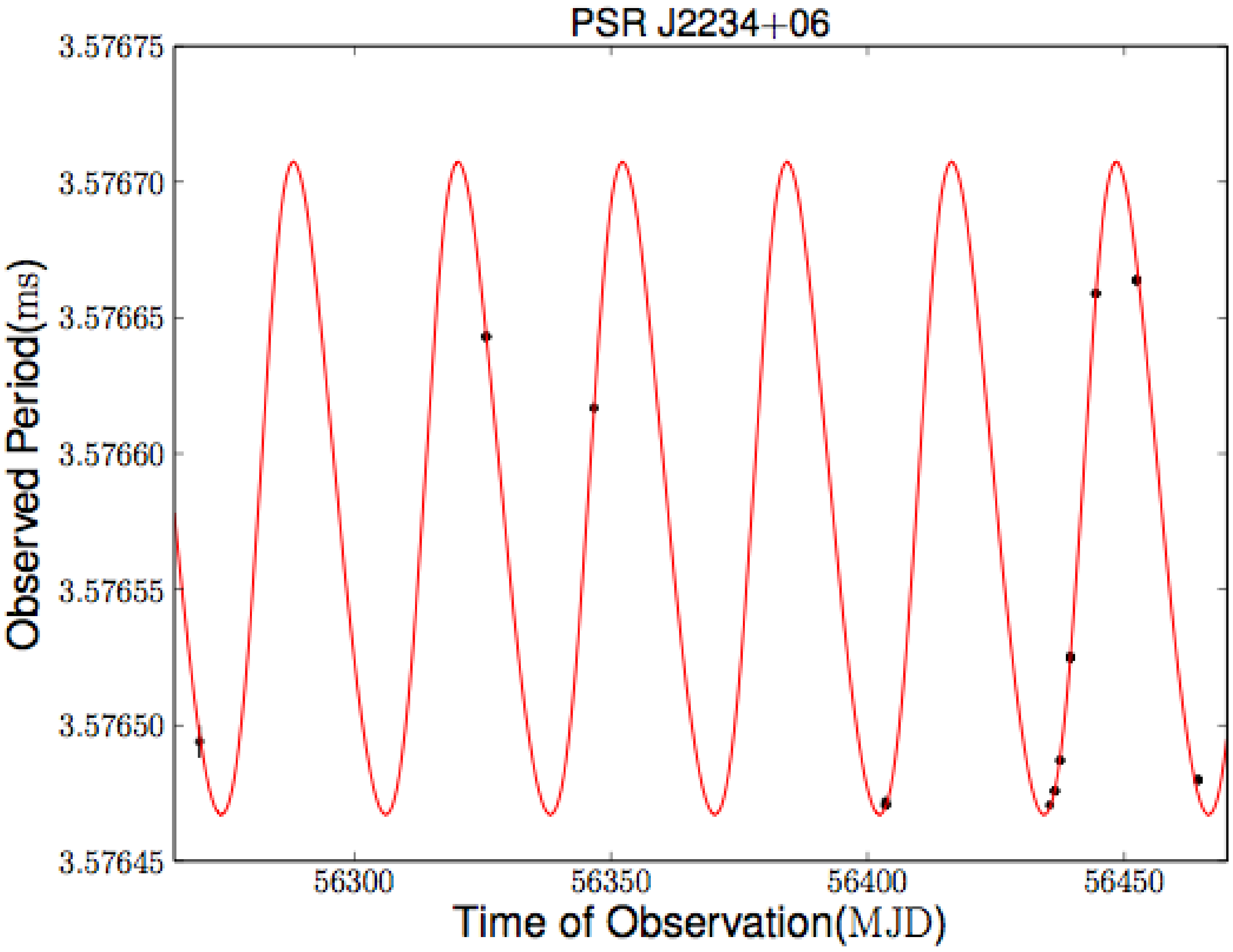


The triple system

- 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

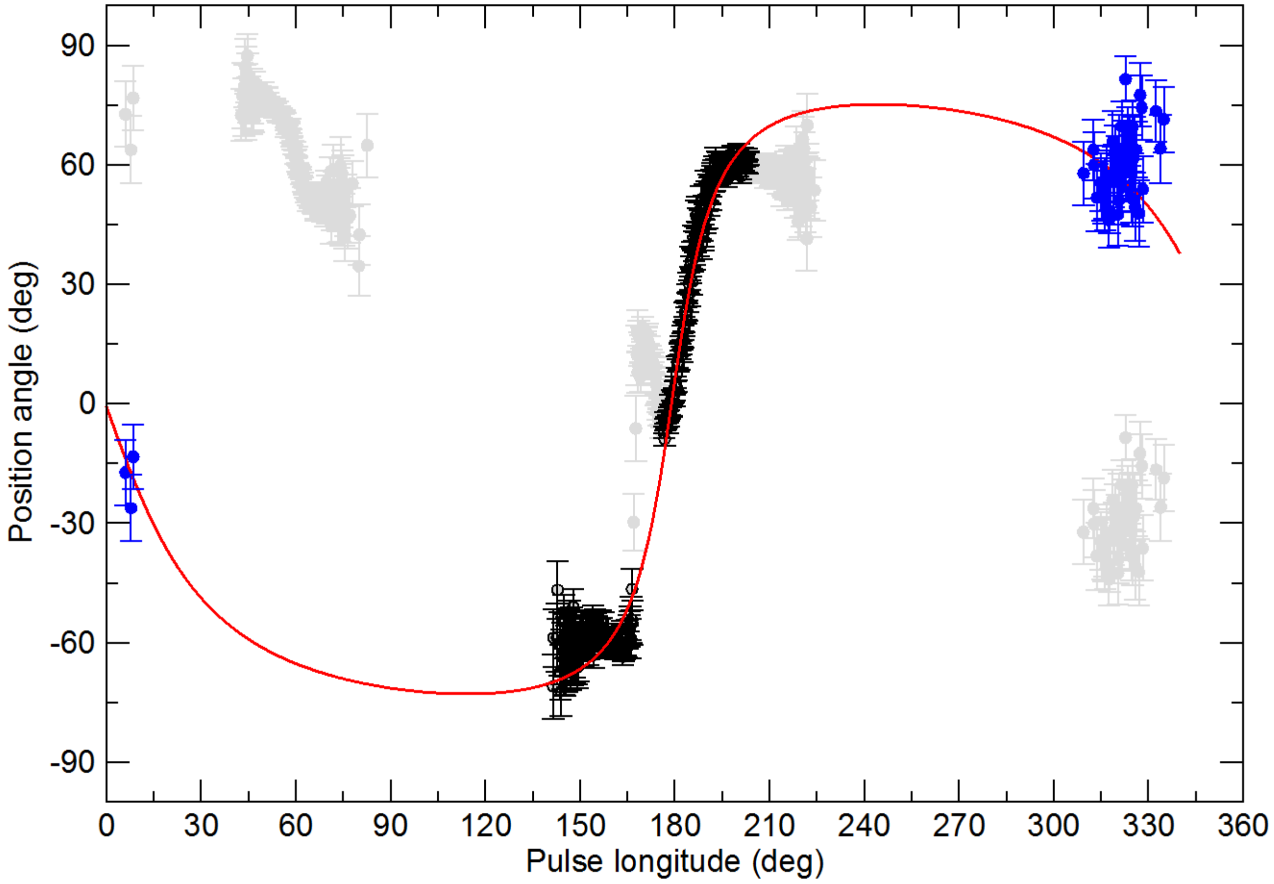
- There is a new class of binary MSPs with P = 2 - 5 ms, e ~ 0.1 and P_b = 22-32 days (4 so far)!
- Formation is not understood (see discussion in Barr et al. 2016).
- One mass measurement submitted, two more being prepared.

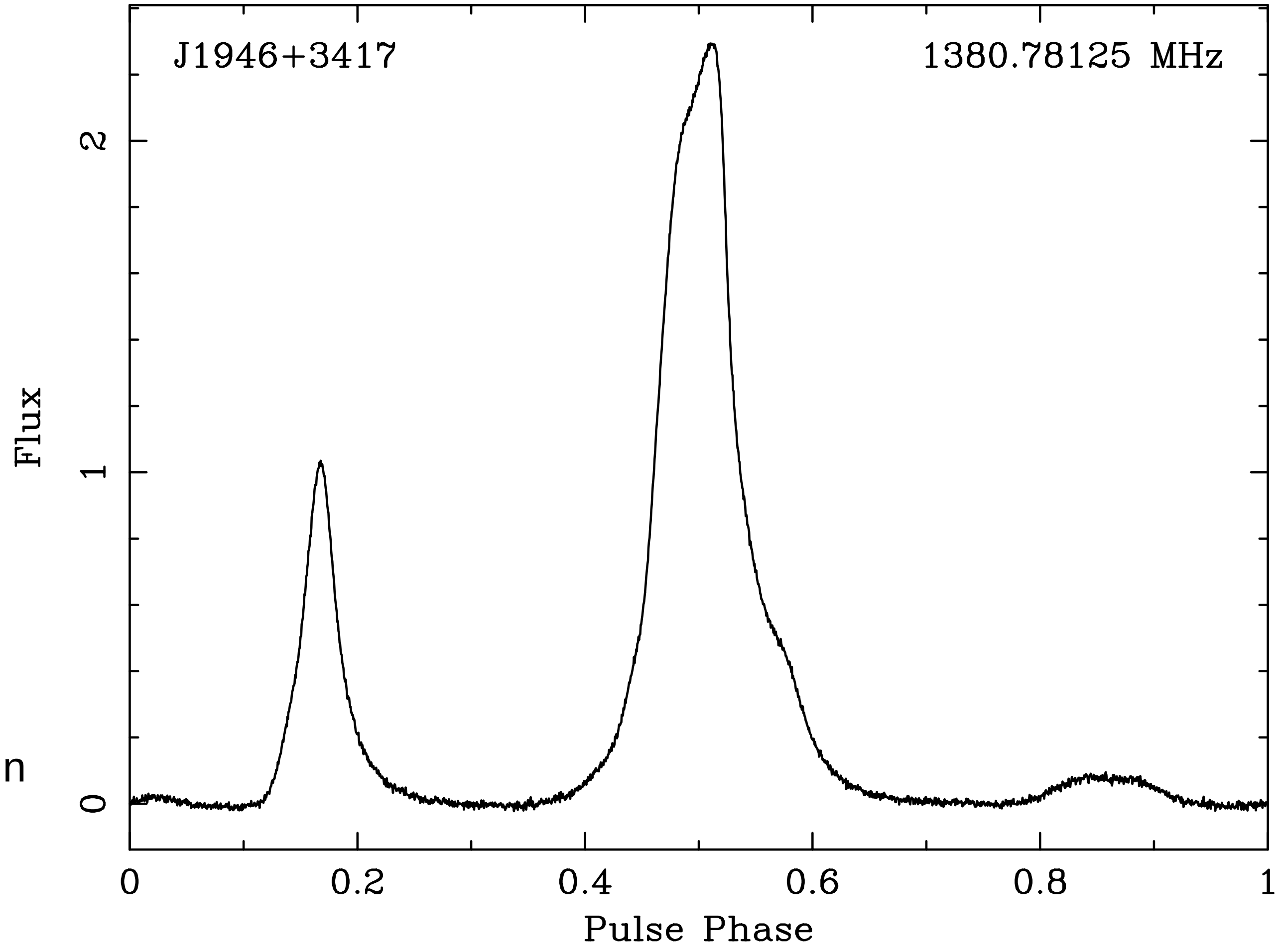


From Deneva et al. 2013, ApJ, 775, 51

J1946+3417

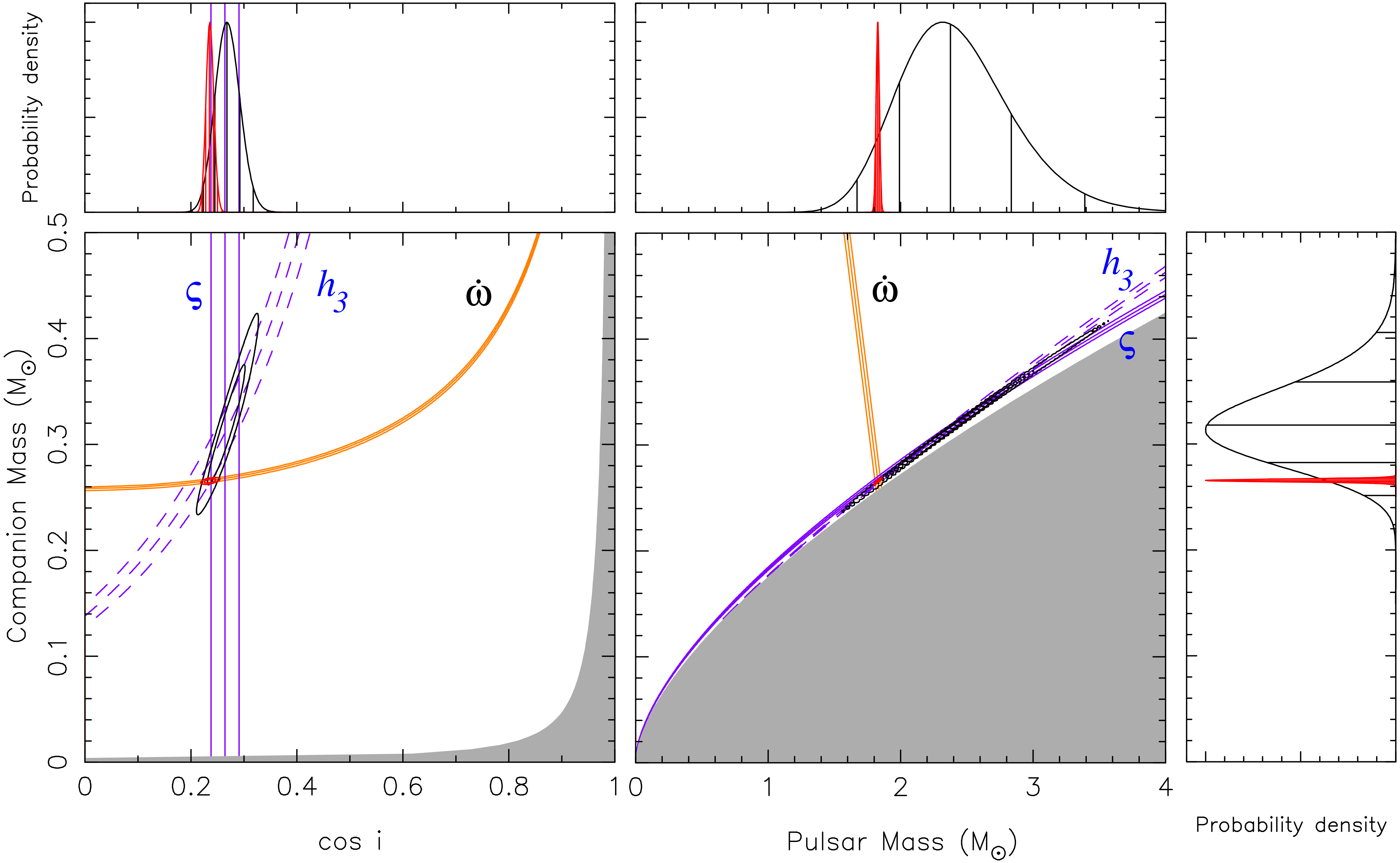
- PSR J1946+3417 is a MSP with a spin period of 3.17 ms discovered with the Effelsberg telescope (Barr et al. 2013, MNRAS, 435, 2234).
- P_b = 27.02 d, e = 0.134





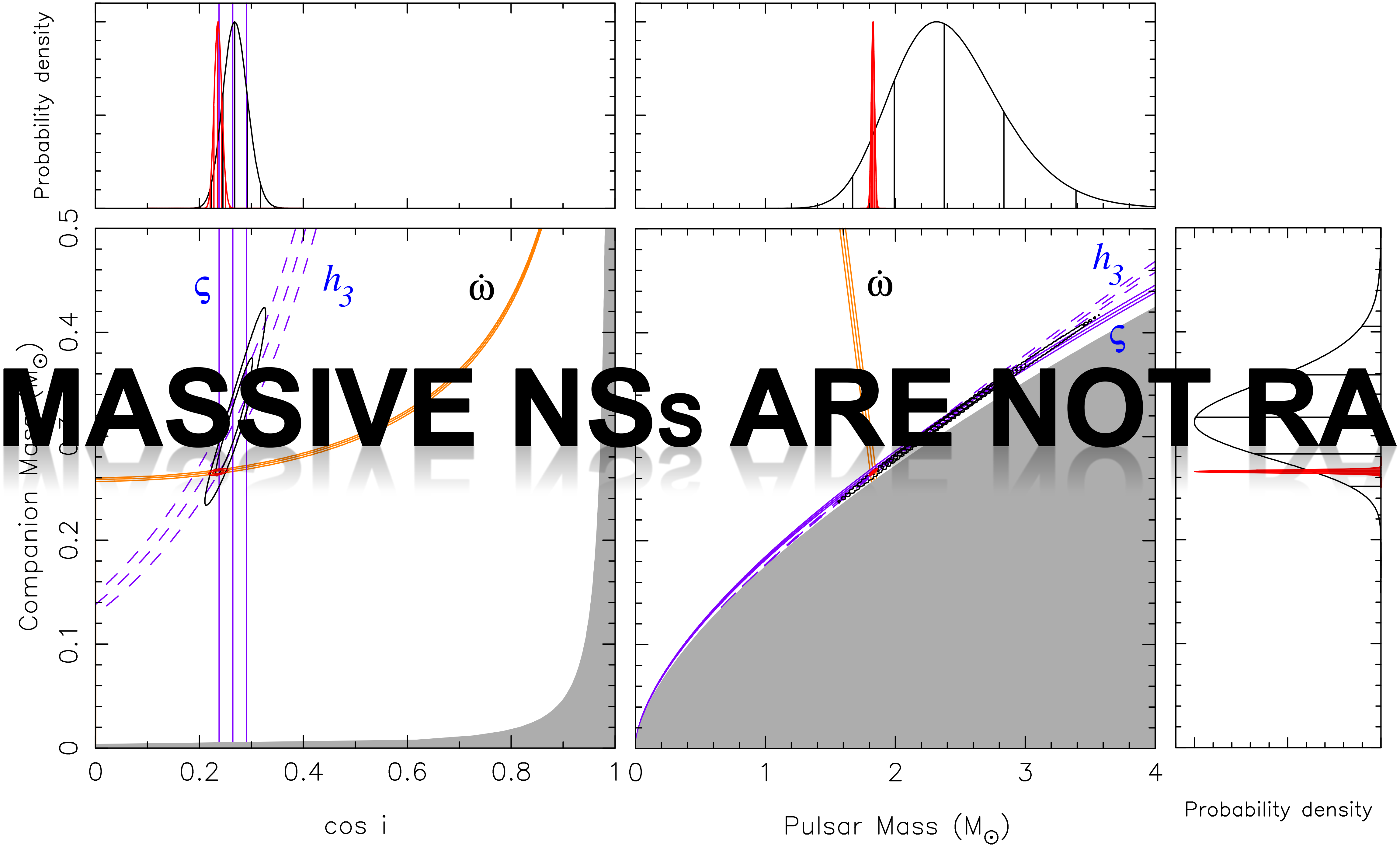
(Barr, Freire et al. 2016, MNRAS, in press, see arXiv:1611.03658)

J1946+3417



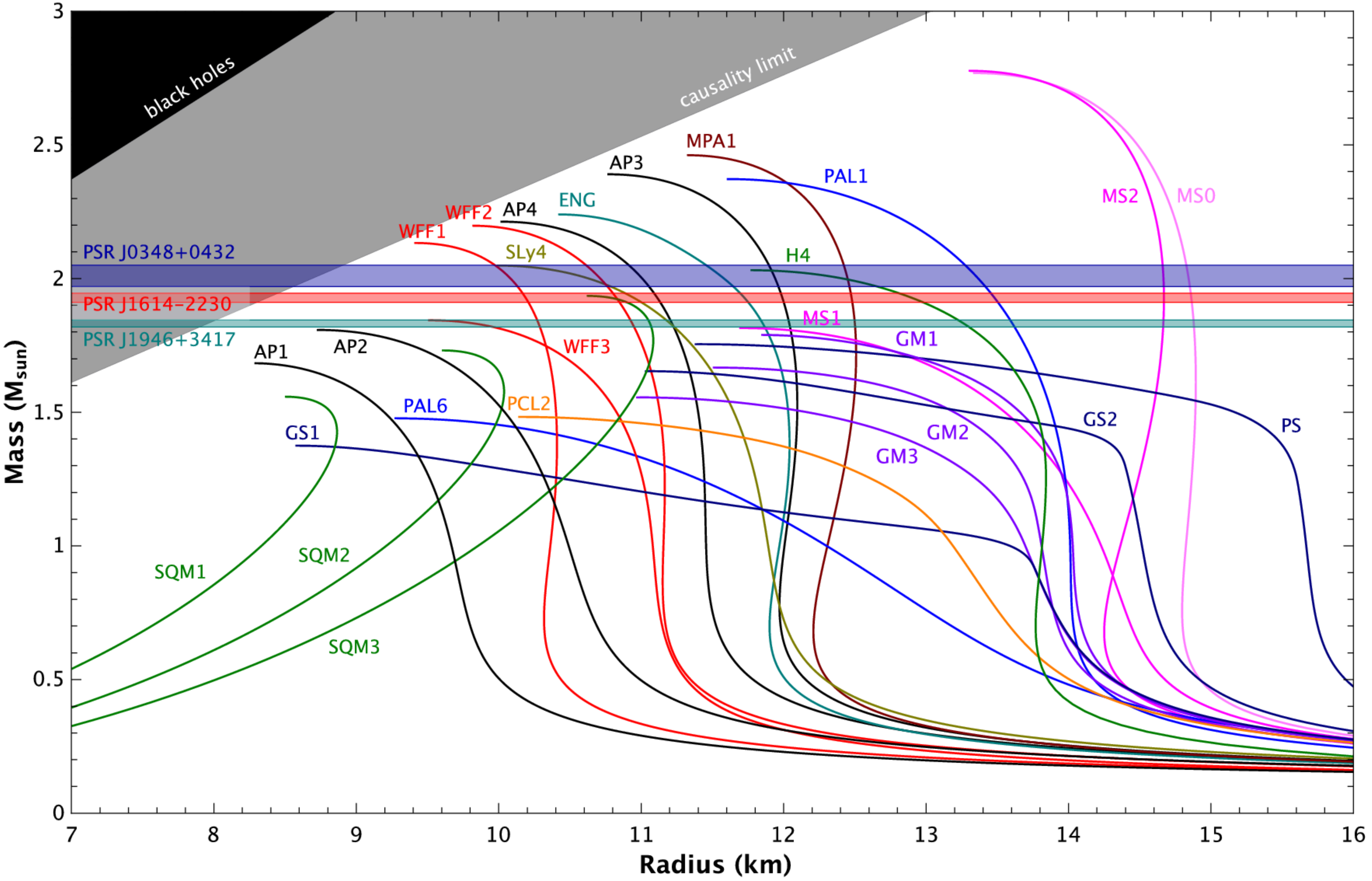
Precise masses derived from Shapiro delay and precession of periastron: $M_p = 1.828(22)\ M_\odot$, $M_c = 0.2656(19)\ M_\odot$ (Barr, Freire et al. 2016,MNRAS, in press, arXiv:1611.03658)

J1946+3417



MASSIVE NSs ARE NOT RARE.

Constraints on the equation of state



Mass measurements have direct implications for the EOS of dense matter!

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

The near future:
Tests of GW emission with asymmetric DNS

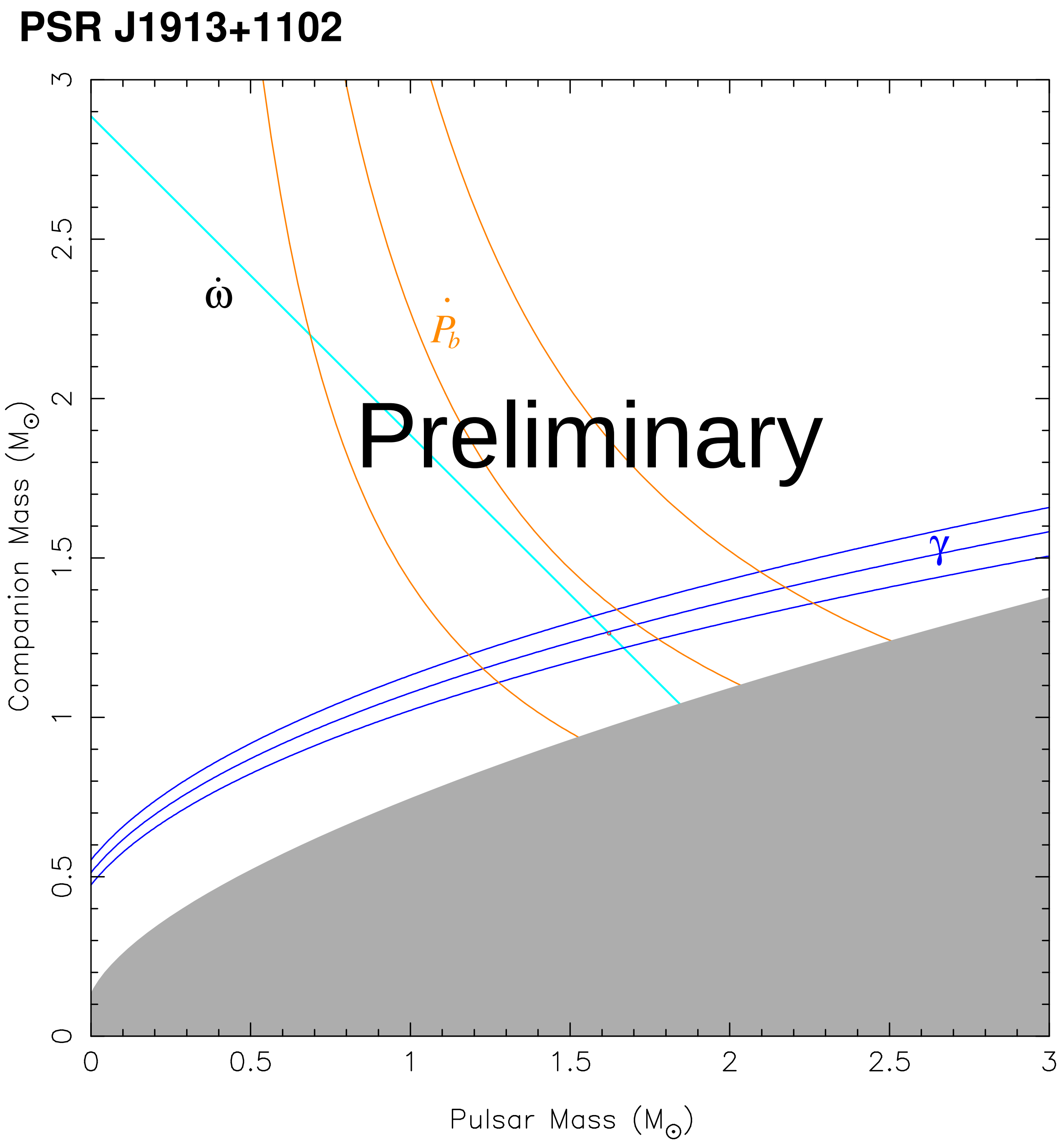
- Until recently, DNS systems are not the best for looking for dipolar GW emission – the component masses are too close to each other.

- In MSP-WD systems, we have reached the limit of what can be done – not possible to measure masses more accurately.

- An asymmetric DNS could in principle combine the best of both worlds.

PSR J1913+1102

- This could represent more than one order of magnitude improvement in sensitivity to DGW over the best current test with J1738+0333 – provided proper motion is about 6 mas/yr.
- Currently: 9 ± 3 mas / yr.



The near future:
NS mass measurements

- Within 2 years, the number of NS mass measurements will double, based only on systems we already know. One would expect that the mass distribution might grow even wider.

- Many NSs will have much more precise masses. Masses J0437-4715 and J0751+1807 will be very interesting in combination with NICER.

- In the future (with MeerKAT): 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.

Summary I - Gravity

- Double neutron stars have provided extremely precise tests of the properties of strong-field gravity. In particular, they allowed the first detection of gravitational radiation, and showed that binary systems lose energy through GW emission at the rate predicted by GR.

- Pulsar – white dwarf systems have introduced very stringent constraints on the existence of dipolar GW emission. This introduces very stringent constraints on the nature of gravitational waves:

    - GW emission does not change (to a measurable level) for asymmetric systems – *no dipolar component, quadrupolar to very high purity*

    - The purely quadrupolar nature of GW emission does not change with the compactness of NSs

- With newly discovered systems and GAIA, the future looks very promising!

Summary II – NS mass measurements

- NSs in DNSs are now showing a wider mass distribution, with some asymmetric systems.

- Measuring masses for MSPs is much more difficult. Diverse strategies employed, all with advantages and disadvantages: WD spectroscopy, Shapiro delay measurements, eccentric Galactic binaries. These show that

    - MSP mass distribution is much wider in MSPs, with upper masses of at least 2 $M_\odot$.

    - Massive NSs are not rare!

Thank you!

For questions and suggestions, contact me at: pfreire@mpifr-bonn.mpg.de, or see my site at http://www3.mpifr-bonn.mpg.de/staff/pfreire/

To stay up to date on the latest precise NS mass measurements and GR tests, check: http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Review on NS masses and radii: Ozel & Freire (2016), ARAA, 54, 401