Constraining the nature of gravitational waves and alternative theories of gravity using binary pulsars

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MULTIMESSENGERS, COMPACT OBJECTS AND FUNDAMENTAL PHYSICS
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In this talk…

1. Pulsars and pulsar timing

2. Binary pulsars, and gravitational wave emission

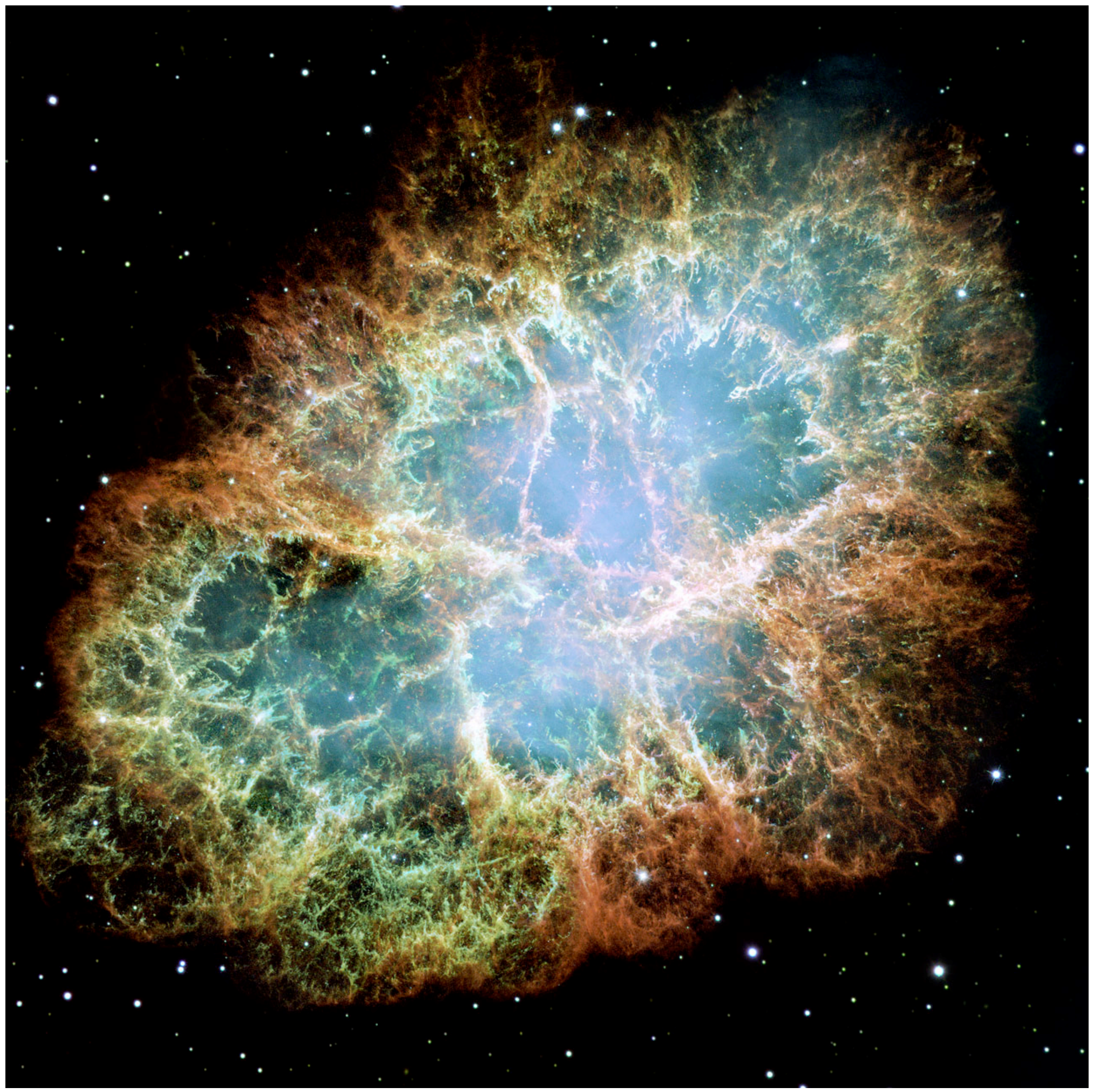
3. Tests of alternative theories of gravity, experiments on the nature of gravitational waves

4. Closing the ``scalarization gap”.

5. Conclusions

1. Pulsars and pulsar timing

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

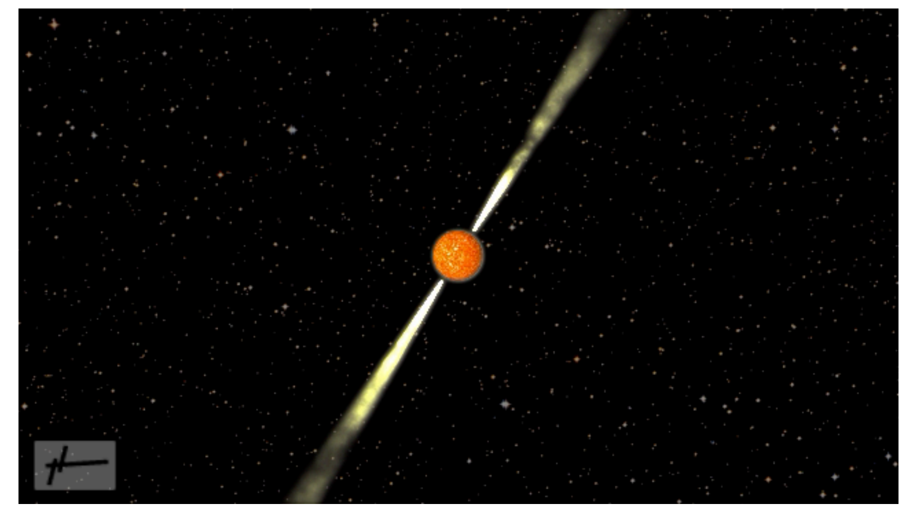
Non-trivial grav. Prop.

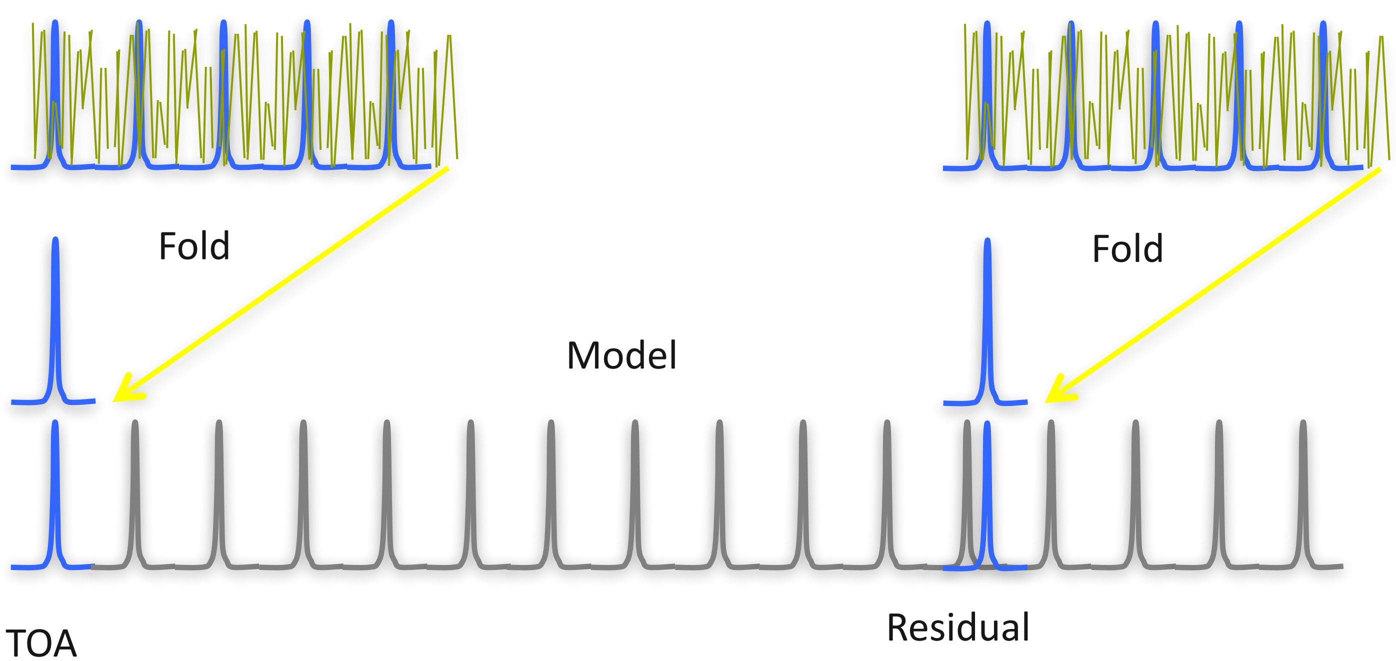
We can time the spin precisely!

Pulsar timing

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

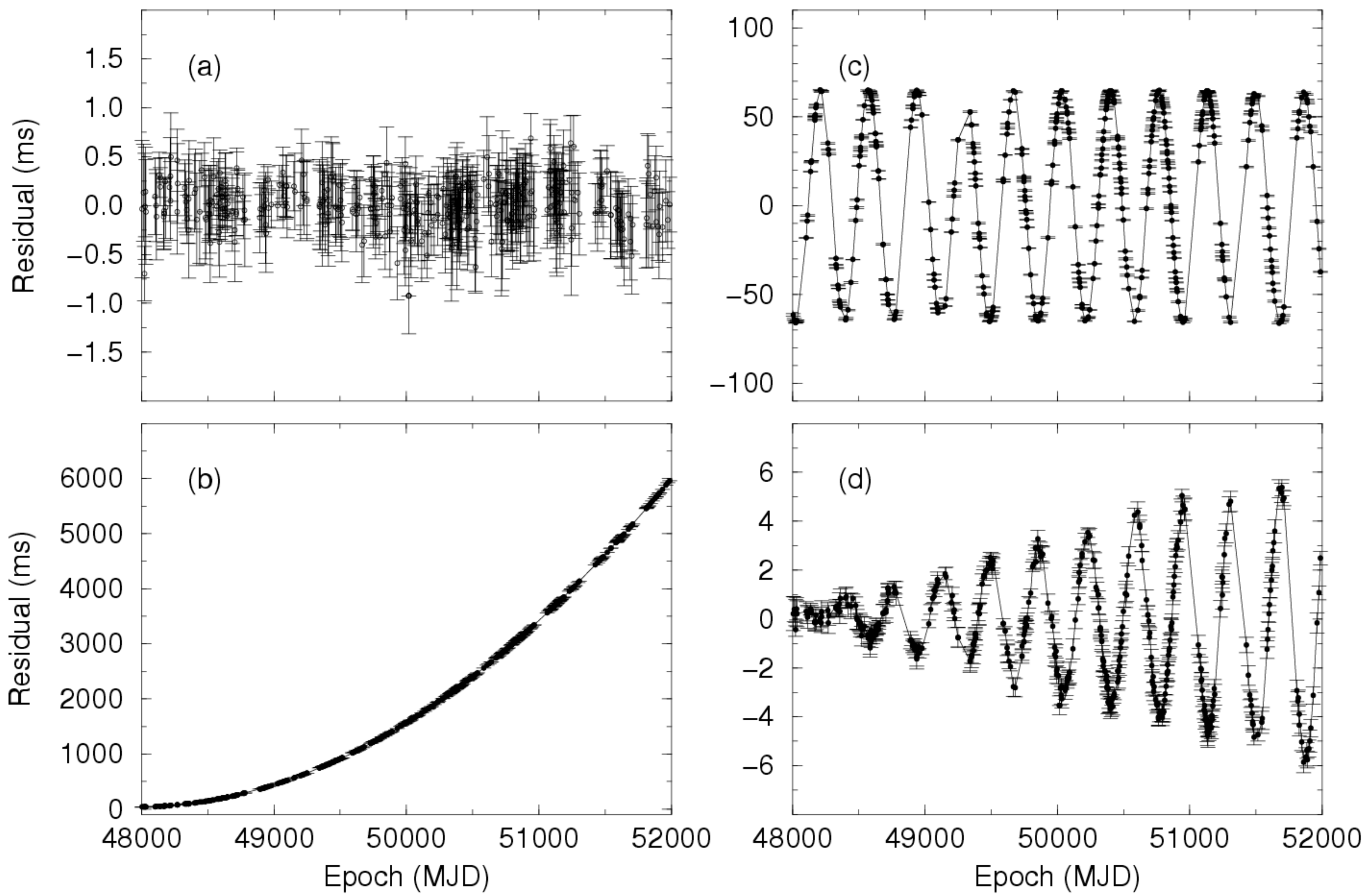
Pulsar timing measures pulsar arrival time at the telescope (TOA):





Pulsar timing

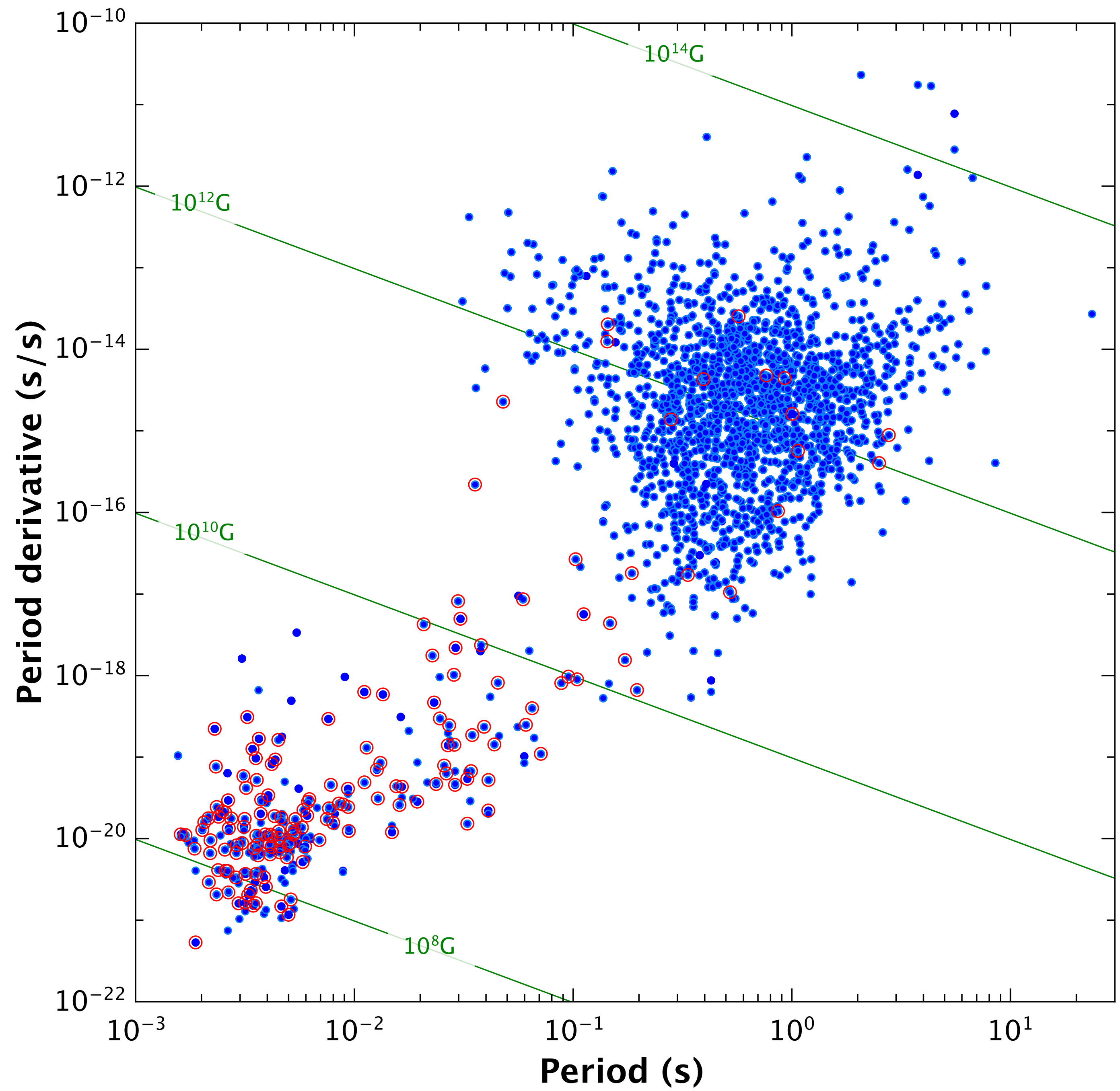
The trends in the residuals will tell us what parameter(s) needs correction: generally, all of them!



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

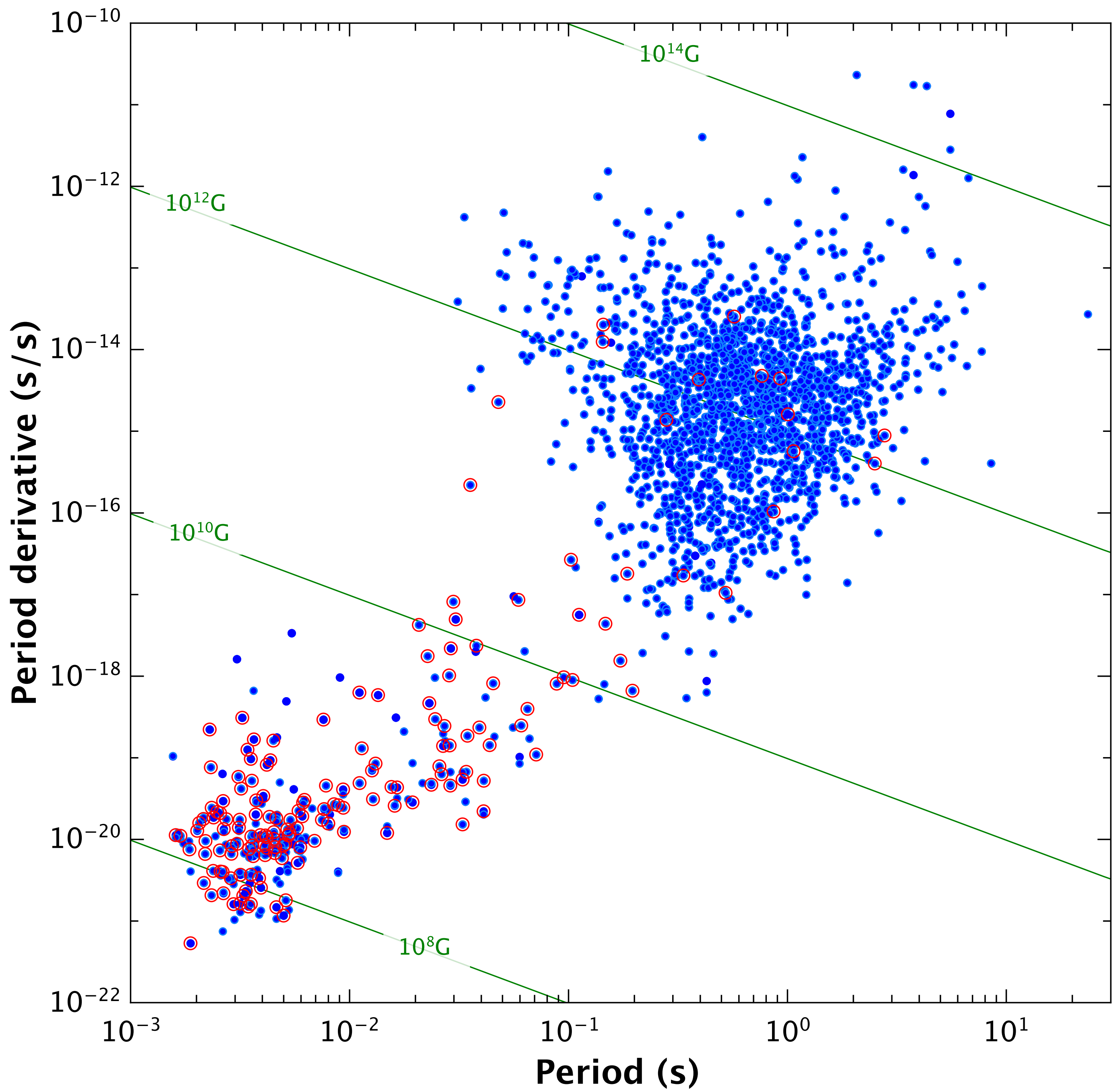
The P-Pdot diagram and binary pulsars

- > 3000 pulsars!
- Periods: 1.396 ms - 23.5 s
- 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*.

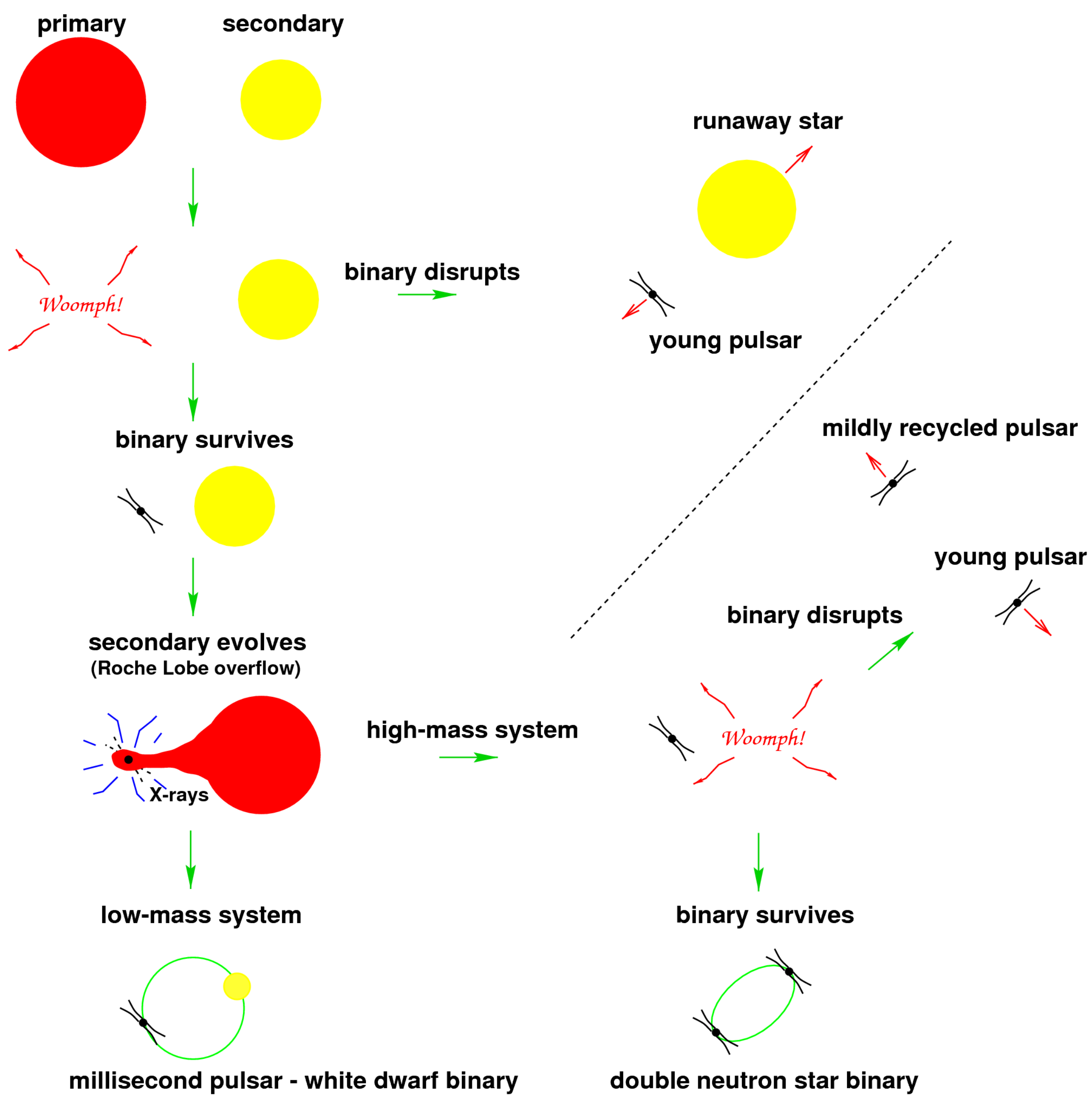


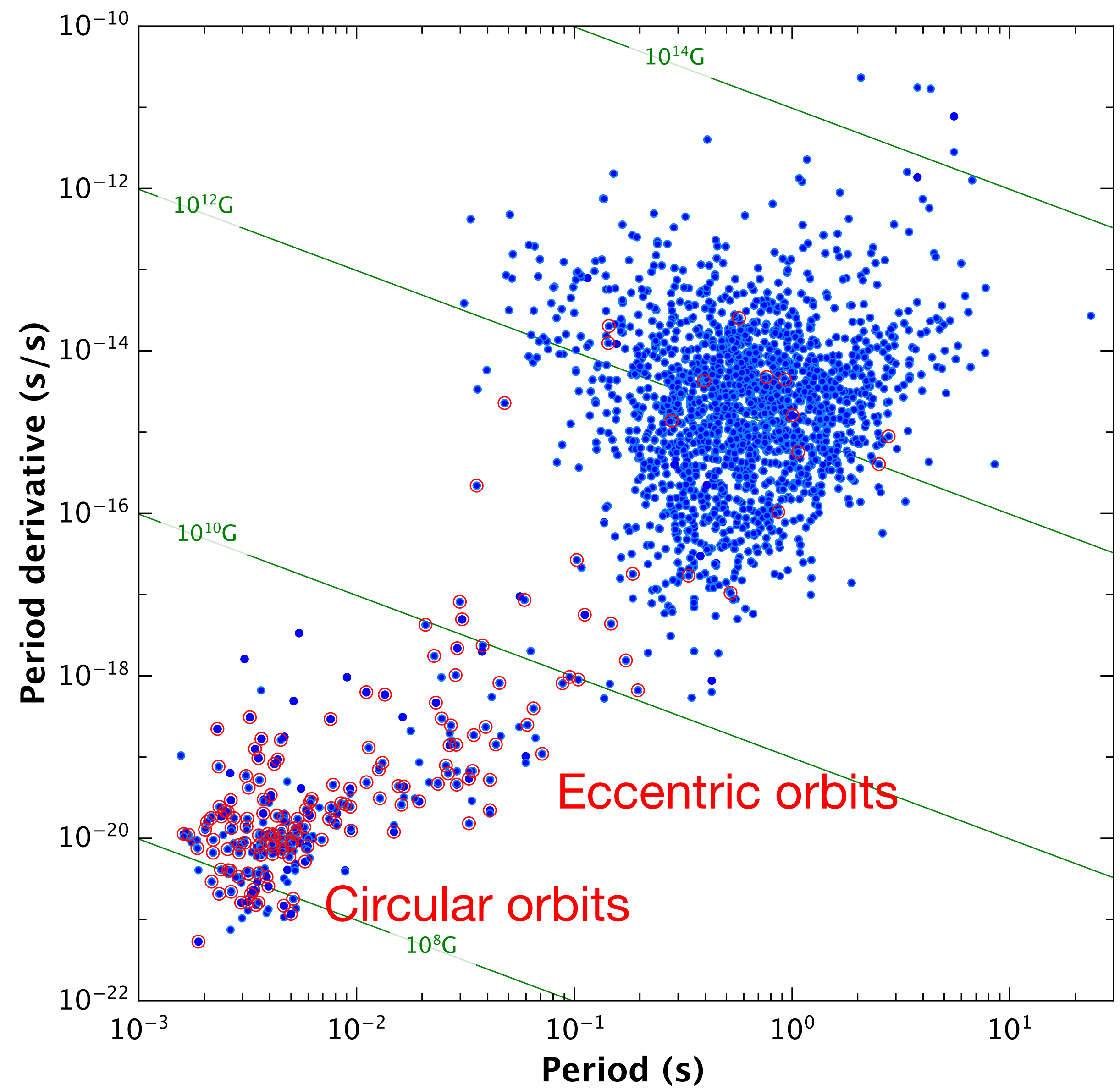
The P-Pdot diagram and binary pulsars

- 10% are in binary systems
- Orbital period range: 95 min to > 200 yr. The companions are:
  - ordinary stars
  - white dwarfs
  - neutron stars
  - black holes ?
- One pulsar (J0337+1715) in a stellar triple!



The P-Pdot diagram and binary pulsars





Timing pulsars in binary systems

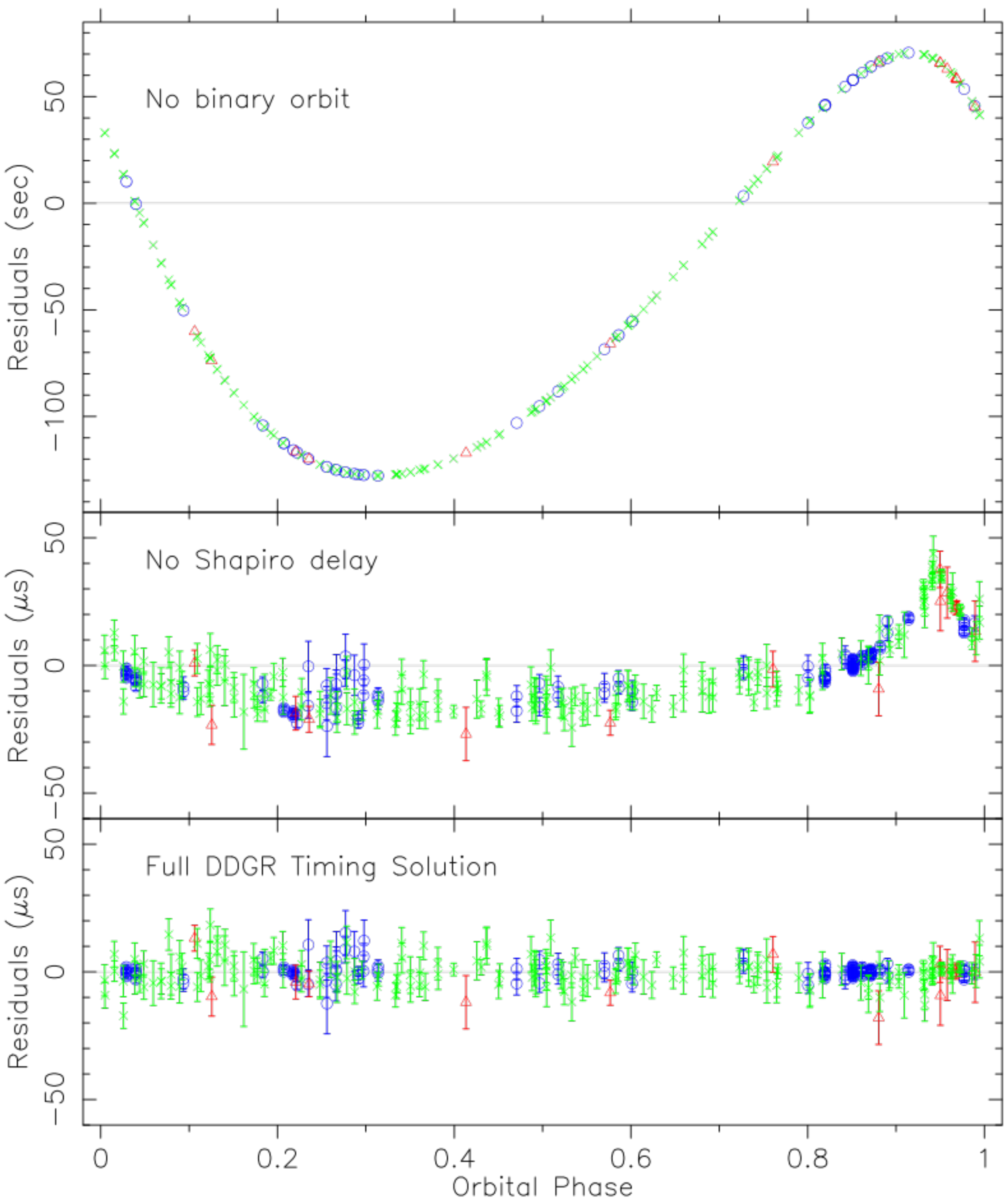


Figure: Scott Ransom

- 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!

An example relevant for this talk: PSR J1738+0333

- Number of rotations between 52872.01692 and 55813.95899 (SSB): **43 449 485 656 ± 0**.
- Spin period at reference epoch: **0.005 850 095 859 775 683 ± 0.000 000 000 000 000 005 s**
- Orbital period: **8^h 30^m 53.919 926 4 ± 0.000 000 3** s
- Semi-major axis of the pulsar’s orbit, projected along the line of sight: **102 957 453 ± 6 m**.
- Eccentricity: **(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**.

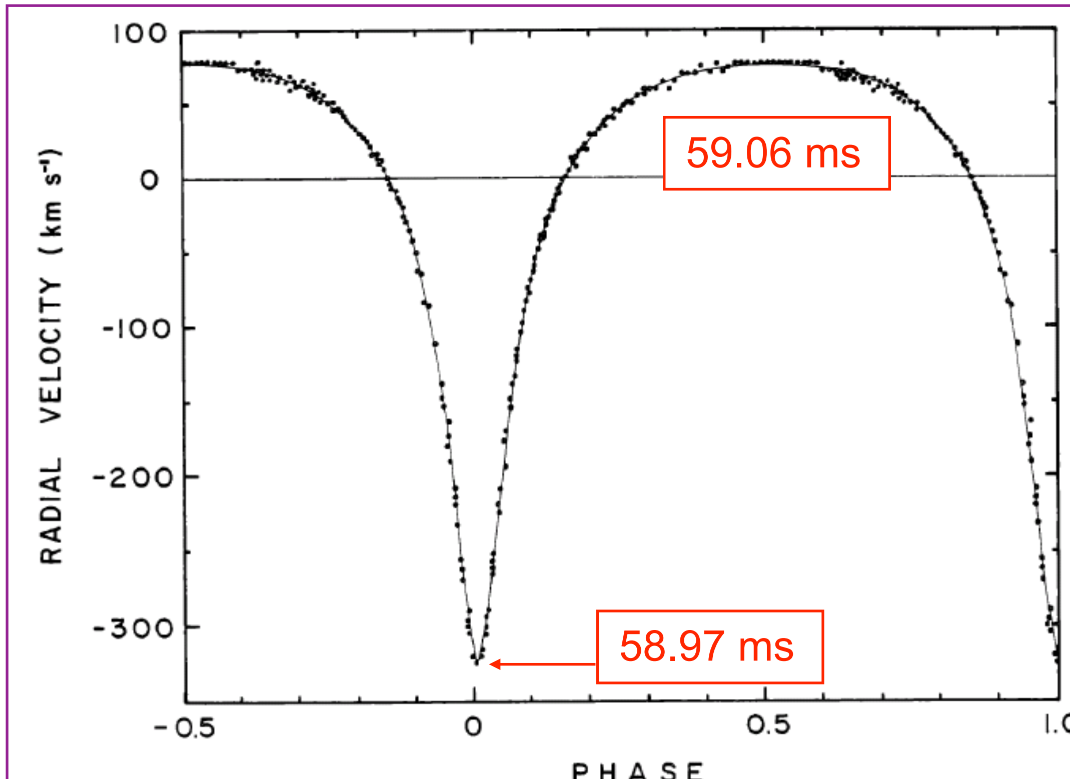
See Freire et al. 2012, MNRAS, 423, 3328.

2. Binary pulsars and GW emission

The first binary pulsar - 1974

*“Here was a system that featured, in addition to significant post-Newtonian gravitational effects, **highly relativistic gravitational fields** associated with the pulsar (and possibly its companion) and the possibility of the **emission of gravitational radiation** by the binary system.” (Clifford Will, TEGP 2018)*

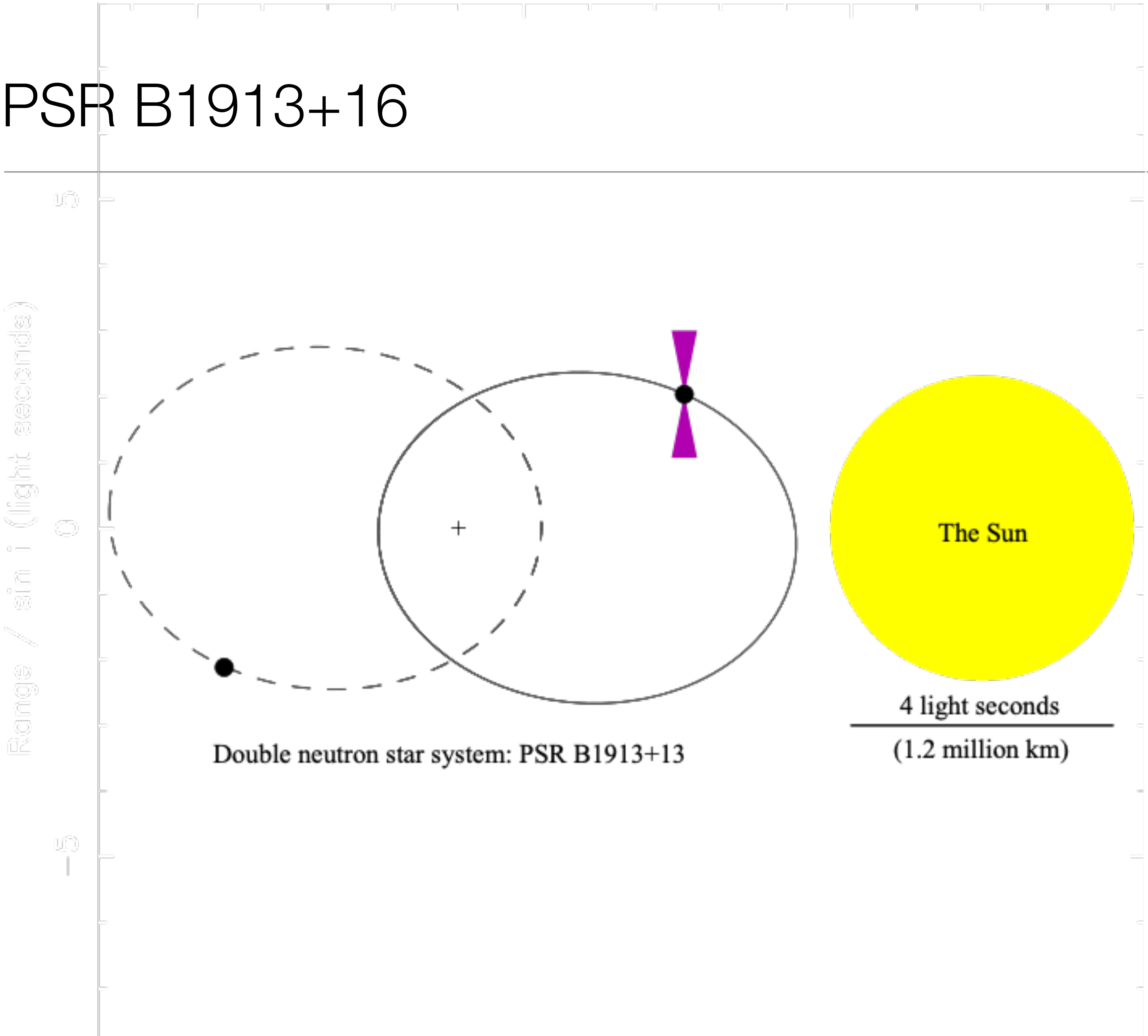
PSR B1913+16



Pulse period P:	59.0 ms
Orbital period P_b:	7.75 h
Eccentricity e:	0.617
Pulsar mass m_p:	1.44 $M_\odot$
Companion mass m_c:	1.39 $M_\odot$ (neutron star)

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

PSR B1913+16



5
0
−5
Range / sin i (light seconds)
The Sun
4 light seconds
(1.2 million km)
Double neutron star system: PSR B1913+13

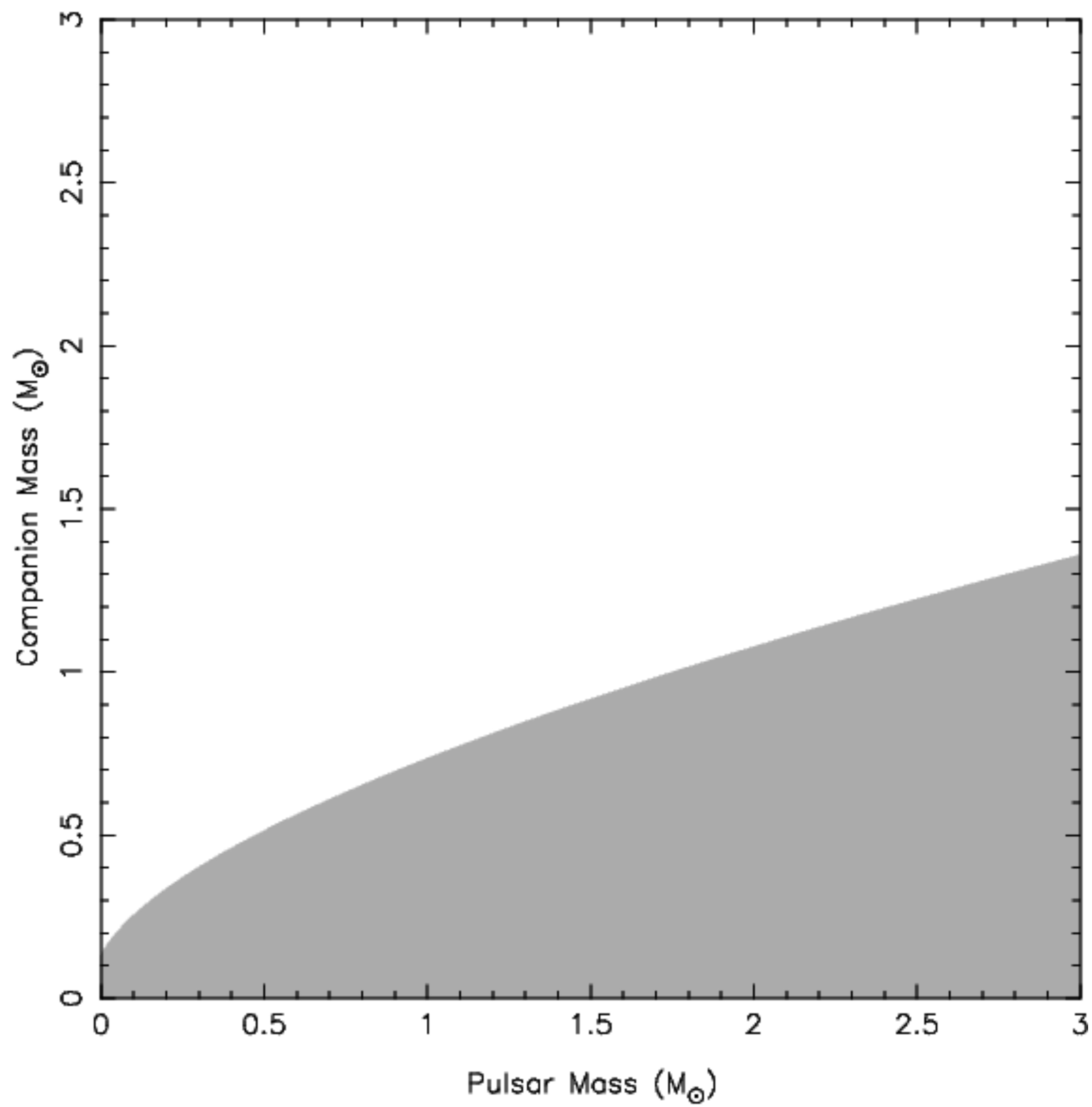
PSR B1913+16

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

$$f(M_p, M_c, i) \equiv \frac{(M_c \sin i)^3}{(M_p + M_c)^3} = \frac{4\pi^2}{T_\odot} \frac{x^3}{P_b^2}$$

$$T_\odot \equiv \frac{GM_\odot}{c^3} = 4.925490947641267 5 \ldots \mu\text{s}$$

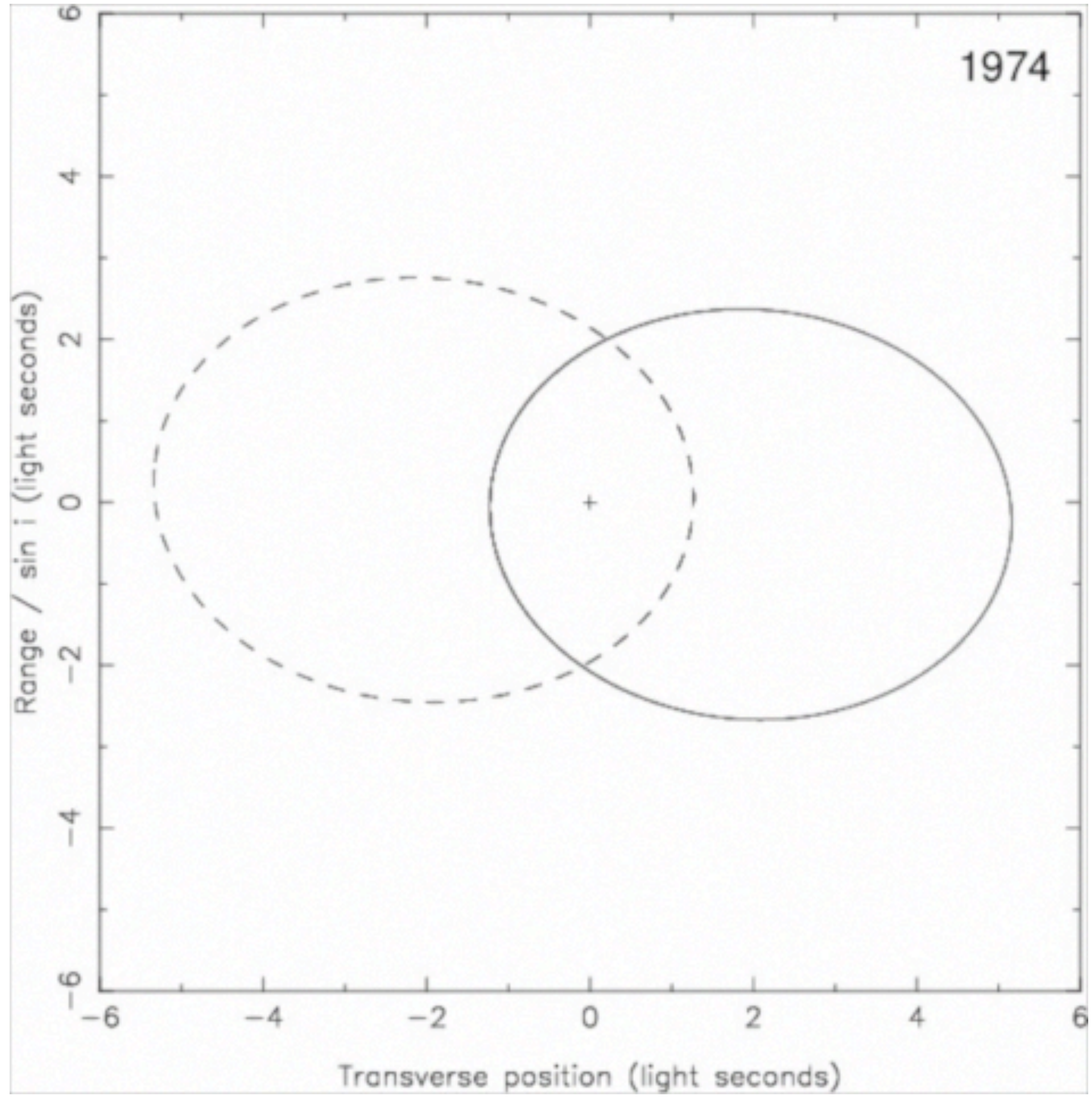
One equation, three (known) unknowns! ☹️



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



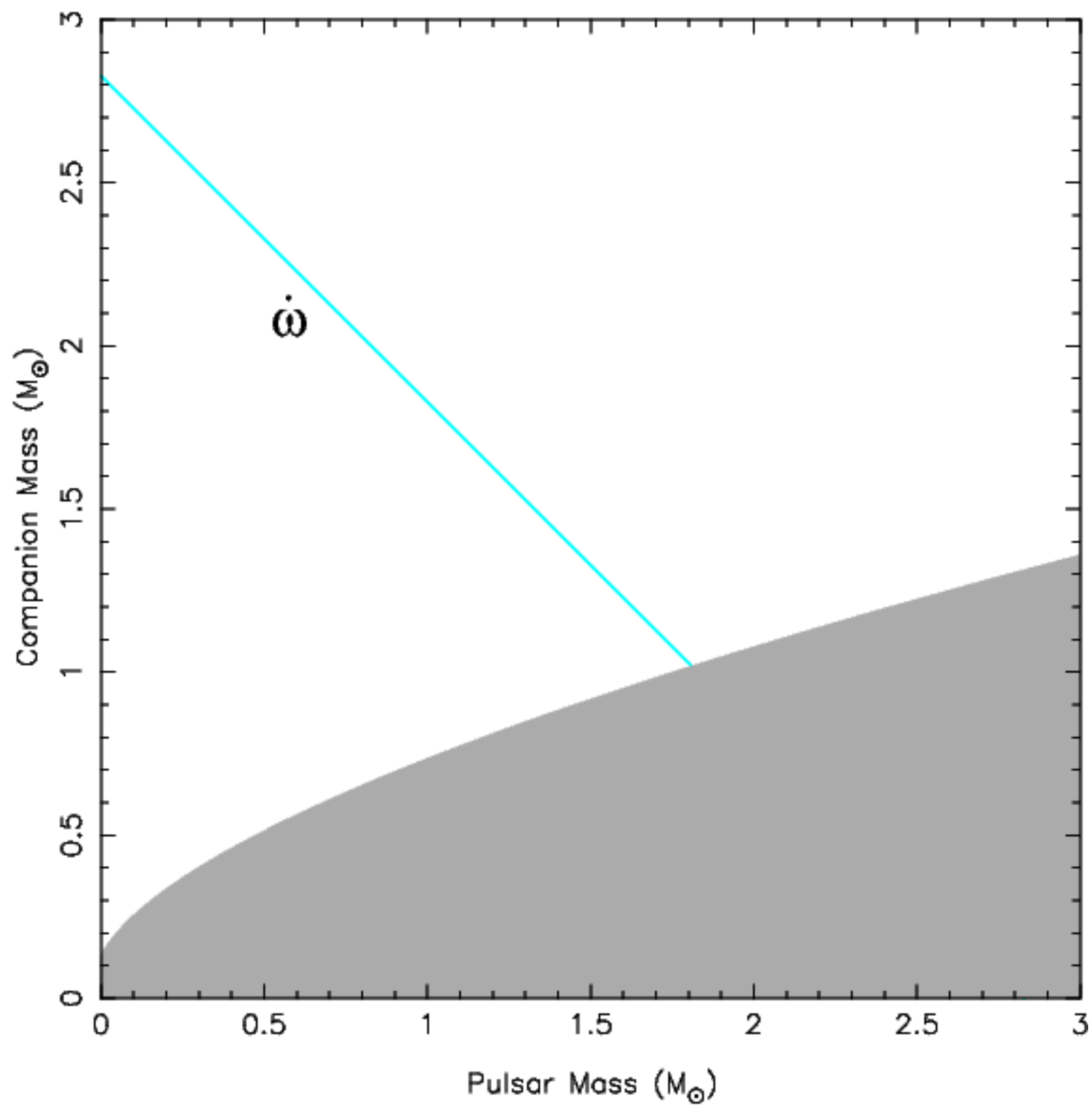
PSR B1913+16

Assuming GR, to 1 PN:

$$M = M_\mathrm{p} + M_\mathrm{c}$$

$$n_\mathrm{b} = \frac{2\pi}{P_\mathrm{b}}$$

$$\dot{\omega} = \frac{3n_\mathrm{b}^{5/3}}{1-e^2}(MT_\odot)^{2/3}$$



PSR B1913+16

Assuming GR, to 1 PN:

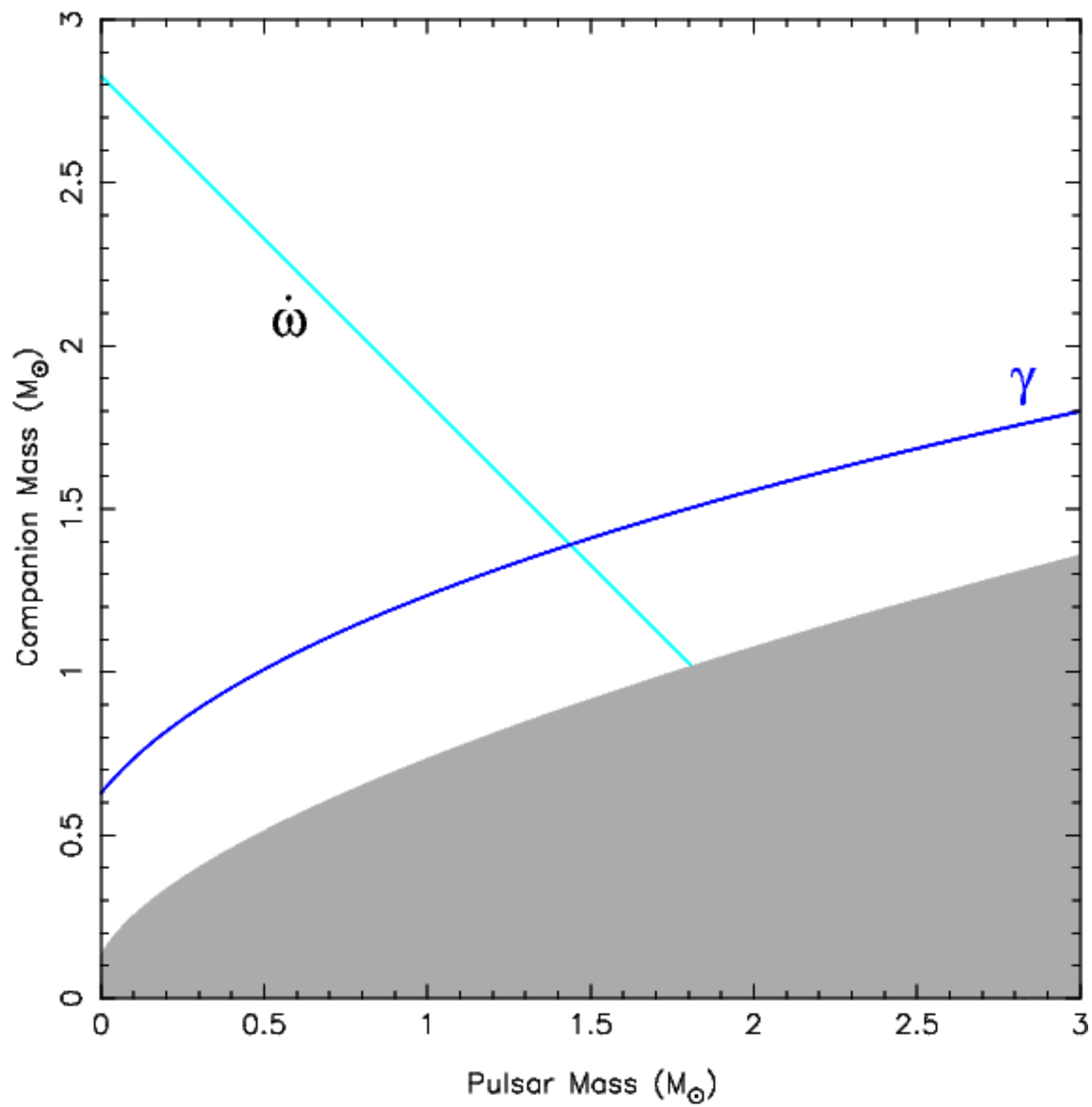
$$M = M_\mathrm{p} + M_\mathrm{c}$$

$$n_\mathrm{b} = \frac{2\pi}{P_\mathrm{b}}$$

$$\dot{\omega} = \frac{3 n_\mathrm{b}^{5/3}}{1-e^2}(M T_\odot)^{2/3}$$

$$\gamma = \frac{e T_\odot^{2/3}}{n_\mathrm{b}^{1/3}} \frac{M_\mathrm{c}(2M_\mathrm{c} + M_\mathrm{p})}{M^{4/3}}$$

- 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.



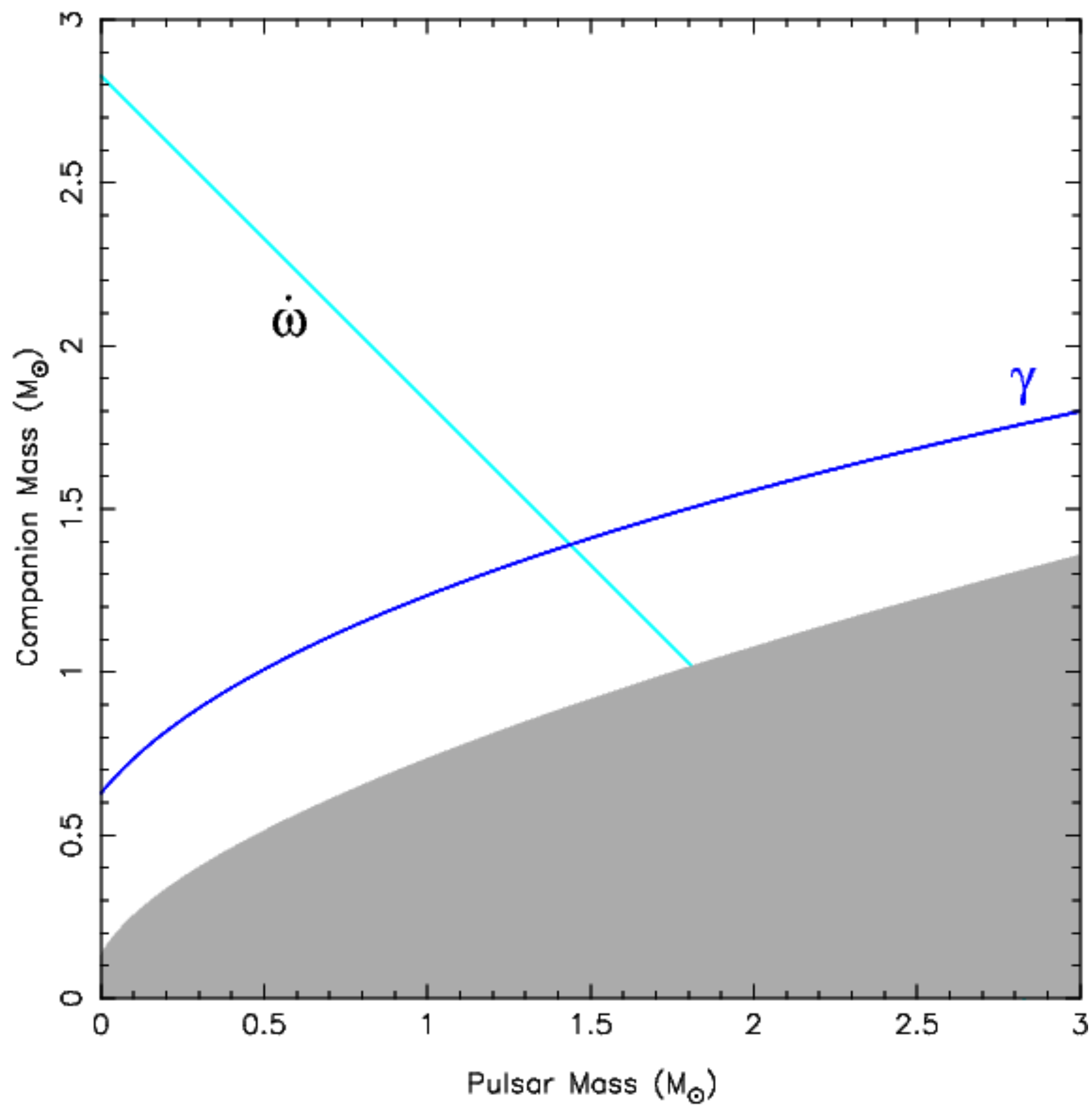
PSR B1913+16

- *A third relativistic effect soon became measurable – the orbital decay due to GW emission!*
- *Assuming* GR, LO PN [(v/c)^5]:

$$\dot{P}_\mathrm{b} = -\frac{192}{5}(n_\mathrm{b}T_\odot)^{5/3} f_e \frac{M_\mathrm{p}M_\mathrm{c}}{M^{1/3}}$$

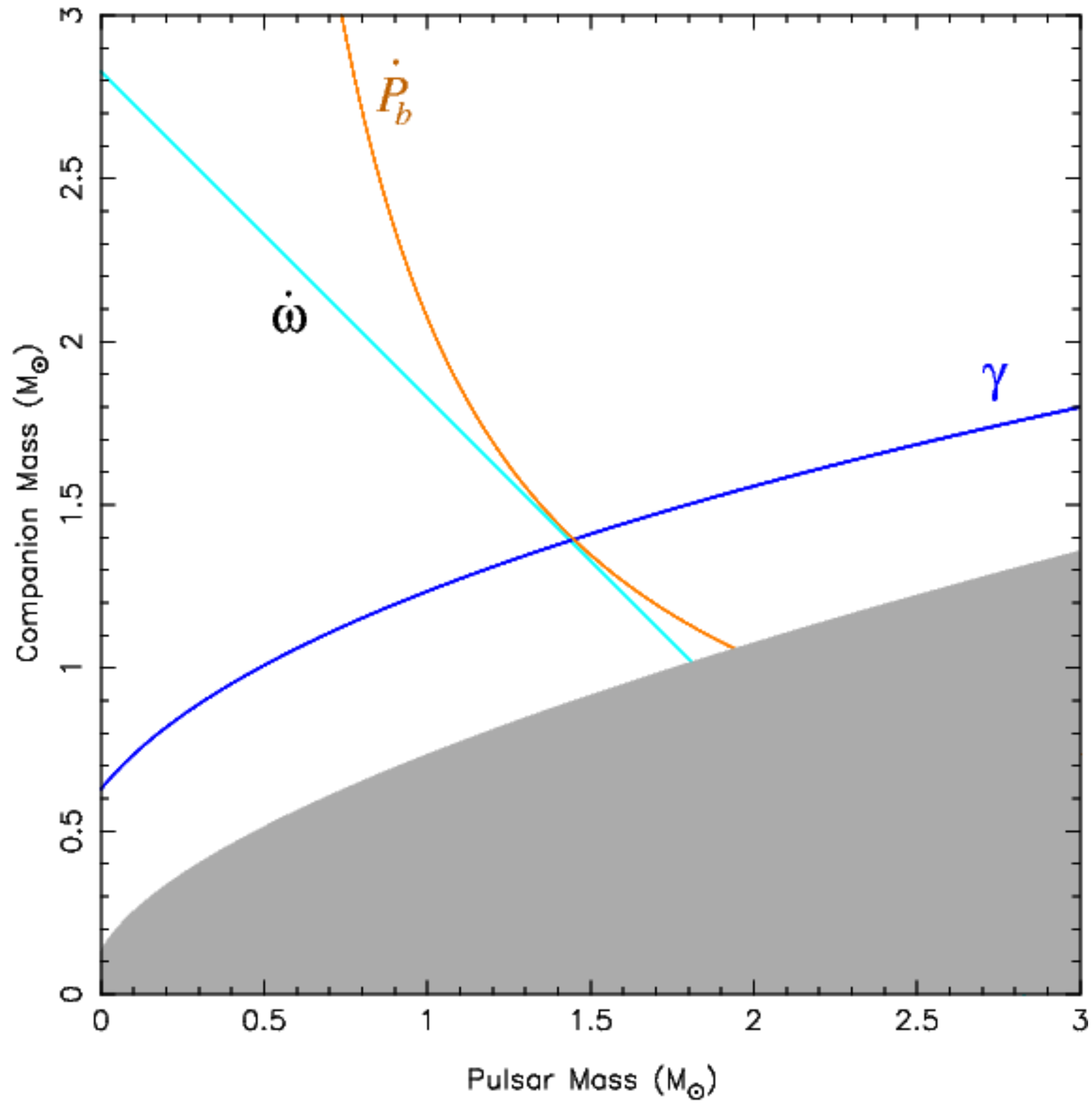
$$f_e = \frac{1}{(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

- 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.



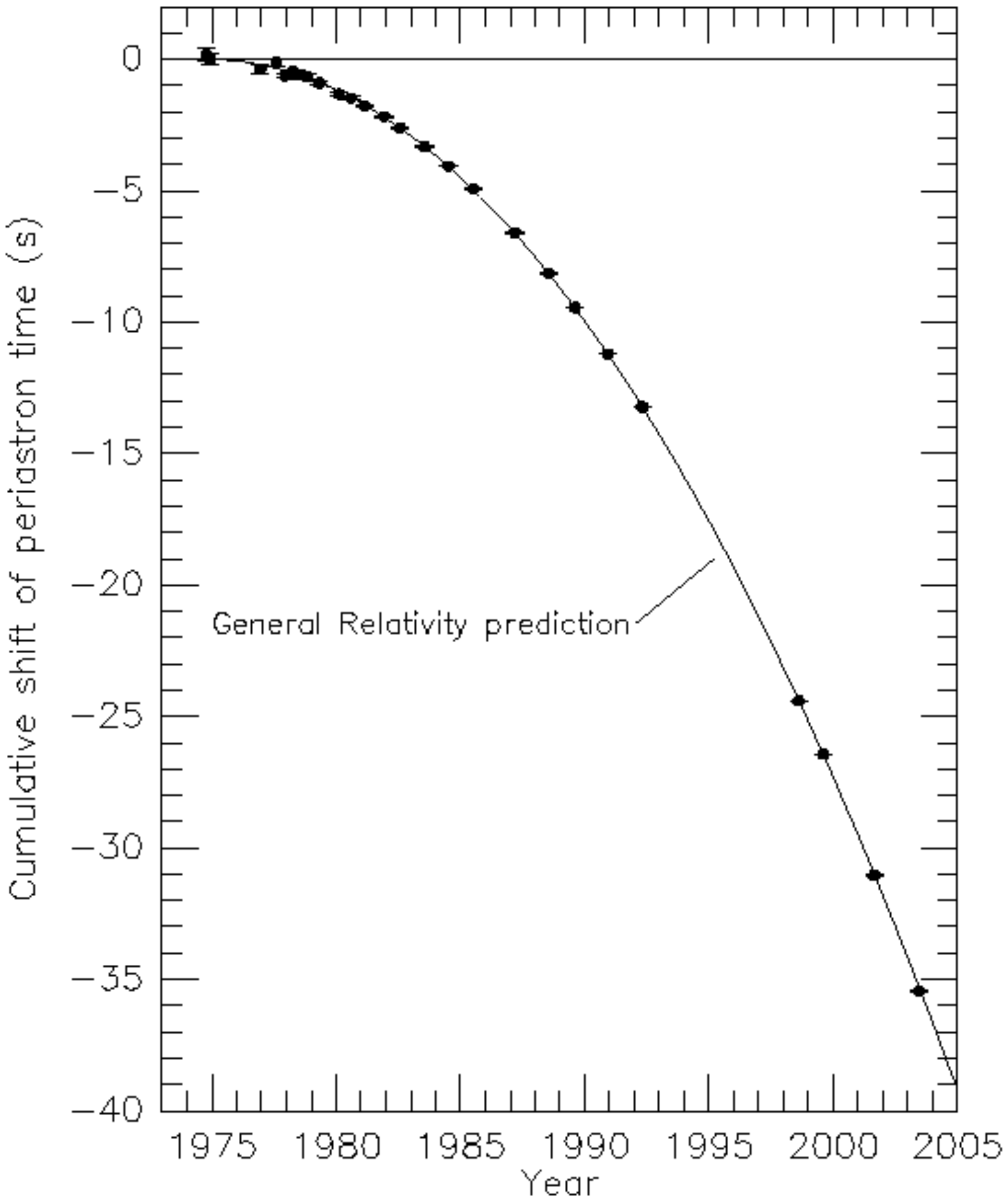
PSR B1913+16

- 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!



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:. 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).

Nobel Prize in Physics, 1993

For the discovery of the binary pulsar, Russel Hulse and Joseph Taylor were awarded the Nobel Prize in Physics, 1993

Gravitational Waves Exist!

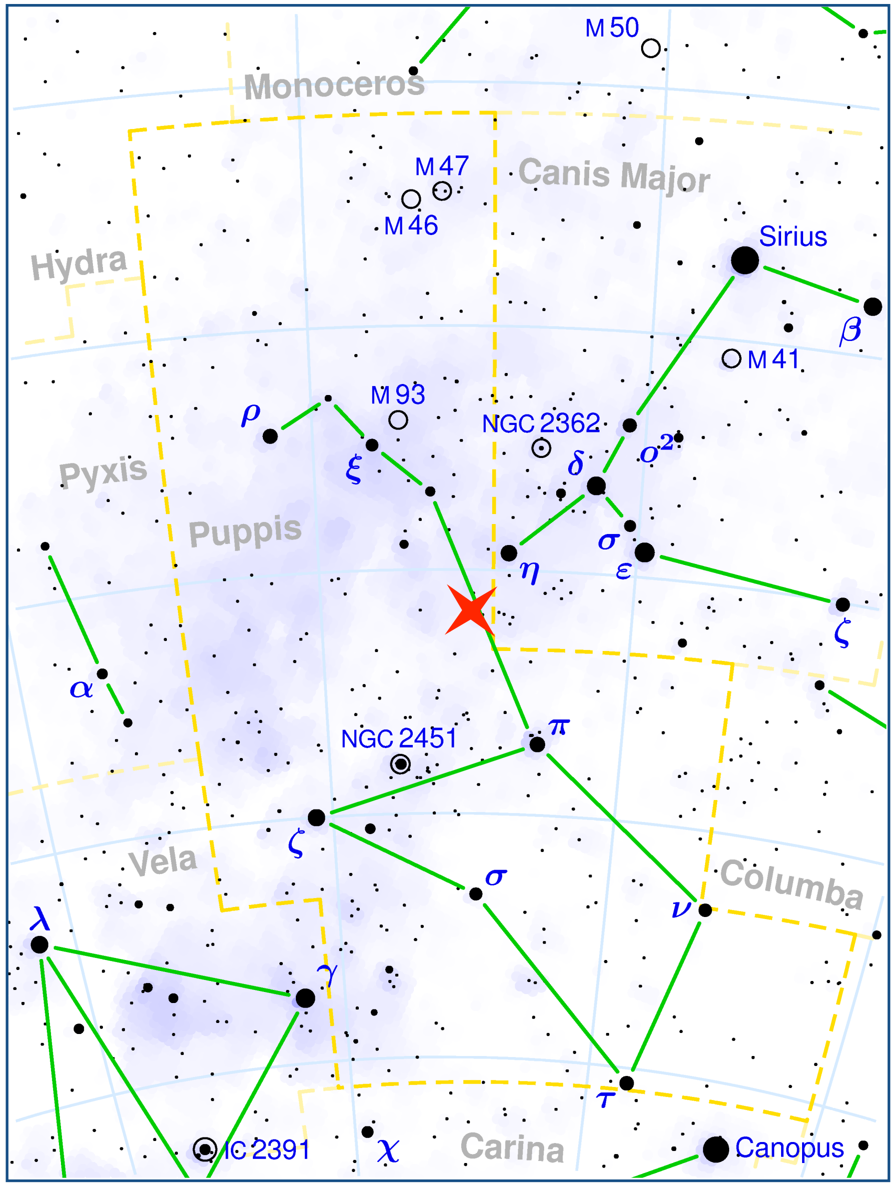
``(…) *the observation of the orbital decay in the TOAs of a binary pulsar is a direct effect of the retarded propagation (at the speed of light, and with a quadrupolar structure) of the gravitational interaction between the companion and the pulsar. In that sense, the Hulse-Taylor pulsar provides a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

Damour, 2014, Classical and Quantum Gravity, Volume 32, Issue 12, article id. 124009 (2015).
He adds:

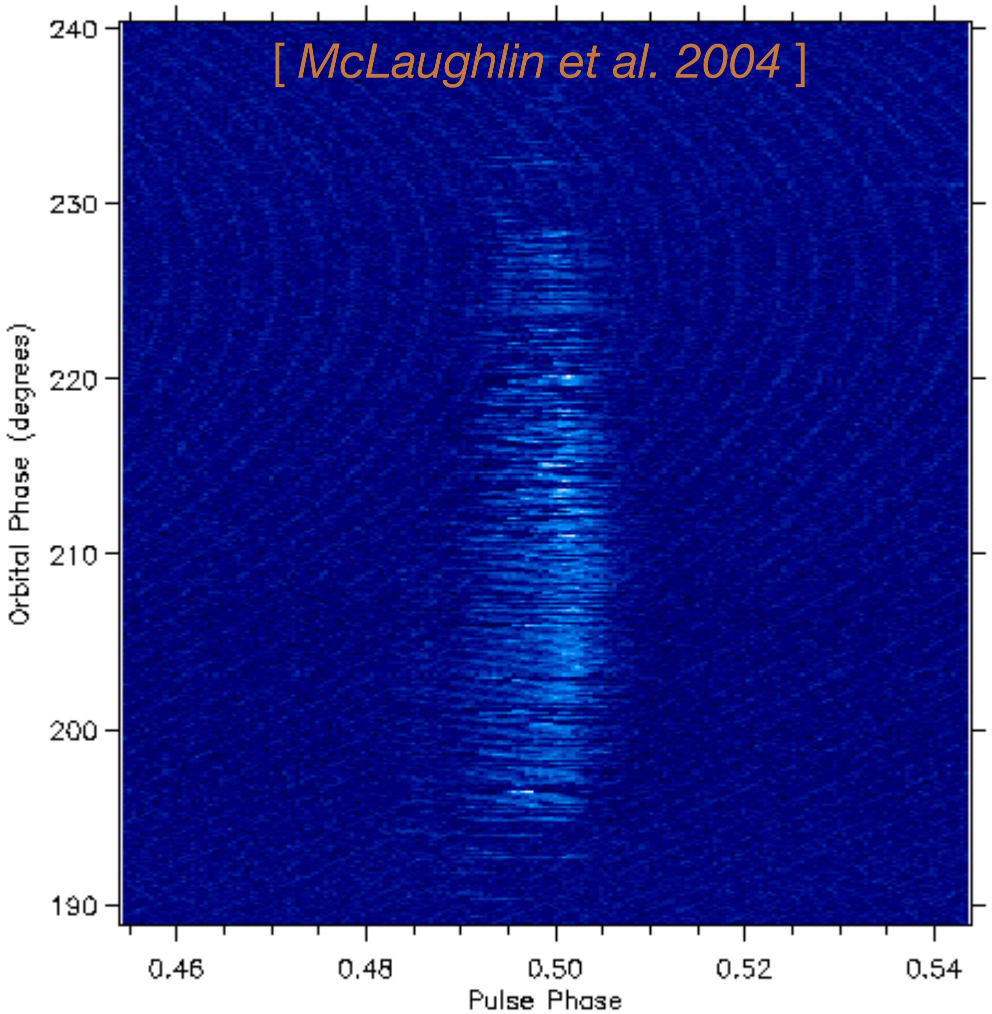
``*The latter point is confirmed by the theoretical computation of the orbital decay in alternative theories of gravity where the non purely quadrupolar (i.e. non purely spin 2) structure of the gravitational interaction generically induces drastic changes* (….)"

The "Double Pulsar": PSR J0737−3039

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



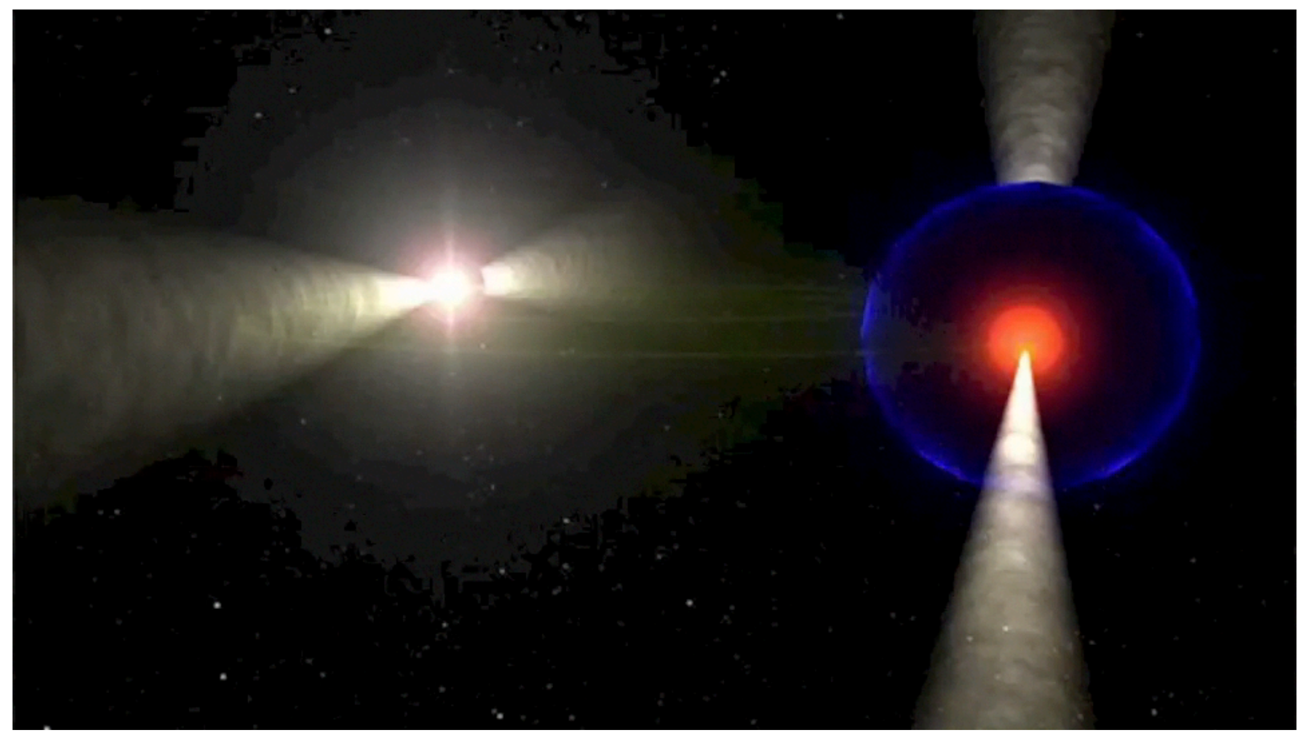
The "Double Pulsar": PSR J0737−3039



Spin periods : 23 ms, 2.8 s

Orbital period : 2.45 h

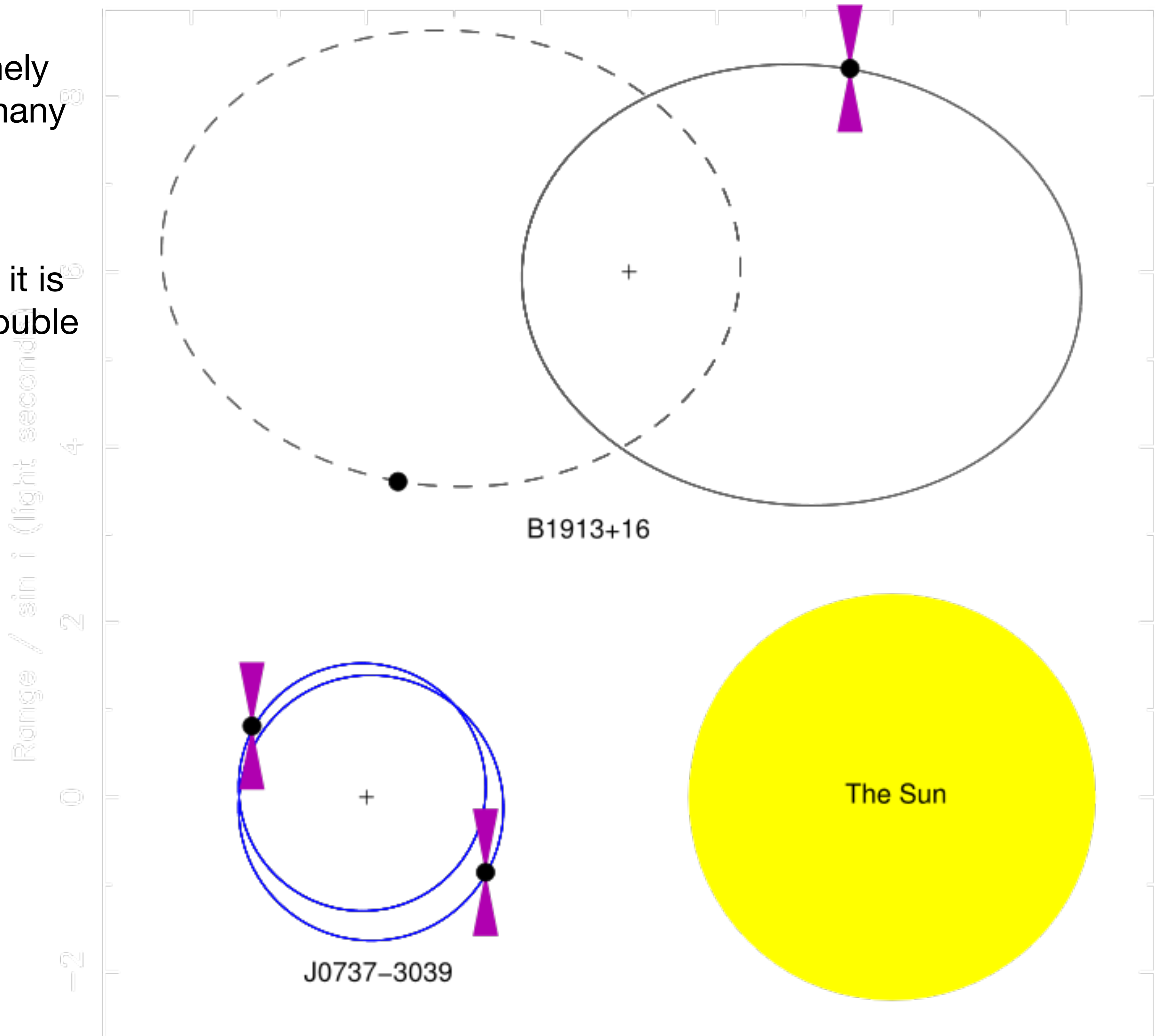
Eccentricity : 0.088



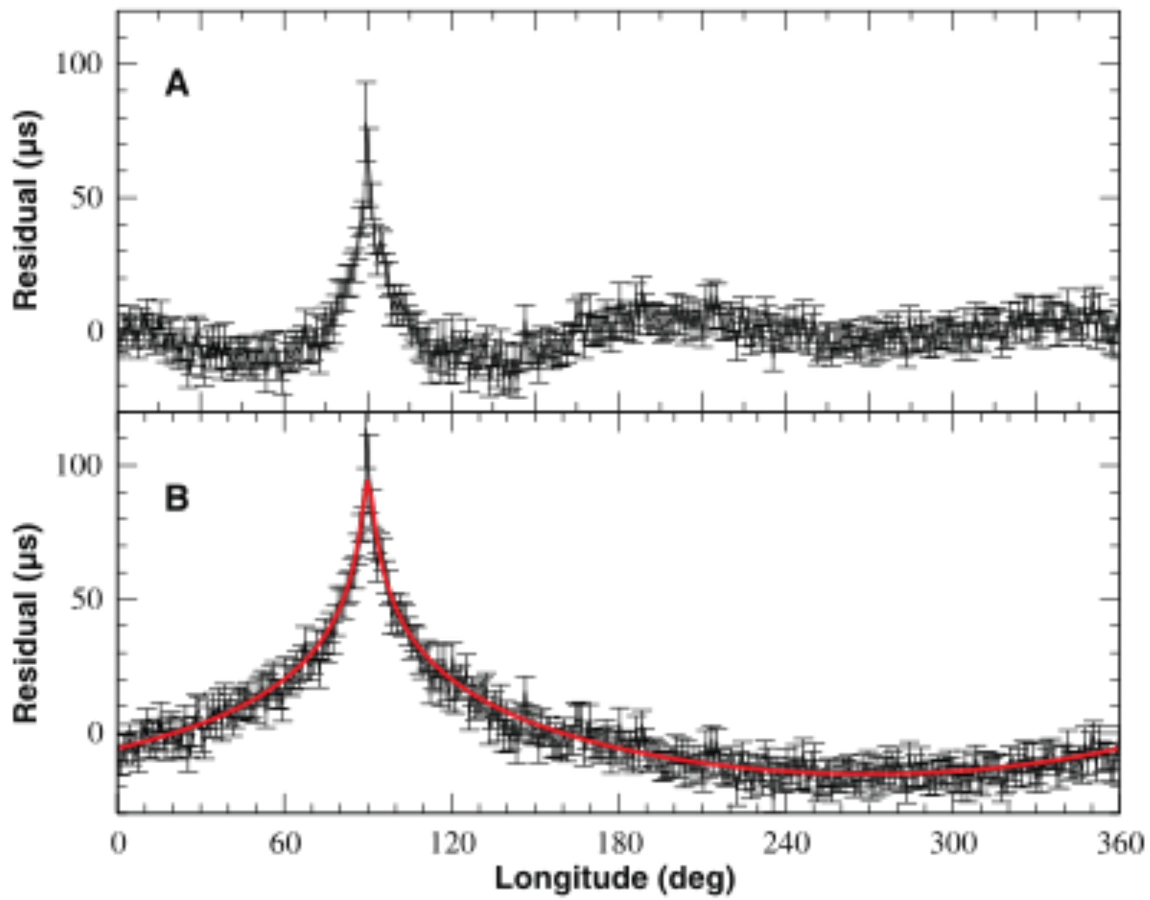
DNS J0737–3039

Nature sometimes is extremely generous! In this case, for many reasons...

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



DNS J0737−3039



From: Kramer et al. 2006

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

$$f(M_\mathrm{p}, M_\mathrm{c}, i) \equiv \frac{(M_\mathrm{c}\sin i)^3}{(M_\mathrm{p}+M_\mathrm{c})^3} = \frac{4\pi^2}{T_\odot}\frac{x^3}{P_\mathrm{b}^2}$$

$$\dot\omega = \frac{3n_\mathrm{b}^{5/3}}{1-e^2}(MT_\odot)^{2/3}$$

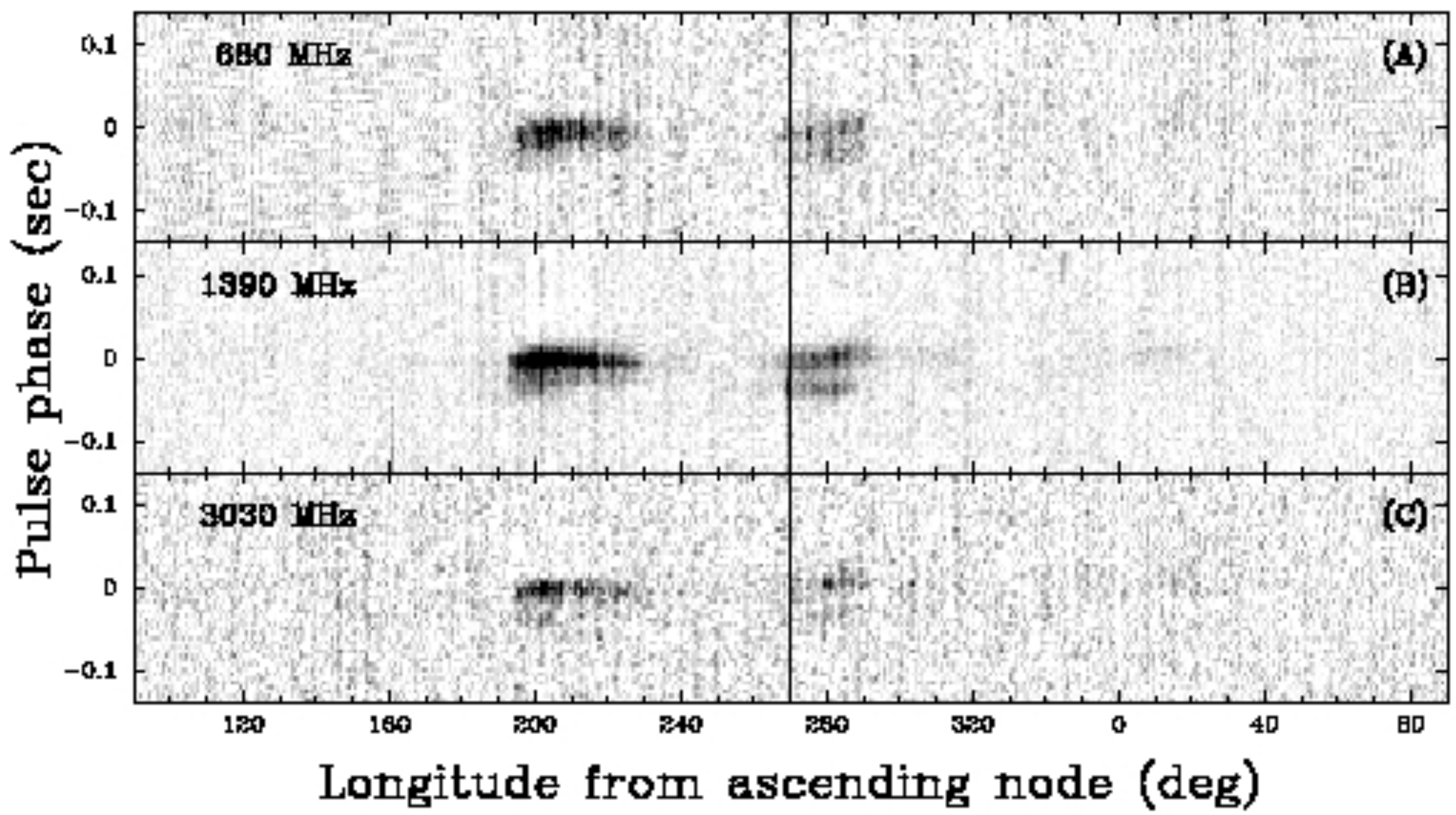
$$\gamma = \frac{eT_\odot^{2/3}}{n_\mathrm{b}^{1/3}}\frac{M_\mathrm{c}(2M_\mathrm{c}+M_\mathrm{p})}{M^{4/3}}$$

$$\dot P_\mathrm{b} = -\frac{192}{5}(n_\mathrm{b}T_\odot)^{5/3}f_e\frac{M_\mathrm{p}M_\mathrm{c}}{M^{1/3}}$$

$$\boxed{\begin{aligned} r &= T_\odot M_\mathrm{c} \\ s &= \sin i = \frac{xn_b^{2/3}}{T_\odot^{1/3}}\frac{M^{2/3}}{M_\mathrm{c}} \end{aligned}}$$

DNS J0737−3039

- **#3**: The second NS in the system (PSR J0737−3039B) was detectable as a radio pulsar!



From: Lyne et al. (2004)

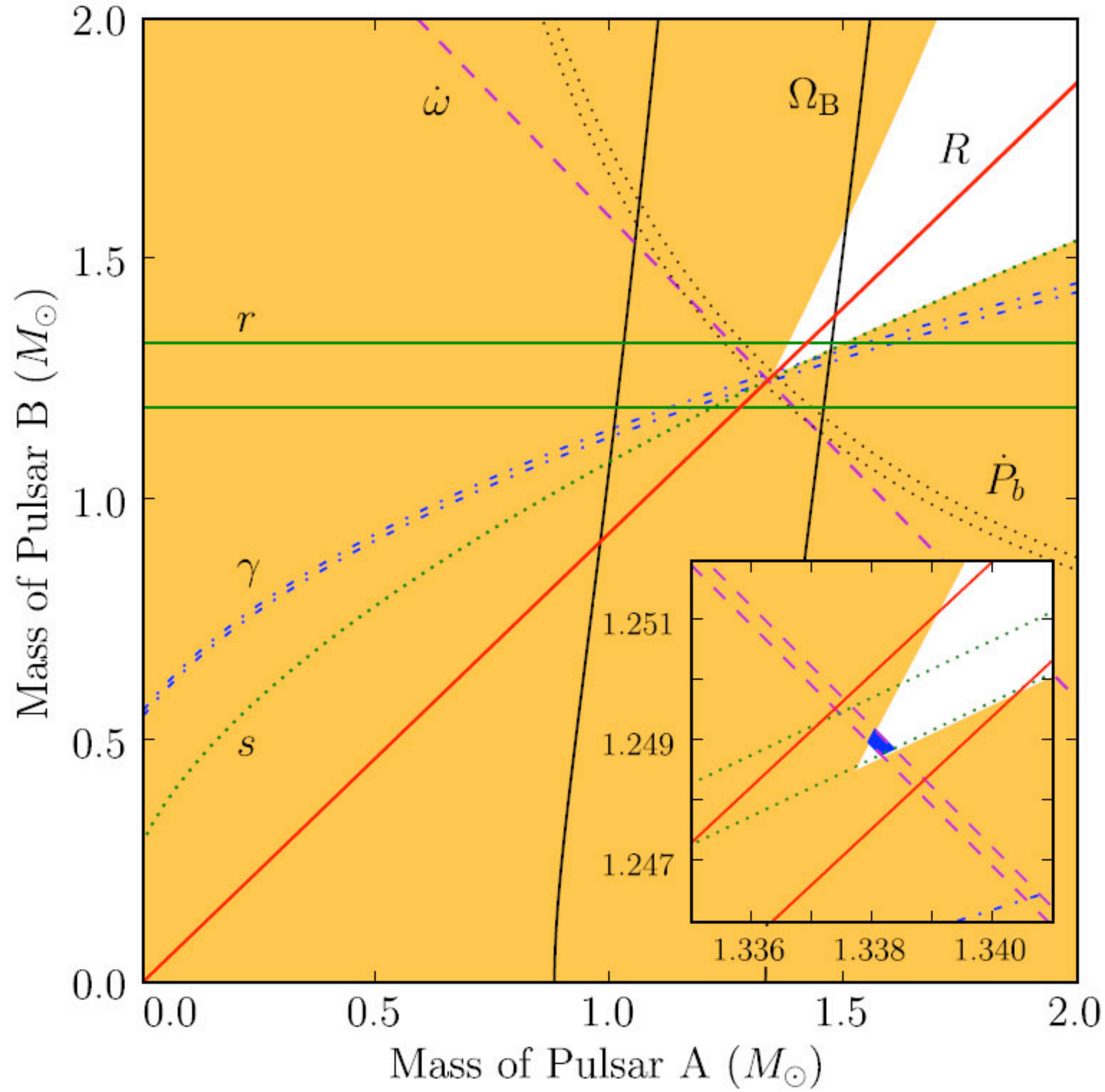
$$\boxed{R = \frac{M_A}{M_B} = \frac{x_B}{x_A}}$$

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

DNS J0737–3039

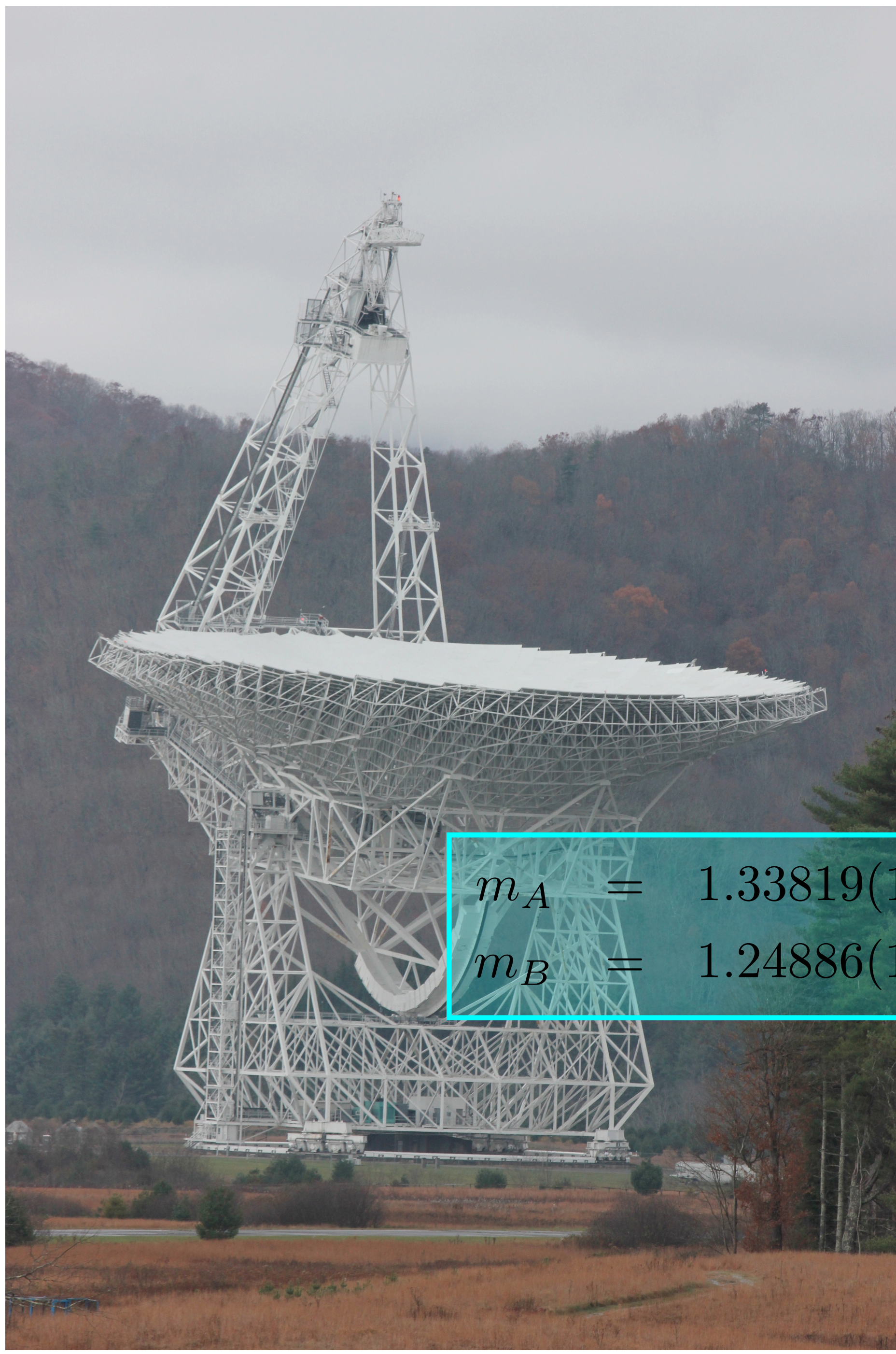
- *GR passes all 4 tests with flying colors!*

- There is a fifth test, from geodetic precession of PSR J0737–3039B (Breton et al. 2008, Science), which we mention later.

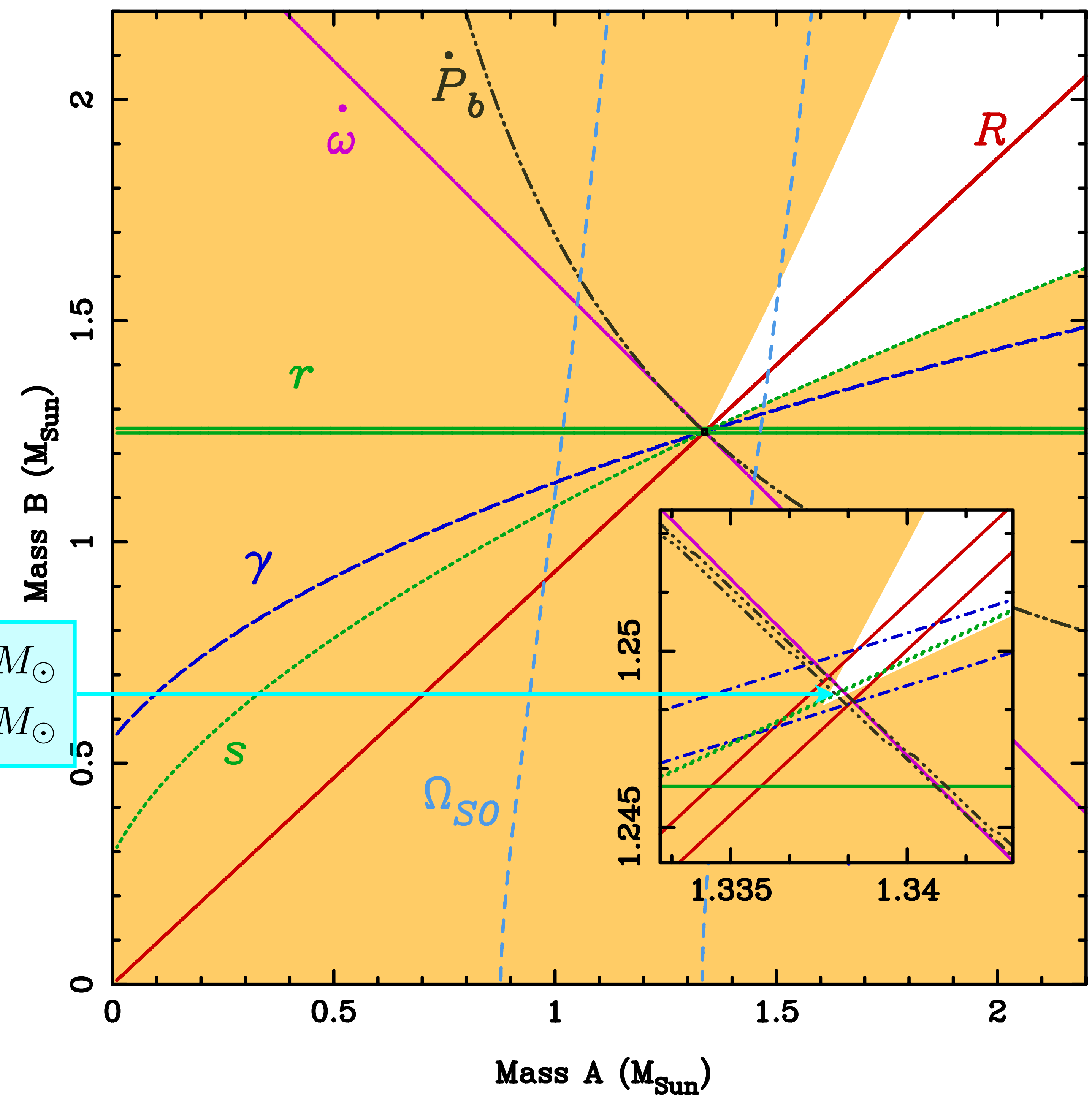


Kramer et al. 2006, Science, 314, 97

DNS J0737−3039

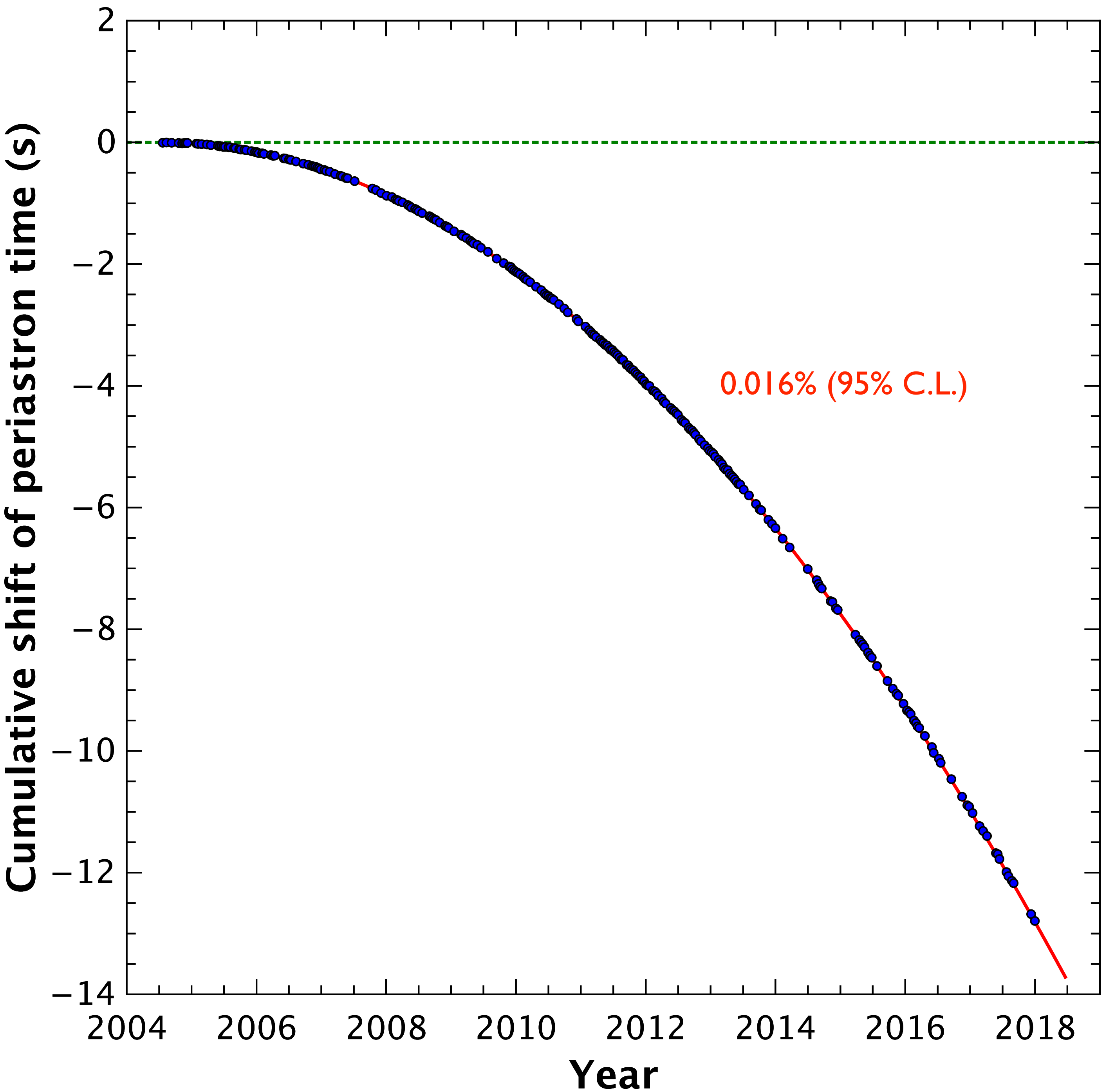


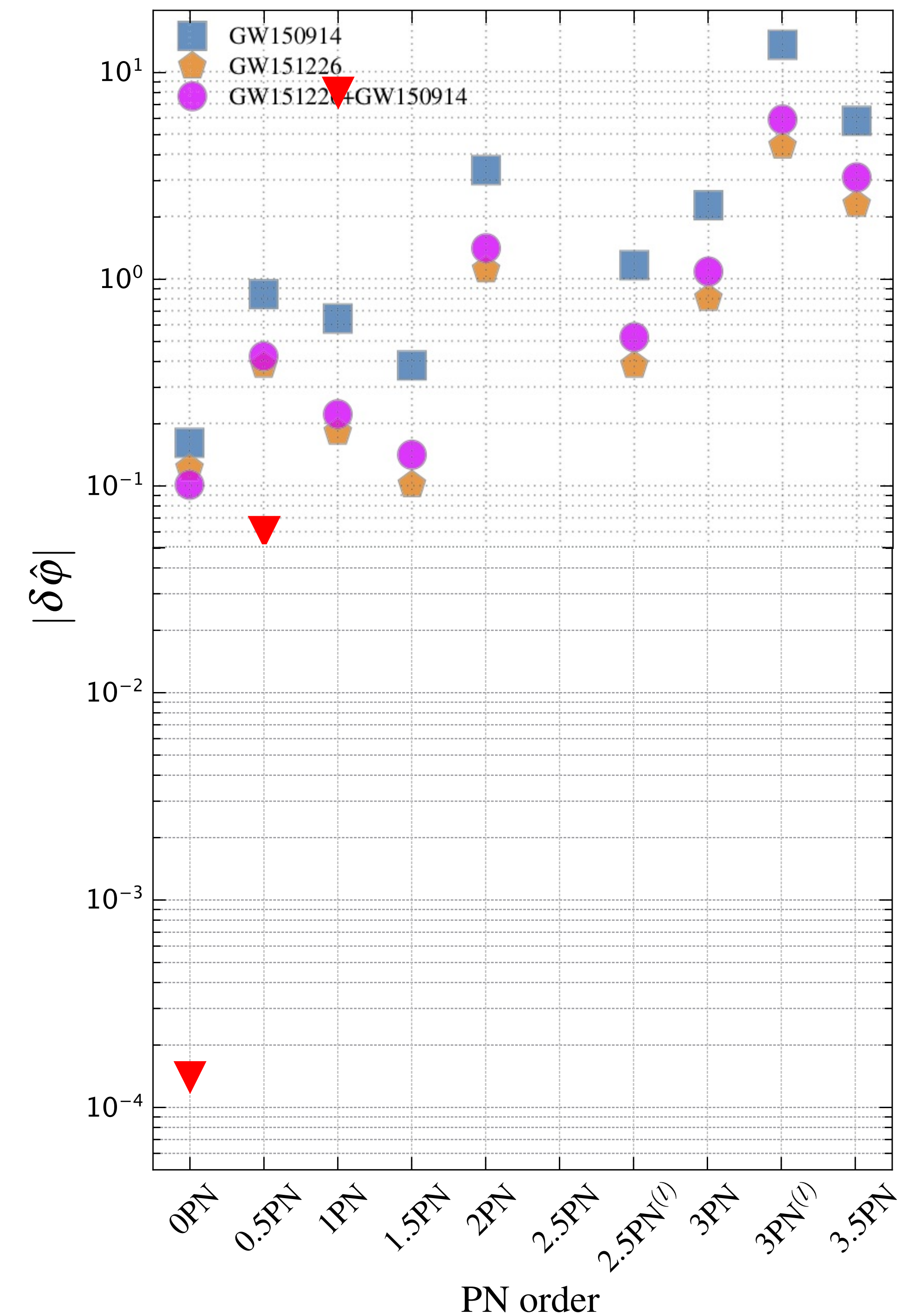
[Kramer et al., in prep.]



$$m_A = 1.33819(1)\, M_\odot$$
$$m_B = 1.24886(1)\, M_\odot$$

DNS J0737–3039



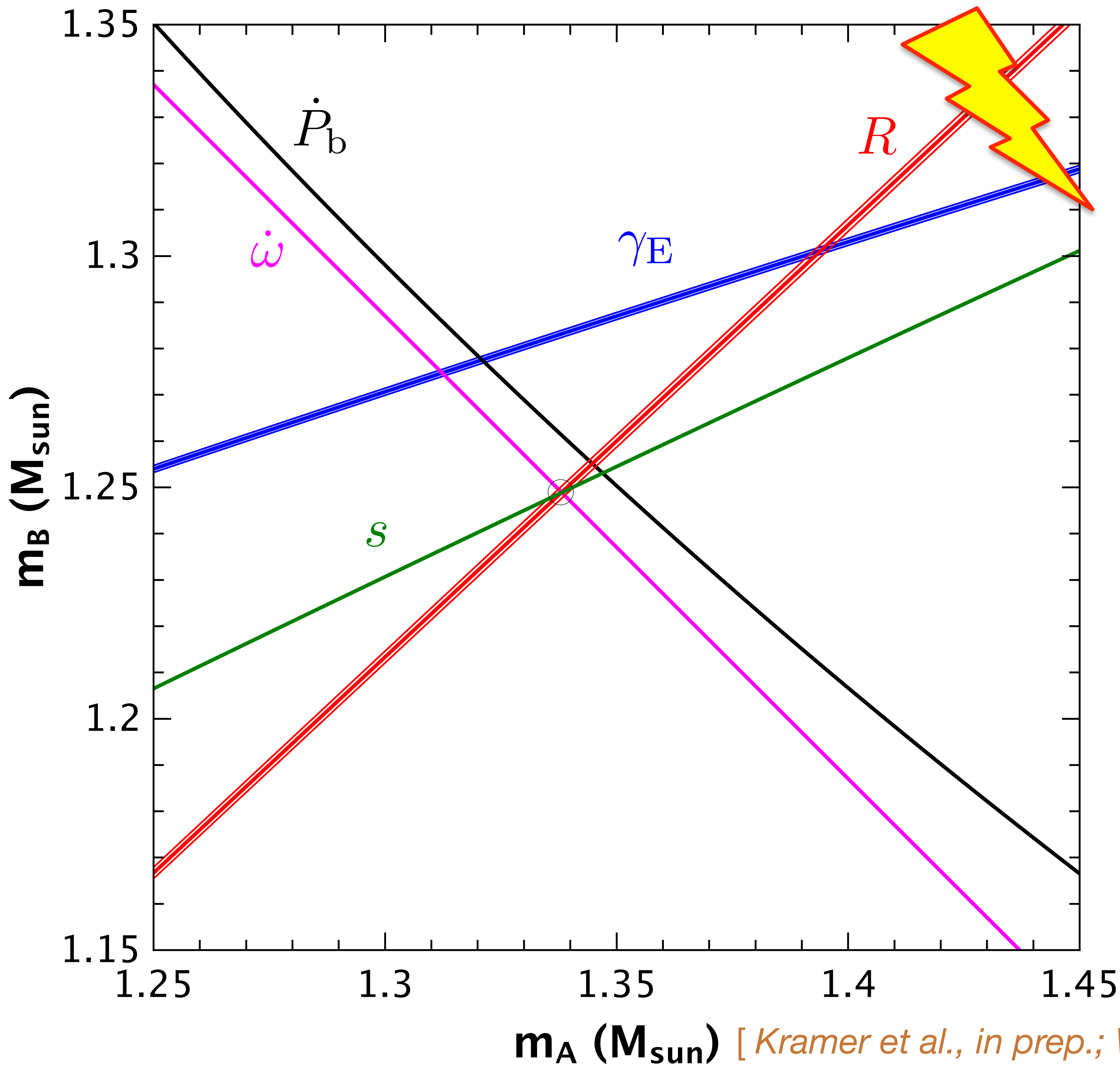


[Kramer et al., in prep.]

[LSC, 2016, 2018, Kramer et al., in prep.]

The double pulsar and TeVeS

These results are already enough to exclude TeVeS - or at least that it yields MOND



[*Kramer et al., in prep.; Wex, Esposito-Farèse et al., in prep.*]

3. Tests of alternative theories of gravity, experiments* on the nature of gravitational waves

*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 $1/c^3$)

$$\dot{P}_{\mathrm{b}}^{D} = -\, 2\pi n_b \frac{G_* M_{\mathrm{WD}}}{c^3} \frac{q}{q+1} \frac{1 + e^2/2}{(1-e^2)^{5/2}} (\alpha_{\mathrm{p}} - \alpha_{\mathrm{WD}})^2$$

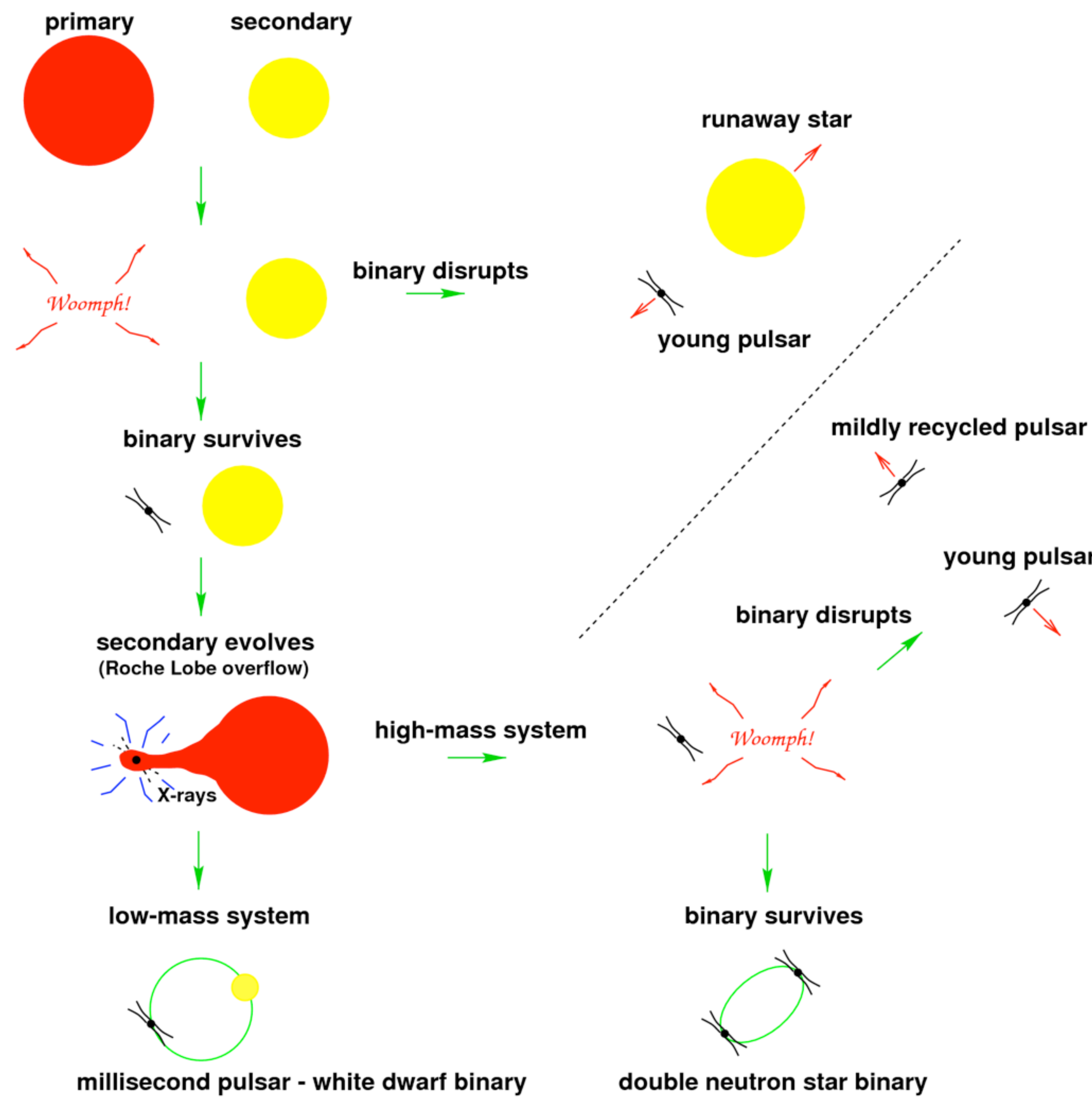
  2. **Orbital polarization** (Nordtvedt effect, for wide orbits AND PULSAR IN TRIPLE SYSTEM)
  3. **Variation of Newton's gravitational constant G.**

- **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!

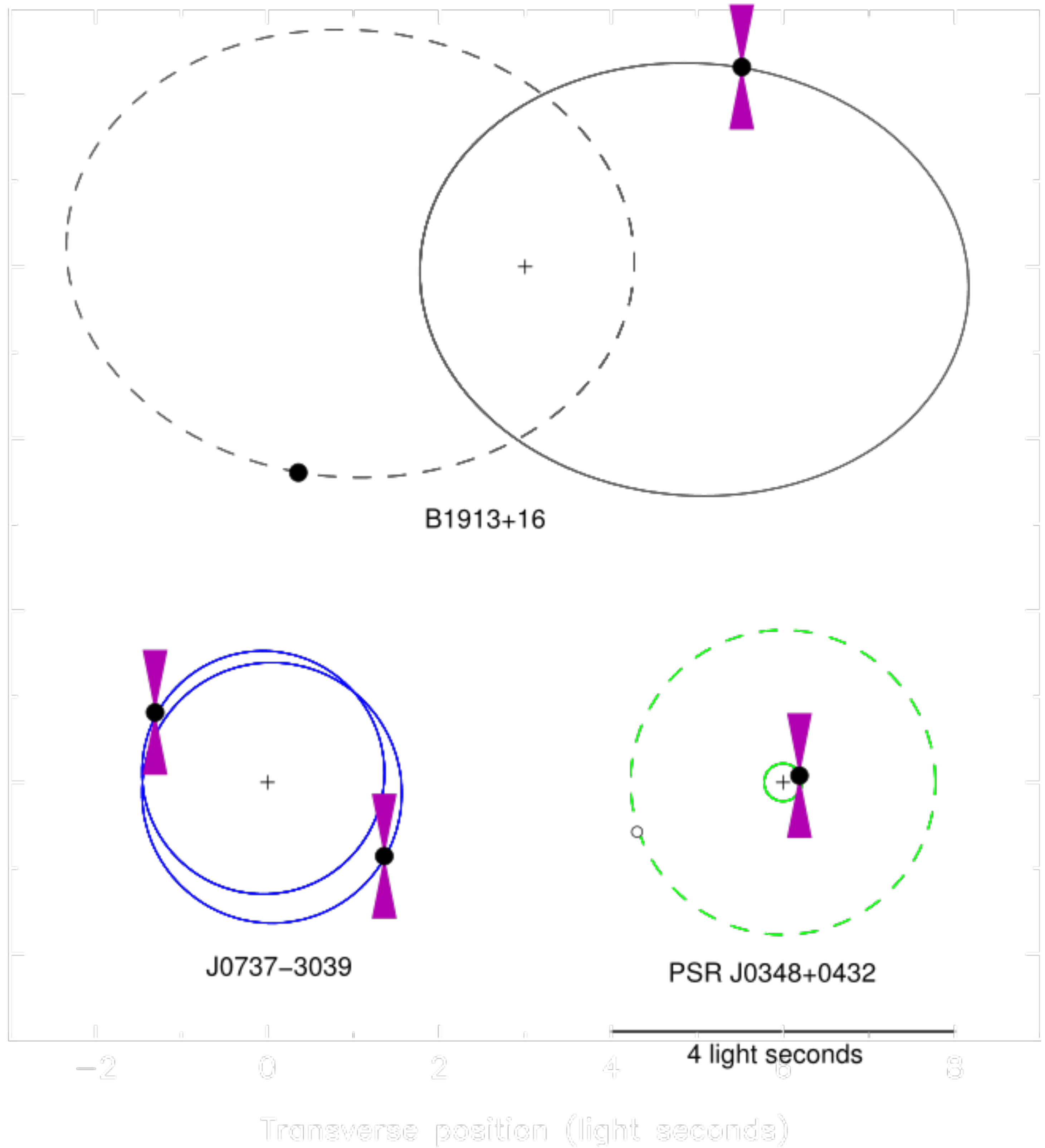


Lorimer, D., *Living Rev. Relativity* 11 (2008), 8

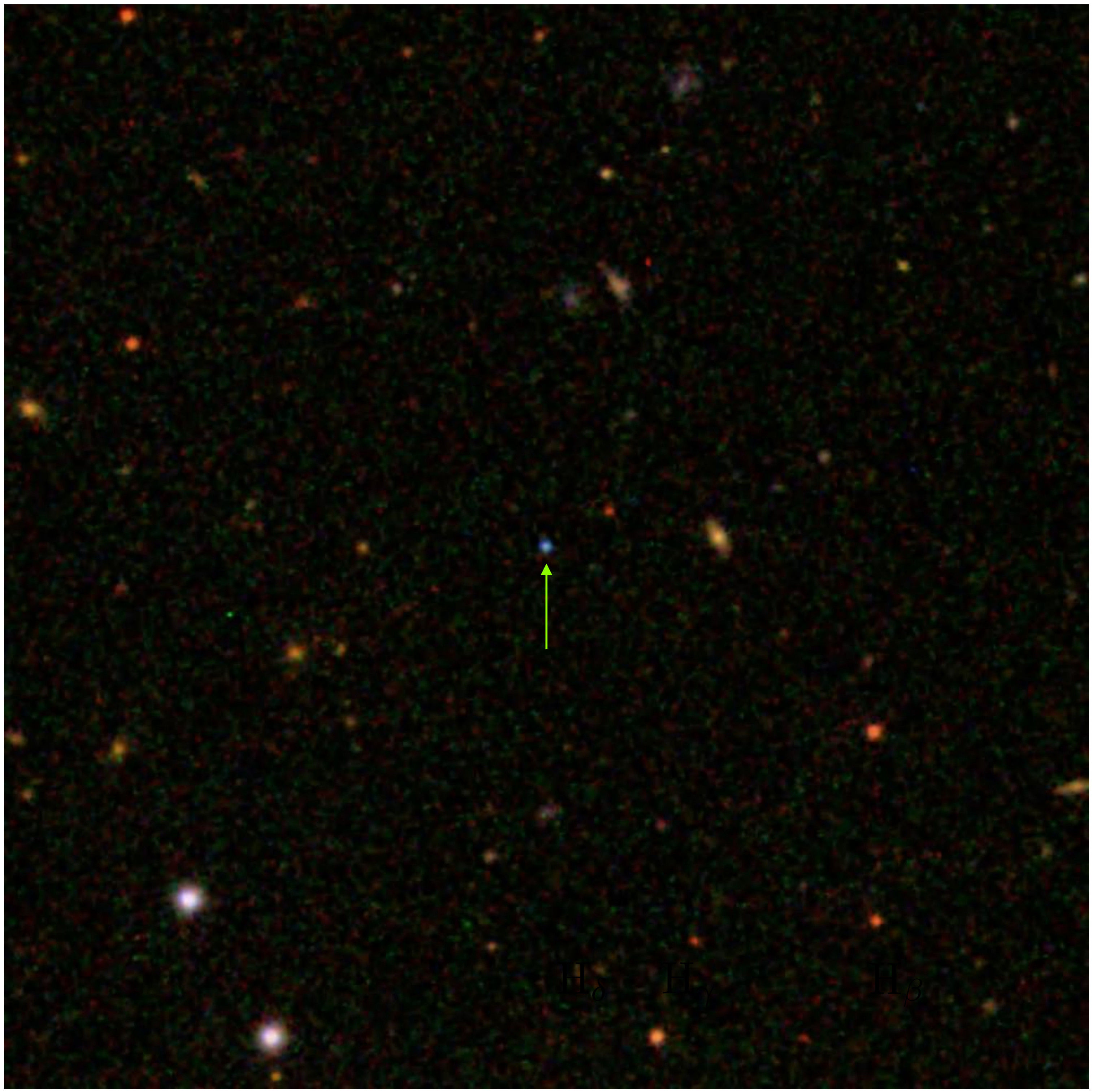
PSR J0348+0432

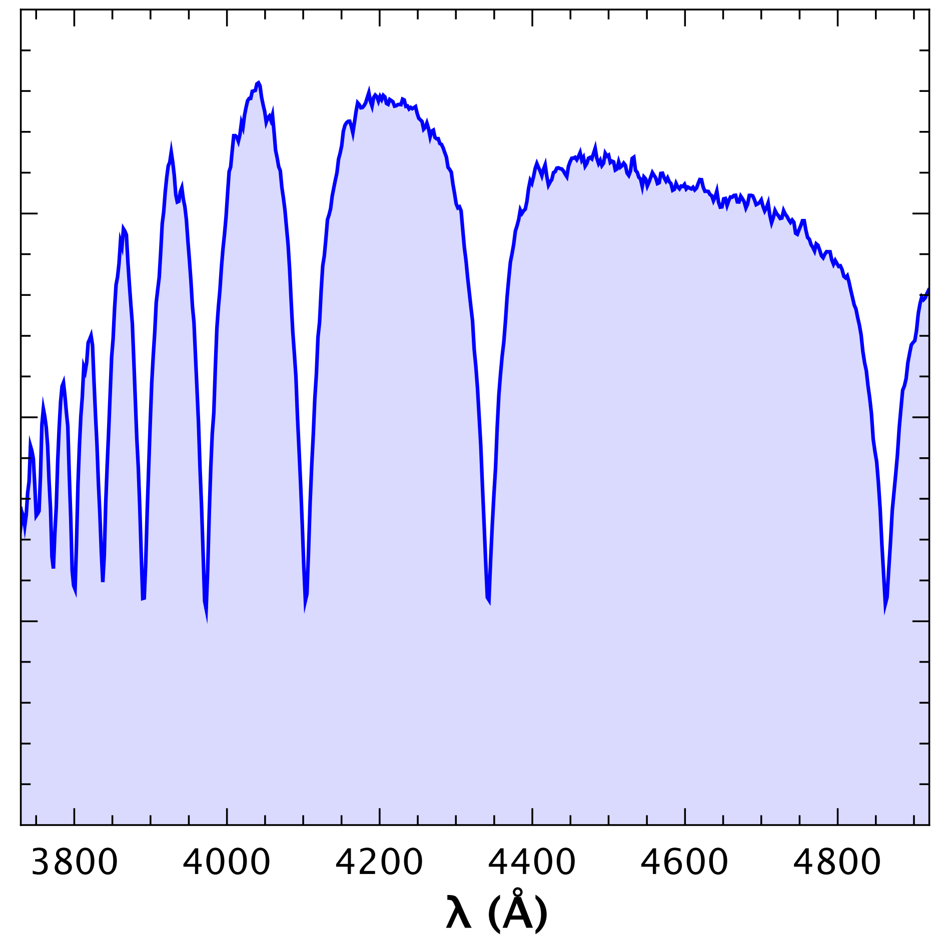
- This is a pulsar with a spin period of 39 ms discovered in a GBT 350-MHz drift-scan survey (Lynch et al. 2013, ApJ. 763, 81).

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



Once again, Nature comes to the rescue!





An analysis of the spectrum of the WD yields a mass of $0.172 \pm 0.003\, M_{\odot}$

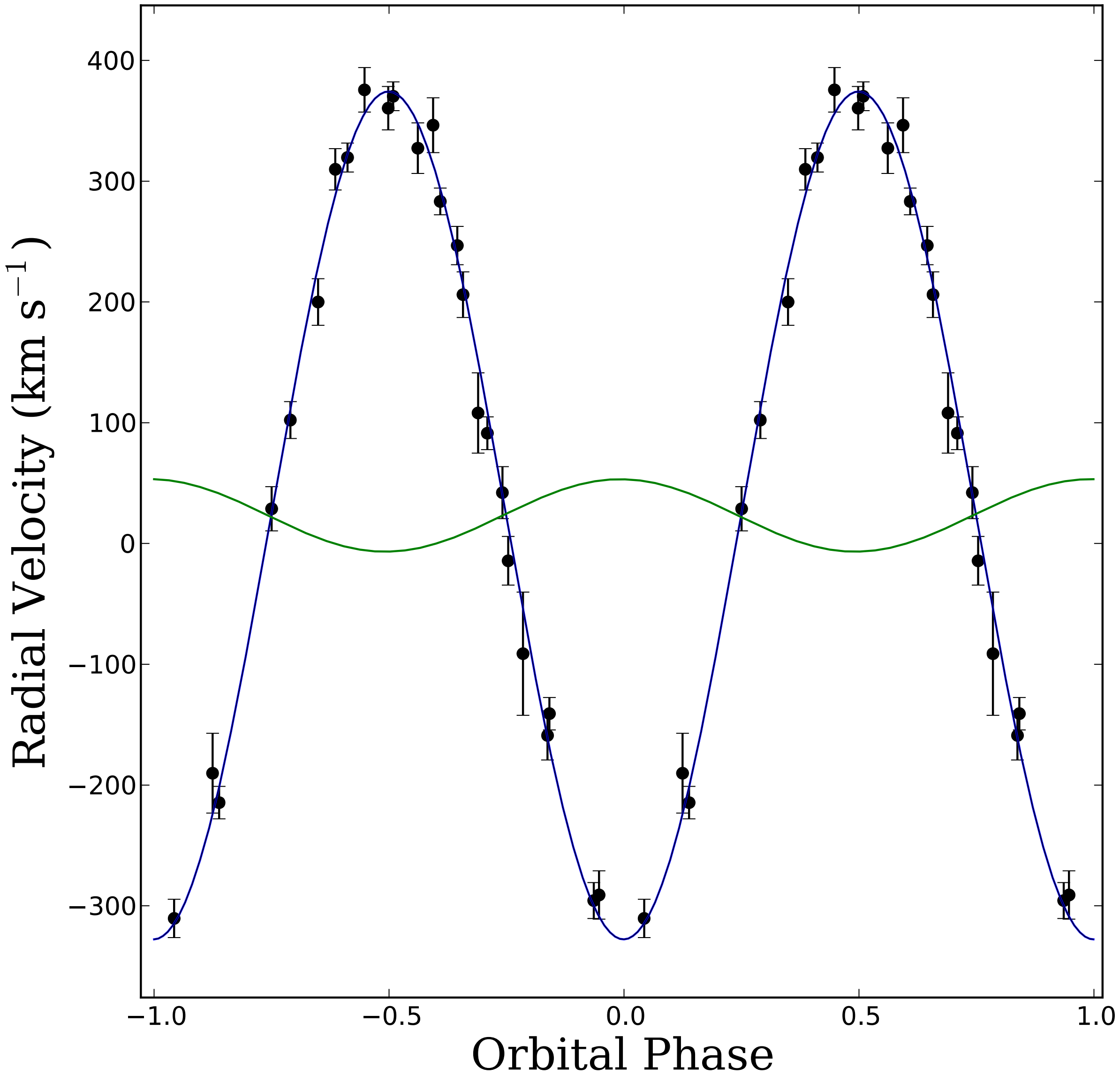
PSR J0348+0432

The same VLT observations also determine the mass ratio!

Pulsar mass: $(2.01 \pm 0.04)\, M_{\odot}$**!**
(Antoniadis, Freire, Wex, Tauris et al. 2013, Science, 340, n. 6131).

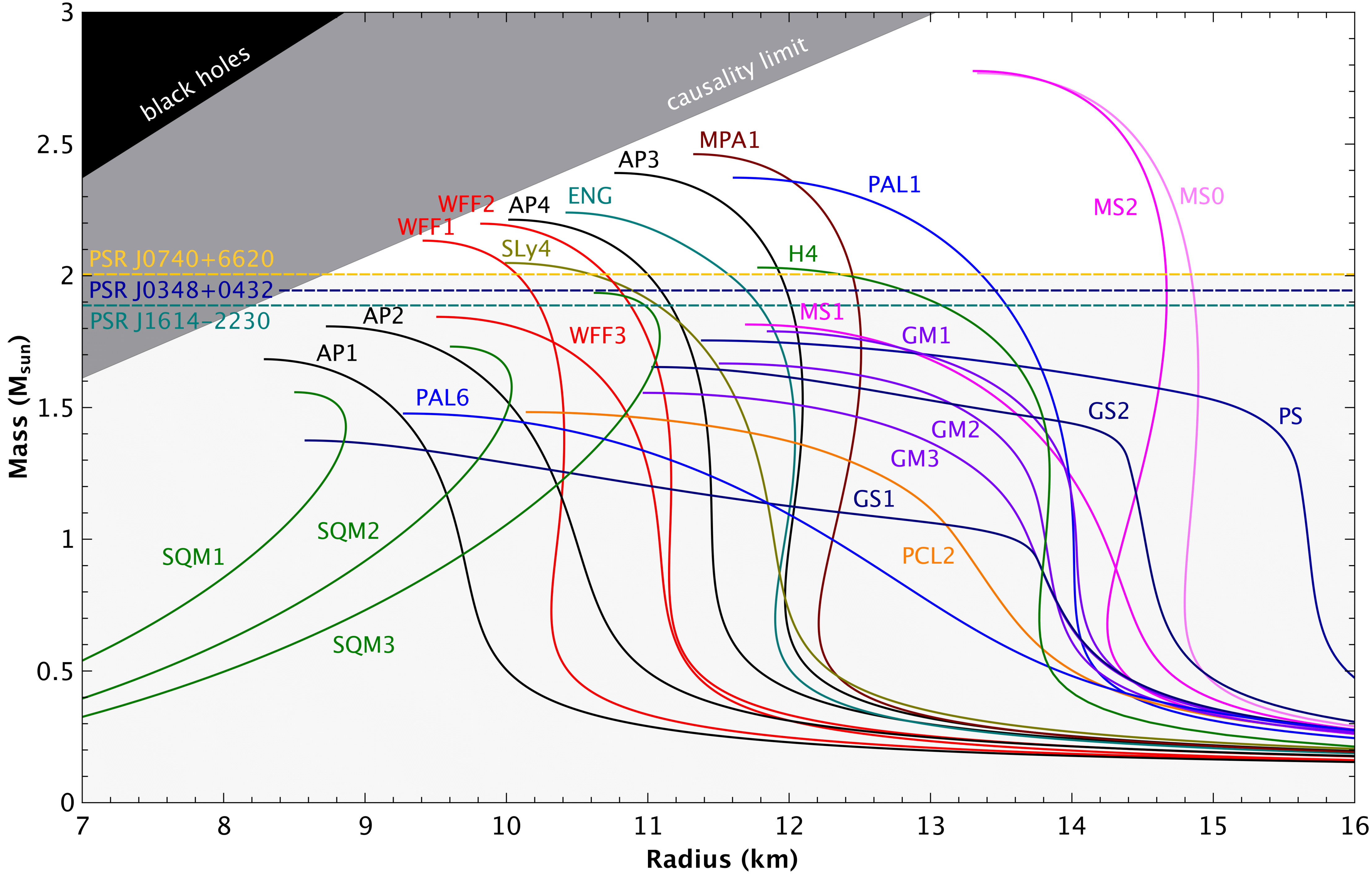
- Most massive NS with a precise mass measurement!

- Prediction for orbital decay: $-8.1\,\mu\mathrm{s\,yr}^{-1}$



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

Constraints on the equation of state

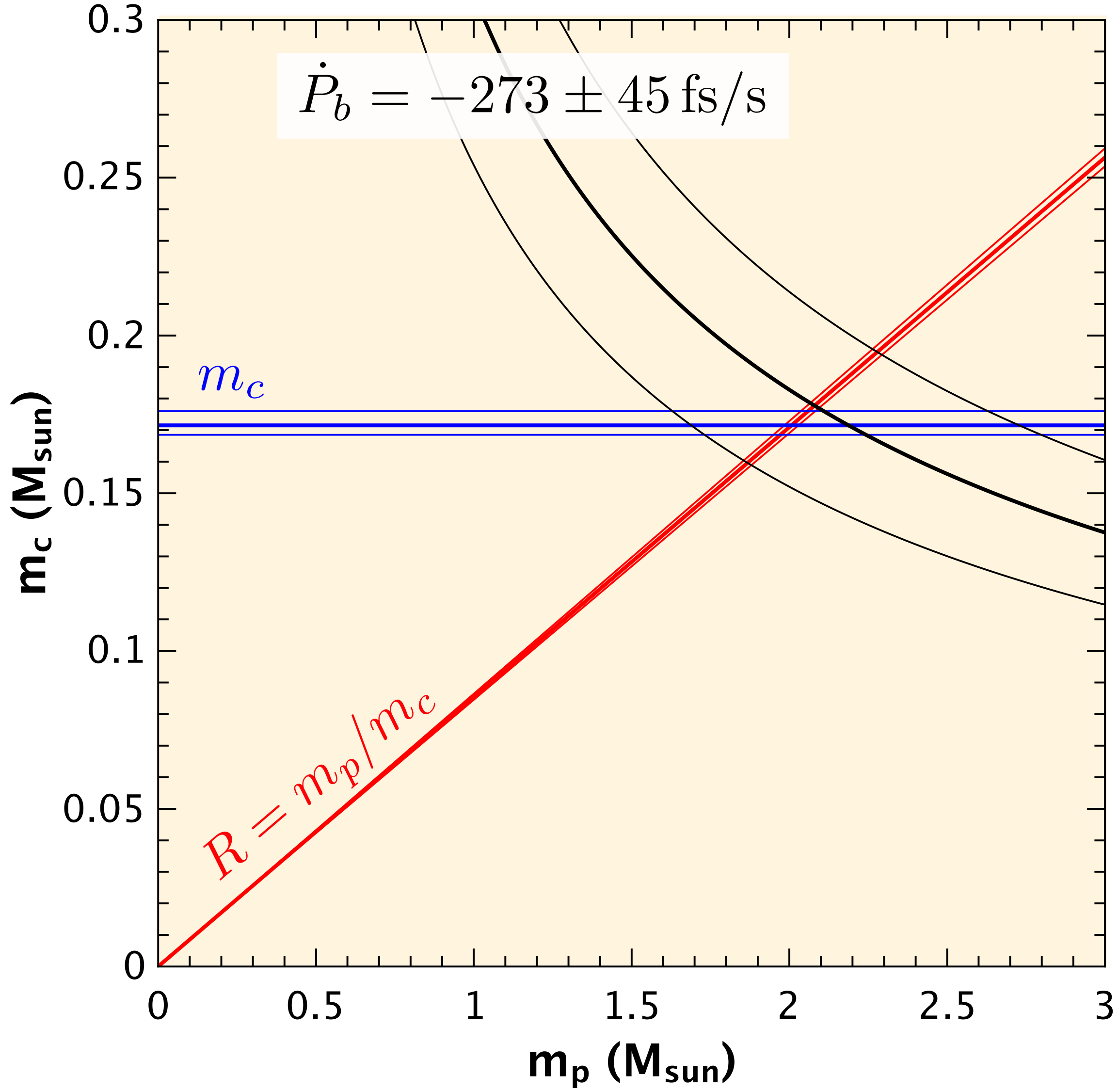


Mass measurements have direct implications for the EOS of dense matter!

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

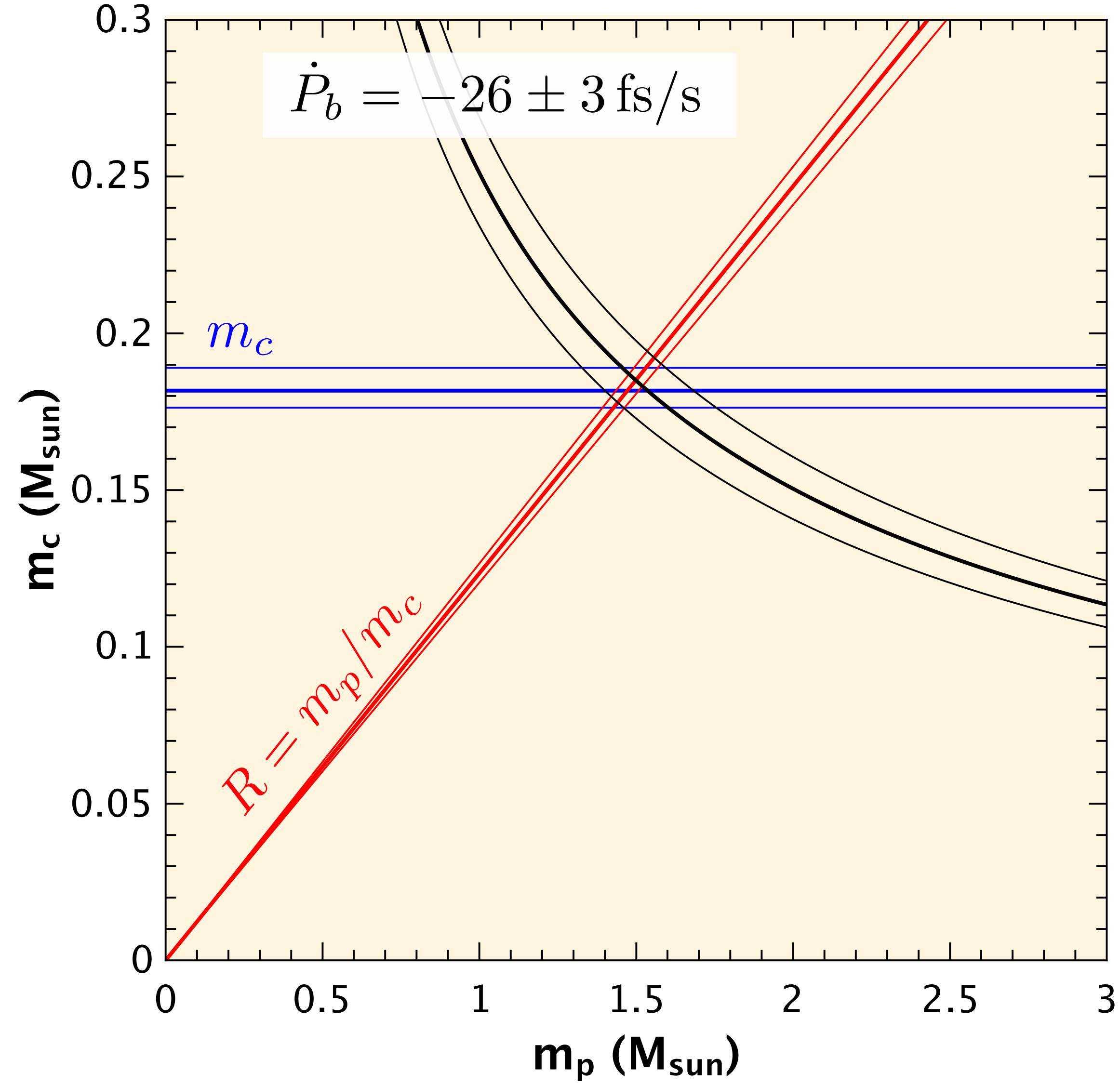
Orbital decay: as expected by GR!

PSR J0348+0432



[*Antoniadis et al. 2013*]

PSR J1738+0333



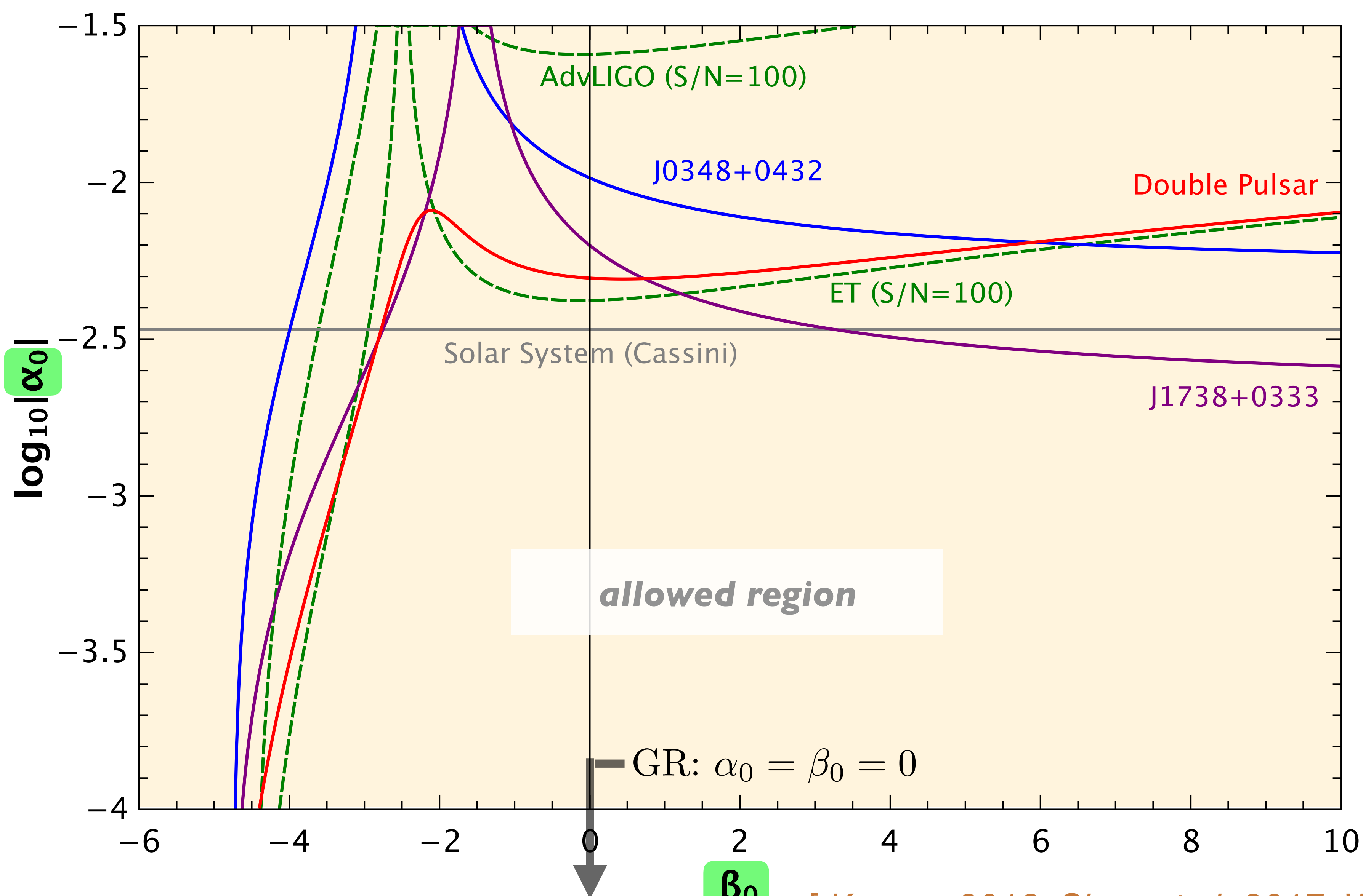
[*Freire et al. 2012*]

Constraints on DEF gravity

$$R^*_{\mu\nu} = \frac{8\pi G_*}{c^4}\left(T^*_{\mu\nu} - \frac{1}{2}T^* g^*_{\mu\nu}\right) + 2\partial_\mu\varphi\partial_\nu\varphi - 2\cancel{V(\varphi)}g^*_{\mu\nu}$$

$$\Box_{g_*}\varphi = -\frac{4\pi G_*}{c^4}(\alpha_0 + \beta_0\varphi)\,T_* - \cancel{V'(\varphi)}$$

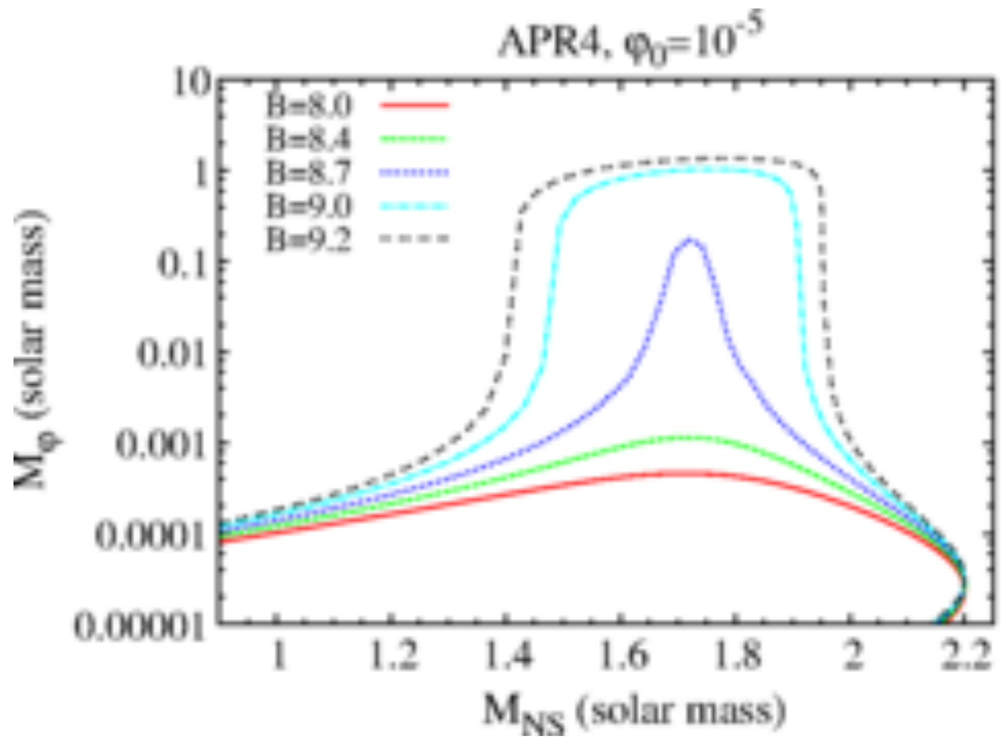
$V''(\varphi) \ll 1/(\text{size of system})^2$

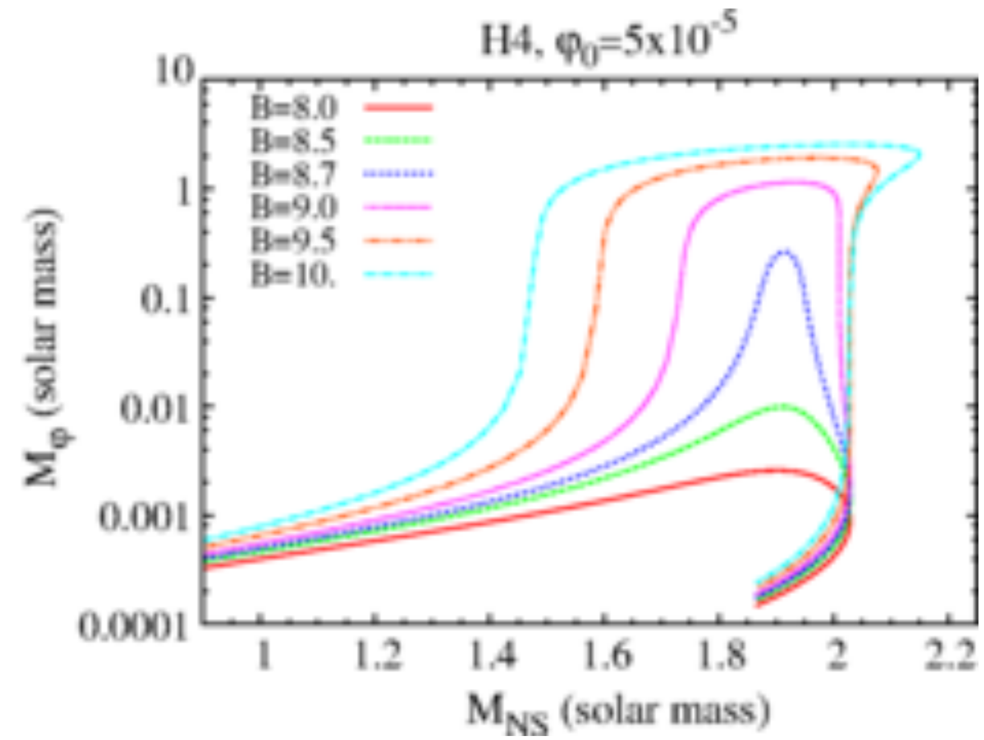


[*Kramer 2016; Shao et al. 2017; Wex et al., in prep.*]

4. Closing the ``scalarization gap”

Constraints on spontaneous scalarization





M. Shibata, K. Taniguchi, H. Okawa, and A. Buonanno, Phys. Rev. D 89, 084005 (2014)

- Stars can de-scalarize at the largest masses allowed by the EOS.
- This implies that, if maximum NS mass is close to 2 solar masses, we can still have spontaneous scalarization in between the masses of PSR J1738+0333 and PSR J0348+0432

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EINSTEIN@HOME DISCOVERY OF A DOUBLE NEUTRON STAR BINARY IN THE PALFA SURVEY

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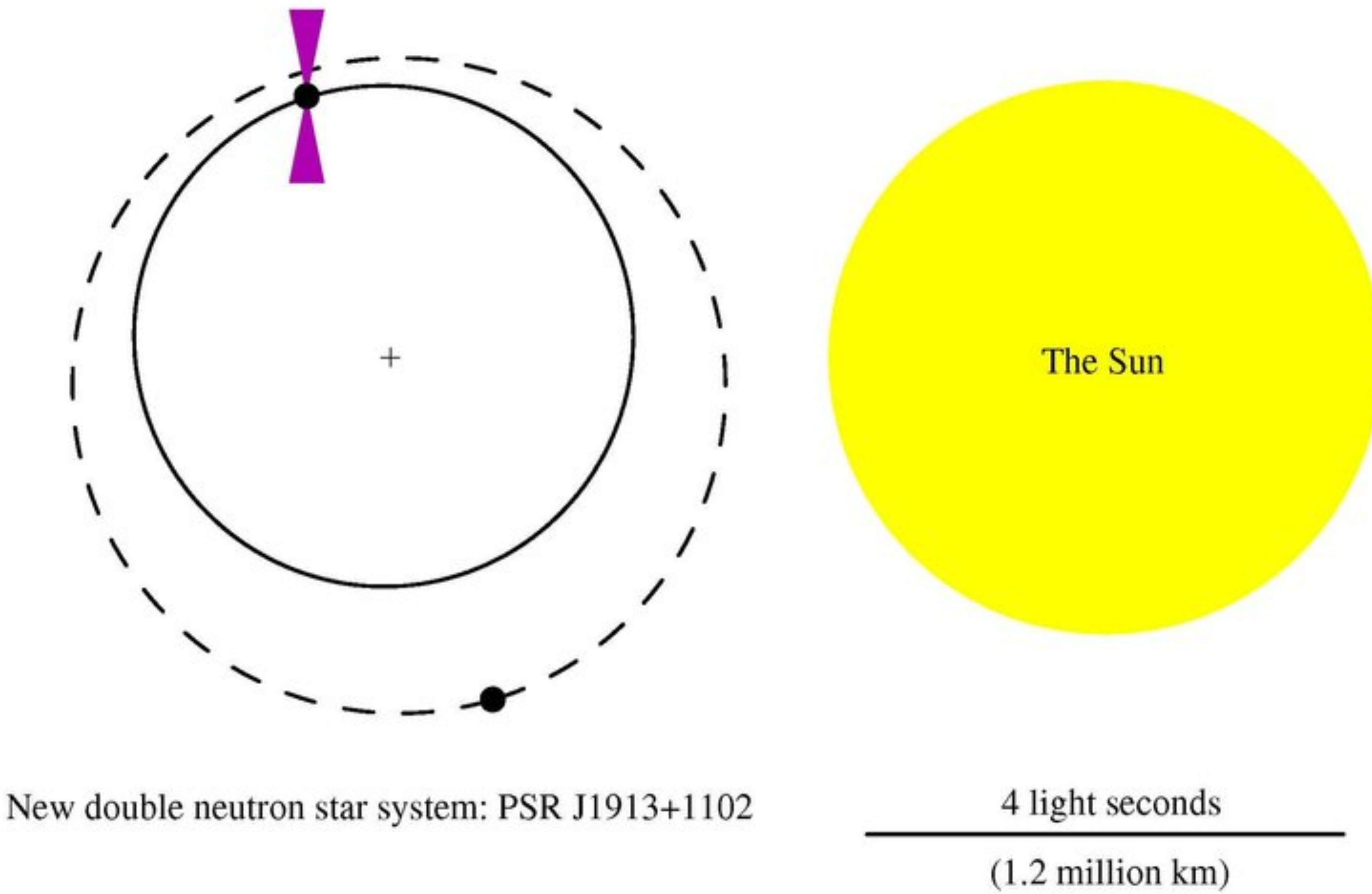
ABSTRACT

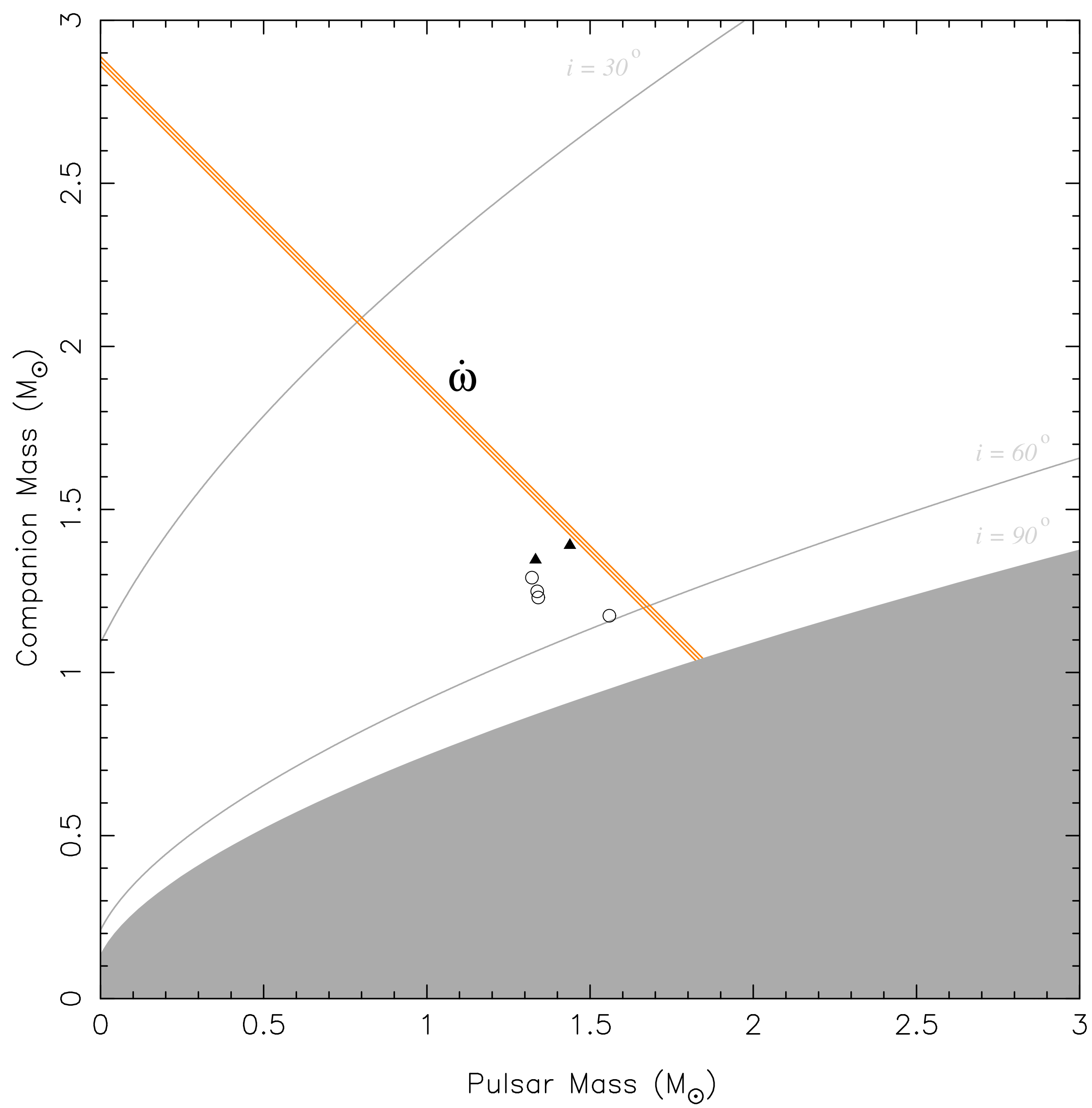
We report here the Einstein@Home discovery of PSR J1913+1102, a 27.3 ms pulsar found in data from the ongoing Arecibo PALFA pulsar survey. The pulsar is in a 4.95 hr double neutron star (DNS) system with an eccentricity of 0.089. From radio timing with the Arecibo 305 m telescope, we measure the rate of advance of periastron to be $\dot{\omega} = 5.632(18)^\circ\ \mathrm{yr}^{-1}$. Assuming general relativity accurately models the orbital motion, this corresponds to a total system mass of $M_{\mathrm{tot}} =\ 2.875(14)\ M_\odot$, similar to the mass of the most massive DNS known to date, B1913+16, but with a much smaller eccentricity. The small eccentricity indicates that the second-formed neutron star (NS) (the companion of PSR J1913+1102) was born in a supernova with a very small associated kick and mass loss. In that case, this companion is likely, by analogy with other systems, to be a light ($\sim$1.2 $M_\odot$) NS; the system would then be highly asymmetric. A search for radio pulsations from the companion yielded no plausible detections, so we cannot yet confirm this mass asymmetry. By the end of 2016, timing observations should permit the detection of two additional post-Keplerian parameters: the Einstein delay (γ), which will enable precise mass measurements and a verification of the possible mass asymmetry of the system, and the orbital decay due to the emission of gravitational waves ($\dot{P}_b$), which will allow another test of the radiative properties of gravity. The latter effect will cause the system to coalesce in $\sim$0.5 Gyr.

Key words: binaries: general – gravitation – pulsars: general – pulsars: individual (PSR J1913+1102) – stars: neutron

PSR J1913+1102



Most massive DNS ever: 2.89 solar masses!



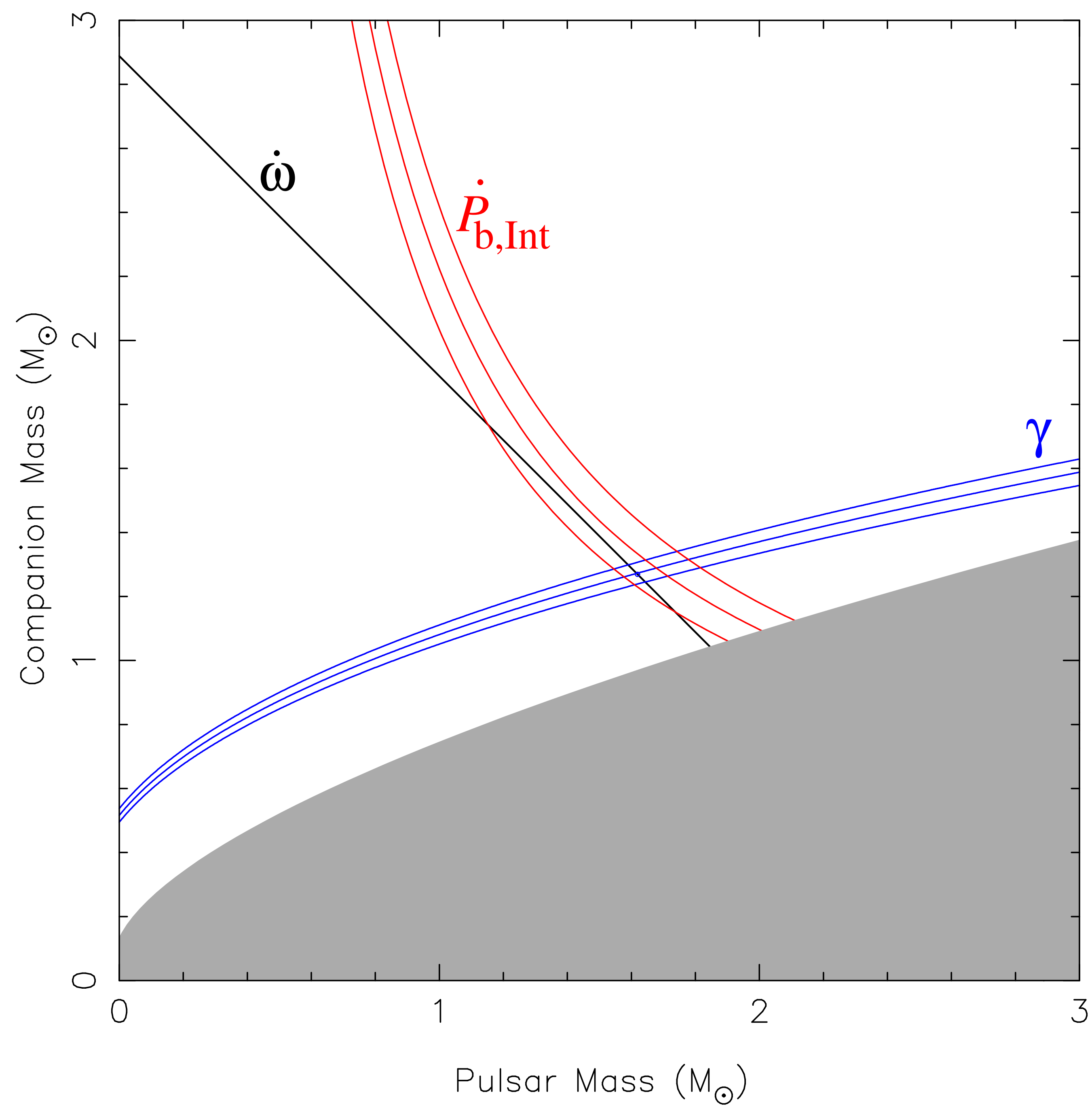
- In discovery paper, there was the suggestion (based on analogy with other low-eccentricity systems, represented by the open circles) that this system is highly asymmetric.

- This would be a big deal: system would then be sensitive to dipolar GWs, but with the advantages of DNSs: very precise measurements of masses and orbital decay!

PSR J1913+1102

<u>Latest timing confirms this!</u>

- Total mass (assuming GR): 2.8887(7) solar masses.
- Mass of the pulsar 1.62(3) solar masses, mass of the companion 1.27(3) solar masses.
- Orbital decay measured already to 15 sigma.
- It matches GR prediction - again, no dipolar GWs!



Freire, Wex, Shao et al. Phys. Rev. Lett, submitted

Mass of pulsar is in the gap!

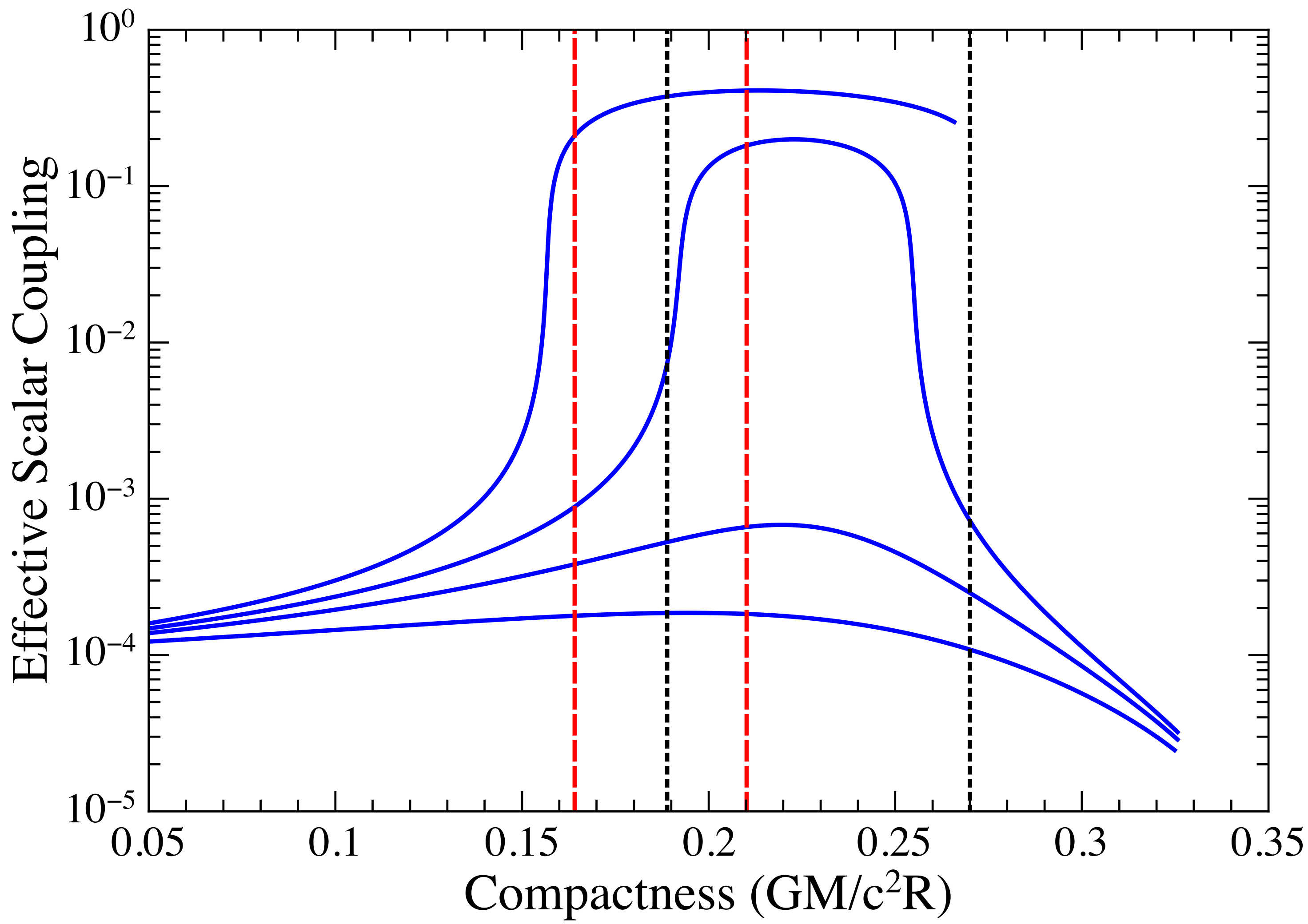


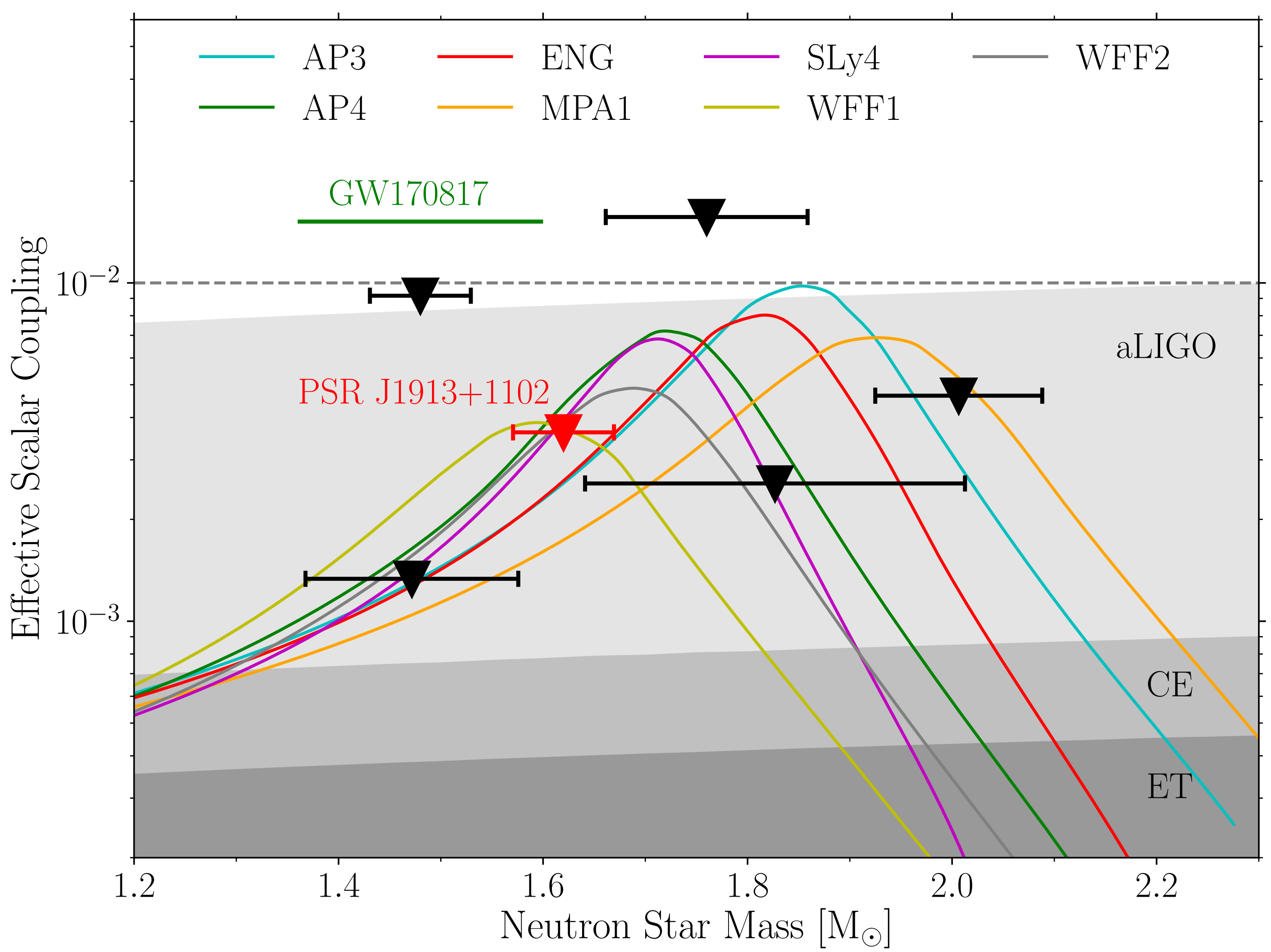
FIG. 2. Effective scalar coupling (α_A) as a function of neutron-star compactness (C_A), for $\alpha_0 = 10^{-4}$ and $\beta_0 = -3, -4, -4.5, -5$ (blue lines from bottom to top). The dashed red lines indicate the compactness of PSR J1913+1102 (right) and its companion (left). For comparison, the dotted black lines correspond to PSR J1738+0333 (left) and PSR J0348+0432. Calculations are based on EOS AP4 of [42]. Note, the blue curves are (nearly) insensitive to a change in the neutron-star EOS, while the compactness of a given NS can be significantly different for different EOSs.

Freire, Wex, Shao et al. Phys. Rev. Lett, submitted

Gap is closed: No spontaneous scalarization!

- The limits on coupling of matter with any extra scalar field already exclude spontaneous scalarization for the whole NS mass range.

- Any effects of scalar fields on insipralling orbits now beyond the reach of Adv. LIGO!



Freire, Wex, Shao et al. Phys. Rev. Lett, submitted

5. Conclusions

- *Symmetric NSs, like the double pulsar system, J0737-3039, are now providing extremely precise tests of the quadrupole formula. These limits win over LIGO tests for the lower PN orders by orders of magnitude.*

- *With pulsar - white dwarf systems like PSRs J1738+0333 and J0348+0432, we have been able to introduce strong constraints on coupling of matter to scalar fields. This has introduced strong constraints on DEF gravity, and many other theories.*

- *With a new double neutron star system, PSR J1913+1102, we have a NS mass intermediate between that of the previous pulsars. Orbital decay for this system excludes spontaneous scalarization.*

- *No DGW emission has been detected for the whole known mass range. This means that GWs are very purely quadrupolar, as expected from GR. <u>This is a fundamental constraint on the nature of gravitational radiation.</u>*

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: Özel & Freire (2016), ARAA, 54, 401