Tests of General Relativity with Pulsars

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BEACON

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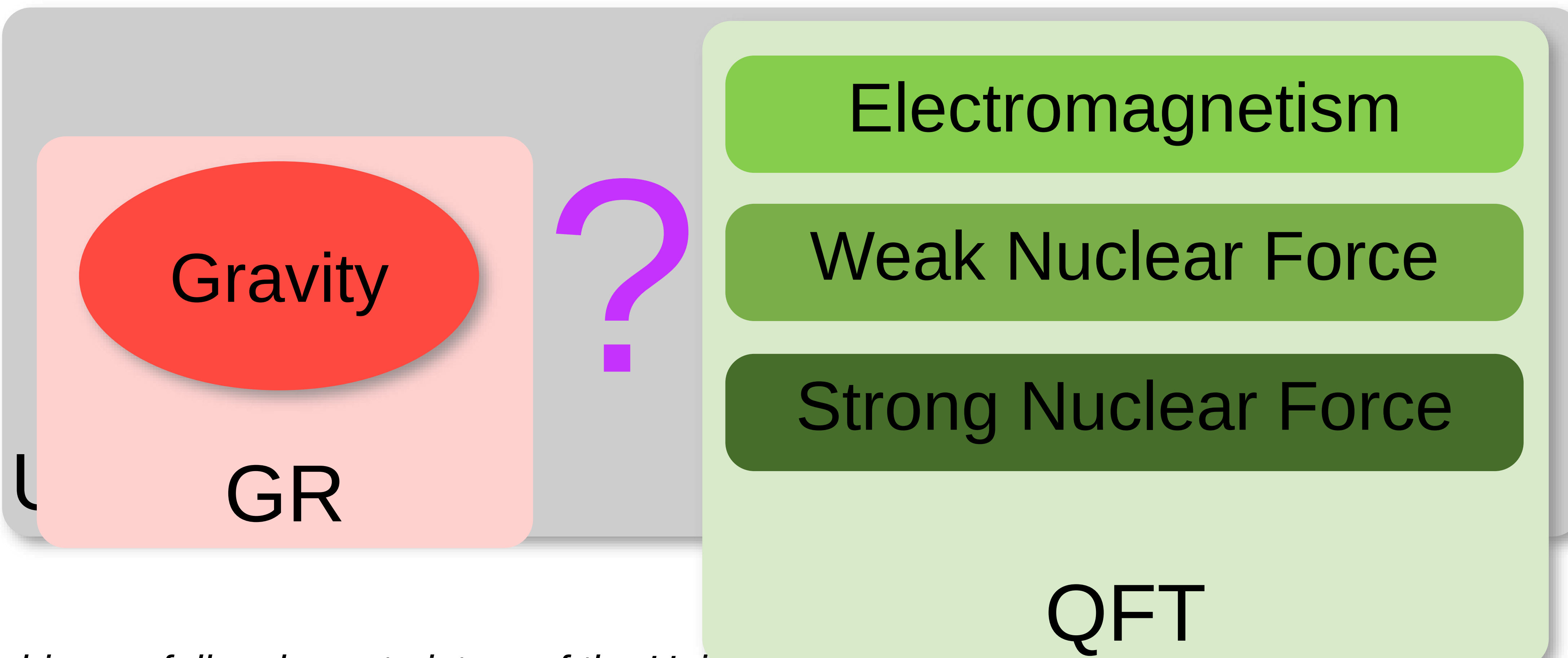
Topics:

- Testing gravity theories: Why do all this? Why do we bother?
- Pulsar timing
- PK timing parameters
- The classical tests – how we know gravitational waves exist
- Current tests with binary pulsars – physics experiments on the fundamental nature of gravitational waves.

Why testing gravity theories?

Nature's most universal and mysterious force



To achieve a full, coherent picture of the Universe, we must understand gravity.

Do we understand it? GR is not compatible with quantum mechanics – it must fail at the Planck scale – furthermore, it is incomplete (singularities). *Therefore, its is not the last word on gravity!*

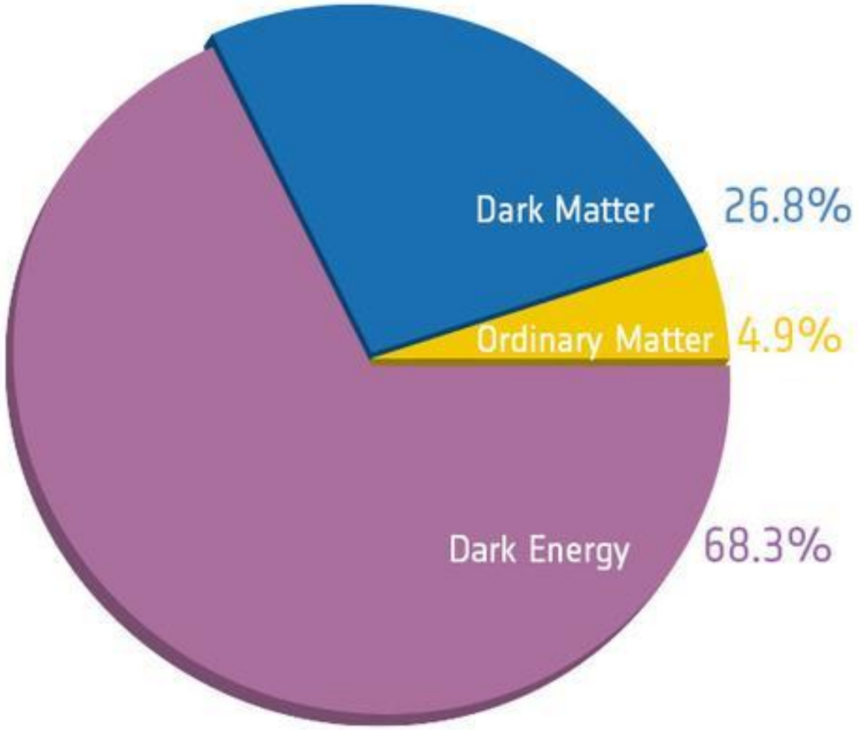
More reasons to doubt Einstein…

We don‘t know many things:

What caused cosmic inflation?

What is Dark Matter?

What is Dark Energy?



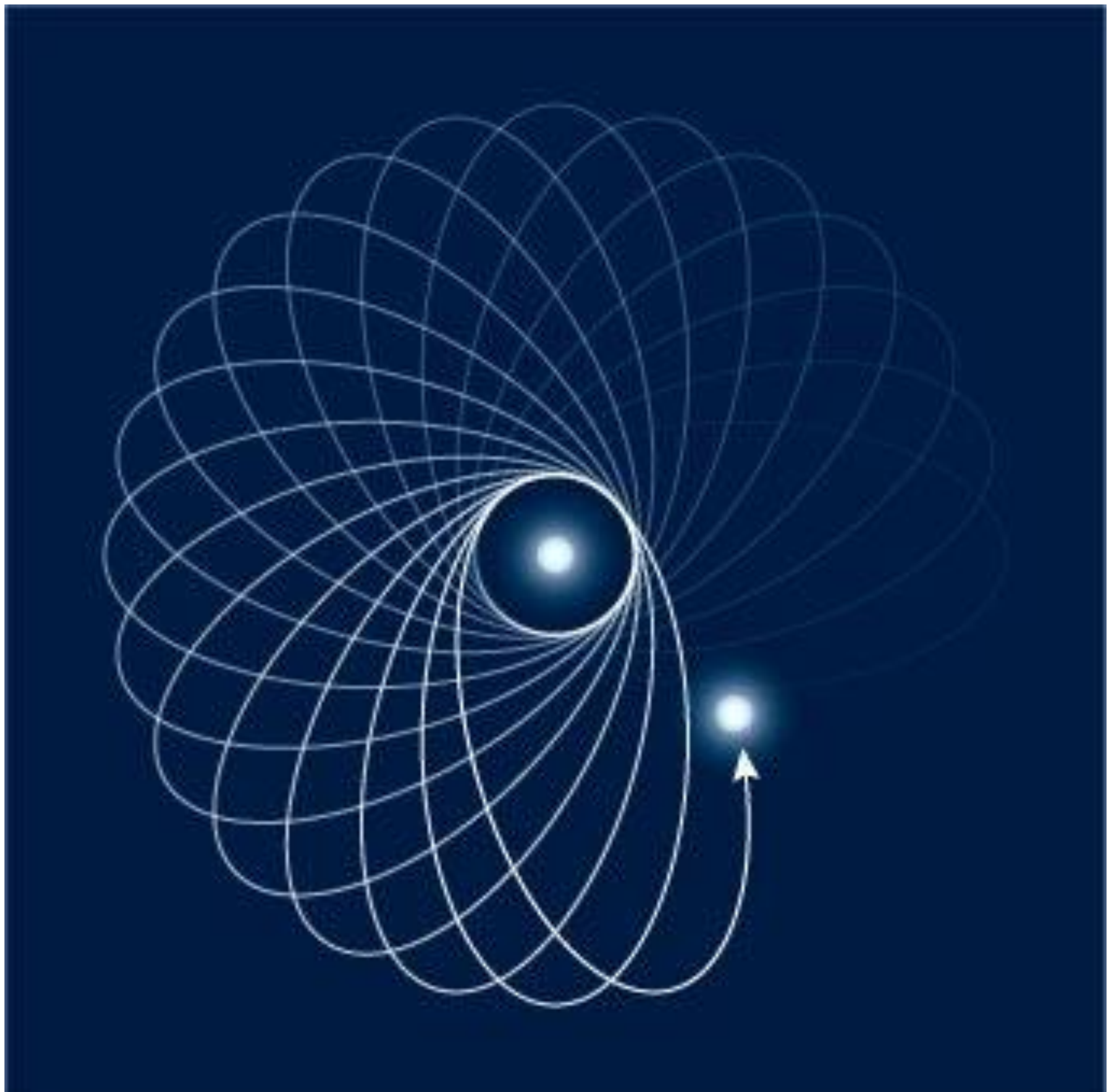
Cosmic "makeup". Credit: ESA/Planck

- *Instead of this many new fields, could our understanding of gravity be at fault?*

- MANY alternative theories of gravity have been proposed to explain these phenomena, **with significant deviations from GR well below the Planck scale - at energies that can be observed in binary pulsar experiments**!

- Thus, falsifying or confirming such theories has implications beyond the study of gravity – also for the study of the origin, evolution and contents of our Universe.

Testing general relativity

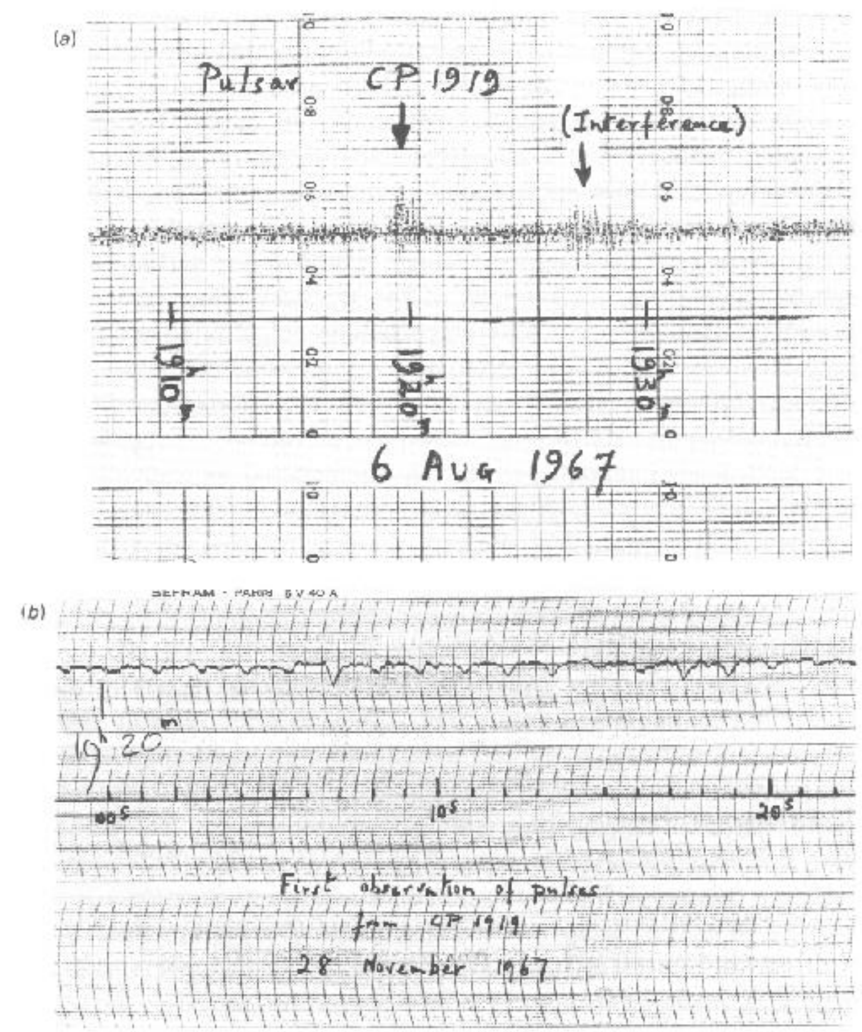


- Einstein published the field equations of general relativity in November 1915.
- General relativity has since passed *all* experimental tests!
- Until 1974, all tests of this theory were made in the Solar System (weak fields, low velocities)
- What if that's not the case?

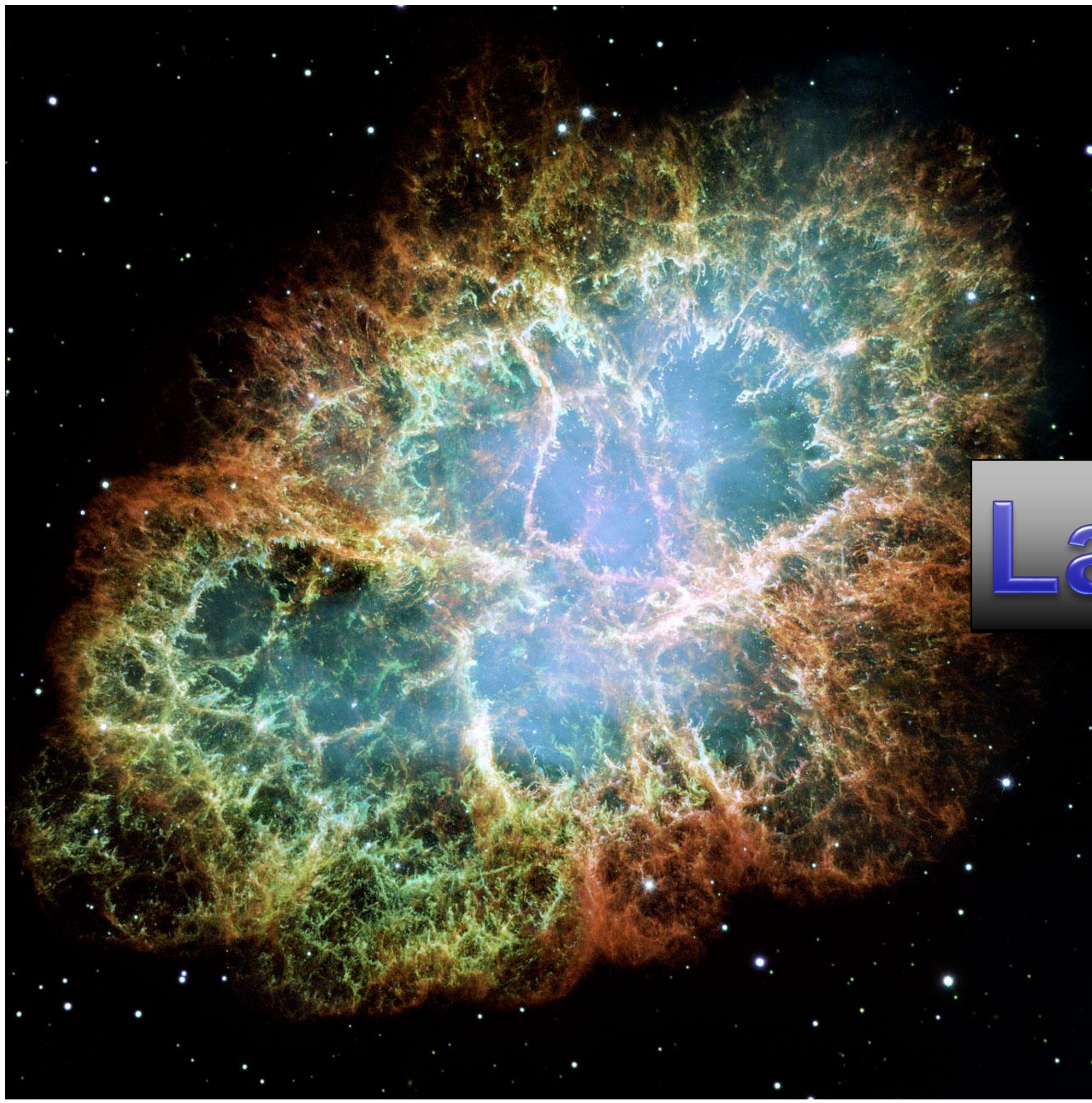
Pulsars!

- In August 1967, Jocelyn Bell finds a radio signal in the constellation Sagitta (the Little Arrow) pulsating with a period of 1.33 seconds. She found this to appear 4 minutes earlier every day, indicating a sidereal source.

- For this discovery, Anthony Hewish earns the Nobel Prize in Physics 1974.



What are pulsars?



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

POINT MASSES

Large Binding Energy

Density in the core is several hundred million

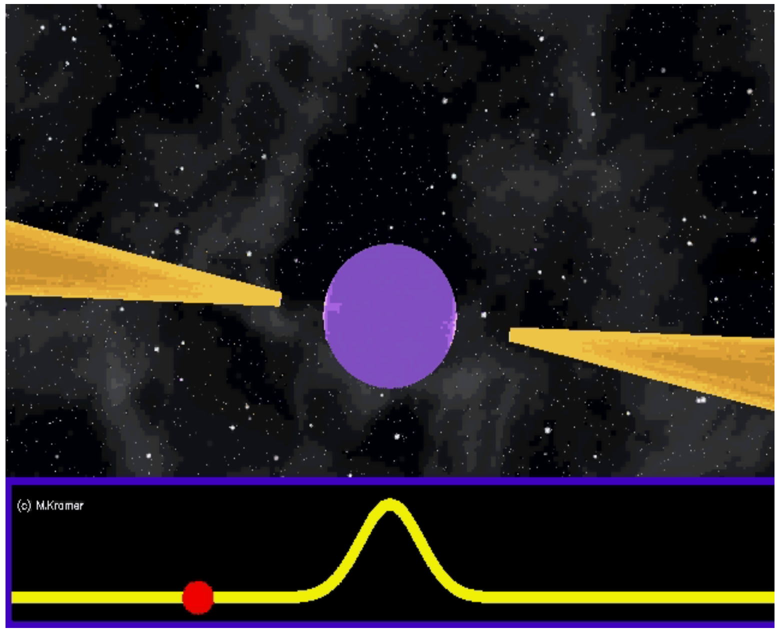
This stuff is so dense we don’t know what it is.

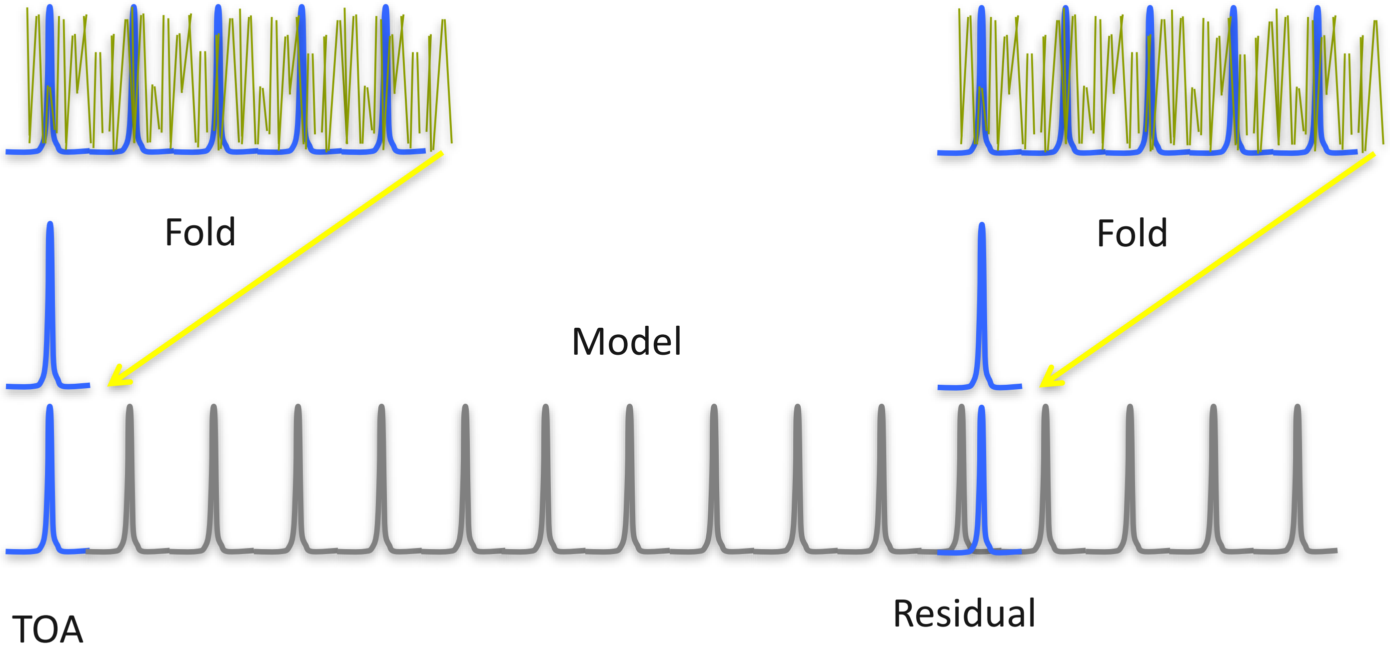
We can time them clearly!

Pulsar timing

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

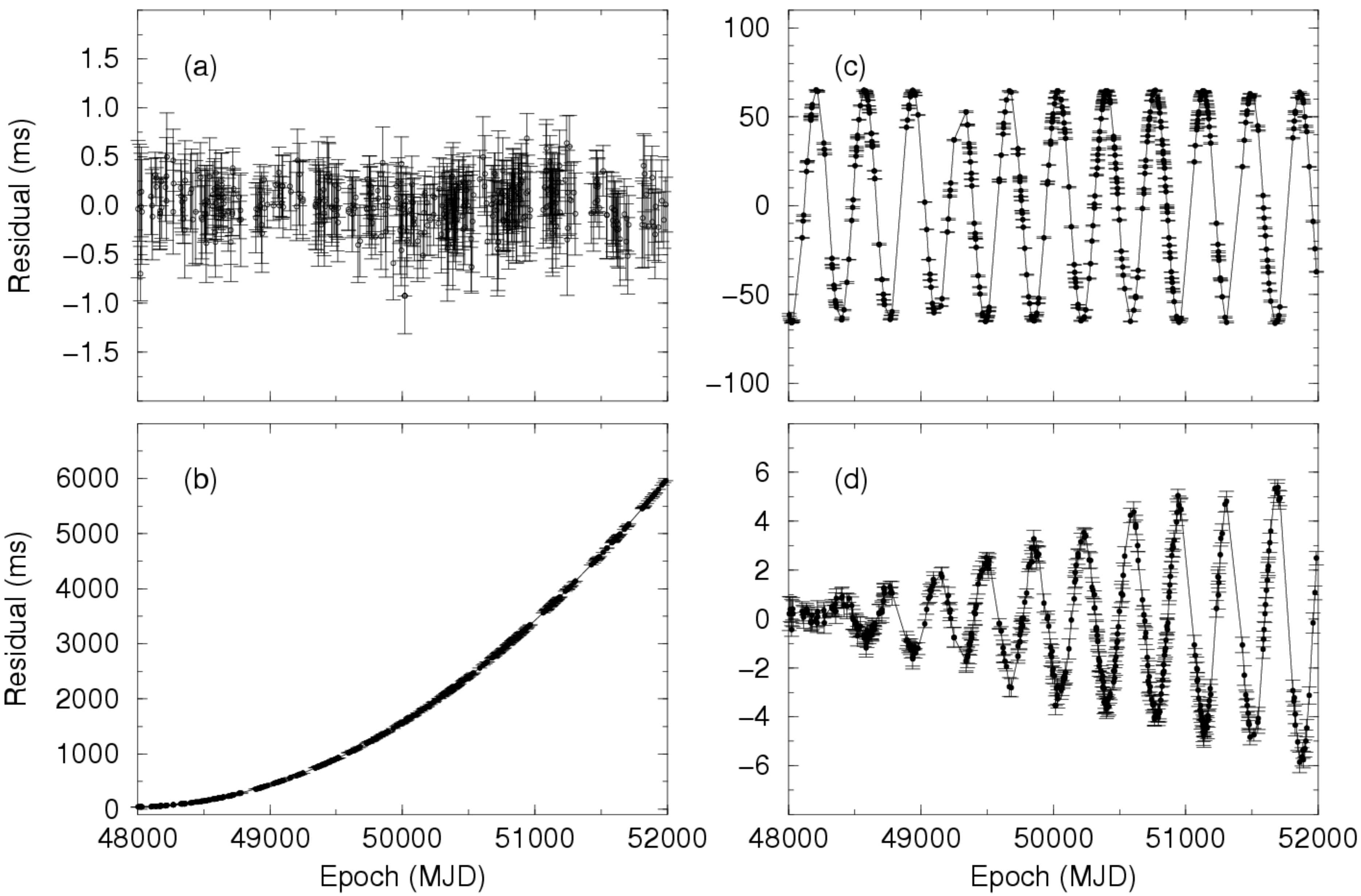
Pulsar timing measures pulsar arrival time at the telescope (TOA):





Pulsar timing

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



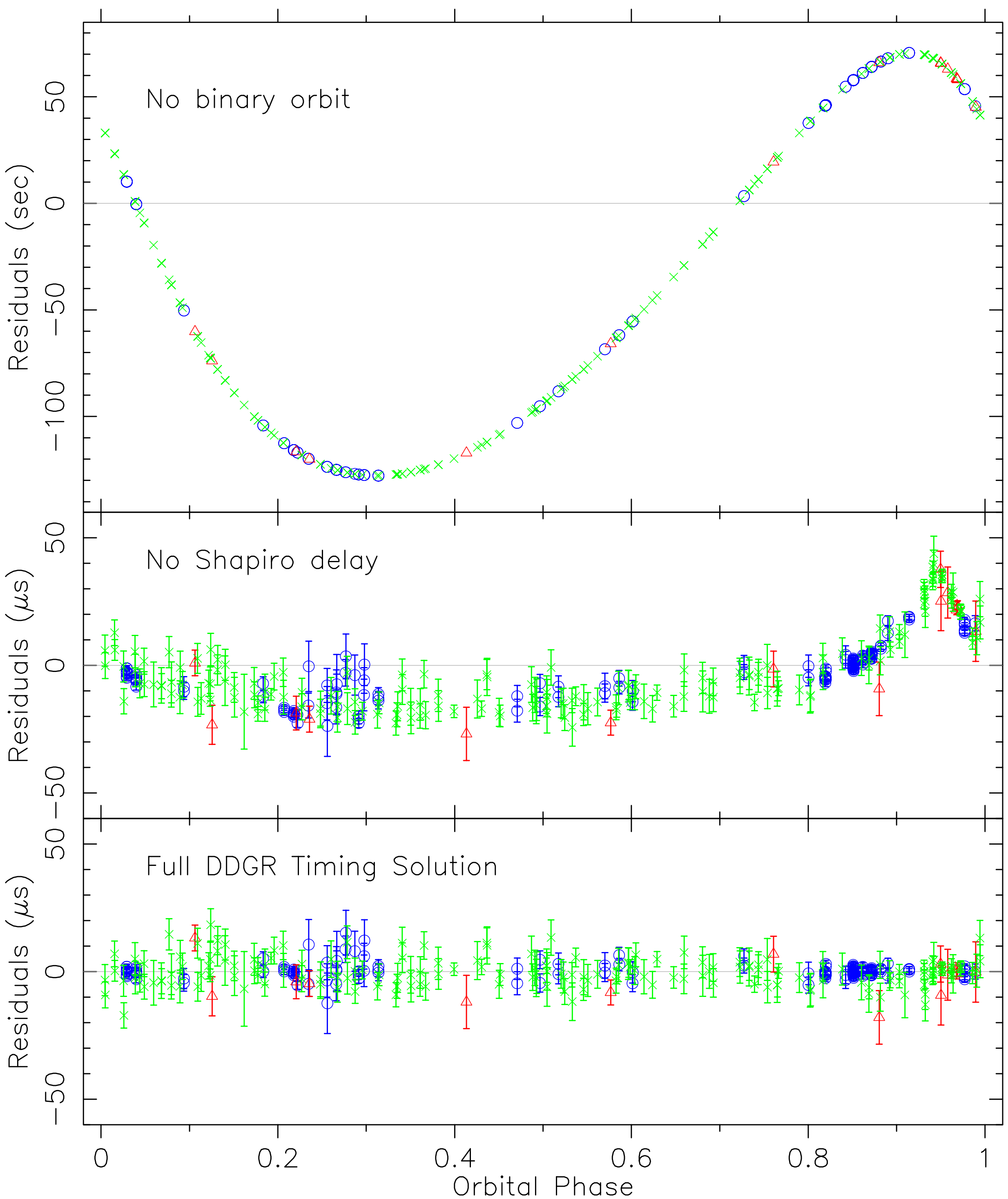
From: ``The Pulsar Handbook'', Lorimer & Kramer 2005

The potential of binary pulsars

- In his NSF grant application, Joseph Taylor applied for funds to conduct a survey for pulsars in the Galactic plane using the Arecibo 305-m radio telescope, which at the time had just received a new surface that greatly enhanced its sensitivity at 430 MHz.

- In this grant application, he specifically alluded to the possibility of finding a binary pulsar, a potentially very exciting tool for testing general relativity!

Why is that exciting?



- In a binary pulsar, having a clock in the system allows us to measure the <u>*range*</u> relative to the center of mass of the binary.
- The 5 Keplerian orbital parameters derived from pulsar timing are <u>thousands of times</u> more precise than derived from Doppler measurements – *with the same observational data*!
- <u>This feature is unique to pulsars</u>, 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 CLEAN!!!!!

The discovery of “the” 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*!

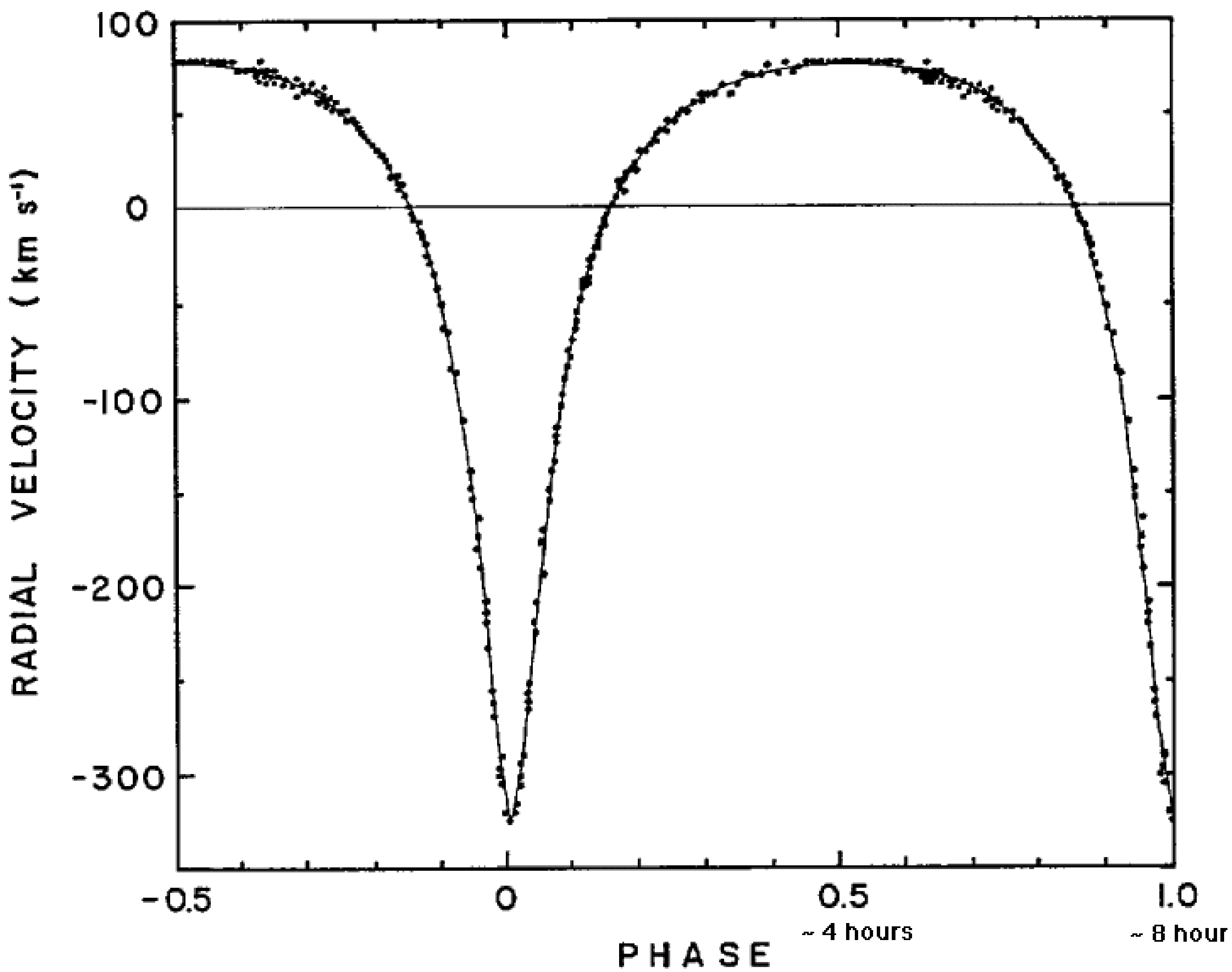


TABLE 1

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	$< 1 \times 10^{-12}$
DM	$= 167 \pm 5$ cm^{-3} pc
S_{430}	$= 0.006 \pm 0.003$ Jy
W_e	< 10 ms

TABLE 2

ELEMENTS OF THE ORBIT

K_1	$= 199 \pm 5$ km s^{-1}
P_b	$= 27908 \pm 7$ s
e	$= 0.615 \pm 0.010$
ω	$= 179° \pm 1°$
T	$=$ 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

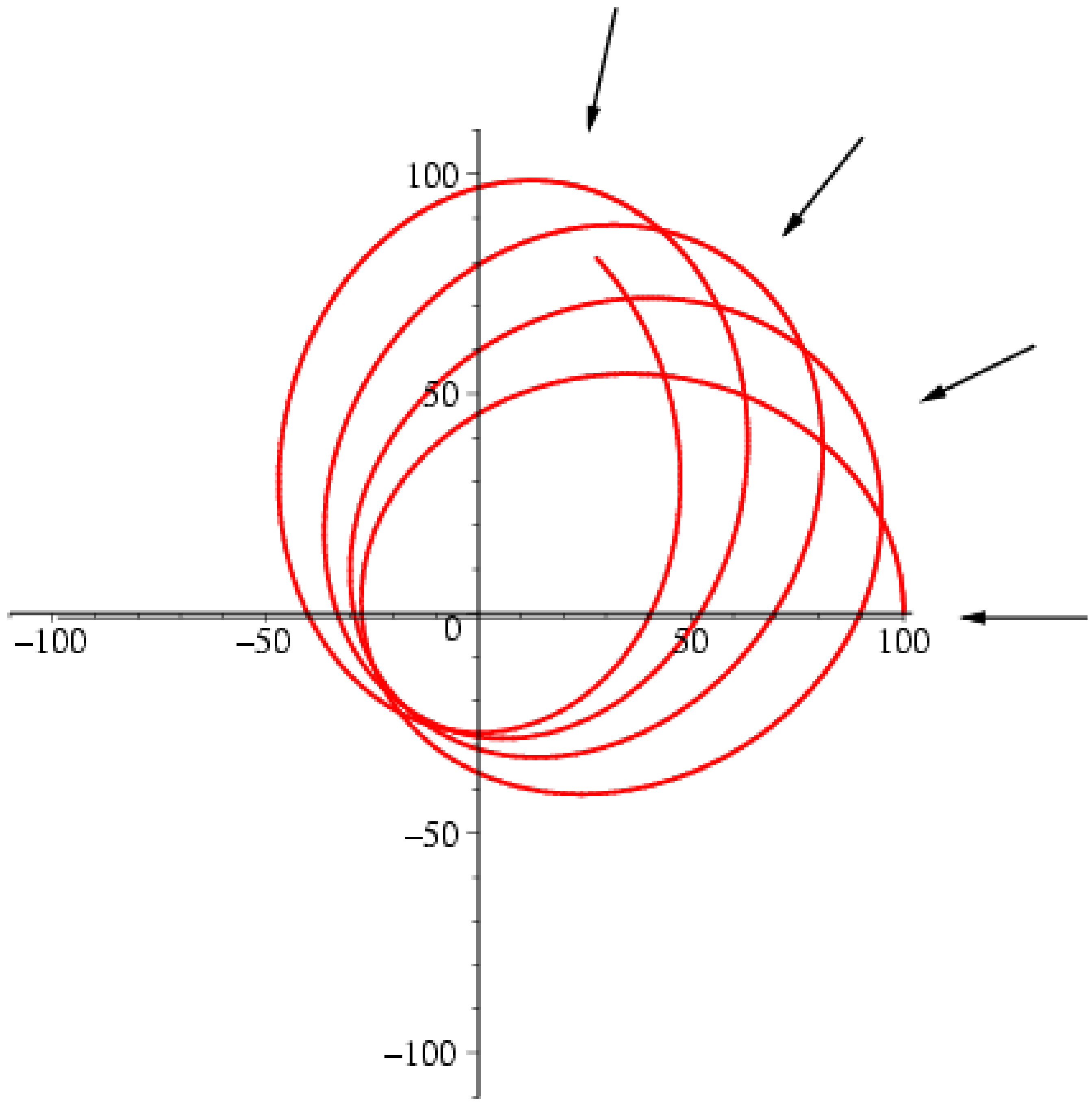
The mass function

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

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

One equation, three (known) unknowns! ☹

PK timing parameters

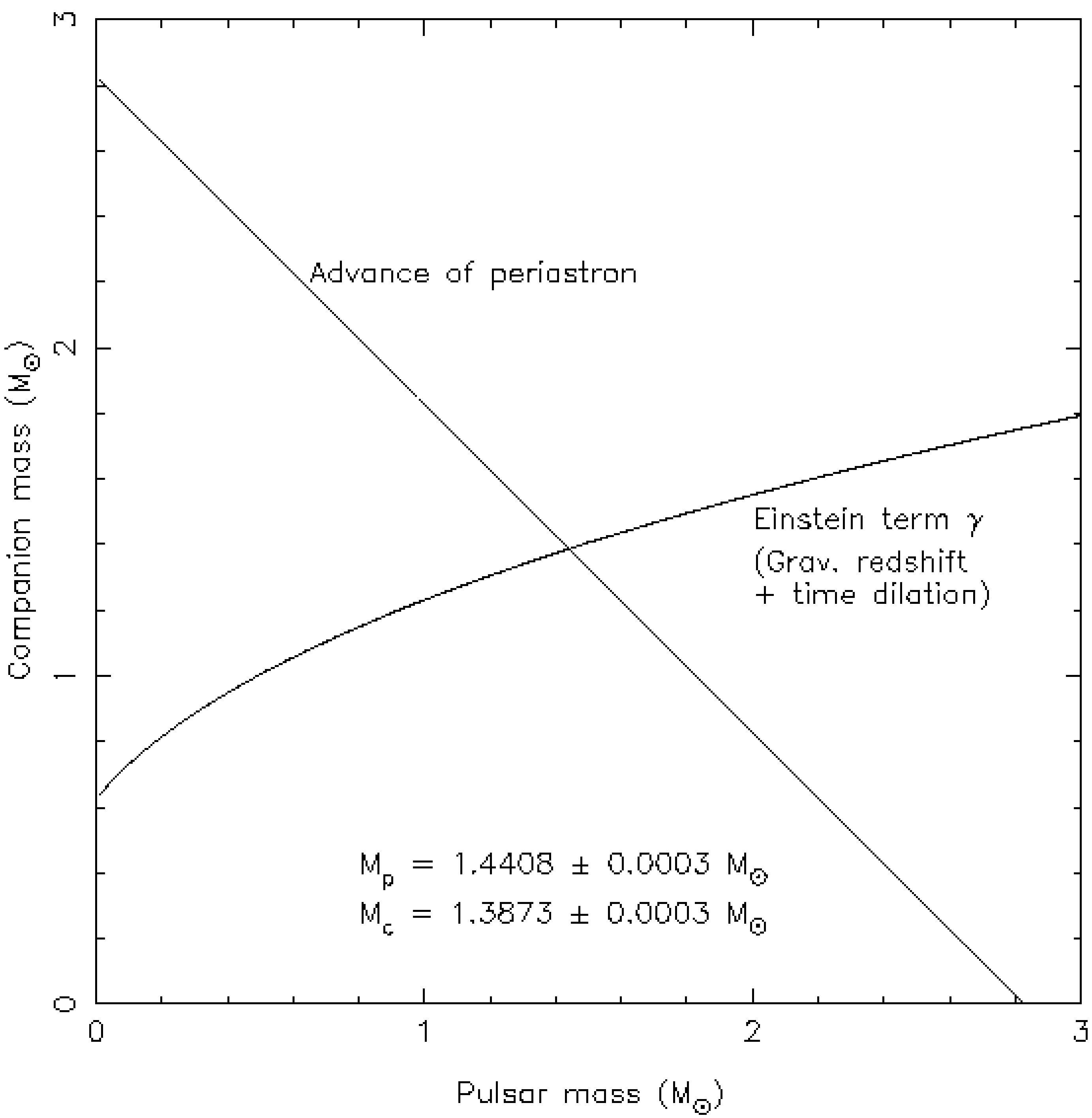


- **IF** a binary pulsar is compact and eccentric – which B1913+16 certainly is – the timing precision allows the measurement of several relativistic effects.

- The periastron of PSR B1913+16 advances 4.226607(7) degrees/year.

- The Einstein delay was also measured: γ = 0.004294(1)s!

PSR B1913+16



Assuming GR:

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

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.

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).

PSR B1913+16

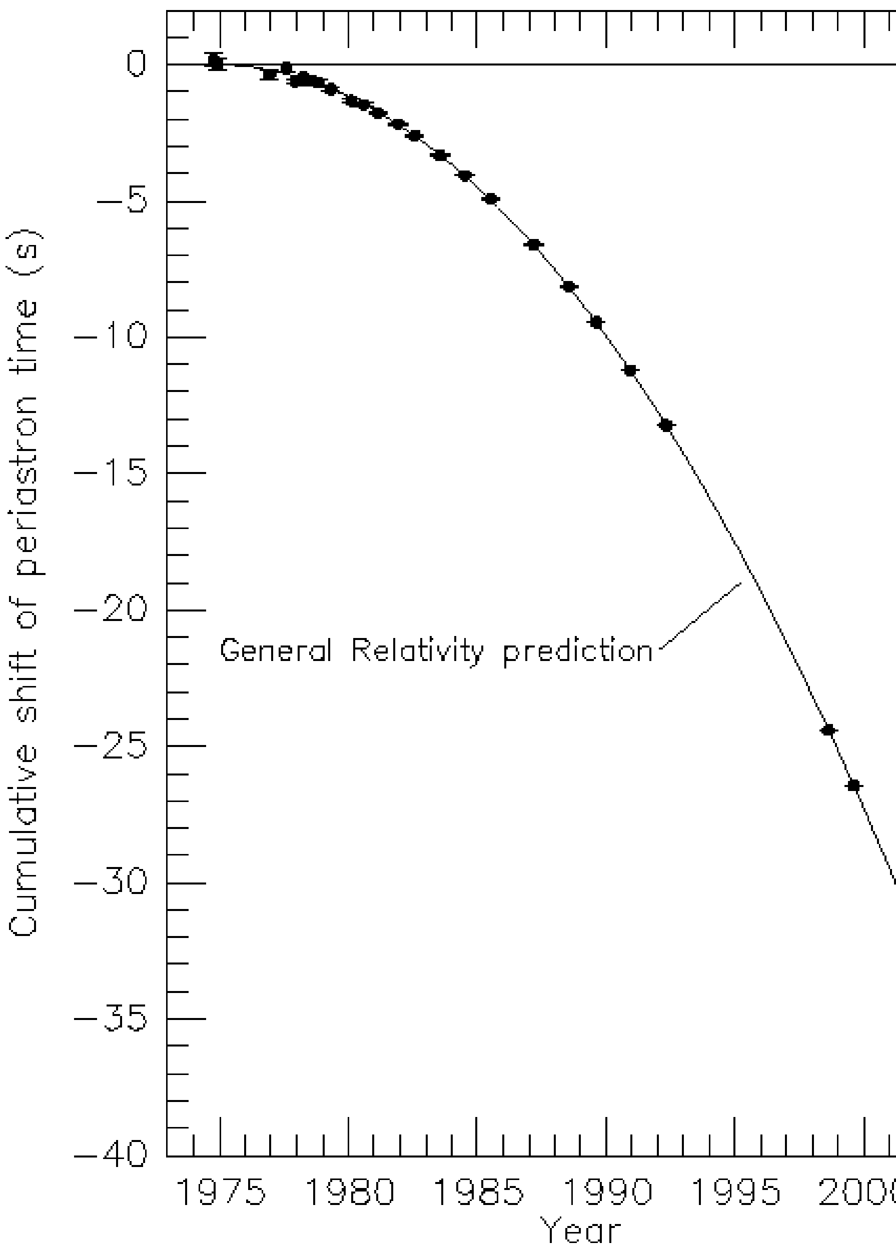
- *A third relativistic effect soon became measurable!*

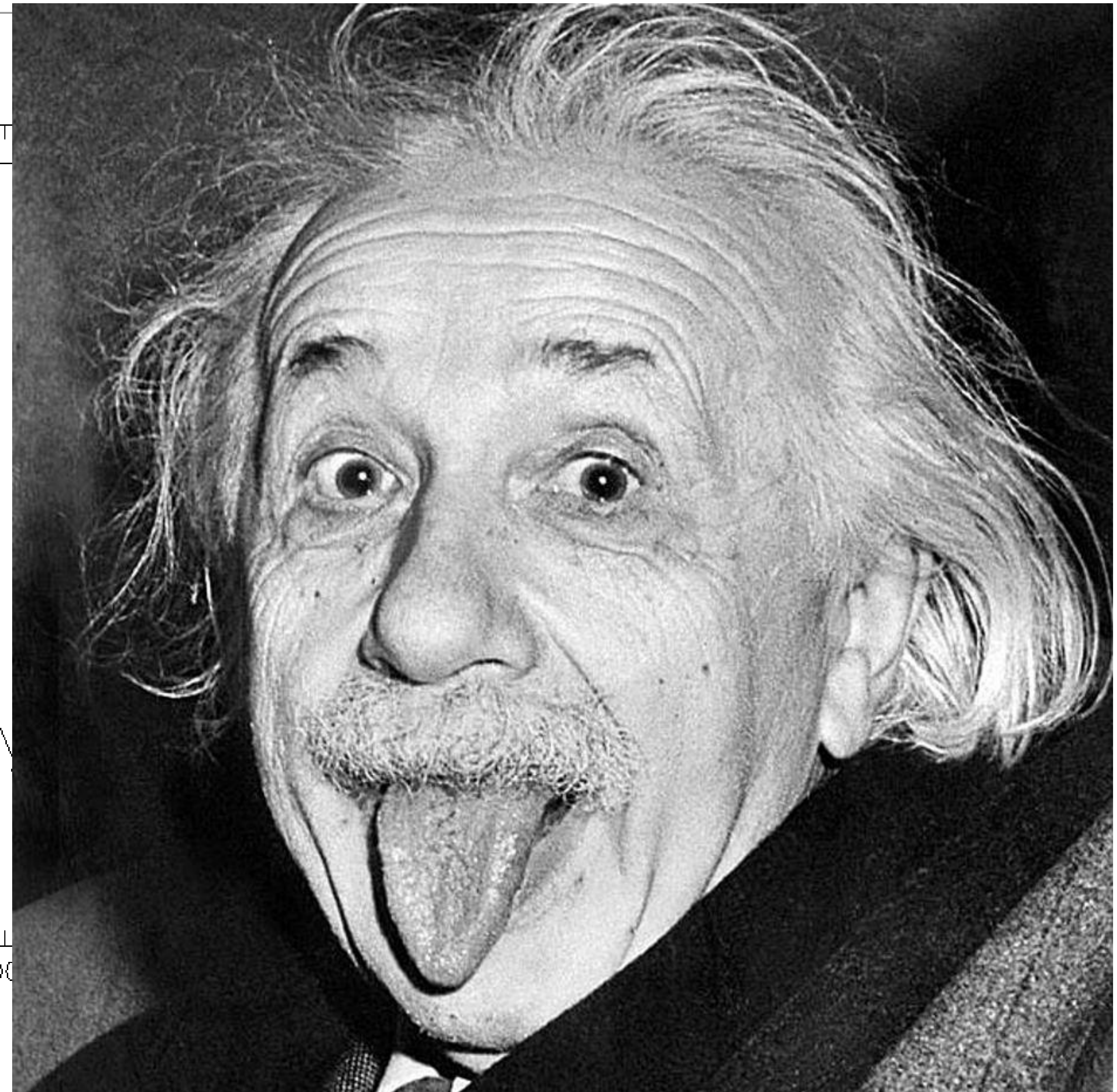
$$\dot{P}_b = -\frac{192}{5} n_b^{5/3} f_e m_1 m_2 M^{-1/3} T_\odot^{5/3}$$
$$f_e = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1 - e^2)^{-7/2}$$

- 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


0
−5
−10
−15
−20
−25
−30
−35
−40
Cumulative shift of periastron time (s)
General Relativity prediction
1975
1980
1985
1990
1995
Year



Gravitational Waves Exist!!

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*.''

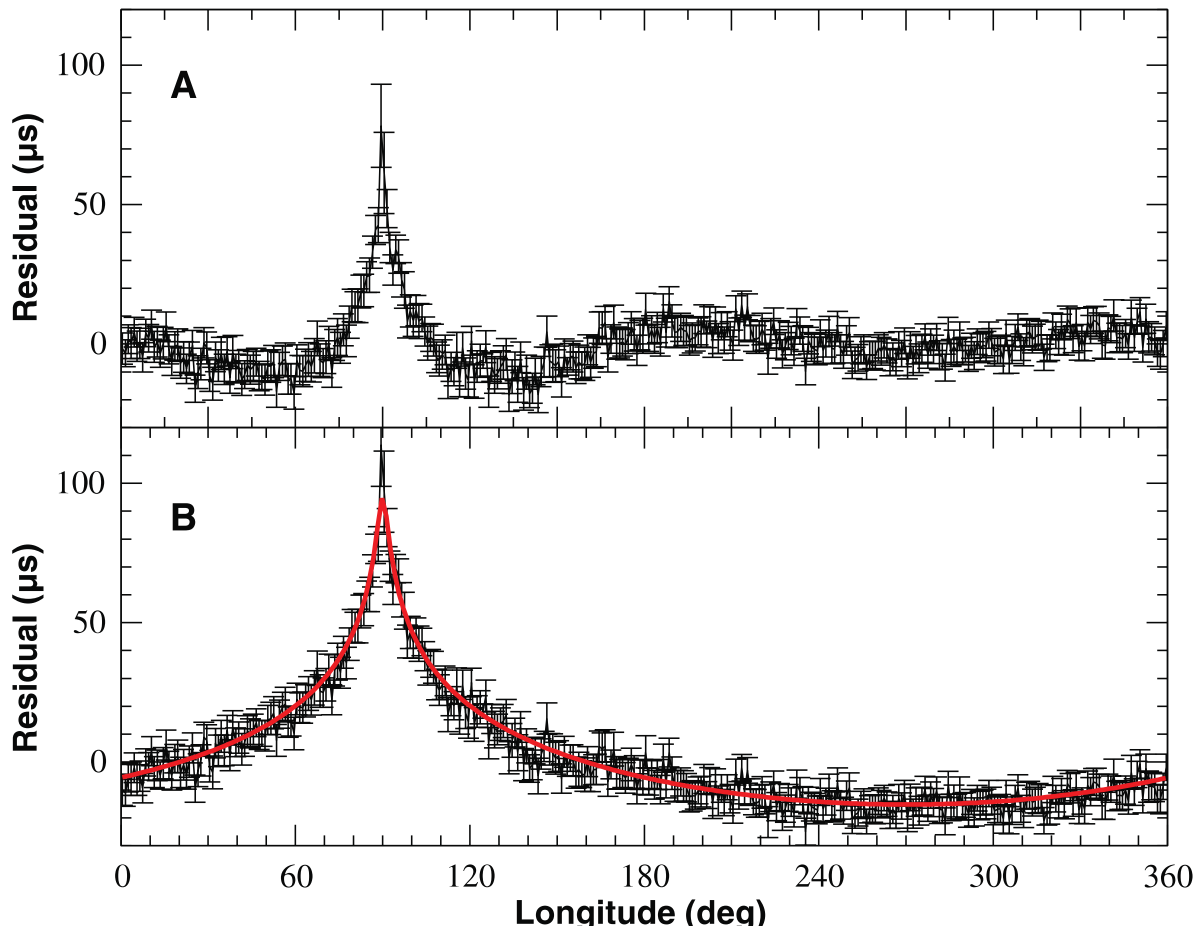
Damour, 2014, arXiv:1411.3930v1. He adds:

``*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)

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

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

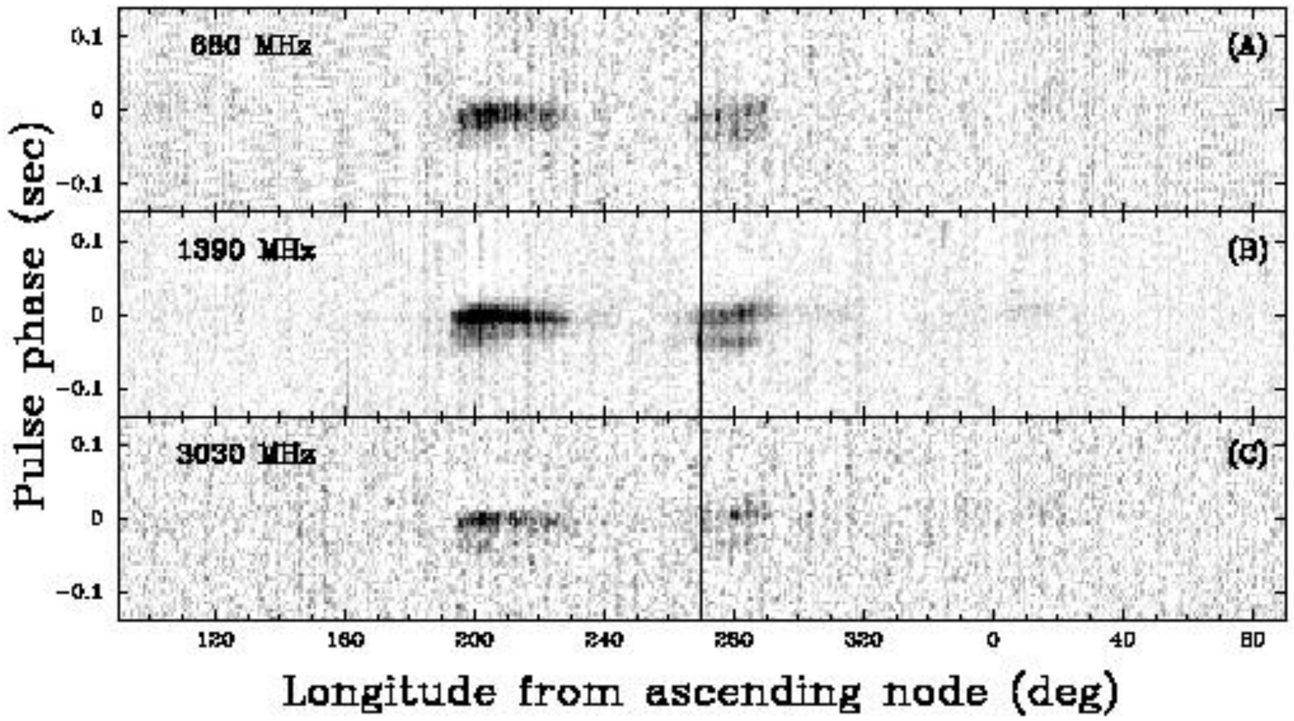
$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3}\, m_2(m_1+2m_2), \tag{32}$$

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

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

PSR J0737−3039

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



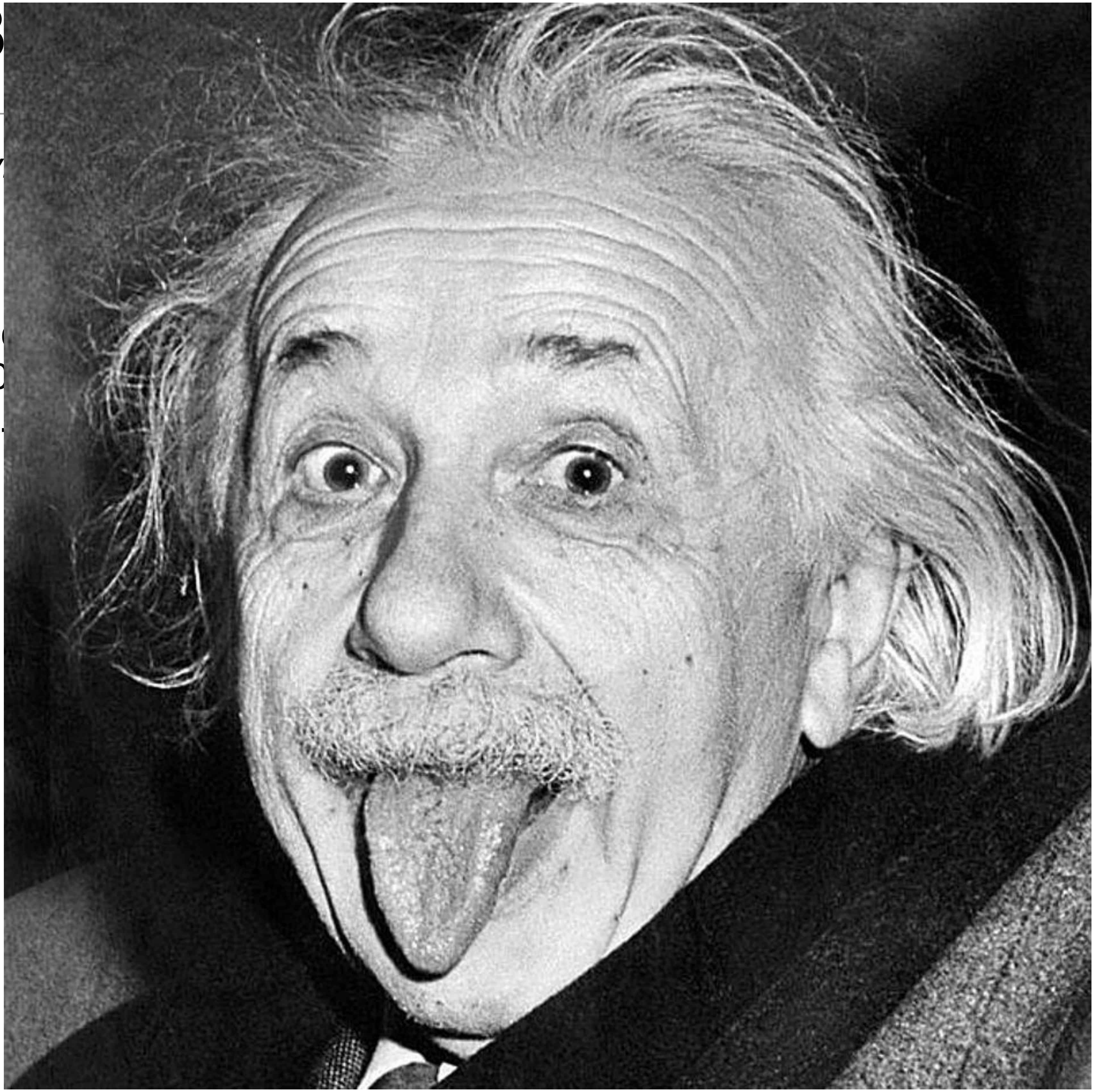
$$\boxed{R = m_A / m_B = x_B / x_A}$$

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

PSR J0737−303

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

- There is a fifth test, from geo
  precession of PSR J0737−30
  (Breton et al. 2008, Science).



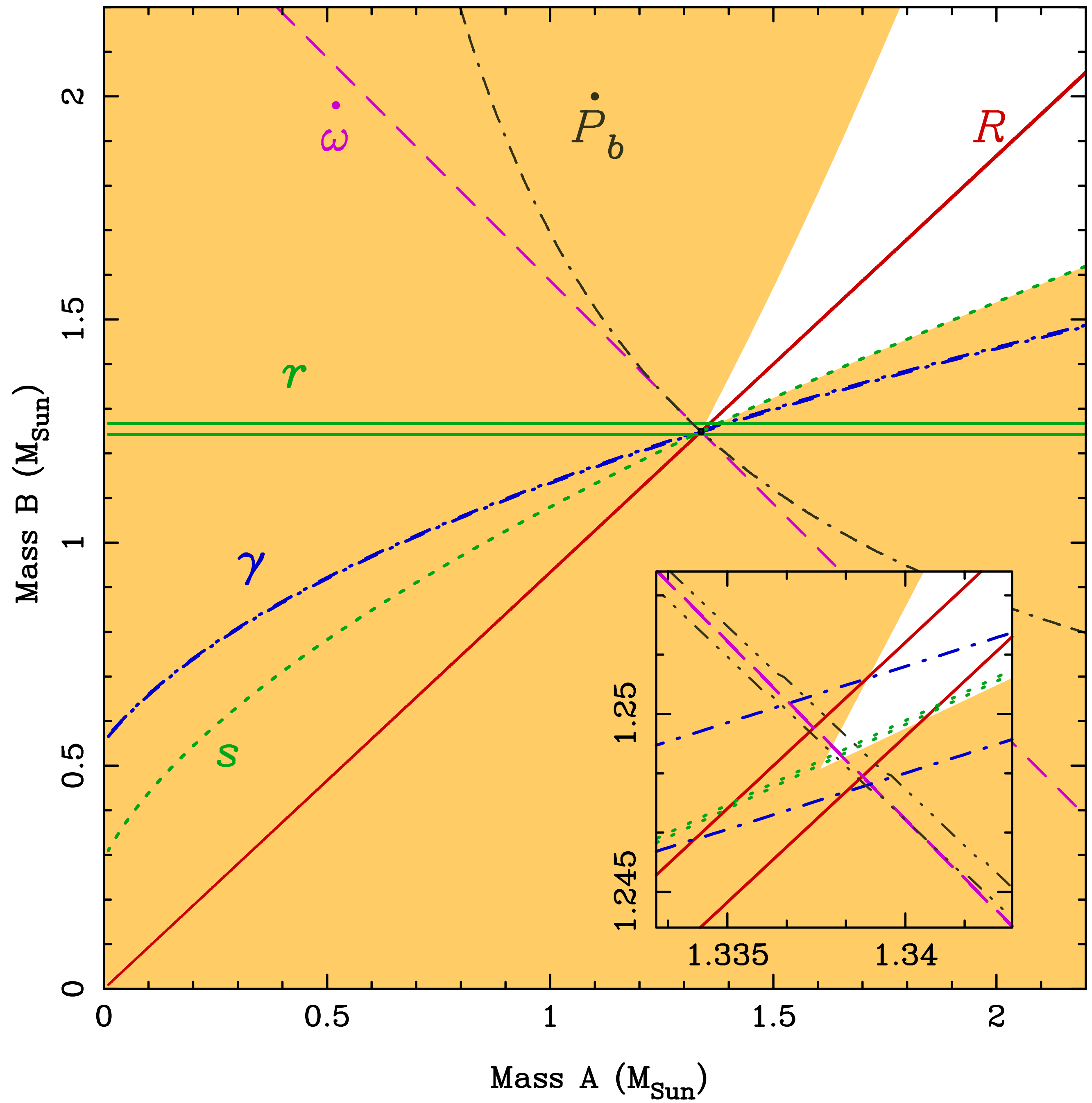
Kramer et al. 2006, Science, 314, 97

PSR J0737−3039: timing solution

Timing parameter	PSR J0737-3039A	PSR J0737-3039B
Right ascension α	$07^h37^m51^s.24927(3)$	—
Declination δ	$-30°39'40''.7195(5)$	—
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)

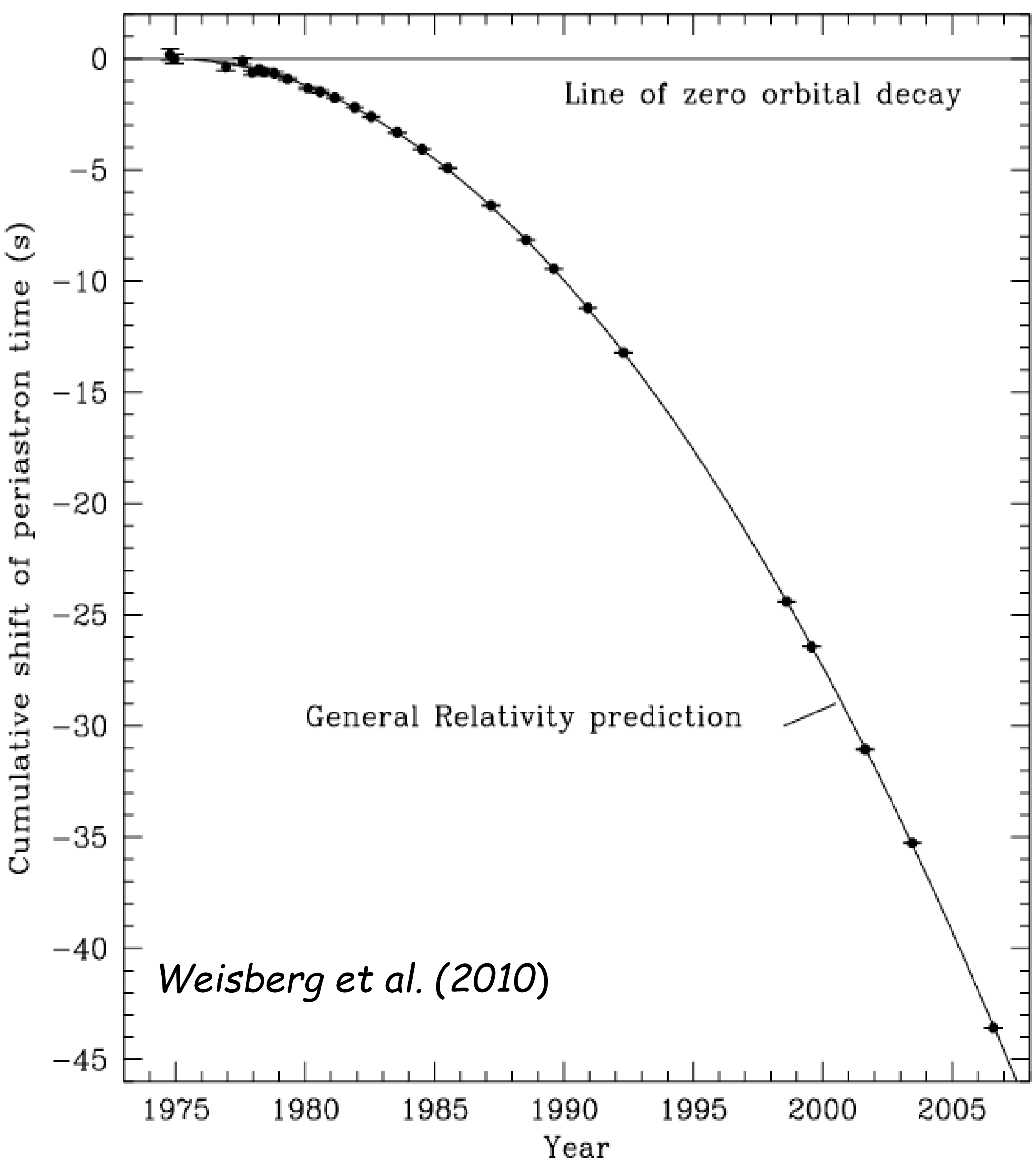
PSR J0737−3039

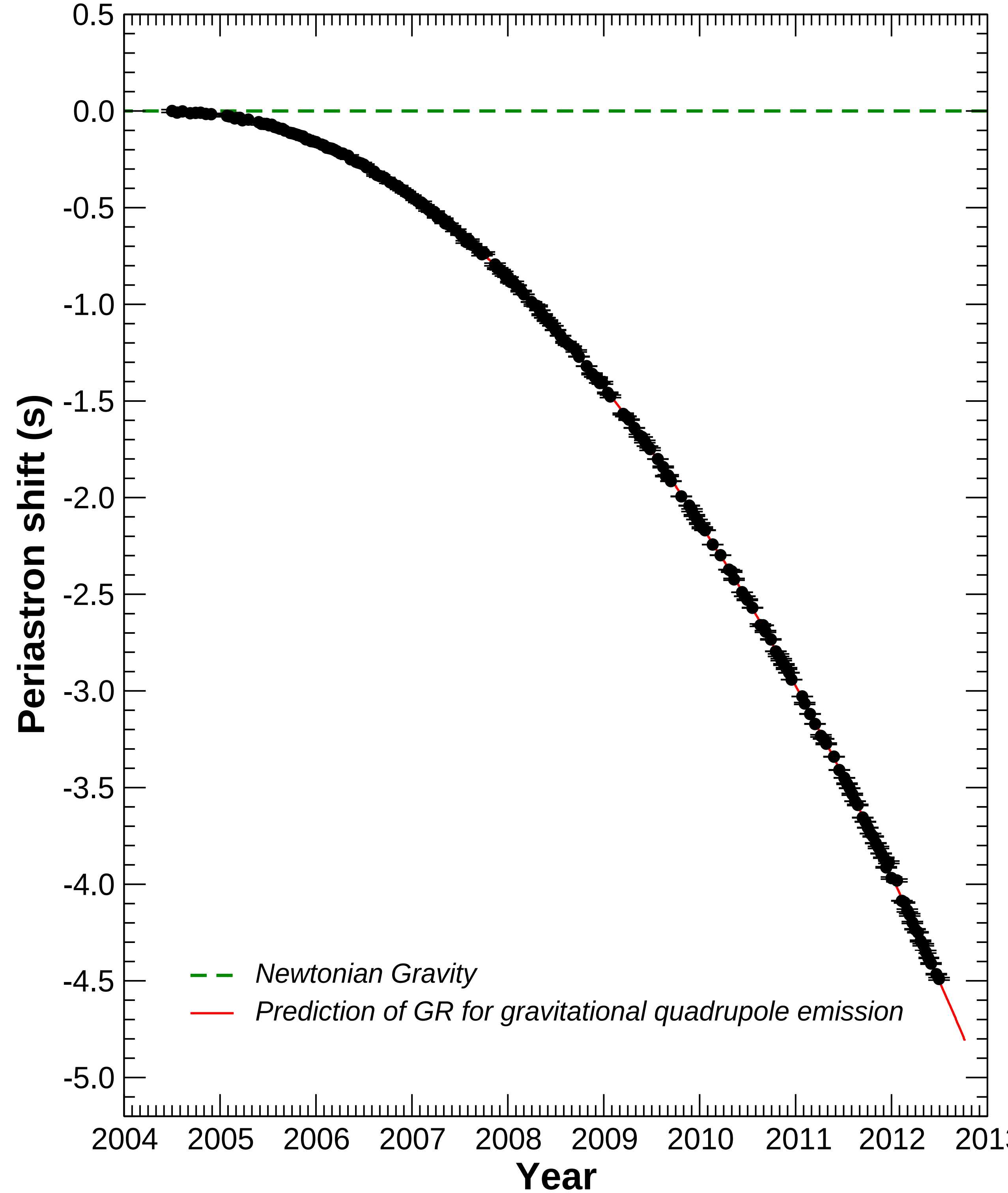
Kramer et al., in prep.



PSR J0737−3039

Kramer et al. (in prep.)





Experiments on the Nature of Gravitational Radiation

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):

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

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.**

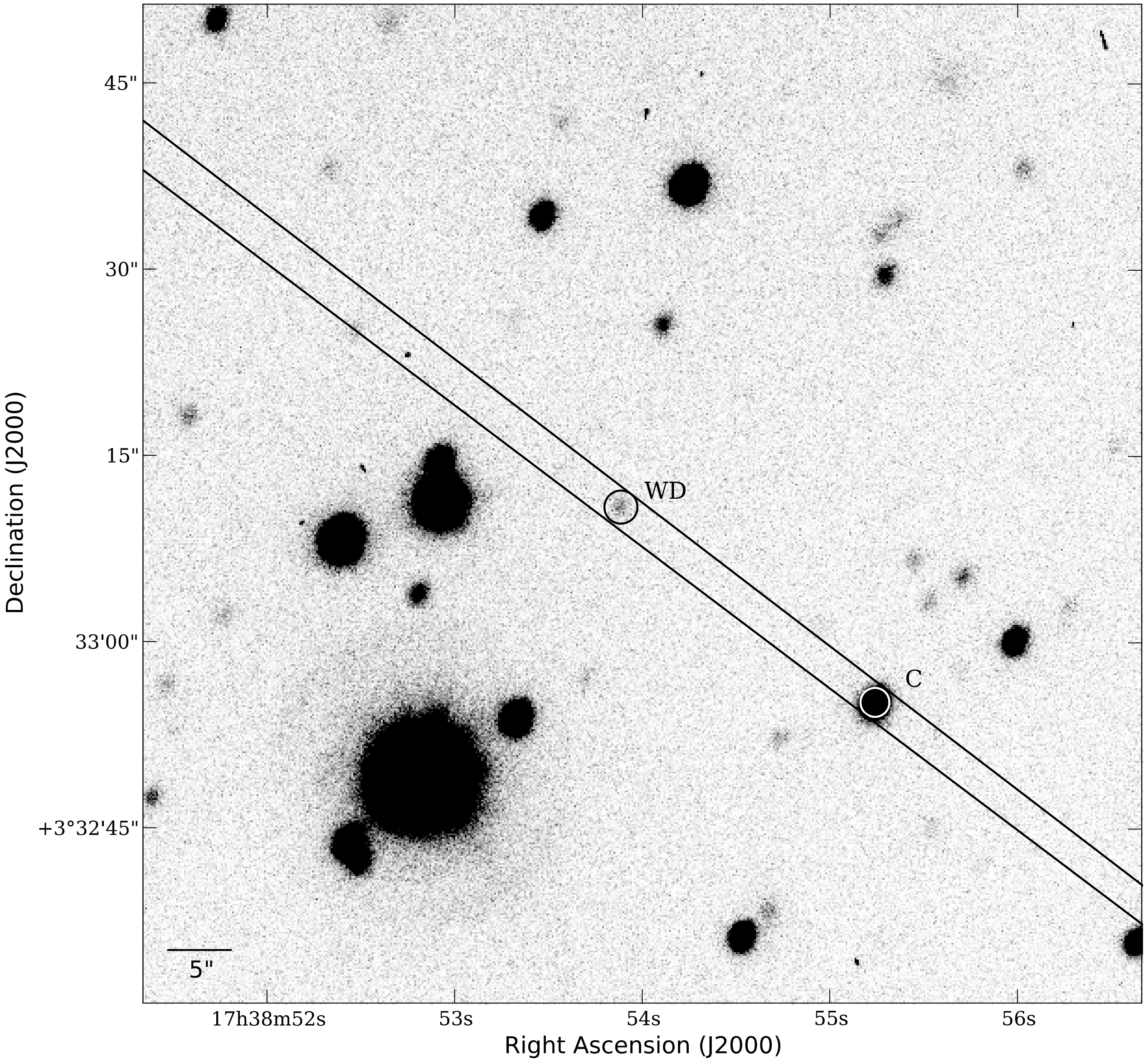
- **Detecting <u>any</u> of these effects would falsify GR**!

- 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!

Sometimes we're lucky!

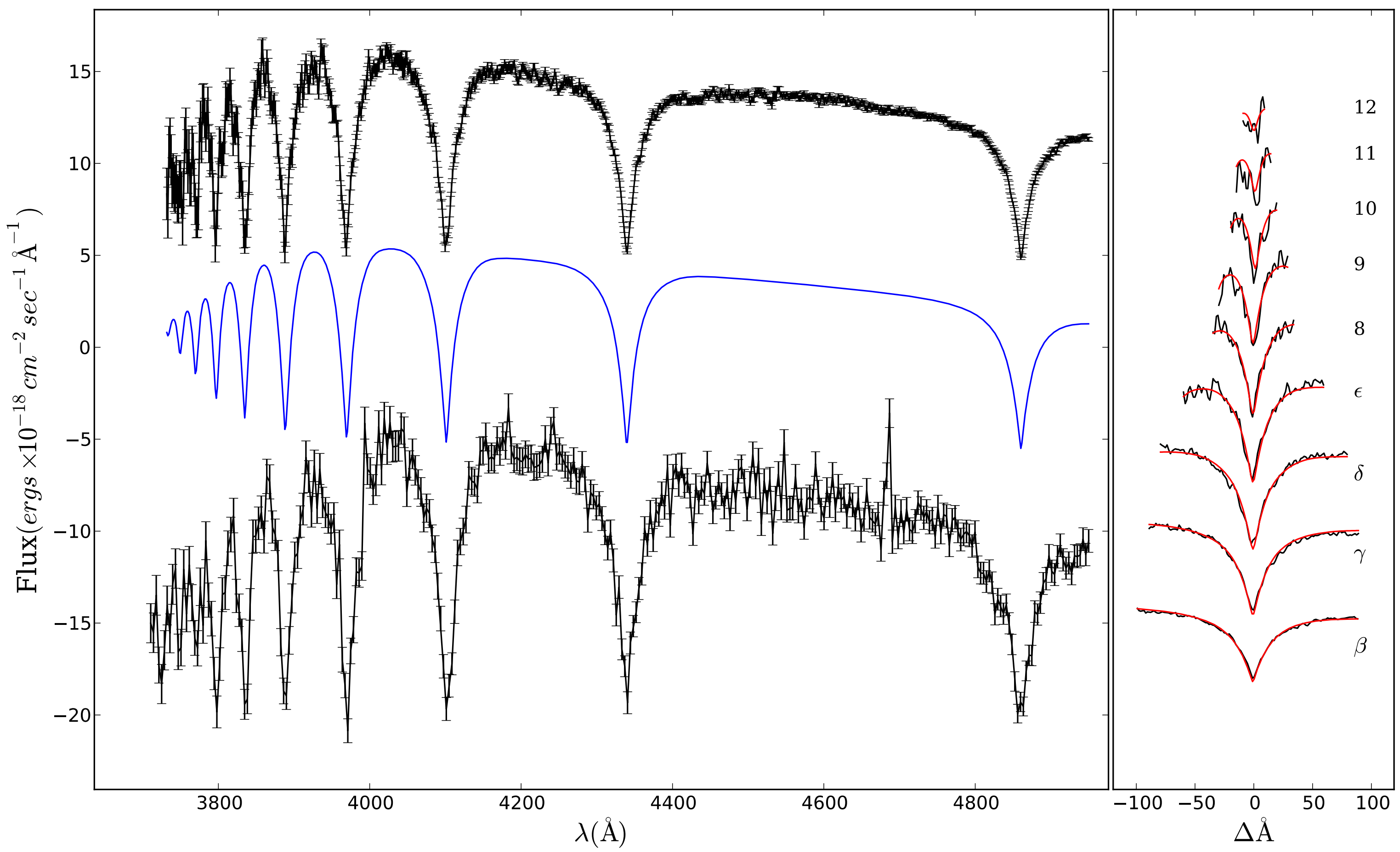
- PSR J1738+0333 is a 5.85-ms pulsar in a 8.5-hour, low eccentricity orbit. It was discovered in 2001 in a Parkes Multi-beam high-Galactic latitude survey (Jacoby 2005, Ph.D. Thesis, Caltech).

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



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

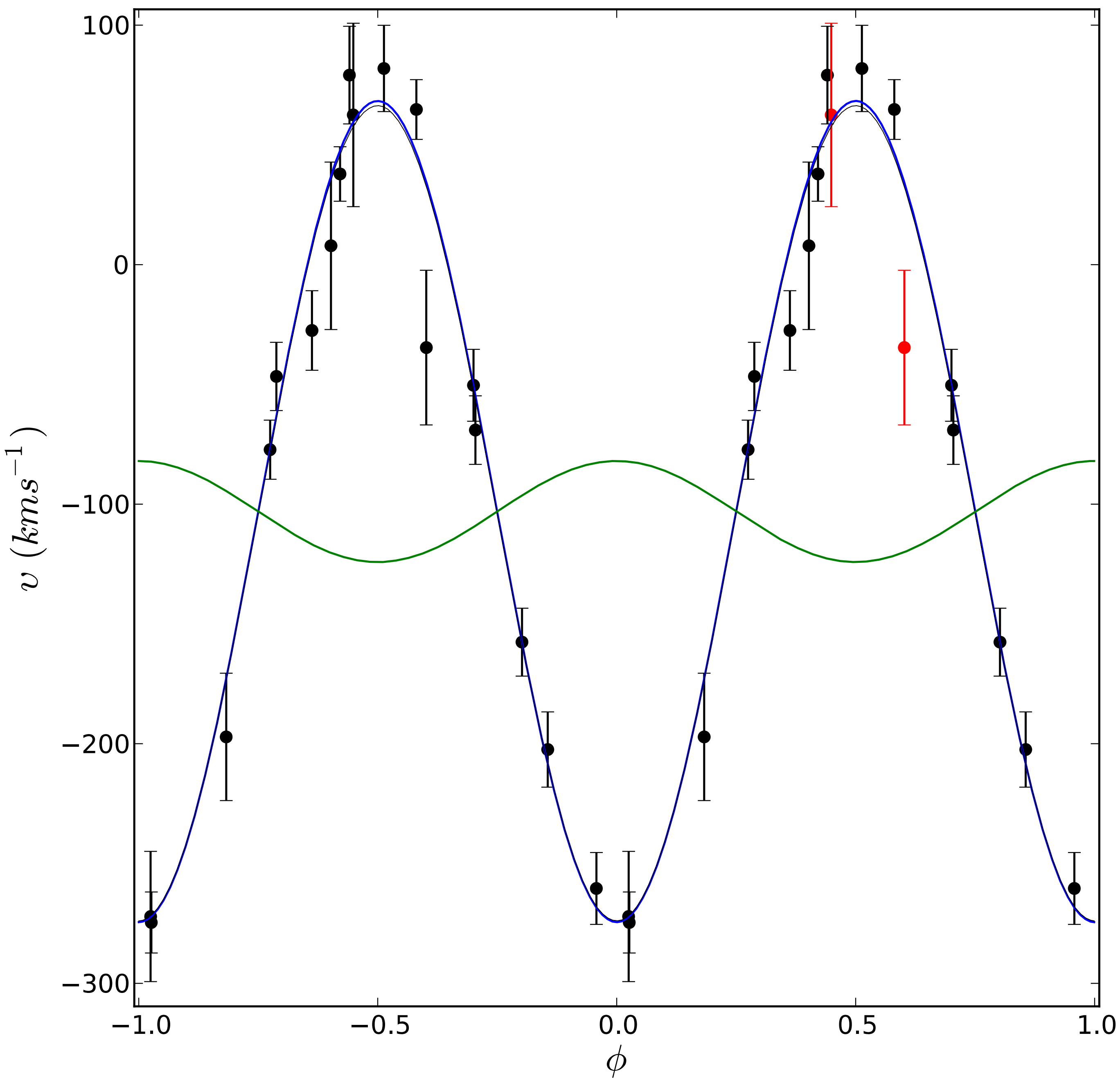
Optical observations of PSR J1738+0333



- 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 $\pm$ 0.2.
- This allows an estimate of the orbital inclination (32.6 $\pm$ 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:

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

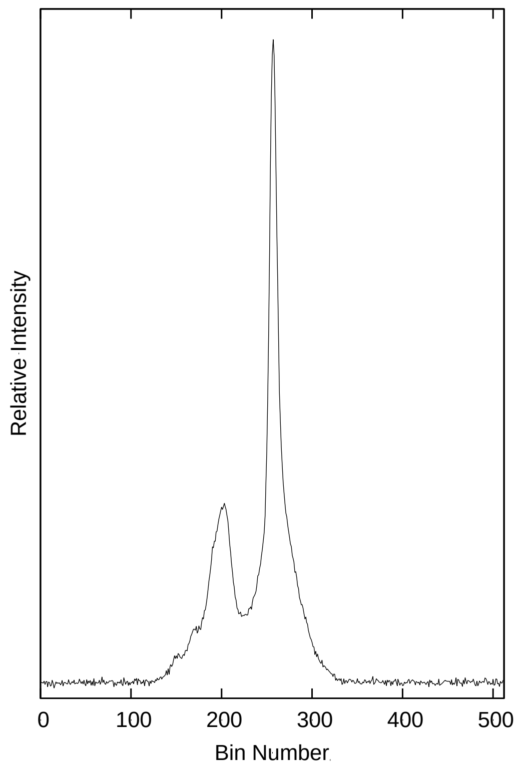
… which is a change on the orbital period of **−0.86 µs per year**!

- In the presence of ***dipolar GW*** emission this quantity must be larger (in absolute value) - If α_p ~1, then orbitald ecay should be **~ −32000 µs per year**!

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

Timing of PSR J1738+0333

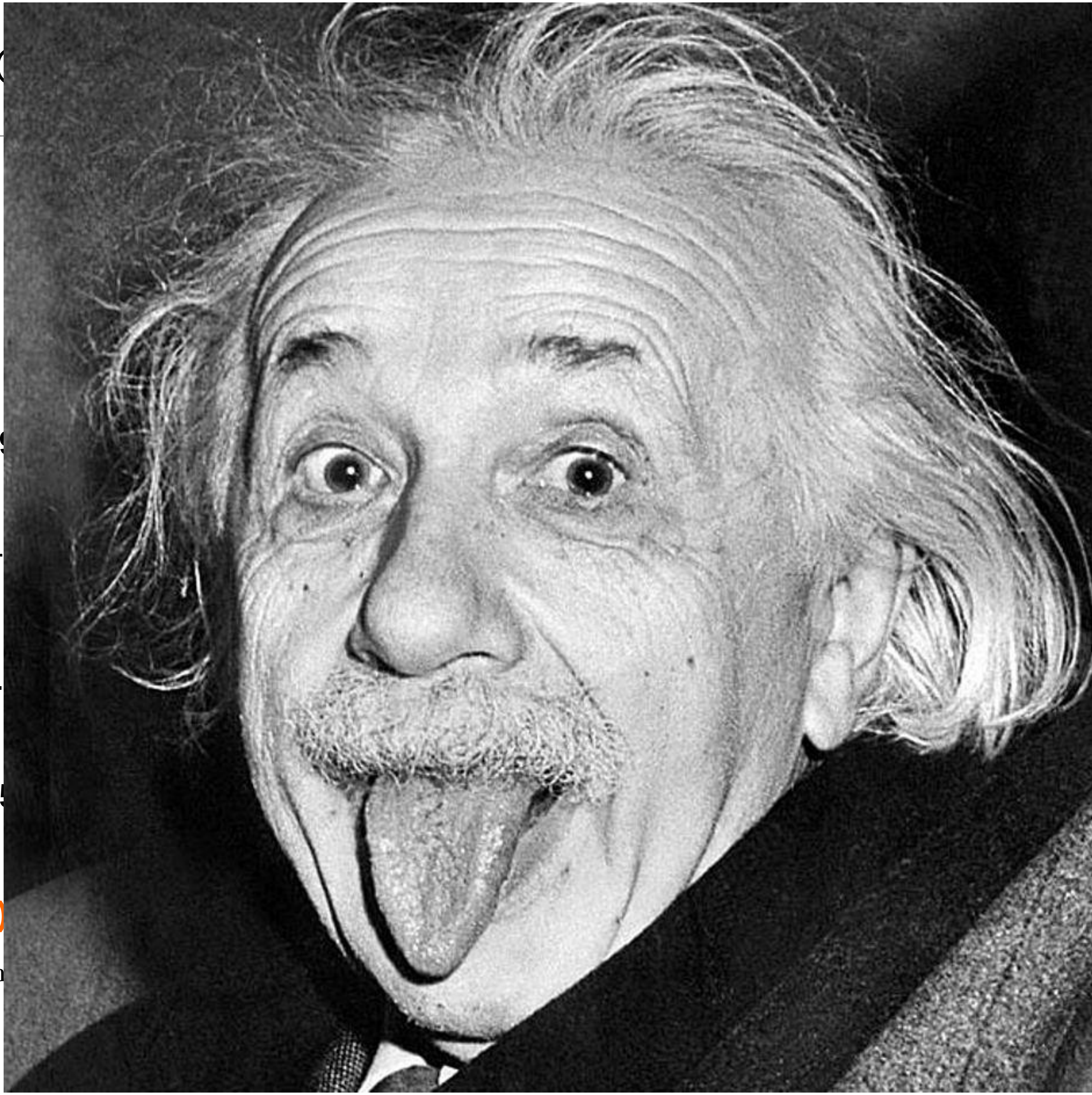
10 years of timing with Parkes and Arecibo were necessary to measure this number precisely!



The (awesome) p

- Number of rotations between
- Spin period (today, at 14:00):
- Orbital period: **8^h 30^m 53.919**
- Semi-major axis of the pulsar
- Eccentricity: **(3 ± 1) × 10^{-7}**
- Proper motion: **7.037 ± 0.00**
- **Orbital decay: −(25.9 ± 3.2)**

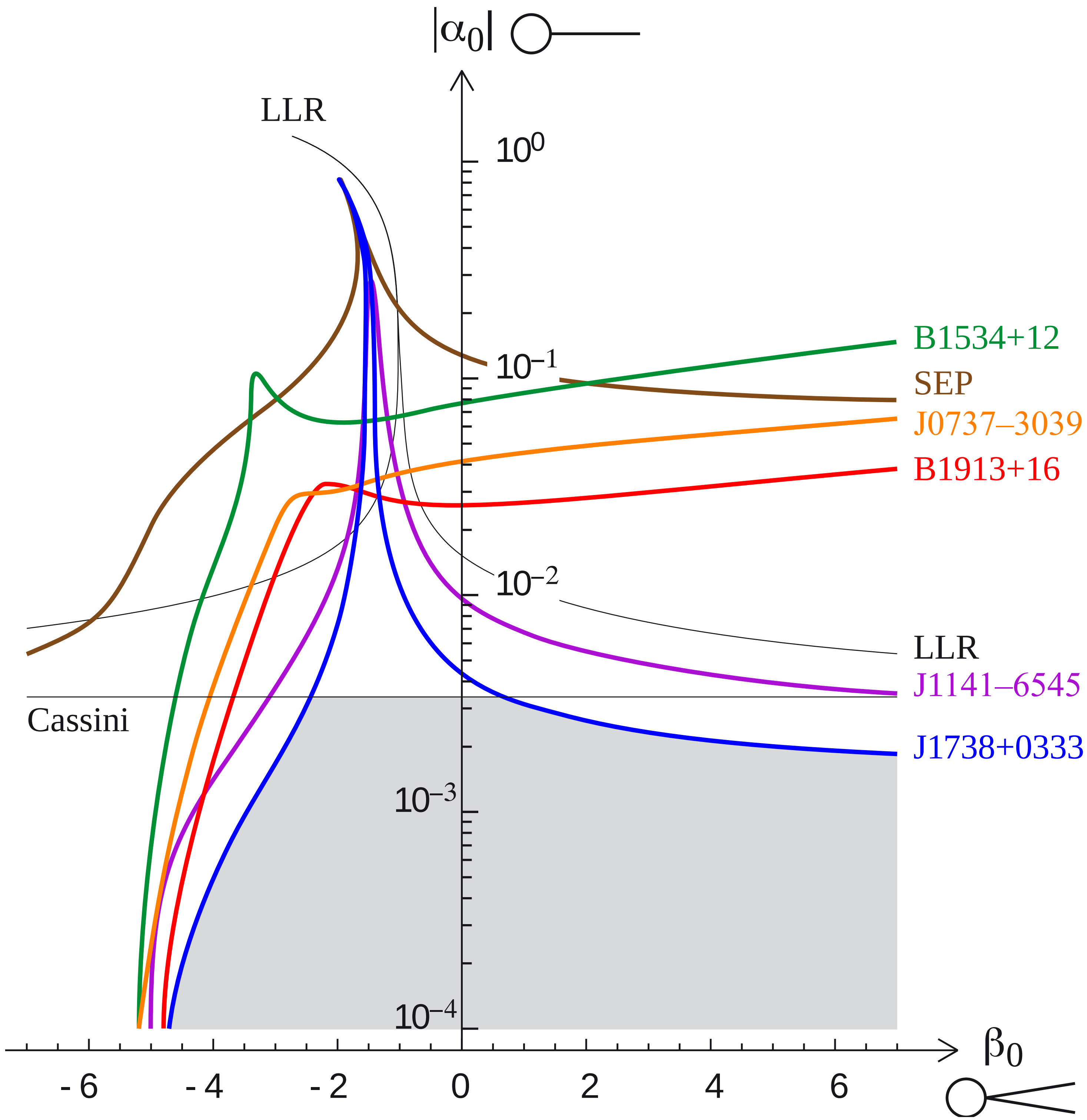
$$\dot{P}_b^{\mathrm{Int}} = \dot{P}_b - \dot{P}_b^{\mathrm{Acc}} - \dot{P}_b^{\mathrm{Sh}}$$



Limit on dipolar GW emission

- Difference between orbital decay predicted by GR (quadrupolar) and observed is +0.06 $\pm$ 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.

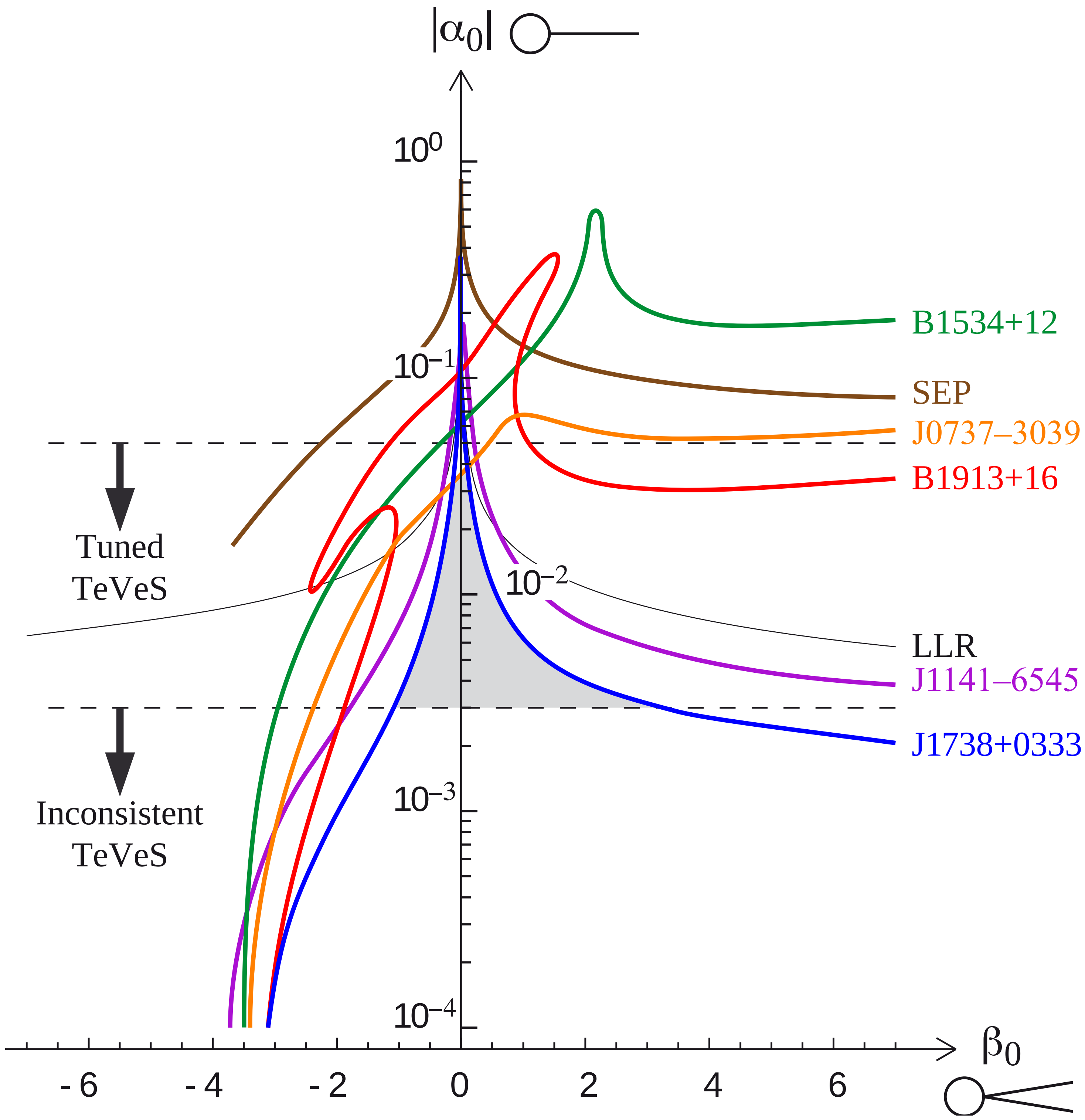
For Scalar-Tensor theories of gravity, this is the most constraining binary pulsar test ever!



Precision of the limits on JFBD theory will soon surpass the Cassini test!

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

Also for TeVeS and friends!



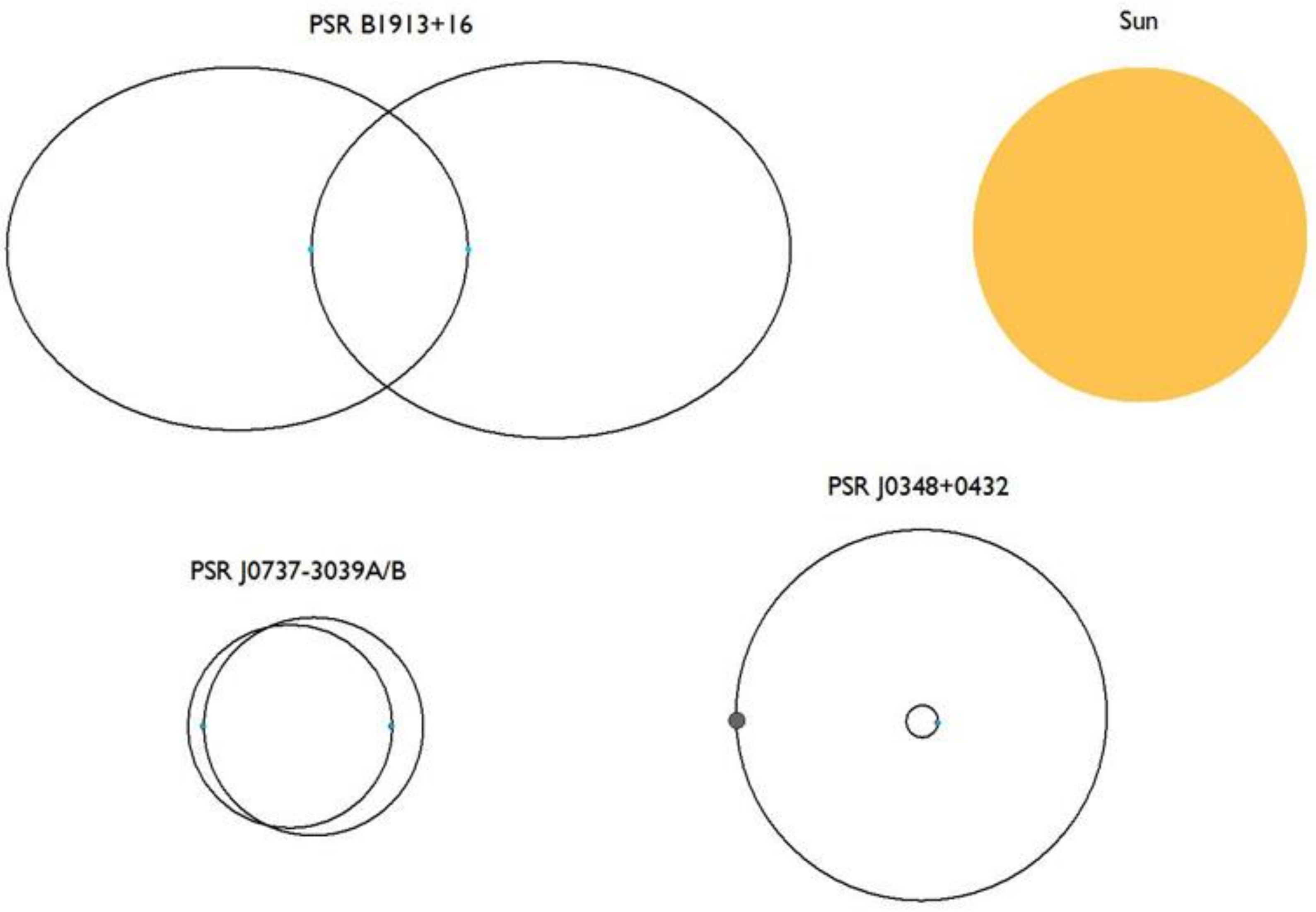
- Tensor-Vector-Scalar theories (based on Bekenstein's 2004 TeVeS theory) can also be constrained, but in this case PSR J1738+0333 is not enough.
- Improvements in the timing precision of the double pulsar (PSR J0737−3039) will be essential to constrain regions near linear coupling*. To be published soon (Kramer et al 2014)*.
- **TeVeS and all non-linear friends will soon be unnaturally fine-tuned theories**.

The strong-field frontier of gravitational wave physics

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) <u>the shortest orbital period for a pulsar-WD system: 2h 27 min</u>.

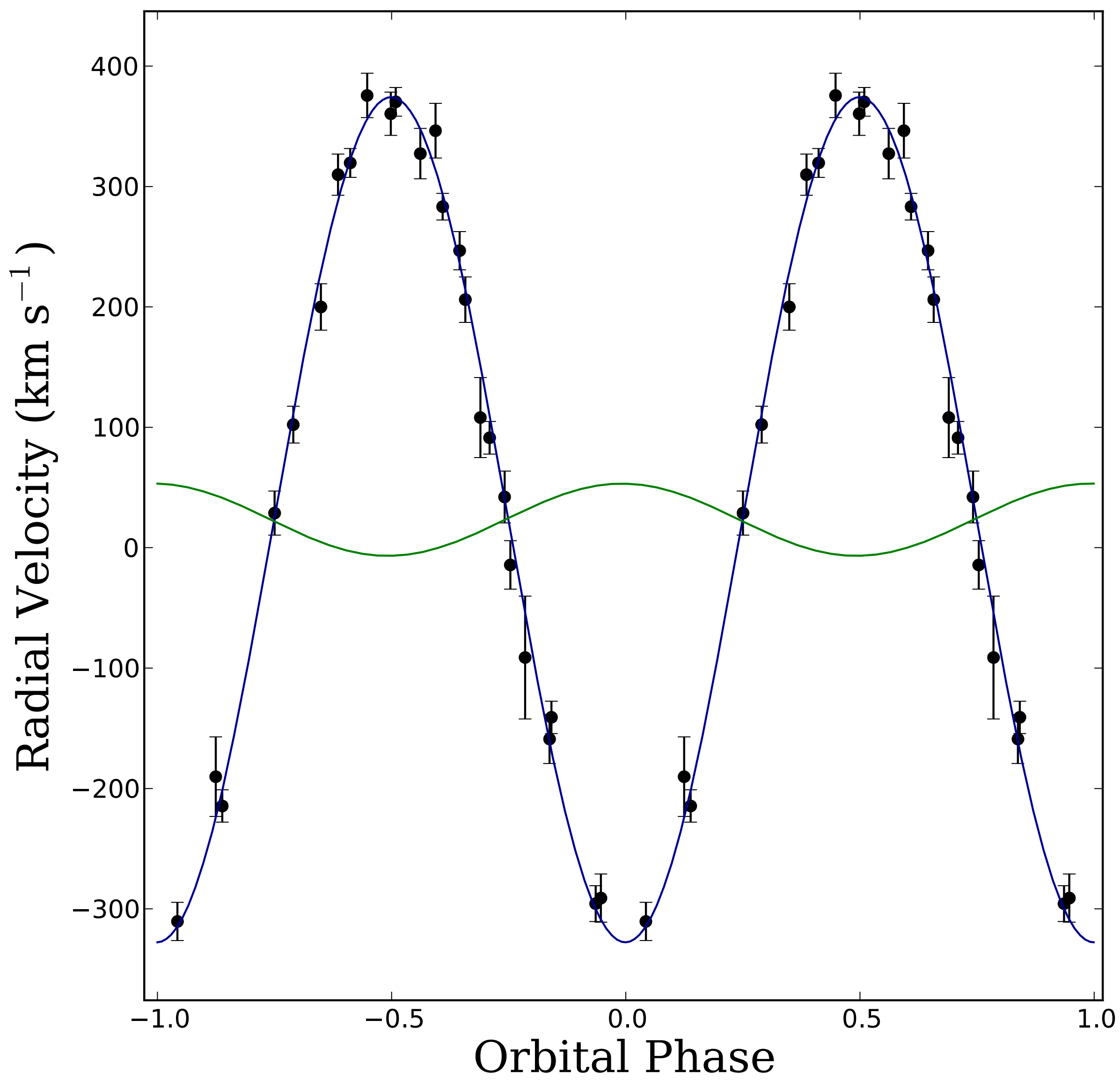


Credit: Norbert Wex

PSR J0348+0432

Recent 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** $\mathbf{M_\odot}$ (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



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

This is important – system is unique!

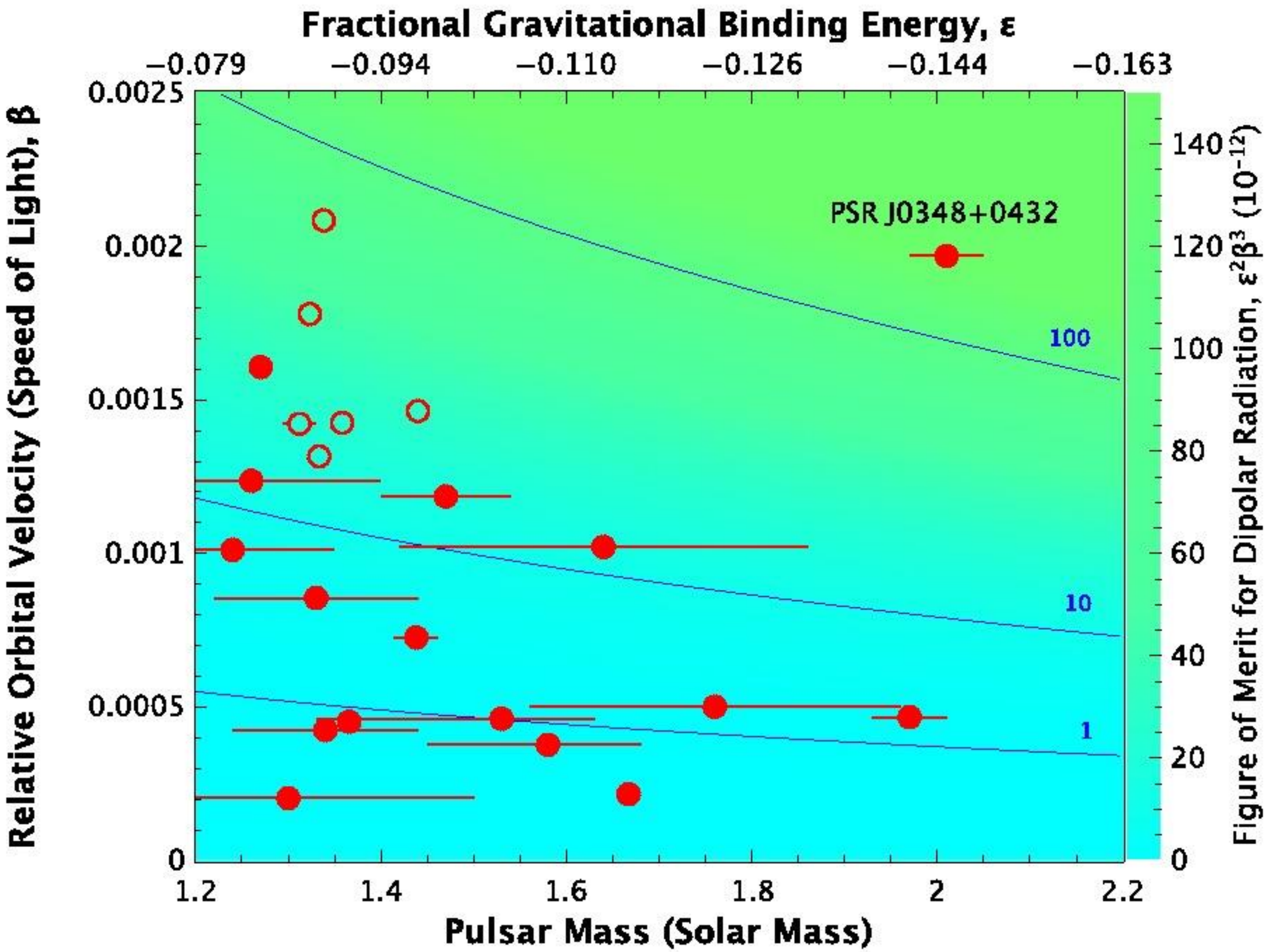
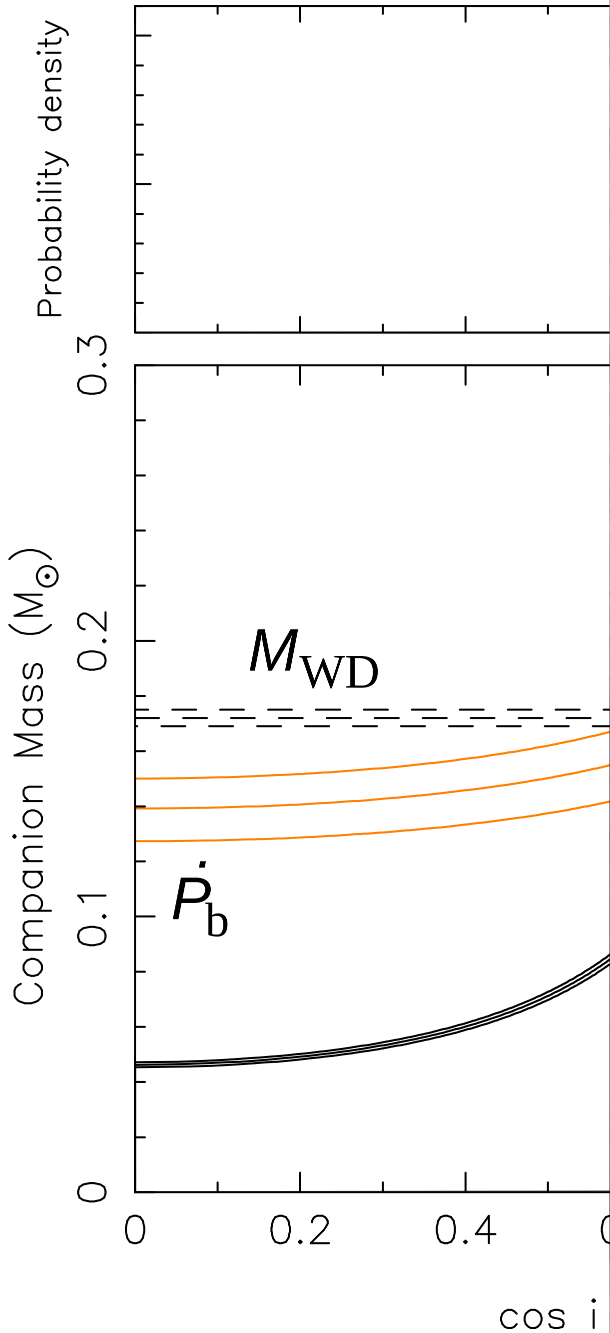
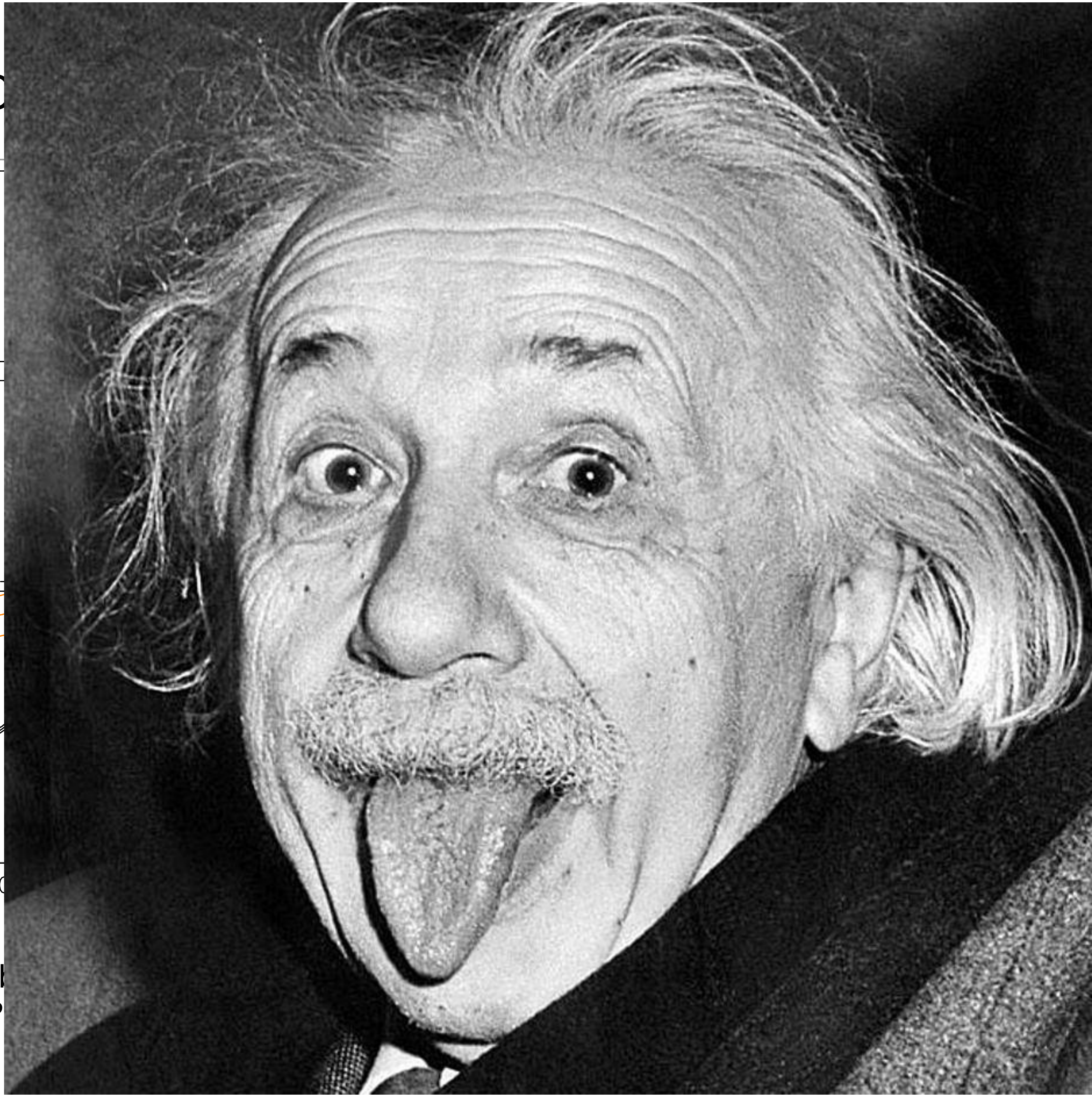


Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

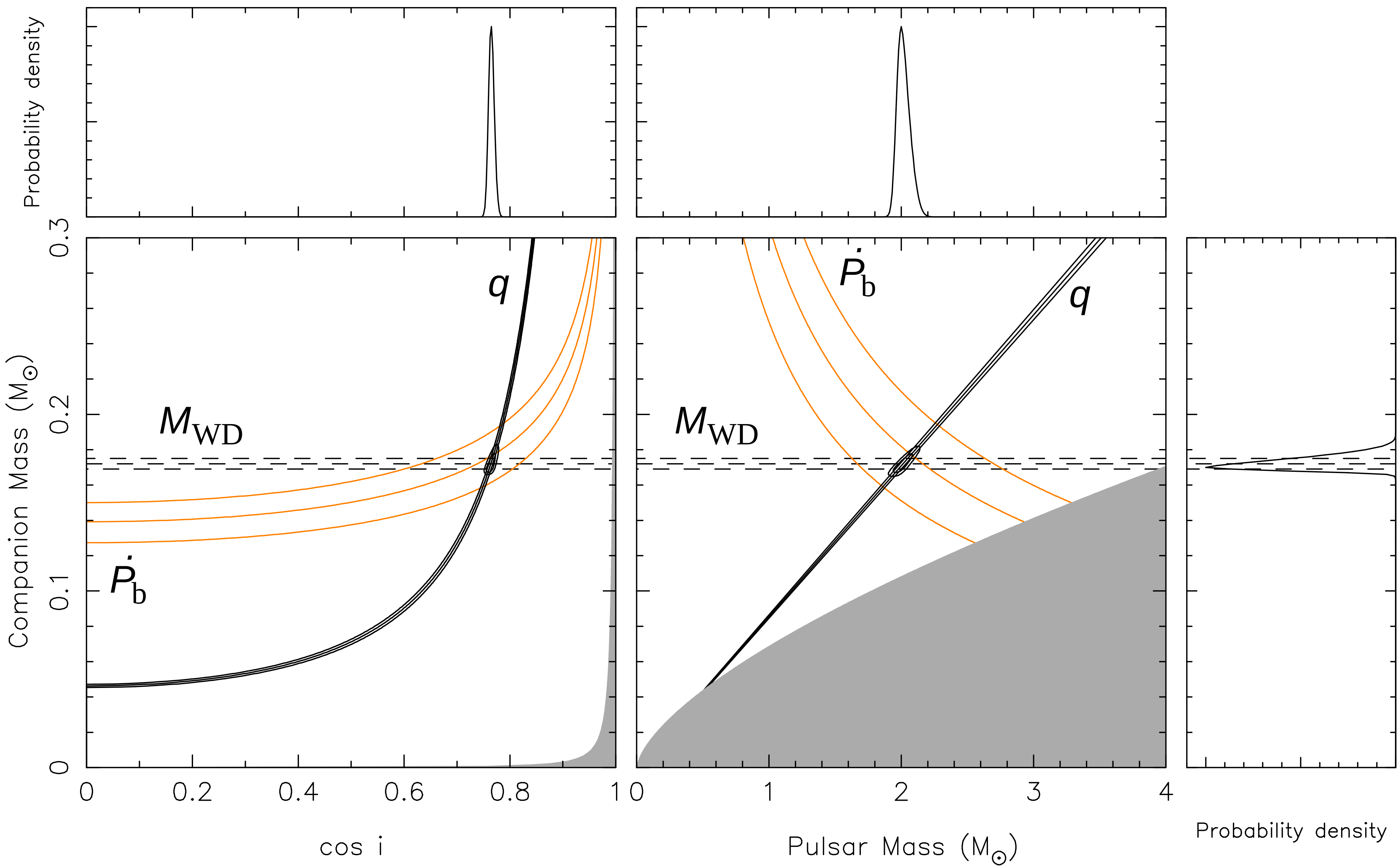
Measurement o





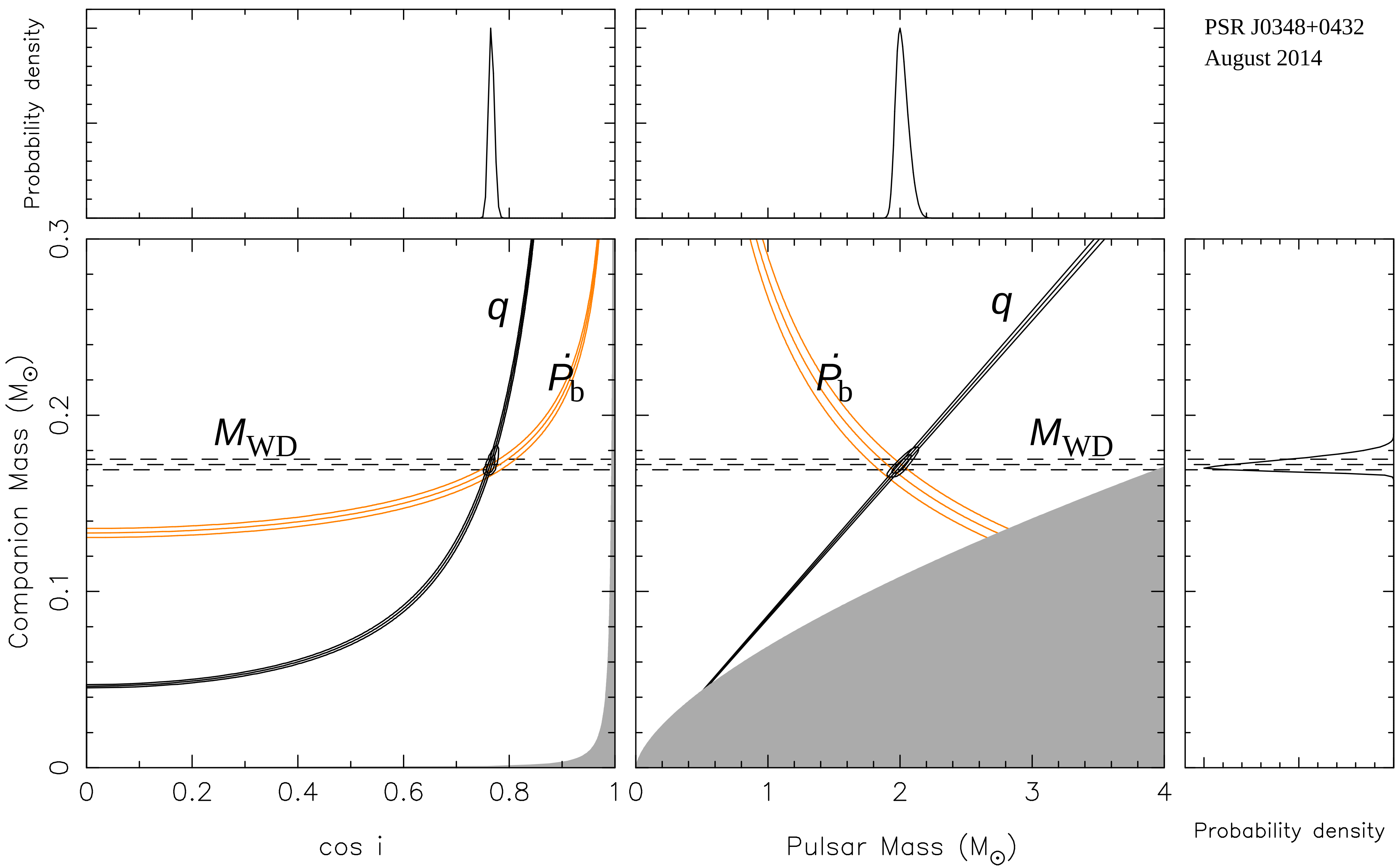
With Arecibo, GBT and Effelsb
Complete agreement with GR

Measurement of orbital decay



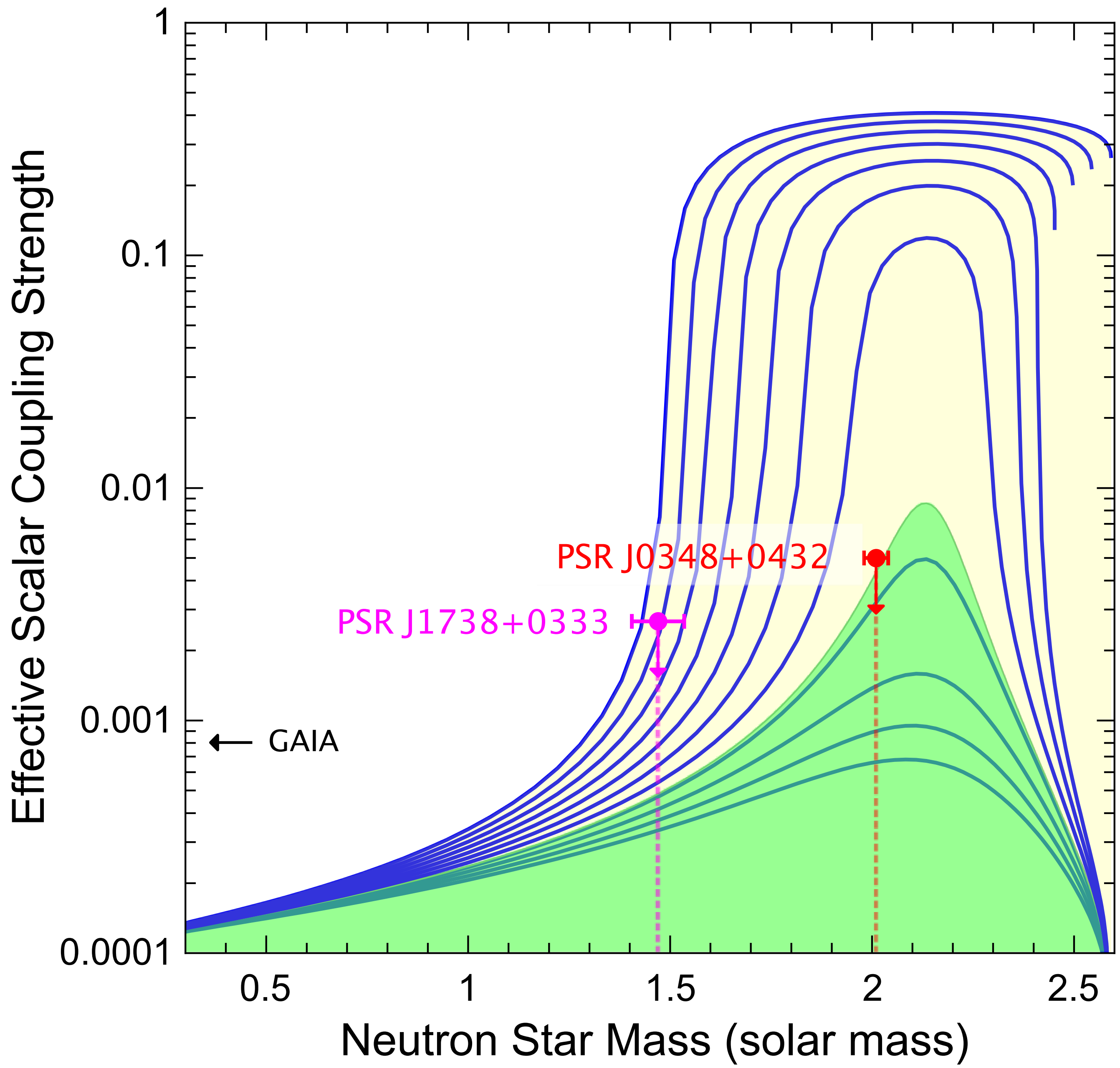
18 months after the Science publication, the orbital decay measurement had improved by a factor of 5 already! We will soon have a very precise mass measurement, *assuming* GR.

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.

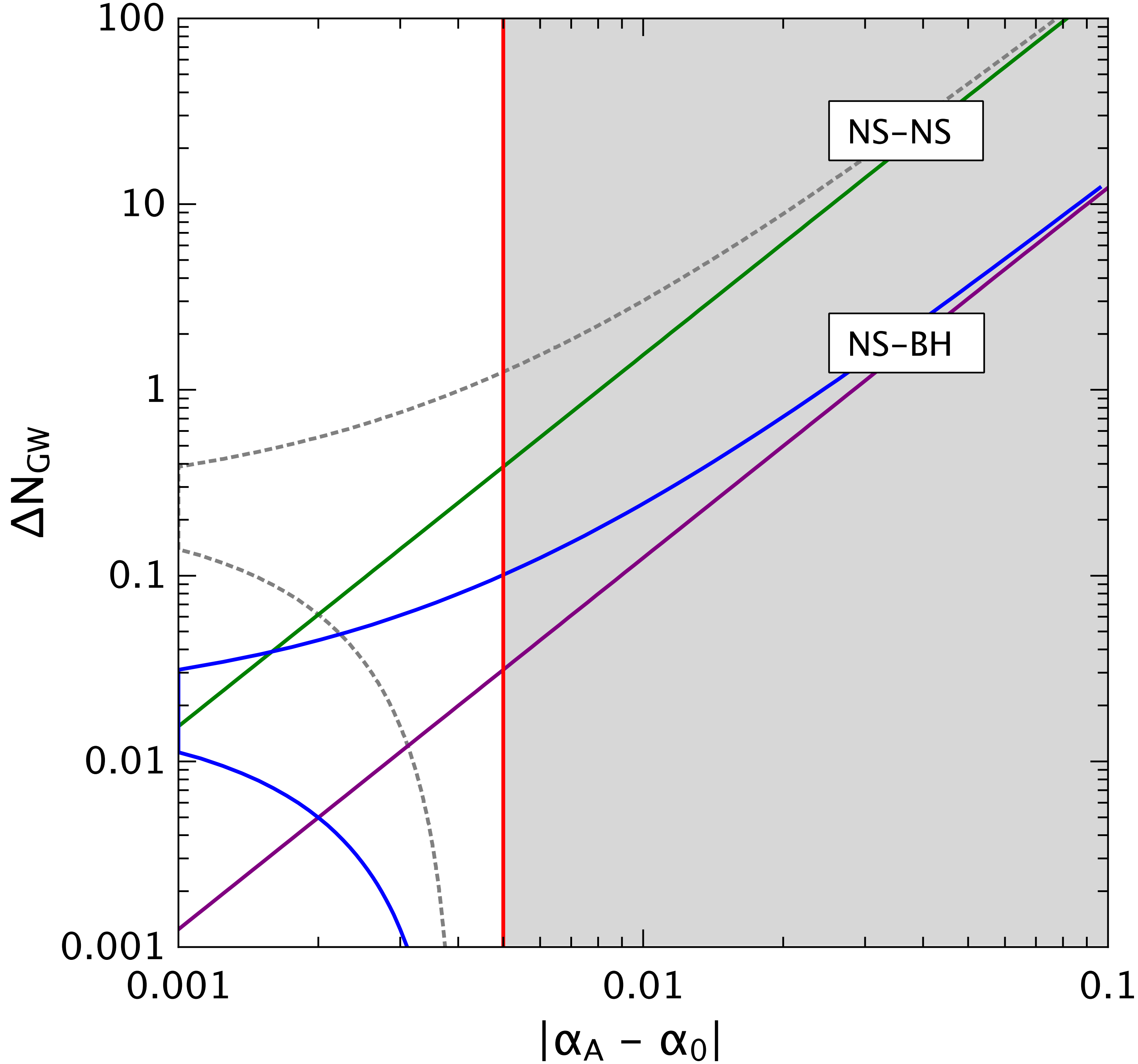
Strong non-linear deviations from GR seriously constrained!



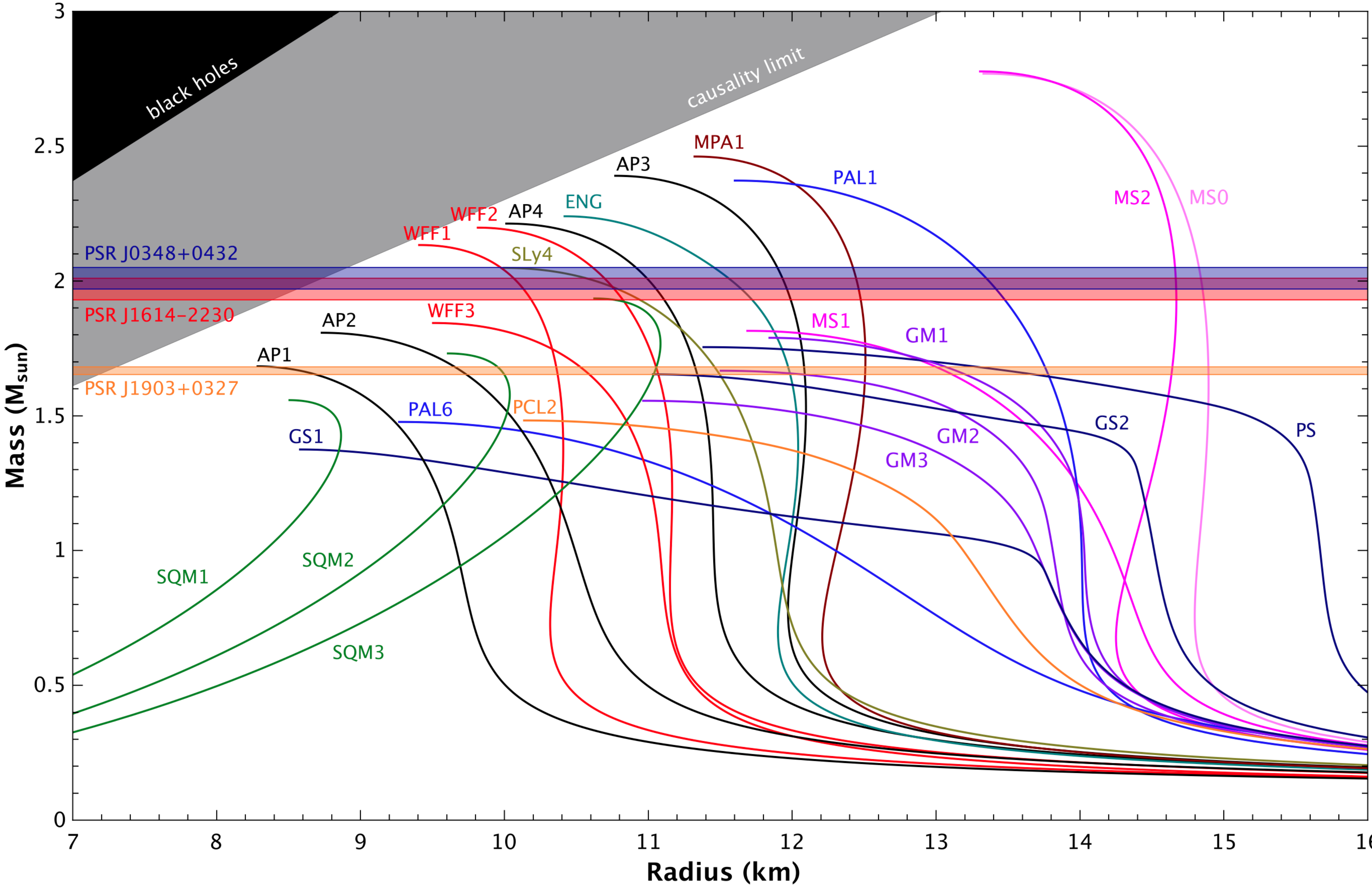
- This is the first time we do a GR test with such a massive NS: Previously, only 1.4 $M_\odot$ NSs had been used for such tests!
- This constrains the occurrence of strong non-linear deviations from GR, like *spontaneous scalarization* (e.g., Damour & Esposito-Farèse, 1996, Phys. Rev. D., 54,1474) – 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!



Constraints on the equation of state



Mass measurement of PSR J0348+0432 has 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

- Current 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.

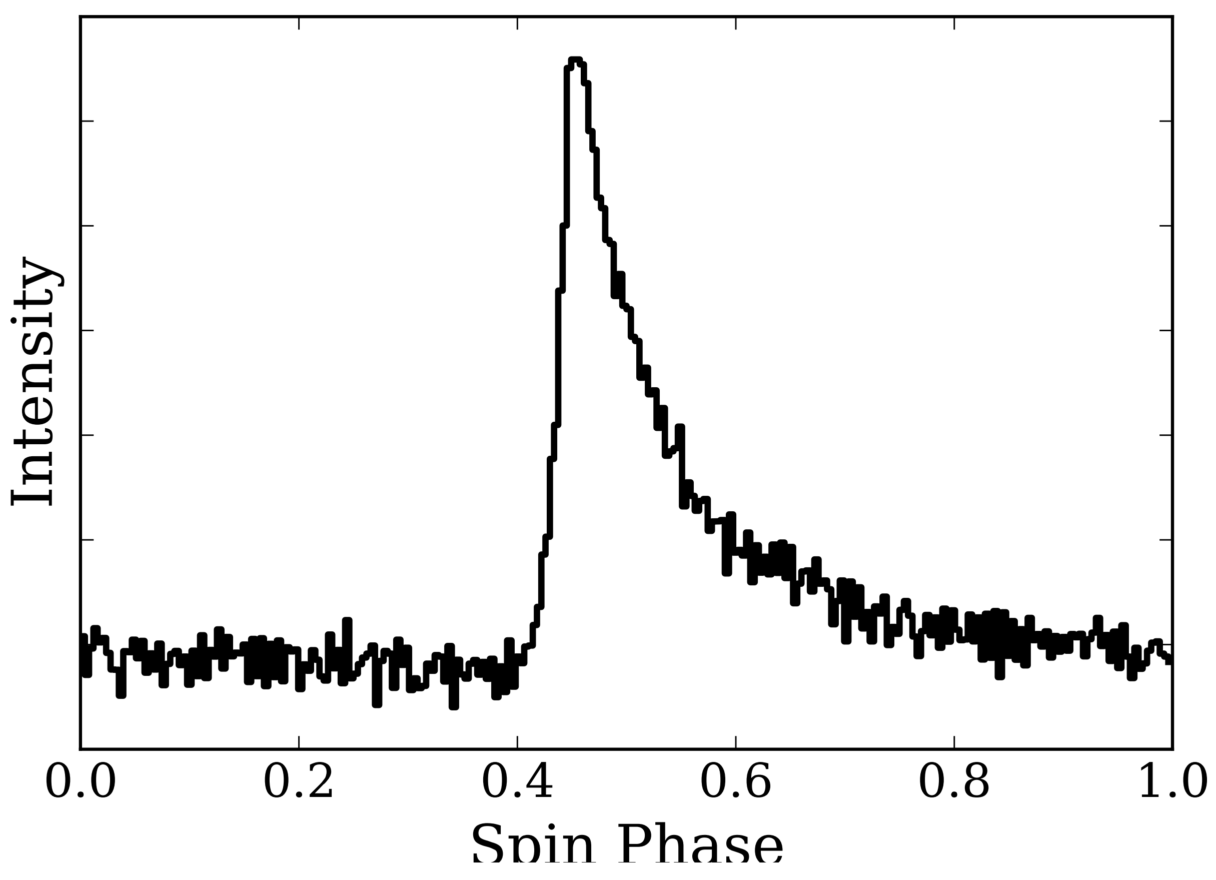
- An asymmetric DNS could in principle combine the best of both worlds.

Tests of GW emission with asymmetric DNS

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).

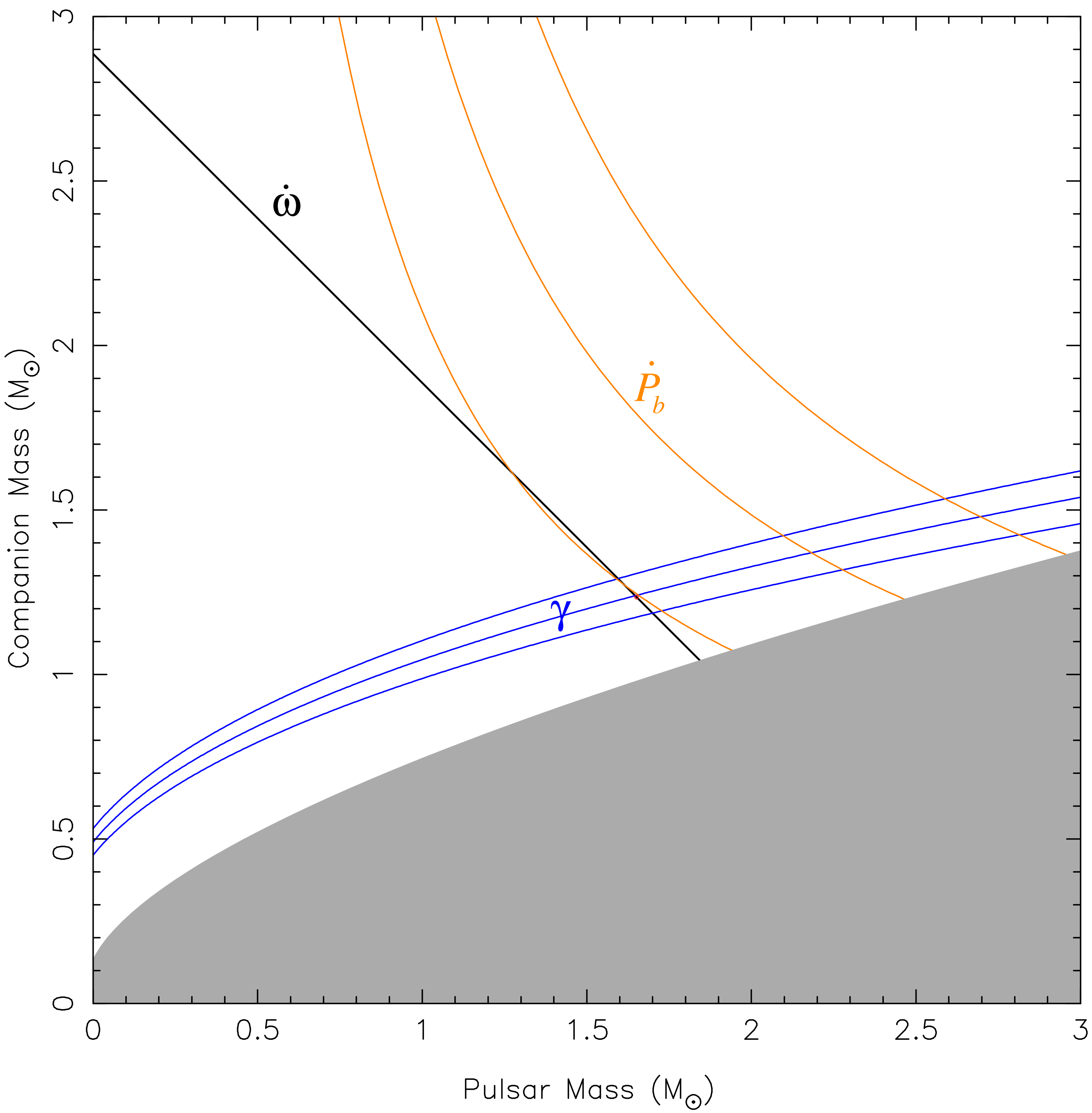
PSR J1913+1102

- Found recently with Arecibo in the PALFA survey
- P = 27 ms
- P_b = 4.95 hr
- e = 0.089
- Companion mass > 1 solar mass
- Double neutron star!



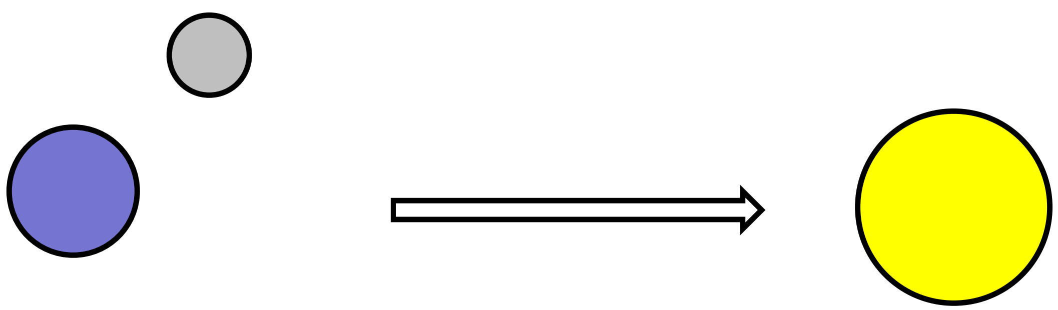
PSR J1913+1102

- Prcession of periastron measured – most massive DNS ever (2.8862 $\pm$ 0.0012 $M_\odot$).
- Einstein delay measured! Companion mass is 1.23 $\pm$ 0.05 $M_\odot$., thus the mass of the pulsar is 1.66 $\pm$ 0.05 $M_\odot$.
- Orbital decay measured to 3-sigma significance – will improve fast during the next few years.
- This will represent at least one order of magnitude improvement in sensitivity to DGW over the best current test with J1738+0333.

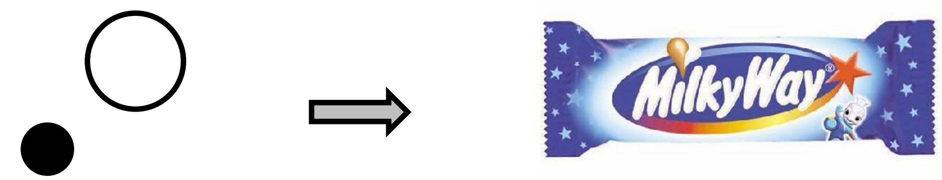


Tests of the Strong Equivalence Principle

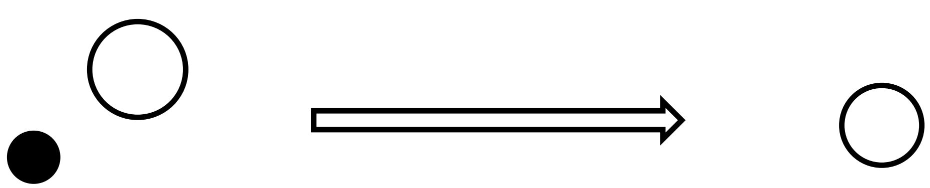
For a summary of SEP tests with pulsars, see Freire, Kramer & Wex (2012, CQGra, 29, 184007)



Lunar Laser Ranging

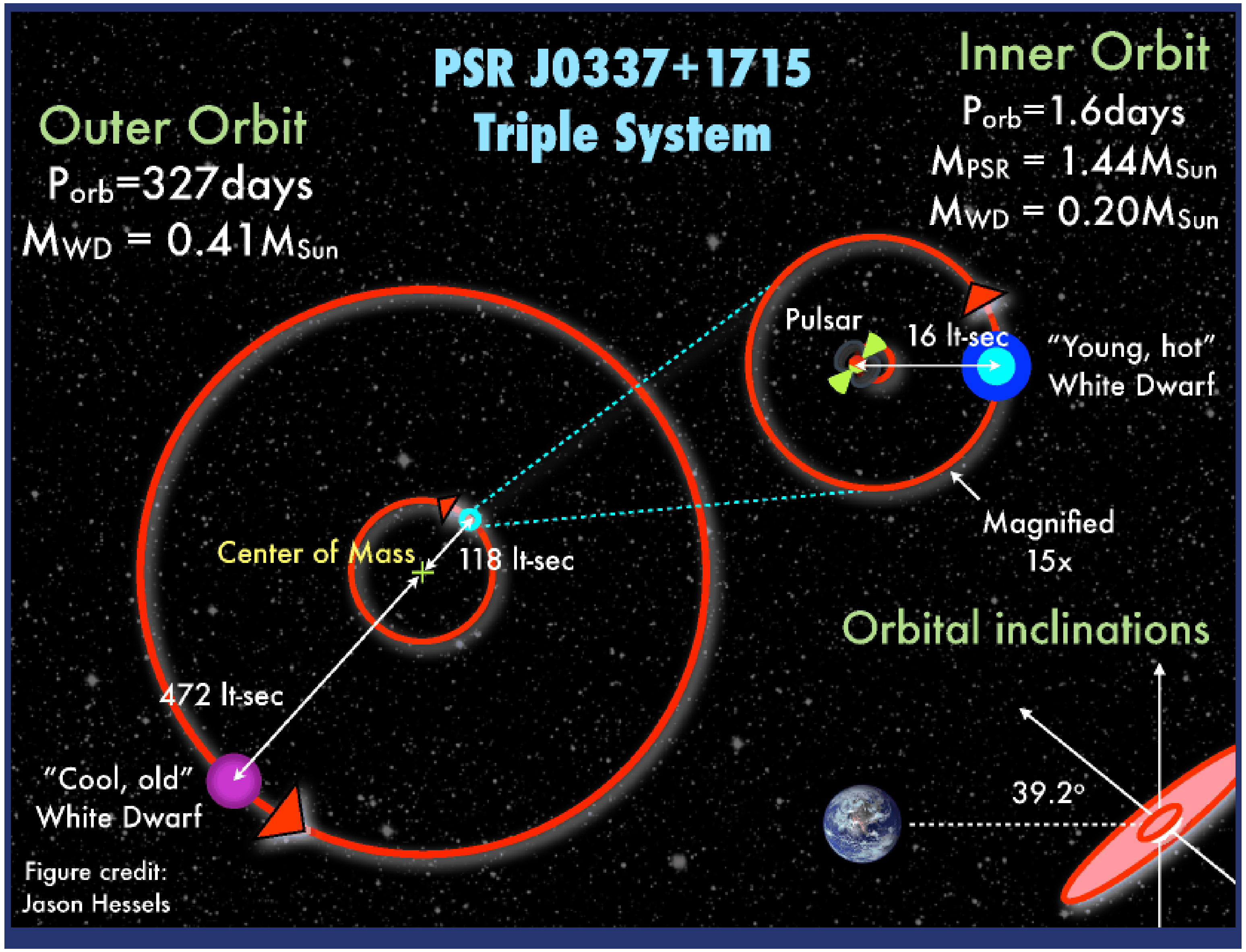


Damour-Schäfer test (1991), Phys. Rev. Lett. 66, 2549
Gonzalez et al. (2011), ApJ, 743, 102
de/dt test (Freire, Kramer, Wex, 2012)



Pulsar in triple test (Freire, Kramer, Wex, 2012)

2.The Nordtvedt effect



- The GBT 350-MHz drift-scan survey found a pulsar in a hierarchical triple, PSR J0337+1715! (Ransom et al., 2014, Nature, 505, 520)

- This will be the best SEP test ever, by many orders of magnitude.

Summary

- 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 represents a very stringent constraint on the nature of gravitational waves, and introduces tight constraints on alternative theories of gravity.

- A massive pulsar in a relativistic orbit now allows for tests of the nature of gravitational radiation for extremely compact objects.

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