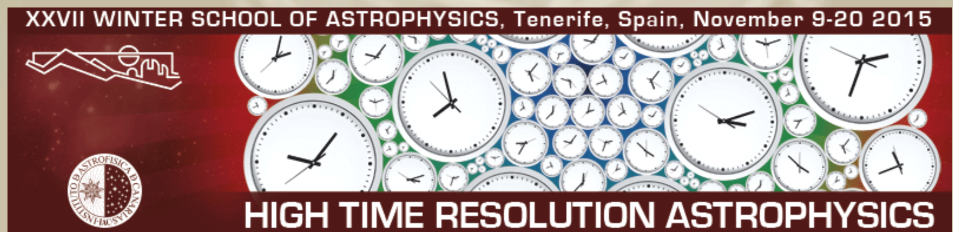
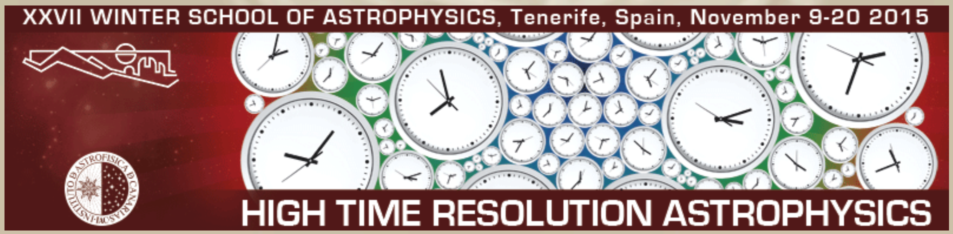
4.

Pulsars Timing as a tool for fundamental physics investigations



4.a

Constraining Gravity Theories



… for some binary pulsars, the accuracy of the ToA data is so high that - by using <u>only the keplerian description</u> - one cannot obtain <u>an acceptable timing solution</u> !

Additional physics is needed!

… but… which physics?

The pulsars with at least one measured post Keplerian parameter: 48 cases (12 in Globular Cluster)

PSR	P_b	Asin$i$	T0	Ecc	ω	$\dot{\omega}$	$\dot{P}_b$	γ	sin$i$	M2
	(days)	(lt-s)	(MJD)		(deg)	(deg/yr)		(sec)		($M_\odot$)
J0024-7204H	2.35769683	2.152813	51602.18629	0.070560	110.603	0.066	–	–	–	–
J0024-7204J	0.12066493779	0.0404021	–	–	–	–	-5.5E-13	–	–	–
J0045-7319	51.169451	174.2576	49169.21361	0.807949	115.2540	0.0259	-3.03E-17	–	–	–
J0437-4715	5.74104646	3.36669708	52009.852429	1.9180E-5	1.2224	0.01600	3.73E-12	–	0.674	0.254
J0514-4002A	18.78517915	36.296588	53623.1550879	0.8879773	82.266550	0.01289	–	–	–	–
J0621+1002	8.3186813	12.0320744	50944.75683	0.00245744	188.816	0.0105	–	–	–	–
J0737-3039A	0.10225156248	1.415032	53155.9074280	0.0877775	87.0331	16.89947	-1.252E-12	0.0003856	0.99974	1.2489
J0737-3039B	0.10225156248	1.5161	53155.9074280	0.0877775	267.0331	16.89947	-1.252E-12	0.00038	–	–
J0751+1807	0.263144266723	0.3966127	–	7.1E-7	45	–	-3.1E-14	–	0.90	0.191
J0823+0159	1232.404	162.14564	44286.49	0.0118689	332.022	0.0008	–	–	–	–
J1022+1001	7.8051302826	16.7654074	53587.3140	9.700E-5	97.75	–	–	–	0.7	1.05
J1023+0038	0.1980962019	0.3433494	–	–	–	–	2.5E-10	–	–	–
J1141-6545	0.1976509593	1.858922	51369.8545515	0.171884	42.4561	5.3096	-0.403E-12	0.000773	–	1.02
J1300+1240	25.262	0.0000030	49765.1	0.0	0.0	–	–	–	–	0.060E-6
J1518+4904	8.6340050964	20.0440029	52857.71084163	0.24948451	342.554394	0.0113725	2.4E-13	–	–	–
J1537+1155	0.420737299153	3.7294626	50300.89497411	0.2736767	274.76928	1.755805	-0.138E-12	0.0020474	0.975	1.35
J1600-3053	14.3484577709	8.801652	53281.191	17.369E-5	181.85	–	–	–	0.8	0.6
J1603-7202	6.3086296703	6.8806610	–	9.28E-6	168.8	–	–	–	0.89	0.14
J1623-2631	191.44281	64.809460	48728.26242	0.02531545	117.1291	-5E-5	4E-10	–	–	–
J1640+2224	175.46066194	55.3297198	51626.1785	0.000797262	50.7308	–	–	–	0.99	0.15
J1713+0747	67.8251298718	32.34242099	51997.5784	0.0000749406	176.1915	–	–	–	0.89	0.28
J1740-3052	231.02965	756.9087	51353.512333	0.5788720	178.64613	0.00021	–	–	–	–
J1748-2021B	20.5500072	4.466994	54005.480292	0.5701606	314.31935	0.00391	–	–	–	–
J1750-3703A	17.3342759	24.39312	54003.127812	0.712431	131.3547	0.00548	–	–	–	–
J1750-3703B	3.60511446	2.865858	54002.7705	0.004046	323.07	0.00391	–	–	–	–
J1756-2251	0.319633898	2.7564	52812.919653	0.180567	322.571	2.585	–	0.0013	–	–
J1802-2124	0.698889243381	3.7188533	–	2.47E-6	20.3	–	–	–	–	0.78
J1804-0735	2.61676335	3.92055	48354.48538	0.21204	164.752	0.0595	–	–	–	–
J1811-1736	18.7791691	34.7827	50875.02452	0.828011	127.6577	0.0090	–	–	–	–
J1823-1115	357.76199	200.6720	47260.5438	0.794608	99.1719	7.4E-5	–	–	–	–
J1829+2456	1.176027941	7.238	52848.579775	0.1391412	229.92	0.2919	–	–	–	–
J1857+0943	12.32717115	9.230788	–	2.09192E-5	275.294	–	–	–	0.93	0.21
J1903+0327	95.1741176	105.60585	54063.8402308	0.436678411	141.65779	2.46E-4	–	–	–	1.051
J1906+0746	0.165993045	1.420198	53553.9126685	0.085303	61.053	7.57	–	–	–	–
J1909-3744	1.533449474590	1.89799106	–	1.302E-7	176	–	5.5E-13	–	0.9980	0.212
J1915+1606	0.322997462727	2.341774	46443.99588317	0.6171338	226.57518	4.226607	-2.4211E-12	4.294E-3	–	–
J1959+2048	0.3819666069	0.0892253	48196.0635242	0.00000	–	–	1.47E-11	–	–	–
J2019+2425	76.51163479	38.7676297	50054.6439021	0.00011109	159.03	–	-3E-11	–	–	–
J2051-0827	0.0991102506	0.045052	50999.9836017	0.0000	0.0	–	-1.55E-11	–	–	–
J2129+1210C	0.33528204828	2.51845	50000.0643452	0.681395	345.3069	4.4644	-3.96E-12	0.00478	–	–
J2145-0750	6.83893	10.1641080	53042.431	1.930E-5	200.63	0.06	4E-13	–	–	–
J2305+4707	12.33954454	32.6878	47452.560747	0.658369	35.0776	0.0099	–	–	–	–

[@ Burgay 2014]

Going beyond Kepler…

Even before publication of General Relativity, a blossom of alternate Gravity Theories appeared

A very large class of these Theories (somehow the only ones which have some chance to be "viable") **are the METRIC THEORIES OF GRAVITY** [e.g Will 2006]

- a symmetric metric exists
- all test bodies follow geodesic of the metric
- in local freely falling reference frames, all the NON-gravitational laws of physics are those written in the language of special relativity

In metric theories, gravitation must be a phenomenon related with the occurrence of a curved "spacetime"

Going beyond Kepler...

In any metric theory, matter and NON-grav fields respond only to the "metric"

Additional fields can exist, though, giving rise to

- Tensor/scalar theories
- Tensor/vectorial theories
- Bimetric theories ...

all of them incorporating their own parameters

These additional fields prescribe how matter and NON-grav fields contribute to create the metric; once determined, the metric alone acts back on the matter

Going beyond Kepler...

The Parametrized Post Newtonian (PPN) approach

A suitable and successful framework for describing the results and constraining a very large class of METRIC theories of gravity is that of the so called Parametrized Post Newtonian formalism

It describes all metric theories of gravity in **WEAK-FIELD** conditions, i.e. at order $1/c^2$ wrt Newtonian physics [e.g Will 2006]

Deviations from Newtonian physics are related to a set of 10 PPN-paramters, each of them associated with a specific physical effect [e.g Will 2006]

Going beyond Kepler...

Parameter	What it measures, relative to general relativity	Value in GR	Value in scalar tensor theory	Value in semi-conservative theories
γ	How much space curvature produced by unit mass?	1	(1+w)/(2+w)	g
β	How "nonlinear" is gravity?	1	1 + L	b
ξ	Preferred-location effects?	0	0	x
α_1	Preferred-frame effects?	0	0	a_1
α_2		0	0	a_2
α_3		0	0	0
ζ_1	Is momentum conserved?	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0

The 10 PPN-parameters and their significance

Going beyond Kepler…

Tests of Gravity theories in the weak-field limit

Weak in which sense?

In term of the compactness parameter ε

$$\varepsilon_{Earth} = \left|\frac{E_{grav}}{E_{rest}}\right| = \frac{GM_{Earth}}{R_{Earth}c^2} \cong 10^{-10}$$

$$\varepsilon_{Sun} = \left|\frac{E_{grav}}{E_{rest}}\right| = \frac{GM_{Sun}}{R_{Sun}c^2} \cong 10^{-6}$$

All the Solar System tests fall in this category… since the experiment about the light deflection by Sun [Eddington 1919] and the observation of the Mercury advance of perihelion

The Parametrized Post Newtonian formalism is well tailored for describing the outcomes of these tests [e.g Will 2006]

So far, GR has passed all these tests with *full marks and cum laude*

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Strong in which sense?

In term of the compactness parameter ε the source should satisfy

$$\varepsilon_{source} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{source}}{R_{source} c^2} \cong 0.1 - 1$$

Where to find a laboratory for testing GR in extreme conditions?

Not on Earth or on Solar System...
but in the Cosmo...very interesting targets are
"relativistic objects in compact binaries"

NSs and BHs are "relativistic" objects

$$\varepsilon_{NS} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{NS}}{R_{NS} c^2} \cong 0.2$$

$$\varepsilon_{BH} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{BH}}{R_{BH} c^2} \cong 0.5$$

"compact" binaries

*Gravitational radiation **inspiral** affects binary evolution **within** an **Hubble time***

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Astrophysical contexts:

- during late stages of coalescence of a binary hosting relativistic objects, the orbital velocity approaches c and the orbital separation approaches the size of the star(s), whence physical processes occur in strong-field conditions: according to the BH mass, they are wonderful targets for LIGO, VIRGO, for the Pulsar Timing Arrays (PTAs) and, in future, LISA
- emission processes occurring in relativistic objects close to the event horizon: e.g. spectral and timing features in the electromagnetic emission (often X-ray) from the neighborhood of the last stable orbit of accretion disks surrounding NS or BH hosted in a binary system: some hints from XMM-Newton and Rossi-XTE but targets for future high energy (most X-ray) observatories: LOFT,...
- compact relativistic binary pulsars: targets for current TIMING observations in the RADIO band

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Wait a minute! Orbits of known binary pulsars are never entering the strong-field limit...

$$\varepsilon_{bin-psr} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{bin-psr}}{a_{bin-psr}c^2} \cong 10^{-5} - 10^{-3}$$

$$\frac{V_{bin-psr}}{c} \cong 10^{-5} - 10^{-3}$$

But in most alternative theories of gravity (e.g. in the tensor-scalar ones) the orbital motion and the gravitational radiation damping depend on the gravitational binding energy (i.e. self gravity, e.g. $\varepsilon_{NS} \approx 0.2$, $\varepsilon_{BH} \approx 0.5$) of the involved bodies

[e.g. Esposito-Farese 2005, Will 2006]

If enough accuracy in the measurements is provided, significant effects are expected to be detectable even in the weak-field limit for the orbits

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

A suitable and successful framework for testing and constraining a very large class of gravity theories is that of the Post-Keplerian (PK) formalism [Damour & Deruelle 1986]

1st → PK parameters are operationally defined:
i.e. they are phenomenological quantities, which there is a prescription to measure for

2nd → In ANY specific gravity theory (picked in a large range of metric theories), and for negligible spin contributions, the PK parameters can be written only as a function of the masses of the two stars and of the keplerian parameters of the binary system
[Damour & Deruelle 1986]

Timing model: post-keplerian params

The easiest to observe post-keplerian parameters

- $\dot{\omega}$: Periastron precession
- γ : Time dilation and gravitational redshift
- r : Shapiro delay “range”
- s : Shapiro delay “shape”
- $\dot{P}_b$: Orbit decay due to Gravitational Wave emission

What do we learn when observing also the Post-keplerian parameters ?

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

Periastron precession

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

Time dilation & gravitational redshift

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

Orbital period decay

$$r = T_\odot m_c,$$

Shapiro delay (amplitude)

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_c^{-1}.$$

Shapiro delay (shape)

... where...

- e orbital eccentricity
- P_b orbital period
- x projected semimajor axis
- m_p pulsar mass
- m_c companion star mass
- $M = m_p + m_c$ total system lagrangian mass

2 PK

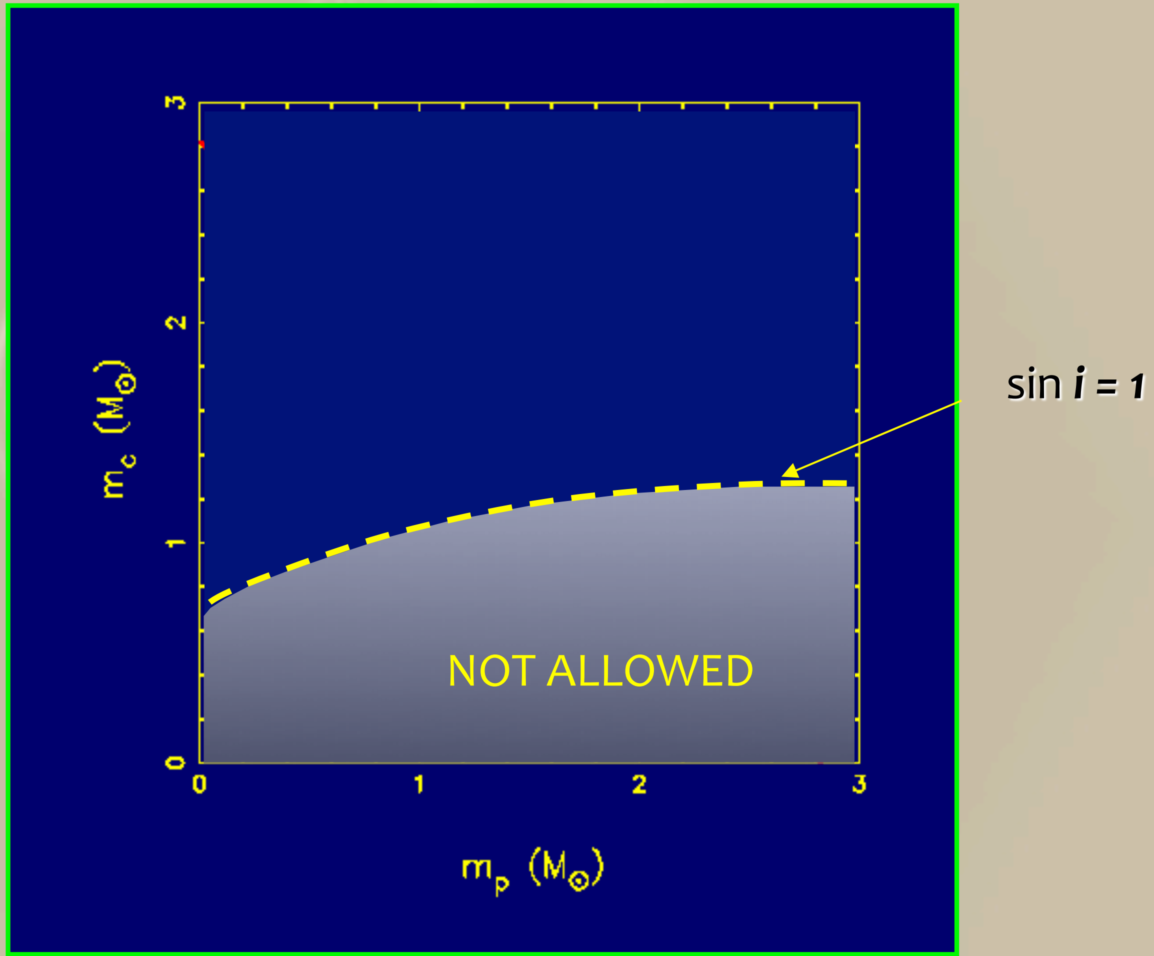
Once more than 2 relativistic PK parameters are known, one derives the masses of the 2 bodies and hence predicts the further PK par on the basis of a given Gravity Theory

↓

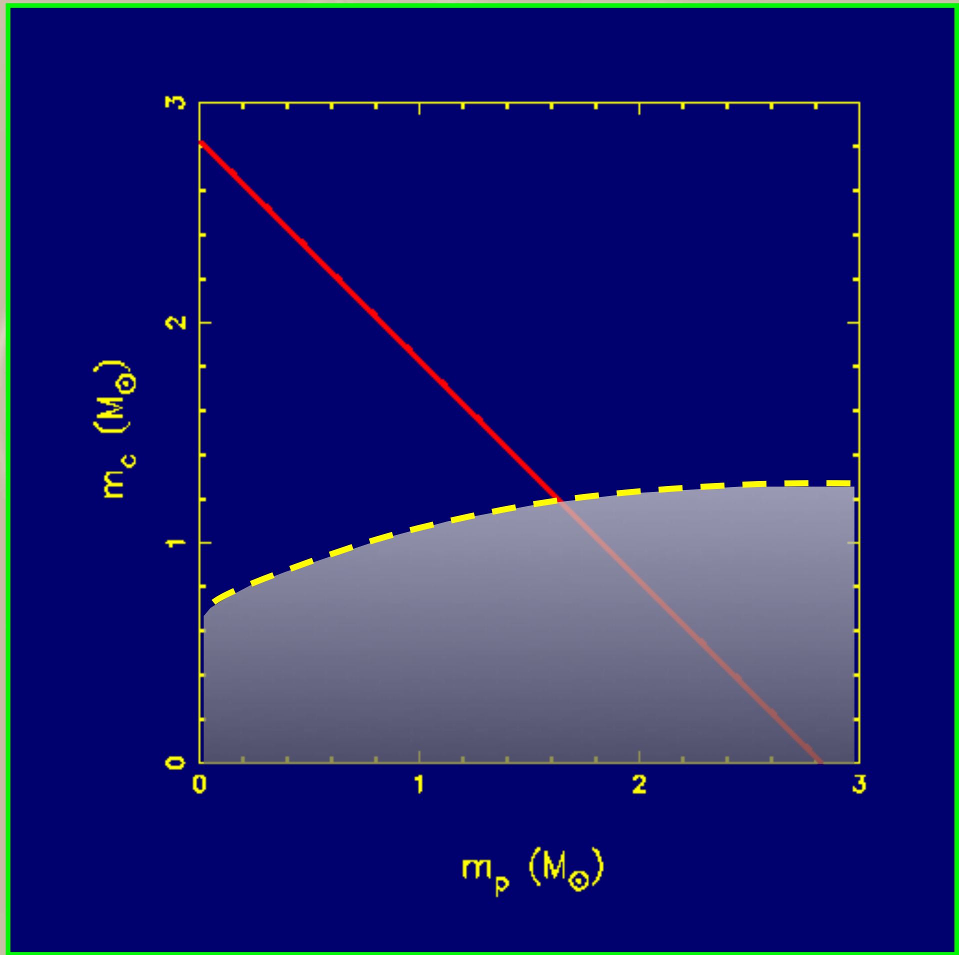
A test for Gravity Theories

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a_p \sin i)^3}{P_{orb}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

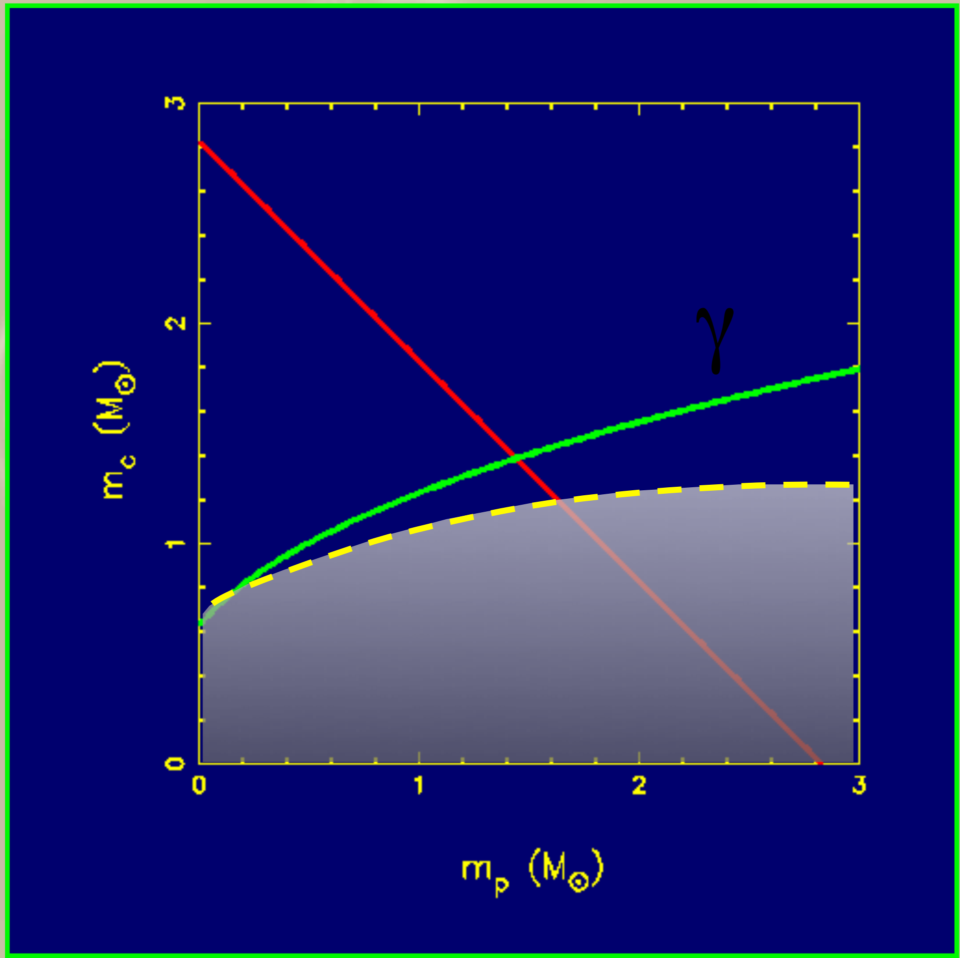
Mass Function constraint



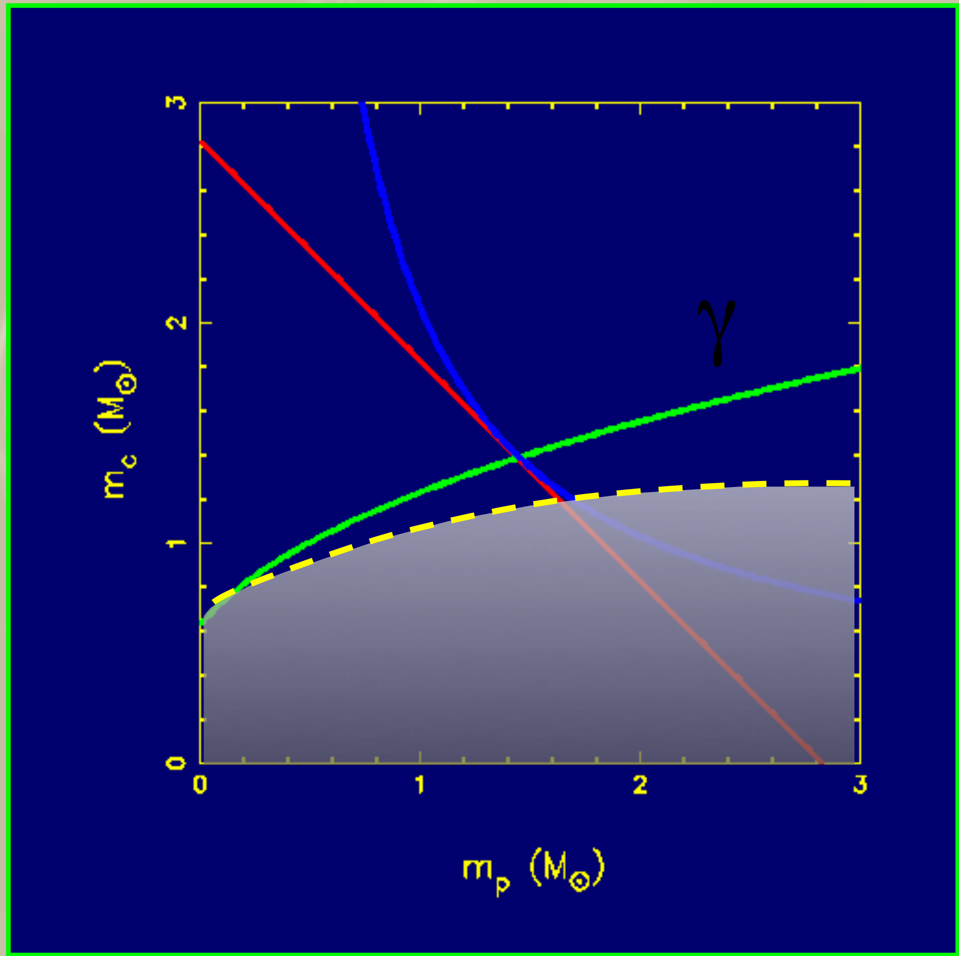
The pulsar and companion star masses are unconstrained



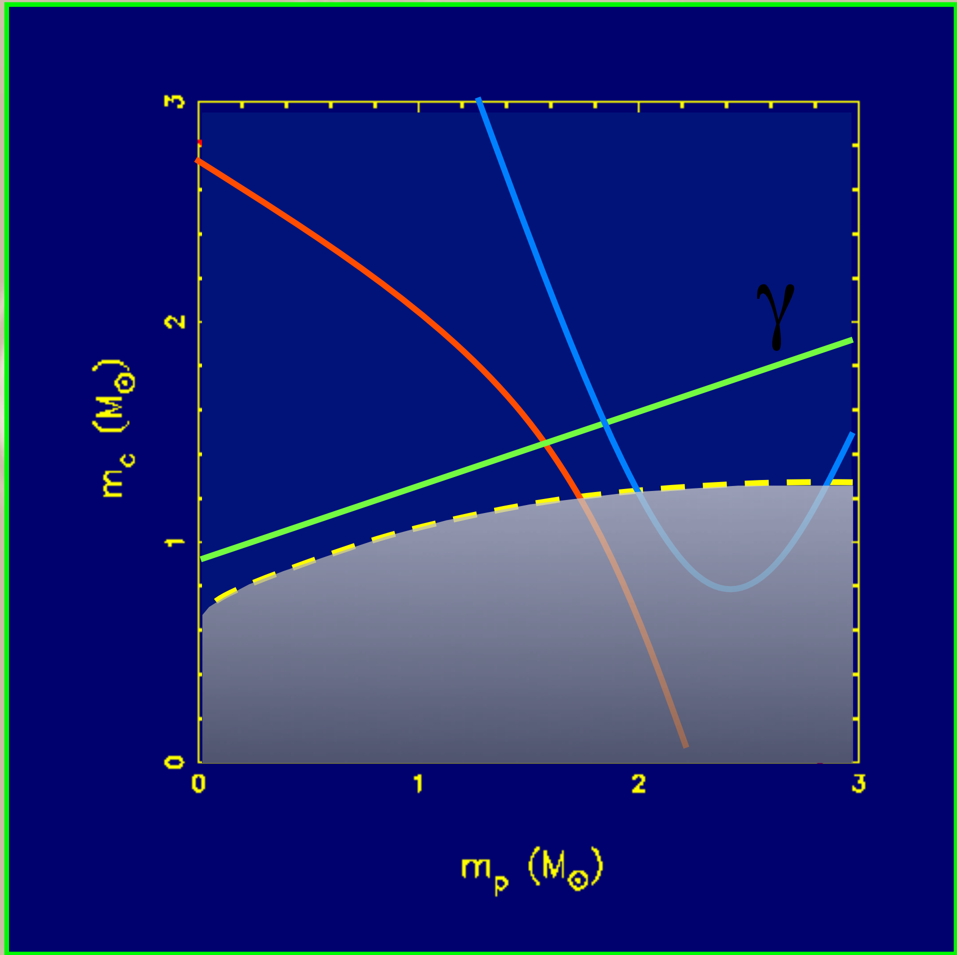
One PK-parameter: constraining mass



Two PK parameters: mass determined within a theory



Three PK parameters: in correct theory lines meet !



But not in a wrong theory !!!

Now the catalog contains ≈ ten Double Neutron Star Binaries

PULSAR	P_{spin} [ms]	DM [cm-3 pc]	P_{orb} [day]	a_p sin(i) [lt-s]	Mc+Mp [Msun]	ecc	TimeSpDwn [10^8 yr]	TimeMerg [10^8 yr]
J0453+1559	45.7	-	4.07	14.5	$M_{c,med}$ = 1.2	0.11	-	NS+WD?
J0737-3039	22.70	48.91	0.10	1.42	1.34+1.25	0.09	210	0.85
J1518+4904	40.93	11.62	8.63	20.04	2.72	0.25	200	>T Hubble
B1534+12	37.90	11.62	0.42	3.72	1.33+1.33	0.27	2.5	27.0
J1756-2251	28.45	121.60	0.32	2.75	2.57	0.18	tbd	11.0
J1811-1736	104.18	477.00	18.78	34.78	2.57	0.82	970	>T Hubble
J1829+2456	41.00	13.90	1.18	7.24	>1.22 <1.38	0.14	tbd	>T Hubble
B1913+16	59.03	168.77	0.32	2.34	1.387+1.441	0.62	1.1	3.0
J1906+0746	144.10	217.78	0.17	1.42	1.25+1.37	0.08	0.001	3.0
B2127+11C	30.53	67.13	0.34	2.52	1.36+1.34	0.68	1.0	2.2

The most interesting for GR tests are:

PULSAR	P_{spin} [ms]	DM [cm-3 pc]	P_{orb} [day]	a_p sin(i) [lt-s]	Mc+Mp [Msun]	ecc	TimeSpDwn [10^8 yr]	TimeMerg [10^8 yr]
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J1811-1736	104.18	477.00	18.78	34.78	2.57	0.82	970	>T Hubble
J1829+2456	41.00	13.90	1.18	7.24	>1.22 <1.38	0.14	tbd	>T Hubble
B1913+16	59.03	168.77	0.32	2.34	1.387+1.441	0.62	1.1	3.0
J1906+0746	144.10	217.78	0.17	1.42	1.25+1.37	0.08	0.001	3.0
B2127+11C	30.53	67.13	0.34	2.52	1.36+1.34	0.68	1.0	2.2

PSR B1913+16

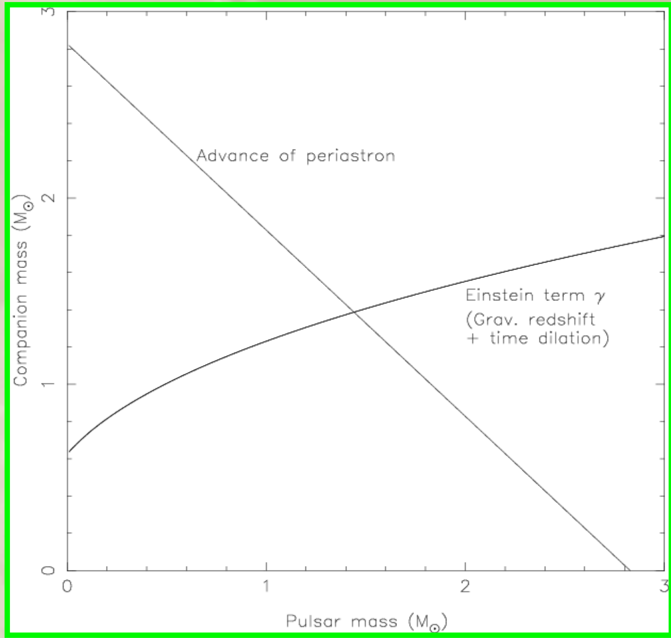
Discovered on 1974 [Hulse & Taylor 75]

Pulsar + Neutron Star

Spin period = 59 ms

Orbital period = 7.8 hrs

Eccentricity = 0.61



Measured 3 PK pars: $\dot{\omega}$ γ $\dot{P}_b$

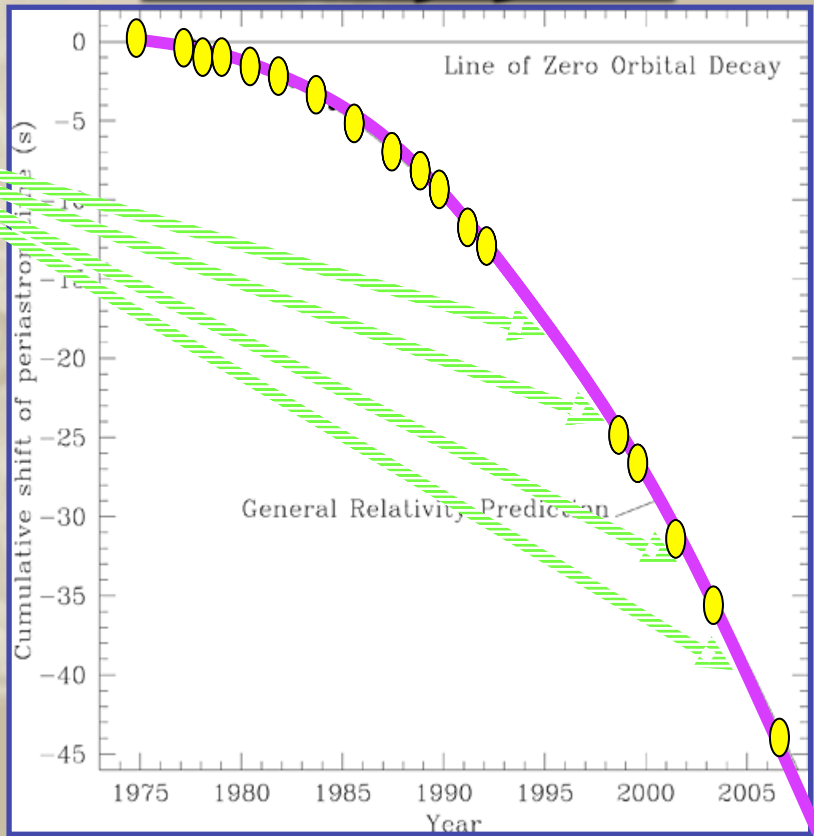
Most precise NS mass determination to date:

1.4414(2) M_{sun} + 1.3867(2) M_{sun} [Weisberg & Taylor 2004]

The measurements of Russell Hulse and of Joe Taylor…

The prediction of the Einstein’s equations…

The (in?)direct proof of GW existence: PSR B1913+16



[Weisberg 2007]

GR provides an accurate

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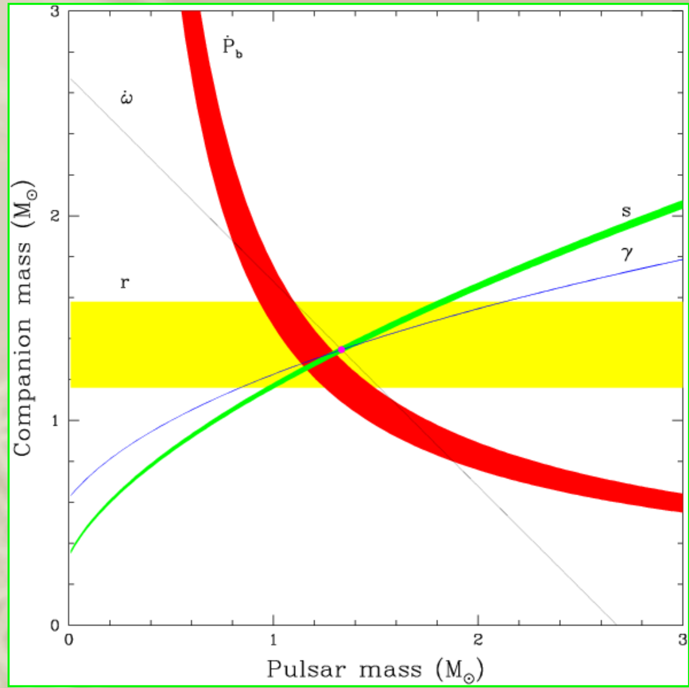
NOBEL PRIZE

1993

Taylor & Hulse

PSR B1534+12

Discovered on 1990 [Wolszczan 90]

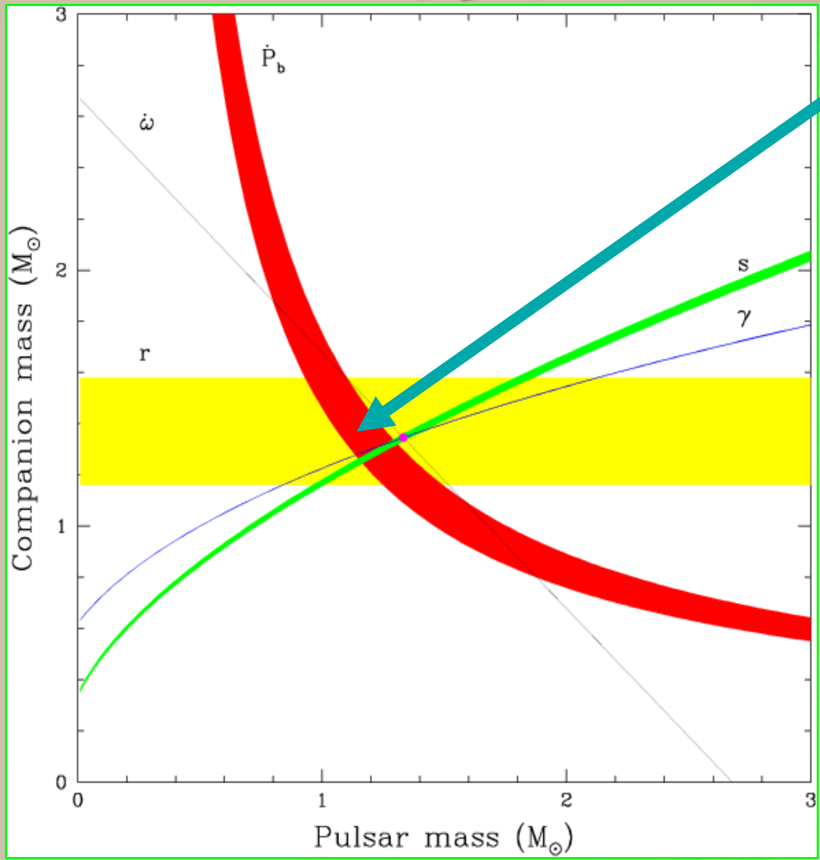


Pulsar + Neutron Star
Spin period = 38 ms
Orbital period = 10 hrs
Eccentricity = 0.27

Measured 5 PK pars: $\dot{\omega}$ γ $\dot{P}_b$ s r

Non-radiative predictions of GR tested at better than ~1% level [Stairs 2002]

PSR B1534+12



$\dot{P}_b$ does not match!

[Stairs 2002]

Affected by relative acceleration of CoM of binary pulsar system wrt Solar System barycenter [Damour & Taylor 1991]

Three terms:

-vertical acc in Galactic potential

-acc in the plane of the Galaxy

-apparent acc due to tranverse motion [Shklovskii 1970]

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\rm gal} = -\frac{a_z \sin b}{c} - \frac{v_0^2}{cR_0}\left[\cos l + \frac{\beta}{\sin^2 l + \beta^2}\right] + \mu^2 \frac{d}{c}.$$

$$\beta = d/R_0 - \cos l$$

This also limits radiative GR tests for B1913+16 at current 0.2% level [Weisberg & Taylor 2004]

PSR J0737-3039A/B

Discovered on 2003 [Burgay et al 2003, Lyne et al 2004]

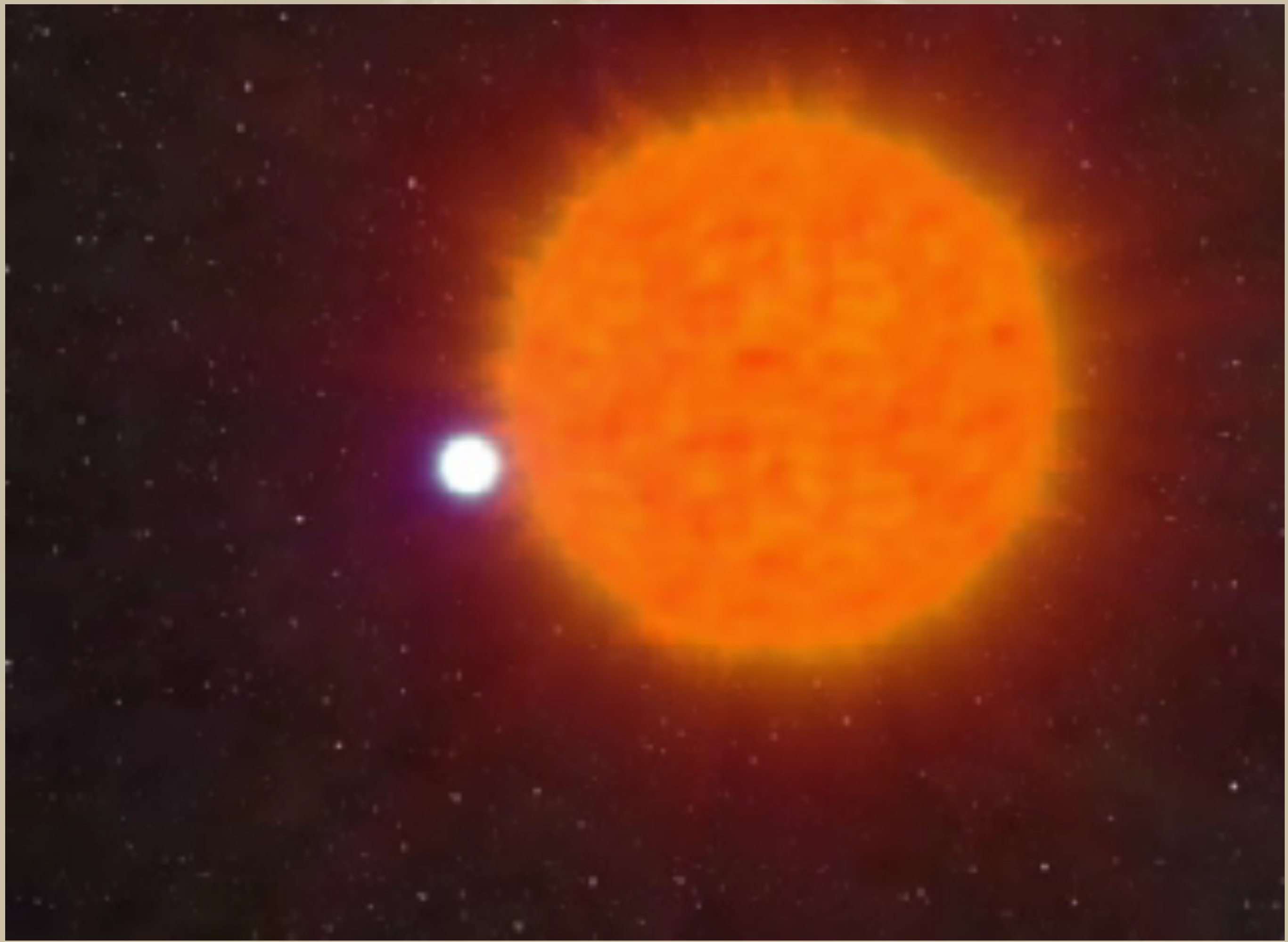
Pulsar + Pulsar
Spin period = 22.7 ms + 2.77 s
Orbital period = 2.5 hrs
Eccentricity = 0.09

Measured 5 PK pars: $\omega\ \dot{\gamma}\ P_b\ \dot{s}\ r$ [Kramer et al 2006]

+ mass ratio R

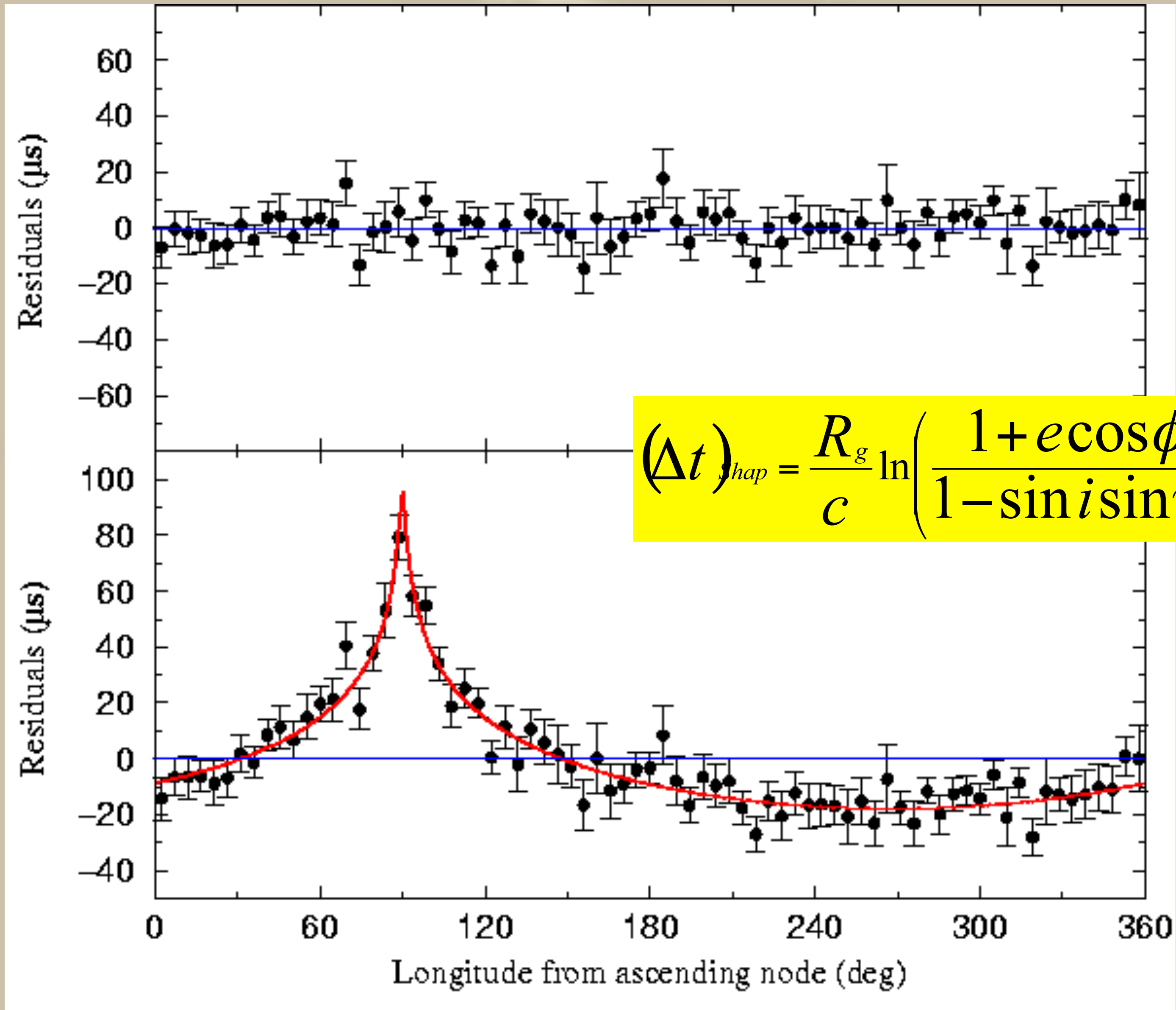
+ geodetic precession rate Ω_{prec} [Breton et al 2008]

The double pulsar PSR J0737-3039A/B



The origin of the double pulsar

Shapiro delay in PSR-A arrival times

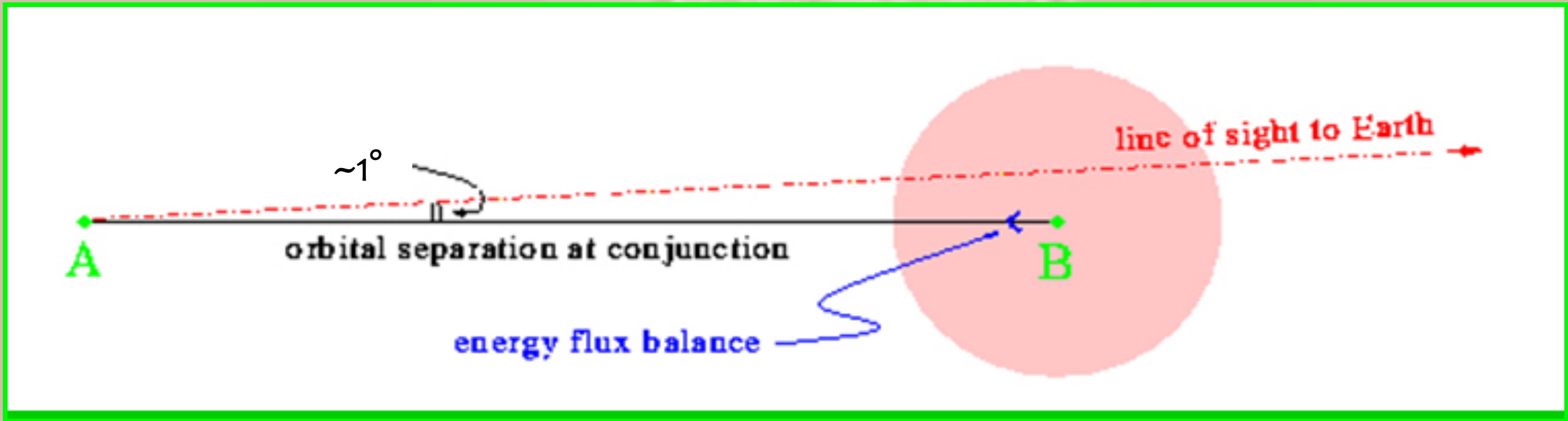


$$(\Delta t)_{Shap} = \frac{R_g}{c}\ln\left(\frac{1+e\cos\phi}{1-\sin i\sin\psi}\right)$$

The orientation of the orbit

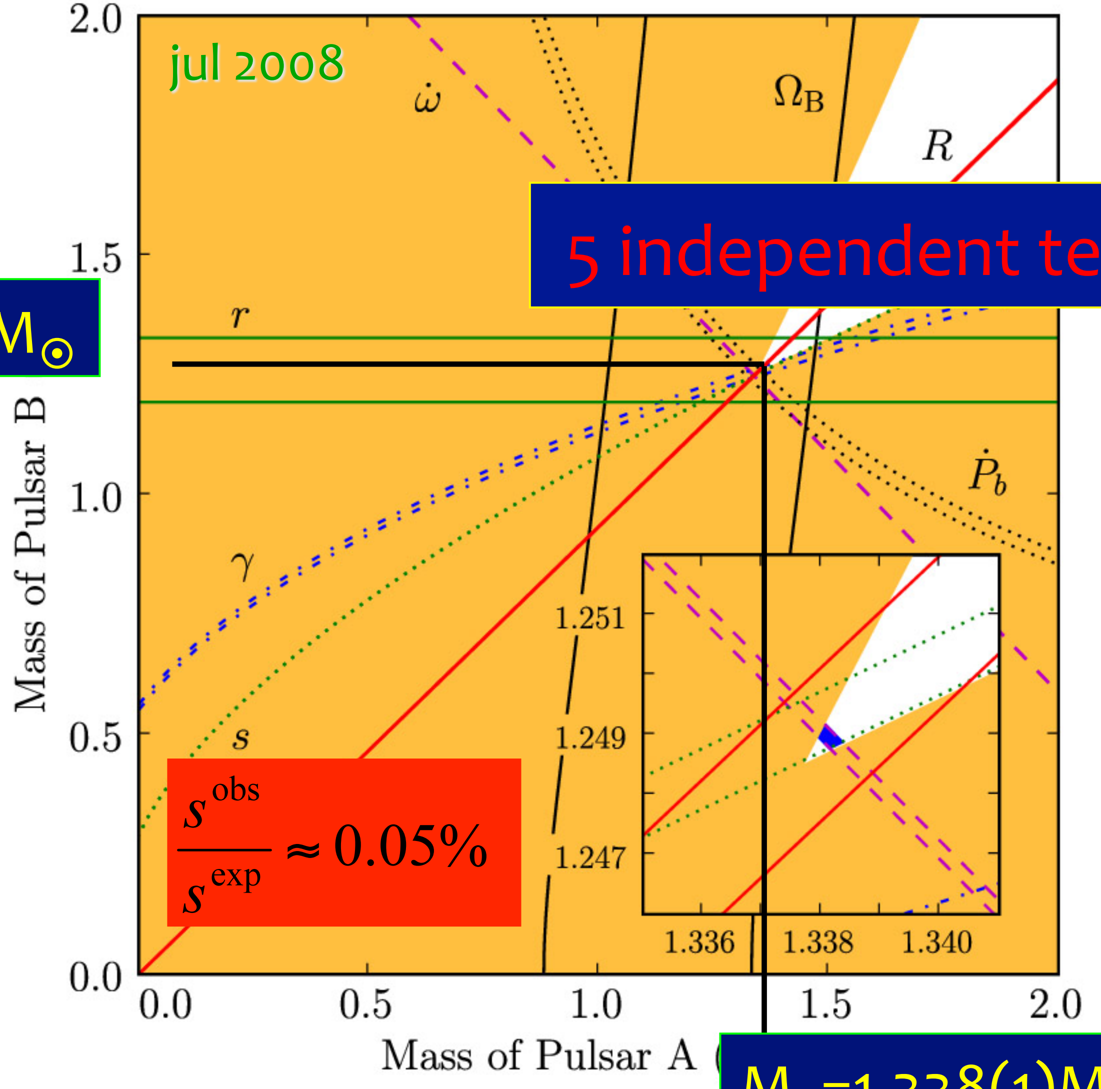
From determination of the "shape" s of the Shapiro delay s=0.99974(-39,+16)

it results i = 88.7(-0.8+0.5) deg



[© Possenti – adapted from Lyne et al 2004]

The last published mass-mass diagram for the "best" Einstein theory benchmark: J0737-3039A/B



M_B=1.249(1)$M_\odot$

5 independent tests of GR!

$$\frac{s^{obs}}{s^{exp}} \approx 0.05\%$$

M_A=1.338(1)$M_\odot$

[Breton et al 2008]

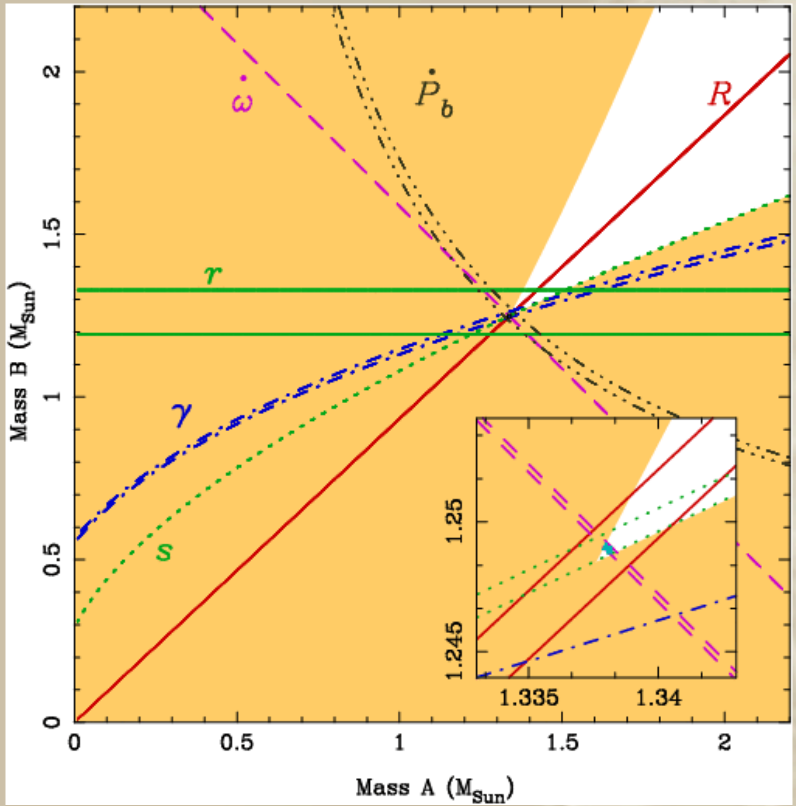
Prospects for timing were excellent:

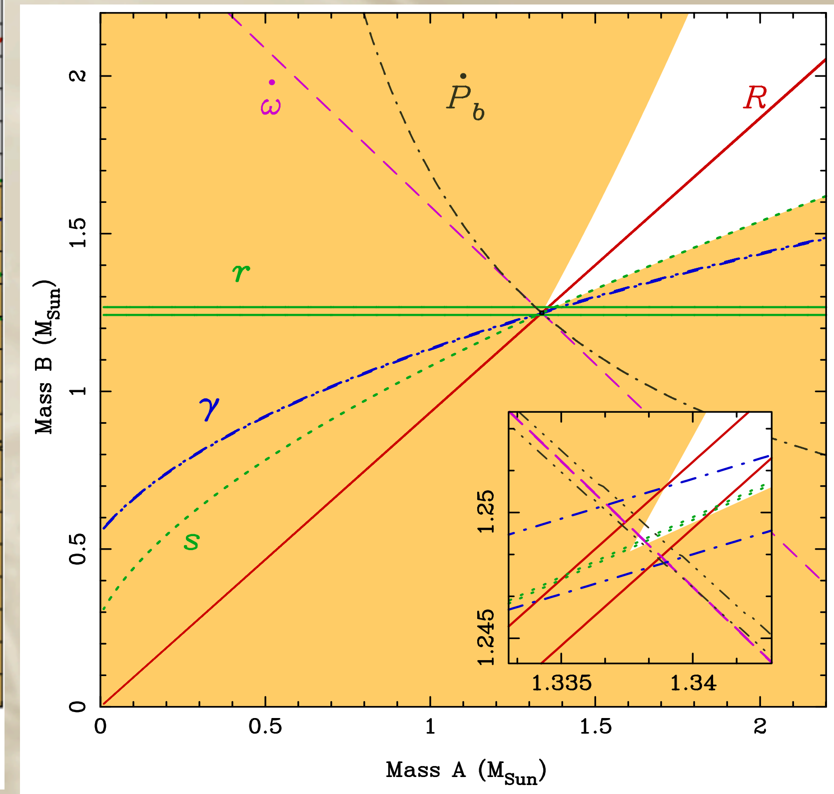
- precision $\dot{\omega} \approx \text{time}^{1.5} P_b$
- precision $\gamma \approx \text{time}^{1.5} P_b^{1.3}$
- precision $dP_b/dt \approx \text{time}^{2.5} P_b^3$
- precision $r, s \approx \text{time}^{0.5}$

...and in fact...

The current mass-mass diagram for the "best" Einstein theory benchmark: J0737-3039A/B

[Kramer et al 2006]





[Kramer et al 2014 (in prep.)]

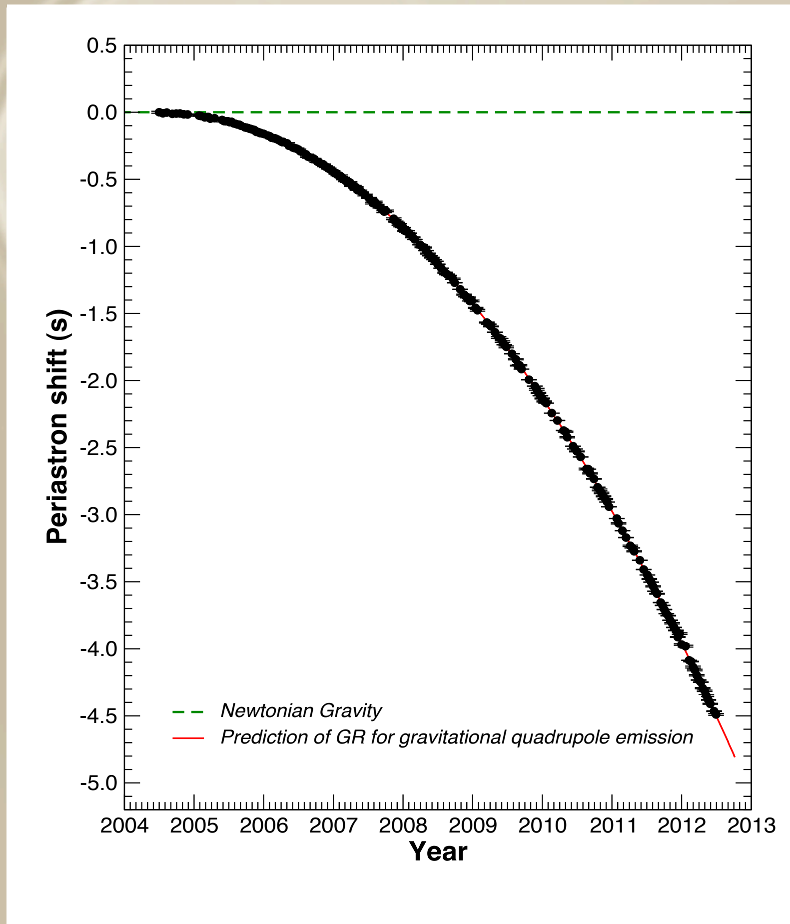
Precision measurements, e.g.

P (ms) = 22.69937884809636 ± 0. 00000000000003 (measured to **30 atto-seconds**!)

P_b (d) = 0.10225156246 5 ± 0.000000000002 (i.e. 2.45h measured to **173 ns**!)

Current radiative GR test for J0737-3039 system is at ~ 0.03% level

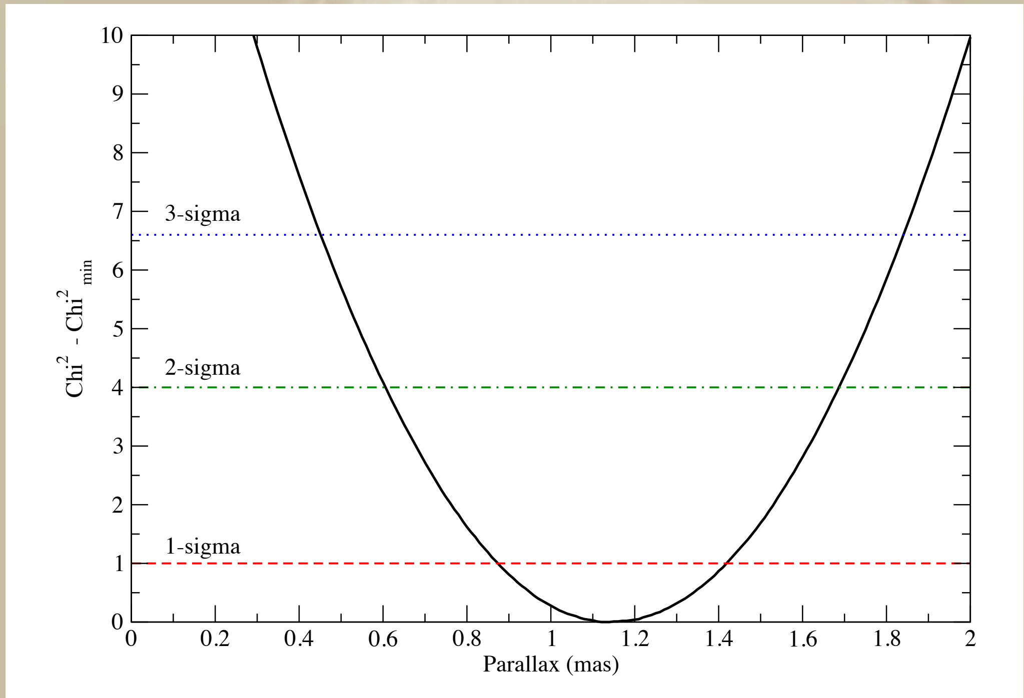
$$dP_b/dt = (-1.2480 \pm 0.0003) \times 10^{-12}$$



[Kramer et al 2014 (in prep.)]

Precision is now so good that from now on, we need to better know kinematic effects and hence Distance

[Kramer et al. 2014 (in prep.)]



D = 0.784(+0.223,-0.145) kpc

Closer than VLBI distance [Deller et al. 2009]

Speed < 10 km/s (effects less severe)

Current radiative GR tests for J0737-3039 system are at ~1% level [Kramer et al 2006]

$$\dot{P}_{\rm b}^{\rm obs} = (-1.252 \pm 0.017) \times 10^{-12}$$

What about galactic potential and kinematic corrections?

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\rm gal} = -\frac{a_z \sin b}{c} - \frac{v_0^2}{cR_0}\left[\cos l + \frac{\beta}{\sin^2 l + \beta^2}\right] + \mu^2 \frac{d}{c}.$$

$$\beta = d/R_0 - \cos l.$$

From recent interferometric determination of the distance of the system: [Deller et al 2009]

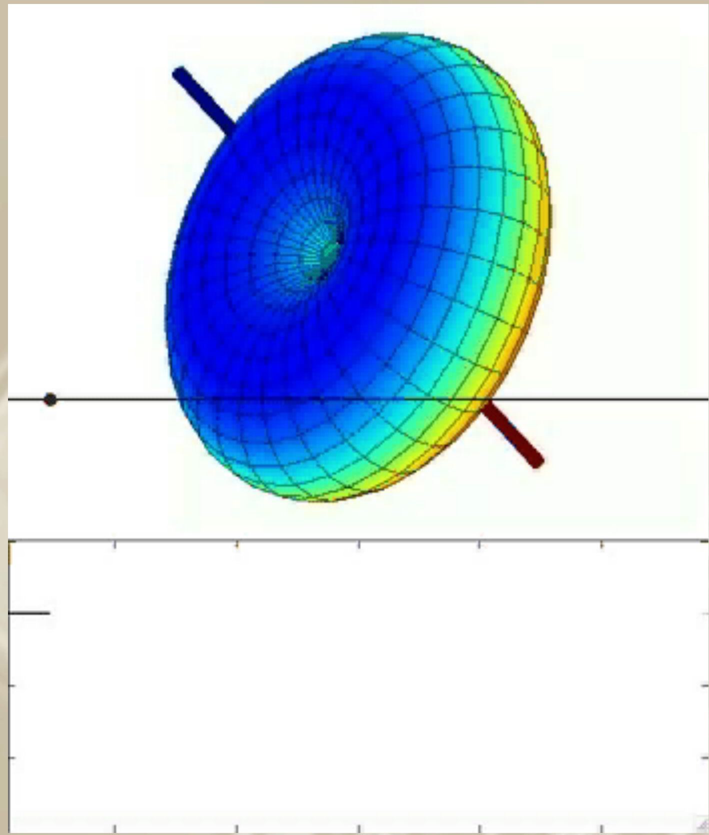
$$\dot{P}_{\rm b}^{\rm rot}/P_{\rm b} = (-4.3 \pm 0.7) \times 10^{-20}\ {\rm s}^{-1}$$

$$\dot{P}_{\rm b}^{\rm z}/P_{\rm b} = (3.8 \pm 0.8) \times 10^{-21}\ {\rm s}^{-1}$$

$$\dot{P}_{\rm b}^{\rm Shk}/P_{\rm b} = (5.3 \pm 1.8) \times 10^{-20}\ {\rm s}^{-1}$$

$$\dot{P}_{\rm b}^{\rm gk} = (1.3 \pm 1.8) \times 10^{-16}$$

Radiative GR tests for J0737-3039 system may reach 0.01% level in a decade [Deller et al 2009]



From the data of 63 eclipses observed at GBT:

Inclination of spin axis of pulsar B wrt orbit normal

$\Theta \approx 130.0^o \pm 0.5^\circ$ (1 σ) or $\Theta \approx 50.0^o \pm 0.5^\circ$ (1 σ)

Angle between magnetic and spin axes of pulsar B

$\alpha \approx 70.9^o \pm 0.5^\circ$ (1 σ)

[Breton et al 2008]

Constraint on spin-orbit coupling

In ANY "fully conservative" theory

$$\Omega_B = \frac{x_A x_B}{s^2}\frac{n^3}{1-e^2}\frac{c^2\sigma_B}{\mathcal{G}}$$

$n = 2\pi/P_b$

σ_B = spin-orbit coupling constant

$\mathcal{G}$ = generalized grav constant

For the special case of the double pulsar only, we can measure

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right) = 3.38^{+0.49}_{-0.46}.$$

… and compare with the GR prediction

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 2 + \frac{3}{2}\frac{m_A}{m_B} = 3.60677 \pm 0.00035$$

… getting…

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm obs} / \left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 0.94 \pm 0.13$$

[Breton et al 2008]

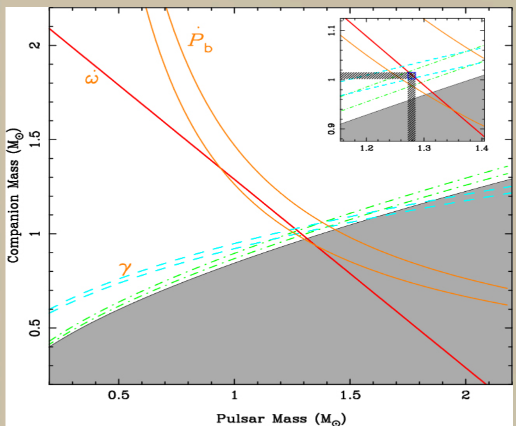
GR "effacement" property of gravity holds also for SPINNING bodies: i.e. NS structure does not prevent it to behave like a spinning test particle in an external field

The relativistic asymmetric NS+WD binaries

PSR J1141-6545
[Kaspi et al 2000]

Pulsar + "Heavy" WD
Spin period = 394 ms
Orbital period = 4.7 hrs
Eccentricity = 0.17

Measured 3 PK pars $\dot{\omega}$ γ $\dot{P}_b$

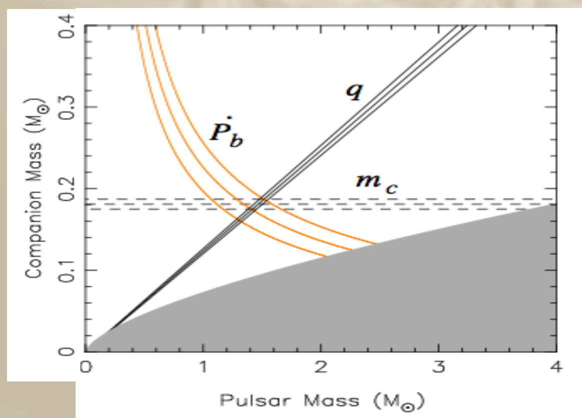


PSR J1738+0333
[Jacoby et al 2001,2005]

Pulsar +"Light" WD
Spin period = 5.8 ms
Orbital period = 8.5 hrs
Eccentricity < 4 x 10^{-7}

Measured 1 PK par $\dot{P}_b$

+ M_{comp}, M_{psr} from optical obs

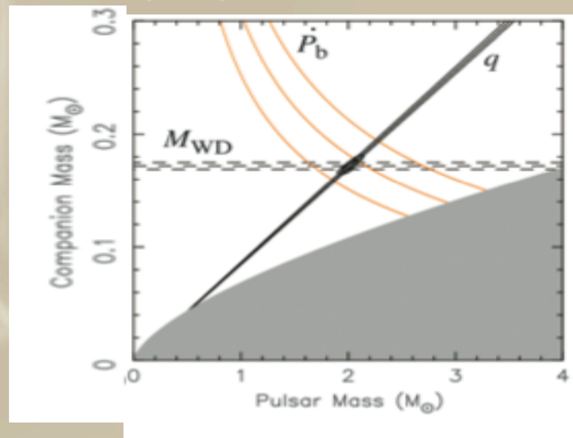


PSR J0348+0432
[Boyles et al 2013; Lynch et al 2013]

"Heavy" Pulsar +"Light" WD
Spin period = 39.1 ms
Orbital period = 2.5 hrs
Eccentricity < 3 x 10^{-6}

Measured 1 PK par $\dot{P}_b$

+ M_{comp}, M_{psr} from optical obs



Radiative predictions of GR tested at better than:

~6% level [Bhat et al 2008]   ~15% level [Freire et al 2012]   ~18% level [Antoniadis et al 2013]

The relativistic asymmetric NS+WD binaries

Tensor-scalar theories predicts the emission of a large amount of DIPOLAR scalar waves (as opposed to the dominant QUADRUPOLAR radiation predicted by GR) in such very asymmetric systems

Masses of the two components and/or radii are very different...

$M_{NS} = (1.27 \pm 0.01)\, M_{sun}$	$M_{NS} = (1.46 \pm 0.06)\, M_{sun}$	$M_{NS} = (2.01 \pm 0.04)\, M_{sun}$
$M_{WD} = (1.02 \pm 0.01)\, M_{sun}$	$M_{WD} = (0.118 \pm 0.008)\, M_{sun}$	$M_{WD} = (0.172 \pm 0.003)\, M_{sun}$

leading to a significant difference in the degree of compactness ε (i.e. in the self-gravity) of the two bodies in these binaries

$$\varepsilon_{NS} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{NS}}{c^2 R_{NS}} \cong 0.2 \qquad \varepsilon_{WD} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{WD}}{c^2 R_{WD}} \cong 10^{-4}$$

These are the best available binary systems for constraining the coupling constant α_0 in tensor-scalar theories

[Esposito-Farese 2005; Freire et al 2012; Verbiest et al 2012]

The relativistic asymmetric NS+WD binaries

$$g_{\mu\nu} = metric$$

$$a(\varphi) = \alpha_0\varphi + \frac{1}{2}\beta_0\varphi^2$$

φ scalar field

$a(\varphi)$ coupling field-matter

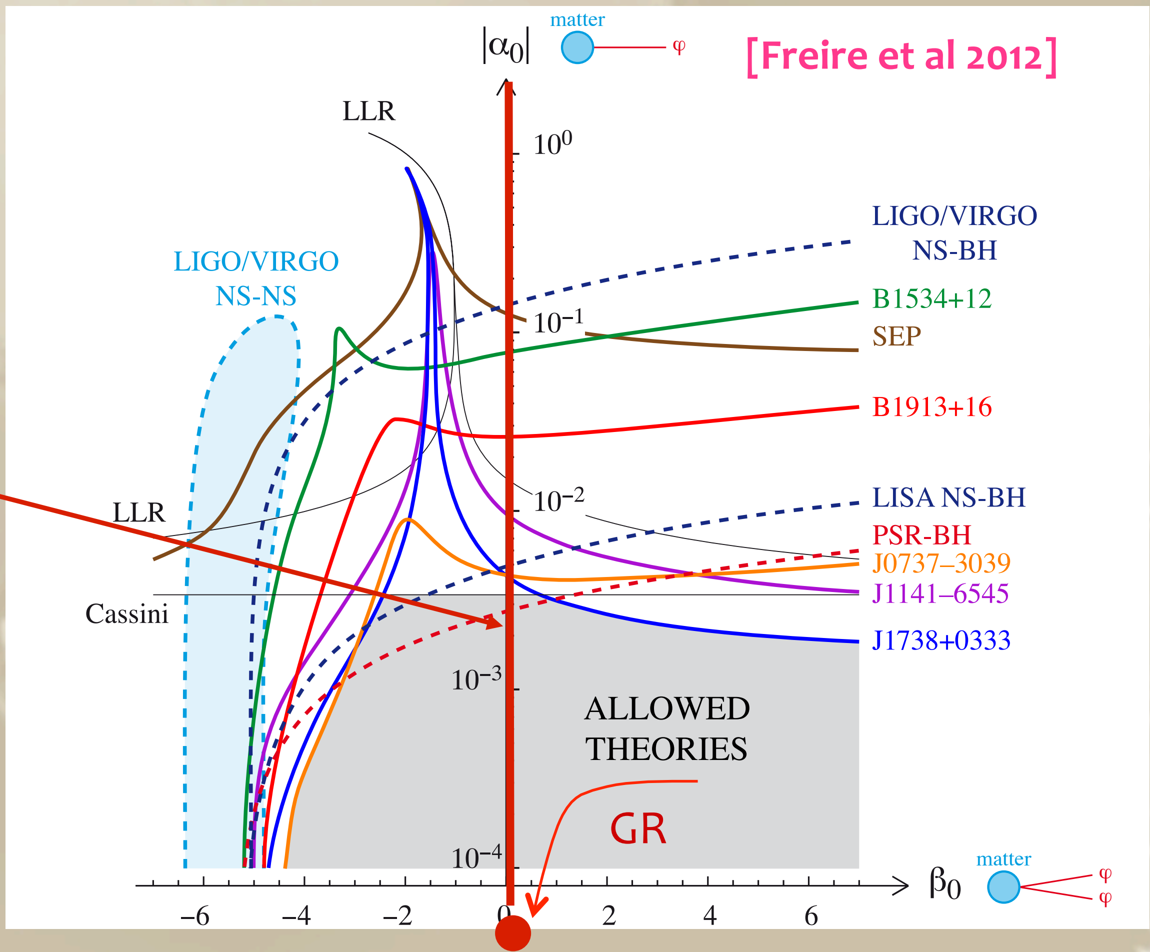
α_0, β_0 coupling parameters

Branse-Dicke

Whence the limits are: [Freire et al 2012]

$\alpha^2_{0,\infty} < 0.5\ 10^{-6} \approx 0.1$ Cassini limit

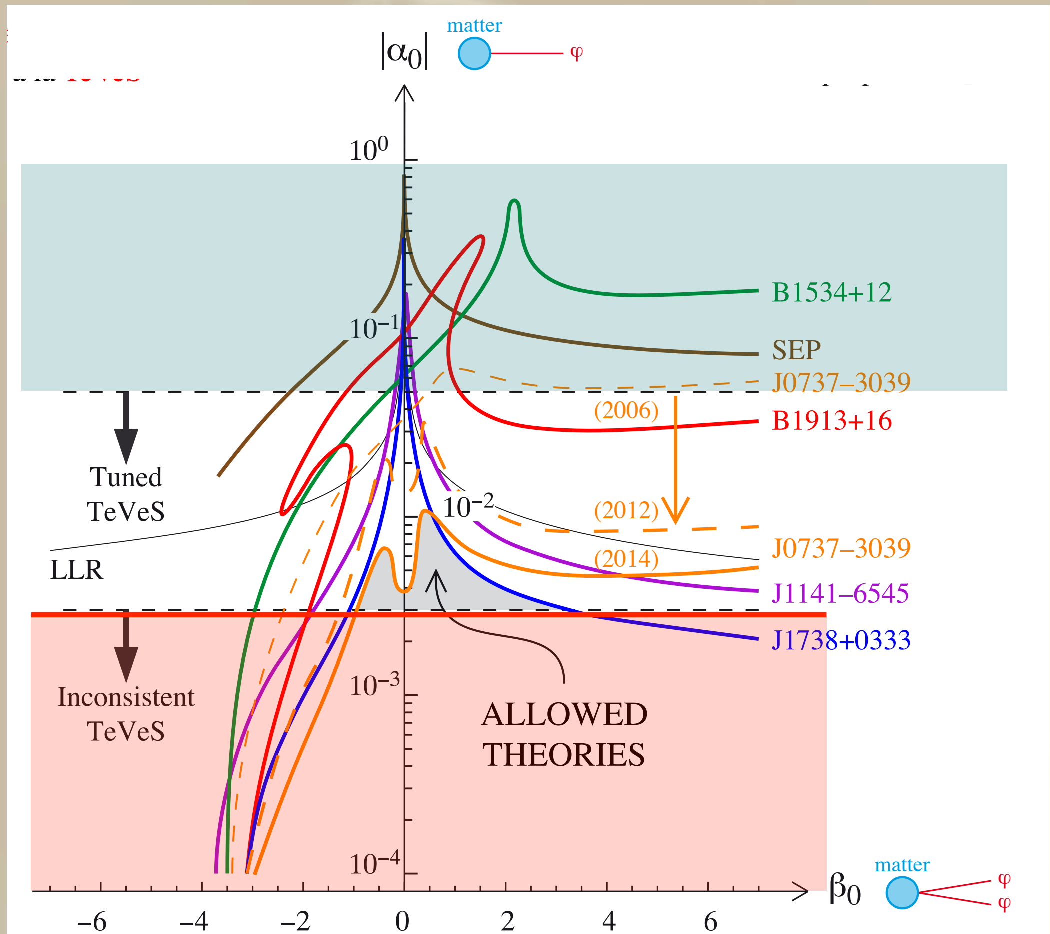
$\alpha^2_{0,B\text{-}D} < 2\ 10^{-5} \approx 1.7$ Cassini limit



The double pulsar put the strongest constraints for the β<0

Limits for general class of TensorVectorialScalar theories

Double Pulsar and PSR-WD systems complement each other perfectly in constraining the allowed space of the parameters



[Kramer et al. 2015(in prep)]

MOND-like TeVeS theories NEED TO BE TUNED and thus deviate from its original form

…some other tests on fundamental physics with binary pulsars

Time derivative of G
PSR J0437-4715

$[dG/dt]/G = (-5 \pm 18) \cdot 10^{-12}\ yr^{-1}$
(about 10 times weaker than lunar ranging but much simpler and in strong-field)
[Damour & Taylor 1991, Verbiest et al 2008]

Strong Equivalence Principle
21 highly circular WD-MSP

$|\Delta| = 5.6 \cdot 10^{-3}$ (weaker than solar system tests, but in strong-field regime)
[Wex 1997, Stairs et al 2005]

Momentum conservation
21 highly circular WD-MSP

$|\hat{\alpha}_3| = 4.0 \cdot 10^{-20}$ (10^{13} better than Earth or Mercury perhelion shifts)
[Bell & Damour 1996, Stairs et al 2005]

Existence of preferred frame
PSR J1012+5307

$|\hat{\alpha}_1| = 1.4 \cdot 10^{-4}$ (slighlty weaker than lunar laser ranging, but in strong-field regime)
[Wex 2000]

the triple system parameters

J0337+1715 - Timing Observations

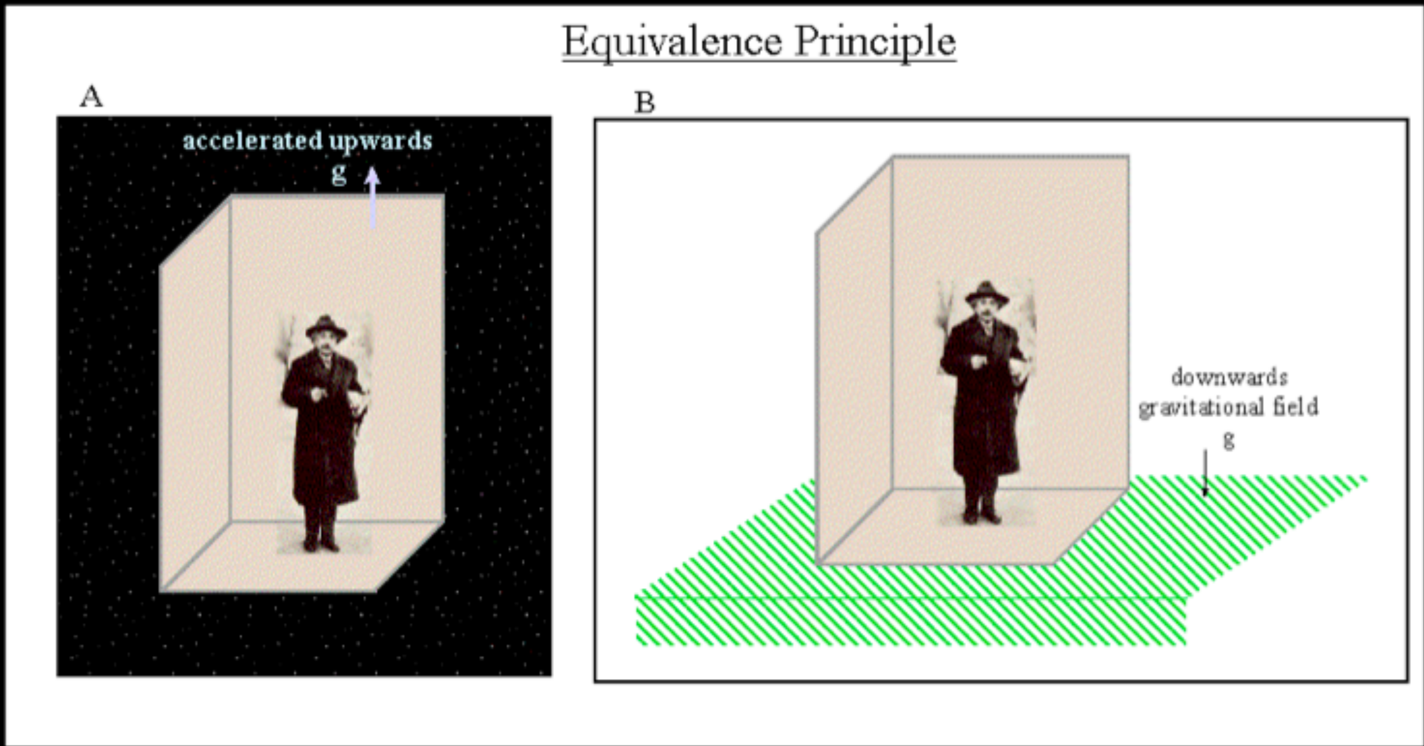
Parameter	Symbol	Value
Fixed values		
Right ascension	RA	$03^h37^m43^s.82589(13)$
Declination	Dec	$17°15'14''.828(2)$
Dispersion measure	DM	$21.3162(3)$ pc cm^{-3}
Solar system ephemeris		DE405
Reference epoch		MJD 55920.0
Observation span		MJD 55930.9 − 56436.5
Number of TOAs		26280
Weighted root-mean-squared residual		1.34 μs
Fitted parameters		
Spin-down parameters		
Pulsar spin frequency	f	365.953363096(11) Hz
Spin frequency derivative	$\dot{f}$	$-2.3658(12) \times 10^{-15}$ Hz s^{-1}
Inner Keplerian parameters for pulsar orbit		
Semimajor axis projected along line of sight	$(a \sin i)_I$	1.21752844(4) lt-s
Orbital period	$P_{b,I}$	1.629401788(5) d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,I}$	$6.8567(2) \times 10^{-4}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,I}$	$-9.171(2) \times 10^{-5}$
Time of ascending node	$t_{asc,I}$	MJD 55920.407717436(17)
Outer Keplerian parameters for centre of mass of inner binary		
Semimajor axis projected along line of sight	$(a \sin i)_O$	74.6727101(8) lt-s
Orbital period	$P_{b,O}$	327.257541(7) d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,O}$	$3.5186279(3) \times 10^{-2}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,O}$	$-3.462131(11) \times 10^{-3}$
Time of ascending node	$t_{asc,O}$	MJD 56233.935815(7)
Interaction parameters		
Semimajor axis projected in plane of sky	$(a \cos i)_I$	1.4900(5) lt-s
Semimajor axis projected in plane of sky	$(a \cos i)_O$	91.42(4) lt-s
Inner companion mass over pulsar mass	$q_I = m_{cI}/m_p$	0.13737(4)
Difference in longs. of asc. nodes	δ_Ω	$2.7(6) \times 10^{-3}$ °
Inferred or derived values		
Pulsar properties		
Pulsar period	P	2.73258863244(9) ms
Pulsar period derivative	$\dot{P}$	$1.7666(9) \times 10^{-20}$
Inferred surface dipole magnetic field	B	2.2×10^8 G
Spin-down power	$\dot{E}$	3.4×10^{34} erg s^{-1}
Characteristic age	τ	2.5×10^9 y
Orbital geometry		
Pulsar semimajor axis (inner)	a_I	1.9242(4) lt-s
Eccentricity (inner)	e_I	$6.9178(2) \times 10^{-4}$
Longitude of periastron (inner)	ω_I	97.6182(19) °
Pulsar semimajor axis (outer)	a_O	118.04(3) lt-s
Eccentricity (outer)	e_O	$3.53561955(17) \times 10^{-2}$
Longitude of periastron (outer)	ω_O	95.619493(19) °
Inclination of invariant plane	i	39.243(11) °
Inclination of inner orbit	i_I	39.254(10) °
Angle between orbital planes	δ_i	$1.20(17) \times 10^{-2}$ °
Angle between eccentricity vectors	$\delta_\omega \sim \omega_O - \omega_I$	−1.9987(19) °
Masses		
Pulsar mass	m_p	1.4378(13) $M_\odot$
Inner companion mass	m_{cI}	0.19751(15) $M_\odot$
Outer companion mass	m_{cO}	0.4101(3) $M_\odot$

Timing modeling by: Anne Archibald

Pulsar mass: 1.4378(13) Msun
Inner WD mass: 0.19751(15) Msun
Outer WD mass: 0.4101(3) Msun

the triple system: Gen Rel tests prospects

Also test the Strong Equivalence Principle



J0337+1715 could be more constraining than lunar laser ranging