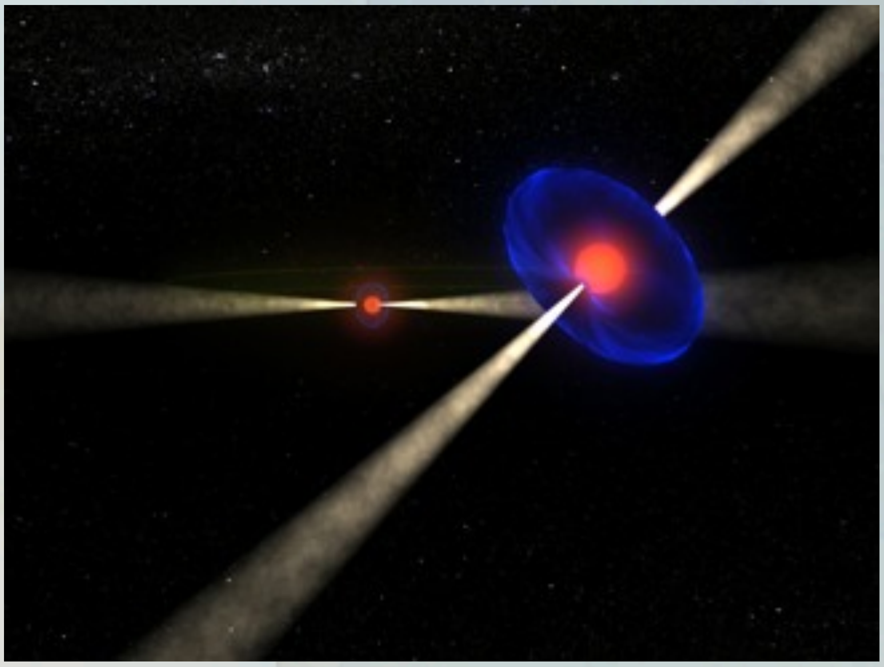
Binary Pulsars as Tools to Study Gravity



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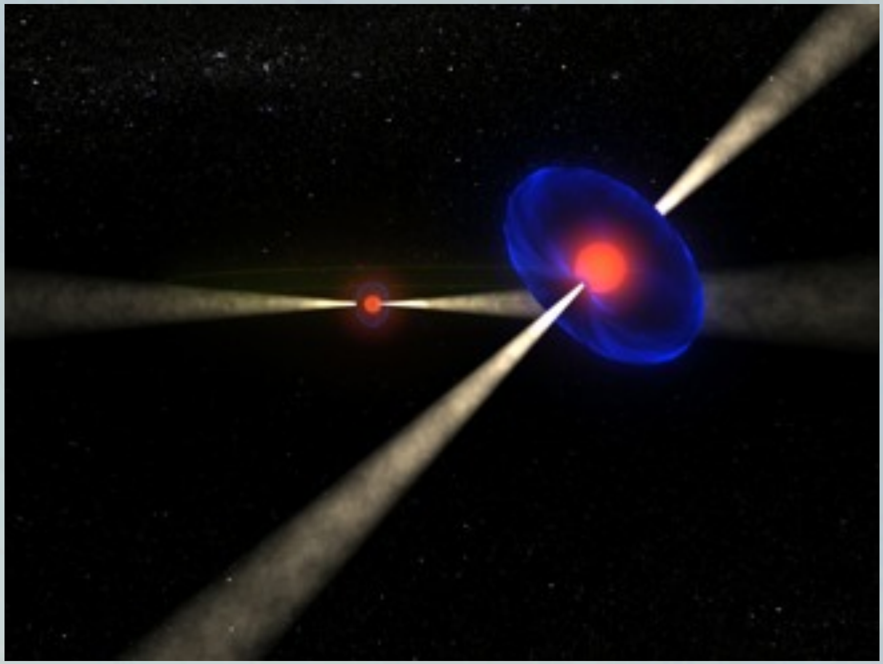
René Breton
University of Southampton

GWPAW 2012
Hannover, 7 June 2012

By the End You Should Remember...

Binary pulsars

- Excellent tools to **test gravity**
- Probe a **different** gravitational field **regime**
- **System diversity** = complementarity



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Pulsars 101

The Binary Pulsar Population

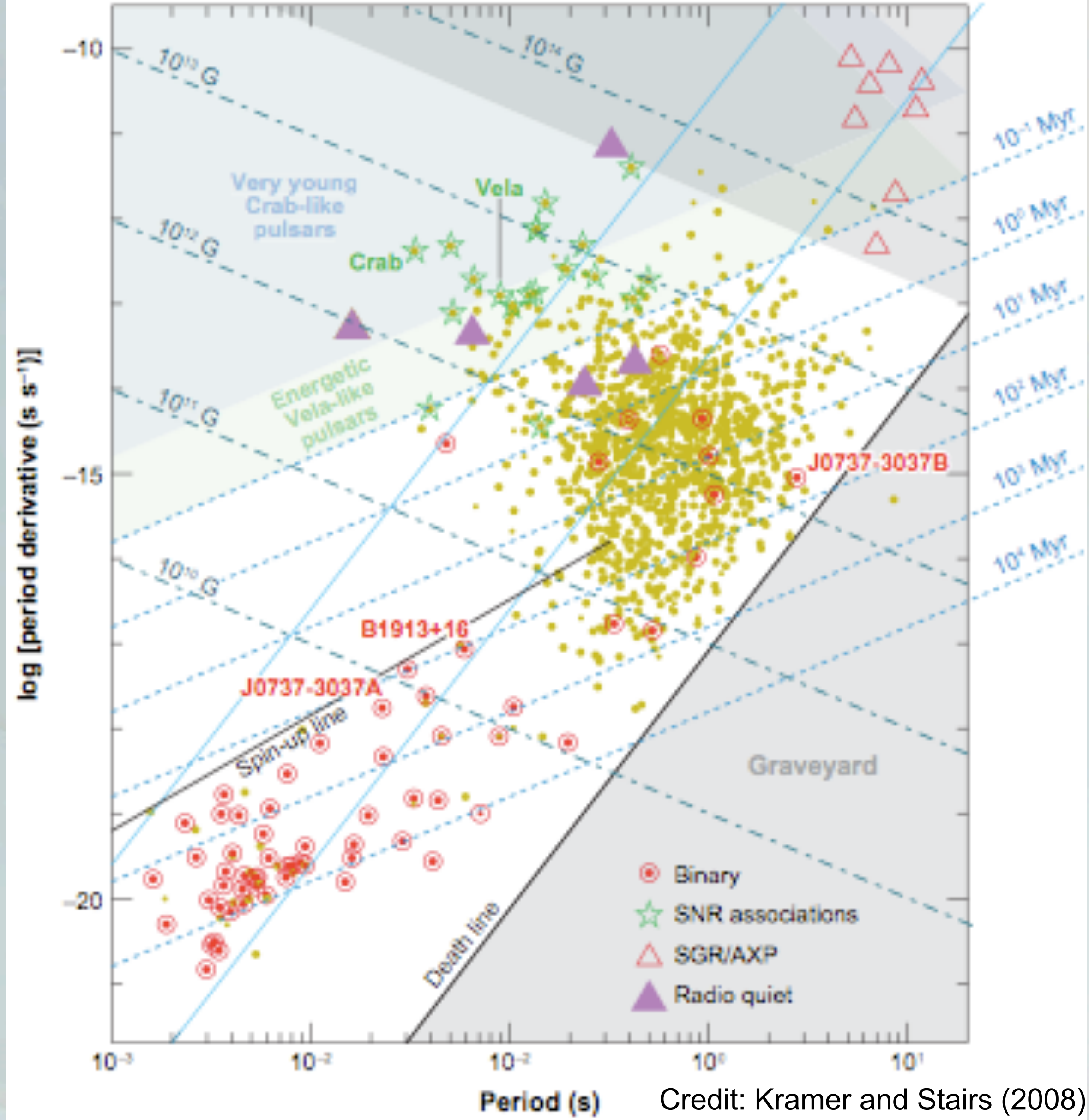
Binary pulsars are "special"

According to the ATNF catalogue:

- 2008 pulsars
- 186 binary pulsars

Binaries:

- **Short** spin periods
- **Old**
- **Low** magnetic fields



Credit: Kramer and Stairs (2008)

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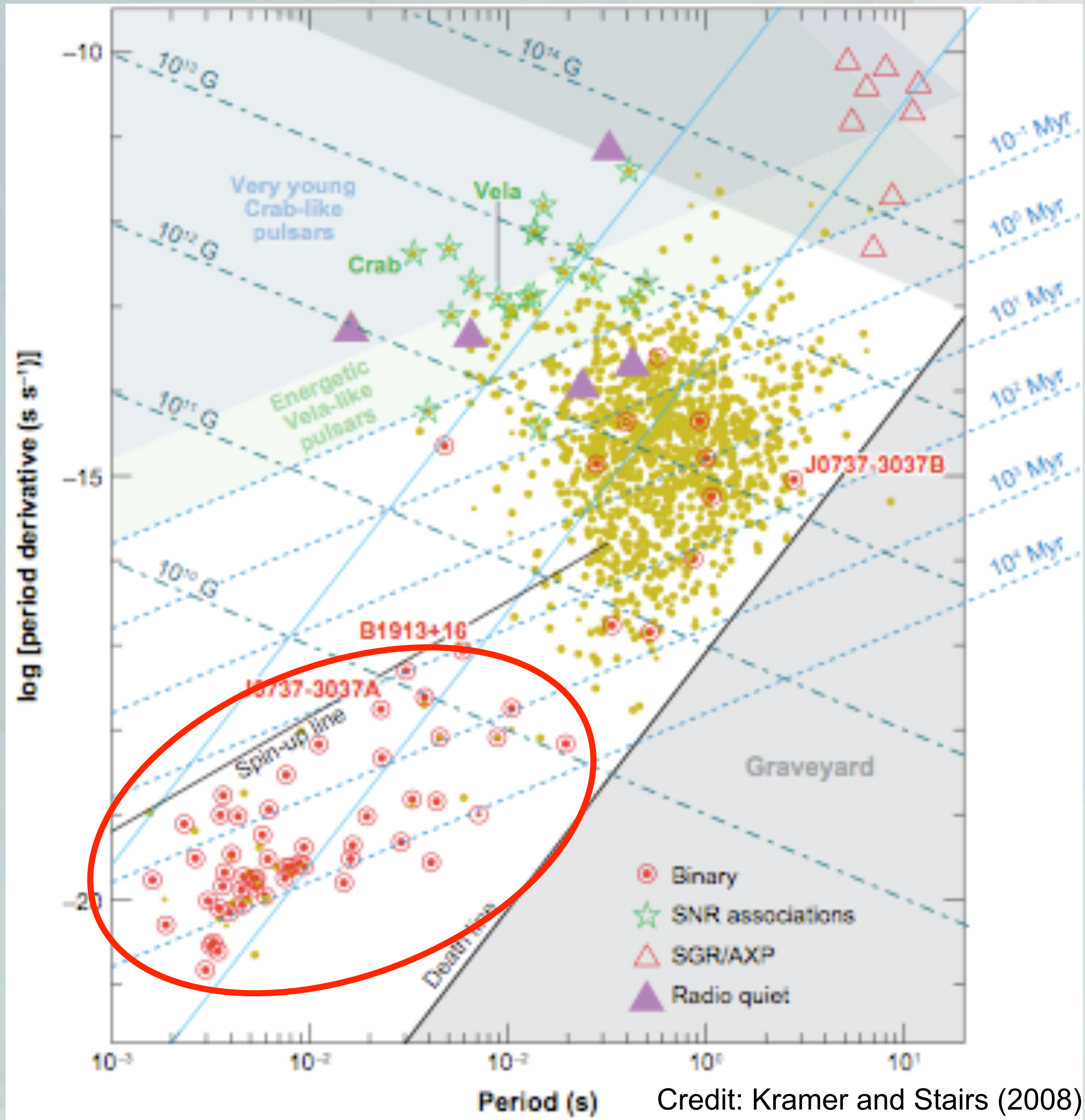
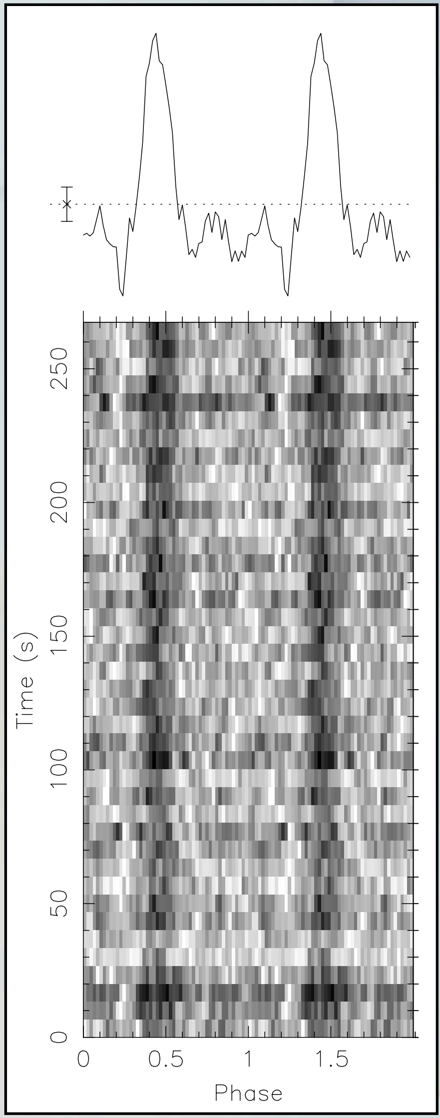


Credit: Kramer and Stairs (2008)

Binary Pulsar Timing and Gravity

Almost textbook examples

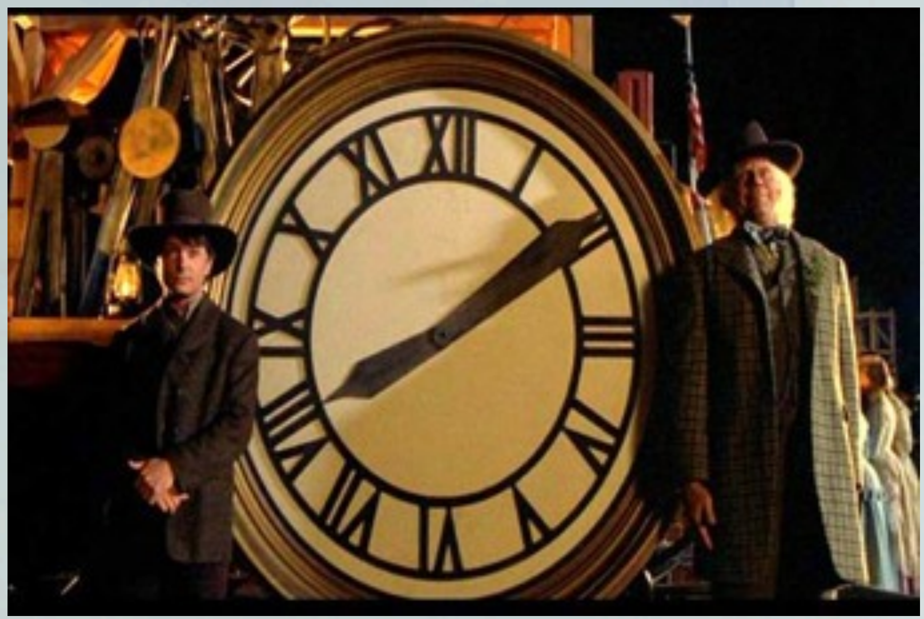


Compact objects (point mass)

Precise timing (frequency standard)

Typical TOAs precision is ~0.1% P_{spin}

$$\phi = \phi_0 + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \ldots$$



Binary Pulsar Dynamics
&
Relativistic Effects

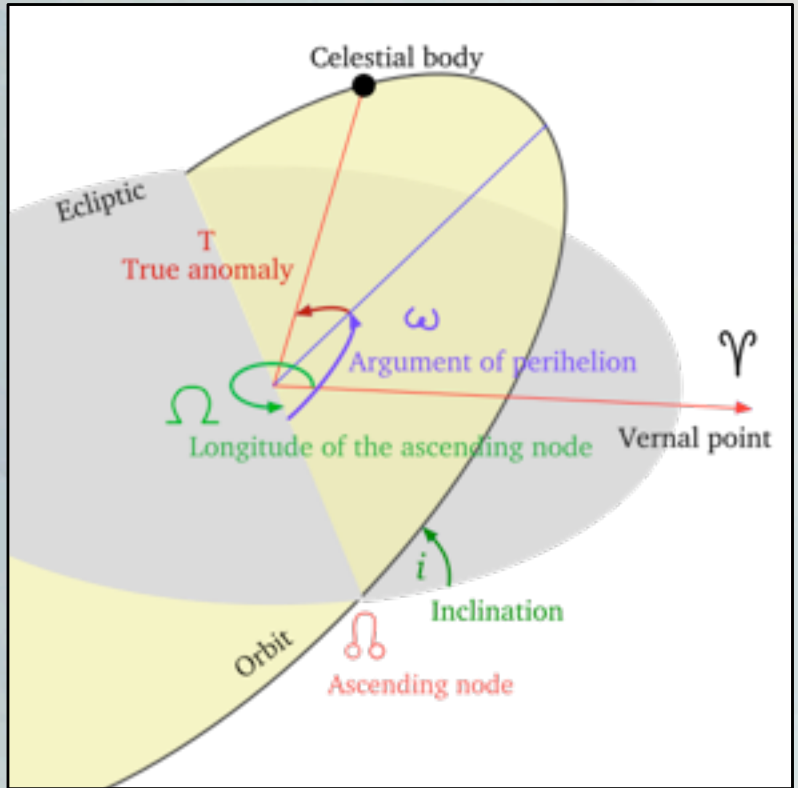
Binary Pulsar Timing

Newtonian orbits

Timing binary pulsars allows one to determine 5 Keplerian parameters:

- Orbital period P_b
- Eccentricity e
- Longitude of periastron ω
- Projected semimajor axis $x_1 \equiv a_1/c \sin i$
- Epoch of periastron T_0

We measure radial Doppler shifts only…
=> The **orbital inclination** angle is **unknown**.



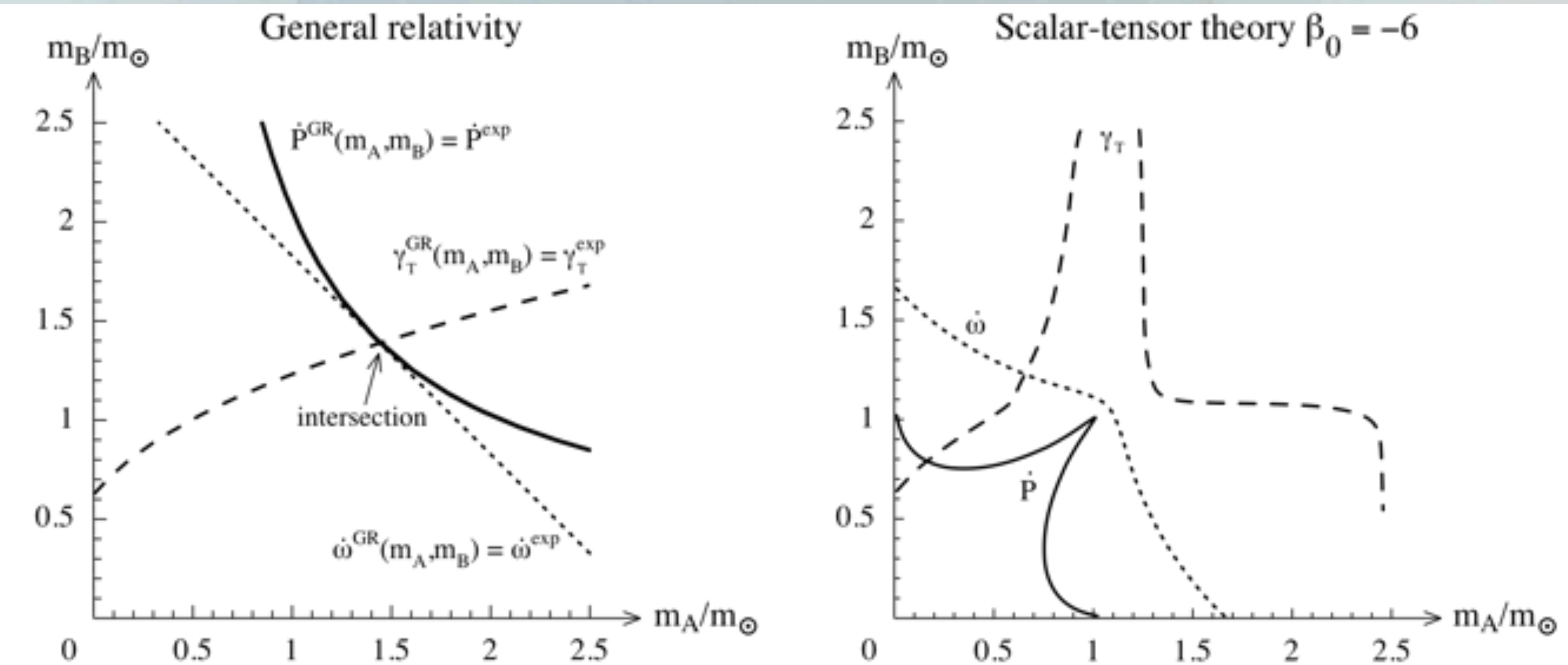
Arpad Horvath (Wikipedia)

Relativistic orbits

Post-Keplerian (PK) parameters: dynamics beyond Newton.

- PKs are **phenomenological corrections** (theory-independent).
- PKs are functions of Keplerian parameters, M_1 and M_2.

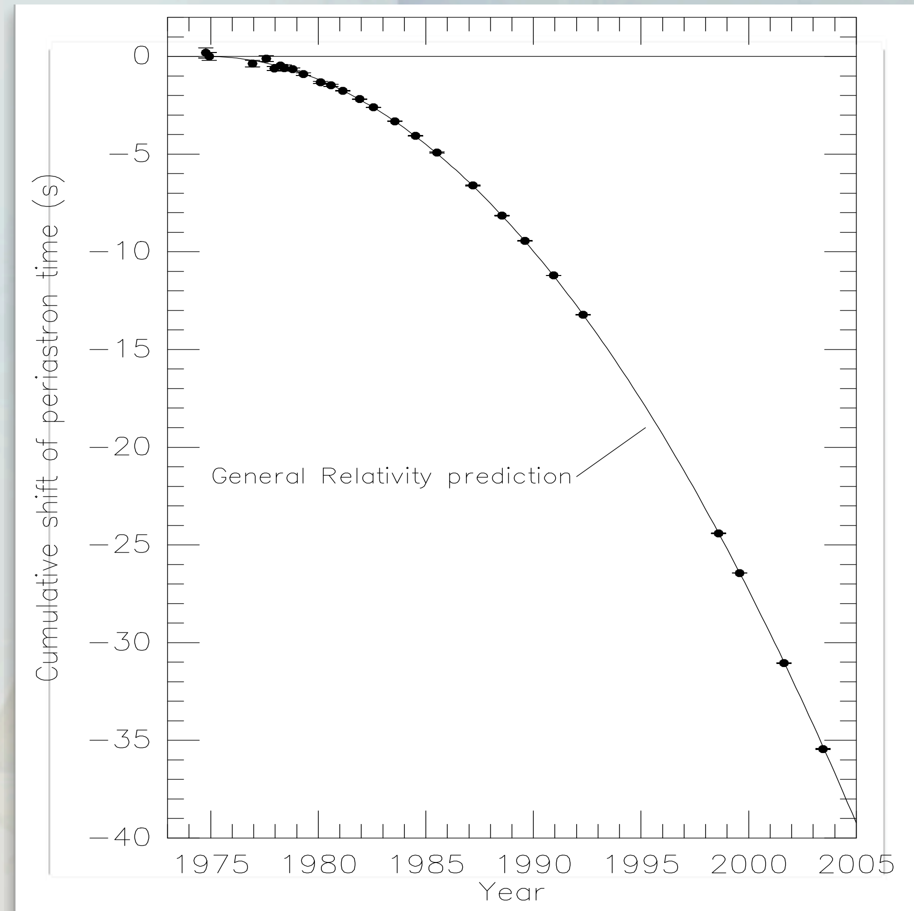
More than 2 PKs = test of a given relativistic theory of gravity.



Esposito-Farese (2004)

Binary Pulsar Timing

Relativistic orbits



Weisberg & Taylor (2005)

- Testing gravity relies on **orbital dynamics**
- Ideally: pulsar + neutron star
  eccentric + compact orbit
- About 10 known “relativistic” pulsar binaries

PSR B1913+16

- First binary pulsar discovered (Hulse & Taylor 1975)
- First indirect evidence of gravitational wave emission (Taylor et al. 1979)

The Double Pulsar

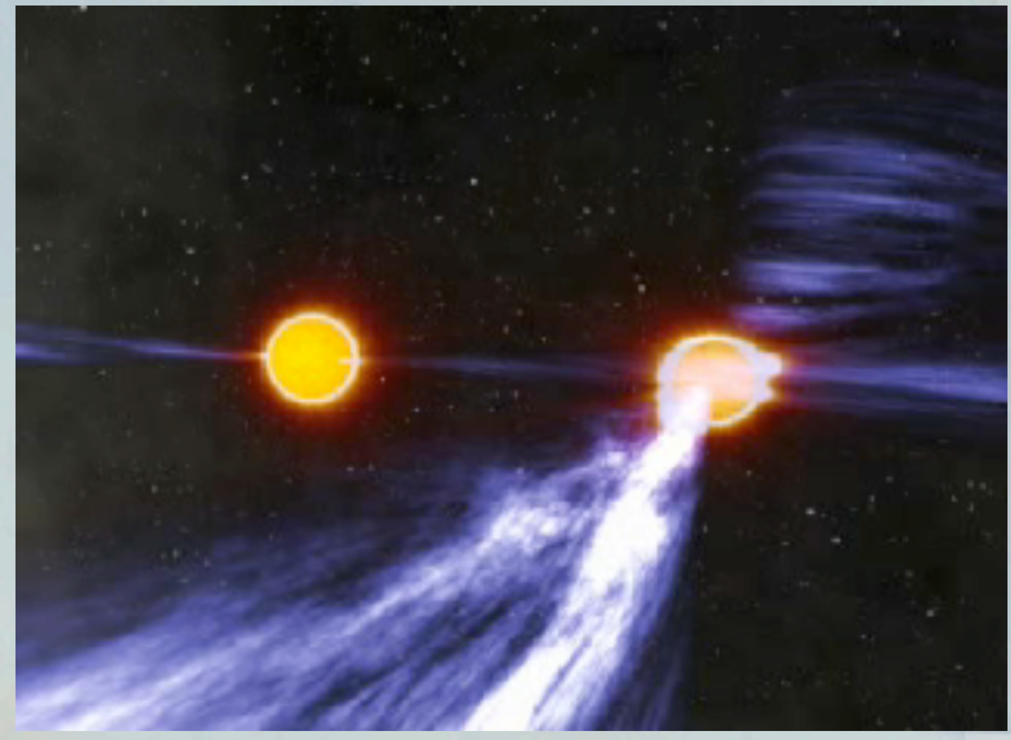
A unique system

The ***Double Pulsar*** (PSR J0737-3039A/B), is the **only known pulsar-pulsar** system.

Pulsar A: 23 ms (Burgay et al., 2003)
Pulsar B: 2.8 s (Lyne et al., 2004)

Eccentricity: 0.08

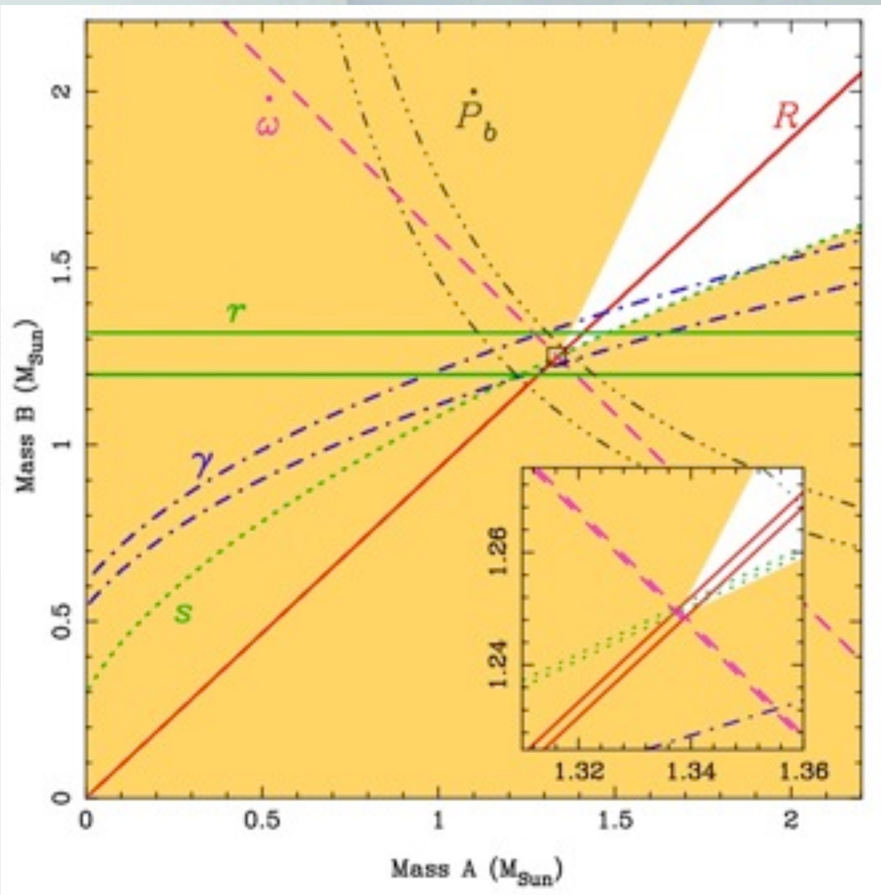
Orbital period: 2.4 hrs !!! ($v_{orbital}$ ~ 0.001 c)



Australia Telescope National Facility, CSIRO

The Double Pulsar

Testing gravity



Kramer et al., 2006

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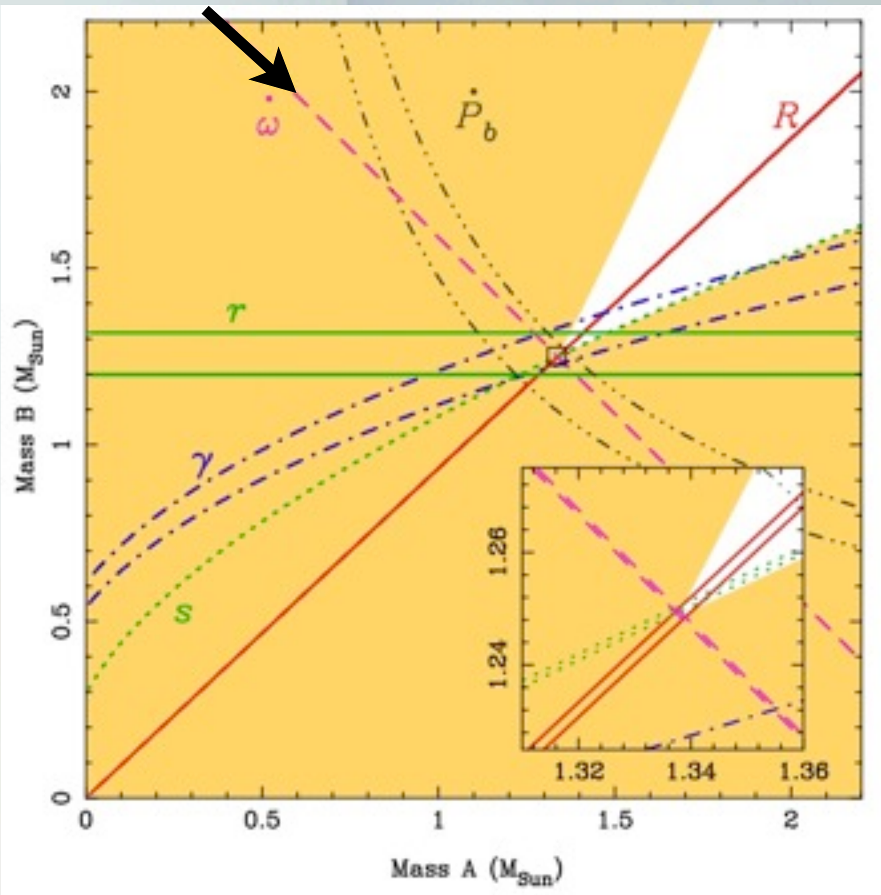
<u>Periastron advance</u>

Rate of precession of the periastron: 17°yr^{-1} !

It takes 21 years to complete a cycle of precession.

The Double Pulsar

Testing gravity



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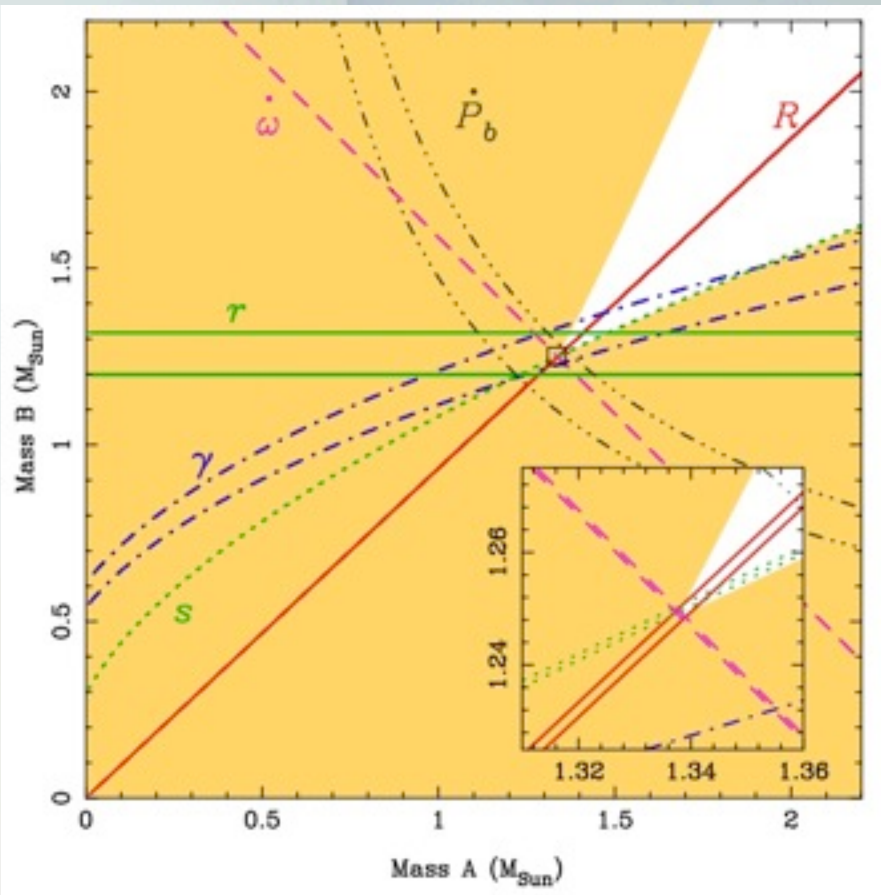

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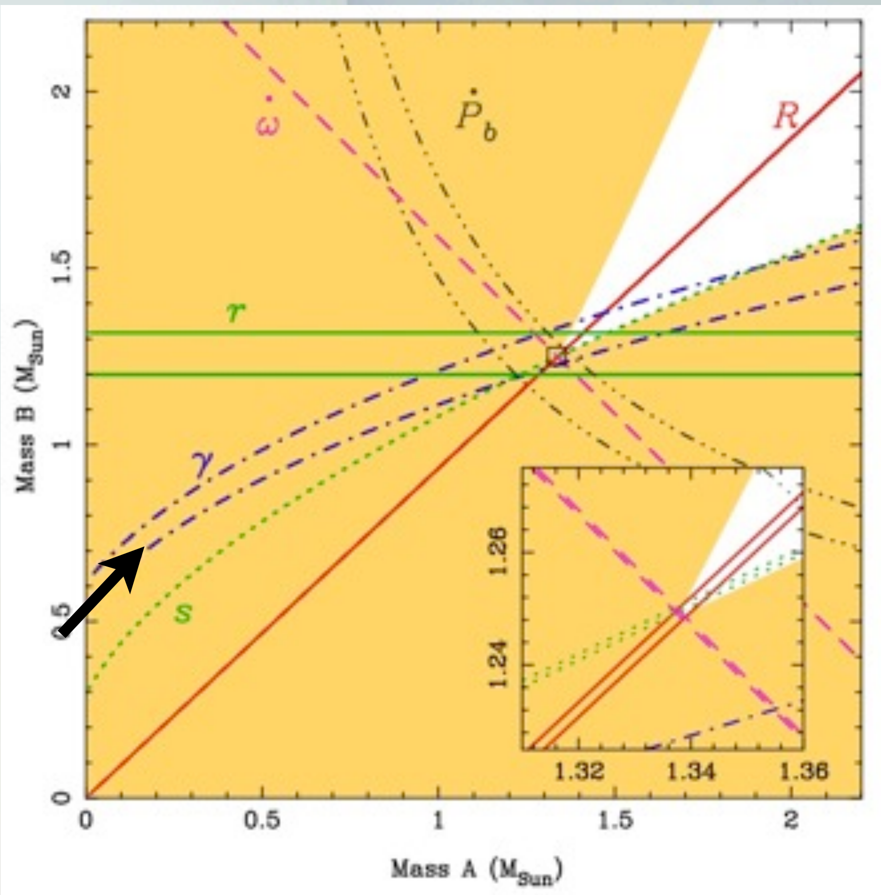
<u>Gravitational redshift and time dilation</u>

Needs to climb to potential well

Clocks tick at variable rate in gravitational potentials

The Double Pulsar

Testing gravity



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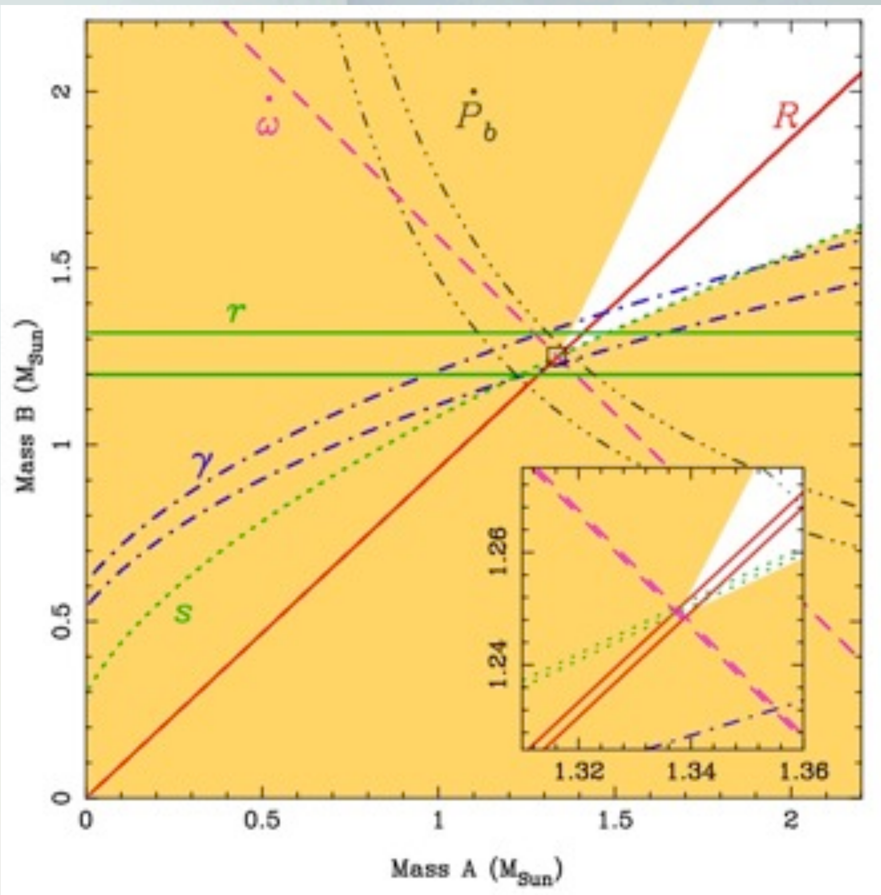

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<u>Orbital period decay</u>

Gravitational wave emission

Orbit shrinks 7mm/day (coalescence timescale ~ 85 Myrs)

The Double Pulsar

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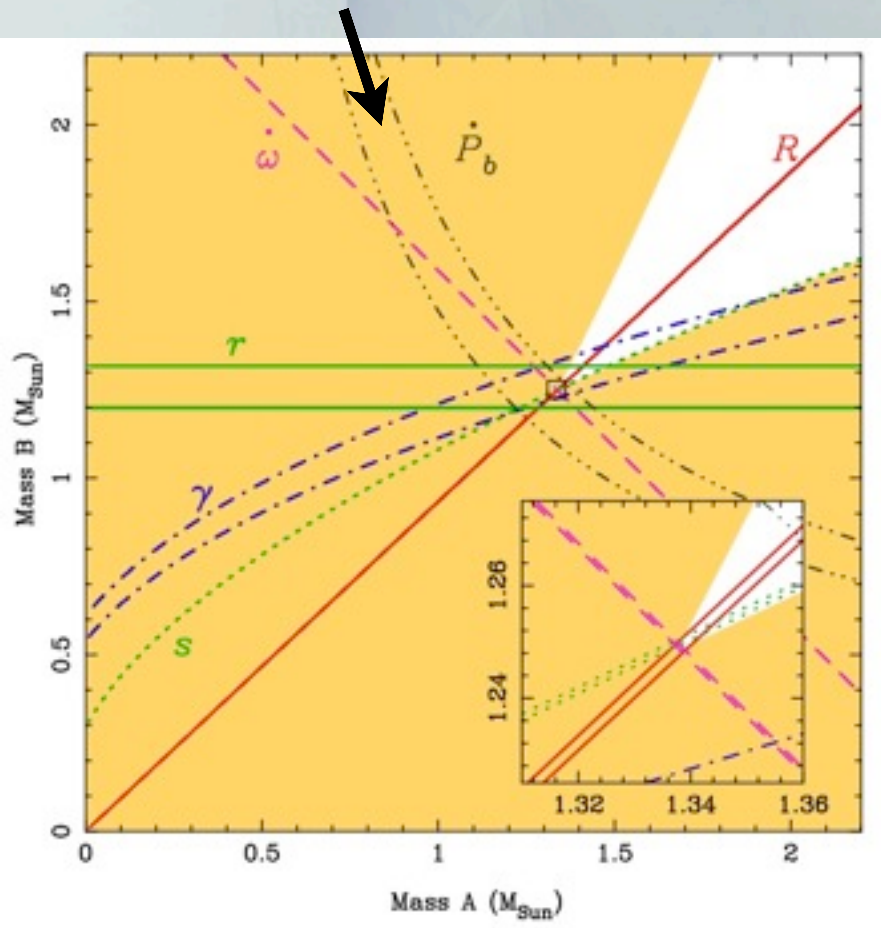

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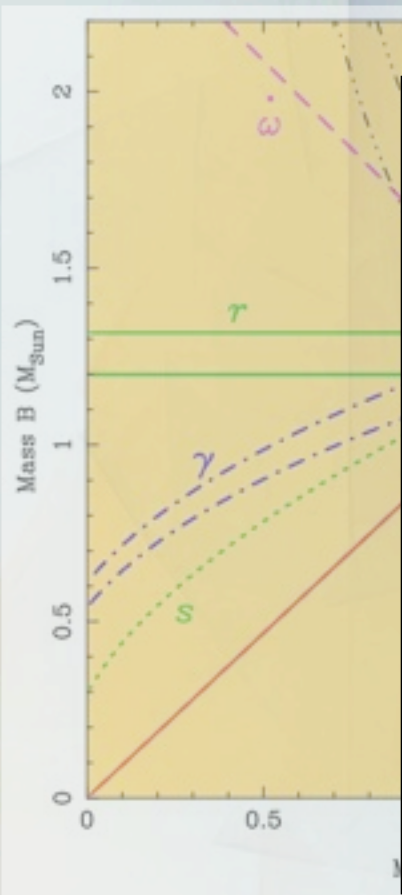

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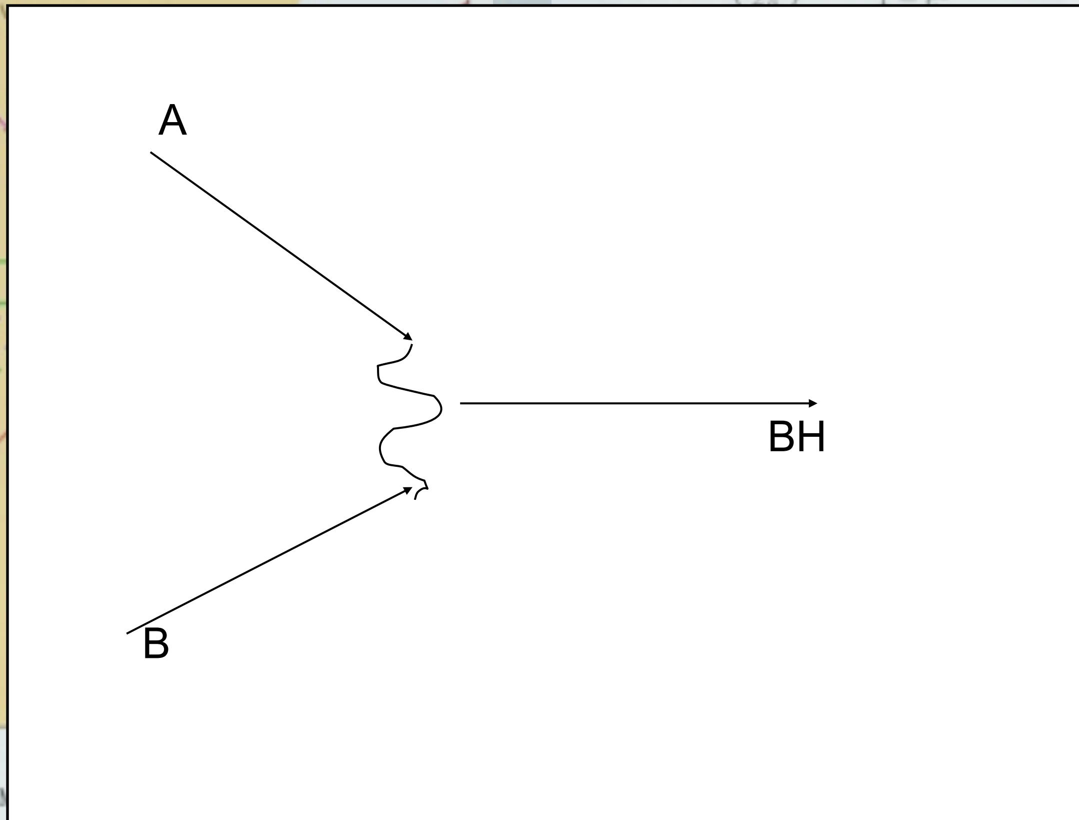

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(coalescence

Kramer et al., 2006

The Double Pulsar

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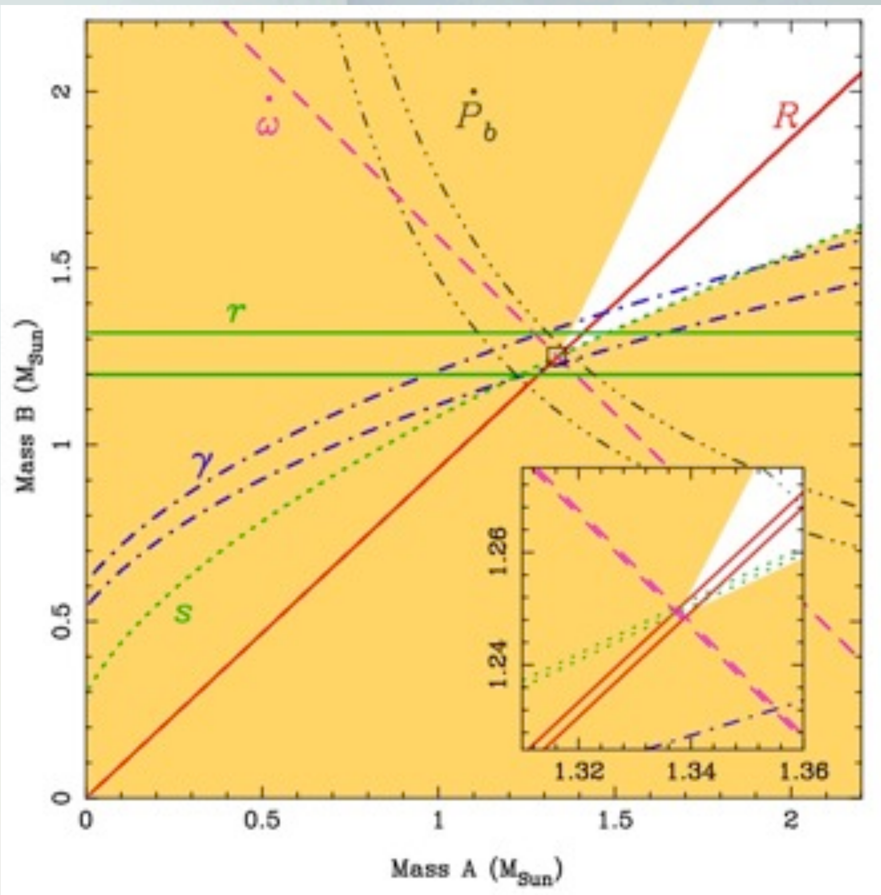

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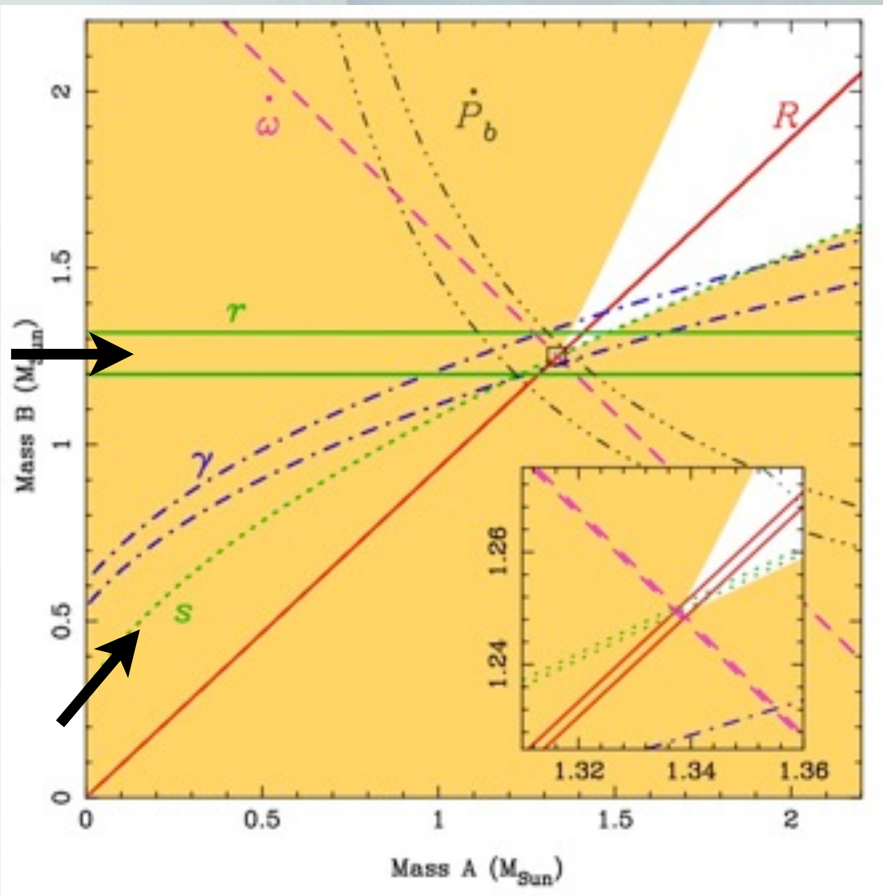
Shapiro delay

Light travels in curved space-time

The Double Pulsar

Testing gravity



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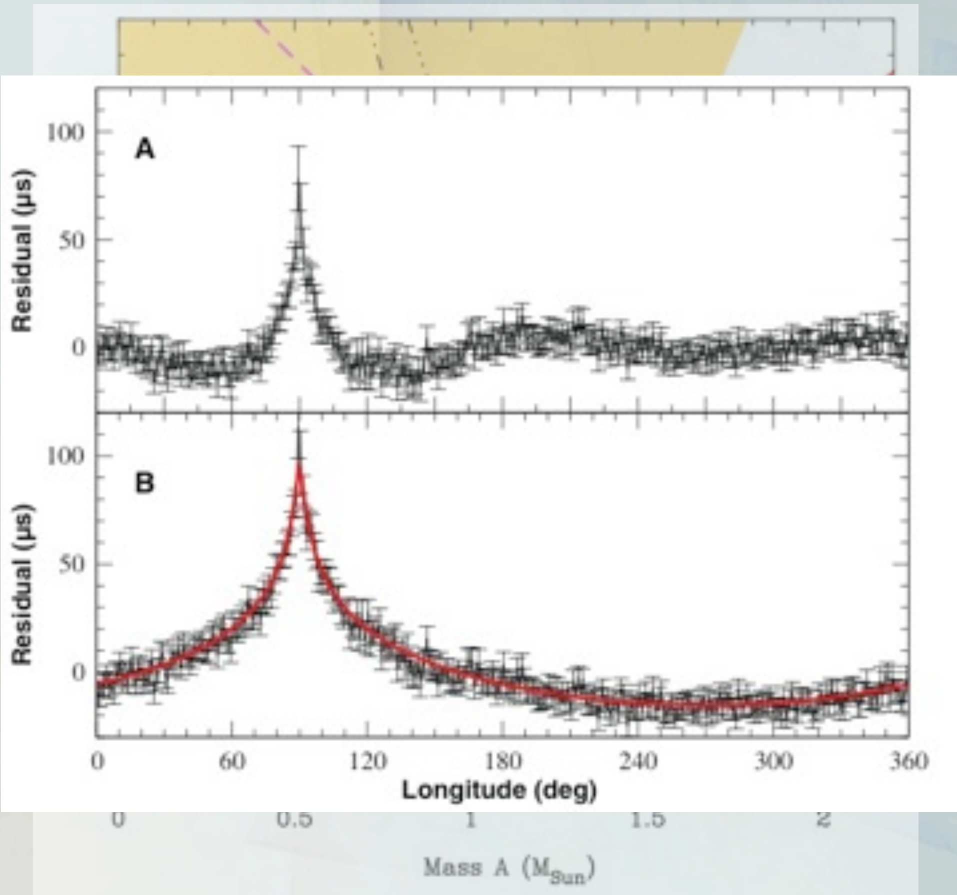

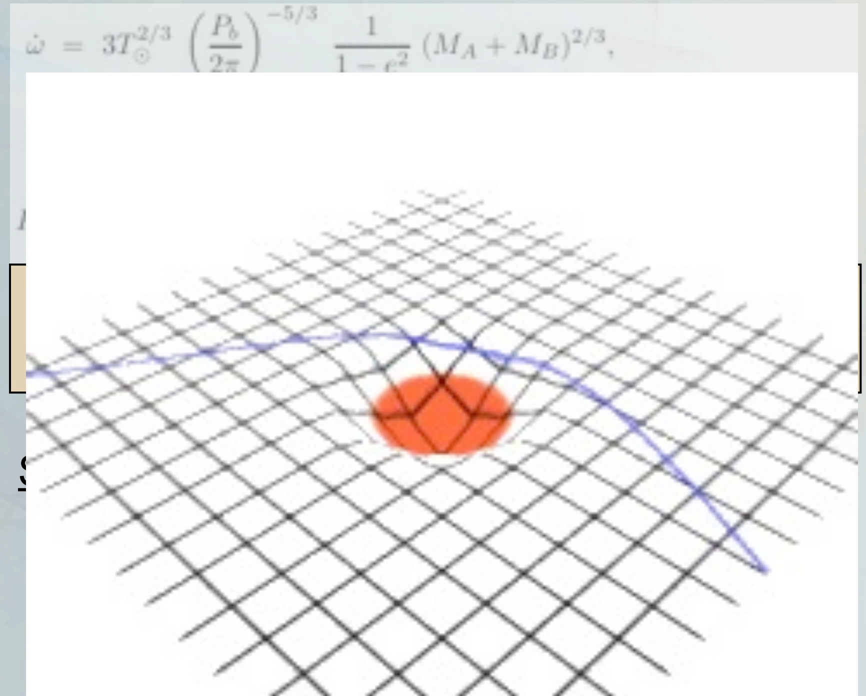

Kramer et al., 2006

The Double Pulsar

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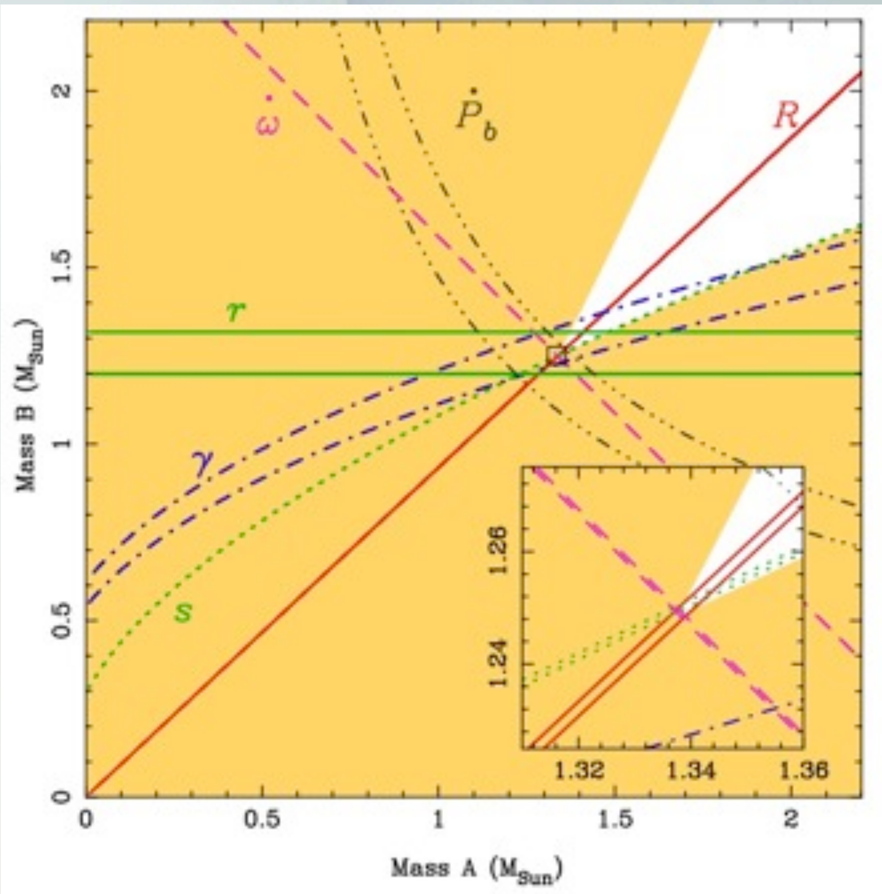


Kramer et al., 2006

<u>Mass ratio</u>

Double Pulsar only:

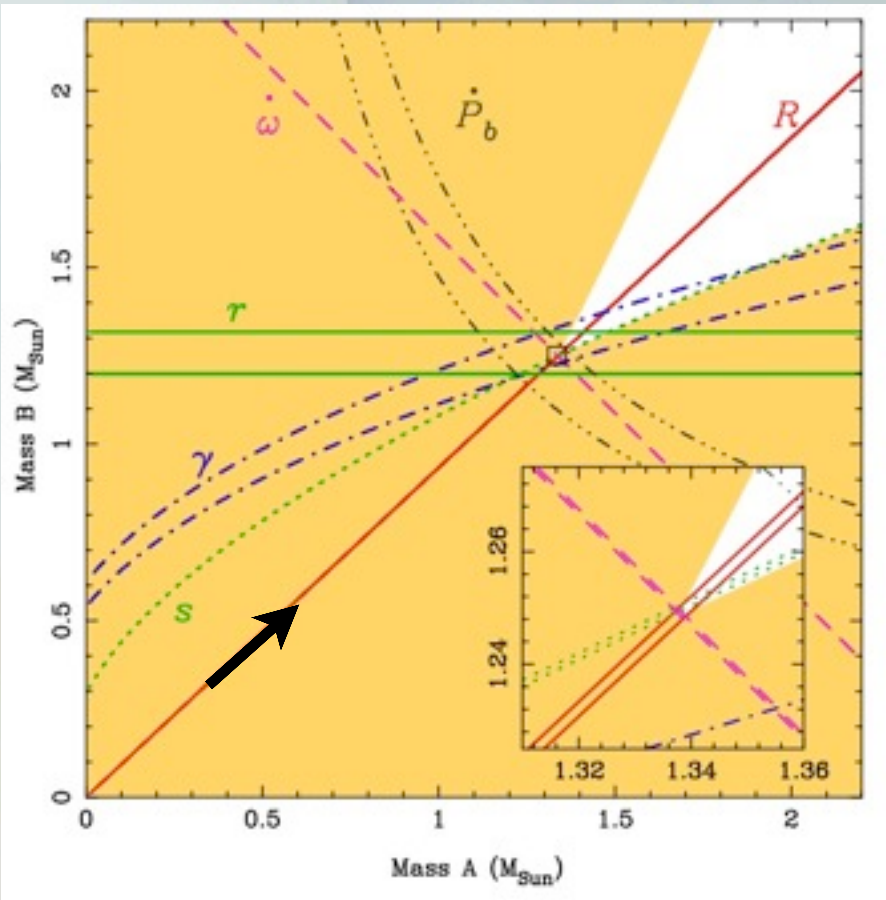
mass ratio, R.

$M_A/M_B = a_B\sin(i) / a_A\sin(i)$

(theory-independent; at 1PN level at least)

The Double Pulsar

Testing gravity



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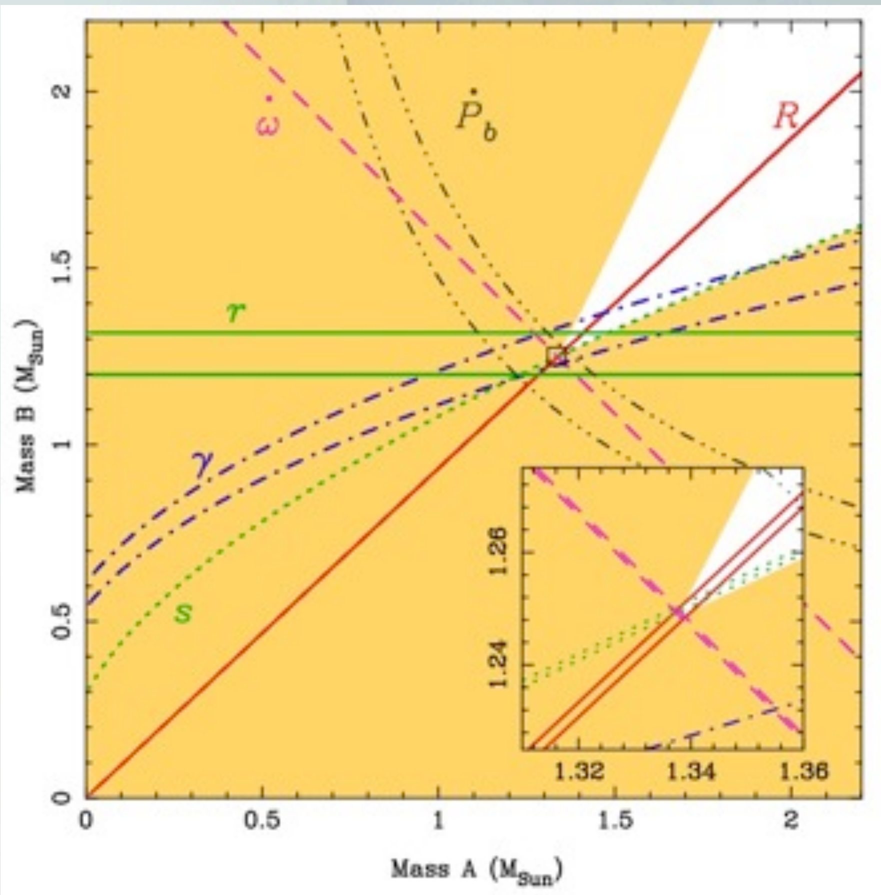


Kramer et al., 2006

Testing GR and gravity

Mass ratio + 5 PK parameters

=> Yields 6-2=4 gravity tests

Best binary pulsar test

Shapiro delay “s” parameter
Agrees with GR within 0.05%
(Kramer et al. 2006)

Hulse-Taylor pulsar is 0.2%

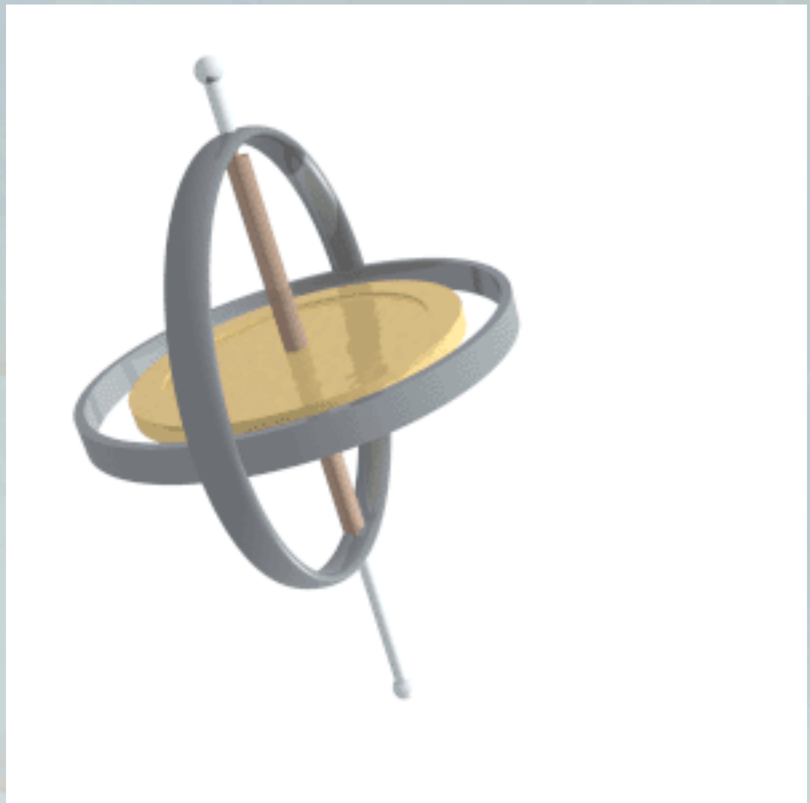
Relativistic Spin Precession

Spin-orbit coupling induces relativistic spin precession

Precession of the spin angular momentum of a body is expected in relativistic systems.

Parallel transport in a curve space-time changes the orientation of a vector relative to distant observers.

Known as **"geodetic precession"** or "de Sitter – Fokker precession".



Relativistic Spin Precession

Observational evidence of precession

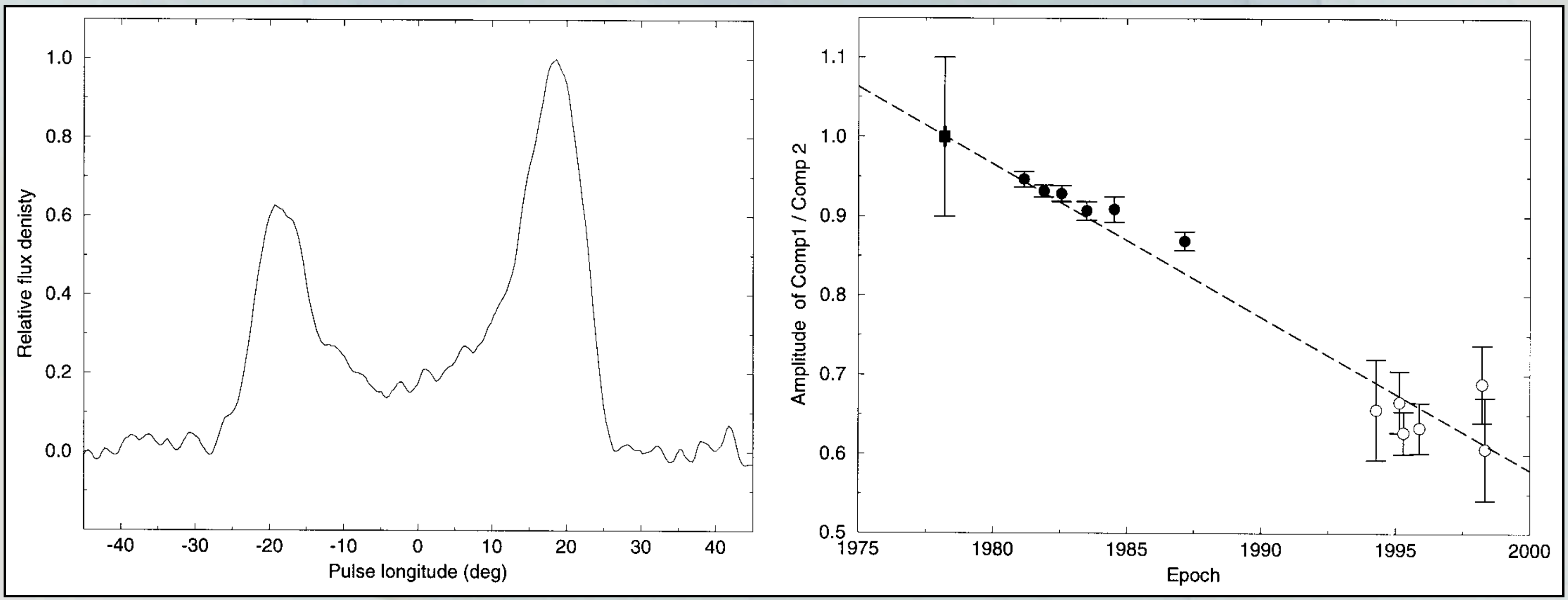
Changes of pulse shape and polarization over time.

PSR B1913+16 (Kramer 1998, Weisberg & Taylor 2002, Clifton & Weisberg 2008):

- Assume the predicted GR rate to map the beam

PSR B1534+12 (Stairs et al. 2004):

- $\Omega_{\rm obs} = 0.44^{+0.48(4.6)}_{-0.16(0.24)}\ ^\circ/{\rm yr}$ $\qquad\qquad \Omega_{\rm GR} = 0.51^\circ/{\rm yr}$



Kramer 1998

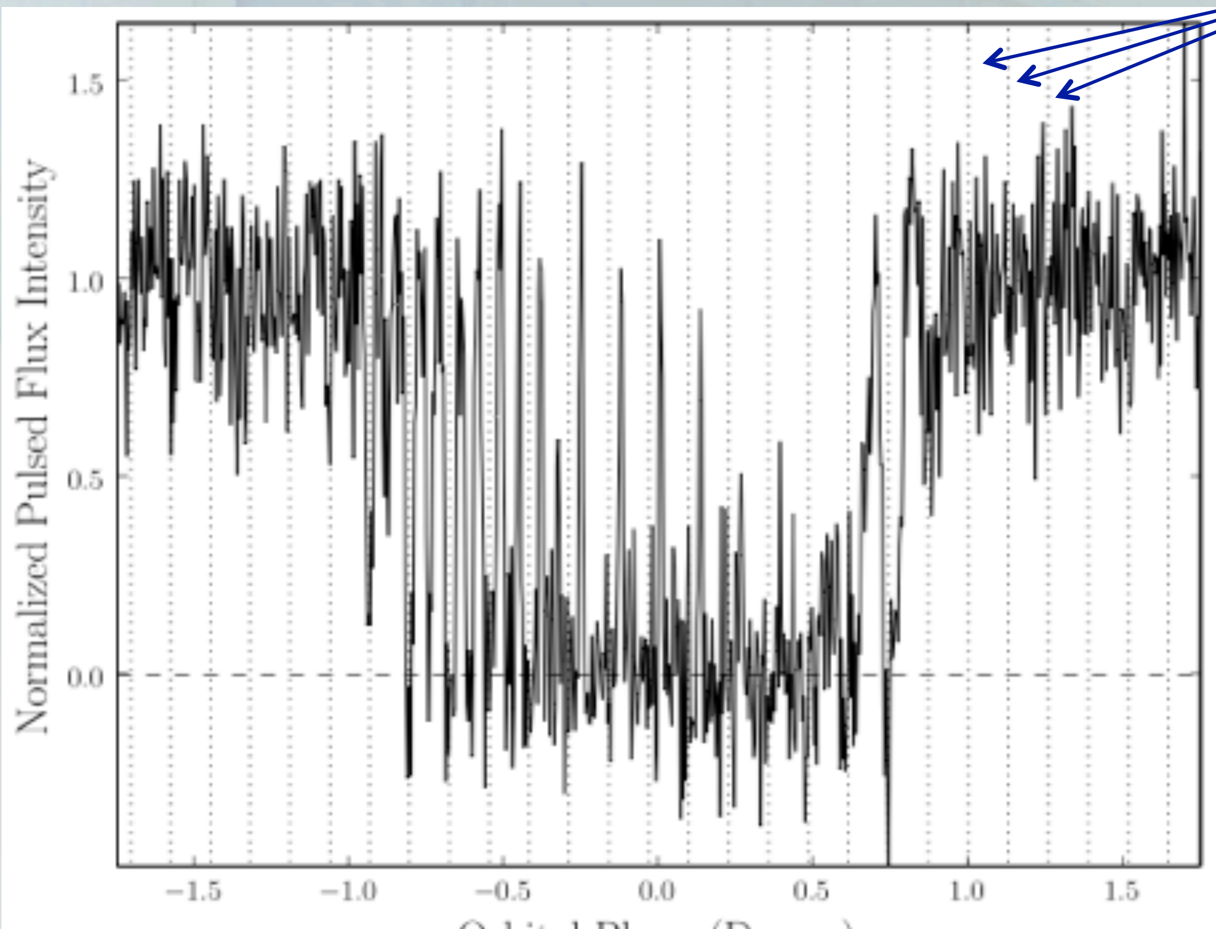
Double Pulsar Eclipses

Phenomenology

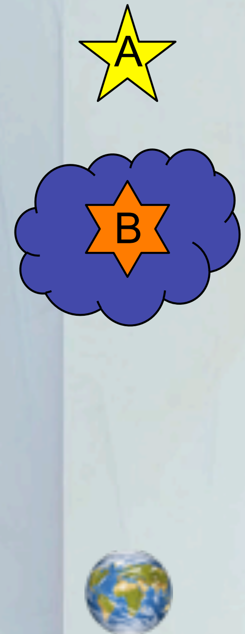
Pulsar A eclipsed by pulsar B for ~30 seconds at conjunction

Rapid flux changes synchronized with pulsar B’s rotation (McLaughlin et al. 2004)

Time of arrival of B’s pulse



Breton et al. 2008



Double Pulsar Eclipses

Modeling using synchrotron absorption in a truncated dipole

The “doughnut model” (Lyutikov & Thompson 2006)

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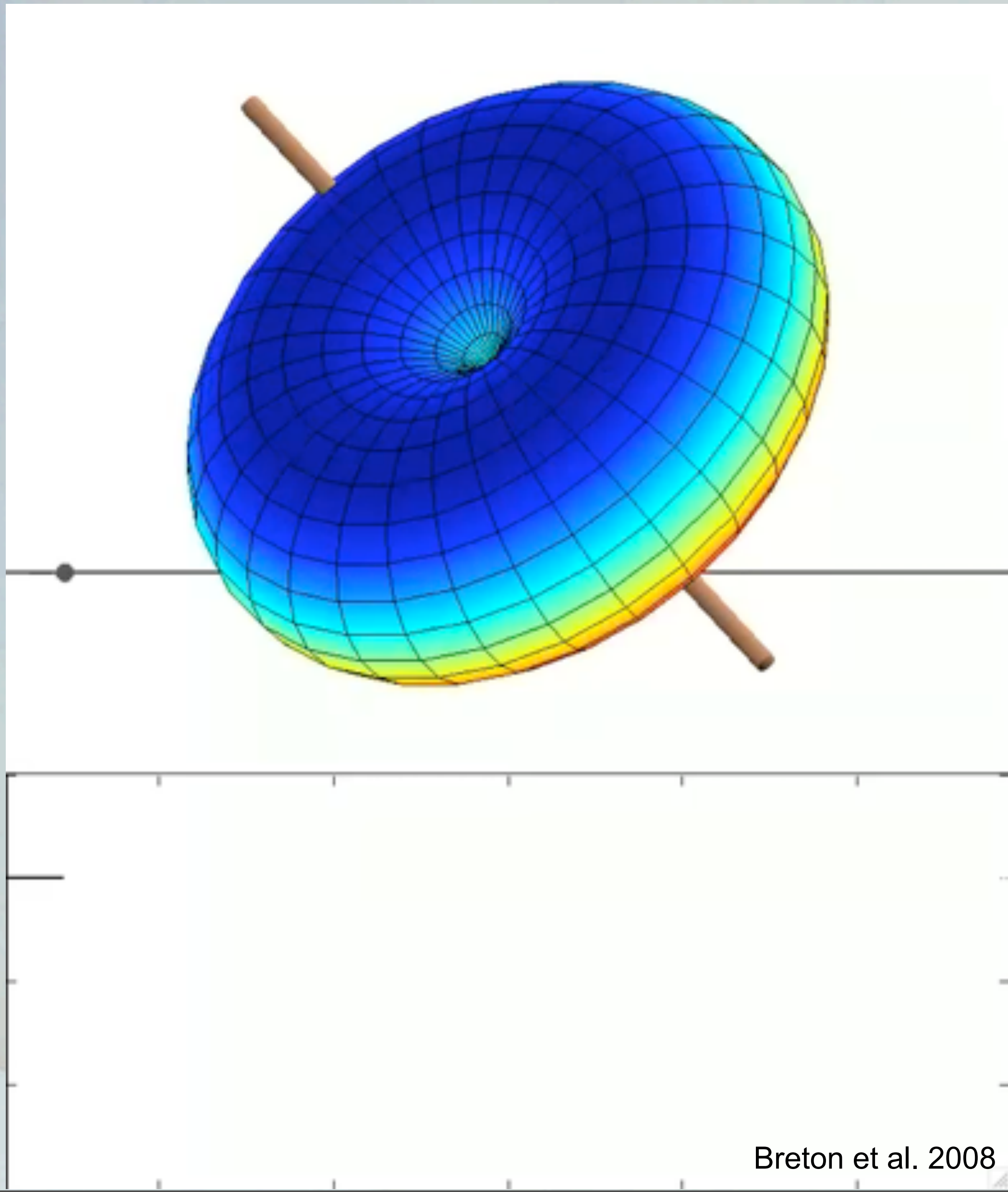


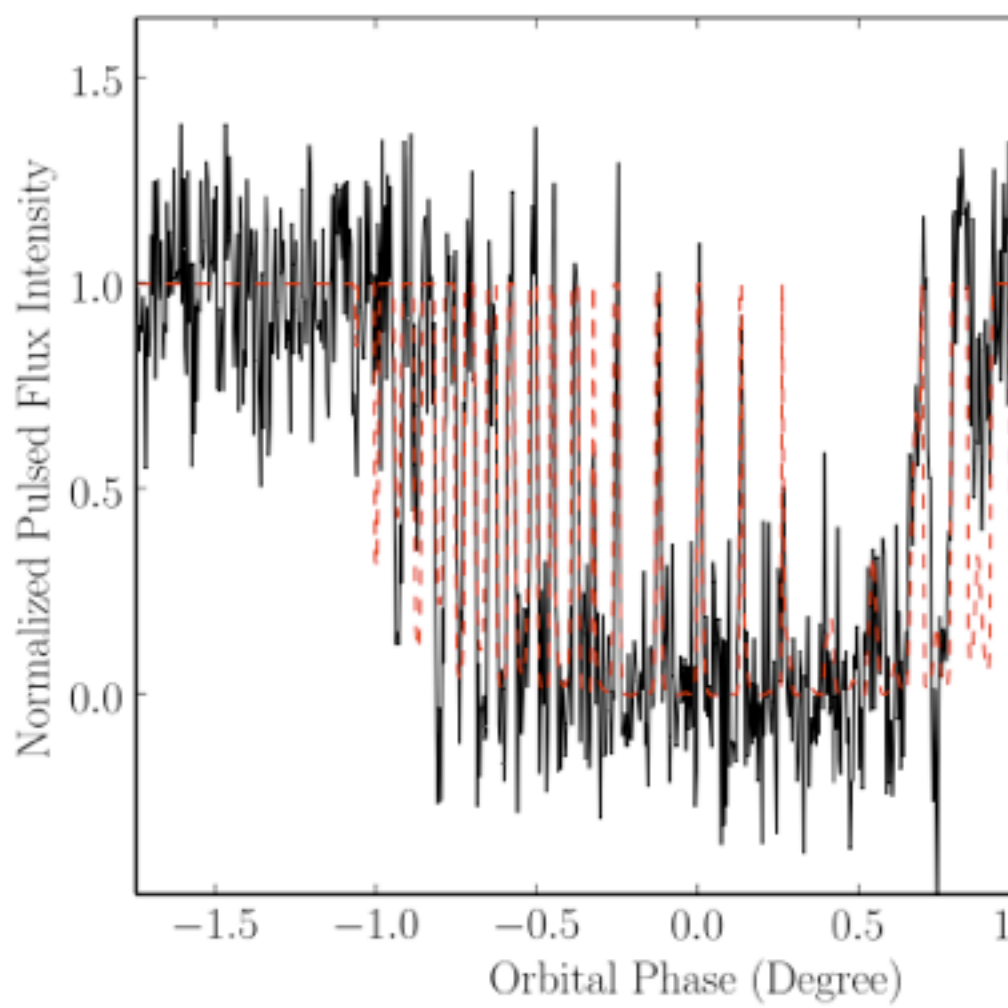
Breton et al. 2008

Double Pulsar Eclipses

It works!

Empirical **evidence of dipolar magnetic** field geometry.

Eclipses are a proxy to infer the orientation of pulsar B.



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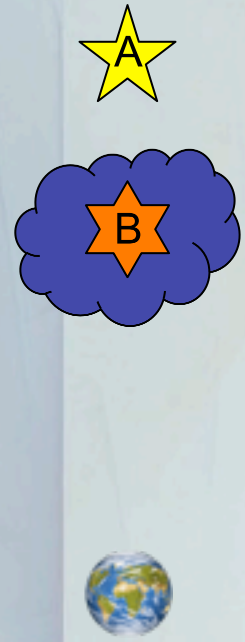


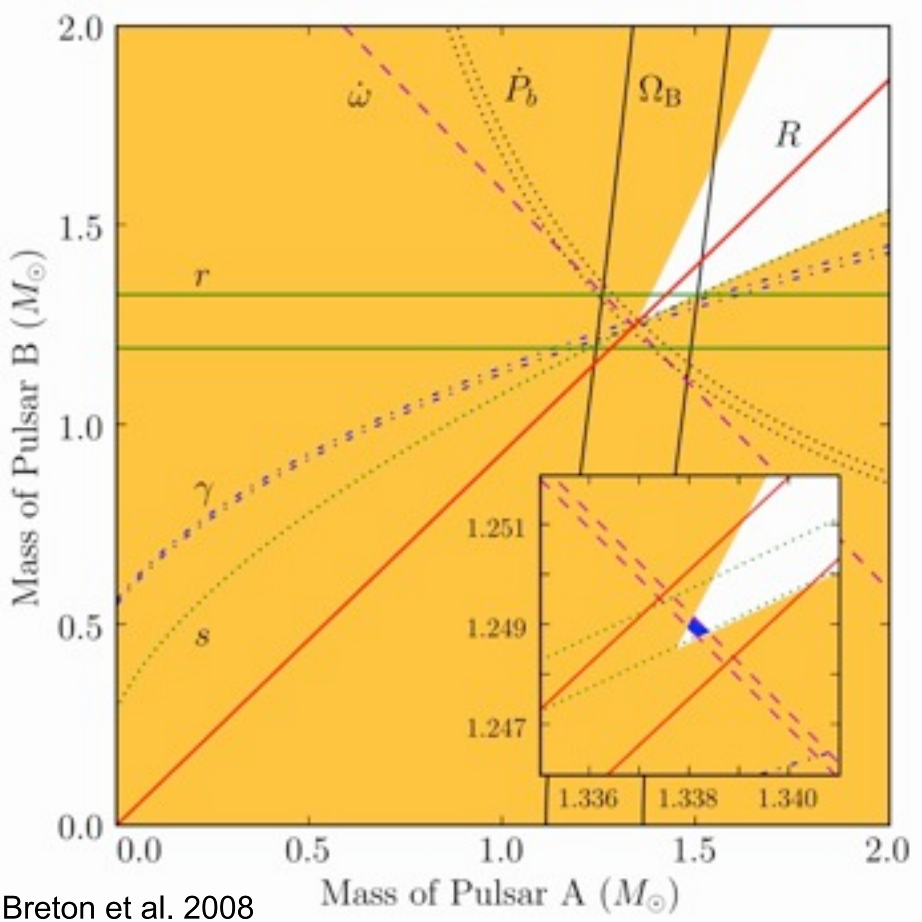
Testing General Relativity in a Strong Field

General relativity passes the test once again!

Quantitative measurement of relativistic spin precession.

$$\Omega_B = \frac{1}{2}\left(\frac{2\pi}{P_{orb}}\right)^{5/3} \frac{m_A(4m_B + 3m_A)}{(1-e^2)(m_B + m_A)^{4/3}} T_\odot^{2/3}$$

GR predicts:	$5.^\circ 07\ \mathrm{yr}^{-1}$
Measurement:	$4.^\circ 77^{+0.^\circ 66}_{-0.^\circ 65}\ \mathrm{yr}^{-1}$



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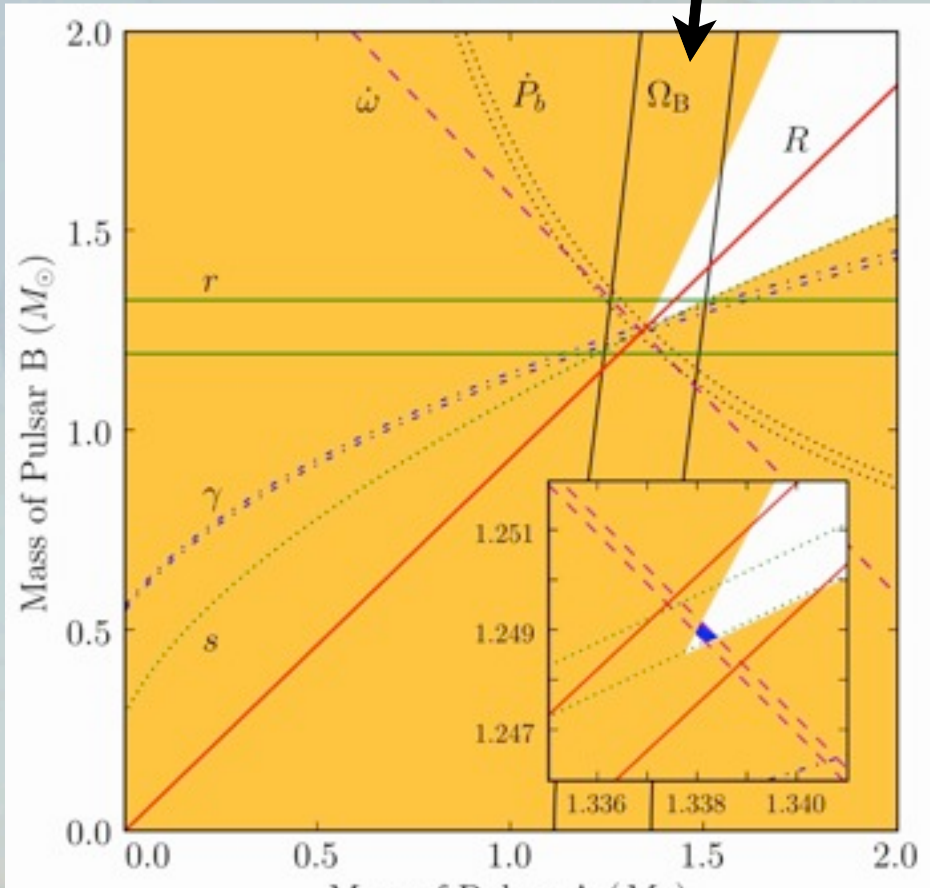
$$\Omega_{\rm B} = \frac{1}{2}\left(\frac{2\pi}{P_{\rm orb}}\right)^{5/3} \frac{m_{\rm A}(4m_{\rm B}+3m_{\rm A})}{(1-e^2)(m_{\rm B}+m_{\rm A})^{4/3}} T_\odot^{2/3}$$

GR predicts: $5.^\circ 07\ {\rm yr}^{-1}$

Measurement: $4.^\circ 77\,^{+0.^\circ 66}_{-0.^\circ 65}\ {\rm yr}^{-1}$



Breton et al. 2008

Testing General Relativity in a Strong Field

By the way...

Pulsar B **disappeared in 2009**... so no more "Double Pulsar"

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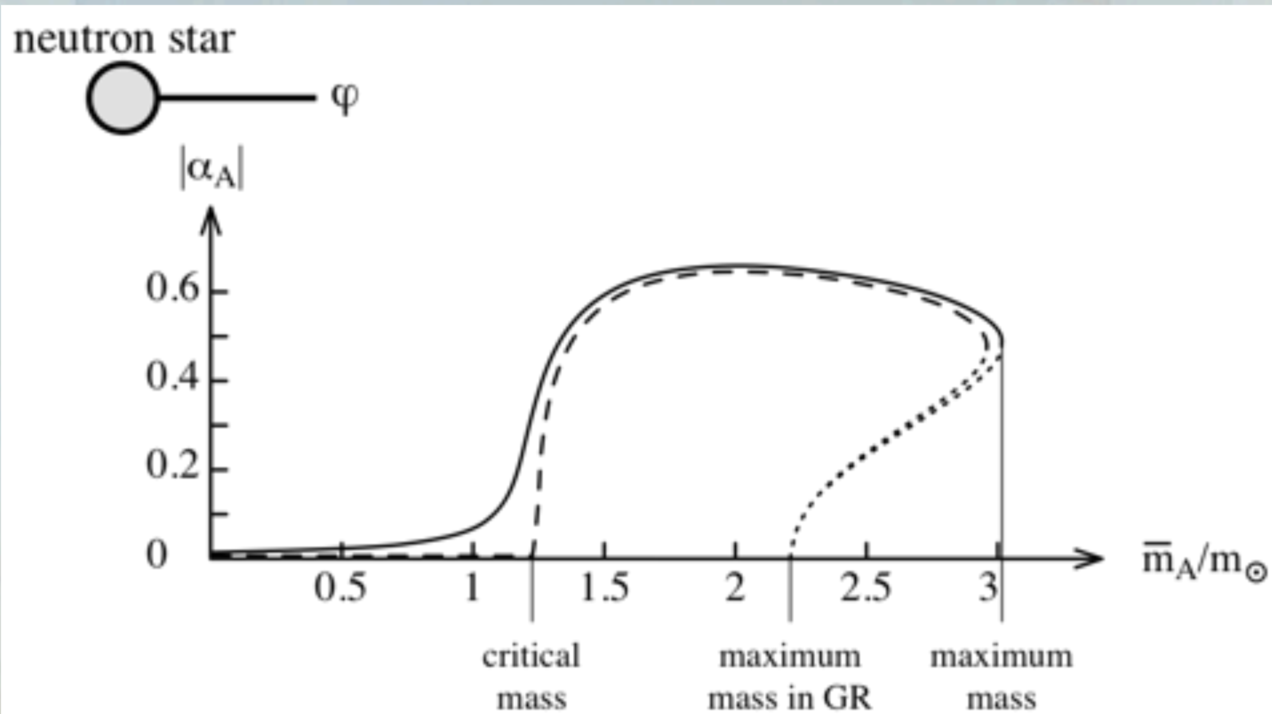
Testing Theories of Gravity

Strong-field regime

Why are tests of gravity involving pulsars interesting?

"Strong-field" regime:

- Still > 250 000 $R_{Schwarzchild}$ in separation but…
- $E_{binding}$ ~ 15% E_{tot}



Esposito-Farese (2004)

Theory-Independent Test of Gravity

Unique test... for a unique double pulsar...

Generalized precession rate is (Damour & Taylor, 1992, Phys. Rev. D):

$$\Omega_{\mathrm{B}} = \frac{\sigma_B L}{a_R^3 (1 - e^2)^{3/2}}$$

In terms of a very particular choice of observable timing parameters:

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

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Test of the strong-field parameters $\frac{\sigma_{\mathrm{B}}}{\mathcal{G}}$.

Any other mixture of timing observables would include additional strong-field parameters.

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Test of the strong-field parameters $\frac{\sigma_{\rm B}}{\mathcal{G}}$.

Any other mixture of timing observables would include additional strong-field parameters.

The *Double Pulsar* is the only double neutron star system in which both semi-major axes can be **measured independently**!

Dipolar Gravitational Waves and MOND

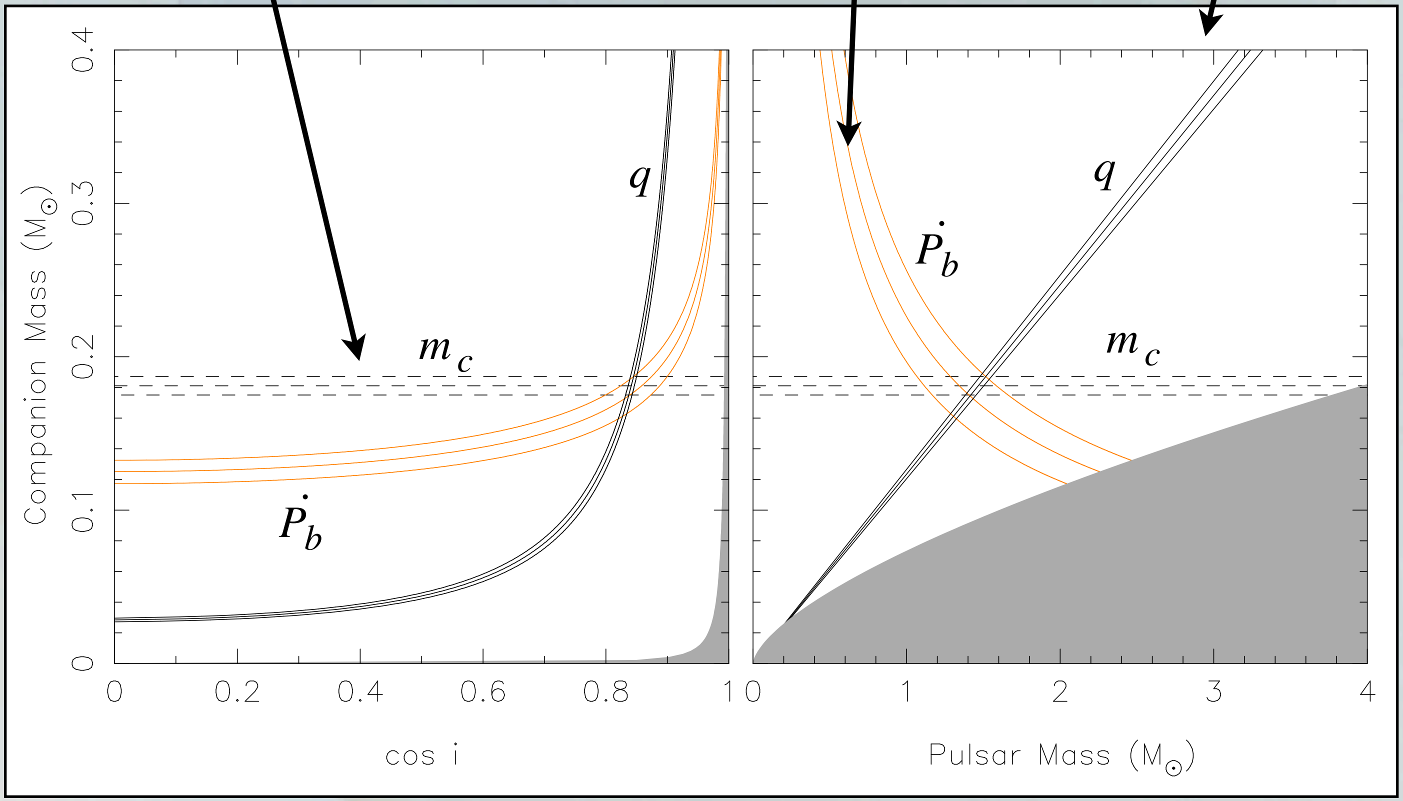
The pulsar-white dwarf binary PSR J1738+0333

See Freire et al. (2012) & Antoniadis et al. (2012)

White dwarf mass from photometry + spectroscopy

Mass ratio from pulsar timing + white dwarf spectroscopy

Orbital period decay from pulsar timing



Freire et al. (2012) & Antoniadis et al. (2012)

Dipolar Gravitational Waves and MOND

Constraining dipolar gravitational waves

The "excess" orbital period decay: $\dot{P}_b^{\rm xs} = \dot{P}_b^{\dot{M}} + \dot{P}_b^{\rm T} + \dot{P}_b^{\rm D} + \dot{P}_b^{\dot{G}}$

mass loss

tides

dipolar gravitational waves

variation of gravitational constant

$$\dot{P}_b^{\rm D} \simeq -2\pi\, n_b {\rm T}_\odot m_c \,\frac{q}{q+1}\,\kappa_D (s_{\rm psr} - s_{\rm comp})^2$$

where $s_{\rm psr,comp} \simeq \epsilon / M_{\rm psr,comp} c^2$

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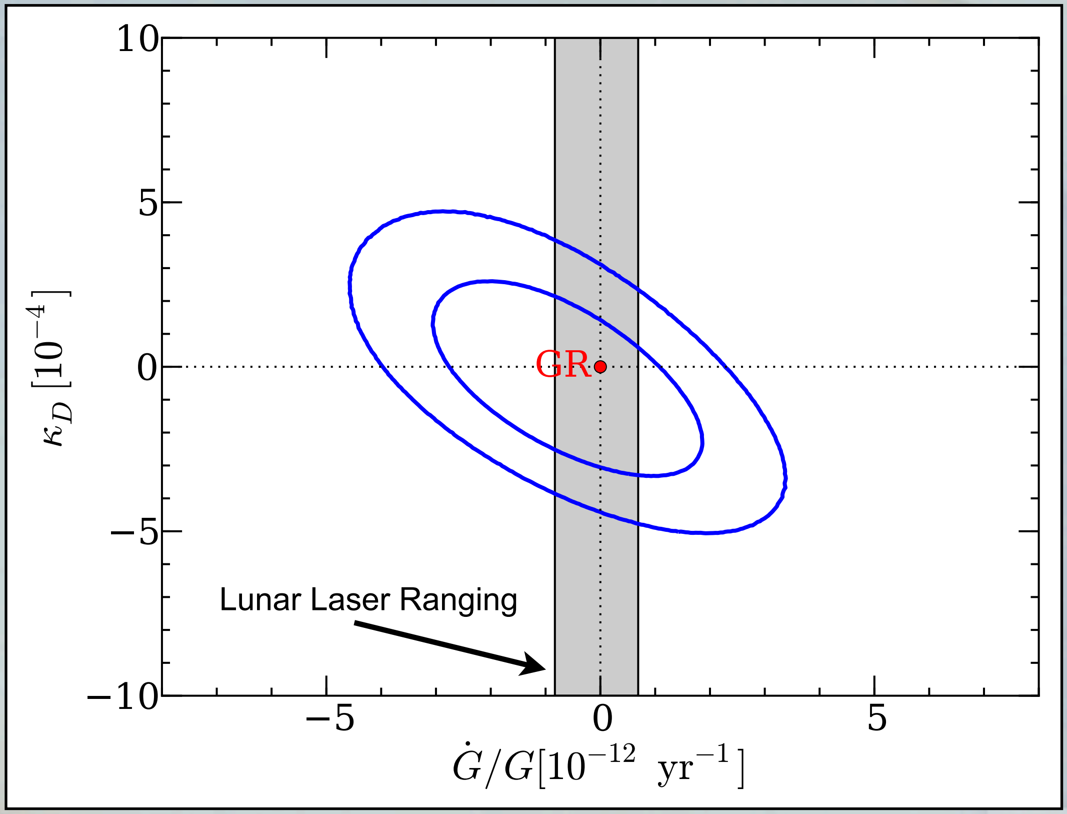
Neutron star + white dwarf binaries have very **different self-gravity**

$$s_{\rm psr} \neq s_{\rm comp}$$

Constraining dipolar gravitational waves

$\dot{P}_b^{\rm D}$ and $\dot{P}_b^{\dot{G}}$ are degenerate

Combining data from PSRs J1738+0333 and J0437-4715 breaks the degeneracy



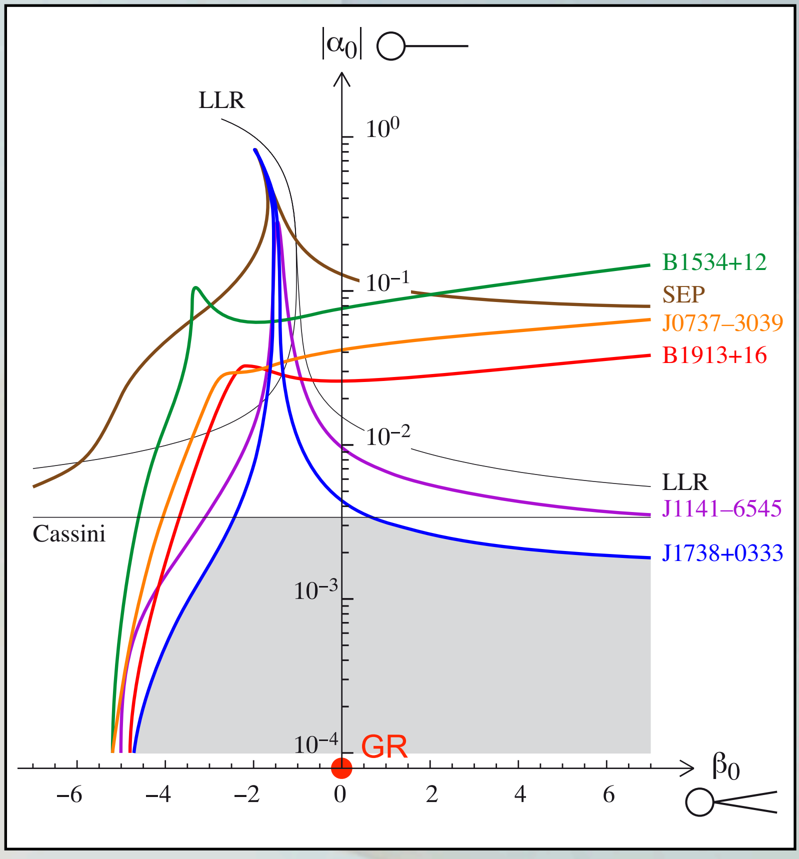
Freire et al. (2012) and, also, Lazaridis et al. (2009)

Dipolar Gravitational Waves and MOND

Constraining tensor-scalar theories

A general tensor scalar field $\ln A(\varphi) - \ln A(\varphi_0) = \alpha_0(\varphi - \varphi_0) + \frac{1}{2}\beta_0(\varphi - \varphi_0)^2$

Associated metric $\tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}$



Freire et al. (2012)

Modify the behavior of gravitational constant

$$\tilde{G}_{AB} \equiv G_* A^2(\varphi_0) \cdot (1 + \alpha_A \alpha_B)$$

And the Eddington's PPN parameters

$$\gamma_{AB} \equiv 1 - 2\frac{\alpha_A \alpha_B}{1 + \alpha_A \alpha_B}$$

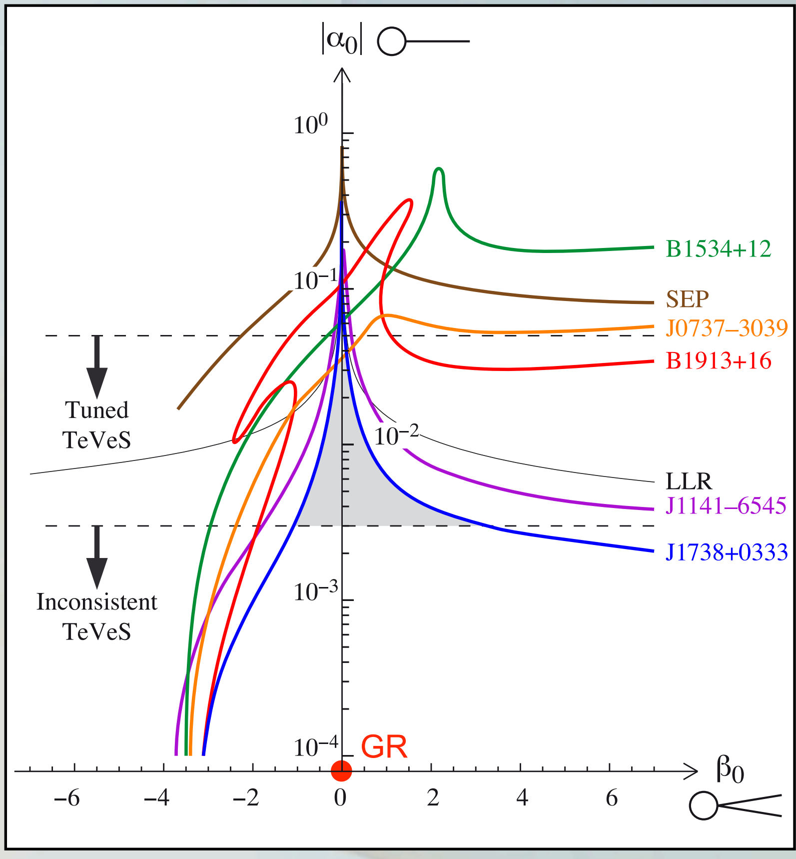
$$\beta^A_{BC} \equiv 1 + \frac{1}{2}\frac{\beta_A \alpha_B \alpha_C}{(1 + \alpha_A \alpha_B)(1 + \alpha_A \alpha_C)}$$

Dipolar Gravitational Waves and MOND

Constraining modified newtonian dynamics

MOND is the non-relativistic limit of tensor-vector-scalar (TeVeS) theories

Associated metric $\tilde{g}_{00} = A^2(\varphi) g_{00}$ and $\tilde{g}_{ij} = A^{-2}(\varphi) g_{ij}$



Freire et al. (2012)

Modify the behavior of gravitational constant

$$\tilde{G}_{AB} = G_*(1 + \alpha_A \alpha_B)$$

And the Eddington's PPN parameters

$$\gamma_{AB} = \gamma^{\mathrm{PPN}} = 1$$

$$\beta^A_{BC} \equiv 1 + \frac{1}{2} \frac{\beta_A \alpha_B \alpha_C}{(1 + \alpha_A \alpha_B)(1 + \alpha_A \alpha_C)}$$

More Tests of Gravity?

SEP violation, preferred-frame effects

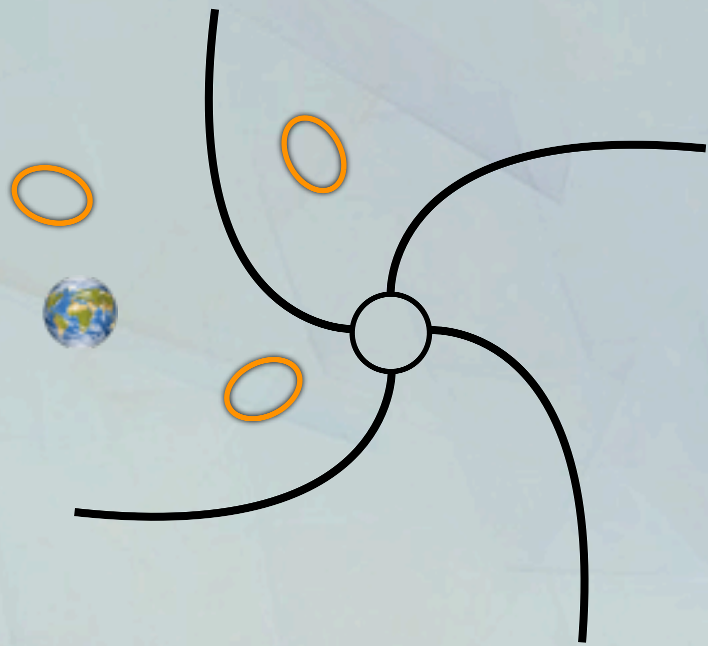
Pulsar + WD in low eccentricity wide orbit

Test strong equivalence principle $\boxed{P_{\rm orb}^2/e^2}$ $|\Delta| < 4.6 \times 10^{-3}$

Test violation of momentum conservation and preferred frame-effects $\boxed{P_{\rm orb}^2/(eP)}$ $\boxed{P_{\rm orb}^{1/3}/e}$

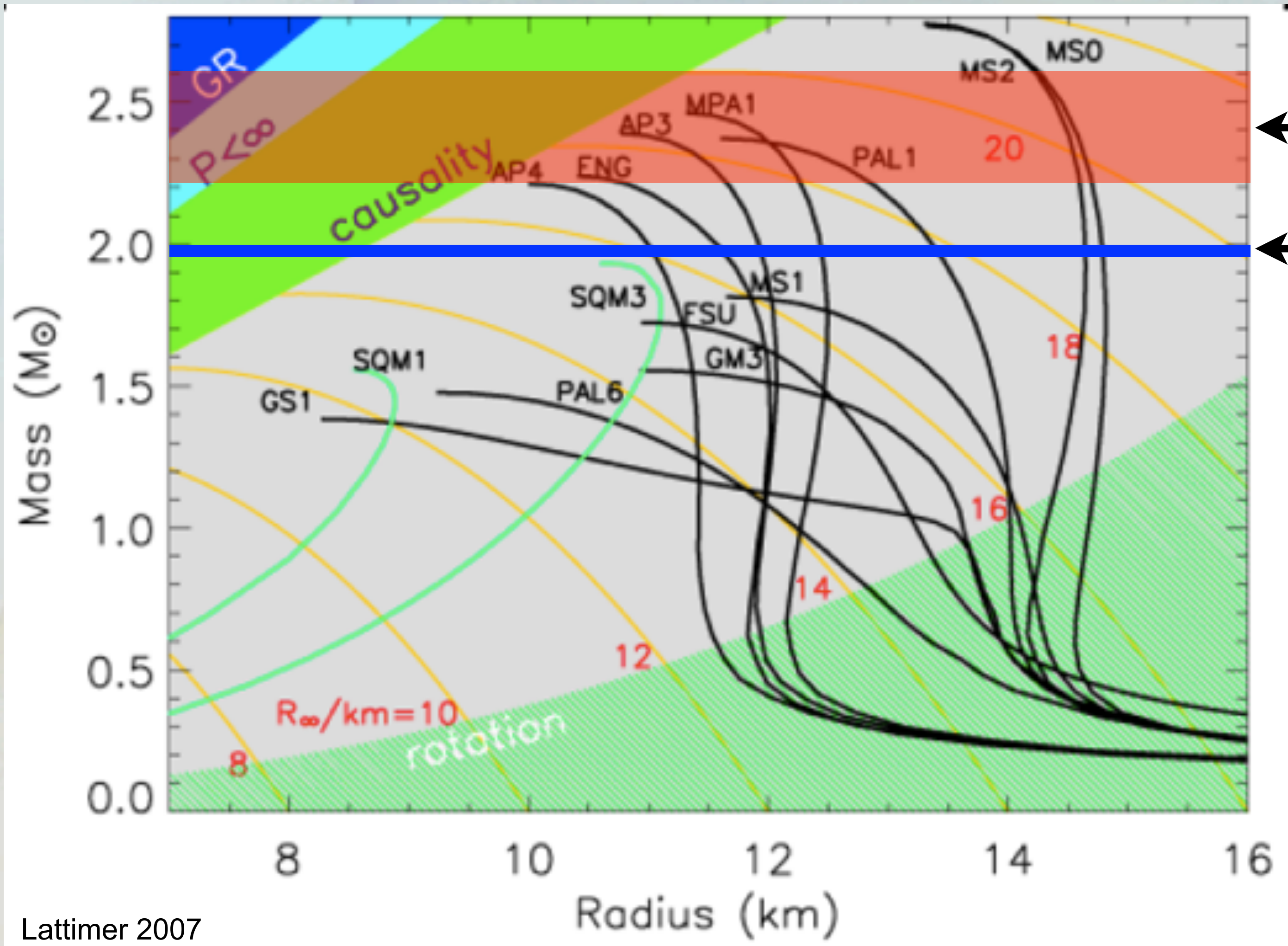
statistical: see, e.g., Gonzalez et al. 2011, Stairs et al. 2005 $|\hat{\alpha}_3| < 5.5 \times 10^{-20}$

individual system: see, e.g., Wex & Kramer 2007



Neutron Star Equation-of-State

Probing the upper mass limit of neutron stars



van Kerkwijk, Breton & Kulkarni (2011)

PSR B1957+20

PSR J1614-2230

Demorest et al. (2010)

The Future Is Bright

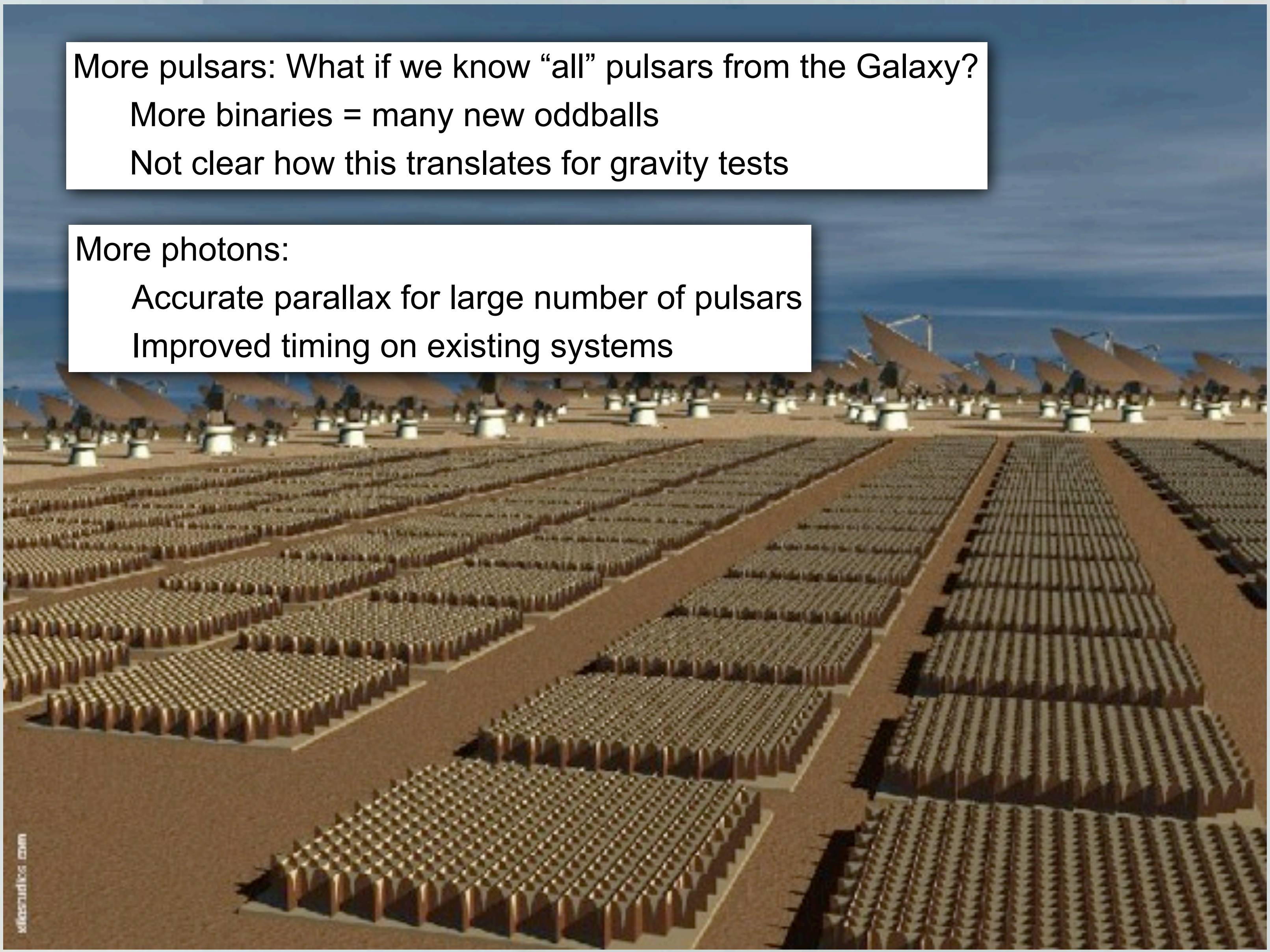
More pulsars, more photons

More pulsars: What if we know “all” pulsars from the Galaxy?

- More binaries = many new oddballs
- Not clear how this translates for gravity tests

More photons:

- Accurate parallax for large number of pulsars
- Improved timing on existing systems



Conclusions

Binary pulsars

- Excellent tools to **test gravity**
- Probe a **different** gravitational field **regime**
- **System diversity** = complementarity