

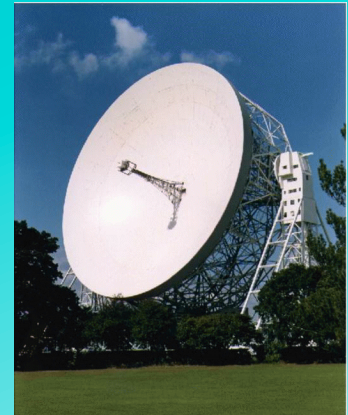
Tests of Strong-Field Gravity with Pulsars

Ingrid Stairs
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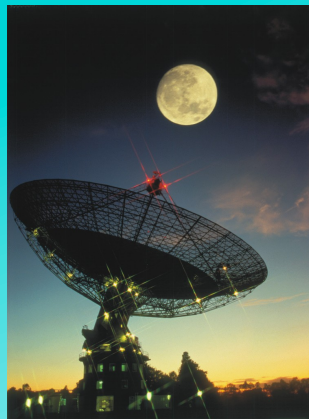
Testing Gravity 2015
Jan. 16, 2015



Green Bank
Telescope



Jodrell Bank



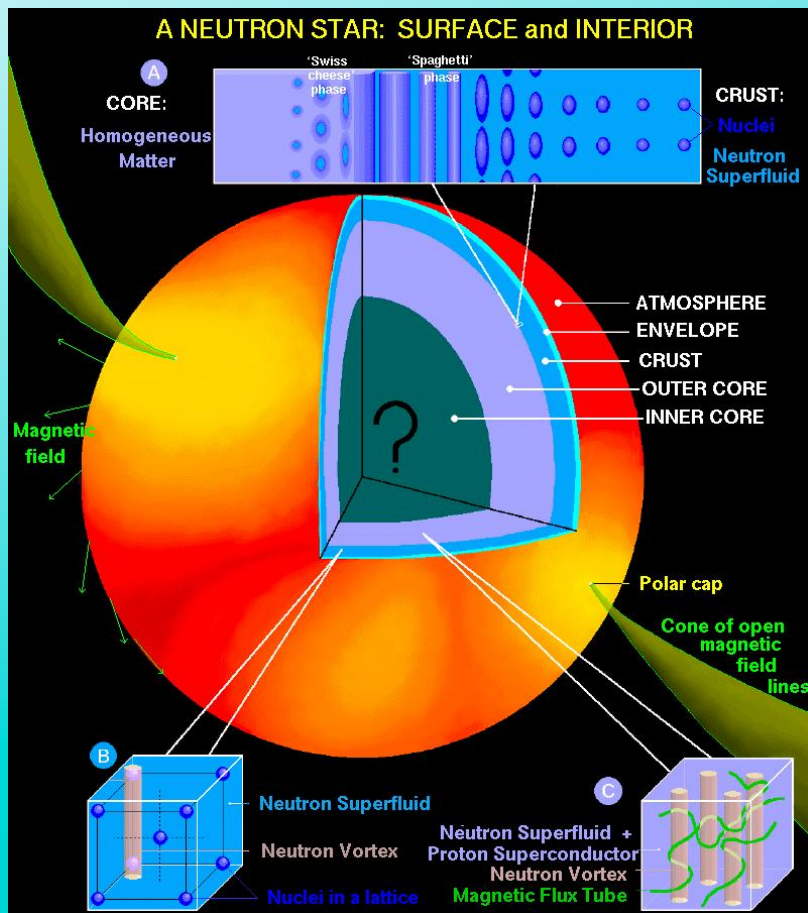
Parkes



Arecibo

Pulsars and other compact objects probe theories near objects with strong gravitational binding energy. These tests are qualitatively different from Solar-system tests!

WD: 0.01% of mass
NS: 10--20% of mass
BH: 50% of mass
is in binding energy.

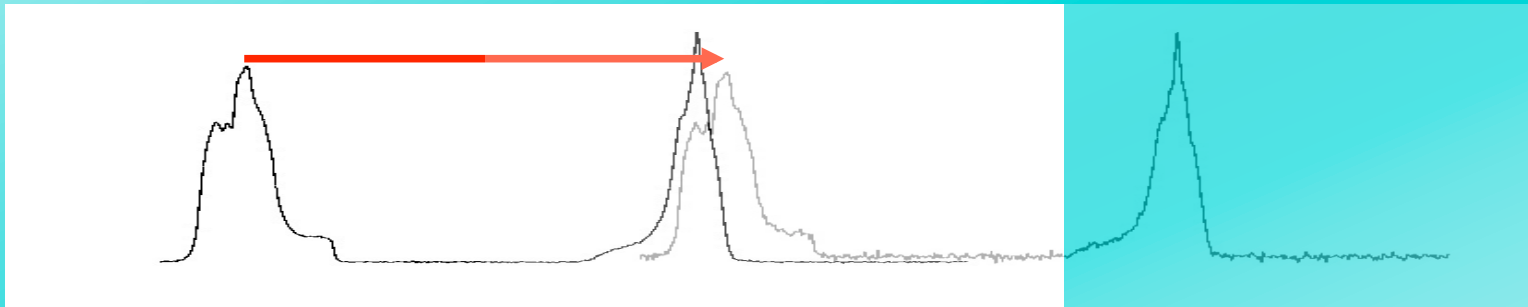


Pulsar Timing in a Nutshell

Standard
profile

Measure
offset

Observed
profile



Record the start time of the observation with the observatory clock (typically a maser).

The offset gives us a Time of Arrival (TOA) for the observed pulse.

Then transform to Solar System Barycentre, enumerate pulses and fit the timing model.

Equivalence Principle Violations

Pulsar timing can:

- set limits on the Parametrized Post-Newtonian (PPN) parameters $\alpha_1, \alpha_2, \alpha_3, \xi, \zeta_1, \zeta_2$
- test for violations of the Strong Equivalence Principle (SEP) through
 - the Nordtvedt Effect
 - dipolar gravitational radiation
 - variations of Newton's constant

(Actually, parameters modified to account for compactness of neutron stars.)

(Damour & Esposito-Farèse 1992, CQG, 9, 2093; 1996, PRD, 53, 5541).

SEP: Nordtvedt (Gravitational Stark) Effect

Lunar Laser Ranging: Moon's orbit is not polarized toward Sun.

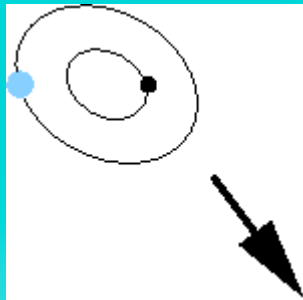
$$\eta = 4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\xi_1 - \frac{1}{3}\xi_2$$

Constraint: $\eta = (-1.7 \pm 2.9) \times 10^{-4}$
(Williams et al. 2012, CGQ **29**, 184004)



WD

NS



Result is a polarized orbit.

Binary pulsars: NS and WD fall differently in gravitational field of Galaxy.

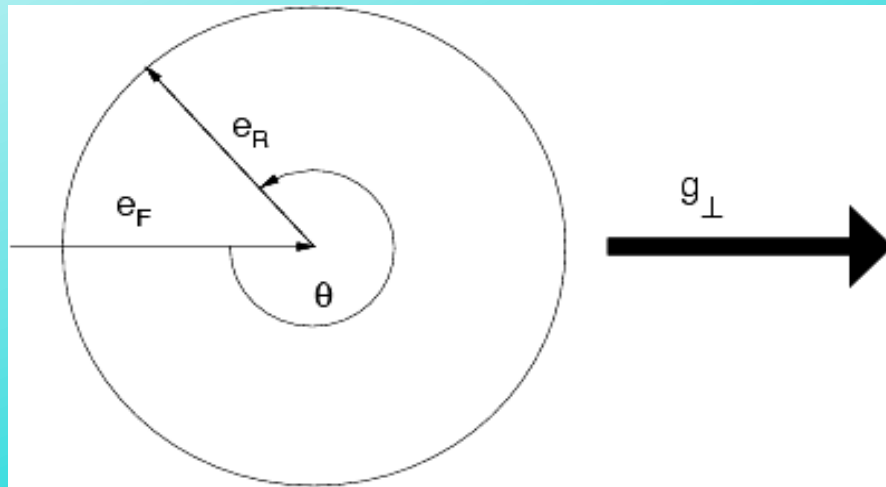
$$\left(\frac{m^{\text{grav}}}{m^{\text{inertial}}} \right) = 1 + \Delta_i$$

$$= 1 + \eta \left(\frac{E^{\text{grav}}}{m_i} \right) + \eta' \left(\frac{E^{\text{grav}}}{m_i} \right)^2 + \dots$$

Constrain $\Delta_{\text{net}} = \Delta_{\text{NS}} - \Delta_{\text{WD}}$

(Damour & Schäfer 1991, PRL, 66, 2549.)

Deriving a Constraint on Δ_{net}



Use pulsar—white-dwarf binaries with low eccentricities ($<10^{-3}$). Eccentricity would contain a “forced” component along projection of Galactic gravitational force onto the orbit. This may partially cancel “natural” eccentricity.

After Wex 1997, A&A, 317, 976.

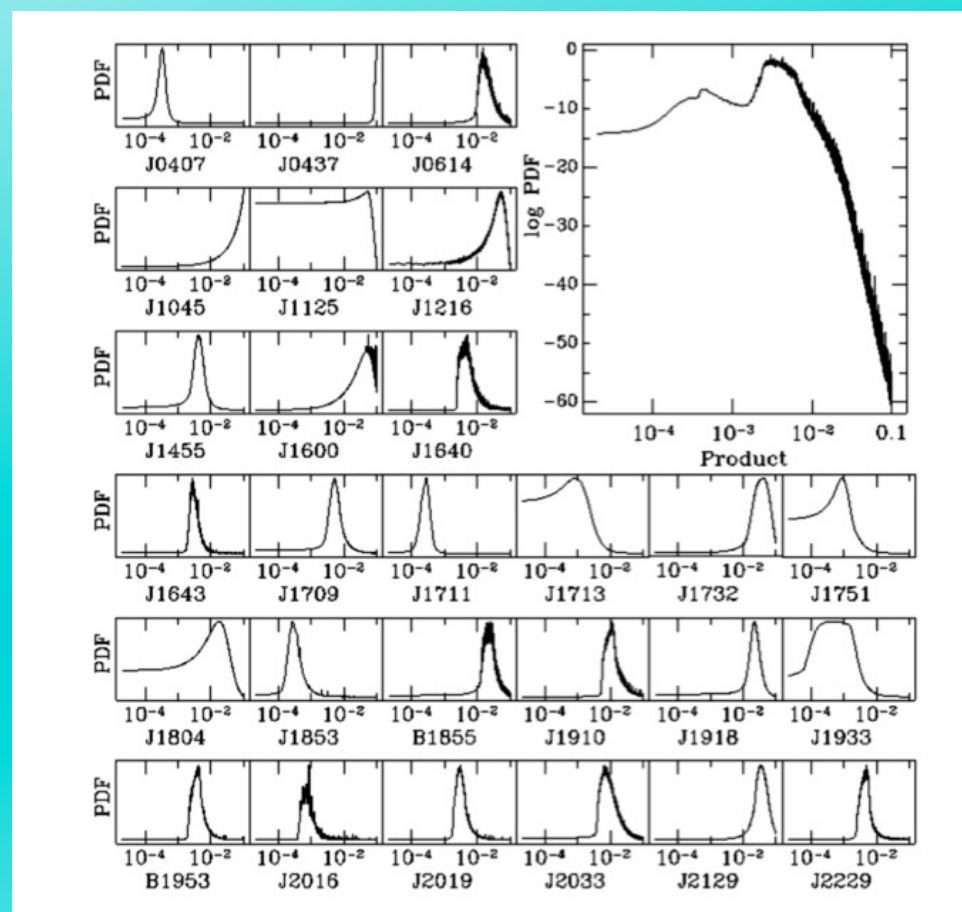
Constraint $\propto P_b^2/e$. Need to estimate orbital inclination and masses.

Formerly: assume binary orbit is randomly oriented on sky.

Use all similar systems to counter selection effects (Wex).

Ensemble of pulsars: $\Delta_{\text{net}} < 9 \times 10^{-3}$ (Wex 1997, A&A, 317, 976; 2000, ASP Conf. Ser.).

More recently: use information about longitude of periastron (previously unused) and measured eccentricity and a Bayesian formulation to construct pdfs for Δ_{net} for each appropriate pulsar, representing the full population of similar objects.



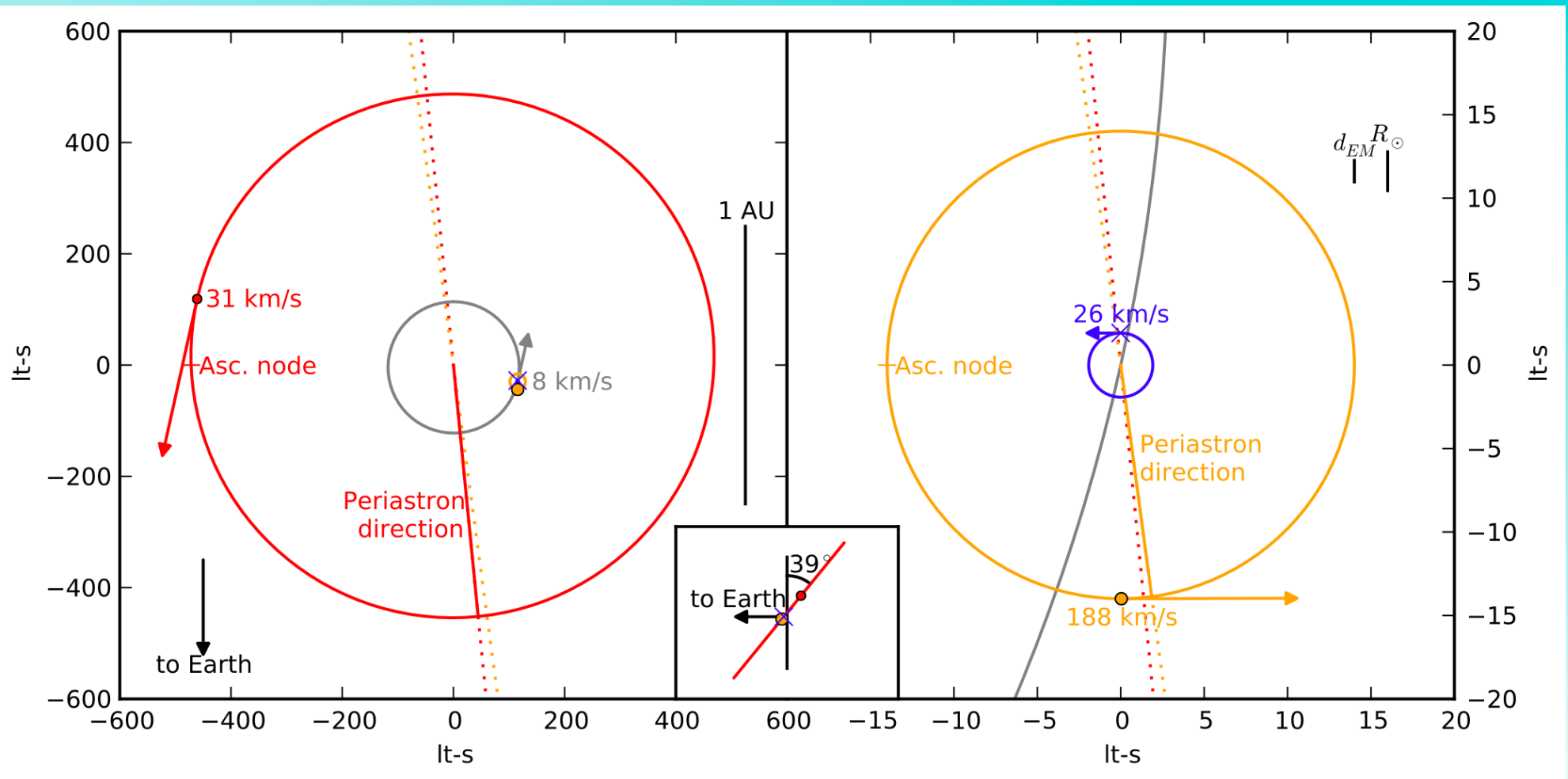
Gonzalez et al. 2011

Result: $|\Delta_{\text{net}}| < 0.0046$ at 95% confidence (Gonzalez et al. 2011, ApJ, **743**, 102, based on method used in Stairs et al. 2005).

Another plan: try to measure \dot{e} in wide-orbit pulsar/WD binaries (Freire et al. 2012, CQG **29**, 400) – any \dot{e} induced by a non-zero Δ should be several orders of magnitude larger than that expected from gravitational radiation or aberration. A detection of \dot{e} would represent an actual detection of Δ , not just an upper limit.

Arguably even better would be a detection of \dot{e} in a system with large eccentricity, such as the millisecond pulsar--main-sequence binary J1903+0327. This particular pulsar is quite massive ($1.667 \pm 0.021 M_{\odot}$) and might therefore have stronger coupling to a non-GR field, eg through spontaneous scalarization.

A new prospect for SEP tests! The system geometry of the triple system J0337+1715 (Ransom et al. 2014, Nature **505**, 520), along with some helpful length scales for reference. The coplanarity, circularity and very hierarchical nature of the orbits imply long-term stability, making it “easier” to find such a triple.



Testing the SEP with PSR J0337+1715

We will do a test that is much more like the Lunar Laser Ranging test: If Δ is non-zero, we would expect the pulsar and the inner WD to fall differently in the gravitational field of the outer WD – in other words, the eccentricity vector of the inner orbit should contain a component that tracks the position of the outer WD. This gravitational field is about 10^6 times stronger than that of the Galaxy, so the test should be correspondingly more stringent.

In practice, the test is being set up so that the gravitational and inertial masses of the pulsar are fit as two separate parameters in a relativistic timing solution that allows for the PPN parameters.

We expect to achieve a constraint on Δ of order 5×10^{-7} , or on η of order 5×10^{-6} . This will be much better than the Solar Systems tests of η and will also test for the violation in the strong-field regime of gravity.

Constraints on α_1 and α_3

α_1 : Implies existence of preferred frames.

Expect orbit to be polarized along projection of velocity (wrt CMB) onto orbital plane. Constraint $\propto P_b^{1/3}/e$.

Ensemble of pulsars: $\alpha_1 < 1.4 \times 10^{-4}$ (Wex 2000, ASP Conf. Ser.).

Comparable to LLR tests (Müller et al. 1996, PRD, 54, R5927).

This test now needs updating with Bayesian approach...

α_3 : Violates local Lorentz invariance and conservation of momentum. Expect orbit to be polarized, depending on cross-product of system velocity and pulsar spin. Constraint $\propto P_b^2/(eP)$, same pulsars used as for Δ test.

Ensemble of pulsars: $\alpha_3 < 5.5 \times 10^{-20}$ (Gonzalez et al. 2011; slightly worse limit than in Stairs et al. 2005, ApJ, 632, 1060, but more information used).

(Cf. Perihelion shifts of Earth and Mercury: $\sim 2 \times 10^{-7}$ (Will 1993, "Theory & Expt. In Grav. Physics," CUP))

New Methods to Constrain α_1 , α_2 and ξ — Shao & Wex 2012, CQG **29**, 215018; Shao et al. 2013, Marcel Grossman Proceedings, , Shao et al. 2013, CQG **30** 165019, Shao & Wex 2013, CQG **30** 165020.

For α_1 , still use short-period PSR-WD binaries, but look for changes in the eccentricity vector, recognizing that periastron precession will eventually reveal the “forced” component of the eccentricity. Limit from PSR J1738+0333: $\alpha_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5}$.

For α_2 , look for an apparent time derivative of the project semi-major axis in short-orbital period PSR-WD systems, indicating precession of the orbital plane about the velocity vector relative to the preferred frame. Limit from PSRs J1012+5307 and J1738+0333: $|\alpha_2| < 1.8 \times 10^{-4}$. Limit from MSP profile stability: $|\alpha_2| < 1.6 \times 10^{-9}$.

A similar argument is used for ξ , with the relevant vector being that of the Galactic gravitational vector. Limit: $|\xi| < 3.1 \times 10^{-4}$. Can also argue from the stability of MSP profiles: $|\xi| < 3.9 \times 10^{-9}$.

Orbital Decay Tests

These rely on measurement of or
constraint on orbital period derivative, \dot{P}_b .
This is complicated by systematic biases:

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Observed}} = \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Accel}} + \cancel{\left(\frac{\dot{P}_b}{P_b}\right)_{\dot{G}}} + \cancel{\left(\frac{\dot{P}_b}{P_b}\right)_{\dot{m}}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Quadrupolar}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Dipolar}}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Accel}} = \left(\frac{\dot{P}_b}{P_b}\right)_{\text{gravitational field}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Shklovskii}}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Shklovskii}} = \mu^2 \frac{d}{c}$$

Dipolar Gravitational Radiation

Difference in gravitational binding energies of NS and WD implies dipolar gravitational radiation possible in, e.g., tensor-scalar theories.

$$\dot{P}_{b \text{ Dipole}} = \frac{4\pi^2 G_*}{c^3 P_b} \frac{m_1 m_2}{m_1 + m_2} (\alpha_{c_1} - \alpha_{c_2})^2$$

Damour & Esposito-Farèse
1996, PRD, 54, 1474.

Test using pulsar—WD systems in short-period orbits. The best test at this time is given by:

PSR J1738+0333, 8.5-hour orbit:

$$(\alpha_{cp} - \alpha_0)^2 < (1.8 \pm 3.6) \times 10^{-6} \text{ (Freire et al. 2012, MNRAS } \mathbf{433}, 3328)$$

Note that we also have a limit of 2.5×10^{-5} for the $2\text{-}M_{\odot}$ pulsar **PSR J0348+0438** (2.5-hour orbit, Antoniadis et al. 2013, Science, **340**, 448) – this will be important when considering mass-dependent deviations from GR.

Orbital decay tests rely on measurement of or constraint on orbital period derivative, \dot{P}_b .

This is complicated by systematic biases:

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Observed}} = \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Accel}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\dot{G}} + \cancel{\left(\frac{\dot{P}_b}{P_b}\right)_{\dot{m}}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Quadrupolar}} + \cancel{\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Dipolar}}}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Accel}} = \left(\frac{\dot{P}_b}{P_b}\right)_{\text{gravitational field}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{Shklovskii}}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{Shklovskii}} = \mu^2 \frac{d}{c}$$

Variation of Newton's Constant

Spin: Variable G changes moment of inertia of NS.

Expect $\frac{\dot{P}}{P} \propto \frac{\dot{G}}{G}$ depending on equation of state, PM correction...

Various millisecond pulsars, roughly: $\frac{\dot{G}}{G} \leq 2 \times 10^{-11} \text{yr}^{-1}$

Orbital decay: Expect $\frac{\dot{P}_b}{P_b} \propto \frac{\dot{G}}{G}$, test with circular NS-WD binaries.

PSR B1855+09, 12.3-day orbit: $\frac{\dot{G}}{G} = (-1.3 \pm 2.7) \times 10^{-11} \text{yr}^{-1}$

(Kaspi, Taylor & Ryba 1994, ApJ, **428**, 713; Arzoumanian 1995, PhD thesis, Princeton).

PSR J1713+0747, 67.8-day orbit: $\frac{\dot{G}}{G} = (1.5 \pm 3.8) \times 10^{-12} \text{yr}^{-1}$

(Splaver et al. 2005, ApJ, **620**, 405, Nice et al. 2005, ApJ, **634**, 1242; update soon by Zhu et al).

PSR J0437-4715, 5.7-day orbit: $\frac{\dot{G}}{G} = (0.5 \pm 2.6) \times 10^{-12} \text{yr}^{-1}$

(Verbiest et al 2008, ApJ **679**, 675, 95% confidence, using slightly different assumptions).

Not as constraining as LLR (Turyshv & Williams 2007, IJMPD **16**, 2165): $\frac{\dot{G}}{G} = (6 \pm 7) \times 10^{-13} \text{yr}^{-1}$

Combined Limit on \dot{G} and Dipolar Gravitational Radiation

Lazaridis et al. 2009 (MNRAS 400, 805) combine the \dot{P}_b limits from J1012+5307 and J0437-4715 to form a combined limit on these two quantities:

$$\frac{\dot{G}}{G} = (-0.7 \pm 3.3) \times 10^{-12} \text{ yr}^{-1}$$

$$\text{and } \kappa_D \approx \frac{(\alpha_{cp} - \alpha_0)^2}{S^2} = (0.3 \pm 2.5) \times 10^{-3}$$

Now updated using 1738+0333:

$$\frac{\dot{G}}{G} = (-0.6 \pm 1.6) \times 10^{-12} \text{ yr}^{-1}$$

$$\text{and } \kappa_D \approx \frac{(\alpha_{cp} - \alpha_0)^2}{S^2} = (-0.3 \pm 2.0) \times 10^{-4}$$

Relativistic Binaries

Binary pulsars, especially double-neutron-star systems: measure post-Keplerian **timing** parameters in a theory-independent way (Damour & Deruelle 1986, AHP, 44, 263). These predict the stellar masses in any theory of gravity. In GR:

$$\dot{\omega} = 3 \left(\frac{P_b}{2\pi} \right)^{-5/3} (T_0 M)^{2/3} (1 - e^2)^{-1}$$

$$\gamma = e \left(\frac{P_b}{2\pi} \right)^{1/3} T_0^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$

$$\dot{P}_b = \frac{-192}{5} \left(\frac{P_b}{2\pi} \right)^{-5/3} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) (1 - e^2)^{-7/2} T_0^{5/3} m_1 m_2 M^{-1/3}$$

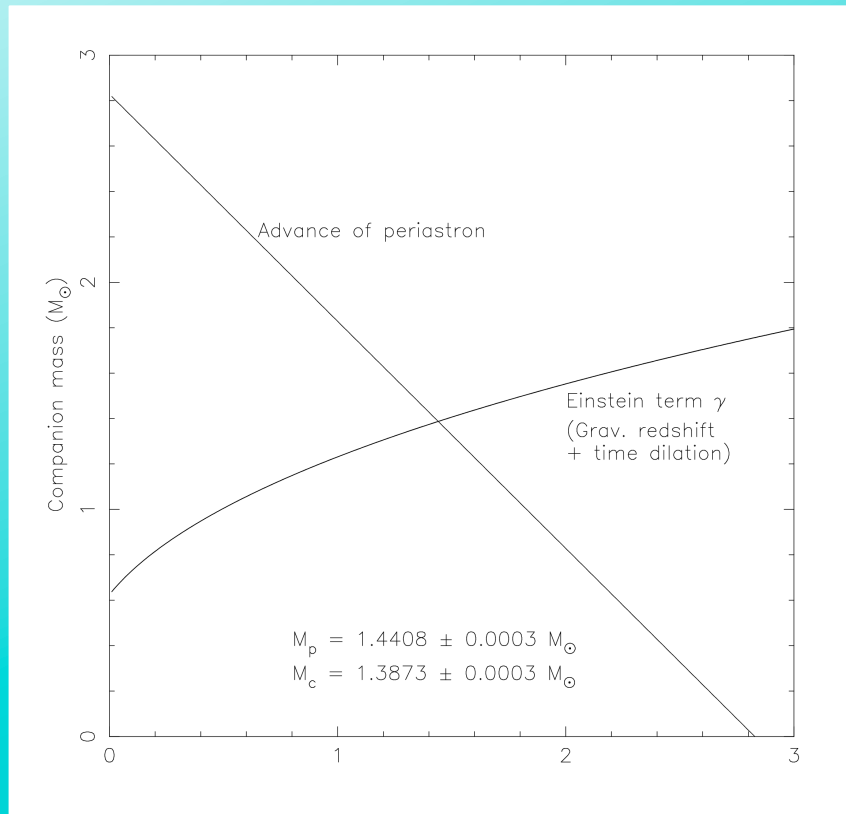
$$r = T_0 m_2$$

$$s = x \left(\frac{P_b}{2\pi} \right)^{-2/3} T_0^{-1/3} M^{-2/3} m_2^{-1}$$

$$M = m_1 + m_2$$

$$T_0 = 4.925490947 \mu s$$

The Original System: PSR B1913+16

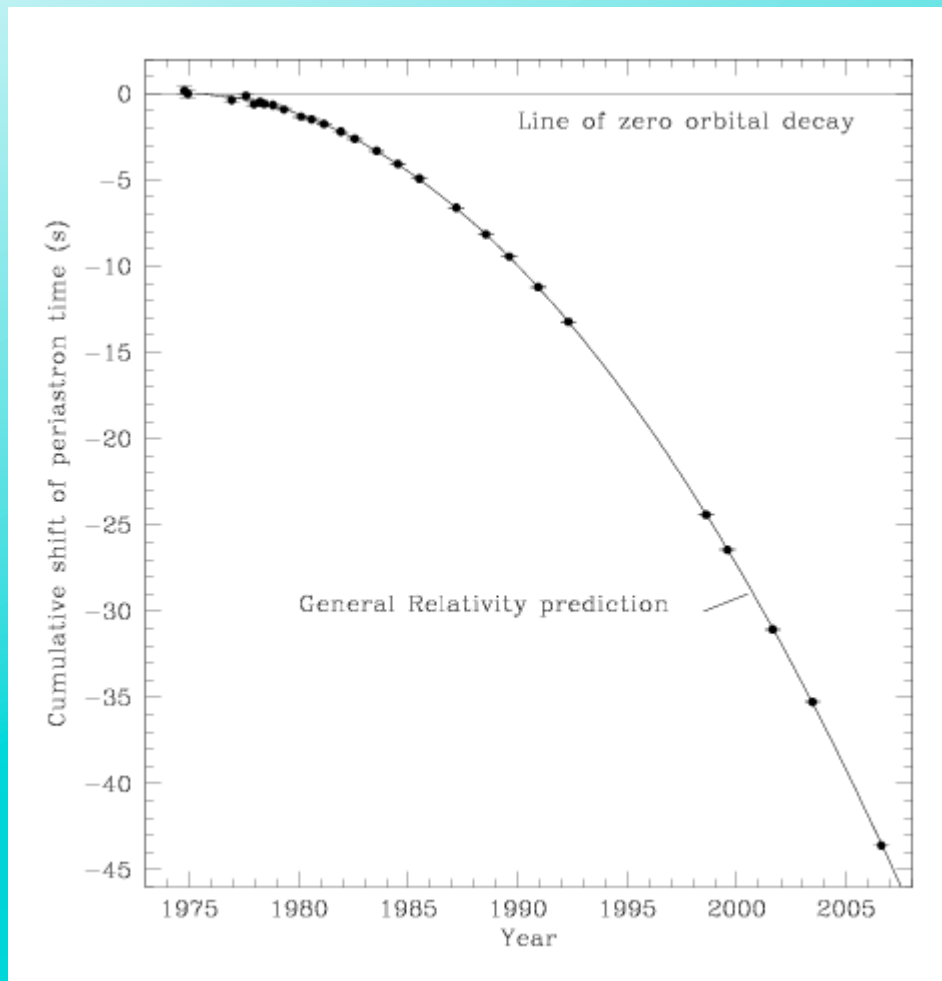


Highly eccentric double-NS system, 8-hour orbit.

The $\dot{\omega}$ and γ parameters predict the pulsar and companion masses.

The \dot{P}_b parameter is in good agreement, to $\sim 0.2\%$. Galactic acceleration modeling now limits this test.

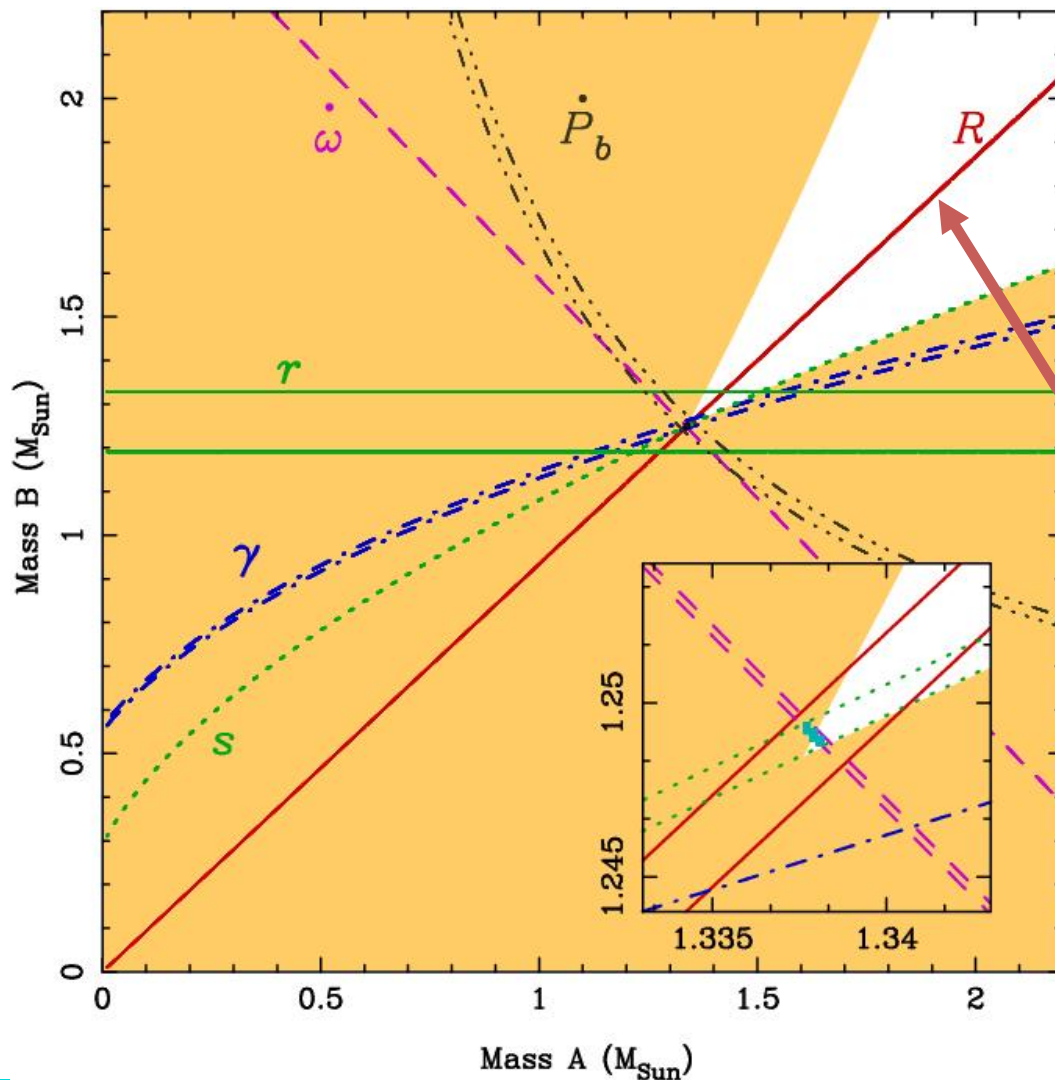
Orbital Decay of PSR B1913+16



The accumulated shift of periastron passage time, caused by the **decay of the orbit**.

A good match to the predictions of GR!

Weisberg, Nice & Taylor, 2010, ApJ **722**, 1030



Kramer et al. 2006, Science **314**, 97

Mass-mass diagram for the double pulsar J0737-3039A and B. In addition to 5 PK parameters (for A), we measure the mass ratio R . This is independent of gravitational theory \Rightarrow whole new constraint on gravity compared to other double-NS systems.

Numbers reported in 2006 (Kramer et al. 2006, Science **314**, 97):
 We can use the measured values of $R = 0.9336 \pm 0.0005$
 and $\dot{\omega} = 16.8995 \pm 0.0007$ °/year to get the masses and
 then compute the other parameters as expected in GR:

Expected in GR:

$$\begin{aligned}\gamma &= 0.38418(22) \text{ ms} \\ \dot{P}_b &= -1.24787(13) \times 10^{-12} \\ r &= 6.153(26) \text{ ms} \\ s &= 0.99987^{+0.00013}_{-0.00048}\end{aligned}$$

Observed:

$$\begin{aligned}\gamma &= 0.3856 \pm 0.0026 \text{ ms} \\ \dot{P}_b &= (-1.252 \pm 0.017) \times 10^{-12} \\ r &= 6.21 \pm 0.33 \text{ ms} \\ s &= 0.99974^{+0.00016}_{-0.00039}\end{aligned}$$

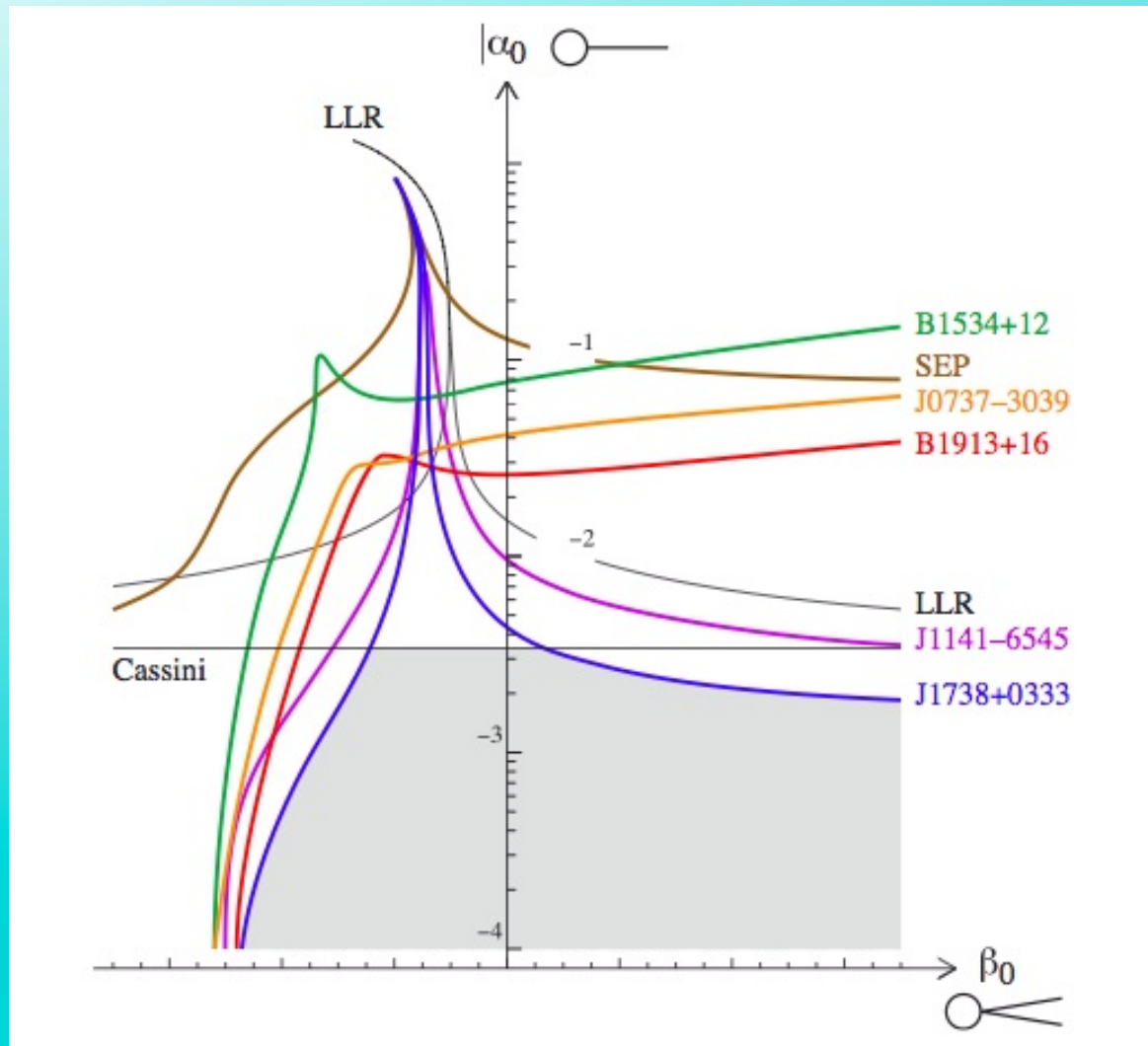
In particular:

$$\left(\frac{\dot{P}_b}{P_b} \right)_{\text{Accel}} \approx 10^{-4} \quad \text{Deller et al 2008, Science } \mathbf{323}, 1327$$

$$\frac{s^{\text{obs}}}{s^{\text{pred}}} = 0.99987 \pm 0.00050$$

This was a 0.05% test of
 strong-field GR – now
 improved, though we don't
 use R anymore...

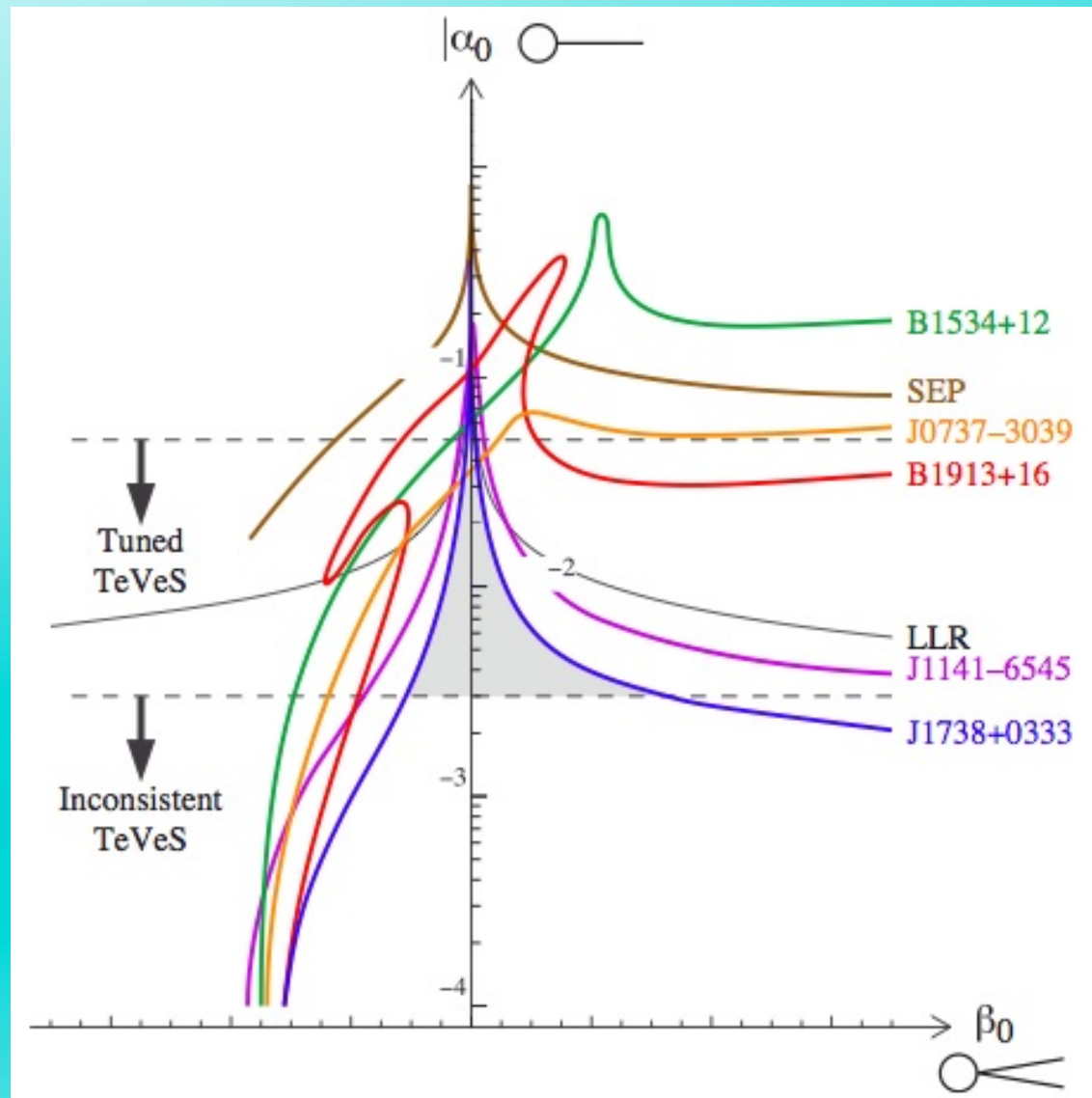
Constraining Generic Theories with Multiple Pulsars



Strong constraints on parameters in alternate theories can be achieved by combining information from multiple pulsars plus solar-system tests (Damour & Esposito-Farese, Wex).

Freire et al. 2012, MNRAS **433**, 3328 for generic tensor-scalar theories of Damour & Esposito-Farese.

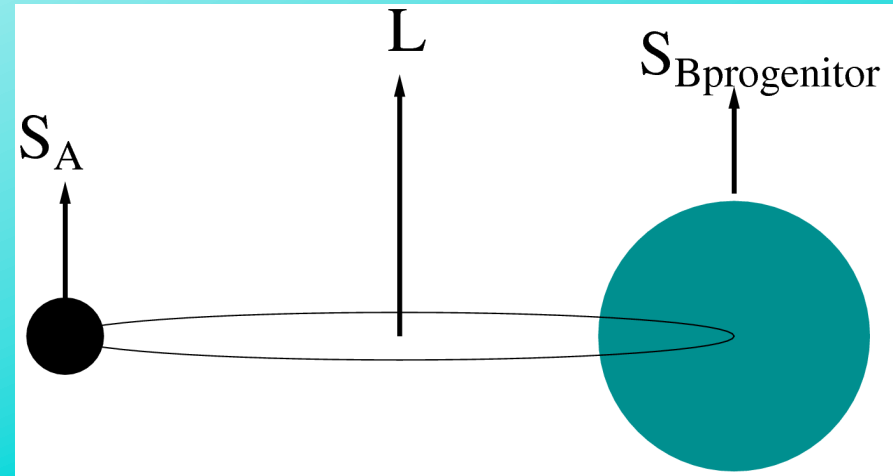
Constraining Generic Theories with Multiple Pulsars



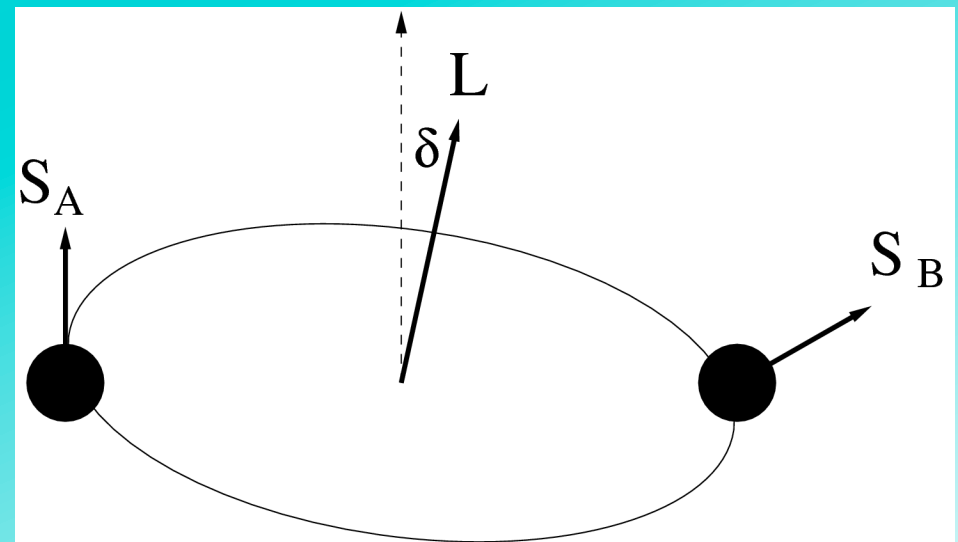
Freire et al. 2012, MNRAS **433**, 3328 for generalized TeVeS theories.

Geodetic Precession

Before the second supernova:
all AM vectors
aligned.



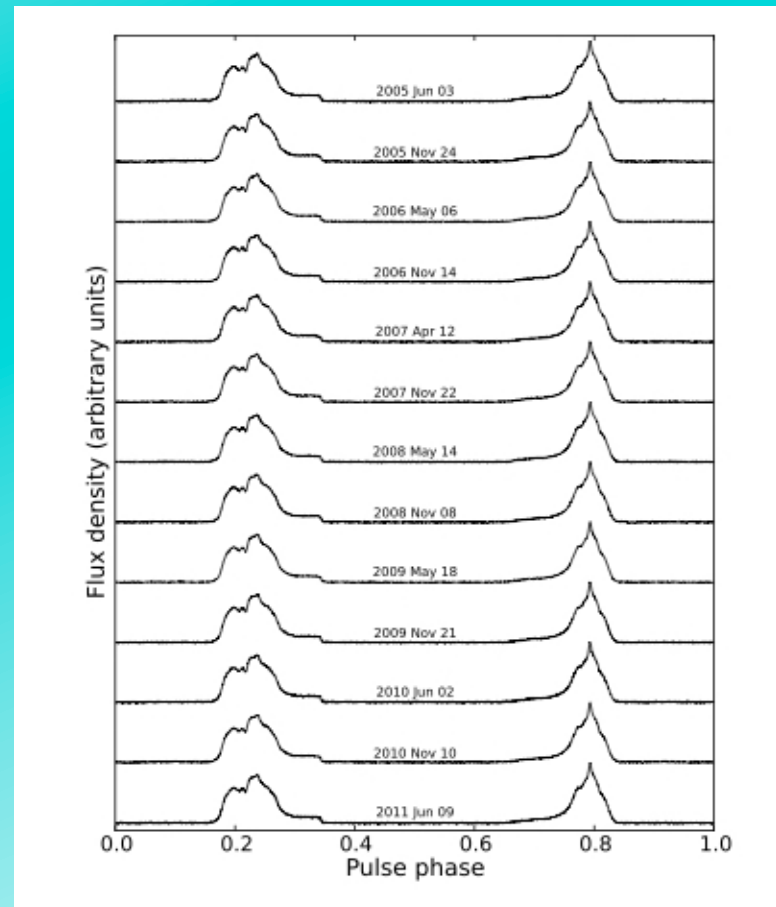
After second supernova:
orbit tilted,
misalignment angle δ
(shown for recycled A);
B spin pointed
elsewhere (defined
by kick?). Expect both
spins to precess.



Geodetic Precession

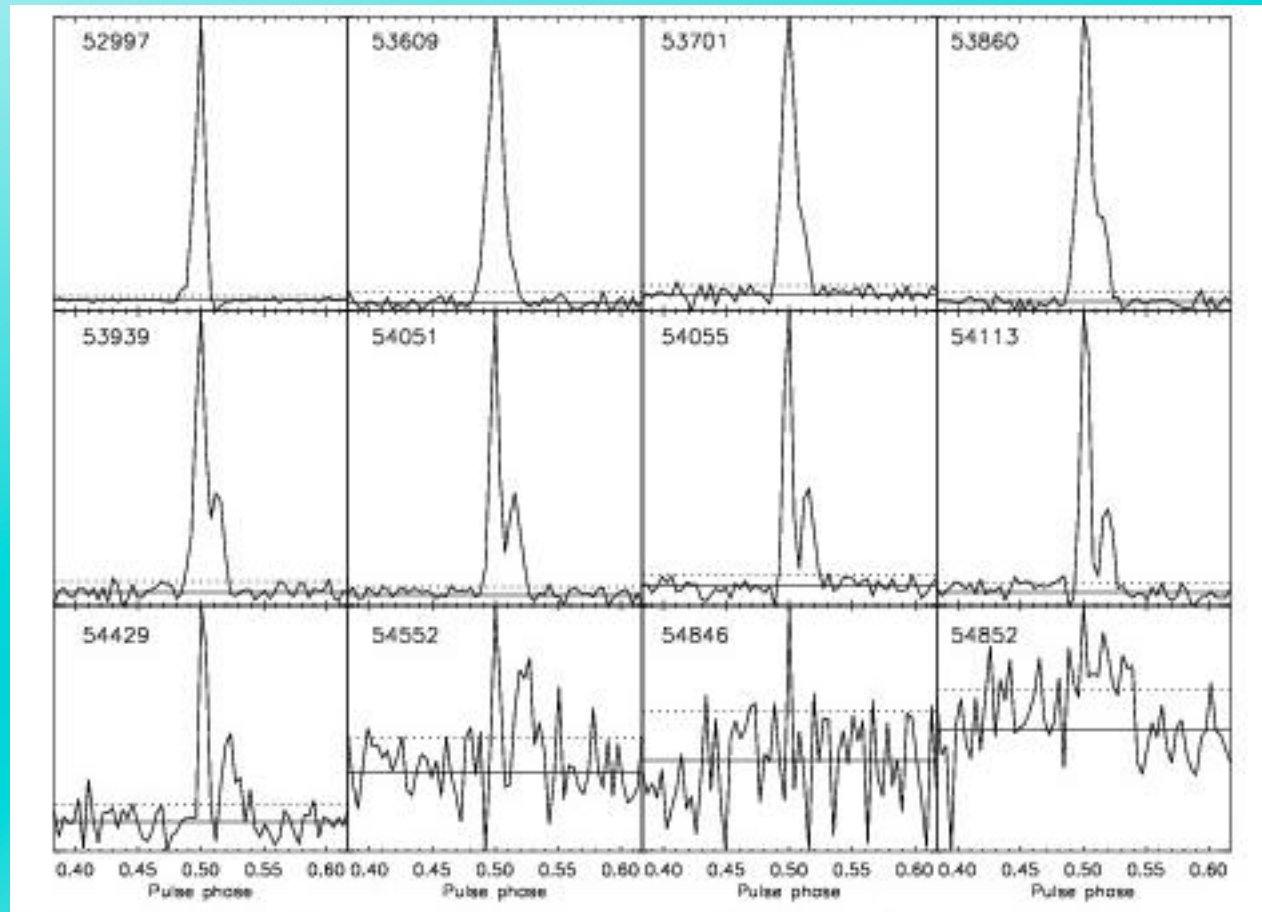
Precession period: **300 years** for B1913+16, **700 years** for B1534+12, **265 years** for J1141-6545, **160 years** for J1906+0746 and only **~70 years** for the J0737-3039 pulsars.

It's seen in all of these (see Emmanuel Fonseca's talk and poster for a rate measurement in B1534+12) except for the recycled pulsar 0737A. This puts a limit on its misalignment angle of 3.2° , assuming two-pole emission (Ferdman et al. 2013, ApJ **767**, 85), implying little asymmetry in the supernova that formed B.



But B has changed a lot....
and has now disappeared completely!

Dec. 2003

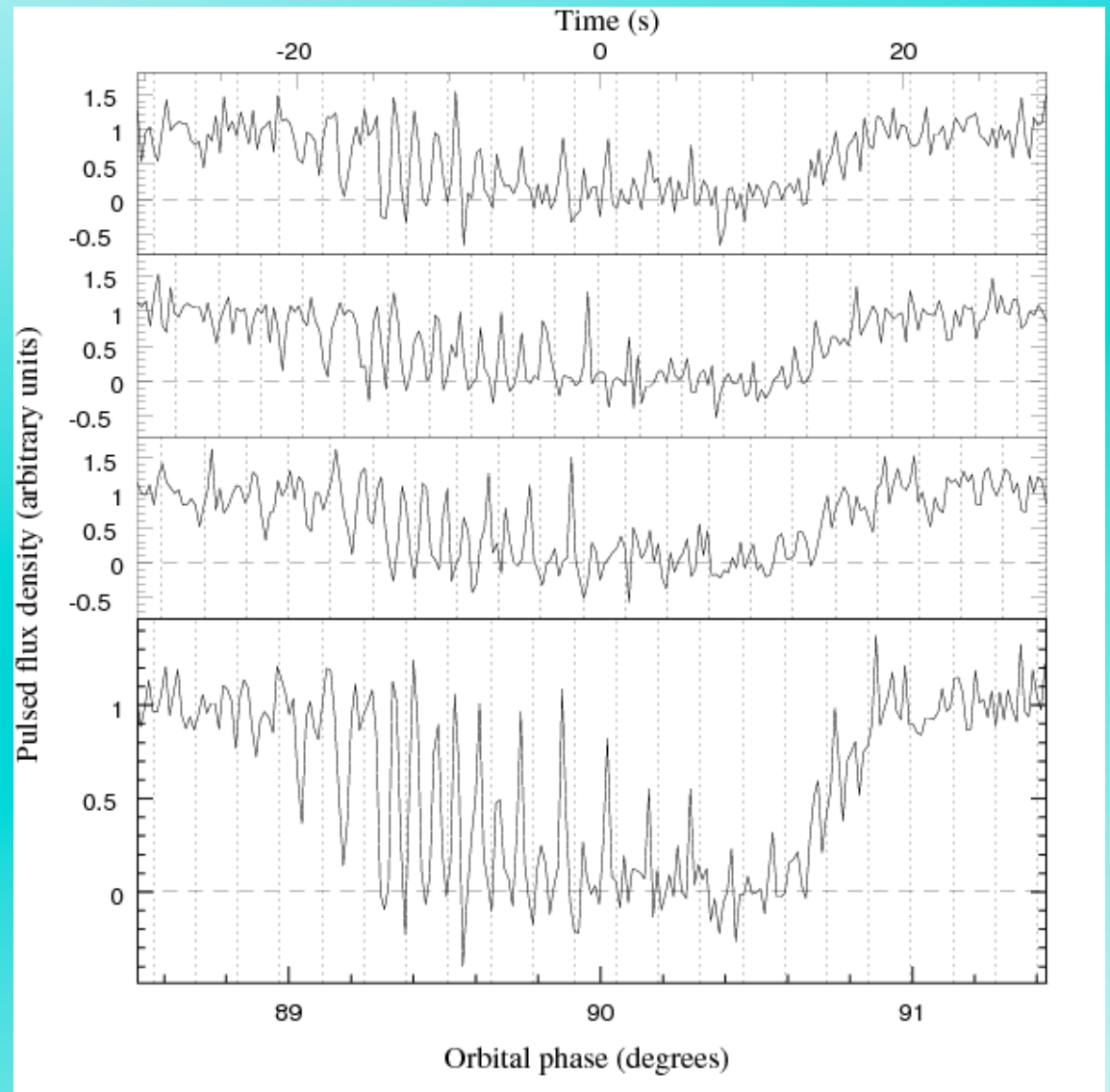


Jan. 2009

Perera et al., 2010, ApJ **721**, 1193

B's effects on A provide another avenue to precession:

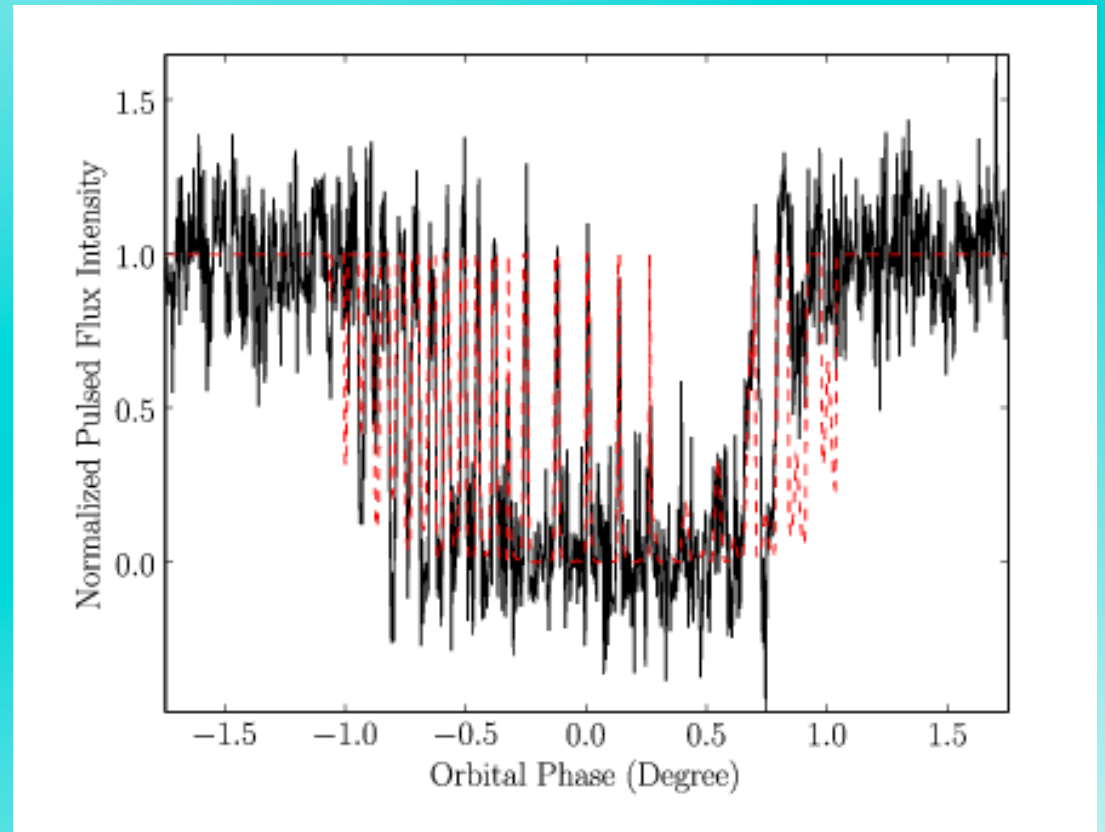
Eclipses of A by B occur every orbit (Lyne et al. 2004, *Science* **303**, 1153; Kaspi et al. 2004, *ApJ* **613**, 137). A's flux is modulated by the dipolar emission from B.



McLaughlin et al. 2004, *ApJ* **616**, 131

See Lyutikov & Thompson 2005, ApJ **634**, 1223 for a simple geometrical model, illustrated here for April 2007 data by Breton et al. 2008, Science **321**, 104.

This model makes concrete predictions if B precesses...

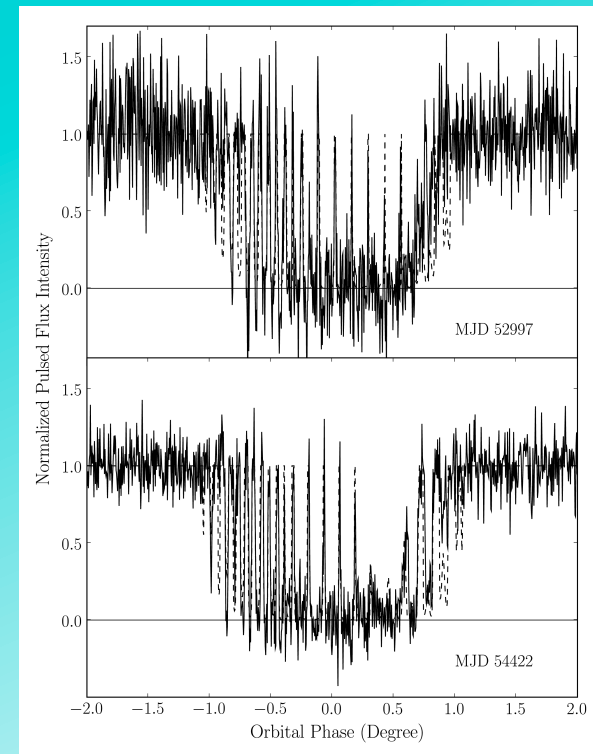
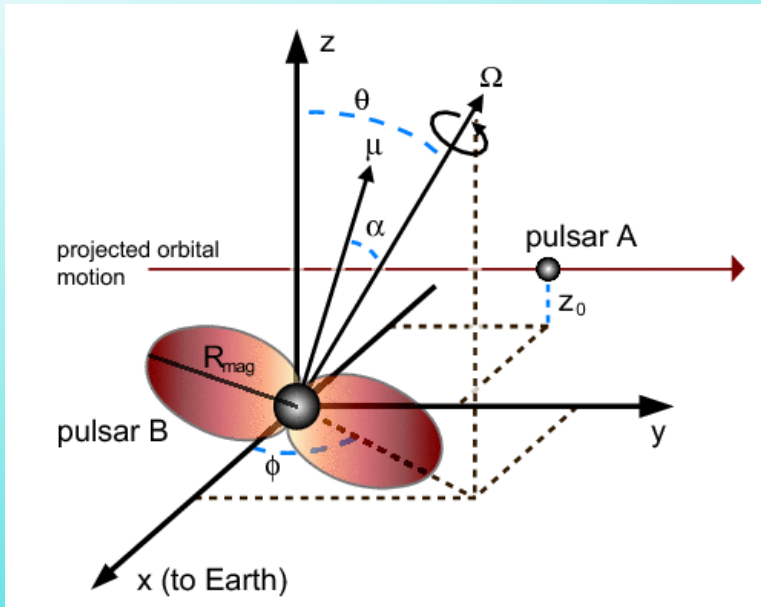


Eclipse geometry, Breton et al 2008.
If B precesses, φ will change with time, and the structure of the eclipse modulation should also change... and it does!

Dec. 2003

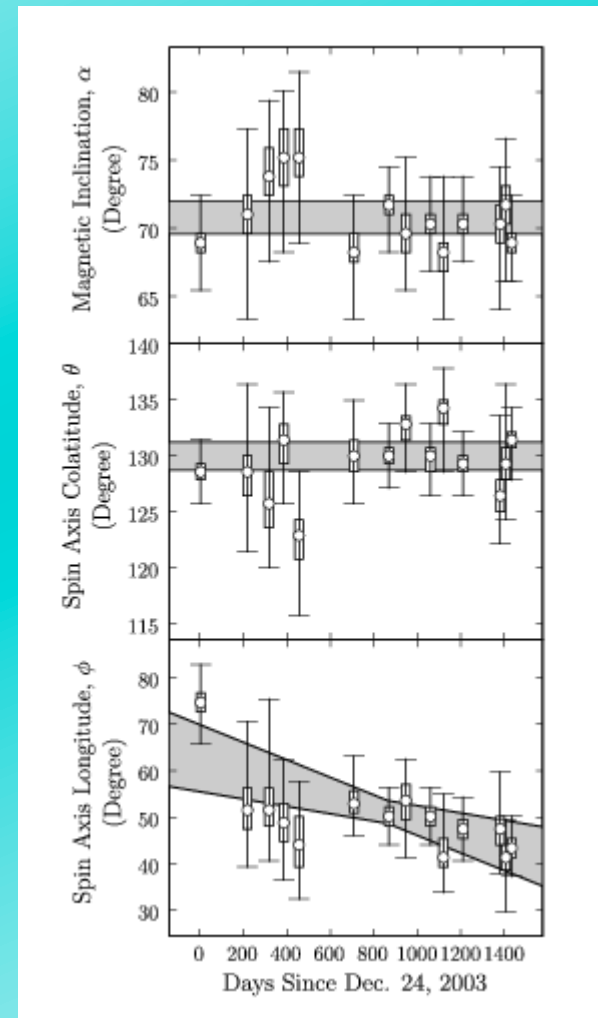
Nov. 2007

Courtesy René Breton



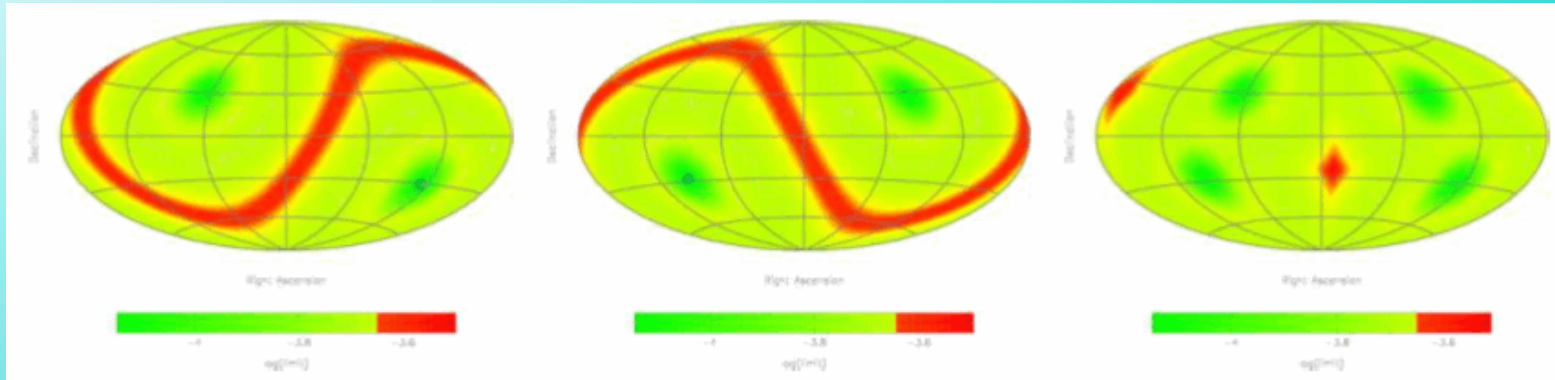
The angles α and θ stay constant, but φ changes at a rate of $4.77^{+0.66}_{-0.65} \text{ }^\circ \text{ yr}^{-1}$. This is nicely consistent with the rate predicted by GR: $5.0734(7) \text{ }^\circ \text{ yr}^{-1}$.

And because we measure both orbital semi-major axes, this actually constrains a generalized set of gravitational strong-field theories for the first time!



Breton et al 2008

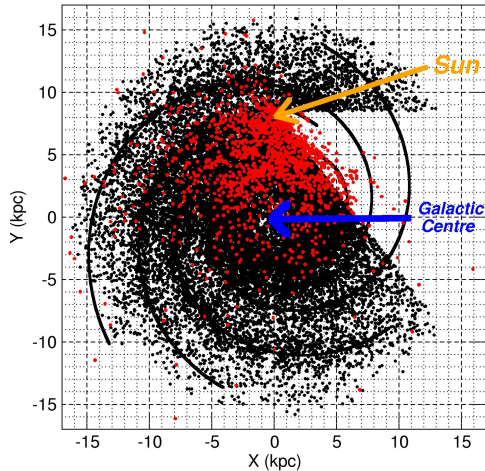
Preferred-frame effects with double-NS systems



Wex & Kramer 2007, MNRAS **380**, 455

Wex & Kramer showed that pulsars similar to the double pulsar are sensitive to preferred-frame effects (within semi-conservative theories) via their orbital parameters. Here they show that the double pulsar (left), a similar system at the Galactic centre (middle) and their combination can lead to strong constraints on the directionality of the preferred frame (PFE antenna).

Future Telescopes



The Galactic Census with the Square Kilometre Array should provide:

~30000 pulsars

~1000 millisecond pulsars

~100 relativistic binaries

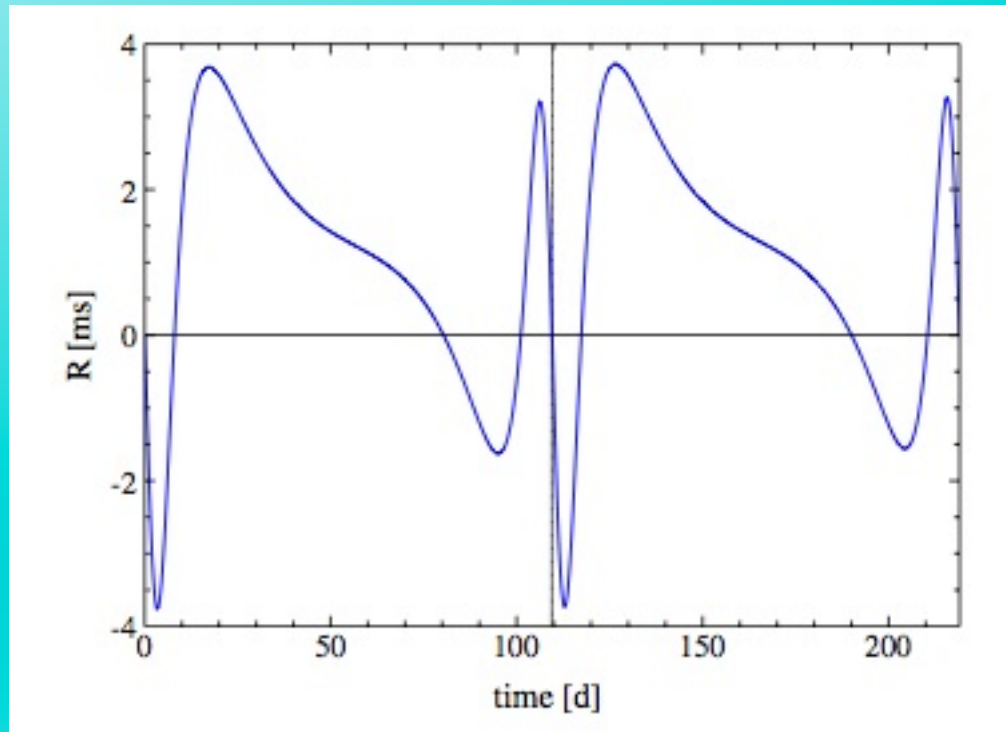
1—10 pulsar – black-hole systems.

With suitable PSR—BH systems, we may be able to measure the BH spin $\chi \equiv \frac{c}{G} \frac{S}{M^2}$ and quadrupole moment $q \equiv \frac{c^4}{G^2} \frac{Q}{M^3}$, testing

the Cosmic Censorship conjecture and the No-hair theorem $q = -\chi^2$.

Residuals from pulsar in 0.3-year, eccentricity 0.5 orbit around Sgr A*: weekly observations over 3 years lead to a measurement of the spin (via frame-dragging) and quadrupole moment (below; could be to better than 1% depending on the orbit and pulsar properties), assuming Sgr A* is an extreme Kerr BH.

Liu et al. 2012, ApJ **747**, 1



The challenge
will be finding
such pulsars!!

Future Prospects

Long-term timing of pulsar – white dwarf systems

- ⇒ better limits on \dot{G}/G and dipolar gravitational radiation, as well as PPN-type parameters
- ⇒ better limits on gravitational-wave background

Long-term timing of relativistic systems

- ⇒ improved tests of strong-field GR.

Potential to measure higher-order terms in $\dot{\omega}$ in 0737A: we may be able to measure the neutron-star moment of inertia!

Profile changes and eclipses in relativistic binaries

- ⇒ better tests of precession rates, geometry determinations.

Large-scale surveys, large new telescopes...

- ⇒ more systems of all types... and maybe some new “holy grails” such as a pulsar—black hole system...

See Shao, Stairs et al. on pulsar tests of GR with the SKA,
arXiv:1501.00058