General Relativity Tests with Pulsars

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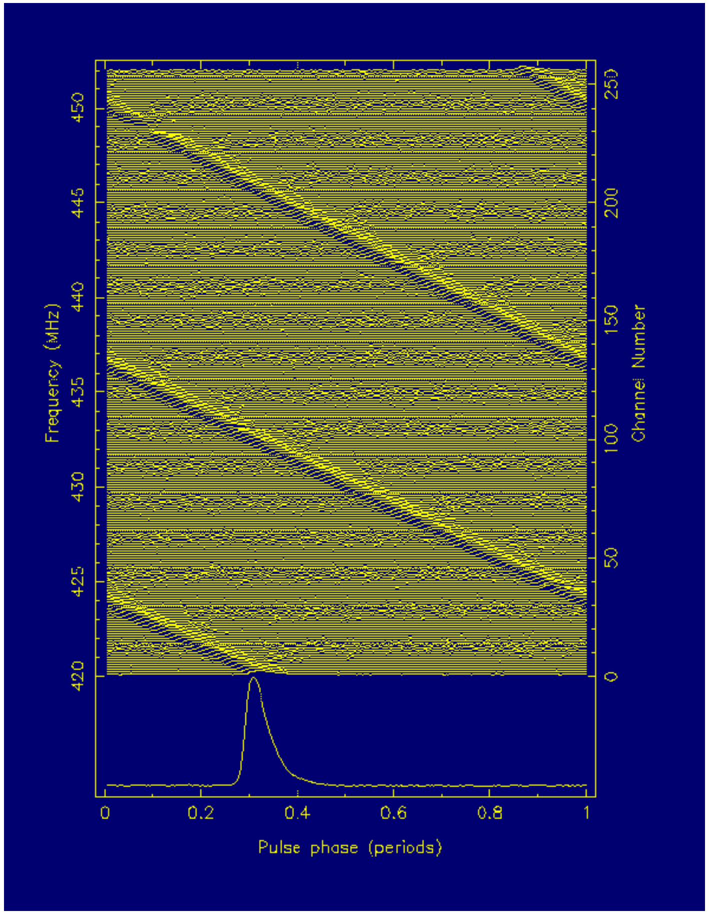
Much of this material is in Living Reviews in Relativity 2003-5.

Pulsars: rotating, magnetized neutron stars.
B: 10^8 G to 10^{14} G
P: 0.00156 s to 8.2 s

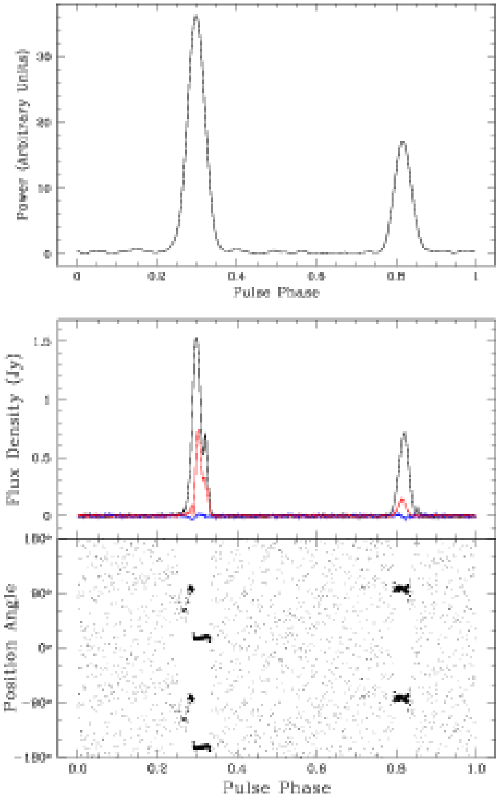
Observations typically done with large single-dish telescopes (Arecibo, GBT, Parkes, Jodrell Bank, Effelsberg...)

Short discussion of some obervational issues...

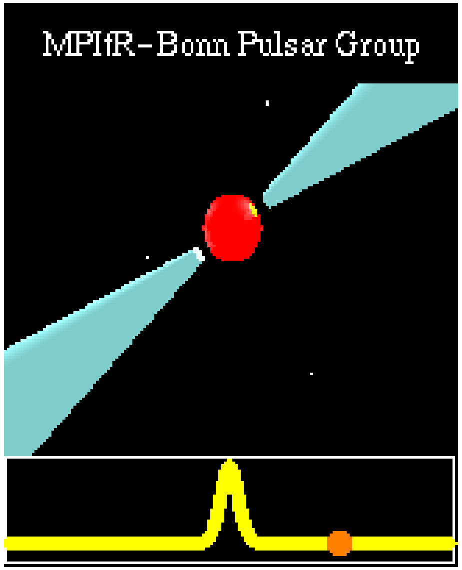
Dispersion: $1/f^2$ law



Filterbank dedispersion:
residual smearing within channels

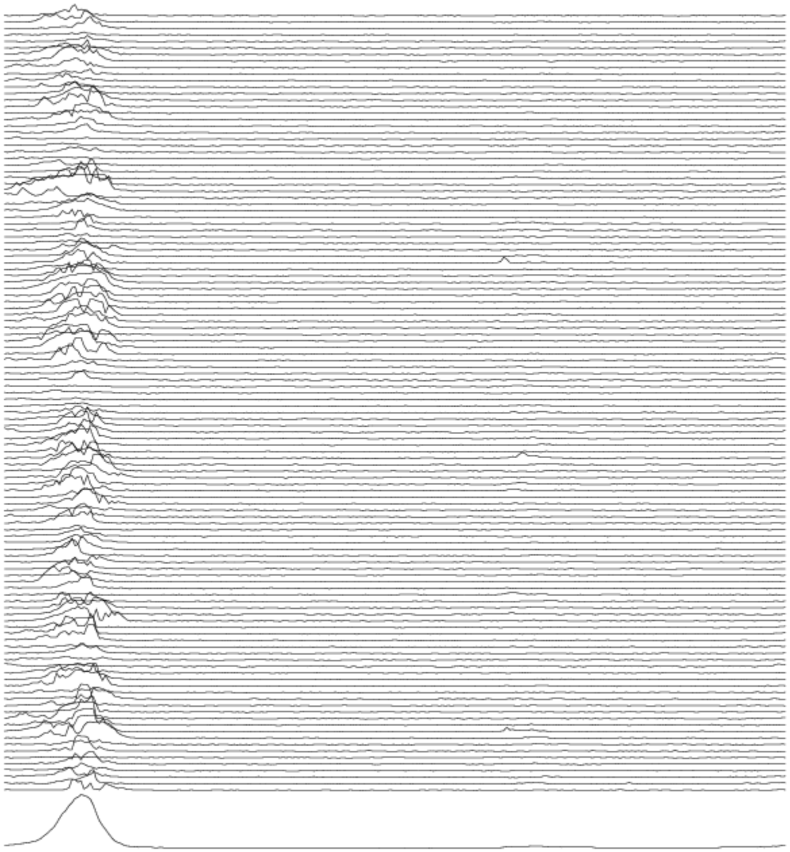


Coherent Dedispersion:
much better timing precision



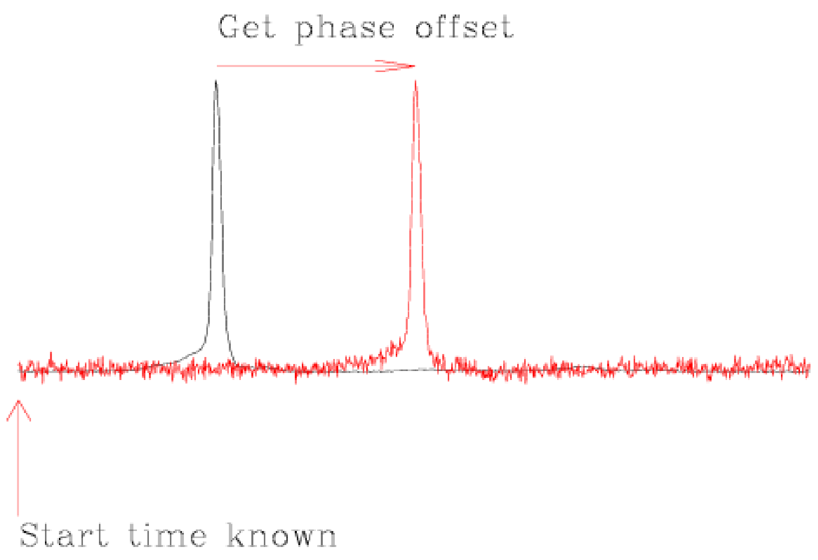
Lighthouse
model

Pulse-to-pulse variations



Integrated profile:
generally stable

Cross-correlation with standard profile: Time-of-Arrival (TOA)



PSR B1534+12: between
23 Aug. 1990 20:56:17.088
and
17 July 2005 01:12:10.368
there were exactly
12402716222 pulses.

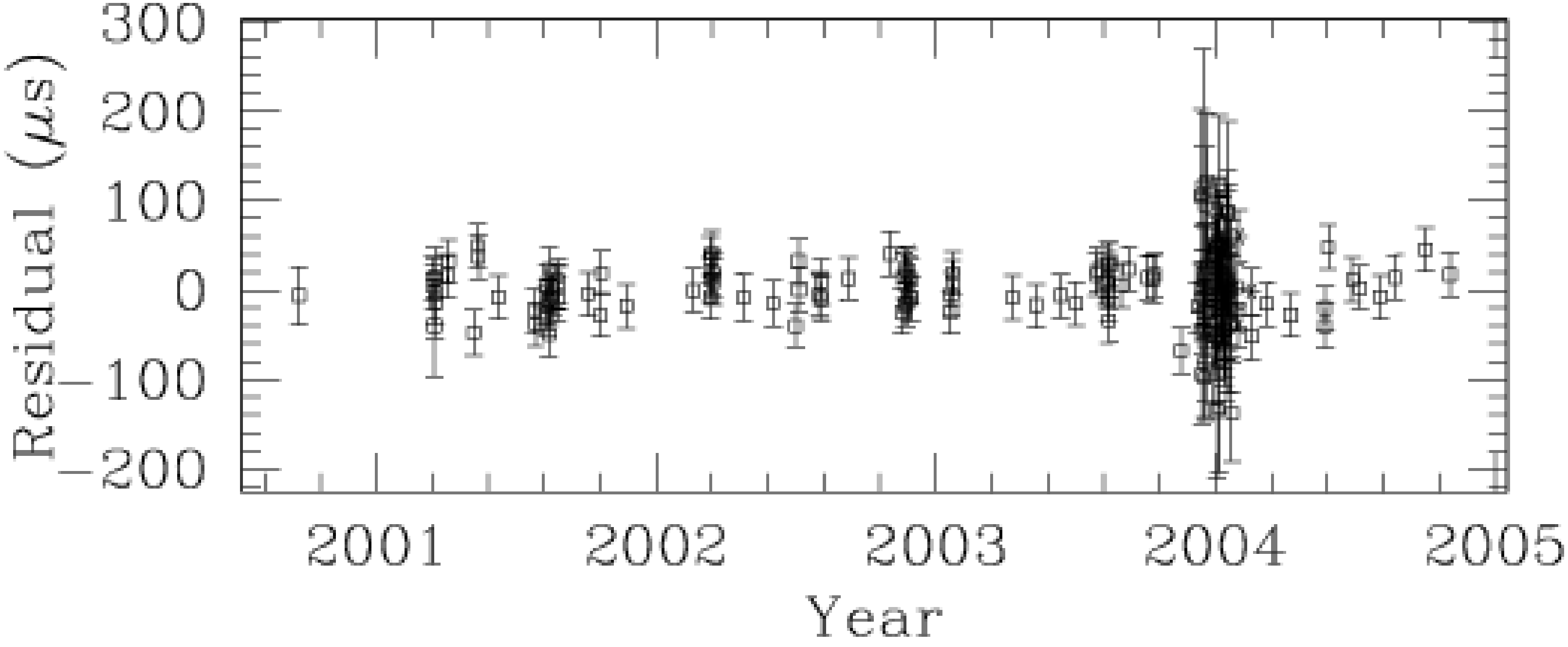
Exact pulse numbering ⇒ high-precision timing

Pulsar Timing

1) Transform TOAs from telescope frame to Solar System Barycentre (roughly inertial relative to pulsar or pulsar system centre of mass)

2) Fit P, P derivatives, position,
proper motion, dispersion measure (DM),
parallax...

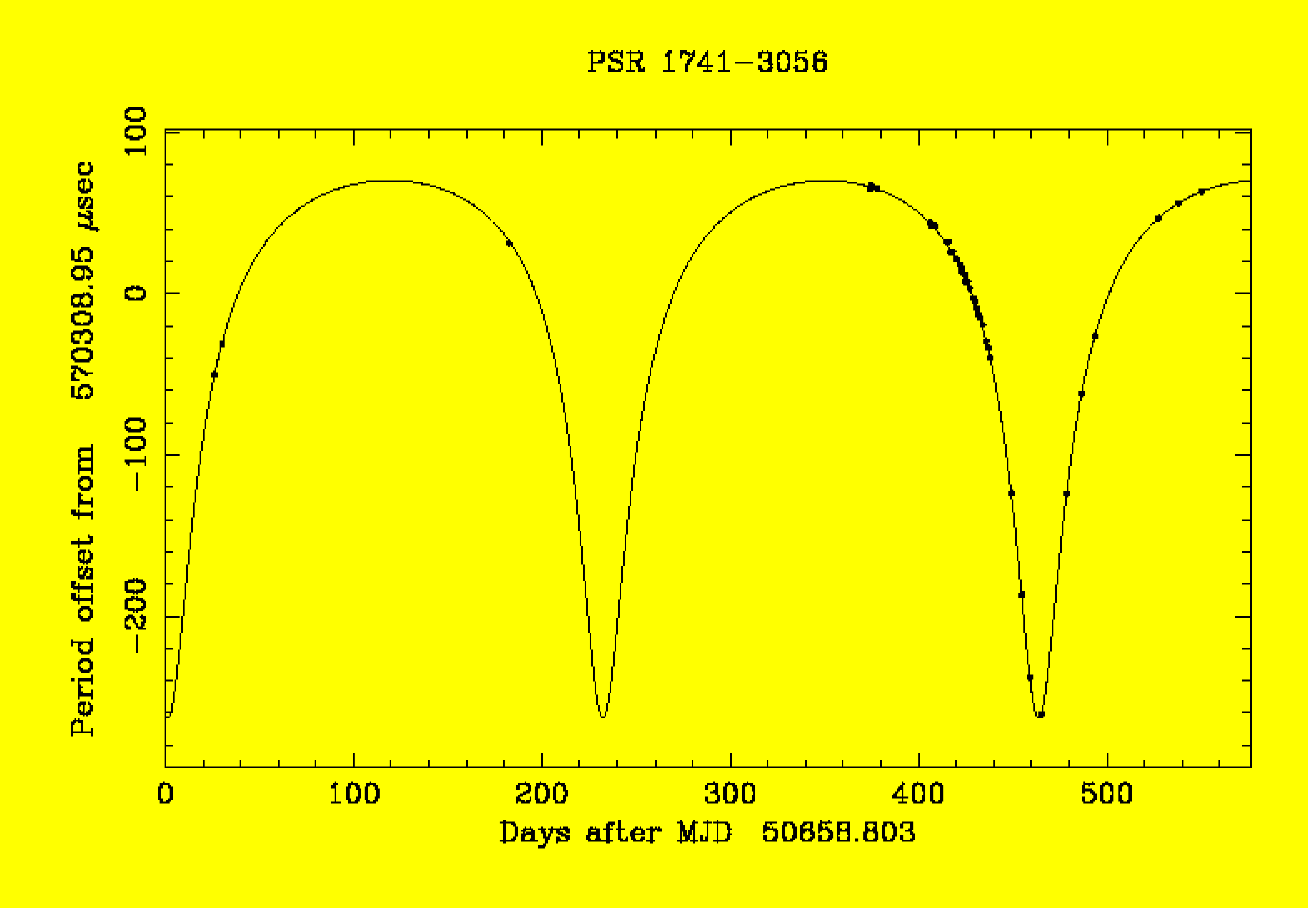
Timing Residuals: Actual TOAs – Predicted



PSR J1751-2857 – Stairs et al., ApJ, in press.

Ideally: no systematics in residuals

Binary Pulsars



Changing period usually quickly obvious.
Binary pulsars are like single-lined spectroscopic binaries.

Timing Binary Pulsars

All binaries: fit 5 Keplerian parameters: orbital period, projected semi-major axis, eccentricity, longitude and epoch of periastron.

Some systems: fit "Post-Keplerian" parameters: e.g., advance of periastron, orbital period derivative, time dilation/gravitational redshift, Shapiro delay.

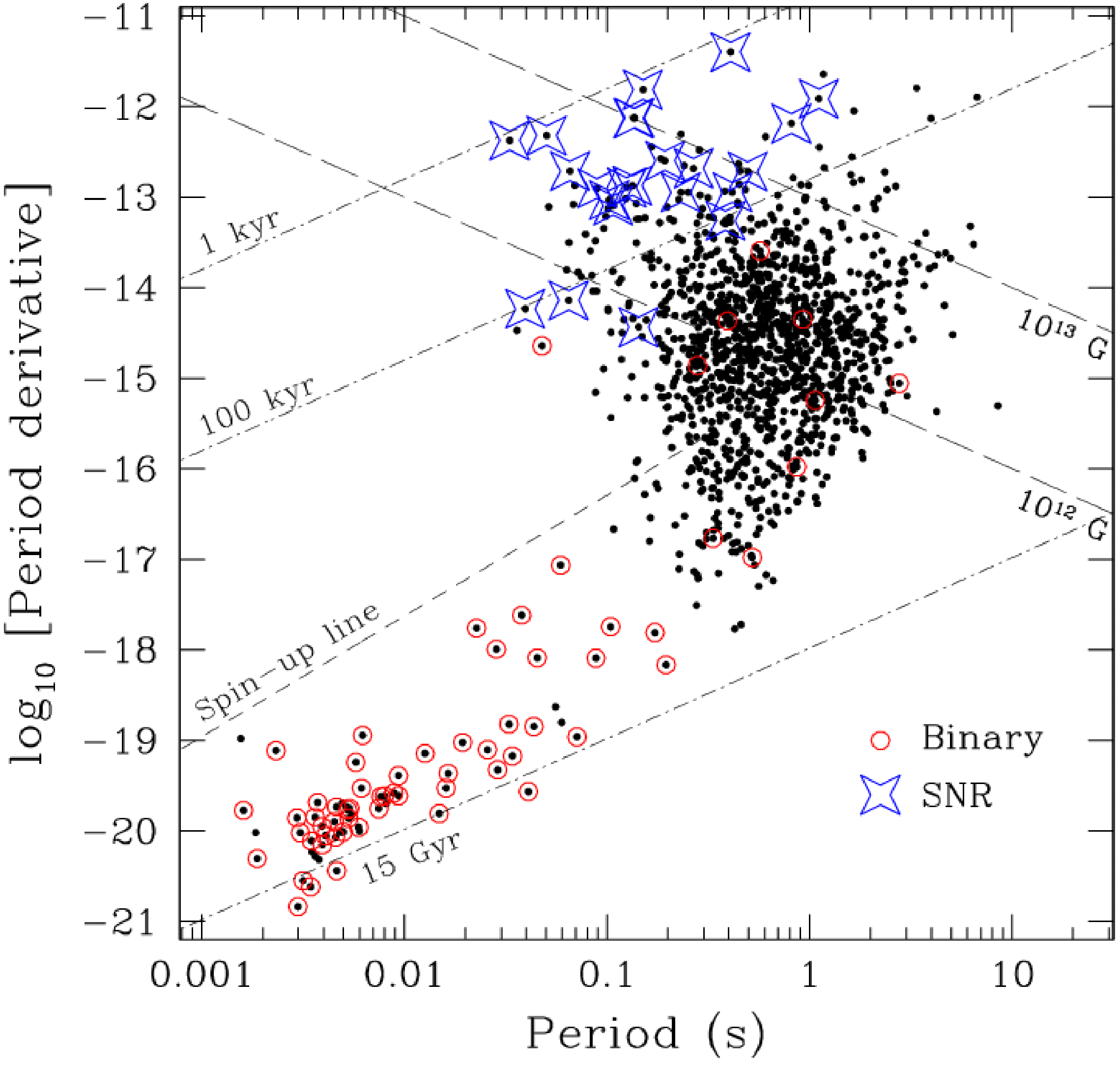
The Pulsar Population

From P, Ṗ and magnetic dipole model, derive estimate of surface B-field:

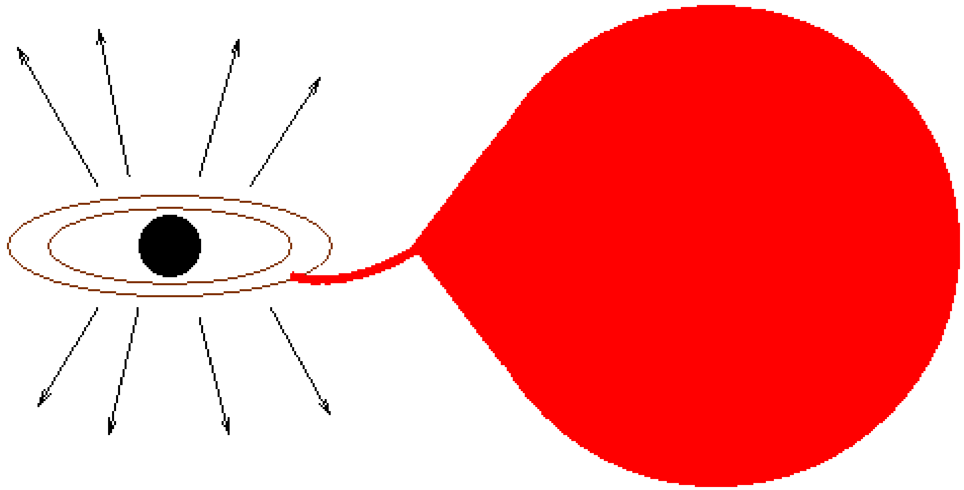
$$B = 3.2\times10^{19}\sqrt{P\dot{P}}\,G$$

and characteristic age:

$$\tau_c = \frac{P}{2\dot{P}}$$



Pulsar spin-up/recycling



Companion Roche-lobe overflow, accretion disk.
Sometimes common-envelope (CE) evolution.

Final result: millisecond pulsar with white-dwarf companion, spins and orbital AM aligned.
Double-NS formation: CE, then second supernova.

Equivalence Principle Violations

Pulsar timing can:

- set limits on the Parametrized Post-Newtonian (PPN) parameters α_1, α_3, ζ_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).

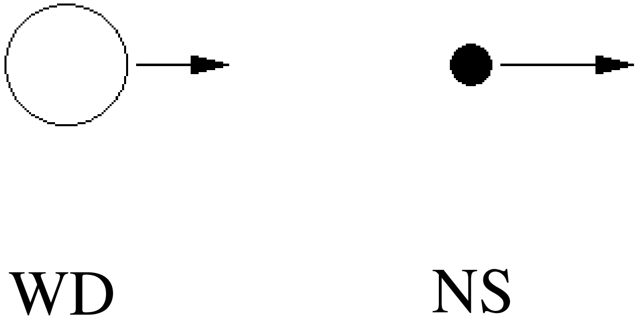
SEP: Nordtvedt (Gravitational Stark) Effect

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

$$\eta = 4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2$$

Constraint: $\eta = (4.4 \pm 4.5) \times 10^{-4}$

Williams et al. 2004, PRL 93, 261101



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

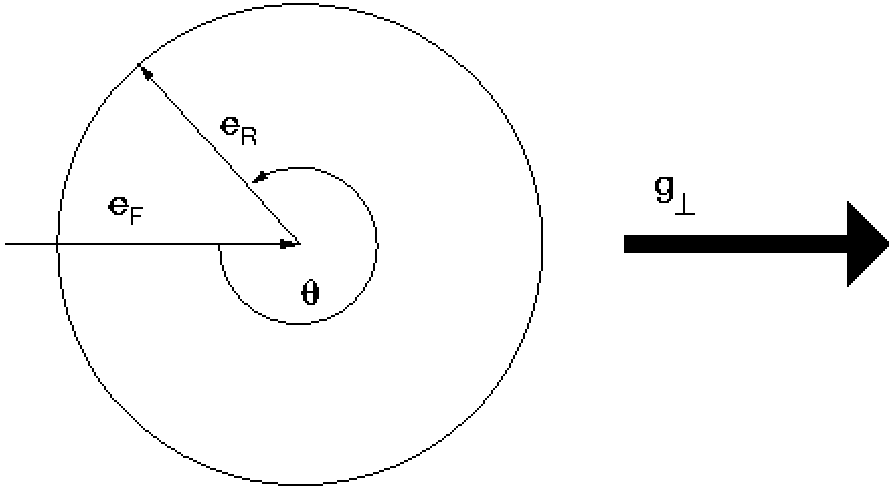
$$\left(\frac{m^{grav}}{m^{inertial}}\right)_i = 1 + \Delta_i$$

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

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

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

Deriving a Constraint on Δ_{net}



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

Use pulsar—white-dwarf binaries with low eccentricities ($<10^{-3}$).

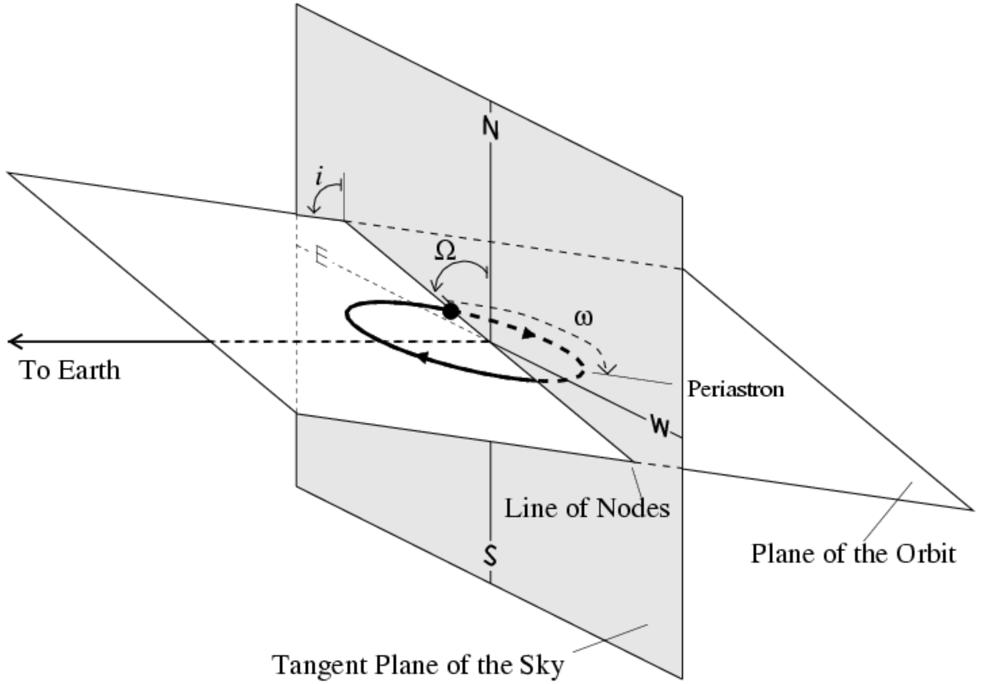
Eccentricity would contain a “forced” component along projection of Galactic gravitational force onto the orbit. This may partially cancel “natural” eccentricity.

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

Formerly: assume binary orbit is randomly oriented on sky.

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

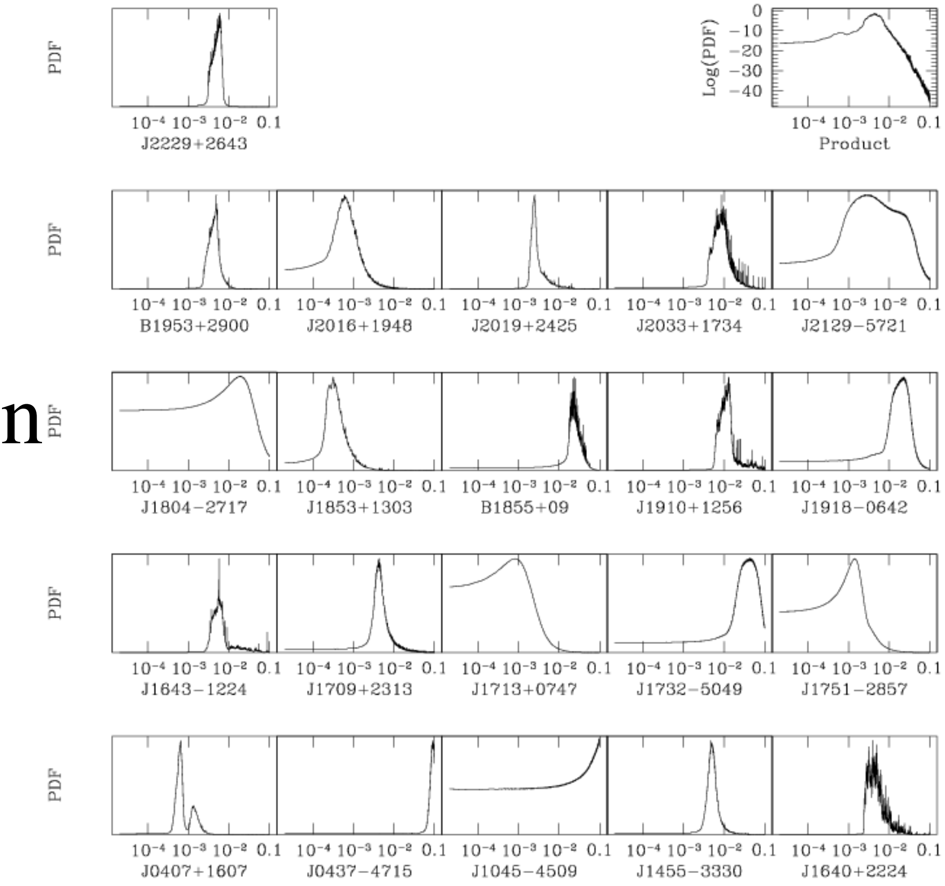
Now, geometric effects measured with pulsar timing ⇒ full orientation of 2 pulsar orbits.



Splaver et al. 2005, ApJ 620, 405

Also, new low-eccentricity pulsars have been discovered: time for an update!

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.



Stairs et al, ApJ, in press.

Final result: $|\Delta_{net}| < 0.0056$ at 95% confidence.

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: $\alpha_1 < 1.4\mathrm{x}10^{-4}$ (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: $\alpha_3 < 4.0\mathrm{x}10^{-20}$ (Stairs et al., ApJ, in press).

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

Constraints on α_3 and ζ_2

α_3 can also be tested by isolated pulsars.

Self-acceleration and Shklovskii effect contribute to observed period derivatives:

$$\dot{P}_{\hat{\alpha}_3} = \frac{P}{c} \hat{\boldsymbol{n}} \cdot \boldsymbol{a}_{self}$$

$$\dot{P}_{pm} = P \mu^2 \frac{d}{c}$$

Young pulsars: $\alpha_3 < 2\text{x}10^{-10}$ (Will 1993, "Theory & Expt. In Grav. Physics," CUP).

Millisecond pulsars: $\alpha_3 < \sim 10^{-15}$ (Bell 1996, ApJ, 462, 287; Bell & Damour 1996, CQG, 13, 3121).

$\alpha_3 + \zeta_2$ also accelerate the CM of a binary system $\Rightarrow$ variable $\dot{\text{P}}$ in eccentric PSR B1913+16: $(\alpha_3 + \zeta_2) < 4\text{x}10^{-5}$ (Will 1992, ApJ, 393, L59).

But geodetic precession and timing noise can mimic this effect.

Dipolar Gravitational Radiation

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

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

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

Test using pulsar—white-dwarf systems in short-period orbits.

PSR B0655+64, 24.7-hour orbit:

$(\alpha_{cp} - \alpha_0)^2 < 2.7\text{x}10^{-4}$ (Arzoumanian 2003, ASP Conf. Ser. 302, 69).

PSR J1012+5307, 14.5-hour orbit:

$(\alpha_{cp} - \alpha_0)^2 < 4\text{x}10^{-4}$ (Lange et al. 2001, MNRAS, 326, 274).

PSR J0751+1807, 6.3-hour orbit:

$(\alpha_{cp} - \alpha_0)^2 < 6\text{x}10^{-5}$ (Nice et al., ApJ, submitted).

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,

Shklovskii proper motion correction...

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

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

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

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

PSR J1713+0747, 67.8-day orbit: $\frac{\dot{G}}{G} < 3\times 10^{-12}\, yr^{-1}$

(Splaver et al. 2005, ApJ, 620, 405, Nice et al., ApJ, submitted).

Cf. LLR: $\frac{\dot{G}}{G} = (4 \pm 9)\times 10^{-13}\, yr^{-1}$ (Williams et al. 2004, PRL, 93, 261101)

Variation of Newton's Constant II

Chandrasekhar mass $M_{CH} \sim \frac{(\hbar c / G)^{3/2}}{m_N^2}$

Most measured pulsar masses cluster around M_{CH}, which appears not to have changed over a Hubble time.

$$\frac{\dot{G}}{G} = (-0.6 \pm 4.2) \times 10^{-12} \, yr^{-1}$$

(Thorsett 1996, PRL, 77, 1432).

But will this test still work once we have measured more pulsar masses, especially of NS in globular clusters?

Strong-Field Gravity

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

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

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

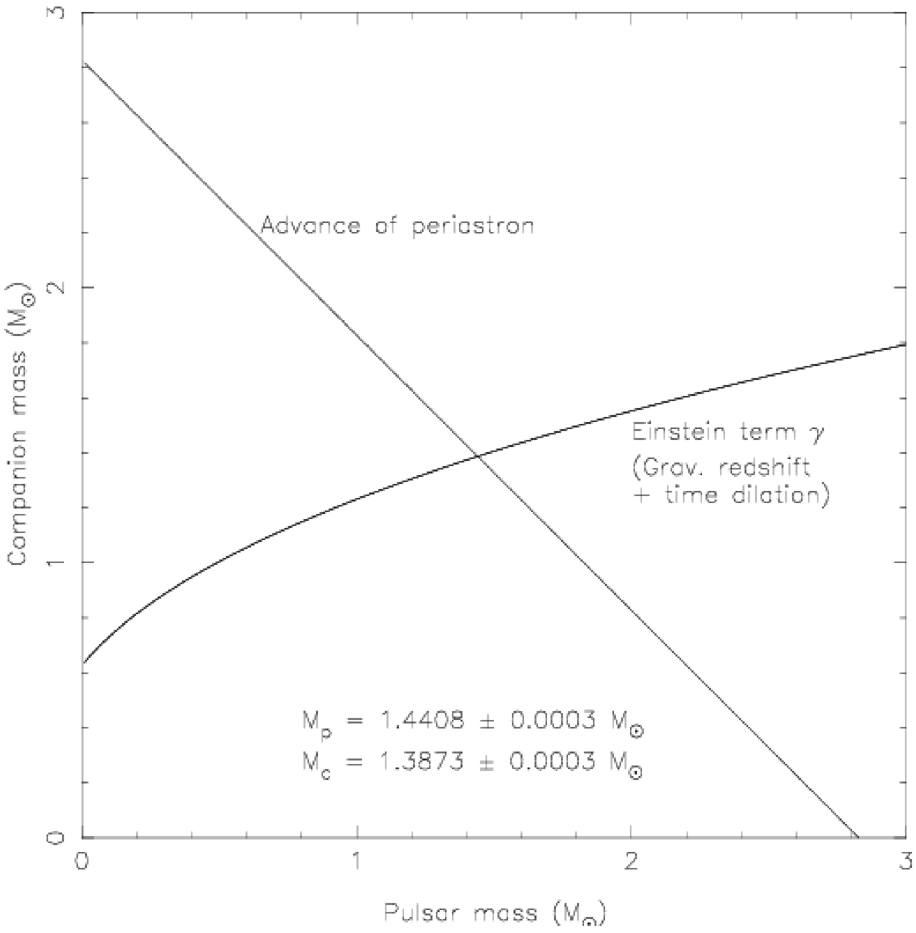
$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_0^{5/3} m_1 m_2 M^{-1/3}$$

$$r = T_0 m_2$$

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

$$(T_0 = 4.925490947\,\mu s)$$

The Original System: PSR B1913+16



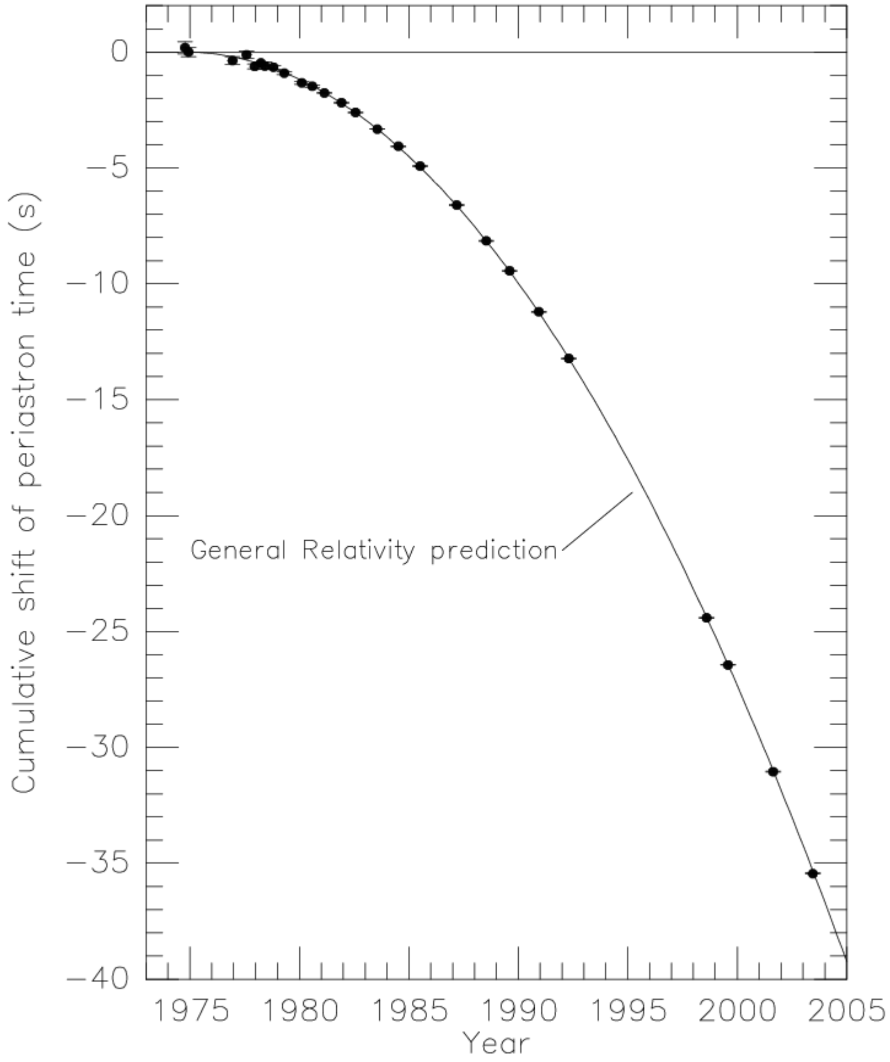
Highly eccentric double-NS system, 8-hour orbit.

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

The $\dot{P}_b$ parameter is in good agreement.

Weisberg & Taylor 2003, ASP Conf. Ser. 302, 93
(Courtesy Joel Weisberg)

Orbital Decay of PSR B1913+16

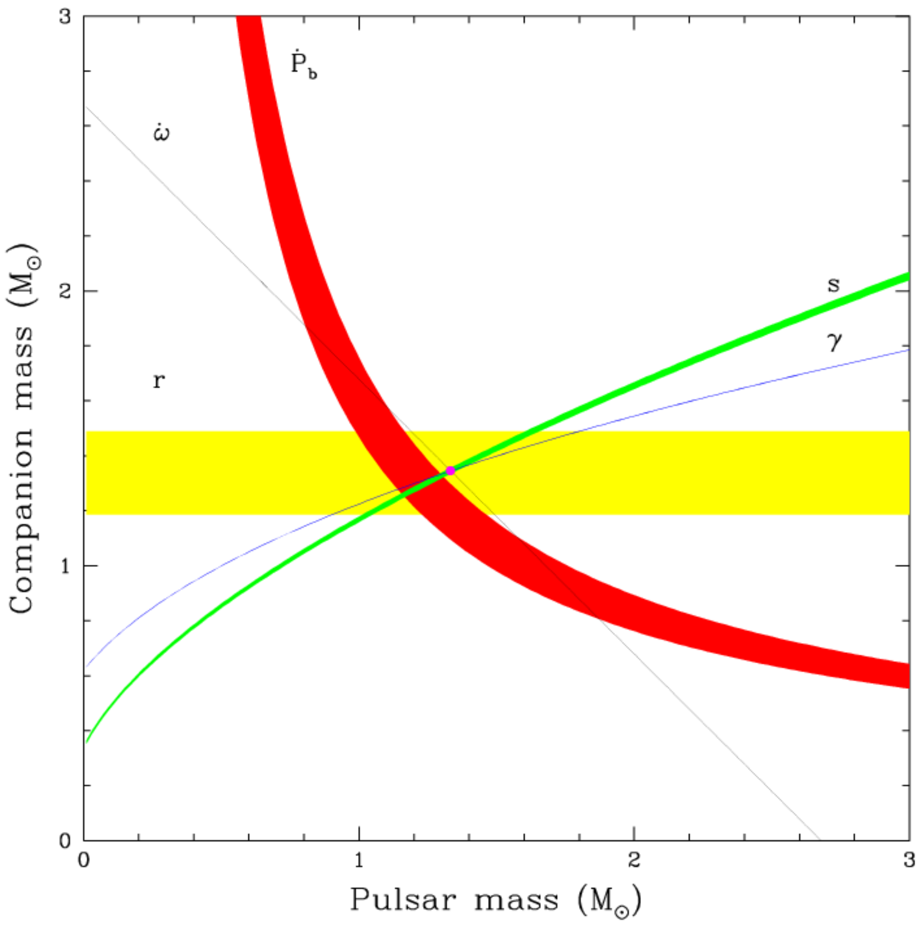


The accumulated shift of periastron passage time, caused by the decay of the orbit.

A good match to the predictions of GR!

Weisberg & Taylor 2005, ASP Conf. Ser. 328, 25.
(Courtesy Joel Weisberg)

PSR B1534+12



After Stairs 2005, ASP Conf. Ser. 328, 3.

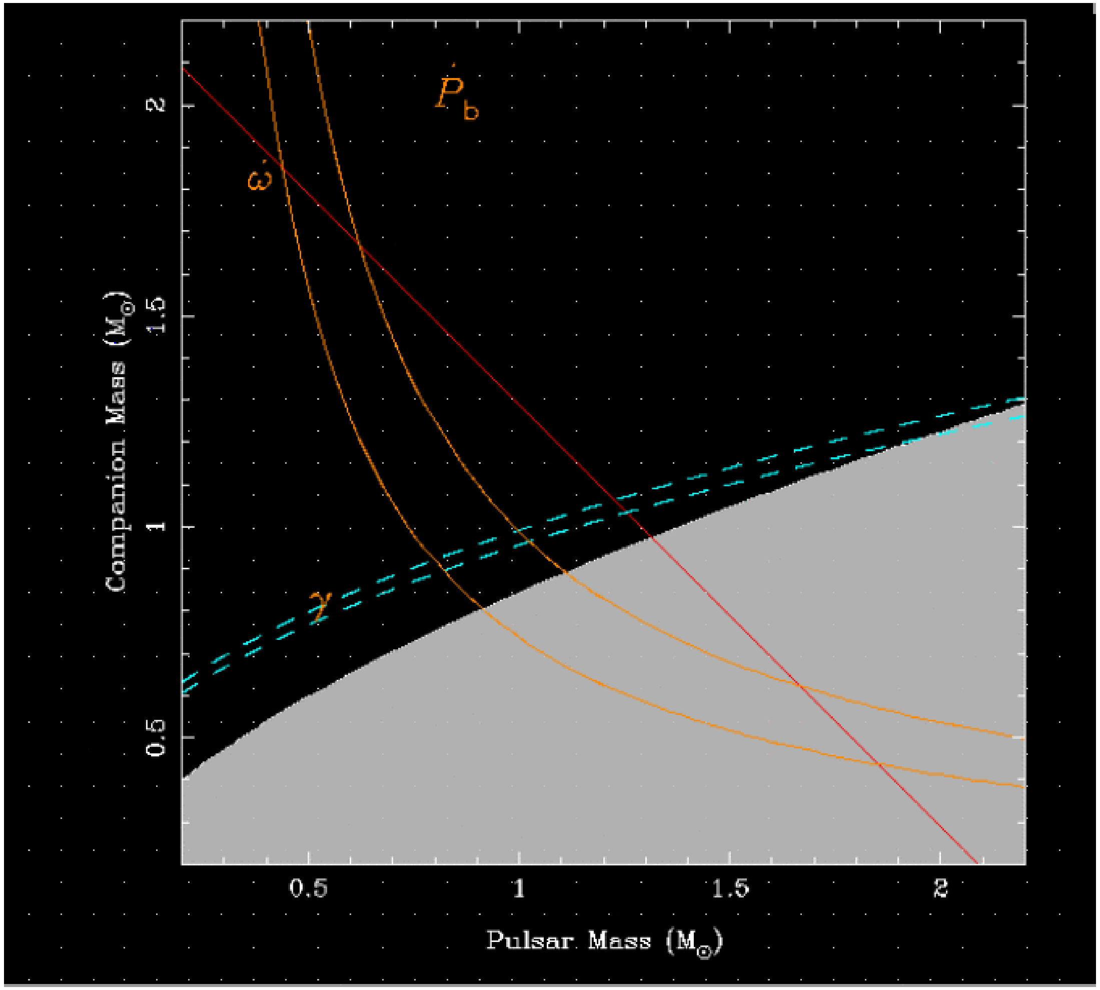
Measure same parameters as for B1913+16, plus Shapiro delay.

The parameters $\dot{\omega}$, s and γ form a complementary test of GR.

The measured $\dot{P}_b$ contains a large Shklovskii v^2/d contribution. If GR is correct, the distance to the pulsar is 1.04 ± 0.04 kpc.

PSR J1141-6545

Young pulsar with a white-dwarf companion, eccentric, 4.45-hour orbit



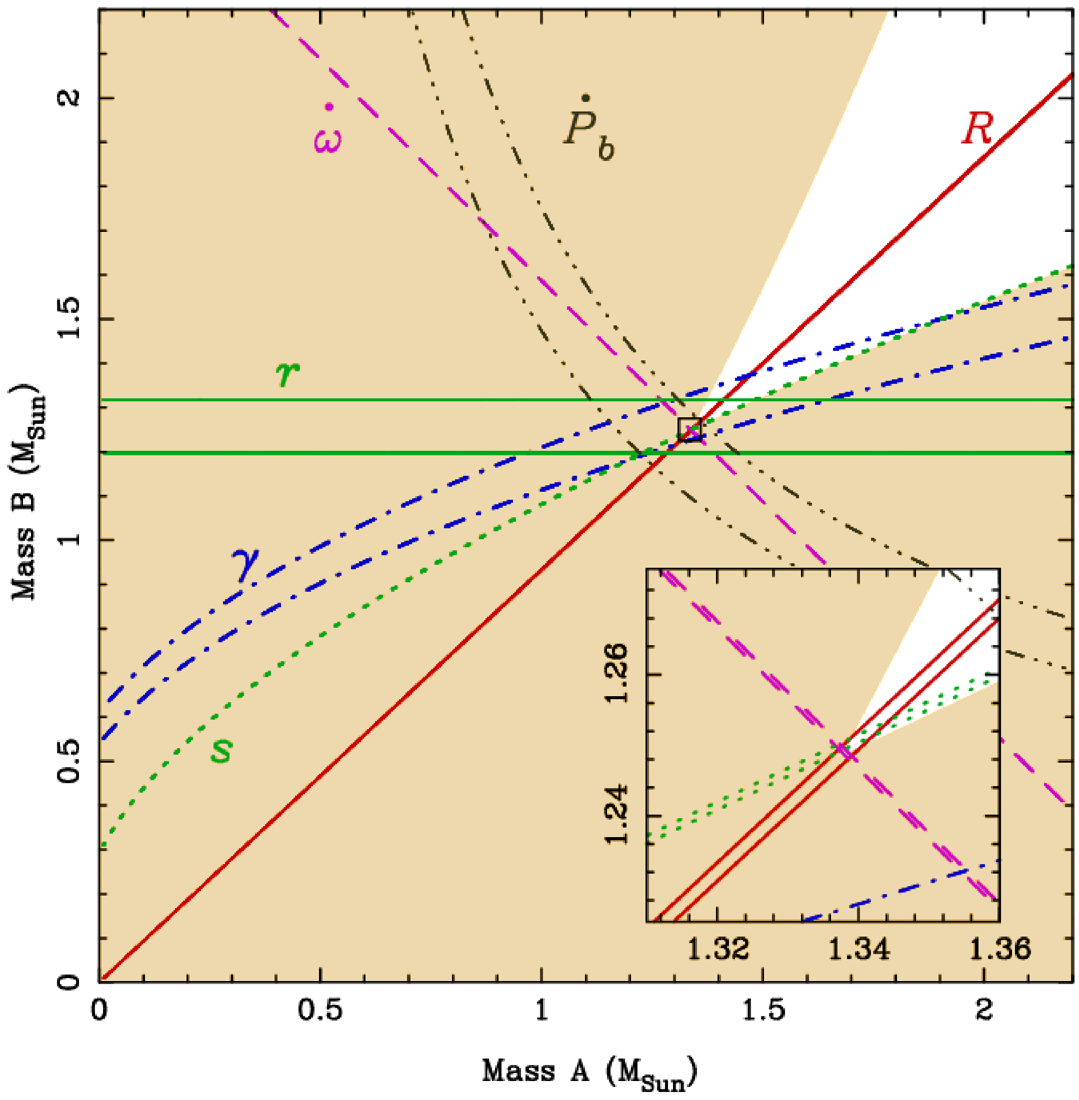
Courtesy Matthew Bailes

$\dot{\omega}$, γ and $\dot{P}_b$ measured through timing.
Sin i measured
by scintillation.

Good agreement with GR, although $\dot{P}_b$ also needs a correction.

$\dot{P}_b$ precision increases as time$^{5/2}$, so this test should improve rapidly.

The Double Pulsar PSR J0737-3039 A and B



Theory-independent constraint available from the mass ratio R of the two pulsars -- a unique constraint!

Most precise test of strong-field GR to date: Predict s from $\dot{\omega}$ and R:

$$\frac{s^{expected}}{s^{observed}} = 1.0002^{+0.0011}_{-0.0006}$$

Kramer et al., in prep.

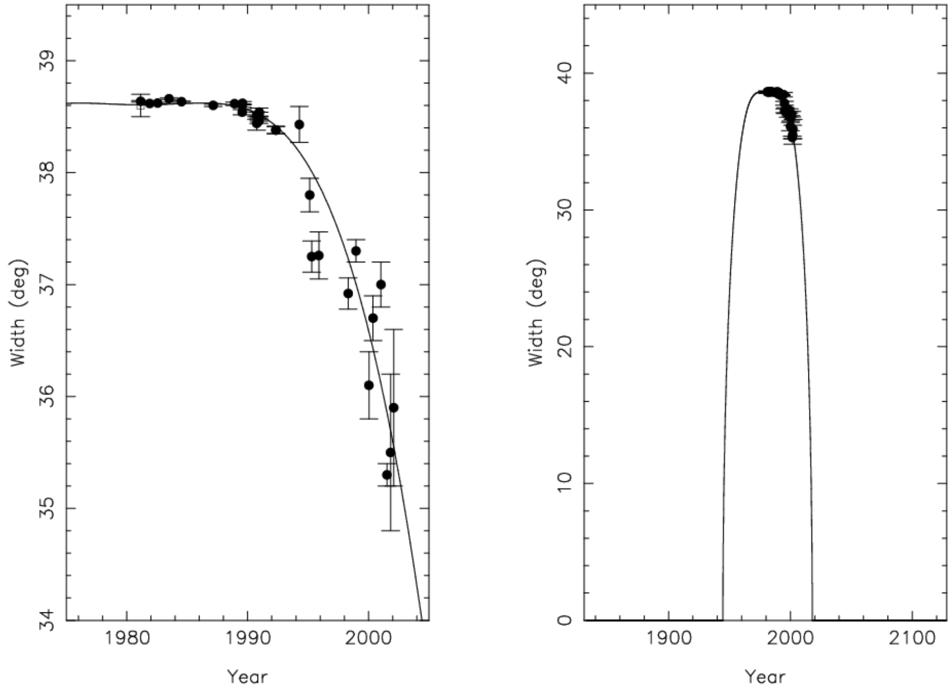
Using Multiple Pulsars

Each pulsar gives unique constraints on alternative theories of gravity. Combining the information can yield stronger tests.

See the talk by Gilles Esposito-Farese this afternoon.

Geodetic Precession

Pulsar's spin axis is misaligned with the total angular momentum, and precesses around it.
Precession period: 300 years for B1913+16, 700 years for B1534+12, 265 years for J1141-6545 and only ~70 years for the J0737-3039 pulsars.



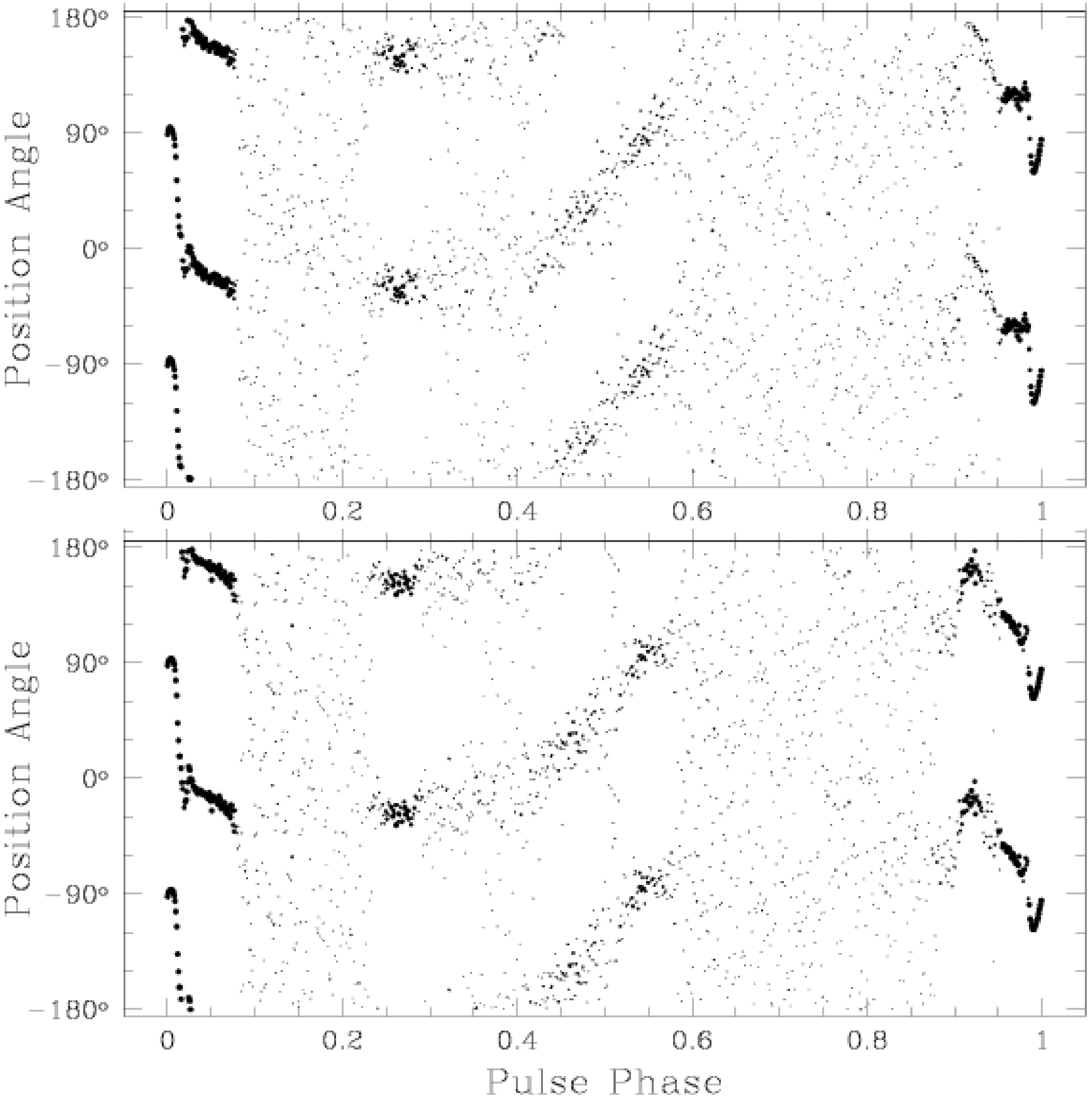
Courtesy Michael Kramer

PSR B1913+16:

Pulse peak ratio changes, and peaks draw closer together.

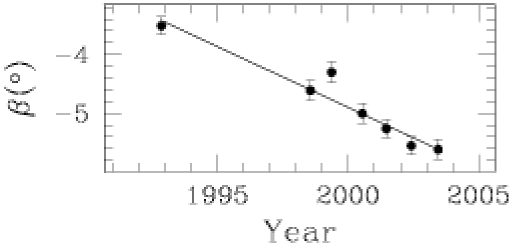
The pulsar will disappear in about 2025!

Geodetic Precession in PSR B1534+12



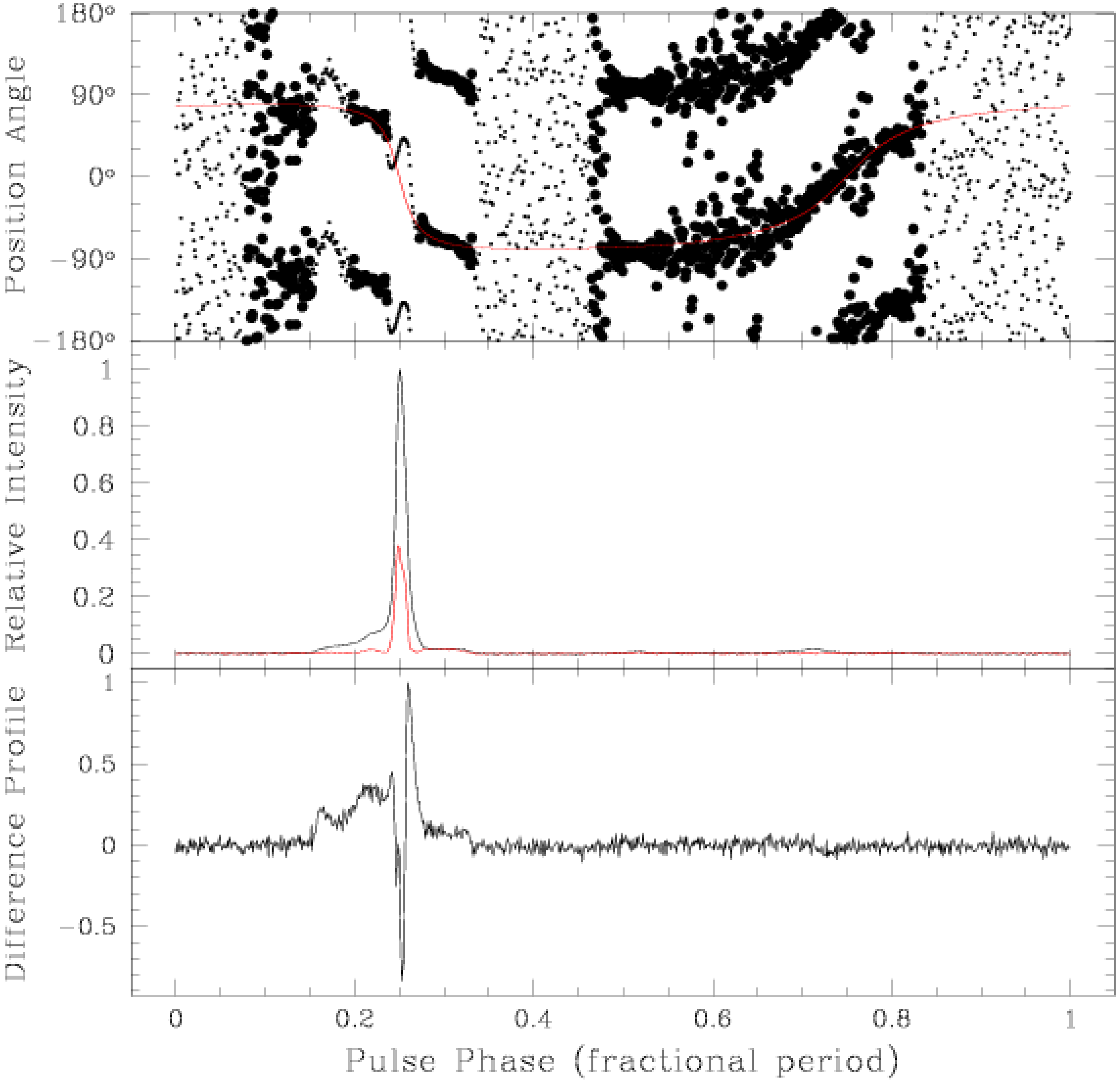
MJD 51018 (top) and 52804 (bottom)

Fit Rotating Vector Model
(Radhakrishnan & Cooke 1969,
Astrophys. Lett 3, 225):
α (magnetic inclination) 102.8°
β (impact parameter) ~ -4.5°
but β is changing!



$d\beta/dt = -0.21(3)$ °/yr
(Stairs, Thorsett & Arzoumanian 2004, PRL 93, 141101)

Profile changes in B1534+12



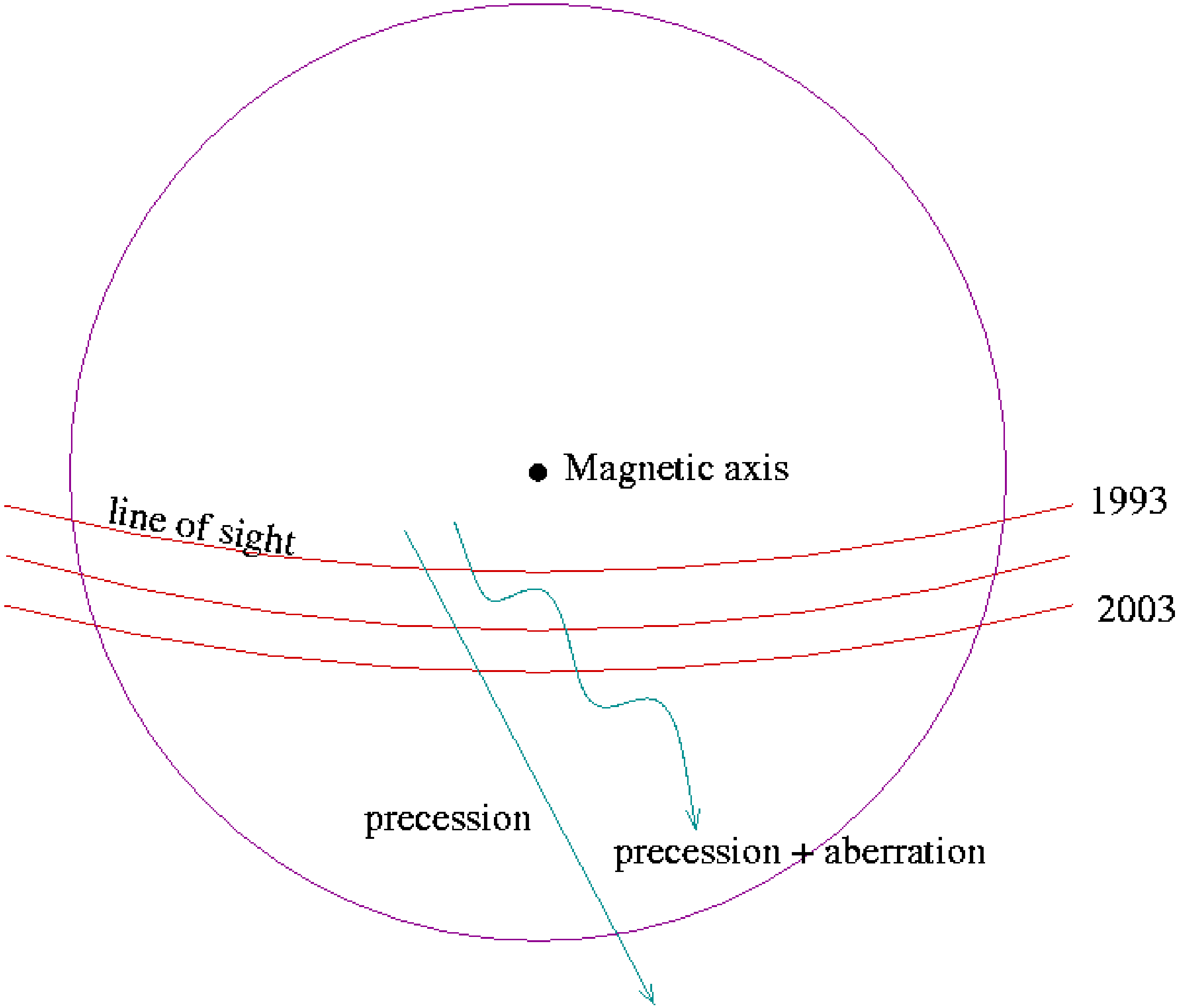
Stairs, Thorsett & Arzoumanian 2004, PRL 93, 141101

Mark IV data: 5 campaigns with good orbital coverage, plus long-term data. Look at 430 MHz data here. Model each profile as a linear combination of the reference profile and the difference profile.

Long-term shape trend is very linear!

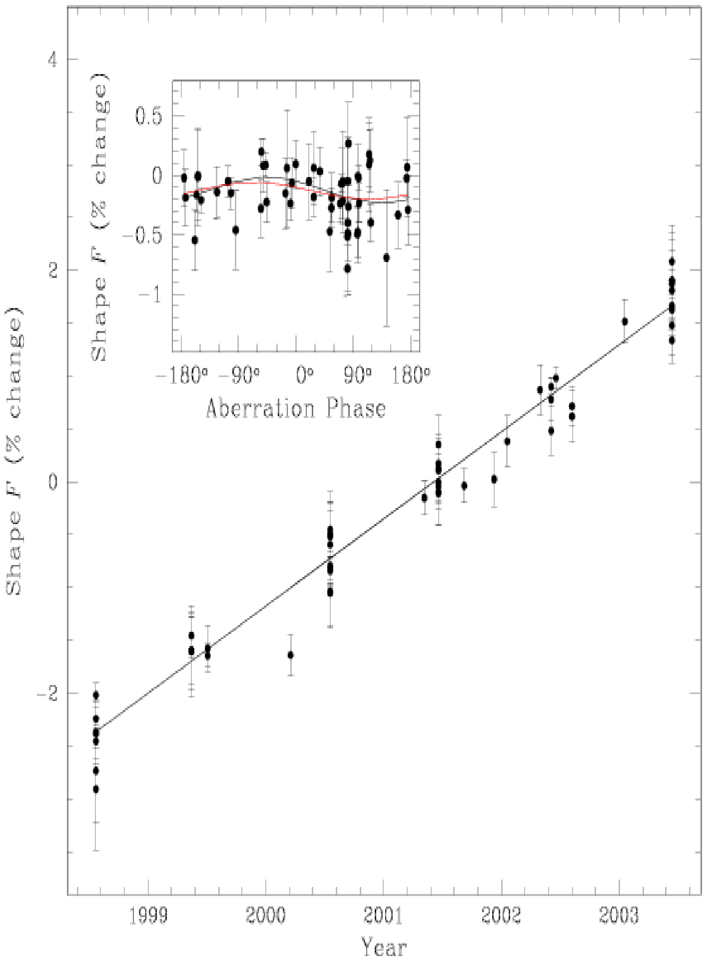
In addition, look at orbital behaviour.....

What part of the pulsar beam do we see?



(NOT to scale!)

Orbital aberration in B1534+12



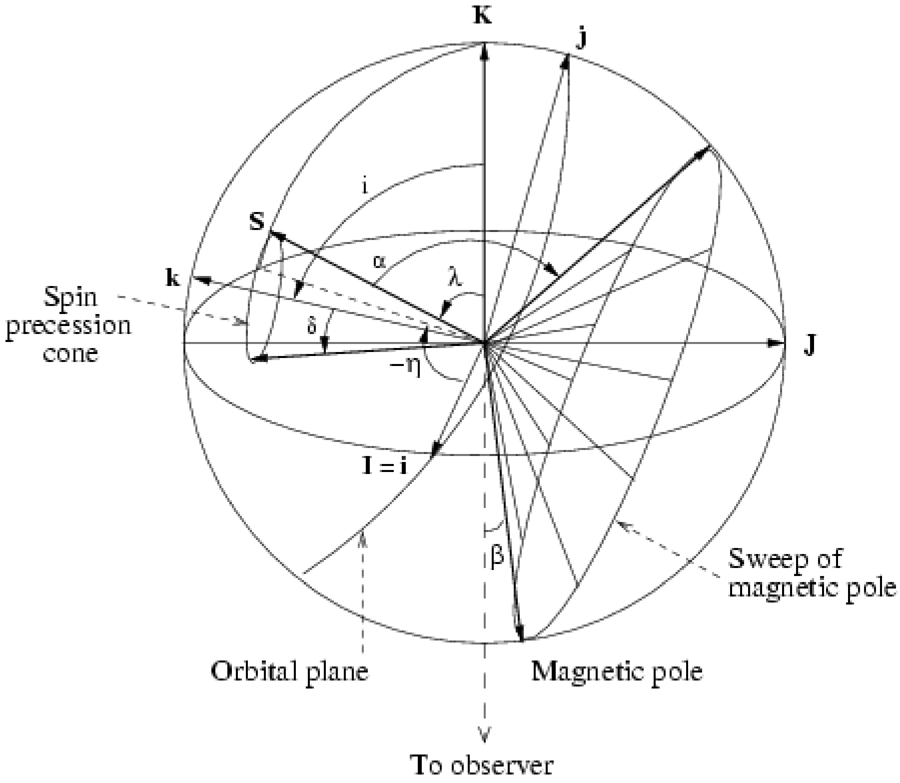
Stairs, Thorsett & Arzoumanian 2004
PRL 93, 141101

Campaign data binned by orbital phase, plus strongest long-term timing scans.

Aberration profile changes are small fraction of long-term changes, with periodicity in True Anomaly. Depend on Ω_1^{spin} (precession rate) and geometry. Simultaneous fit to MJD and orbital phase.

Results:
spin orientation angle η: +/-257° +/- 10°
cf $d\beta/dt$ in GR predicts +/-245.0° +/- 3.8°
and... beam-model-free measurement of precession rate:
$\Omega_1^{spin} = (0.44^{+0.48}_{-0.16})$ °/year (68% confidence)
cf GR prediction: 0.51 °/year

Full geometry of B1534+12



Stairs, Thorsett & Arzoumanian 2004,
PRL 93. 141101

Use λ from RVM fit and assume δ more likely to be near 20° (Bailes 1988, A&A 202, 109) to
break degeneracies in η and δ
=> know full geometry!

$i = 77.2^{\circ}$
$\eta = 245^{\circ}$
$\delta = 25.0^{\circ}$
$\phi_{SO} = 278^{\circ}$

And we can also confirm that δ is 25.0° rather than 155.0°.

Aside: recent history of B1534+12

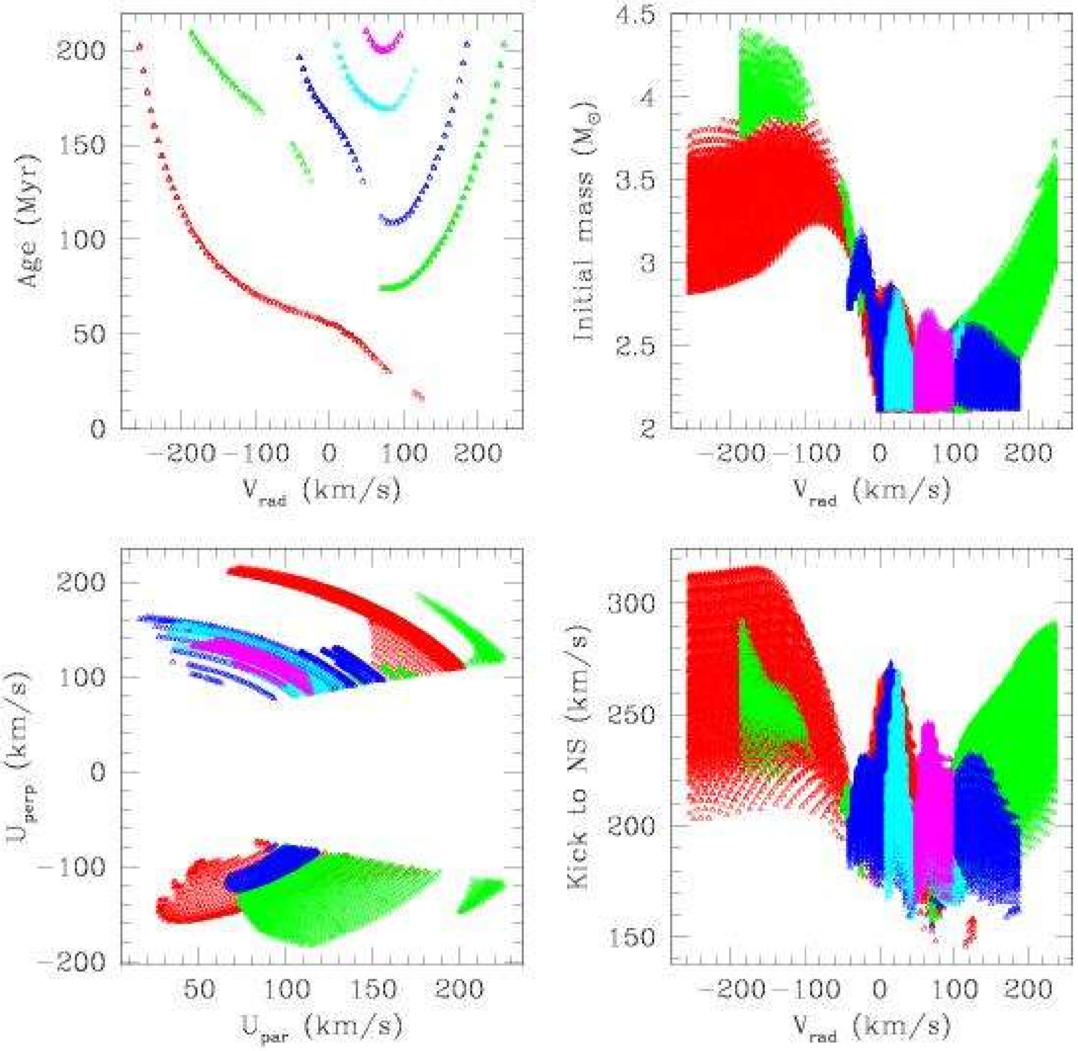
B1534+12 has survived two supernova explosions!

The second explosion can be constrained by the full set of observations of the system.

Would like to know:

- The pre-SN companion mass
- The pre-SN separation
- The magnitude and direction of the "kick" to the newly formed NS

Full kick constraints



Thorsett, Dewey & Stairs 2005, ApJ 619, 1036

For range of (unmeasurable) radial velocities, trace back motion through Galaxy to birth sites in the Galactic Plane.

From scintillation (Bogdanov et al 2002 ApJ, 581, 495) and velocity measurements, infer orientation of orbit relative to velocity after the supernova explosion (uses formalism developed by V. Kalogera in several papers).

For each birth site, one pre-SN mass/separation is possible.
=> very tight constraints
on the kick and companion type

B1534+12 before the second SN

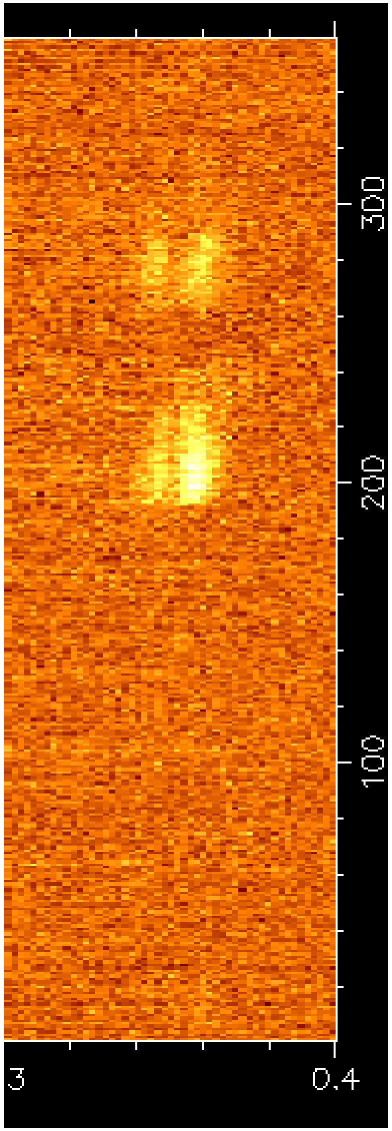
Pre-SN companion mass was almost certainly less than 4 solar masses. Orbital separation (constrained only by current eccentricity) was small.

Best interpretation: companion was a low-mass He star overflowing its Roche Lobe. (Note similar conclusions for 0737-3039 progenitor (Willems, Kalogera & Henninger 2004, ApJ 616, 414).)

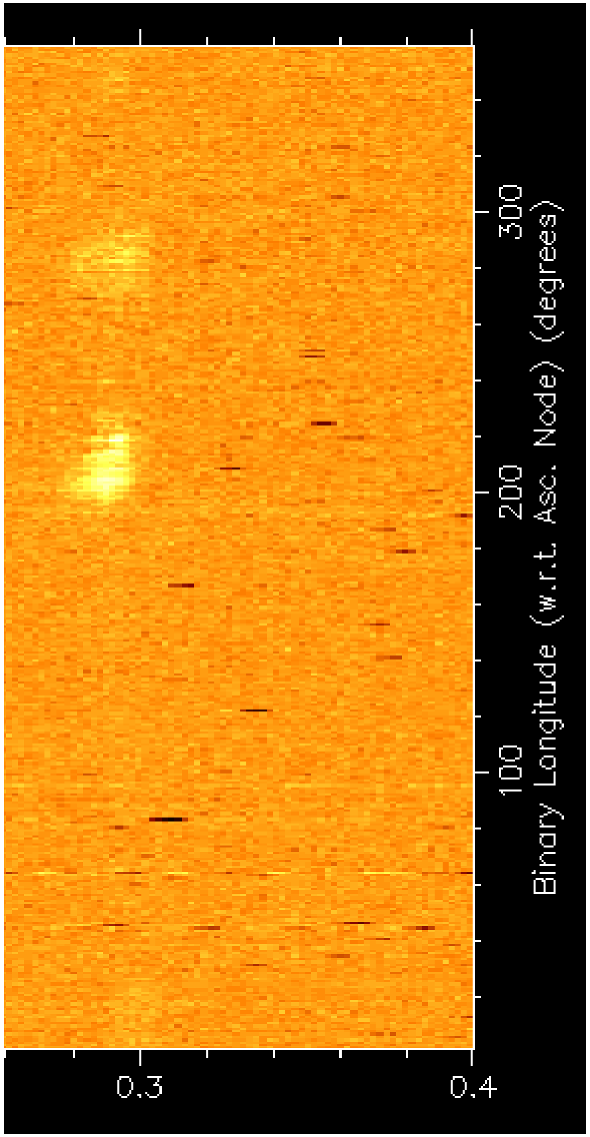
Kick: 1-σ range is 230±60 km/s, oriented between 20°—40° (or 140°—160°) of the pre-SN AM axis, and mostly retrograde to the companion's pre-SN motion.

These are the tightest constraints on a progenitor mass and kick -- for now, at least....

Evidence for geodetic precession in the double pulsar?



May 2003



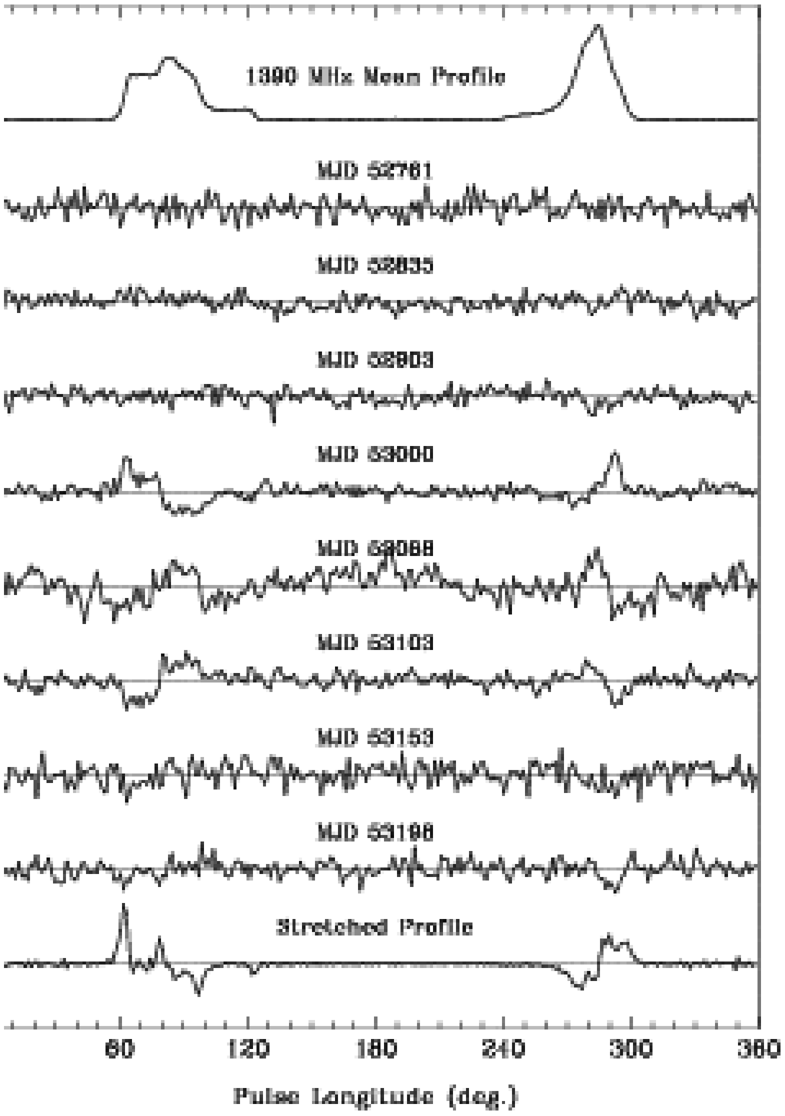
June 2004

Profile shape and visibility changes in the young B pulsar.

Geodetic precession plus magnetospheric interactions with A's wind.

Burgay et al. 2005 ApJ, 624, L113.

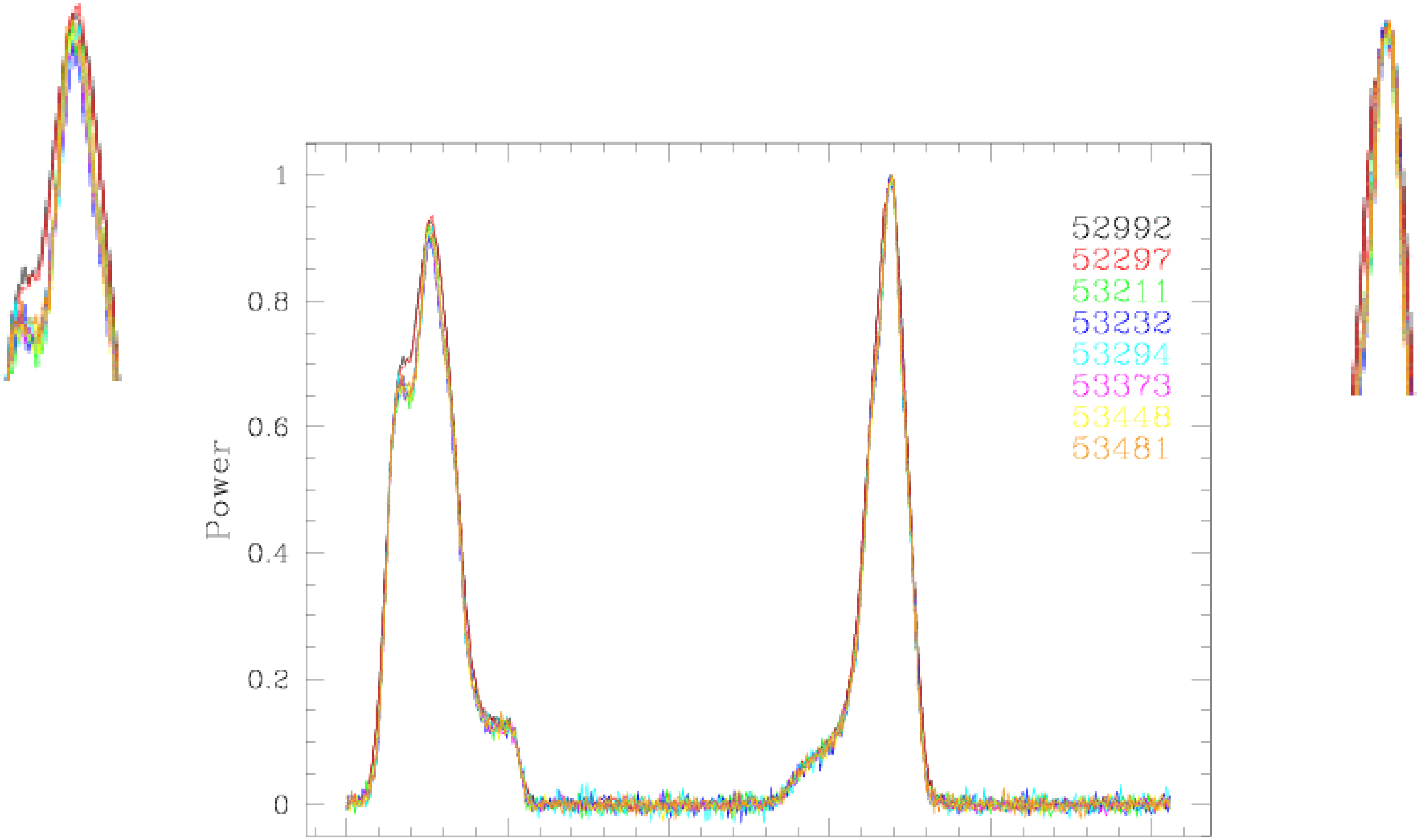
What about the A pulsar?



Until recently,
A's profile appeared
not to be changing!

Manchester et al 2005, ApJ, 621, L49.

Geodetic precession in 0737A: GBT BCPM data at 820 MHz



Apparently a "patchy" beam and maybe nonlinear changes: it will be hard to interpret the beam shape, precession phase, any detected aberration effects...

Future Prospects

Long-term timing of pulsar – white dwarf systems

⇒ better limits on $\dot{G}/G$ and dipolar gravitational radiation

⇒ better limits on gravity-wave background (Don Backer's talk)

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 in relativistic binaries

⇒ better tests of precession rates, geometry determinations.

Large-scale surveys

⇒ more systems of all types... and maybe some new "holy grails" such as a pulsar—black hole system... stay tuned!