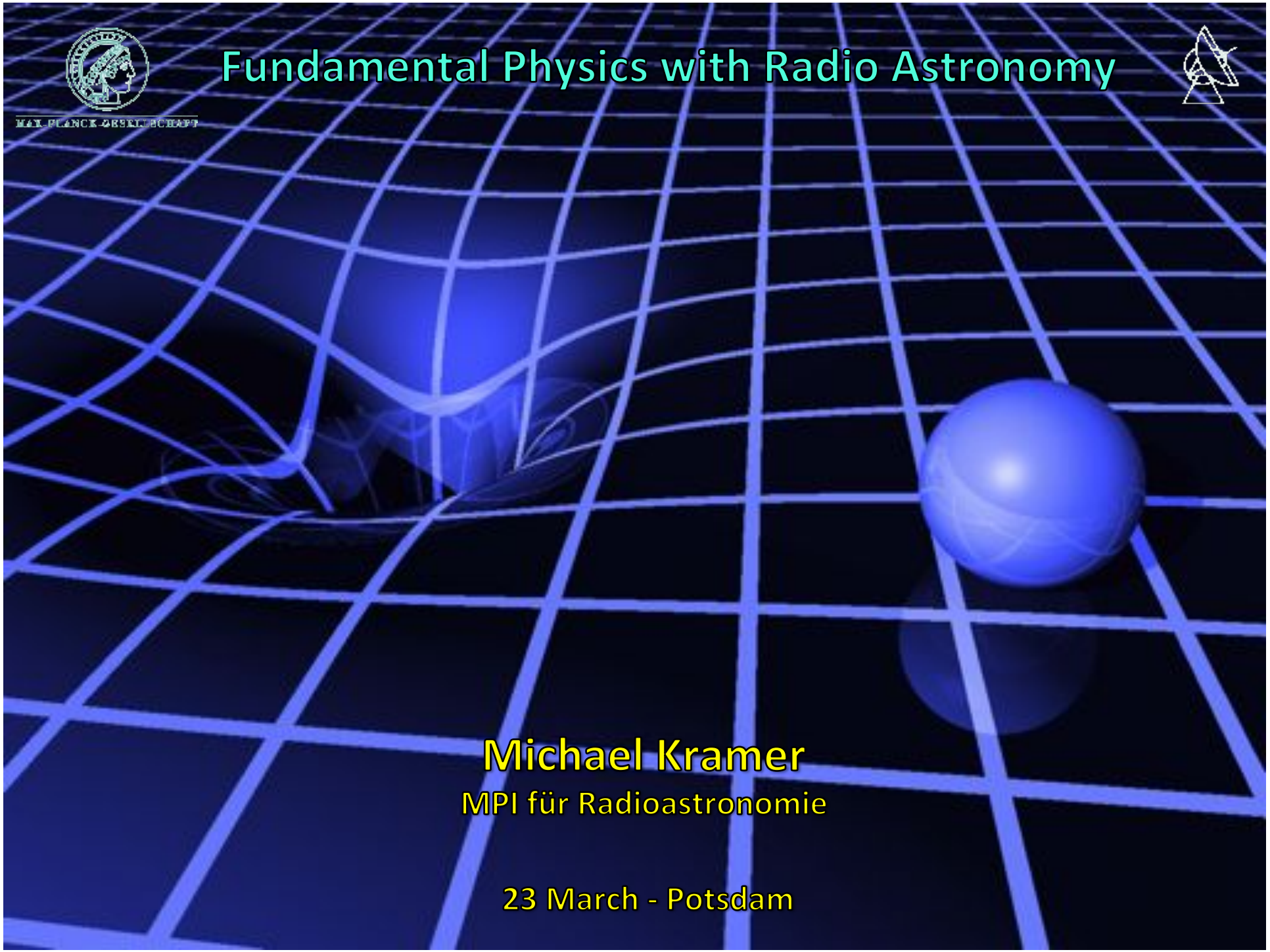
Fundamental Physics with Radio Astronomy



Michael Kramer

MPI für Radioastronomie

23 March - Potsdam

Fundamental physics

= fundamental laws which describe the physical world, its properties and its evolution – from the smallest to the largest scales

Are the physical laws derived here on Earth the same as in the rest of the Universe?

For instance, does the astronaut fall in the same way everywhere in the universe?

Even near exotic matter in strong gravitational fields?

Fundamental physics and astronomy

A lot of physics is obviously known, but some fundamental questions remain,

e.g. Is general relativity the last word in our understanding of gravity ?
Do new fundamental forces exist and/or what is Dark Energy ?
Who is wrong – Einstein or the Standard Model ?
What is the equation of state of super dense matter?

A lot of these questions involve large scales and we need to go to the extremes of our known parameter space – into the Cosmos!

Radio astronomy is ideal as

- we observe extreme and energetic processes and objects
- get lots of photons that are easy to copy and multiply
- can probe the complete Universe, undisturbed from dust etc.
- can get polarization (magn. fields!) and dynamic information (pulses!)

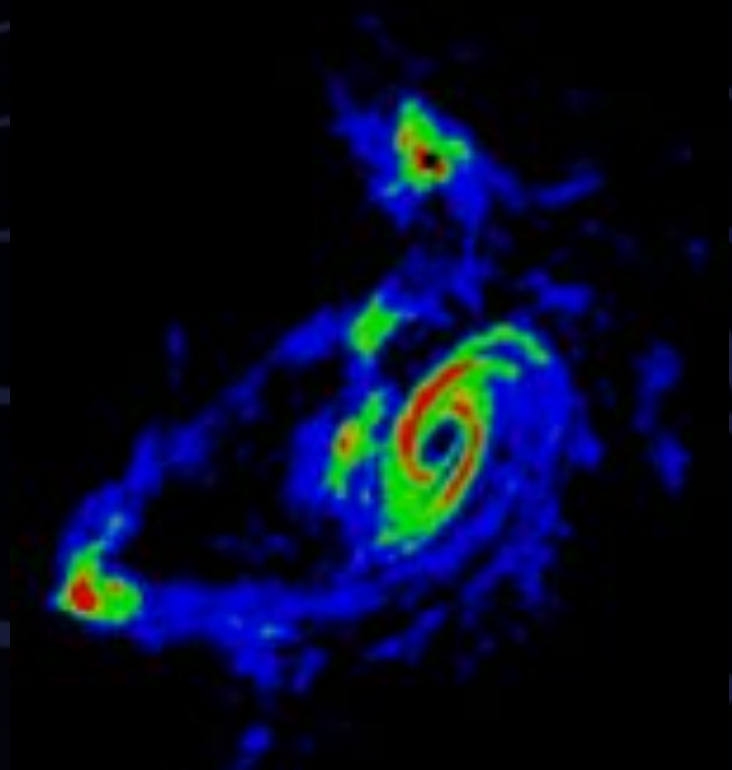
Undisturbed and different view…

Radio waves penetrate dust: e.g. view into inner Galaxy
Sharpest images in all astronomy

Gives vastly different view of universe, e.g.

A Universe of stars

A Universe of hydrogen gas



Fundamental physics & radio astronomy

Some examples:

Astrometry (Quasars, Masers, Pulsars)

➔ Reference frame ties, cosmology, GR tests

Young & binary pulsars

➔ Equation of state, core collapse physics, equation-of-state

Millisecond & binary pulsars

➔ Gravitational physics, Equivalence principles, Lorentz invariance fundamental constants, gravitational wave physics, dark energy

Spectroscopy (Quasar absorption, Masers)

➔ Fundamental constants, distance scale, cosmology

Surveys (HI, Continuum, CMB)

➔ Dark energy, dark matter, lensing, cosmology

This talk

- Introduction
- Gravity – tests of general relativity
- Tests of alternative theories

I won't have time to speak about:*

- Detecting gravitational waves with pulsars
- Studying black hole properties with pulsars
- What enormous difference the SKA would make…

*But I do have some slides prepared…

Understanding Gravity

- General relativity conceptually different than description of other forces
- But GR has been tested precisely, e.g. in solar system
- Classical tests:
  - Mercury perihelion advance
  - Light-deflection at Sun
  - Gravitational redshift
- Modern tests in solar system (see PPN formalism by Will & Nordvedt), e.g.
  - Lunar Laser Ranging (LLR)
  - Radar reflection at planets, Cassini spacecraft signal
  - LAGEOS & Gravity Probe B

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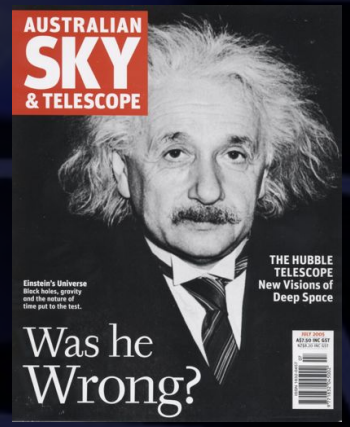

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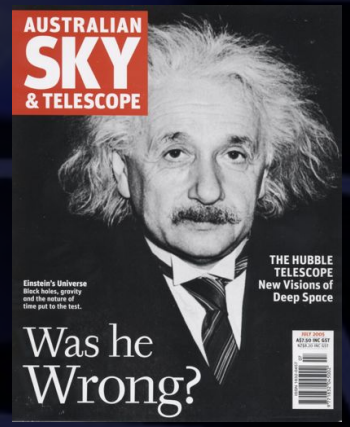
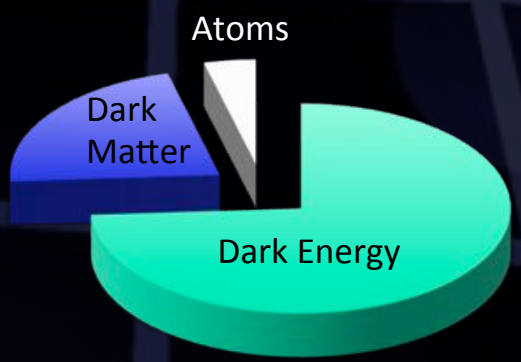


Accept it, or may there be a problem??

- Precision Cosmology: Inflation?
  Dark Matter?
  Dark Energy?

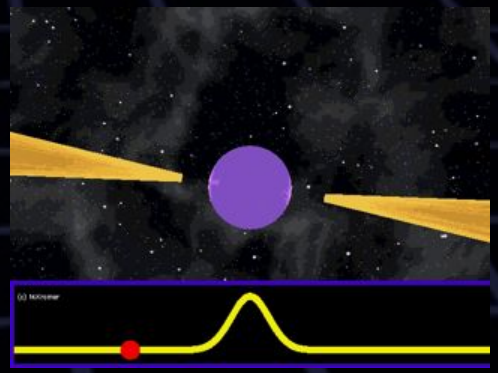


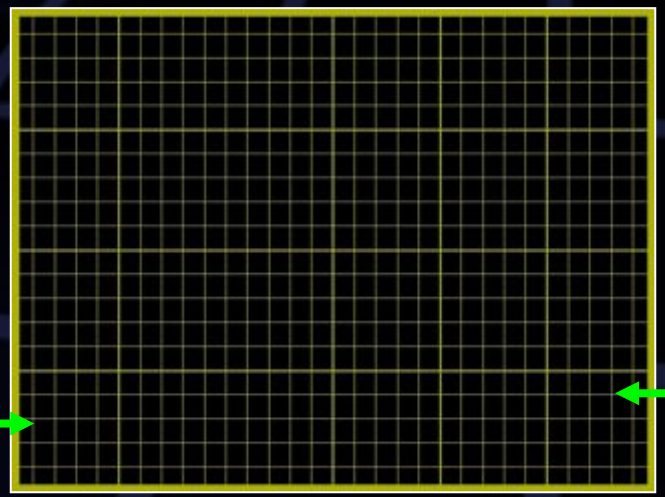
We need simple and clean experiments in strong gravitational fields!

A simple and clean experiment: Pulsar Timing

Pulsars are…

- …cosmic lighthouses
- …almost Black Holes: ~1.4 $M_\odot$ within 20km
- …objects of extreme matter : 10x nuclear
- …massive flywheels, hence very stable clocks
- …pulsar timing measures arrival time (TOA):





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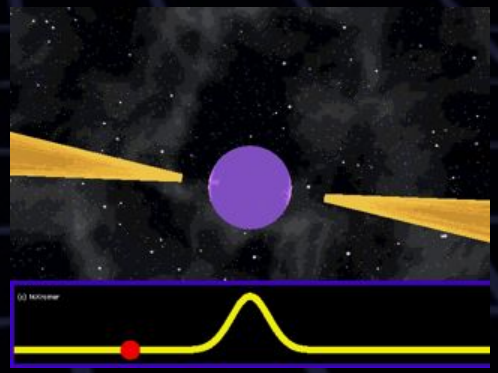

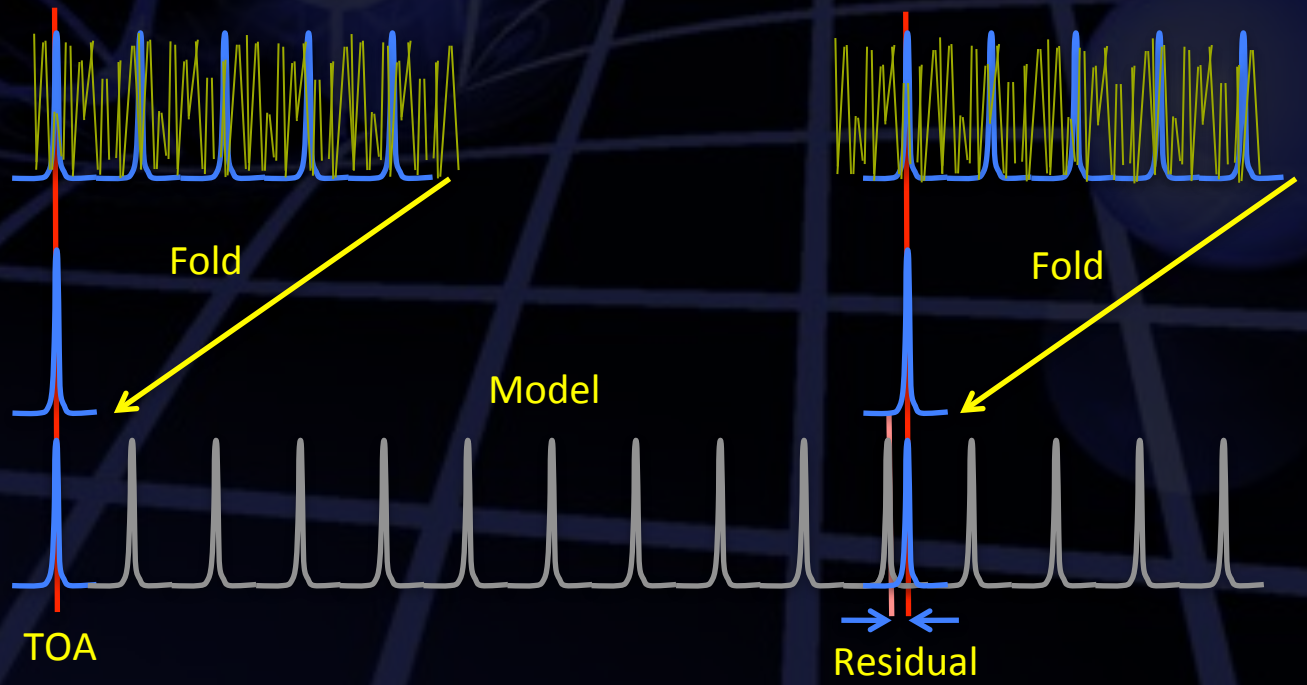

Coherent timing solution about 1,000,000 more precise than Doppler method!

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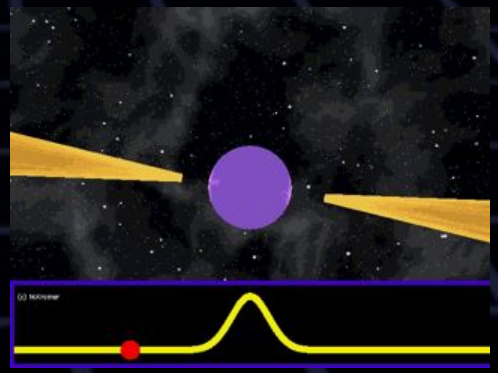


PSR J1012+5307: 15 years of observations with EPTA

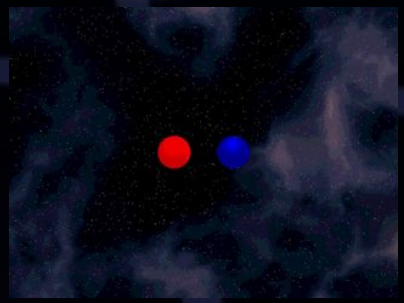
P = 0.005255749014115410 ± 0.000000000000000015 s

[*Lazaridis et al. 2009*]

→ 100 billion rotations since discovery & not lost a single count!

Measure how a pulsar falls as a test mass in the gravitational potential of a companion (and in the Galaxy)

- with very high pecision!



We can do precision measurements! Best of…

Masses:

- Masses of neutron stars: m1 = 1.4398(2) $M_\odot$ and m2 = 1.3886(2) $M_\odot$ (Weisberg et al. 2010)
- Mass of WD companions:
  - Shapiro: 0.204(2) $M_\odot$ (Jacoby et al. 2005)
  - Optical: 0.181(7) $M_\odot$ (Antoniadis et al. subm.)
- Mass of millisecond pulsar: 1.67(2) $M_\odot$ (Freire et al. 2010)
- Main sequence star companion: 1.029(8) $M_\odot$ (Freire et al. 2010)

Spin parameters:

- Period: 5.757451924362137(2) ms (Verbiest et al. 2008) = 2 atto seconds uncertainty!

Orbital parameters:

- Period: 0.102251562479(8) day (Kramer et al. in prep.)
- Eccentricity: 3.5 (1.1) × 10^{-7} (Freire et al. subm.)

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2008)
- Proper motion: 140.915(1) mas/yr (Verbiest e t al. 2008)

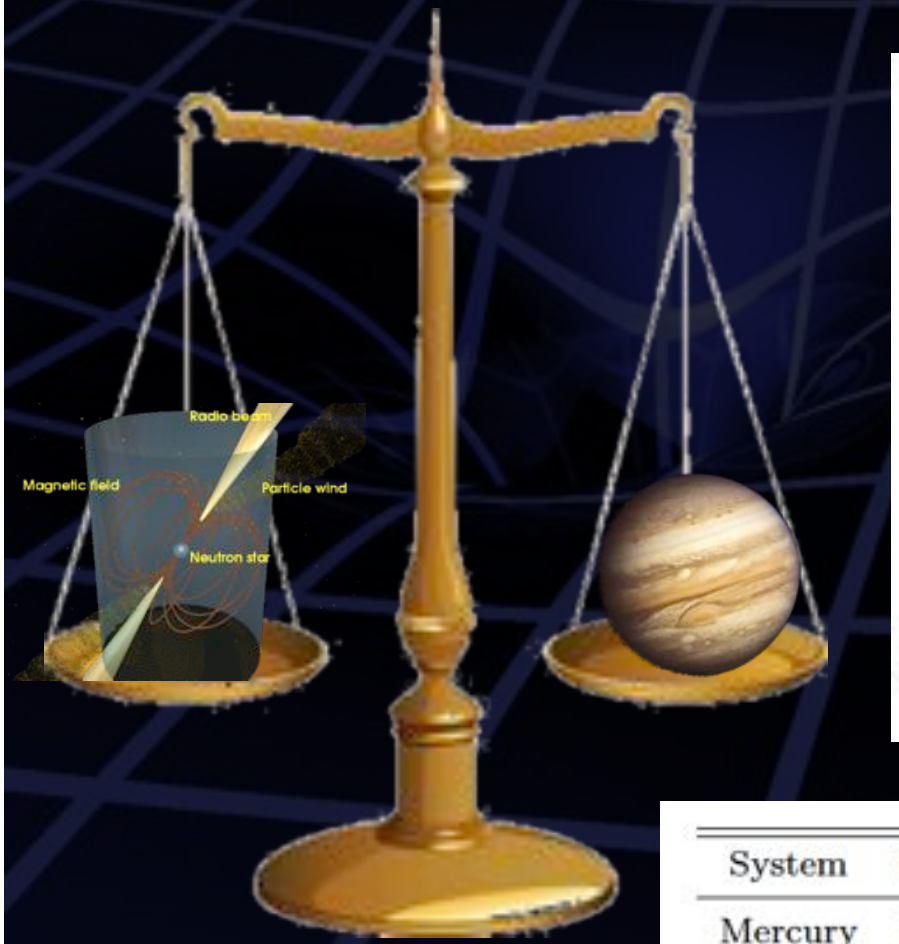
GR tests:

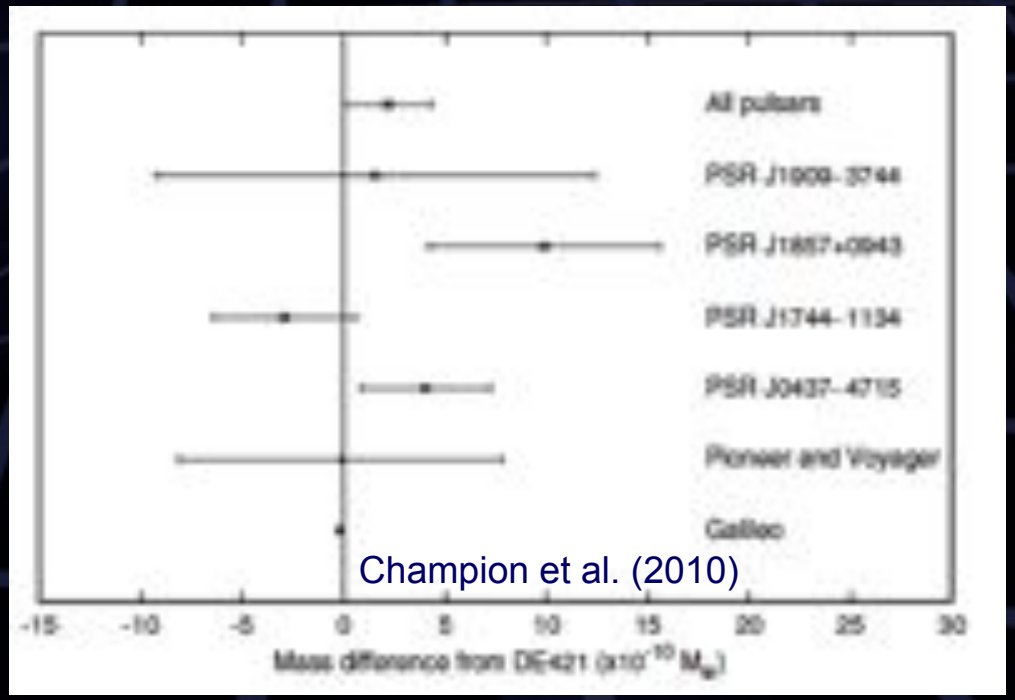
- Periastron advance: 4.226598(5) deg/yr (Weisberg et al. 2010)
- Shrinkage due to GW emission: 7.152±0.008 mm/day (Kramer et al. in prep)
- GR validity (obs/exp): 1.0000(5) (Kramer et al. in prep.)

In the Future:

- Measure mass of SGR A* to 10^{-6}!
- Measure spin of SGR A* to precision of 10^{-4} to 10^{-3}: Cosmic Censorship!
- Measure quadrupole moment to 10^{-3} to 10^{-2}: No hair! (Liu et al. 2012)

We even measure the masses of our planets…





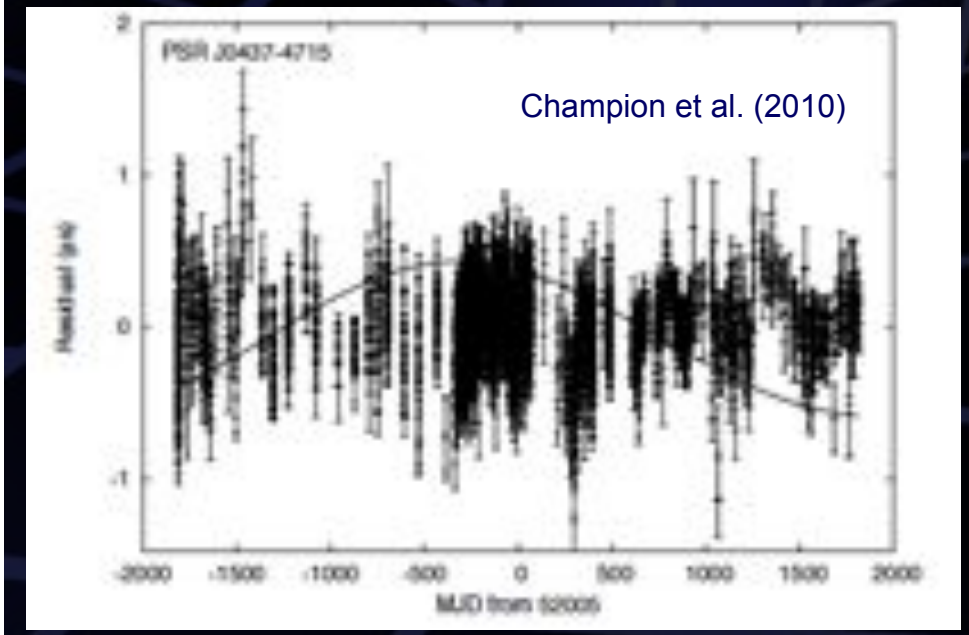
System	Best-Known Mass ($M_\odot$)	Ref.	This Work ($M_\odot$)	δ_j/σ_j
Mercury	$1.66013(7)\times10^{-7}$	1	$1.6584(17)\times10^{-7}$	1.02
Venus	$2.44783824(4)\times10^{-6}$	2	$2.44783(17)\times10^{-6}$	0.05
Mars	$3.2271560(2)\times10^{-7}$	3	$3.226(2)\times10^{-7}$	0.58
Jupiter	$9.54791898(16)\times10^{-4}$	4	$9.547921(2)\times10^{-4}$	1.01
Saturn	$2.85885670(8)\times10^{-4}$	5	$2.858872(8)\times10^{-4}$	1.91

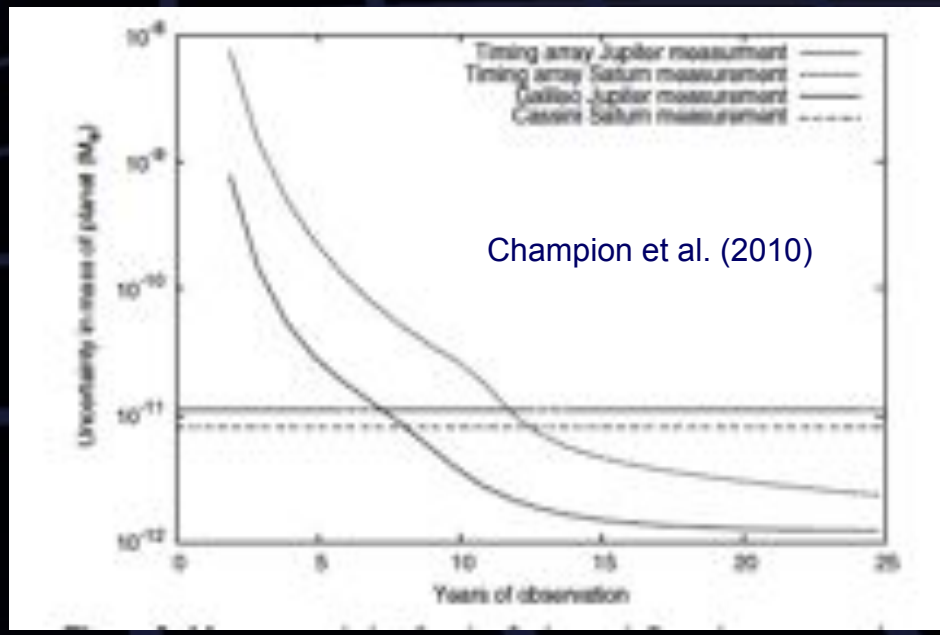
Putting the planets on the pulsar scale…

- incorrect planet masses have severe impact on our timing residuals

  = measured – expected pulse times of arrival

- in the future, a PTA should measure planet masses very precisely

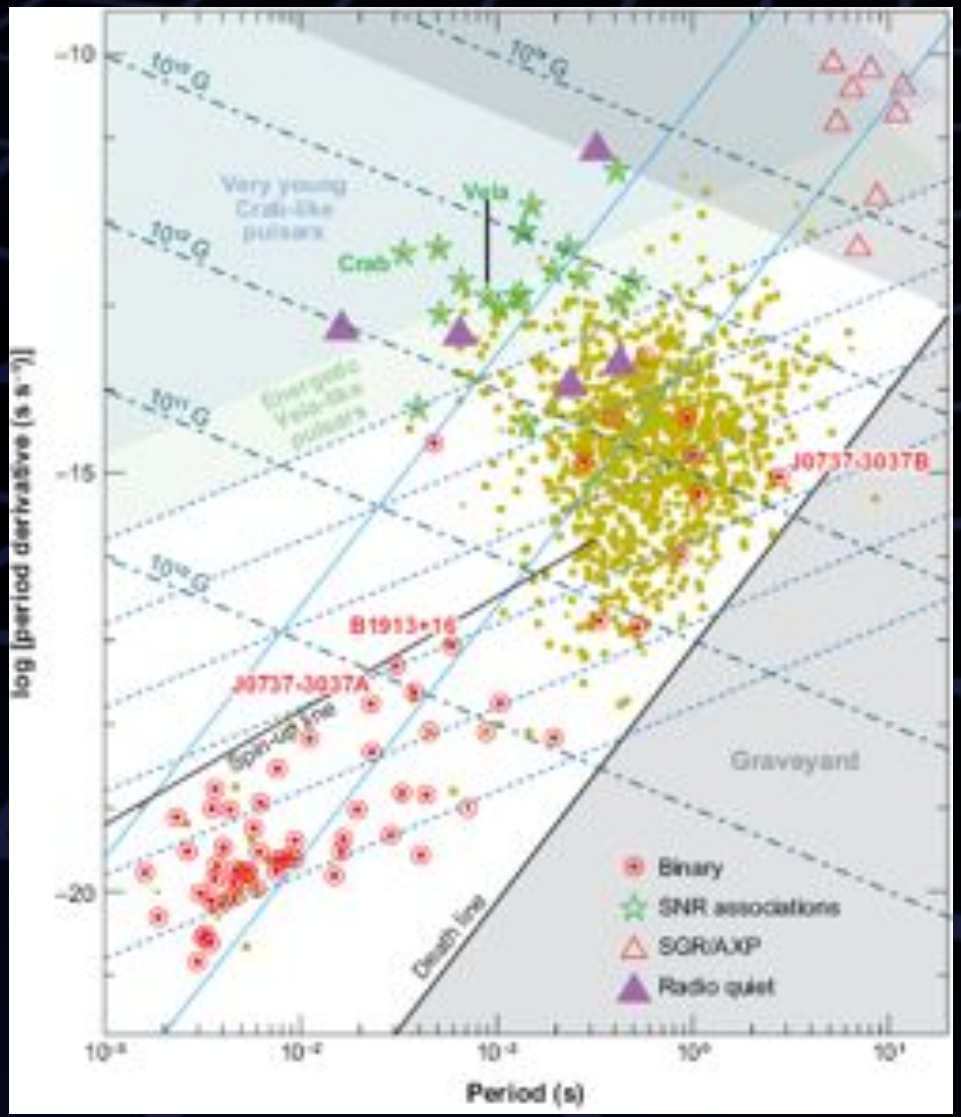




Effect of a Jupiter mass modified by $5 \times 10^{-10}\ M_{\odot}$

PTA with biweekly observations of 20 psrs

Best labs: Pulsars with companions



~ 2000 radio pulsars

1.40 ms (PSR J1748-2446ad)
8.50 s (PSR J2144-3933)

~ 140 binary pulsars

Orbital period range

95 min (PSR J0024-7204R)
5.3 yr (PSR J1638-4725)

Companions

MSS, WD, NS, planets

and 1 Double Pulsar!

PSR J0737-3039A/B

22.7 ms / 2.77 s
P_{orb} = 147 min
e = 0.088

Gravitational physics tested by pulsars

General Relativistic effects observed and/or precisely measured:

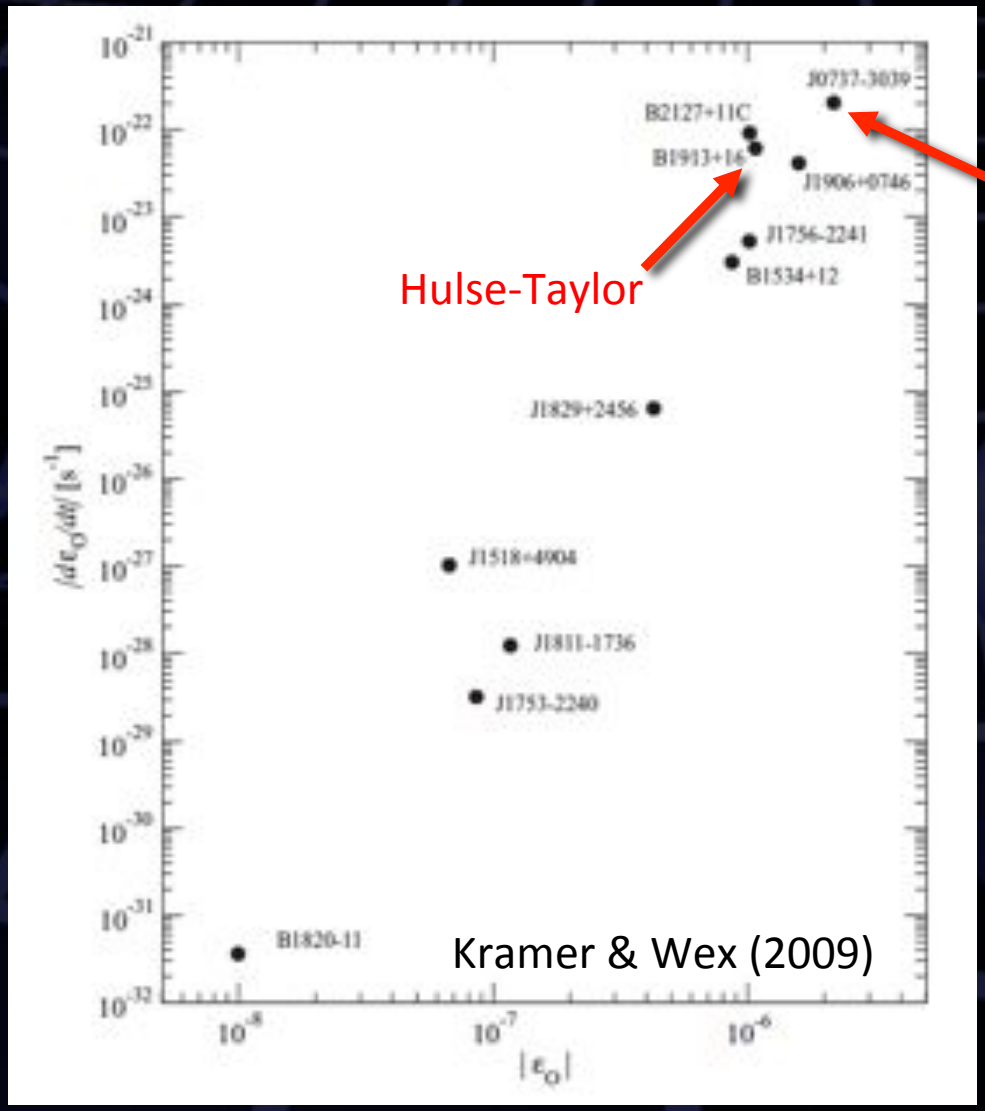
- Precession of periastron
- Gravitational redshift
- Shapiro delay due to curved space-time
- Gravitational wave emission
- Geodetic precession, relativistic spin-orbit coupling
- Speed of gravity, frame dragging
- …

Tested concepts imbedded within General relativity (GR) framework:

- Strong Equivalence Principle
- Lorentz invariance
- Non-existence of preferred frames
- Conservation of total momentum
- Non-existence of gravitational Stark-effect
- Non-variation of gravitational constant
- …

Limits on alternative theories, e.g. tensor-scalar theories

Gravitational physics tested by pulsars



Recent Update on Hulse-Taylor Pulsar

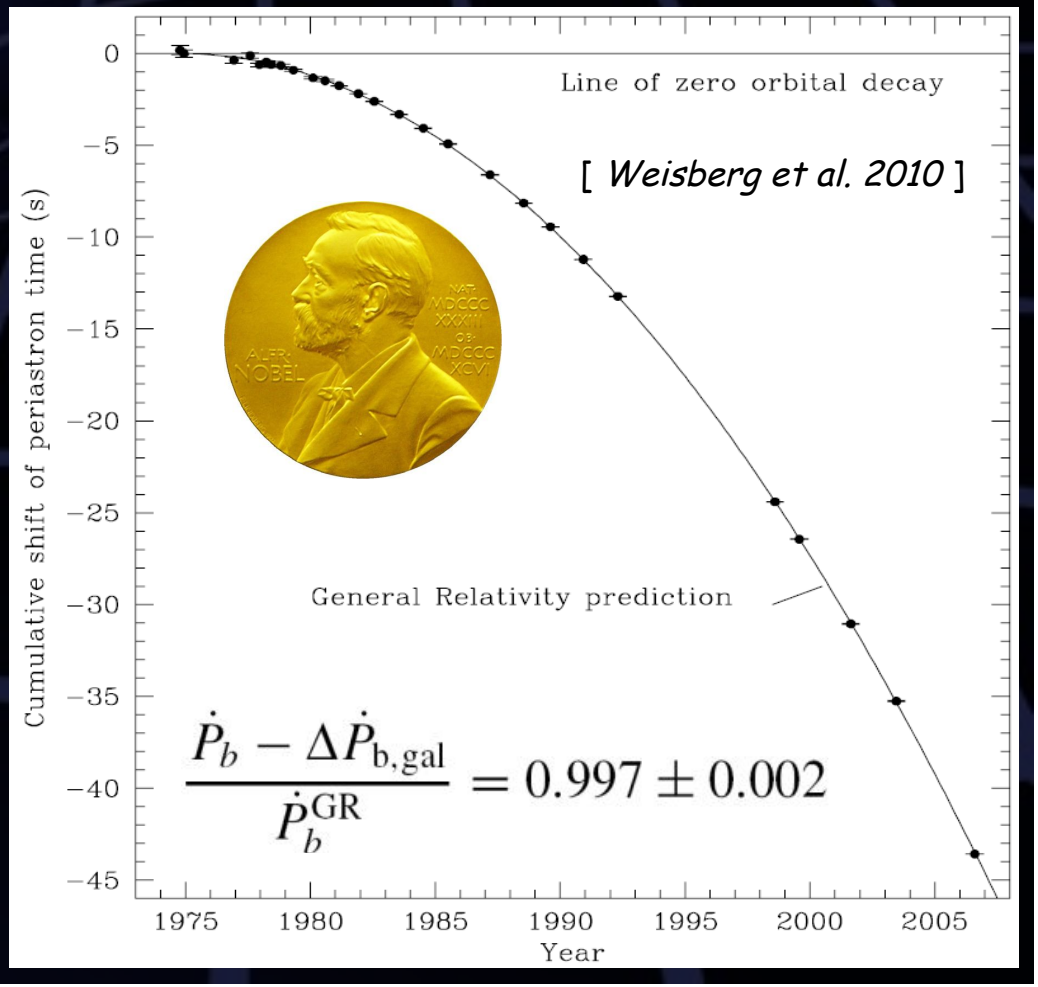
- First binary pulsar
- Decay of orbit as first evidence for existence of gravitational waves
- Data in agreement with GR's gravitational quadrupole emission:

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

Observed value:

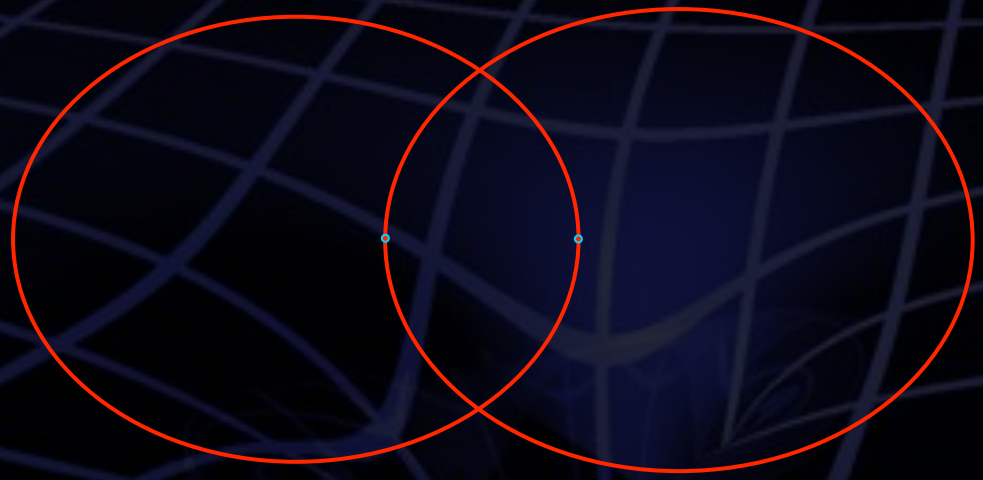
$dP_b/dt = -2.423 \pm 0.001 \times 10^{-12}$

Test limited by systematic effects due to relative acceleration in the Galactic gravitational potential and our (limited) knowledge of it.



Comparison Hulse-Taylor vs Double Pulsar

PSR B1913+16



PSR J0737-3039A/B

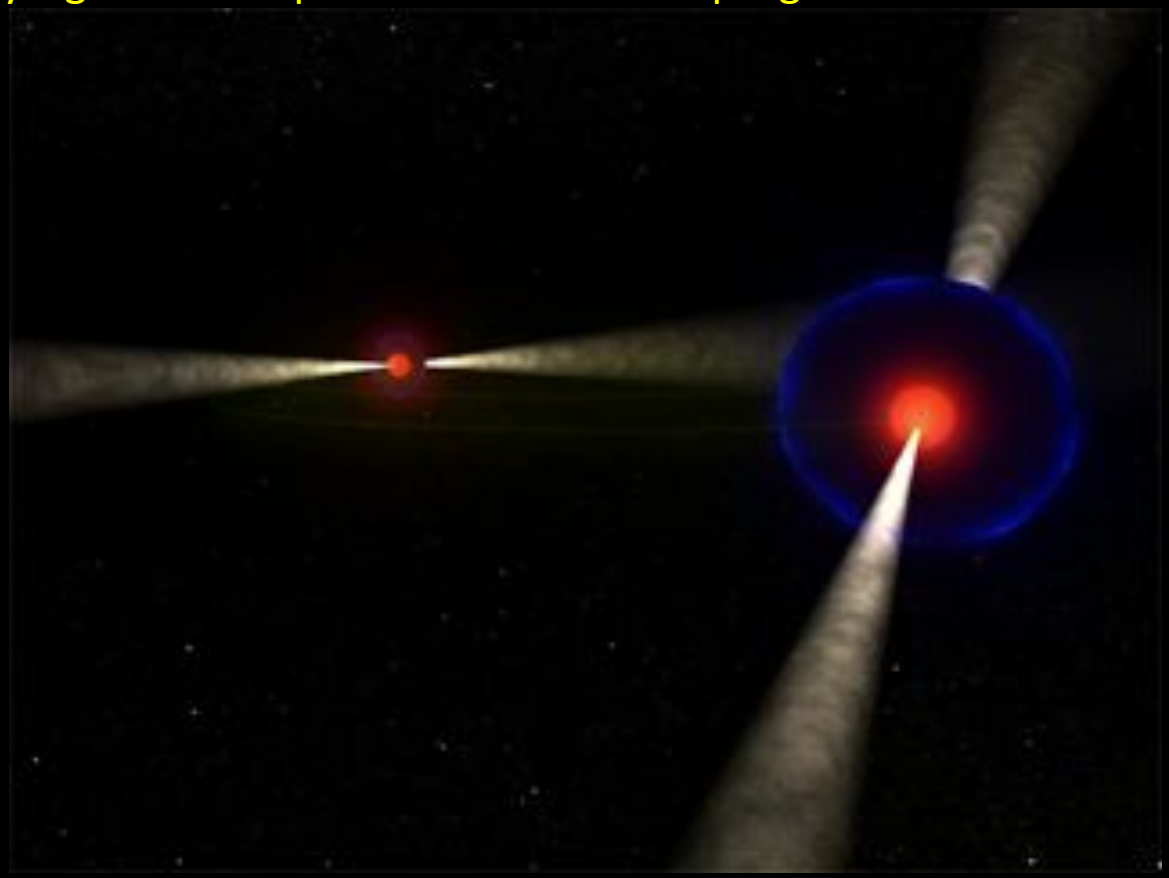
More compact…

… and much closer!

Sun

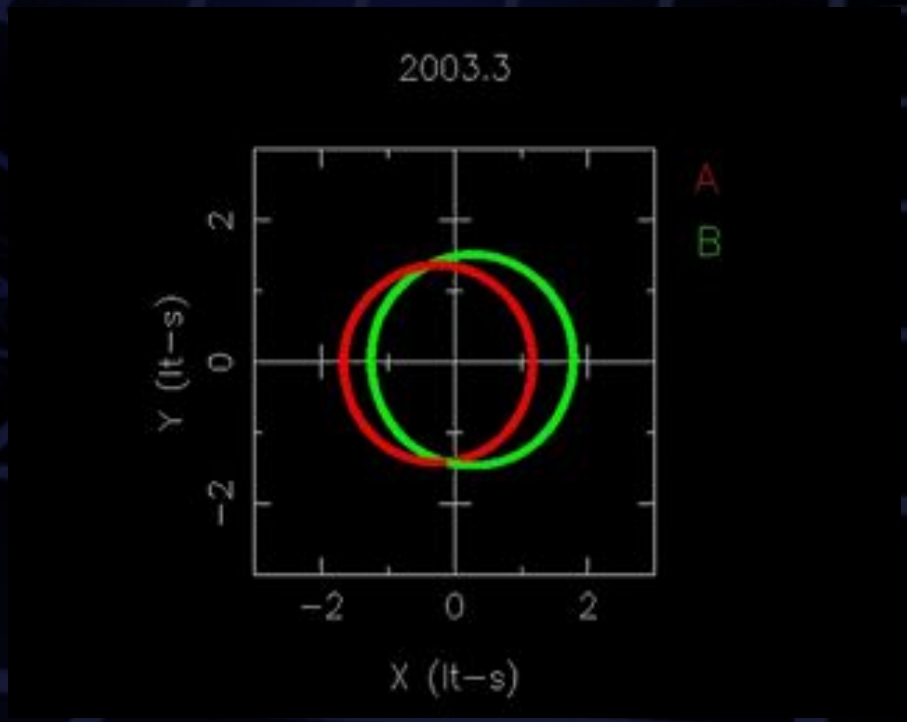
The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Old 22-ms pulsar in a 147-min orbit with young 2.77-s pulsar
- Orbital velocities of 1 Mill. km/h
- Eclipsing binary in compact, slightly eccentric and edge-on orbit
- Ideal laboratory for gravitational and fundamental physics
- In particular, exploitation for GR (Kramer et al. 2006)
- Recent very significant improvement – work in progress!



Most relativistic system: orbital precession

- Huge precession of 16.8991±0.0001 deg/yr!



Compare to Mercury:

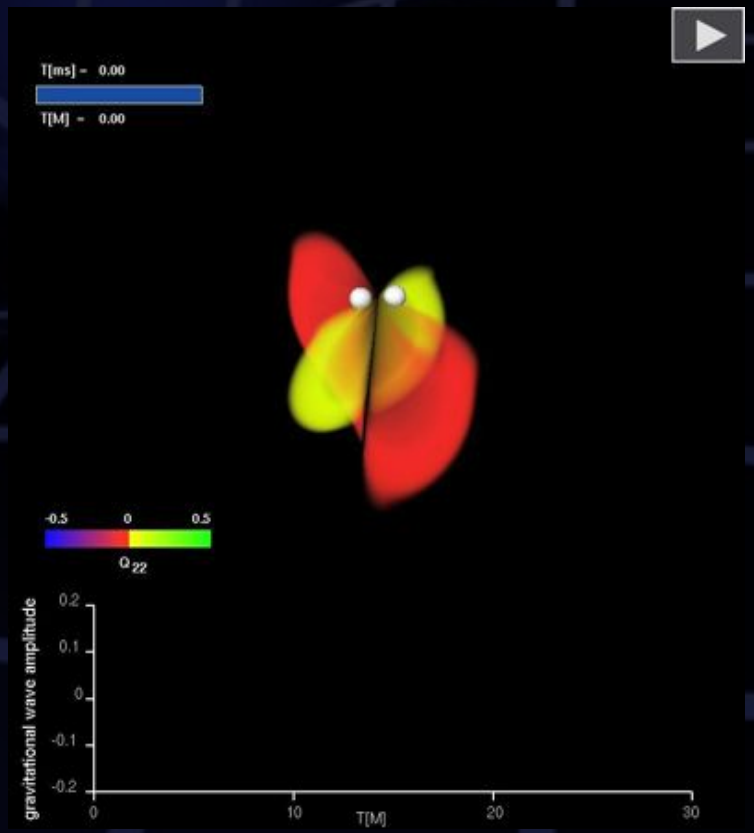
$$\dot{\omega} = 0.00012\,\mathrm{deg}/yr$$

- Measured within a few days of observations!
- One full revolution in about 20 years!
  (cf. to 3 Million years for Mercury's orbit)

Most relativistic system: orbital decay

- Effects of gravitational wave emission detected
- Orbit shrinks every day by 7.152±0.008 mm/day
- Merger of the two pulsars in 85 Million years

Animation by AEI:

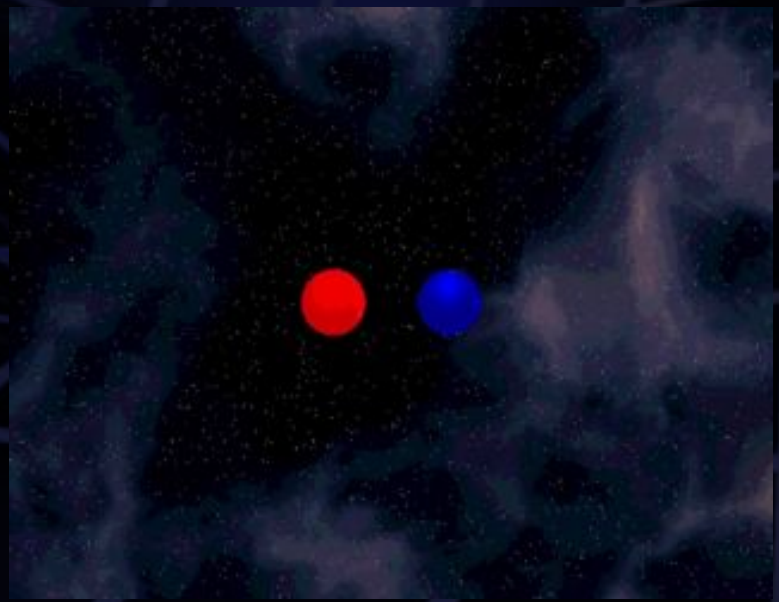


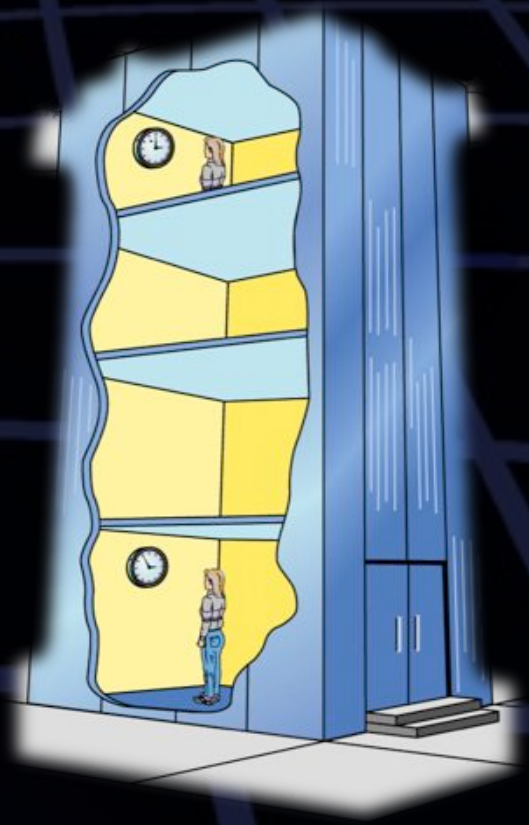
Rezzolla (AEI)

- Exactly the kind of source to be detected with GW detectors

Most relativistic system: gravitational redshift

- As other clocks, pulsars run slower in deep gravitational potentials
- Changing distance to companion (and felt grav. potential) during elliptical orbit:



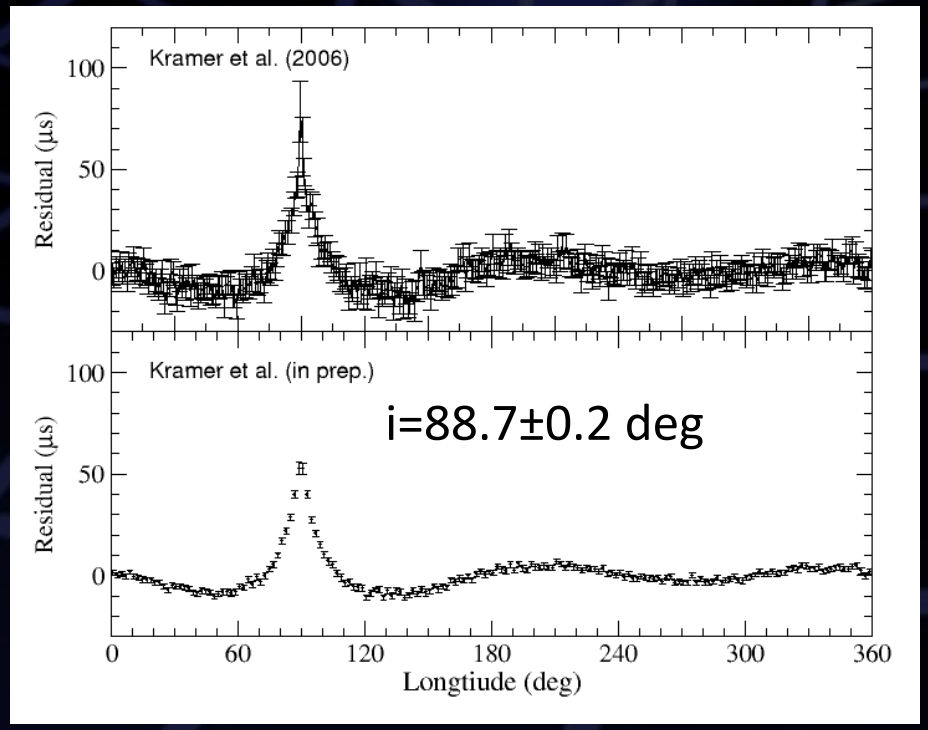


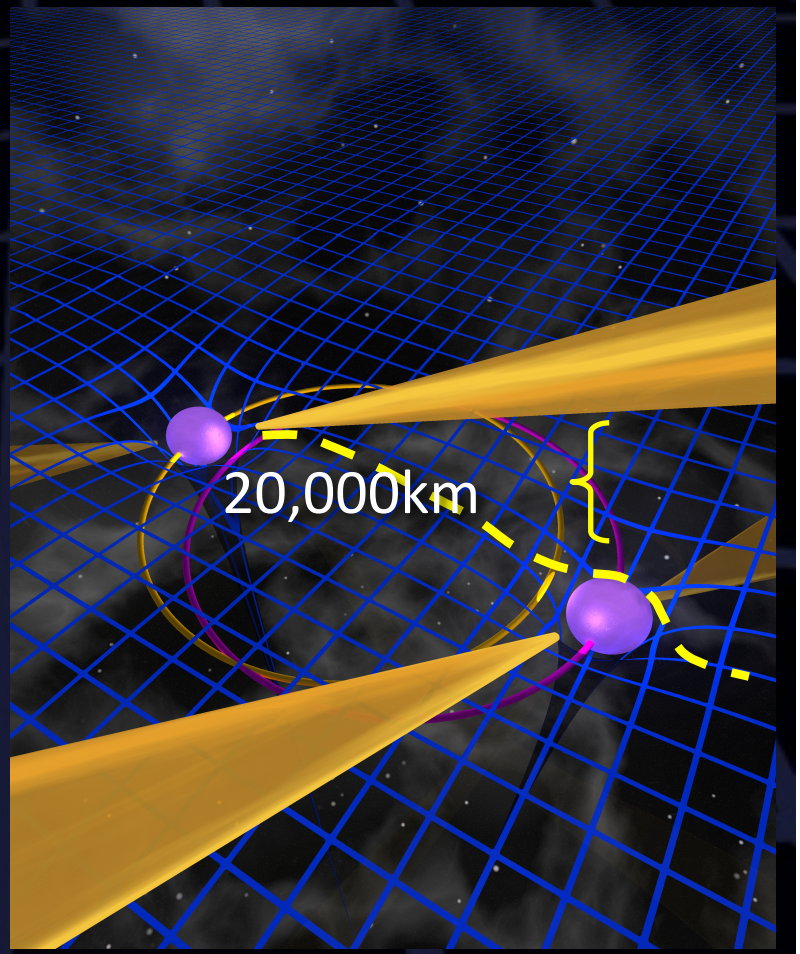
- Pulsars are running slower and faster during orbit by 383.9±0.6 microseconds!

Most relativistic system: Shapiro delay

- At superior conjunction, pulses from pulsar A pass near pulsar B
- Space-time near companion is curved
- Additional path length
- Delay in arrival time:

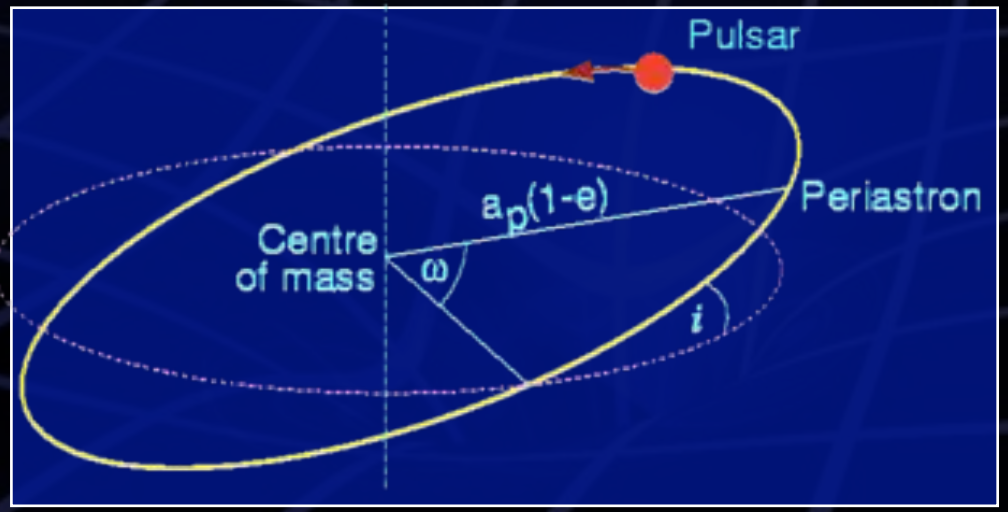
  s = sin(i)=0.99975±0.00009





Testing theories of gravity

Relativistic effects measured as corrections to Keplerian orbit:



Post-Keplerian Parameters = theory independent corrections to describe pulse arrival times

Keplerian parameter:

- Binary period, P_b
- Projected semi-major axis, $x = a_p \sin(i) / c$
- Eccentricity, e
- Longitude of periastron, ω
- Epoch periastron, T_0

Post-Keplerian (PK) parameters:

Among others:

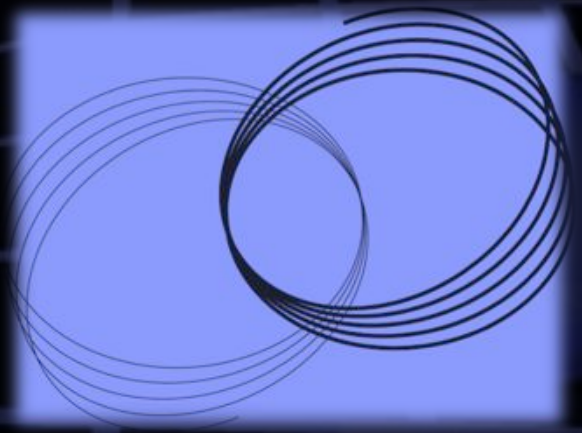
- Shapiro delay, r and s
- Gravitational redshift, γ
- Decay of orbit, dP_b/dt
- Precession of orbit, dω/dt

Idea: Compare measured magnitude of PK parameters with theory prediction!

Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity
(Damour & Taylor '92)

All PK parameter can be written as function of only observed Keplerian and the masses of pulsar and companion, e.g. in GR we can write orbital precession rate as:



$$d\omega / dt = 3T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{\left(m_p + m_c\right)^{2/3}}{1-e^2}$$

Periastron advance

For every post-Keplerian parameter, we can write:

Mass $_{\text{companion}}$ = Function $_{\text{Theory}}$ (Mass $_{\text{pulsar}}$ | Keplerian, PK paramteters)

Strong-field tests with binary pulsars

For every post-Keplerian parameter, we can write:

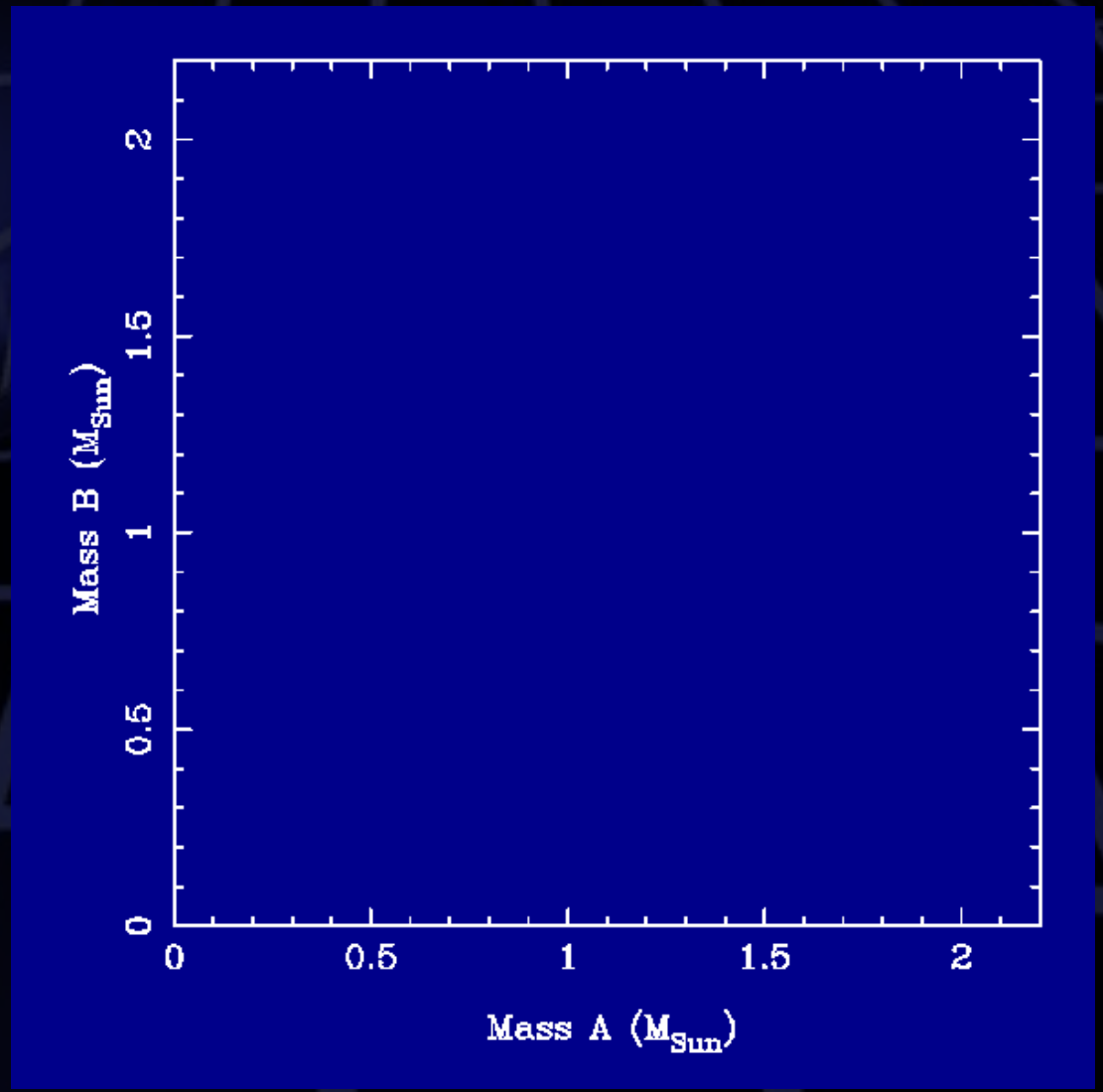
$\text{Mass}_{\text{companion}} = \text{Function}_{\text{Theory}}(\text{Mass}_{\text{pulsar}} \mid \text{Keplerian, PK paramteters})$

All lines given by PK measurements need to meet in a single point for theory to pass test!

We need 2 PK parameters to define intersection point.

Every additional PK-line can potentially miss this intersection point and hence tests the theory!

$N_{PK} - 2$ tests possible



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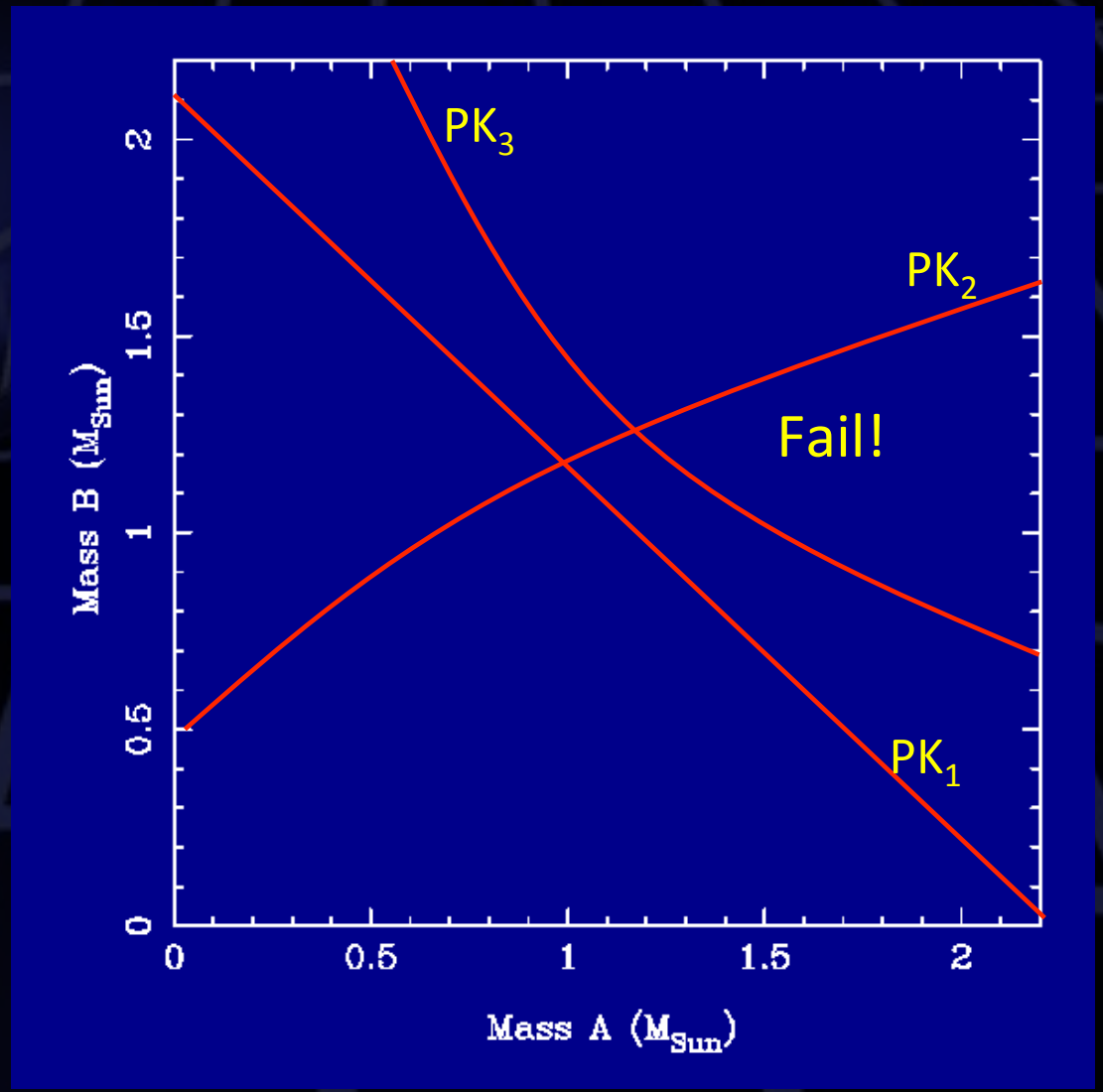

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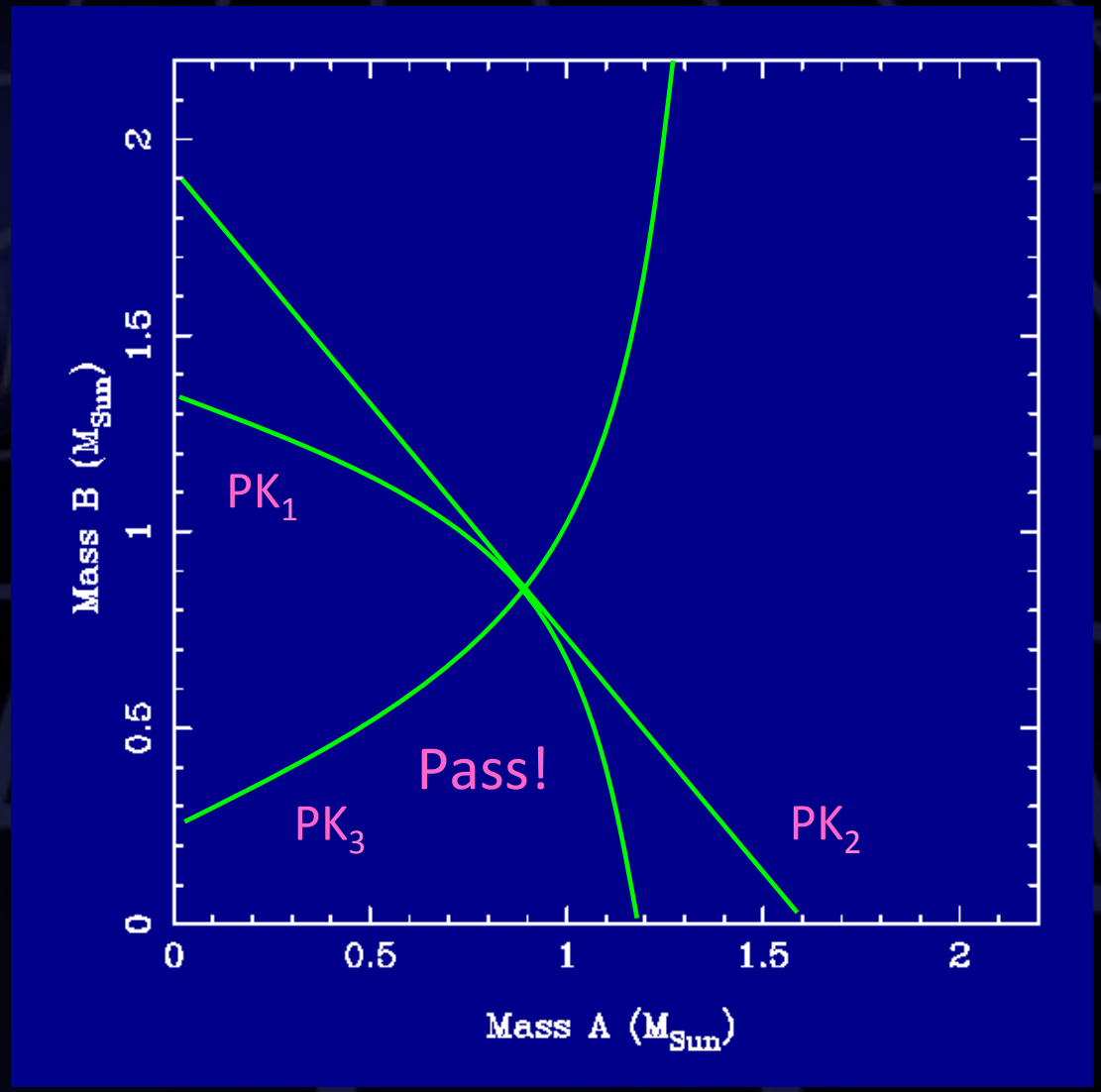
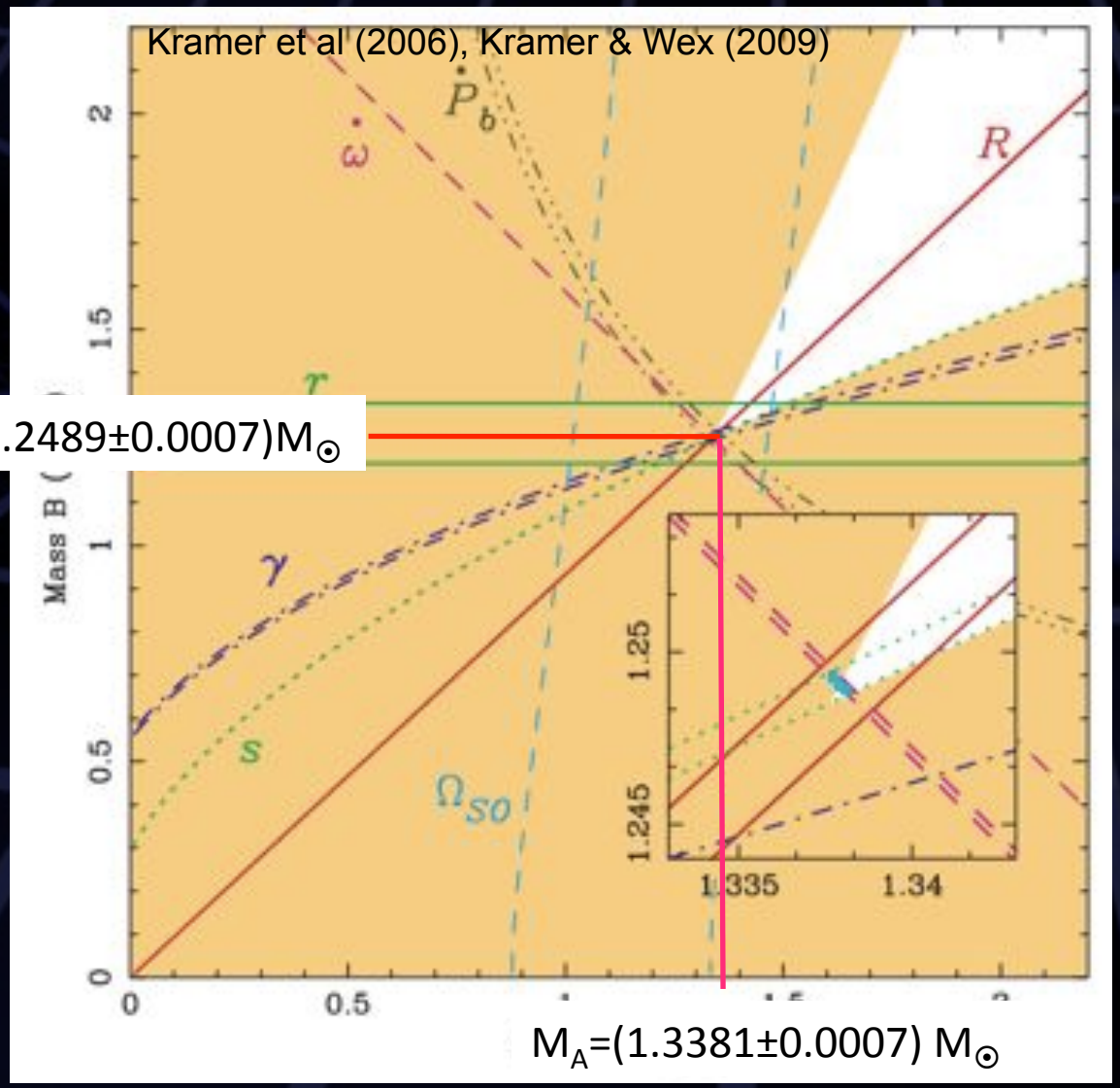


GR test with the Double Pulsar

Five(!) unique strong-field tests, represented in a single mass-mass plot:

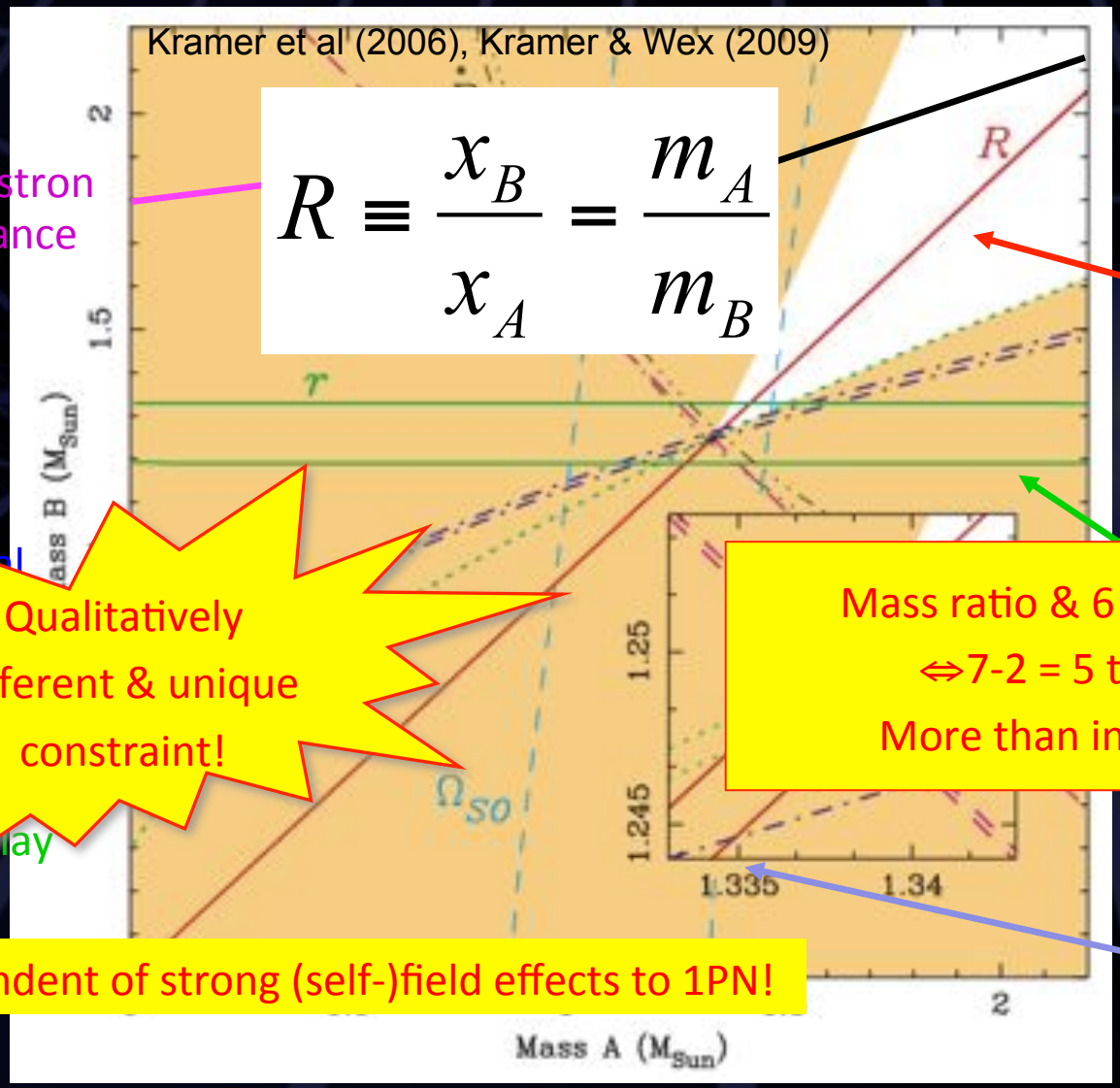


M_B=(1.2489±0.0007)$M_\odot$

M_A=(1.3381±0.0007) $M_\odot$

GR test with the Double Pulsar

Five(!) unique strong-field tests, represented in a single mass-mass plot:



$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

Grav. wave emission

Periastron advance

Mass ratio (two orbits!)

Gravitational redshift

Shapiro delay

Qualitatively different & unique constraint!

Mass ratio & 6 PK parameters ⇔7-2 = 5 tests of GR! More than in any system!

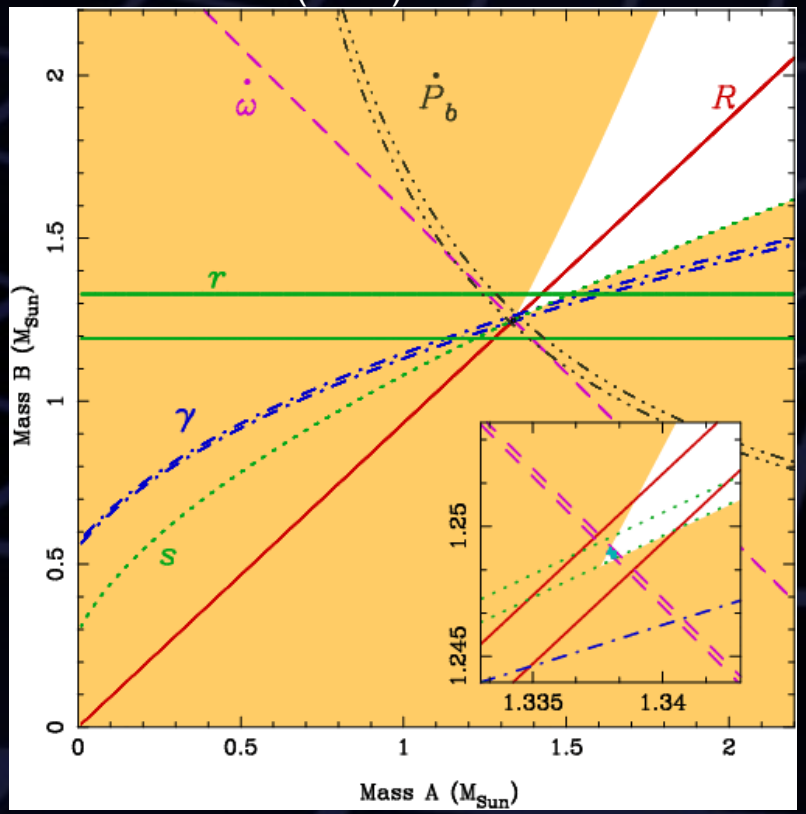
Spin-orbit coupling

R is independent of strong (self-)field effects to 1PN!

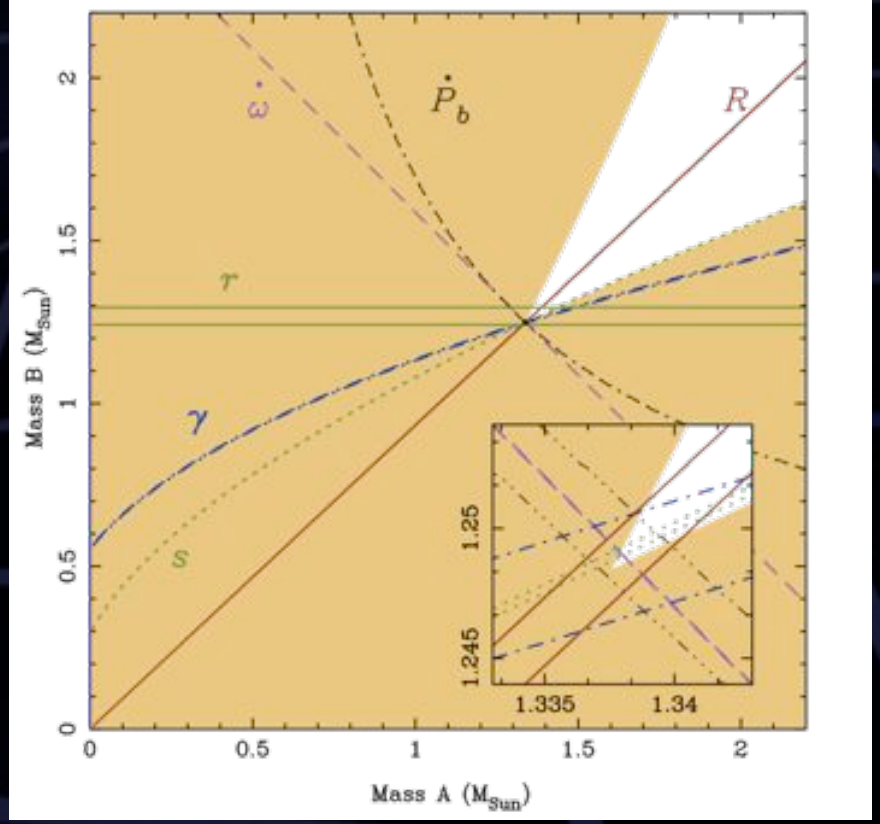
Best strong-field test of General Relativity

Recent big improvements:

Kramer et al (2006)



Kramer et al (in prep.)



Precision measurements, e.g.

P (ms) = 22.6993785996213 ± 0.0000000000002 (measured to 0.2 picoseconds!)

P_b (d) = 0.102251562452 ± 0.000000000008 (i.e. 2.45h measured to 691 ns!)

dP_b/dt = (-1.248±0.001) x 10^{-12} - agreement with GR at 0.1% - best radiation test!

Double Pulsar: Latest tests of GR

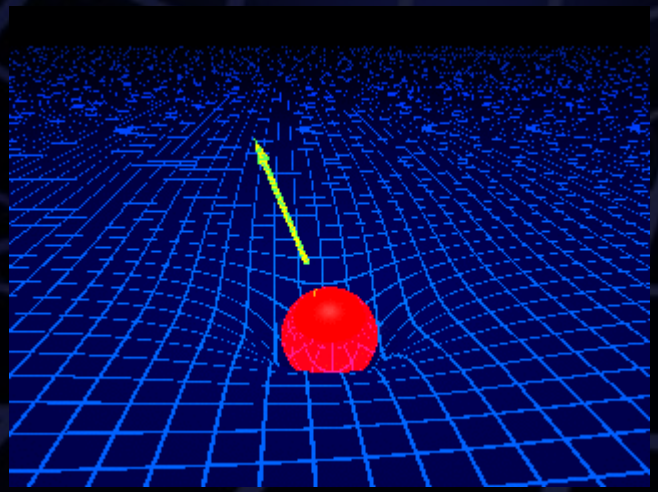
Based on: R = 1.0714±0.0011 & $\dot{\omega}$=16.8991±0.0001 deg/yr

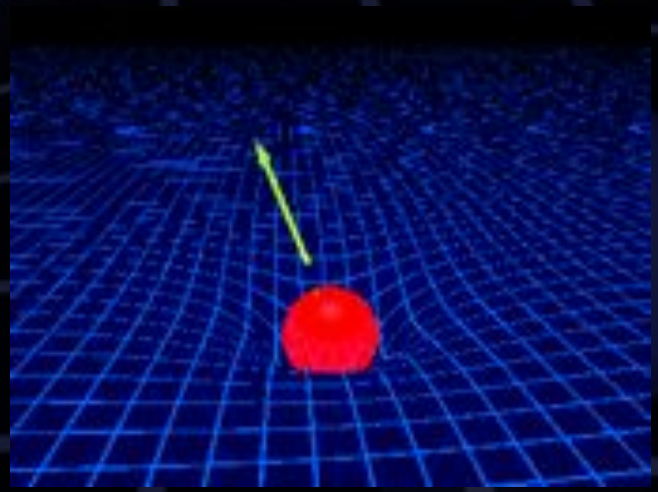
Expected in GR:	Observed:	Ratio:
γ = 0.3840(4) ms	0.3839(6) ms	1.000(2)
dP_b/dt=-1.248(1)x10^{-12}	-1.248(1)x10^{-12}	1.000(1)
r =6.151(3) μs	6.26(14) μs	0.98(2)
s=0.99988(50)	0.999750(90)	1.0000(5)

- Most precise test in strong-field regime:
- Shapiro delay measured to 9x10^{-5} ! – More precise than we can predict!
- Best radiative test ever: 0.1%
- Precision will improve with time: expect to supersede solar system tests

Relativistic spin precession – SO coupling

Due to the curvature of space-time the proper reference frame of a freely falling object suffers “geodetic precession”



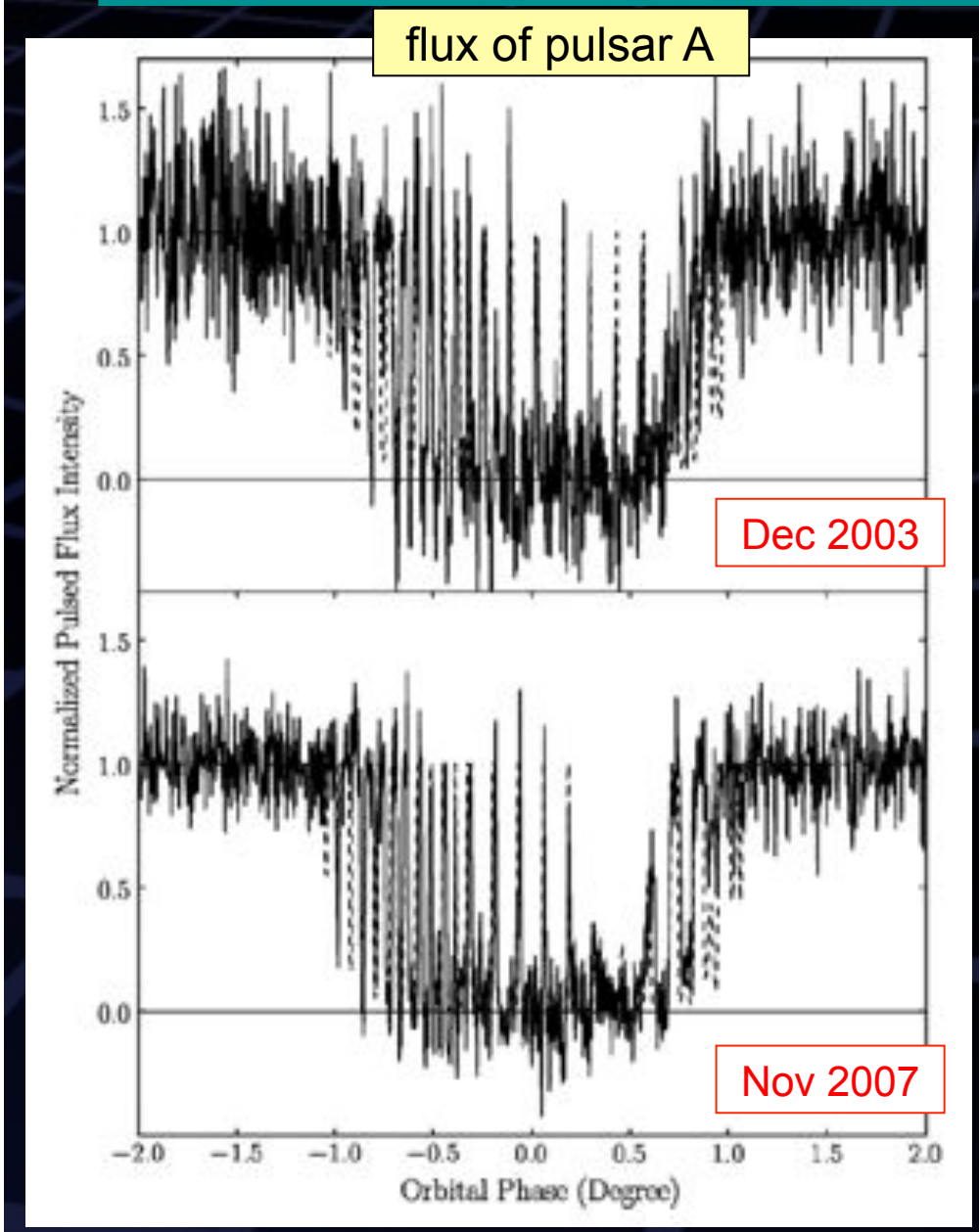


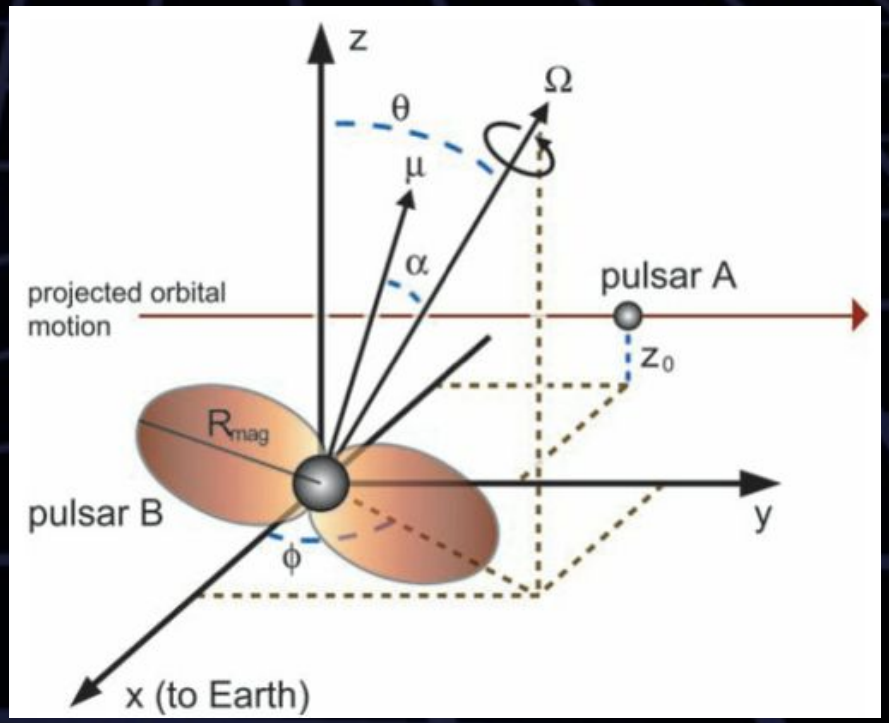
Experiments made in Solar System provide precise tests for thiseffect and confirm it, e.g.,

- Lunar Laser Ranging
- Gyro-experiments, i.e. Gravity-Probe B

…but no strong-field test until recently

Geodetic Precession and the Double Pulsar





Breton et al. (2008):

- Eclipse profile is changing with time
- Pattern is changing due to relativistic spin precession

$$\Omega_B = 4.77^{\circ}{}^{+0^{\circ}.66}_{-0^{\circ}.65}\ \mathrm{year}^{-1}$$

[*Breton et al. 2008*]

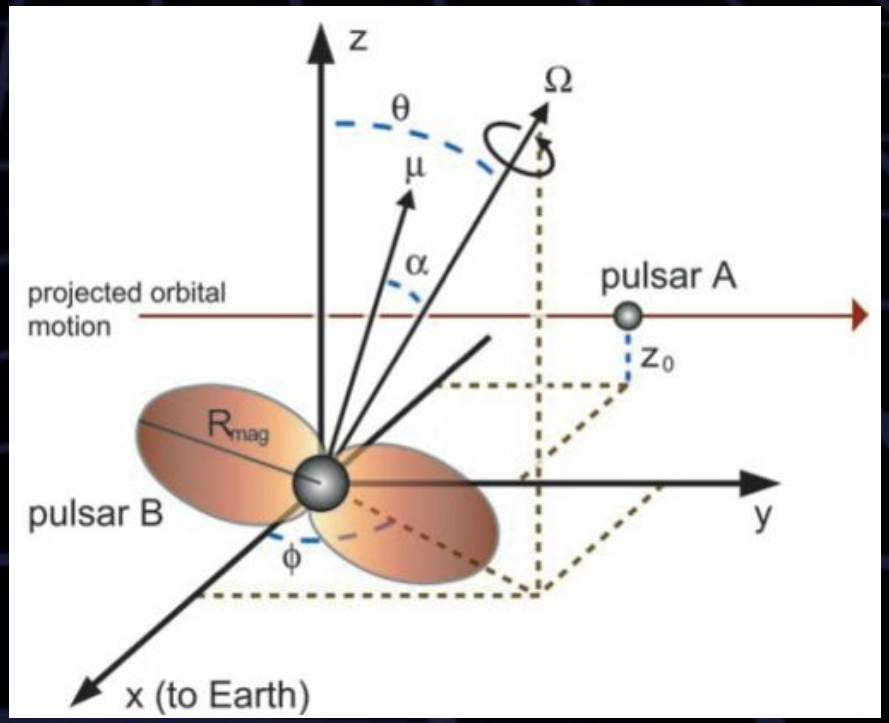
Geodetic Precession and the Double Pulsar

Relativistic Spin Precession in the Double Pulsar

See Breton et al. (Science, 2008)

Movie Description

The eclipses in the double pulsar PSR J0737-3039A/B occur when pulsar A's projected orbital motion, represented by a gray circle moving on a black line, passes behind its companion, pulsar B. Radio emission from pulsar A is absorbed via synchrotron resonance with the plasma trapped in the closed field lines of the truncated dipolar magnetosphere of pulsar B, shown as a colored dipolar structure. Since pulsar B's magnetic dipole axis is misaligned with respect to its spin axis (represented by a diagonal rod), the optical depth along our sight line to pulsar A varies as a function of pulsar B's spin phase. The theoretical light curve resulting from the eclipse animated in the upper panel is drawn as a black curve in the bottom panel and real eclipse data, observed with the Green Bank Telescope in April 2007, are overlaid in red. The animation speed corresponds to real time and the audio track is the sound that one would hear if the radio signal detected from pulsar A by the radio telescope was noise-filtered and amplified into an audio device. While individual pulsations from pulsar A are too fast to be distinguished, we can hear a mixture of F musical tones harmonically related to 44 Hz (F1 tone), the spin frequency of the pulsar, which is modulated in intensity as a result of the eclipse.



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$$\Omega_B = 4.77^{\circ}{}^{+0^{\circ}.66}_{-0^{\circ}.65}\ \mathrm{year}^{-1}$$

[*Breton et al. 2008*]

Precession: Theory-independent constraint

- We can both explain the eclipse pattern and measure the precession rate as a new test of general relativity (Breton et al 2008):

- In agreement with GR's precession rate of 5.1 deg/yr
- Also, first unique constraint on alternative theories due to first measurement of theory-independent spin-precession parameter:

$$L_{SO} = \sum_A \frac{1}{c^2} S_A^{ij} \left(\frac{1}{2} v_A^i a_A^j + \sum_{B \neq A} \frac{\Gamma_A^B m_B}{r_{AB}^3} \times (v_A^i - v_B^i)(z_A^j - z_B^j) \right)$$

$$\Gamma_B^A / 2G_{AB} = 0.89 \pm 0.13$$

All alternative theories need to predict this value!

Relativistic Spin Precession in the Double Pulsar

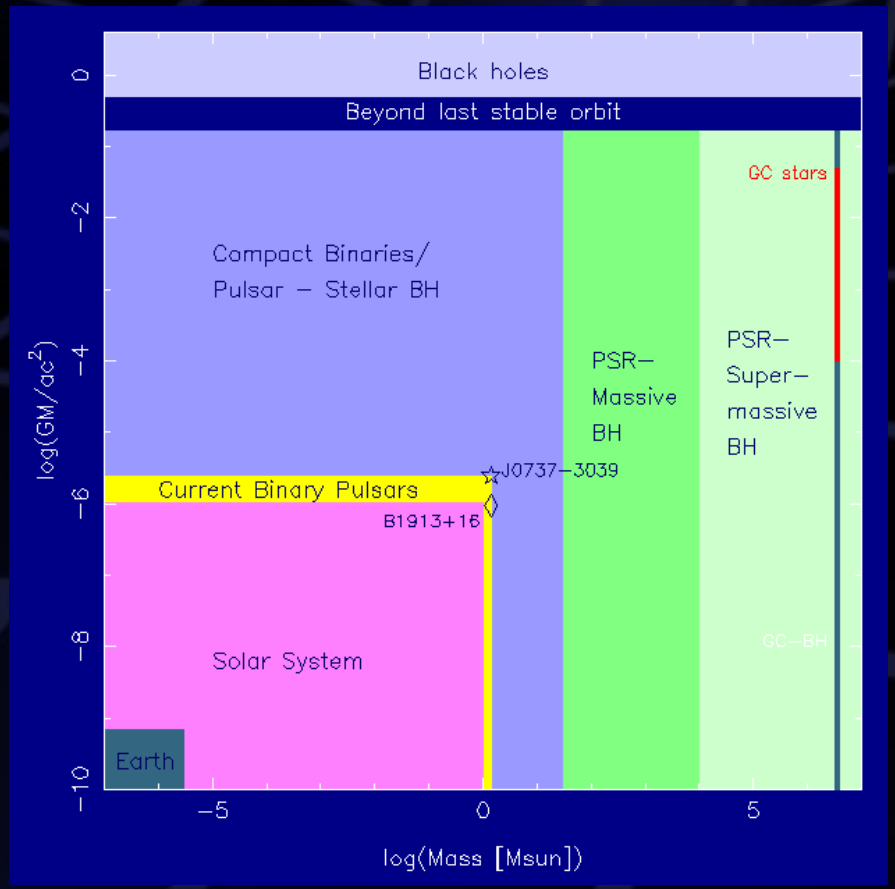
See Breton et al. (Science, 2008)

Movie Description

Time-lapse animation displaying the evolution of pulsar B's geometry in the double pulsar PSR J0737-3039A/B due to relativistic spin precession between January 2004 and January 2029. The truncated dipolar magnetosphere of pulsar B, shown as a colored dipolar structure, rotates about its spin axis, pictured as a diagonal rod. The apparent orbital motion of pulsar A during the eclipse corresponds to the horizontal black line intersecting pulsar B's magnetosphere. Relativistic spin precession is similar to the wobbling of a spinning top and induces a motion of the spin-axis orientation around the orbital angular momentum, which is vertical in this movie. The theoretical light curve corresponding to the eclipse animated in the upper panel is drawn in the lower panel. The angle ϕ corresponds to the longitude of the spin axis, with 0° being the direction coincident with the line of sight.

Pulsar – Black Hole Systems

- Various types: stellar BH, intermediate mass BH in globular clusters and pulsars around super-massive BH in Galactic Centre
- Not just enlarging the parameter space, but qualitatively different probe for GR and especially alternative theories

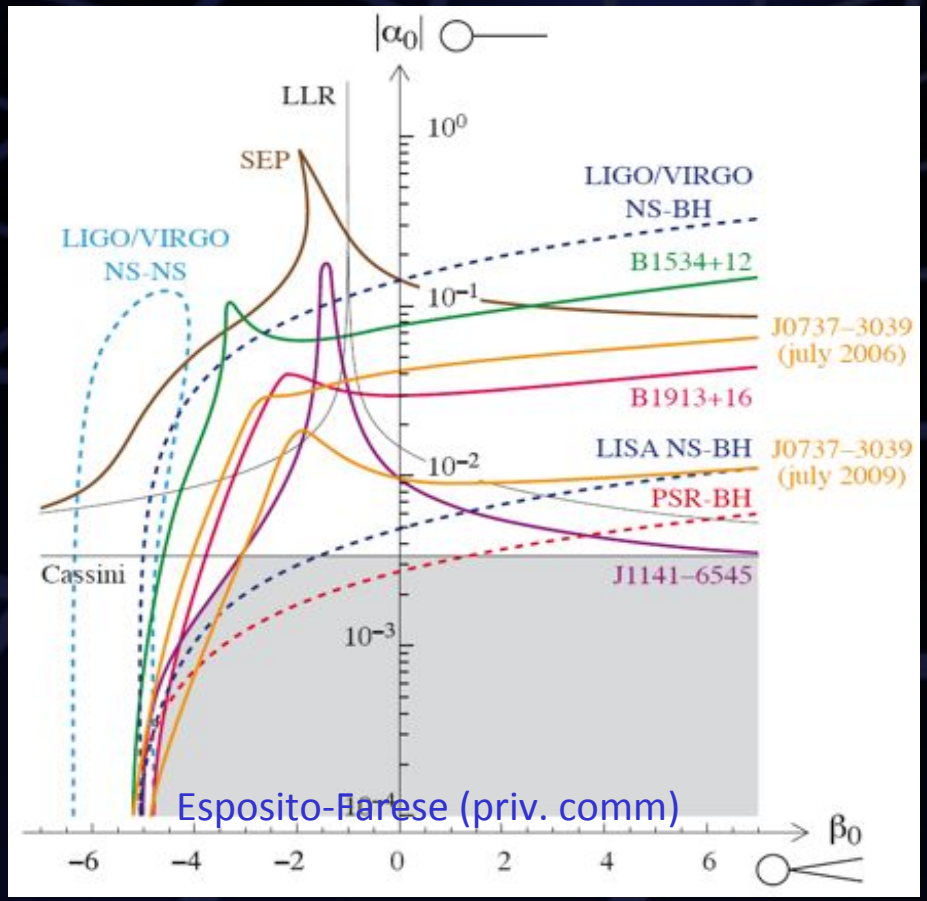


"…a binary pulsar with a black-hole companion has the potential of providing a superb new probe of relativistic gravity. The discriminating power of this probe might supersede all its present and foreseeable competitors…"

(Damour & Esposito-Farese 1998)

Pulsar – Black Hole Systems

- Various types: stellar BH, intermediate mass BH in globular clusters and pulsars around super-massive BH in Galactic Centre
- Not just enlarging the parameter space, but qualitatively different probe for GR and especially alternative theories, e.g. Tensor-Scalar theories



Esposito-Farese (priv. comm)

"…a binary pulsar with a black-hole companion has the potential of providing a superb new probe of relativistic gravity. The discriminating power of this probe might supersede all its present and foreseeable competitors…"

(Damour & Esposito-Farese 1998)

Limits on Tensor-Scalar Theories

Tensor-Scalar theories

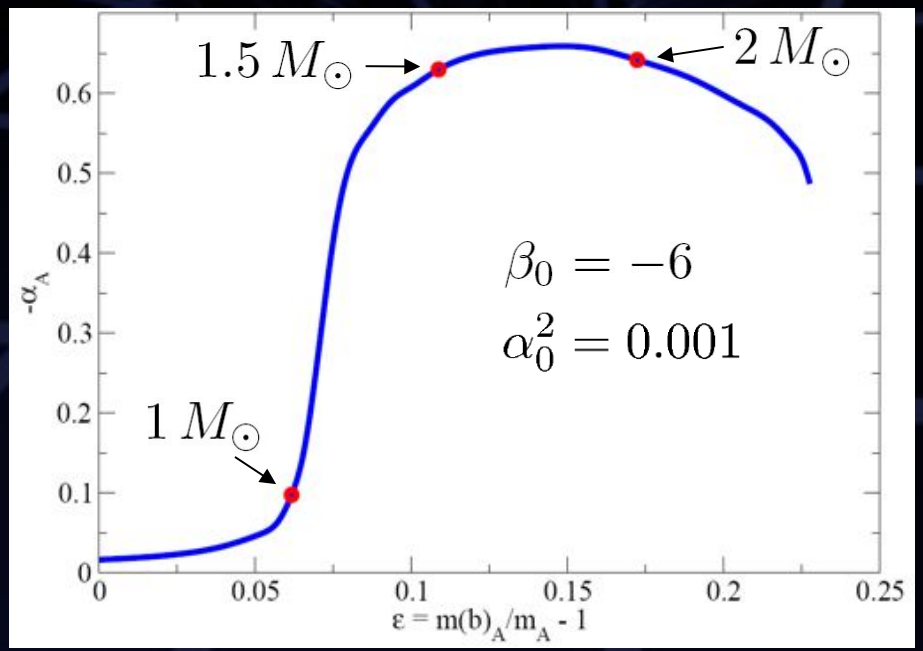
Best studied: ``Quadratic Model´´ by Damour & Esposito-Farèse - $T_1(\alpha_0, \beta_0)$

$$R^*_{\mu\nu} = \frac{8\pi G_*}{c^4}\left(T^*_{\mu\nu} - \tfrac{1}{2}T^* g^*_{\mu\nu}\right) + 2\partial_\mu\varphi\partial_\nu\varphi$$

$$g^{\mu\nu}_* \nabla^*_\mu \nabla^*_\nu \varphi = -\frac{4\pi G_*}{c^4}\left(\alpha_0 + \beta_0\varphi\right) T_*$$

Physical metric: $\tilde{g}_{\mu\nu} = g^*_{\mu\nu} \exp\left(2\alpha_0 + \beta_0\varphi^2\right)$

Effective coupling constant $\alpha_A = -q_A / m_A$:



Can reach order unity in neutron stars, even if α_0 is extremely small (spontaneous scalarization)

Black holes have no scalar charge (no-hair theorem)

[*Damour & Esposito-Farèse 1996*]

Dipolar Gravitational Radiation in a PSR-BH System

$$\dot{P}_{b\varphi}^{\mathrm{dipole}}(m_A, m_B) = -2\pi \frac{G_* \, m_A \, m_B \, n}{c^3 (m_A + m_B)} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} (\alpha_A - \alpha_B)^2 \, .$$

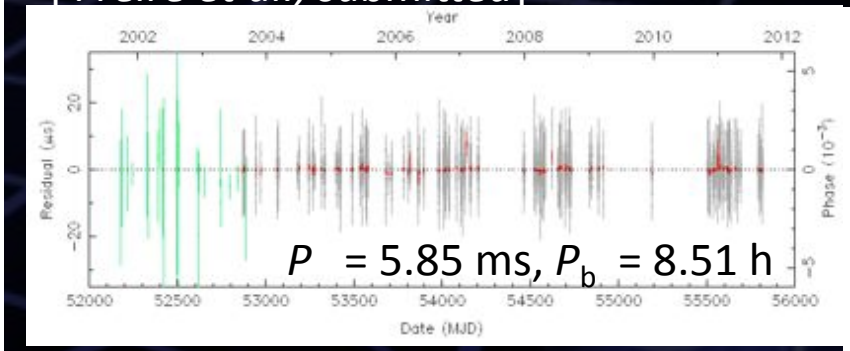
no (regular) 'scalar hair' 0

→ efficient emitter of dipolar radiation – which we could precisely measure if it exists

Efforts to find PSR-BH system: HTRU survey (Effelsberg + Parkes), GC searches…

Next best thing: PSR J1738+0333 – a PSR-WD system

Precision timing observations of PSR
[*Freire et al., submitted*]



P = 5.85 ms, P_b = 8.51 h

From radial velocities:

$q = m_p/m_c = 8.1 \pm 0.2$

From spectrum (surface gravity & T):

$m_c = 0.181 \pm 0.008\ M_{sun}$

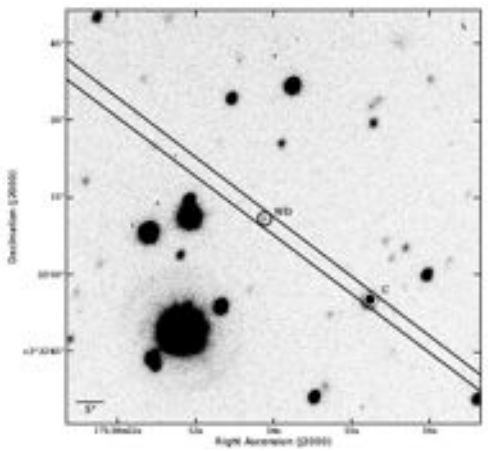
Hence: $m_p = 1.47 \pm 0.07\ M_{sun}$

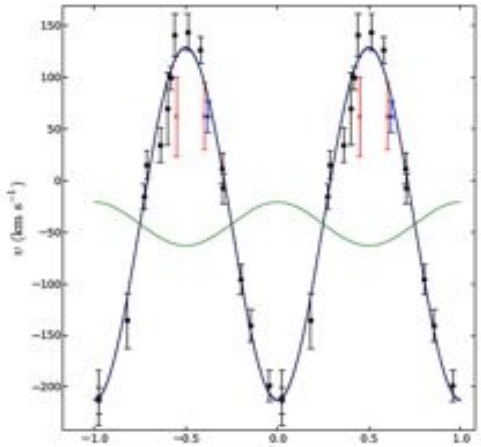
From pulsar timing:

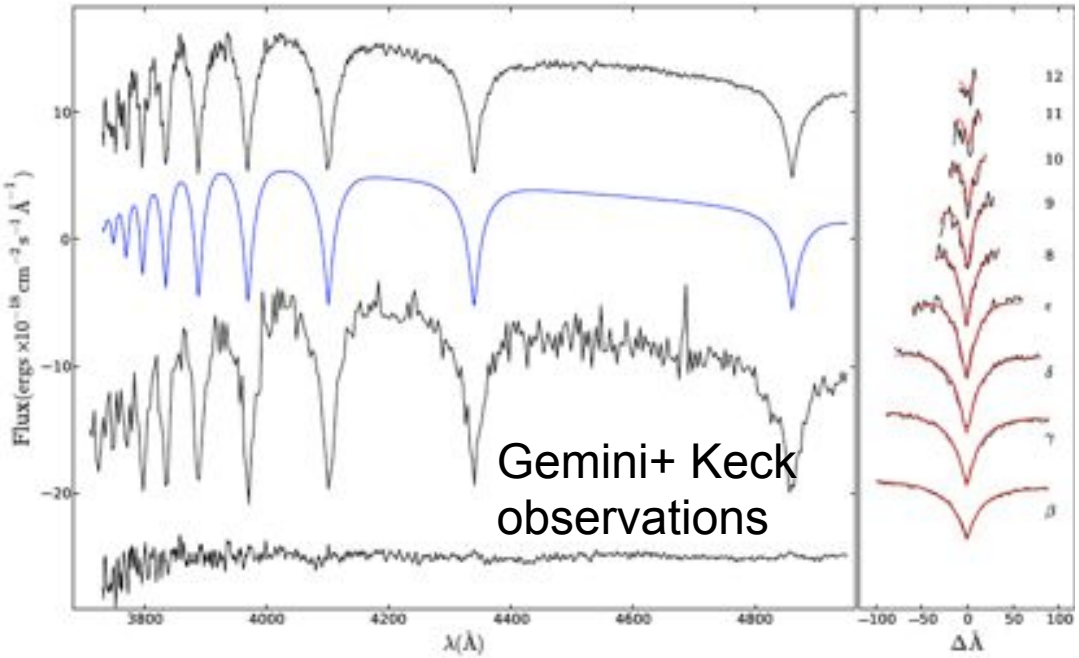
$D_p = 1.4 \pm 0.1$ kpc

$P_b/dt = (-27.7 \pm 1.5) \times 10^{-15}$

Optical observations of the WD companion
[*Antoniadis et al., submitted.*]

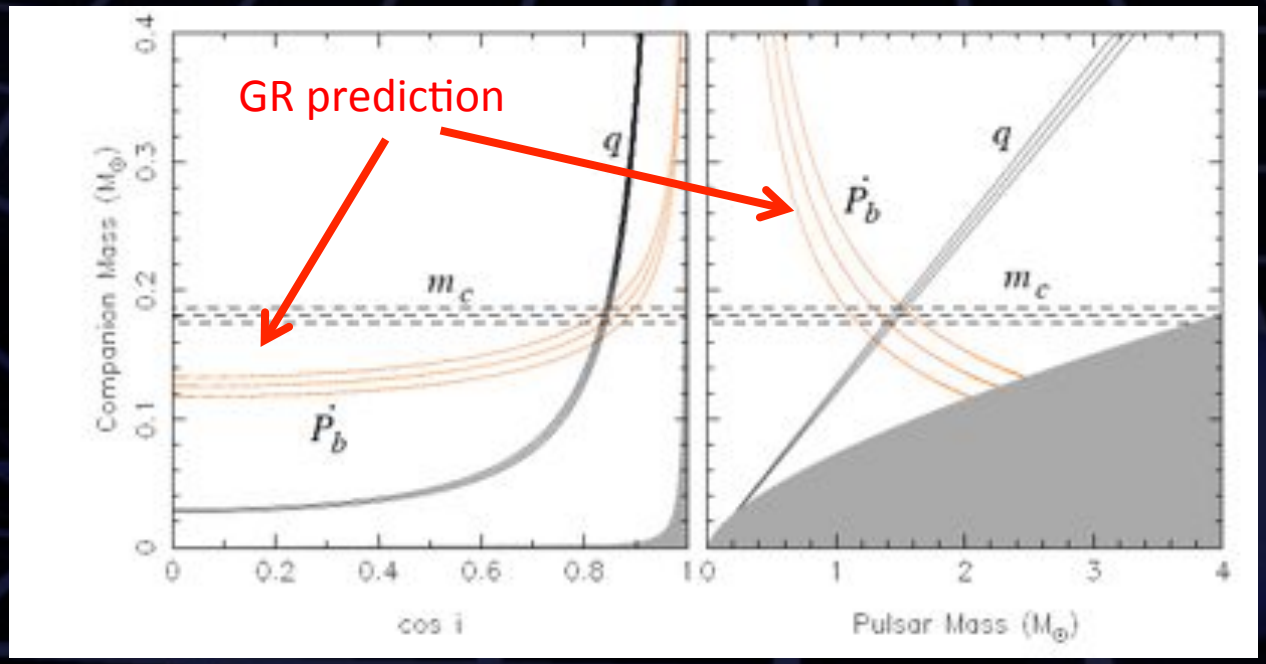






Limits on dipole radiation and change in G

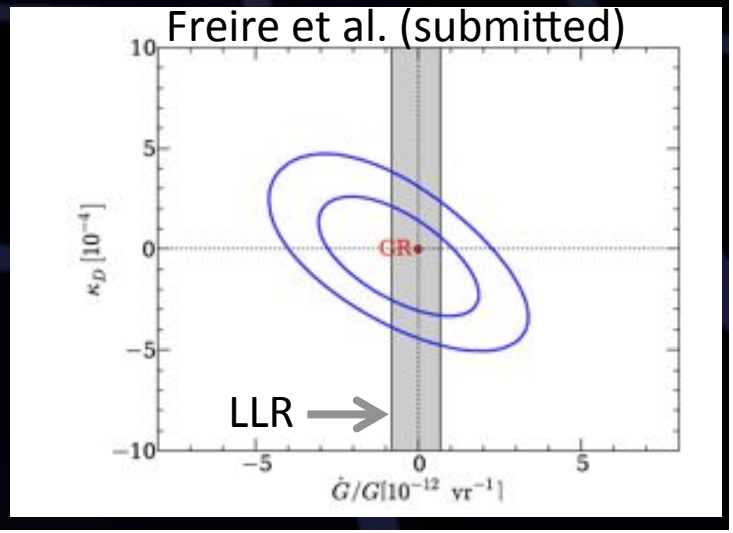
Observed orbital decay agreement with GR's quadrupole emission:



Hence, limit on contribution from dipole rad or change in G:

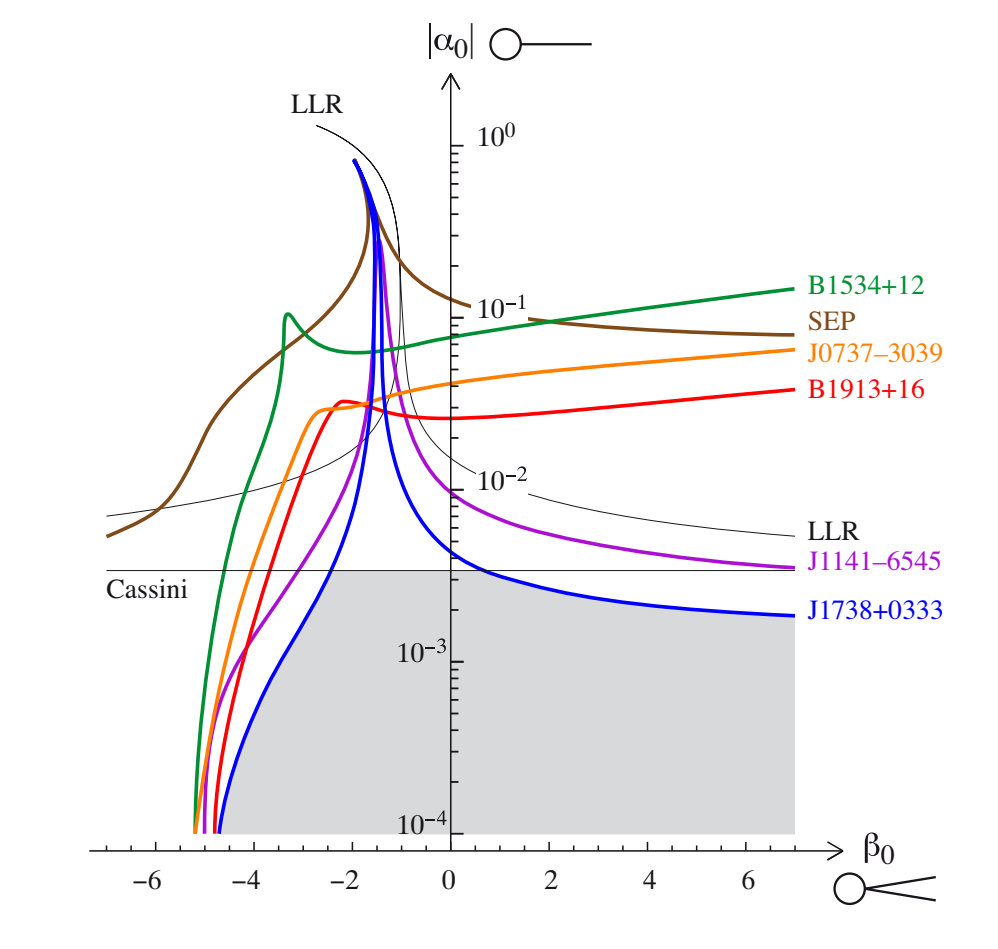
$$\dot{P}_b^{exc} = \dot{P}_b^{obs} - \dot{P}_b^{GR} = \dot{P}_b^{dipole} + \dot{P}_b^{\dot{G}}$$

$$\frac{\dot{P}_b^{exc}}{P_b} = -2\frac{\dot{G}}{G}\left[1-\left(1+\frac{m_c}{2M}\right)s_p\right] - 4\pi^2\frac{T_{Sun}\mu}{P_b^2}\kappa_D s_p^2$$



Tensor-scalar theories

Limits exceed solar system limits for most of the parameter space:



Coupling of matter to scalar field:

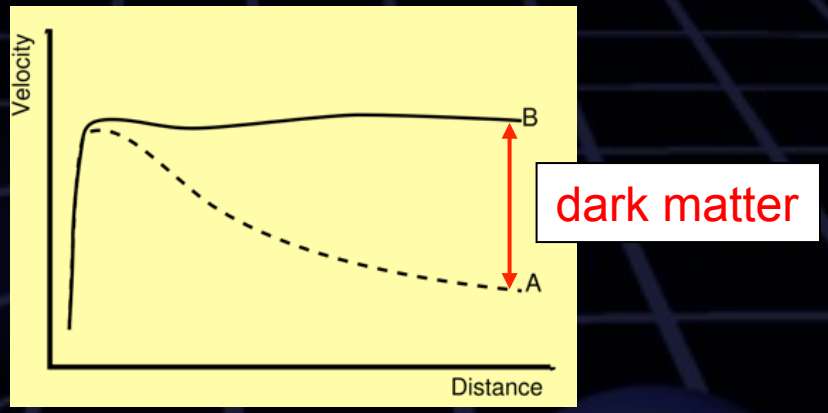
$$a(\varphi) = \alpha_0(\varphi - \varphi_0) + \frac{1}{2}\beta_0(\varphi - \varphi_0)^2 + \ldots$$

Note:

- In GR, $a(\phi) = 0$
- Jordan-Fierz-Brans-Dicke:

  $\beta_0=0$ and $a(\phi) = \alpha_0(\phi-\phi_0)$

MOND-like tensor-vector-scalar (TeVeS) theories



Modified Newtonian dynamics (MOND)

$$a = a_N = \frac{GM}{r^2} \qquad \text{if } a > a_0$$

$$a = \sqrt{a_0 a_N} = \frac{\sqrt{GMa_0}}{r} \qquad \text{if } a < a_0$$

$$a_0 \approx 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$$

[*Milgrom 1983*]

TeVeS with aquadratic kinetic term:

$$S = \frac{c^3}{16\pi G_*}\int d^4x\sqrt{-g^*}\left\{R^* - 2f\left(g_*^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\right)\right\}$$
$$+S_{\text{matter}}\left[\text{matter}; g_{\mu\nu} \equiv A^2(\varphi)g^*_{\mu\nu} + B(\varphi)U_\mu U_\nu\right]$$
$$+S_{\text{vector}}\left[U_\mu; g^*_{\mu\nu}\right]$$

To reproduce MOND:

$f(x) \propto x^{3/2}$ for small values of x

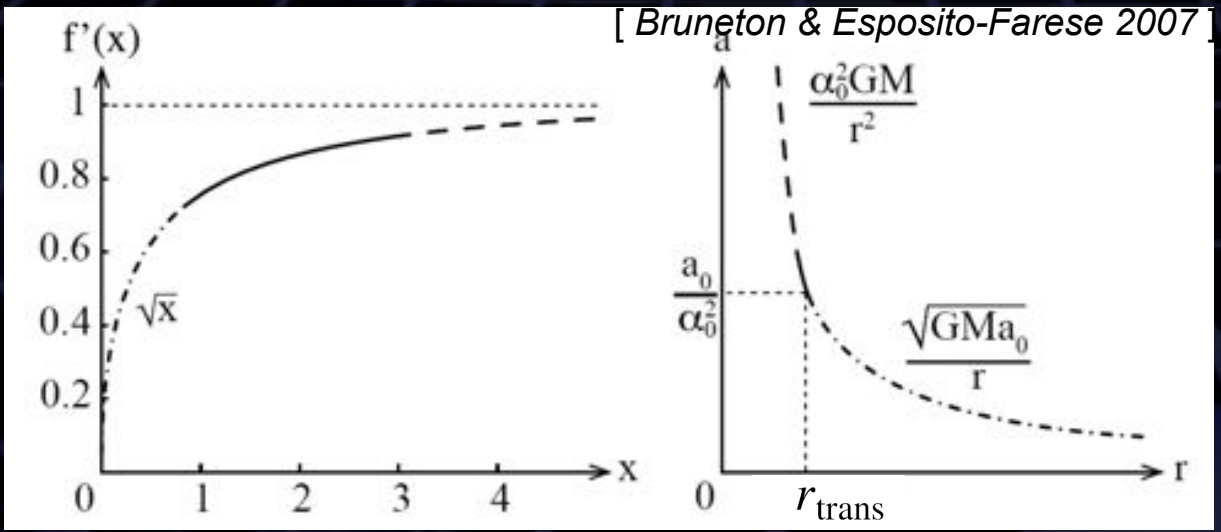
$f(x) \rightarrow x$ for large x (Newtonian regime)

$f'(x) > 0 \quad 2xf''(x) + f'(x) > 0$

[*Bekenstein & Milgrom,Bekenstein*]

“Natural“ MOND and binary pulsars

[*Bruneton & Esposito-Farese 2007*]



MOND potential appears at a distance larger than:

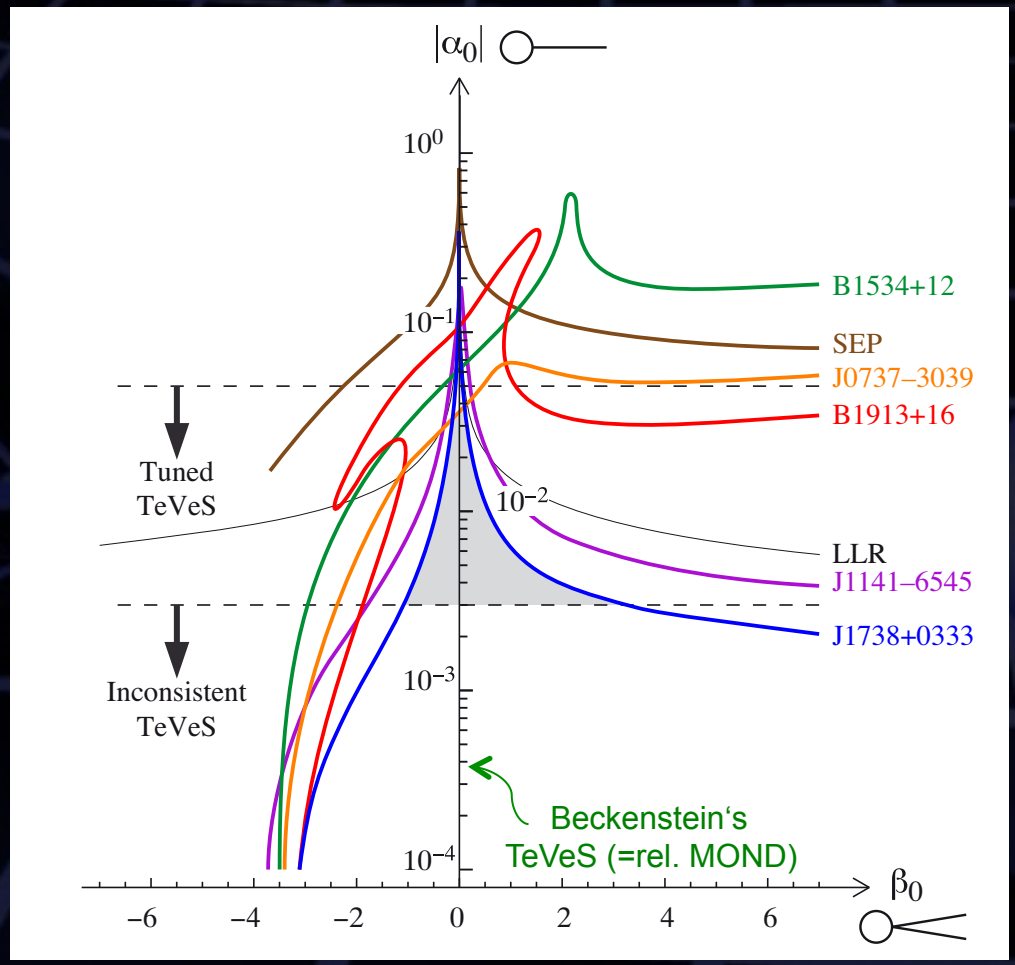
$$r_{\rm trans} = \alpha_0^2 \sqrt{\frac{GM}{a_0}} \sim 7000\ \mathrm{AU} \times \alpha_0^2$$

If $\alpha_0^2 < 0.002$: MOND effects should be apparent in the solar system dynamics

$\alpha_0^2 > 0.002$ would lead to a significant emission of dipolar gravitational radiation in pulsar-white dwarf binaries with ~ 1 day orbital period:

$$\dot{P}_b^{\rm dipole} = -\frac{4\pi^2}{P_b}\frac{G\mu}{c^3}\frac{1+e^2/2}{(1-e^2)^{5/2}}\,(\alpha_0\, c_{\rm p})^2$$

Limits from PSR J1738+0333 for general class of TeVeS



"MOND-like TeVeS theories are essentially ruled out or will soon be untenable – unless you twist it into a very unnatural form (e.g. invoke special screening of scalar charge on small scales)!

Possible, but natural or physical…?

Summary & Conclusions

- Pulsars are unique tools for the study of fundamental physics, esp gravitation
- They provide clean and simple experiments as test masses with clocks
- The best example, the Double Pulsar, just gets better and better
- Best strong-field tests (incl. radiation test) provided by Double Pulsar
- Relativistic spin-precession now tested in strong-field regime
- Stringent limits for alternative theories of gravity
- MOND-like TeVeS theories are expected to be ruled out very soon
- Best test would be a PSR-BH system – we're looking for it!
- Pulsar around SGR A* would allow to test no-hair theorem at %-level!
- GW studies using pulsars would allow new probe of gravitational physics
- Direct detection of stochastic GW background may "soon" be possible
- Of course, studies will be "easy" and at a new level with the SKA, until then…