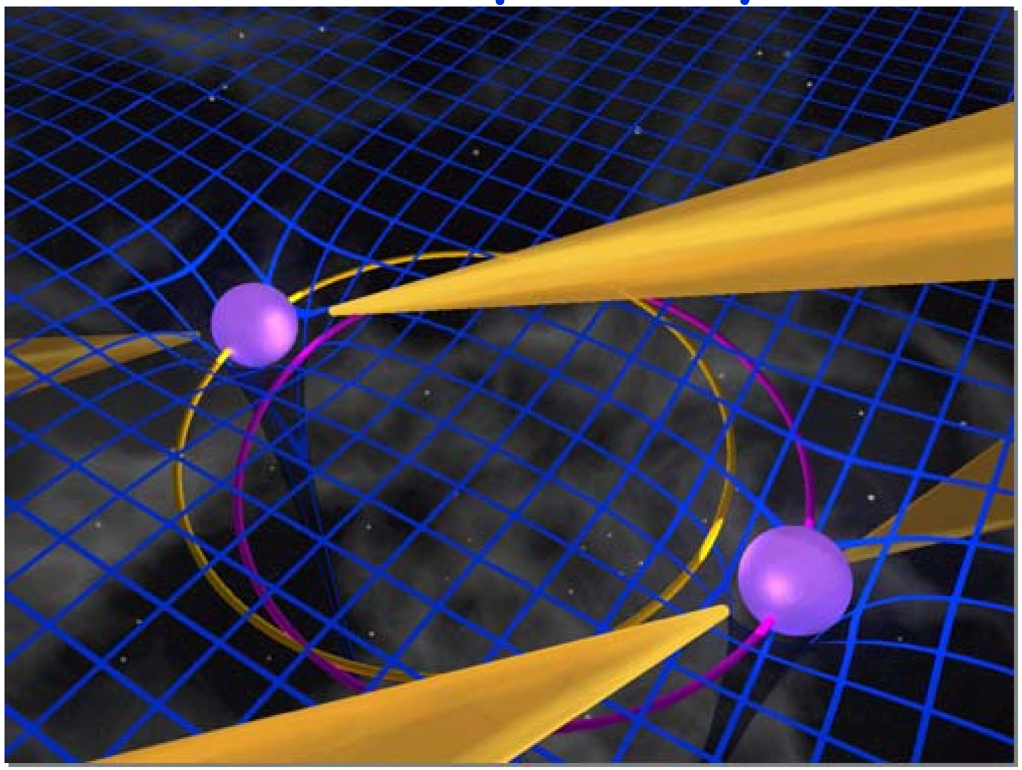
The University of Manchester
Jodrell Bank Observatory

The double pulsar system:



A unique lab for relativistic plasma physics and tests of general relativity

Michael Kramer

Bad Honnef – 15th May 2006

Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

The University of Manchester Jodrell Bank Observatory

MANCHESTER 1824

Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

Collaborators

I. Stairs, M.McLaughlin, R.Manchester, A. Lyne, R. Ferdman, M.Burgay, N.D'Amico, A.Possenti, I.Stairs R., P.Freire, F.Camilo

and N. Wex

The University of Manchester
Jodrell Bank Observatory

MANCHESTER 1824

Outline

- **The double pulsar**
- **A plasma & gravity lab**
- **Precision tests of GR**
- **Moment-of-inertia**
- **Frame-dragging**
- **Summary**

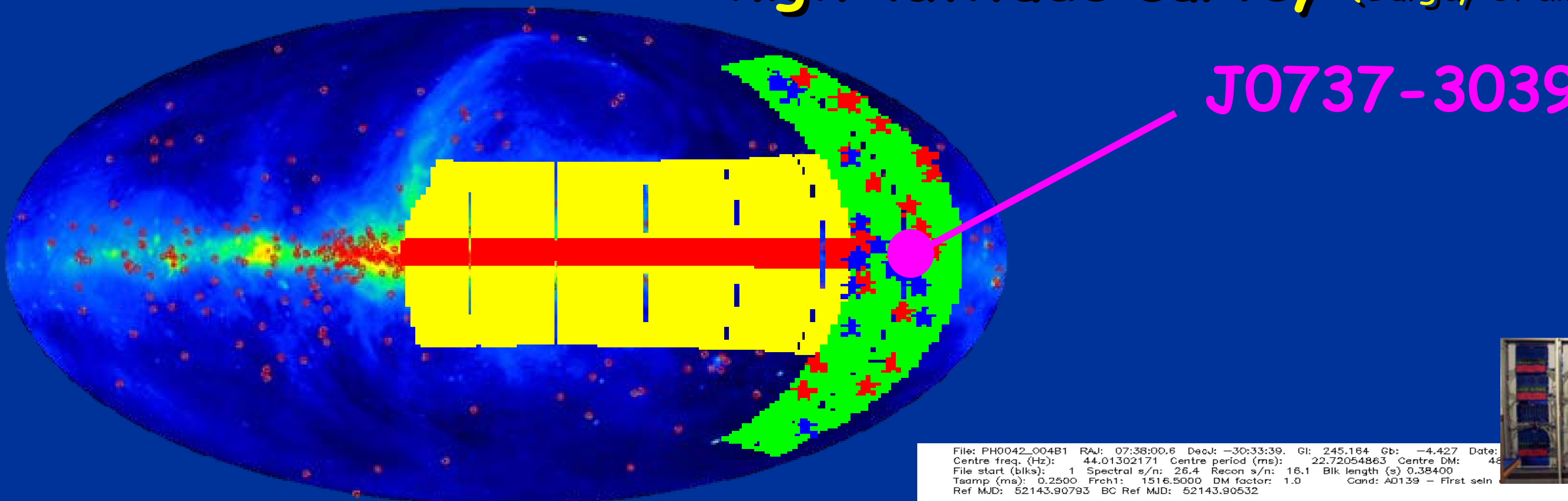
Collaborators

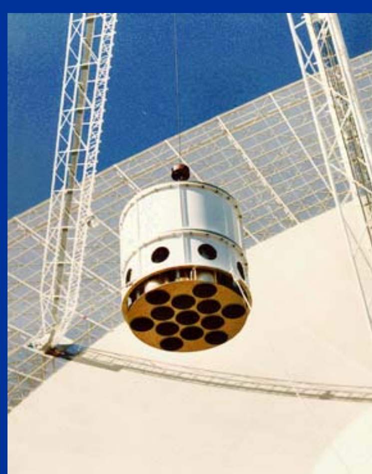
I. Stairs, M.McLaughlin, R.Manchester, A. Lyne, R. Ferdman, M.Burgay, N.D'Amico, A.Possenti, I.Stairs R., P.Freire, F.Camilo

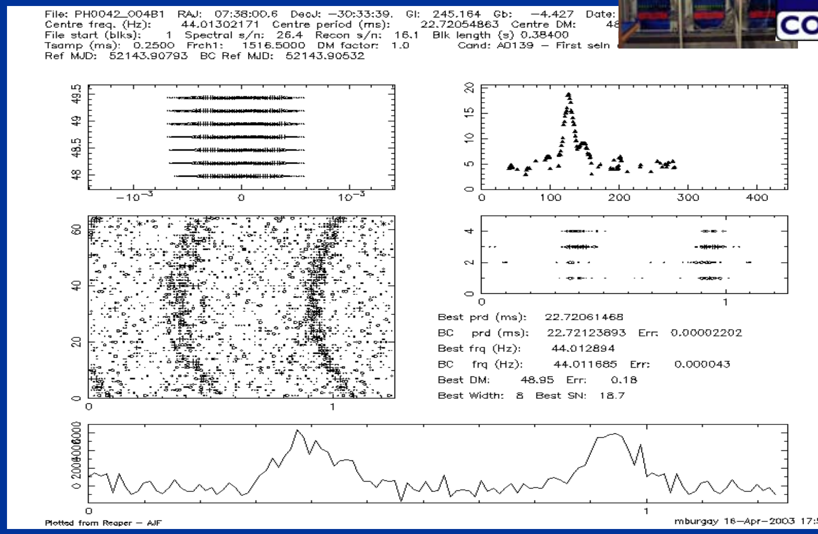
and N. Wex

The double pulsar

PSR J0737-3039 discovered in April 2003 at Parkes in high-latitude survey (Burgay et al. 2006) **:**

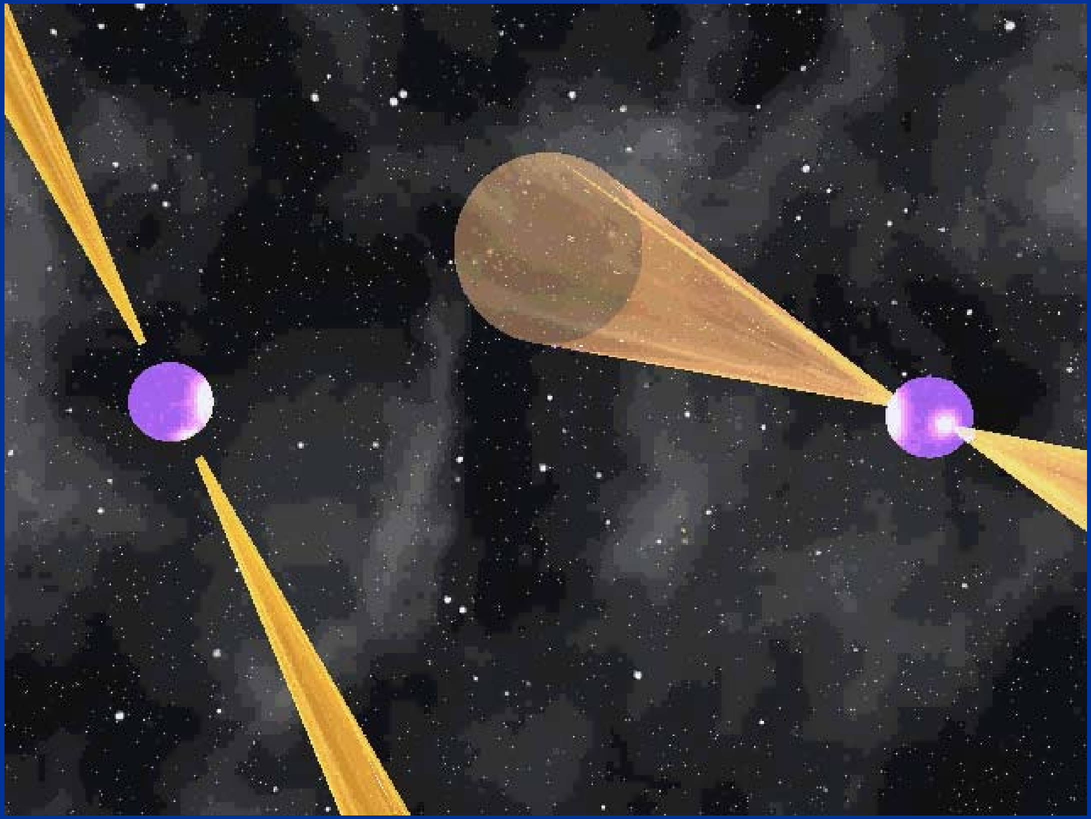






MANCHESTER 1824
The University of Manchester
Jodrell Bank Observatory

The first double pulsar system



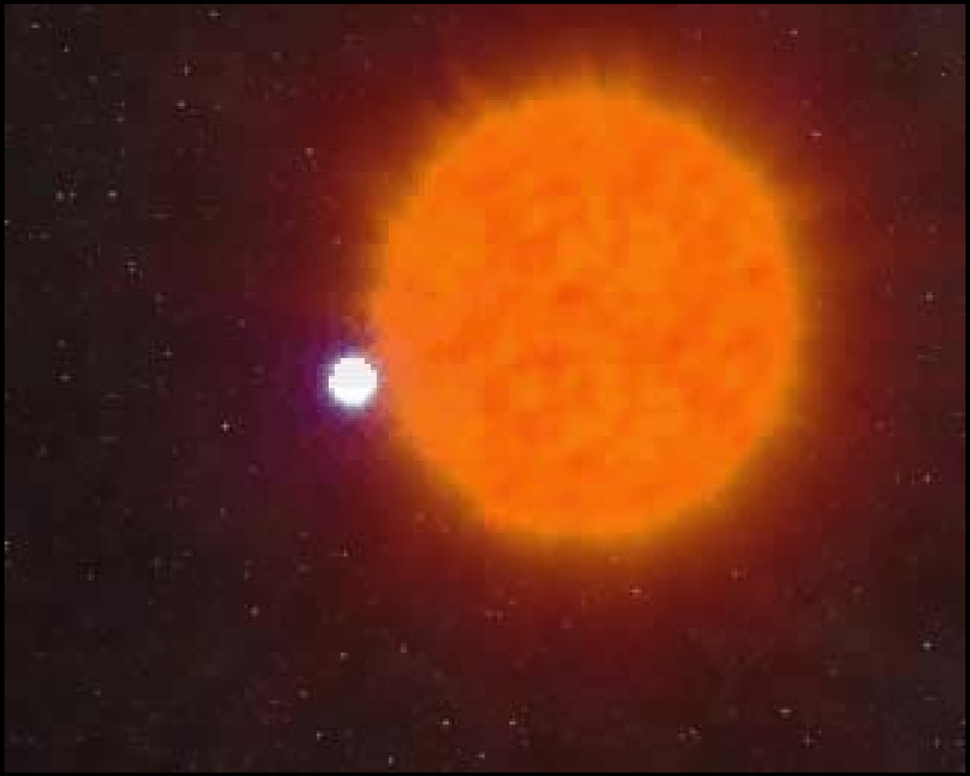
- A young 2.77-s pulsar in a 2.4-hr orbit with an old 22-ms pulsar.
- Orbit size ~ Sun, with orbital velocities of 1 Million km/h!
- Ideal lab for gravitational physics and understanding pulsars.

Burgay et al. (2003), Lyne et al. (2004)

Basic parameters

	A:	B:
P	22.7 ms	2.77 s
$\dot{P}$	1.7×10^{-18}	0.82×10^{-15}
Char.age	200 Myr	50 Myr
B_{surf}	6×10^{9} G	1.6×10^{12} G
R_{LC}	1,080 km	1.32×10^{5} km
B_{LC}	5×10^{3} G	0.7 G
dE/dt	6×10^{33} erg s^{-1}	1.6×10^{30} erg s^{-1}
Mean V_{orb}	301 km s^{-1}	323 km s^{-1}

Birth & Rebirth in the double pulsar

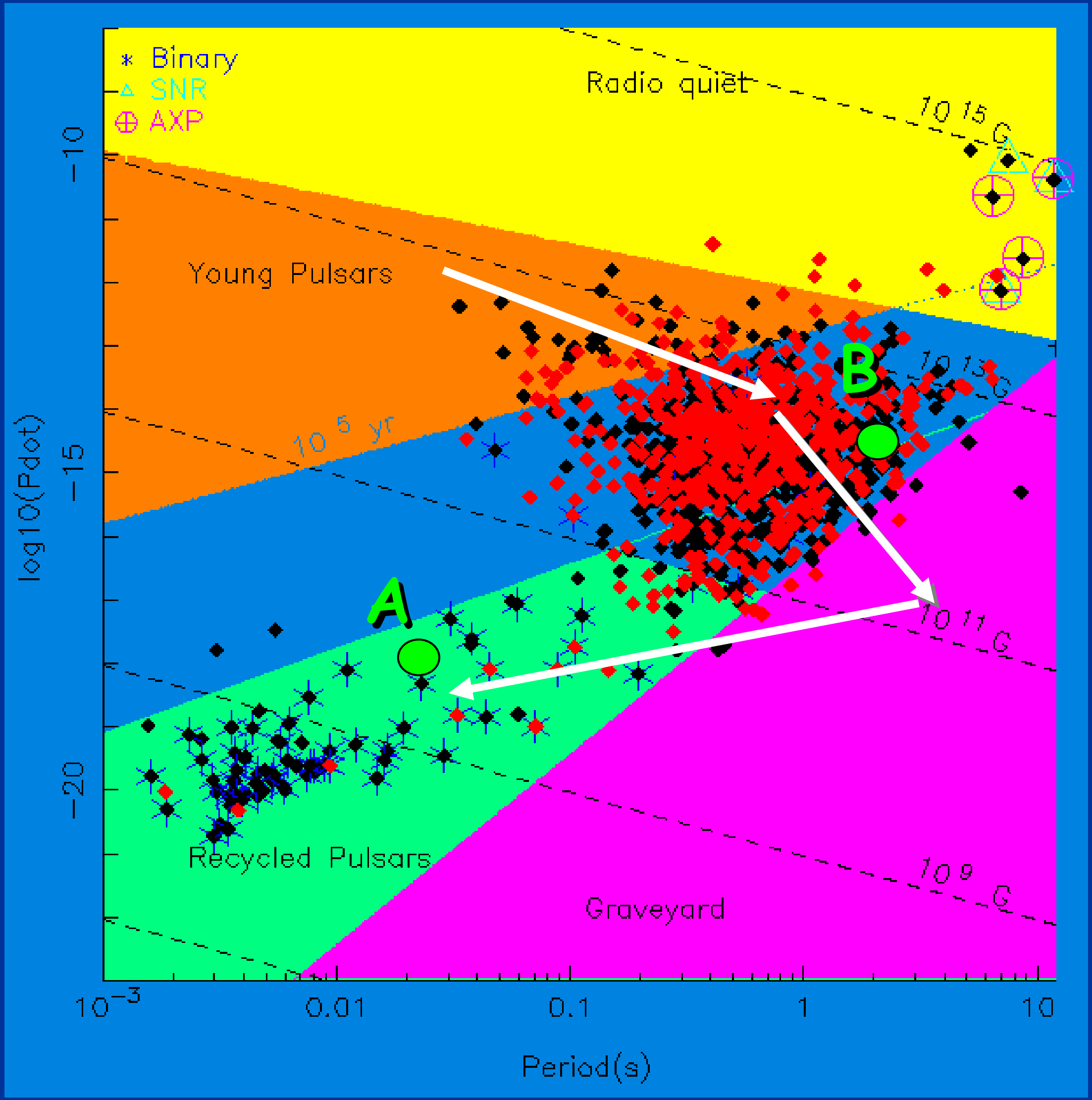


1. First pulsar is born in Supernova explosion
2. First pulsar is spun up by mass transfer from companion
3. Second pulsar is born in Supernova explosion

Dramatic confirmation of evolutionary theories!

The University of Manchester
Jodrell Bank Observatory

The life of pulsars



Outline

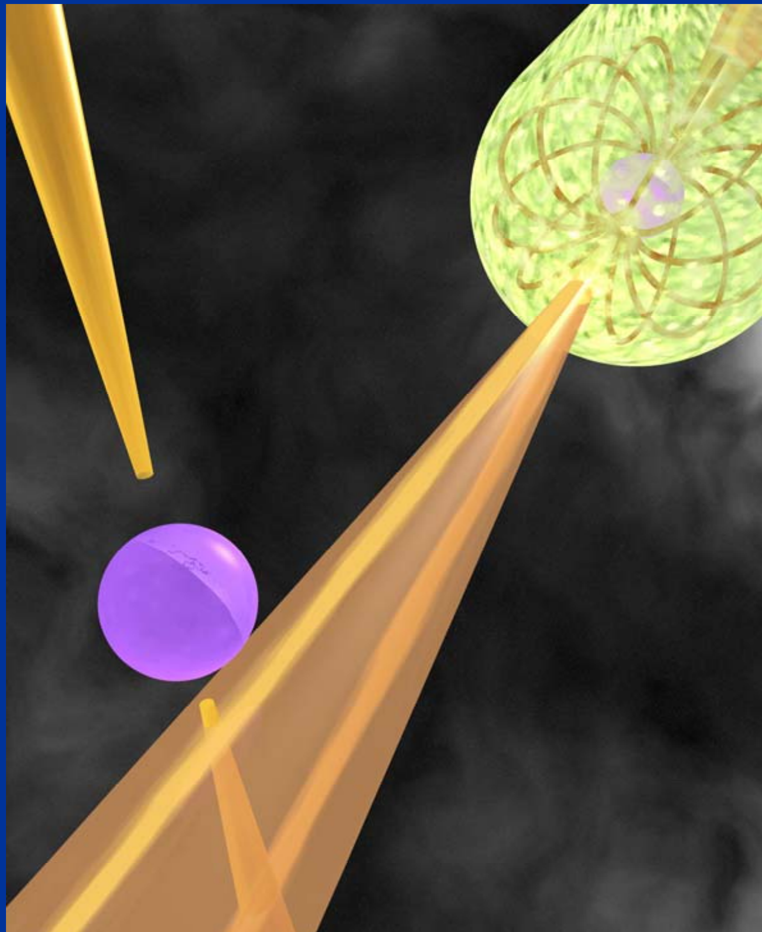
- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

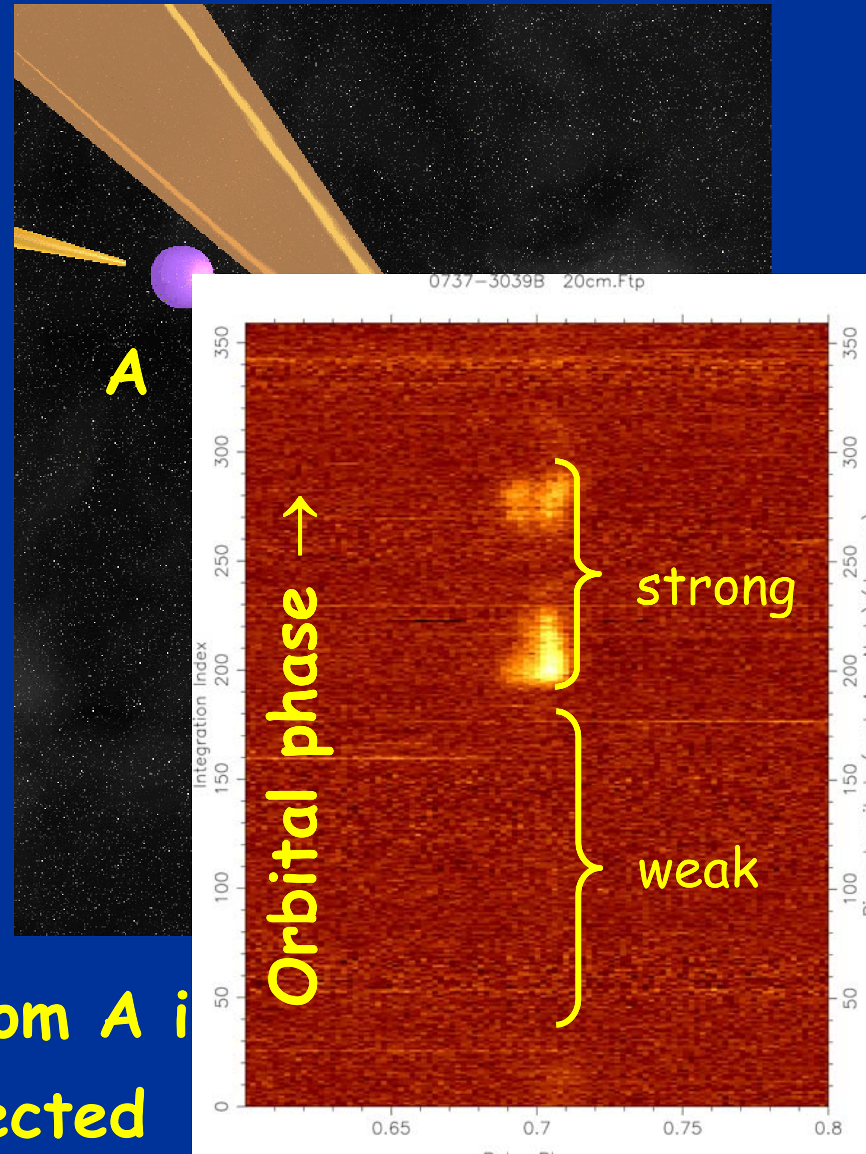
Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

The University of Manchester
Jodrell Bank Observatory
MANCHESTER 1824

Blowing in the wind...

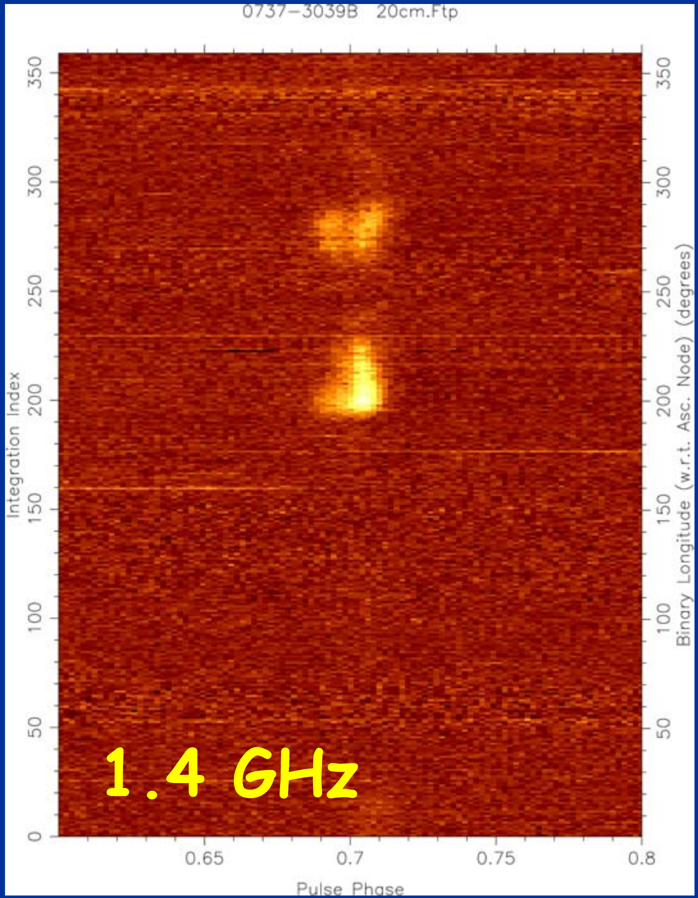


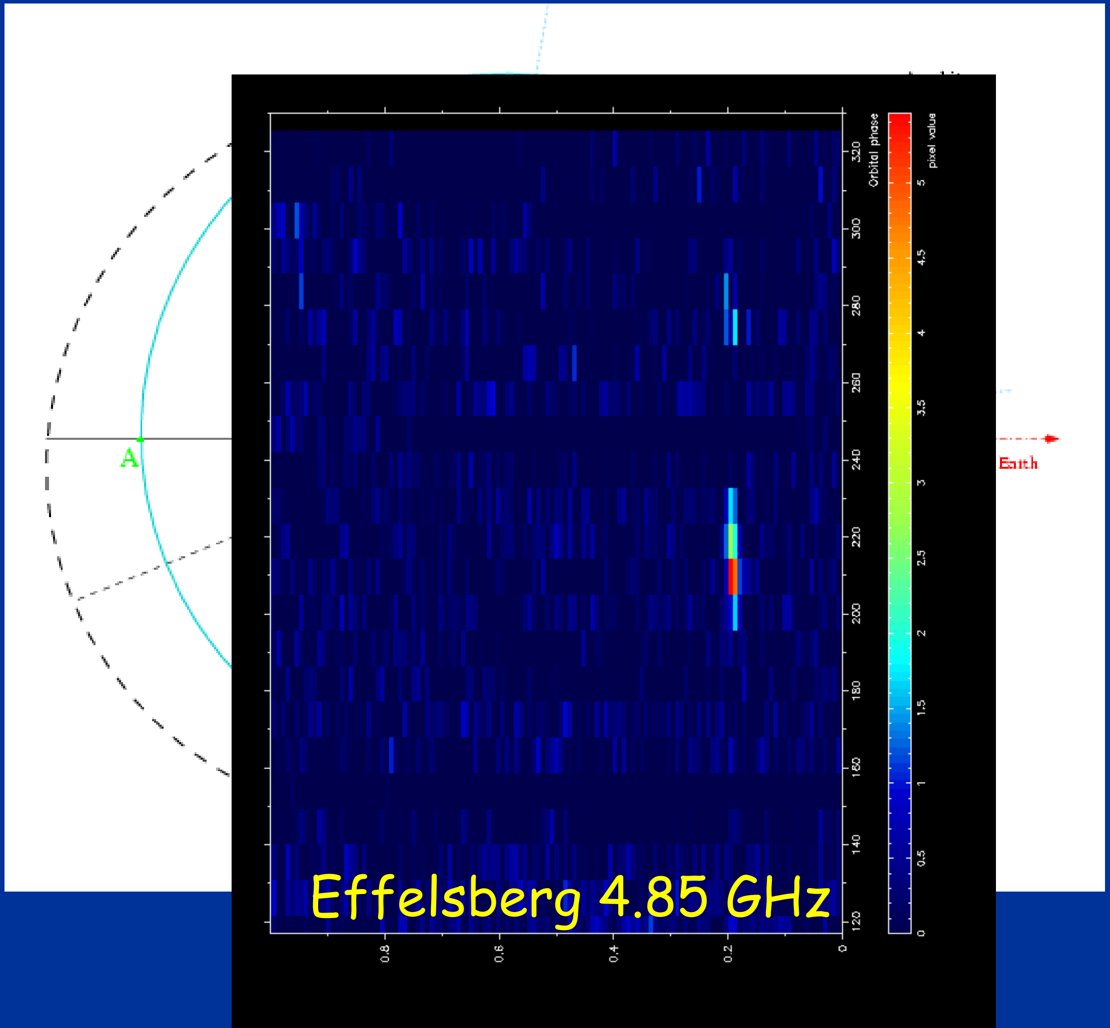


- An energetic pulsar wind from A i
- The emission from B is affected
- B is only visible for short parts of the orbit!

Orbital modulation of “B” emission

Two bright intervals near inferior conjunction:

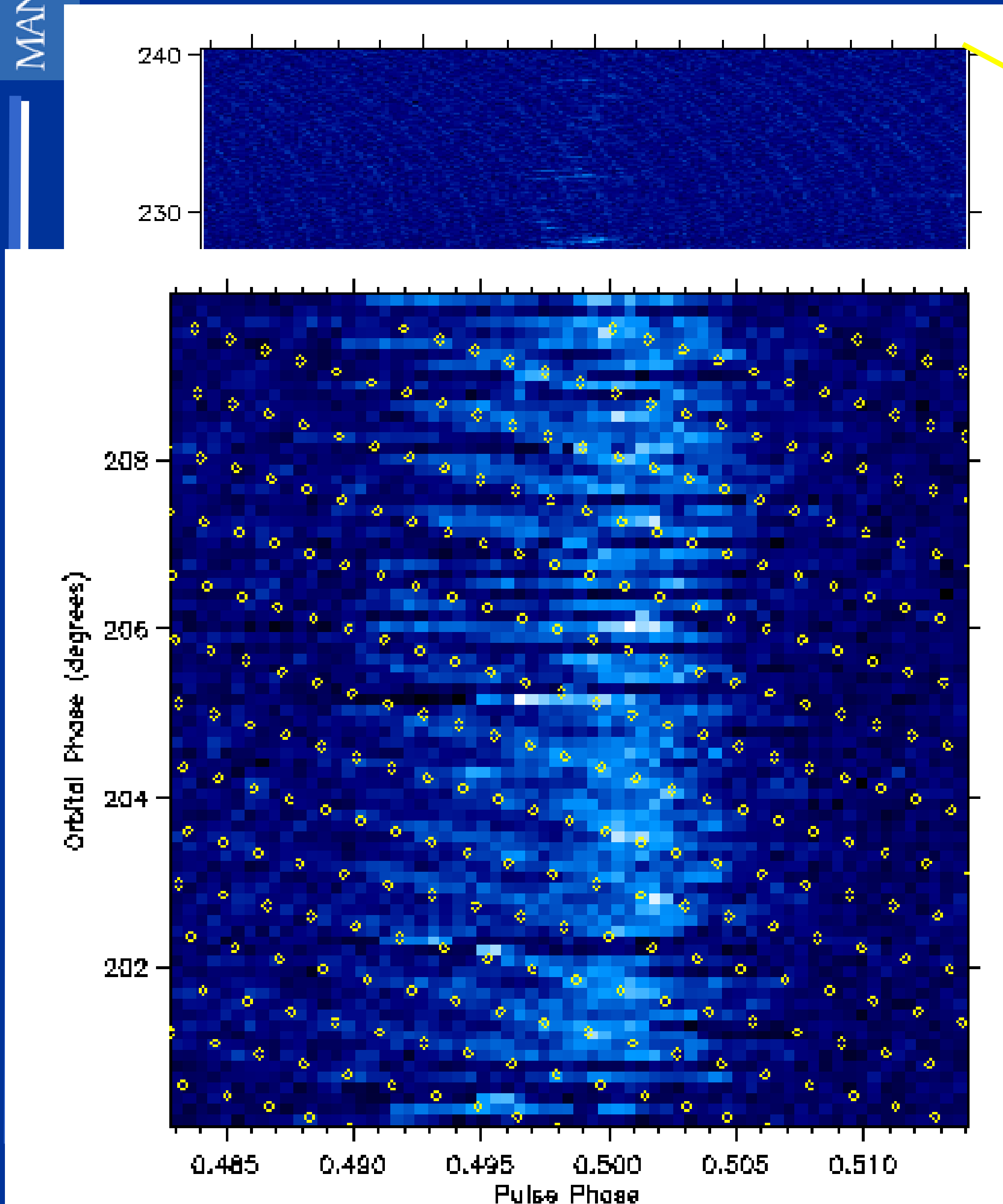


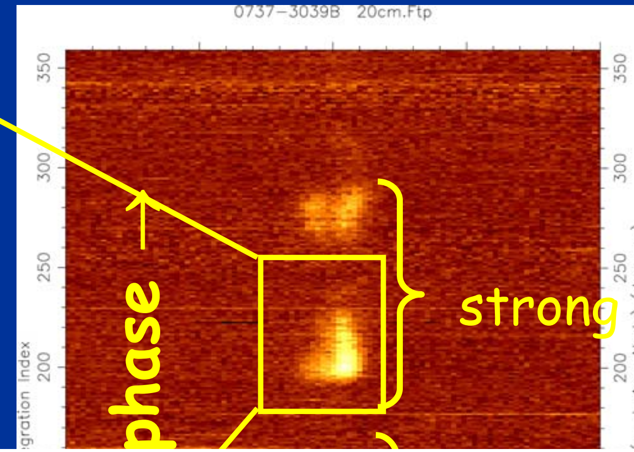


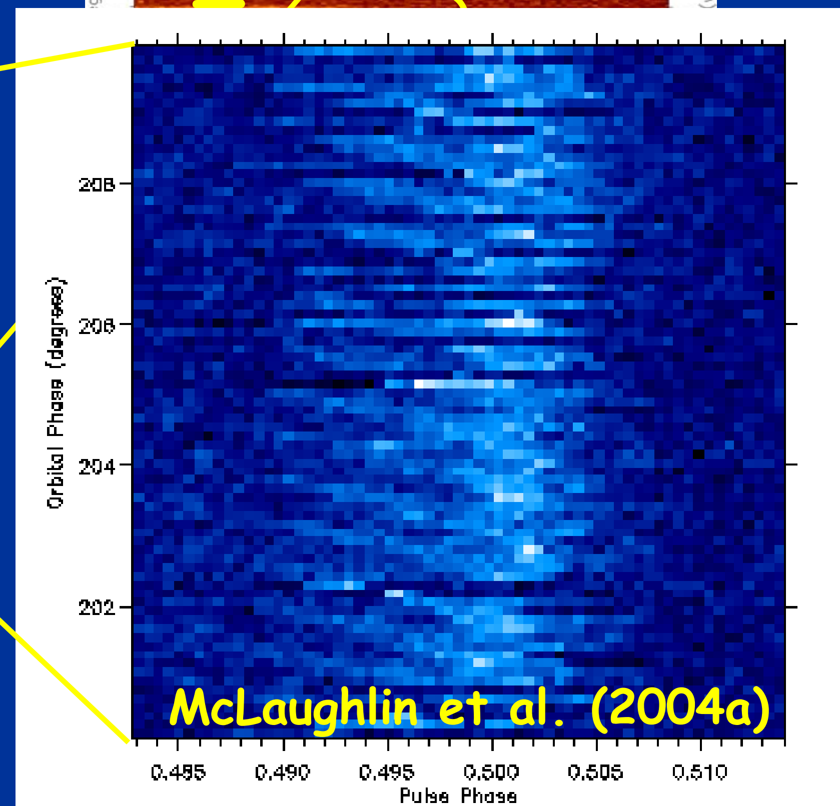
The University of Manchester
Jodrell Bank Observatory

MANCHESTER 1824

Direct modulation of B's emission by A

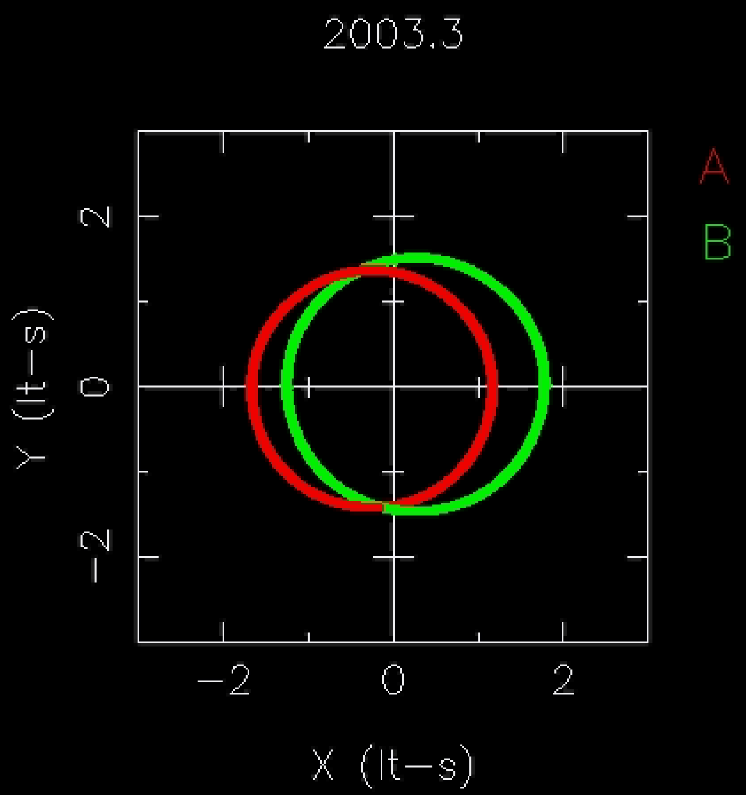




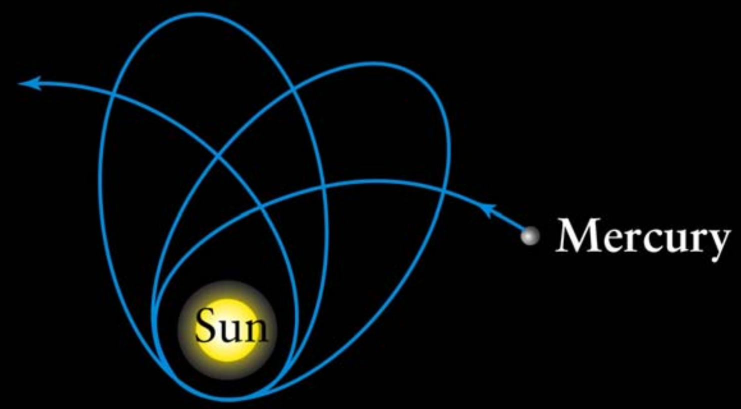


Huge precession of orbit!

Orbit precesses by 17 deg/yr!



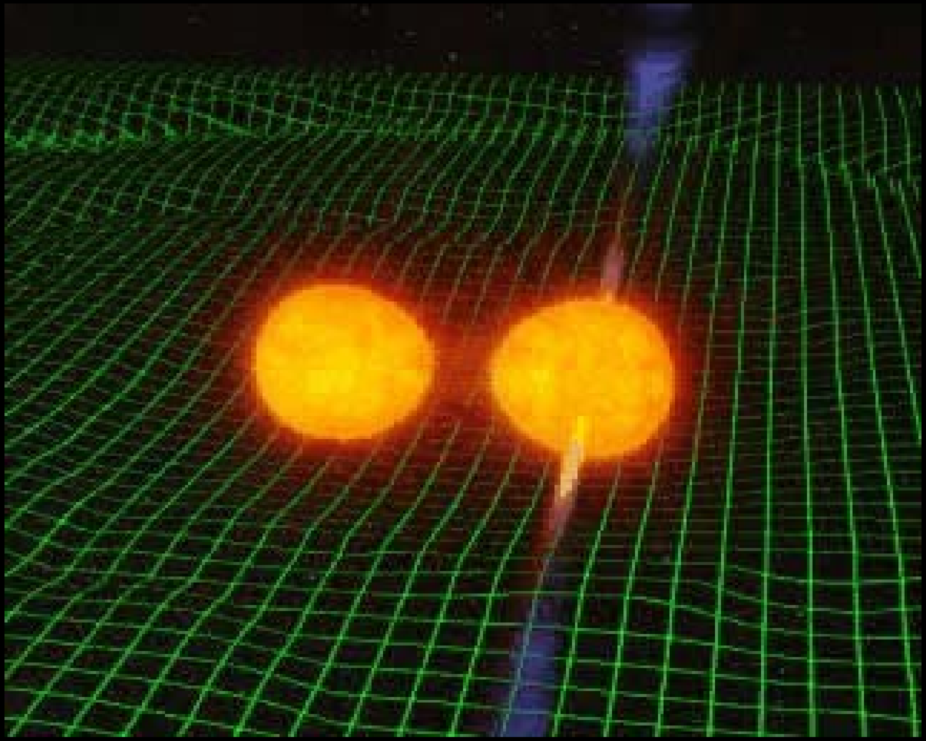
Remember Mercury:
$\dot{\omega} = 0.00012 \mathrm{deg}/yr$

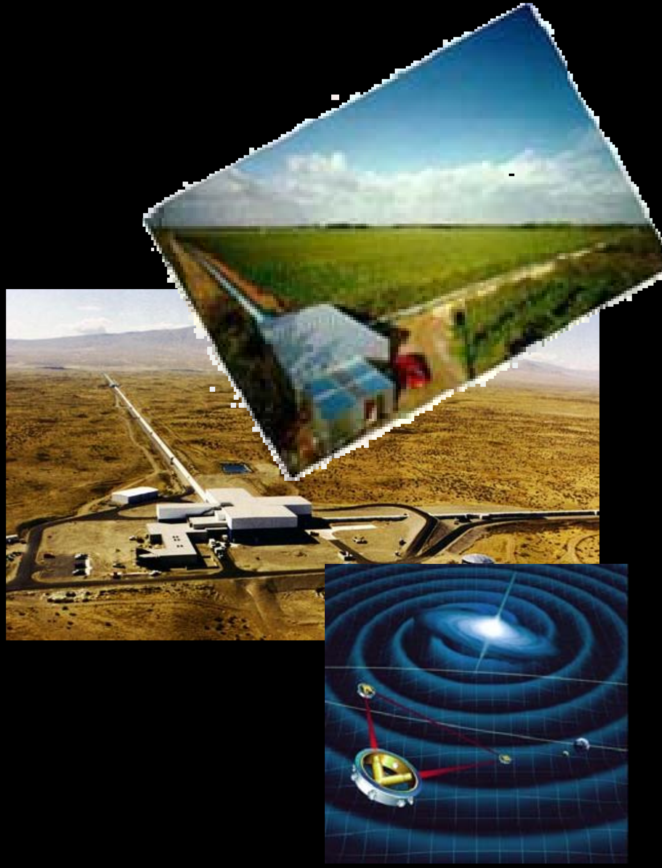


- Measured within a few days of observations!
- One full revolution in about 20 years!
  (compared to 3 Million years for Mercury)

Orbit is shrinking by 7mm per day!

- Change in orbital period due shrinking orbit
- Neutron stars will collide in 85 Million years due to gravitational wave emission!

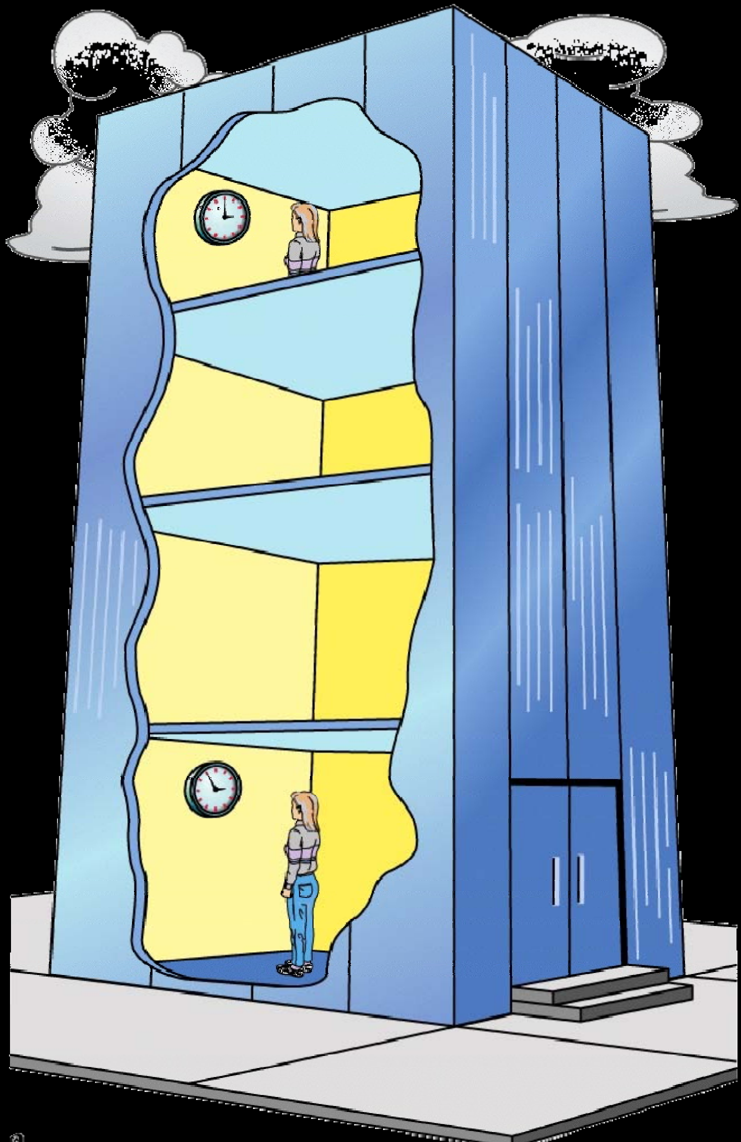




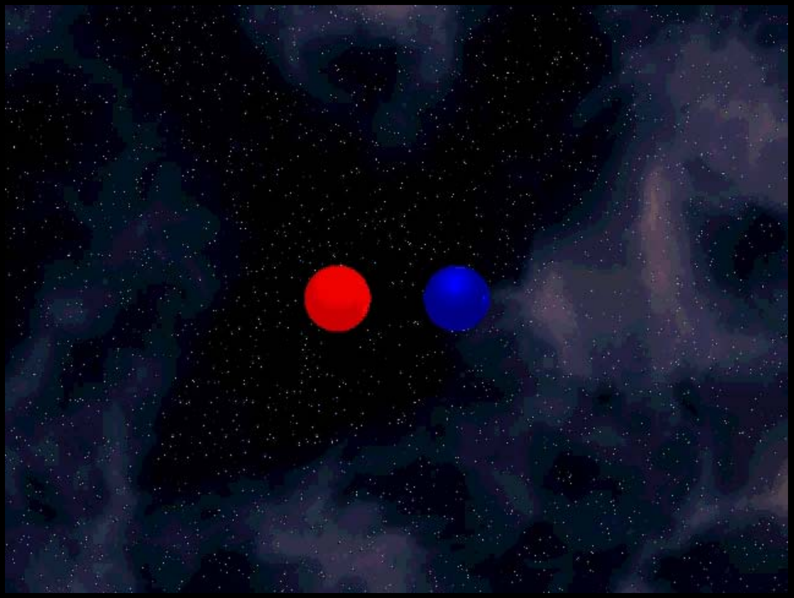
- Discovery boosts expected LIGO detection rates by almost an order of magnitude…!

Pulsar clock slows down near companion!

Clocks are running slower in deep gravitational fields



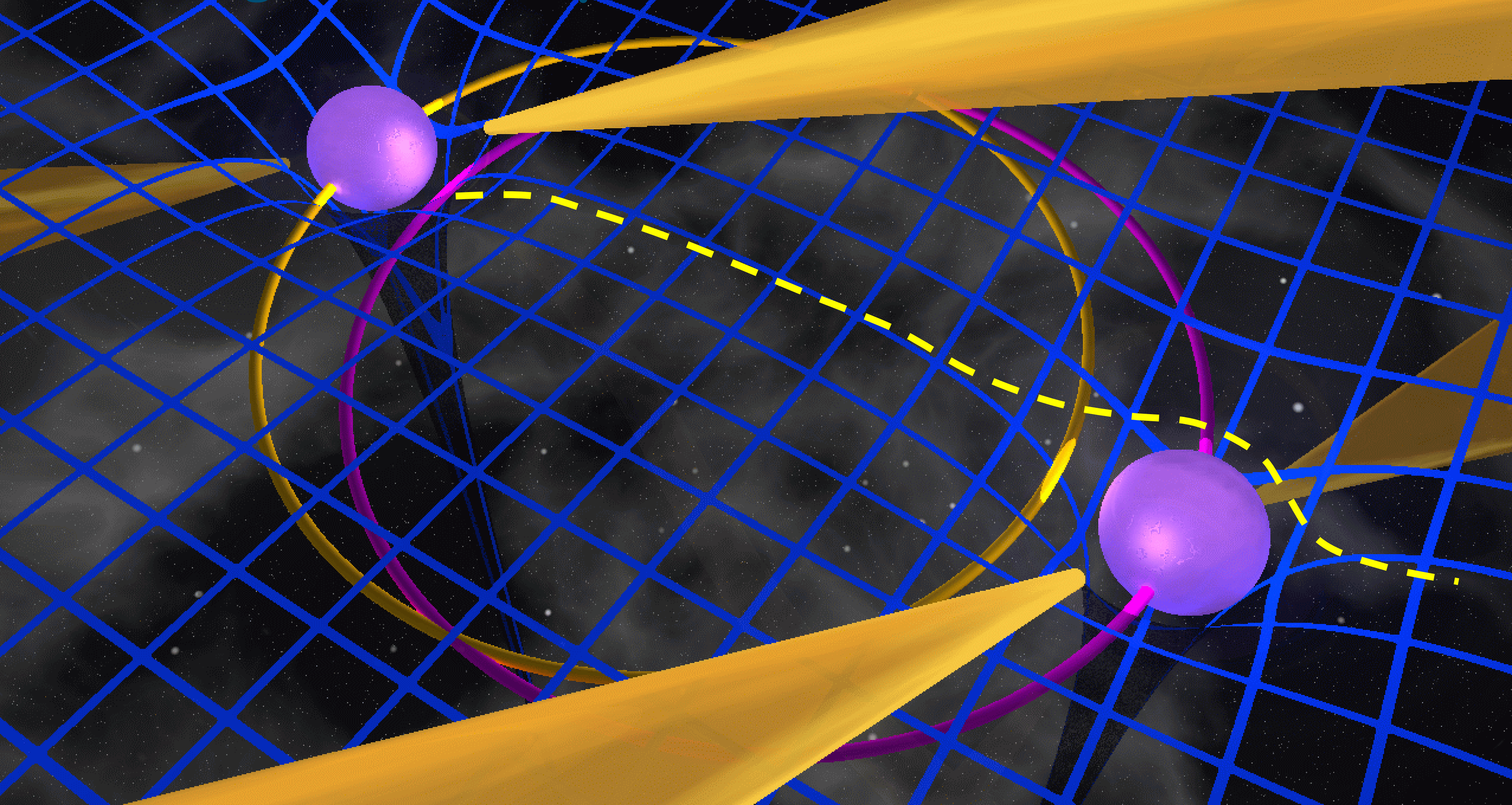
Pulsars' separation is changing during orbit:



Pulsars are running slower and faster during orbit by about 380 microseconds! (grav.redshift + 2nd order Doppler)

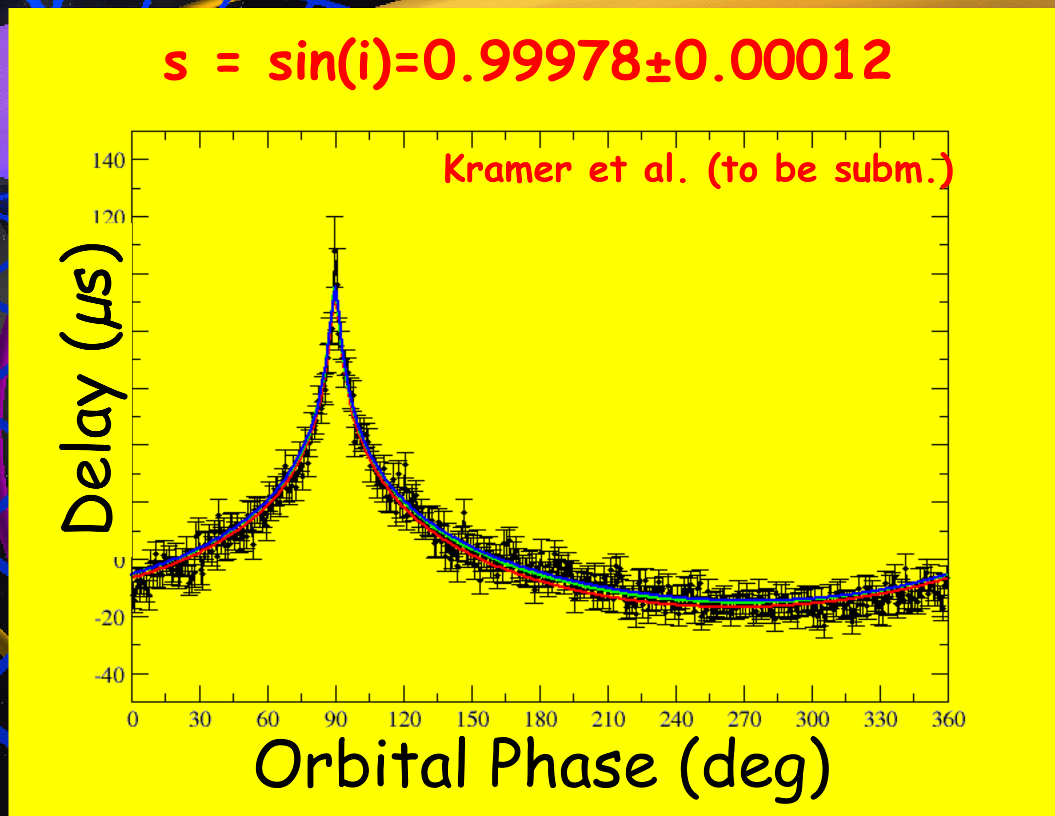
Space-time is curved near pulsar

Pulses of A are delayed when propagating through curved space-time near B:



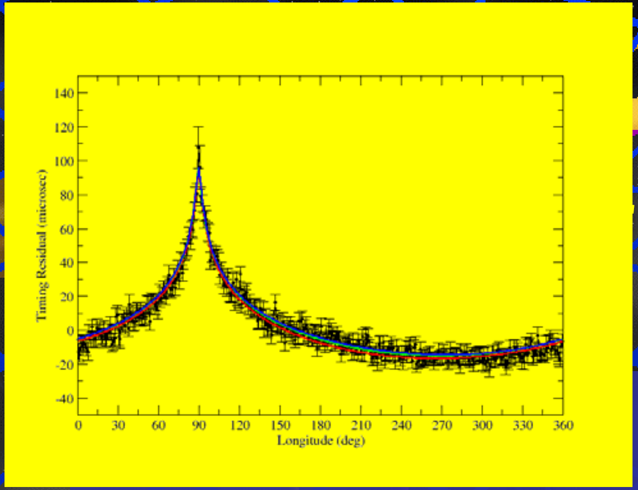
Space-time is curved near pulsar

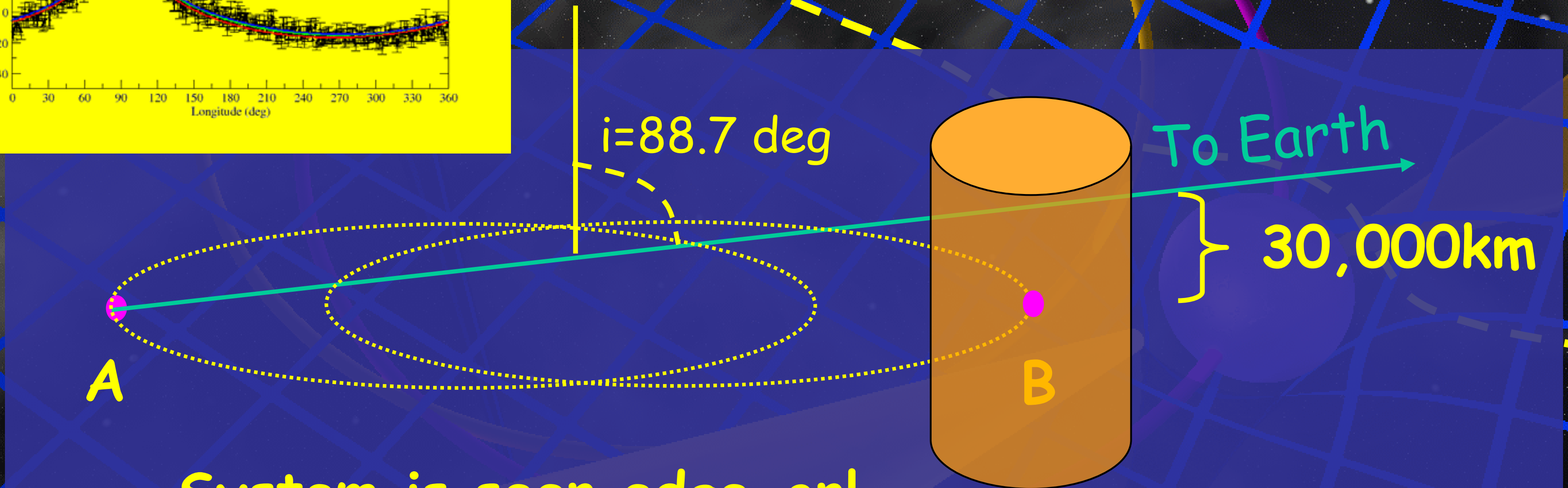
Pulses of A are delayed when propagating through curved space-time near B:



Space-time is curved near pulsar

Pulses of A are delayed when propagating through curved space-time near B:

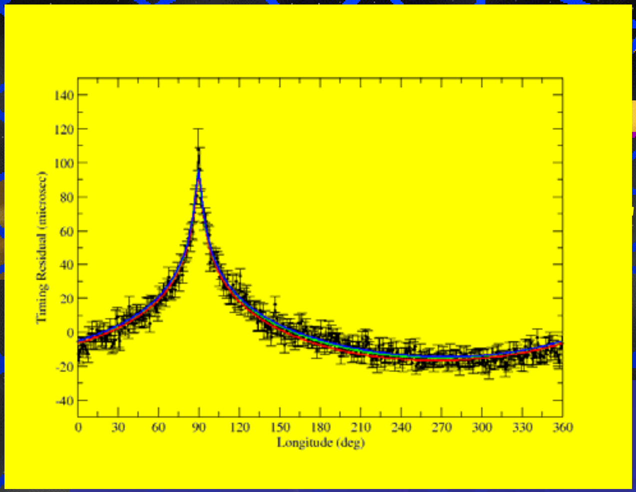


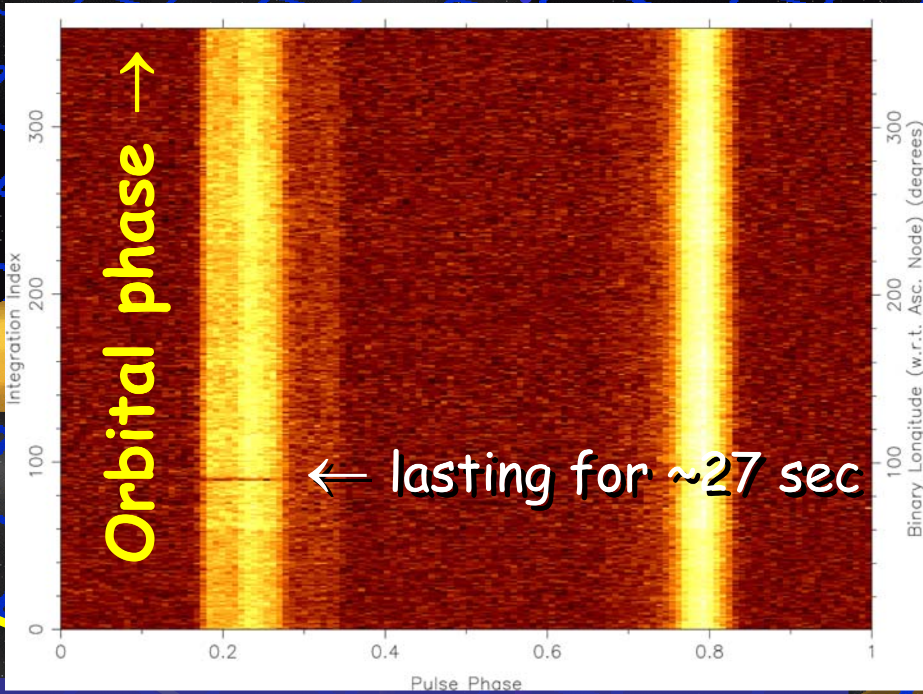


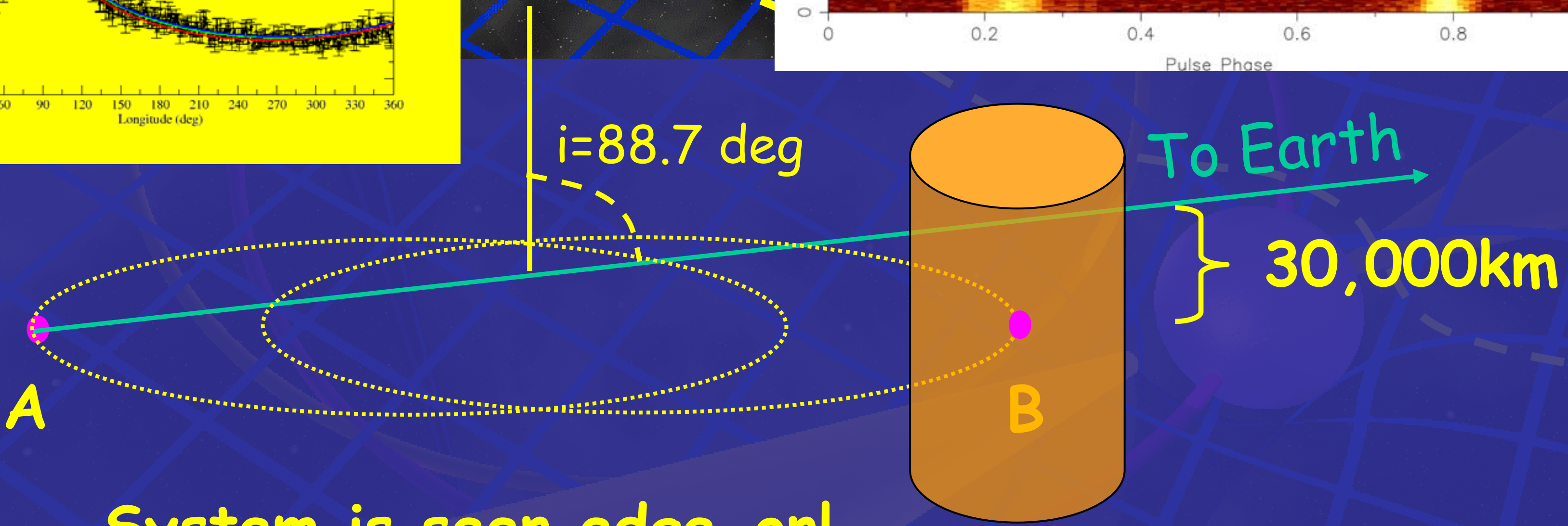
System is seen edge-on!

Space-time is curved near pulsar

Also, eclipses of A:

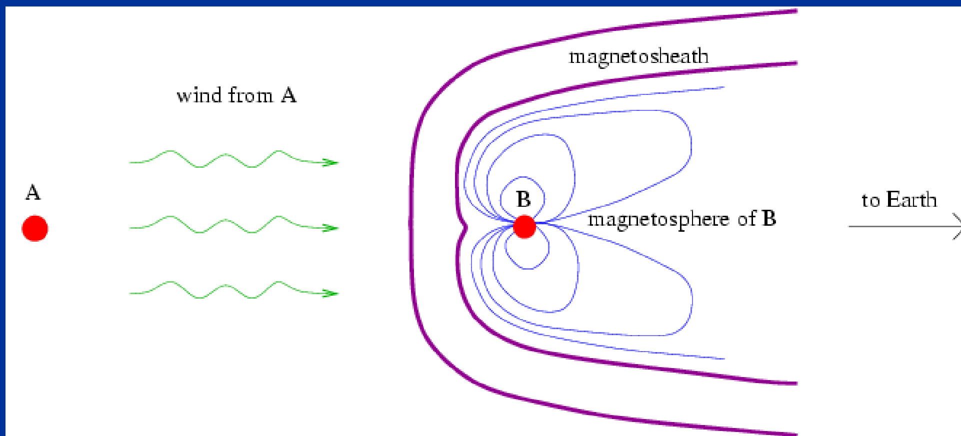


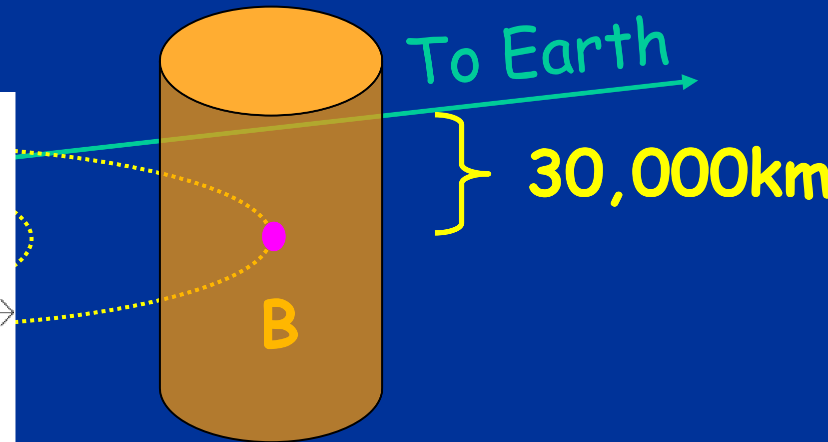


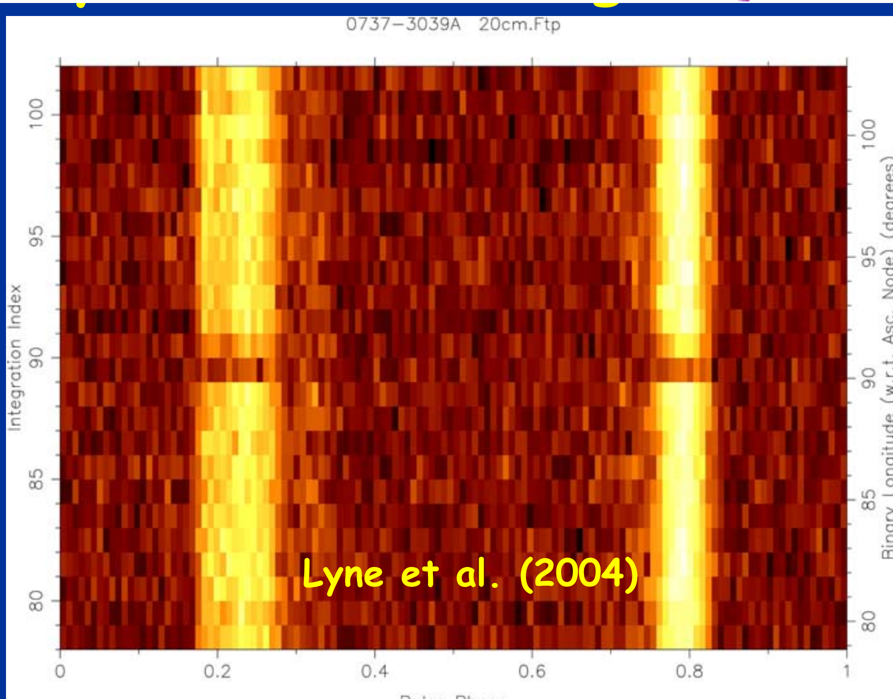


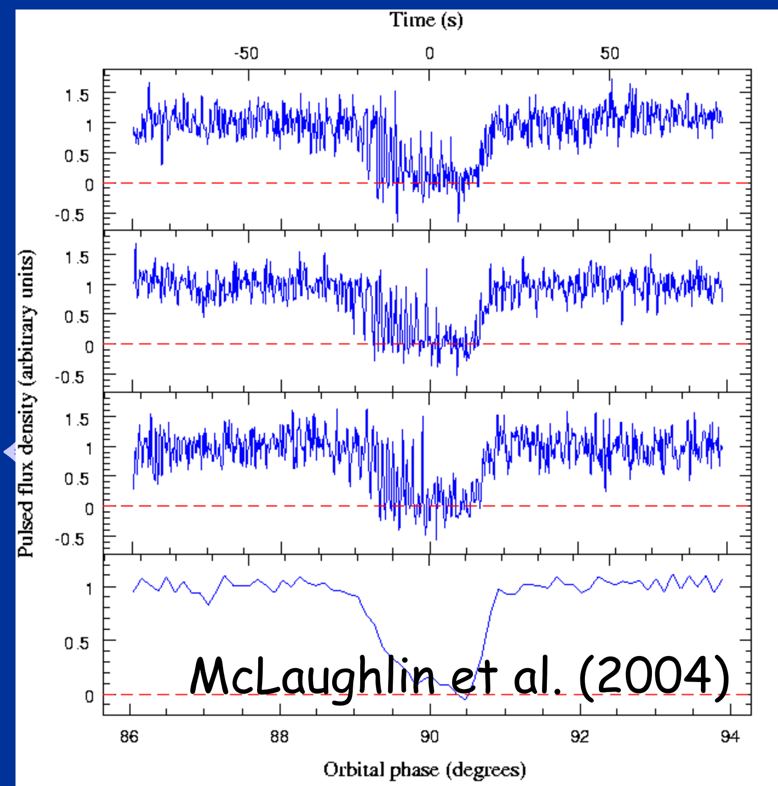
System is seen edge-on!

Eclipses of A

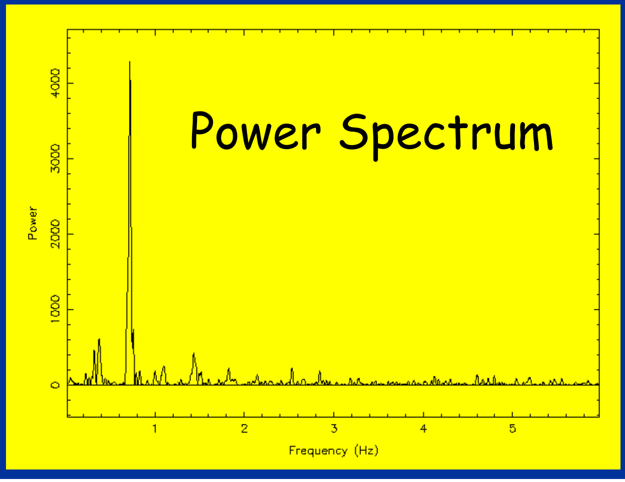


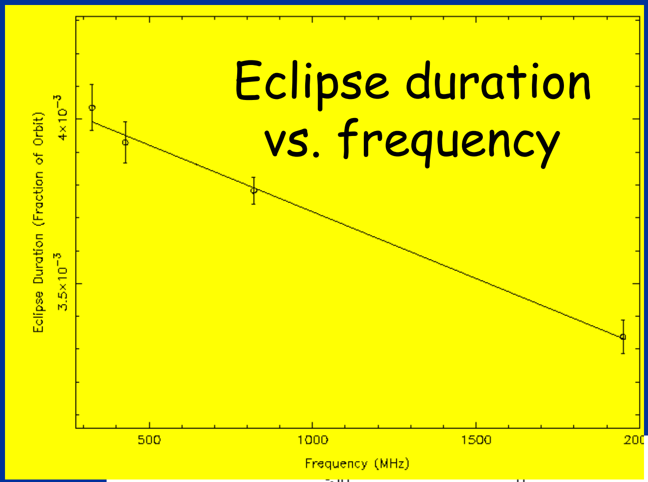


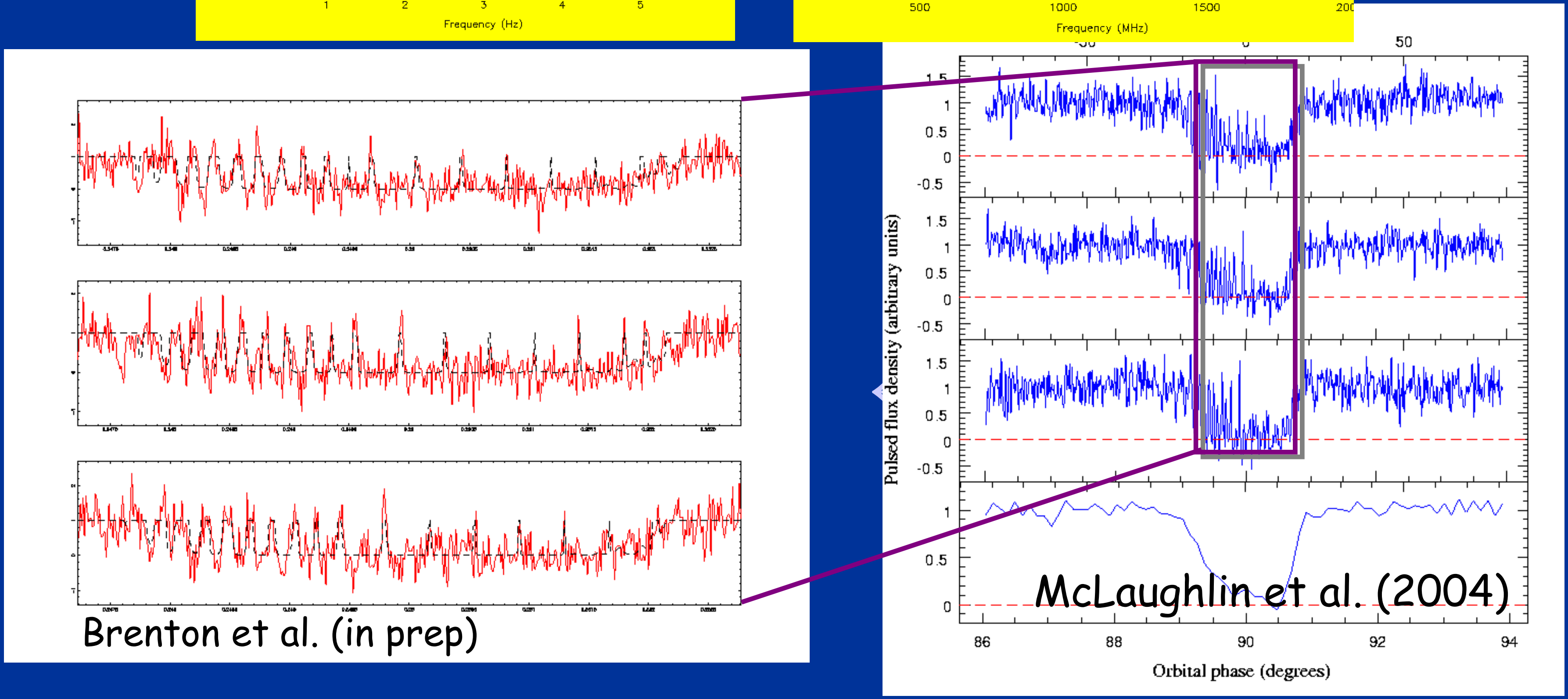




Eclipses of A







Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

Outline

- The double pulsar
- A plasma & gravity lab
- **Precision tests of GR**
- Moment-of-inertia
- Frame-dragging
- Summary

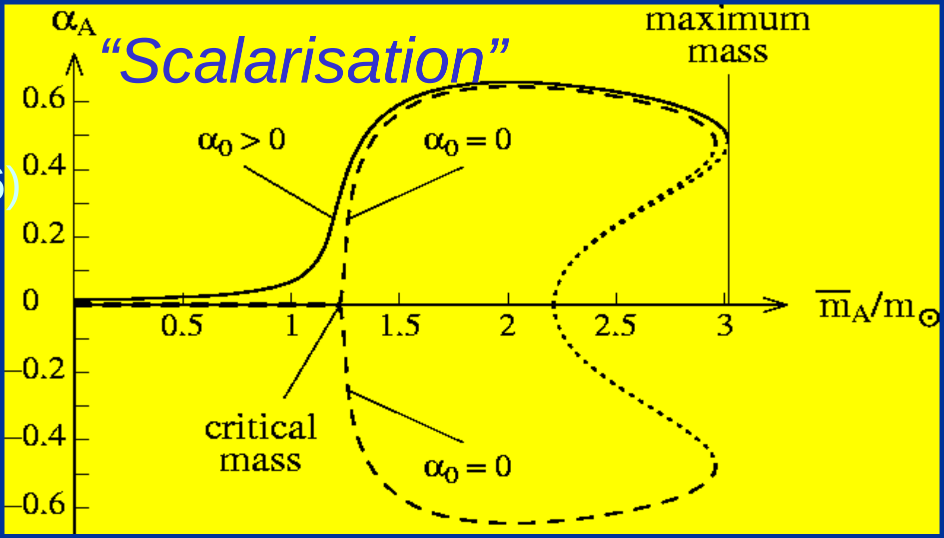
Testing Einstein

Experiments made in Solar System provide accurate tests …but only in weak gravitational field!

In strong gravitational fields, physics may be different!

E.g. additional scalar field may appear in strong fields:

Scalar Charge (for β_0=-6)



Damour & Esposito-Farese (1996)

Testing Einstein

Experiments made in Solar System provide accurate tests
...but only in weak gravitational field!

In strong gravitational fields, physics may be different!

Compute energy in gravitational field:

$$\varepsilon = \frac{E_{gravity}}{mc^2}$$

Neutron stars & Black Holes:

$$\varepsilon_{NS} \approx 0.15$$

$$\varepsilon_{BH} \approx 0.5$$

Solar system:

$$\varepsilon_{Sun} \approx 0.000001$$

$$\varepsilon_{Earth} \approx 0.0000000001$$

$$\varepsilon_{Moon} \approx 0.00000000001$$

Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity

(Damour & Taylor '92)

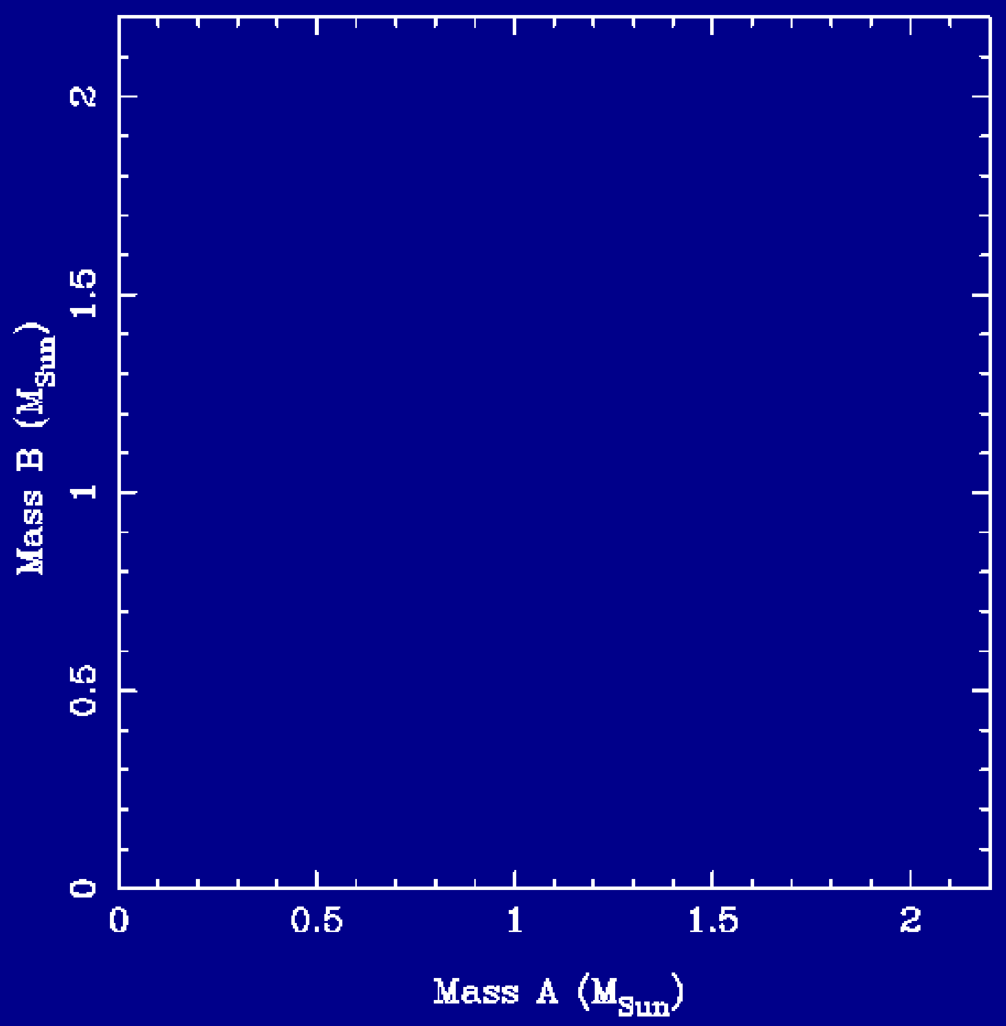
Effects can be described as Post-Keplerian params as function of only the observed Keplerian parms and the masses of pulsar and companion, eg in GR:

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

$$PK = f(K, m_p, m_c)$$

f, g depend on theory!

$$m_c = g(K, PK, m_p)$$



Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity

(Damour & Taylor '92)

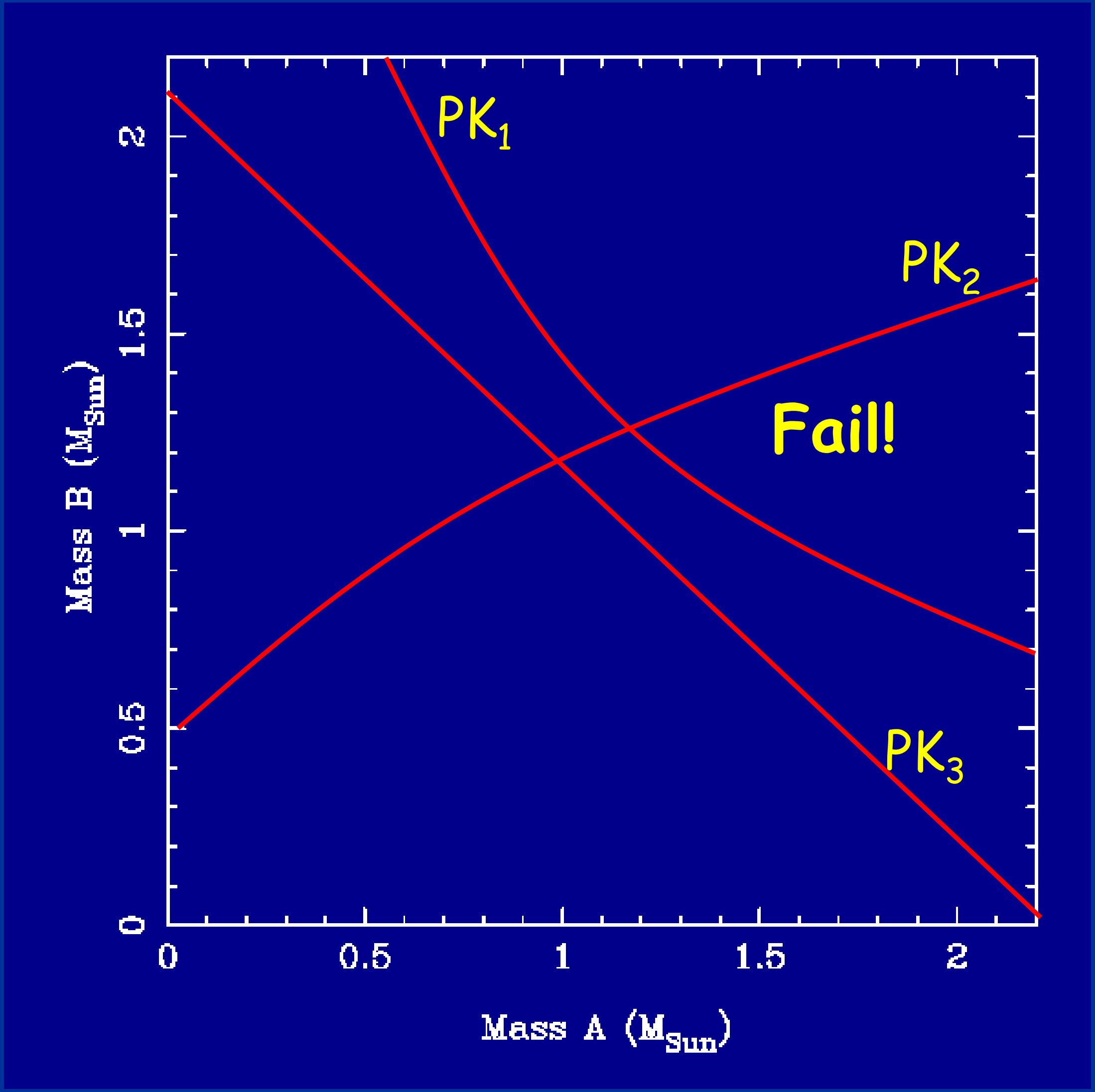
Effects can be described as Post-Keplerian params as function of only the observed Keplerian parms and the masses of pulsar and companion, eg in GR:

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

$$PK = f(K, m_p, m_c)$$

f, g **depend on theory!**

$$m_c = g(K, PK, m_p)$$



Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity

(Damour & Taylor '92)

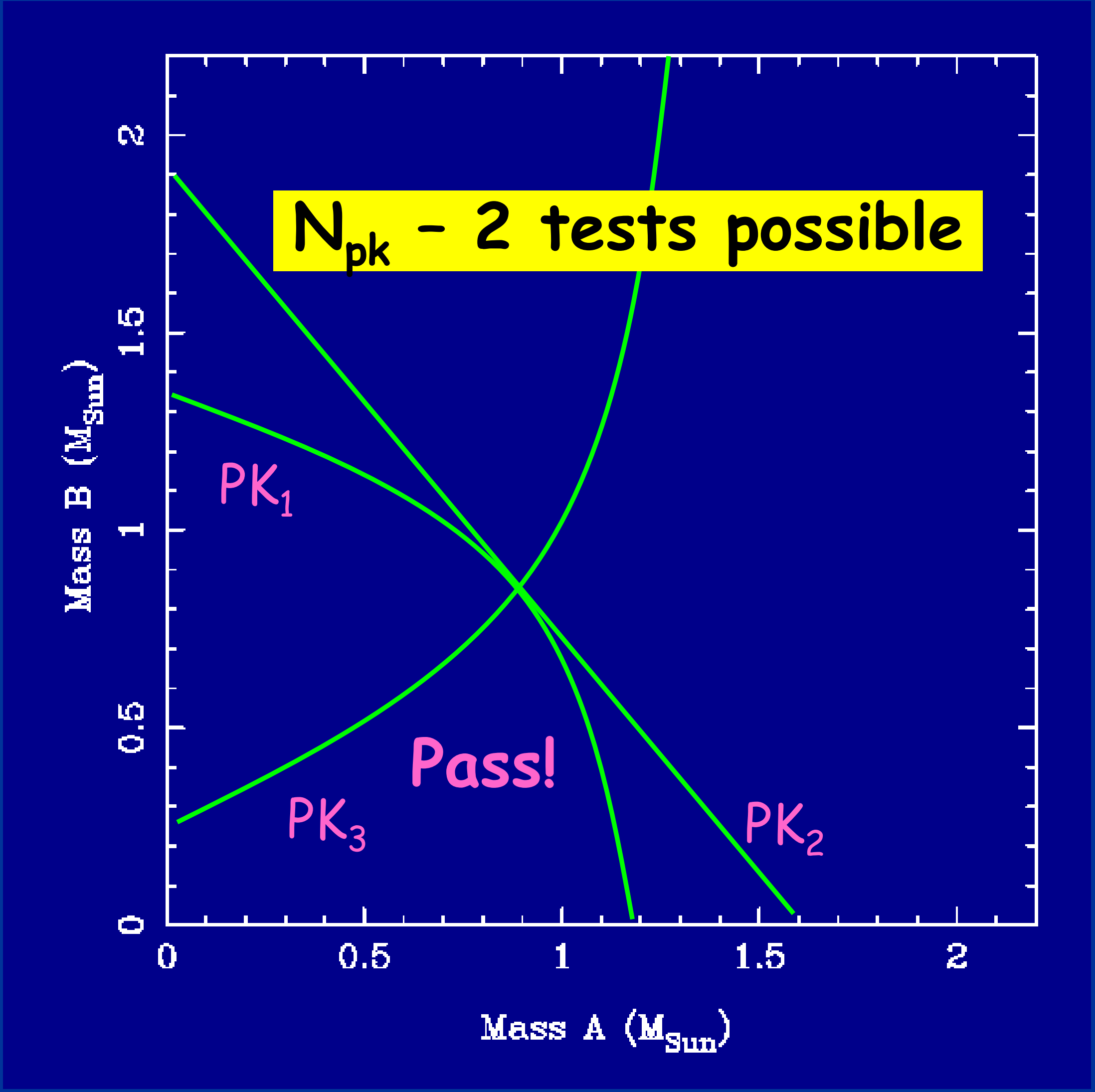
Effects can be described as Post-Keplerian params as function of only the observed Keplerian parms and the masses of pulsar and companion, eg in GR:

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

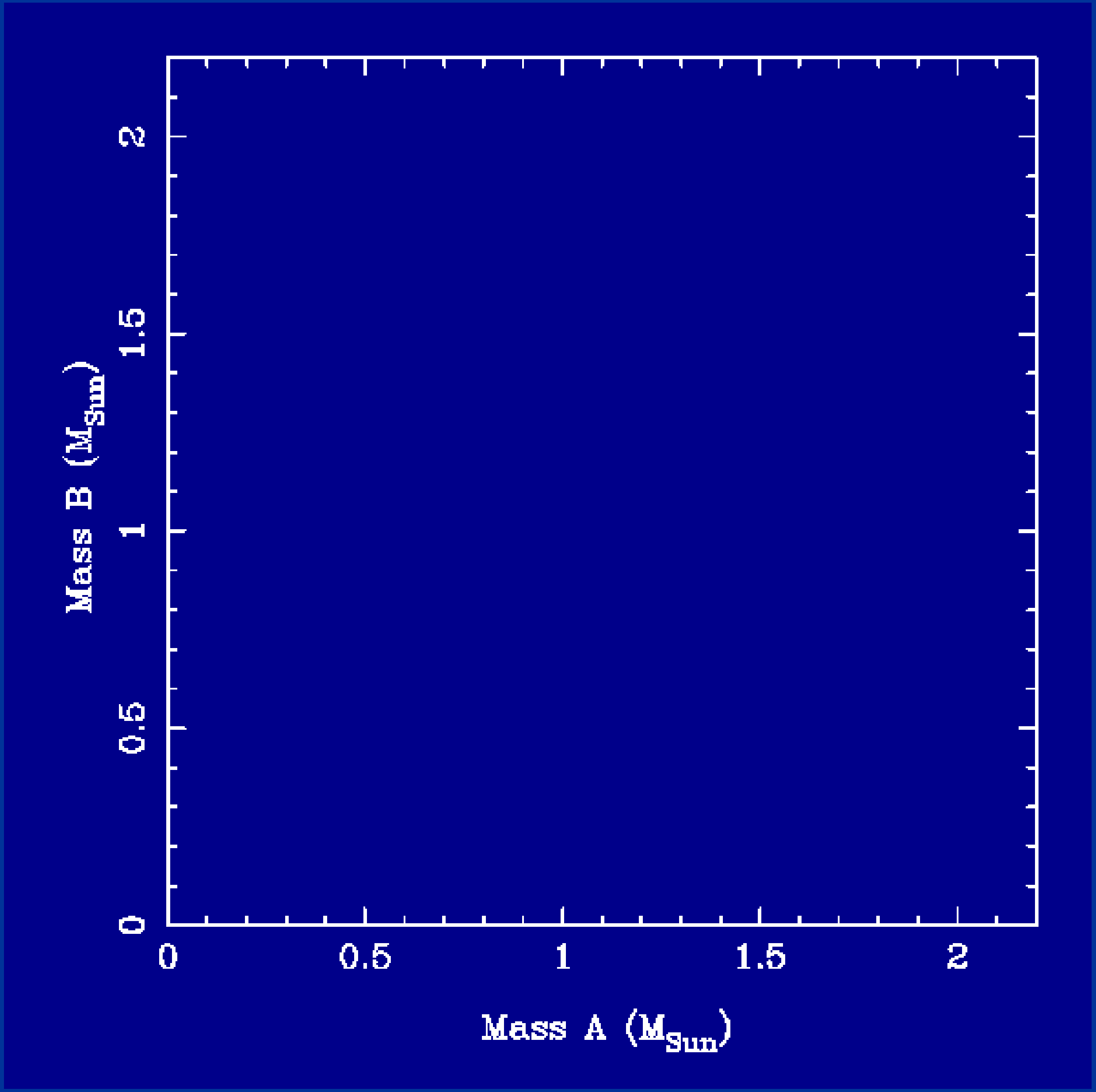
$$PK = f(K, m_p, m_c)$$

f, *g* depend on theory!

$$m_c = g(K, PK, m_p)$$

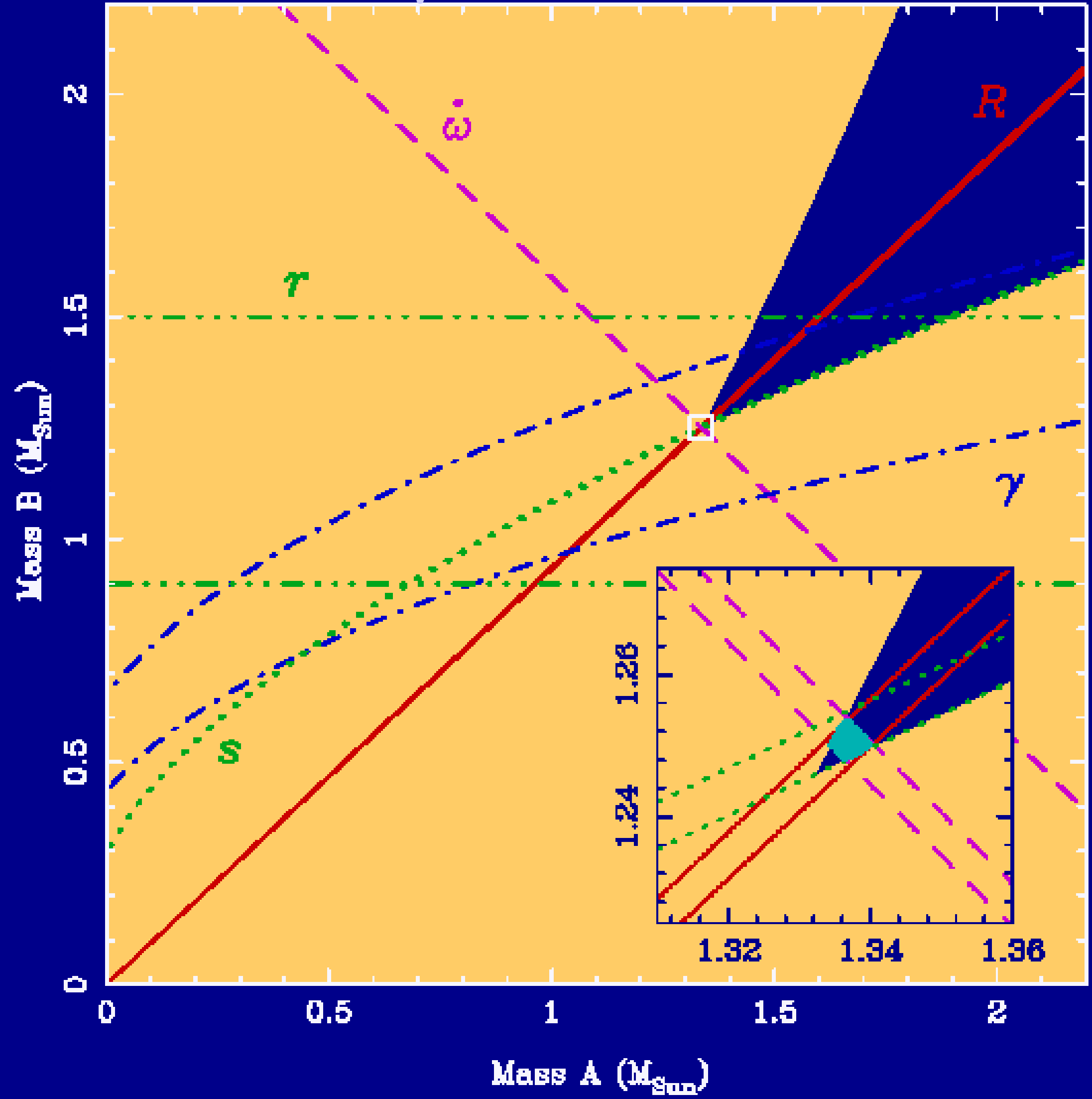


Double Pulsar: Tests of GR

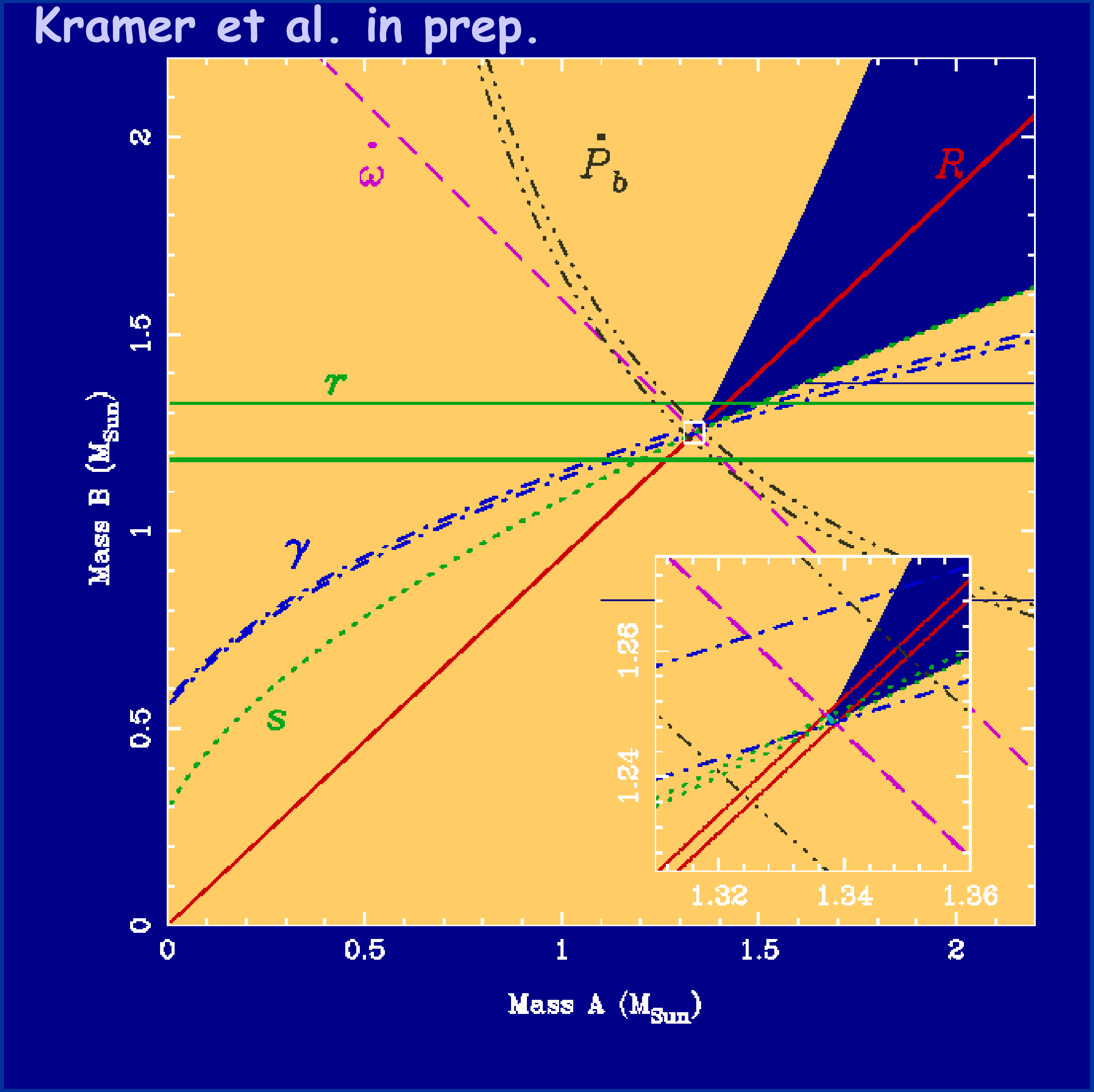


Double Pulsar: Tests of GR

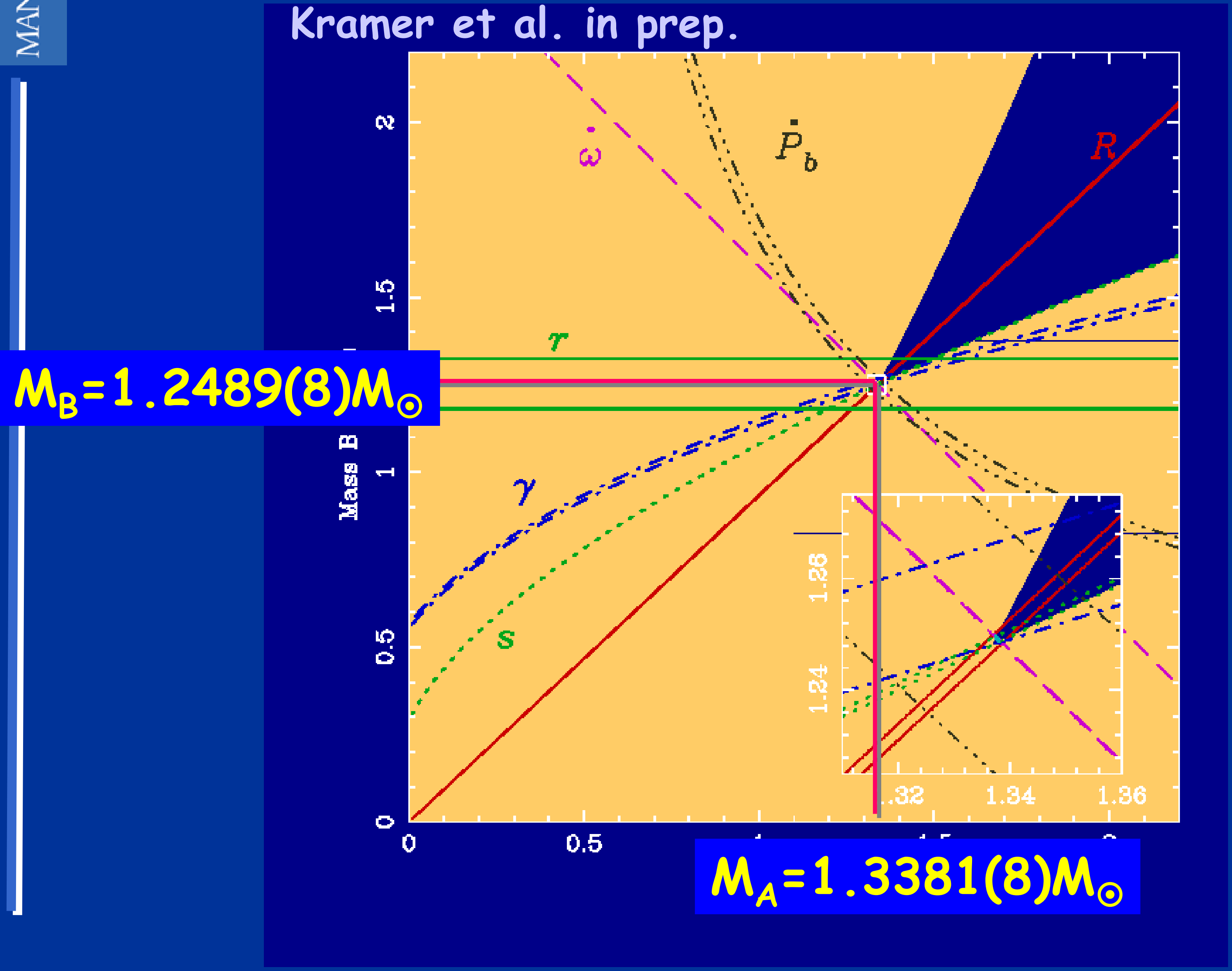
December 2003 (Lyne et al. 2004)



Double Pulsar: Tests of GR

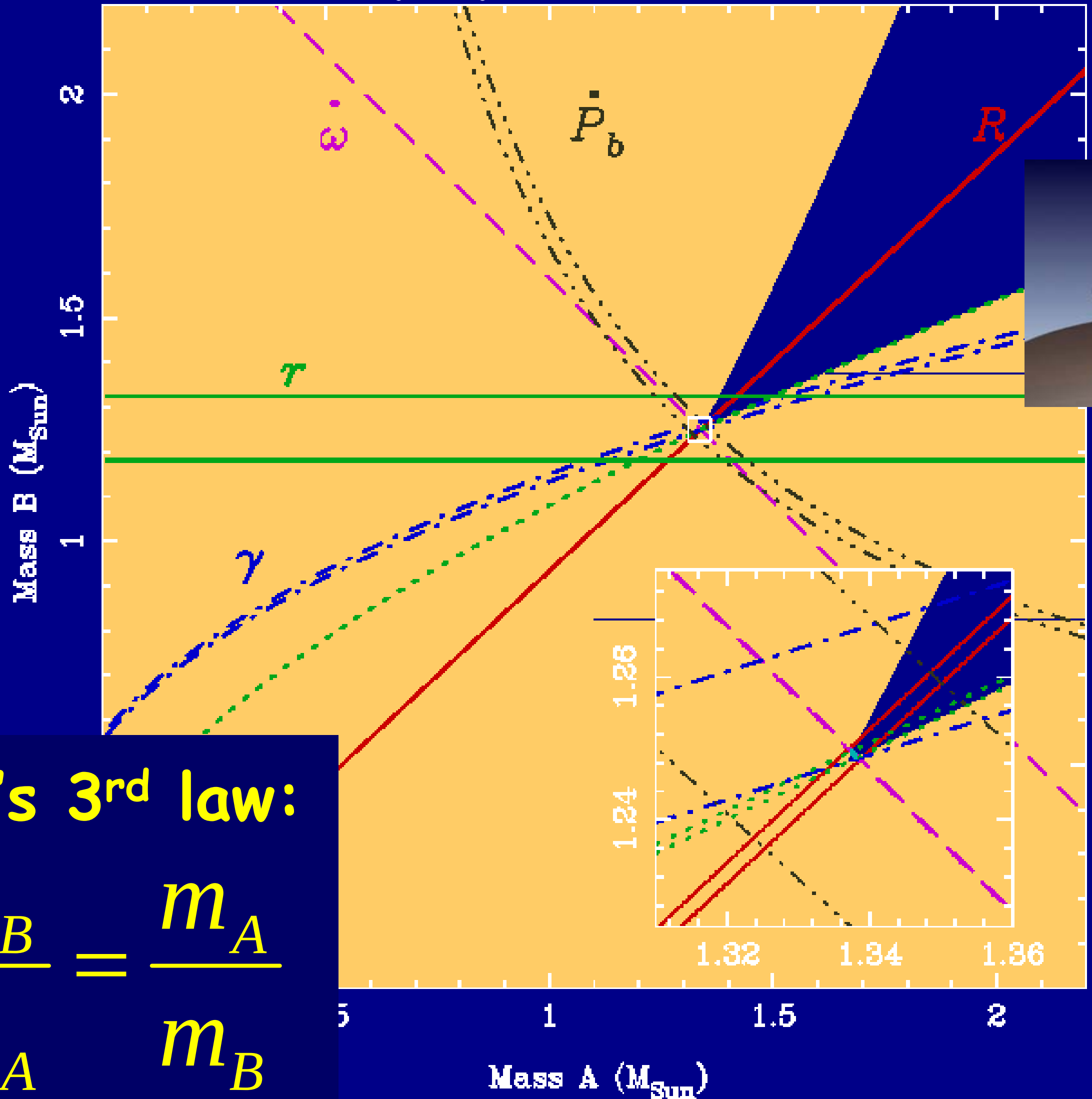


Double Pulsar: Tests of GR



Double Pulsar: Tests of GR

Kramer et al. in prep.



Kepler's 3rd law:

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

The University of Manchester
Jodrell Bank Observatory

Significance of “R”

To 1PN order, Kepler’s 3^rd law given in generic form as:

$$a_R = \left(\frac{G_{AB} M_{tot}}{n^2}\right)^{1/3} \left[1 - \frac{1}{6}\left(5\varepsilon + 3 - 2\nu\right)\left(\frac{G_{AB} M_{tot} n}{c^3}\right)^{2/3}\right]$$

e.g. Damour & Taylor ’92

$$n = (2\pi / P_b), \quad \nu = m_A m_B / M_{tot}^2, \quad \varepsilon = 2\hat{\gamma} + 1, \quad G_{AB} = G_{AB}(\text{strong field})$$

…so that for “any” theory of gr… o 1…N order:

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

…dent of …eld effects!

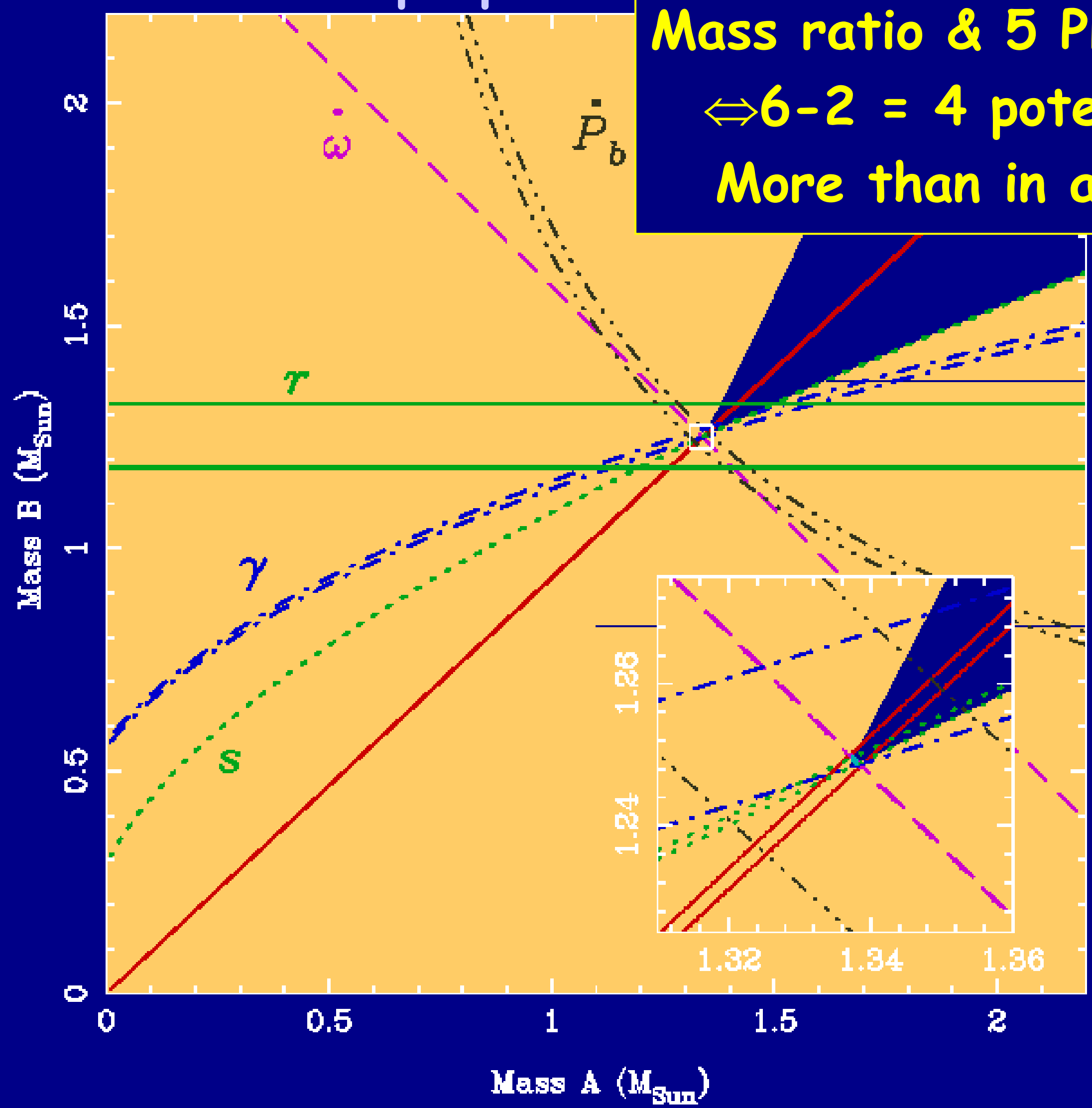
Qualitatively different constraint!

Different to other PK p…arameters, which all depend on strong-field modified “constants”!

(e.g. G_{AB} differs from G^{Newton} depending on strong-field effects

Double Pulsar: Tests of GR

Kramer et al. in prep.



Mass ratio & 5 PK parameters
⇔6-2 = 4 potential tests!
More than in any system!

MANCHESTER 1824

The University of Manchester
Jodrell Bank Observatory

Double Pulsar: Tests of GR

Based on:

R = 1.071±0.001 & $\dot{\omega}$=16.8995±0.0007 deg/yr (0.004%)

Expected in GR:	Observed:
γ = 0.3840 ms	γ = 0.3839±0.0011 ms (0.3%)
$dP_b/dt = -1.248\times10^{-12}$	$dP_b/dt = (-1.252\pm0.014)\times10^{-12}$ (1.2%)
r =6.152 μs	r =6.21 ±0.24 μs (4%)
s=0.99987	s =0.99978 ± 0.00012 (0.01%)

Kramer et al. to be submitted.

$$\frac{s^{\exp}}{s^{\mathrm{obs}}} = 1.0000 \pm 0.0007$$

- Best test in strong-field
- Purely non-radiative with fundamentally different constraint!

Outline

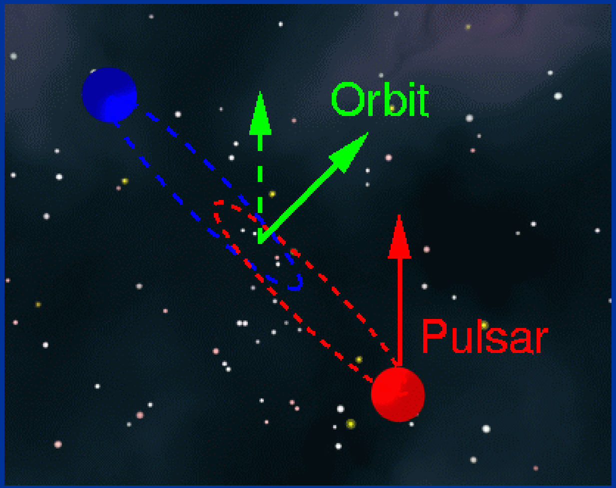
- The double pulsar
- A plasma & gravity lab
- **Precision tests of GR**
- Moment-of-inertia
- Frame-dragging
- Summary

Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- **Moment-of-inertia**
- Frame-dragging
- Summary

Geodetic Precession

- Relativistic Spin-Orbit Coupling
- First prediction for binary pulsar by Damour & Ruffini (1974)



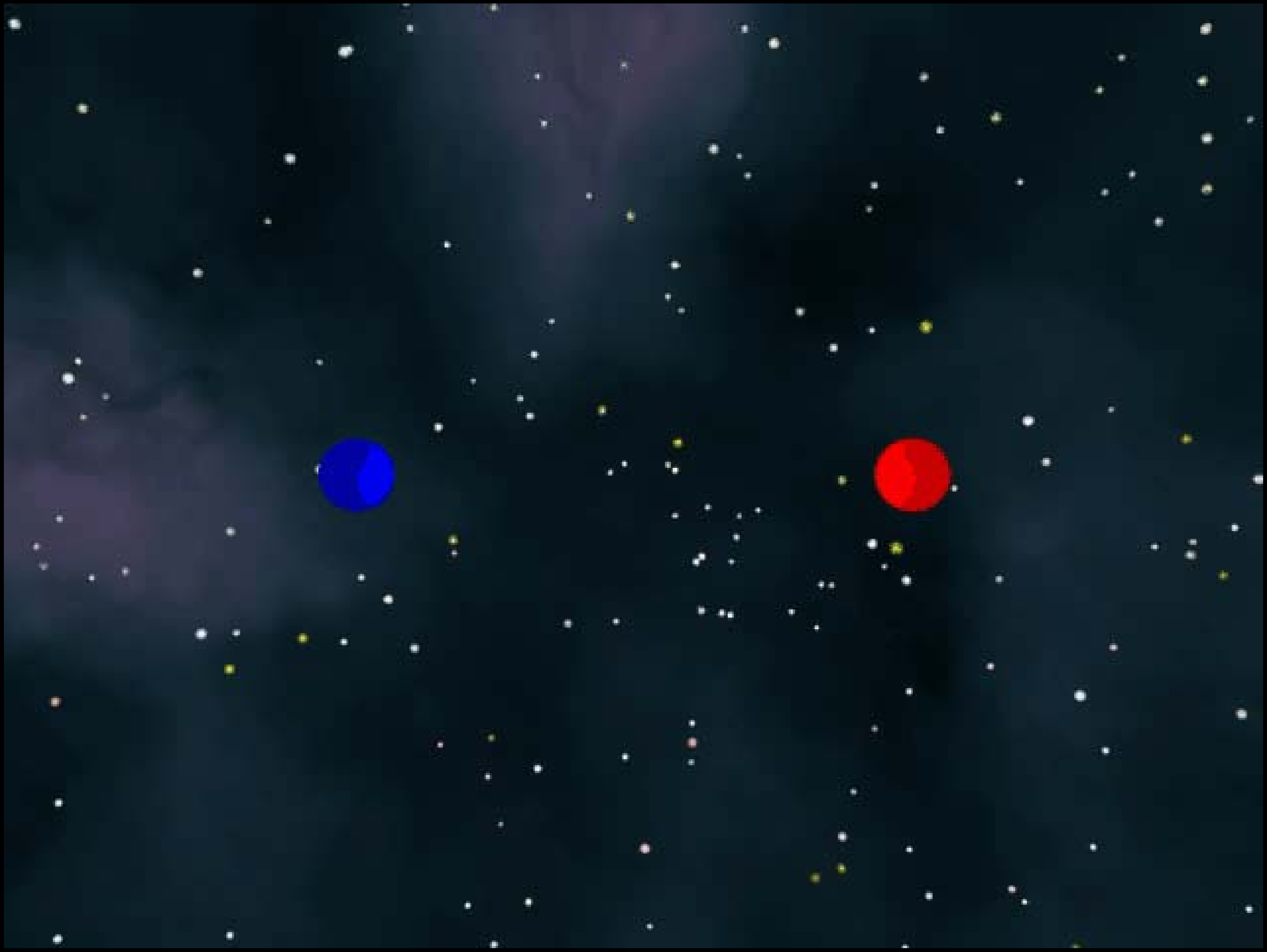
- Precession rate expected in GR:

(e.g. Barker & O'Connell 1975, Börner et al. 1975)

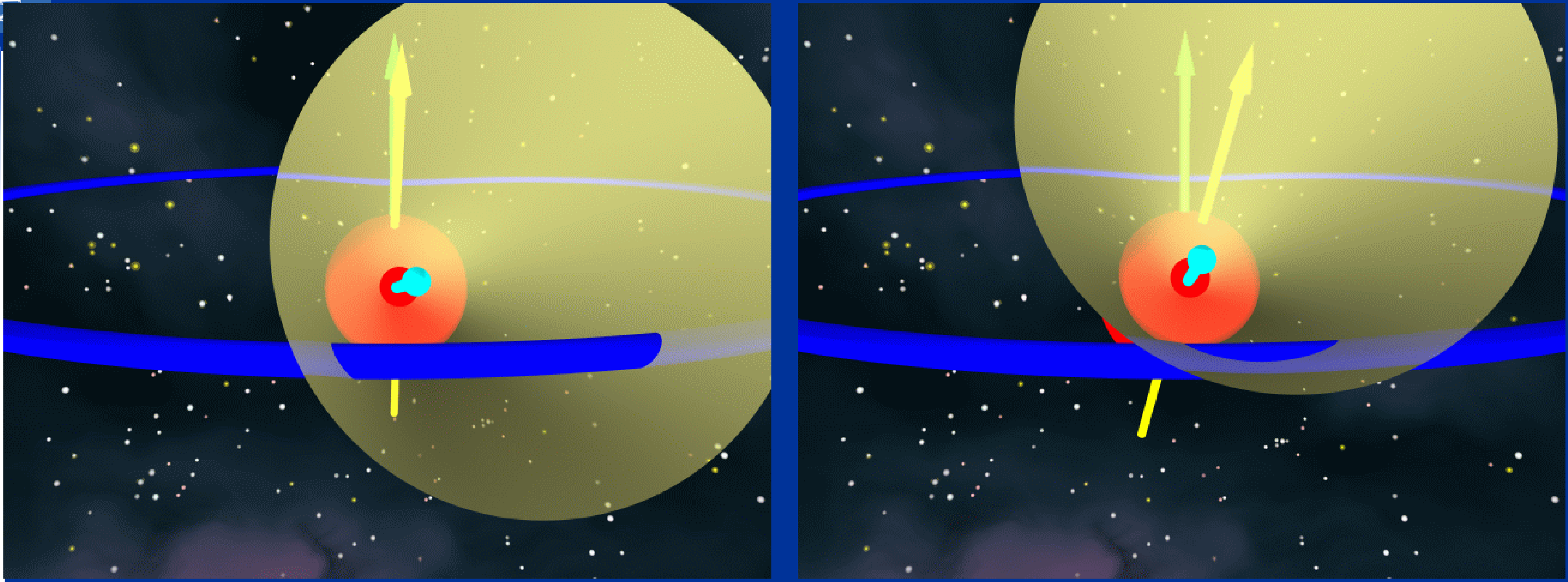
$$\Omega^p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \frac{1}{1-e^2}, \quad T_\odot = GM_\odot c^{-3}$$

What effects do we expect to observe?

Effects of Geodetic Precession



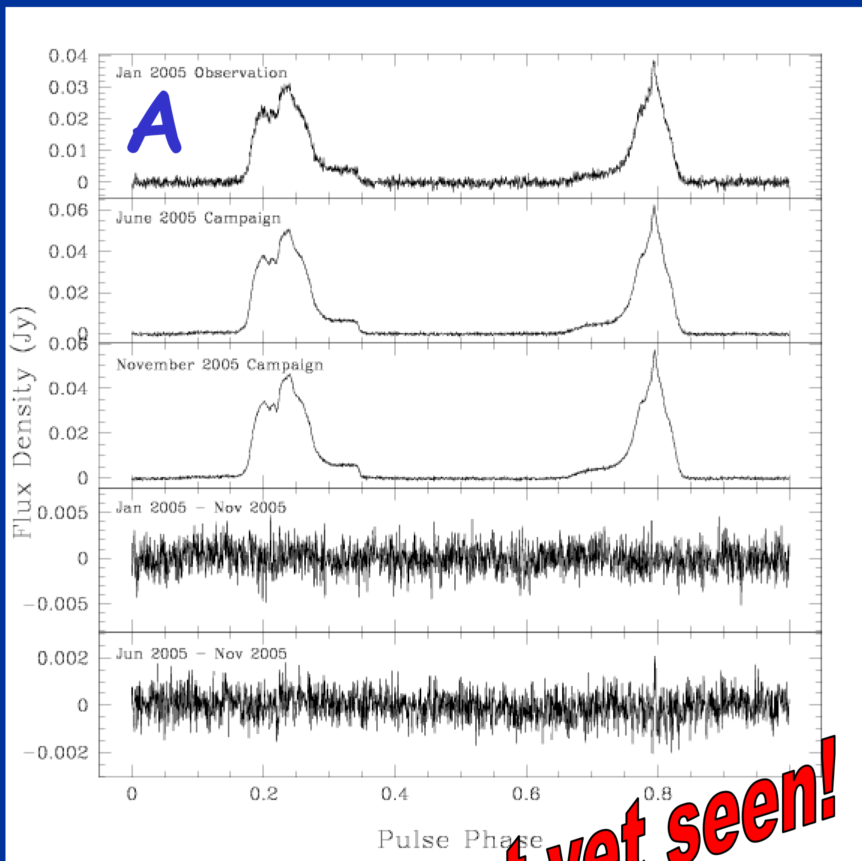
The Effects of Geodetic Precession

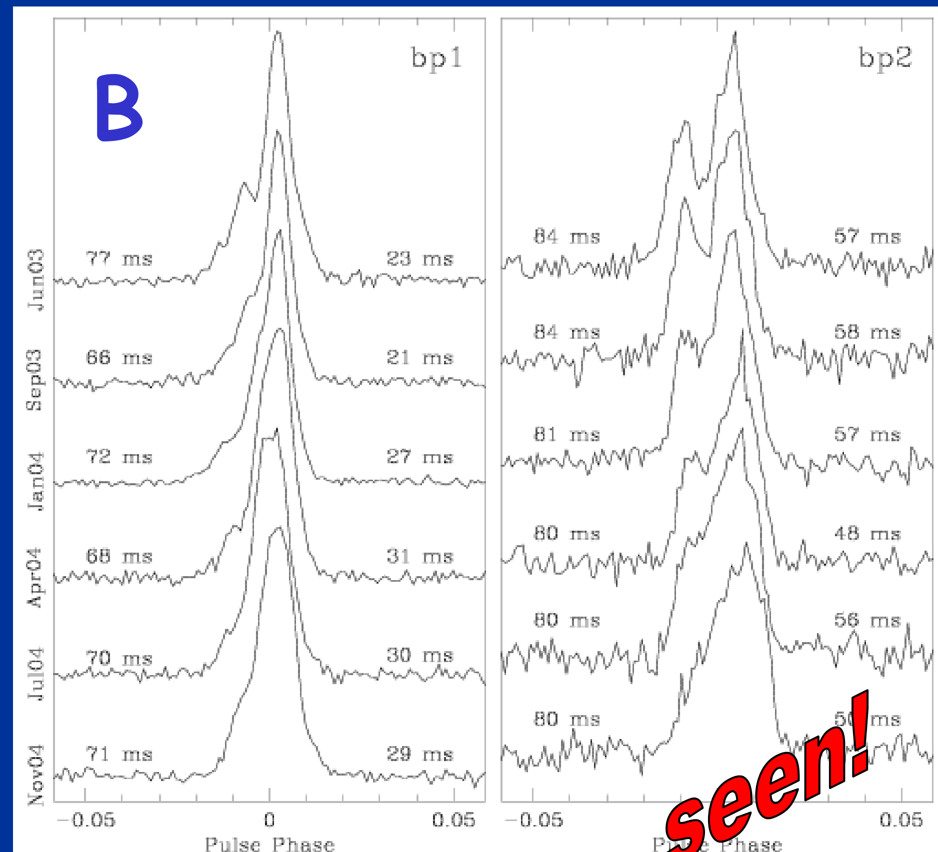


- Pulsar may not always be visible
- Line-of-Sight will change
- Changes in pulse shape, width and polarization

Geodetic Precession in J0737-3039A

- Precession period of double pulsar only 71/74 years!
- Expect to see effects already!





Spin-orbit coupling

Relativistic spin-orbit coupling contributions to observed periastron advance:

- Formally, spin-orbit coupling enters at 1PN level!
- For binary pulsars however, numerically they are of size of 2PN effects (Wex 1995), so usually they are ignored
- However, for double pulsar, precision in periastron advance measurements has reached 2PN limit!

Spin contributions in Double Pulsar

Total periastron advance at 2PN level: Damour & Schaefer (1988)

$$k^{tot} = \frac{3\beta_0^2}{1-e_T}\left[1 + f_0\beta_0^2 - g_S{}^A \beta_0 \beta_S{}^A - g_S{}^B \beta_0 \beta_S{}^B\right]$$

1PN | 2PN | Spin A | Spin B

Geometry dependent ($g_S{}^A$, $g_S{}^B$)

Neutron star dependent ($\beta_S{}^A$, $\beta_S{}^B$)

Assuming 'canonical' values:

1PN = 16.9 deg/yr

2PN = 0.0004 deg/yr

SpinA= 0.0002 deg/yr

Need two other parms with similar precision… Not easy! sin(i), Pbdot?

Neutron star structure

Total periastron advance to 2PN level: Damour & Schaefer (1988)

$$k^{tot} = \frac{3\beta_0^2}{1-e_T}\left[1 + f_0\beta_0^2 - g_S{}^A \beta_0 \beta_S{}^A - g_S{}^B \beta_0 \beta_S{}^B\right]$$

1PN 2PN Spin A Spin B

Neutron star dependent

$$\beta_S = \frac{2\pi c}{G} \frac{1}{P_p} \frac{I}{m^2}$$

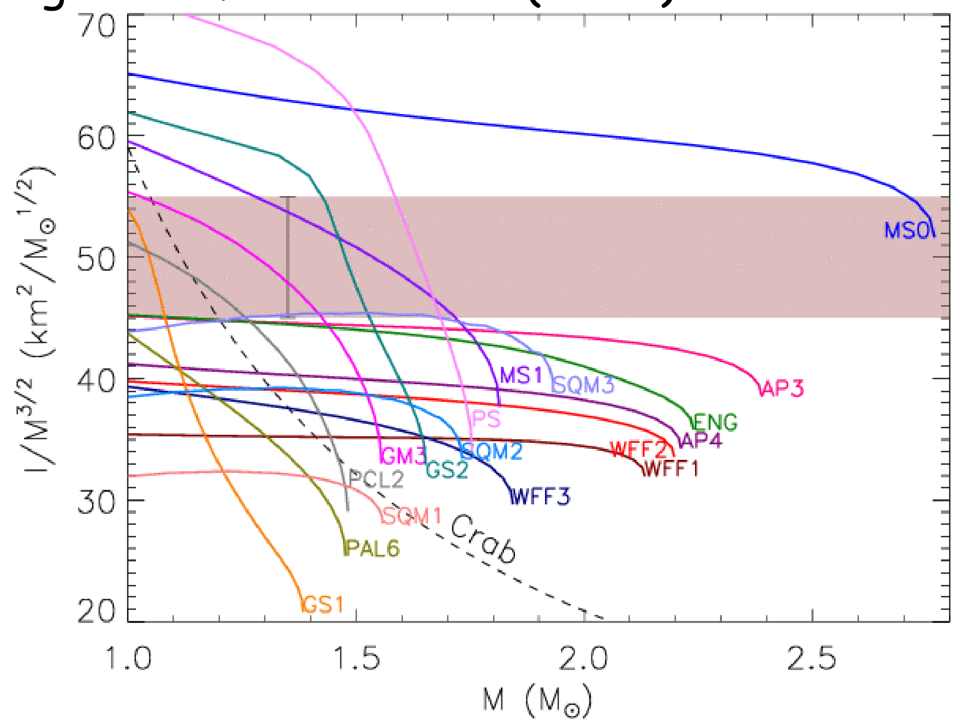
Equation-of-State!

Measure NS moment of inertia!!!

Equation of State

- **Measurement of M & I better than M & R**
- **Even low precision with important consequences for EOS**

E.g. Lattimer & Schutz (2005)



Already some constraints from mass of B under assumption about supernova explosion (see Podsiadlowski et al. 2005)

Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary

The University of Manchester
Jodrell Bank Observatory

Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- **Frame-dragging**
- Summary

The University of Manchester
Jodrell Bank Observatory

This week

New Scientist, Sep.'04

They get in your hair

One louse or two?

THE argument has been raging for almost 250 years: are the head louse and the body louse distinct species or one and the same creature? A genetic analysis may finally settle the question, and even help when it comes to getting rid of the little parasites, which are staging a comeback in rich countries.

Linnaeus named the human louse *Pediculus humanus* in 1758, but later realised there might be two sorts. Debate has gone on ever since. Those who regard body lice as a separate species point out that they are bigger than head lice and live in clothes rather than in head hair. They can also transmit diseases such typhus and trench fever, something head lice have never been shown to do.

Other experts dismiss these differences and argue that, because head and body lice interbreed if kept together in the lab, they must be the same species. Then again, breeding under artificial conditions is a poor test of a species.

To find out if head and body lice interbreed in the "wild", Natalie Leo and Stephen Barker of the University of Queensland in Brisbane, Australia, collected lice from seven boys in Nepal and four girls in Inner Mongolia in China. A form of DNA fingerprinting of 443 lice showed there were two genetically distinct populations. "The head lice were one big family; the body lice were one big family," says Barker.

Further studies on children who shared sleeping quarters showed that the lice travelled from the body of one child to the body of another, or from head to head, but never between the body and head – evidence that the two populations were not interbreeding and that head and body lice are different species.

The best way to treat head lice is hotly contested. Many health authorities, including the US Centers for Disease Control, advise treating clothes and sheets. Other experts say parents should not waste time boiling clothes. The latest findings, reported at an entomology conference in Brisbane last month, support the idea that the parents of children with head lice should concentrate on their heads. "For a head louse, shifting to clothes would be like setting out across the desert," says Barker.
Rachel Nowak, Melbourne

Neutron stars steal space probe's glory

IT HAS taken almost 50 years to conceive and build and has cost more than $700 million, but now NASA's Gravity Probe B spacecraft could be upstaged by telescopes on the ground.

The craft is designed to accurately test Einstein's general theory of relativity. According to the theory, a gyroscope orbiting a massive object such as the Earth should experience two forces that gradually cause it to "precess", pushing its axis of spin out of alignment. The stronger force, known as the geodetic effect, is caused by the Earth warping the fabric of space-time. The other, known as the gravitomagnetic effect, is caused by the rotating Earth dragging space and time around with it.

Gravity Probe B, which carries ultra-sensitive gyroscopes, was conceived in the 1950s to measure these forces, but was only launched in April this year. It has yet to take any measurements. Francis Everitt, the physicist in charge of the project at Stanford University, says the probe should produce results by mid-2006.

Meanwhile, astronomers have been studying binary pulsars – two rapidly spinning neutron stars orbiting each other – to measure these effects. The gravitational fields of pulsars are so strong that both of the forces predicted by Einstein should show up relatively clearly in the precession of each pulsar in a binary system, much like that in a gyroscope.

Last week, Ingrid Stairs of the University of British Columbia in Vancouver and colleagues reported for the first time that the observed precession in a binary pulsar due to the geodetic effect was consistent with that predicted by general relativity (www.arxiv.org/astro-ph/0408457).

So the big prize for Gravity Probe B is now the gravitomagnetic effect, which is hundreds of times weaker than the geodetic effect and is unlikely to be seen in the near future by Stairs's team. But earlier this year, astronomers announced the discovery of a binary system in which the pulsars are much closer together and orbit each other every 2.4 hours. The discovery has triggered a burst of activity to gather data on the pulsars from radio telescopes all over the world and a hunt through historical records for past observations of the system.

The huge gravitational forces at work in it should make some of the effects predicted by relativity easy to see, says Robert O'Connell, a theoretical physicist at Louisiana State University in Baton Rouge. For instance, the geodetic effect should cause the axes of the pulsars to precess 2500 times faster than the gyros on Gravity Probe B, says O'Connell.

The gravitomagnetic force will be harder to see, however. "We have run simulations, and we could see it within three years, maybe sooner," says Michael Kramer, an astronomer at the UK's Jodrell Bank Observatory run by the University of Manchester and a member of the team that discovered the pulsars. If he's right, the team could challenge Gravity Probe B for the first observation of this force.

But Everitt insists that the discovery of the new pulsar system has little significance for the Gravity Probe B project. He points out that astronomers trying to detect gravitomagnetic effects in pulsar data will have to make significant assumptions about an important property of the way the stars spin, known as their moments of inertia. These are currently unknown. "In that case, it is not a proper test of general relativity," says Everitt.

> "The gravitational fields of pulsars are so strong that the forces predicted by Einstein should show up relatively clearly"

Nevertheless, Kramer is confident that physicists will find some way to avoid this assumption and believes he has Gravity Probe B in his sights. "Of course, we would like to be first," he says. Everitt is unmoved by the challenge. "I would be very surprised if he is," he says. Justin Mullins

Evidence for Frame-dragging Effects

Illustration of frame dragging effects using simple model:

- Following Nordtvedt (1988) look at theories in PPN limit that differ from GR only in PPN parms $\alpha_1, \ \alpha_2$
- **without preferred-frame effects, we get:**

(see Nordtvedt 1988, Will 1993)

$$g_{00} = -1 + 2U - 2U^2 + \ldots$$

$$g_{0j} = -\frac{1}{2}(7 + \alpha_1 - \alpha_2)V_j - \frac{1}{2}(1 + \alpha_2)W_j$$

$$g_{ij} = (1 + 2U)\delta_{ij}$$

Hence, no framing-dragging effects only for $g_{0j}=0$, or $\alpha_1 = -8, \ \alpha_2 = -1$

Evidence for Frame-dragging Effects

- In this simple framework, one can show that

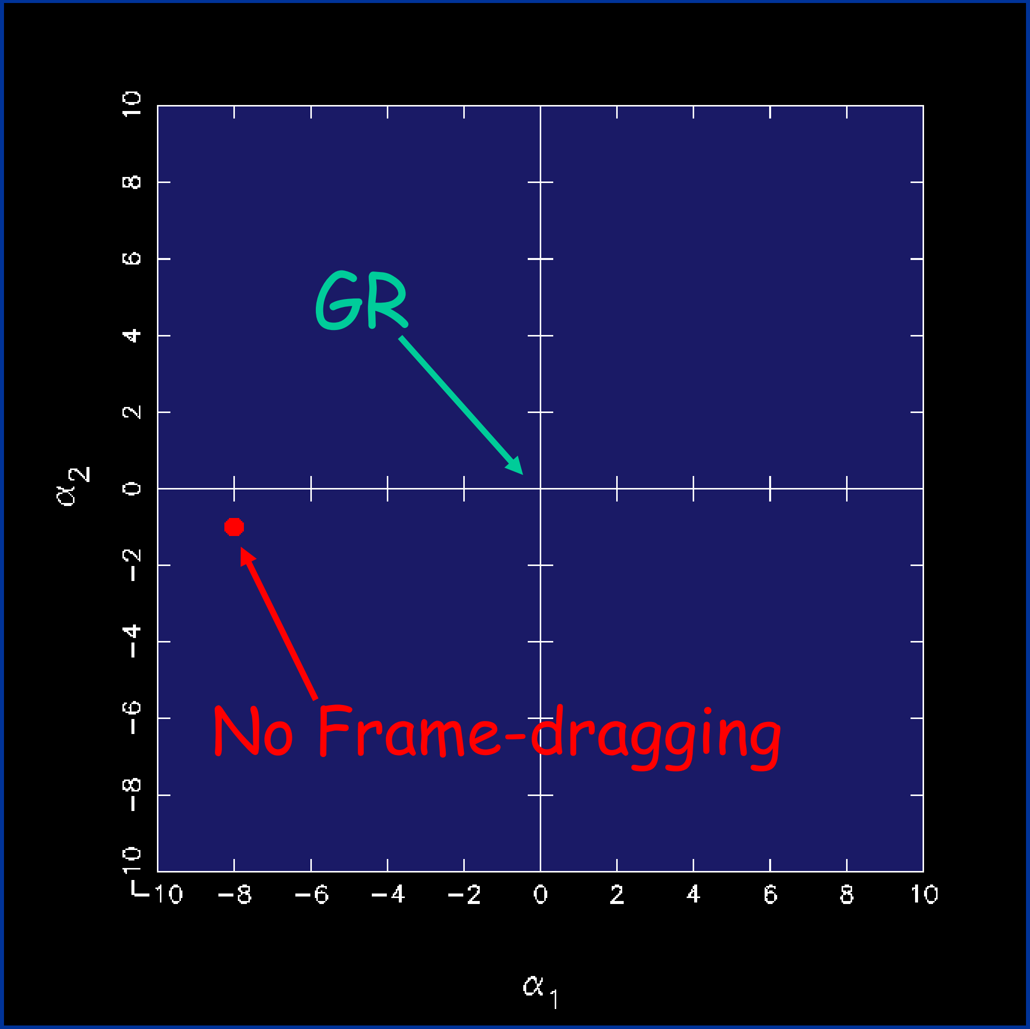
$$\dot{\omega}_{obs} = (1+\Delta)\dot{\omega}_{GR} \quad \text{with} \quad \Delta = \frac{1}{6}(2\alpha_1 - \alpha_2)\frac{\mu}{M}$$

Nordtvedt (1988), Will (1993)

- Determine GR value from Shapiro and mass ratio which are independent of frame-dragging effects
- Compare predicted GR value to observed value, obtaining a limit on Δ and hence non-existing of frame-dragging

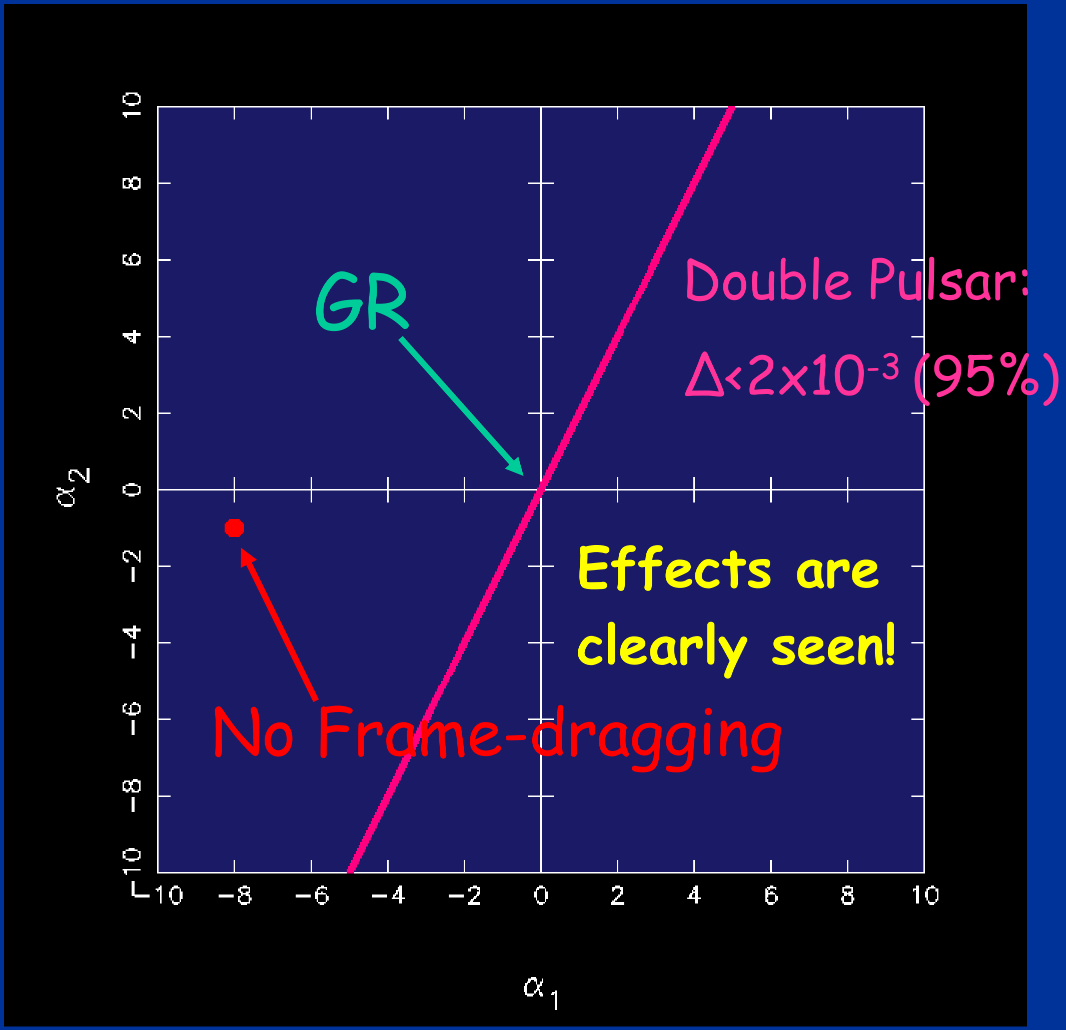
Evidence for Frame-dragging Effects

In our choice of theories, we have 2d-plane for illustration:



Evidence for Frame-dragging Effects

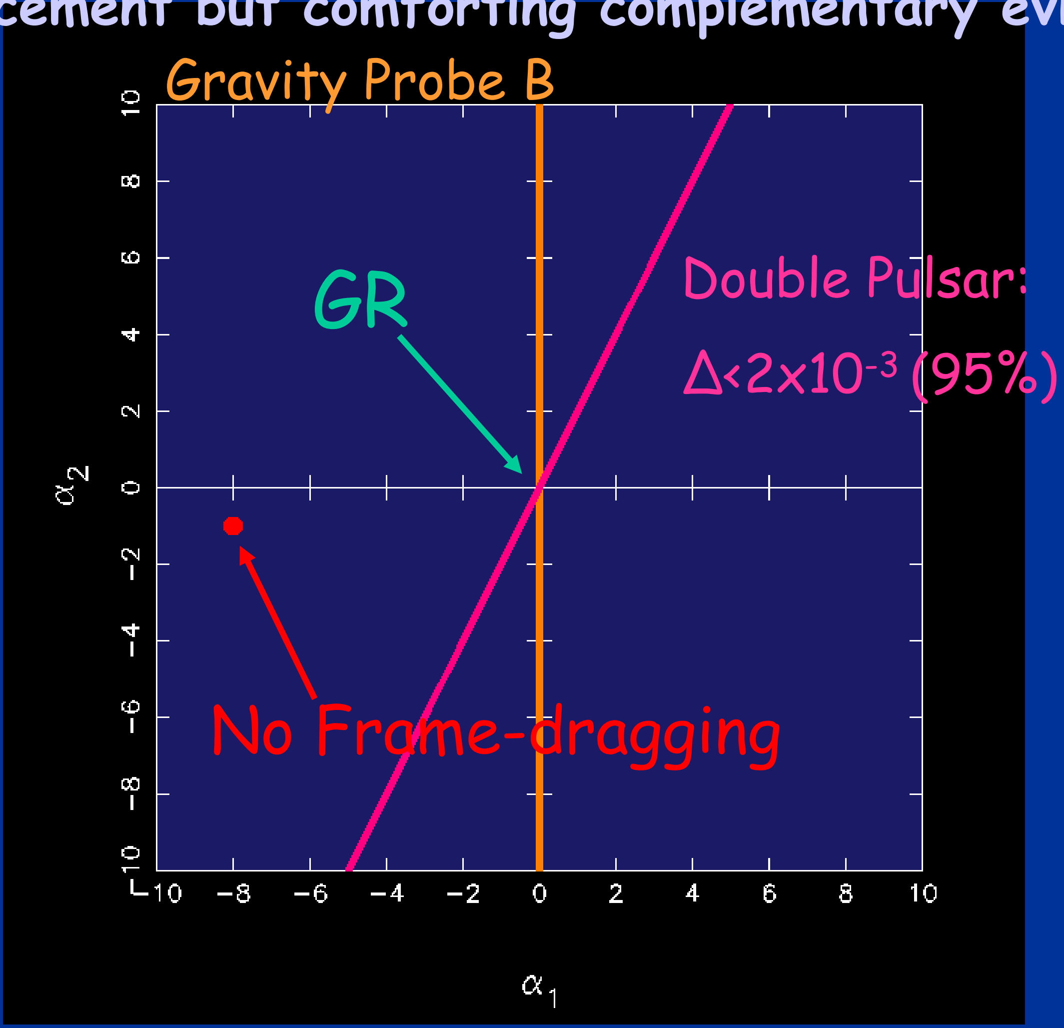
In our choice of theories, we have 2d-plane for illustration:



Evidence for Frame-dragging Effects

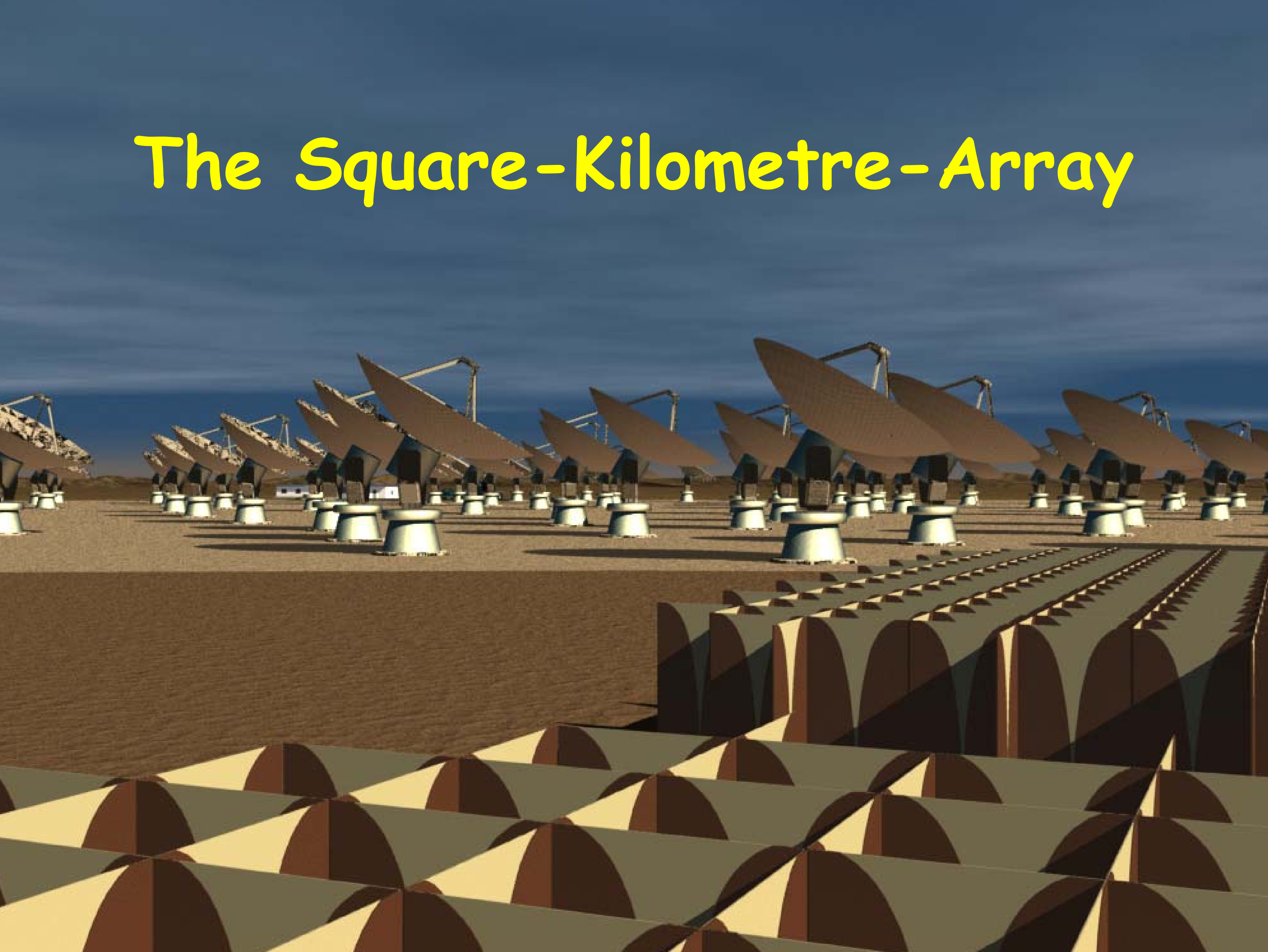
Even in this simple framework with only two parameters, one sees that Gravity Probe-B is testing different aspects:

No replacement but comforting complementary evidence!



Outline

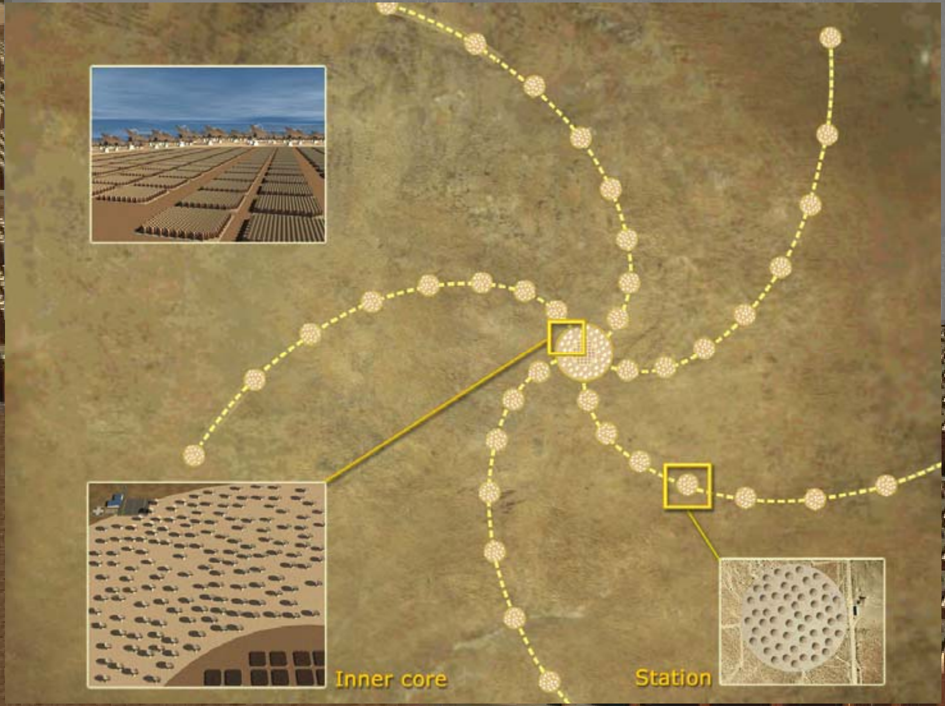
The Future

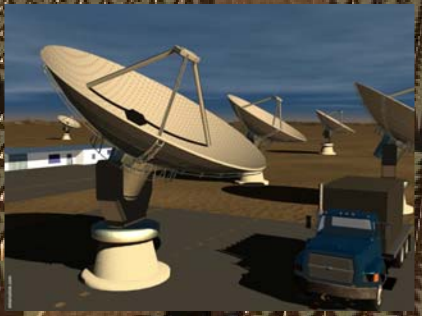

The Square-Kilometre-Array

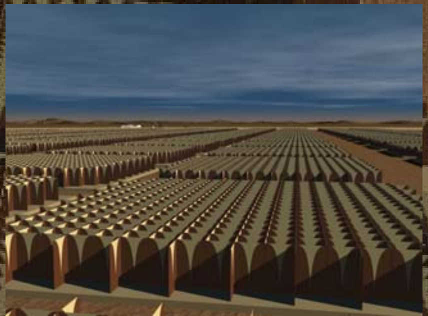
The "Square-Kilometre-Array"

The "Square-Kilometre-Array"

- The biggest telescope ever built
- Tackling Noble-prize science
- Construction 2012-2020, first science by 2015
- The science case requires: gigantic collecting area
  huge field-of-view (FOV)
  large spatial resolution
  multiple, independent FOVs

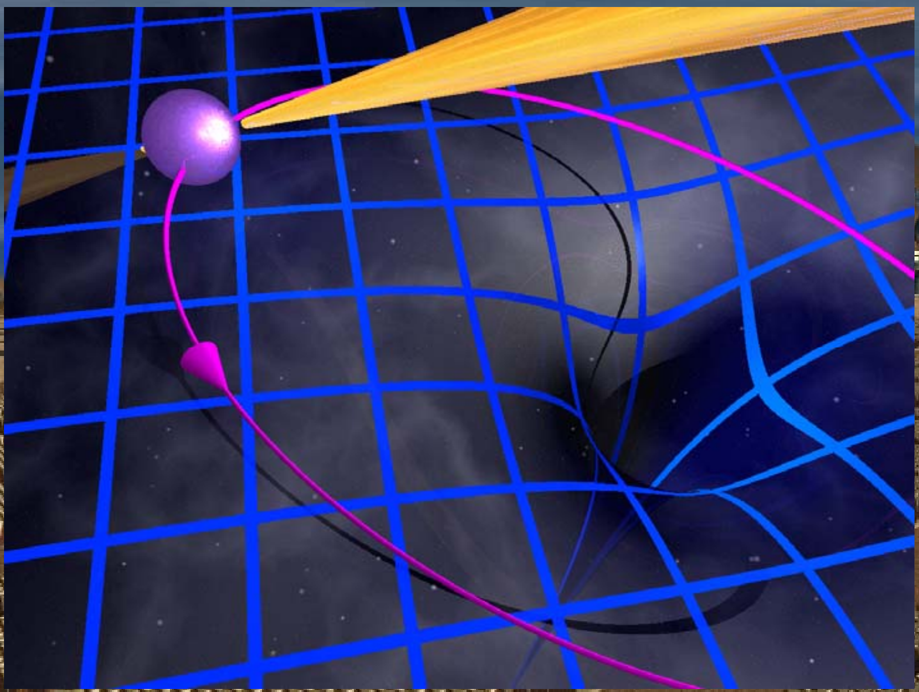
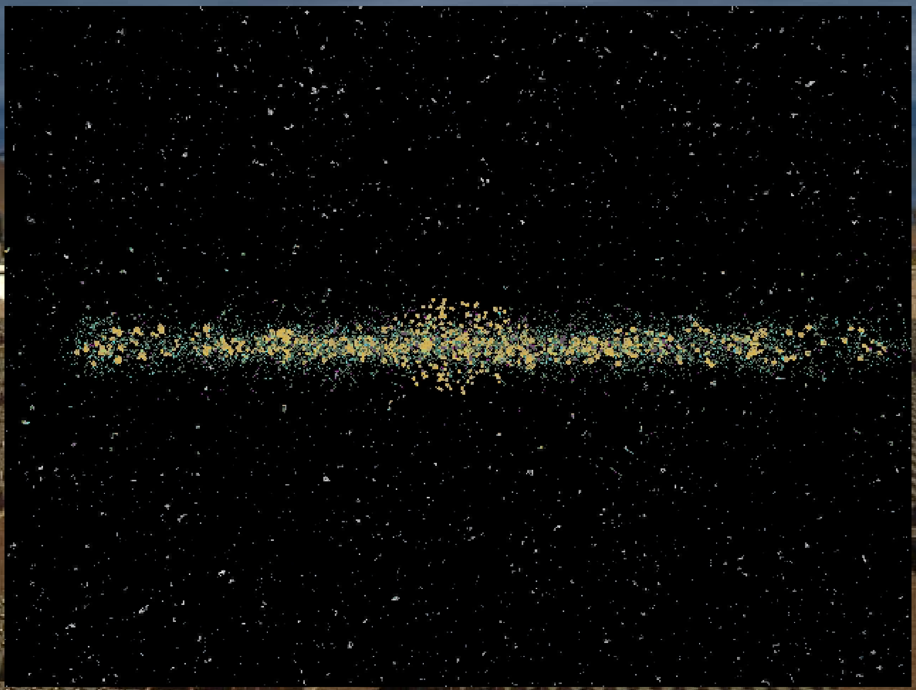






A Galactic Census of pulsars

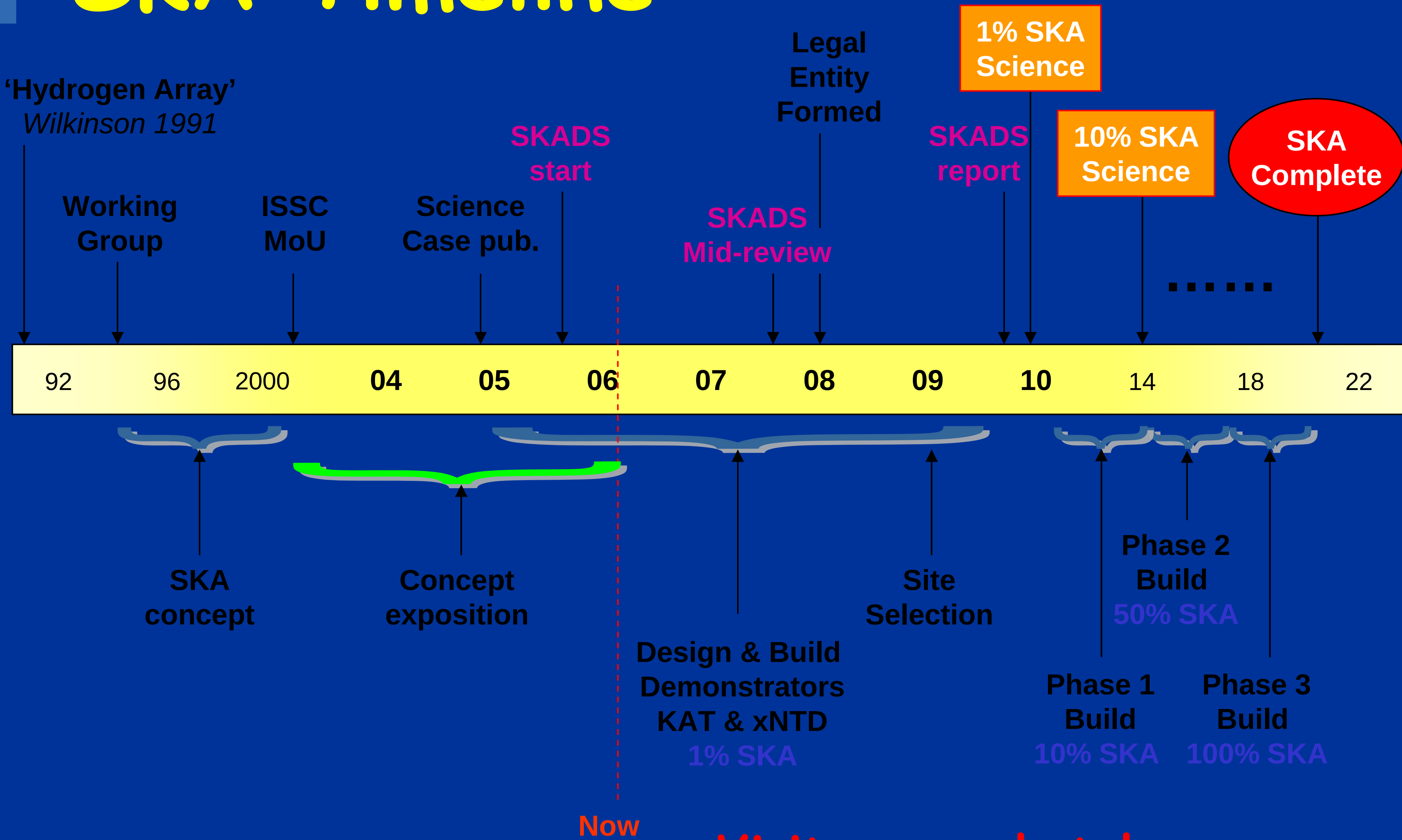
- SKA will essentially discover 'all' Galactic pulsars!

- Find pulsars around stellar BH and in Galactic Centre
- Measure BH properties: masses, spin & quadrupole moment
- Testing GR description of BHs, such as
  Cosmic Censorship Conjecture & No-hair theorem

see Kramer et al (2004), Cordes et al. (2004)

SKA Timeline



Visit: www.skatelescope.org

Until then…

- Double pulsar has lived up to all its expectations
- Valuable tool to probe a pulsar magnetosphere
- Most relativistic system ever found
- Unique testbed for theories of gravity
- Best strong-field test of GR ever
- With continuing timing observations precision will continue to improve ("No show-stopper")
- Double Pulsar will surpass ALL solar system tests!
- Measure relativistic orbital deformation and aberration for the first time soon
- Measure moment of inertia of a neutron star

The University of Manchester
Jodrell Bank Observatory

Final comment…