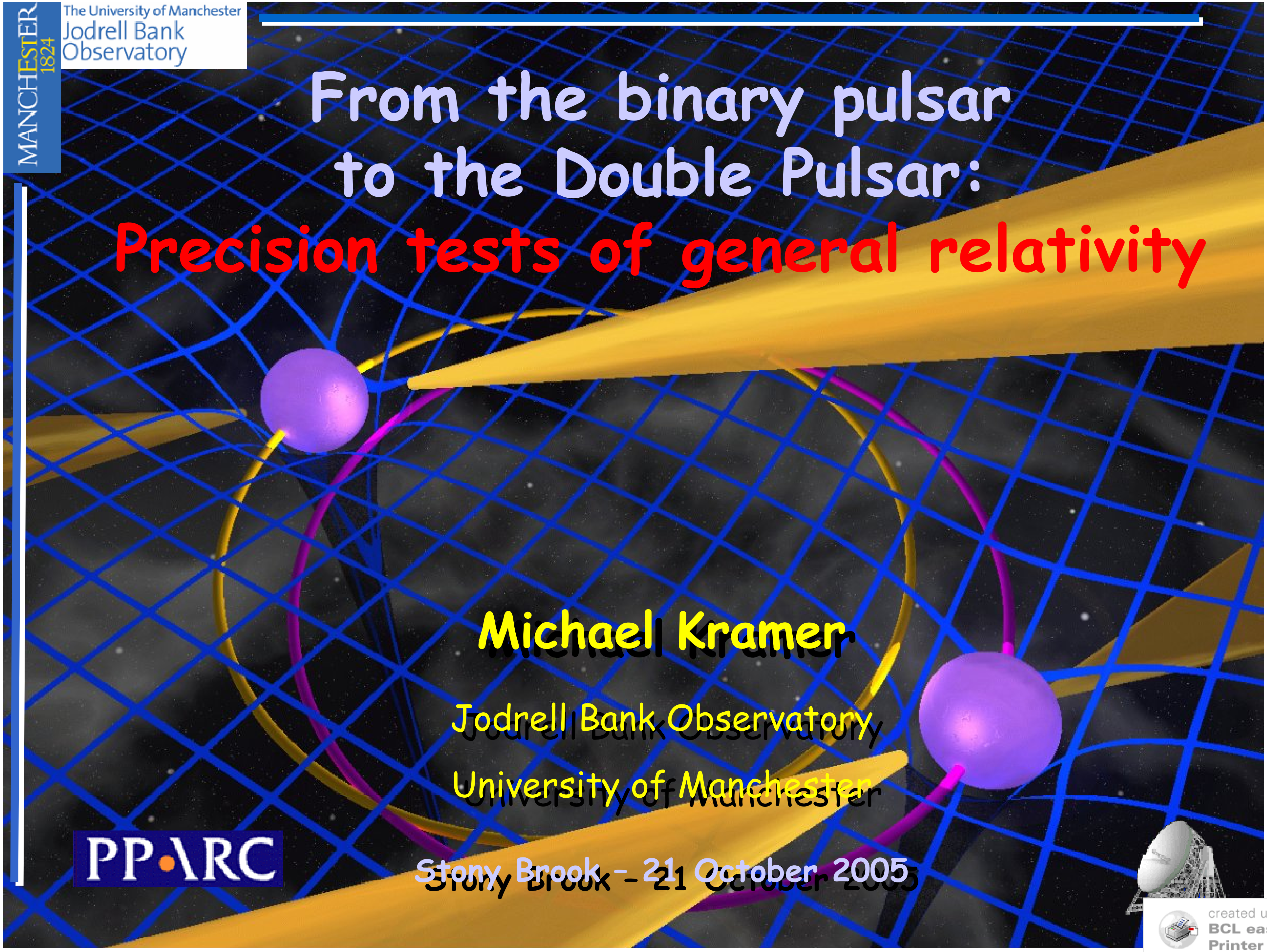
MANCHESTER 1824 The University of Manchester Jodrell Bank Observatory



From the binary pulsar to the Double Pulsar:

Precision tests of general relativity

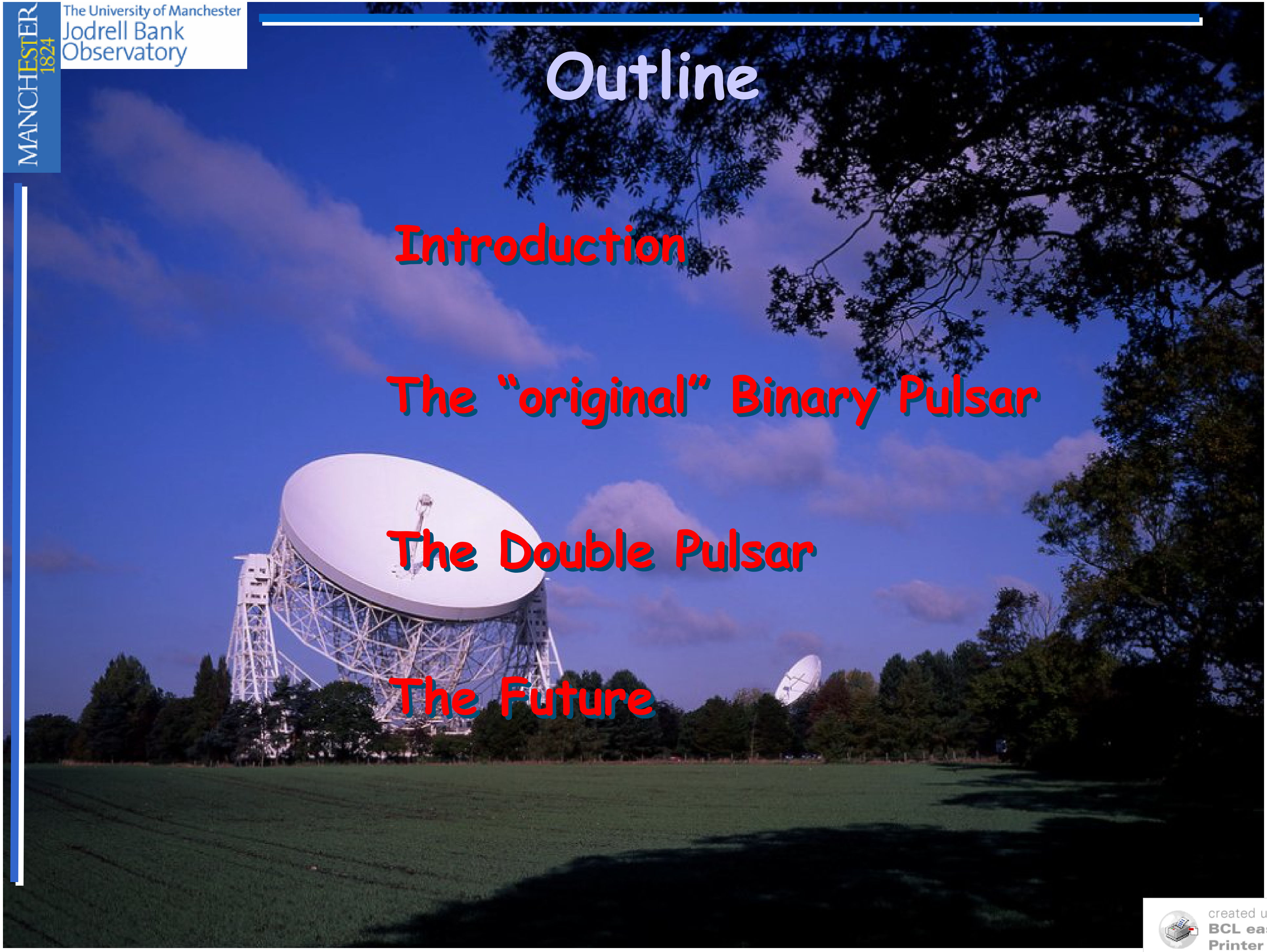
Michael Kramer

Jodrell Bank Observatory

University of Manchester

Stony Brook – 21 October 2005

PPARC



Outline

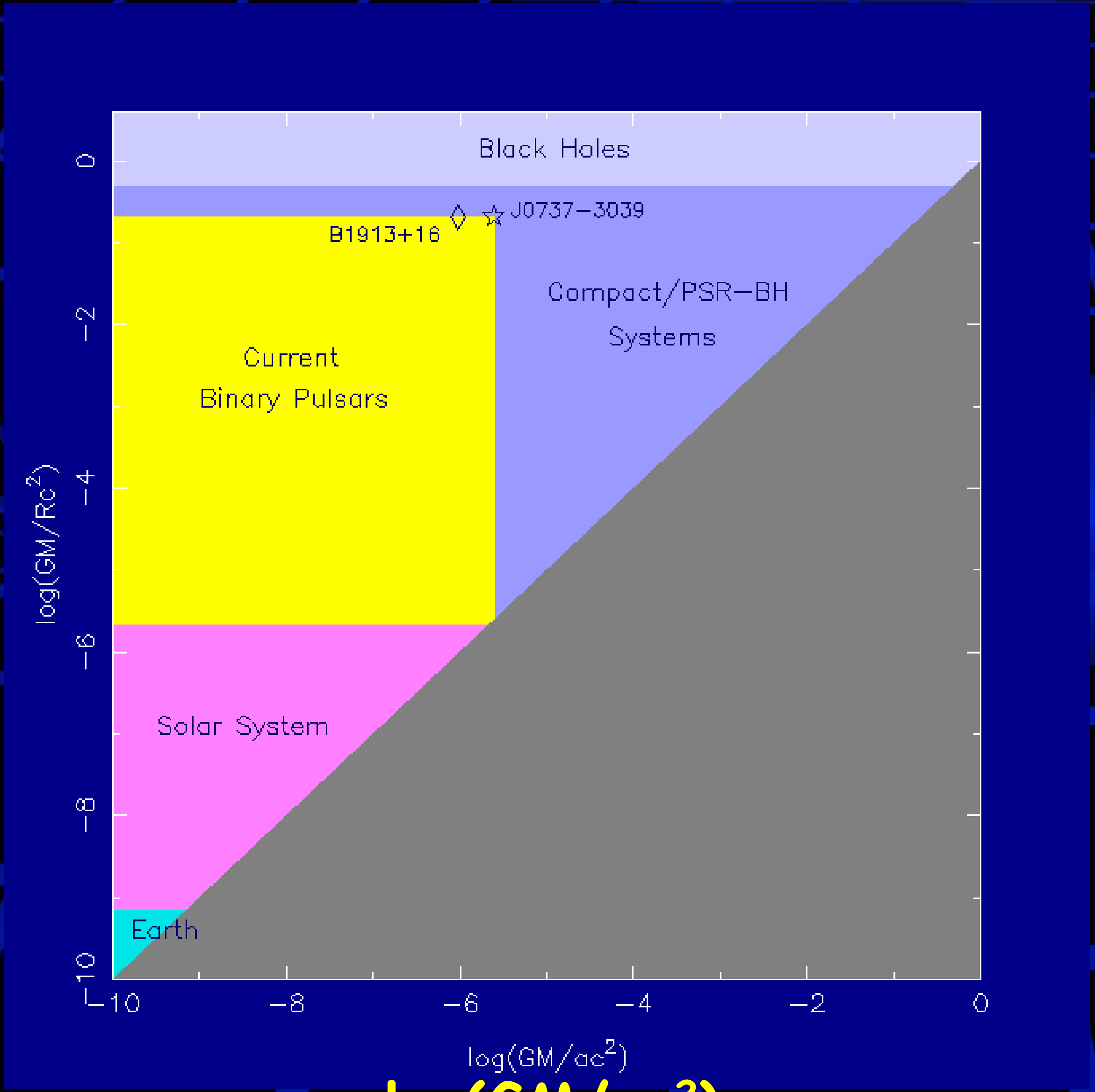
Introduction

The “original” Binary Pulsar

The Double Pulsar

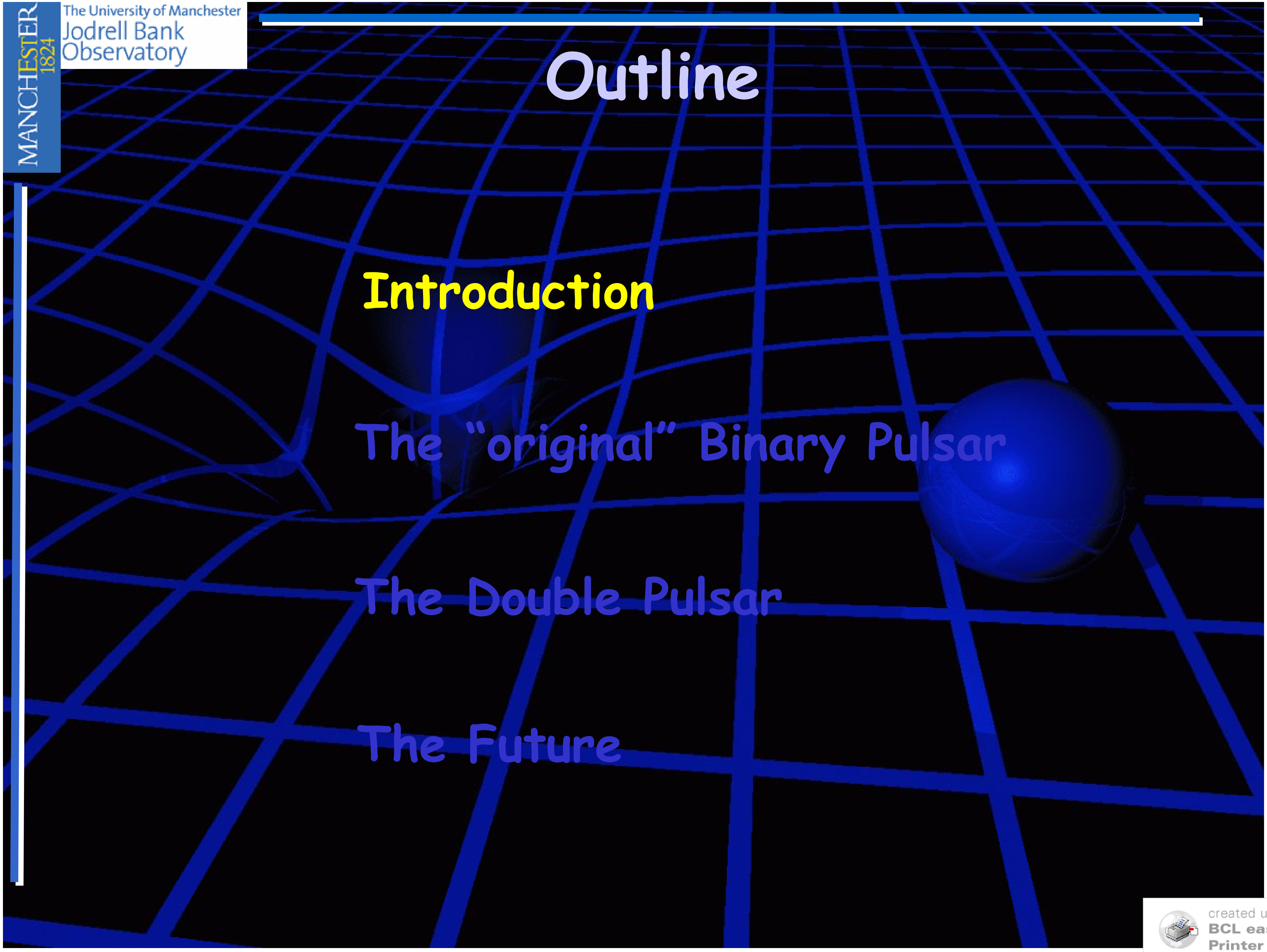
The Future

Outline



$\log(GM/Rc^2)$

$\log(GM/ac^2)$



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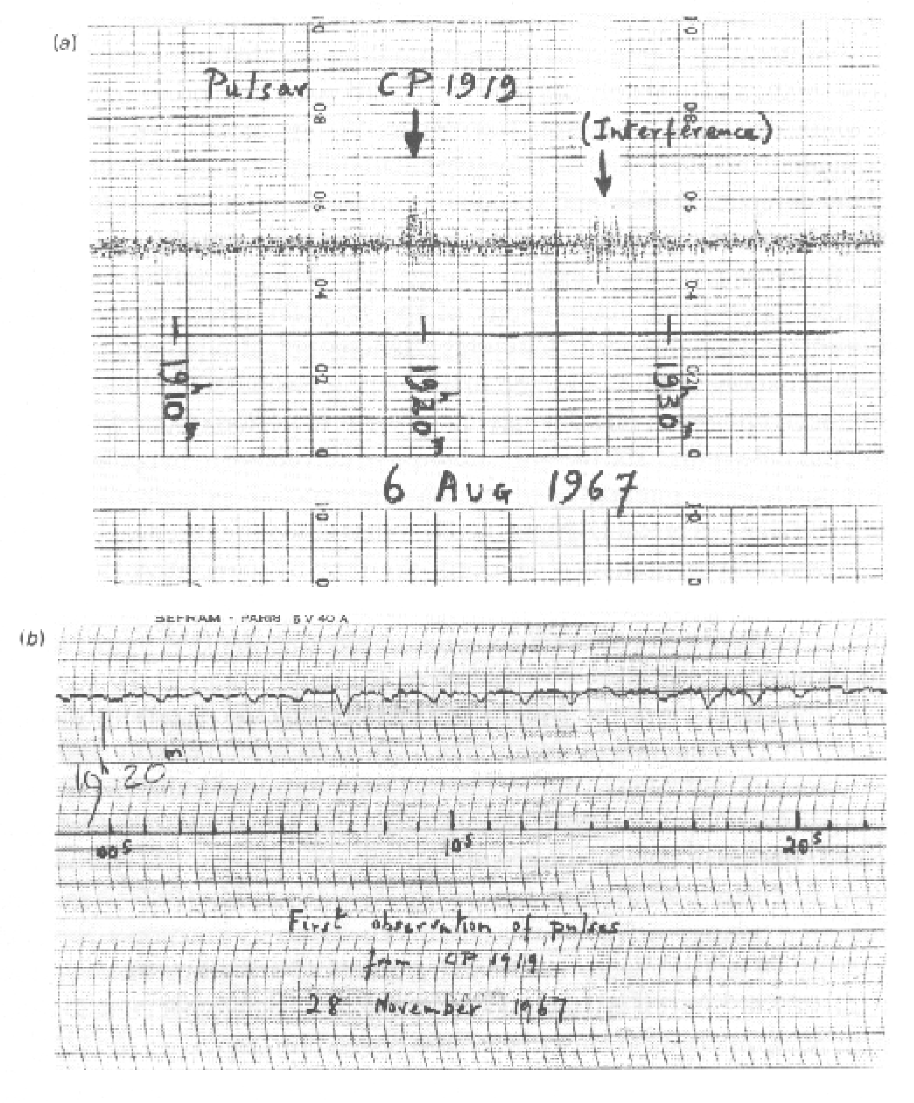
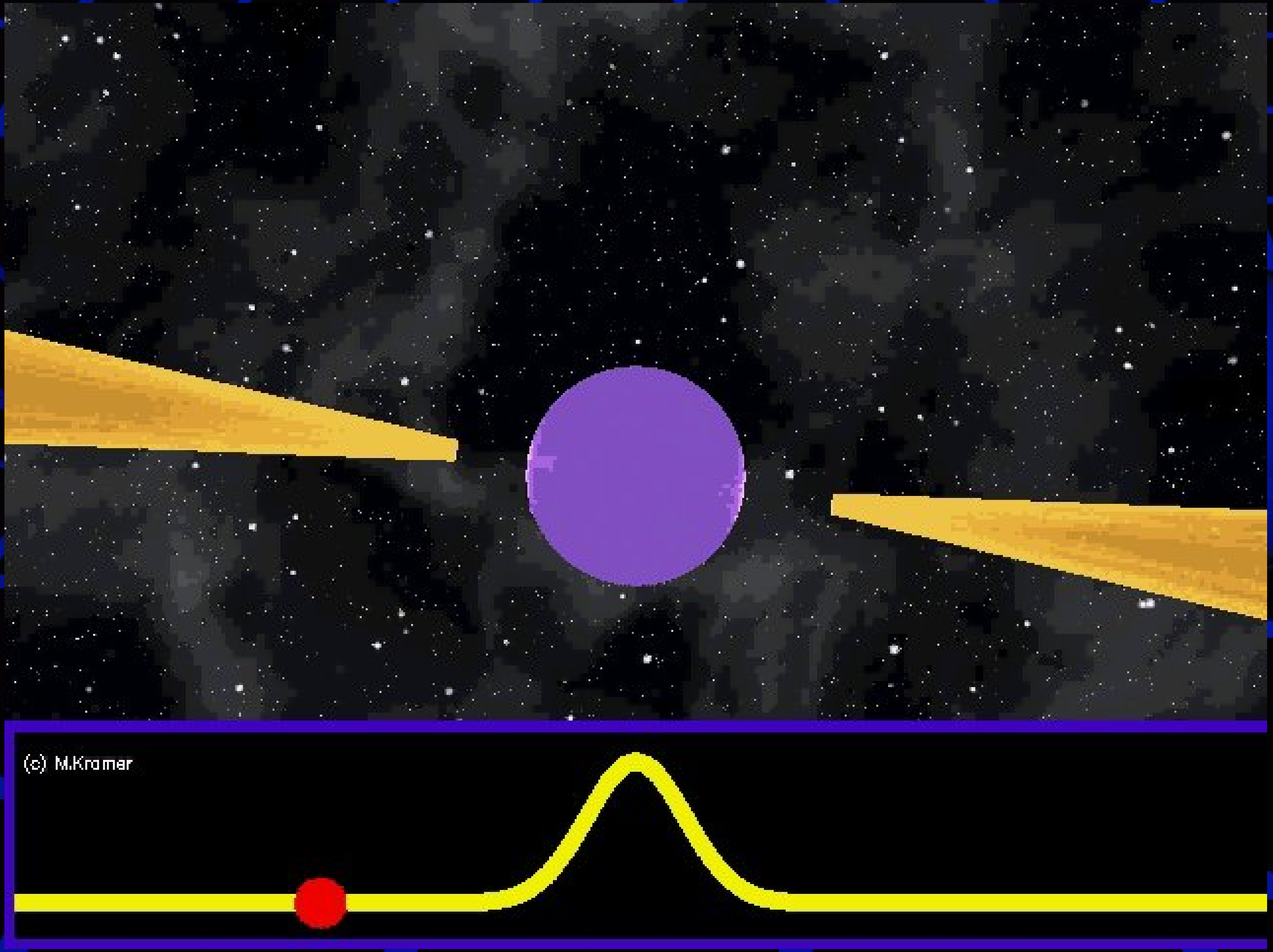
Pulsars…

- Jocelyn Bell discovers a periodic extra-terrestrial signal of 1.337s at celestial position
- A journalist calls these sources “PULSARs”



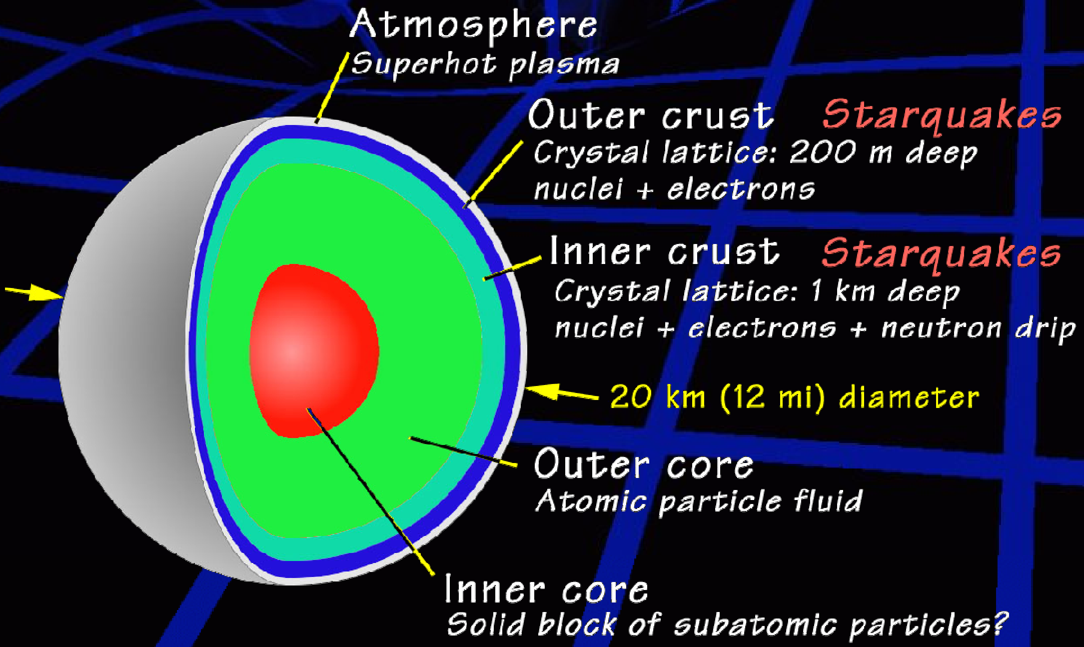
PULSAting Radiosource

Pulsars are Cosmic Lighthouses…



Pulsars are Neutron stars

- Average mass is close to $1.4\ M_{\odot}$
- Radius is about 10 km
- Size and structure depends on "Equation-of-State"
- Current research suggests:



Atmosphere
Superhot plasma

Outer crust Starquakes
Crystal lattice: 200 m deep
nuclei + electrons

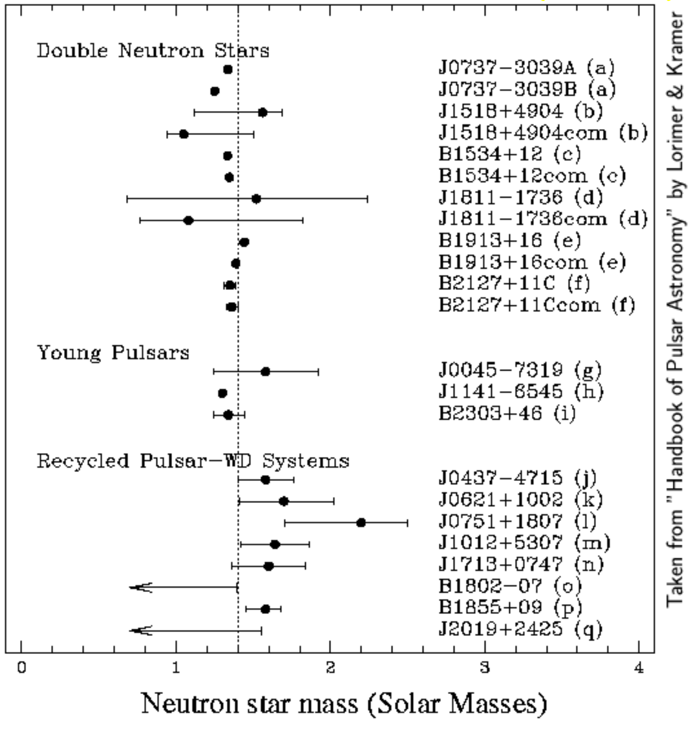
Inner crust Starquakes
Crystal lattice: 1 km deep
nuclei + electrons + neutron drip

20 km (12 mi) diameter

Outer core
Atomic particle fluid

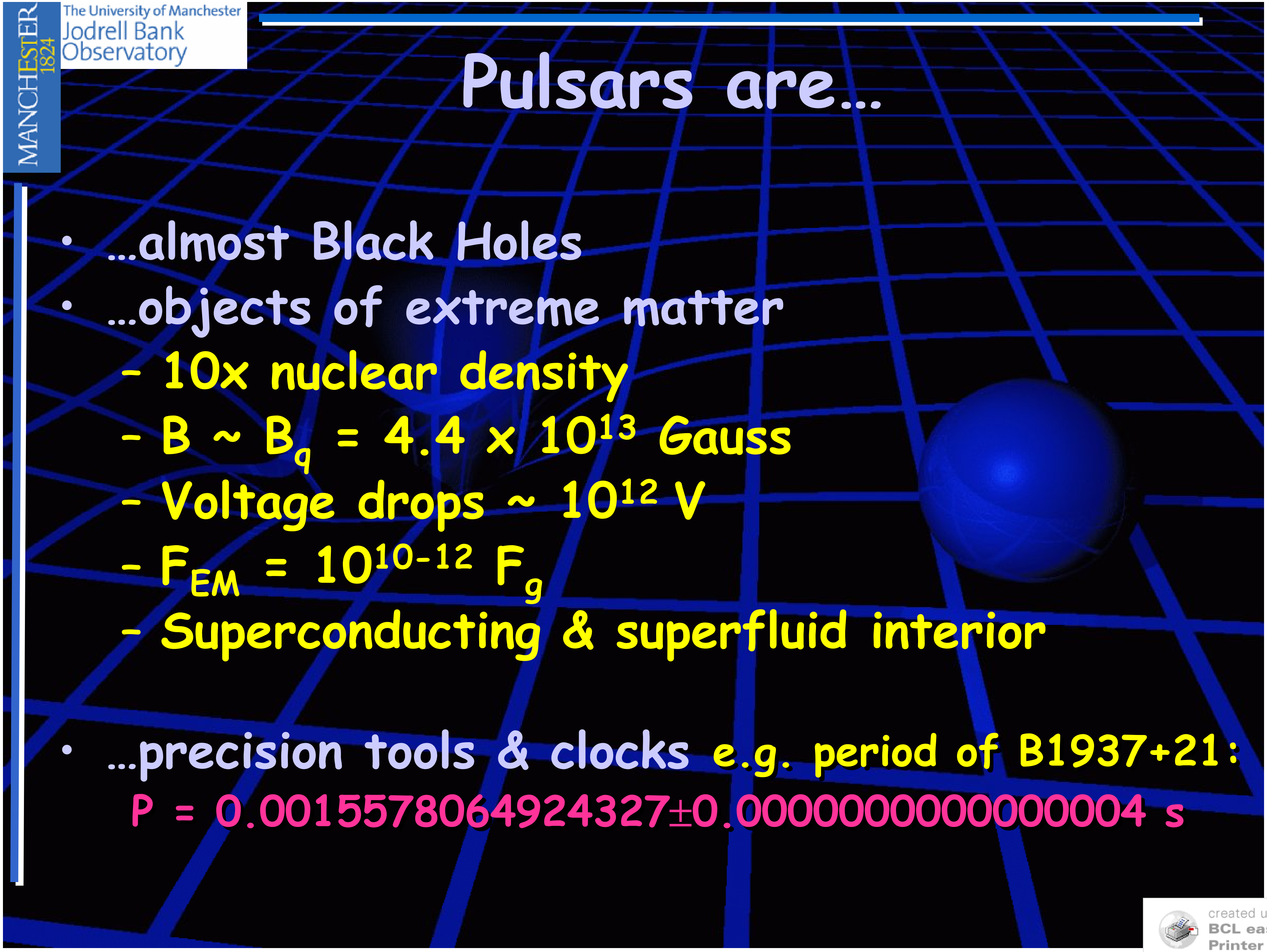
Inner core
Solid block of subatomic particles?

Stairs (2004)



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Pulsars are…



- …almost Black Holes
- …objects of extreme matter
  - 10x nuclear density
  - $B \sim B_q = 4.4 \times 10^{13}$ Gauss
  - Voltage drops $\sim 10^{12}$ V
  - $F_{EM} = 10^{10-12} F_g$
  - Superconducting & superfluid interior

- …precision tools & clocks e.g. period of B1937+21:

  $P = 0.0015578064924327 \pm 0.0000000000000004$ s

Wide range of applications…

Test of the Strong-Equivalence Principle:

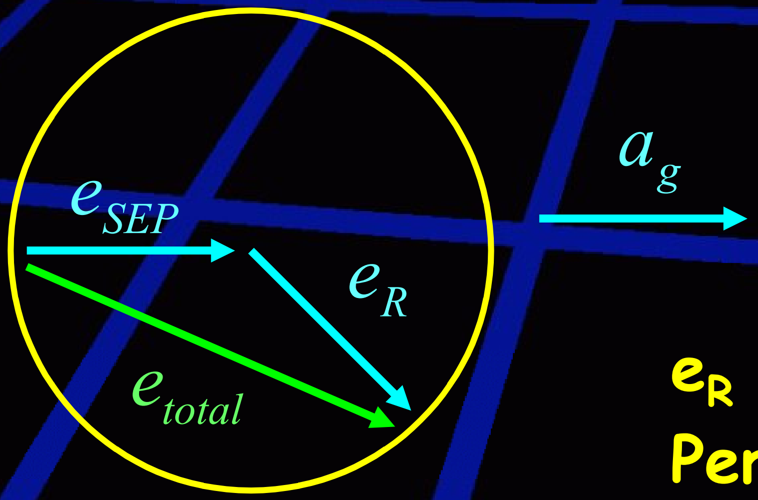
- Use low-eccentricity Pulsar-White Dwarf systems
- See Stairs et al. (2005) for latest result:

$$\left.\begin{array}{l}\boxed{\varepsilon(\mathrm{NS}) \approx 0.15} \\ \boxed{\varepsilon(\mathrm{WD}) \approx 10^{-4}}\end{array}\right\}$$

polarization of orbit

"Grav. Stark effect"

Damour & Schaefer (1991)



Induced eccentricity due to galactic acceleration

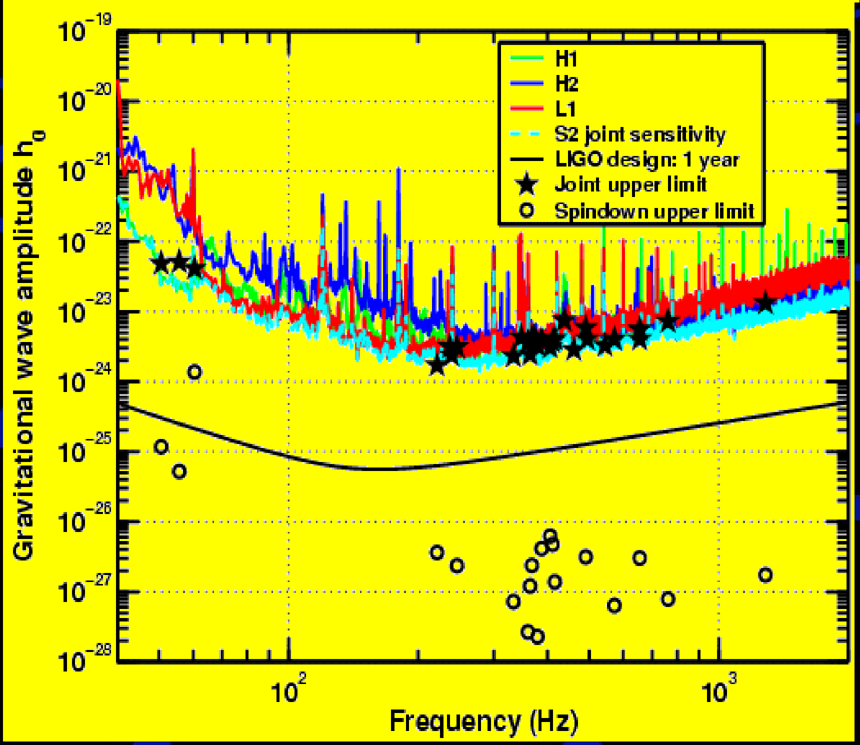
e_R moves due to rel. advance of Periastron ⇒ stat. analysis

Wide range of applications…

Sources of gravitational wave emission:

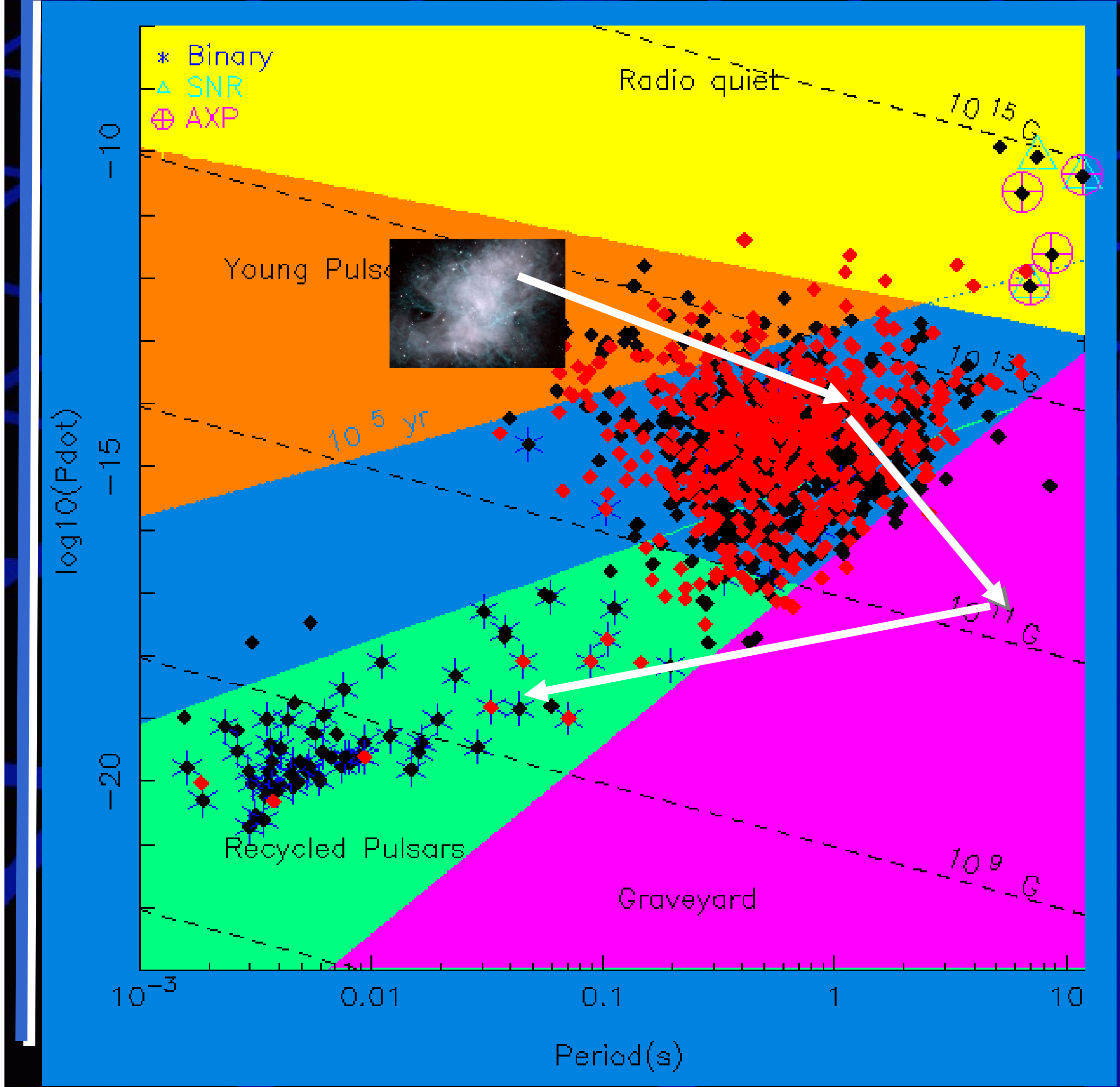
- Spinning neutron stars may emit continuous GW signal
- For pulsars we know where to look in space & frequency

LIGO Consortium, Kramer & Lyne (2005)




Limits on gravitational wave emission from selected pulsars using LIGO data

Making precise clocks or the life of pulsars

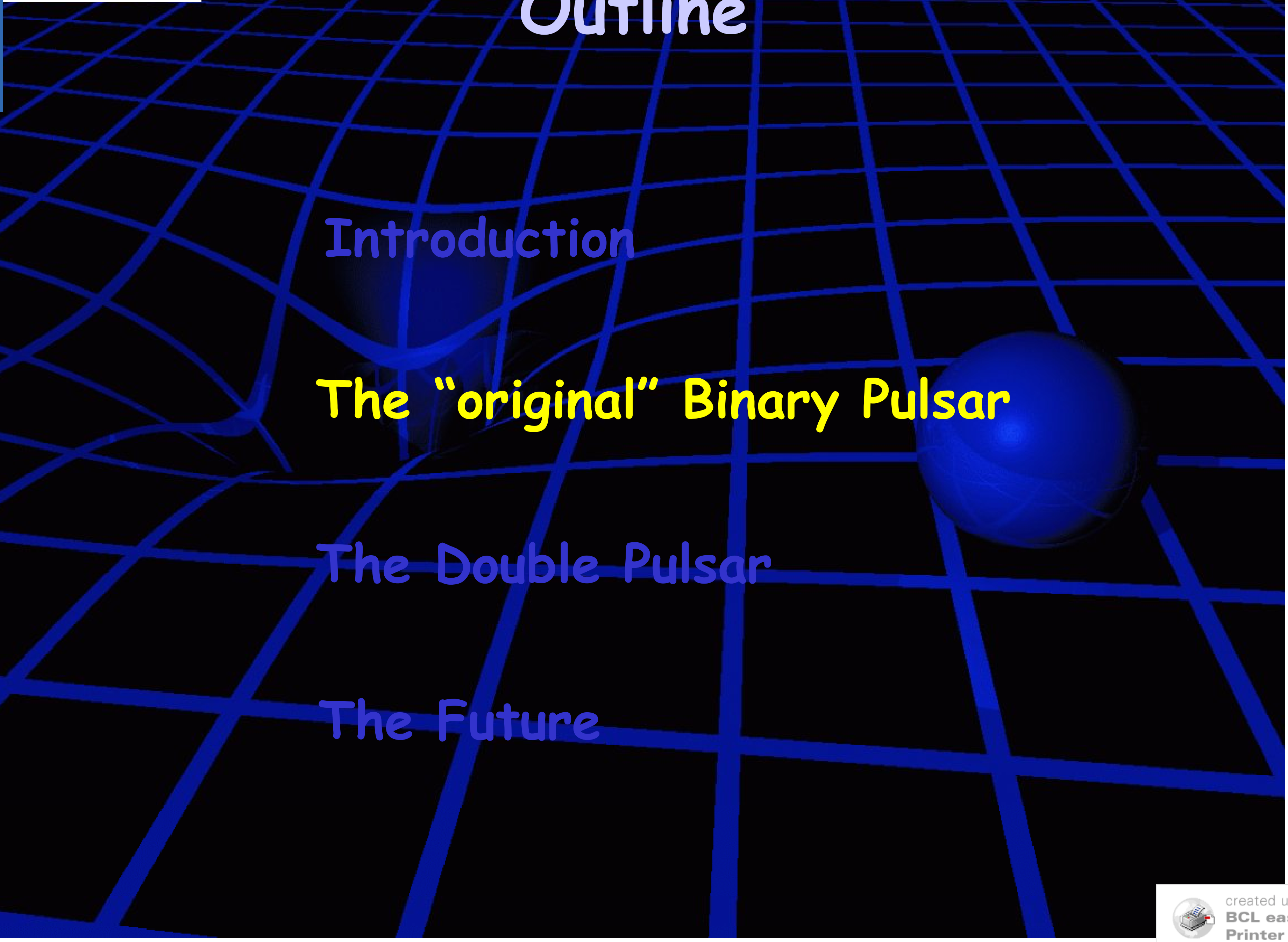


The smaller the period, the better the timing!

(NASA)

Some dead pulsars with companion will be spun up (recycled) as millisecond pulsars

Outline



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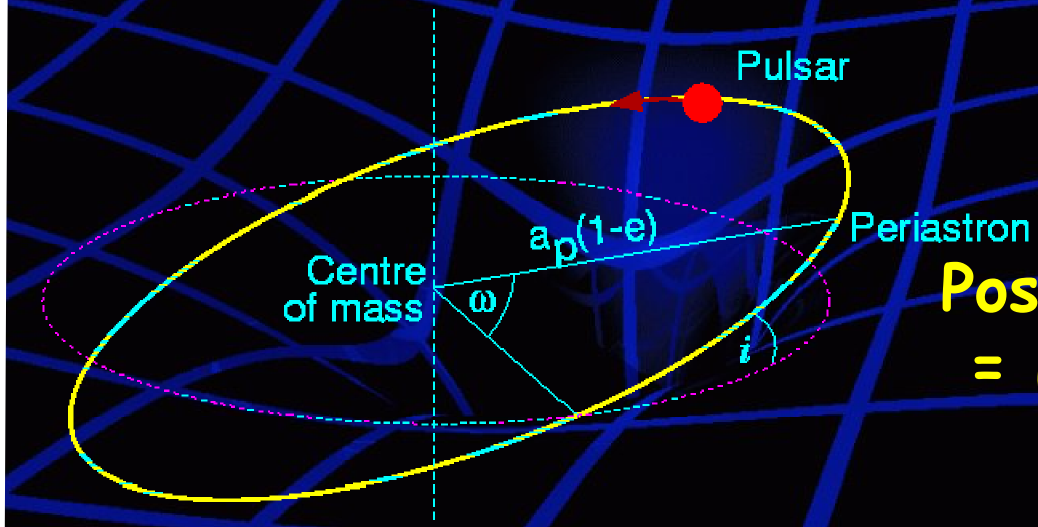
Timing Binary Pulsars

- Five Keplerian parameters are measurable:



Post-Keplerian Parameters
= necessary corrections to describe observed pulse times of arrival (TOAs)

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

Most common PK parameters:
(see Damour & Deruelle '85,'86)

- Precession of orbit, $d\omega/dt$
- Decay of orbit, dP_b/dt
- Shapiro delay, r and s
- Gravitational redshift, γ

Strong-field tests with binary pulsars

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

(see Damour & Taylor '92)

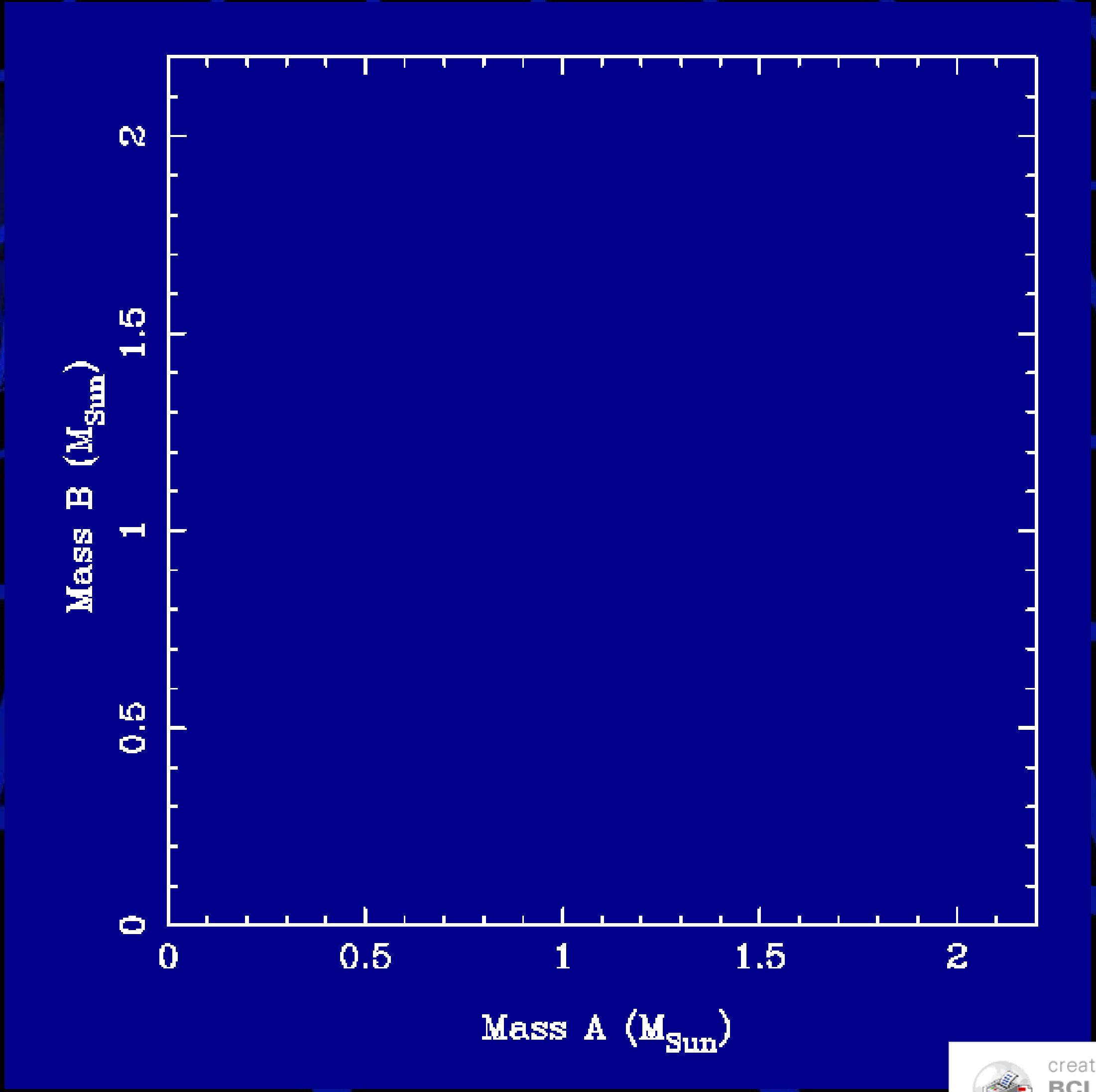
All PK parameter can be written as function of only observed Keplerian and the masses of pulsar and companion, eg in GR:

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

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

f, *g* depend on theory!

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



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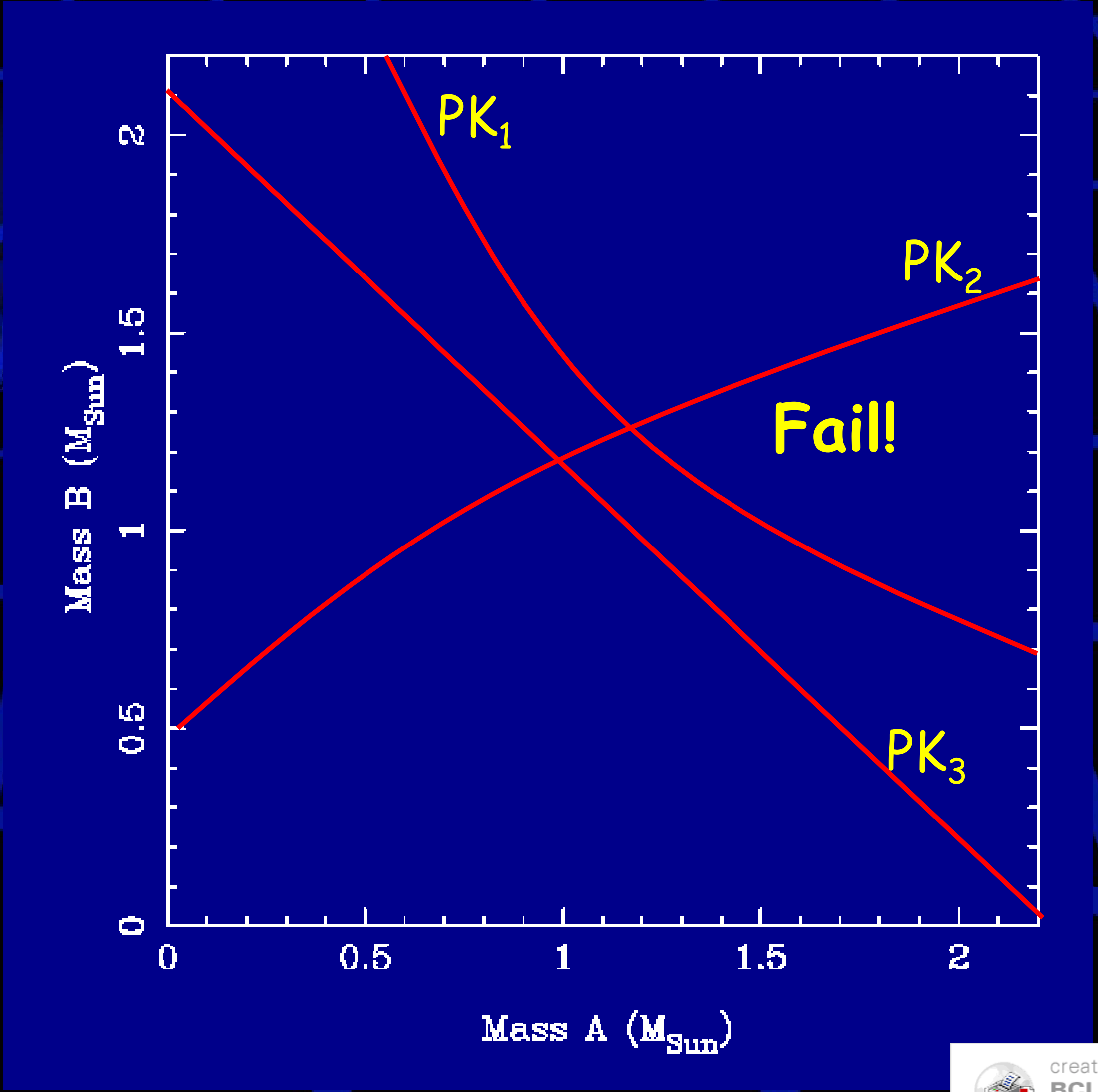

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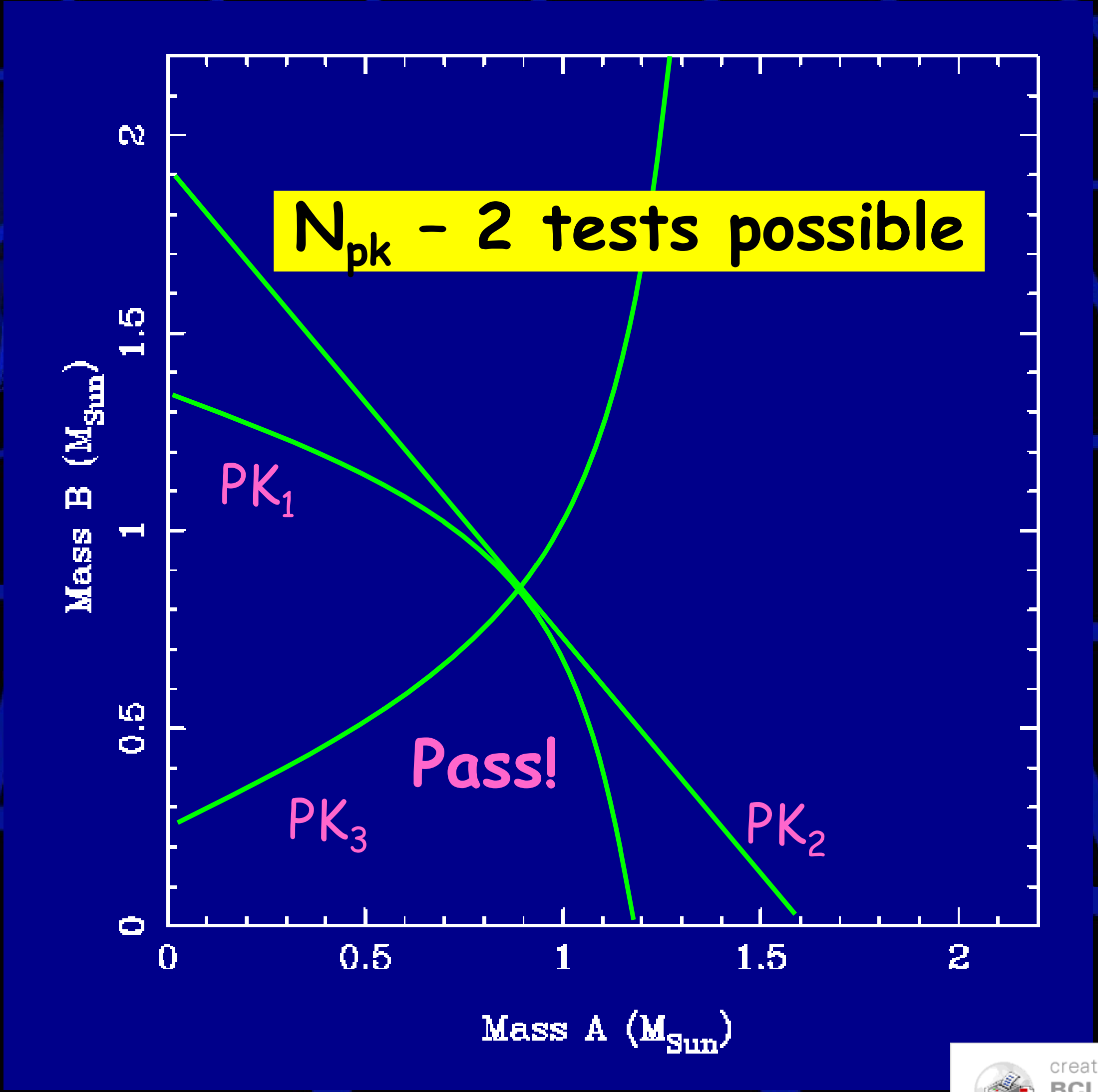
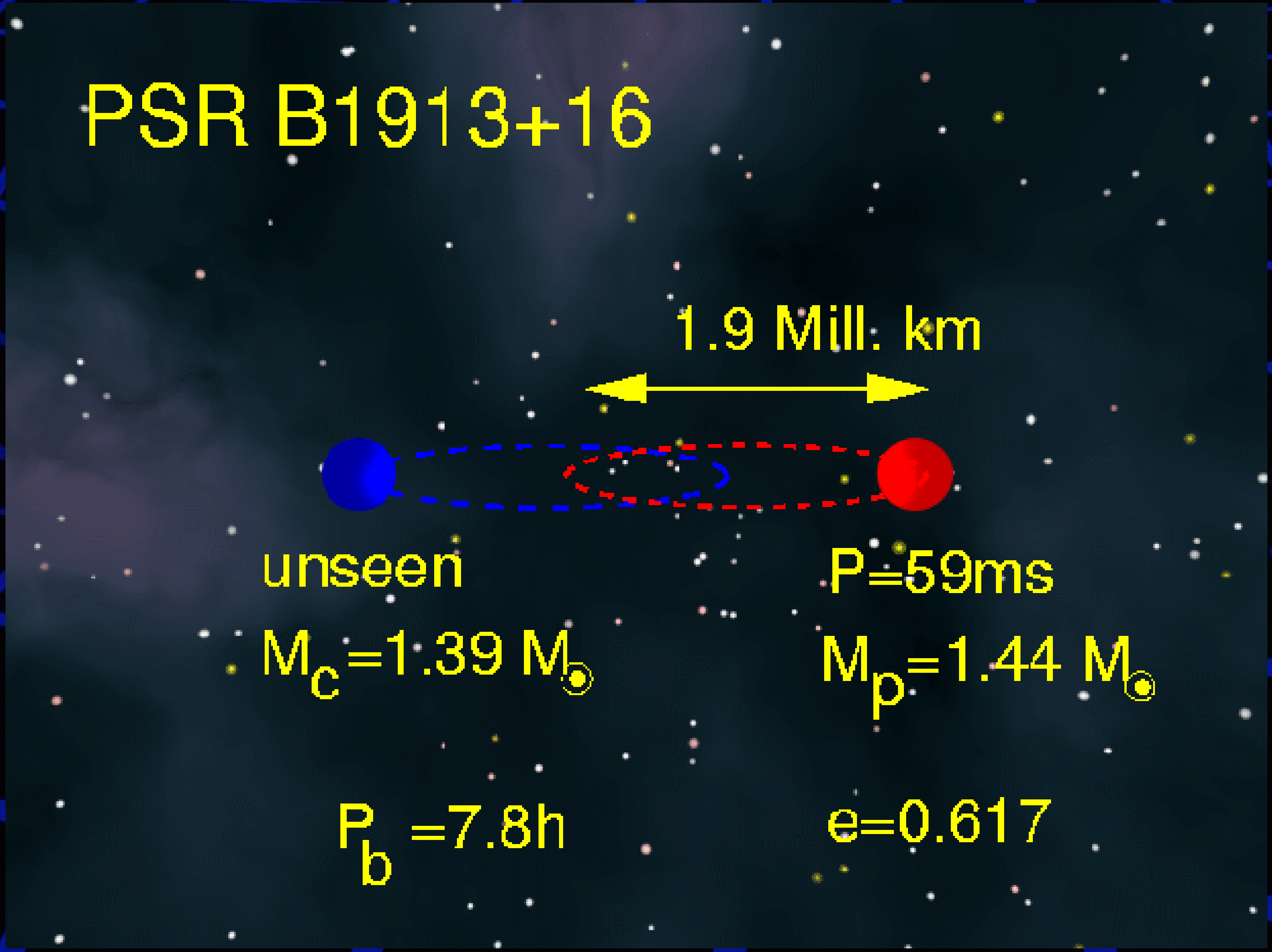


The binary pulsar: PSR B1913+16



Discovered by Hulse & Taylor in 1974

The binary pulsar: PSR B1913+16

3 PK parameters measured:

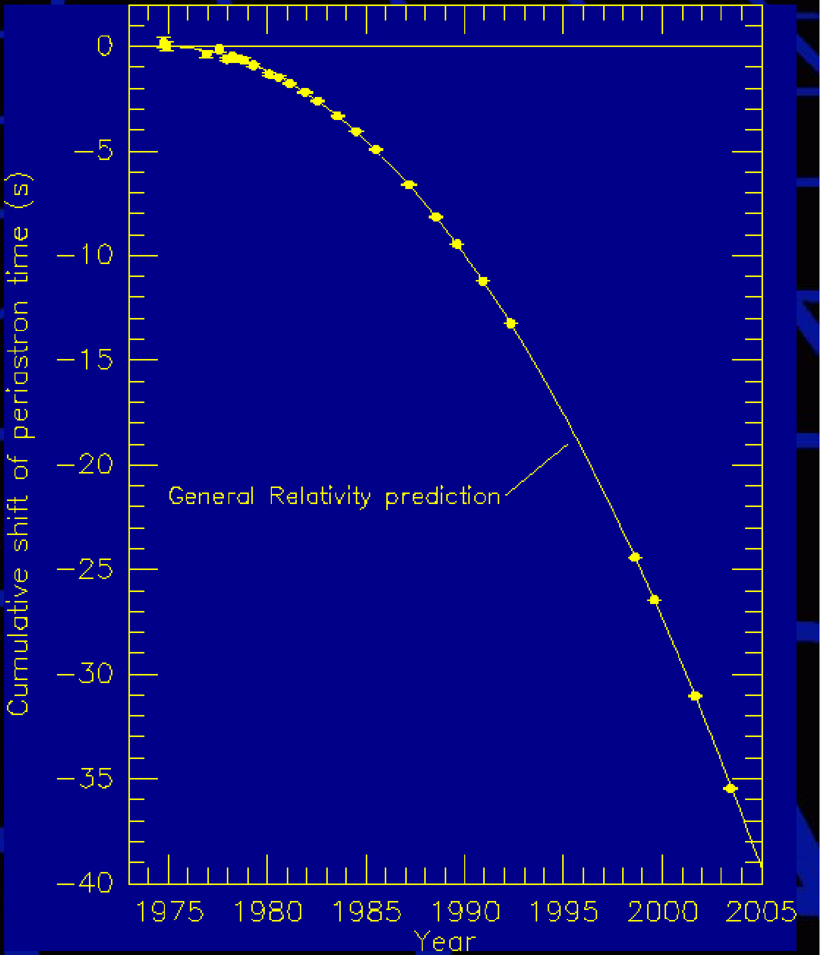
(Weisberg & Taylor 2003)

$$\dot{\omega} = 4.226607(7)\,\mathrm{deg/yr}$$

$$\gamma = 4.294(1)\ \mathrm{ms}$$

$$\left(\dot{P}_b\right)^{obs} = -2.4211(14) \times 10^{-12}$$

Weisberg & Taylor (priv. comm)

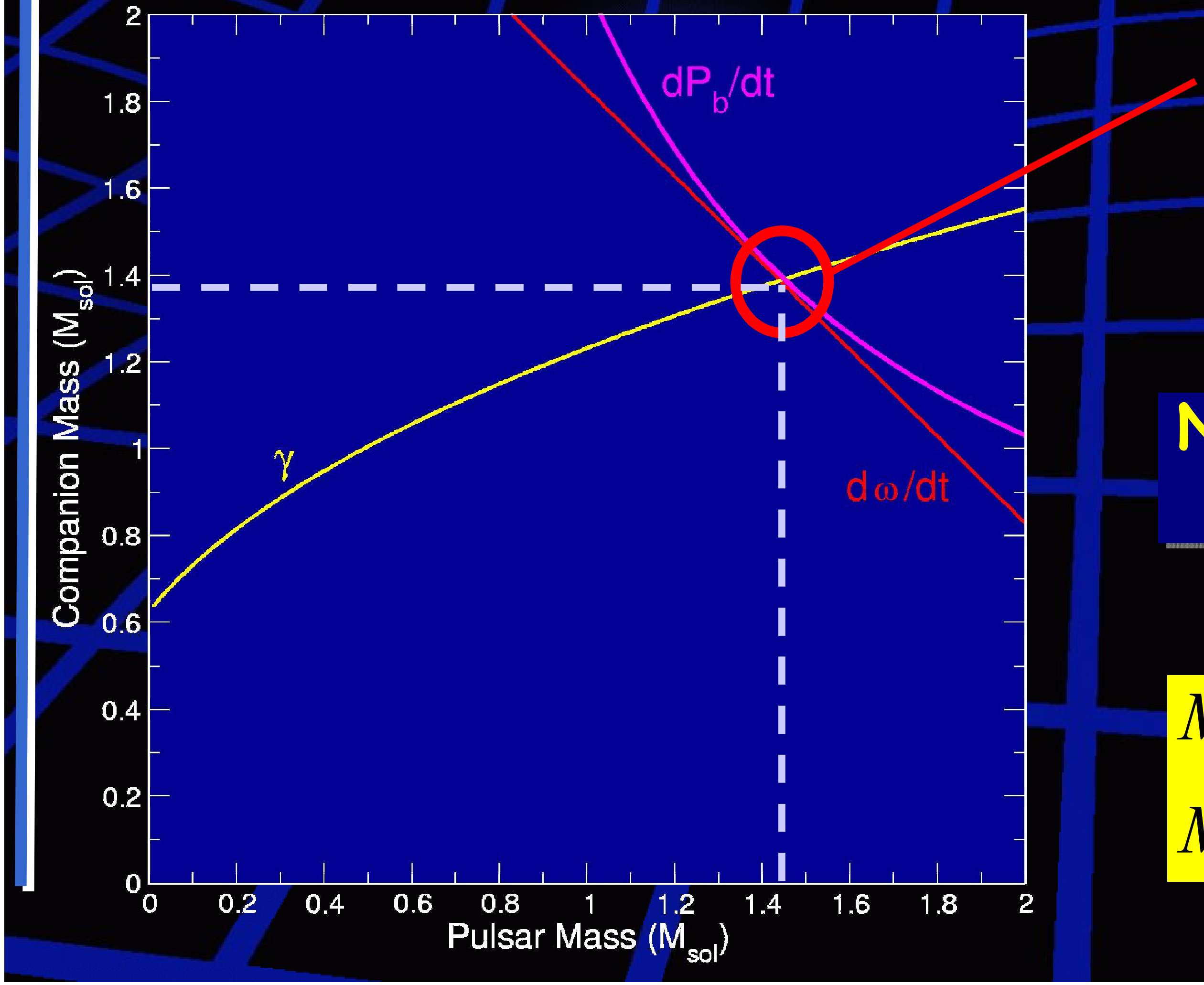


- **Orbit shrinks by 1cm/day!**
- **Measurement first announced at 1978 Texas Symposium in Munich.**

The binary pulsar: PSR B1913+16

3 PK parameters measured:

(Weisberg & Taylor 2003)

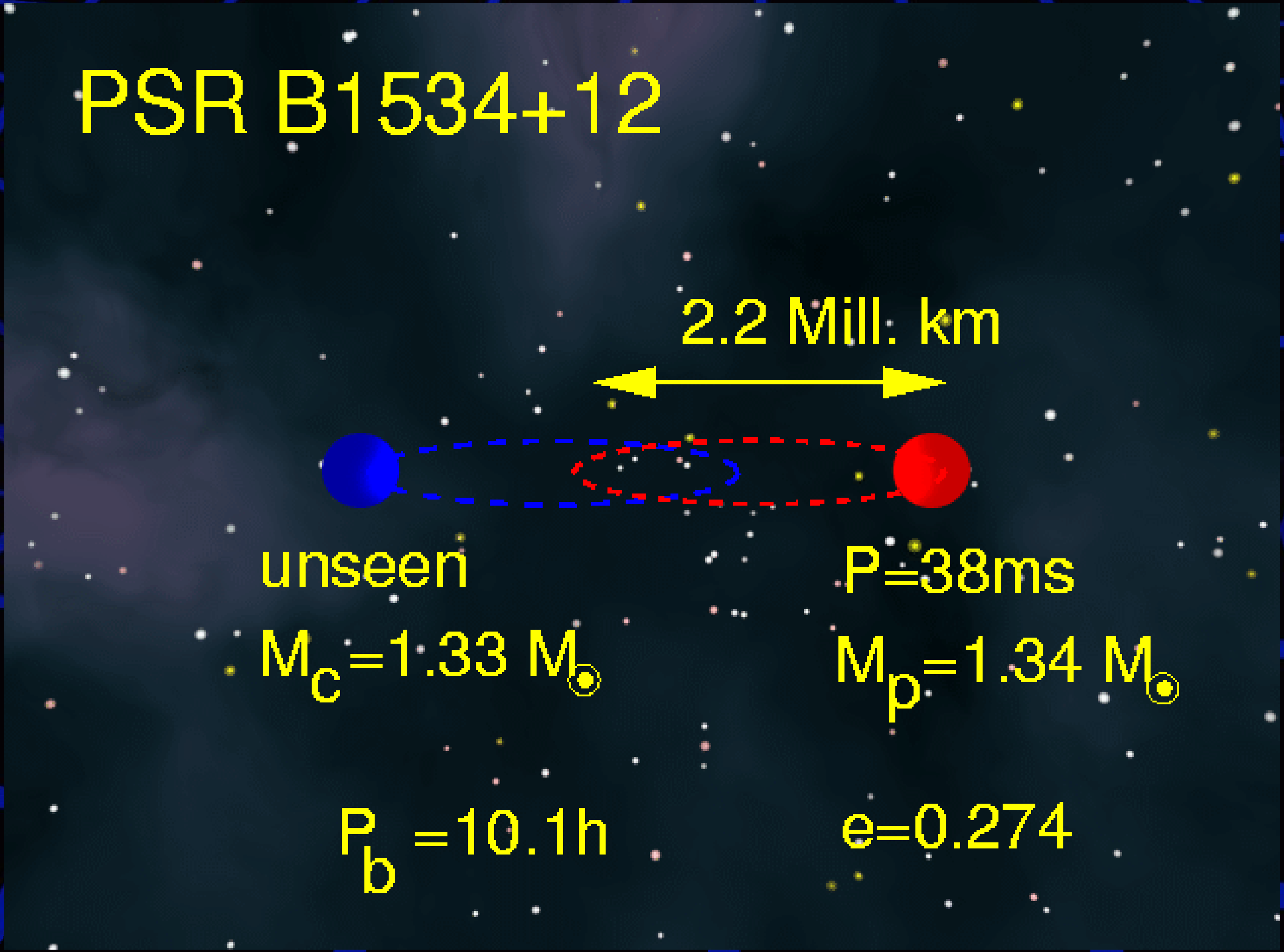


Precision limited by extrinsic effects: At ~0.2% level.

$$N_{test} = N_{PK} - 2$$
$$= 3 - 2 = 1$$

$$M_p = 1.4408(3) M_\odot$$
$$M_c = 1.3873(3) M_\odot$$

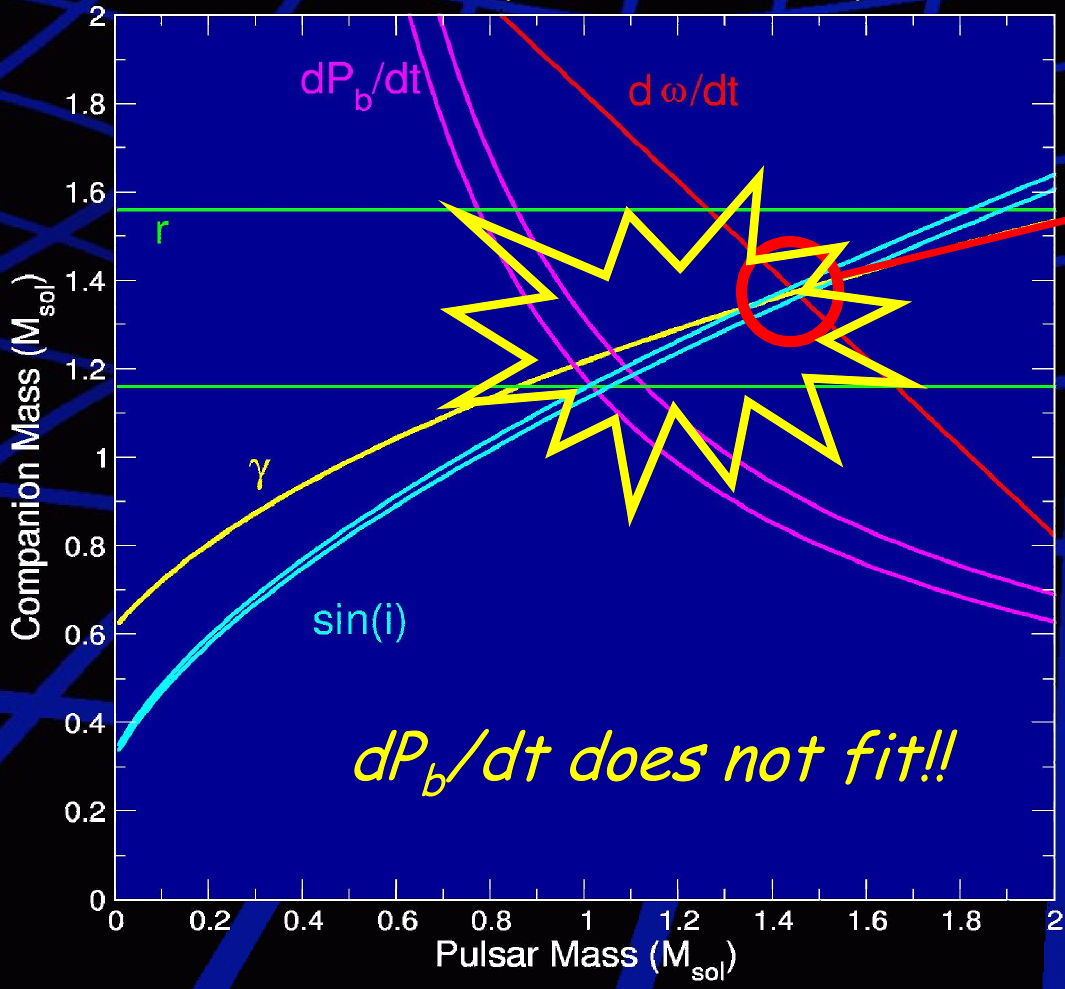
The second DNS: PSR B1534+12



Discovered by Wolszczan et al. in 1990

The second DNS: PSR B1534+12

B1534+12 (Stairs et al. '02)



dP_b/dt does not fit!!

Theoretically:

$N_{test} = N_{PK} - 2$
$= 5 - 2 = 3$

But: only three PK parms usable: test at ~1% level.

$$\dot{\omega} = 1.755789(9)\ \mathrm{deg/yr}$$

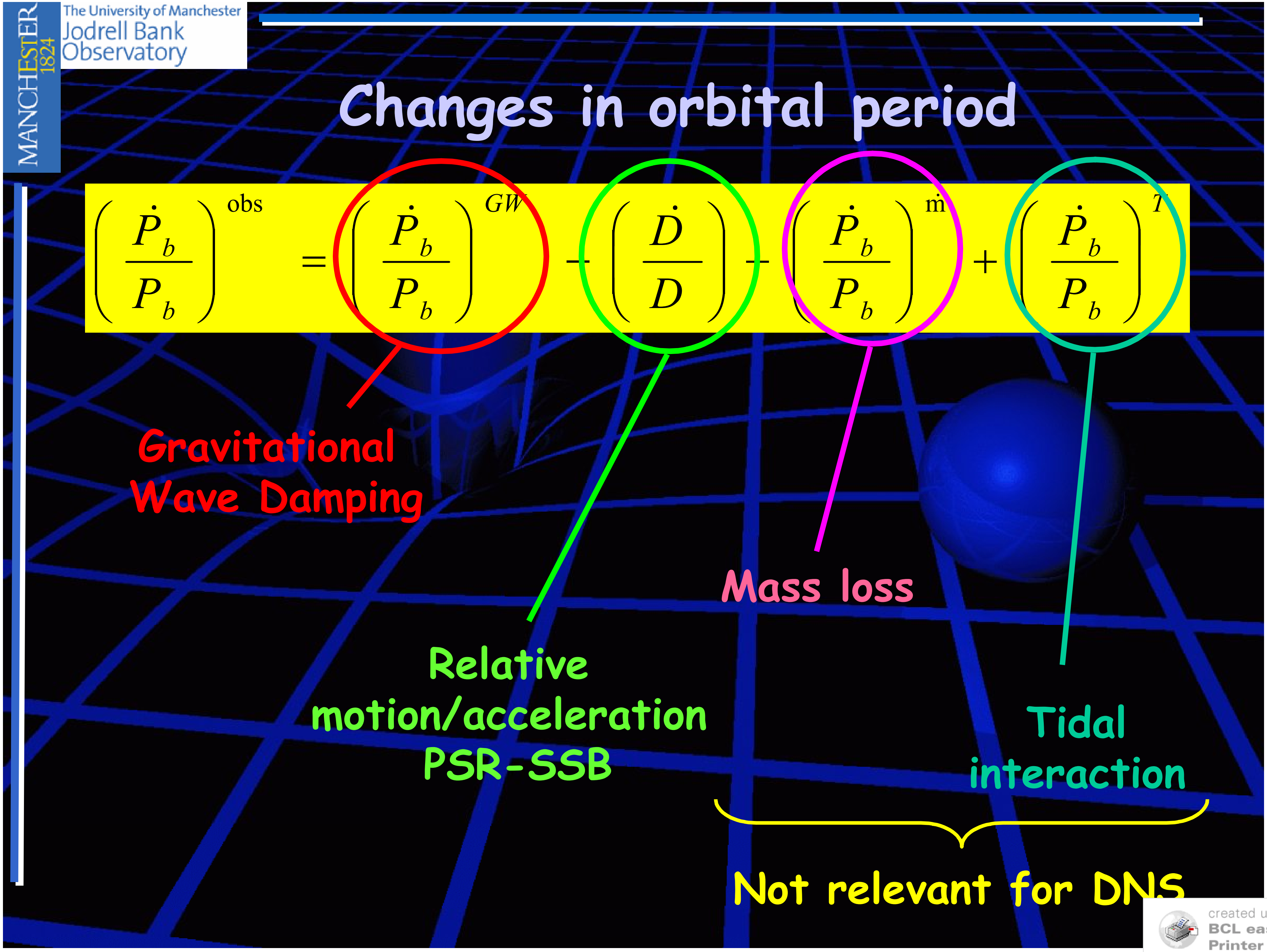
$$\gamma = 2.070(2)\ \mathrm{ms}$$

$$\left(\dot{P}_b\right)^{obs} = -0.137(3) \times 10^{-12}$$

$$\mathrm{s} = 0.975(7)$$

$$\mathrm{r} = 6.7(1.0)\ \mu\mathrm{s}$$

Changes in orbital period



$$\left(\frac{\dot{P}_b}{P_b}\right)^{\mathrm{obs}} = \left(\frac{\dot{P}_b}{P_b}\right)^{GW} - \left(\frac{\dot{D}}{D}\right) - \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{m}} + \left(\frac{\dot{P}_b}{P_b}\right)^{T}$$

Gravitational Wave Damping

Relative motion/acceleration PSR-SSB

Mass loss

Tidal interaction

Not relevant for DNS

Changes in orbital period: kinematic contributions

Damour & Taylor (1991)

$$-\left(\frac{\dot{D}}{D}\right) = \frac{1}{c}\vec{K}_0\left(\vec{a}_{PSR} - \vec{a}_{SSB}\right) + \frac{v_T^2}{c \cdot d}$$

$$= -\frac{a_z \sin b}{c} - \frac{v_0^2}{cR_0}\left(\cos l + \frac{d/R_0 - \cos l}{\sin^2 l + \left(d/R_0 - \cos l\right)^2}\right) + \frac{v_T^2}{c \cdot d}$$

Acceleration perpendicular to Galactic plane

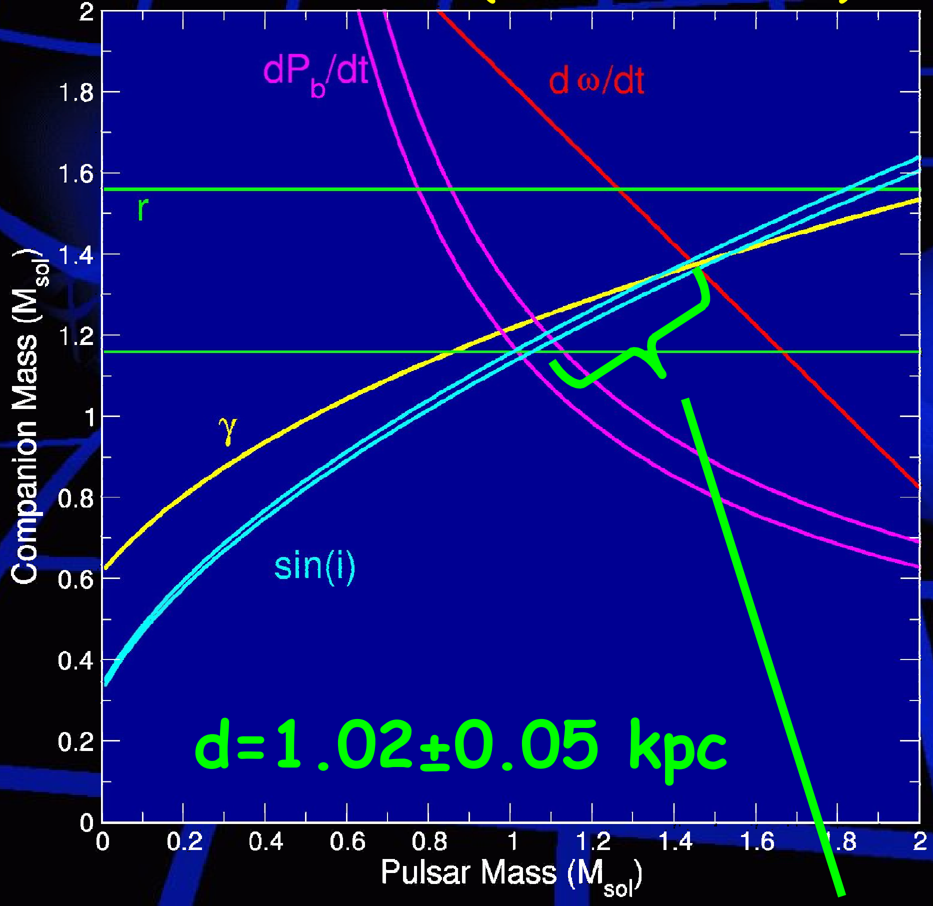
Acceleration parallel to Galactic plane

Secular acceleration "Shklovskii term"

- With knowledge of Galactic potential, distance and velocity, one can correct for it: e.g. PSR B1913+16
- Accuracy of corrections limits precision of 1913's test
- For B1534, one can use deviation from intersection for distance measurement – assuming that GR is corre

Changes in orbital period: kinematic contributions

B1534+12 (Stairs et al. '02)



d=1.02±0.05 kpc

- For B1534, one can use deviation from intersection for distance measurement – assuming that GR is corre

Binary pulsars testing GR

- Depending on kind of test, different systems useful
- For Scalar-Tensor theories: use PSR-WD systems!
- For strong-field effects: double neutron stars (DNS)

DNS	P(ms)	Pb(d)	x(lt-s)	e
J0737-3039	22.7/2770	0.102	1.42/1.51	0.09
B1534+12	37.9	0.421	3.73	0.27
J1518+4904	40.9	8.64	20.0	0.25
J1756-2251	28.5	0.320	2.76	0.18
J1811-1736	104.2	18.8	34.8	0.83
J1829+2456	41.0	1.18	7.24	0.14
B1913+16	59.0	0.323	2.34	0.62
B2127+11C	30.5	0.335	2.52	0.68

Possibly another addition: see lat

Binary pulsars testing GR

- Depending on kind of test, different systems useful
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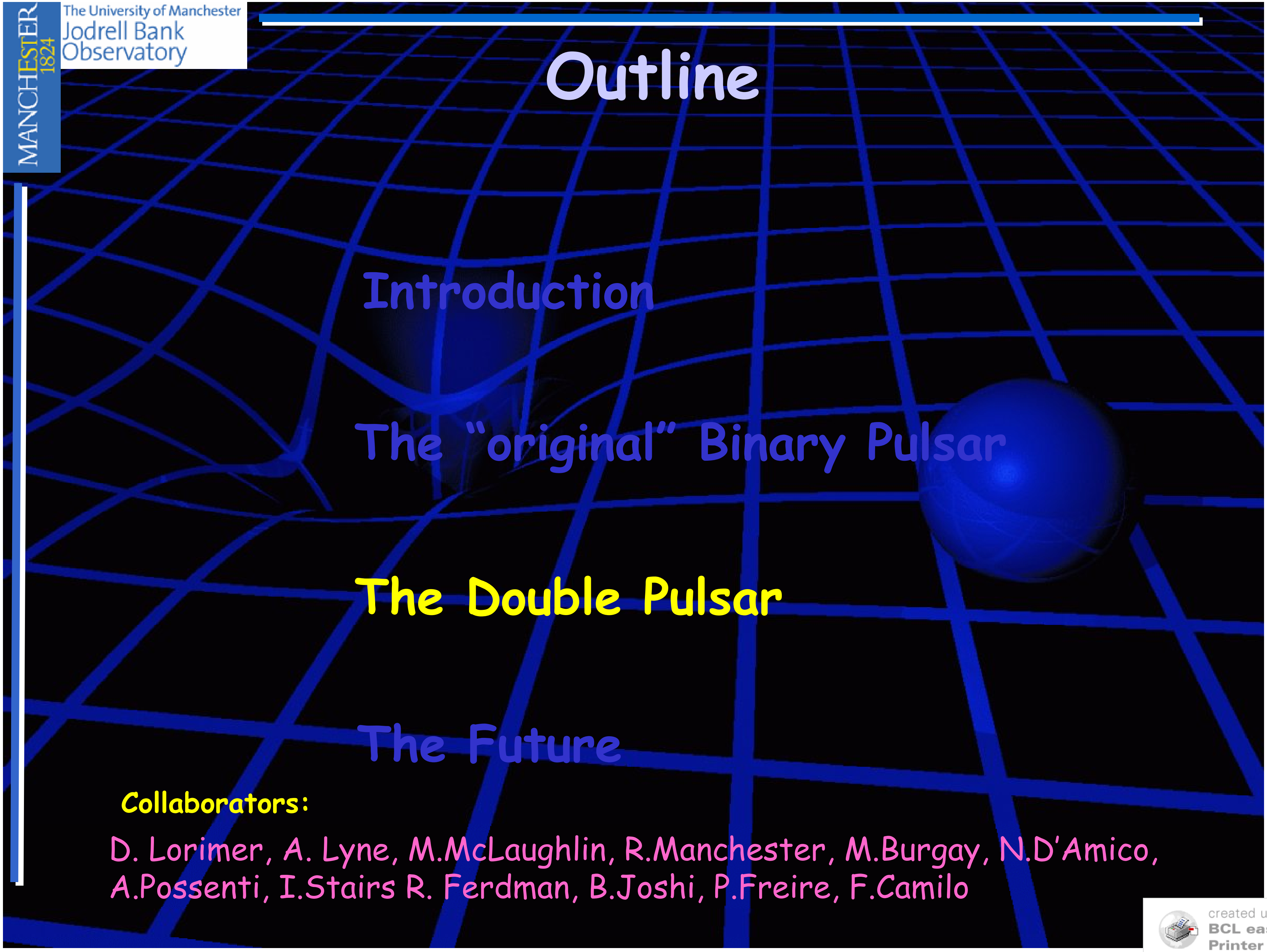
- For strong-field effects: double neutron stars (DNS)

DNS	P(ms)	Pb(d)	x(lt-s)	e
J0737-3039	22.7/2770	0.102	1.42/1.51	0.09

The Double pulsar!

Outline

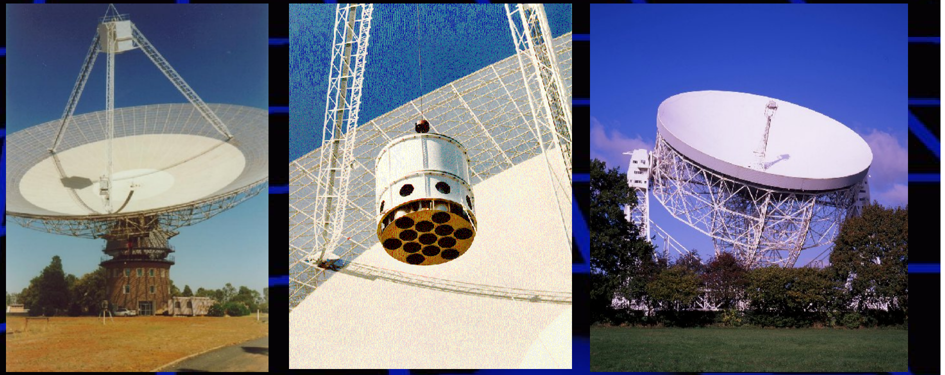


- Introduction
- The "original" Binary Pulsar
- **The Double Pulsar**
- The Future

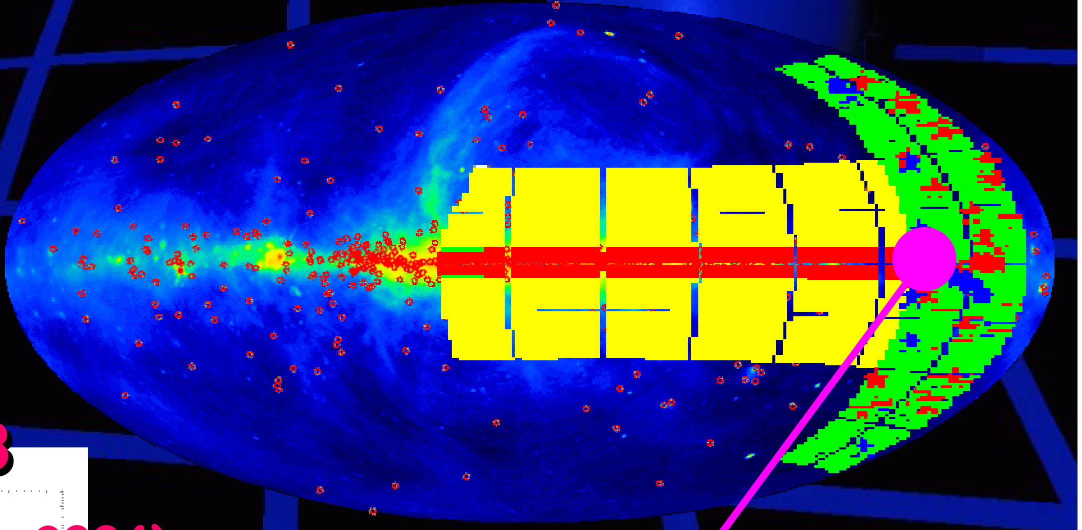
Collaborators:

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

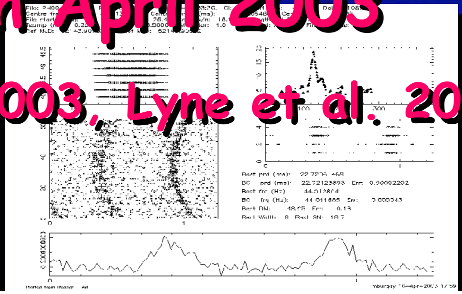
Parkes Multibeam Survey(s)



- Survey led by Jodrell Bank
- Most sensitive & most successful survey ever
- More than 740 discoveries
- More than all previous surveys put together!
- Still counting…
- Lots of exciting systems…



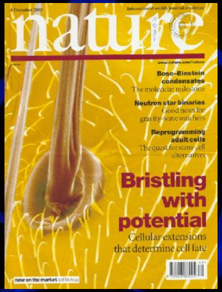
PSR J0737-3039 was discovered in April 2003



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

The first double pulsar system

- A young 2.8-s pulsar in a 2.4-hr orbit with an old 23-ms pulsar



nature

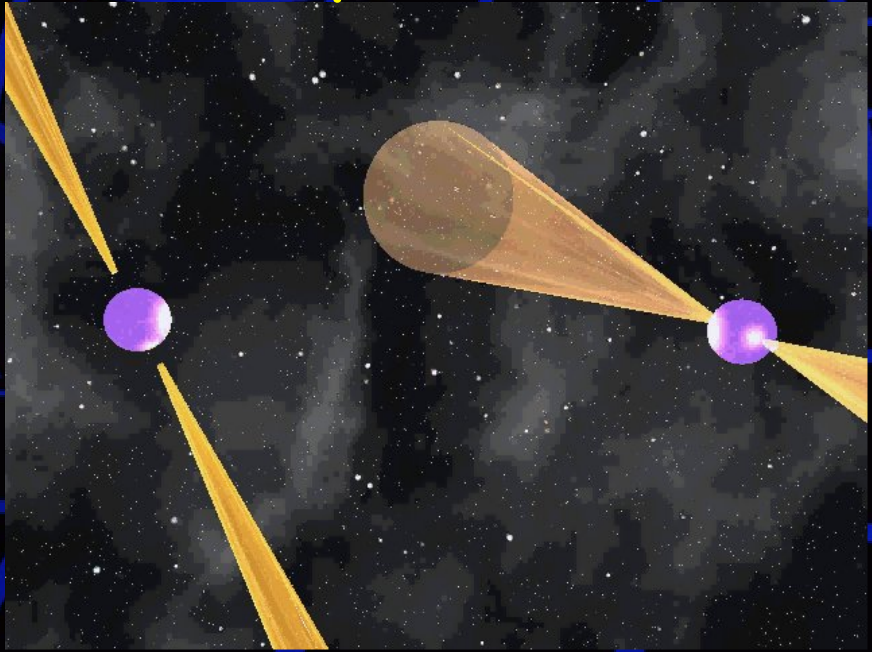
Bose-Einstein condensates

Neutron star binaries

Reprogramming adult cells

Bristling with potential

Cellular extensions that determine cell fate



Science

AAAS

PhysicsWorld

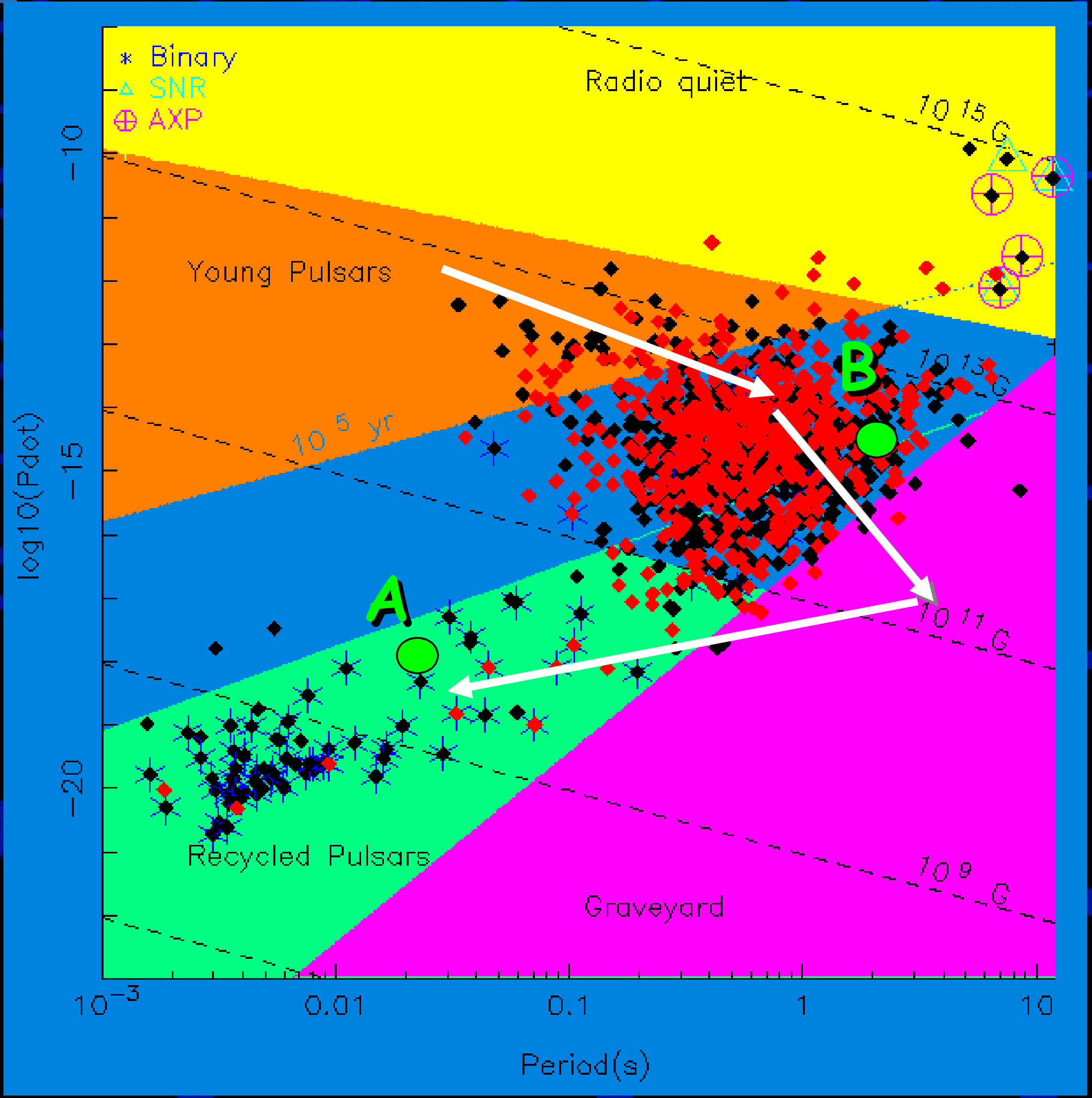
It takes two

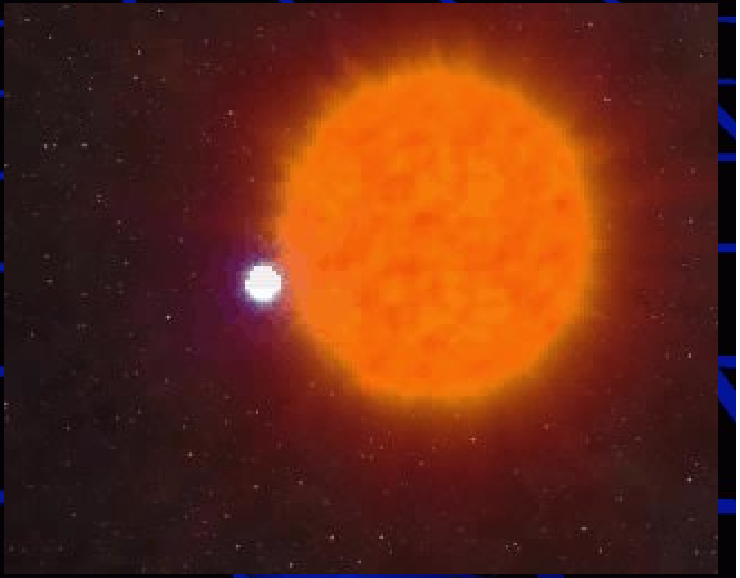
Double pulsars and general relativity

A double pulsar magnetosphere

- Orbital velocities of 1 Million km/h!
- Unique lab for gravitational physics, plasma physics and understanding of pulsar magnetospheres and radiation
- Dramatic confirmation of theories about binary evol

The life of pulsars: **confirmed!**





As expected:

- A is old & recycled
- B is young

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}

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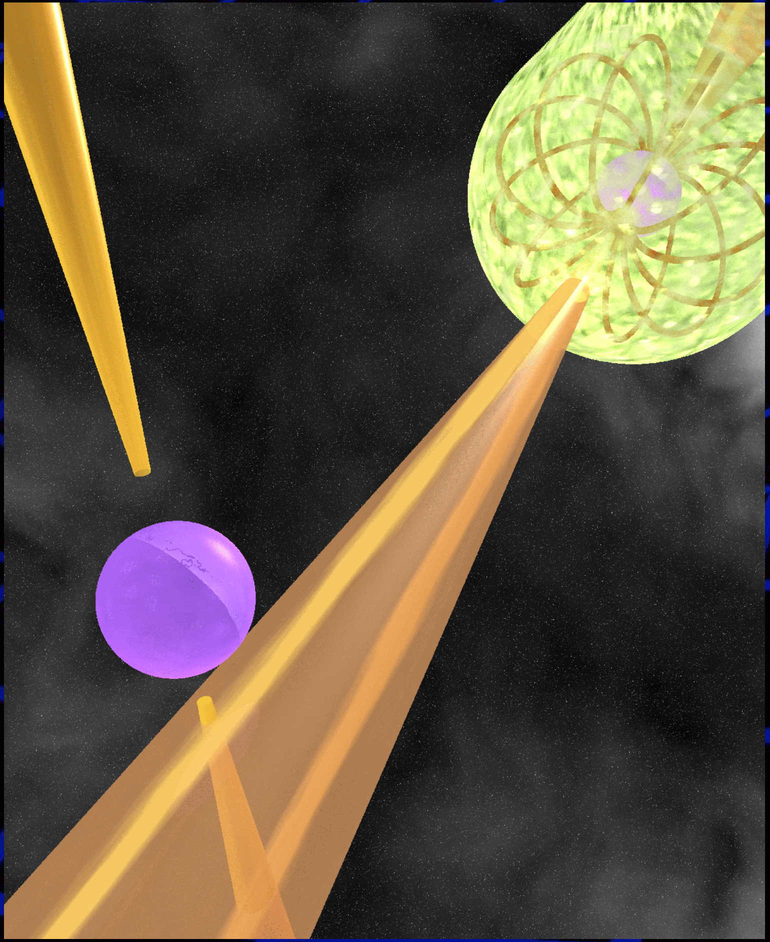
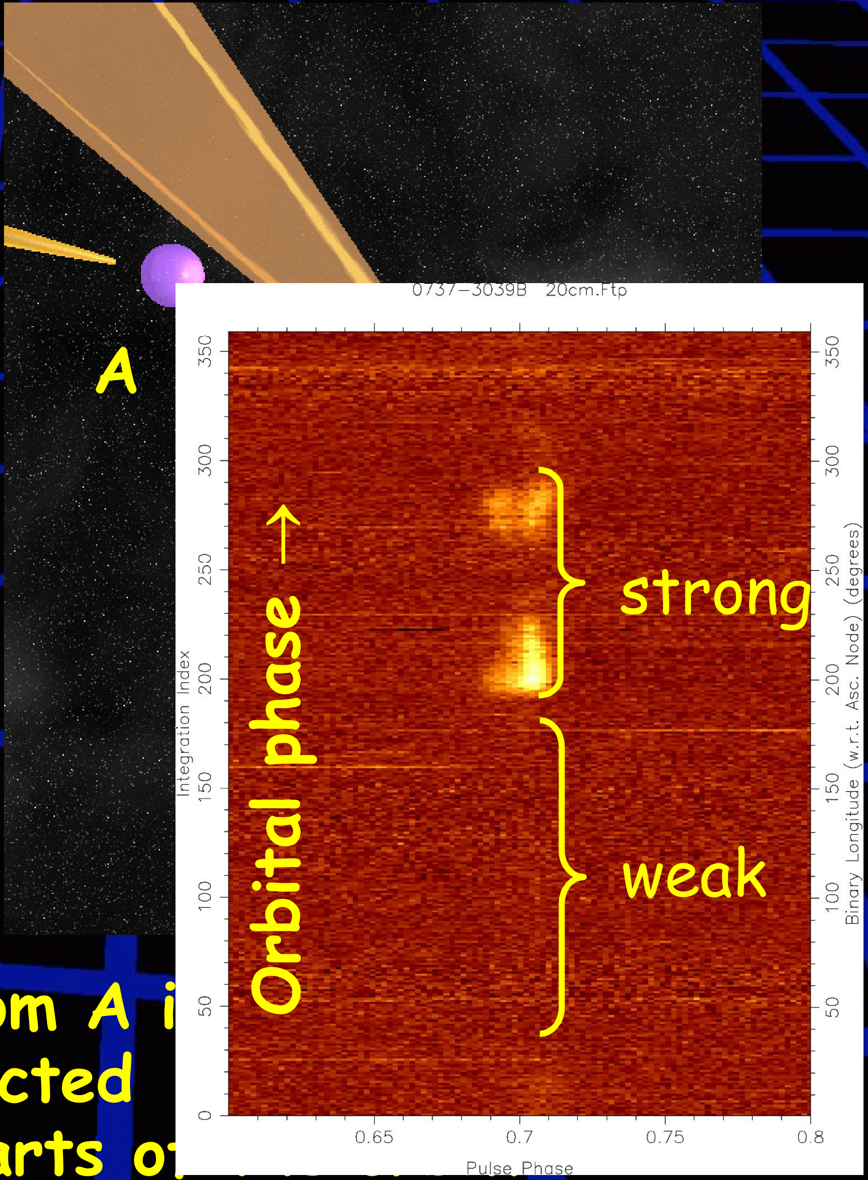
MANCHESTER 1824

The University of Manchester
Jodrell Bank
Observatory

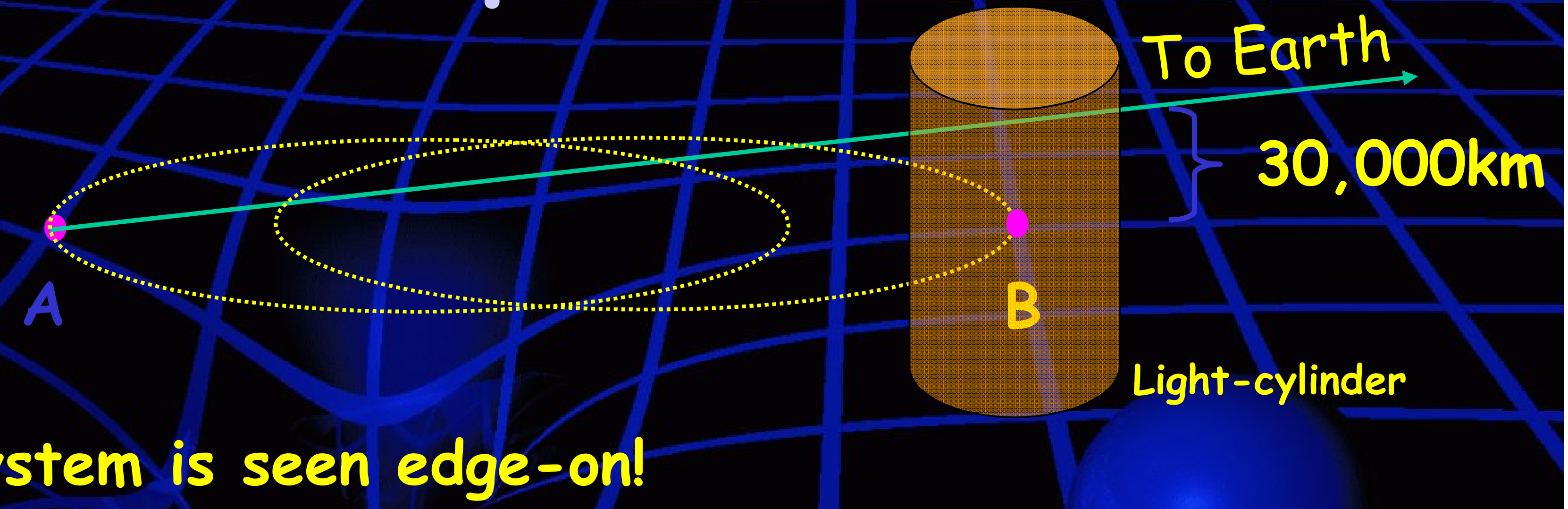
Blowing in the wind…



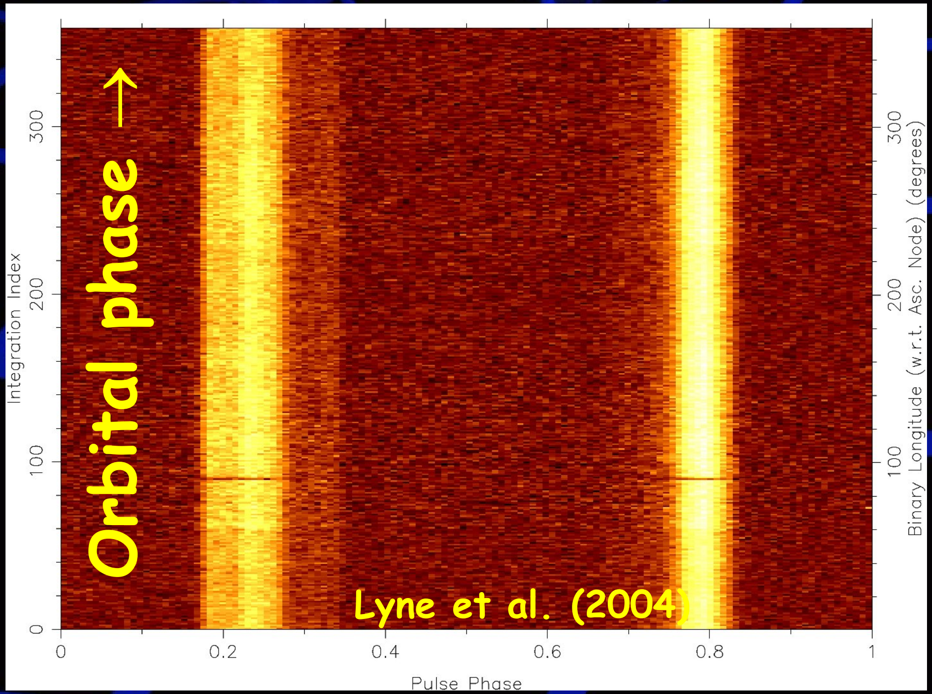


- An energetic pulsar wind from A i
- The emission from B is affected
- B is only visible for short parts o

Eclipses of A

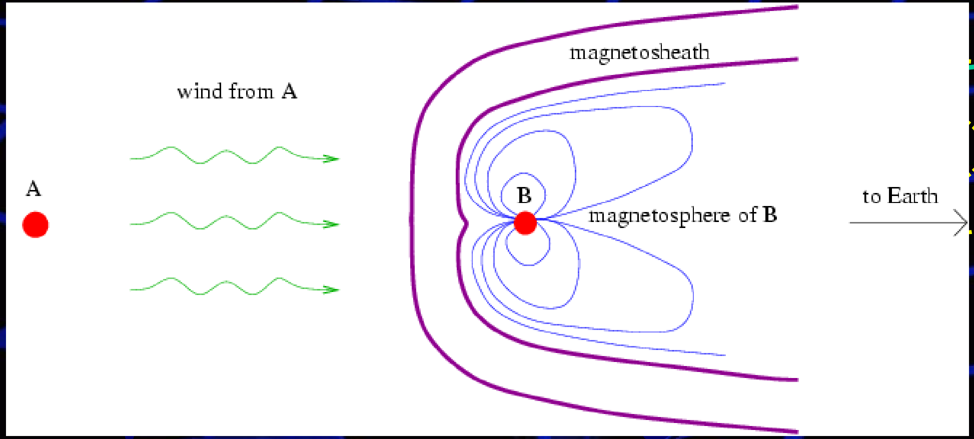


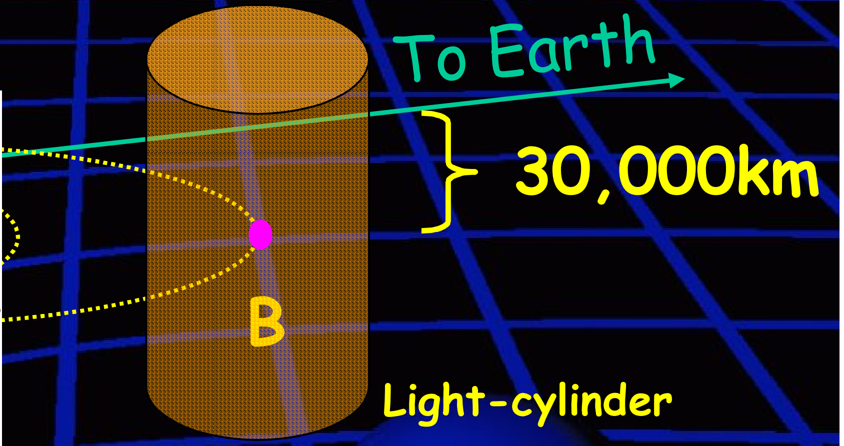
System is seen edge-on!

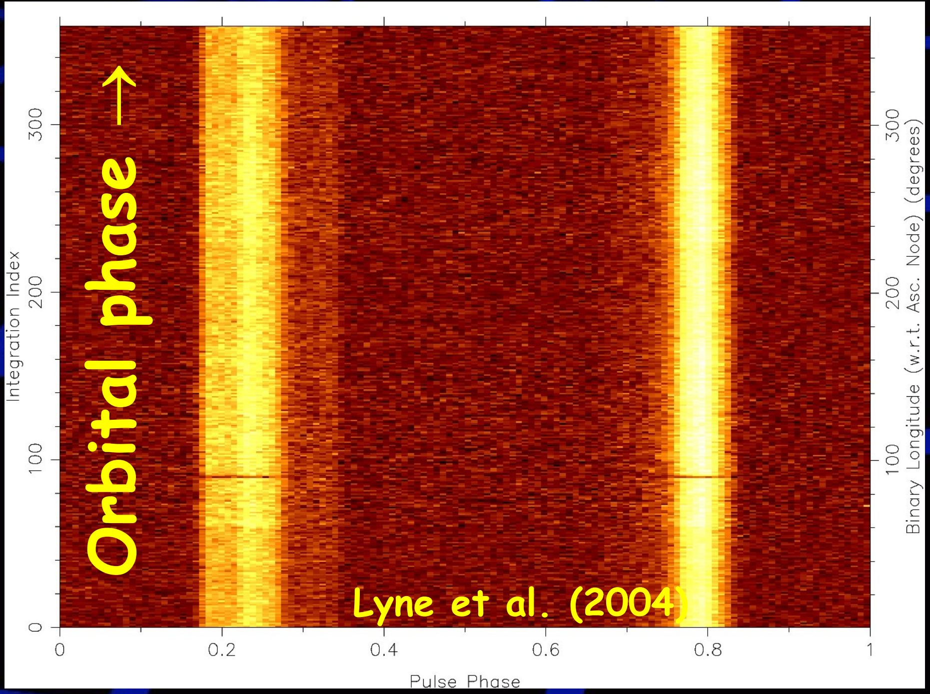


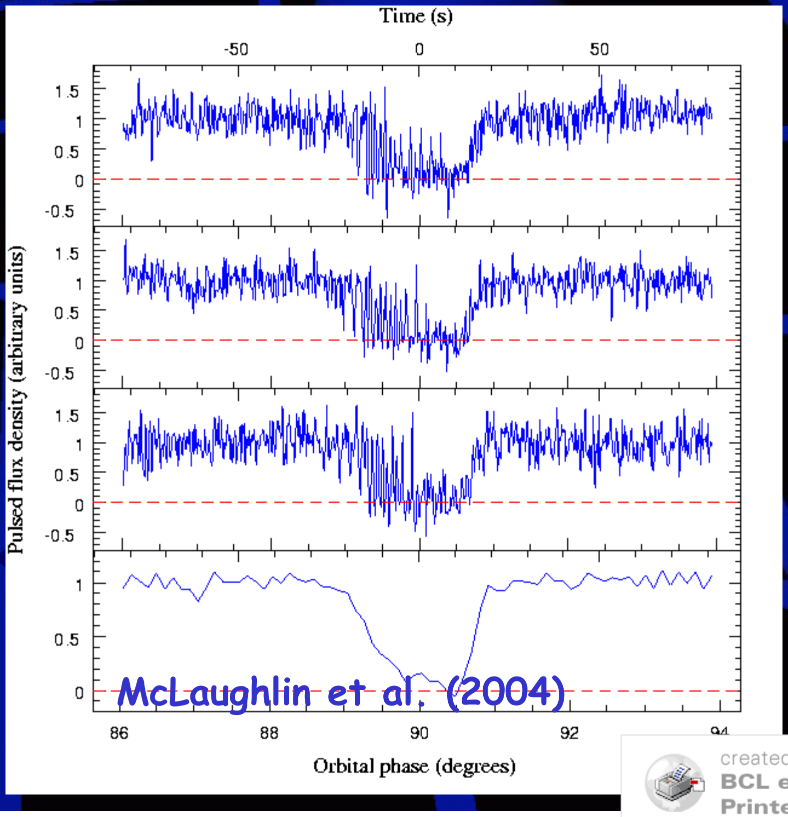
← At superior conjunction lasting for ~27 sec

Eclipses of A

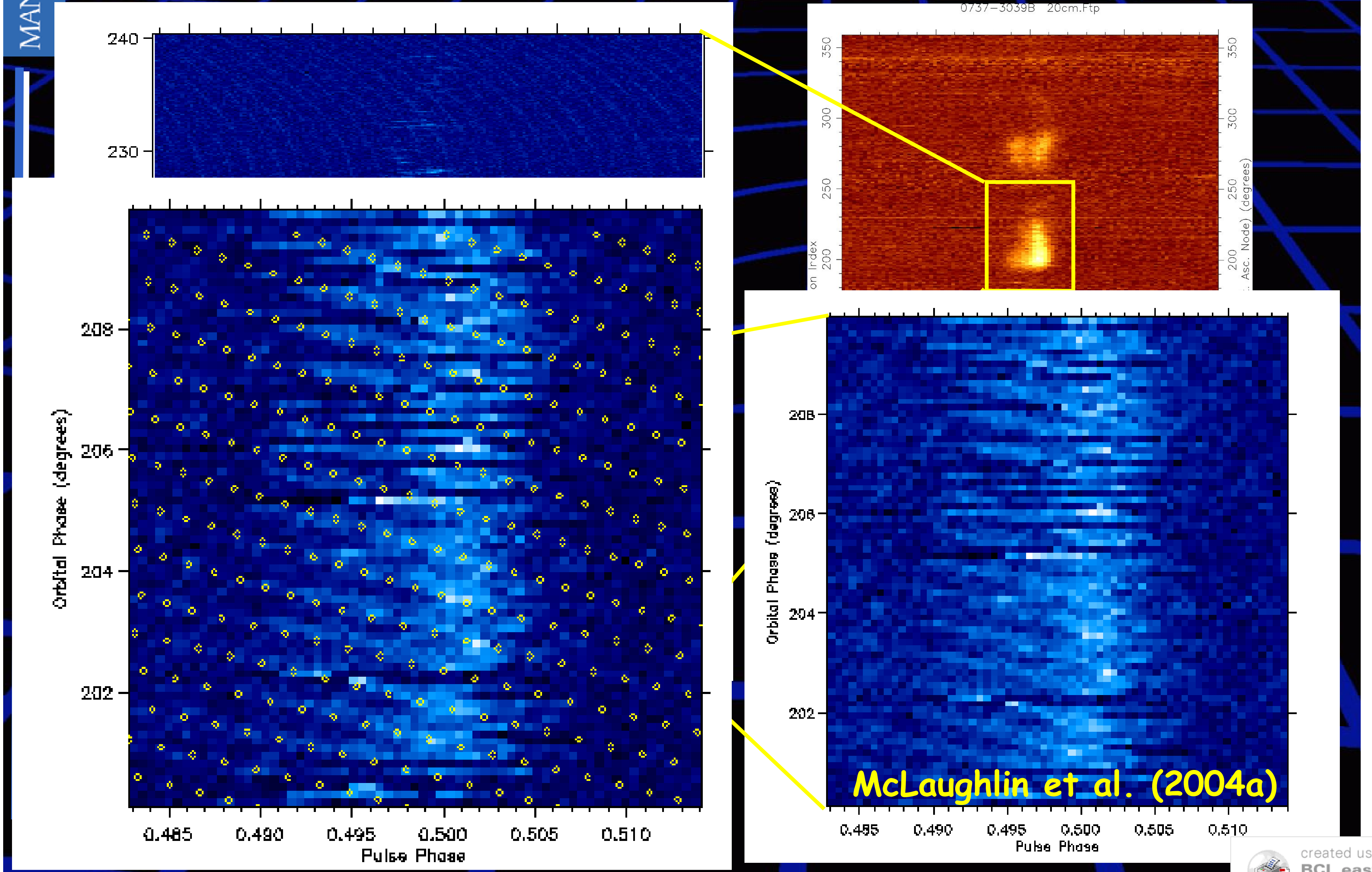








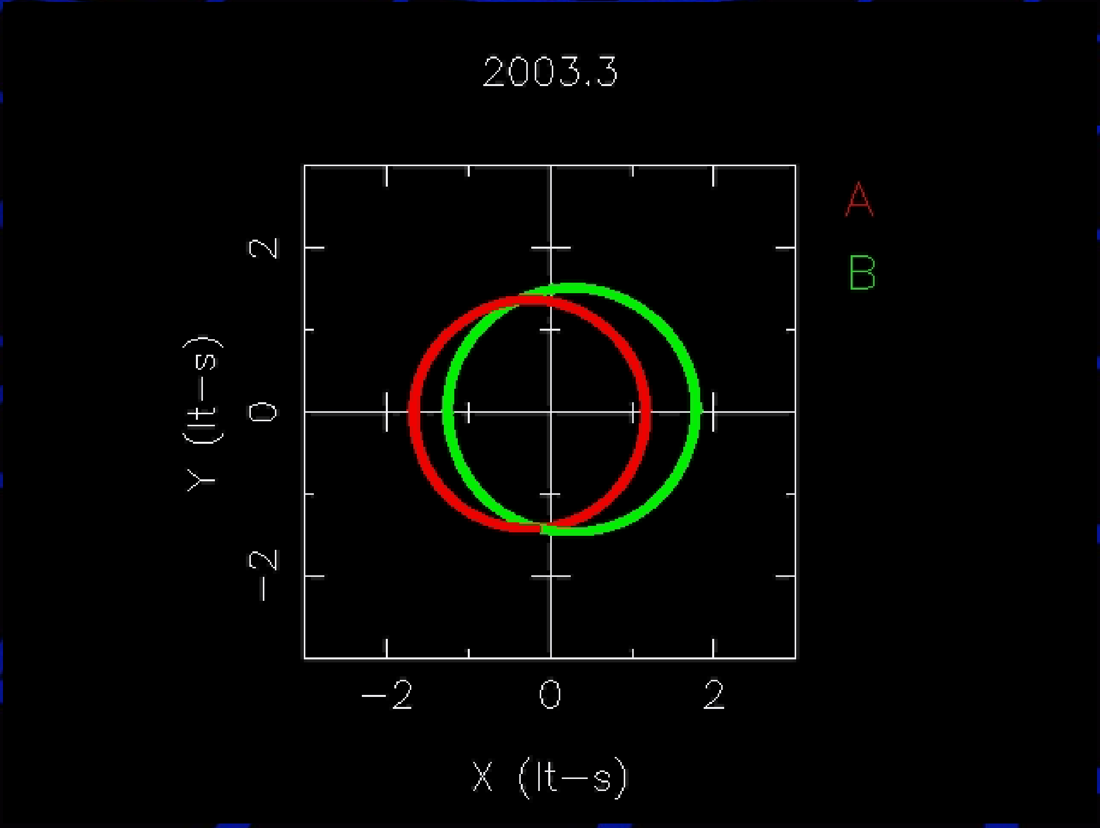
Direct modulation of B's emission by A



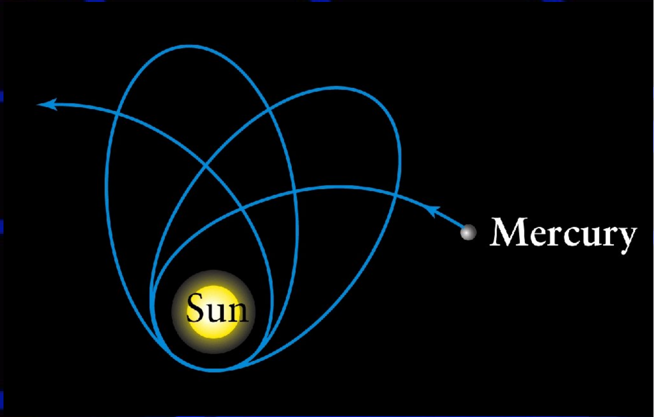
McLaughlin et al. (2004a)

Most relativistic system ever!

Huge relativistic precession of the orbit:
periastron advance of 17 deg/yr!



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

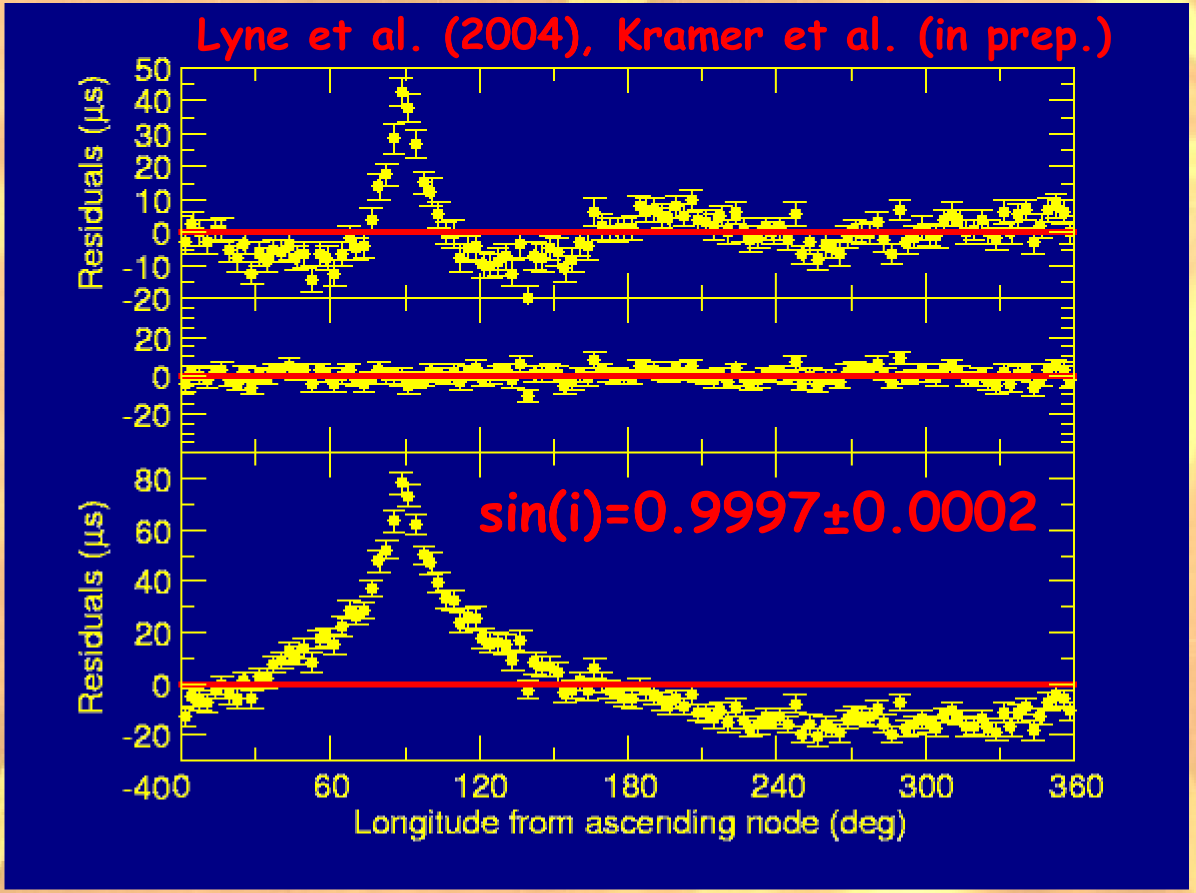


Remember B1913+16:
$\dot{\omega} = 4.23 \deg / yr$

- Measured within a few days of observations!
- A full revolution of orbits in 20 years!

Detection of Shapiro delay

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

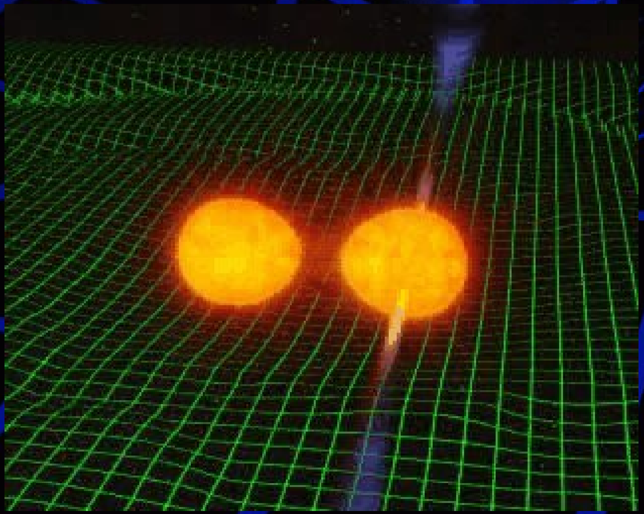


Lyne et al. (2004), Kramer et al. (in prep.)

sin(i)=0.9997±0.0002

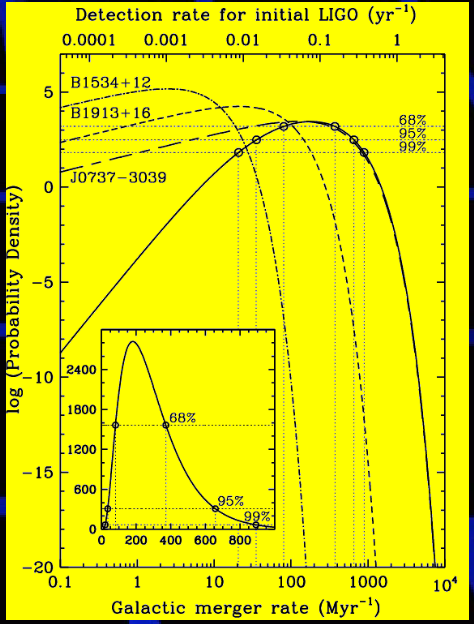
Orbit is shrinking by 7mm/day!

- Change in orbital period due shrinking orbit
- Neutronstars will collide in only 85 Myr due to gravitational wave emission!



$$R = \frac{N_{PSR}}{\tau_{life}} \times f_{beam}$$

Burgay et al. 2003

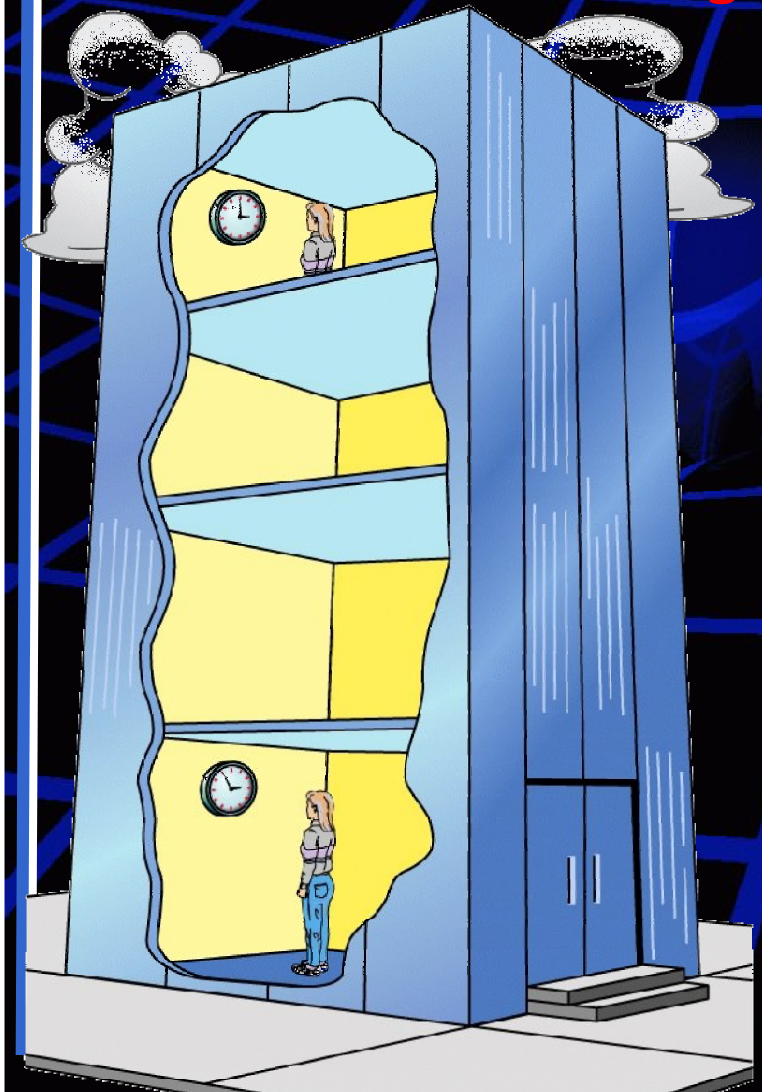


Kalogera et al. 2003

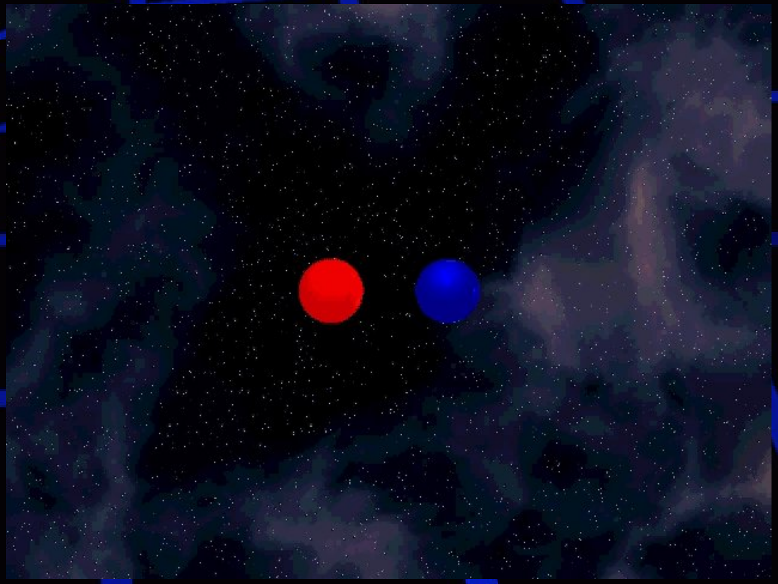
Resulting in increased merger and detection rates predicted for first-generation of ground-based gravitational wave detectors.

Measurement of gravitational redshift

Clocks are running slower in deep gravitational fields

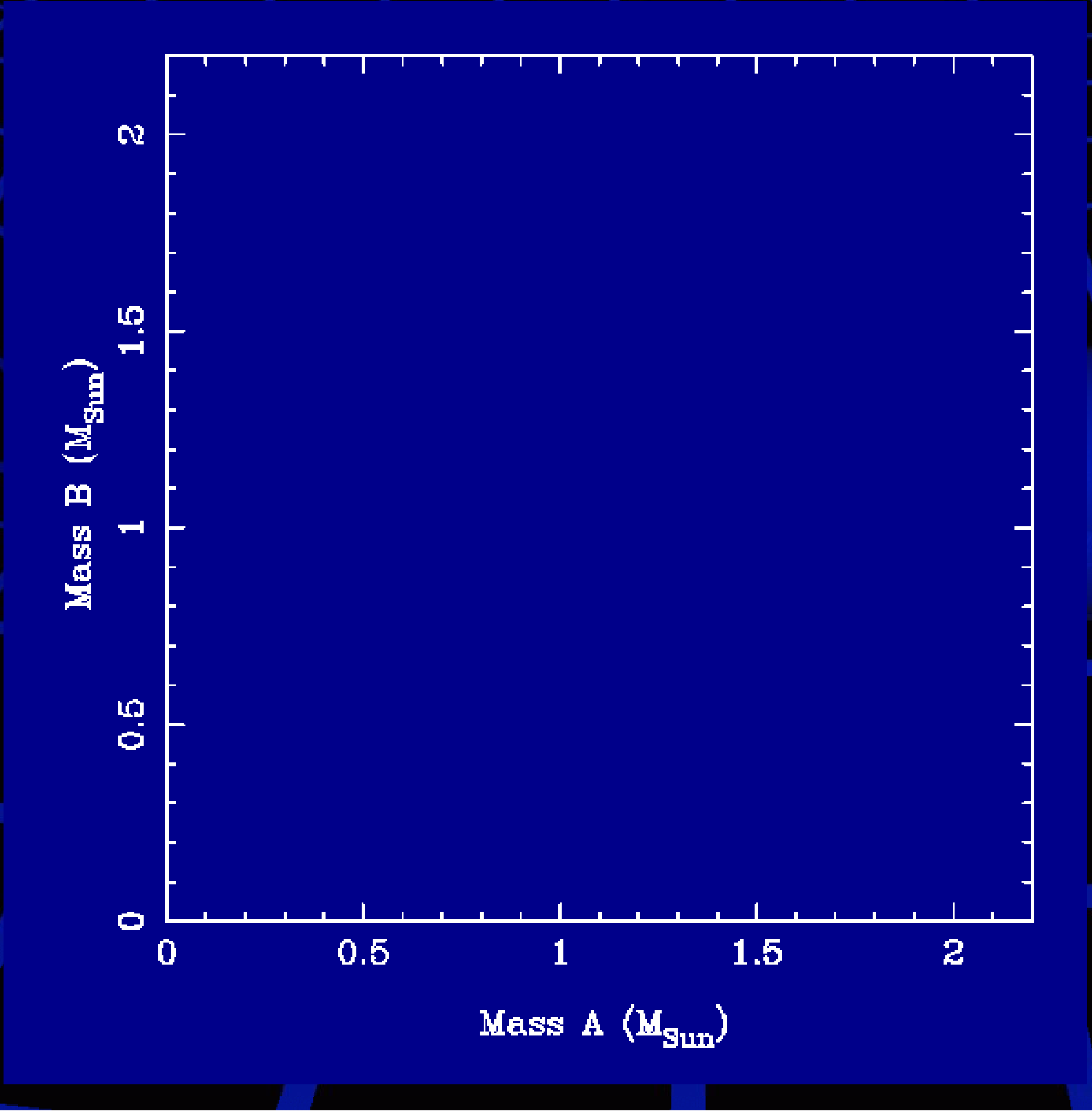


Pulsars' separation is changing during orbit:



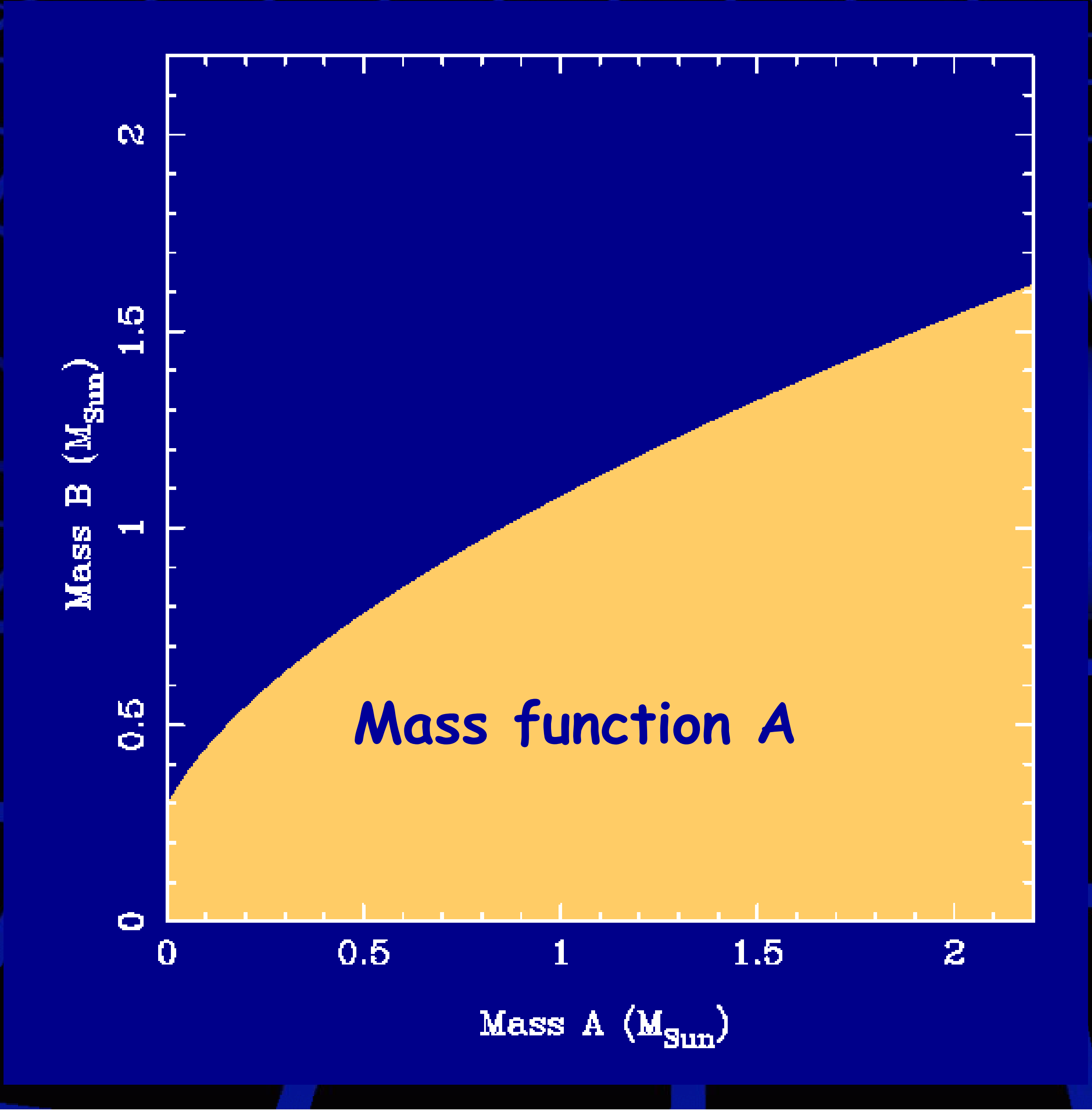
- Pulsars are running slower and faster during orbit
- Combined with 2nd order Doppler: amplitude ~380 microseconds

Tests of GR

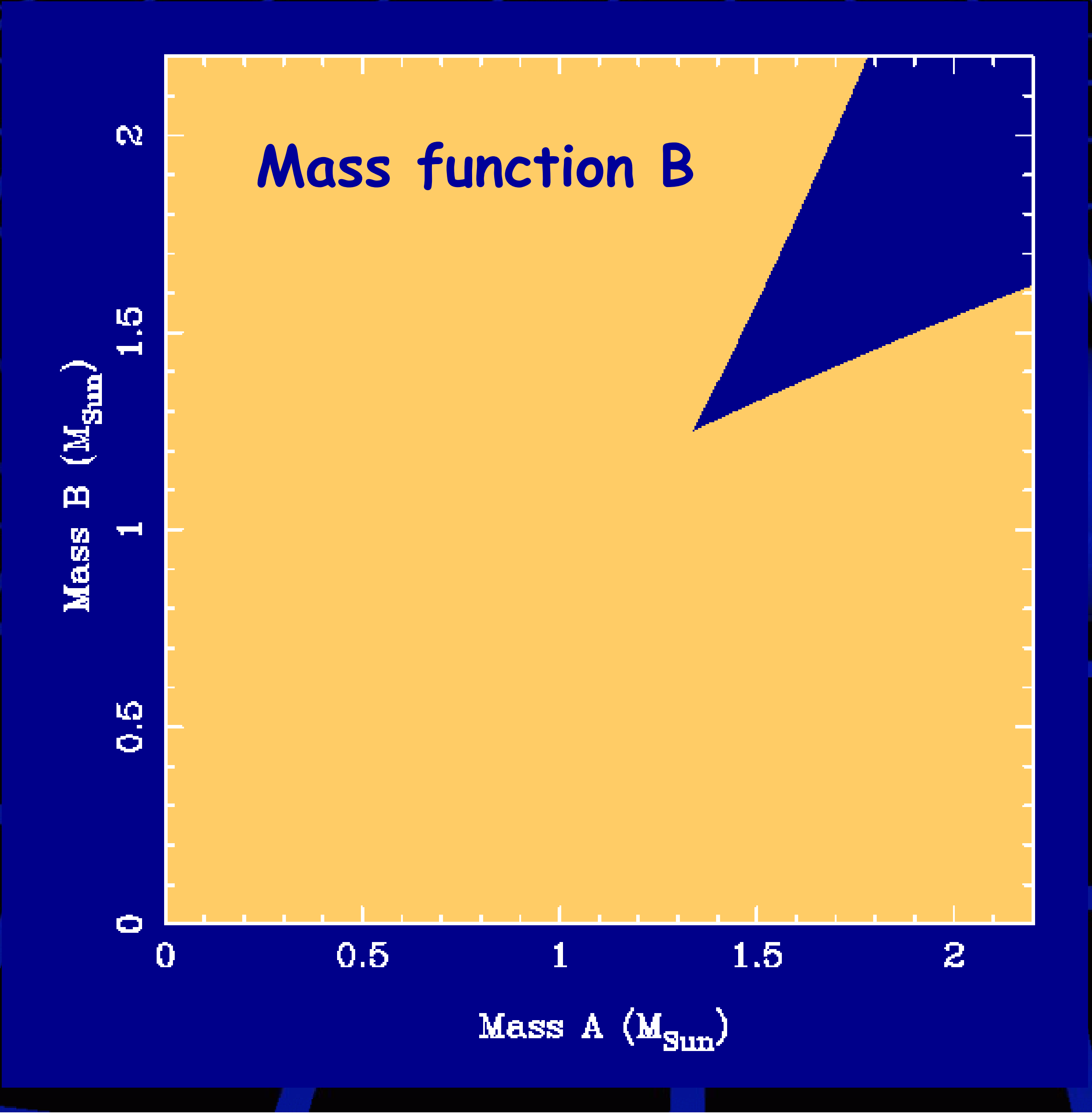


MANCHESTER 1824
The University of Manchester
Jodrell Bank Observatory

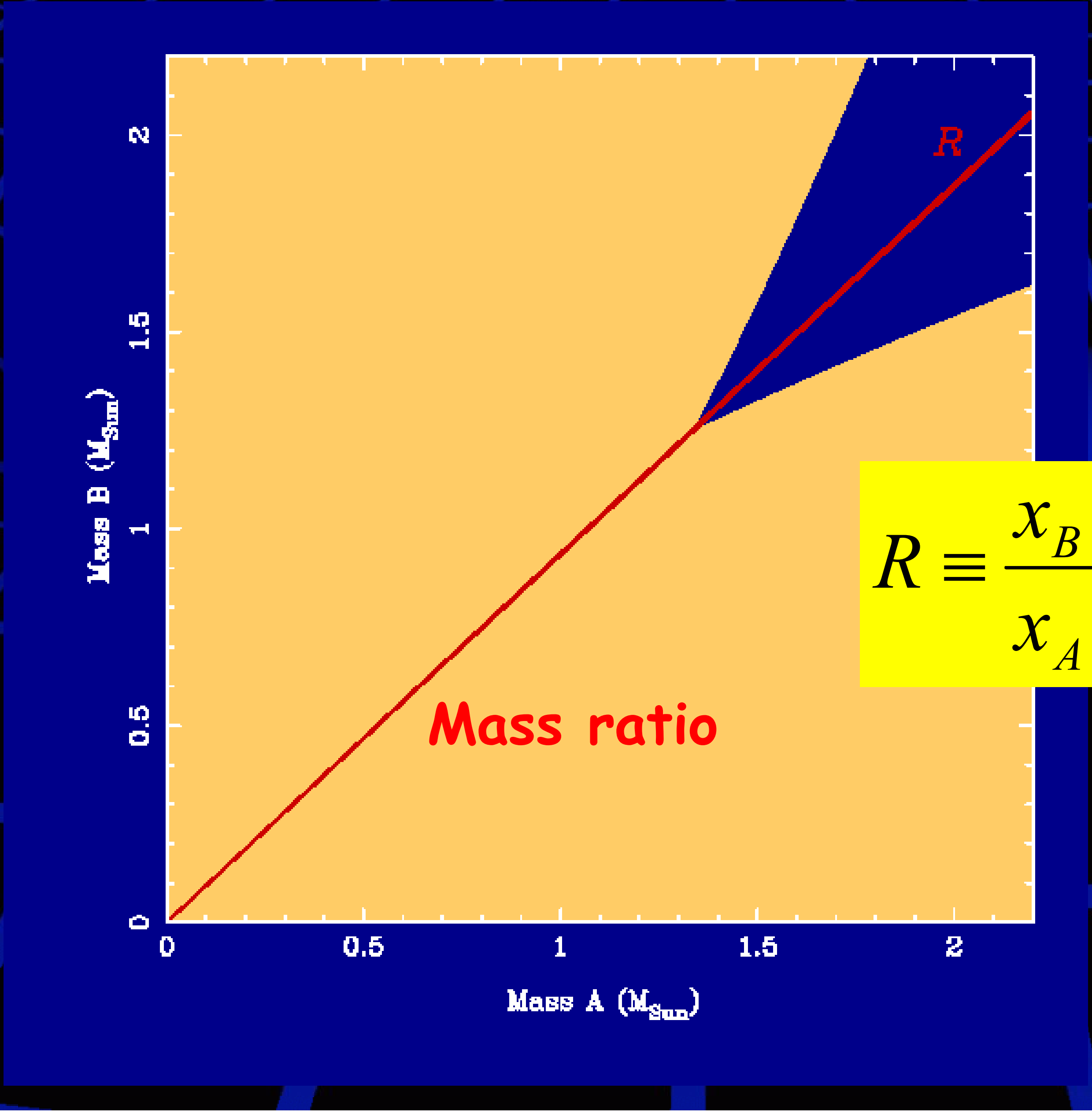
Tests of GR



Tests of GR



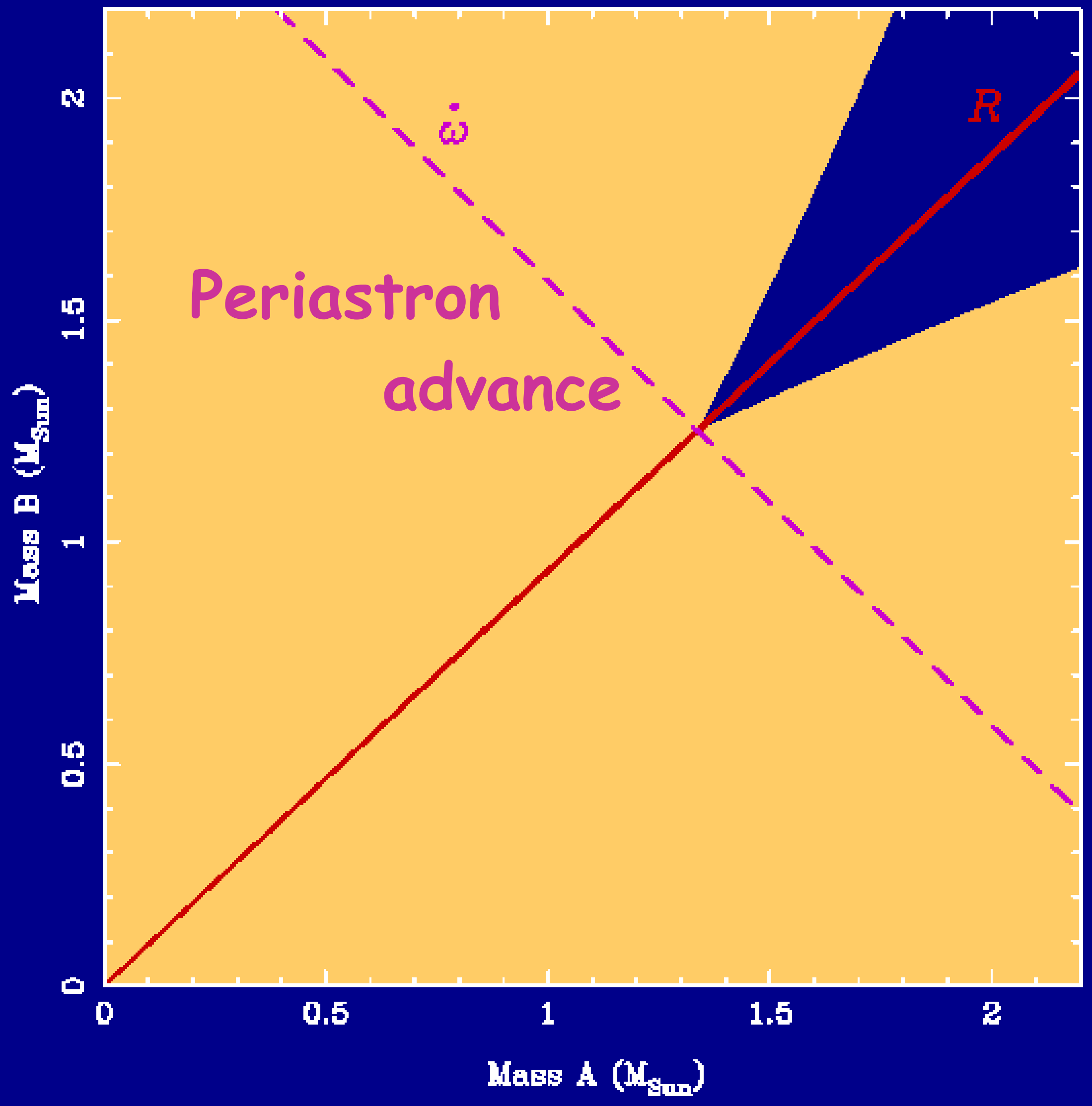
Tests of GR



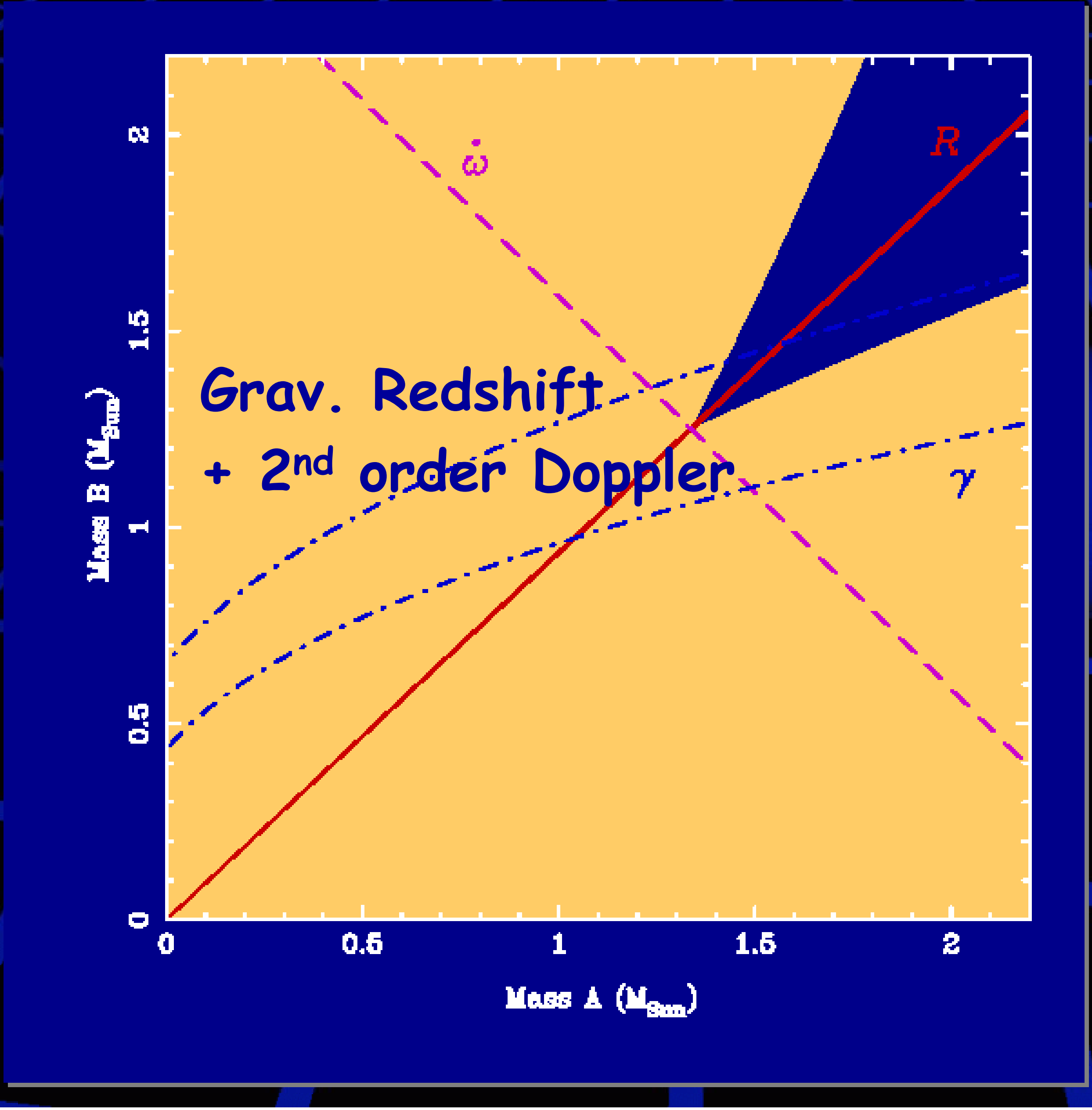
$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

Mass ratio

Tests of GR

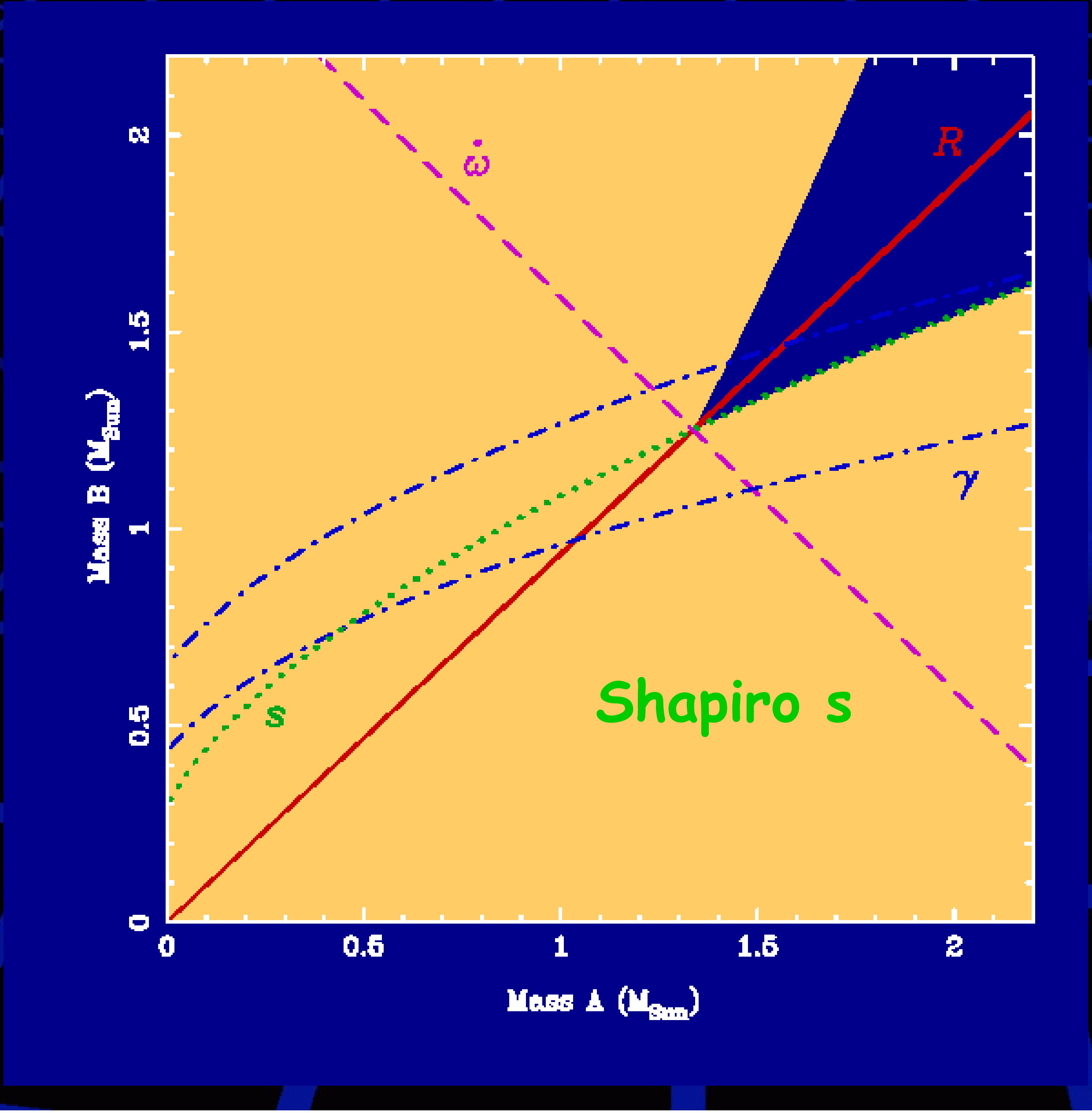

$\dot{\omega}$
R
Periastron advance
Mass B (M_{Sun})
Mass A (M_{Sun})
0
0.5
1
1.5
2
0
0.5
1
1.5
2

Tests of GR

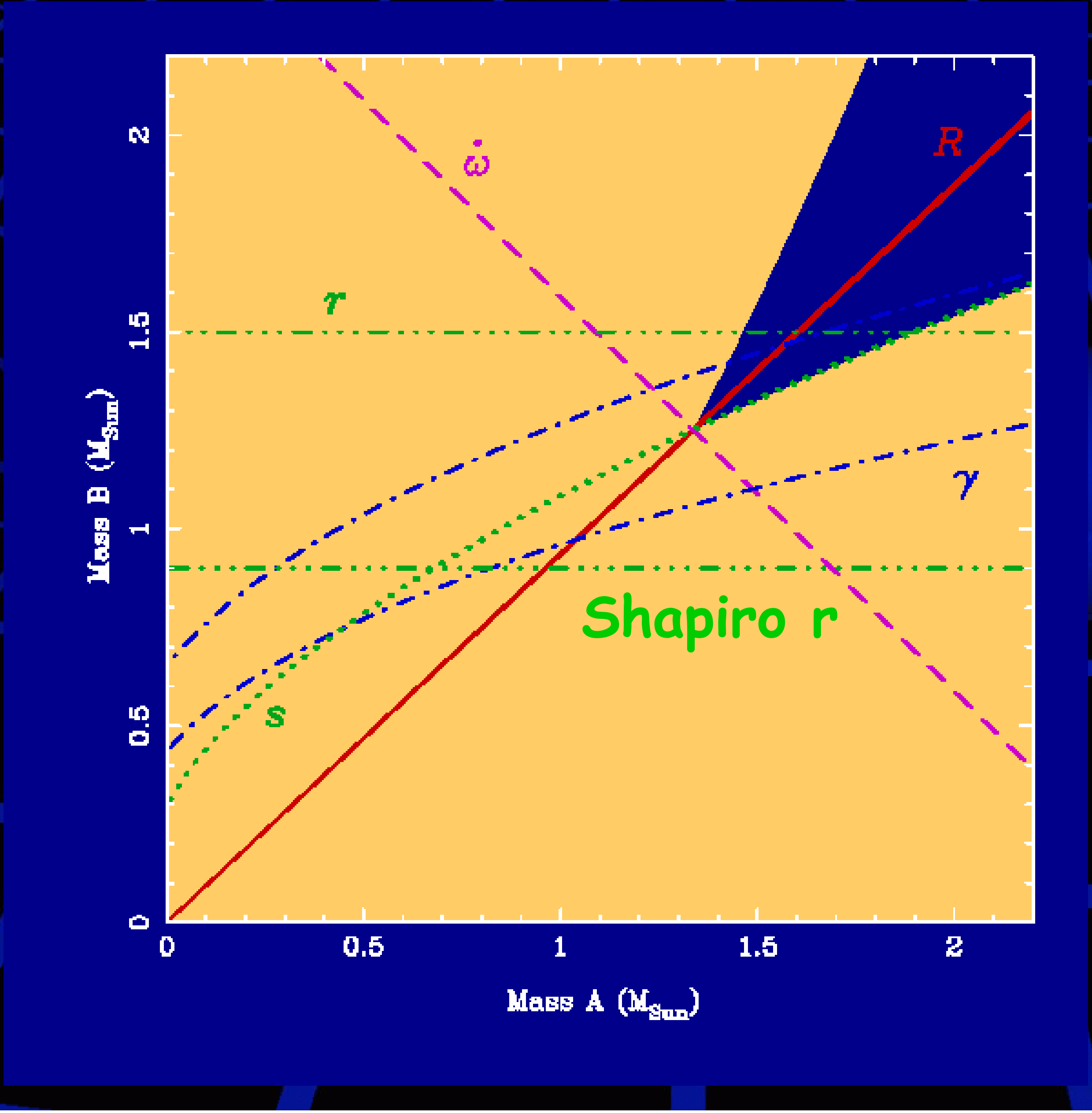


Grav. Redshift
+ 2nd order Doppler

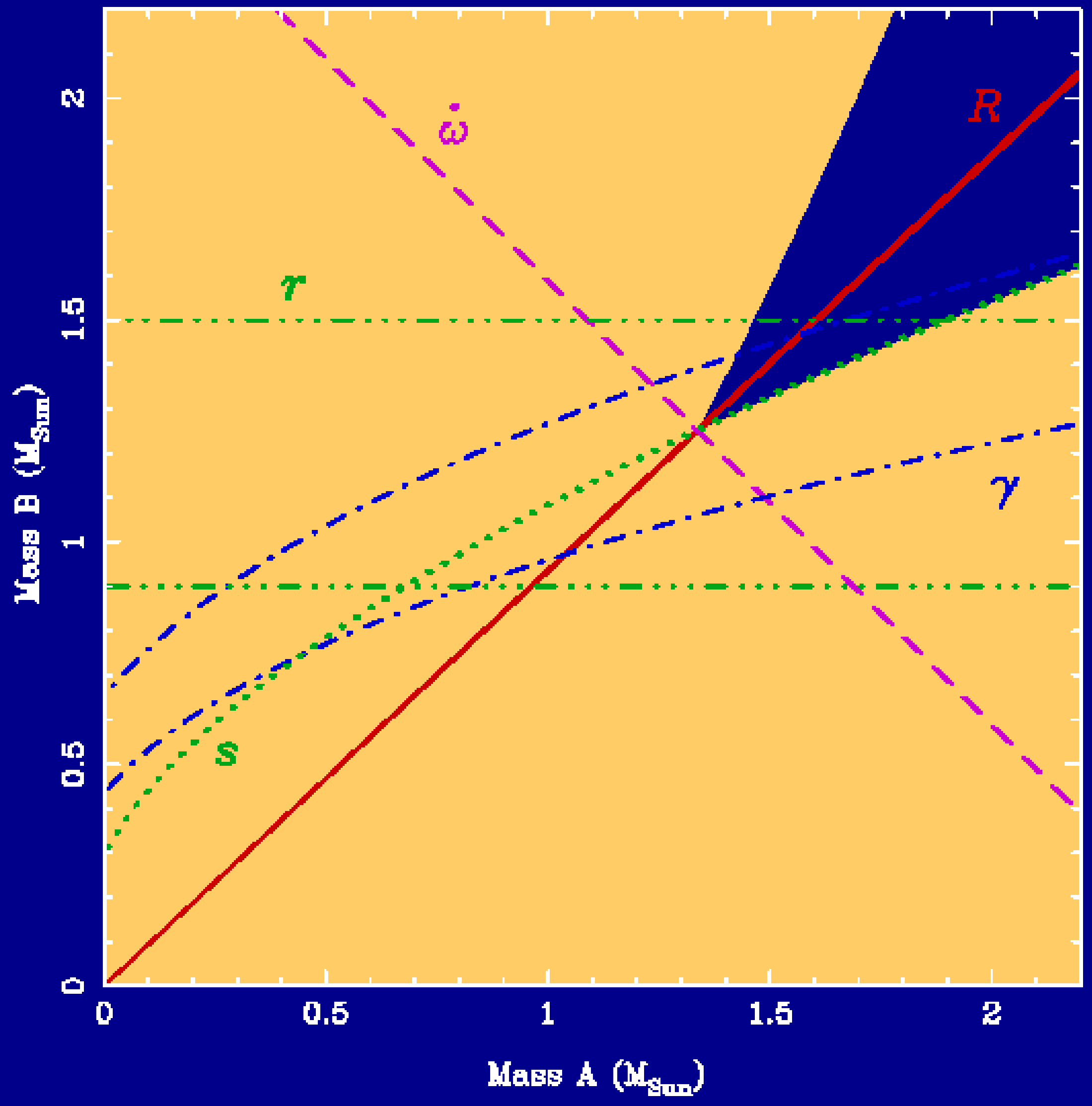
Tests of GR


$\dot{\omega}$
R
γ
s
Shapiro s
Mass B (M_{Sun})
0
0.5
1
1.5
2
Mass A (M_{Sun})
0
0.5
1
1.5
2

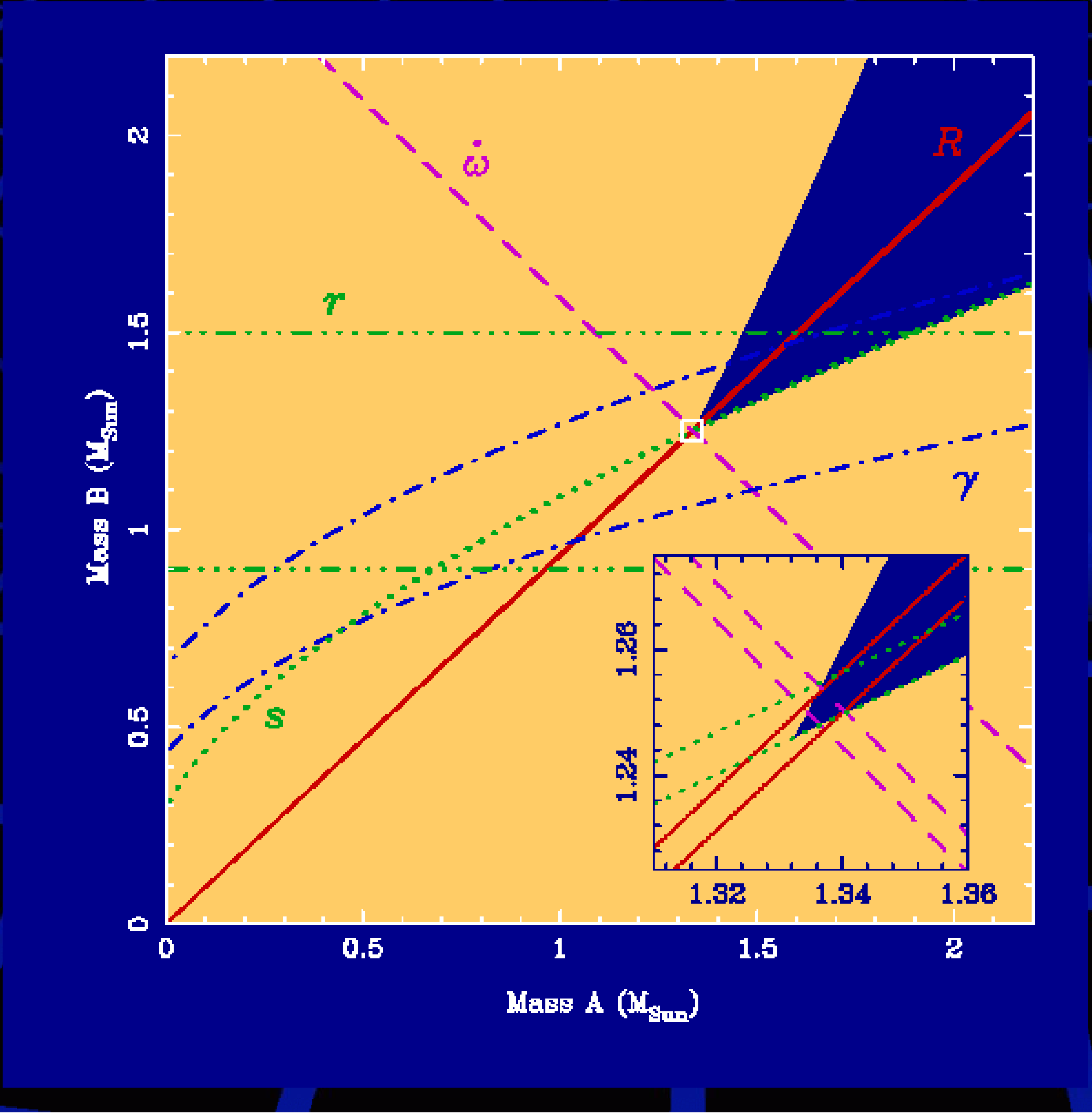
Tests of GR



Tests of GR

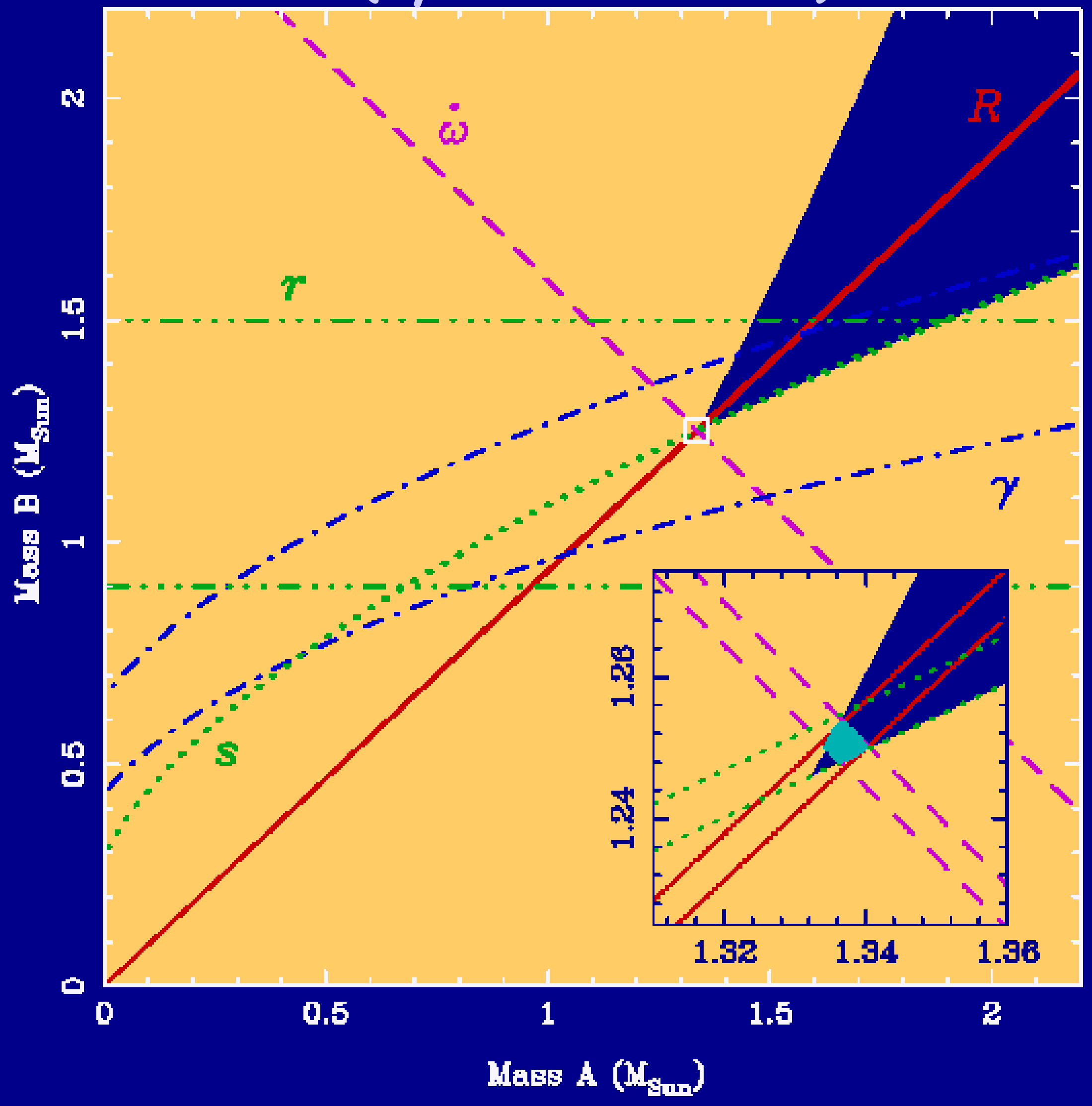


Tests of GR


$\dot{\omega}$
R
r
s
γ
Mass B (M_{Sun})
Mass A (M_{Sun})
0
0.5
1
1.5
2
1.24
1.28
1.32
1.34
1.36

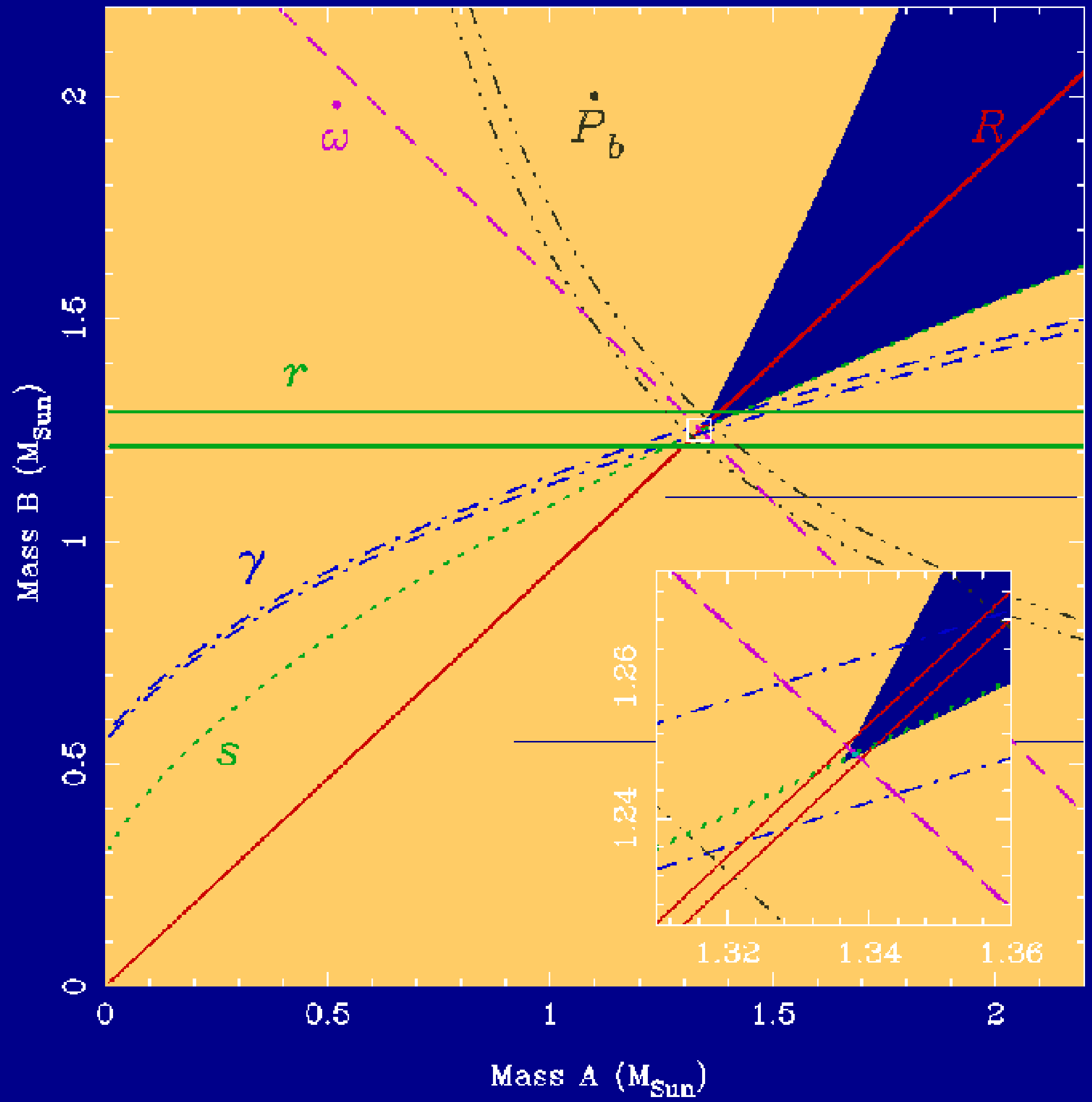
Tests of GR

December 2003 (Lyne et al. 2004)



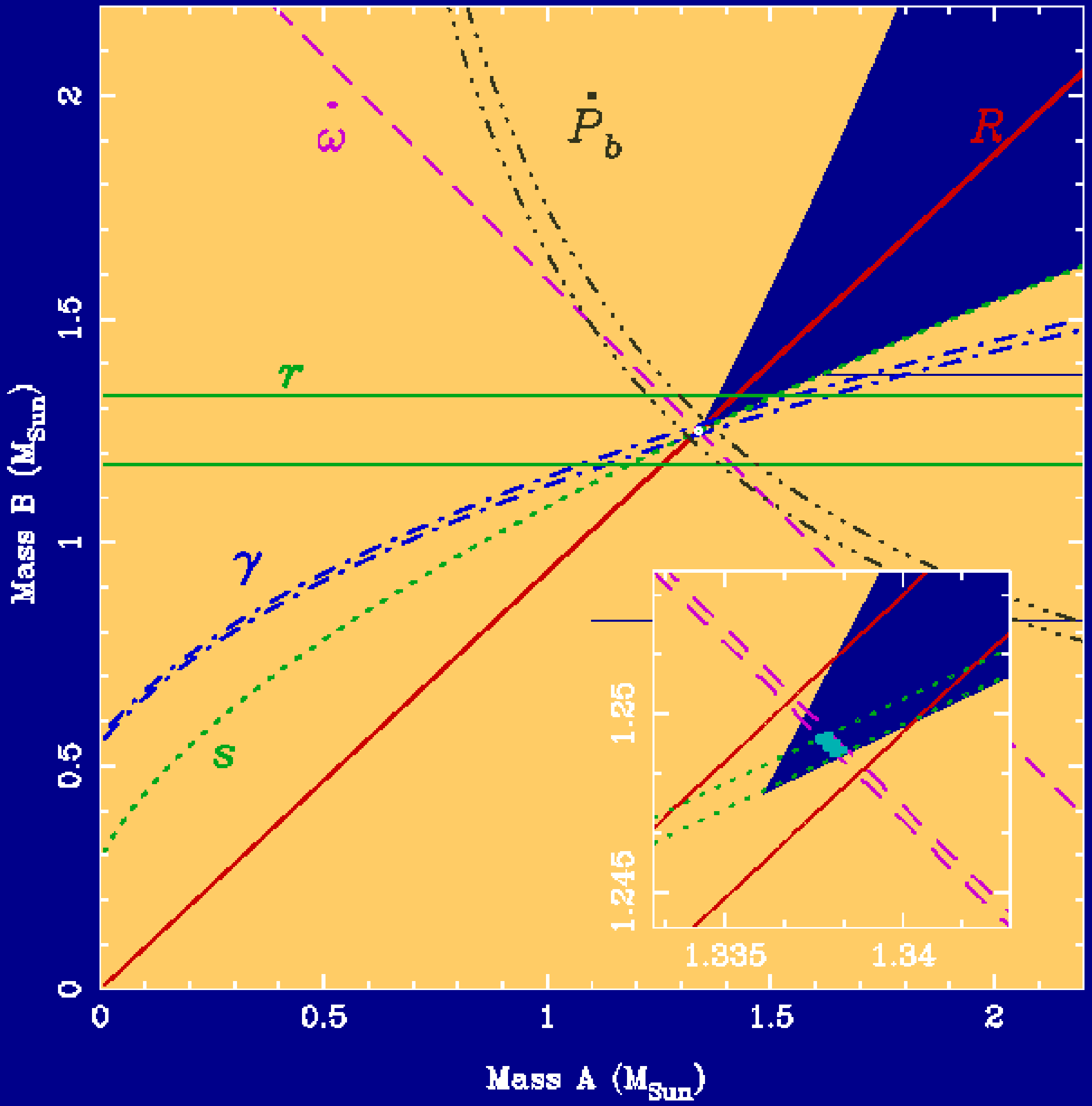
Tests of GR

Kramer et al. in prep.



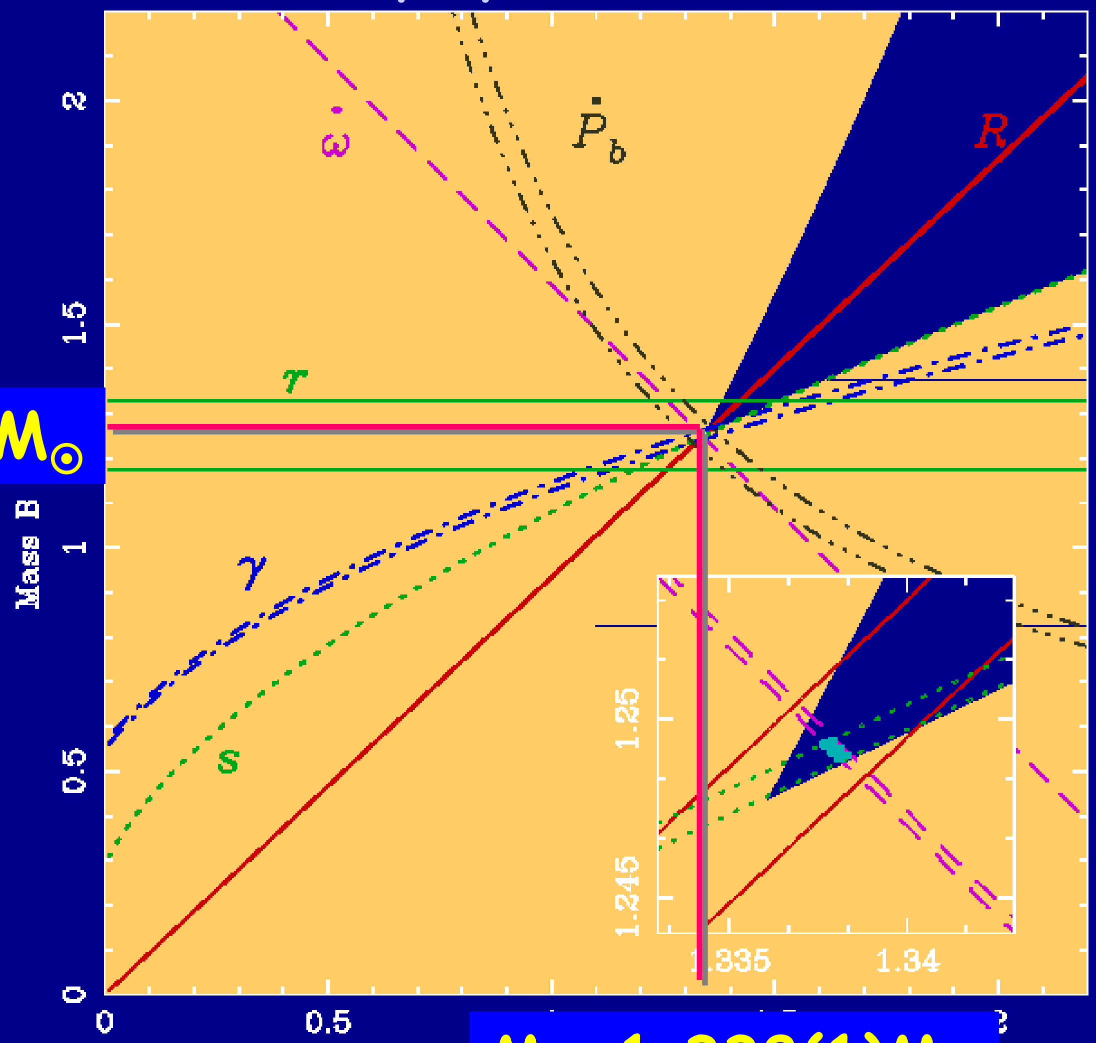
Tests of GR

Kramer et al. in prep.



Tests of GR

Kramer et al. in prep.

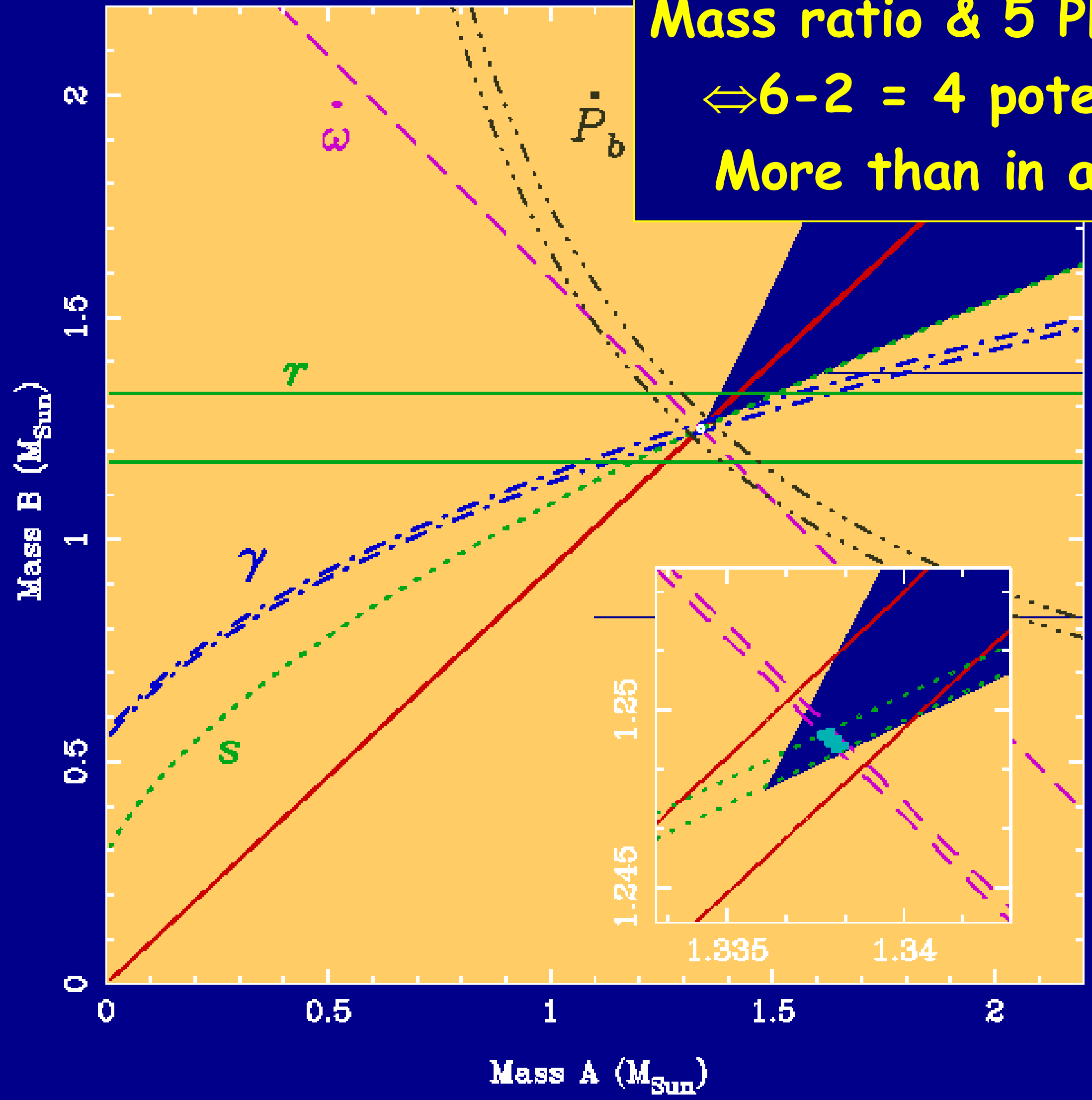


$M_B = 1.249(1) M_\odot$

$M_A = 1.338(1) M_\odot$

Tests of GR

Kramer et al. in prep.



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

The University of Manchester
Jodrell Bank
Observatory

Tests of GR

Based on:

$R = 1.071 \pm 0.001$ & $\dot{\omega} = 16.9000 \pm 0.0008$ deg/yr (5×10^{-5})

Expected in GR:	Observed:
$\gamma = 0.384$ ms	$\gamma = 0.385 \pm 0.003$ ms (7×10^{-3})
$dP_b/dt = -1.25 \times 10^{-12}$	$dP_b/dt = (-1.25 \pm 0.02) \times 10^{-12}$ (1.6×10^{-2})
$r = 6.2$ μs	$r = 6.2 \pm 0.1$ μs (10^{-1})
$s = 0.9997$	$s = 0.9997 +0.0002, -0.0003$ (4×10^{-4})

Kramer et al. in prep.

$$\frac{s^{\exp}}{s^{\mathrm{obs}}} = 1.000 \pm 0.001$$

precision of 0.1%!!

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

Significance of "R"

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

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

e.g. Damour & Taylor '92

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

..so that for "any" theory of g … o 1 … N order:

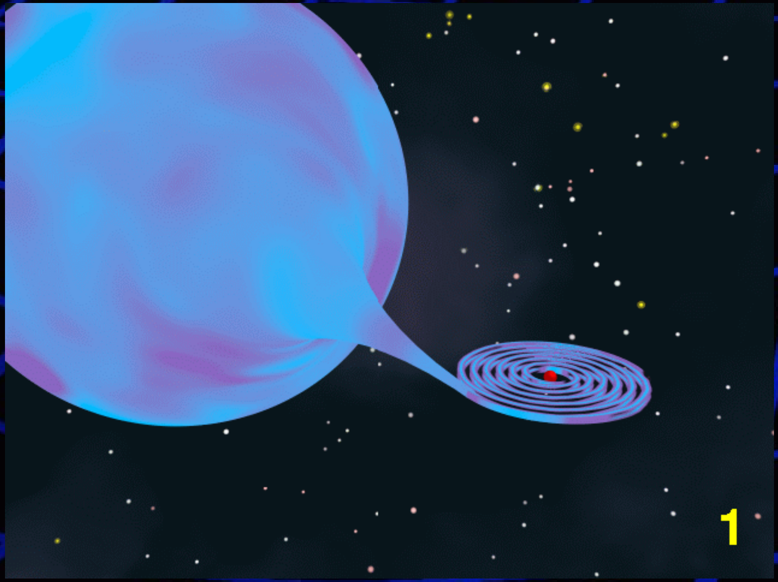
$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

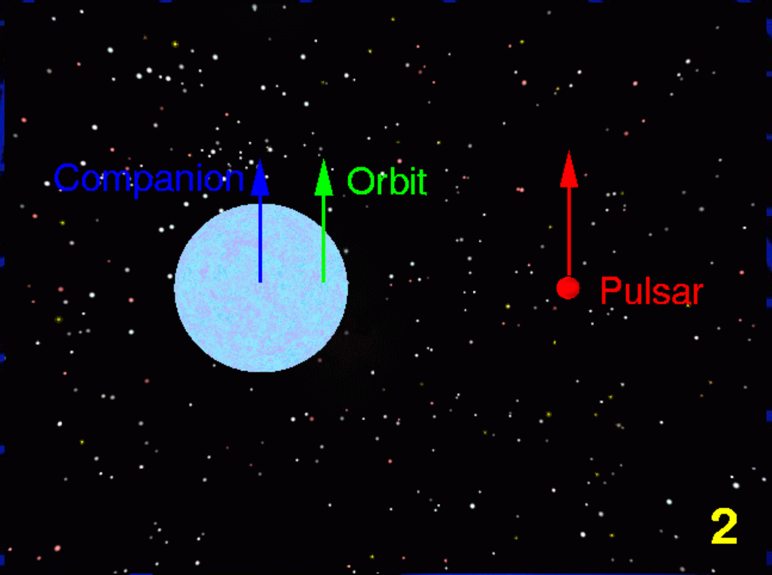
… dent of … eld effects!

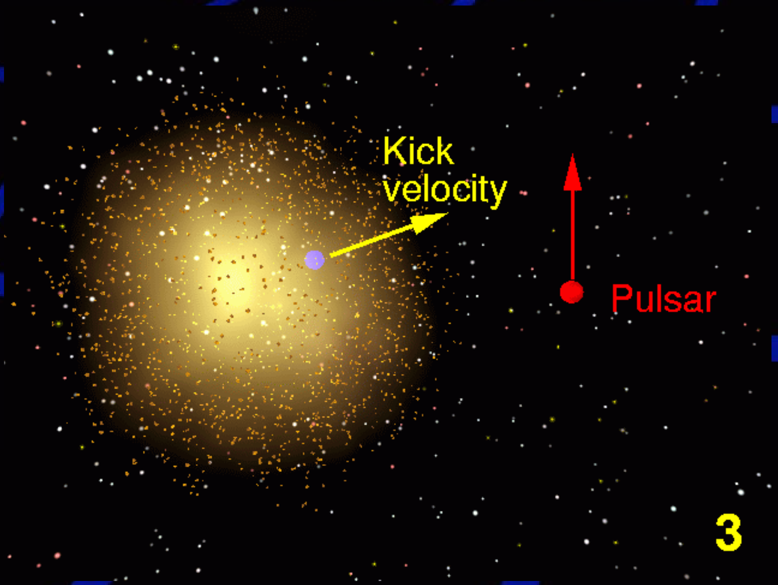
Qualitatively different constraint!

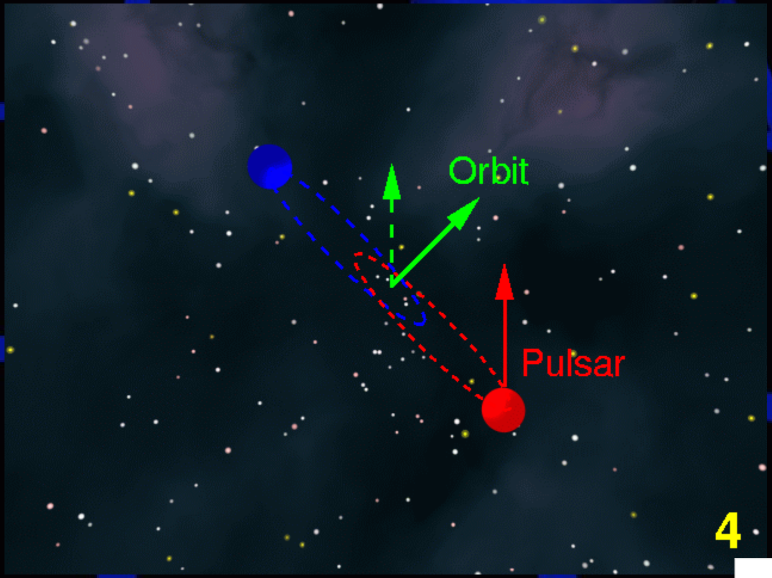
Different to other PK parameters, which all depend on strong-field modified "constants" like G_{AB} which differs from G^{Newton} depending on strong-field effects in theory!

Spin-Orbit Coupling due to misaligned spins



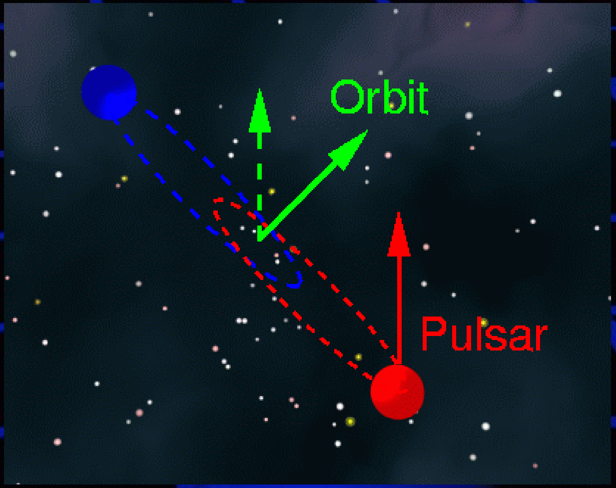






Geodetic Precession

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



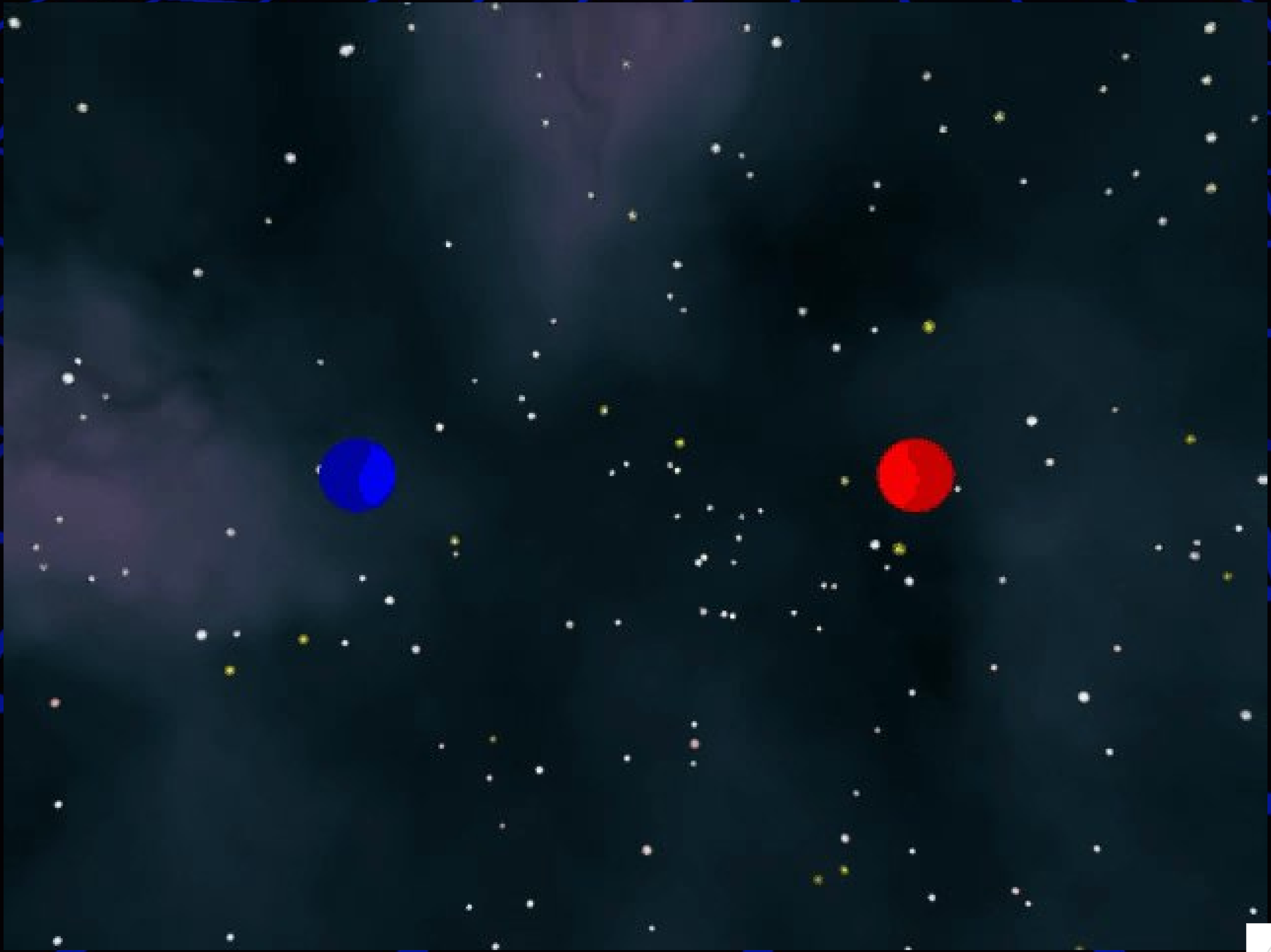
- Precession rate expected in GR:

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

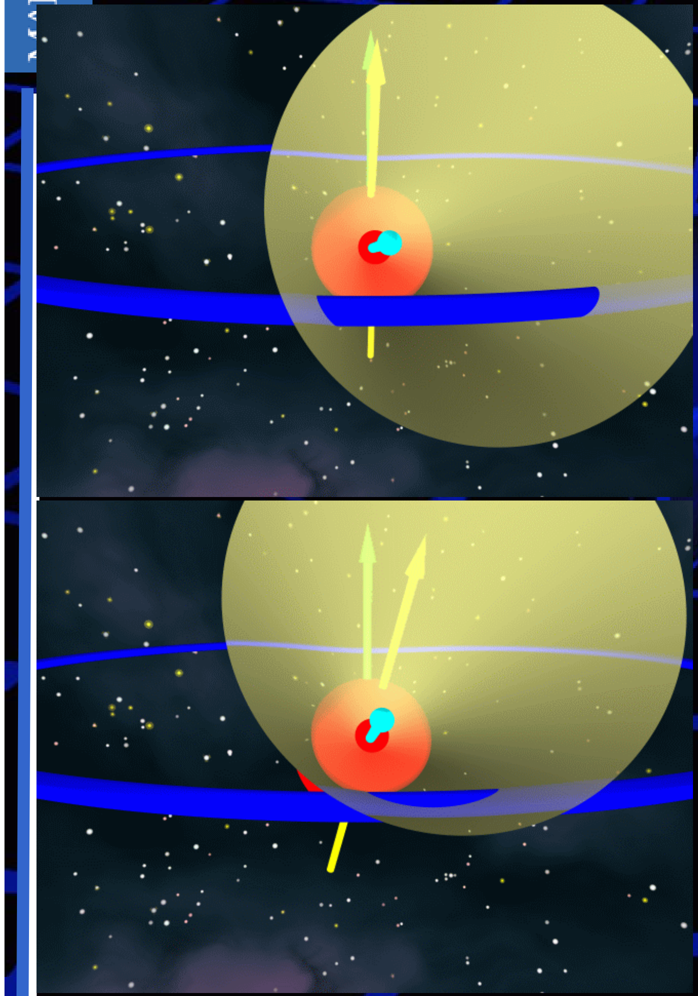
$$\Omega^p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \frac{1}{1-e^2}, \quad T_\odot = GM_\odot c^{-3}$$

What effects do we expect to observe?

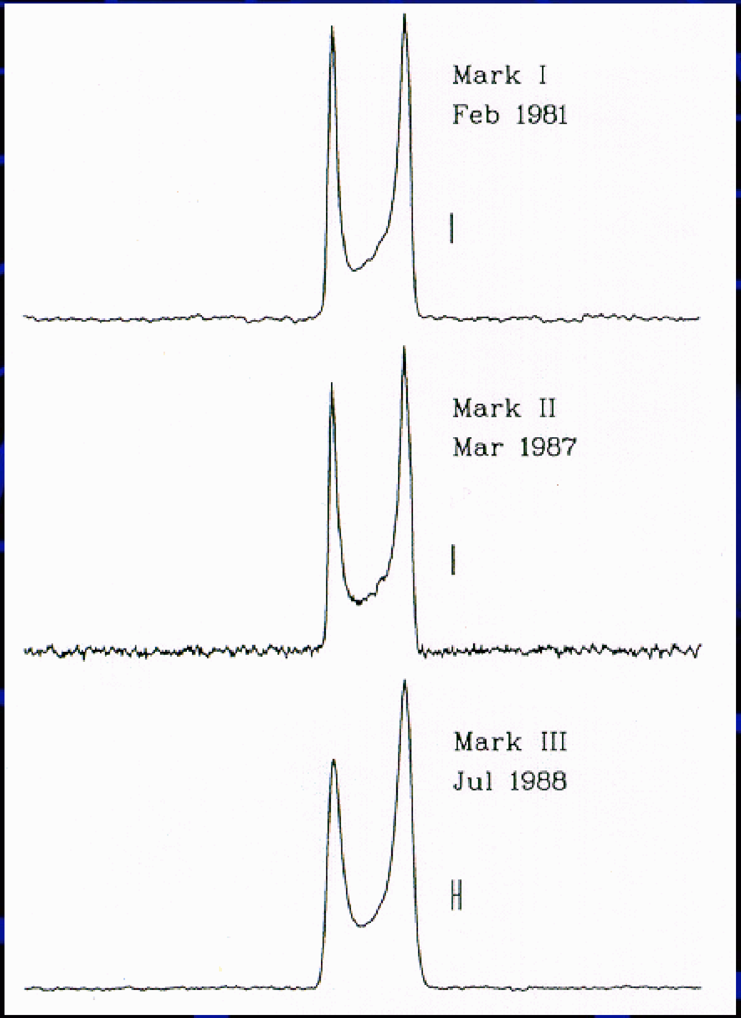
Effects of Geodetic Precession



Effects of Geodetic Precession

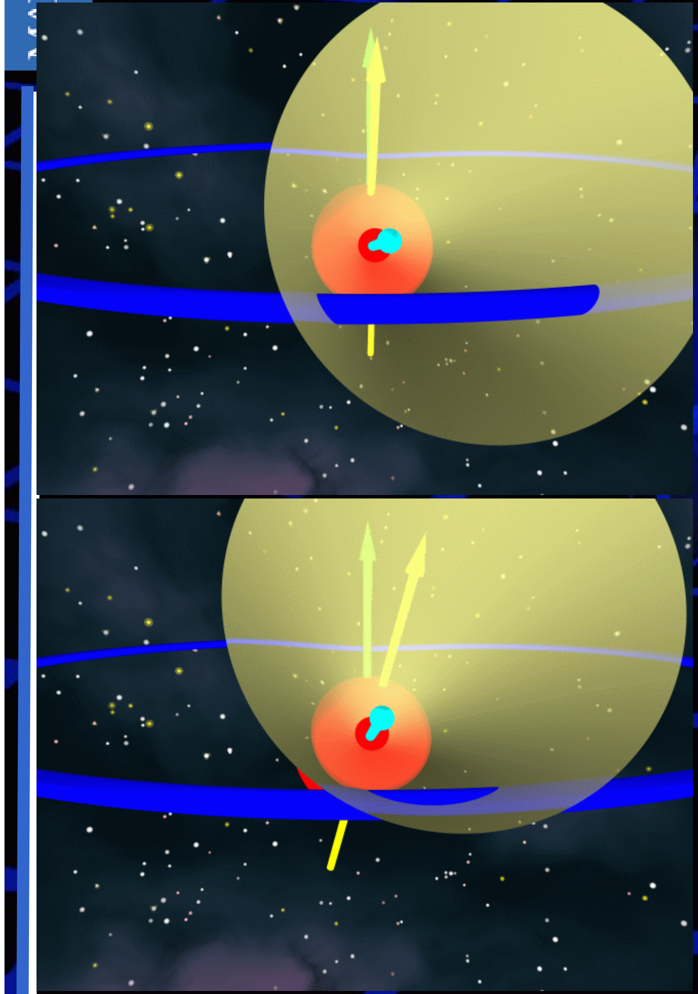


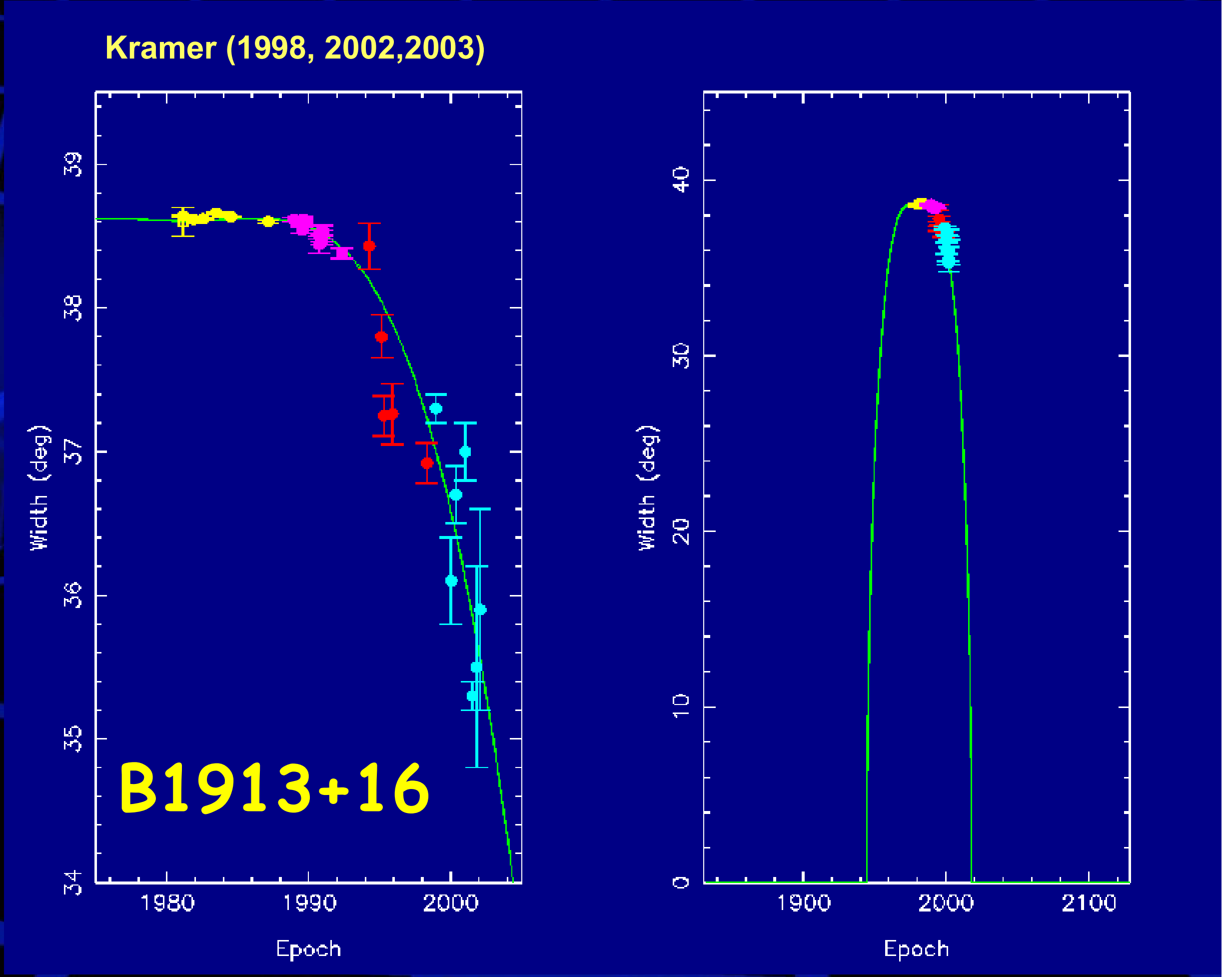
- **Pulse shape changes!**



Taylor & Weisberg'89

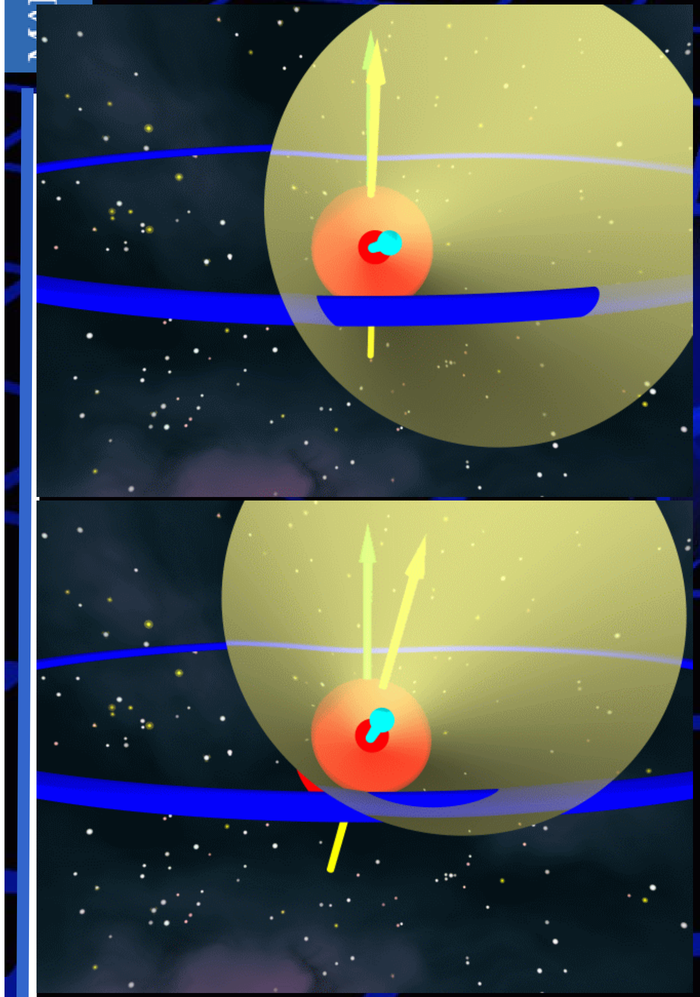
Effects of Geodetic Precession

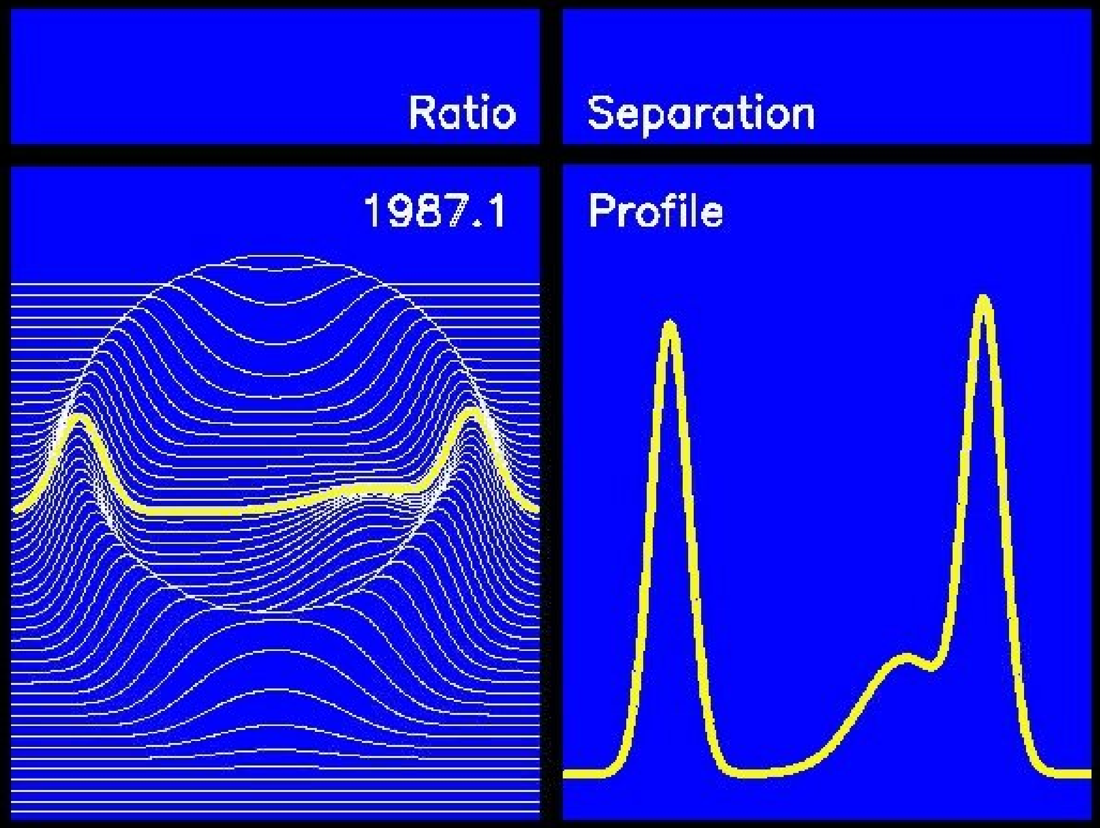



Kramer (1998, 2002,2003)

- Pulse shape changes!

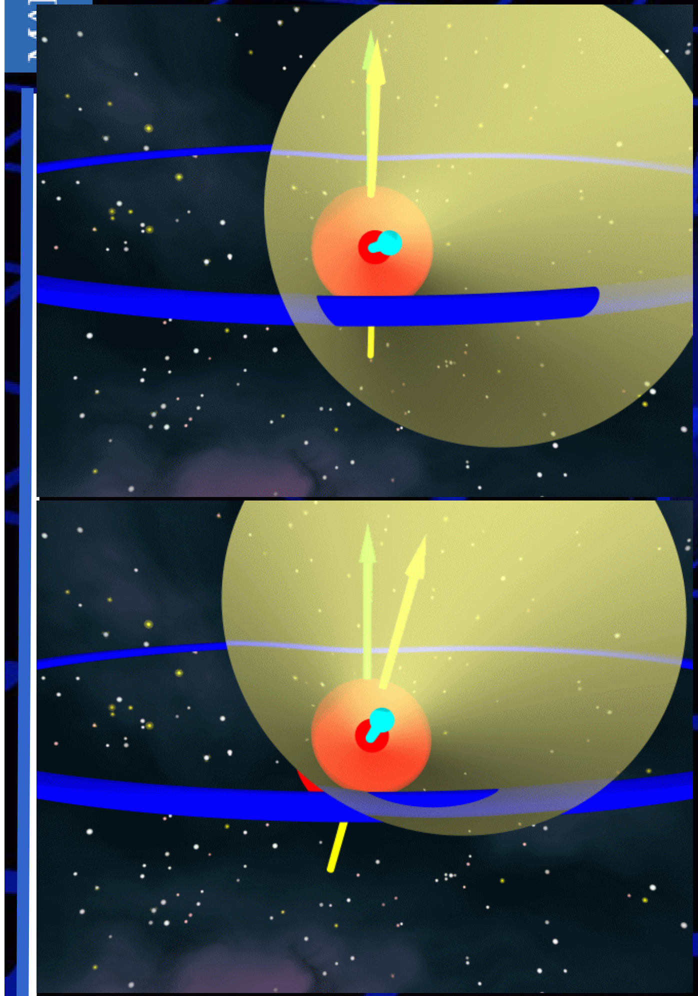
Effects of Geodetic Precession

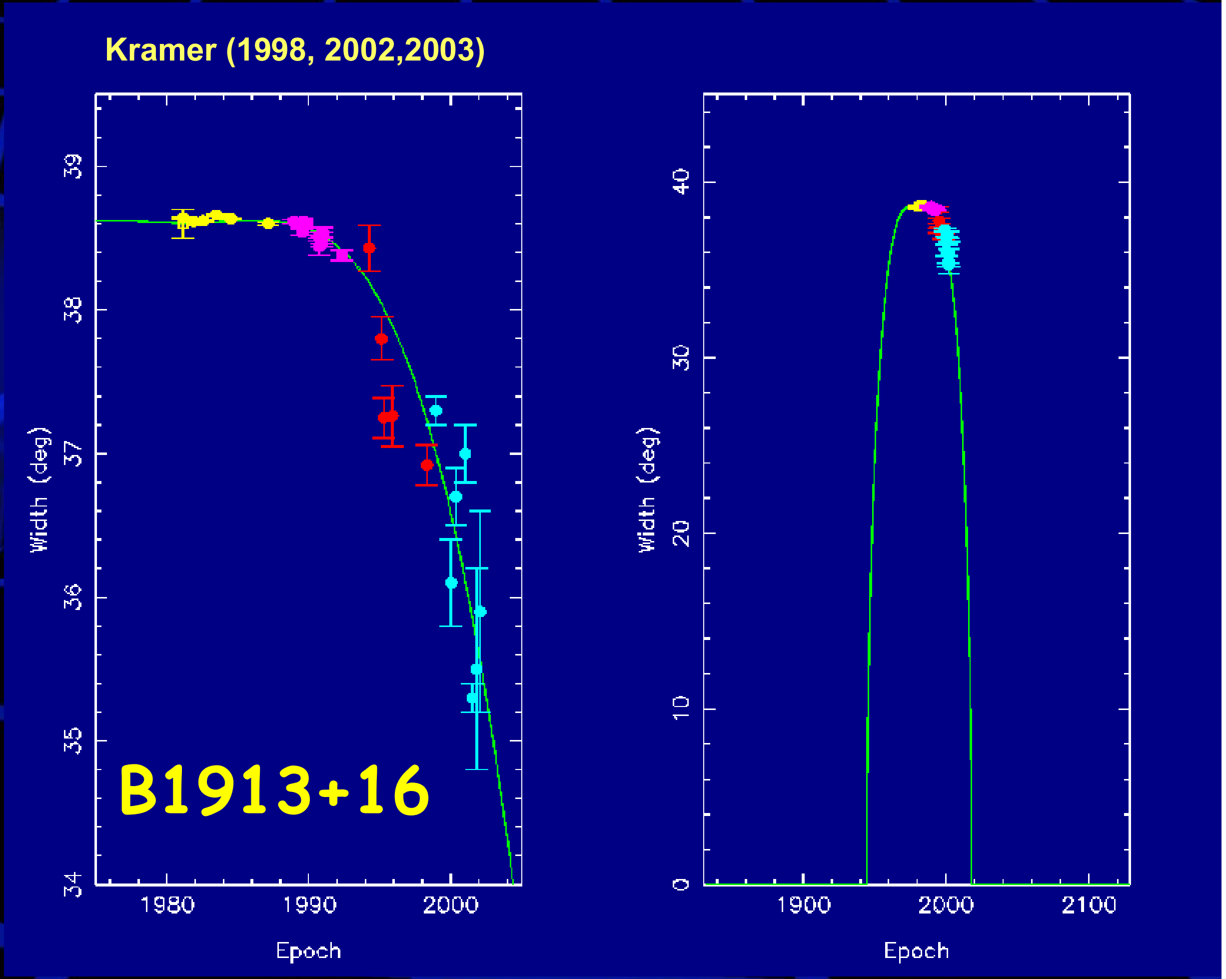




- Pulse shape changes!

Effects of Geodetic Precession



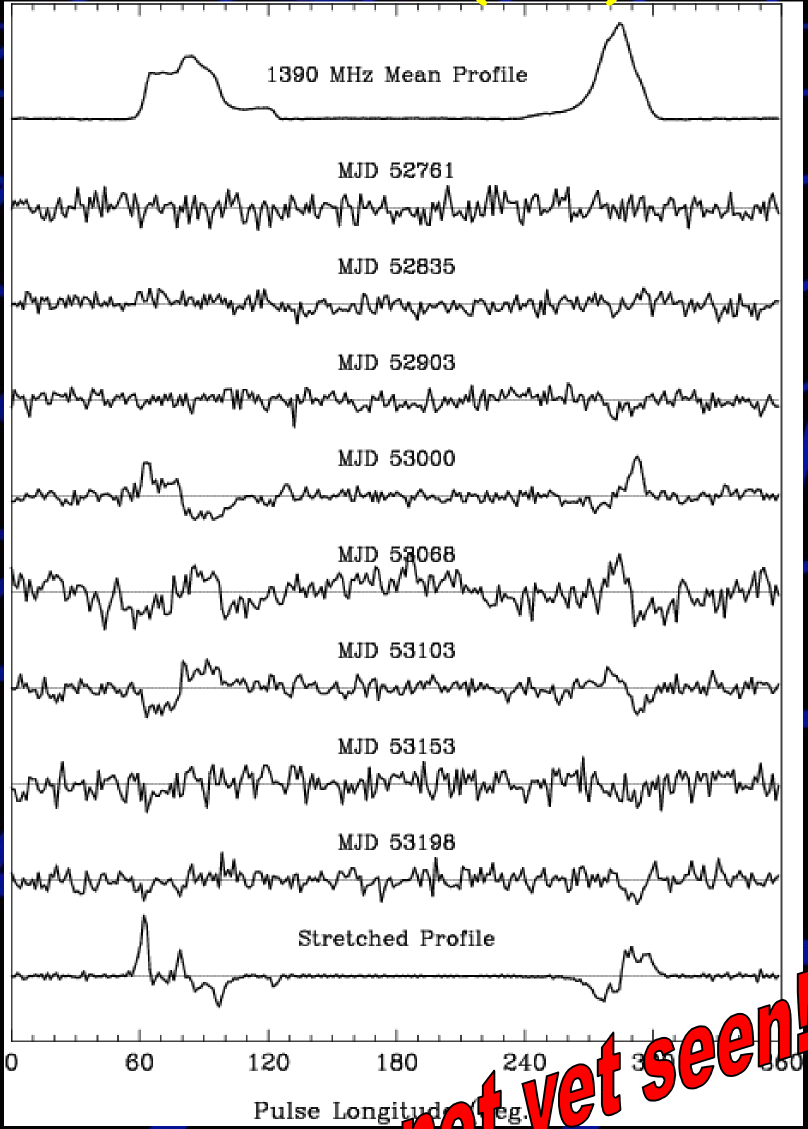


Kramer (1998, 2002,2003)

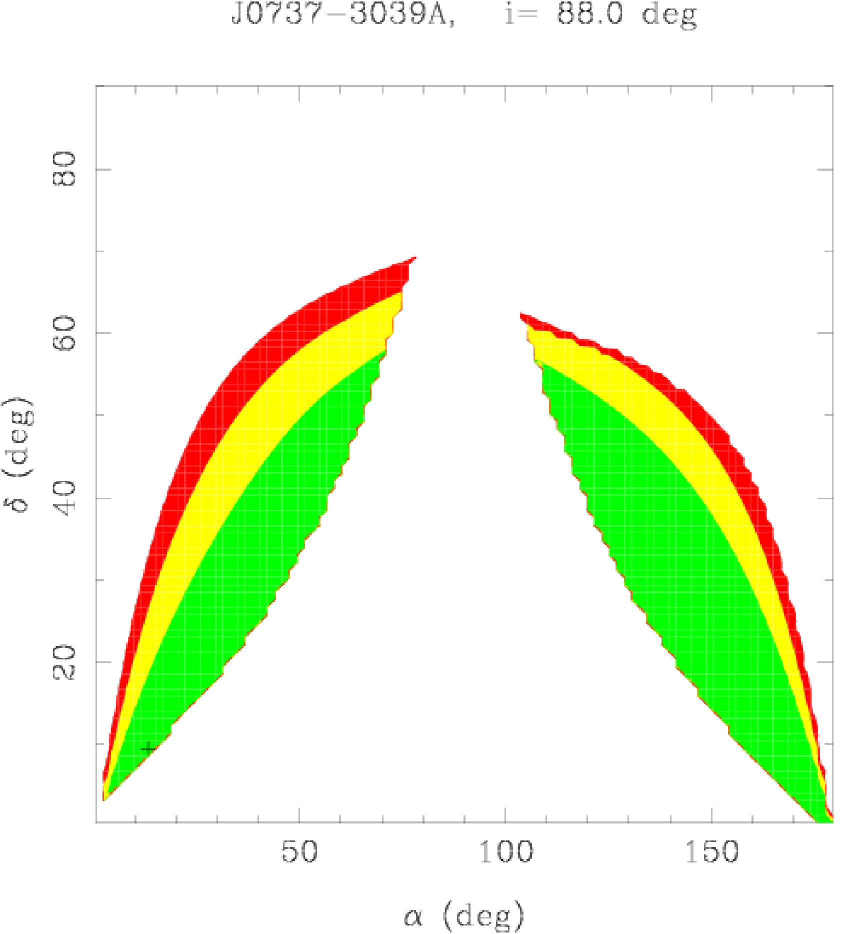
- **Pulse shape changes** (seen in B1913+16, B1534+12, J1141-6545!)
- B1913+16 (Period 300 yr) will disappear ~2025! (Kramer 1998)
- Total precession period of J0737-3039 only 75 yea

Geodetic Precession in J0737-3039A

Manchester et al. (2005)



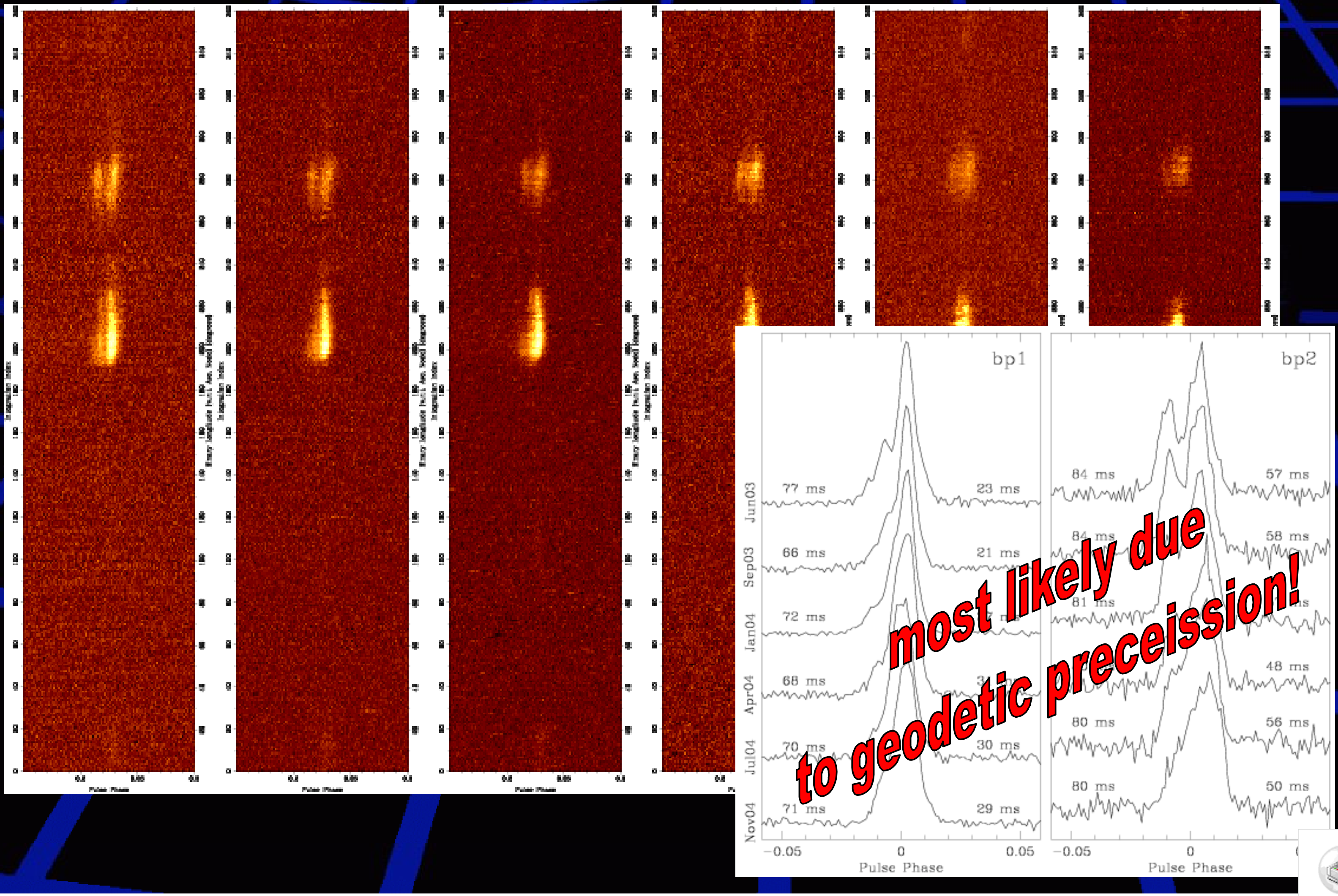
not yet seen!



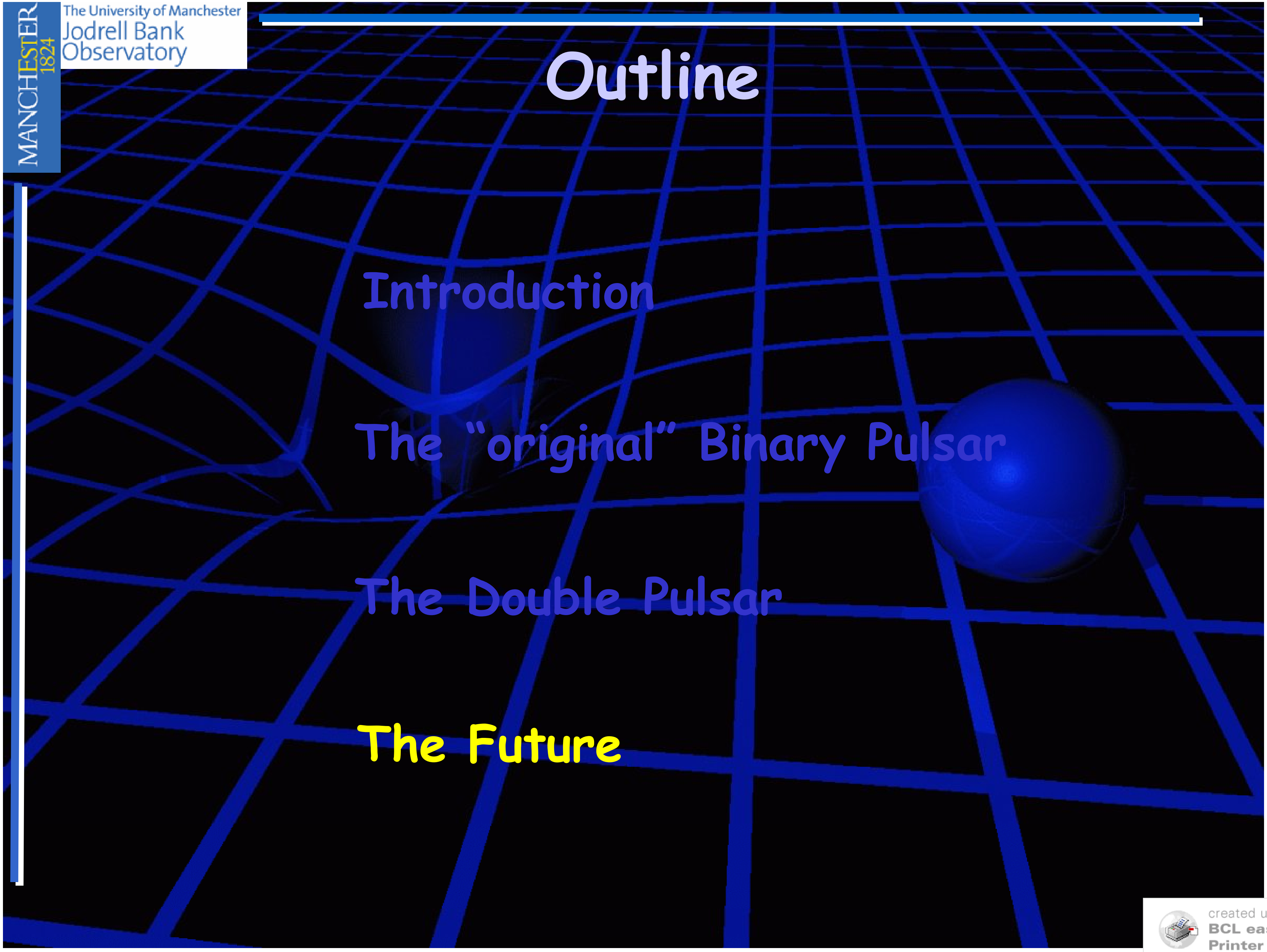
- Geometry still unconstrained
- Jenet & Ransom (2004) model ruled out

Geodetic Precession in J0737-3039B?!

Changes in light curve & profile:



most likely due to geodetic preceission!



Outline

- Introduction
- The "original" Binary Pulsar
- The Double Pulsar
- **The Future**

Will we be able to use dP_b/dt?

- Orbit shrin
- Observed v

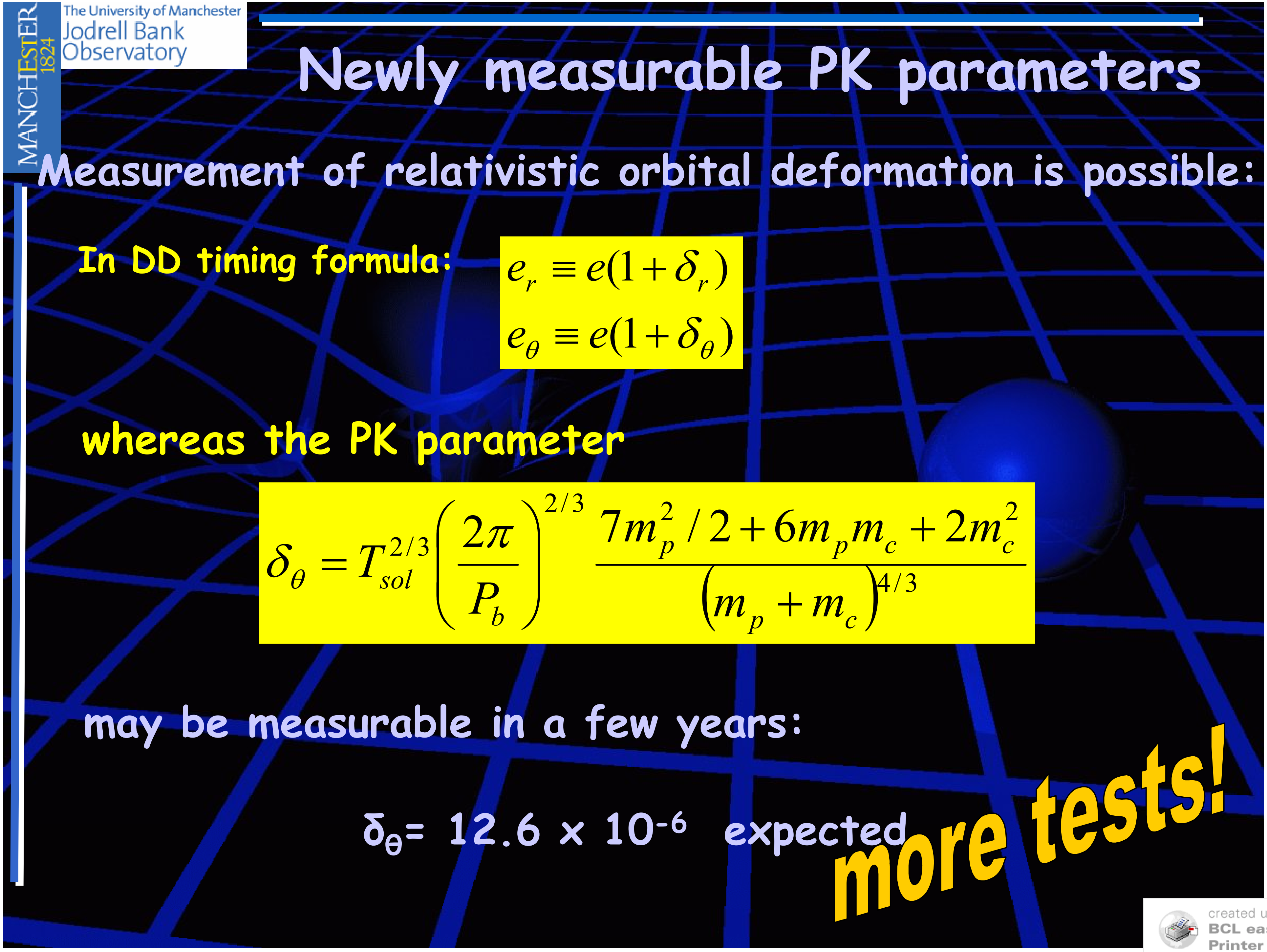
$$\left(\frac{\dot{P}_b}{P_b}\right)^{\mathrm{ext}} = -\frac{a_z \sin b}{c} - \frac{v_0^2}{cR_0}\left(\cos l + \frac{d/R_0 - \cos l}{\sin^2 l + \left(d/R_0 - \cos l\right)^2}\right) + \frac{v^2}{cd} \; P_b$$

Observed: -1.36×10^{-16}

Vertical: -1.26×10^{-20}
Plane: -3.10×10^{-20}
} **negligible**

Transverse motion: $+2.18 \times 10^{-20}$

⇒ **Needed correction: < 0.02%**



Newly measurable PK parameters

Measurement of relativistic orbital deformation is possible:

In DD timing formula:

$$e_r \equiv e(1+\delta_r)$$

$$e_\theta \equiv e(1+\delta_\theta)$$

whereas the PK parameter

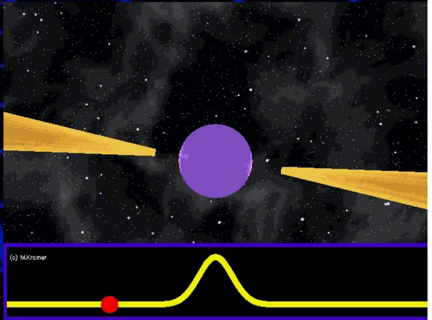
$$\delta_\theta = T_{sol}^{2/3}\left(\frac{2\pi}{P_b}\right)^{2/3}\frac{7m_p^2/2+6m_pm_c+2m_c^2}{\left(m_p+m_c\right)^{4/3}}$$

may be measurable in a few years:

$\delta_\theta = 12.6 \times 10^{-6}$ expected

more tests!

Aberration



- Pulsar rotates rather than pulses
- Aberration contributes to timing & profile
- ToAs are modified by “aberration delay” (DD86)

$$\begin{aligned}\Delta_A &= A\{\sin[\omega + A_e(u)] + e\sin\omega\} \\ &\quad + B\{\cos[\omega + A_e(u)] + e\cos\omega\}\end{aligned}$$

with PK parameters A and B which are usually absorbed in Roemer delay, but…

…aberration parameters will change due to geodetic precession:

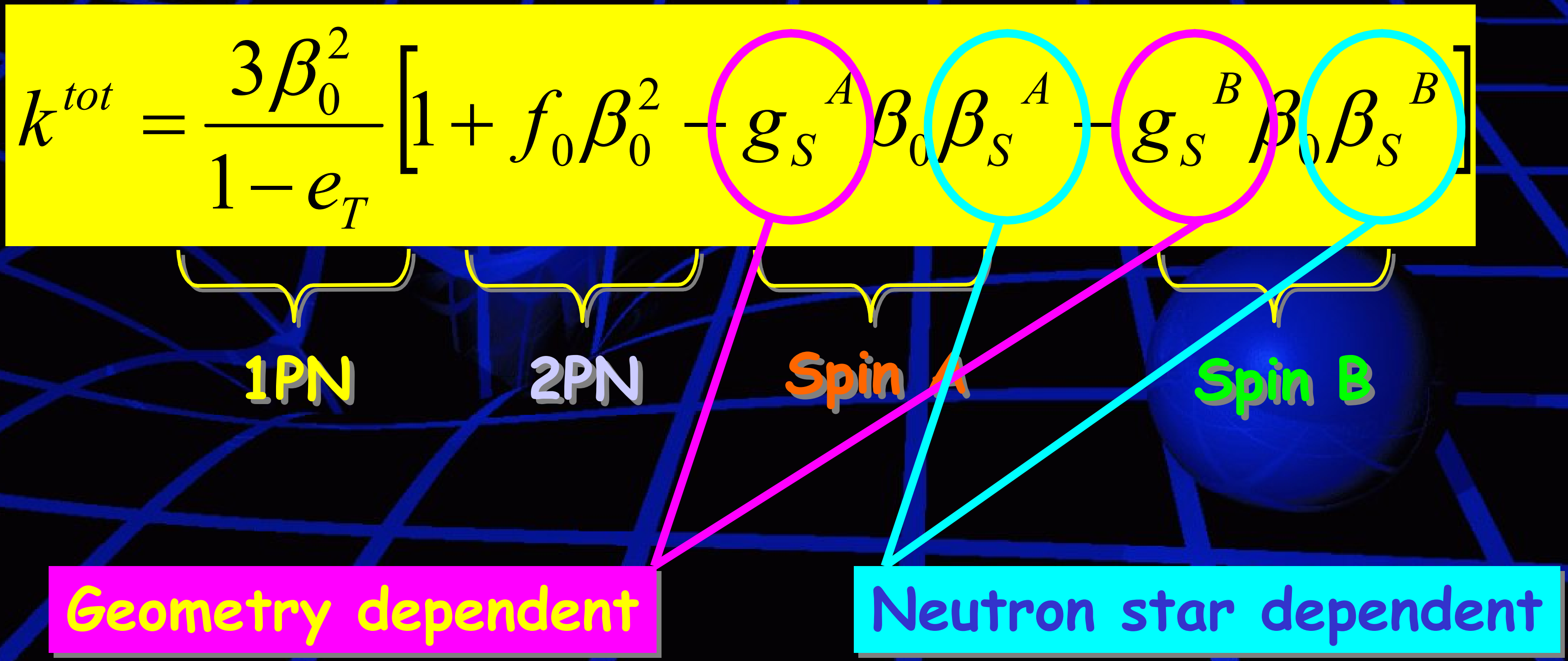
$$\frac{d(A/x)}{dt} = -\frac{P_p}{P_b}\,\frac{1}{\sin i(1-e^2)^{1/2}}\,\frac{d}{dt}\left(\frac{\sin\eta}{\sin\lambda}\right)$$

Damour & Taylor (1992

Spin contributions

Total periastron advance at 2PN level:

Damour & Schaefer (1988)



$$k^{tot} = \underbrace{\frac{3\beta_0^2}{1-e_T}}_{\text{1PN}}\Big[1 + \underbrace{f_0\beta_0^2}_{\text{2PN}} - \underbrace{g_S{}^A\beta_0\beta_S{}^A}_{\text{Spin A}} - \underbrace{g_S{}^B\beta_0\beta_S{}^B}_{\text{Spin B}}\Big]$$

Geometry dependent

Neutron star dependent

Assuming 'canonical' values:

1PN = 16.9 deg/yr

2PN = 0.0004 deg/yr

SpinA= 0.0002 deg/yr

already at 2PN limit!

14 x 1913+16's value!

Not easy! Need two other parms with similar precision... Need to

Neutronstar structure

Total periastron advance at 2PN level:

Damour & Schaefer (1988), Konigsdorffer & Gopakumar (2005)

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

Neutron star dependent

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

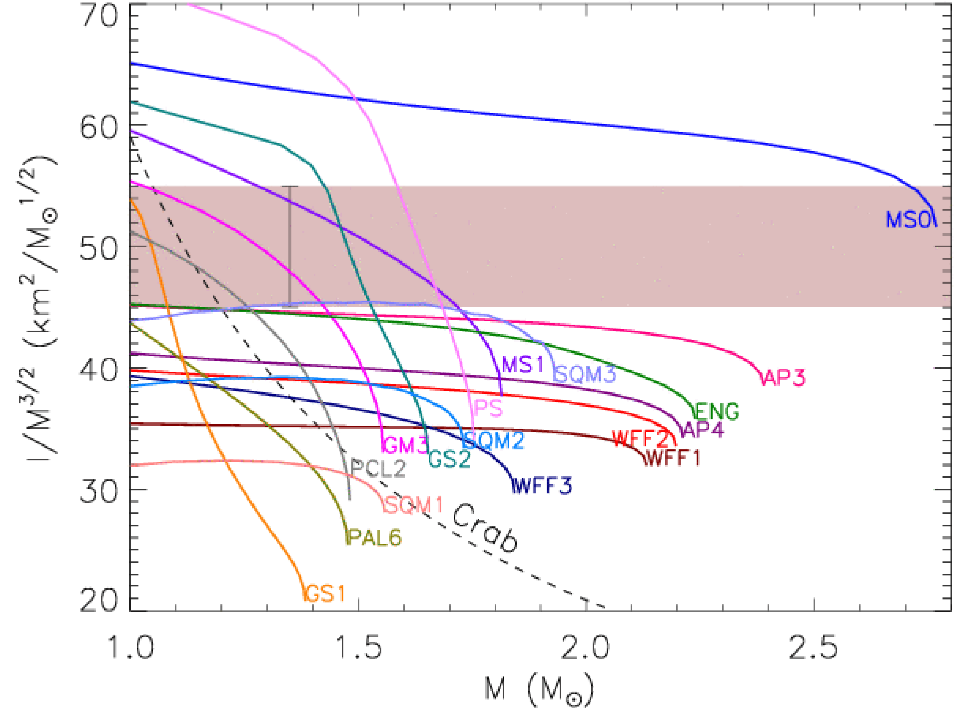
Equation-of-State!

Measure NS moment of inertia!!!

Moment of Inertia

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

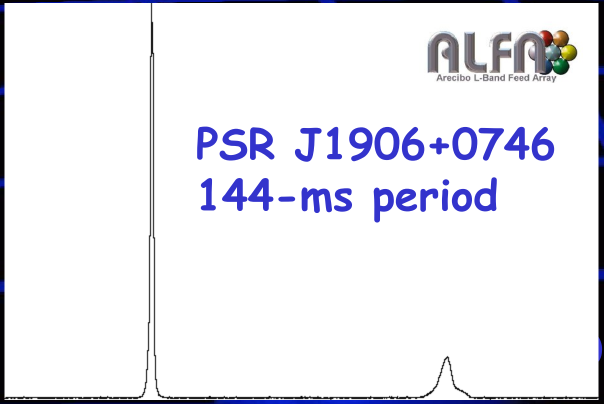
E.g.Lattimer & Schutz (2005)



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

The searches continue

- More searches at major telescopes, e.g.
- ALFA survey at Arecibo:
  - Huge ALFA consortium
  - First discoveries are rolling in
  - 4-hr relativistic binary pulsar
  - 2nd most relativistic system
  - A double neutron star?

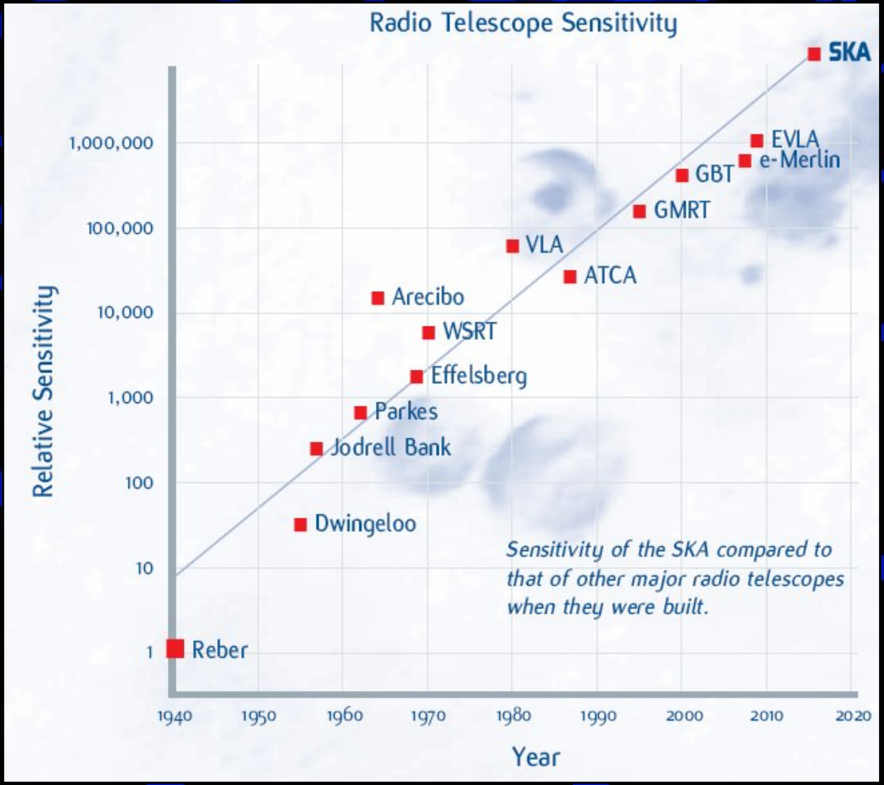


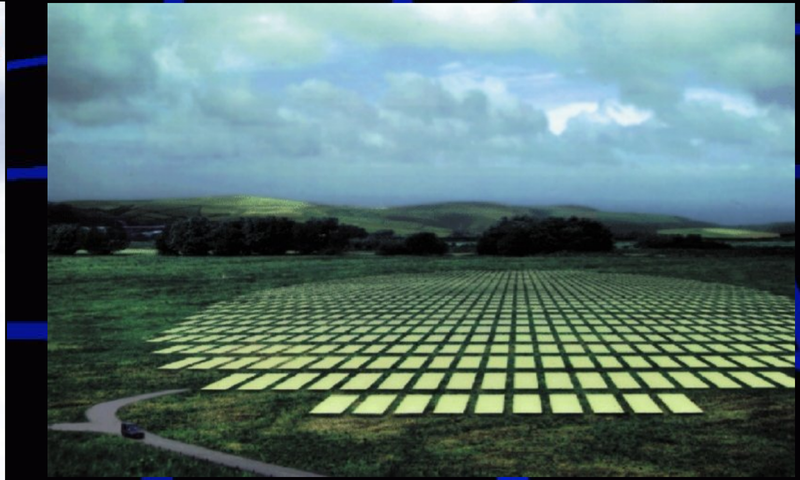
- The remaining "holy grail": a pulsar – black hole system!
- Wanted: millisecond pulsar around black hole

> *"...Finally, we pointed out that the discovery of 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)

The Square-Kilometer Array

- **The SKA will be the largest telescope ever built!**
- **A radio-telescope with a collecting area of 1 sq-km!**
- **With huge field-of-view (several sq-deg!)**
- **With 100's of beams on the sky at the same time**

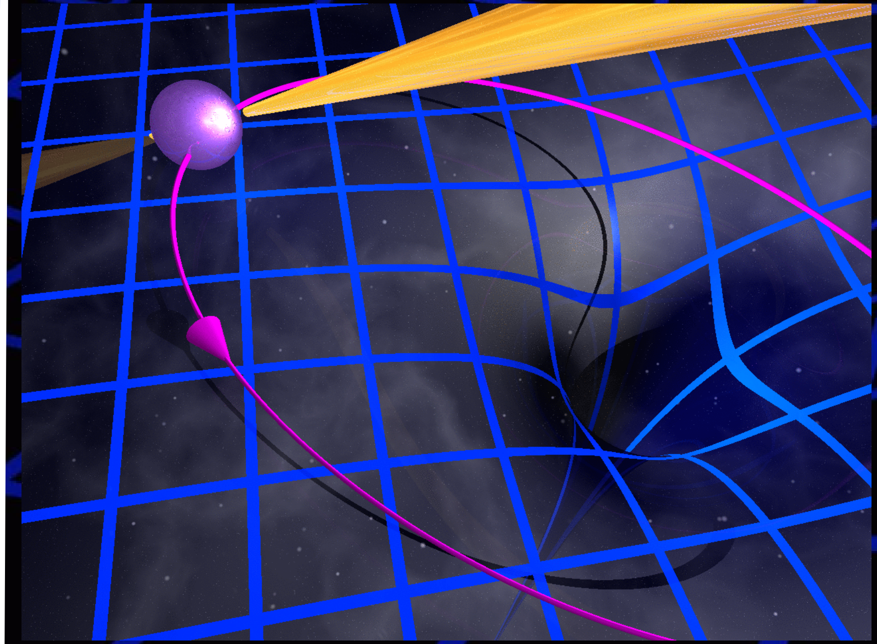


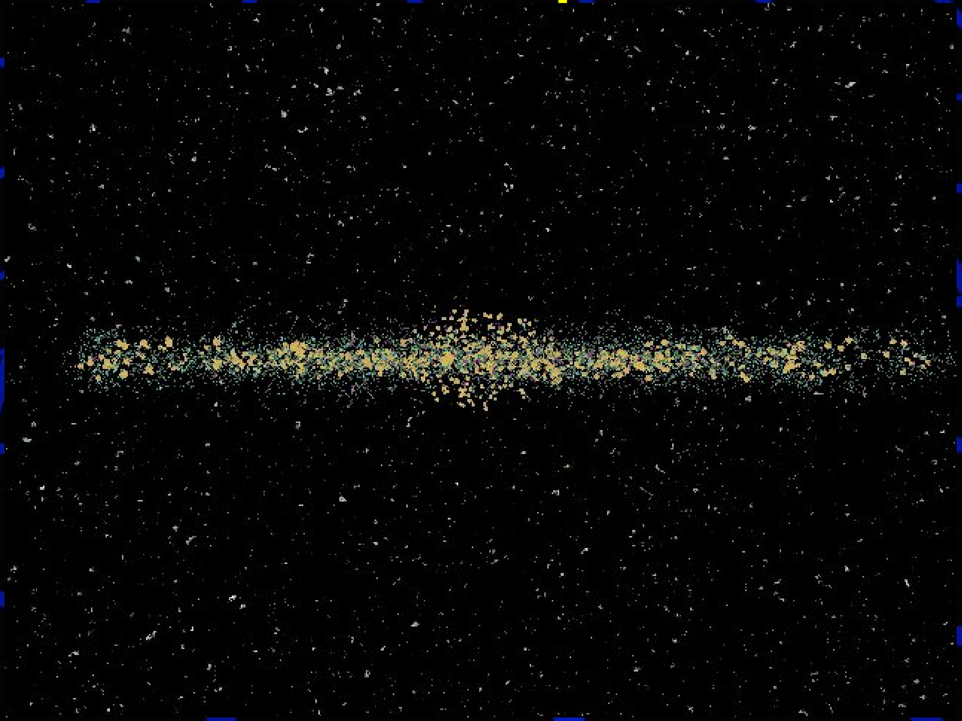


Ideal to search for and time pulsars!

A Galactic Census of pulsars

- SKA will essentially discover 'all' Galactic pulsars!



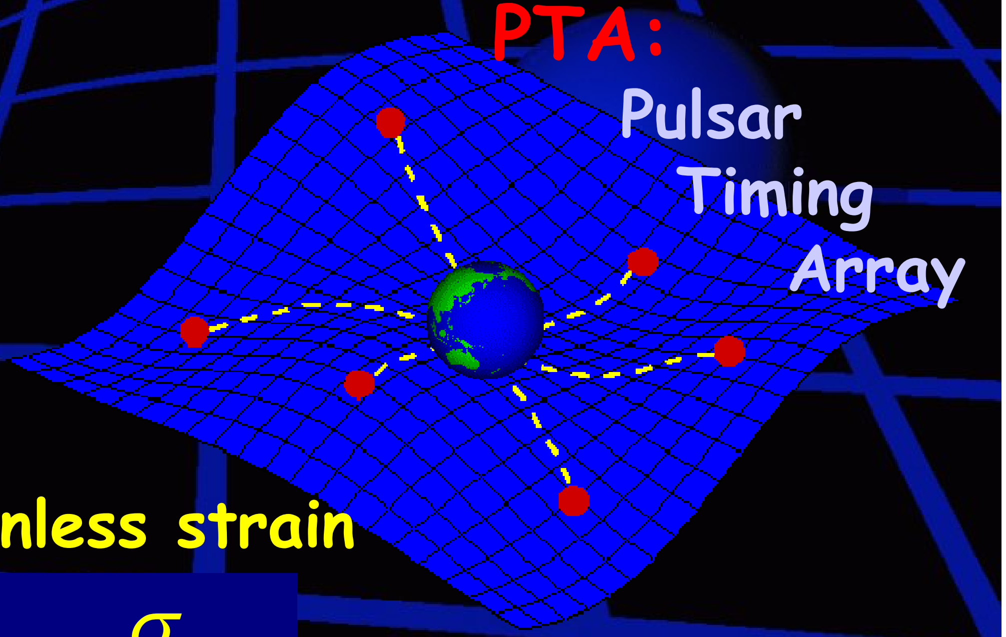


- Find pulsars around stellar BH and in Galactic Centre
- Measure BH properties: masses, spin & quadrupole moment
- Testing GR description of BHs, such as
  Cosmic Censorship Conjecture & No-hair theorem

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

Stochastic Gravitational Wave Background

- Pulsars discovered in Galactic Census also provide network of arms of a huge cosmic gravitational wave detector

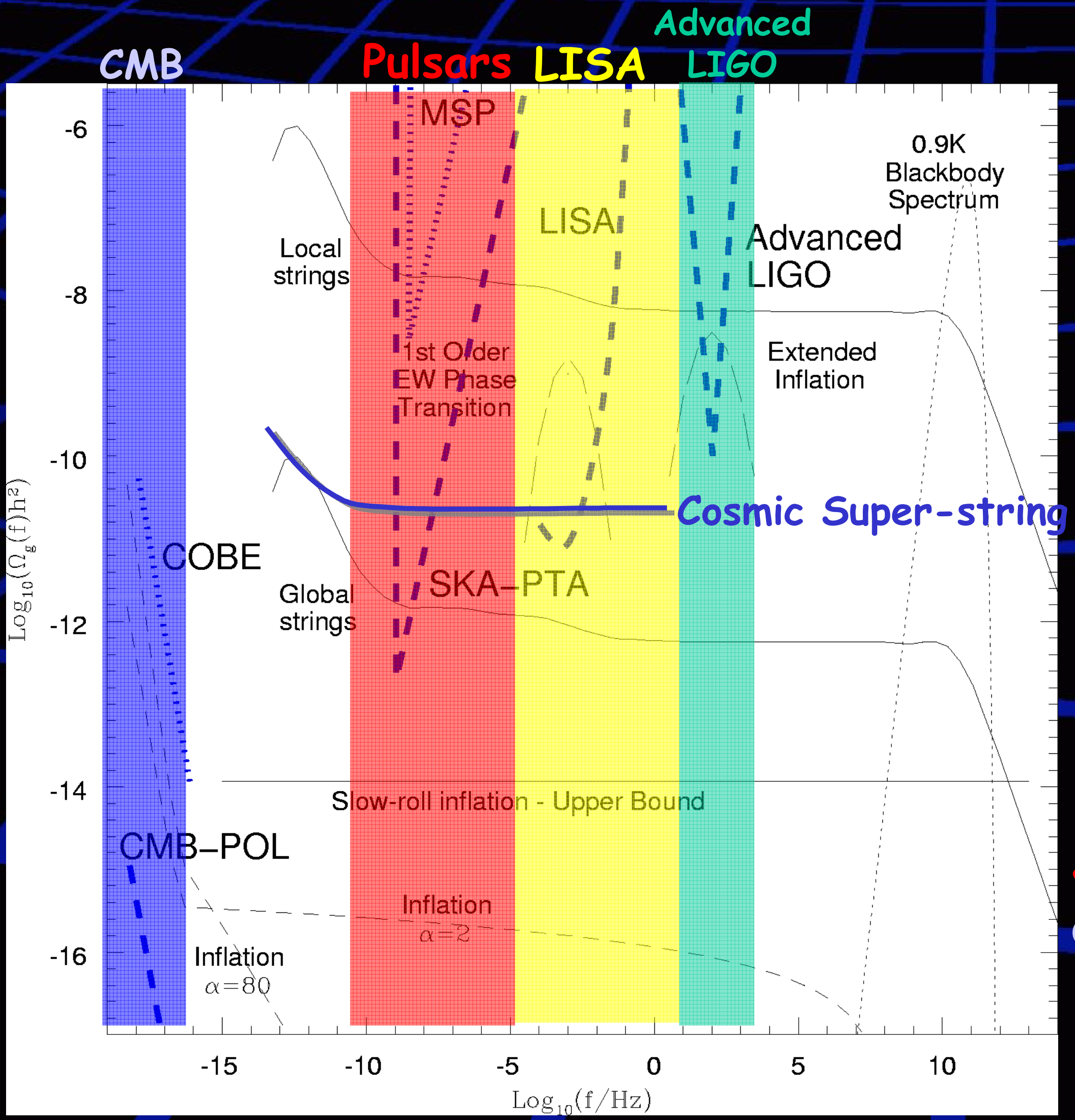


- Perturbation in space-time can be detected in timing residuals

- Sensitivity: dimensionless strain

$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

Stochastic Gravitational Wave Background

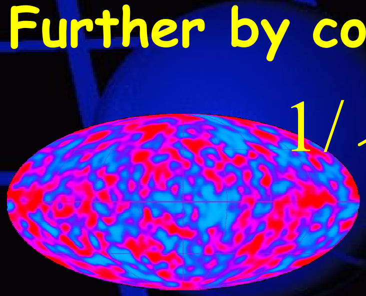


PTA limit:

$$h_0^2\Omega_{GW}(f) \sim \sigma_{TOA}^2 f^4$$

Further by correlation:

$$1/\sqrt{N_{PSR}}$$

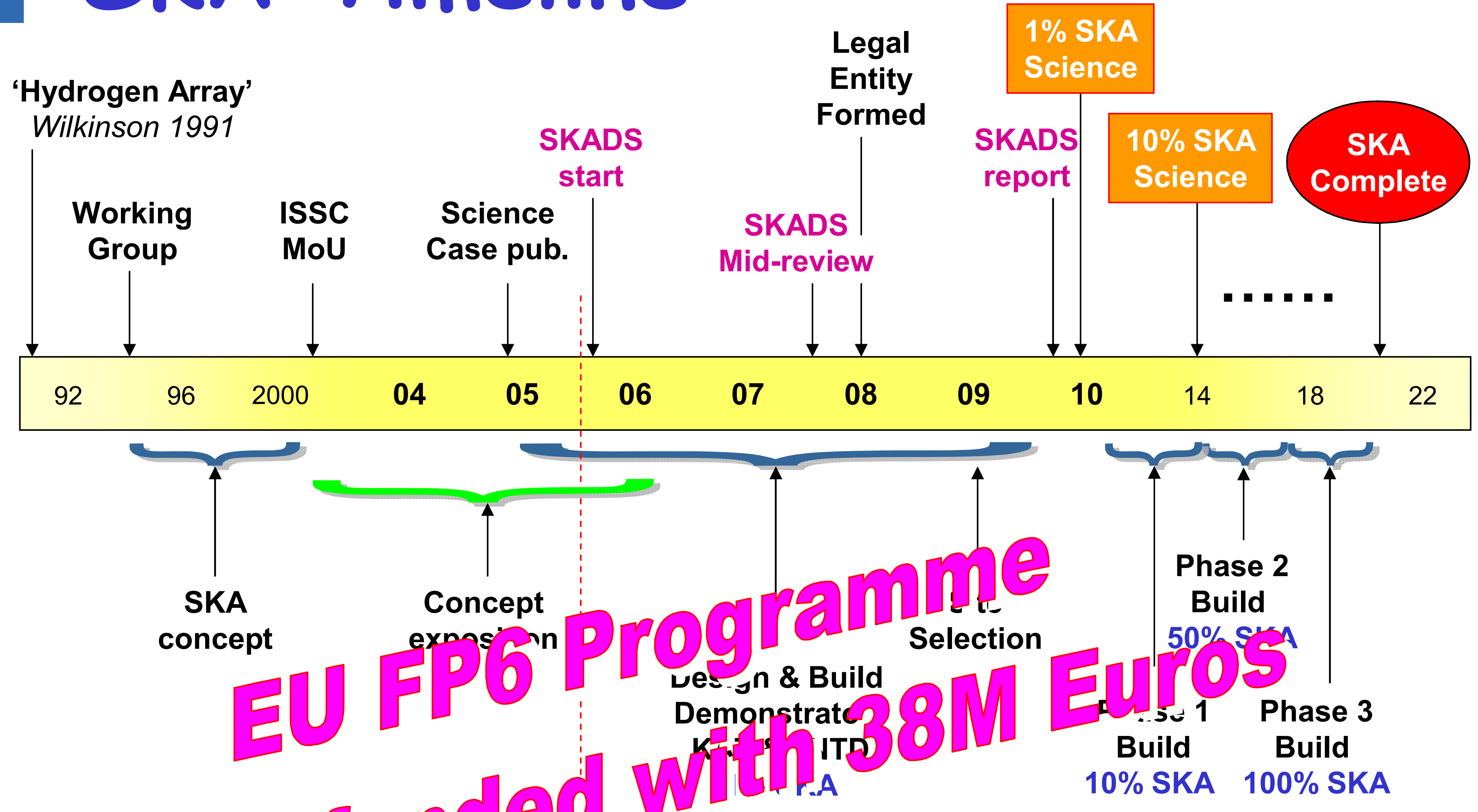


Improvement: 10^4!

Spectral range: nHz only accessible with SKA!

complementary to LISA, LIGO & CMB

SKA Timeline



EU FP6 Programme
SKADS funded with 38M Euros

Visit: www.skatelescope.org

From the binary to the double pulsar…

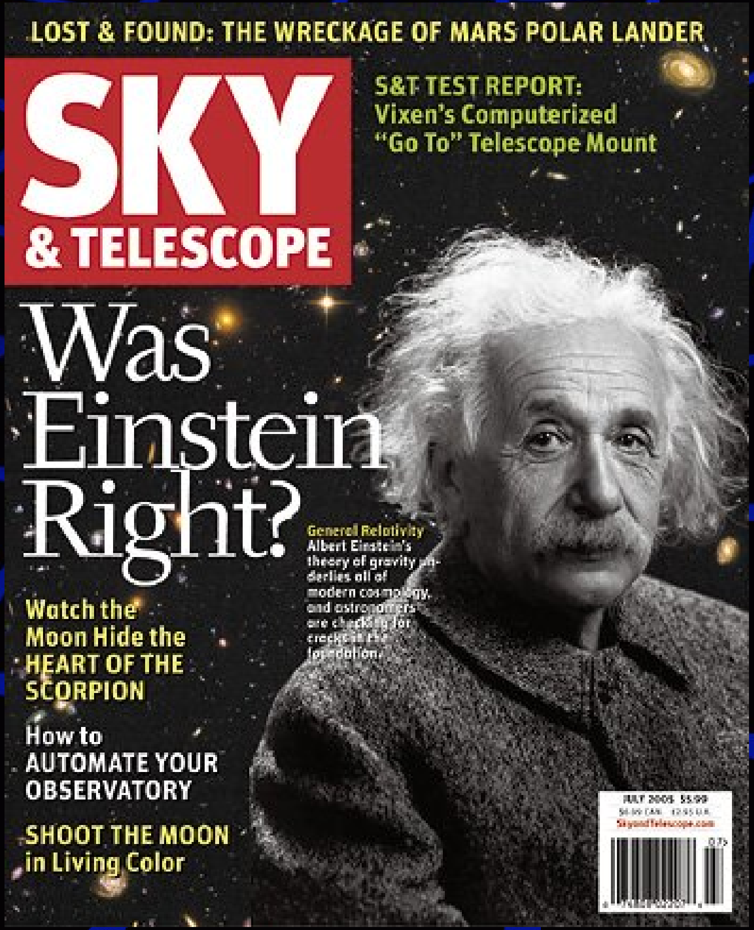
- Pioneering work in observations and theory with B1913+16
- Further discoveries allowed different tests
- Culmination (so far!) in the double pulsar:
- Most over-constrained system already
- Only system with constraint independent of self-field
- Most precise test already
- More PK parameter/effects potentially measurable, e.g.
  - Measurement of orbital deformation
  - Measurement of aberration

Summary:

Pulsars are amazing tools in testing theories of gravity!

The quest for the Pulsar –Black Hole System has begun!

Until then, we'll continue to ask the question…



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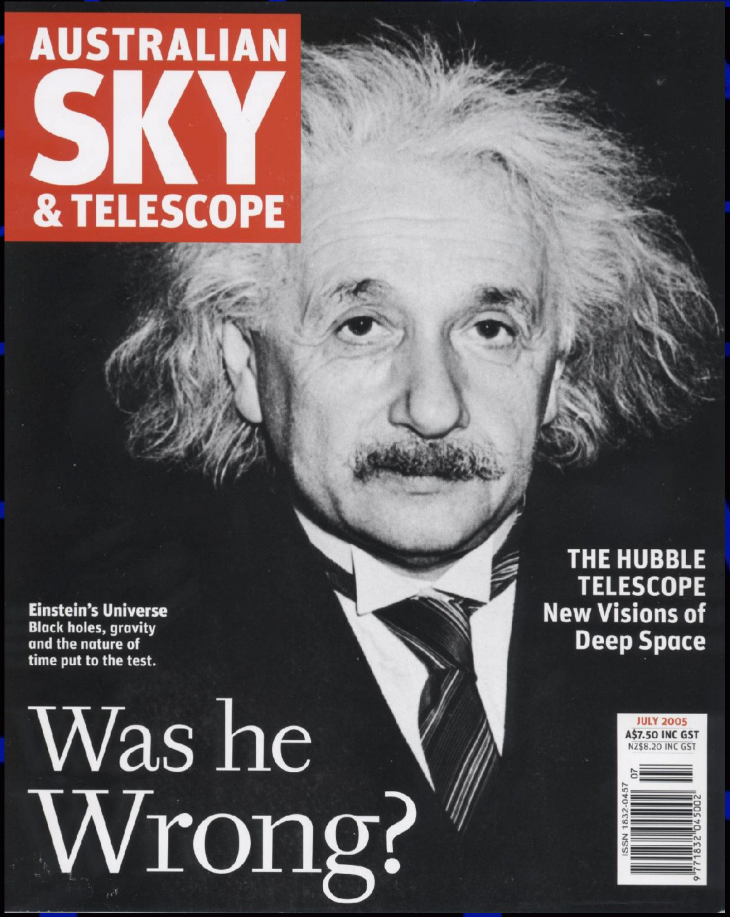

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