The University of Manchester Jodrell Bank Observatory

Testing GR with the Double Pulsar: Recent Results

Michael Kramer

With:

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PPARC

Texas Symposium – 16 December 2004

Outline

Introduction

- The system
- Interaction between A&B

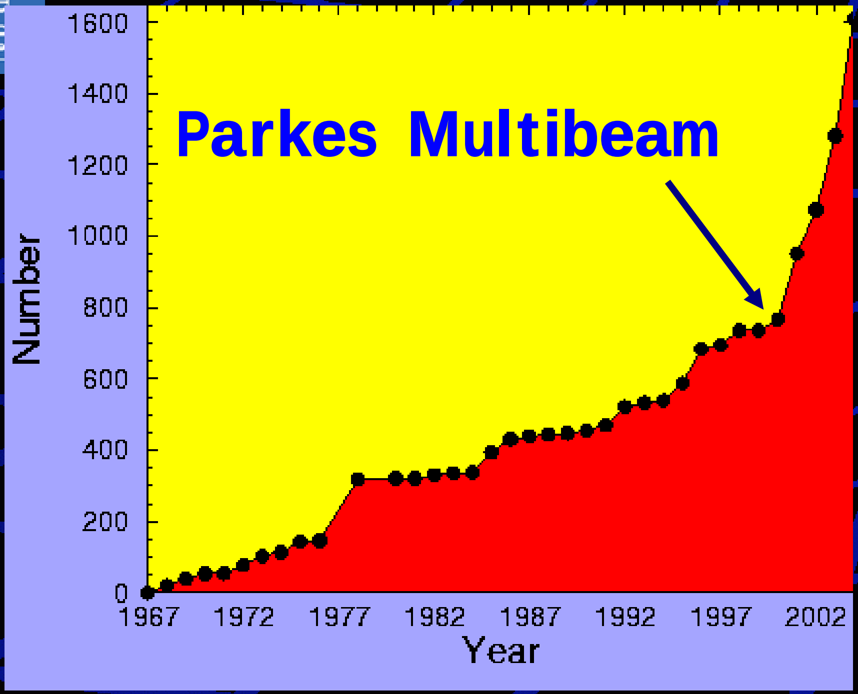
Tests of General Relativity

- Improved parameters
- New measurements & tests

The Future

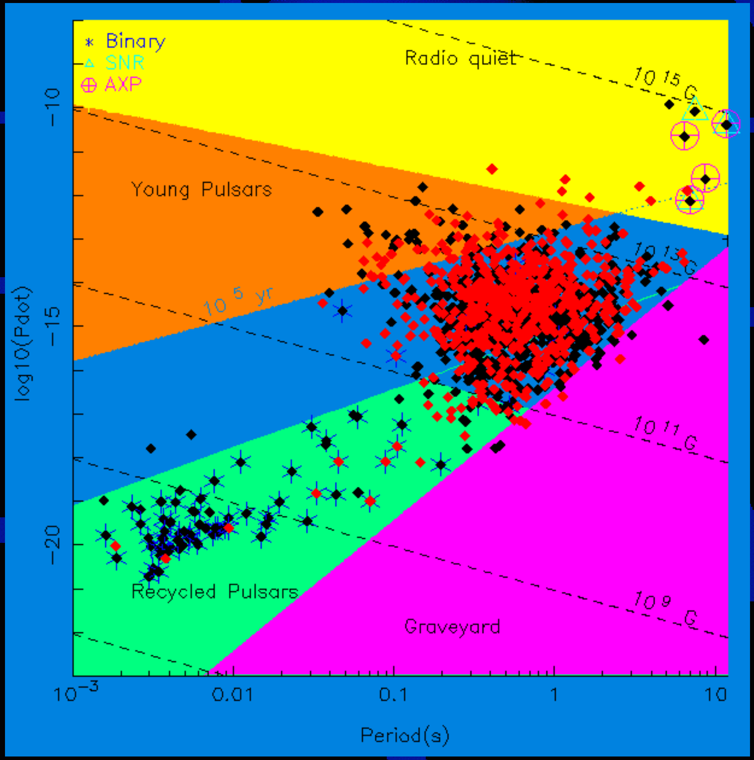
Parkes Multibeam Survey

lead by Jodrell Bank & ATNF in collaboration with many partners



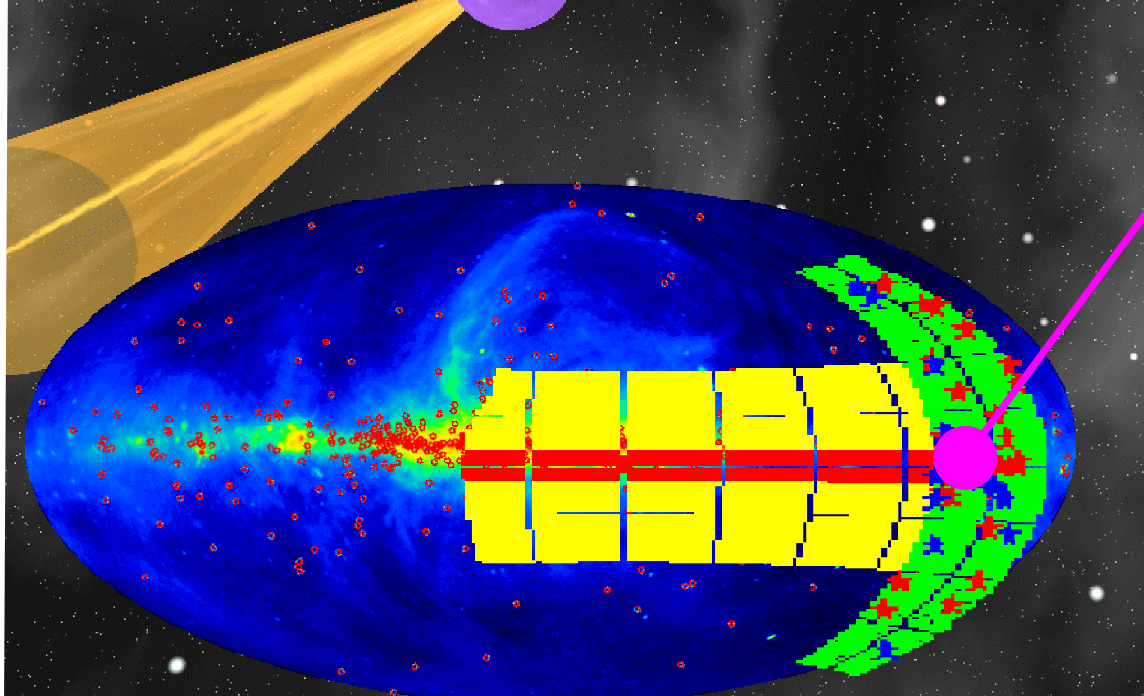
- Most sensitive & most successful
- More than 700 discoveries
- Still counting...
- Lots of exciting systems...

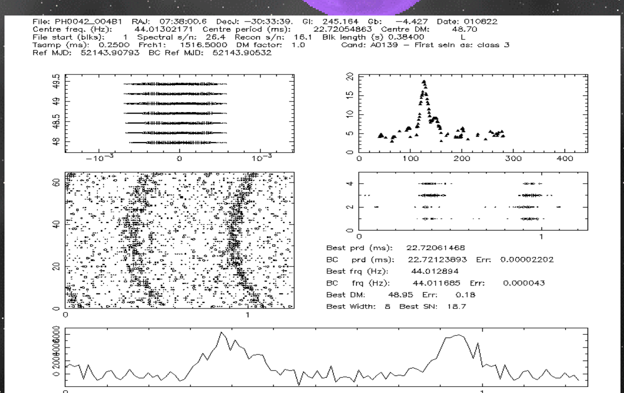
Manchester et al. 2001, Morris et al. 2002
Kramer et al. 2003, Hobbs et al. 2004,
Faulkner et al. 2004



Discovery of "A"

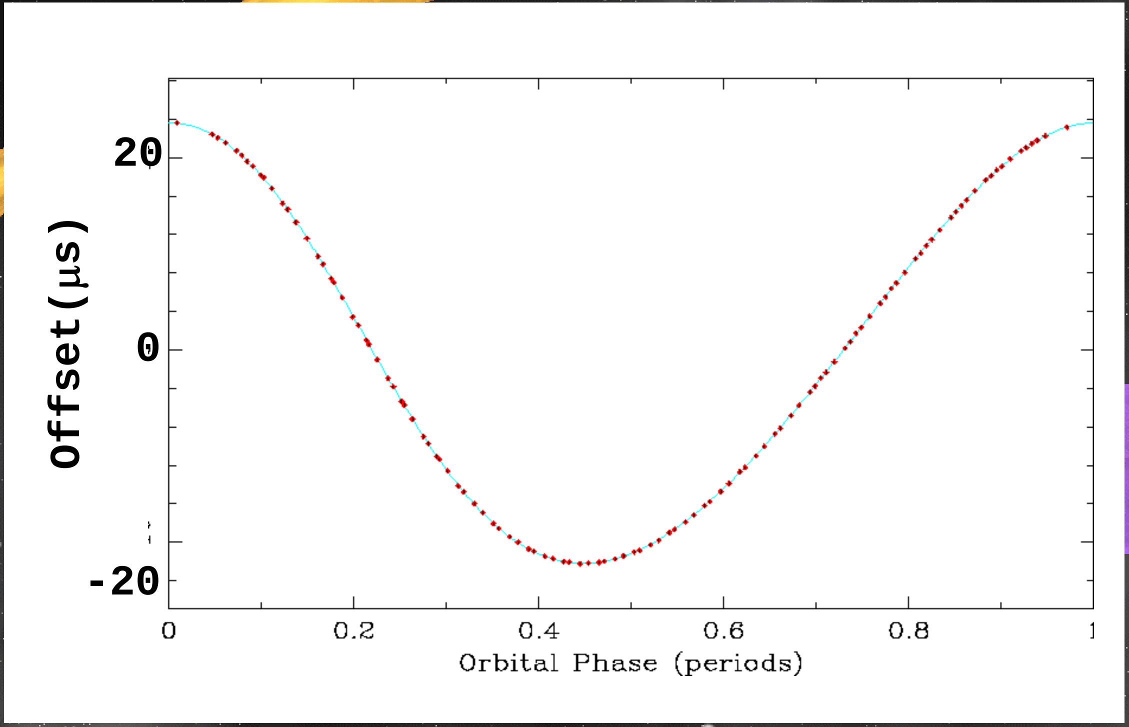
PSR J0737-3039 discovered in April 2003 in an PKSMB extension: the Parkes High-LatitudePulsar Survey (Burgay et al., Nature, 2003)





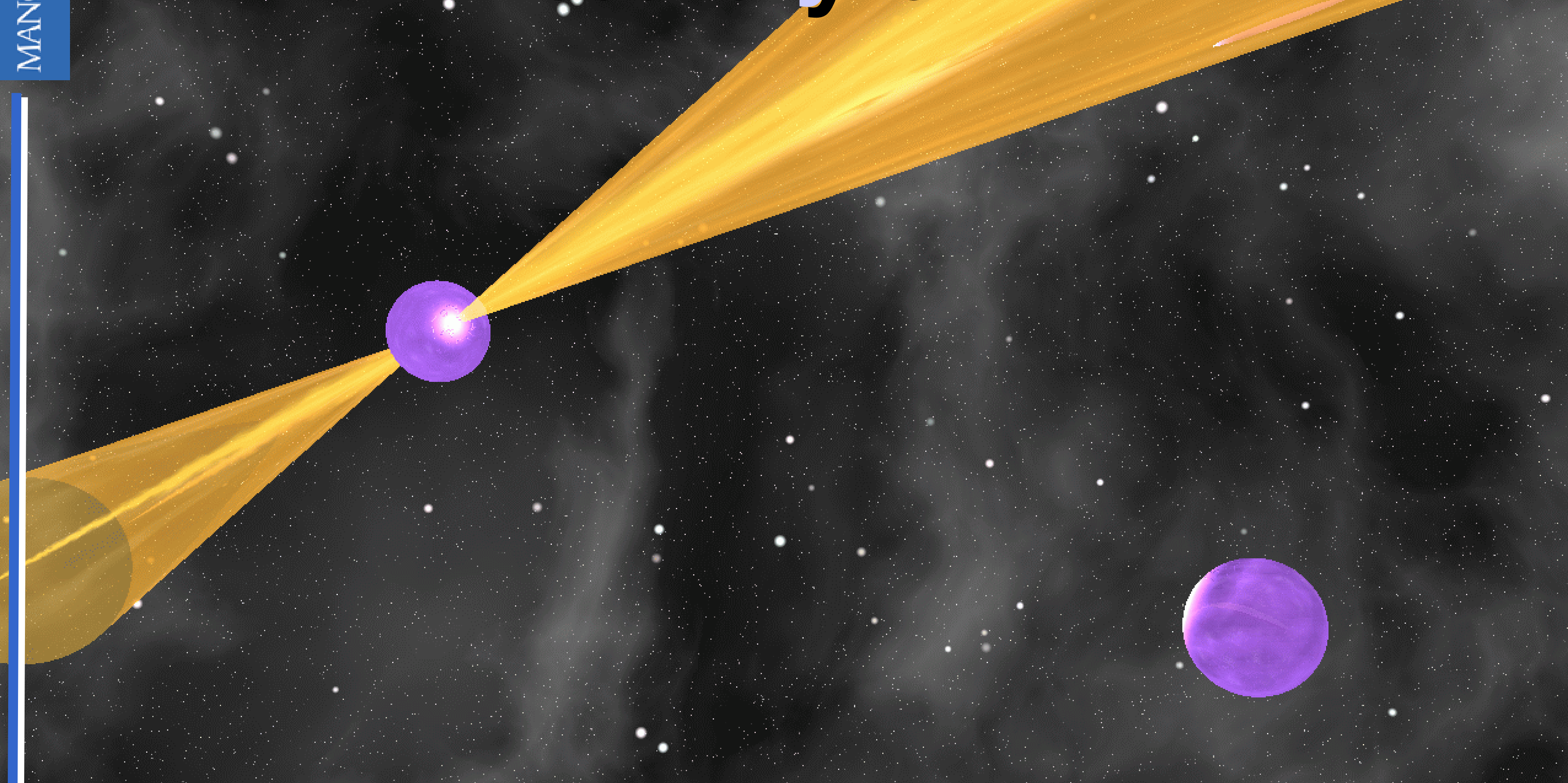
Discovery of “A”

- **Observations showed that the orbit is very tight (P_b=2.4 hrs) and eccentric (e = 0.088) with orbital velocities of ~300 km/s!**



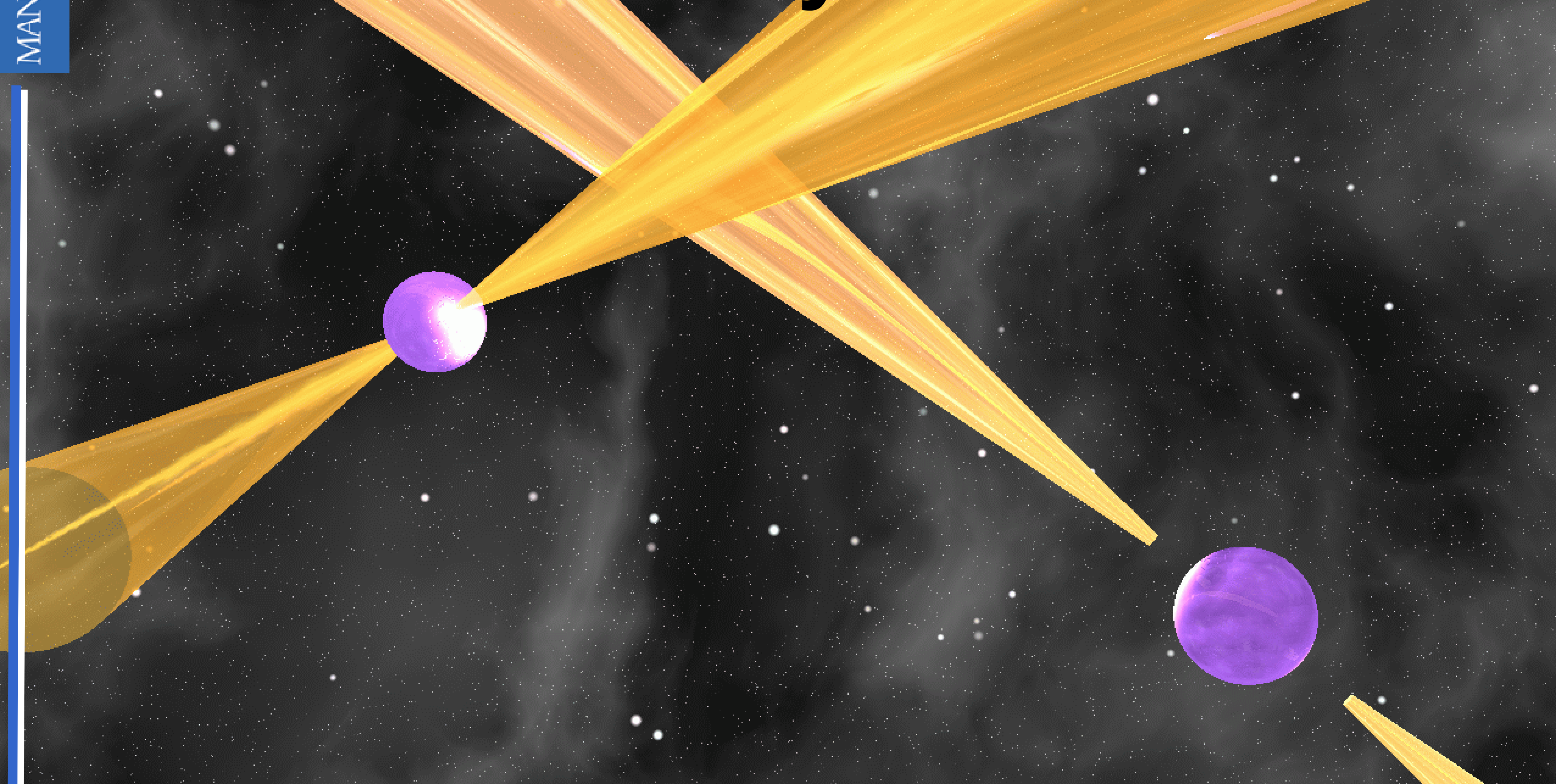
- **Orbital parameters suggested that the companion to 22-ms pulsar is probably another neutron star**

Discovery of “B”



In October 2004 the system became sensational:

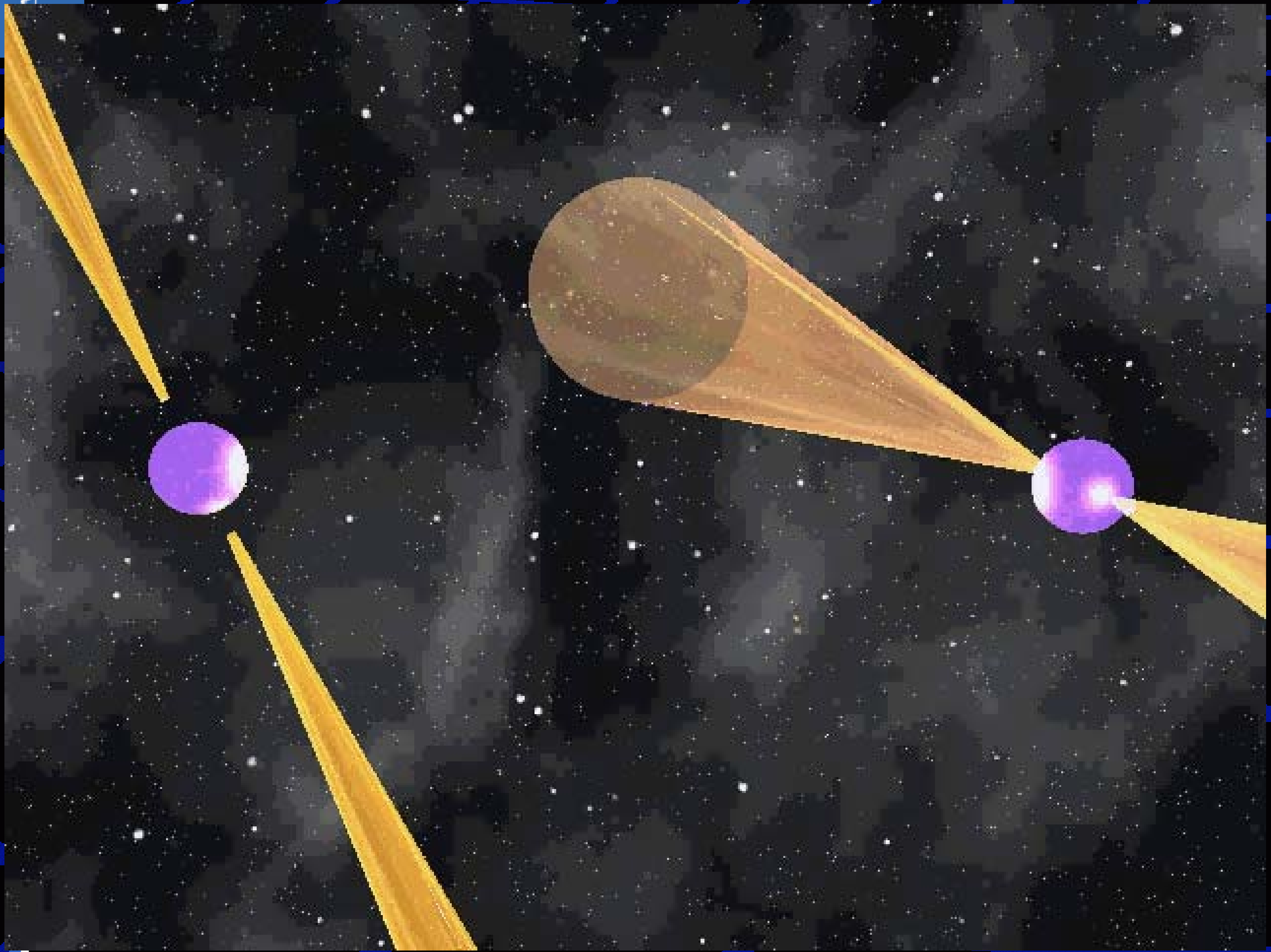
Discovery of “B”

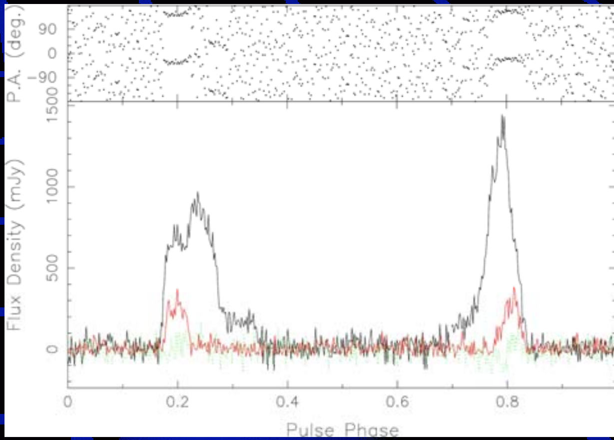


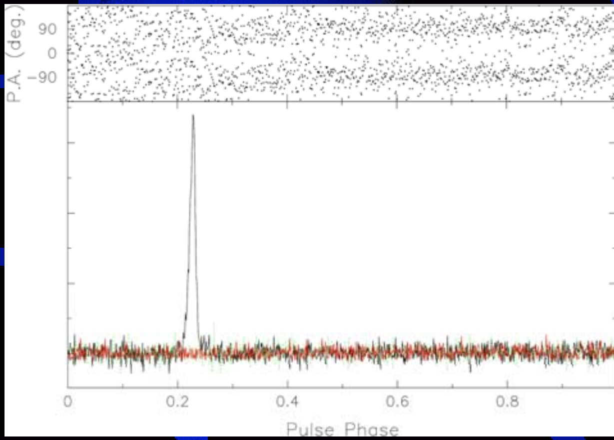
In October 2004 the system became sensational:

A “holy grail” was discovered - the first double pulsar!

A double pulsar system







Discovery of an additional 2.77-sec periodicity!

(Lyne et al., Science, 2004)

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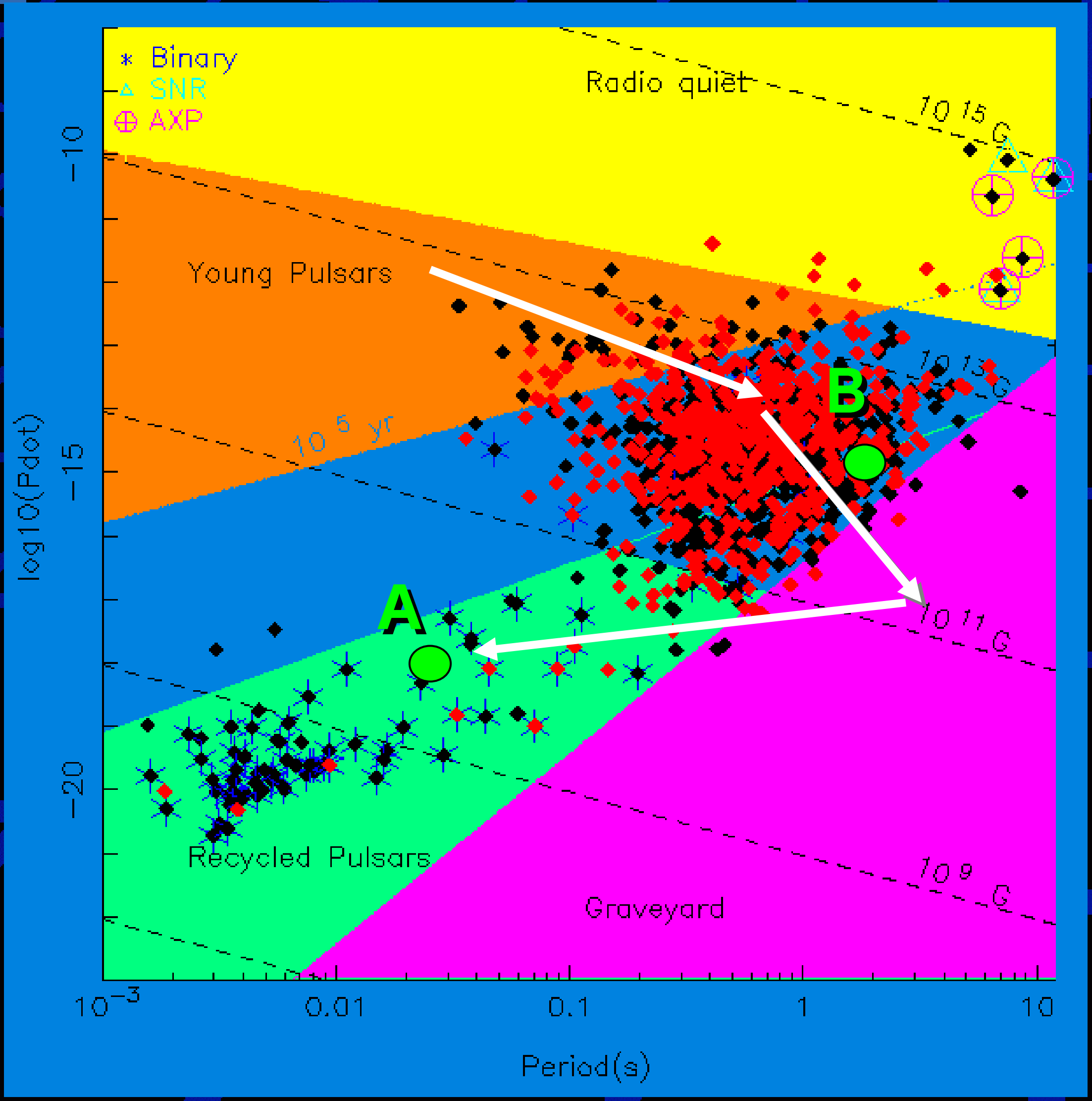
Basic parameters

	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}

Evolution of the Double Pulsar

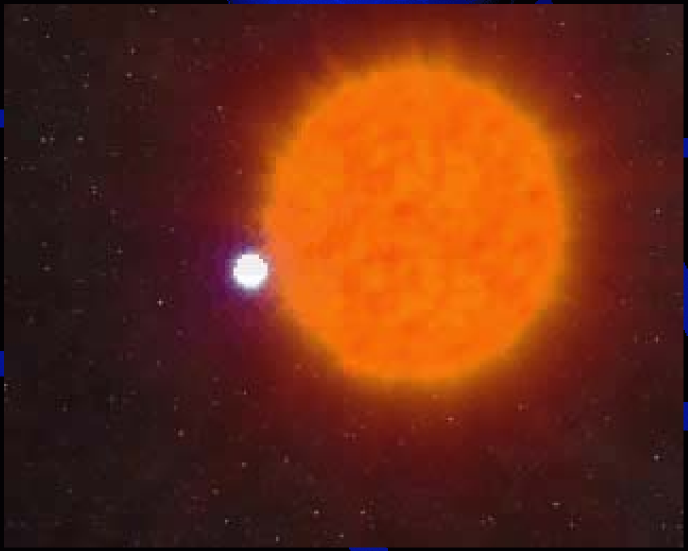
"P-Pdot diagram:"



A is old & recycled

B is young

Their life in short:



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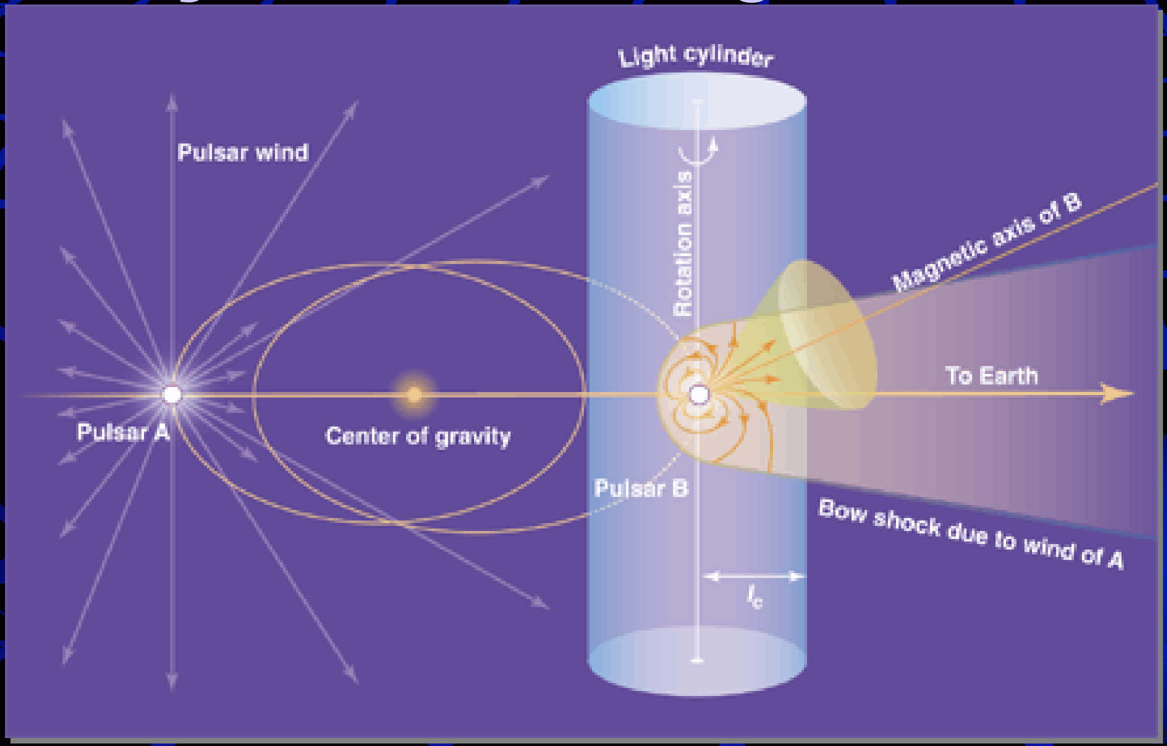
System Configuration

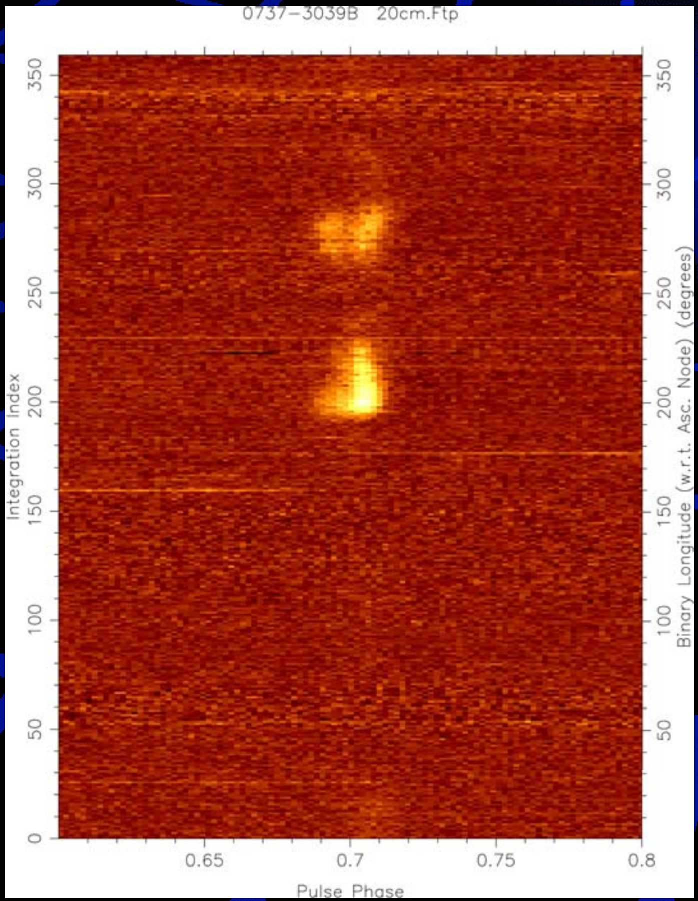


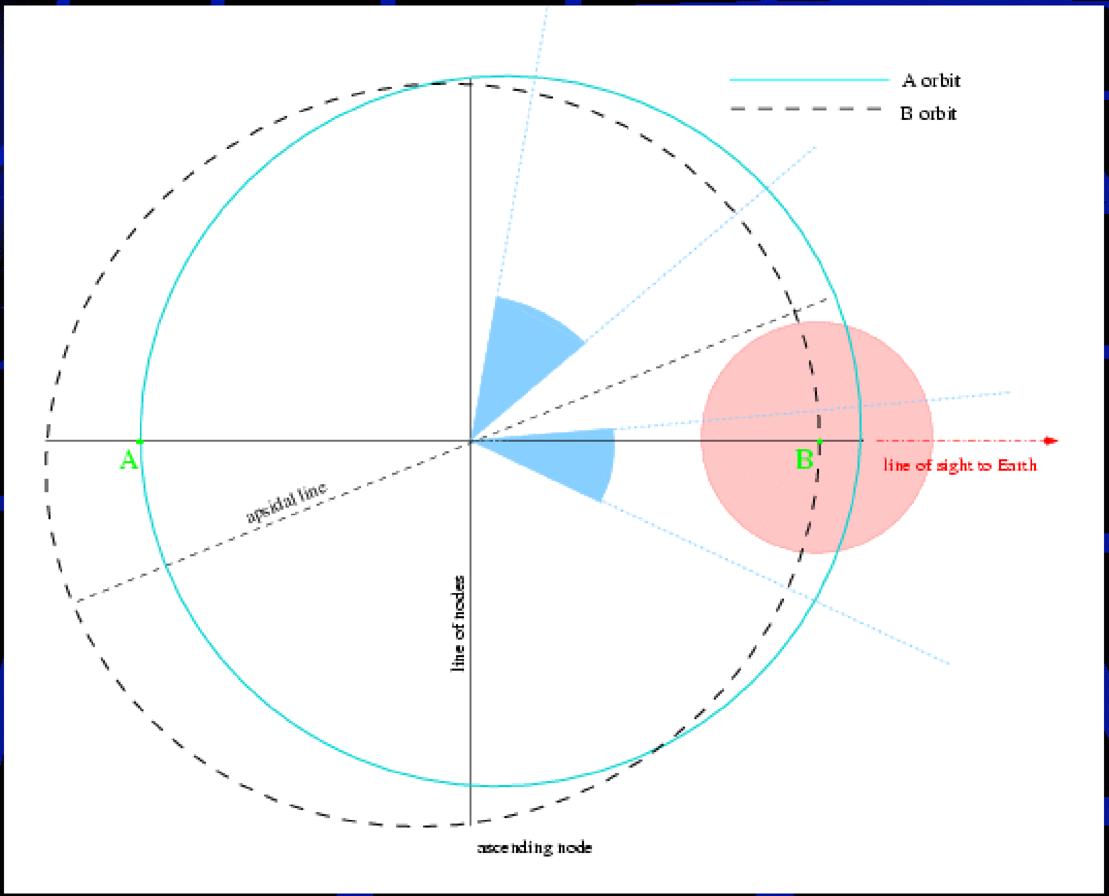
- Wind energy density at B light cylinder:

  A: ~ 2.1 erg cm^{-3} B: ~ 0.024 erg cm^{-3}
- Therefore, A wind will penetrate B magnetosphere.
- Approximate pressure balance with B's magnetic field at $r \sim 0.5\ R_{LC}$. Will vary with spin and orbital phase.

Orbital modulation of “B” emission

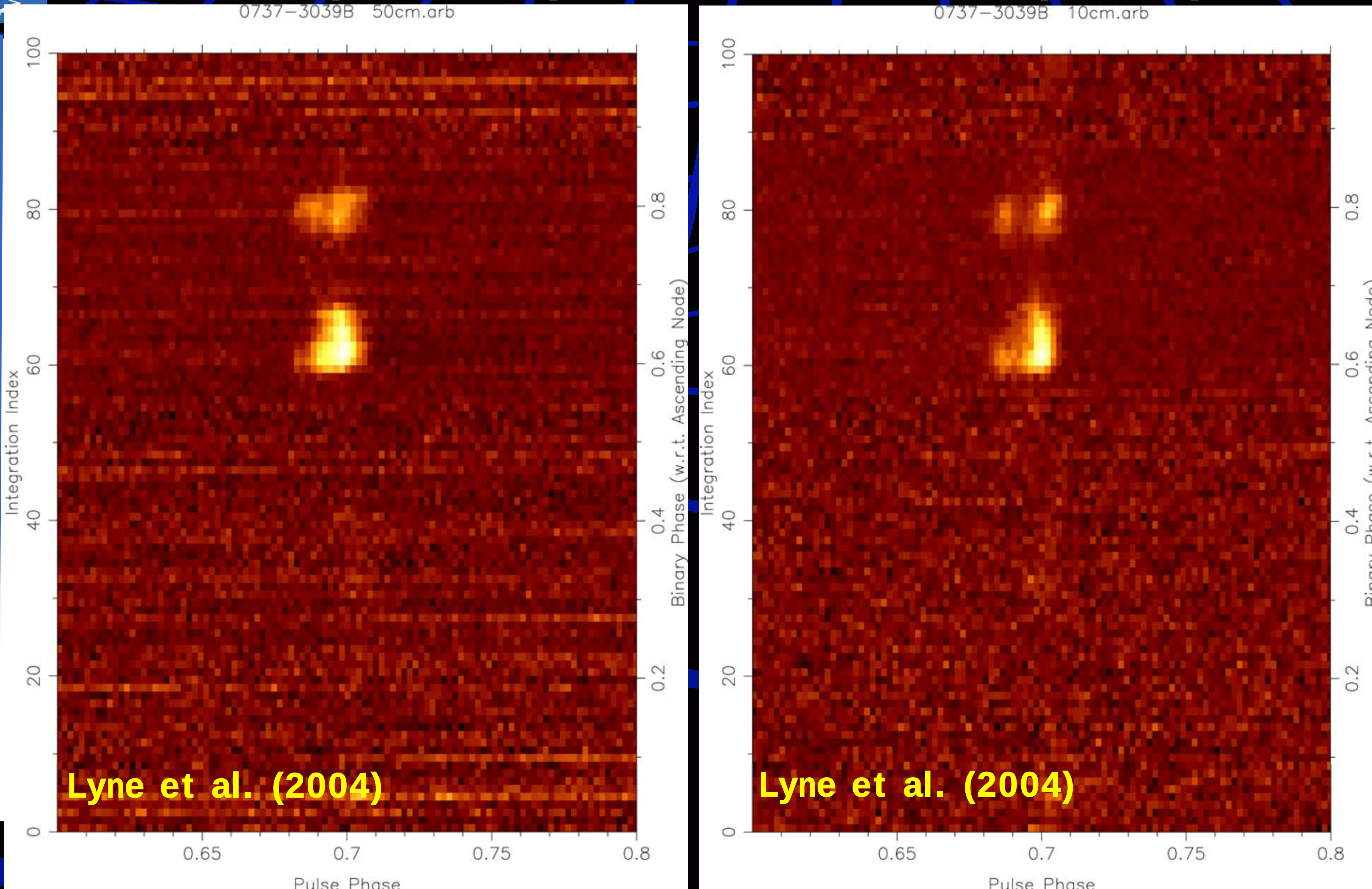
Two bright intervals near inferior conjunction:





Orbital modulation of "B" emission

50cm (680 MHz) 10cm (3 GHz)



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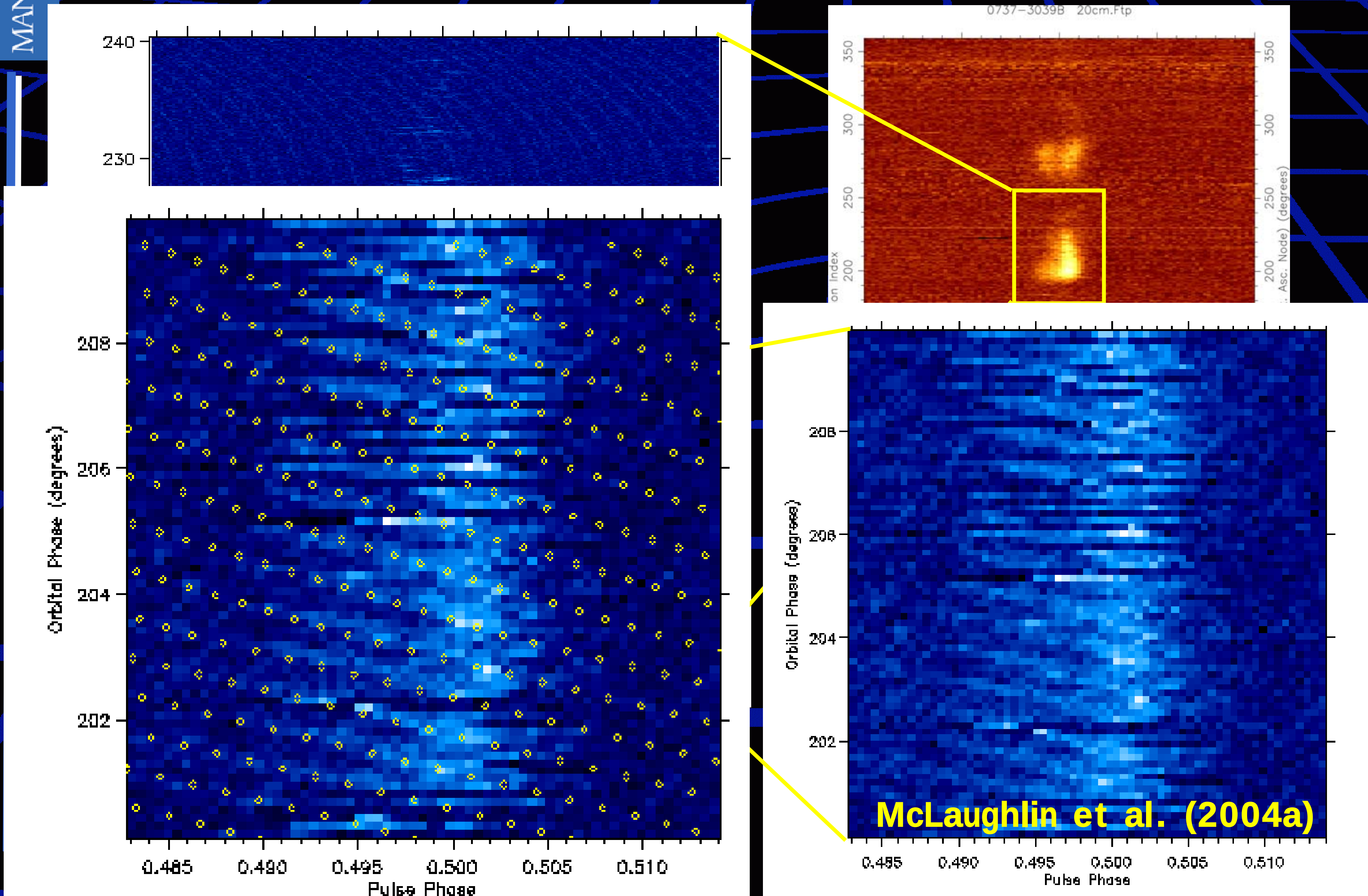
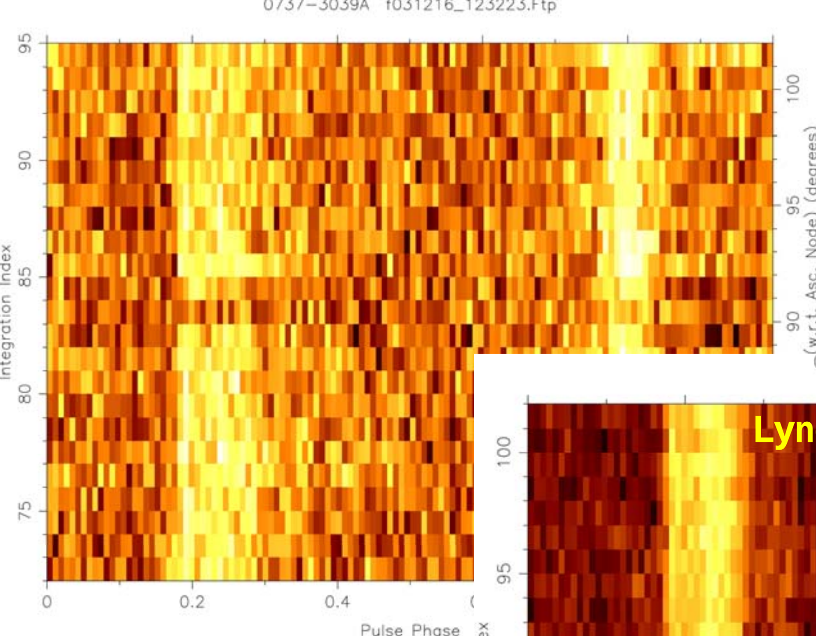
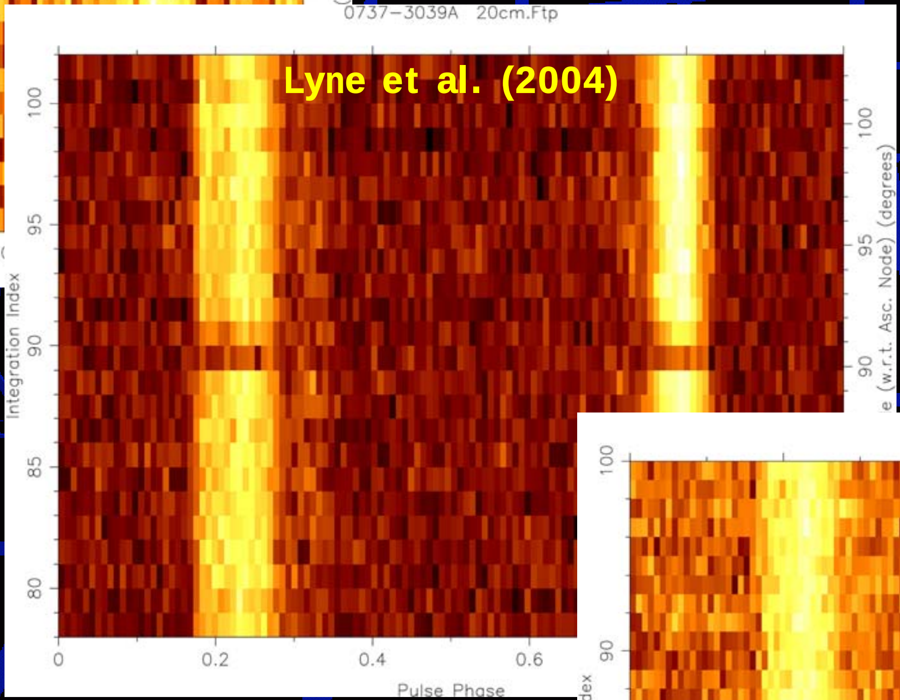
Direct modulation of B's emission by A



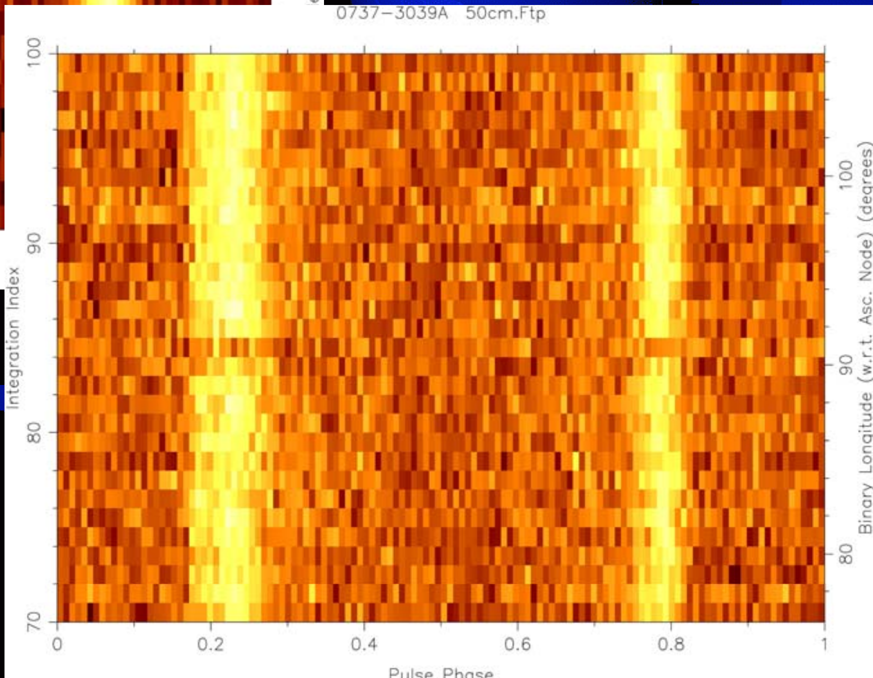
Eclipses of A



10cm



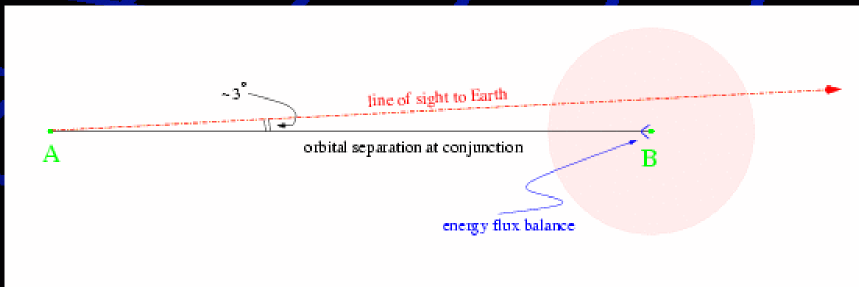
20cm



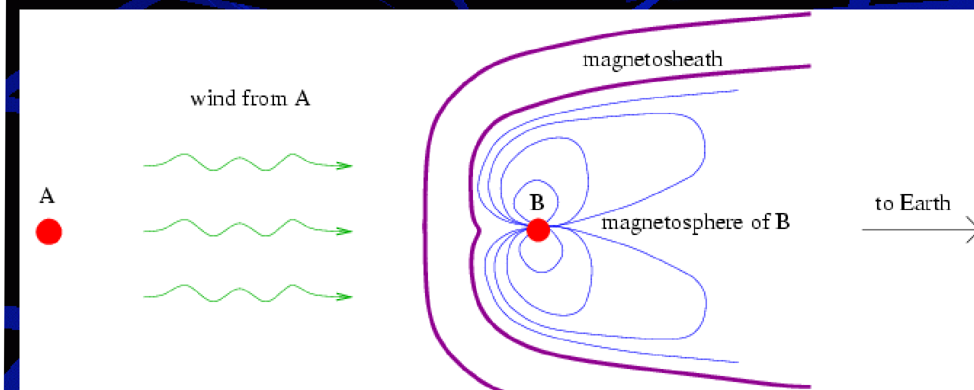
50cm

- At superior conjunction
- Lasting for ~27 sec
- Deepest just AFTER superior conjunction

Eclipses of A

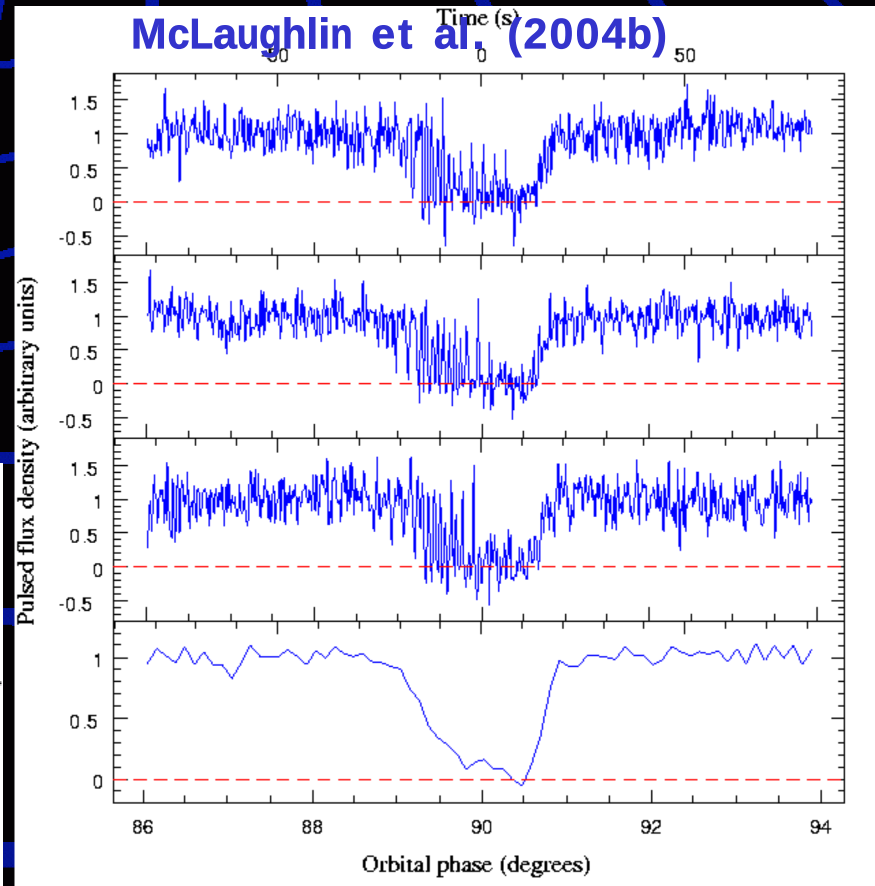


At 88° inclination, LOS to A passes 30,000 km from B



(cf. Arons et al.2004, Kaspi et al. 2004)

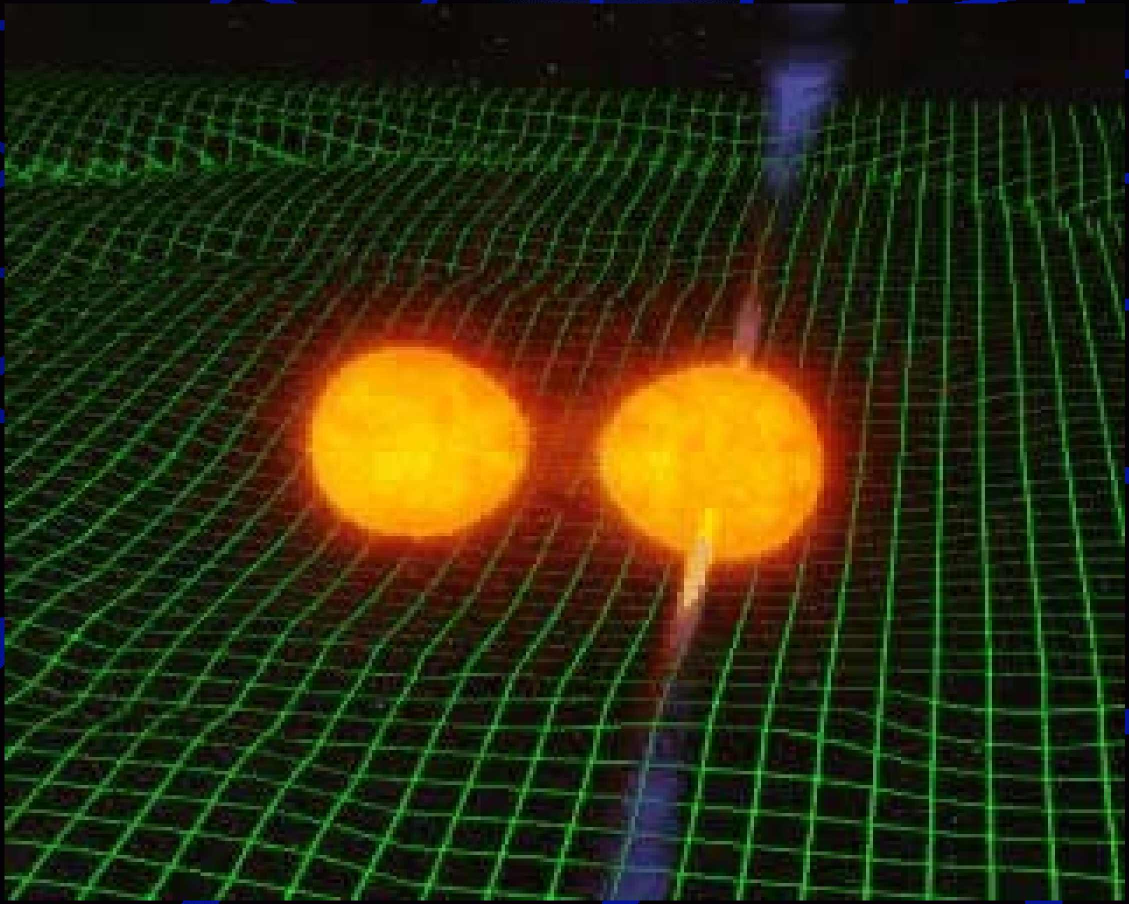
McLaughlin et al. (2004b)



We can see the rotation of B!

Boost for gravitational wave hunters

- Neutronstars merge after only 85 Myr due to gravitational wave emission!

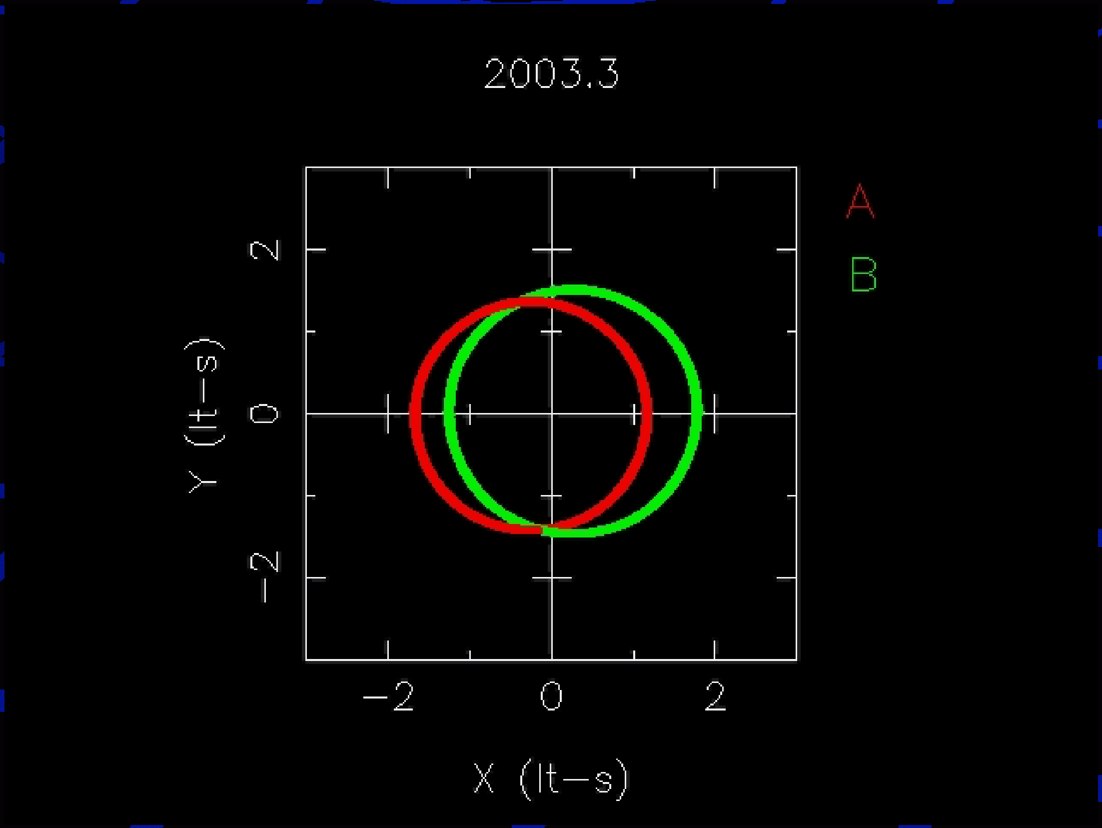


Since system…
…is accelerated
…merges “soon”
…is close
…not very luminous

Most relativistic system ever!

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

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



- **Also, orbital decay and huge rel.spin-orbit coupling!**

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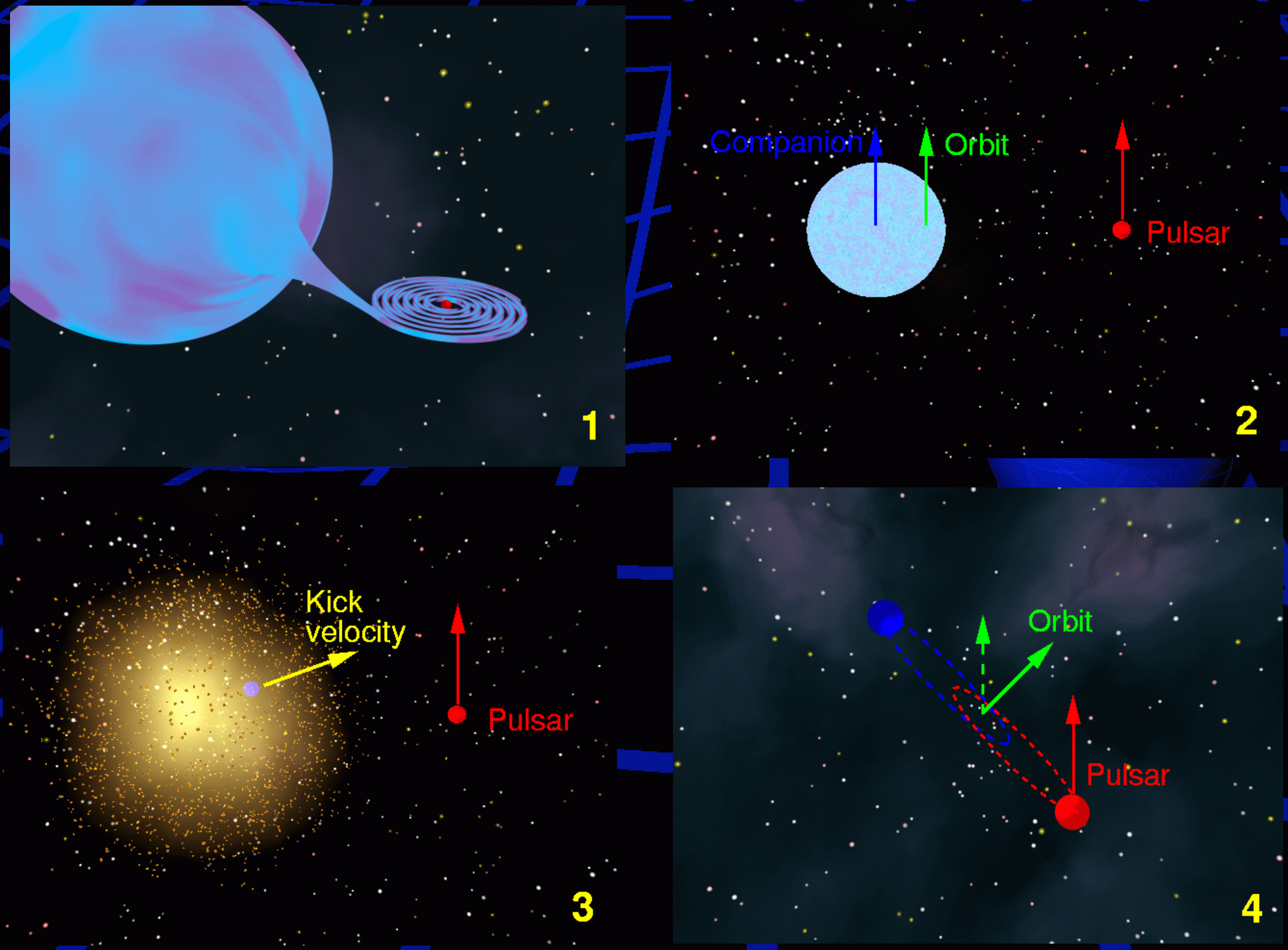
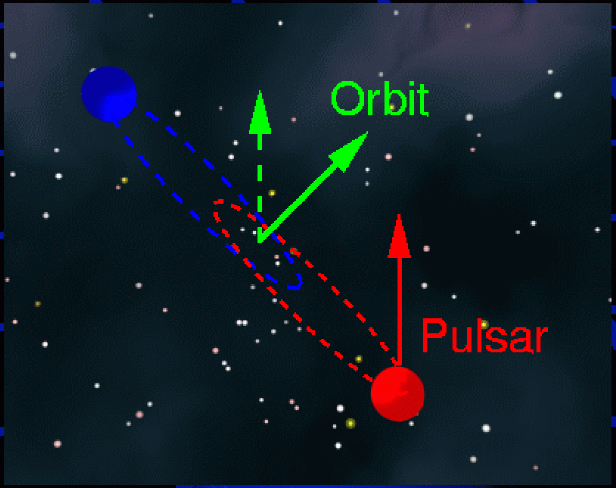
Spin-Orbit Coupling due to misaligned spins



Geodetic Precession

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

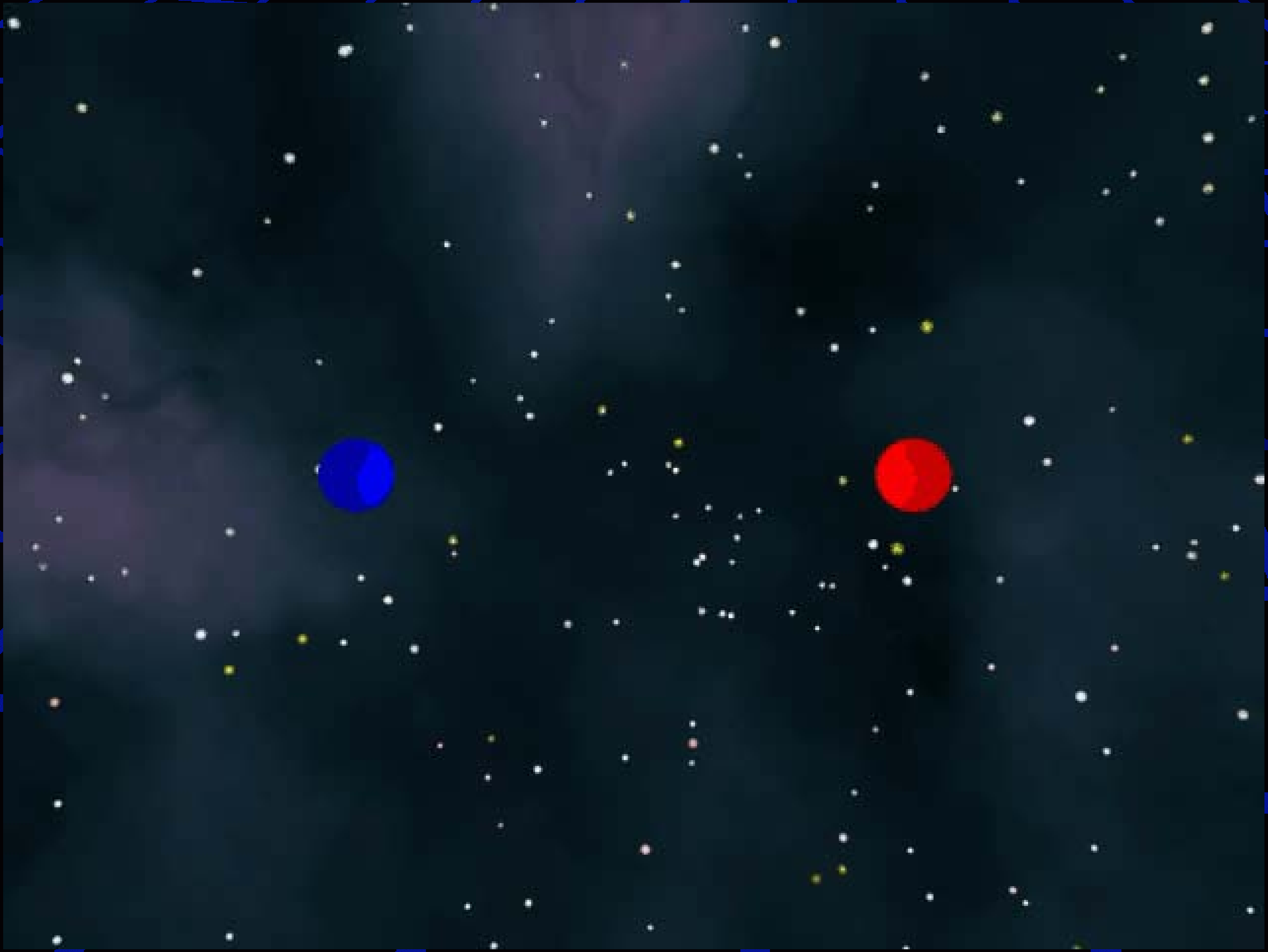


- Precession rate expected in GR: (e.g. Barker & O'Connell 1975, Börner et al. 1975)

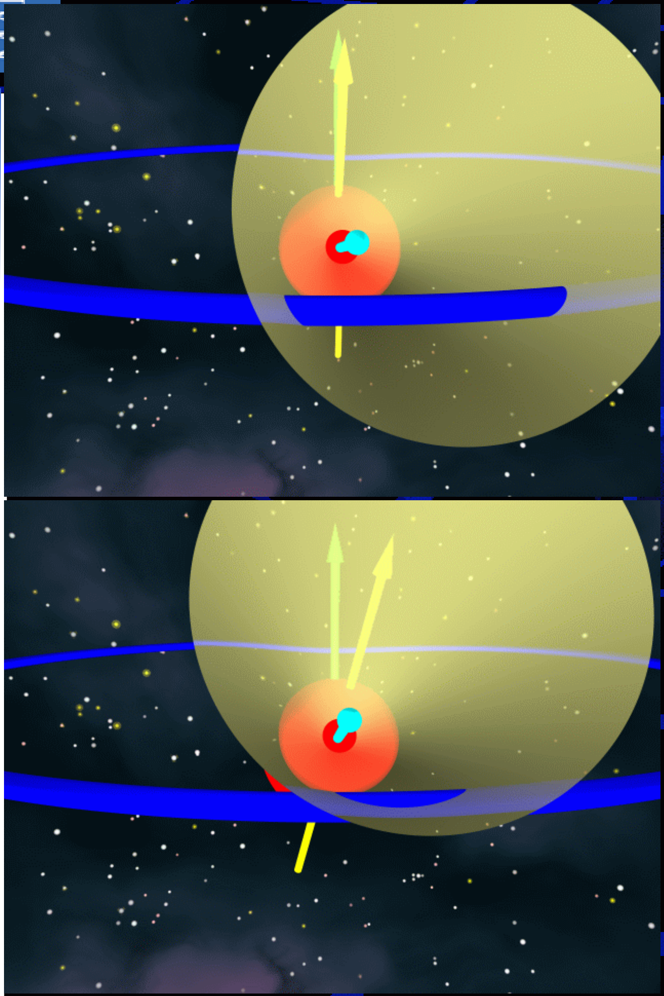
$$\Omega^p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \frac{1}{1-e^2}, \quad T_\odot = GM_\odot c^{-3}$$

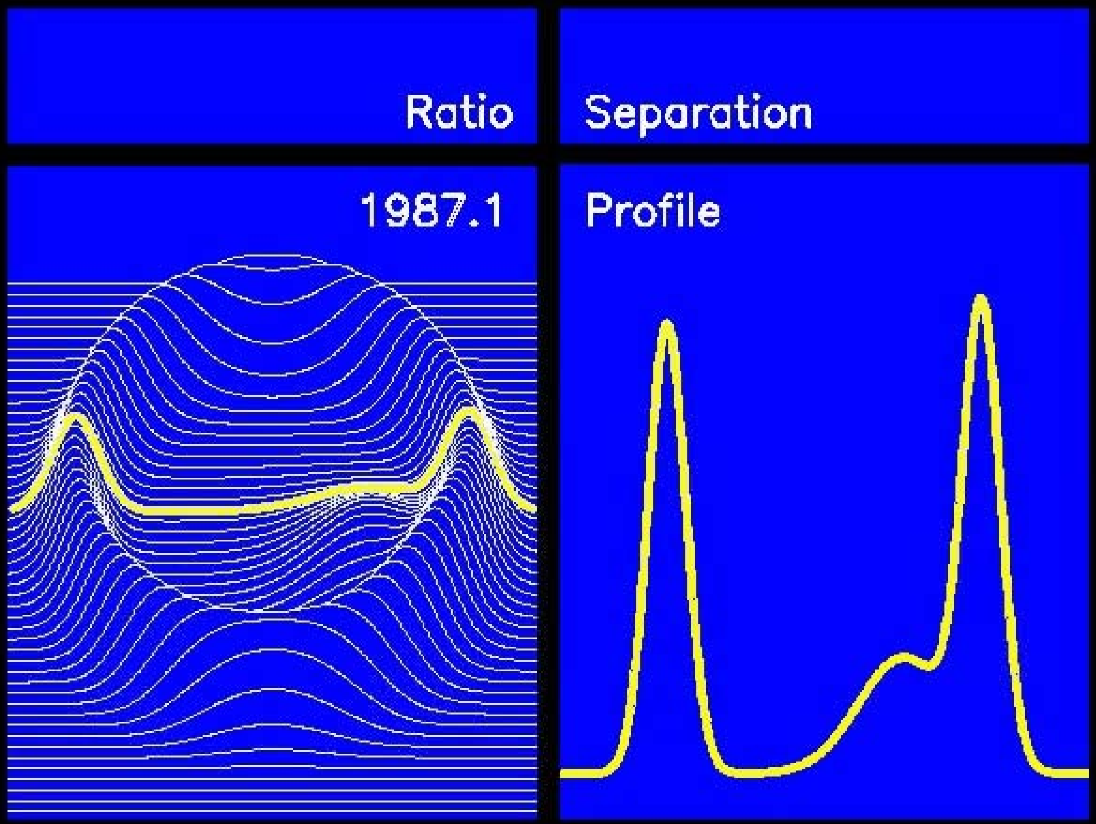
What effects do we expect to observe?

Effects of Geodetic Precession



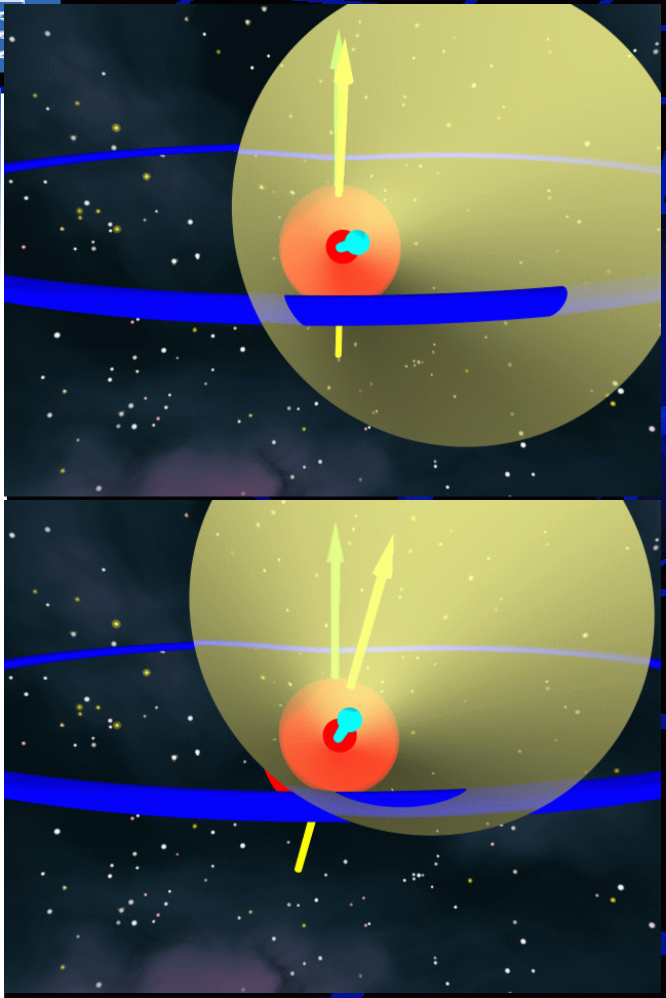
Effects of Geodetic Precession

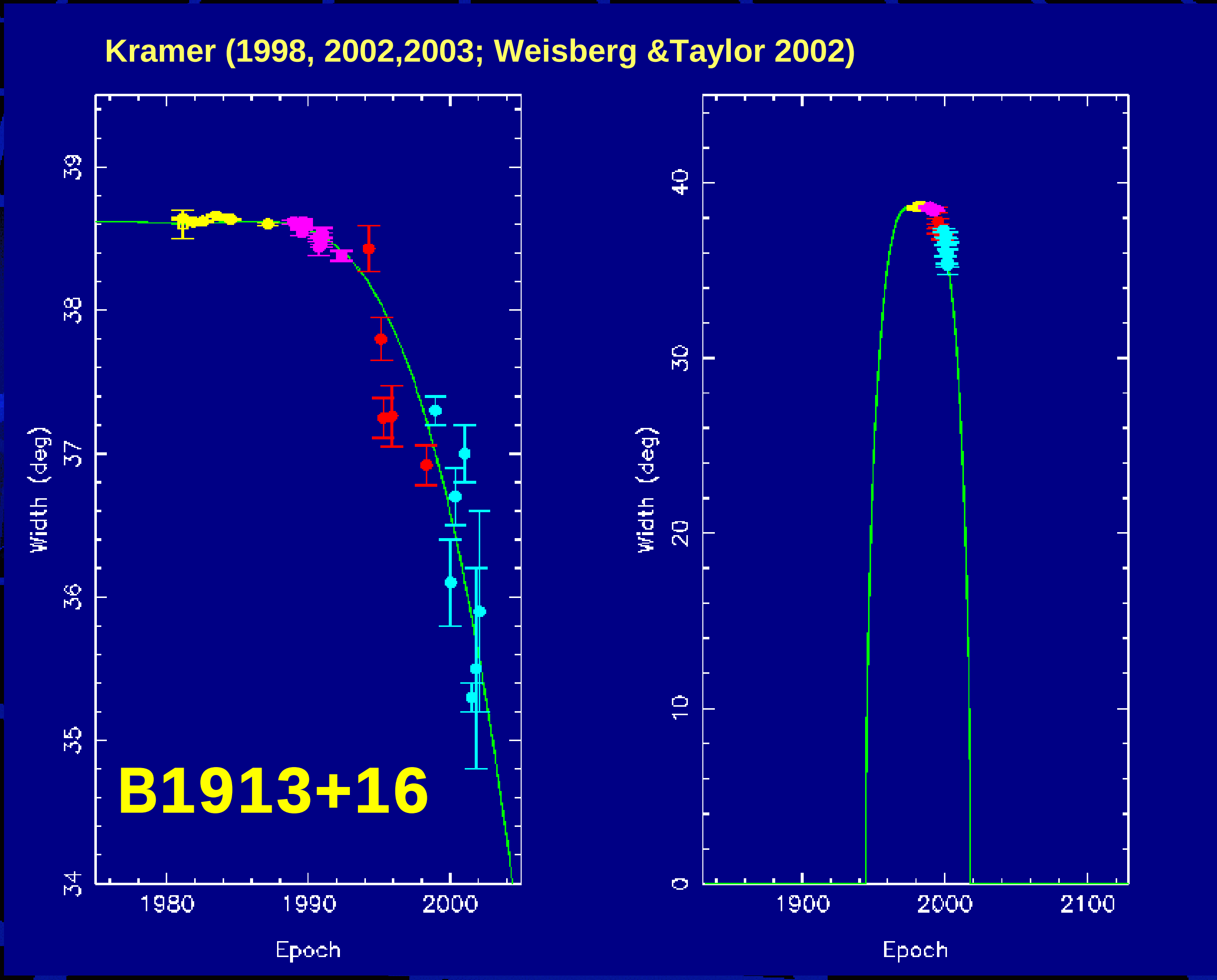




- Pulse shape changes!

Effects of Geodetic Precession

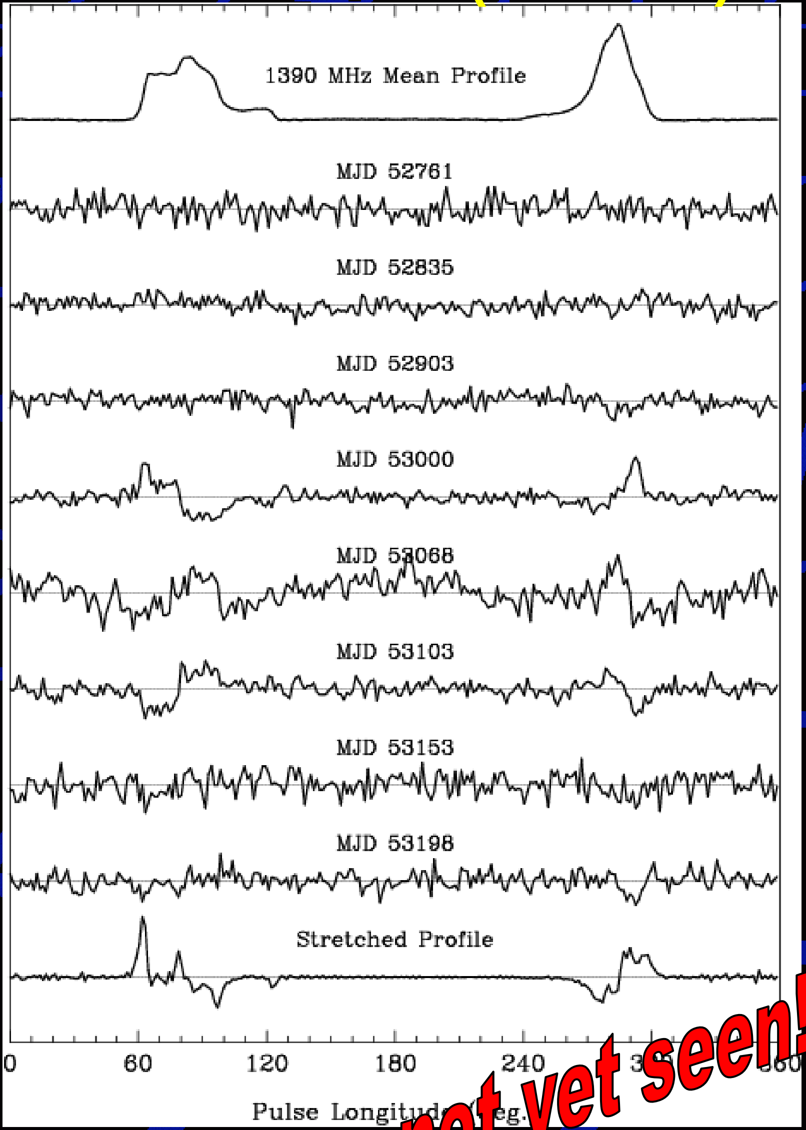




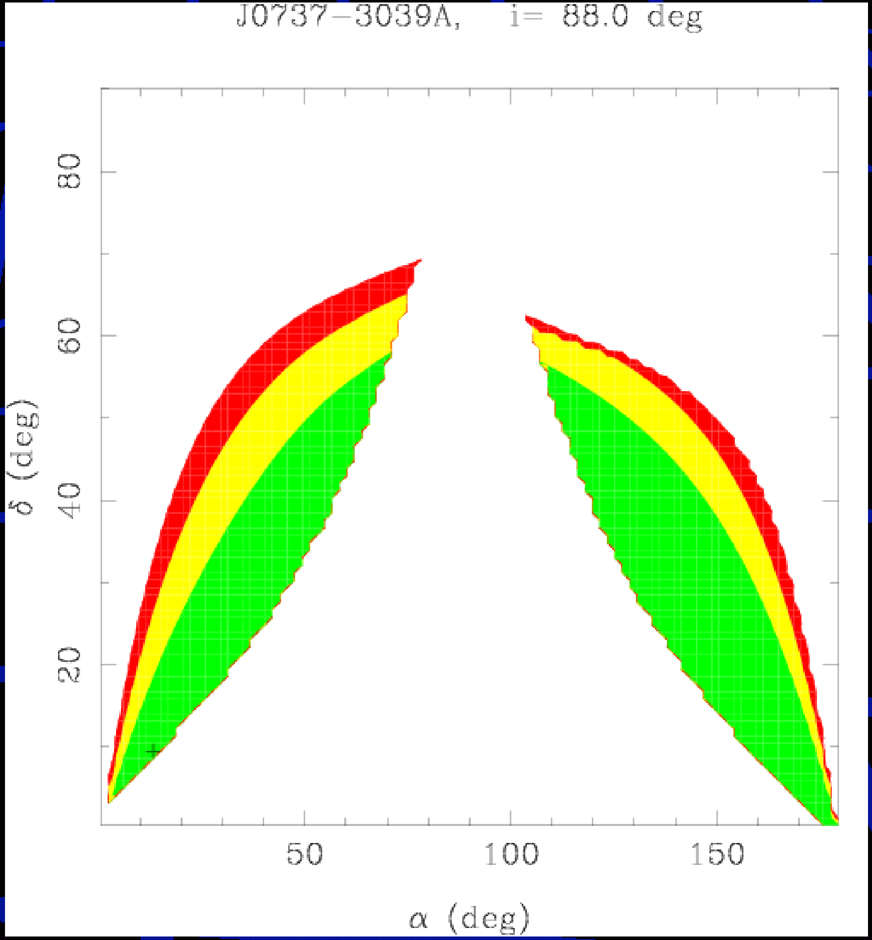
- **Pulse shape changes** (seen in B1913+16, B1534+12, J1141-6545!)
- **B1913+16 (Period 300 yr) will disappear ~2025!** (Kramer 1998)
- **Total precession period of J0737-3039 only 75 years!!**

Geodetic Precession in J0737-3039

Manchester et al. (submitted)



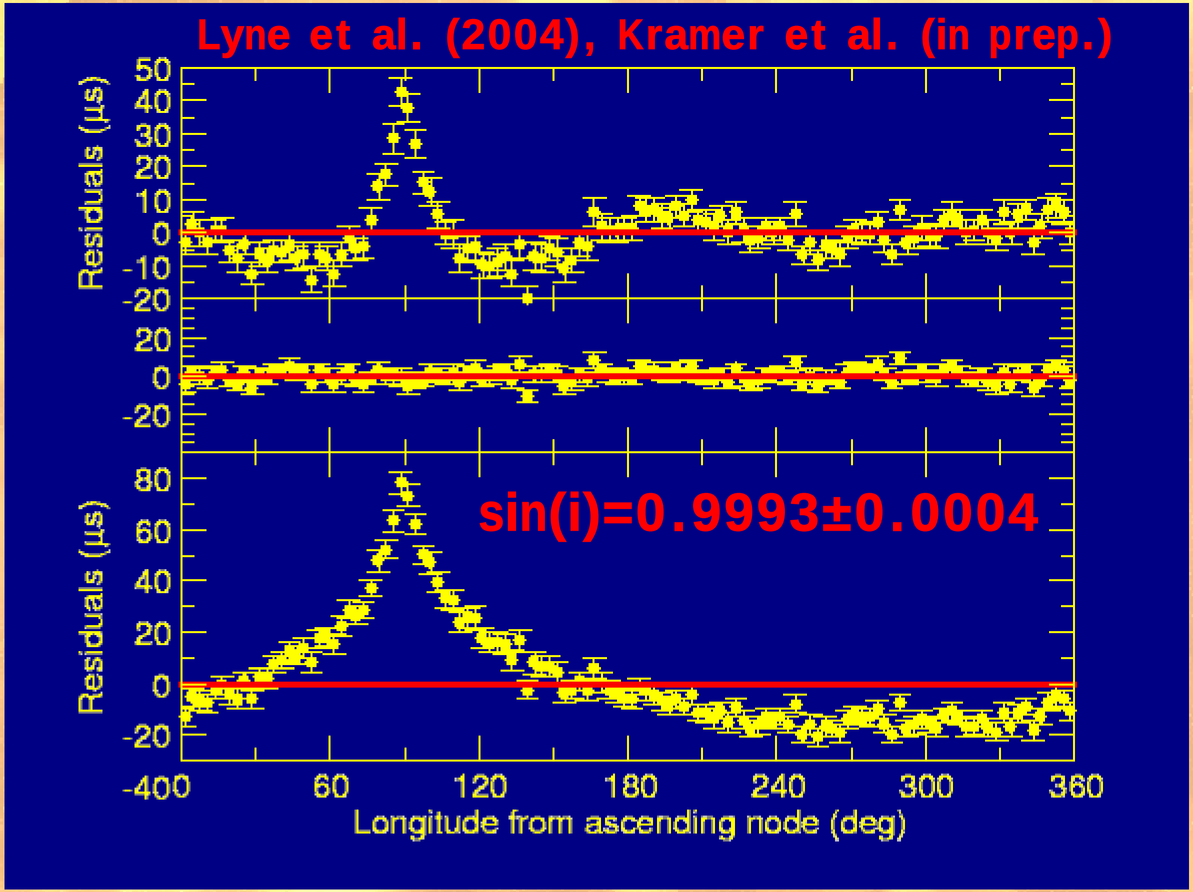
not yet seen!



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

Detection of Shapiro delay

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

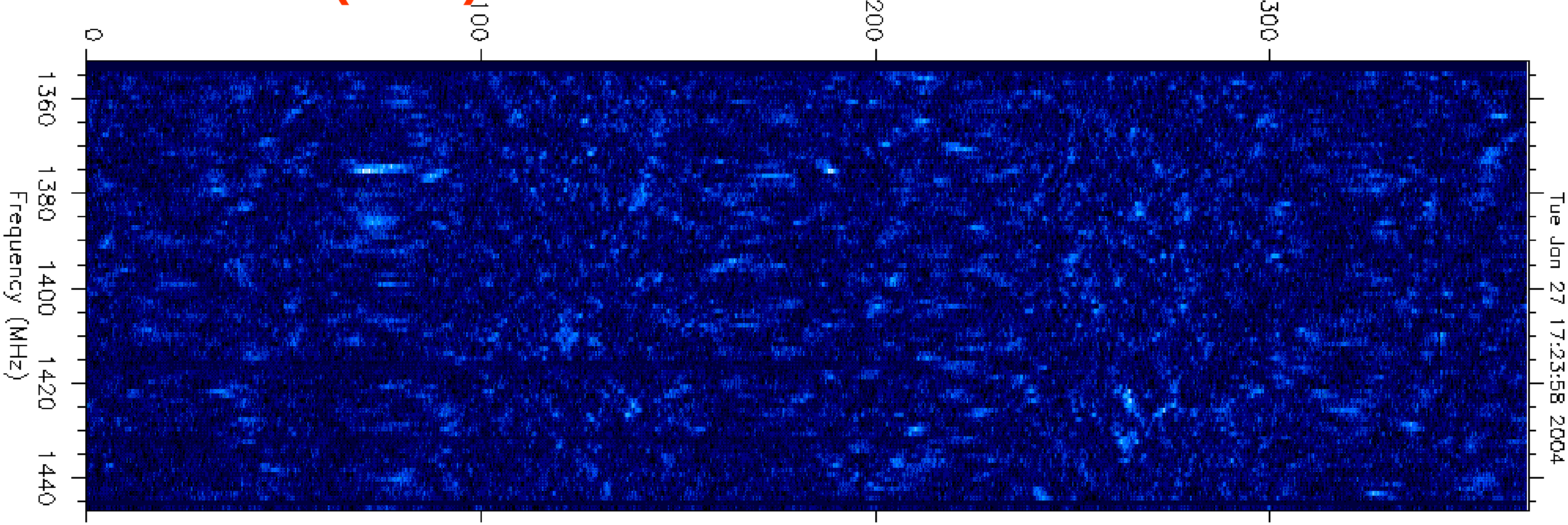


Compare to scintillation measurements…

Scintillation measurements

Intensity variation due to ISM depending on relative vel.:

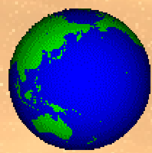
Ransom et al. (2004)



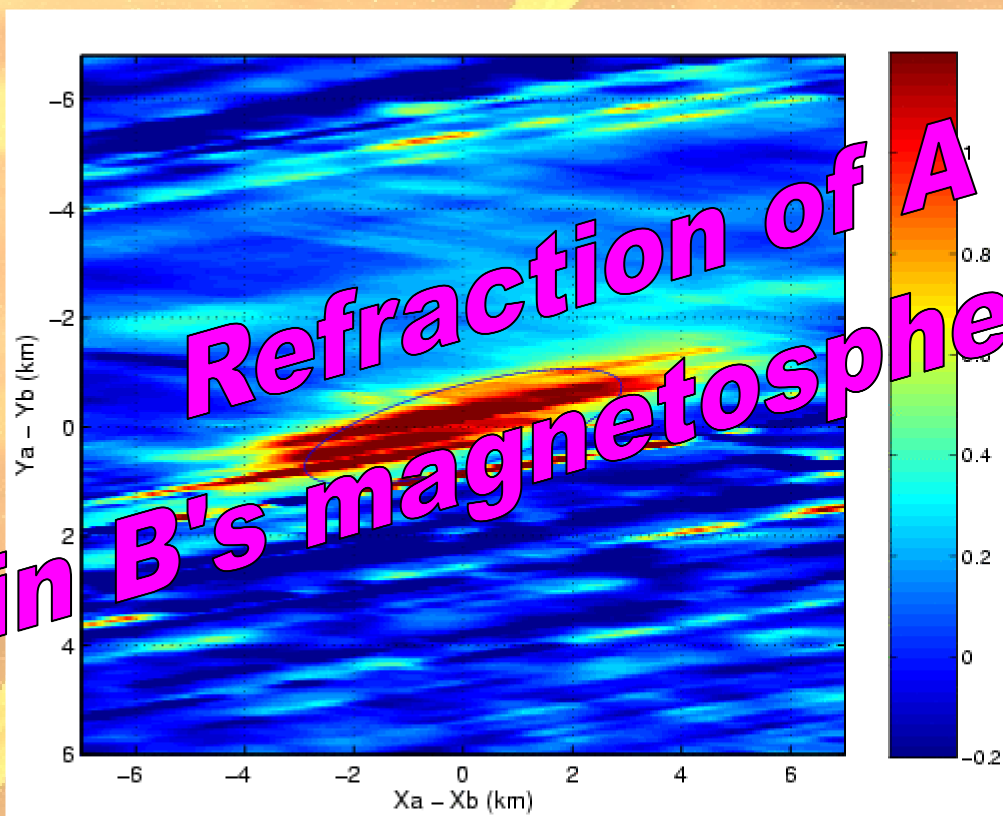
Scintillation measurements

Even better: at conjuction they see the same ISM

⇒ correlation of scintillation properties:

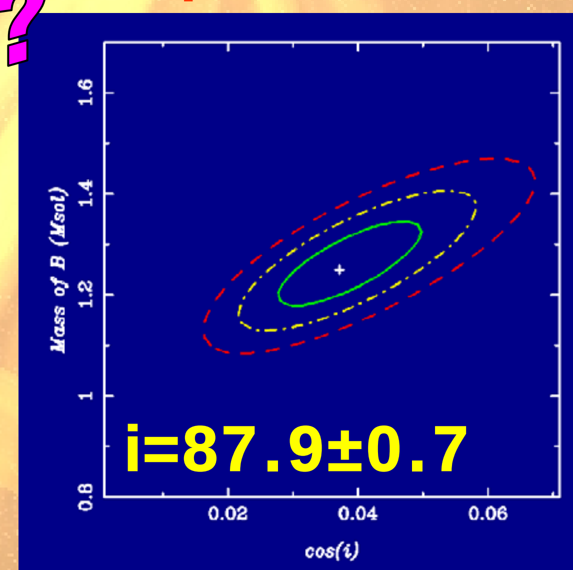


However, ISS result of i=90.26±0.13 inconsistent with Shapiro result:



Refraction of A in B's magnetosphere?

Coles et al.(in press)



Kramer et al.(in prep.)

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Binary pulsars as gravity labs: mass-mass plot

Elegant method to test any theory of gravity

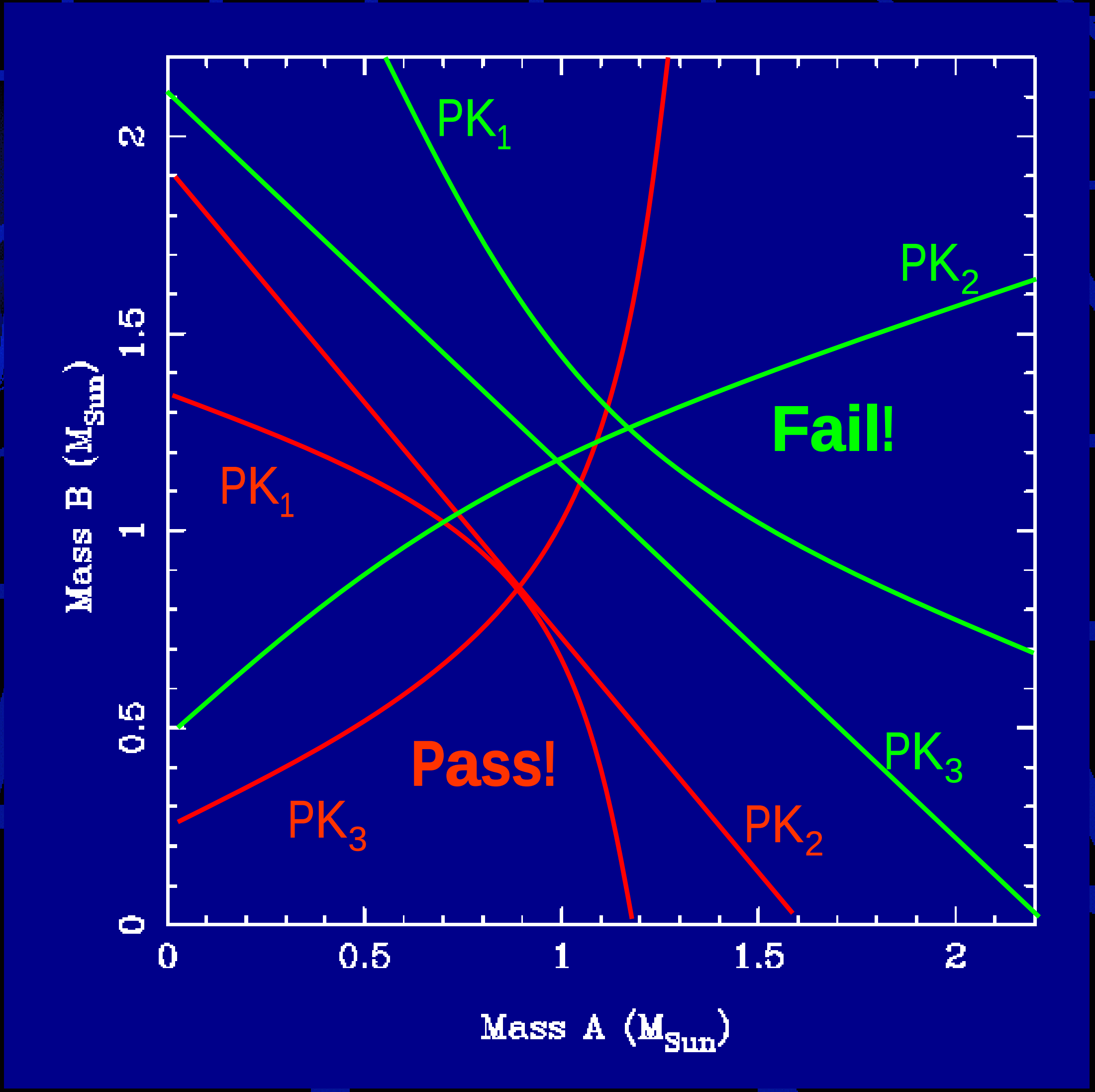
(see Damour & Deruelle 1986, Damour & Taylor '92)

All PK parameter can be written as function of only observed Keplerian and the masses of pulsar and companion

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

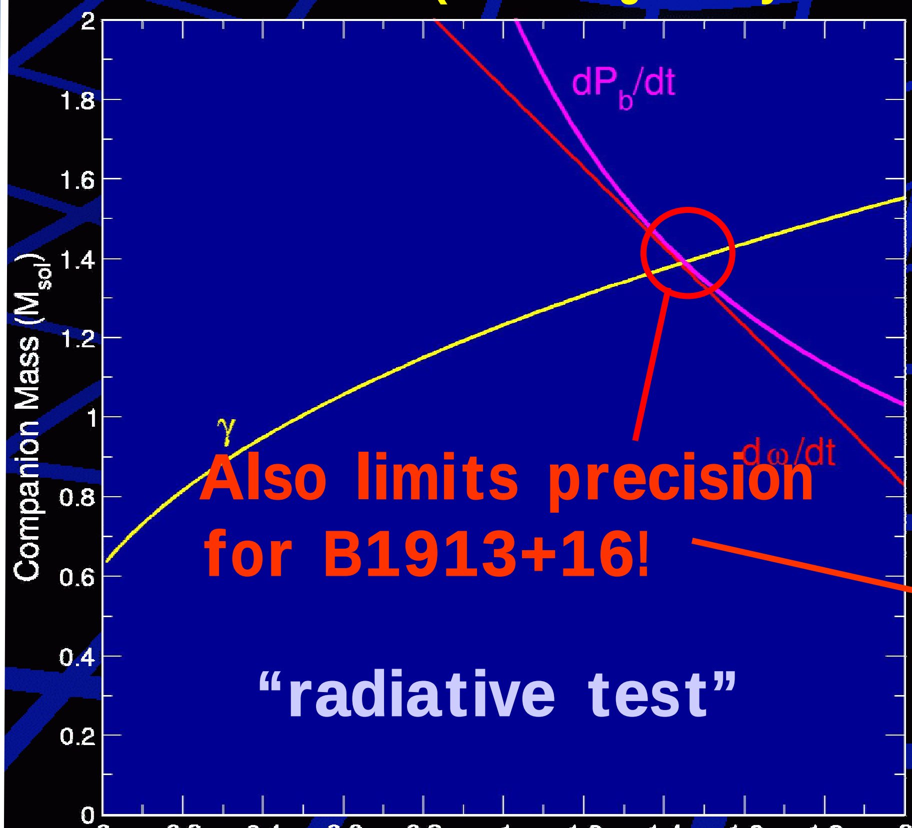
f, g depend on theory!

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



Binary pulsars as gravity labs: mass-mass plot

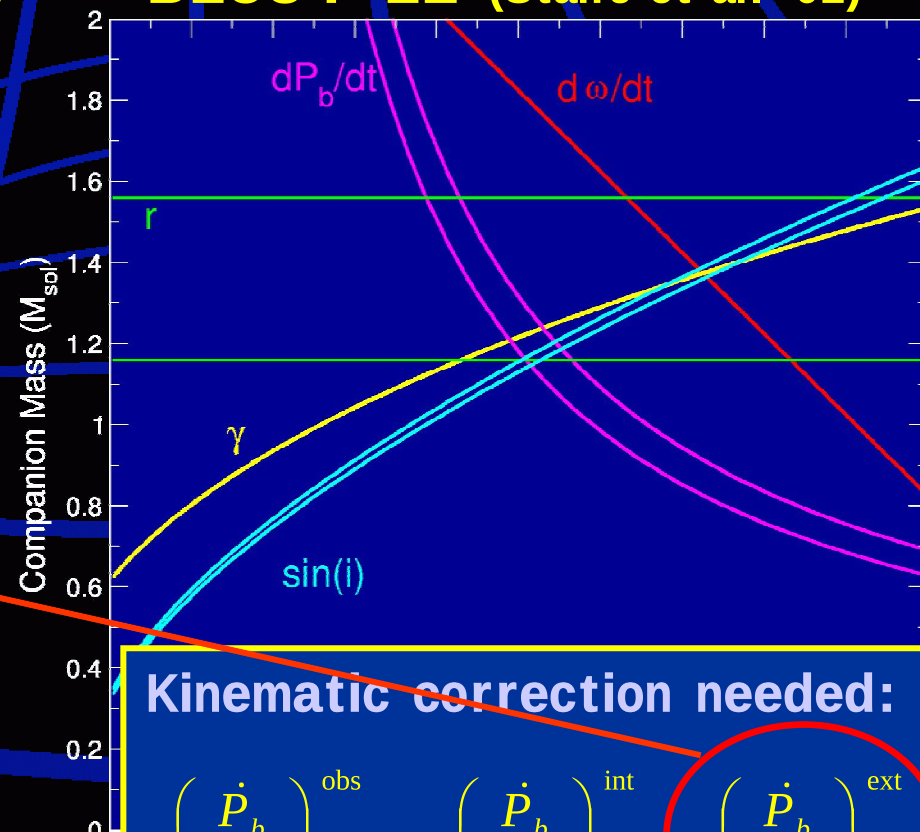
B1913+16 (Weisberg & Taylor '03)



Also limits precision for B1913+16!

"radiative test"

B1534+12 (Stairs et al. '02)

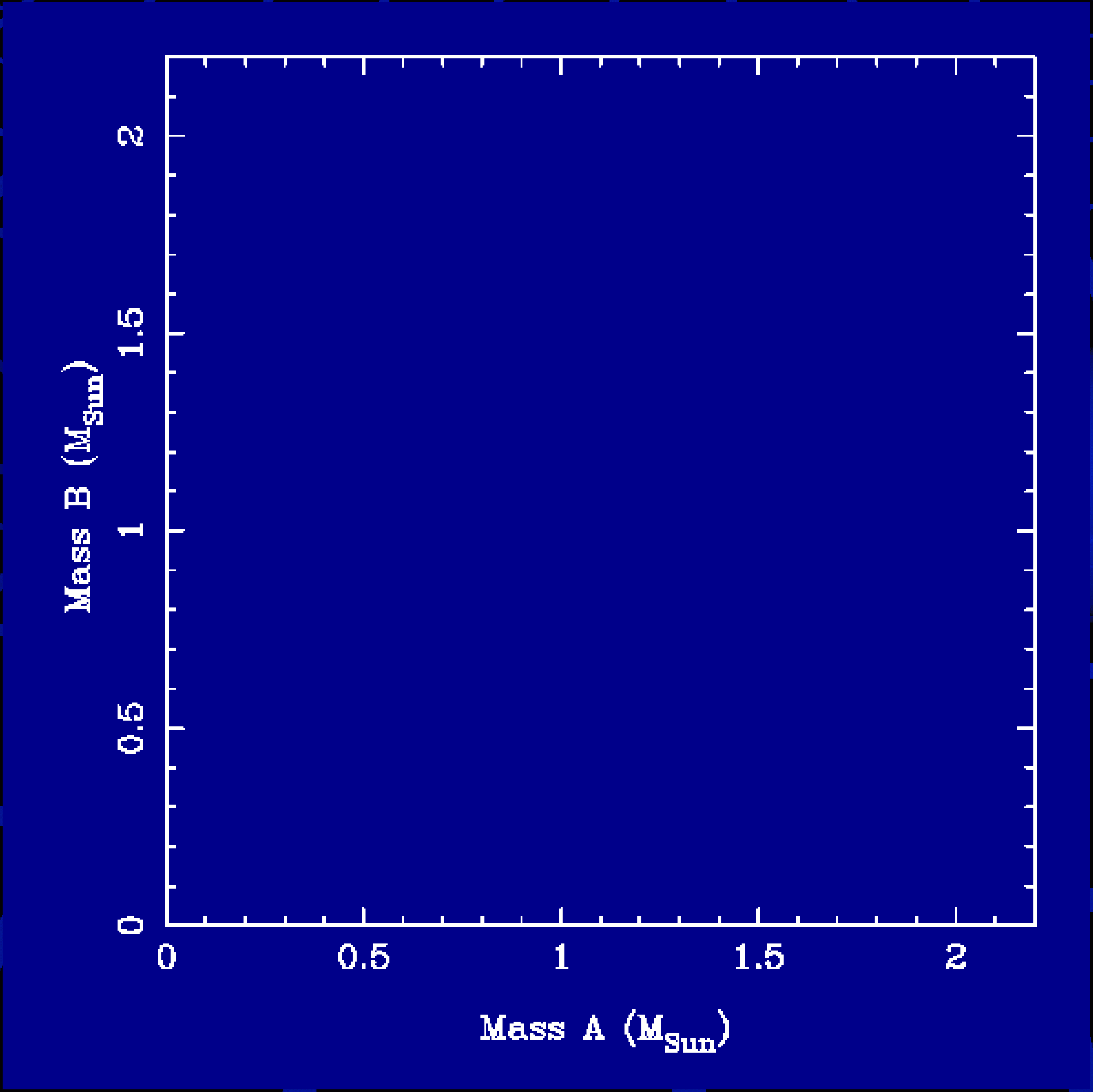


Kinematic correction needed:

$$\left(\frac{\dot P_b}{P_b}\right)^{obs} = \left(\frac{\dot P_b}{P_b}\right)^{int} + \left(\frac{\dot P_b}{P_b}\right)^{ext}$$

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

Tests of GR



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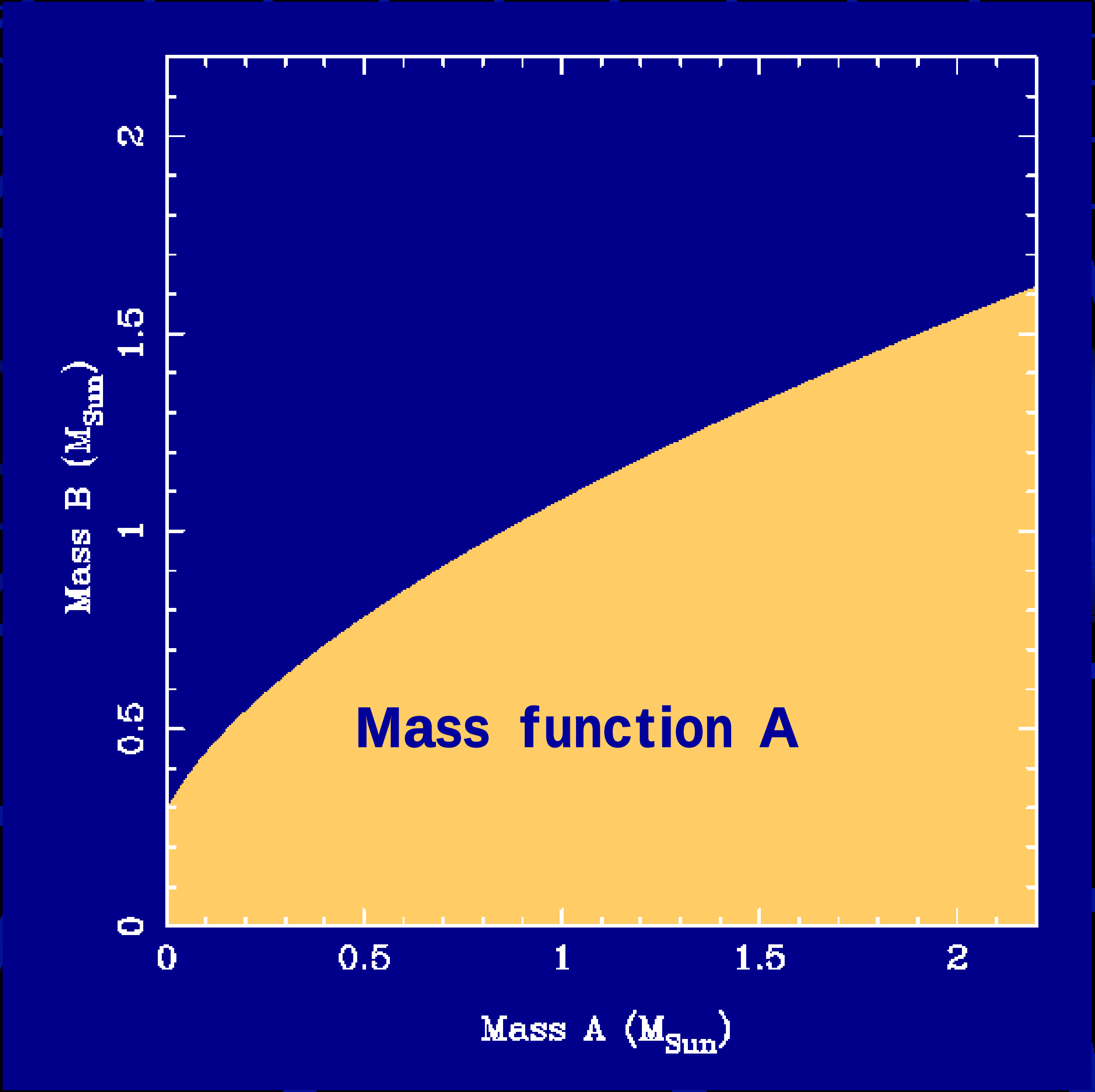

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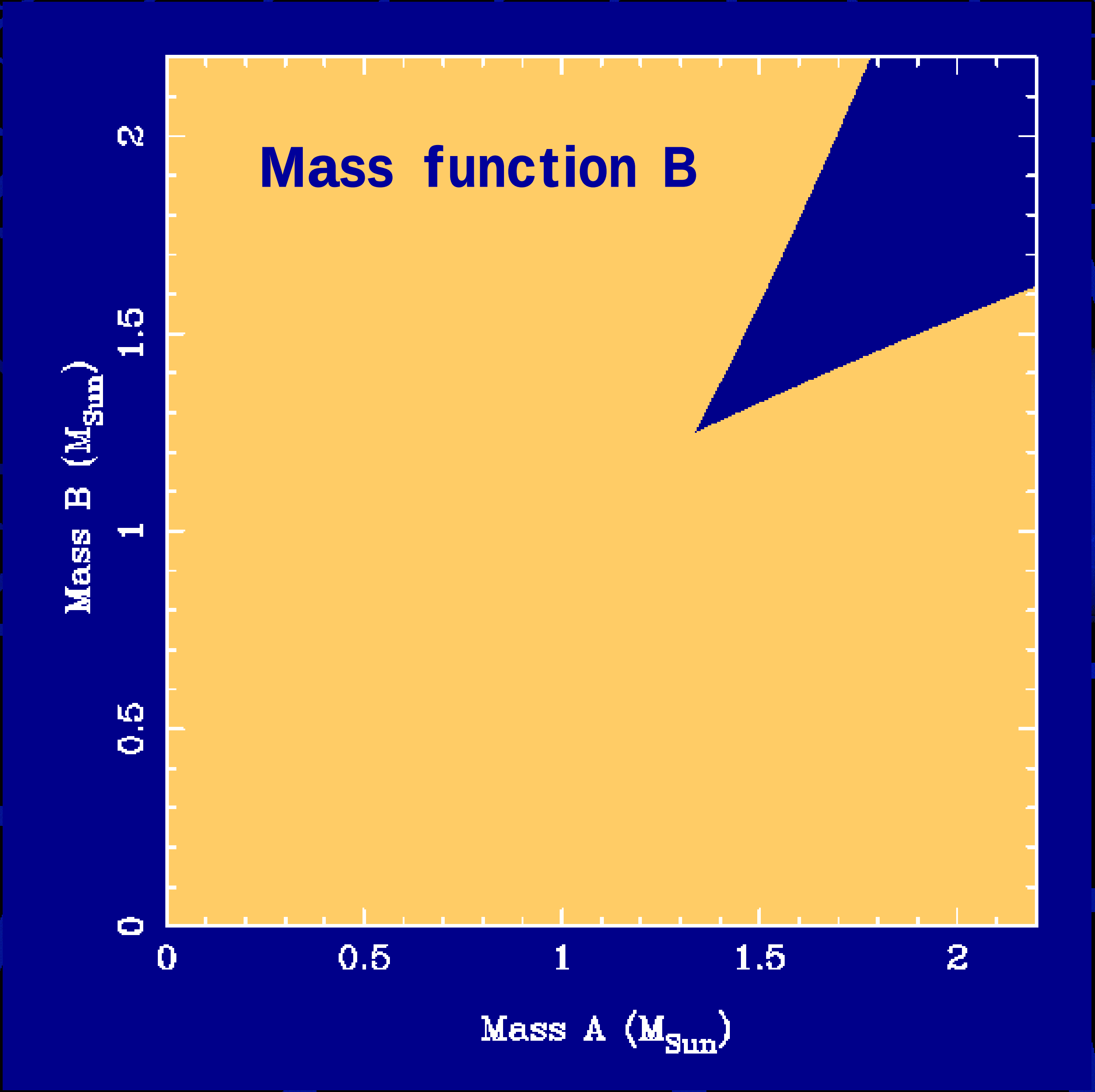
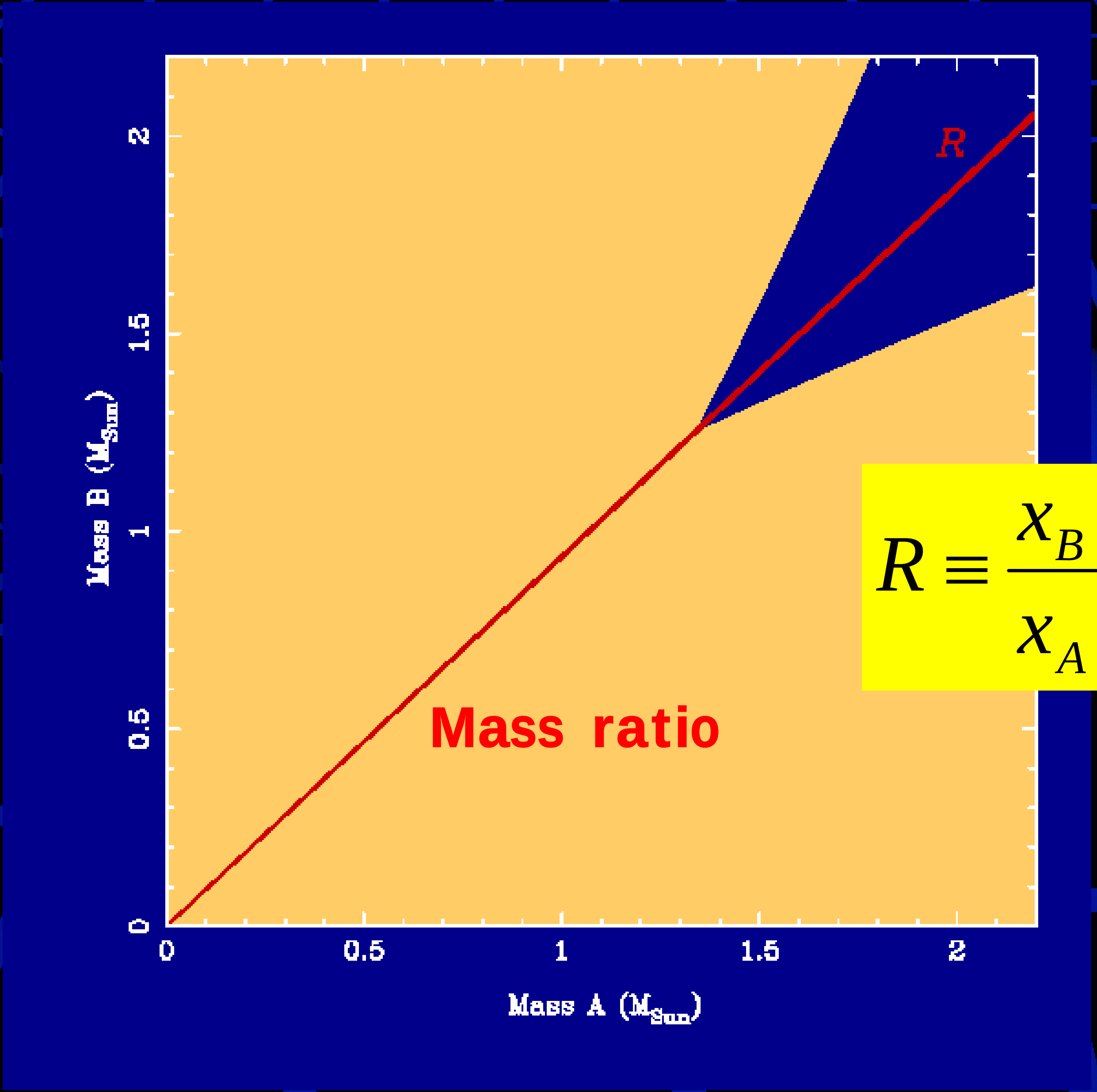
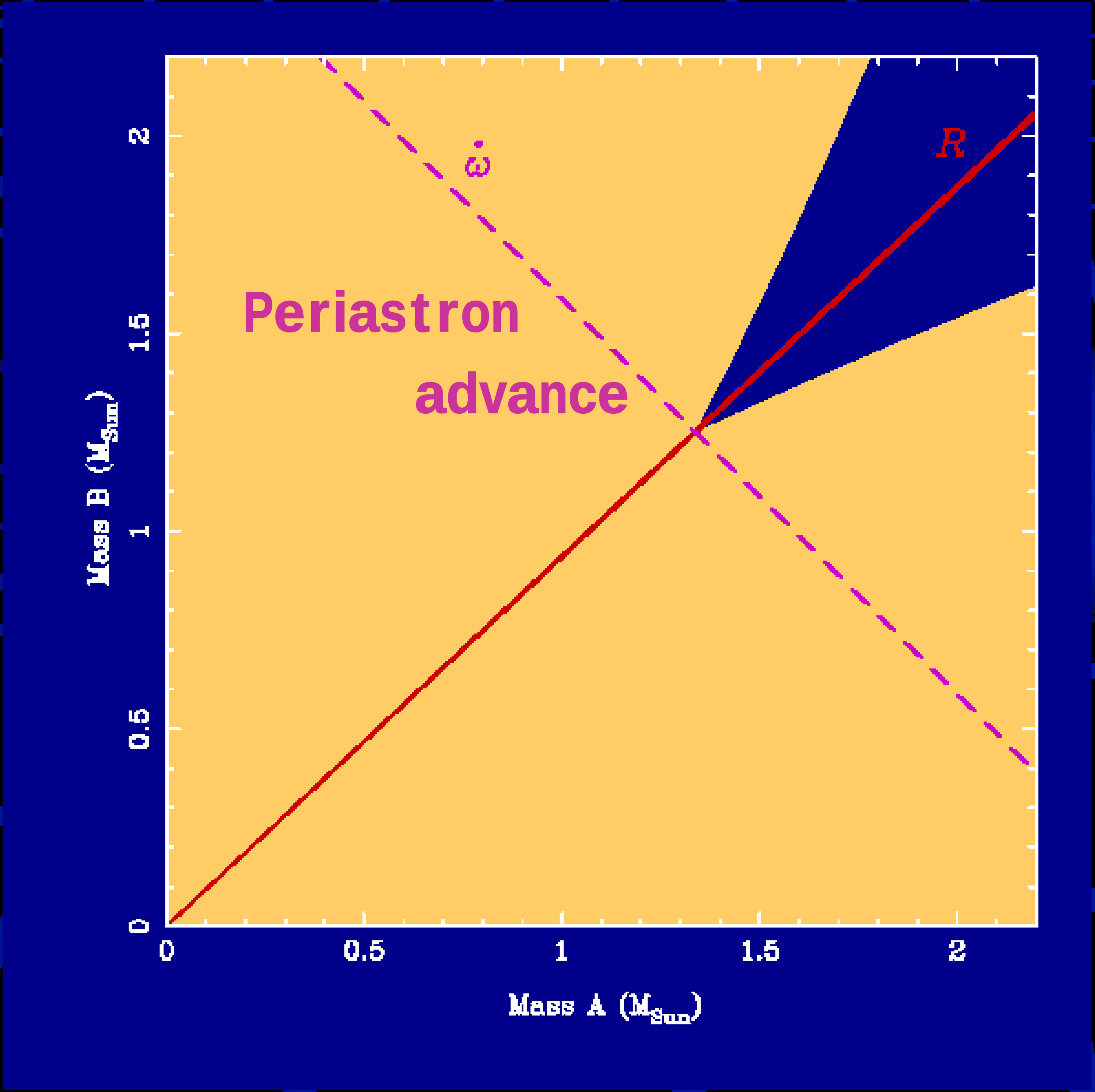


Tests of GR



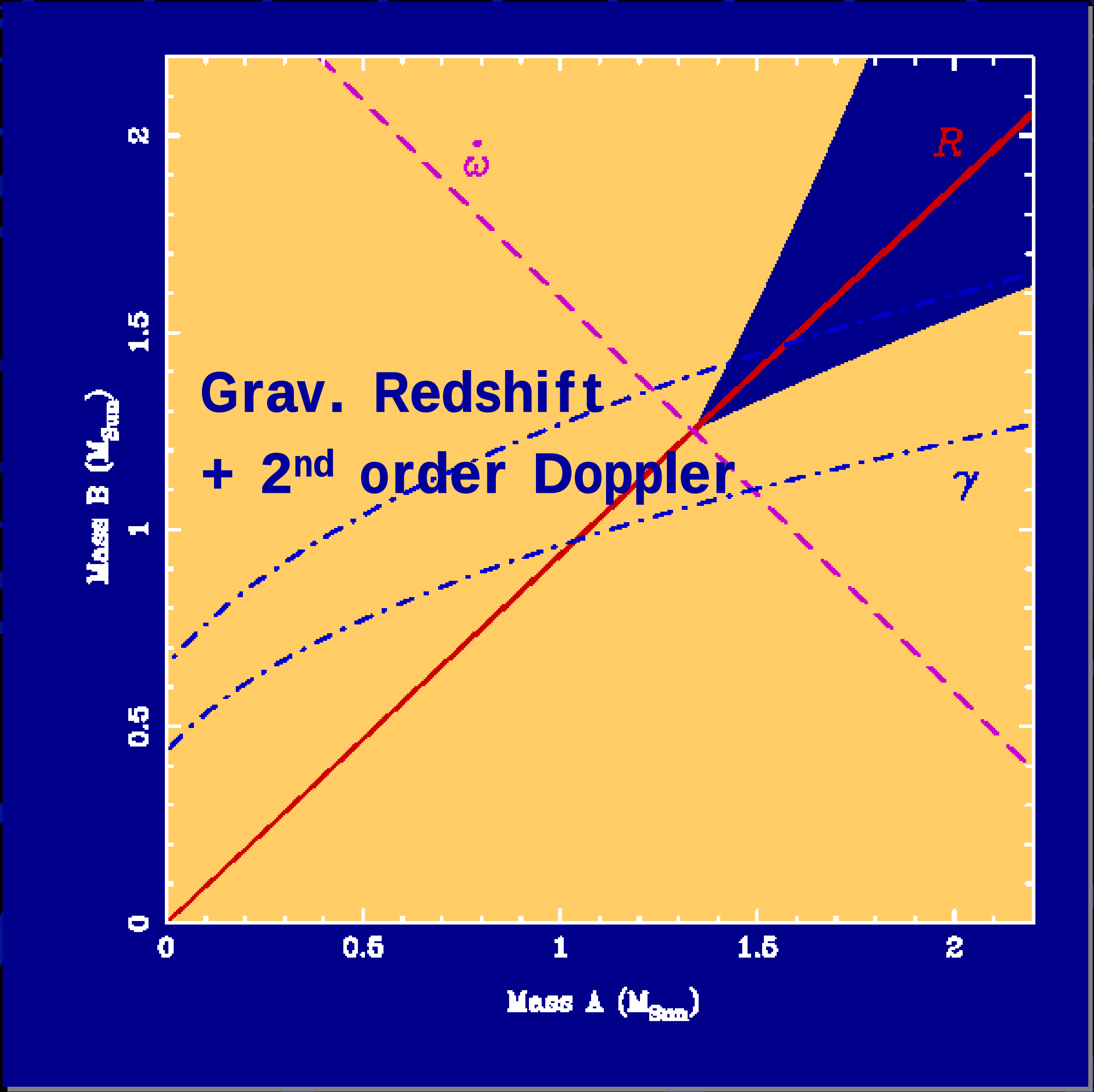
$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

Tests of GR

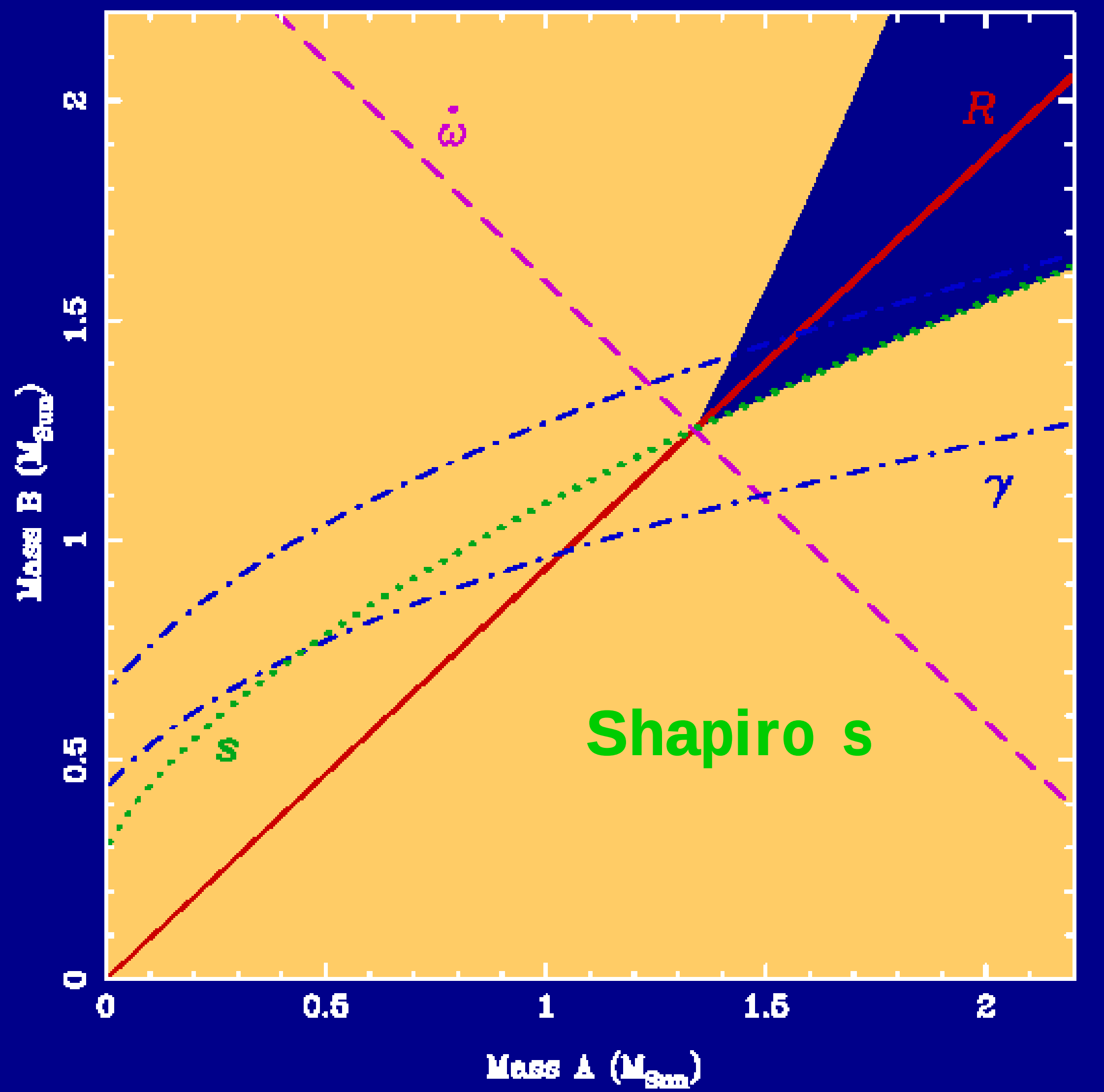


Periastron
advance
$\dot{\omega}$
R
Mass A (M_{Sun})
Mass B (M_{Sun})
0
0.5
1
1.5
2

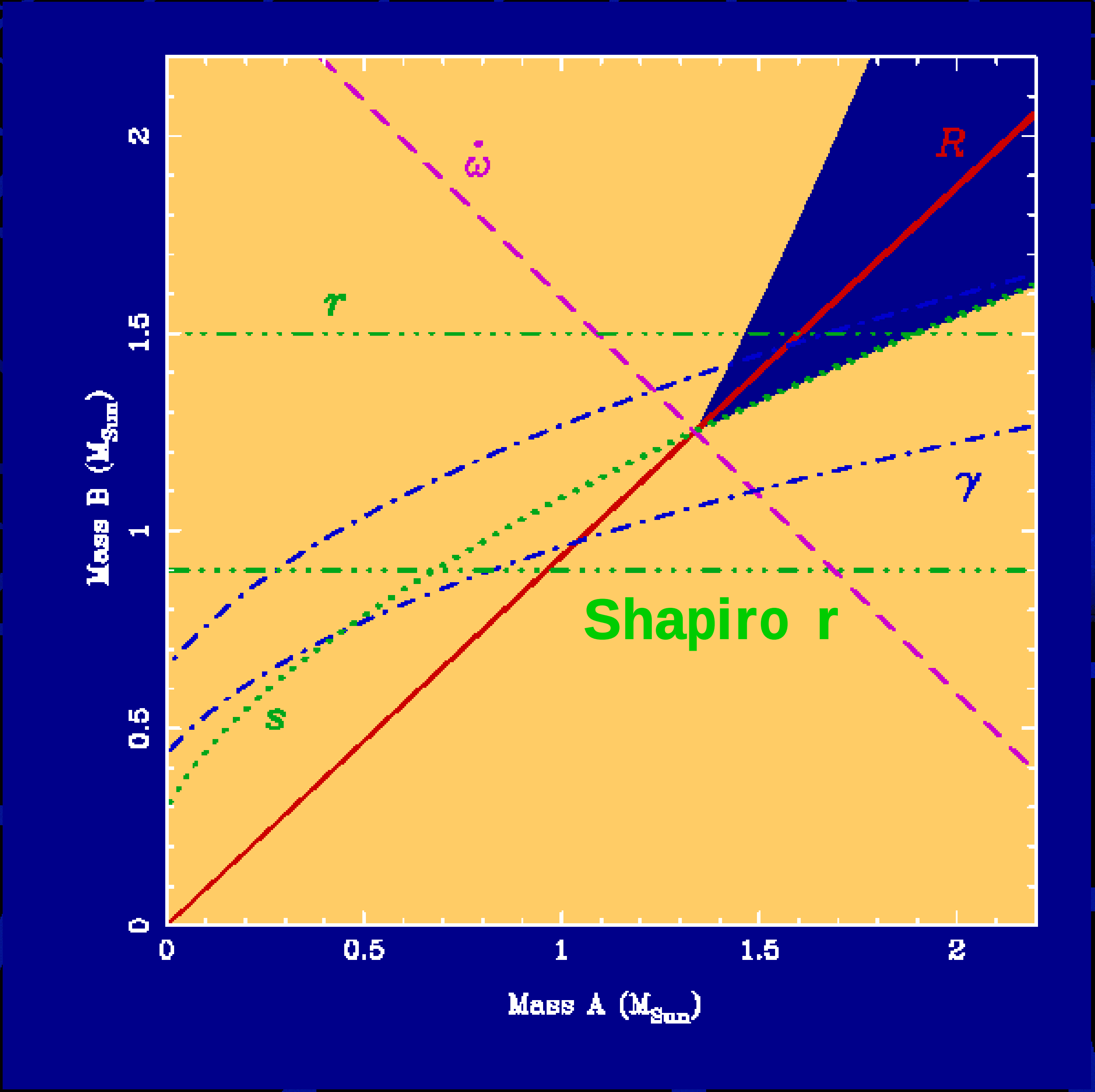
Tests of GR


Grav. Redshift
+ 2nd order Doppler
$\dot{\omega}$
R
γ
Mass A (M_{Sun})
Mass B (M_{Sun})
0
0.5
1
1.5
2

Tests of GR



Tests of GR



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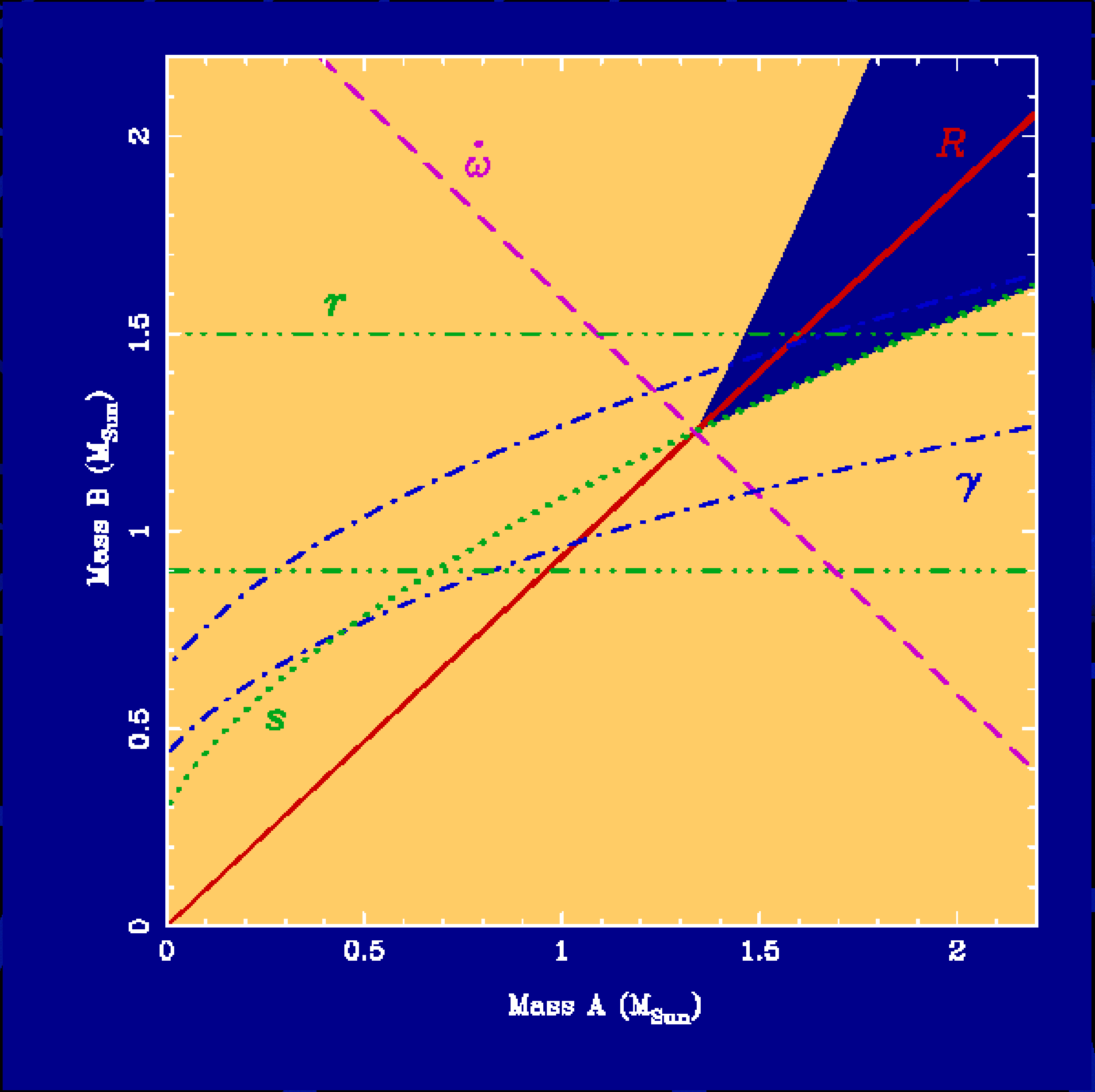

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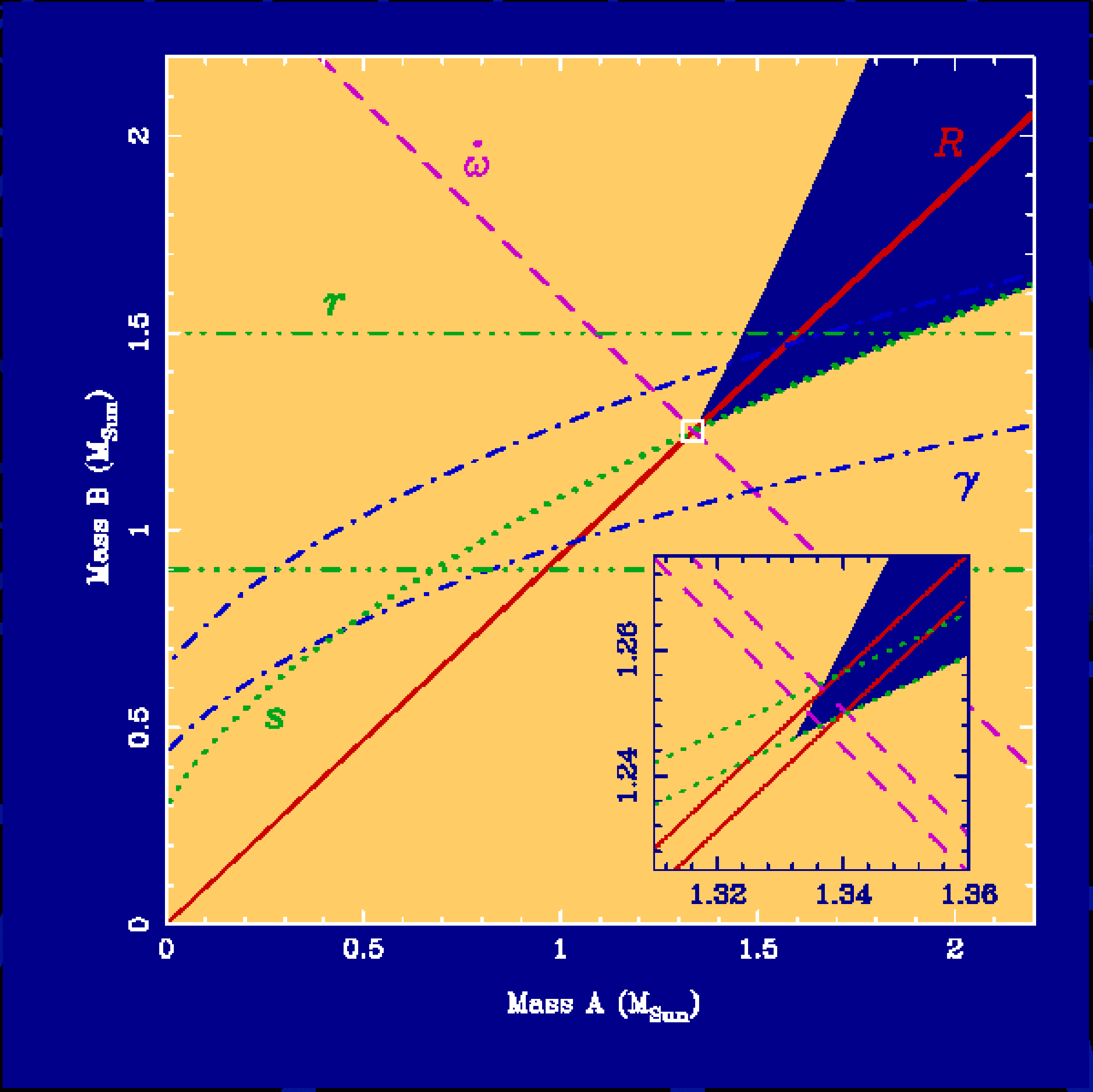
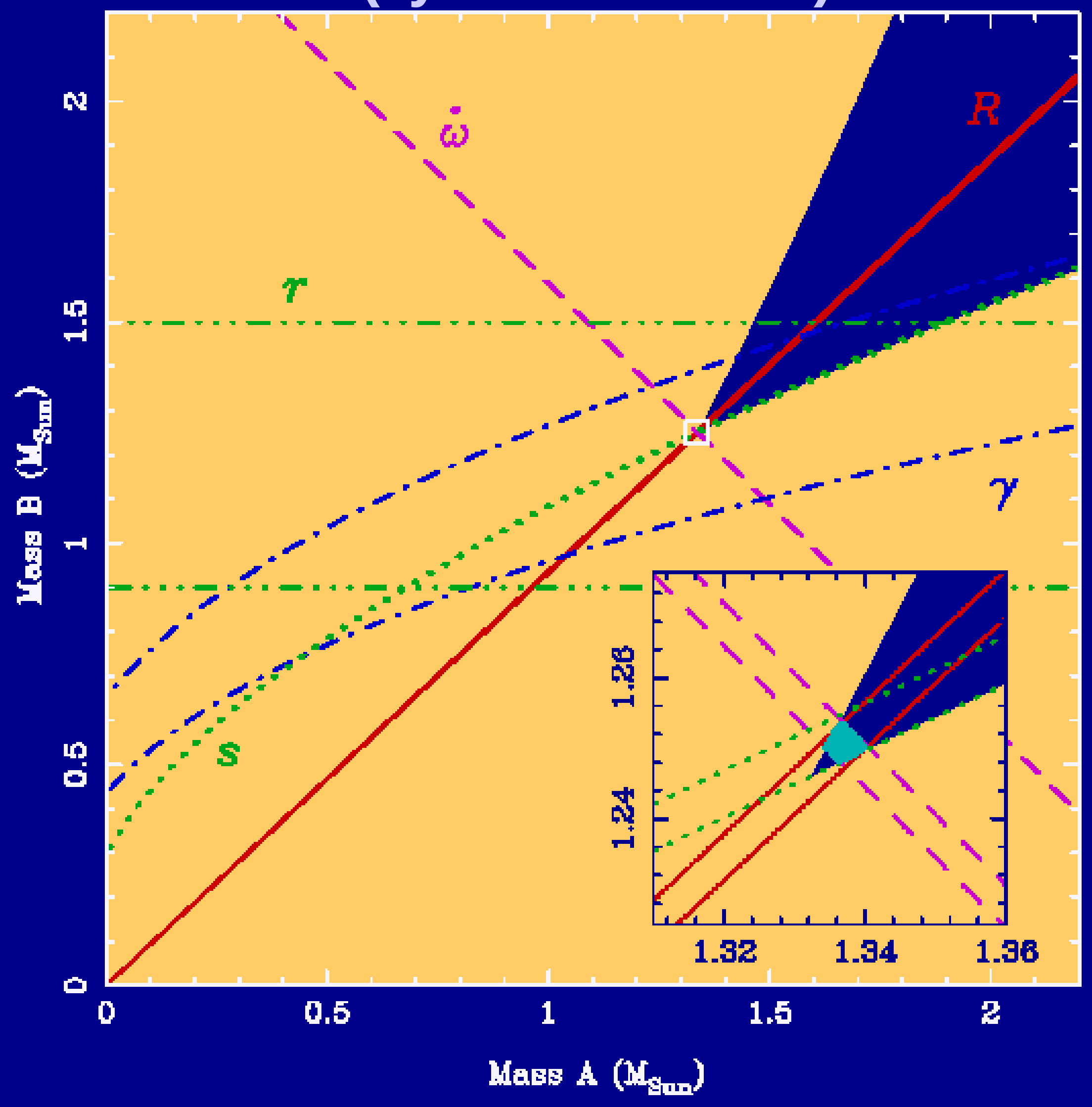
Tests of GR



Tests of GR

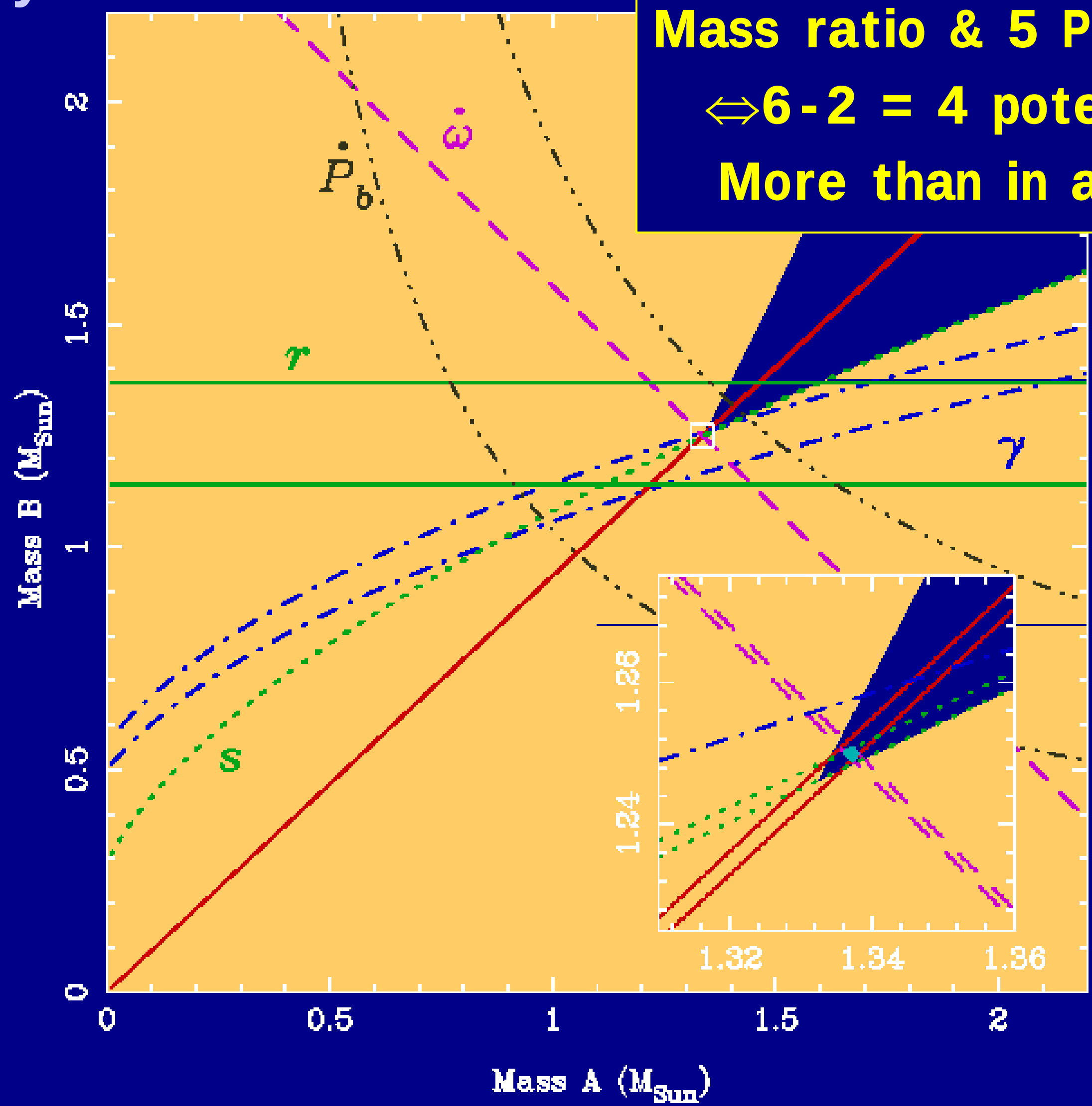
December 2003 (Lyne et al. 2004)



Tests of GR

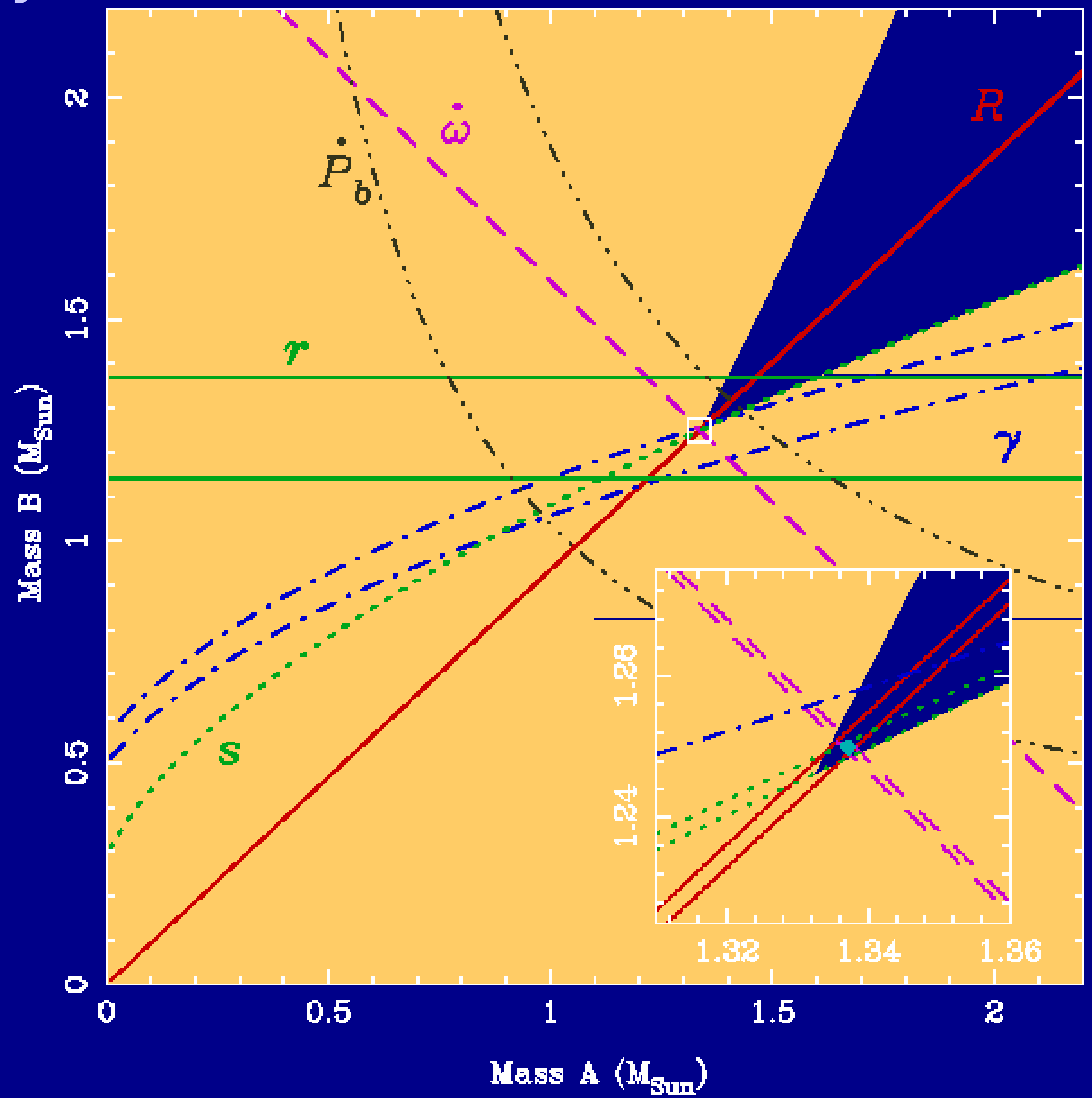
July 2004

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

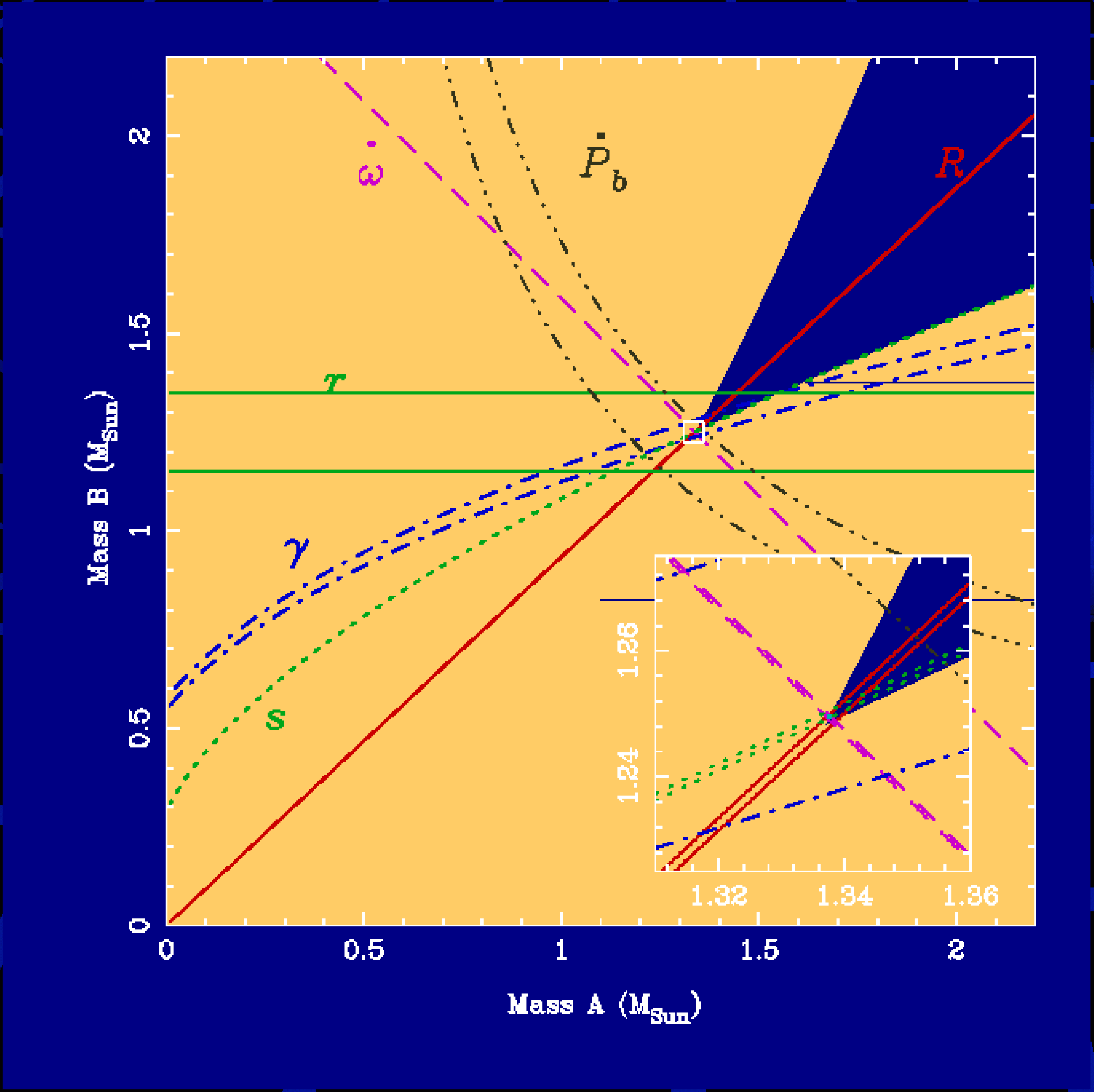


Tests of GR

July 2004



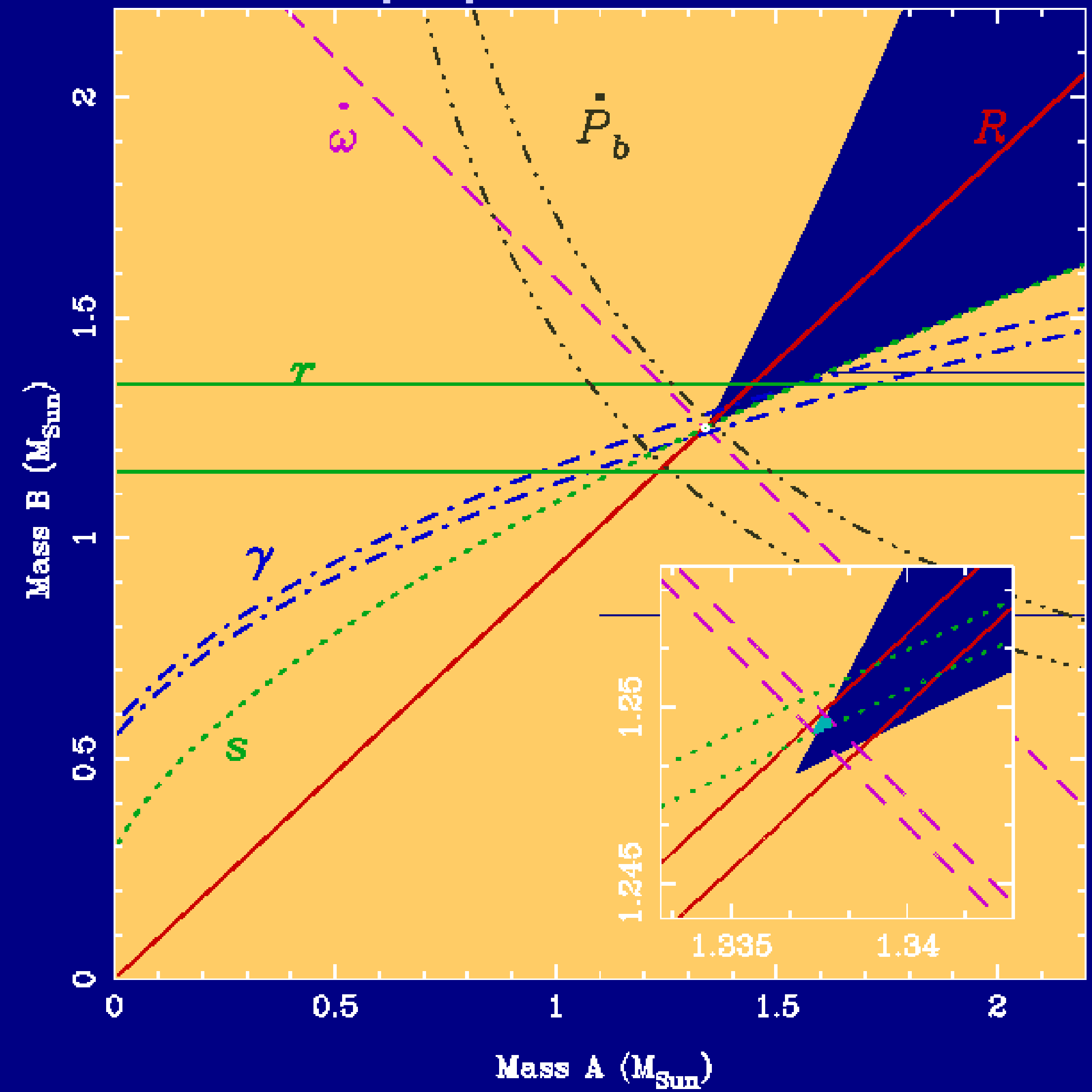
Tests of GR



$\dot{\omega}$
$\dot{P}_b$
R
r
γ
s
Mass B (M_{Sun})
Mass A (M_{Sun})
0
0.5
1
1.5
2
1.24
1.26
1.32
1.34
1.36

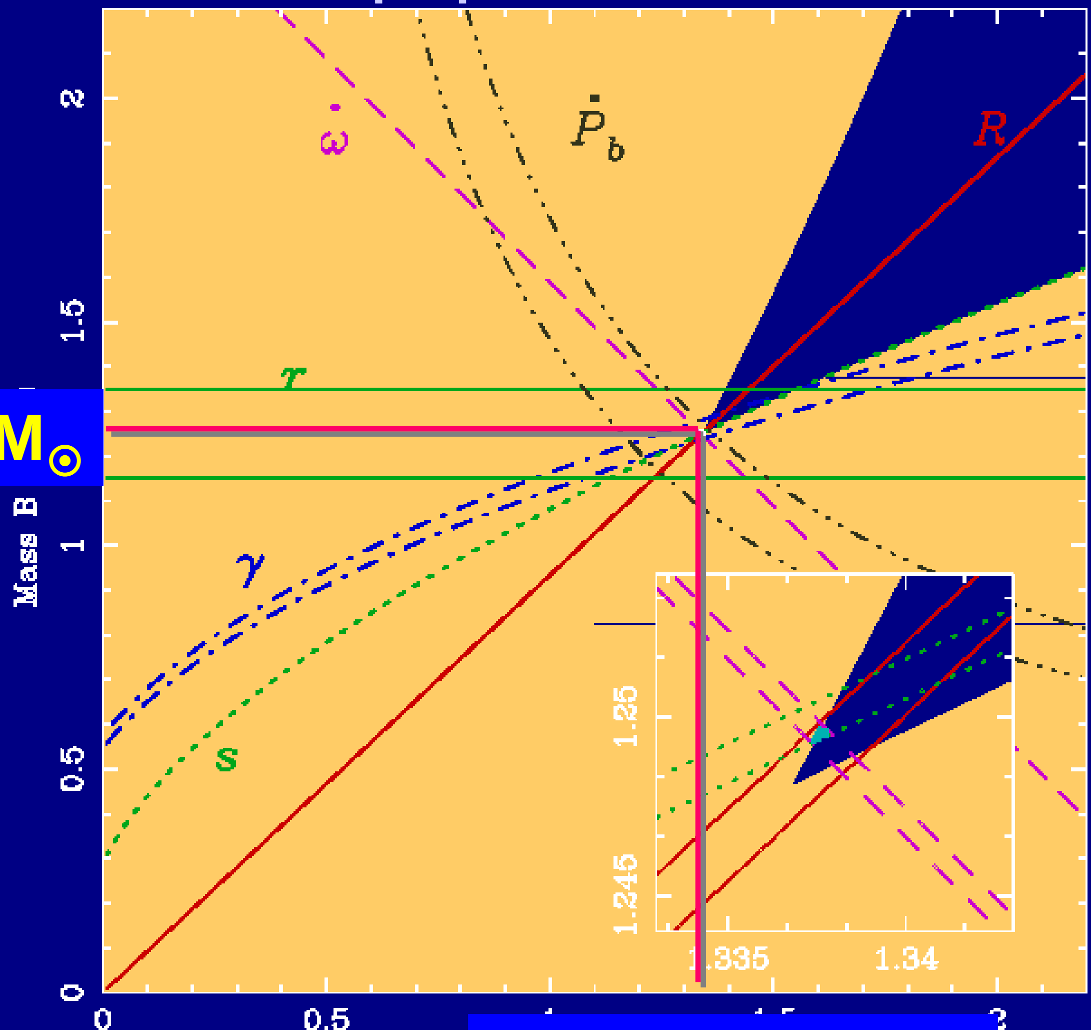
Tests of GR

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)$M_\odot$

Precision of 0.08%

Tests of GR

Based on:

R = 1.071±0.001 & $\dot{\omega}$=16.899±0.001 deg/yr (6×10^{-5})

Expected in GR:	Observed:
γ = 0.384 ms	γ = 0.387±0.006 ms (10^{-2})
$dP_b/dt = -1.24\times10^{-12}$	$dP_b/dt = (-1.19\pm0.08)\times10^{-12}$ (7×10^{-2})
r = 6.2 μs	r = 6.2 ±0.5 μs (10^{-1})
s = 0.9997	s = 0.9993 ±0.0004 (4×10^{-4})

$$\frac{s^{exp}}{s^{obs}} = 1.0004^{+0.0011}_{-0.0006}$$

precision of 0.1%!!

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

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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. Daumour & 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 g… o 1PN 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!

Significance of "R"

- Beyond 1PN approximation, used coordinate system and mass definition important:

$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} + O(c^{-4})$$

may deviate from straight line

- In >1PN, probably with precision much below that of PK parameters.

Future: Predicted precision

- Difficult to predict behaviour of mass ratio, R
- For PK parms, precision increases due to more but also more precise data:

(also depends on orbital orientation!)

$\Delta\dot{\omega}/\dot{\omega} \propto T^{-1.5}$: expected since Science paper factor 4
actual improvement a factor of 100!

$\Delta \sin i/\sin i \propto T^{-0.5}$: expected since Science paper factor 1.6
actual improvement a factor of 10!

$\Delta\gamma/\gamma \propto T^{-1.5}$: expected since Science paper factor 4
actual improvement a factor of 10!

Further expected scaling: $\Delta(dP_b/dt)/(dP_b/dt) \propto T^{-2.5}$

$\Delta\delta_\theta/\delta_\theta \propto T^{-2.5}$

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Will we be able to use dP_b/dt?

- Orbit shrin
- Observed v

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

Observed: -1.36×10^{-16}

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

Upper limit on velocity from timing: 17 km/s
Velocity from scintillation: 66 km/s?!?

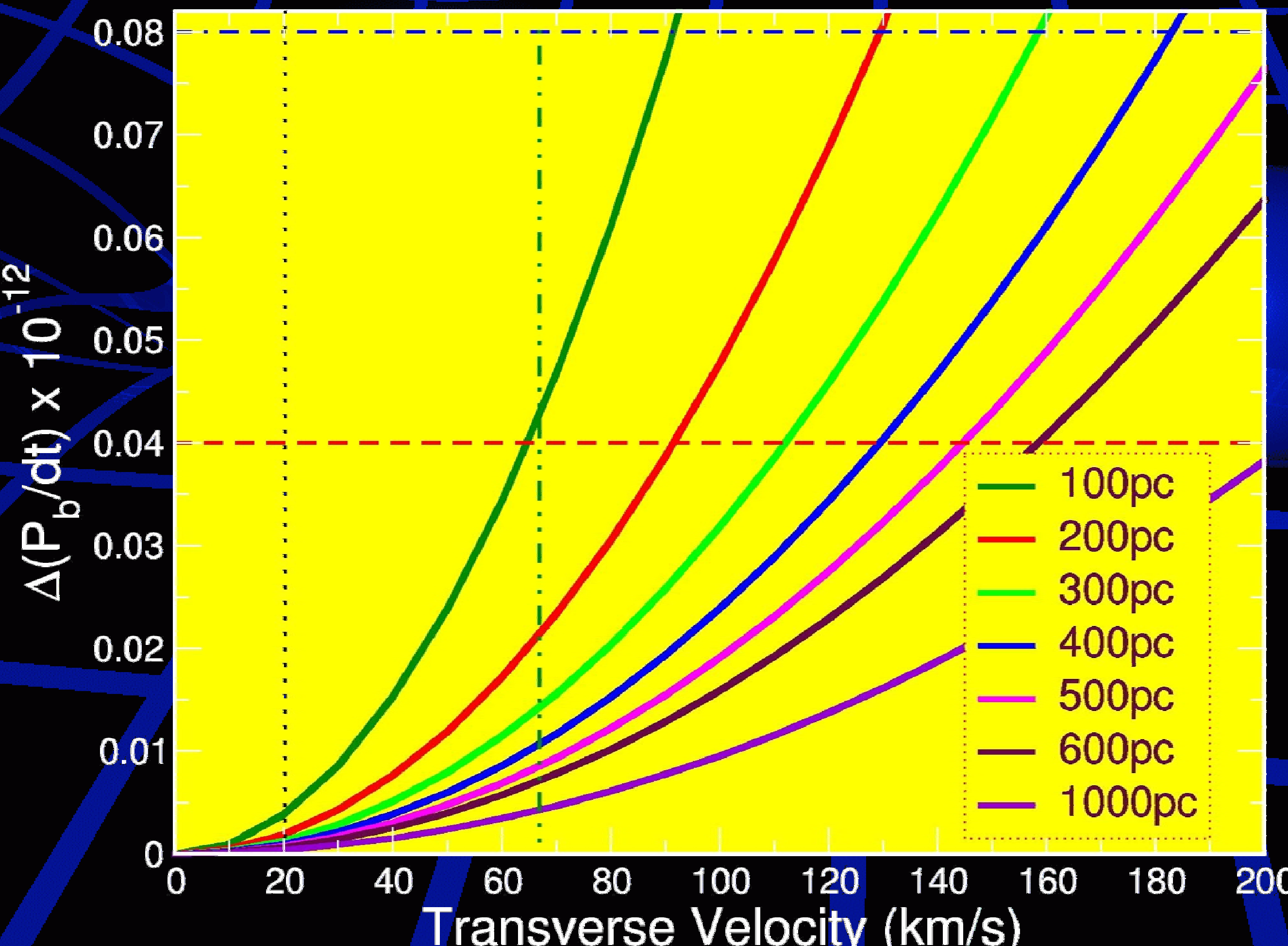
Transverse motion (17km/s): 5.25×10^{-20}
Transverse motion (66km/s): 7.91×10^{-19}
$\Rightarrow$ **Needed correction: < 1%**

Dominated by transverse speed: VLBI obs.underway

Will we be able to use dP_b/dt?

yes!

- **Summary of transverse motion:**



Newly measurable PK parameters

- Relativistic orbit is deformed
- Two, rather than a single eccentricity needed (DD86):

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

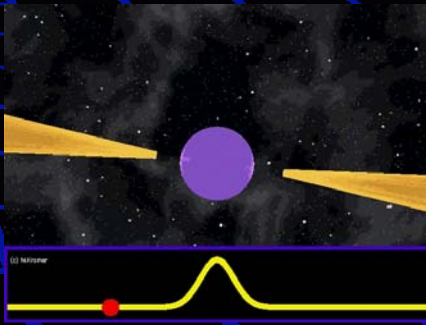
while the PK parameter

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

may be measurable in a few years:

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

Aberration



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

$$\Delta_A = A\{\sin[\omega + A_e(u)] + e\sin\omega\} + B\{\cos[\omega + A_e(u)] + e\cos\omega\}$$

with PK parameters A and B which are usually absorbed in Roemer delay as:

$$x_{\rm obs} = (1+\varepsilon_A)\, x_{\rm int}$$

$$e_{\rm obs} = (1+\varepsilon_A)\, e_{\rm int}$$

$$\delta_\theta^{\rm obs} = \delta_\theta^{\rm int} - \varepsilon_A$$

$$\delta_r^{\rm obs} = \delta_r^{\rm int} - 3\varepsilon_A,\ \varepsilon_A \equiv \frac{A}{x}$$

Damour & Taylor (1992)

However...

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Aberration & Geodetic Precession

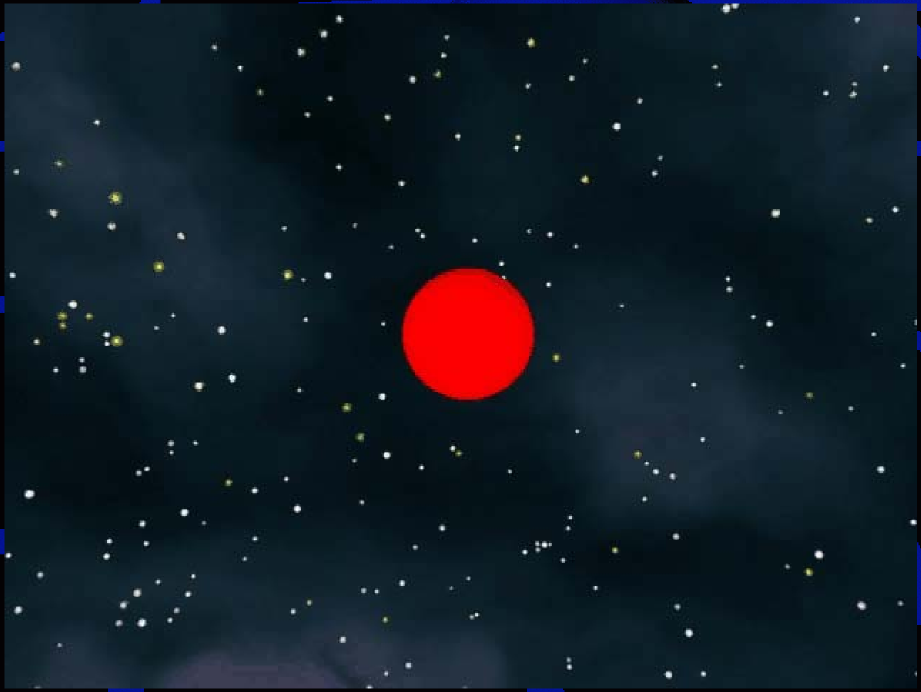
- **Aberration parameters will change due to geodetic precession:**

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

Damour & Taylor (1992)

leading to different geometries, so that A & geometry may be determined! Expected:

A = -0.365μs x geometry!!



But spin-orbit coupling is likely to visible in other ways too…

Spin contributions

We have seen that spin-coupling is large:

- PK parameters are only expected to meet in a single point of mass-mass diagram IF spin contributions are negligible
- For instance, periastron advance is usually only used in 1PN approximation ignoring spin
- Formally, spin-orbit coupling enters at 1PN level!
- For binary pulsars however, numerically they are of size as 2PN effects (Wex 1995)

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Spin contributions

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

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

Geometry dependent

Neutron star dependent

Assuming 'canonical' values: 1PN = 16.9 deg/yr

2PN = 0.0004 deg/yr

14 x 1913+16's value! SpinA= 0.000 deg/yr

already at 0.001deg/yr!

Not easy! Need two other parms with similar precision… Worth trying…

Neutronstar structure

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

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

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!!!

Summary

- Beautiful laboratory for plasma physics
- Invaluable for studying pulsar magnetospheres
- Unique test-bed for relativistic gravity
- Most over-constrained system already
- Only system with constraint independent of self-field
- Most precise tests already (0.1%)
- More PK parameter/effects potentially measurable:
  - Measurement of orbital deformation
  - Measurement of aberration
- Measurement of 2nd order PN effects

  (Lightbending, How do Kepler's laws look like??)
- Moment of inertia & Equation of State

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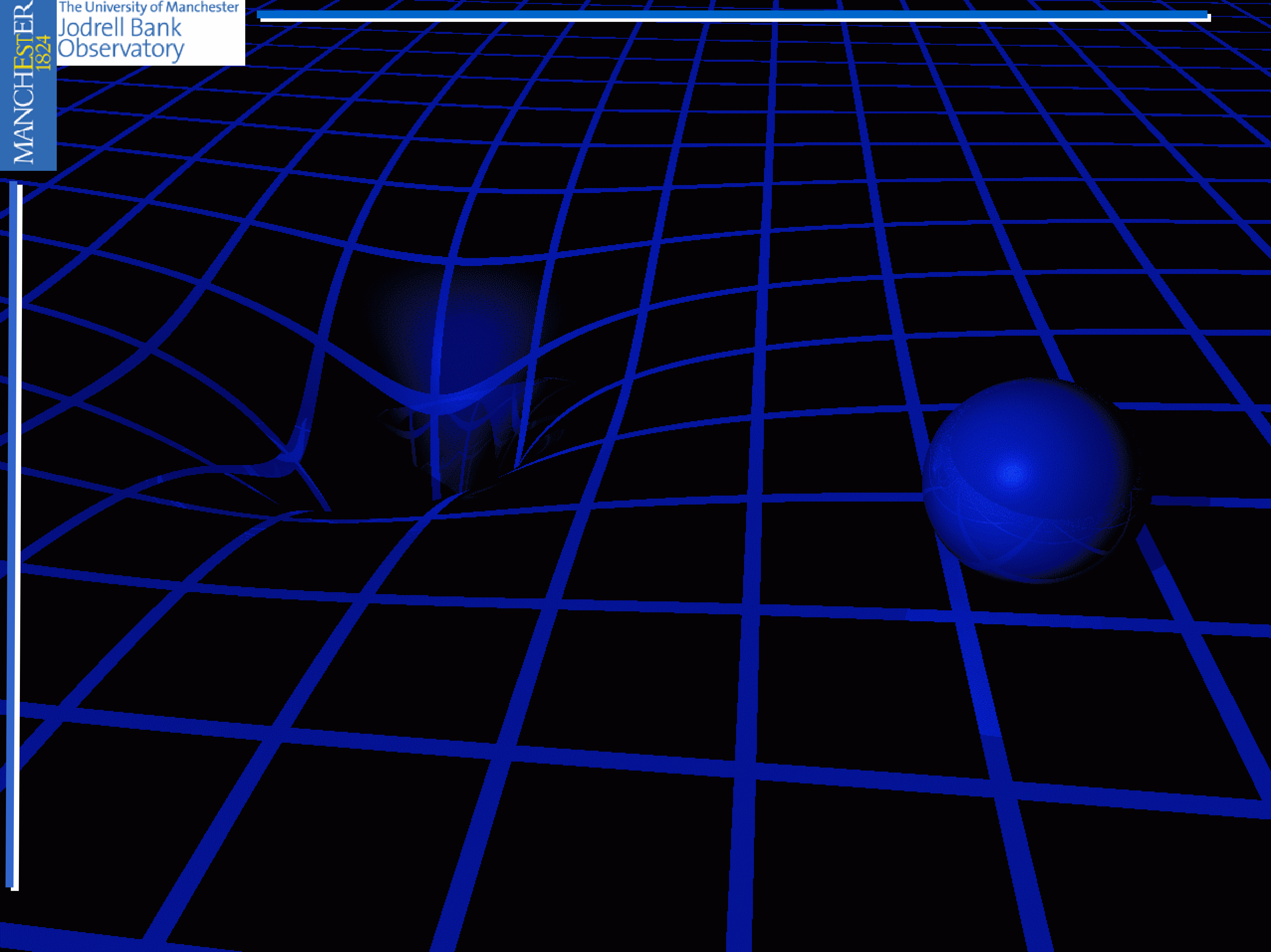

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Finally…

Hopefully, next time that you type “double pulsar” into Google, you get something different than this: