General Relativity with Double Pulsars

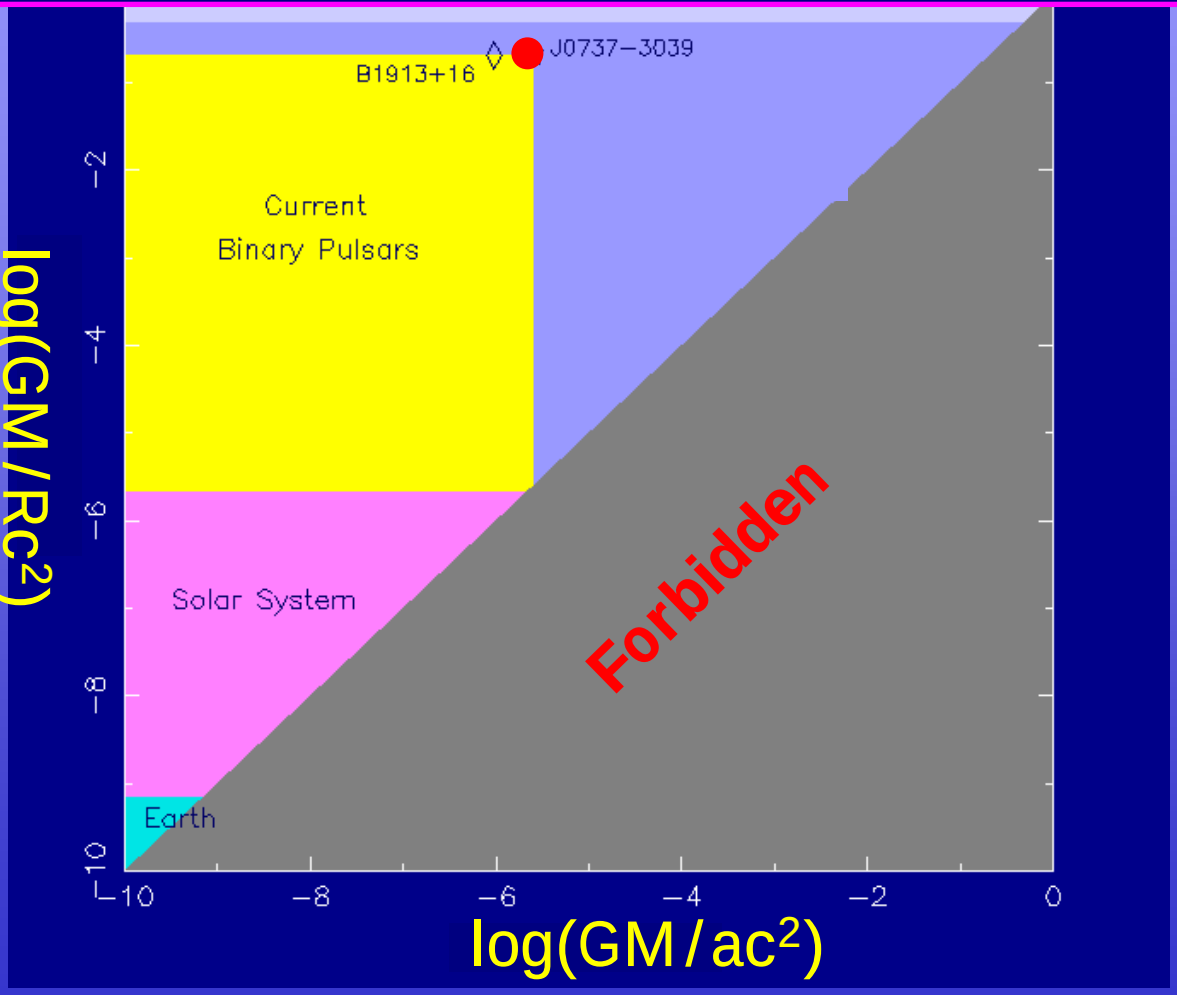
Michael Kramer

Jodrell Bank Observatory

SLAC – 9 August 2004

Was Einstein right?

Only pulsars can probe the strong-field limit as precise clocks!!



Outline

Introduction

- Pulsar properties
- Binary pulsars as gravity labs

The Double Pulsar

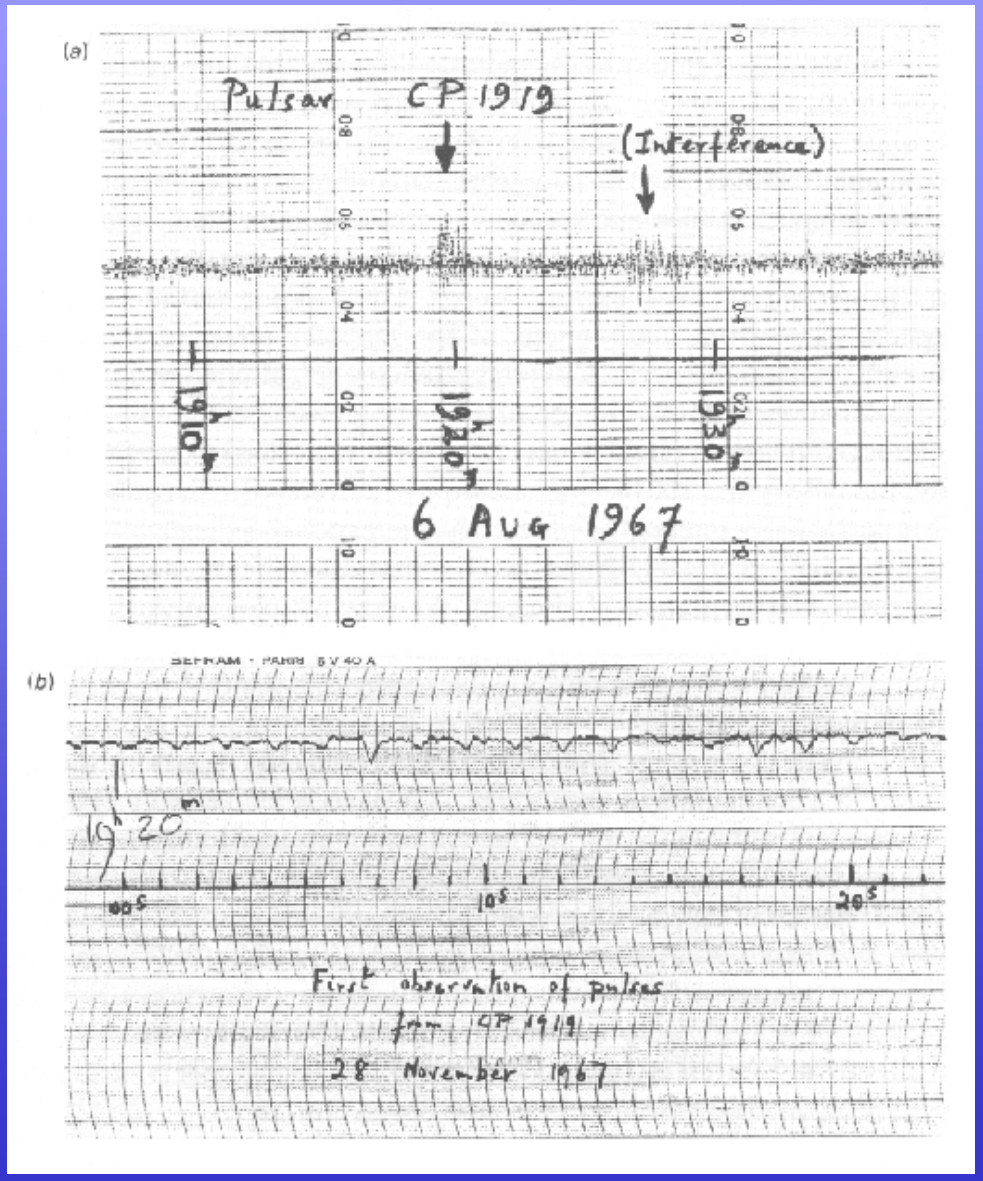
- Discovery of “A” and “B”
- A unique testbed for GR

The Future

Pulsars…

- …almost Black Holes
- …objects of extreme matter
  - 10x nuclear density
  - $B \sim B_q = 4.4 \times 10^{13}$ Gauss
  - Voltage drops ~ 10^{12} volts
  - $F_{EM} = 10^9 F_g = 10^{11} F_{gEarth}$
  - High-temperature & superfluid superconductor
- …relativistic plasma physics in action
- …probes of turbulent and magnetized ISM
- …precision tools

The Discovery…



Jocelyn Bell & Tony Hewish discover a periodic extra-terrestrial signal of 1.337 s at position:

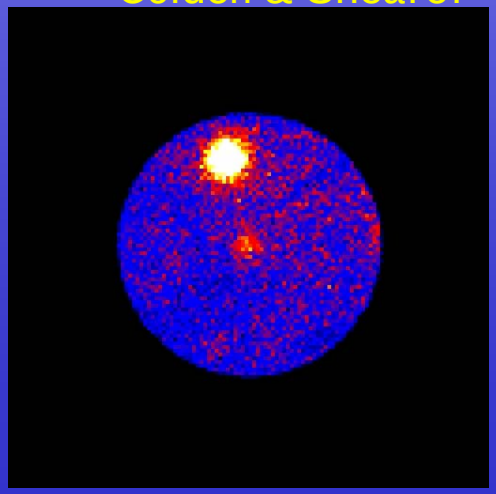
RA 19:19:36

DEC +21:47:16

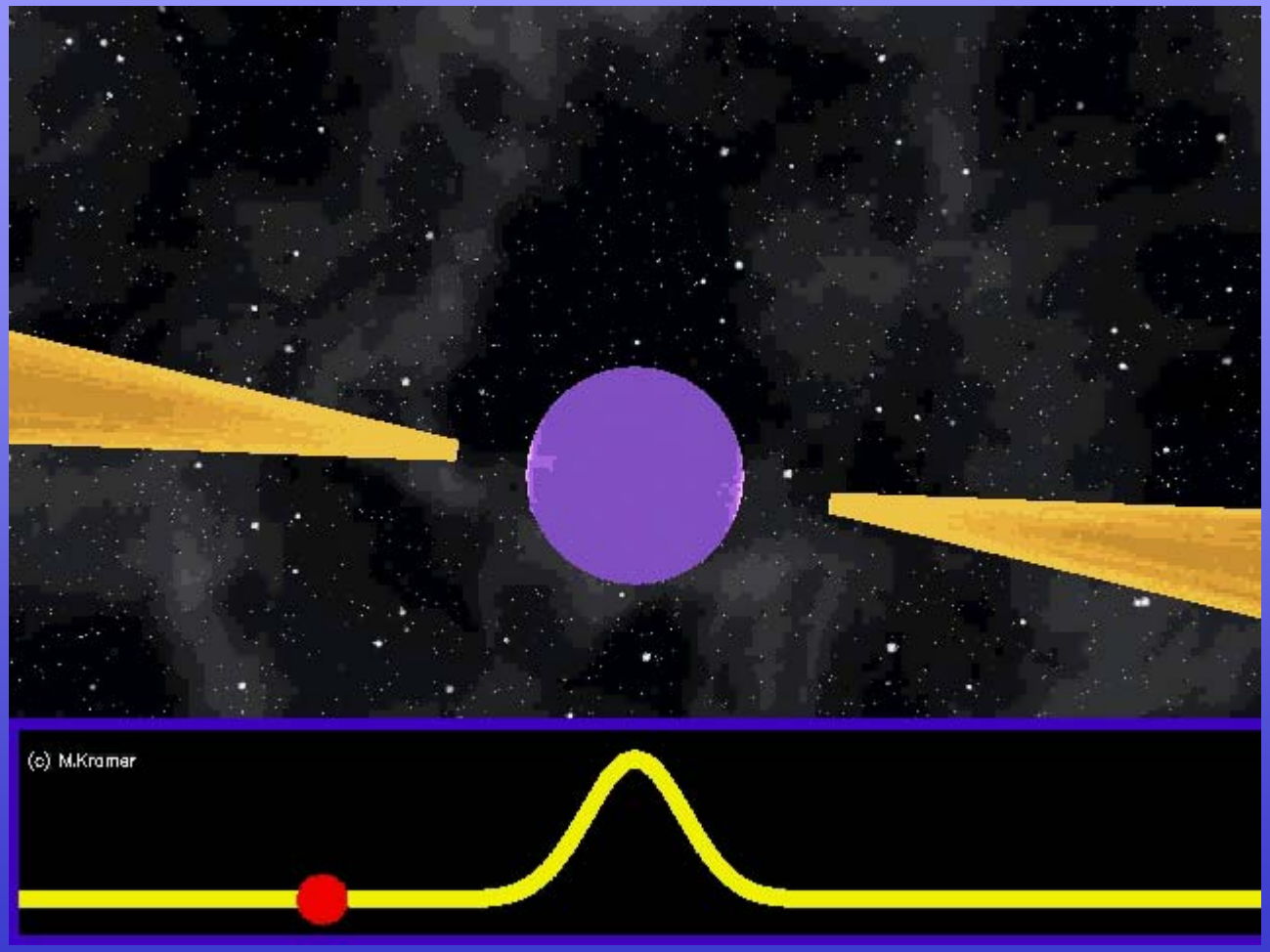
Pulsars = Neutronstars...

...born in Supernova-explosions: e.g. Crab pulsar

Golden & Shearer



Pulsars: Cosmic Lighthouses...



...spinning fast...very fast!

typically once per second, but spanning four orders of magnitude:

B1937+21
1.5 ms

Crab
33 ms

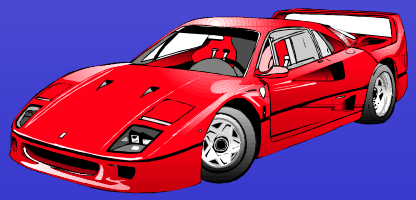
Periods

J2144-3933
8.5 s

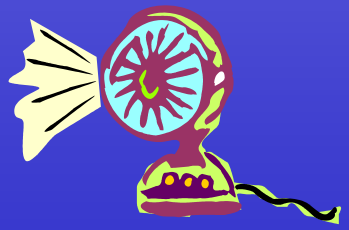
Rotations per Minute

38,400

7

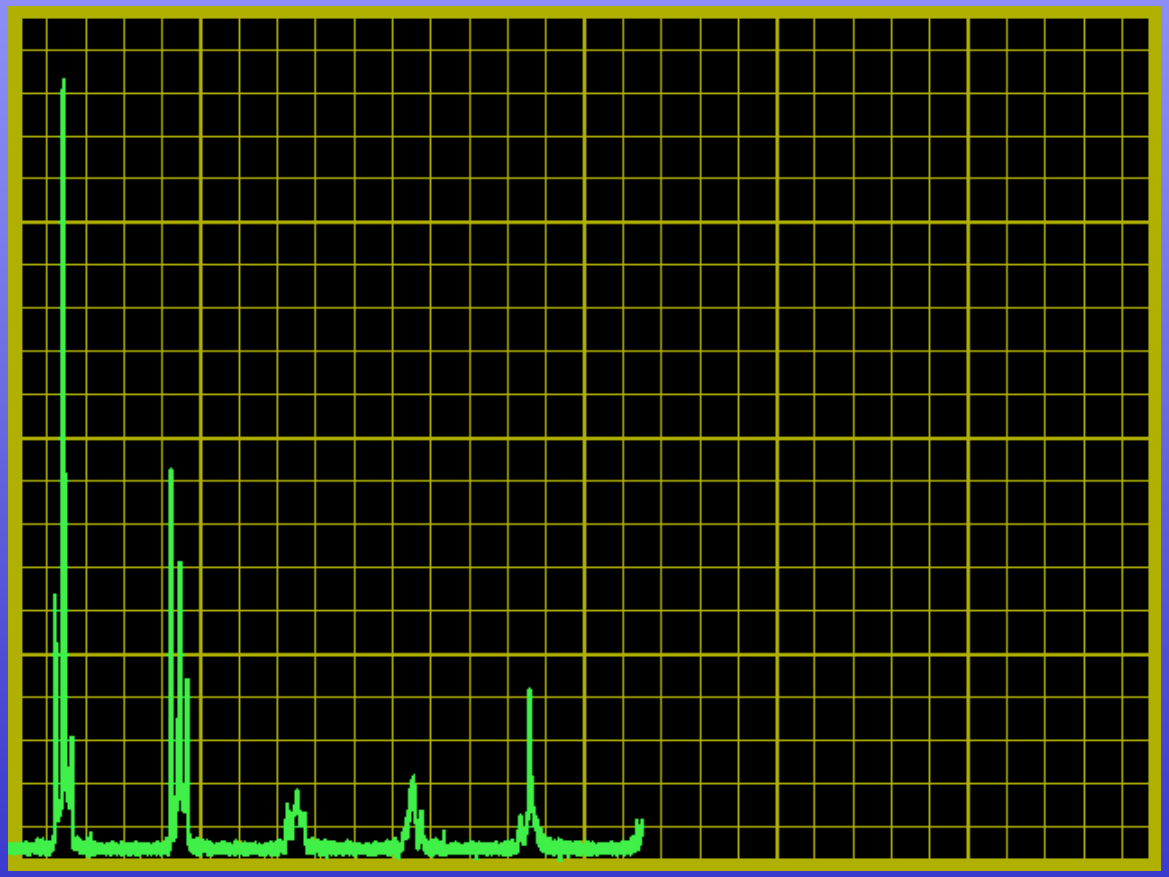


20,000

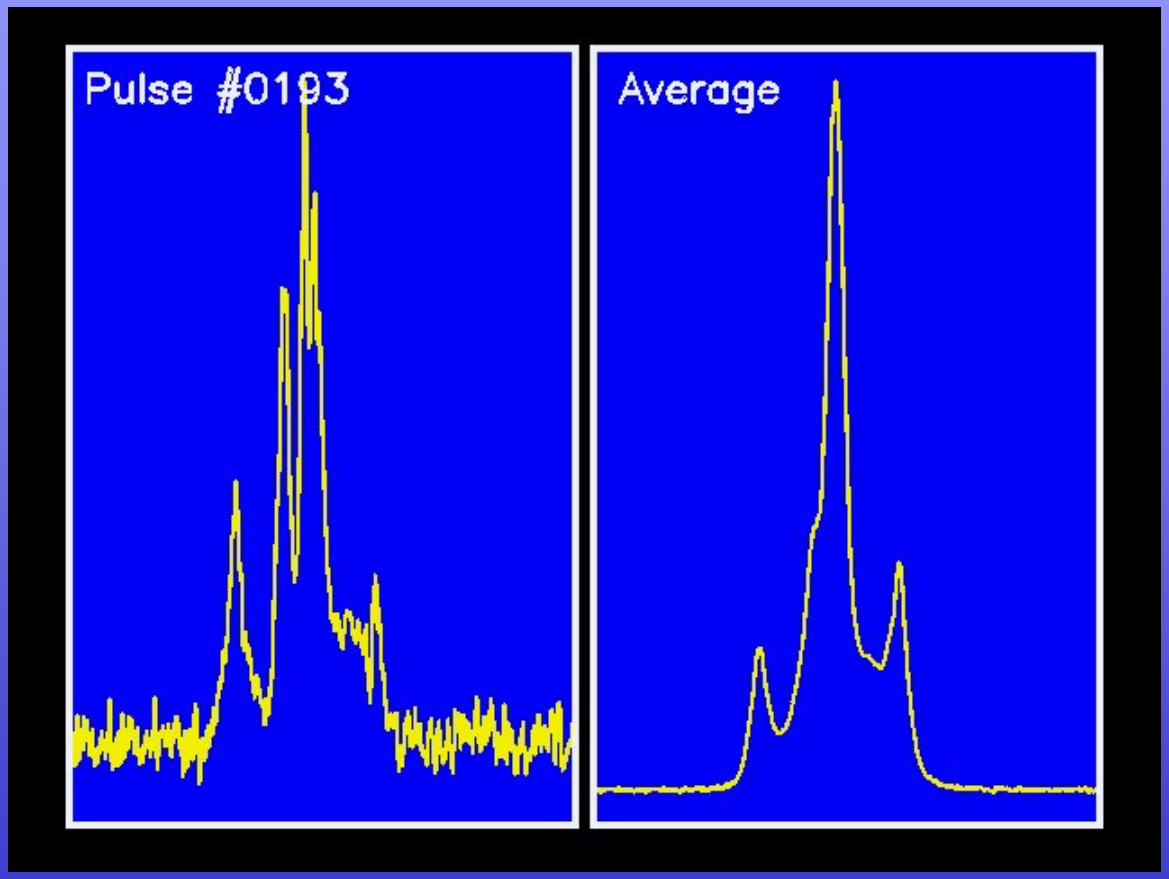


3,000

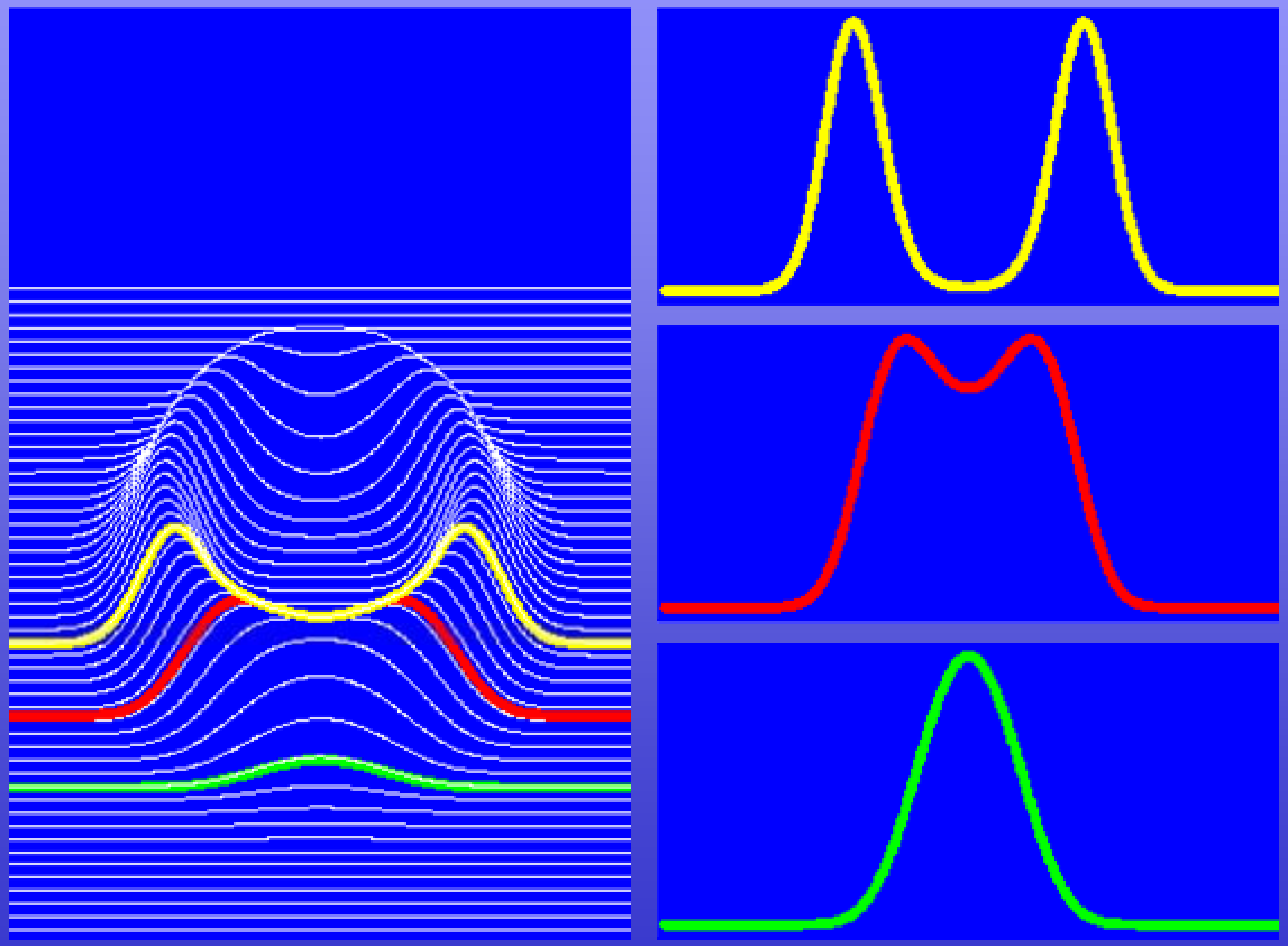
Single pulses are quite different…



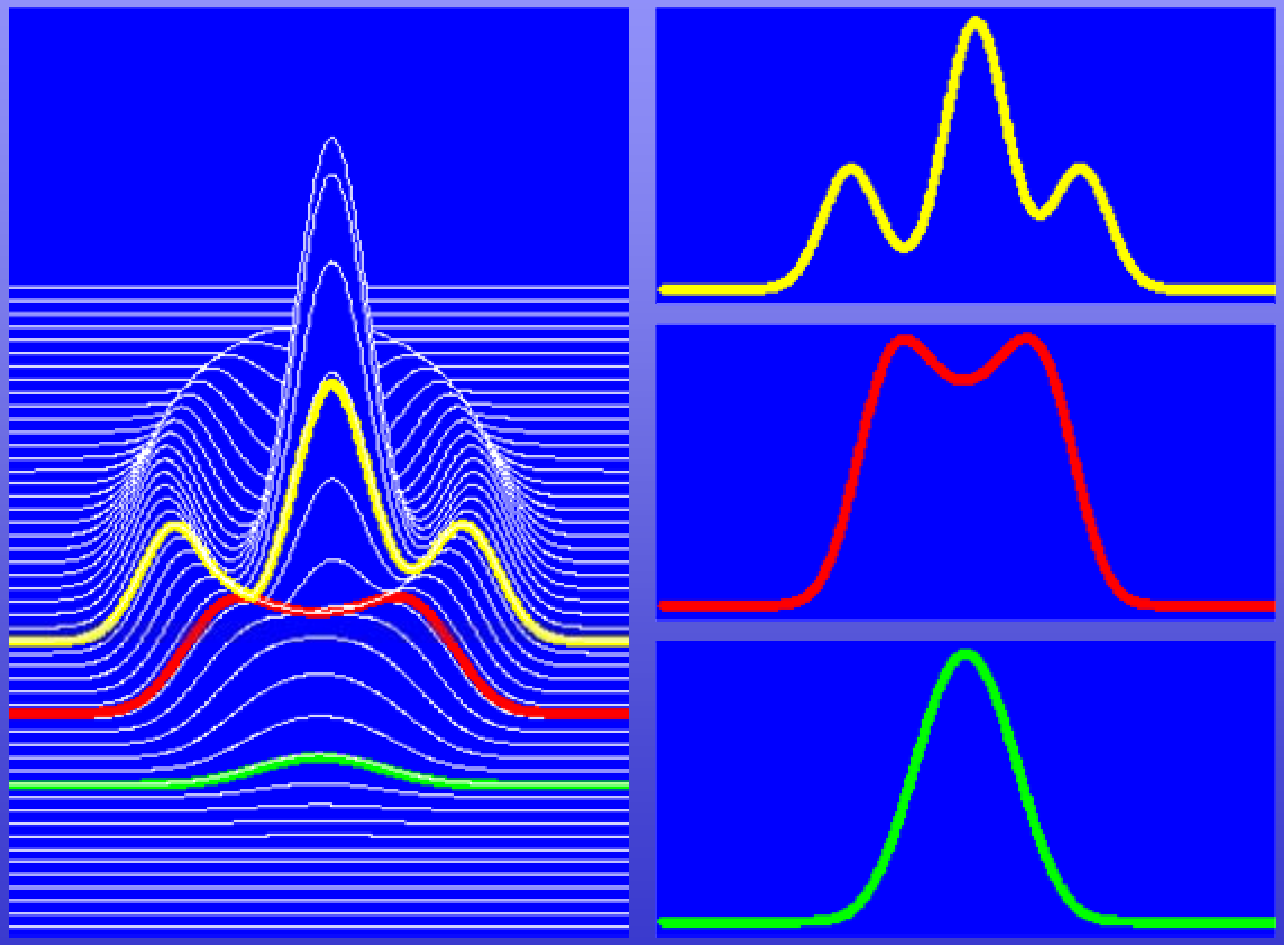
...but average profiles are stable!



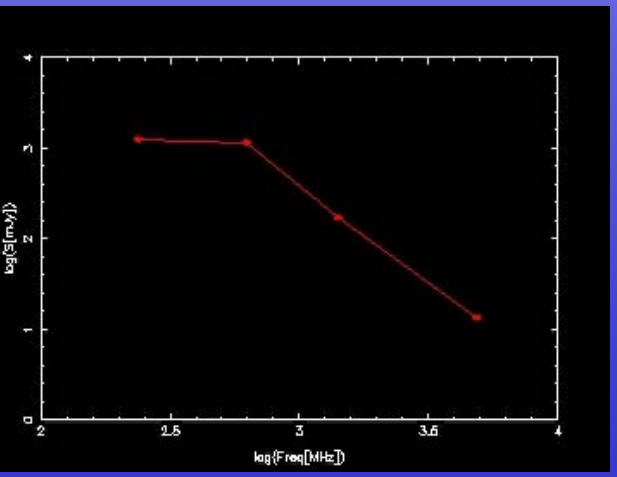
Pulse Structure: Hollow Cone Model

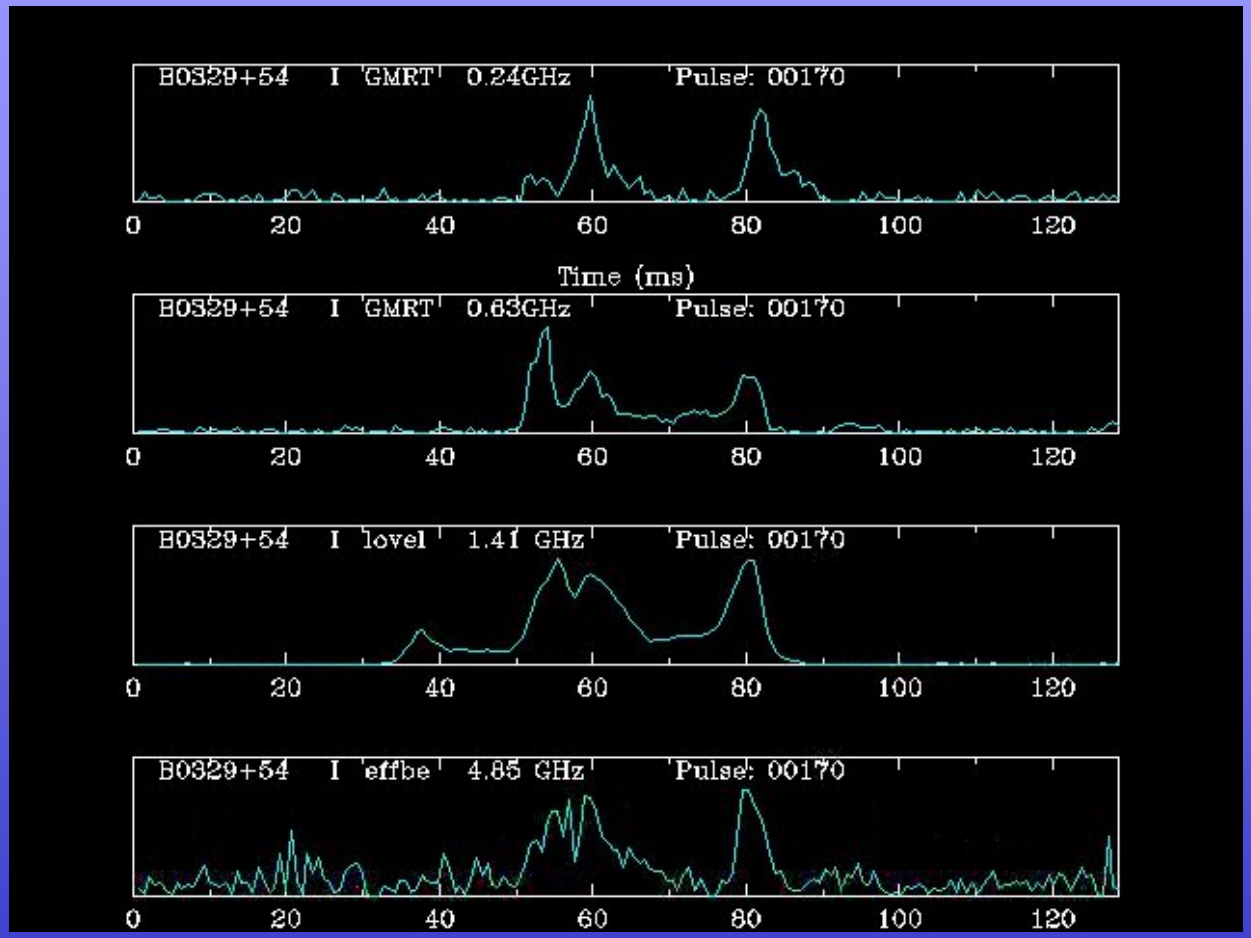


Pulse Structure: Hollow Cone with Core



Pulse structure is intrinsic and broadband

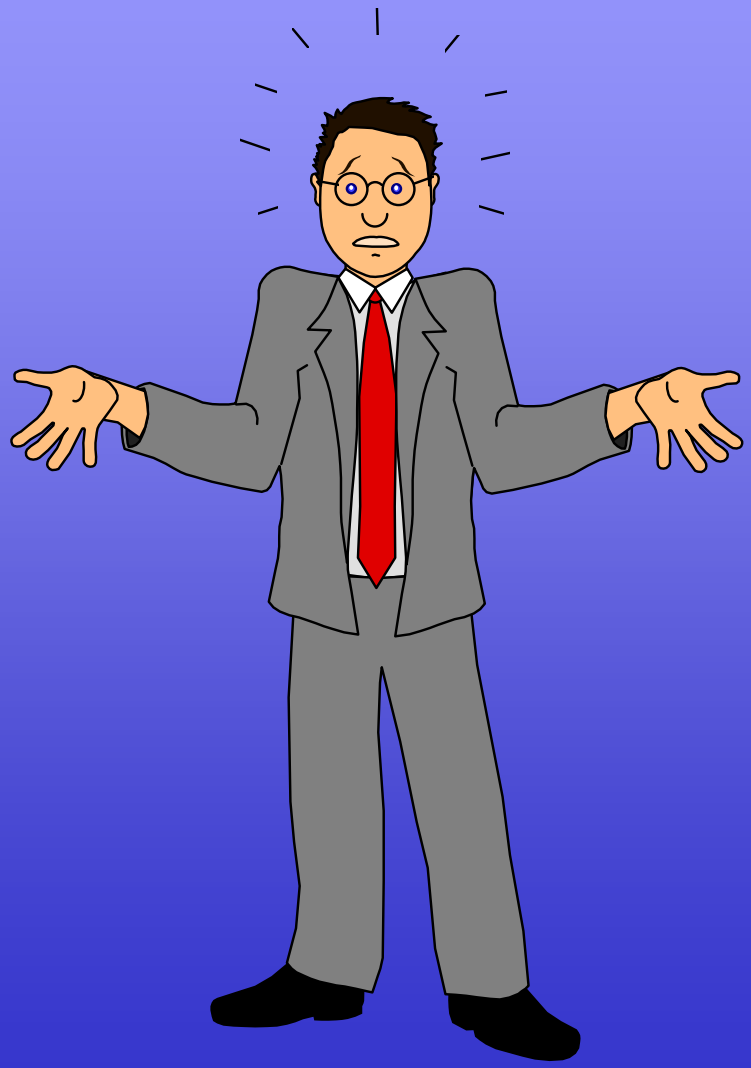




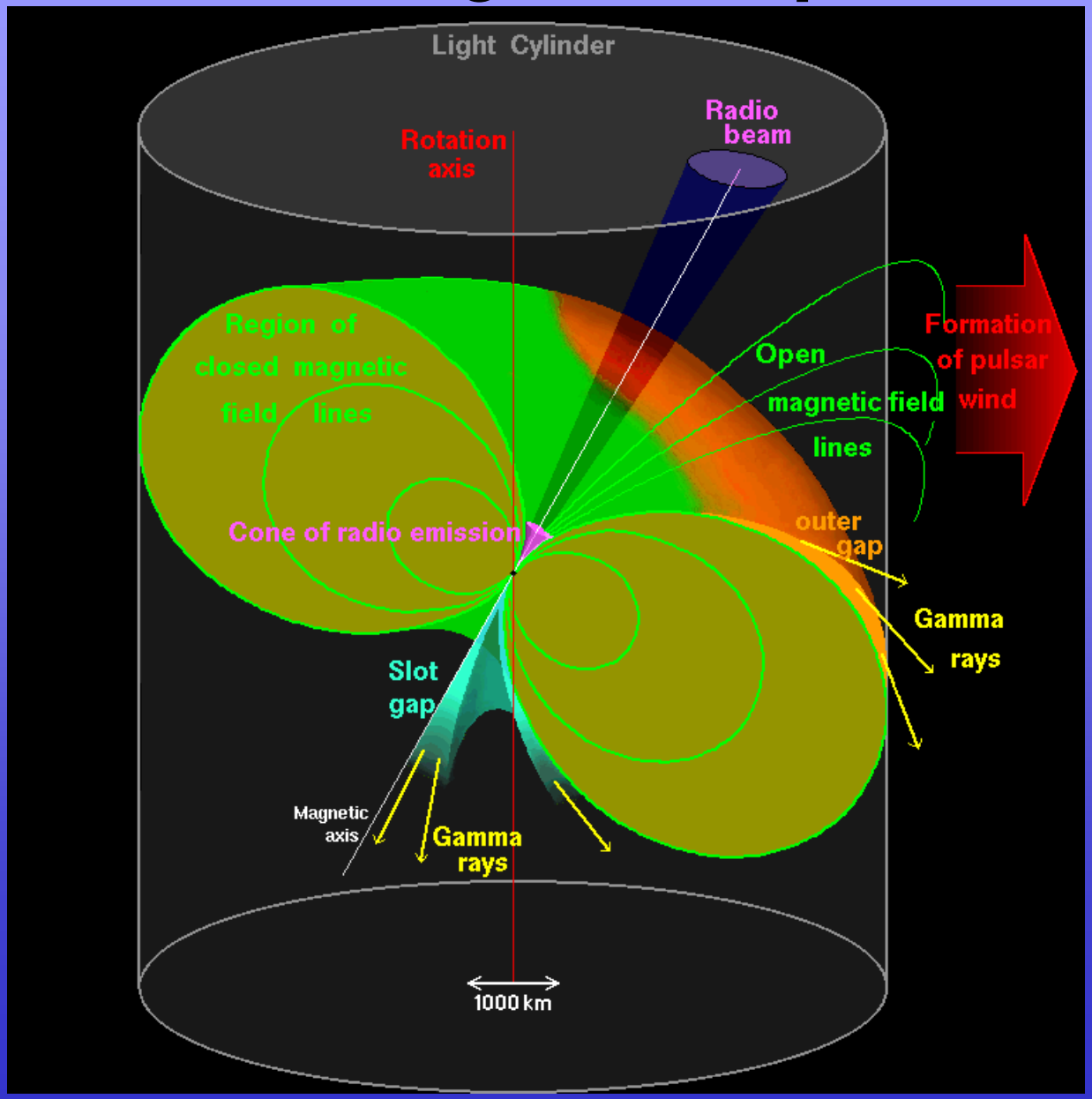
Longitude (deg)

Kramer et al. 2003c

The pulsar emission process

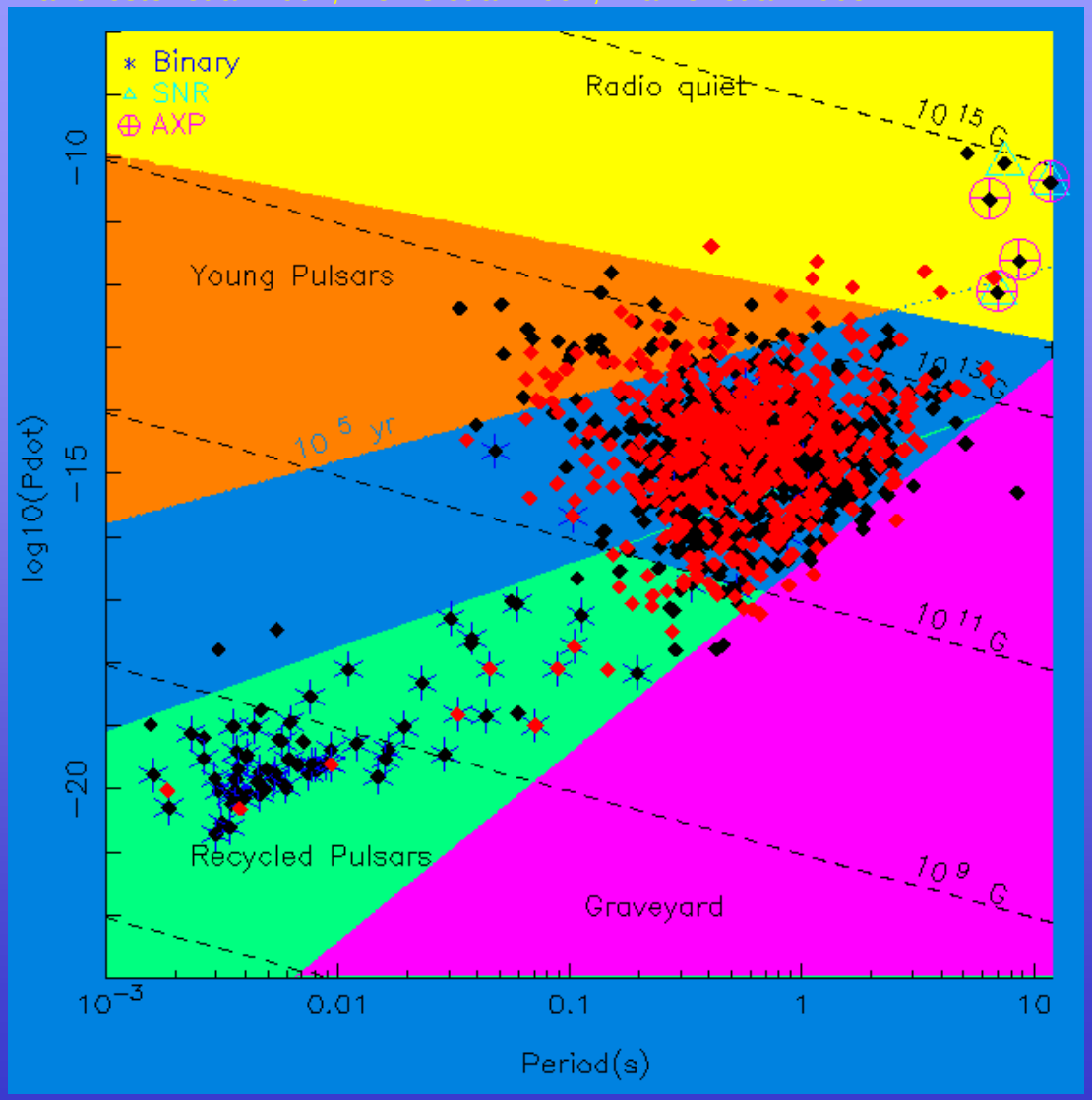


Straw-man design of a pulsar model



The life of pulsars

Manchester et al. 2001, Morris et al. 2002, Kramer et al. 2003



Spin-down age

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

Surface magnetic field

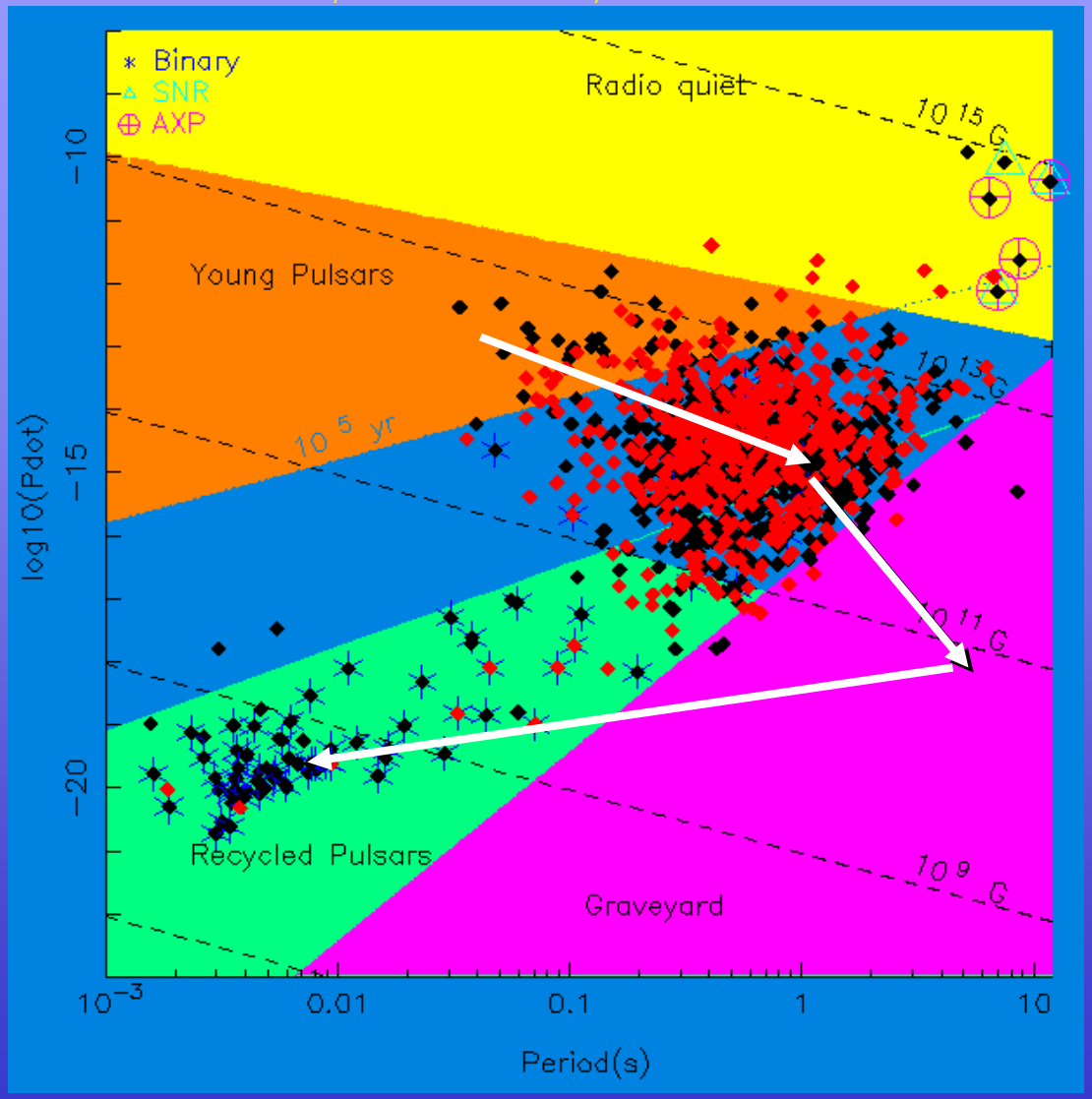
$$B = 3.2 \cdot 10^{15} \sqrt{P\dot{P}} \text{ Tesla}$$

Typical values:

$$B_{pulsar} = 1000000000000 \times B_{Earth}$$

The life of pulsars

Manchester et al. 2001, Morris et al. 2002, Kramer et al. 2003



Double Neutron Stars:

Some will be spun up as millisecond pulsars

Science with Pulsars

Pulsars are very useful tools in many areas…

For instance:

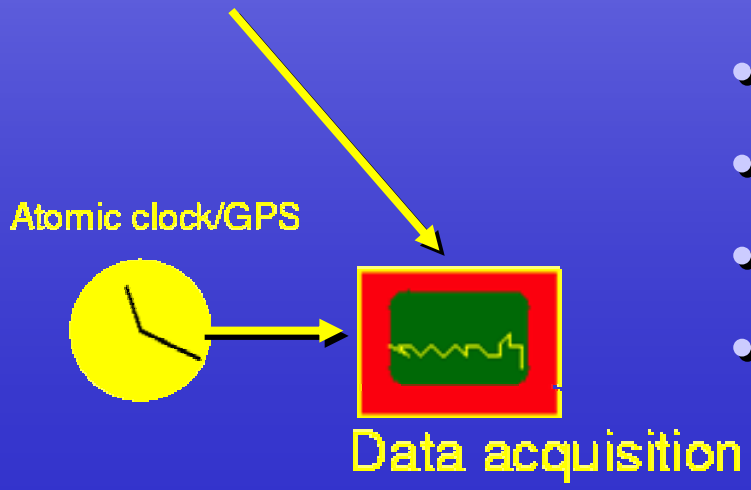
- **Relativistic gravity**
- **High precision astrometry**
- **Cosmology**
- **Solid state physics under extreme conditions**
- **Population: stellar and binary evolution, Supernovae**
- **Plasma physics and electrodynamics**
- **Galactic probes:** Interstellar medium
  Magnetic field
  Star formation history
  Dynamics

The Art of Pulsar Timing

High precision possible, e.g. period of B1937+21:

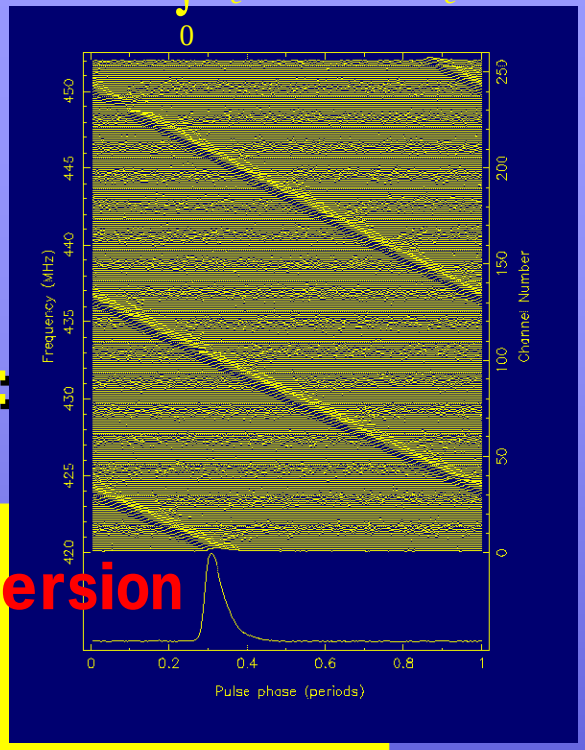
P = 0.0015578064924327±0.0000000000000004 s

- Measuring arrival times
- Time transfer to TT using GPS
- Transfer to solar system barycentre
- Comparison to timing model
- Identify deviations:
  - Pulsar/Telescope/Earth position
  - Pulsar spin down
  - Binary motion
  - Relativistic effects
  - Star-quakes in young pulsars



Timing model

$$DM = \int_0^L n_e \, dl \overset{n_e = const}{=} n_e L$$



- Measure time of arrival (TOA)
- Refer TOA (local time) to time of emission in co-moving frame of pulsar:

Time to SSB

Dispersion

$$T = \tau - \tau_0 + \frac{\vec{r} \cdot \vec{s}}{c} - \frac{D}{\nu^2}$$

$$+ \frac{(\vec{r} \cdot \vec{s})^2 - |\vec{r}|^2}{2cd}$$

Spherical waveforms (timing parallax)

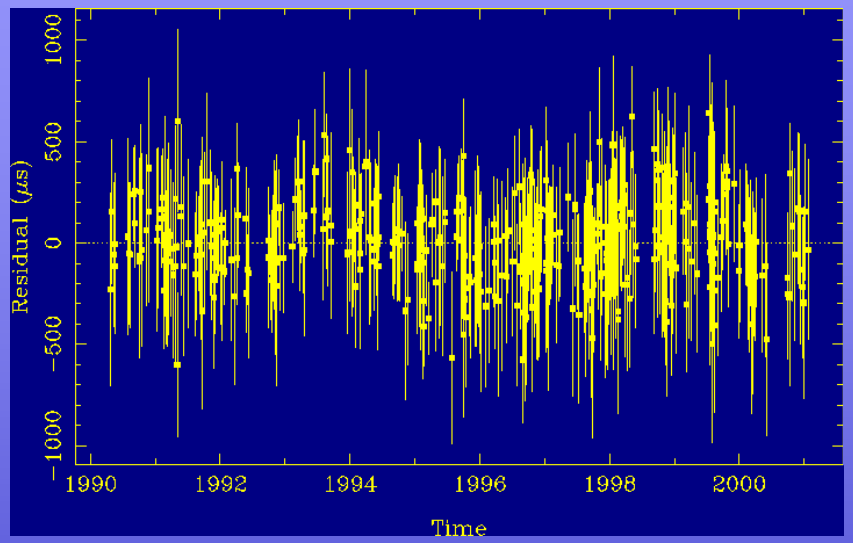
$$+ \Delta t_{rel,\odot} \quad \left(+ \Delta t_{roemer,bin} + \Delta t_{rel,bin} \right)$$

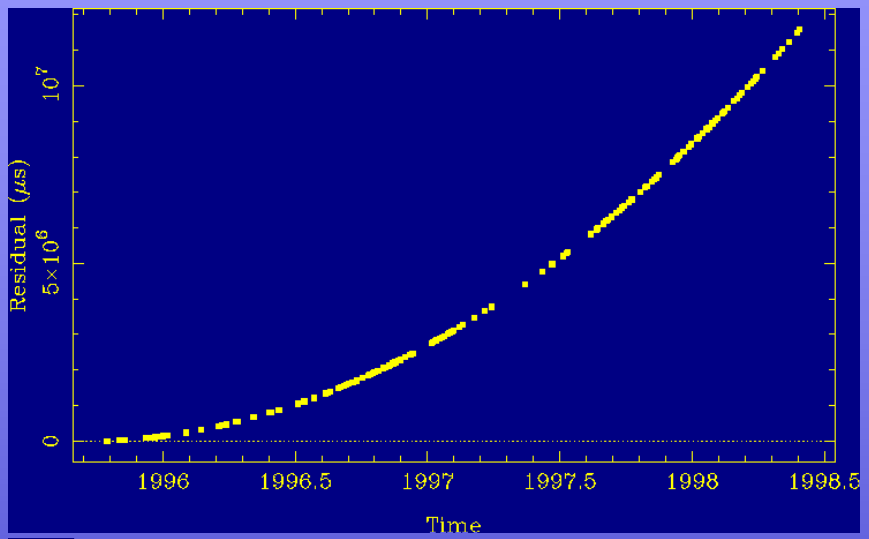
Rel.effects in Solar system

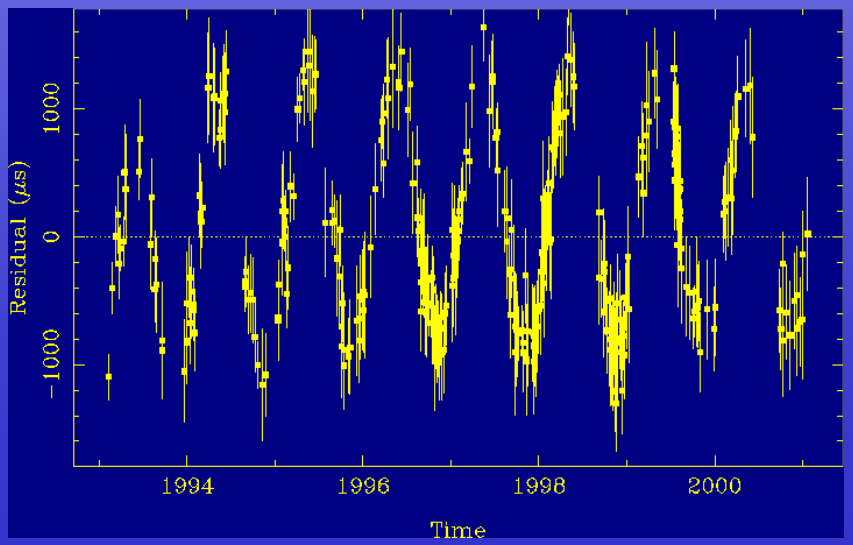
Effects in binary system

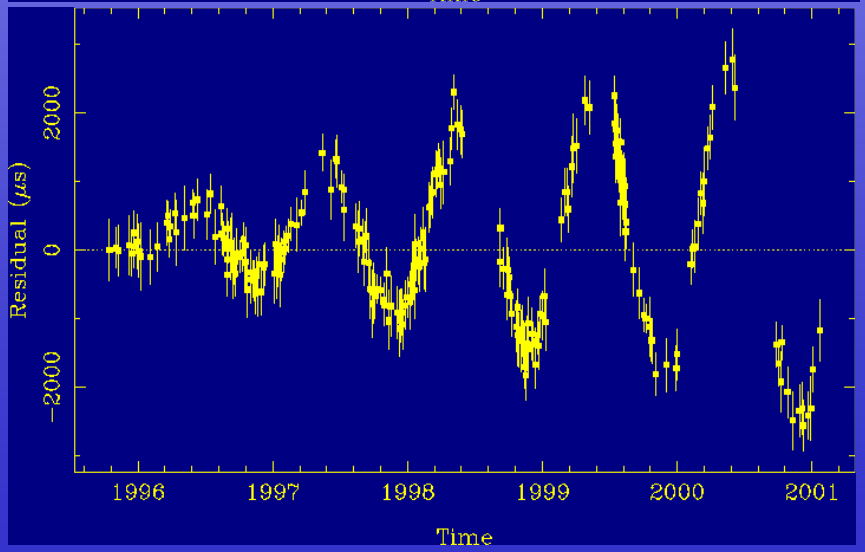
Timing Parameters

- Spin parameters: $\nu, \dot{\nu}, \ddot{\nu} \ldots$
- Astrometric parameters: position, proper motion, parallax

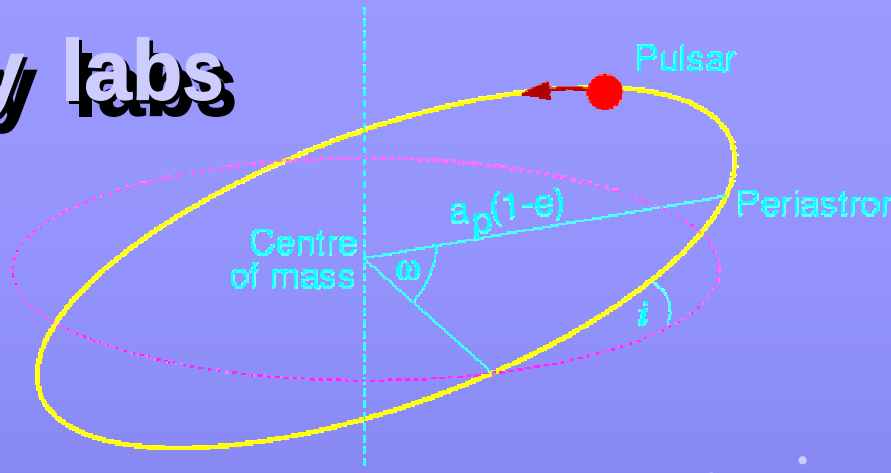








Binary pulsars as gravity labs



- **5 Keplerian-parameters:**

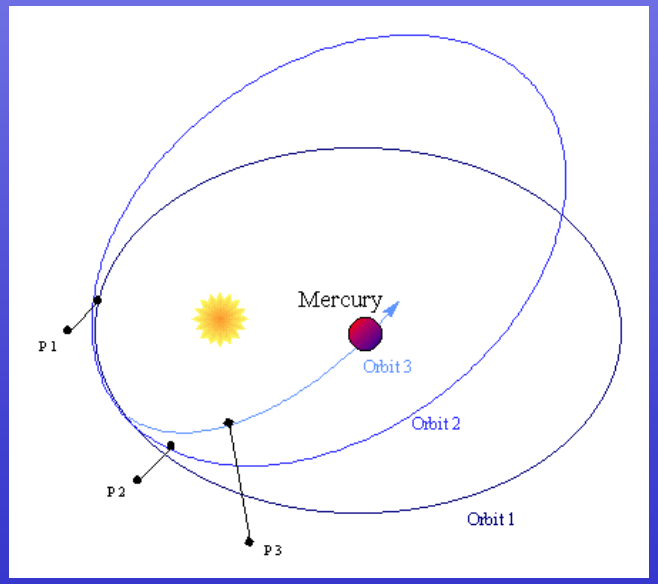
  P_b, a_p, e, ω, T_0

$\dot{\omega}, \dot{P}_b$

- **Rel. correction to Keplerian parameter – so called Post-Keplerian parameters: e.g. Periastron advance $\dot{\omega}$**

In case of Mercury:

$$\dot{\omega} = 0.43'' / yr = 0.00012 \deg / yr$$

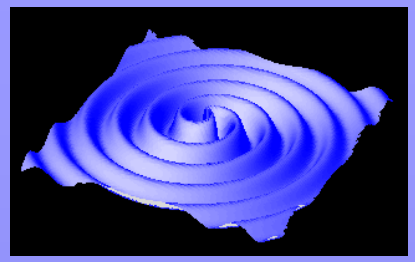


In any theory of gravity, PK-parameters only functions of observables and star & companion mass, e.g. in GR:

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

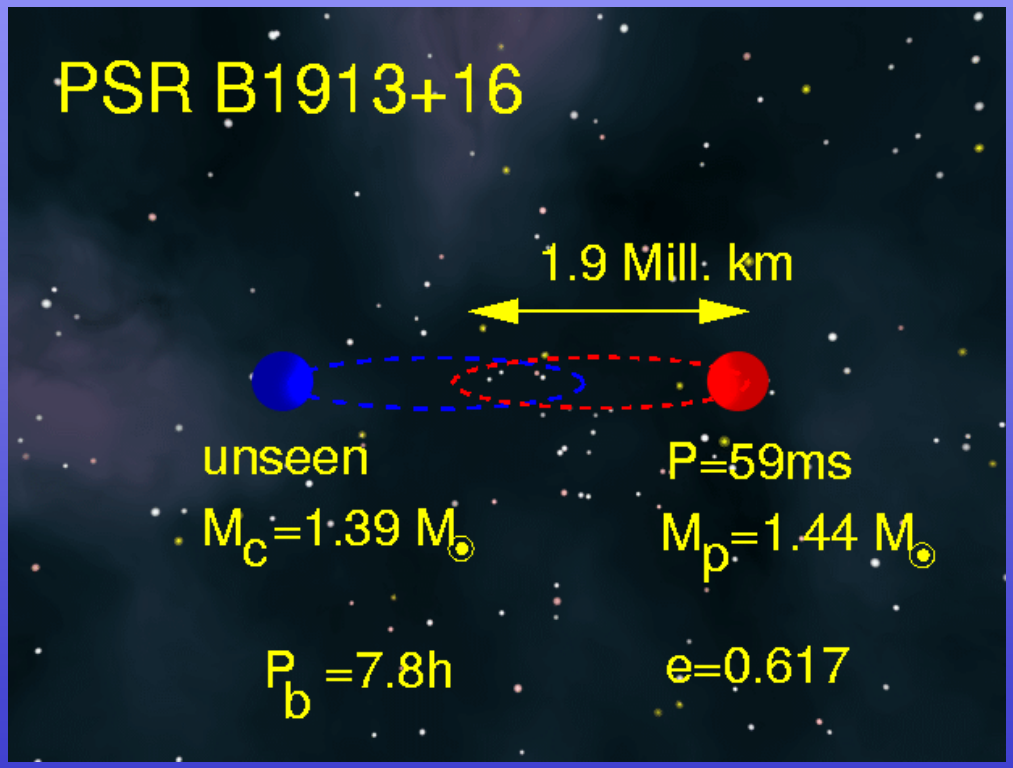
to order $(v/c)^2$ – '1PN'

Binary pulsars as gravity labs

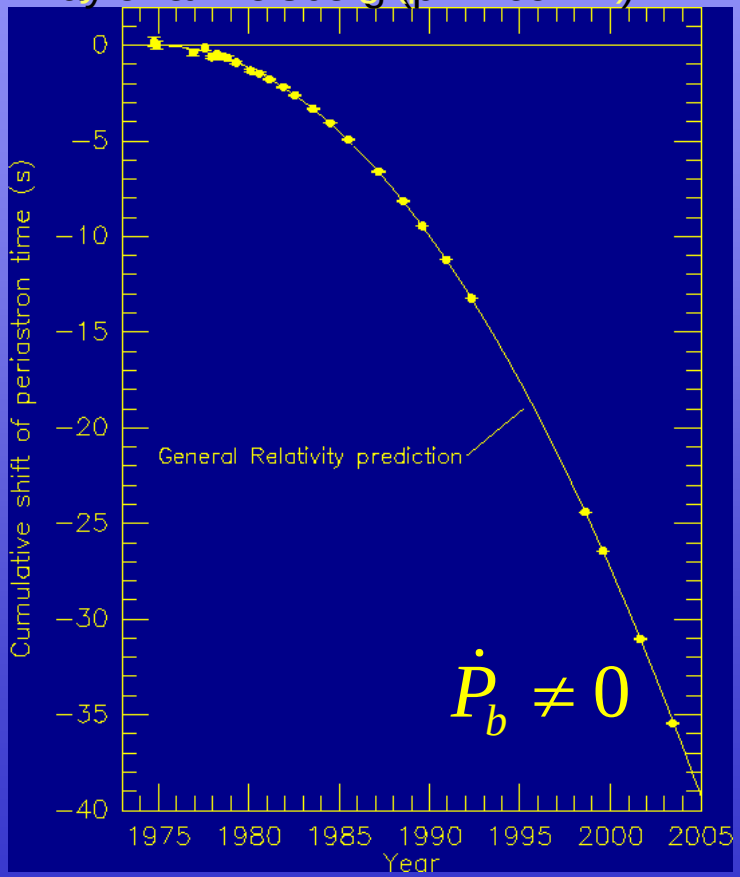


- Another example: **PK parameter** $\dot{P}_b$

  Orbital decay due to gravitational wave emission



Taylor & Weisberg (priv. comm)



- **Orbit shrinks by 1cm/day**
- **Evidence for gravitational waves!**

Outline

Introduction

- Pulsar properties
- Binary pulsars as gravity labs

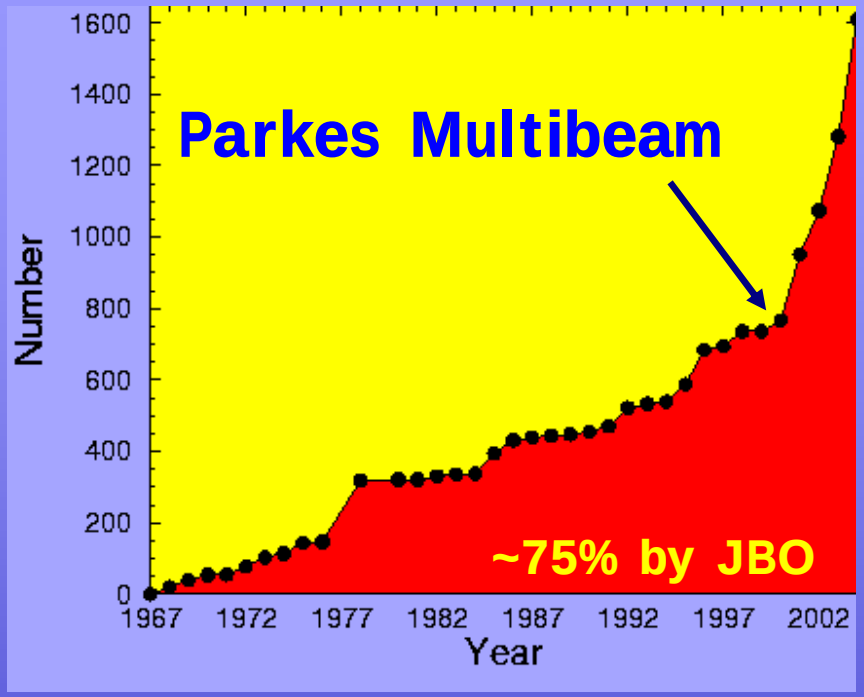
The Double Pulsar

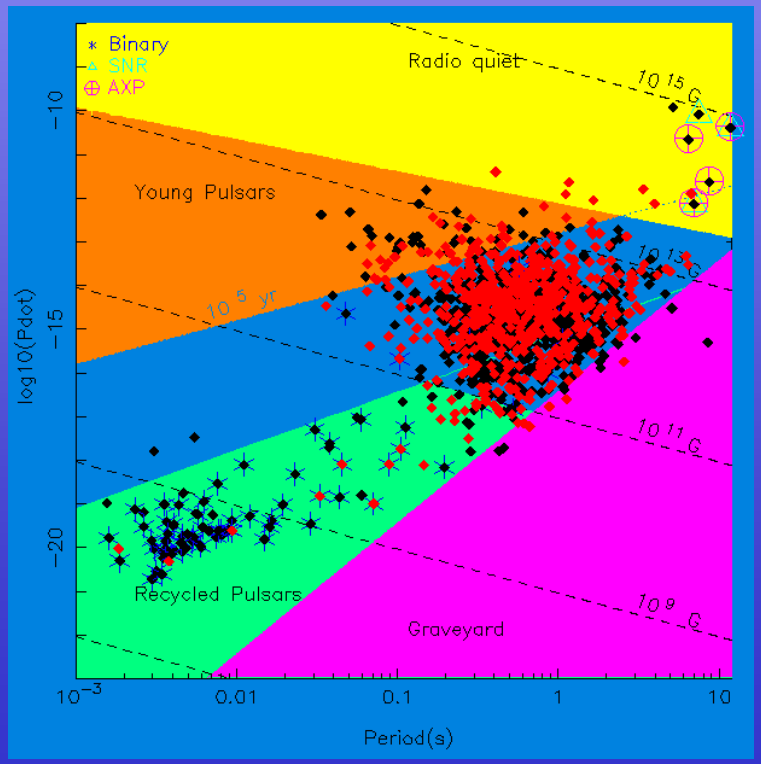
- Discovery of “A” and “B”
- A unique testbed for GR

The Future

Parkes Multibeam Survey(s)

lead by Jodrell Bank in collaboration with ATNF, Bologna, UBC et al.

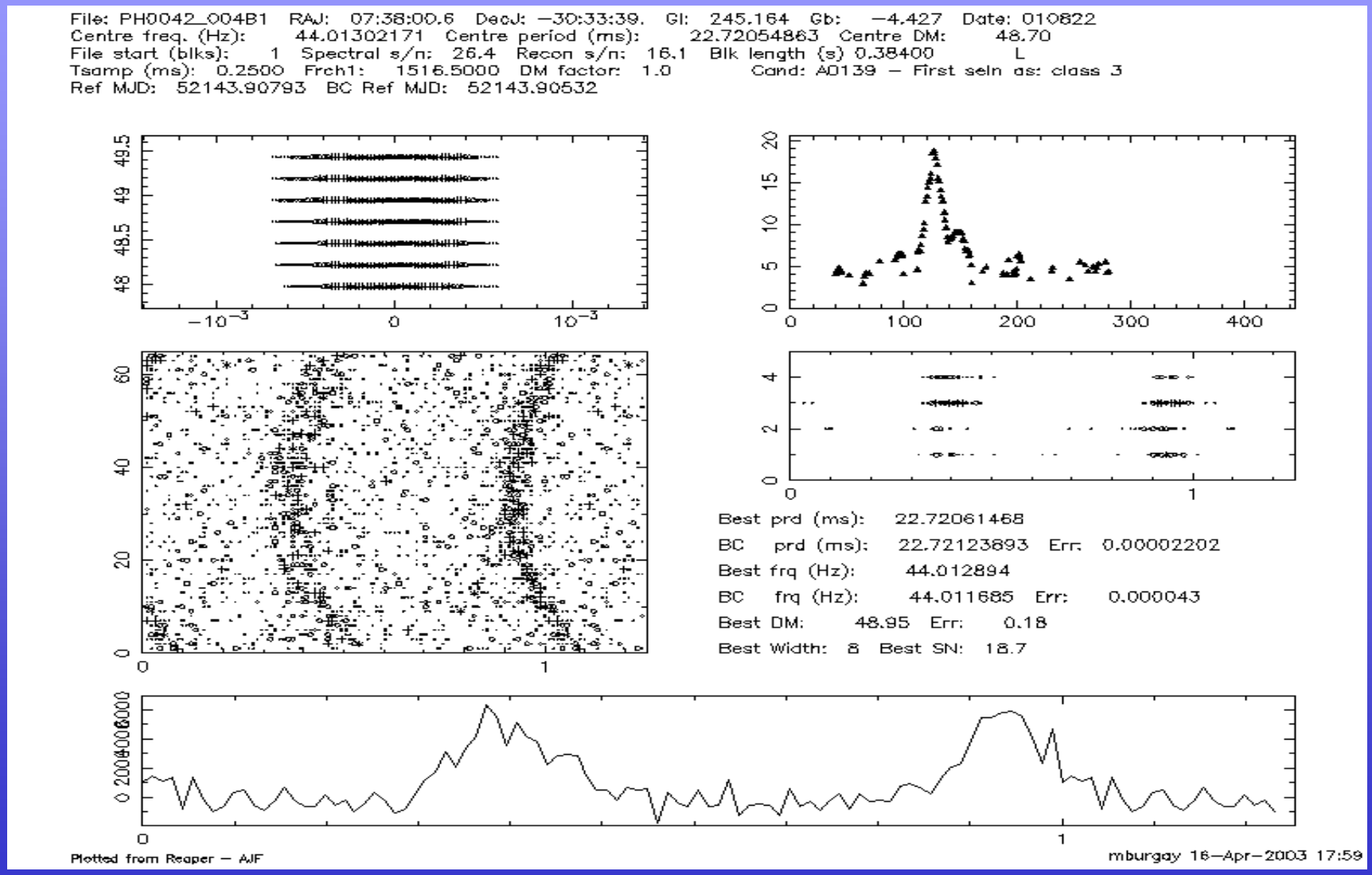




- Most sensitive & most successful
- More than 700 discoveries
- Still counting…
- Lots of exciting systems…

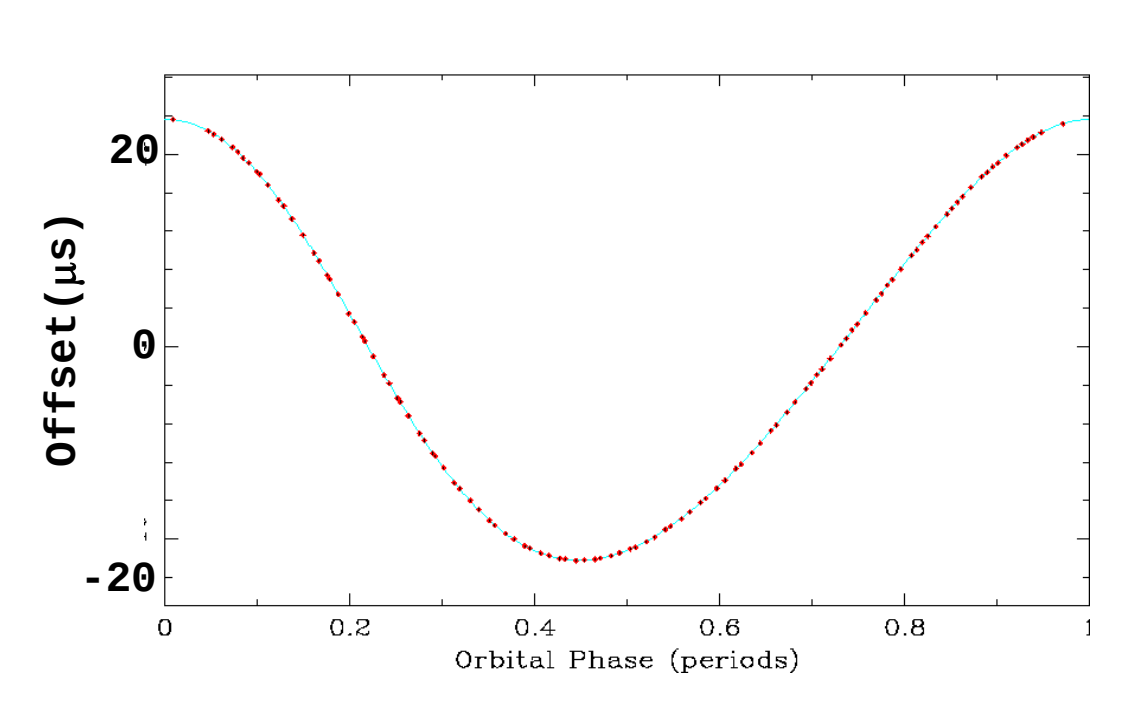
Manchester et al. 2001, Morris et al. 2002
Kramer et al. 2003, Hobbs et al. 2004,
Faulkner et al. 2004

Discovery of "A"



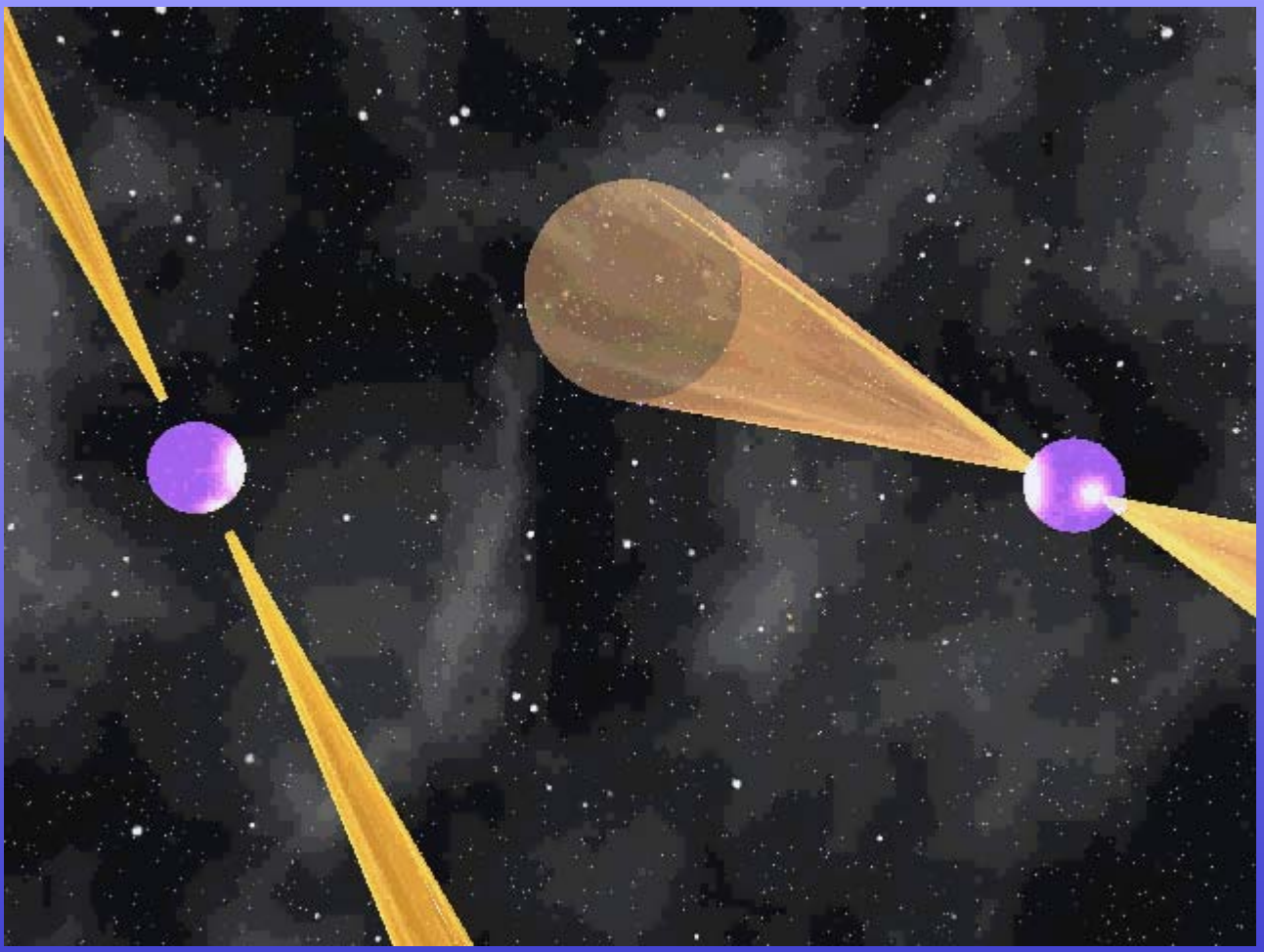
Discovery of "A"

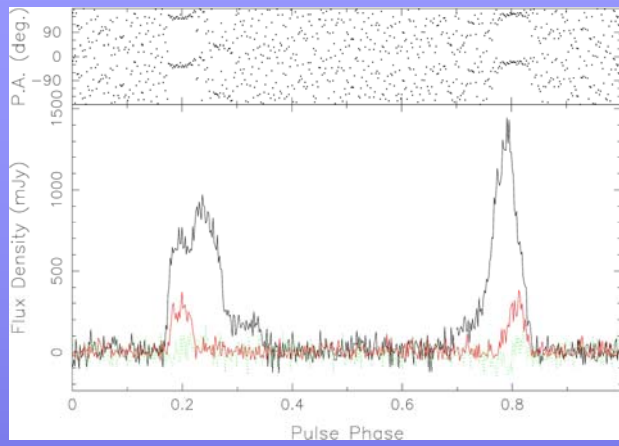
- Observations showed that the orbit is very tight (2.4 hrs) and eccentric (e = 0.088).

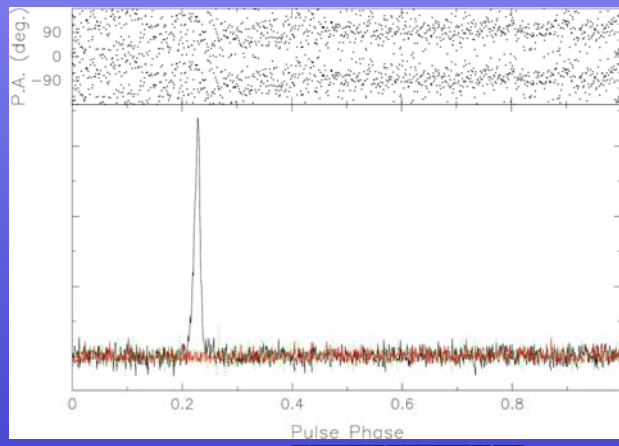


- Orbital parameters suggested that the companion to 22-ms pulsar is probably another neutron star

Discovery of "B"





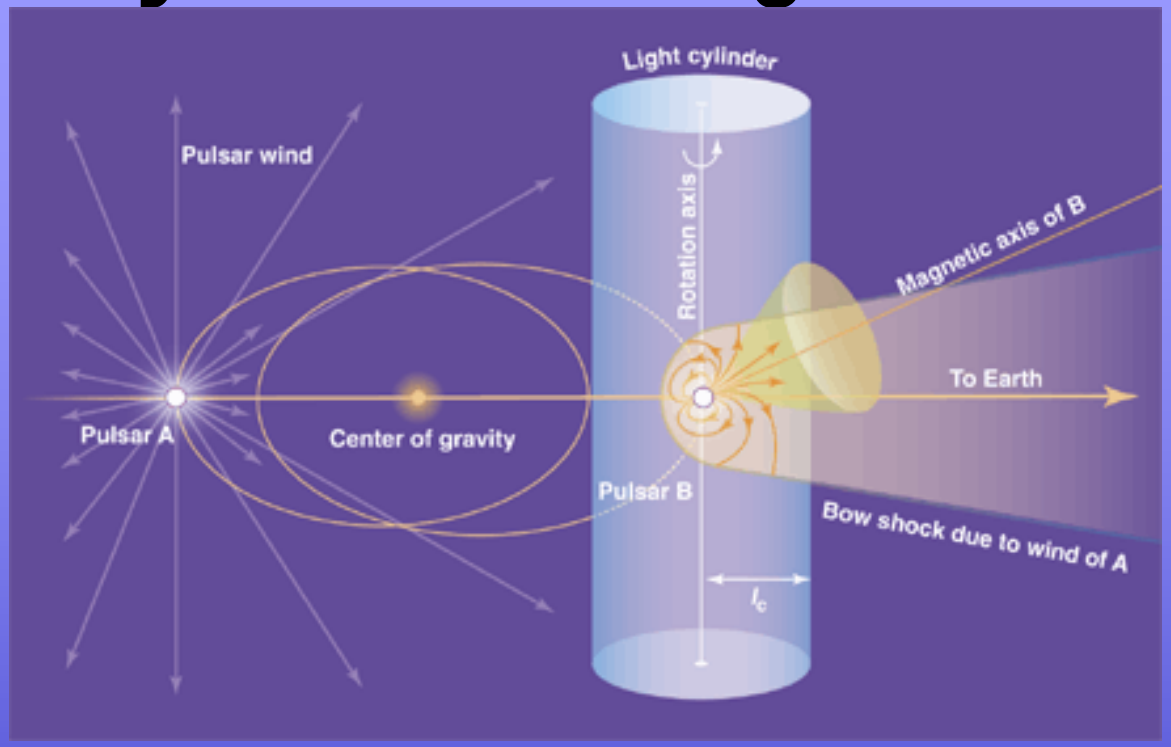


Discovery of an additional 2.77-sec periodicity!
(Lyne et al., Science, 2004)

Basic parameters

	A:	B:
P	22.7 ms	2.77 s
$\dot{P}$	1.7×10^{-18}	0.88×10^{-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}

System Configuration

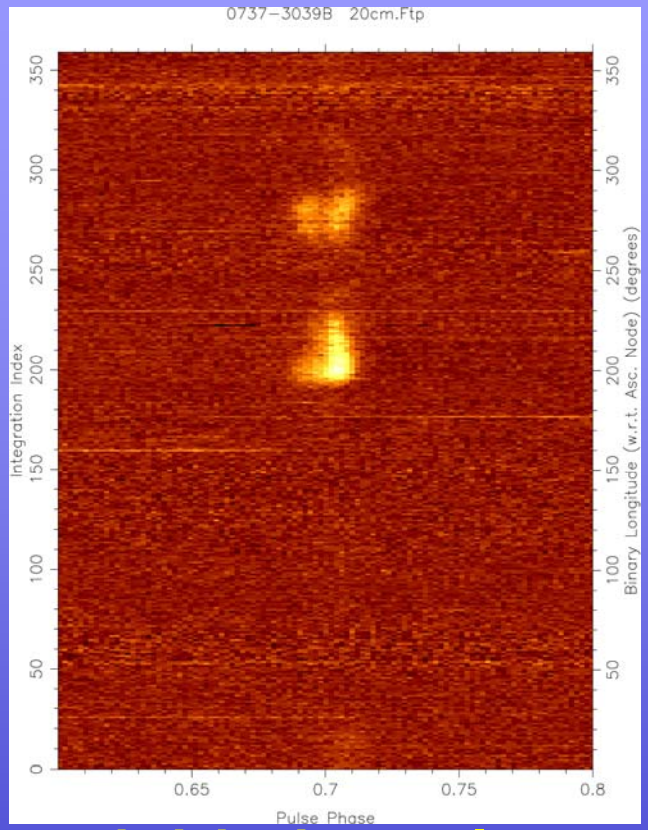


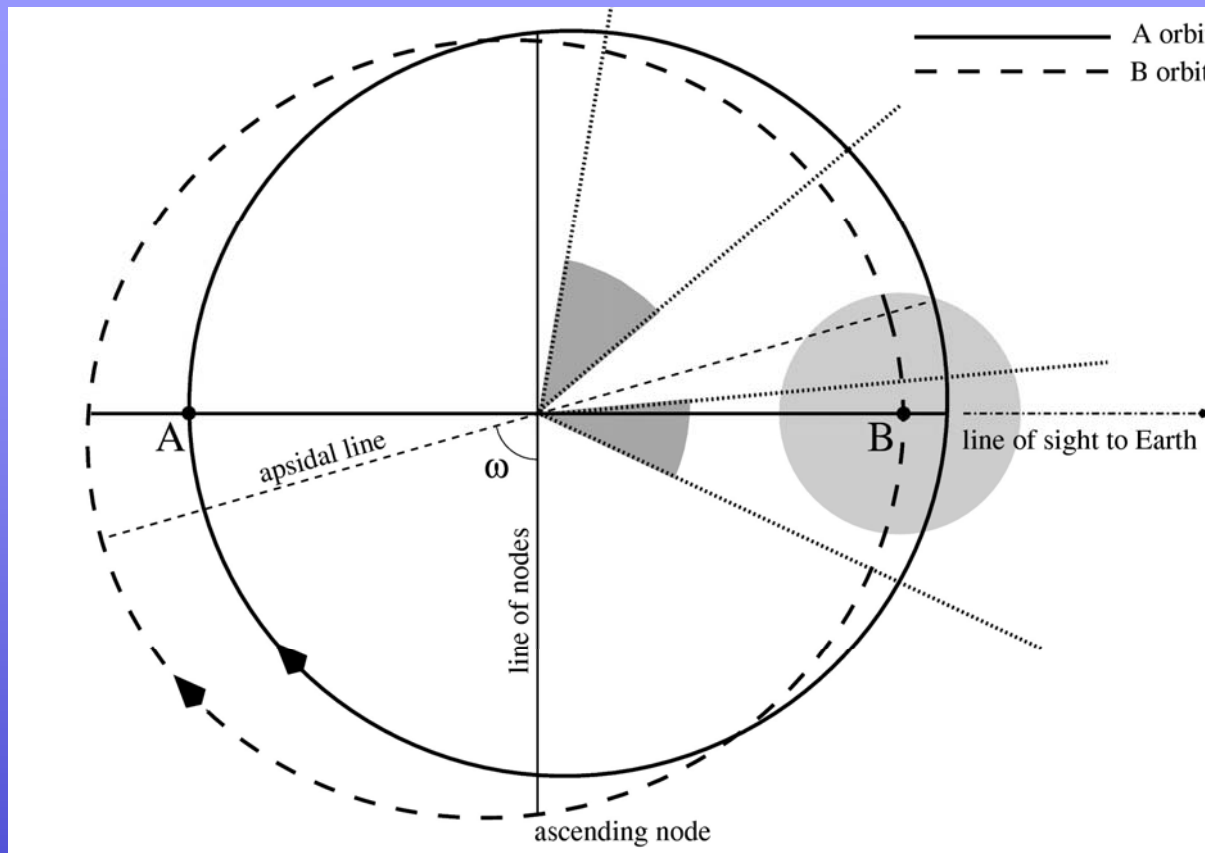
- Wind energy density at B light cylinder:

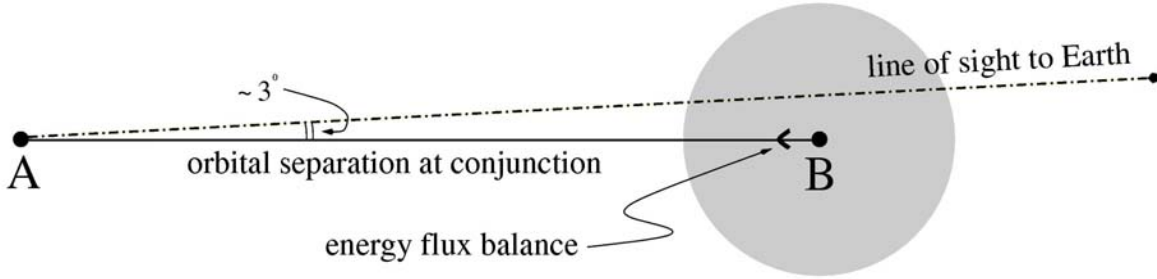
  A: ~ 2.1 erg cm^{-3} B: ~ 0.024 erg cm^{-3}

- Therefore, A wind will penetrate B magnetosphere.
- Approximate pressure balance with B's magnetic field at r ~ 0.45 R_{LC}. Will vary with spin and orbital phase.

Orbital modulation of "B" emission



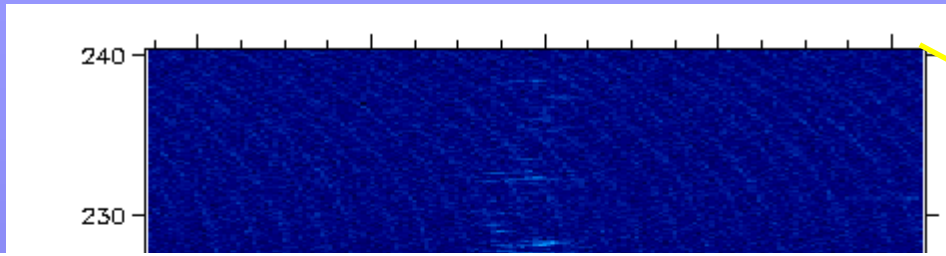


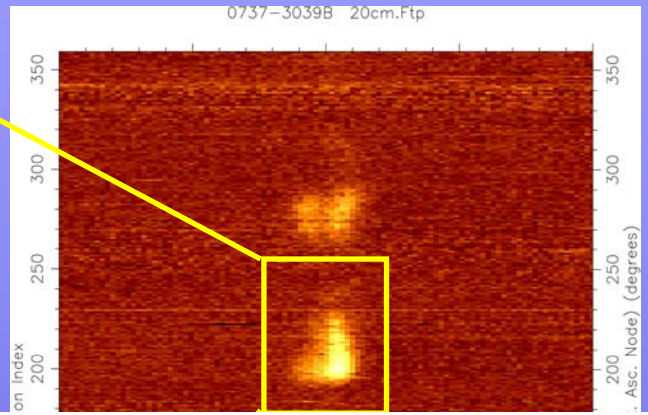


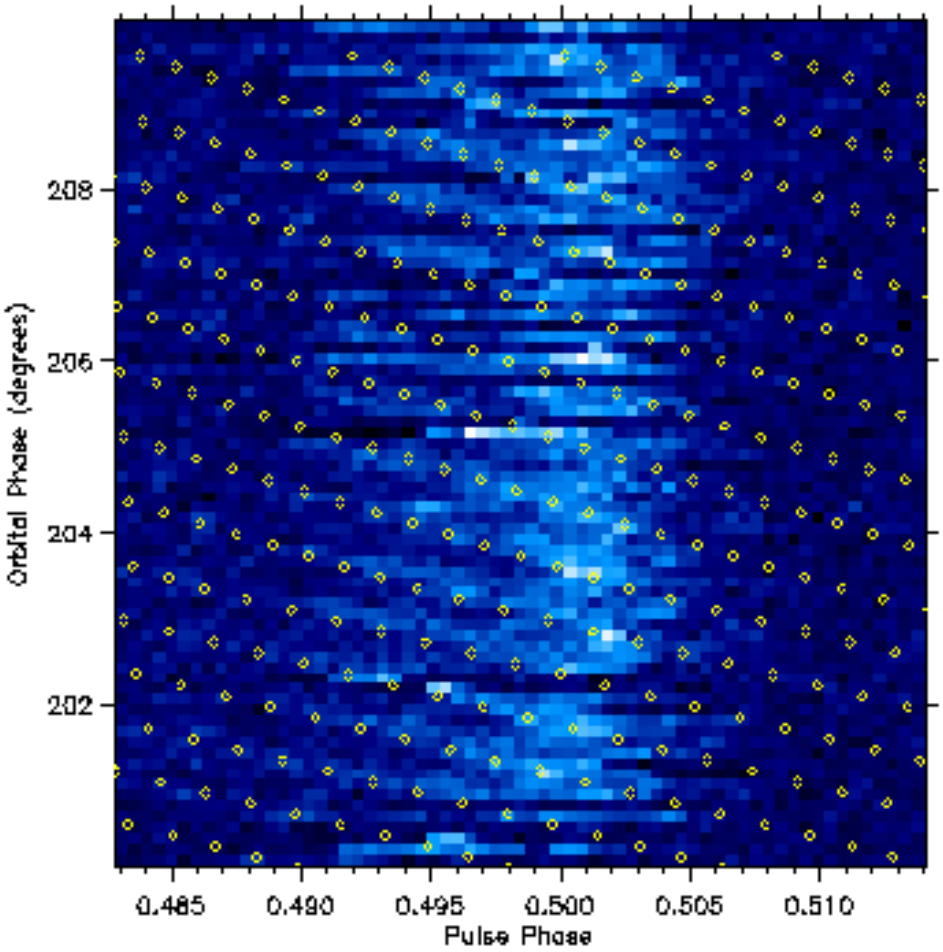
Two bright intervals near inferior conjunction

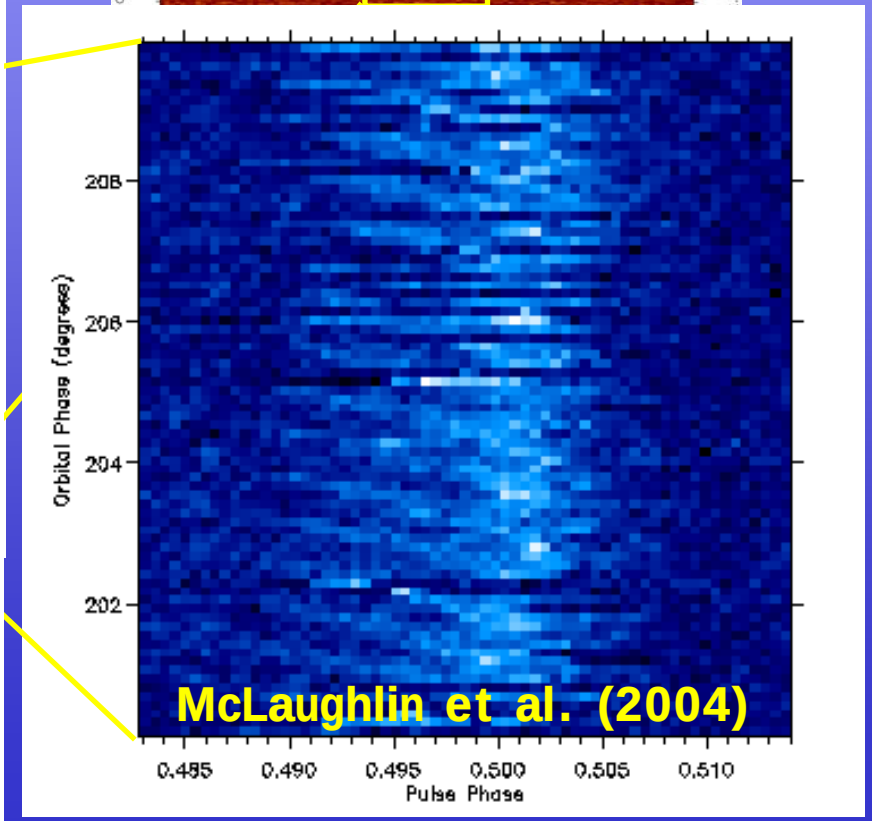
At 88° inclination, l.o.s. to A passes 46,000 km from B.

When A meets B: modulation of B emission by A



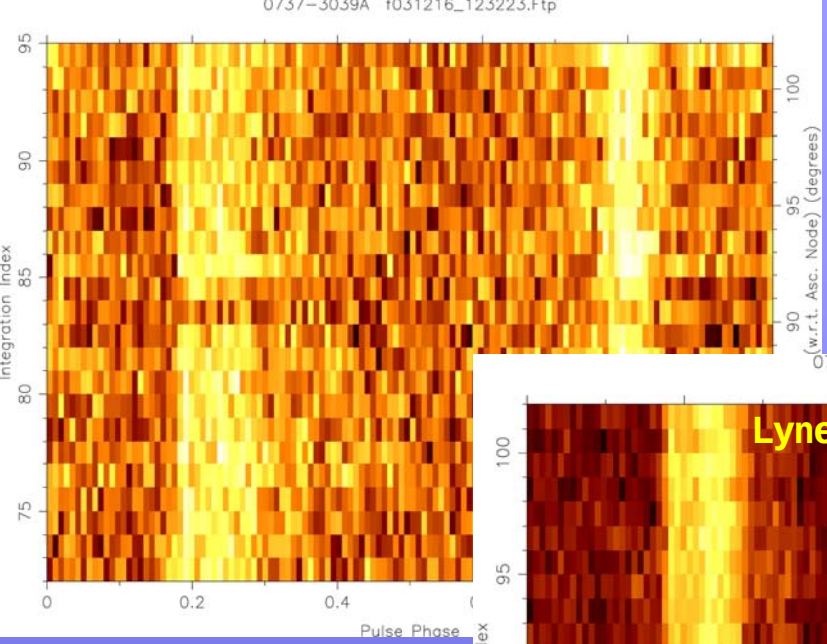




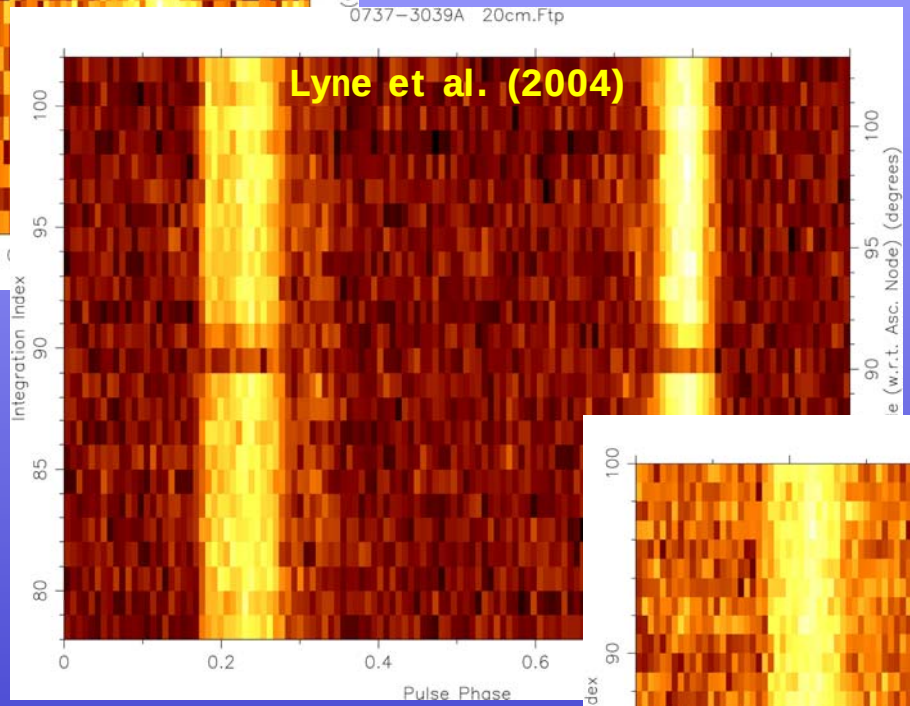


McLaughlin et al. (2004)

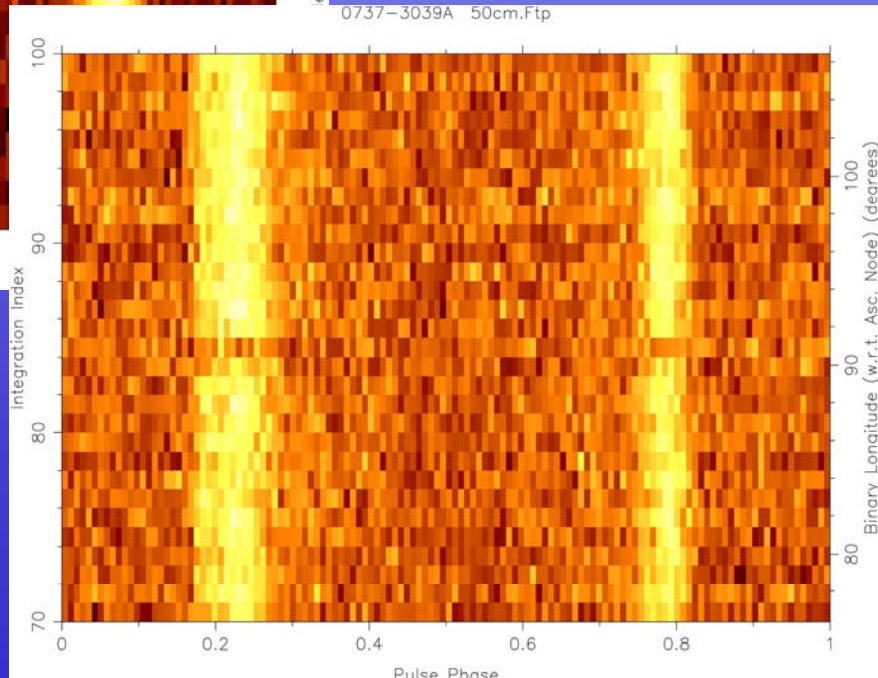
Eclipses of A



10cm



20cm



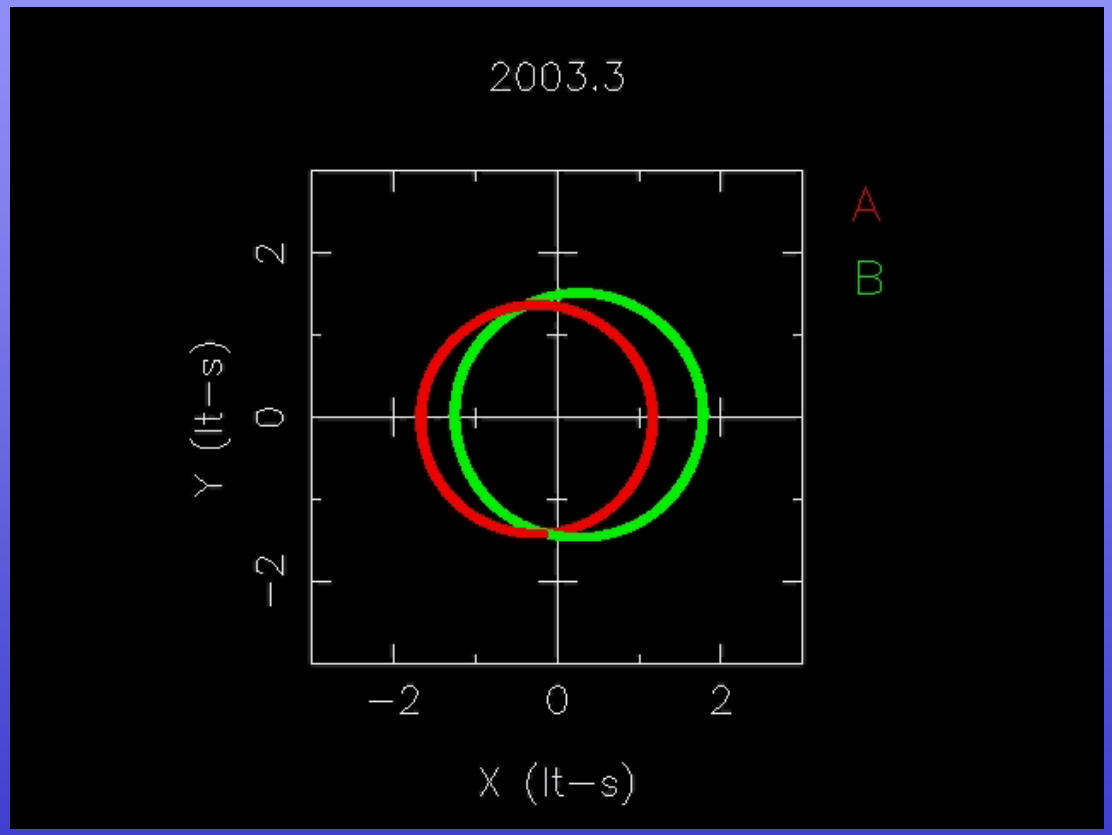
- At superior conjunction
- Lasting for ~27 sec
- Deepest just AFTER superior conjunction

50cm

GR with the double pulsar: The most relativistic system ever!

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

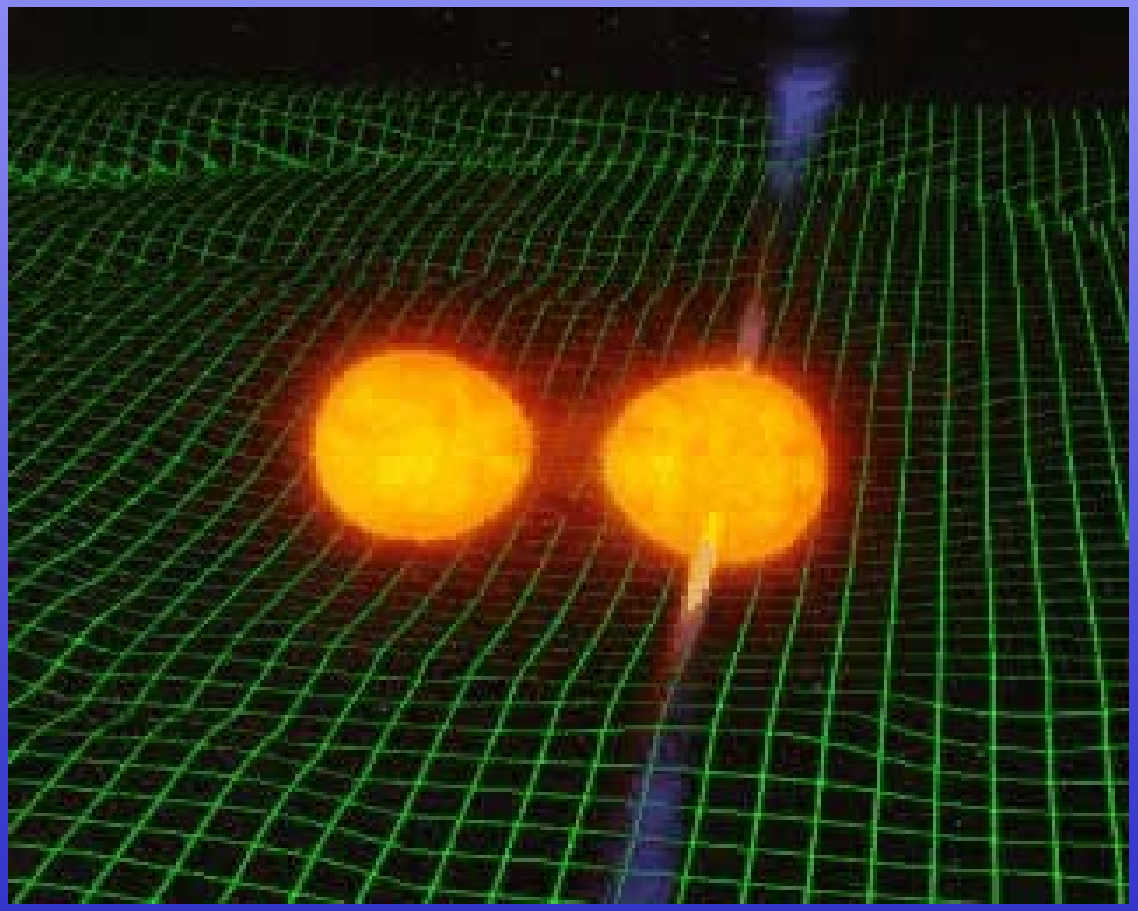
Remember Mercury?
$\dot{\omega} = 0.00012\,\mathrm{deg}/\,yr$



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

The double pulsar: Boost for gravitational wave hunters

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



Boost for gravitational wave hunters

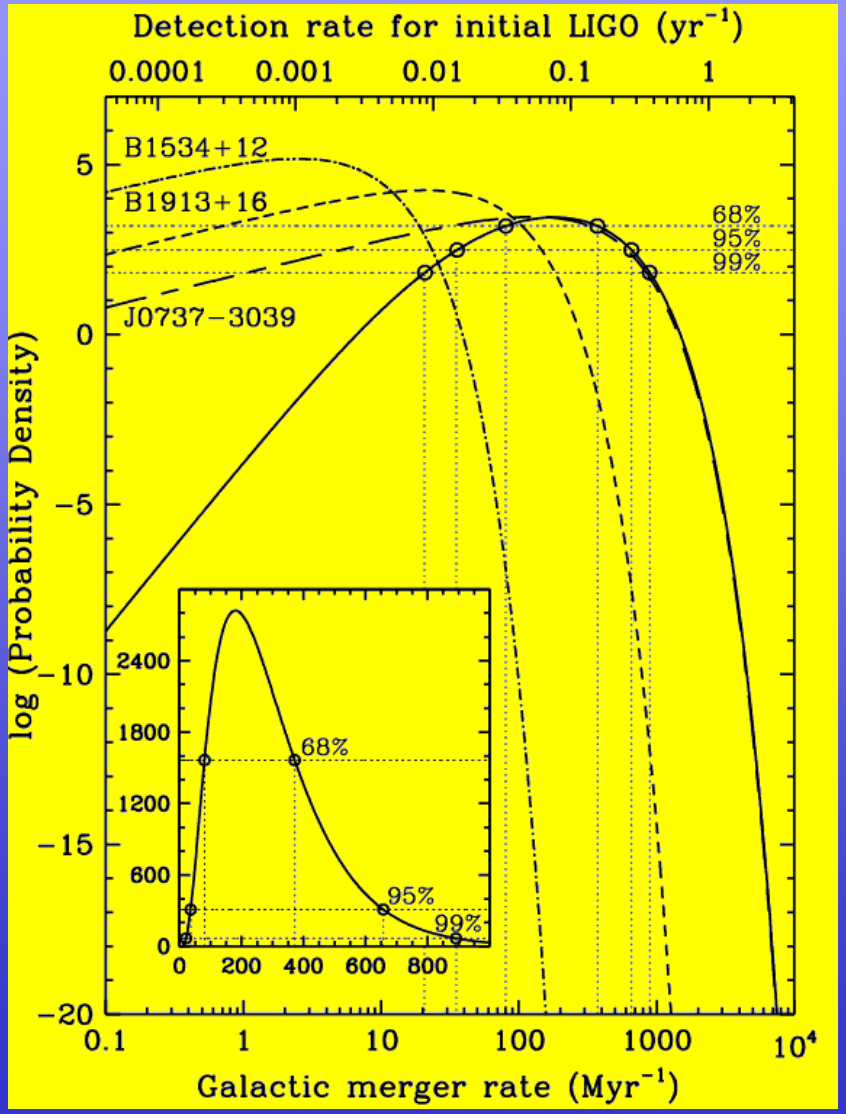
- Huge consequences for the detection rate of gravitational wave detectors!.

- The system is accelerated
- The system merges “soon”
- The system is close
- The luminosity is low

- Increase of about order of magnitude in the coalesence rate estimates of DNS systems.

Boost for gravitational wave hunters

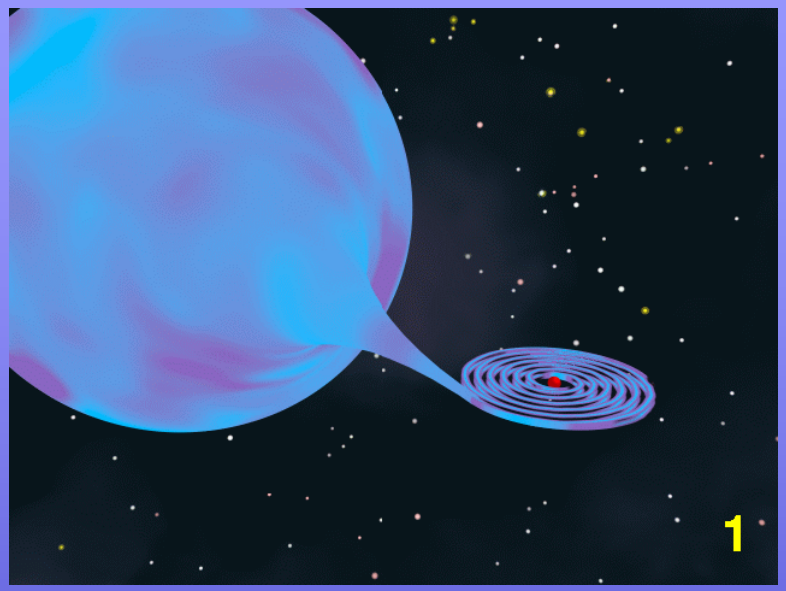
- Huge consequences for the detection rate of gravitational wave detectors!.

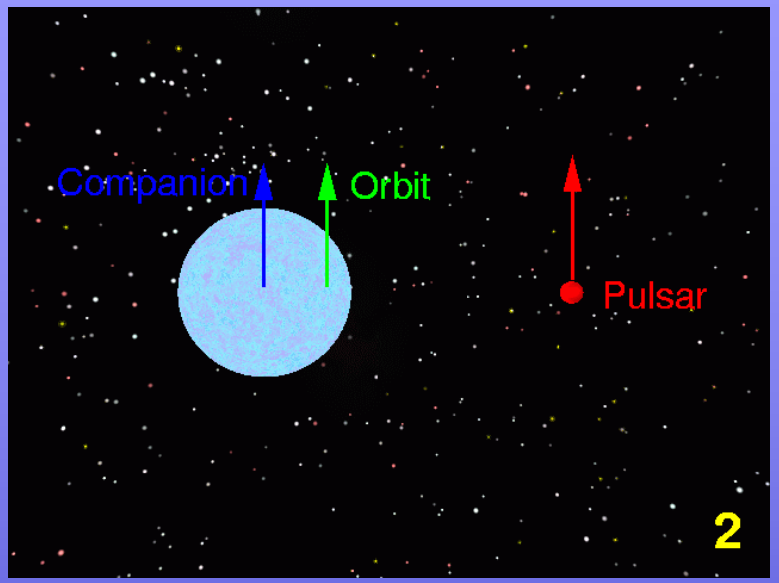


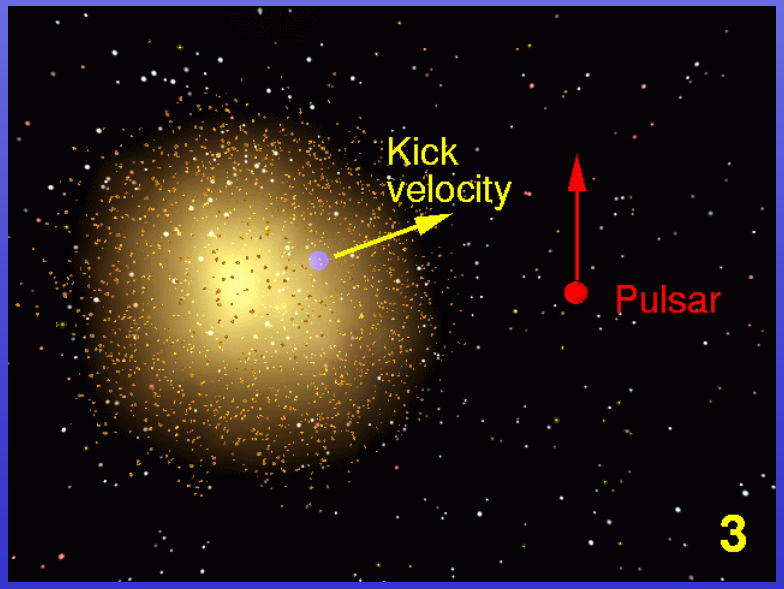
Kalogera et al. 2004

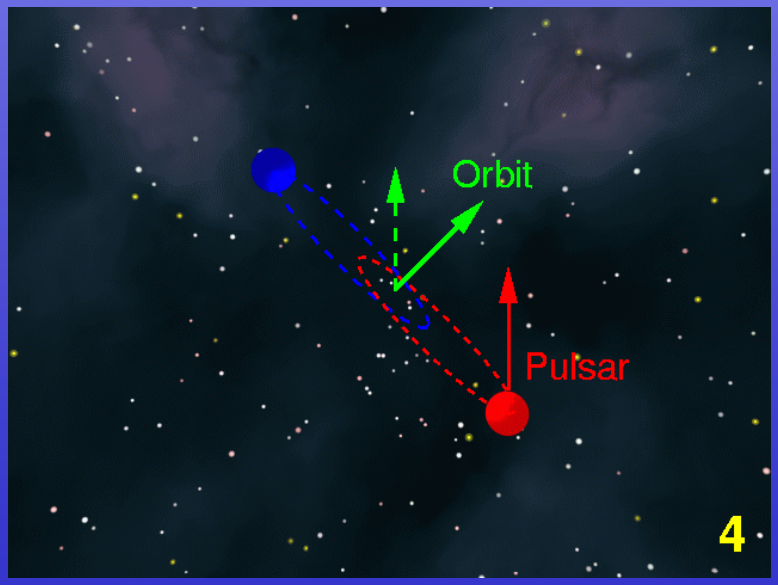
- **Increase of about order of magnitude in the coalesence rate estimates of DNS systems.**

Spin-Orbit Coupling due to misaligned spins



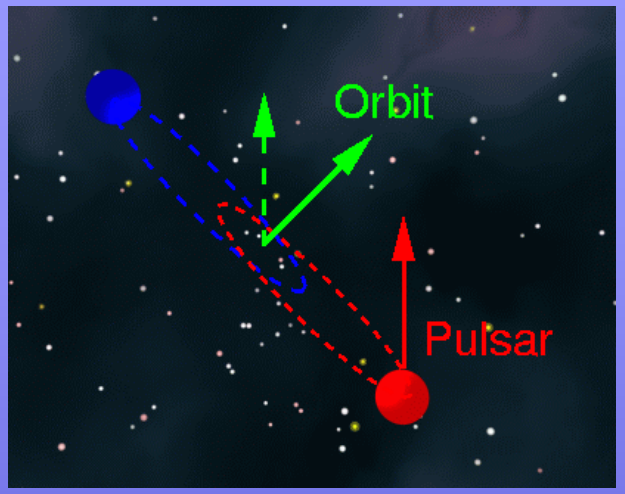






Geodetic Precession

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



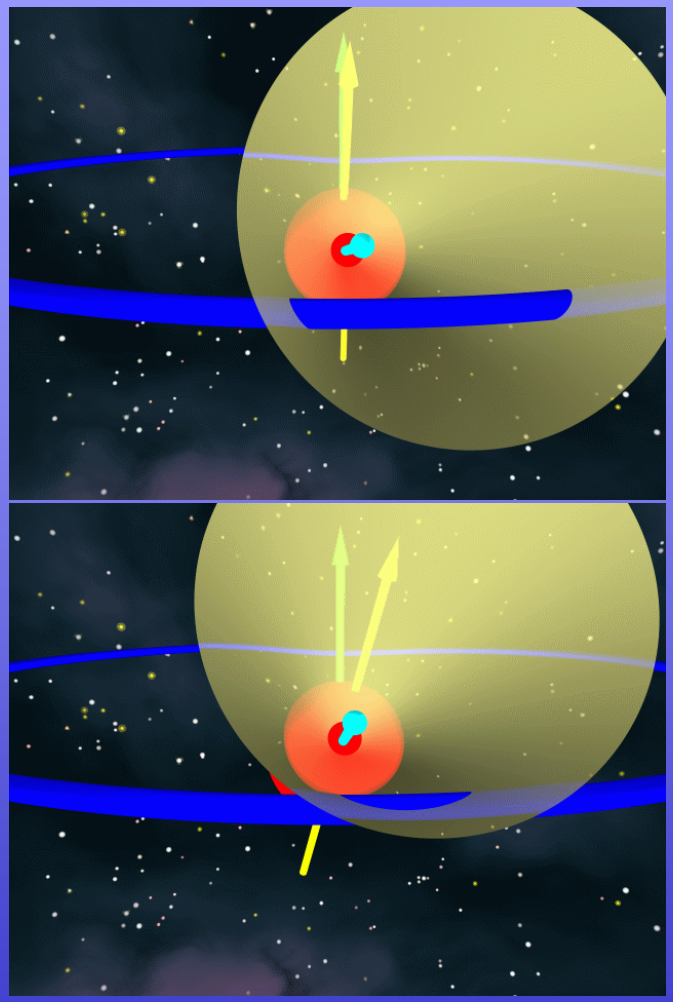
- Precession rate expected in GR: (e.g. Barker & O'Connell 1975, Börner et al. 1975)

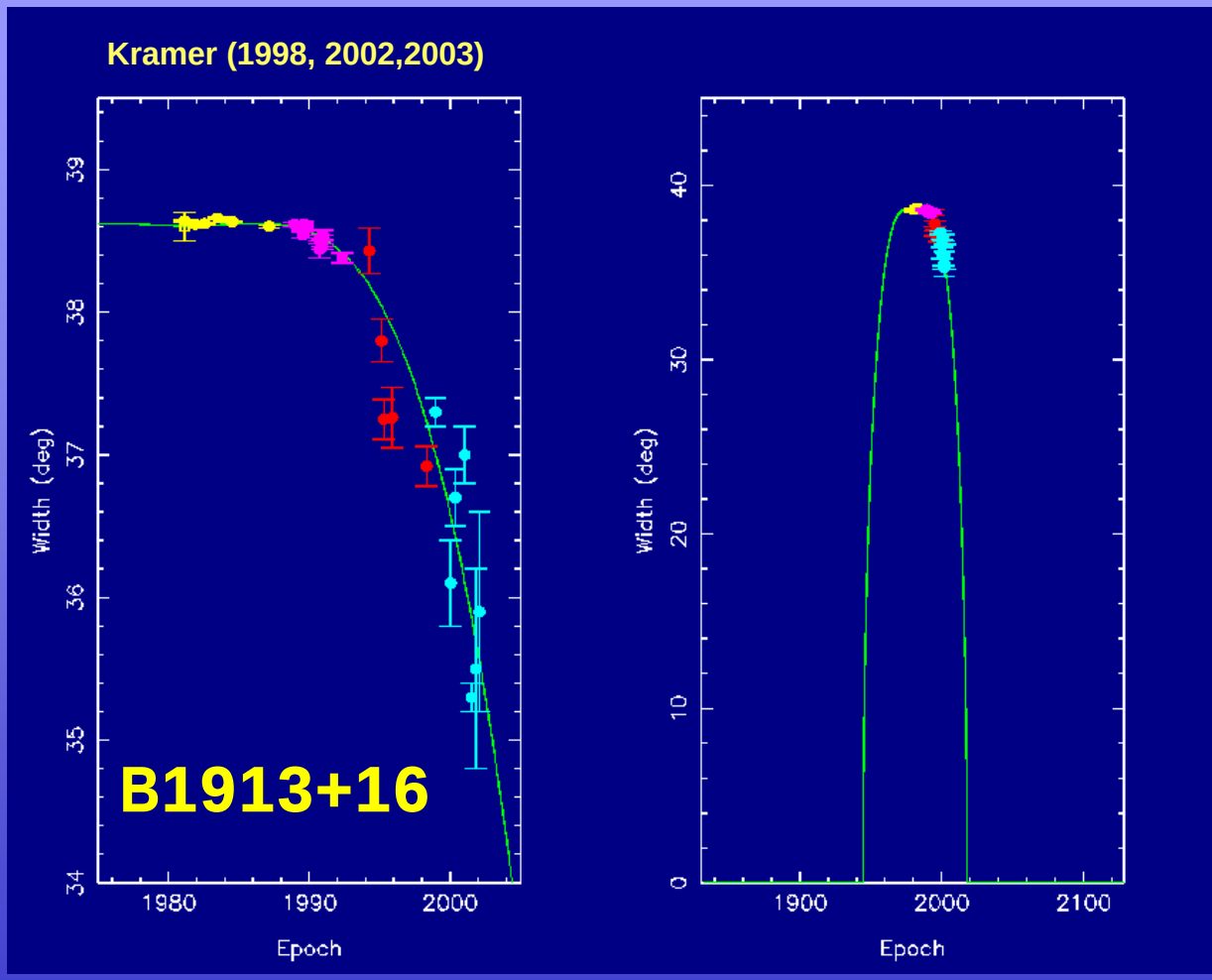
$$\Omega^p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \frac{1}{1-e^2}, \quad T_\odot = GM_\odot c^{-3}$$

(Again, only dependant on masses and Keplerian parms)

What effects do we expect to observe?

Effects of Geodetic Precession

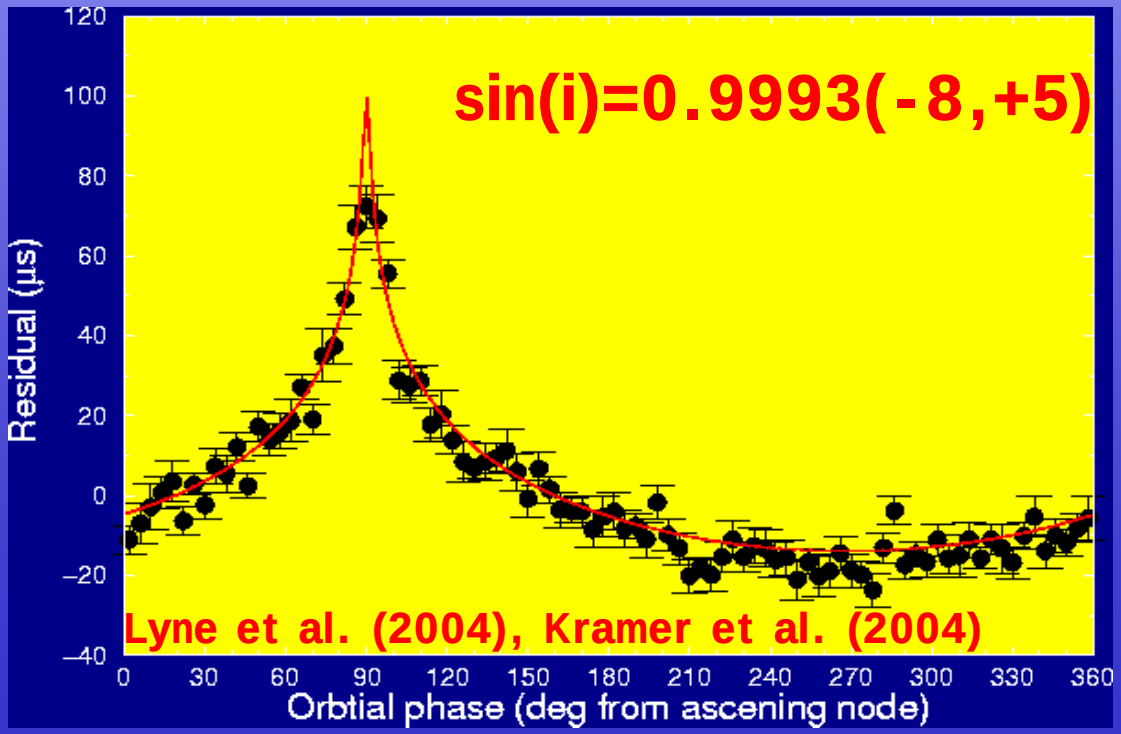




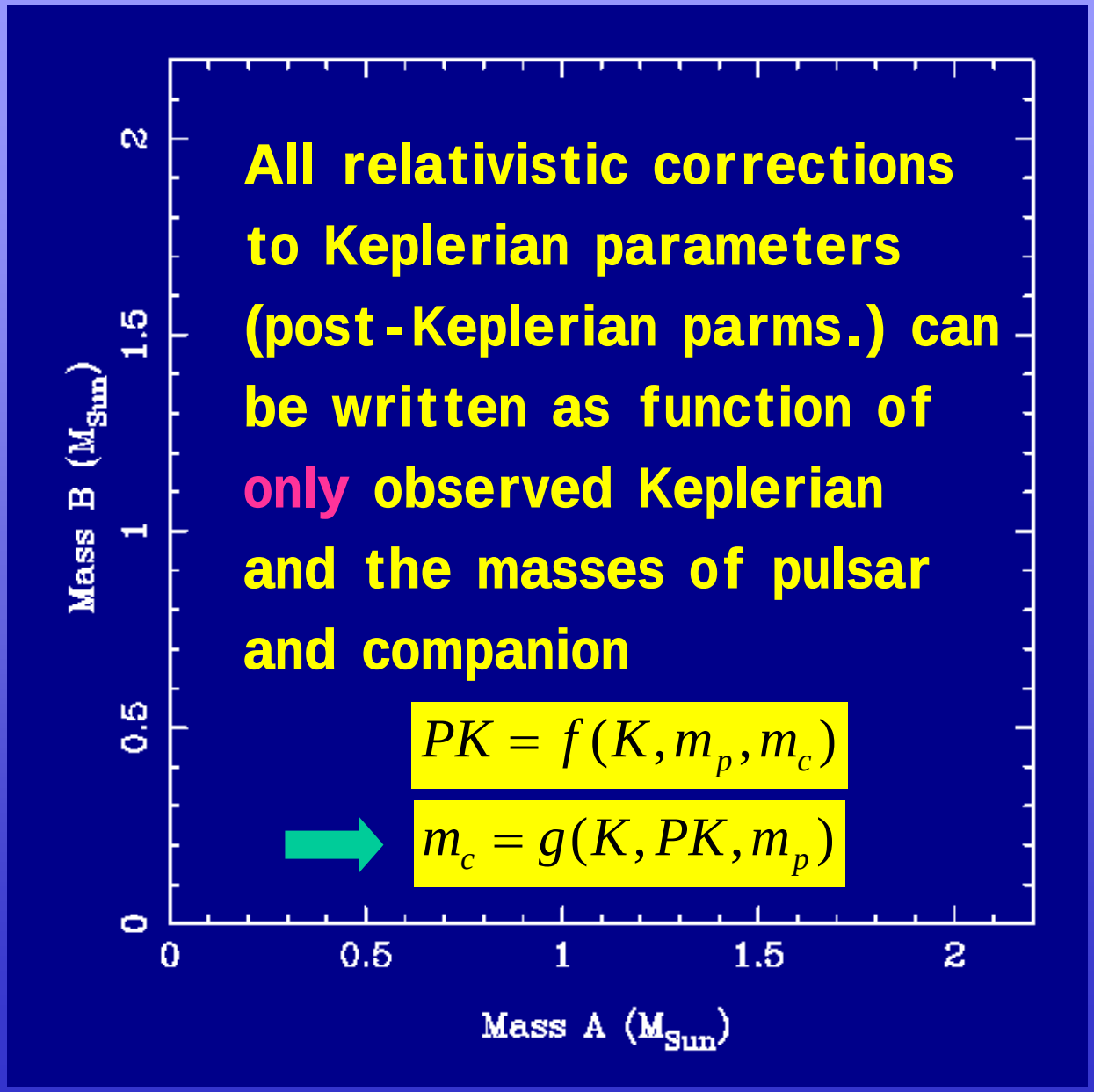
- Pulse shape changes expected – and seen!!
- B1913+16 (Period 300 yr) will disappear ~2025! (Kramer 1998)
- Total precession period of J0737-3039 only 75 years!!

Detection of Shapiro delay

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



Tests of relativistic gravity

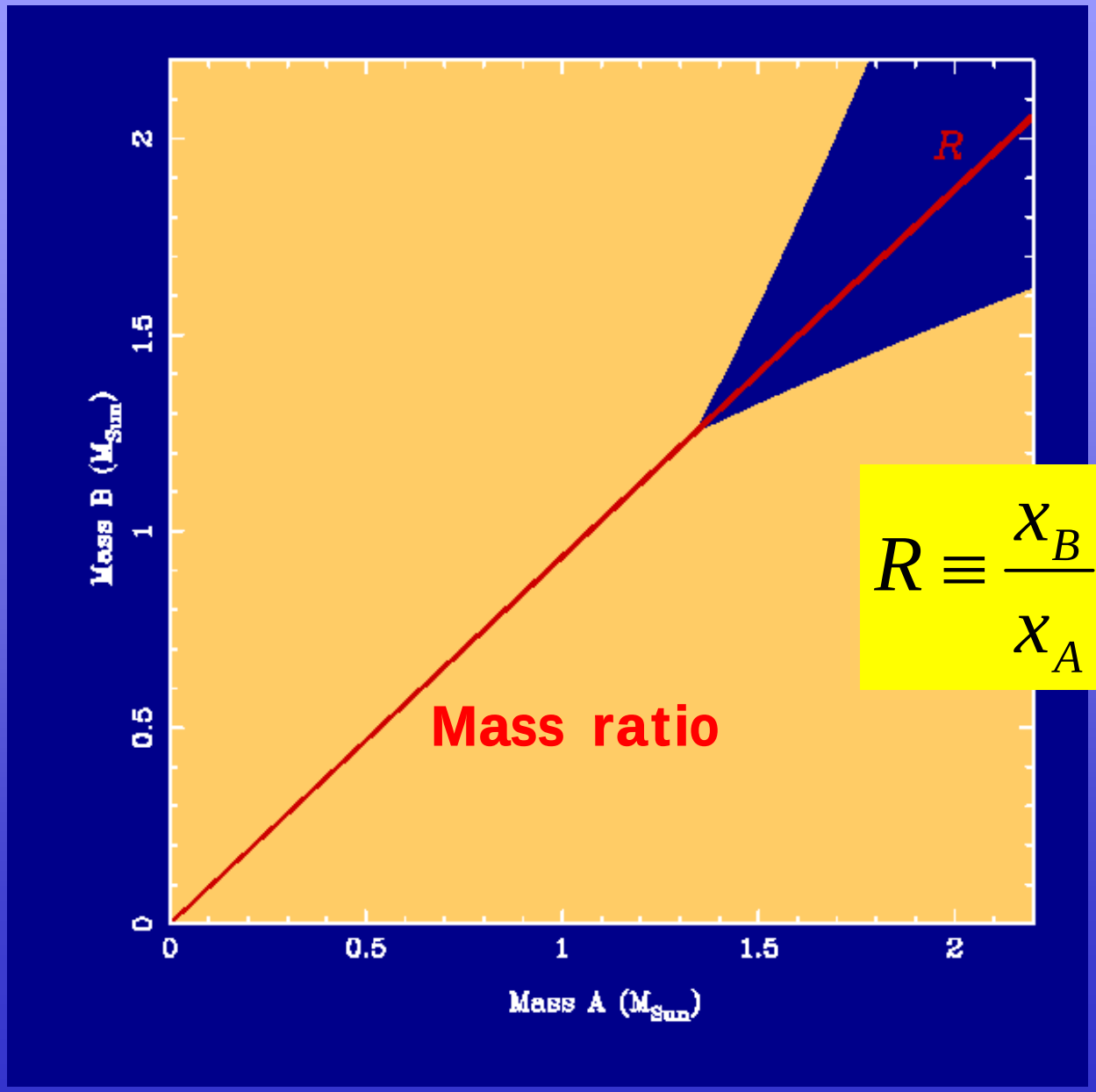


All relativistic corrections to Keplerian parameters (post-Keplerian parms.) can be written as function of only observed Keplerian and the masses of pulsar and companion

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

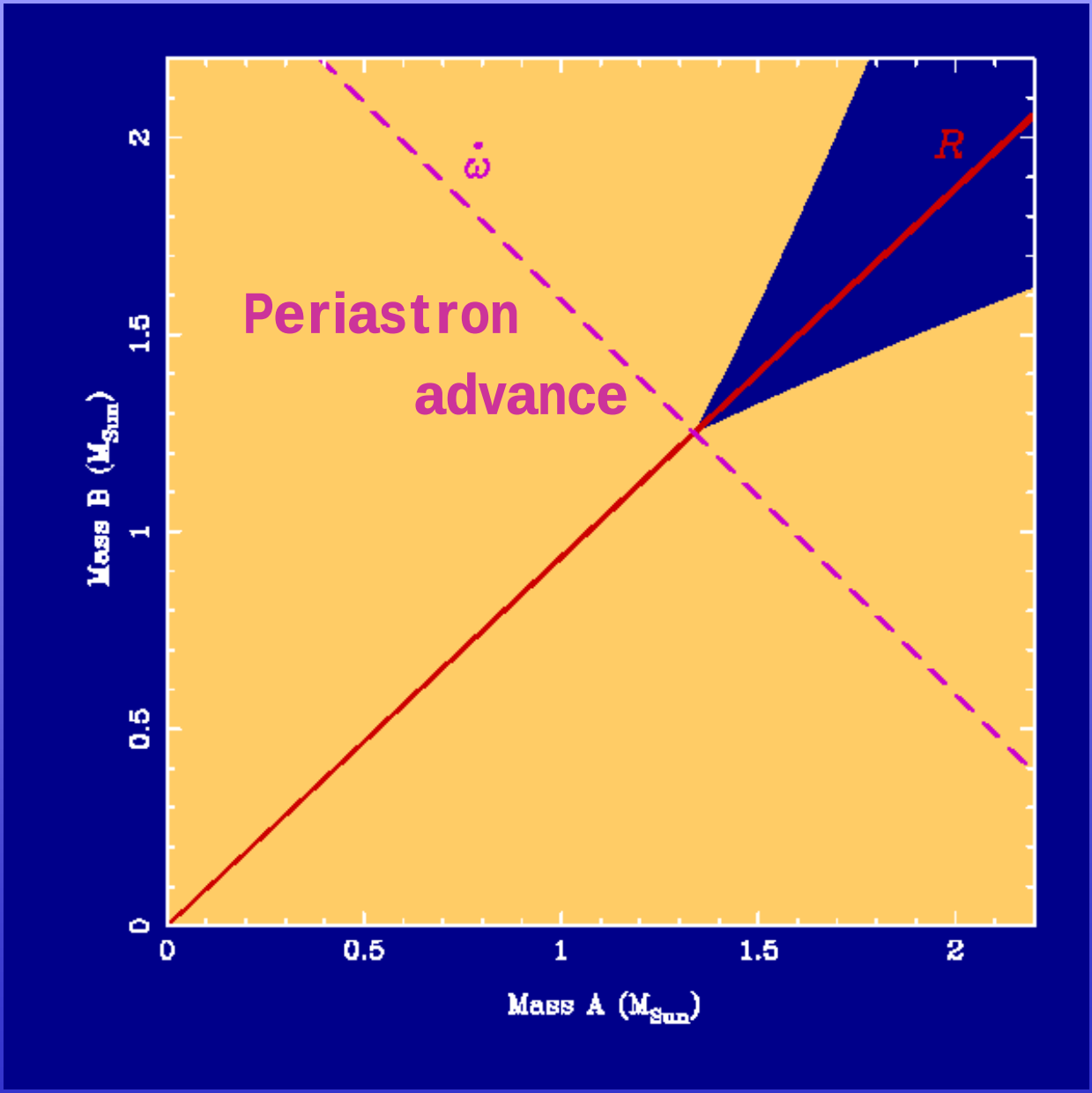
$$m_c = g(K, PK, m_p)$$

Tests of relativistic gravity

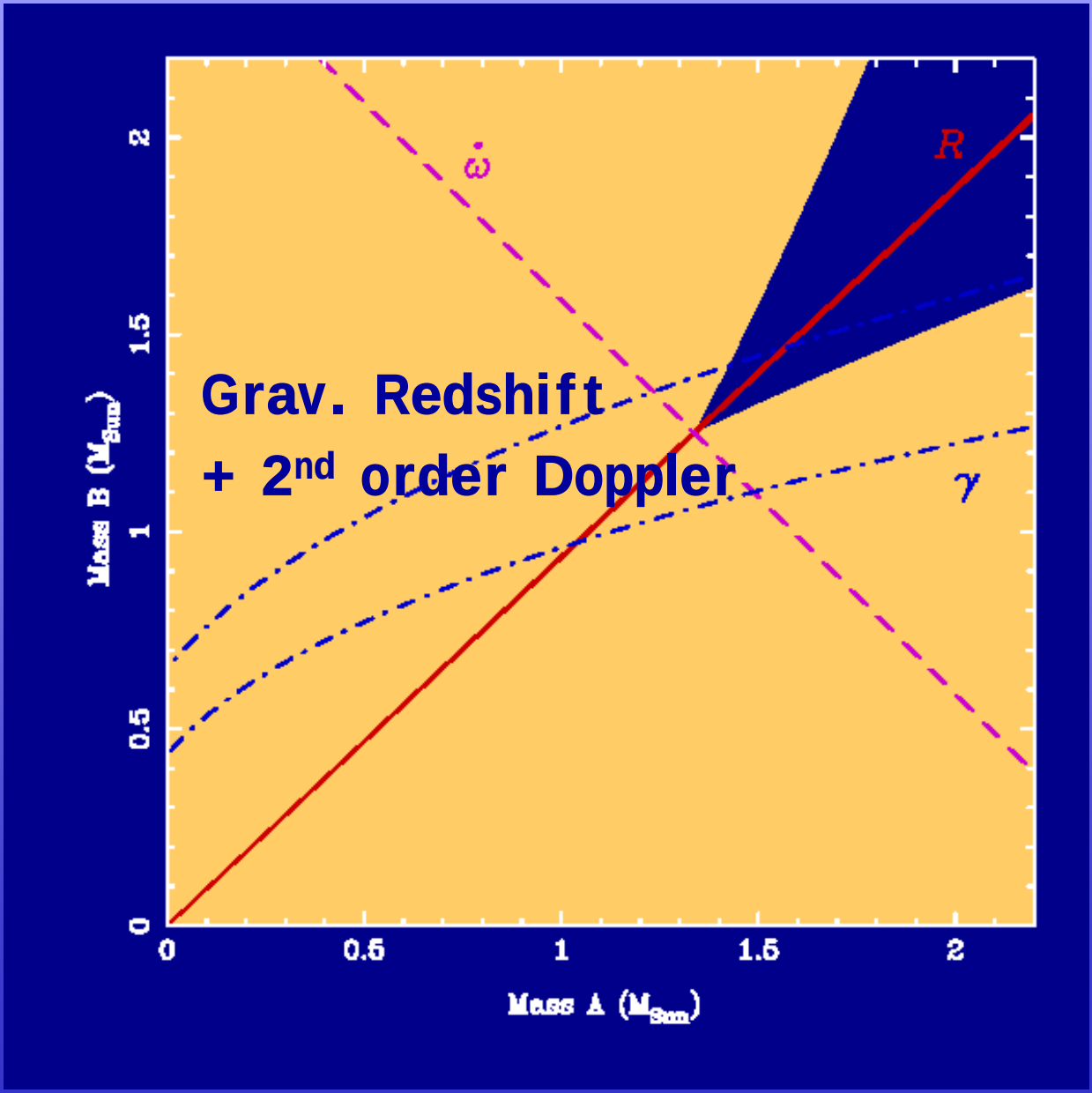


$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

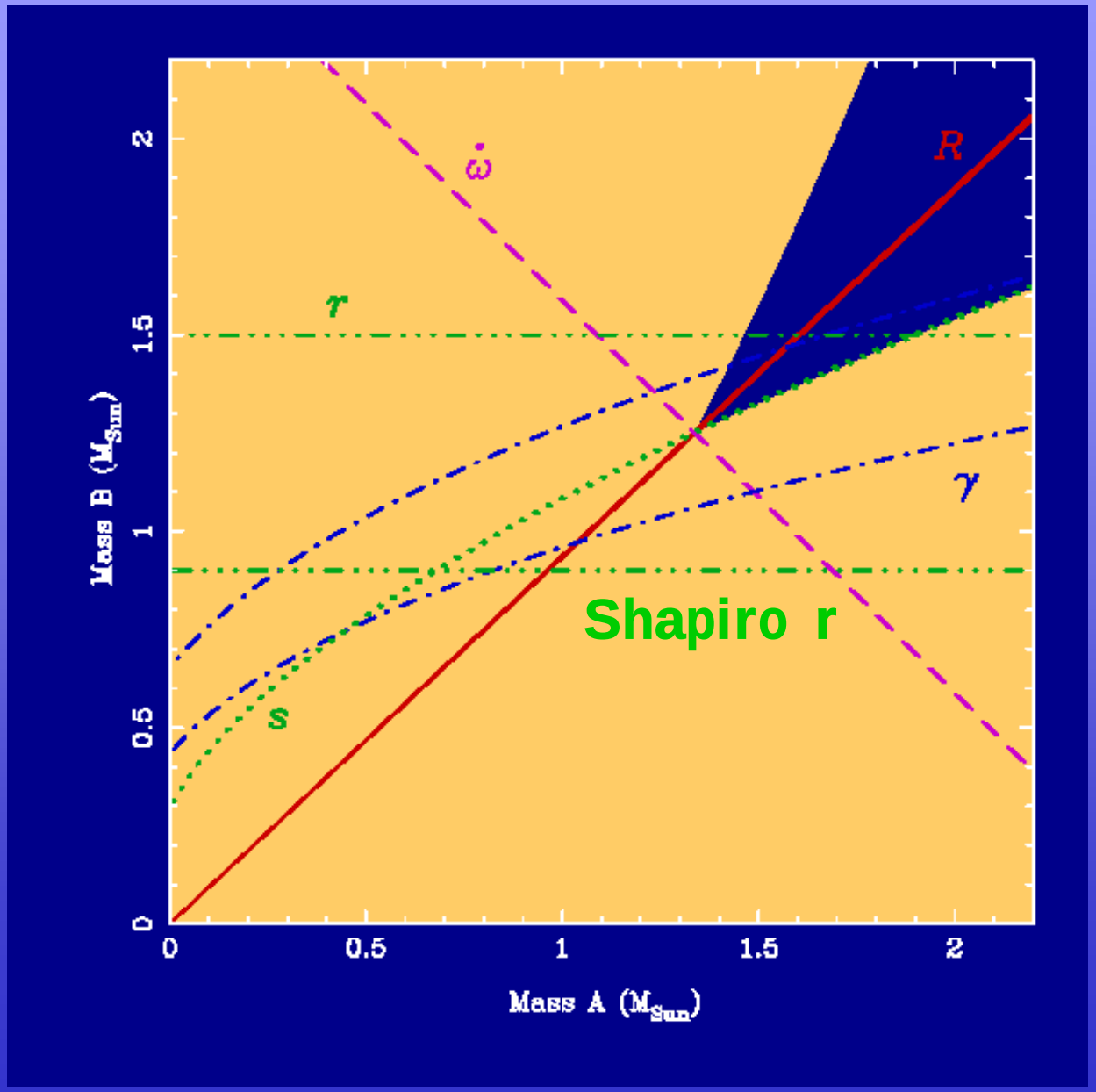
Tests of relativistic gravity



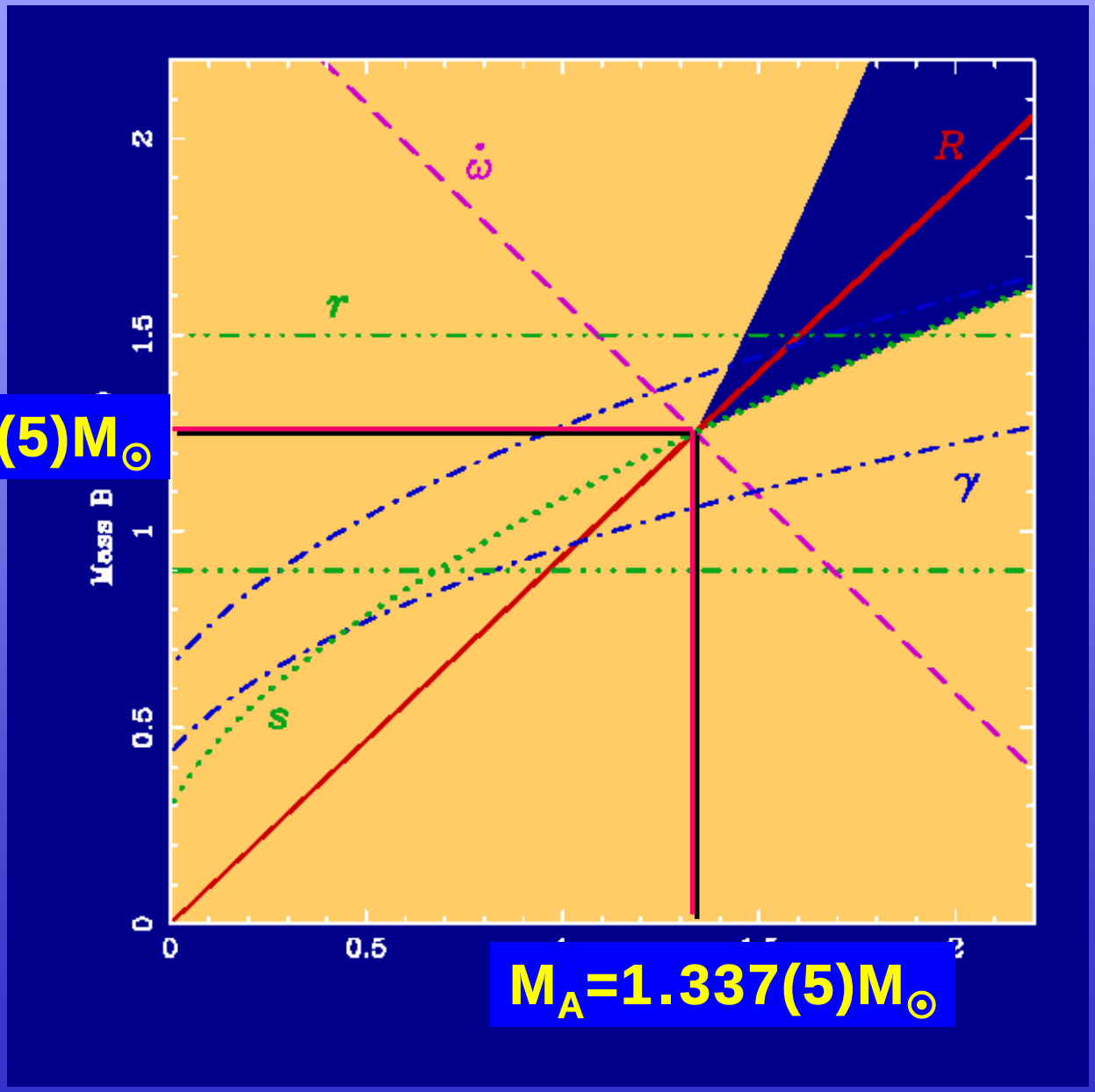
Tests of relativistic gravity



Tests of relativistic gravity

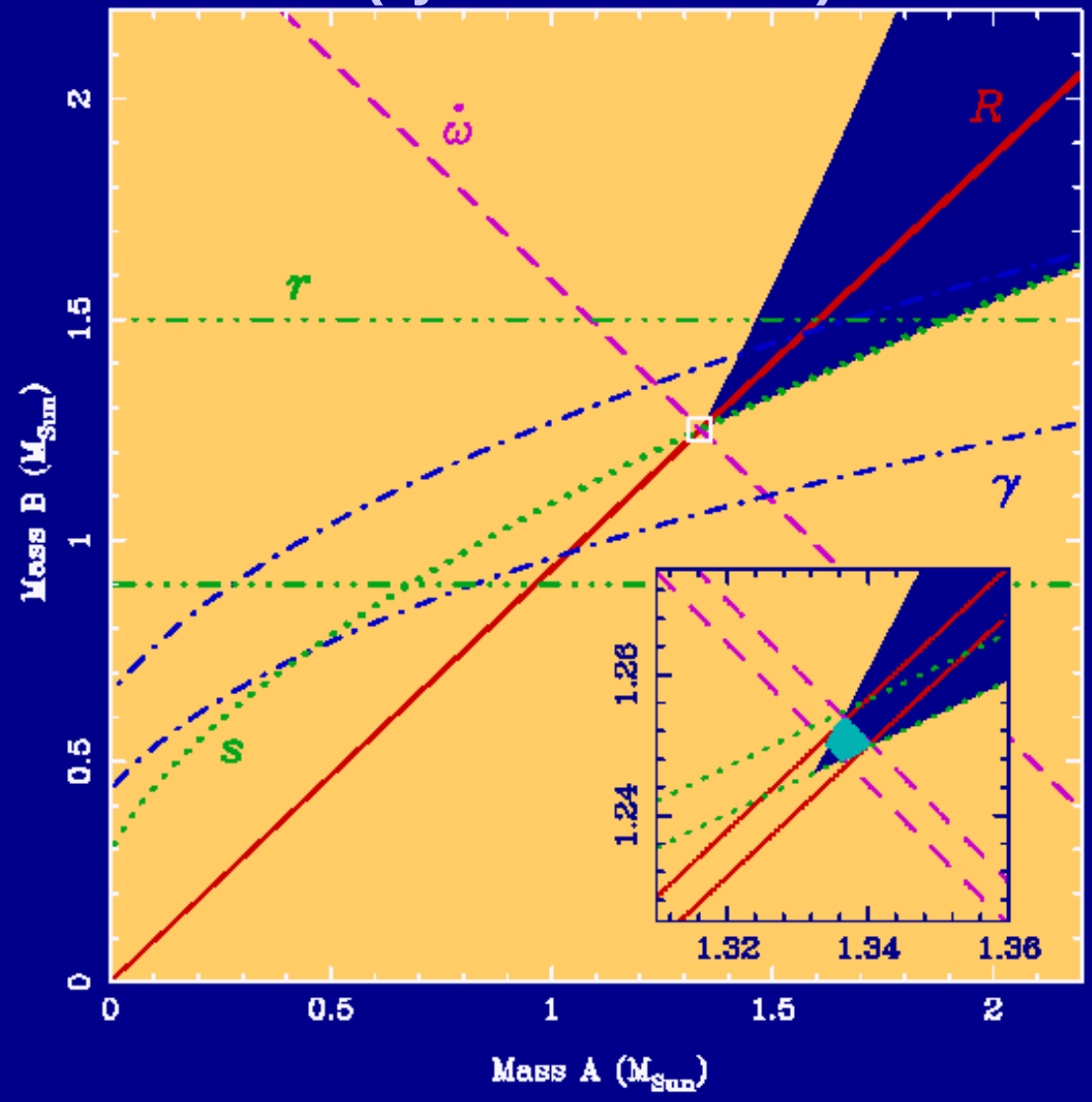


Tests of relativistic gravity

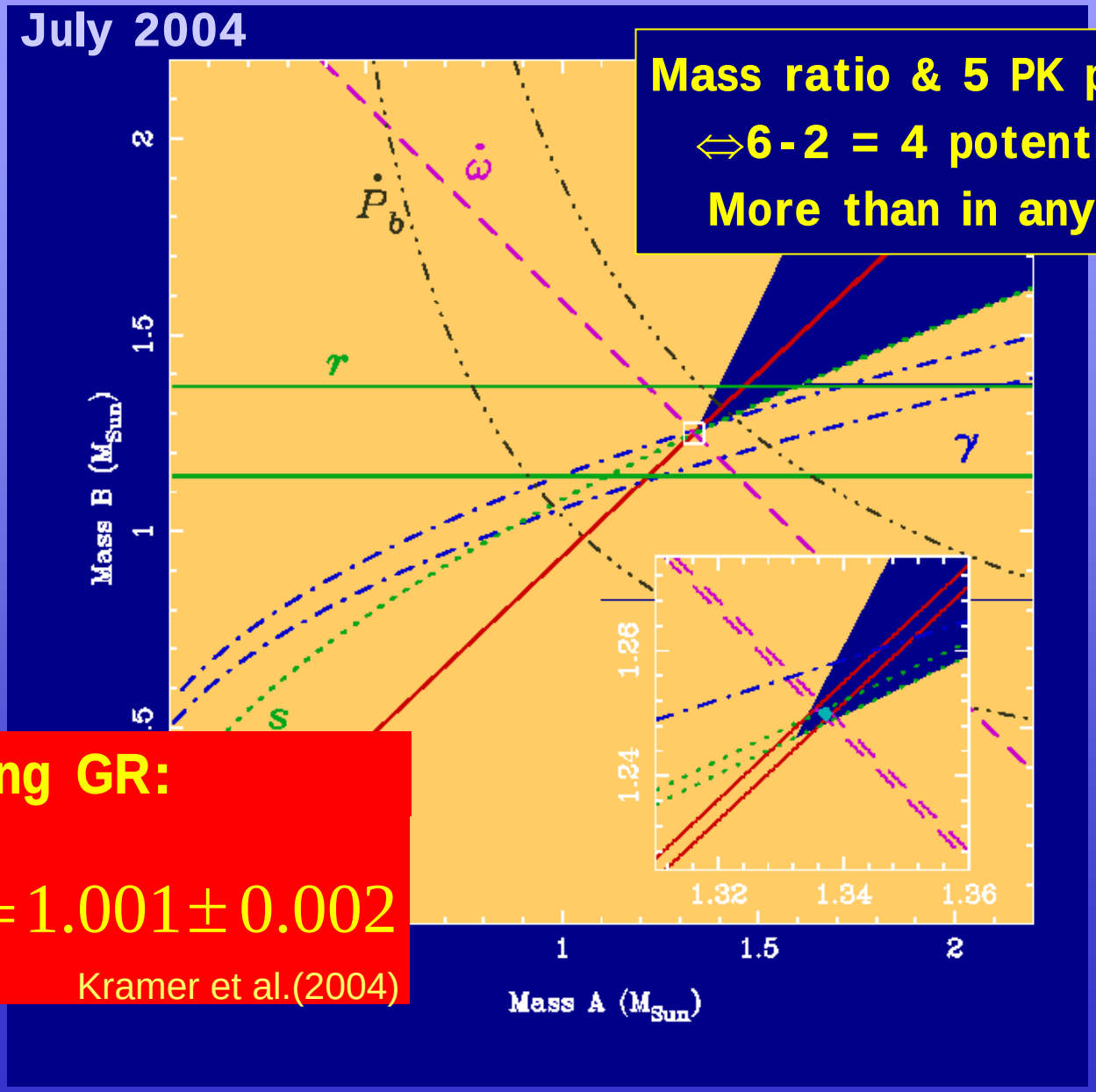


Tests of relativistic gravity

December 2003 (Lyne et al. 2004)



Tests of relativistic gravity



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

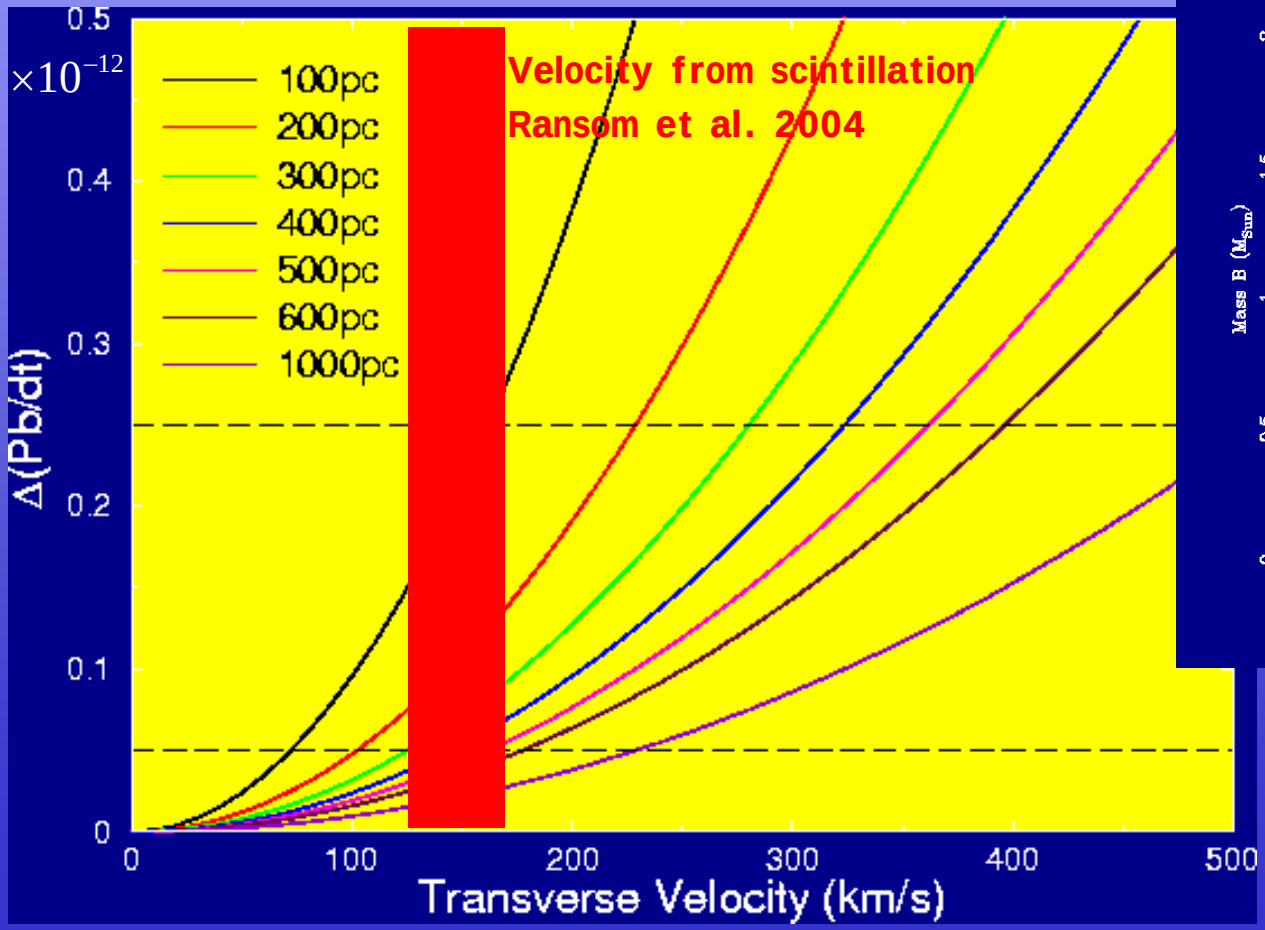
Testing GR:

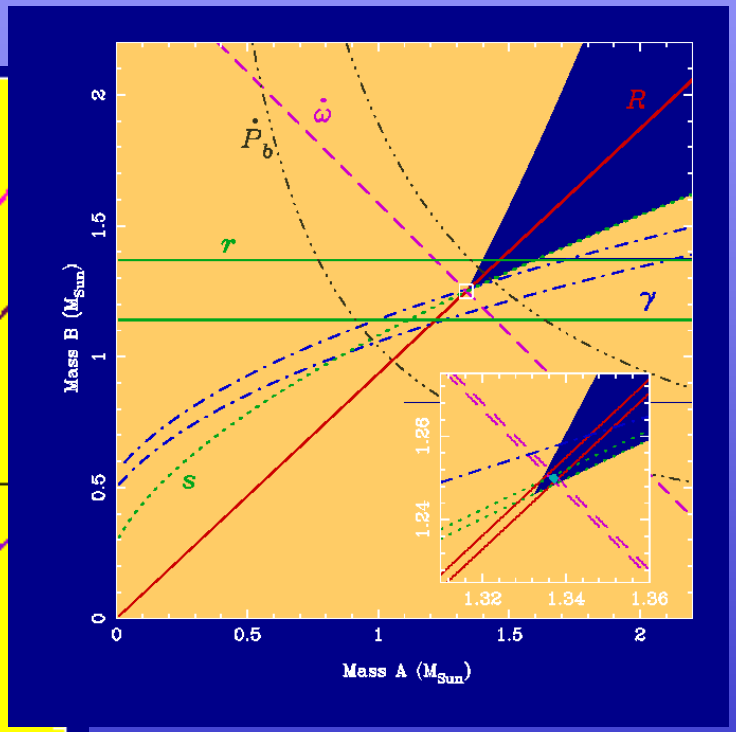
$$\frac{s^{\mathrm{obs}}}{s^{\mathrm{exp}}} = 1.001 \pm 0.002$$

Kramer et al.(2004)

Orbital decay detected

- Orbit shrinks 7mm/day
- Observed value biased by kinematics
- VLBI observations underway





$$\left(\frac{\dot{P}_b}{P_b}\right)^{Obs} = \left(\frac{\dot{P}_b}{P_b}\right)^{Int} + \frac{V_T^2}{c\,d}$$

Kepler's 3rd law: Significance of "R"

To 1PN [$(v/c)^2$] order, relative separation given by:

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

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

...so that for "any" theory [illegible] vity to 1PN order:

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

Qualitatively different constraint!

[illegible]dent of [illegible]eld effects!

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!

The significance of "R"

- Beyond 1PN approximation, definition of "centre-of-mass" difficult
- All depends on actual choice of coordinate system and mass definition, so that

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

will deviate from straight line in >1PN but with a precision which is probably much below what is measurable or comparable for PK parameters.

Also to consider: Aberration & Spin-Orbit Coupling

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)

Spin contributions

Total periastron advance to 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

14 x 1913+16's value! **SpinA= 0.0002 deg/yr**

Neutronstar 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!!!

Outline

Introduction

- Pulsar properties
- Binary pulsars as gravity labs

The Double Pulsar

- Discovery of “A” and “B”
- A unique testbed for GR

The Future

The Future

Double Pulsar:

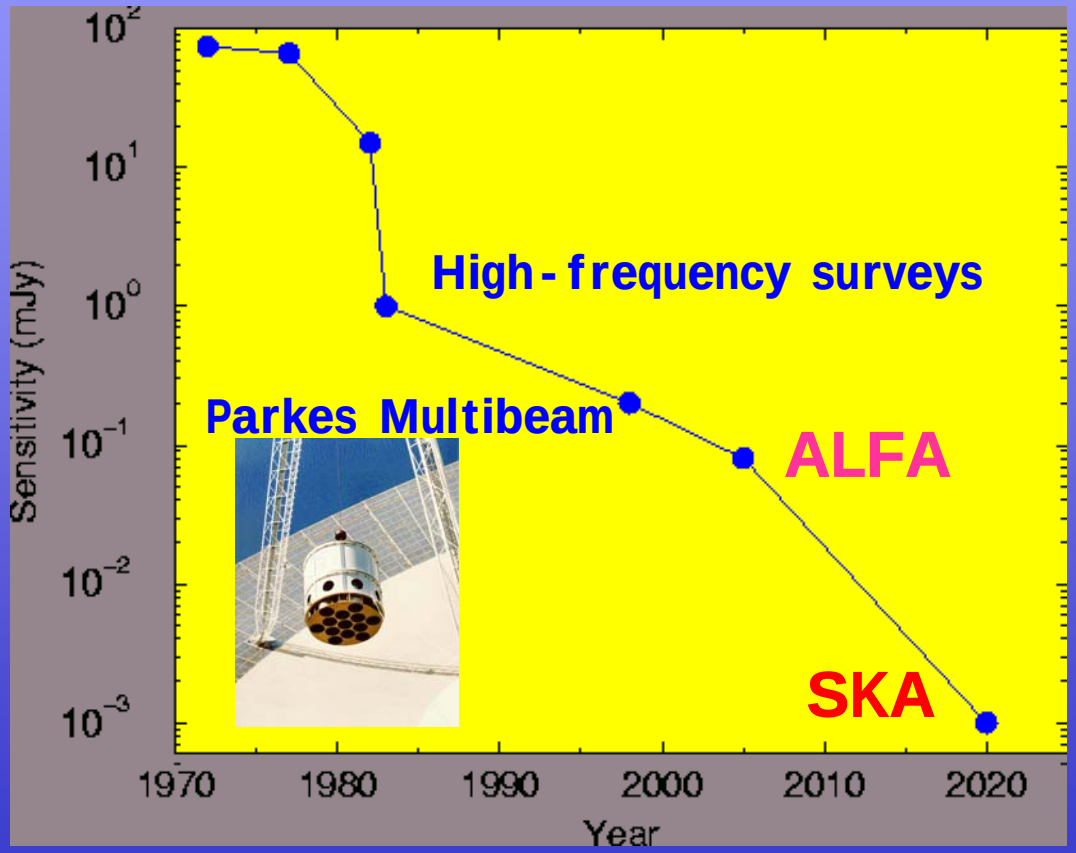
- Most over-constrained tests
- Measurement of aberration
- Measurement of 2nd order PN effects
  (How do Kepler's laws look like??)
- Moment of inertia

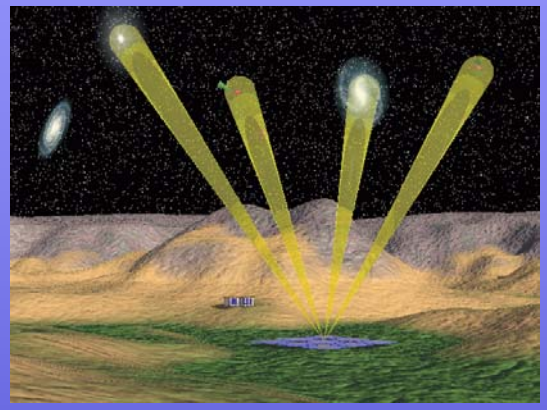
Black Holes:

- Black Hole Properties: Mass, Spin, Q-moment
- Cosmic Censorship Conjecture
- No-hair theorem

Cosmological Gravitational Wave Background

The Square-Kilometre-Array:
The biggest telescope on Earth!



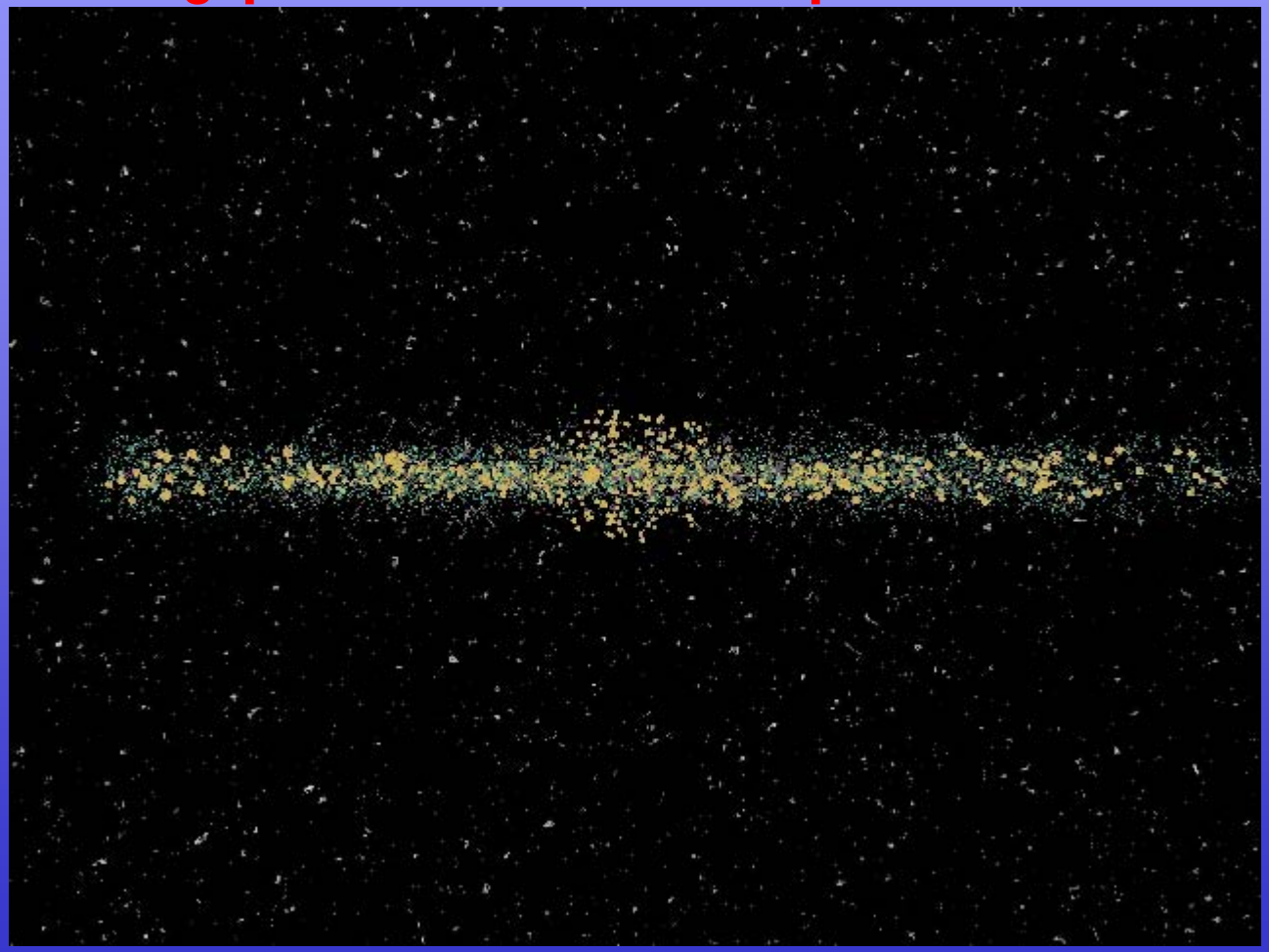


Collecting area = 1 square km!

Galactic Census with the SKA

Pulsar-Astrophysics will benefit from SKA twice:

- **Unique sensitivity: essentially all ~20,000 pulsars**
- **Unique timing precision and multiple beams!**



- **Blind survey for pulsars will discover PSR-BH systems!**

Black Hole properties

- Astrophysical black holes are expected to rotate
- BH have **spin** and **quadrupole moment**
- Both can be measured by high precision pulsar timing via **relativistic and classical spin-orbit coupling**

See Wex & Kopeikin (1999)

- **Not easy! It is not possible today!**
- **Requires SKA sensitivity!**

Test Cosmic Censorship Conjecture & No-Hair Theorem!

Cosmological Gravitational Wave Background

Pulsar timing can also detect a

stochastic gravitational wave background

Sources:

- **Inflation**
- **String cosmology**
- **Cosmic strings**
- **phase transitions**

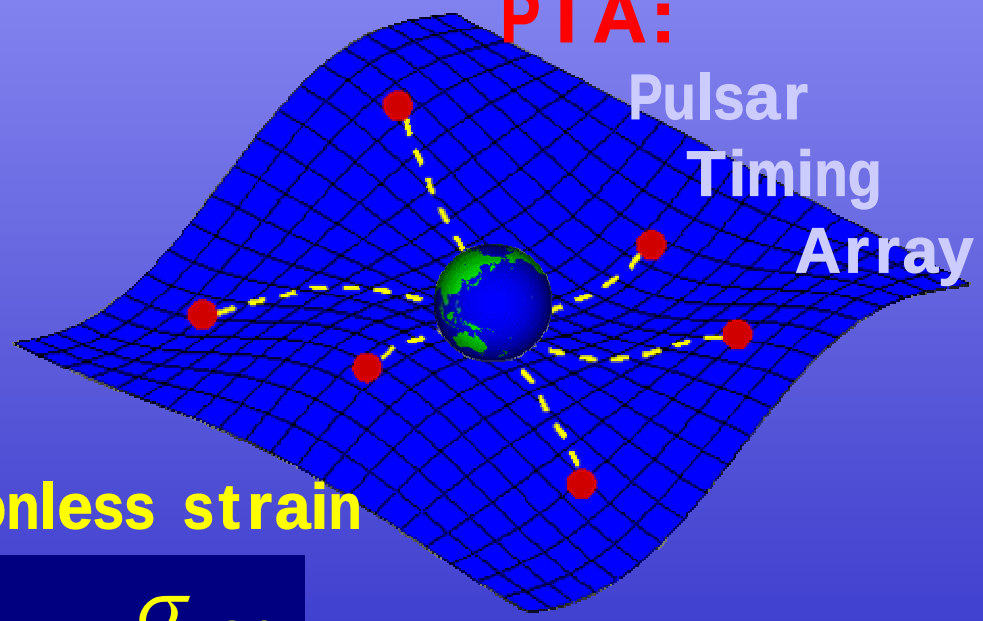
$$h_0^2 \Omega_{GW}(f) \sim const.$$

and also: **merging massive BH binaries in early galaxy evolution**

$$h_0^2 \Omega_{GW}(f) \propto f^{2/3}$$

Cosmological Gravitational Wave Background

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

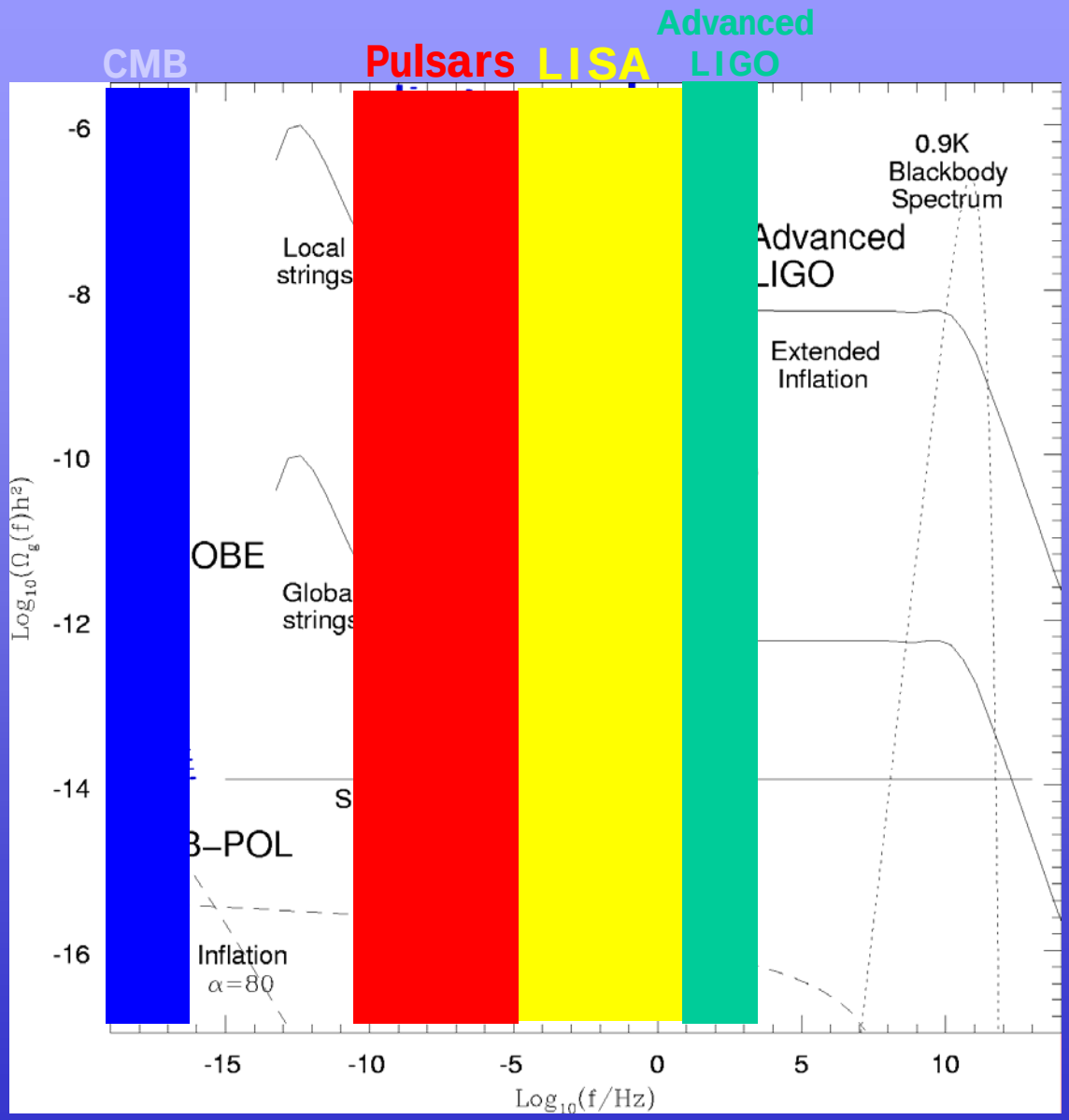


- Perturbation in space-time can be detected in timing residuals

- Sensitivity: dimensionless strain

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

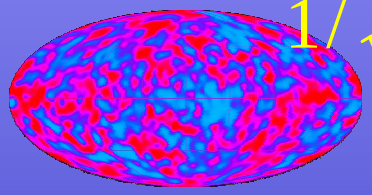
Cosmological Gravitational Wave Background



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

Summary

- The double pulsar is most wonderful system to study relativistic gravity and pulsar magnetospheres!
- Amazing possibilities already, e.g. most precise test
- Even more achievable with the SKA
- Science will be qualitatively different
- Finally, we may able to give the reward to Einstein

Or not?