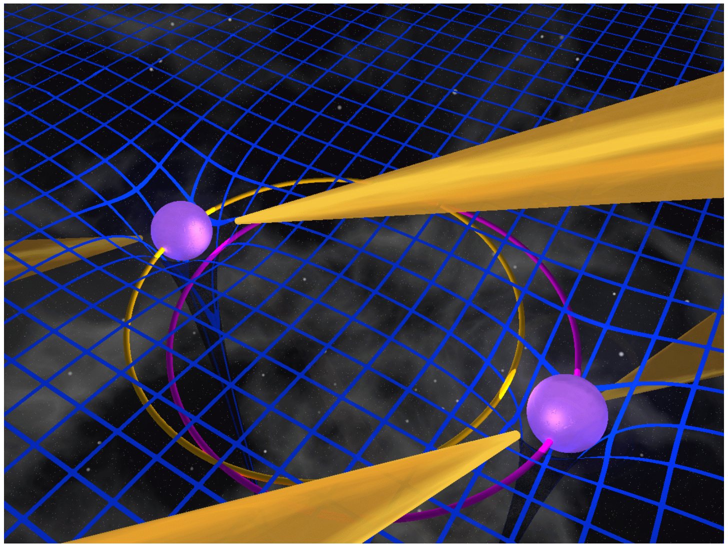
The Double Pulsar: A Decade of Discovery

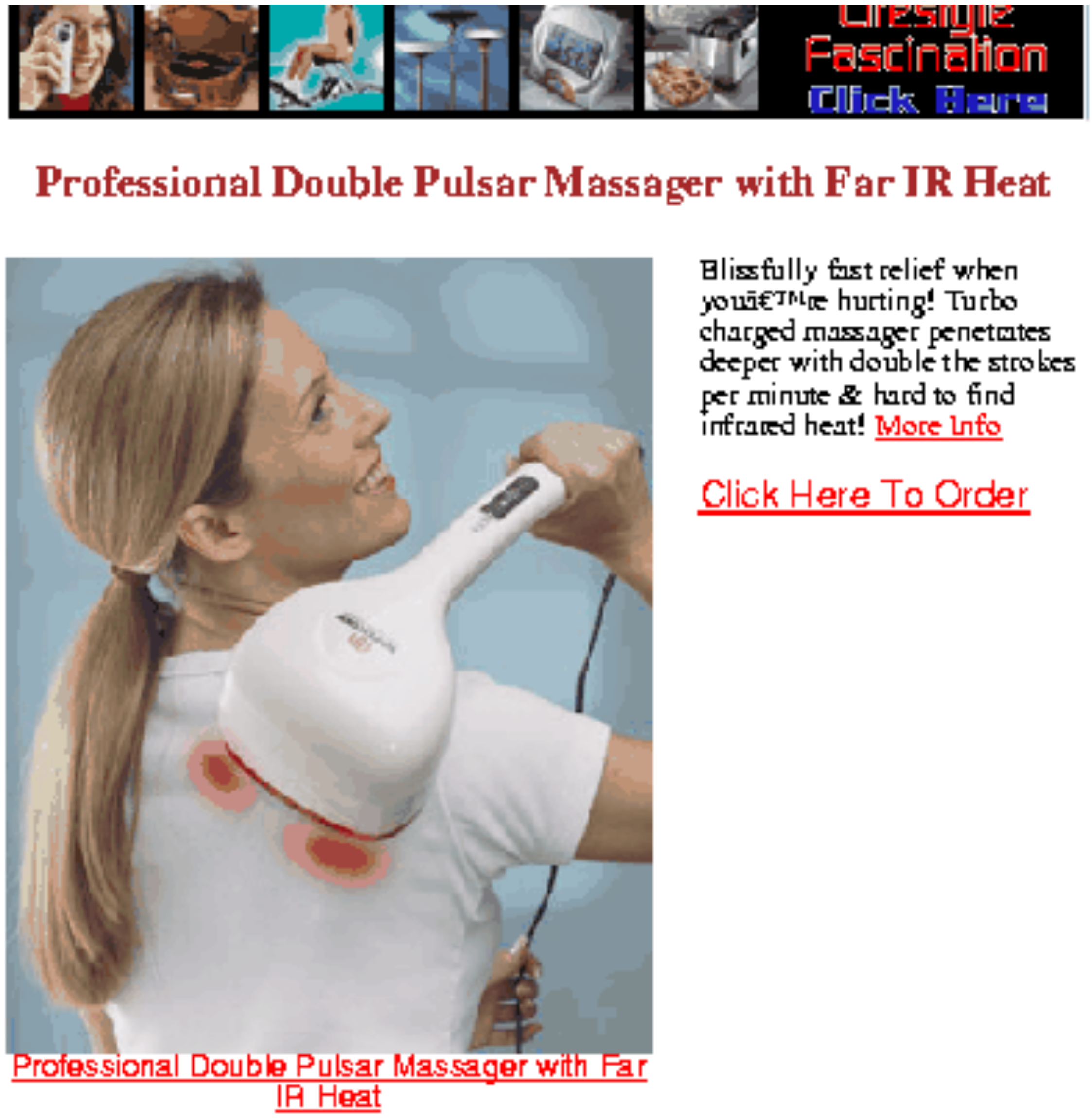
(and what you can do over the next decade with FAST!)



Maura McLaughlin
West Virginia University

20 May 2014

:

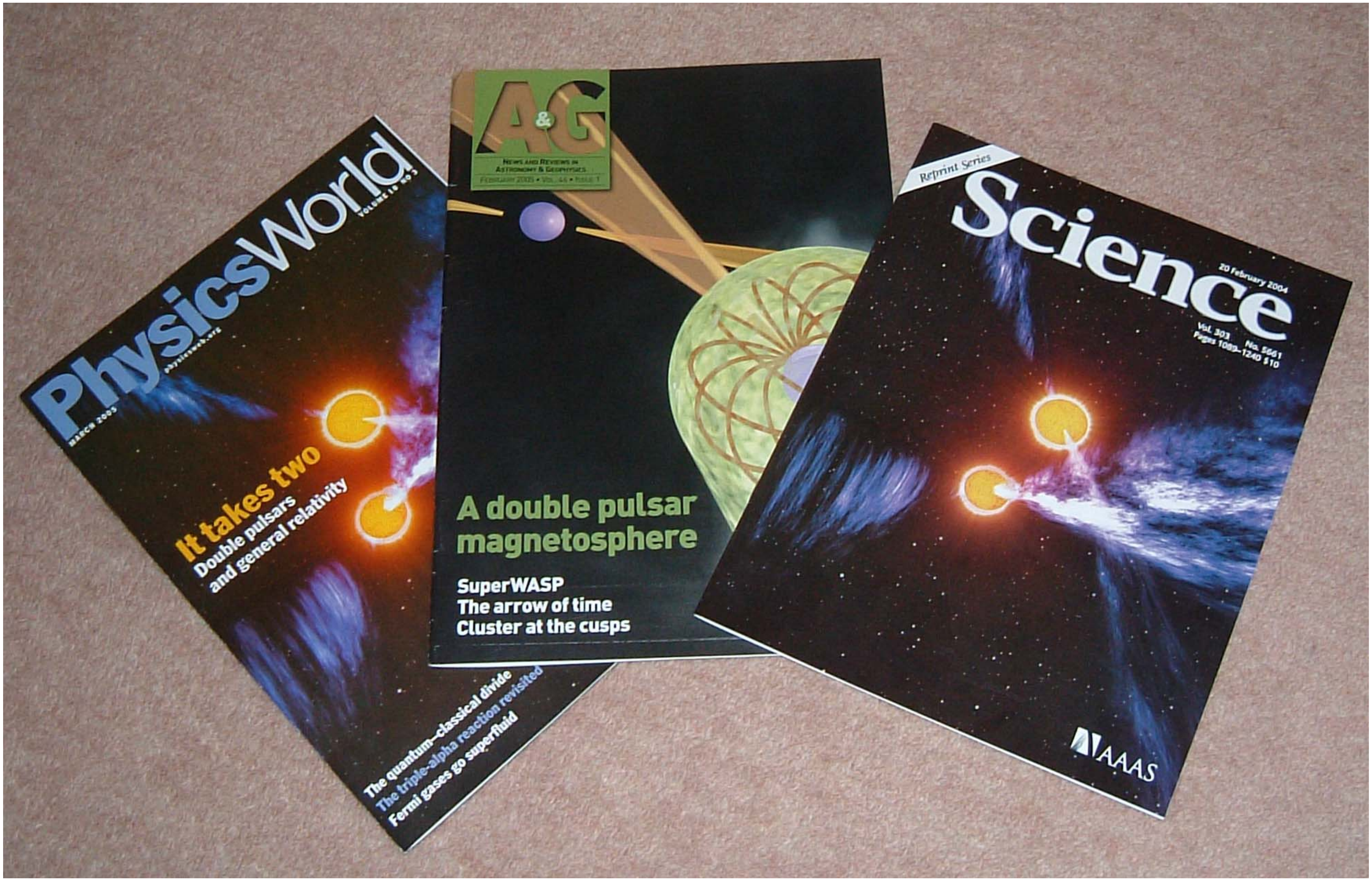


Professional Double Pulsar Massager with Far IR Heat

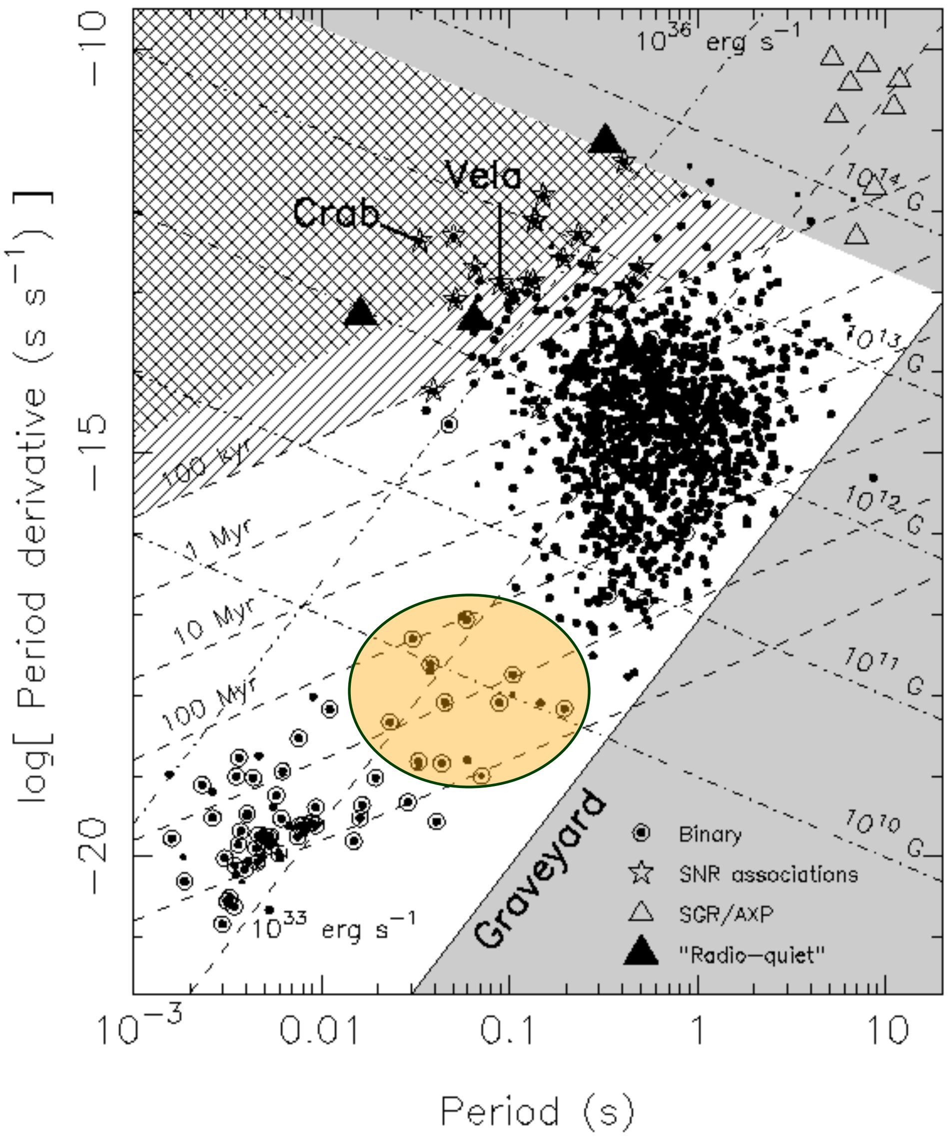
Blissfully fast relief when youâ€™re hurting! Turbo charged massager penetrates deeper with double the strokes per minute & hard to find infrared heat! More Info

Click Here To Order

Professional Double Pulsar Massager with Far IR Heat


PhysicsWorld
March 2005
It takes two
Double pulsars and general relativity
The quantum–classical divide
The triple-alpha reaction revisited
Fermi gases go superfluid
A&G
News and Reviews in Astronomy & Geophysics
A double pulsar magnetosphere
SuperWASP
The arrow of time
Cluster at the cusps
Reprint Series
Science
20 February 2004
Vol. 303 No. 5661
Pages 1089–1240 $10
AAAS

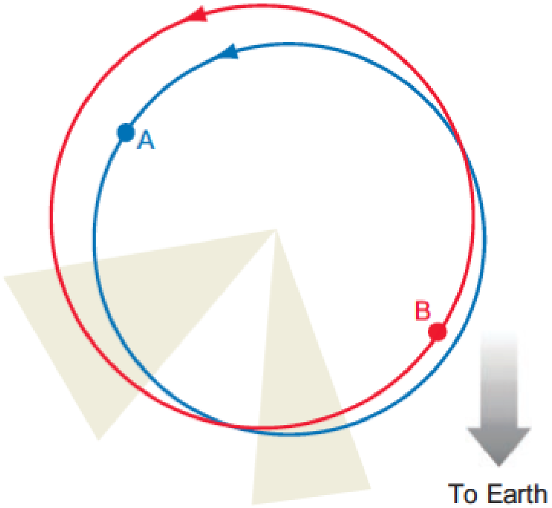
Double neutron star systems



- The pulsar catalog lists 2328 pulsars.
- Of those, 229 are in binaries, most with white dwarf companions.
- Of these, 10 are double neutron star systems (and we have discovered two more recently!)
- The high masses and short orbits of these systems make them excellent laboratories for GR.

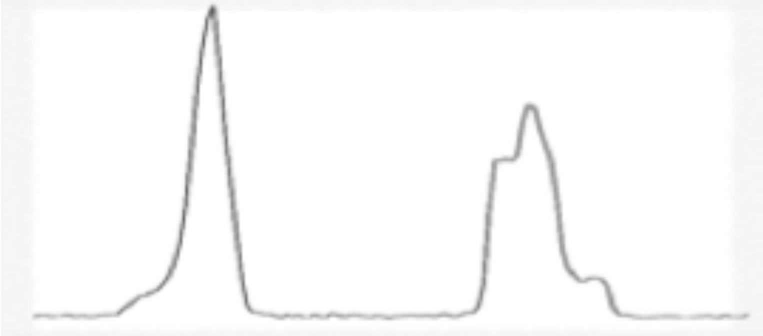
The Double Pulsar System

Discovered in 2003 with Parkes, with B bright in two ~15 min orbital phase regions.

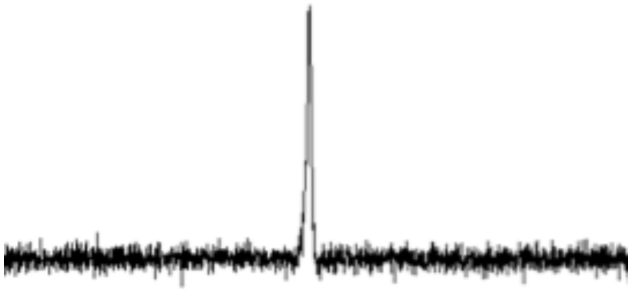


Nearly edge-on orbit, with a 2.45-hr orbital period and eccentricity of 0.9.

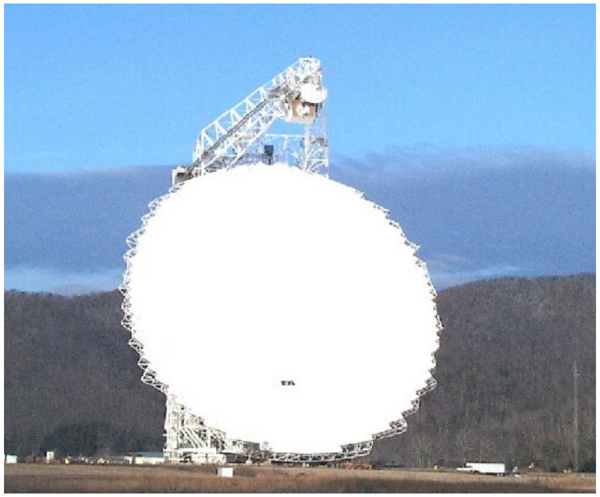
A P = 22 ms



B P = 2.7 s

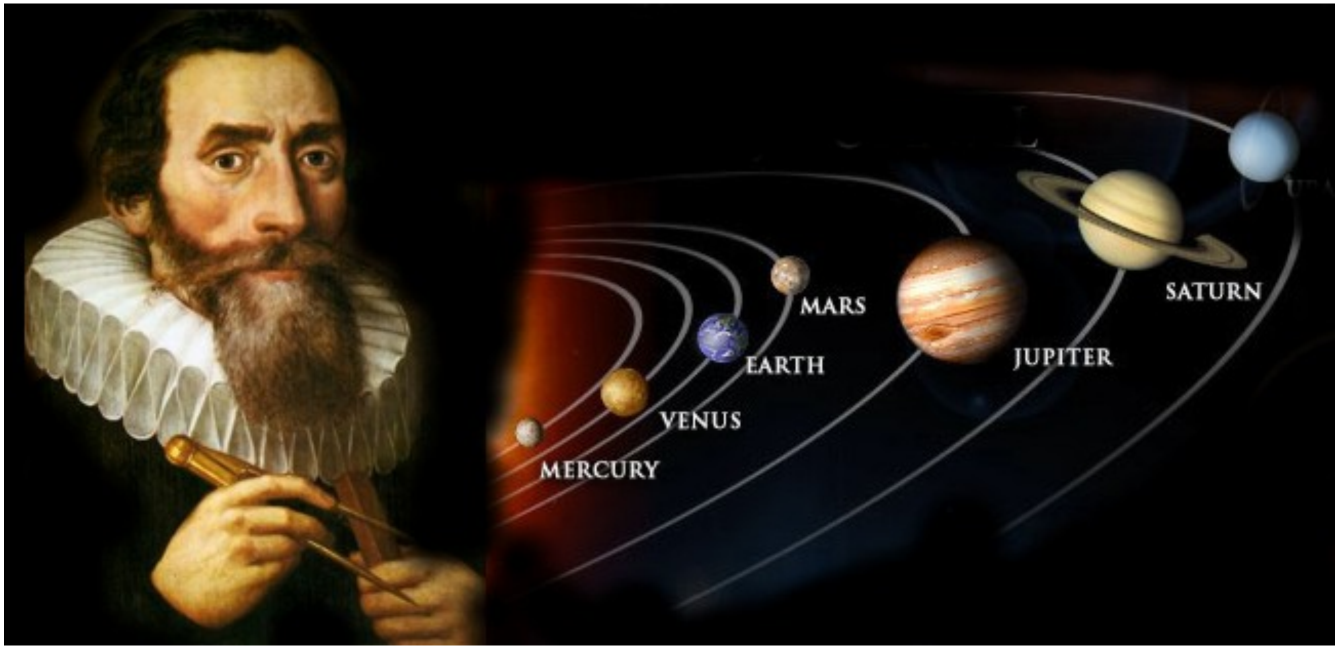


10 years of GBT observations (two orbits a month, plus yearly dense campaign!)



- We can measure five Keplerian orbital parameters. This characterizes the orbit and gives us the mass function.

$$f(m_p, m_c) = \frac{(m_c \sin i)^3}{(m_p + m_c)^2} = \frac{4\pi^2}{G}\frac{(a_p \sin i)^3}{P_b^2}$$



10 years of GBT observations (two orbits a month, plus yearly dense campaign!)

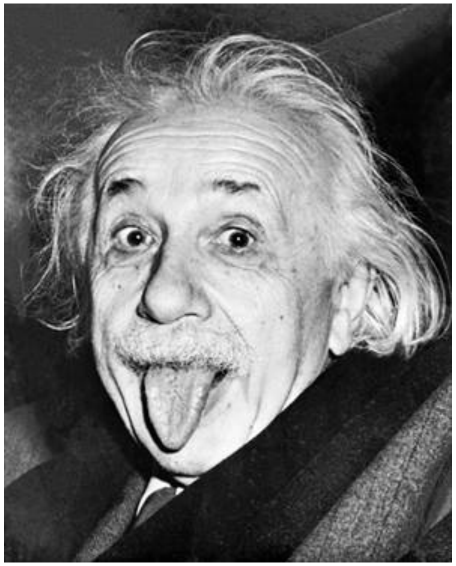
- We can also measure 5 PK parameters:

  - periastron advance

  - gravitational redshift and time dilation

  - orbital shrinkage due to gravitational radiation

  - two Shapiro delay parameters



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

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2(m_1+2m_2),$$

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

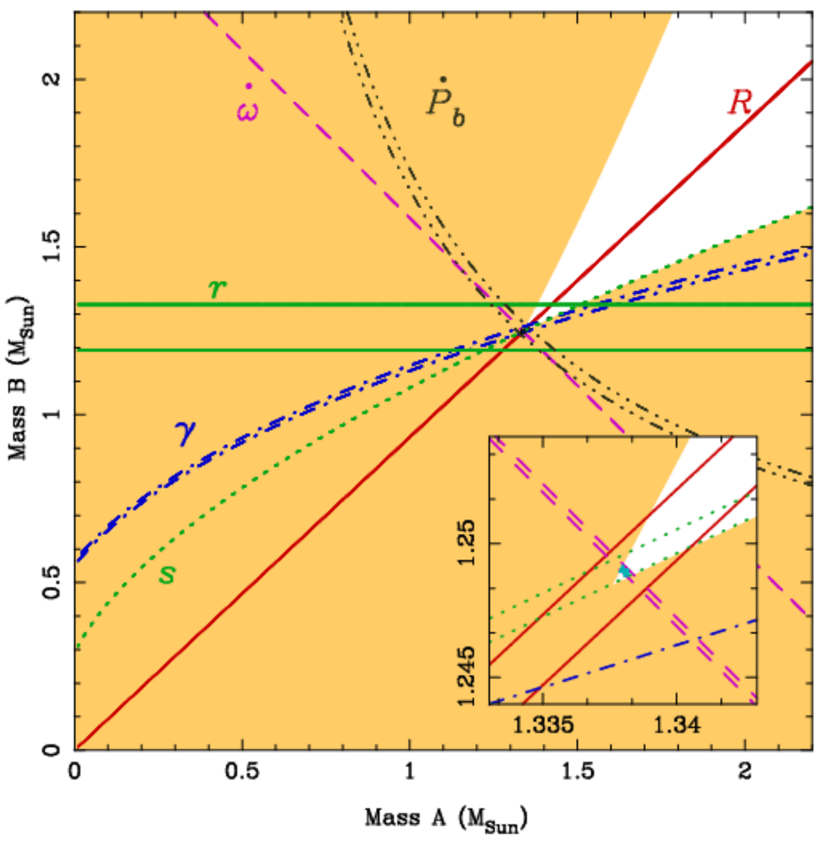
$$r = T_\odot m_2,$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}.$$

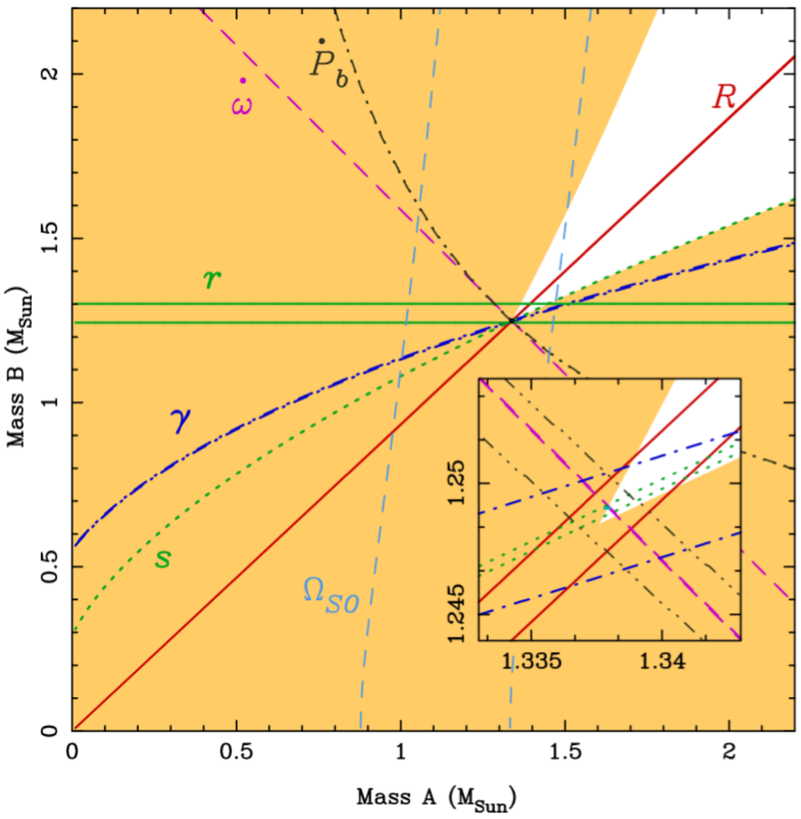
We therefore have three variables and six equations!
We can measure masses precisely AND test GR.

Mass-Mass Diagram

Kramer et al. 2006



Kramer et al. in preparation



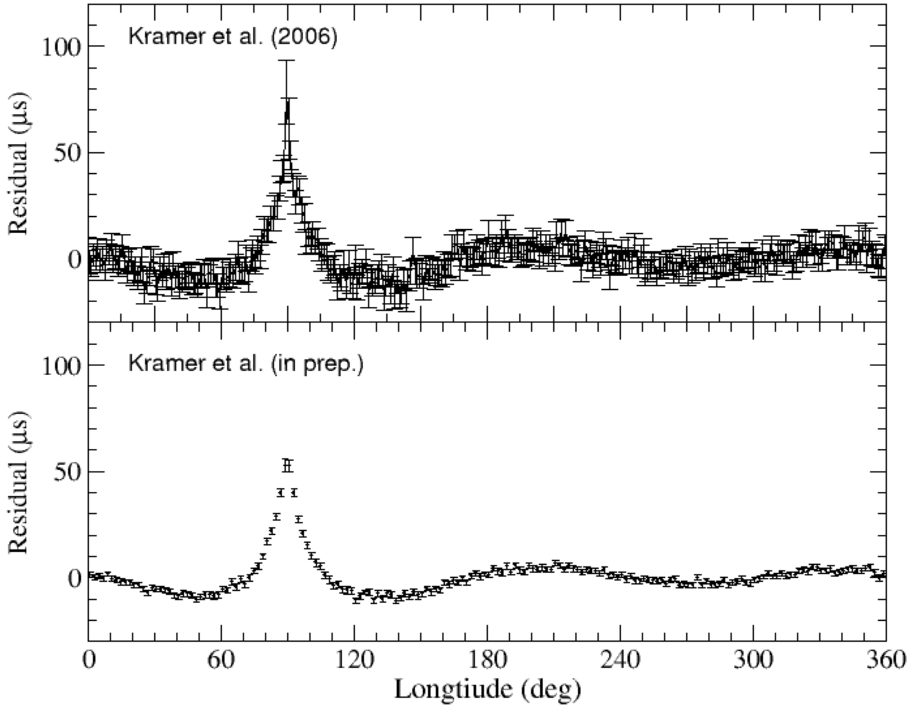
P (ms) = 22.6993785996213 ± 0.0000000000002 (measured to 0.2 picoseconds!)

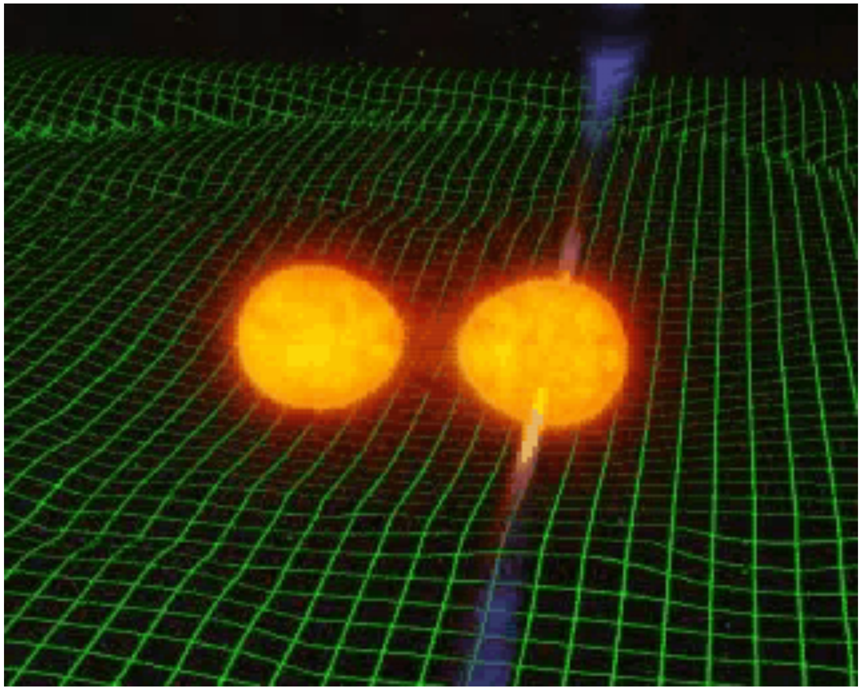
P_b (d) = 0.102251562452 ± 0.000000000008 (i.e. 2.45h measured to 691 ns!)

dP_b/dt = $(-1.248\pm0.001) \times 10^{-12}$ - agreement with GR at 0.1%

$m_A = (1.3381\pm0.0007)\ M_\odot$ and $m_B = (1.2489\pm0.0007)\ M_\odot$

Best Test of GR in strong-field regime





Pulsars approach each other by 7.152 ± 0.008 mm/day and will merge in 85 million years.

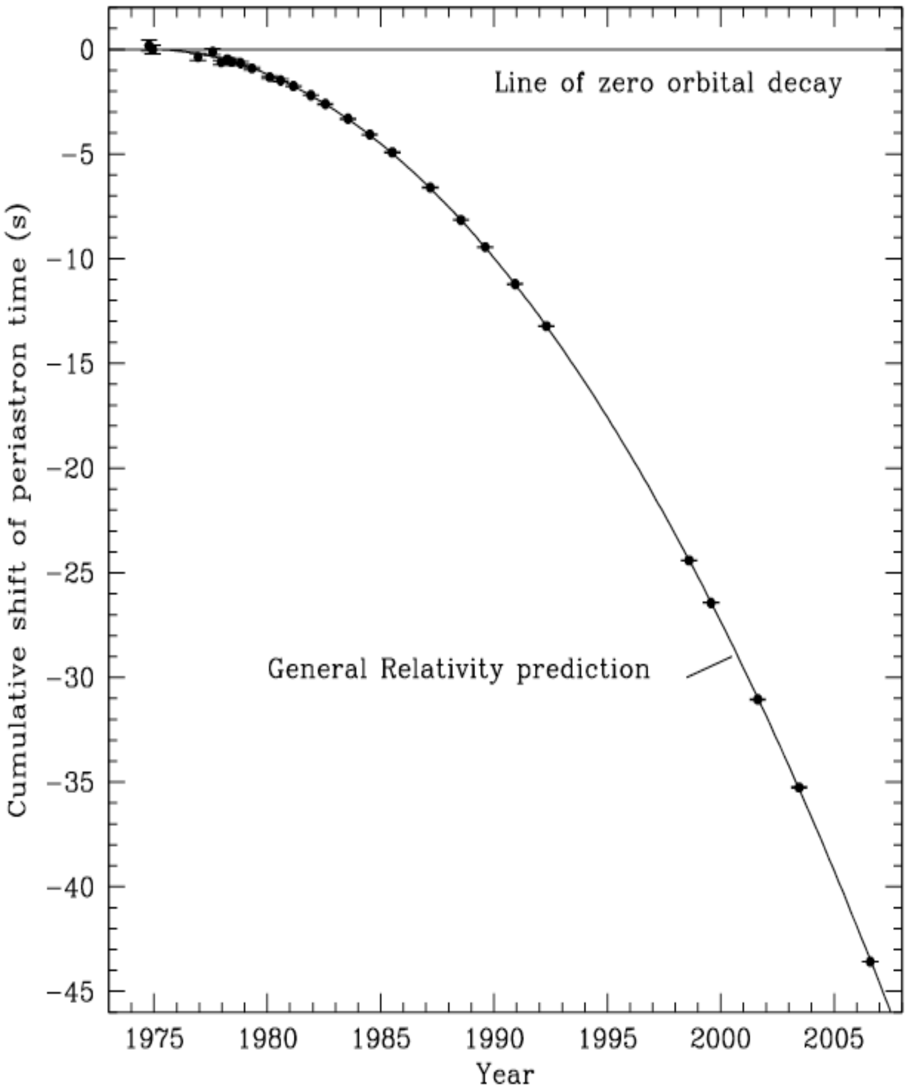
Expected/Observed: 1.000(2) for γ , 1.000(1) for dP_b/dt, 0.98(2) for r, and 1.0000(5) for s.

Measurement of s ➔ agreement with GR to 0.05%!

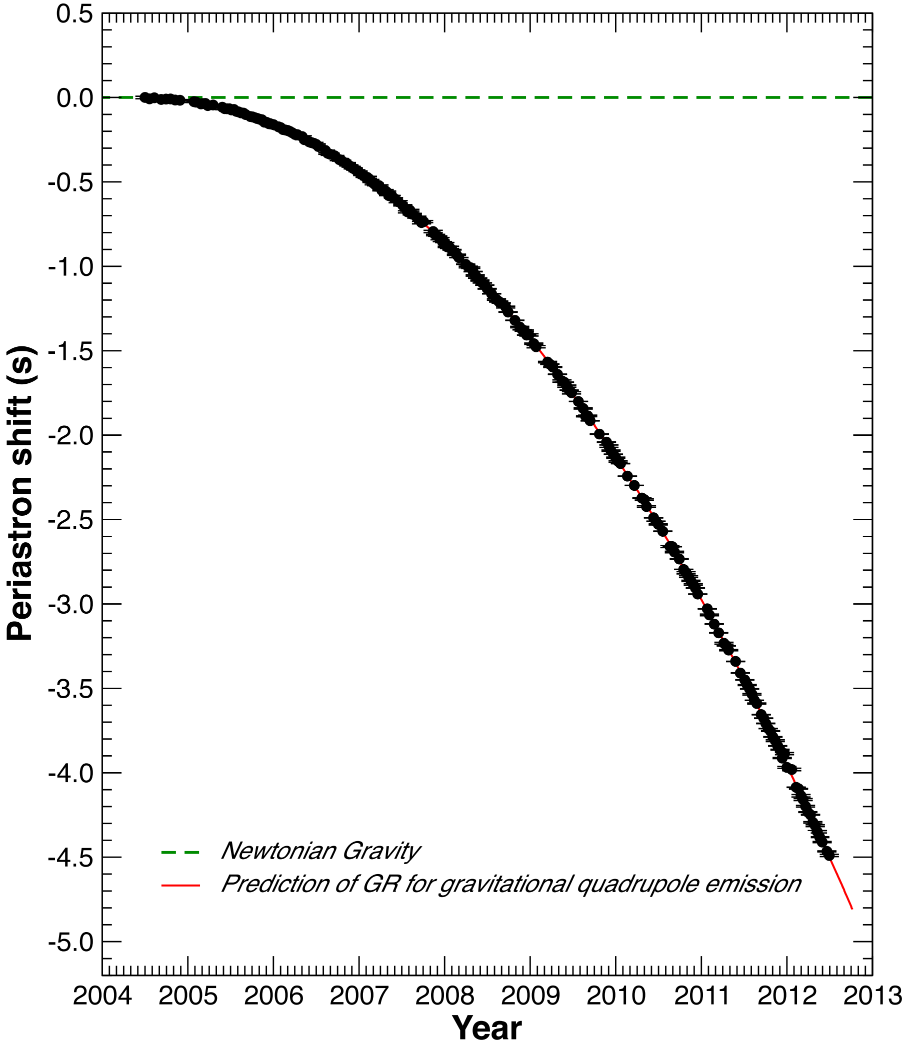
Precision will continue to improve, superseding solar system tests.

Best proof for GWs so far (0.01% level!)

Weisberg et al. (2010)



Kramer et al. (in prep.)

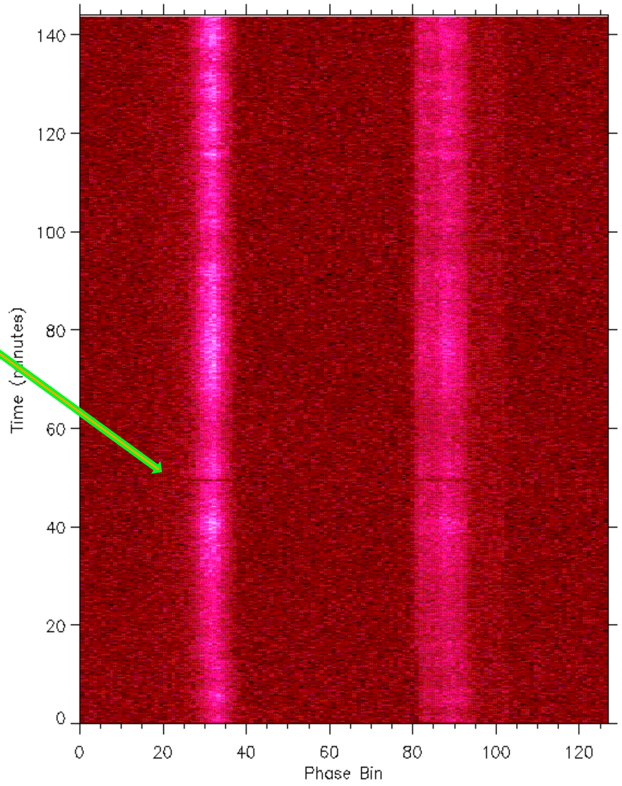


Influence of B on A: Eclipses

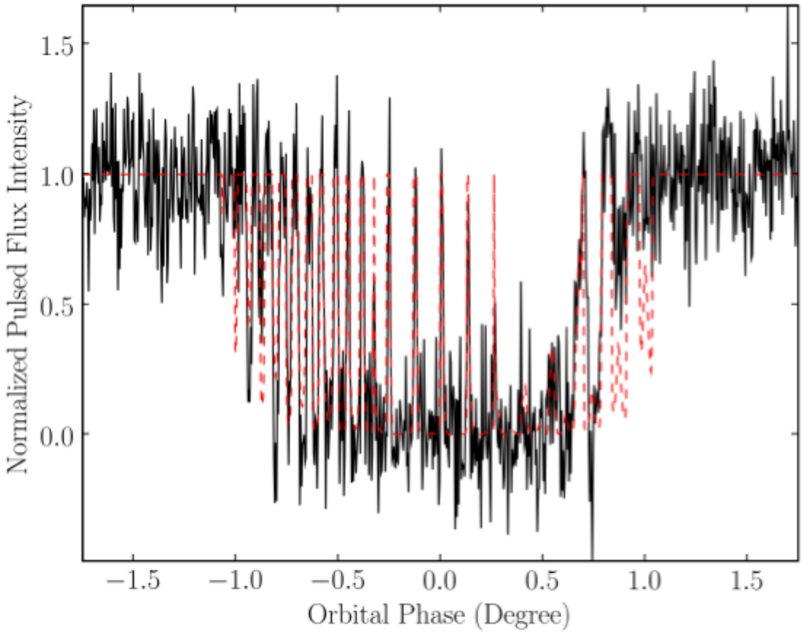
A is eclipsed for ~ 30 seconds per orbit.

Occulting region of 0.05 lt-s; 10% of light-cylinder radius ($\sim 10^{10}$ cm) of B.

GBT @ 820 MHz



GBT @ 820 MHz



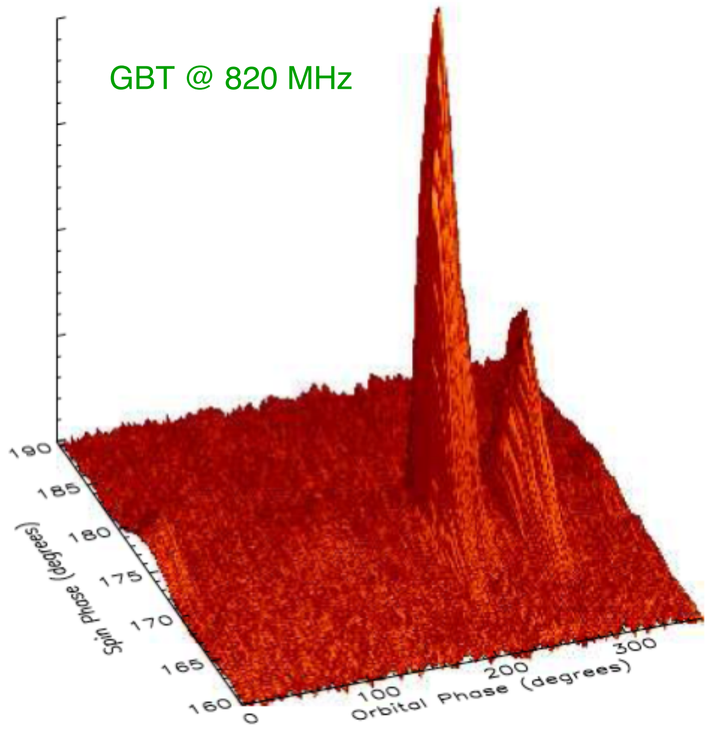
Can model eclipse shape to derive geometrical parameters of B ($\alpha = 70^{o}$, $\theta = 130^{o}$) and measure $5^{o}\ \mathrm{yr}^{-1}$ rate of geodetic precession of B (Breton et al. 2008)

Pulsar B field is dipolar!

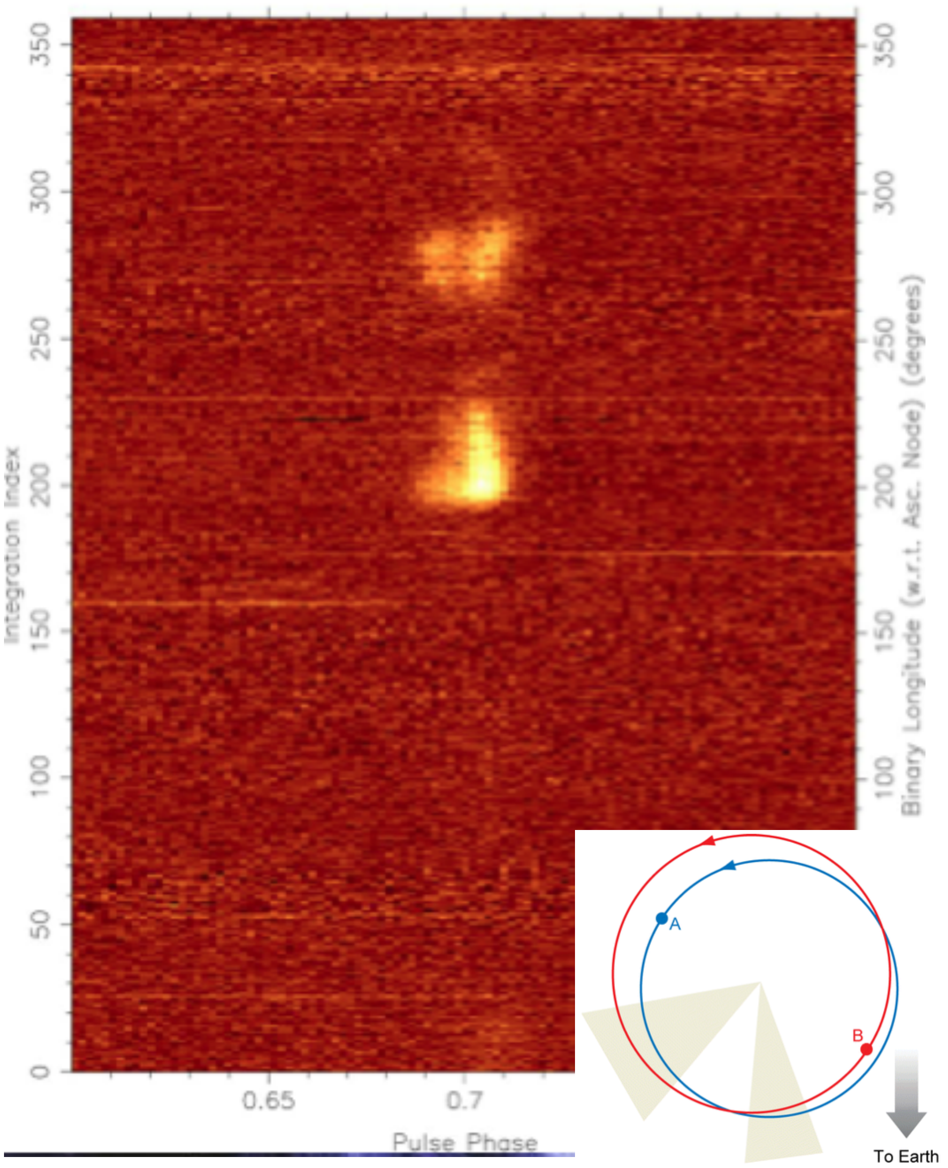
Influence of A on B: Bright Phases

B bright at only two orbital phases.

Due to A distorting B’s magnetosphere (Lyutikov 2005).

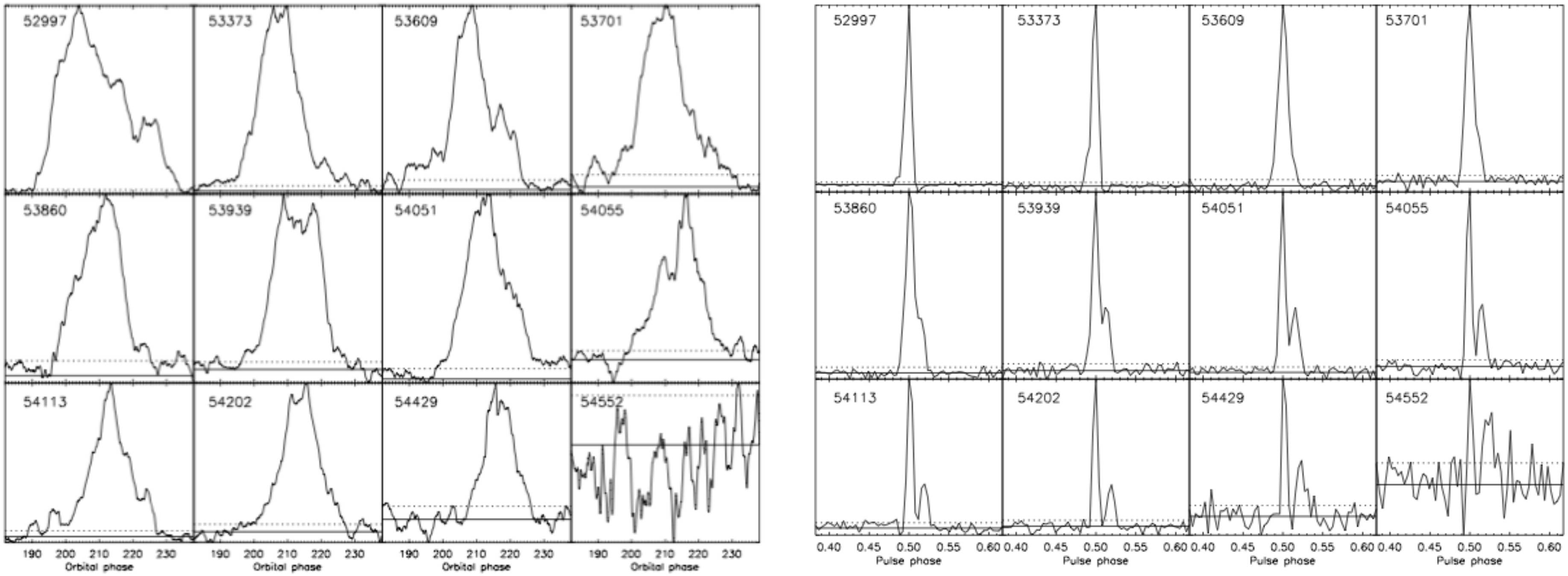


GBT @ 820 MHz



Influence of A on B: Bright Phases

B shows dramatic lightcurve and pulse profile changes across orbit and with time due to periastron advance (17^{o} yr^{-1}) and geodetic precession (5^{o} yr^{-1}) .



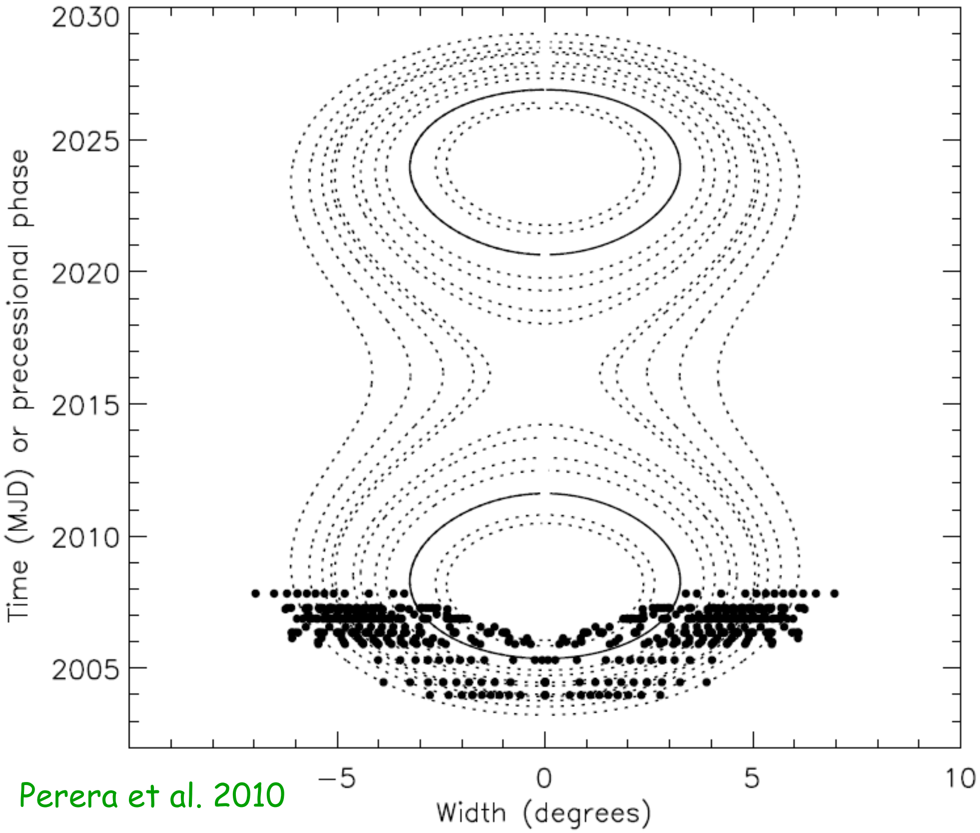
Lightcurves (left) and pulse profiles (right) of B during BP1 from December 2003 to March 2008 (Perera et al. 2010).

Geodetic Precession: Pulse Profiles

We can fit the pulse profile evolution to a geometrical model. We find similar geometrical parameters as from eclipse model fitting ($\alpha = 70^o$, $\theta = 130^o$).

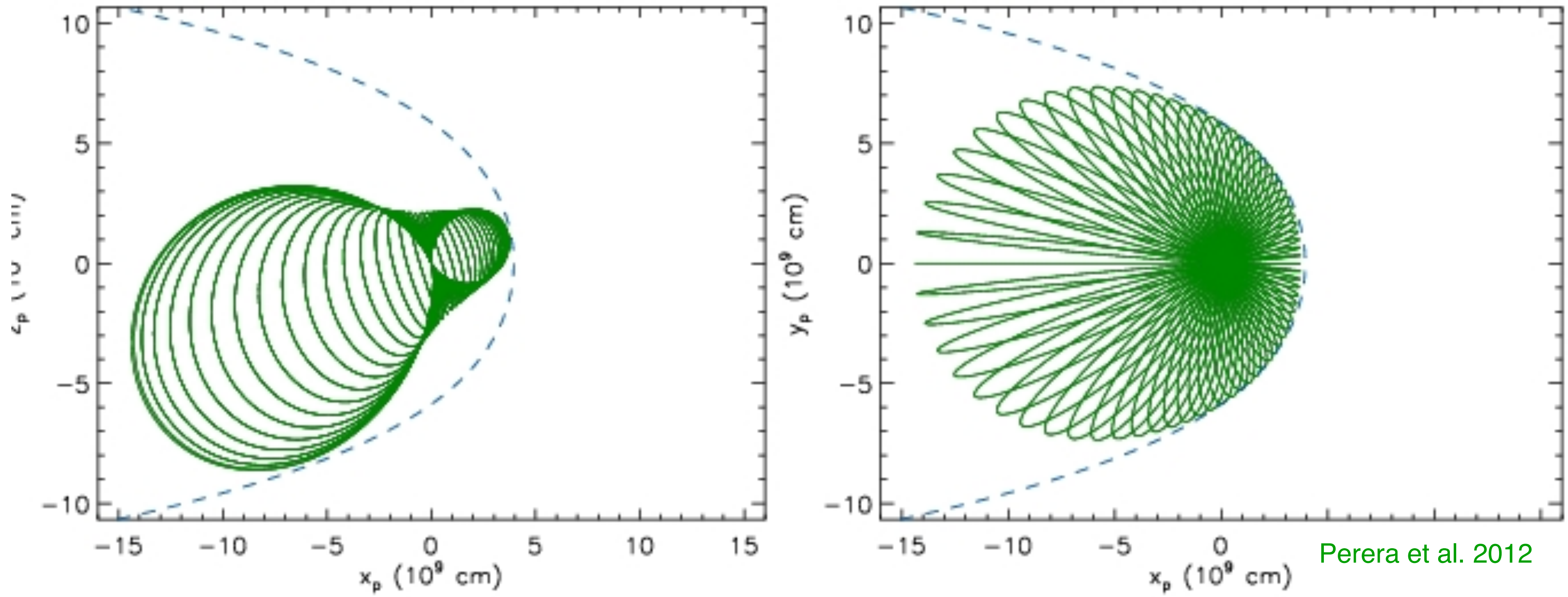
Emission beam is elliptical ($a/b = 2.6$) and only partially filled (intrinsic or extrinsic!)

Radio reappearance is expected to occur in 2014 or 2024 (with caveats!)



Perera et al. 2010

Influence of A on B: Emission Heights

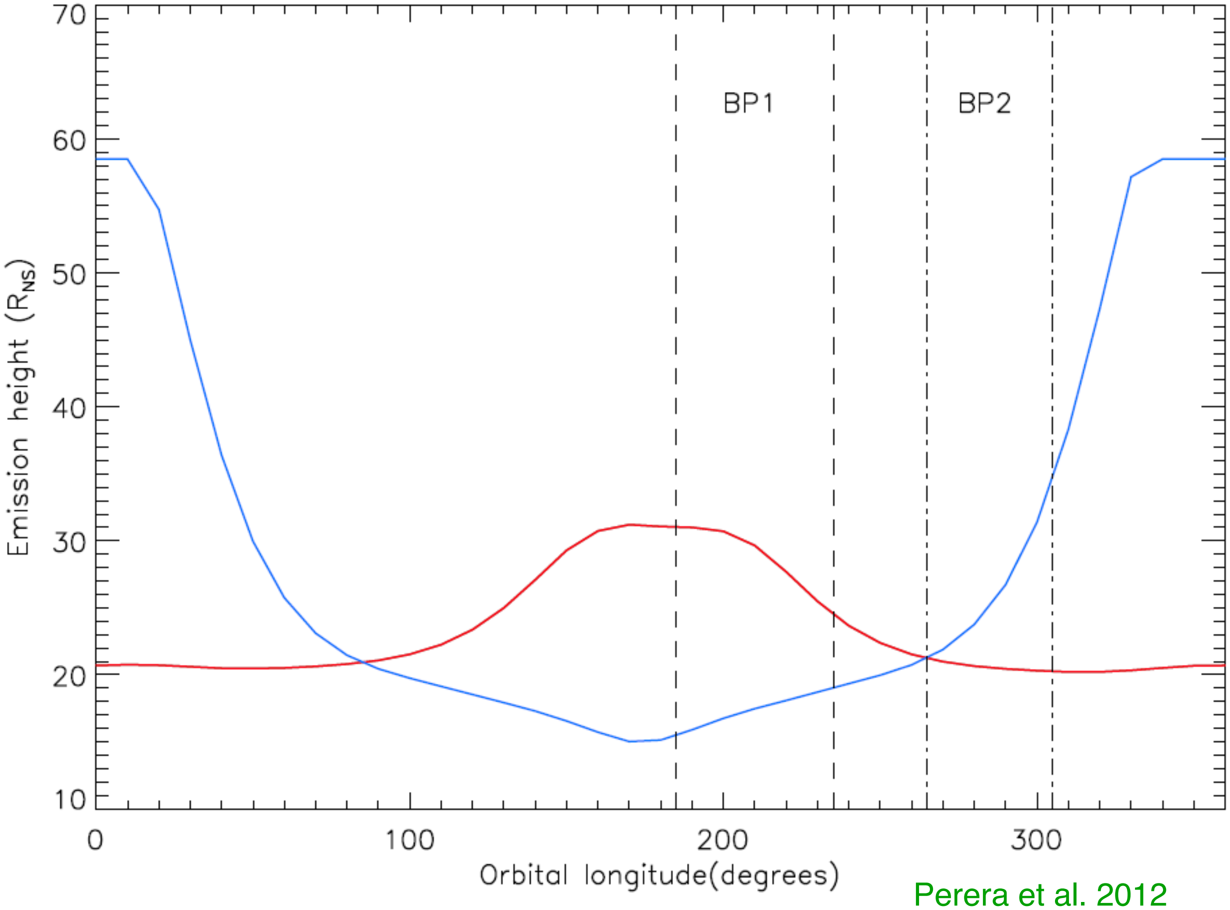


Perera et al. 2012

Bow shock at 4 x 10^9 cm (30% R_{LC}) from B. Can trace the magnetic field lines structure within this bow shock, given solved geometry. Will change with orbital phase and B spin phase.

Influence of A on B: Emission Heights

Can estimate (minimum) emission heights given magnetic field structure and shape of pulse profile.



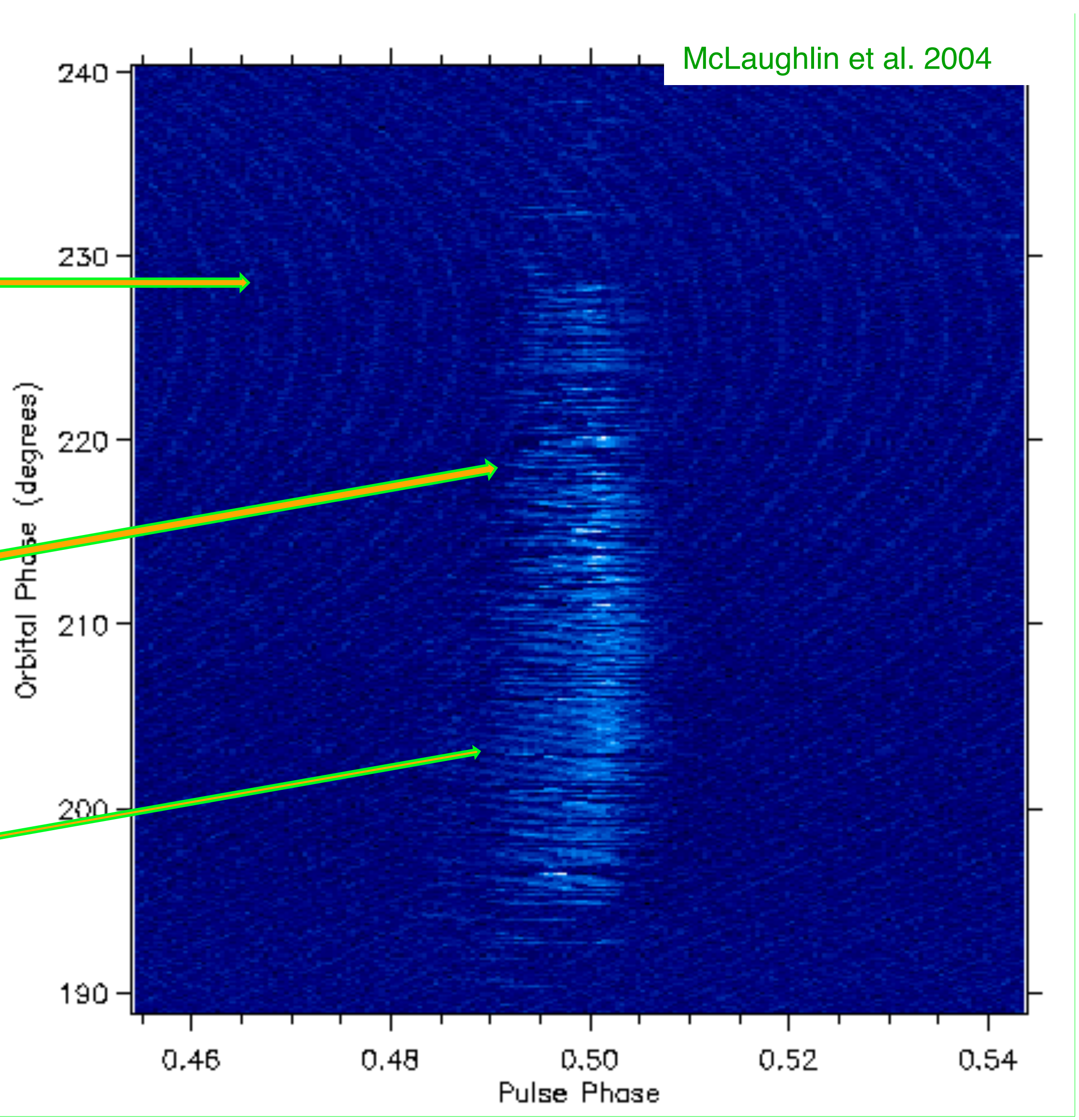
Perera et al. 2012

Influence of A on B: Drifting Features

Single pulses from A

Single pulses from B

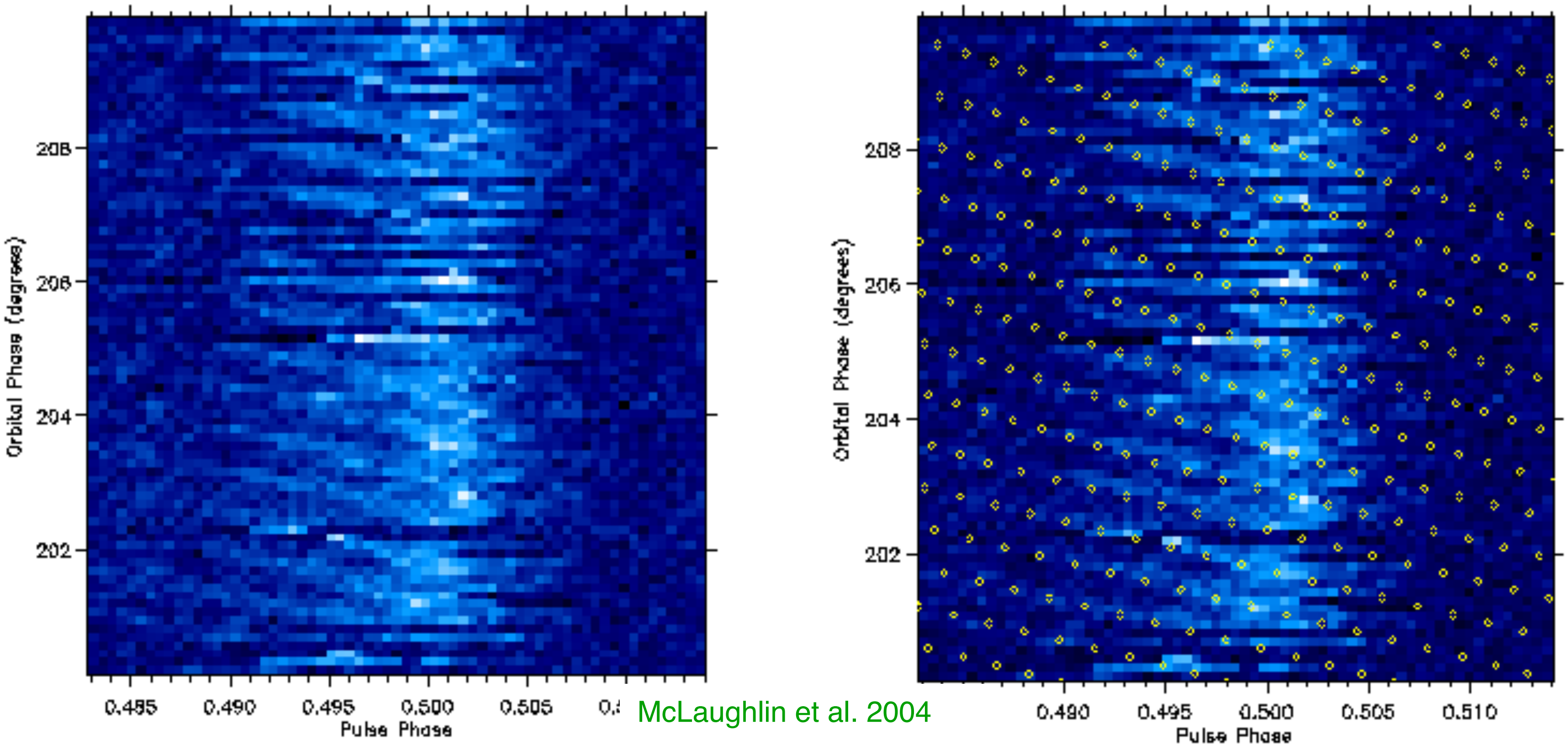
Drifting



GBT @ 820 MHz

McLaughlin et al. 2004

Influence of A on B: Drifting Features



McLaughlin et al. 2004

The drifting is a direct signature of the influence on the EM radiation from A on B!

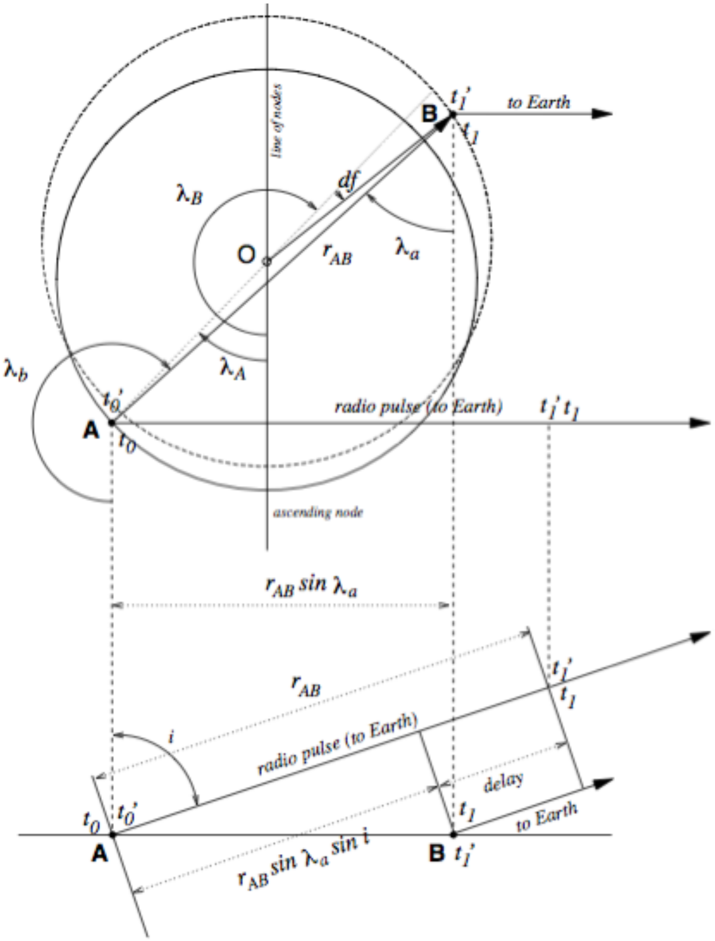
Influence of A on B: Drifting Features

Through a geometrical model (Freire et al. 2009, Rosen et al. in preparation), can fit for:

1) Rotation direction of A

2) Emission altitude in B, ε

3) Angle between A's radio and EM beam, ϕ_e



Response Delay =

$$\Delta(\lambda_A) - K(\lambda_A) = \frac{\epsilon}{c}(\sin\lambda_a \sin i - 1) \pm P'_A\left(\frac{\lambda_a}{2\pi} - \frac{\phi_e}{2\pi} - \frac{1}{4}\right)$$

Influence of A on B: Drifting Features

Through a geometrical model (Freire et al. 2009, Rosen et al. in prep.), can fit for:

1) Rotation direction of A

   likely in direction of orbit

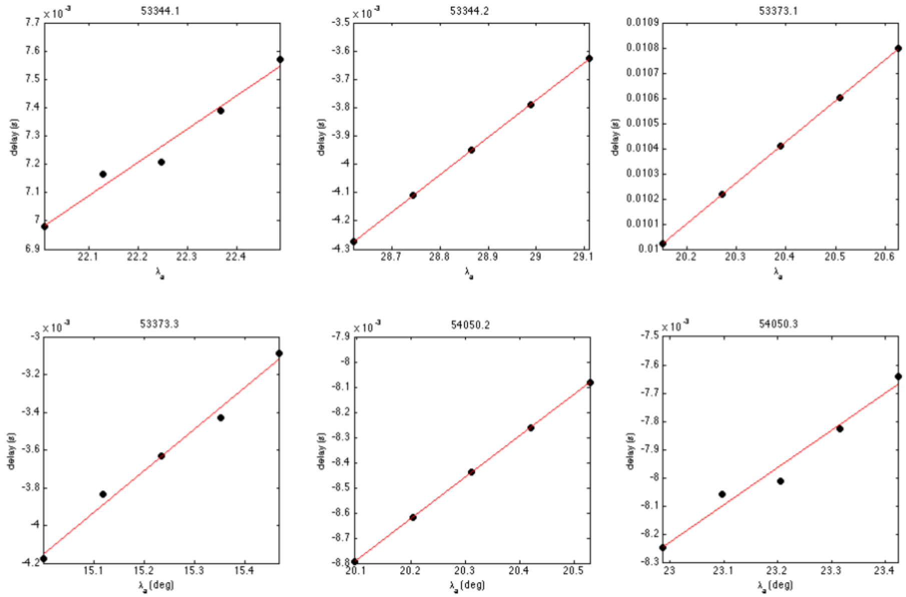
2) Emission altitude in B, ε

   ~500 R_{NS} (within the bow shock)

3) Angle between A's radio and EM beam, ϕ_e

   small and varying

preliminary!



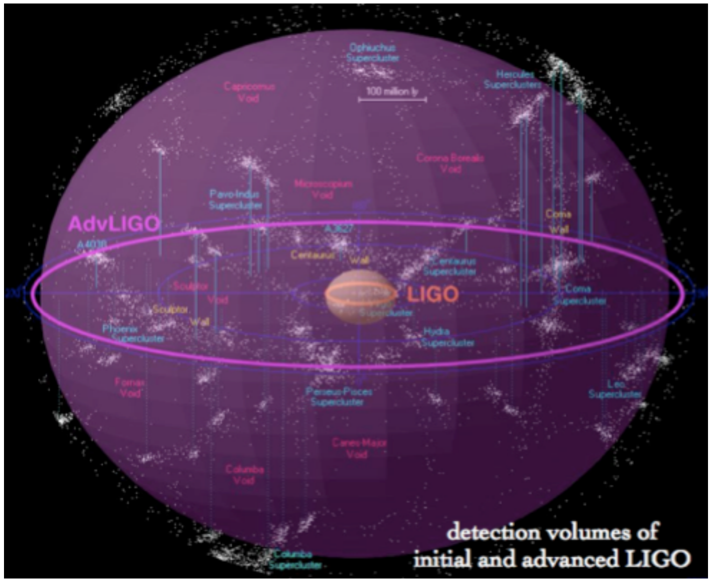
Response Delay =

$$\Delta(\lambda_A) - K(\lambda_A) = \frac{\epsilon}{c}(\sin\lambda_a \sin i - 1) \pm P'_A\left(\frac{\lambda_a}{2\pi} - \frac{\phi_e}{2\pi} - \frac{1}{4}\right)$$

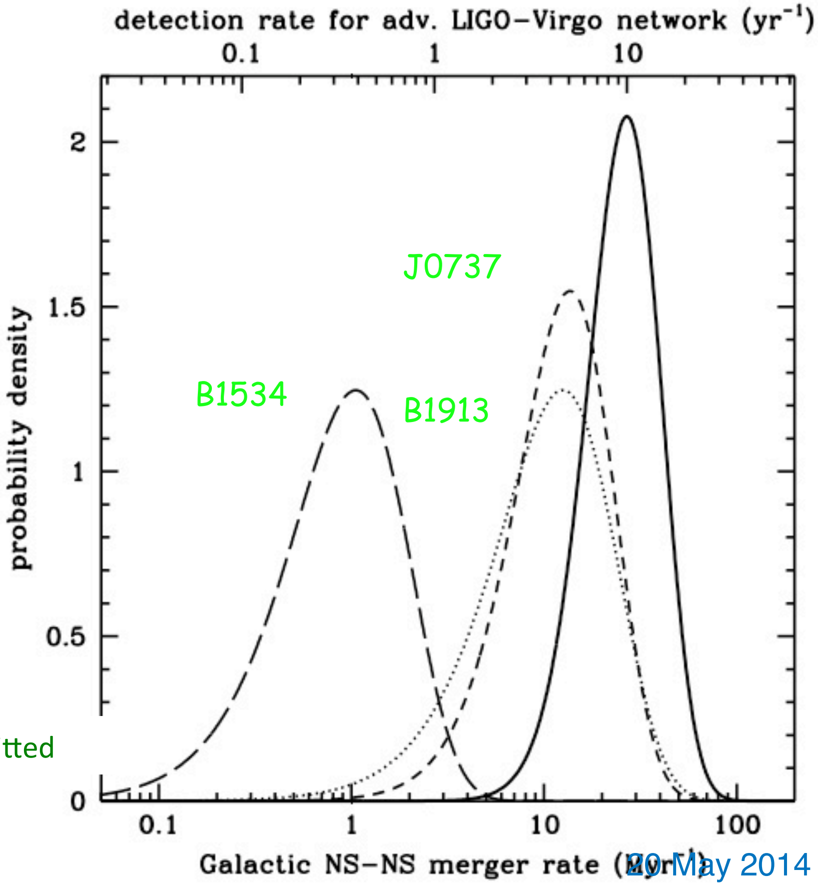
Application: NS-NS Inspiral Rates

DP will merge in 85 Myr. There are roughly 1400(+4100,-900) DP-like systems in MW.

Given 445 Mpc horizon distance for Advanced LIGO, we calculate a detection rate of 8(+11,-5) yr $^{-1}$. This is a significant revision of past rates, based on new beaming models.



detection volumes of initial and advanced LIGO



Kim et al. submitted

Conclusions (1)

After nearly ten years, the Double Pulsar is still providing new insights.

It remains the best test ever of GR in the strong-field regime.

We can fit B pulsar data with an elliptical, partially filled beam and can determine the geometrical parameters of the system.

B is expected to reappear in 2014 or 2024.

We see evidence for the direct modulation of B pulsar emission through the EM field of A.

We estimate B emission heights of ~100 R_{NS} (minimum) through geometrical modeling and ~500 R_{NS} through drift-band fitting.

New beaming models for A and B have led to a revised LIGO event rate.

Advances in timing and GR tests will come with improved B timing precision.

Conclusions (2)

FAST will allow more accurate timing of existing DNS systems, allowing the measurement of additional effects, and even better tests of GR. (Maybe it will redetect B!)

FAST should reveal similar double pulsar systems and “dozens” of double neutron star systems. Acceleration searches and multiple passes will be important!

The FAST DNS discoveries will dramatically improve LIGO event rate predictions, allow for new studies of pulsar beams and emission mechanisms, and reveal new phenomenology.