Synthesis talk : relativistic pulsars winds from inside to far out

Maxim Lyutikov (UBC)

Plan of the talk: $x=r/r_{LC}$

x<< 1: PSR J0737-3039A/B – probe of magnetosphere

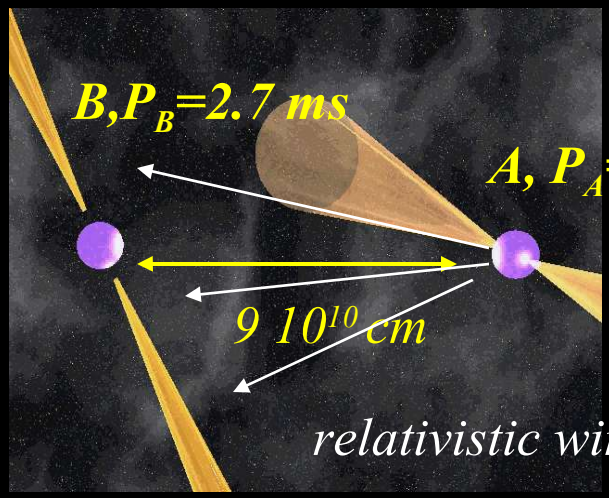
x <= 1 : EM structure of magnetosphere

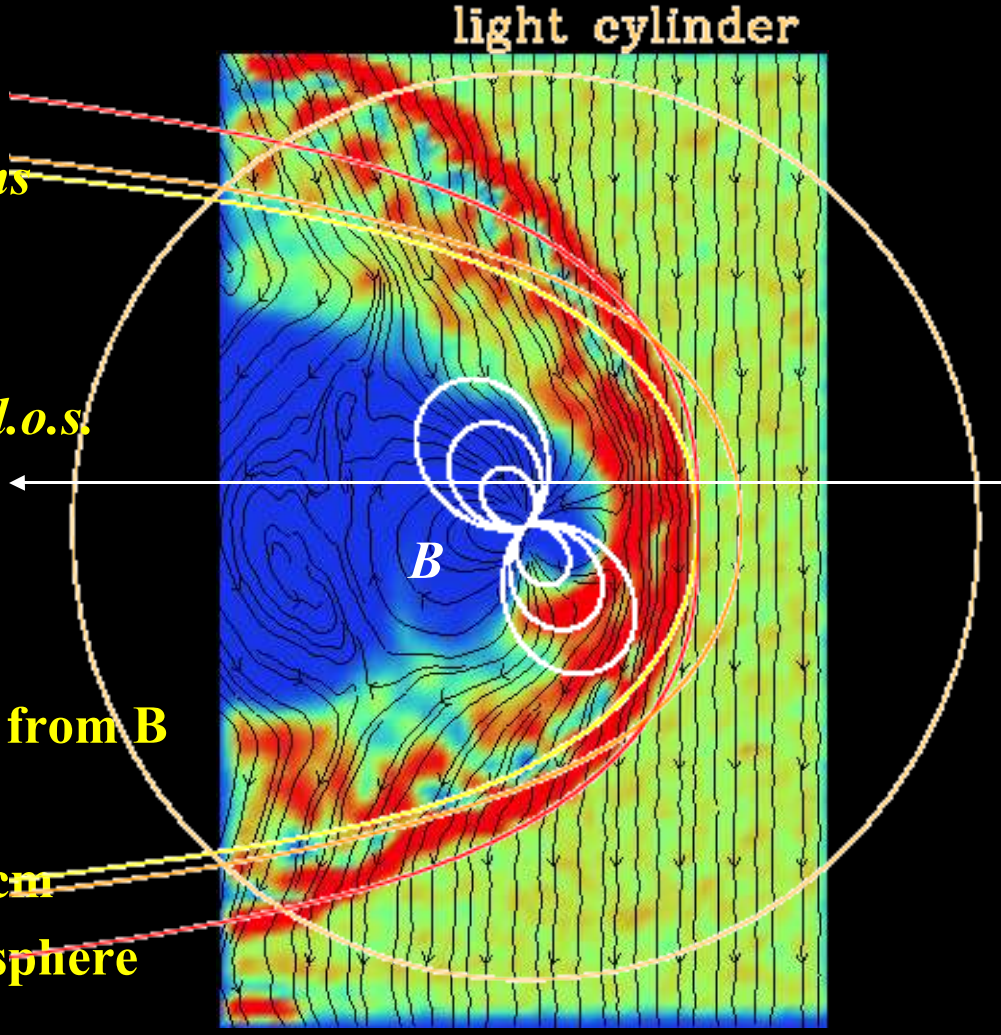
x ~ 1000 : PSR J0737-3039A/B - probe of wind

x~ 10^6 : Pulsar wind nebular

PSR J0737-3039: A probes B magnetosphere, B probes A wind

x< 1: Binary pulsar PSR J0737-3039A/B





Sixth most important scientific discovery of 2004 (Science)

Line of sight to A passes 7 10^8 cm from B

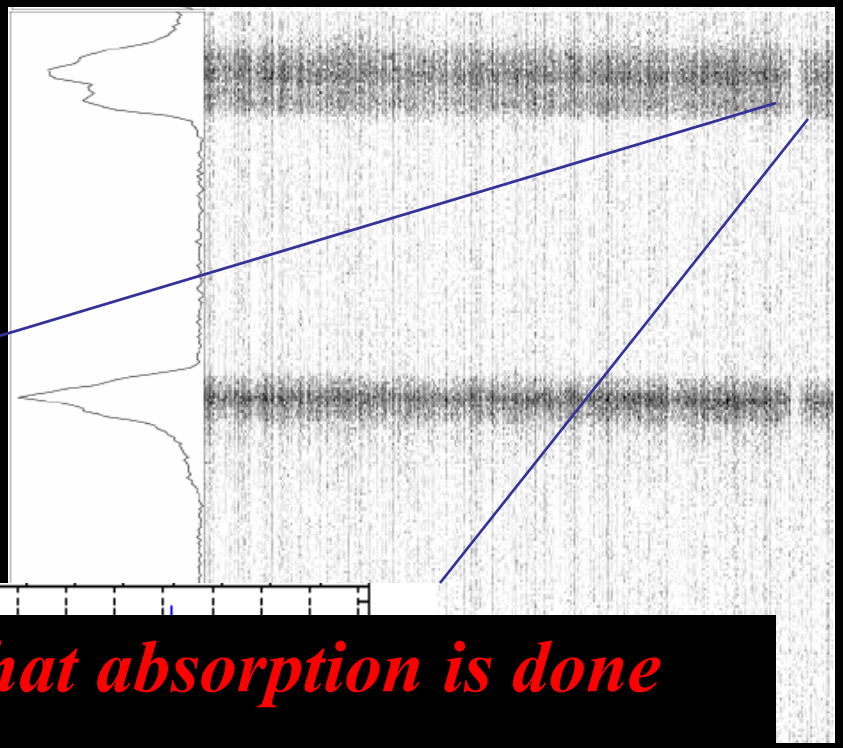
B light cylinder 1.3 10^{10} cm

Size of B magnetosphere 1.6 10^9 cm

Direct probes of pulsar magnetosphere and plasma physics

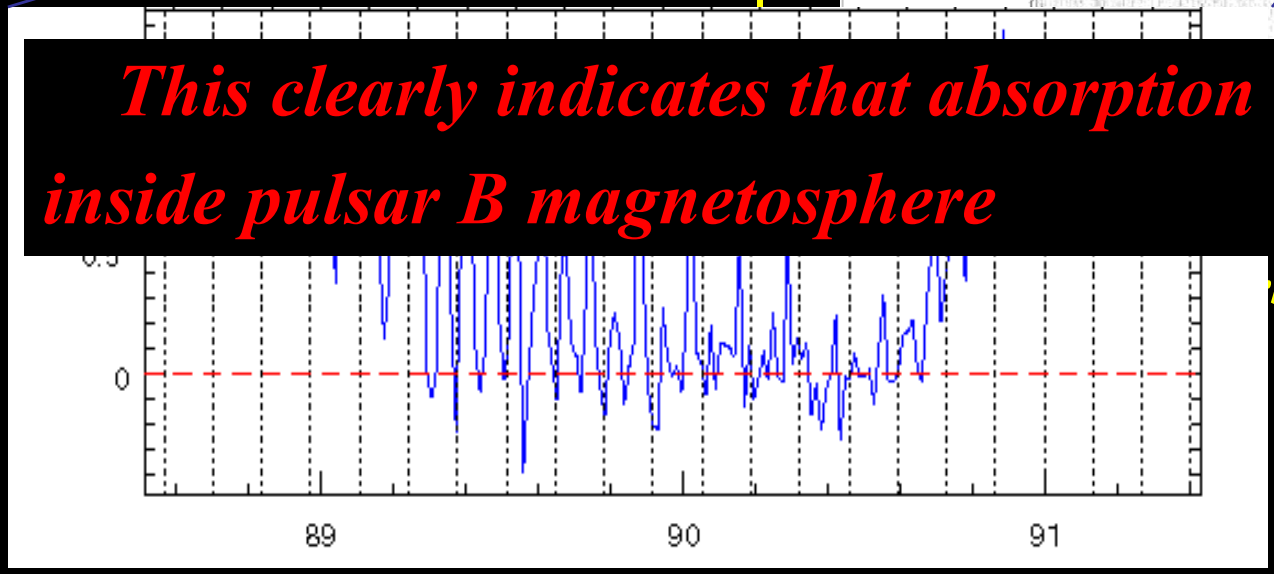
Spitkovsky (2004) Lyutikov (2004)

A is eclipsed for ~30 sec each orbit



Rotational phase of A

This clearly indicates that absorption is done inside pulsar B magnetosphere

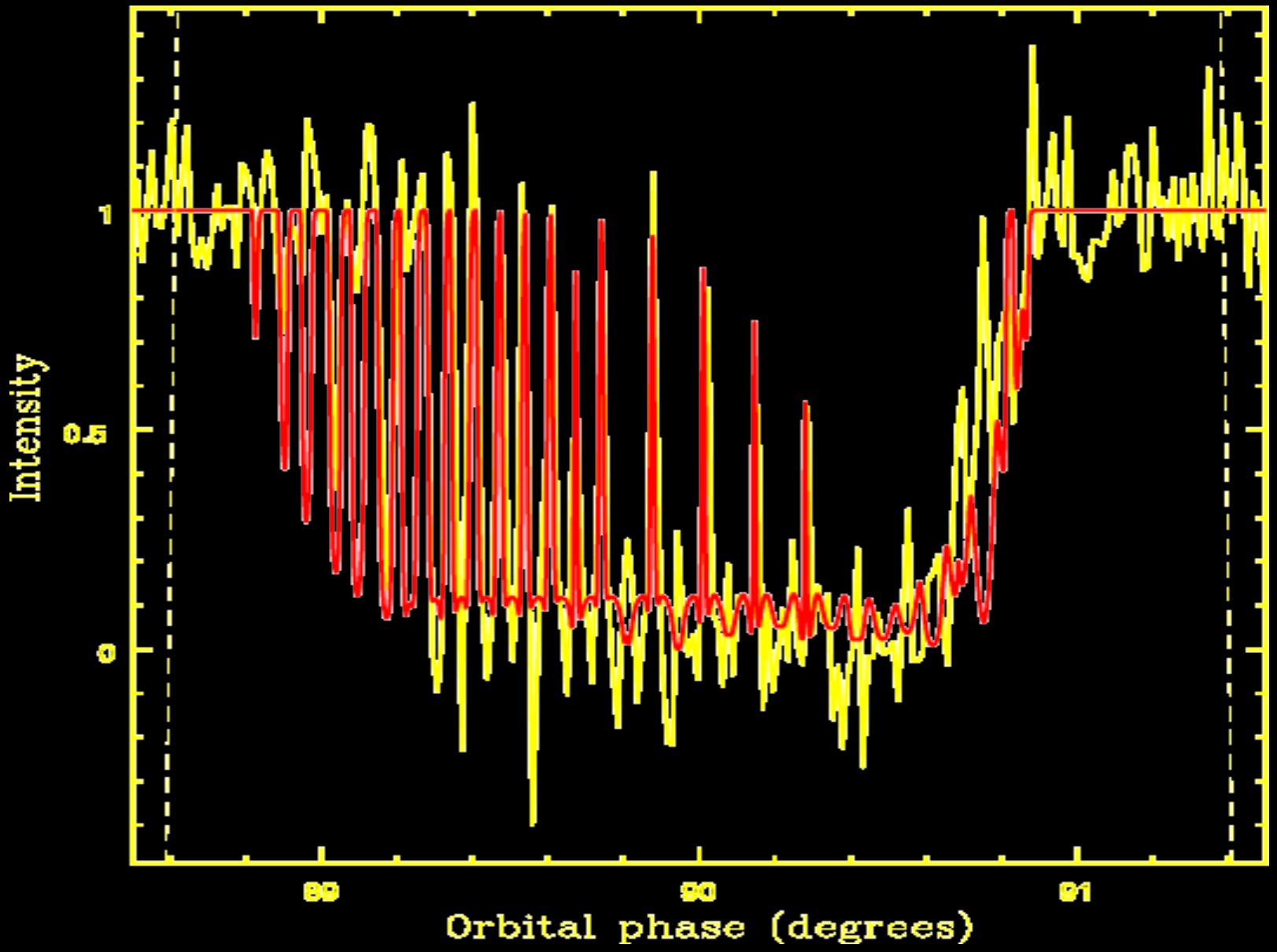


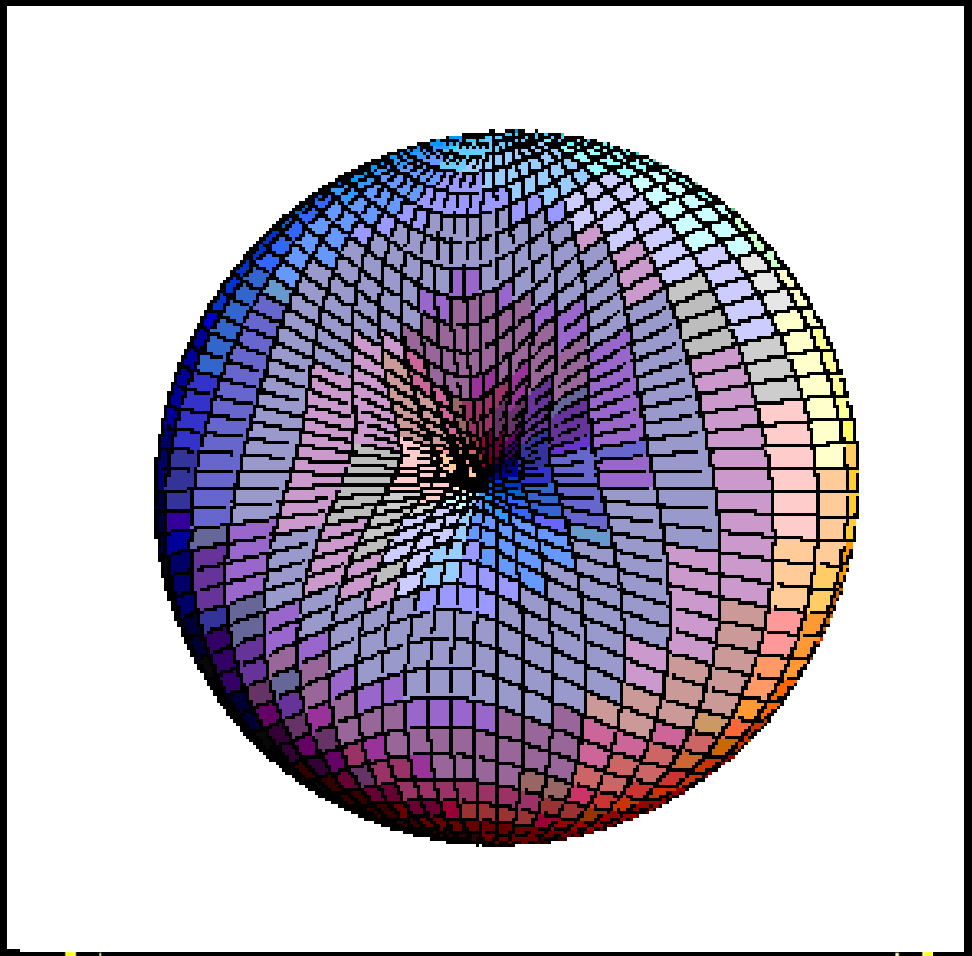
bital phase

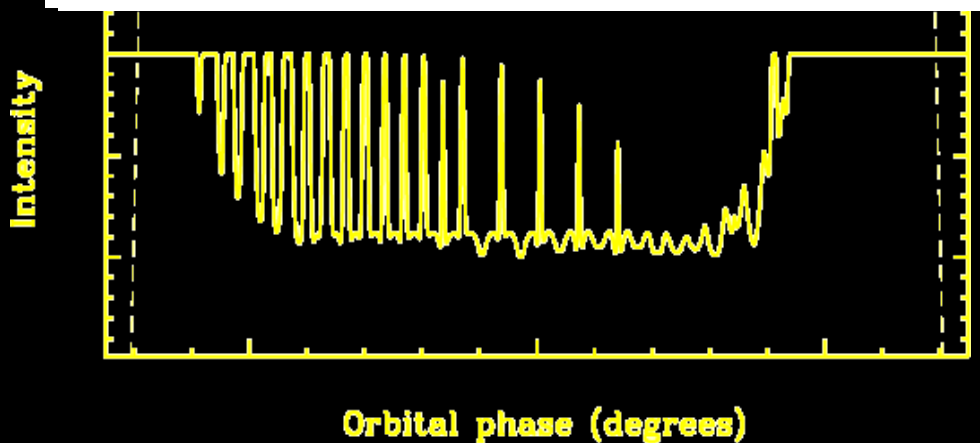
Modulation is at $0.5P_B$, P_B and full eclipse after the conjunction

Absorption when magnetic axis of B is pointing towards us.

Data: McLauphlin et al. 2004, Model: Lyutikov&Thompson 2005






Intensity
Orbital phase (degrees)

Implications

B-field is dipolar at ~ 7 10^8 cm: direct confirmation of the long standing assumption in pulsar physics

Large density on closed field lines: $\frac{n}{n_{GJ,mag}} \sim 10^5$***, relativistically hot, γ~ 10; property of interaction with wind, do not really expect for isolated pulsar***

x<=1, what is electro-magnetic structure of pulsar magnetosphere? Michel's talk.

Goldreich-Julian 1969, Michel 1971,1973

*Except in (insignificant) gaps, plasma is nearly ideal, E*B=0*

needed plasma density is generated by vacuum pair production

(aligned) Pulsar is an active current sou

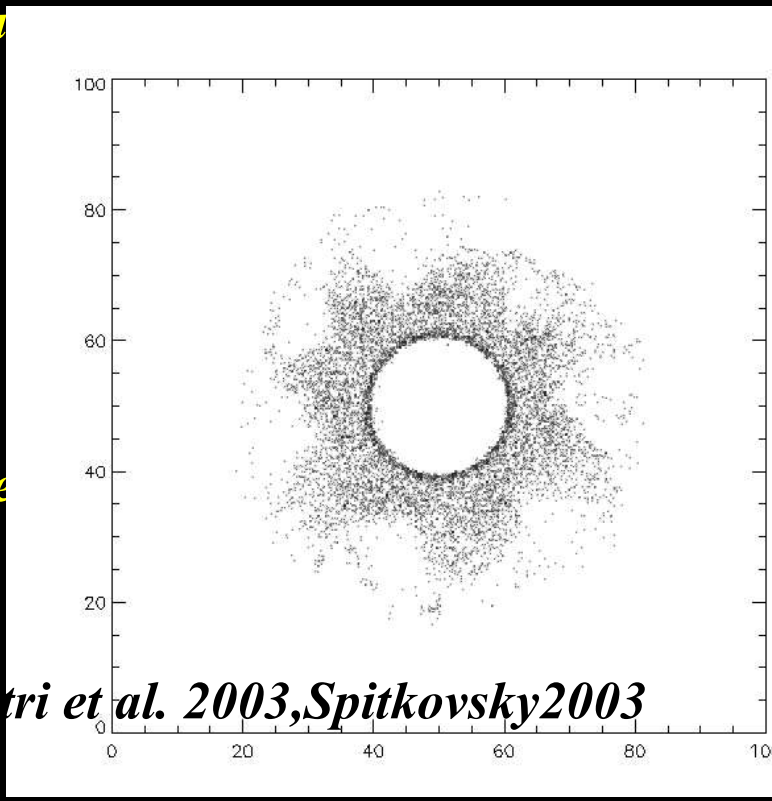
Michel (this conference):

Non-MHD

PIC simulations have not been able to relax to the "current source"-type solution

particle creation?

Charged "dome-torus" may be unstable especially in oblique case



tri et al. 2003,Spitkovsky2003

x ~ 1: what's the "point"?

Force-free structure of aligned dipolar rotator (should have been solved 35 years ago)

2. *Steady state: integro-differential (force-free=Grad-Shafranov) equation:*

how to chose current distribution

Where Y-point is located and how last closed field line approaches it

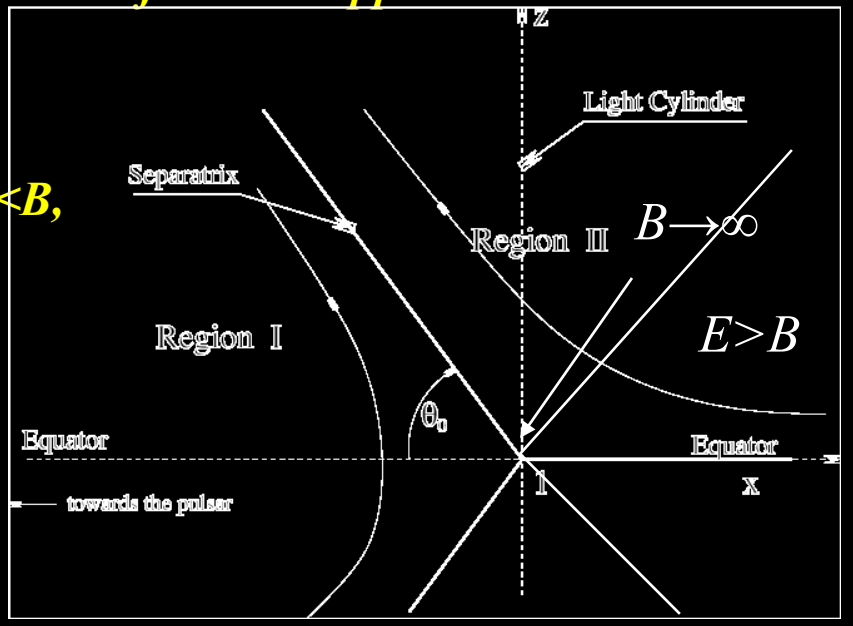
Uzdenski (2003): no current sheet

→ E>B @ $r > r_{LC}$: not self-consistent

Gruzinov (2004) with current sheet, E<B,

B → ∞ on LC (integrable divergence)

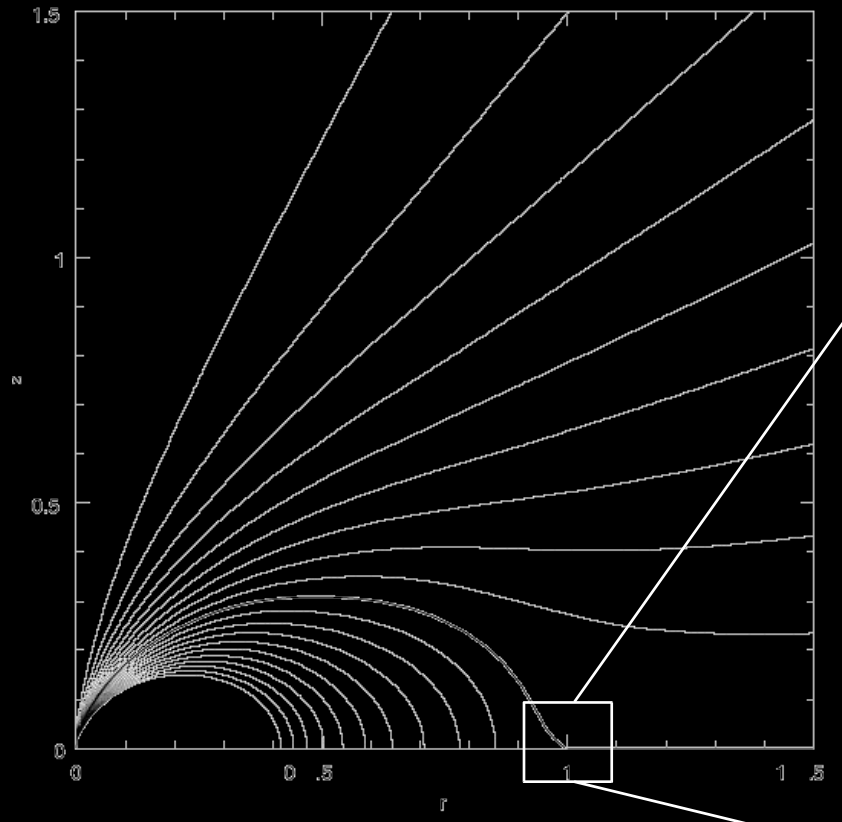
In both solutions separatrix approaches equator at finite angle

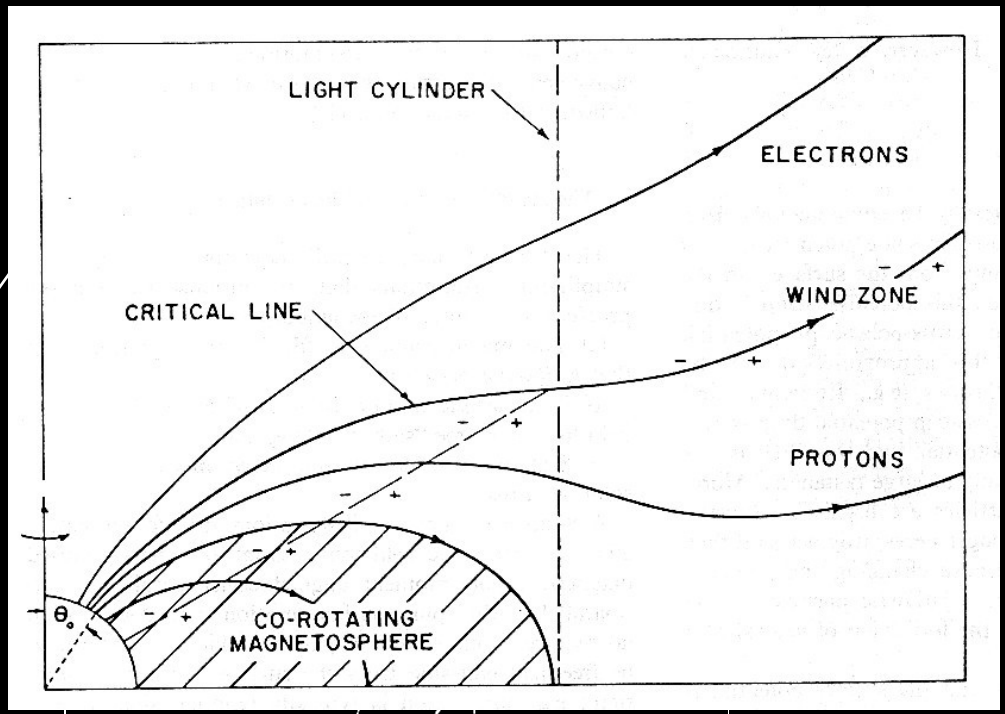


Solving Grad-Shafranov eq. (force-free)

(Contopolous et al. 1999, Uzdenski 2003, Gruzinov 2004)

At large distances solution approach monopole Bφ~ sin θ, energy flux ~ sin² θ (Michel 1973)



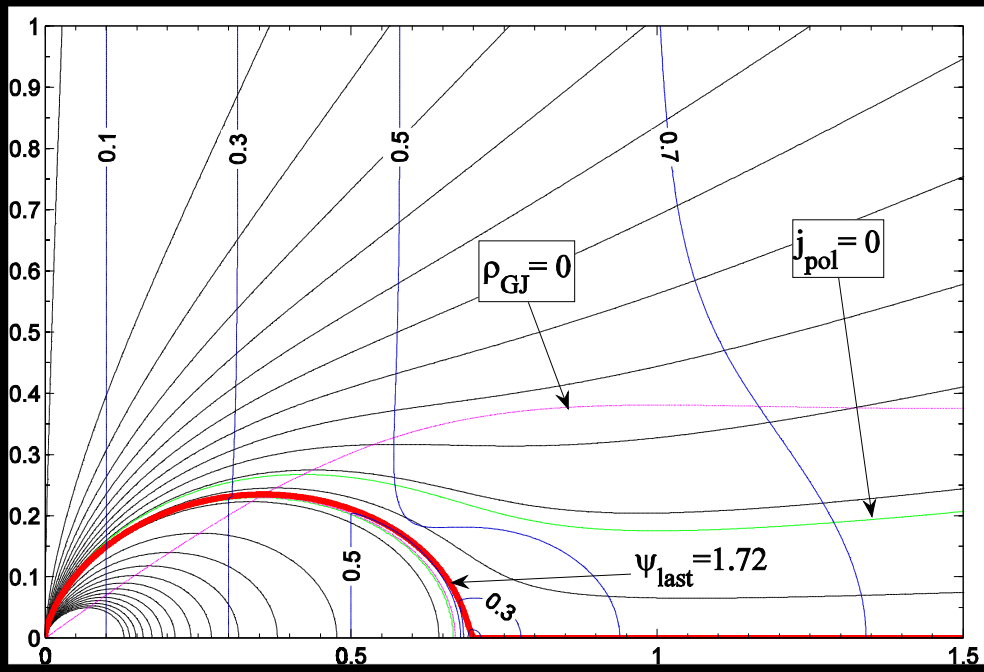


Goldreich-Julian

What if plasma cannot generate enough current: $x_0 < 1$

x0=1 is mininum energy, maximum current (somewhat large than GJ) configuration

If system cannot create such current (e.g. in old pulsars), x0 will move in (Timokhin 05)



Dynamical simulations: A. Spitkovsky

1. *Dynamically: just simulate it! (Take dipole, impose (EB)=0 and run).*

   B-field = 0 on equator → numerical problems (force-free breaks down)

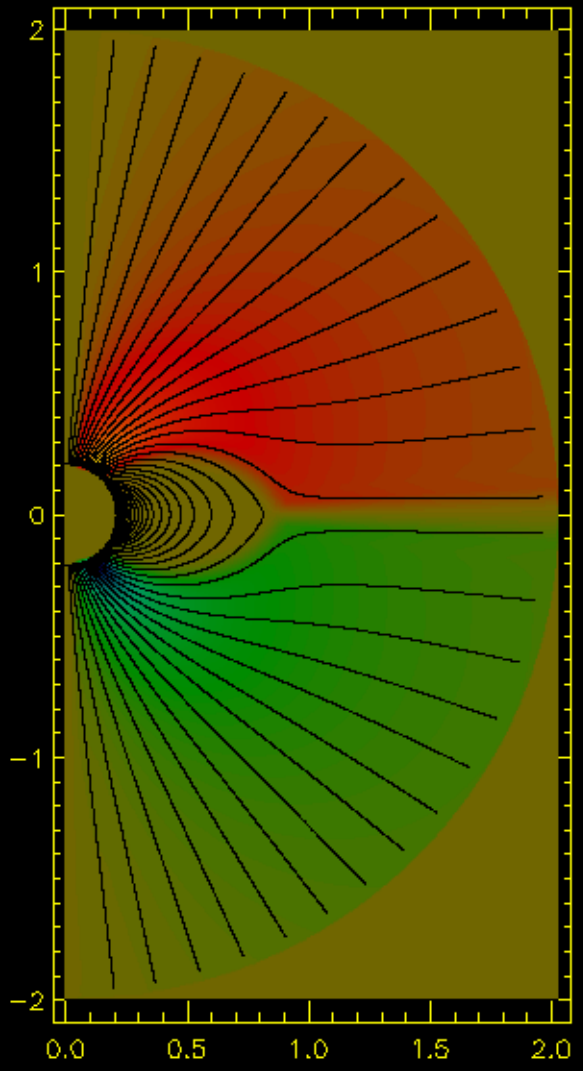
   - *Inertia*
   - *Resitvitiy*

   Resistive force-free code (kills E>B near equator)

   System dynamically reaches ~ Gruzinov solution

   Oblique?

This is a very promising step to prove pulsar as current source



Spitkovsky (priv. comm.)

x ~ 1000 : PSR J0737-3039 modulation of B's pulses by A

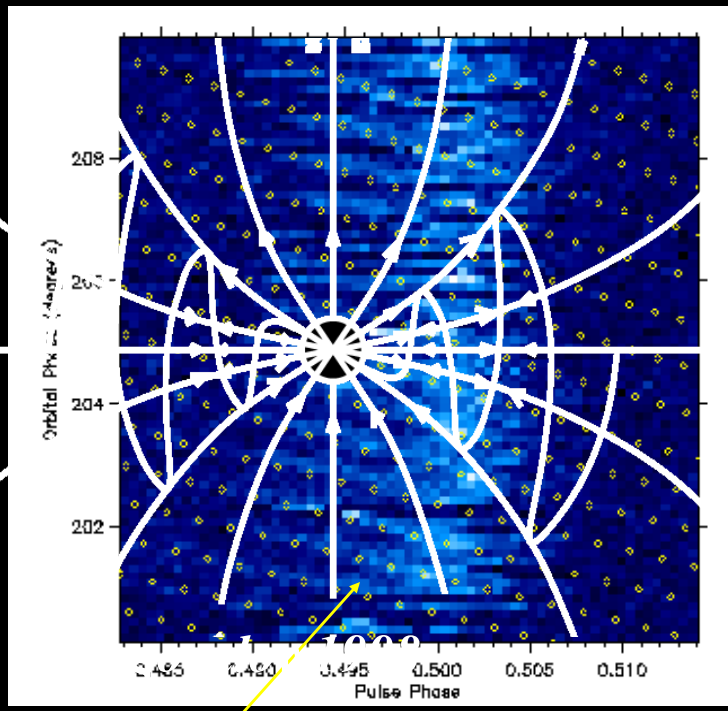
Drifting subpulses in B emission at beat frequency between A & B

EM field of pulsar A wind (and NOT pressure) is causing this modulation

Large fraction of A's spin-down energy is carried by EM wave (at least at some A latitudes), large Poynting flux

Confirmation of Coroniti (1990) & Bogovalov (1998) picture; consistent with Michel's statement, wave, not wind

Modulation is caused by reconnection between A wind B-field and B-field of B magnetosphere



McLaughin et al, ApJL 04

Predicted arrival times of A pulses at B

Largest, observable, scales, x>>1
talk by Del Zanna

Step forward from (20 yrs old) Kennel & Coroniti model

σ problem (conversion of B-field energy into particle) remains with us:

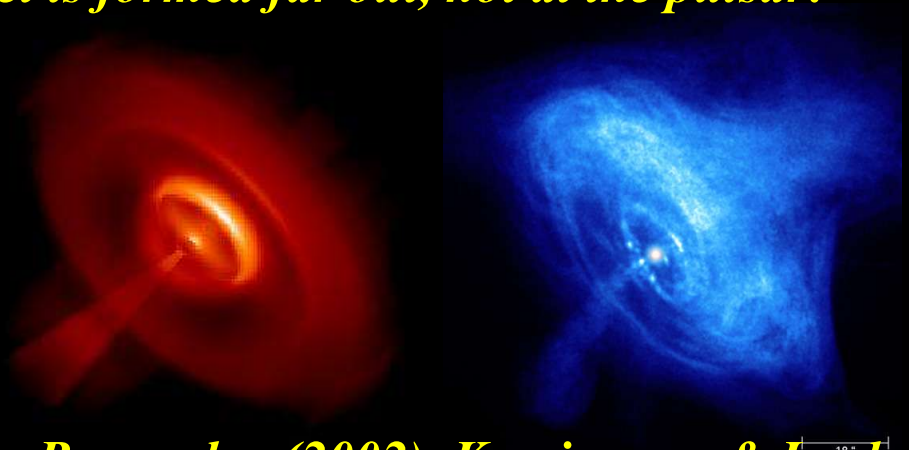
Take Michel (MHD) prescription for energy flux ~ $\sin^2\theta$

Magic: this is not Poynting flux but particle dominated

Self-consistent calculation of emissivity

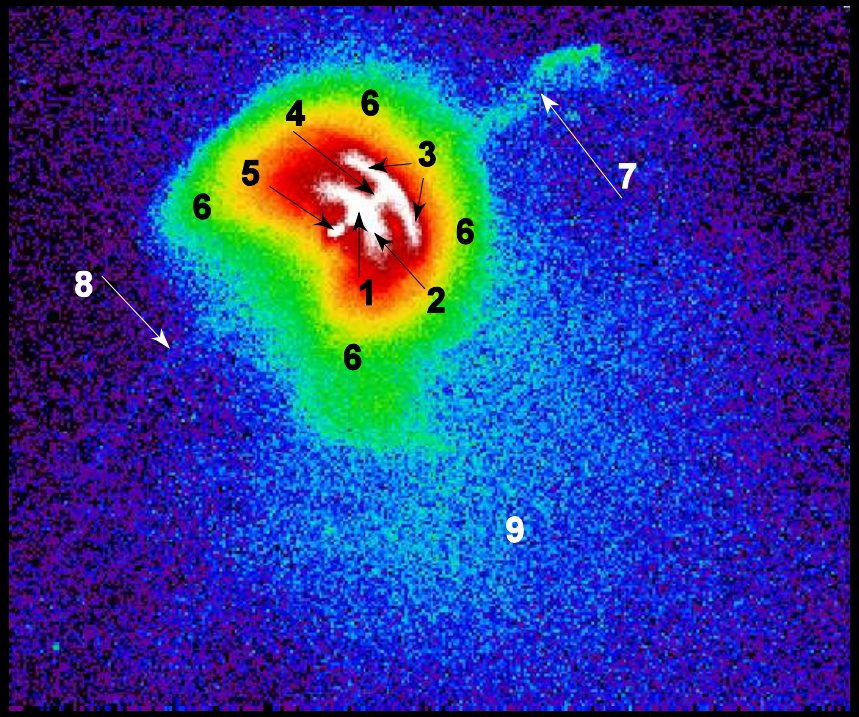
Simulations reproduce observations down to fairly intricate details

Jet is formed far out, not at the pulsar!



also Bogovalov (2002), Komissarov & Lyubarsky (2002)

Can you do Vela?



Kargaltsev et al 2002

Jet appears on the "wrong" side of torus

1509: talk by DeLaney

Rapid variability of knots

no kinking, need 3D simltns.

caution with (superluminal) v: G11: cannot connect X-ray knots separated by 2 month

Last slide

Though questions remain, there is a steady progress in validating pulsar as current source ("standard" model)

Michel "dome-torus" model is viable and needs more attention (=work)

hope: kinetic (PIC) simulations would approach MHD limit

σ problem: where and how does the conversion occur? x>1000

ν experiments (AMANDA, IceCube) and HESS (will) probe wind composition (ions), bulk Γ and acceleration spectrum (talk by Nagataki)

Particle acceleration @ shocks with

Prospects

(Surprisingly): we do find observational and numerical confirmation to our basic pictures (dipolar fields, current flow, structure of wind shocks).

Soon it may become possible to simulate oblique pulsars (Spitkovsky)

pc scales: HESS

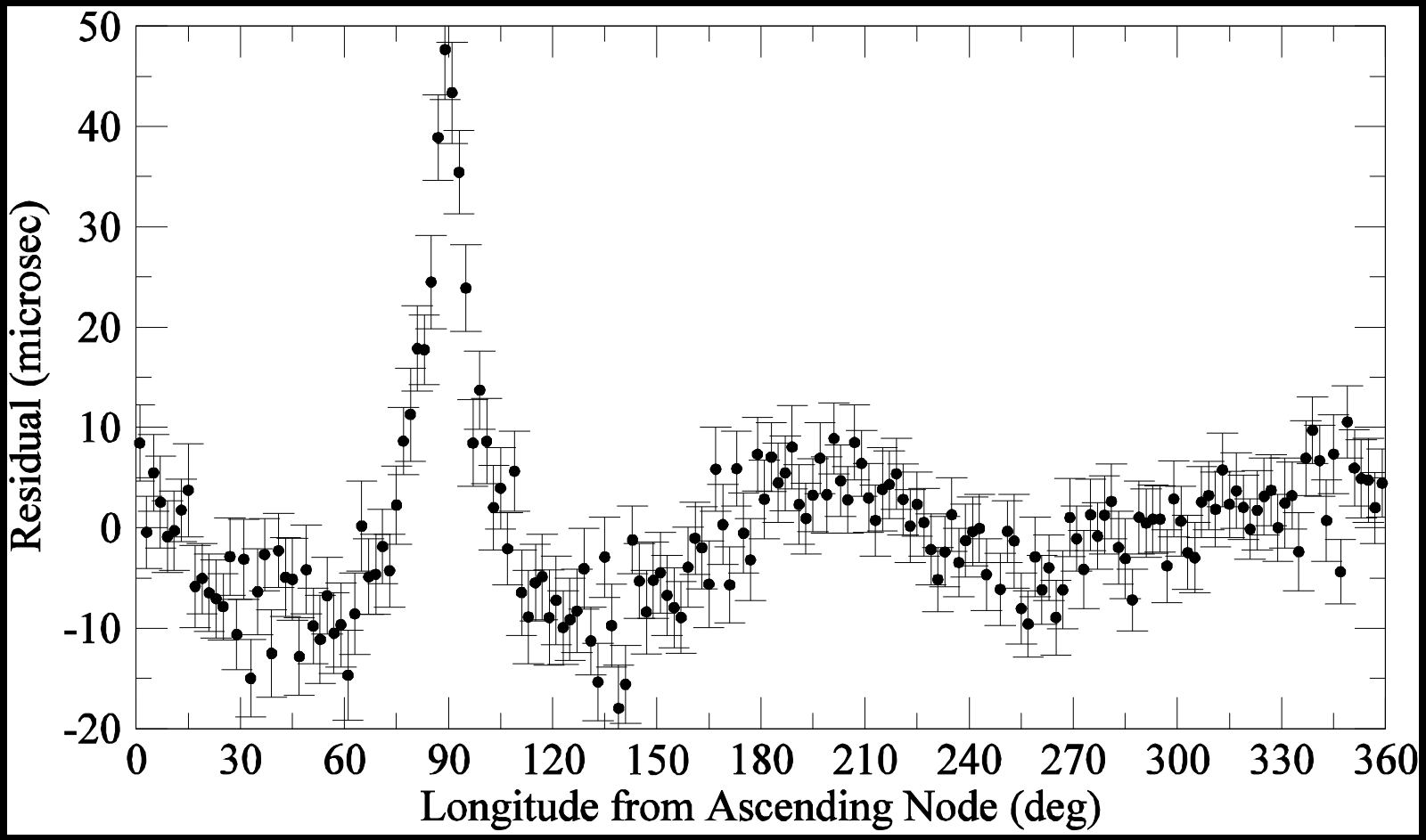
Dark accelertors: only TeV emission

low Galactic latitudes: confusion

identified SNR (PWR?), e.g. HESS J1813-178

Shapiro delay

$$\frac{s_{\exp}}{s_{obs}} = 1.0002 \begin{matrix} +0.0011 \\ -0.00006 \end{matrix}$$



This is a 0.1% test of strong-field gravity best yet!
And purely non-radiative, so complementary to B1913+16

Crab nebular: two populations

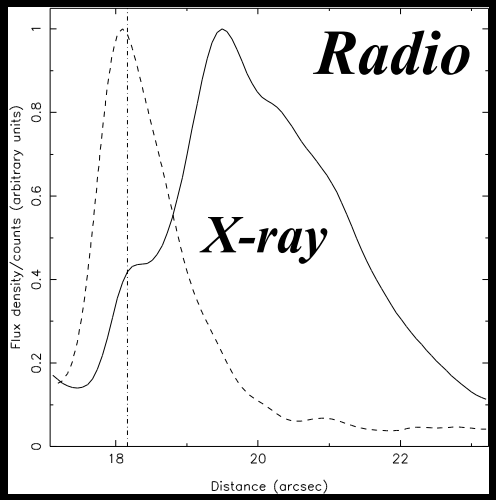
Radio population IS different from optical – X-ray

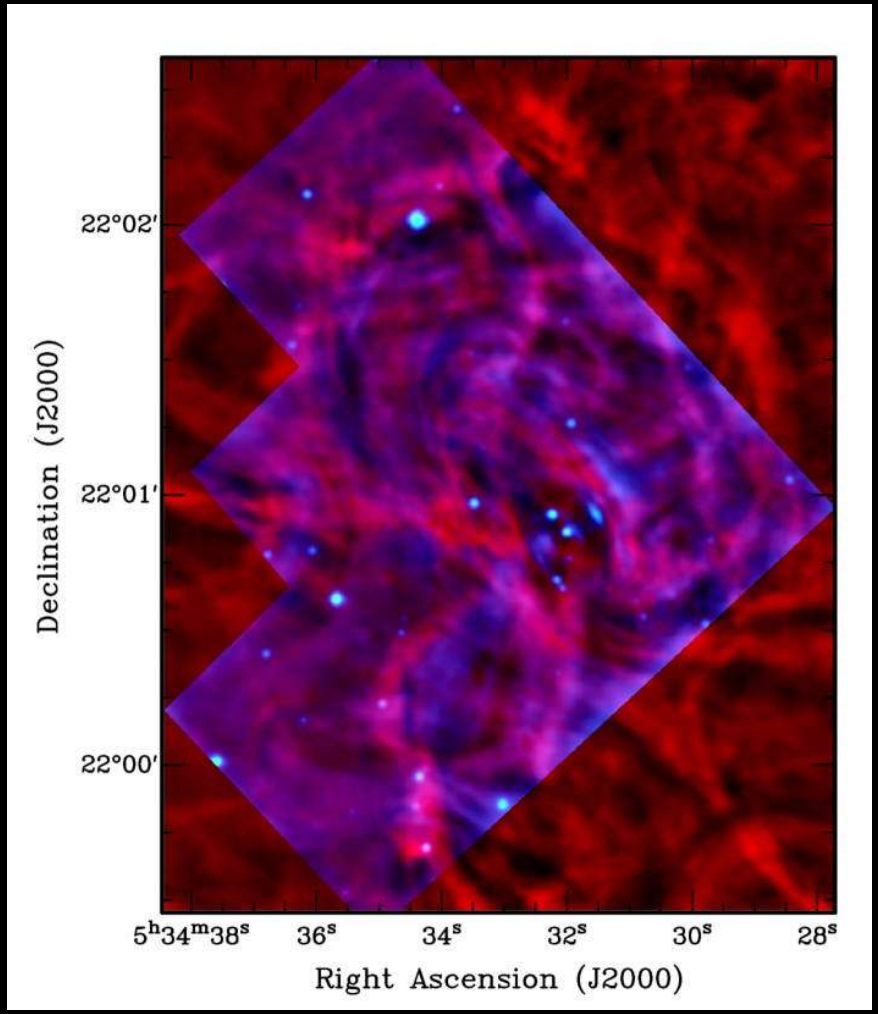
spectral break < 0.5

spacially separated features

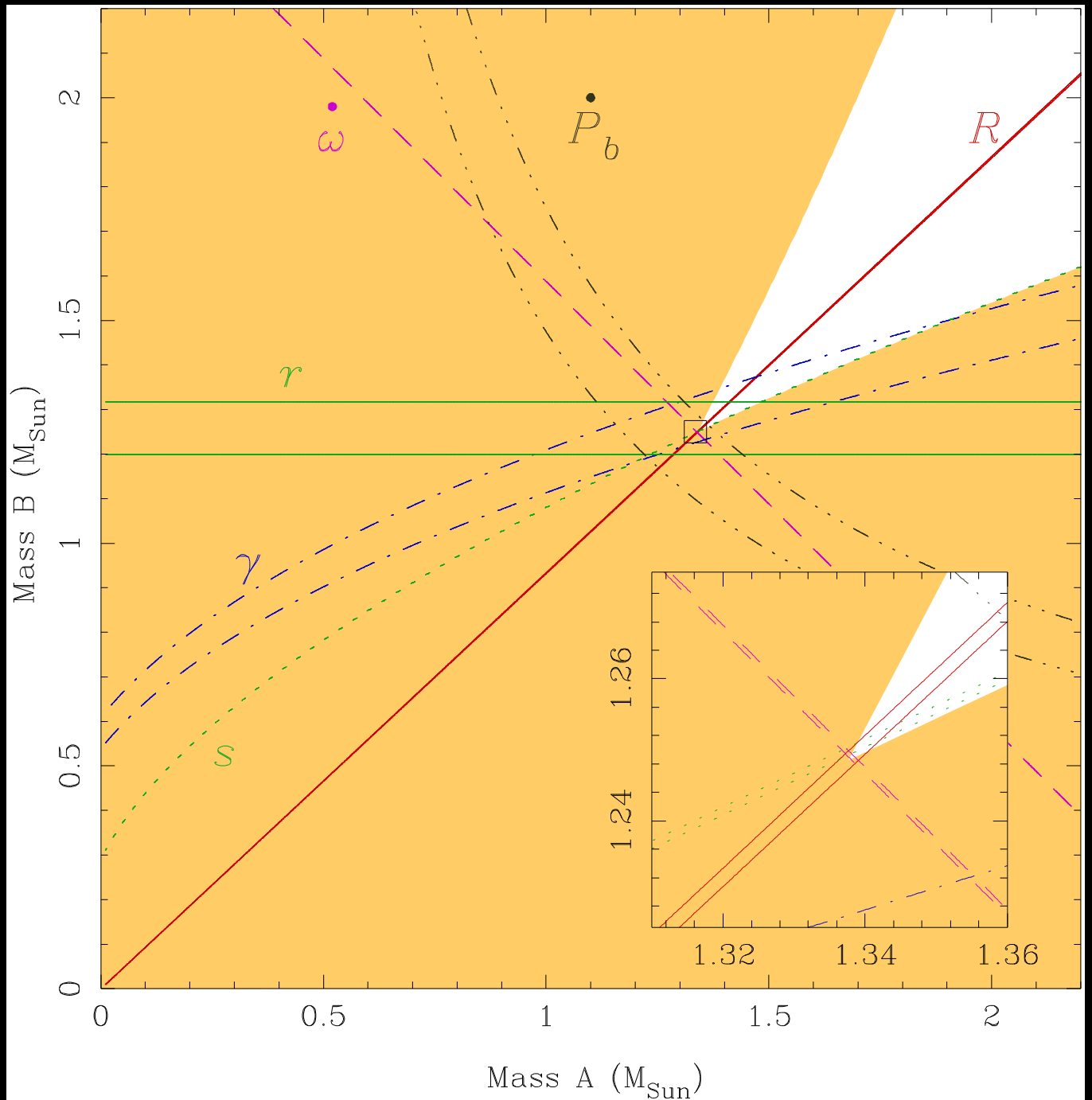
Two accelerations schemes? (E.g. Fermi @ shocks and magnetic dissipation, Kirk)

Cen A (Hardcastle et al 2003)





Bietenholz et al 2004


$\dot{\omega}$
$\dot{P}_b$
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: post Keplerian parameters

Expected in GR	*Observed*
$g = 0.384$ ms	$g = 0.382 \pm 0.0005$ms
$dP_b/dt = -1.24\times10^{-12}$	$dP_b/dt = (-1.21 \pm 0.06)\times10^{-12}$
$r = 6.2$ ms	$r = 6.2 \pm 0.5$ ms
$s = 0.9997$	$s = 0.9995 \pm 0.0004$

Orbital decay due to GR waves 7mm/day

Coalesence time due to GR waves: 85Myr

GR passes all tests