Title: The Double Pulsar: testing GR in strong regime

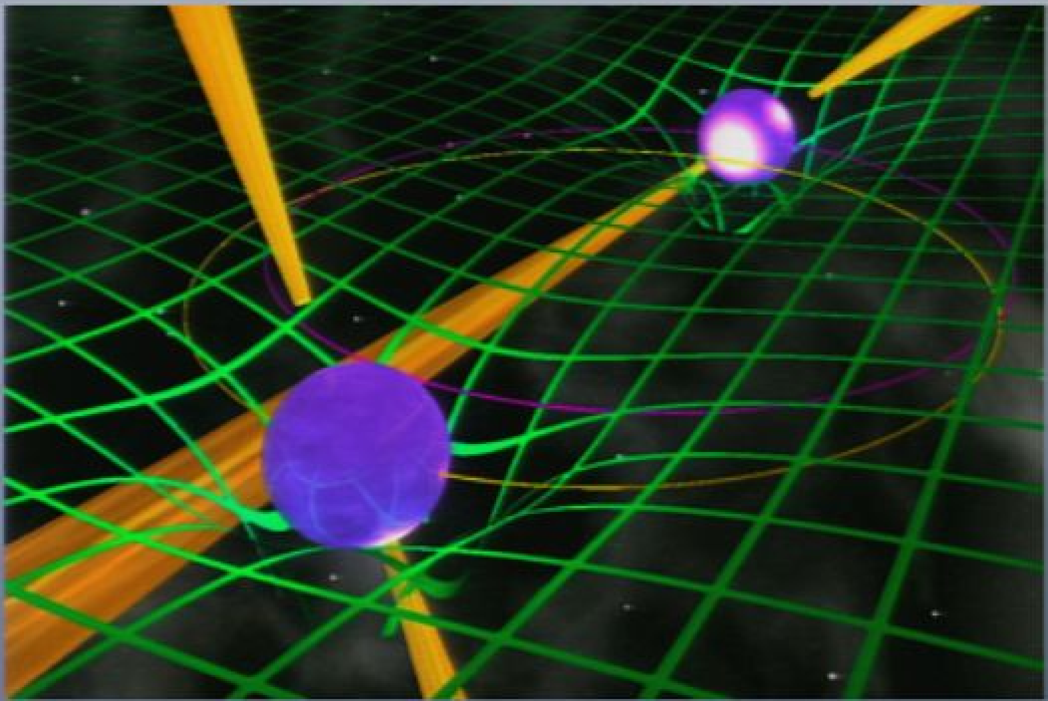
Date: Feb 04, 2011 01:00 PM

URL: http://pirsa.org/11020087

Abstract: The long awaited discovery of the double radio pulsar system, PSR J0737-3039A/B, surpassed most expectations, both theoretical and observational, as a tool to probe general relativity, stellar evolution and pulsar theories. The Double Pulsar provides a unique and the most complete and clean test of theories of gravity in a regime sensitive to possible strong-gravitational self-field effects. All six post-Keplerian parameters have been measured (including the measurement of the relativistic spin precession), some parameters to a precision of 10^{-4}.

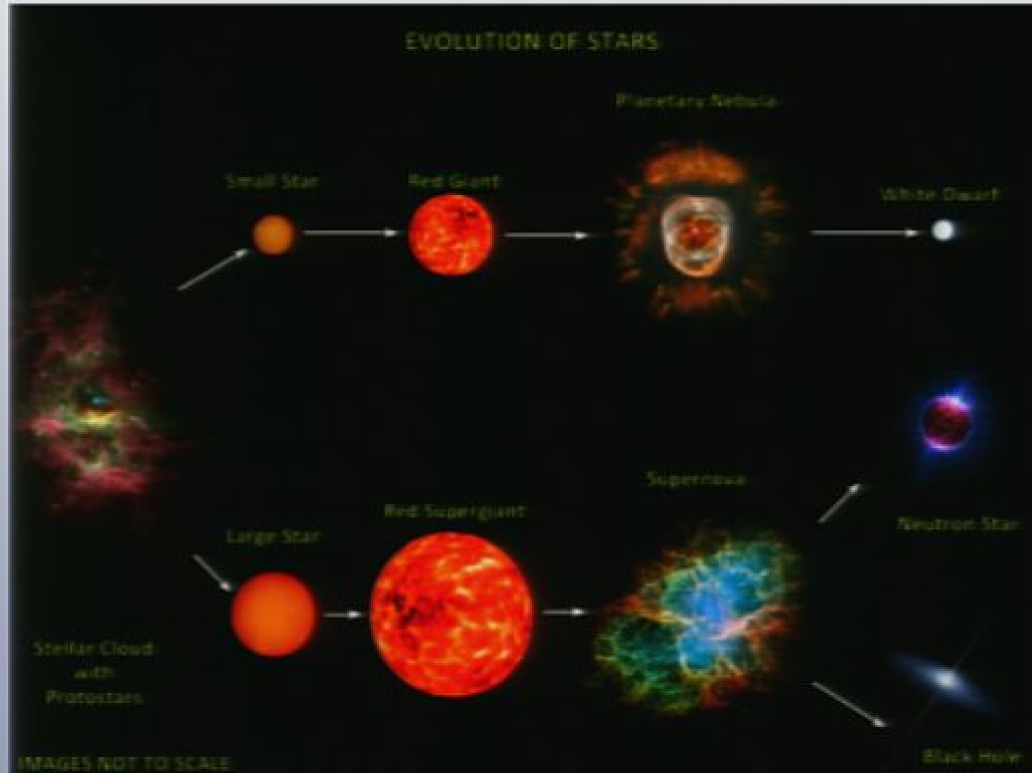
The Double Pulsar, Aurora Borealis and testing theories of gravity

Maxim Lyutikov (Purdue U.)



The Double Pulsar

Three ways for a star to die



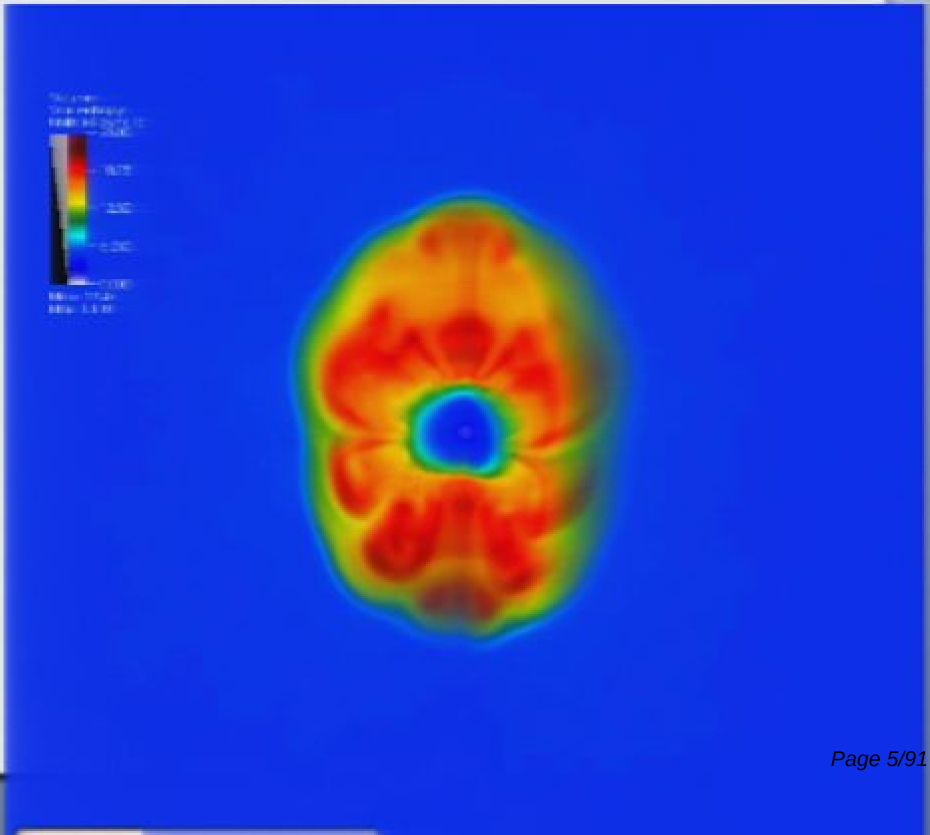
$$1 - 8 M_\odot \rightarrow \text{White dwarf}$$

$$8 - 40 M_\odot \rightarrow \text{Neutron star}$$

$$> 40 M_\odot \rightarrow \text{Black hole}$$

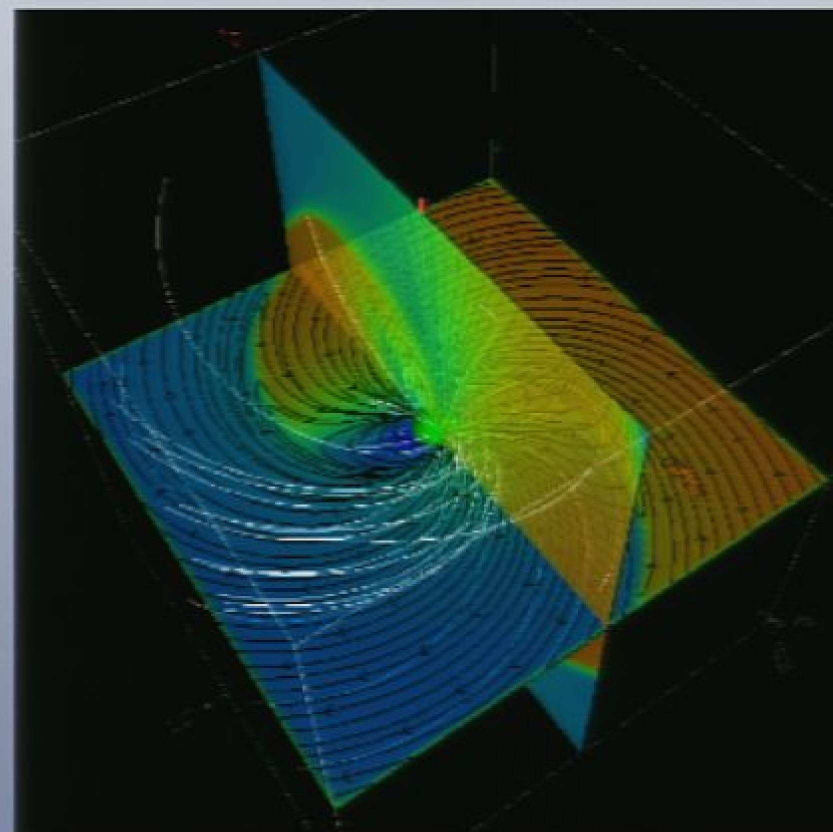
Supernova explosion

- Nuclear fuel exhausted in the core: nothing counteracts gravity -> collapse
- Optically thick to neutrinos: convection.
- Neutron star forms -> envelope bounces off and is expelled
- Convection + rotation -> dynamo action (amplification of B-field)



Structure of magnetosphere: rotating magnetized dipole

- Highly non-linear E&M problem.
- Inductive E-field, E ~ v B, tears vacuum, fills magnetosphere with plasma & currents



Simulations by Spitkovsky

The Double Pulsar: the sixth most important scientific discovery of 2004 (Science)

- Parkes Multi-beam Survey; Burgay et al (2003)
- First ever double pulsar system (6^{th} binary NS system)
  - PSR J0737-3039A: P=22 ms (old)
  - PSR J0737-3039B: P=2.7 s (young)
  - P_{orb}= 2.4-hr (pulsars separated by 9 10^{10}cm = 3 lt-s)
- Only ~ 1 kpc away (relatively close)
- System observed nearly edge on (<0.5°)
- Allows
  - Precise measurement of masses
  - Testing GR (0.05% agreement)
  - Possibly measuring I_A (EOS)
  - Direct probes of pulsar magnetospheres

Parkes Multibeam Receiver

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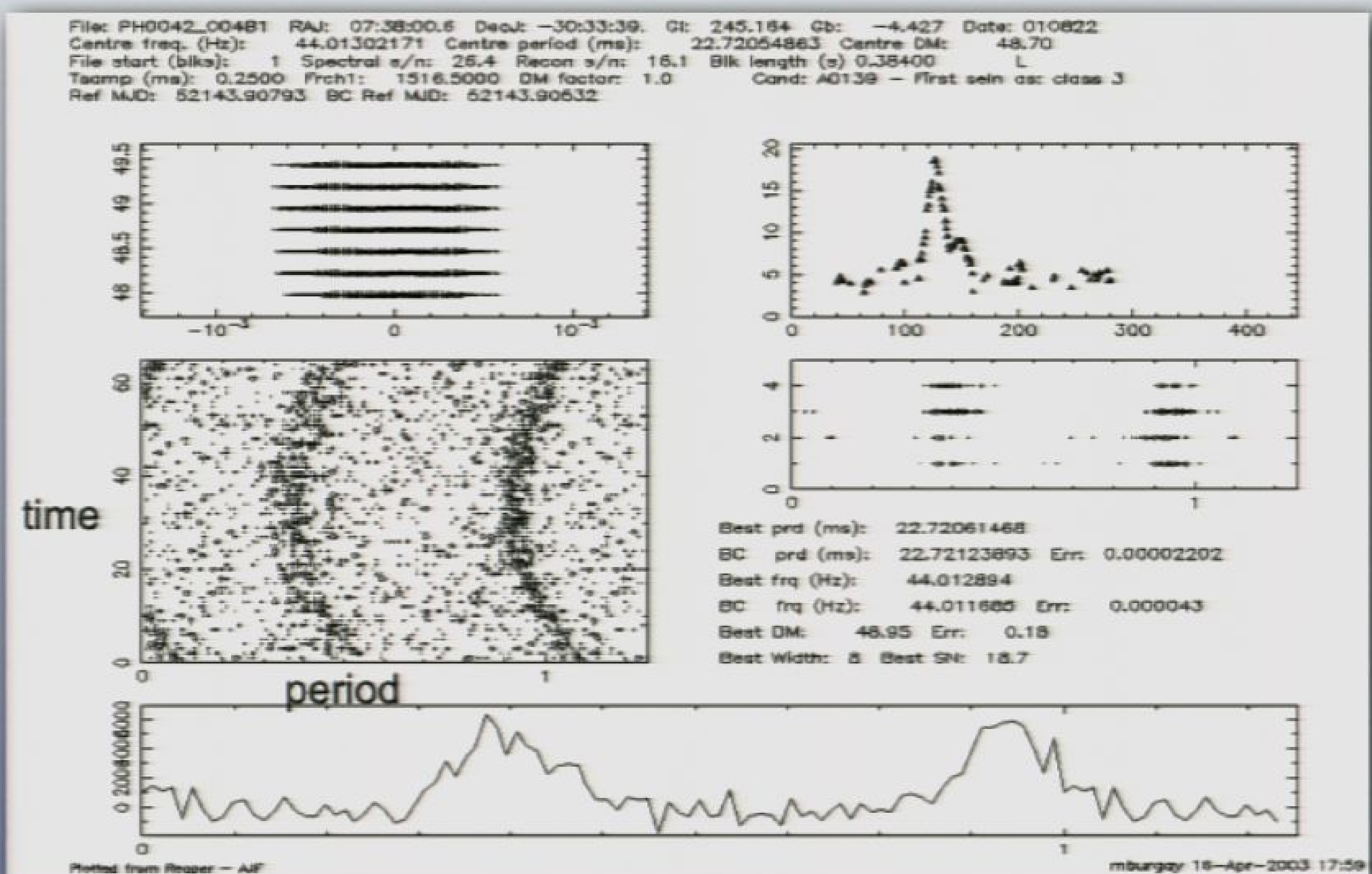
Parkes Multibeam Receiver

Discovery of “A” pulsar



(Burgay, et al. 2003)

Formation & LIGO predictions

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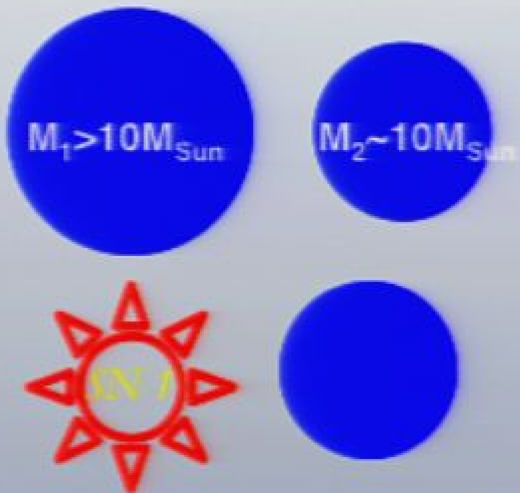

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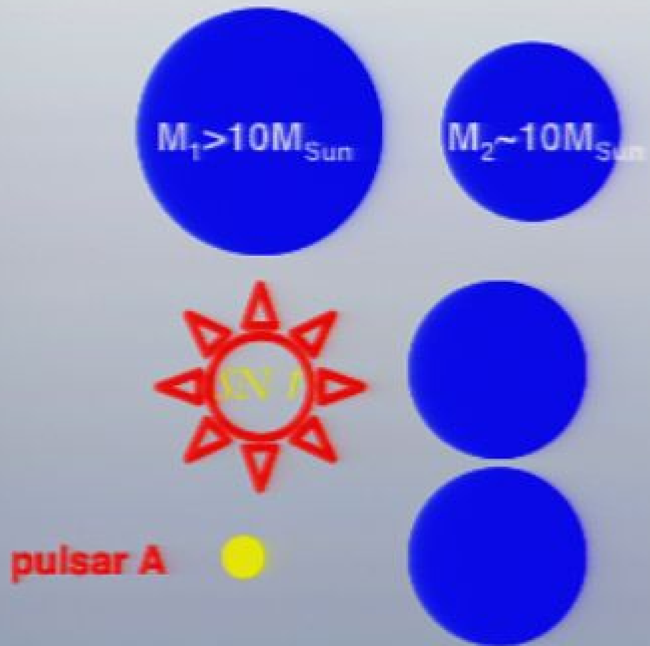

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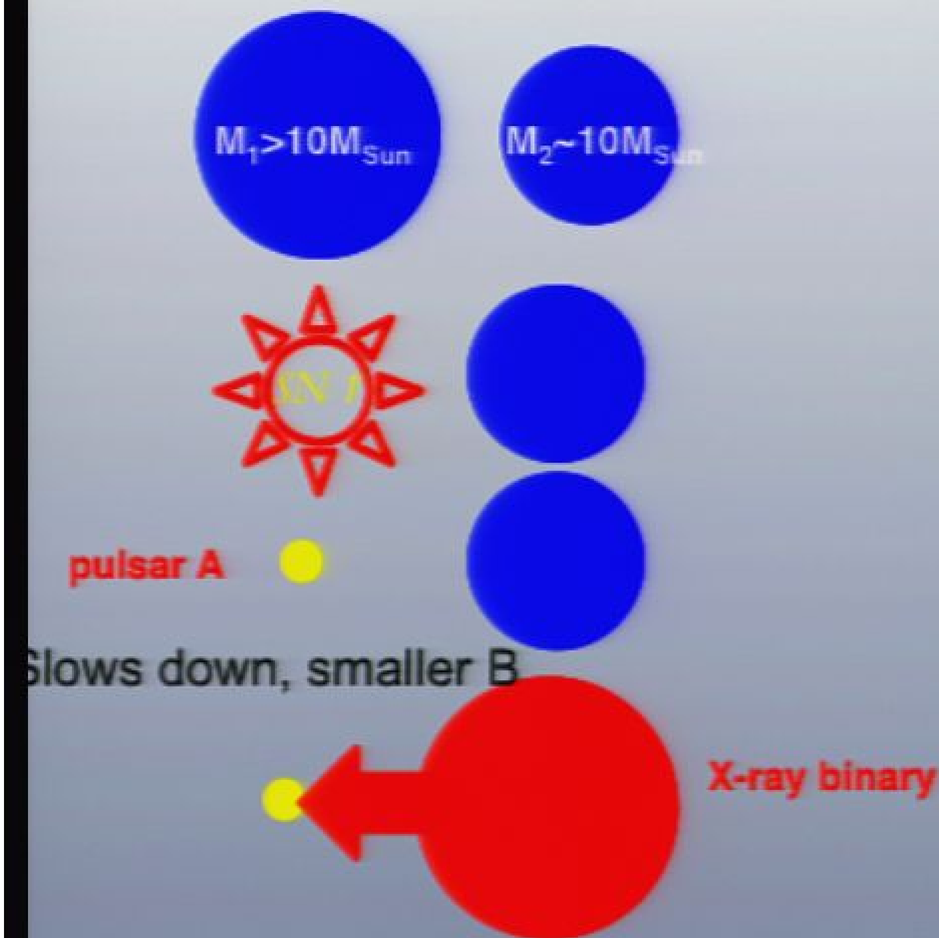

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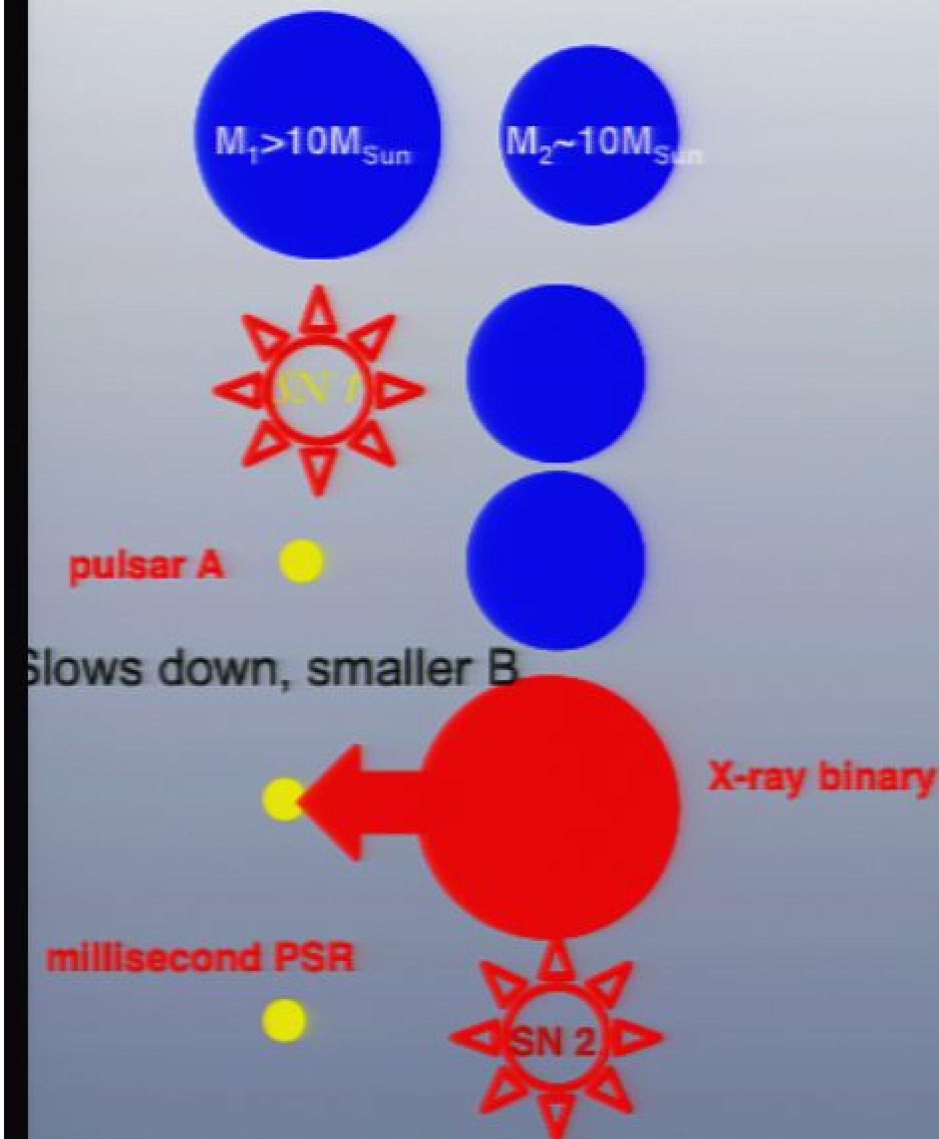

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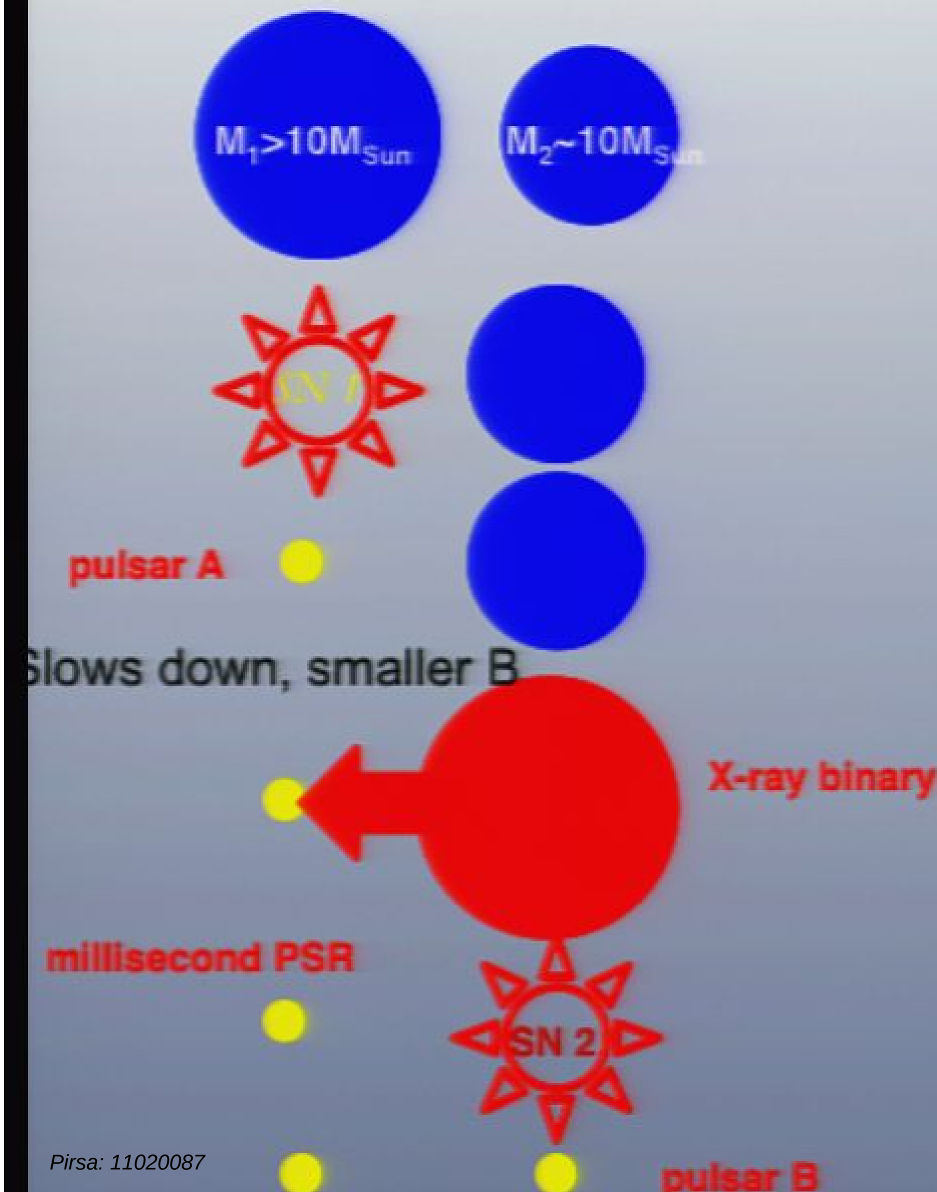
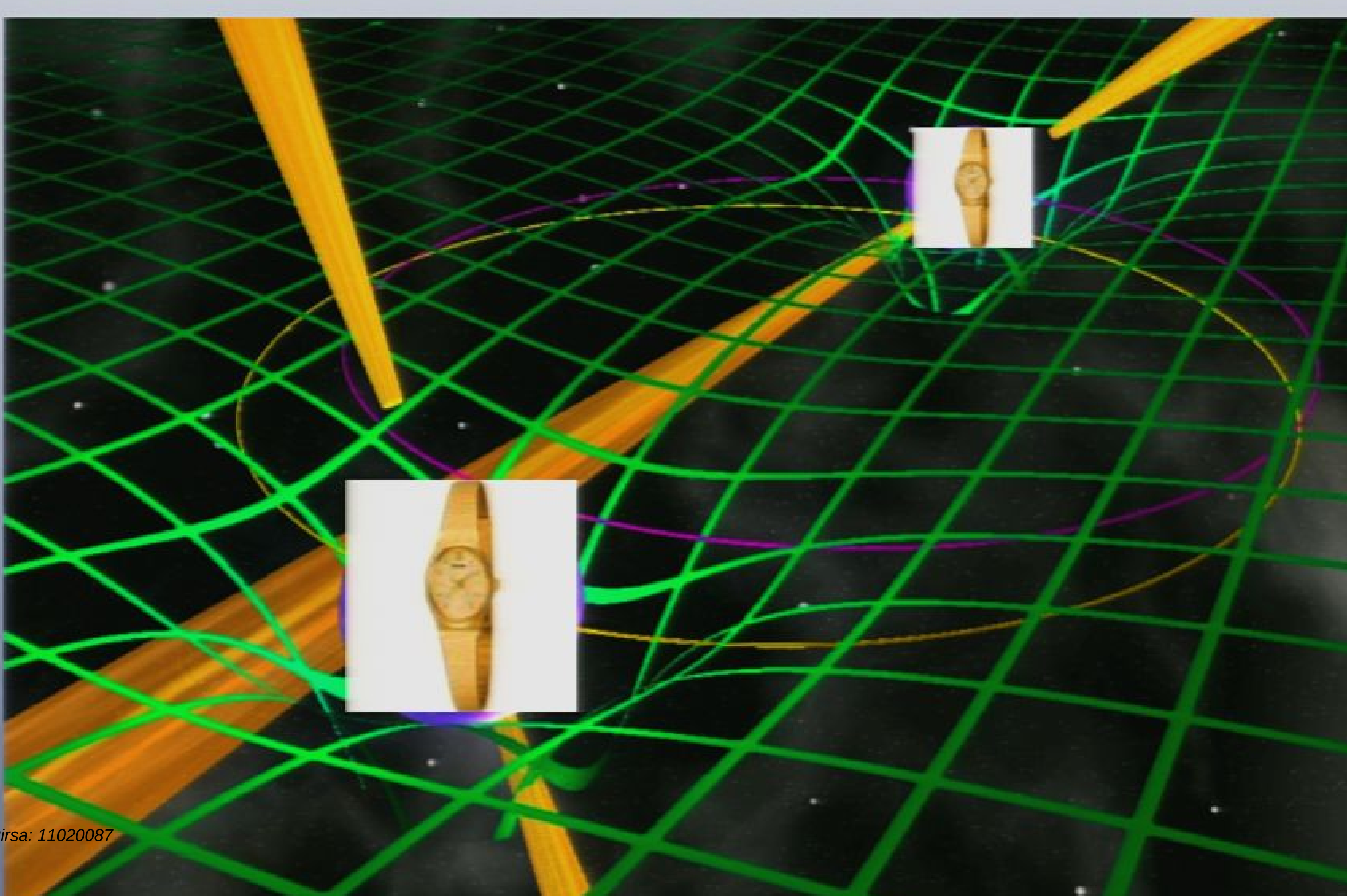


- Details are not clear ("population synthesis")
- Rate of NS-NS coalecence increased by 10 times (Kalogera et al)
- Good for LIGO

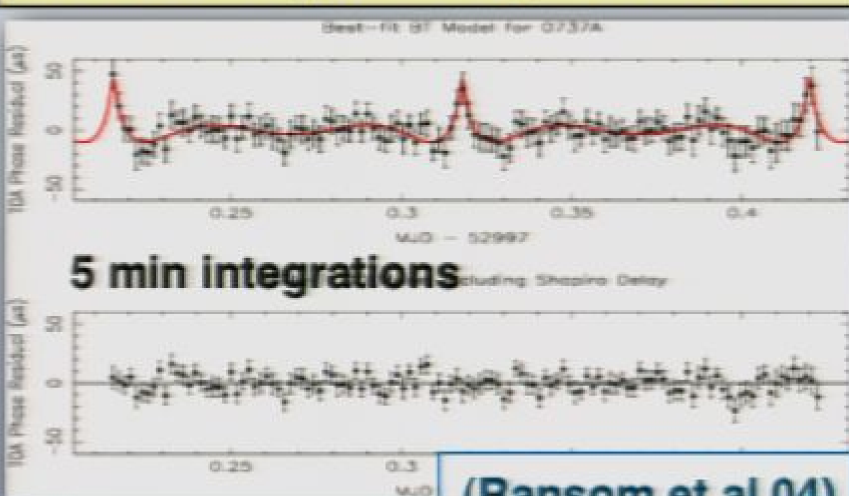
Excellent test ground for GR

Two Pulsar watches (clocks) moving in curved space



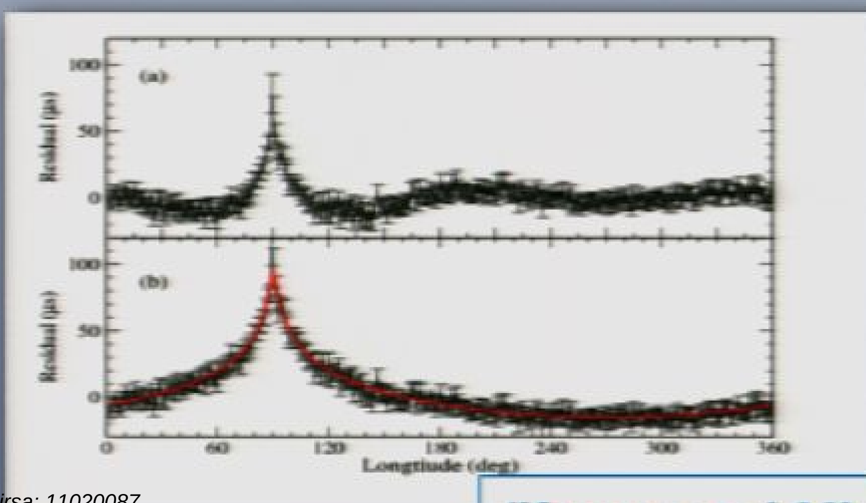
Excellent test ground for GR

0737A Shapiro Delay at the GBT

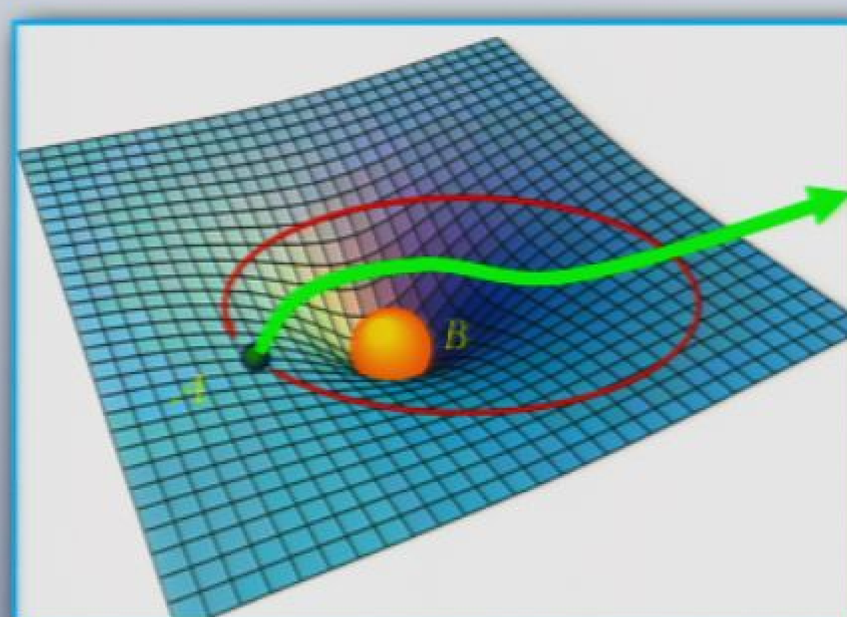


5 min integrations

(Ransom et al 04)



(Kramer et al 06)



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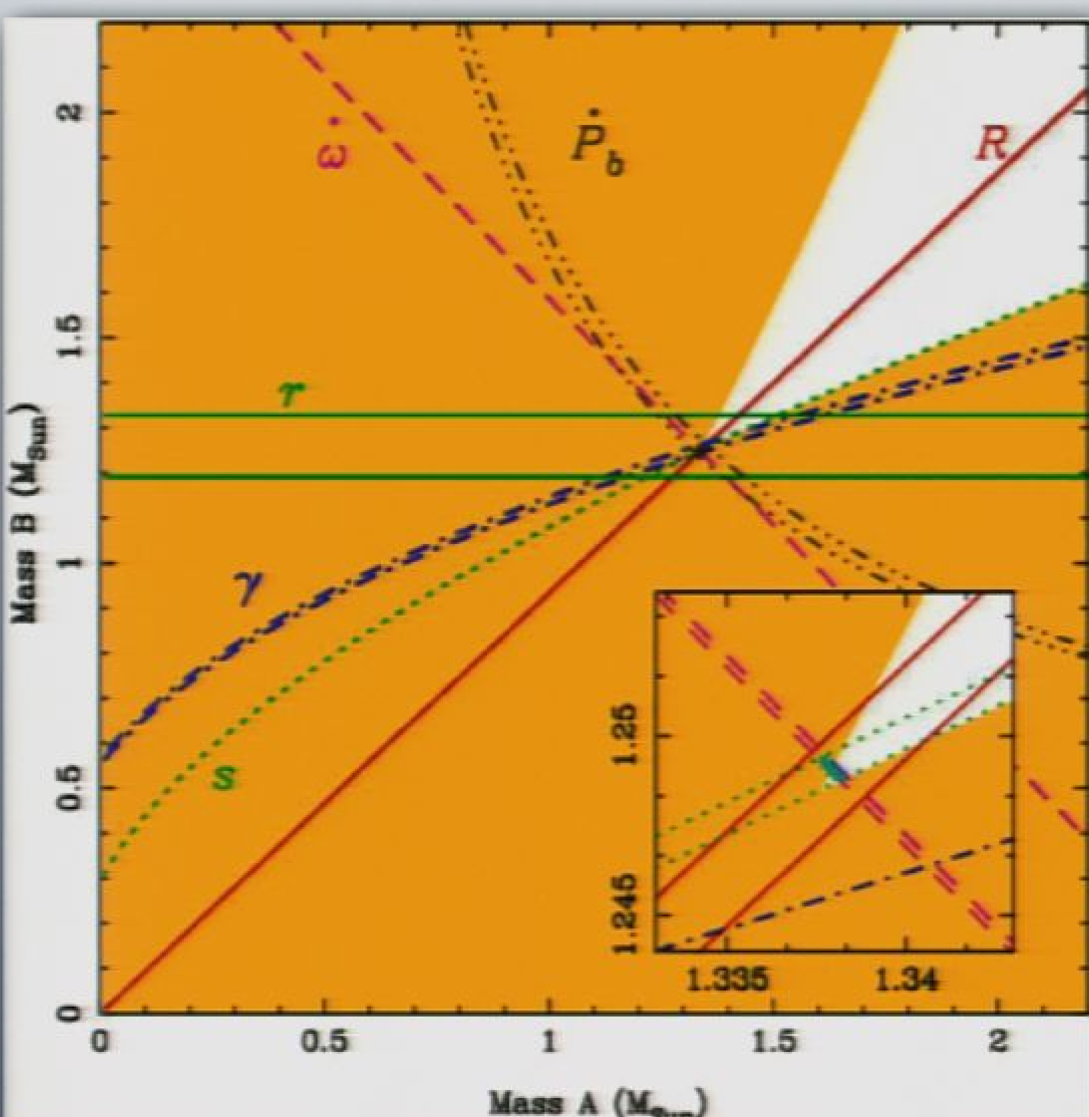

- *System is highly over-constrained*

→ *can be used to test GR*

M_A=1.3381(7) M_{Sun}

M_B=1.2489(7) M_{sun}

- *Orbit shrinks by 7mm a day,* $\Delta a/D = 3\ 10^{-22}$

$$\frac{s^{obs}}{s^{exp}} \approx (100 \pm 0.05)\%$$

- *Different (non-radiative) test of GR than Hulse-Taylor*
- *Maybe possible to measure* I_A *(from gravito-magnetic precession,* 10^{-4} *deg/yr)*

$$\dot{\omega} = 16.89947(7)\,\mathrm{deg/yr}$$

(Lyne etal, 04, 05; Kramer 06)

PK parameters agree with GR down to few hundredth of percent

- PK parameters are functions of masses and Keplerian parameters (spins are sufficiently small).
- Actual dependence can be different in different theories
- Four independent tests of GR from timing the Double Pulsar

PK parameter	Observed	GR expectation	Ratio
$\dot{P}_b$	1.252(17)	1.24787(13)	1.003(14)
γ (ms)	0.3856(26)	0.38418(22)	1.0036(68)
s	0.99974(−39, +16)	0.99987(−48, +13)	0.99987(50)
r(μs)	6.21(33)	6.153(26)	1.009(55)

Kramer et al. 2006

- 5th PK test - see later

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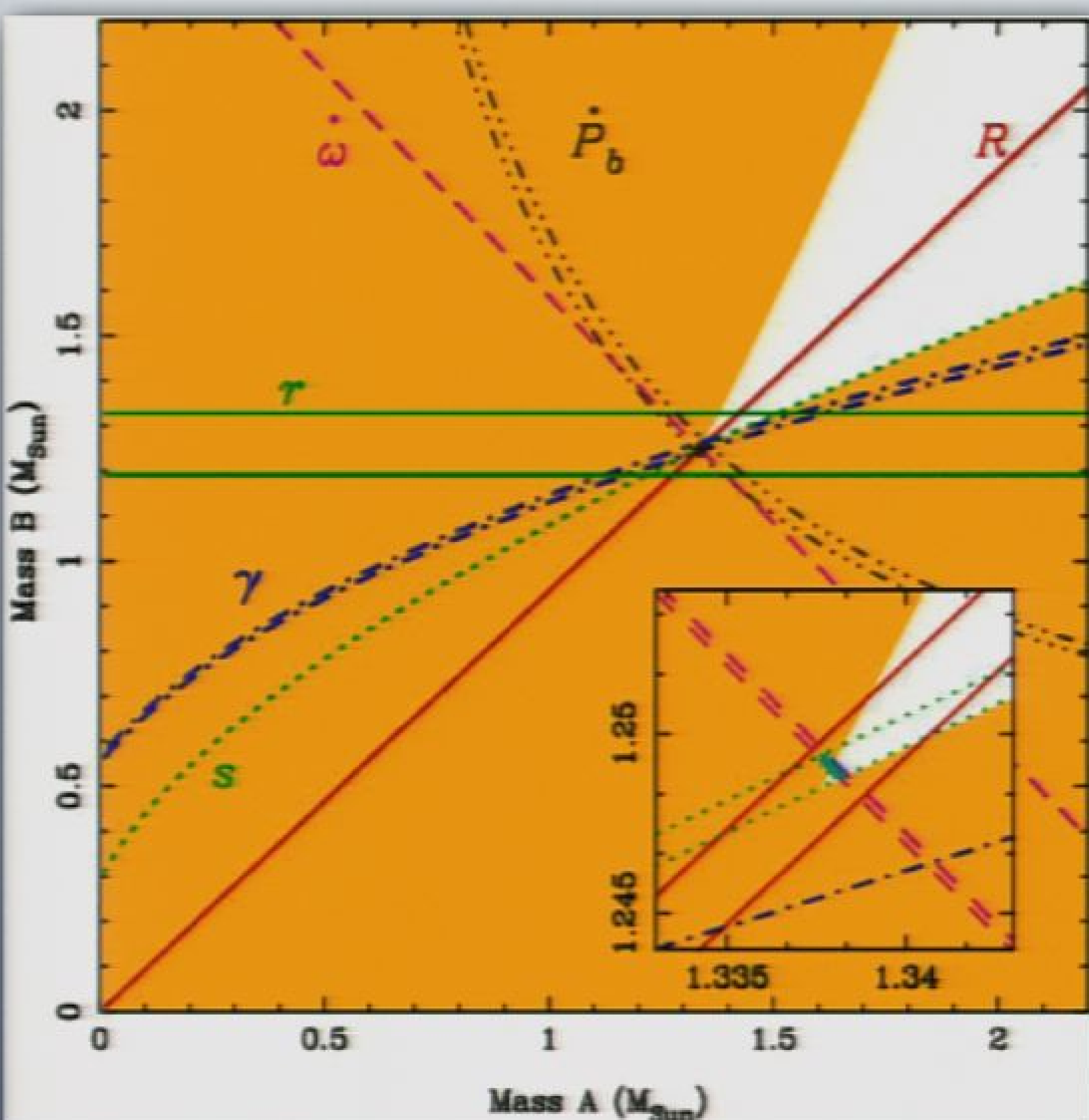

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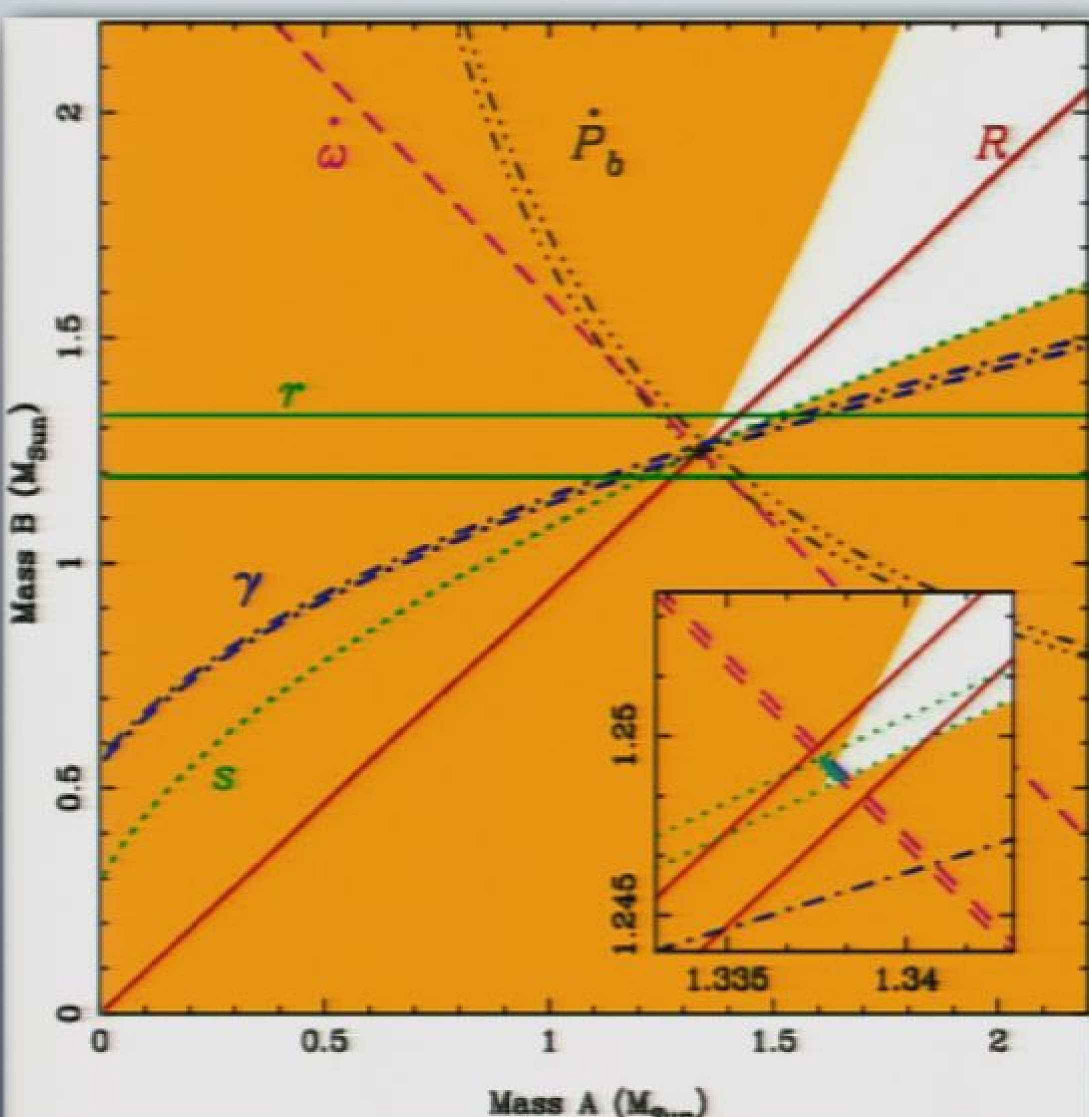

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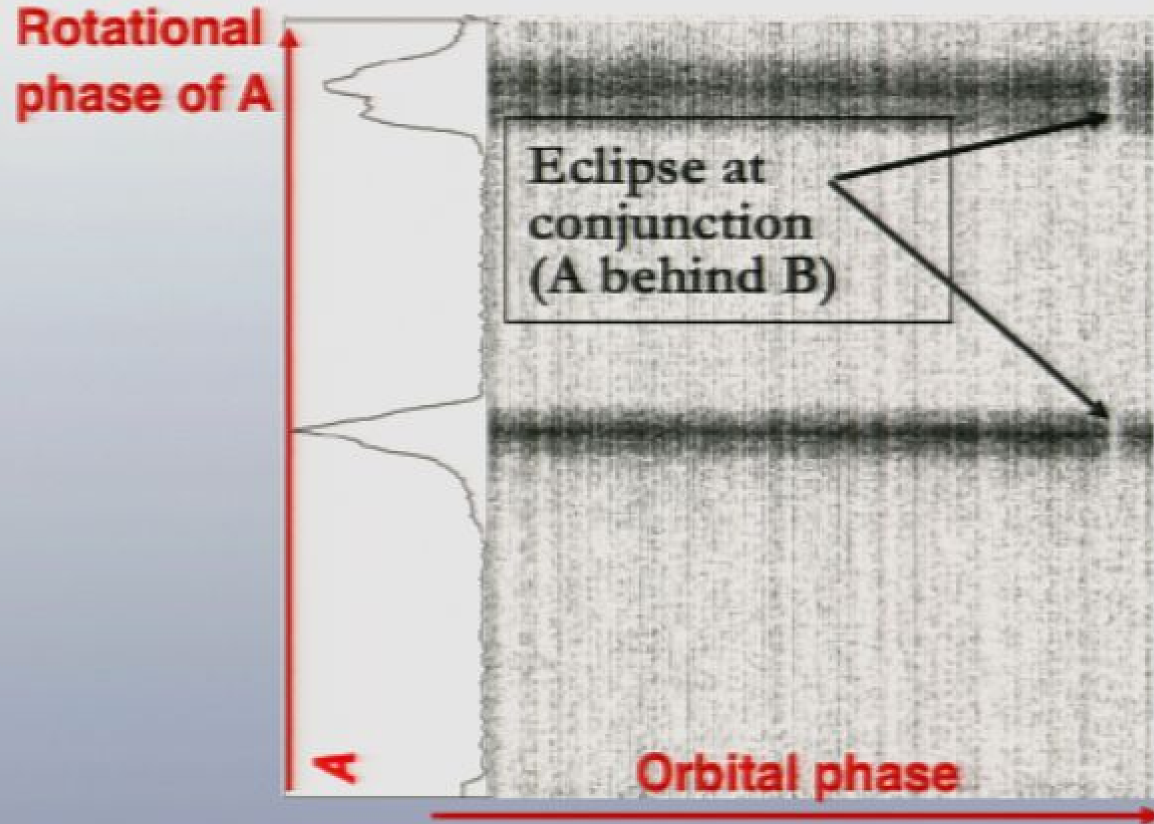
Direct probes of pulsar magnetospheres and plasma physics (and another GR test)

"A" eclipse: modulated at B rotation



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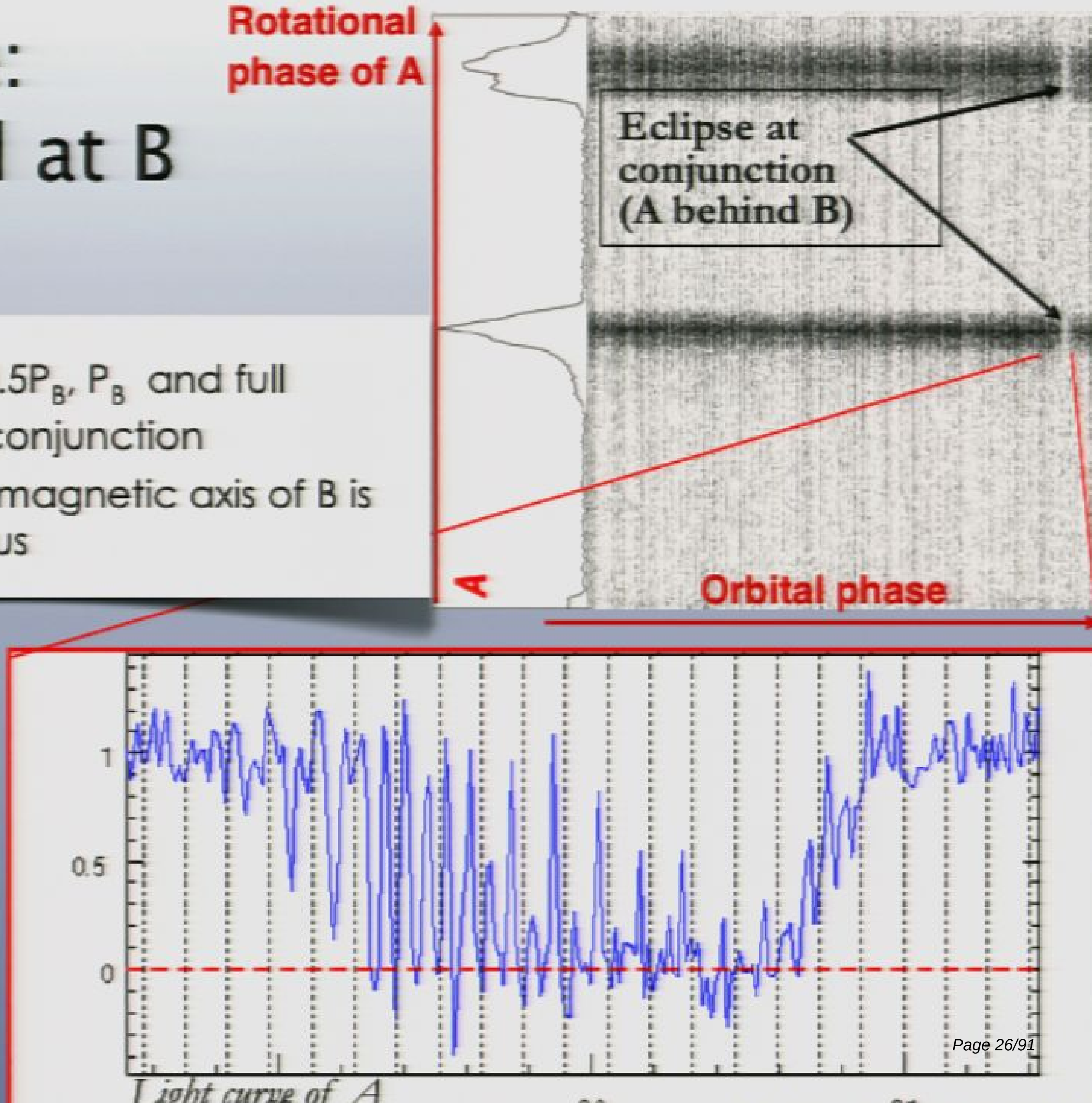
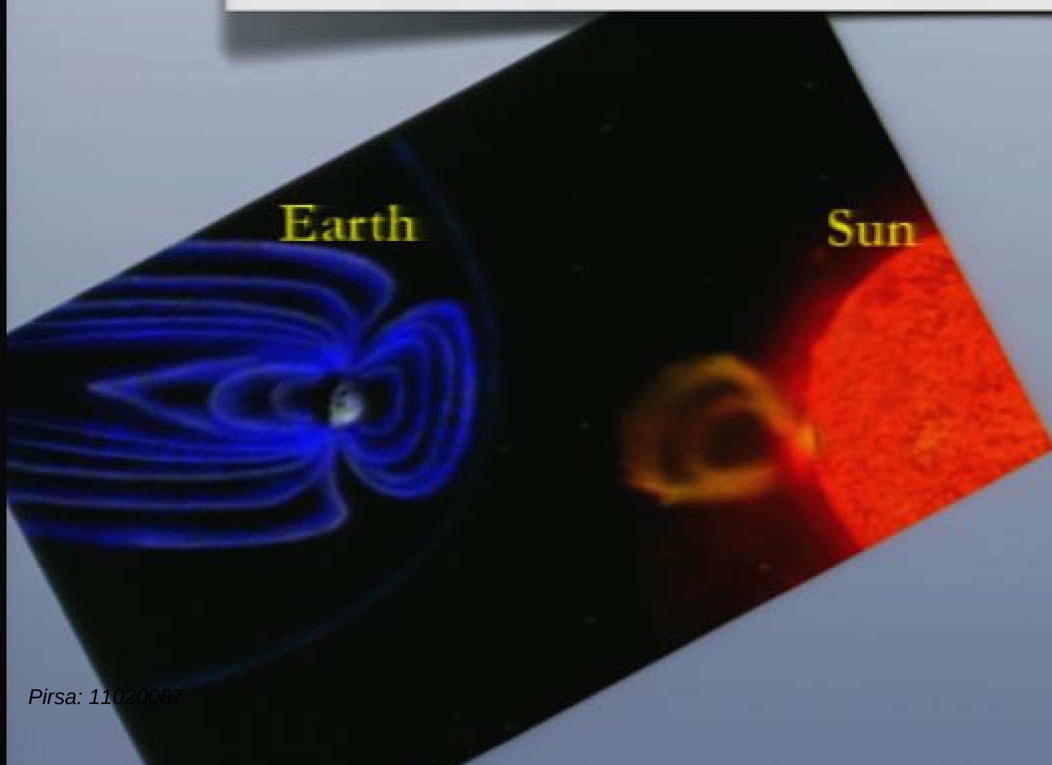
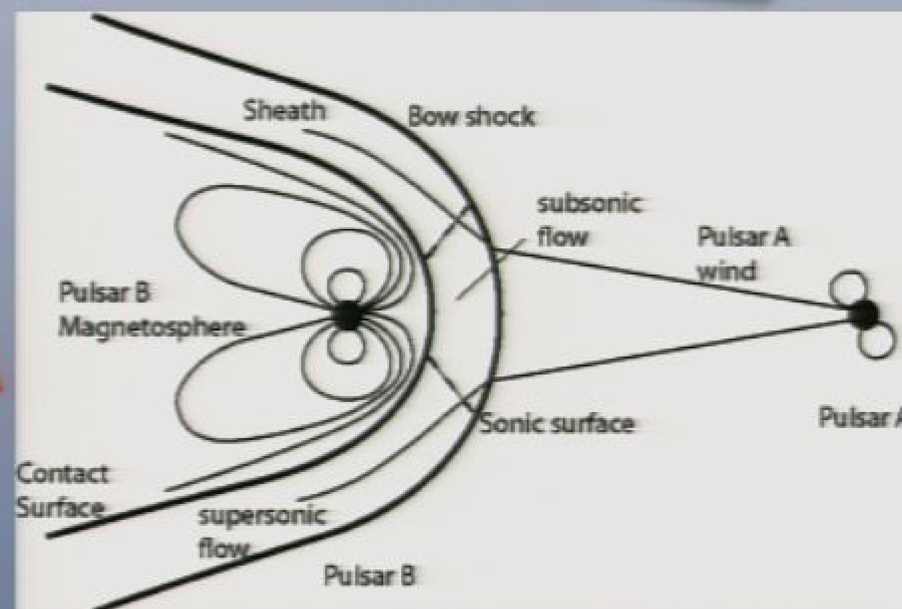
- Modulation is at $0.5P_B$, P_B and full eclipse after the conjunction
- Absorption when magnetic axis of B is pointing towards us



Magnetosphere of B is modified by the wind of A

- Similar to Solar wind – Earth Magnetosphere
- Pulsar A wind blows off pulsar B magnetosphere
- Bow shock, magnetospheath.





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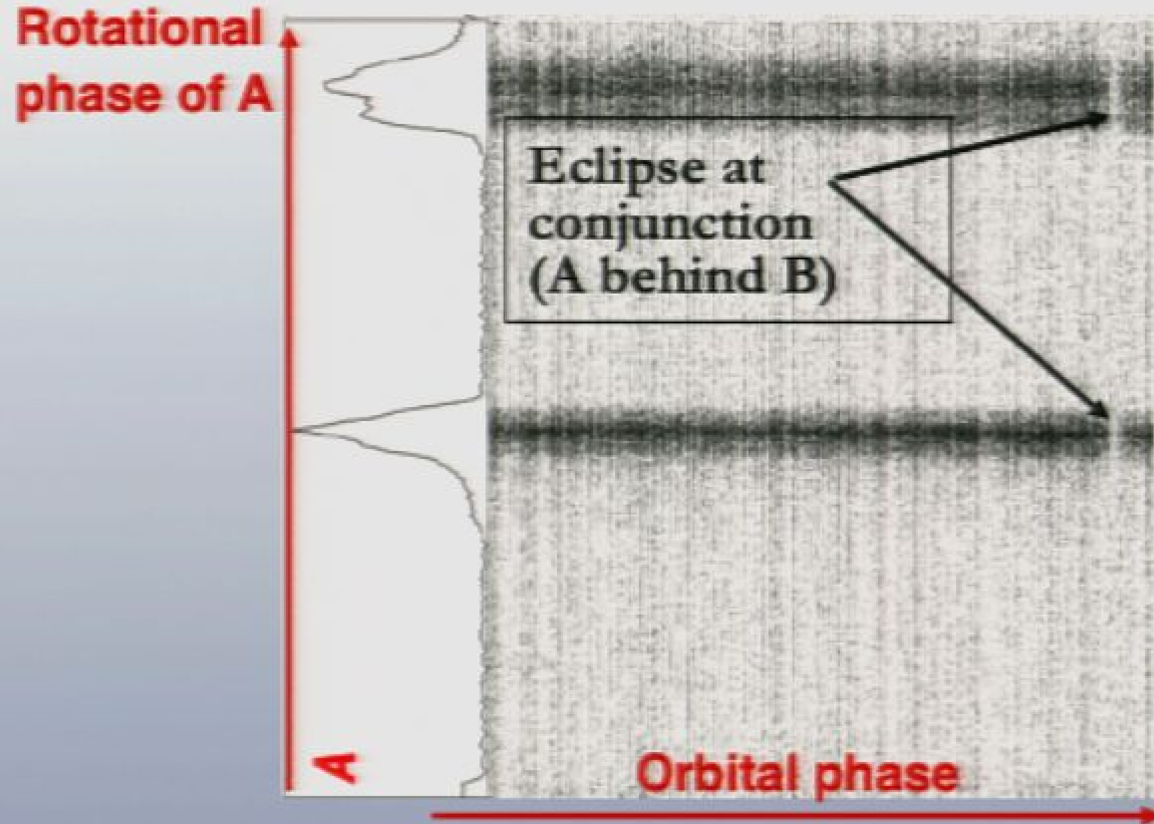

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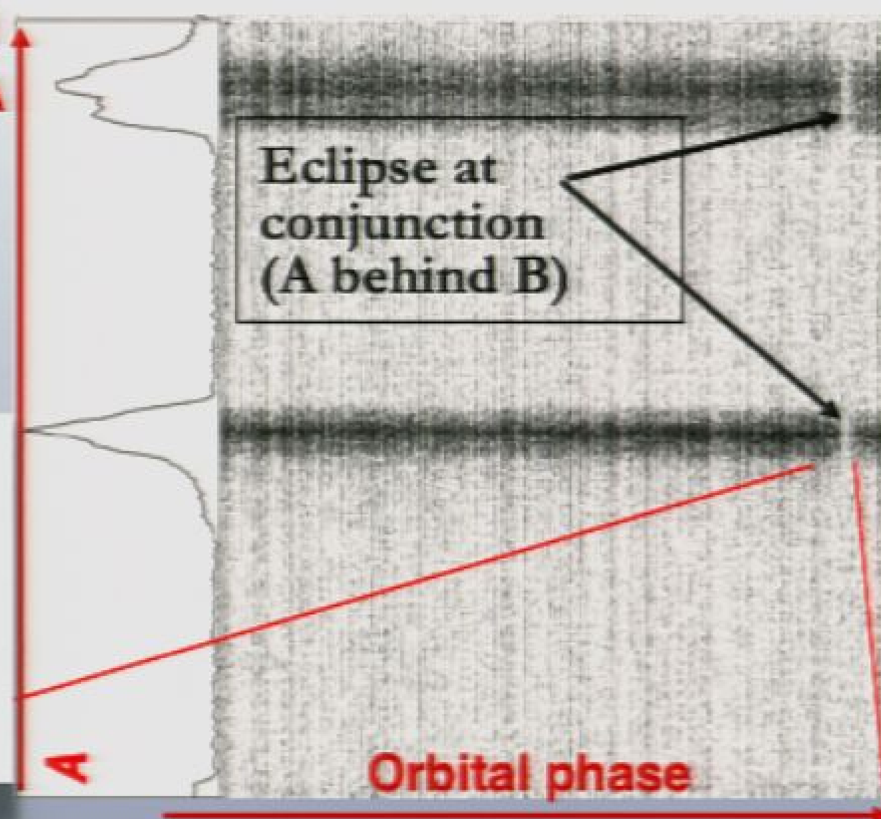

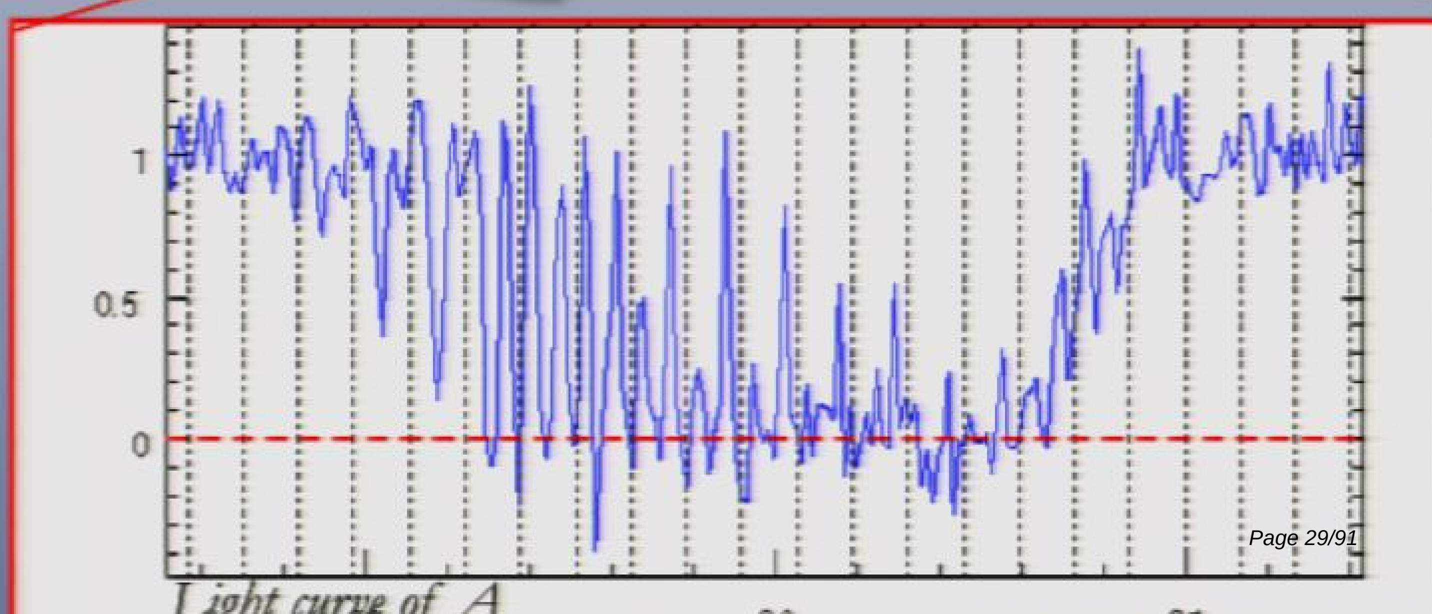

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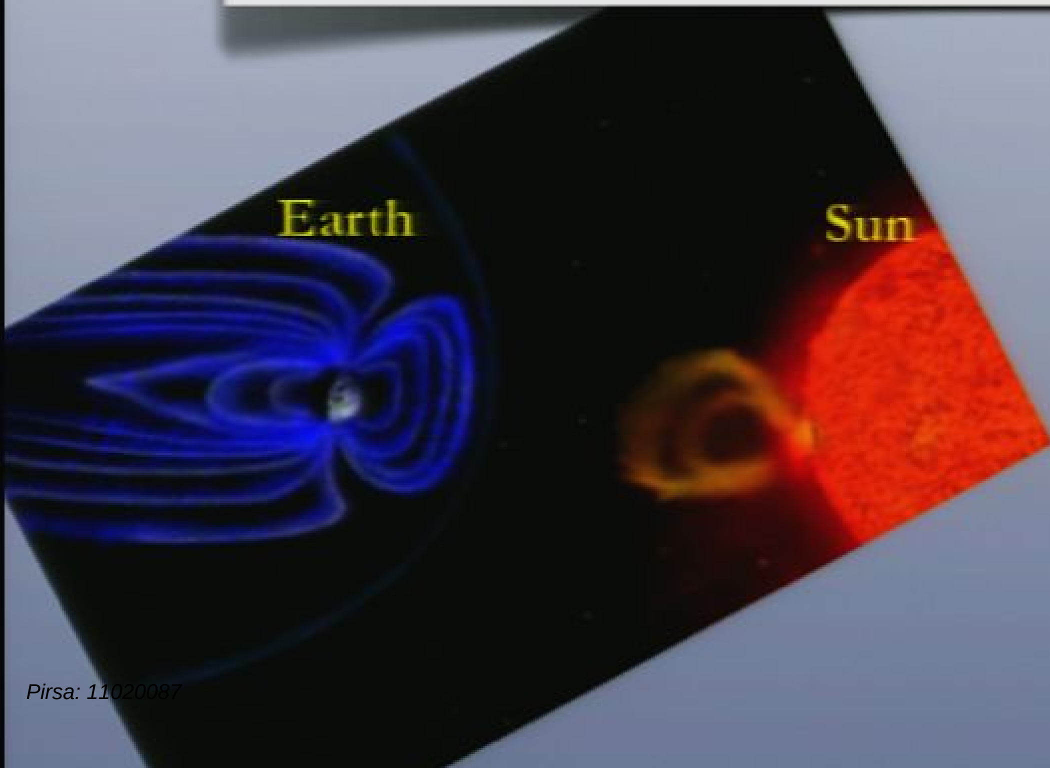

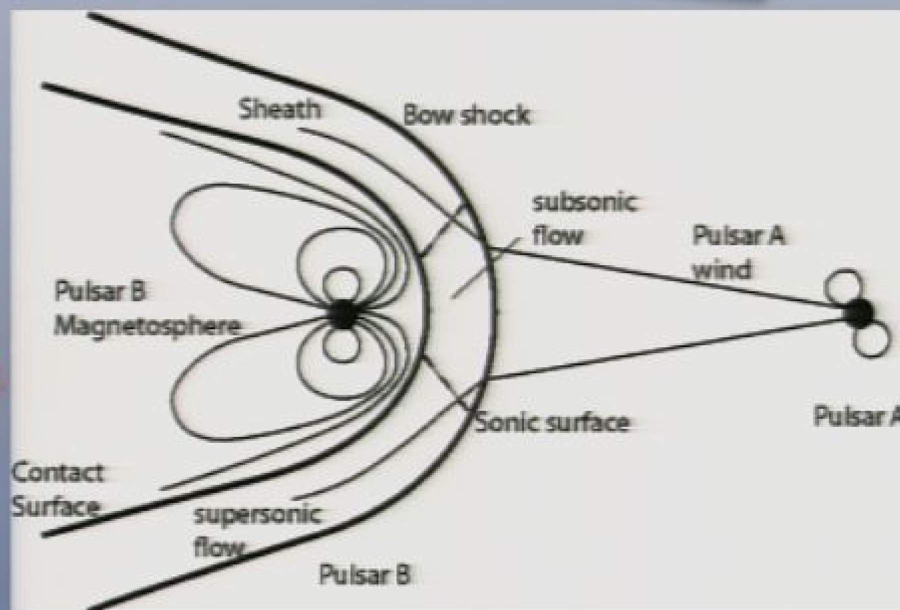

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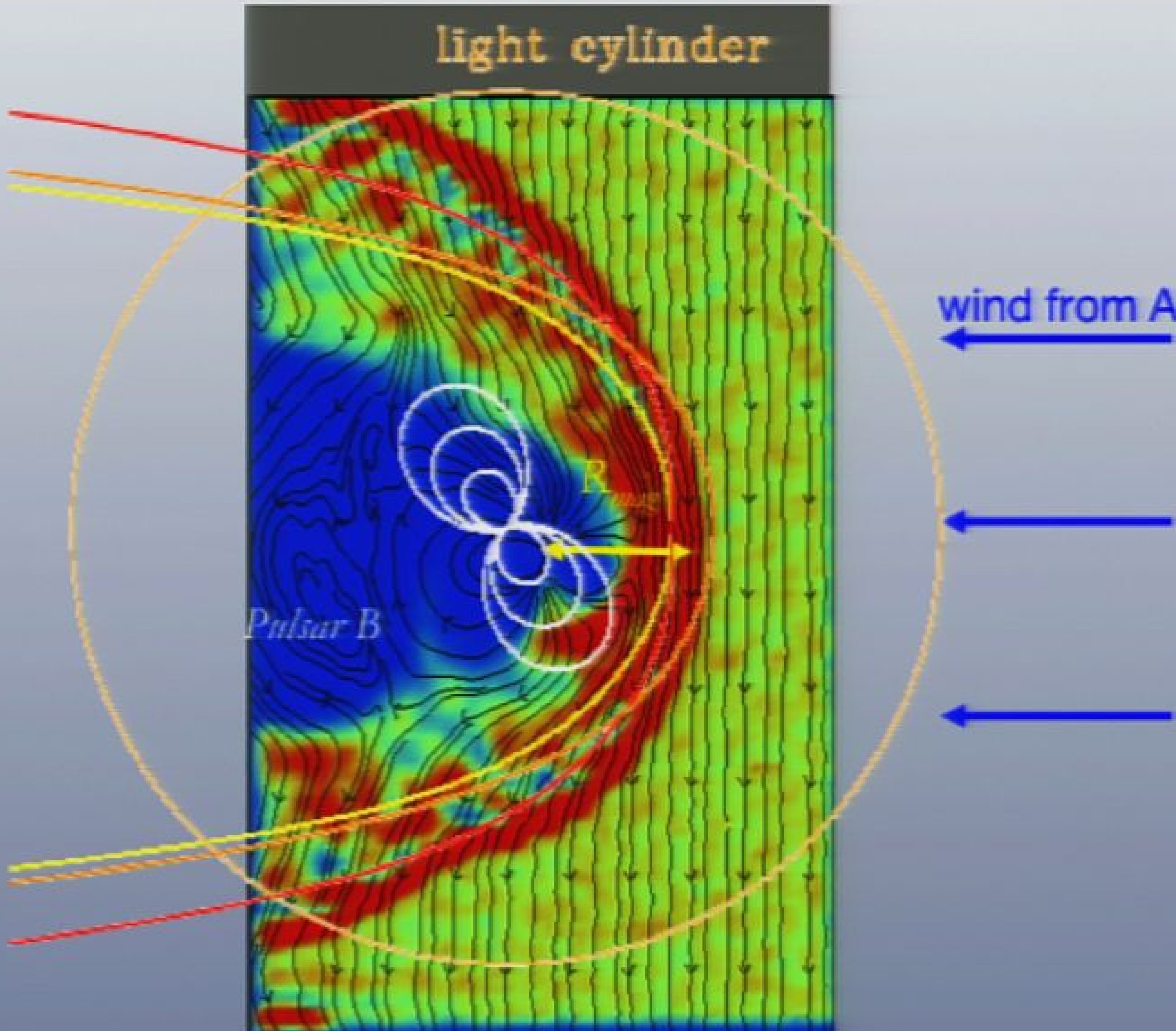
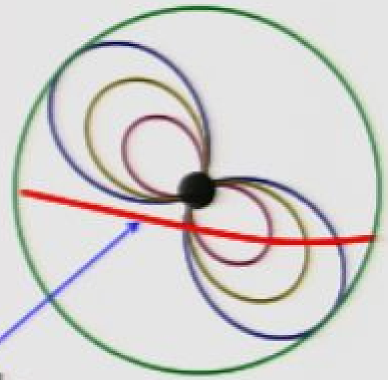
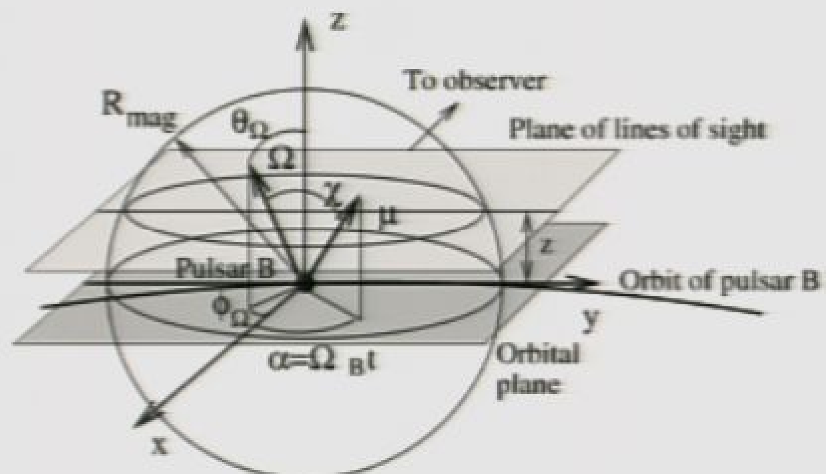


Spitkovsky (2004) Lyutikov (2004)

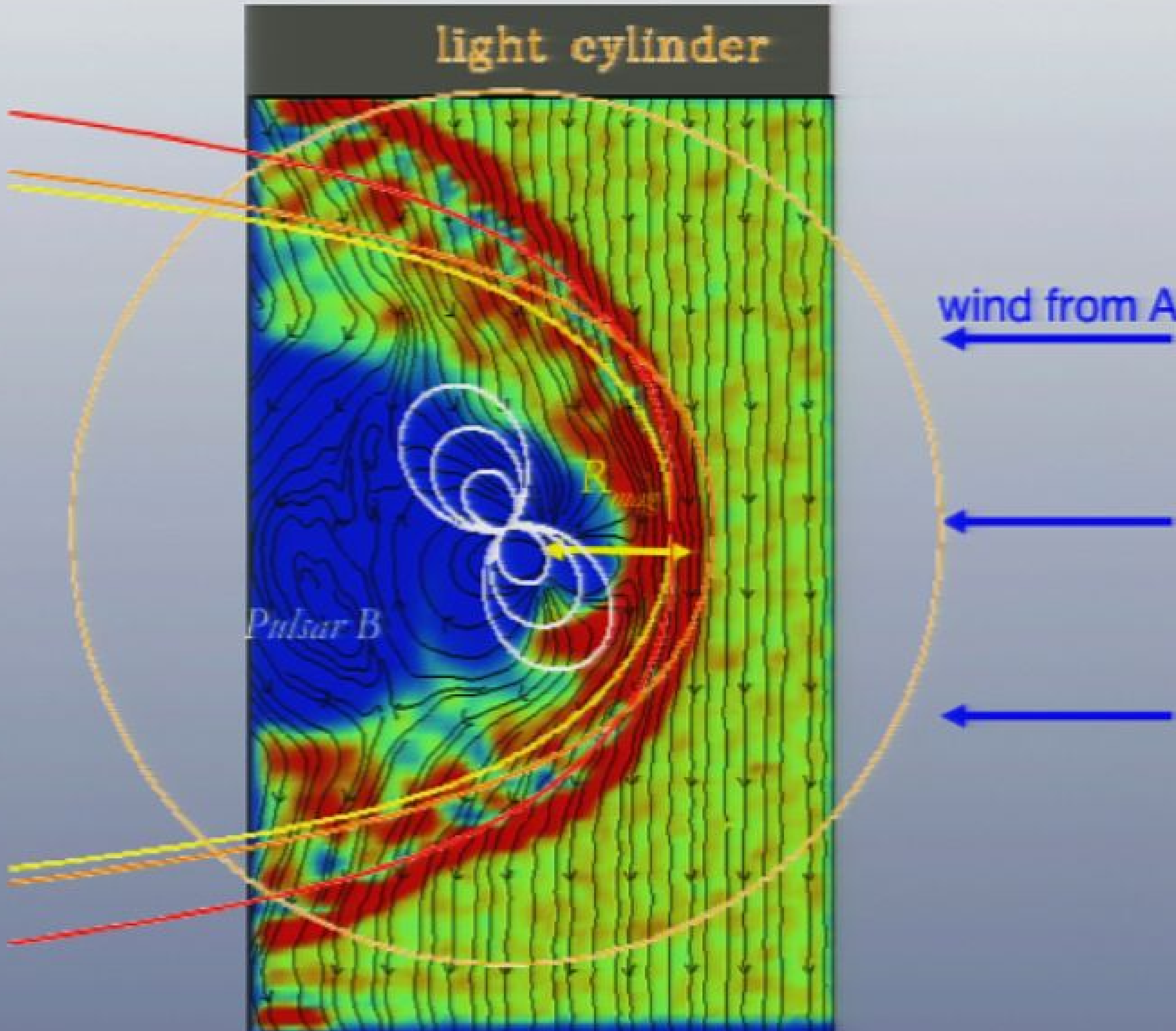
Model of eclipses

- There are open and closed field lines
- Closed field lines are dipolar
- Relativistic plasma, $\gamma \sim 10$, n
- Synchrotron absorption on closed field lines of a rotating dipole
  - optical depth along line of sight through rotating dipole, including refraction
  - Eclipse profile is determined mostly by geometrical factors
- Parameters to be fitted :
  - θ_Ω, φ_Ω – orientation of Ω
  - impact parameter z
  - χ angle between Ω and μ
  - Plasma density, normalized to $n_{GJ,mag}$





Pulsar A wind blows off most of B magnetosphere



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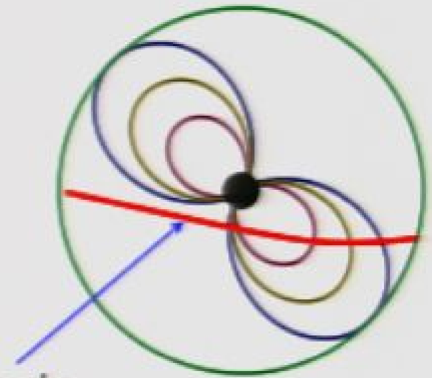
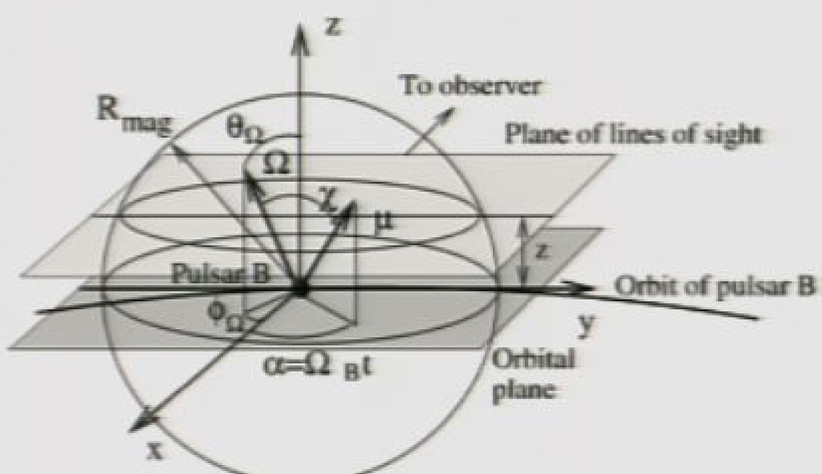
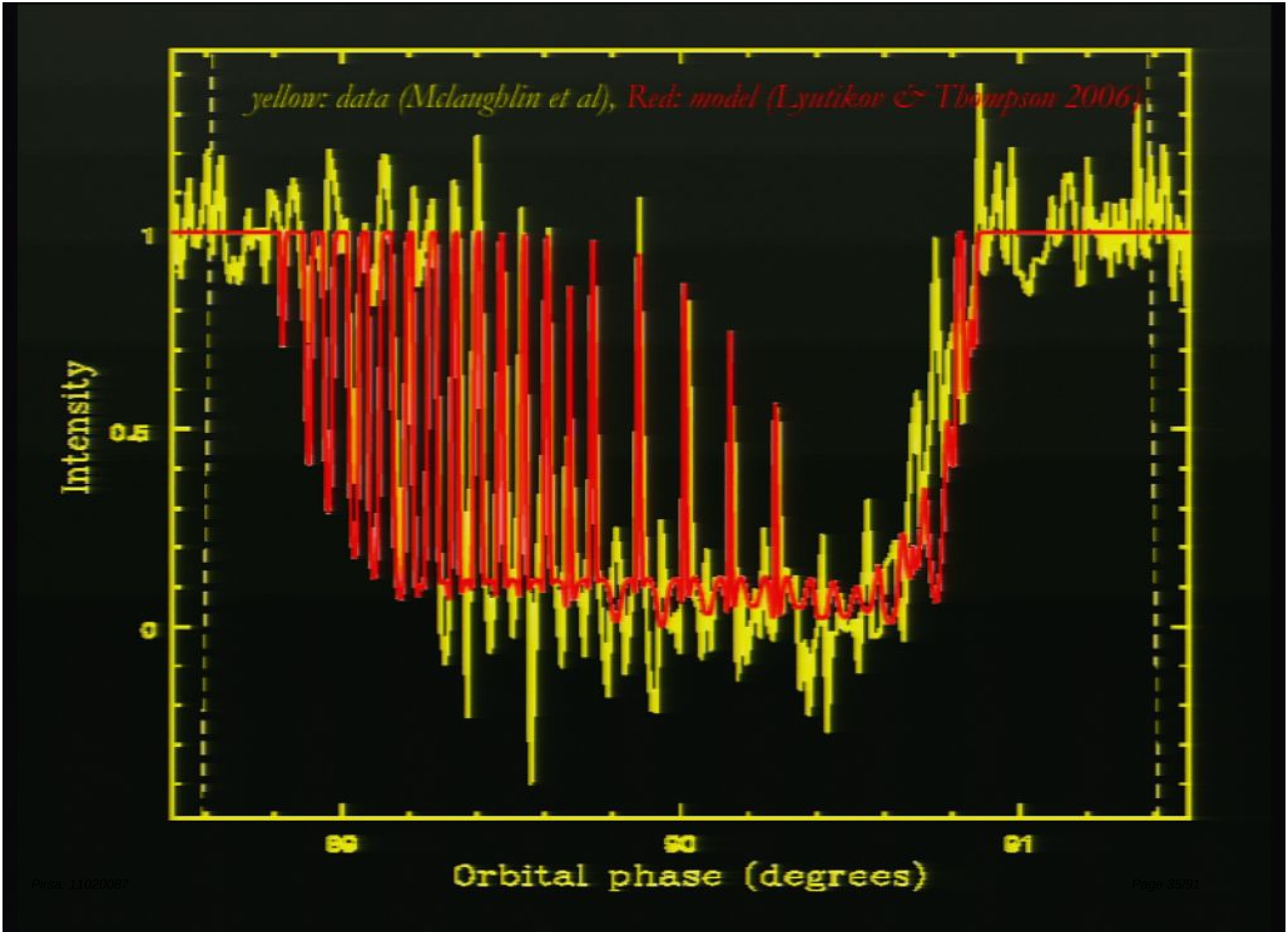
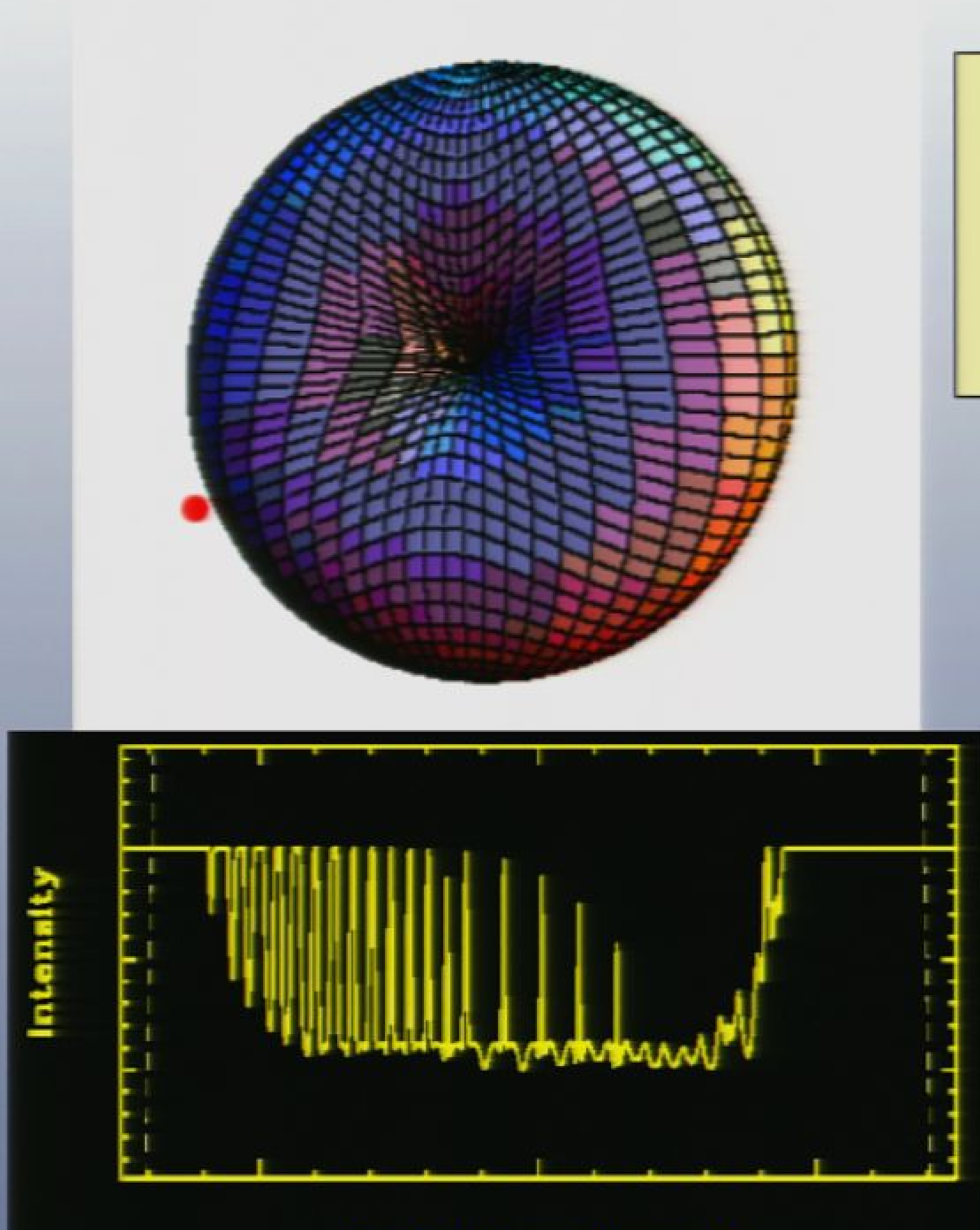
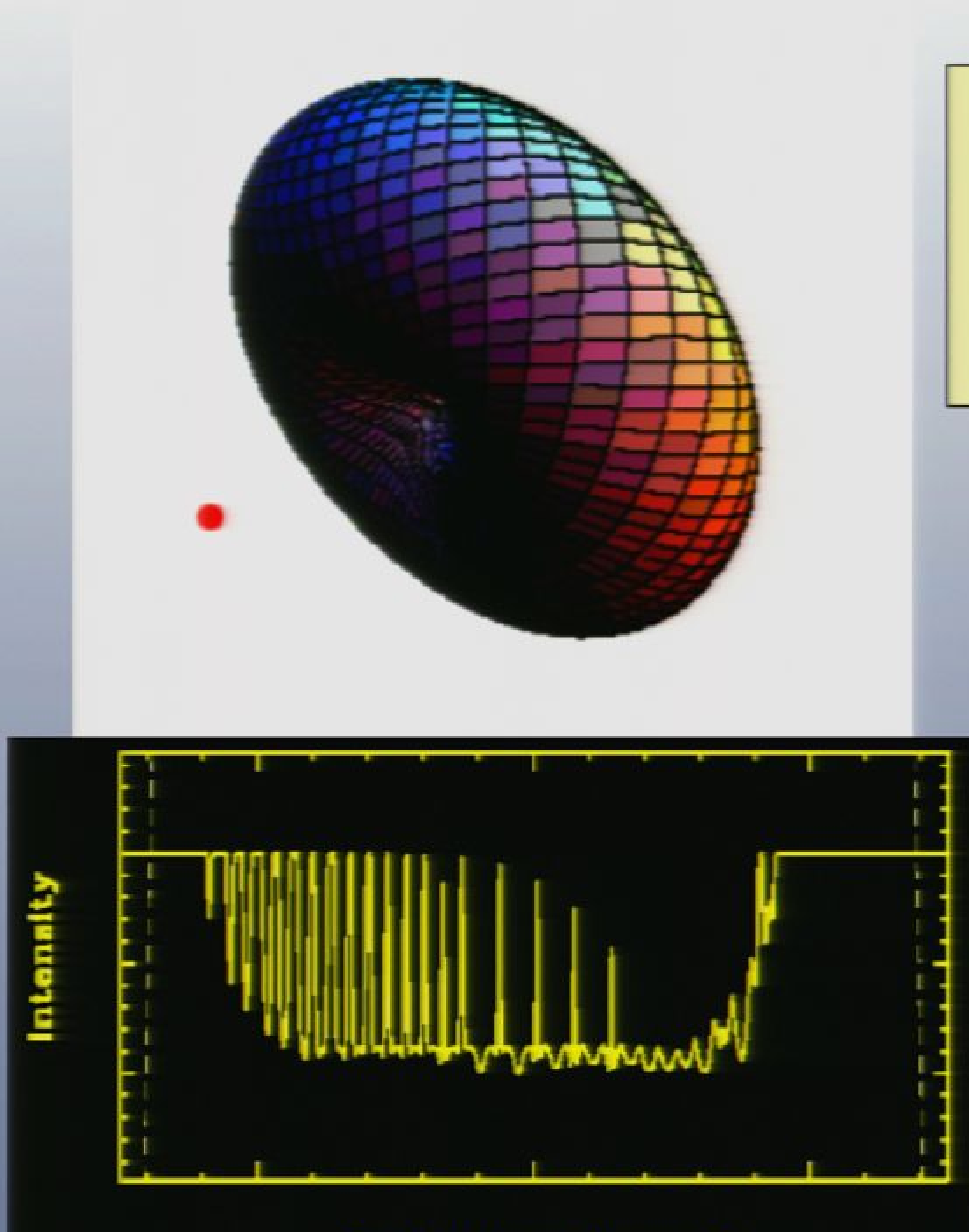





yellow: data (Mclaughlin et al), Red: model (Lyutikov & Thompson 2006)
Intensity
1
0.5
0
89
90
91
Orbital phase (degrees)



- Red dot: line of sight to pulsar A.
- "Donut": last closed surface of B magnetosphere



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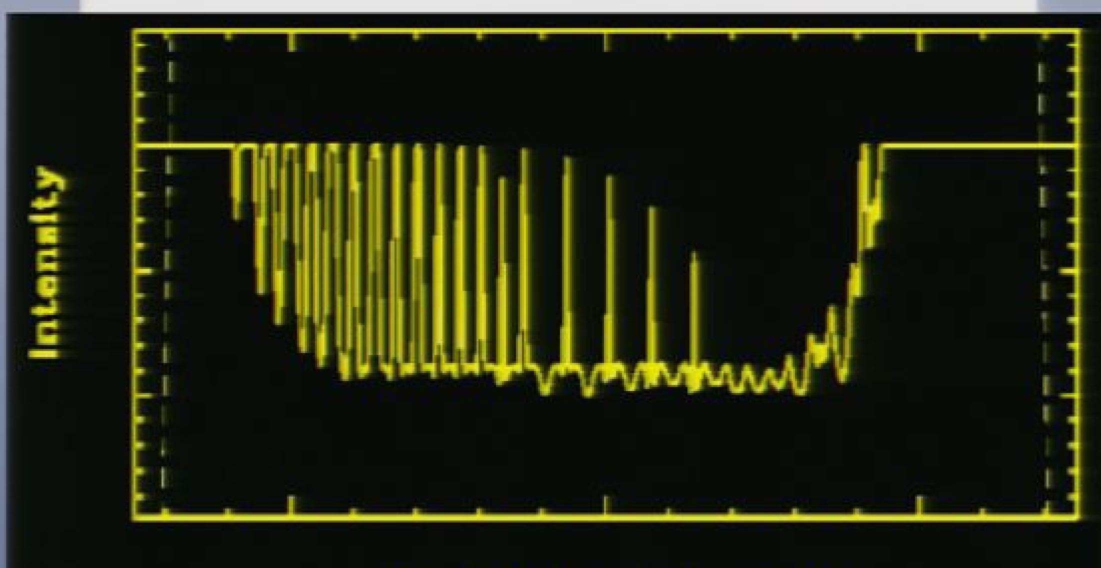
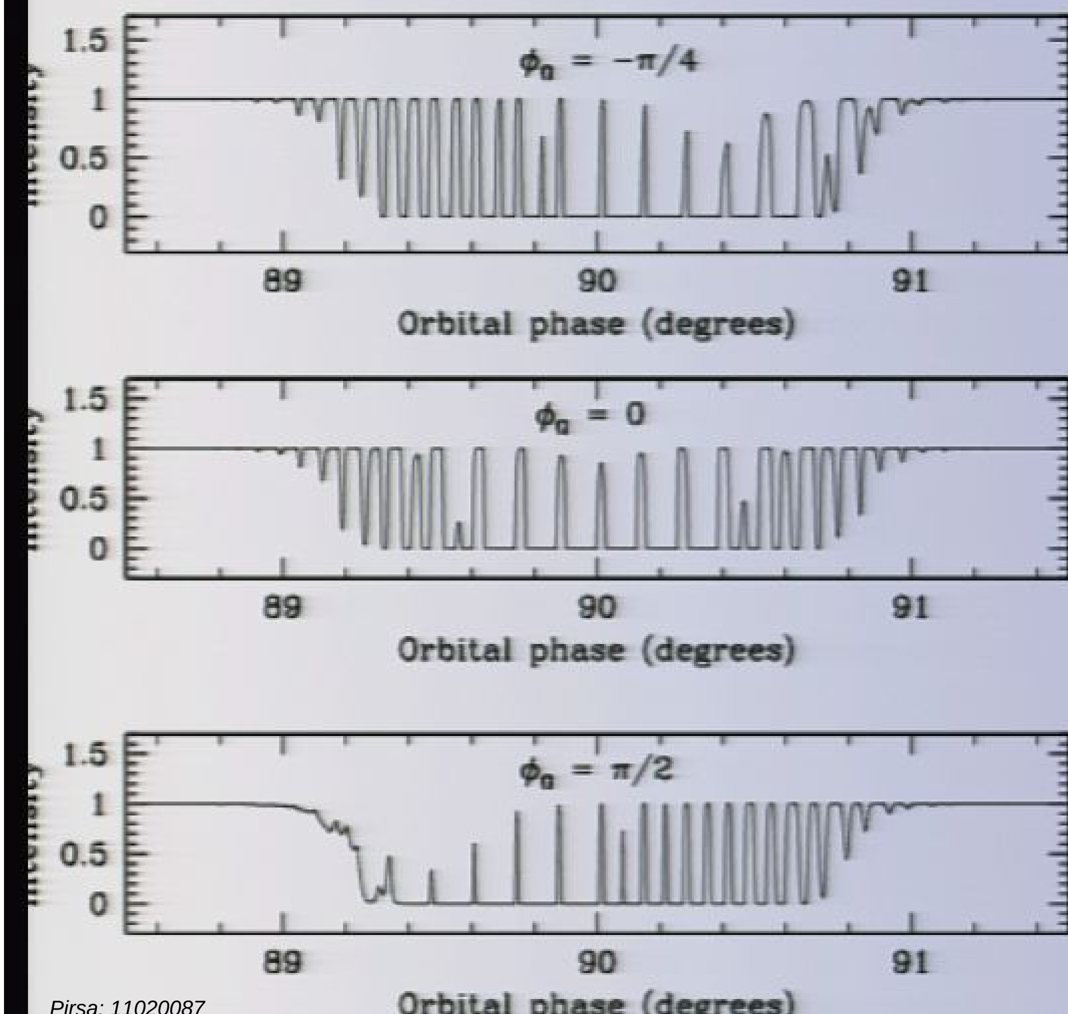
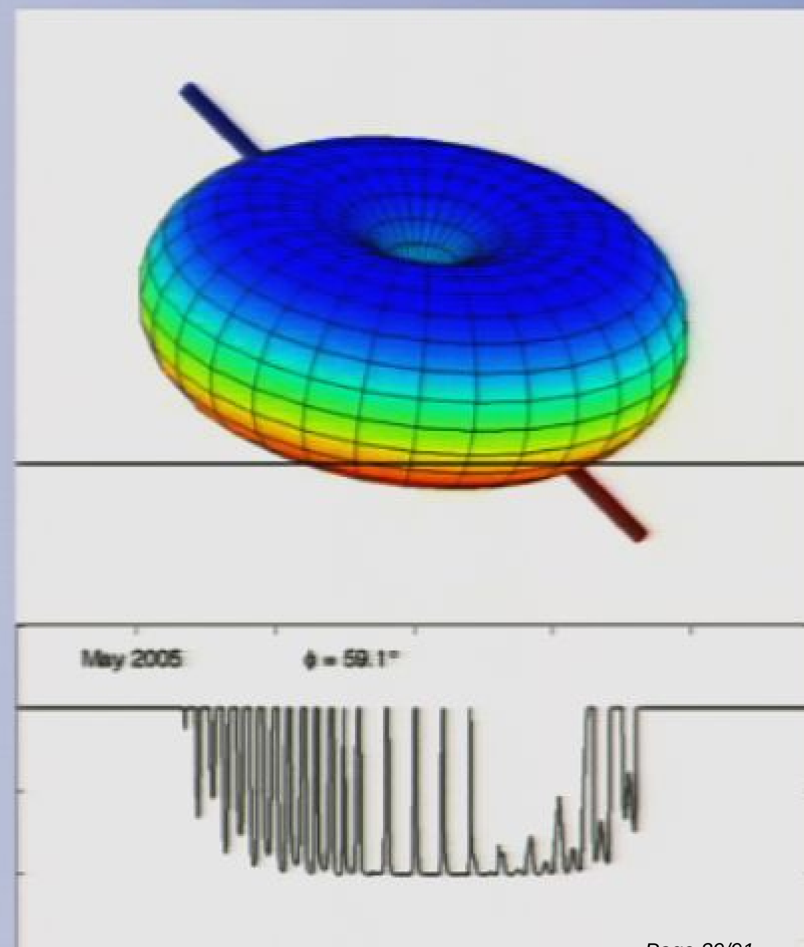
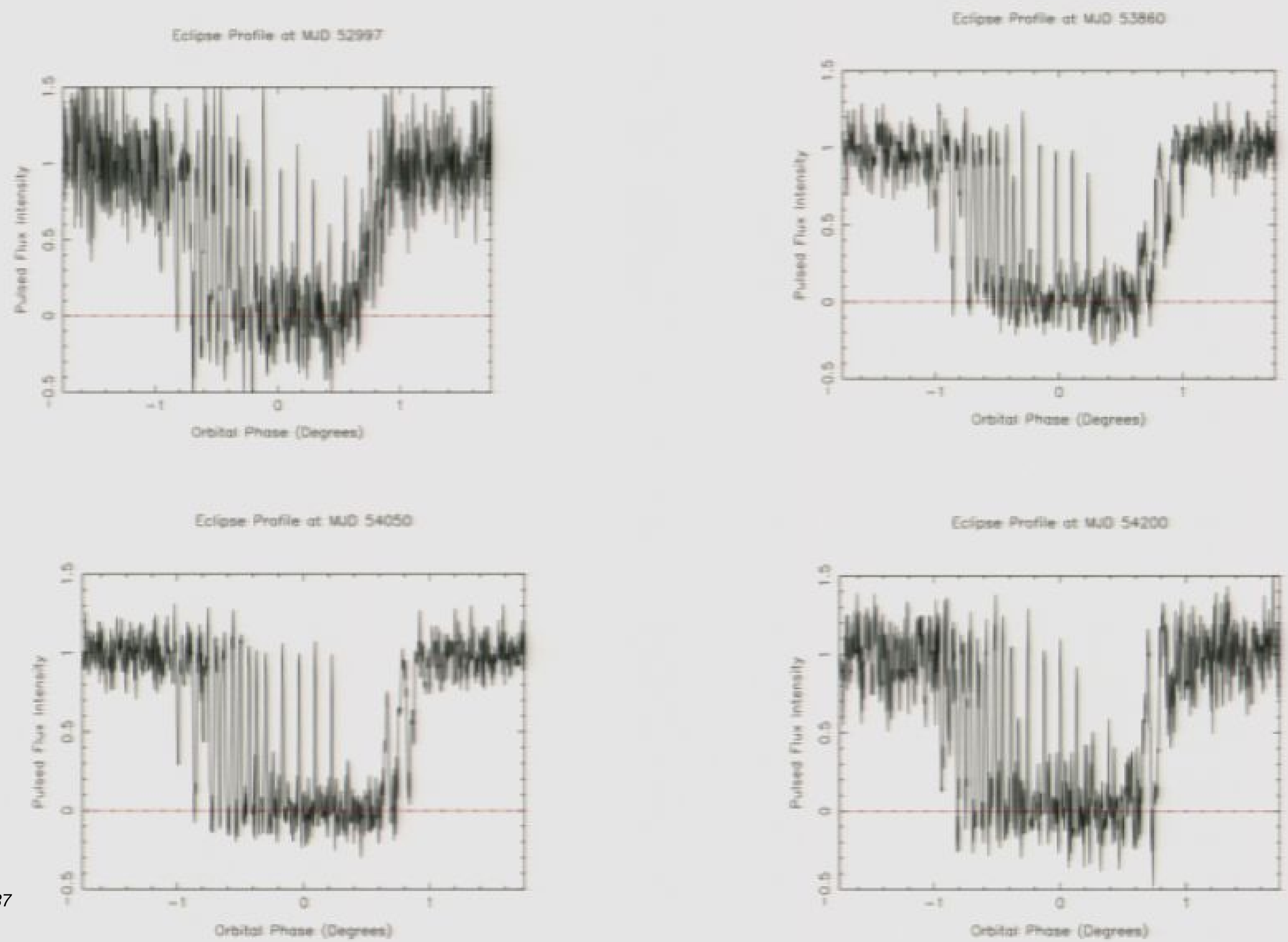


Predictions: change of eclipse profile due to geodetic precession



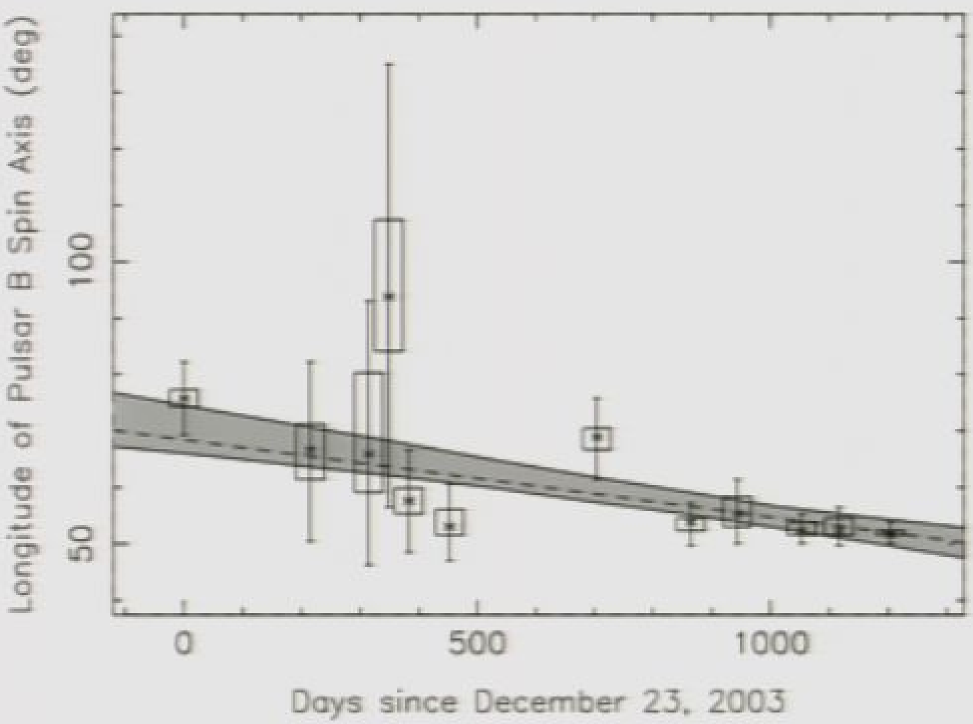


Changes in eclipse profile

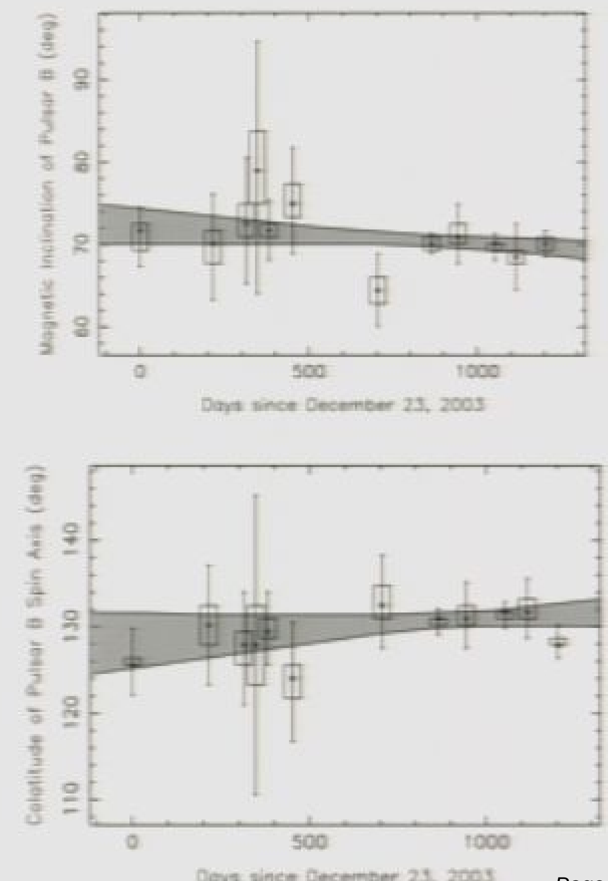


Geodetic precession

Angle of spin of B wrt line of sight



Angles of spin of B wrt orbital plane and spin-B-moment: do not change



(Breton et al., Science, 2008)

New test of theories of gravity

- Precession rate $\Omega_B = \frac{x_A x_B}{s^2} \times \frac{n^3}{1-e^2} \times \frac{c^2\sigma_B}{G}$
- Observed $\Omega = 4.98_{+0.43\,-0.23}$ °/yr

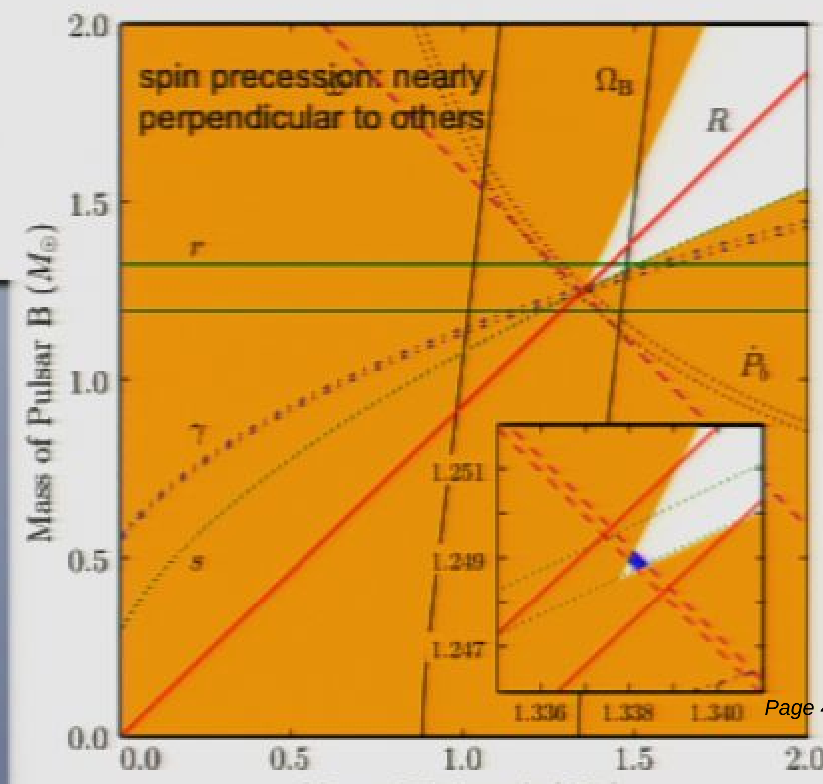
$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right) = 3.38^{+0.49}_{-0.46}.$

$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 2 + \frac{3}{2}\frac{m_A}{m_B} = 3.60677 \pm 0.00035.$ $\Omega_B = 5.07°/yr$

$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm obs} / \left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 0.94 \pm 0.13.$

- C.f. Gravity Probe B, same accuracy, weak field regime, ~ $1bn.

- G - generalized Newton's constant
- σB is a strong-field spin-orbit coupling constant
- the first term accessible only for the Double Pulsar



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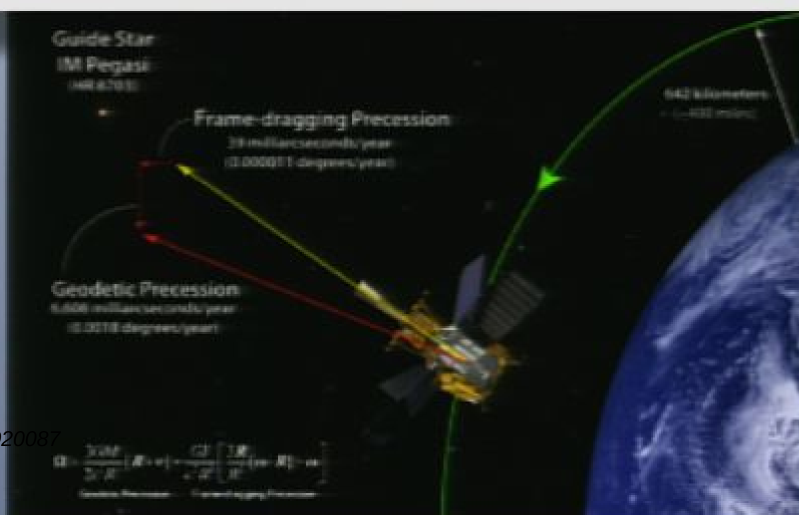
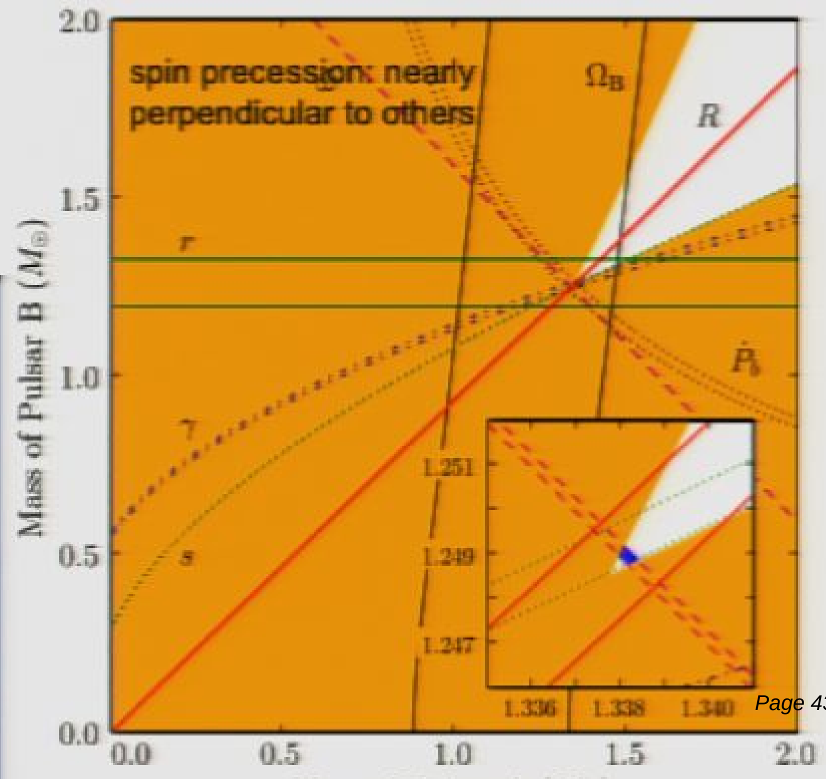




Testing theories of gravity in strong regime

- In theories of gravity based on generalized Lagrangian, PPN parameters are function of masses only, but these dependancies are different.
- **Depends on properties at the source.**
- Strong gravity at the source: $$\frac{E_G}{Mc^2} \sim \frac{GM^2/R}{Mc^2} = \frac{GM}{Rc^2}$$
  - ~ 20% for NS
  - 10^{-10} for Earth
- 6 PK parameters+ ratio of masses - two masses = 5 GR tests.
- Only in the double pulsar we can measure mass ratio R = 1.0714±0.0011

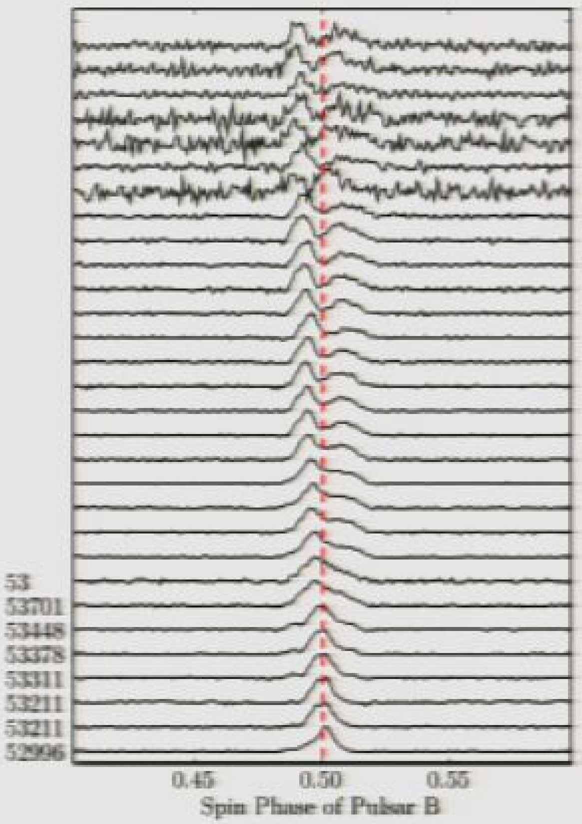
Testing GR with double pulsar

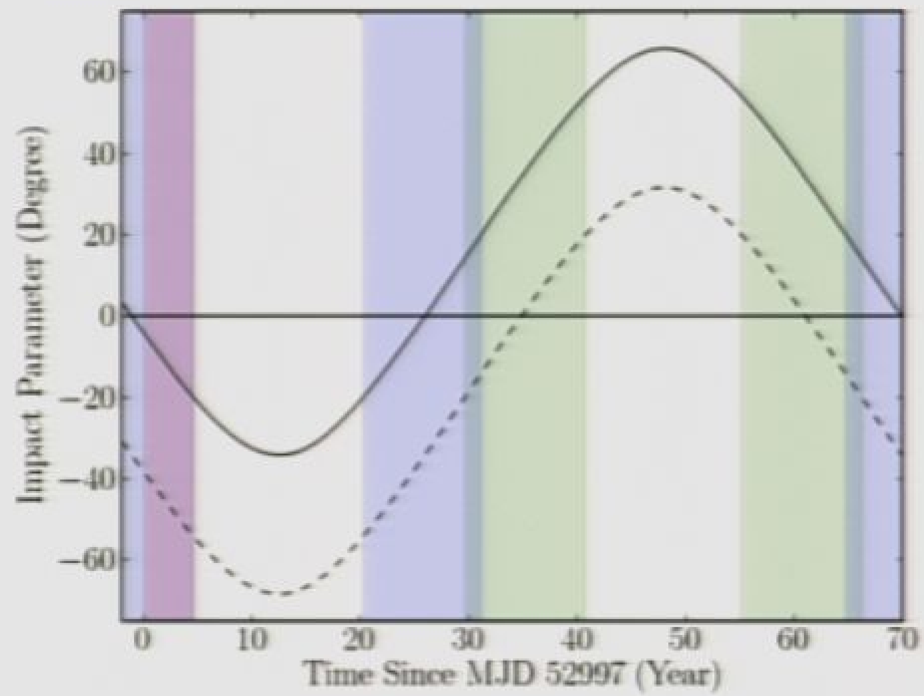
- Corrections to Newtonian (Keplerian) motion: 6 post-Keplerian parameters (5 independent tests)
  - advance of periastron - (0.004% precision)
  - Shapiro delay s (0.04%)
  - Shapiro delay r (0.5%)
  - gravitational red-shift (0.7%)
  - decay of orbit due to emission of gravitational waves (1.4%) - strong equivalence principle (gravitation independent of velocity)
  - **spin precession (10%)**
- No preferred-frame effects (in strong field regime)

Damour & Kramer

We are loosing B - the second clock is breaking down

- Due to precession beam of B is now missing Earth
- B will reappear around 2030.





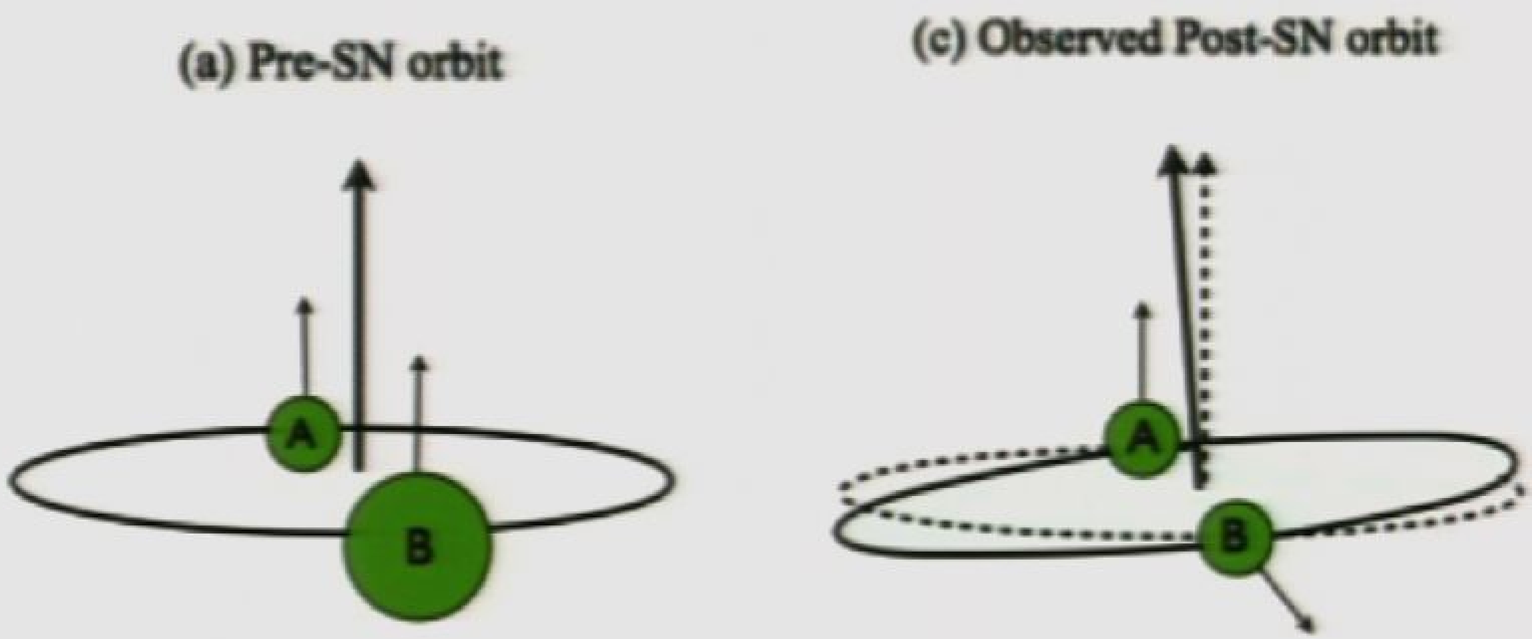
Angular separation between line of sight and B's magnetic axis

Testing General Relativity with the Double Pulsar

- GR **in strong regime** is satisfied in the most complete test
- In some parameters to 10^{-4} precision
- Any competing theory of gravity should reproduce not only Newtonian, but first PPN corrections.
- Relevant scales ~ au

Kick and tumble in SN explosion

- Pulsar A shows no precession: spin still aligned with the orbit
- Small kick was in the orbital plane (small eccentricity)
- Second SN explosion spun-up and tumbled B



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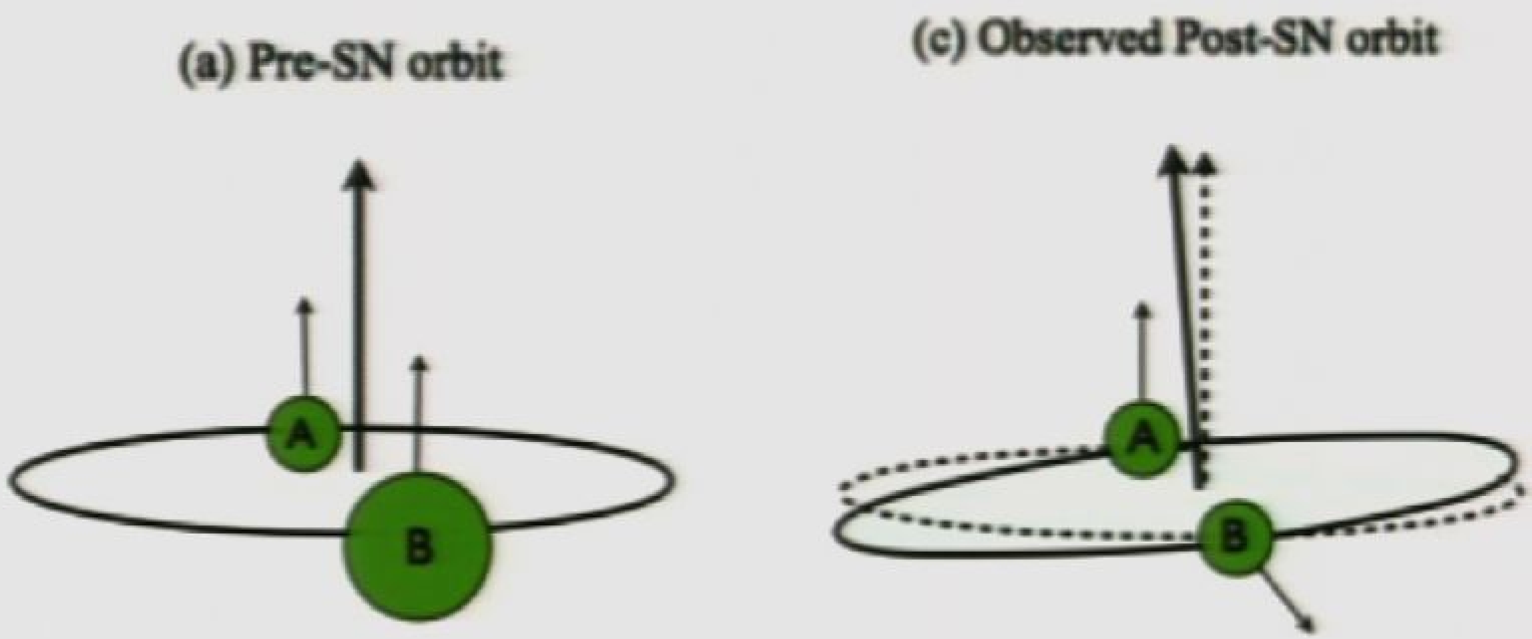

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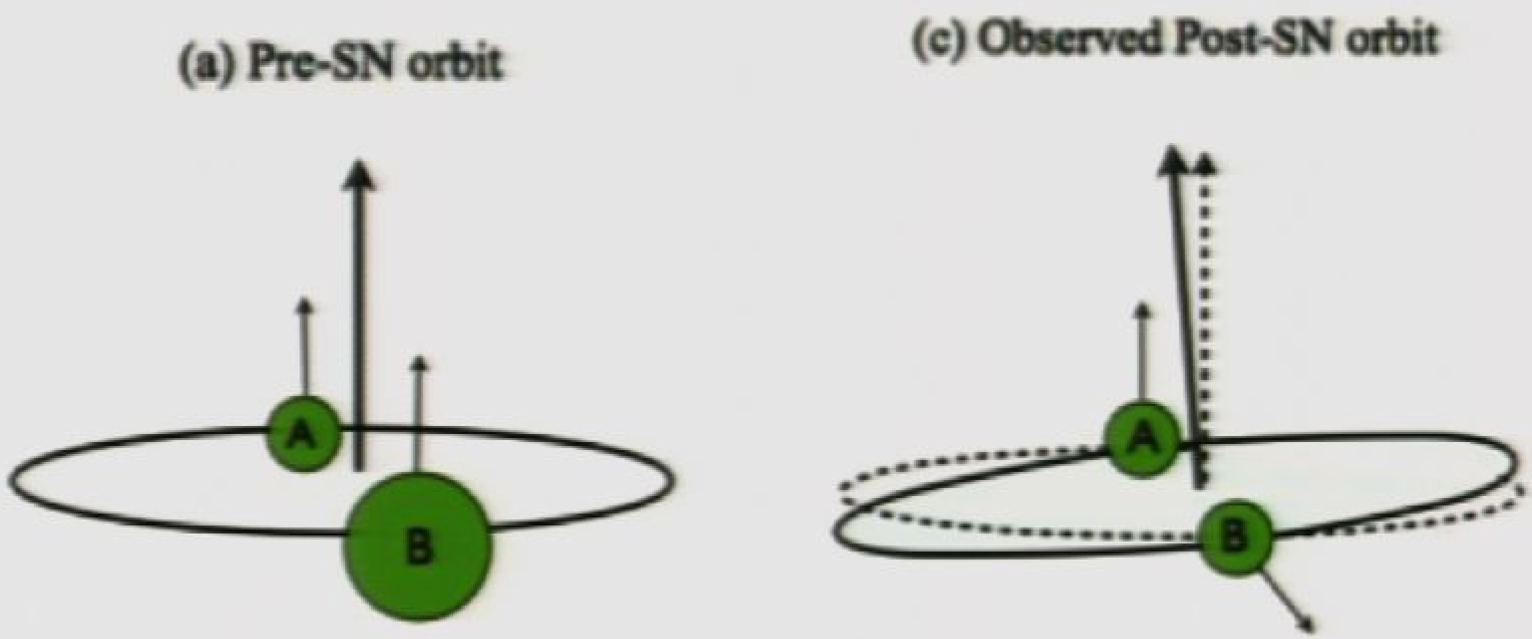

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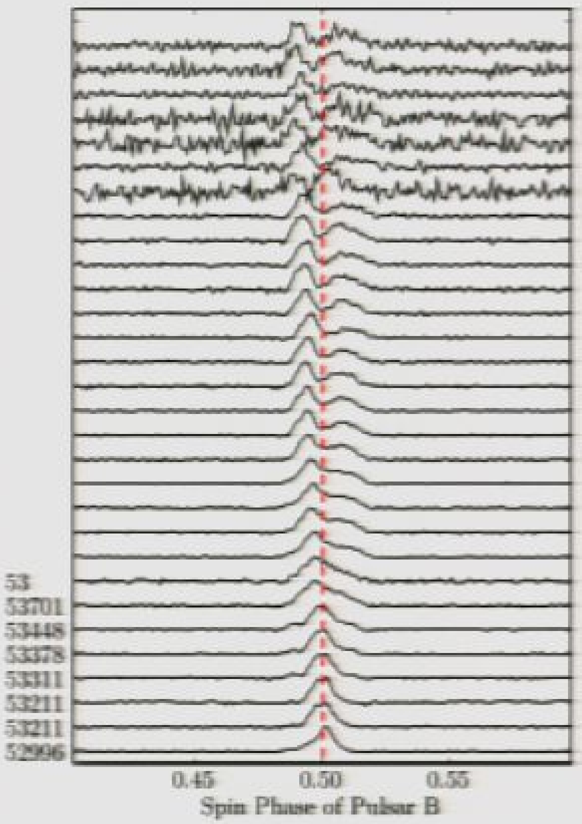

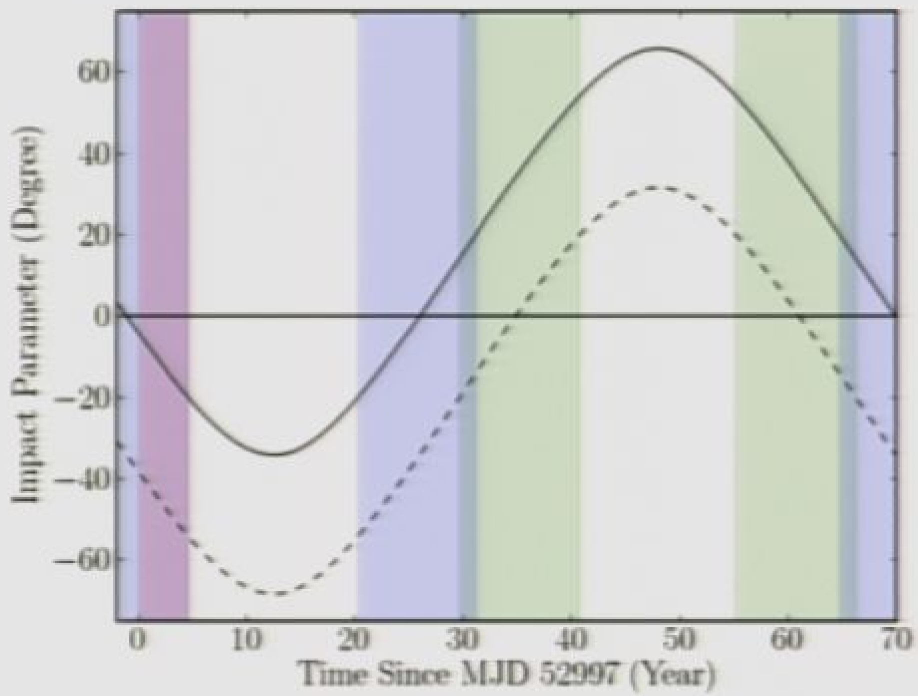

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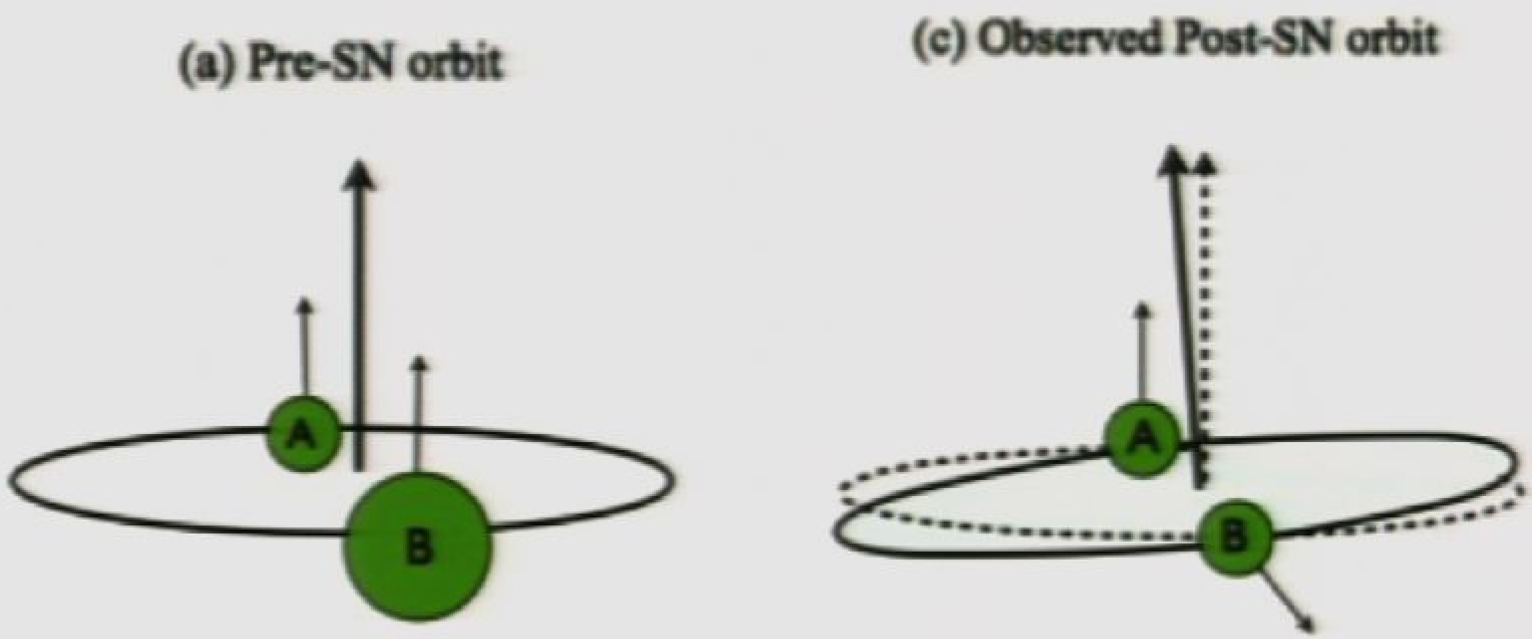
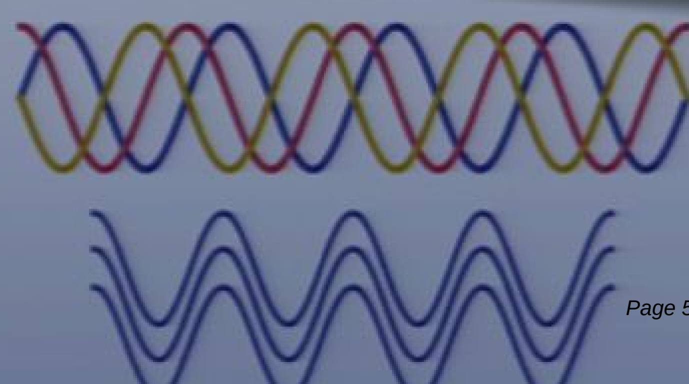


Enter plasma physics

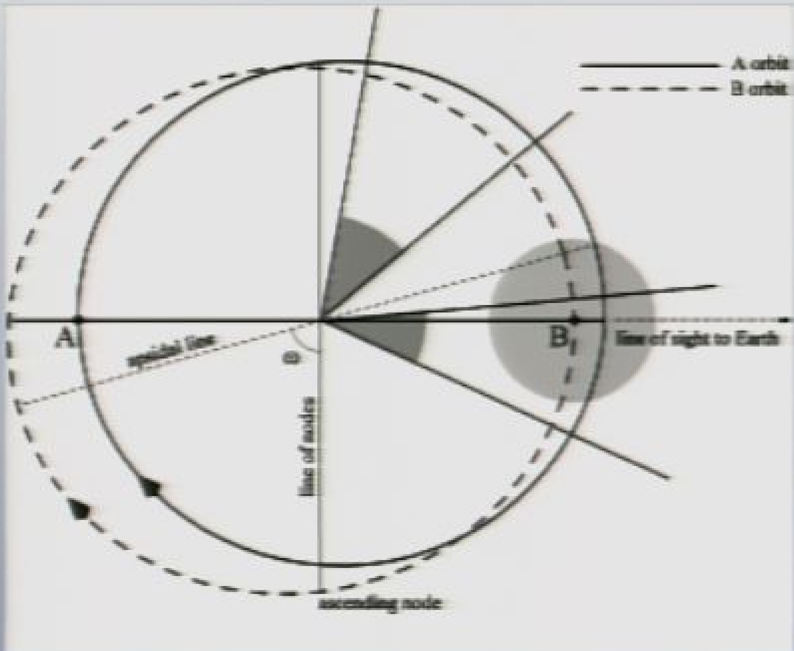
Pulsar radio emission: the brightest lasers in the Universe

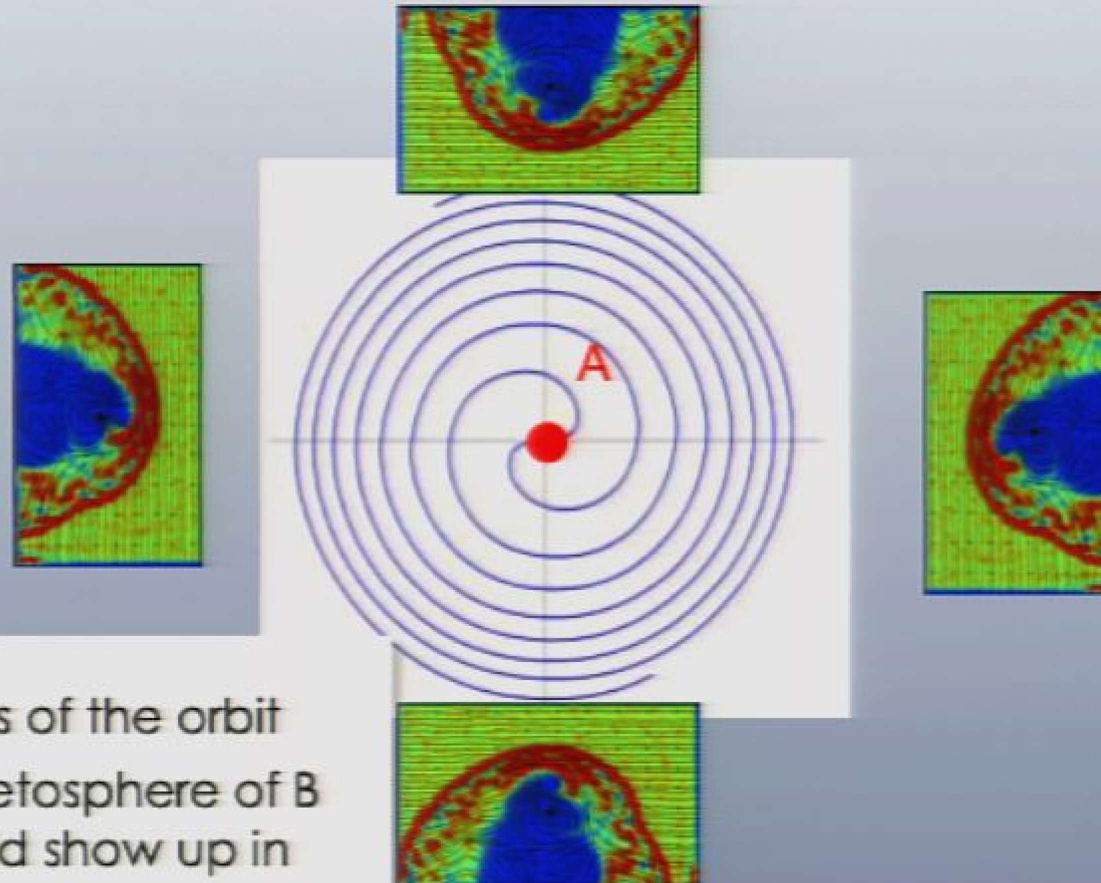
- The Double Pulsar can be used as an exclusive probe of still unknown pulsar coherent radio emission mechanism.
- Pulsar radio emission:
  - Generated within ~ 100 km, seen across the Galaxy.
  - Still a mystery, but must be coherent: maser/laser
  - Power ~ 10^{30} Watt, brightness temperatures 10^{40} K
  - Plasma maser: leptons with non-equilibrium distribution, with "population inversion"
  - Still do not know the radio emission mechanism, even location within the magnetosphere. (Ask me later about my favorite)

- Intensity: $I = A^2$
- Incoherent: $I = \sum_i I_i \sim n I_i$
- coherent: $I = (\sum_i A_i)^2 \sim n^2 I_i$



Orbital variations

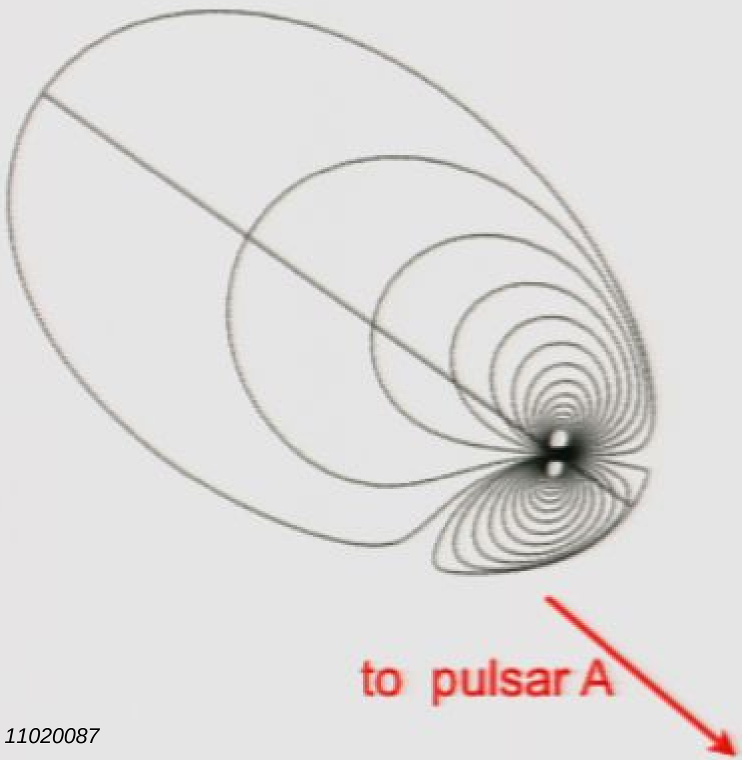




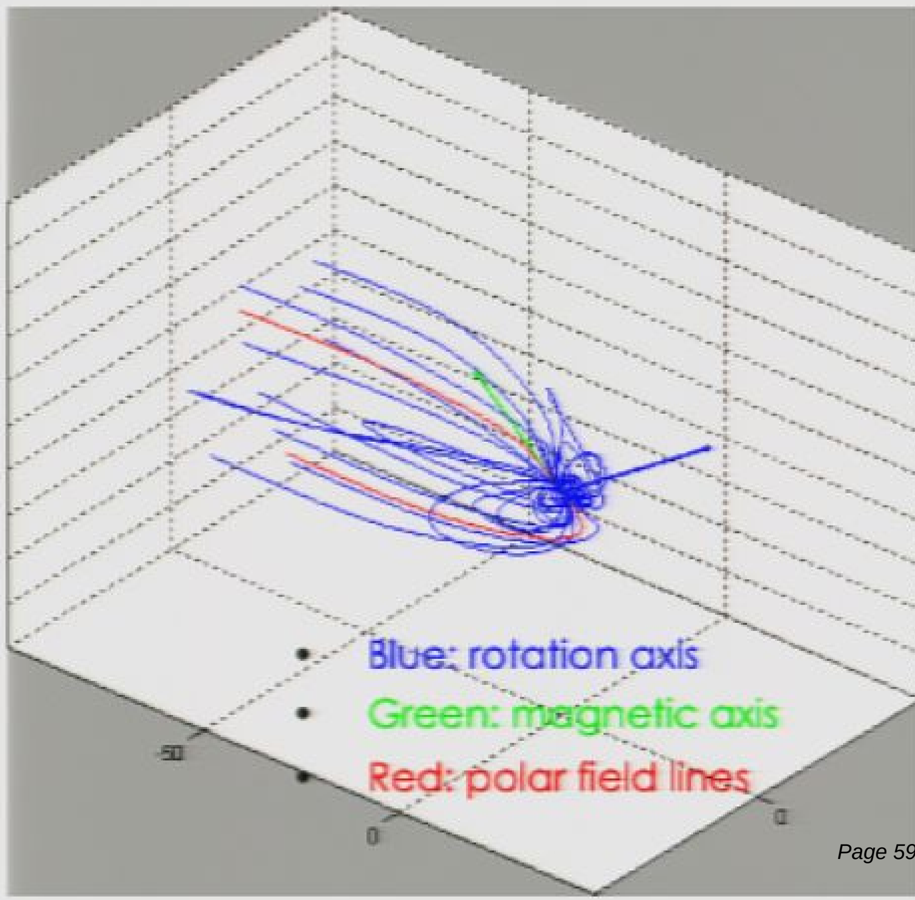
- Pulsar B is seen only at some parts of the orbit
- At different orbital phases magnetosphere of B has different distortions: this should show up in emission properties of B.
- By studying these variation we can infer the structure of the magnetosphere and location of emission region

3D view of distorted magnetosphere

Use Solar physics models of wind-Earth magnetosphere interaction (Tsyganenko)



3D view of the distorted magnetosphere. **Lomiashvili, in prep**



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Perera et al., in prep.

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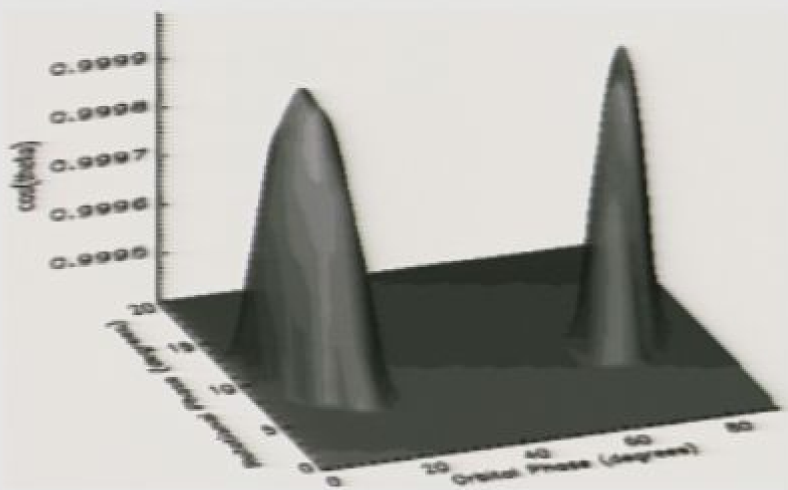
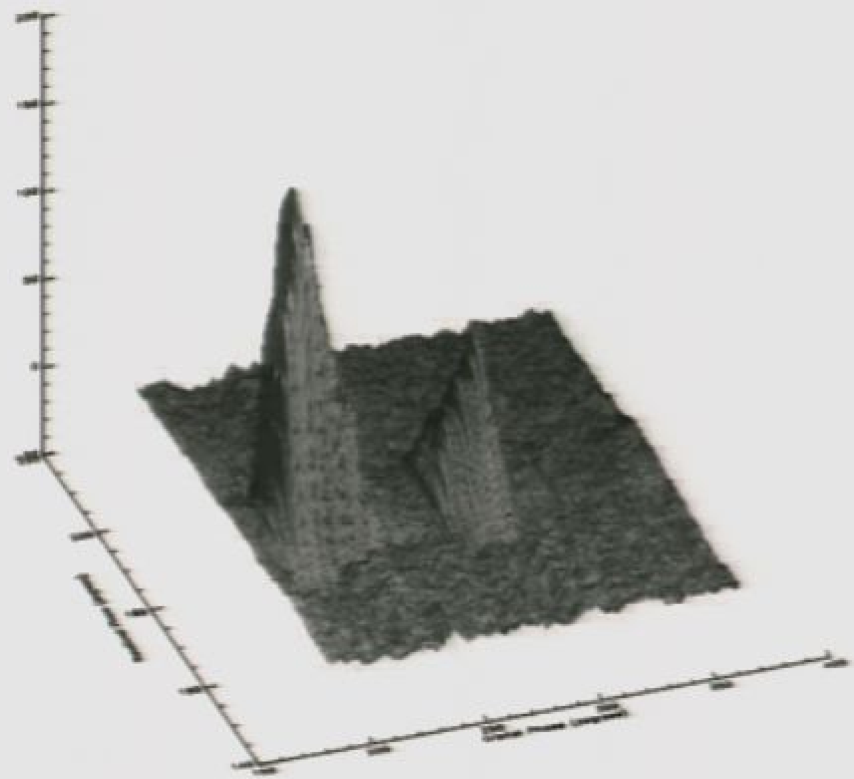


Parameters of the model are: θ=73.6°, φ=22.5°, χ=60°

3D view of real data



3D plot of MJD 54050

Geodetic precession: stereoscopic view of the emission region

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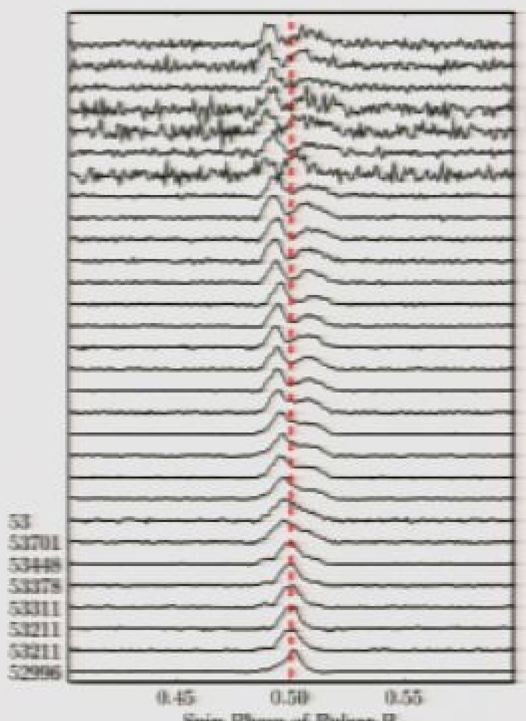
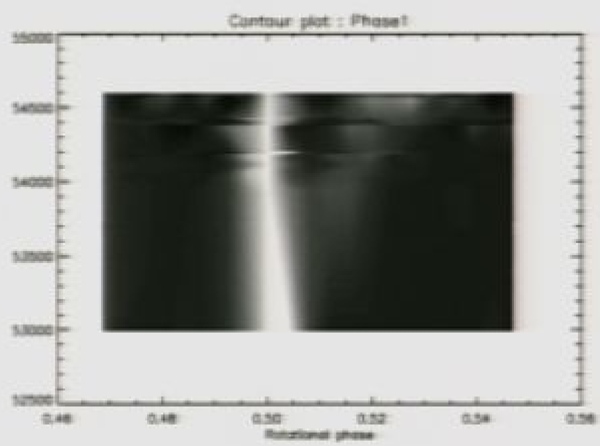
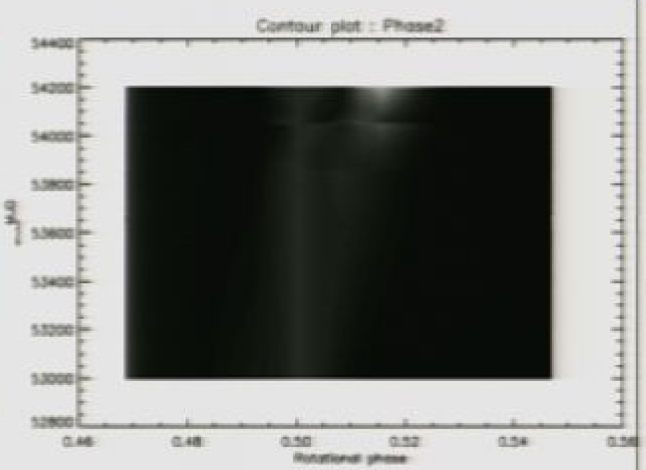




Phase1



Phase2

Lomiashvili et al., in prep.

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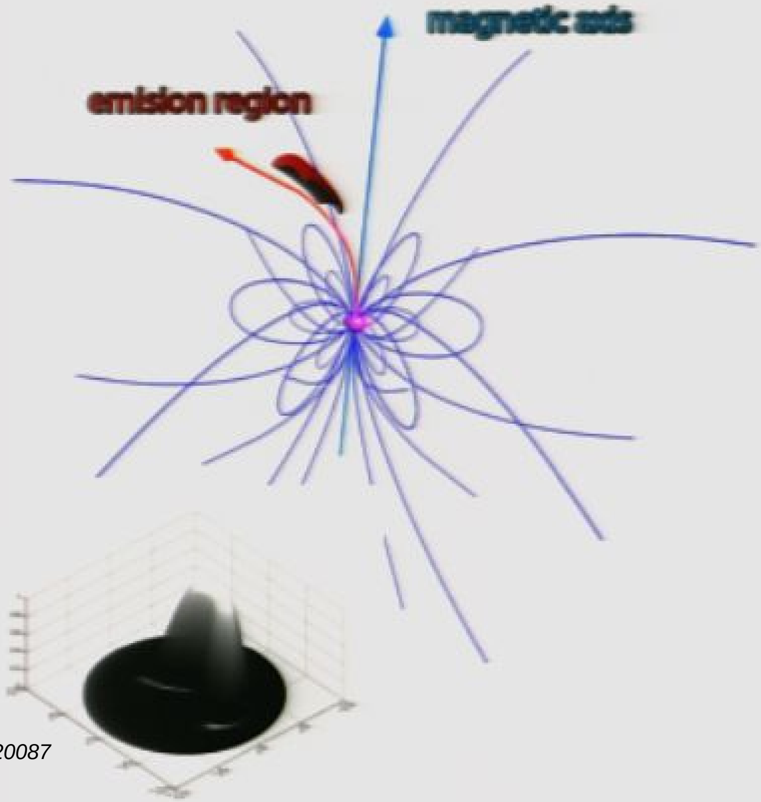
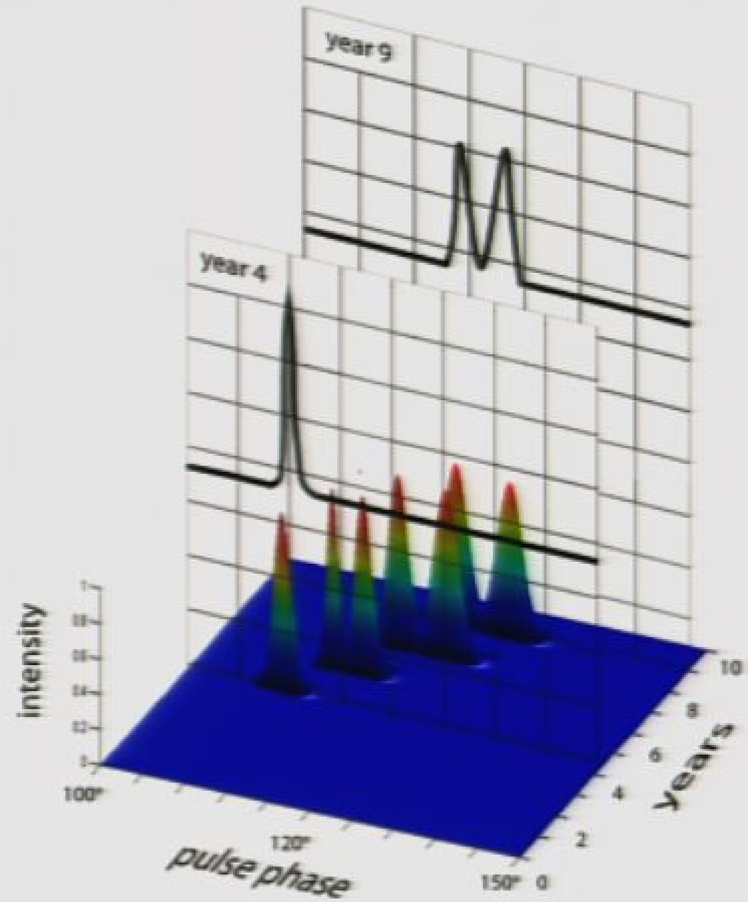
We can reproduce singe -> double profile change

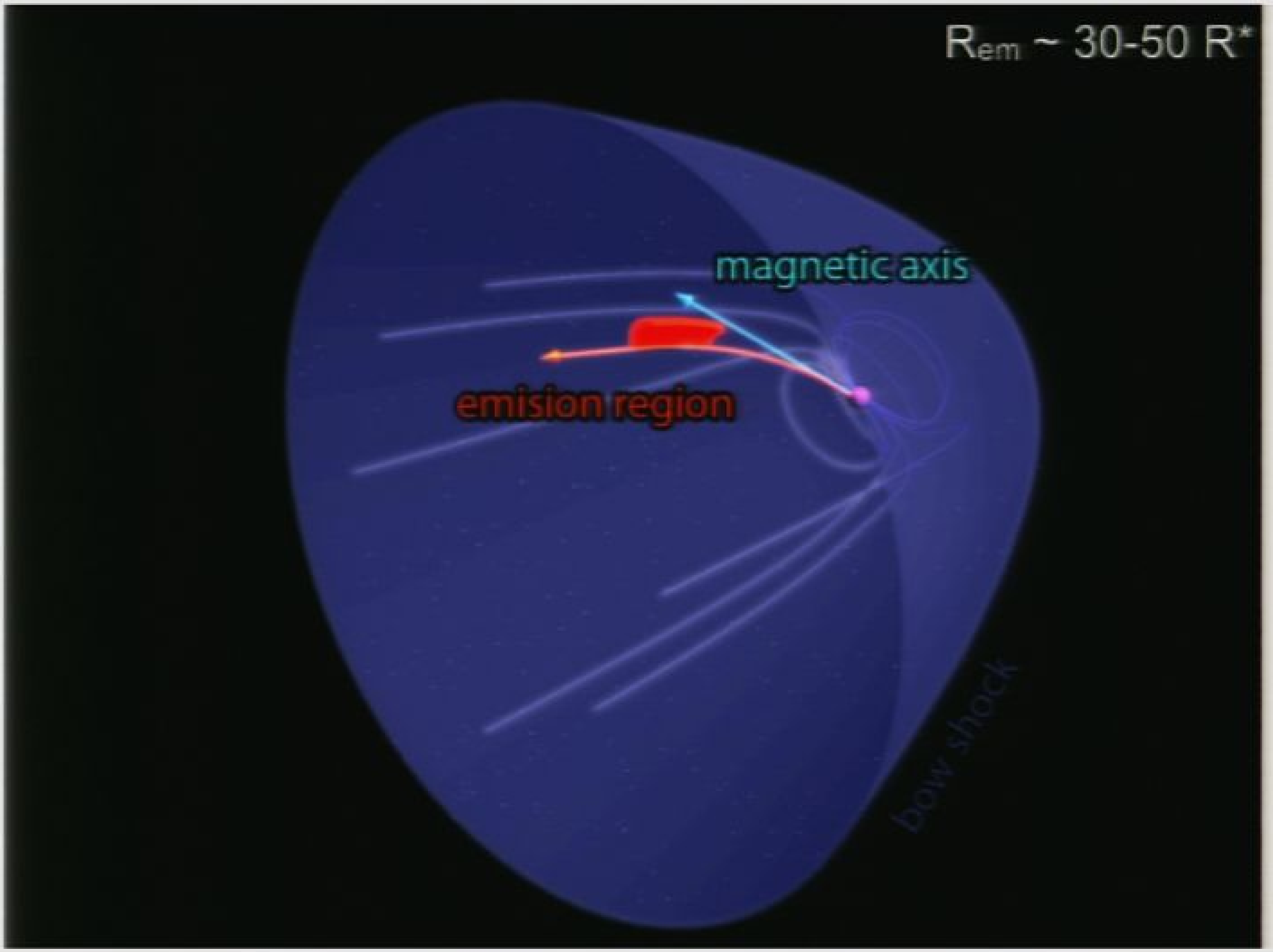




Location of radio emission generation

Lomiashvili, in prep

- Combine the two models (orbital and secular variation)



Relativistic reconnection, probes of pulsar winds

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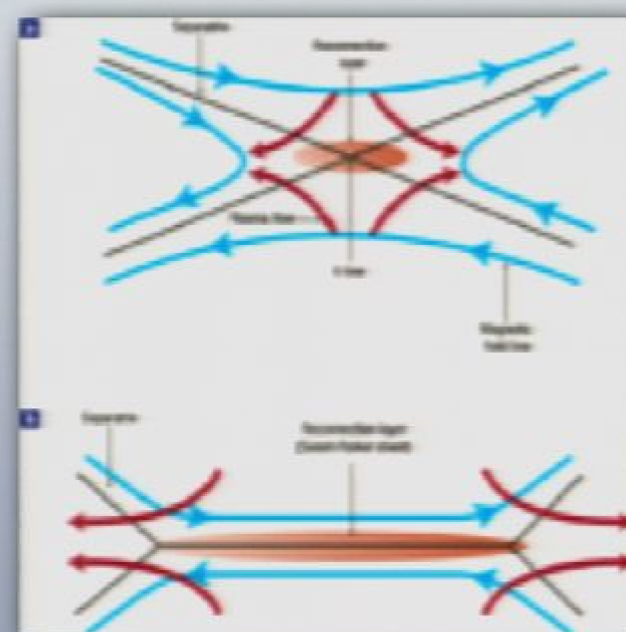

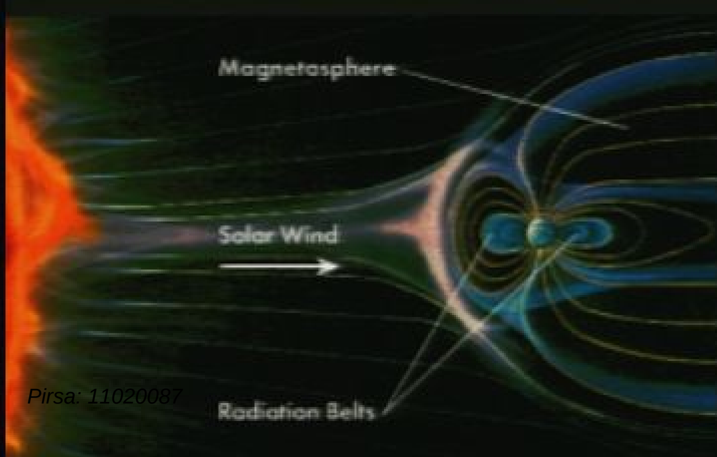

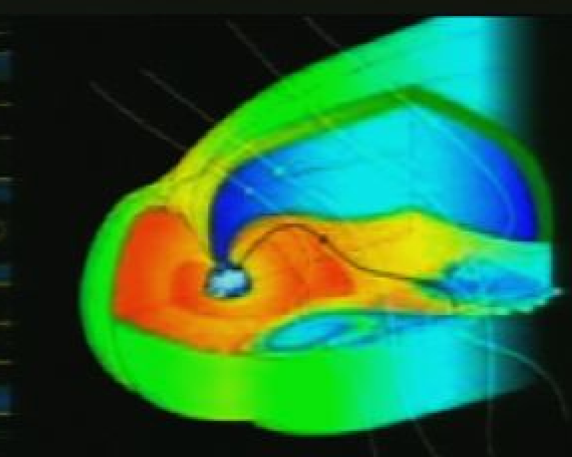

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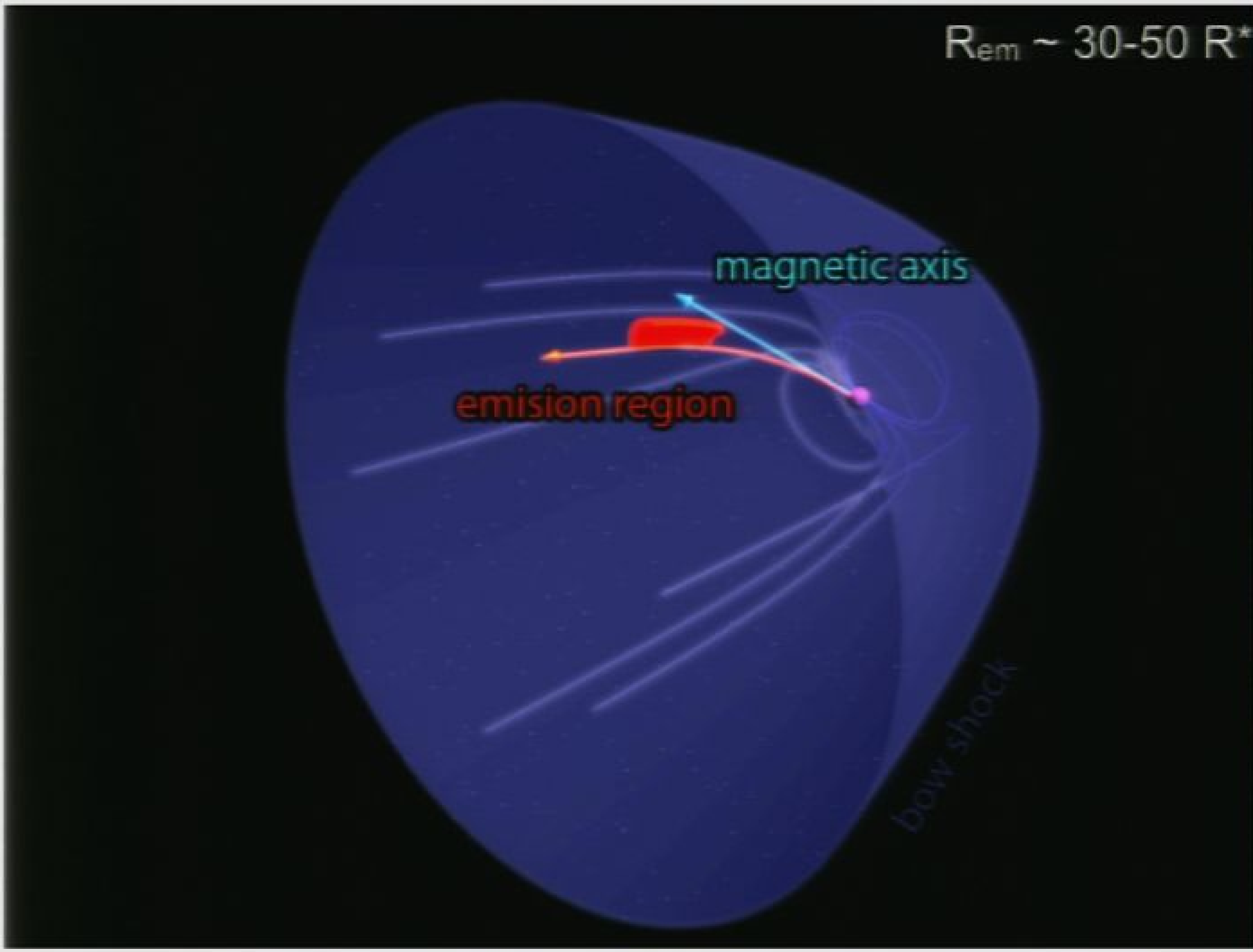

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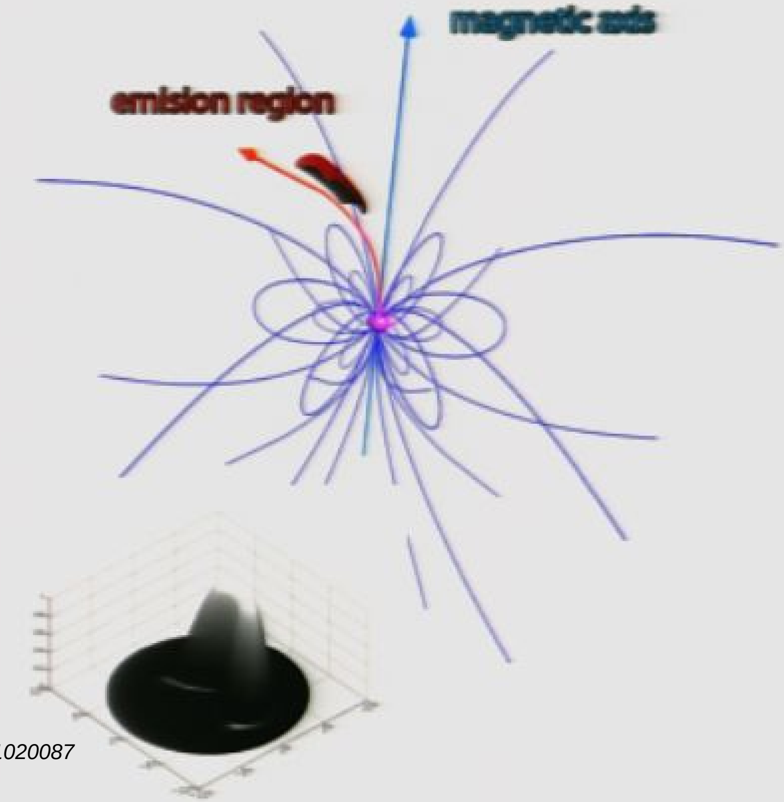

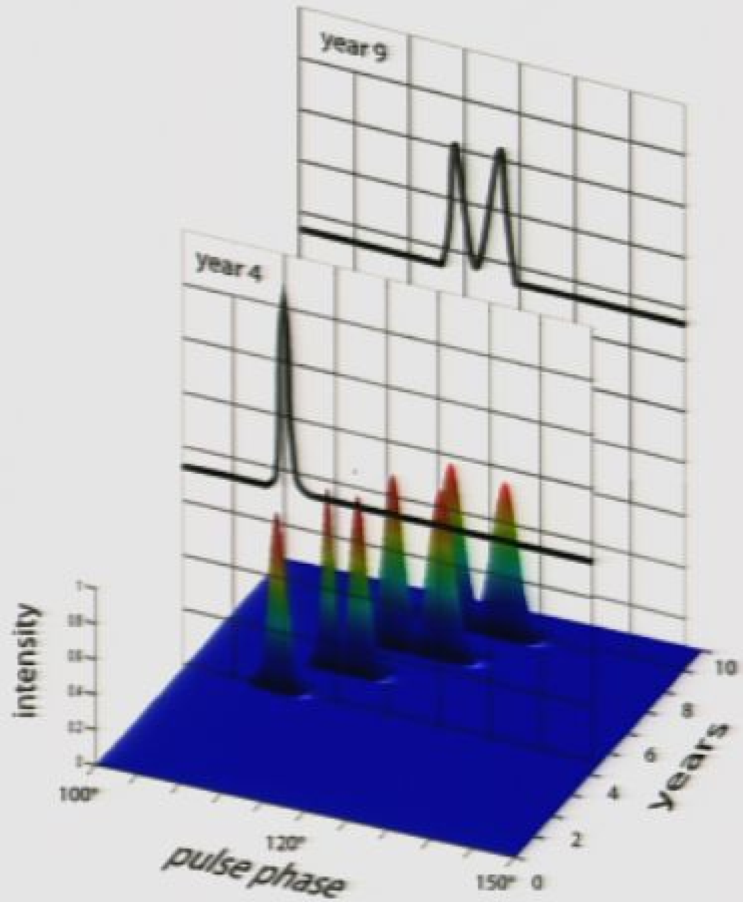

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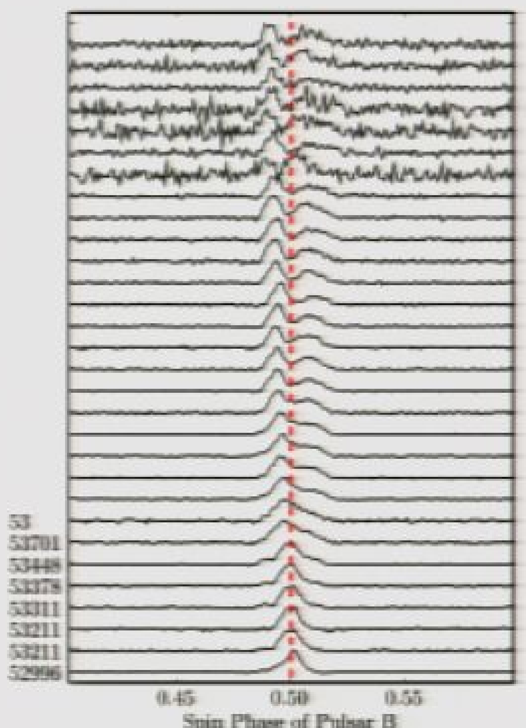

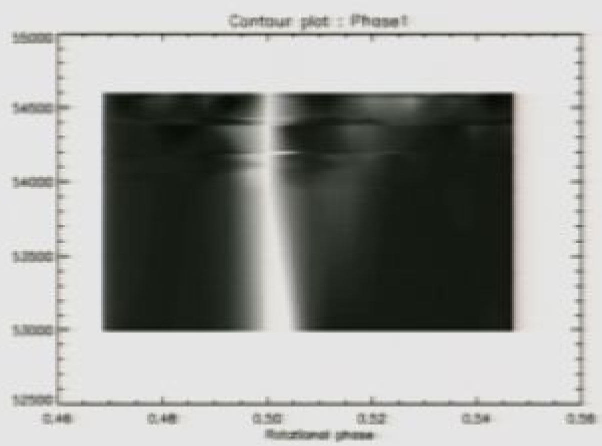

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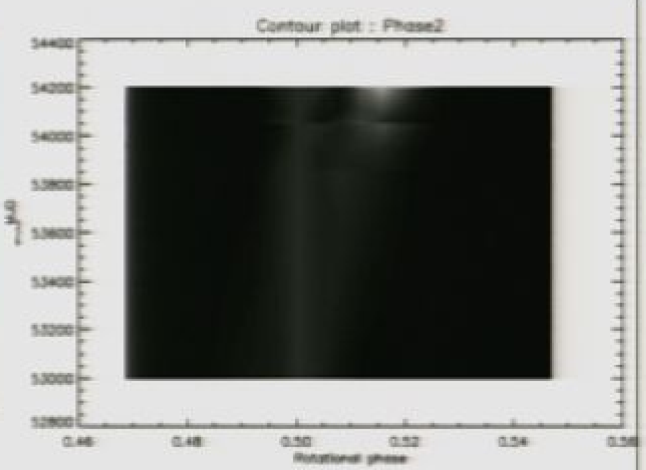

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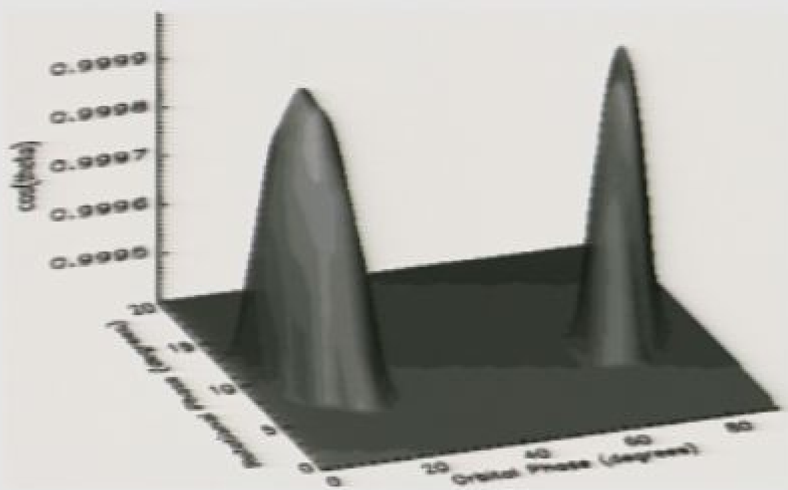

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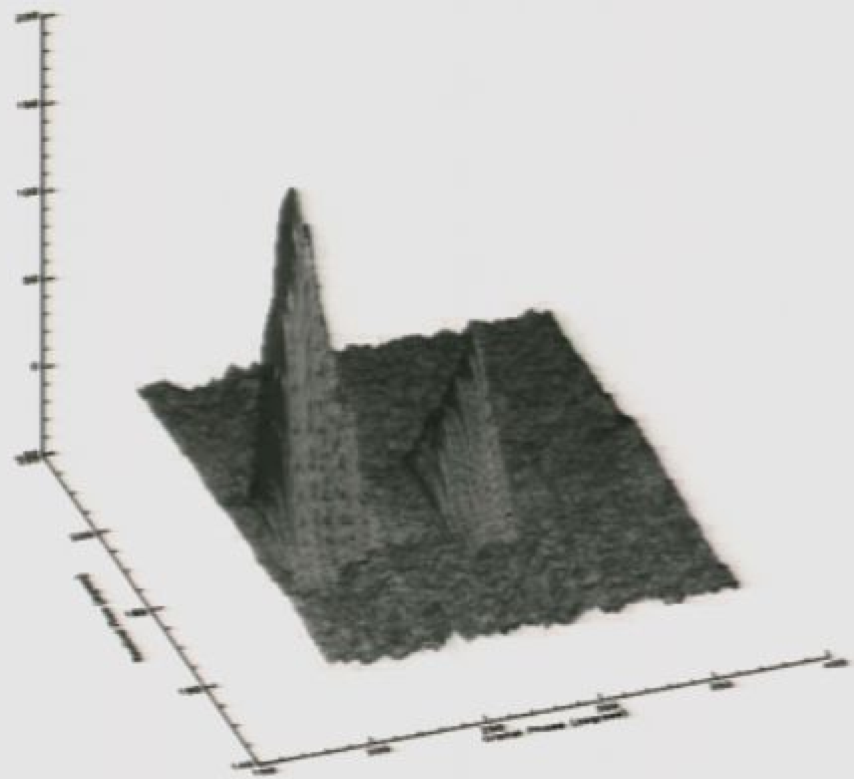

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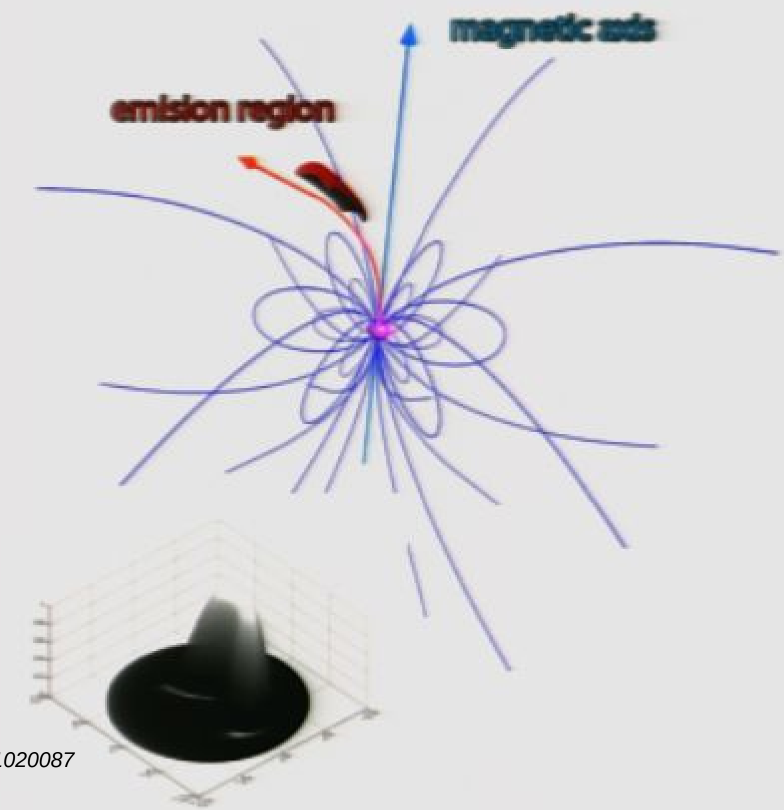

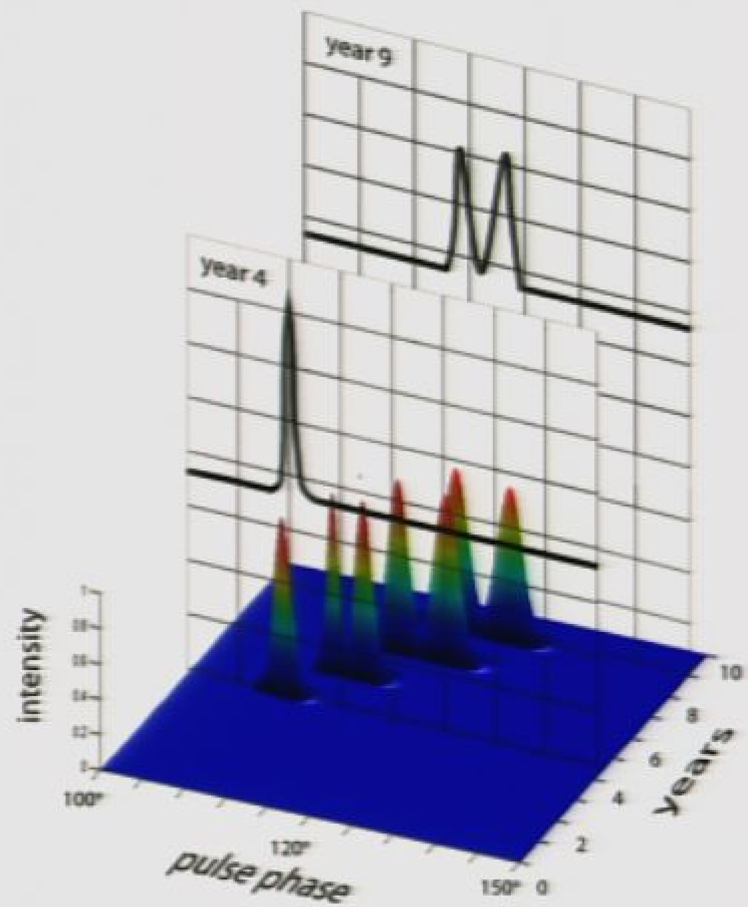

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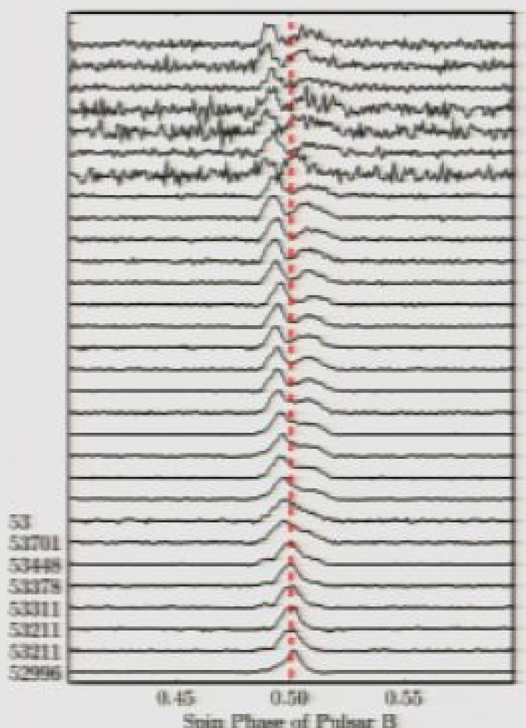

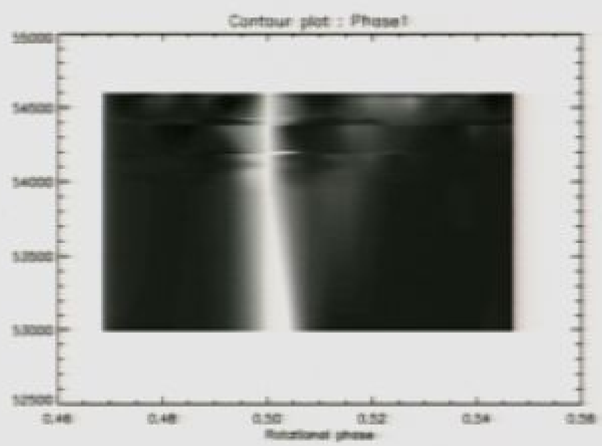

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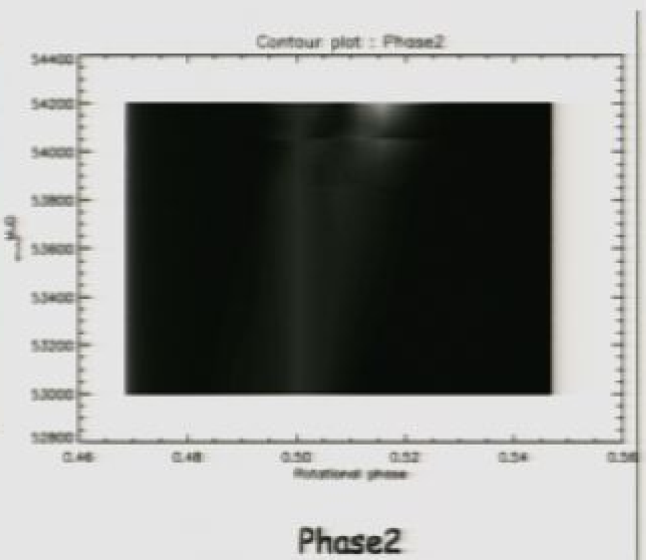

Phase2

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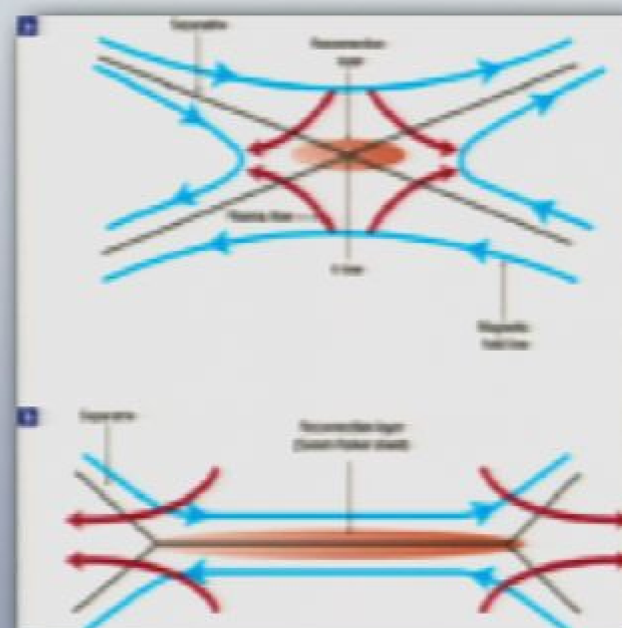
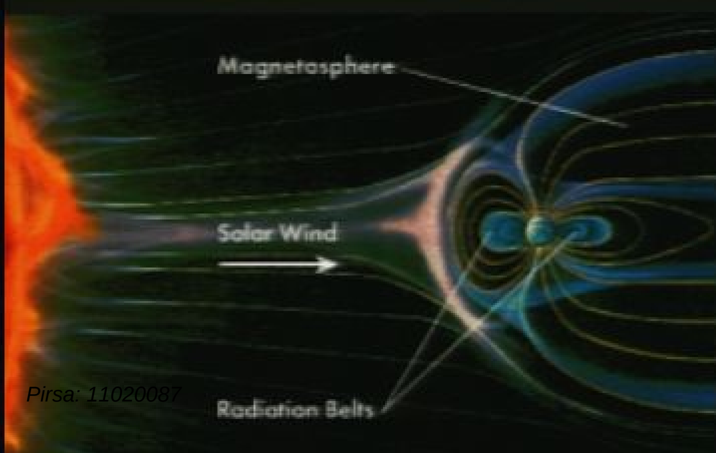
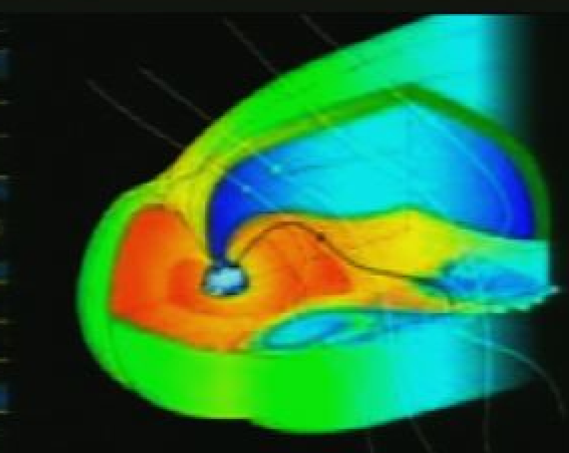
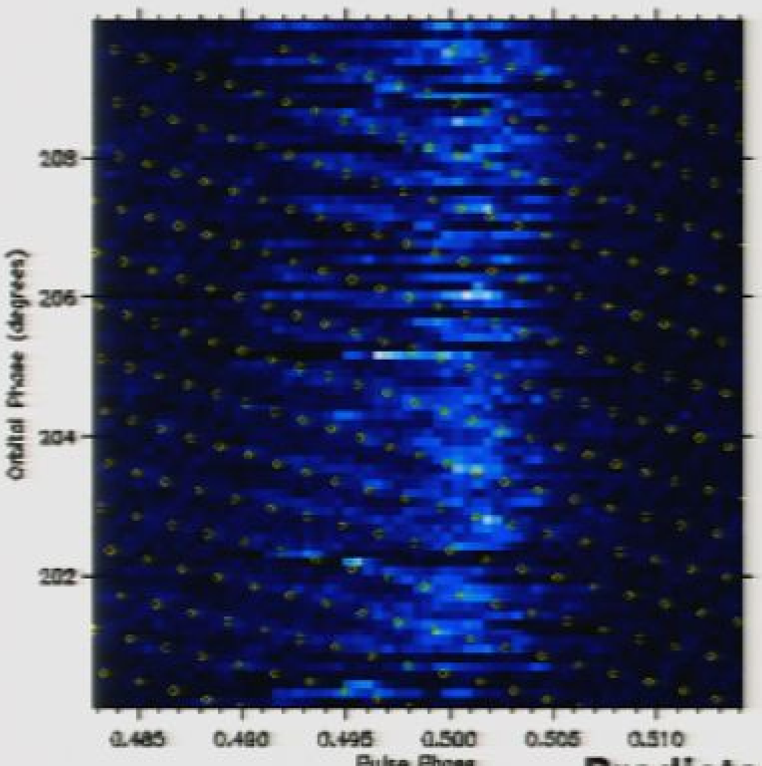




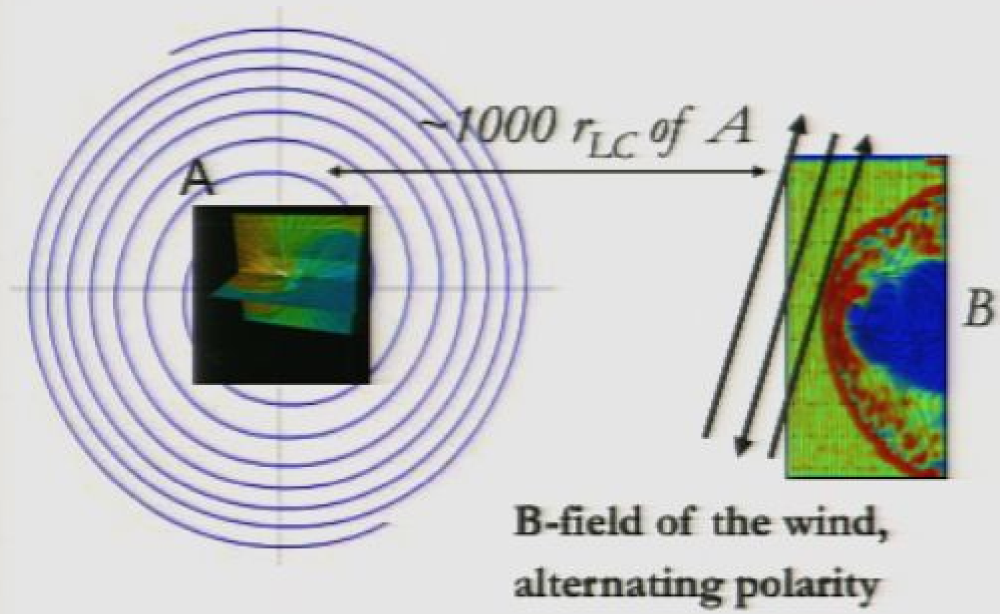


Relativistic reconnection, probes of pulsar winds

- Magnetosphere of B is "shaking" with the period of A: reconnection between B-field in the wind and the magnetosphere: a probe of the NS wind very close in: striped wind



(McLaughin et al., 04)

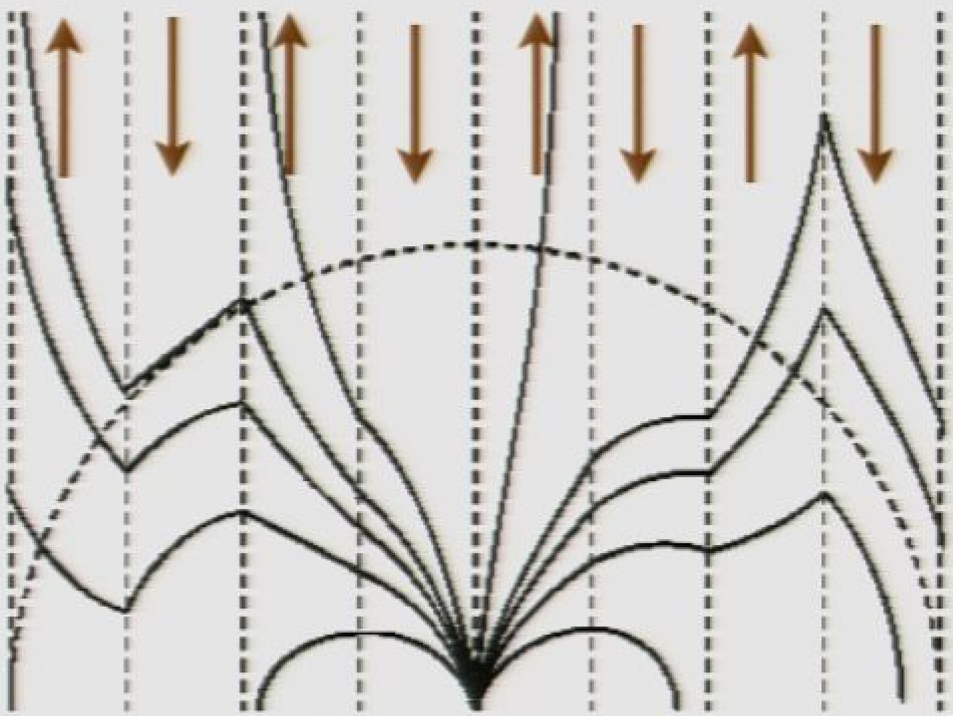


Predicted arrival times of A pulses at B

Relativistic reconnection, probes of pulsar winds

Earth-like models of magnetosphere-wind interaction

B-field in the wind



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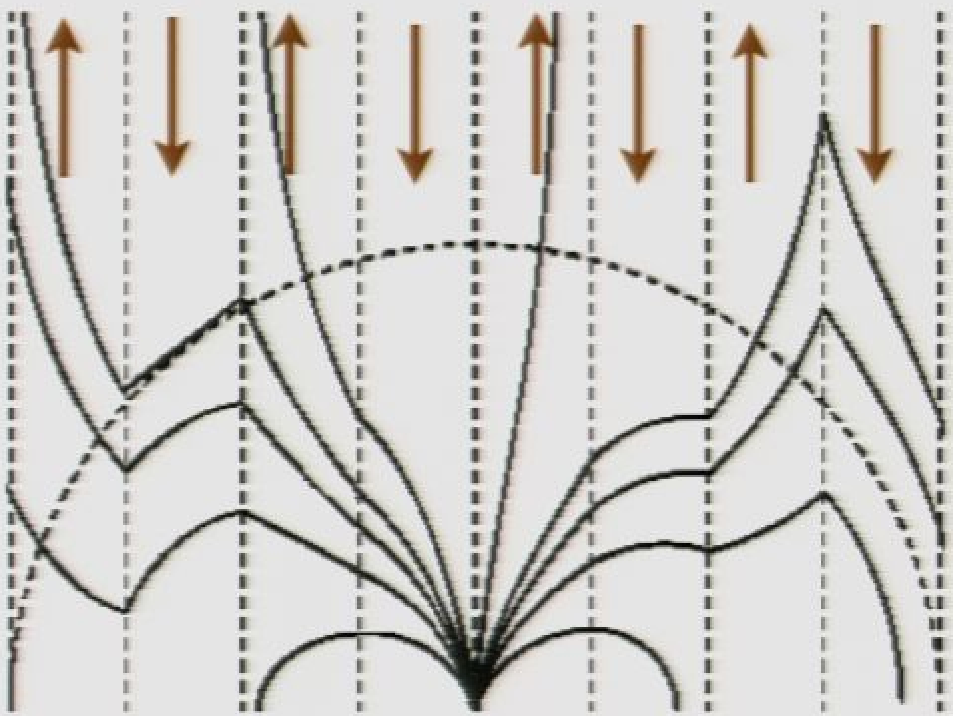

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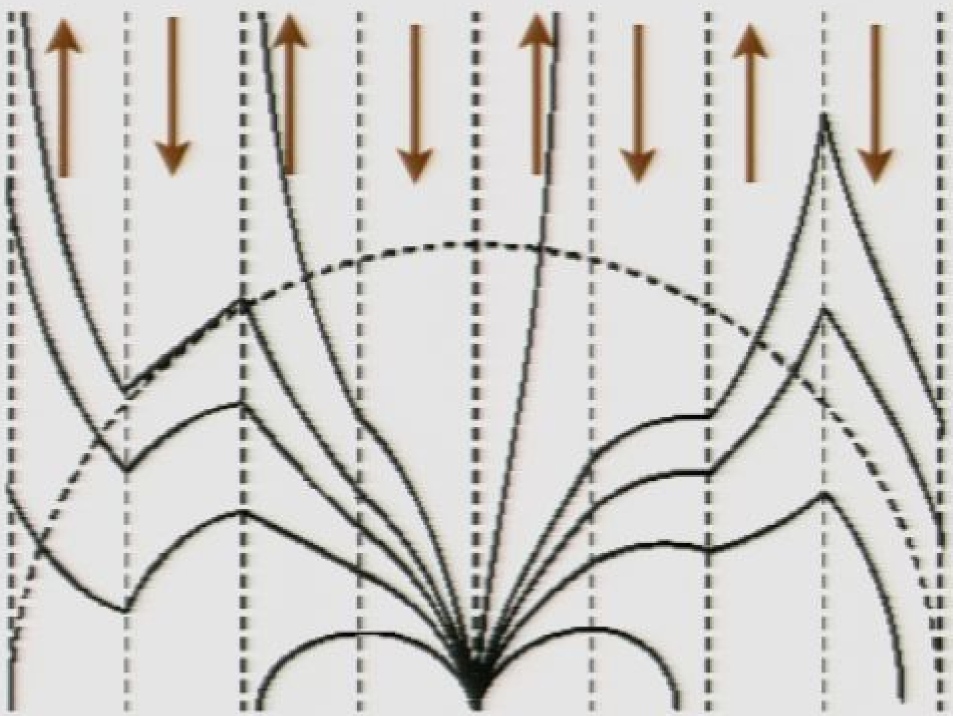
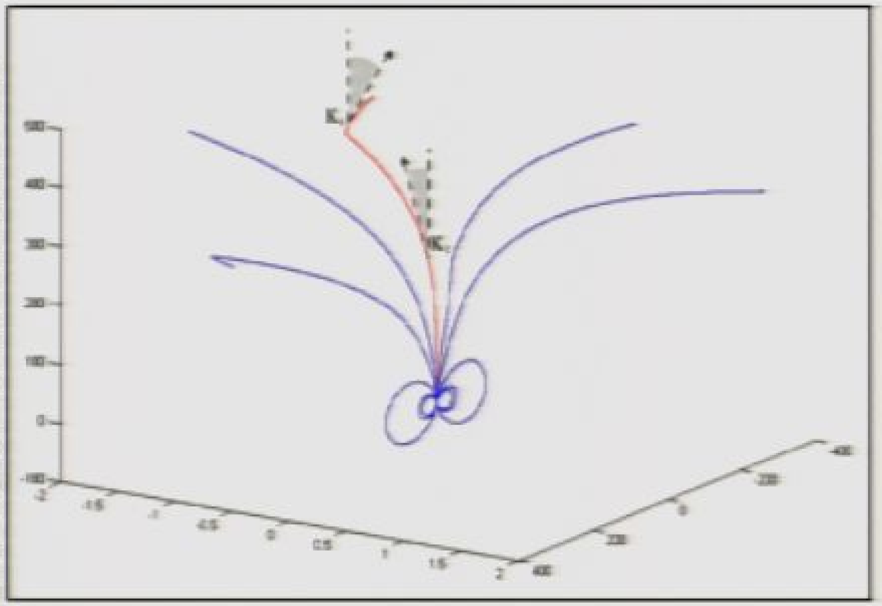
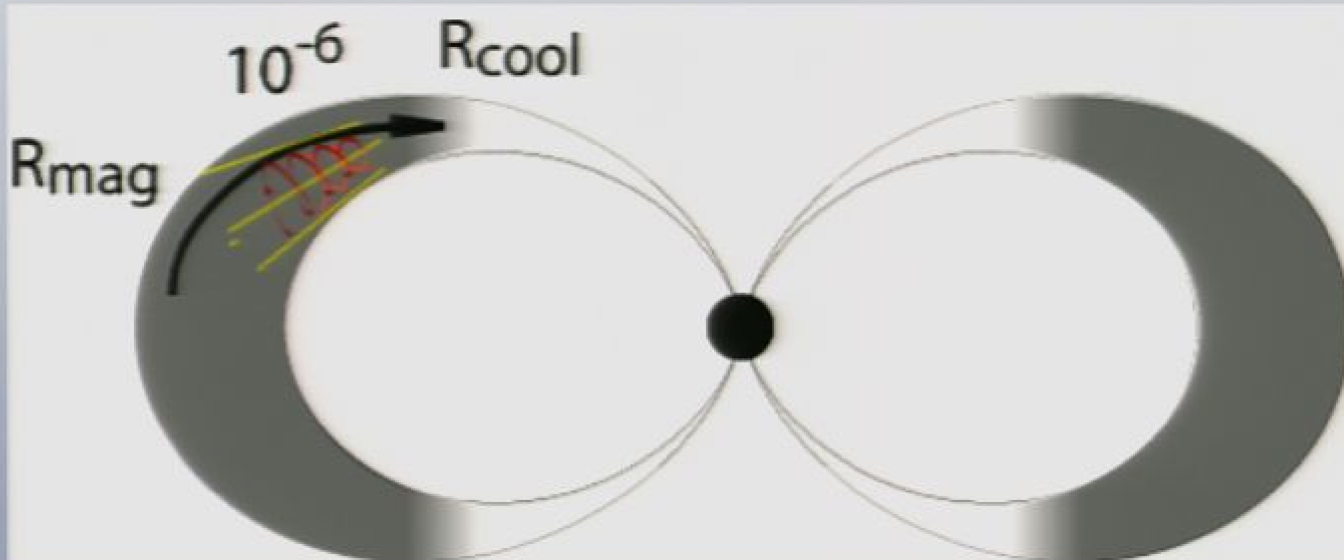




Dungy-type model of magnetosphere ,

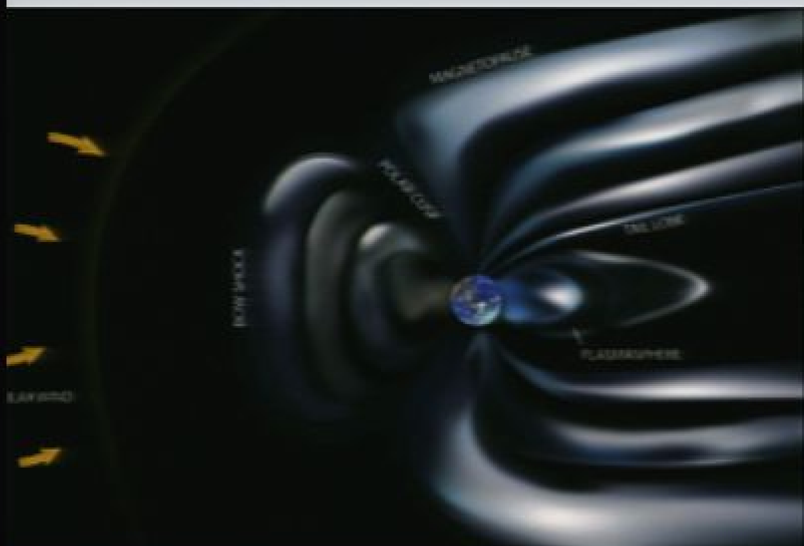
Lomiashvili, in prep

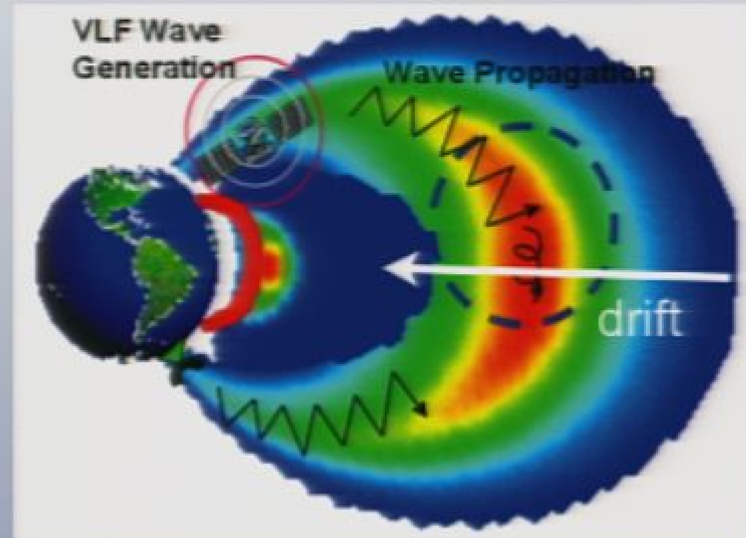
Need high density of particles in the magnetosphere: magnetic bottling



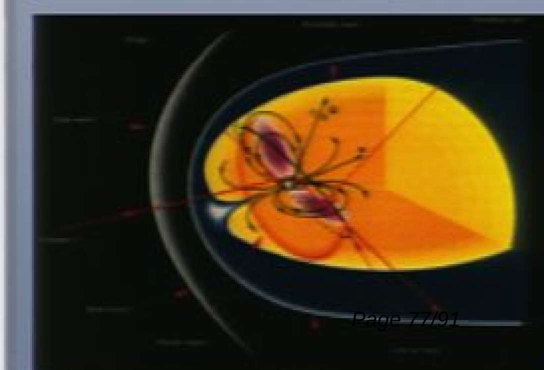
- Synchrotron cooling: $R_{cool} \sim 10^8$cm $\sim 0.05\ R_{mag}$
- Most particles are reflected by magnetic bottling, only 10^{-6} reach cooling radius.
- At R_{mag} particles live $\sim 10^6\ P_B$, density $\sim 10^4$- $10^5 n_{GJ,mag}$
- Need to re-supply at a rate ~ 0.01 - $0.1\ n_{GJ,mag}$ per period

Origin of particles in pulsar B magnetosphere: van Allen radiation belts





- Radial diffusion in co-rotating magnetosphere - testing density distribution
- Testing scaling relations (geometry) over a much wider parameter range than that provided by Solar planets alone. (~ Jupiter turns into Neptune every half period).



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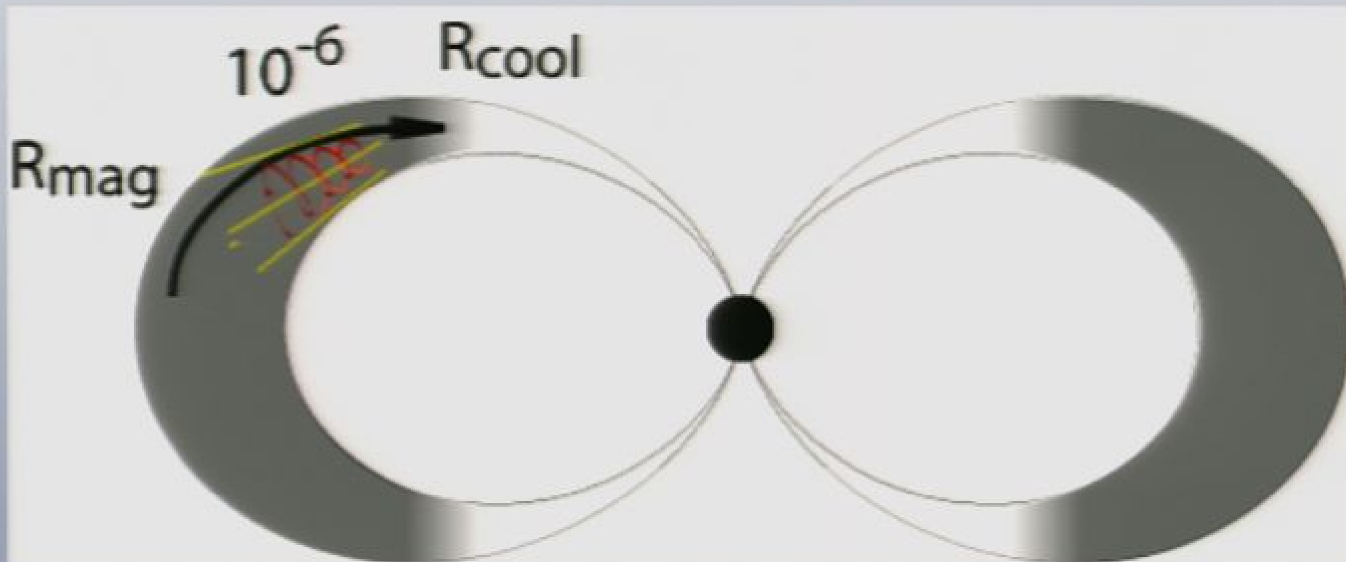

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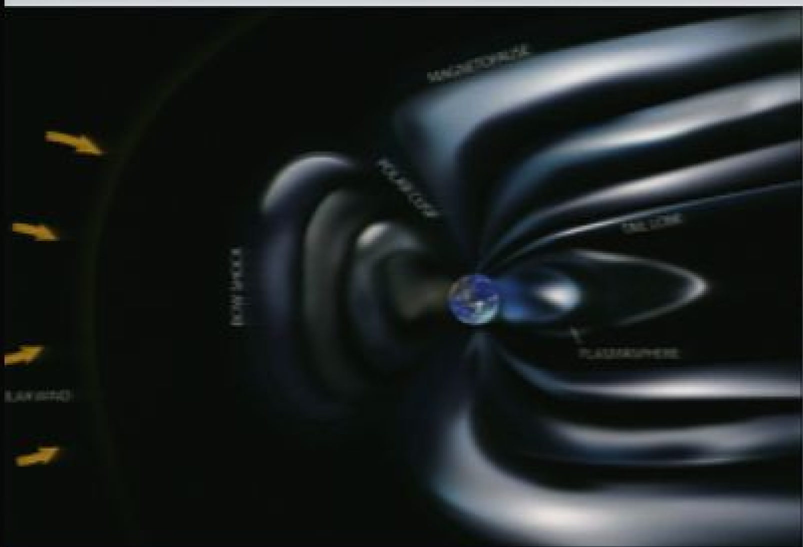
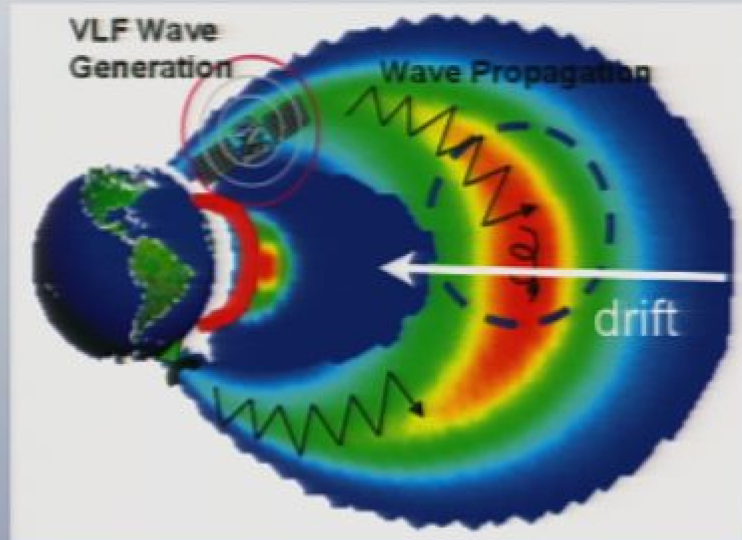
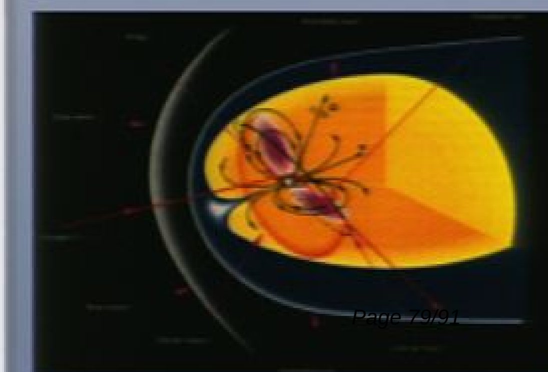




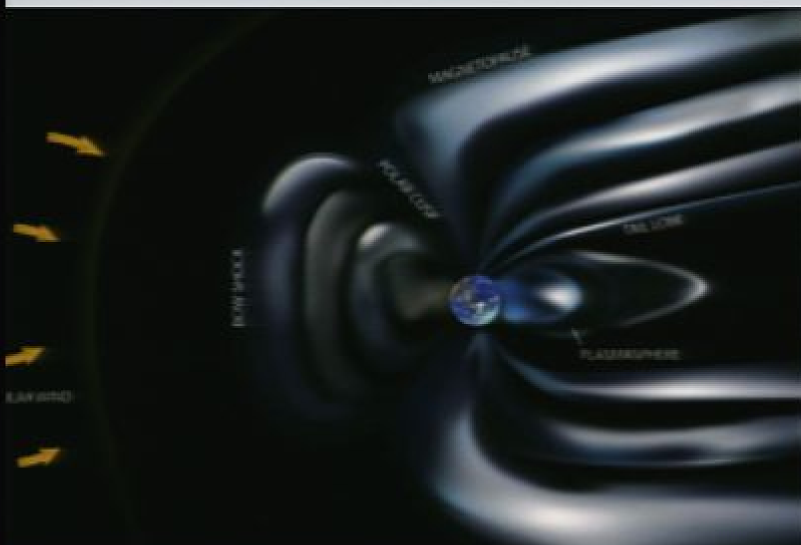
- Radial diffusion in co-rotating magnetosphere - testing density distribution
- Testing scaling relations (geometry) over a much wider parameter range than that provided by Solar planets alone. (~ Jupiter turns into Neptune every half period).

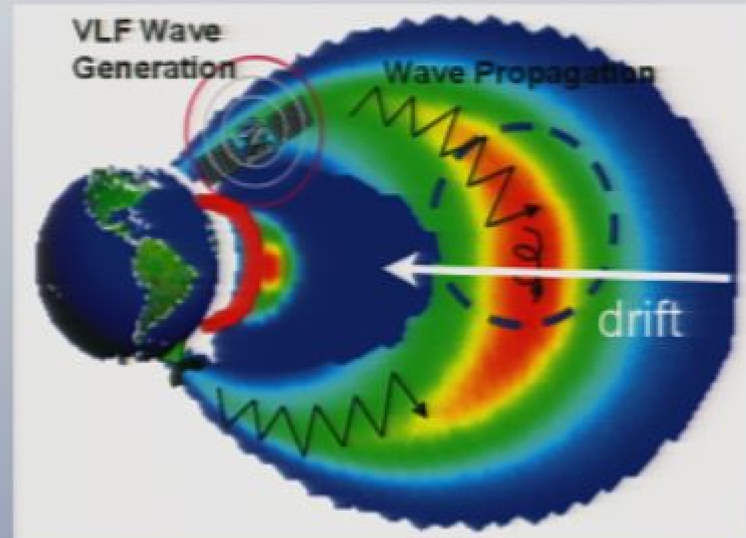


And back to General Relativity

- Rotation of pulsar B is very noisy - the main error in the GR tests.
- Understanding the plasma dynamics will lead to improvements of the GR tests

Origin of particles in pulsar B magnetosphere: van Allen radiation belts





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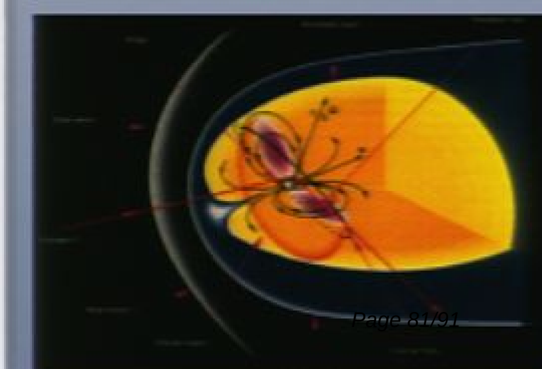

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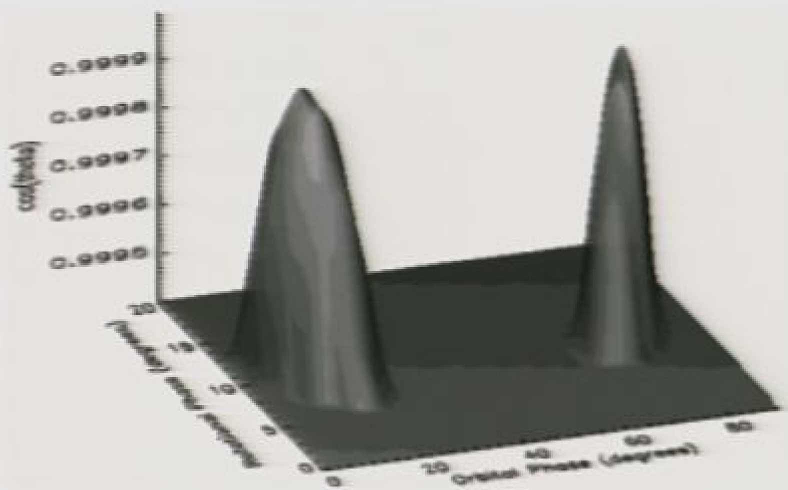
Orbital variations in B emission

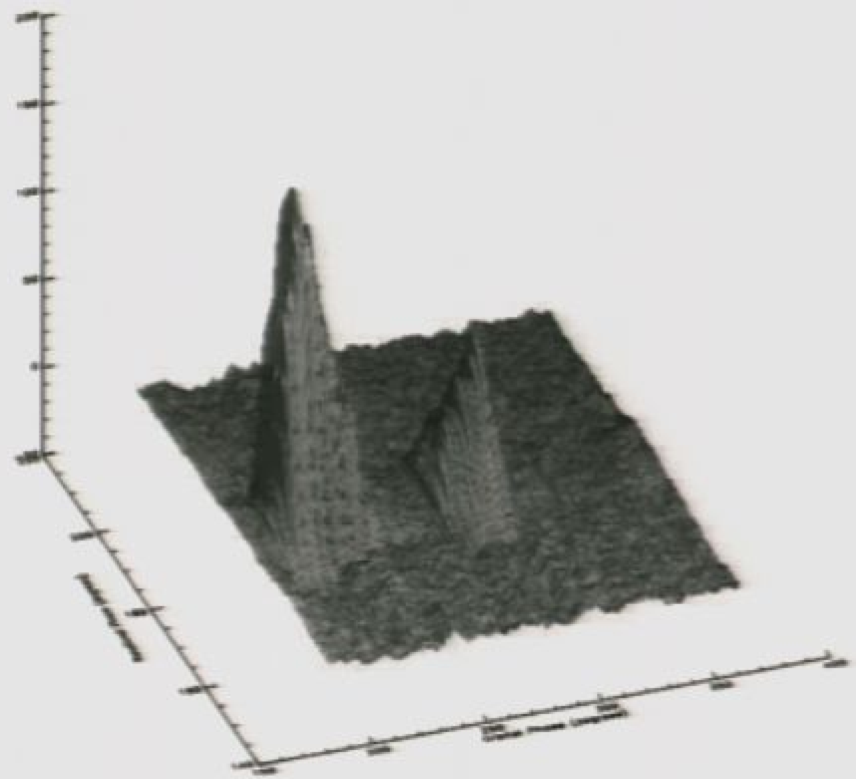
Perera et al., in prep.

Modeling of B



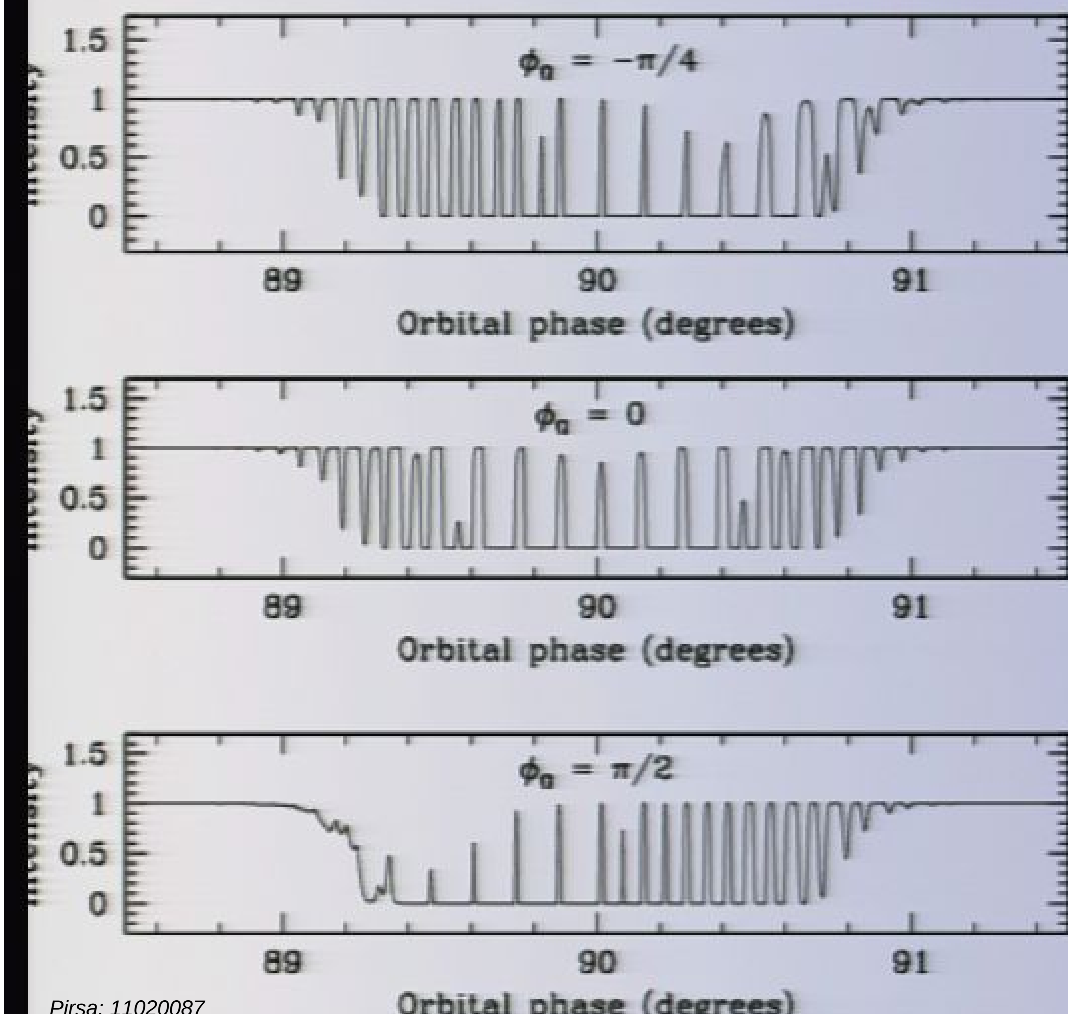
Parameters of the model are: θ=73.6º, φ=22.5º, χ=60º

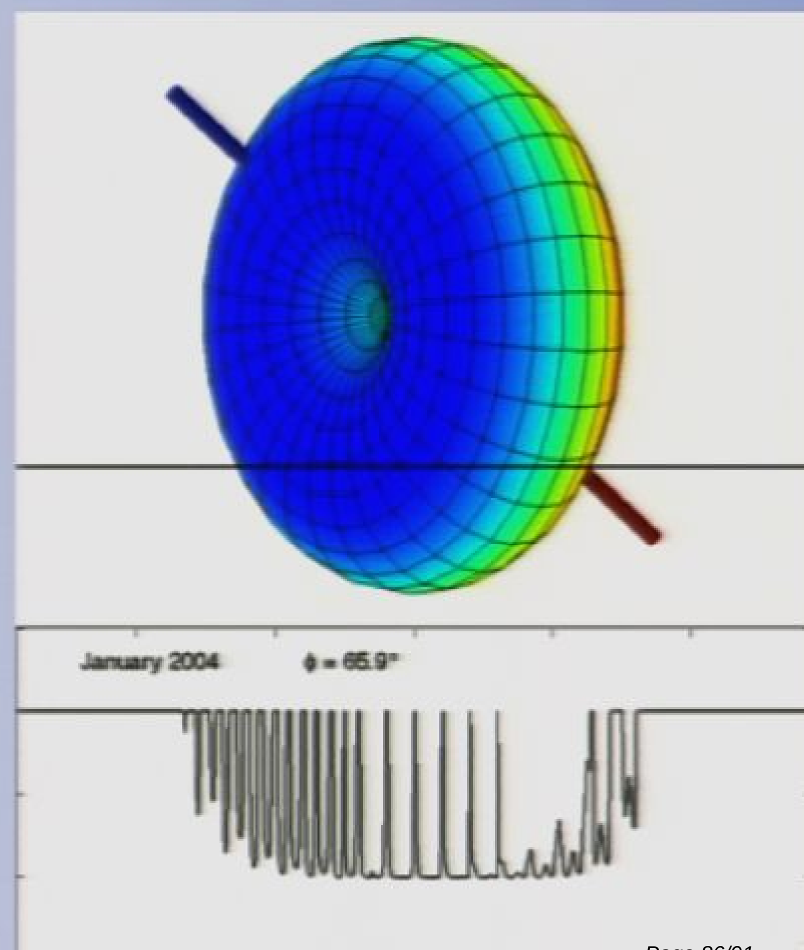
3D view of real data



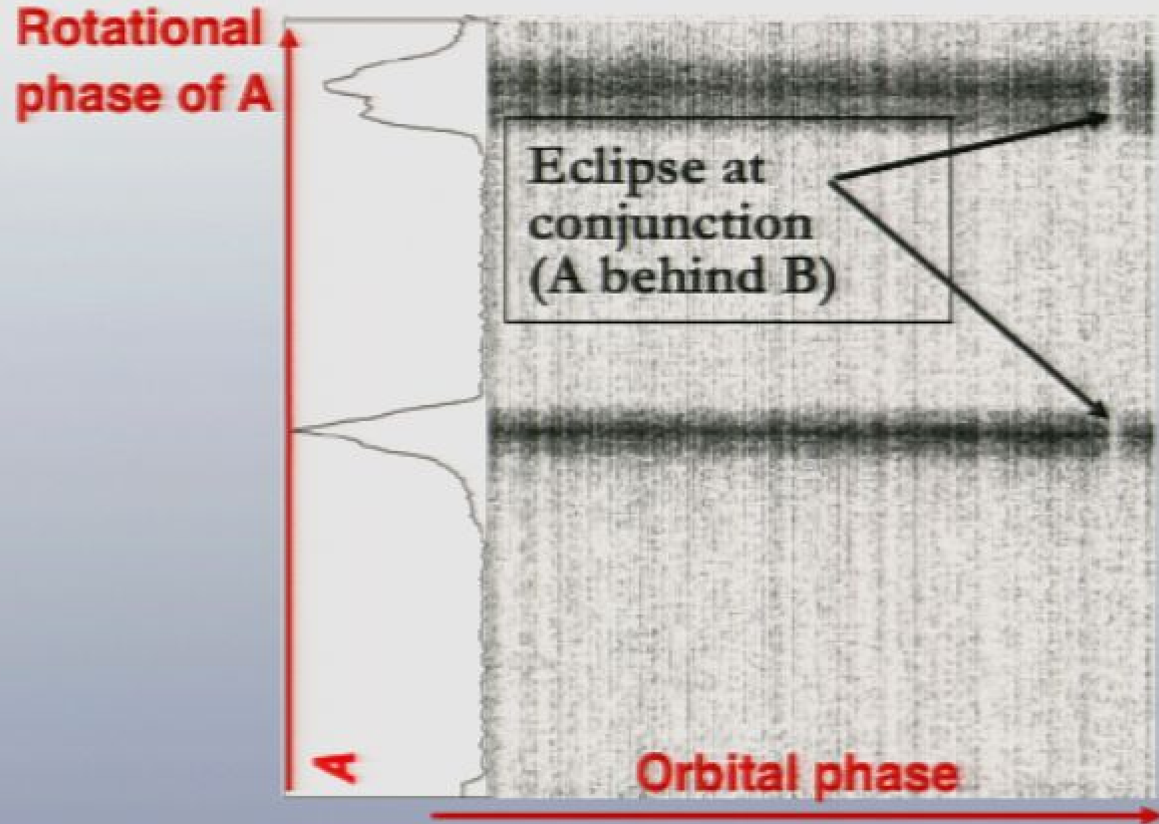
3D plot of MJD 54050

Predictions: change of eclipse profile due to geodetic precession

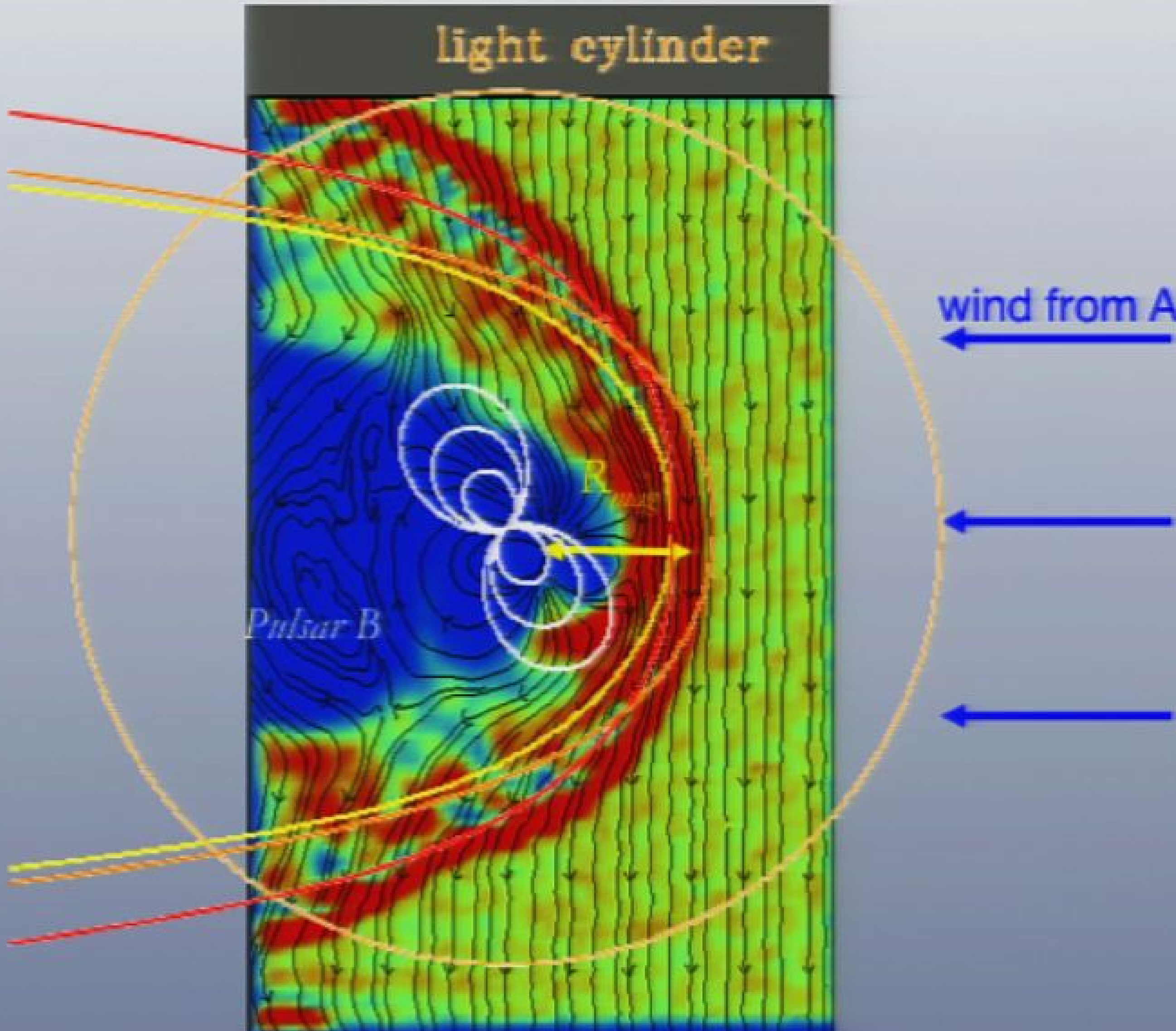




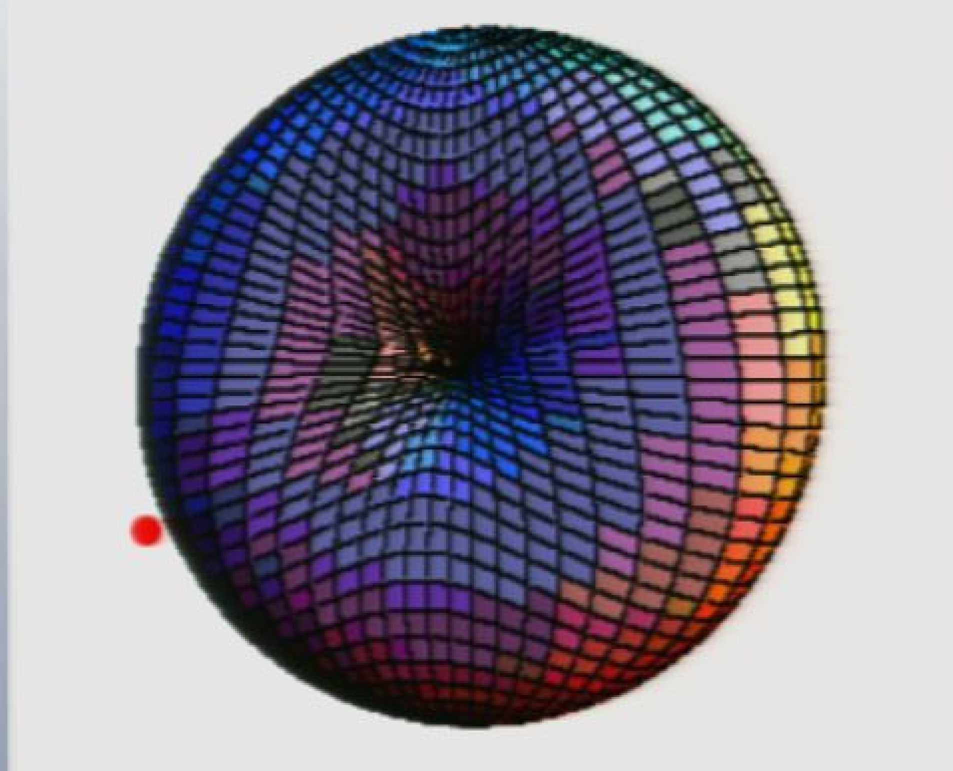
"A" eclipse: modulated at B rotation



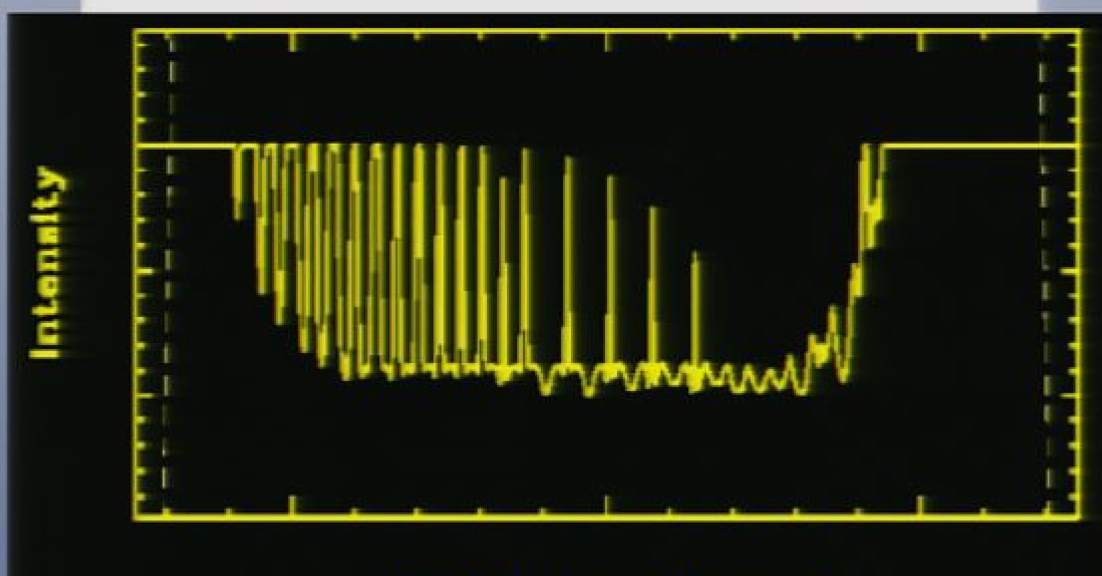
Pulsar A wind blows off most of B magnetosphere



Spitkovsky (2004) Lyutikov (2004)



- Red dot: line of sight to pulsar A.
- “Donut”: last closed surface of B magnetosphere



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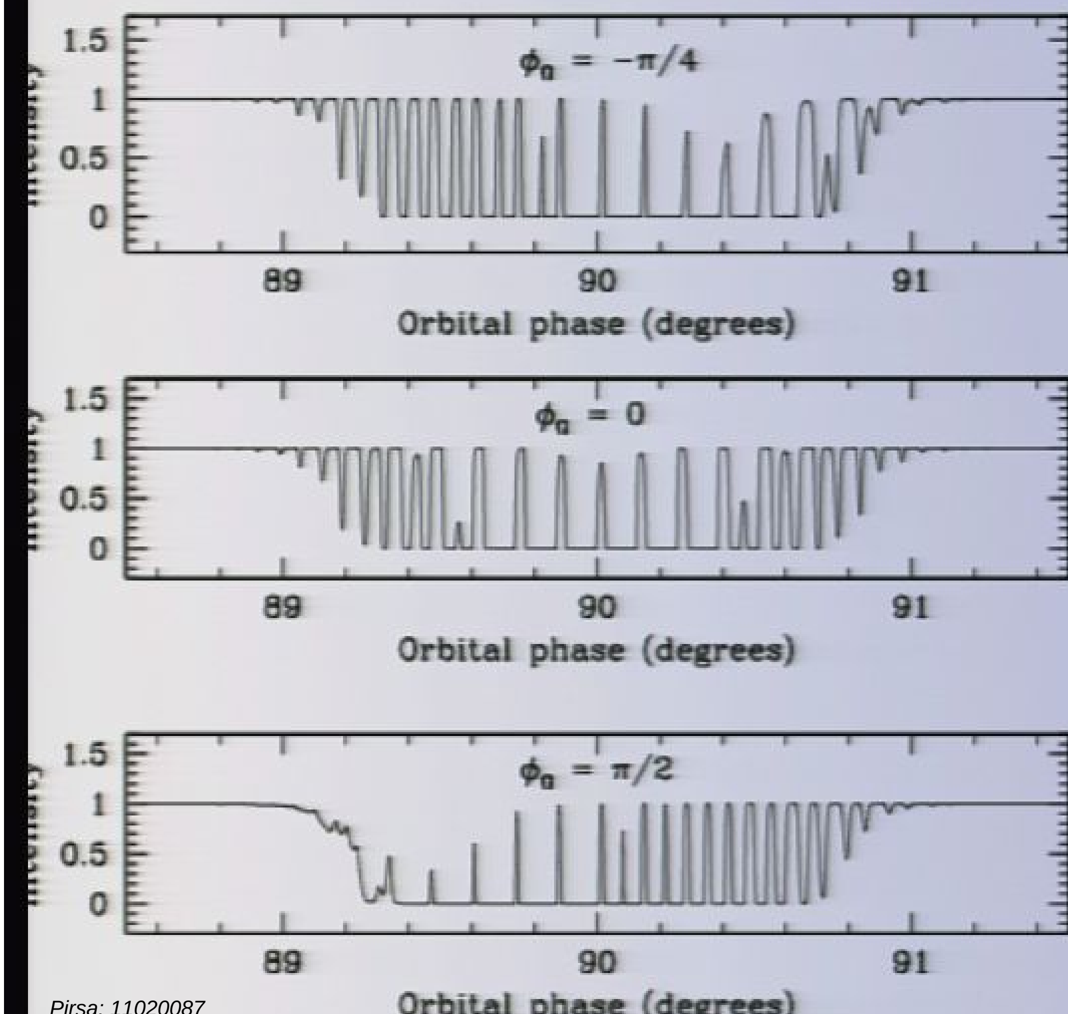

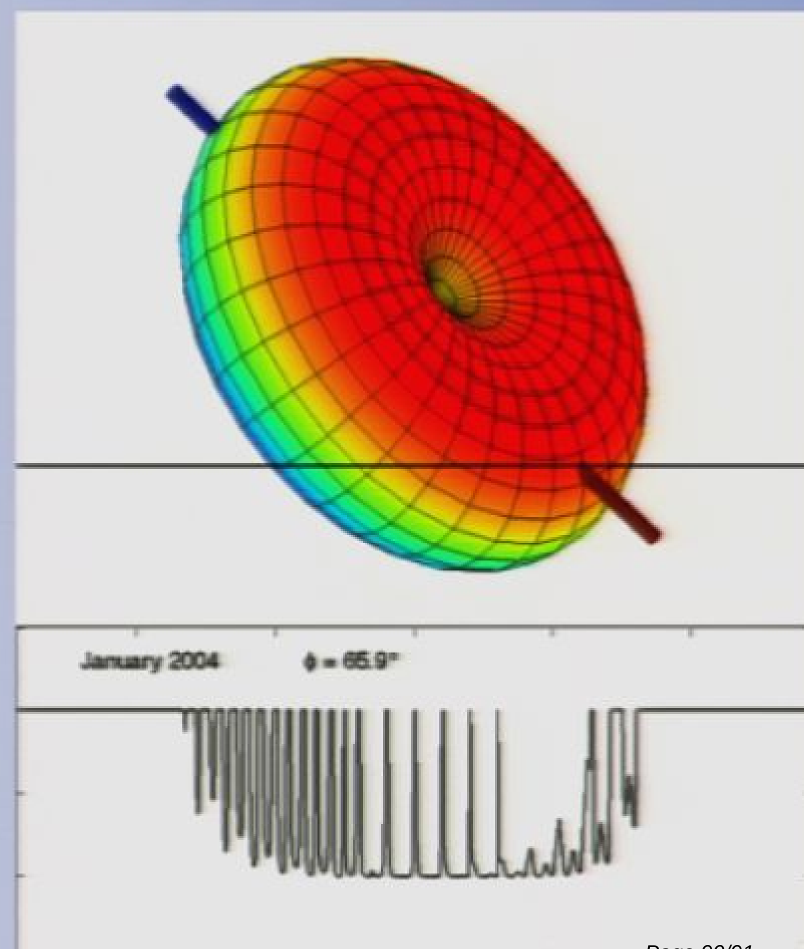

New test of theories of gravity

- Precession rate $\Omega_B = \frac{x_A x_B}{s^2} \times \frac{n^3}{1-e^2} \times \frac{c^2\sigma_B}{G}$
- Observed $\Omega = 4.98_{+0.43\,-0.23}$ °/yr

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right) = 3.38^{+0.49}_{-0.46}.$$

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 2 + \frac{3}{2}\frac{m_A}{m_B} = 3.60677 \pm 0.00035. \quad \Omega_B = 5.07°/yr$$

$$\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm obs} \Big/ \left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 0.94 \pm 0.13.$$

- C.f. Gravity Probe B, same accuracy, weak field regime, ~ $1bn.

- G - generalized Newton's constant
- σB is a strong-field spin-orbit coupling constant
- the first term accessible only for the Double Pulsar