Resistivity and Dissipation in Pulsar Magnetospheres

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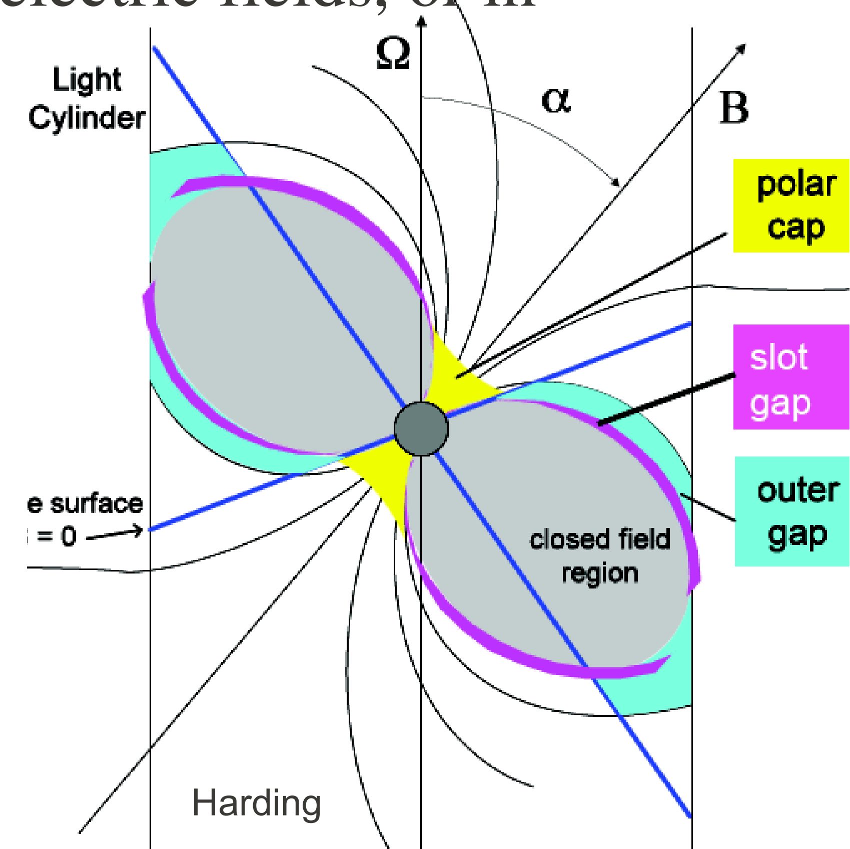
Overview

- Pulsars provide a unique laboratory to study plasma processes, dissipation, in high magnetic field environments
- 3 classes of pulsar solutions
  - Vacuum (no plasma in magnetosphere)
  - Force-free (abundant ideal plasma everywhere)
  - Resistive (solutions that combine plasma and accelerating fields)
- Applications of resistive solutions to intermittent pulsars, gamma ray pulsars

Non-ideal nature of Pulsar Magnetospheres

- We expect bulk of magnetosphere to have abundant ideal plasma due to pair cascade, but need accelerating electric fields to get high-energy radiation
- Finite $E_{||}$ can arise in “gap” regions due to variations in plasma supply and insufficient shorting of electric fields, or in reconnecting current sheets
- $E_{||}$ drives current and gives rise to resistivity, we specify $\vec{j}_{fluid} = \sigma \vec{E}_{fluid}$



Lab frame:

$$\vec{j} = \frac{\rho c \vec{E} \times \vec{B} + \sqrt{\frac{B^2+E_0^2}{B_0^2+E_0^2}}\sigma E_0 (B_0 \vec{B} + E_0 \vec{E})}{B^2 + E_0^2}.$$

E_0, B_0 magnitude of E, B in fluid frame

Pulsar electrodynamics

- We use a Finite Difference Time Domain Method to solve Maxwells equations with our resistive current closure

$$\partial_t \vec{E} = c\vec{\nabla} \times \vec{B} - 4\pi\vec{j},$$
$$\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E},$$

$$\vec{j} = \rho\vec{v} + \sigma\vec{E}_{\text{fluid}}$$
$$\vec{v} = c(\vec{E} \times \vec{B})/(B^2 + E_0^2)$$
$$\vec{E}_{\text{fluid}} = \gamma(\vec{E} + \vec{v} \times \vec{B})$$

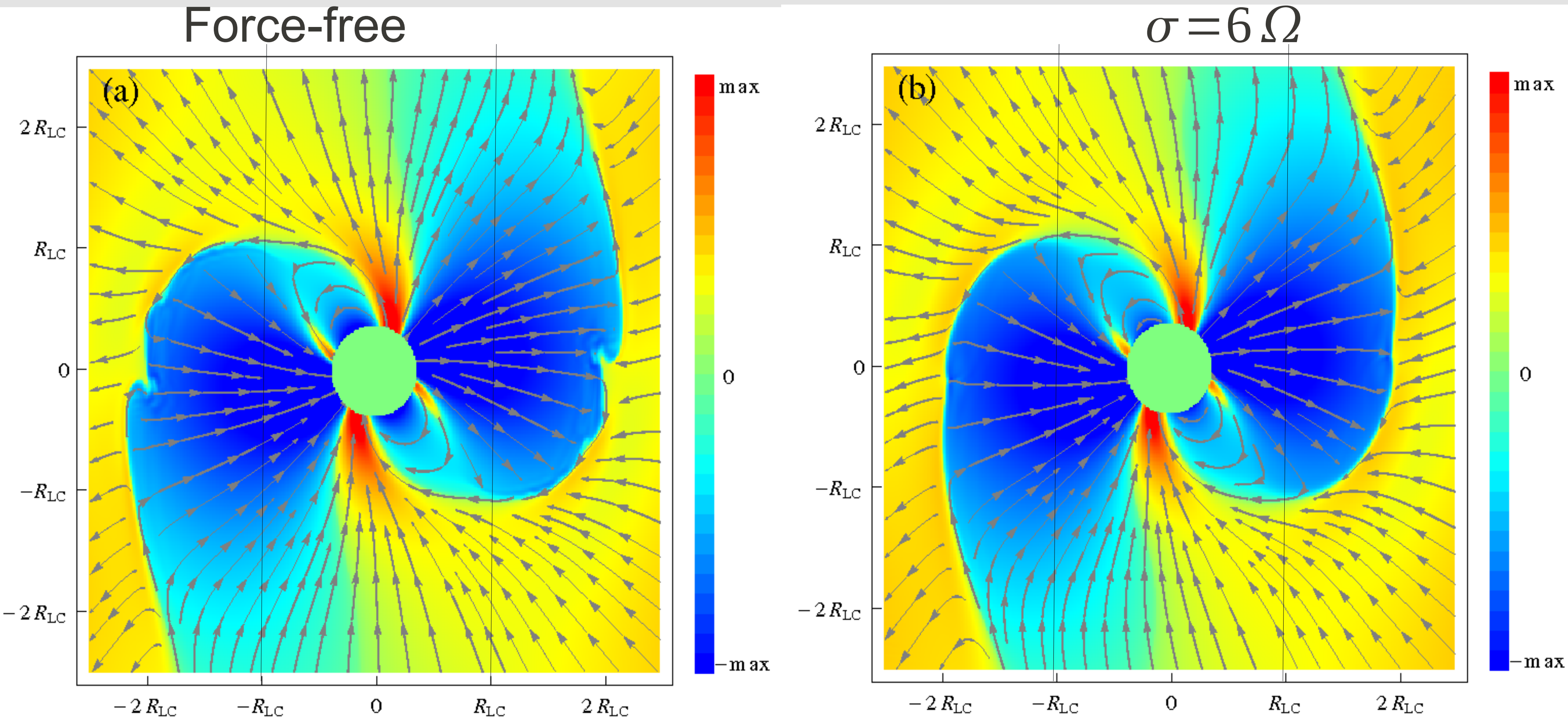
- Problem: conducting neutron star with dipole field immersed in resistive plasma
- Method applicable to magnetically dominated systems in which plasma pressure and inertia are negligible
- Main application here to pulsar magnetospheres
- Potential applications to black hole magnetospheres, stellar and disk coronas, binaries, NS collapse

Resistive Pulsars

- Movie of field lines and current sheet for 60 degree inclined resistive pulsar solution with high but finite conductivity at:

http://www.astro.princeton.edu/~jgli/rotator.mpeg

Force-free and high conductivity similar

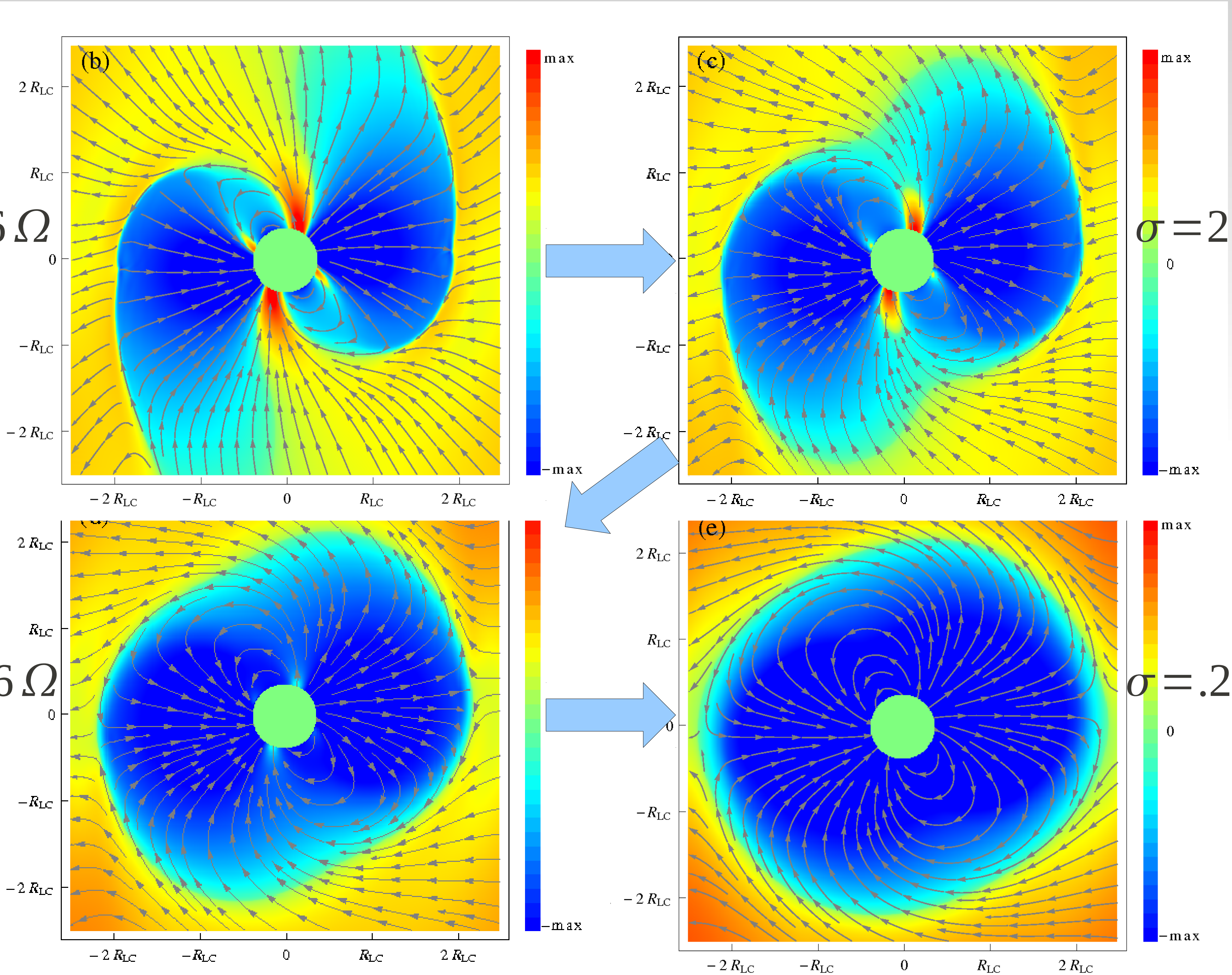


Li, Spitkovsky, Tchekhovskoy '12, ApJ 746, 60

Smooth transition to vacuum

$\sigma = 6\,\Omega$

$\sigma = 2\,\Omega$

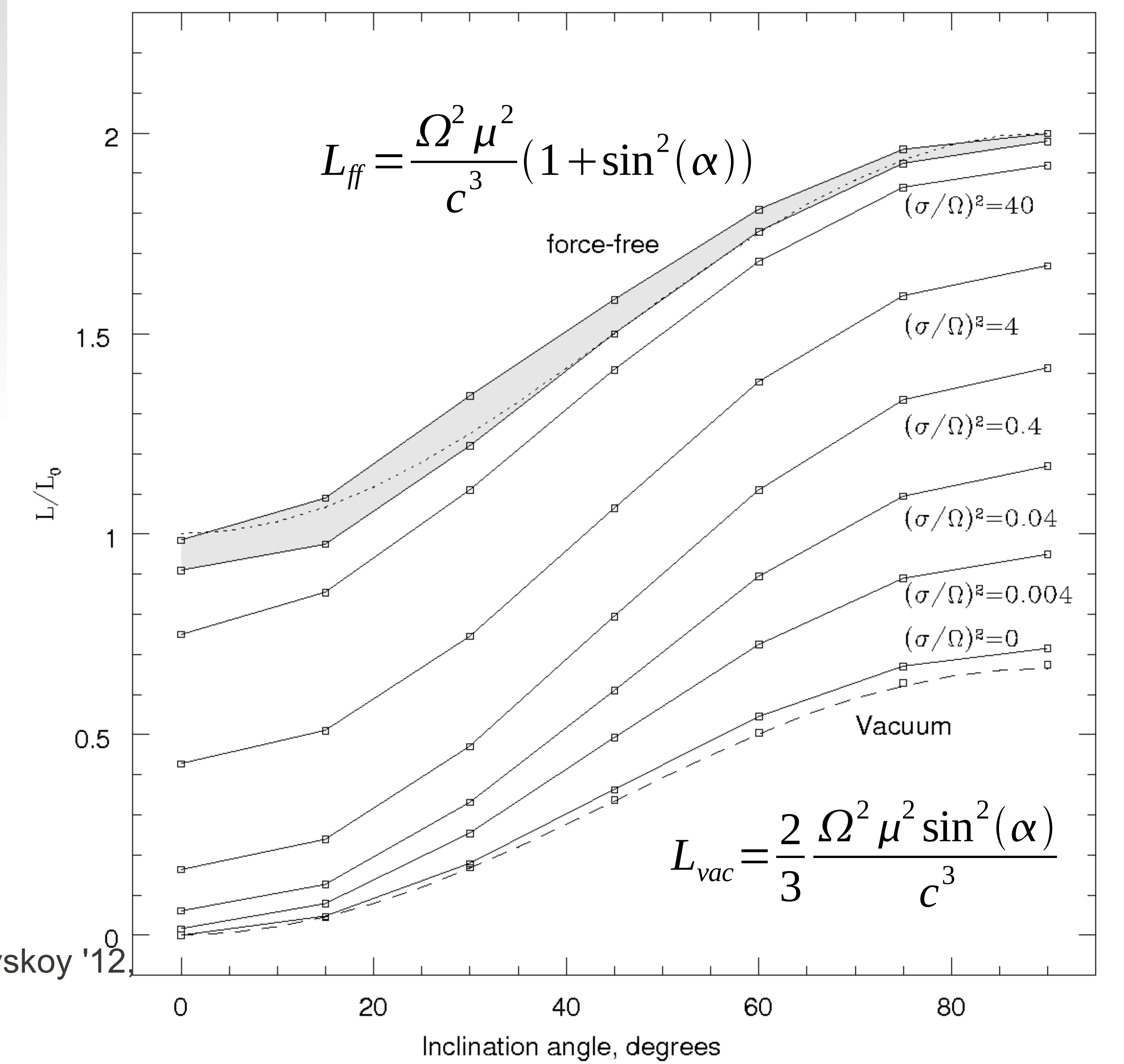


$\sigma = .6\,\Omega$

$\sigma = .2\,\Omega$

Spin-down

- Magnetodipole radiation
- Conduction currents add to energy loss: W=IV
- Spin-down increases with conductivity
- What values of σ are observationally motivated?



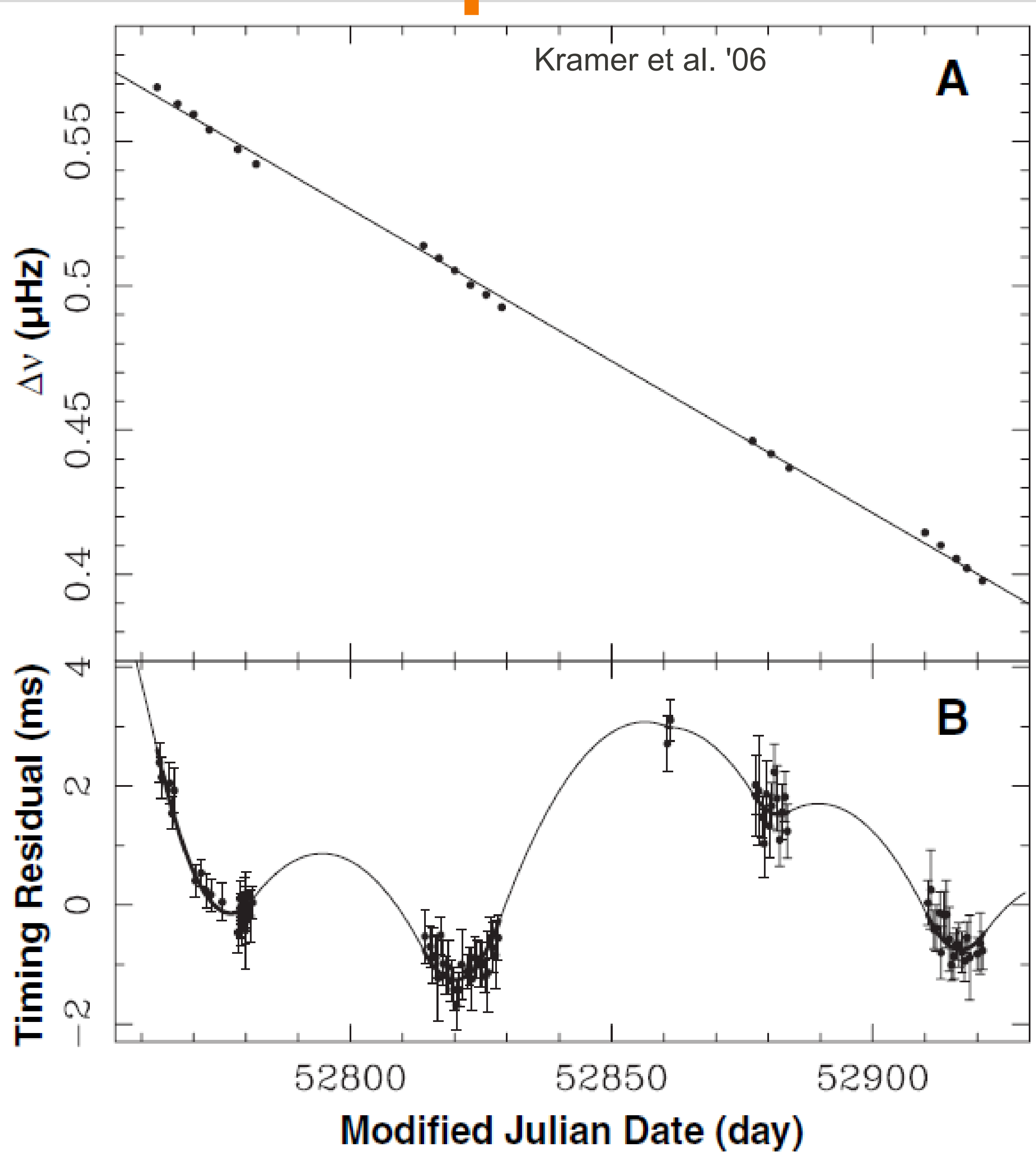
Li, Spitkovsky, Tchekhovskoy '12,
ApJ 746, 60

How do real pulsars spin down? A look at Intermittent pulsars

- Switch between two distinct spin-down states
- Spin-down rates differ by factor of ~1.5-2.5

PSR B1931+24
PSR J1832+0029
PSR J1841-0500

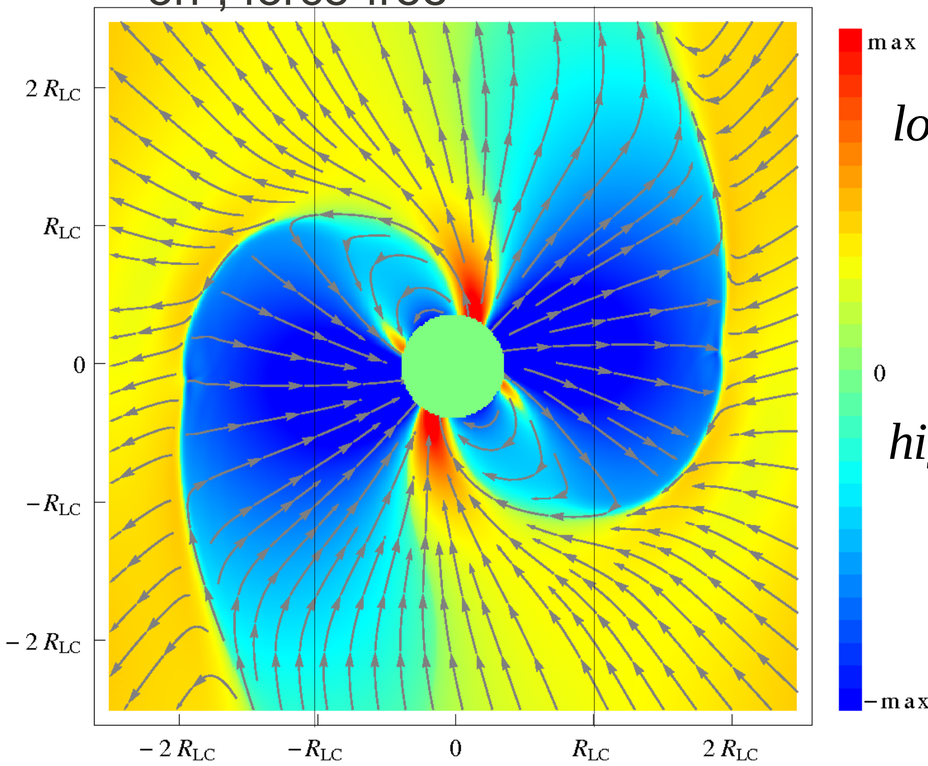
- “on” radio-loud state and “off” radio-quiet state



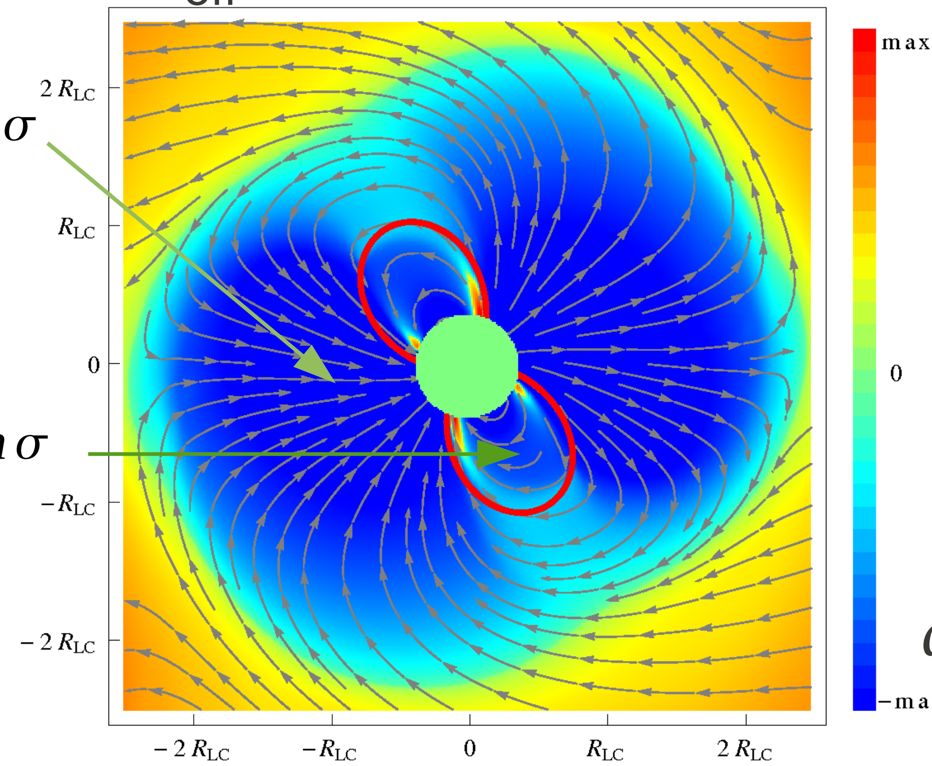
Why do Intermittent pulsars turn "on" and "off"?

- Switching suggests (Kramer et al. '06) some process is affecting plasma supply, giving us direct handle on plasma currents
- We construct quantitative model
  - "on" state is force-free with abundant plasma everywhere
  - In "off" state plasma supply on open field lines has been disrupted, but plasma remains trapped in closed zone

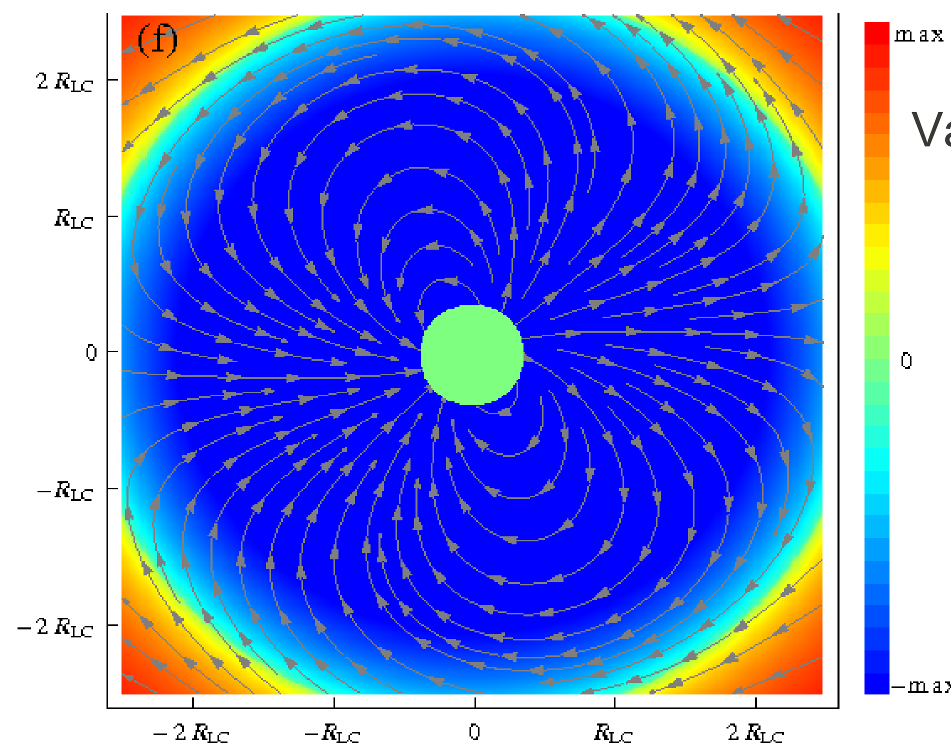
“on”, force-free



“off”



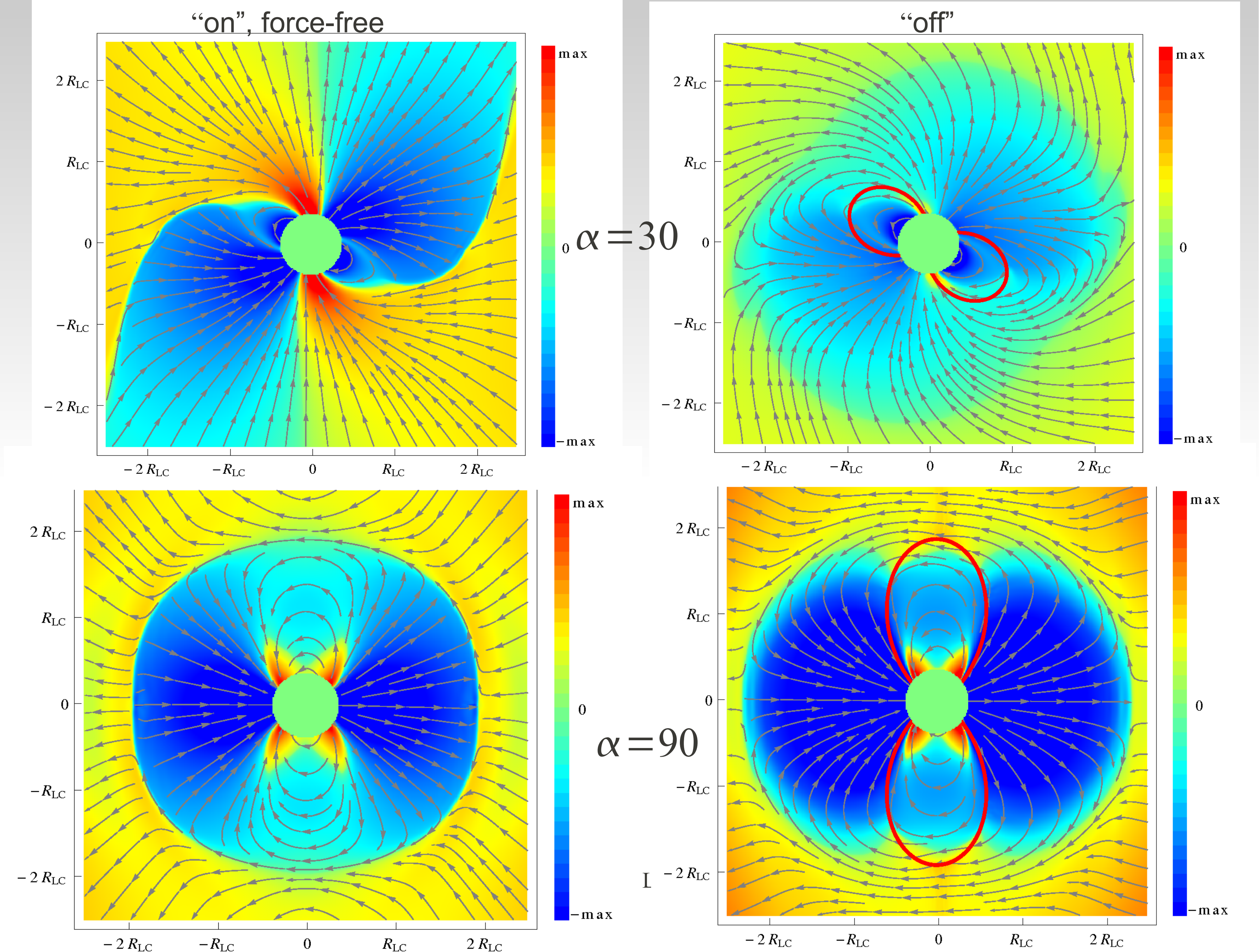
$\alpha = 60$



Vacuum

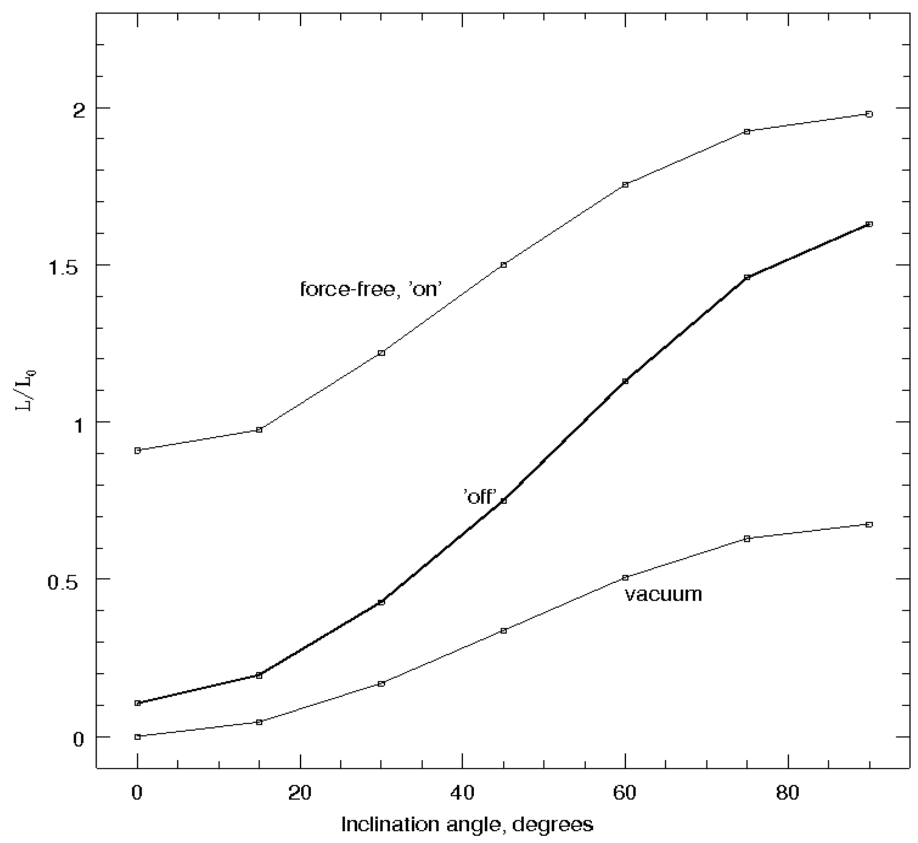
Current from toroidal advection of charged plasma in the closed zone leads to larger magnetic flux passing through the light cylinder and a larger fraction of open field lines (over vacuum)

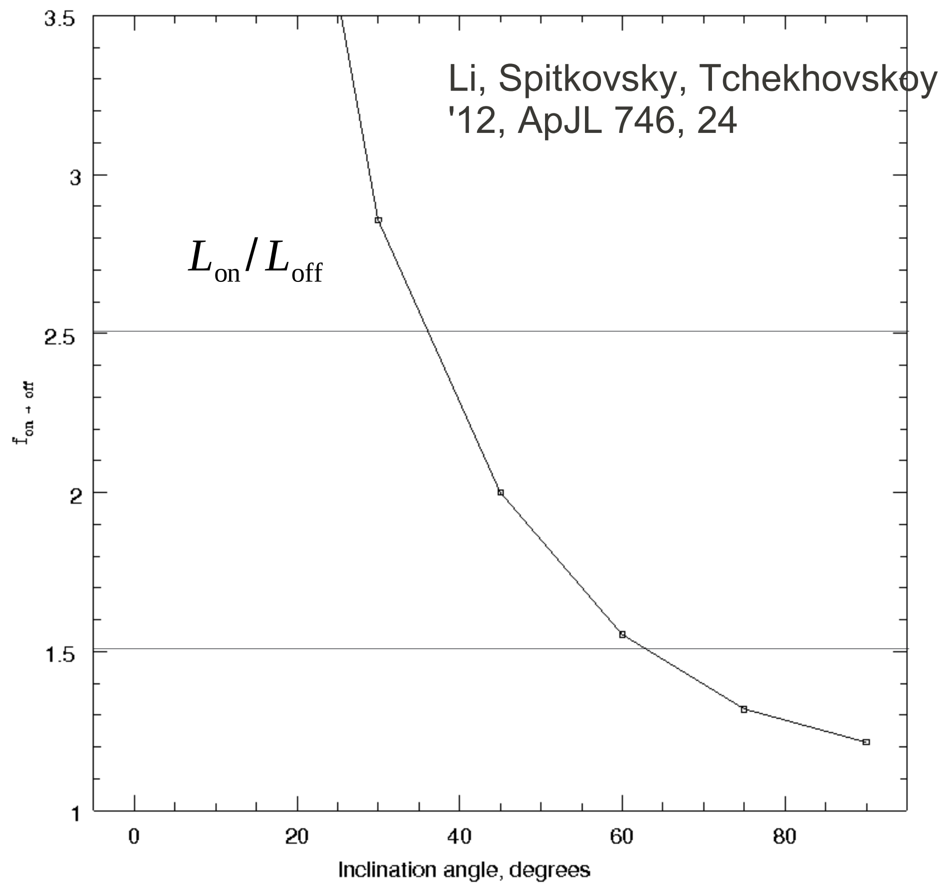
Li, Spitkovsky, Tchekhovskoy '12, ApJL 746, 24



“on”, force-free
“off”
α=30
α=90
max
0
−max
2 R_LC
R_LC
0
−R_LC
−2 R_LC

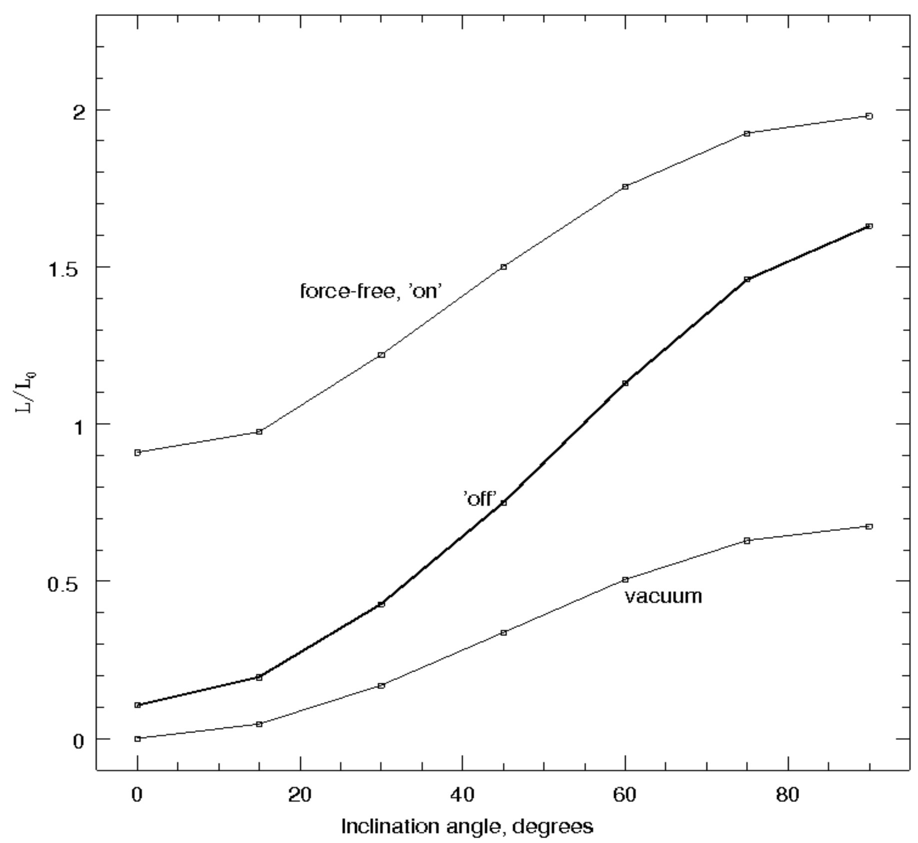
Implications for Spin-down

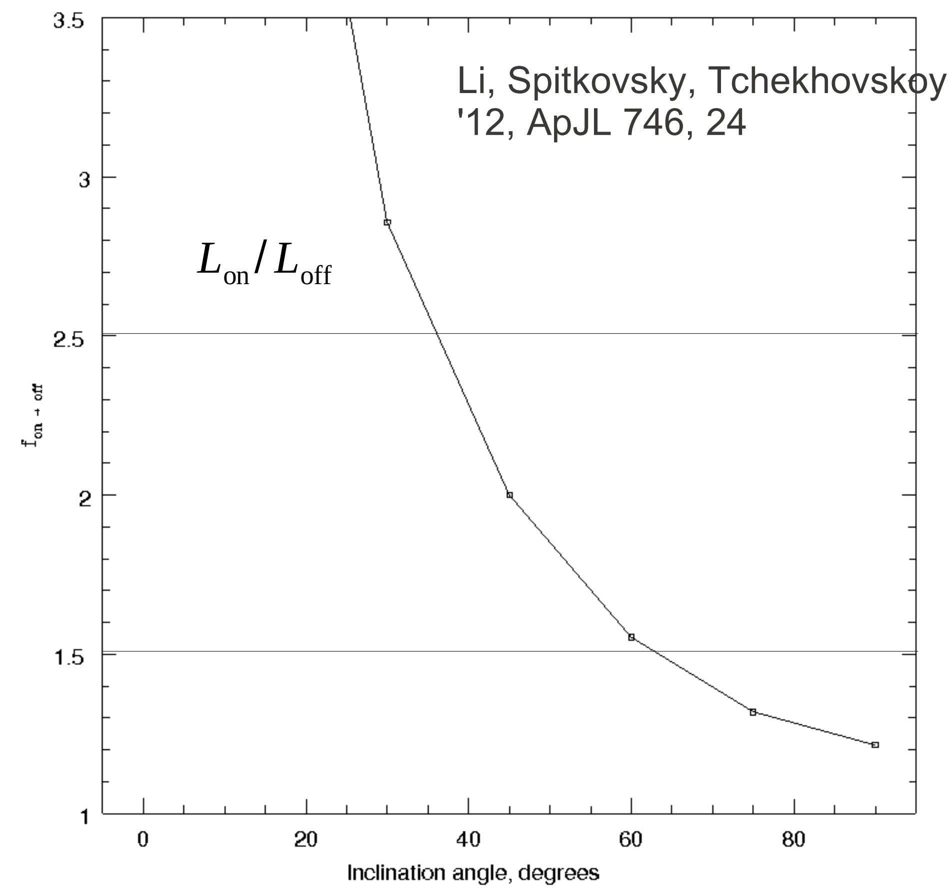




$L_{ff}/L_{vac}=3/2(1+\sin^2(\alpha))/\sin^2(\alpha)\geq 3$ cannot explain intermittent pulsars

- Open field lines carry Poynting flux, so the larger fraction of open field lines in "off" state leads to spin-down factor of 2 higher than vacuum



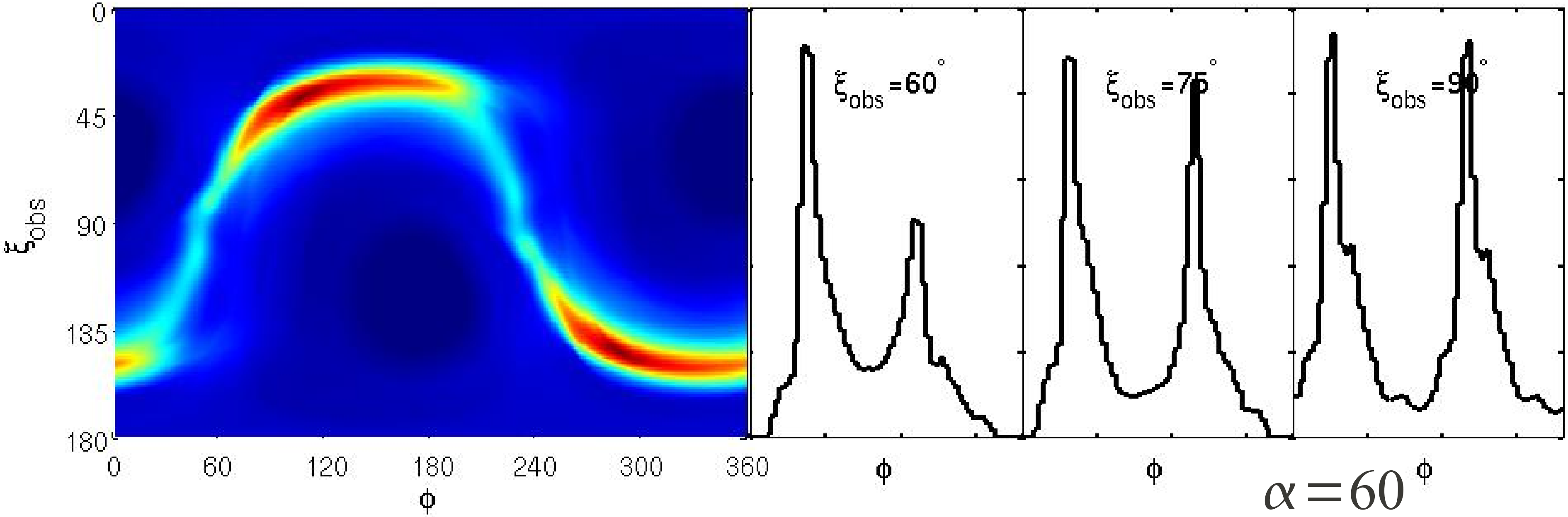


- Missing physics is toroidal advection of plasma in closed zone
- Uncertainties in "off" state spin-down ~ 10% of aligned force-free spin-down
- The spin-down ratio is broadly consistent with observations
- Intermittency may be related to nulling (also timing noise, rotating radio transients)

Gamma-ray pulsars

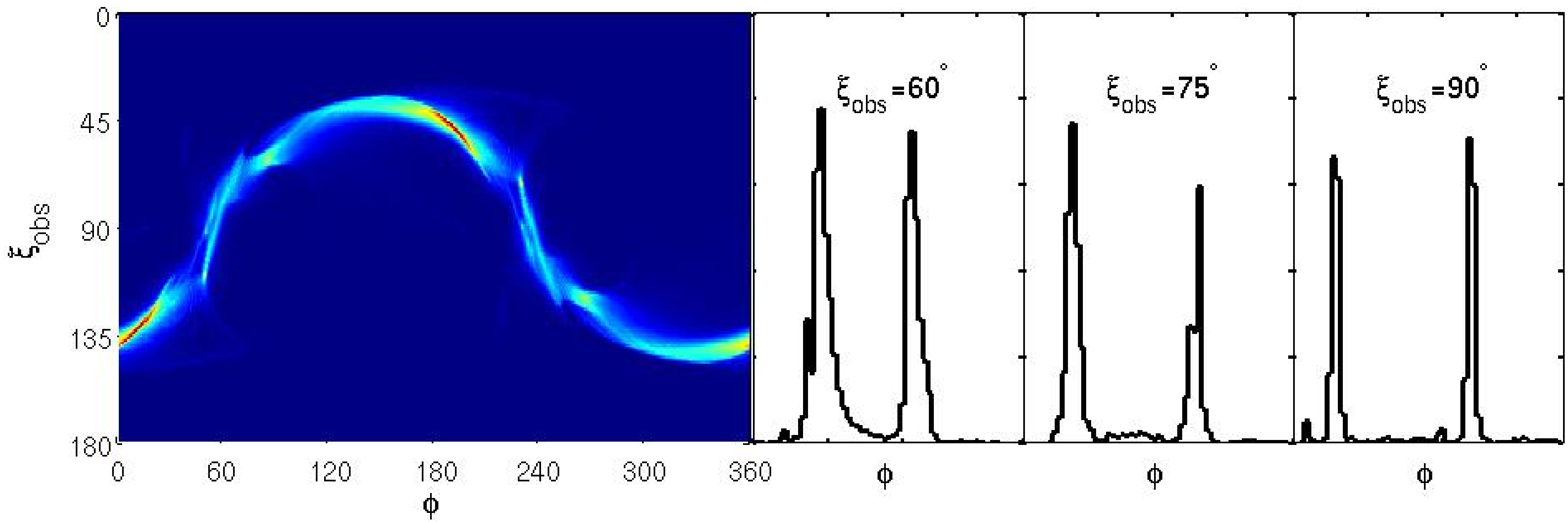
- Fermi LAT has discovered >100 Gamma-ray pulsars, many with double peaked light curves
- Main question: in what direction do gamma-ray emitting particles fly and beam?
- Reconnection heating in current sheets may be able to produce gamma ray emission (Bai & Spitkovsky '10, Petri '12, Petri & Kirk '05, Arka '12)
- MegaGauss B fields near light cylinder can produce comoving T ~ 100 MeV, boosted to GeV emission with modest $\gamma \sim 10$

Separatrix Layer Model (Bai & Spitkovsky '10), particles slipping down magnetic field and flying outwards radially in lab frame, emission from near sheet



$\alpha = 60^\circ$

Magnetic fields extrapolated to center of sheet, particles assumed to remember their trajectory from before entering sheet

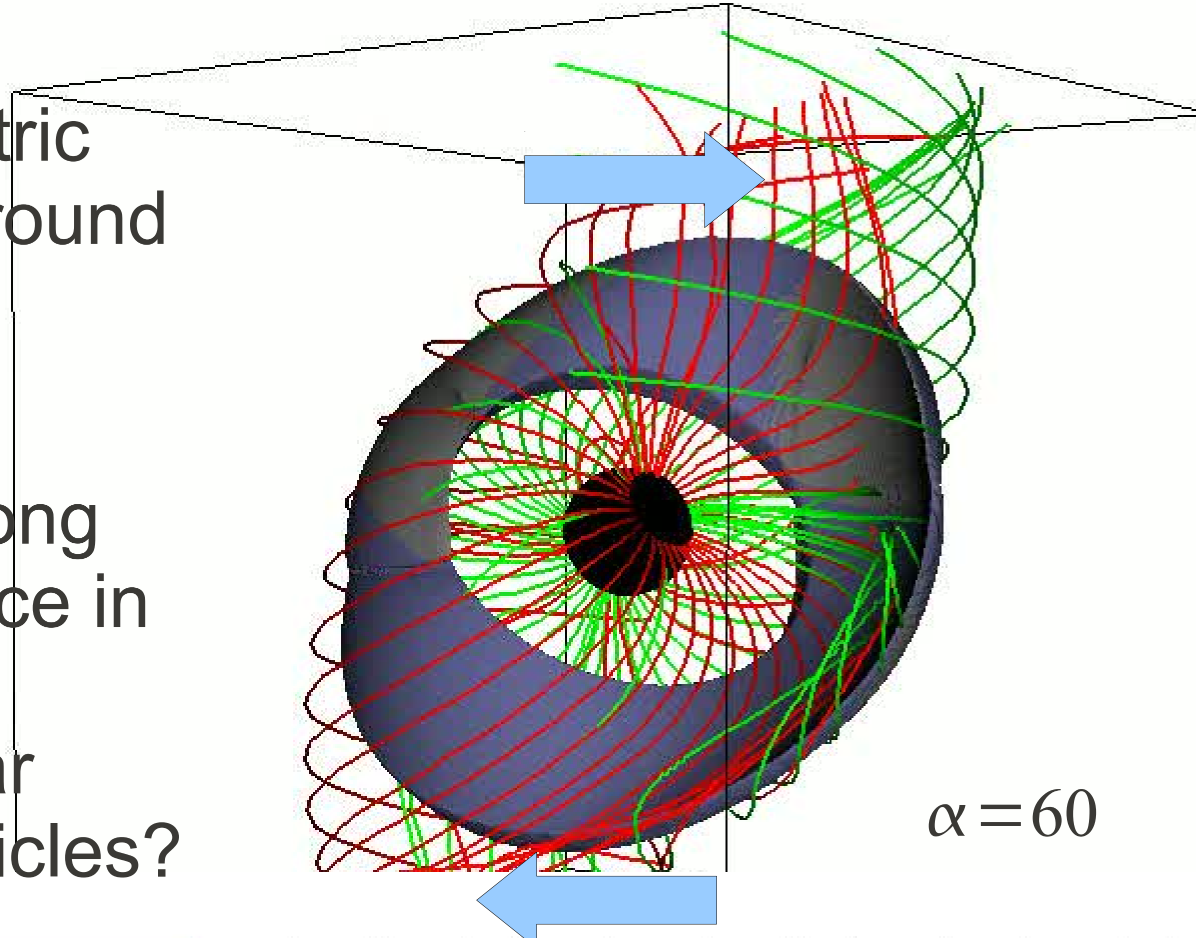


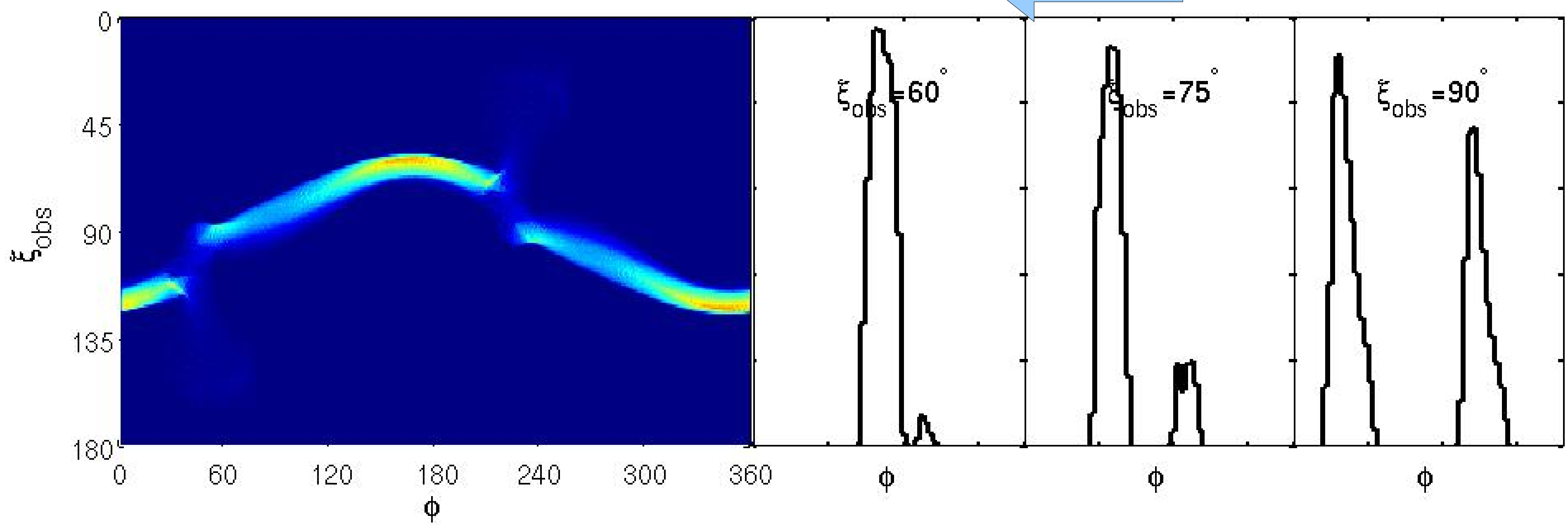
Gamma-ray pulsars

- Reconnection microphysics may modify particle momenta
- Advantage of our resistive force-free method is that we can spatially resolve current sheet (unlike in ideal force-free)
- Beam along $E_{||}$? Inwards streaming species won't give strong caustics and double-peaked light curves
- Should consider Lorentz force and relativistic dynamics?

Accelerating electric field circulating around sheet

Particles given strong kick by Lorentz force in current sheet, transferring angular momentum to particles?





Conclusions

- We have formulated a resistive force-free prescription to model plasma processes in pulsar magnetospheres
- More realistic physics opens new avenues of research:
  - We have produced quantitative models of intermittent pulsars
  - Resistivity naturally allows us to study high-energy emission from Gamma-ray pulsars

Open Questions

- What regulates plasma supply in pulsar magnetospheres?
- The importance of current sheet reconnection microphysics?
  - Localized reconnection in x-points may eject plasma relativistically in plasmoids
  - Particle In Cell simulation of current sheet structure would address momentum transfer to particles