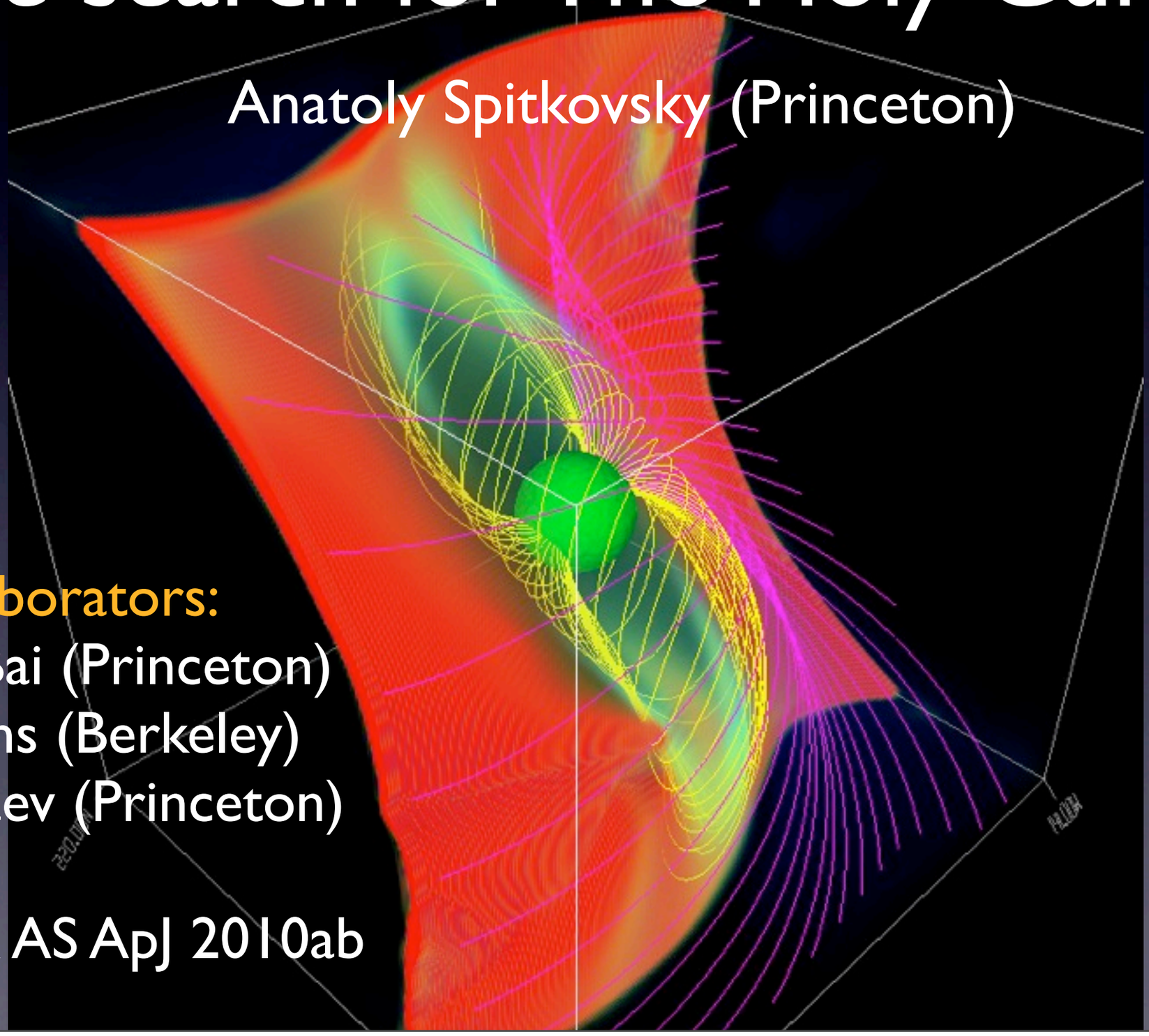
Pulsar Magnetosphere and the search for The Holy Current

Anatoly Spitkovsky (Princeton)

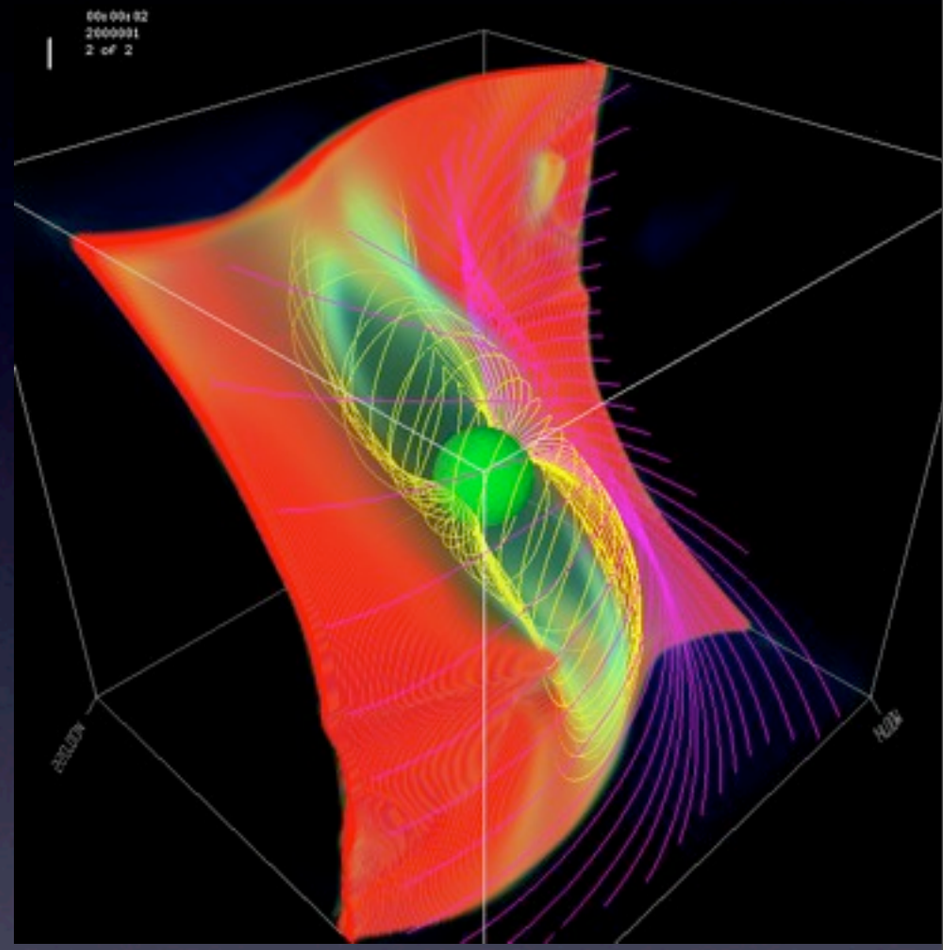


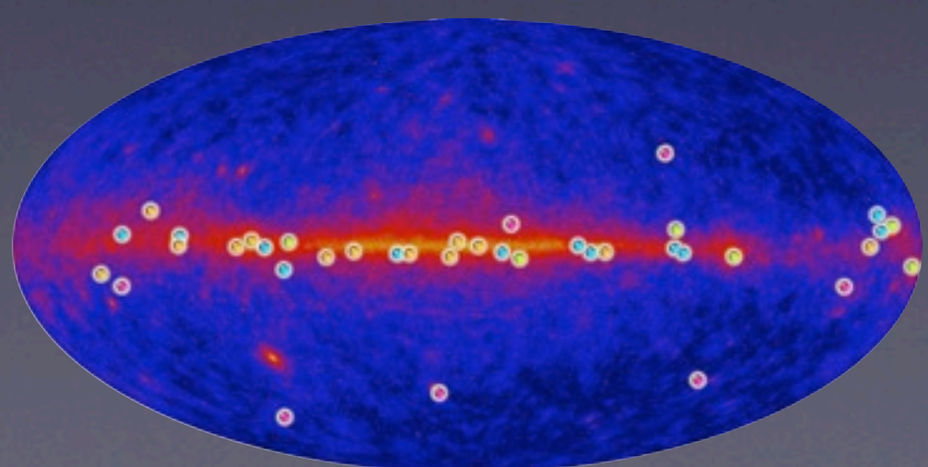
Collaborators:
Xuening Bai (Princeton)
Jon Arons (Berkeley)
Mike Belyaev (Princeton)

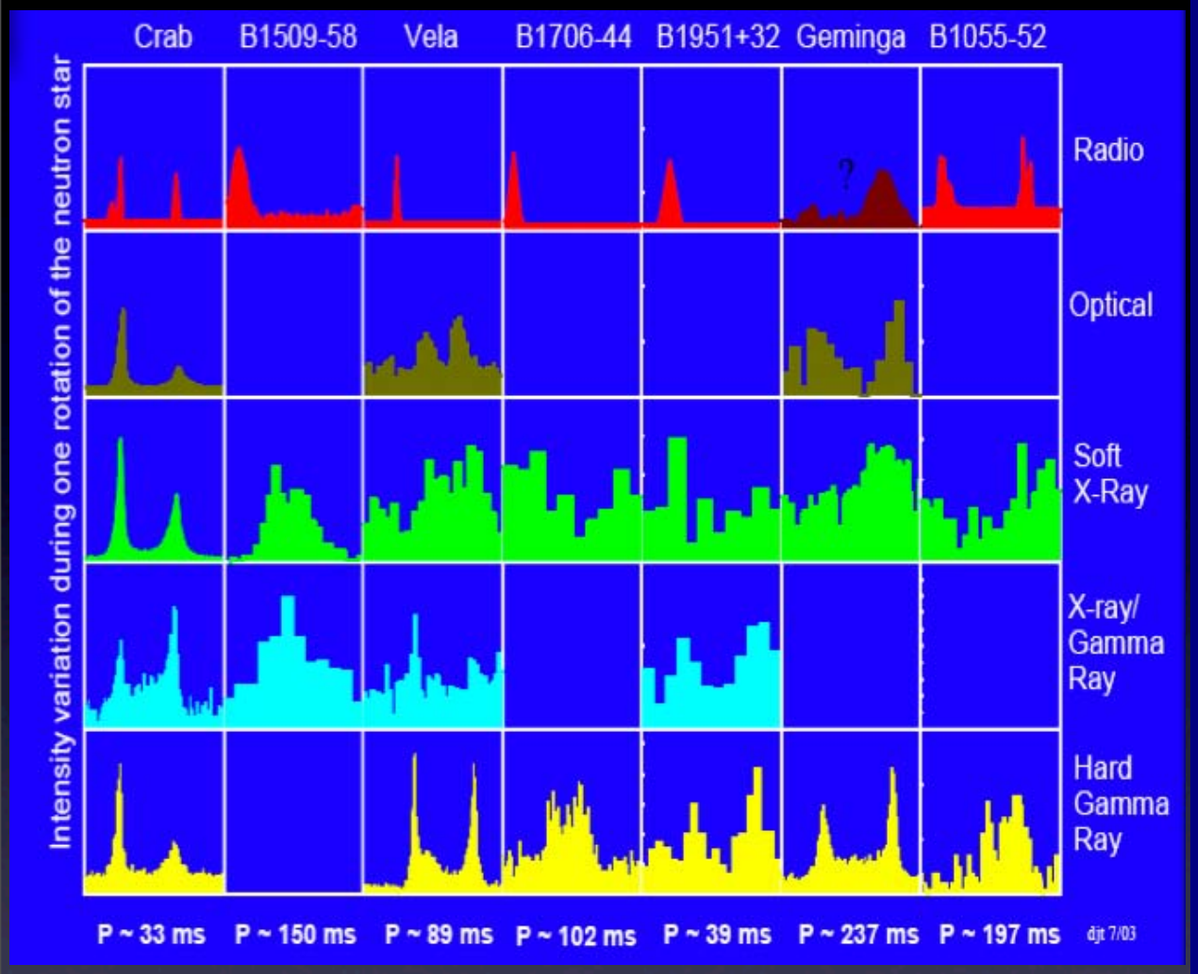
AS06; Bai & AS ApJ 2010ab

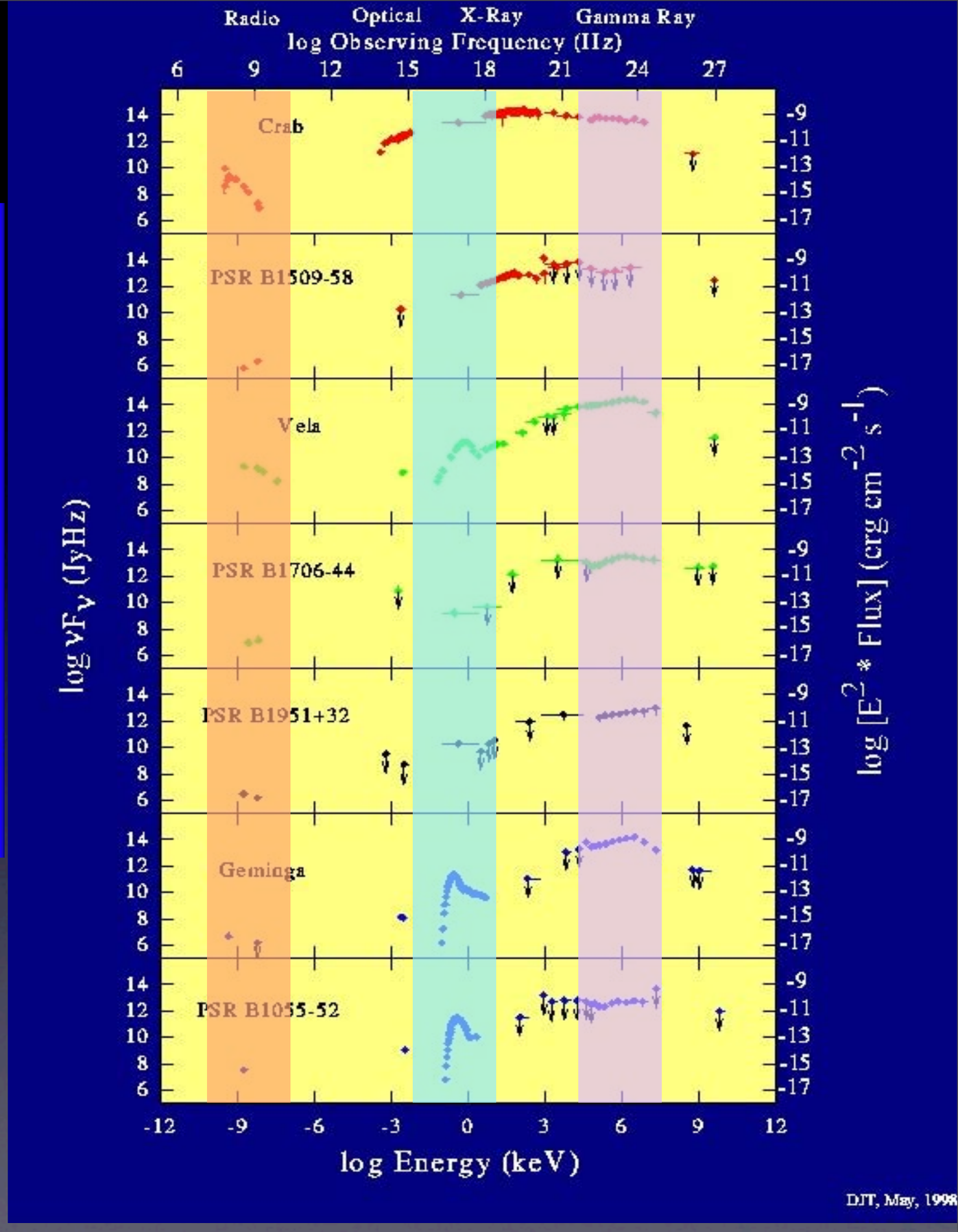
Outline

- Pulsar basics: energy source and plasma creation
  - Vacuum and charge-separated models
  - Dense-plasma models
- Observables: light curves
- Origin of high-energy emission









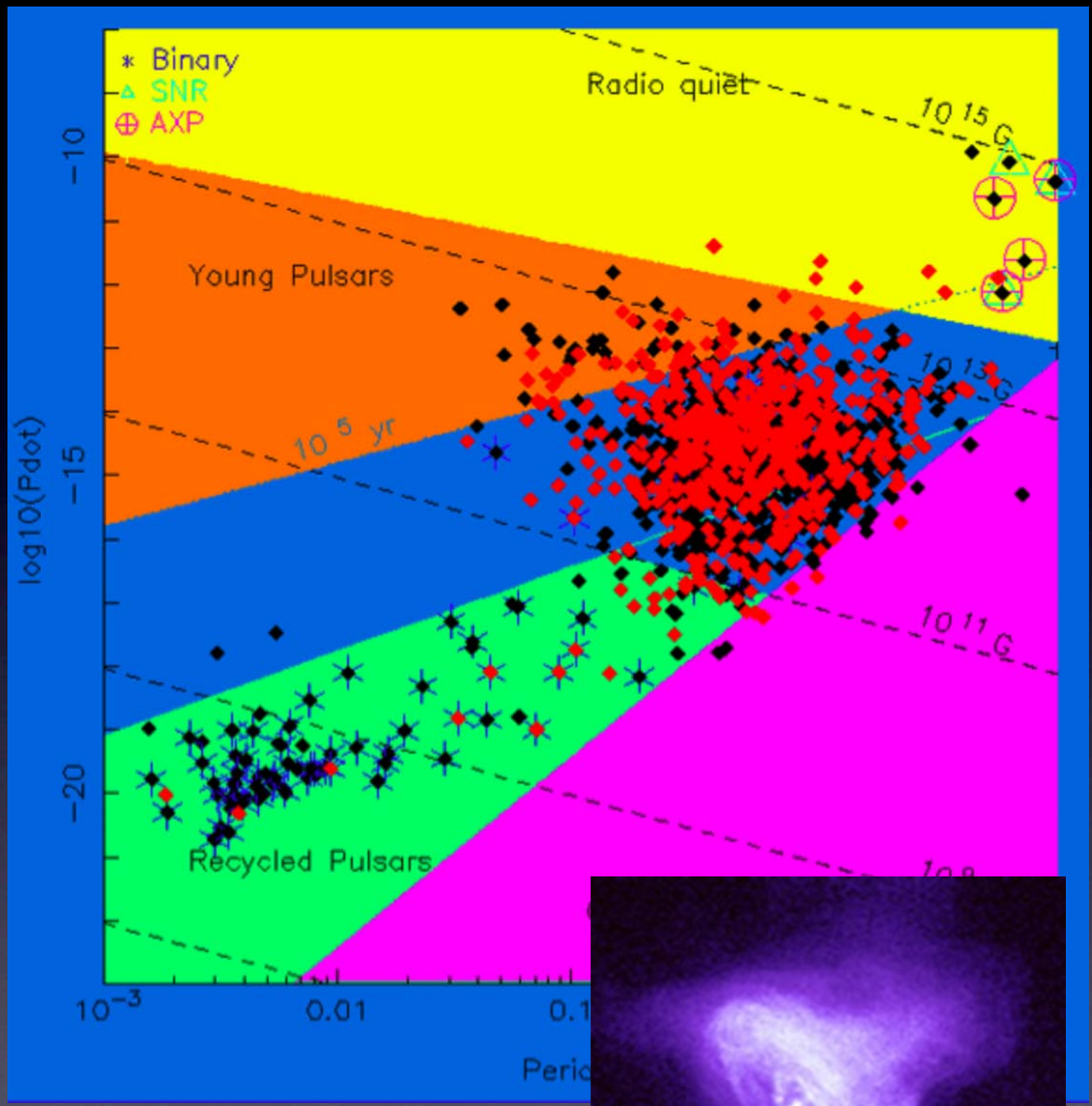
Most of the *observable* energy is coming out in gamma-rays

Main energy loss is invisible, but detectable -- pulsar spin-down

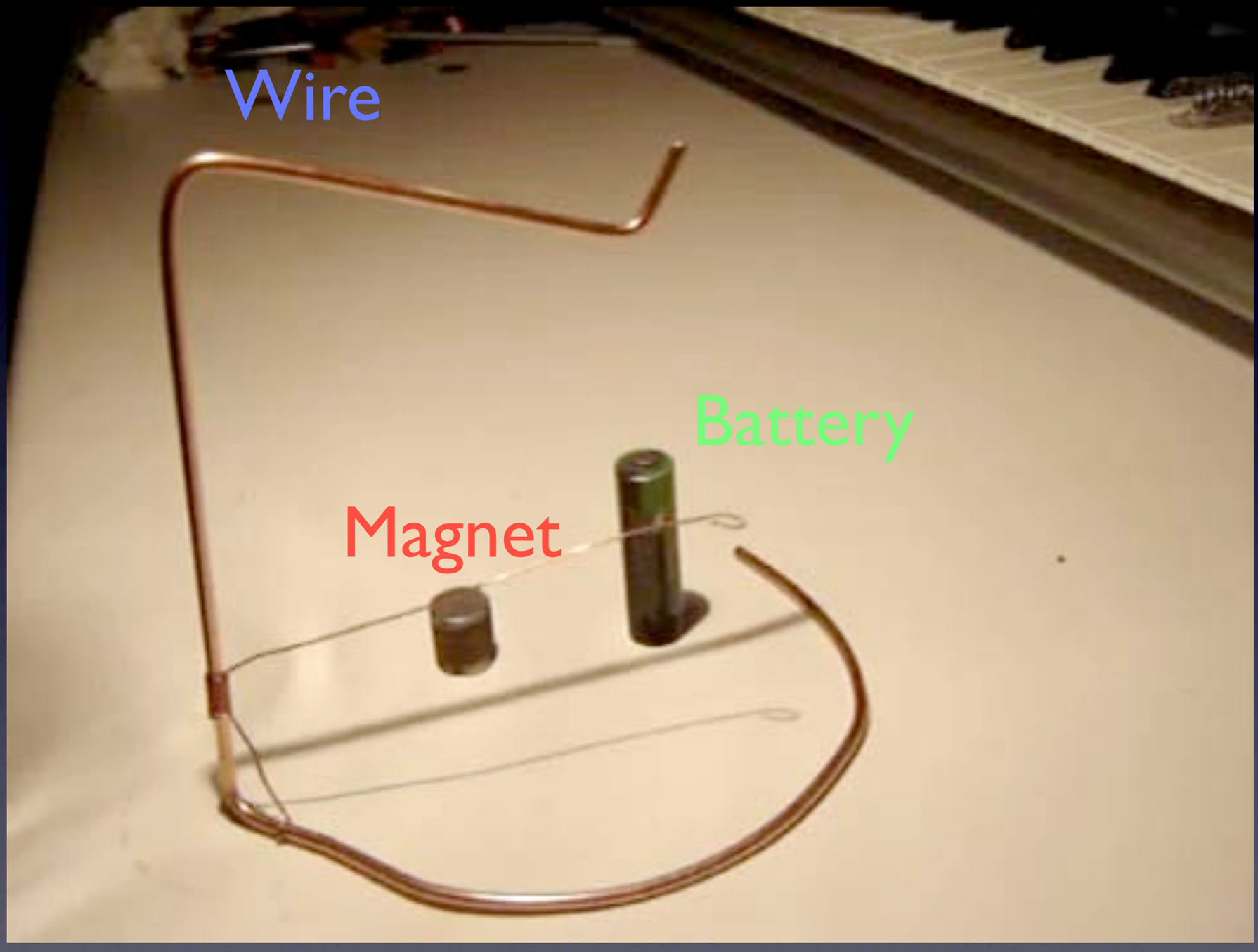
Leaves as magnetized wind (carrying Pointing flux)

The fact that γ-ray power reaches 10-s of percent of spin-down power implies that we are tapping the main magnetospheric currents

Need to understand how magnetosphere works

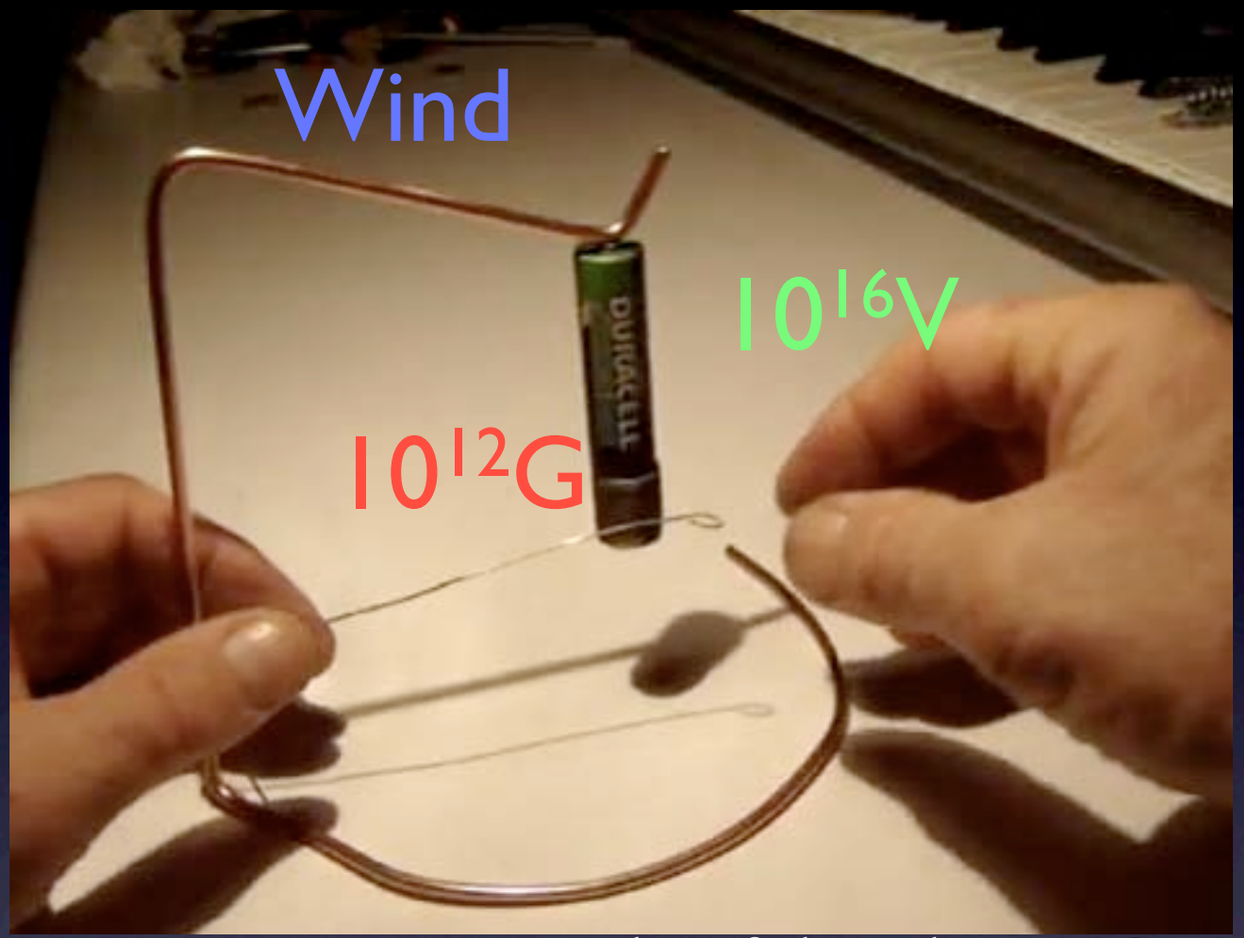


Pulsar physics @ home

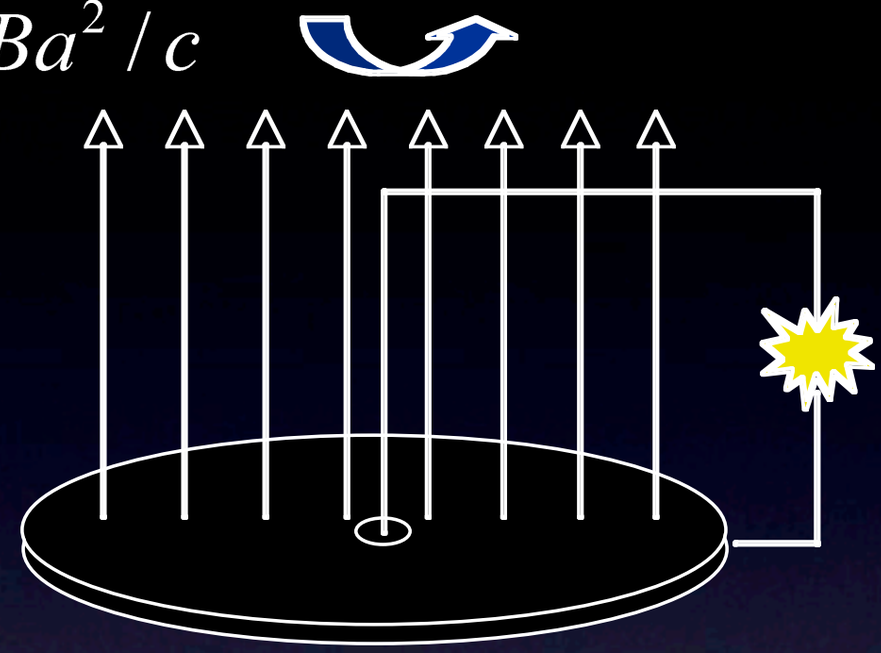


Unipolar induction

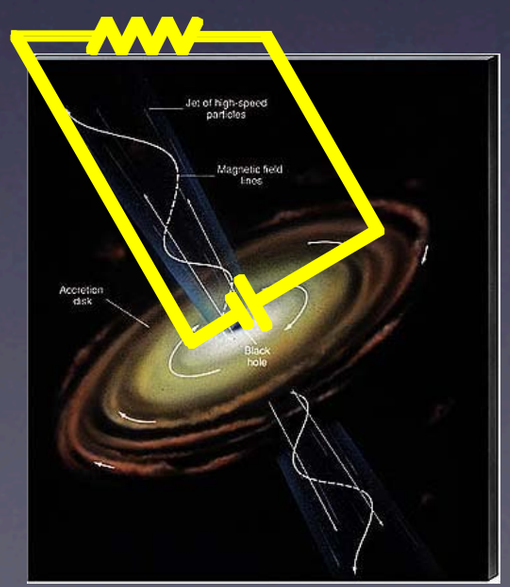
Pulsar physics in space



$\phi_0 = \Omega B a^2 / c$



Faraday disk
Unipolar induction



from R. Blandford

Rule of thumb: $V \sim \Omega\Phi$; $P \sim V^2 / Z_0 = I\,V$

Crab Pulsar

B ~ 10^{12} G, Ω ~ 200 rad s^{-1}, R ~ 10 km

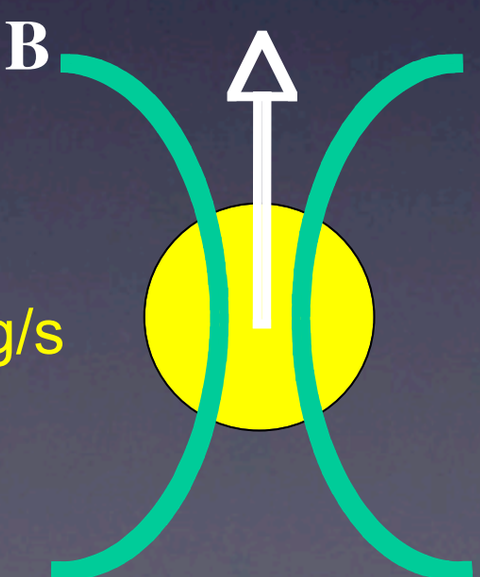
Voltage ~ 3 x 10^{16} V; I ~ 3 x 10^{14} A; P ~ 10^{38}erg/s

Magnetar

B ~ 10^{14} G; P ~ 10^{44}erg/s

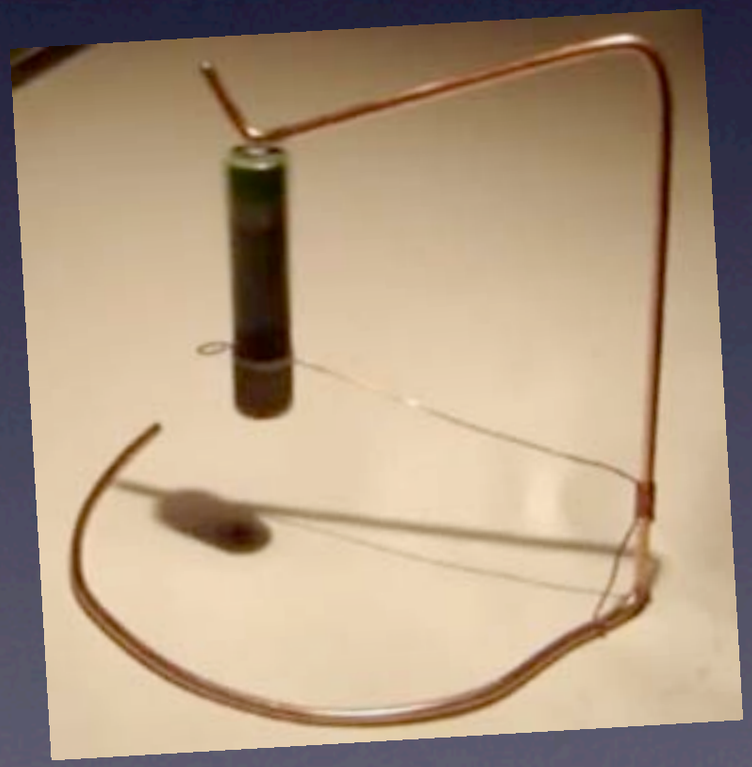
Massive Black Hole in AGN

B ~ 10^{4} G; P ~ 10^{46} erg/s



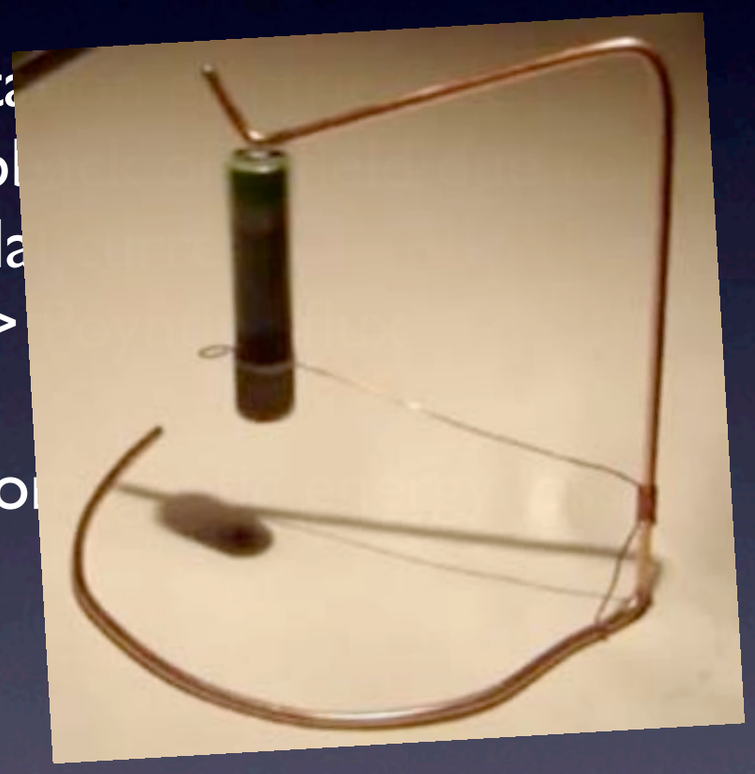
The goal of this talk:

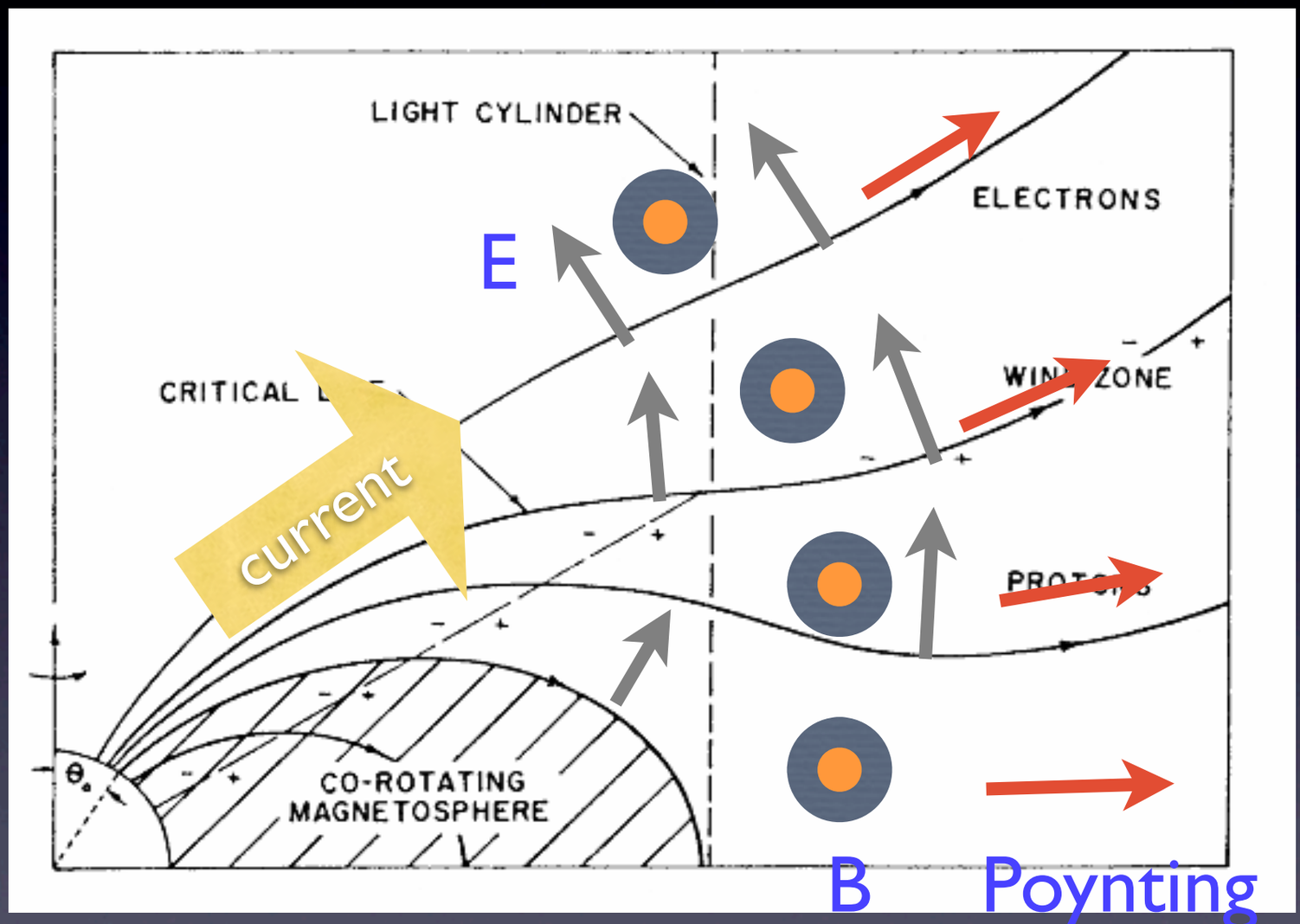
Understand how this circuit works
and what are its observational implications



Pulsars: energy loss

- Corota
- Sweepl
  poloida
- ExB ->
- Electro





Goldreich & Julian 1969

Radiator in Fermi band is tapping into the spin-down energy flux

Magnetospheric cartoon

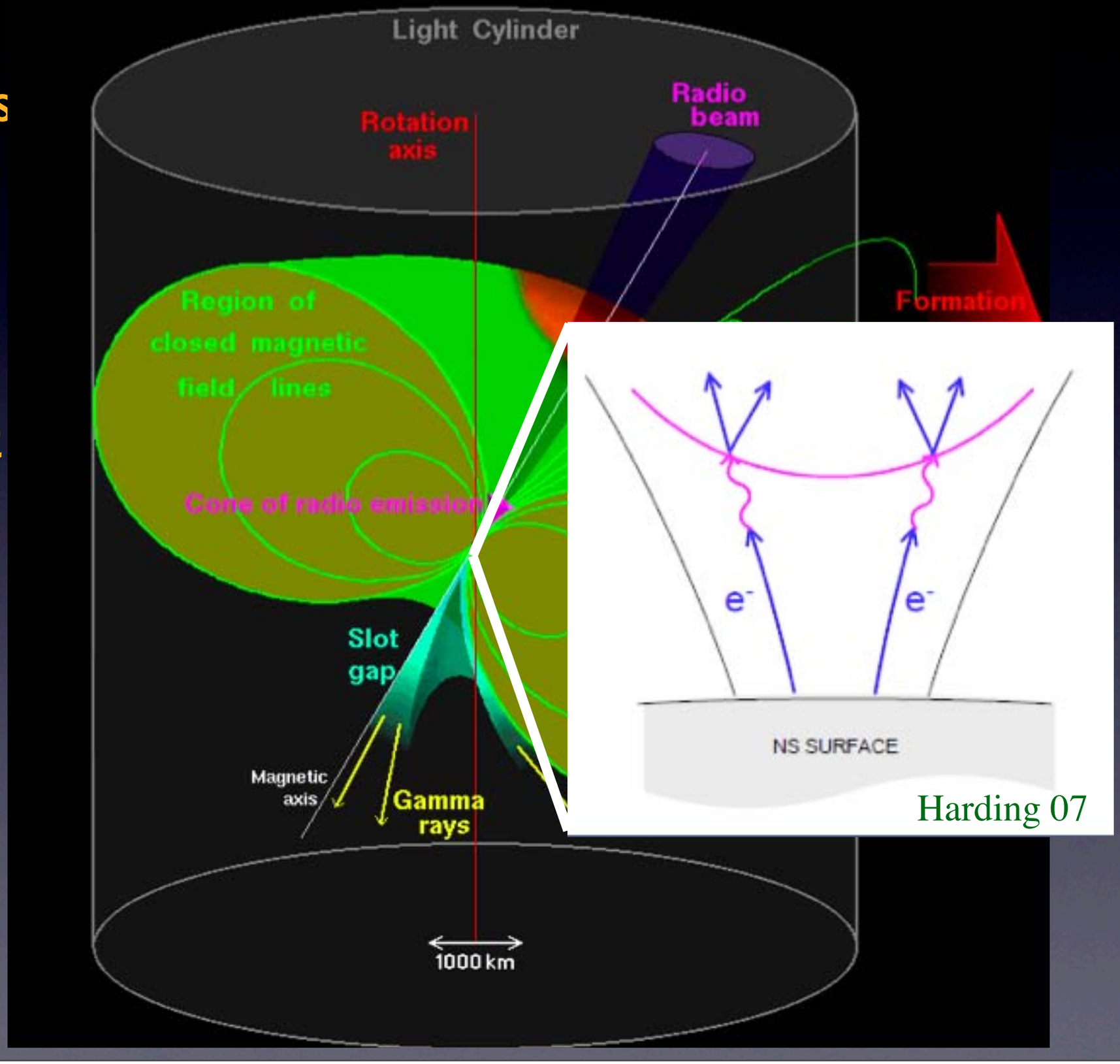
Open + closed (corotating) zones

Light Cylinder

Sweepback (part due to dB/dt, part due to current)

Current modifies the field

How does it spin down?



Harding 07

MODELING: TWO PATHS

Is there dense ($n >> n_{GJ}$) plasma in the magnetosphere?

No!

Charge separated magnetosphere

as in Golderich & Julian '69
Michel et al 1980s+

Yes, but not everywhere, and not always

Gapology

(Ruderman et al, Cheng et al, Romani, Harding)

Yes!

MHD / force-free

Contopoulos et al 1999, AS 06
+ many others

Magnetospheric models: two classes

vacuum

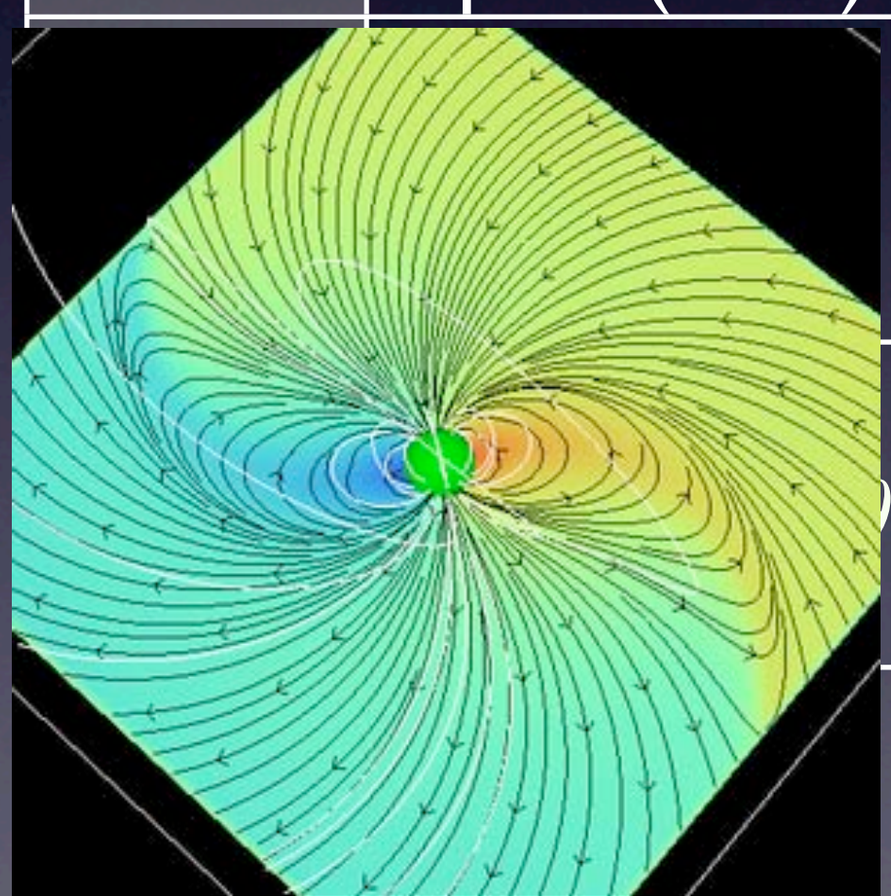
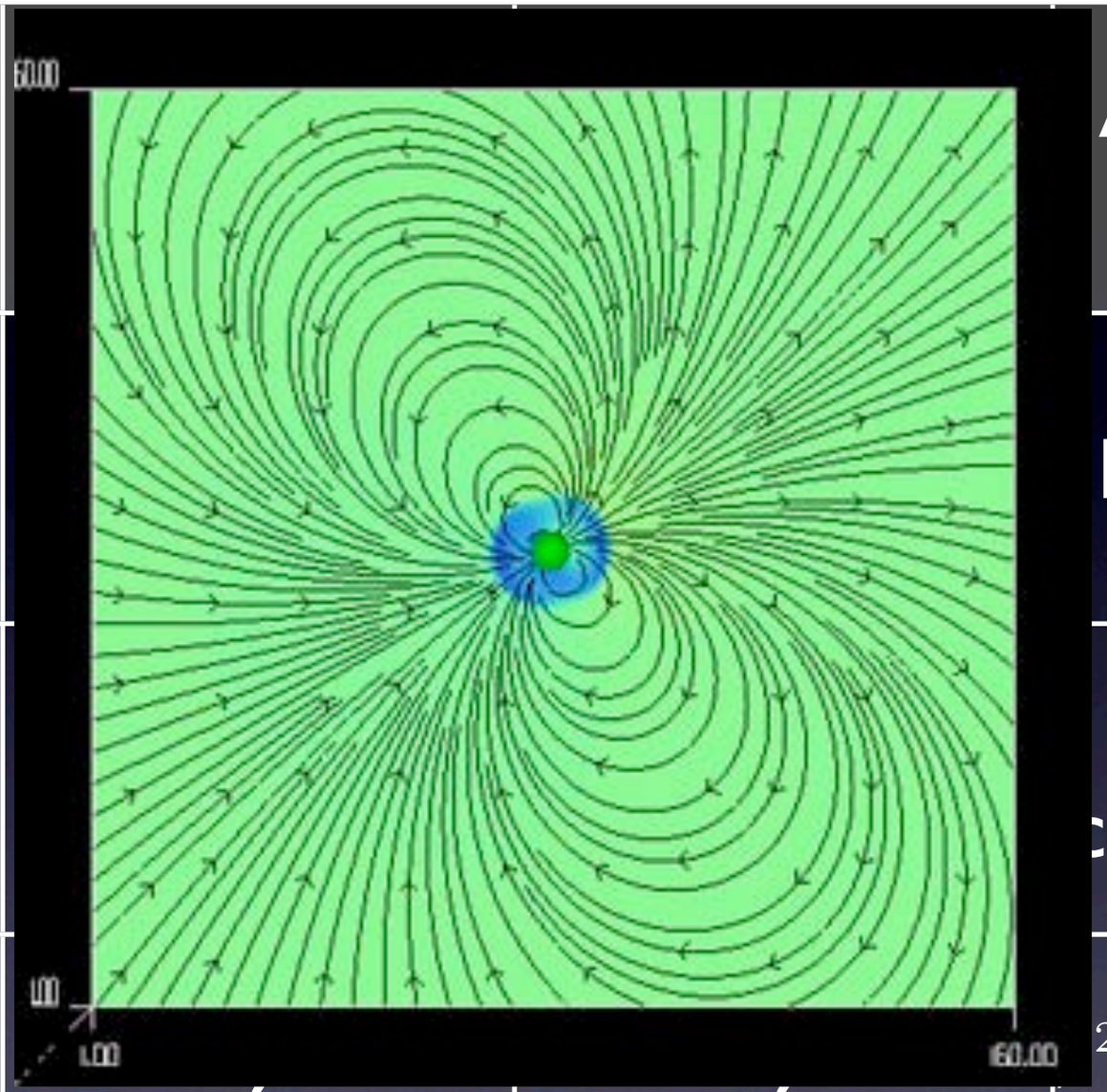
plasma + gaps

plasma

Magnetospheric models

	Vacuum	Space charge limited	Space charge limited+pairs	Abundant plasma
Field	Rotating vacuum dipole (RVD)	?	Assume RVD	Force-free
Acceleration	wild	gaps	Slot / Outer gaps	none / re-connection?
Spin down	$\frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\theta$	?	?	$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$
	Ostriker & Gunn 70	Goldreich & Julian 69 Michel 85, 00; AS +Arons 02	Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;	Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

Magnetospheric models

	Vacuum	Abundant plasma
Field	Rotating vacuum dipole (RVD)	Force-free
		
	none / re-connection?	
	?	?
	$\frac{2\Omega^4}{c^3}(1+\sin^2\theta)$	
	Goldreich & Julian 69 Michel 85, 00; AS +Arons 02	Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;
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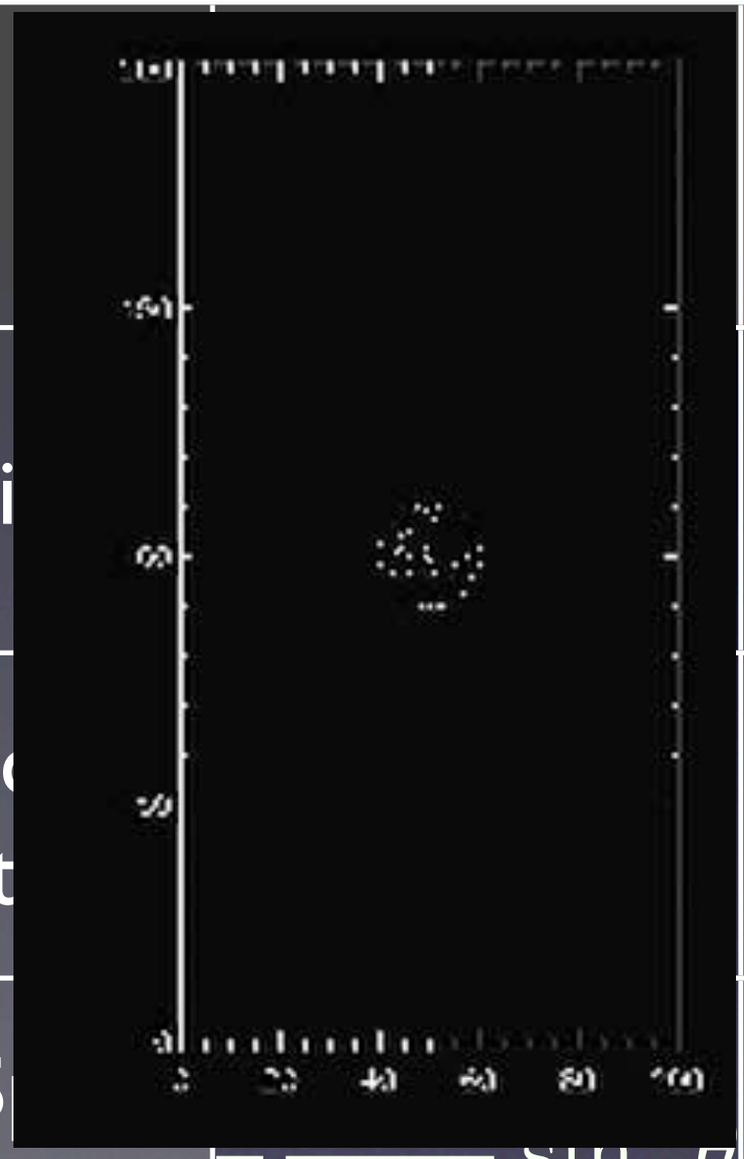
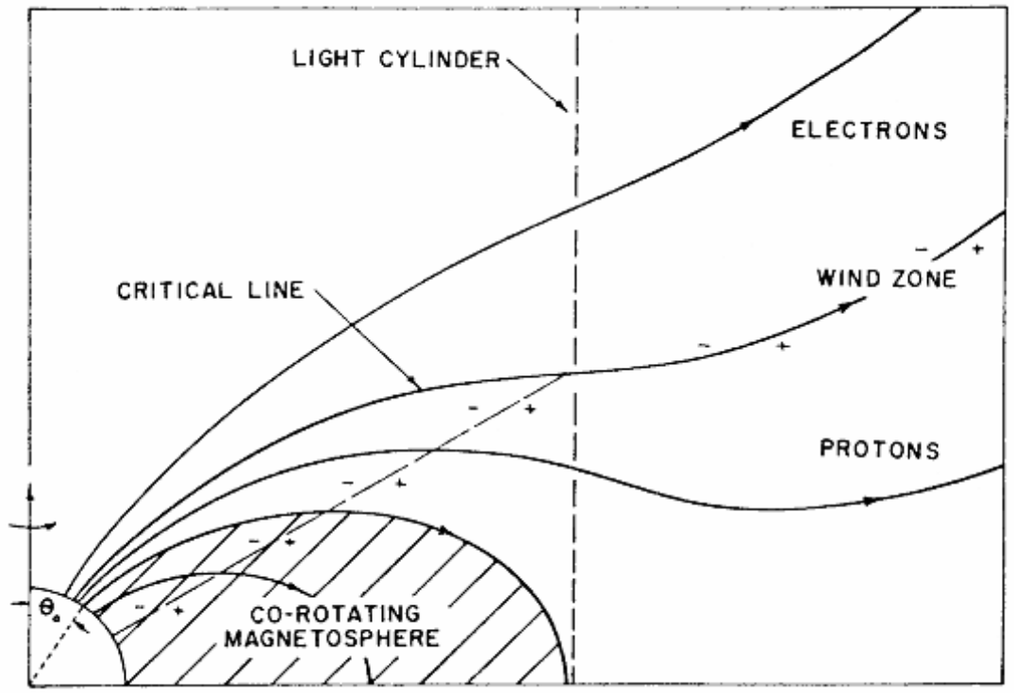
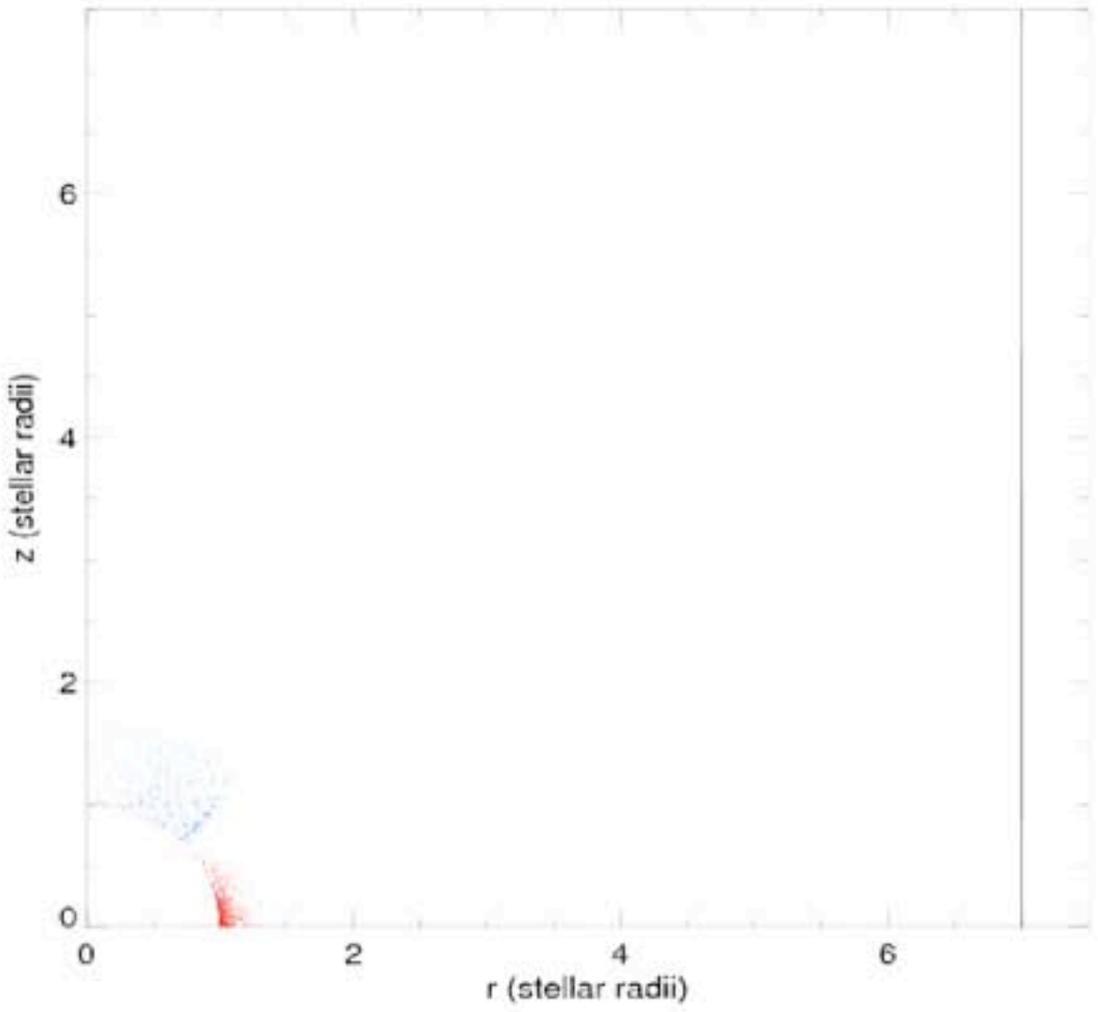
Magnetospheric models

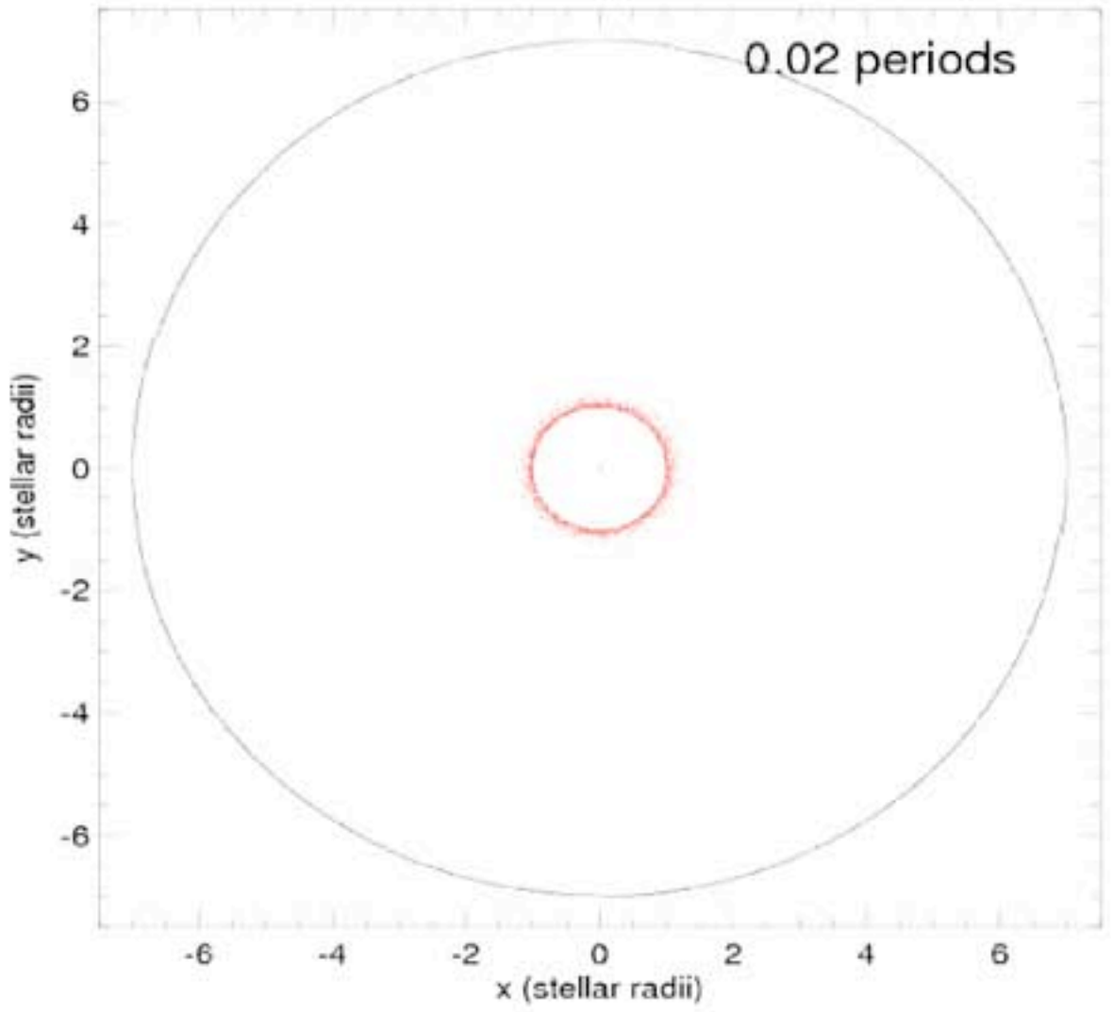




Fi		Space charge limited	?	
Ac at		gaps	gaps	none / re-connection?
S down	$\frac{}{3}\frac{}{c^3}\sin^2\theta$	?	?	$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$
		Goldreich & Julian 69 Michel 85, 00; AS +Arons 02	Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;	Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

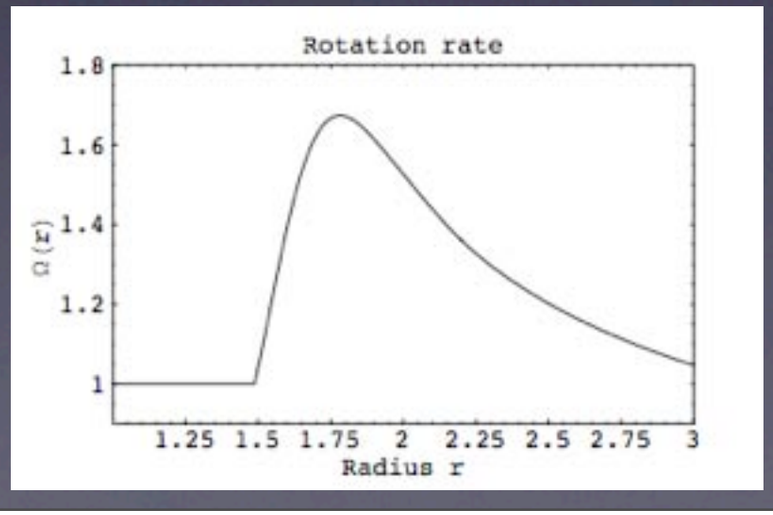
Magnetospheric models





Disk-Torus Electrosphere
Michel et al `84-01

Diocotron instability
AS & Arons 02;
Petri et al 02-



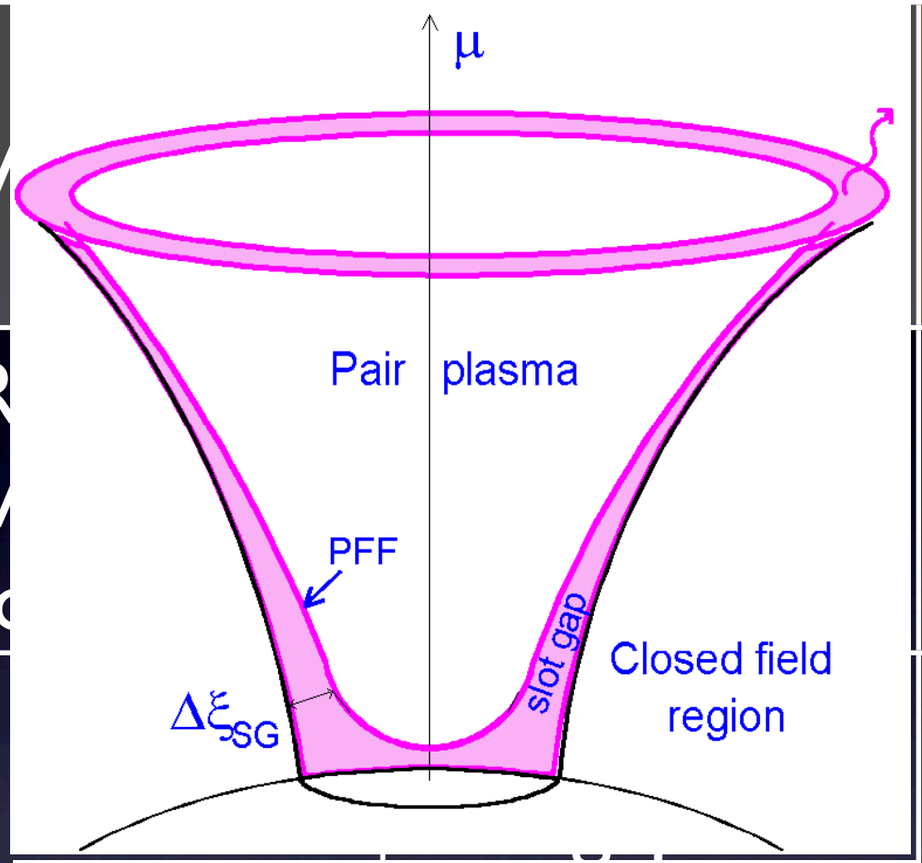
Petri et al 02

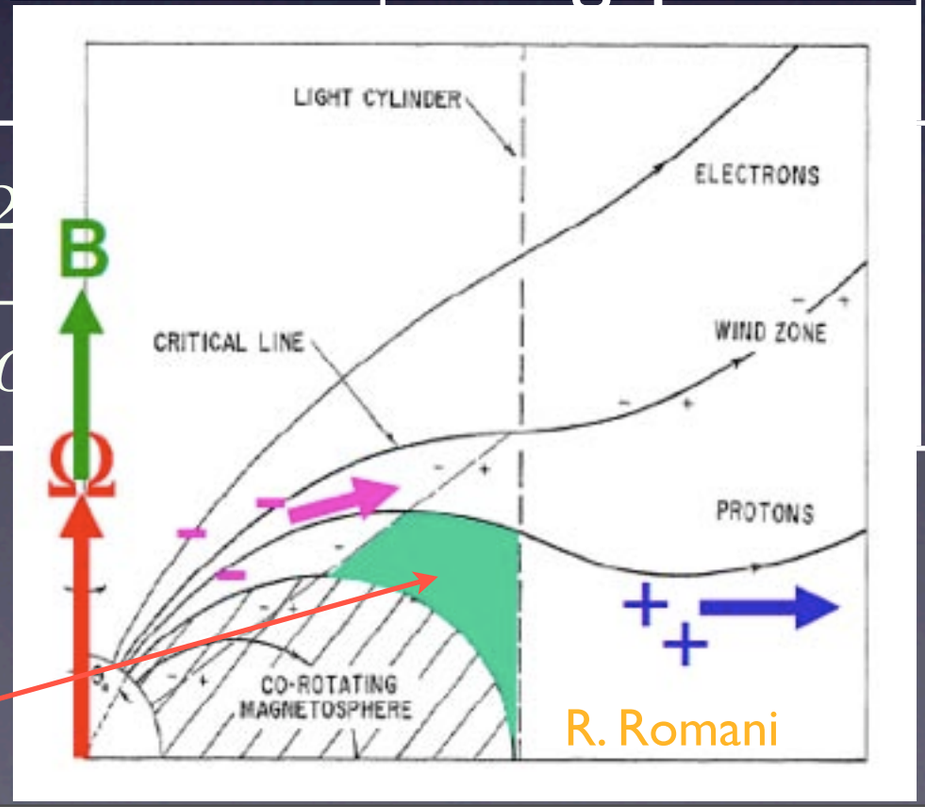
Belyaev & AS, in prep

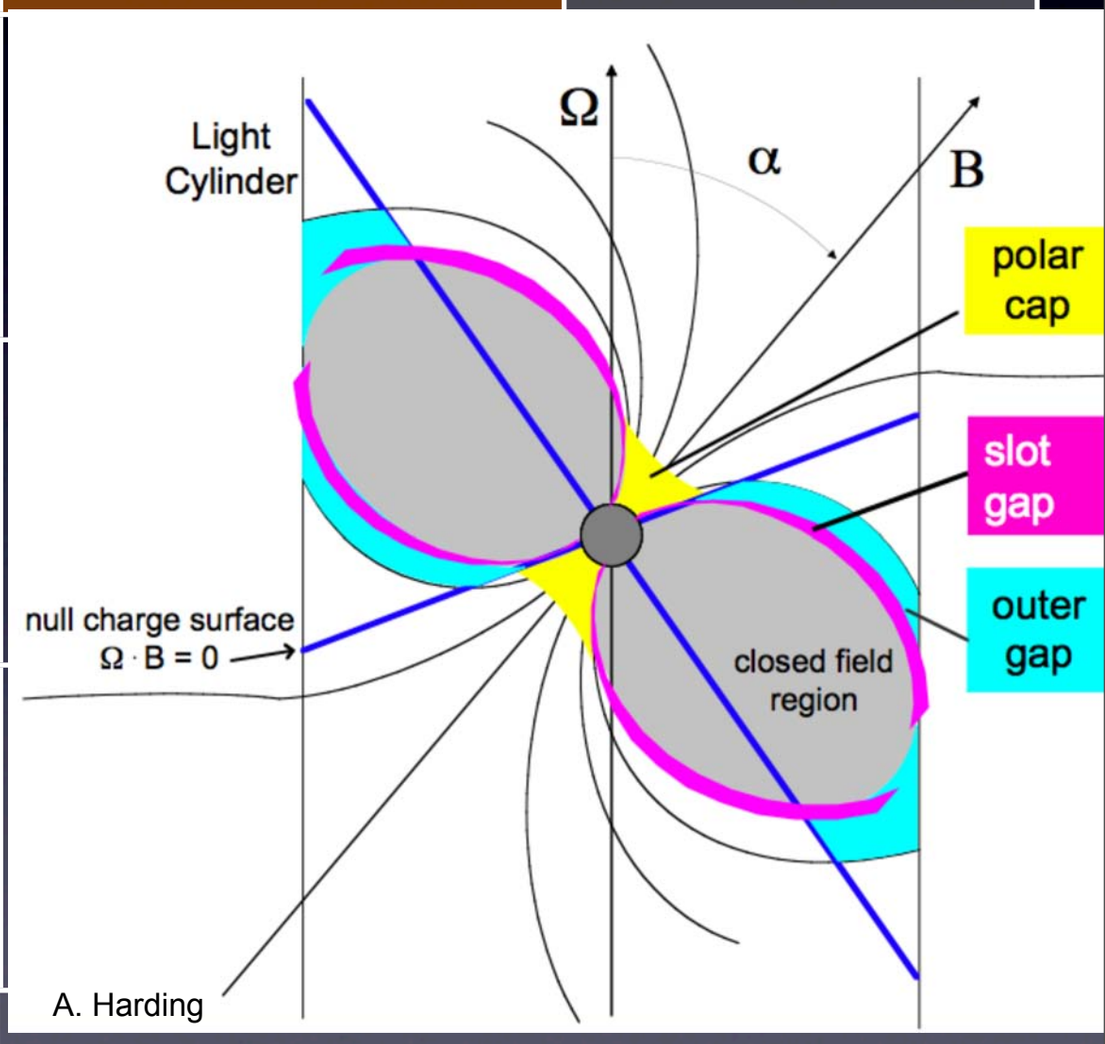
Possibility of radial current
Electrospheres are a curiosity
Add pairs?

Magnetospheric models

	V	Space charge limited+pairs	Abundant plasma
Field	R dipo		
Acceler ation			
Spin down	$\frac{2}{3}\frac{\mu^2}{c}$		







Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;

Holloway's paradox

Slot/Outer gaps:

Linear accelerators with $E_{||}$ due to charge starvation

Imply a charge-separated background flow, even though pairs are thought to be created in the gaps.

These are local models, decoupled from the global magnetosphere; use vacuum field.

But they provide a way to calculate acceleration and emission!

Polar gap may be more physics-based

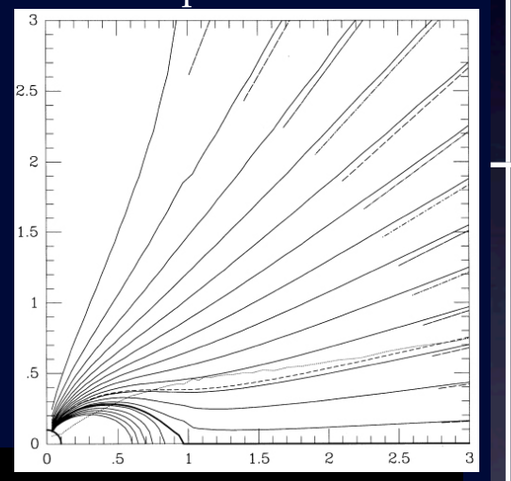
Pulsar wind nebulae suggest plasma densities >> GJ charge density in the magnetosphere.

Magnetospheric models

- NS is immersed in massless conducting fluid. Includes plasma currents.
- Force-free evolution. B field dominates. Inertia is small:

$$mn\frac{\partial \gamma \vec{v}}{\partial t} = \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} \approx 0$$

Contopoulos et al 1999



"Pulsar equation" (Michel '73; Scharleman &Wagoner '73):

$$\frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial z^2} - \frac{1+x^2}{x(1-x^2)}\frac{\partial\Psi}{\partial x} = -\frac{I(\Psi)I'(\Psi)}{R_L^2(1-x^2)}$$

$$\left.\begin{aligned} \frac{1}{c}\frac{\partial E}{\partial t} &= \nabla\times\vec{B} - \frac{4\pi}{c}\vec{j} \\ \frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla\times\vec{E} \\ \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} &= 0 \\ \frac{\partial}{\partial t}\vec{E}\cdot\vec{B} &= 0 \end{aligned}\right\} \quad \vec{j} = \frac{c}{4\pi}(\nabla\cdot\vec{E})\frac{\vec{E}\times\vec{B}}{B^2} + \frac{c\vec{B}(\vec{B}\cdot\nabla\times\vec{B} - \vec{E}\cdot\nabla\times\vec{E})}{4\pi B^2}$$

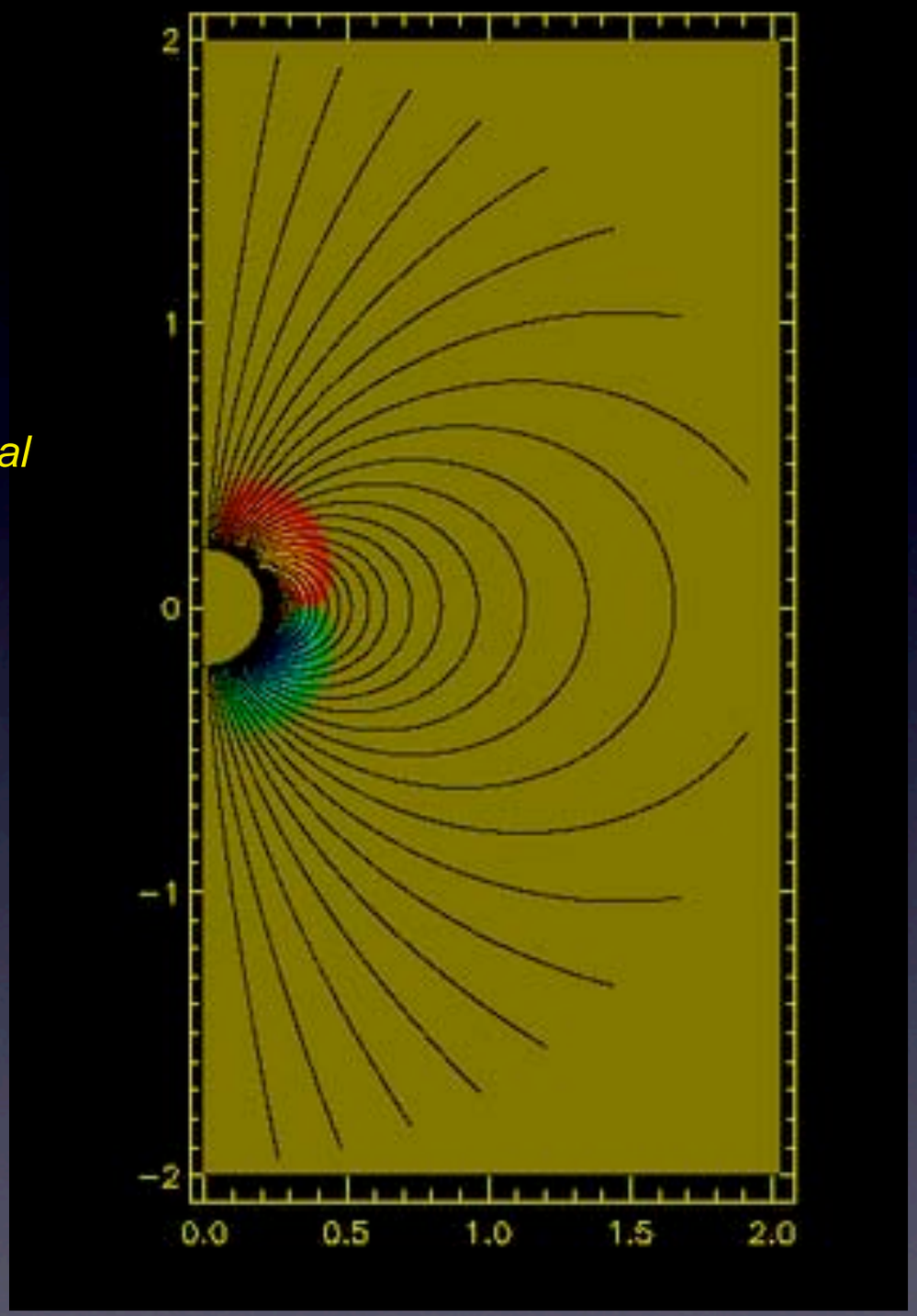
Perpendicular current — *Parallel current*

Gruzinov 99, Blandford 01

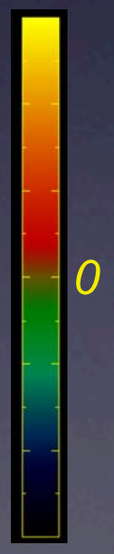
Hyperbolic equations, can be evolved in time

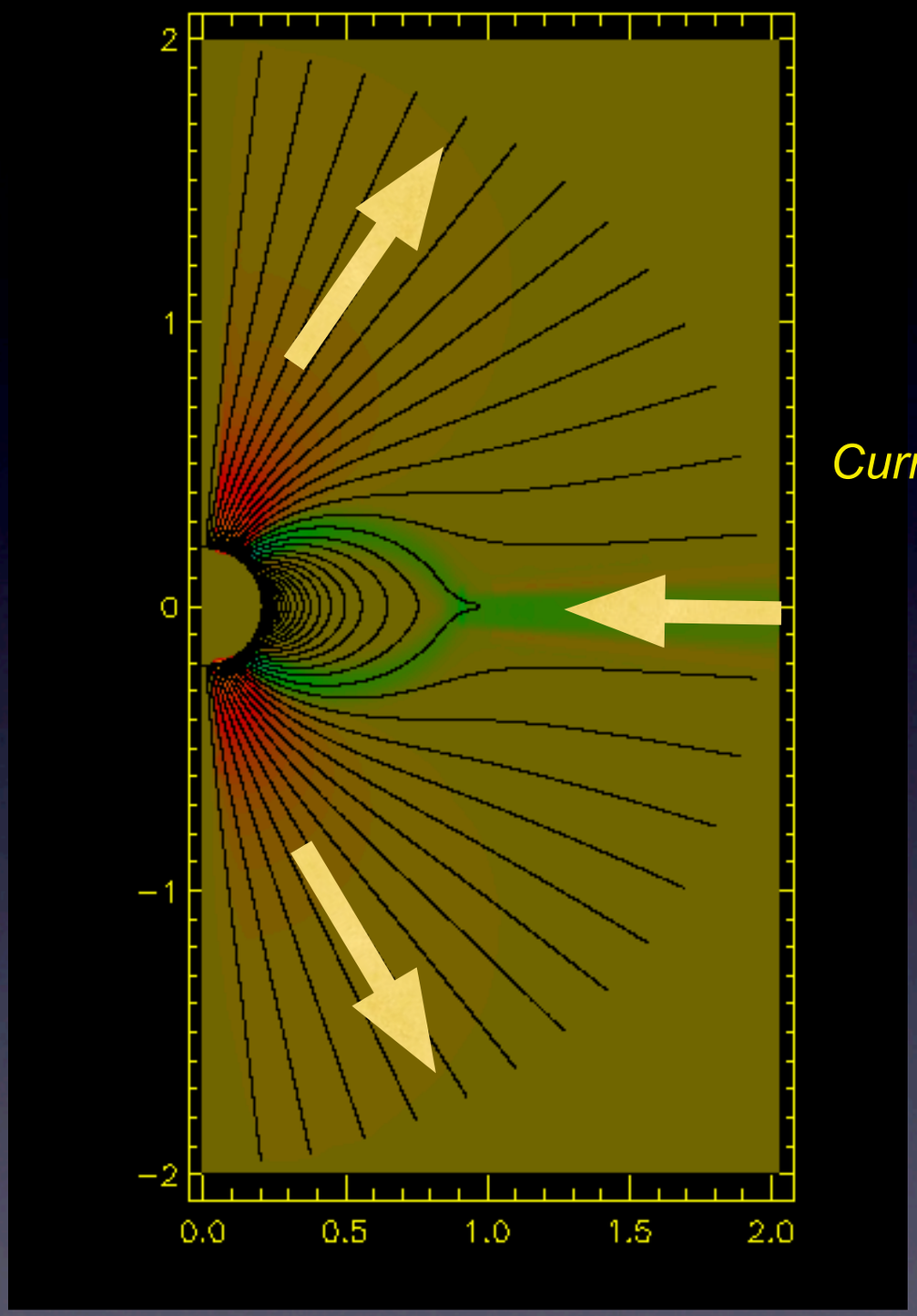
Abundant plasma	Force-free	none / re-connection?
	$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$	Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

Aligned rotator: plasma magnetosphere



Toroidal field

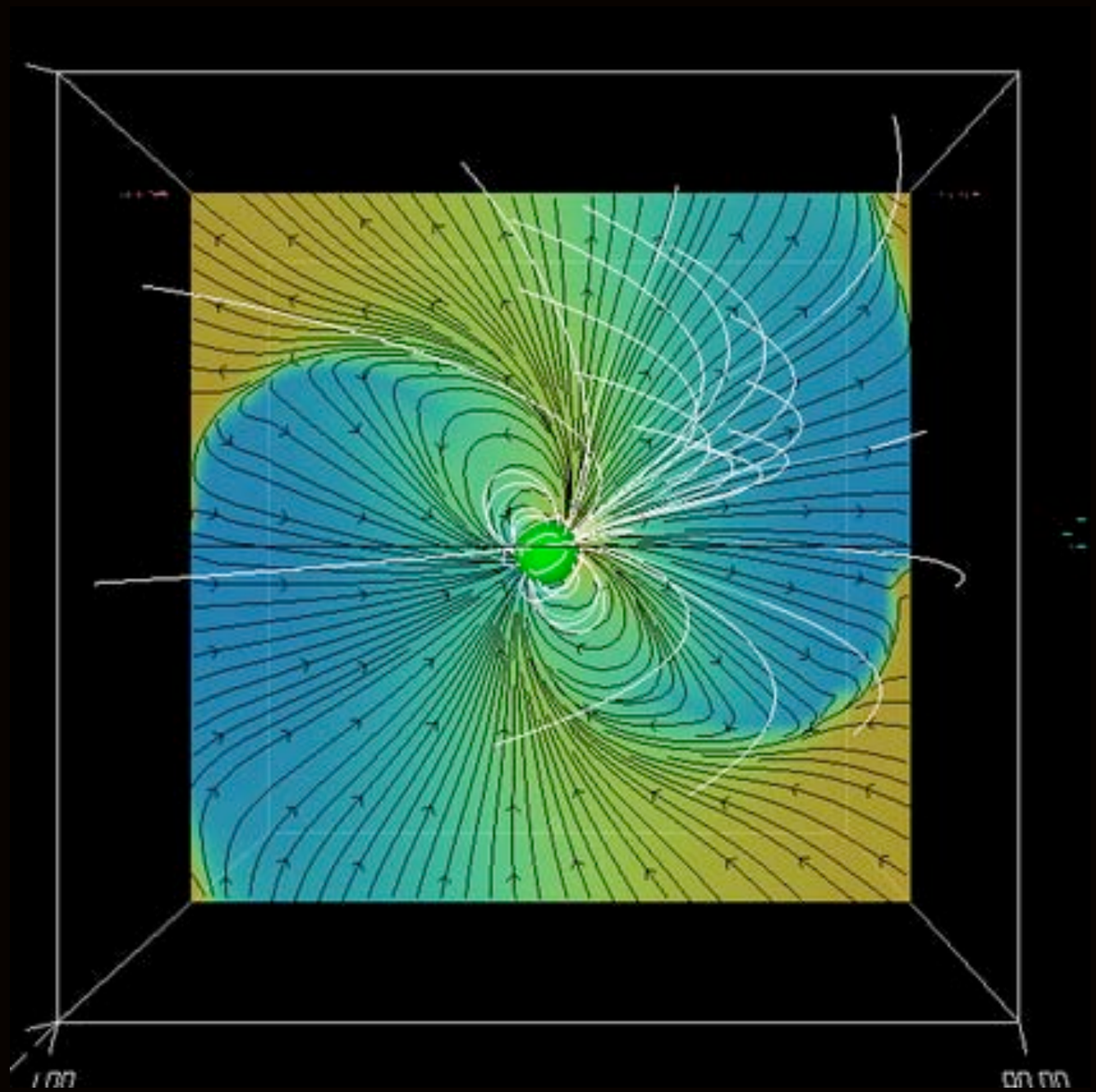




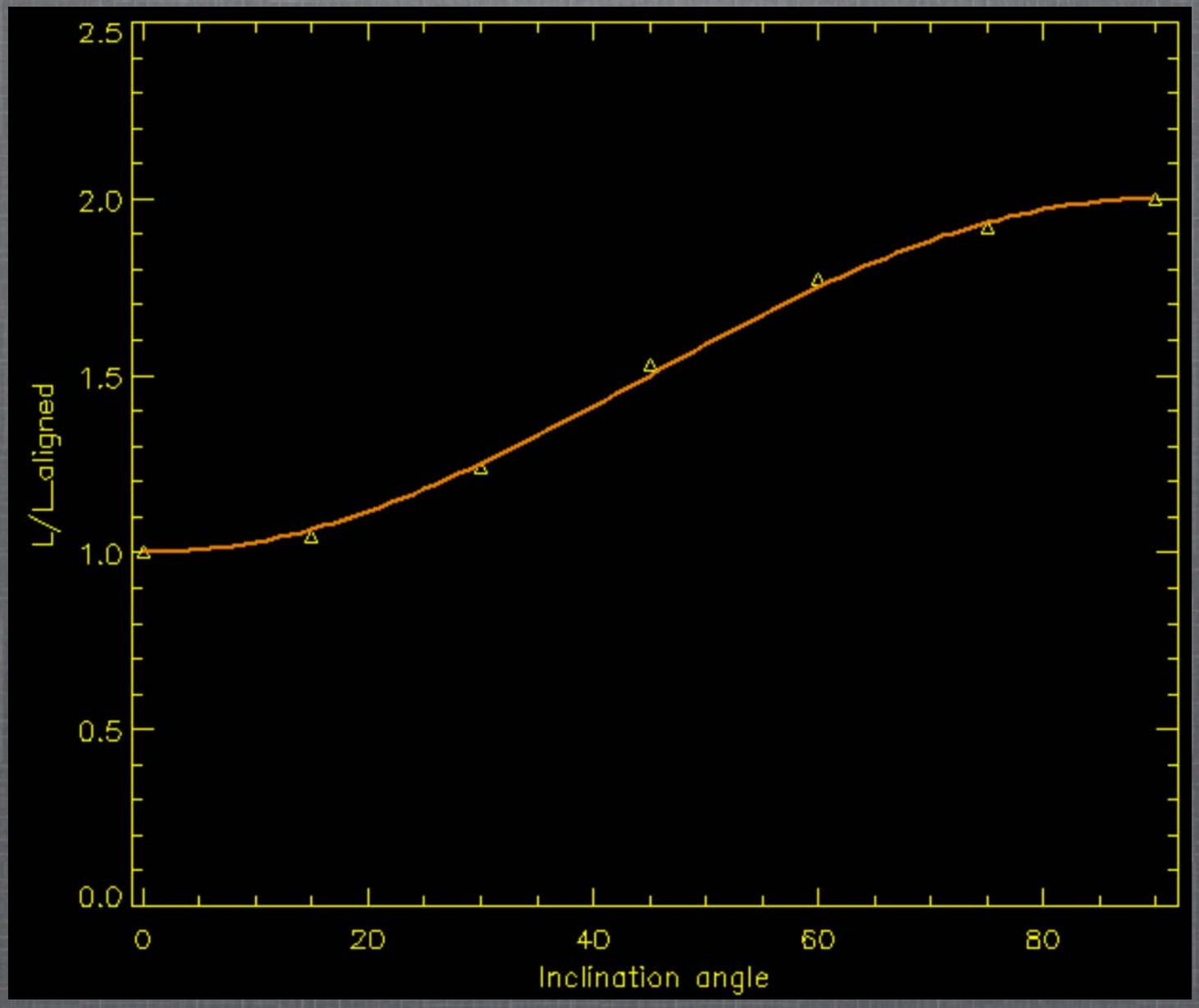
Current

Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting.

Oblique rotator: force-free



SPIN-DOWN POWER



Spin-down of oblique rotator

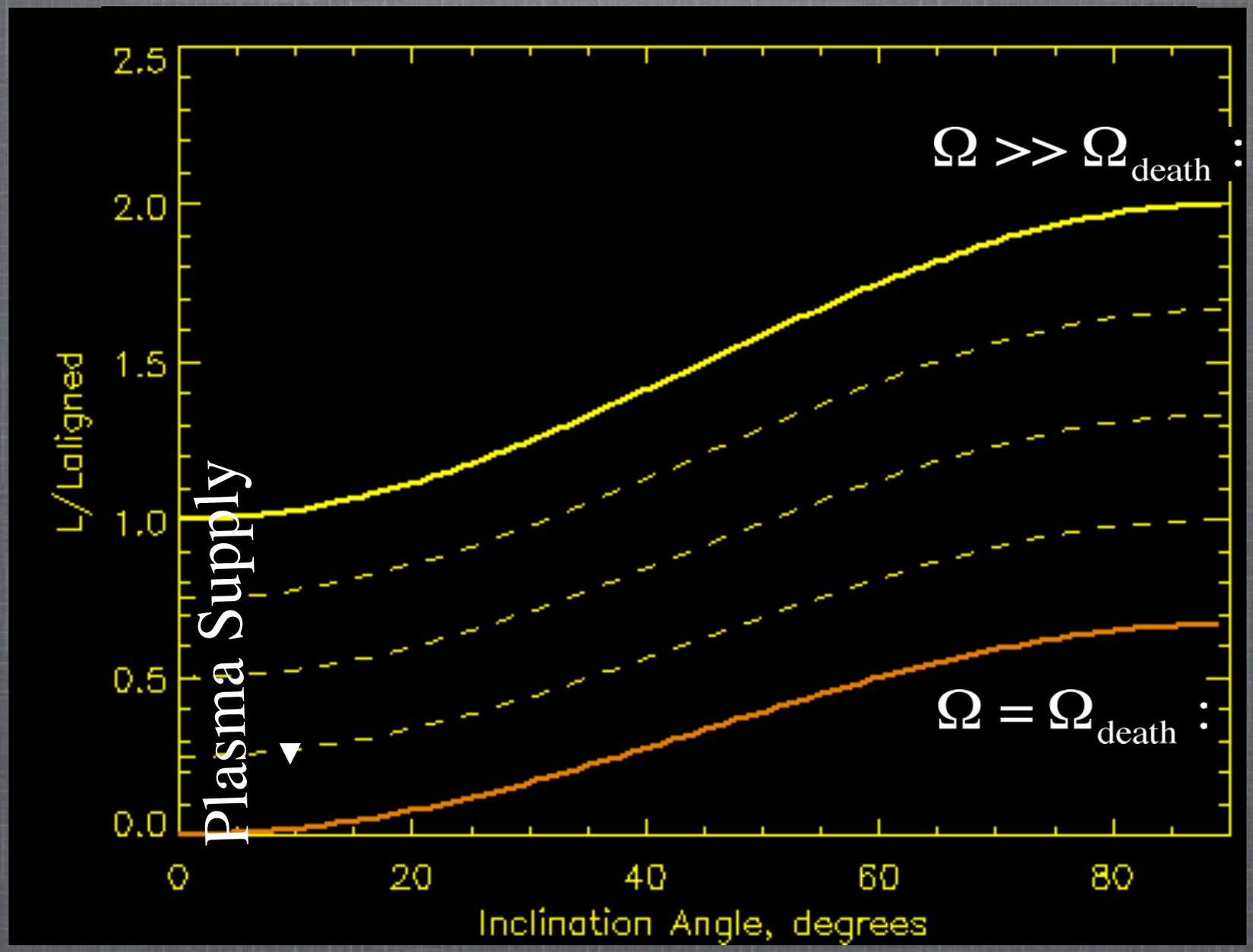
NB: this is a fit!

$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3}(1 + \sin^2\theta)$$

$$\dot{E}_{vac} = \frac{2}{3}\frac{\mu^2 \Omega^4}{c^3}\sin^2\theta$$

A.S.'06

SPIN-DOWN POWER



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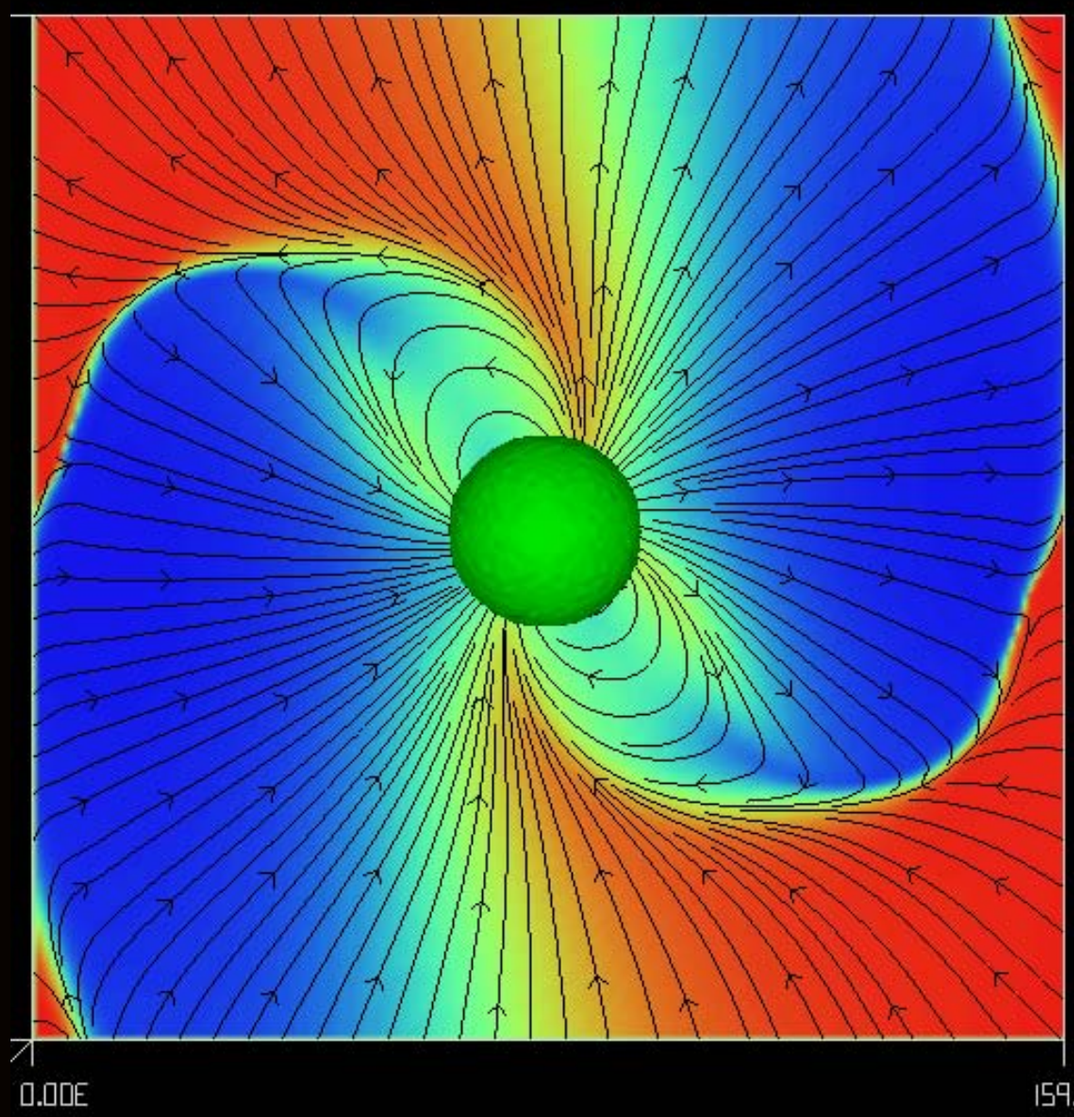
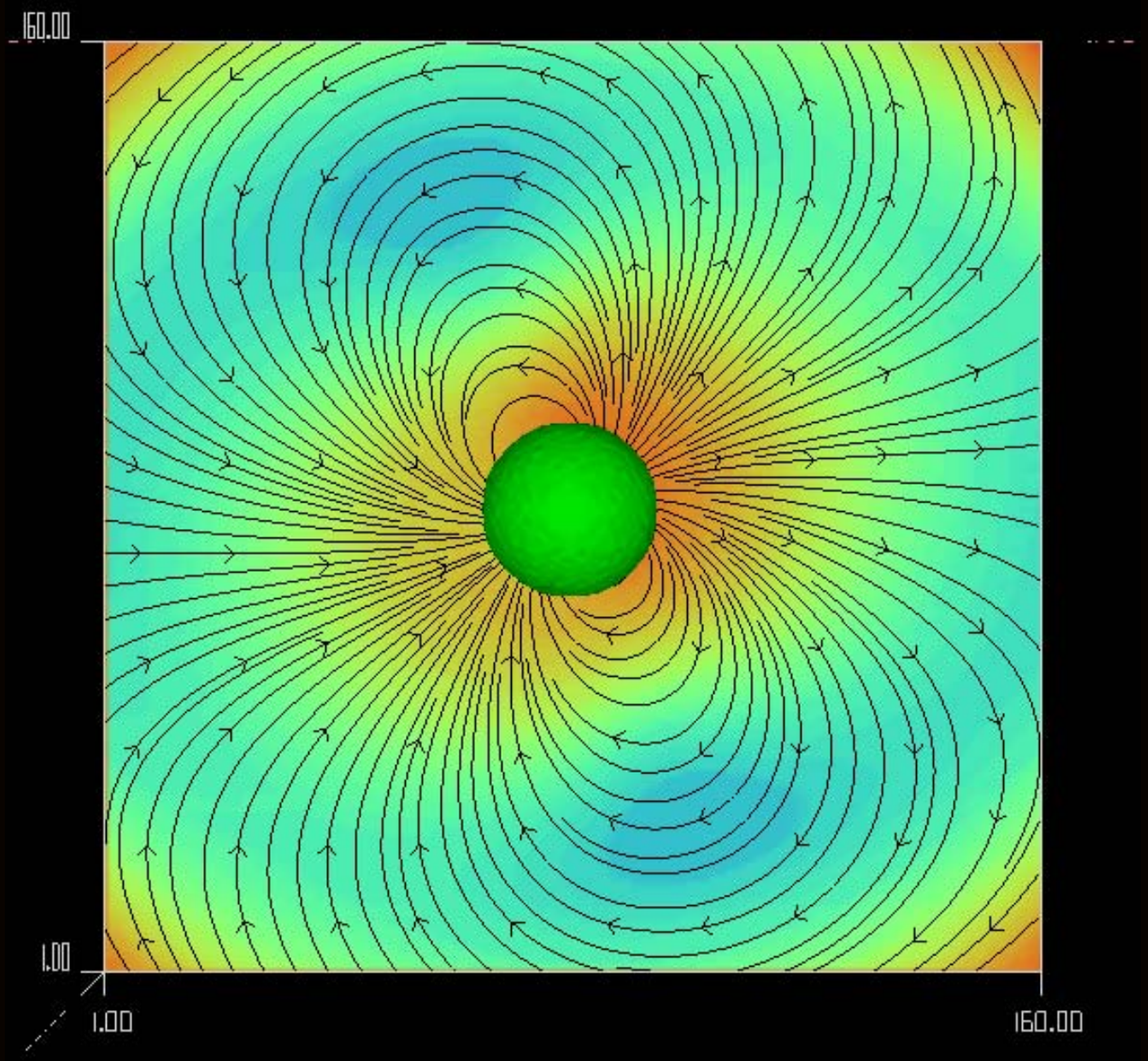
A.S.'06

IN COROTATING FRAME

60 degree inclination



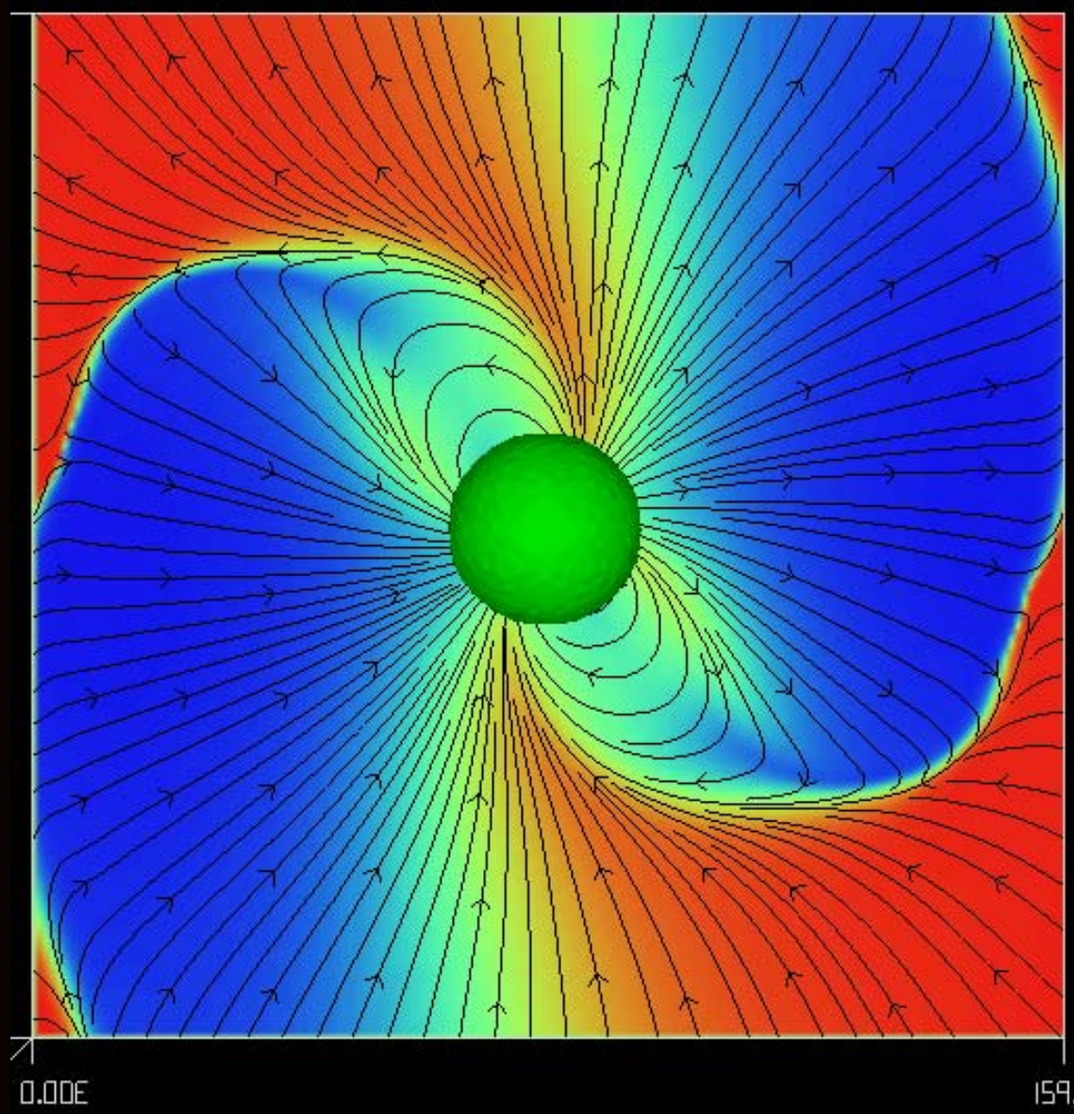


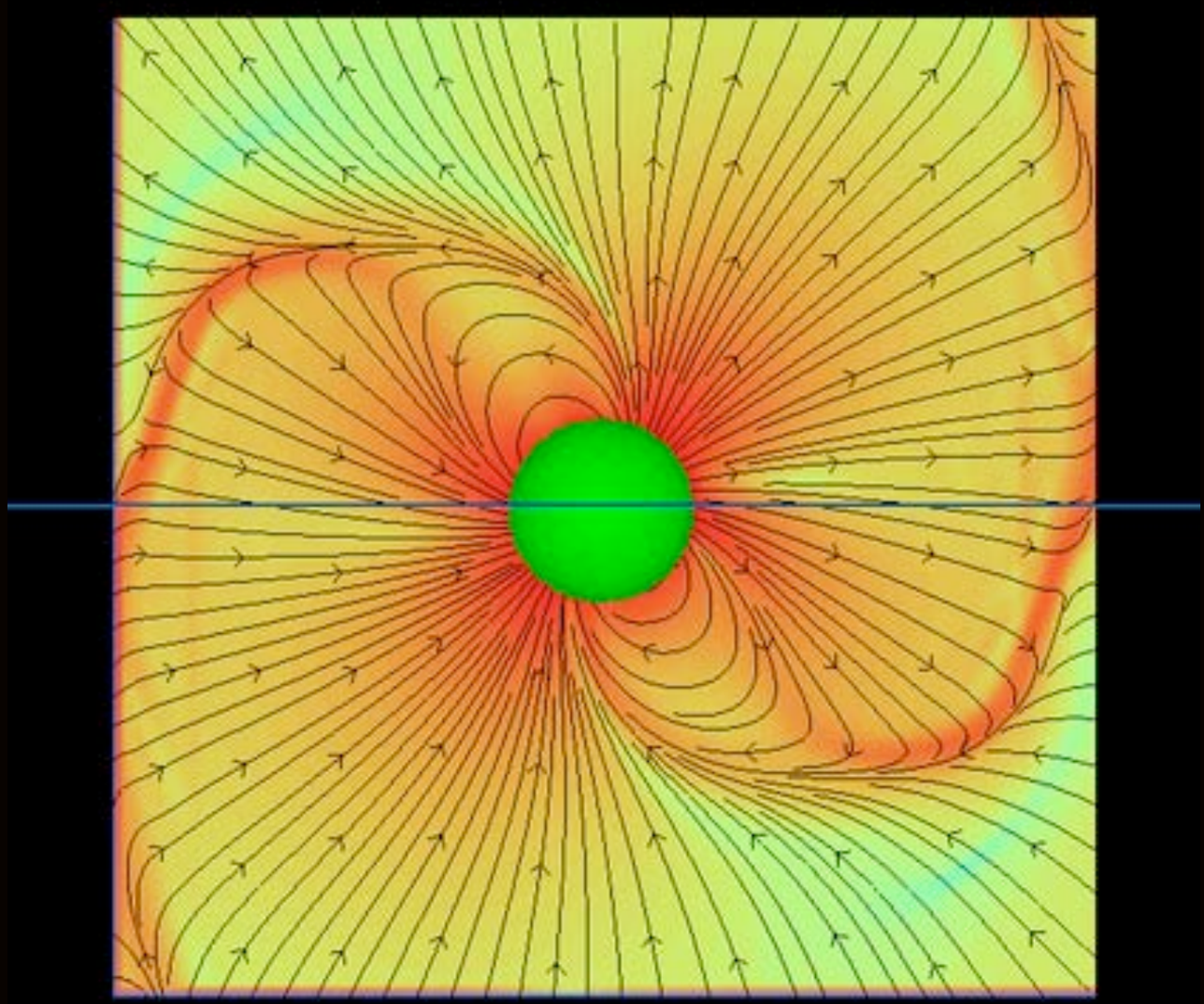
Force-free

Vacuum in mu-Omega plane

IN COROTATING FRAME

60 degree inclination

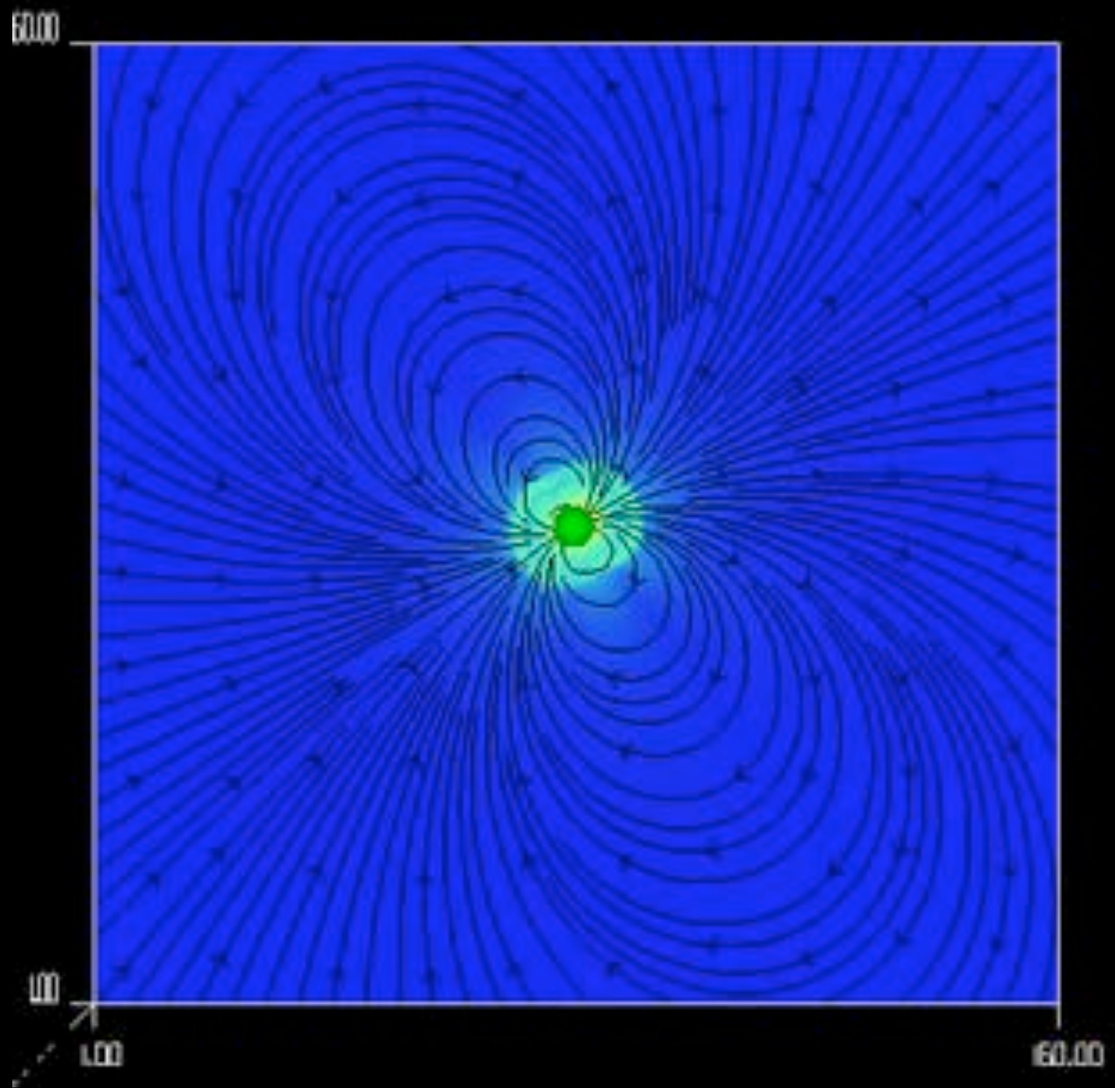




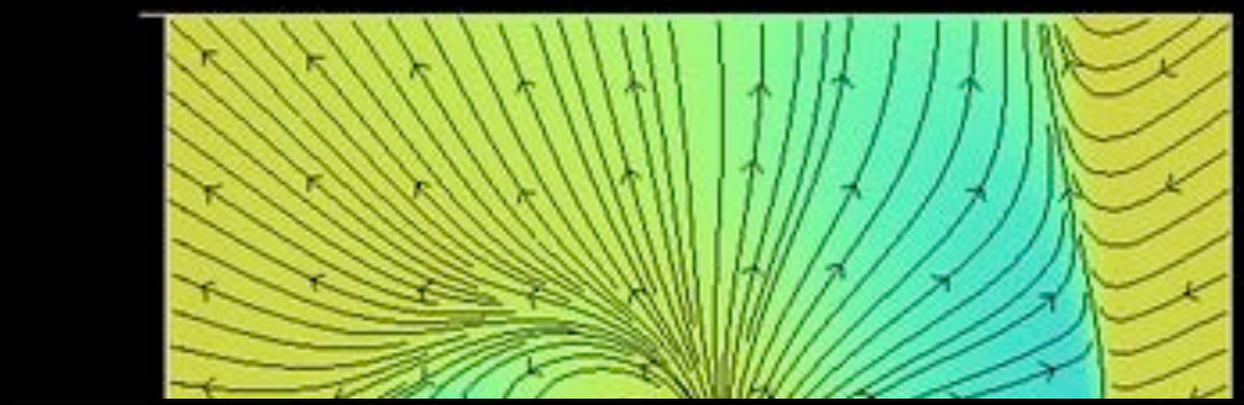
Force-free

Force-free current density

3D force-free magnetosphere: 60 degrees inclination



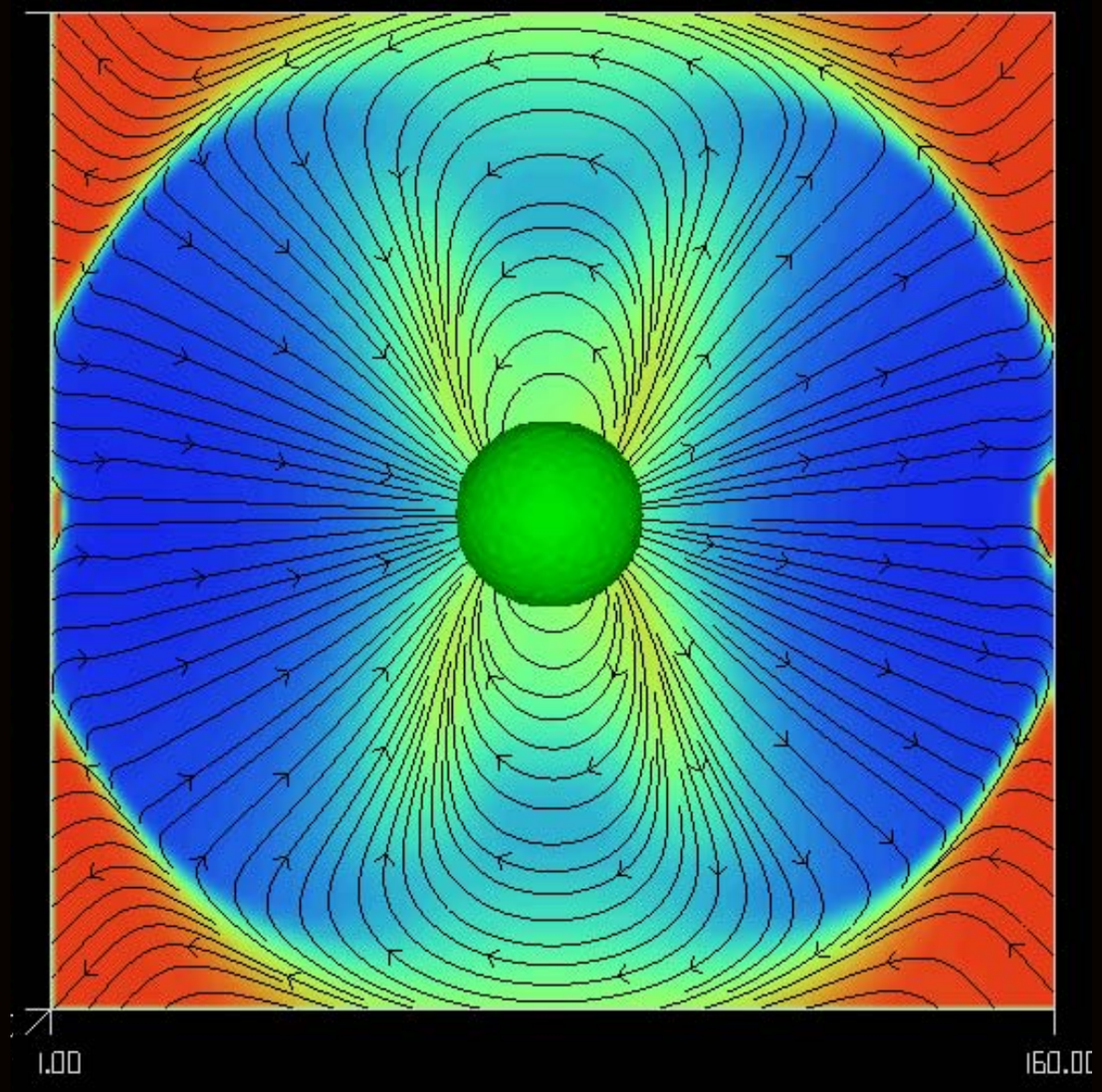
60 degrees force-free current

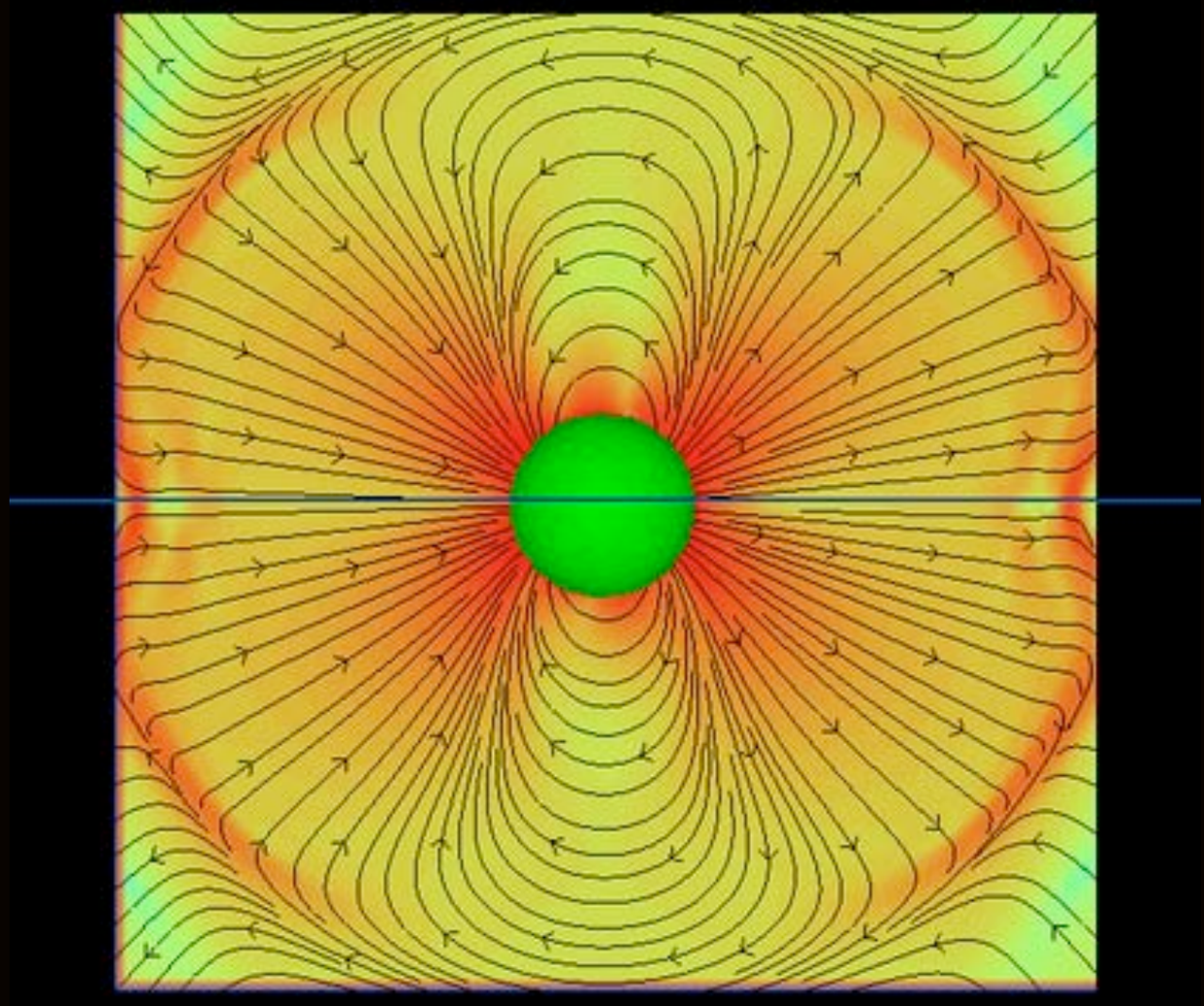


Similar to heliospheric current sheet

IN COROTATING FRAME

90 degree inclination





Force-free

Force-free current density

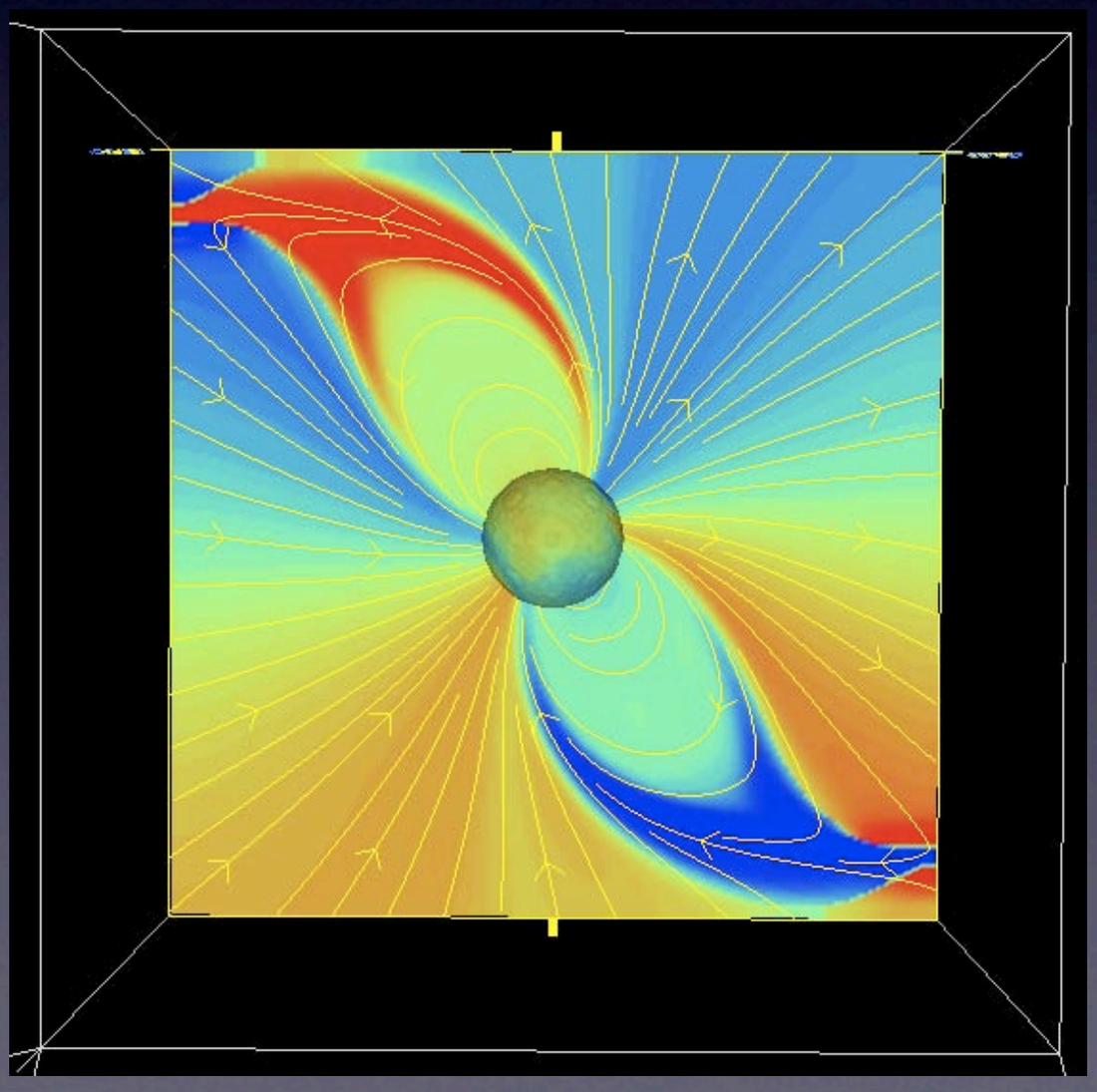
Oblique rotator: force-free

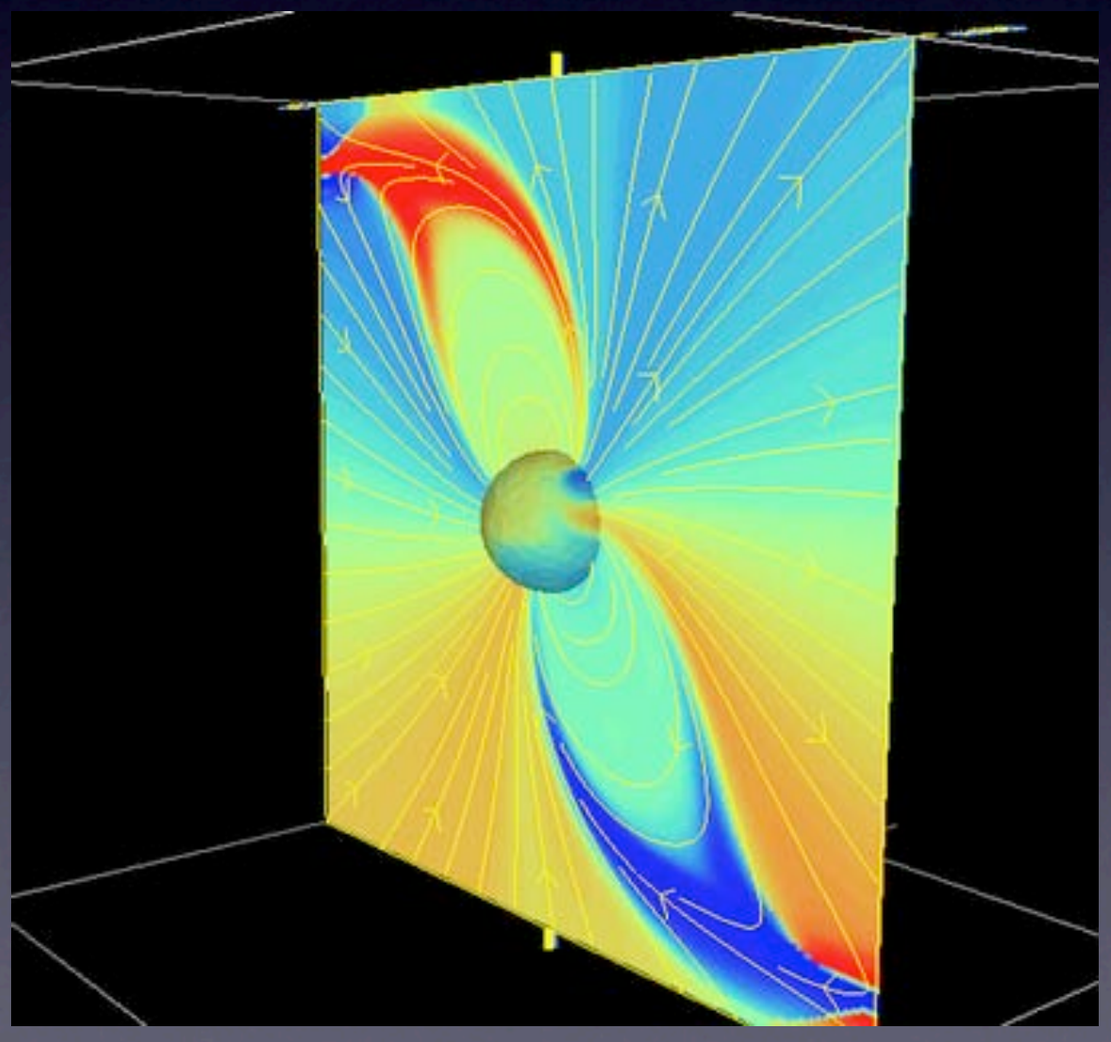
Distribution of current in the magnetosphere

$$\lambda = \nabla \times (\mathbf{B} + \mathbf{V} \times (\mathbf{V} \times \mathbf{B})) \cdot \mathbf{B}/\mathbf{B}^2; \quad \mathbf{V} = \Omega \times \mathbf{R}$$

Gruzinov 2005 Invariant on field lines

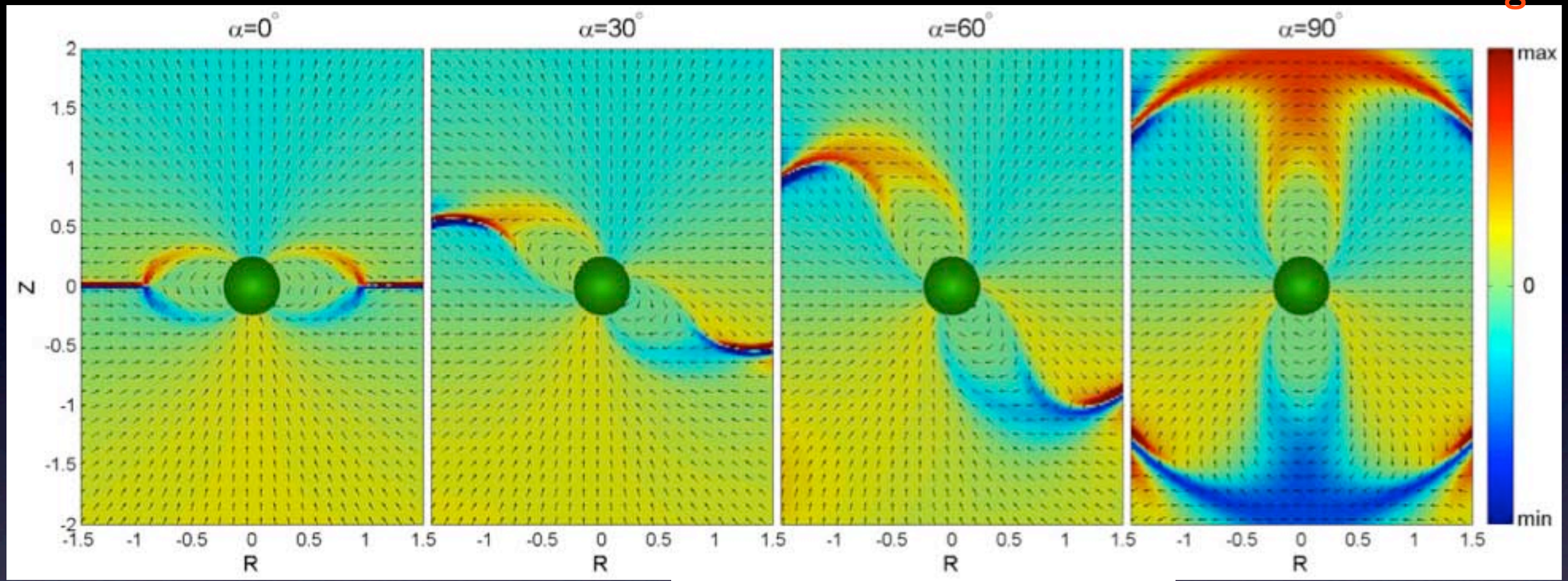
Interpretation: current in the corotating frame is field-aligned





Oblique rotator: force-free

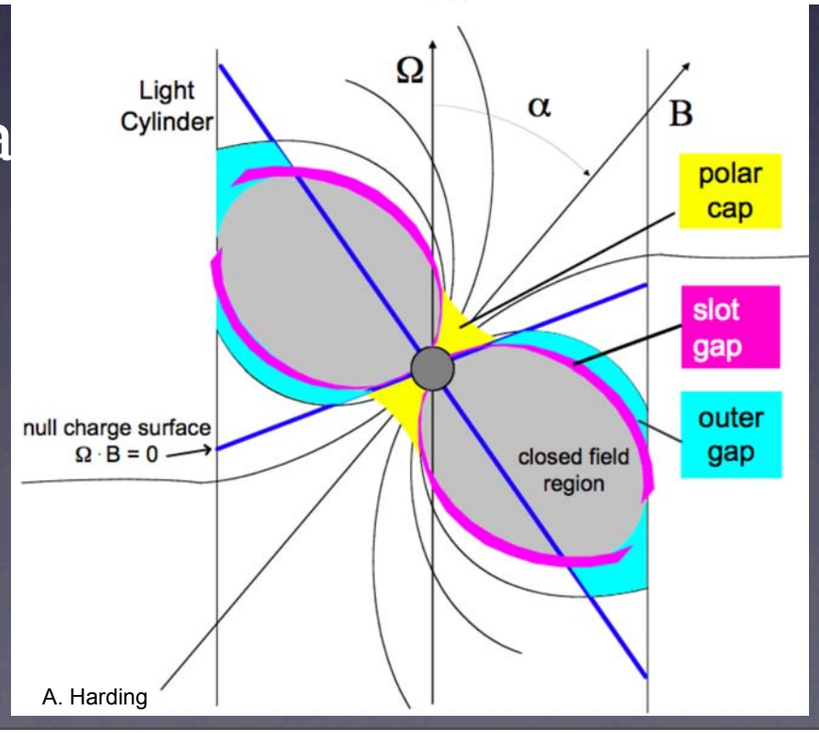
color -- current strength



Bai & A. S. 2010

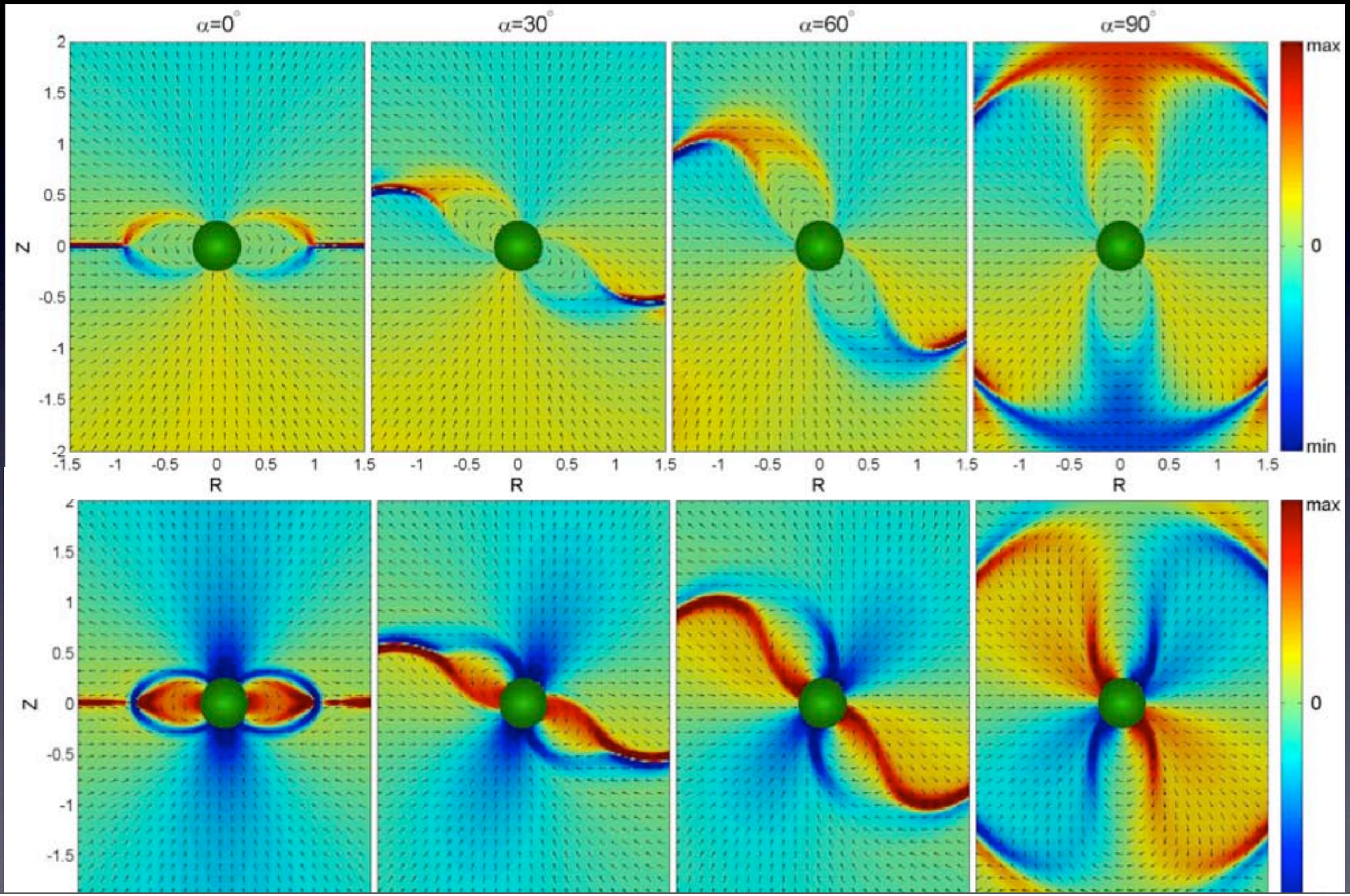
Distribution of current in the ma

Force-free field provides a more realistic magnetic geometry

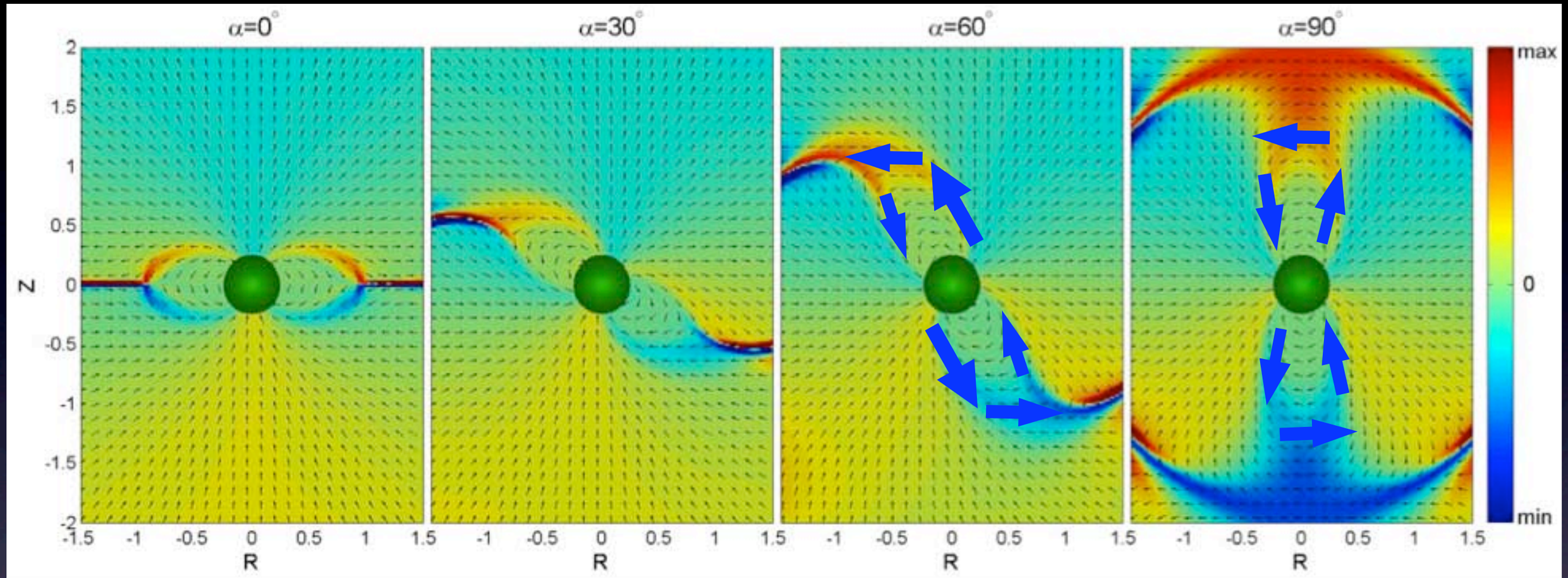


Tempting to associate gaps with currents. Can we?

Oblique rotator: force-free

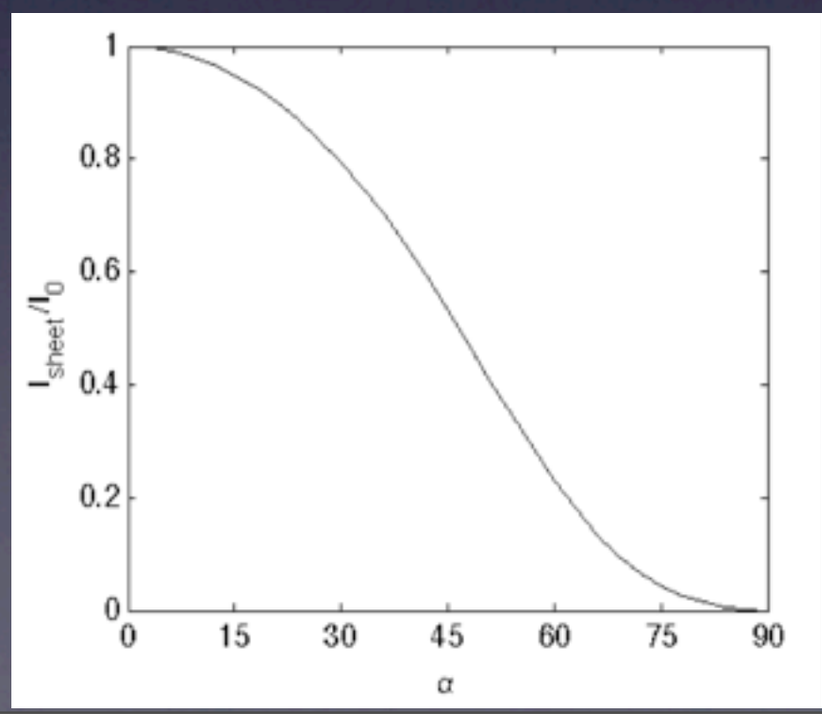


Oblique rotator: force-free



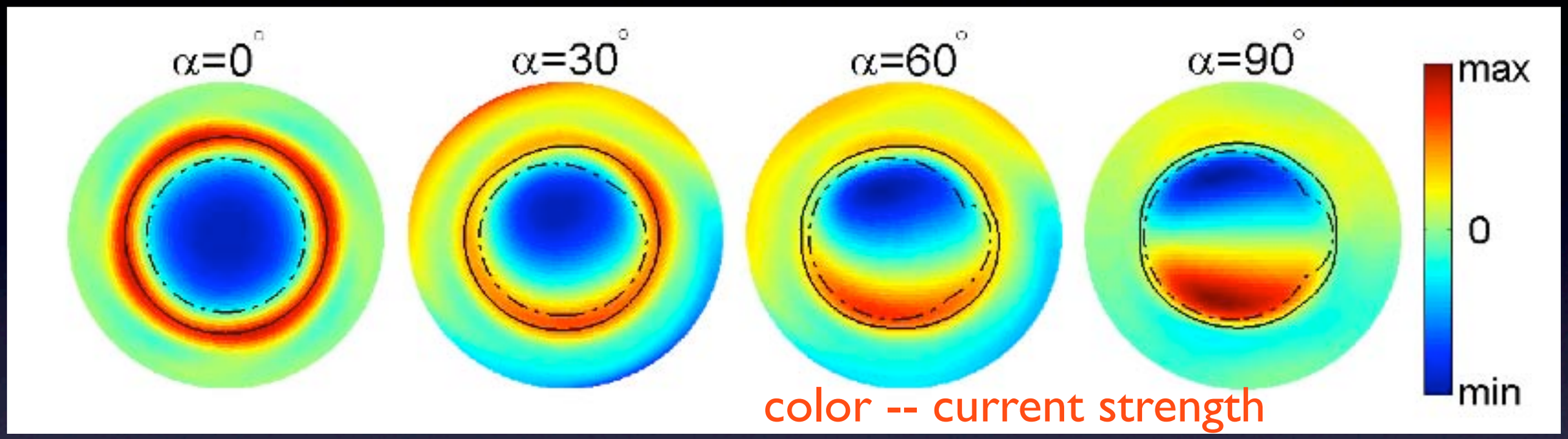
Distribution of current in the magnetosphere

Peculiarities:
with angle Y-region becomes thicker, and the strength of current sheet inside the magnetosphere reduces.
Current flows to the other pole!



Bai & A. S. 2010

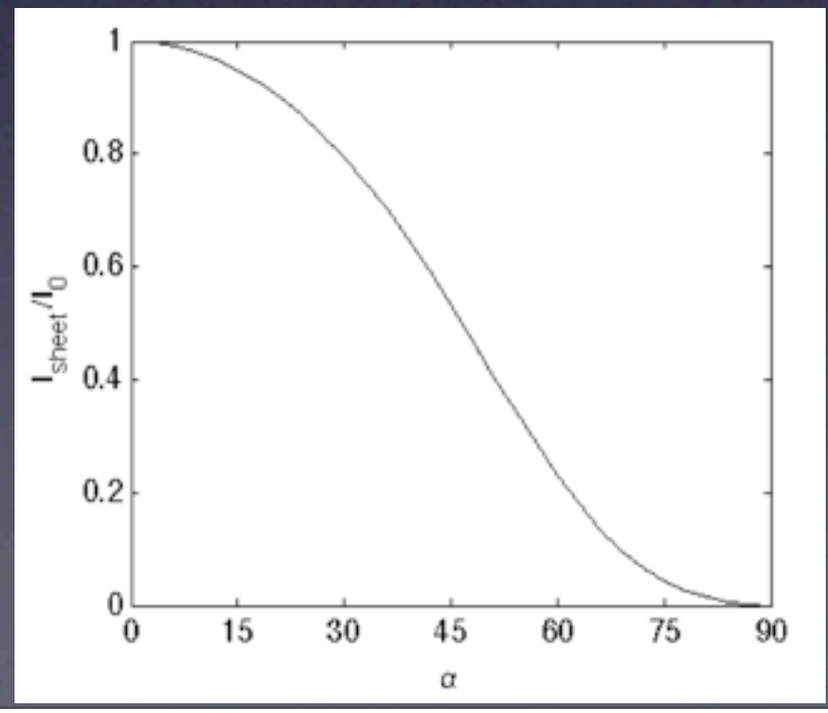
Oblique rotator: force-free



Distribution of current in the magnetosphere

Polar cap in force-free is more circular

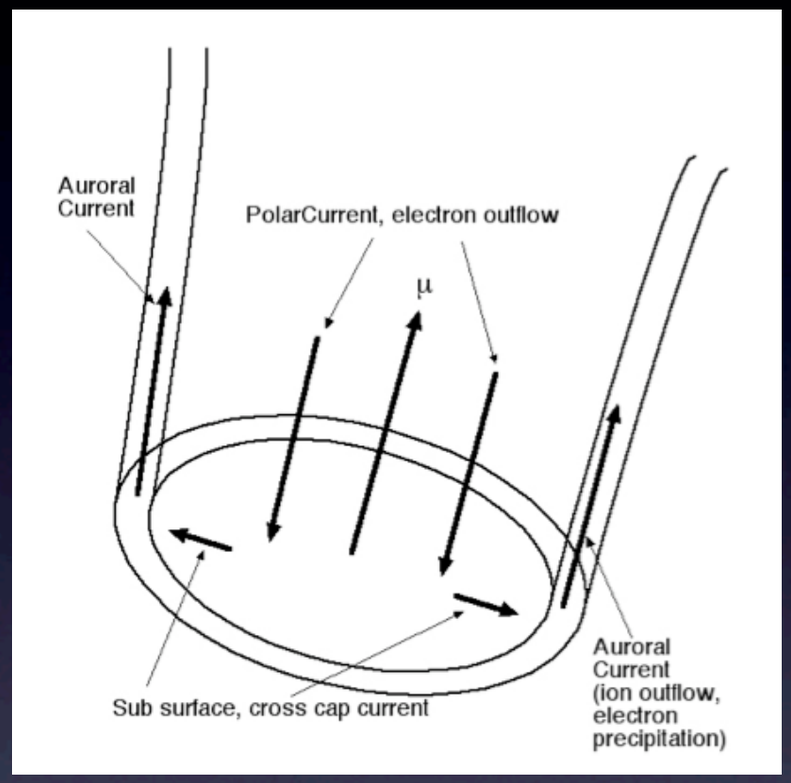
Peculiarities:
with angle Y-region becomes thicker, and the strength of current sheet inside the magnetosphere reduces.
Current flows to the other pole!

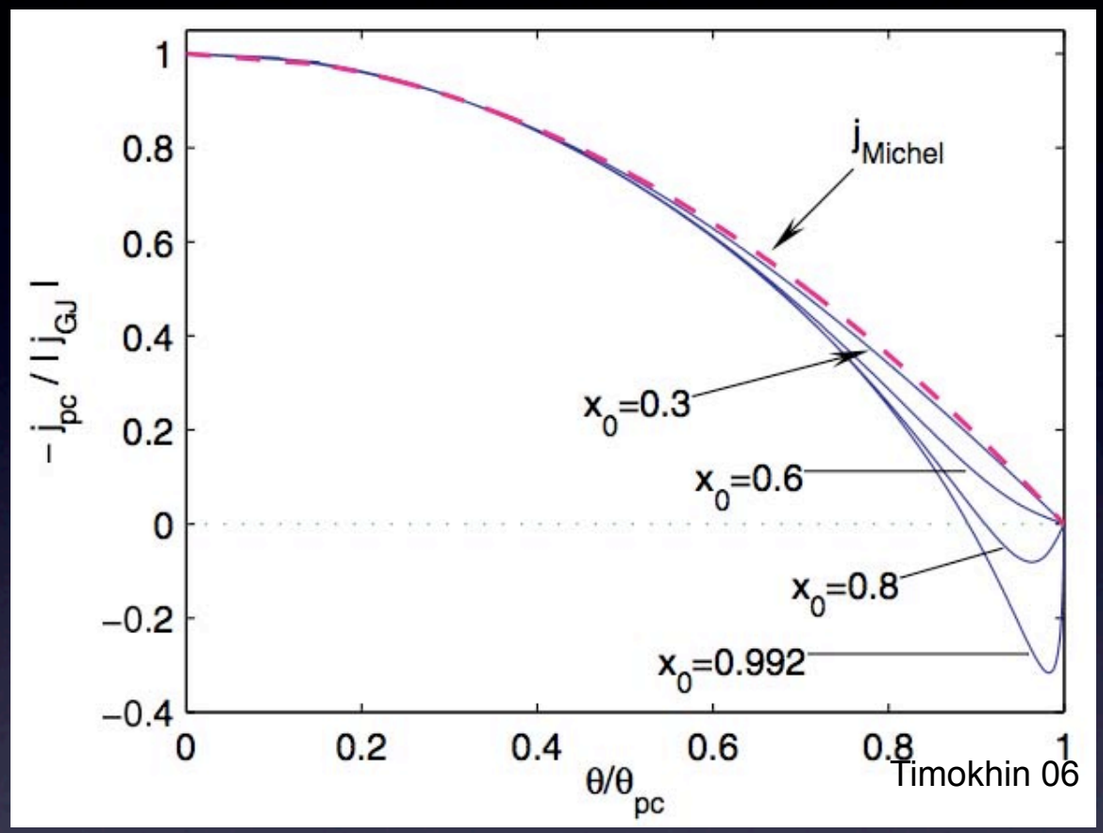


Bai & A. S. 2010

Mind the gap: origin of the current

$$j = j_{GJ}[1 - (\theta/\theta_{PC})^2]$$





Timokhin 06

Force-free current is inconsistent with convenional gap physics: space-charge limited flow makes $j=j_{GJ}$ which does not vary fast enough over polar cap.

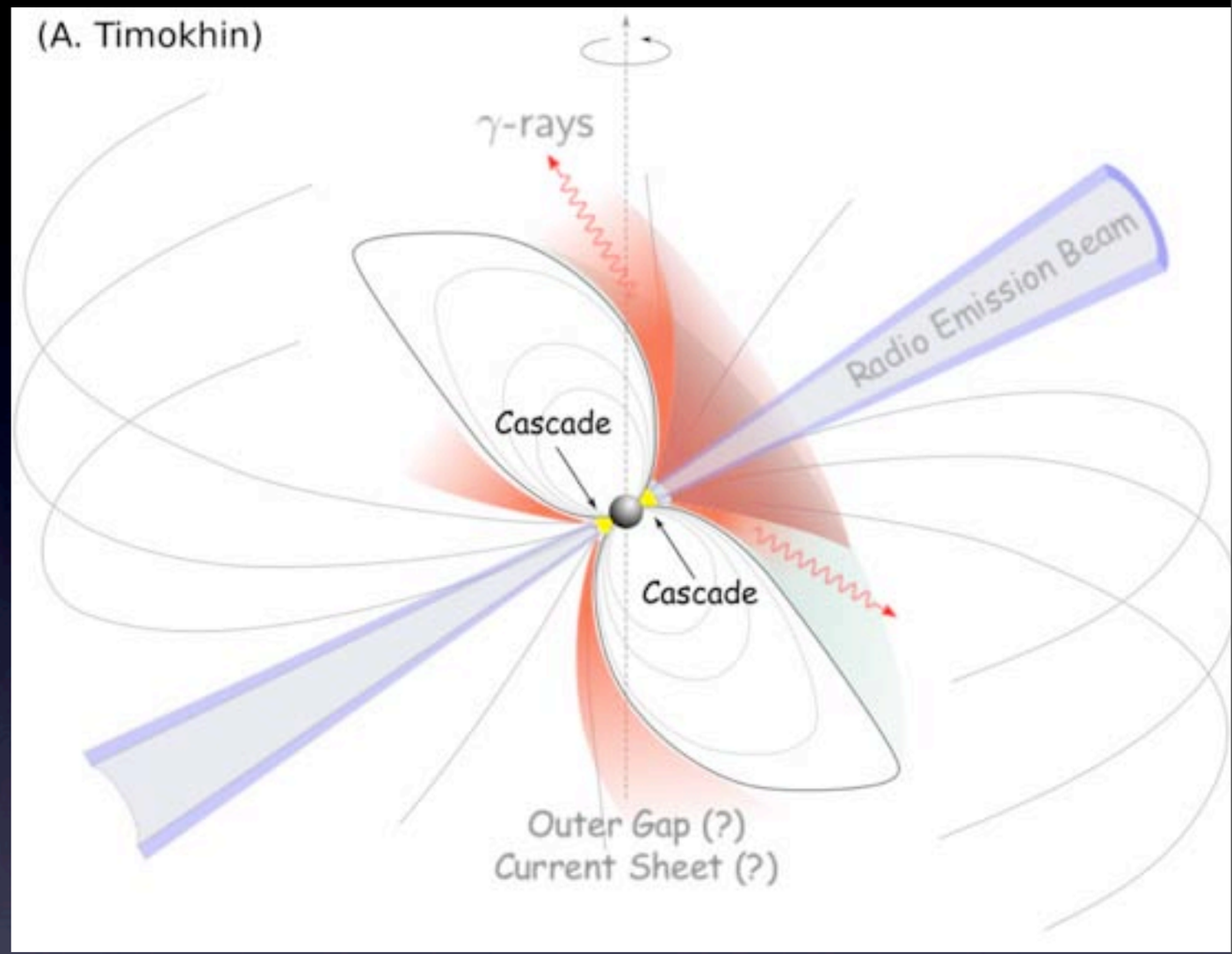
Also, for large inclinations current is >> than local GJ current, yet is of the same order as GJ current for aligned rotator

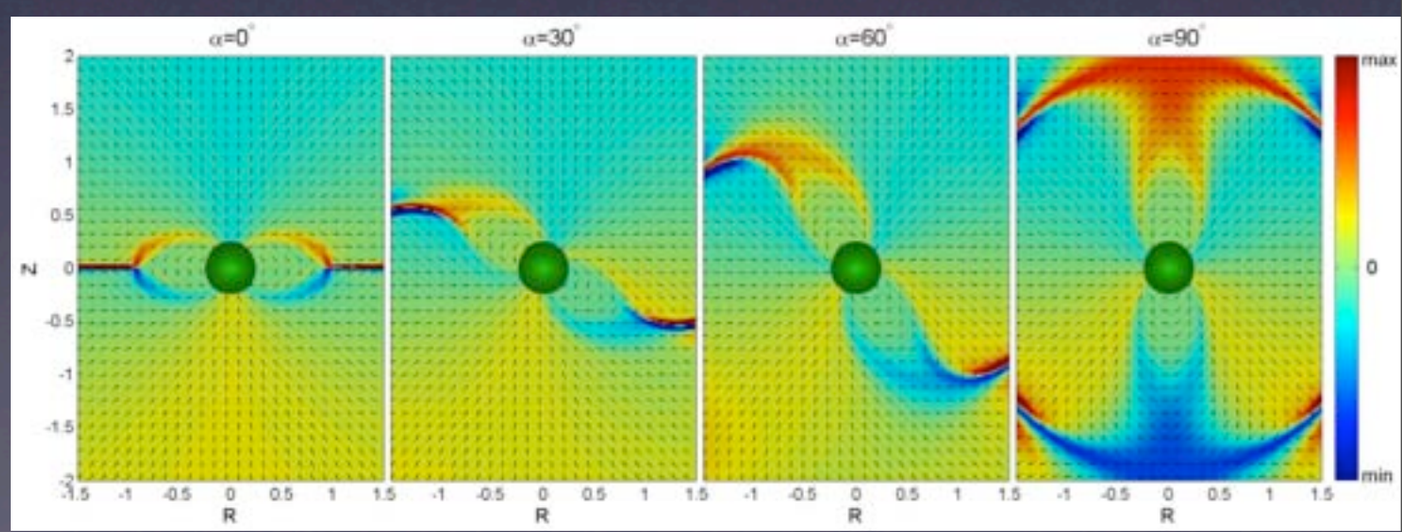
Are gaps time-dependent as a result?

What emits?

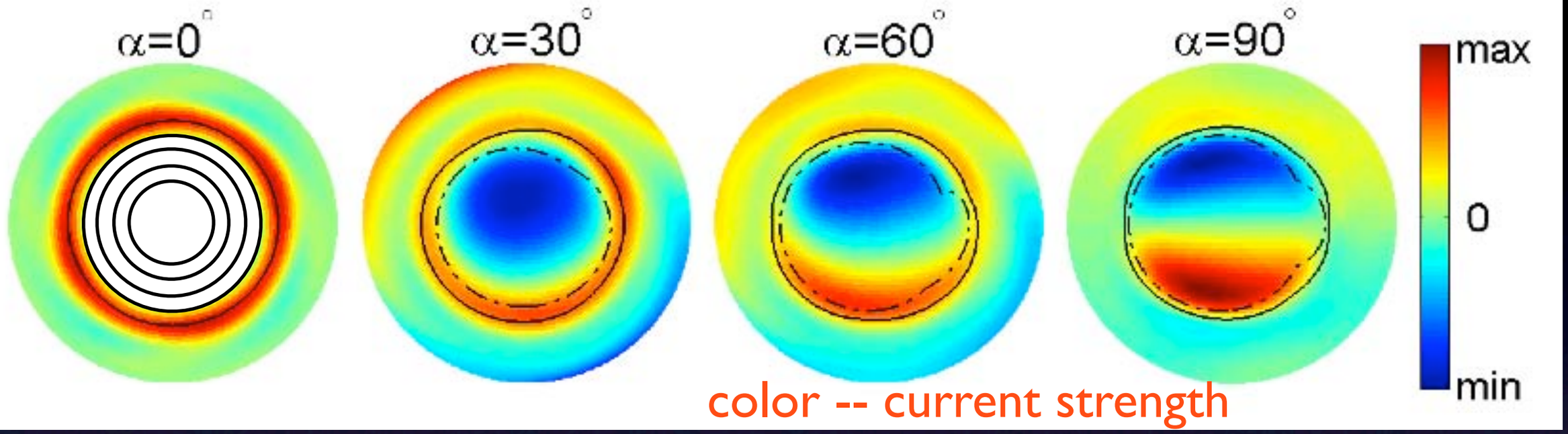
Emission process in γ less complicated than in the radio: curvature, IC, or synchrotron.

- Need acceleration of particles
- Particles radiate while moving along B field lines. Relativistic effects (aberration and time delay) are important.
- Where is the region that emits? Determined by field geometry.
- Extensive studies in vacuum field geometry (Harding; Romani; Cheng)
- Try this in force-free field. Geometry is crucial!!!





What emits?

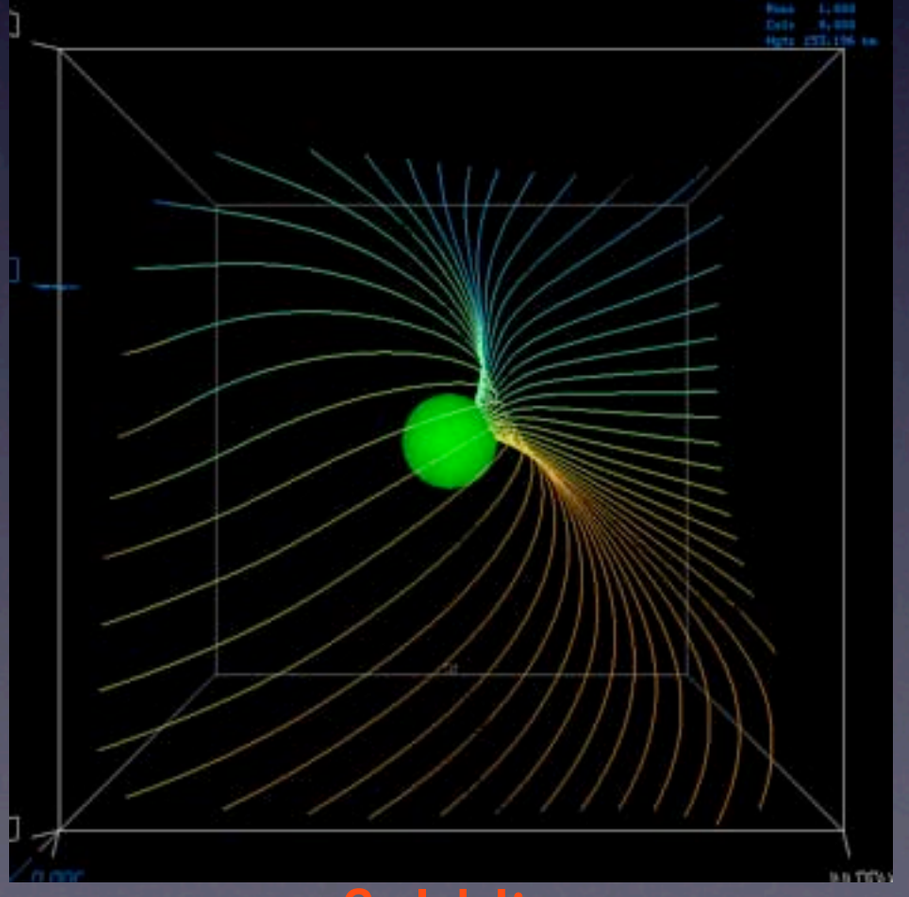


color -- current strength

- Select flux tubes that map into rings on the polar caps. The rings are congruent to the edge of the polar cap.

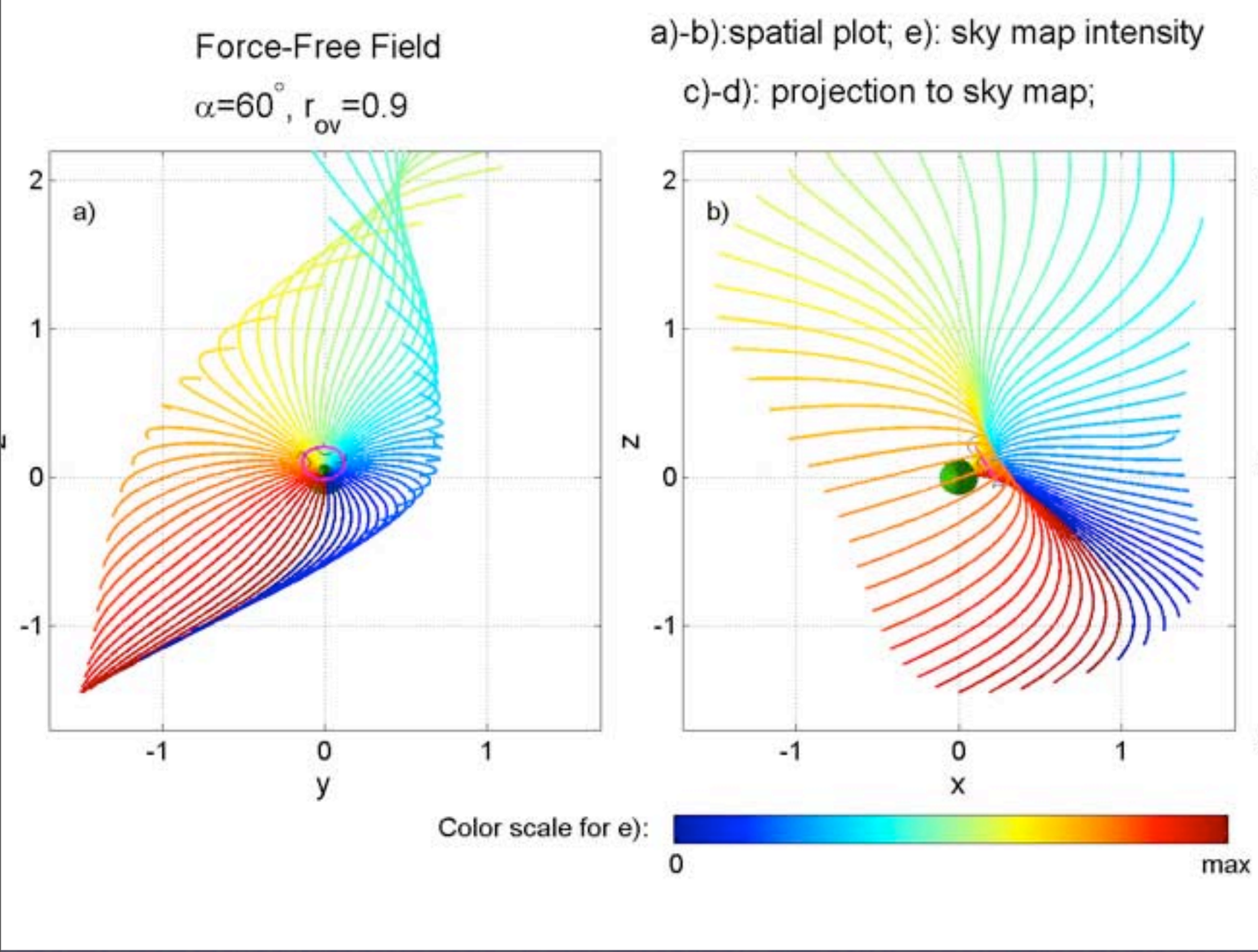
- This is arbitrary, but the point is to study the geometry of the possible emission zone.

- Emission is along field lines, with aberration and time delay added



open field lines

Emission from one flux tube



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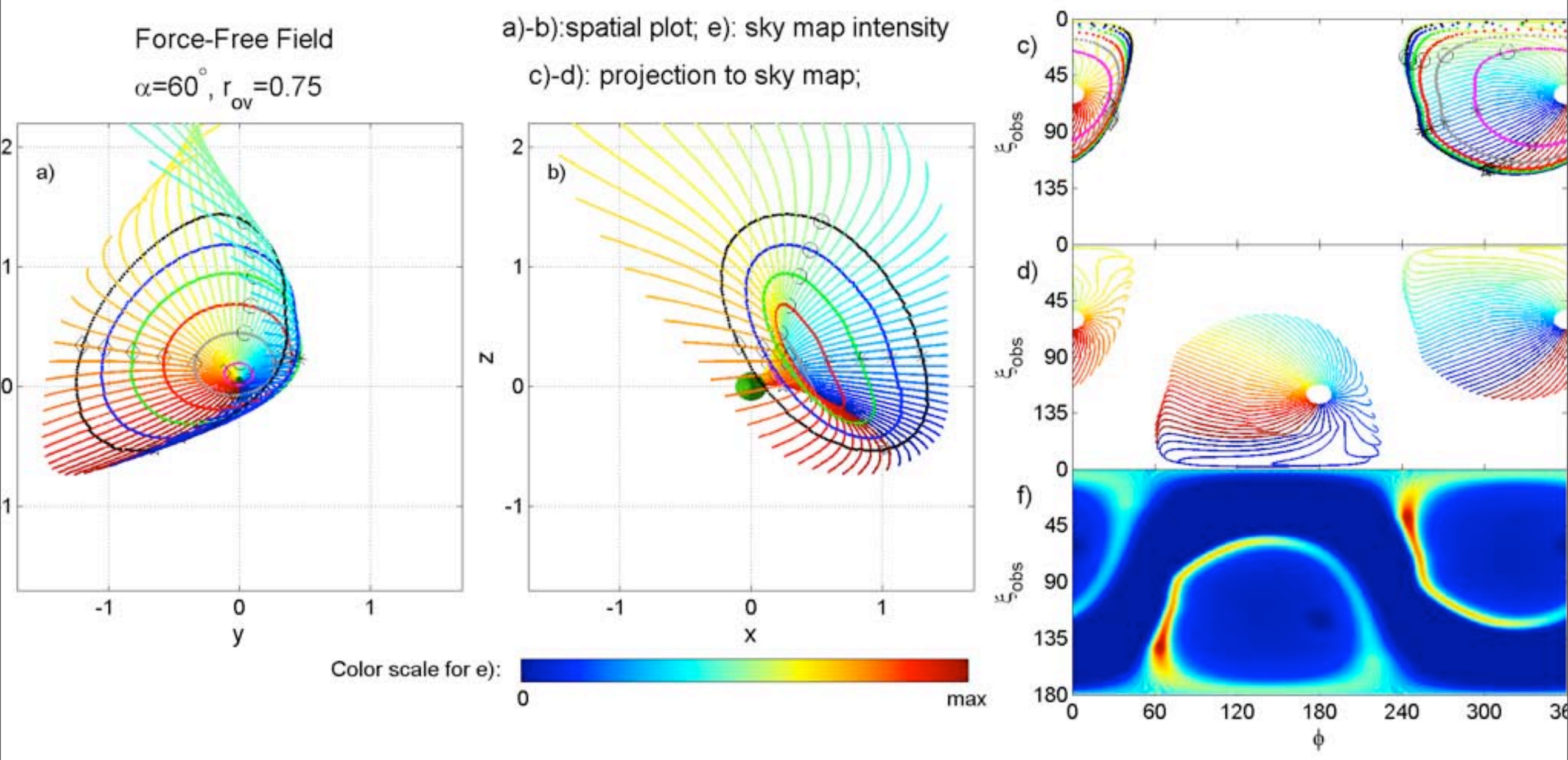
Emission from different flux tubes



Emissions from two poles merge at some flux tubes: what's special about them?

Bai & A. S. 2010

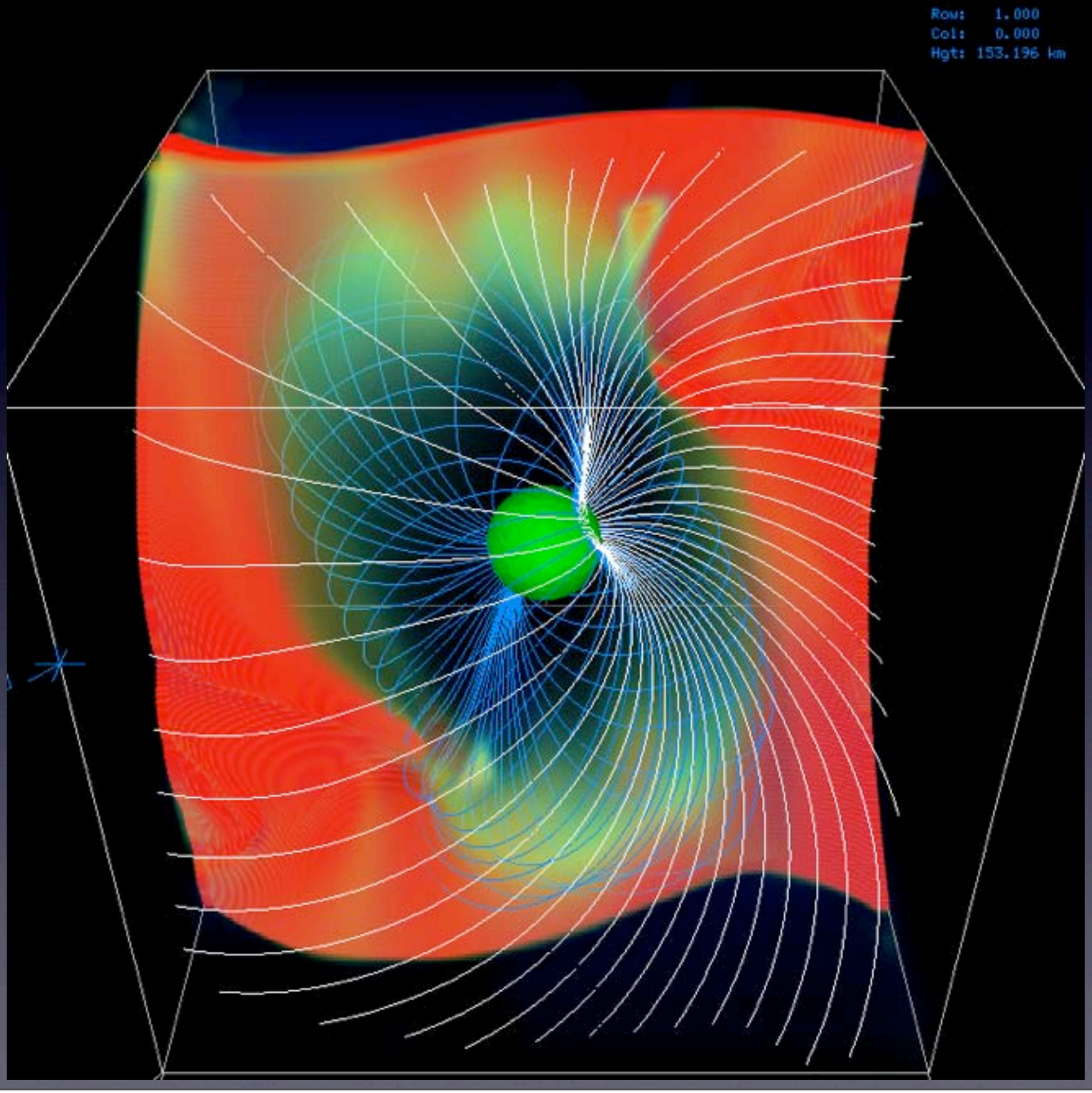
Association with the current sheet

Color -> current

Field lines that produce best force-free light curves seem to "hug" the current sheet at and beyond the LC.

Significant fraction of emission comes from beyond the light cylinder.

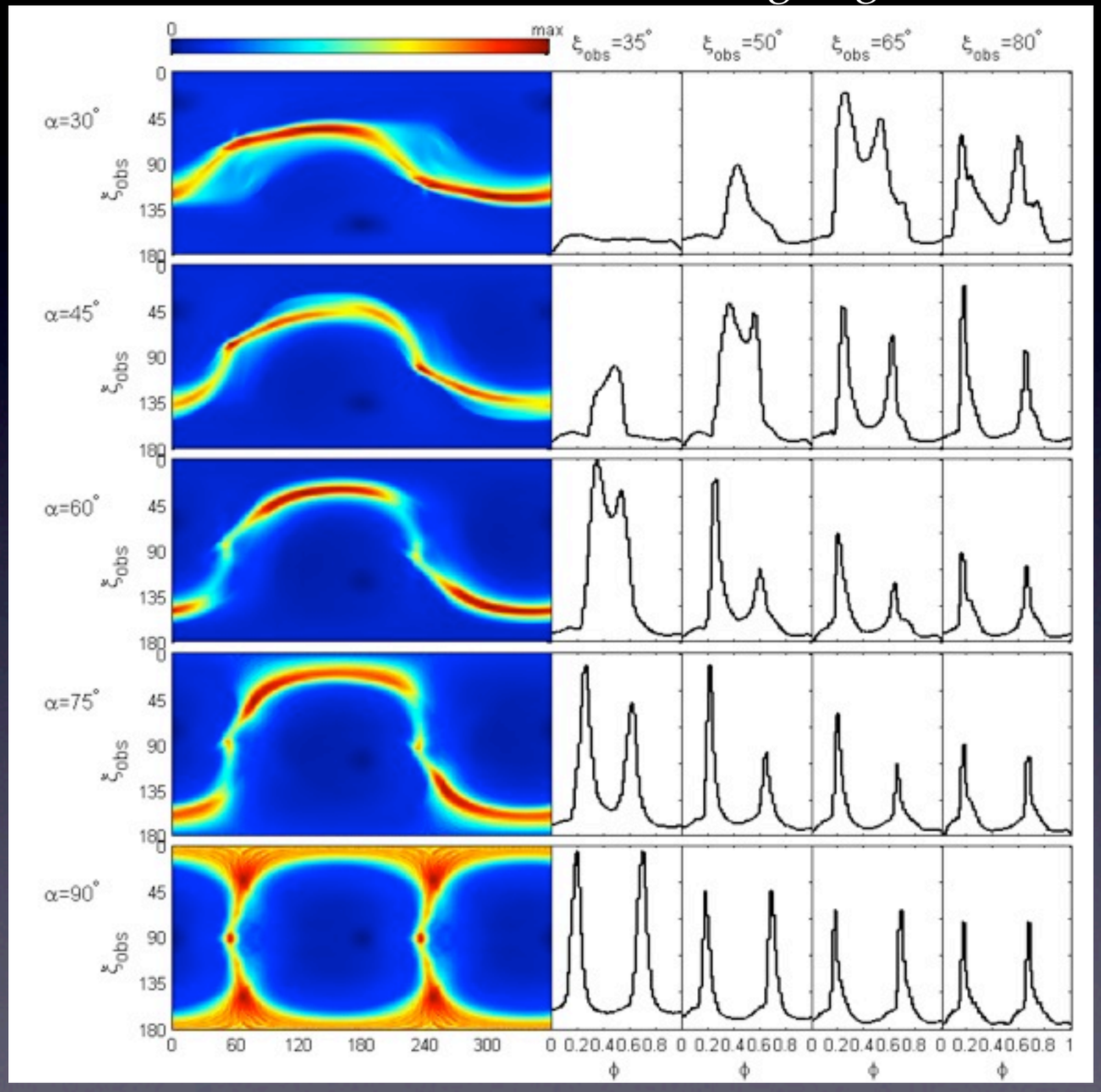
Current sheet good place to put resistor in the circuit!



Force-free gallery

Viewing angle

Inclination angle of magnetic axis



Double peak profiles very common.

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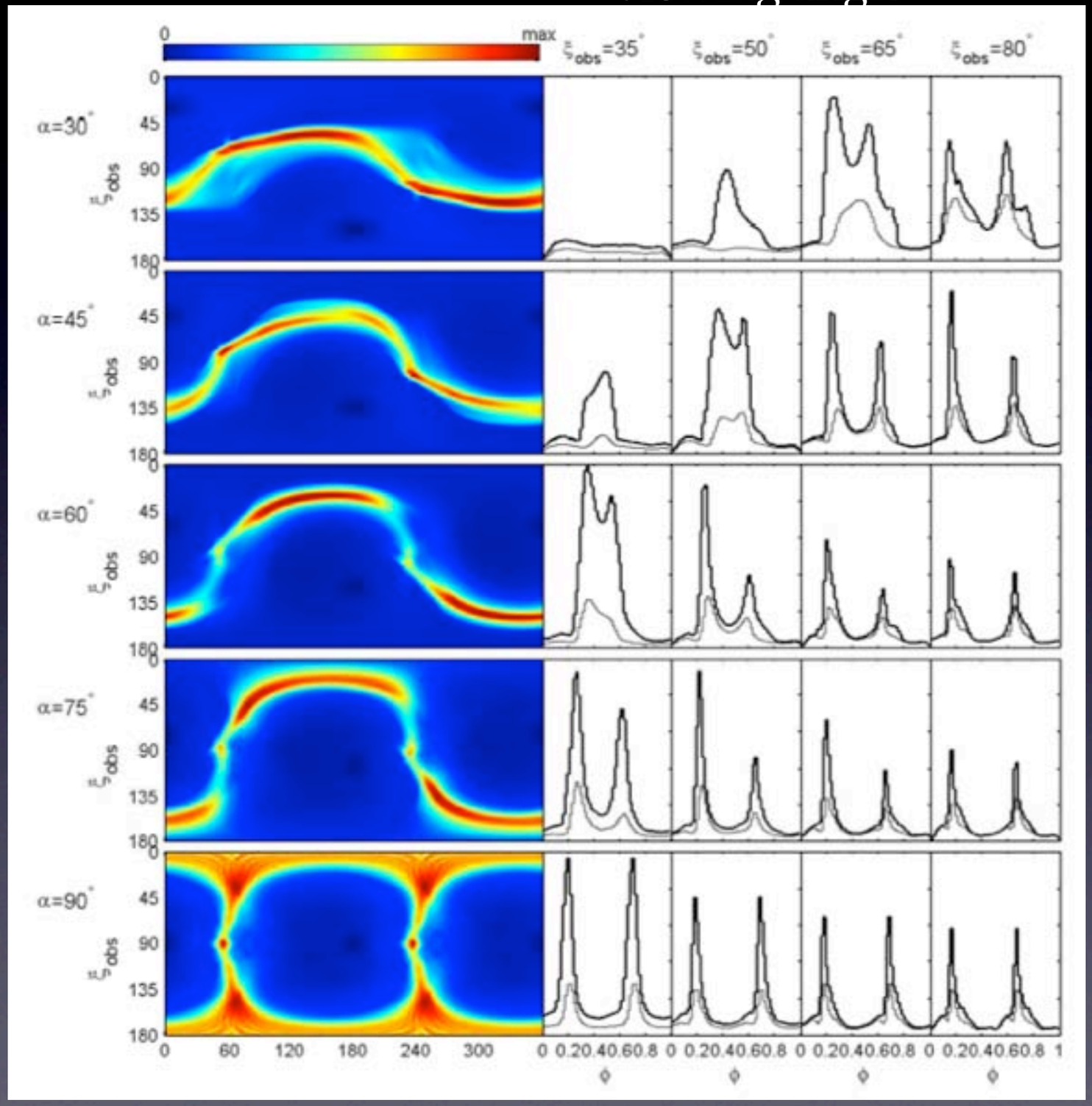
Force-free gallery

Viewing angle

Inclination angle

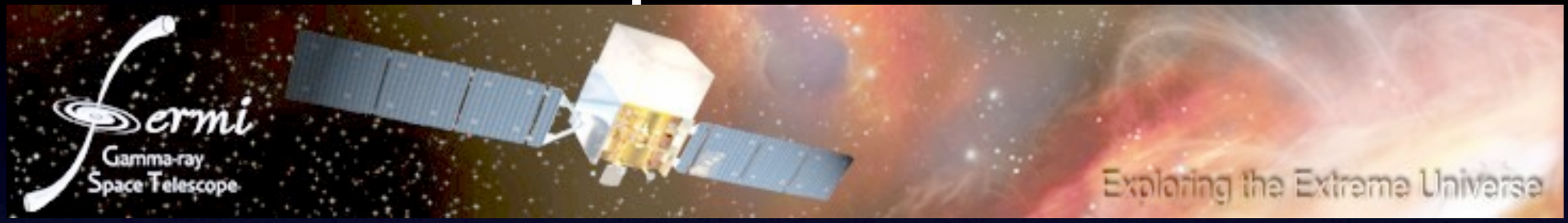
Most of the emission in FF model accumulates beyond 0.9 Rlc

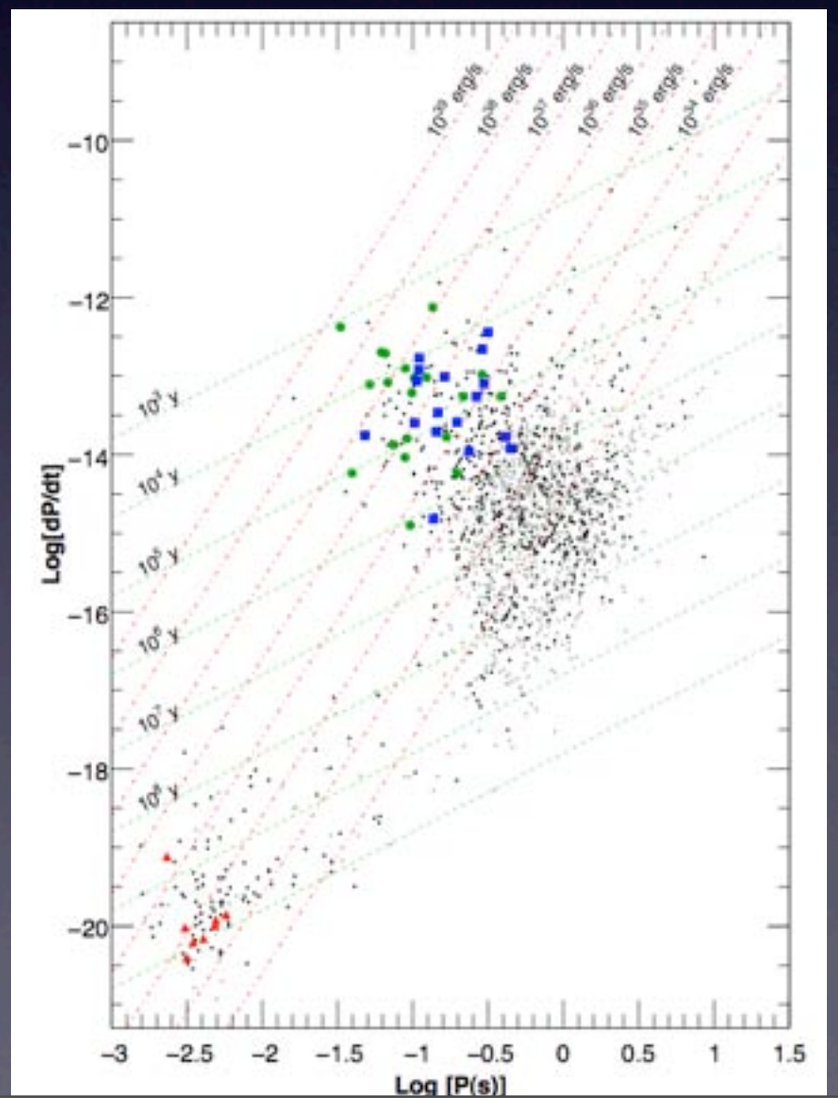


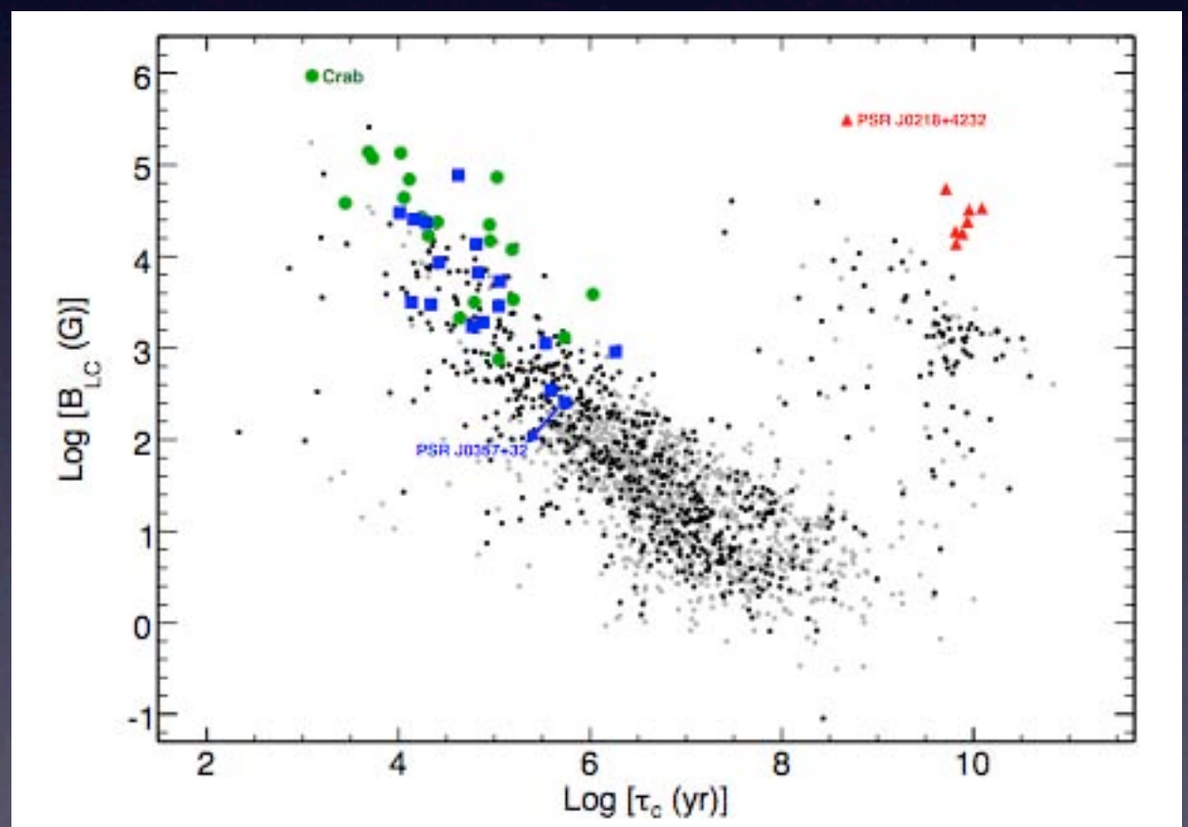
Double peak profiles very common.

Bai & A. S. 2010

Gamma-ray emission from pulsars

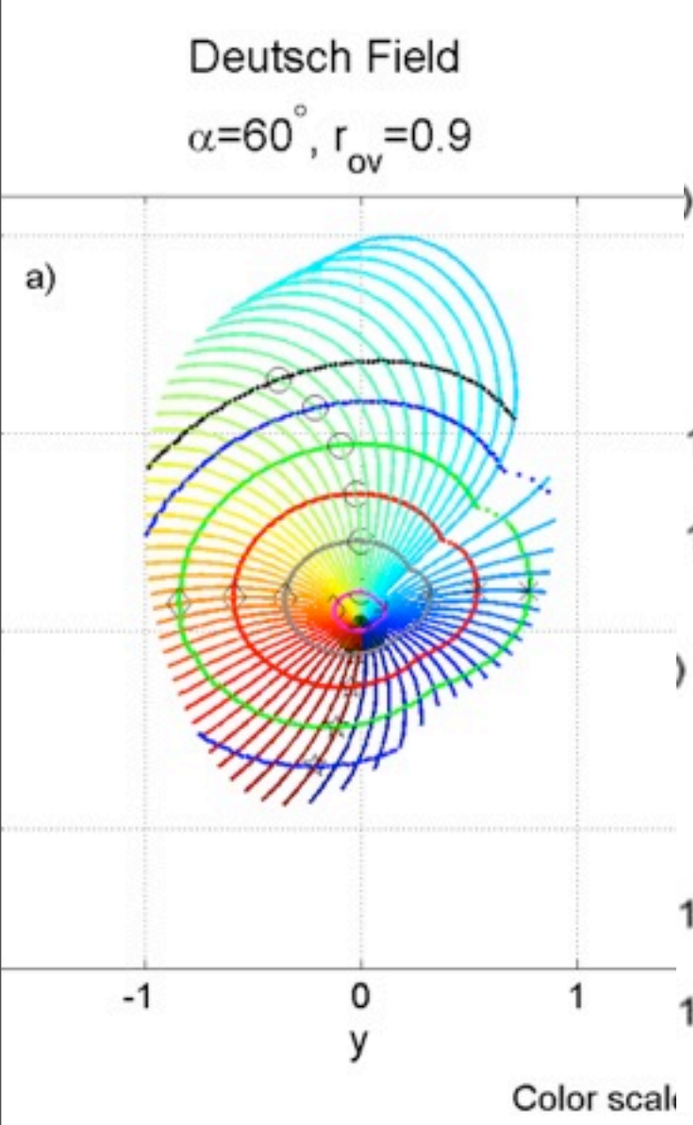


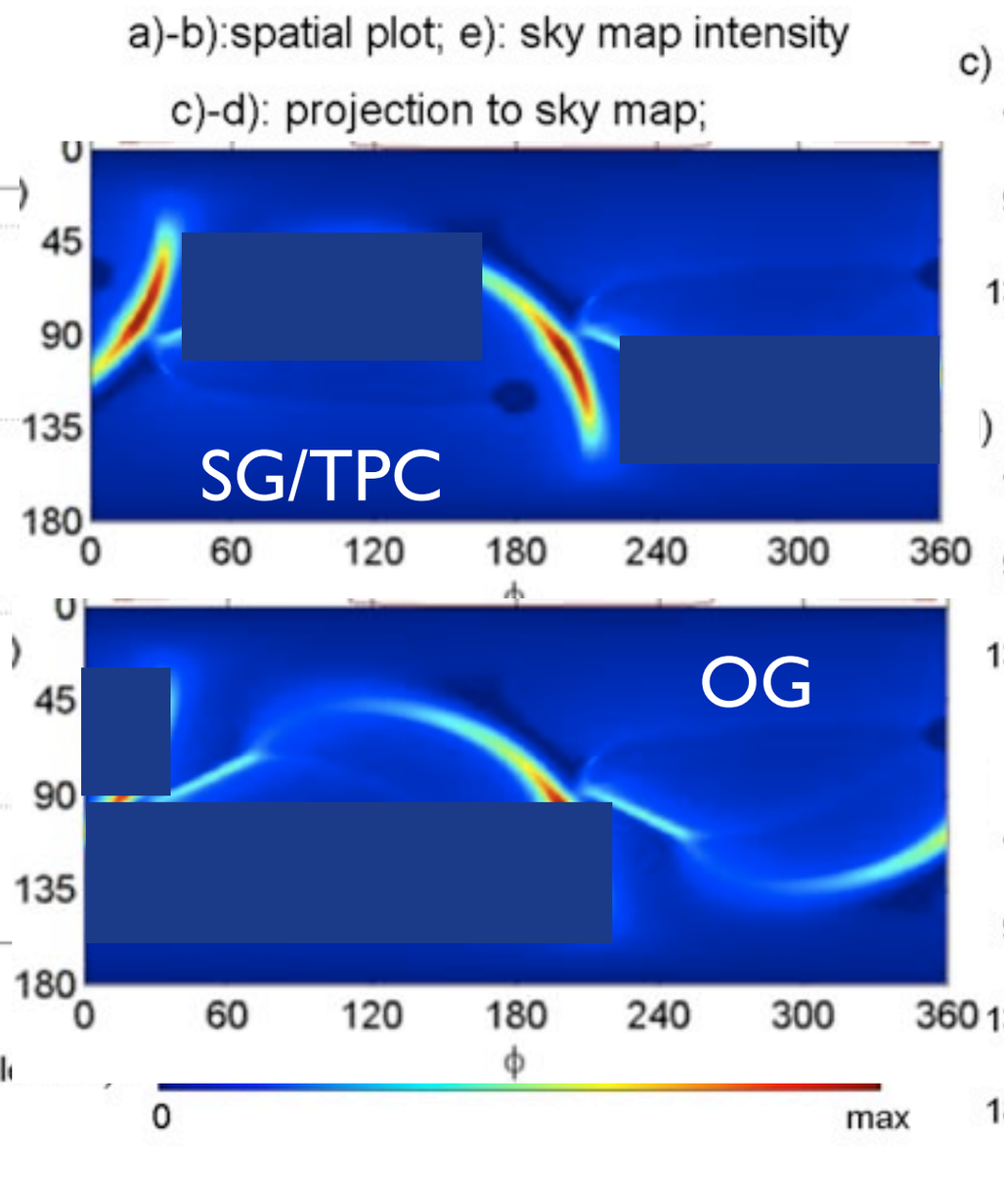


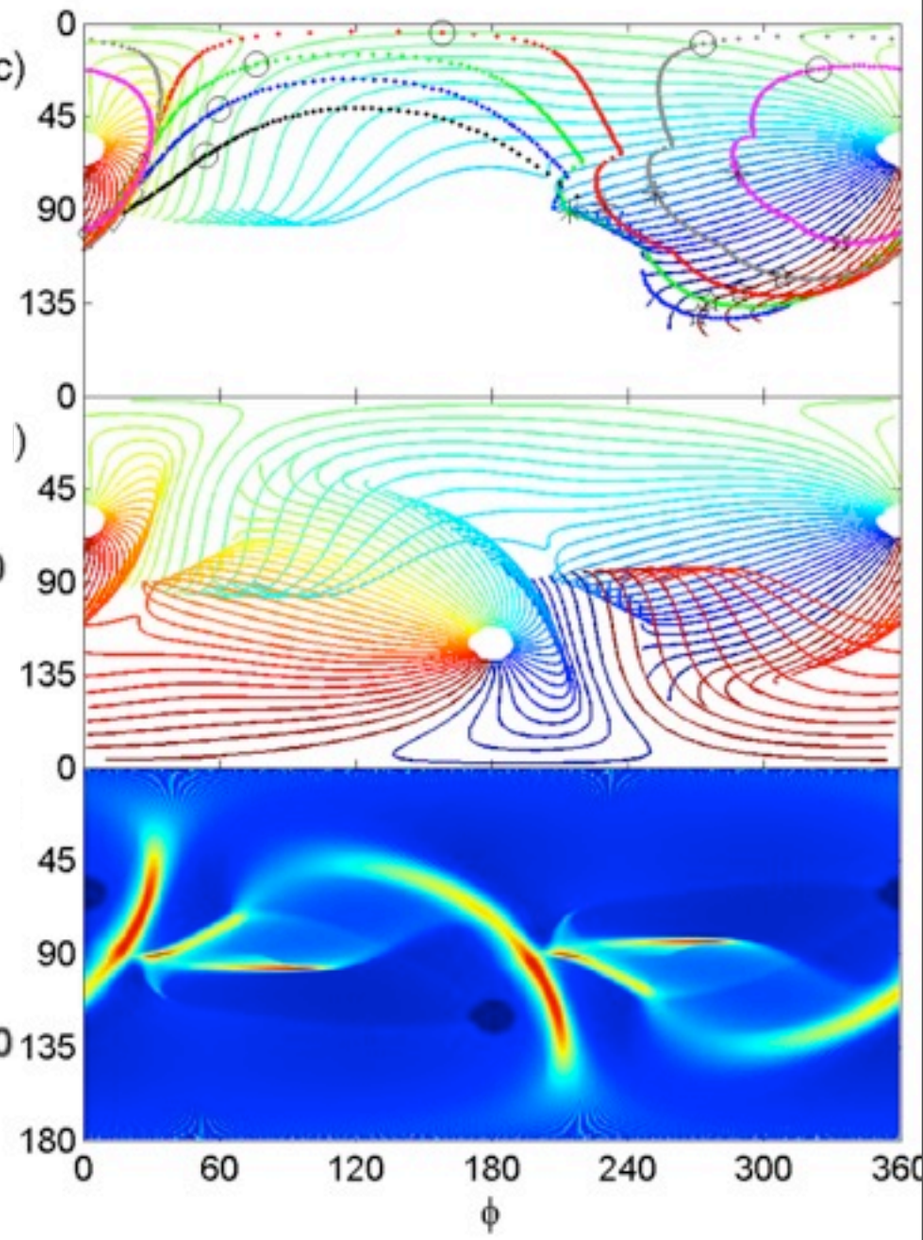


High B at light cylinder required

Vacuum sky map

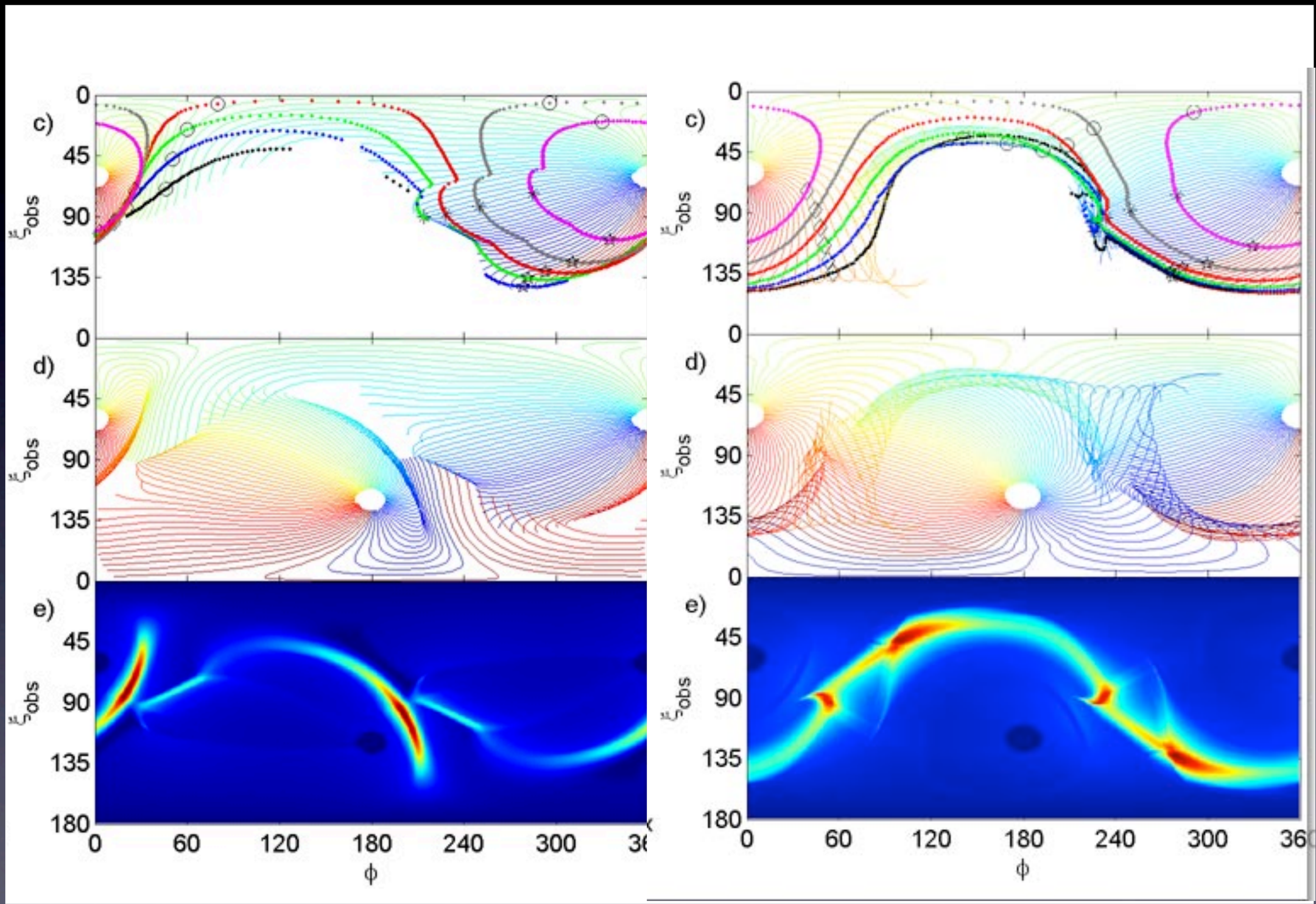






Vacuum field, 60 degree inclination, flux tube starting at 0.9 of the polar cap radius.

Vacuum vs Force-free



All caustics in force-free form near LC. No close caustic like in TPC

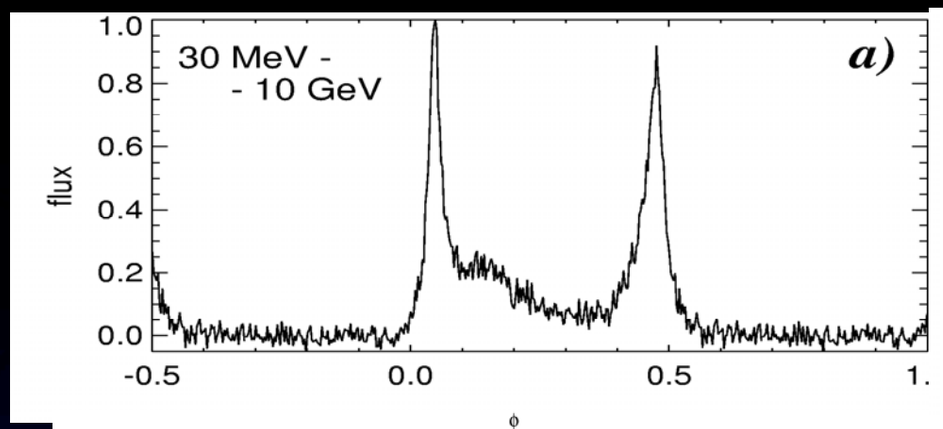
Bai & A. S. arXiv:0910.5741

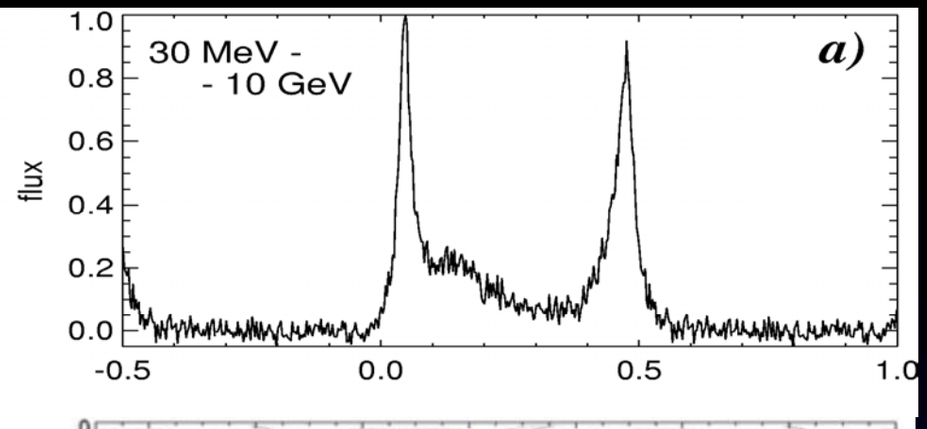
Vacuum light curve fitting

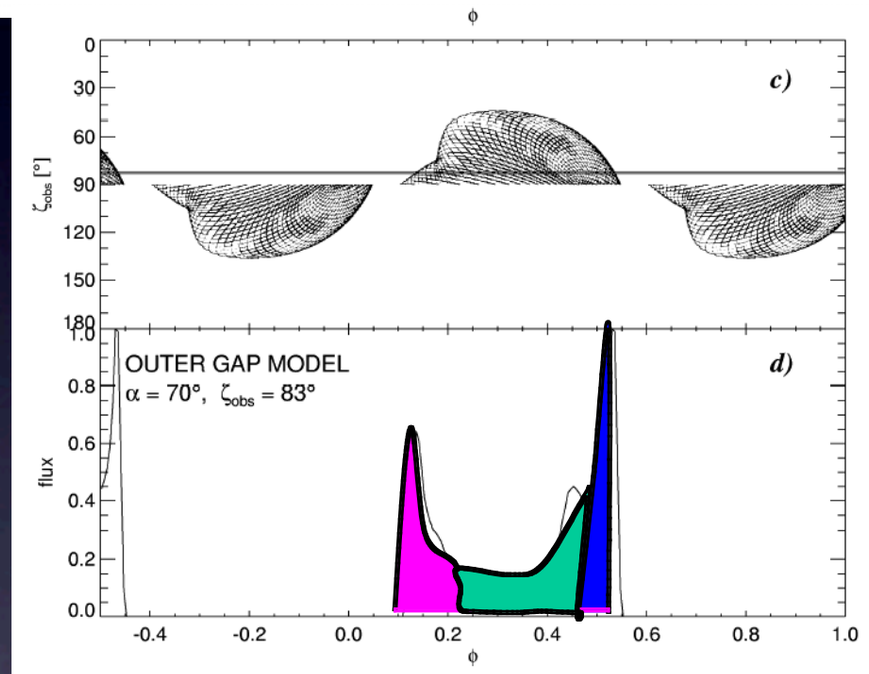
Impressive fits can be achieved with both "slot gap" and "outer gap" models based on the vacuum field.

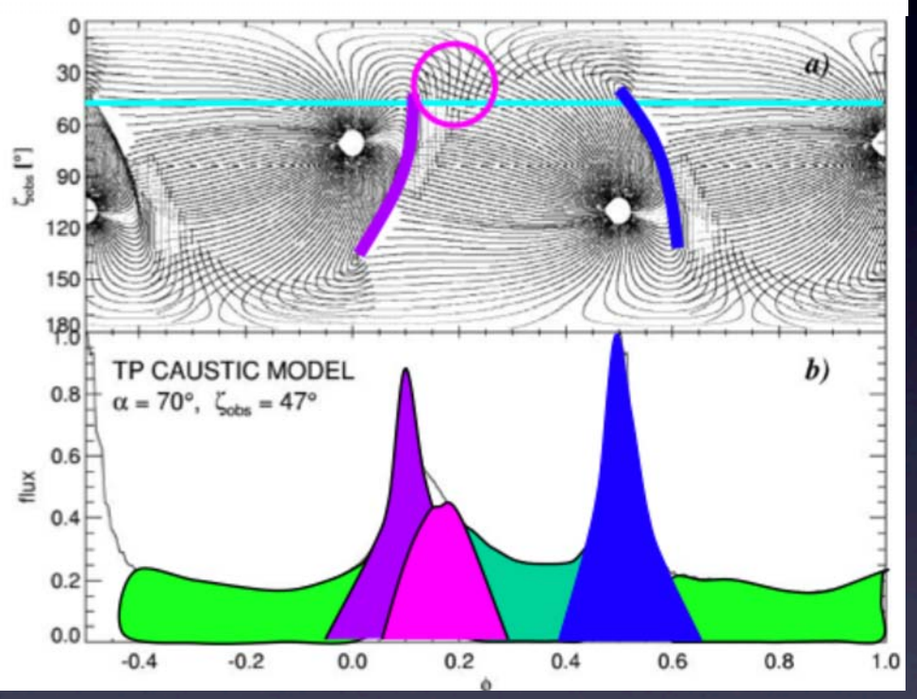
In force-free, similar region of emission, but different geometry and acceleration physics (likely reconnection)

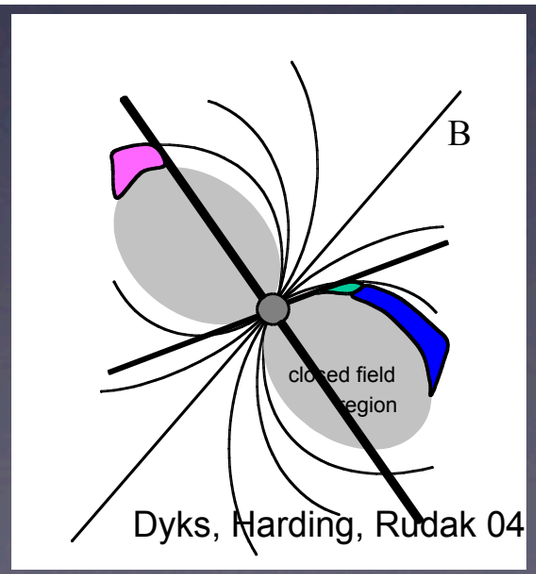
Detailed work to reconcile models is ongoing. Is FF emission just extended slot gap?



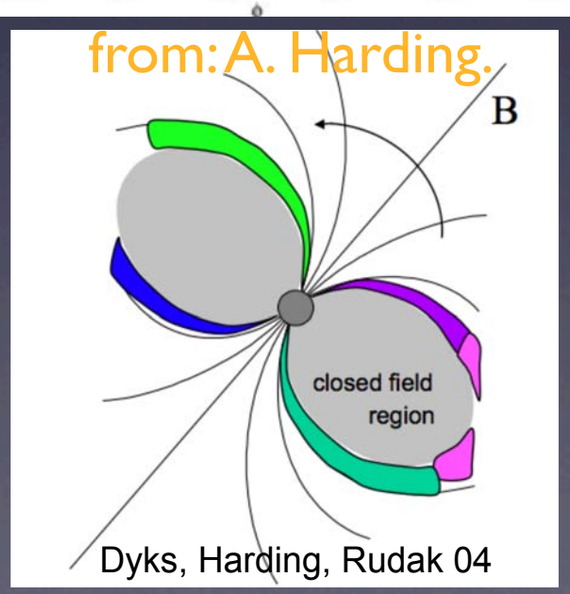






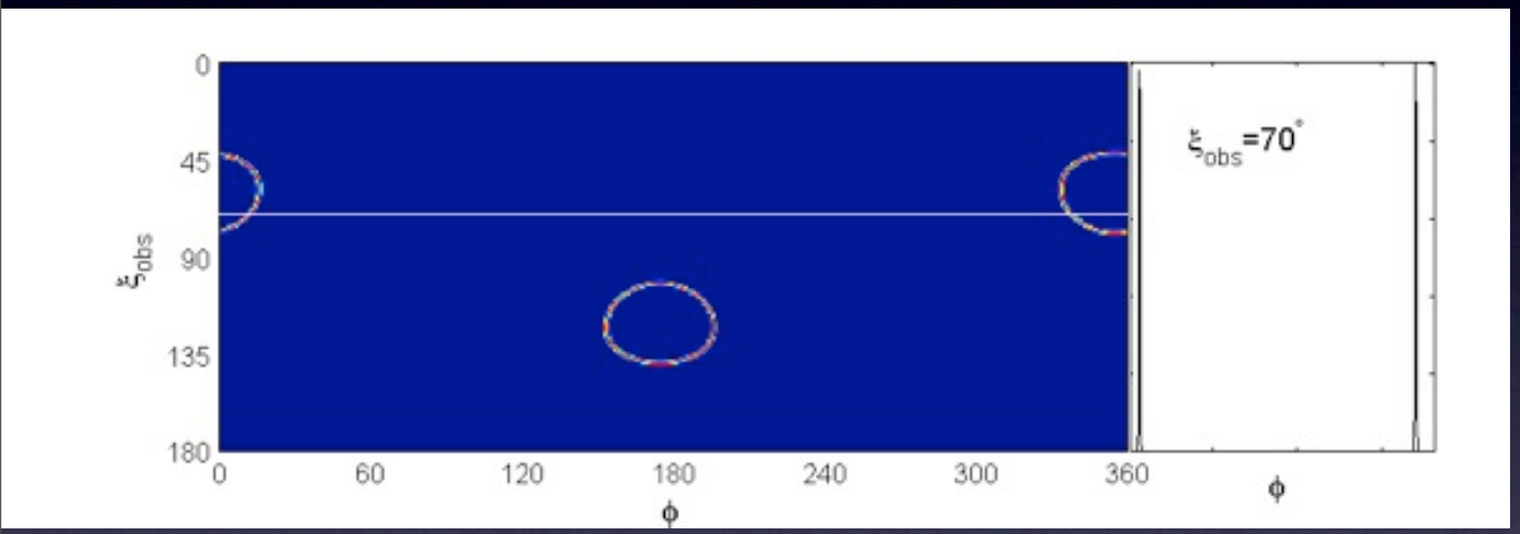


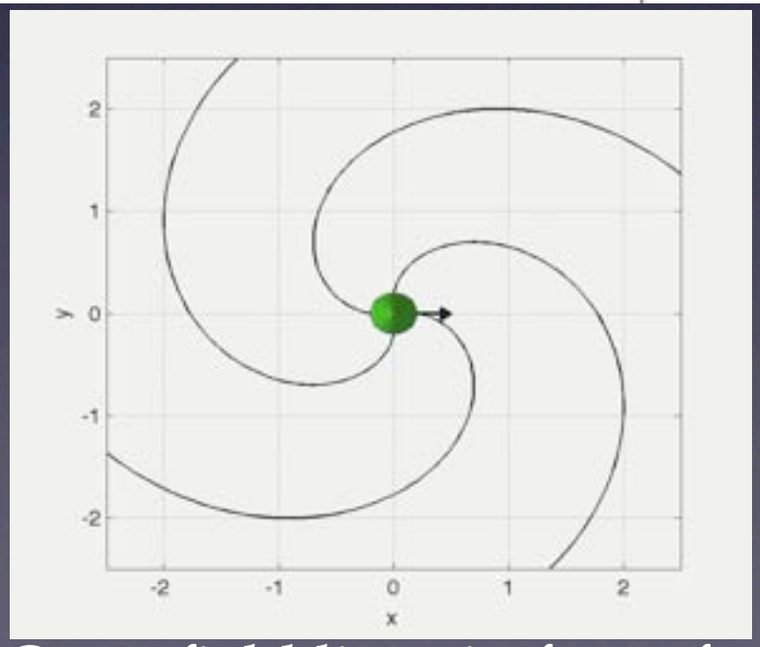
from: A. Harding.

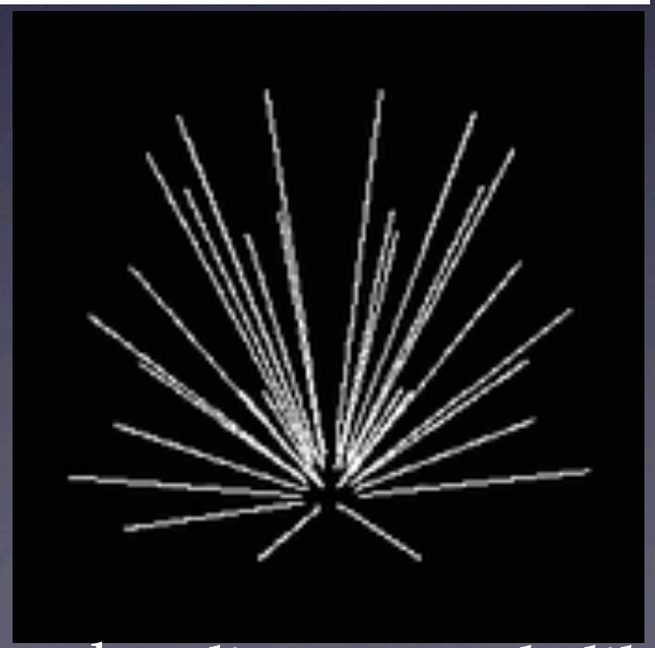


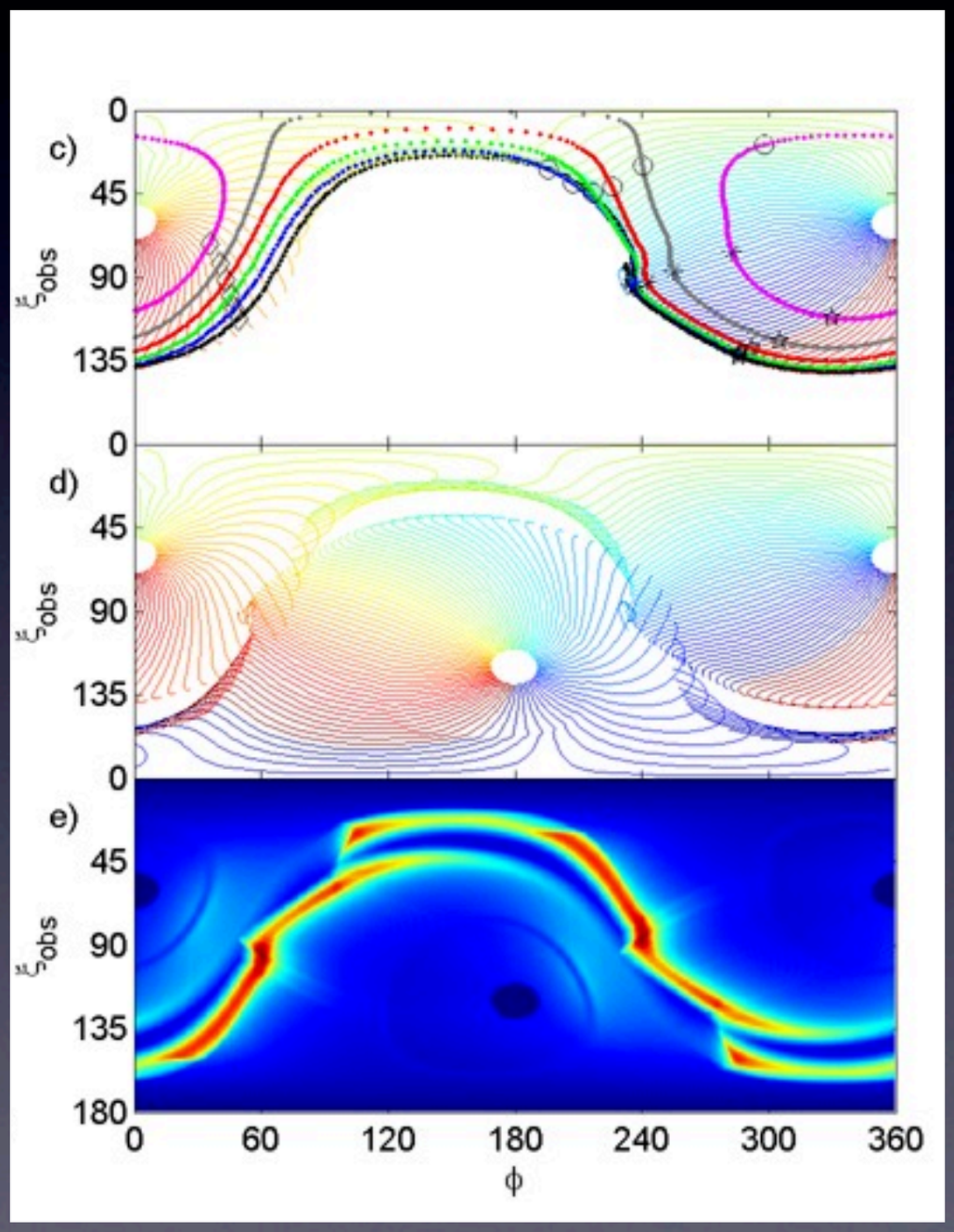
“Sky map stagnation”

Split-monopolar field is a perfect caustic. Particle trajectory is near straight-line, compensating rotation and sweepback. Sky map of monopole.









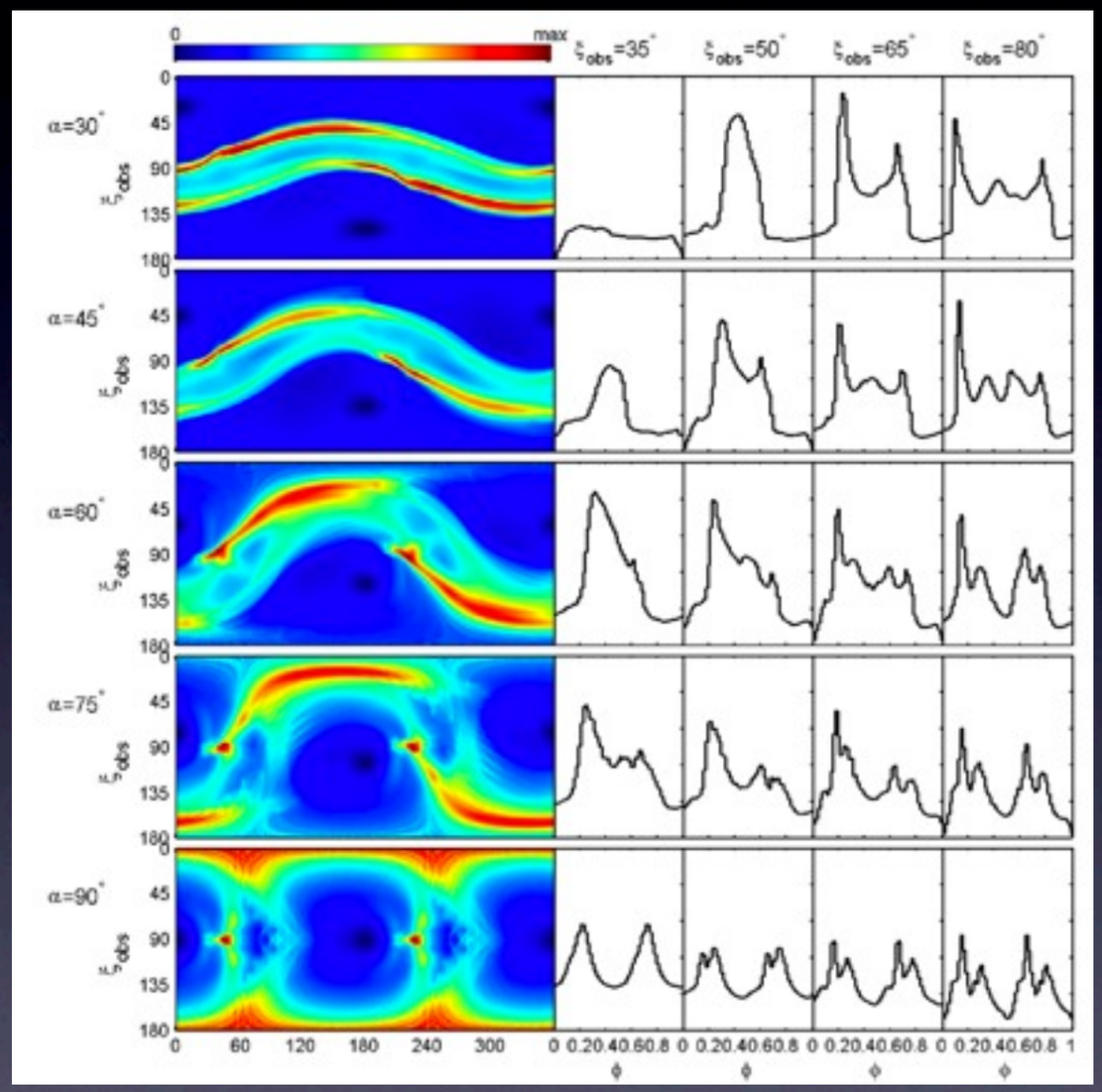
“Sky map stagnation”

Open field lines in force-free reach split-monopole like solution at LC.

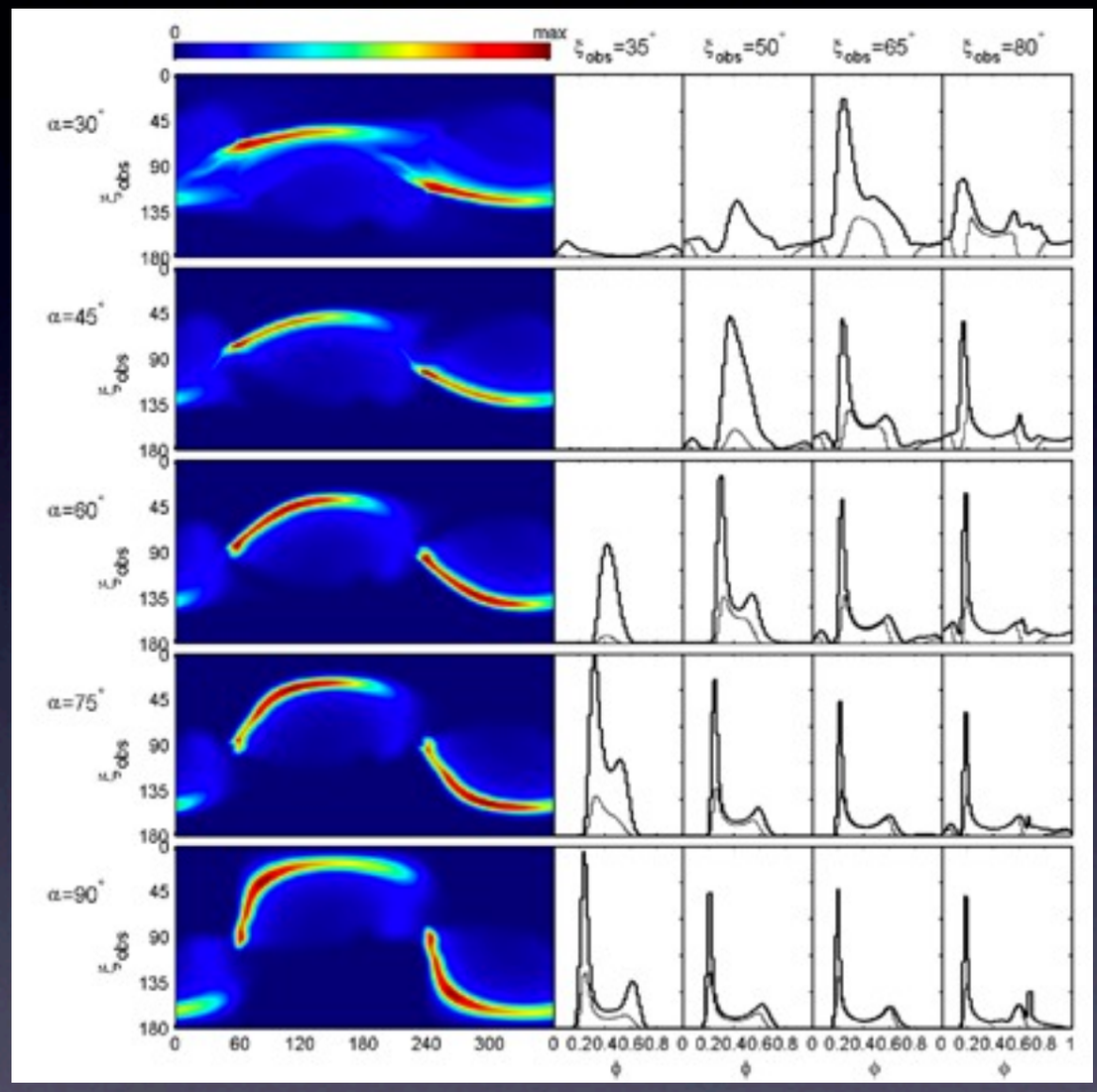
Force-free gallery: TPC and OG

Viewing angle

Inclination angle



SG/TPC with FF



OG with FF

SG/TPC and OG with FF field do not produce double peaks!

Bai & A. S. 2010

Spectral fitting

Radiation reaction limited curvature radiation is invoked in gaps

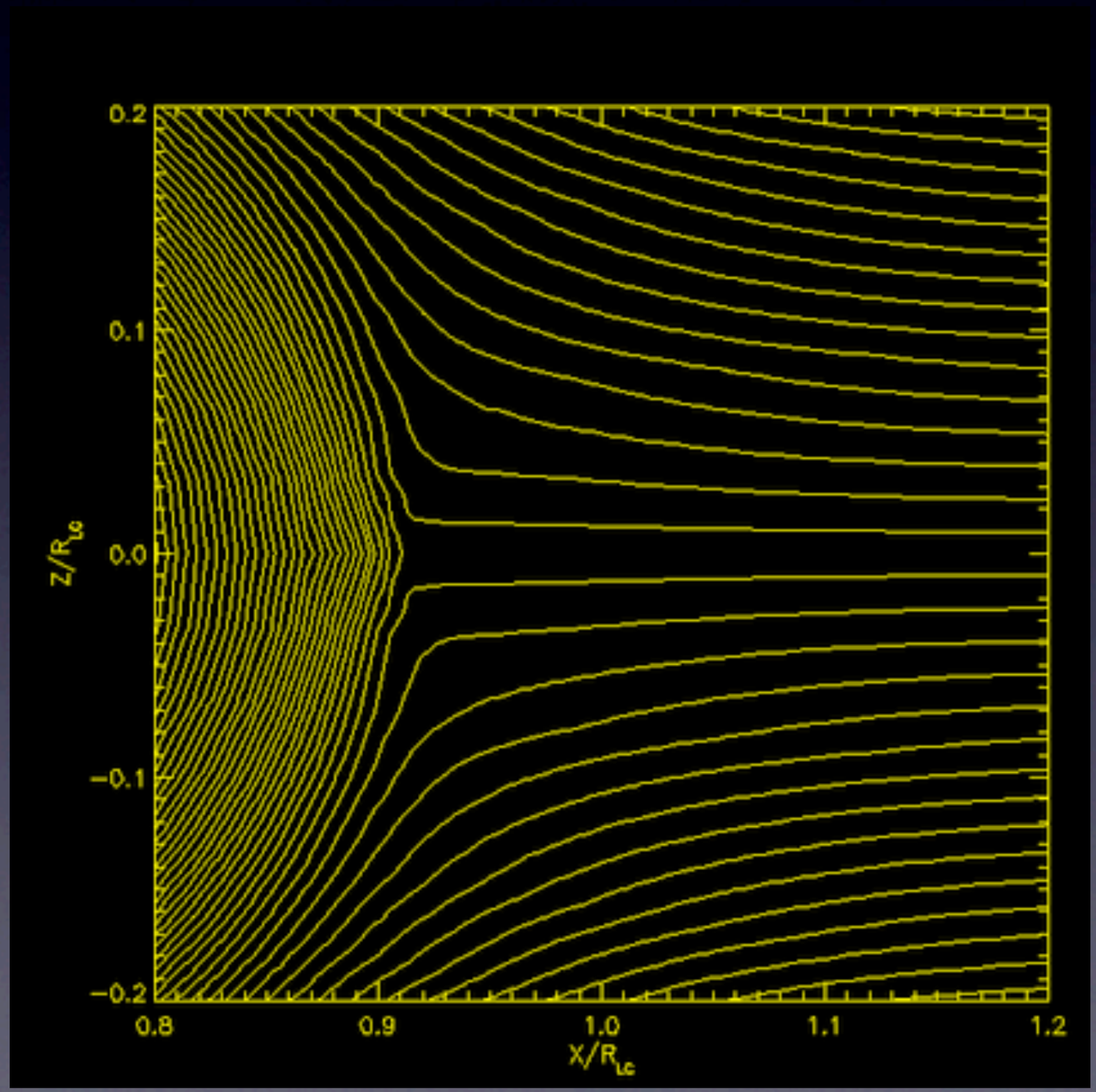
What is the acceleration and radiation mechanism in current sheet?

Relativistic reconnection and its acceleration spectrum is an unsolved problem. Vacuum gaps are not necessary to have accelerating E field.
Particles backstreaming from the Y-point.

Rad. reaction may still be important.

Radiation could be synchrotron, not curvature

Time-dependent phenomena possible, e.g. drifting subpulses.



Spectral fitting

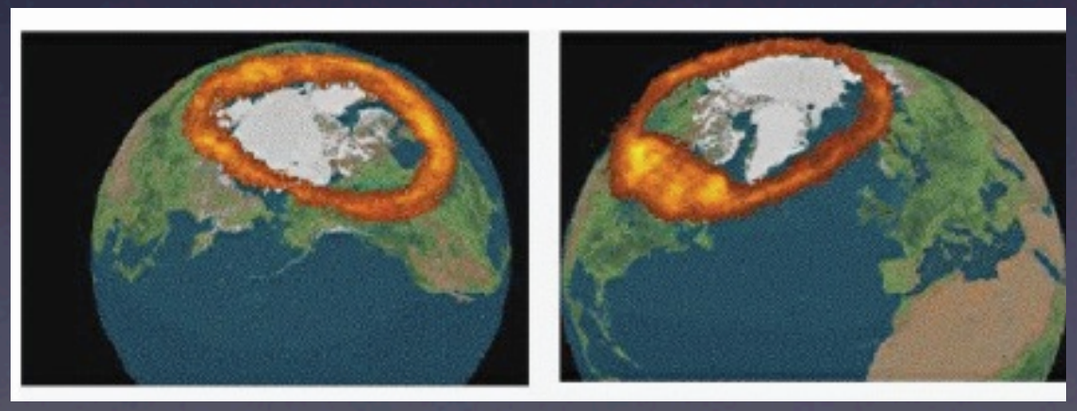
Another possibility: "auroral" electric field

No vacuum gap is needed in boundary layer plasma:

Consequence of Ohm's law and particle inertia:

$$E_{\parallel} = \frac{4\pi}{\omega_p^2}\frac{DJ_{\parallel}}{Dt} \propto \frac{m\gamma}{n_{current}}\frac{I}{\Delta_{current}\rho_B}, I \propto \sqrt{\dot{E}_R}$$

In planetary auroras, electron beams are accelerated to energies of the order of potential, but there are NO vacuum gaps!



See J. Arons' talk next week

Mind the gap: origin of the current

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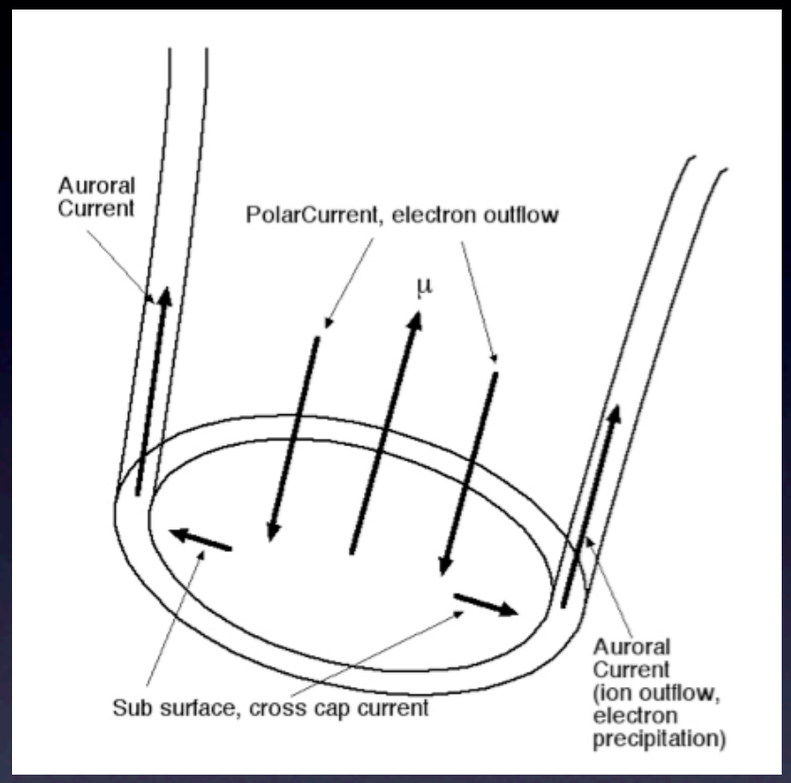
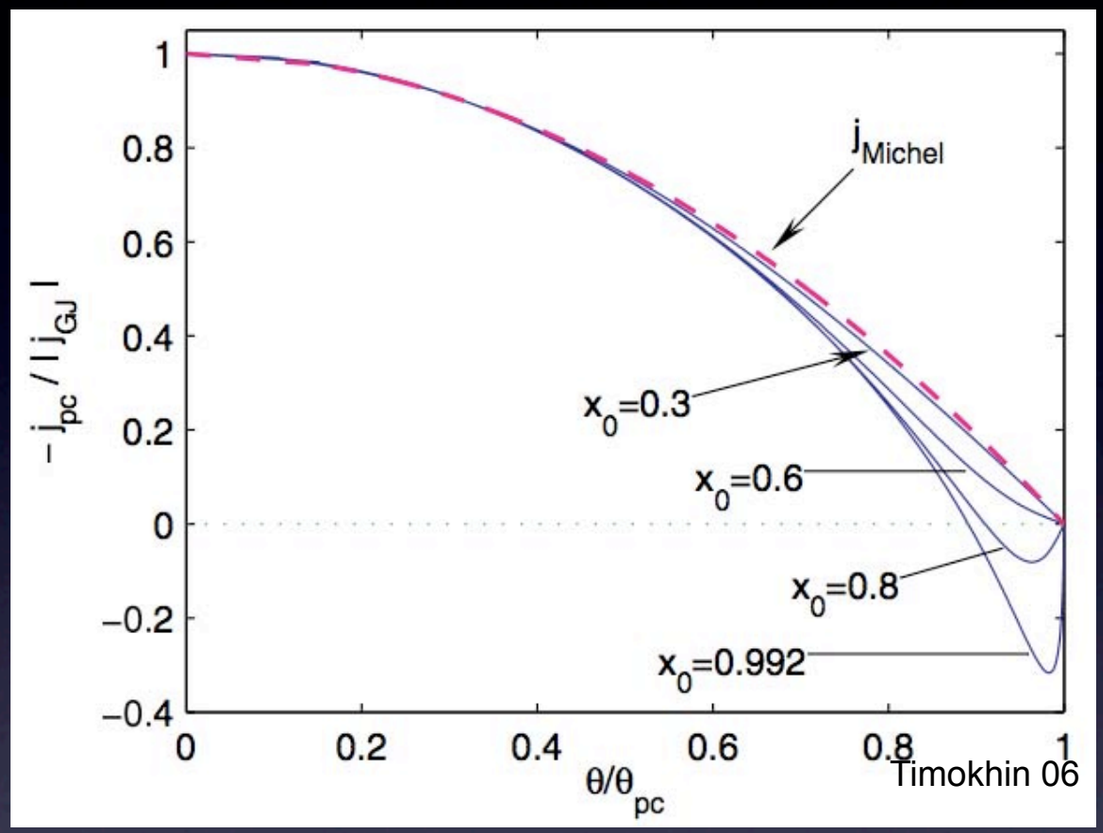




Timokhin 06

Force-free current is inconsistent with convenional gap physics: space-charge limited flow makes $j=j_{GJ}$ which does not vary fast enough over polar cap.

Also, for large inclinations current is >> than local GJ current, yet is of the same order as GJ current for aligned rotator

Are polar gaps time-dependent as a result?

Conclusions

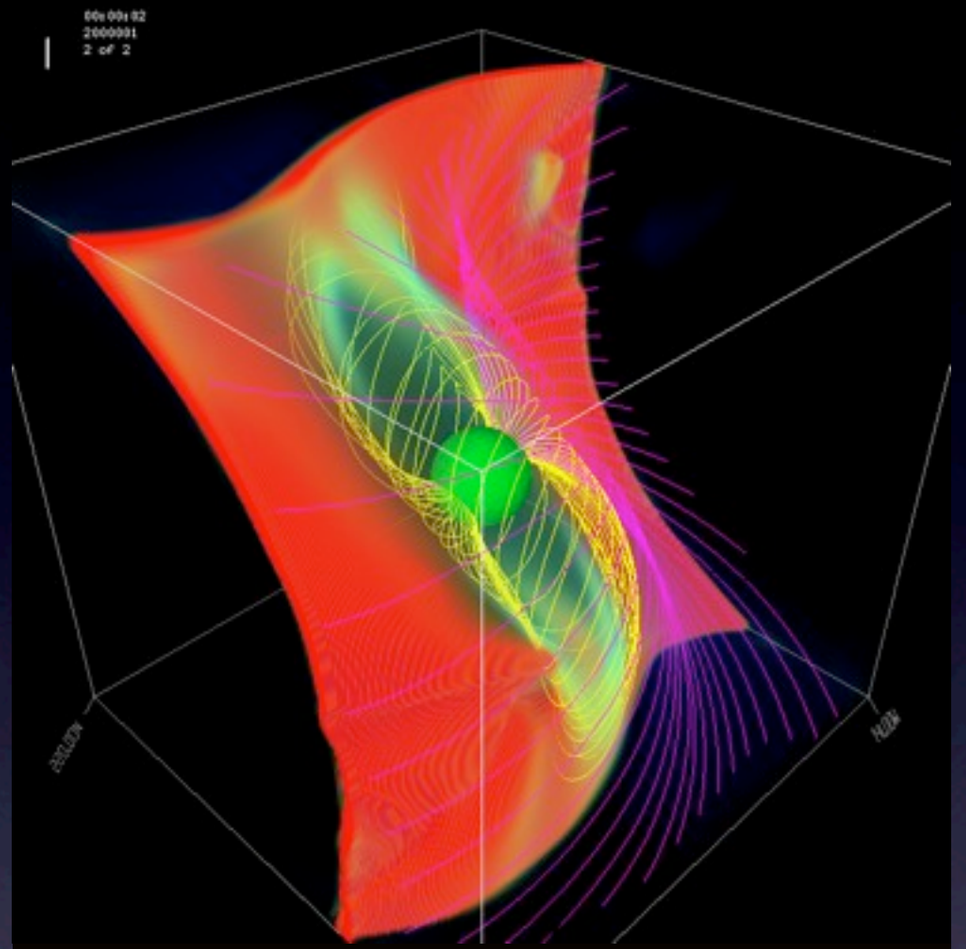
Magnetospheric shape with plasma effects is now known under the force-free framework.

Spin-down of arbitrary inclination rotators can be calculated. Spin down power scales as $(1+\sin^2\theta)$.

Braking index still 3, but slow reconnection at Y-point may make n<3.

Expect older pulsars to be preferentially aligned.

Gamma-ray emission from Fermi is emitted in the outer magnetosphere, in the region directly tied to the current sheet.



$$\dot{\Omega} = K\Omega^n \qquad n = \frac{\ddot{\Omega}\Omega^2}{\dot{\Omega}^3} < 3$$

$$\dot{E} \approx \frac{\mu^2\Omega^2}{c\, r_c^2}\left(1+\sin^2\theta\right)$$

$$r_c = R_{LC}\left(\frac{\Omega}{\Omega_0}\right)^{\alpha}$$

$$n = 3 - 2\alpha < 3$$

Magnetospheric models

	Vacuum	Space charge limited	Space charge limited+pairs	Abundant plasma
Field	Rotating vacuum dipole (RVD)	?	Assume RVD	Force-free
Acceleration	wild	gaps	Slot / Outer gaps	none / re-connection?
Spin down	$\frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\theta$	?	?	$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$

verdict? No Unlikely Workhorse Contender

problems not global no microphys.

Conclusions

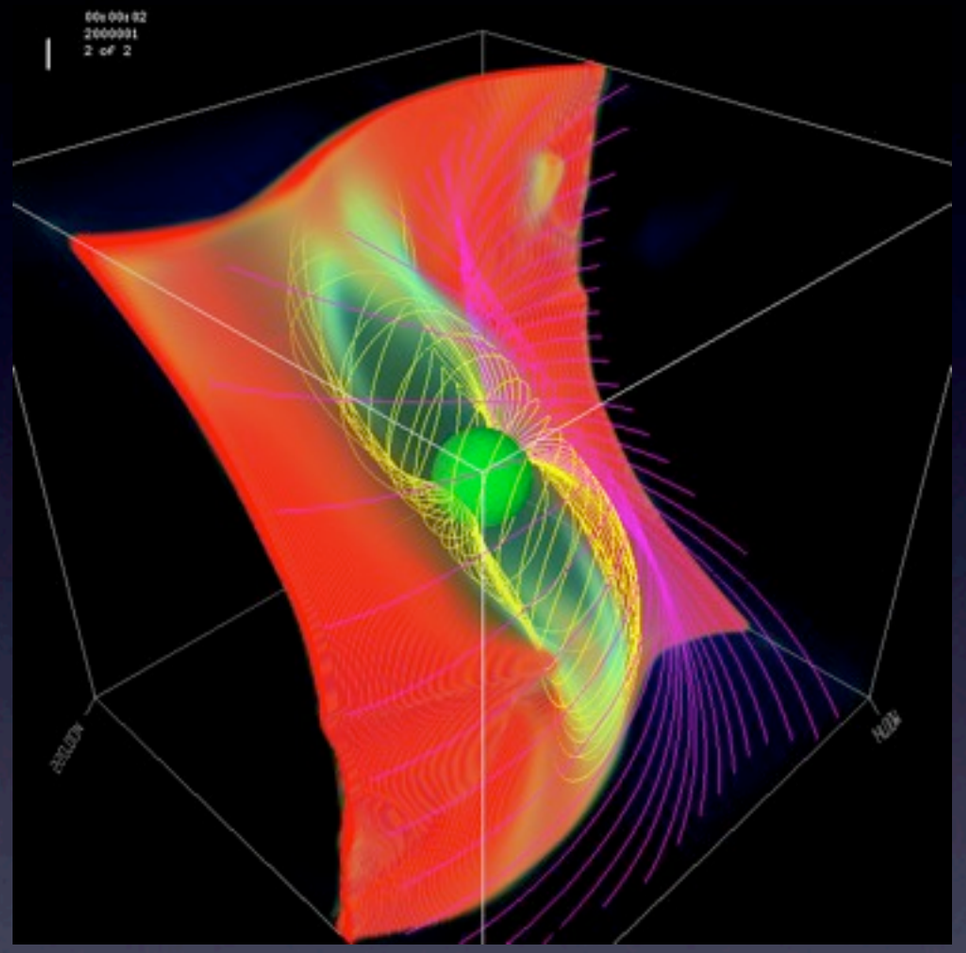
Pulsar high-energy emission is coming from the outer magnetosphere.

Two well-established models for the location of emission in magnetosphere exist: SG & OG. Both rely on the vacuum field. The physical basis for existence of these accelerating regions and their extents is very uncertain, but they fit the data!

More realistic field, force-free magnetosphere, can produce double peaks. However, neither SG nor OG locations work for FF. The best fit is from emission near the current sheet at and beyond the LC.

Caustics in FF due to split-monopolar asymptotics. Theory of emission from current sheet is not well developed at all, and much more theoretical work has to be put in. Large L_γ makes sense w/cur sheet.

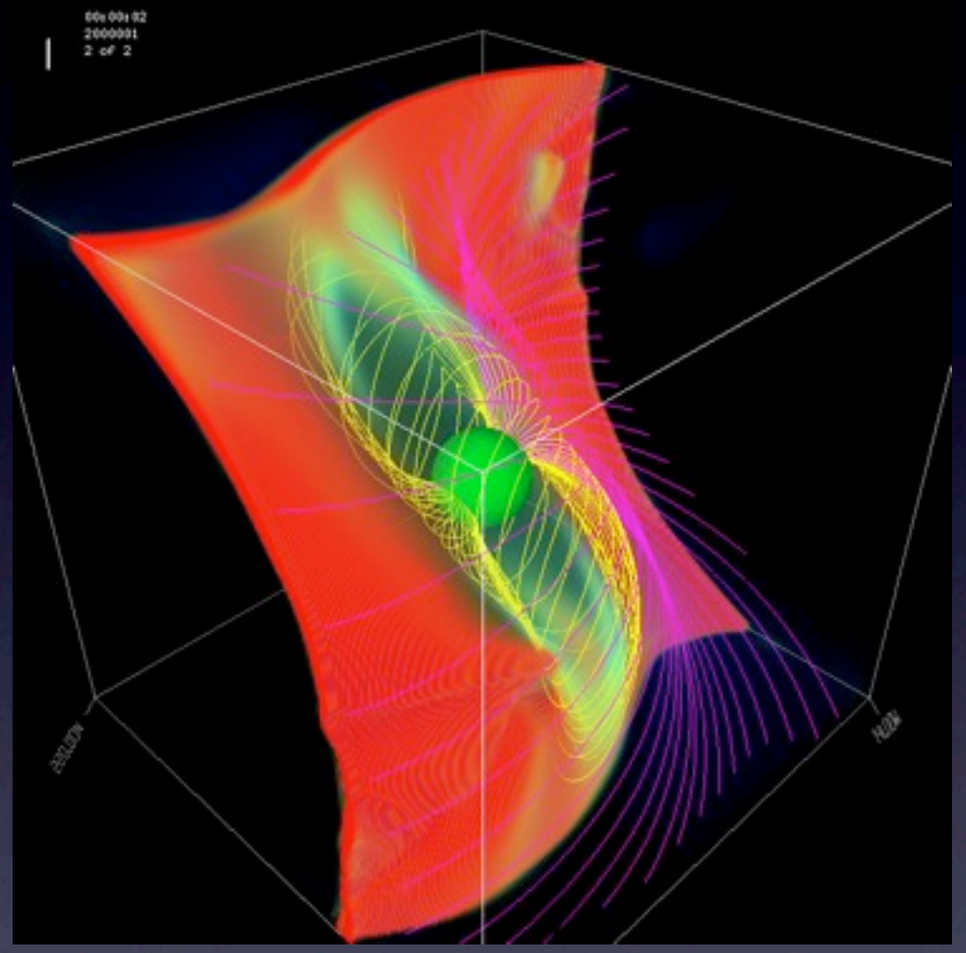
Large B@LC--> reconnection.
Phase-resolved spectra from Fermi will be crucial!



Kirk et al 02,
Lyubarsky 96
Petri 09

Conclusions

Pulsars are not just about “outer gap vs slot gap”!!! Both of these are decoupled from the global magnetosphere, and cannot be correct even if they will fit all the data!



At the present, there is a disconnect between the current that can be supplied by polar cap or gaps. The gap current is not the same as required by the force-free magnetosphere. Where then do the currents originate from, and does that constrain the gap models?

Are pulsars charge starved or full of dense plasma?

How do relativistic current sheets make emission? (Is there a population of MeV-emitting pulsars?)