

Pulsars: status and prospects

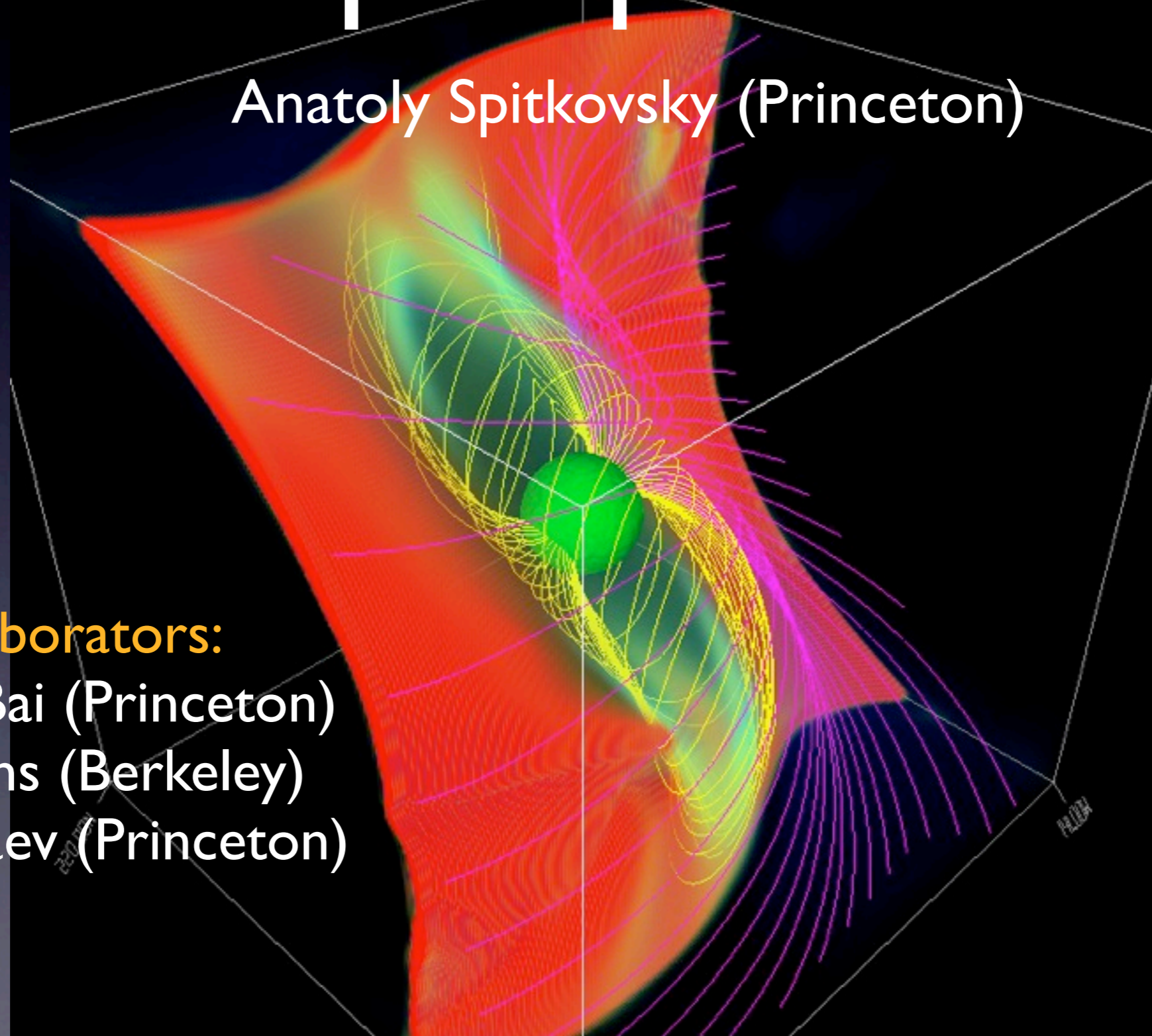
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Collaborators:

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Jon Arons (Berkeley)

Mike Belyaev (Princeton)



Pulsars are rotating neutron stars, born in supernova explosions. They emit periodic pulses of radiation.

The Crab Nebula

In the year 1054 A.D., Chinese astronomers were startled by the appearance of a new star, so bright that it was visible in broad daylight for several weeks. Today, the Crab Nebula is visible at the site of this violent stellar explosion. In this view, NASA's Hubble Space Telescope has zoomed in on a portion of the Crab to reveal its detailed structure.

Located about 2 kpc (6,500 ly) from Earth in the direction of the constellation Taurus, the Crab Nebula is the remnant of a star that began its life with about 8-10 times the mass of our Sun. Such a massive star consumes its nuclear fuel so rapidly that it lives only about 50 million years before exploding as a supernova. For this star, the end came on July 4, 1054. The explosion was witnessed as a naked-eye "Guest Star" by Chinese astronomers, and is also depicted in rock paintings of native Americans in the southwestern United States.

This image was created by the Hubble Heritage Team from data obtained by Hubble's Wide Field and Planetary Camera 2. Images taken with five different color filters, totaling over 10 hours of exposure time, have been combined to construct this false-color picture. Resembling an abstract painting, the image shows ragged gaseous shreds of the original star that are expanding away from the explosion site at over 1,500 km/s (3.4 million mph). The colorful network of filaments is the material from the outer layers of the star that was expelled during the explosion.

The core of the star has survived the explosion as a "pulsar," visible in the Hubble image as the lower right of the two moderately bright stars near the center. The pulsar has about 1.4 times the mass of the Sun, crammed by gravity into an object only about 10 miles in diameter. This incredible object, a "neutron star," is even more remarkable because it spins on its axis 30 thirty times a second. The spinning pulsar heats its surroundings, creating the ghostly diffuse bluish-green synchrotron cloud in its vicinity, including a blue arc toward the upper right of the neutron star.

The picture is somewhat deceptive in that the filaments appear to be close to the pulsar. In reality, the yellowish green filaments toward the right side of the image are closer to us, and approaching at some 350-800 km/s. The orange and pink filaments toward the top of the picture, including the "backwards question mark," is material behind the pulsar, rushing away from us at 200-1000 km/s.

The various colors in the picture arise from different chemical elements in the expanding gas, including hydrogen (orange), nitrogen (red), sulfur (pink), and oxygen (greenish-blue). The shades of color represent variations in the temperature and density of the gas, as well as changes in the elemental composition.

These chemical elements, some of them newly created during the evolution and explosion of the star and now blasted back into space, will eventually be incorporated into new stars and planets. Astronomers believe that the chemical elements in the Earth and even in our own bodies, such as carbon, oxygen, and iron, were made in other exploding stars billions of years ago.

Blair, W. P., Davidson, K., Fesen, R. A., Uomoto, A., MacAlpine, G. M., & Henry, R. B. C., "HST/WFPC2 Imaging of the Crab Nebula. I. Observational Overview," 1997, *ApJS*, **109**, 473

<http://heritage.stsci.edu>

HST • WFPC2

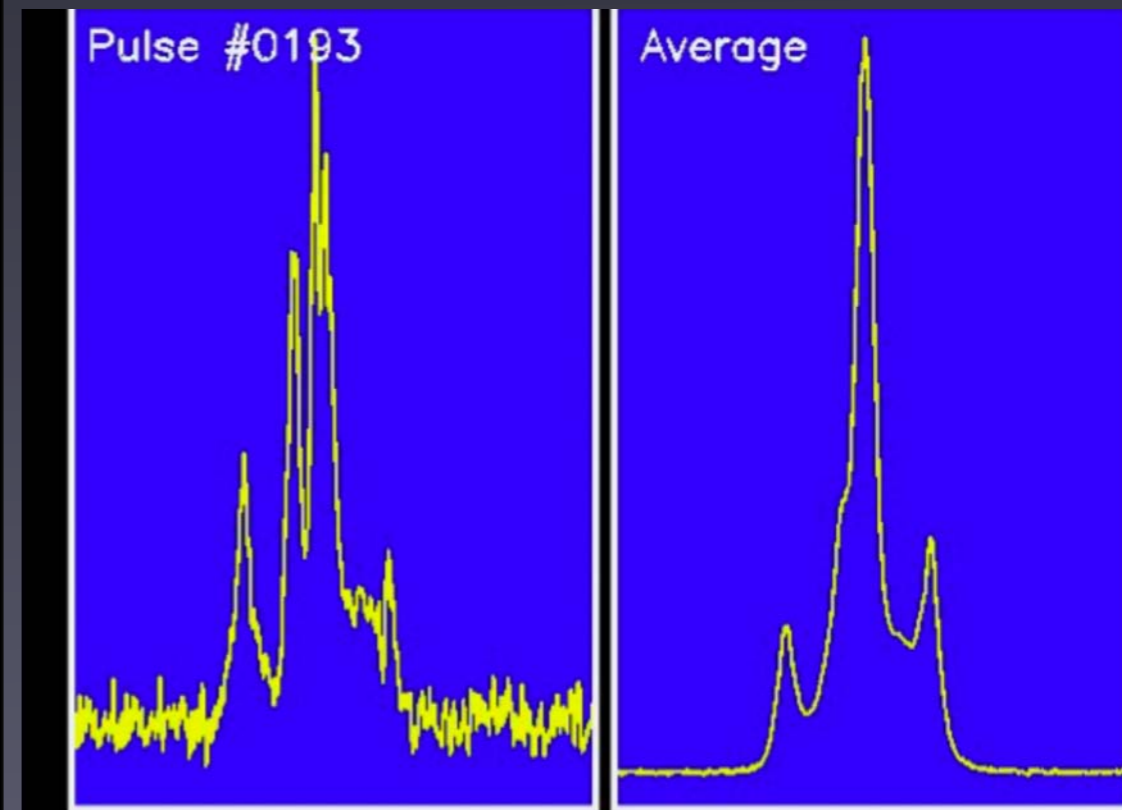
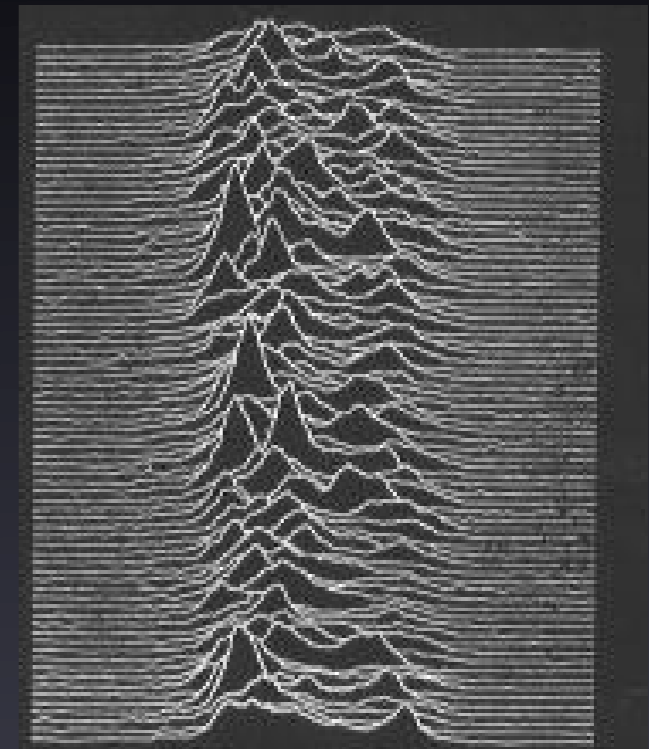
VLT

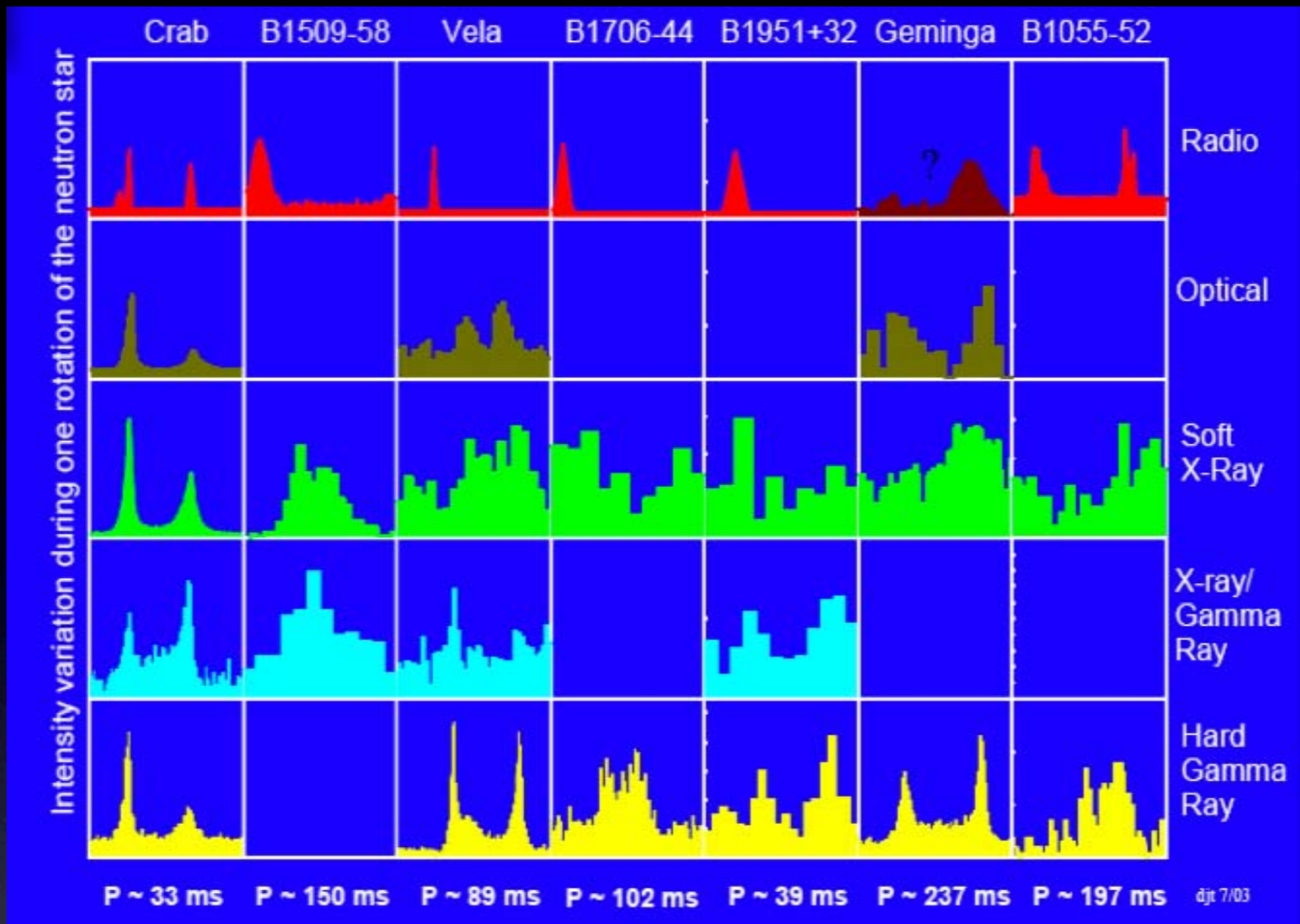
W.P. Blair (JHU),
K. Davidson (U. Minnesota) and
The Hubble Heritage Team:
K. Noll, H. Bond,
C. Christian, J. English,
L. Frattare, F. Hamilton,
and Z. Levay (STScI)

Green F502N [O III]
Blue F547M Strömgren γ
Orange F656W H α
Red F658N [N II]
Pink F673W [S II]

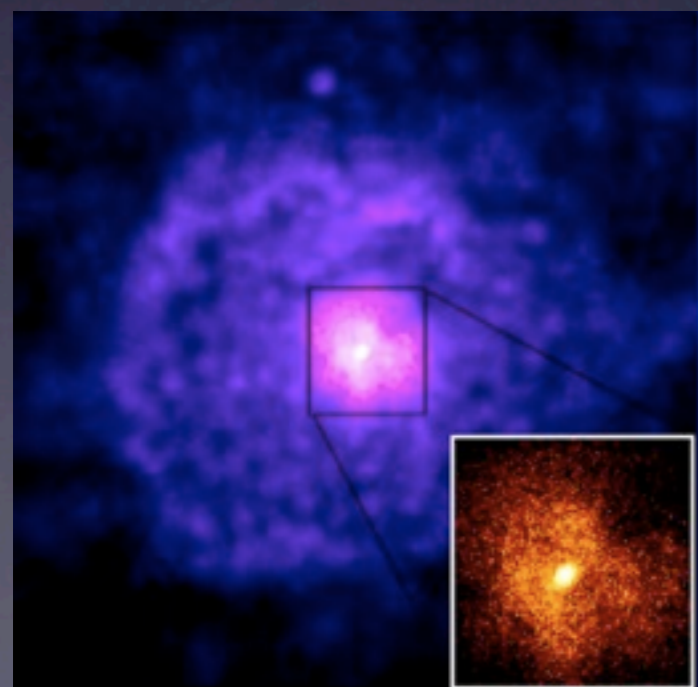
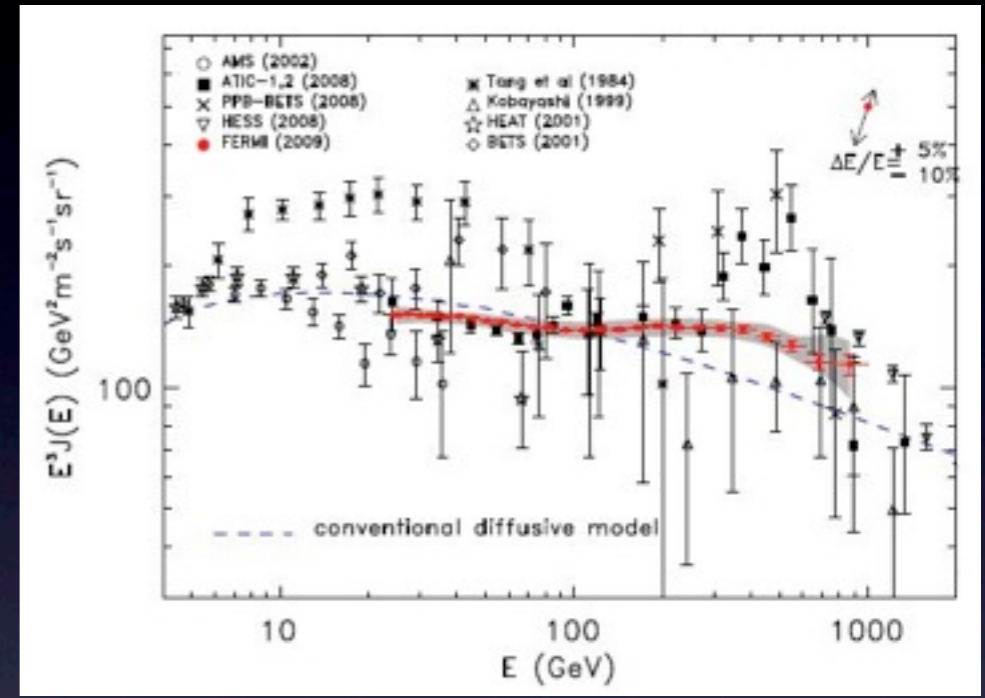
10"

N
E

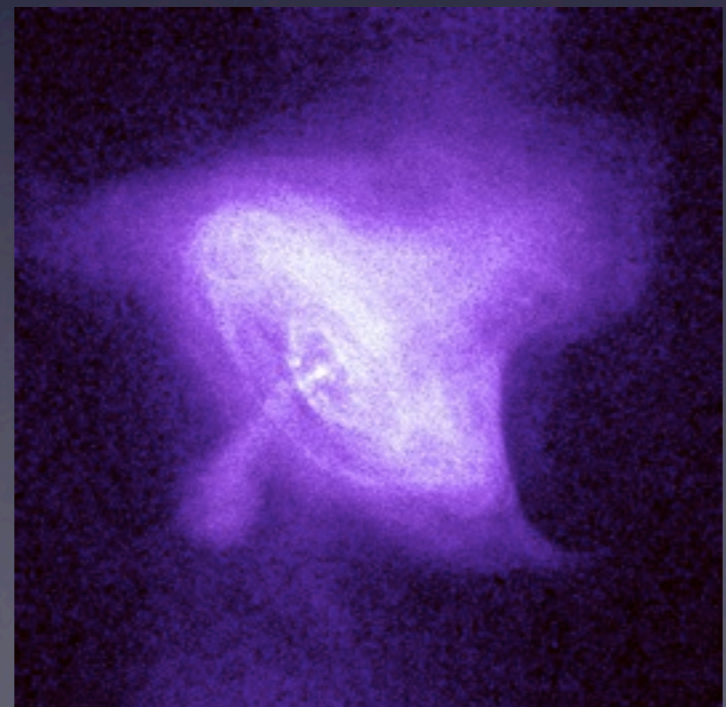




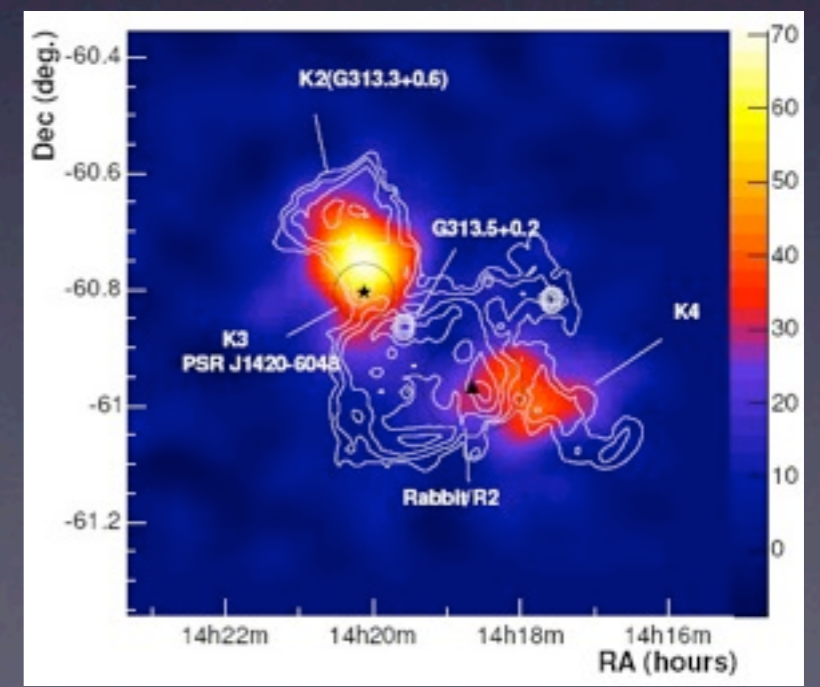
Broadband pulsed emission
 Power PWNe: radio-TeV
 Possible positron excess



G21.9 (Safi-Harb et al 2004)

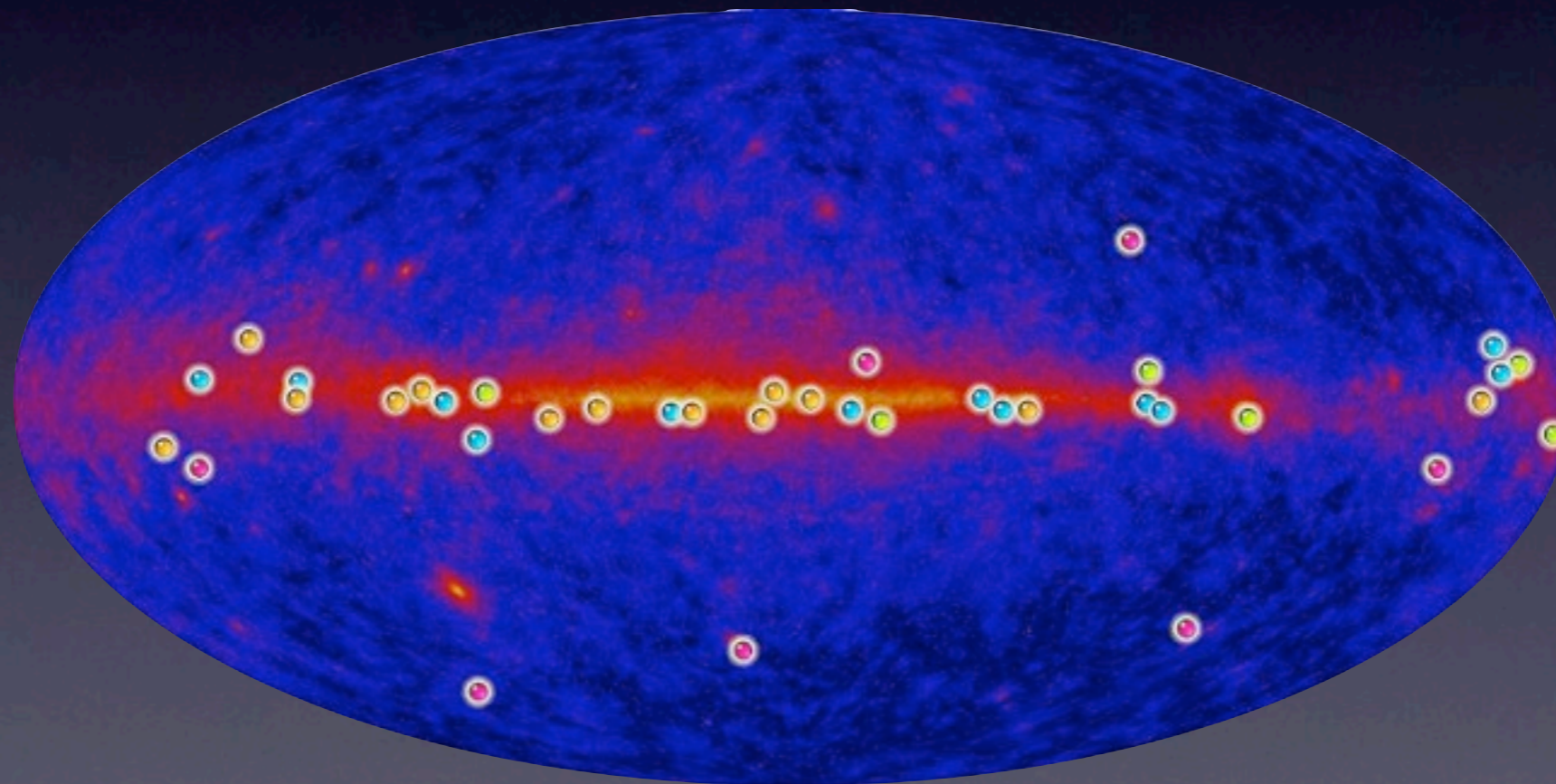


Crab (Weisskopf et al 2000)



HESS J1420 (Aharonian et al 2006)

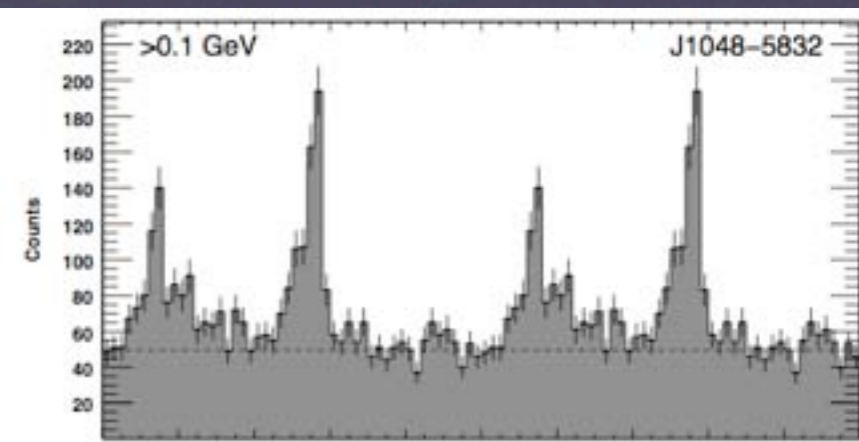
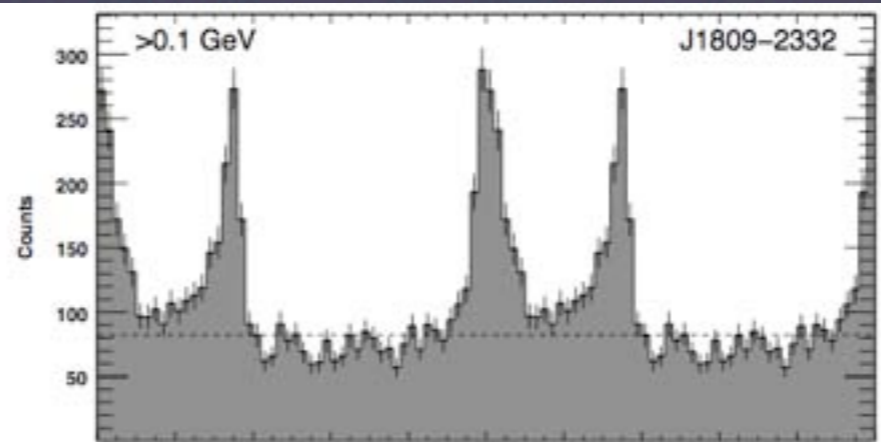
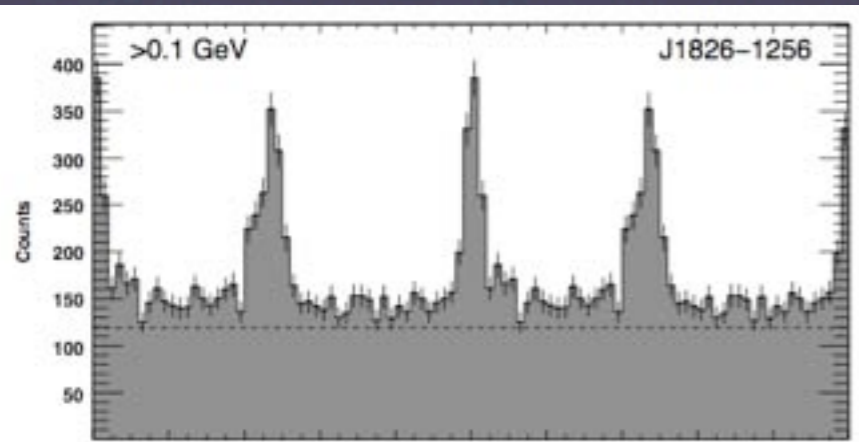
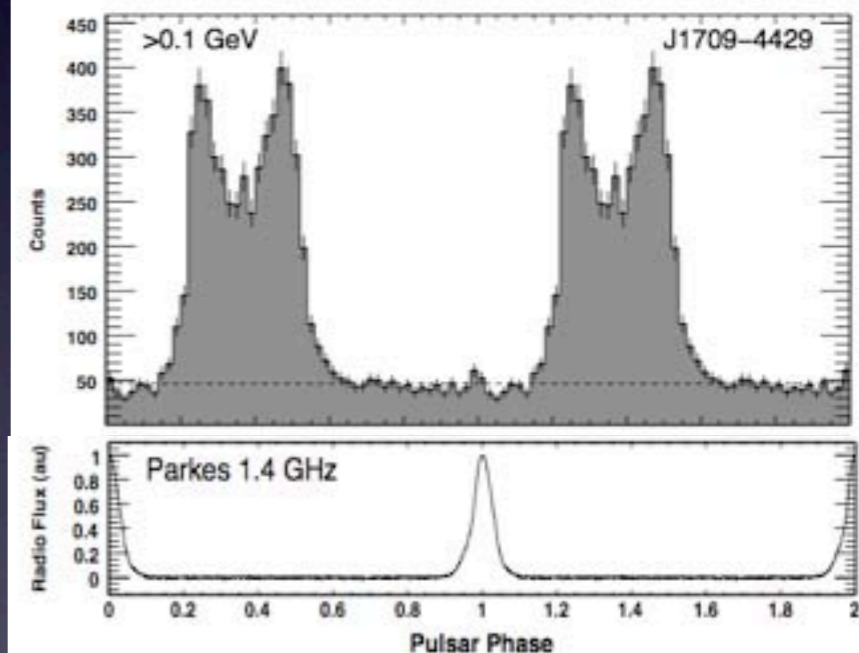
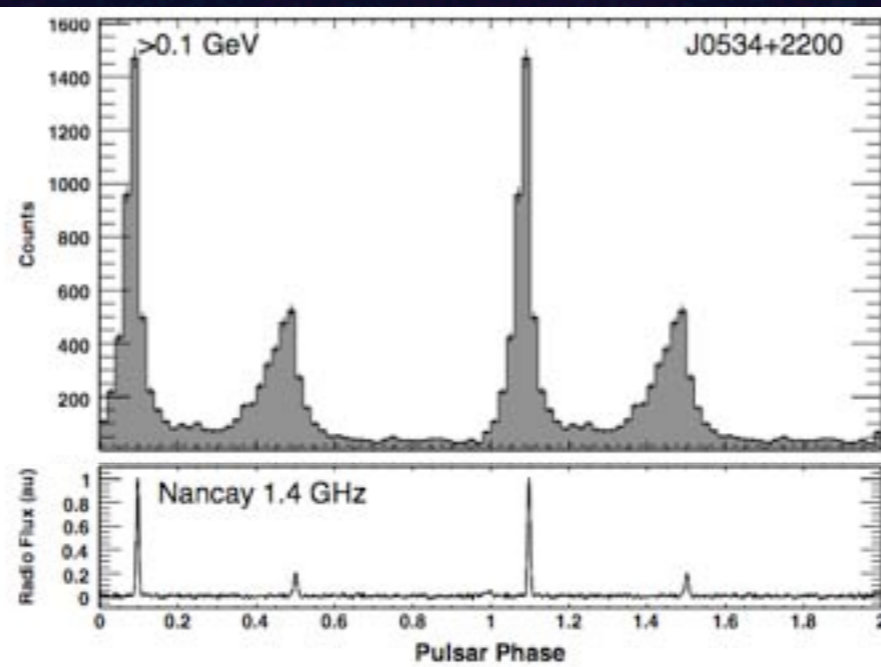
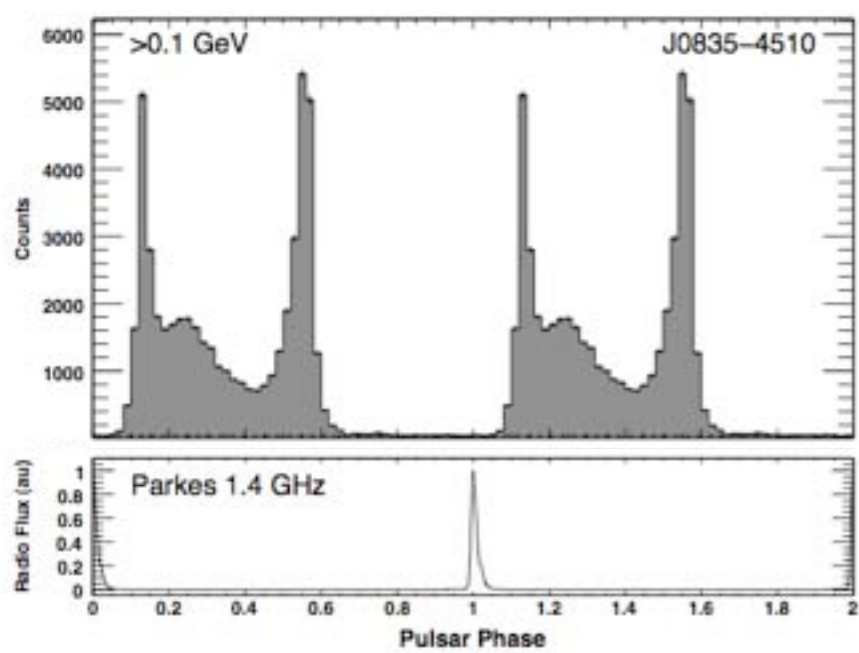
Gamma-ray emission from pulsars



Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

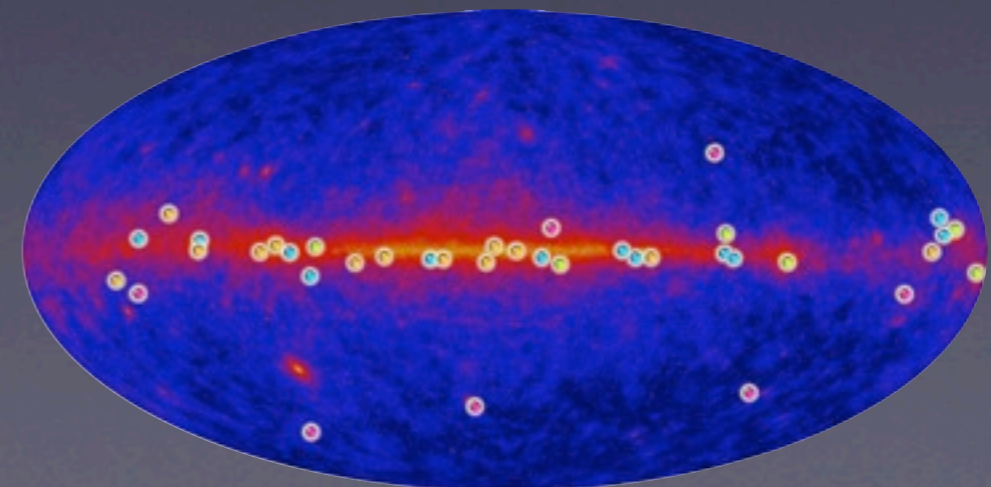
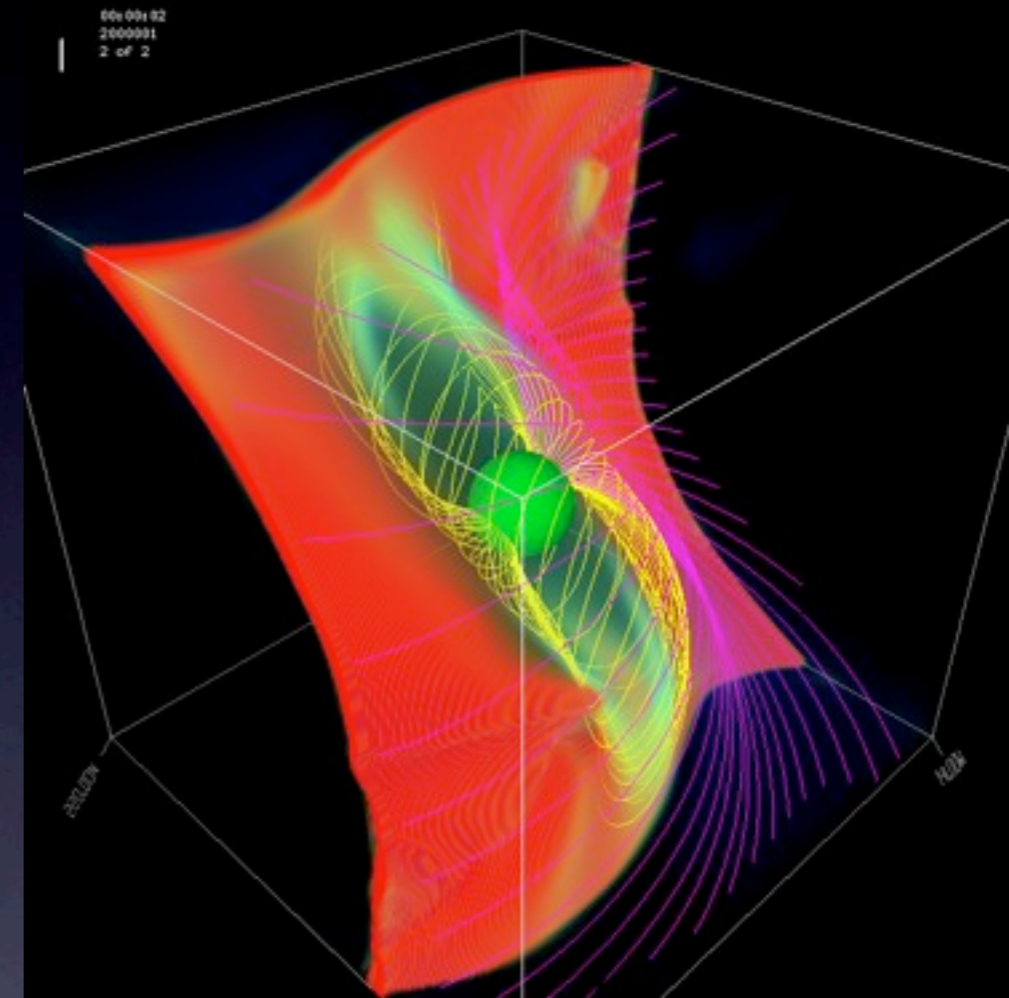
Gamma-ray emission from pulsars



Pulsars in Fermi era

Why are pulsars interesting?

- Unique laboratory for strong B fields and relativistic plasmas
- Prototypes of other astrophysical objects: accretion disks, jets, black hole magnetospheres
- Not understood for > 40 yrs
- Prime sources for Fermi
- Incredible electromagnetic machines



Open questions:

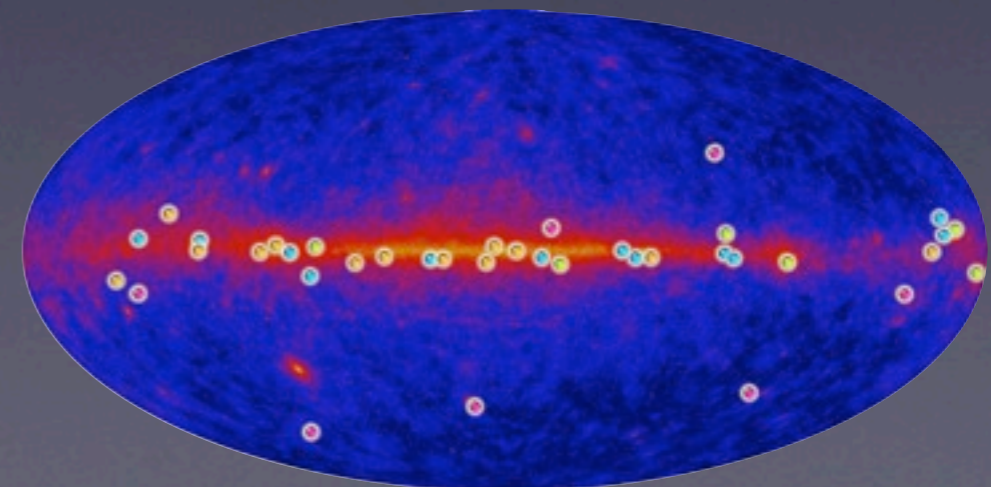
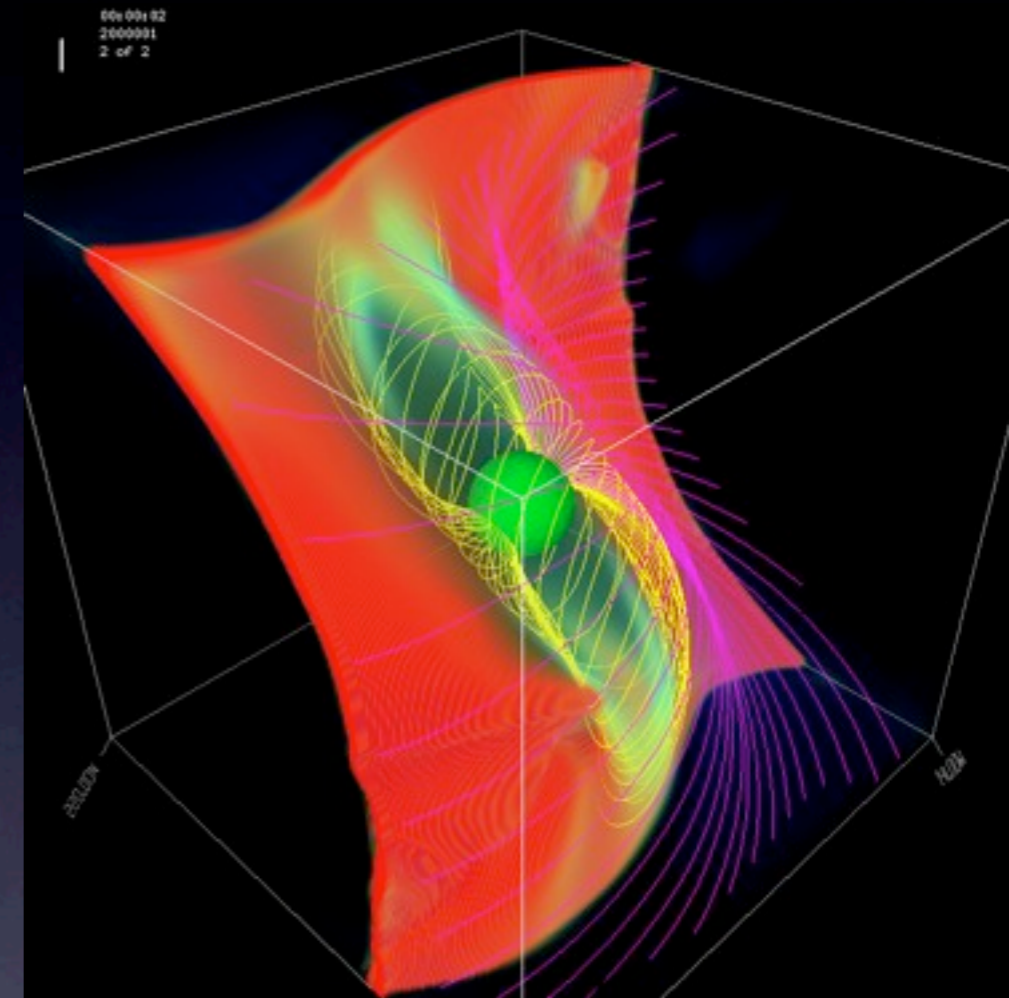
How pulsar magnetosphere works?

How pulsar wind works?

How pulsar wind nebula works?

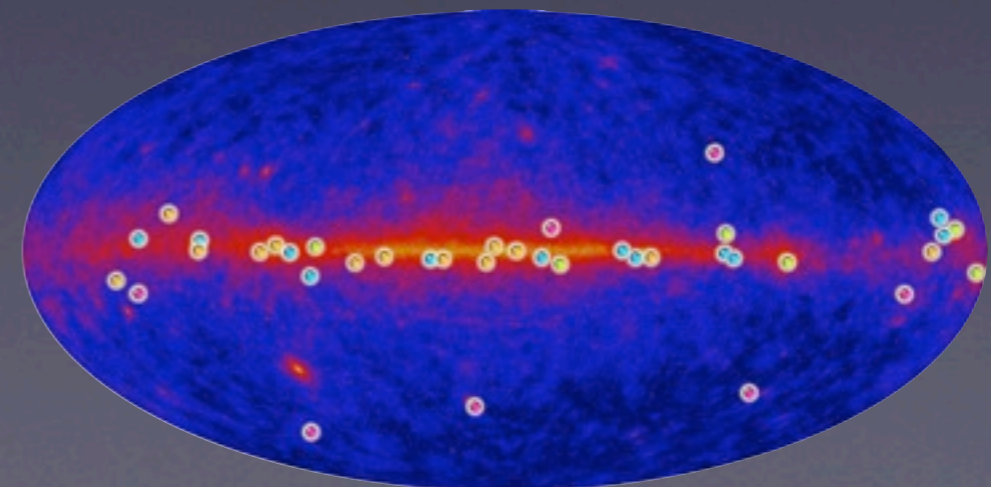
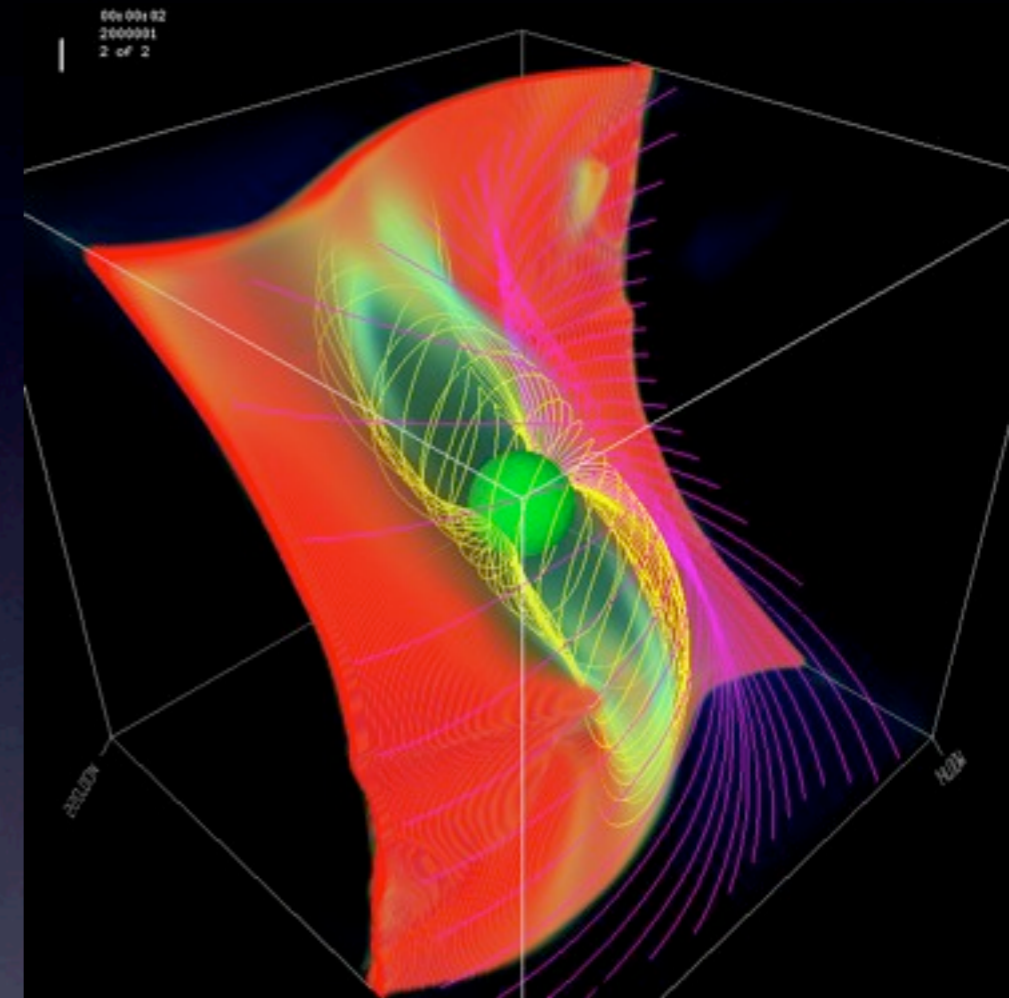
How particle acceleration works?

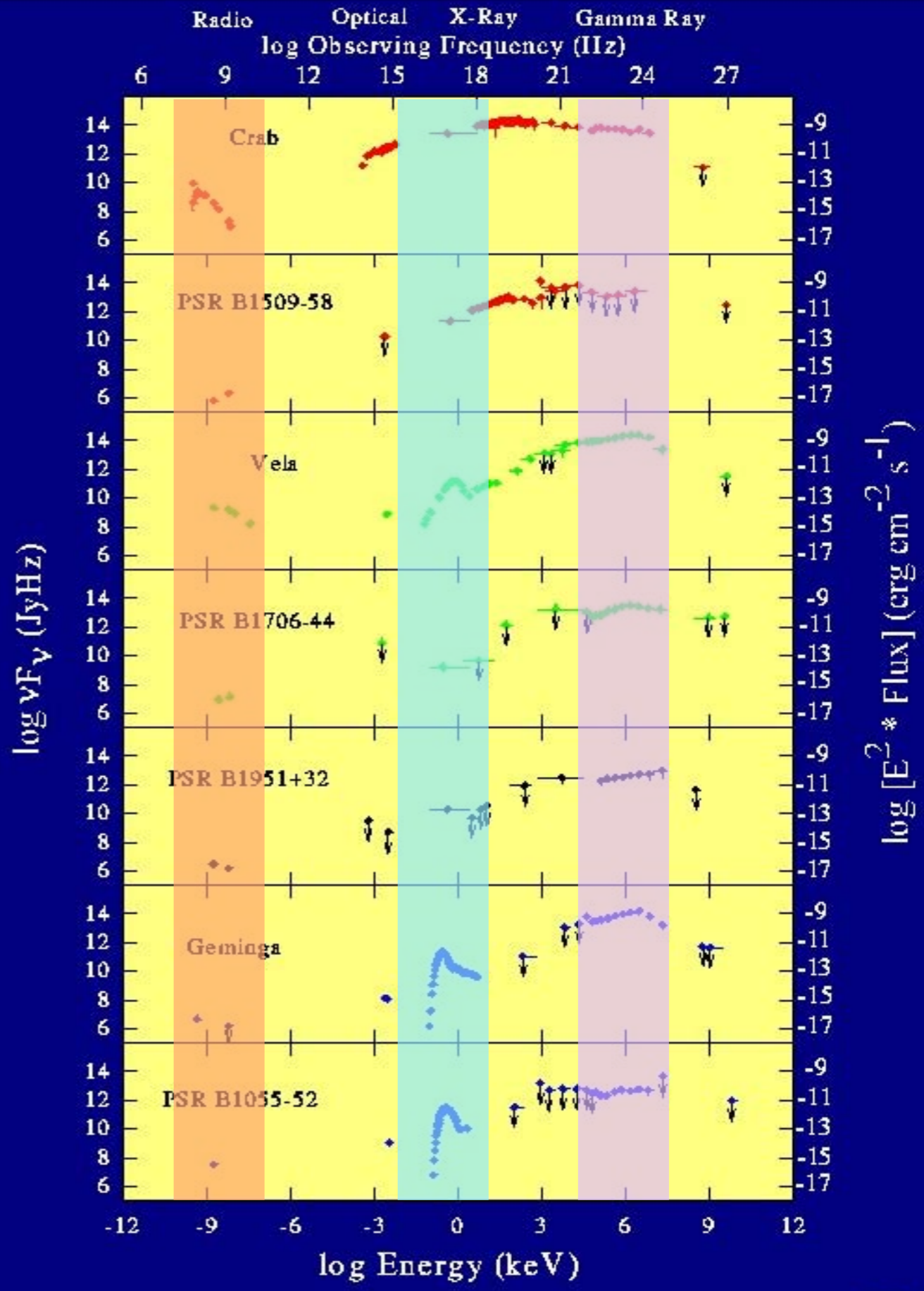
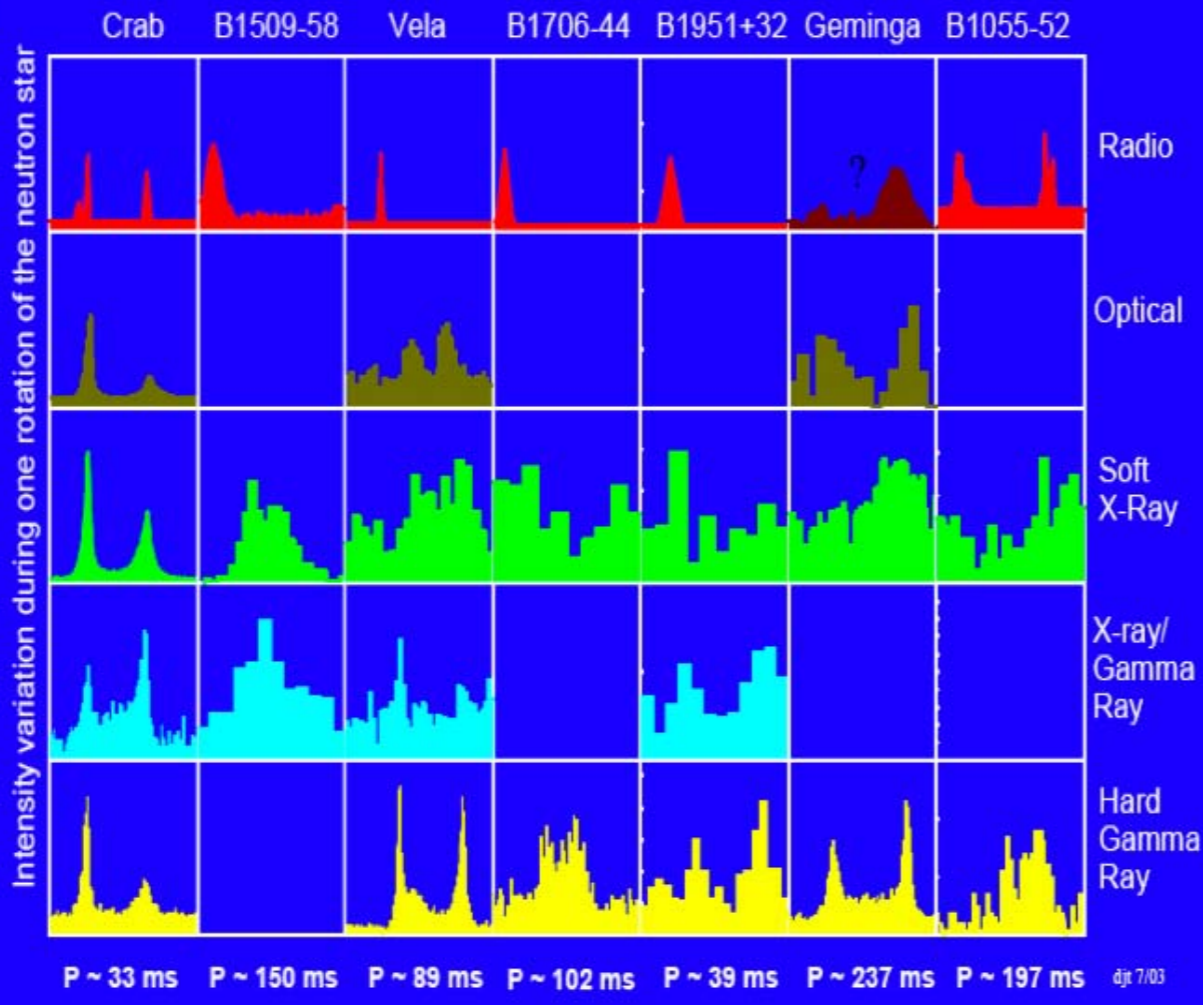
How emission works?



Outline

- Magnetospheric models: energy source and plasma creation
 - Vacuum and charge-separated models
 - Dense-plasma models
- Origin of high-energy emission
- Implications for pulsar winds
- Particle acceleration in PWNe





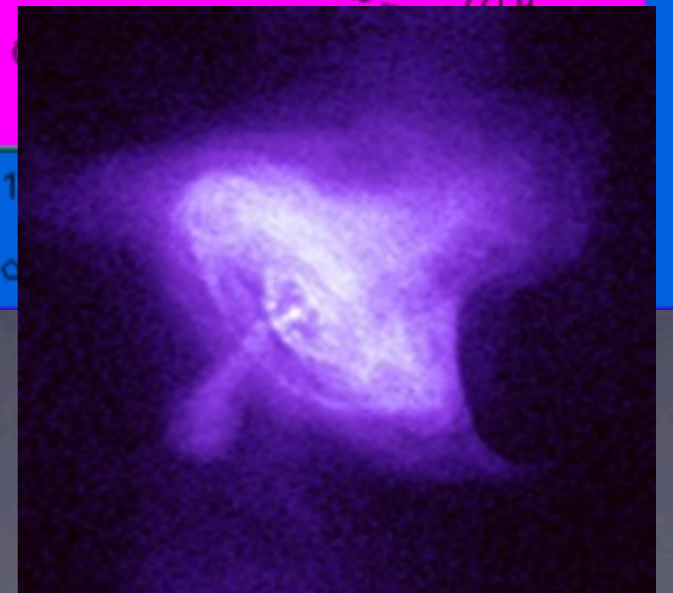
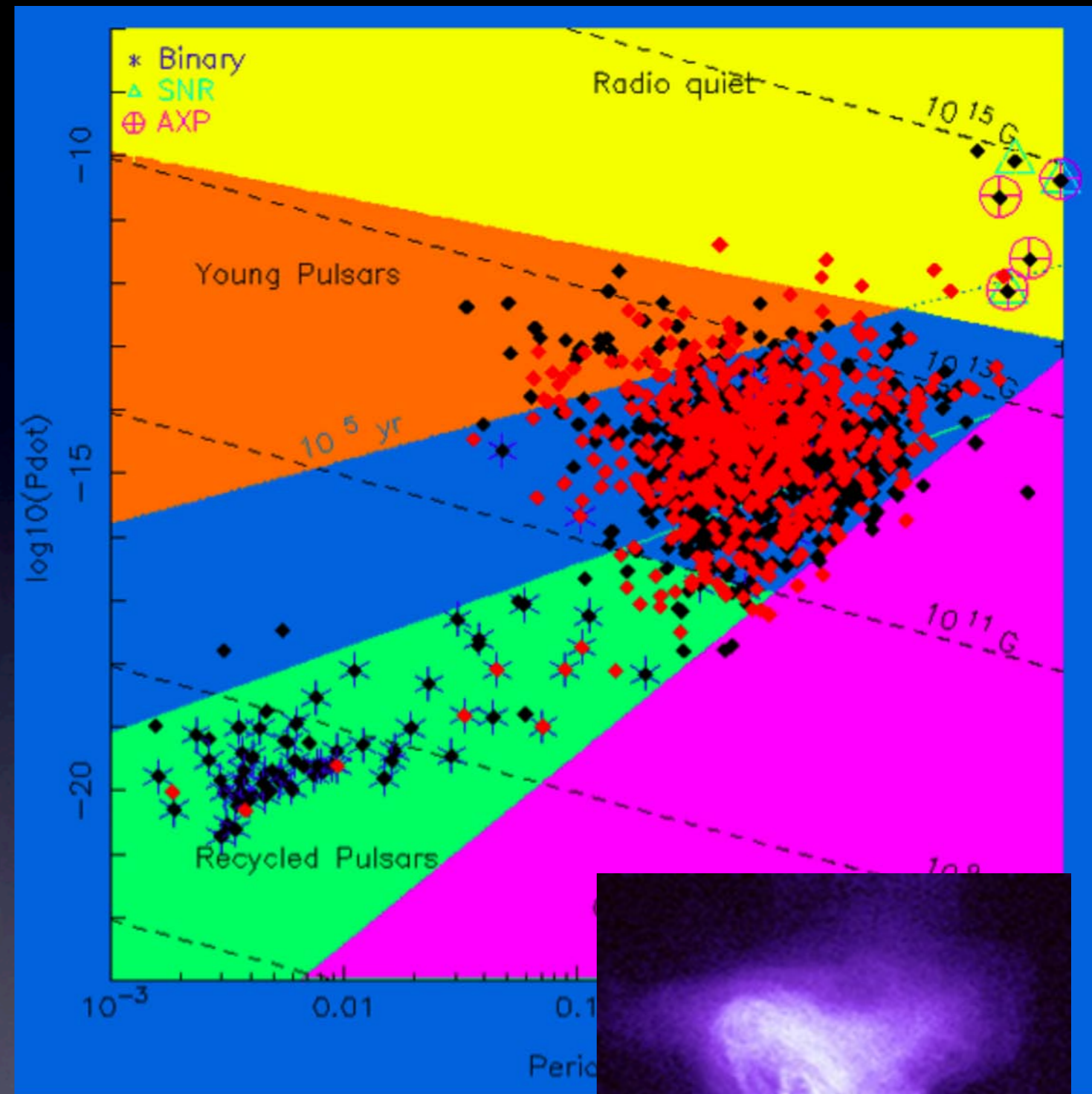
Most of the *observable* energy is coming out in gamma-rays

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

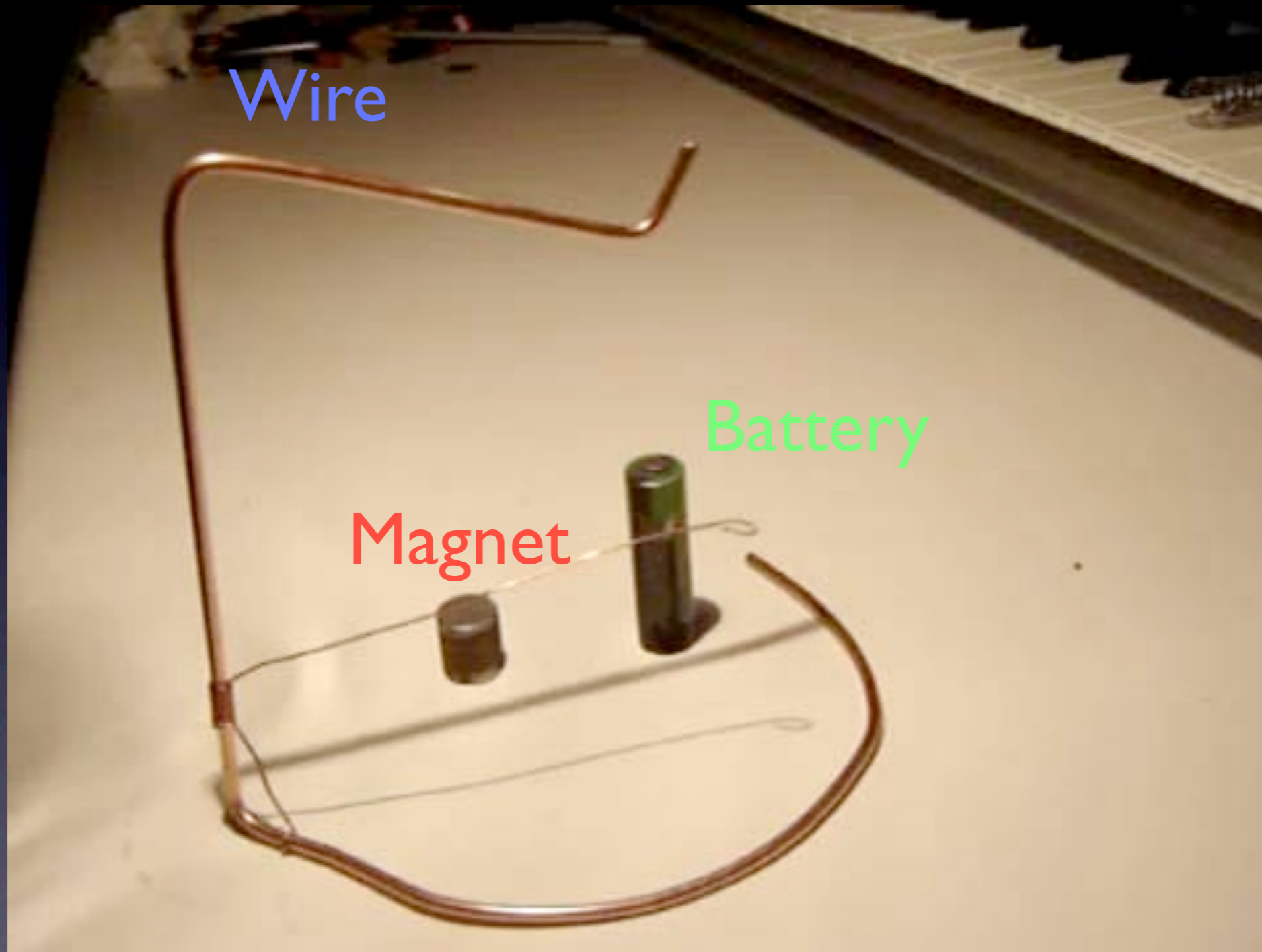
Leaves as magnetized wind
(carrying Poincaré flux)

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

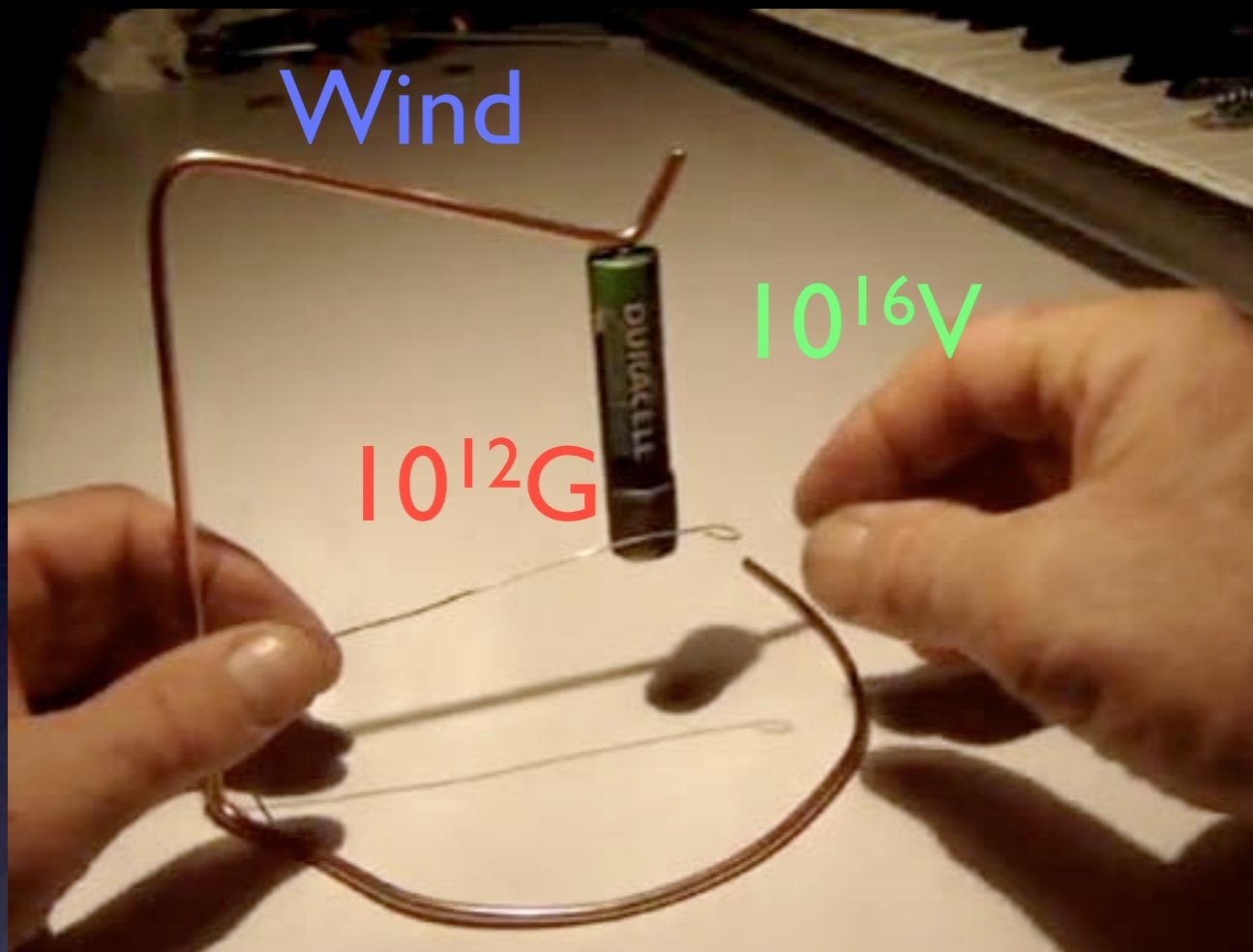


Pulsar physics @ home

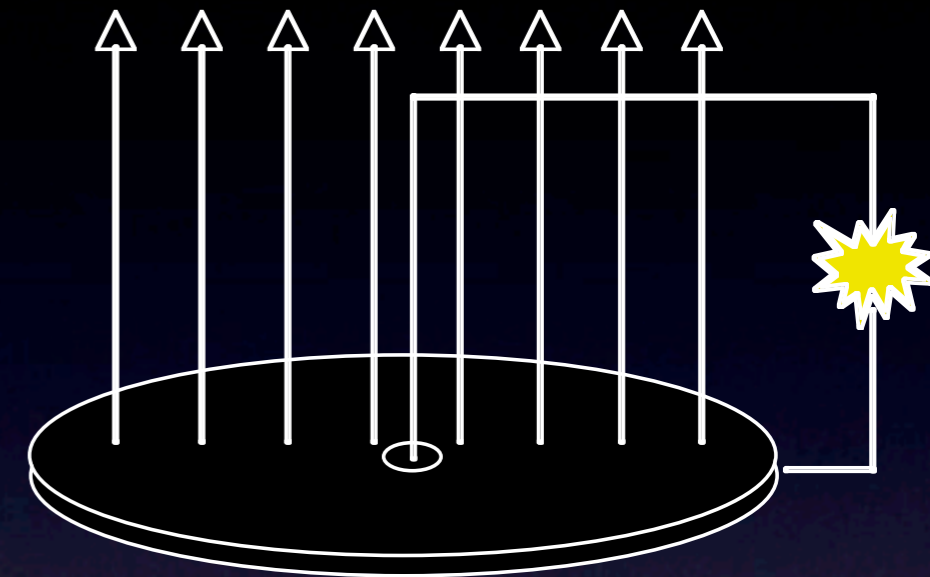


Unipolar induction

Pulsar physics in space



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



Faraday disk
Unipolar induction

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

Crab Pulsar

$B \sim 10^{12} \text{ G}$, $\Omega \sim 200 \text{ rad s}^{-1}$, $R \sim 10 \text{ km}$

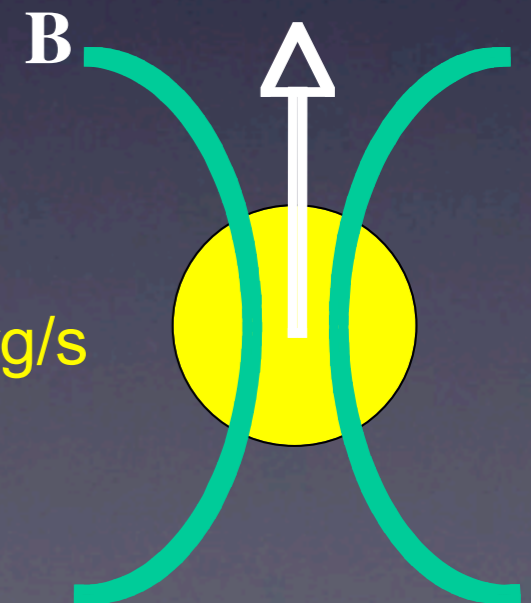
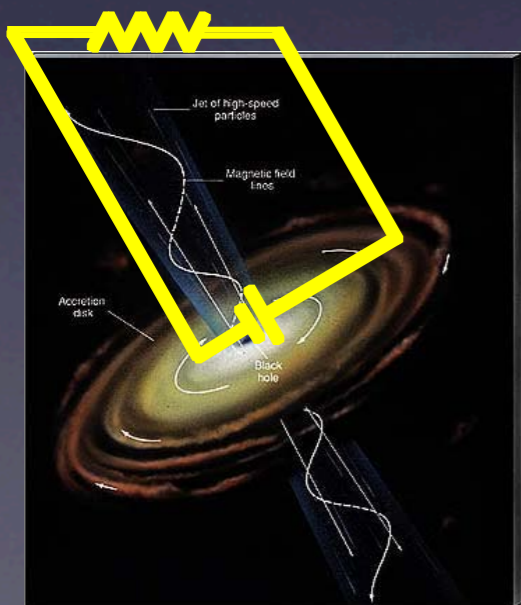
Voltage $\sim 3 \times 10^{16} \text{ V}$; $I \sim 3 \times 10^{14} \text{ A}$; $P \sim 10^{38} \text{ erg/s}$

Magnetar

$B \sim 10^{14} \text{ G}$; $P \sim 10^{44} \text{ erg/s}$

Massive Black Hole in AGN

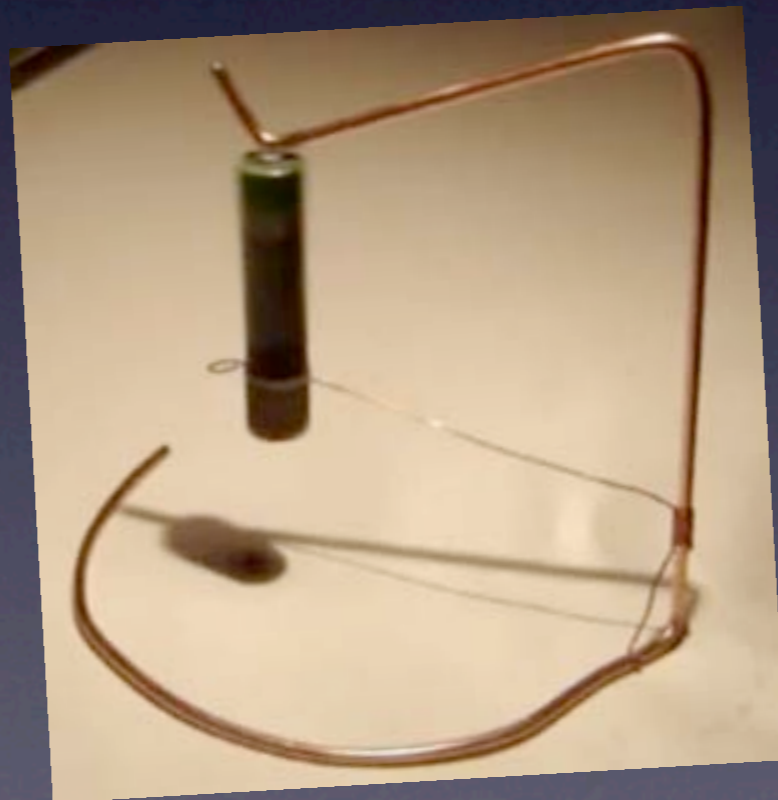
$B \sim 10^4 \text{ G}$; $P \sim 10^{46} \text{ erg/s}$



from R. Blandford

The goal of this talk:

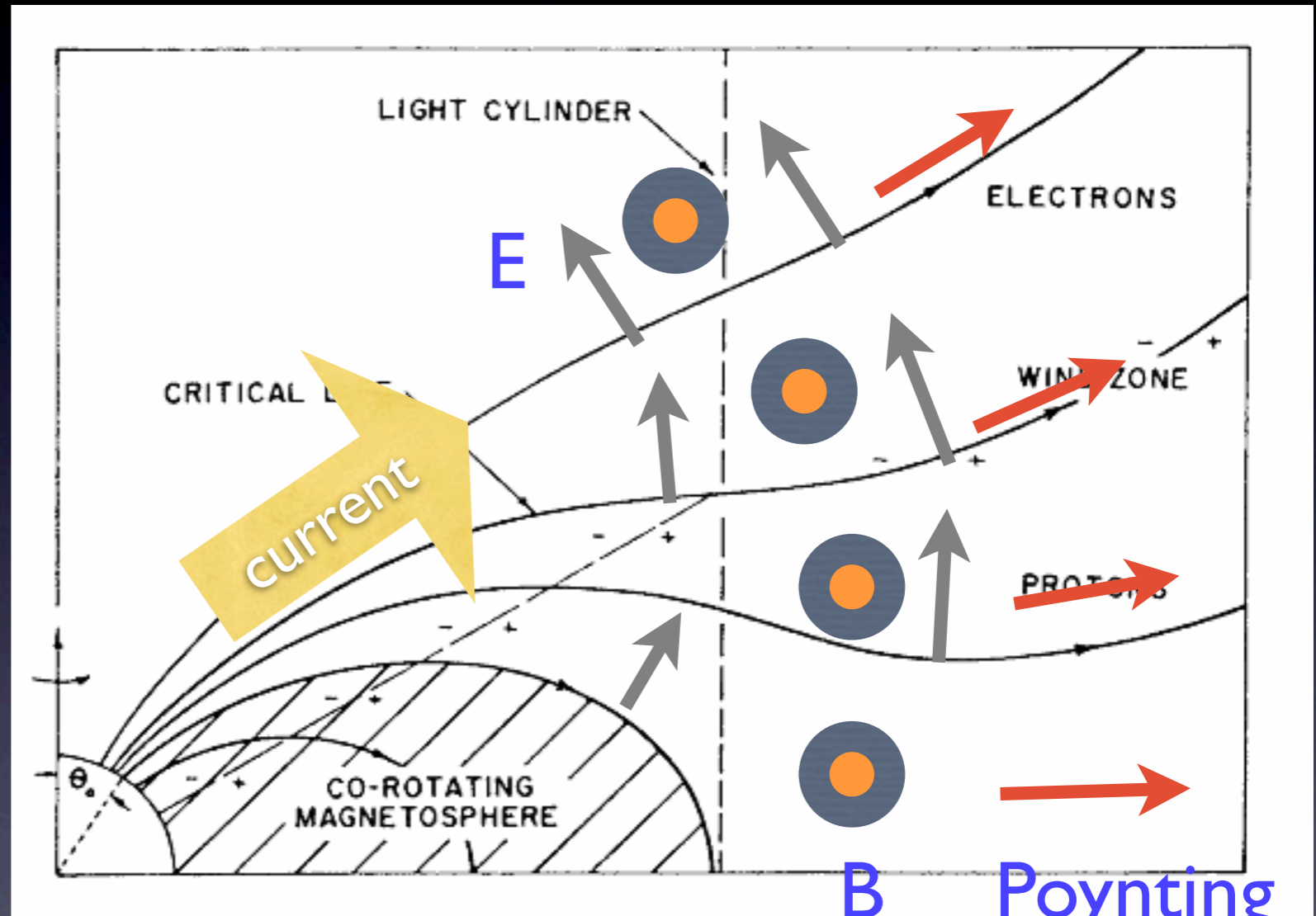
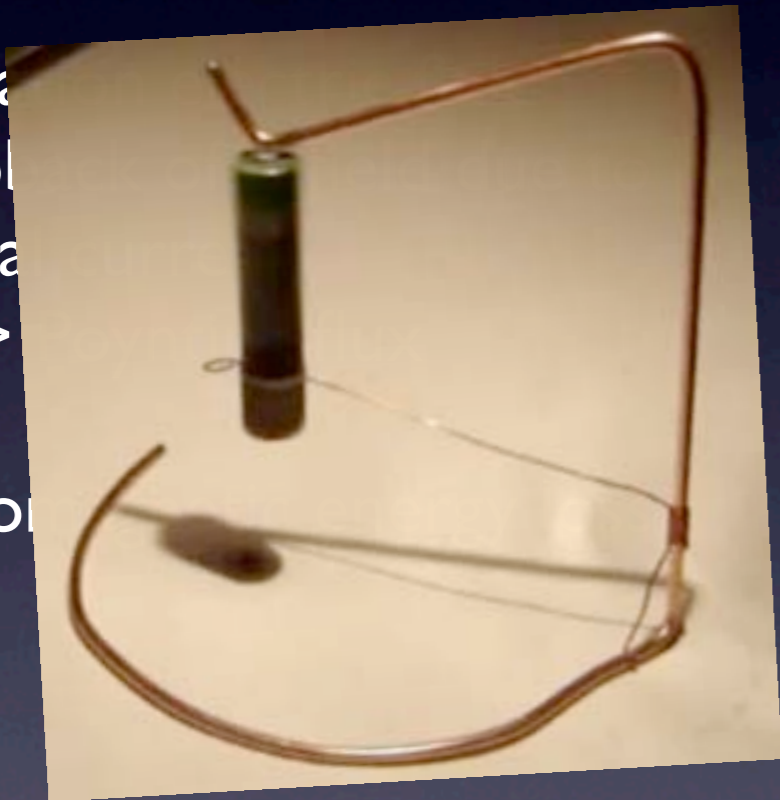
Understand how this circuit works
and what are its observational implications



Pulsars: energy loss

$$\rho_{GJ} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

- Corotating
- Sweeping
- poloidal
- $E \times B \rightarrow$
- Electron



B Poynting
Goldreich & Julian 1969

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

Magnetospheric cartoon

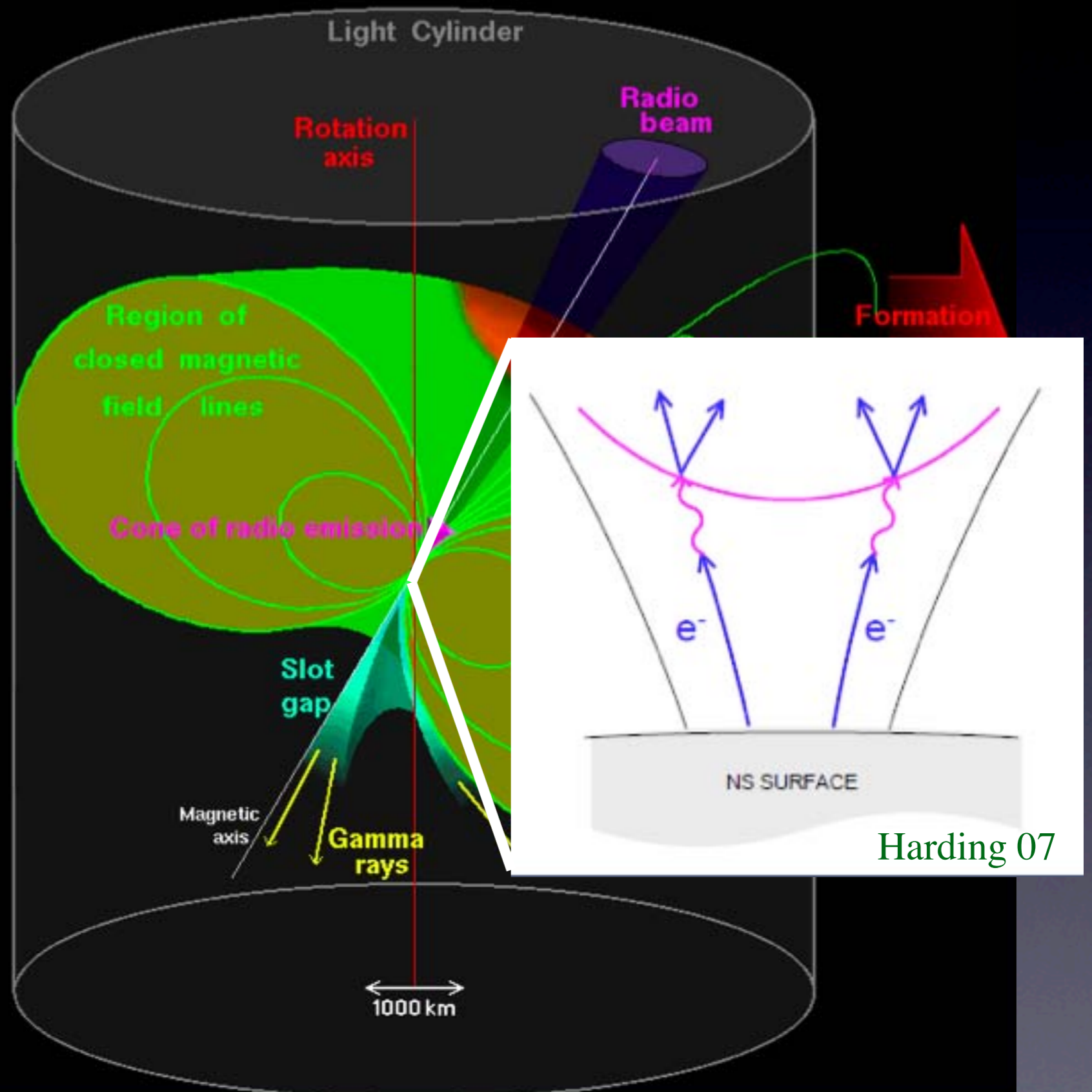
Open + closed
(corotating) zones

Light Cylinder

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

Current modifies
the field

How does it spin
down?

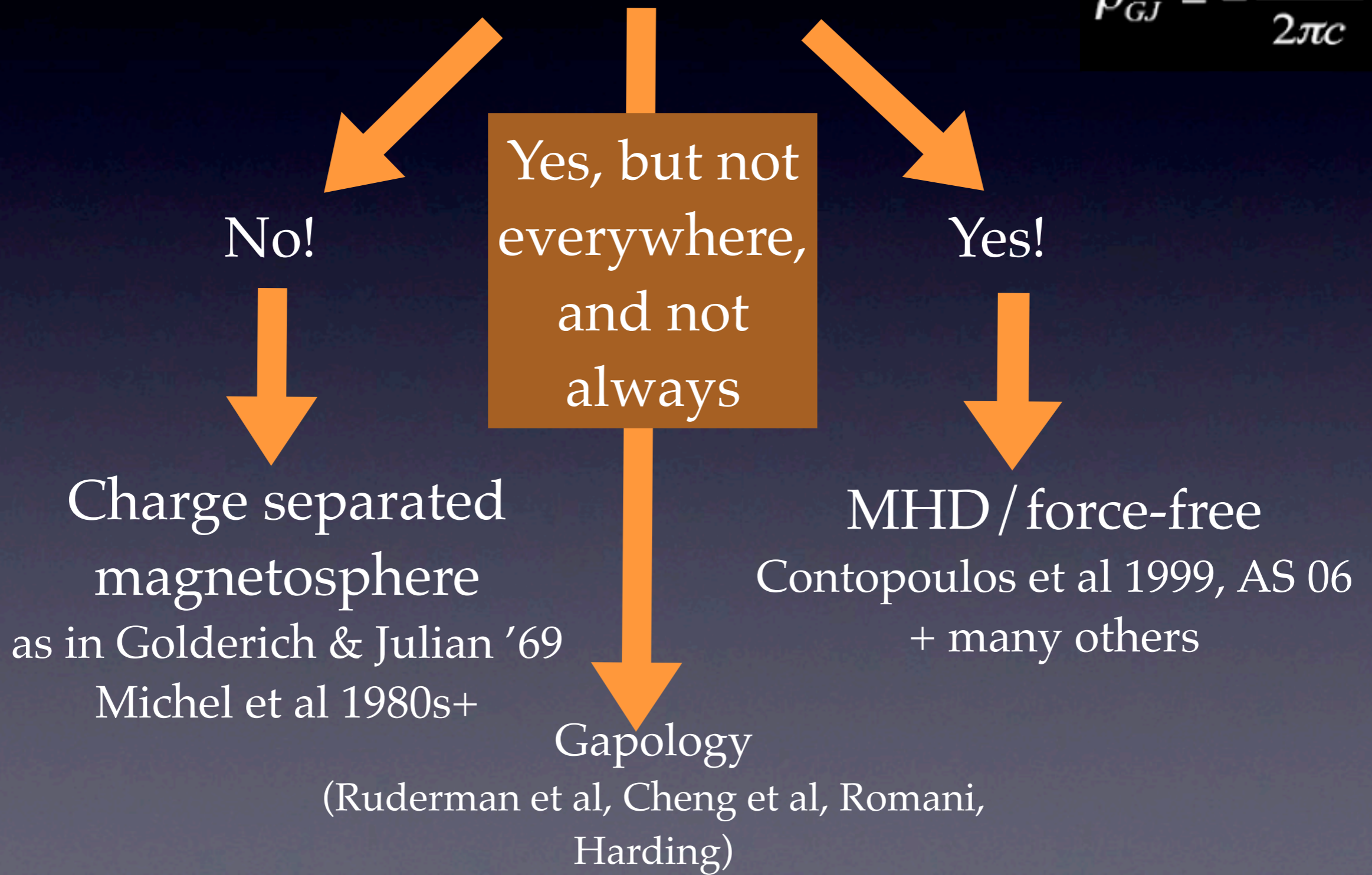


Harding 07

MODELING: TWO PATHS

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

$$\rho_{GJ} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$



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

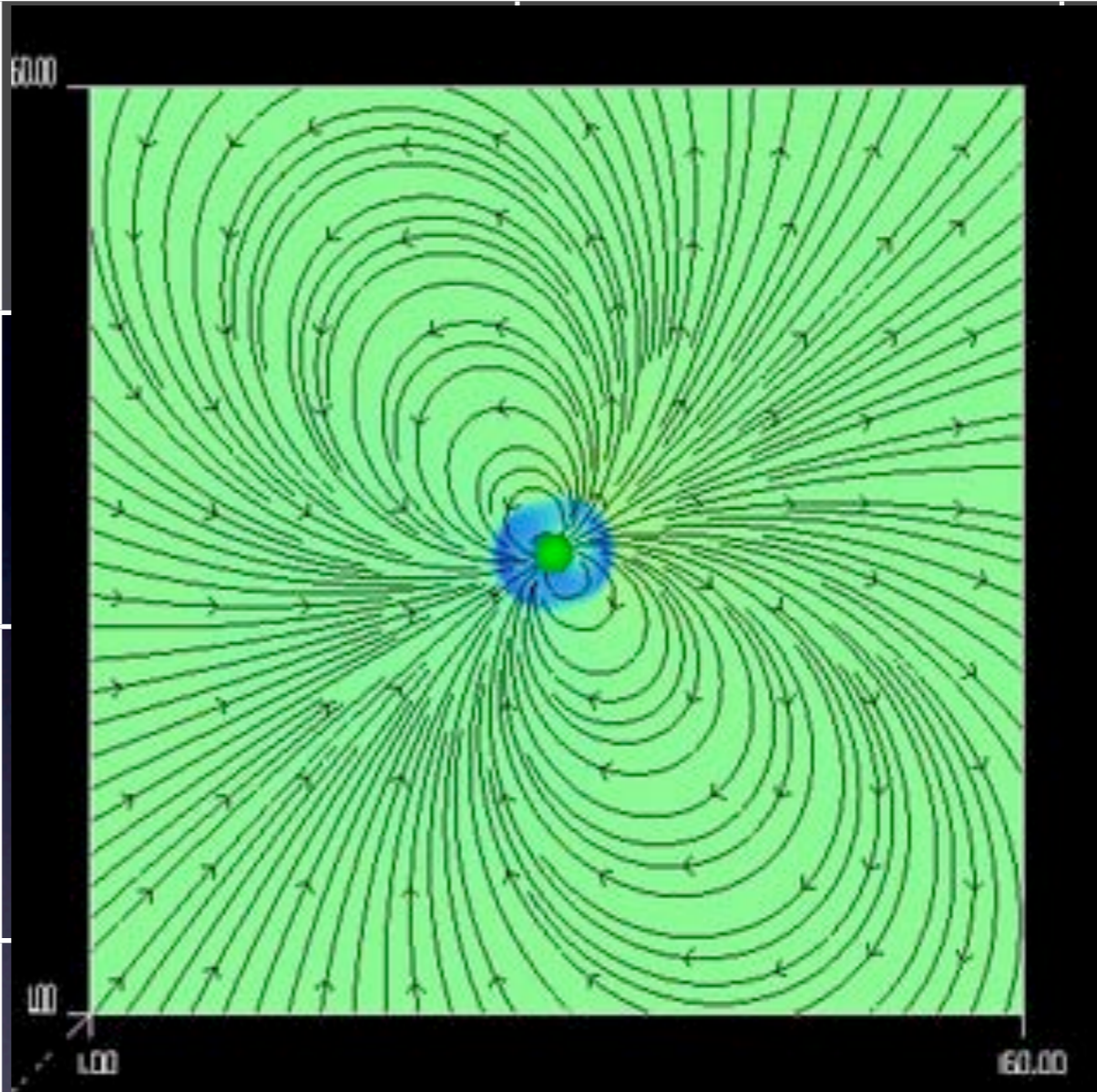
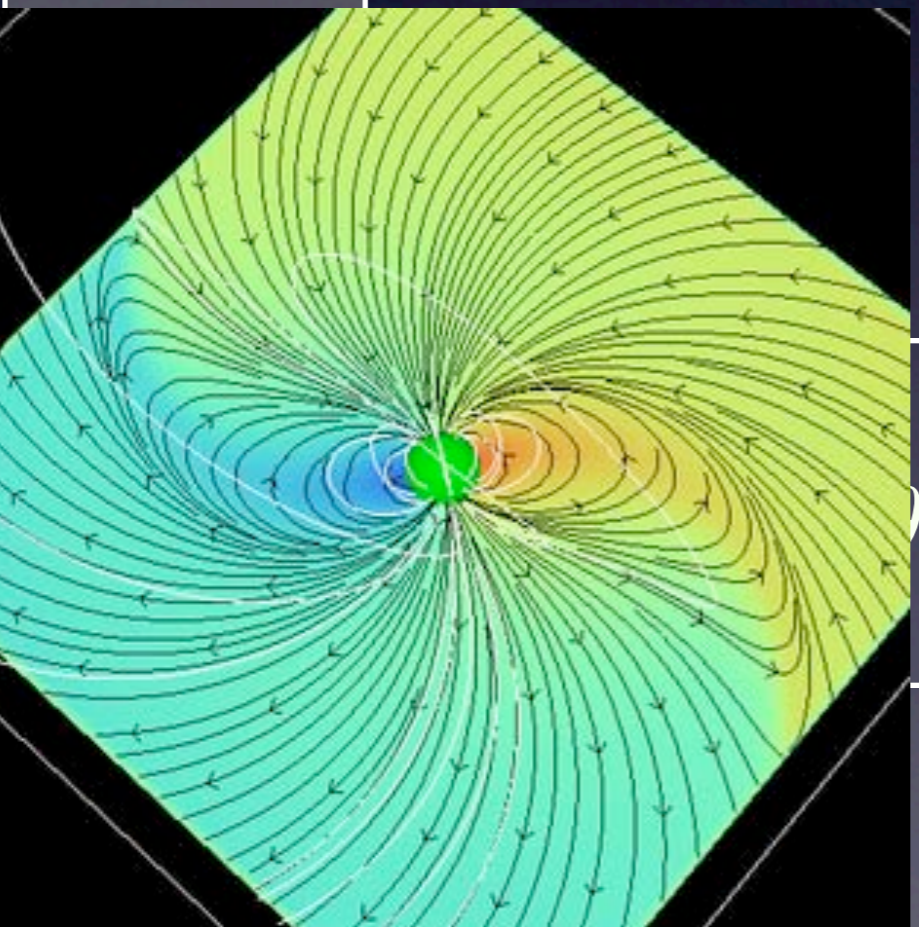
Ostriker & Gunn 70

Goldreich & Julian 69
Michel 85, 00; AS
+Arons 02

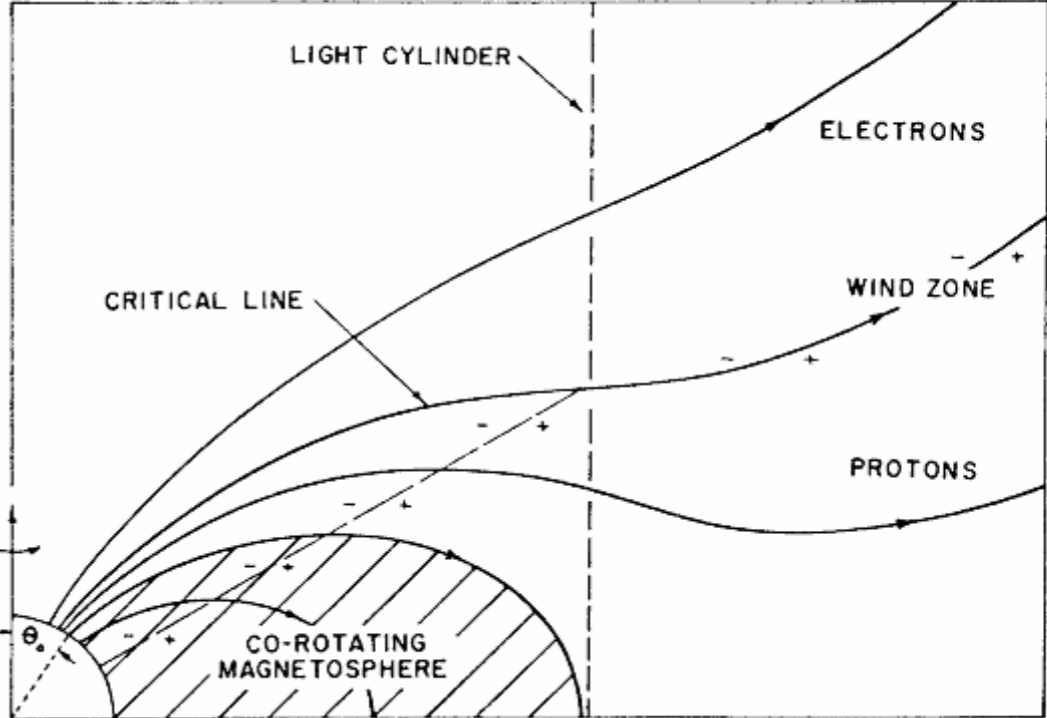
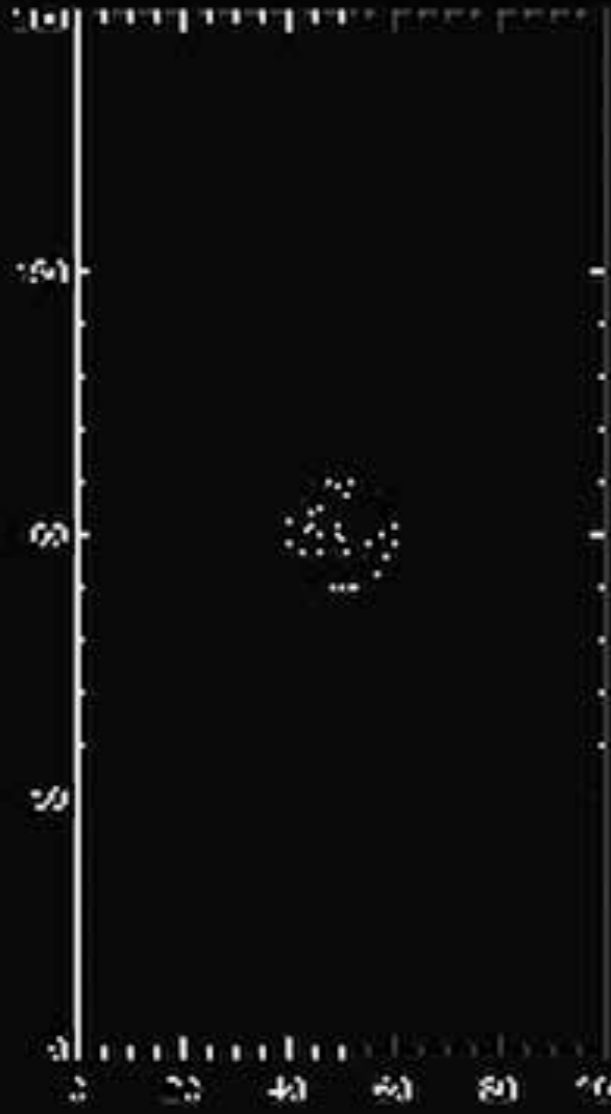
Arons 78, Cheng et al
86; Romani et al;
Harding et al; Hirovani;

Contopoulos 99;
Gruzinov 05;
Timokhin 06;
AS 06

Magnetospheric models

	<p>Vacuum</p>		<p>Abundant plasma</p>
<p>Field</p>	<p>Rotating vacuum dipole (RVD)</p>		<p>Force-free</p>
	<p>?</p>	<p>?</p>	<p>none / reconnection?</p>
	<p>Goldreich & Julian 69 Michel 85, 00; AS +Arons 02</p>	<p>Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirovani;</p>	<p>$\frac{2\Omega^4}{c^3} (1 + \sin^2 \theta)$</p> <p>Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06</p>

Magnetospheric models

		Space charge limited		
Fi		?		
Acc at		gaps	gaps	none / re-connection?
S down	$\frac{3}{c^3} \sin^2 \theta$?	?	$\frac{\mu^2 \Omega^4}{c^3} (1 + \sin^2 \theta)$

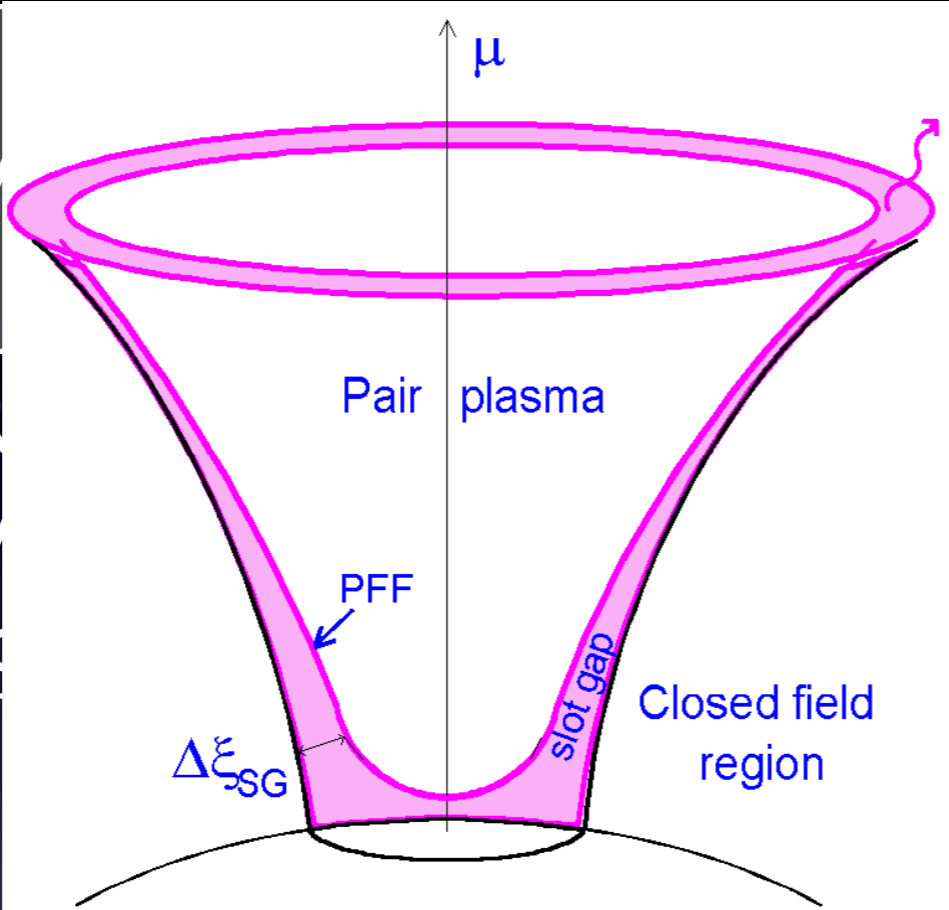
Goldreich & Julian 69
Michel 85, 00; AS
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AS 06

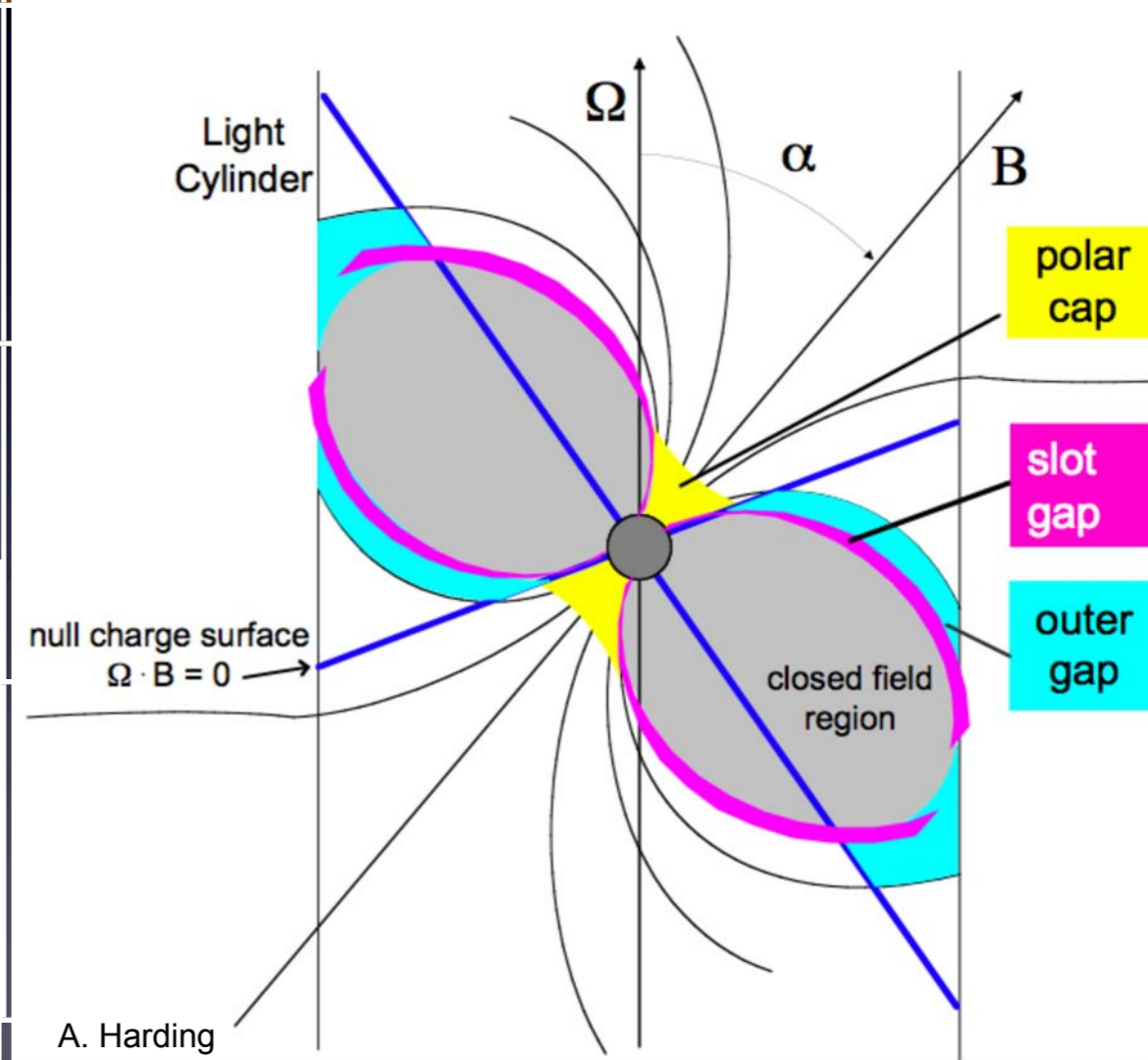
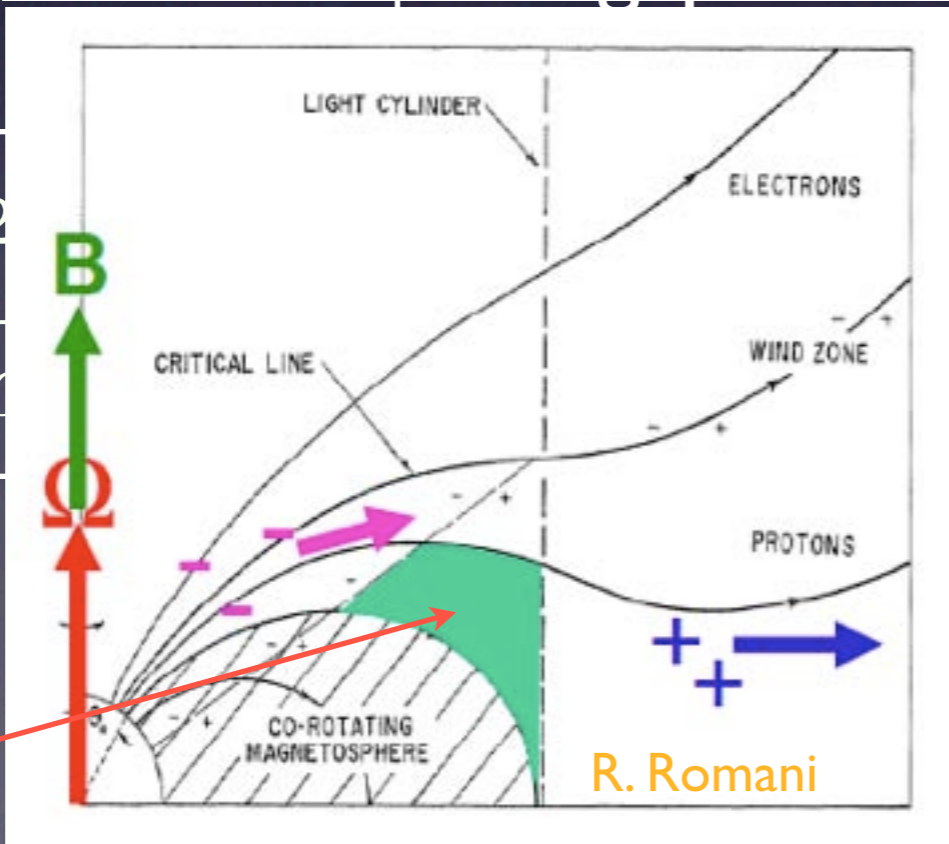
Magnetospheric models

	v
Field	R v dipole
Acceleration	
Spin down	$\frac{2}{3} \frac{\mu^2}{c^3}$



Space charge limited + pairs

Abundant plasma



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

Holloway's paradox

Slot/Outer gaps:

Linear accelerators with E_{\parallel} 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!

Pulsar wind nebulae suggest plasma densities $\gg GJ$ charge density in the magnetosphere.

Magnetospheric models

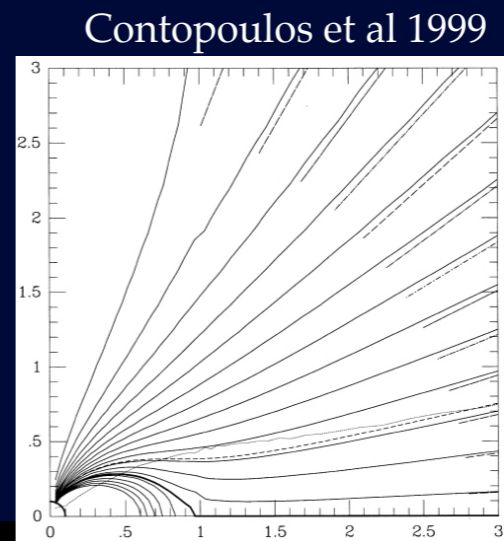
- NS is immersed in massless conducting fluid. Includes plasma currents.

- Force-free evolution. B field dominates. Inertia is small:

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

“Pulsar equation” (Michel ‘73; Scharleman & Wagoner ‘73):

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



Abundant plasma

Force-free

none / re-connection?

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

Perpendicular current
Parallel current

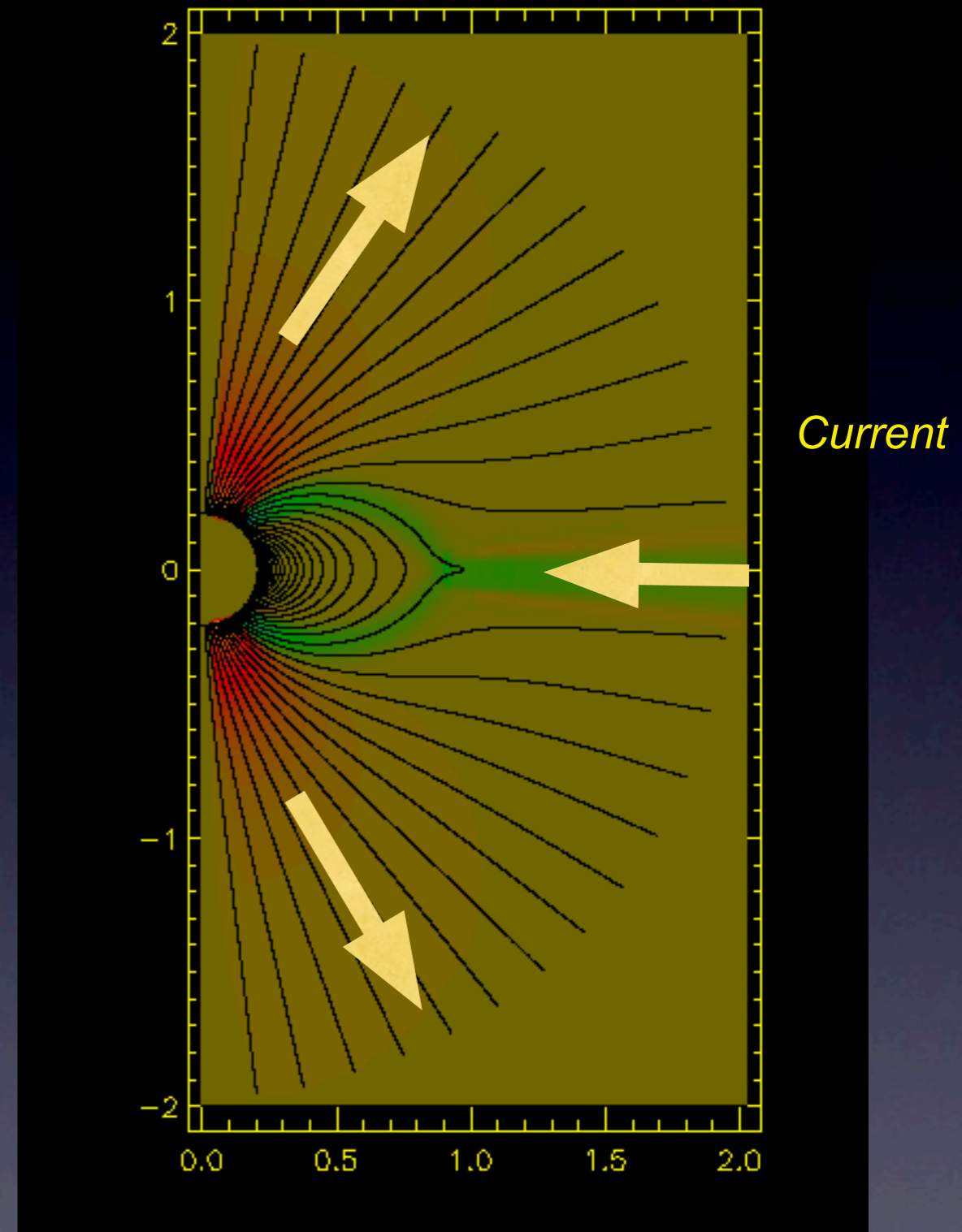
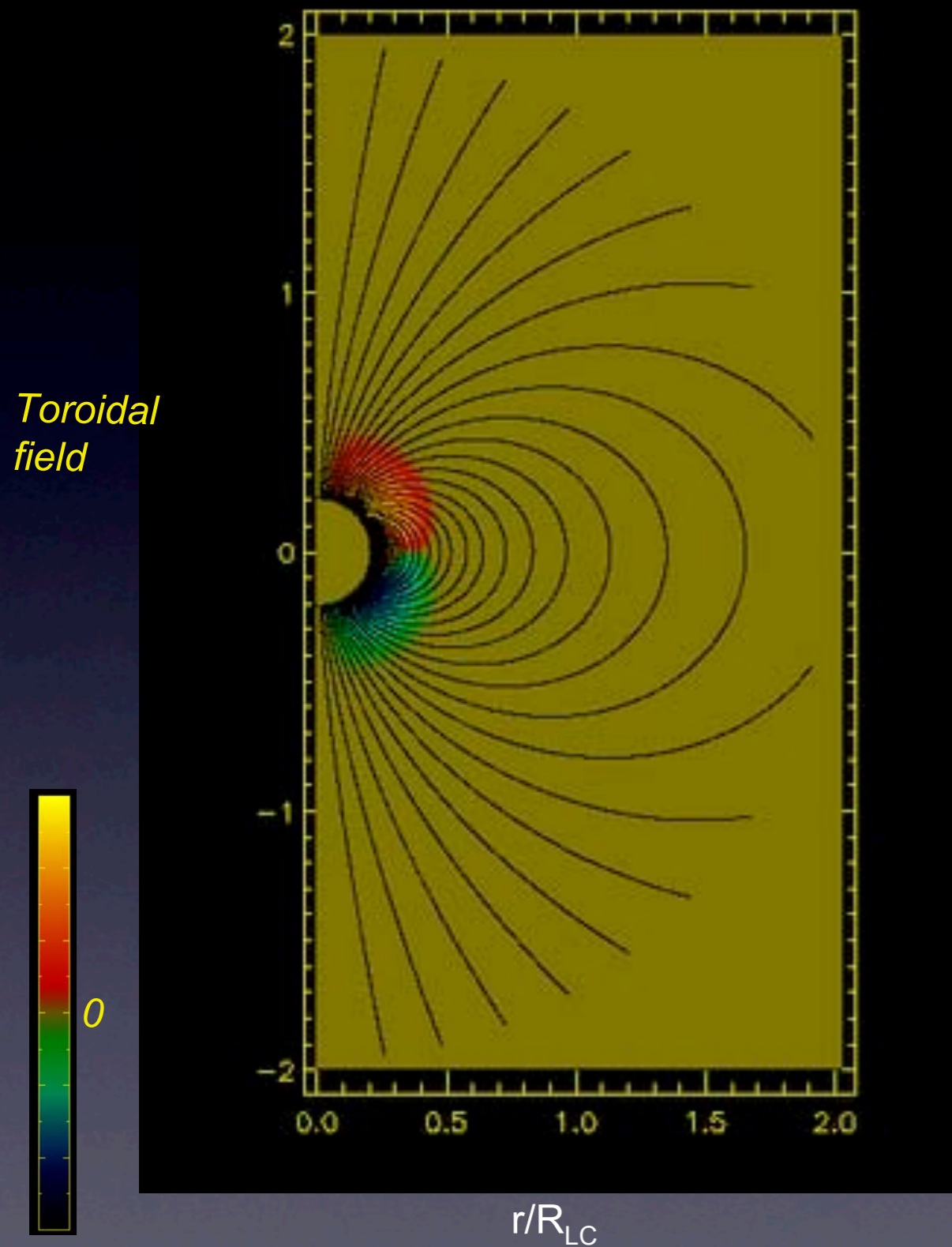
Gruzinov 99, Blandford 01

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

Contopoulos 99;
Gruzinov 05;
Timokhin 06;
AS 06

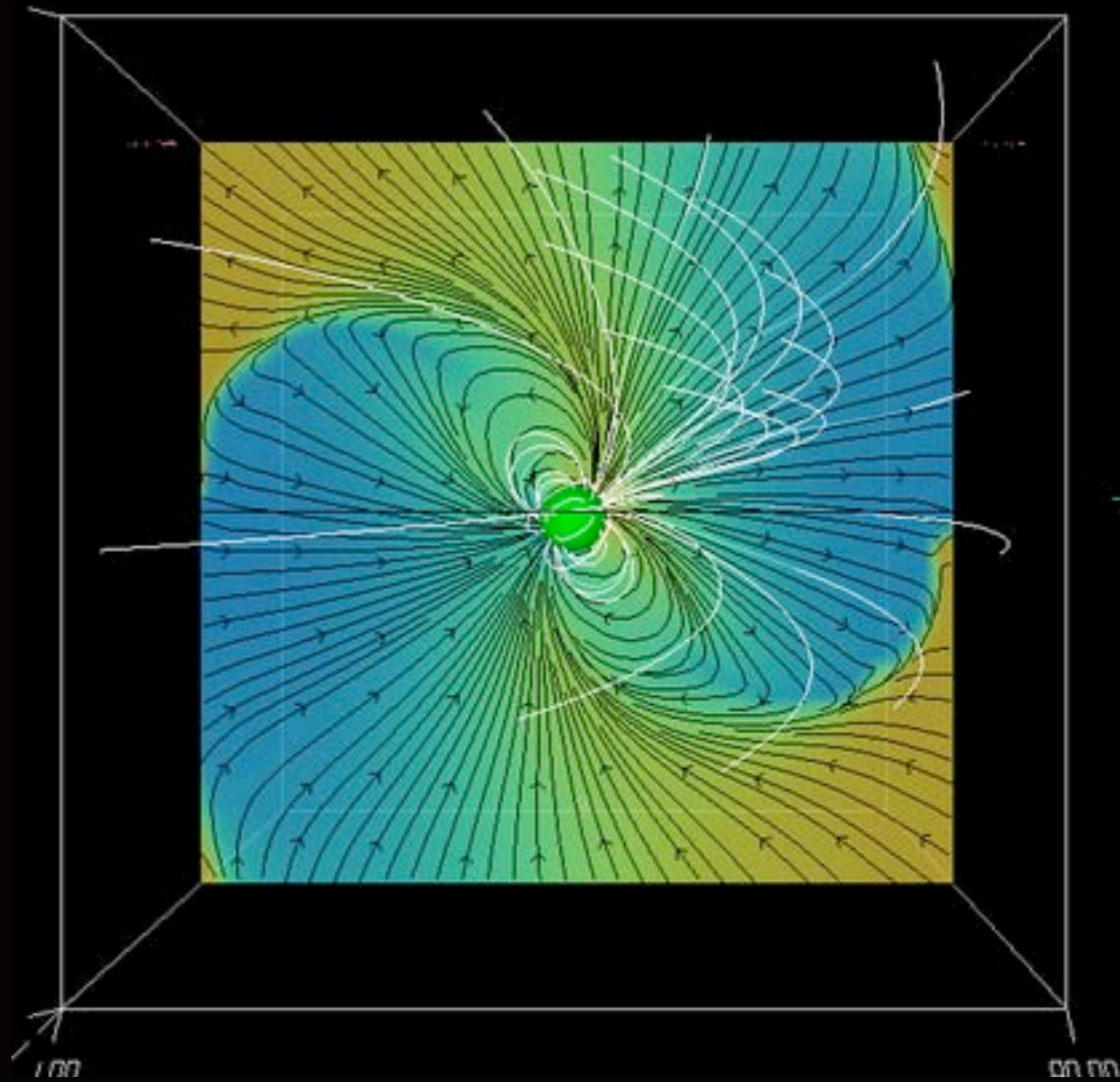
Hyperbolic equations, can be evolved in time

Aligned rotator: plasma magnetosphere

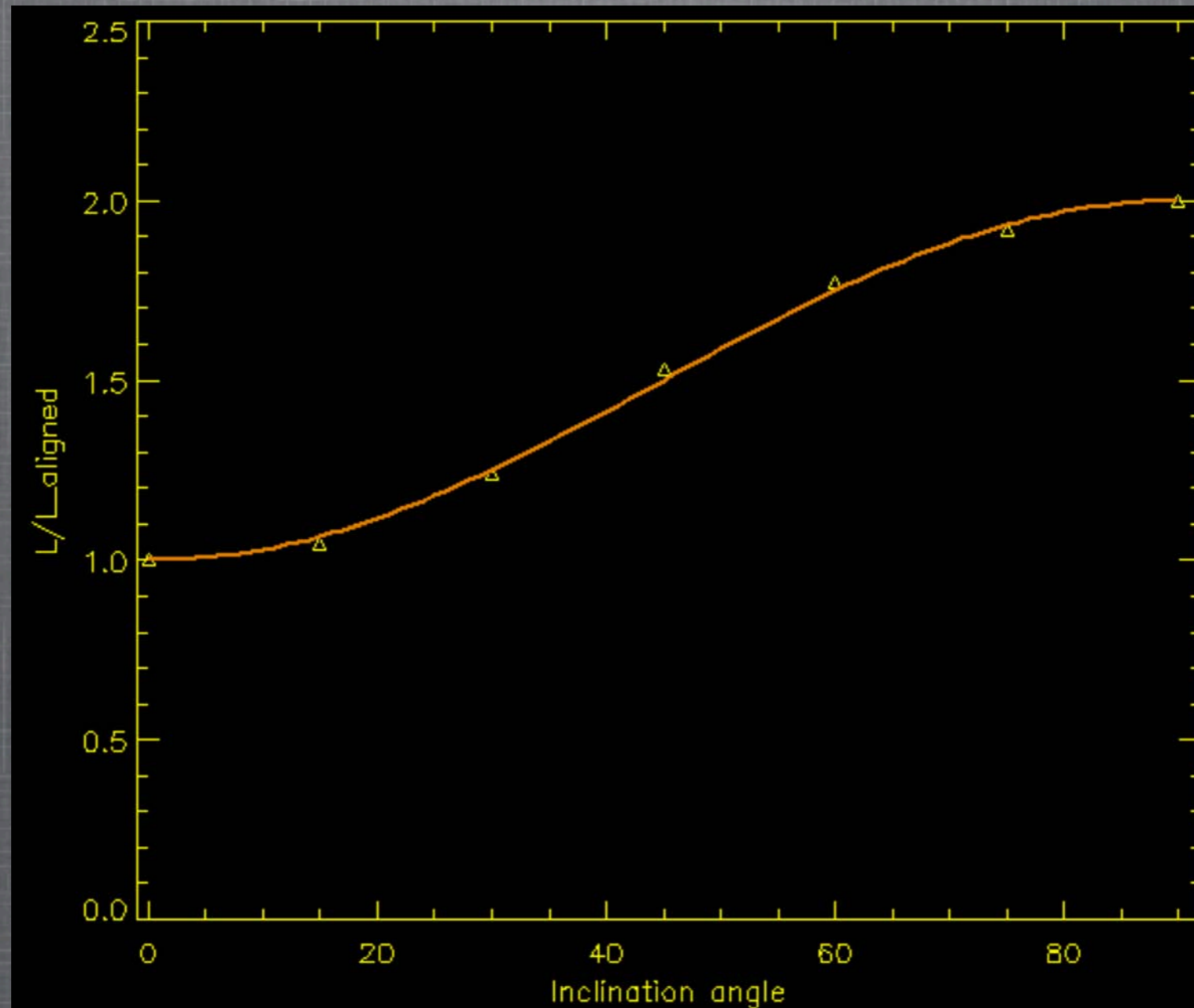


Properties: current sheet, split-monopolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting.

Oblique rotator: force-free



SPIN-DOWN POWER



Spin-down of oblique rotator

NB: this is a fit!

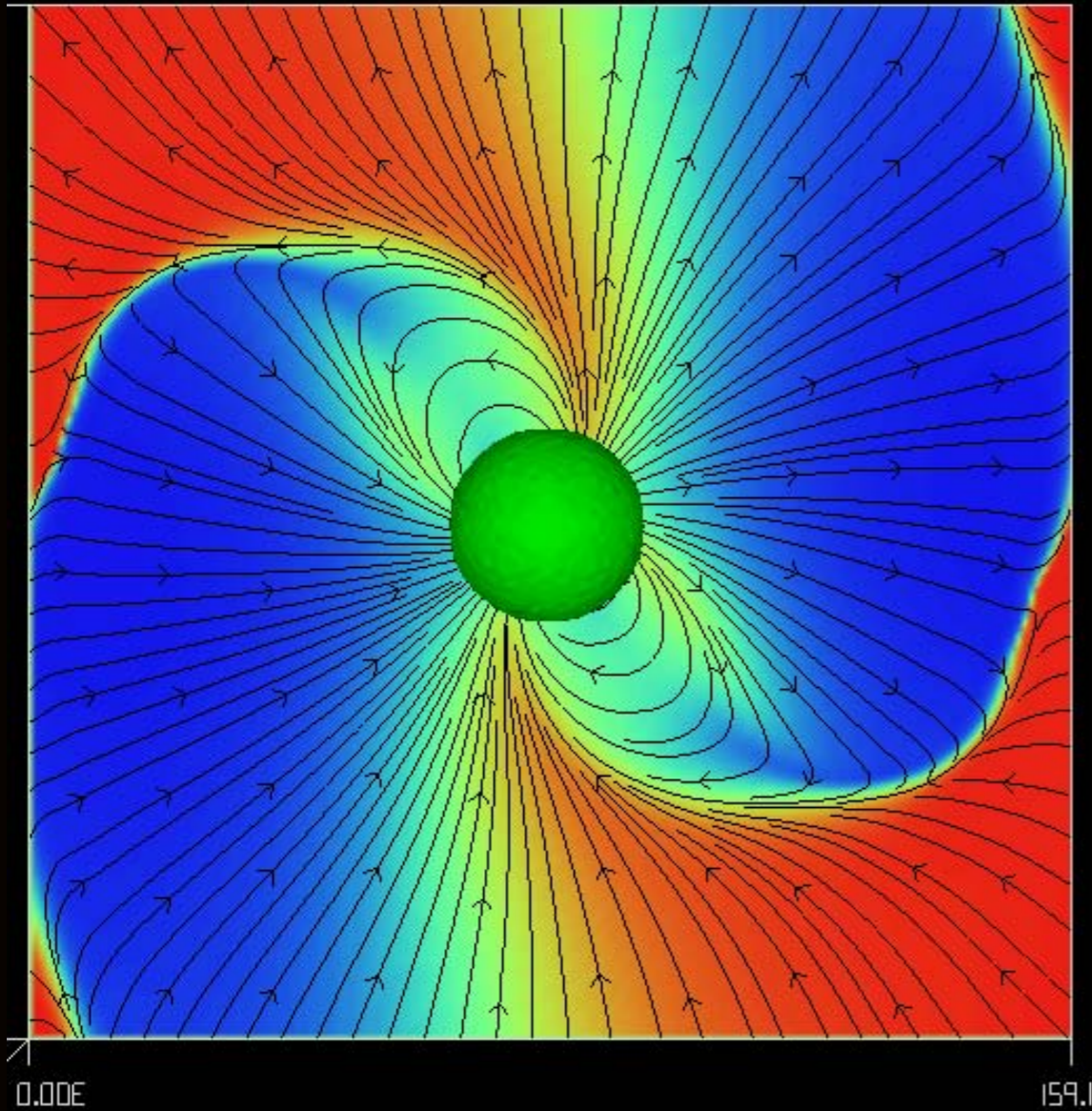
$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3} (1 + \sin^2 \theta)$$

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

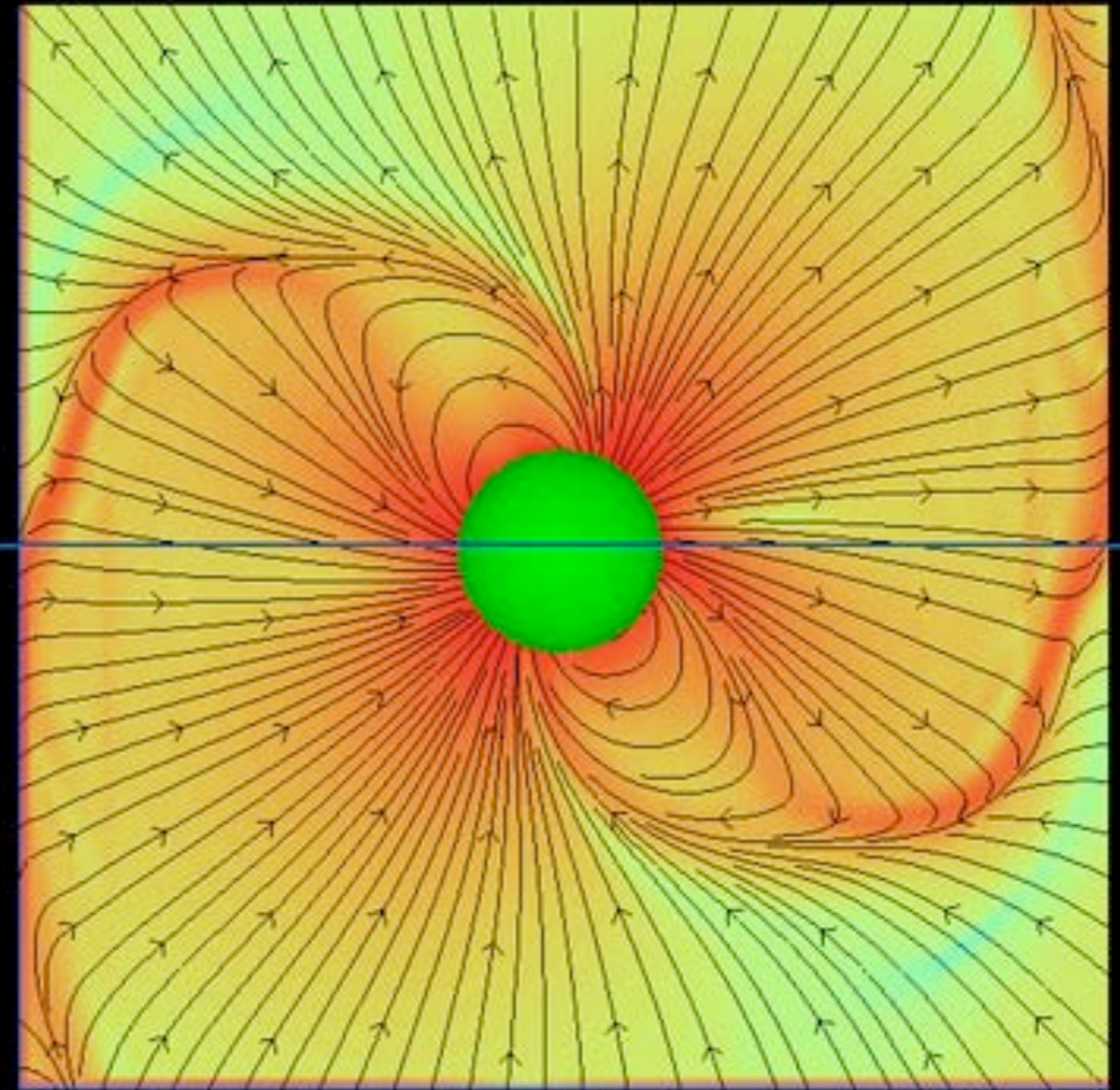
A.S.'06; also confirmed by Kalapotharakos & Contopoulos 09

IN COROTATING FRAME

60 degree inclination

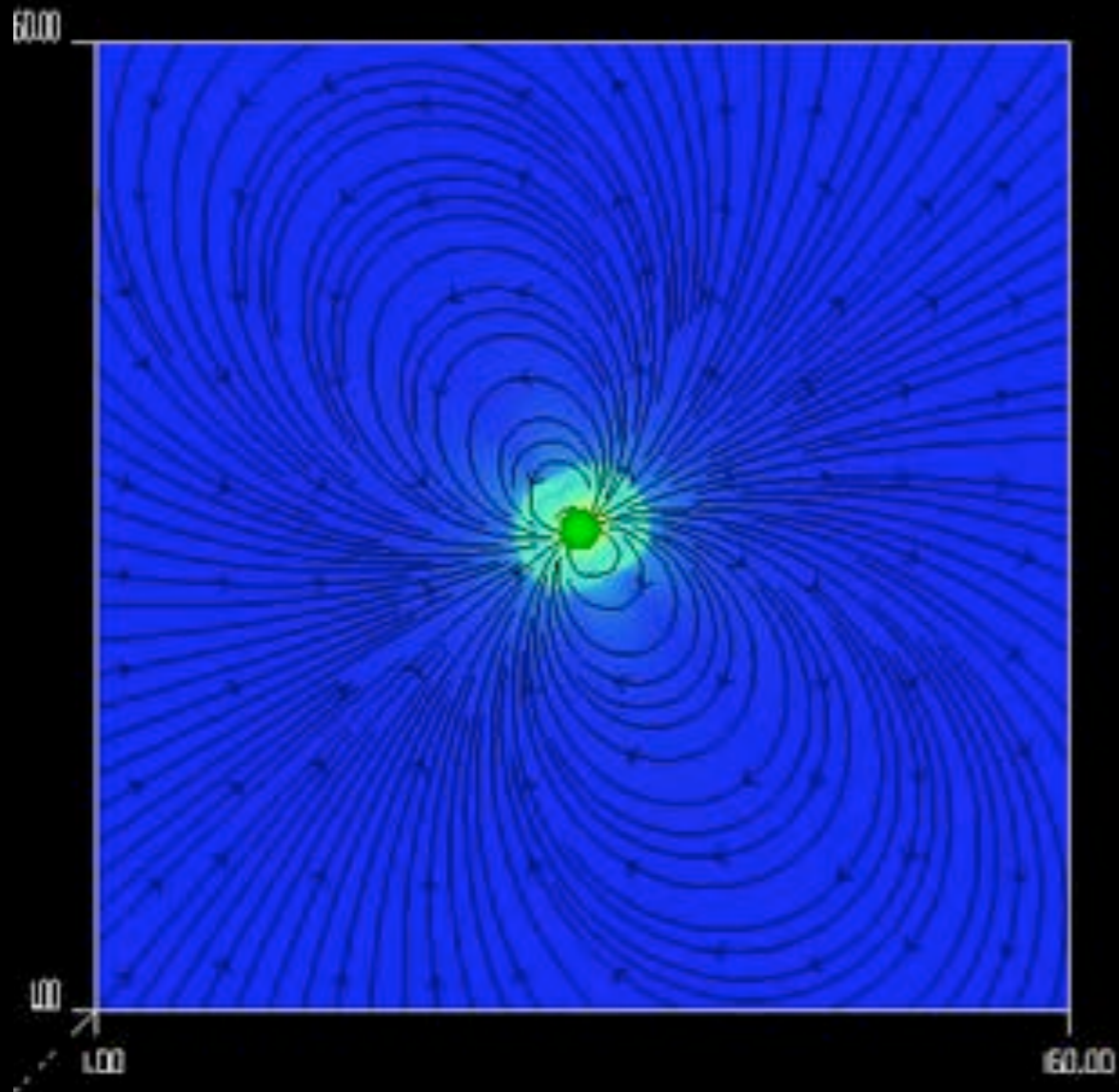


Force-free

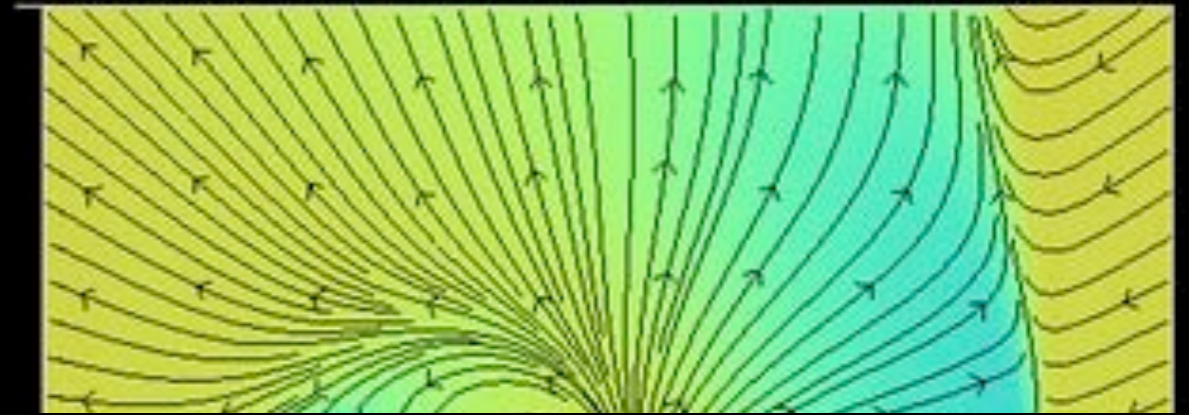


Force-free current density

3D force-free magnetosphere: 60 degrees inclination



60 degrees force-free current

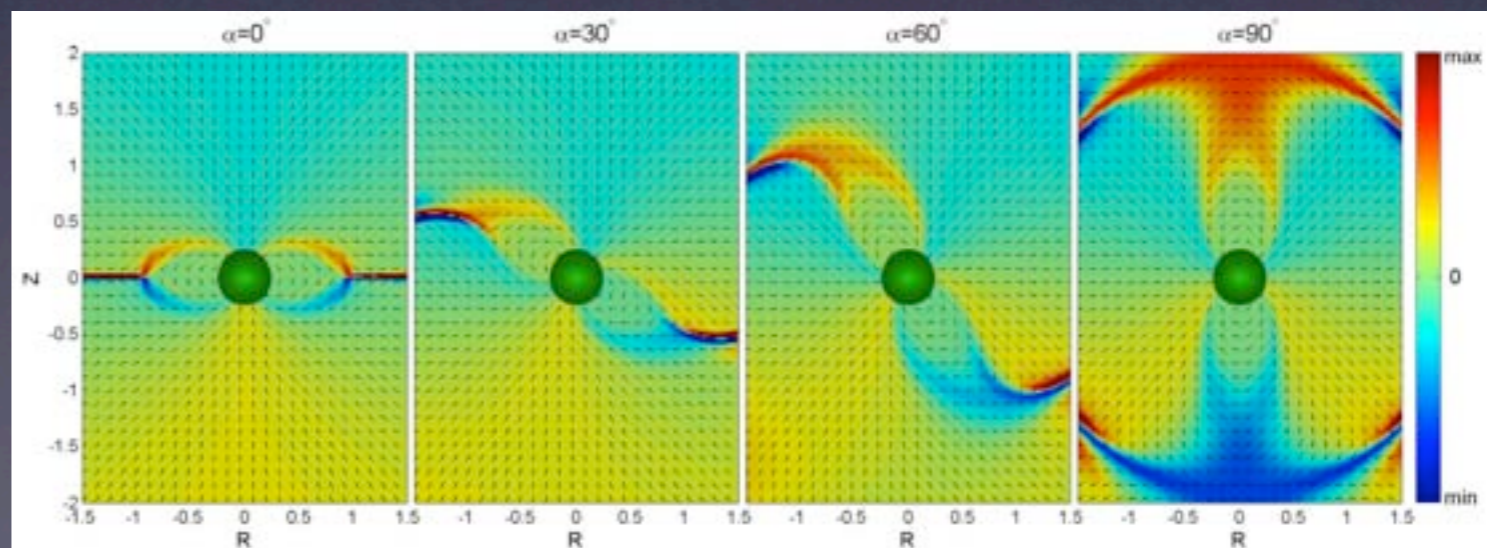
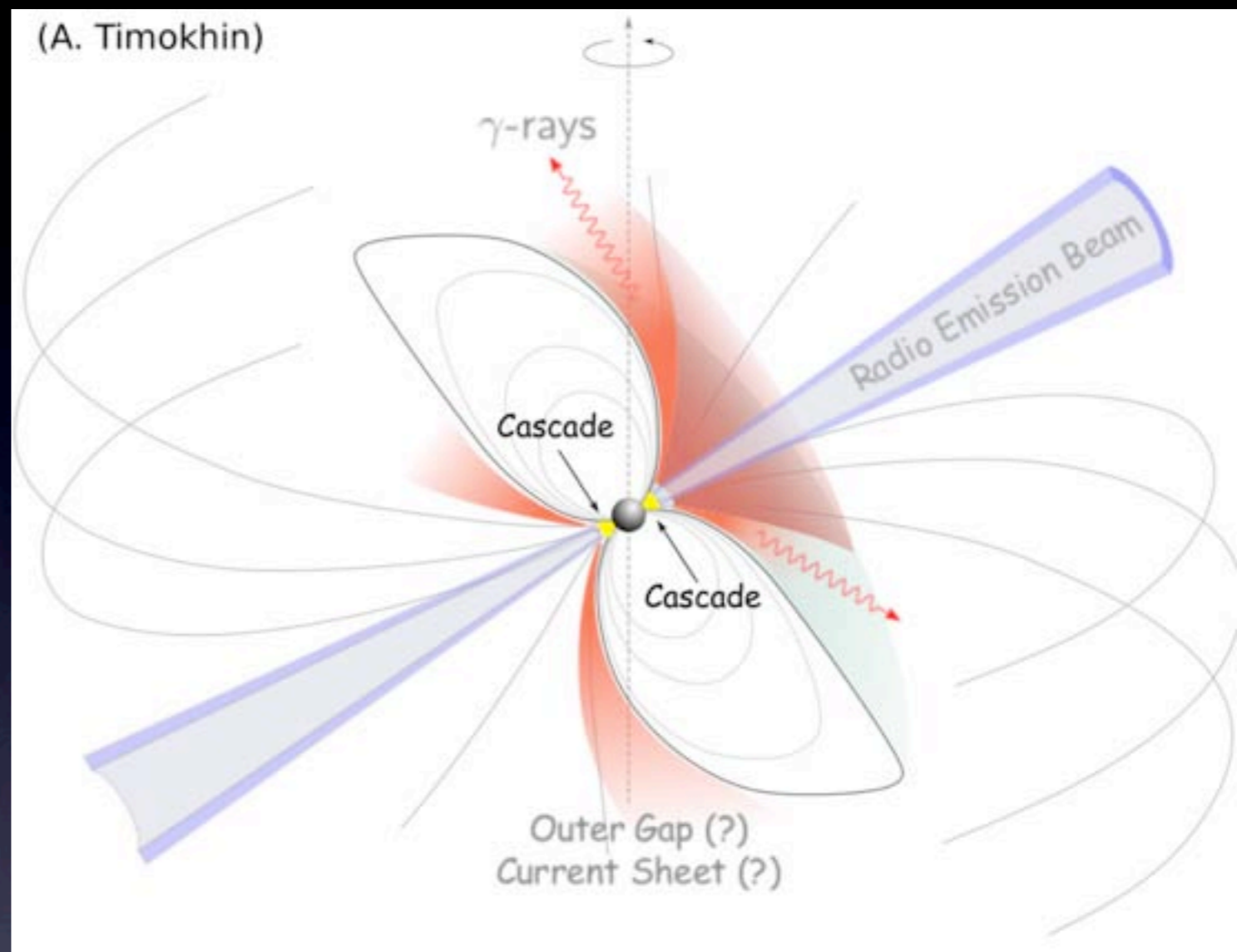


Similar to heliospheric current sheet

What emits?

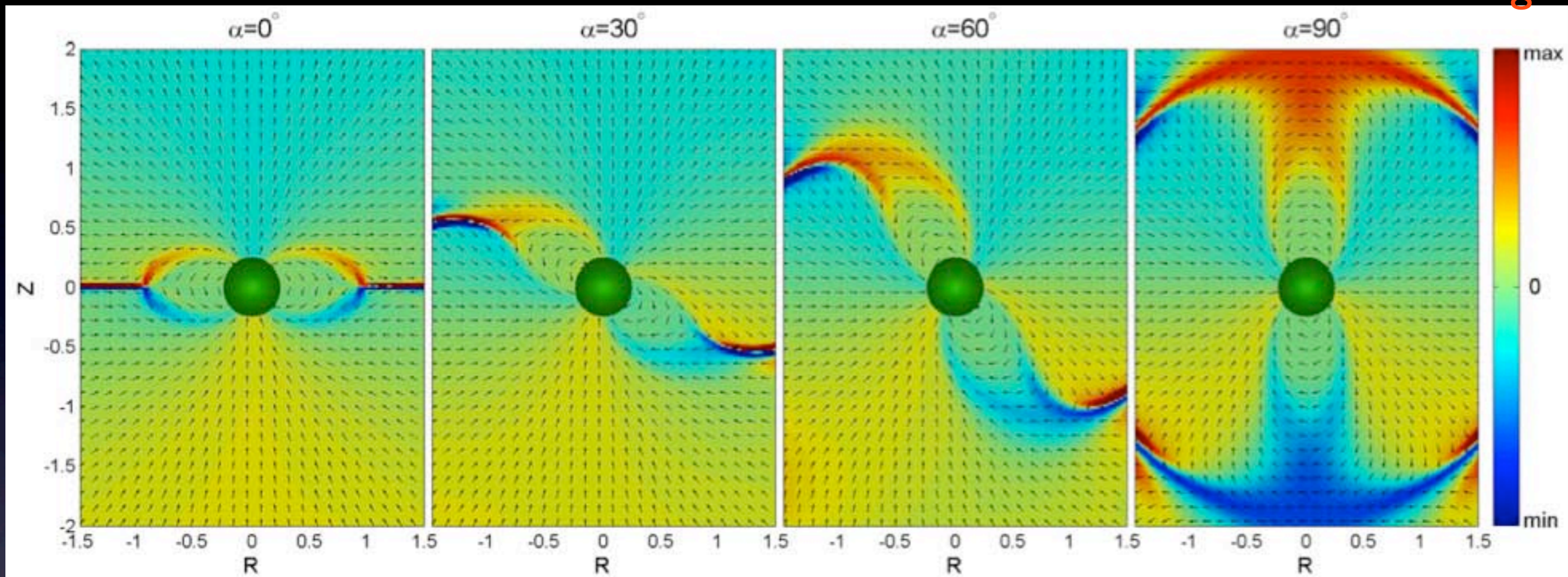
Emission process in γ less complicated than in the radio: curvature, IC, or synchrotron.

- 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!!!



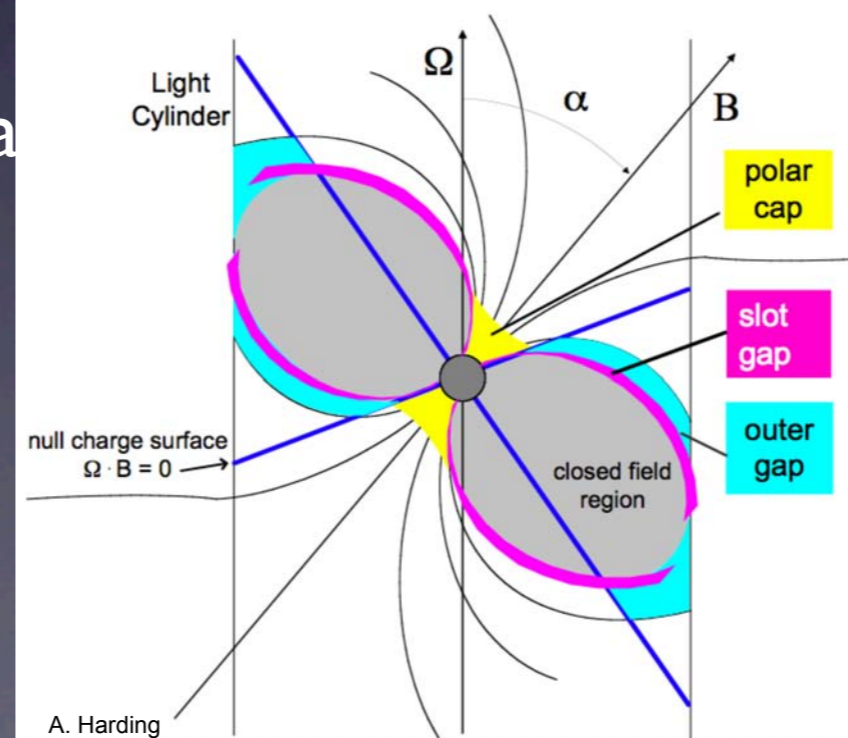
Oblique rotator: force-free

color -- current strength



Distribution of current in the ma

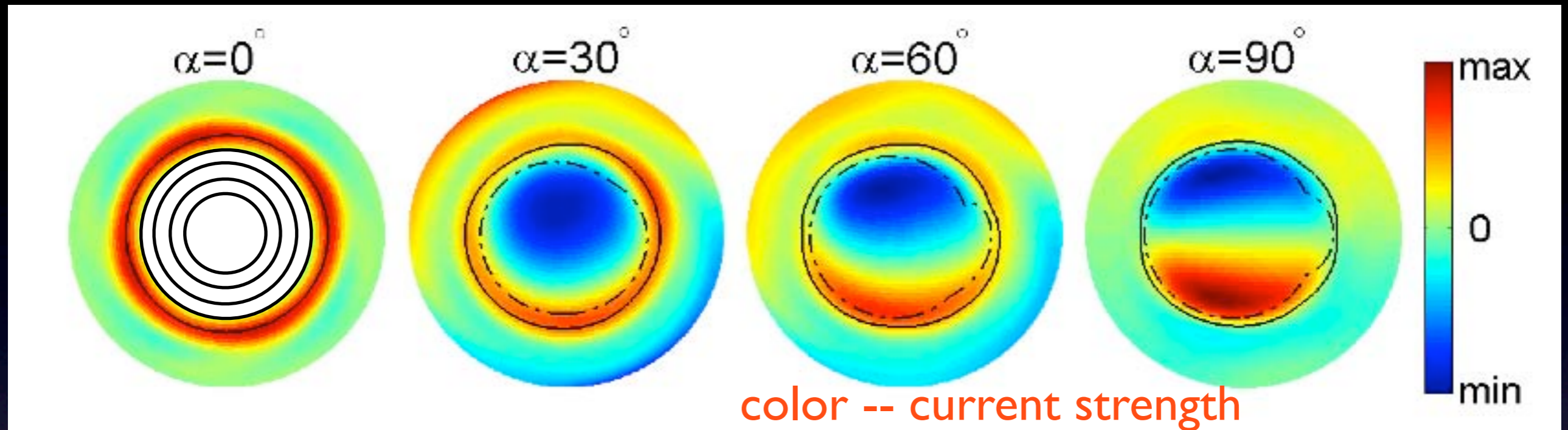
Force-free field provides a more realistic magnetic geometry



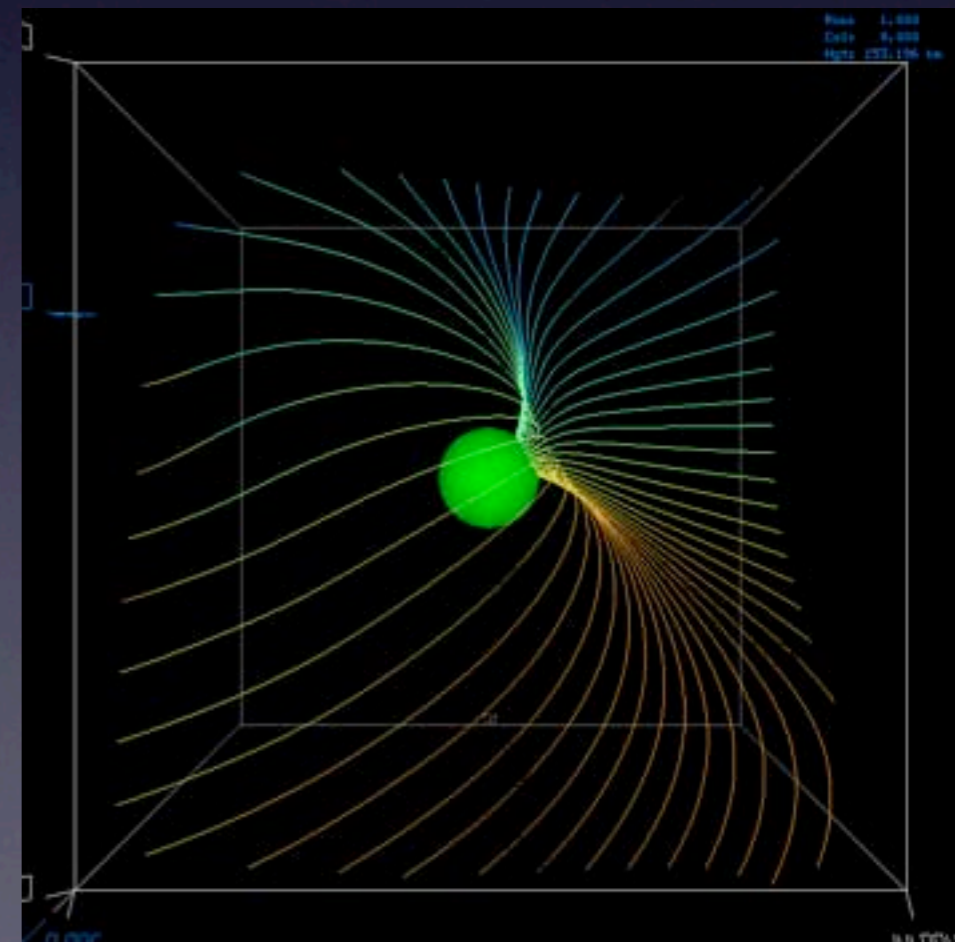
Bai & A. S. 2010

Tempting to associate gaps with currents. Can we?

What emits?

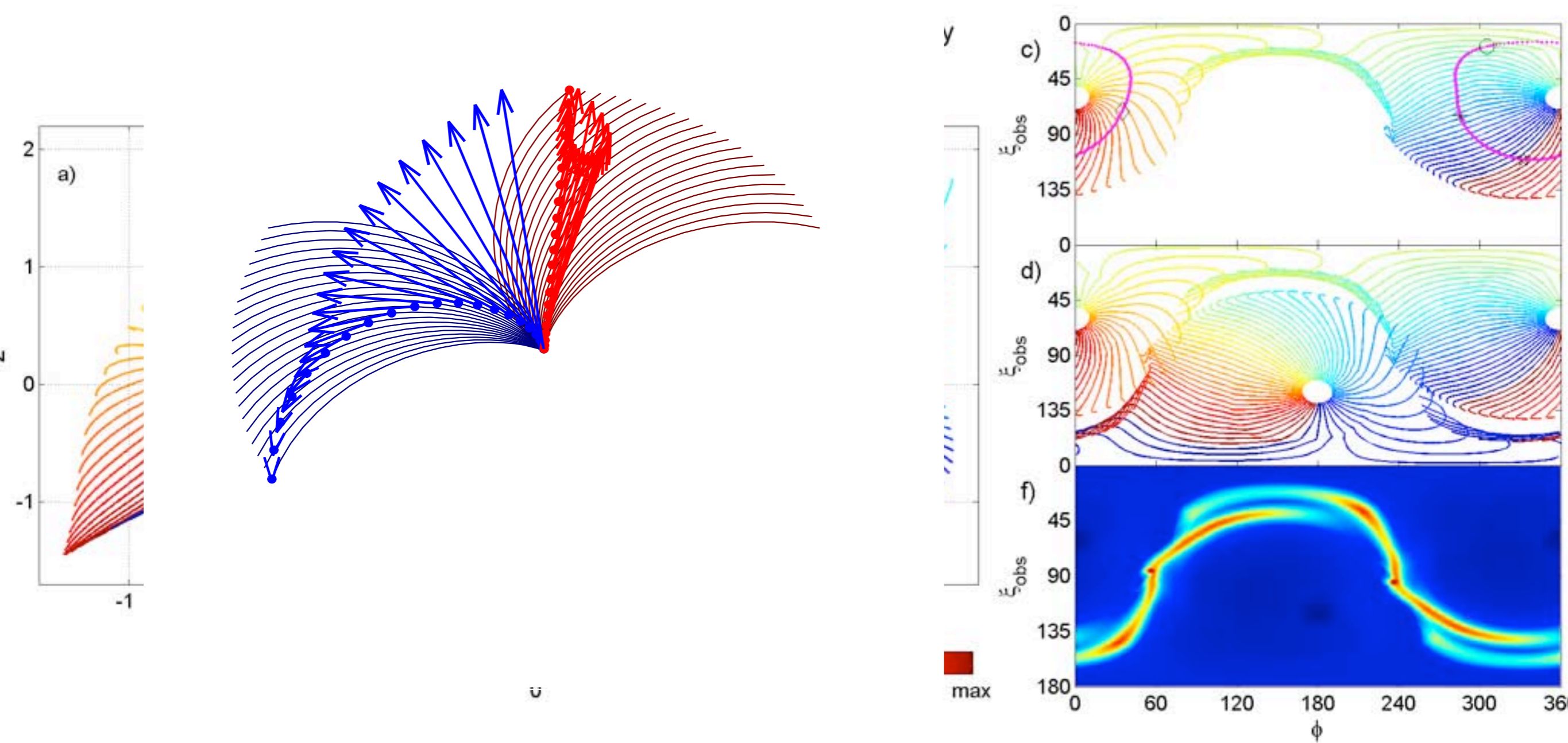


- Select flux tubes that map into rings on the polar caps. The rings are congruent to the edge of the polar cap.
- This is arbitrary, but the point is to study the geometry of the possible emission zone.
- Emission is along field lines, with aberration and time delay added

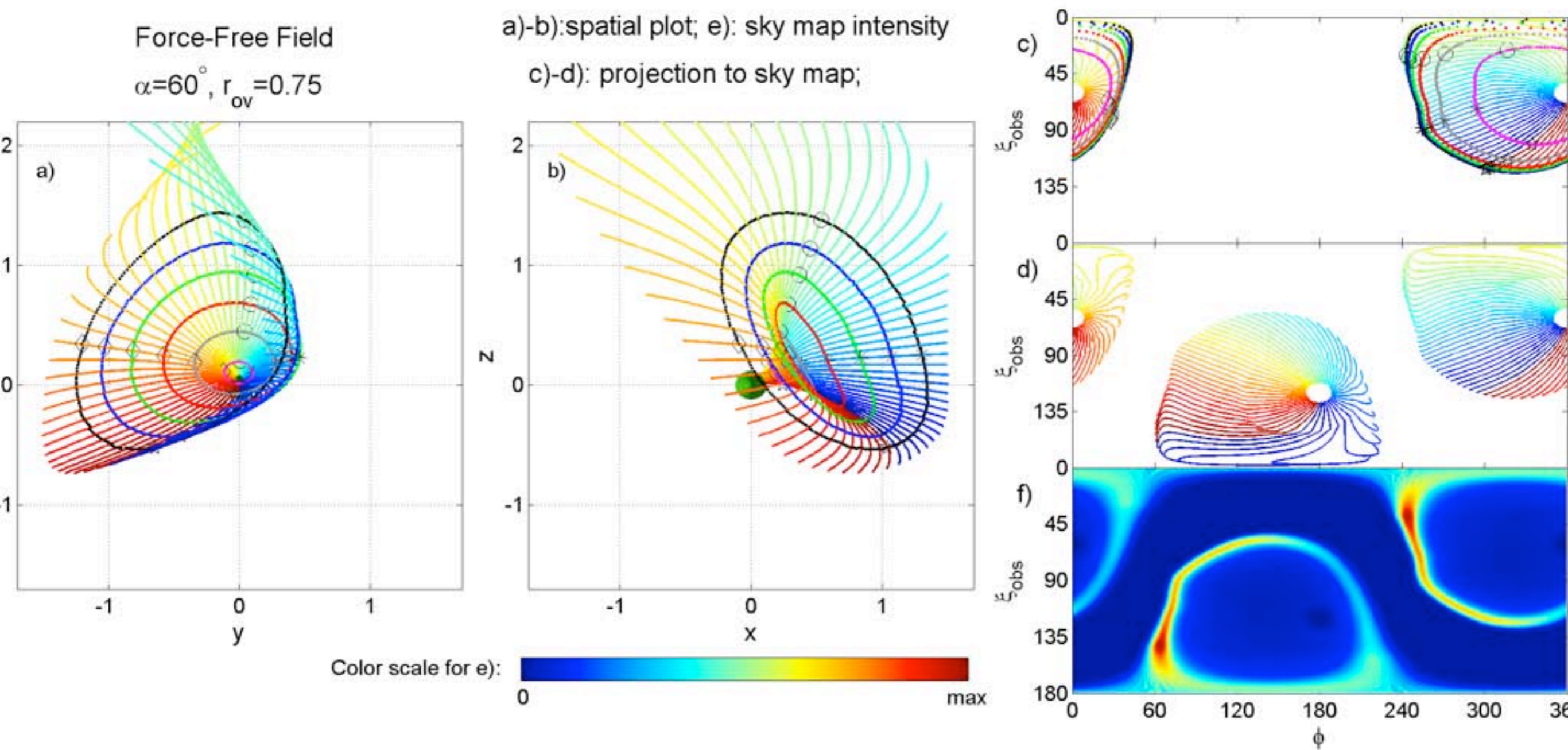


open field lines

Emission from one flux tube



Emission from different flux tubes



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

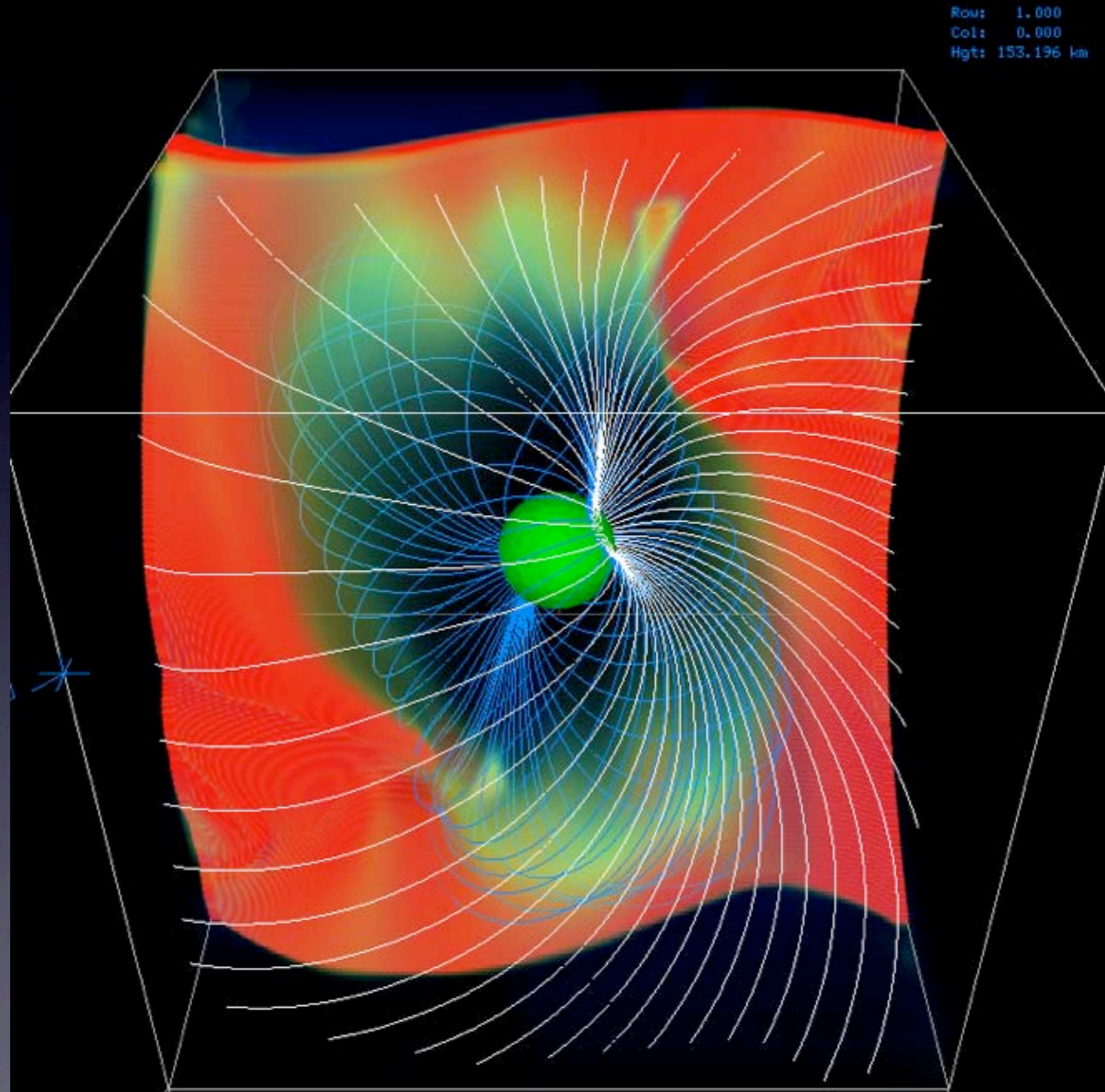
Association with the current sheet

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.

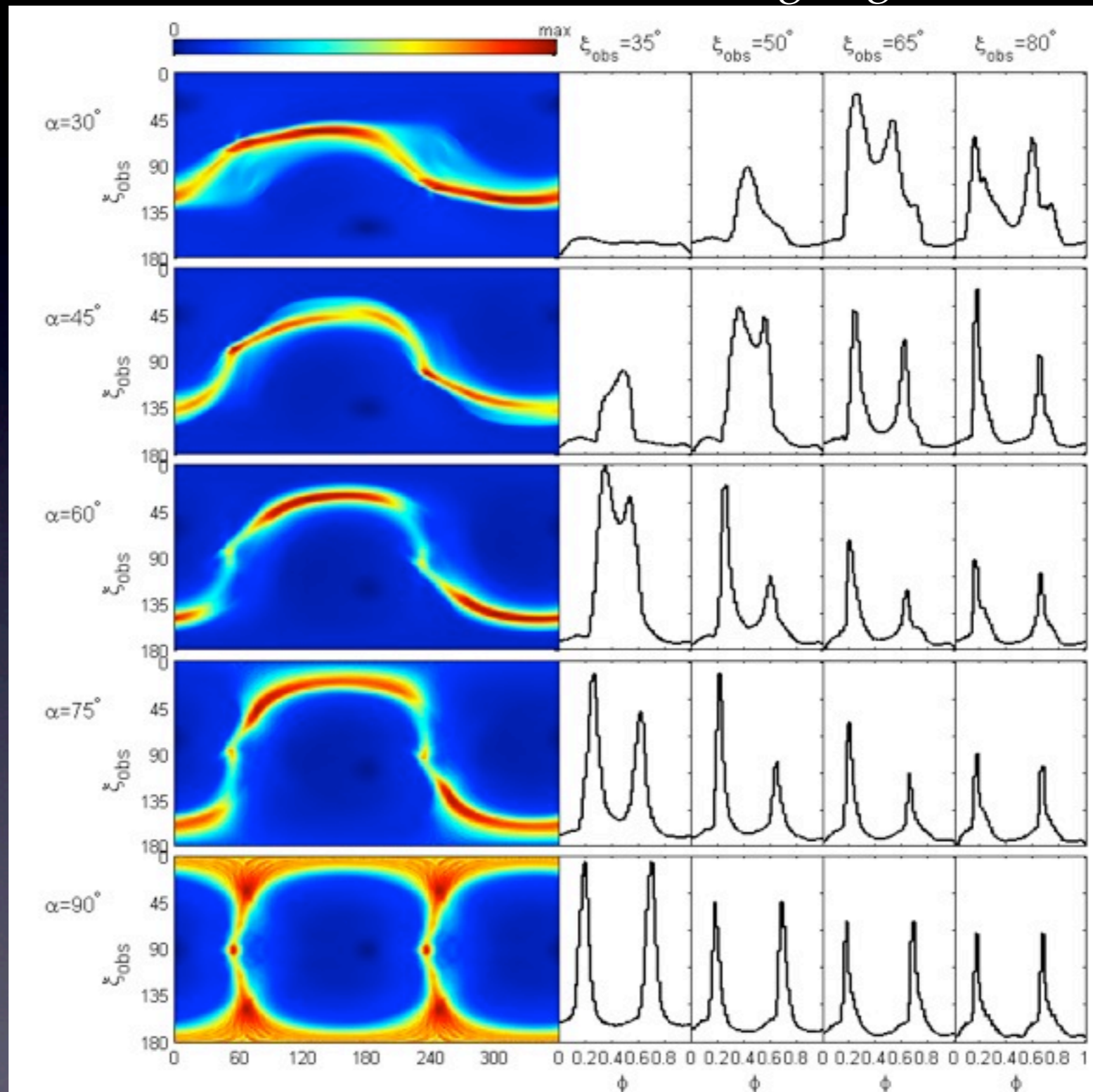
Current sheet good place to put resistor in the circuit!



Force-free gallery

Viewing angle

Inclination angle of magnetic axis



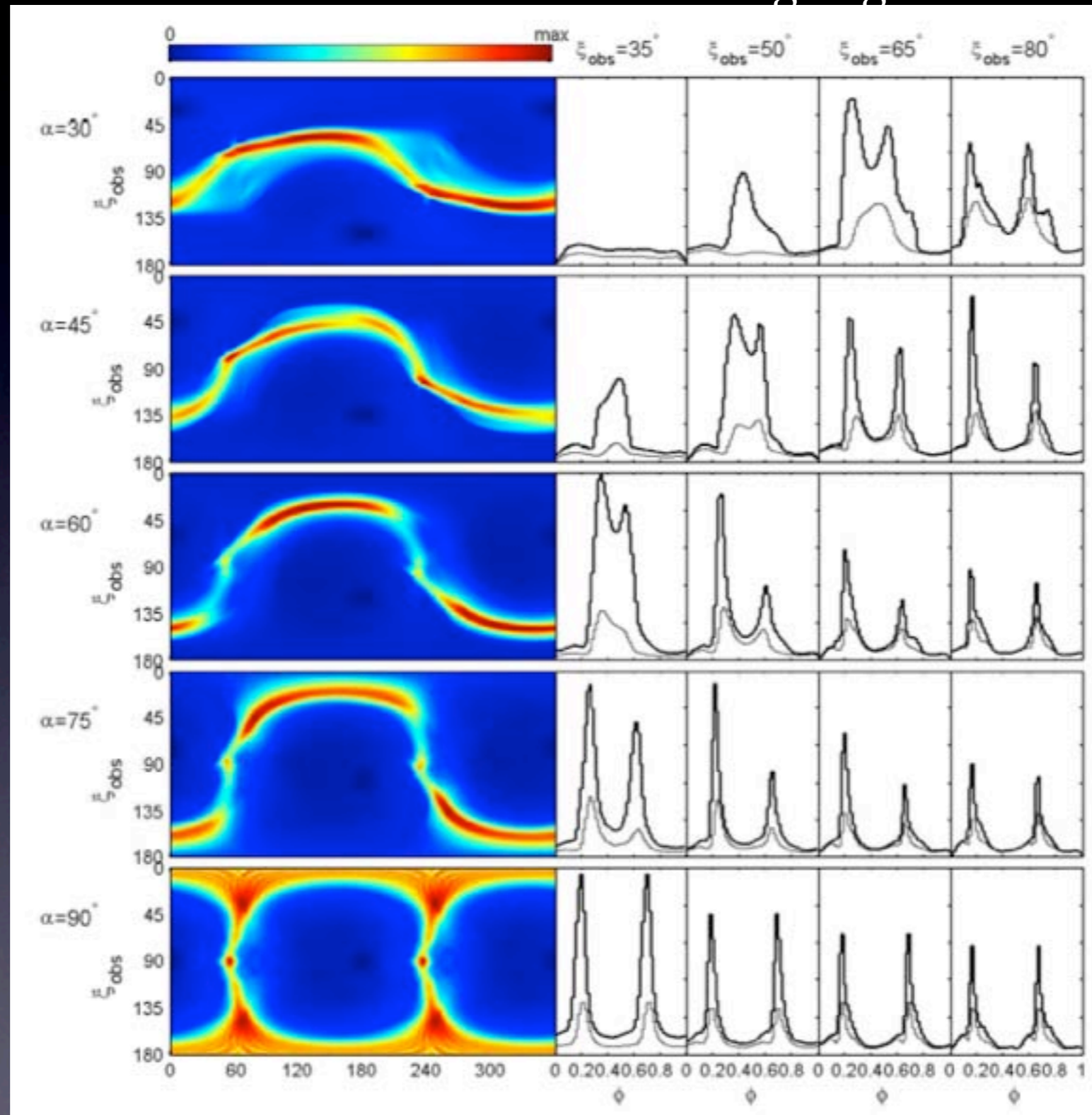
Double peak profiles very common.

Force-free gallery

Viewing angle

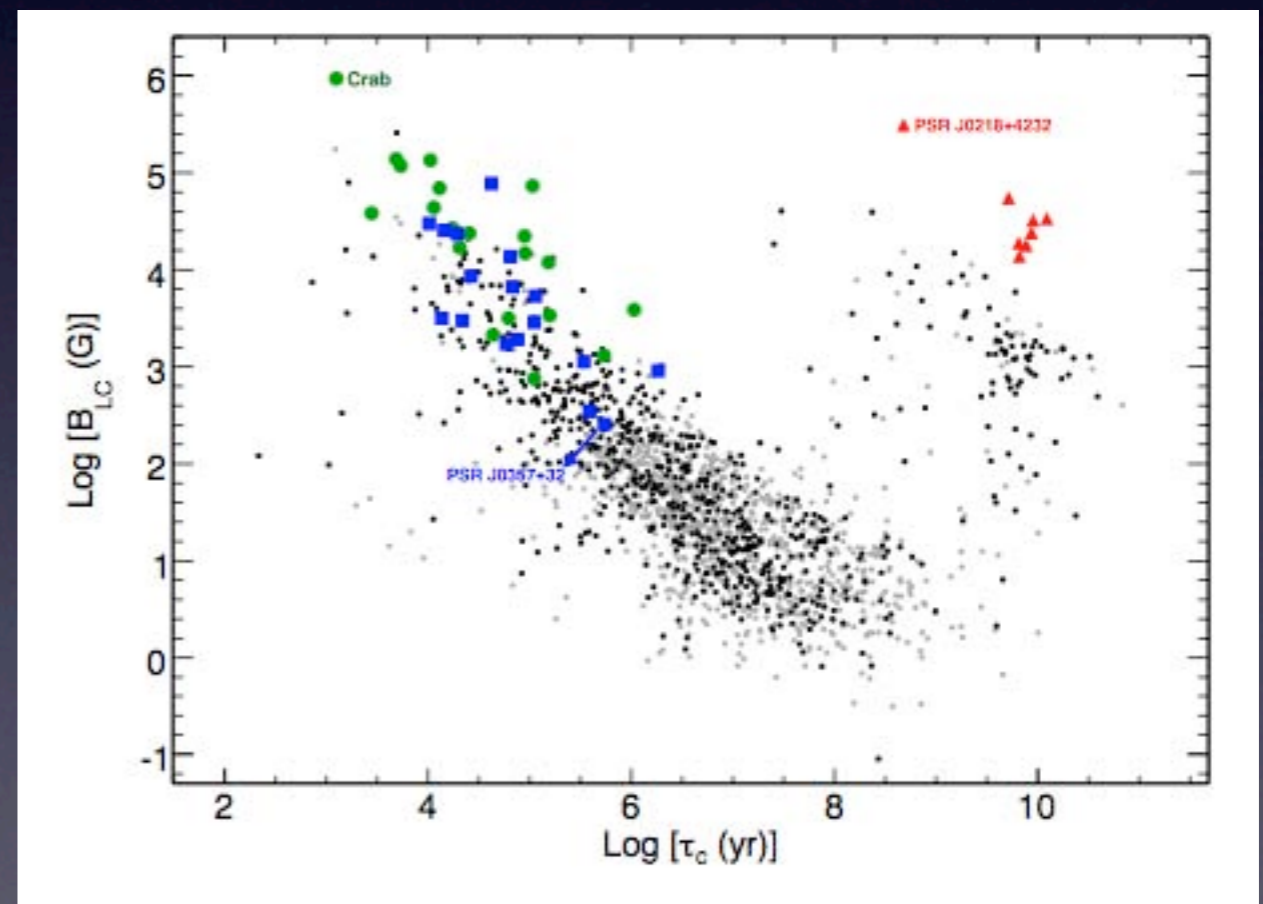
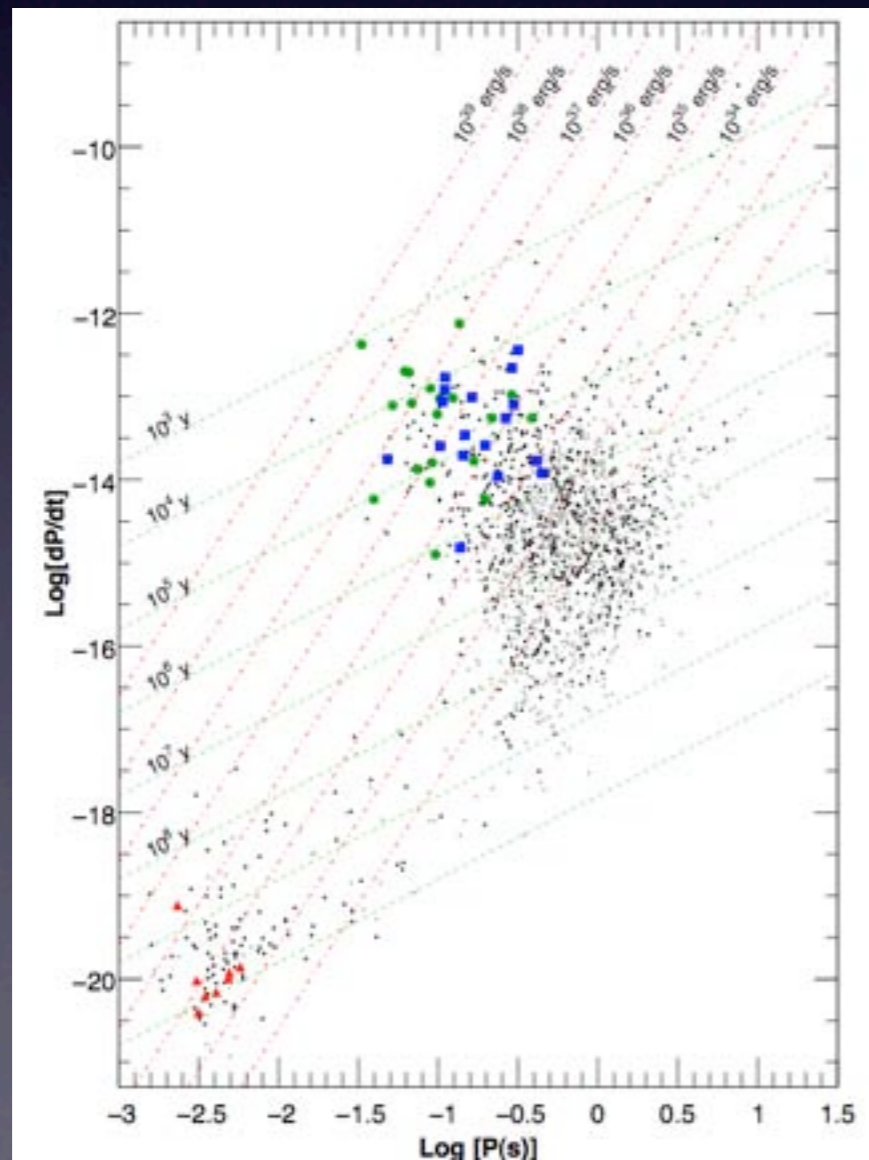
Inclination angle of magnetic axis

Most of the emission in FF model accumulates beyond $0.9 R_{lc}$



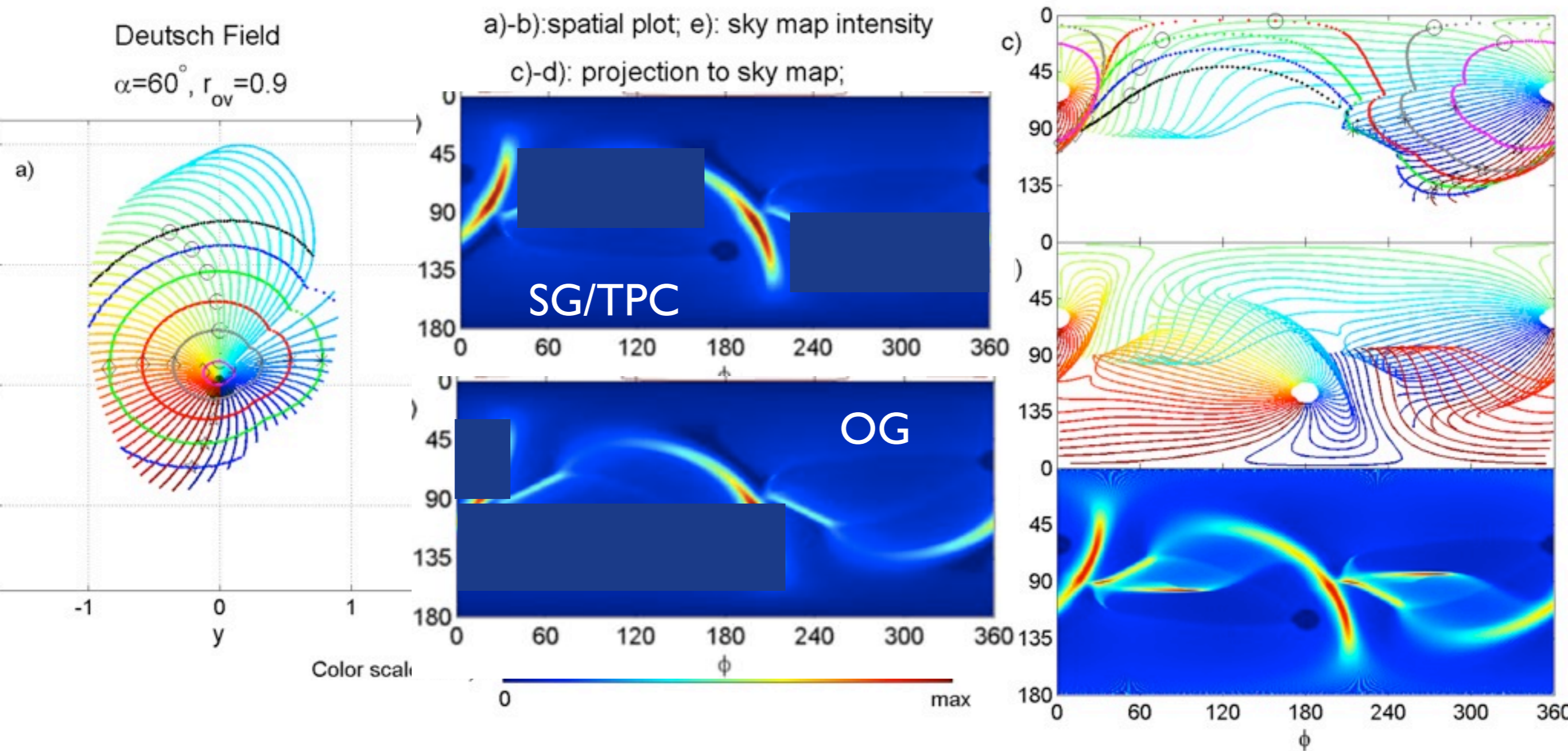
Double peak profiles very common.

Gamma-ray emission from pulsars



High B at light cylinder required

Vacuum sky map



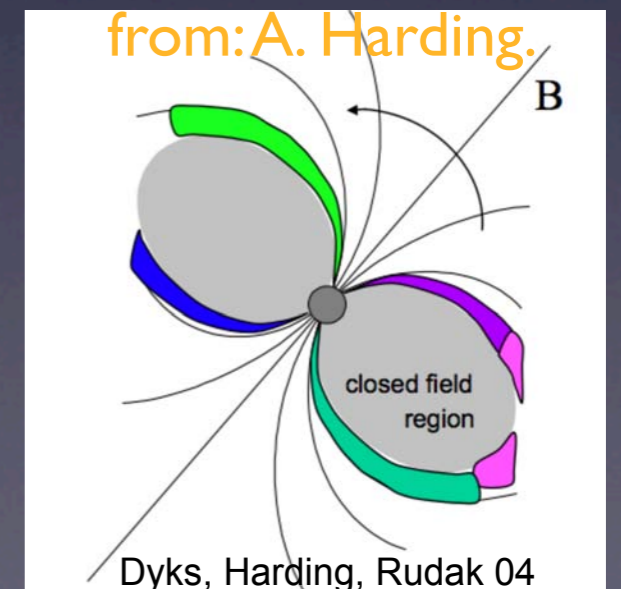
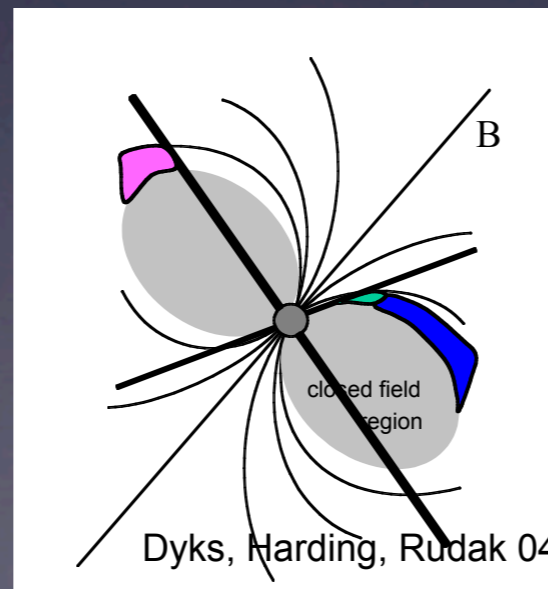
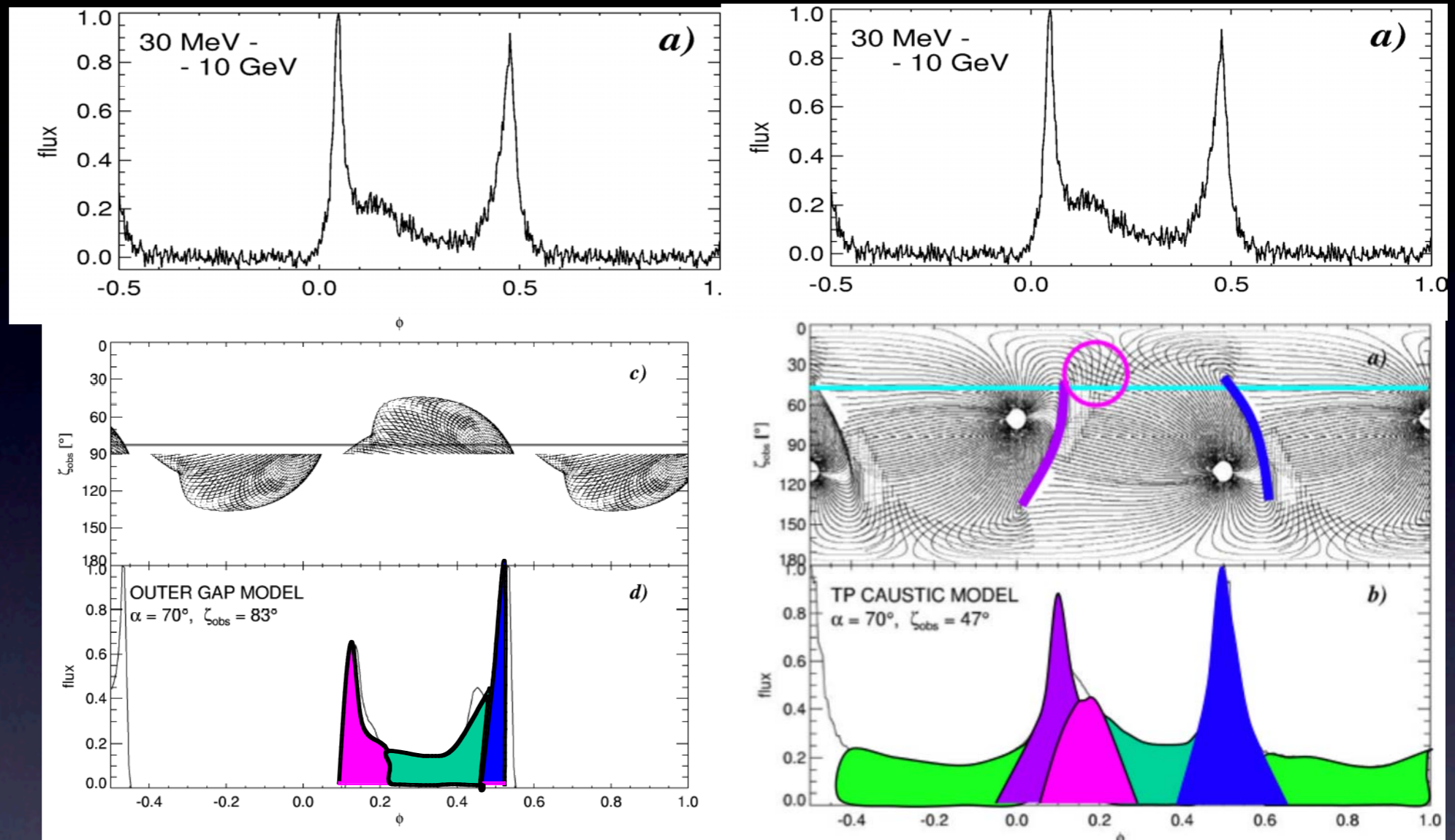
Vacuum field, 60 degree inclination, flux tube starting at 0.9 of the polar cap radius.

Vacuum 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)

Both FF and vacuum models point to outer magnetosphere.



from: A. Harding.

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.

Spectrum formation

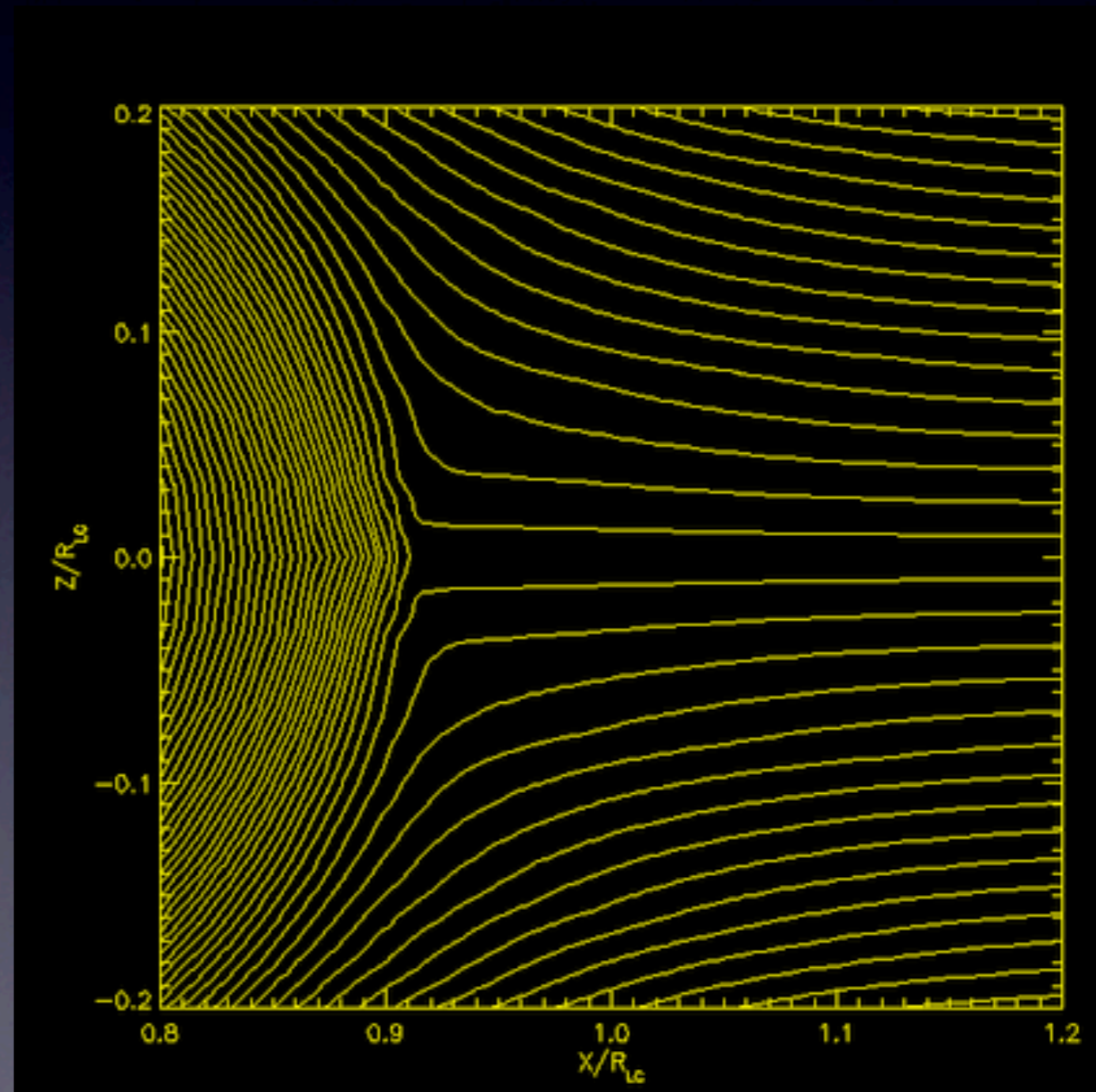
Radiation reaction-limited curvature radiation is invoked in gaps

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.

Radiation could be synchrotron, not curvature

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



Recap:

Pulsars generate plasma: magnetosphere is filled with (quasineutral) plasma (density $\sim 10^4$ - 10^6 nGJ)

Plasma currents result in spin down; wind carries Poynting flux

Wind is strongly magnetized @LC (magnetic/kinetic energy $\sim 10^4$)

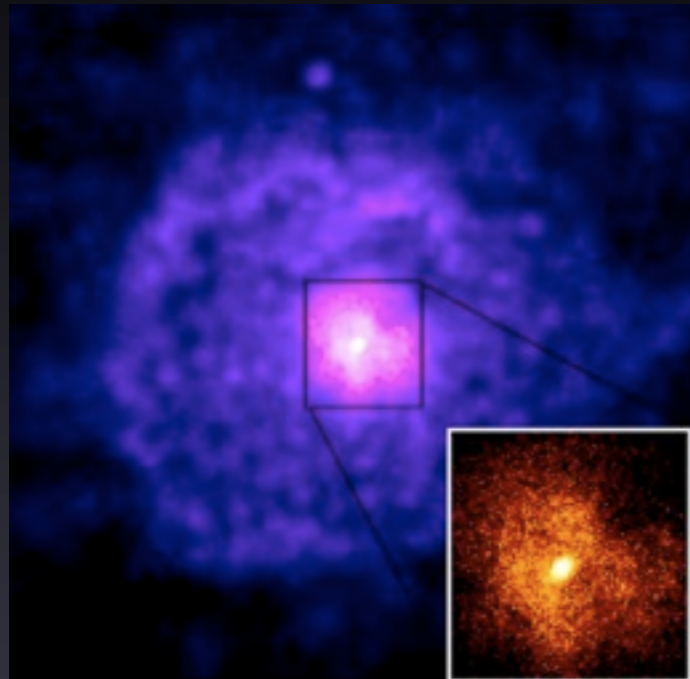
Wind is “striped”

High-energy emission near LC is related to current sheets

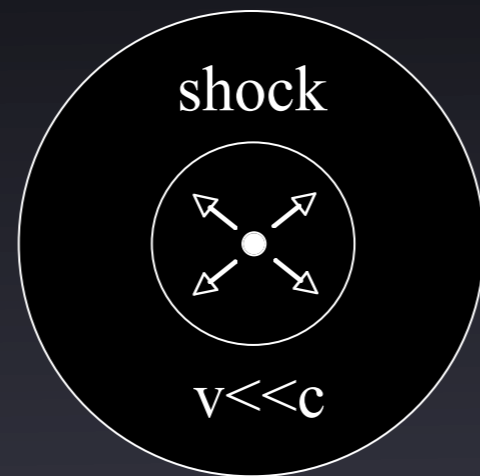
Particle spectrum accelerated near LC is irrelevant to the particle spectrum in the outside world, due to adiabatic losses in the wind.

Pulsar Wind Nebulae

Properties of pulsar winds:



G21.9 (Safi-Harb et al 2004)

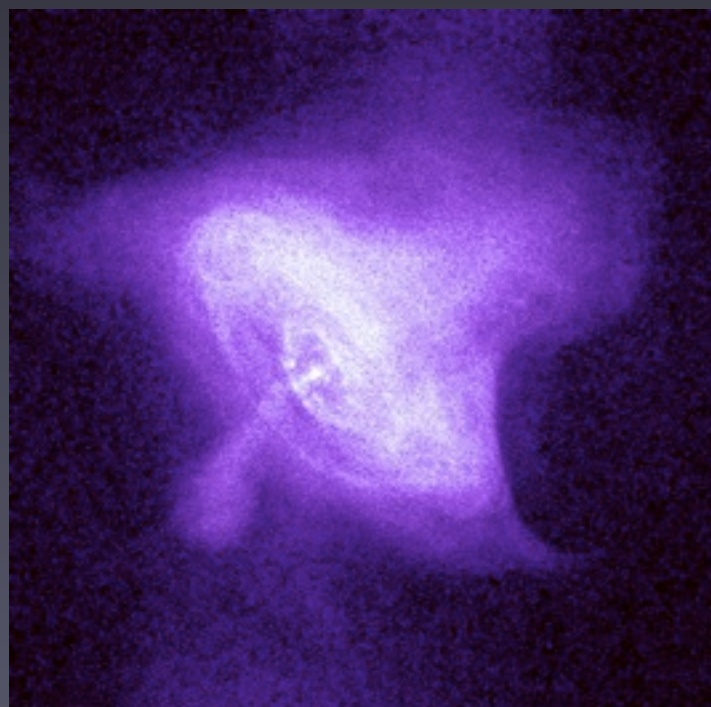


Kennel & Coroniti 84
Rees & Gunn 74

- Highly relativistic ($\gamma \sim 10^6$) upstream, $\sim c/3$ downstream
- Kinetic energy dominated at the nebula (“ σ -problem”). \sim Toroidal field

$$\sigma = B^2 / (4\pi\gamma n m c^2) \sim 10^{-3} - 10^{-1}$$

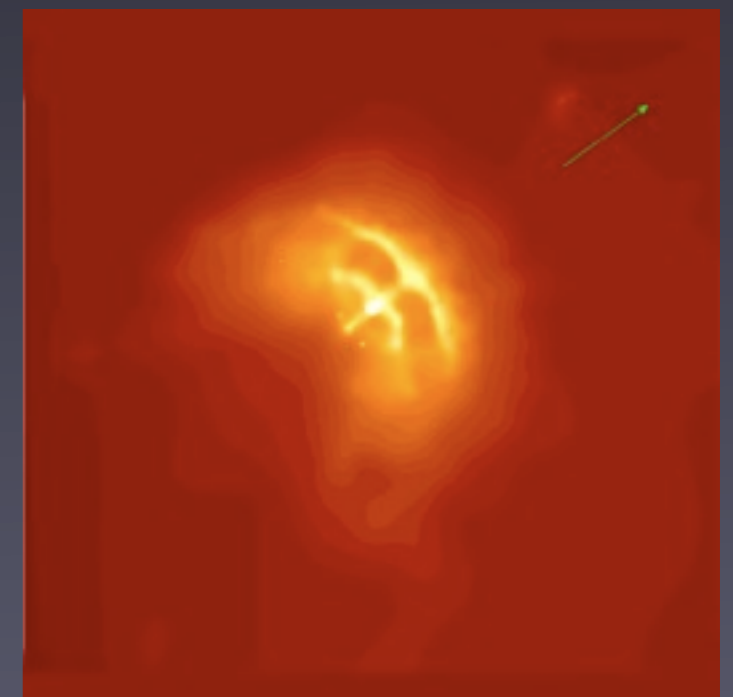
- Pole-equator asymmetry and collimation
- Produce nonthermal particles (at the termination shock?); $\gamma > 10^9$



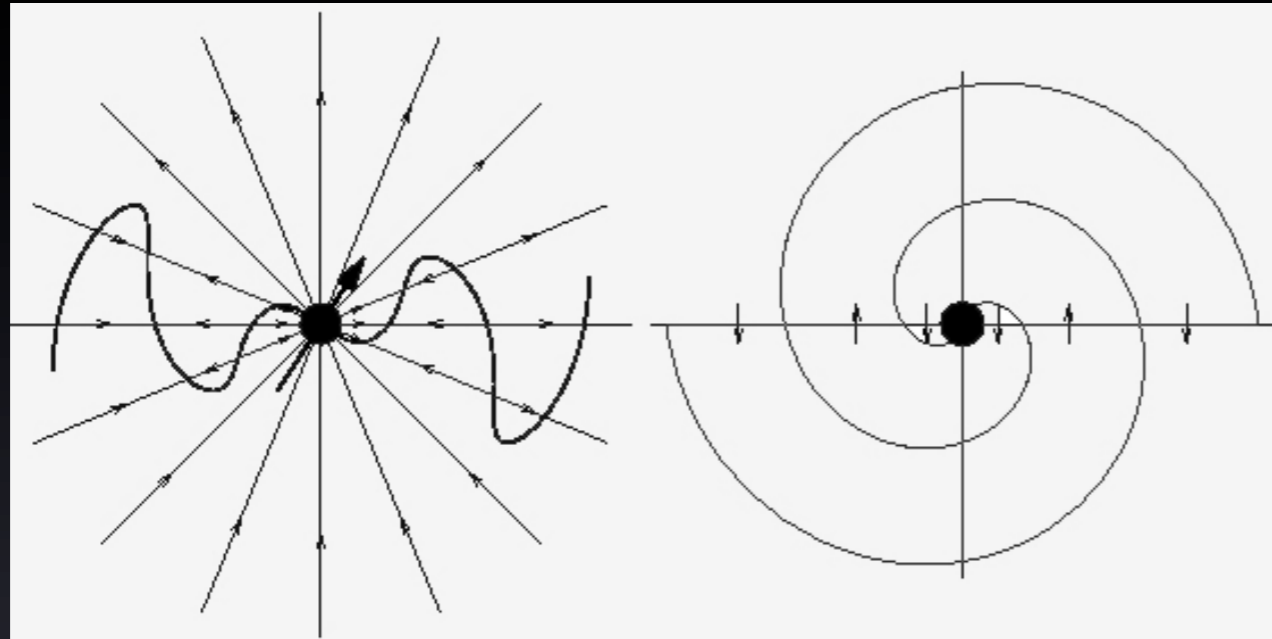
Crab (Weisskopf et al 2000)



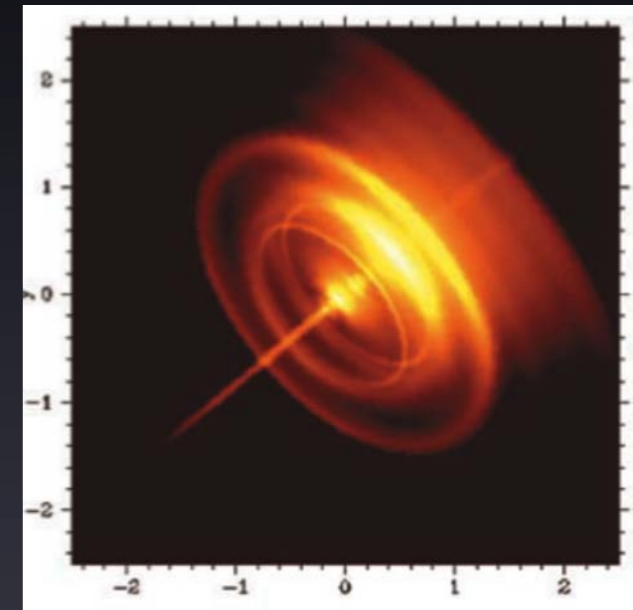
PSR B1509-58 (X-rays; Slane et al 2006)



Vela (Pavlov et al 2001)



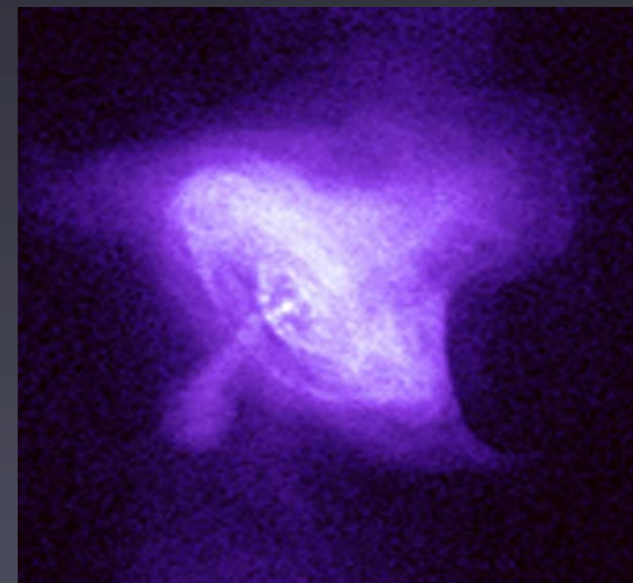
Komissarov & Lyubarsky



Somewhere in the wind magnetic dissipation should occur, because the wind is low magnetization when it comes to the nebula.

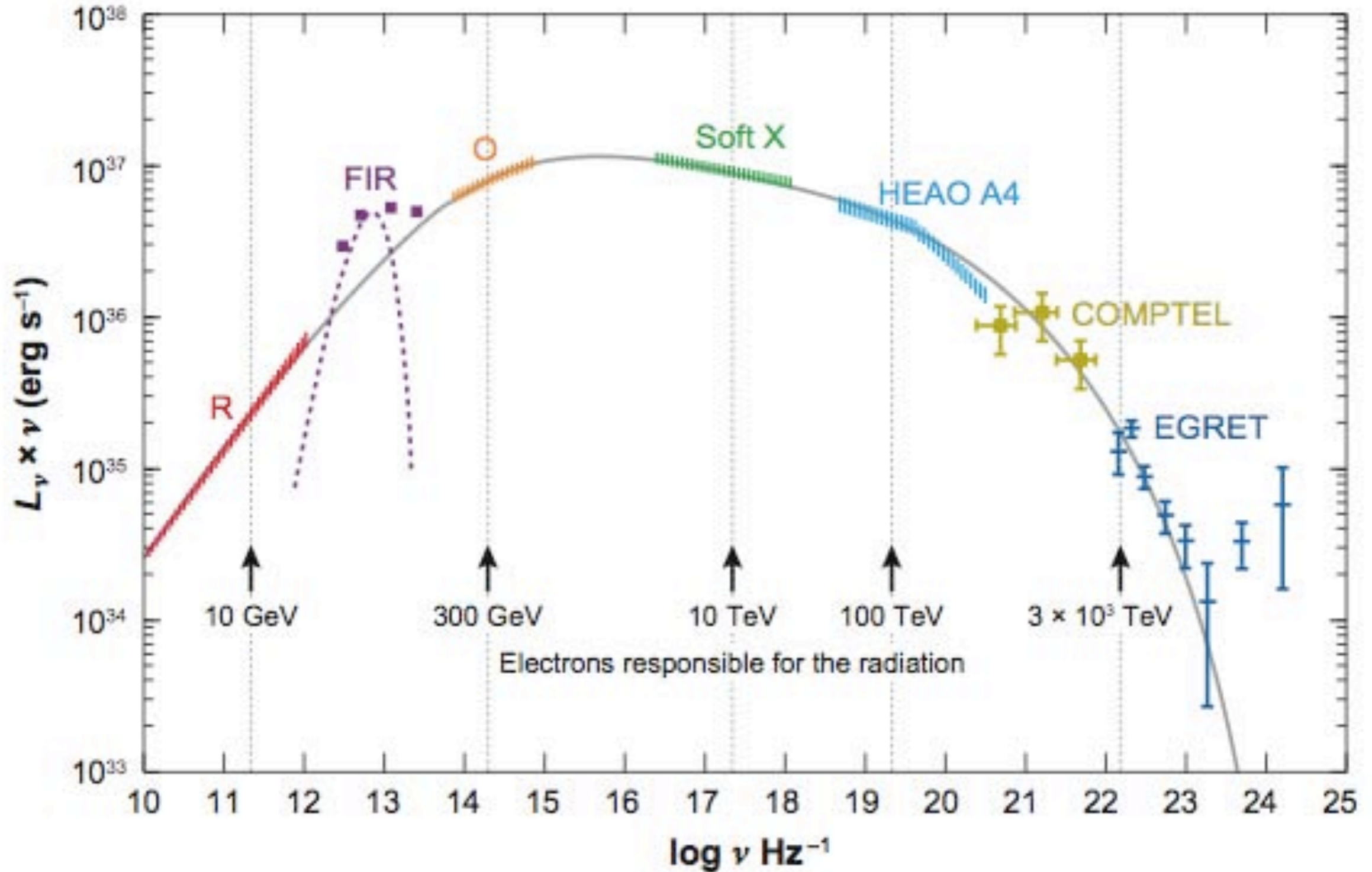
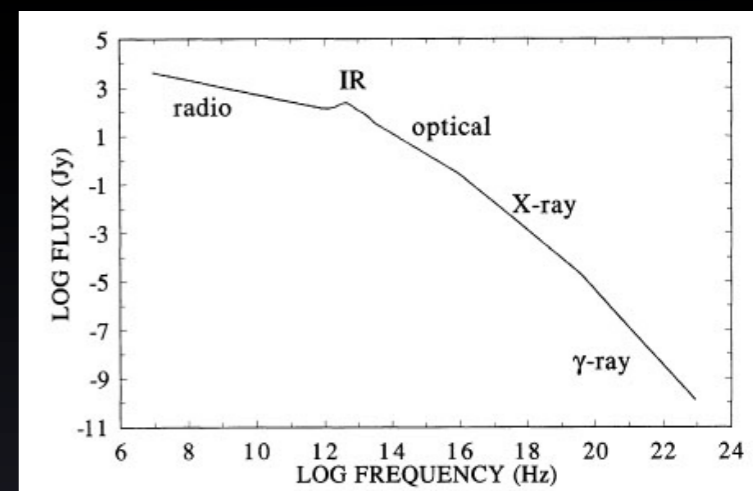
How this happens is a big uncertainty (“sigma”-problem)

The wind comes into the shock cold, with $\Gamma = 10^6$, depending on how much dissipation occurred

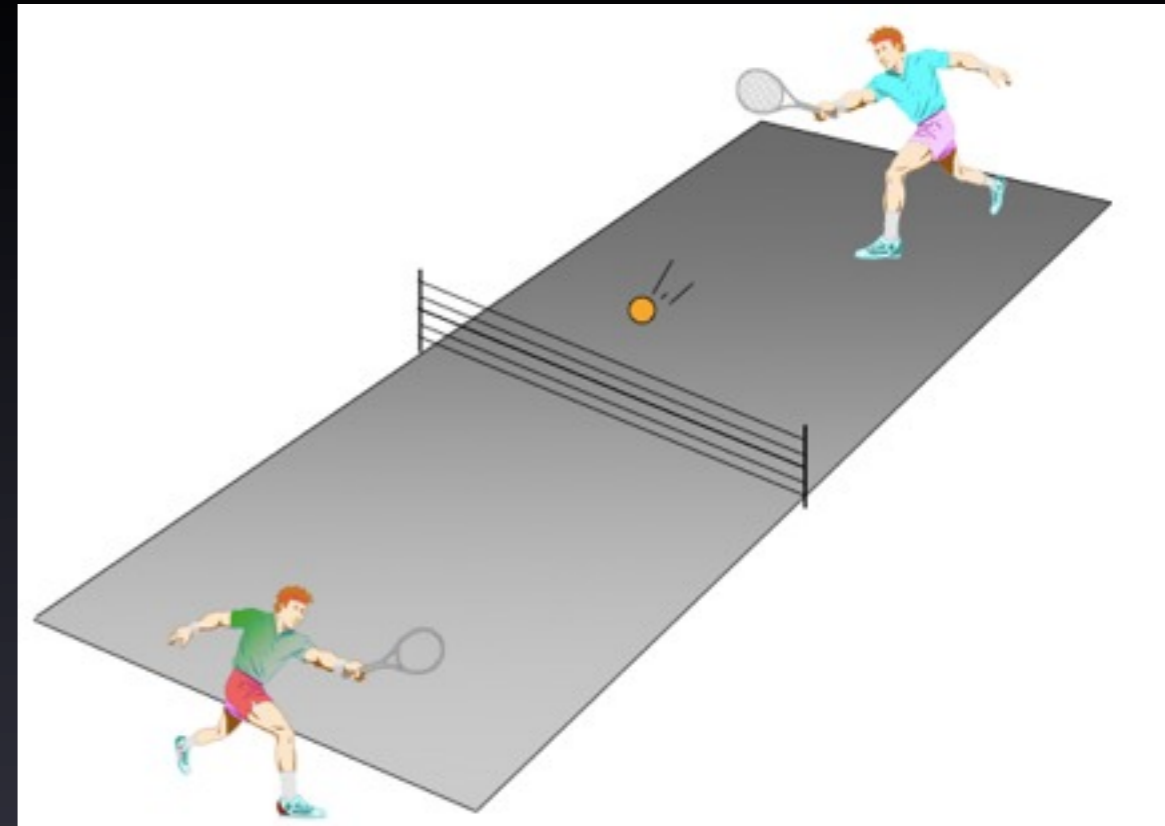
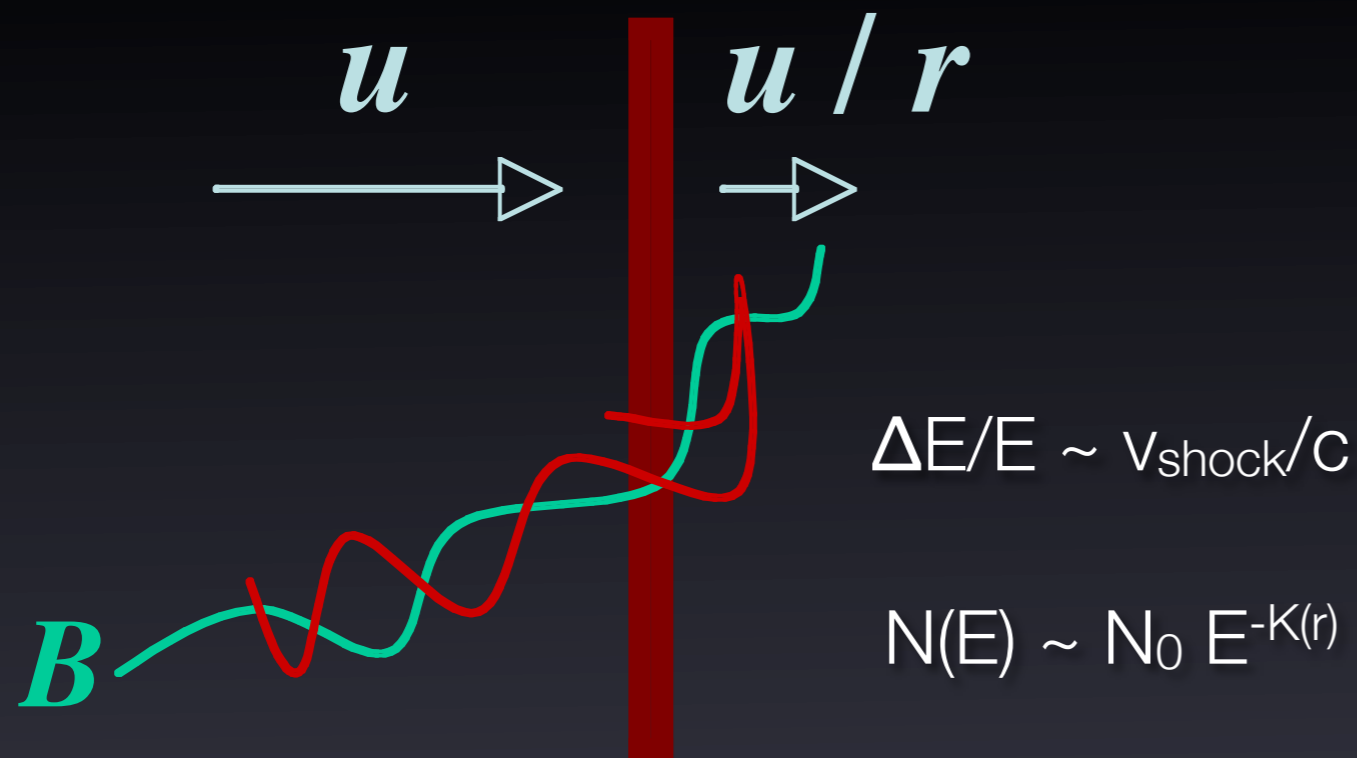


$$B_{\varphi} \propto \sin \theta \left(1 - \frac{2\theta}{\pi} \right)$$

Spectrum of the Crab

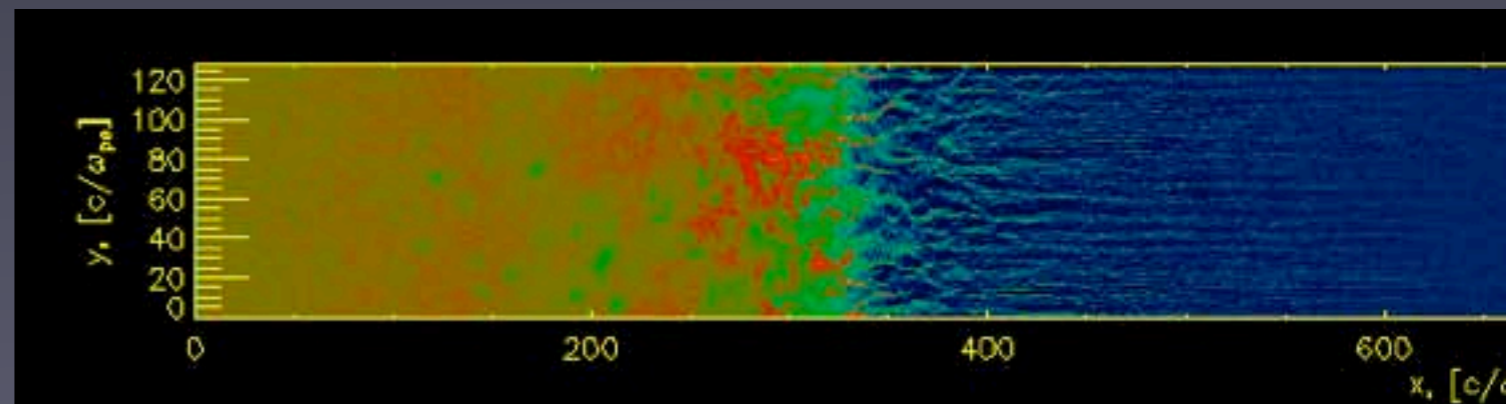


Particle acceleration:



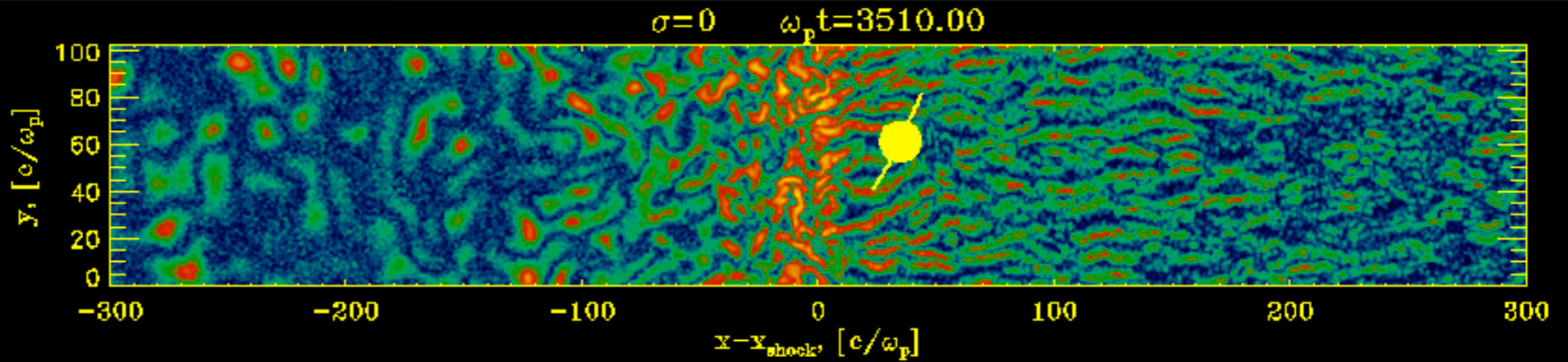
Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?

We performed a series of particle-in-cell (PIC) simulations of relativistic shocks in pair and e-ion plasmas varying level and angle of magnetic field.

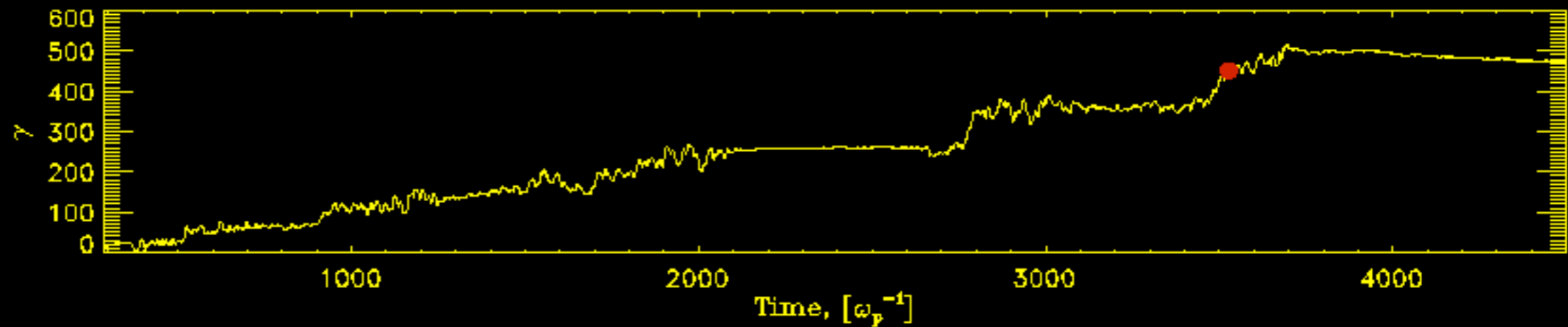


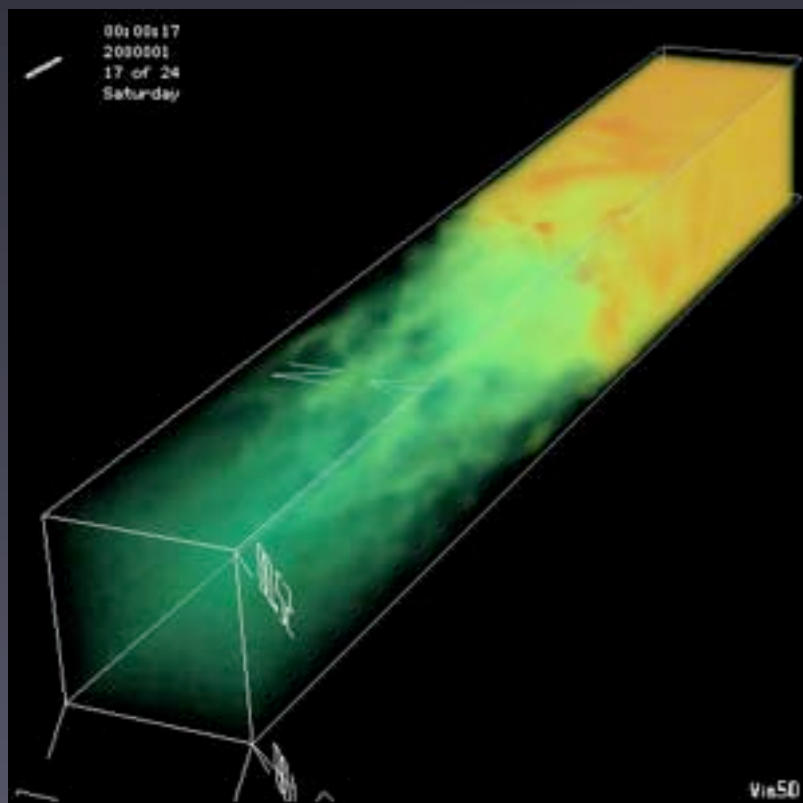
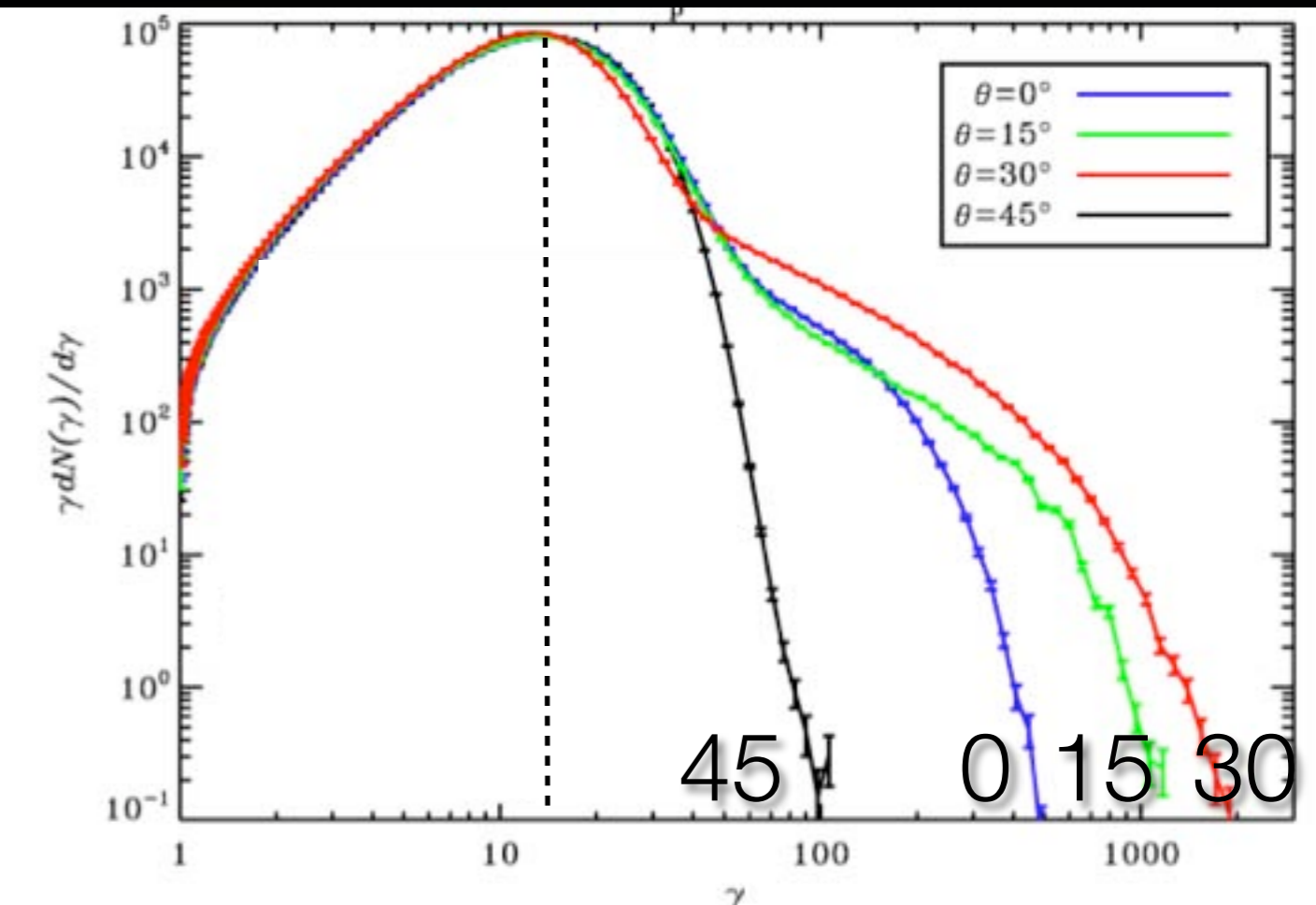
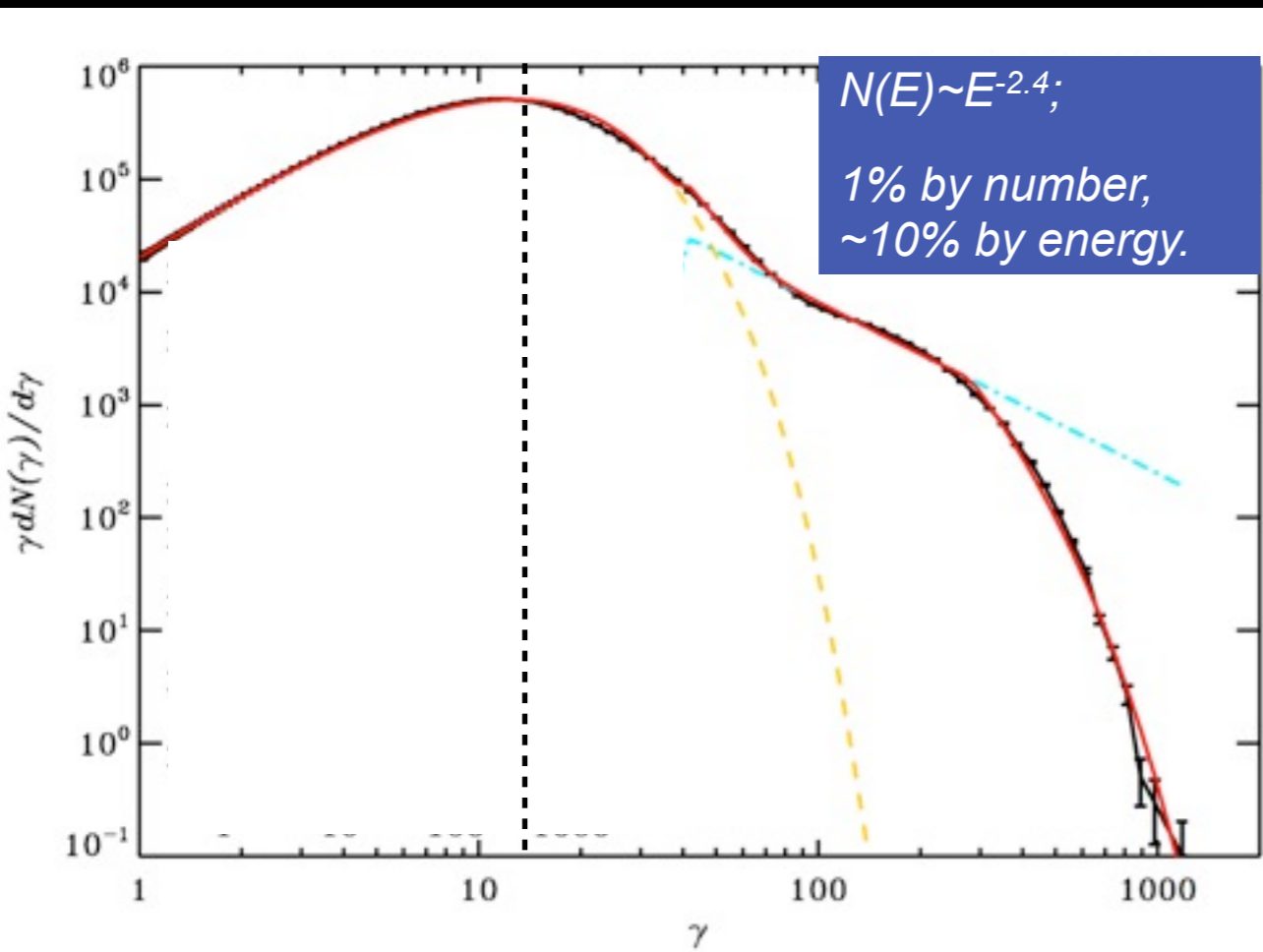
Unmagnetized pair shock: particle trajectories

Magnetic
filaments



Particle
energy

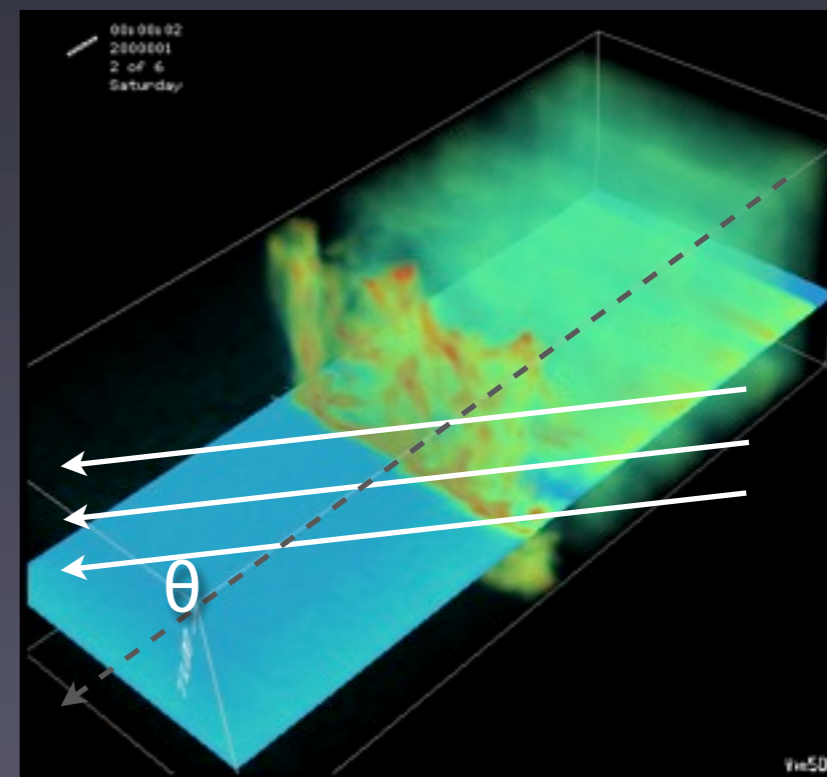


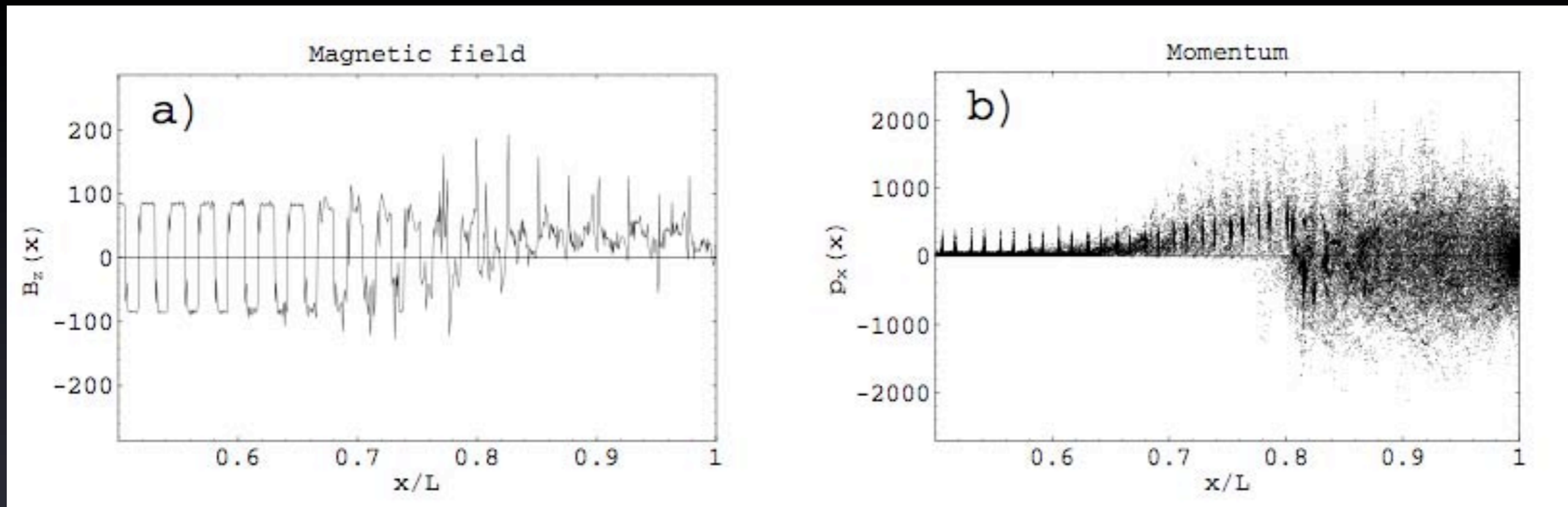


Efficient acceleration occurs for low magnetization shocks or for quasi-parallel shocks.

PWNe have highly toroidal fields, so the magnetization has to be very low near the shock to efficiently accelerate

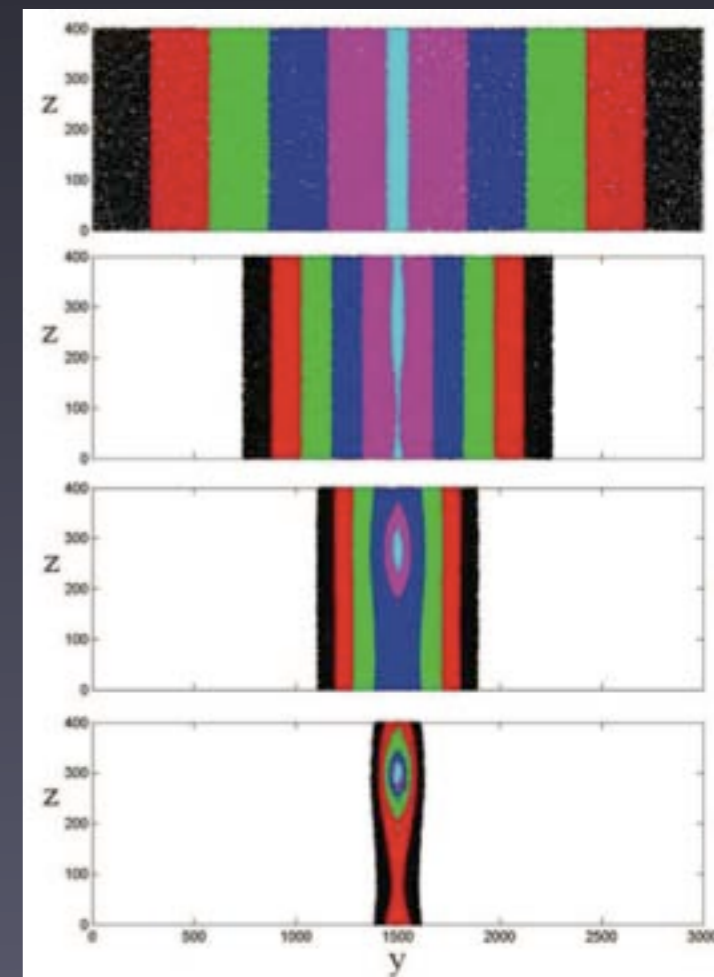
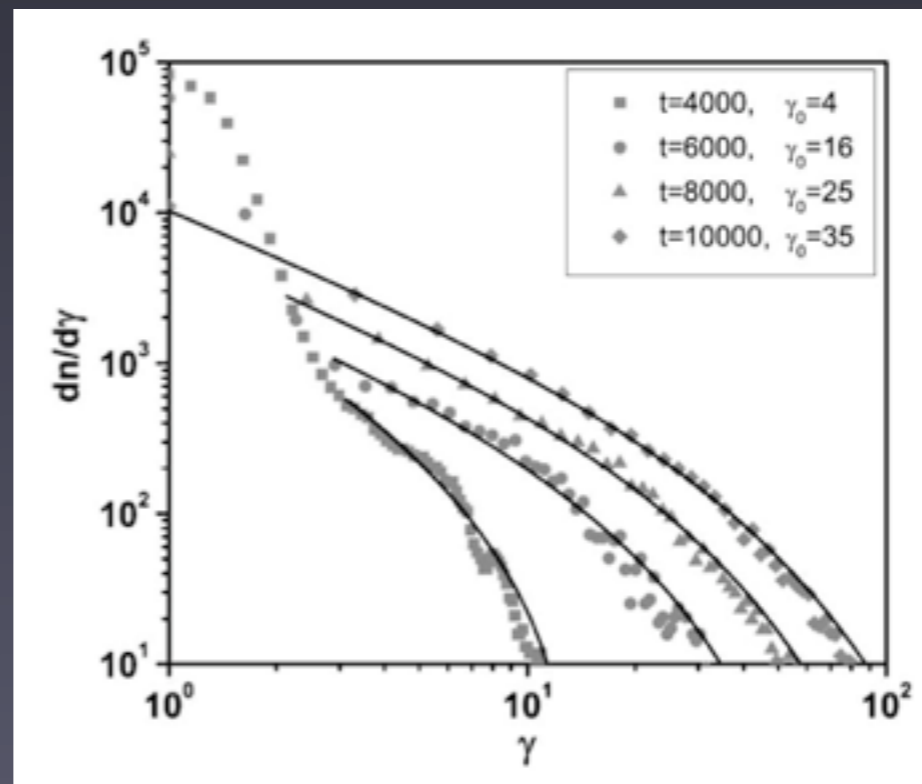
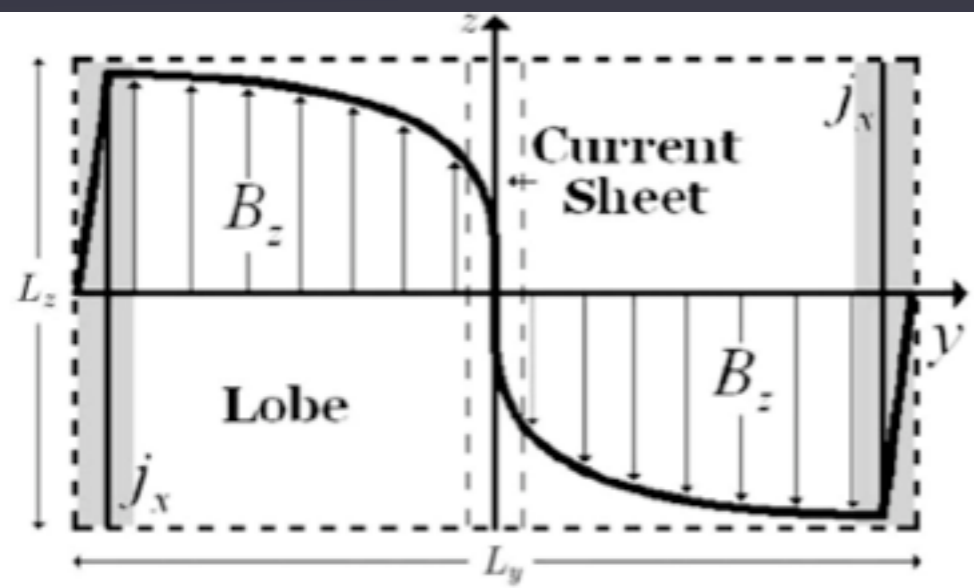
Alternative: current sheet dissipation at the shock.





Petri & Lyubarsky 2008
 Lyubarsky & Liverts 2009

reconnection @ shock
 may create flat spectra



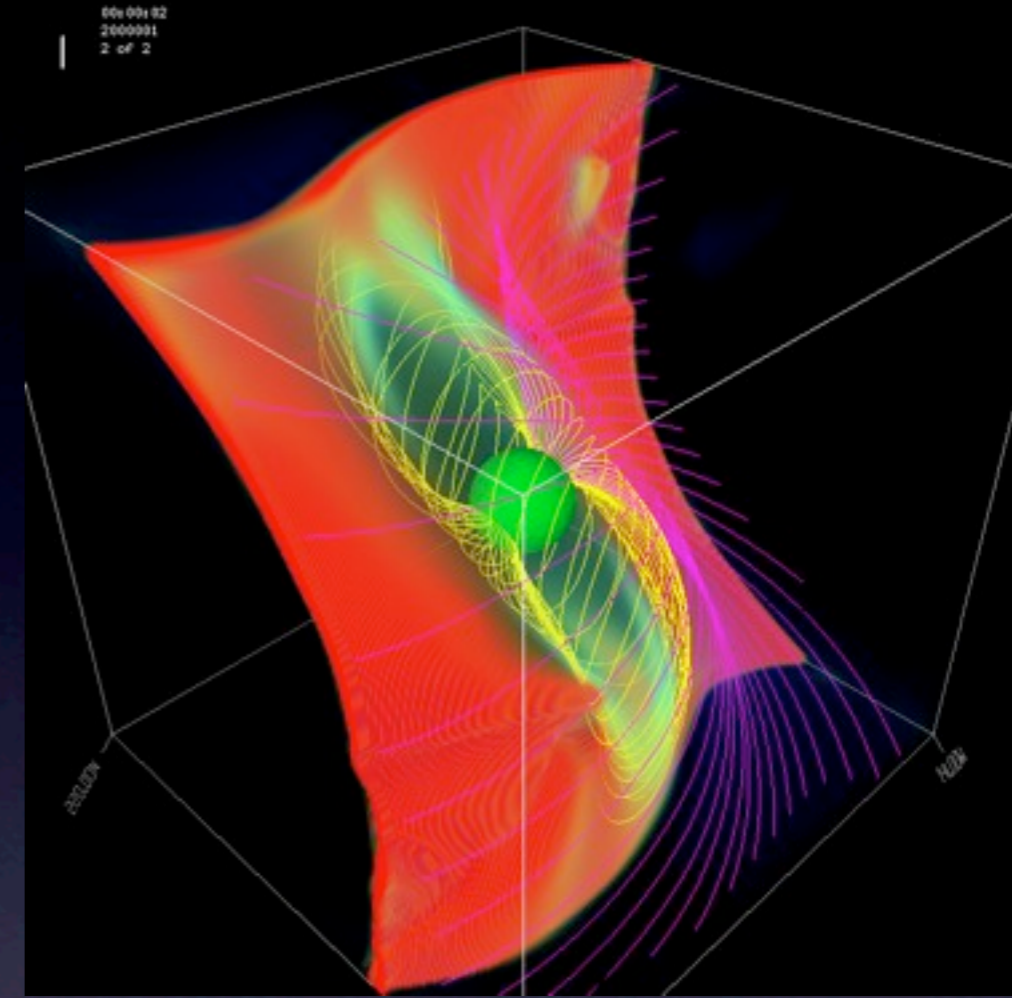
Conclusions

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 $(1+\sin^2\theta)$.

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

Current sheet dissipation in the wind or at the shock is needed to inject nonthermal particles into the nebula, SNR, and ultimately, into ISM.



Open physics question: how relativistic reconnection results in gamma-ray emission @LC, wind dissipation and influences acceleration at PWN shocks.