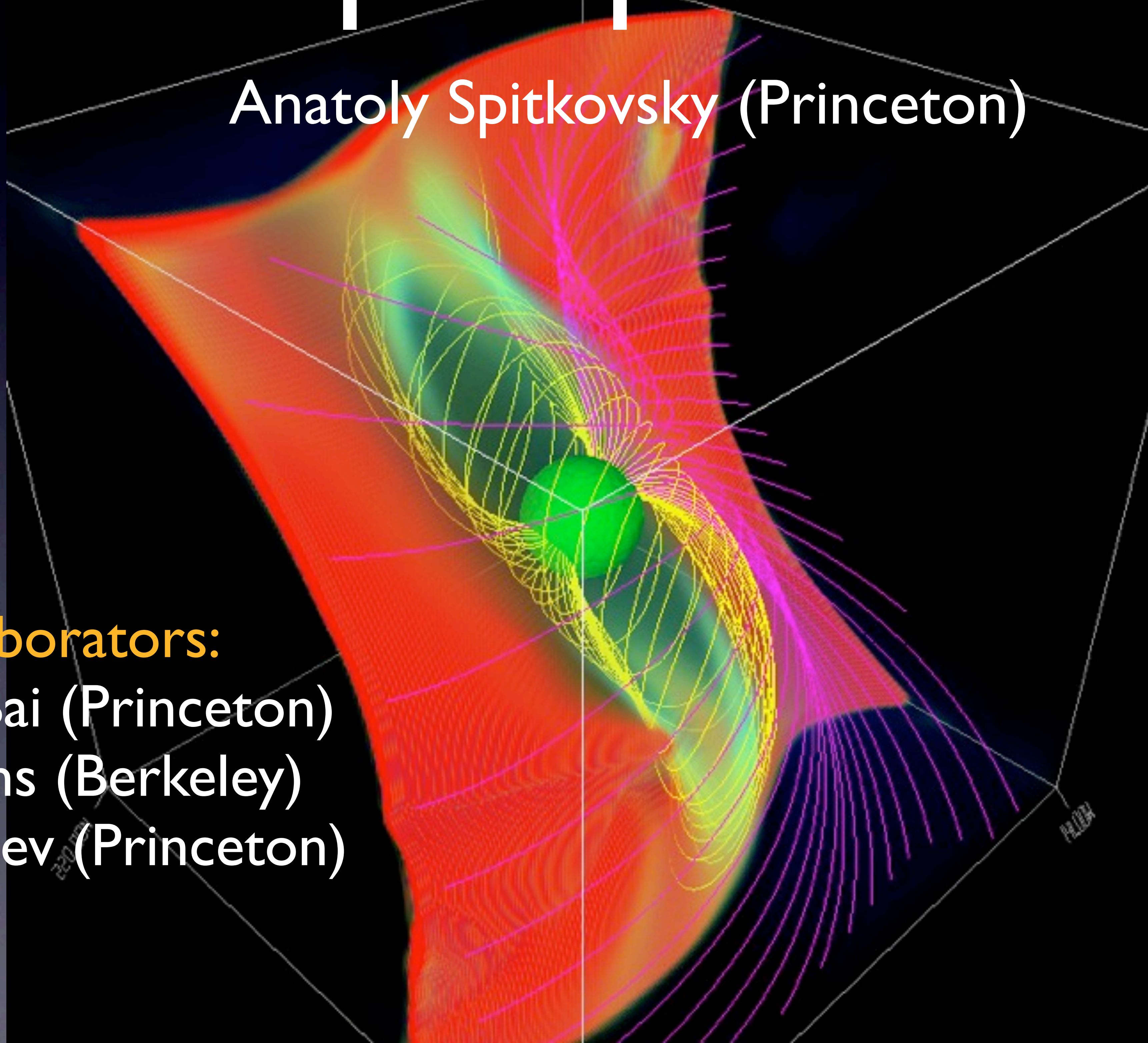
# Pulsars: status and prospects



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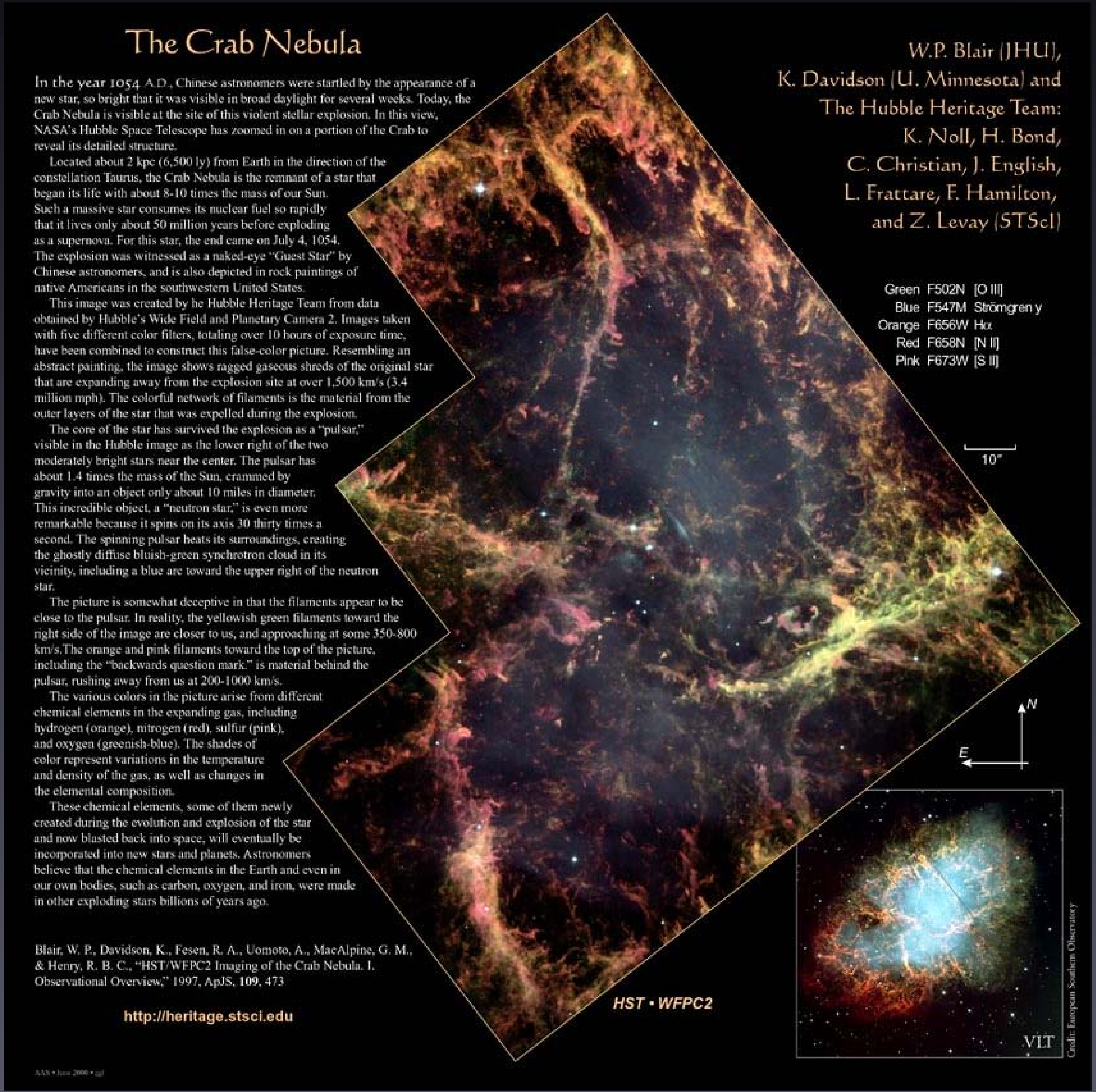
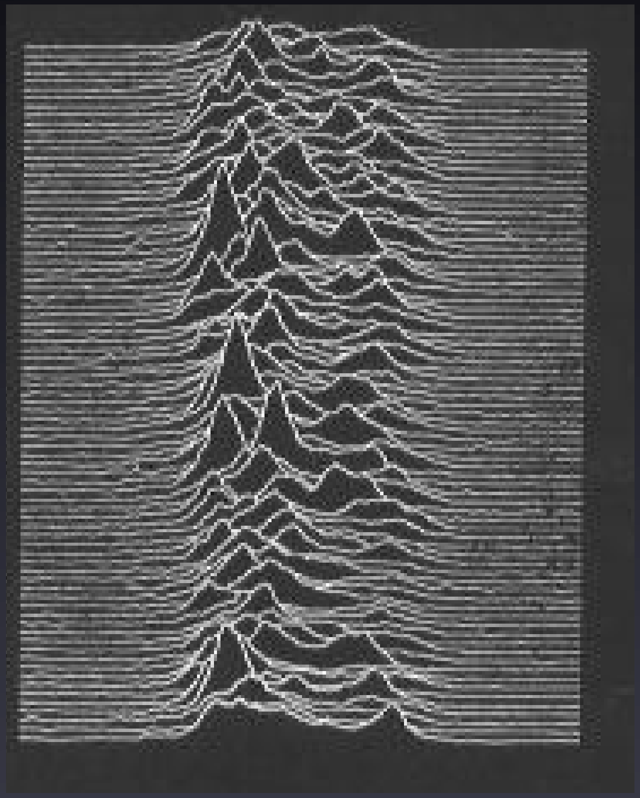
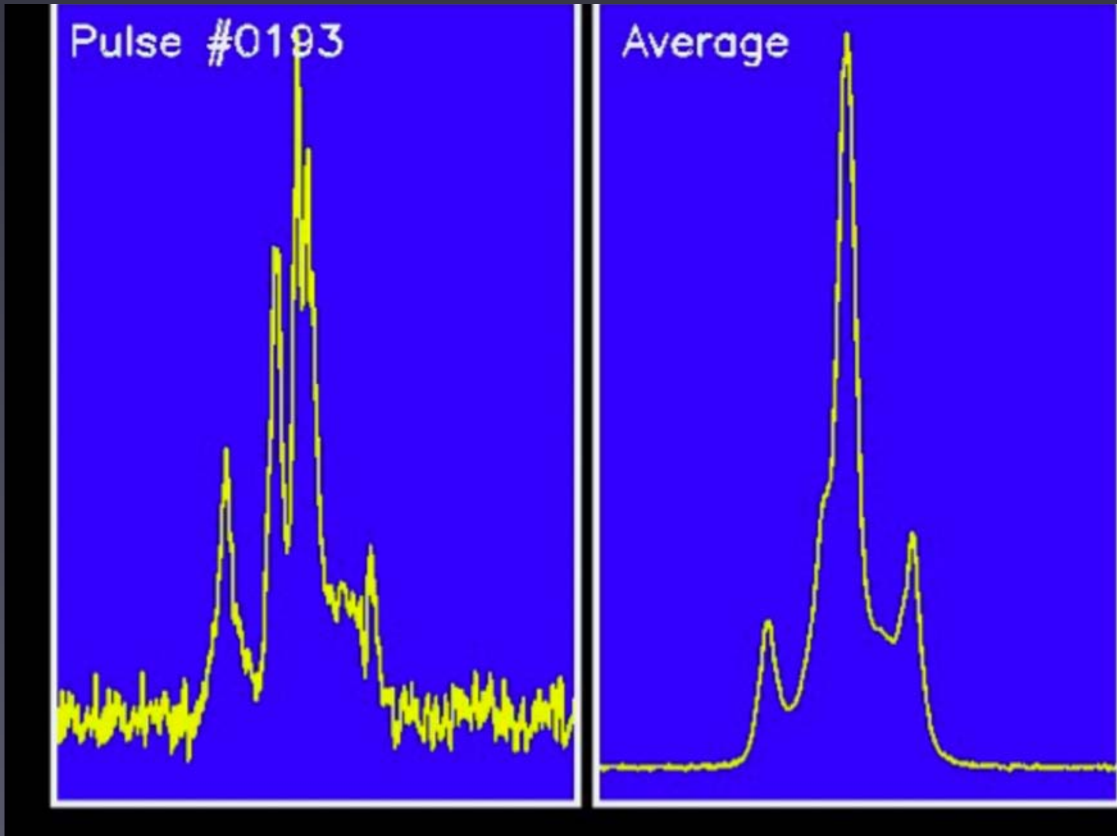
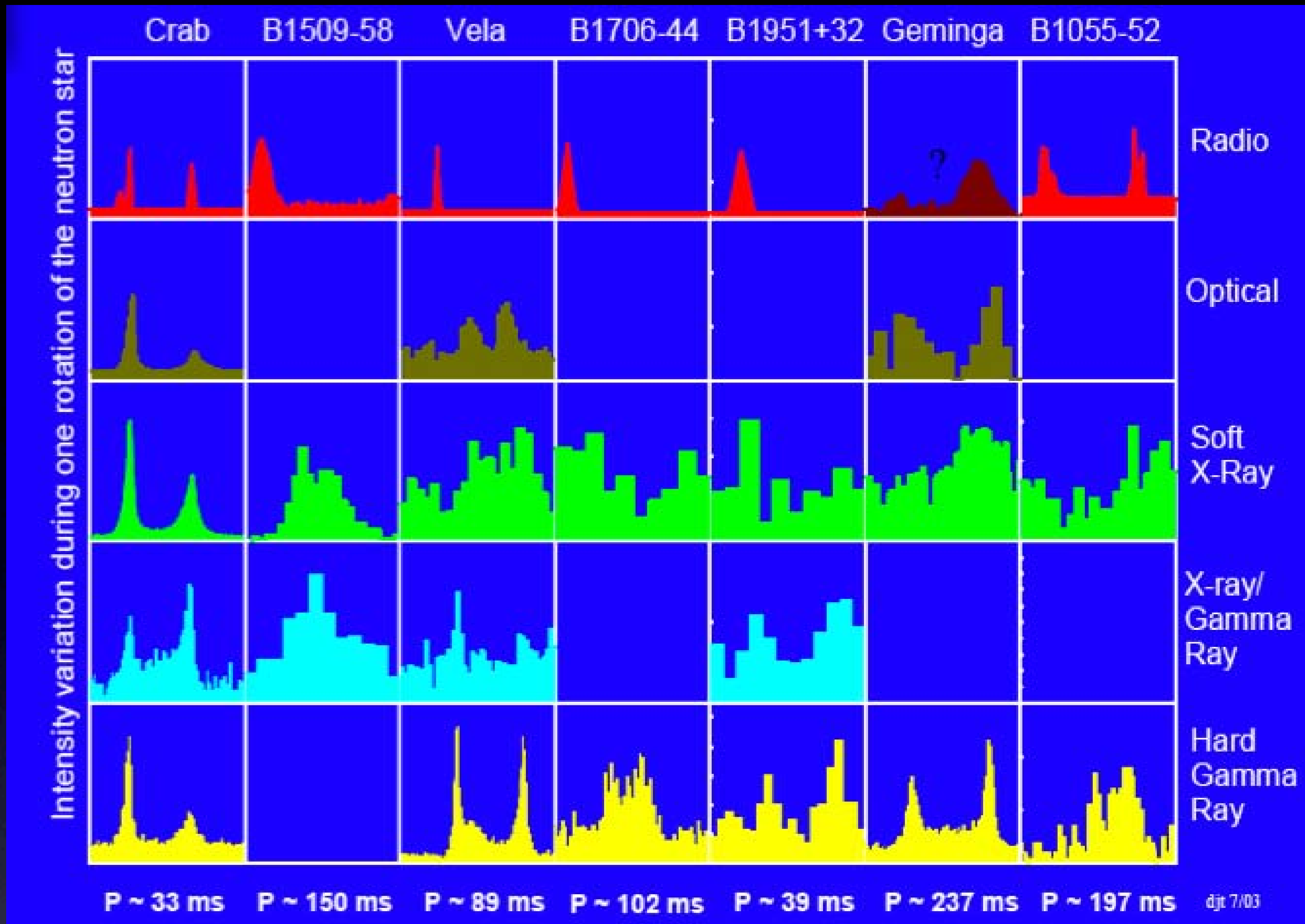
Jon Arons (Berkeley)
Mike Belyaev (Princeton)

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

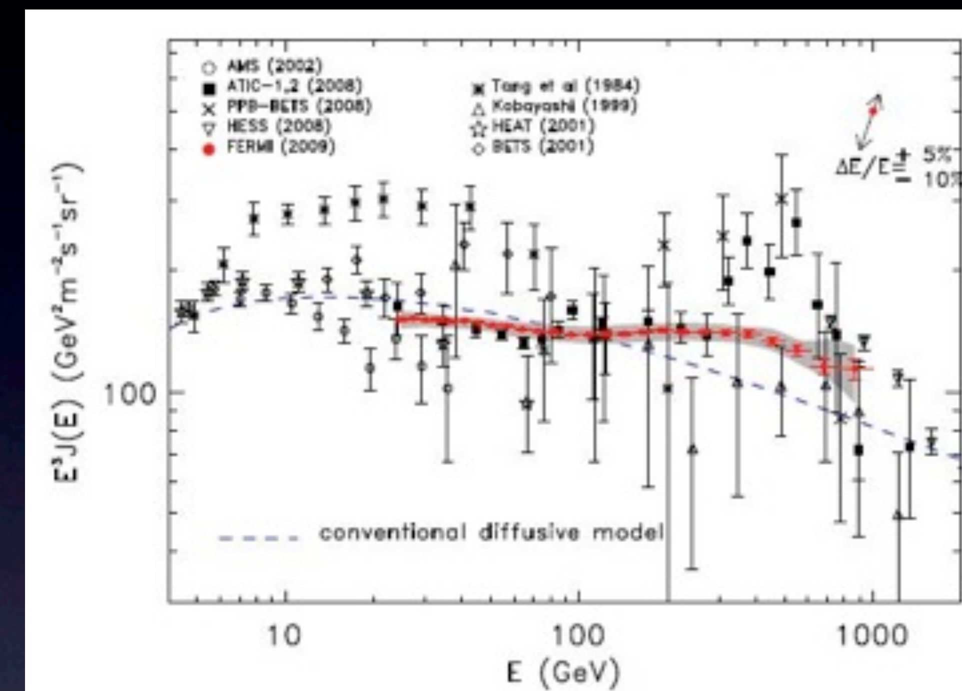


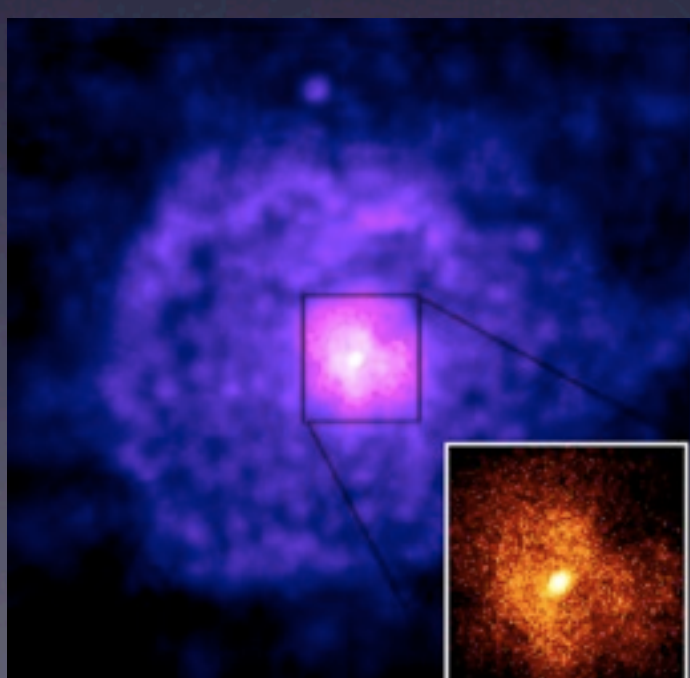





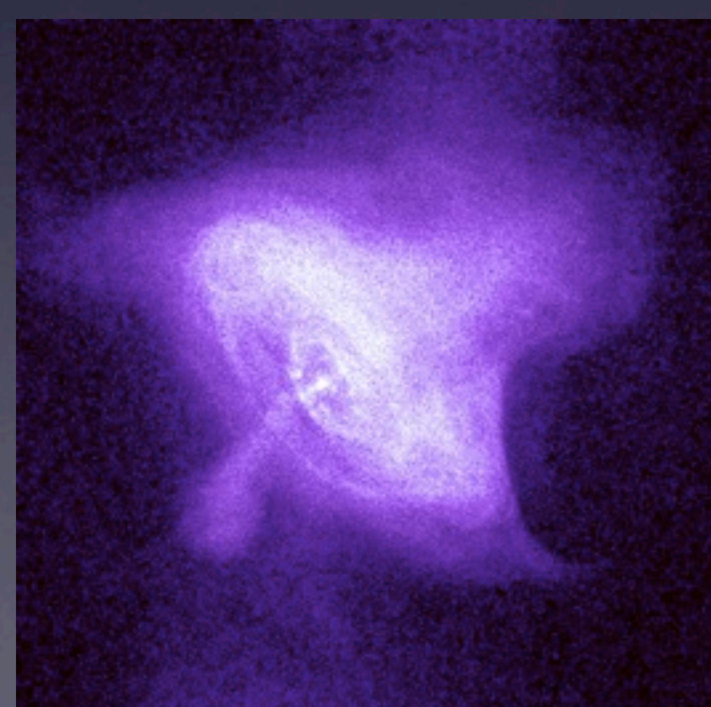



Broadband pulsed emission
Power PWNe: radio-TeV
Possible positron excess

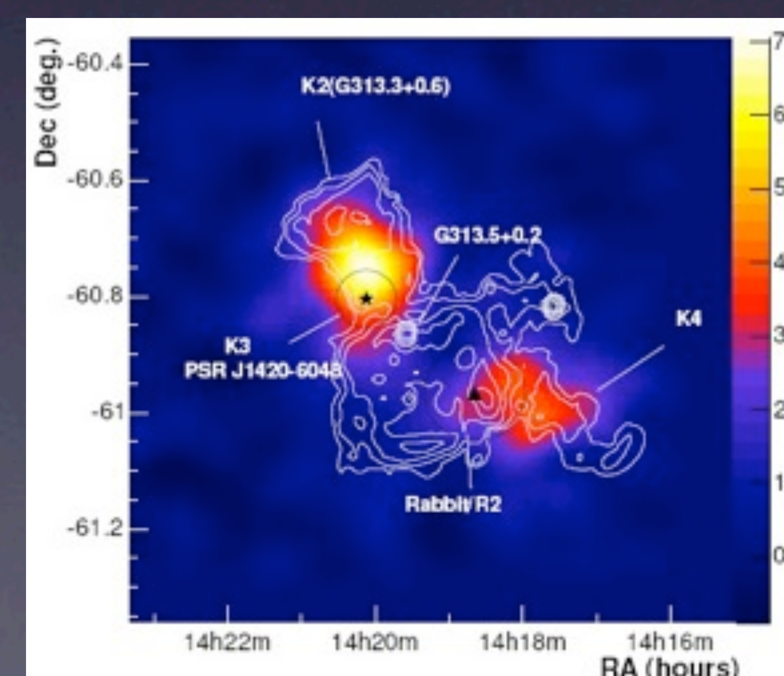


G21.9 (Safi-Harb et al 2004)

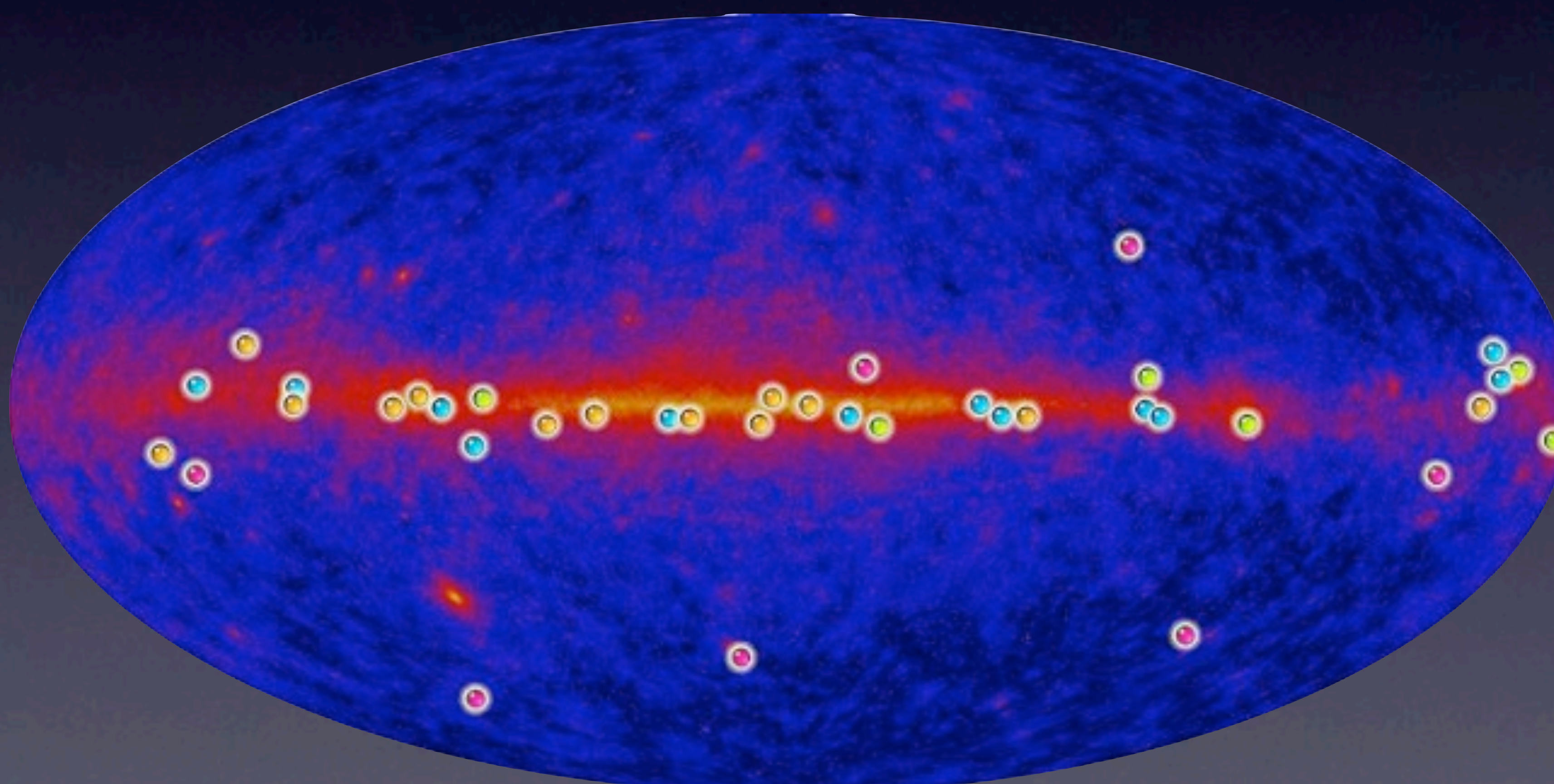


Crab (Weisskopf et al 2000)




HESS J1420 (Aharonian et al 2006)

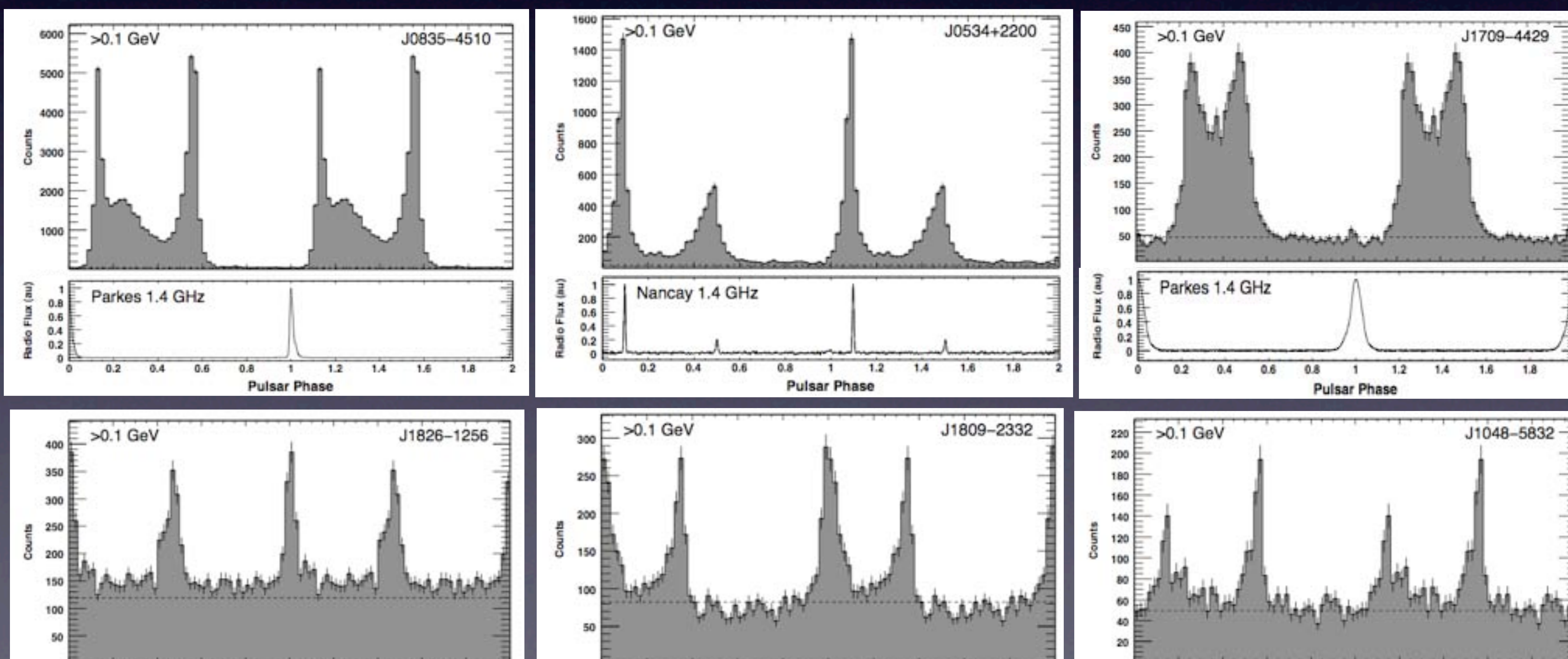
# Gamma-ray emission from pulsars

Fermi Pulsar Detections

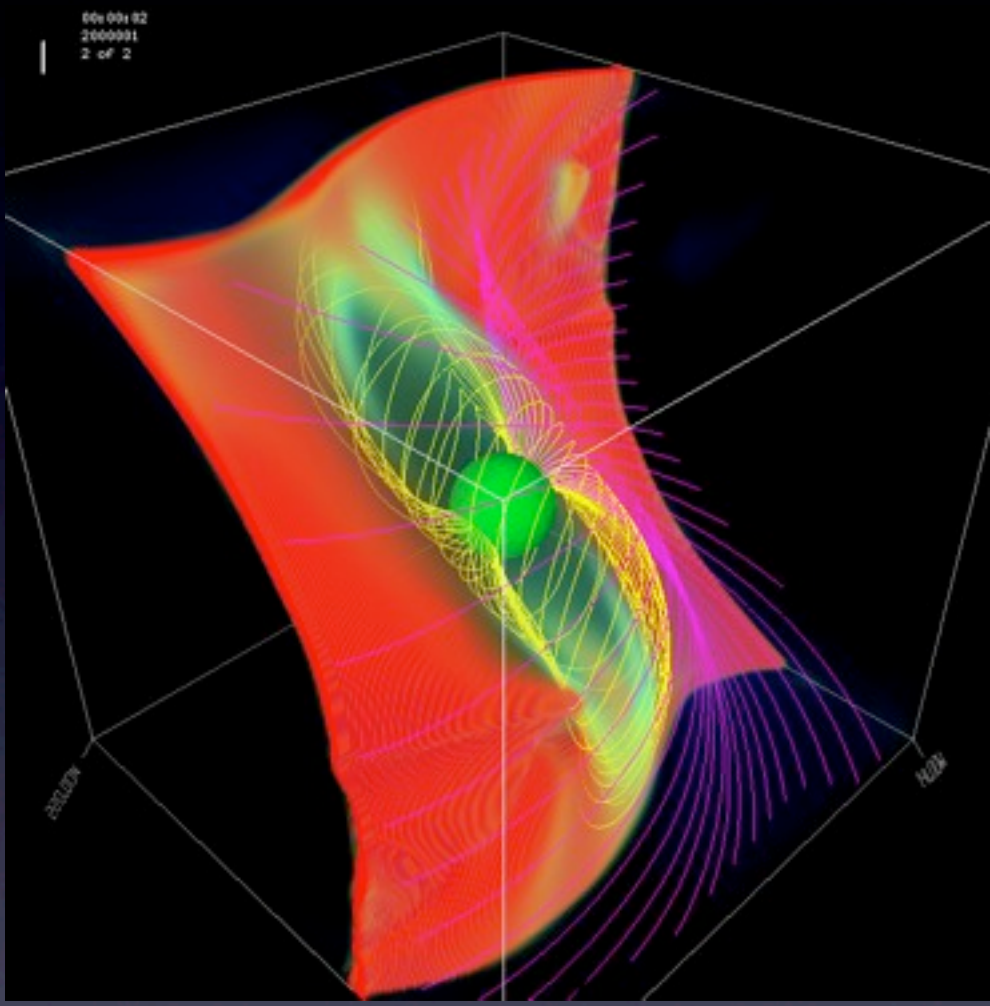
- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

# Gamma-ray emission from pulsars

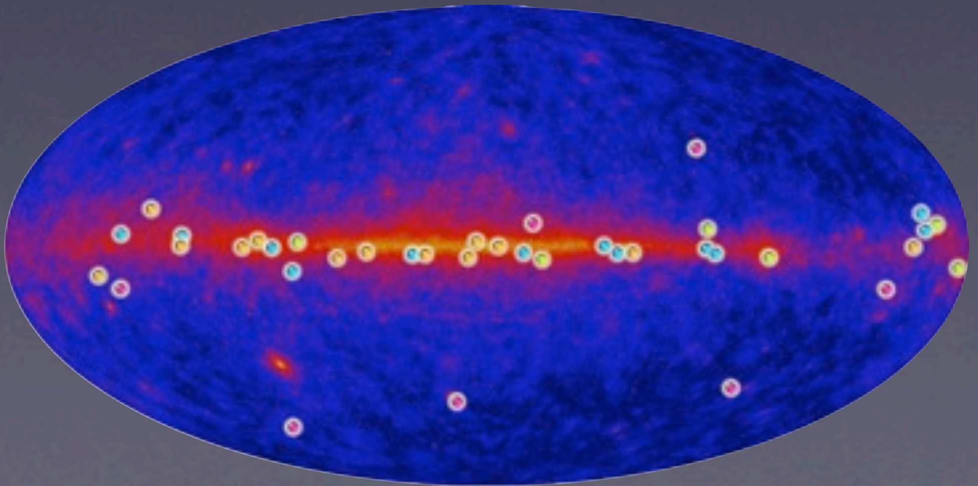



# Pulsars in Fermi era

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:

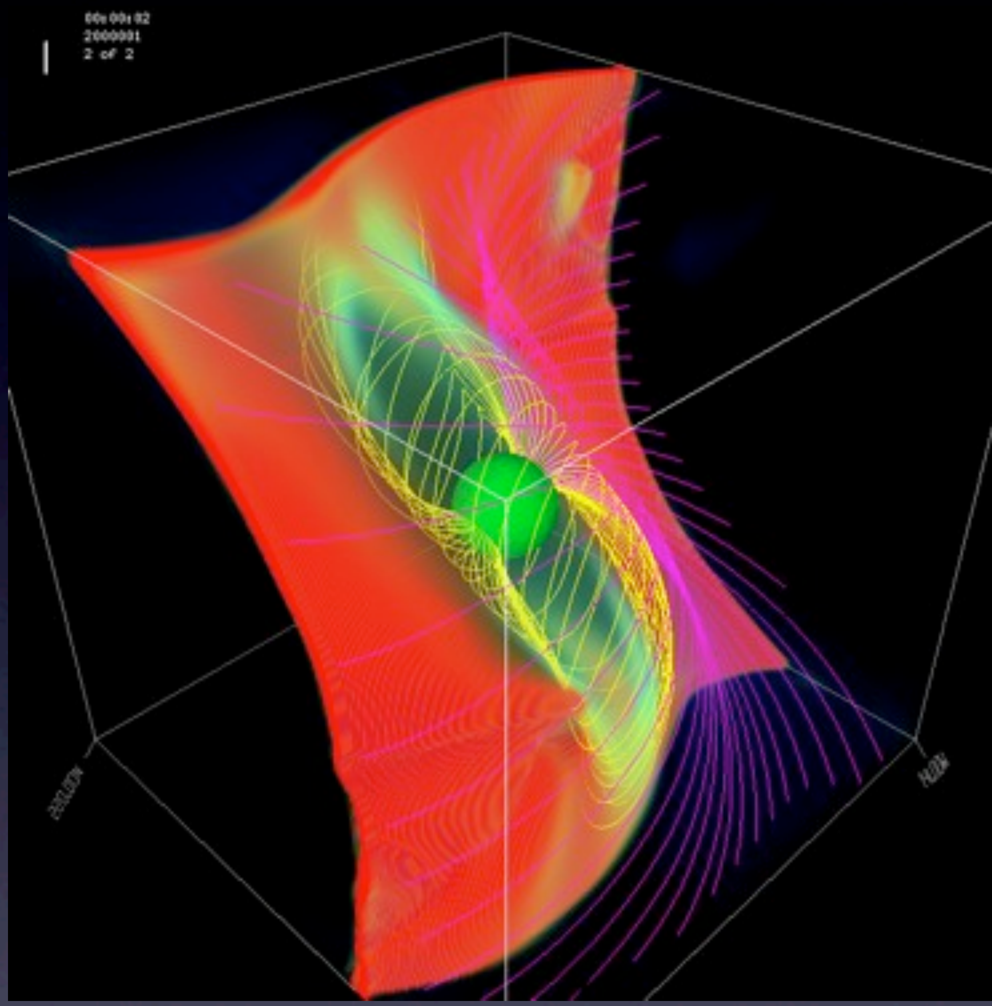
How pulsar magnetosphere works?

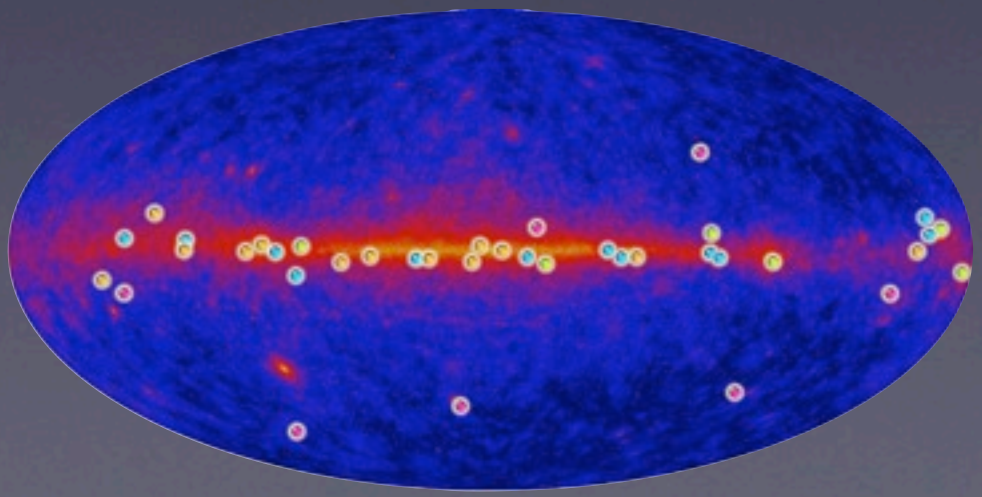
How pulsar wind works?

How pulsar wind nebula works?

How particle acceleration works?

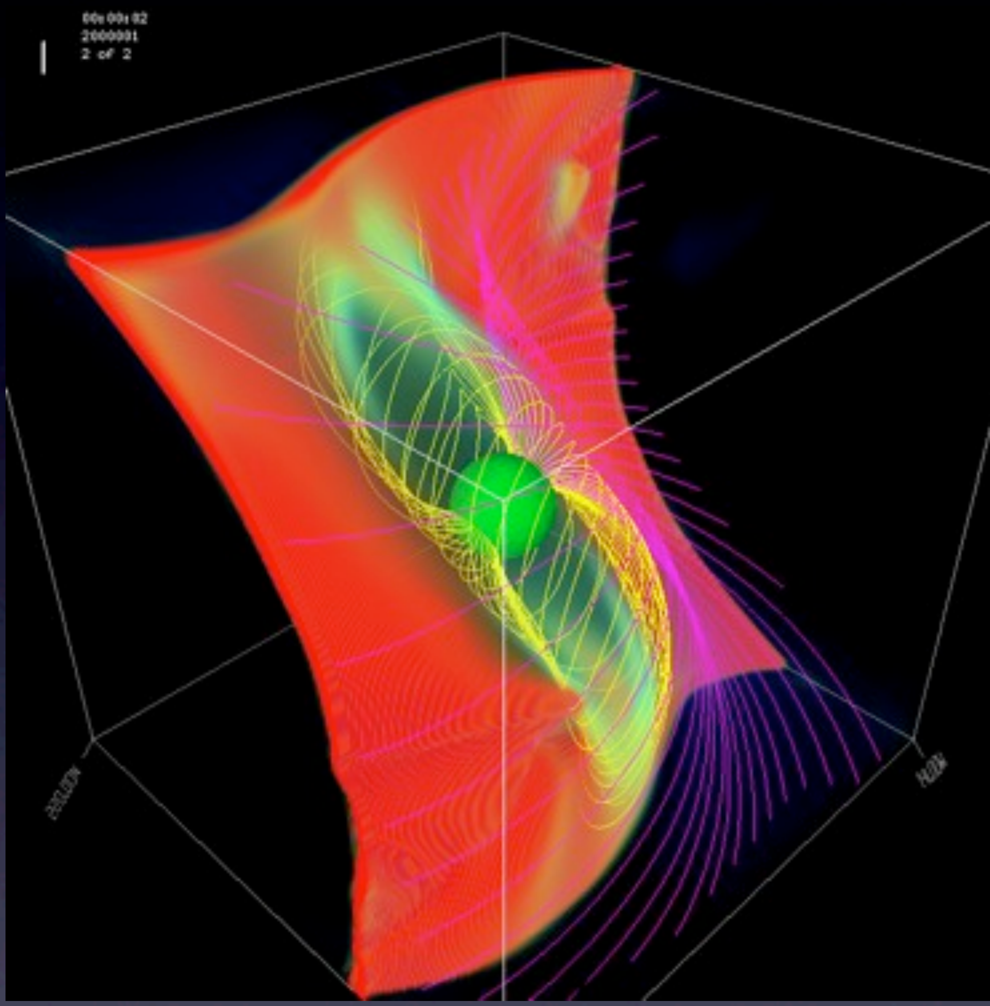
How emission works?

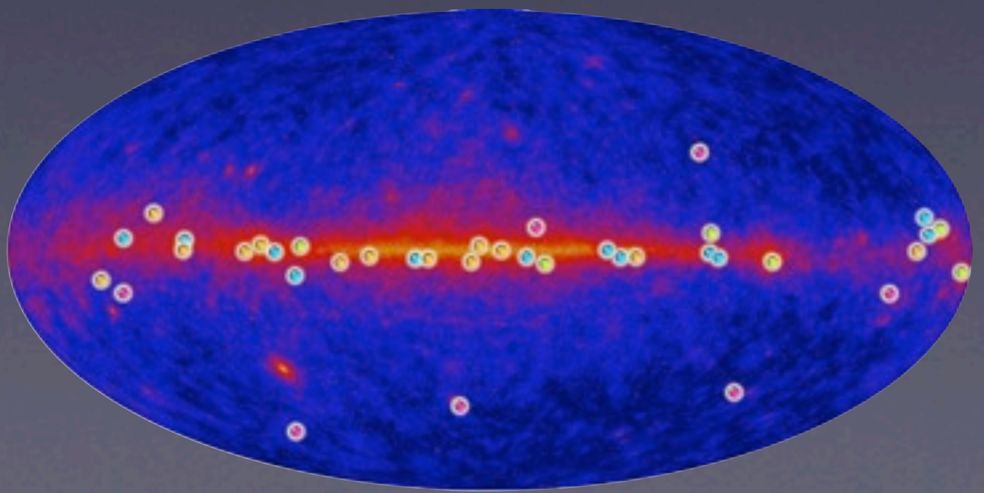


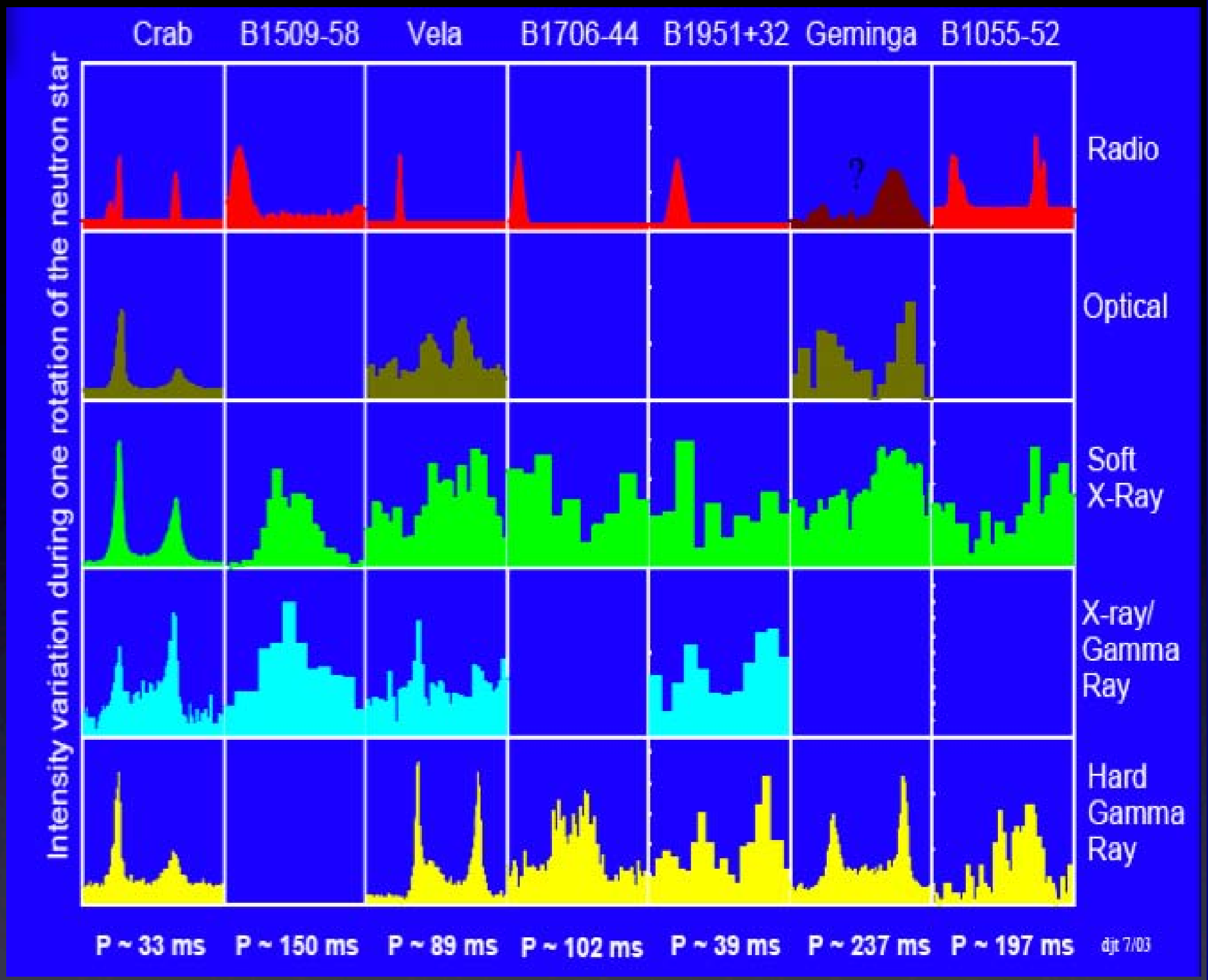


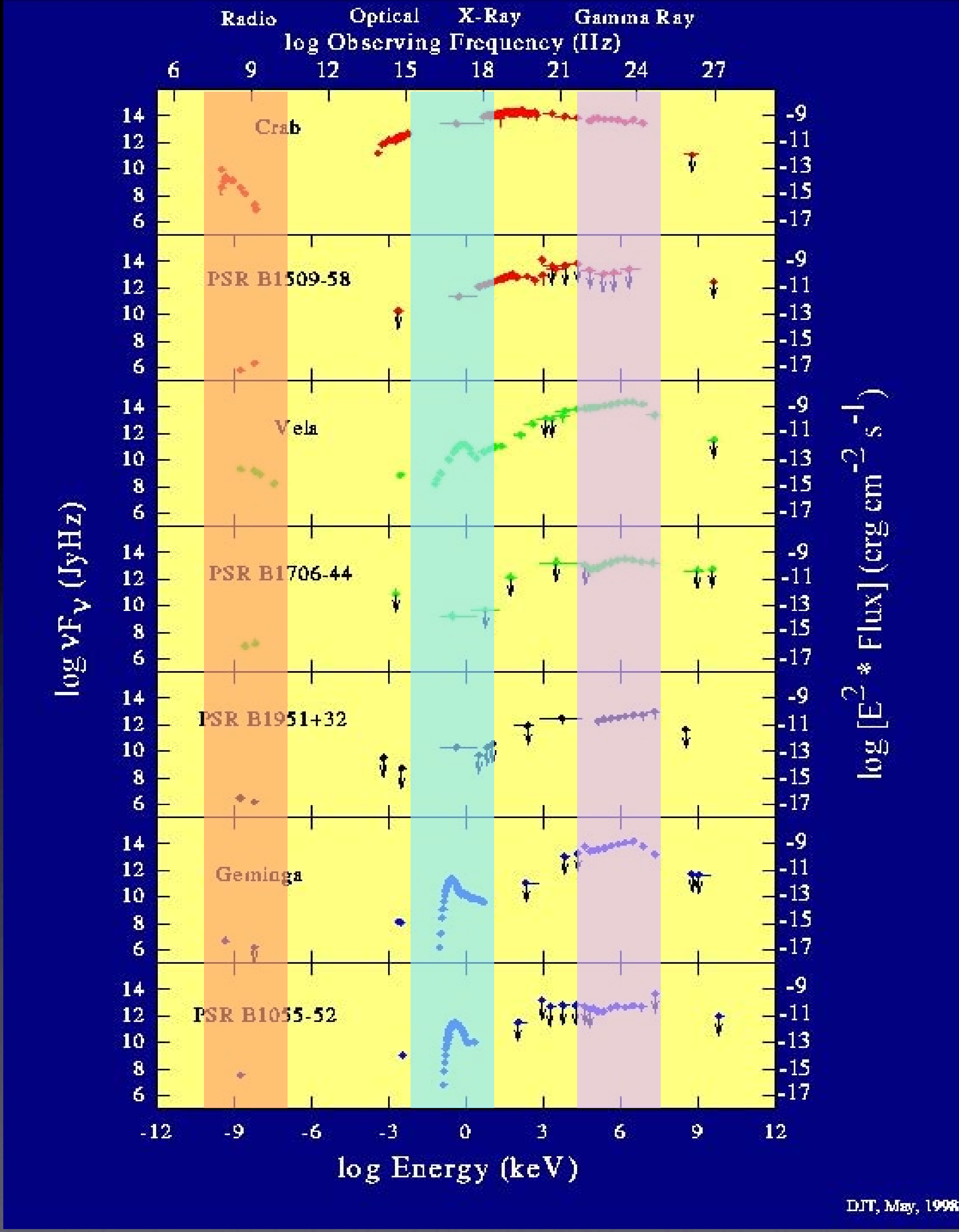
# Outline

- 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







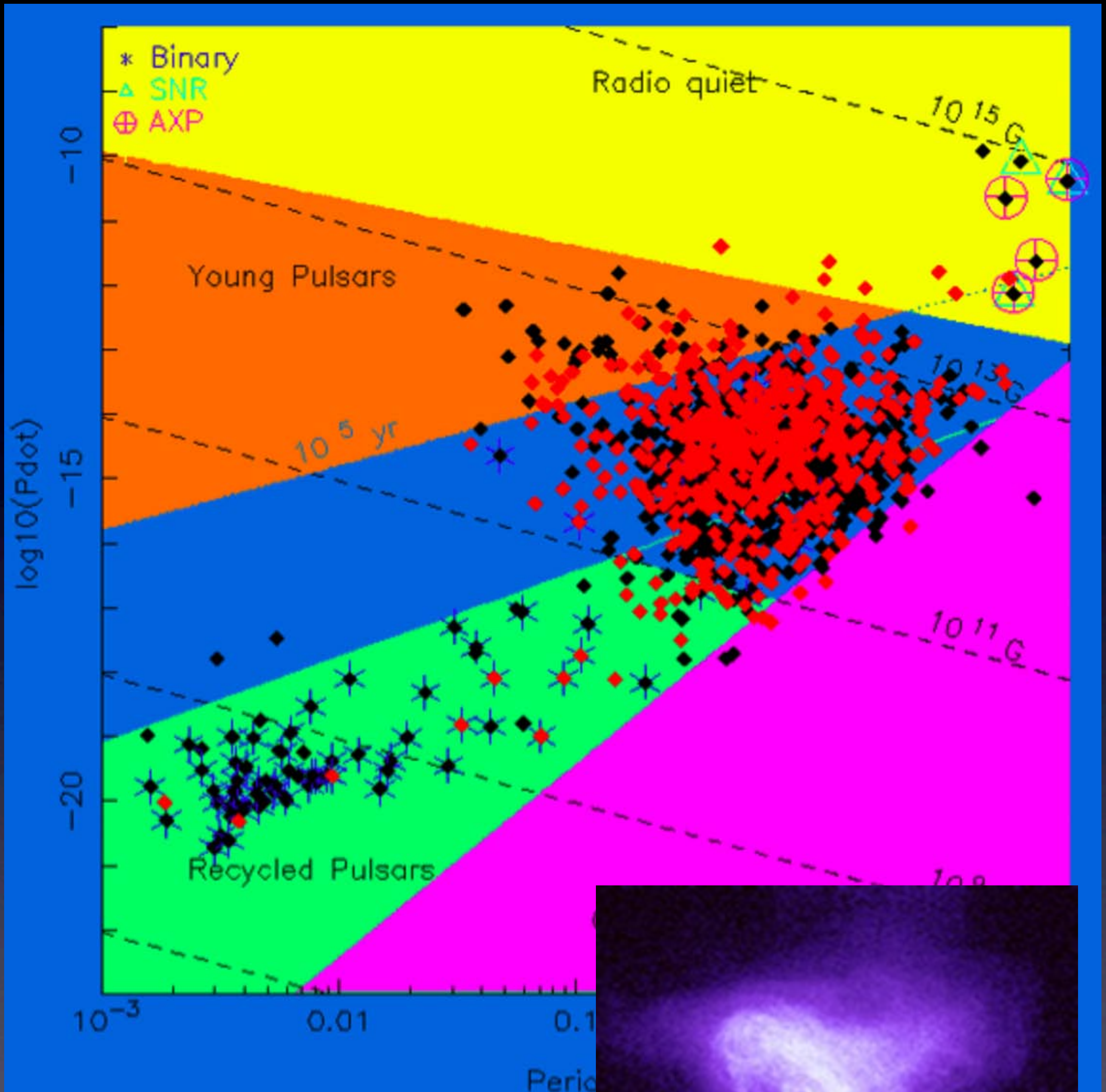

Most of the *observable* energy is coming out in gamma-rays

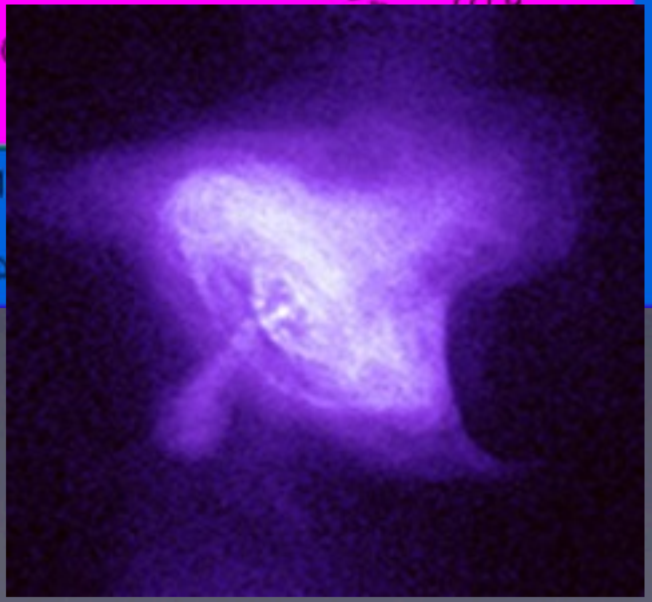
Main energy loss is invisible, but detectable -- pulsar spin-down

Leaves as magnetized wind (carrying Pointing flux)

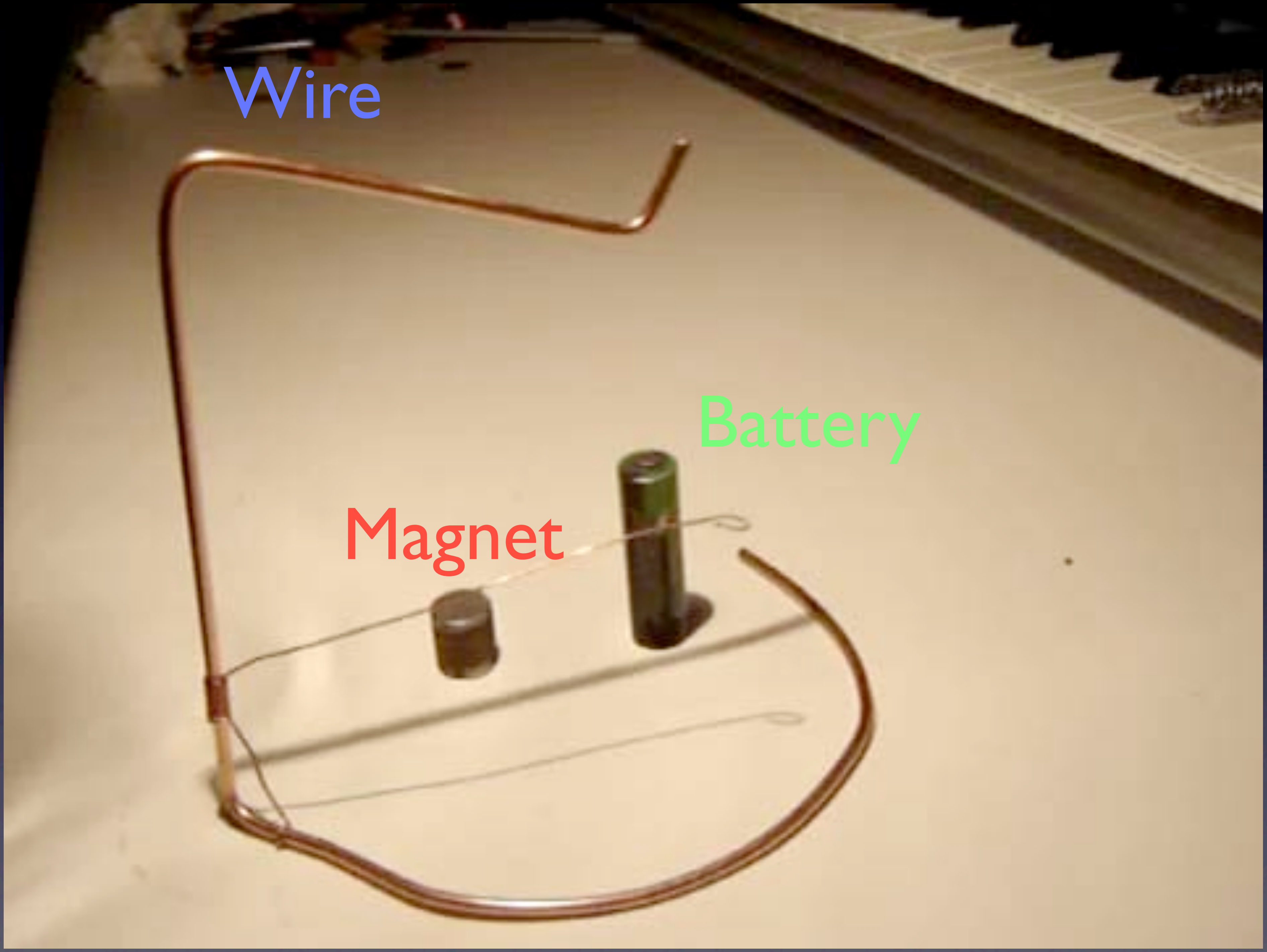
The fact that γ-ray power reaches 10-s of percent of spin-down power implies that we are tapping the main magnetospheric currents

Need to understand how magnetosphere works



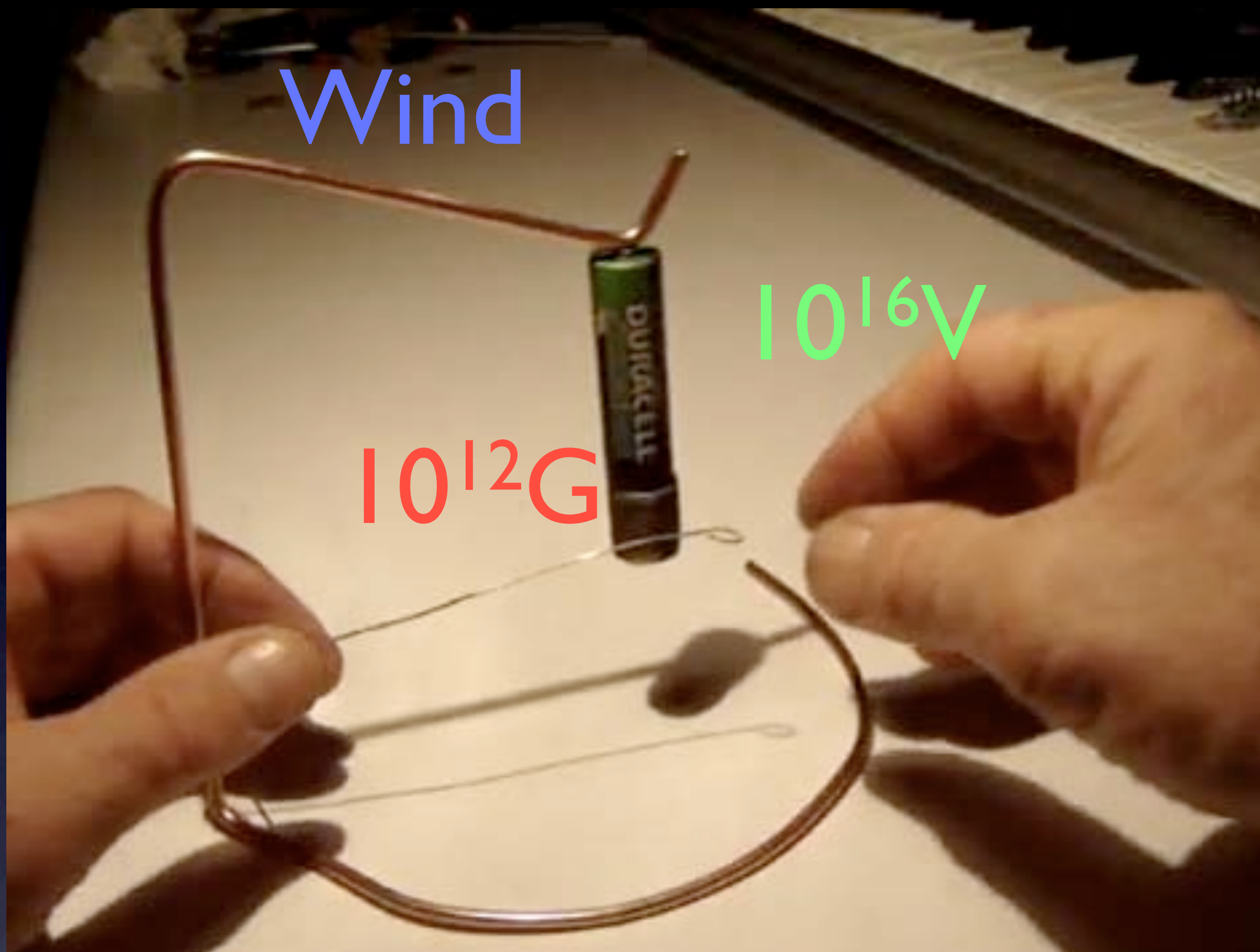



# Pulsar physics @ home

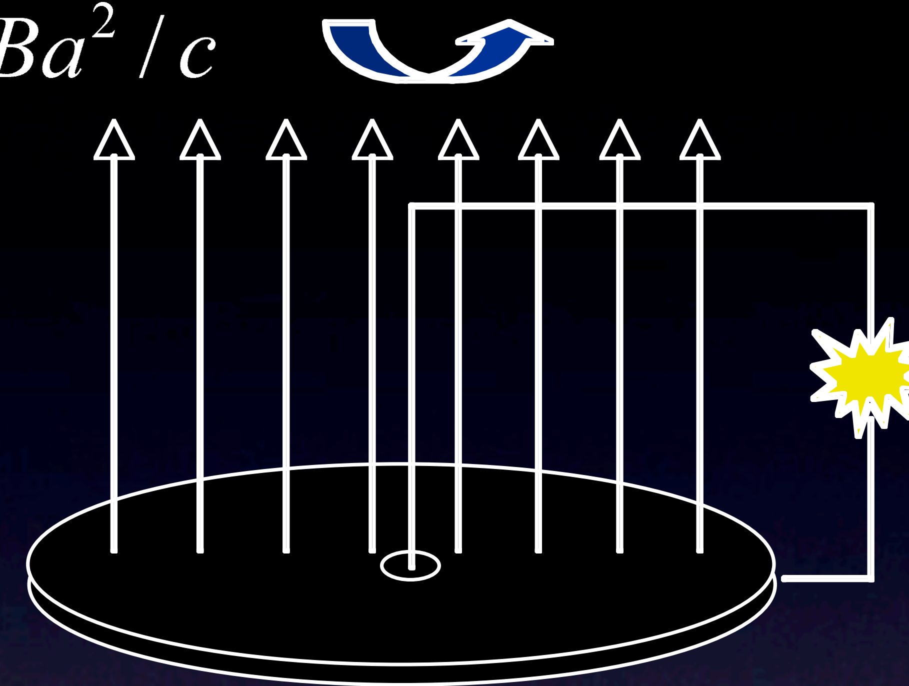



Unipolar induction

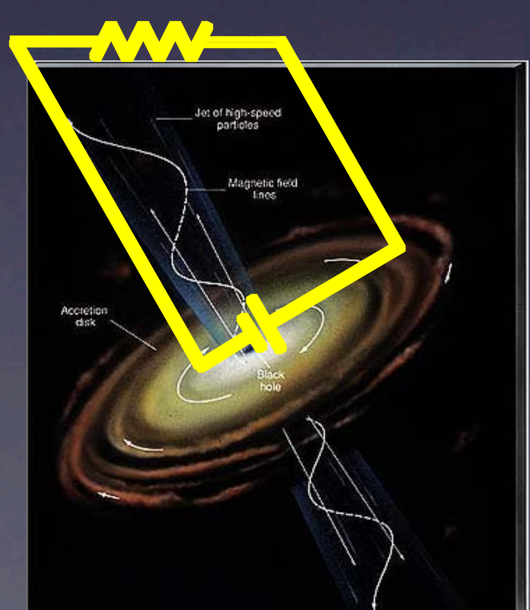
# Pulsar physics in space




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

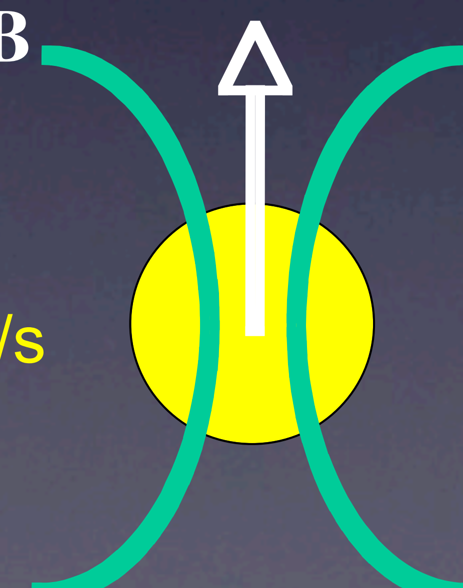


Faraday disk
Unipolar induction



from R. Blandford

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




Crab Pulsar

- $B \sim 10^{12}$ G,  $\Omega \sim 200$ rad $s^{-1}$, $R \sim 10$ km
- Voltage ~ 3 x $10^{16}$ V; I ~ 3 x $10^{14}$ A; P ~ $10^{38}$erg/s

Magnetar

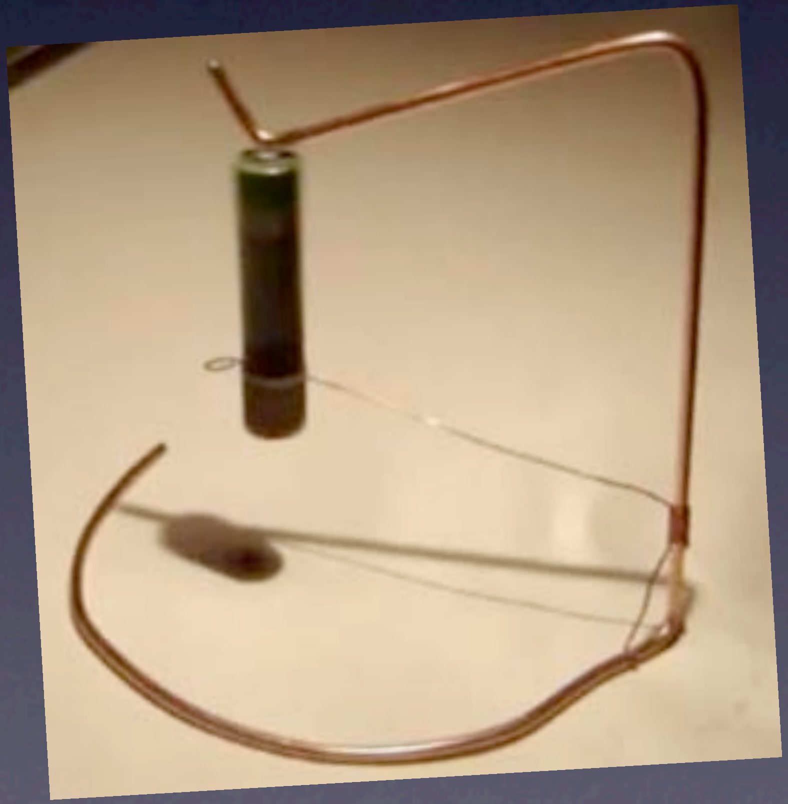
- B ~ $10^{14}$ G; P ~ $10^{44}$erg/s

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

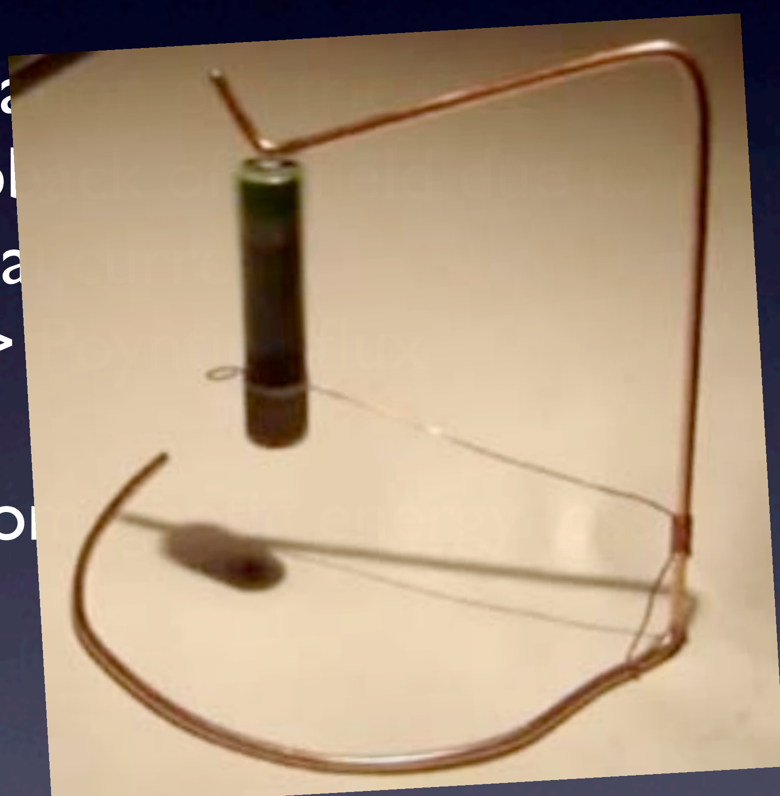


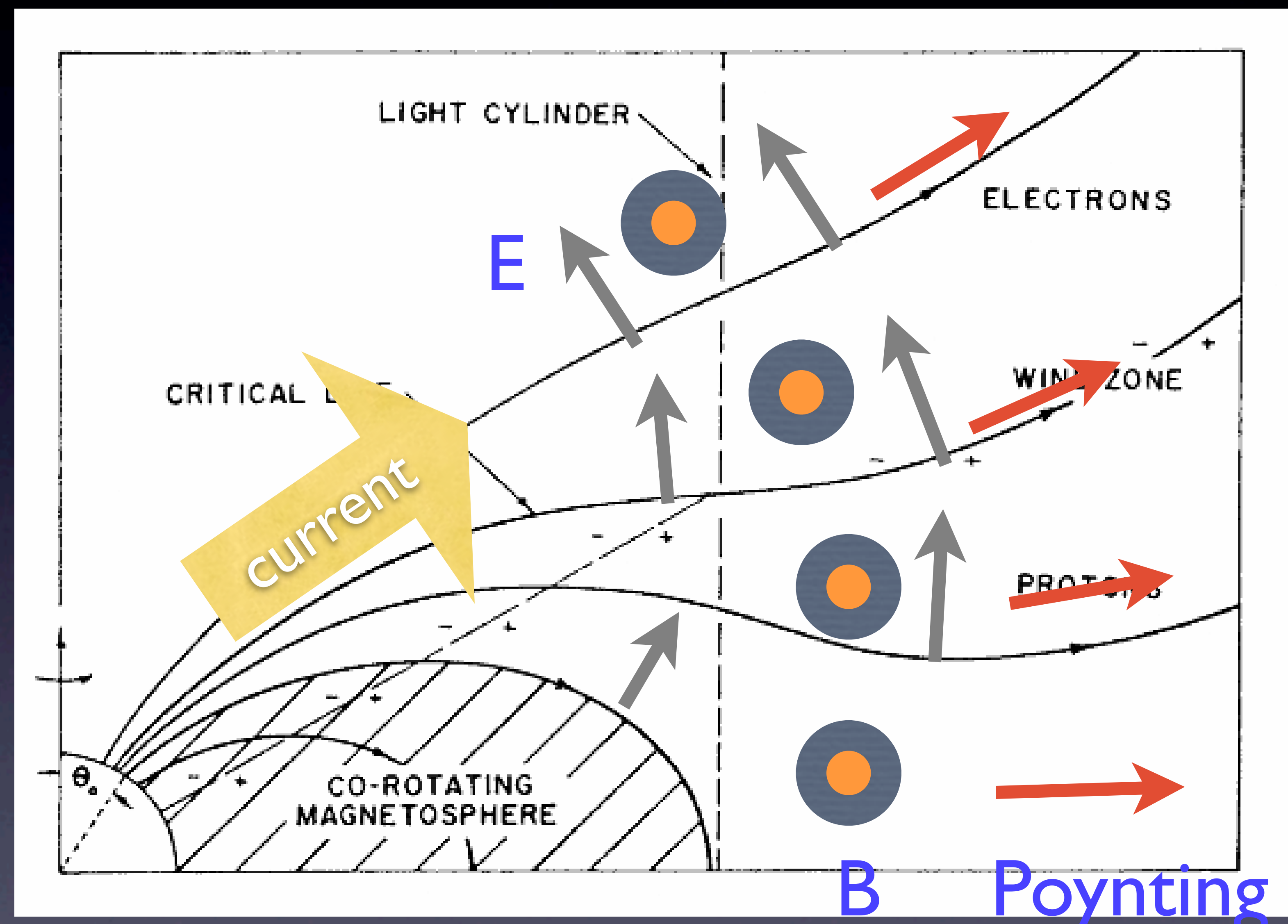
# Pulsars: energy loss

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

- Corota
- Sweepl poloida
- ExB ->

- Electro






Goldreich & Julian 1969

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

# Magnetospheric cartoon

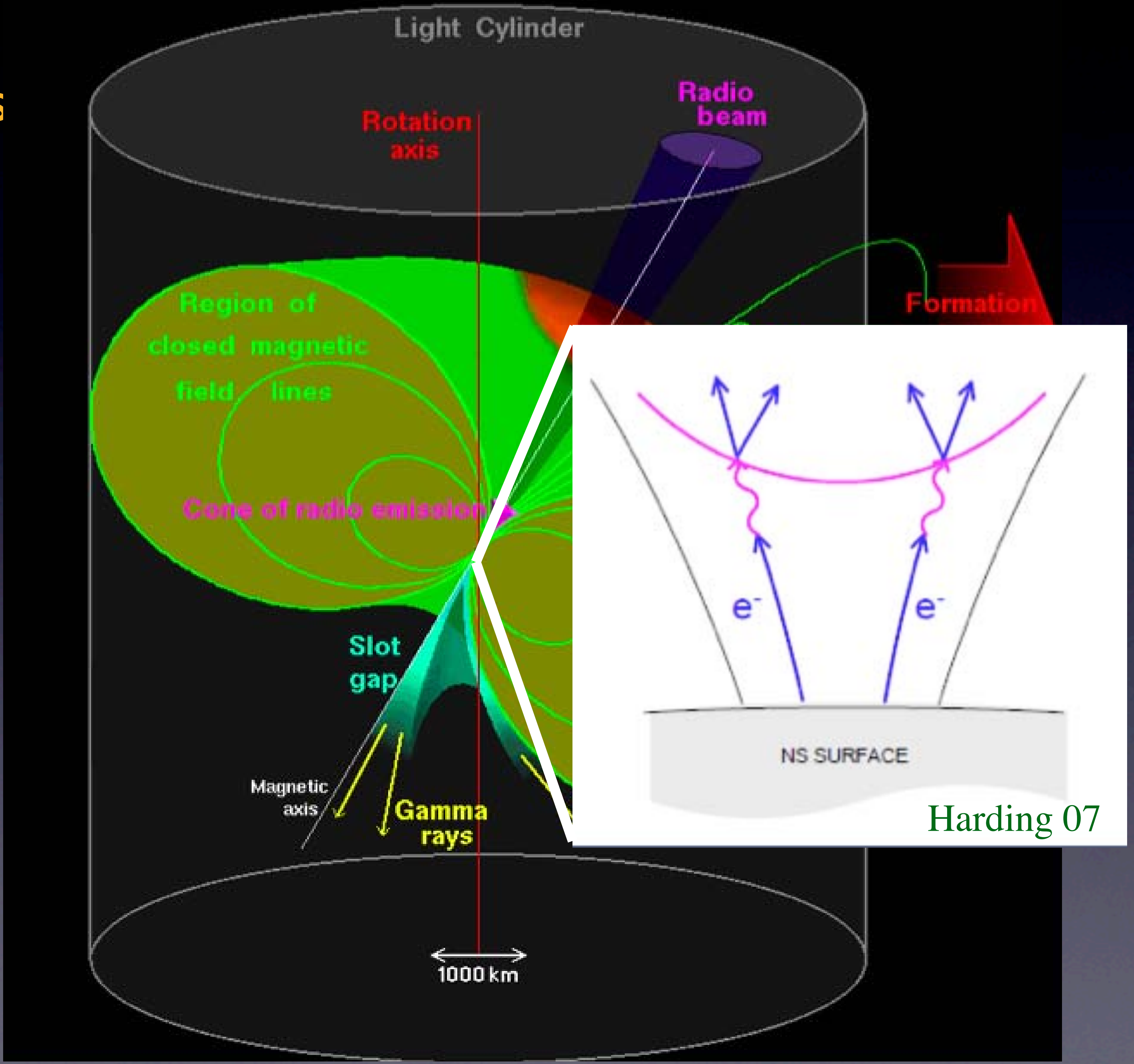
Open + closed (corotating) zones

Light Cylinder

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

Current modifies the field

How does it spin down?



# MODELING: TWO PATHS

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

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

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

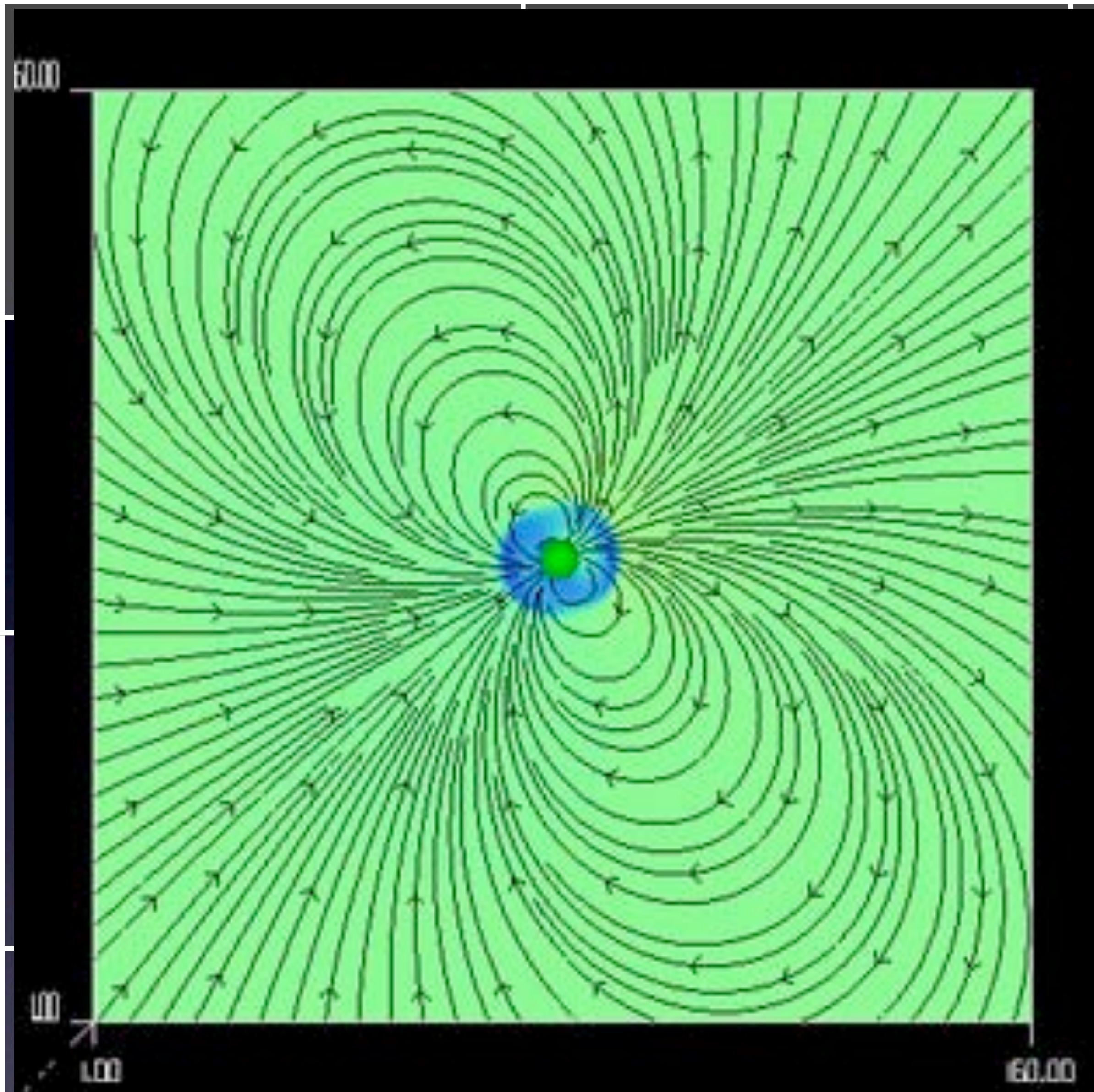
plasma

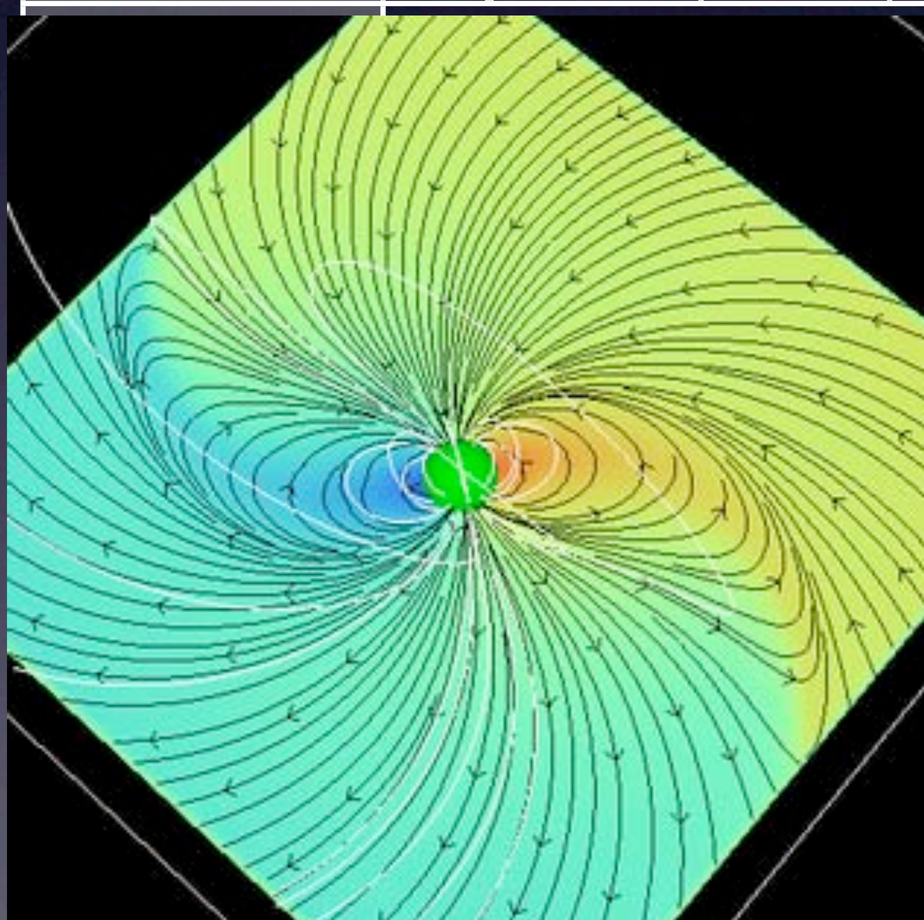
# Magnetospheric models

| | 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 |

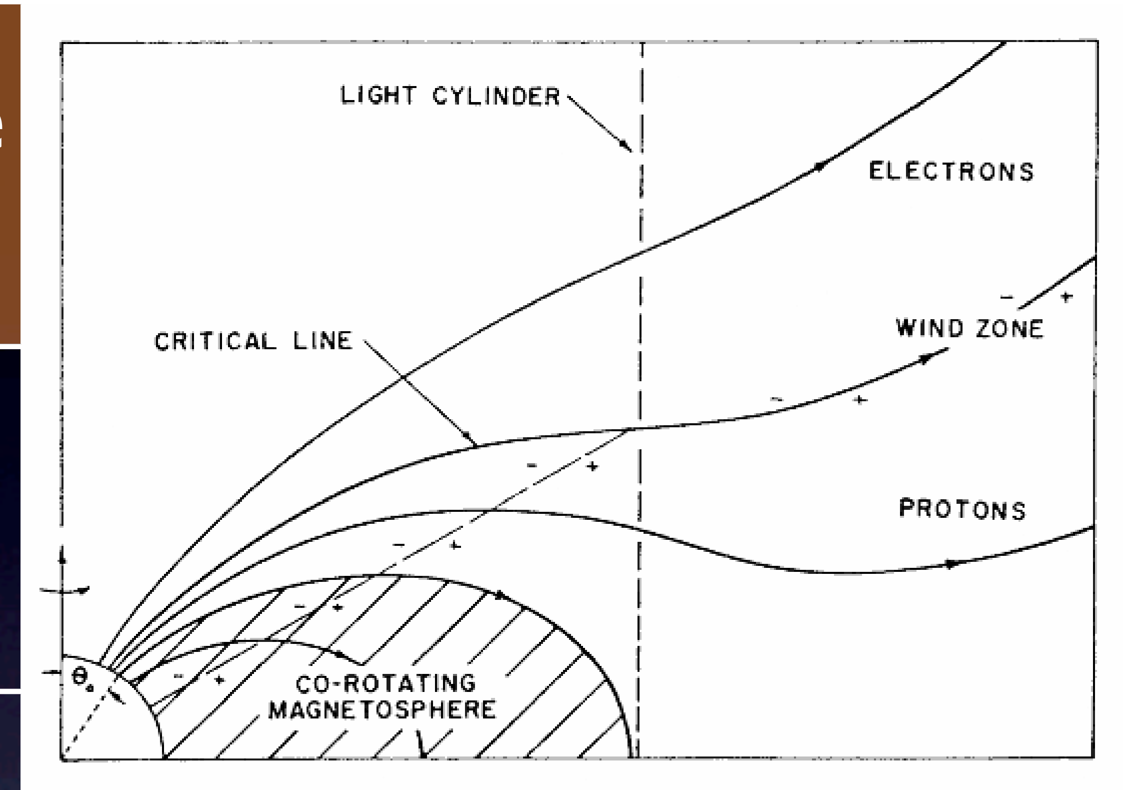
# Magnetospheric models

| | | | | |
|---|---|---|---|---|
| | 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; | Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06 |



# Magnetospheric models




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

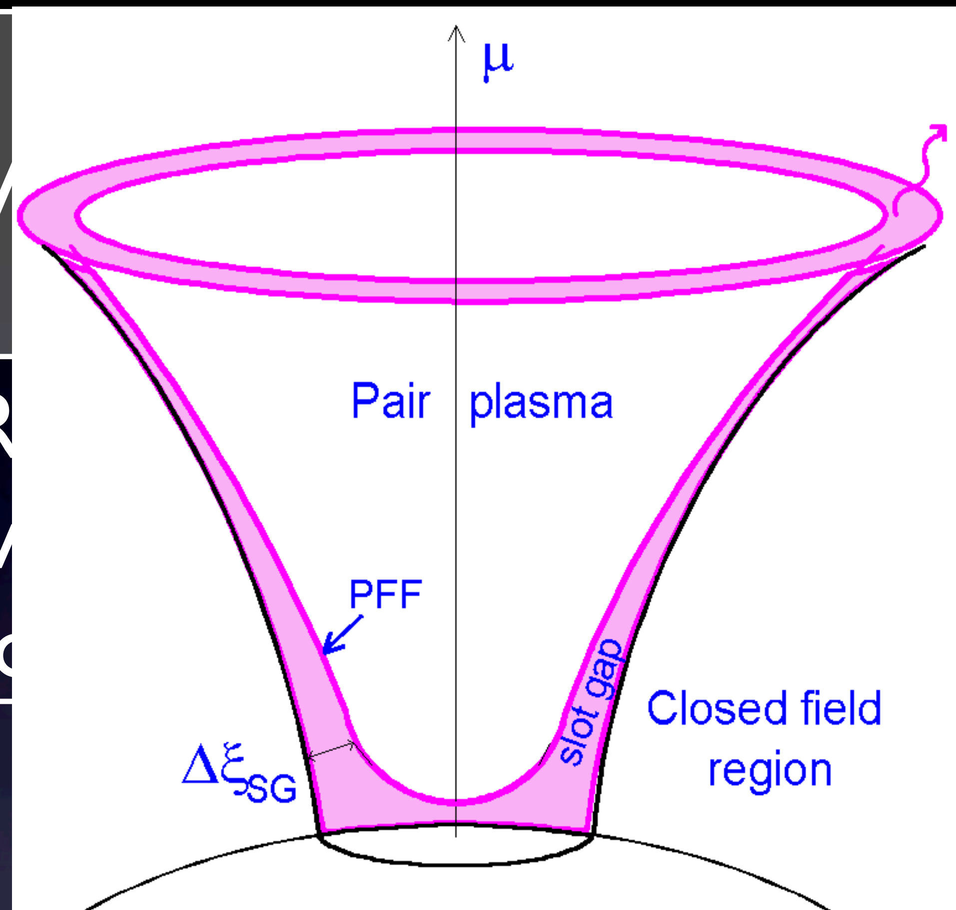
Goldreich & Julian 69 Michel 85, 00; AS +Arons 02

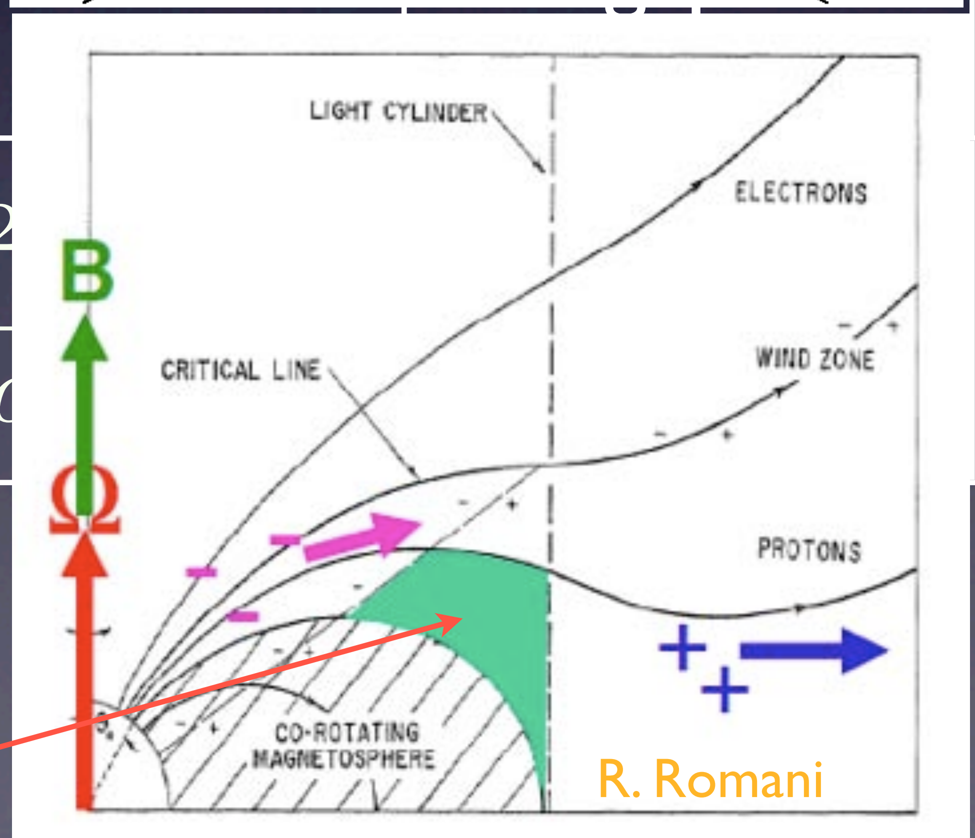
Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;

Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

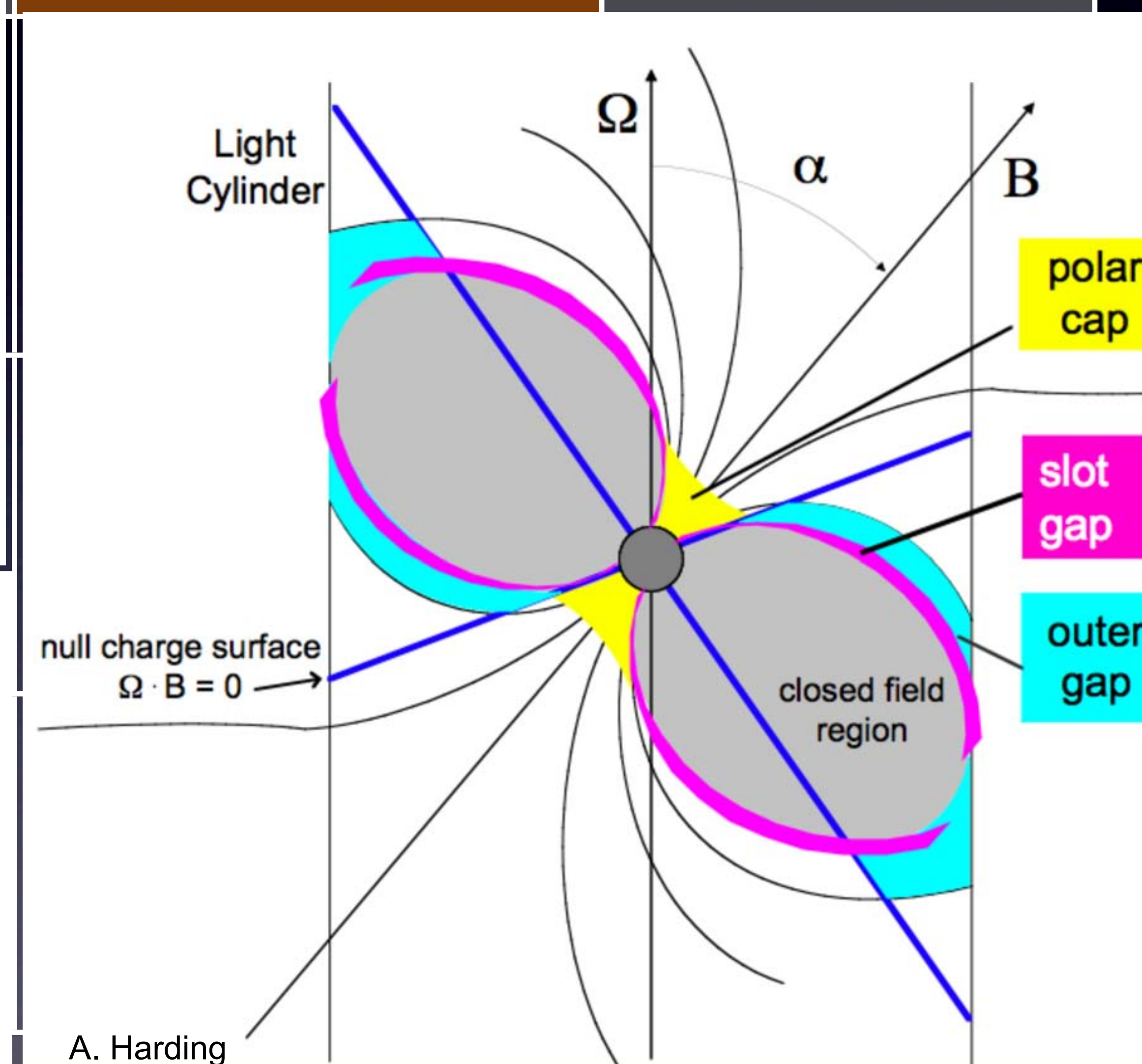
# Magnetospheric models

| | V... | | Space charge limited+pairs | Abundant plasma |
|---|---|---|---|---|
| Field | R... v... dipo... | | | |
| Acceleration | | | | |
| Spin down | $\frac{2}{3}\frac{\mu^2}{c...}$ | | | |




Holloway's paradox




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

# 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!

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

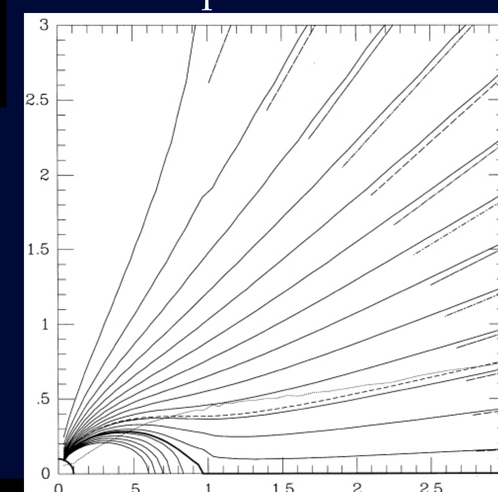
# Magnetospheric models

- 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

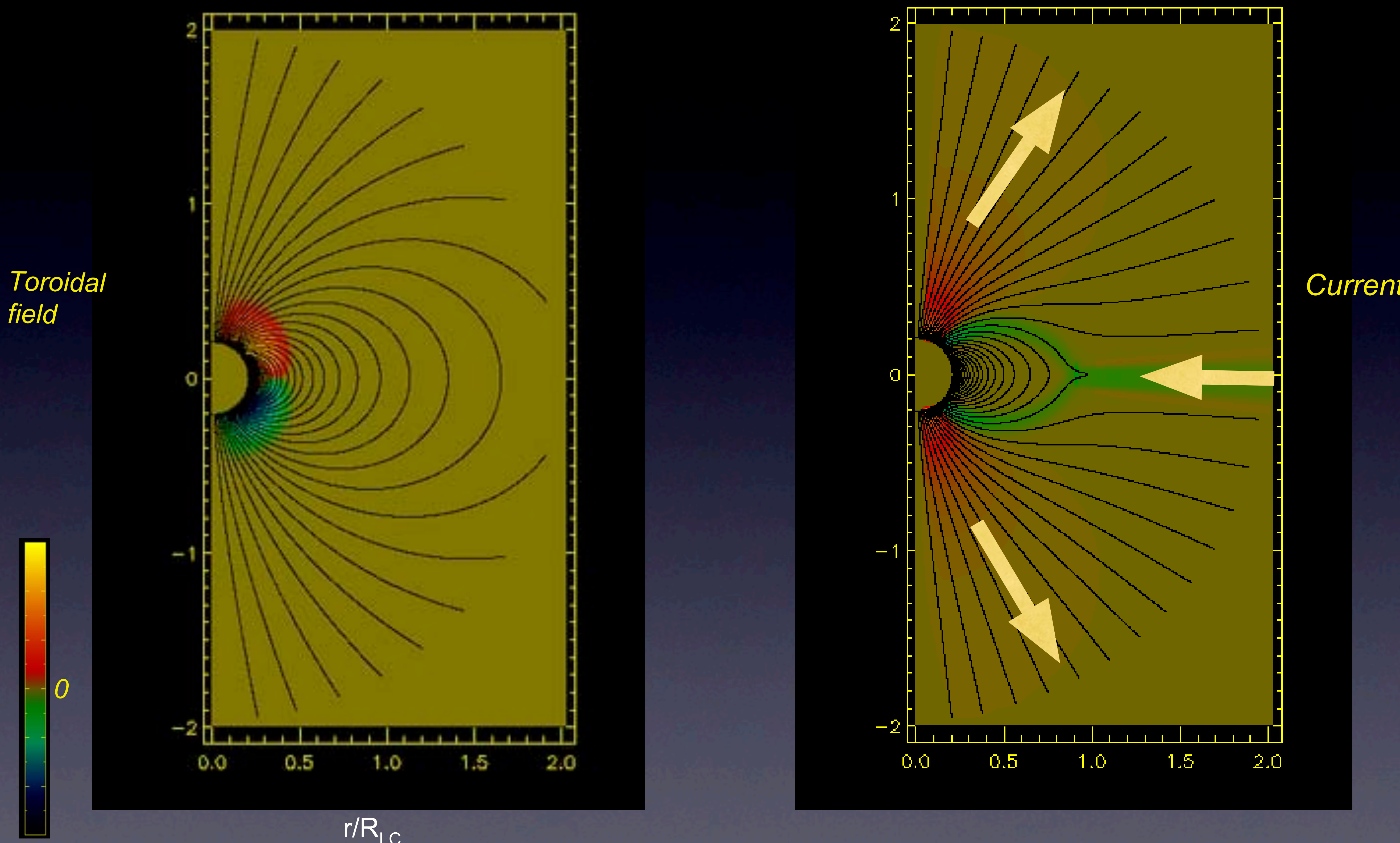
Gruzinov 99, Blandford 01

Hyperbolic equations, can be evolved in time

| |
|---|
| Abundant plasma |
| Force-free |
| none / re-connection? |
| $\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$ |

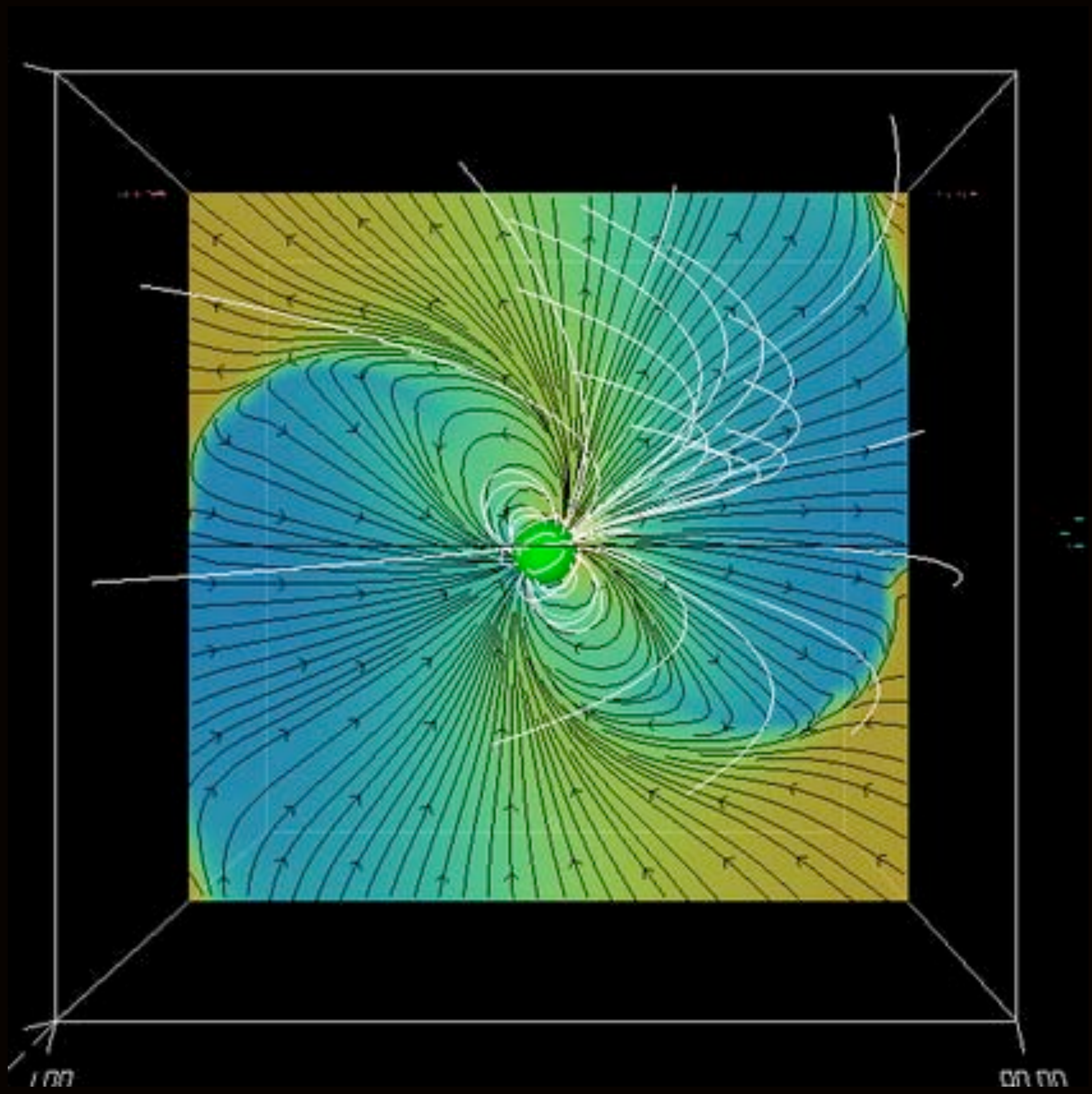
Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

# Aligned rotator: plasma magnetosphere

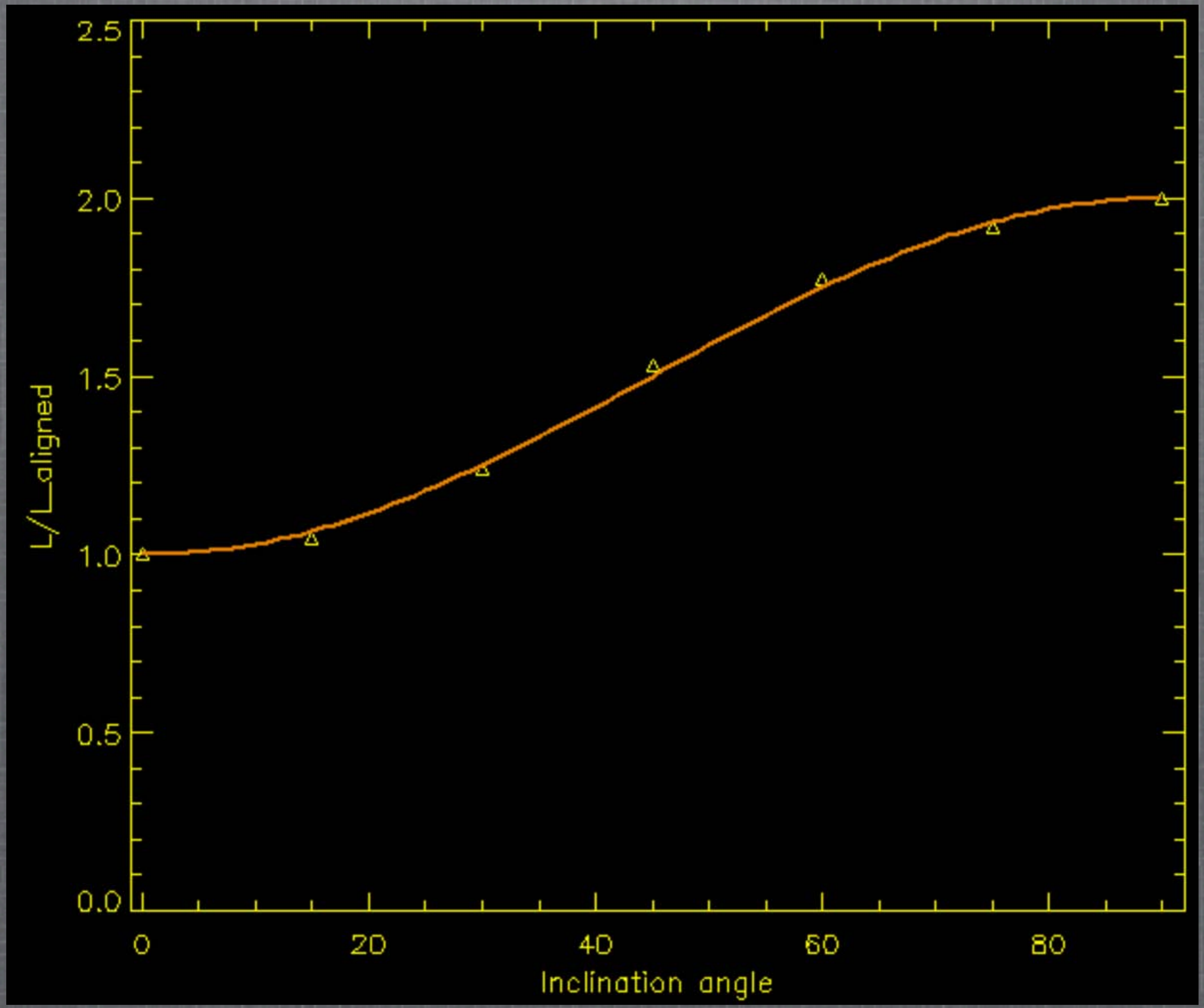



Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting.

# Oblique rotator: force-free



# SPIN-DOWN POWER




Spin-down of oblique rotator

NB: this is a fit!

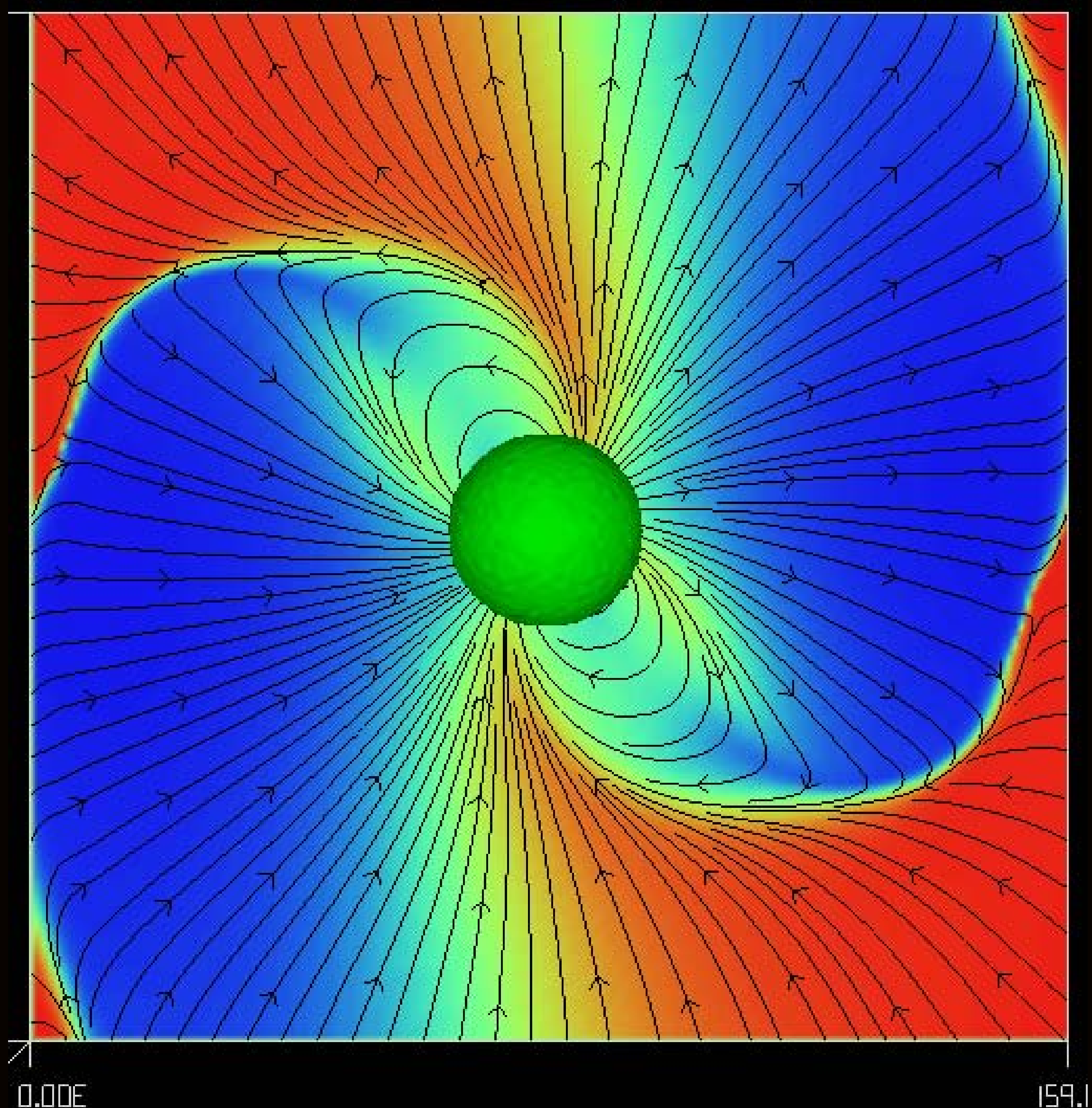
$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3}(1 + \sin^2\theta)$$

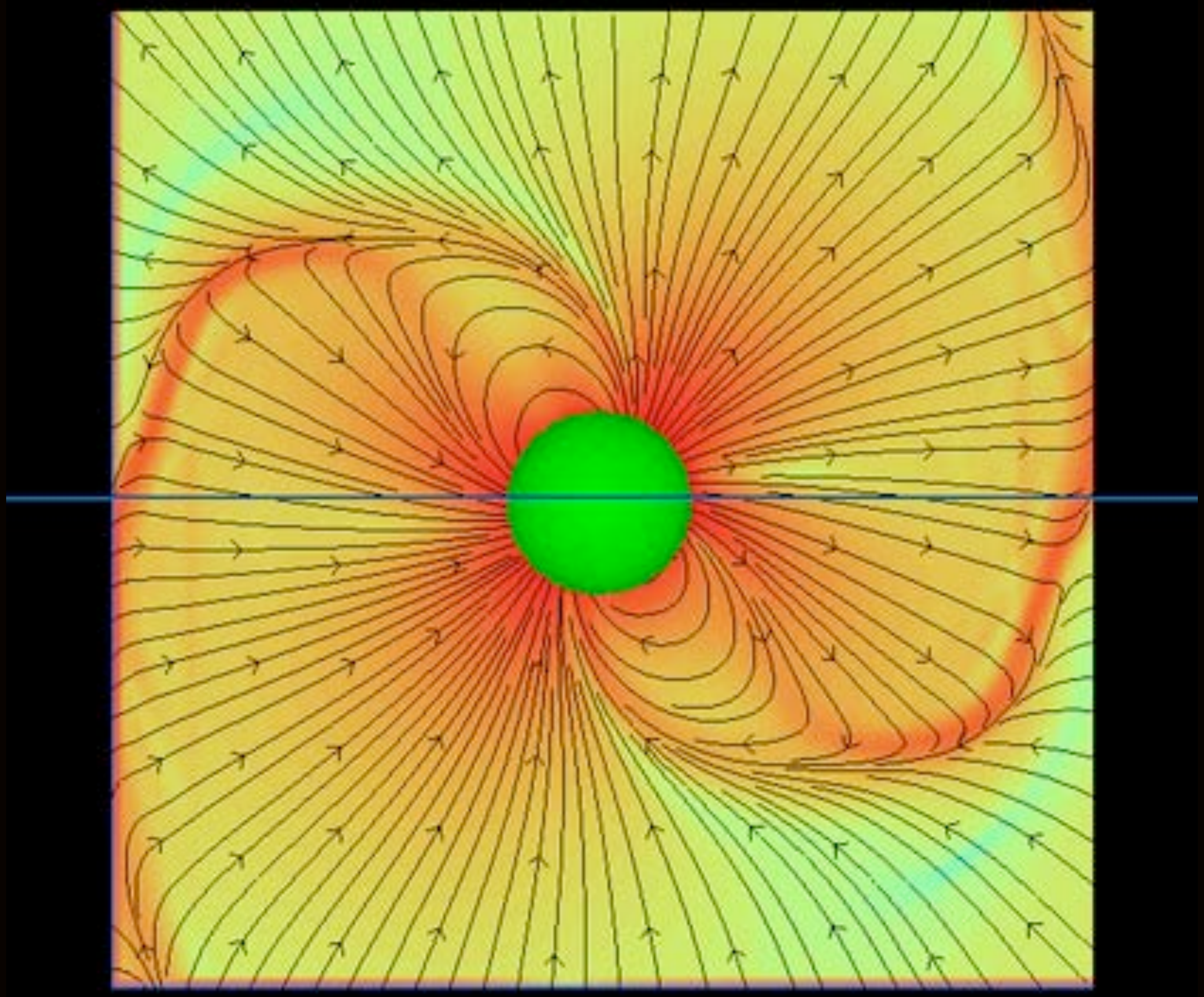
$$\dot{E}_{vac} = \frac{2}{3}\frac{\mu^2 \Omega^4}{c^3}\sin^2\theta$$

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

# IN COROTATING FRAME

## 60 degree inclination

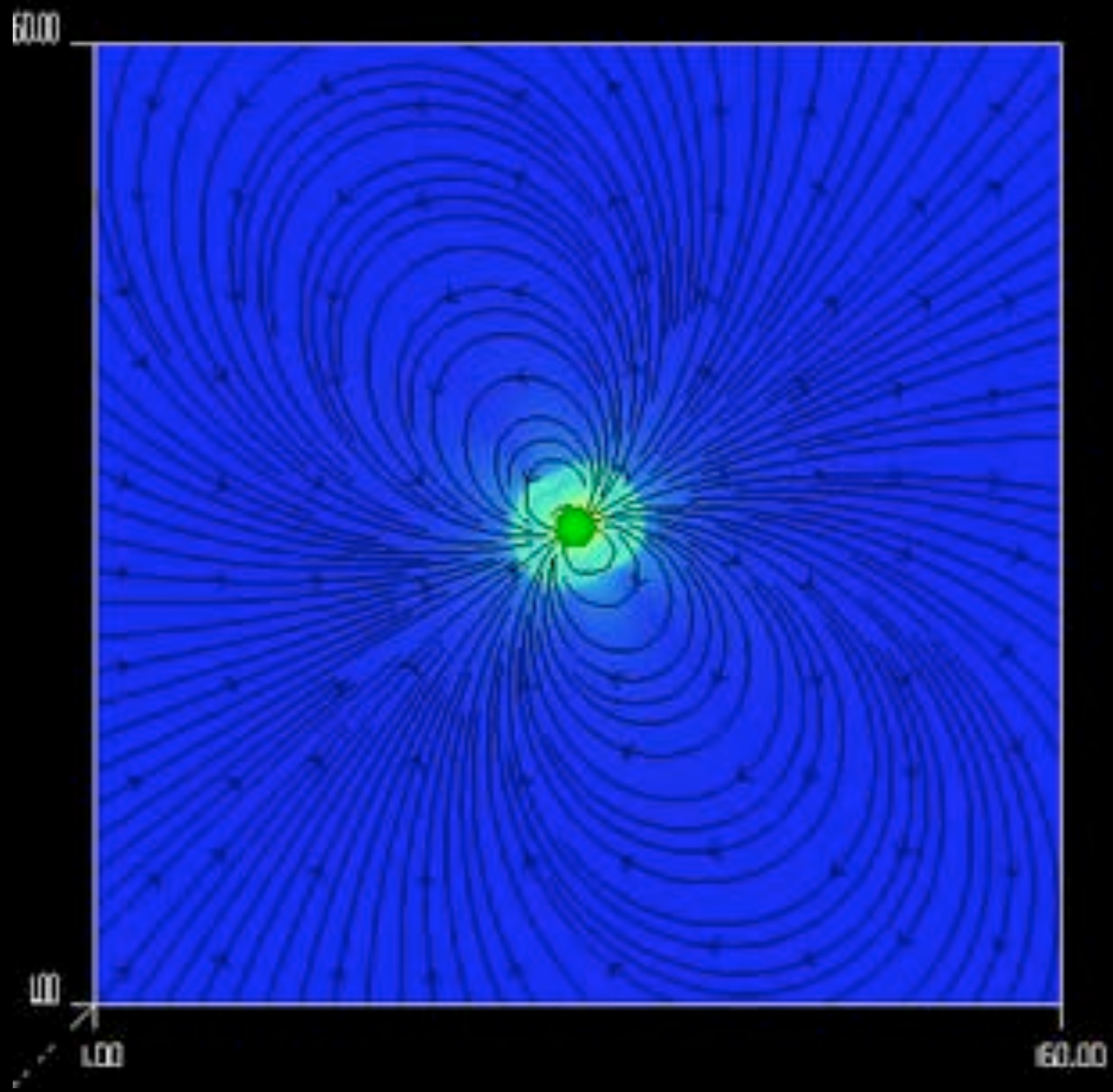


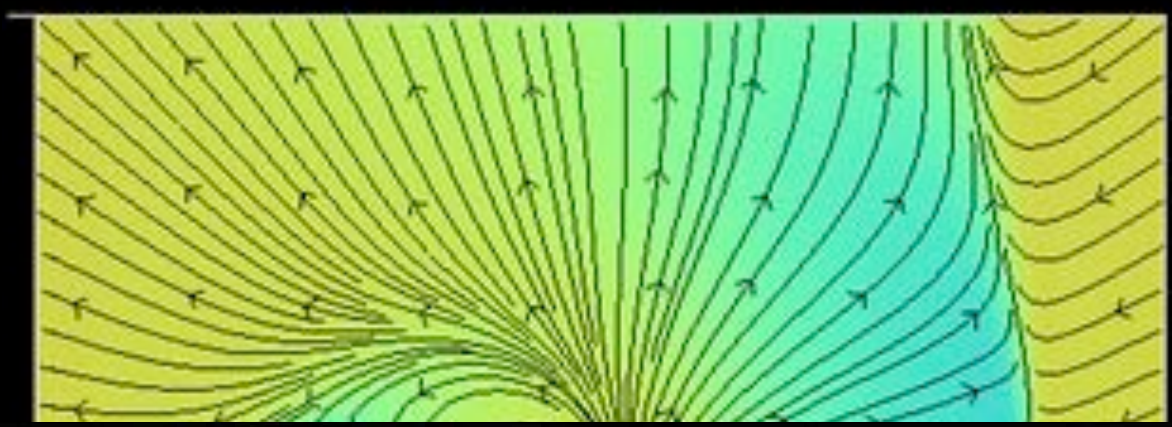
Force-free

Force-free current density

# *3D force-free magnetosphere: 60 degrees inclination*




60 degrees force-free current

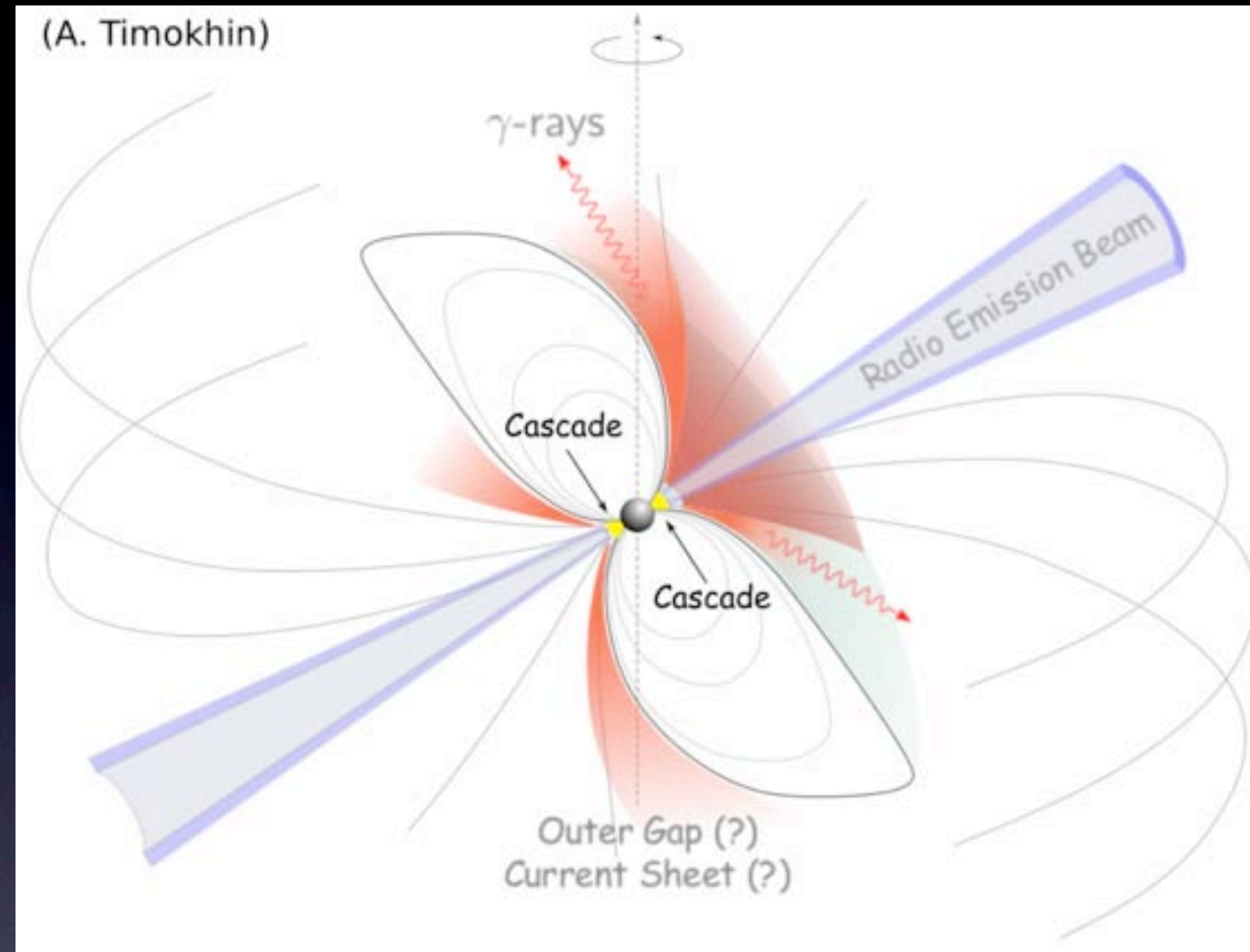


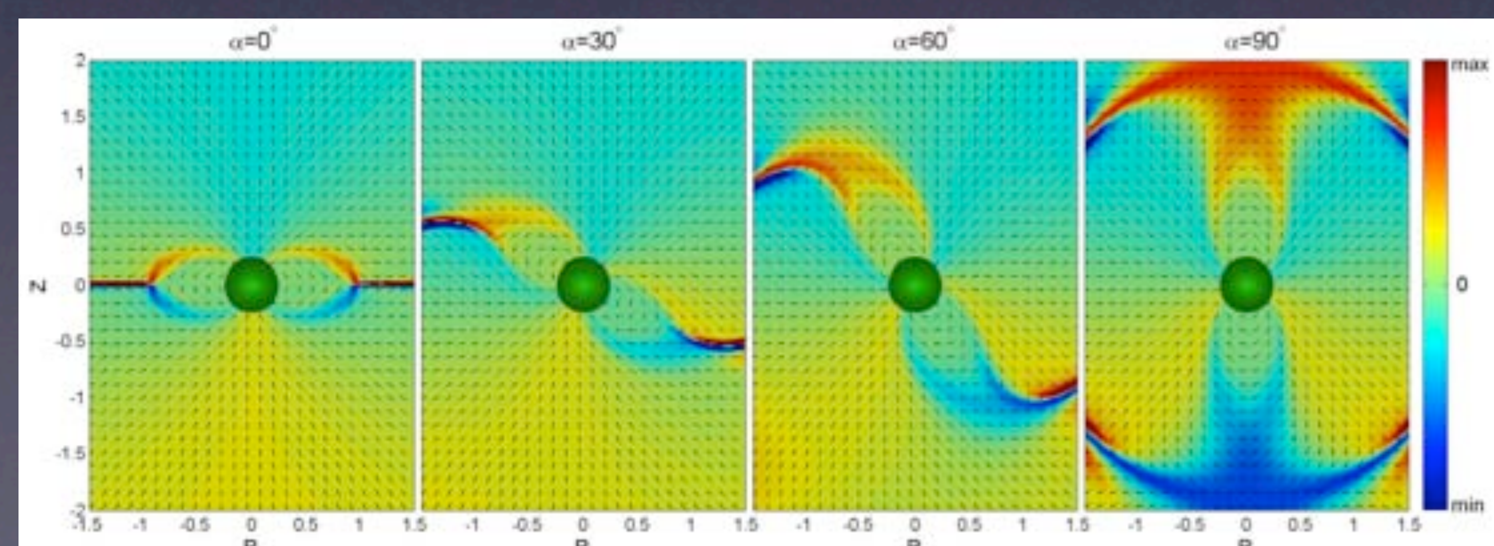
Similar to heliospheric current sheet

# What emits?

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

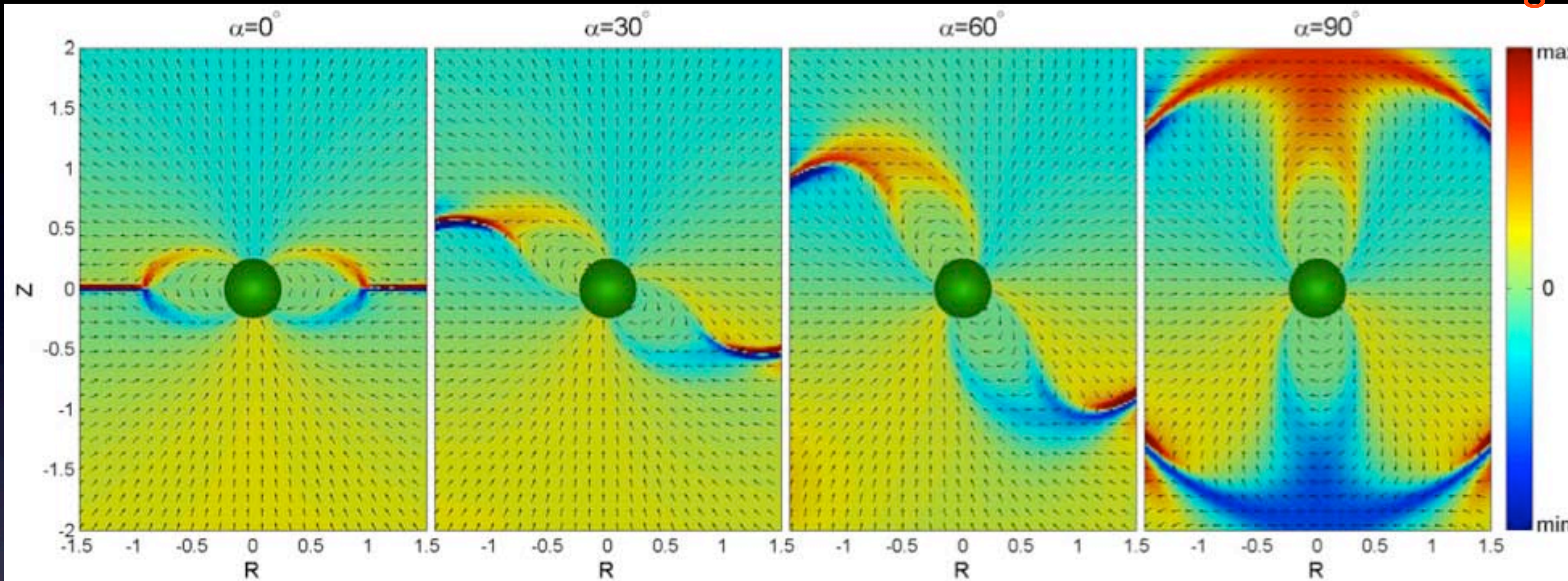
- Need acceleration of particles
- Particles radiate while moving along B field lines. Relativistic effects (aberration and time delay) are important.
- Where is the region that emits? Determined by field geometry.
- Extensive studies in vacuum field geometry (Harding; Romani; Cheng)
- Try this in force-free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



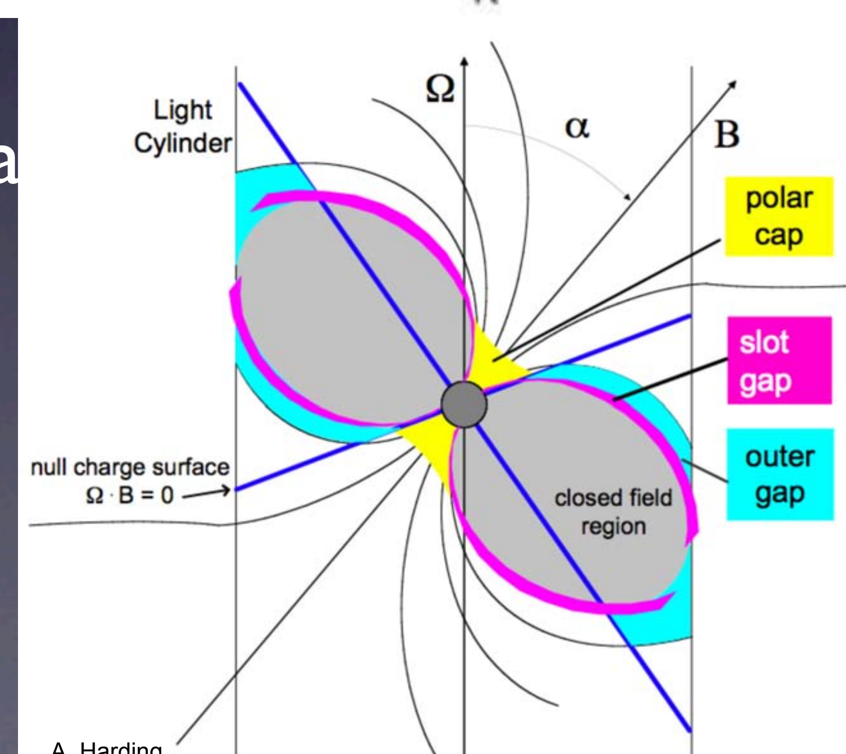
# Oblique rotator: force-free

color -- current strength




Bai & A. S. 2010

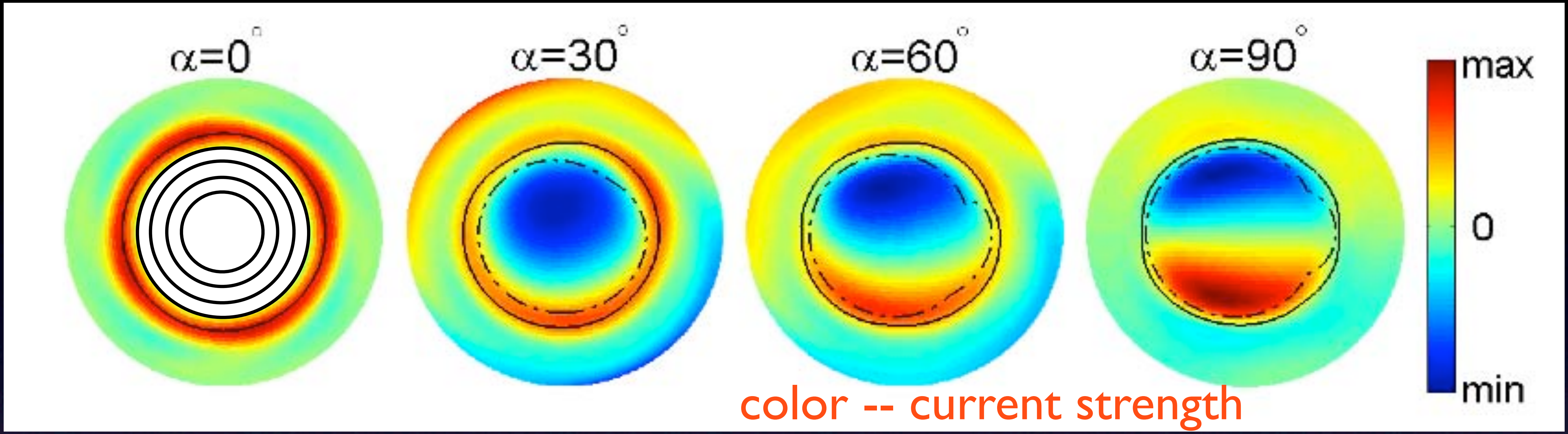
Distribution of current in the ma




Force-free field provides a more realistic magnetic geometry

Tempting to associate gaps with currents. Can we?

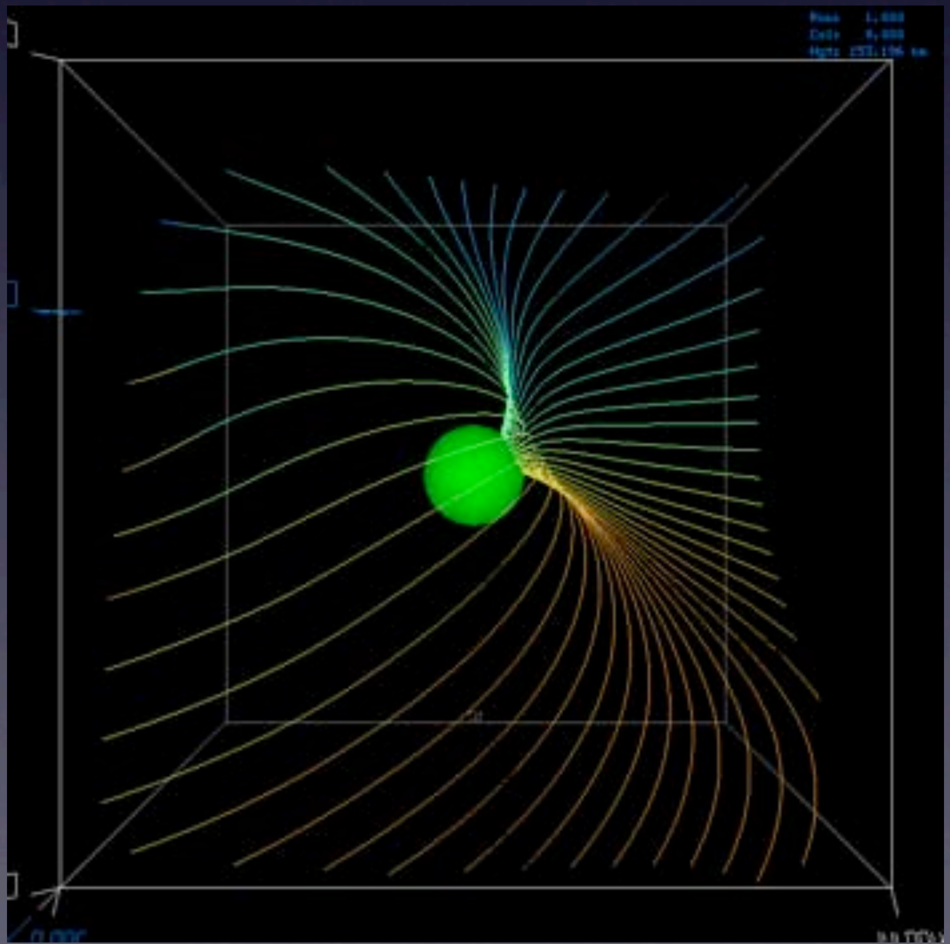
# What emits?




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

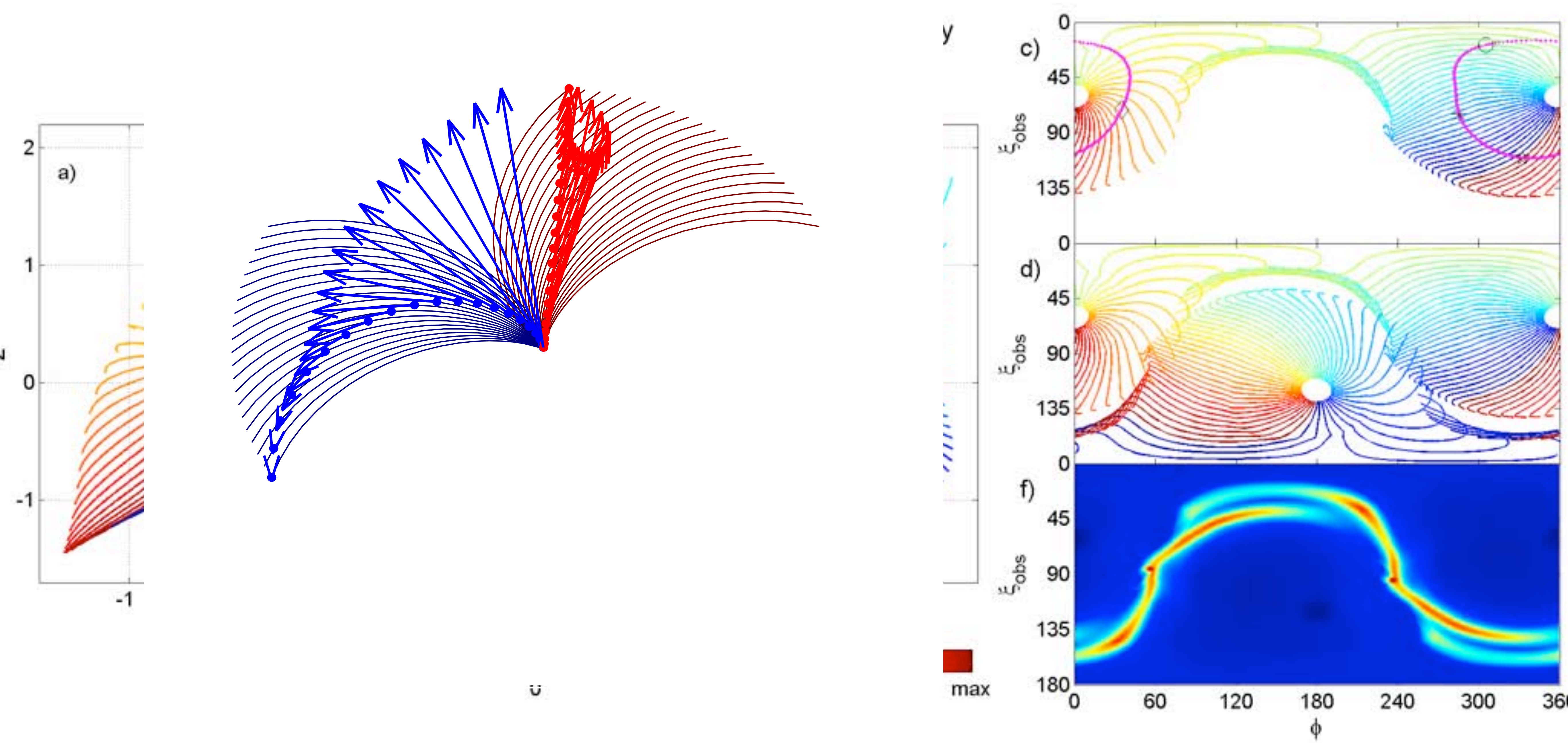
- This is arbitrary, but the point is to study the geometry of the possible emission zone.

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



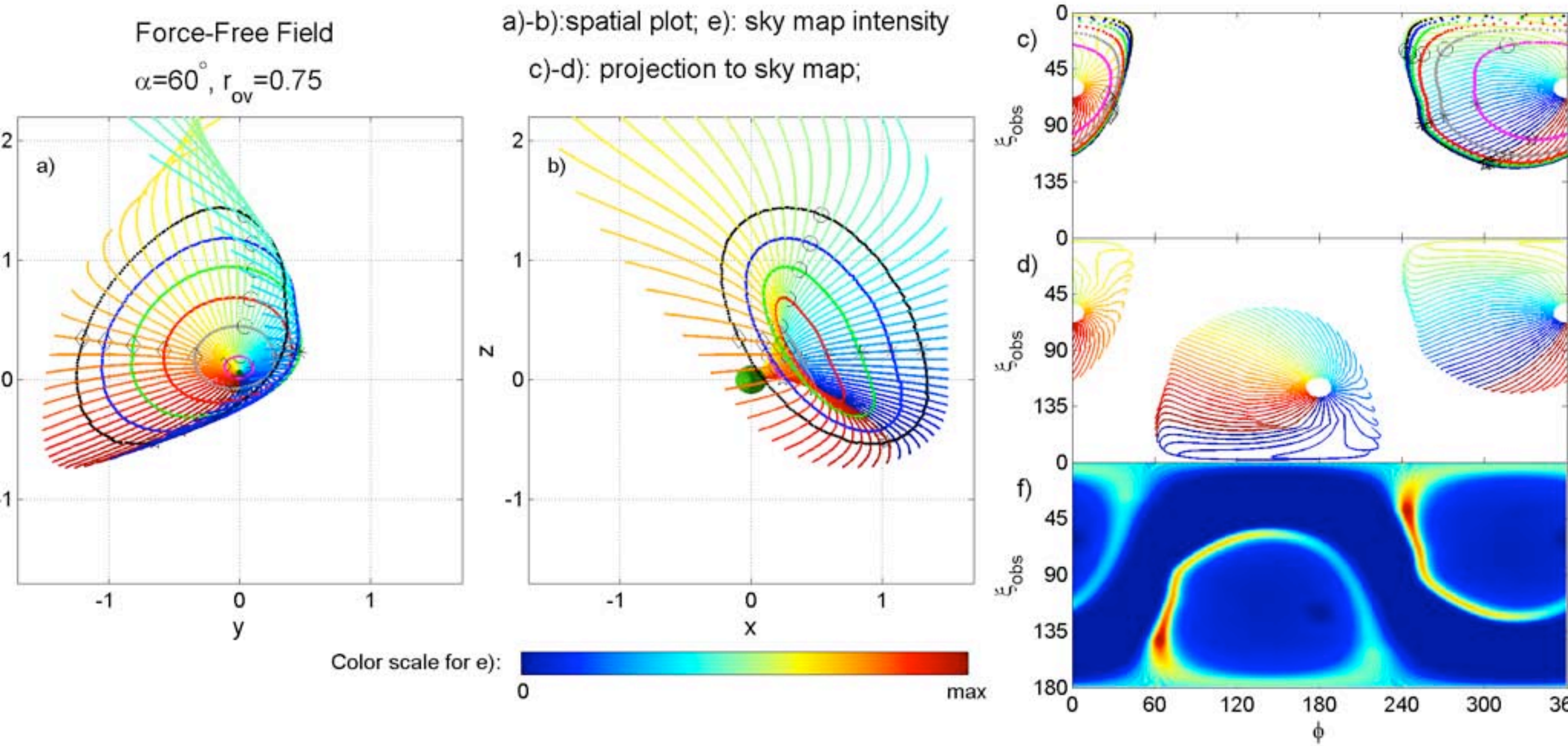
open field lines

# Emission from one flux tube




Bai & A. S. 2010

# Emission from different flux tubes




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

Bai & A. S. 2010

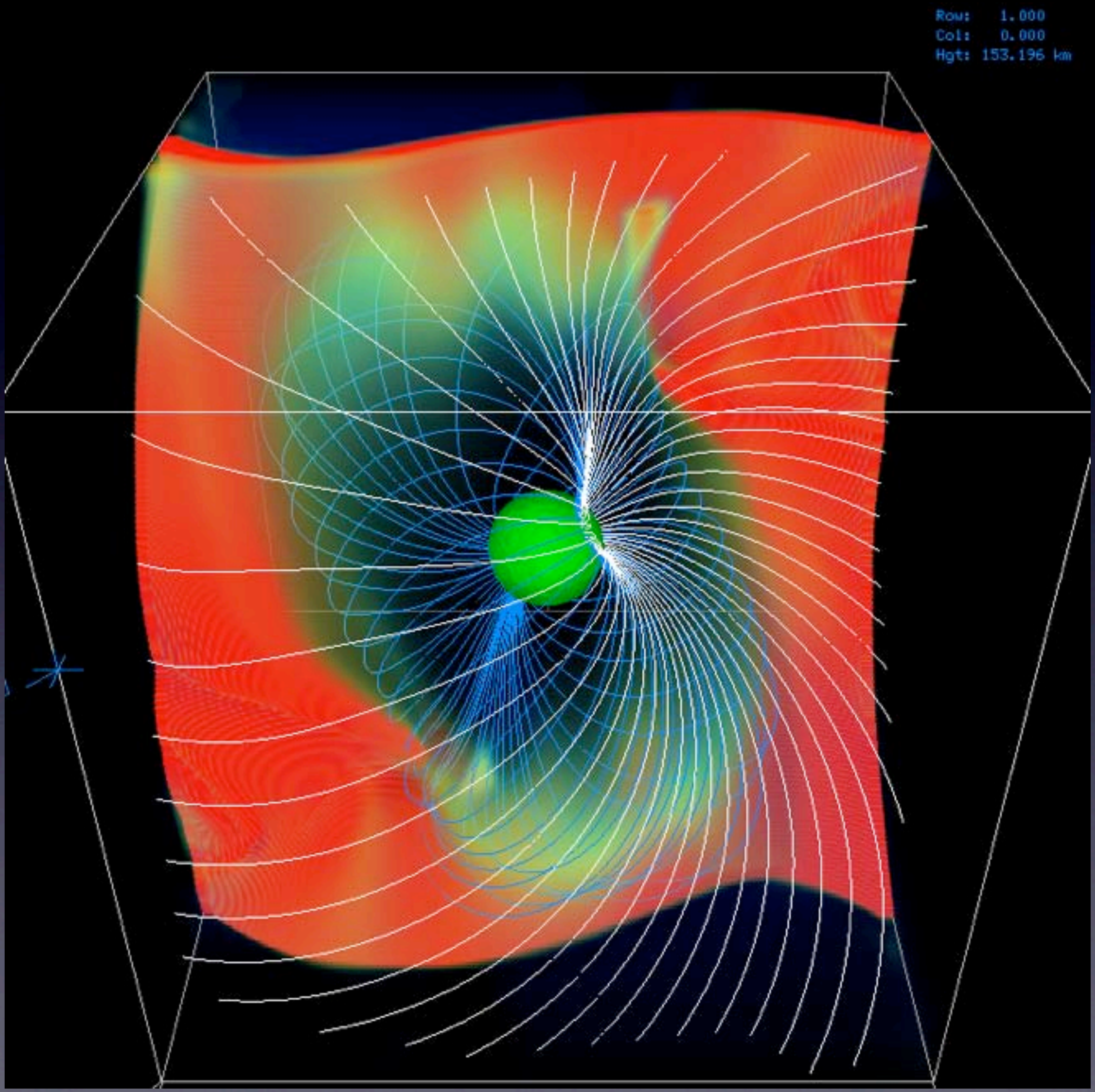
# Association with the current sheet

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.

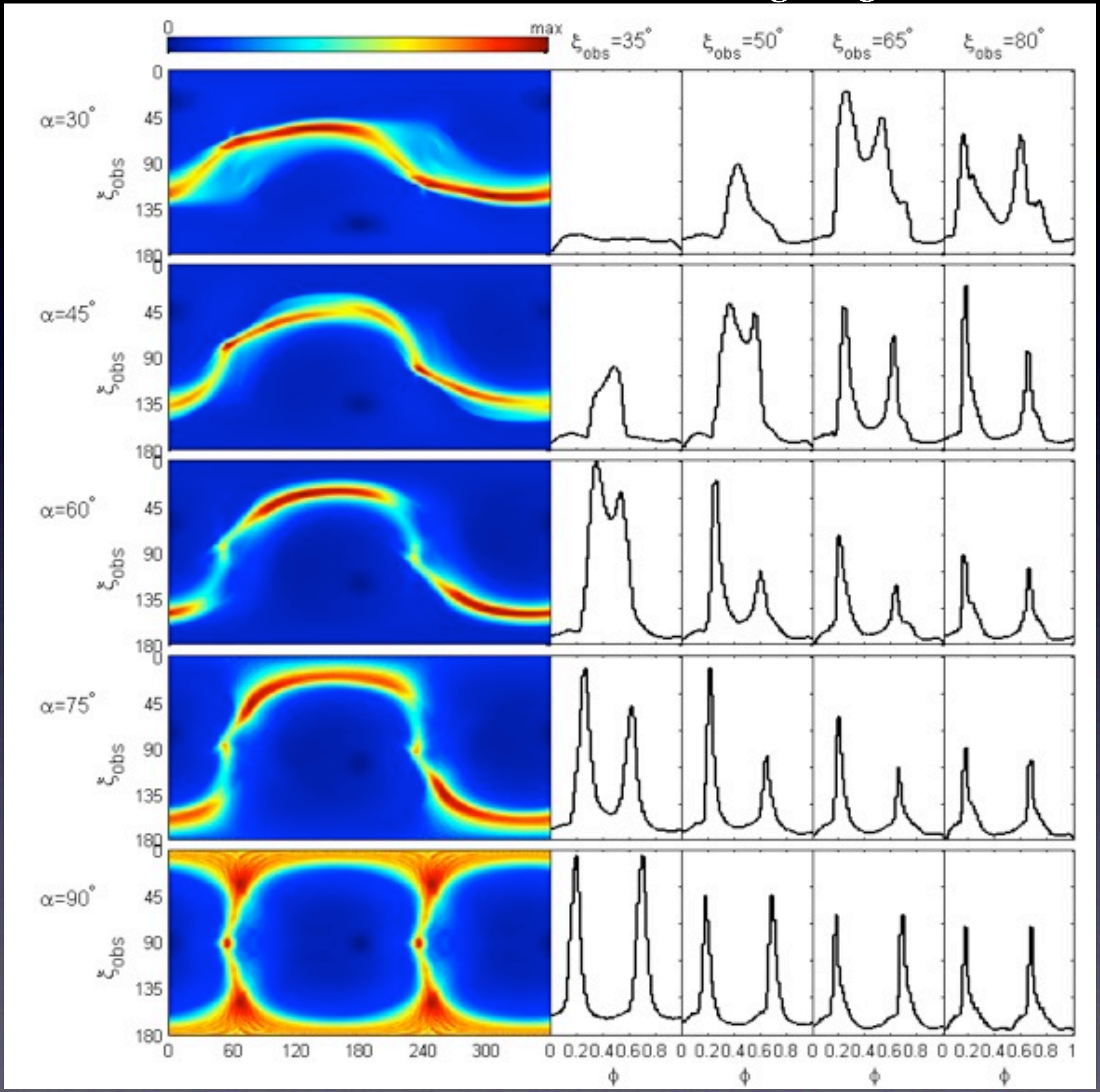
Current sheet good place to put resistor in the circuit!



# Force-free gallery

Viewing angle

Inclination angle of magnetic axis




Double peak profiles very common.

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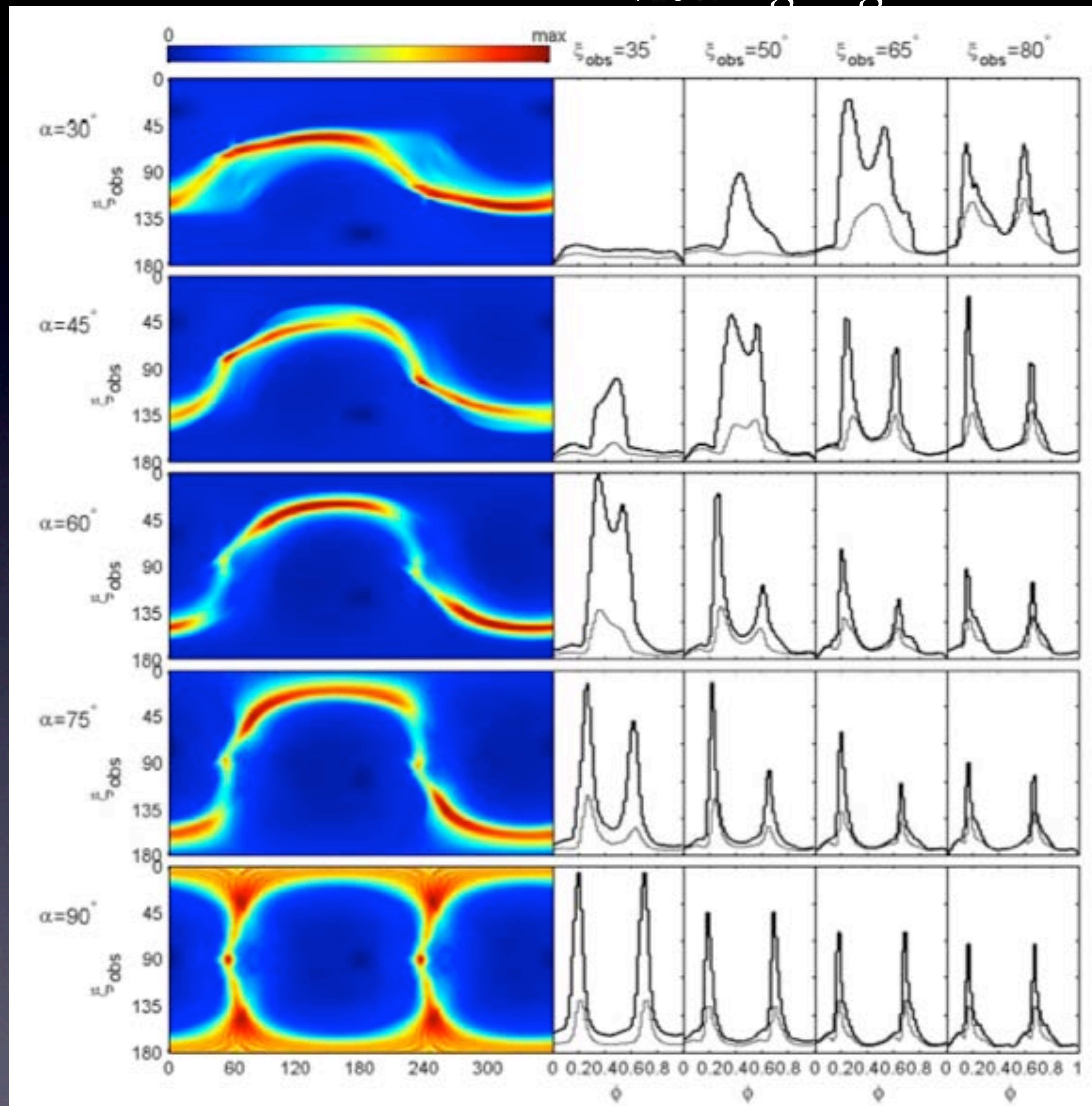
# Force-free gallery

Viewing angle




Inclination angle of magnetic axis

Most of the emission in FF model accumulates beyond 0.9 Rlc

Double peak profiles very common.

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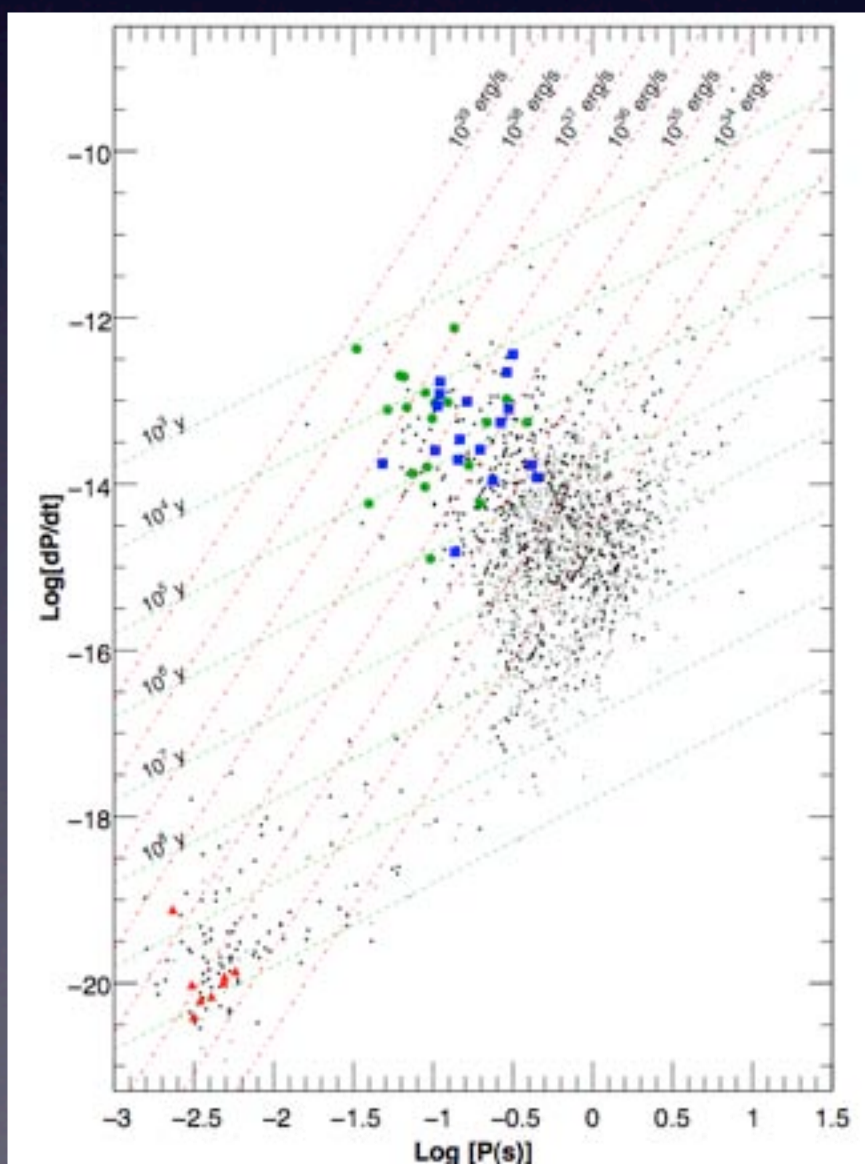
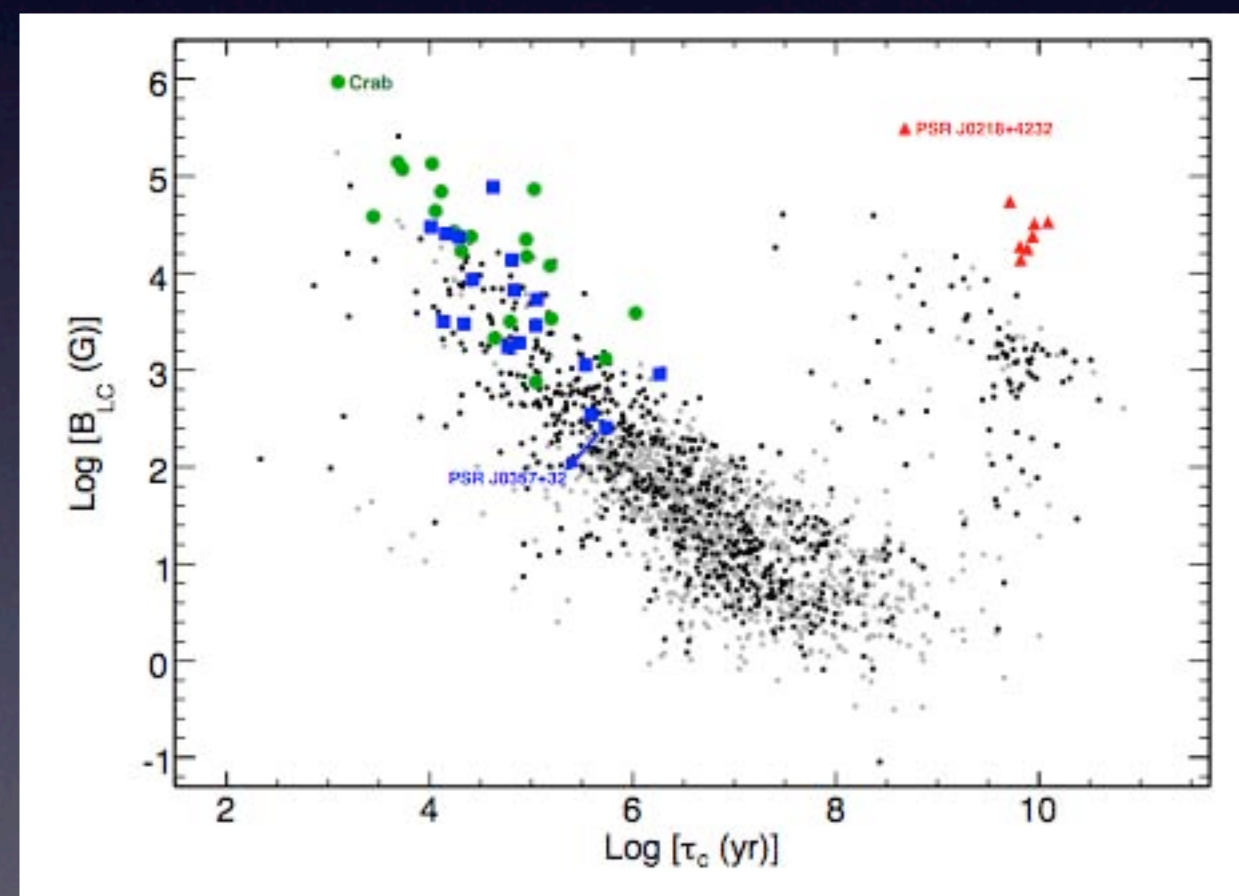
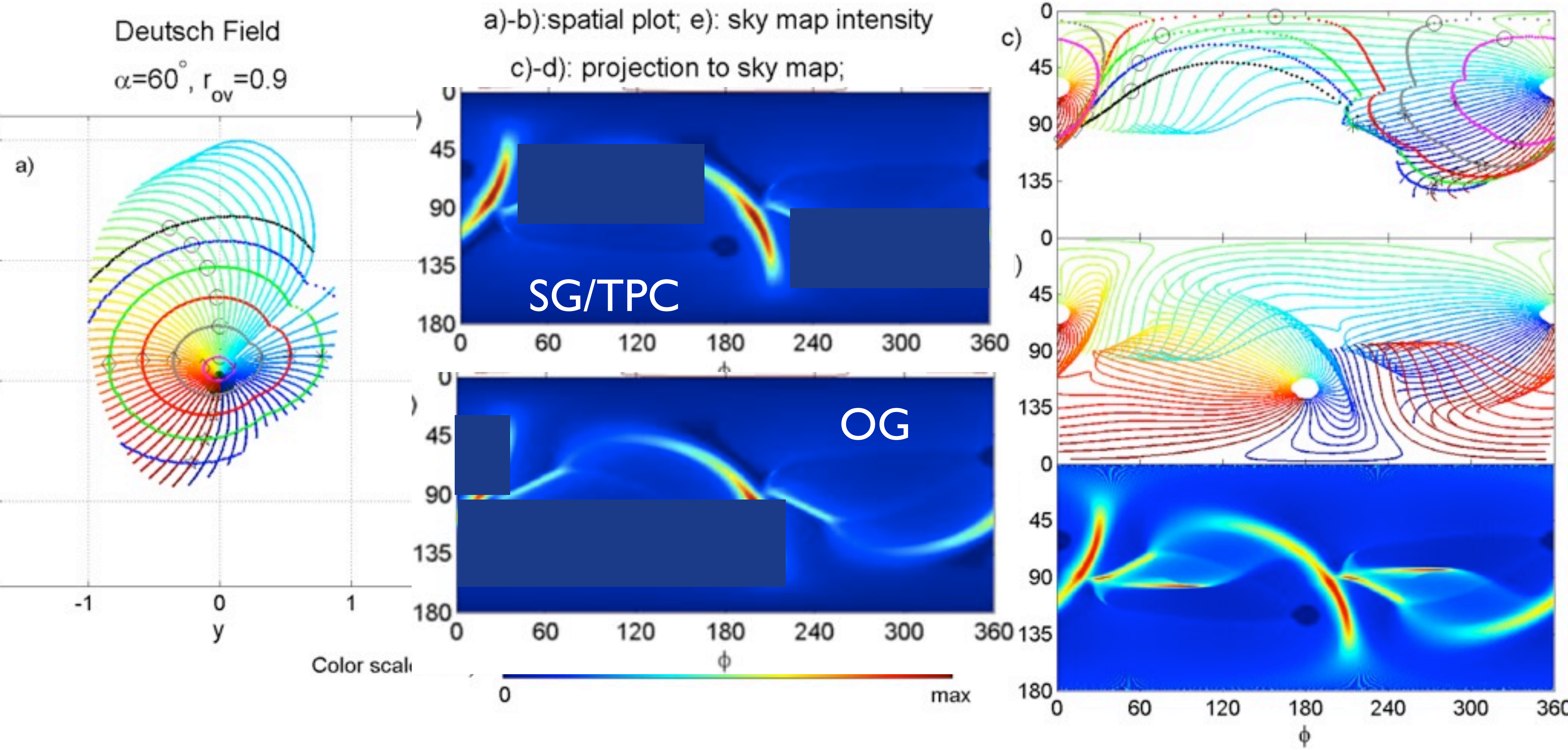
# Gamma-ray emission from pulsars


High B at light cylinder required

# Vacuum sky map



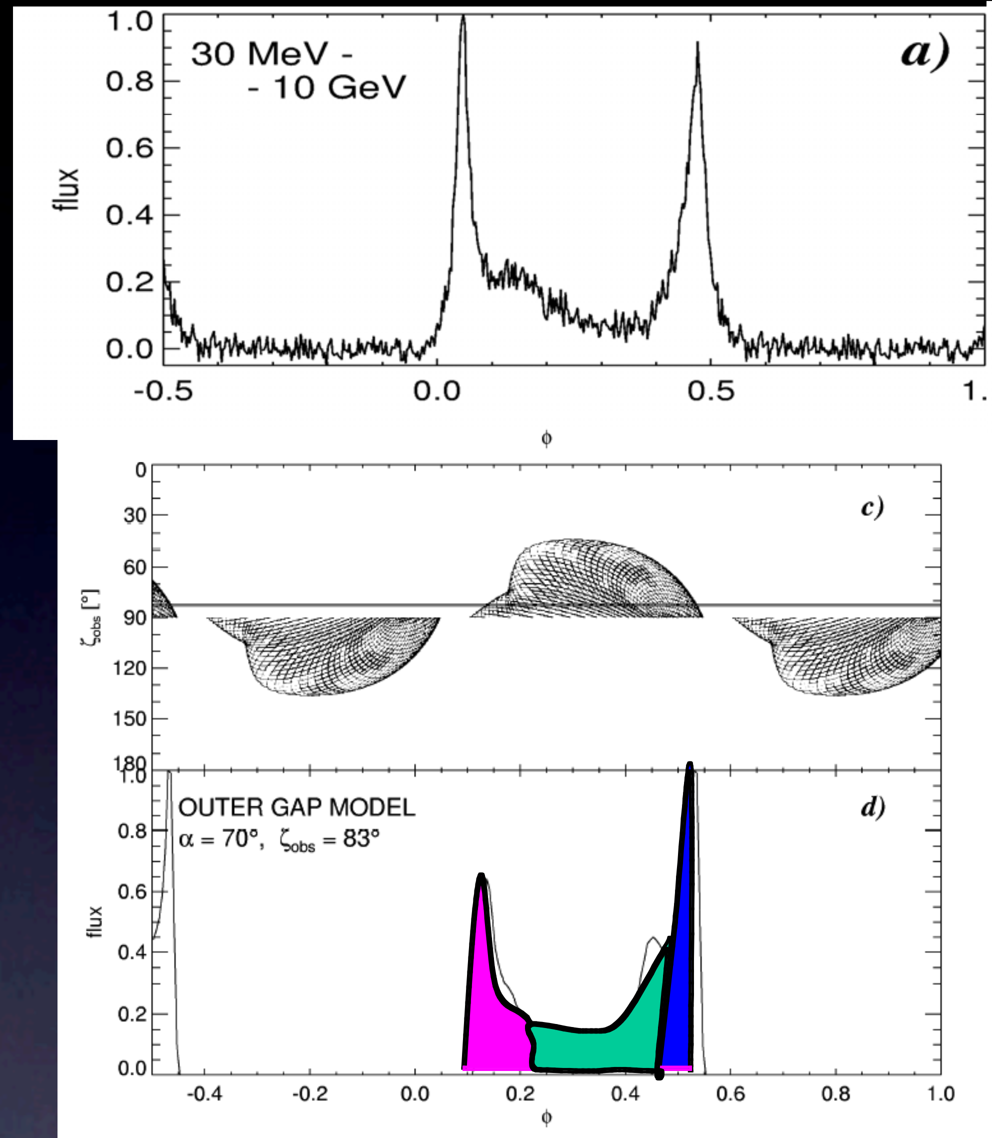

Vacuum field, 60 degree inclination, flux tube starting at 0.9 of the polar cap radius.

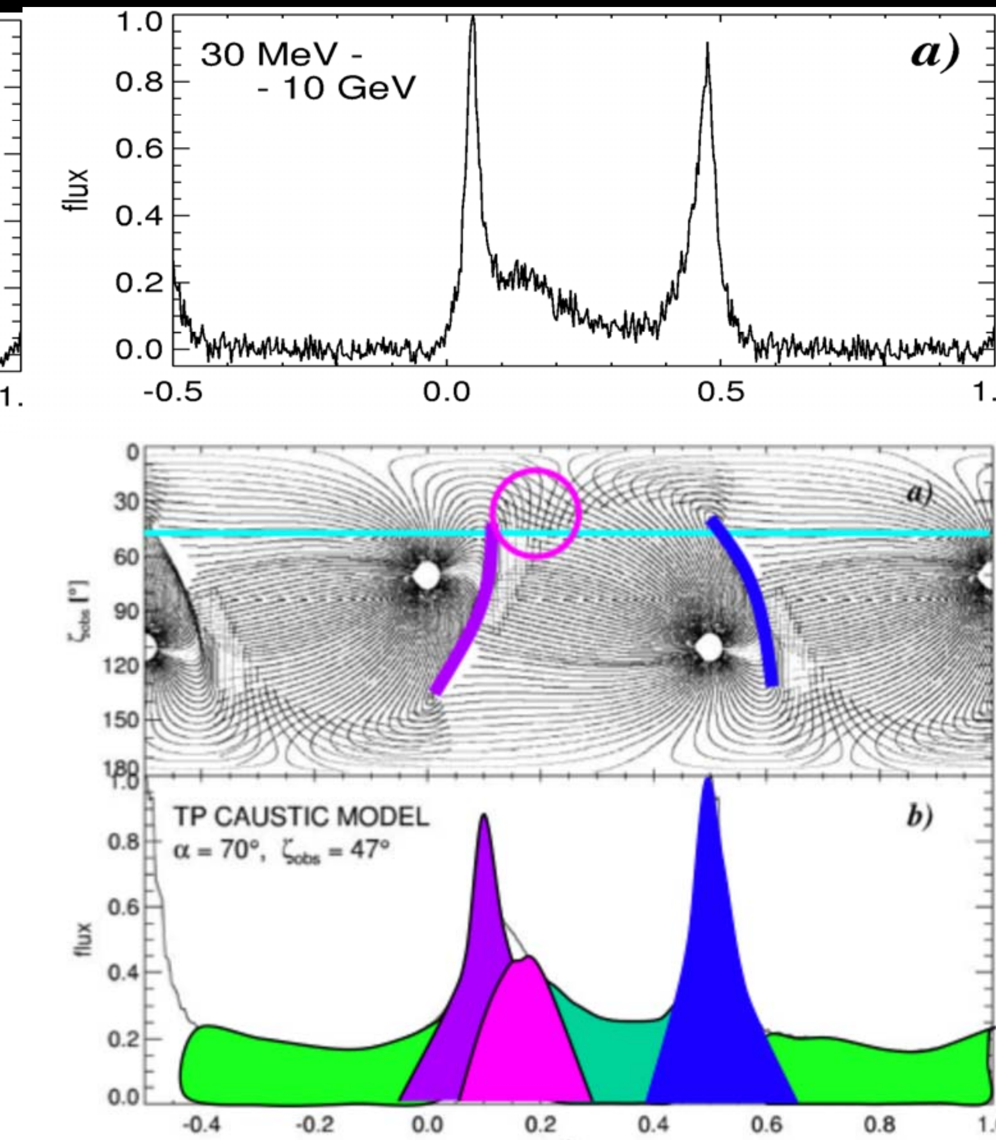
# Vacuum light curve fitting

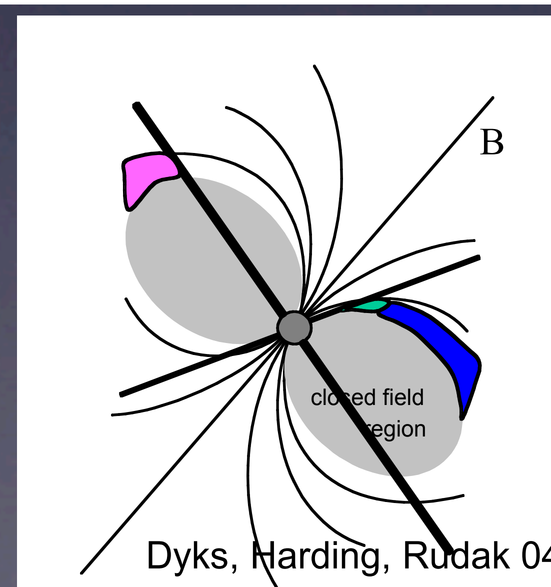
Impressive fits can be achieved with both "slot gap" and "outer gap" models based on the vacuum field.

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

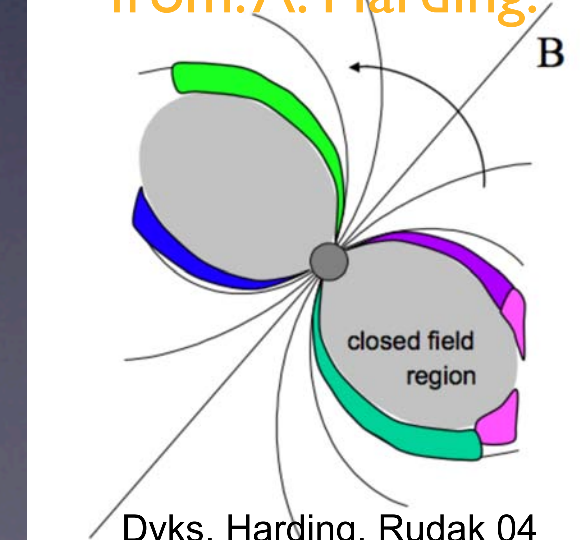
Both FF and vacuum models point to outer magnetosphere.




from: A. Harding.



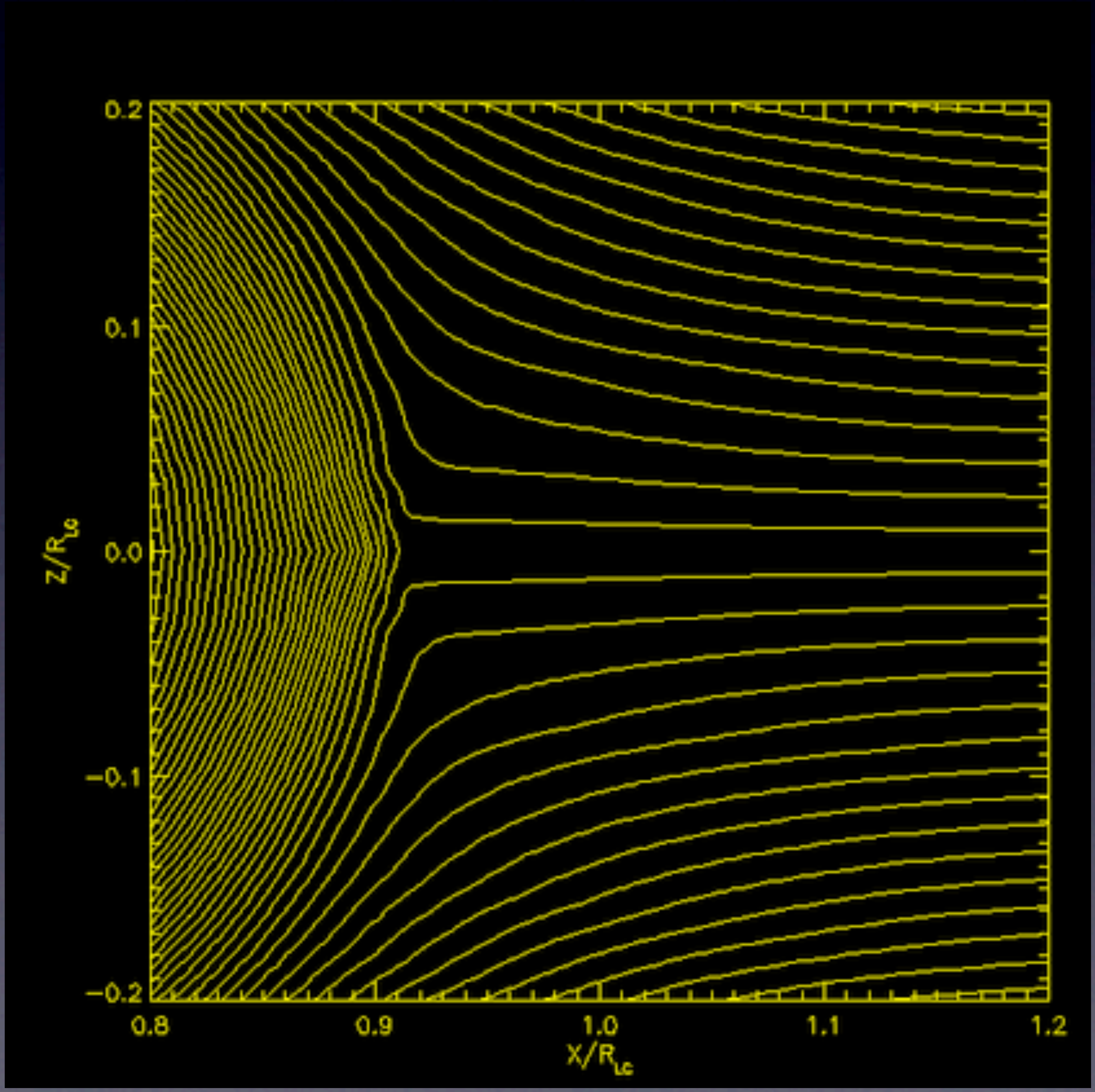
# Magnetospheric models

| | 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 ~ $10^4$-$10^6$ $n_{GJ}$)

Plasma currents result in spin down; wind carries Poynting flux

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

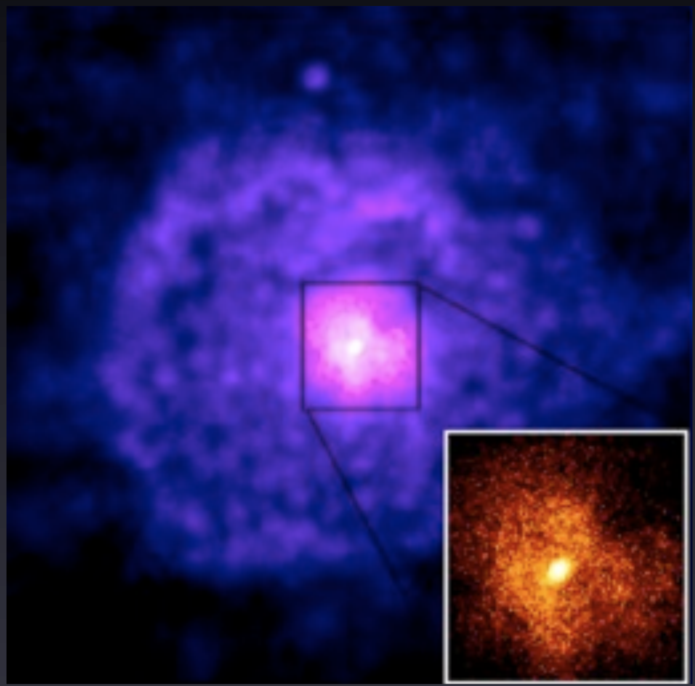
Wind is "striped"

High-energy emission near LC is related to current sheets

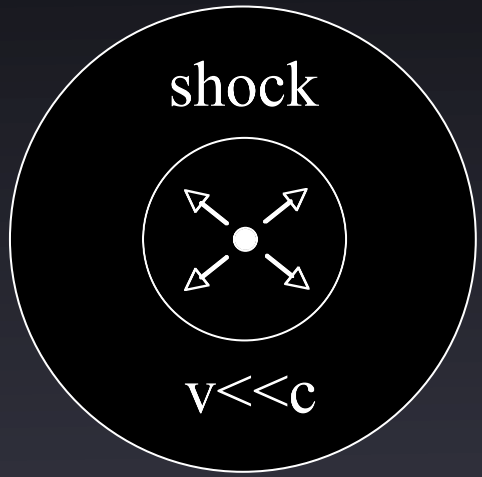
Particle spectrum accelerated near LC is irrelevant to the particle spectrum in the outside world, due to adiabatic losses in the wind.

# Pulsar Wind Nebulae

Properties of pulsar winds:



G21.9 (Safi-Harb et al 2004)

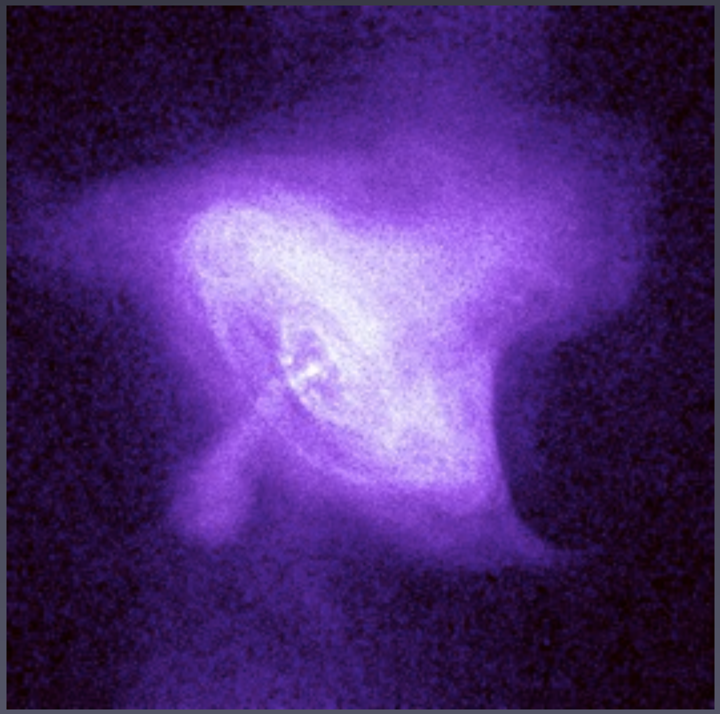



Kennel & Coroniti 84
Rees & Gunn 74

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

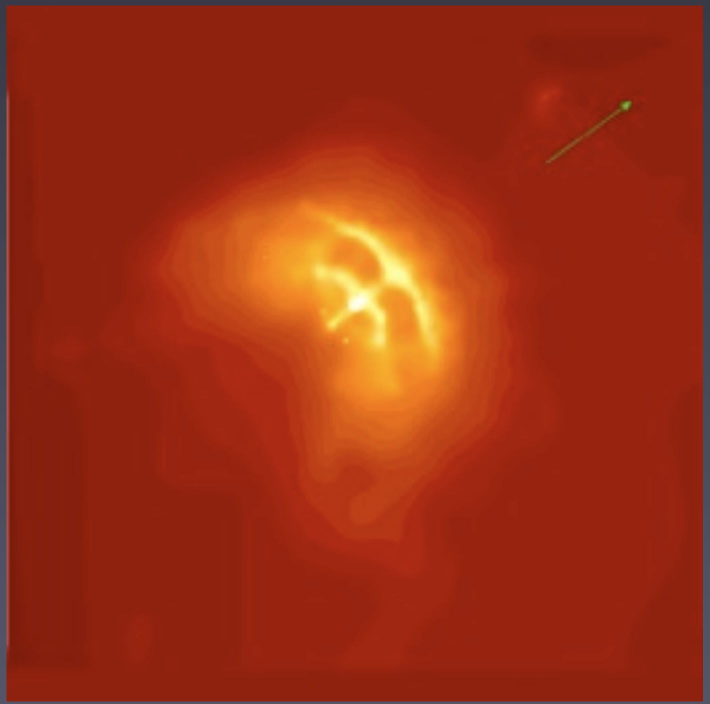
$$\sigma = B^2/(4\pi\gamma n m c^2) \sim 10^{-3}\text{-}10^{-1}$$

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

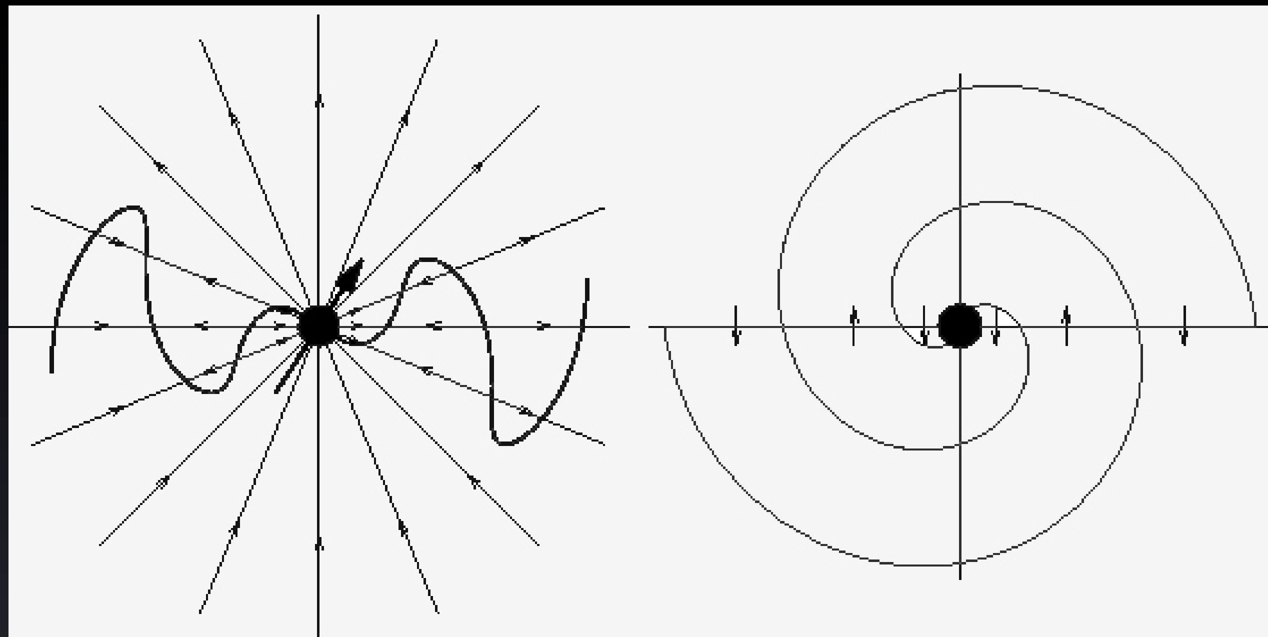


Crab (Weisskopf et al 2000)

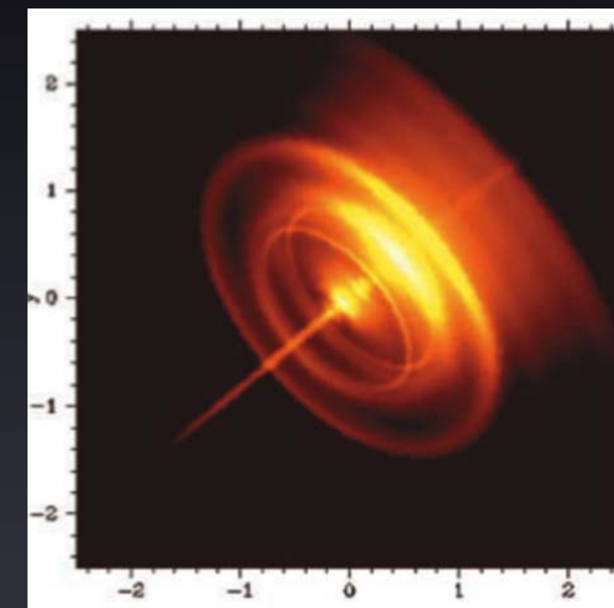
PSR B1509-58 (X-rays; Slane et al 2006)

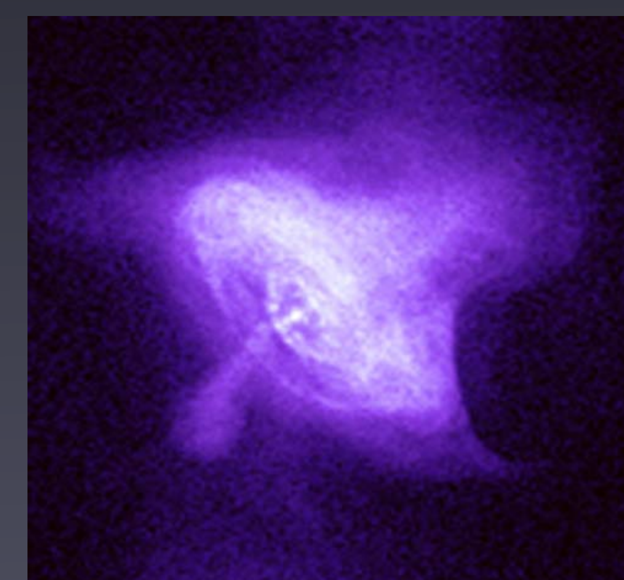


Vela (Pavlov et al 2001)



Komissarov & Lyubarsky





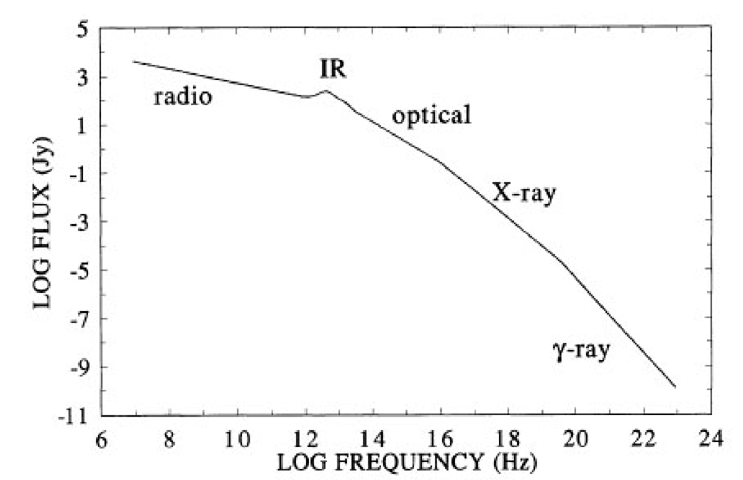
Somewhere in the wind magnetic dissipation should occur, because the wind is low magnetization when it comes to the nebula.

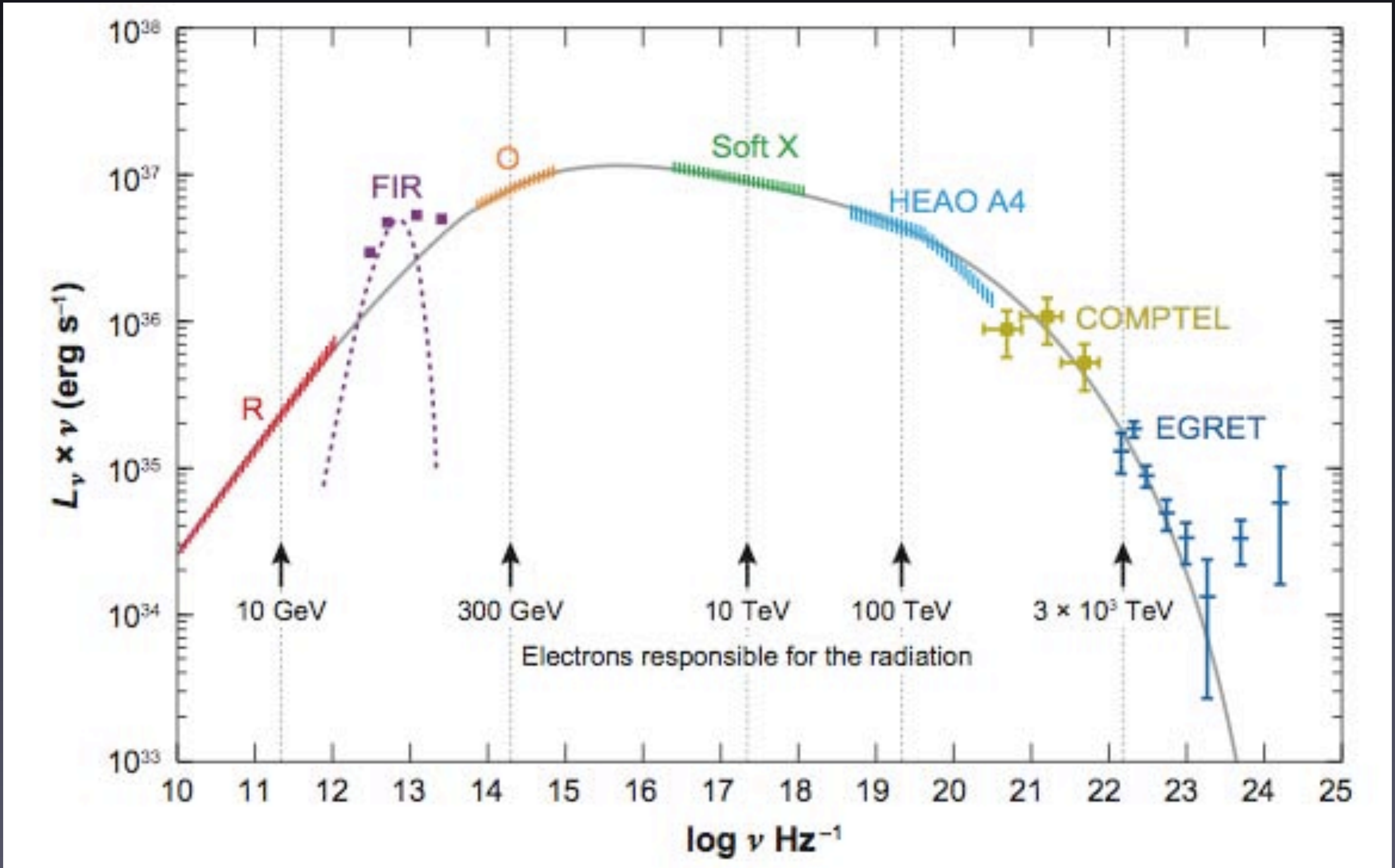
How this happens is a big uncertainty ("sigma"-problem)

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

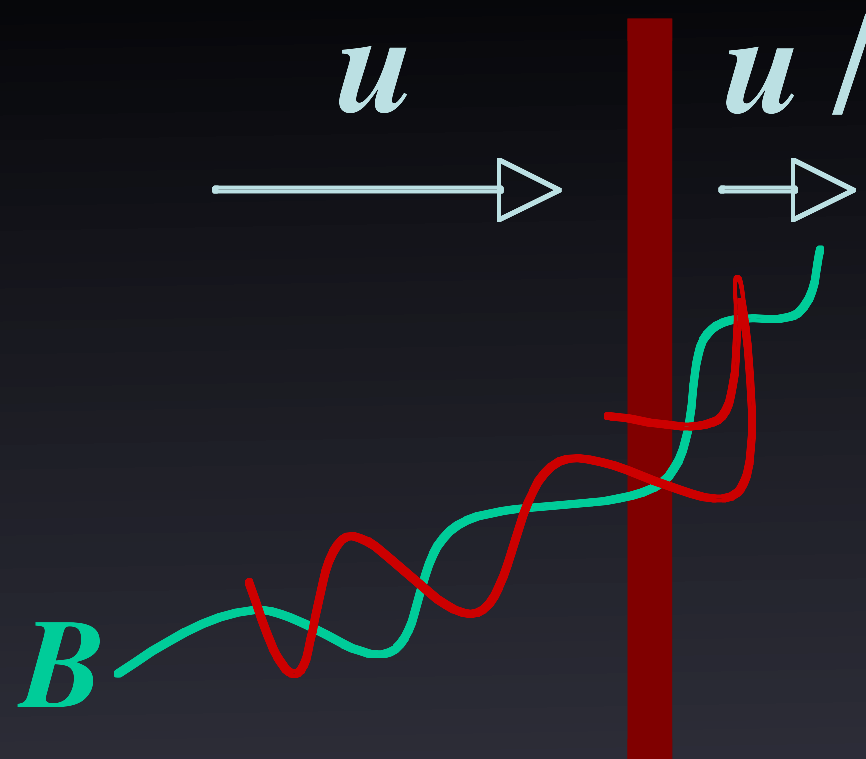
$$B_\varphi \propto \sin\theta\left(1-\frac{2\theta}{\pi}\right)$$

# Spectrum of the Crab



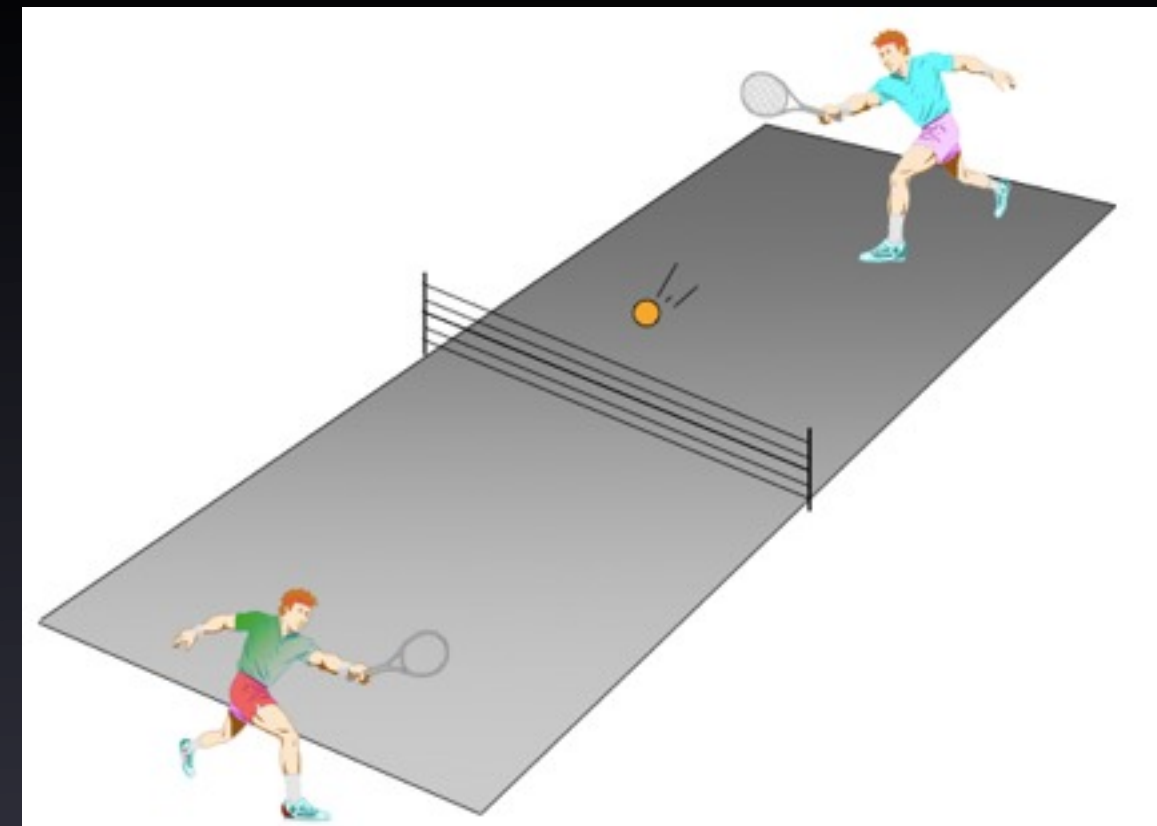



# Particle acceleration:



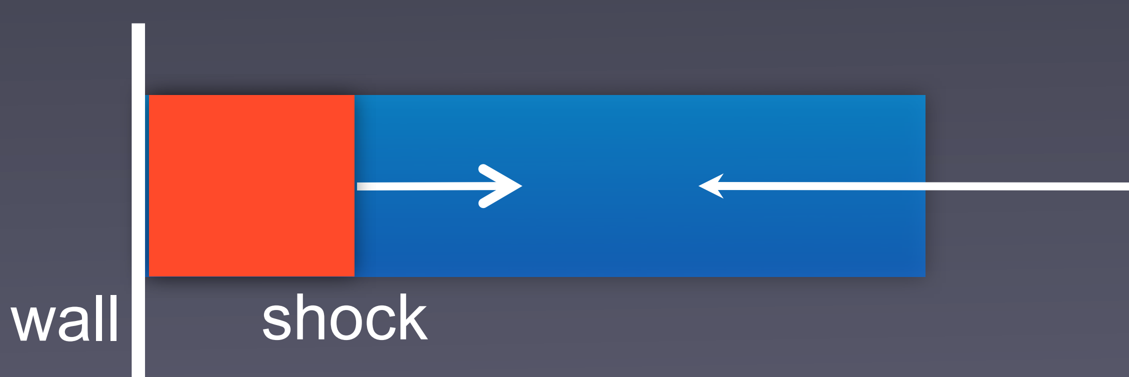

$\Delta E/E \sim v_{shock}/c$

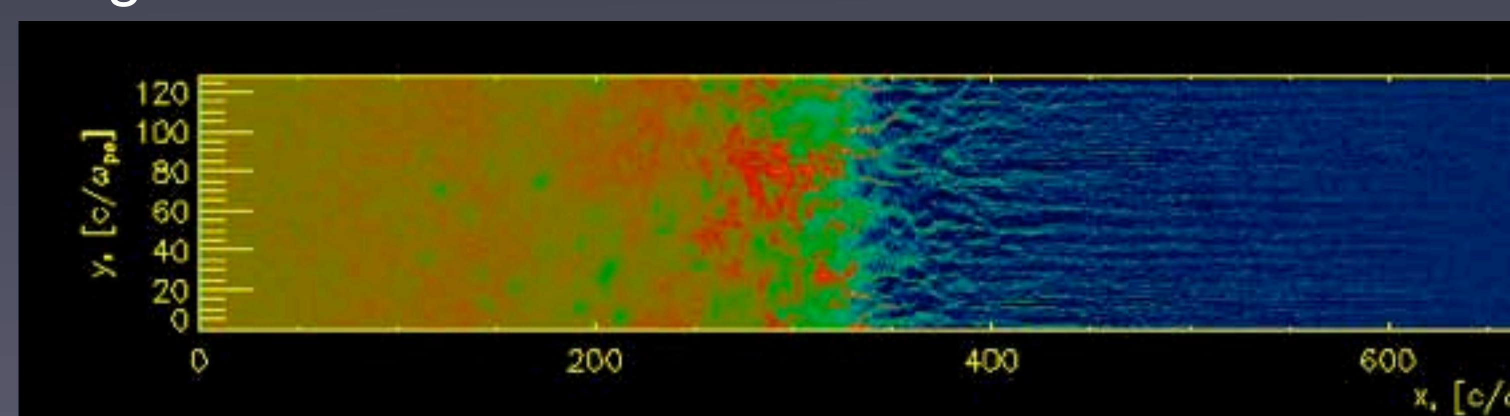
$N(E) \sim N_0\, E^{-K(r)}$



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.

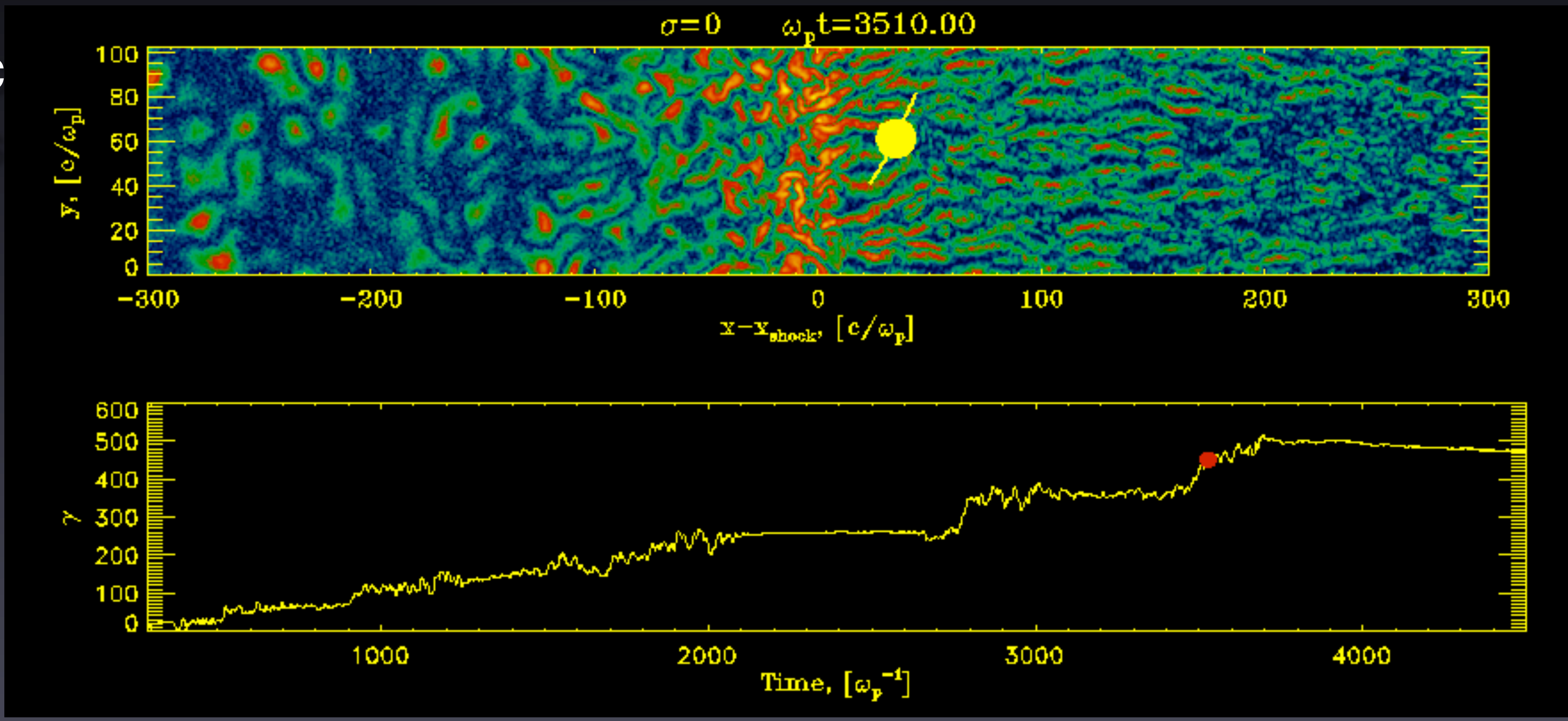


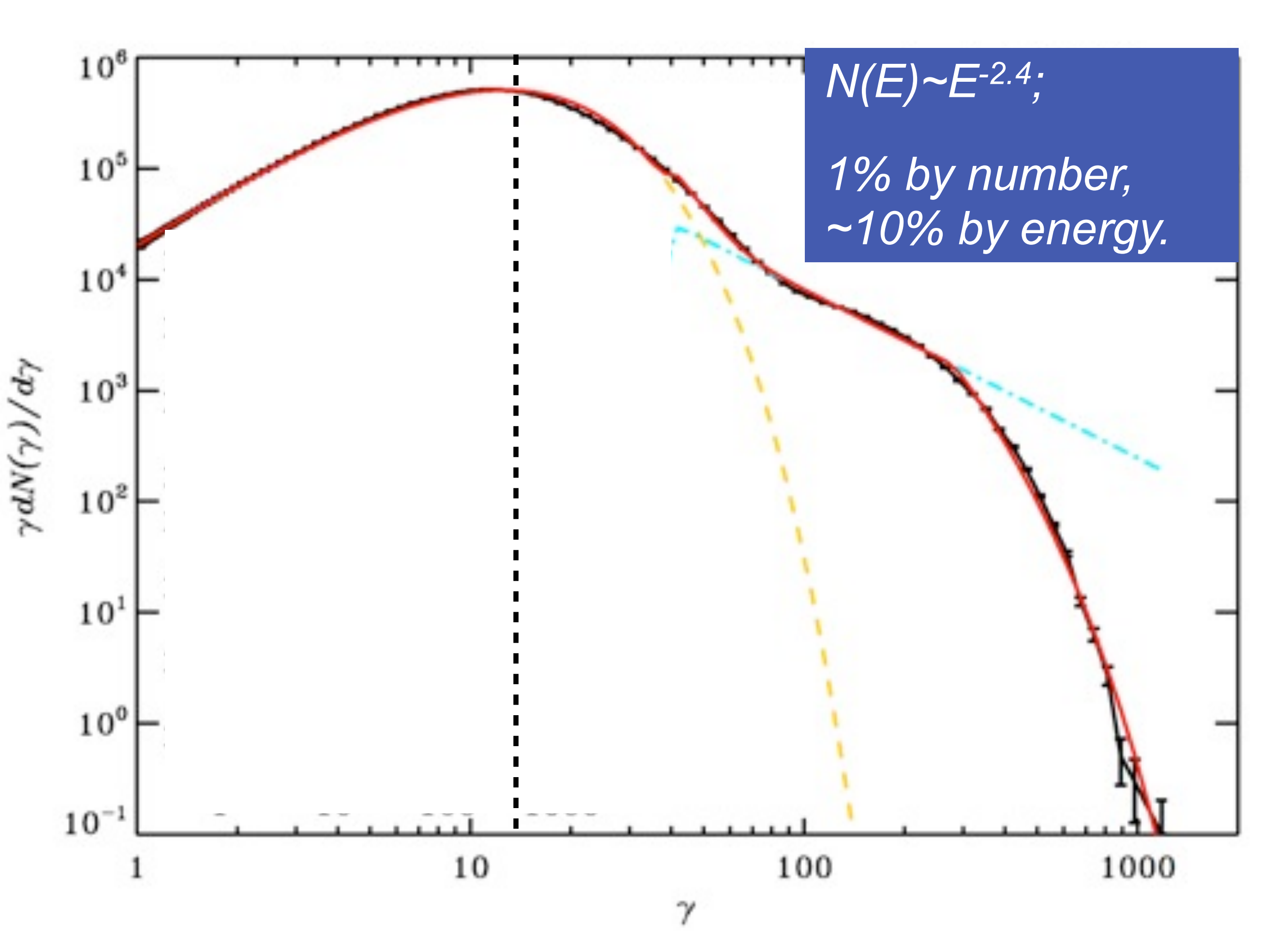



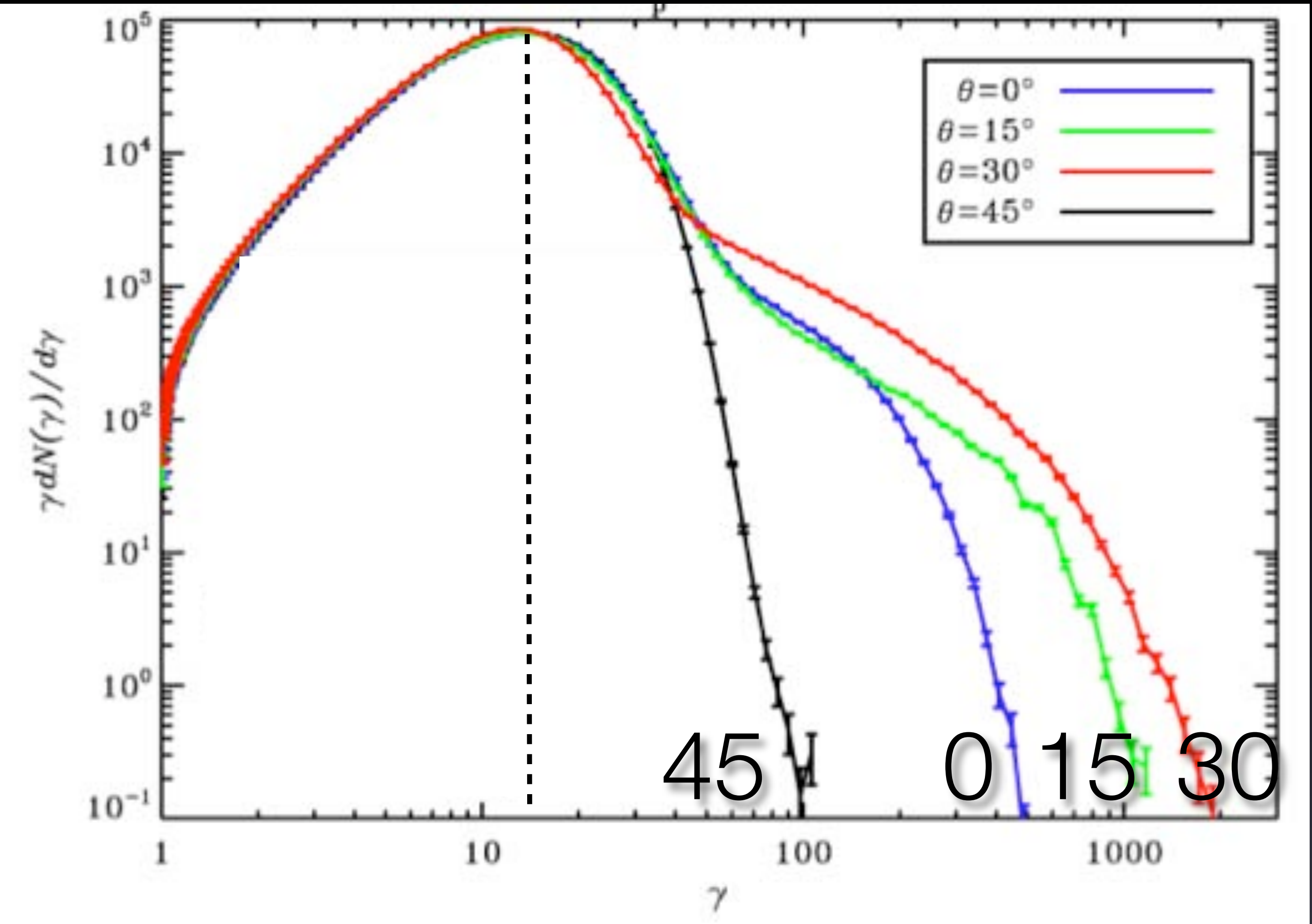
# Unmagnetized pair shock: particle trajectories

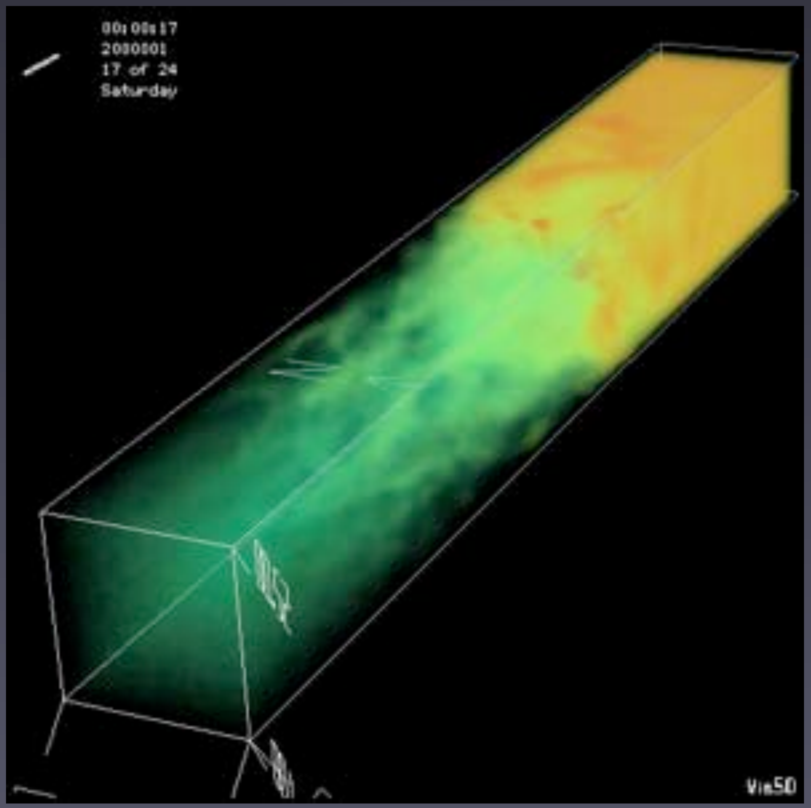
Magnetic filaments

Particle energy





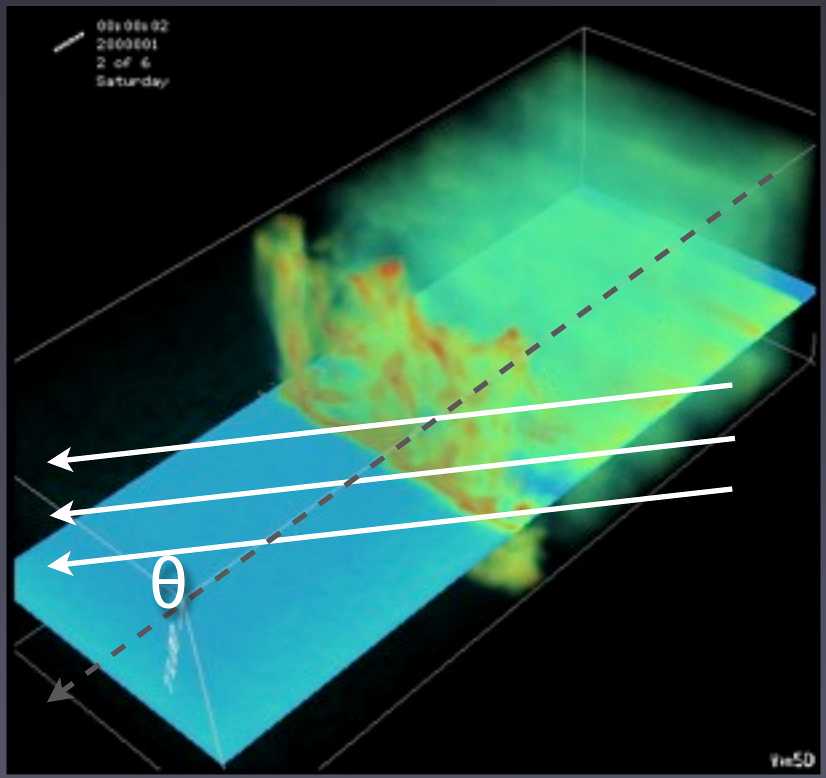



AS 06

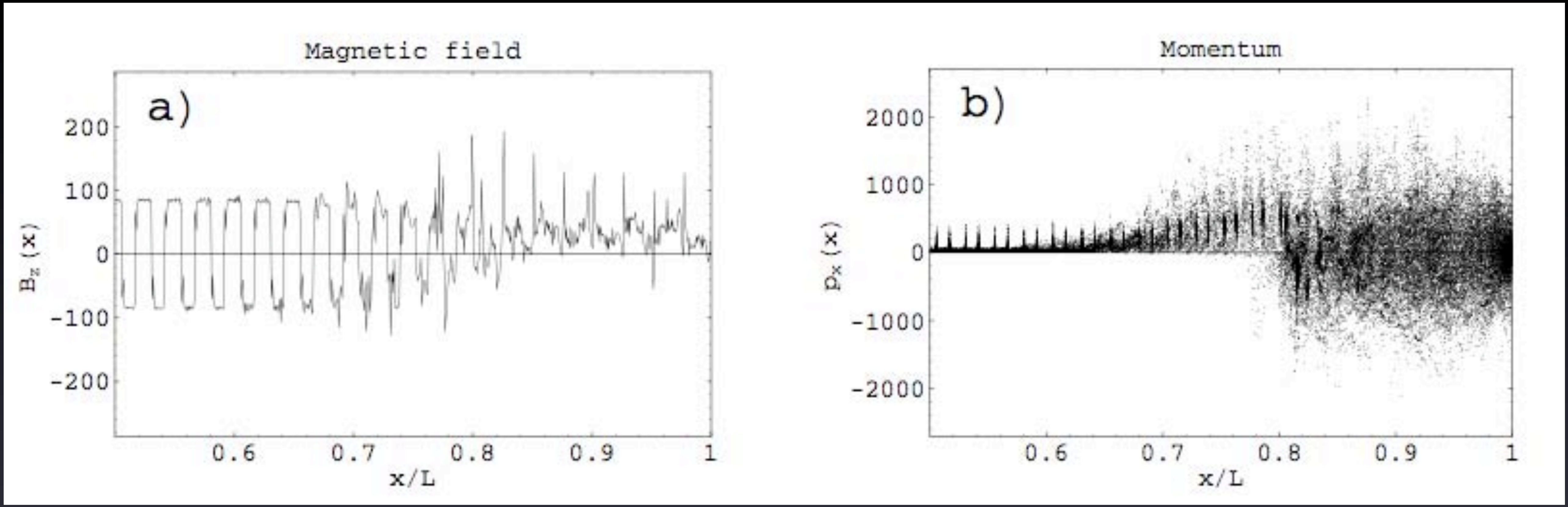
Efficient acceleration occurs for low magnetization shocks or for quasi-parallel shocks.

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.

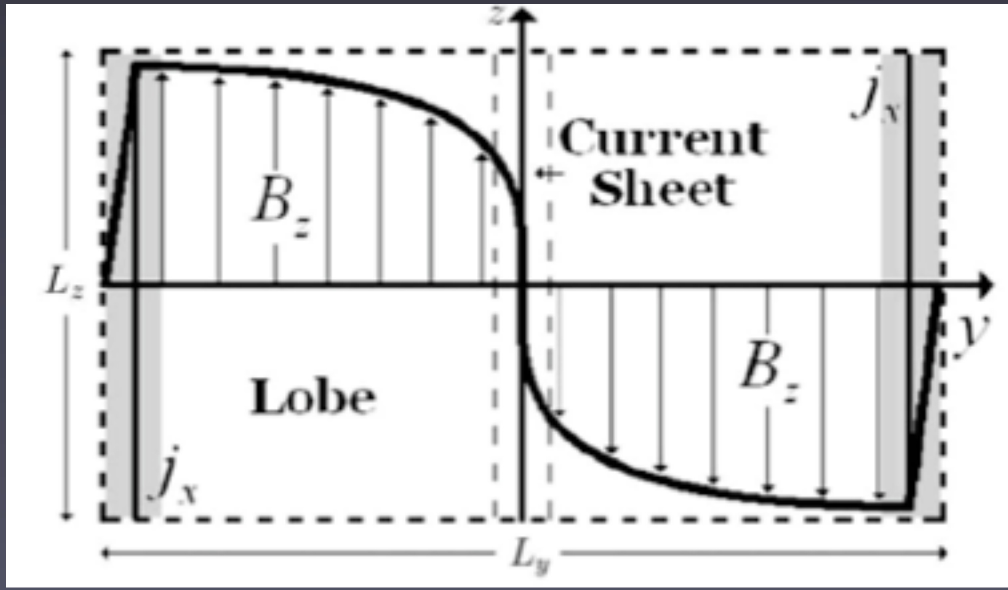


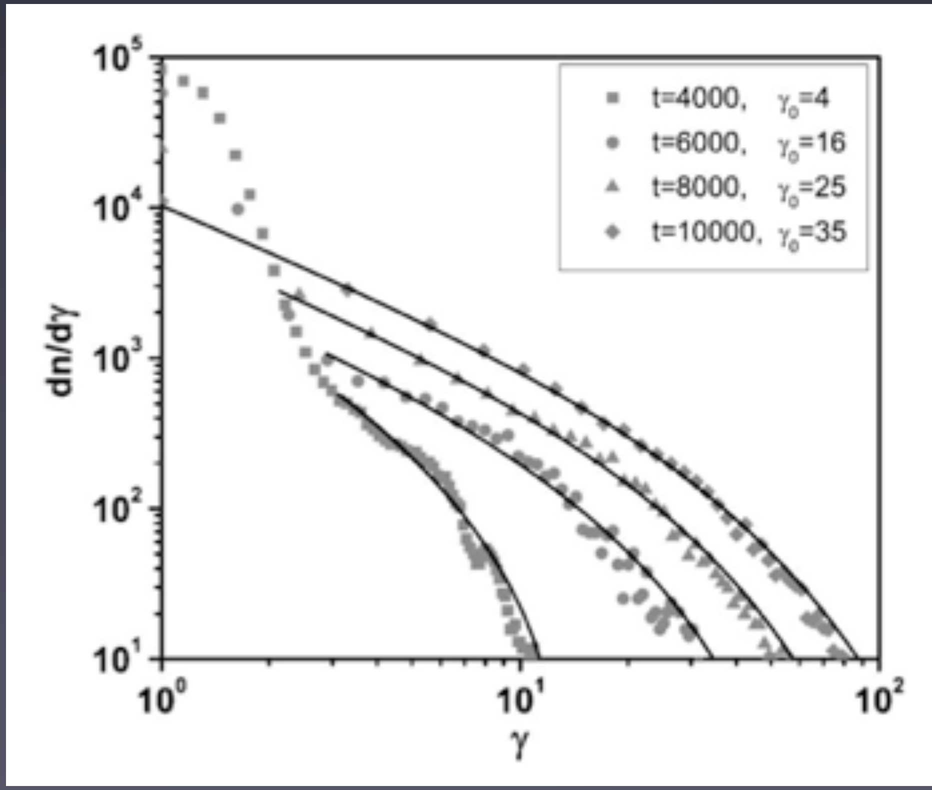

Sironi & AS 09

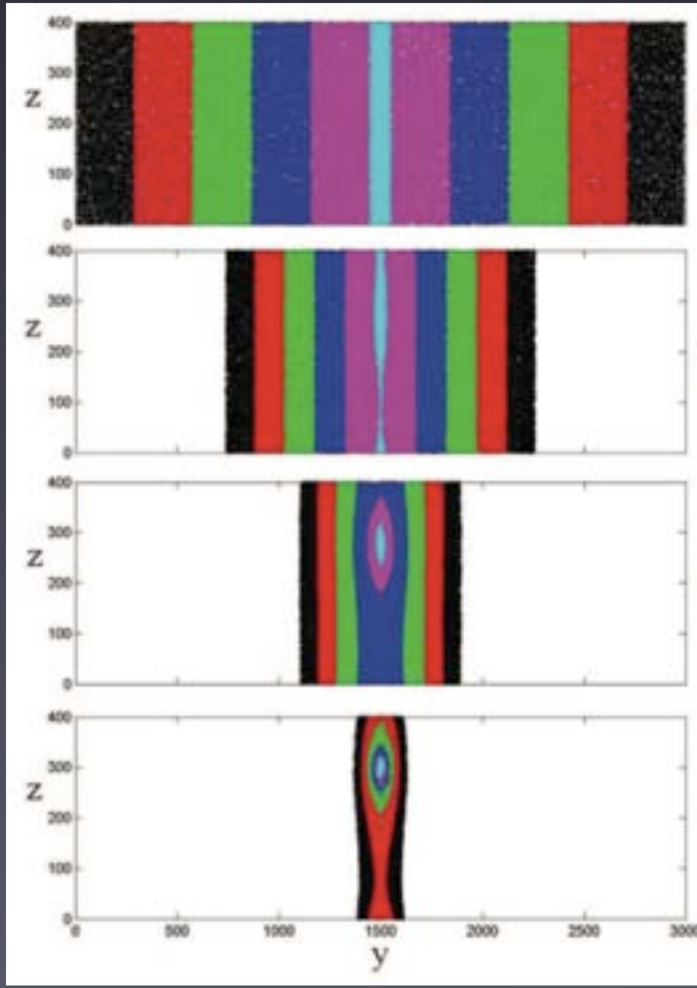



Petri & Lyubarsky 2008
Lyubarsky & Liverts 2009

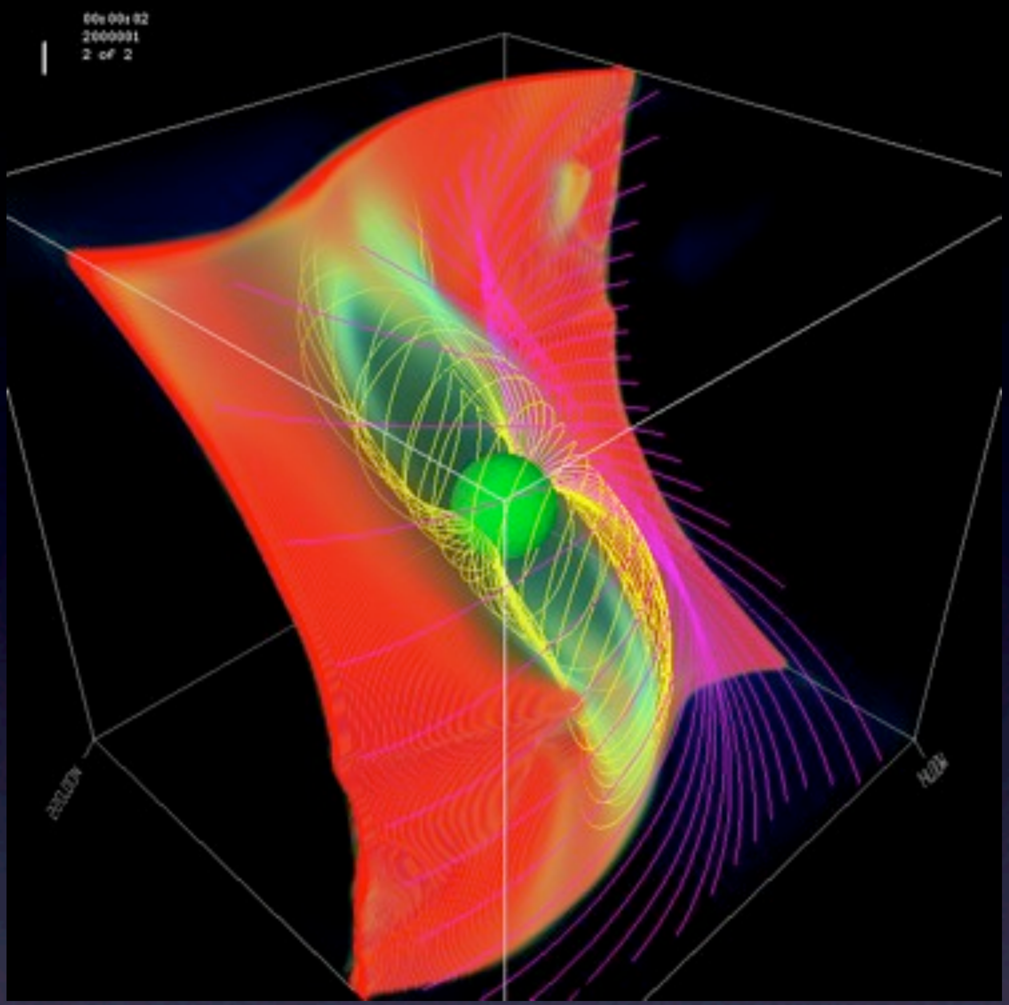
reconnection @ shock
may create flat spectra



# 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.