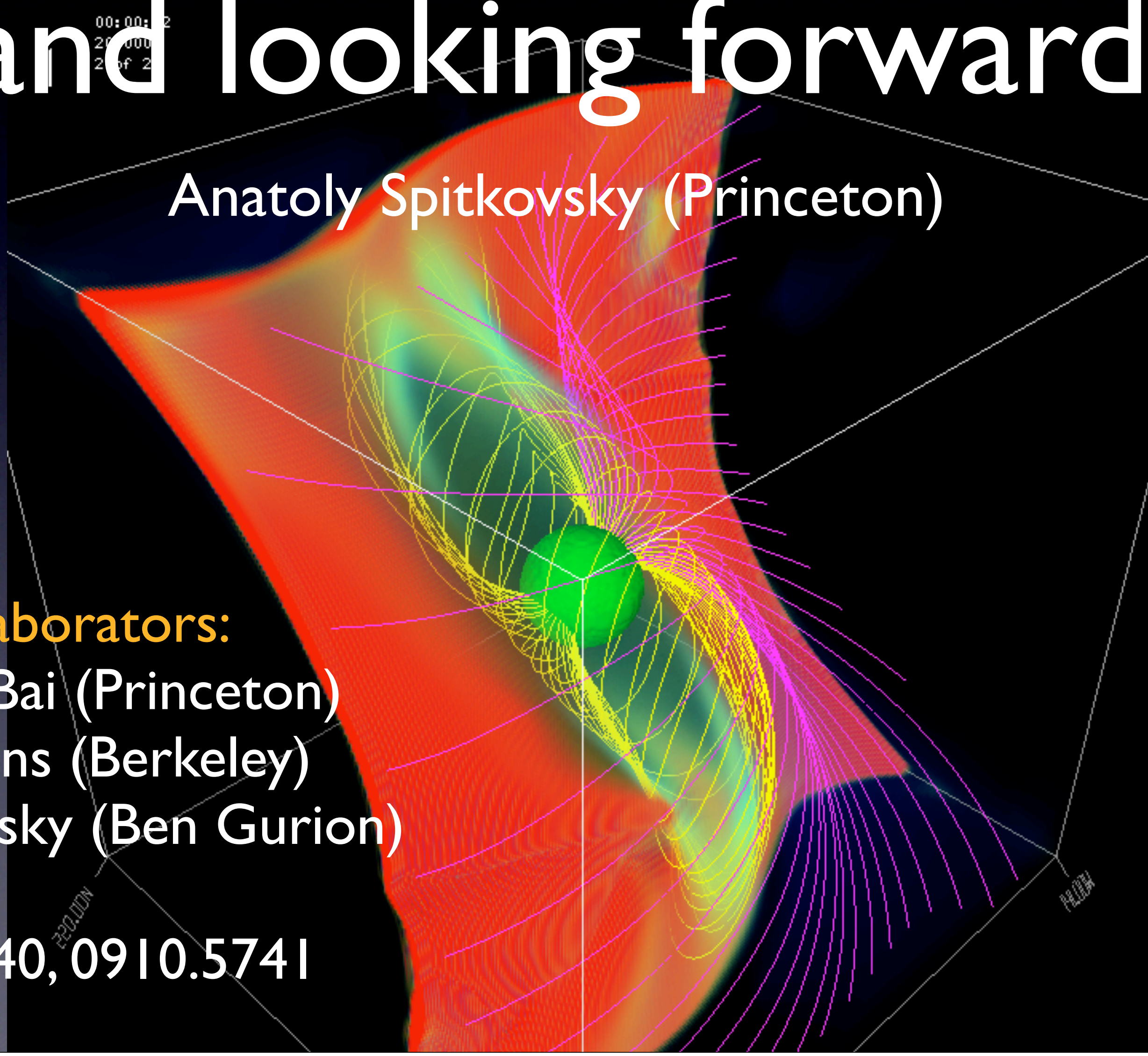
Pulsars: open questions and looking forward

Anatoly Spitkovsky (Princeton)



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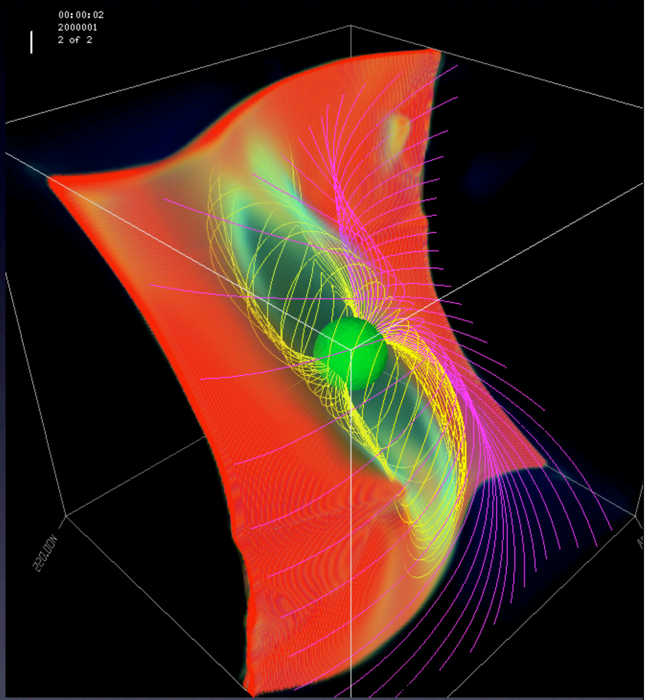
Yury Lyubarsky (Ben Gurion)

0910.5740, 0910.5741

Outline

- Pulsar basics: spin down and plasma creation
- Magnetic geometry: vacuum v. force-free
- Emission modeling: gaps/sheets
- Spectral inferences
- Future directions



Pulsars in Fermi era

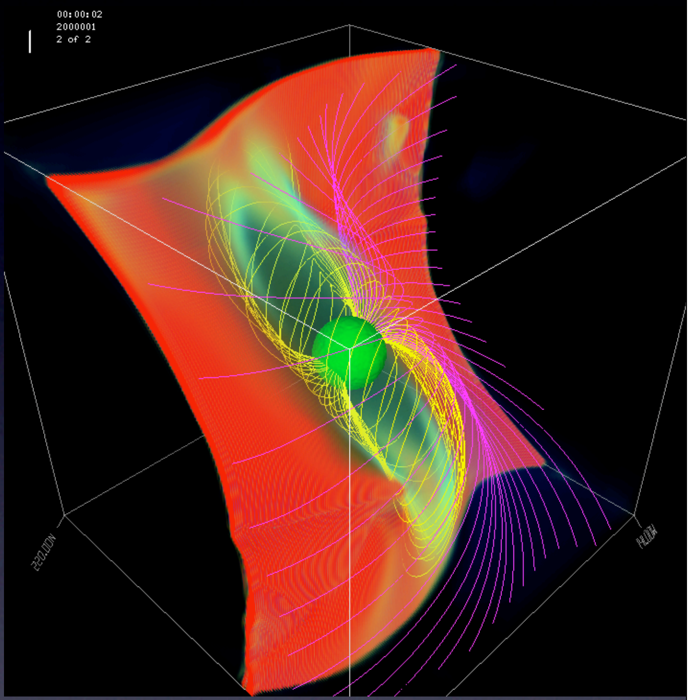
Why pulsars are interesting?

- Unique laboratory for strong B fields and relativistic plasmas

- Prototypes of other astrophysical objects: accretion disks, jets, black hole magnetospheres

- Fascinating electromagnetic machines

- Not understood for > 40 yrs



Fermi is probing where most of the energy is.

Properties in gamma-rays

Double peaks with phase separation 0.2-0.5

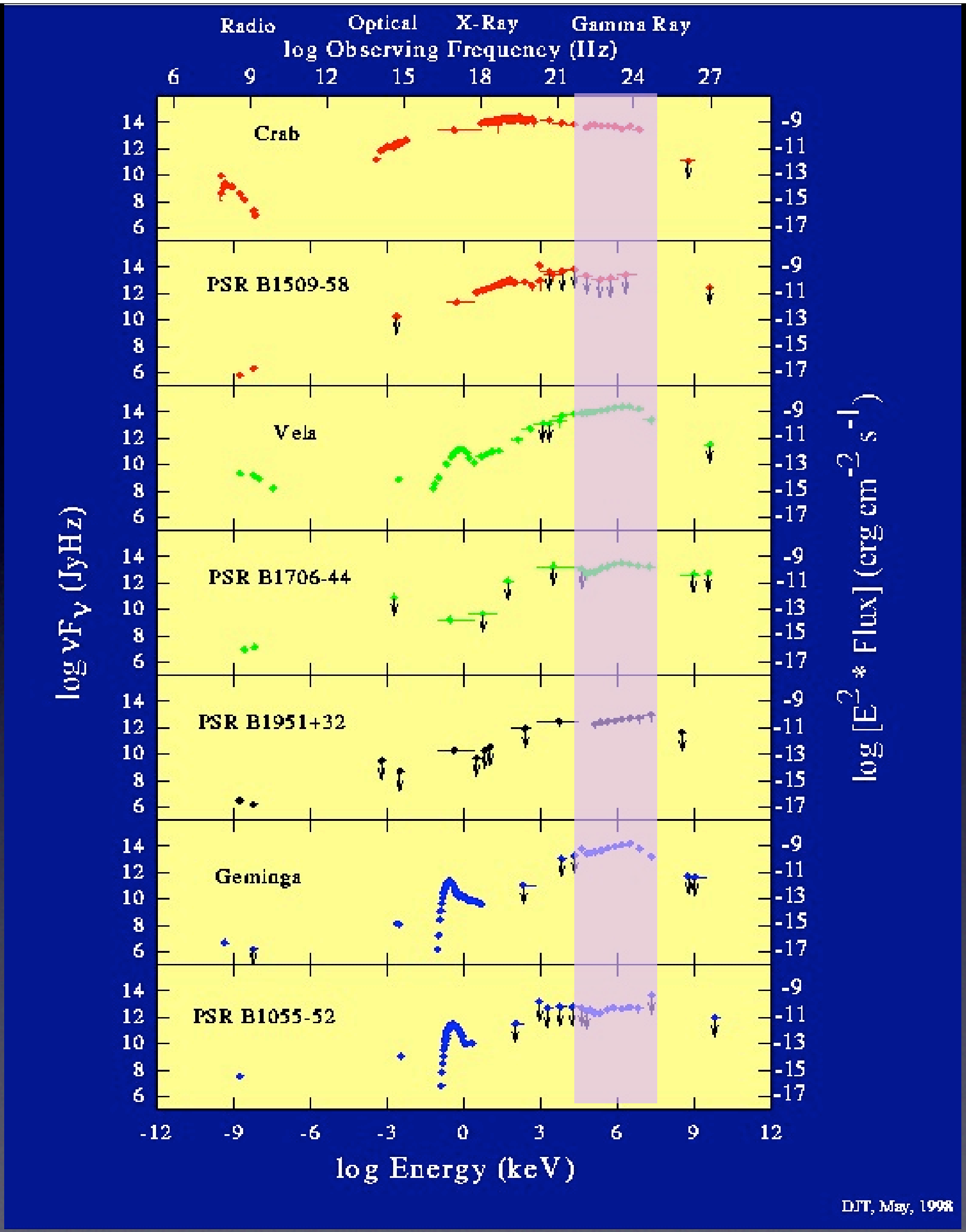
Offset from the radio

γ-ray beams larger than radio

Spectra are power-laws with exponential cutoffs

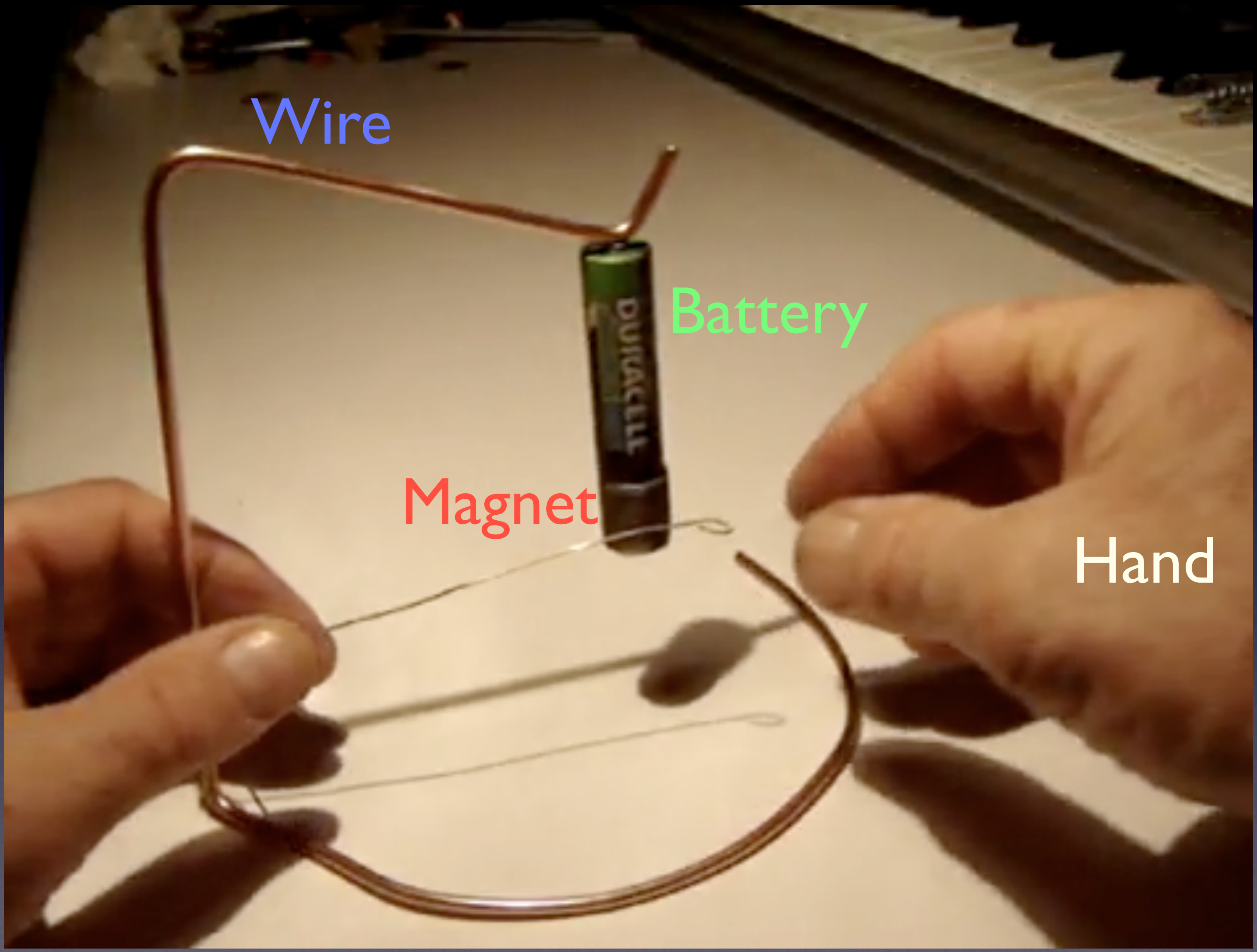
Large B at LC

Large fraction of spin-down in γ-rays



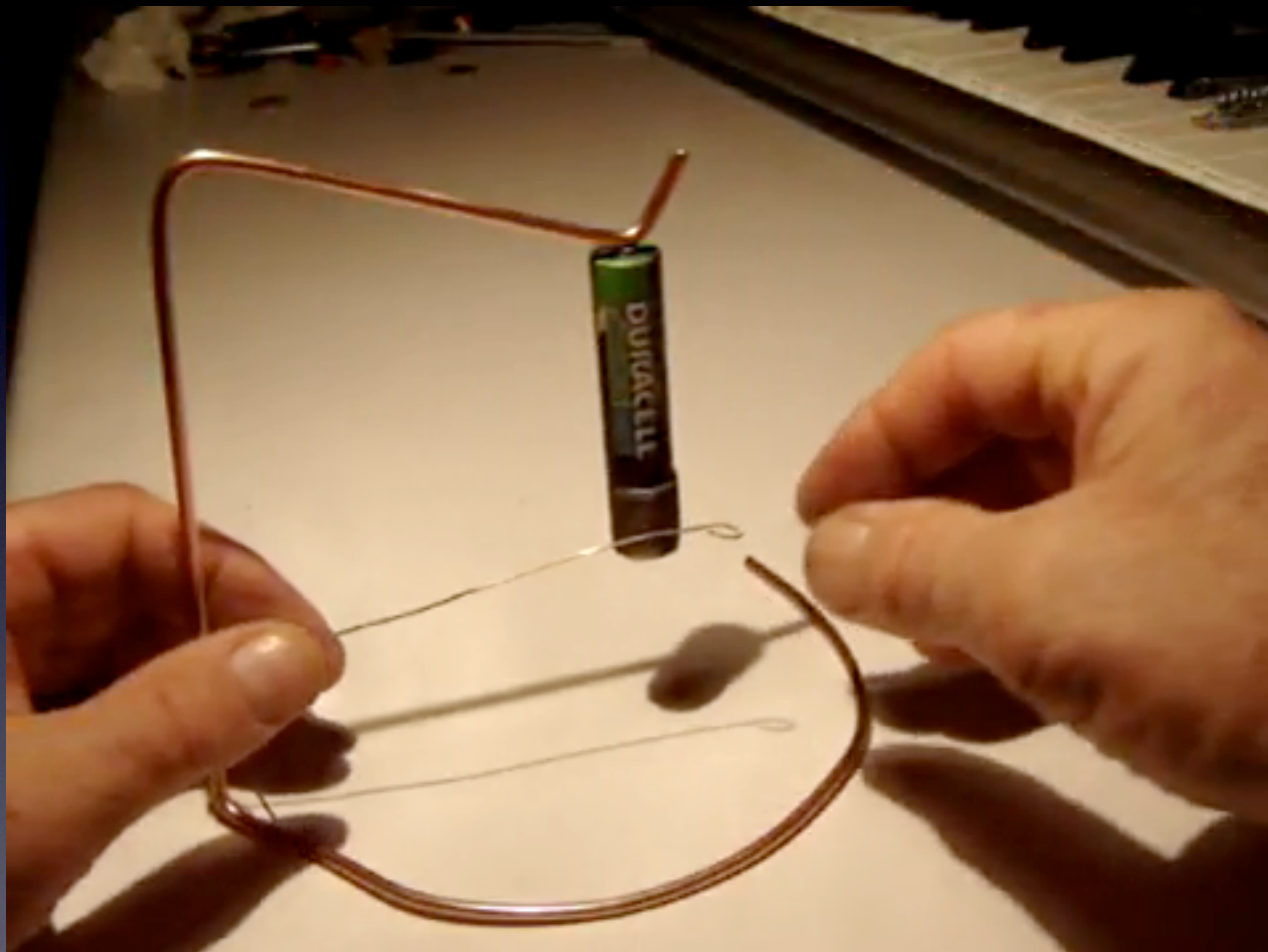
Fermi is probing where most of the energy is

Pulsar physics @ home



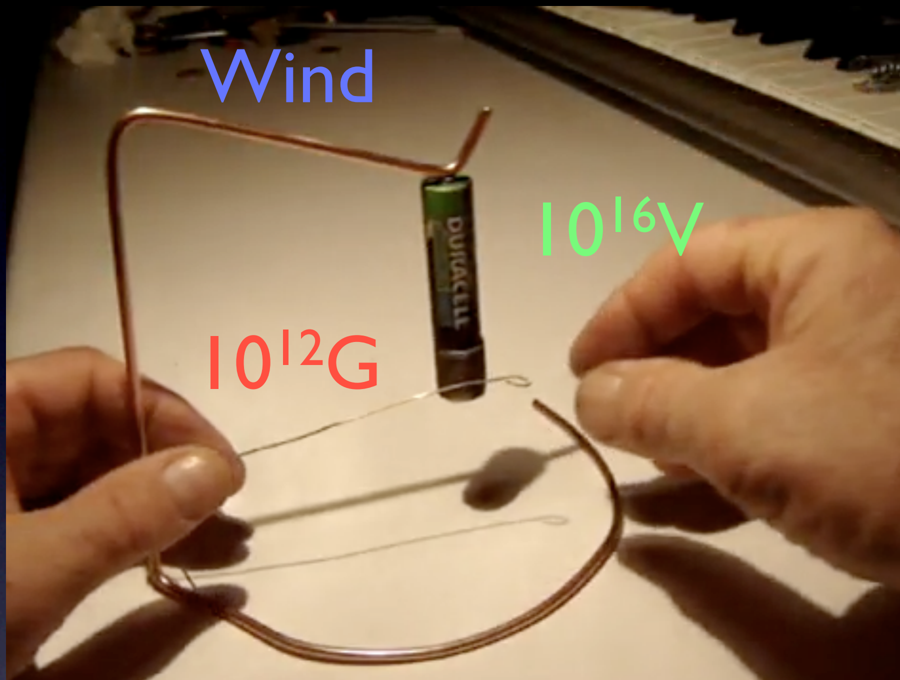
Unipolar induction

Pulsar physics @ home

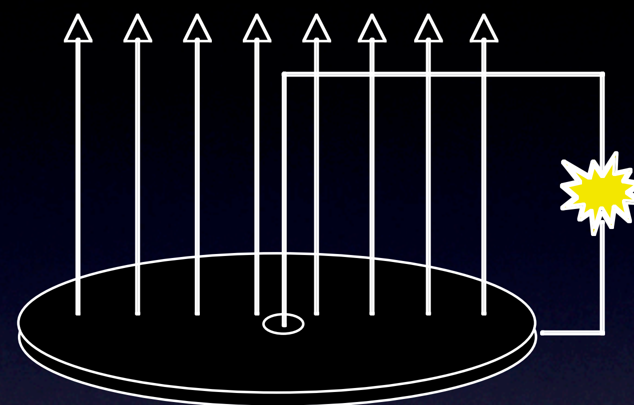


Simple?

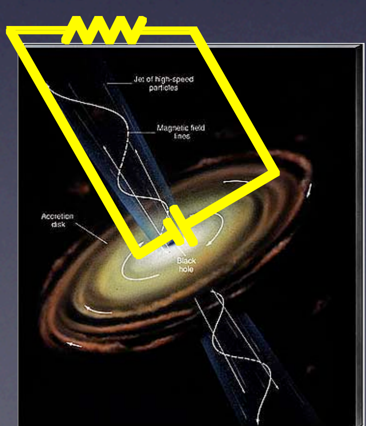
Pulsar physics in space



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



Faraday disk



from R. Blandford

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

Crab Pulsar

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

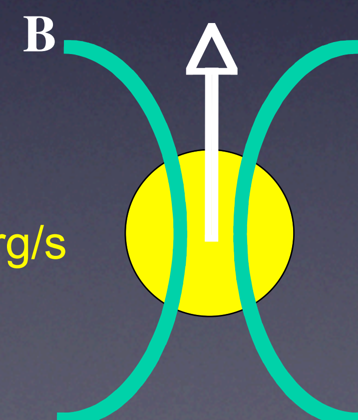
Voltage ~ 3 x 10^{16} V; I ~ 3 x 10^{14} A; P ~ 10^{38}erg/s

Magnetar

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

Massive Black Hole in AGN

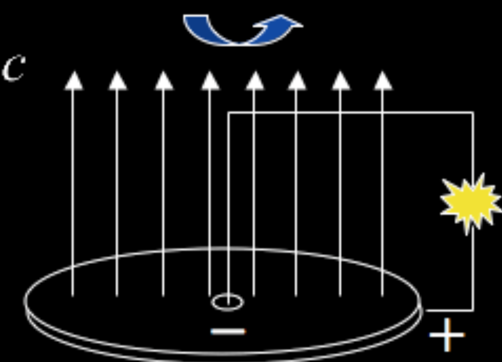
B ~ 10^{4} G; P ~ 10^{46} erg/s



Plasma source

Where does the plasma come from?

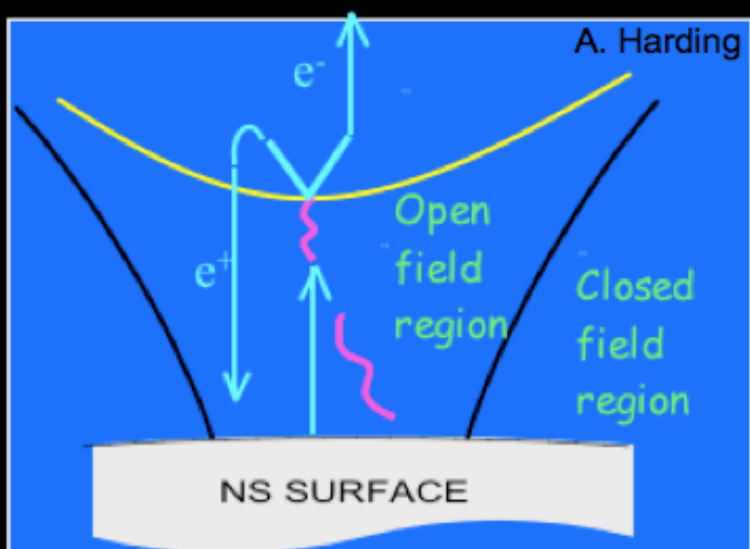
$$\phi_0 = \Omega B a^2 / c$$



Faraday disk: unipolar induction

Polar cap is a space-charge limited accelerator.
Accelerated primary particles radiate curvature radiation, and pair produce in the strong field.
Pair cascade shorts out E*B.

$\gamma_{\rm primary} \sim 10^7 \quad \gamma_{\rm secondary} \sim 10^{2-3} \quad \sigma_{\rm LC} \sim 10^4$



Arons & Scharleman 79, Muslimov & Harding 03

$$\vec{E} = -\frac{\vec{v}}{c} \times \vec{B} = -\frac{\vec{\Omega}}{c} \times \vec{R} \times \vec{B}$$

$$\frac{1}{4\pi} \nabla \cdot \vec{E} = \rho_{GJ} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

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

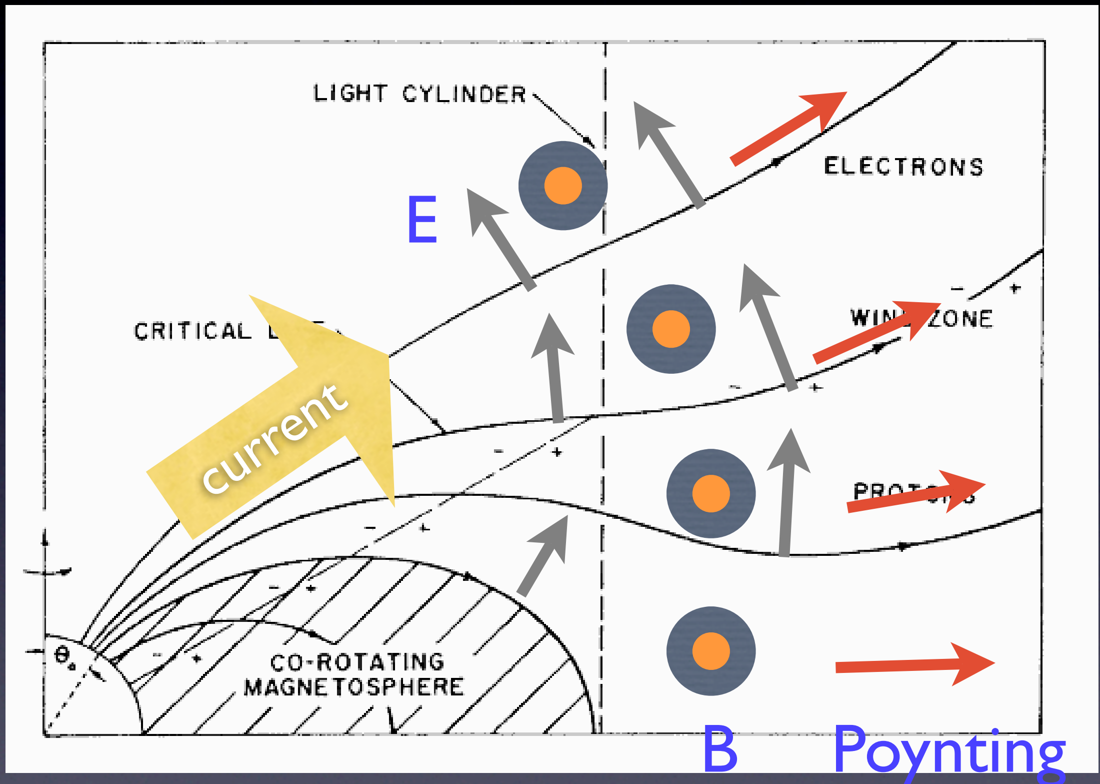
Electrostatic accelerator, non-MHD region

After pair formation front -- enough plasma to use MHD.

Pulsars: energy loss

- Corotation electric field
- Sweepback of B field due to poloidal current
- ExB -> Poynting flux

- Electromagnetic energy loss



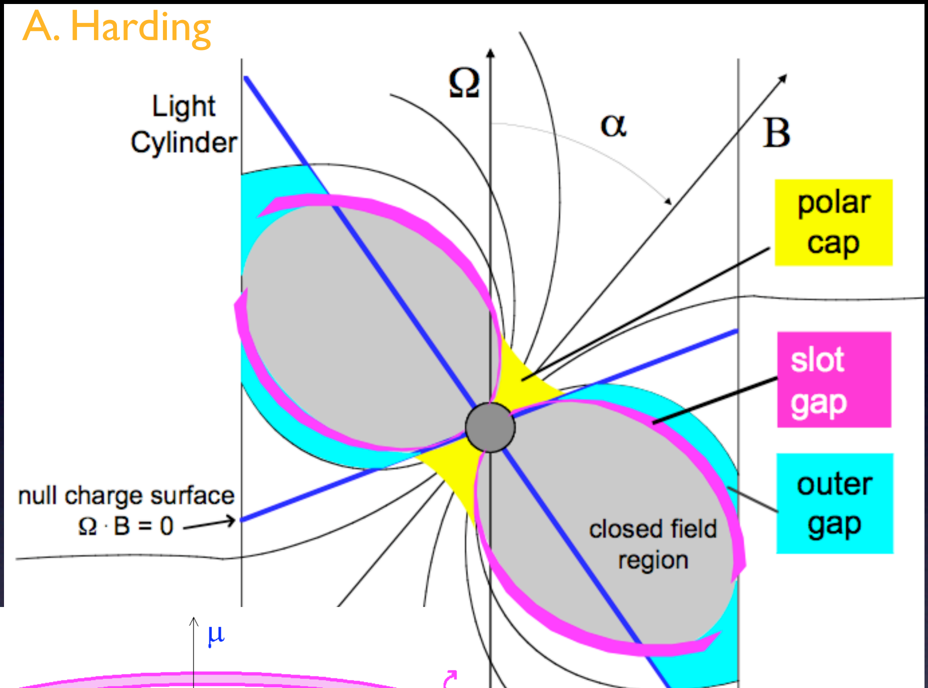
Goldreich & Julian 1969

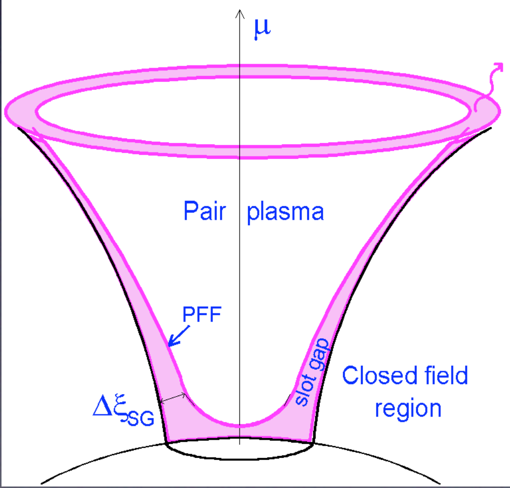
Radiator in Fermi band is tapping into this energy flux

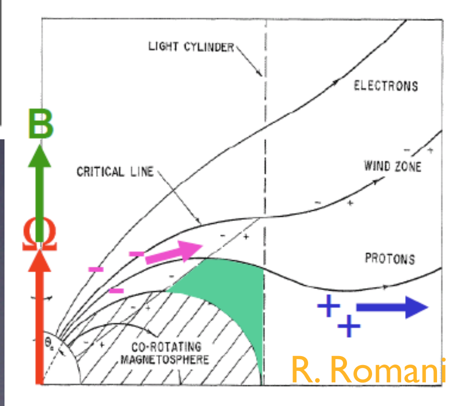
What emits?

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

- Need acceleration of particles
- Depending on how much plasma is in the magnetosphere, postulate emission regions, where E field is not shorted out: gap models
- Trace emission in field geometry, usually assumed to be rotating vacuum dipole
- Remarkably successful in fitting the light curves and spectra







Geometry is crucial to the formation of light curves

Is vacuum geometry ok?

- We can find the field structure in two limits: all vacuum (gap), or all plasma (force-free). Reality is in-between.

- Force-free evolution. Inertia is small:

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

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

Perpendicular current

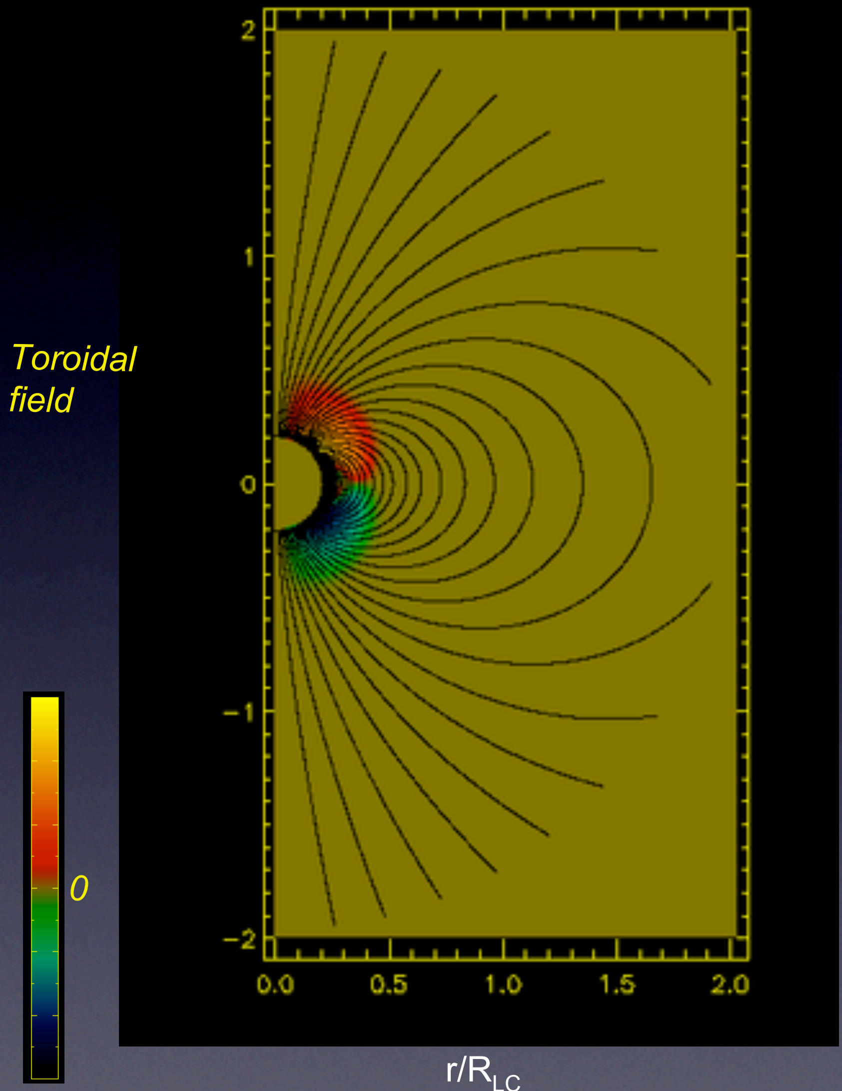
Parallel current

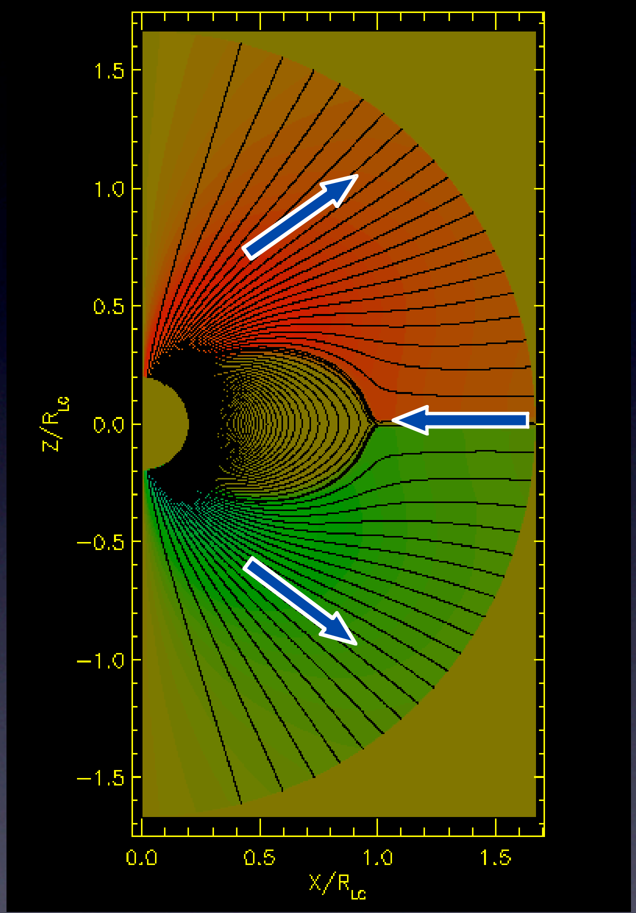
Gruzinov 99, Blandford 01

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

Hyperbolic equations, can be evolved in time

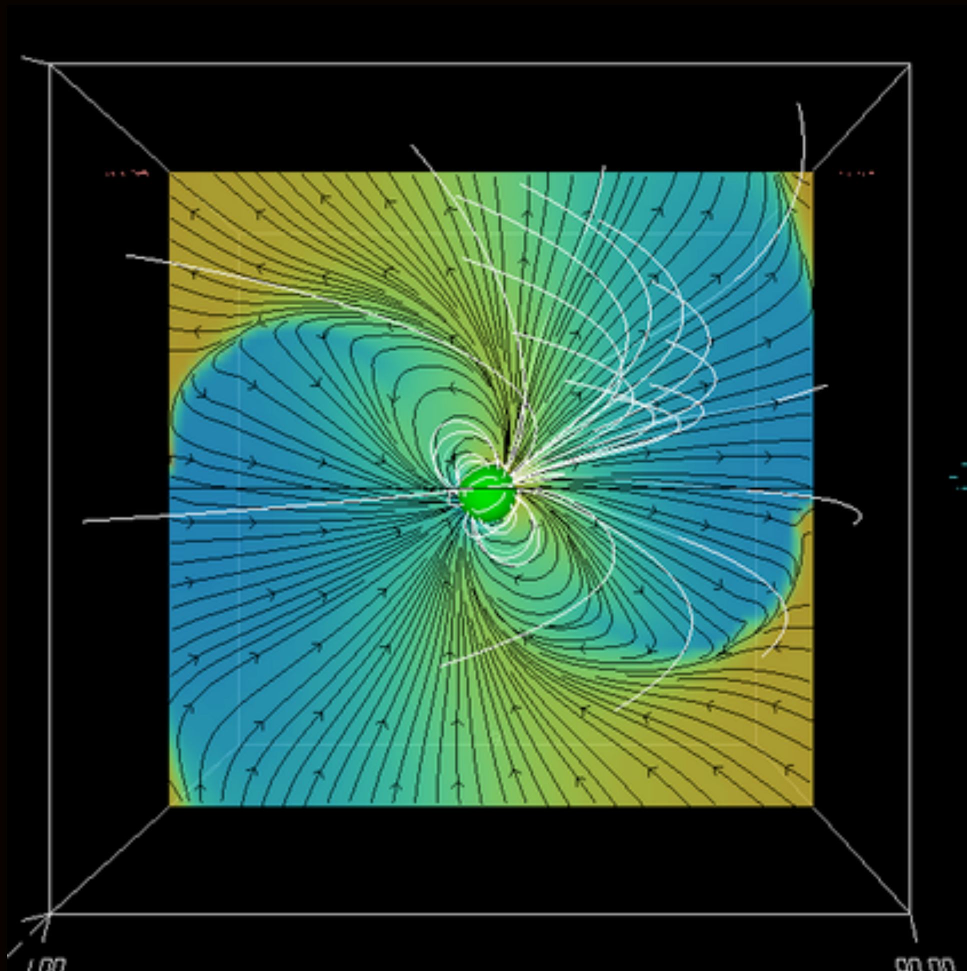
Aligned rotator: plasma magnetosphere



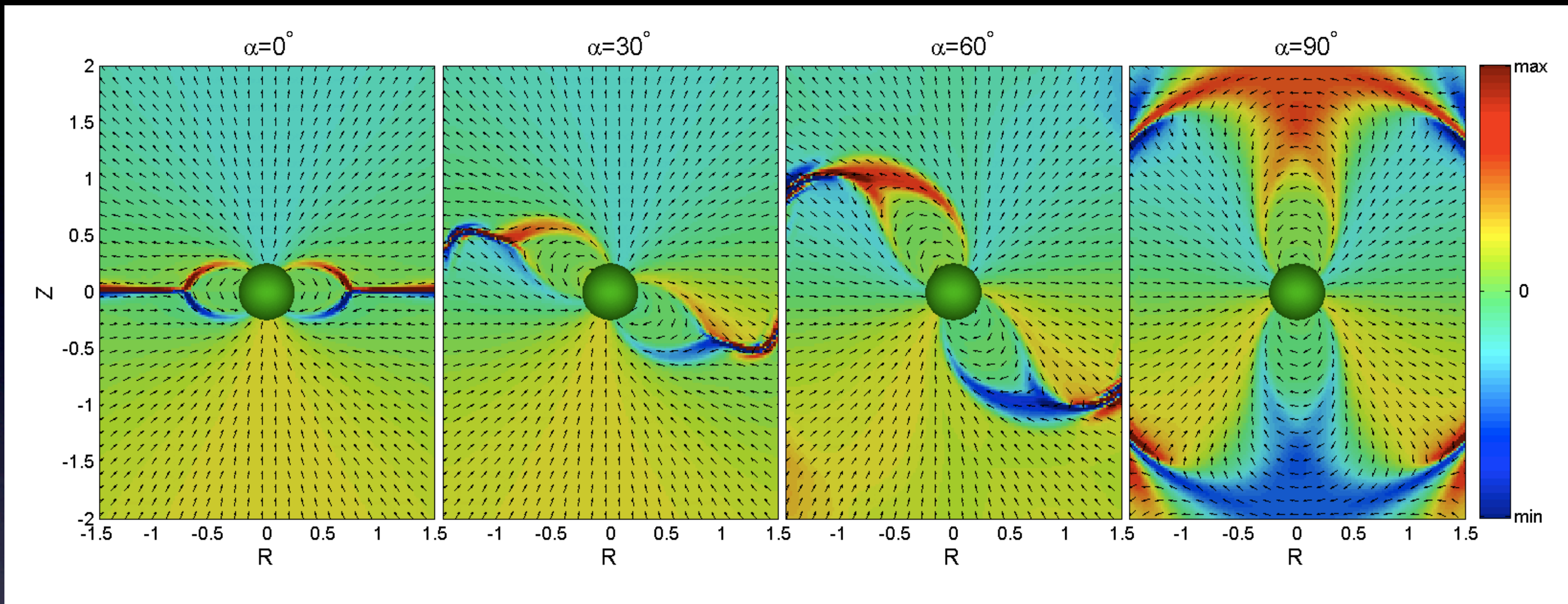


Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting.

Oblique rotator: force-free

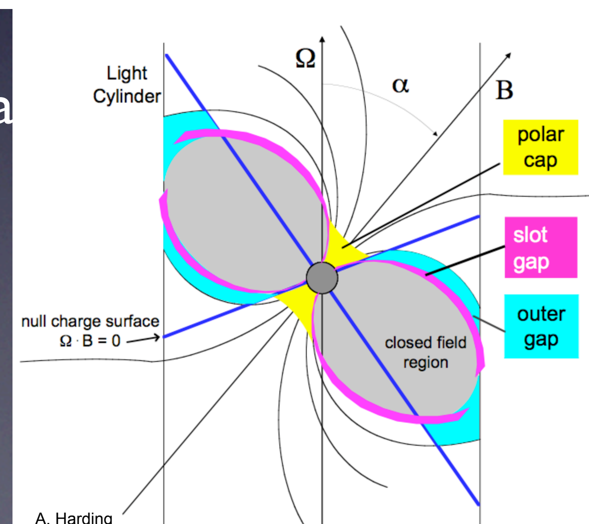


Oblique rotator: force-free



Distribution of current in the ma… i & A. S. arXiv:0910.5041

Force-free field provides a more realistic magnetic geometry



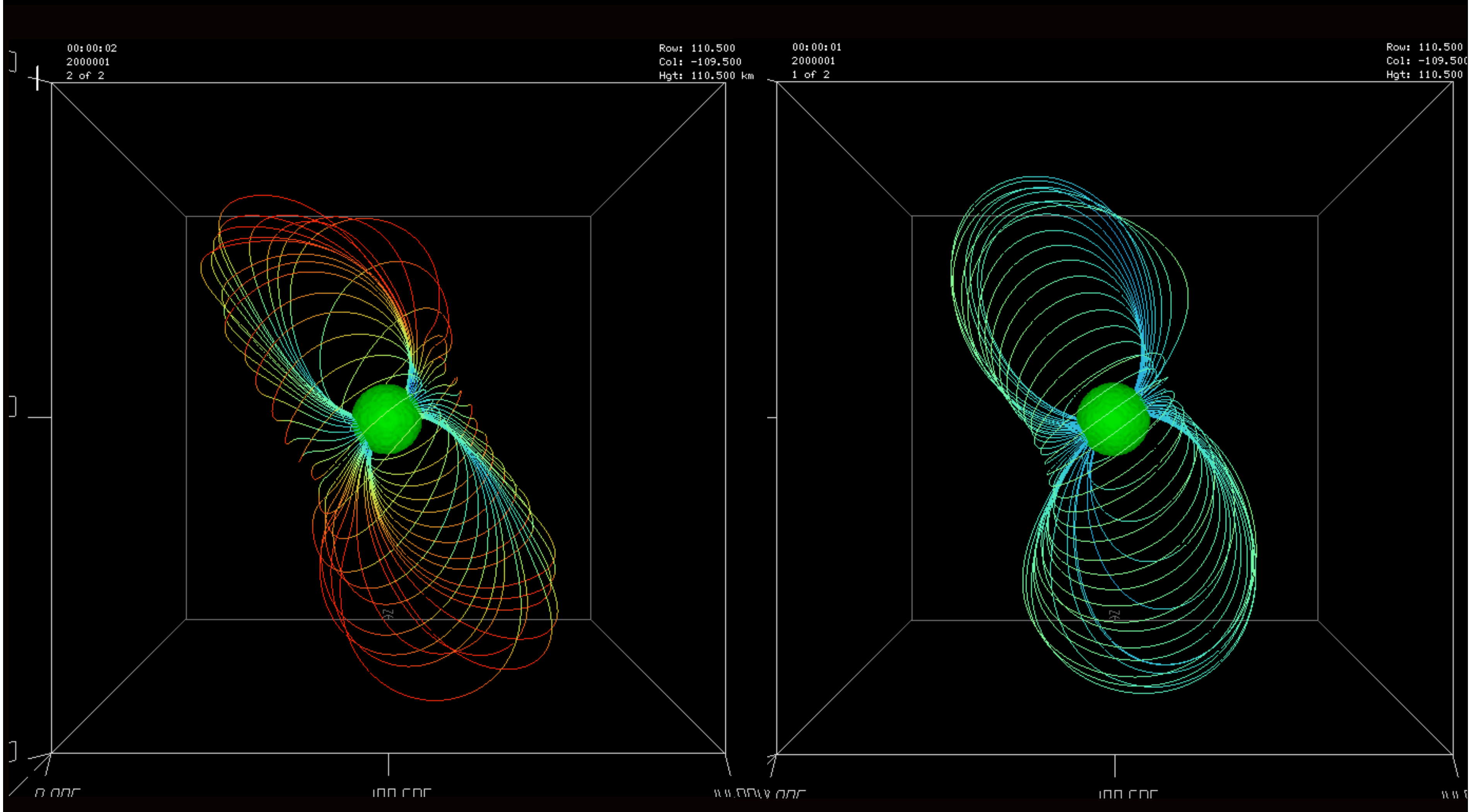
Tempting to associate gaps with currents. Can we?

Light curve calculation

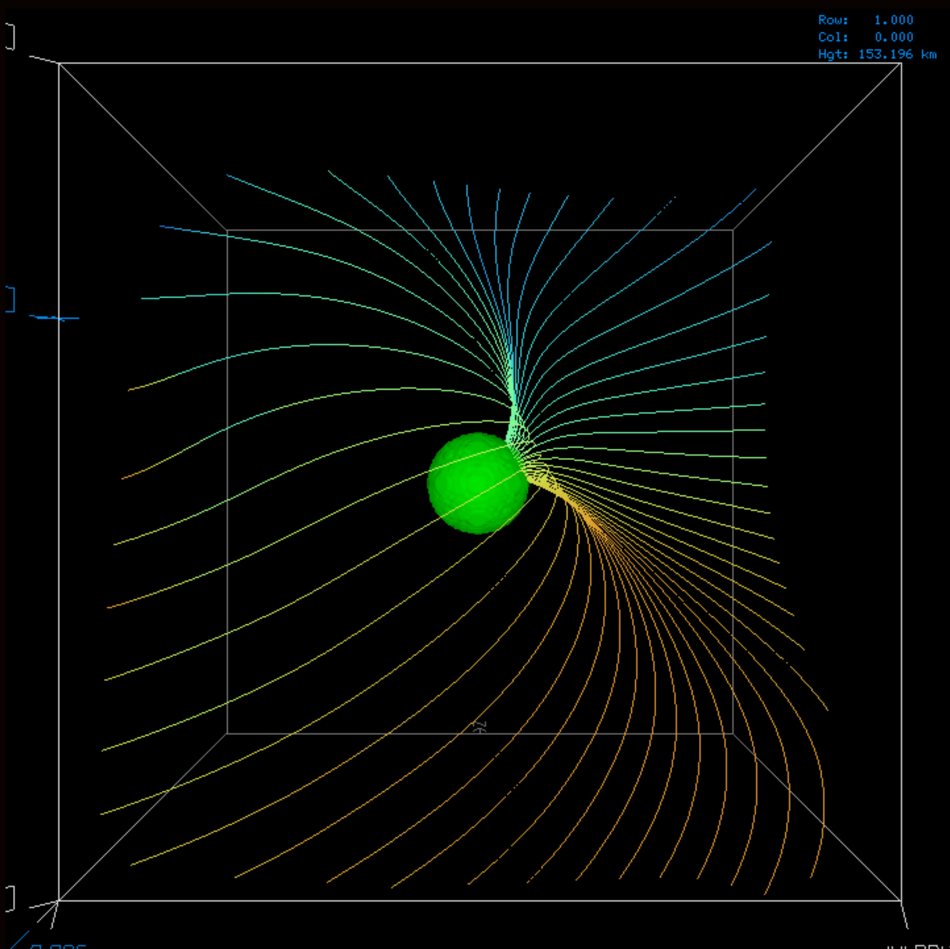
1. Pick field (static dipole, retarded dipole [Deutch], force-free)
2. Find the polar cap (field lines touching LC, or all closed?)
3. Decide which field lines emit
4. Assume uniform emissivity (with cuts in radius)
5. Trace field lines emitting photons along field line
6. Add aberration and time of flight effect
7. Bin photons on the sky -- > sky map + light curves
8. Repeat

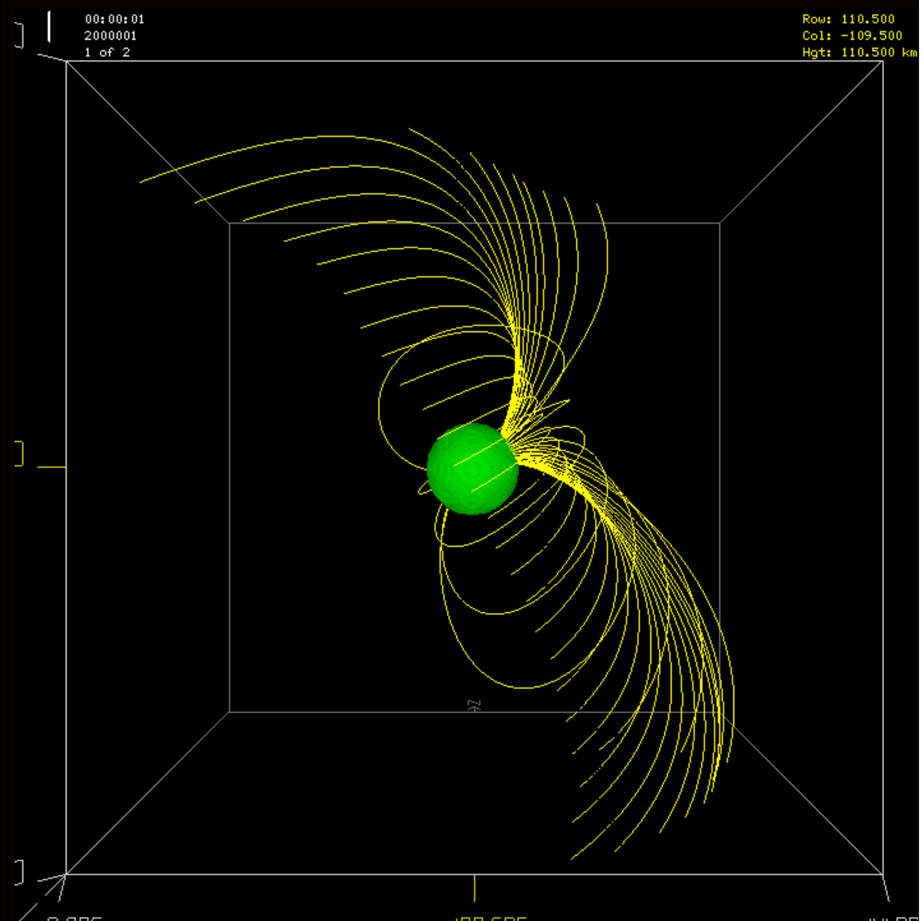
Geometry is crucial to the formation of light curves: affects aberration and definition of polar cap.

Force-free vs Vacuum: Last Closed Lines

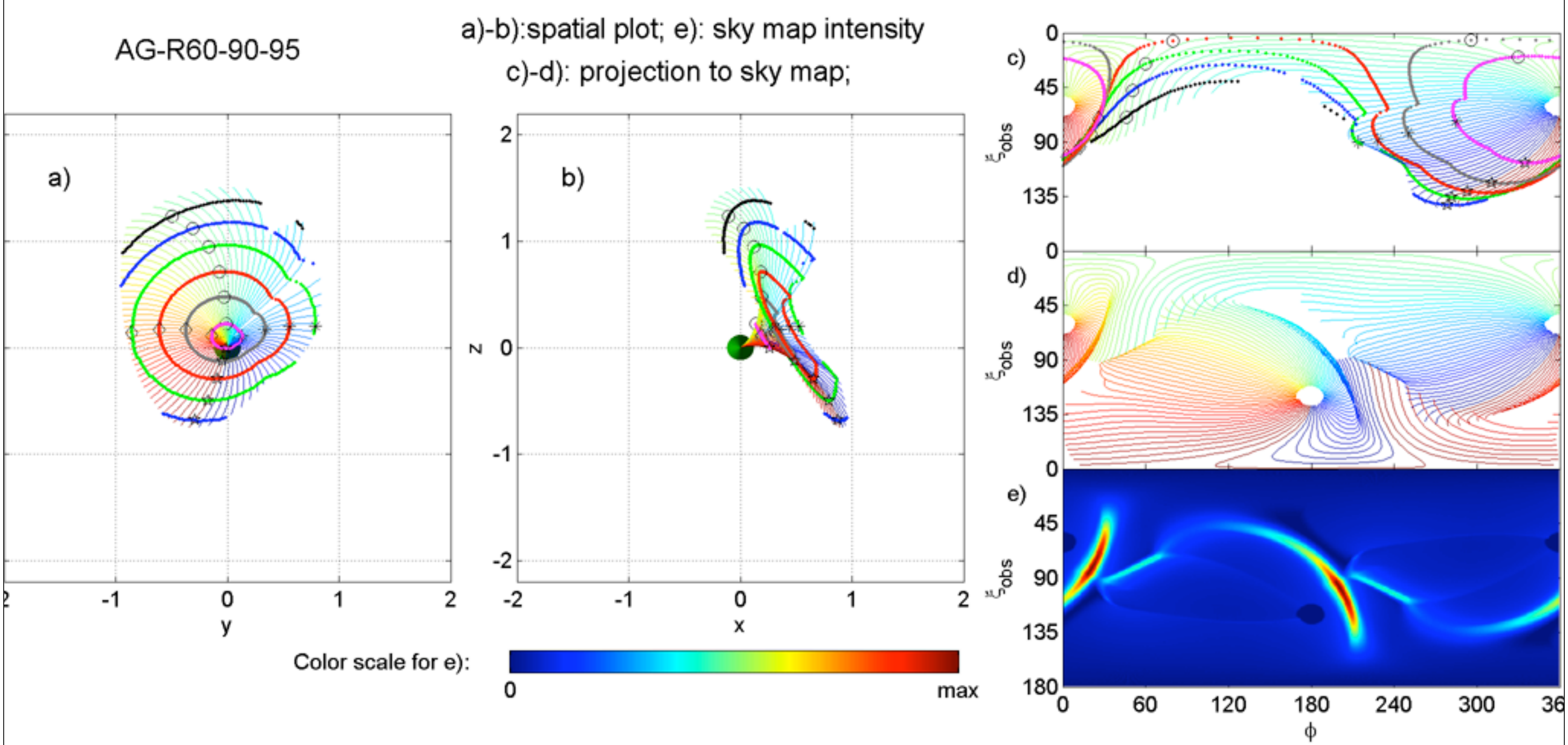


Force-free vs Vacuum: Last Open Lines





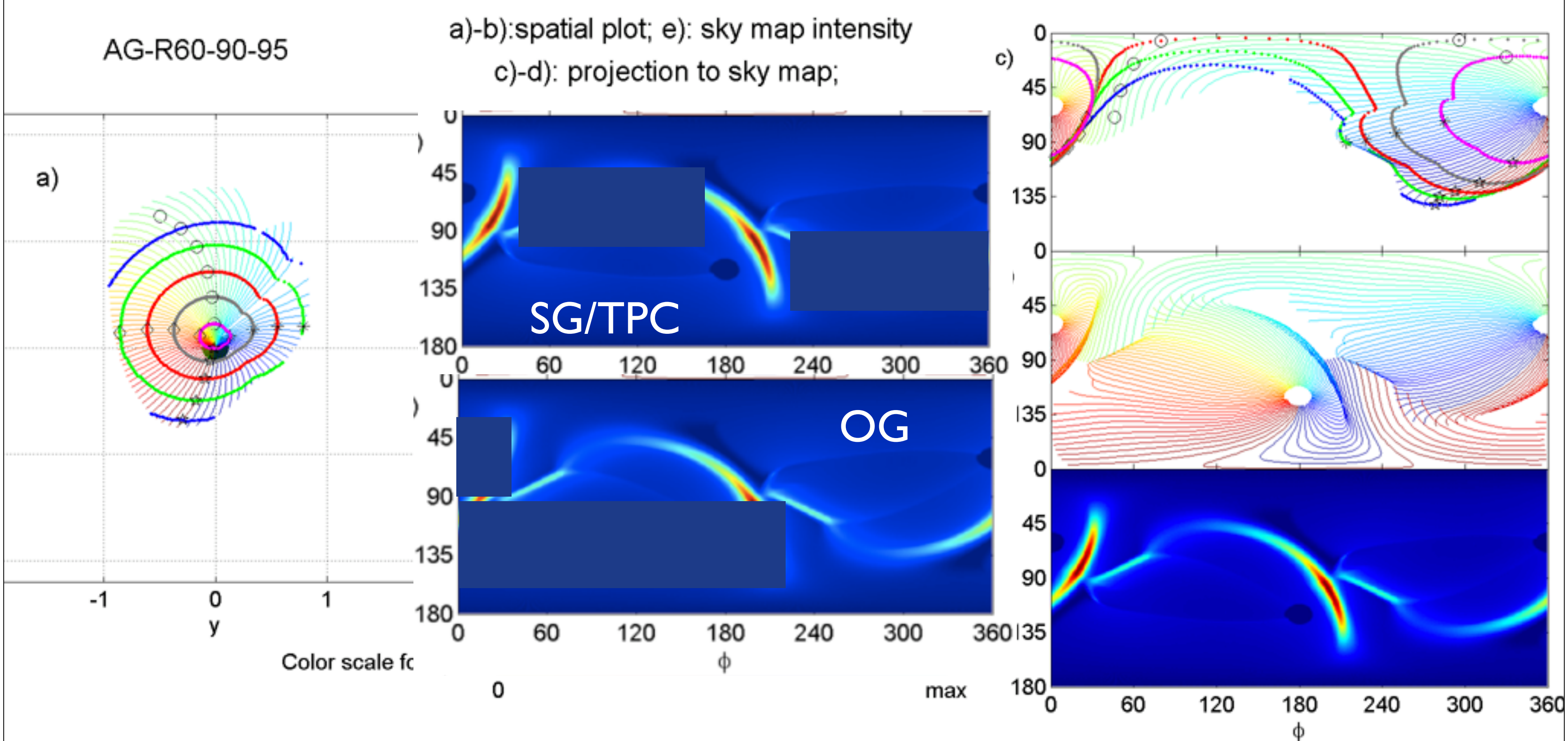
Vacuum sky map



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

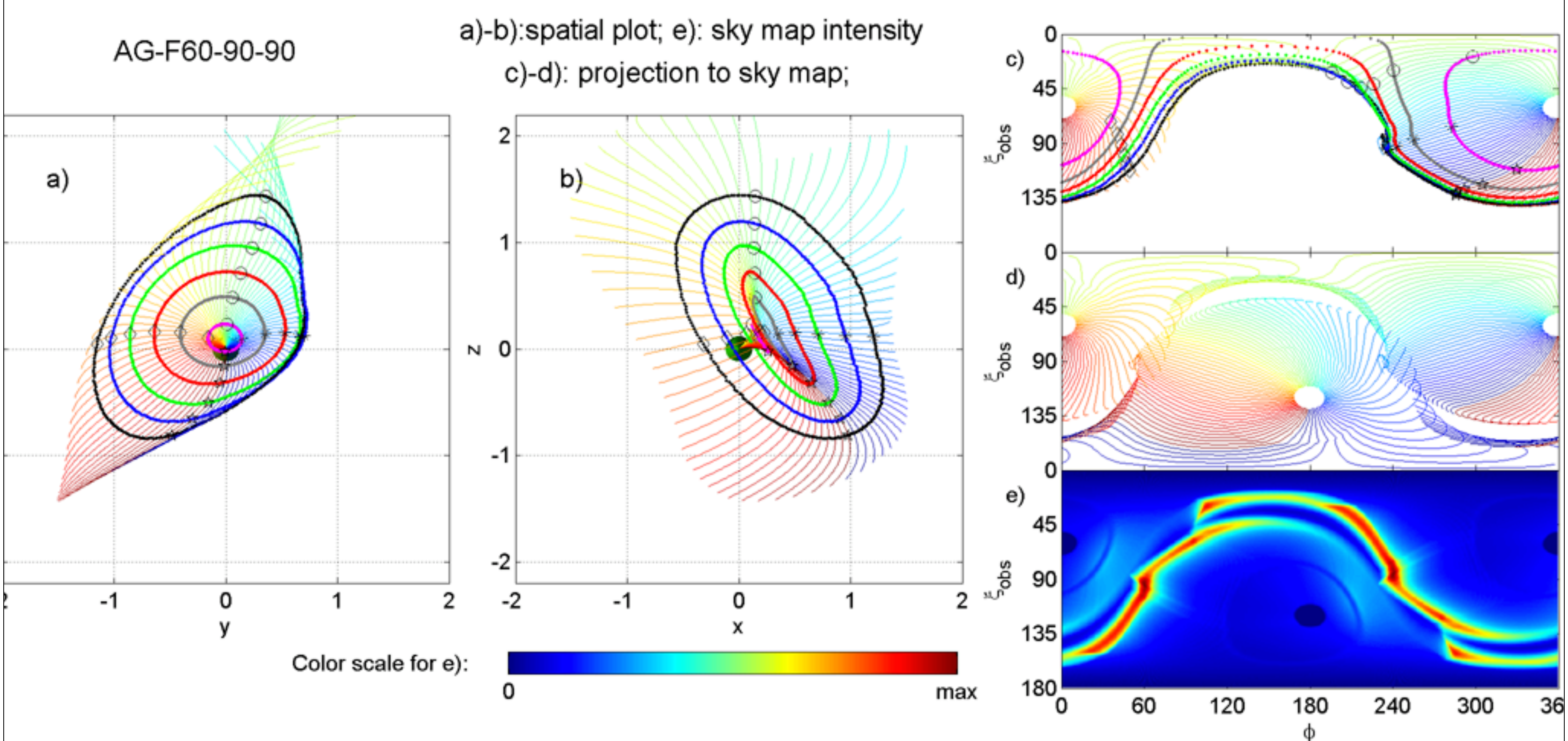
cf. work by Harding et al, Romani et al, Cheng et al.

Vacuum sky map



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

Force-free sky map

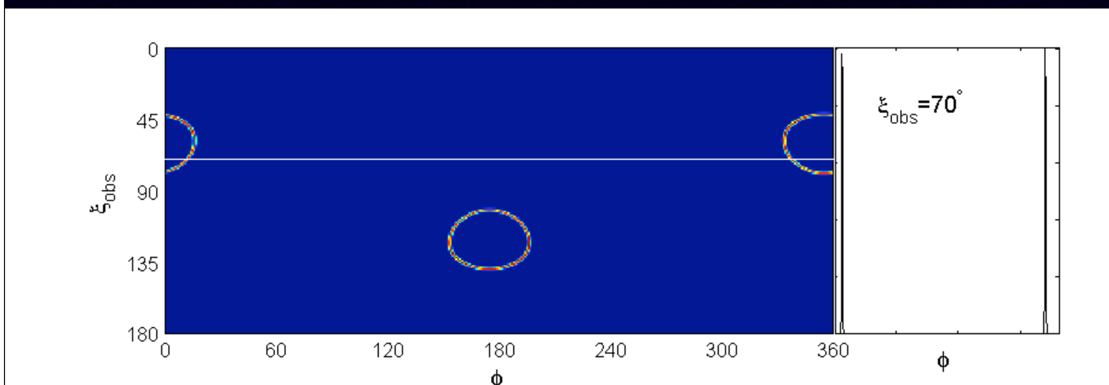


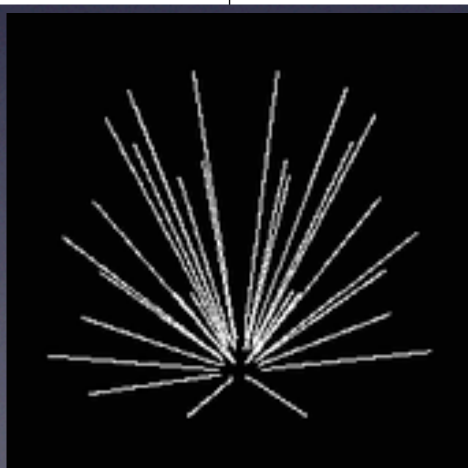
Force-free field, 60 degree inclination, flux tube starting at 0.9 of the polar cap radius.

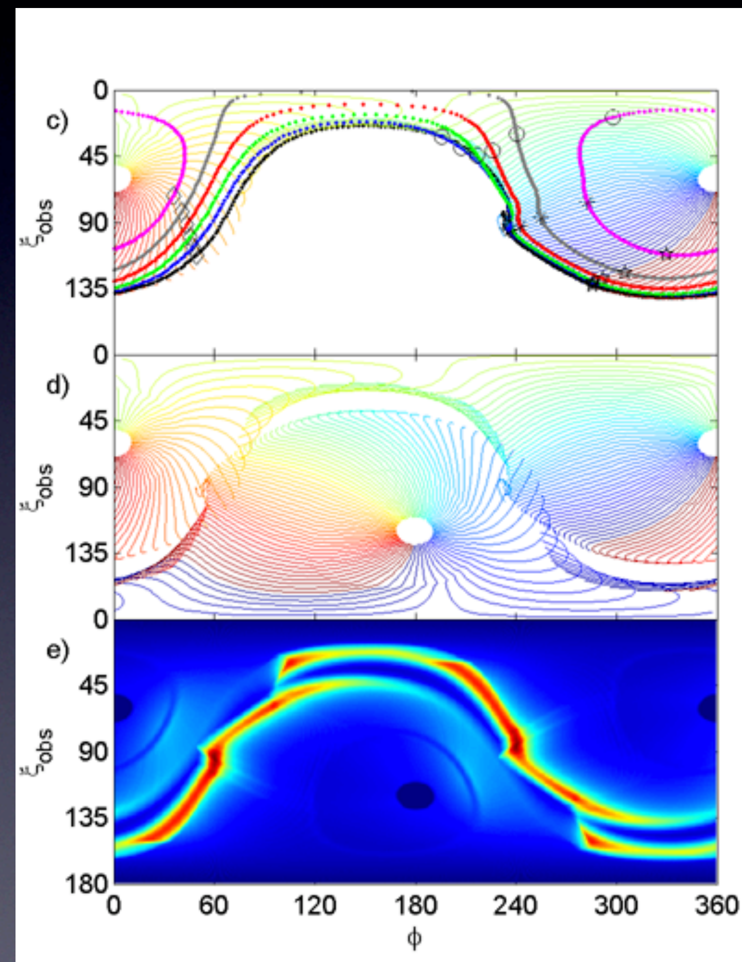
"Sky map stagnation"

“Sky map stagnation”

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



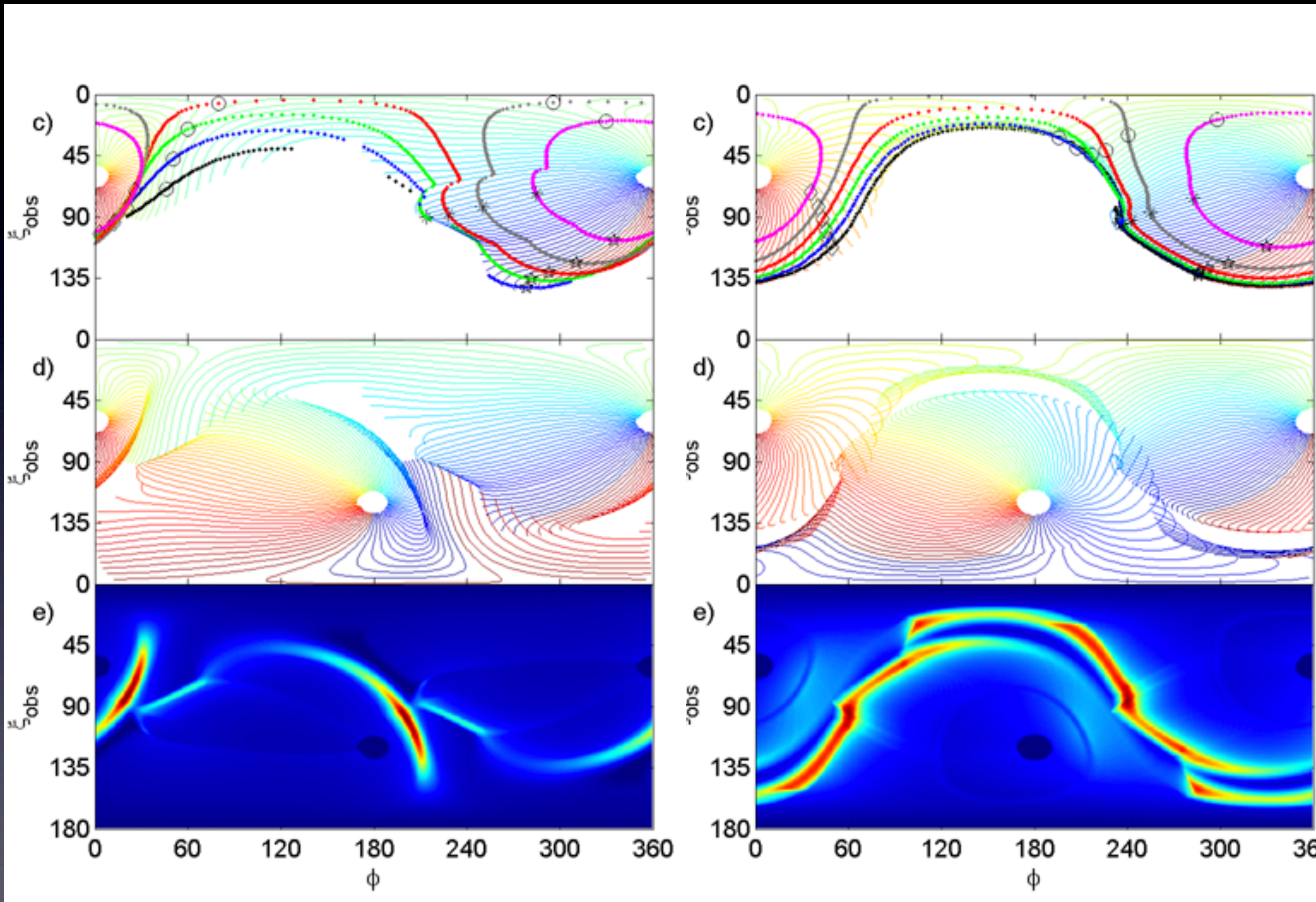




“Sky map stagnation”

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

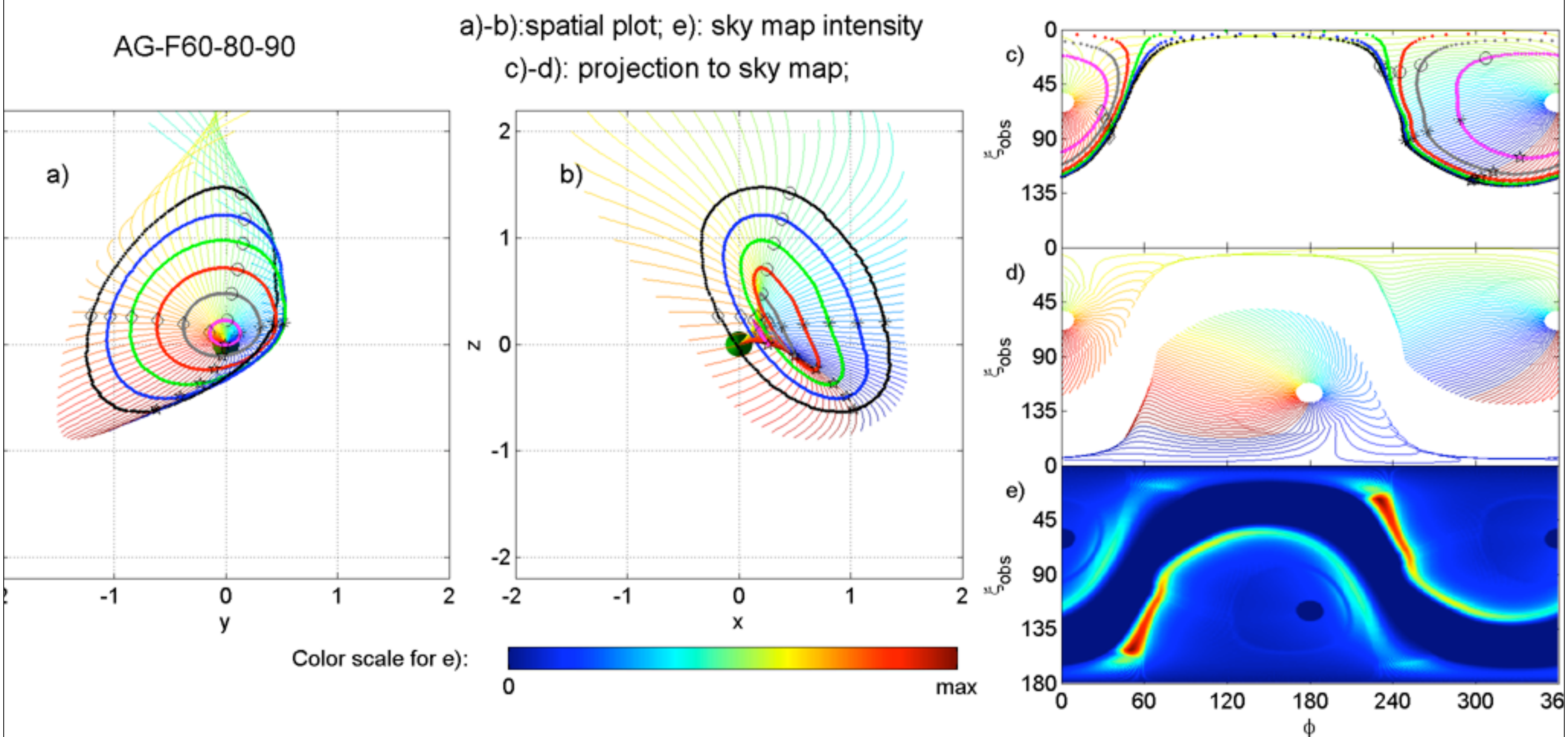
Vacuum vs Force-free



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

Bai & A. S. arXiv:0910.5741

Force-free from different flux tubes

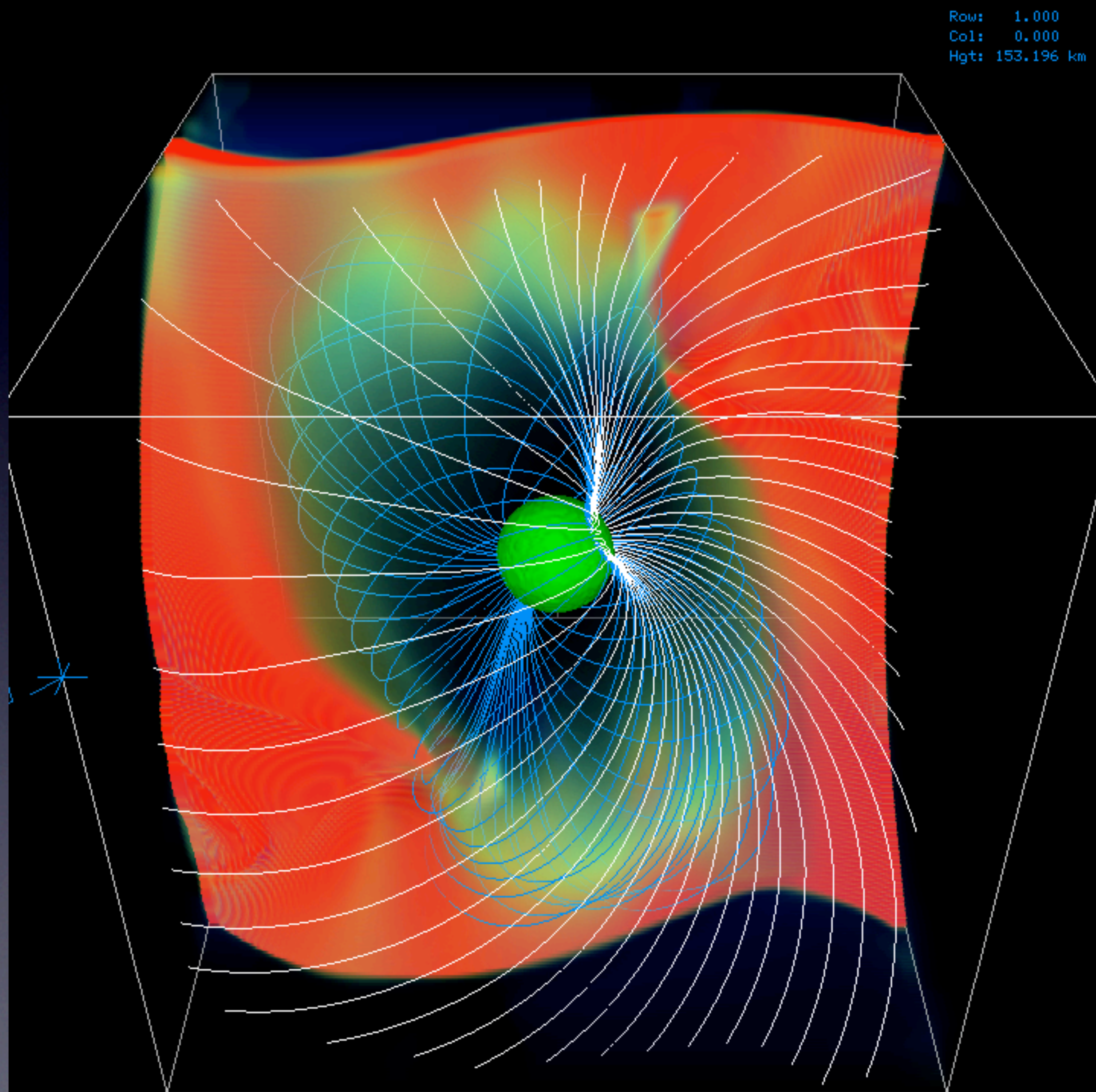


Emissions from two poles merge at some flux tubes: what's special about them?

Bai & A. S. arXiv:0910.5041

Association with the current sheet

Color -> current

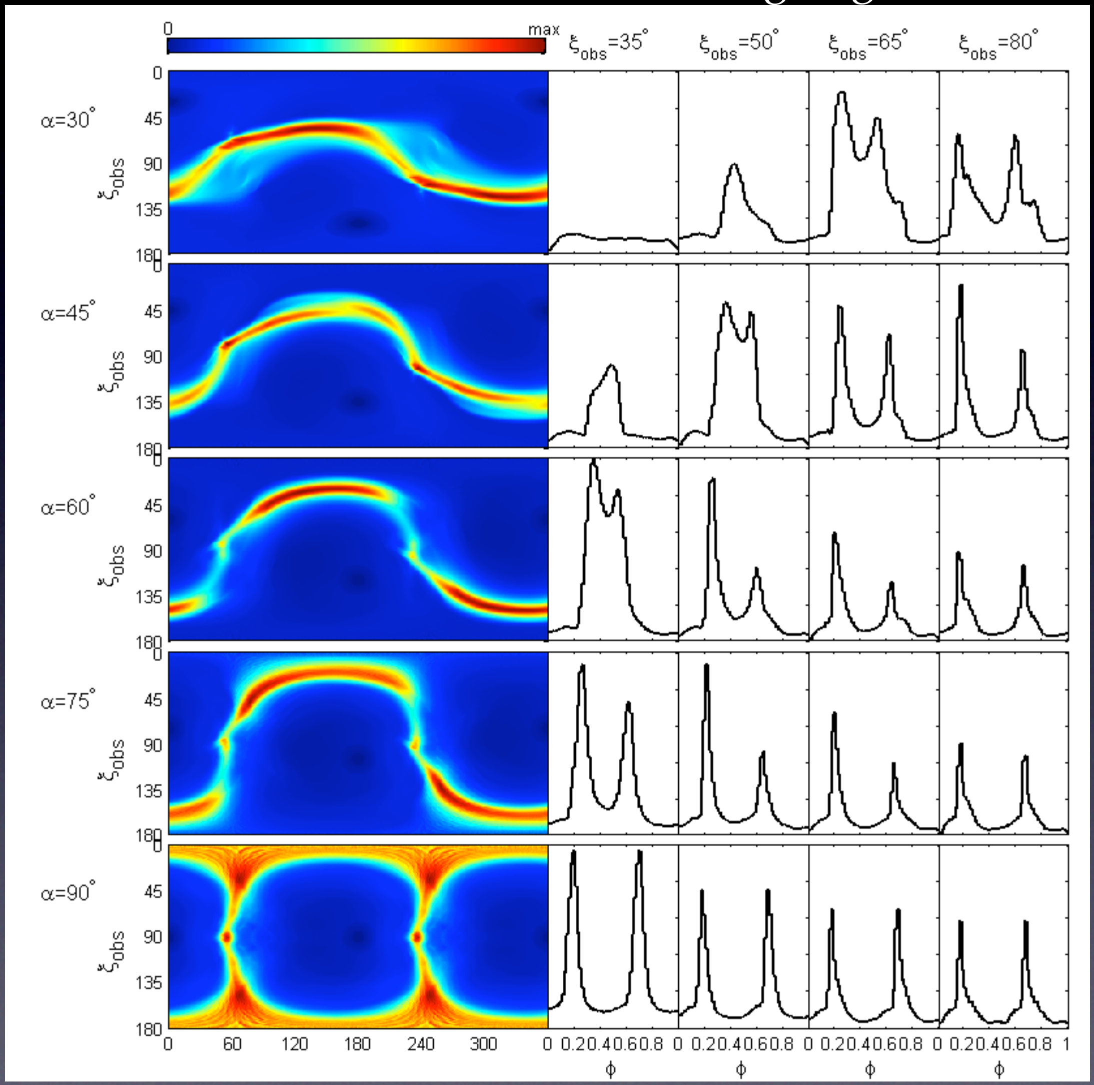


Field lines that produce best force-free caustics seem to “hug” the current sheet at and beyond the LC.

Force-free gallery

Viewing angle

Inclination angle



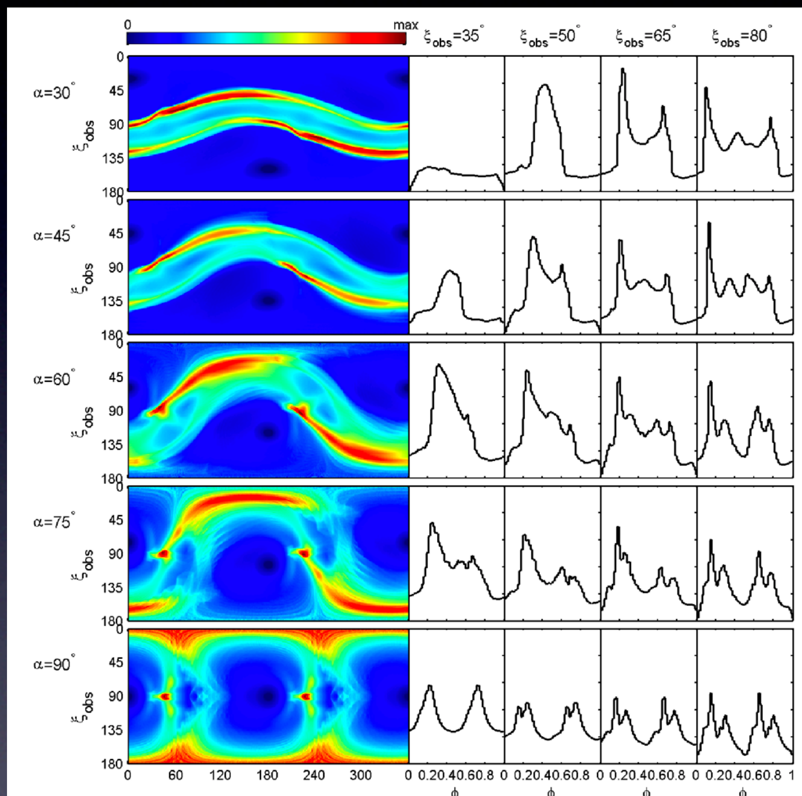
Double peak profiles very common.

Bai & A. S. arXiv:0910.5041

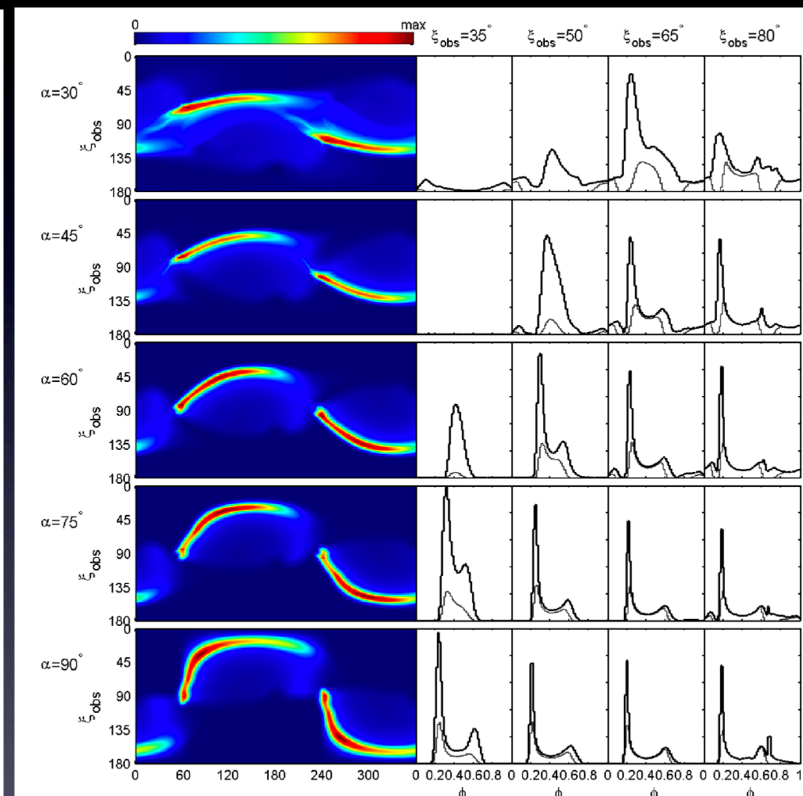
Force-free gallery: TPC and OG

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. arXiv:0910.5041

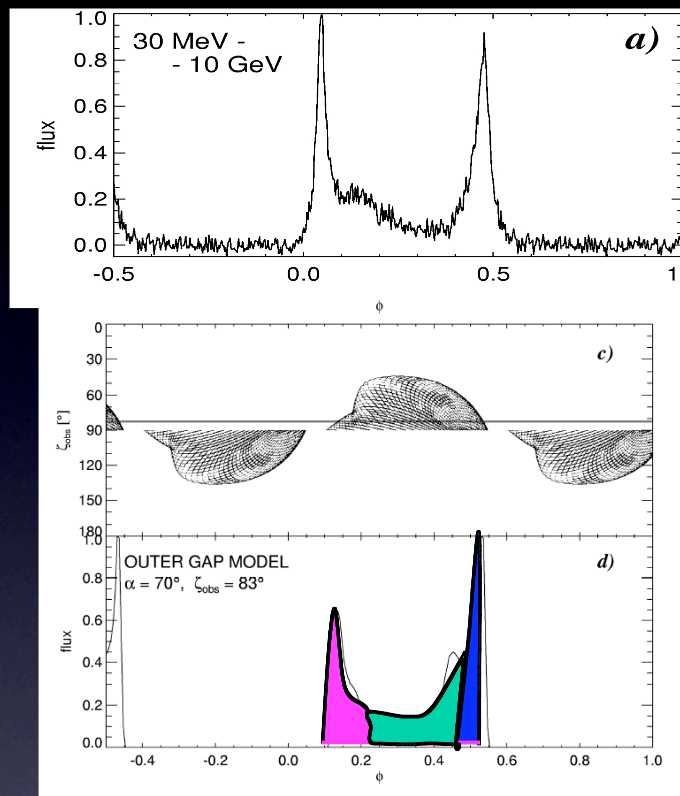
Light curve fitting

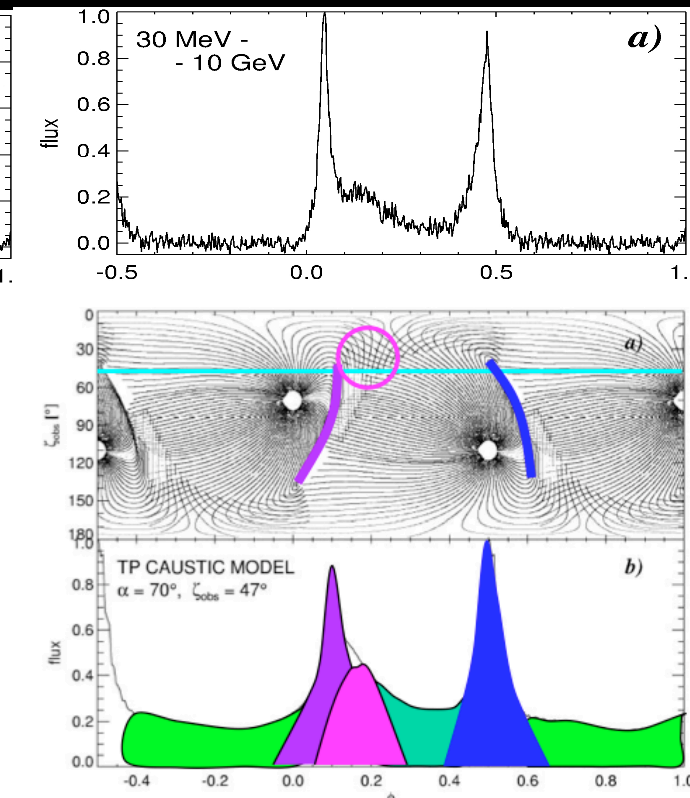
Impressive fits can be achieved with both TPC and OG models based on the vacuum field.

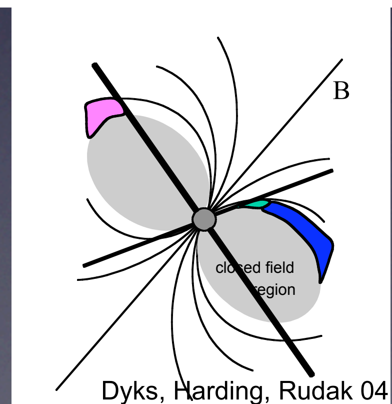
However, similar emission zones for force-free field do not work. We have to use other field lines.

How to discriminate?

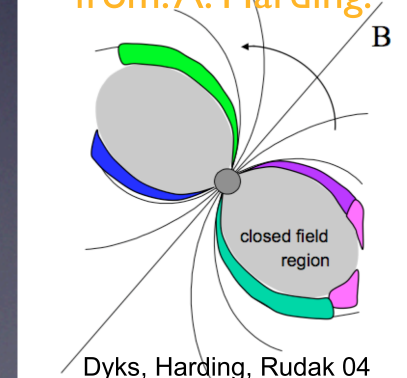
Spectra. Both phase-resolved and averaged.







from: A. Harding.



Spectral fitting

Spectra are power laws with exponential cutoff.
The shape of the cutoff indicates high altitude emission.

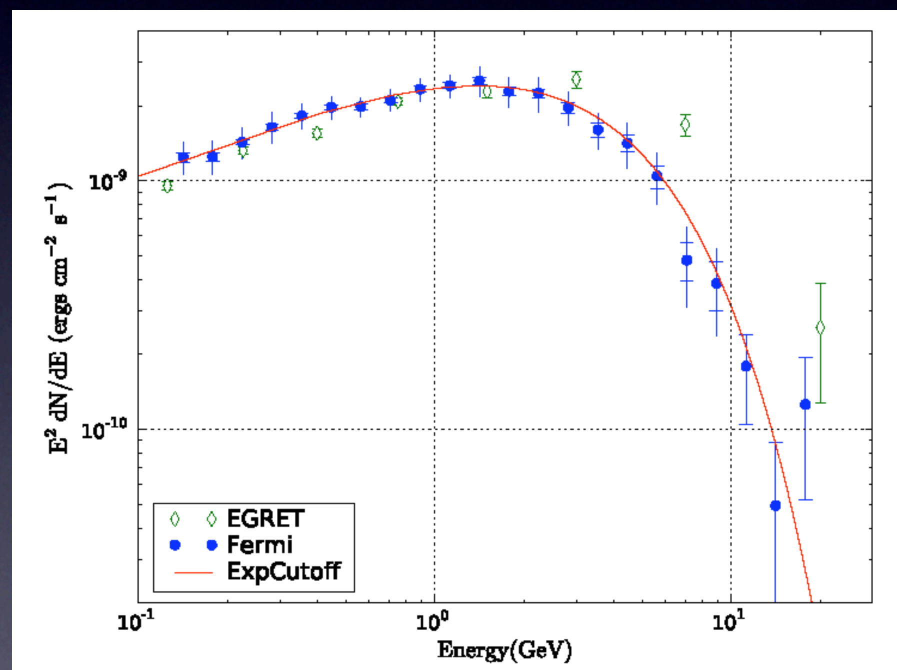
Near surface pair production would attenuate γ-rays with super-exponential cutoff, which is not observed.

$$f(\varepsilon) = A\varepsilon^{-a}\exp(-\tau_{1\gamma})$$

$$\tau_{1\gamma} \approx C(B)\exp\left[-\frac{8}{3\varepsilon B'\sin\theta}\right]$$

Highest energy photons constrain emission to be at > 5Rstar

This is consistent with OG, SG/TPC or FF models.
Contradicts polar cap models



Abdo et al. 2009

Daugherty & Harding 1982
Zhang & Harding 2000
Hibschmann & Arons 2001

Spectral fitting

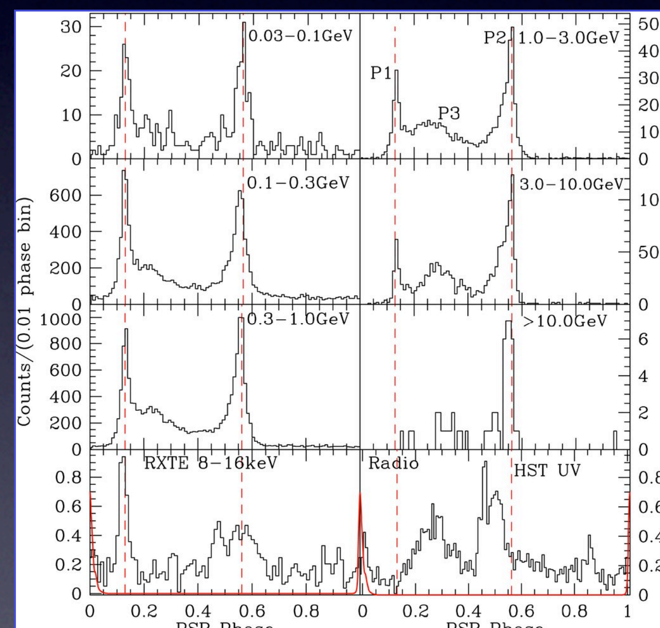
Phase integrated spectra can be fitted rather well now. Phase-resolved spectra could be more challenging.

Variations in cut-off energy indicate changing height of emission. Different models predict particular variation of height with phase.

Radiation reaction-limited curvature radiation cutoff -- depends on height.

Another puzzle: variation of location of peaks with energy.

Other discriminants: statistics of peak separations, offsets from radio, etc. (Watters et al 2009).



Abdo et al. 2009

Conclusions

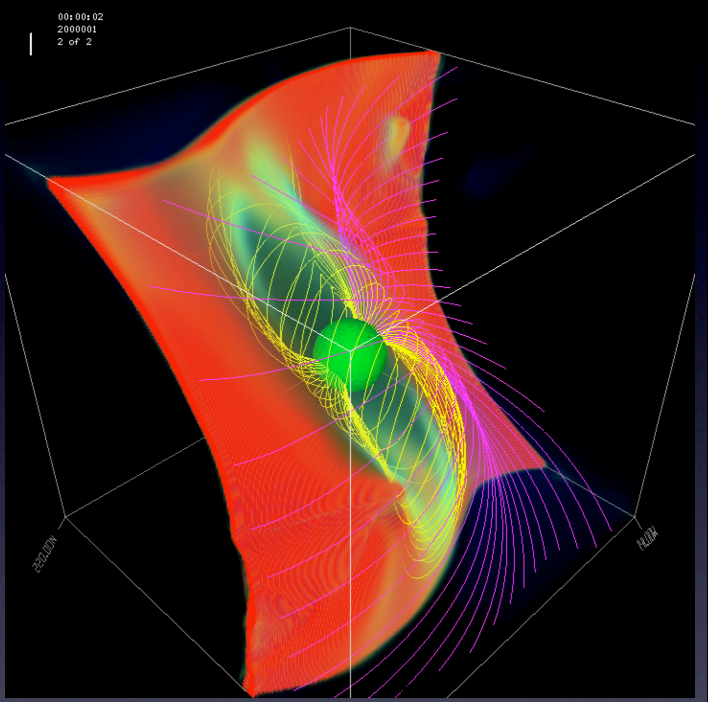
Pulsar emission is coming from the outer magnetosphere.

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