Modeling of Pulsar Magnetospheres and other EMF*

(* ElectroMagnetic Fun)

Anatoly Spitkovsky (Princeton)

(with J. Arons, X. Bai, J. Li, A. Philippov, A. Tchekhovskoy)

Outline

* Pulsar magnetosphere: open questions
* Pulsar models: pros, cons and fails.
* High energy emission models: emerging role of reconnection
* Conclusions and outlook

Pulsars: observationally driven

Pulsar theory:

Open questions:

- What is the structure of pulsar magnetosphere and how do pulsars spin down?
- What are the properties of the wind near pulsar? In the nebula?
- What causes pulsed emission?
- How are observed spectra generated? (how particles are accelerated?)

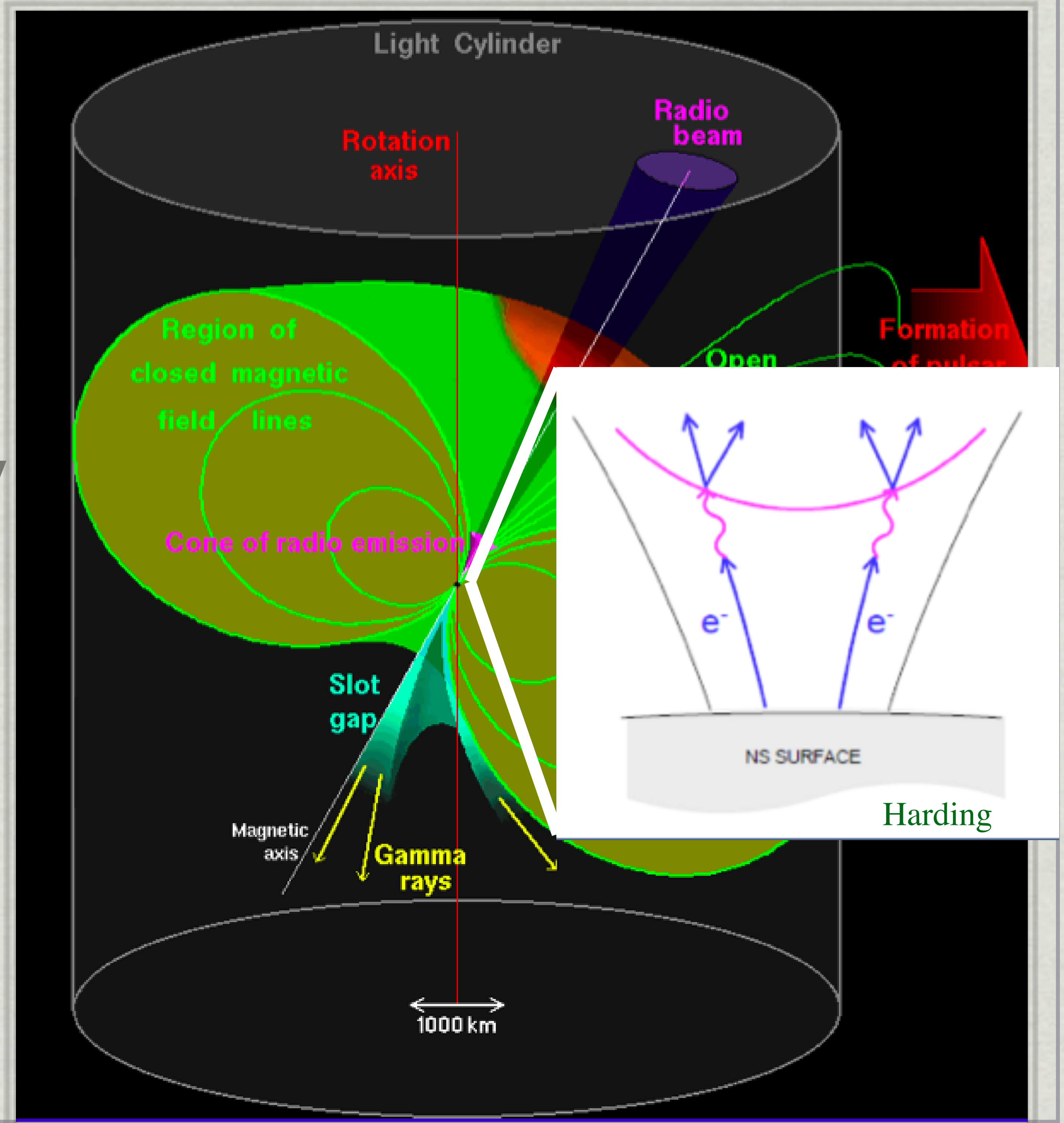
Open questions:

- The structure of the magnetosphere is the primary question, as all emission physics must be done in the context of proper magnetospheric geometry.

- Related question is the nature of the spin-down: most energetic, but mostly invisible, process in normal pulsars.

Magnetospheric cartoon

- Open & closed (corotating) zones.
- Minimal (Goldreich-Julian) charge density
- Light cylinder
- Sweepback
- Plasma is born in discharges

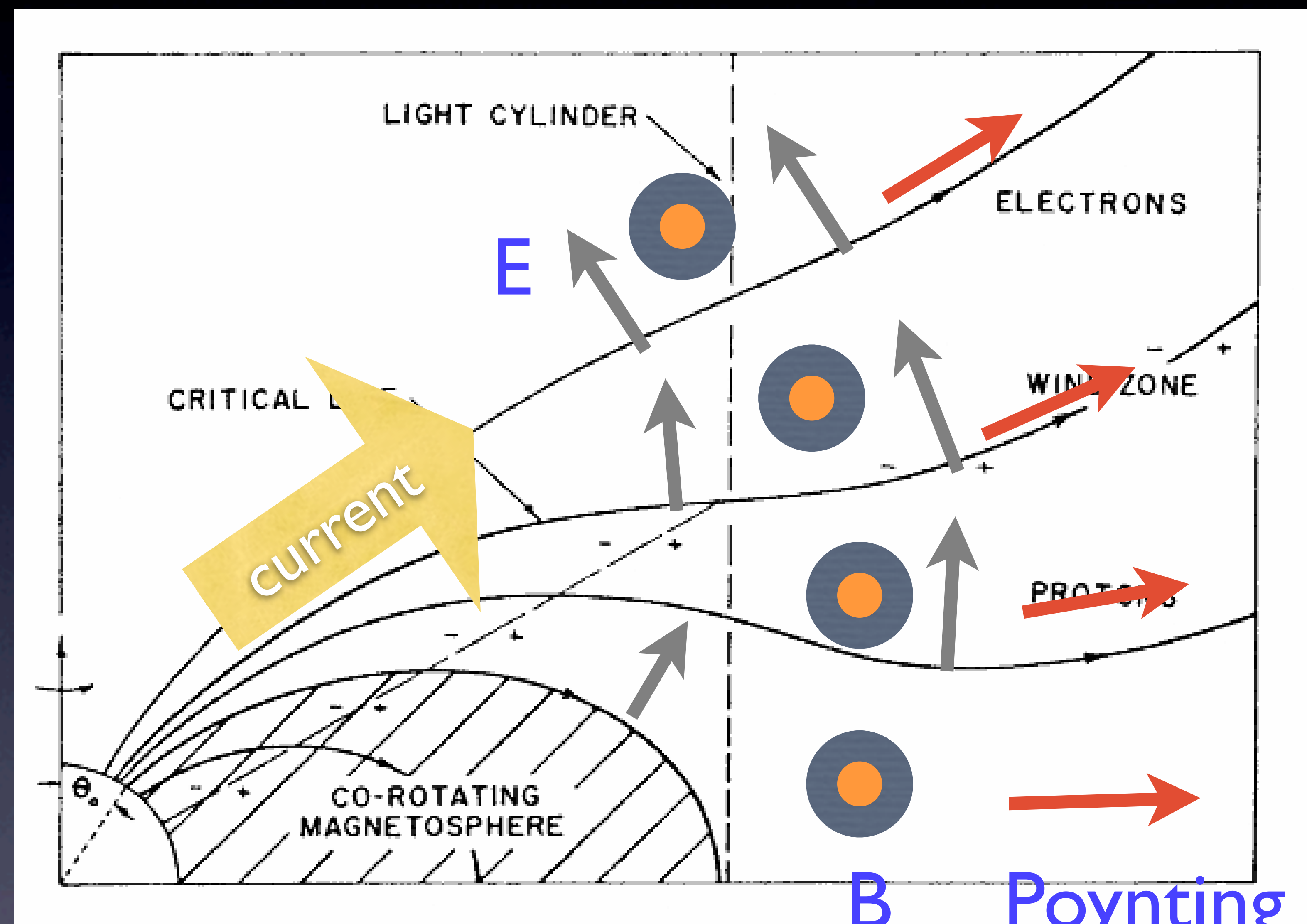


Pulsars: energy loss

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

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

- Electromagnetic energy loss



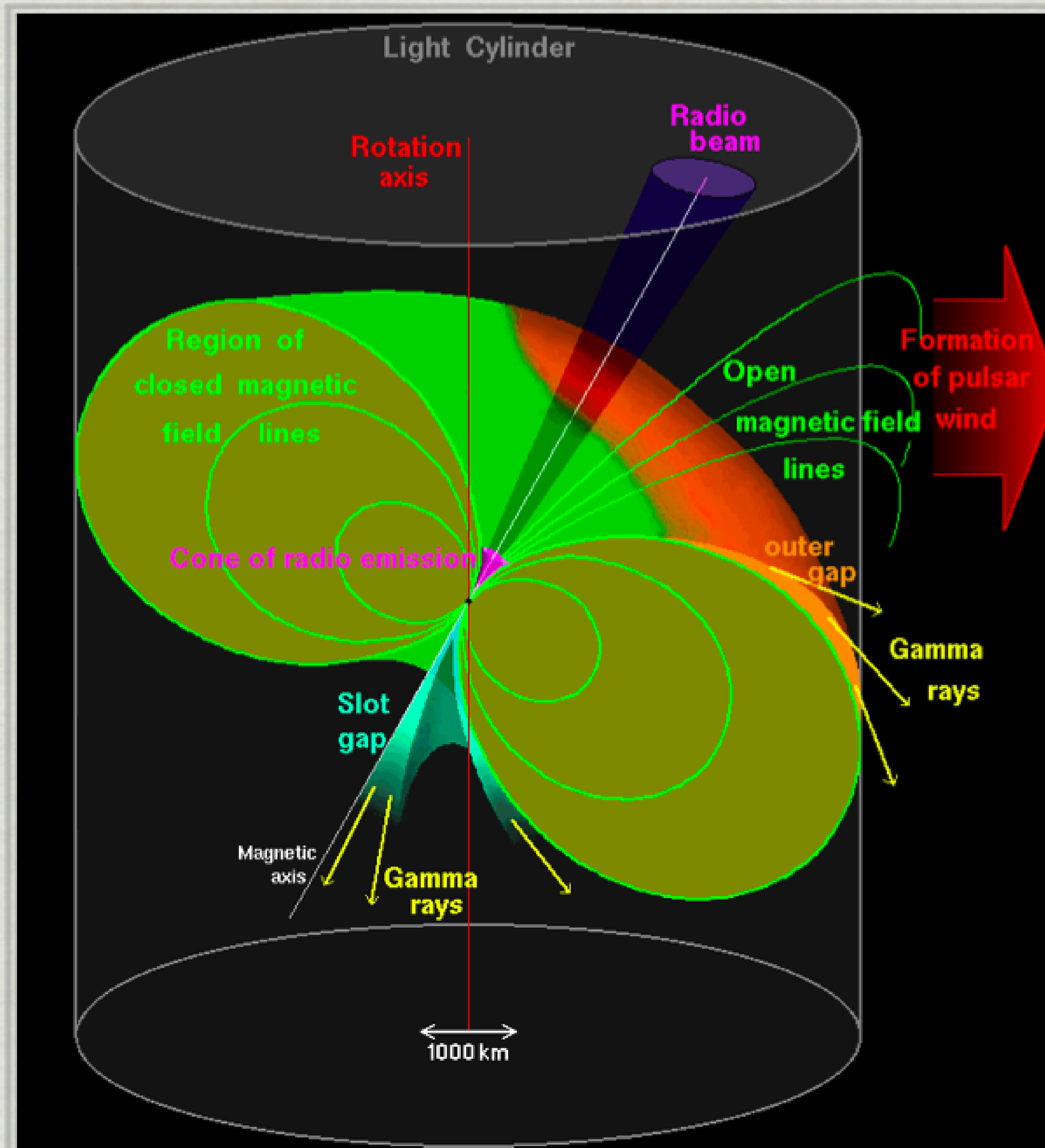
Goldreich & Julian 1969

Only gamma-ray output of pulsars is an interesting (<10%) fraction of the main spin-down energy flux.

Magnetospheric shape

Several ways of modeling, depending on charge supply:

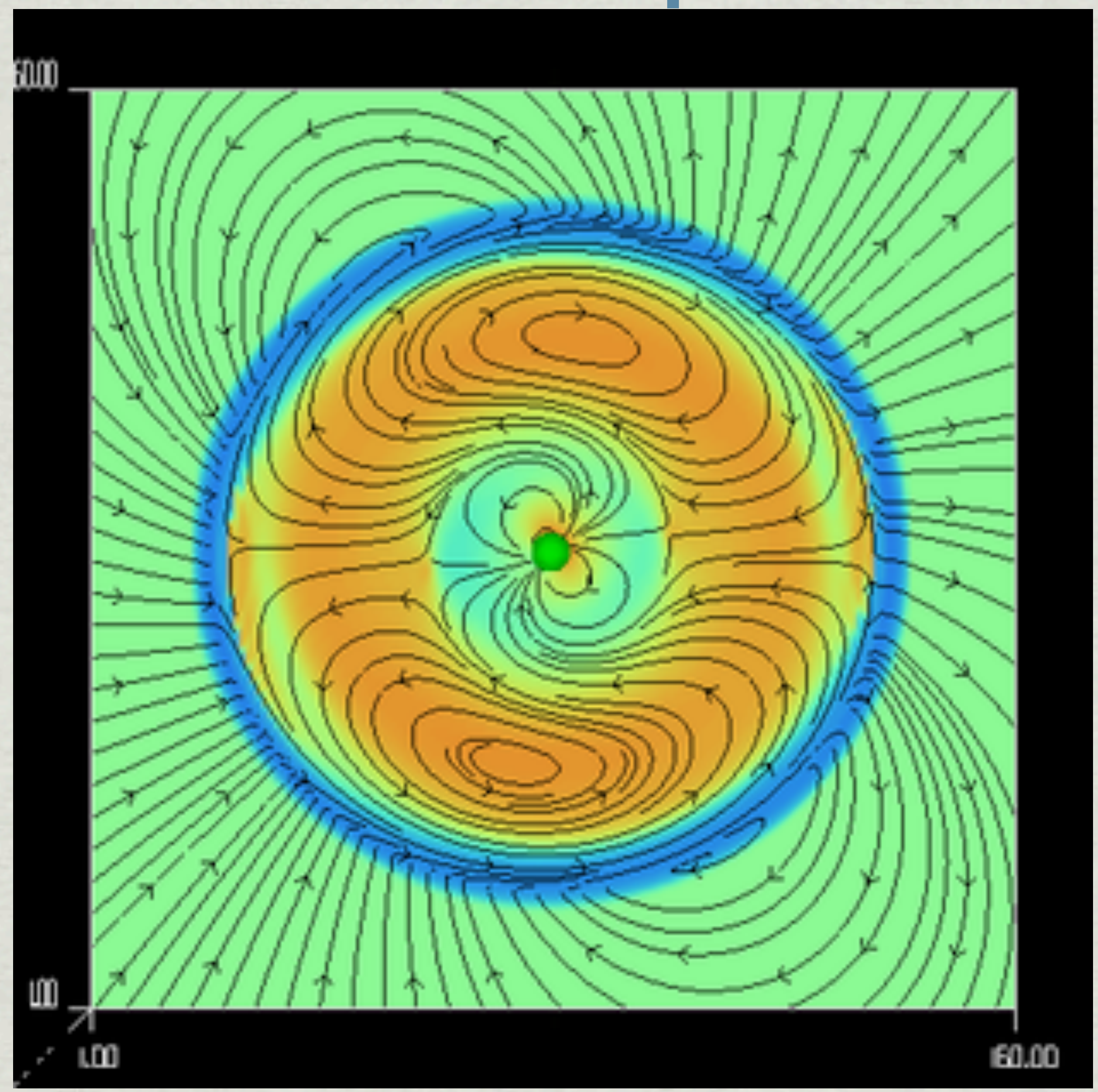
- Vacuum rotator
- Ab-initio particle
- Full RMHD
- Force-free variants
- "Pulsar equation"



Magnetospheric shape

Several ways of modeling, depending on charge supply:

- **Vacuum rotator**
- Ab-initio particle
- Full RMHD
- Force-free variants
- “Pulsar equation”

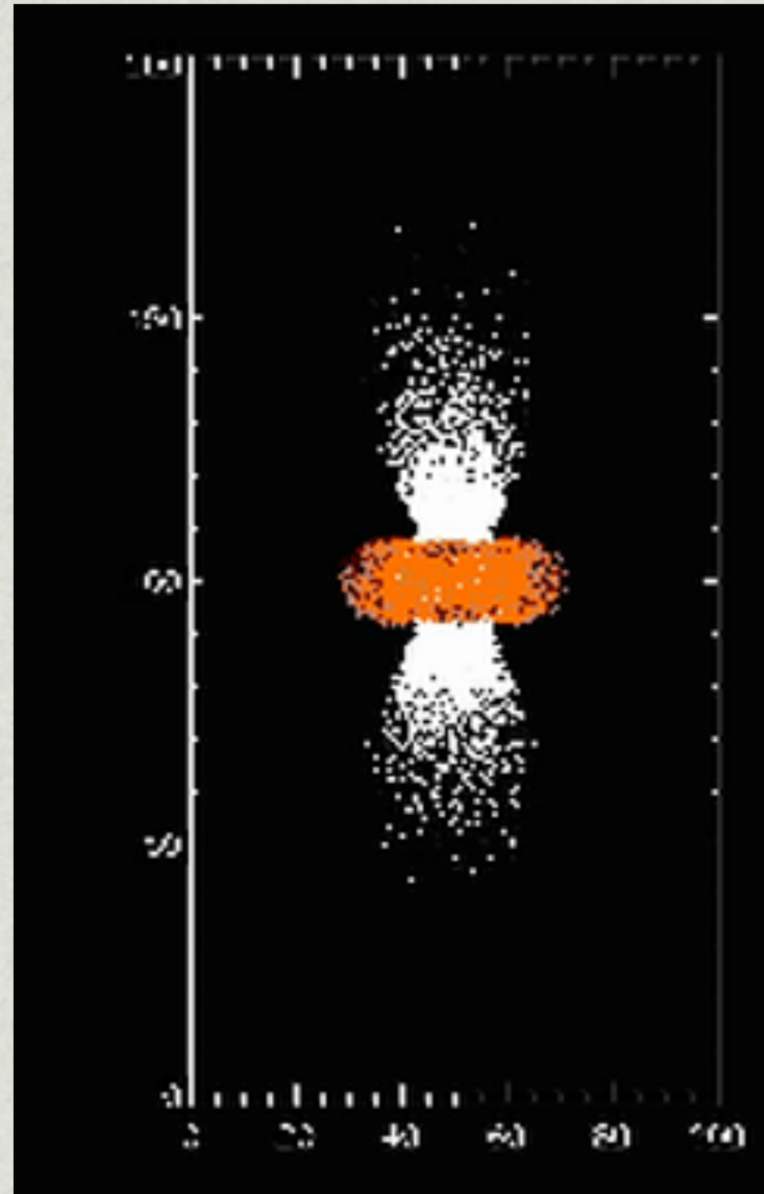


Analytic field line shape and spin down power formula

Magnetospheric shape

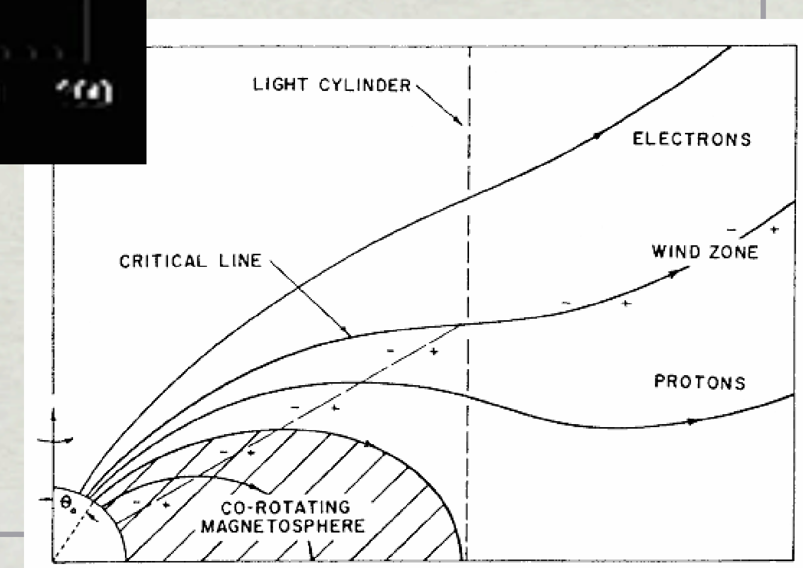
Several ways of modeling, depending on charge supply:

- Vacuum rotator
- **Ab-initio particle**
- Full RMHD
- Force-free variants
- “Pulsar equation”

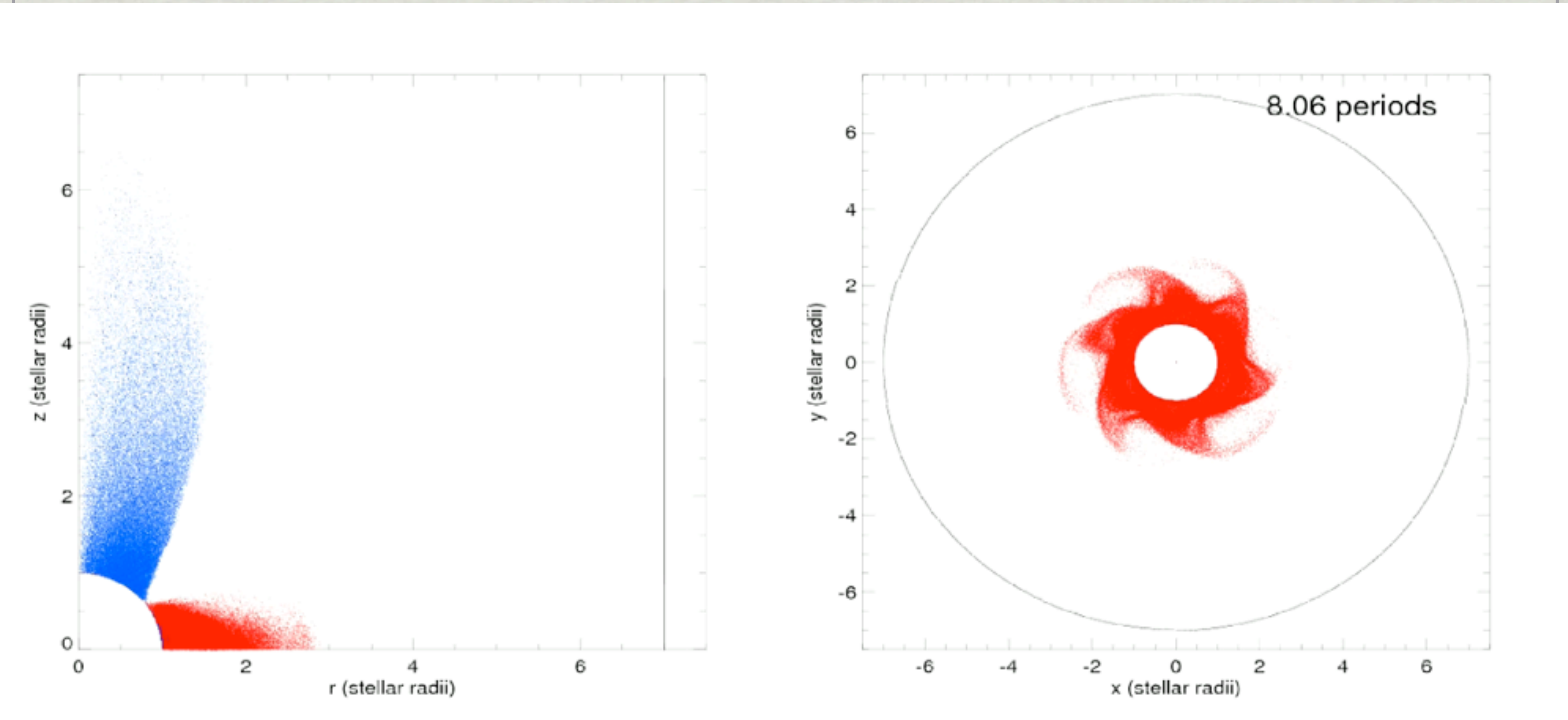


AS & Arons 02; Michel et al 84, 01

Is the charge-separated solution dead?



Non-axisymmetric instabilities



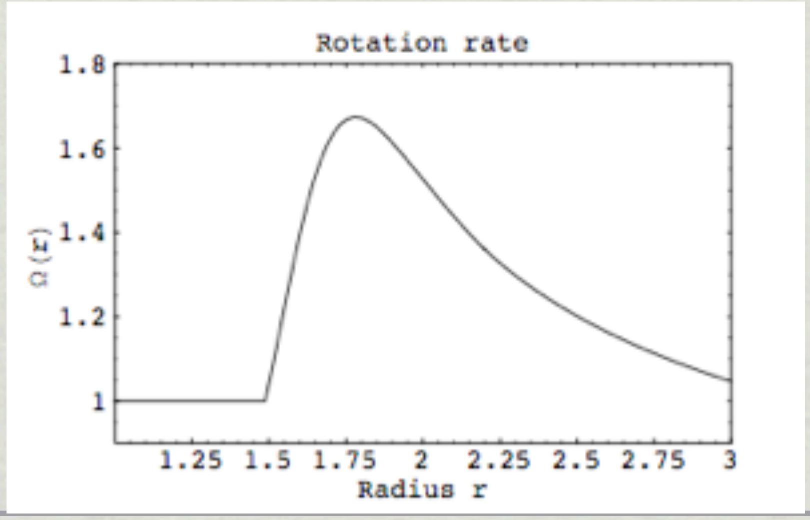
Disk-Torus Electrosphere

Michel et al `84-01

Diocotron instability

AS & Arons 02;

Petri et al 02-



Belyaev & AS, in prep

Possibility of radial current

Electrospheres are a curiosity

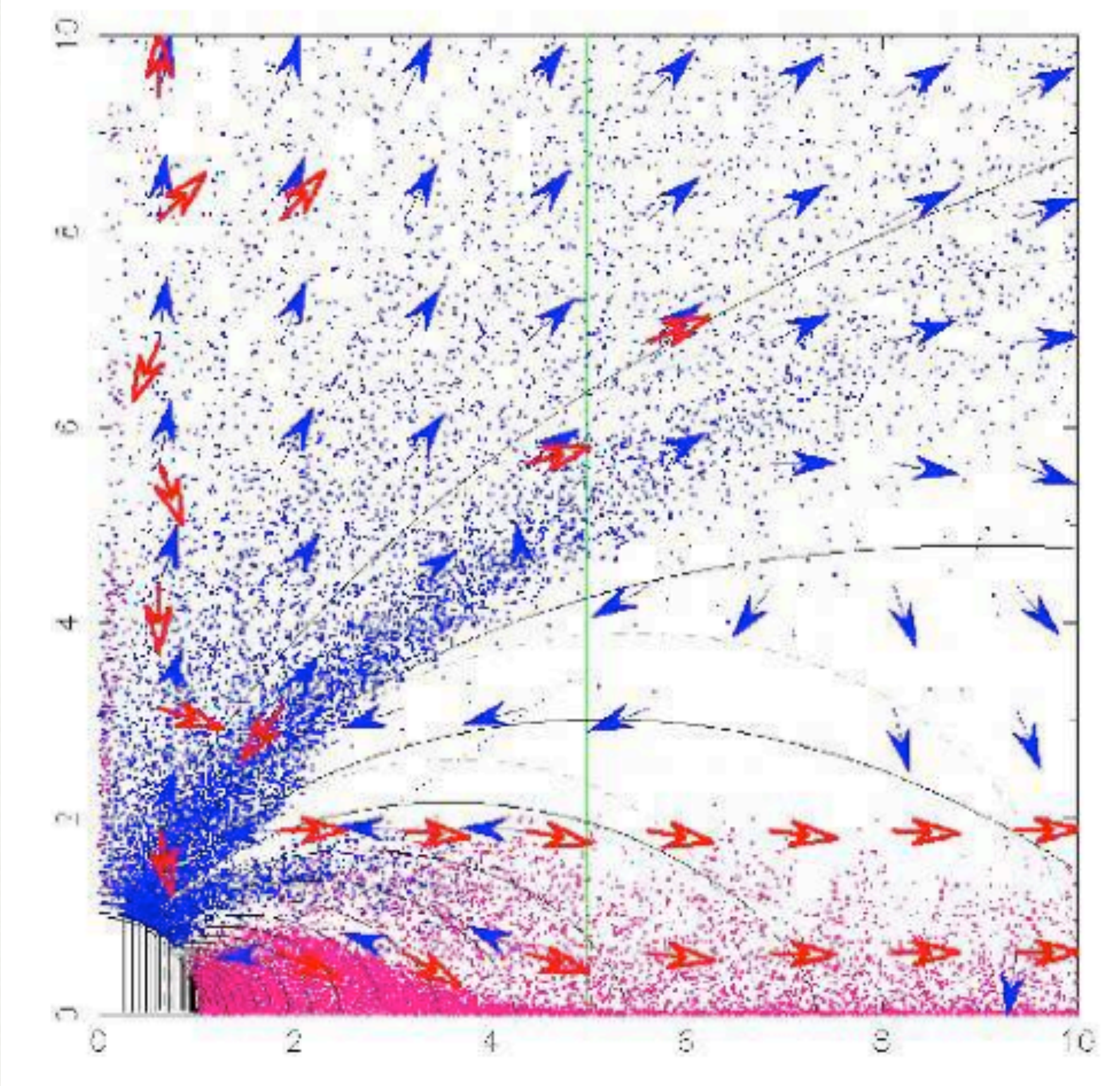
Add pairs?

Petri et al 02

Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- **Ab-initio particle**
- Full RMHD
- Force-free variants
- “Pulsar equation”



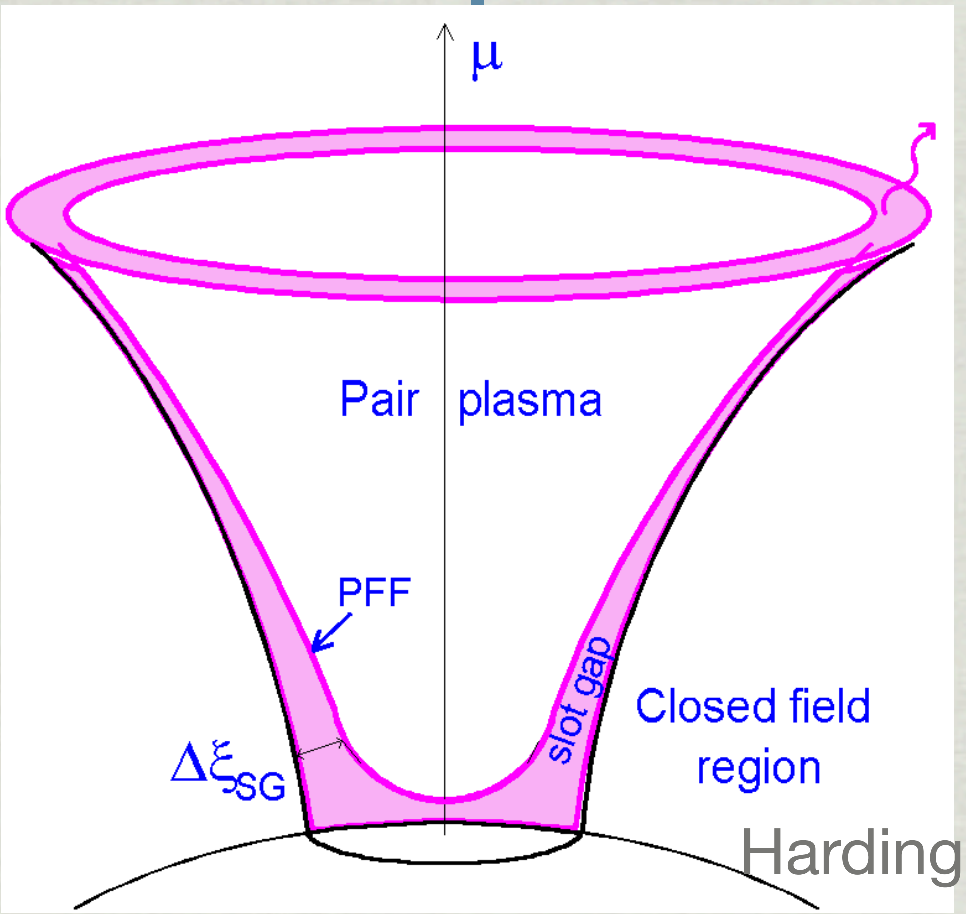
Not spinning down?

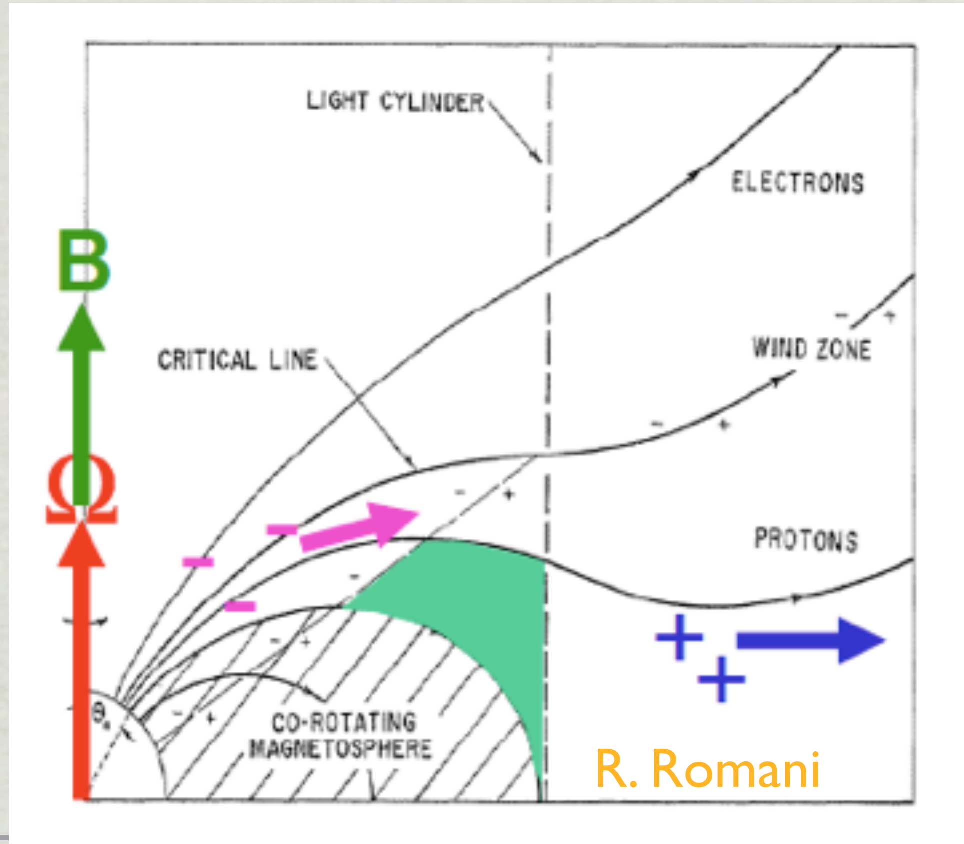
Wada & Shibata 11; Yuki & Shibata 12

Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- **Particle/Vacuum+**
- Full RMHD
- Force-free variants
- “Pulsar equation”

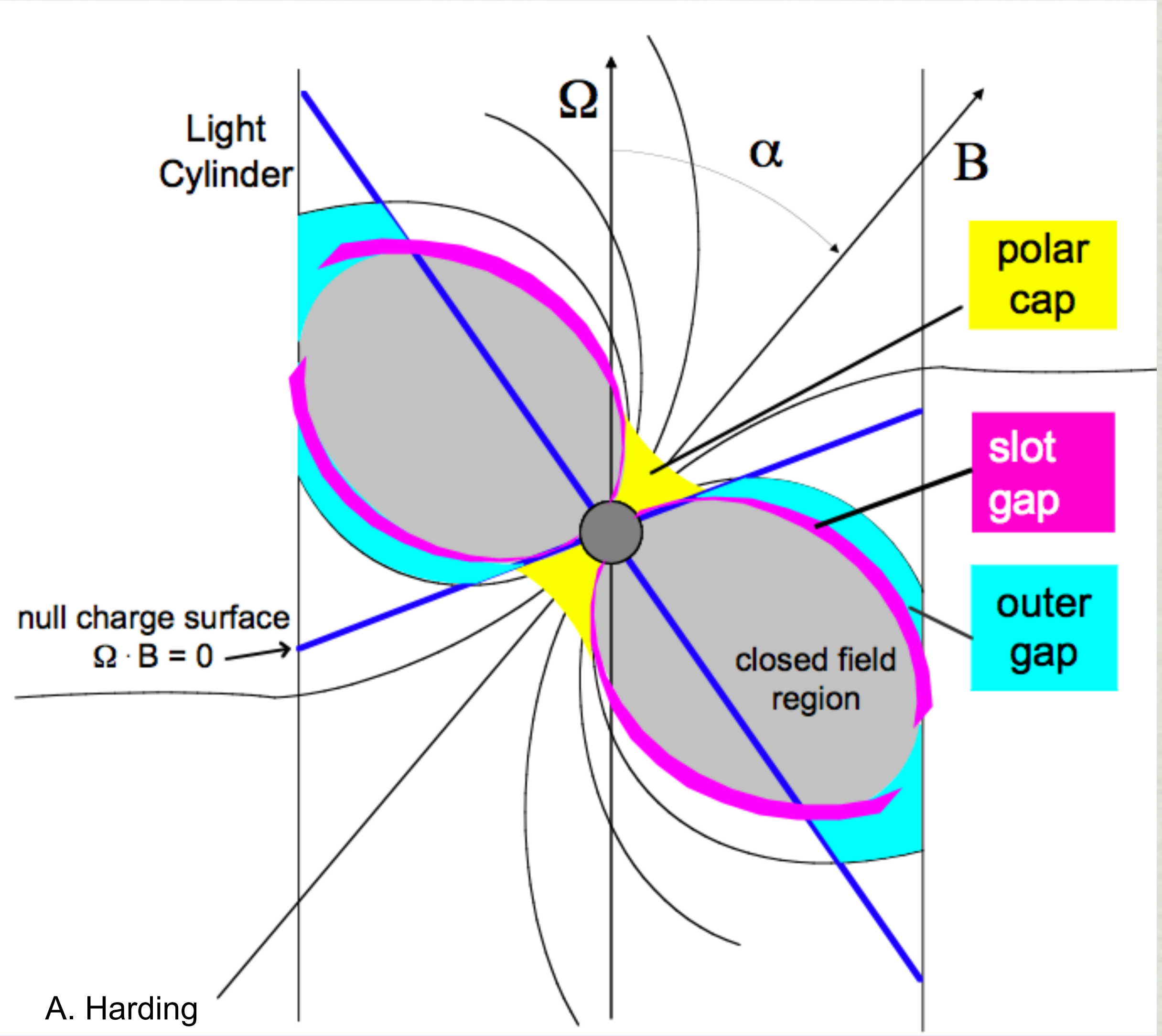




Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- **Particle/Vacuum+**
- Full RMHD
- Force-free variants
- “Pulsar equation”

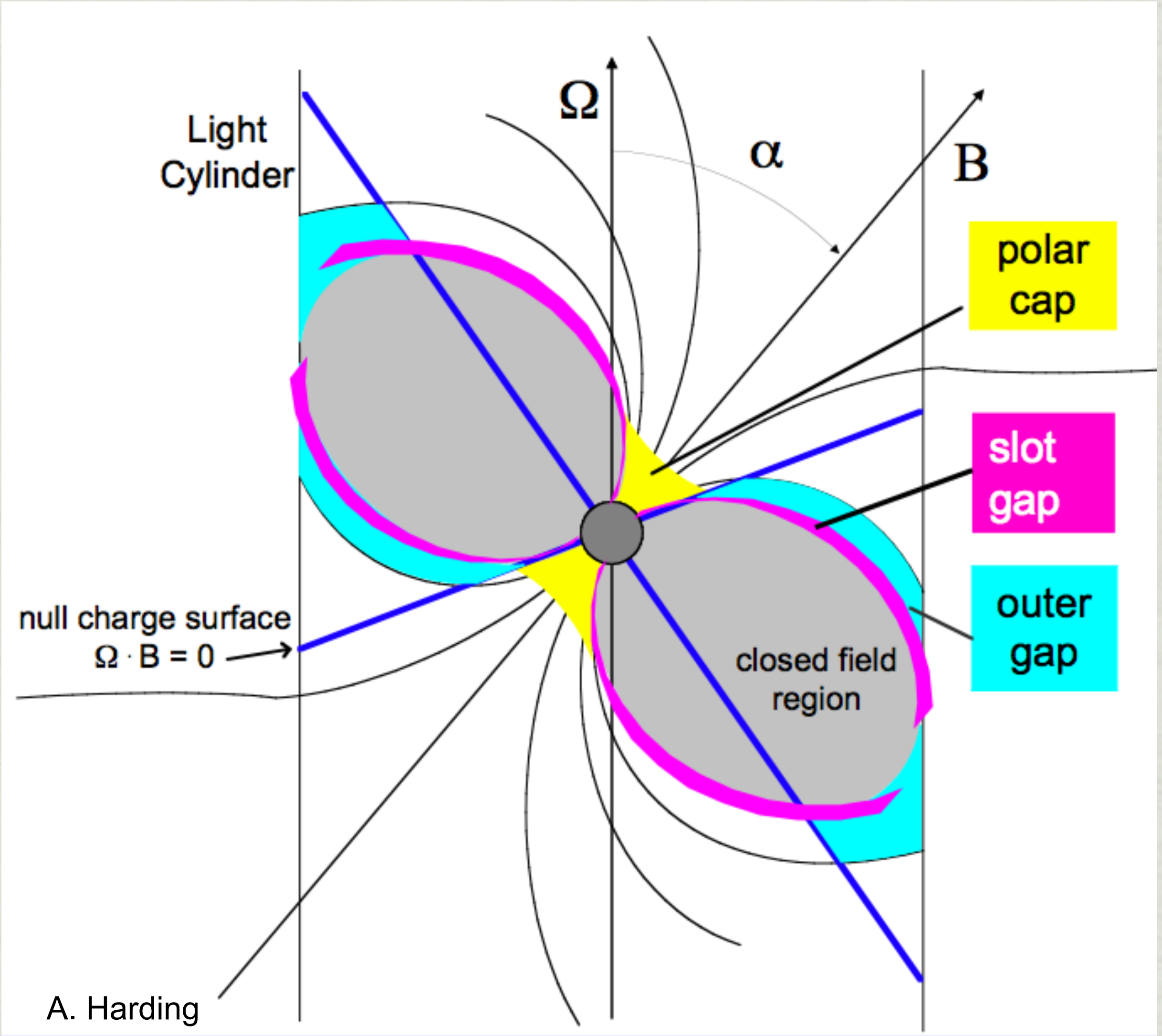


Harding

Space-charge limited flow + pairs + gaps. Curvature radiation from radiation reaction limited acceleration.

Gaps in understanding of gaps...

- Acceleration due to charge starvation
- Gaps imply space-charge separated background flow, even though pairs are created.
- PWNe require pair densities >> minimum charge separated density.



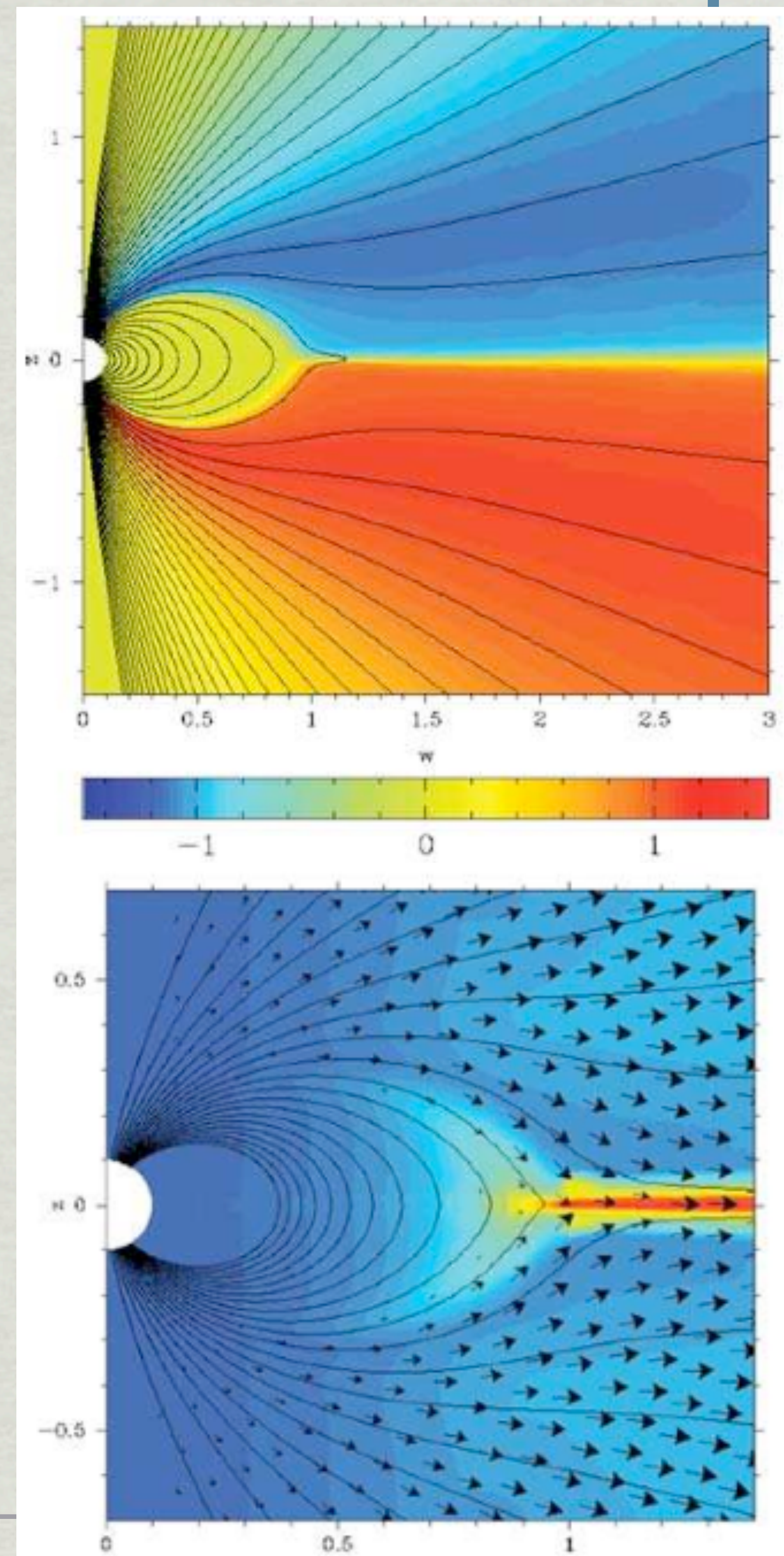
Harding

Gap models are best developed but are not self-consistent.

Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- Ab-initio particle
- **Full RMHD**
- Force-free variants
- "Pulsar equation"

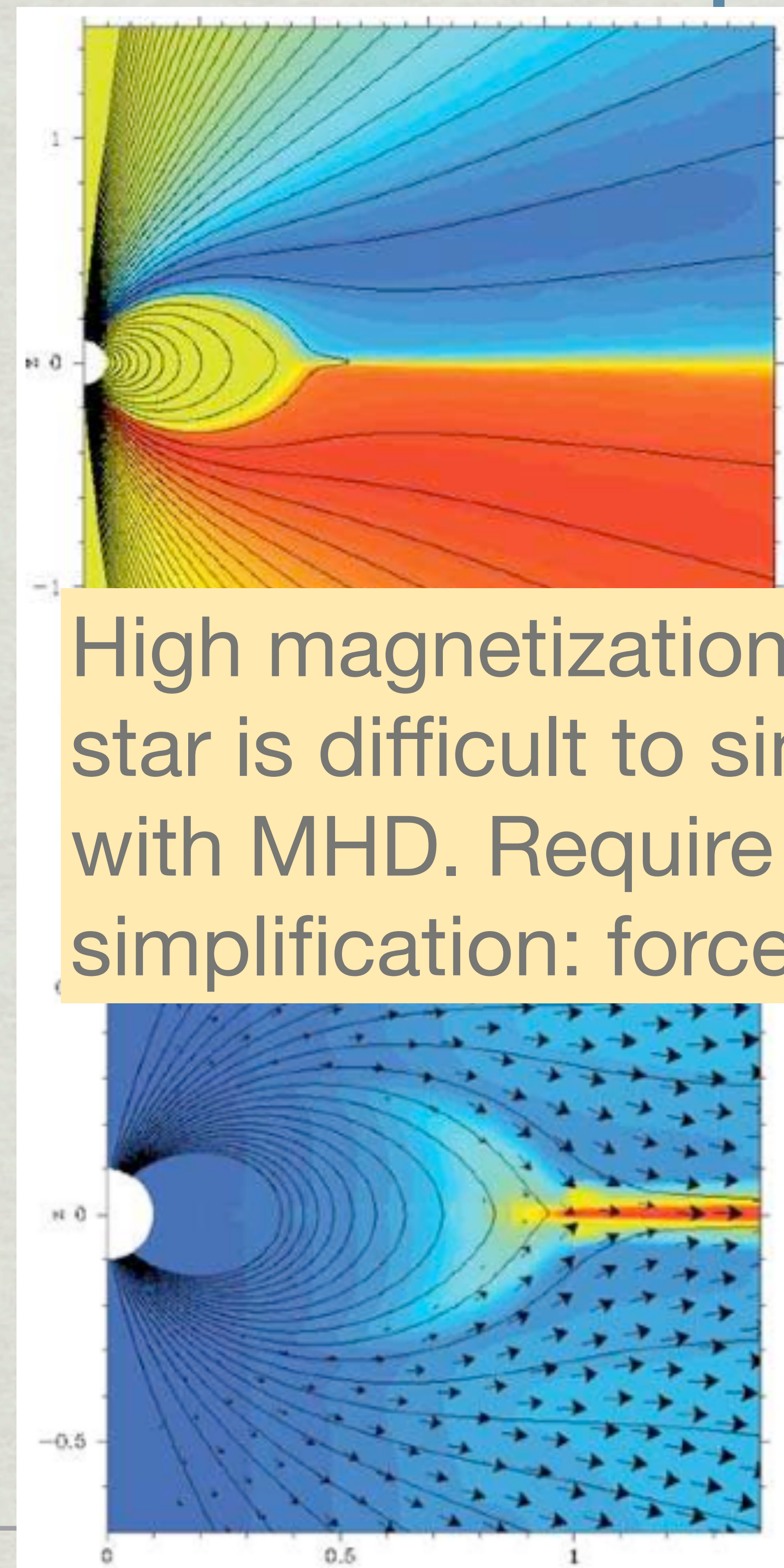


Komissarov 06

Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- Ab-initio particle
- **Full RMHD**
- Force-free variants
- “Pulsar equation”



High magnetization near the star is difficult to simulate with MHD. Require simplification: force-free

Komissarov 06

Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- Ab-initio particle
- Full RMHD
- **Force-free:**
- "Pulsar equation"

NS is immersed in massless conducting fluid with no inertia.

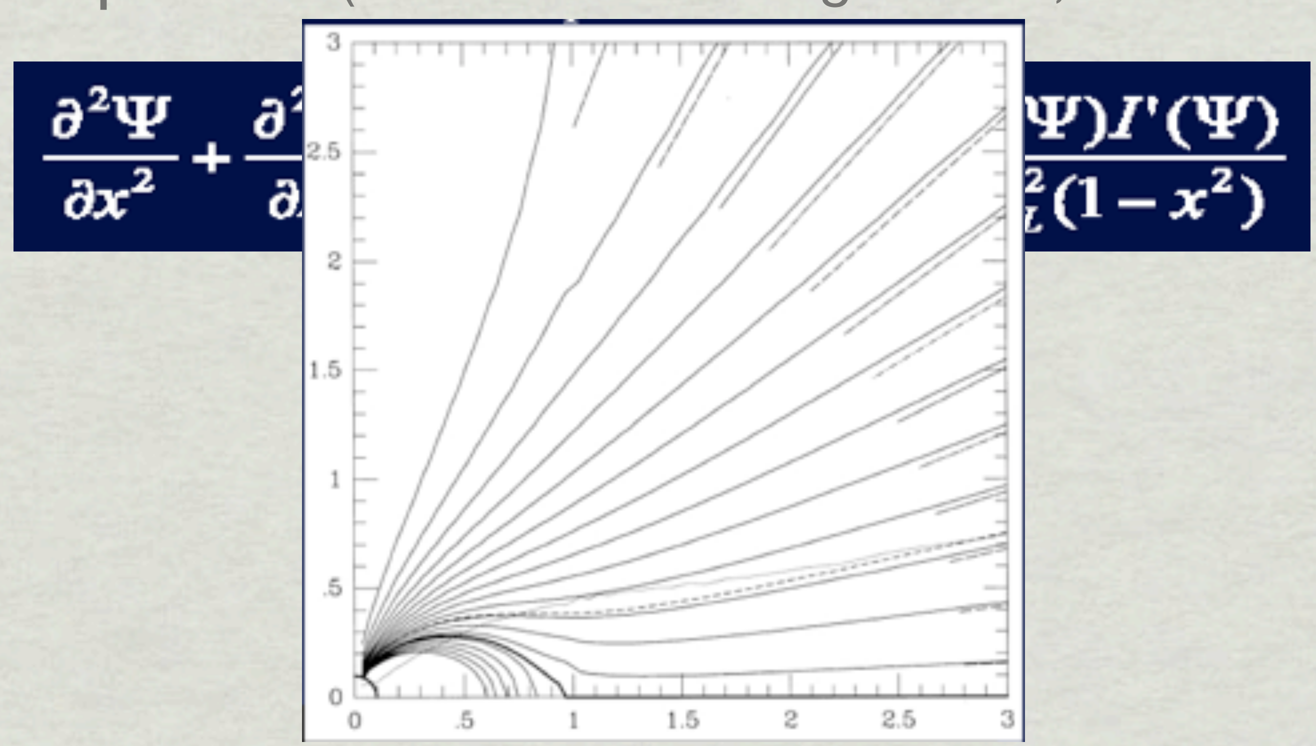
$$\rho \boldsymbol{E} + (1/c)\boldsymbol{j} \times \boldsymbol{B} = 0$$

$$\frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} = \boldsymbol{\nabla} \times \boldsymbol{B} - \frac{4\pi}{c}\boldsymbol{j}, \quad \frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \boldsymbol{E},$$

$$\boldsymbol{j} = \frac{c}{4\pi}\boldsymbol{\nabla} \cdot \boldsymbol{E}\,\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} + \frac{c}{4\pi}\frac{(\boldsymbol{B} \cdot \boldsymbol{\nabla} \times \boldsymbol{B} - \boldsymbol{E} \cdot \boldsymbol{\nabla} \times \boldsymbol{E})\boldsymbol{B}}{B^2}$$

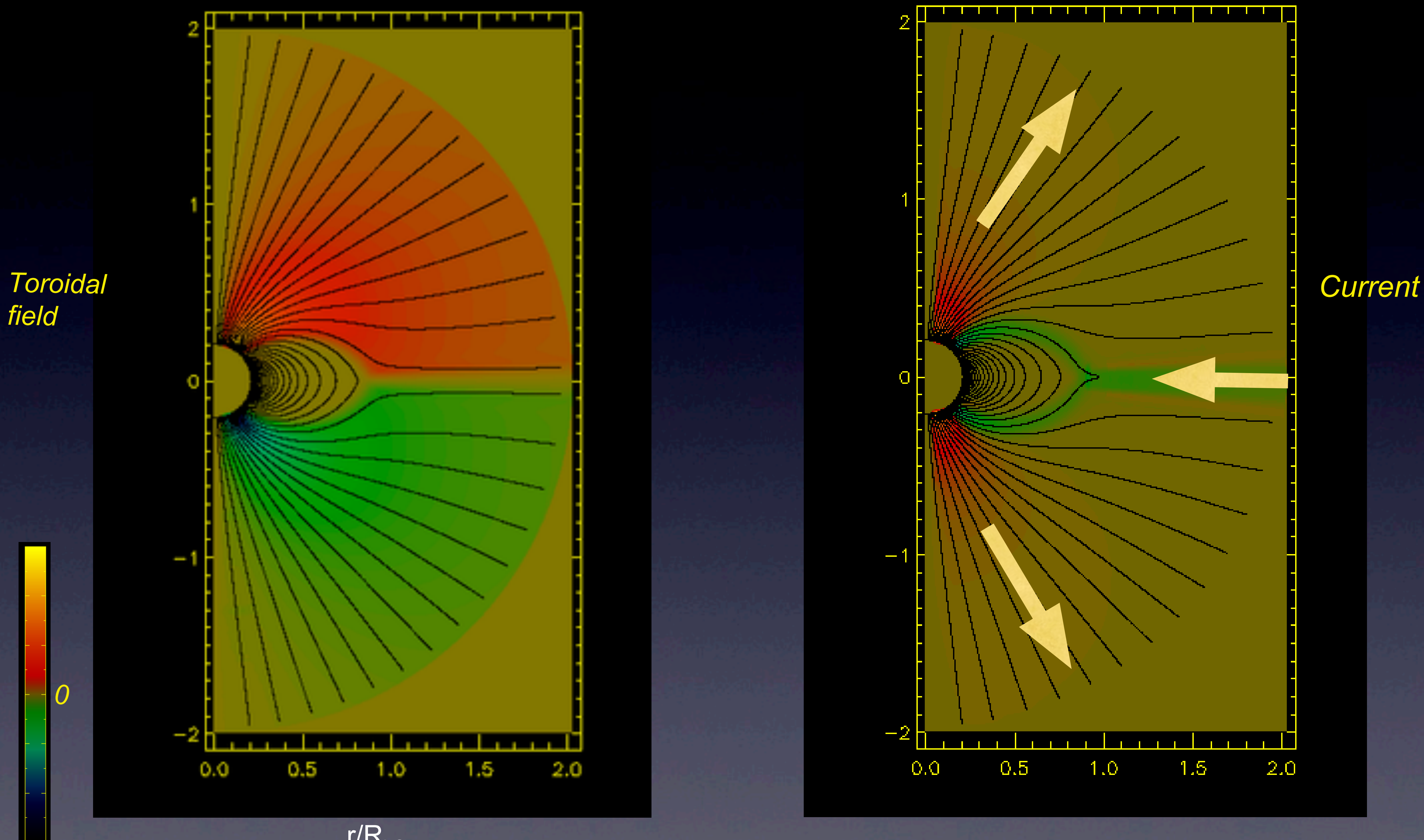
Gruzinov 99, Blandford 02

Time-independent version -- pulsar equation (Scharleman & Wagoner 73, Michel 73)



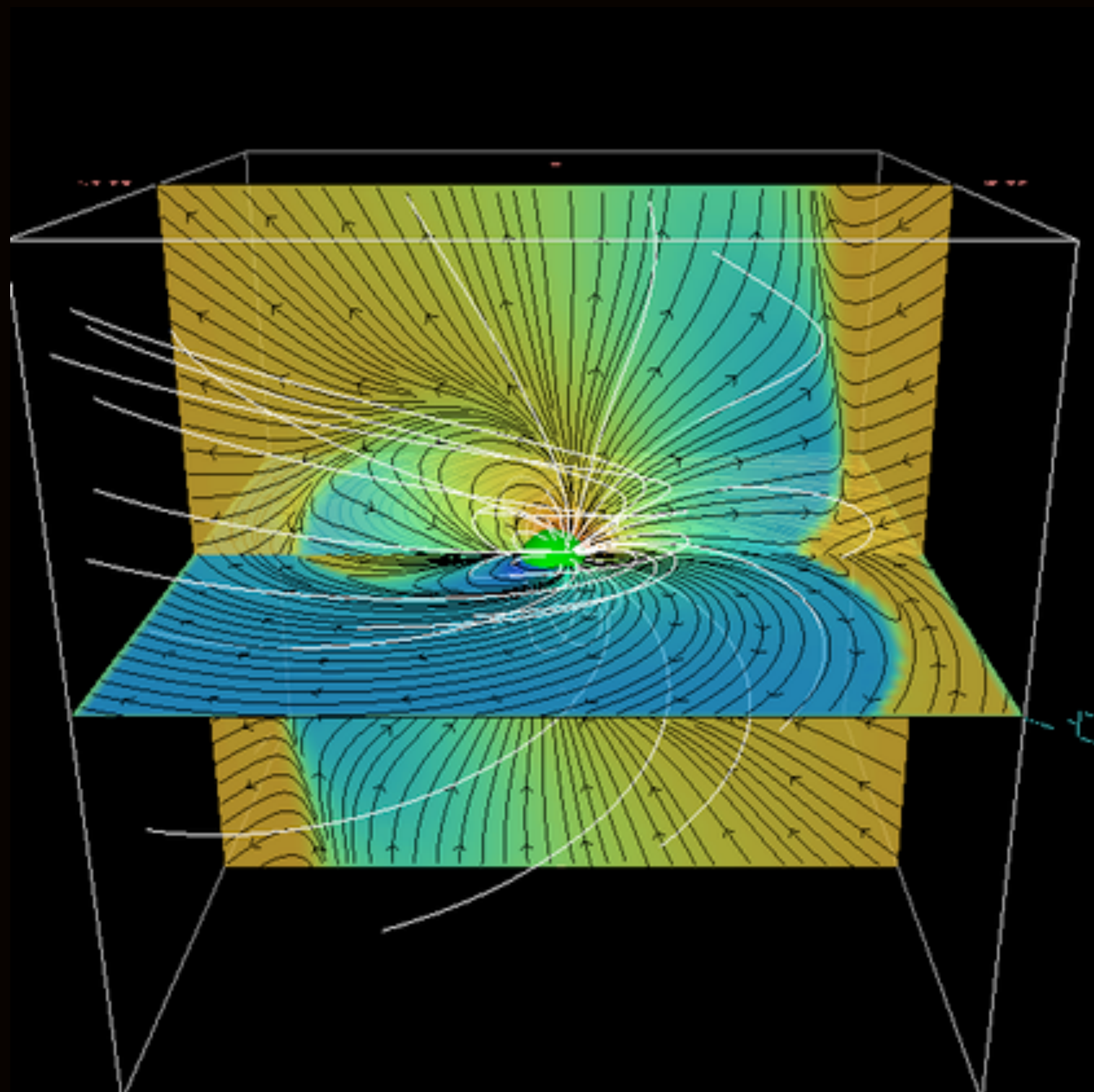
Contopoulos, Kazanas & Fendt 1999

Aligned rotator: plasma magnetosphere



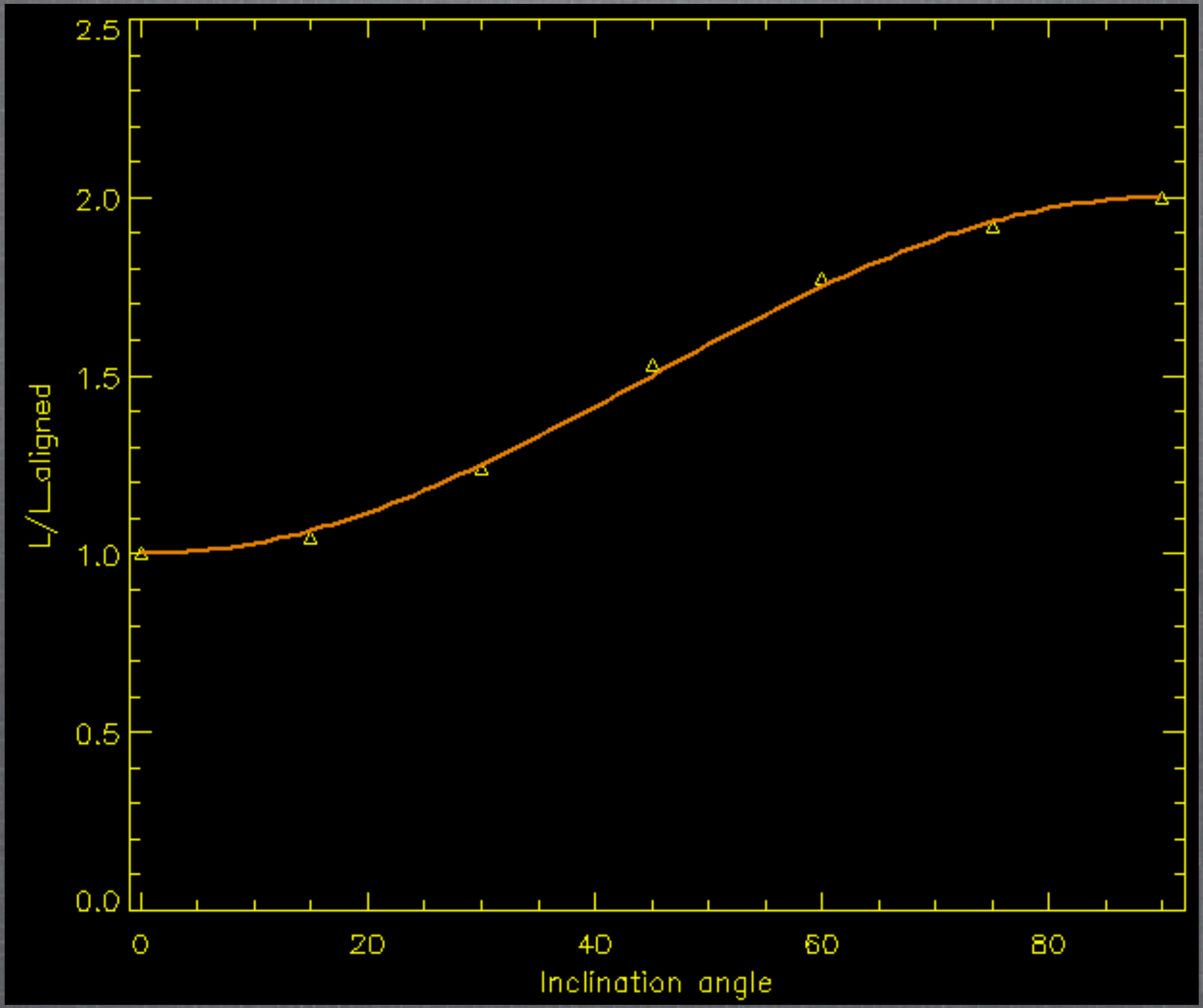
Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting. Now at least 5 groups can do this (recently, Yu 11, Parfrey 11, Petri 12, Palenzuela 12 in addition to AS 06, McKinney 06, Kalapotharakis 09)

Oblique rotator: force-free



A.S. 2006

SPIN-DOWN POWER



Spin-down of oblique rotator

NB: this is a fit!

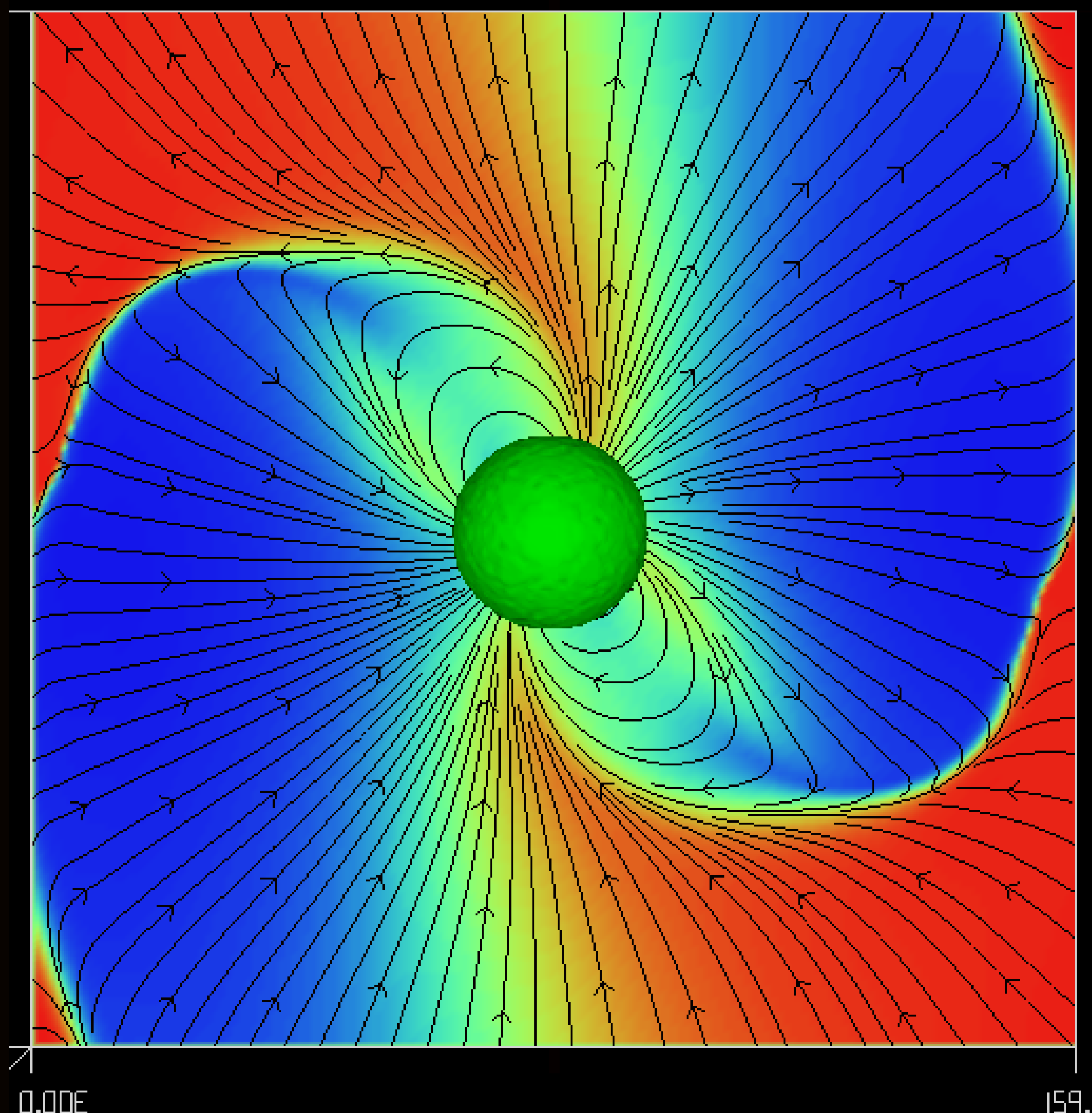
$$\boxed{\dot{E} = \frac{\mu^2 \Omega^4}{c^3}(1 + \sin^2\theta)}$$

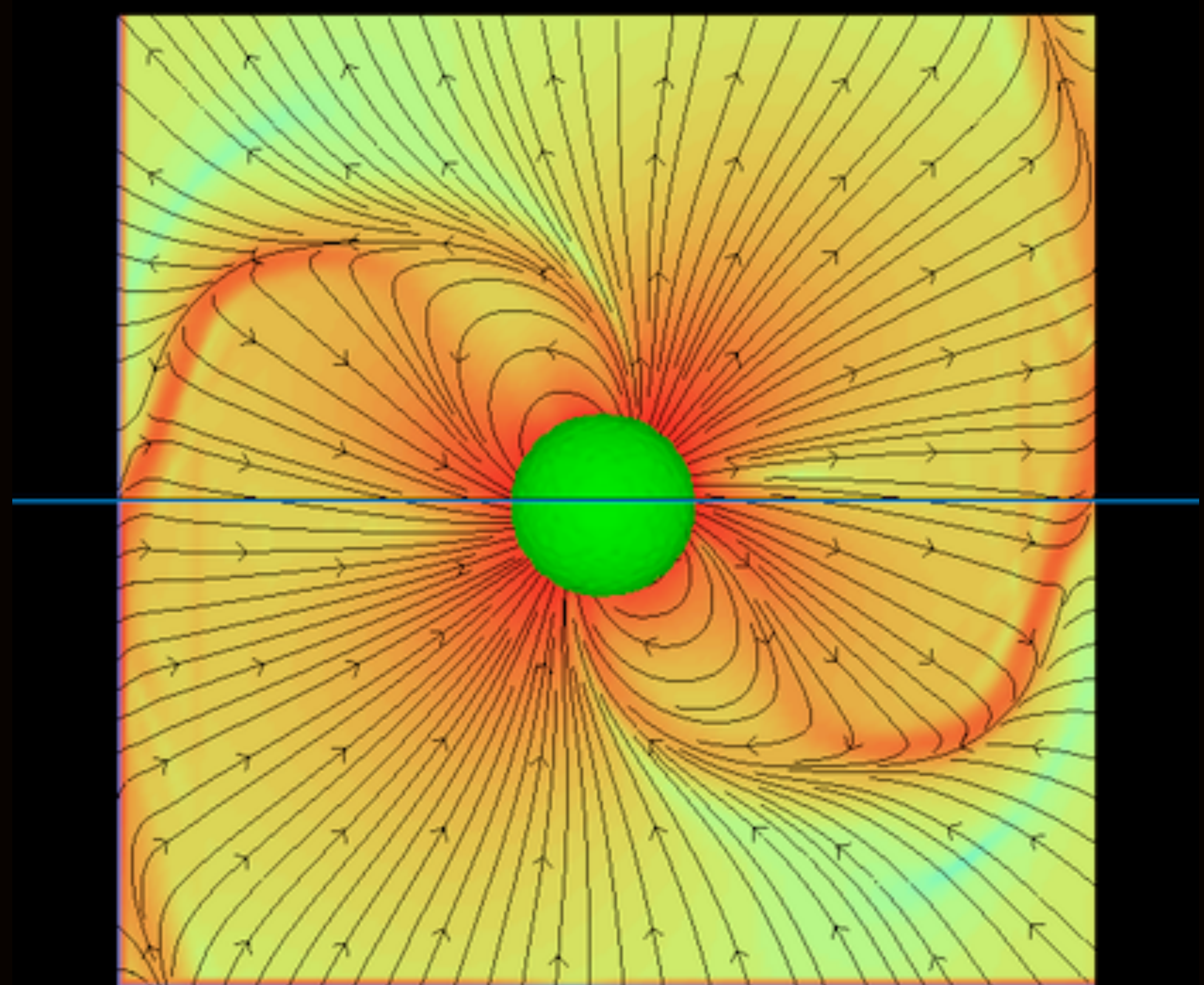
$$\dot{E}_{vac} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\theta$$

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

IN COROTATING FRAME

60 degree inclination

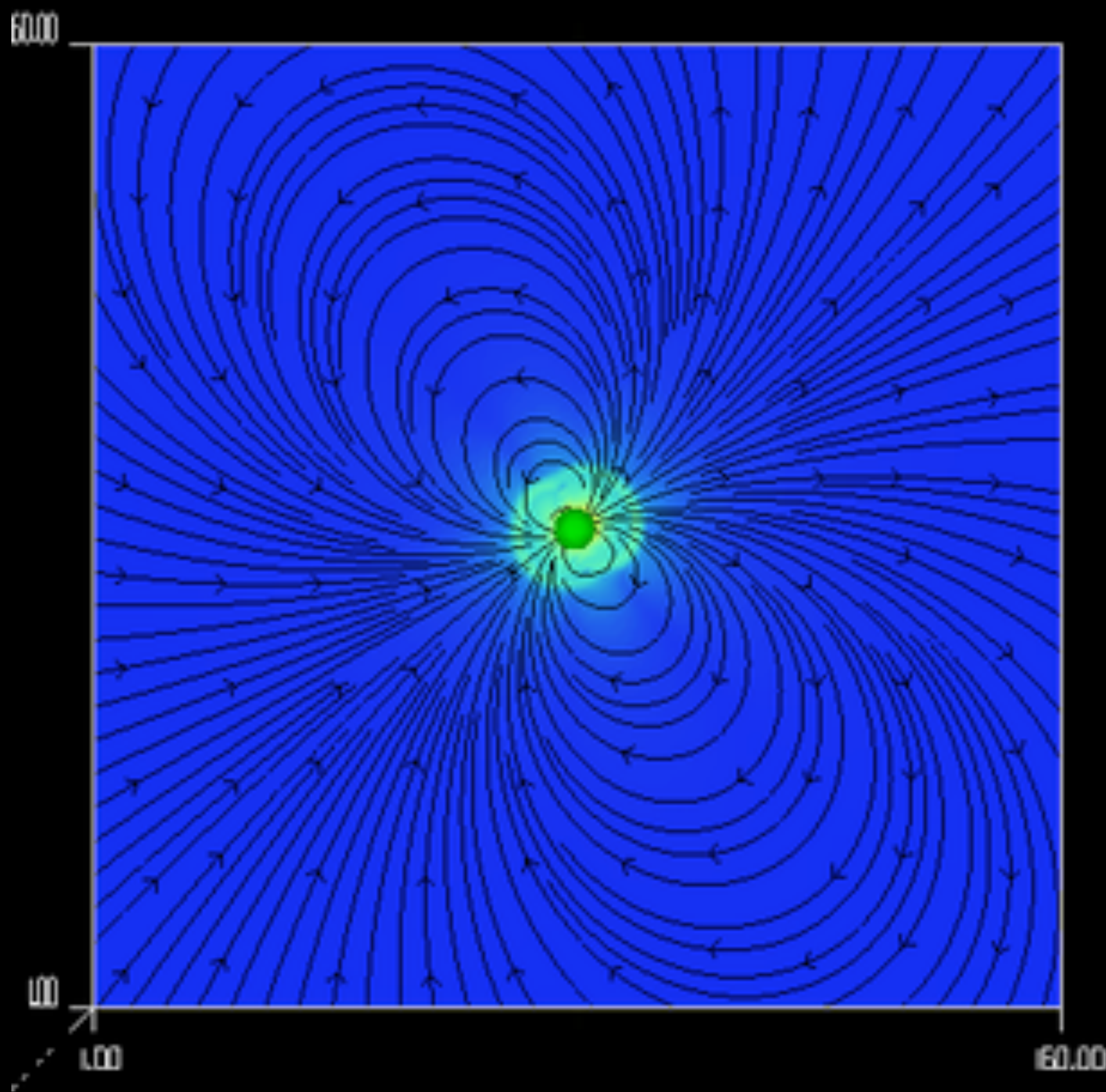




Force-free

Force-free current density

3D force-free magnetosphere: 60 degrees inclination

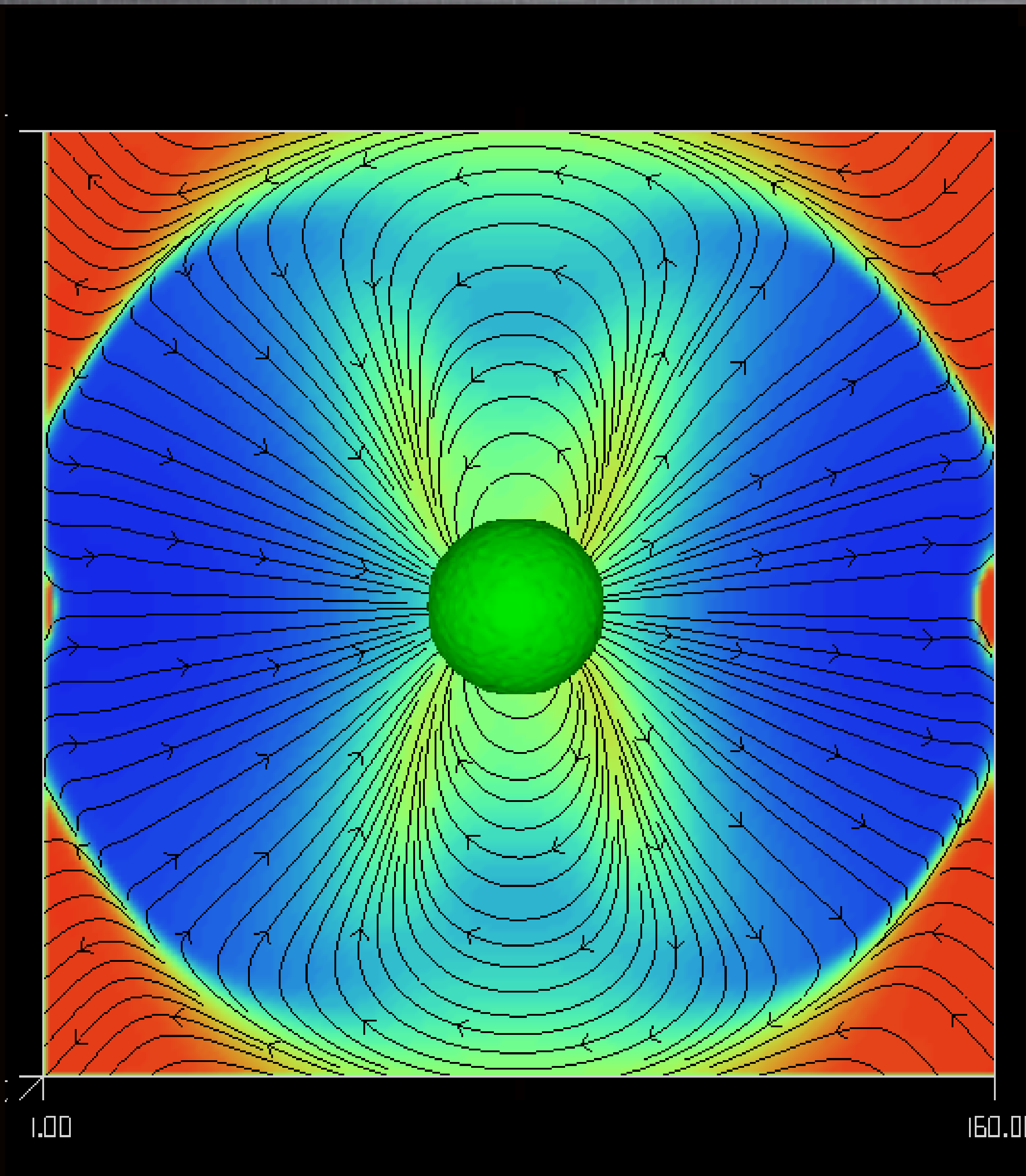


Similar to heliospheric current sheet

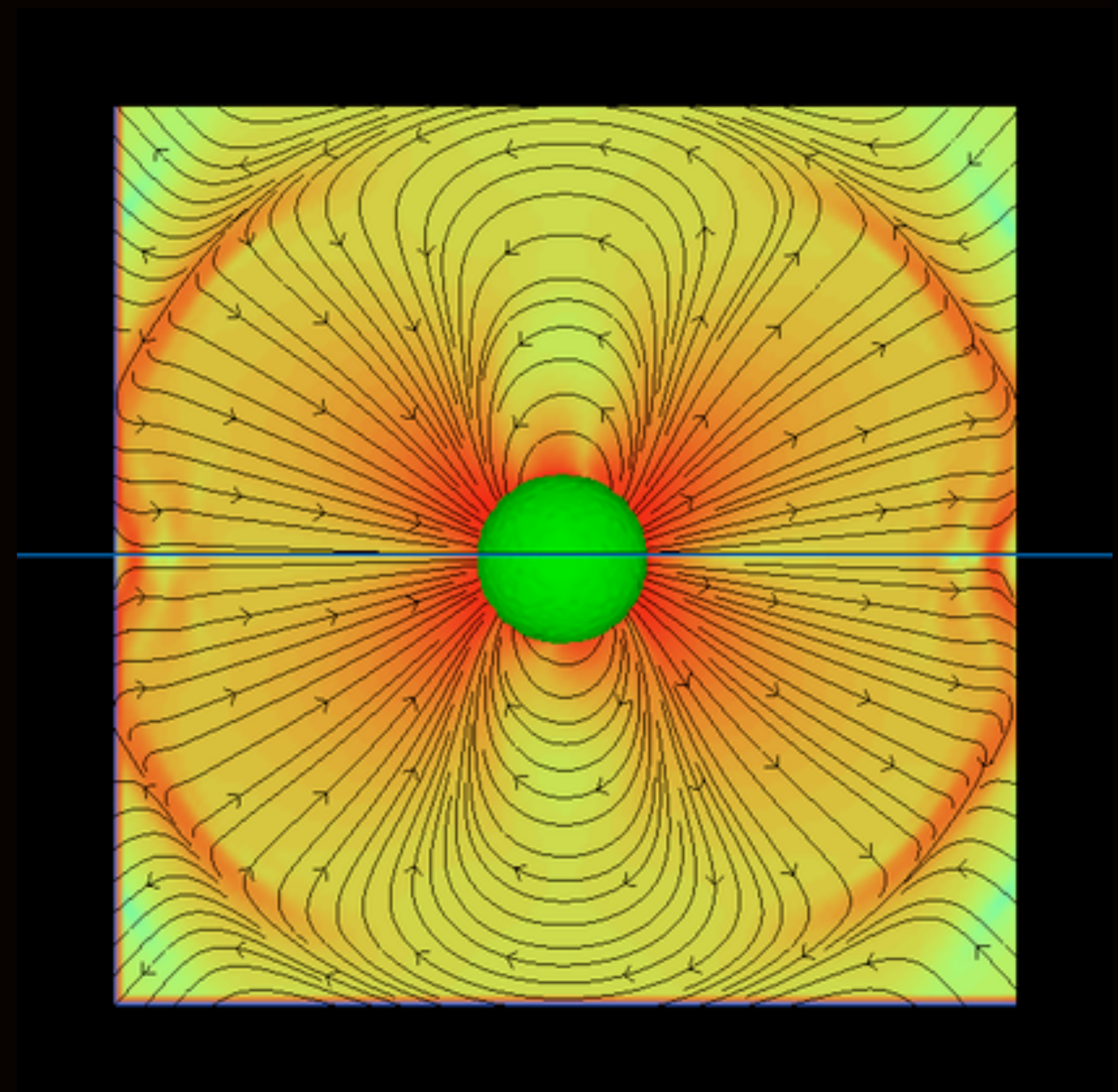
60 degrees force-free current

IN COROTATING FRAME

90 degree inclination

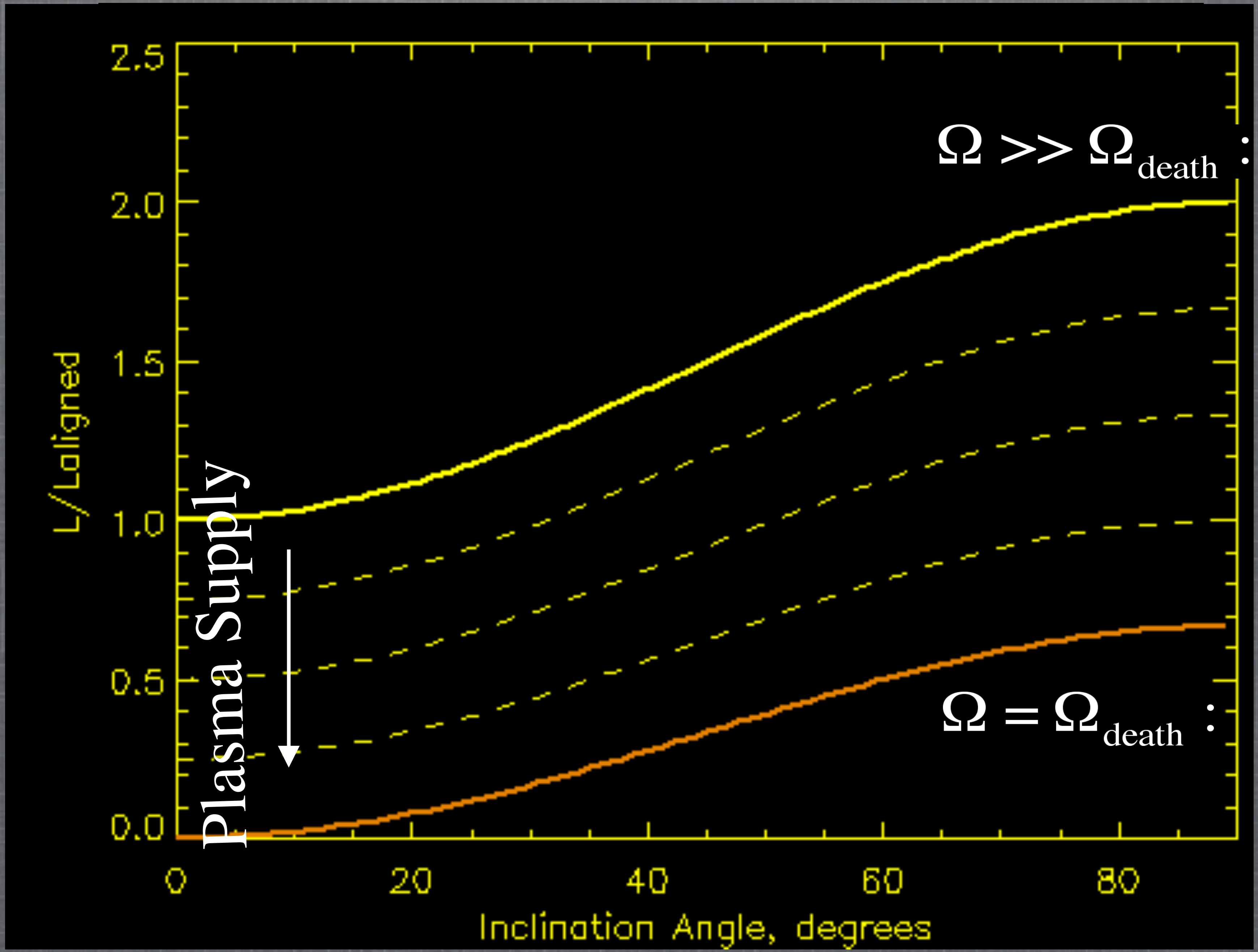


Force-free



Force-free current density

SPIN-DOWN POWER



There is a continuum of solutions that depend on plasma supply. These can be characterized by the presence of accelerating E field, or resistivity.

Resistive force-free

- There is a continuum of solutions between vacuum and ideal conducting force-free magnetosphere if plasma is not perfect everywhere.
- Can parameterize these with resistivity in the proper frame.
- Nice feature: re-emergence of parallel E field.

Ohm's law in the proper frame:

$$\vec{j}_{\rm fluid} = \sigma \vec{E}_{\rm fluid}$$

In lab frame:

$$\vec{j} = \frac{\rho c \vec{E} \times \vec{B}}{B^2 + E_0^2} + \frac{\left(-\beta_{||}\rho c + \sqrt{\frac{B^2+E_0^2}{B_0^2+E_0^2}}(1-\beta_{||}^2)\sigma E_0\right)(B_0\vec{B} + E_0\vec{E})}{B^2 + E_0^2}$$

$$B_0^2 = \frac{\vec{B}^2 - \vec{E}^2 + \sqrt{(\vec{B}^2 - \vec{E}^2)^2 + 4(\vec{E}\cdot\vec{B})^2}}{2},$$

$$E_0 = \sqrt{B_0^2 - \vec{B}^2 + \vec{E}^2},$$

$$B_0 = \mathrm{sign}(\vec{E}\cdot\vec{B})\sqrt{B_0^2},$$

cf. Lyutikov 03
Gruzinov 07-11

Li, AS, Tchekhovskoy, 2011

Resistive force-free

- There is a continuum of solutions between vacuum and ideal conducting force-free magnetosphere if plasma is not perfect everywhere.
- Can parameterize these with resistivity in the proper frame.
- Nice feature: re-emergence of parallel E field.

Ohm's law in the proper frame:

$$\vec{j}_{\rm fluid} = \sigma \vec{E}_{\rm fluid}$$

Minimal || velocity frame:

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

$$B_0^2 = \frac{\vec{B}^2 - \vec{E}^2 + \sqrt{(\vec{B}^2 - \vec{E}^2)^2 + 4(\vec{E}\cdot\vec{B})^2}}{2},$$

$$E_0 = \sqrt{B_0^2 - \vec{B}^2 + \vec{E}^2},$$

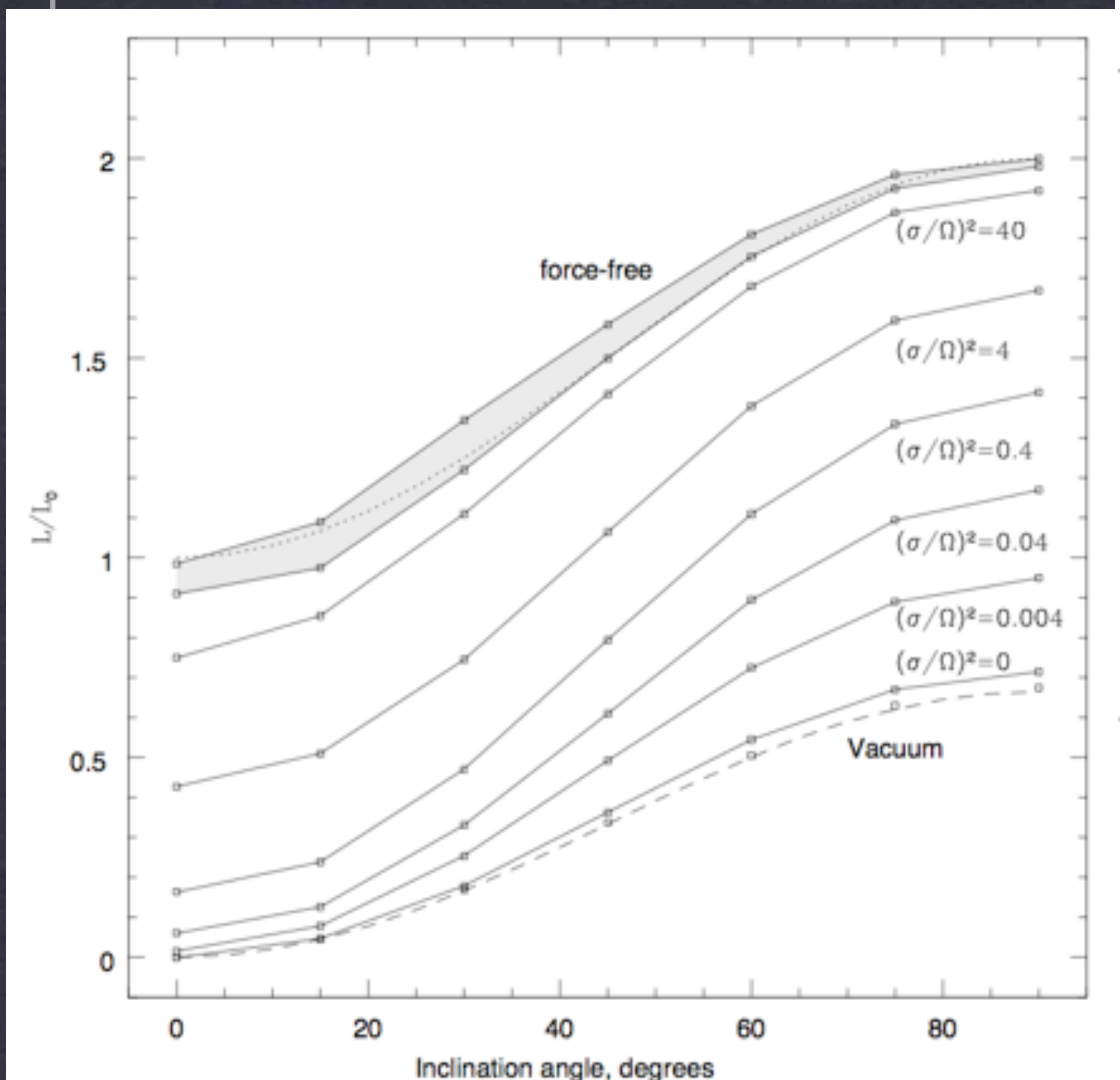
$$B_0 = \mathrm{sign}(\vec{E}\cdot\vec{B})\sqrt{B_0^2},$$

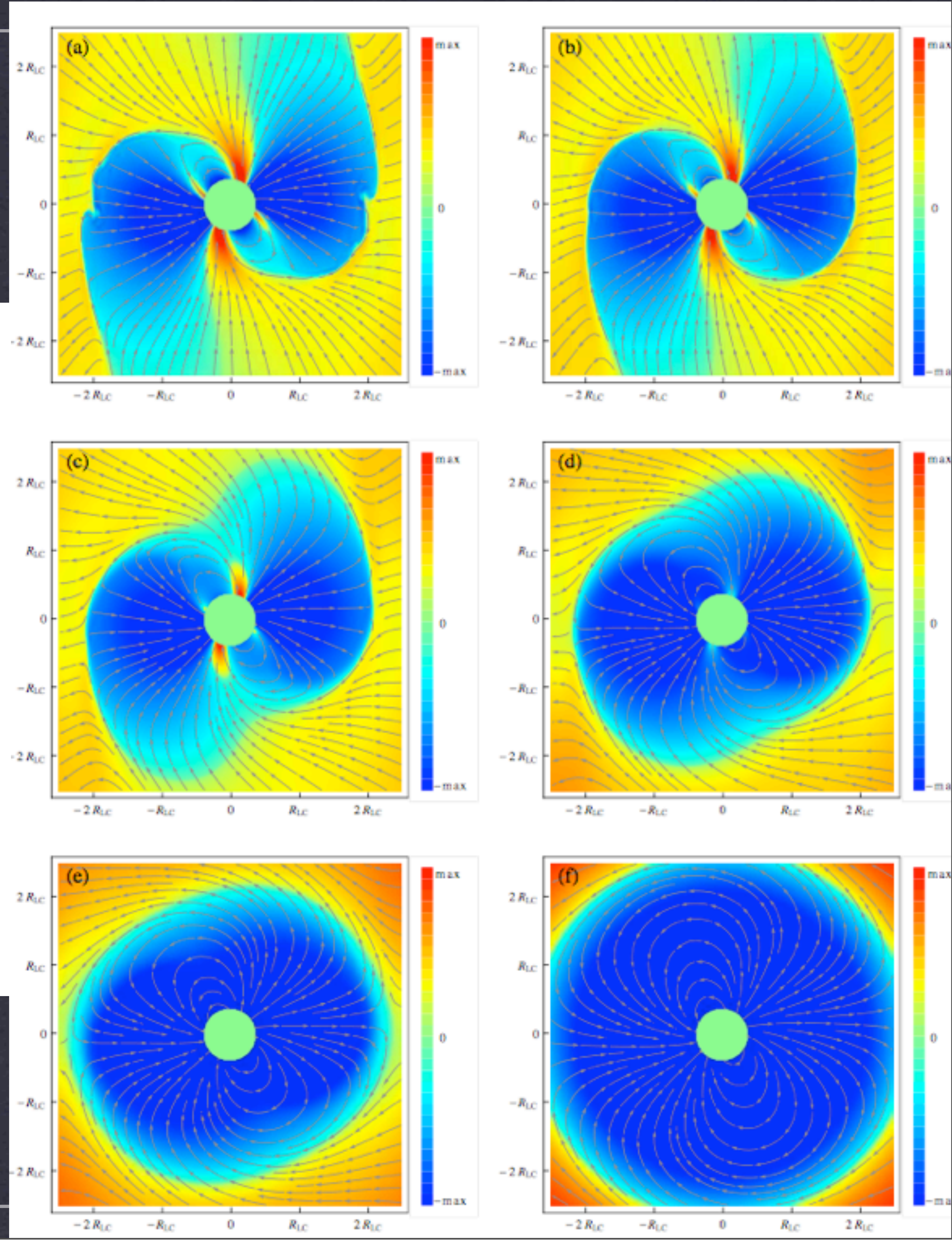
cf. Lyutikov 03
Gruzinov 07-11

Li, AS, Tchekhovskoy, 2011
also, Kalapotharakos et al 11

Resistive:

Vary σ/Ω

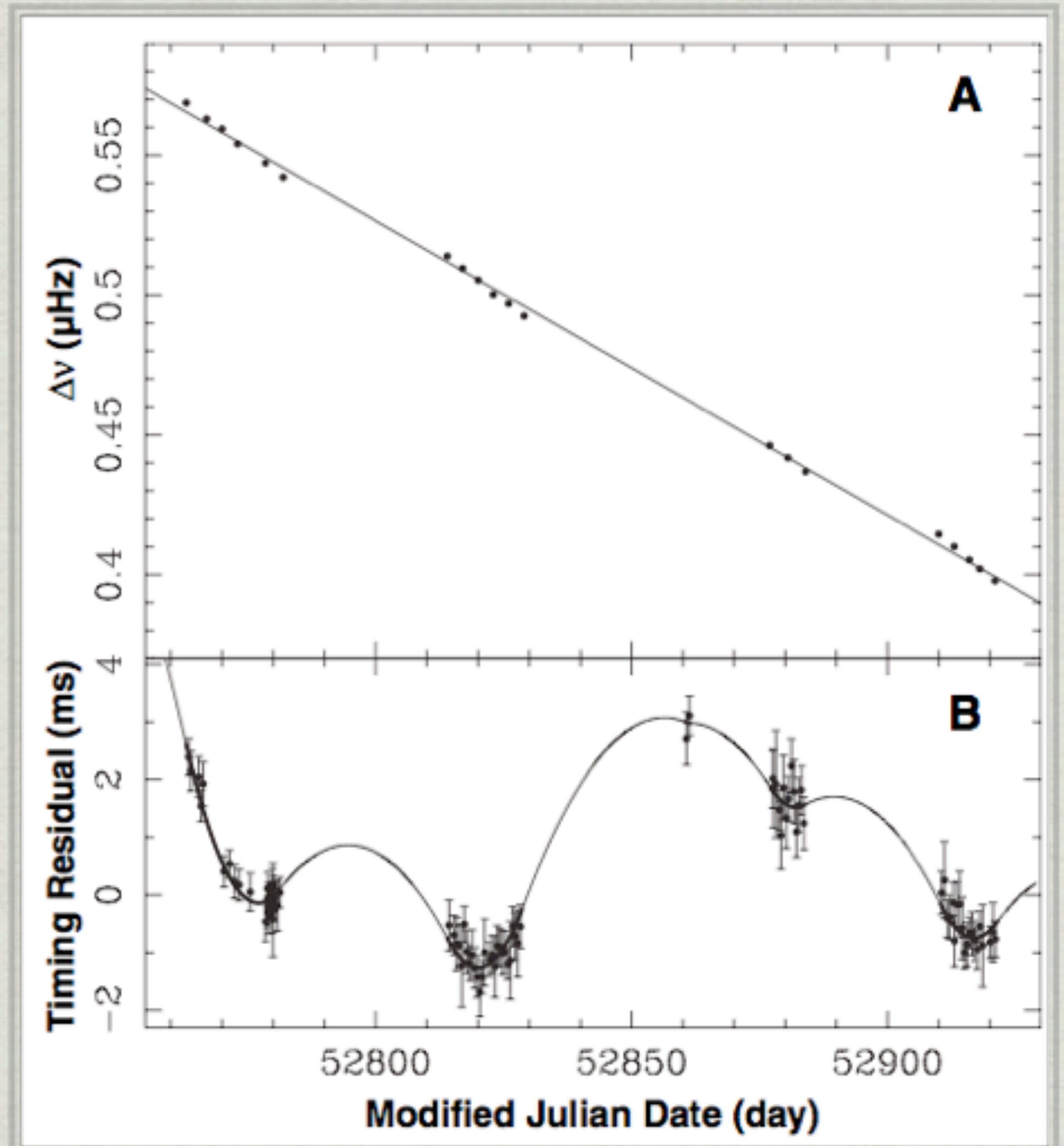




Spin-down power

Application: intermittent pulsars

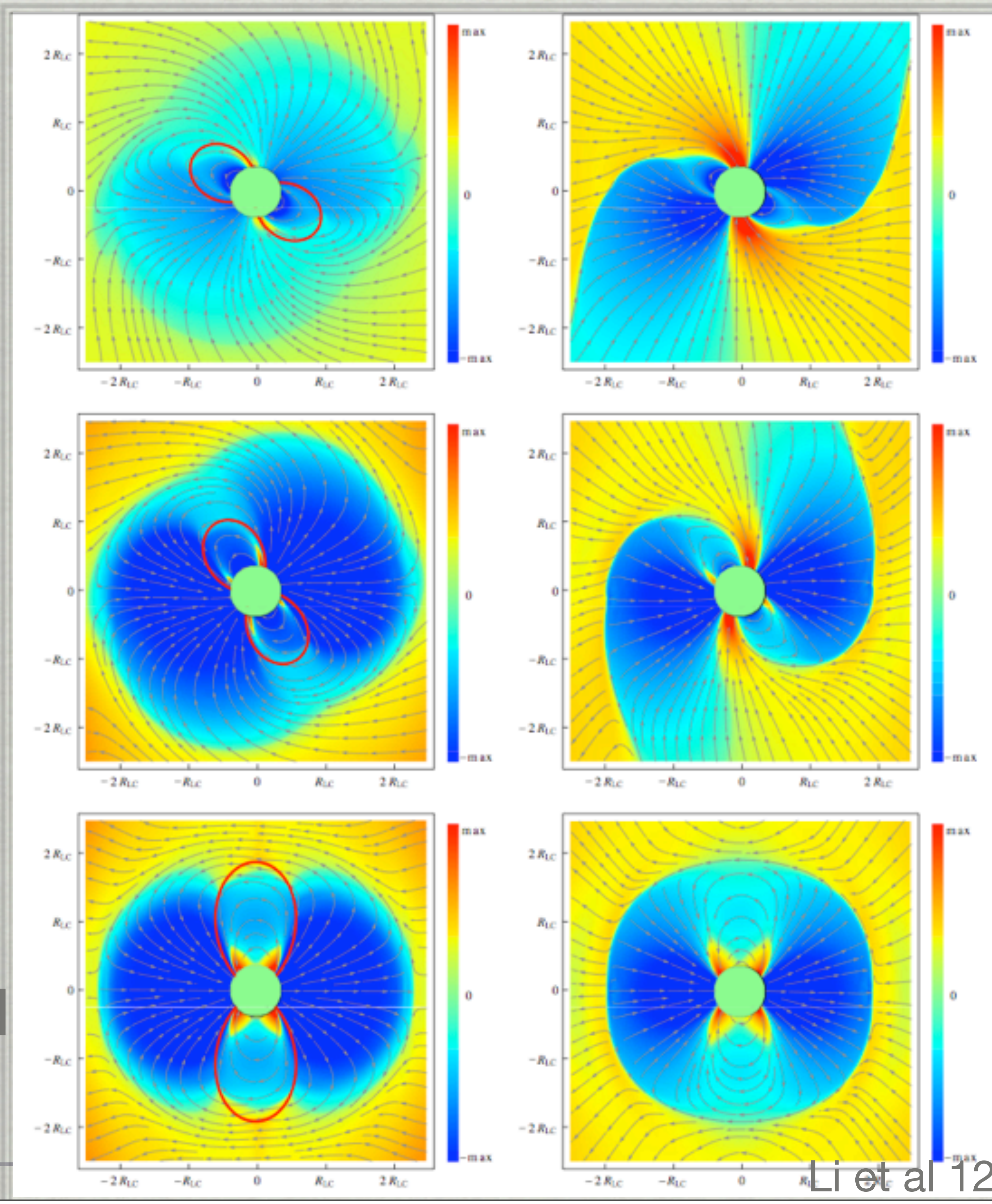
- Intermittent pulsars display changes in spin-down power when they are ON and OFF in radio by factor >1.5
- One possibility: conducting closed zone, vacuum-like open zone; Interrupted plasma production



Kramer et al 06

Application: intermittent pulsars

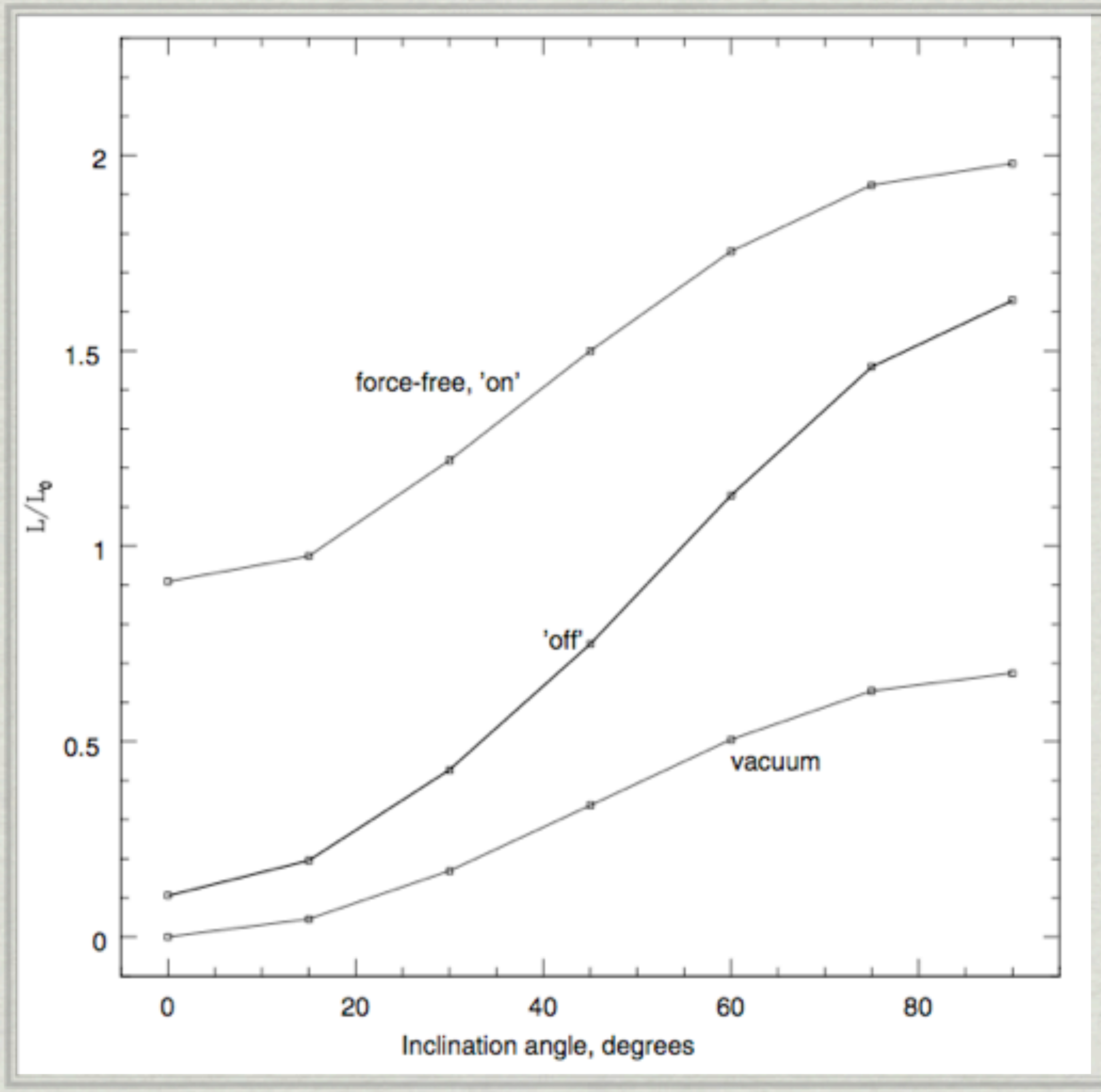
- Intermittent pulsars display changes in spin-down power when they are ON and OFF in radio by factor >1.5
- One possibility: conducting closed zone, vacuum-like open zone; Interrupted plasma production



Li et al 12

Application: intermittent pulsars

- Factor of > 1.5 can be explained with “hybrid” vacuum-conducting magnetosphere.
- The physical origin of switch is completely unclear.

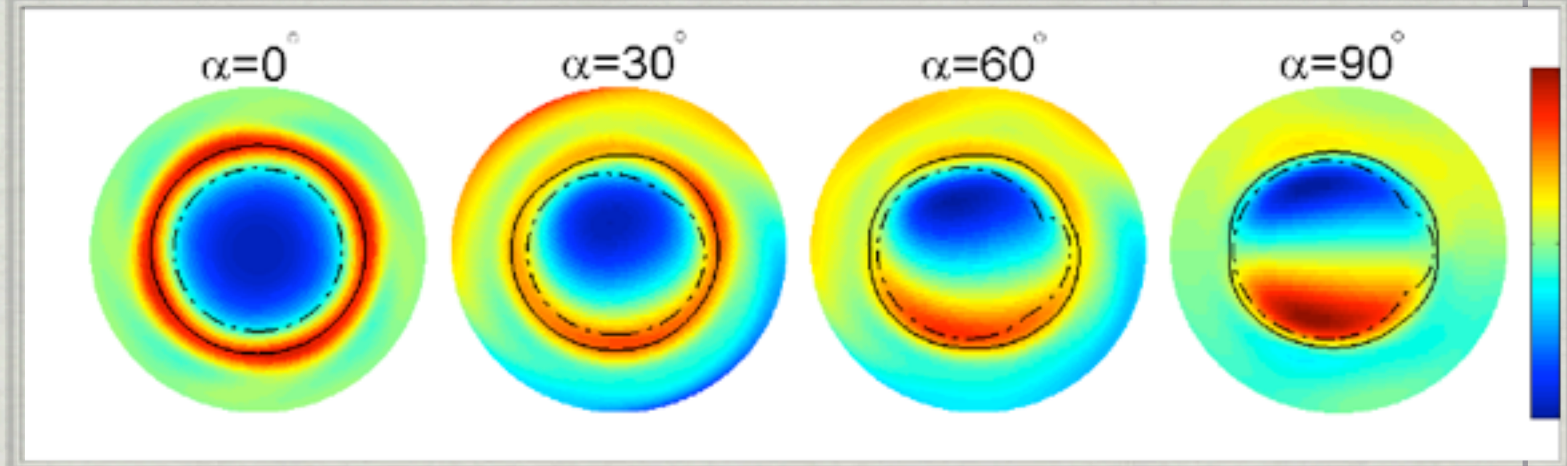


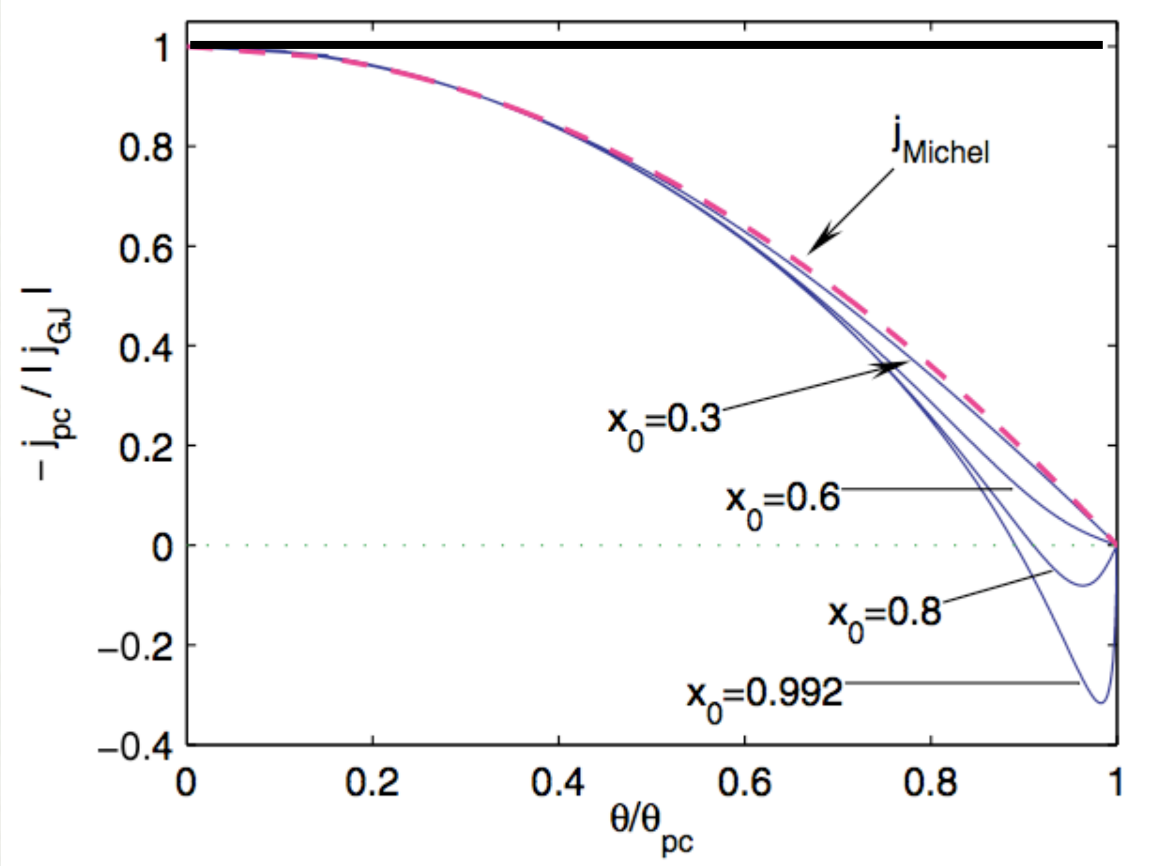
Li et al 12

Recent advances:

- Better understanding of the cascades and driving of current (see Timokhin's talk)
- Polar cascades can supply current both > and < than GJ current. Implies time-dependence. Interestingly, current <GJ does not pair produce.

Current density on polar cap





$j<j_{GJ}$

Timokhin 06

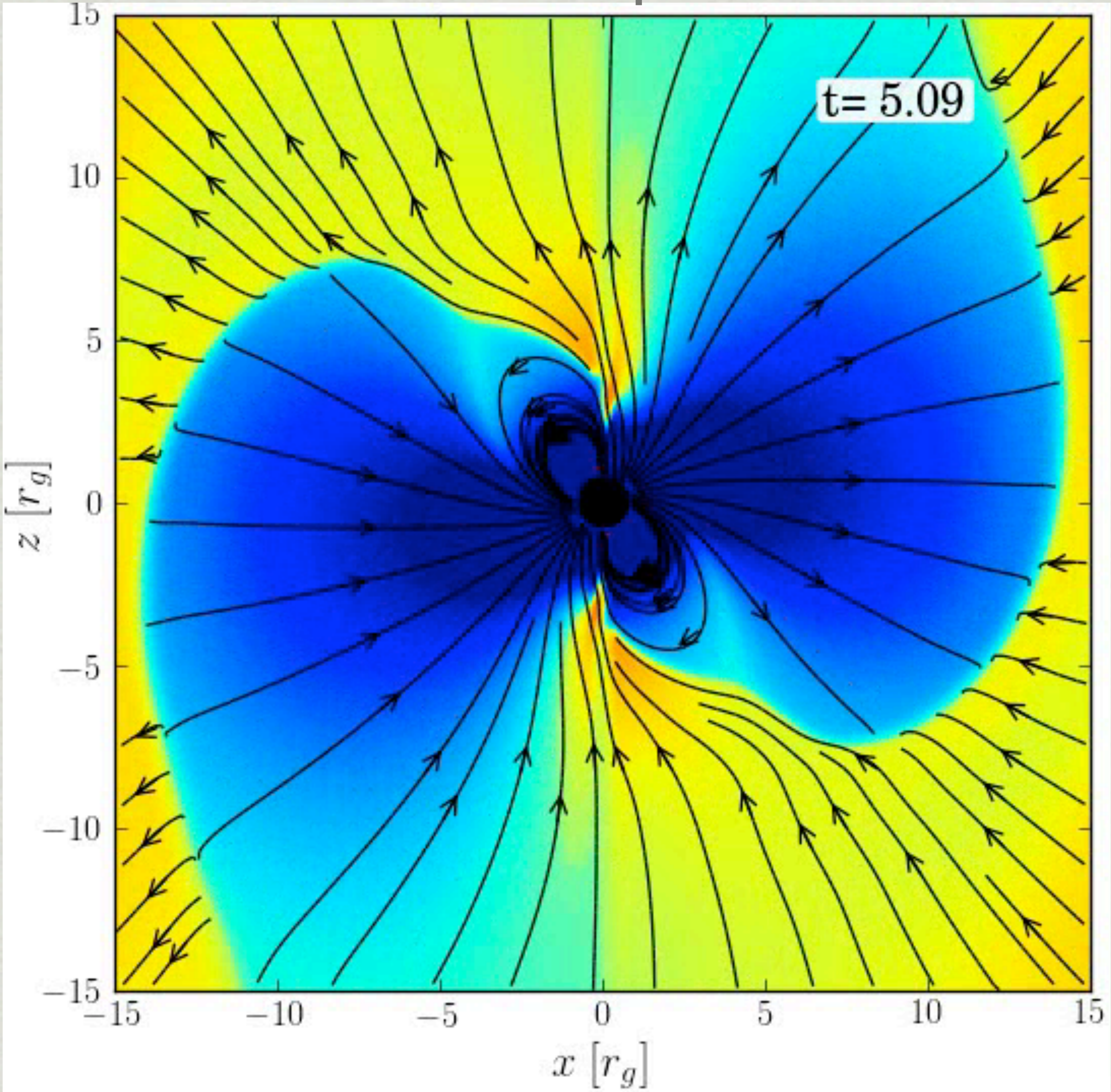
Recent advances:

- Full RMHD is now in 3D!
- Oblique rotator can now be studied in ideal MHD (Tchekhovskoy, AS, Li 2013)

Recent advances:

- Full RMHD is now in 3D!
- Oblique rotator can now be studied in ideal MHD (Tchekhovskoy, AS, Li 2013)
- Spherical grid which allows non-axisymmetric solutions. Magnetization > 100. Fixed magnetization inside 0.7 LC

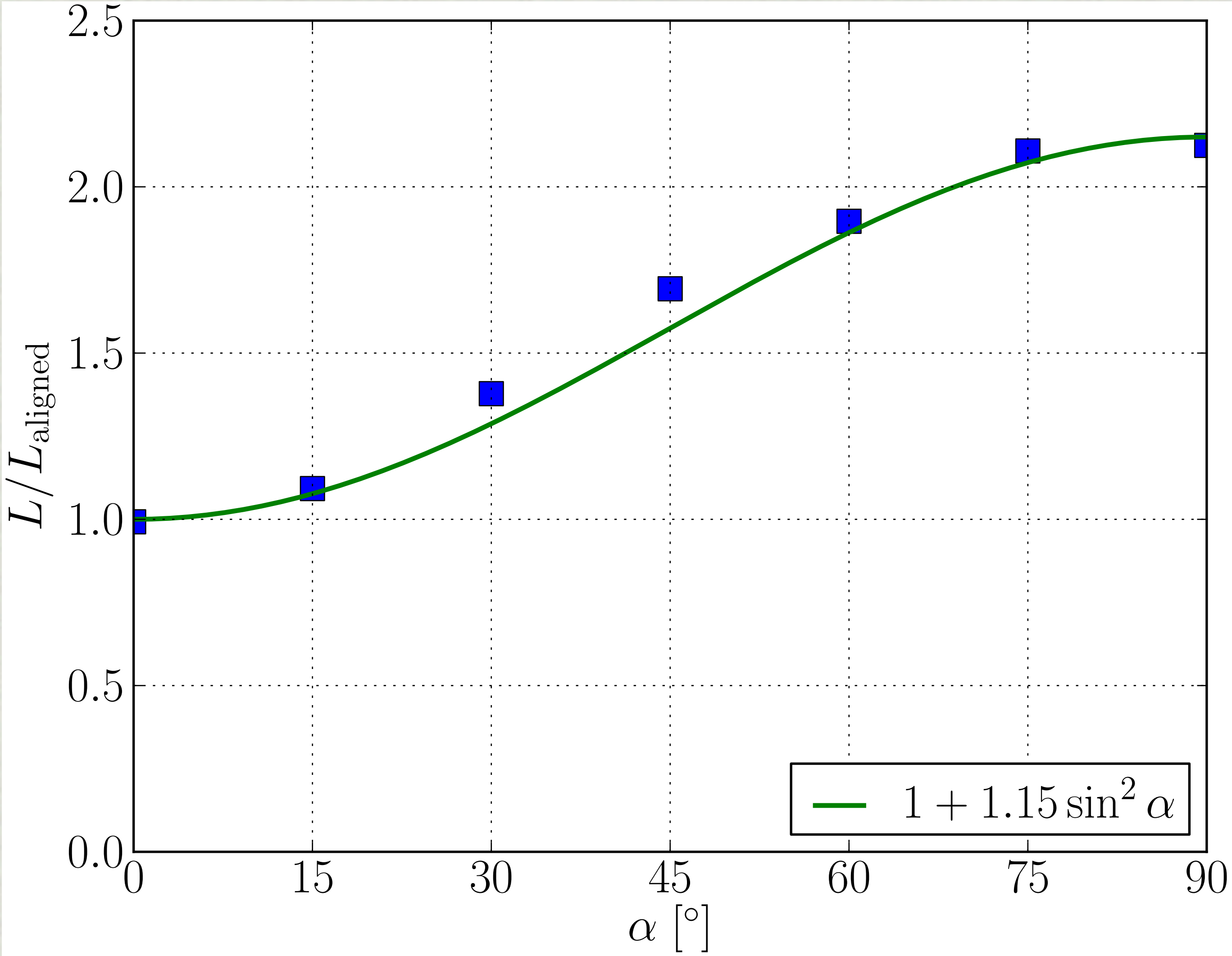
color: out of plane B field



Recent advances:

- Full RMHD is now in 3D!
- Oblique rotator can now be studied in ideal MHD (Tchekhovskoy, AS, Li 2013)
- Spherical grid which allows non-axisymmetric solutions. Magnetization > 100.

Spin down luminosity



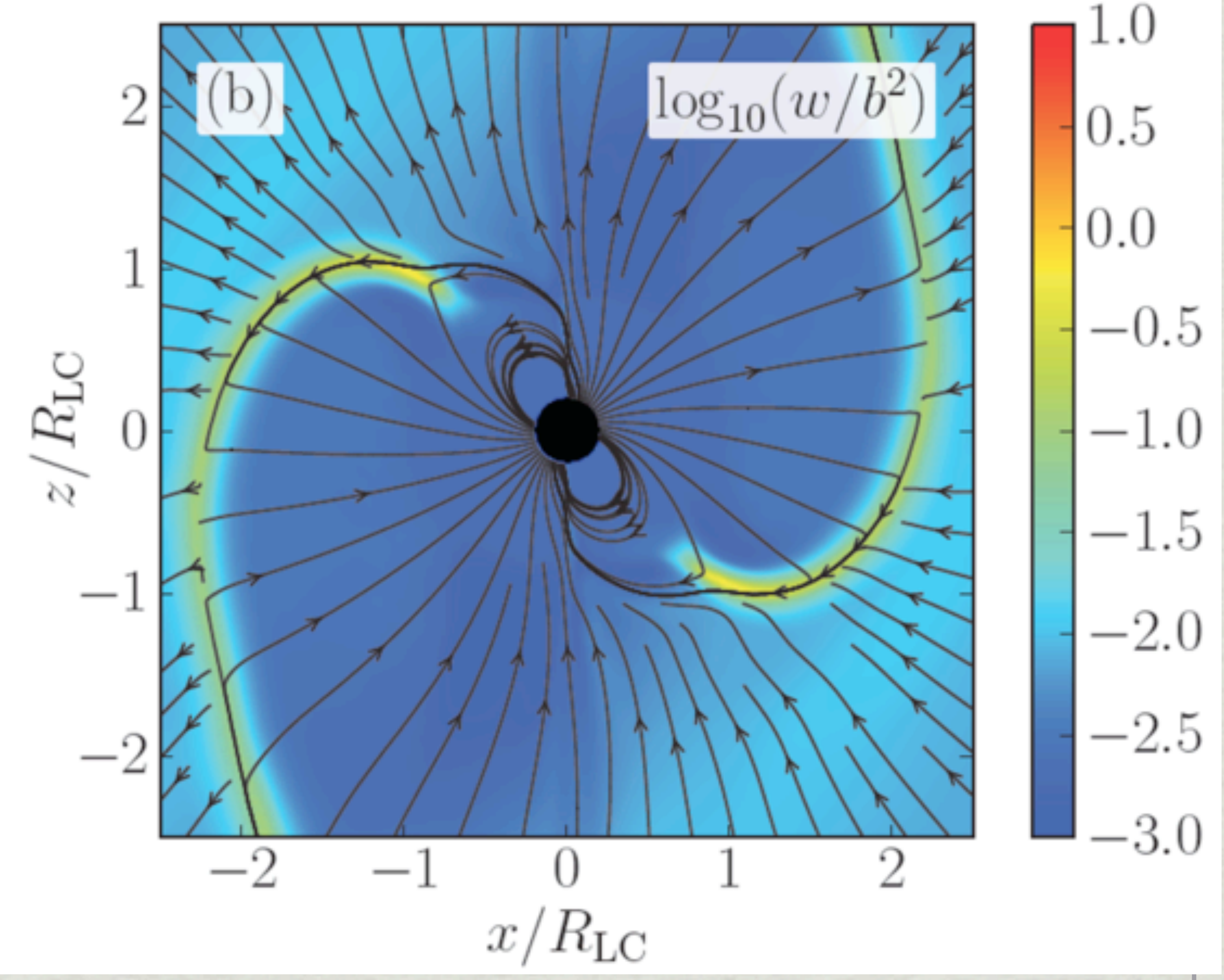
Obliqueness

Variation with angle is similar to force-free

Recent advances:

- Thermal pressure support in the sheet
- Low dissipation, <10% (cf. Gruzinov's 50%)
- Big uncertainty: velocity along the field lines is not self-consistent (depends on cascades).

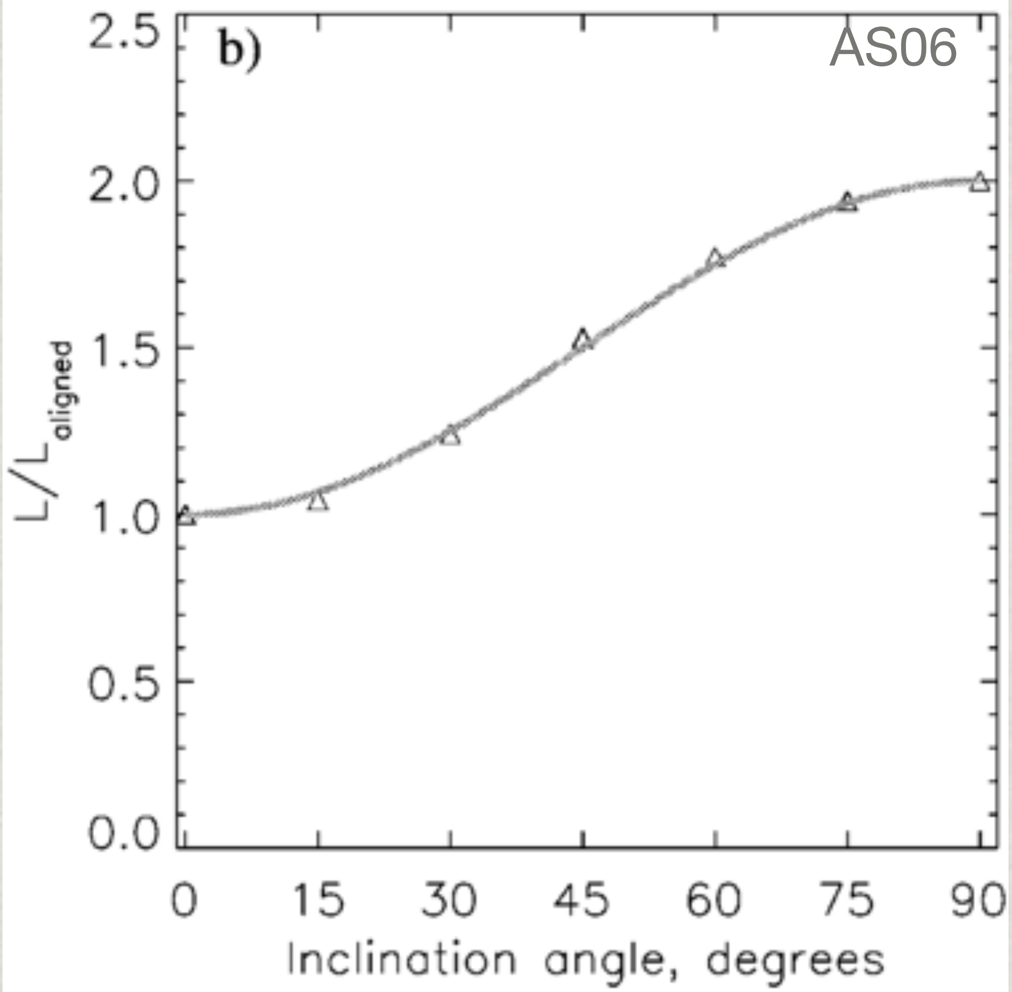
Magnetization

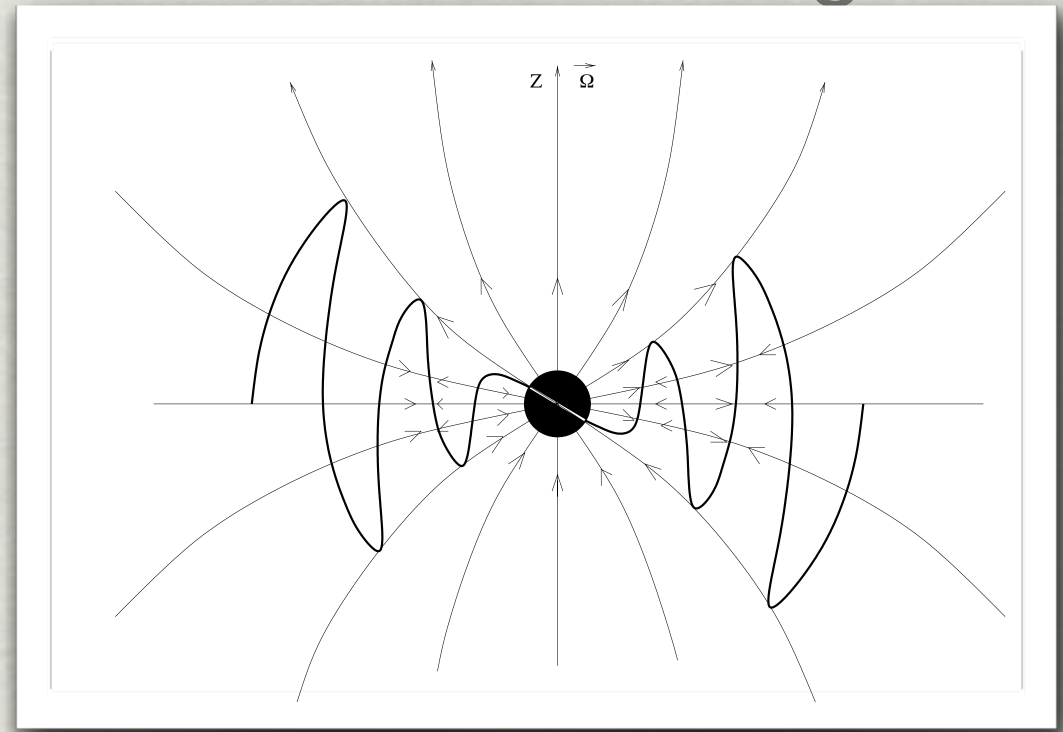


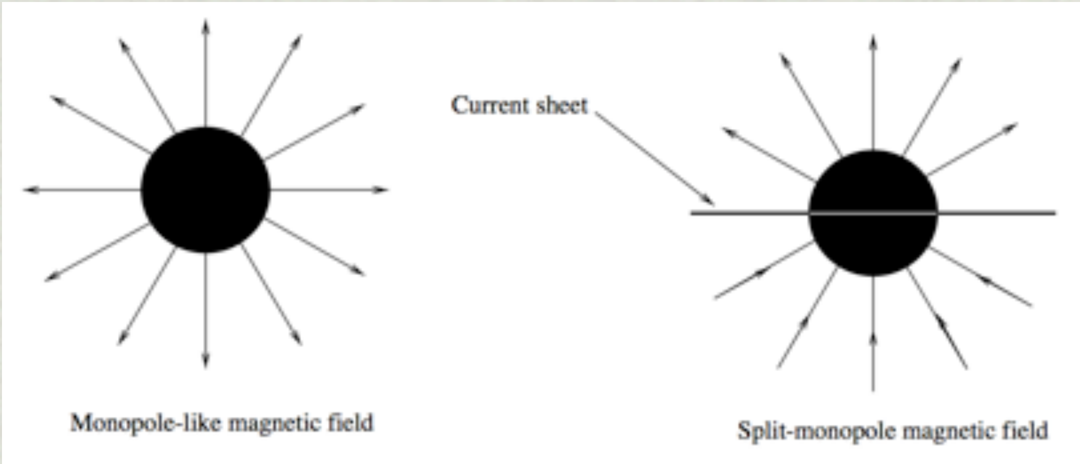
Current sheet is formed and has gas pressure in it

More on the magnetosphere

- Can we understand 1+sin^2 alpha dependence of spin-down?
- Bogovalov 1999 split monopole: spin-down constant with angle!



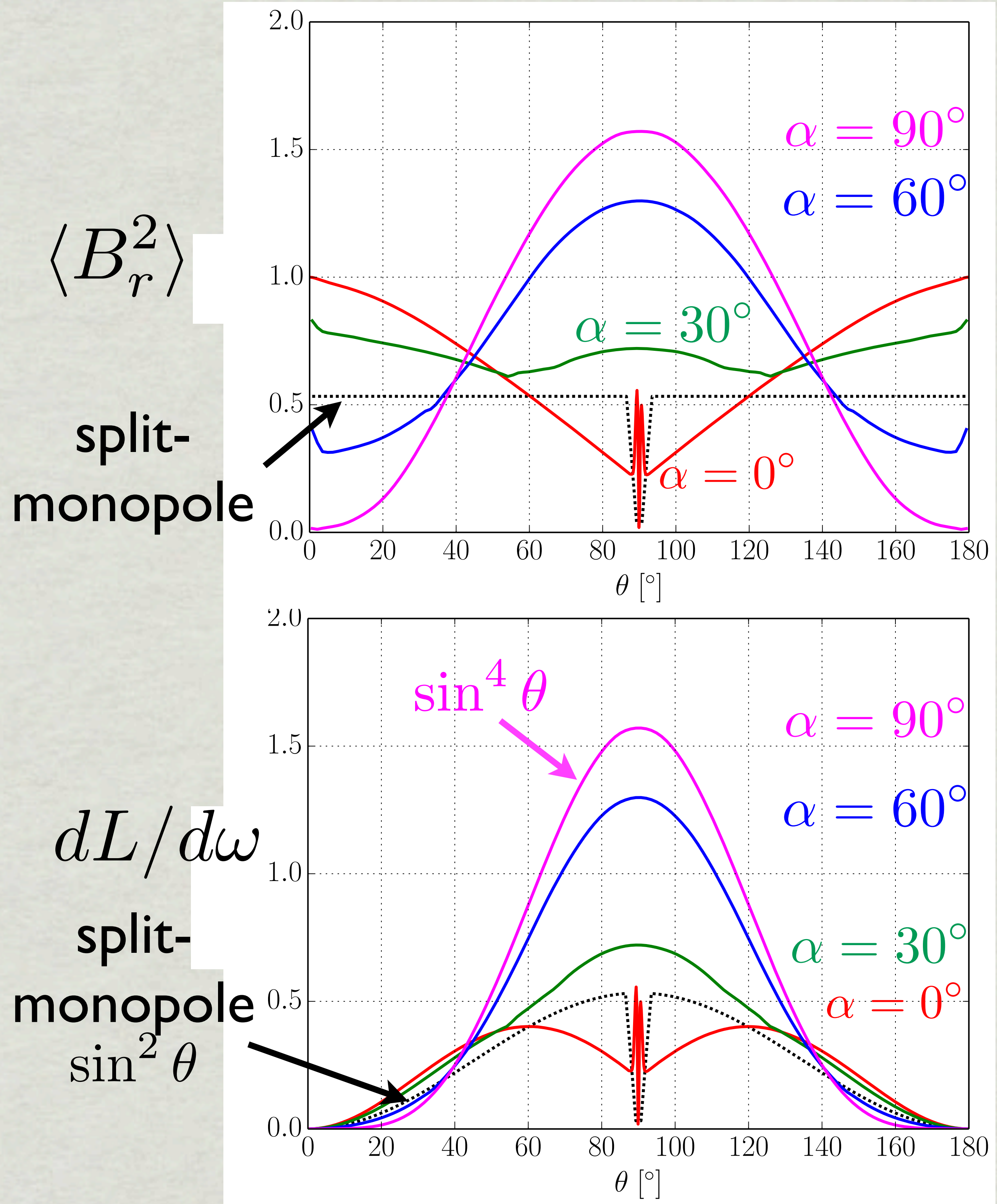




Are asymptotic field lines like split-monopole?

More on the magnetosphere

- B-field is equatorially-concentrated
- Wind luminosity is more equatorially concentrated than monopole
- This effect needs to be included for gamma-ray emission light curve calculation and PWN models.



Tchekhovskoy, Spitkovsky, Li 2013,
Tchekhovskoy, Philippov, Spitkovsky in prep.

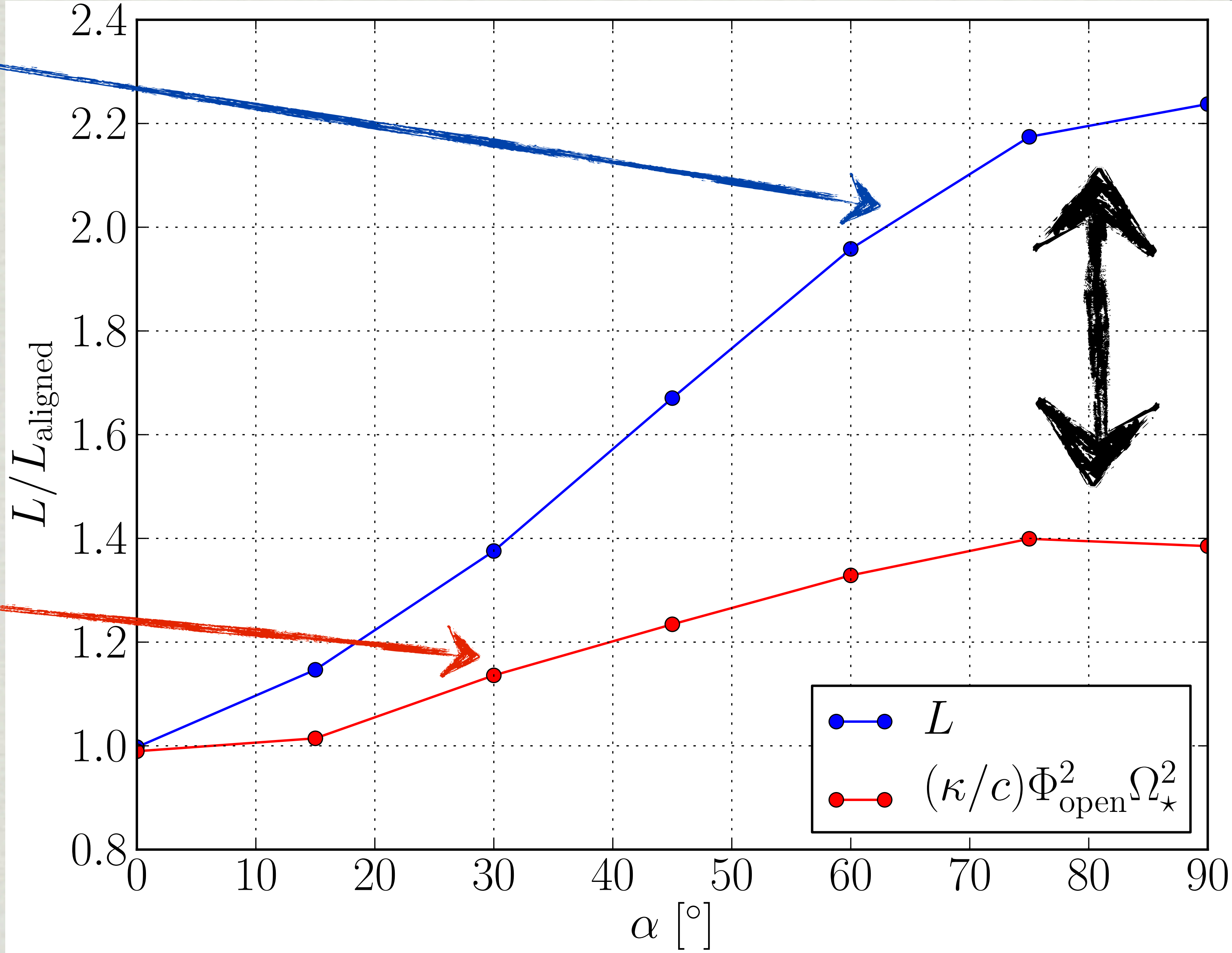
Field Non-uniformity Explains Enhanced Spindown of Oblique Pulsars

Enhanced spindown due to non-uniformity of B-field?

Assumption of uniform B-field under-predicts spindown

$$P_{\rm NS} = \frac{\kappa}{c}\Phi_{\rm open}^2\Omega_\star^2$$

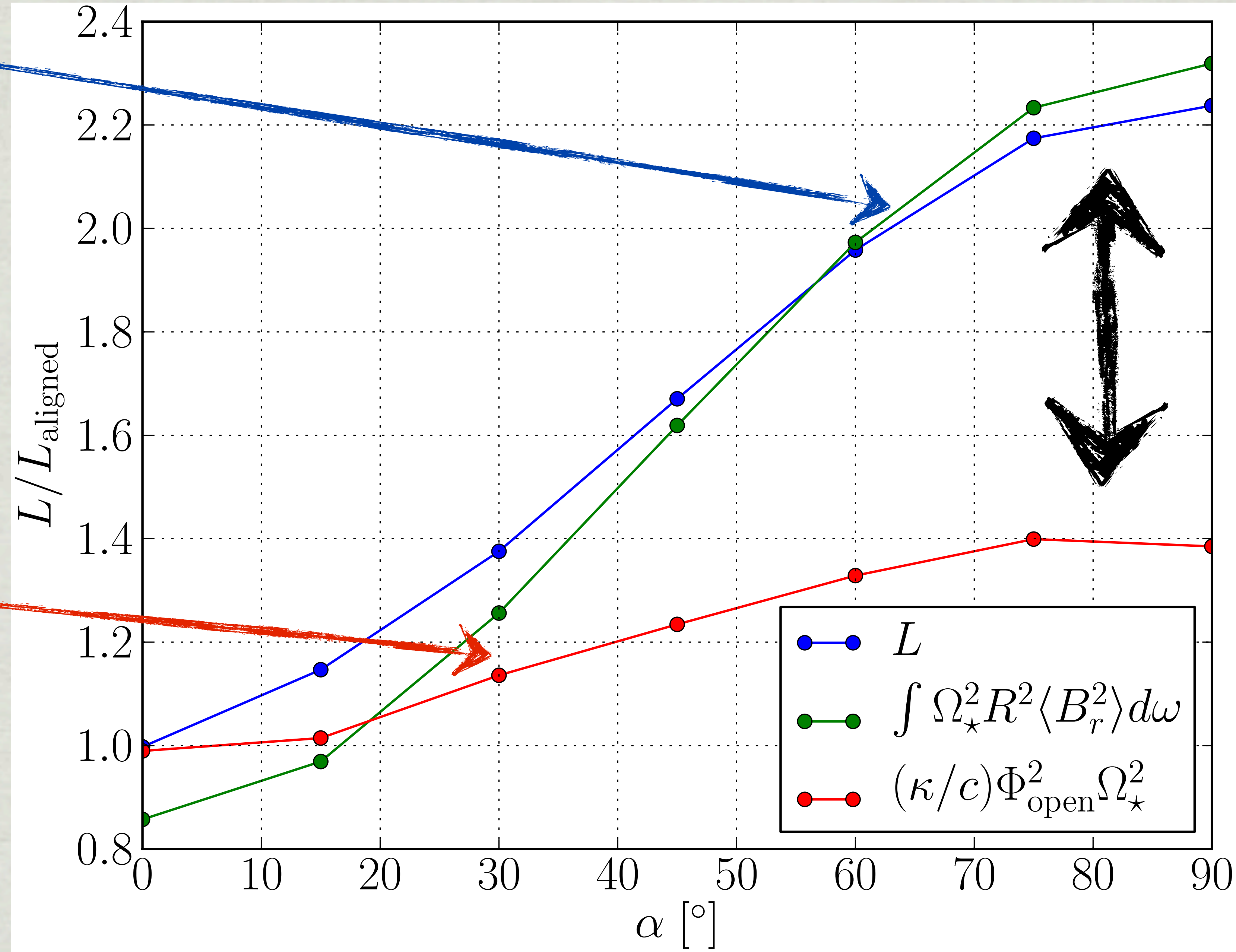
(Spitkovsky'06, Petri'12, AT, Spitkovsky, Li'13)



Field Non-uniformity Explains Enhanced Spindown of Oblique Pulsars

Enhanced spindown due to non-uniformity of B-field?

(Spitkovsky'06, Petri'12, AT, Spitkovsky, Li'13)



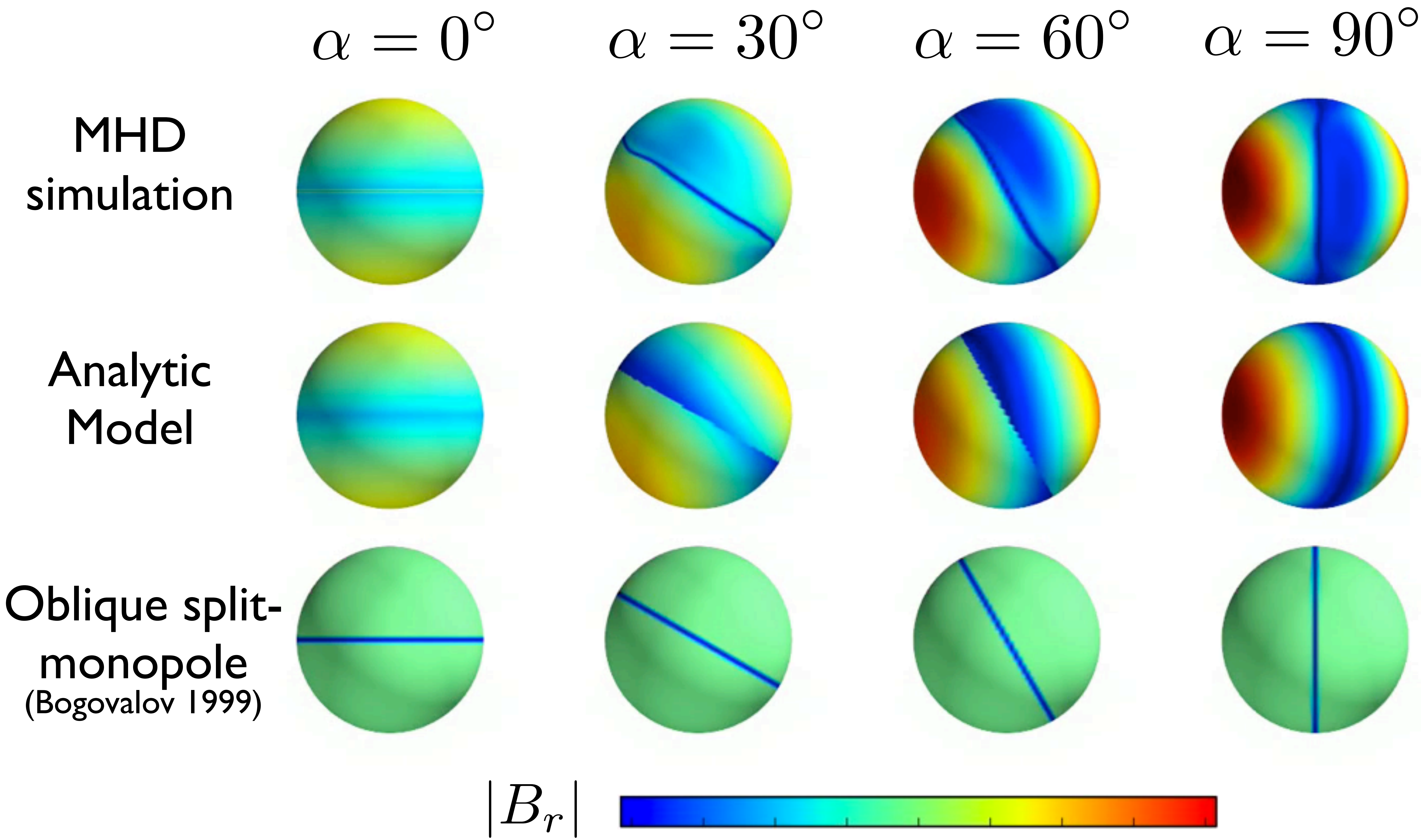
Assumption of uniform B-field under-predicts spindown

$$P_{\rm NS} = \frac{\kappa}{c}\Phi^2_{\rm open}\Omega_\star^2$$

Tchekhovskoy, Philippov, Spitkovsky in prep.

just Br variation from inclined dipolar field gives $1+\sin^2\alpha$

Analytic fitting model of 3D pulsar wind



Fitting model for oblique pulsar wind is now available

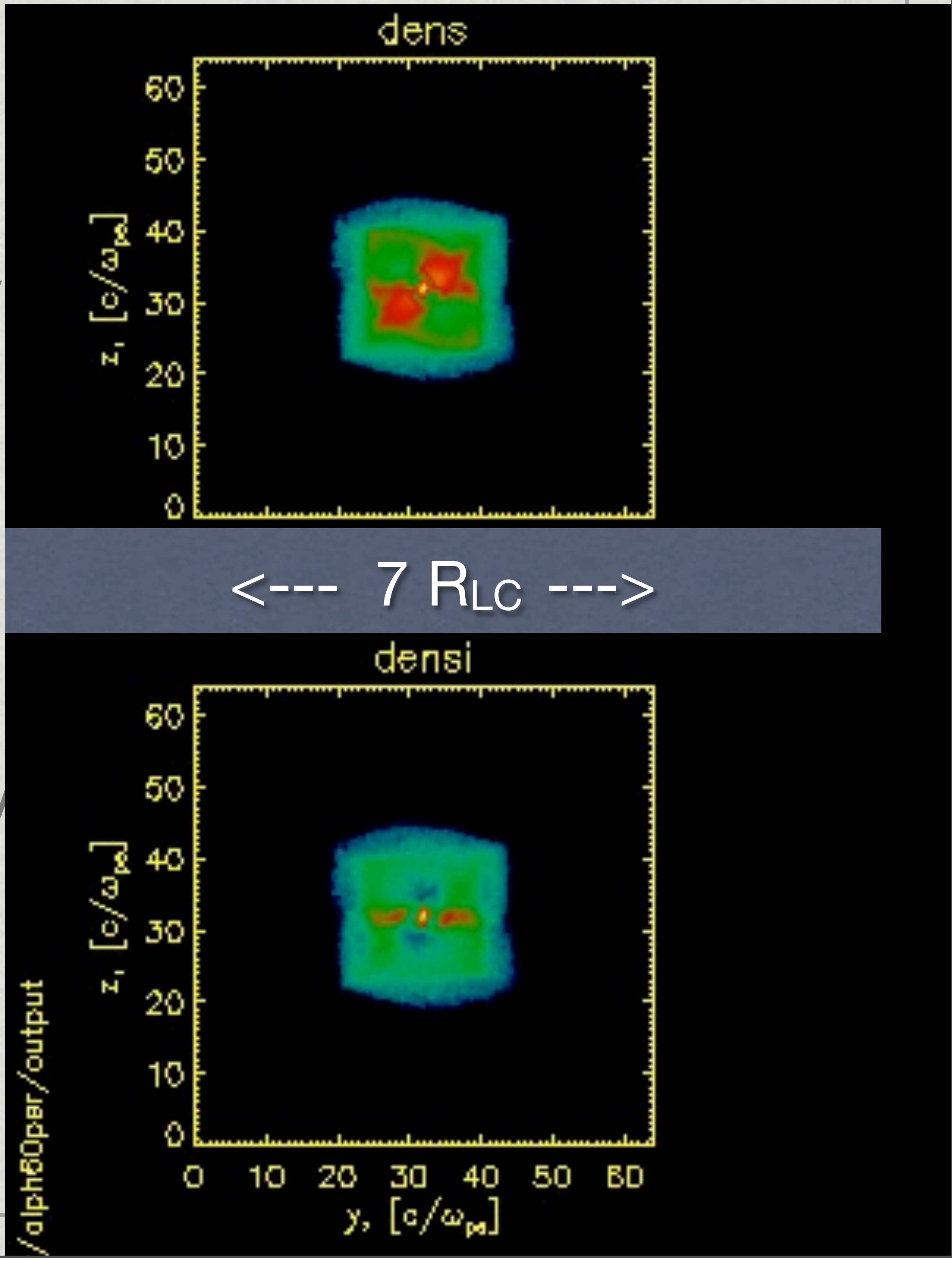
More recent advances:

Vacuum field + test particles

- Full particle modeling with PIC (particle-in-cell) in 3D (AS in prep).
- Idea: supply enough neutral plasma and “let it figure it out.”
- $E=E_{plasma}+E_{Deutsch}$; $B=B_{plasma}+B_{Deutsch}$

Full density

Ion density



Step 1: Test electrons & ions become distributed in different locations -- no clear sheet

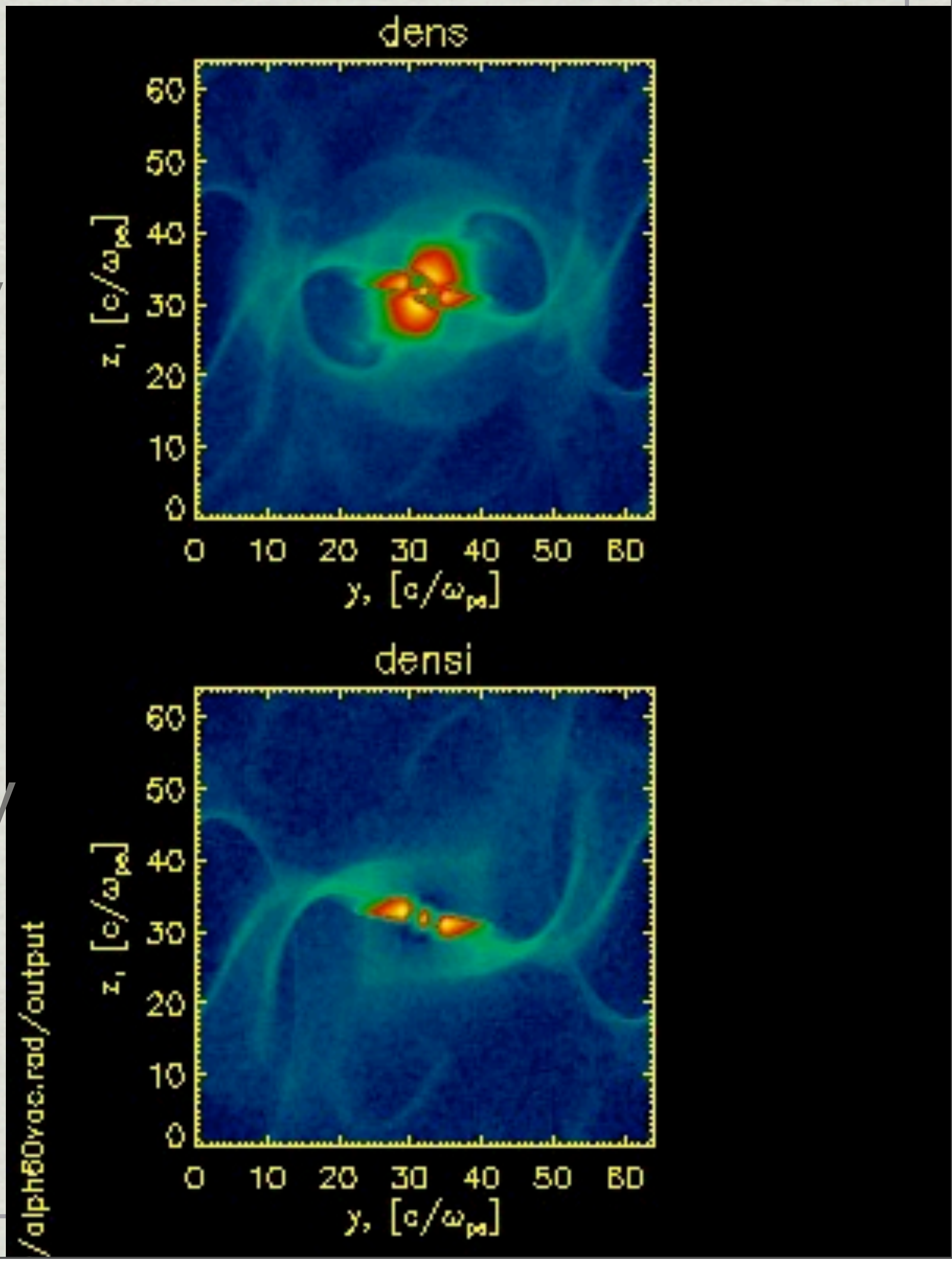
Recent advances:

Vacuum field + test particles

- Full particle modeling with PIC (particle-in-cell) in 3D (AS in prep).
- Idea: supply enough neutral plasma and "let it figure it out."
- $E=E_{plasma}+E_{Deutsch}$; $B=B_{plasma}+B_{Deutsch}$

Full density

Ion density



Step 1: Test electrons & ions become distributed in different locations -- no clear sheet

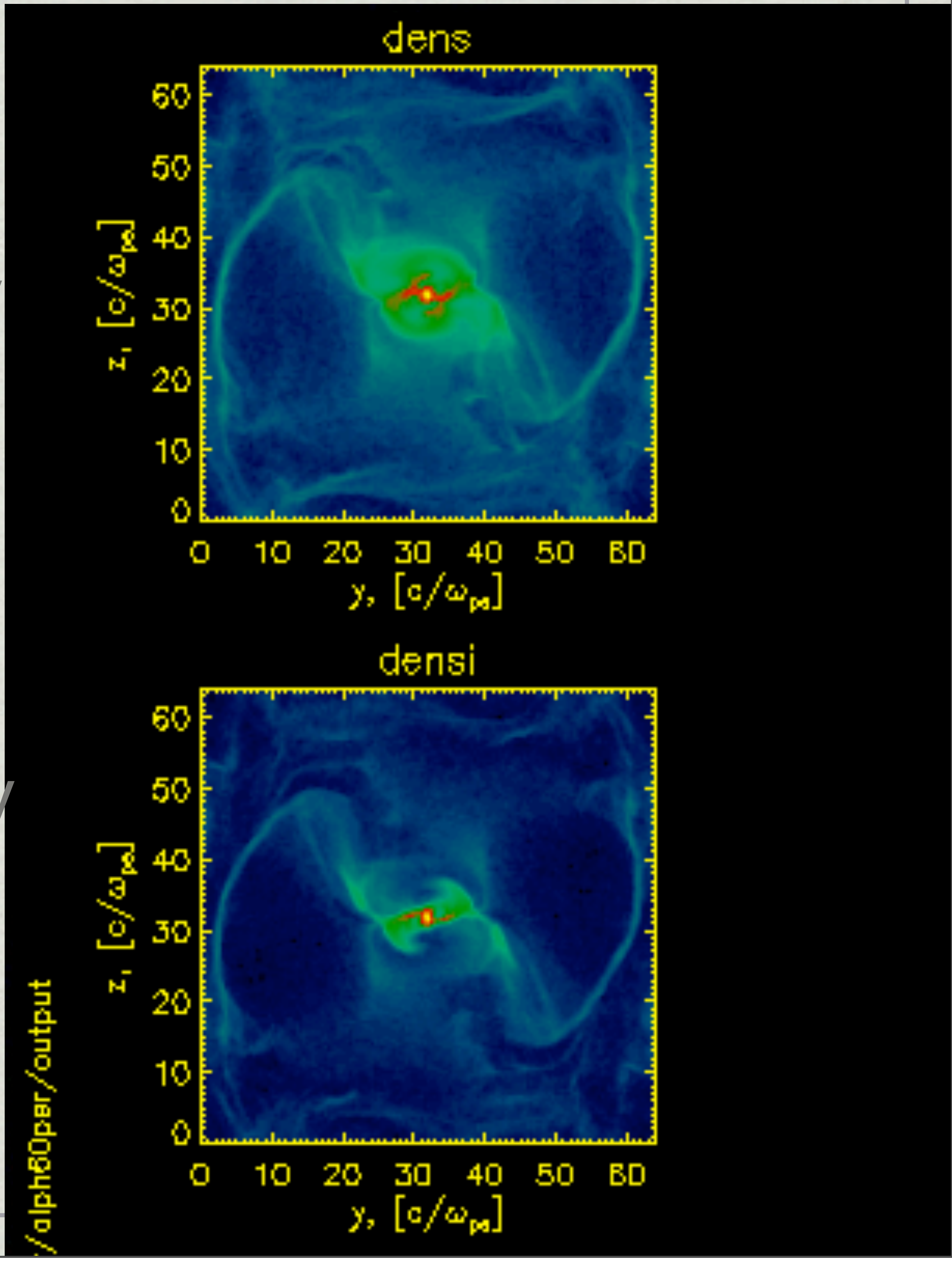
Recent advances:

Vacuum field + plasma

- Full particle modeling with PIC (particle-in-cell) in 3D.
- Turn on plasma back reaction:

Full density

Ion density



Electrons & ions now are together and form a current sheet. Approaches force-free.

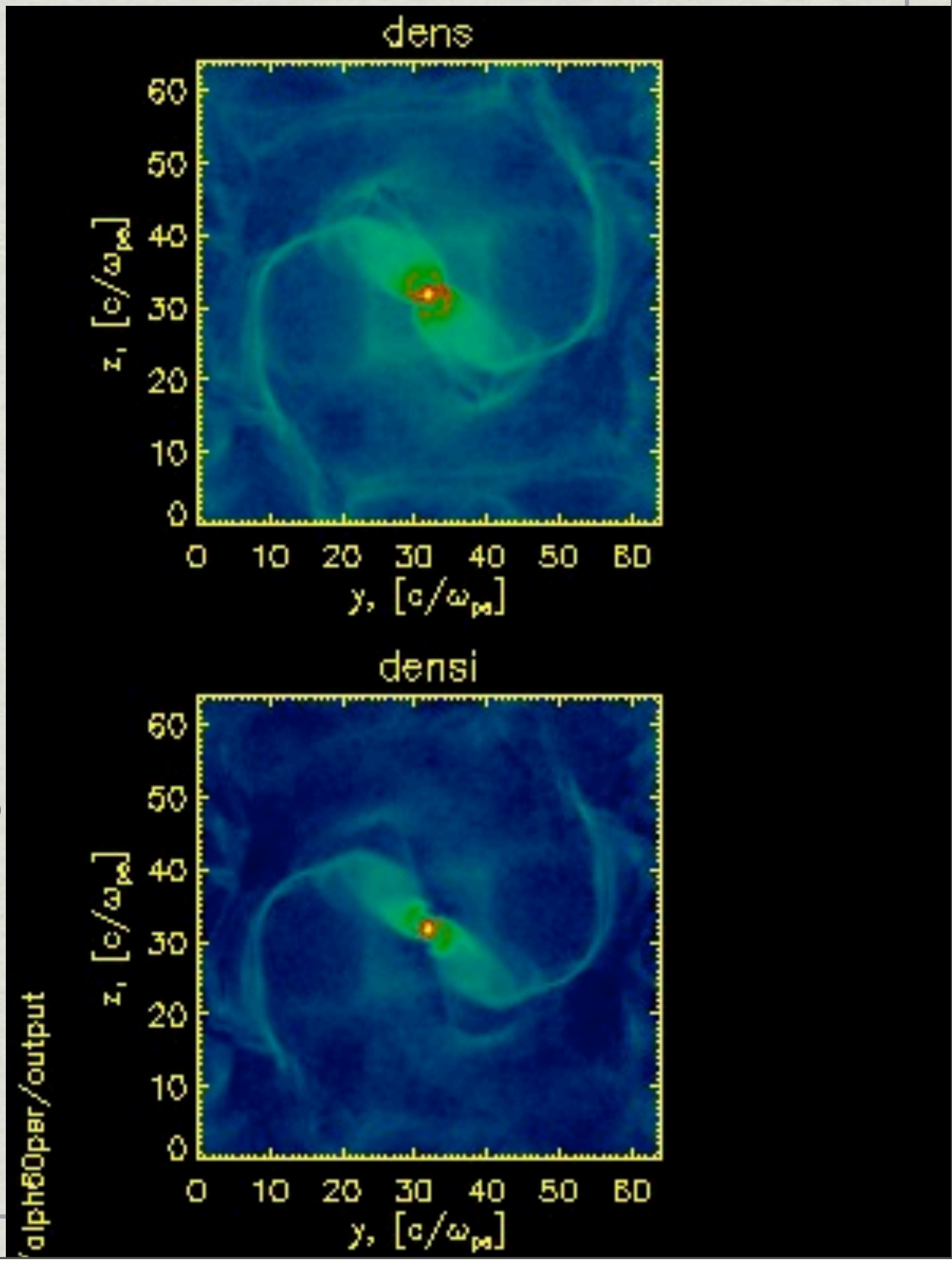
Recent advances:

Vacuum field + plasma

- In principle, such a solution has everything: acceleration, plasma velocity, reconnection.
- In practice the resolution will always be limited.
- Also, the aligned rotator part depends on good BCs on the star.

Full dens

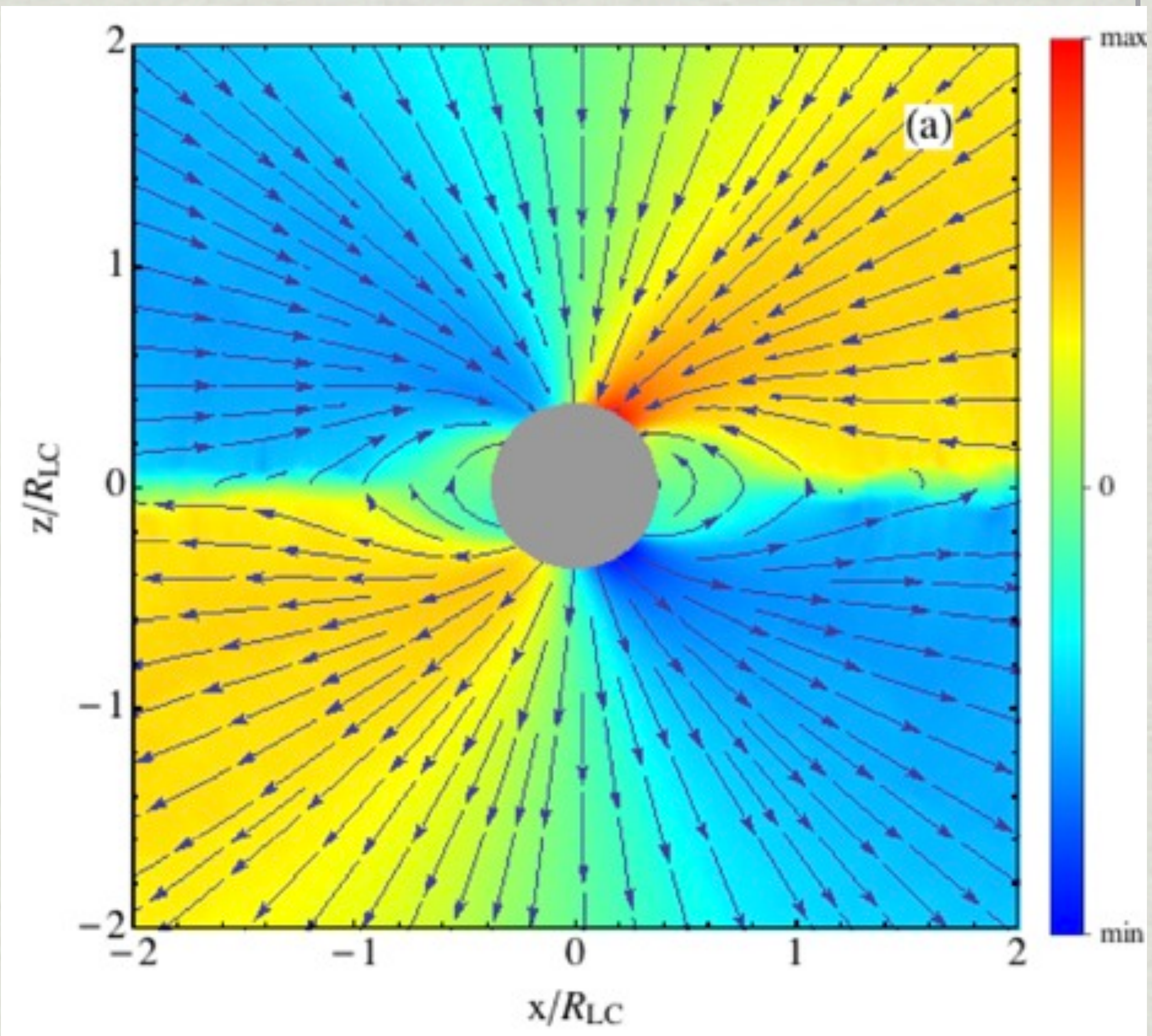
Ion dens



Ab-initio pulsars

Philippov + AS 2014

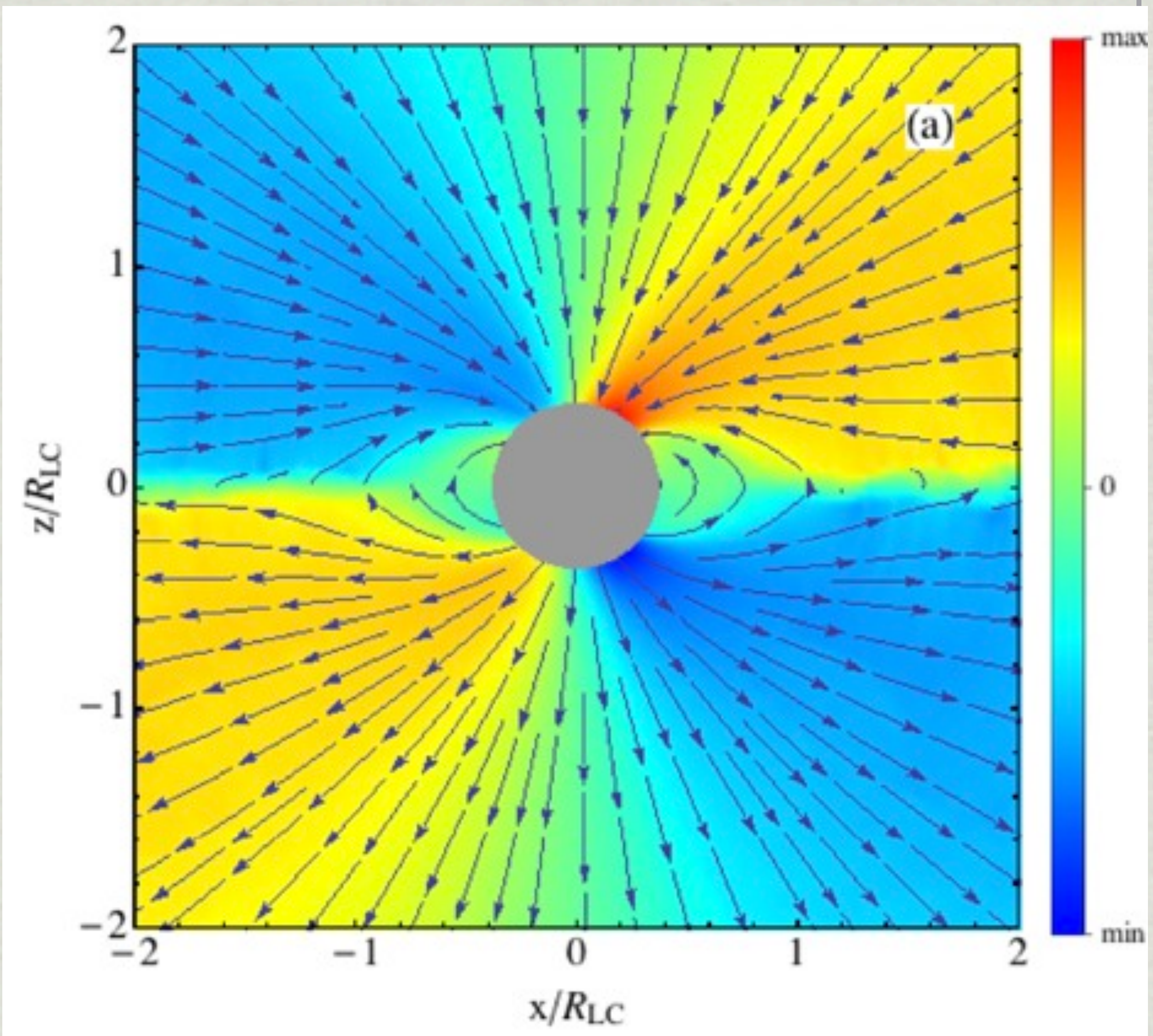
- BC on the star: space-charge limited flow, particle escape, good spherical conductor (challenge on Cartesian grid) .
- Use spherical polar coordinates (Cerutti, Belyaev) -- 2D limitation
- We used “plasma sphere” BC (see Philippov’s talk)



Ab-initio pulsars

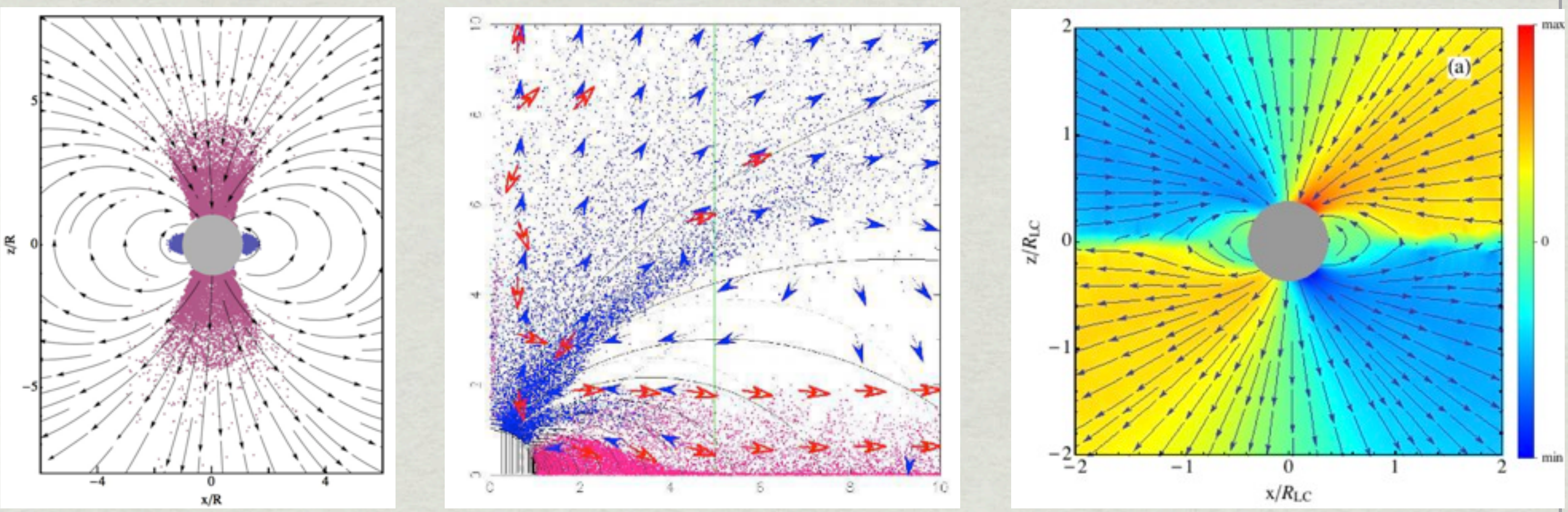
Philippov + AS 2014

- Abundant pair plasma with PIC reproduces force-free
- Small dissipation (~10% in current sheet)
- Particle acceleration mainly in the sheet
- Drift-kink instability of the sheet



Ab-initio pulsars

- There may be other solutions depending on plasma supply; we are experimenting with pair formation prescriptions.

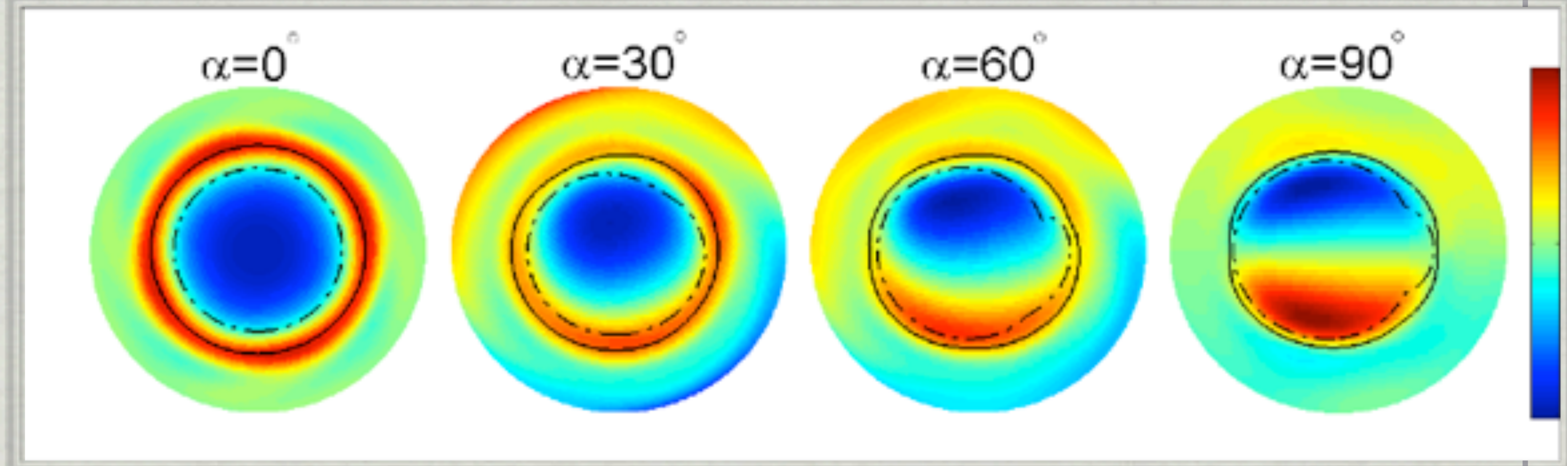


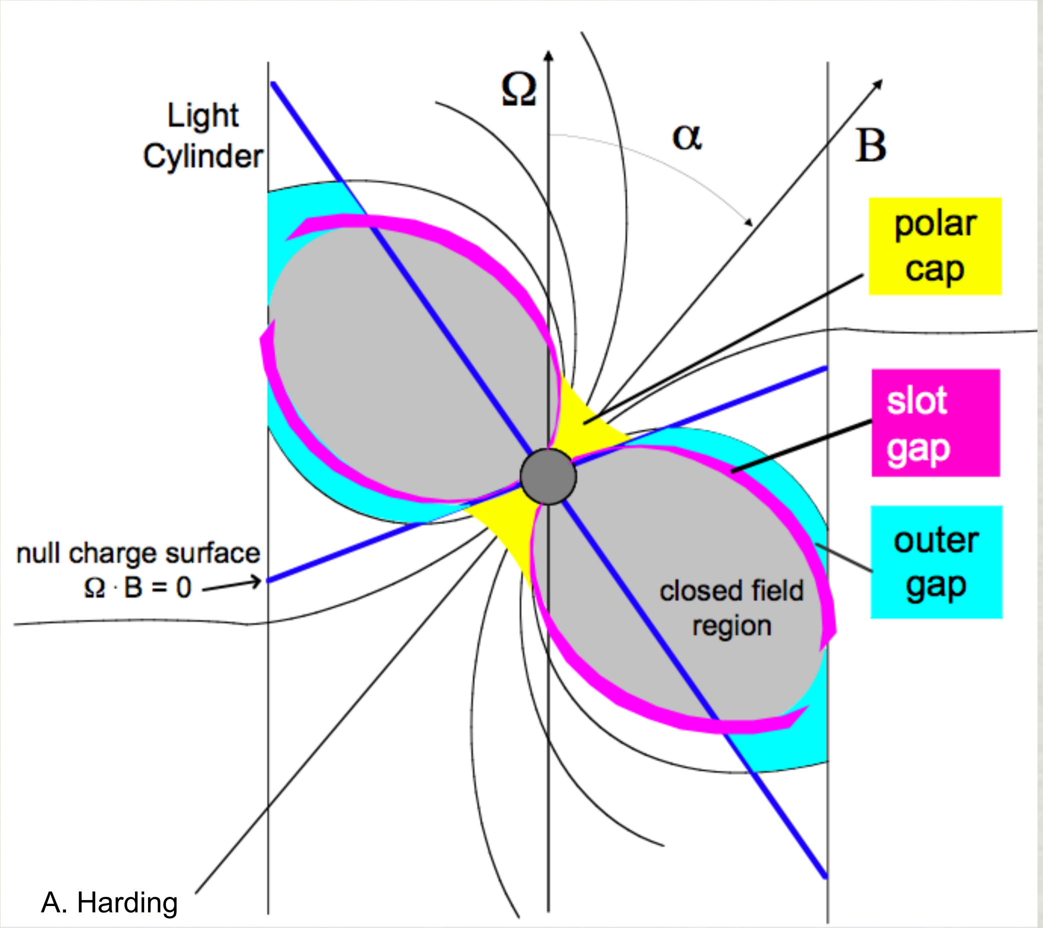
There is a class of solutions with E>B and accelerated particles (e.g. Gruzinov's talk). They must be low-multiplicity states, that may not produce abundant pulsar wind as needed by observations.

Where does emission come from?

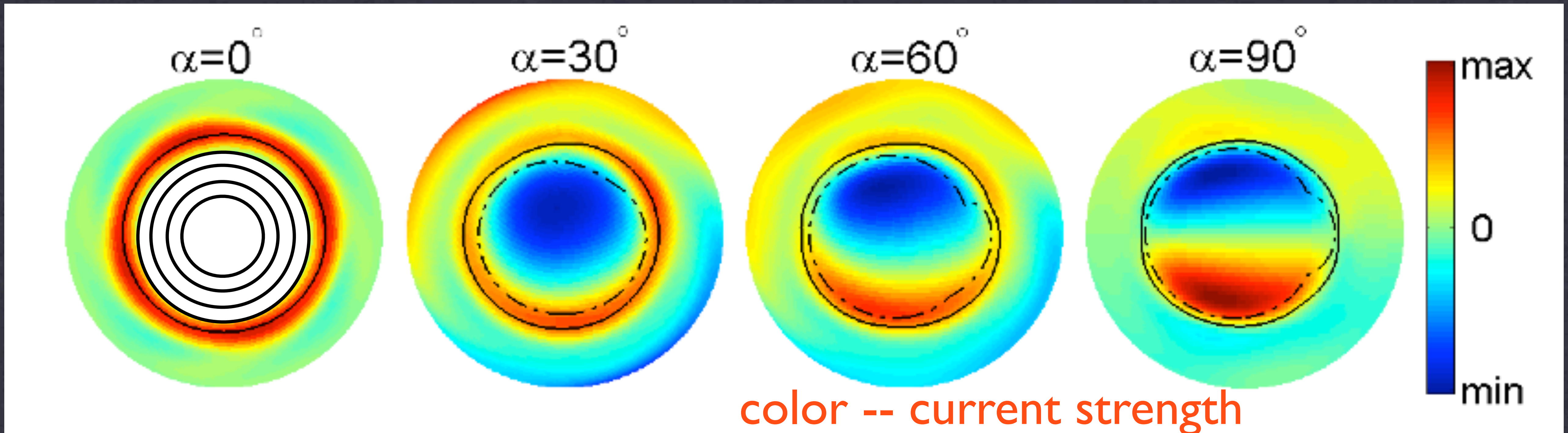
- With force-free shape of the magnetosphere at hand, emission physics can be studied again.
- Most progress so far is on the geometry of the emission so far (gamma-rays).
- Does the emission come from gap regions? Inside or outside LC?

Current density on polar cap





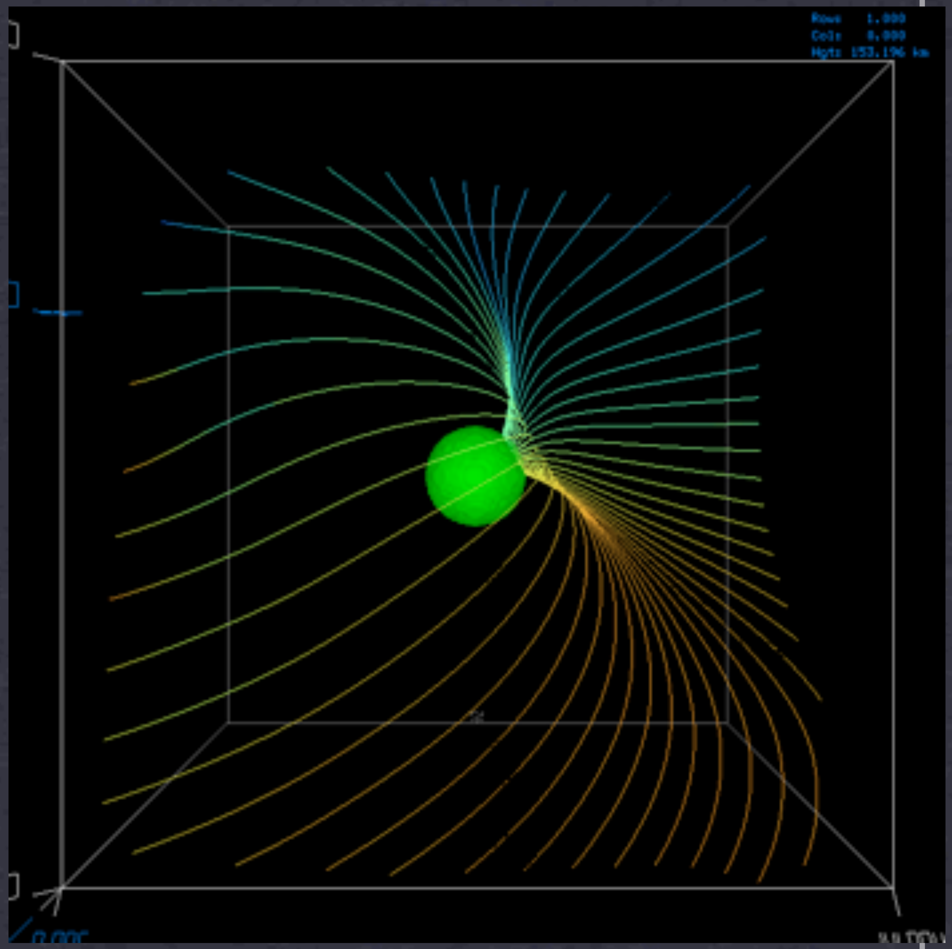
Where does emission come from?



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

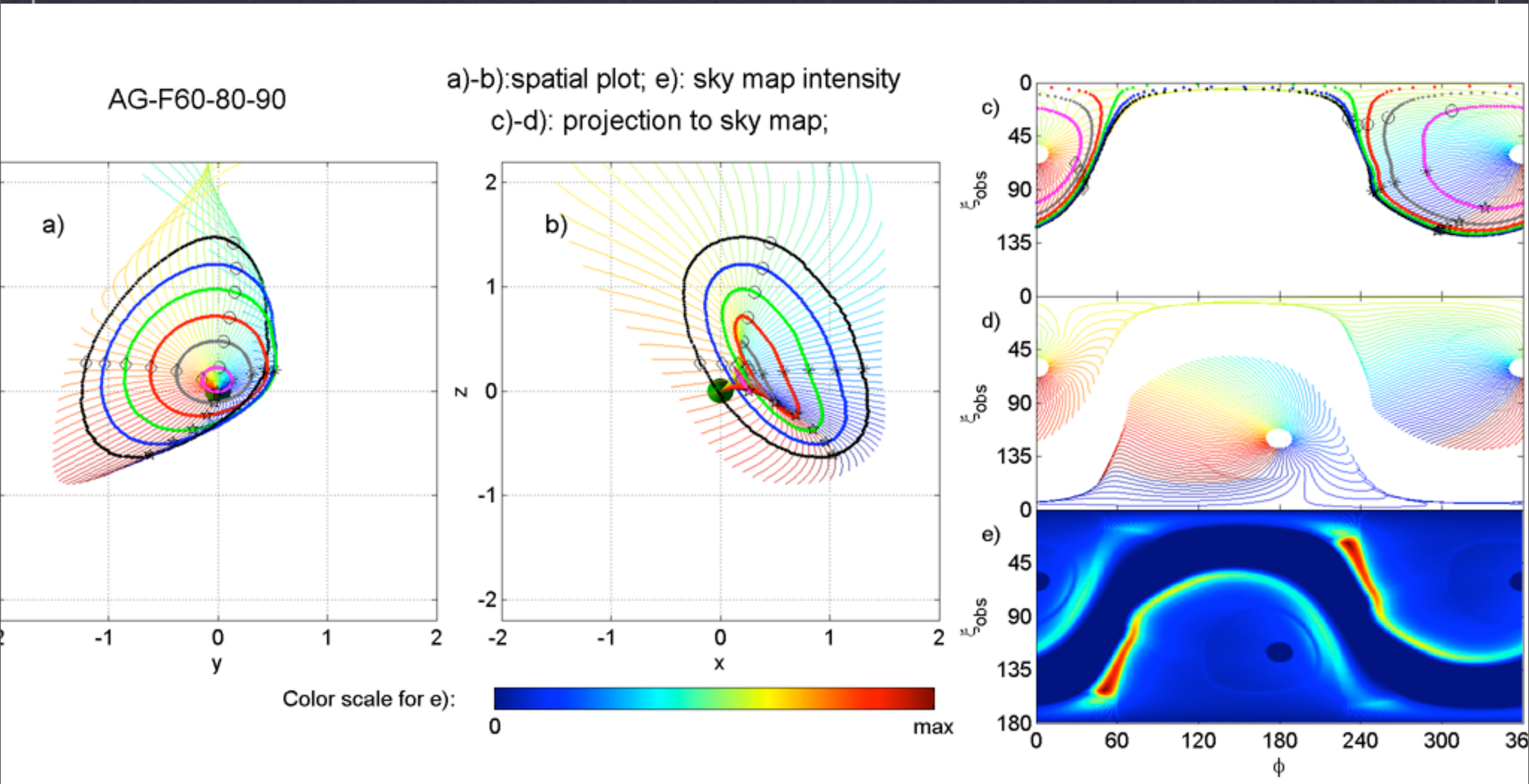
- While ad-hoc, the point is to study the geometry of the possible emission zone.

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



Emission from different flux tubes

Bai & A. S. 2010



Emission from two poles merges on some flux tubes: what's special about them?

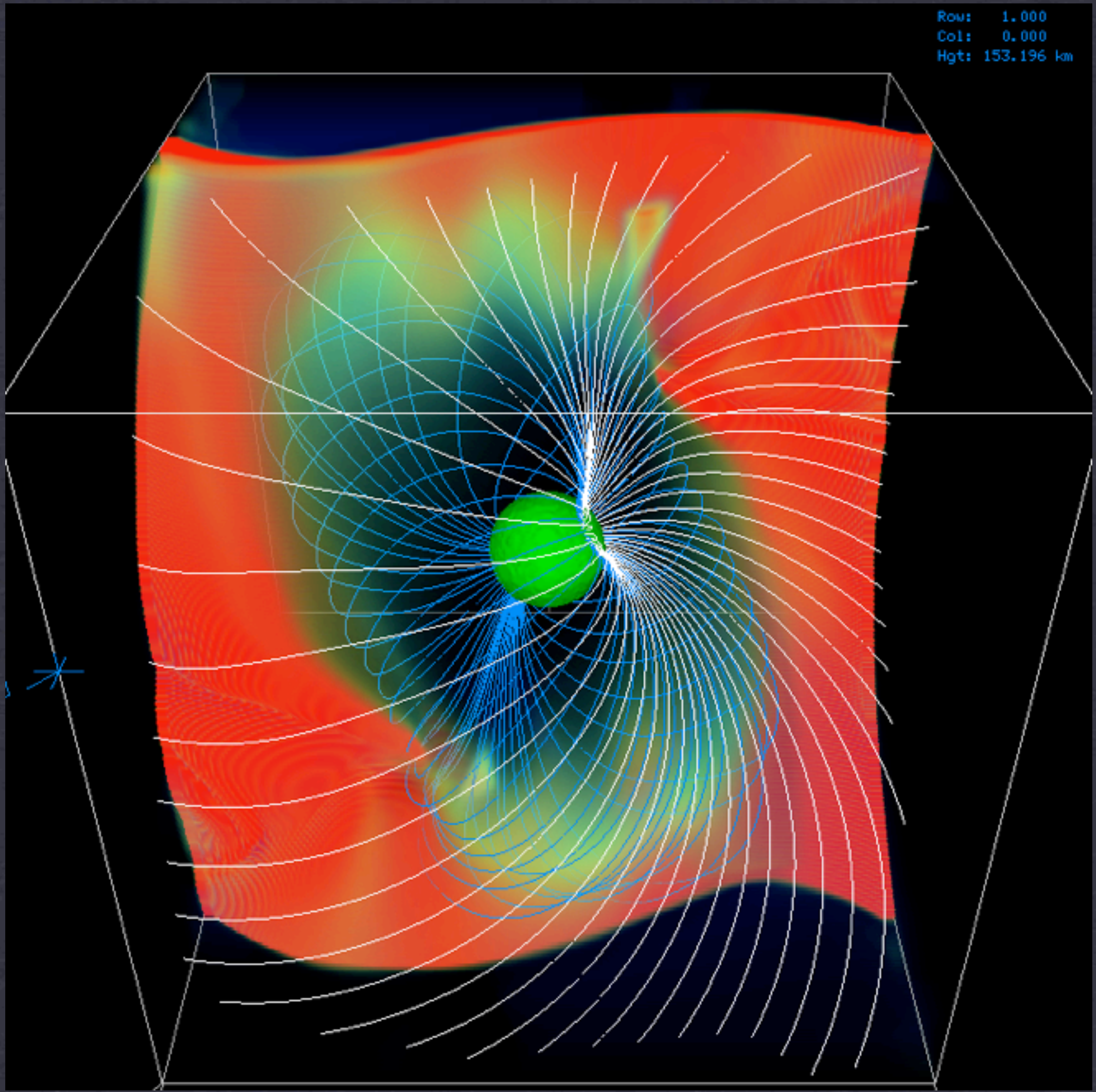
Association with the current sheet

Color -> current

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

Significant fraction of emission comes from beyond the light cylinder.

Best place to put a resistor in the circuit!

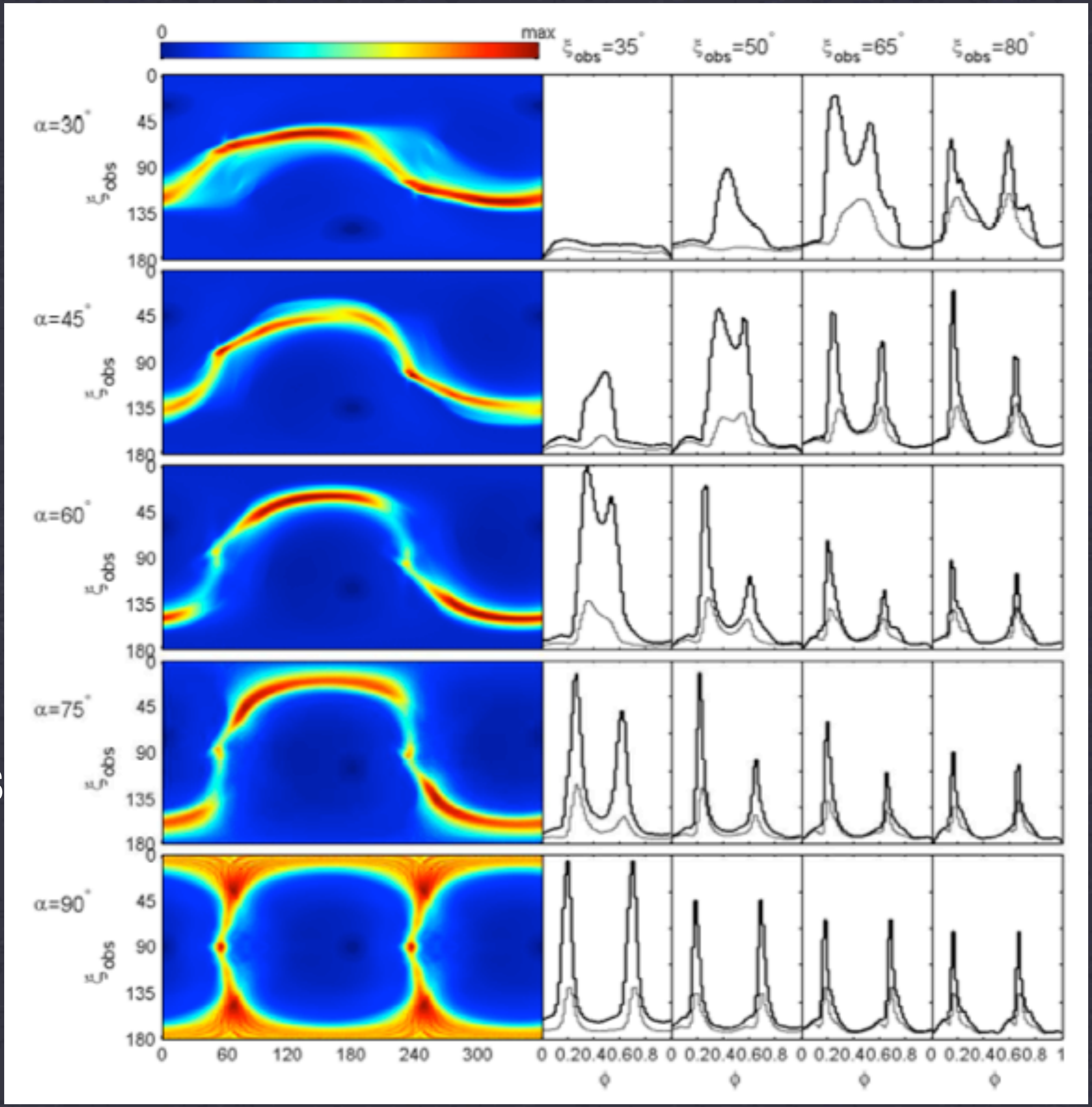


Force-free light curves

Viewing angle

"Separatrix Layer" model is a real contender. It's not just outer gap vs slot gap anymore!

Inclination angle



Most of the emission in FF model accumulates beyond 0.9 Rlc

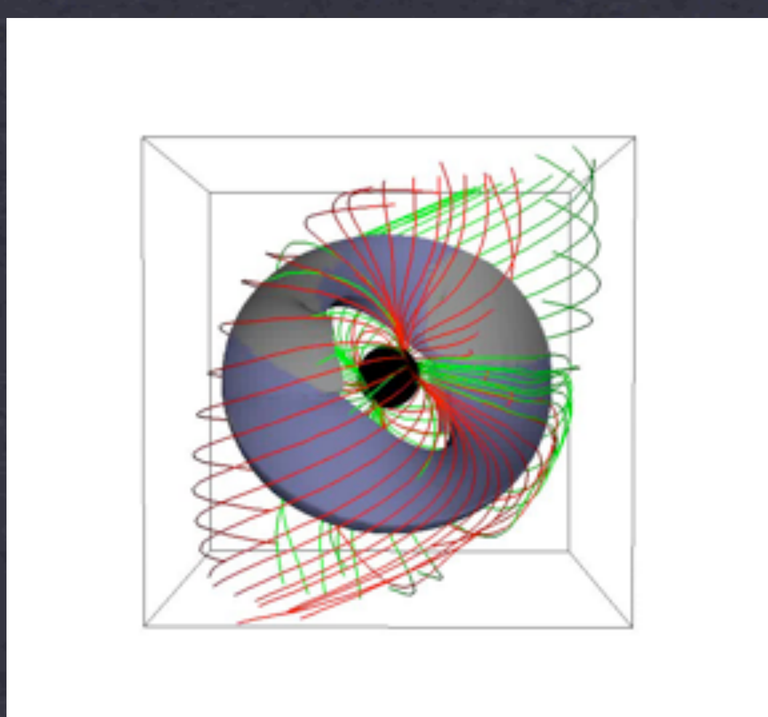
Double peak profiles very common.

Bai & AS, 2010

Resistive Force-free light curves

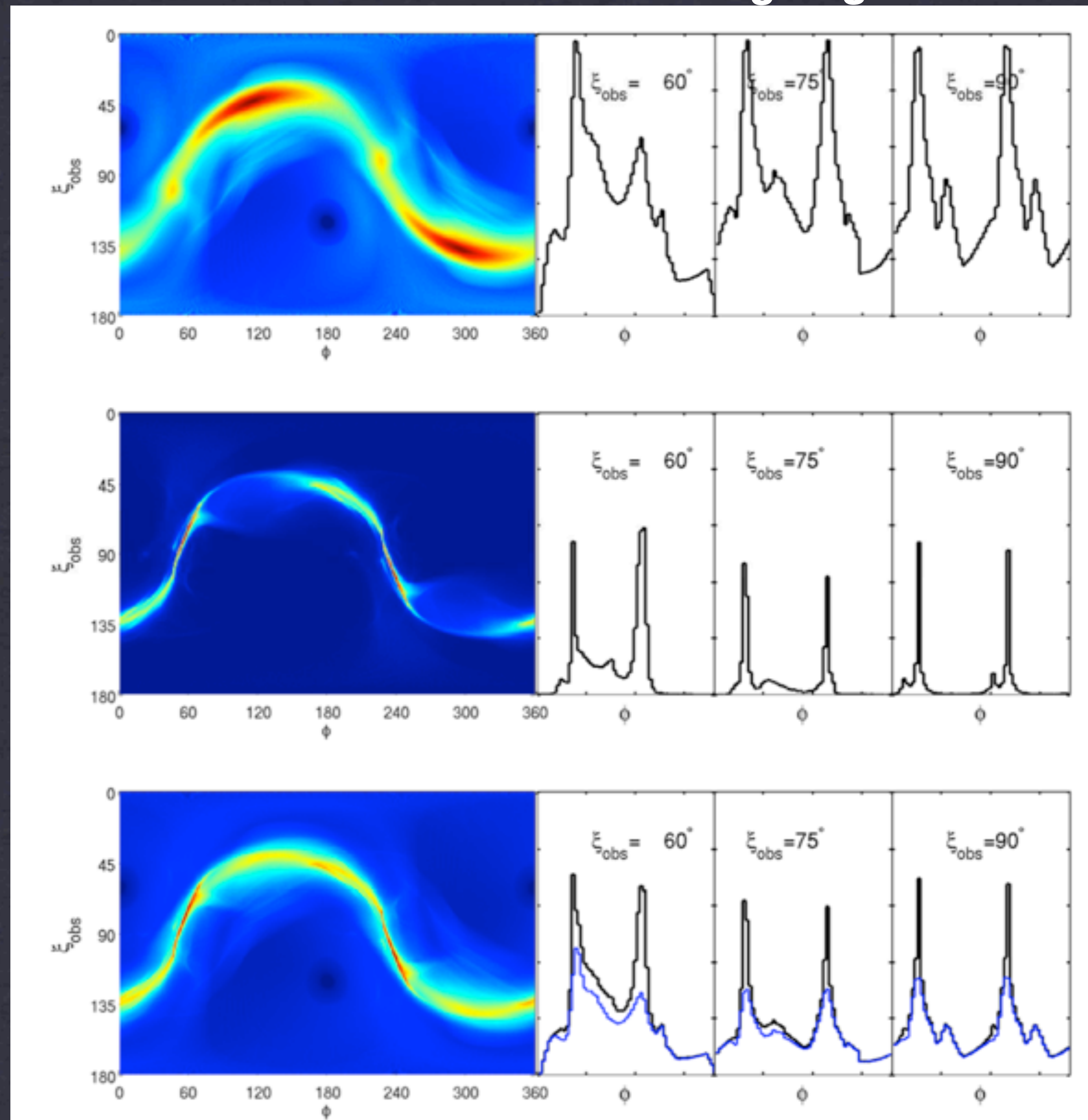
Beaming: along interpolated B field into the sheet. Results in radial beaming.

Combine emission from current layer (<Rlc) for bridge emission with current sheet (>Rlc) for peaks



Viewing angle

Inclination angle



Li, AS, Tchekhovskoy 2014

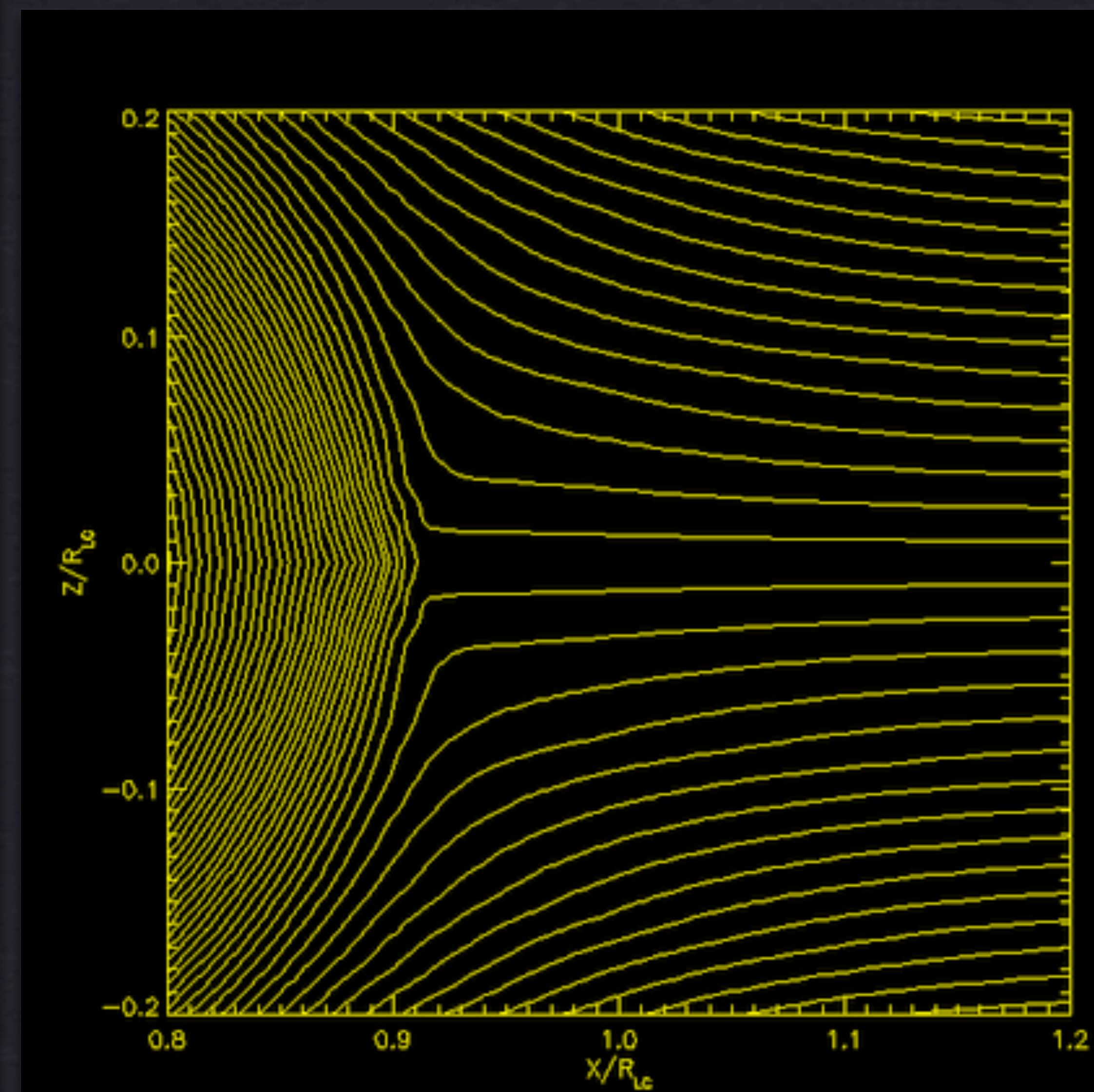
Source of emission

- Emission is geometrically associated with the current sheet
- What is the acceleration and radiation mechanism in current sheet?

  Most likely culprit -- relativistic reconnection. This is different from conventional picture of accelerating gaps starved of plasma and curvature emission

- Boosted synchrotron from heated plasma can work

Reconnection controls magnetospheric shape!

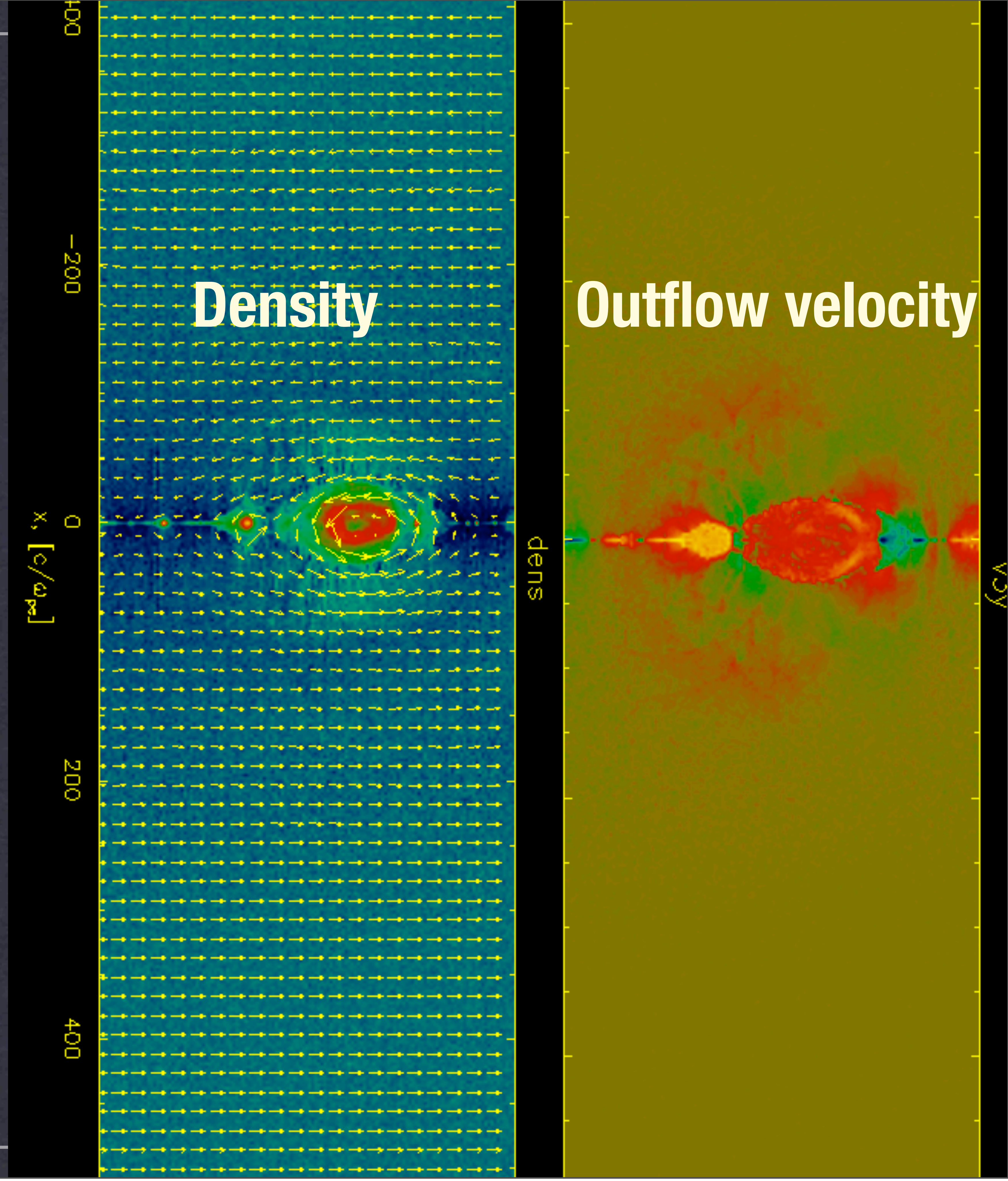


Better ideas of
flow direction in the
current sheet needed.

In PIC simulations
get outflows near
sqrt(sigma).

Minijets?

Since beaming along
extrapolated B field in the
current sheet makes
double peaks, it's a
contender



Why reconnection makes sense

- Conditions in the sheet can be obtained from:

Pressure balance

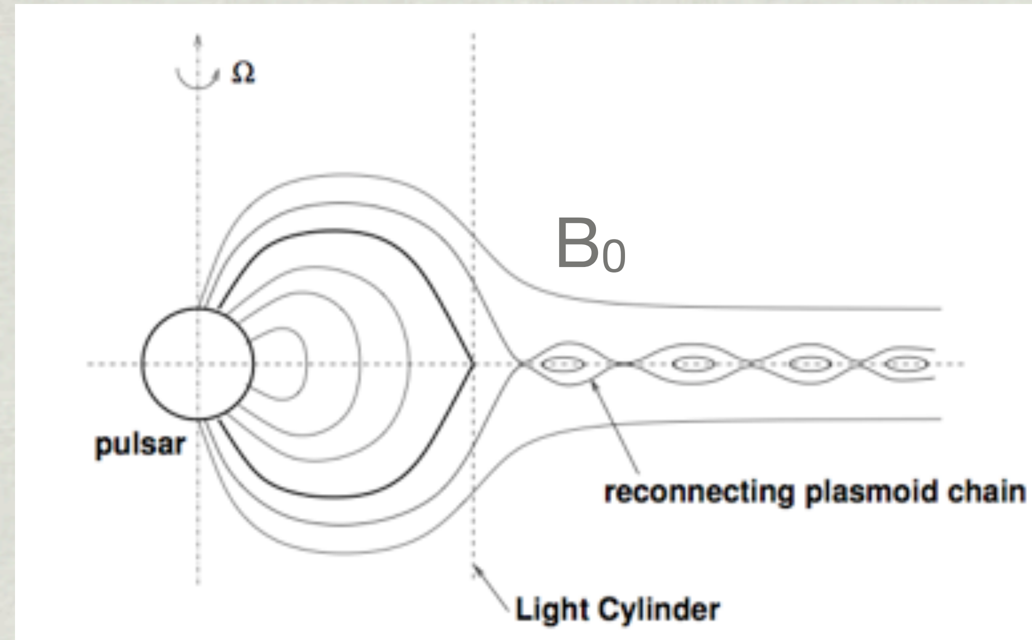
$B_0^2/8\pi = 2\,n\,T$

Strong synchr. cooling:

$S_{in} = (c/4\pi)\,E_z\,B_0 \sim Q_{rad} \sim \delta\,(2n)\,P_{sync}(T)$

Ampere's law:

$j_z = 2ne\,v_{dr} = 2\,nec\,\beta_{dr} \sim (c/4\pi)\,B_0/\delta$



Uzdensky & AS 2014 (also, Lyubarsky 96, Petri 12, Arca 12)

Temperature, density and thickness depend on B at LC. $\gamma_T = T/m_e c^2 \sim [\beta_{dr}\,\beta_{rec}\,8\pi e/\sigma_T\,B_0]^{1/2}$

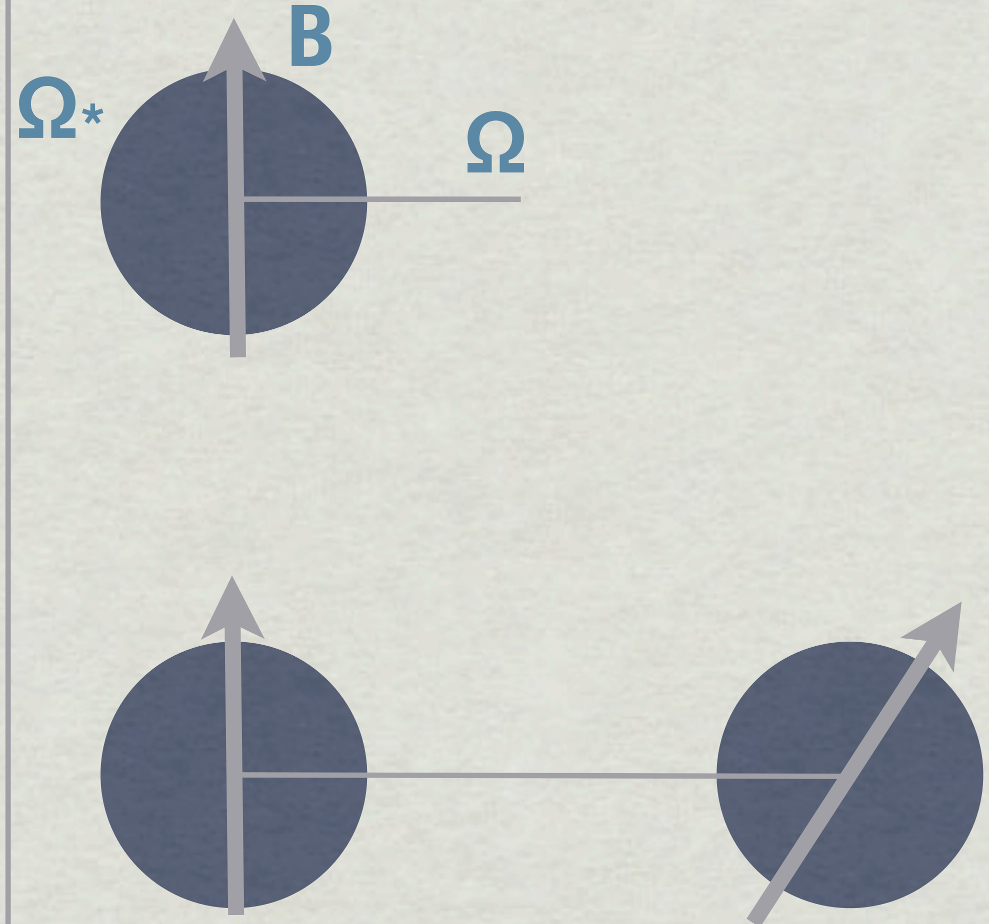
$\sim (\beta_{dr}\,\beta_{rec})^{1/2}\,4 \times 10^4$

Temperature at 10GeV comoving --> 160MeV synch radiation --> GeV pulsed emission in the lab boosted by bulk gamma of ~10. IC gives VHE.

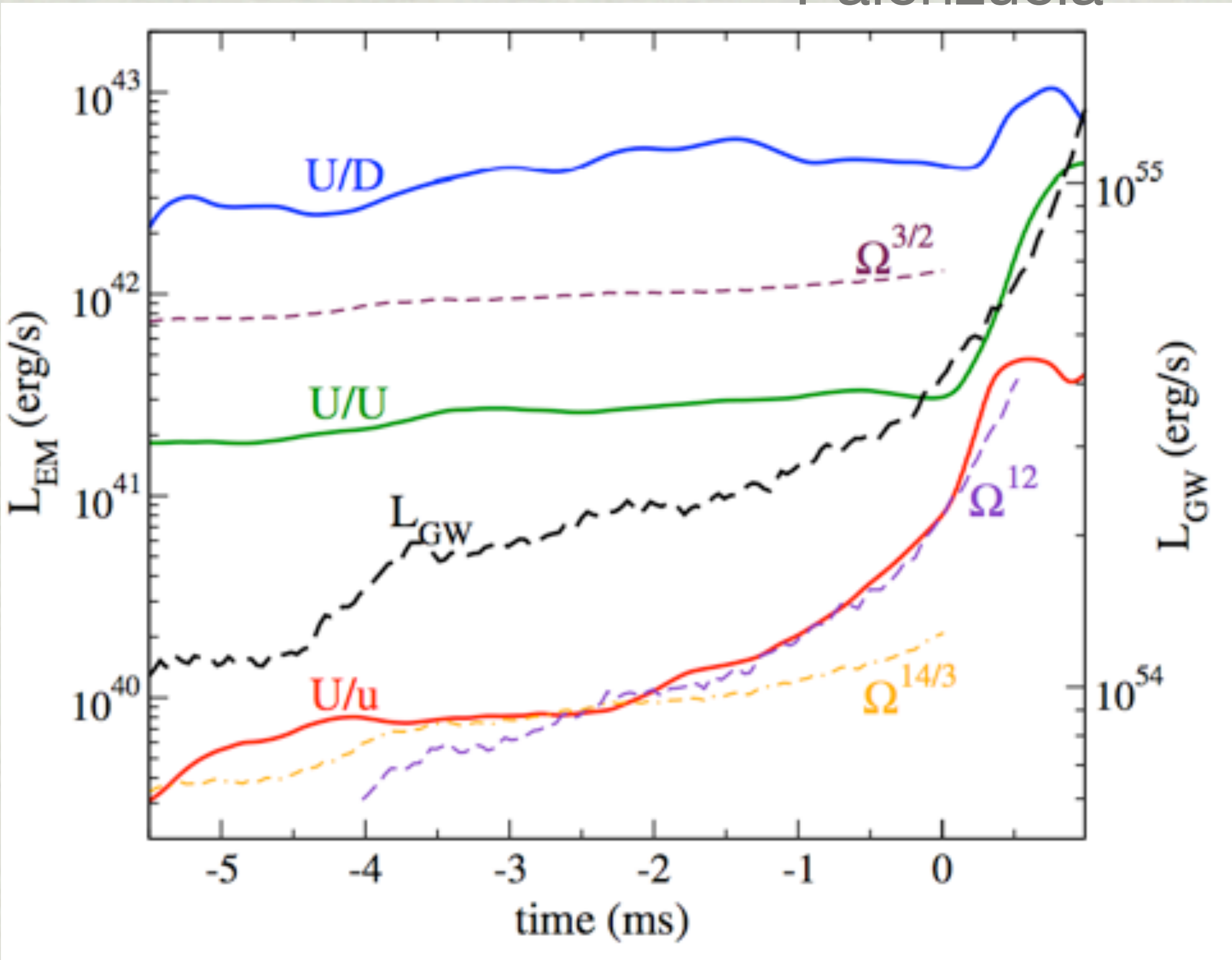
Other EMF: binary inspiral

- Inspired by prospects for precursor emission for LIGO, we studied spin-down of single and binary NS in orbit (Li + AS 2014). Cf. work by Palenzuela et al 2013-14.

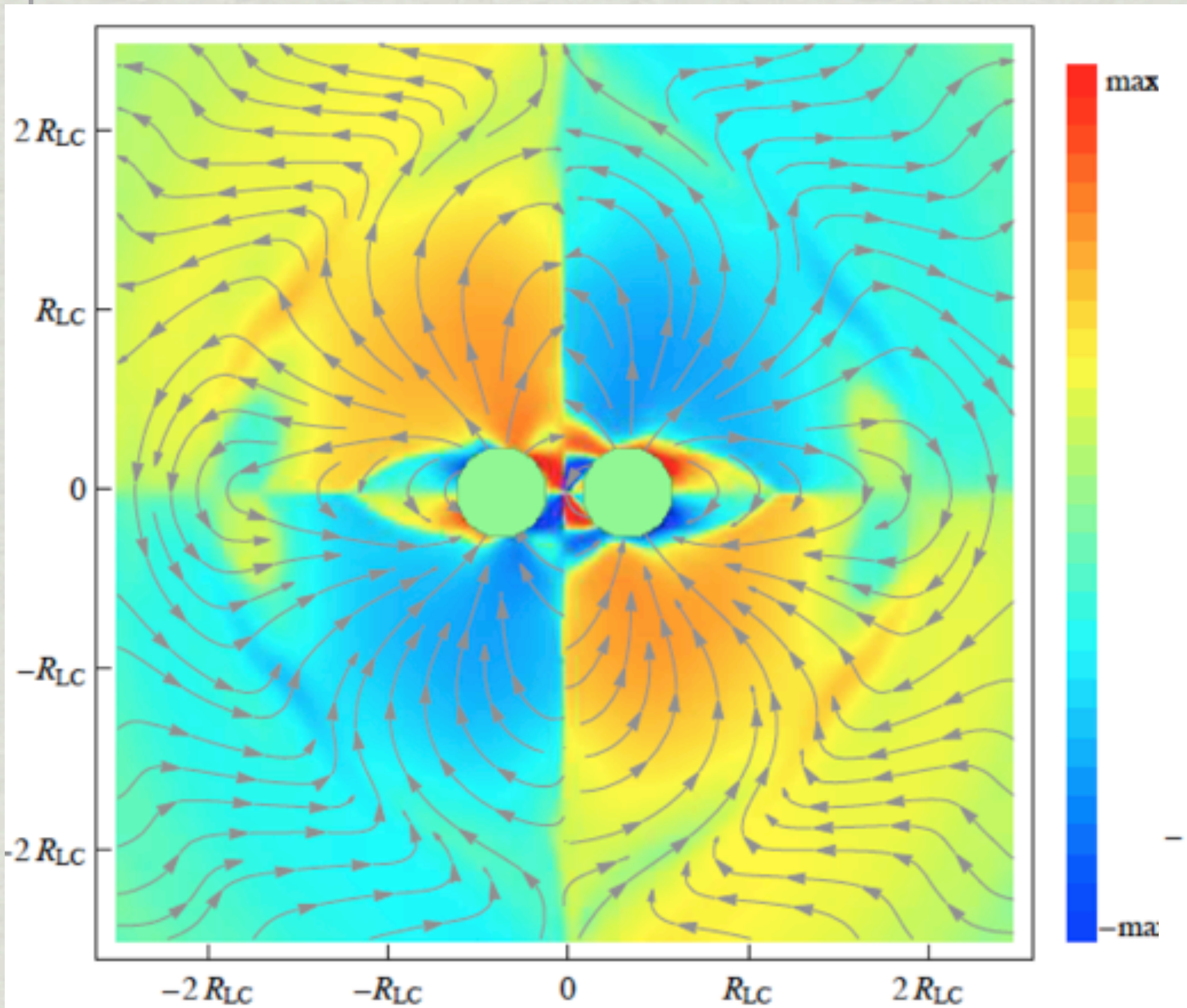
- How does the spin-down depend on orbital frequency and spin and orientation of NSs?



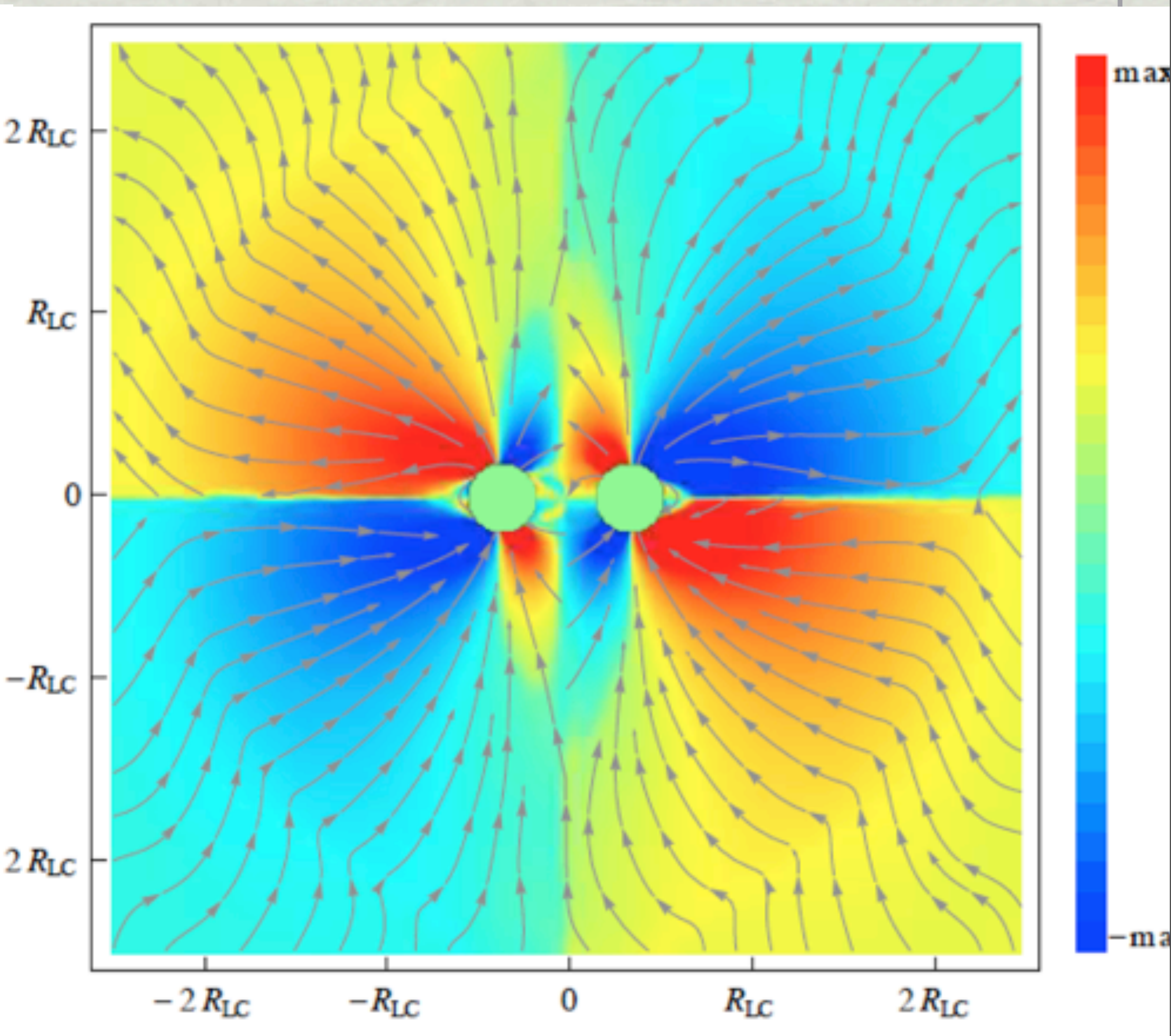
Palenzuela



Binaries: field patterns

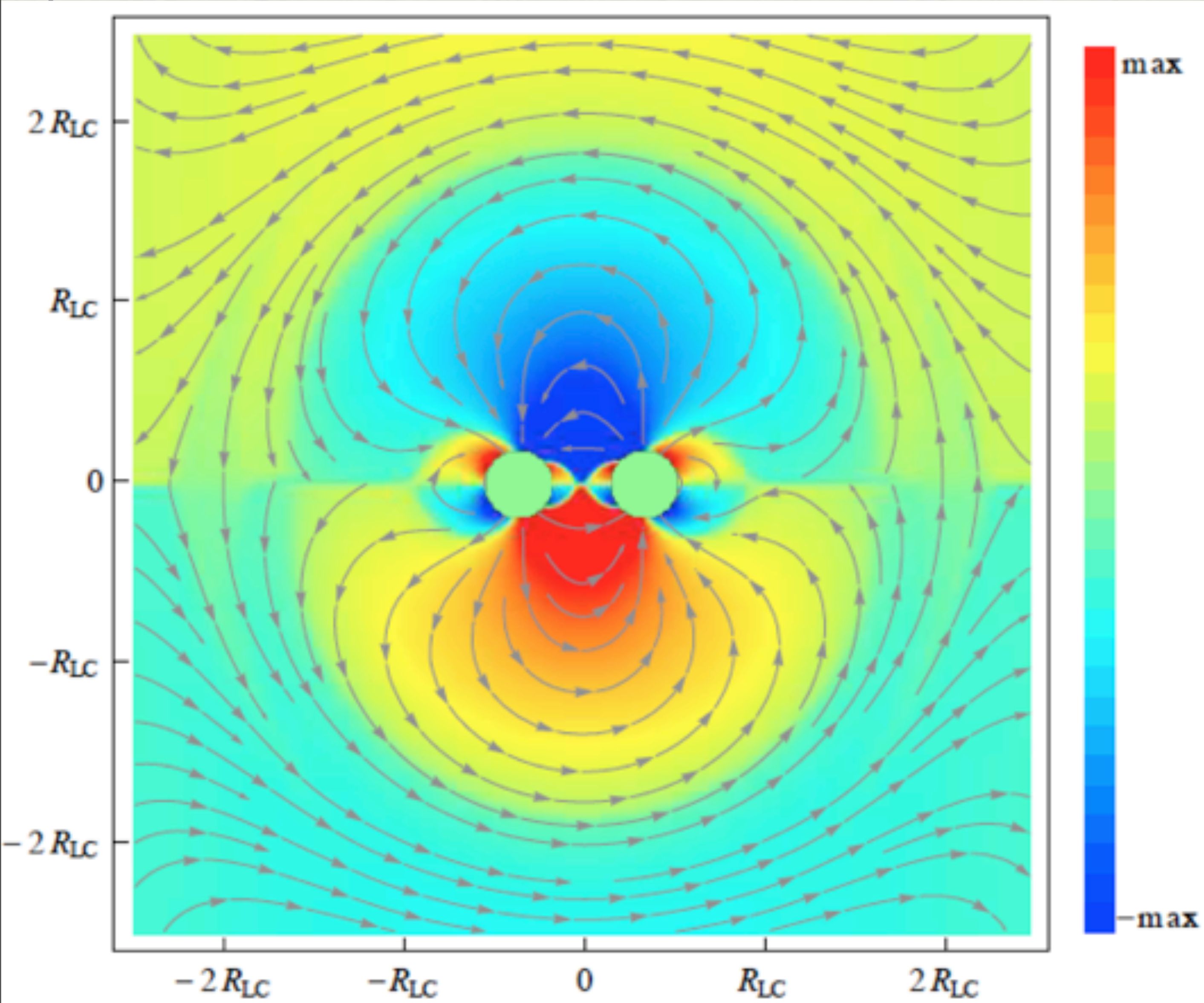


U/U, no NS spin

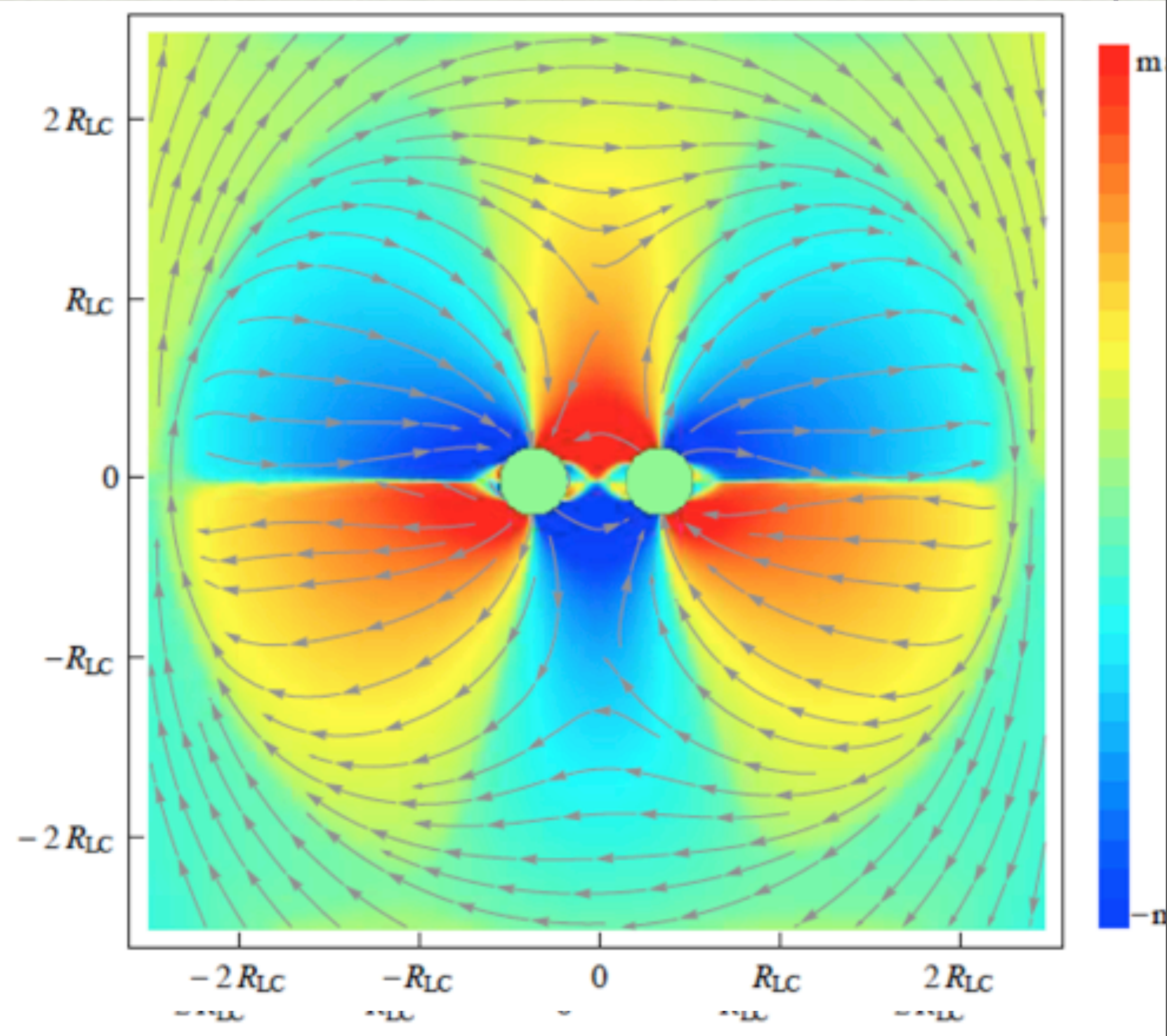


U/U, with spin

Binaries: field patterns

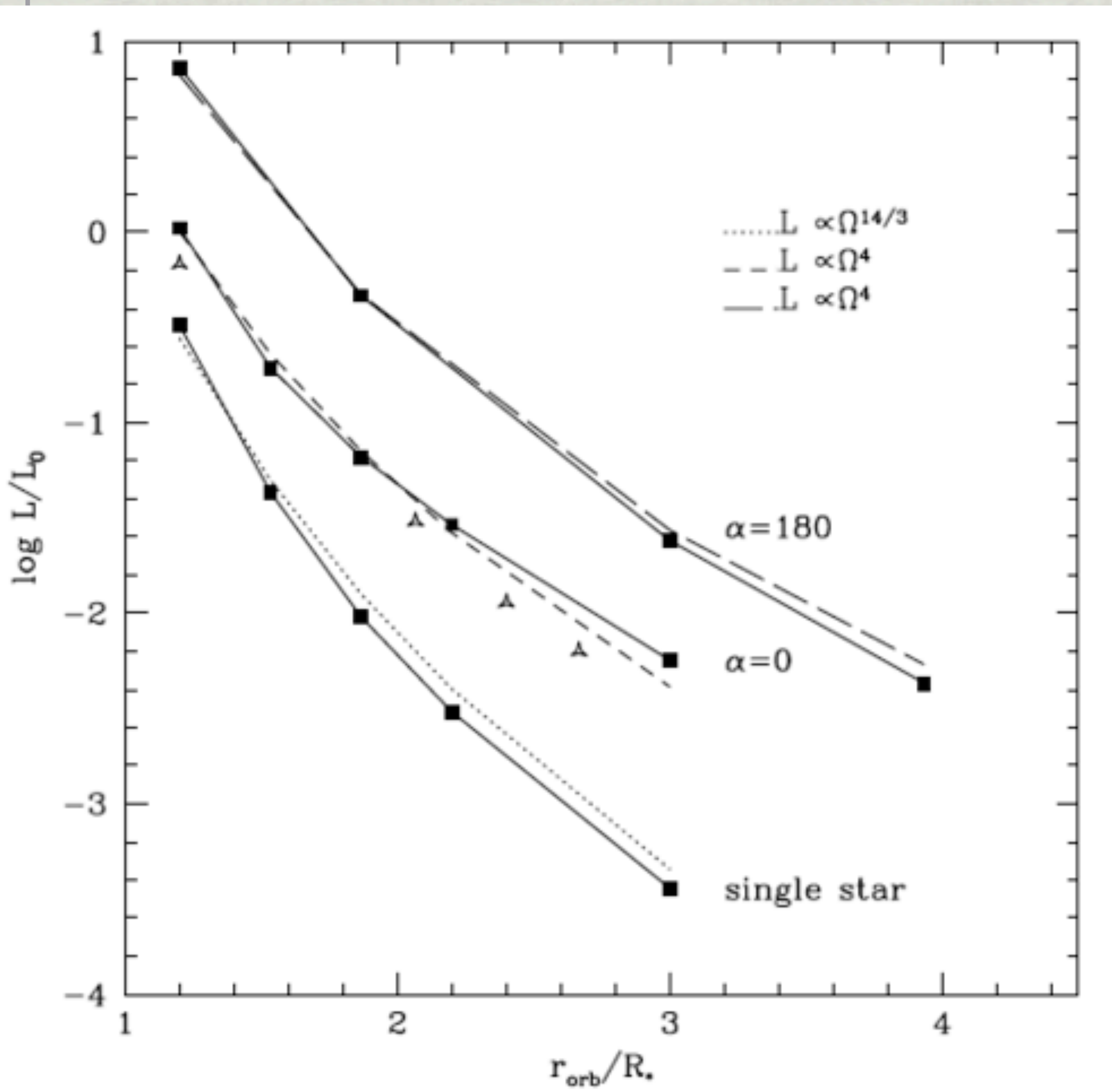


U/D, no NS spin

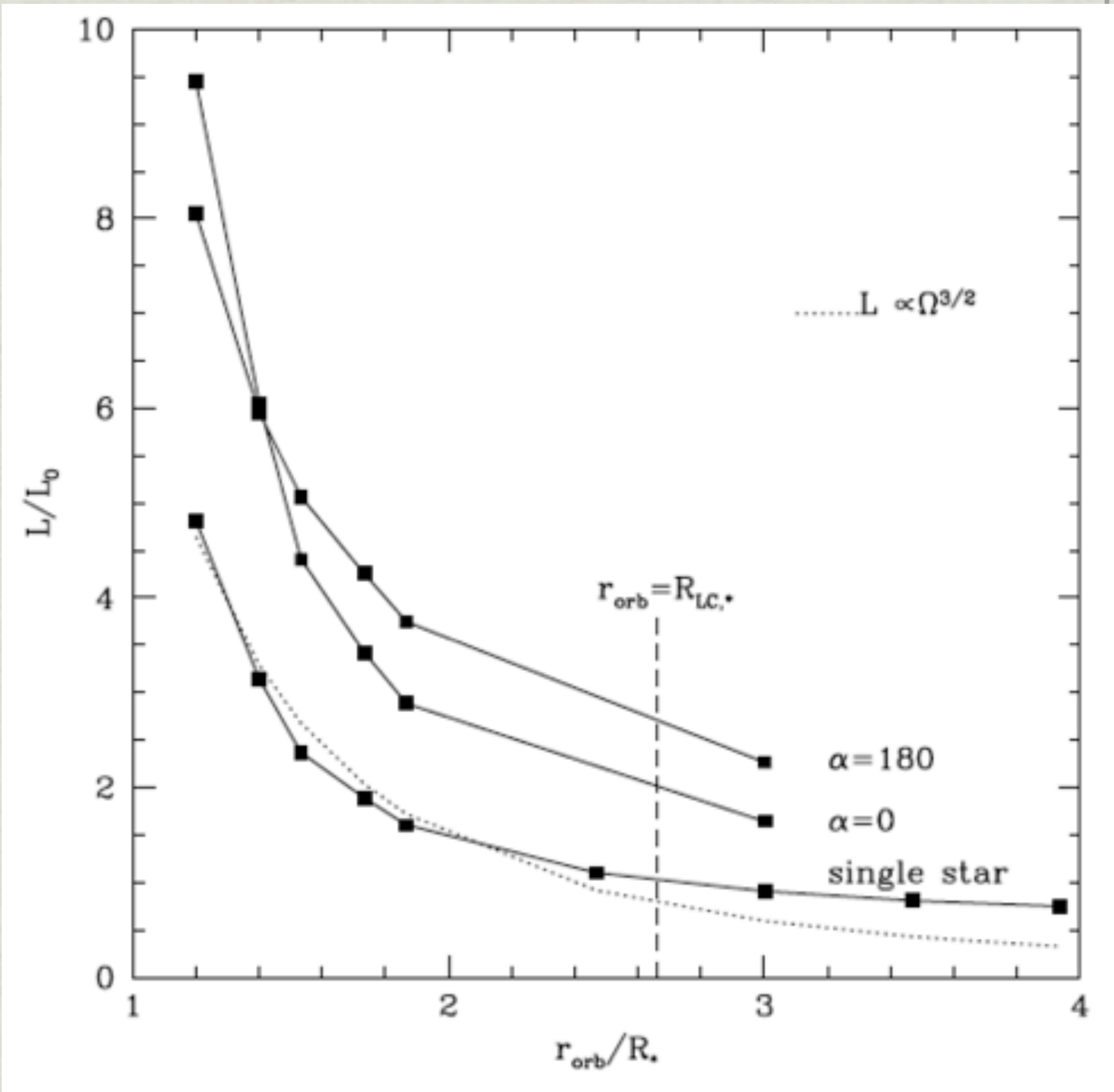


U/D, with spin

Binaries: EM luminosity

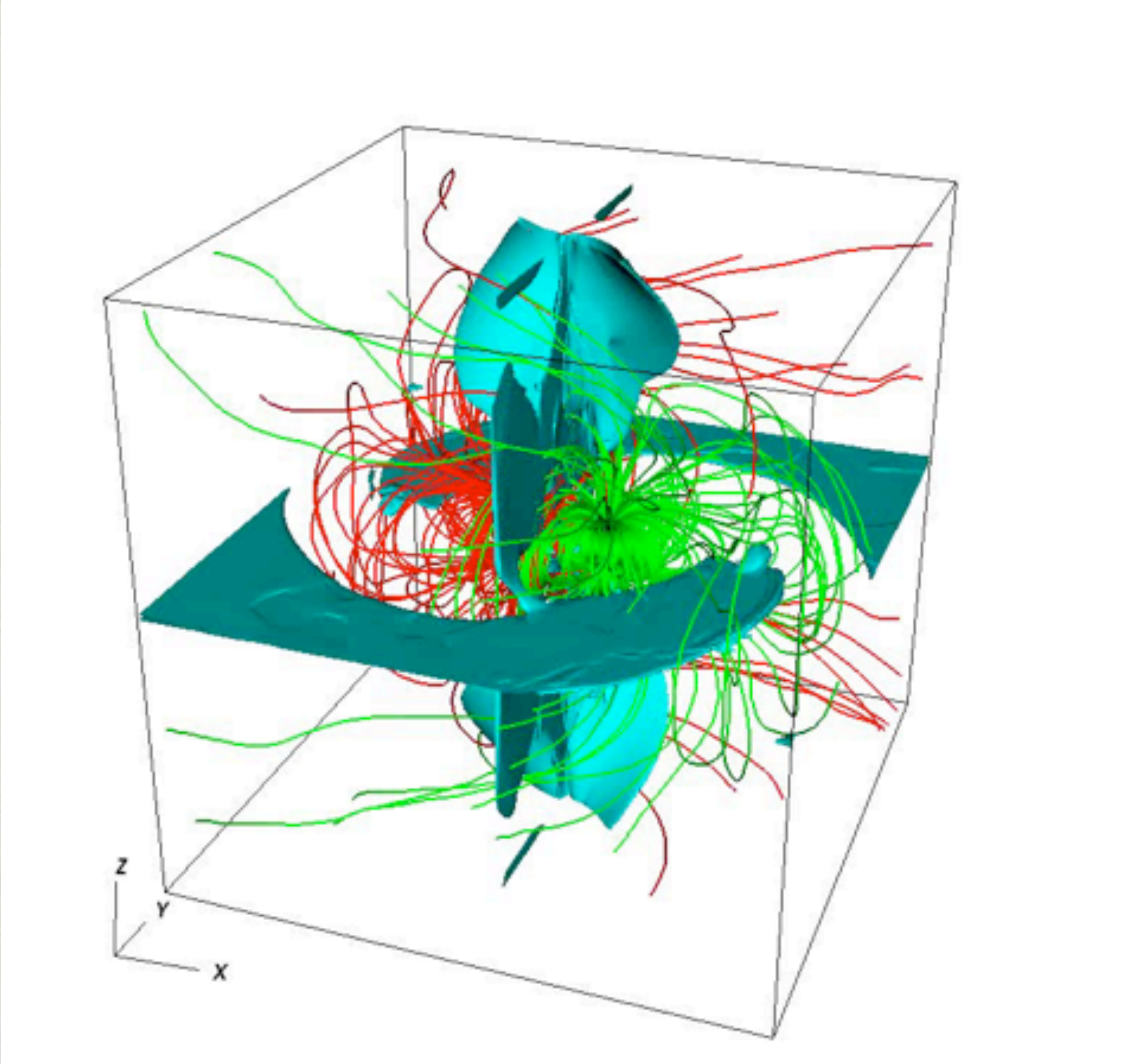


Non-spinning

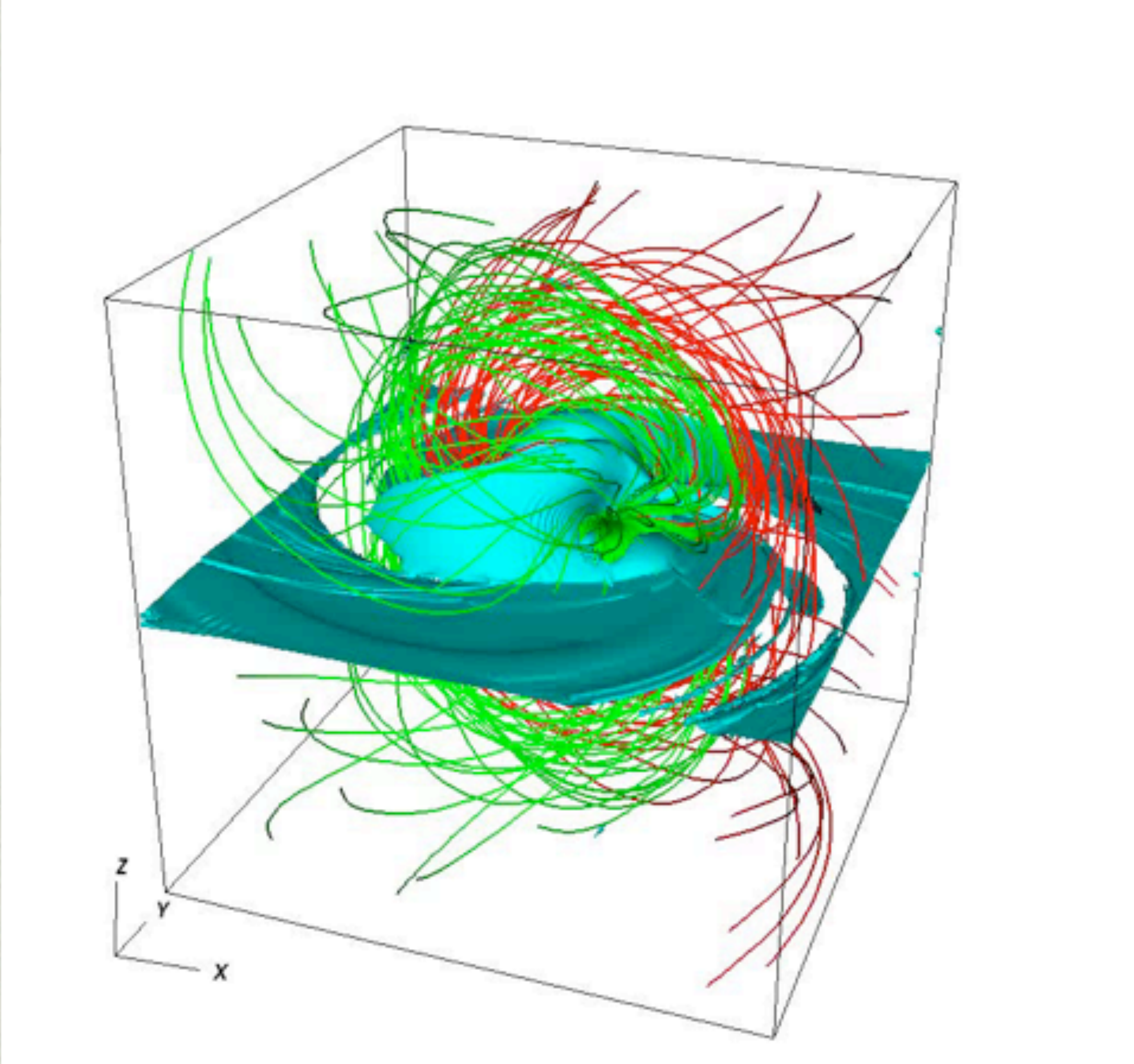


ms-period spin

Binaries: field patterns

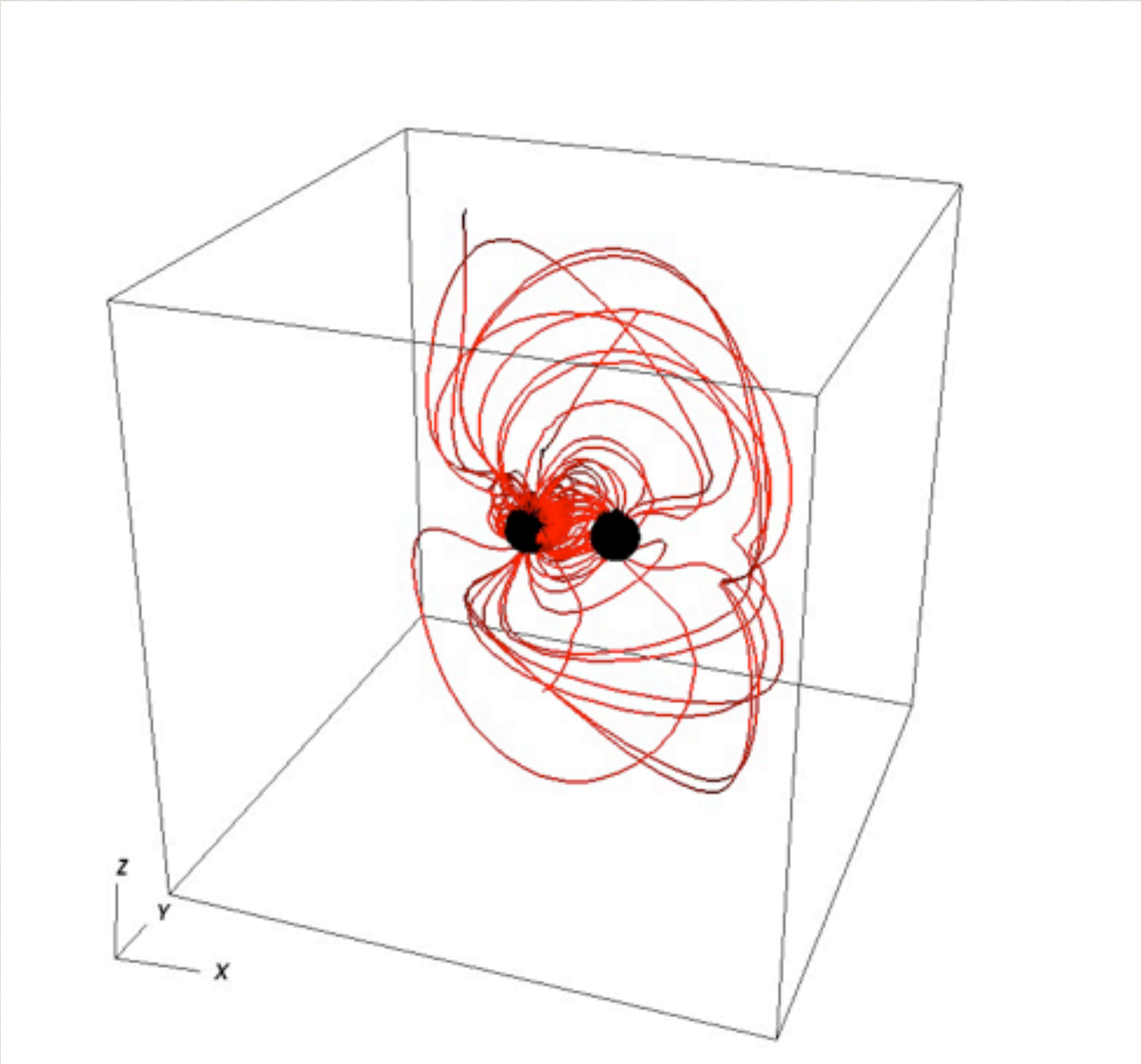


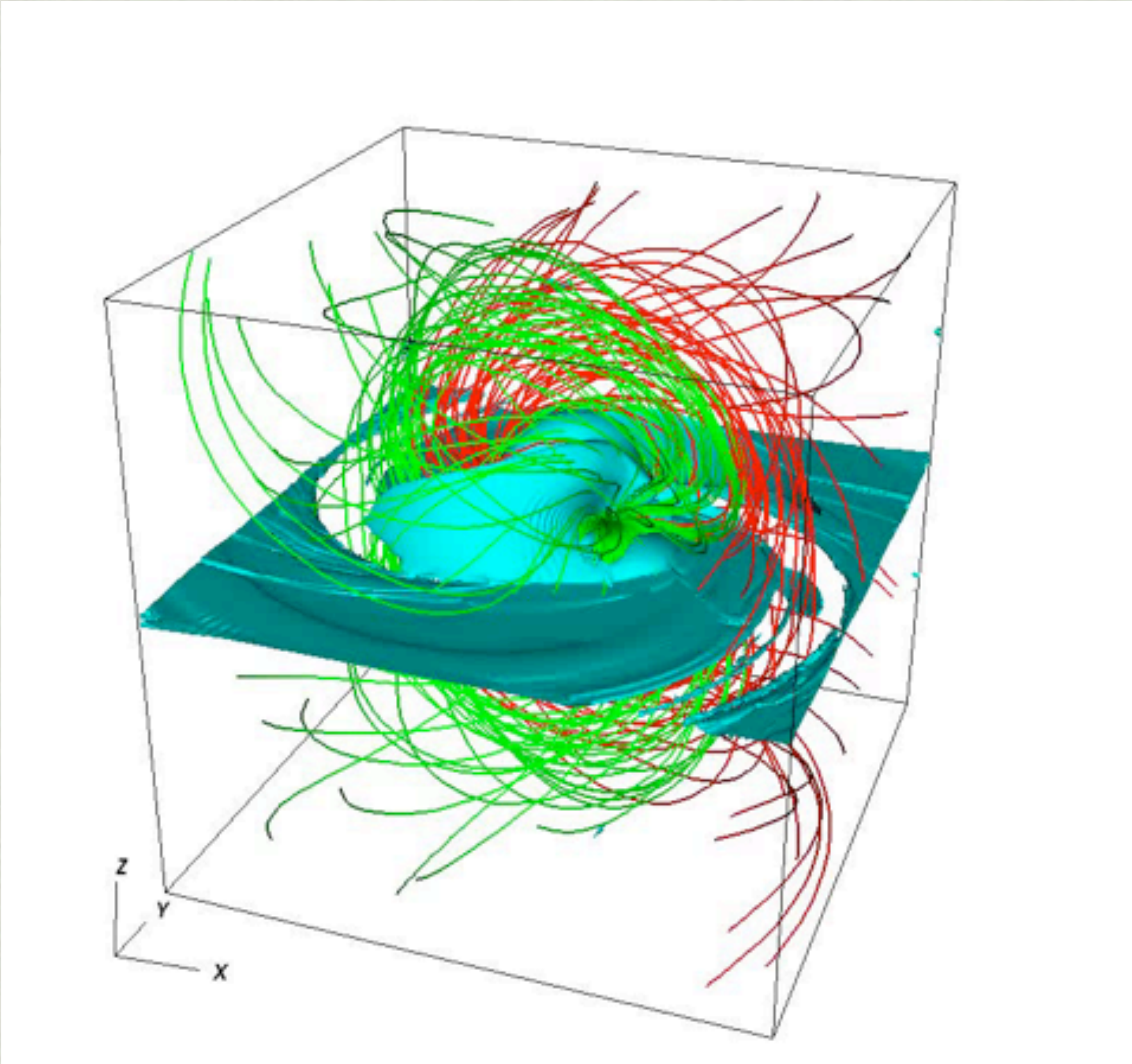
U/U, no spin



U/D, no spin

Binaries: field patterns





U/D, no NS spin

U/D, no NS spin

Analytic Guidance

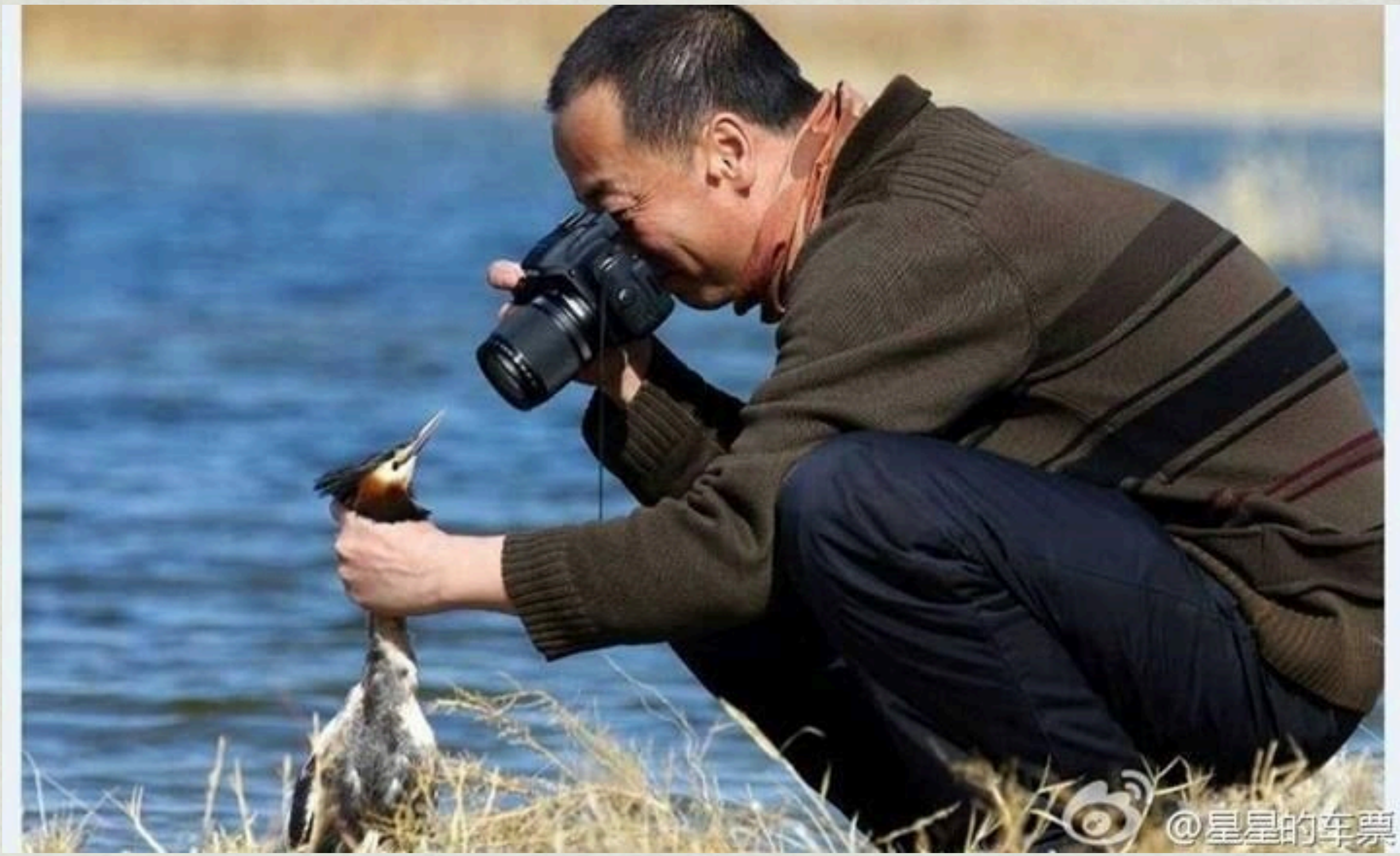
- In vacuum (e.g., Ioka & Taniguchi '00; Drell+ '65):
  - Electric dipole radiation $L \propto (\vec{v} \times \vec{\mu})'' \propto \Omega^{14/3}$
    - Cancels for aligned dipoles
  - Magnetic Quadrupole radiation $L \sim (r\,\mu)''' \propto \Omega^{14/3}$
    - Cancels for aligned dipoles
  - Potential drop $\Phi \approx (\Omega r_{\rm orb}/c) B R_*$ yields $L \propto \Phi^2 \propto \Omega^{14/3}$
- In highly conducting plasma:
  - At LC $B_p \approx E_p \approx B_\phi \approx 1/R_{LC}^{1+\zeta}$ gives $L \propto \int \vec{E} \times \vec{B}\, d\vec{A} \propto \Omega^{2\zeta}$
  - $\zeta \rightarrow 0 \; when \; R_{LC,*} \rightarrow \infty, \zeta \rightarrow 2 \; when \; R_{LC,*} \rightarrow 0$
  - Aligned binaries:

$$L = 2\frac{\mu^2 \Omega_*^4}{c^3} + \frac{\mu^2}{c^3} \left(1 + 6.5(\Omega_*/\Omega_0)^{1.7}\right) \Omega_0^{2.5\Omega_*/\Omega_0} \Omega^{4-2.5\Omega_*/\Omega_0},$$

Conclusions

- Magnetospheric shape is now known and confirmed in the limit of abundant plasma in 3D.
- Geometrically these models are being contrasted with gamma-ray observations (Separatrix Layer vs Gaps).
- More realistic models with 3D RMHD, cascade physics and full PIC are advancing -- expect cool results in the next few years. Benefit a lot from Moore's law.
- Reconnection may play an important and under-appreciated role in both emission and determining the magnetospheric shape.
- The origin of long time scale variability is likely not magnetospheric.

Conclusions



Conclusions

Pulsar Magnetosphere

Particle Simulations