Προσεγγίζοντας την πραγματική μαγνητόσφαιρα των pulsars

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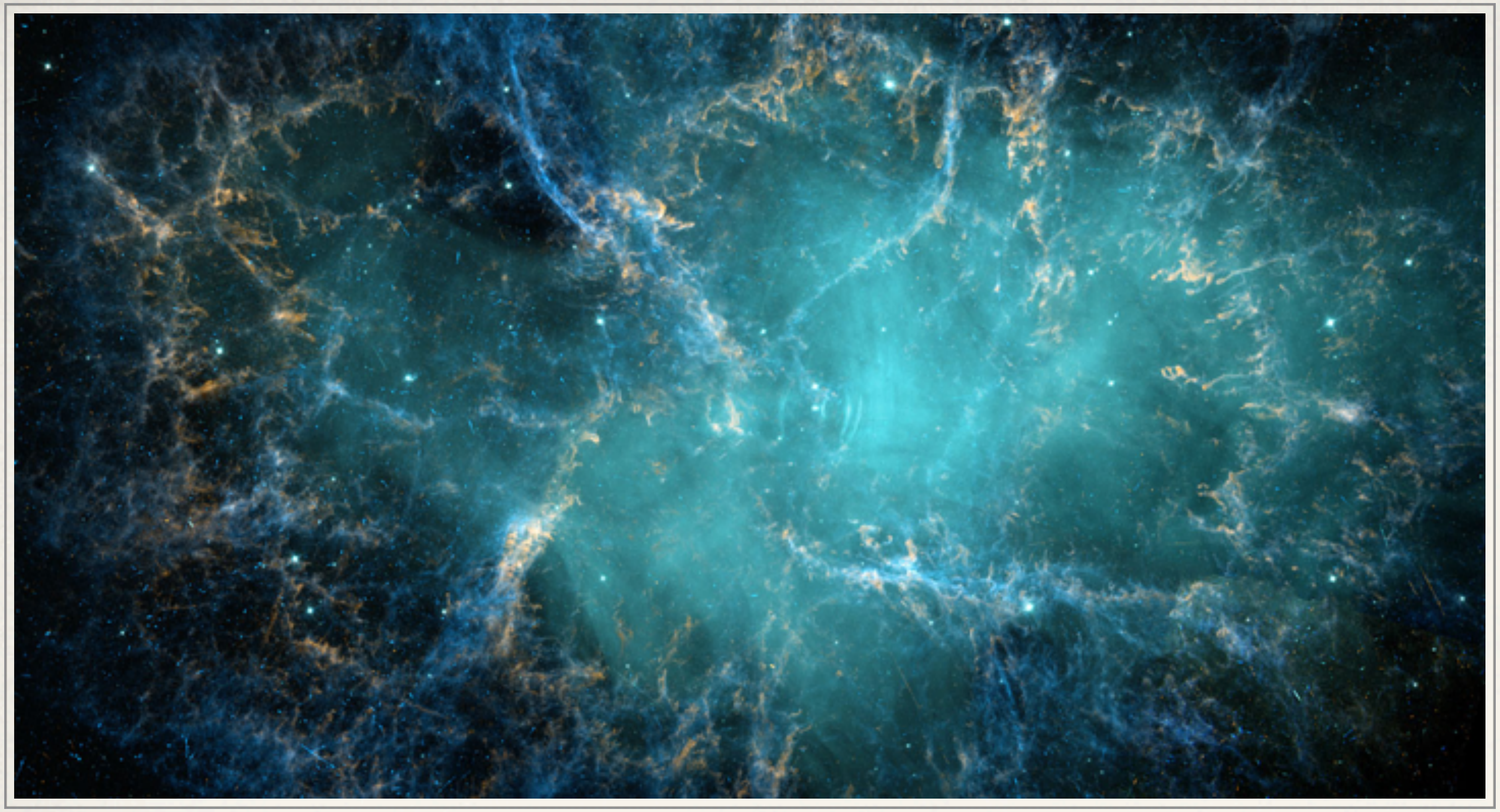
Τμήμα Φυσικής, Πανεπιστήμιο Αθηνών, 3-11-2011

Towards a realistic pulsar magnetosphere

Ioannis Contopoulos, Research Center for Astronomy & AM, Academy of Athens

Physics Department, University Of Athens, 3-11-2011



Towards a realistic pulsar magnetosphere

Contopoulos + Kazanas, Kalapotharakos, Harding, Spitkovsky 1999-2011

KK, Kazanas, Harding & IC 2011, Towards a realistic pulsar magnetosphere
Harding, DeCesar, Miller, KK & IC 2011, γ-ray pulsar light curves
Li, Spitkovsky & Tchekhovskoy 2011, Resistive solutions for pulsar magnetospheres

Physics Department, University Of Athens, 3-11-2011

Electrodynamics

Electrodynamics

.....Vacuum

1955

aligned

3D

Electrodynamics

Vacuum

1955

Ideal + force-free MHD

Relativistic plasma

Light cylinder

Current sheets

Y-point reconnection

γ-ray pulses...

1999

aligned

3D

Electrodynamics ····Vacuum

1955

Non-ideal MHD ····Spindown

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1999

Light cylinder

Current sheets

aligned

3D

Y-point reconnection

γ-ray pulses...

axisymmetric vacuum:
nothing much...

$$\nabla \times B = 0$$

$$\nabla \times E = 0$$

$$\nabla \cdot B = 0$$

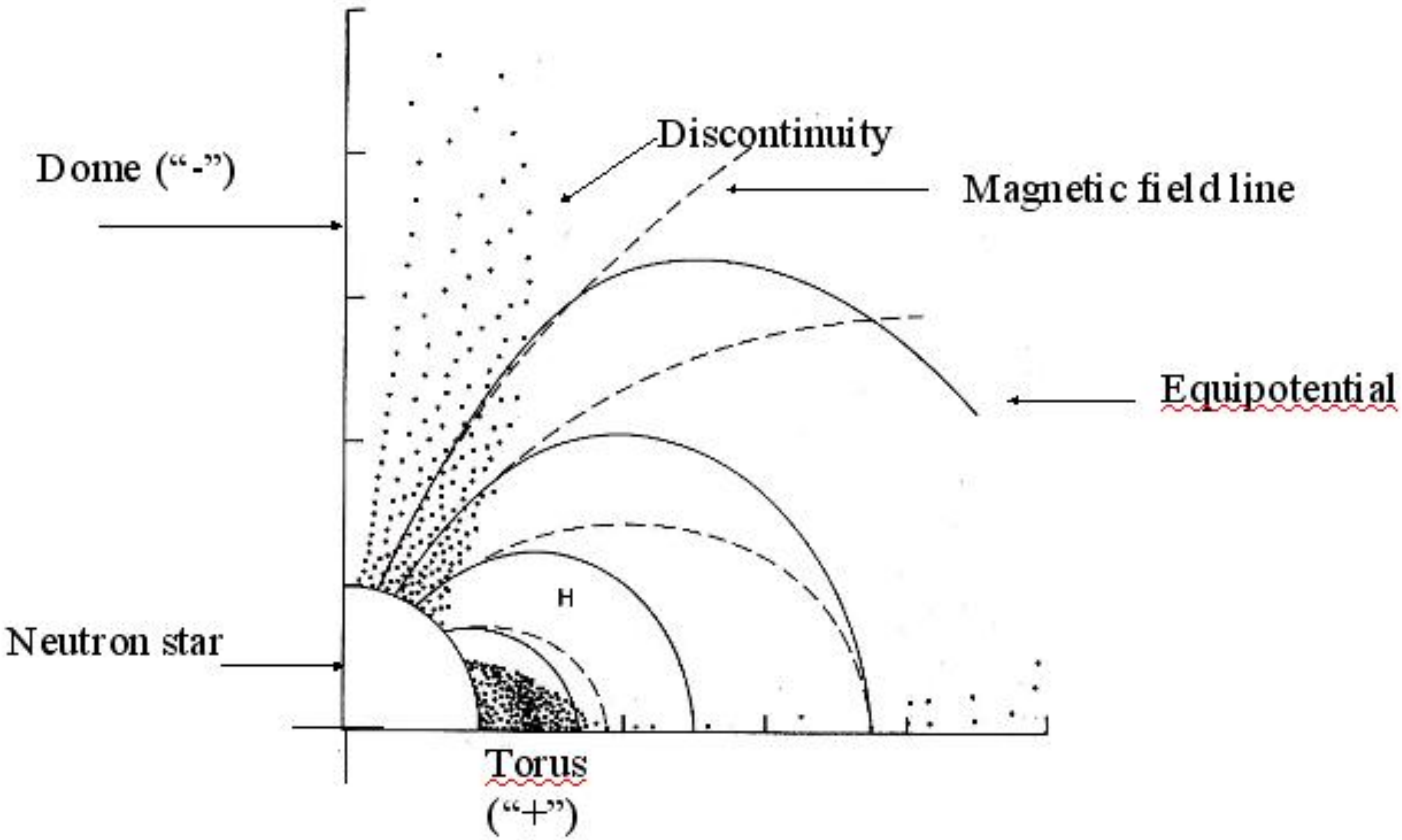
axisymmetric vacuum:
nothing much...

$$\nabla \times B = 0 \qquad \nabla \cdot B = 0$$

$$\nabla \times E = 0$$

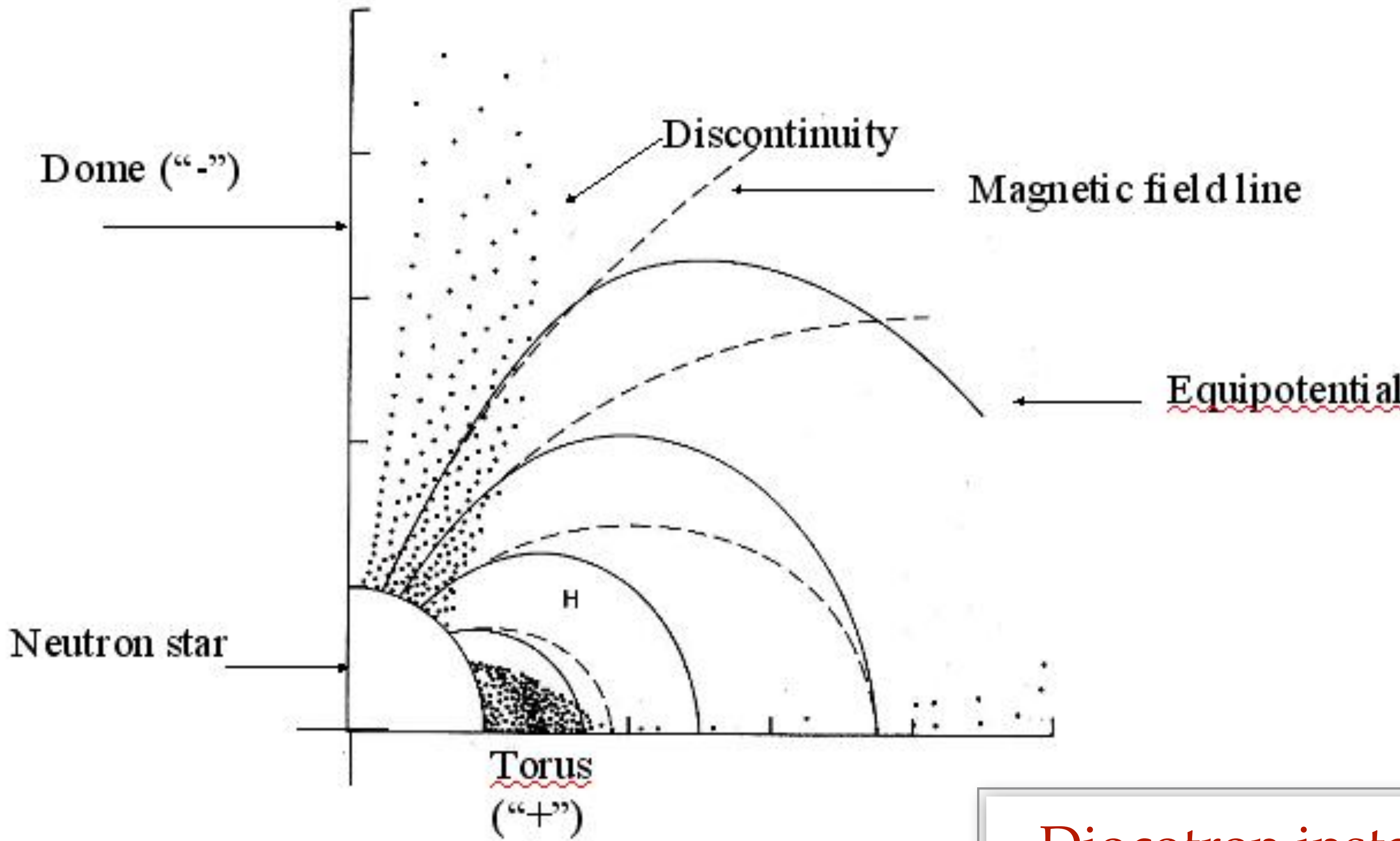
Spinning aligned dipole
Quadrupole electrostatic field

The dome/torus of Krause-Polstorff



Dome & torus, electrospheres (Michel, Shibata, Spitkovsky, Petri)

The dome/torus of Krause-Polstorff



Diocotron instability

Dome & torus, electrospheres (Michel, Shibata, Spitkovsky, Petri)

axisymmetric force-free ideal relativistic MHD: the pulsar equation

$$\nabla \times B = (4\pi/c)J \qquad \nabla \cdot B = 0$$

$$\nabla \times E = 0 \qquad E \cdot B = 0$$

$$\rho_e E + J \times B = 0$$

$$(1-x^2)\left(\frac{\partial^2 \Psi}{\partial x^2} - \frac{1}{x}\frac{\partial \Psi}{\partial x} + \frac{\partial^2 \Psi}{\partial z^2}\right) - 2x\frac{\partial \Psi}{\partial x} = -AA'$$

$x \equiv R/R_{LC}, \quad B_z \equiv R^{-1}\partial\Psi/\partial R, \quad A \equiv A(\Psi)$

The aligned rotator (Scharleman & Wagoner 1973)

axisymmetric force-free ideal relativistic MHD: the pulsar equation

$$(1-x^2)\left(\frac{\partial^2\Psi}{\partial x^2}-\frac{1}{x}\frac{\partial\Psi}{\partial x}+\frac{\partial^2\Psi}{\partial z^2}\right)-2x\frac{\partial\Psi}{\partial x}=-AA'$$

$$\rho_e=\frac{\Omega}{4\pi c}\frac{-2B_z+AA'}{1-x^2}=\rho_{GJ}$$

regularization condition at light cylinder: $2B_z=AA'$

unique poloidal current distribution: $A(\Psi)=A_{CKF}$

$x\equiv R/R_{LC},\quad B_z\equiv R^{-1}\partial\Psi/\partial R,\quad A\equiv A(\Psi)$

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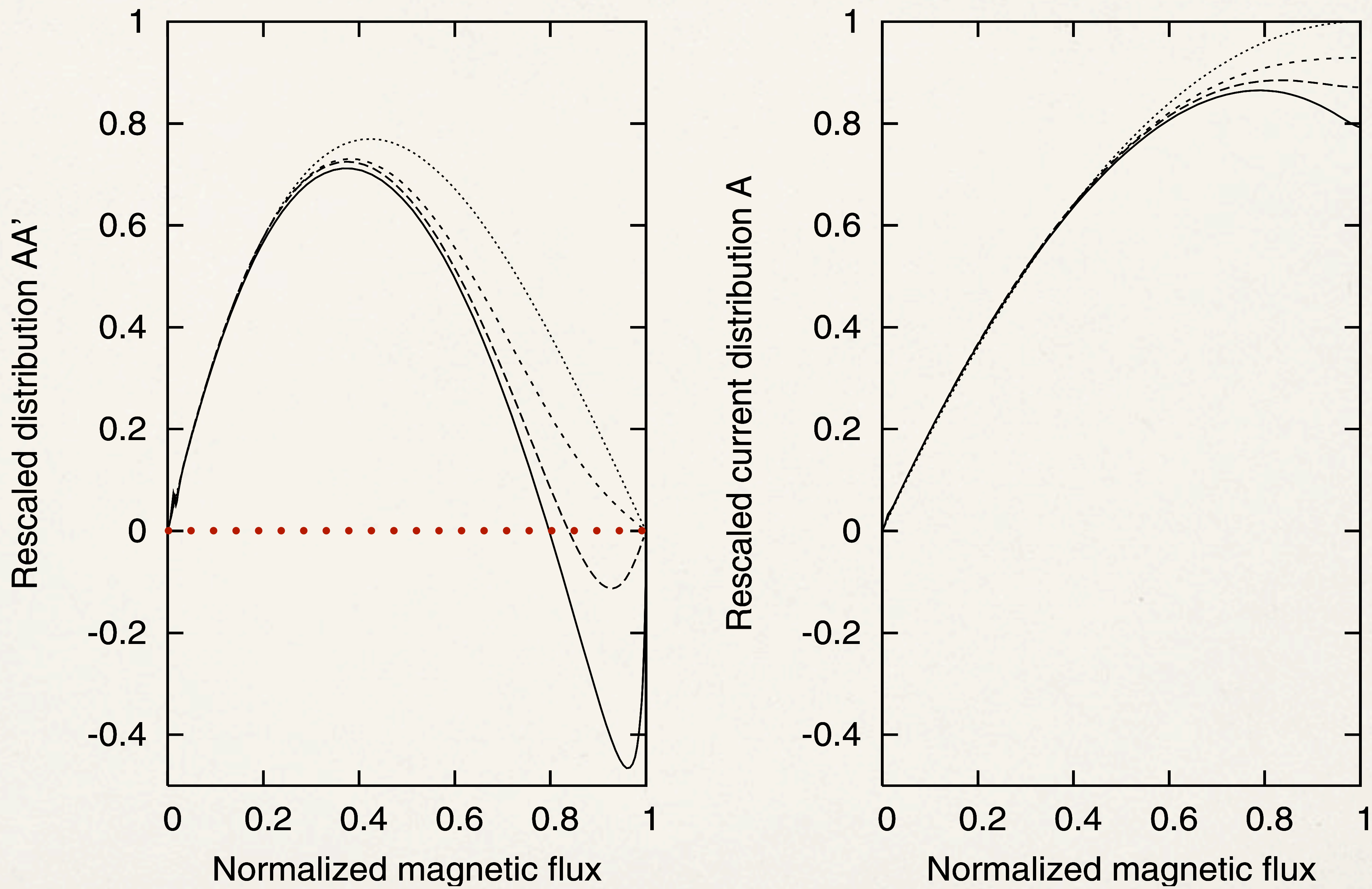
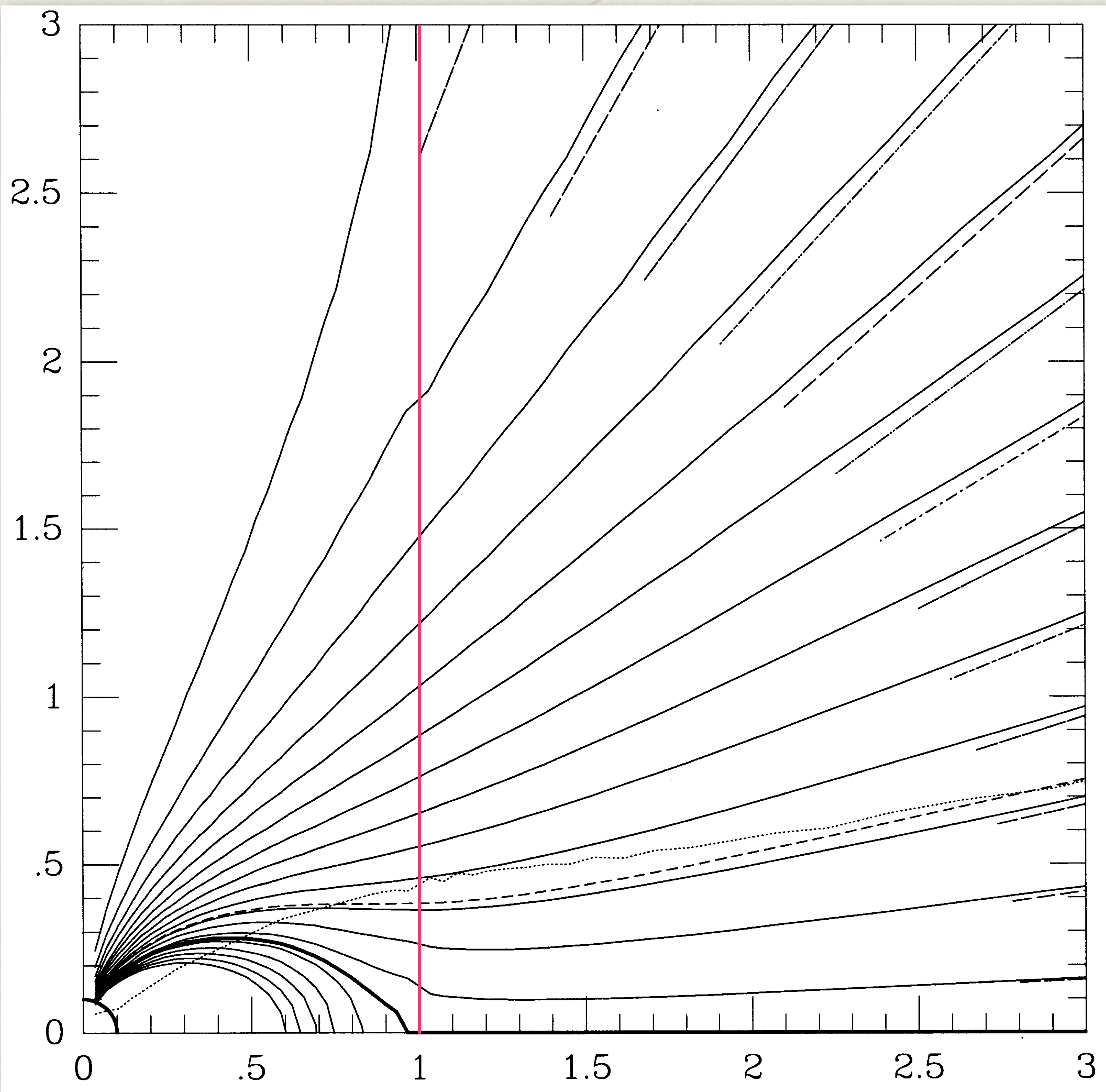
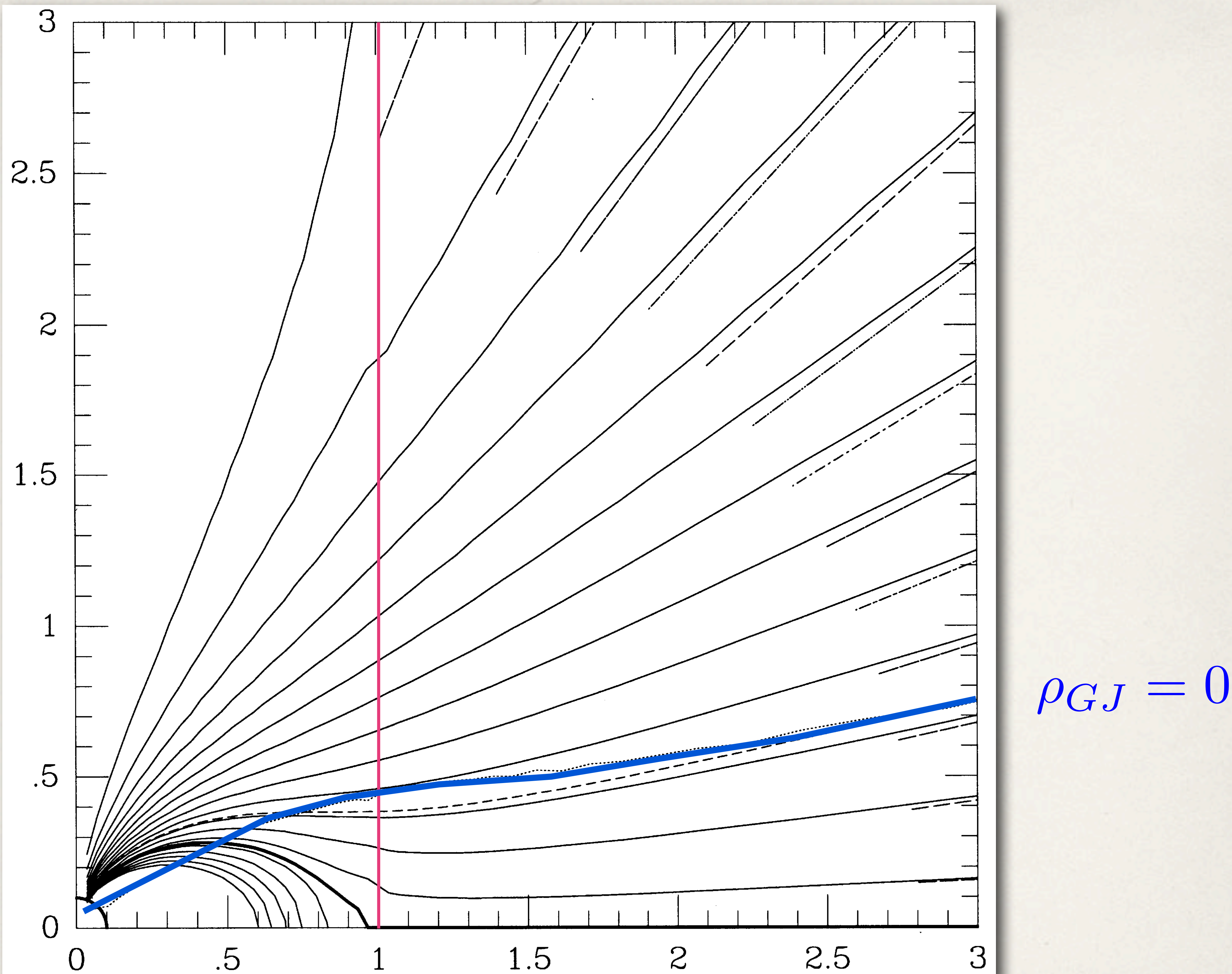


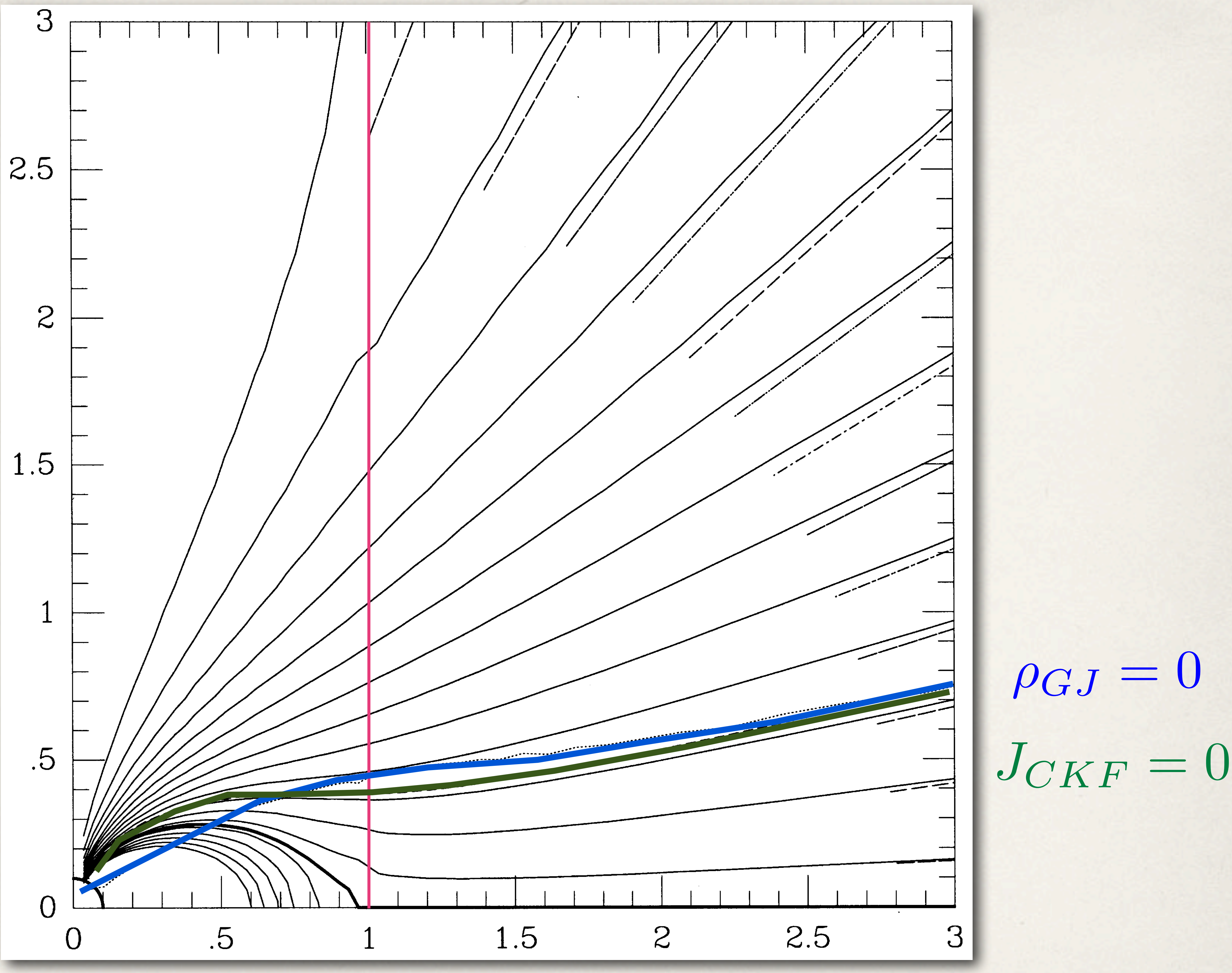
The aligned rotator (Contopoulos, Kazanas & Fendt 1999; Contopoulos 2005)



The aligned rotator (Contopoulos, Kazanas & Fendt 1999)



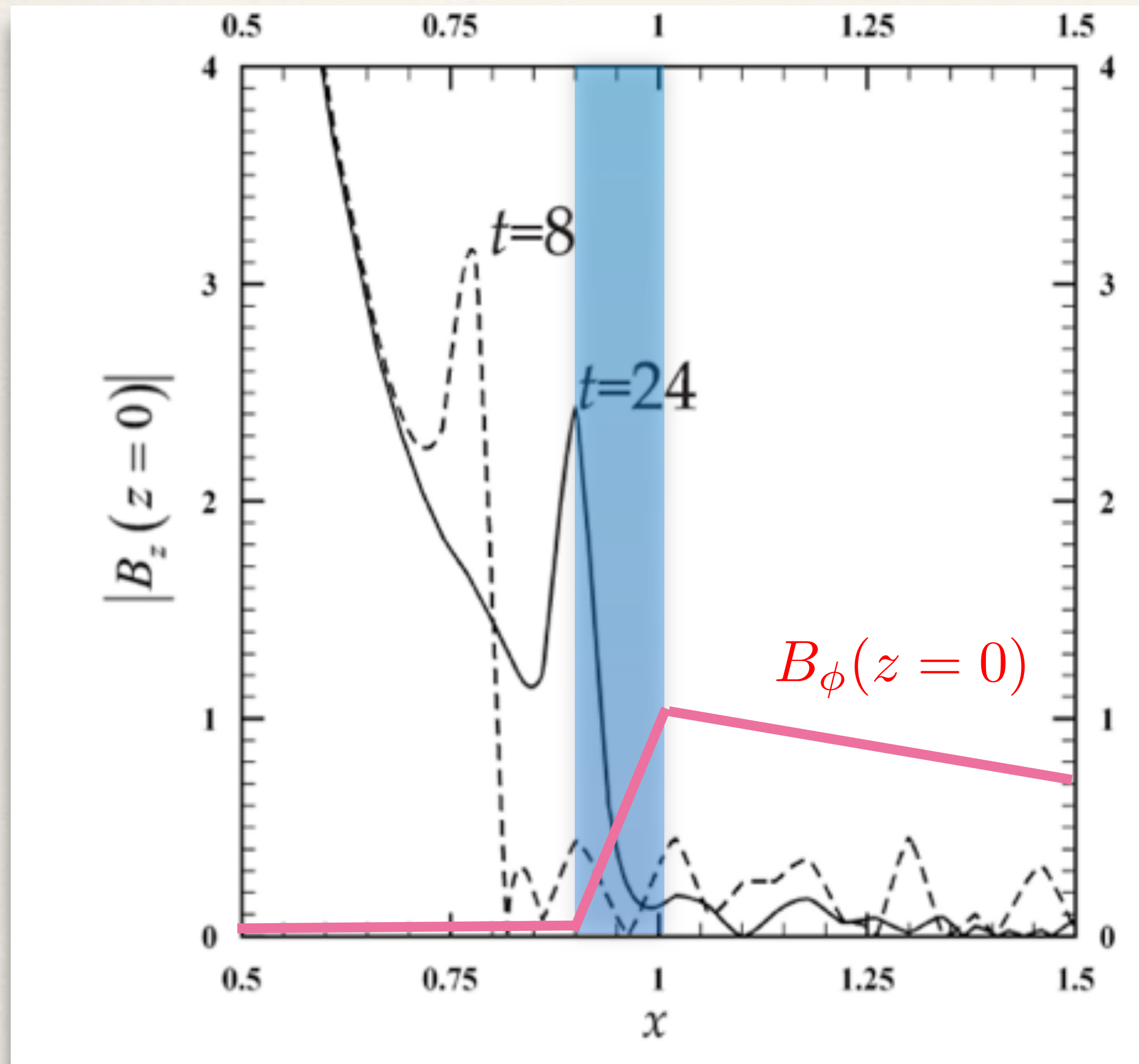
The aligned rotator (Contopoulos, Kazanas & Fendt 1999)

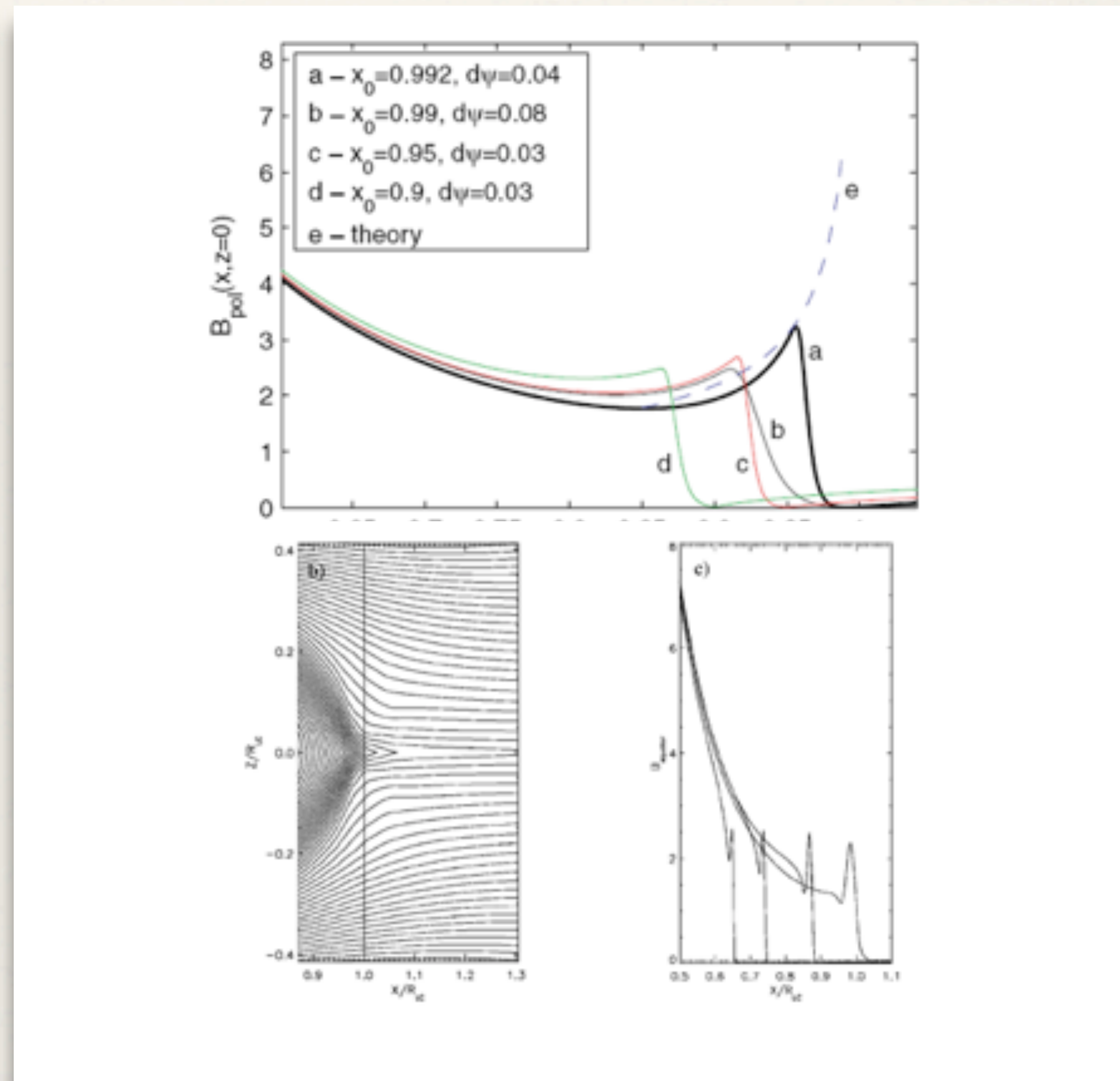


The aligned rotator (Contopoulos, Kazanas & Fendt 1999)

axisymmetric force-free ideal relativistic MHD:

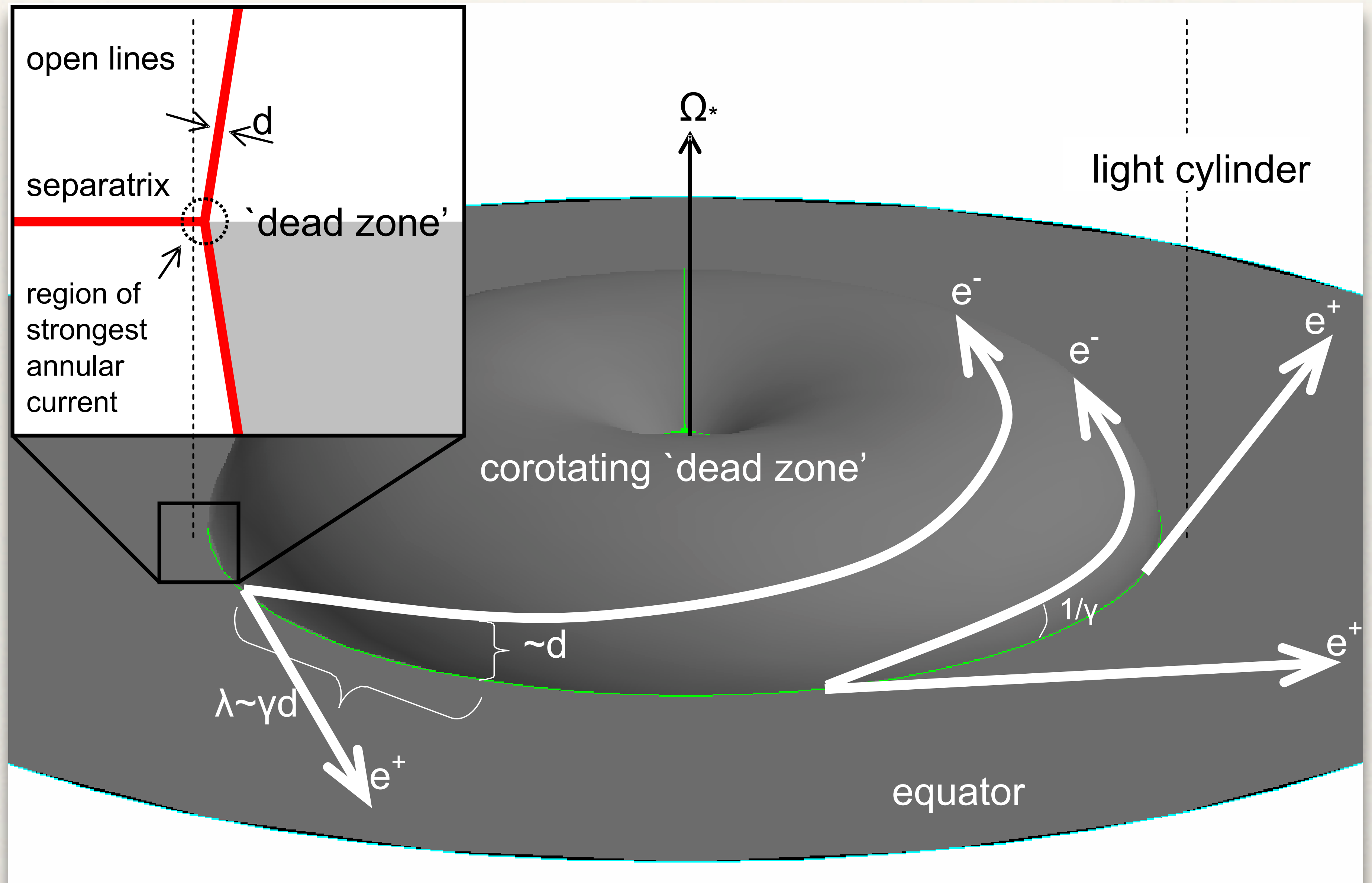
the Y-point





The Y-point singularity (Uzdensky 2003; Kalapotharakos & Contopoulos 2009)

axisymmetric force-free ideal relativistic MHD:
the Y-point



The equatorial current sheet (Contopoulos 2009)

3D vacuum:
Electrodynamics

$$\begin{aligned}\dot{E} &= c\nabla \times B \\ \dot{B} &= -c\nabla \times E\end{aligned}$$

$$\nabla \cdot B = 0$$

Spinning inclined dipole
Radiating antenna
Analytic solution (retarded dipole)

Retarded dipole (Deutsch 1955)

3D force-free ideal relativistic MHD:

Force-Free Electrodynamics (FFE)

$$\dot{E} = c\nabla \times B - 4\pi J \qquad \nabla \cdot B = 0$$

$$\dot{B} = -c\nabla \times E \qquad E \cdot B = 0$$

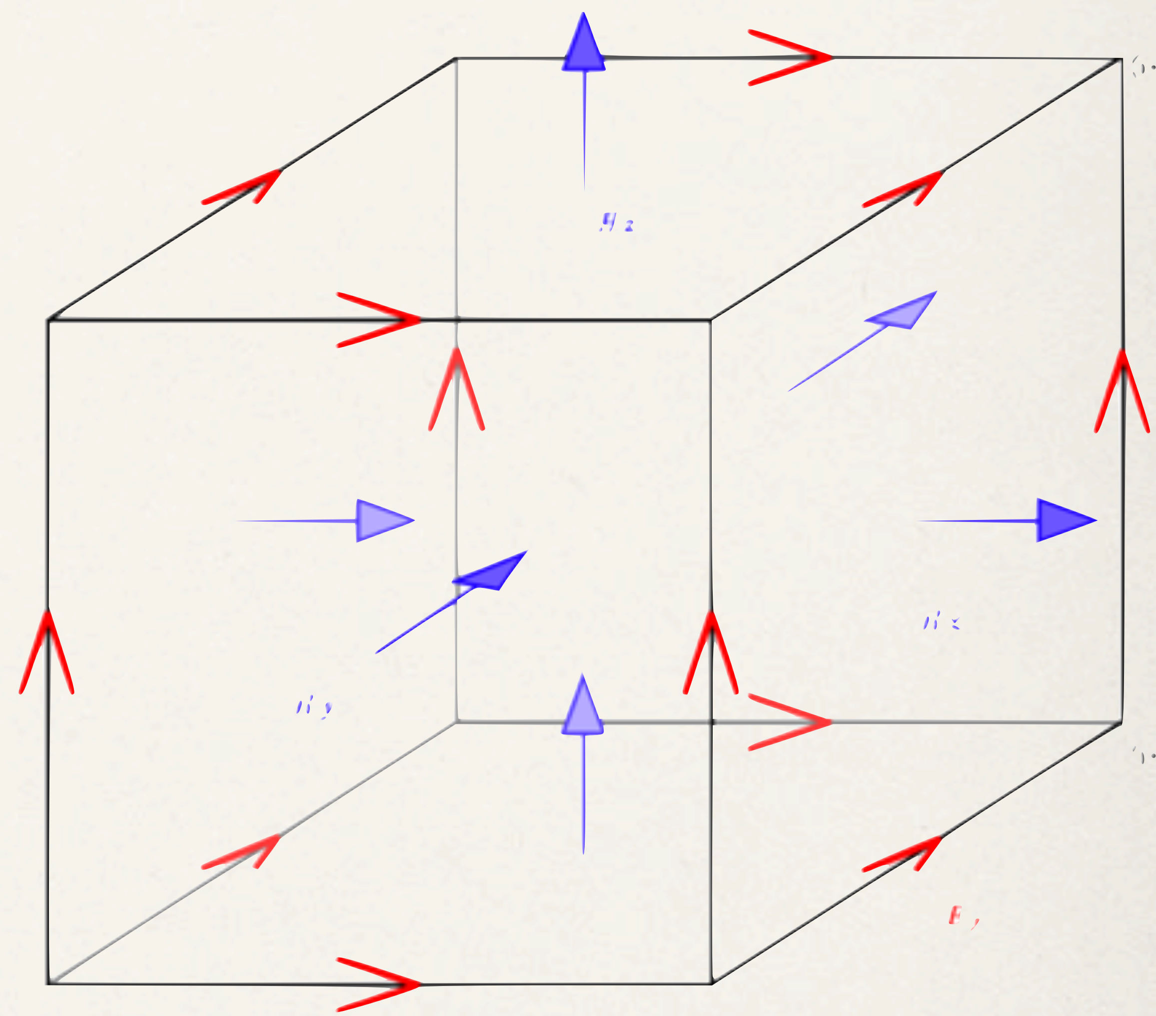
$$\rho_e E + J \times B = 0$$

$$J = \rho_e c \frac{E \times B}{B^2} + \frac{1}{4\pi} \frac{(B \cdot \nabla \times B - E \cdot \nabla \times E)}{B^2} B$$

FFE (Osherovich & Gliner 1988; Gruzinov 1999; Blandford 2002)

3D force-free ideal relativistic MHD:
numerical simulations

Staggered cartesian mesh (Yee 1966)
We "force" $E \perp B, \quad E \leq B$
3rd order Runge-Kutta:
    synchronous E, B (more accurate)
Courant stability condition
Tests of the code:
    vacuum
    aligned rotator
    spindown



FFE code (Spitkovsky 2006; Kalapotharakos & Contopoulos 2009)

3D force-free ideal relativistic MHD:
numerical simulations

Perfectly Matched Layer (PML):

absorbing non-reflecting outer boundary

many rotations (instead of 1.5)

$L=2\ R_{LC}$, $\delta=0.04\ R_{LC}$

1 CPU, 4 Gb

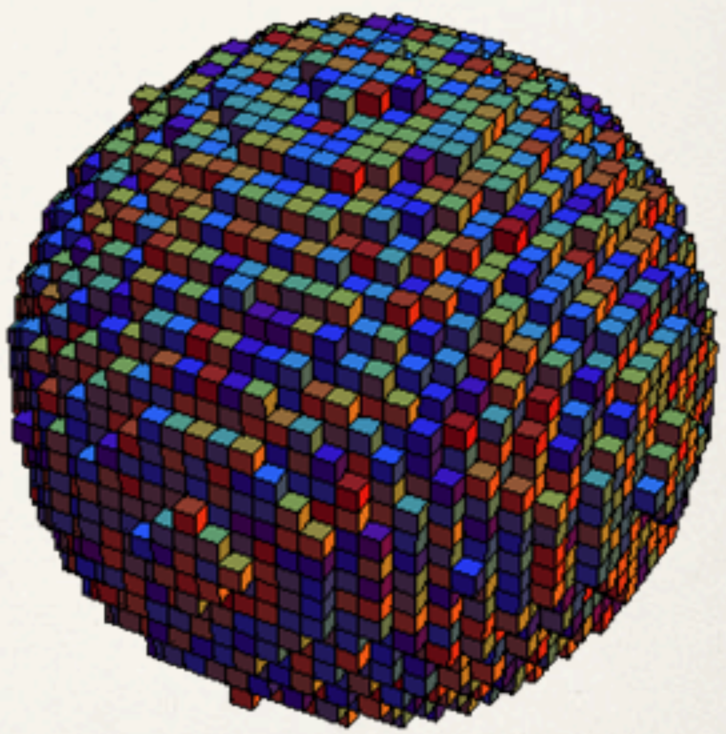
24 hours

Parallel code (MPI):

$L=20\ R_{LC}$, $\delta=0.02\ R_{LC}$

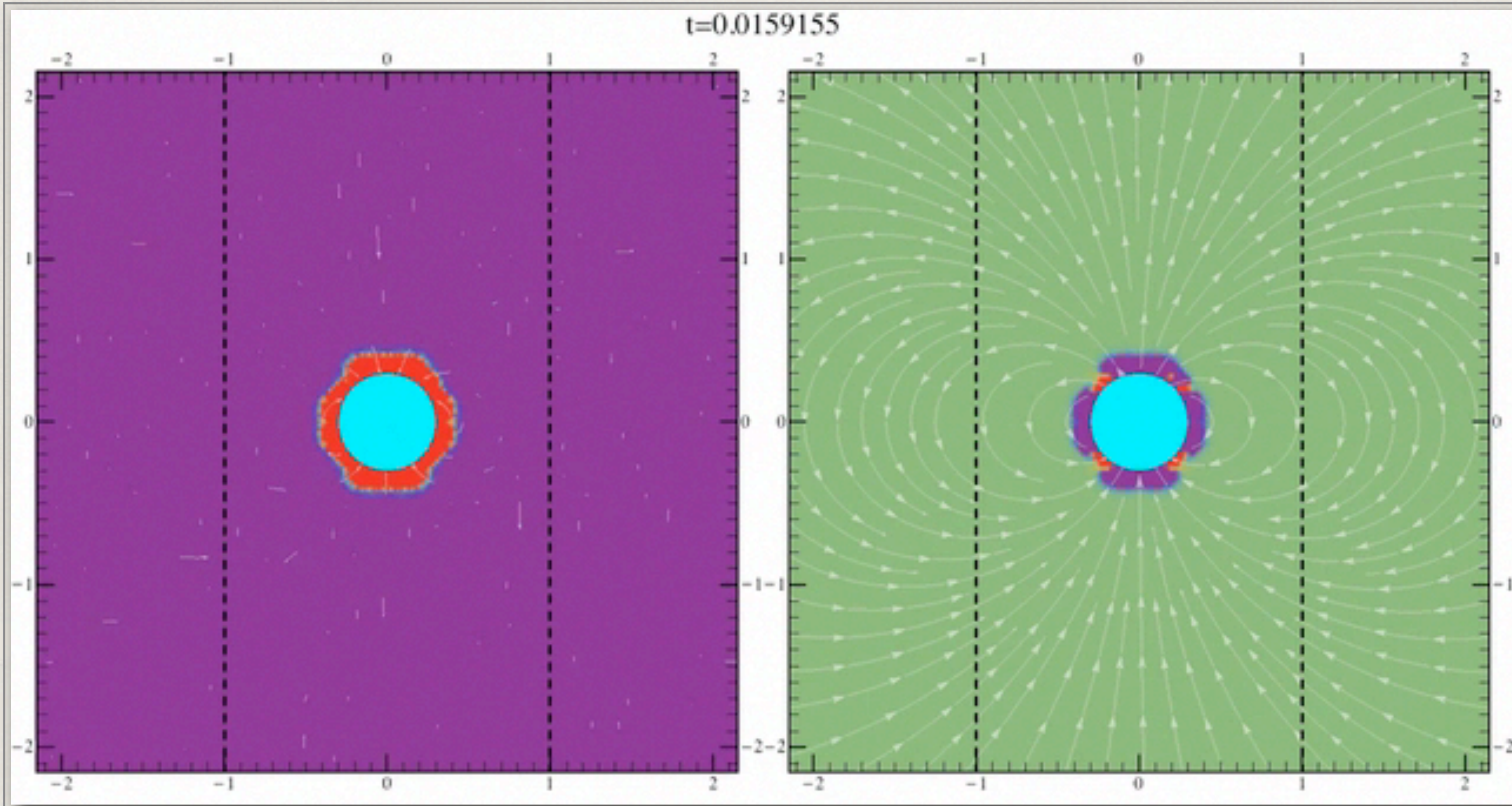
1000 CPUs

less than one day ...



Spherical star in cartesian grid...

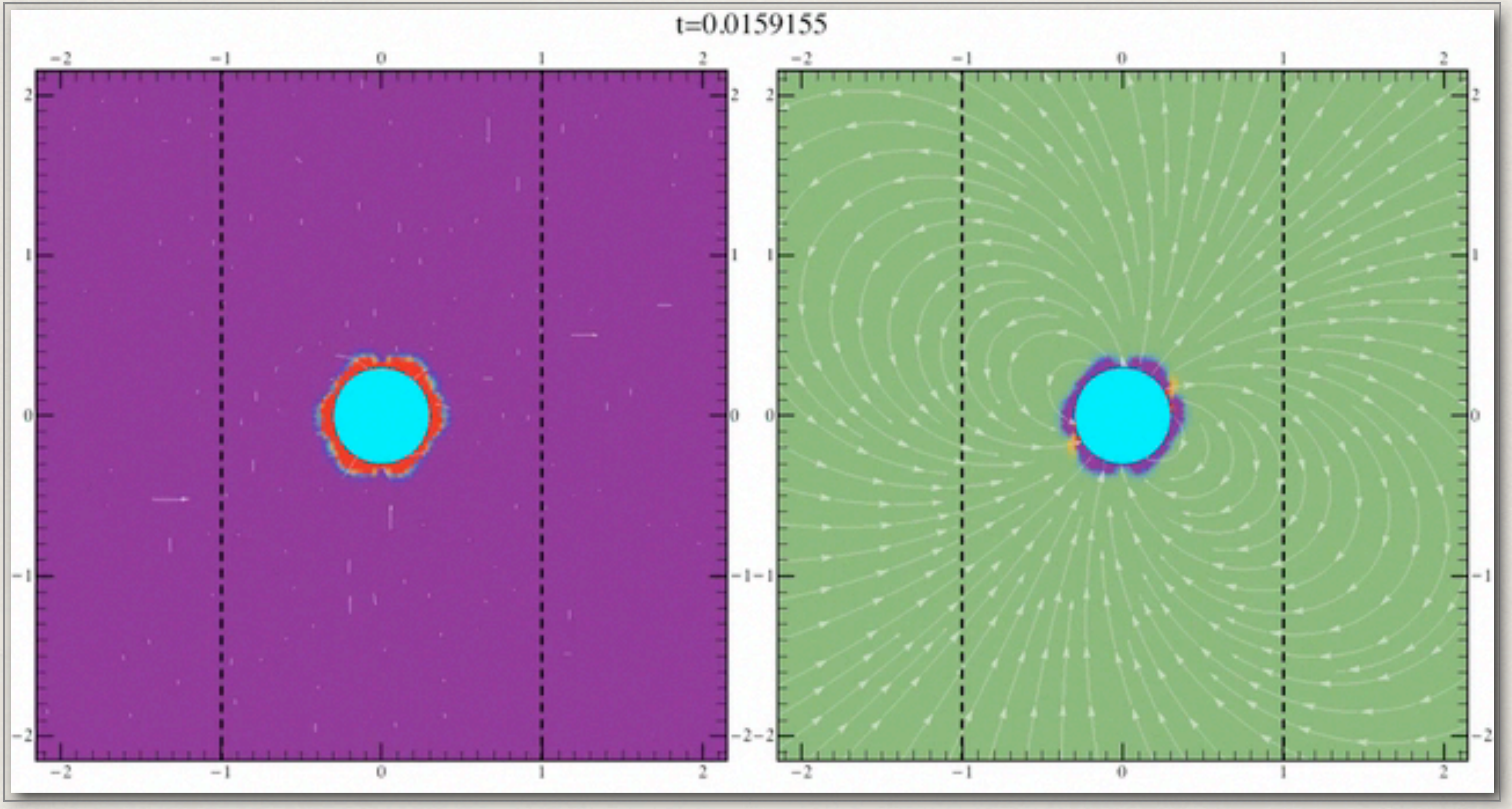
FFE code (Kalapotharakos & Contopoulos 2009)



J

ϱ, B

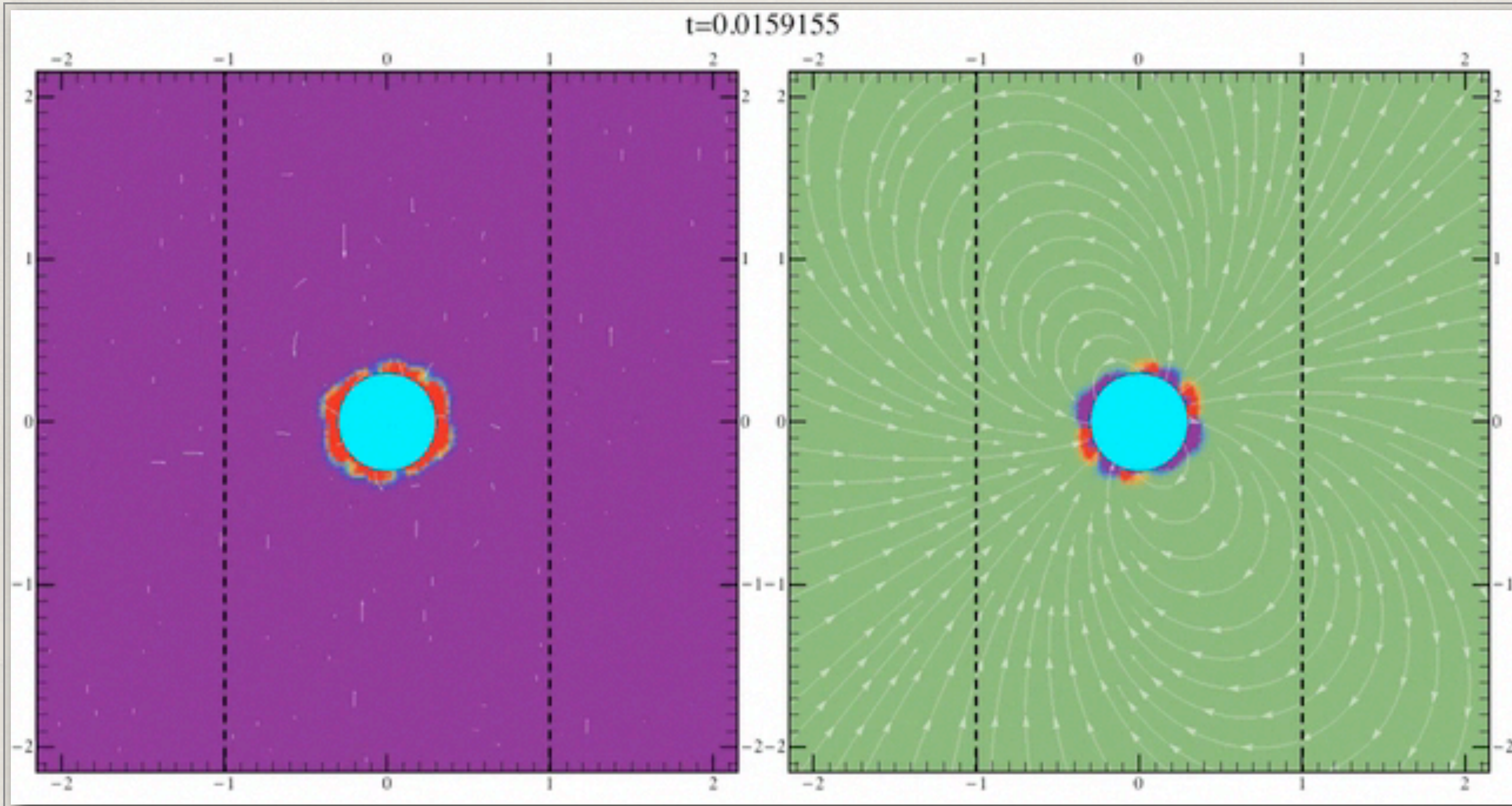
The axisymmetric pulsar magnetosphere (Contopoulos & Kalapotharakos 2010)



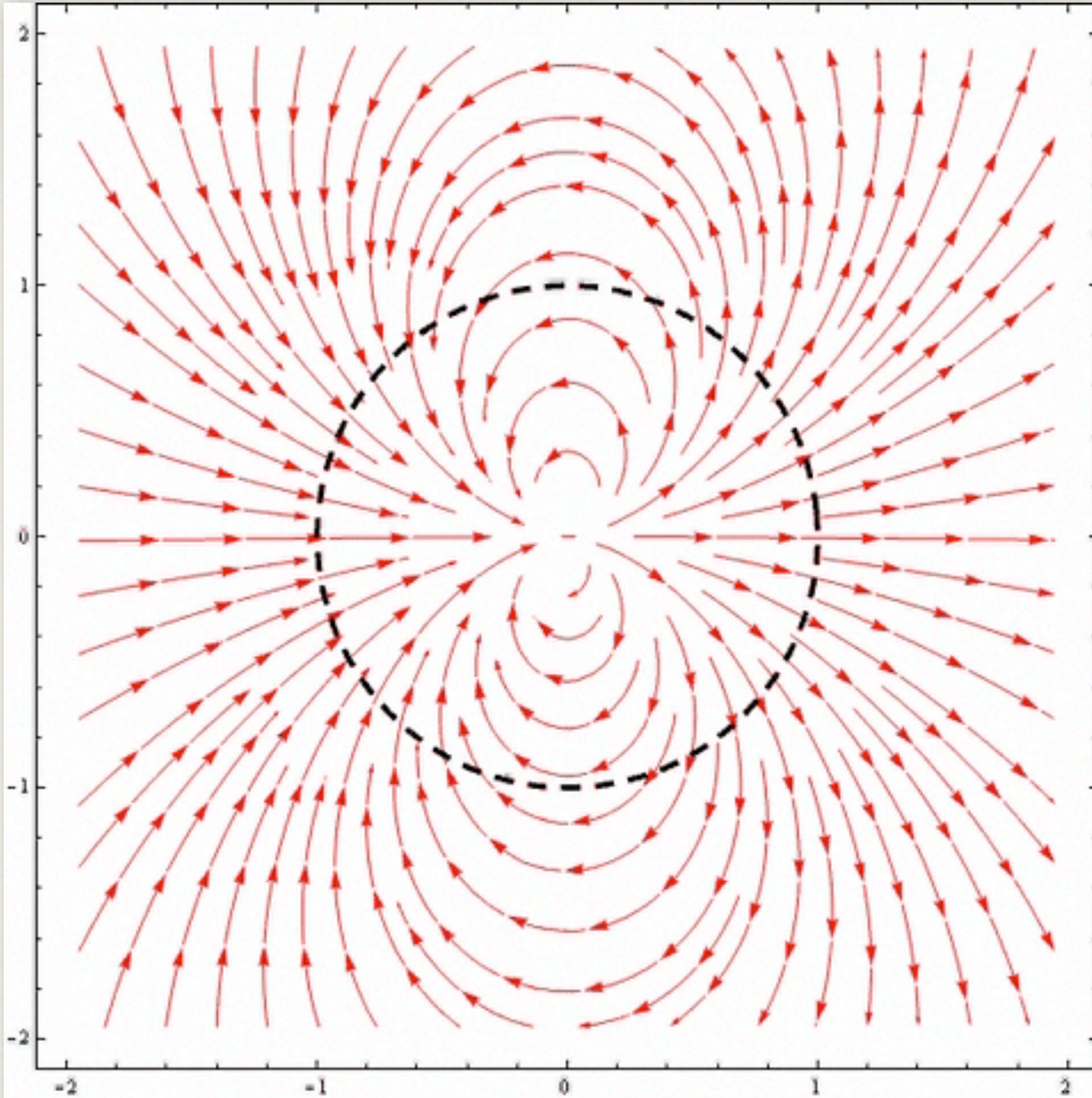
J

ϱ, B

The 3D pulsar magnetosphere: 30^o (Contopoulos & Kalapotharakos 2010)



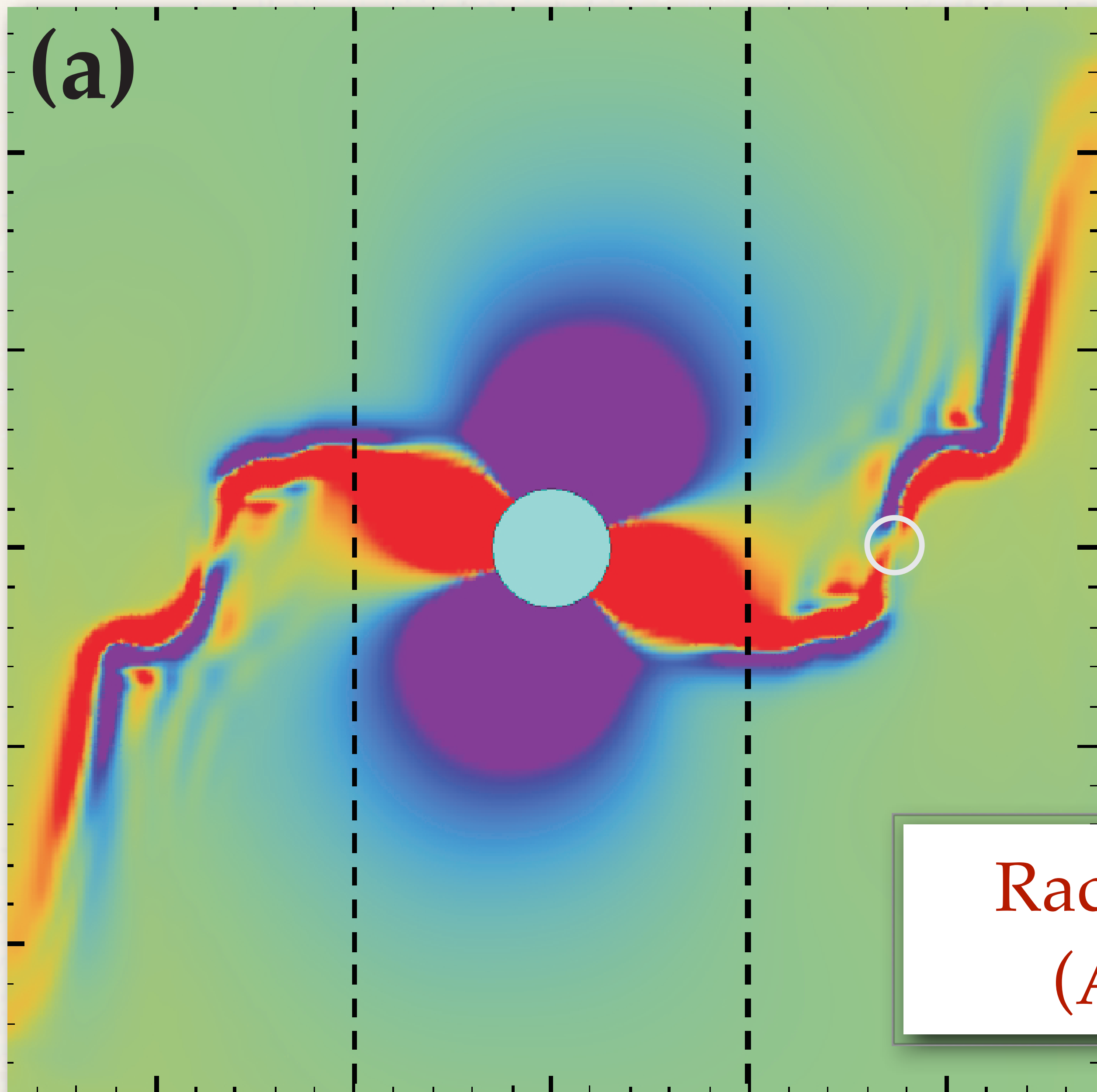
The 3D pulsar magnetosphere: 60º (Contopoulos & Kalapotharakos 2010)



The 3D pulsar magnetosphere: 90° (Contopoulos & Kalapotharakos 2010)

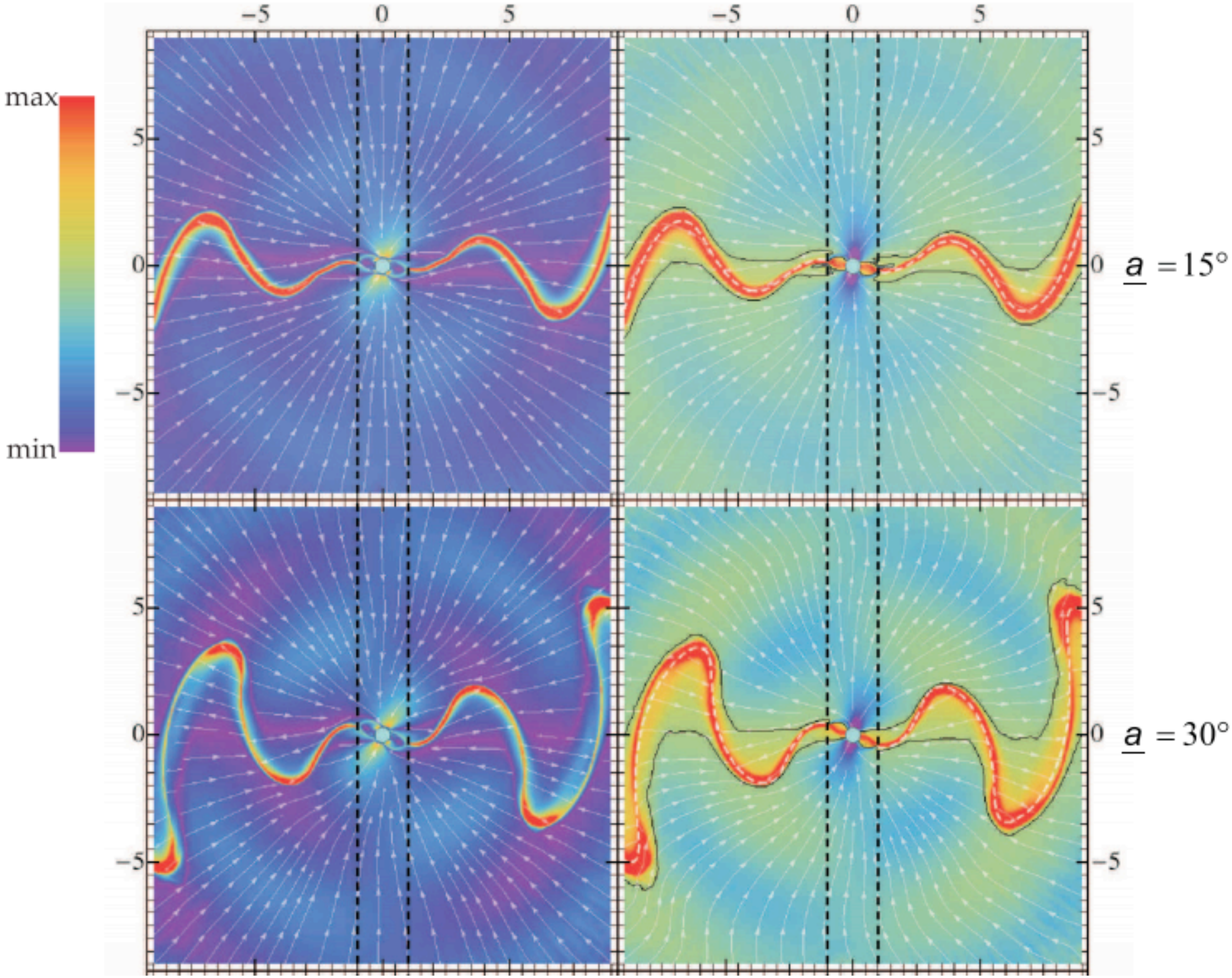
3D force-free ideal relativistic MHD:

extended numerical simulations

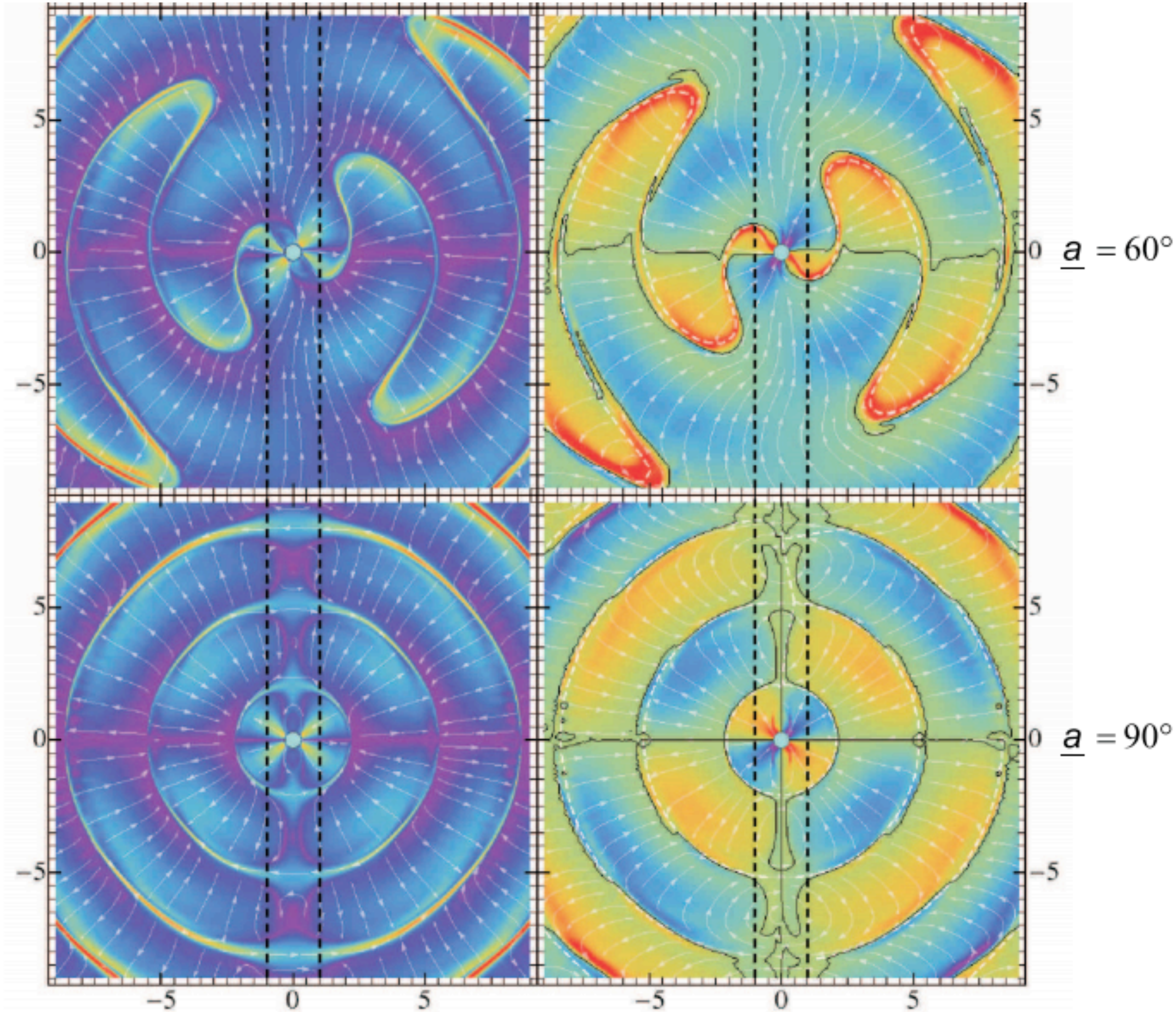


Radiation caustics?
(Ardavan 1998)

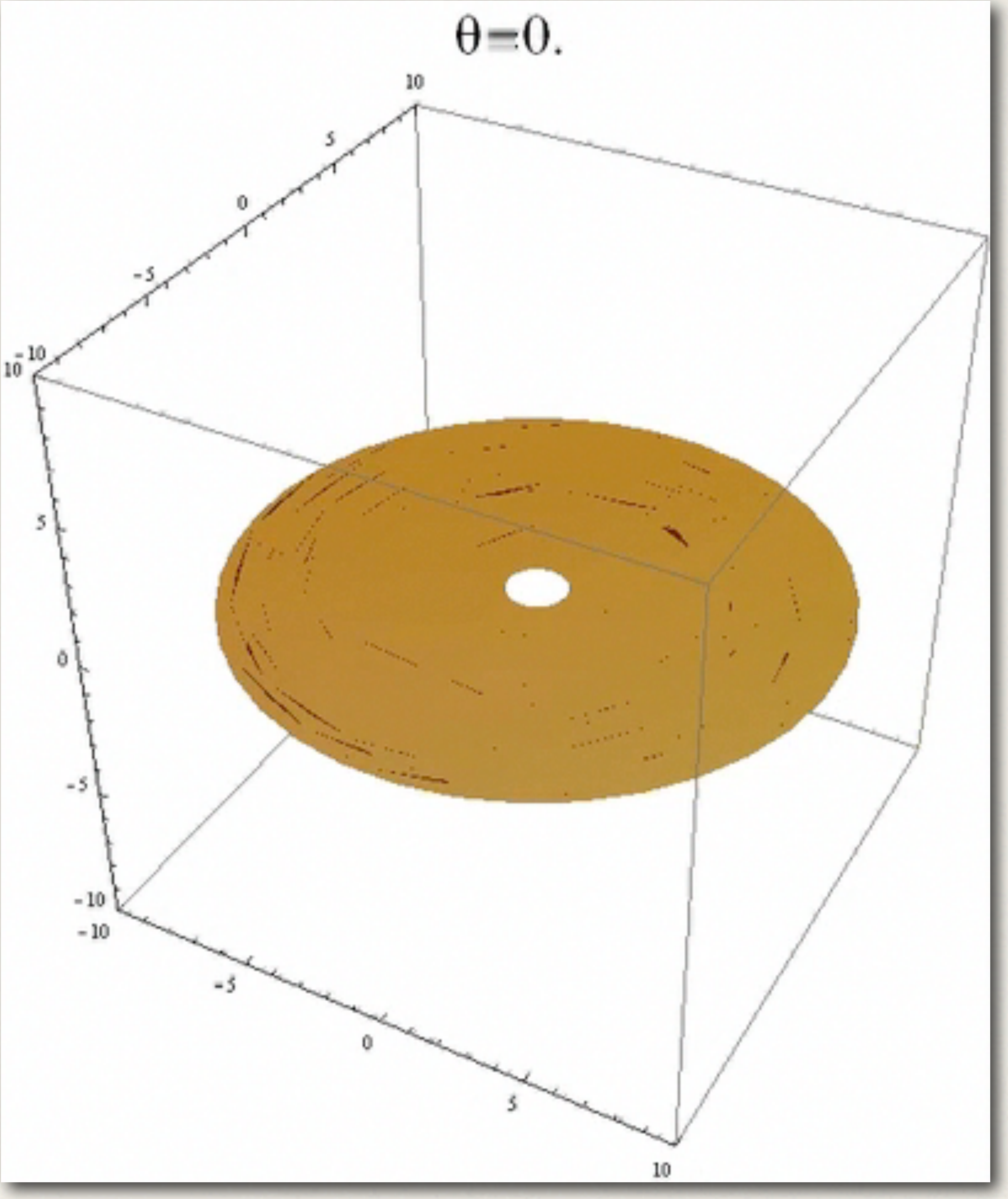
The extended magnetosphere (Kalapotharakos, Contopoulos & Kazanas 2011)



The extended magnetosphere (Bogovalov 1999; Kalapotharakos, IC & Kazanas 2011)



The extended magnetosphere (Bogovalov 1999; Kalapotharakos, IC & Kazanas 2011)

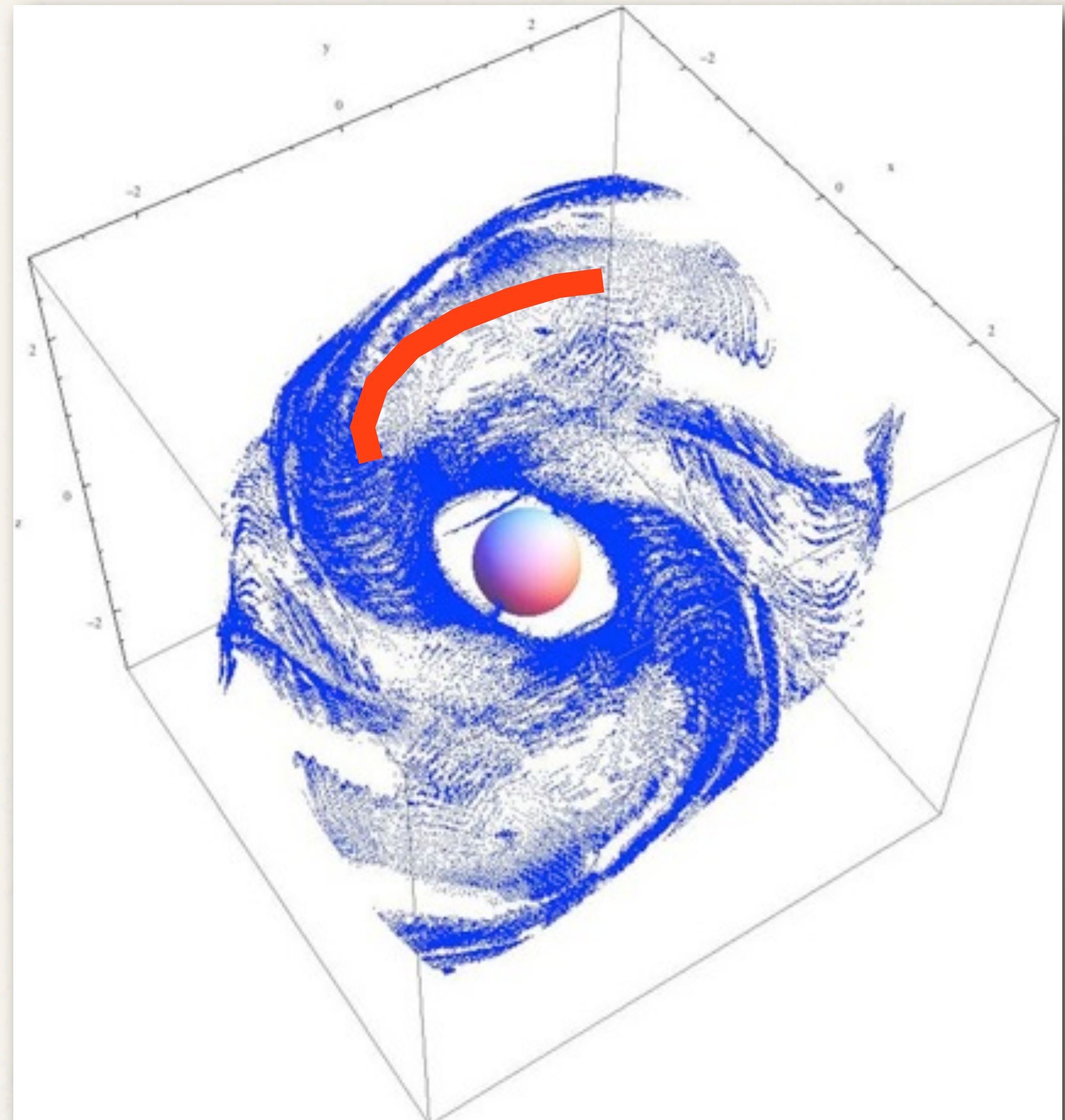


The extended magnetosphere (Bogovalov 1999; Kalapotharakos, IC & Kazanas 2011)

3D force-free ideal relativistic MHD:
high-energy light curves

$$L_{CR} \propto \frac{n\gamma^4}{R_c^2}$$

$$J_{eq} \approx \rho_e c = nec$$



Pulses are narrow, emission regions have significant azimuthal extent

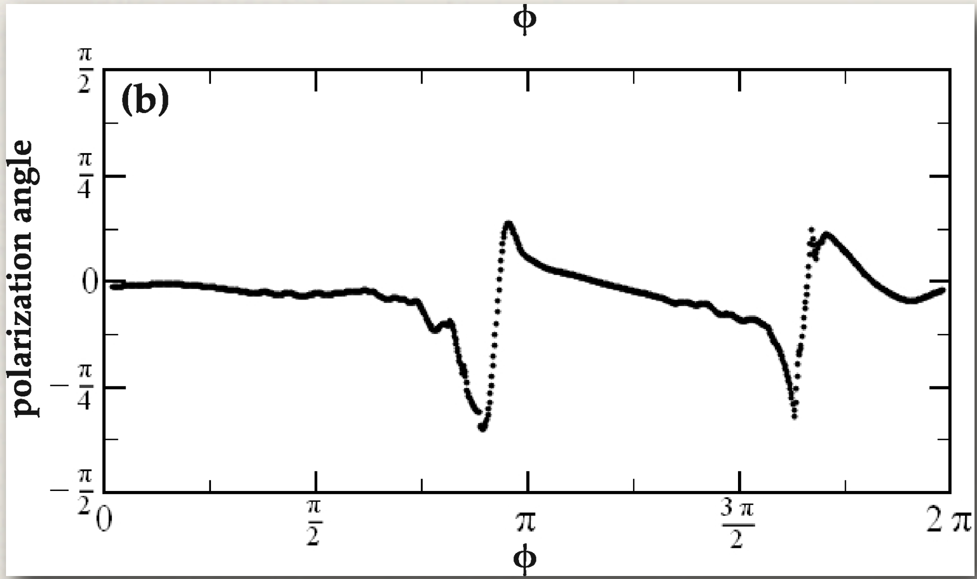
Curvature radiation along equatorial current sheet (Kalapotharakos & Contopoulos 2010)

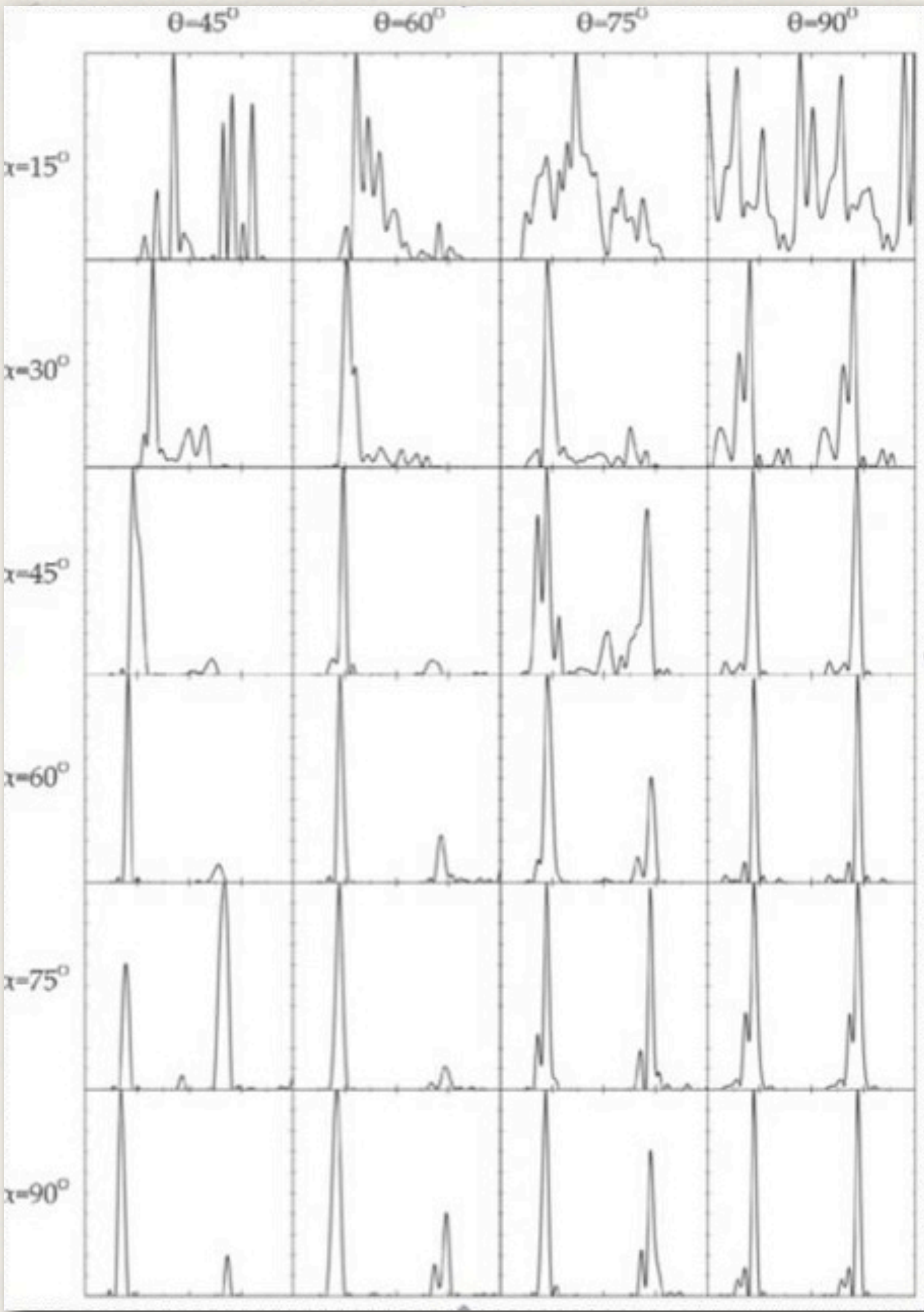
Narrower pulses from higher latitudes

Interpulse decreases fast as observer moves away from equatorial plane

Pulse-interpulse: 0.4-0.5P

Polarization angle sweep

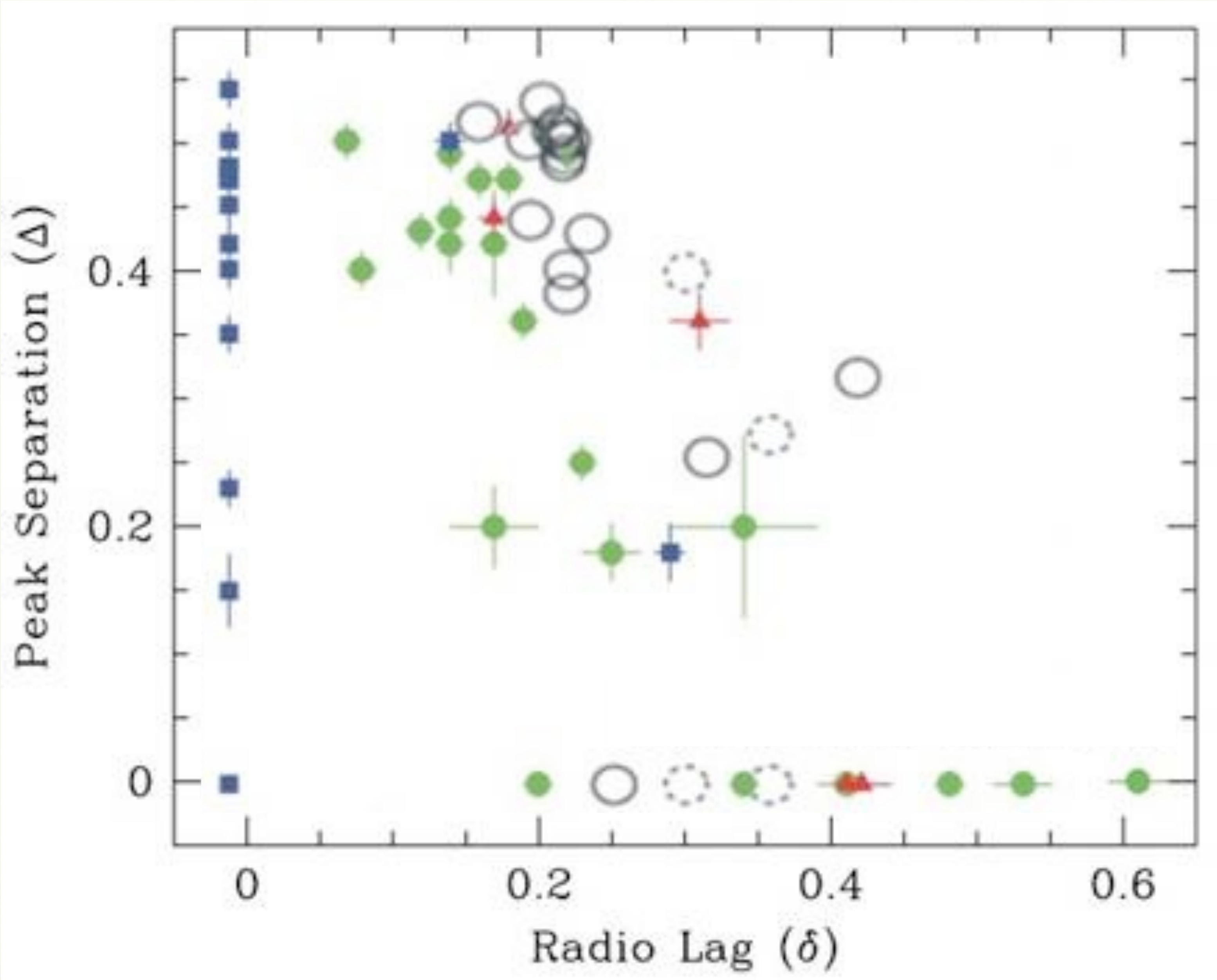




Curvature radiation along equatorial current sheet (Kalapotharakos & Contopoulos 2010)

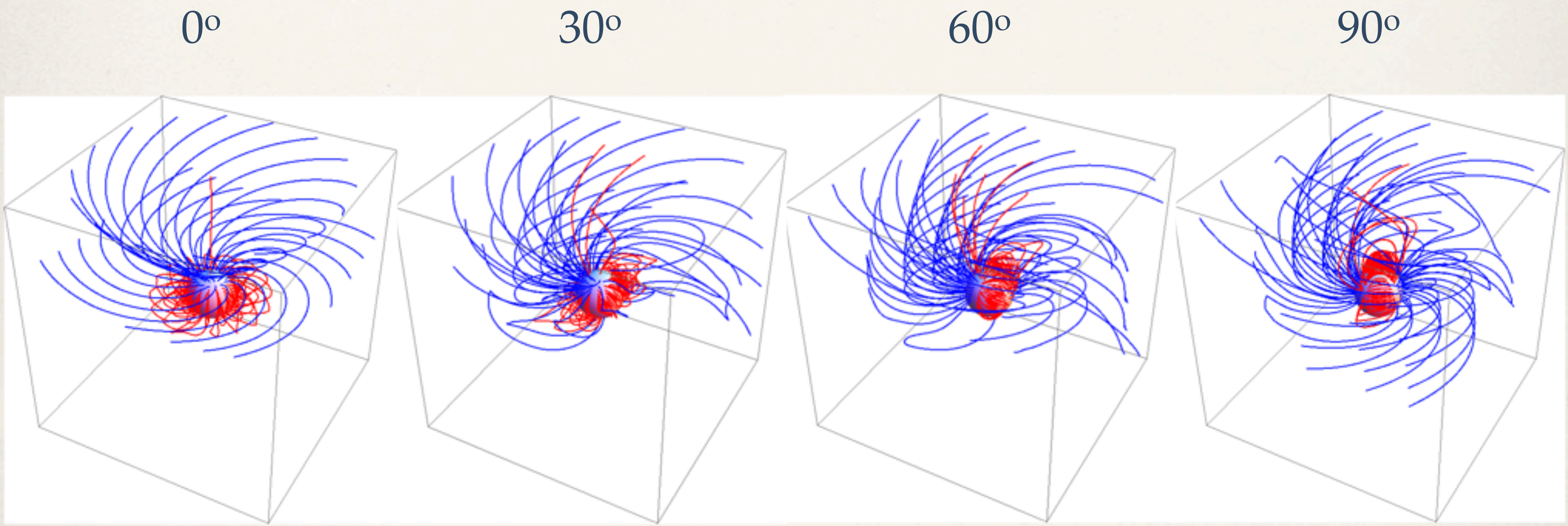
3D force-free ideal relativistic MHD:
high-energy light curves

Higher radio lags



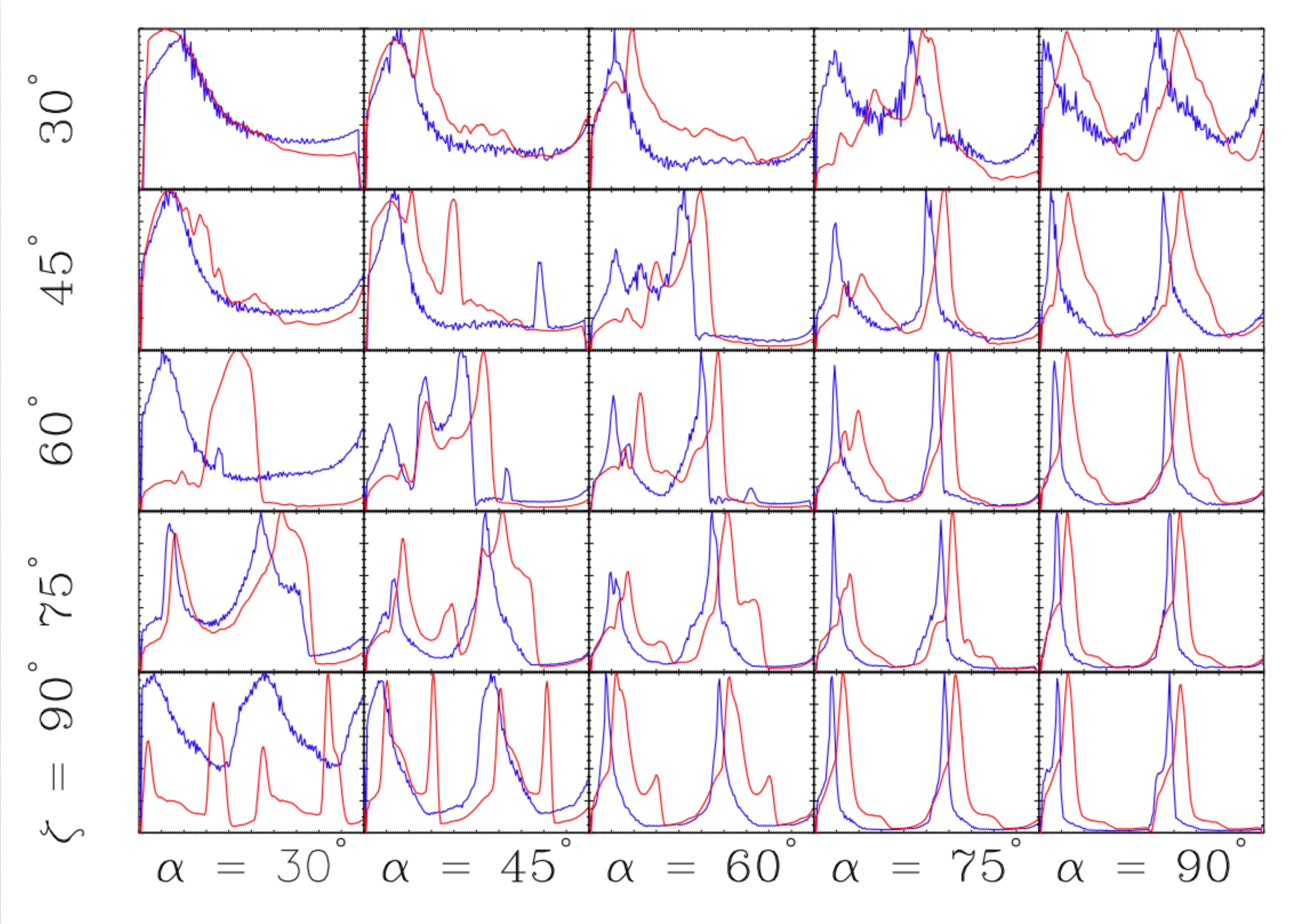
High energy light curves (Kalapotharakos & Contopoulos 2010)

3D force-free ideal relativistic MHD:
high-energy light curves



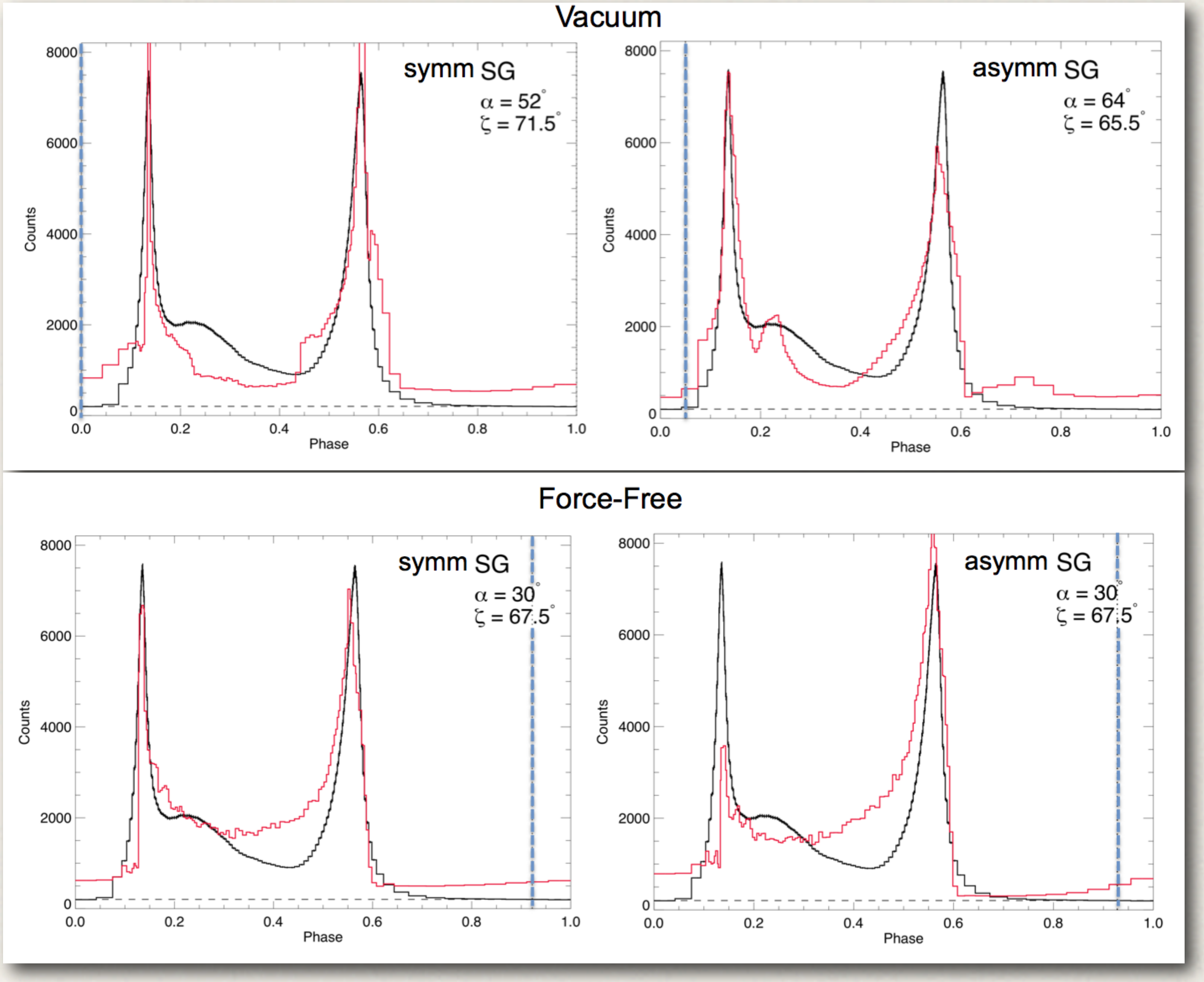
"Lighting up" field lines (Romani *et al.* 2009; Bai & Spitkovsky 2010; Harding *et al.* 2011)

3D force-free ideal relativistic MHD: high-energy light curves



"Lighting up" field lines (Harding, DeCesar, Miller, Kalapotharakos & IC 2011)

3D force-free ideal relativistic MHD:
high-energy light curves



Higher radio lags
(vacuum works better)...

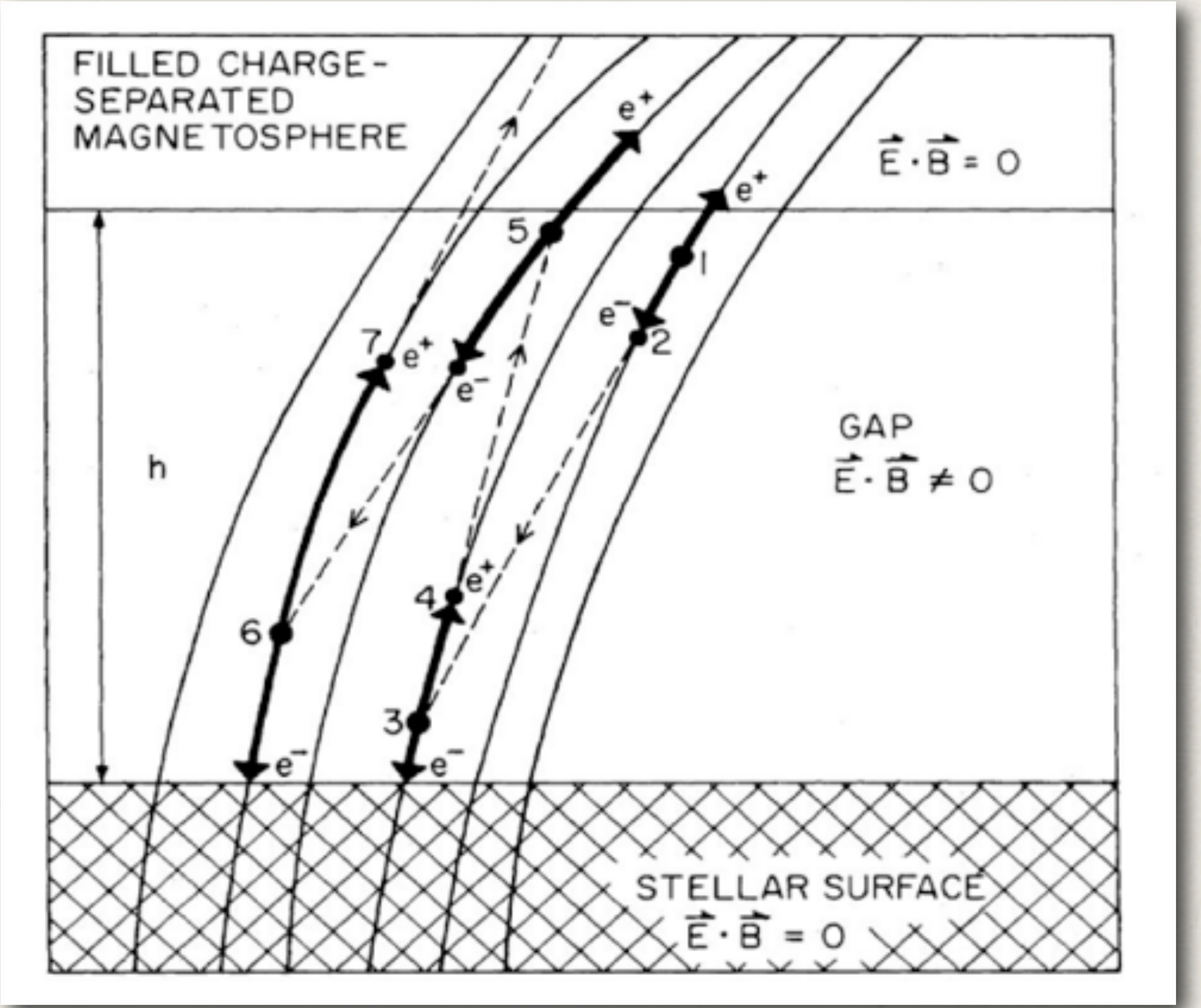
"Lighting up" field lines (Harding, DeCesar, Miller, Kalapotharakos & IC 2011)

3D resistive relativistic MHD:
towards the real pulsar magnetosphere

No microphysics in FFE:

- no particle production
- no particle acceleration
- space-like: $J > \rho_e c$
- time-like : $J < \rho_e c$

Physical resistivity needed



Li, Spitkovsky & Tchekhovskoy 2011; Kalapotharakos, Kazanas, Harding & IC 2011

3D resistive relativistic MHD:
towards the real pulsar magnetosphere

Strong Field Electrodynamics (SFE; Gruzinov 2008):

$$J = \rho_e c \frac{E \times B}{B^2 + E_o^2} + \frac{1}{4\pi} \frac{\sqrt{\rho_e^2 + \sigma^2 \gamma^2 E_o^2}(B_o B + E_o E)}{B^2 + E_o^2} B$$

Lorentz covariant

$\sigma=0$: $J=\varrho_e c$ (not vacuum!)

space-like everywhere (oscillatory where FFE time-like)

Kalapotharakos, Kazanas, Harding & Contopoulos 2011

3D resistive relativistic MHD:
towards the real pulsar magnetosphere

Other resistivity prescriptions:

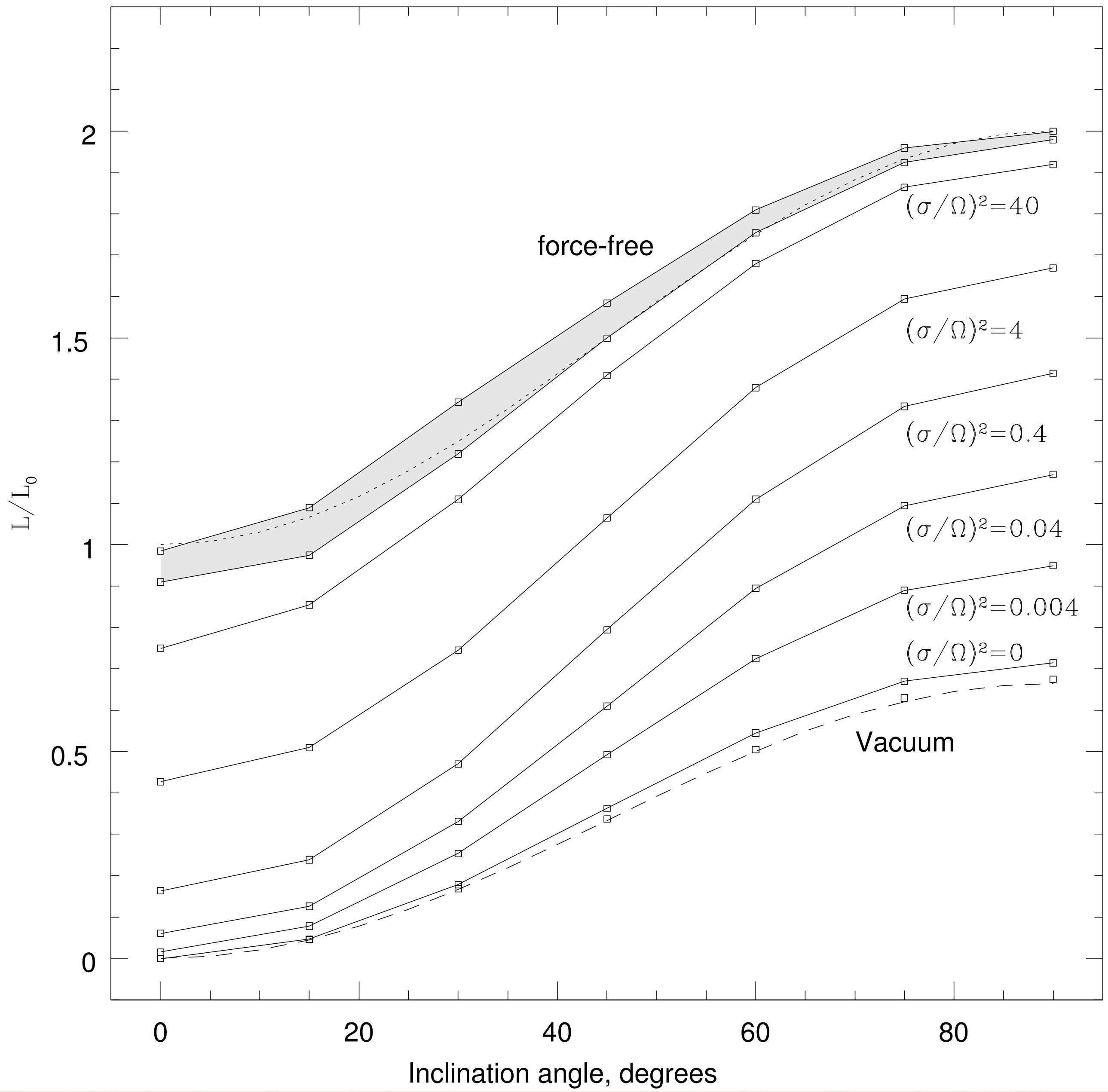
$$J = \rho_e c \frac{E \times B}{B^2 + E_o^2} + \sigma E_{\parallel}$$

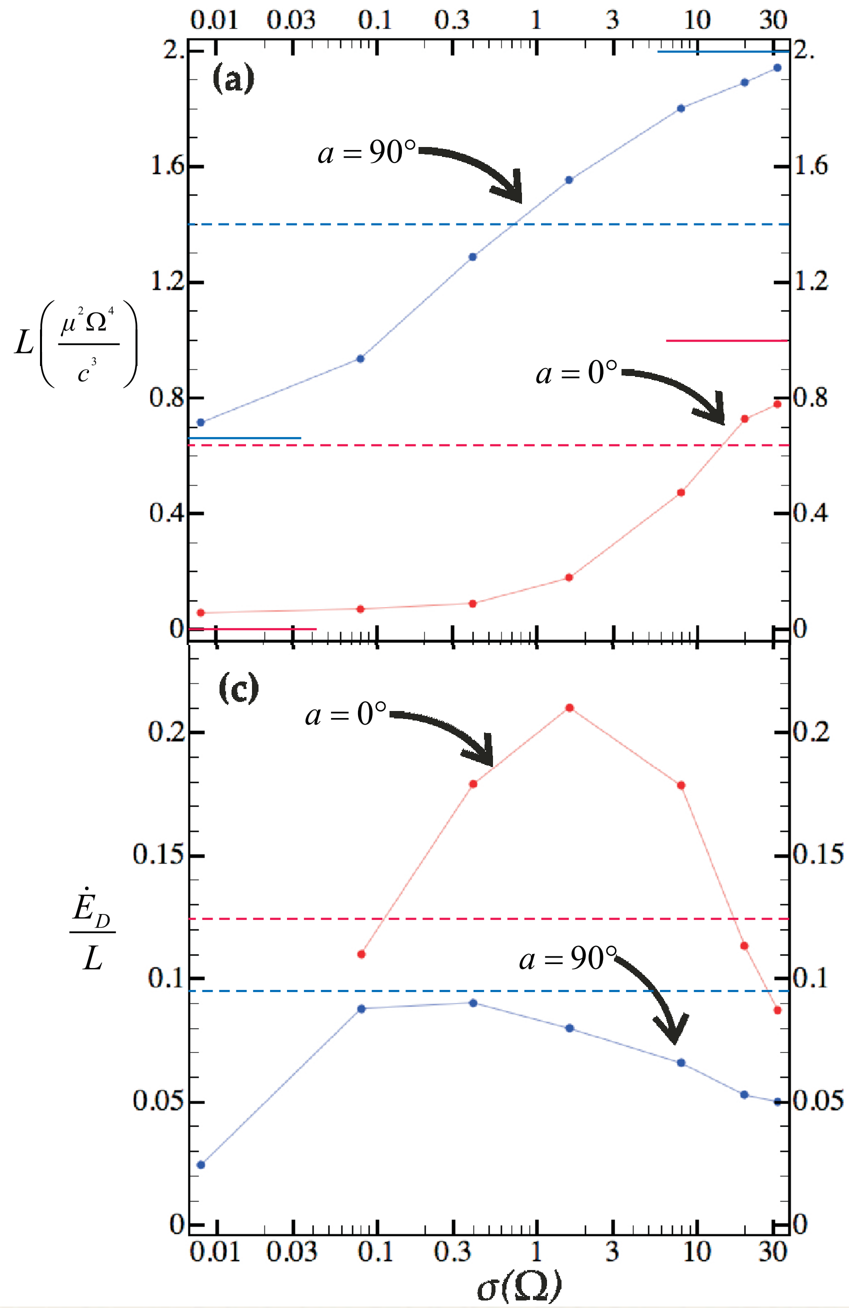
- non-covariant σ
- require $J = \varrho_e c$
- combination of SFE + FFE (space-like + time-like)

Intermediate between vacuum and FFE

Li, Spitkovsky & Tchekhovskoy 2011; Kalapotharakos, Kazanas, Harding & IC 2011

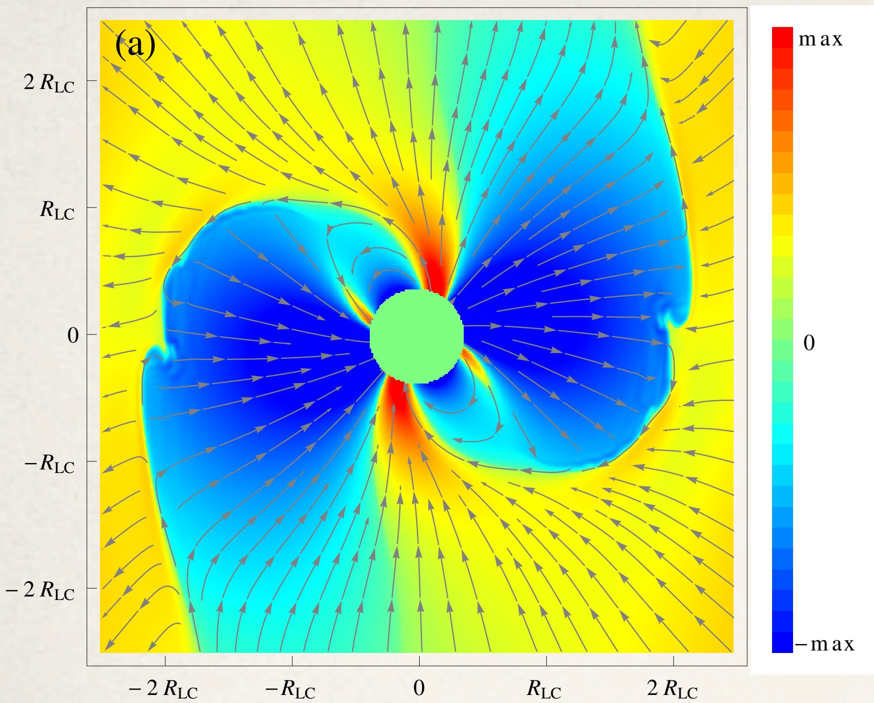
3D resistive relativistic MHD:
towards the real pulsar magnetosphere



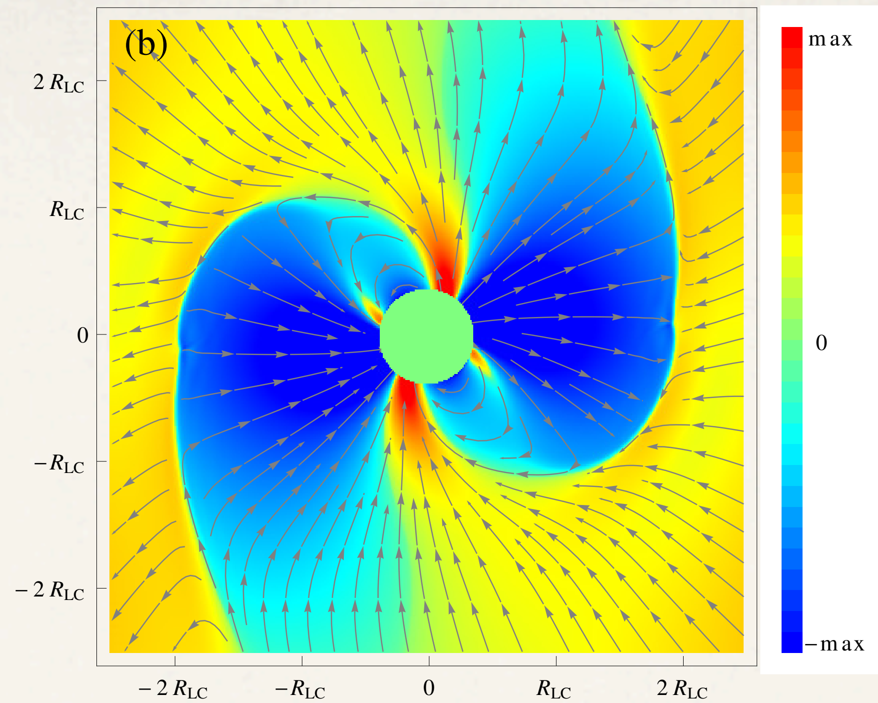


Li, Spitkovsky & Tchekhovskoy 2011; Kalapotharakos, Kazanas, Harding & IC 2011

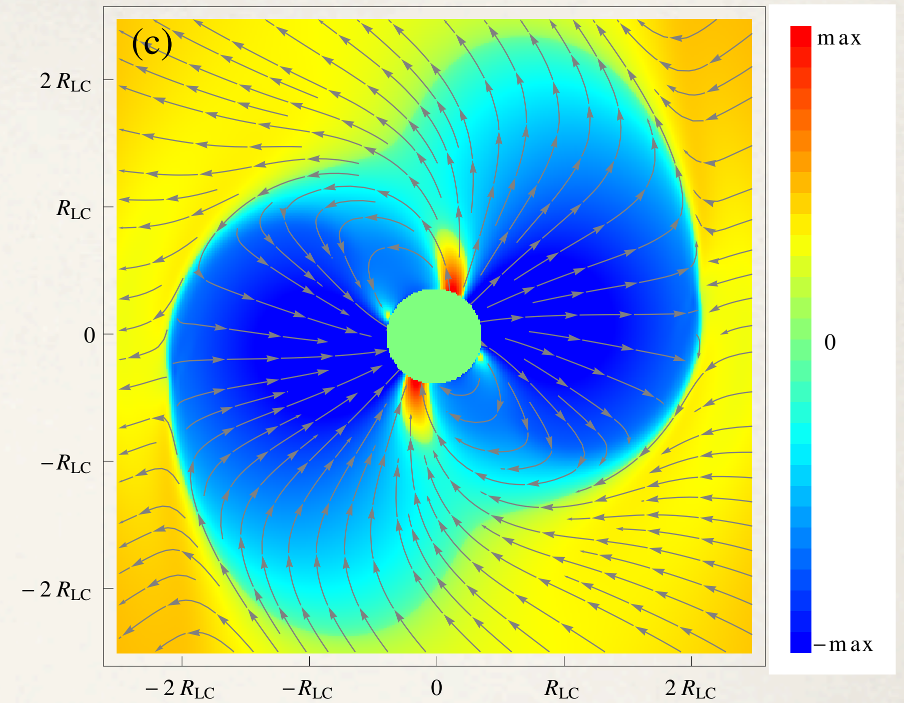
σ=infinity (FFE)



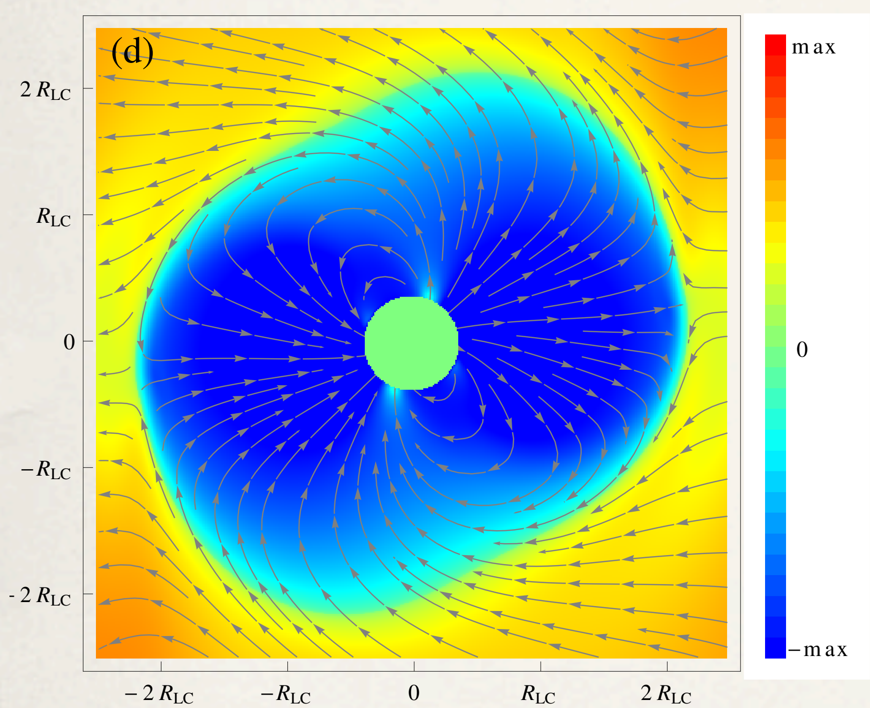
σ=40



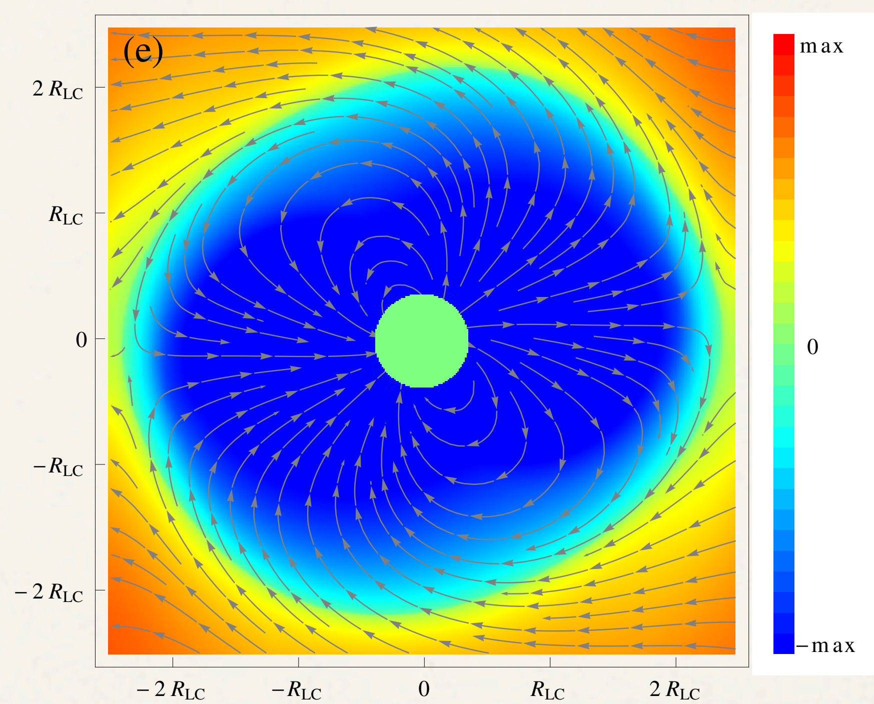
σ=4



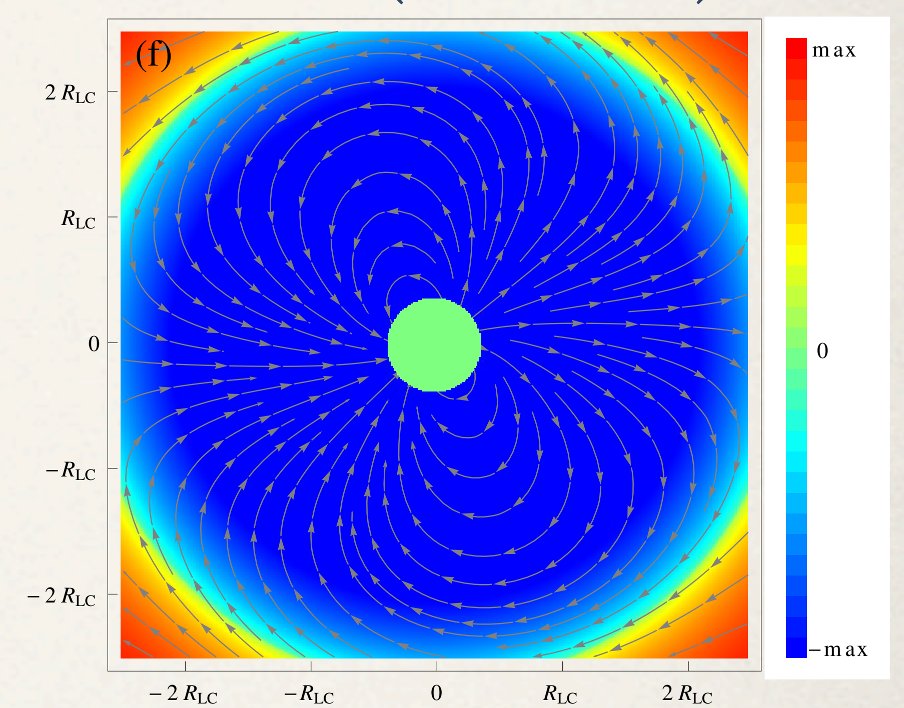
σ=0.4



σ=0.04

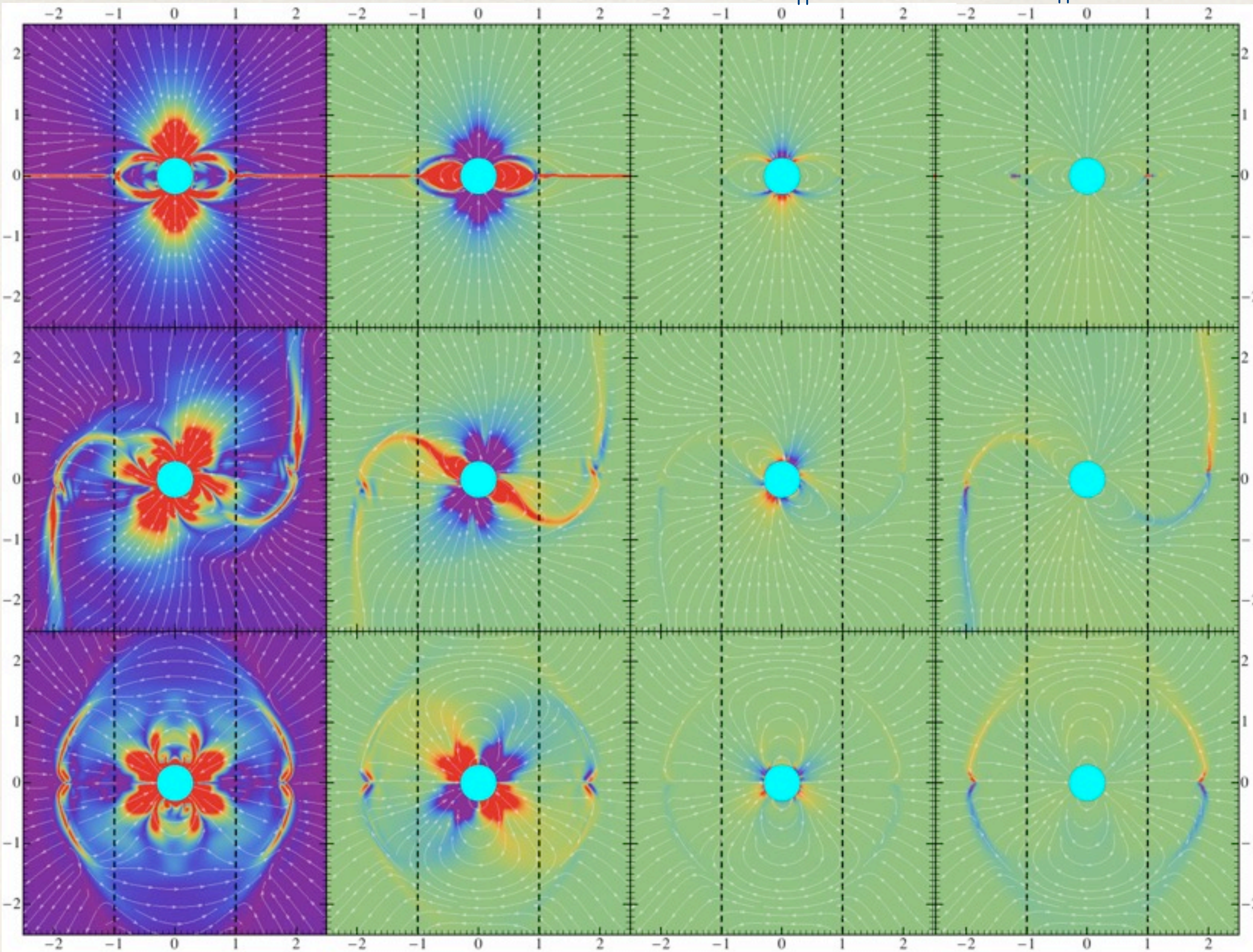


σ=0 (vacuum)

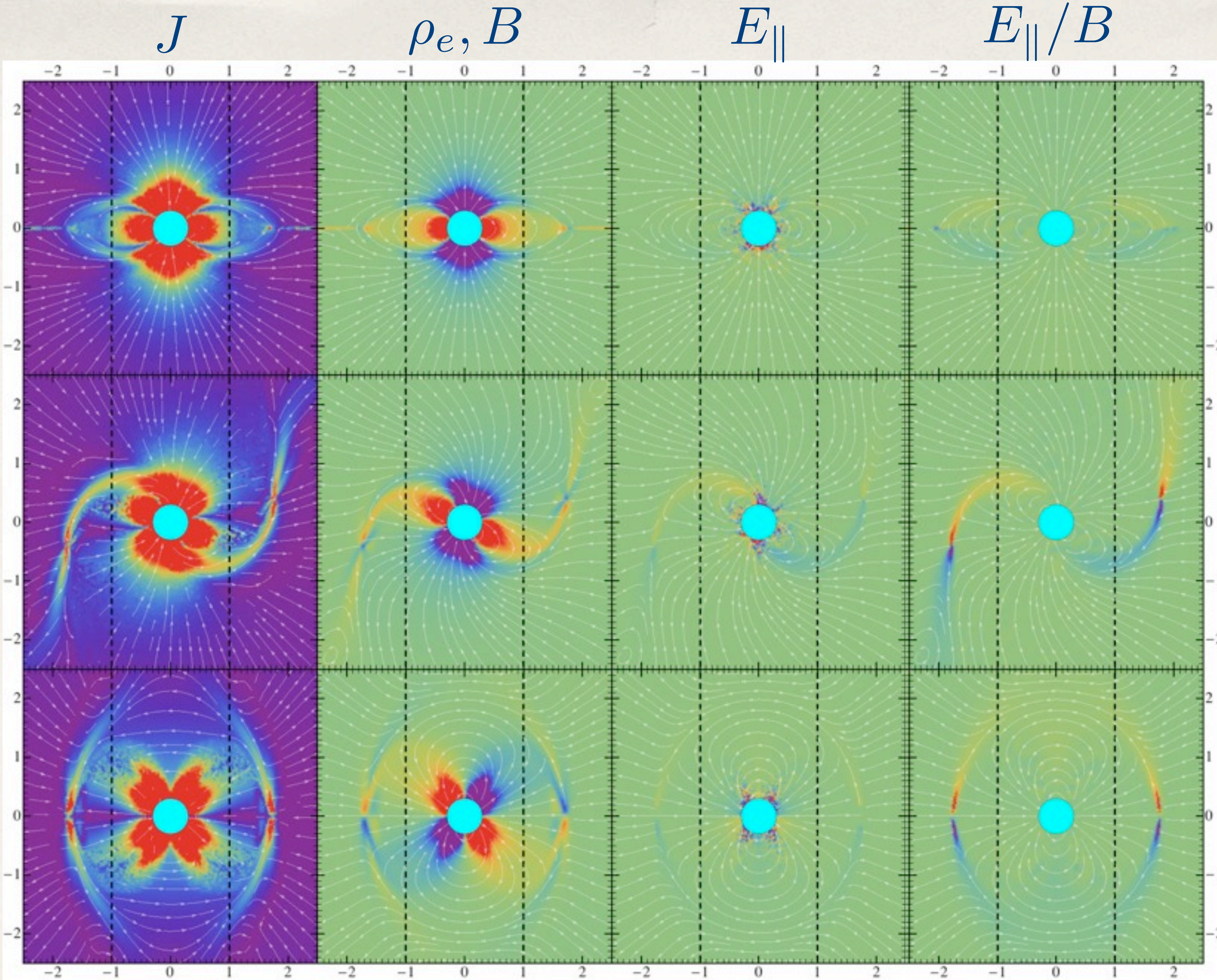


Non-ideal magnetospheres *60º* (Li, Spitkovsky & Tchekhovskoy 2011)

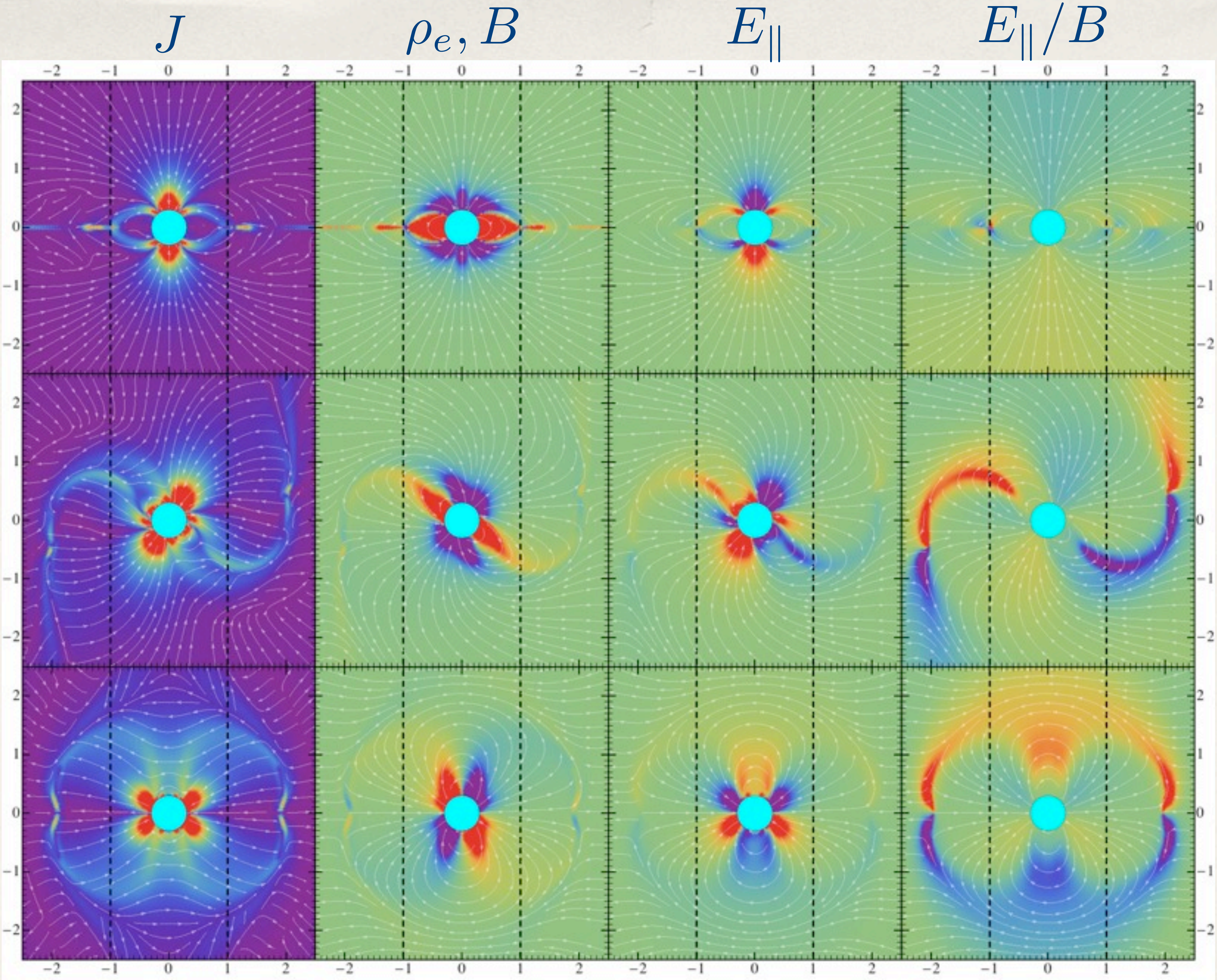
J ρ_e, B $E_\parallel$ $E_\parallel / B$



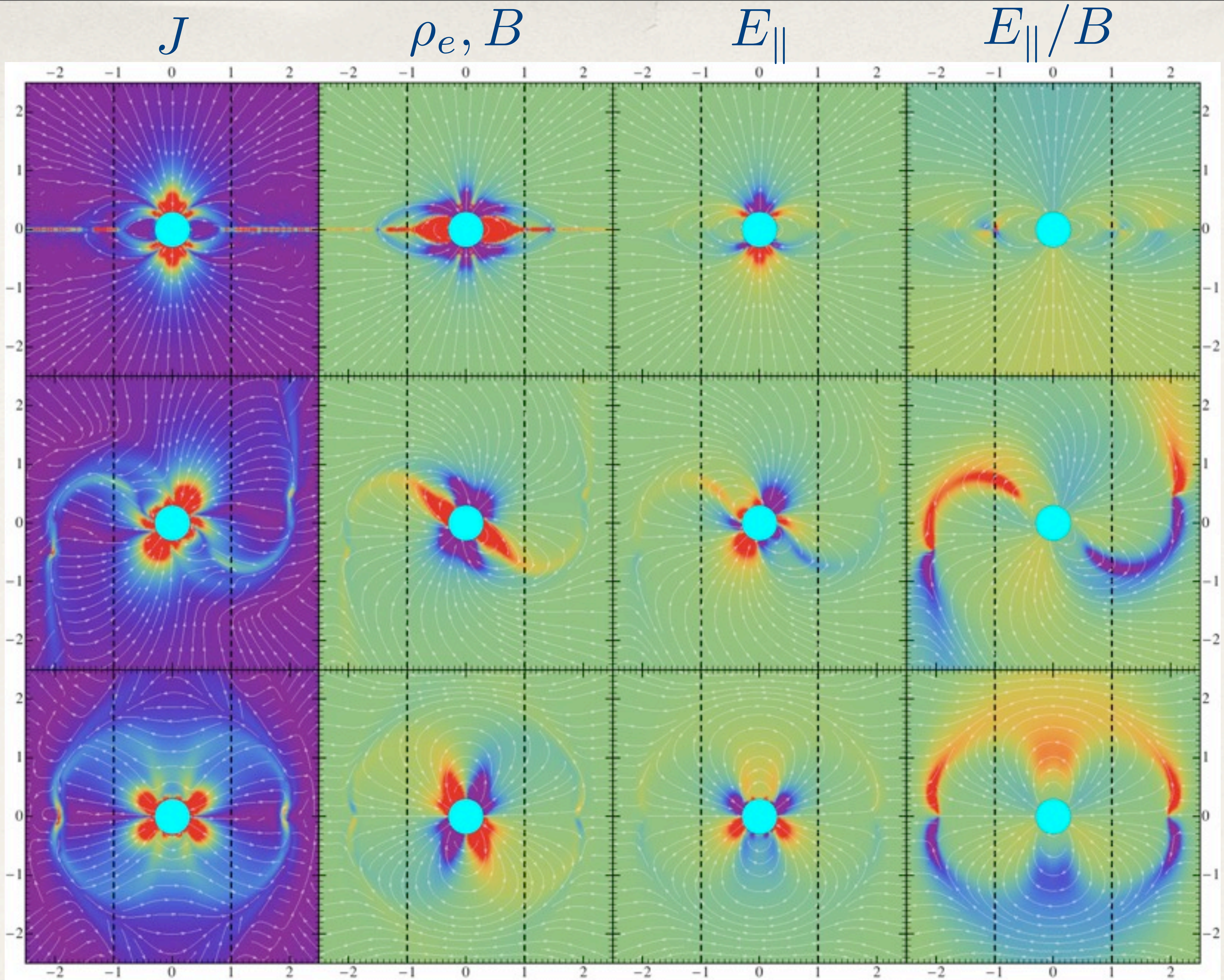
Non-ideal magnetospheres: *0°, 45°, 90°*, *$\sigma E_{parallel}$, σ=300* (KKHC 2011)



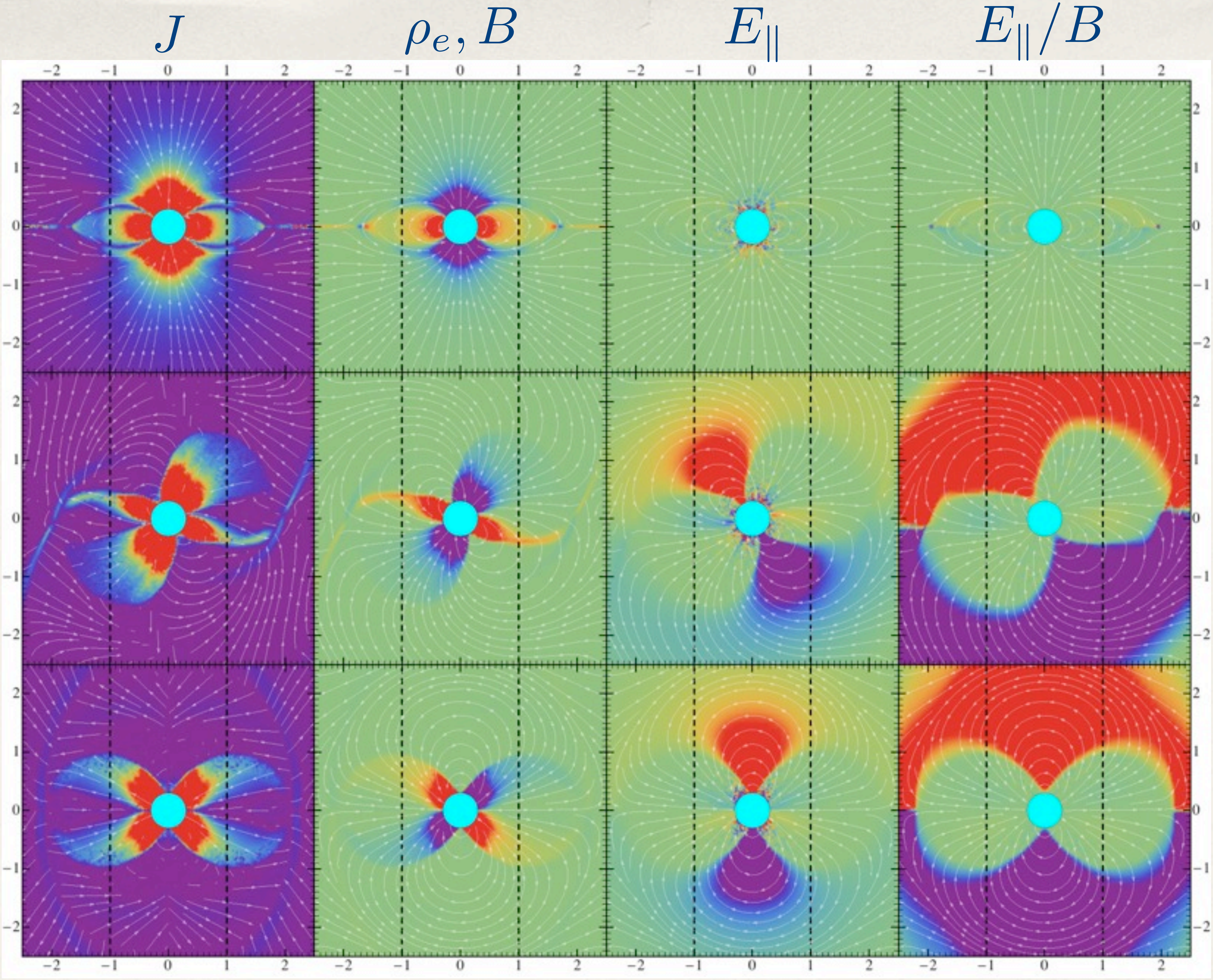
Non-ideal magnetospheres: *0°, 45°, 90°*, SFE, *σ=100* (KKHC 2011)



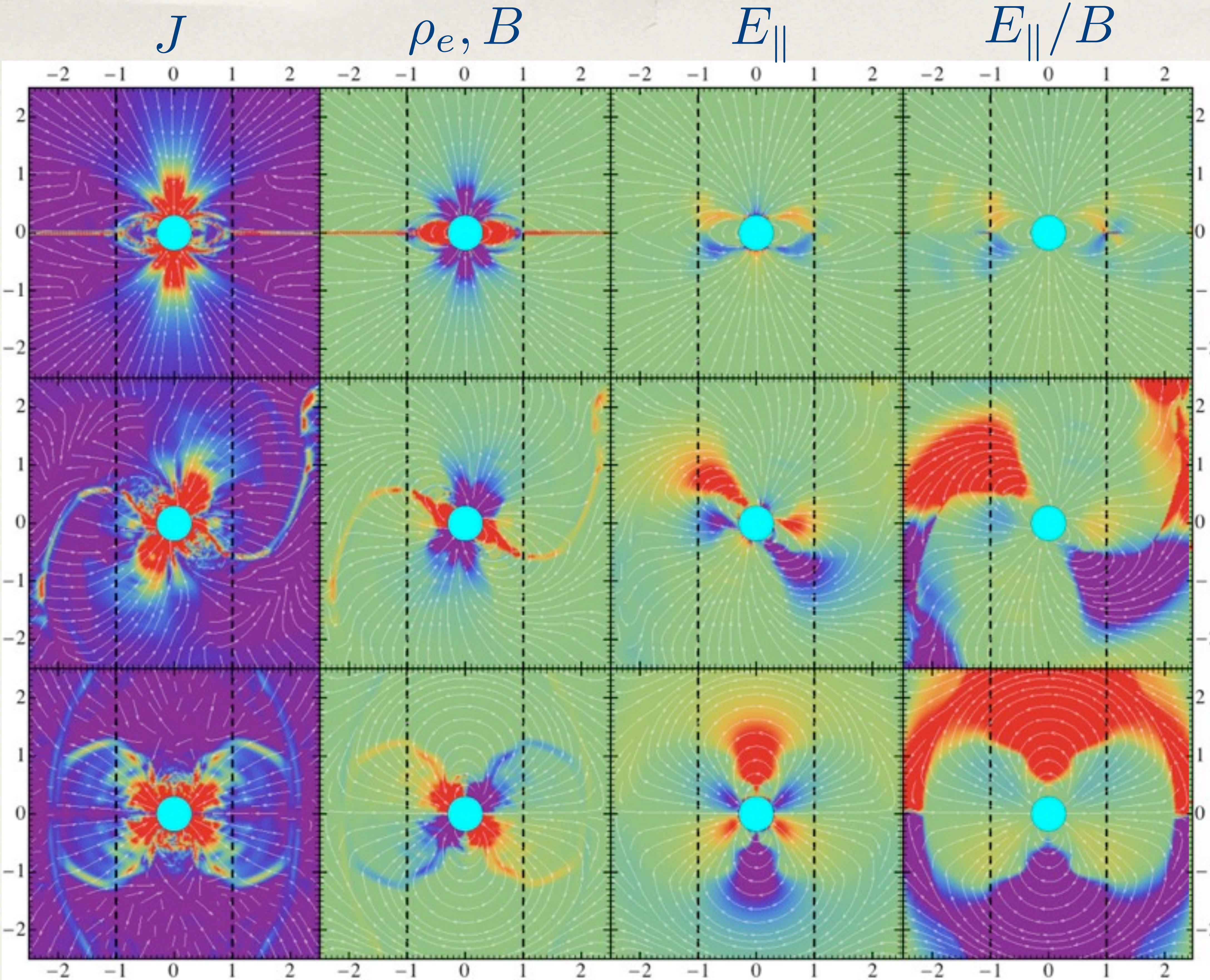
Non-ideal magnetospheres: *0^o, 45^o, 90^o*, *$\sigma E_{parallel}$, σ=20* (KKHC 2011)



Non-ideal magnetospheres: *0°, 45°, 90°*, *75% of $E_{parallel}$* (KKHC 2011)



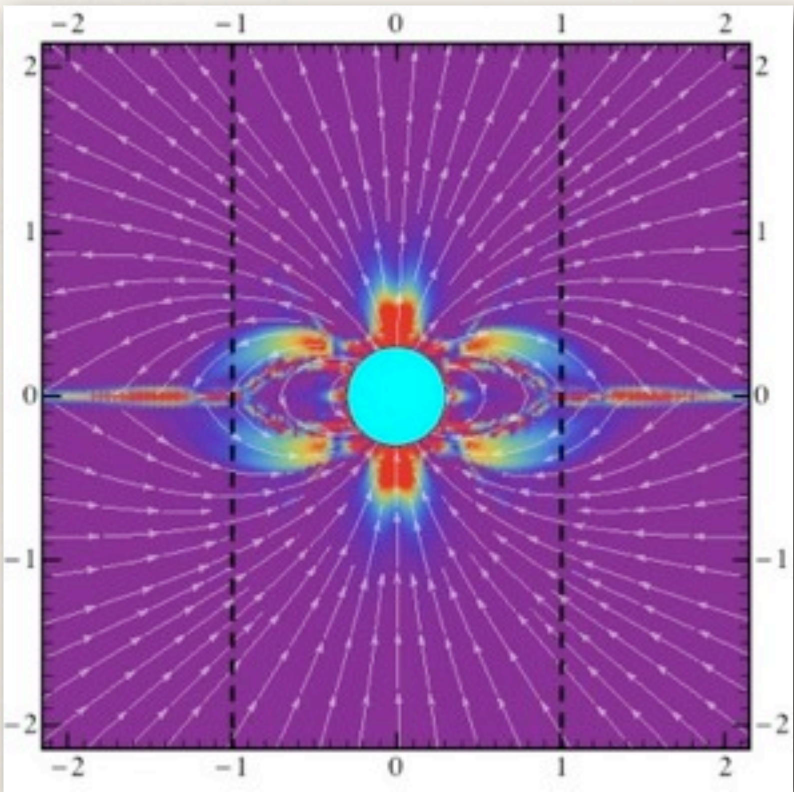
Non-ideal magnetospheres: *0º, 45º, 90º*, SFE, *σ=0* (KKHC 2011)



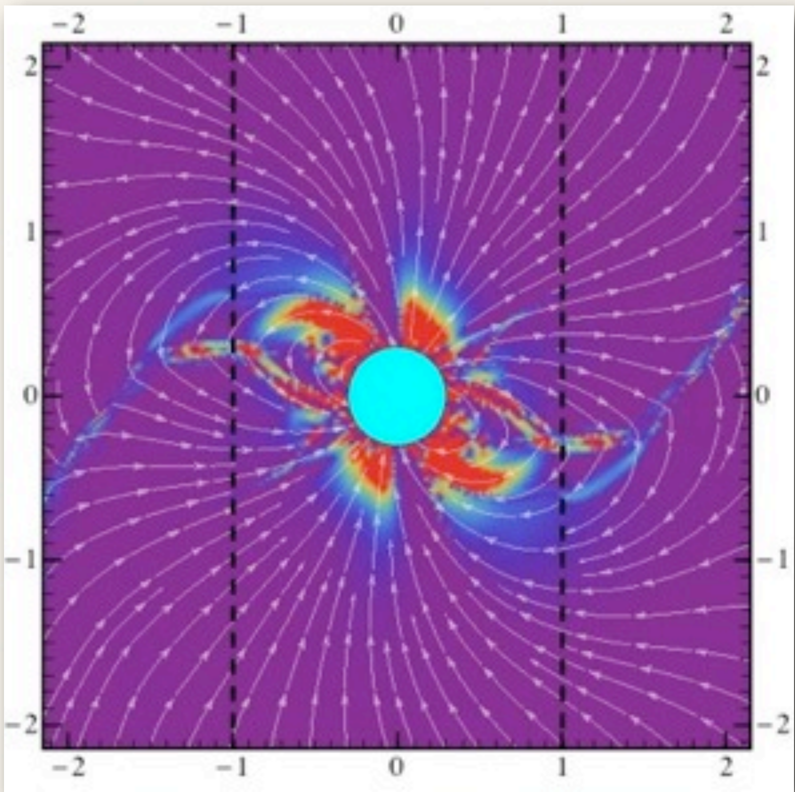
Non-ideal magnetospheres: *0°, 45°, 90°*, $J=\varrho_e c$ (KKHC 2011)

3D resistive relativistic MHD:
towards the real pulsar magnetosphere

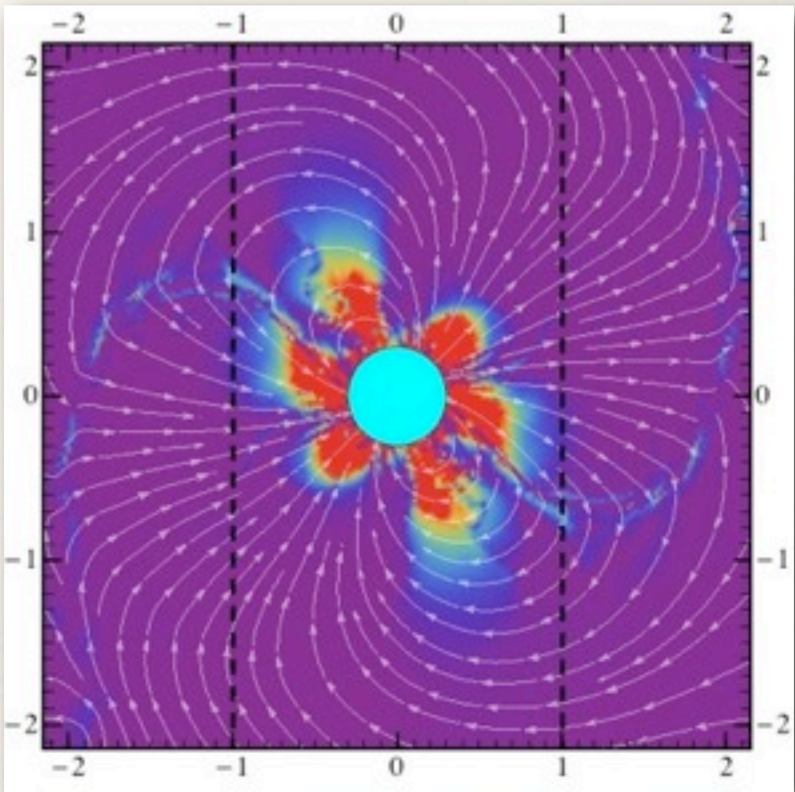
$E \cdot J$



0°



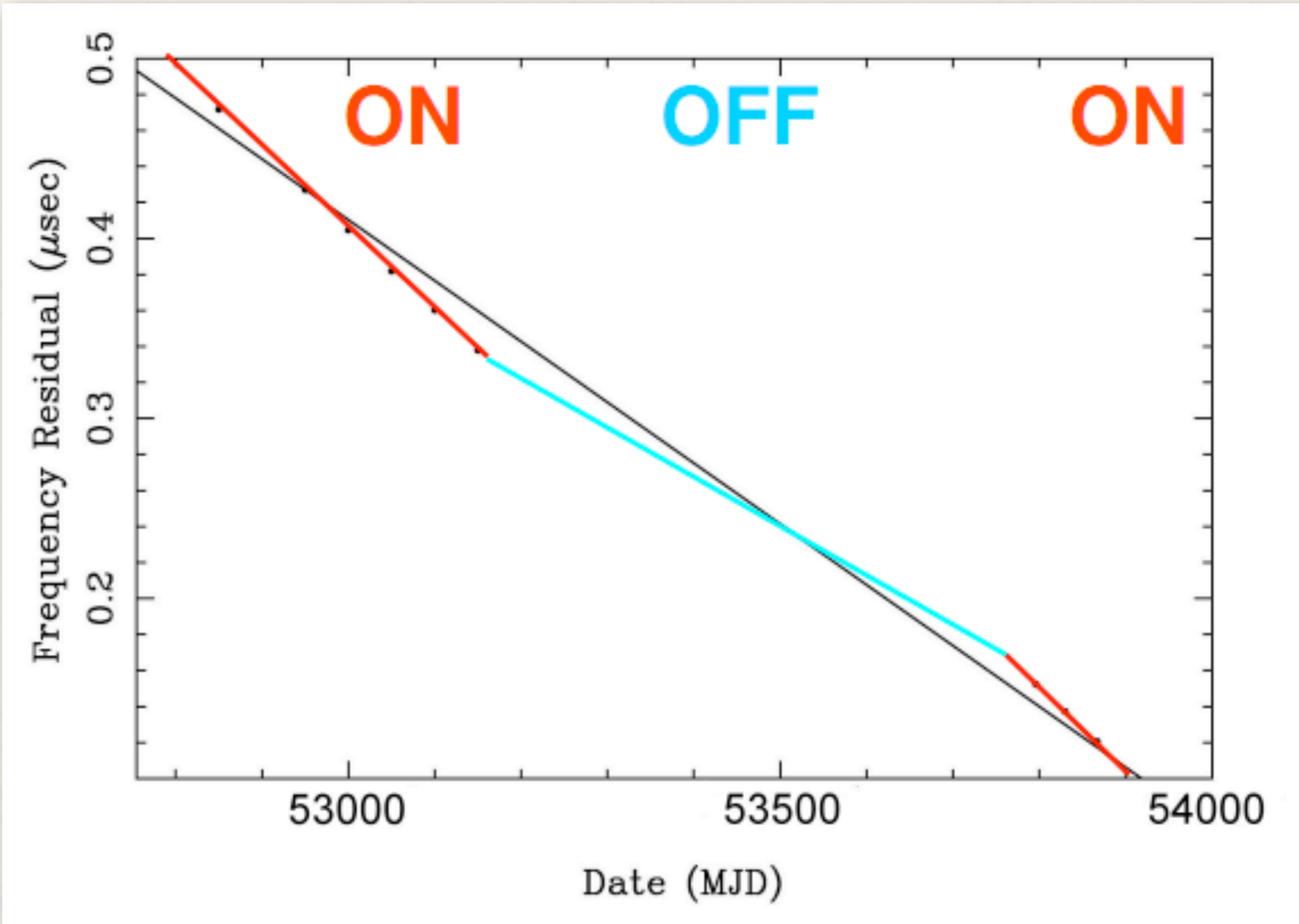
30°



60°

Non-ideal magnetosphere with $J = \rho_e c$ (KKHC 2011)

3D resistive relativistic MHD:
intermittent pulsars



Kramer et al. 2006; Lyne et al. 2010; Camilo et al. 2012

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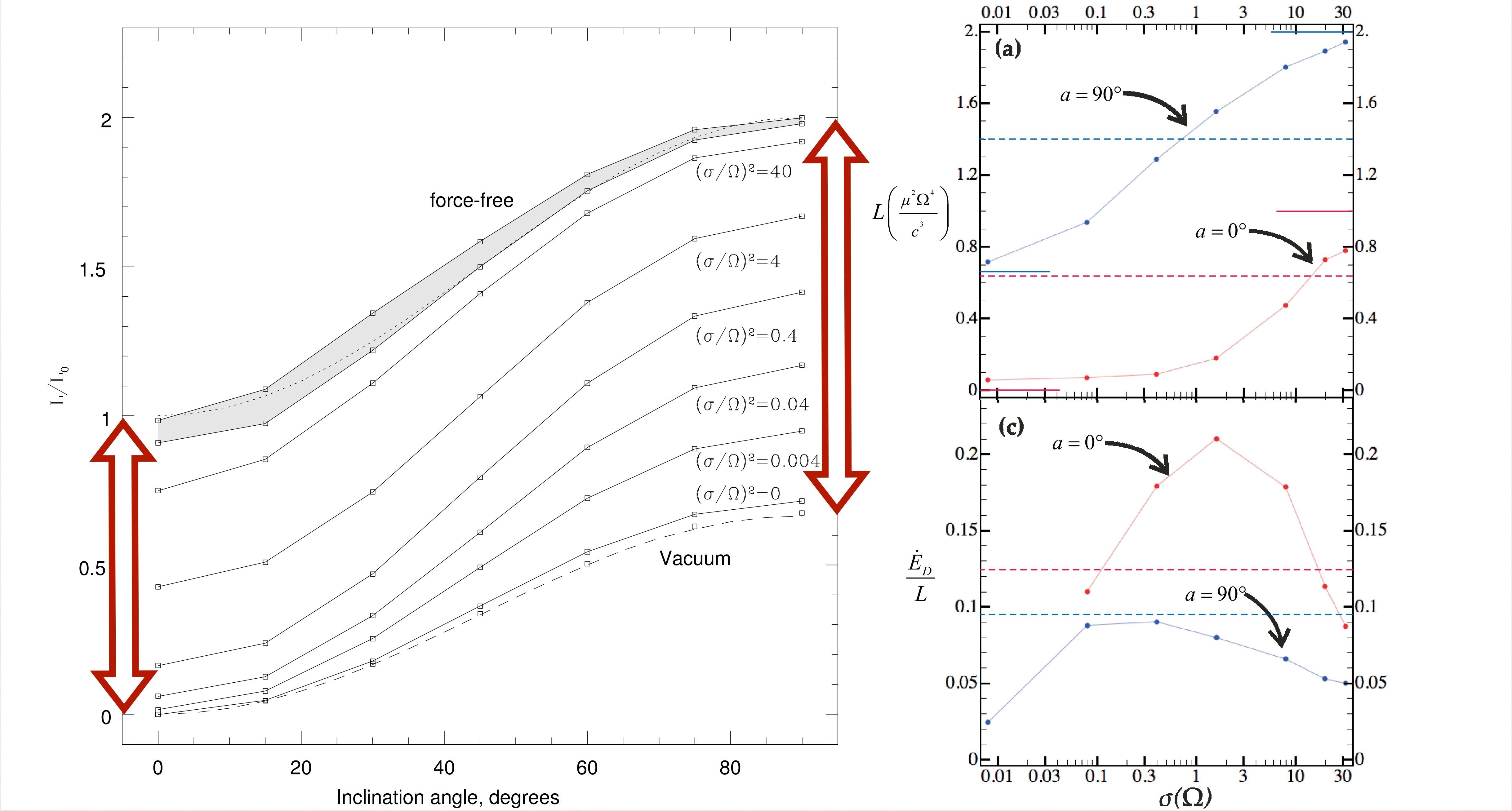

Li, Spitkovsky & Tchekhovskoy 2011; Kalapotharakos, Kazanas, Harding & IC 2011

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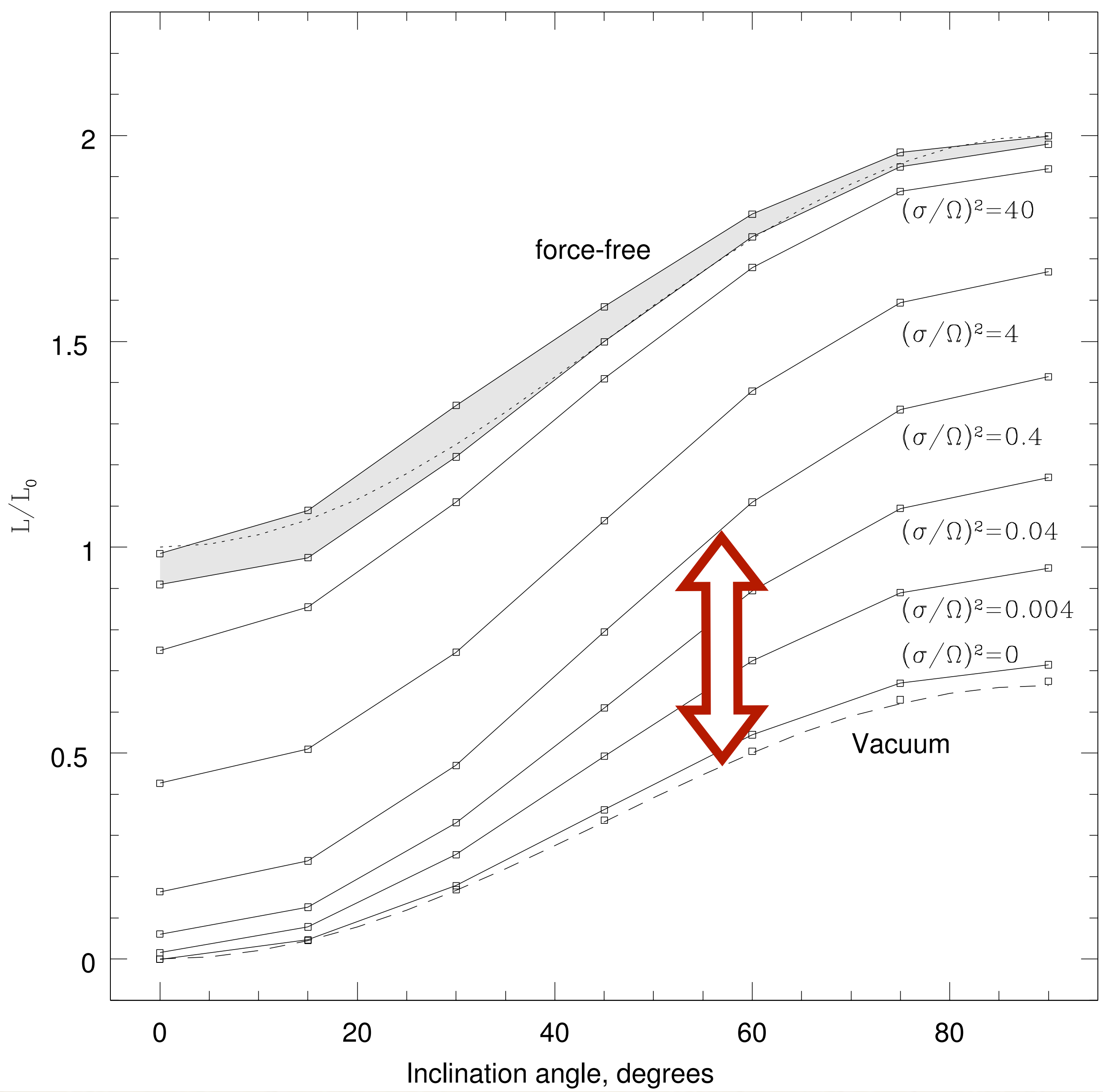

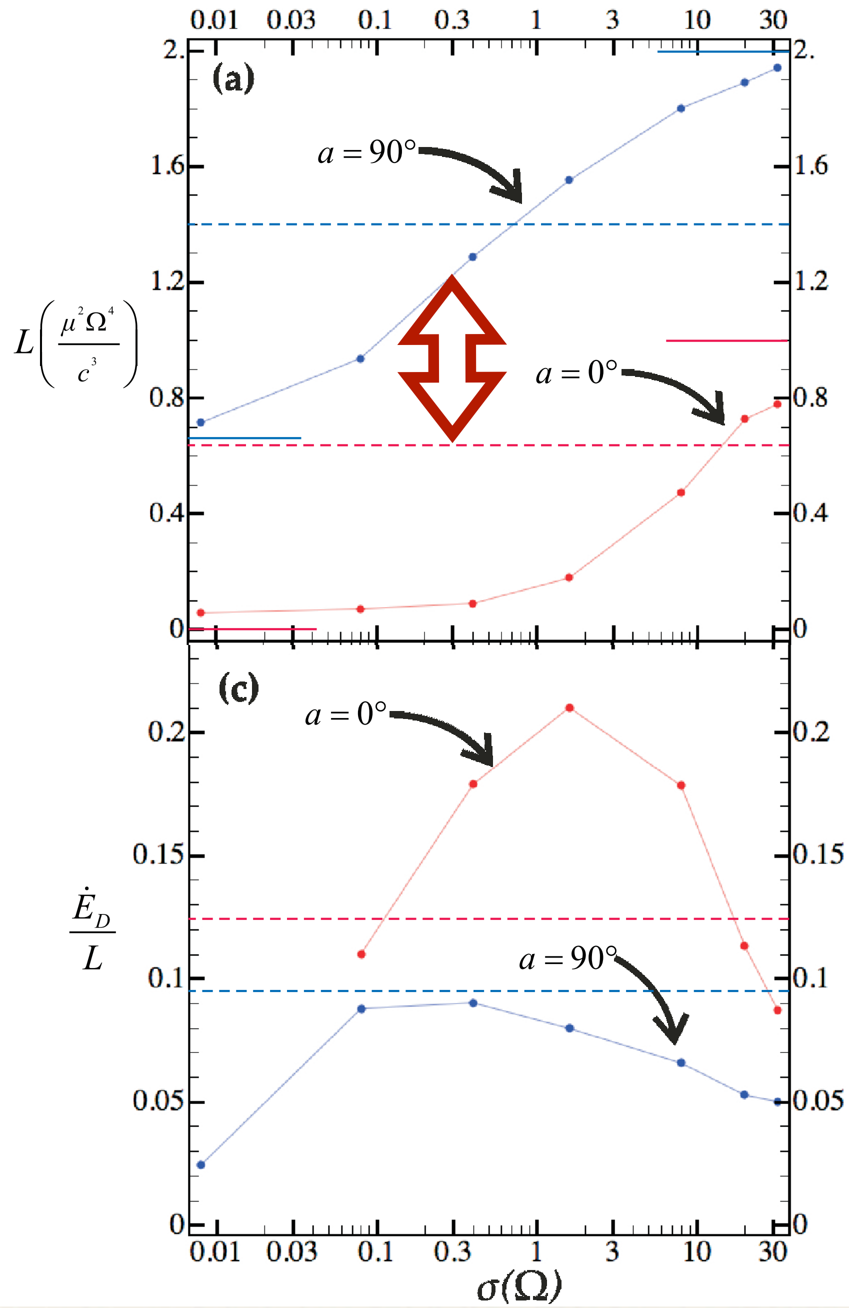

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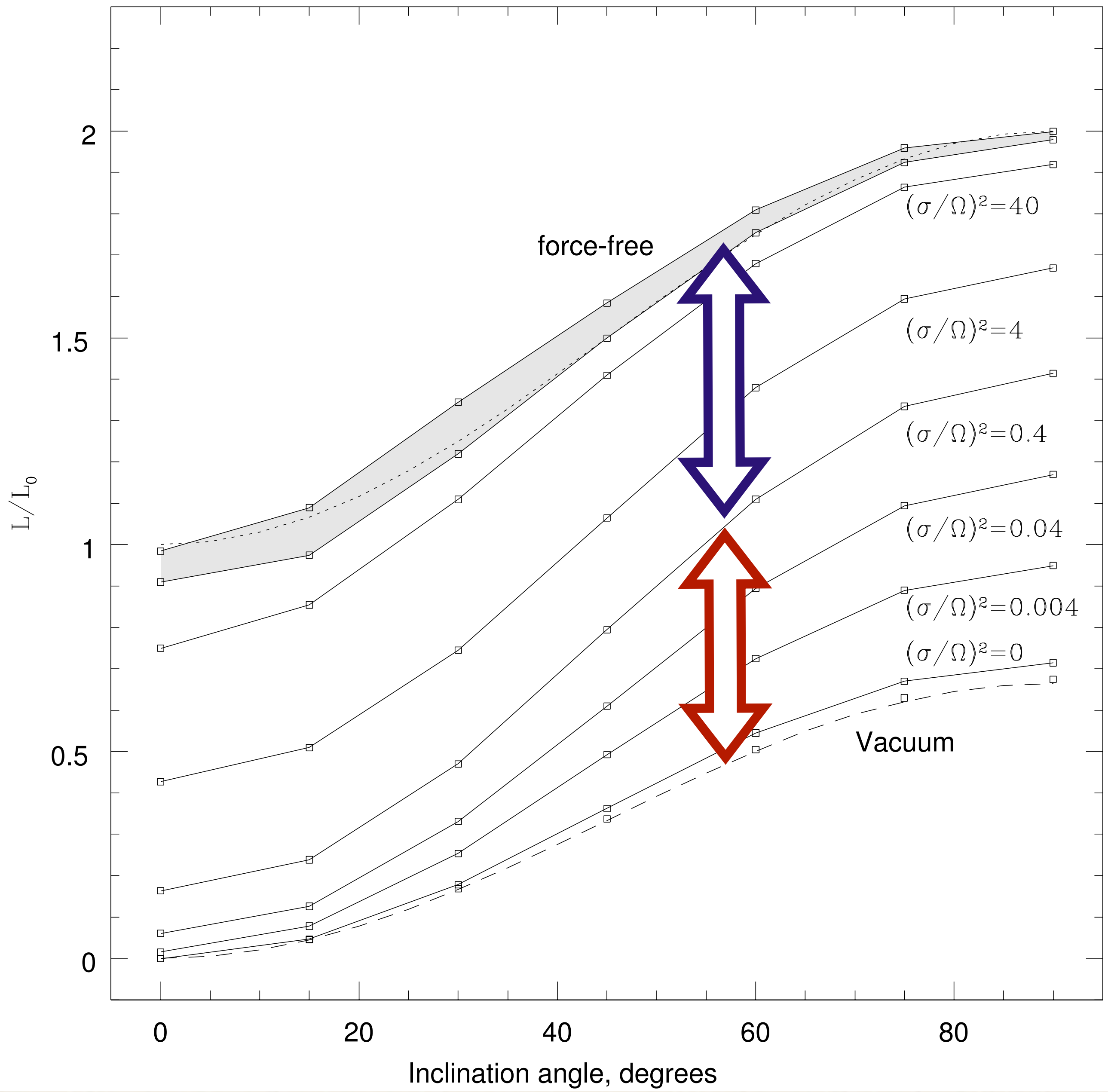

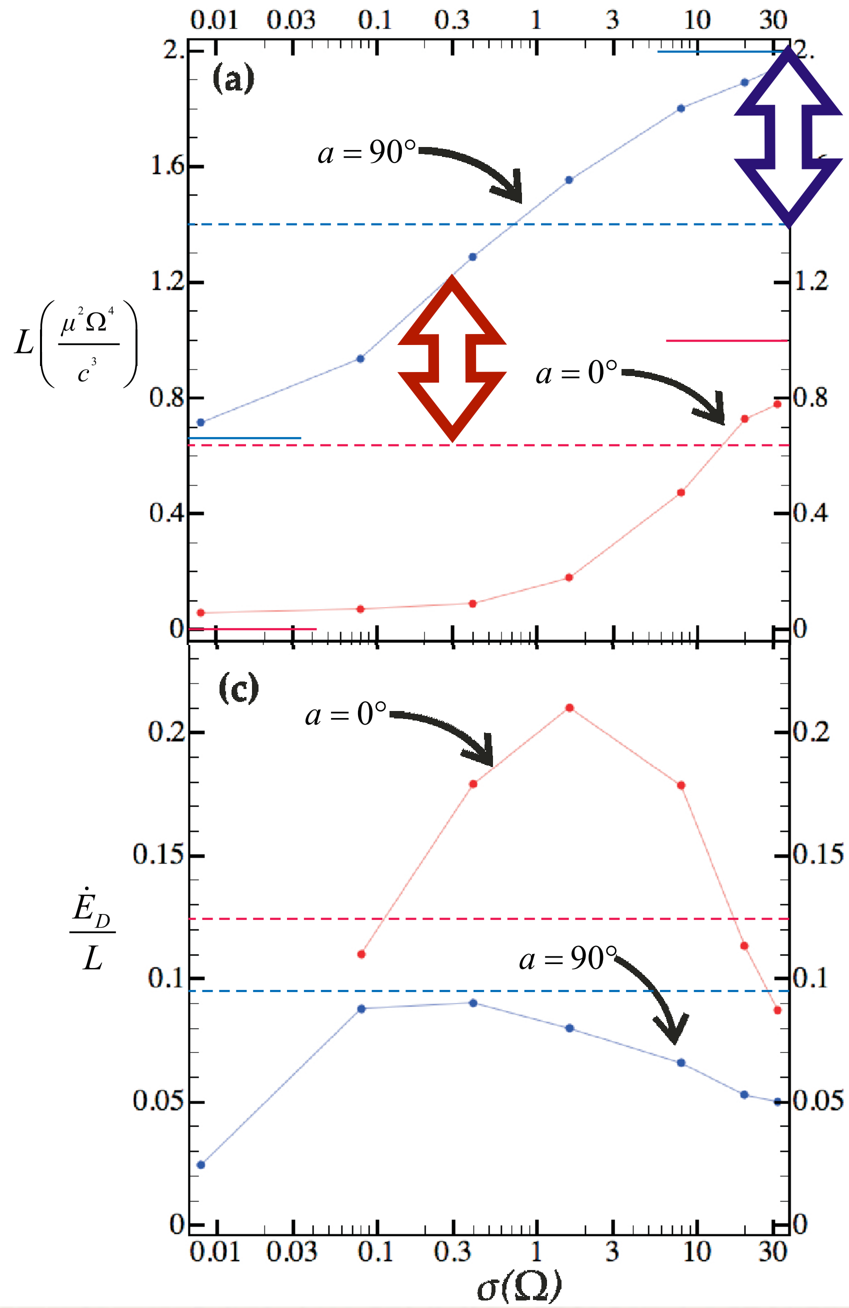

Li, Spitkovsky & Tchekhovskoy 2011; Kalapotharakos, Kazanas, Harding & IC 2011

Electrodynamics ····· Vacuum

Non-ideal MHD ····· $J=\rho_e c$

Ideal + force-free MHD ····· $E.B=0$

	on / off
B1931+24:	1.5
J1832+0029:	1.7

Electrodynamics

····Vacuum

ideal / vacuum spindown = 3 -- infinity

Non-ideal MHD

····$J=\rho_e c$

ideal / non-ideal spindown ~ 1.5

Ideal + force-free MHD

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Ideal + force-free MHD

····$E.B=0$ on

	on / off
B1931+24:	1.5
J1832+0029:	1.7
J1841-0500:	2.5

Electrodynamics	Vacuum	off
Non-ideal MHD	$J=\rho_e c$	on
Ideal + force-free MHD	$E.B=0$	

vacuum work better for radio lags

	on/off
B1931+24:	1.5
J1832+0029:	1.7
J1841-0500:	2.5

Prospects for the future

Physics:

- Investigate resistivity prescriptions
- Reconnection in current sheet
- Radiation from "live" magnetosphere (radio, γ-rays)
- Spectrum, polarization

Numerics:

- Adaptive Mesh Refinement
- Pseudo-spectral methods
- The ultimate simulation: PIC + MHD