The 3D structure of the pulsar magnetosphere

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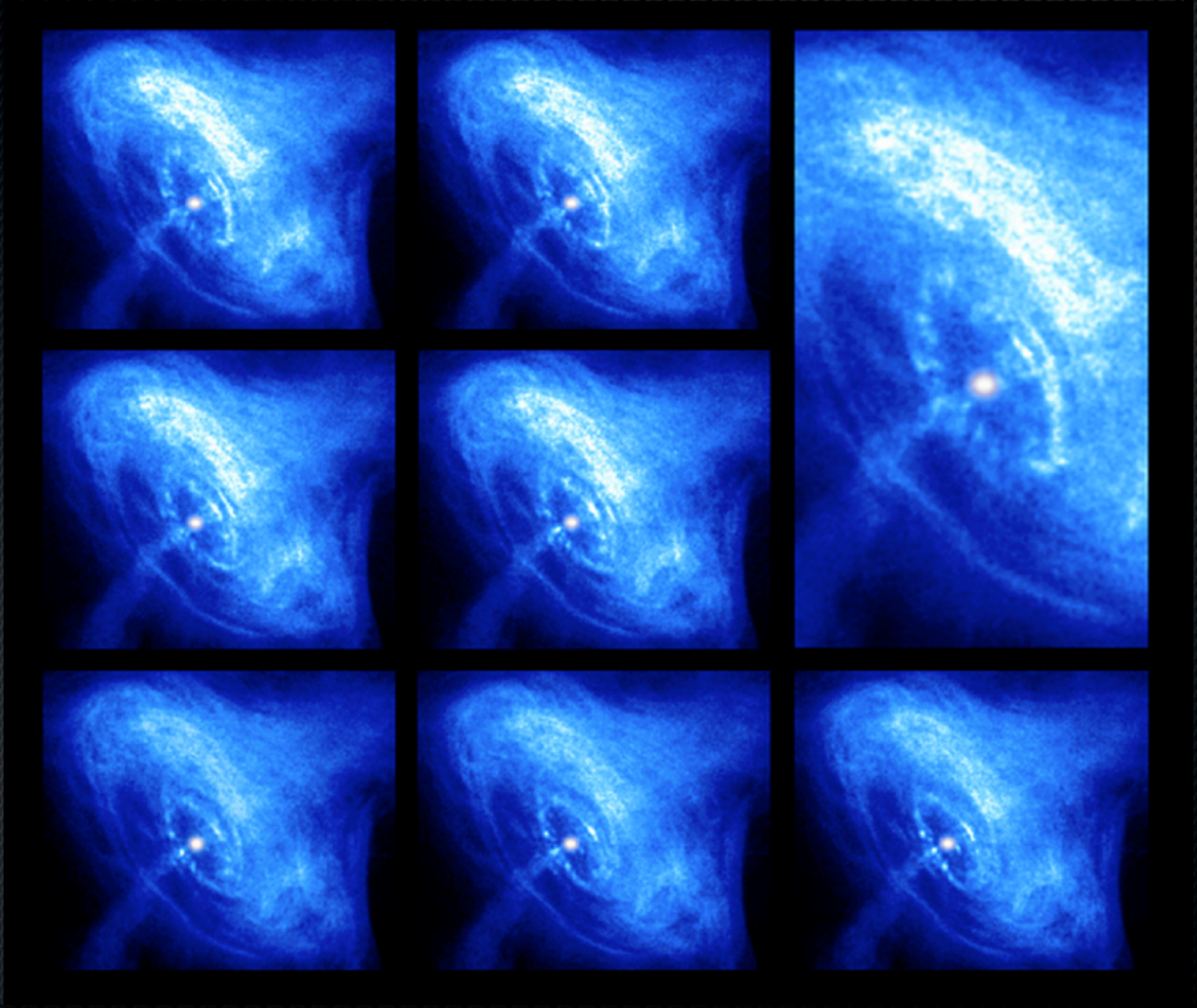
Outline

- The aligned rotator
  - Smooth crossing of the light cylinder
  - Singular magnetospheric current
- The 3D rotator
  - Relativistic MHD on a desktop PC
- Prospects for the future



The aligned rotator

- Steady-state force-free axisymmetric relativistic MHD
Scharleman & Wagoner 1973

$$0 = \nabla \times B - 4\pi J \qquad \nabla \cdot B = 0$$

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

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

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

The aligned rotator

- Regularization condition at x=1: $2B_z = AA'$
- Yields THE poloidal electric current distribution $A(\Psi)$
- Space charge density: $\rho_e = \frac{\Omega}{4\pi c}\frac{-2B_z + AA'}{1 - x^2}$

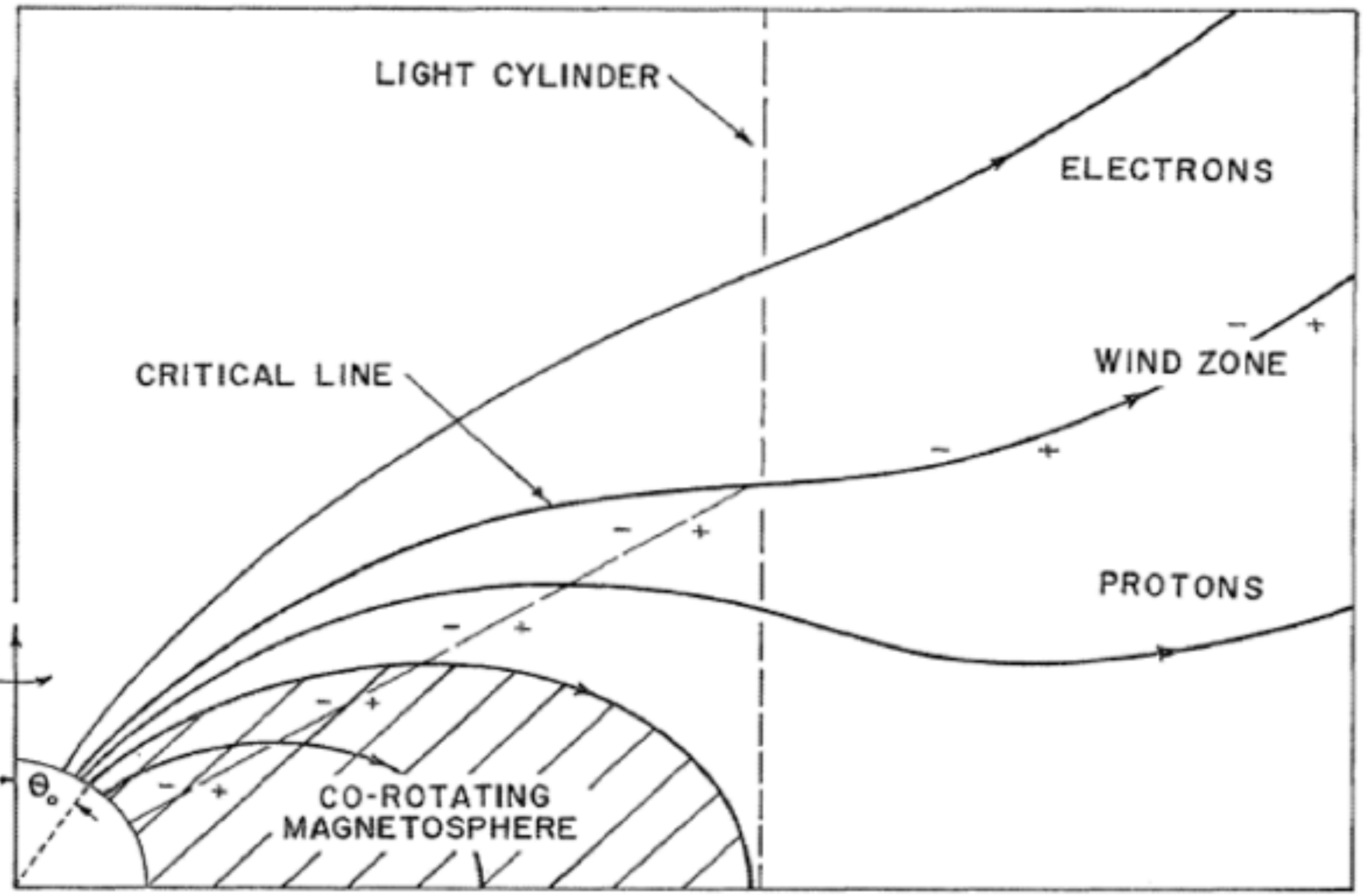
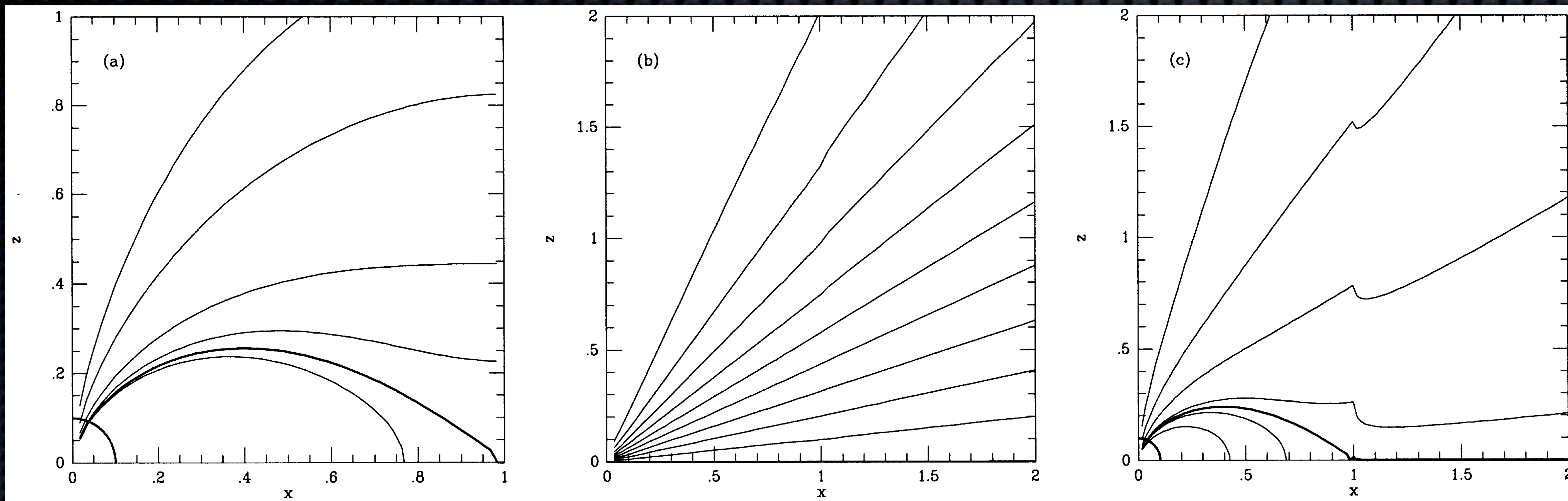
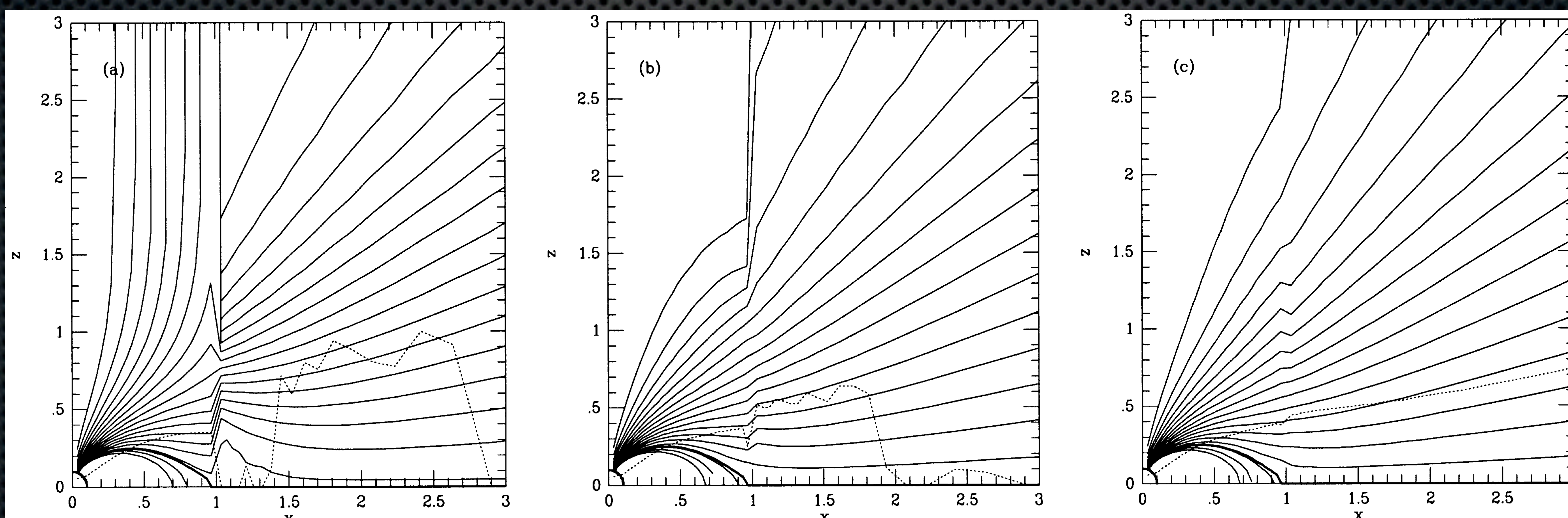


FIG. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

The aligned rotator

Goldreich & Julian 1969


(a)
(b)
(c)
z
x


(a)
(b)
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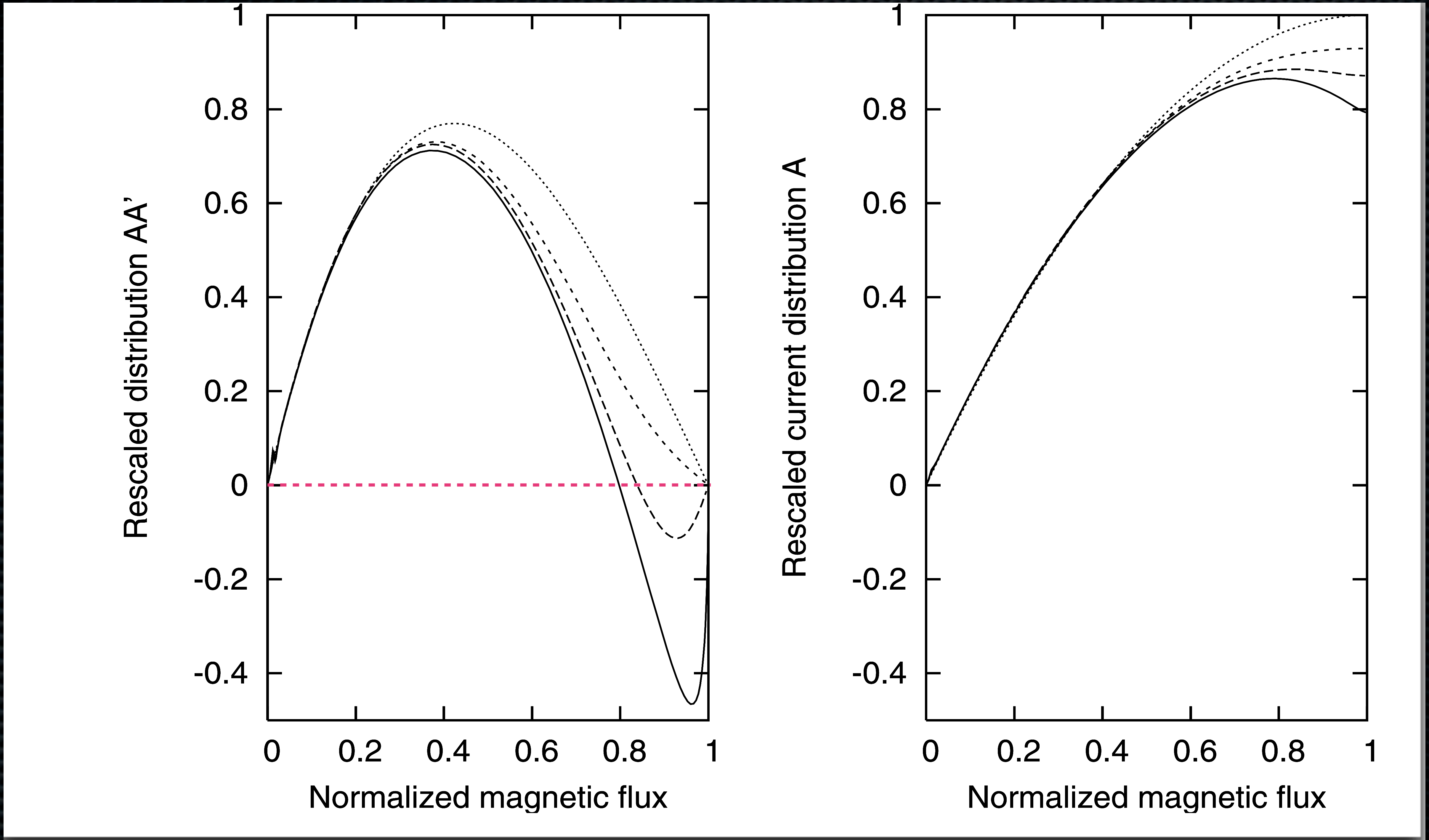
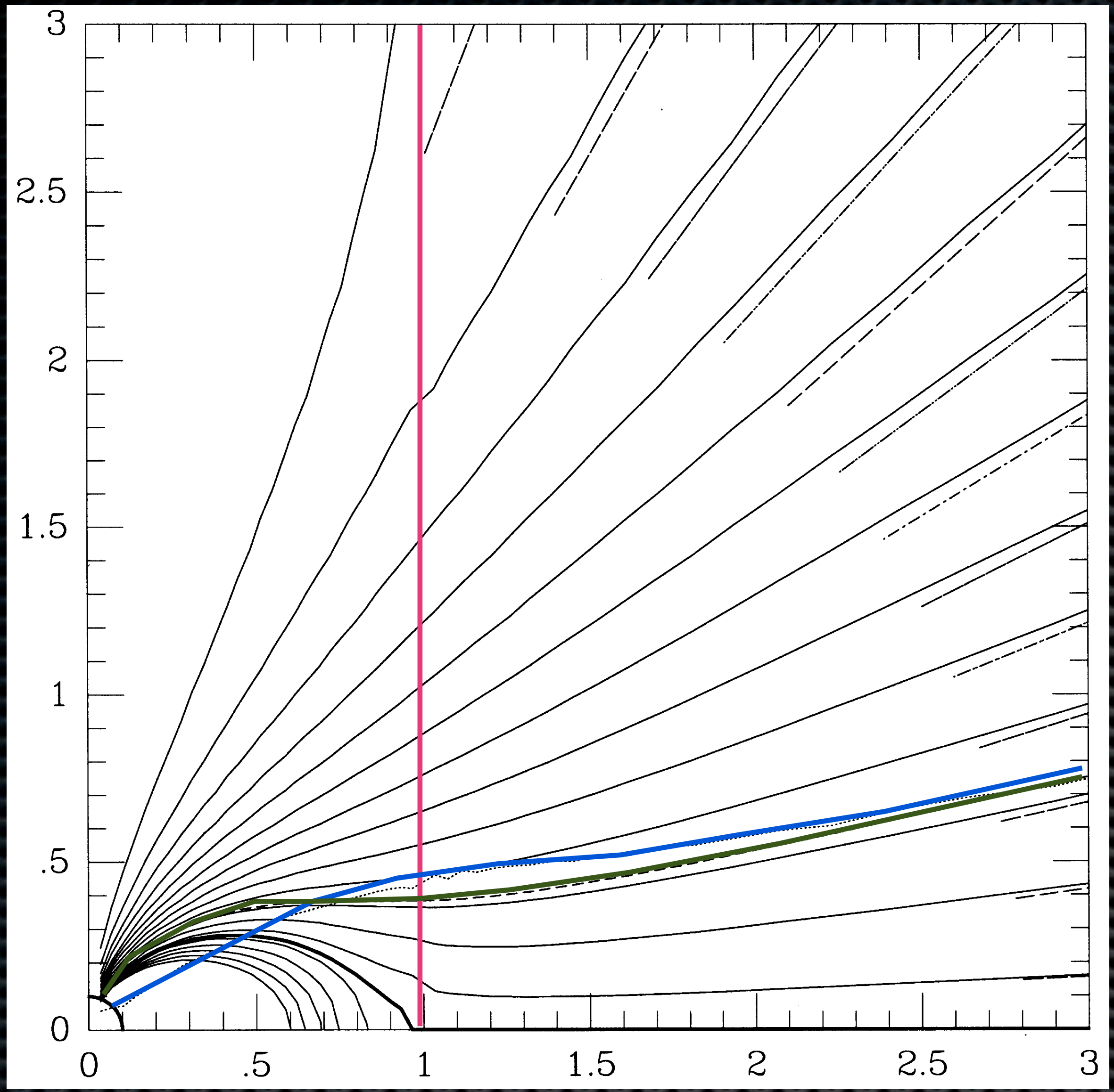
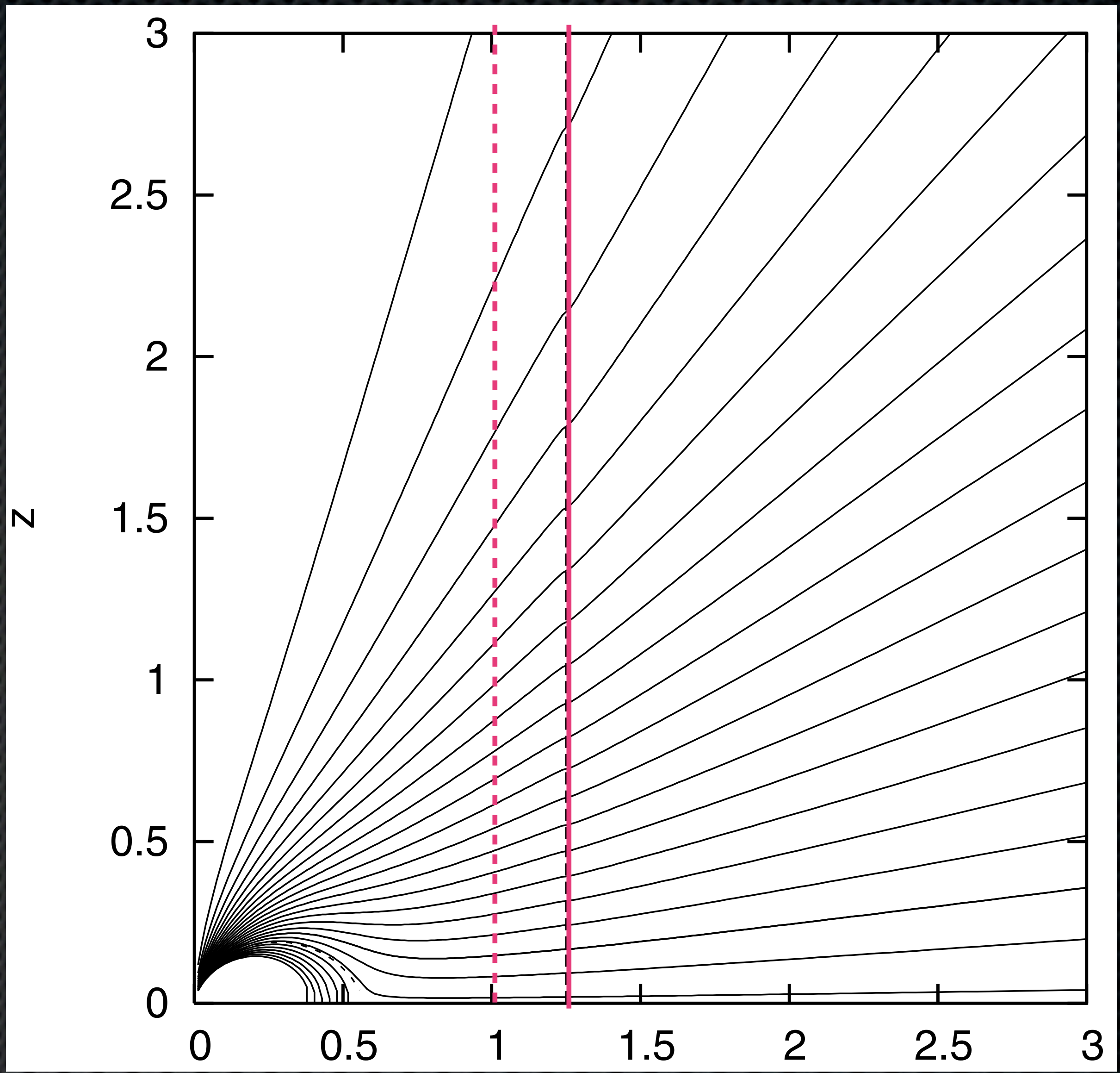


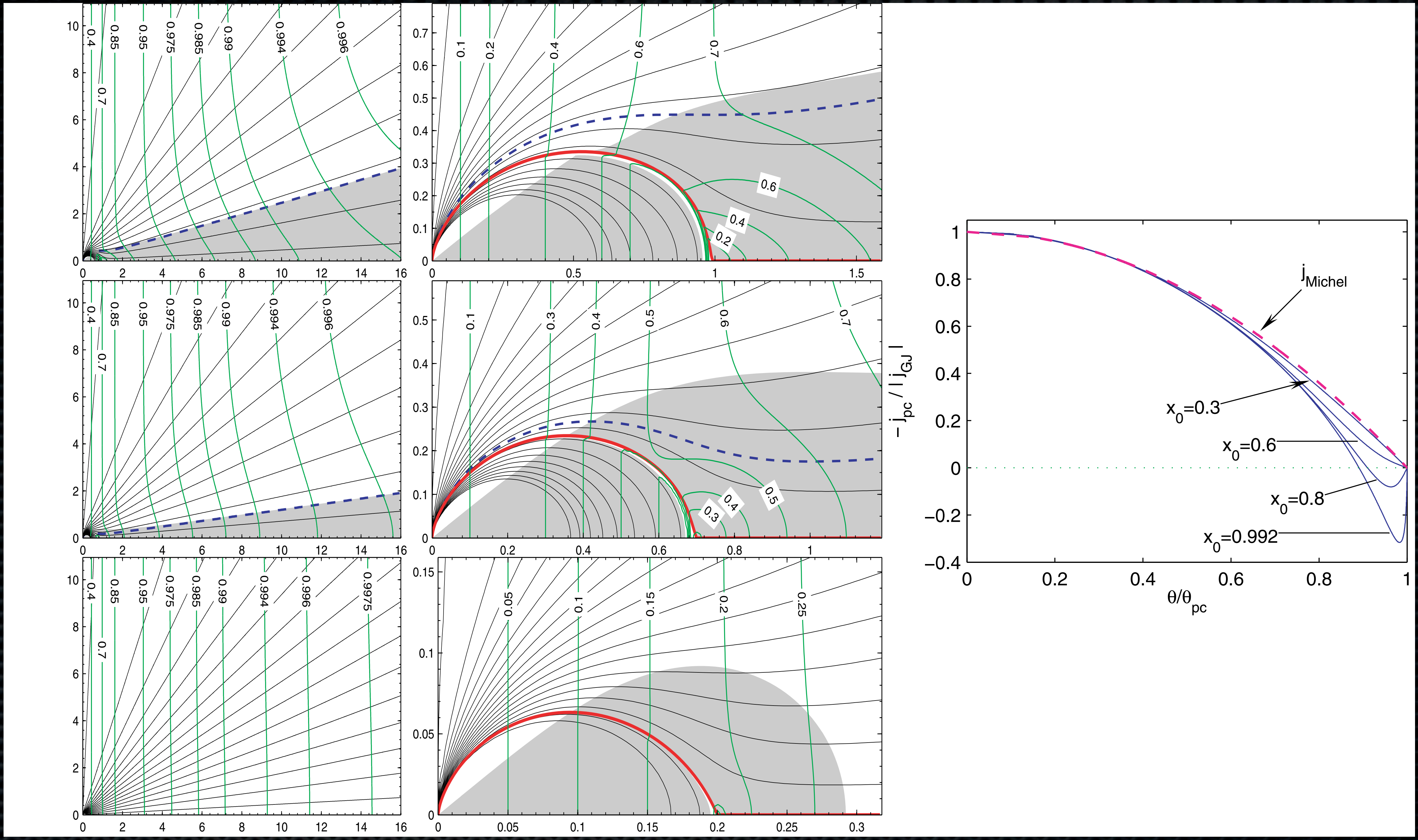
Contopoulos, Kazanas & Fendt 1999
Contopoulos 2005





The aligned rotator

Contopoulos, Kazanas & Fendt 1999



Timokhin 2006

The 3D rotator

- Time-dependent force-free electrodynamics
  Gruzinov 1999; Blandford 2002

$$\frac{\partial E}{\partial t} = \nabla \times B - 4\pi J \qquad \nabla \cdot B = 0$$

$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad E \cdot B = 0$$

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

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

The 3D rotator

- Gruzinov 2006

$$V = \Omega \times r$$

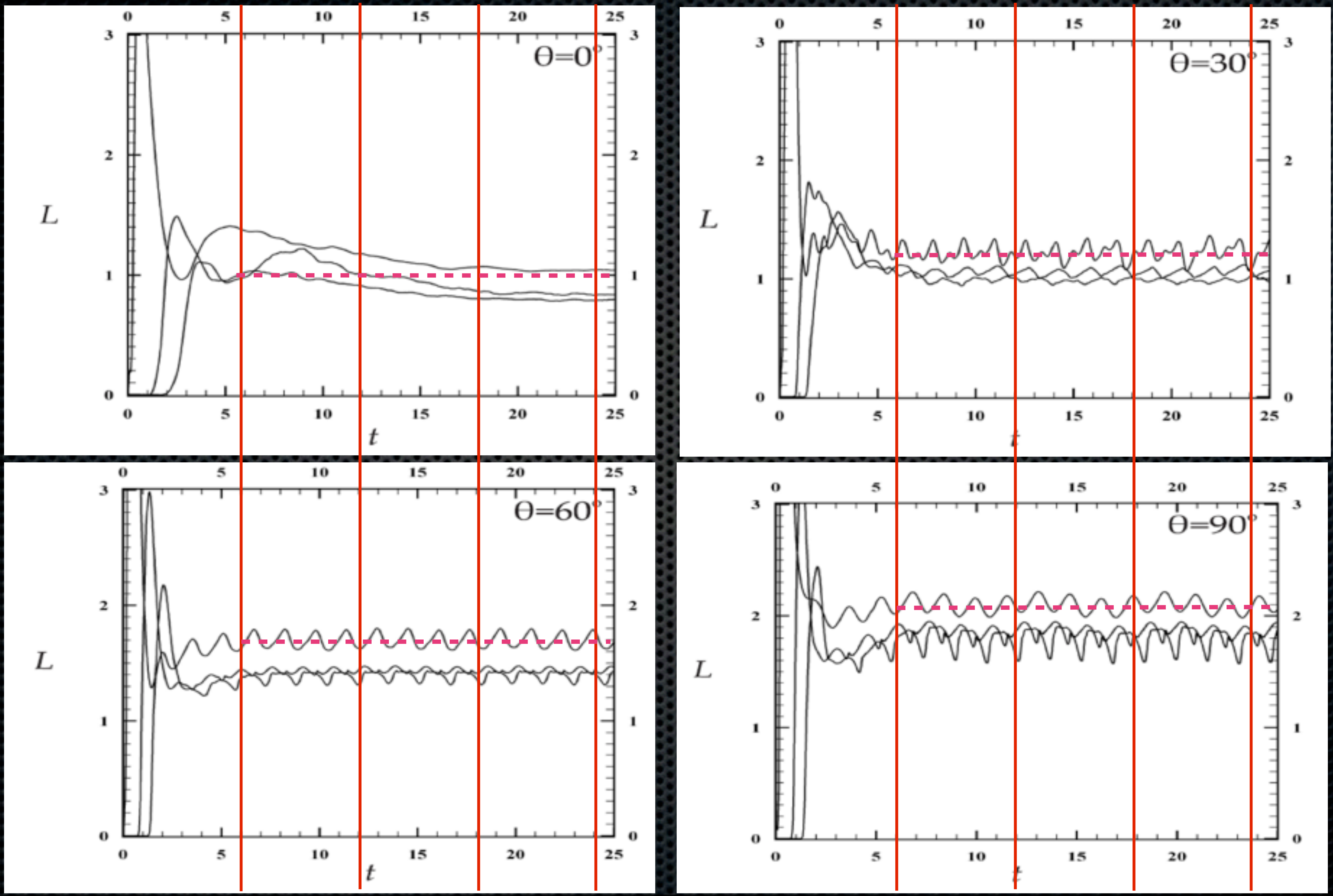
$$E = -V \times B$$

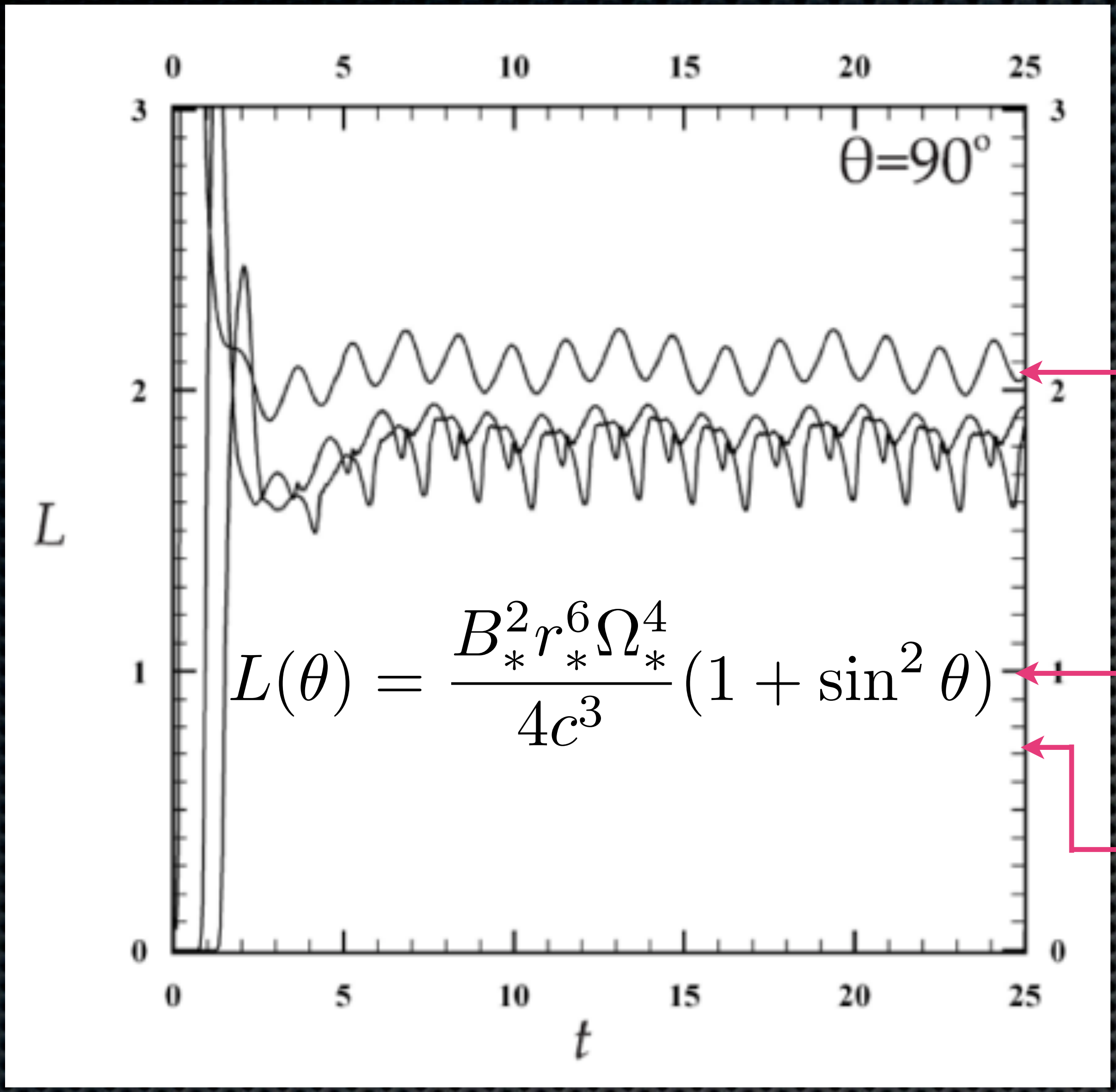
$$\nabla \times (B + V \times (V \times B)) = \lambda B$$

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

The 3D rotator

- Staggered cartesian mesh ($\delta = 0.025 R_{lc}$)
- Finite difference time domain (Yee 1966)
- Non-reflecting absorbing boundaries (PML)
- We impose the conditions $E \perp B$ and $E < B$

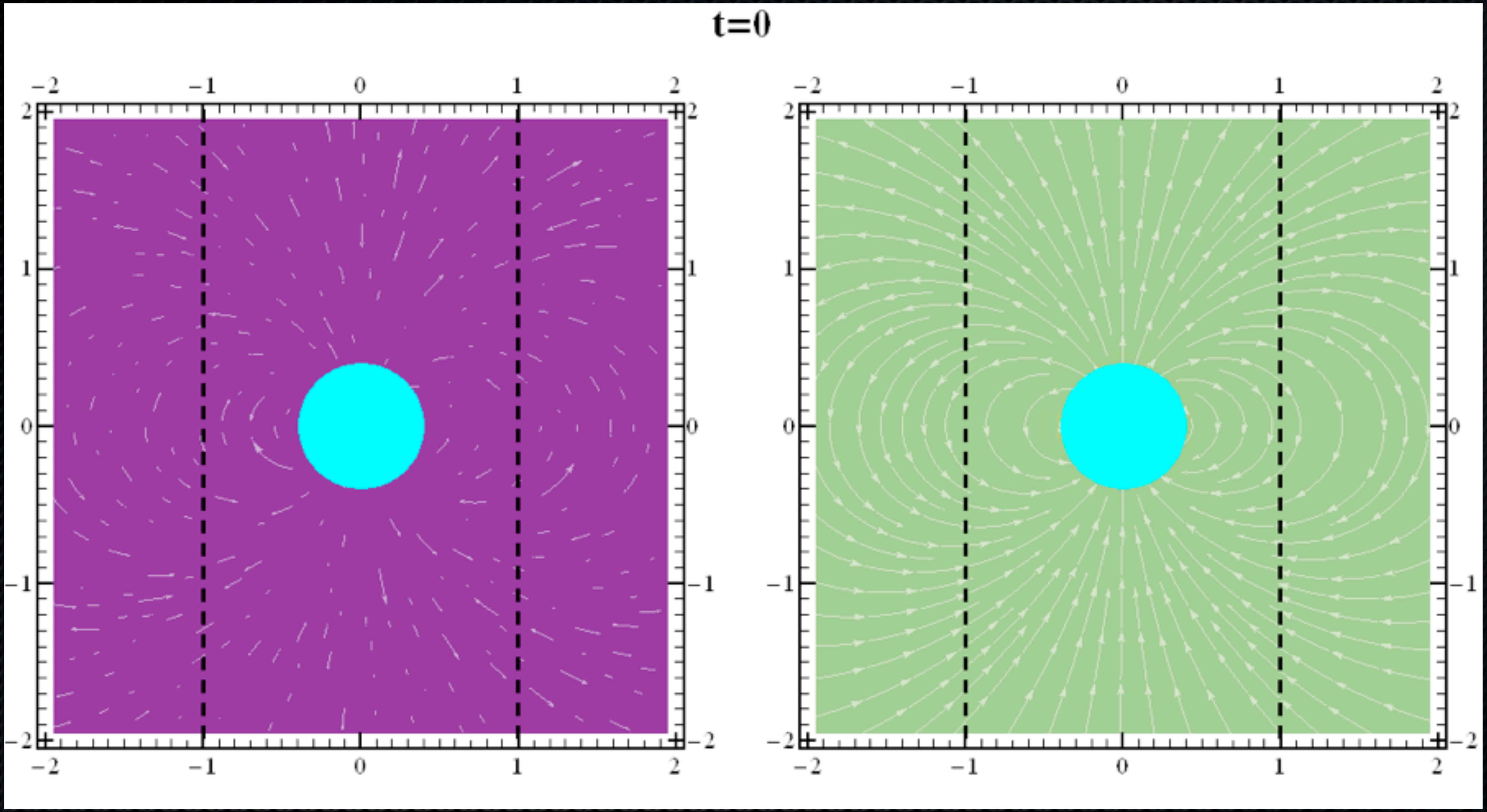

Θ=0°
Θ=30°
Θ=60°
Θ=90°
L
t
0
5
10
15
20
25
0
1
2
3



FFE orthogonal rotator

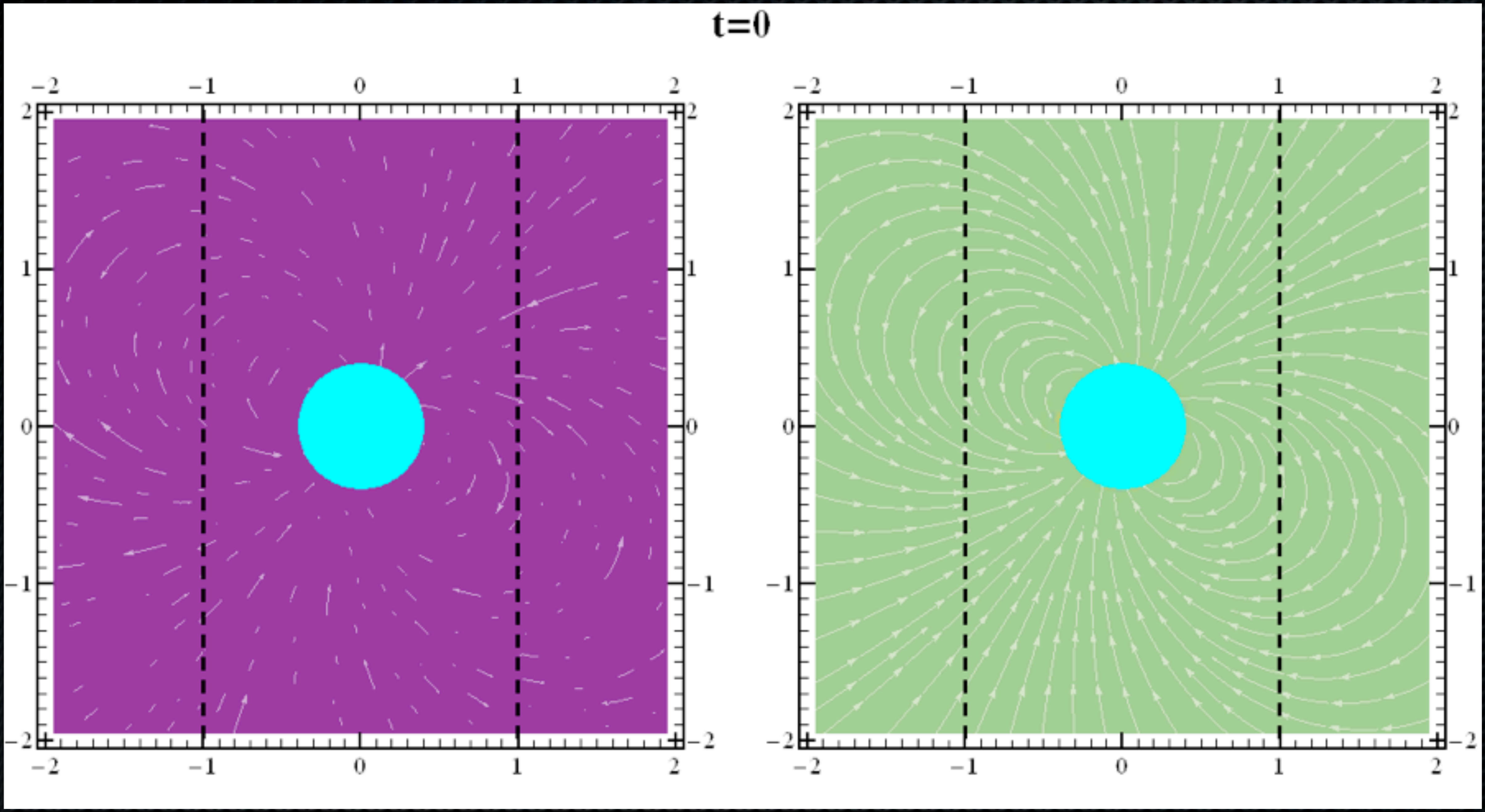
Spitkovsky 2006

Kalapotharakos & Contopoulos 2009



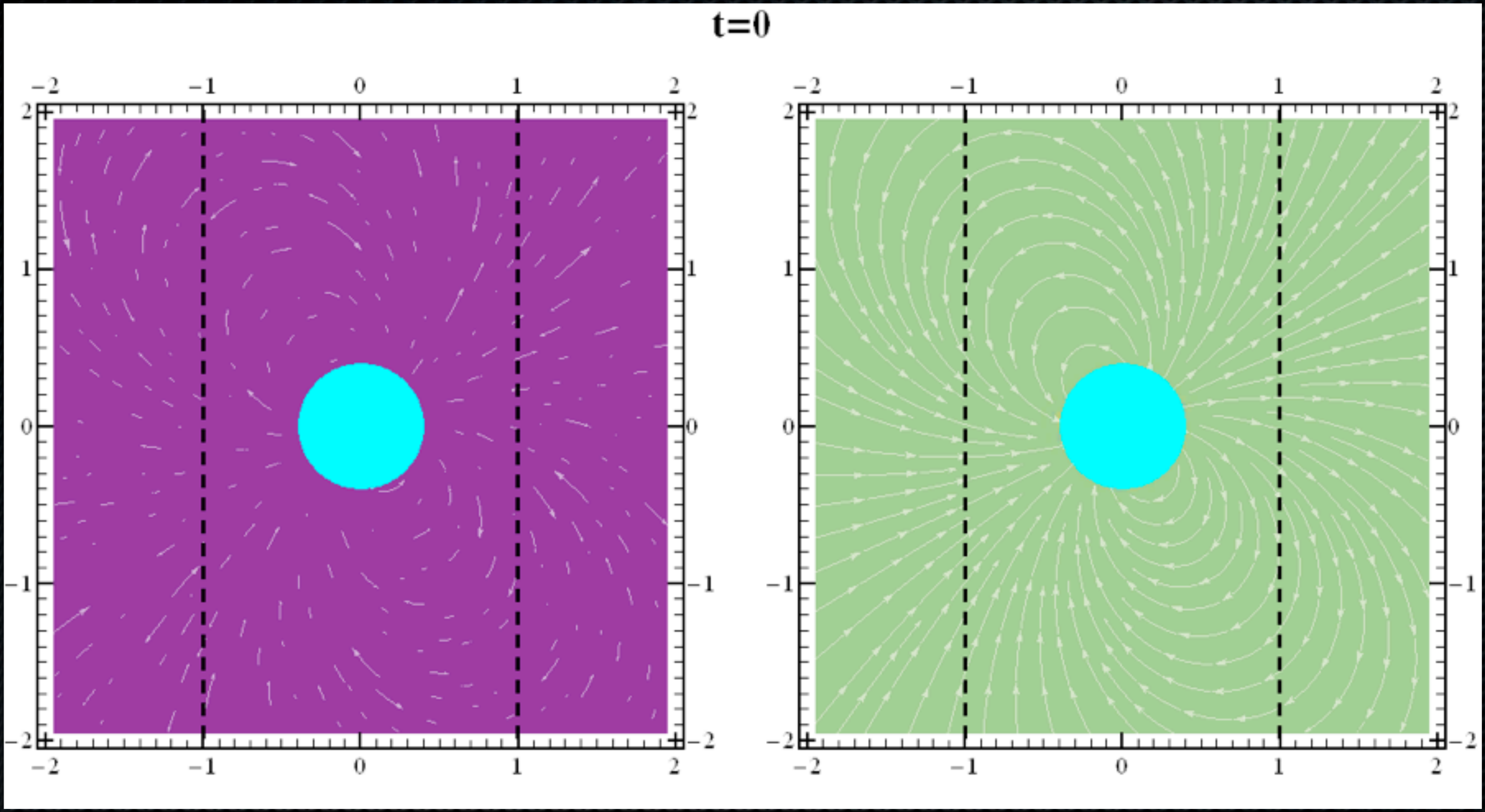
Aligned rotator

Contopoulos & Kalapotharakos 2010



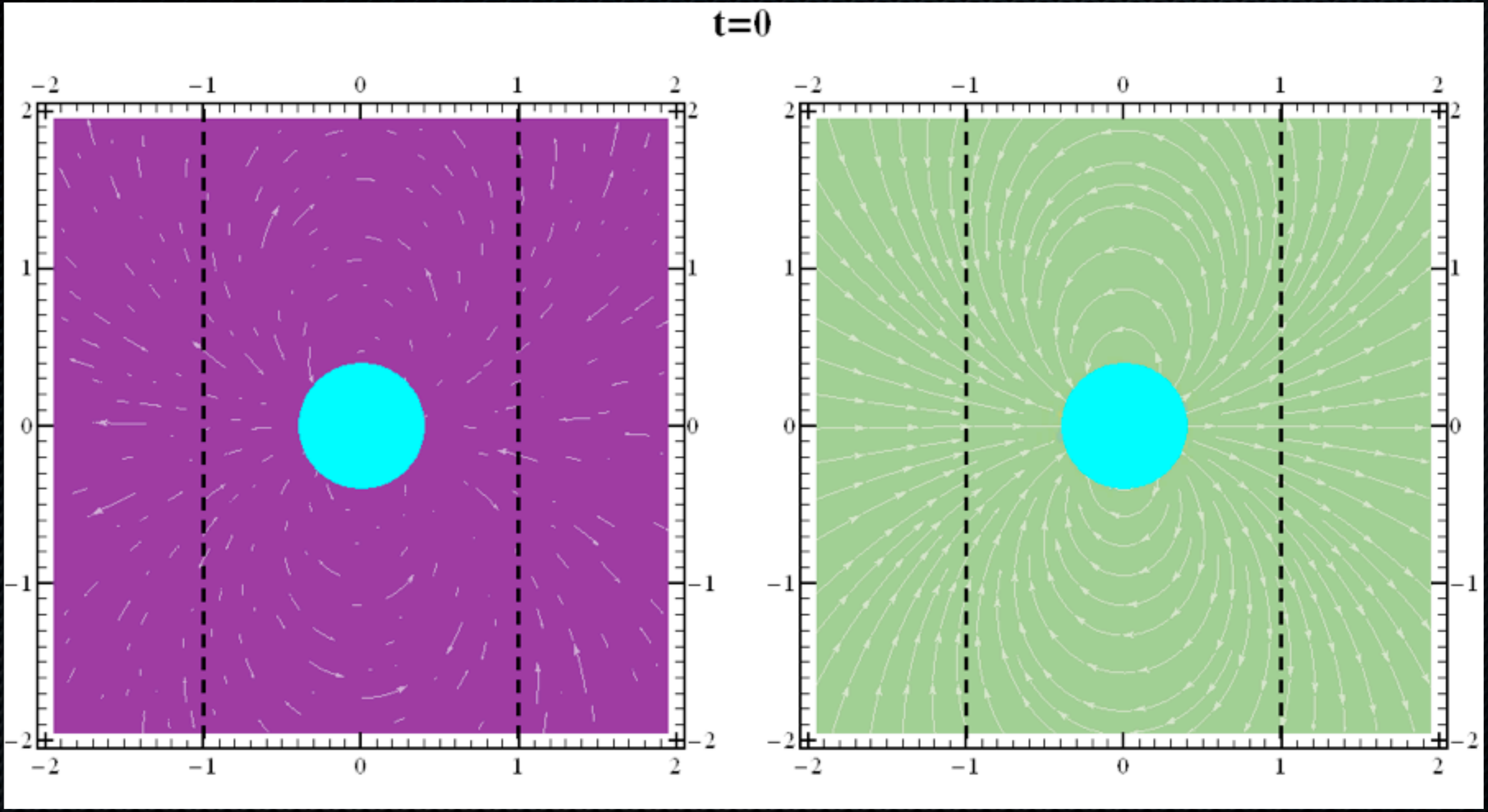
30º inclination

Contopoulos & Kalapotharakos 2010



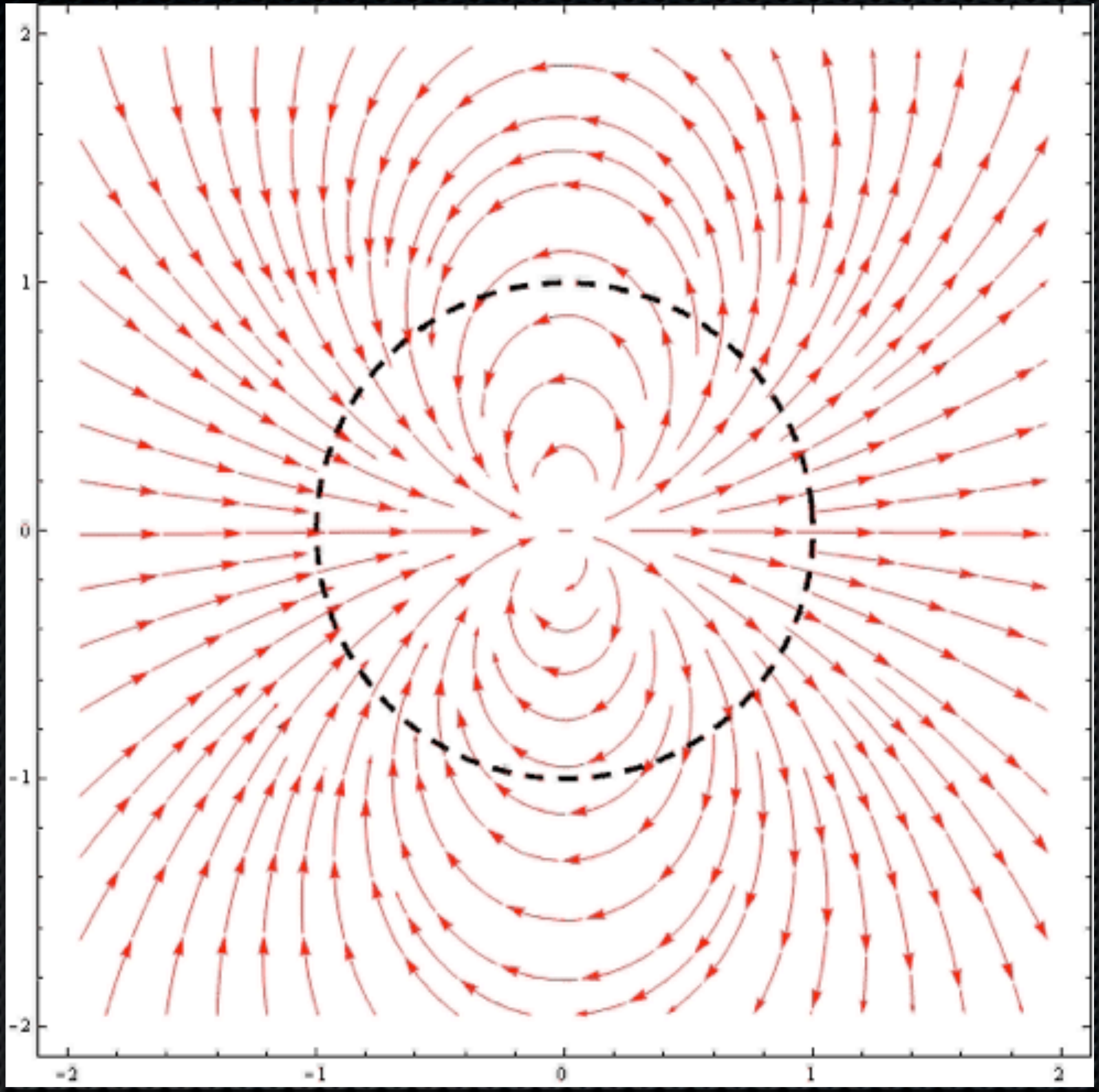
60º inclination

Contopoulos & Kalapotharakos 2010



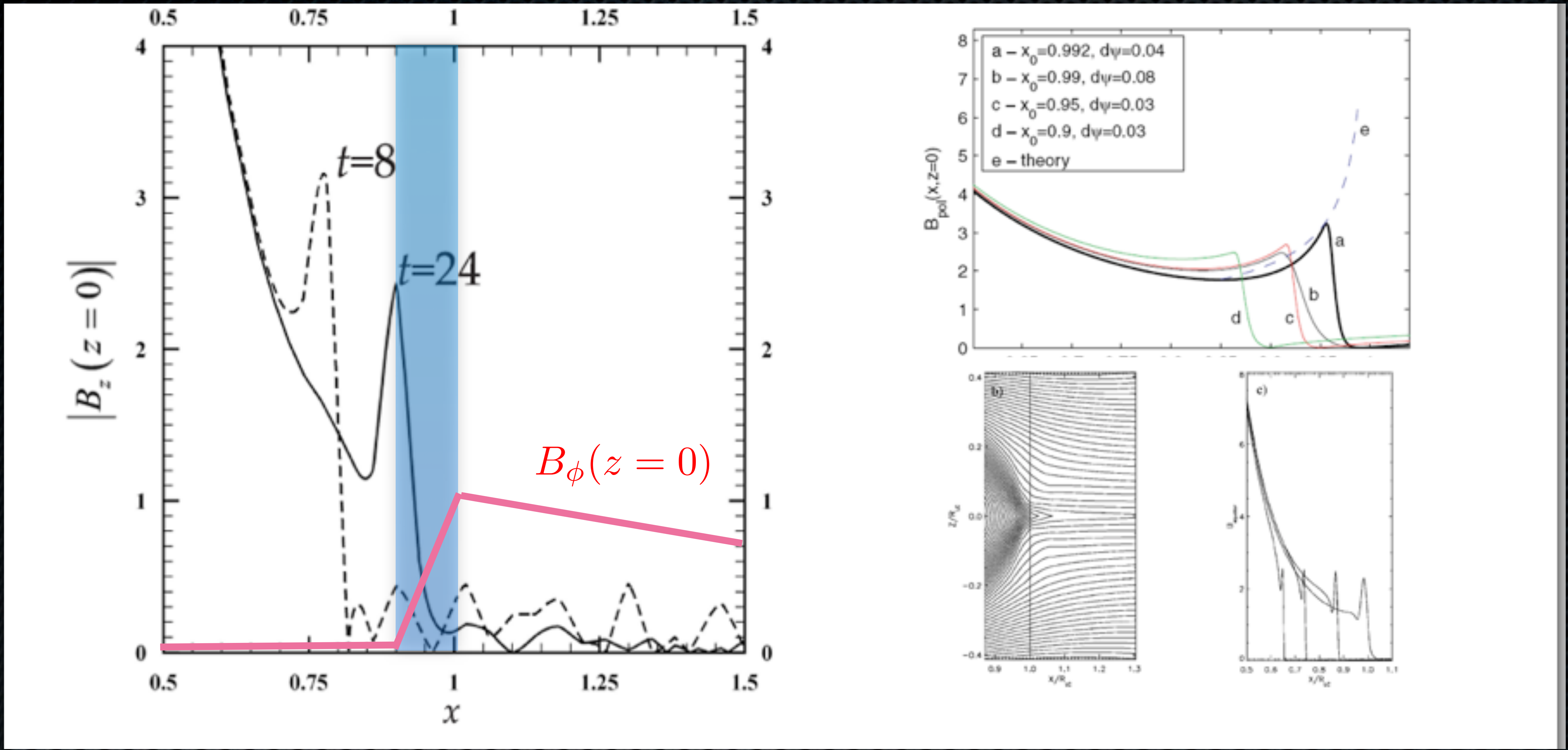
Orthogonal rotator

Contopoulos & Kalapotharakos 2010



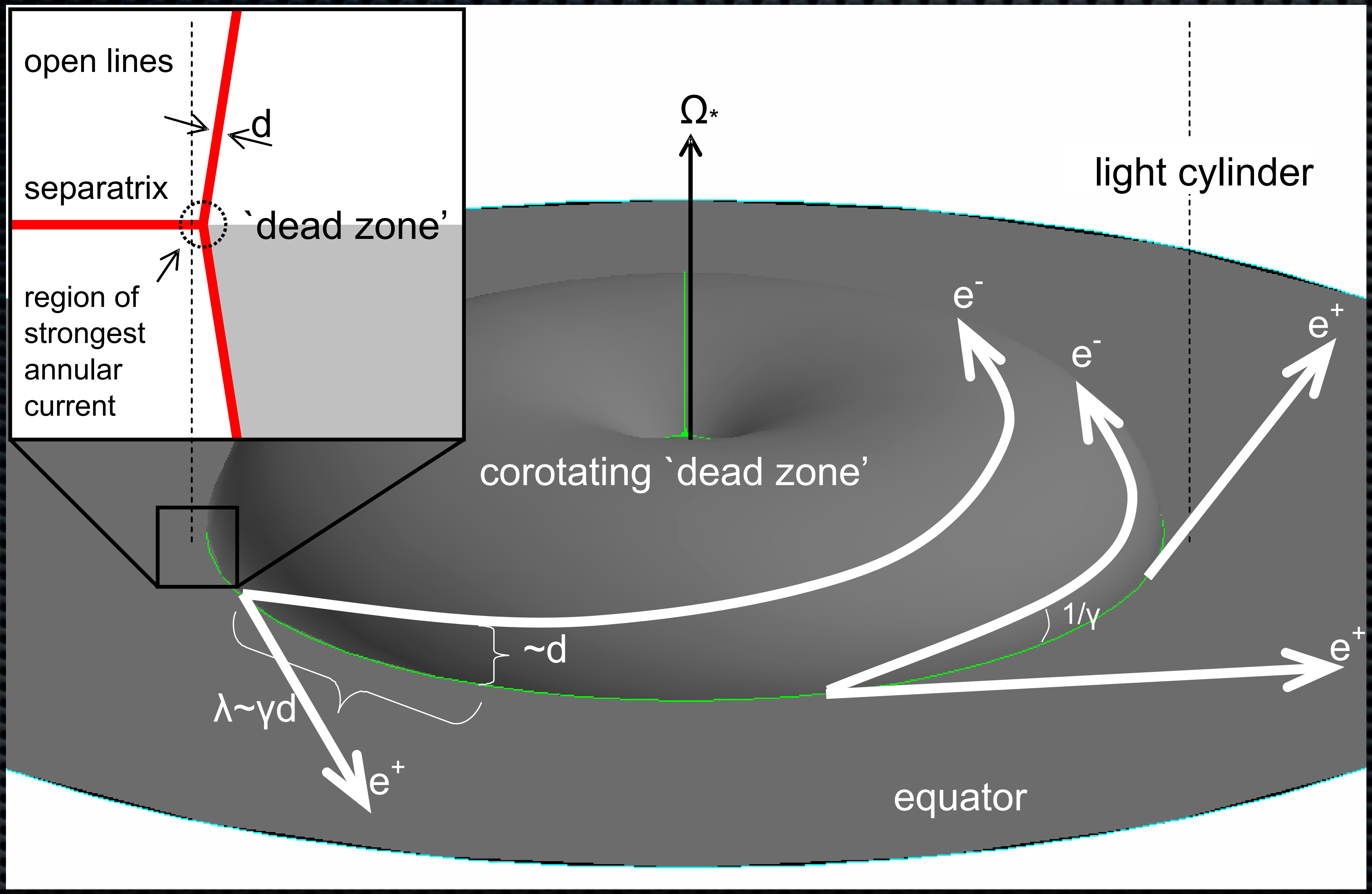
Orthogonal rotator

Contopoulos & Kalapotharakos 2010



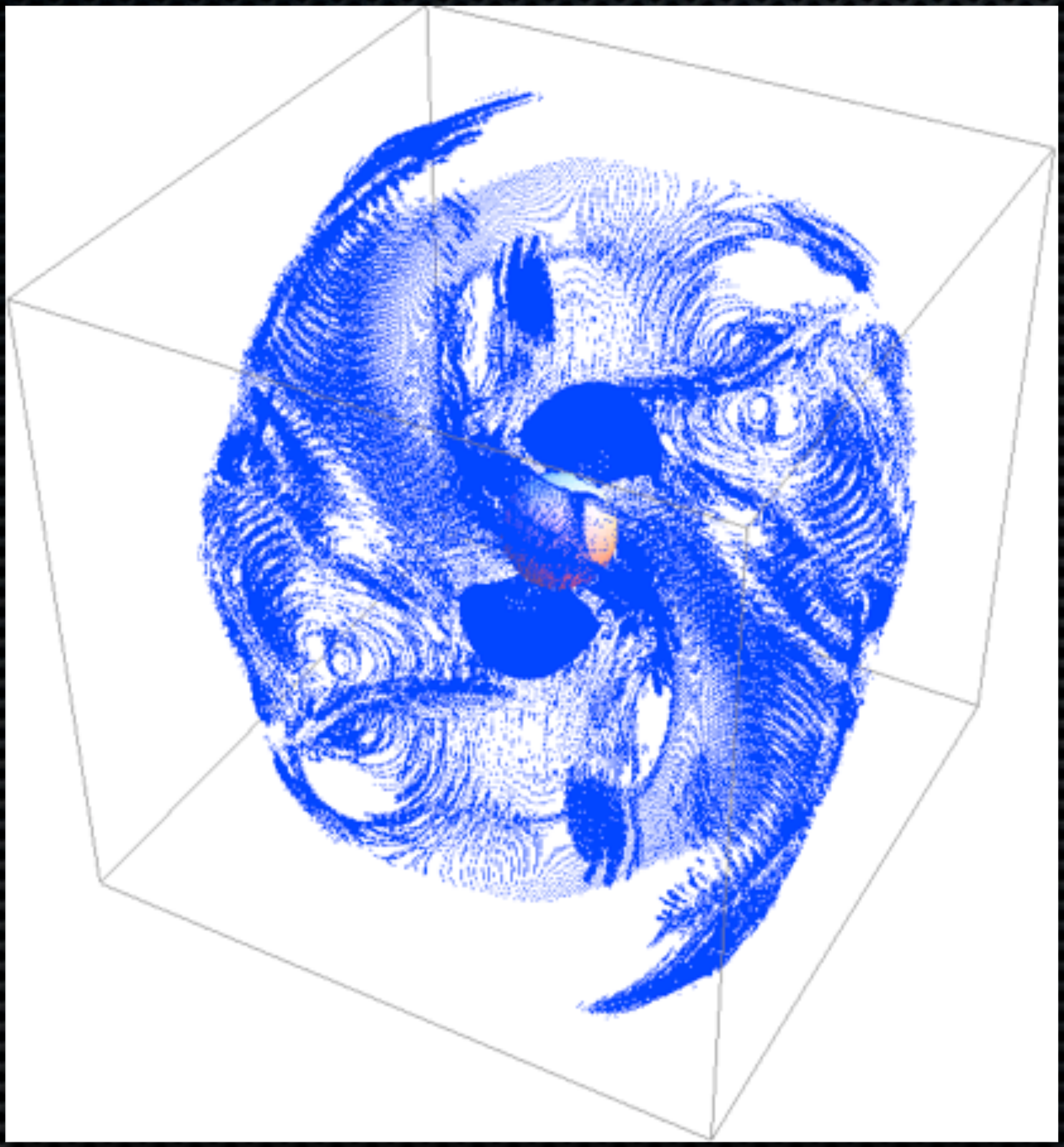
The aligned rotator

Kalapotharakos & Contopoulos 2009



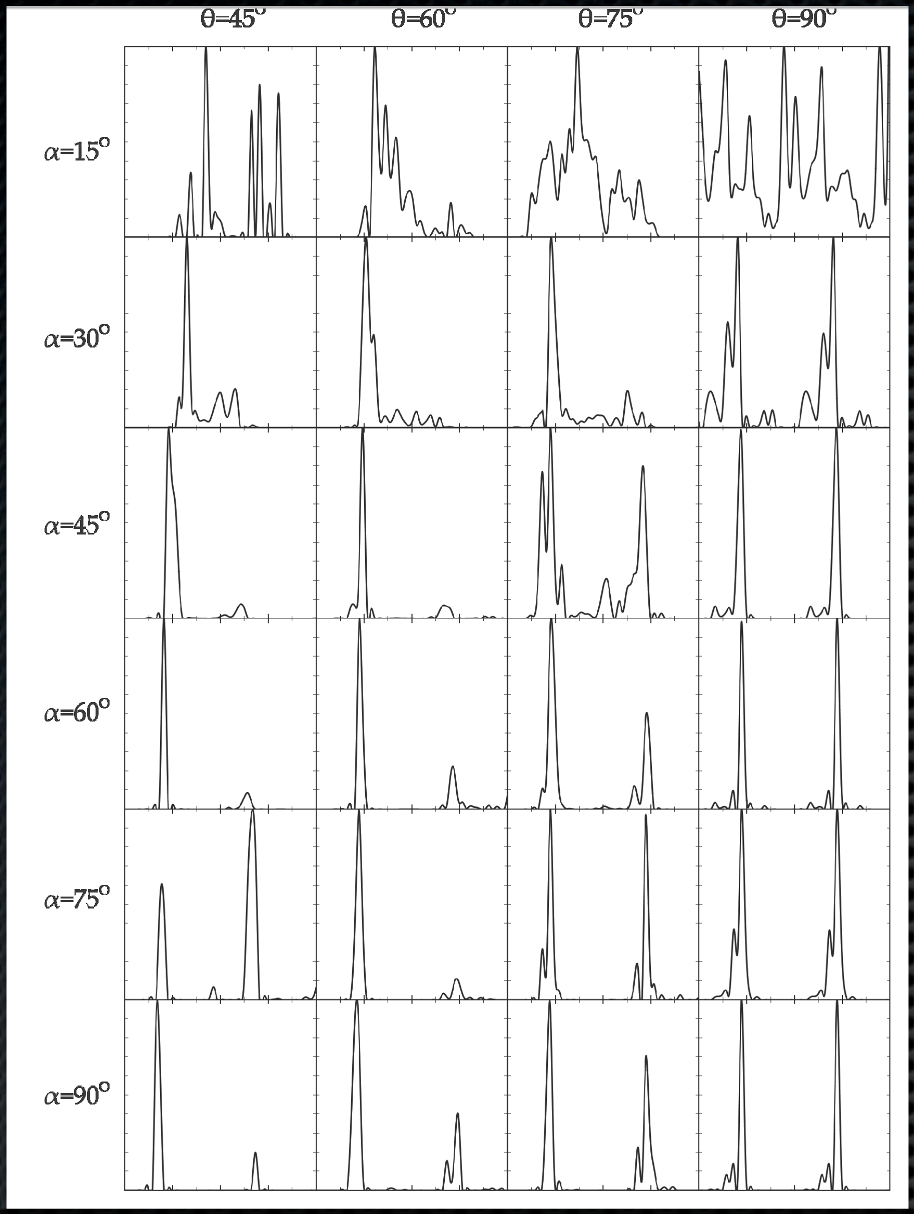
Equatorial current sheet

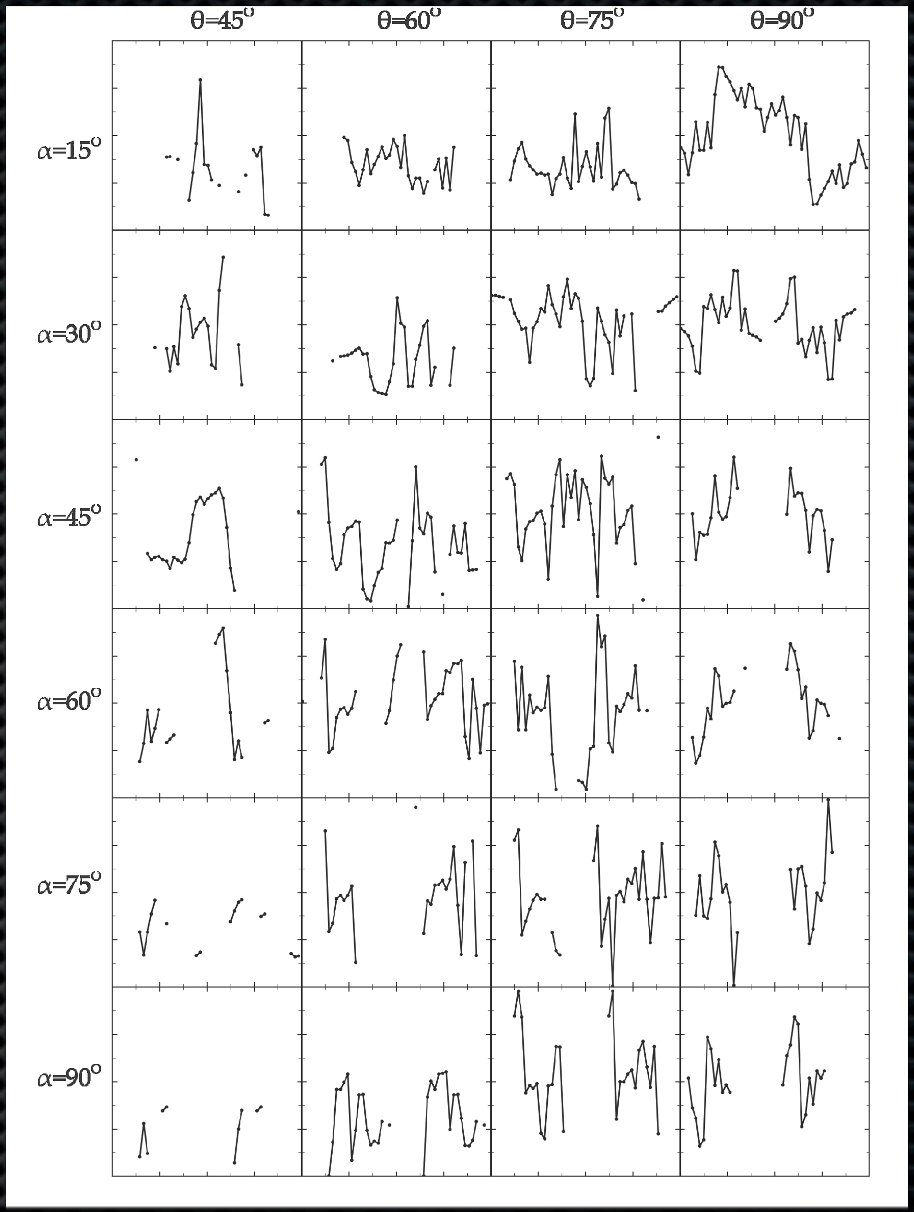
Contopoulos 2009



Equatorial current sheet

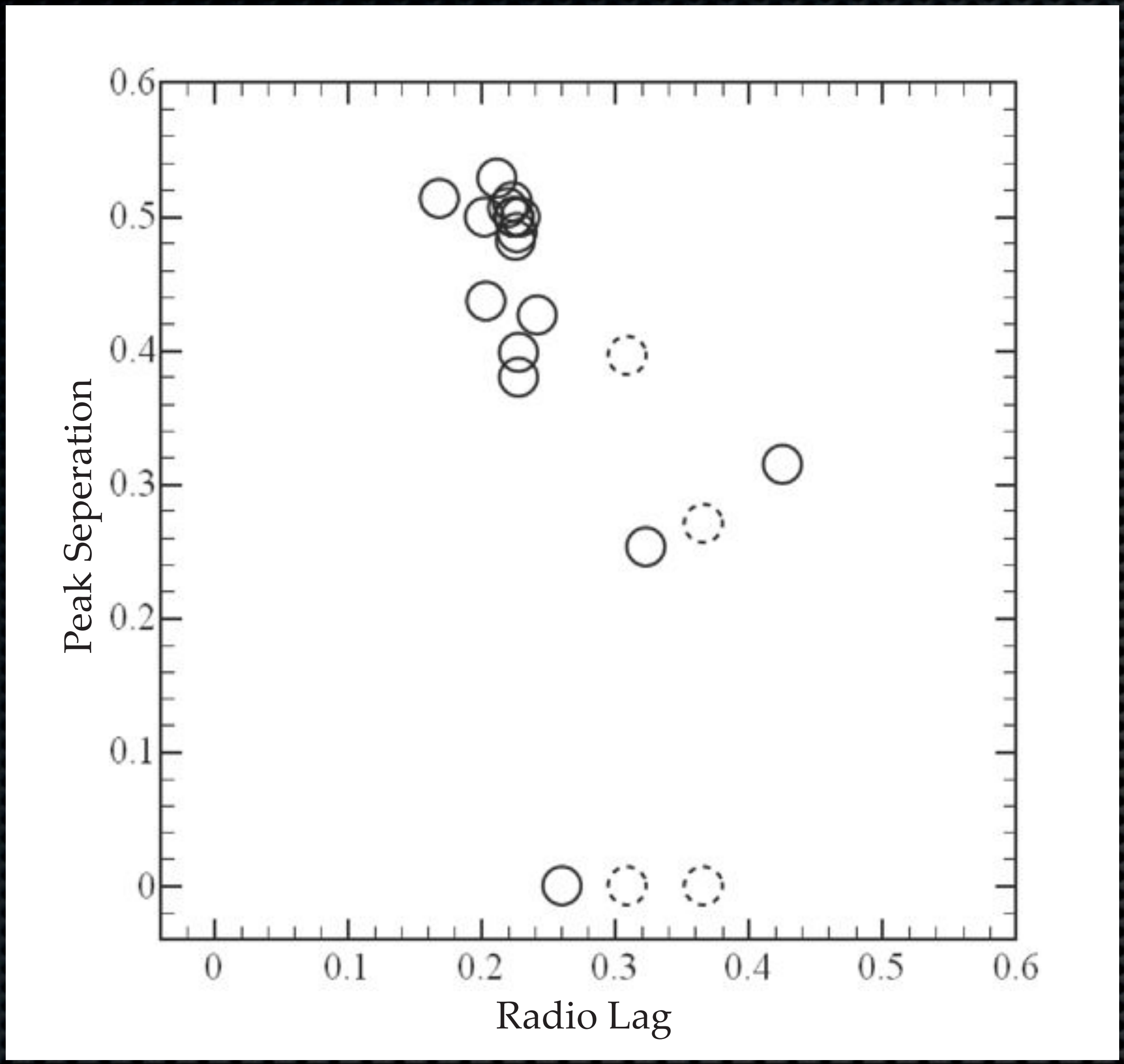
Contopoulos & Kalapotharakos 2010

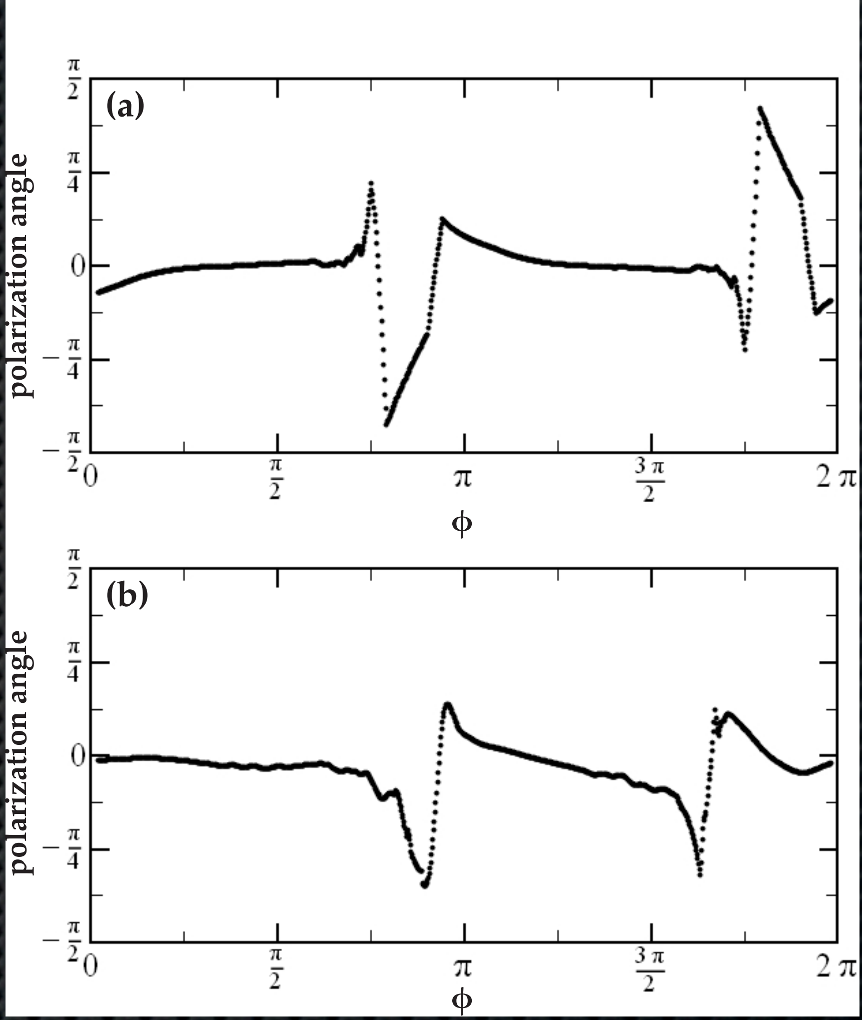




3D rotator

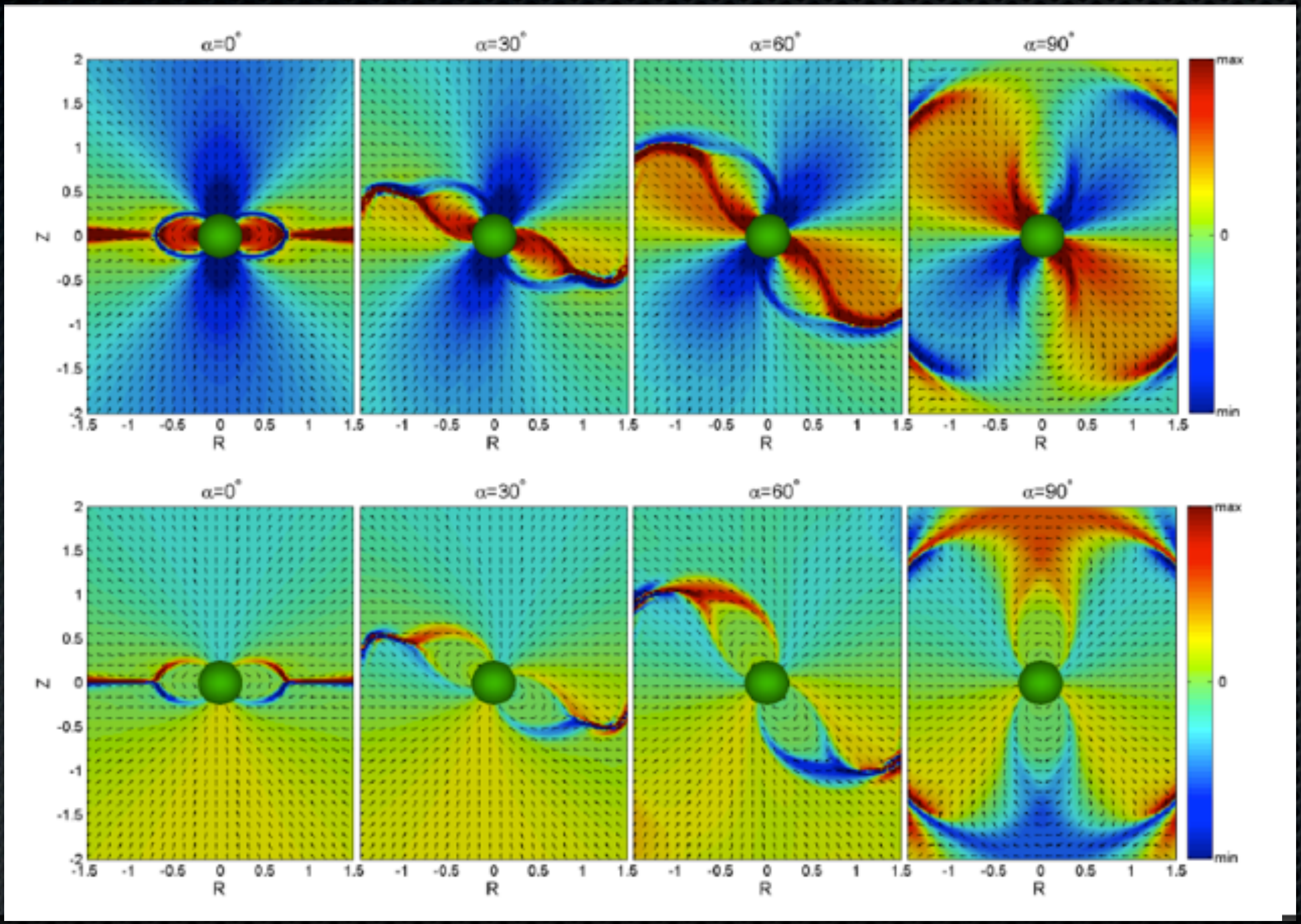
Contopoulos & Kalapotharakos 2010





3D rotator

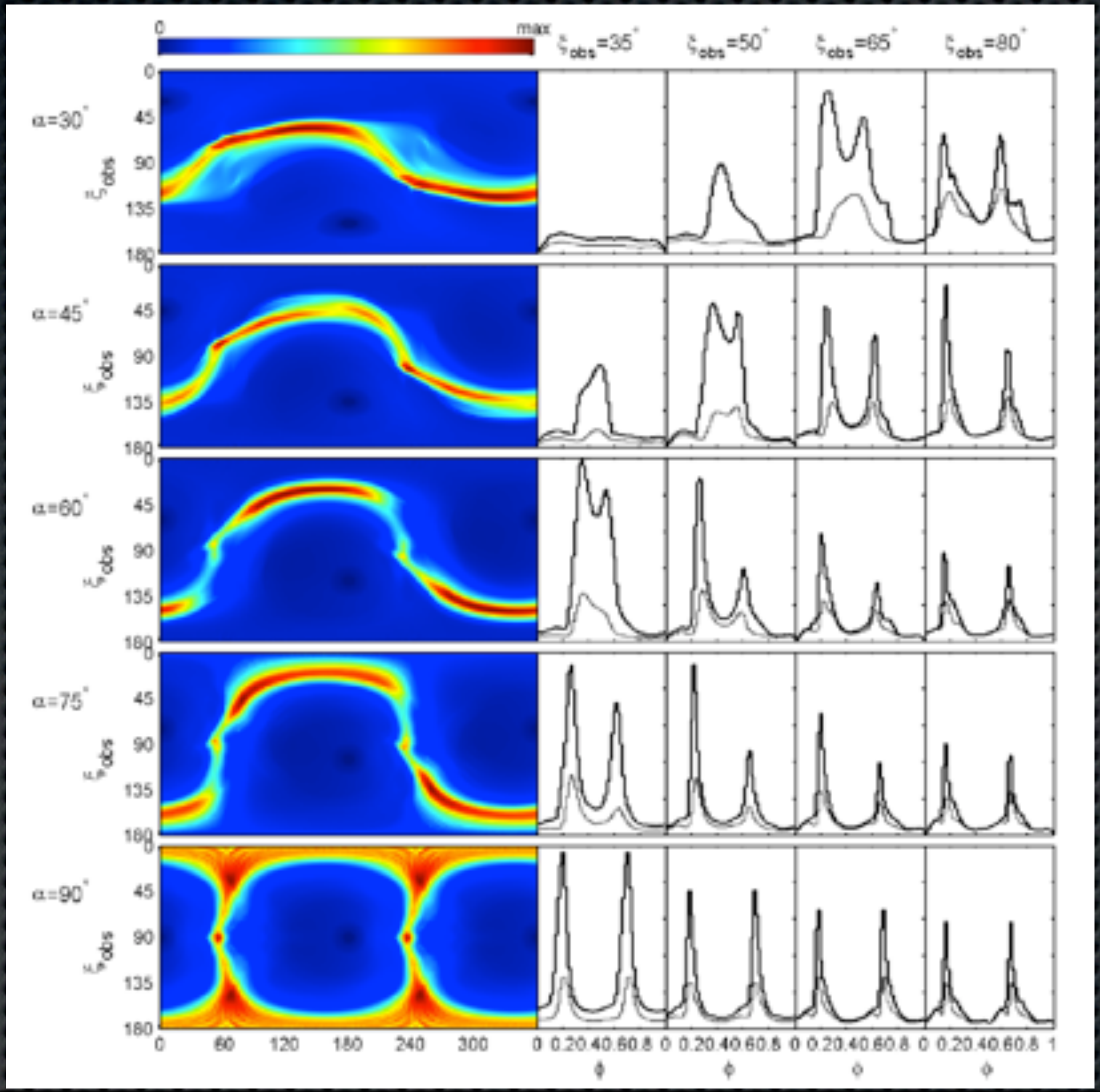
Contopoulos & Kalapotharakos 2010



3D rotator

Bai & Spitkovsky 2010

Spitkovsky 2006



3D rotator

Bai & Spitkovsky 2010

Prospects for the future

- Parallelize code to run on ~1000 CPUs
  - Higher grid resolution (δ=0.0025R_{lc})
  - Extended integration region
- Adaptive Mesh Refinement (AMR) on current sheet
- Relax force-free assumption
  - Singular regions with E || B
  - Include radiation reaction
- Relax ideal MHD condition
  - Reconnection in equatorial current sheet