Are there two types of pulsars?

(The “Aristotelian” current sheet)

Ioannis Contopoulos

RCAAM, Academy of Athens

NRNU MEPhI

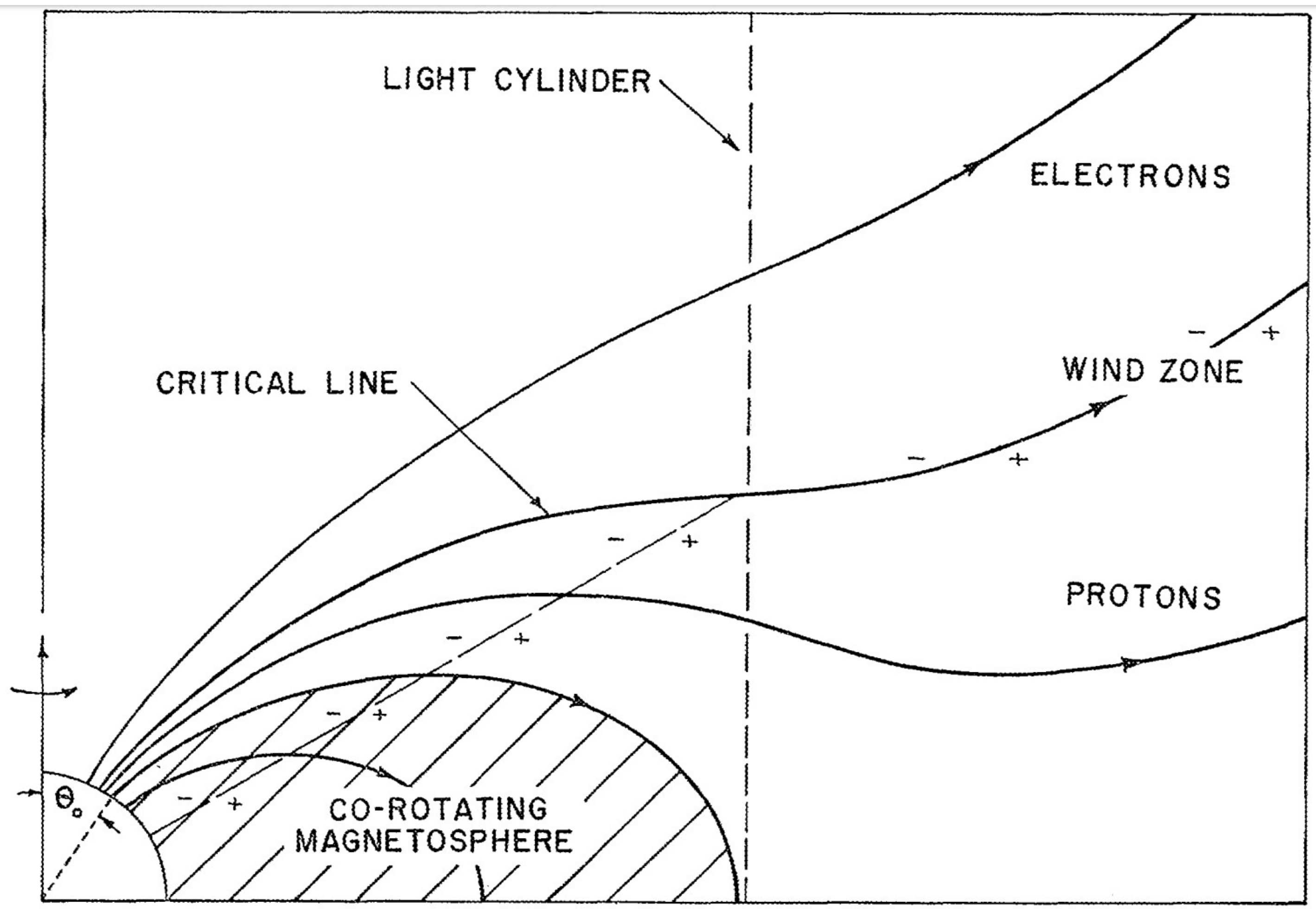
Currently, we have (a) good understanding of (the) overall electromagnetic structure of (the) pulsar magnetosphere

and

Large scale kinetic modeling of the magnetosphere is required

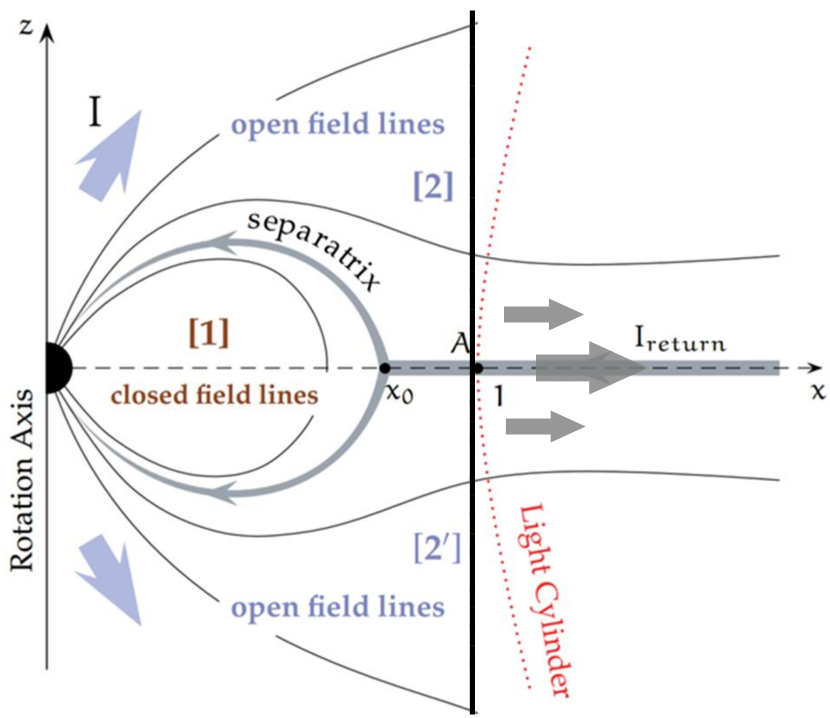
Maxim Lyutikov 2016

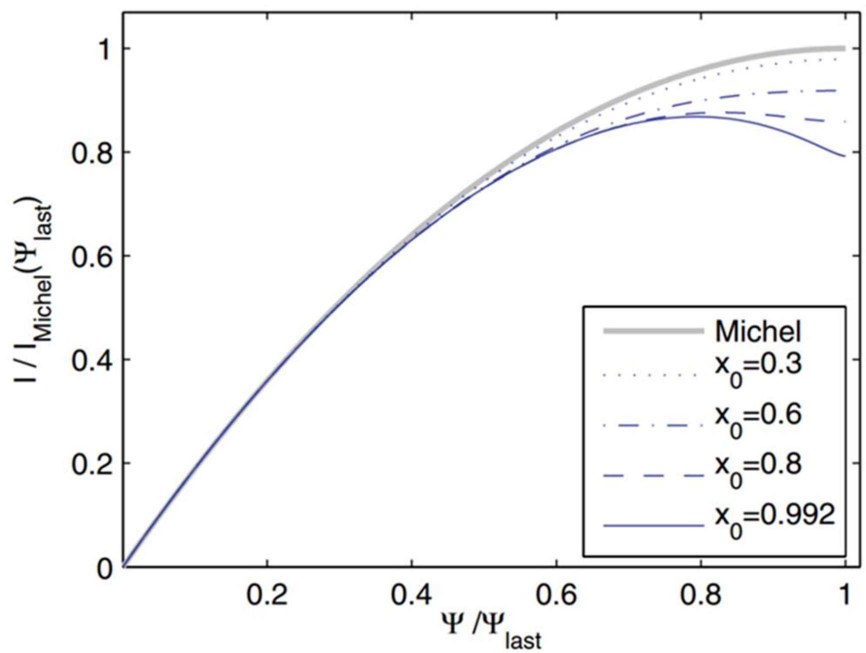
Ideal Magnetospheres



1969

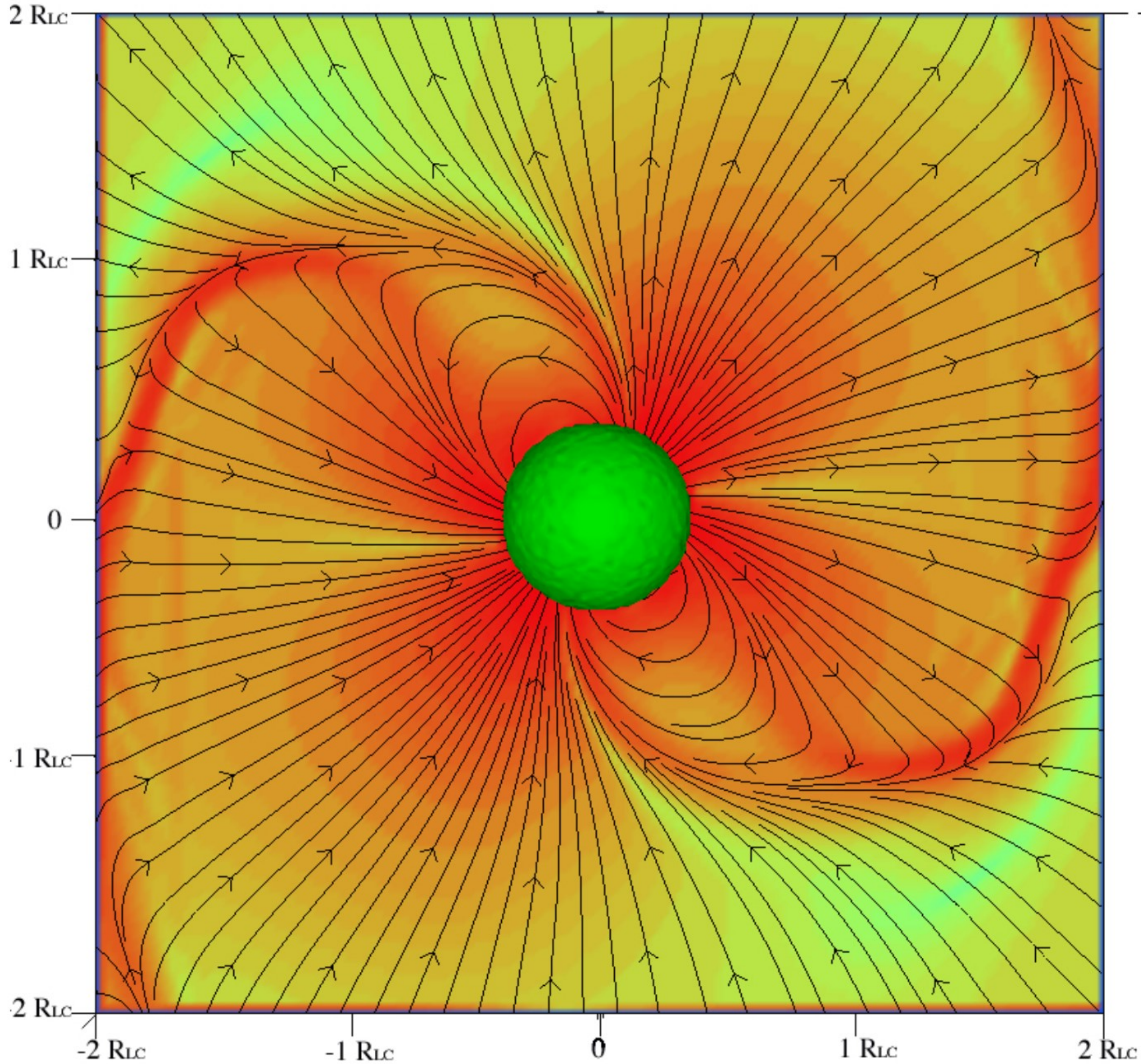
Ideal Magnetospheres





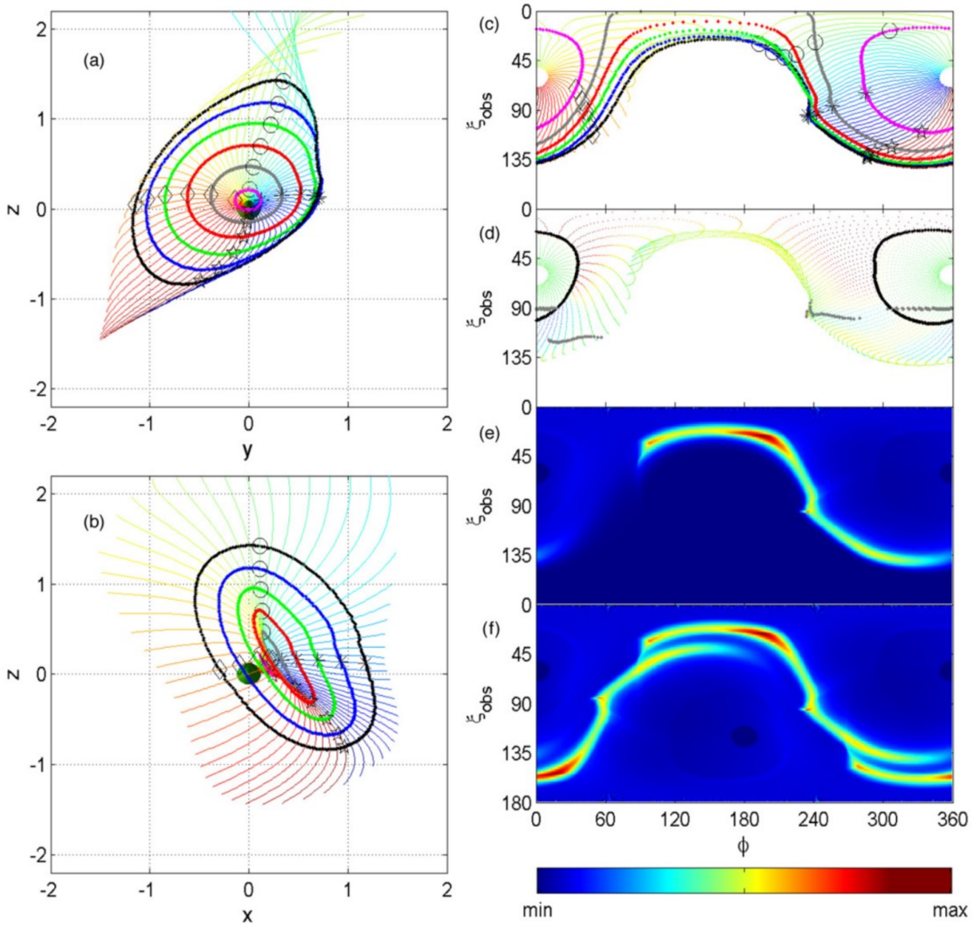
1999, 2005, 2006

Ideal Magnetospheres

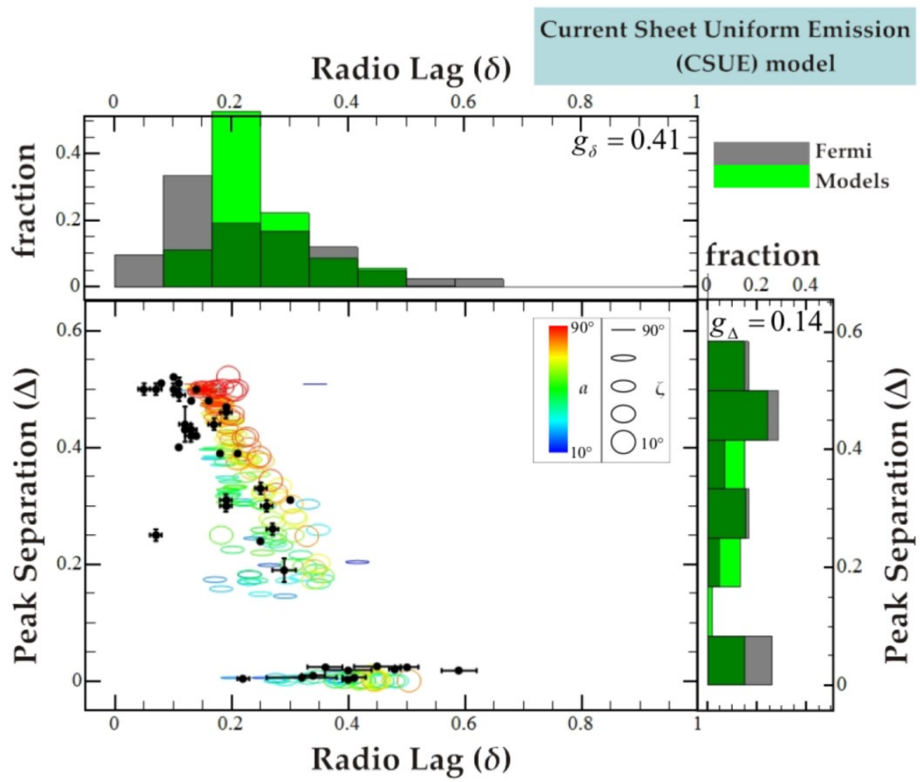


2006, 2009, 2016

Ideal Magnetospheres with particle tracing

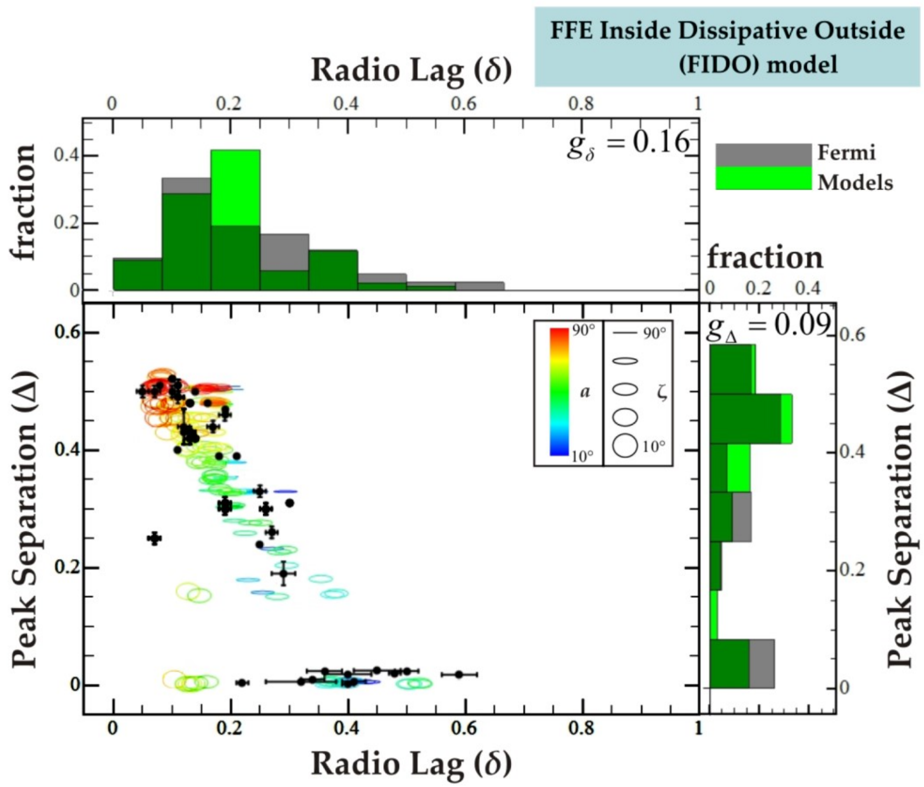


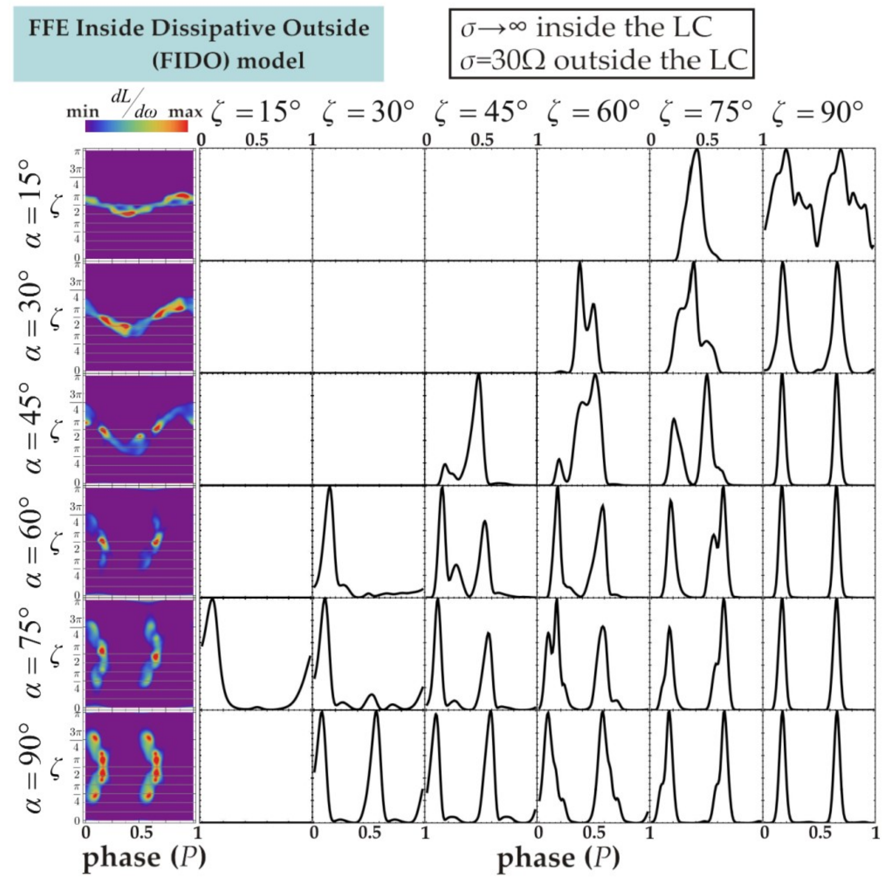
Princeton Group 2010



(Athens)-Goddard Group 2014

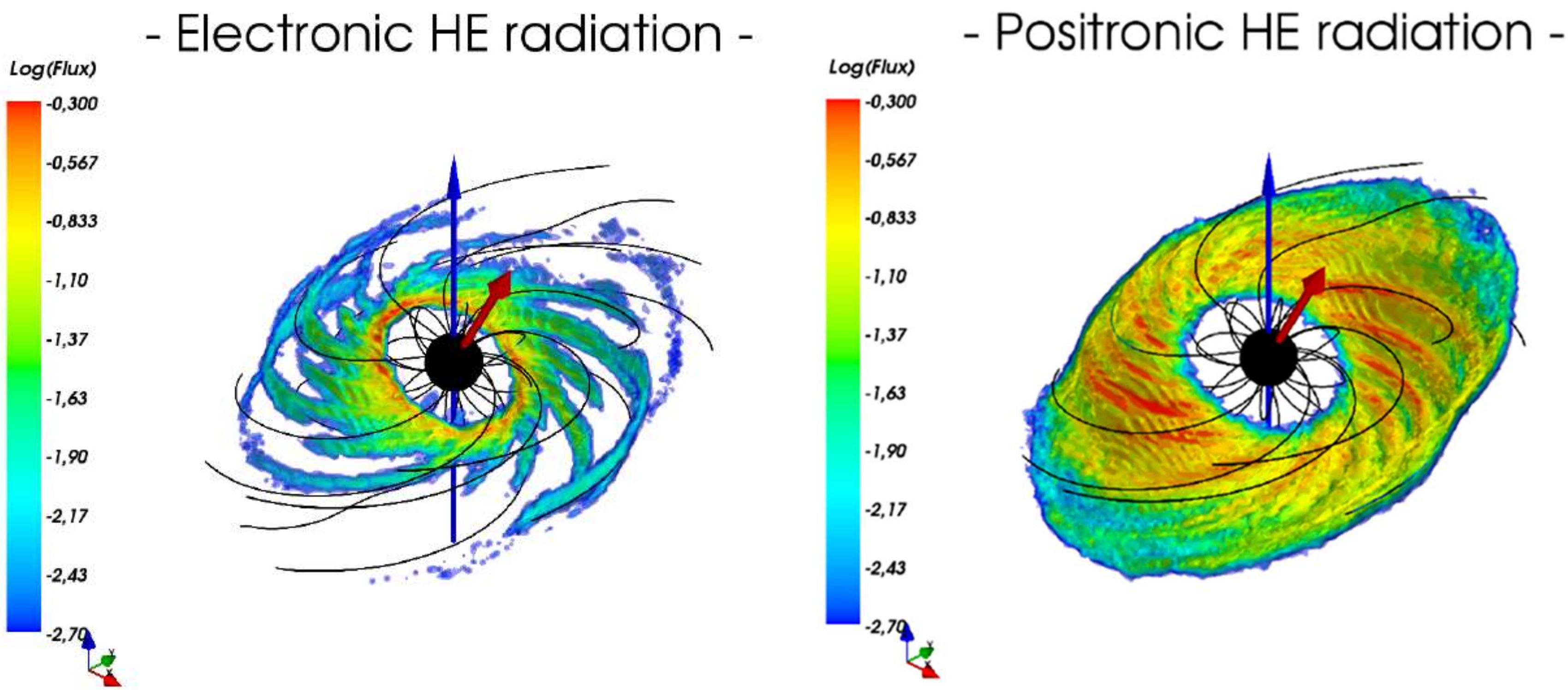
Dissipative Magnetospheres with finite conductivity σ





Goddard Group 2012, 2014

“Ab initio” Magnetospheres



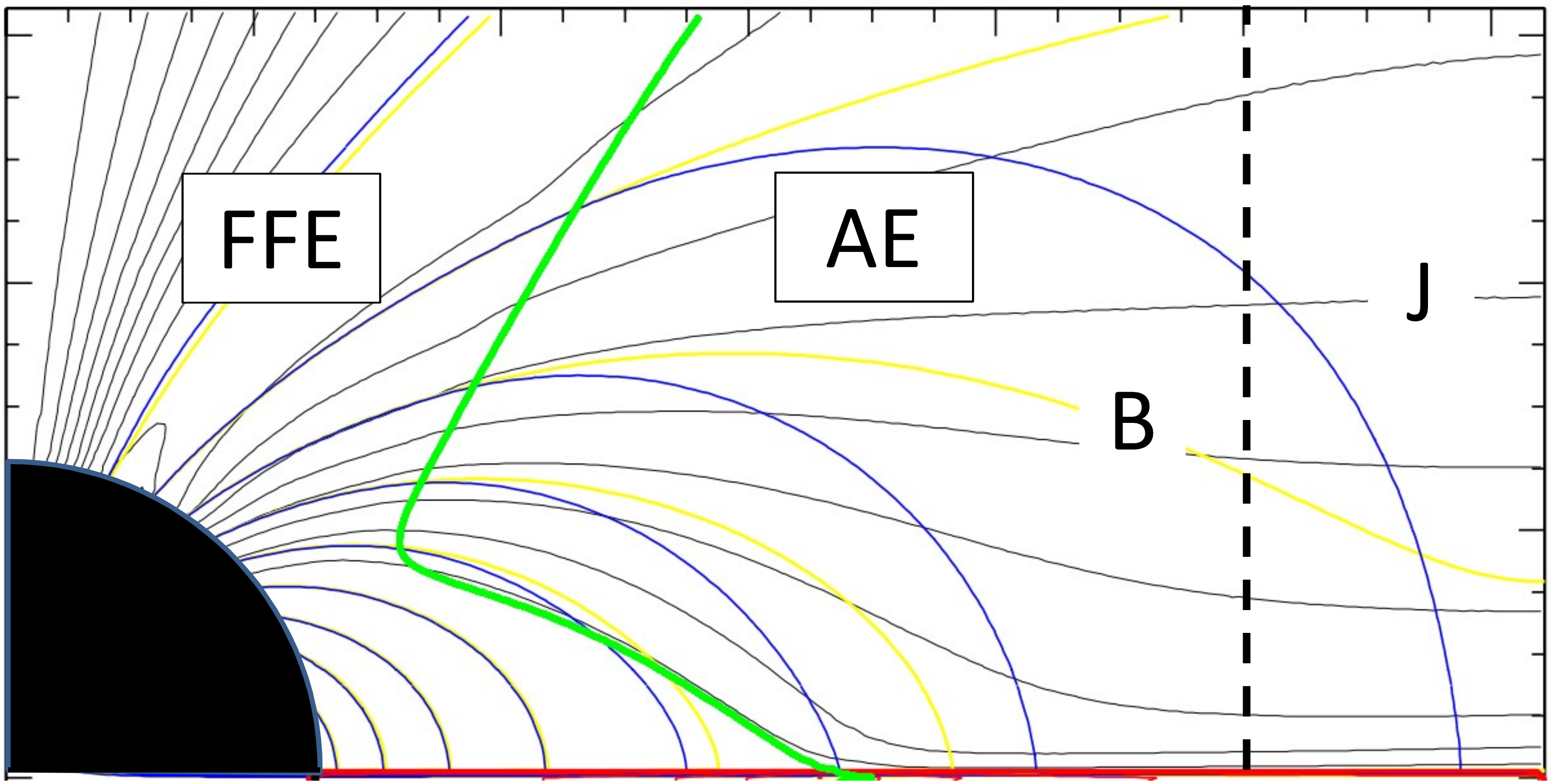
PIC with radiation reaction + pair formation!

$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E} \right] - \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right] \boldsymbol{\beta}$$

$$F_\nu(\nu) = \frac{\sqrt{3} e^3 \tilde{B}_\perp}{m_e c^2} \left(\frac{\nu}{\nu_c} \right) \int_{\nu/\nu_c}^{+\infty} K_{5/3}(x) dx$$

Princeton Group 2014, 2015, 2016…

Dissipative Magnetospheres in Aristotelian Electrodynamics



Gruzinov 2015, 2016

Are there `weak' and `strong' pulsars?

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A MODEL FOR THE ELECTRICALLY CHARGED CURRENT SHEET OF A PULSAR

C. R. DeVore[1], S. K. Antiochos[1], C. E. Black[1,2], A. K. Harding[3],
C. Kalapotharakos[3,4], D. Kazanas[3], and A. N. Timokhin[3,4]
[1] Heliophysics Science Division, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA; c.richard.devore@nasa.gov
[2] Catholic University of America, 620 Michigan Avenue Northeast, Washington, DC 20064, USA
[3] Astrophysics Science Division, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
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Received 2014 October 2; accepted 2014 December 11; published 2015 March 12

A NEW STANDARD PULSAR MAGNETOSPHERE

Ioannis Contopoulos[1], Constantinos Kalapotharakos[2,3], and Demosthenes Kazanas[3]
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[3] Astrophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
Received 2013 October 9; accepted 2013 November 25; published 2014 January 7

Pulsar Efficiency

Andrei Gruzinov
CCPP, Physics Department, New York University, 4 Washington Place, New York, NY 10003

ABSTRACT

Pulsar efficiency, defined as the ratio of the pulsed bolometric luminosity to the spin-down power, is calculated to be $\approx 15\%$ (averaged over the spin-dipole inclination angle, ranging between $\approx 50\%$ for the aligned and $\approx 10\%$ for the orthogonal). We also estimate the characteristic photon energy and argue that our results agree with the Fermi pulsar catalog – in a sense.

AB INITIO PULSAR MAGNETOSPHERE: THREE-DIMENSIONAL PARTICLE-IN-CELL SIMULATIONS OF AXISYMMETRIC PULSARS

ALEXANDER A. PHILIPPOV AND ANATOLY SPITKOVSKY
Department of Astrophysical Sciences, Princeton University, Peyton Hall, Ivy Lane, Princeton, NJ 08544, USA; sashaph@princeton.edu
Received 2013 December 19; accepted 2014 March 15; published 2014 April 4

Also, we find little evidence for dramatic dissipation of Poynting flux beyond the light cylinder (unlike Gruzinov 2012 and Contopoulos et al. 2013), a conclusion that is likely to only strengthen with improved current sheet resolution.

Particle acceleration in axisymmetric pulsar current sheets

Benoît Cerutti⋆†, Alexander Philippov, Kyle Parfrey and Anatoly Spitkovsky
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA.

We find that about 30% of the outgoing Poynting flux is dissipated in the current layer, mostly in the vicinity of the Y-point (Philippov & Spitkovsky 2014).

J. Plasma Phys., page 1 of 13.

The equatorial current sheet and other interesting features of the pulsar magnetosphere

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[2]National Research Nuclear University, 31 Kashirskoe Highway, Moscow 115409, Russia

(Received 3 February 2016; revised 13 April 2016; accepted 13 April 2016)

We want to understand what drives magnetospheric dissipation in the equatorial current sheet. Numerical simulations have limitations and, unless we have a clear a priori understanding of the physical processes involved, their results can be misleading. We argue that the canonical pulsar magnetosphere is strongly dissipative and that a large fraction (up to 30–40 % in an aligned rotator) of the spindown luminosity is redirected towards the equator where it is dissipated into particle acceleration and emission of radiation. We show that this is due to the failure of the equatorial electric current to cross the Y-point at the tip of the corotating zone.

Mon. Not. R. Astron. Soc. **000**, 1–?? (2015) Printed 1 June 2016

Are there two types of pulsars?

I. Contopoulos[1,2]

[1]*Research Center for Astronomy and Applied Mathematics, Academy of Athens, Athens 11527, Greece*

[2]*National Research Nuclear University, 31 Kashirskoe highway, Moscow 115409, Russia*

Accepted ... Received ...; in original form ...

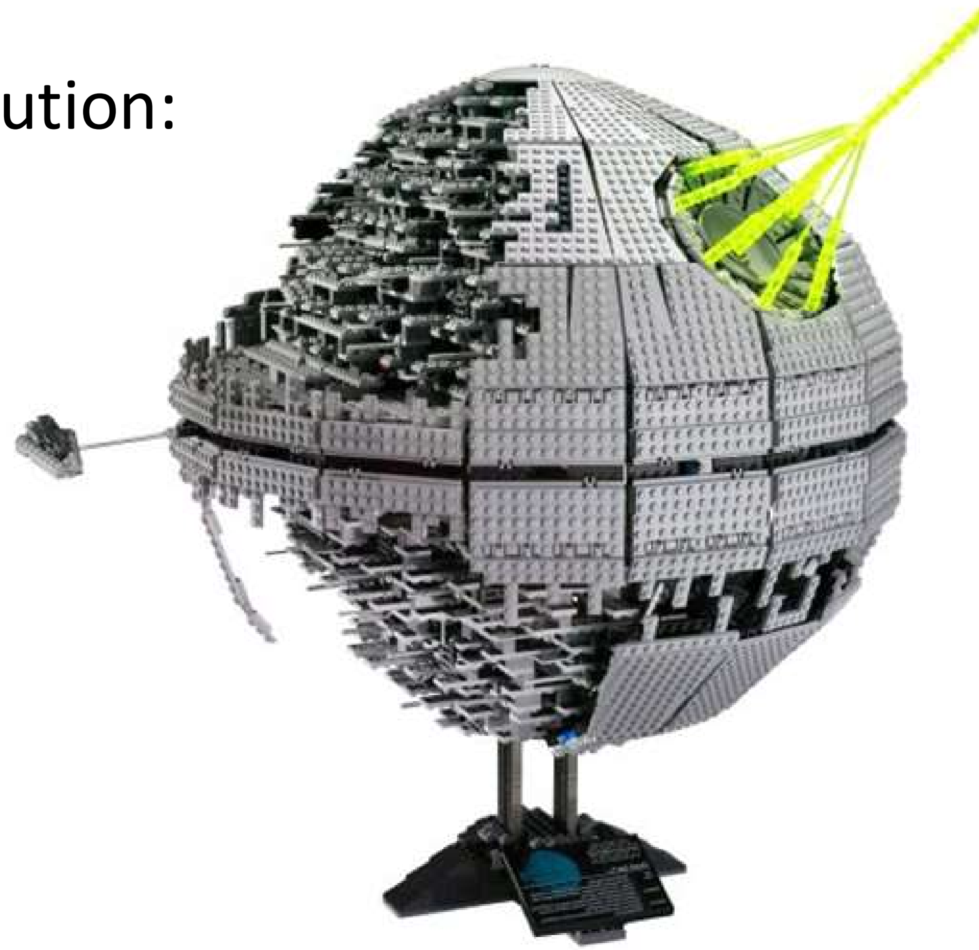
ABSTRACT

In order to investigate the importance of dissipation in the pulsar magnetosphere we combined Force-Free with Aristotelian Electrodynamics. We obtain solutions that are ideal (non-dissipative) everywhere except in an equatorial current sheet where Poynting flux from both hemispheres converges and is dissipated into particle acceleration and radiation. We obtain significant dissipative losses similar to what is found in global PIC simulations in which particles are provided only on the stellar surface. We conclude that there might indeed exist two types of pulsars, strongly dissipative ones with particle injection only from the stellar surface, and ideal (weakly dissipative) ones with particle injection in the outer magnetosphere and in particular at the Y-point.

Key words: MHD; Pulsars

Limitations of numerical simulations

- Lego tiles:
  - Light cylinder resolution:
    - 2D: 10,000
    - 3D: 100



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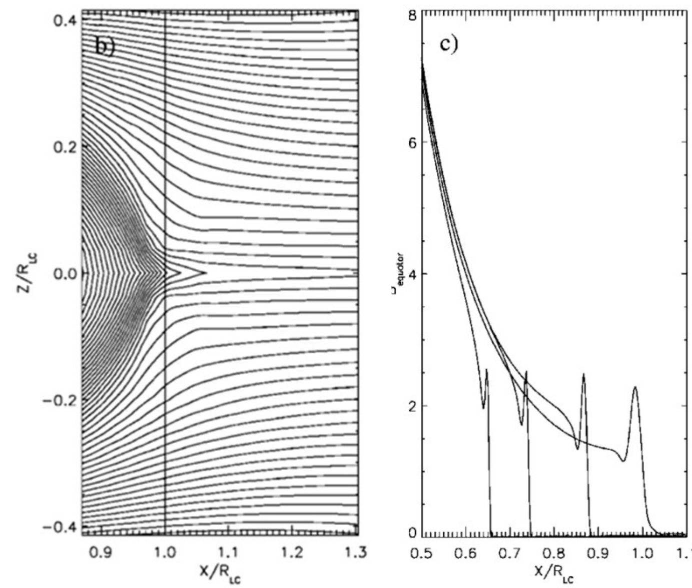
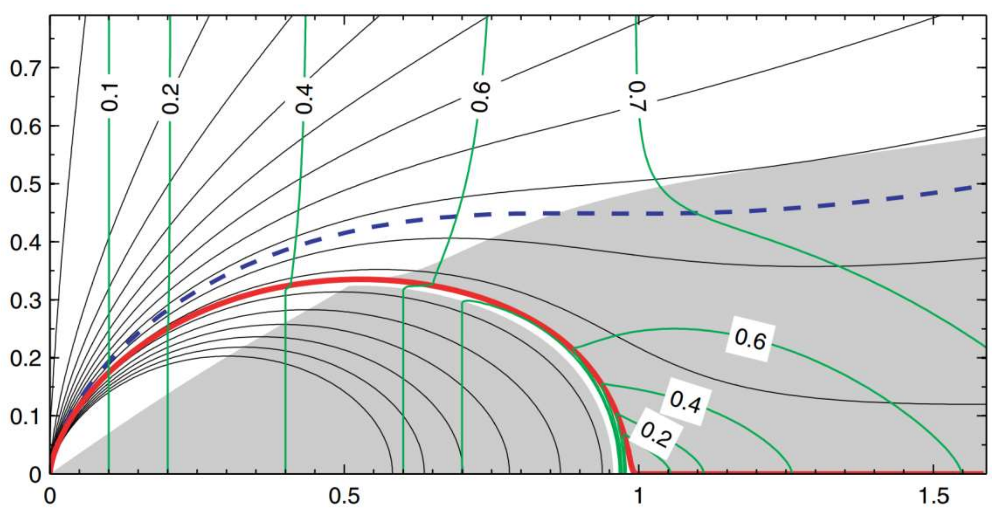
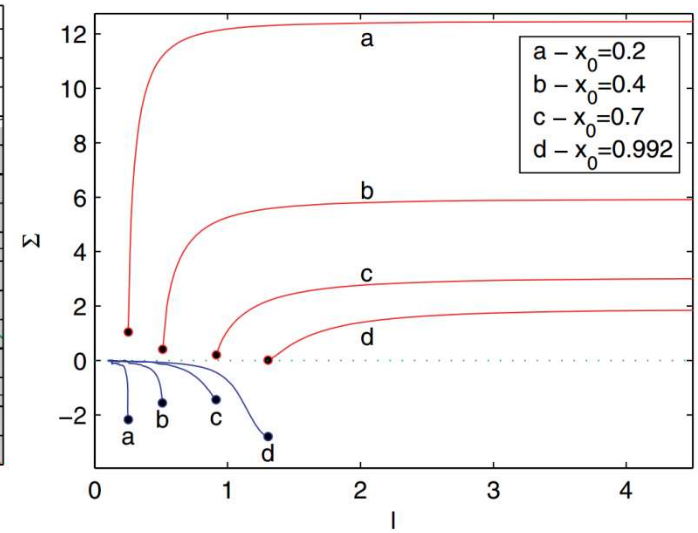
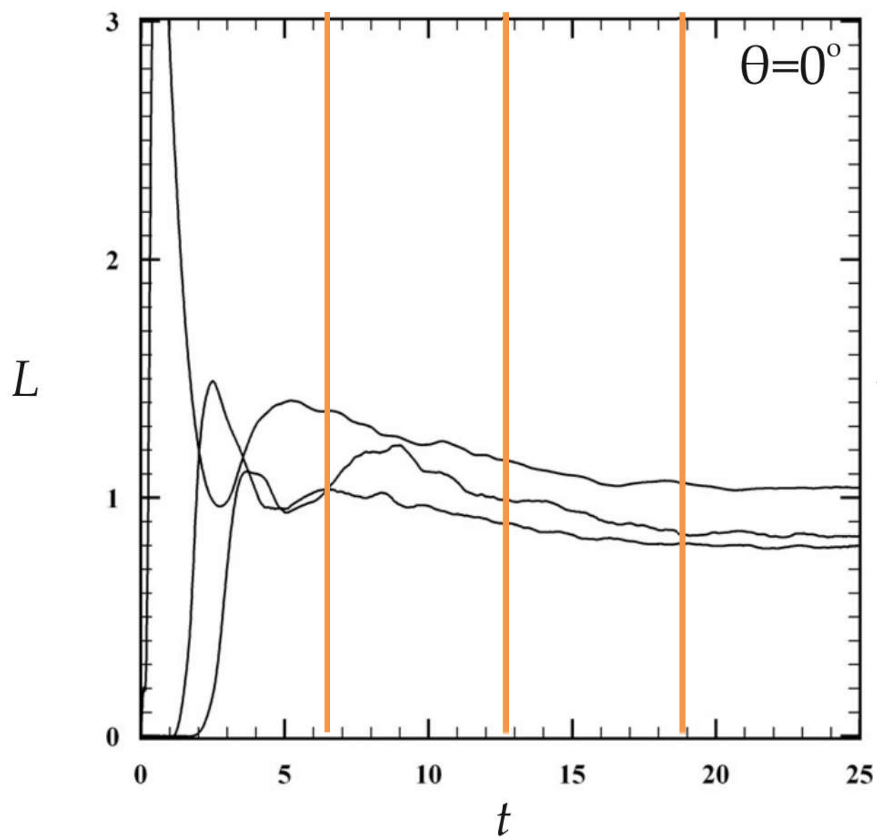


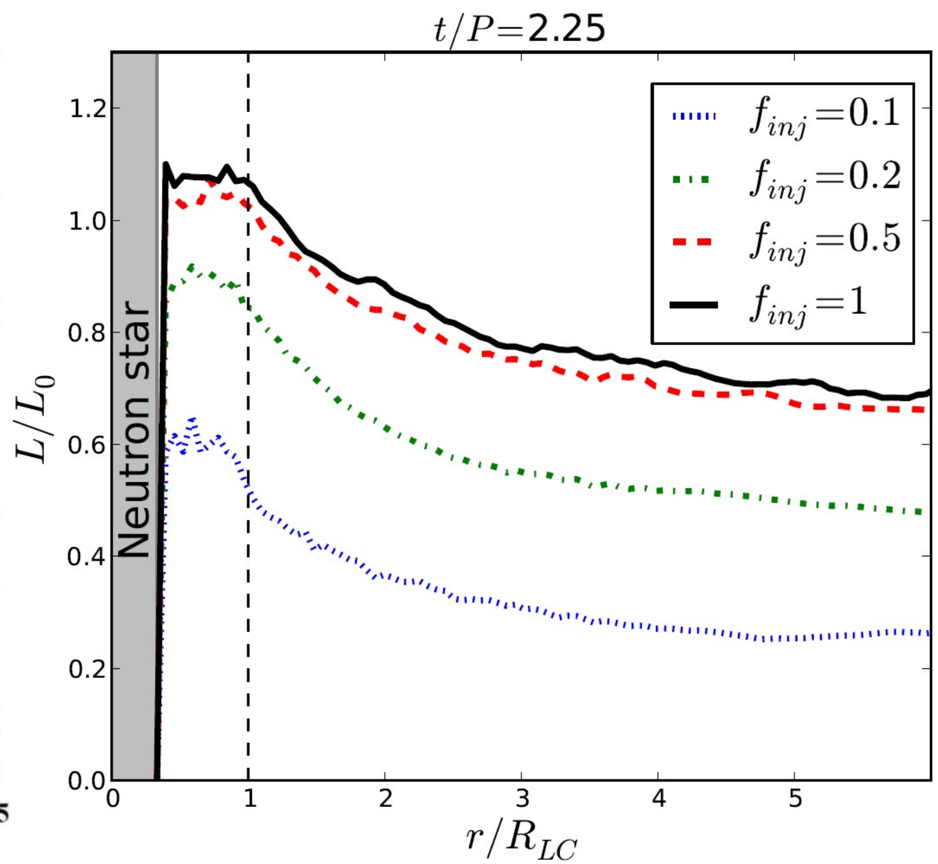


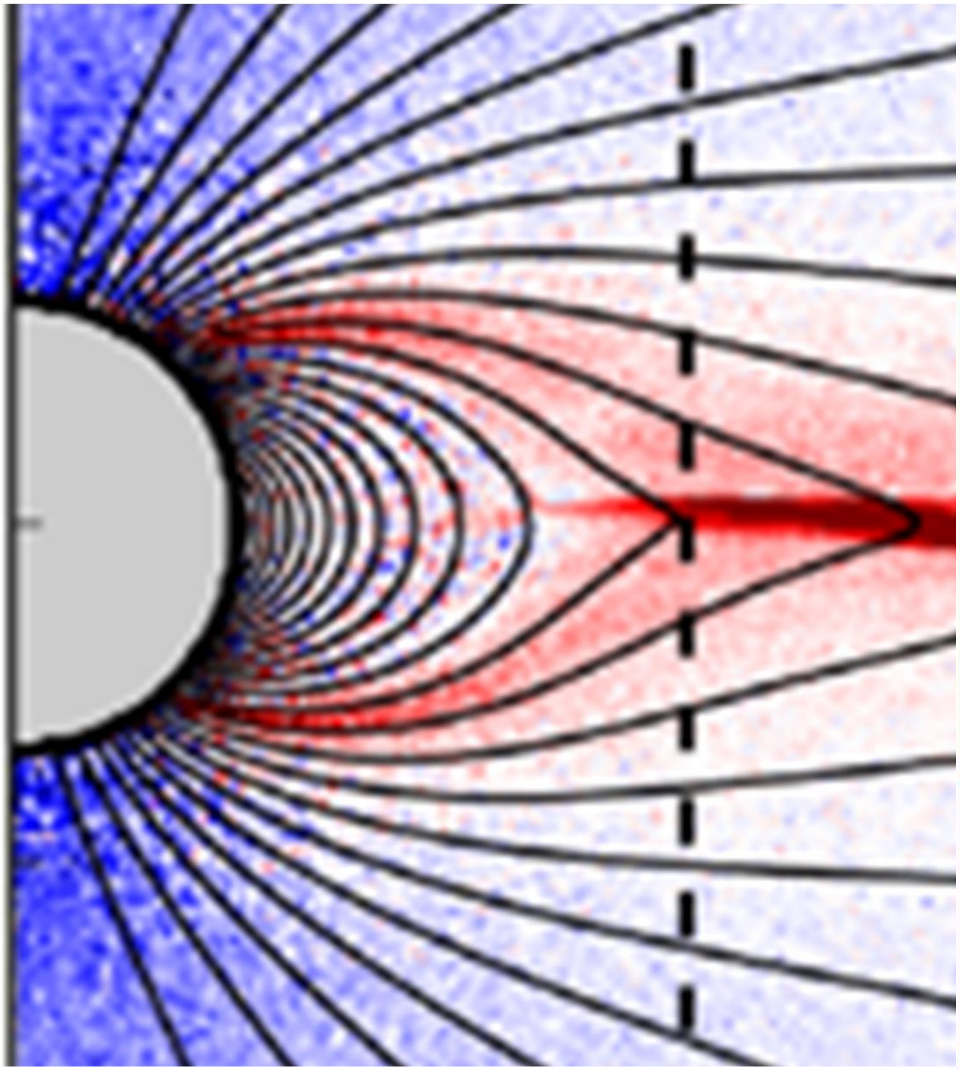


Limitations of numerical simulations

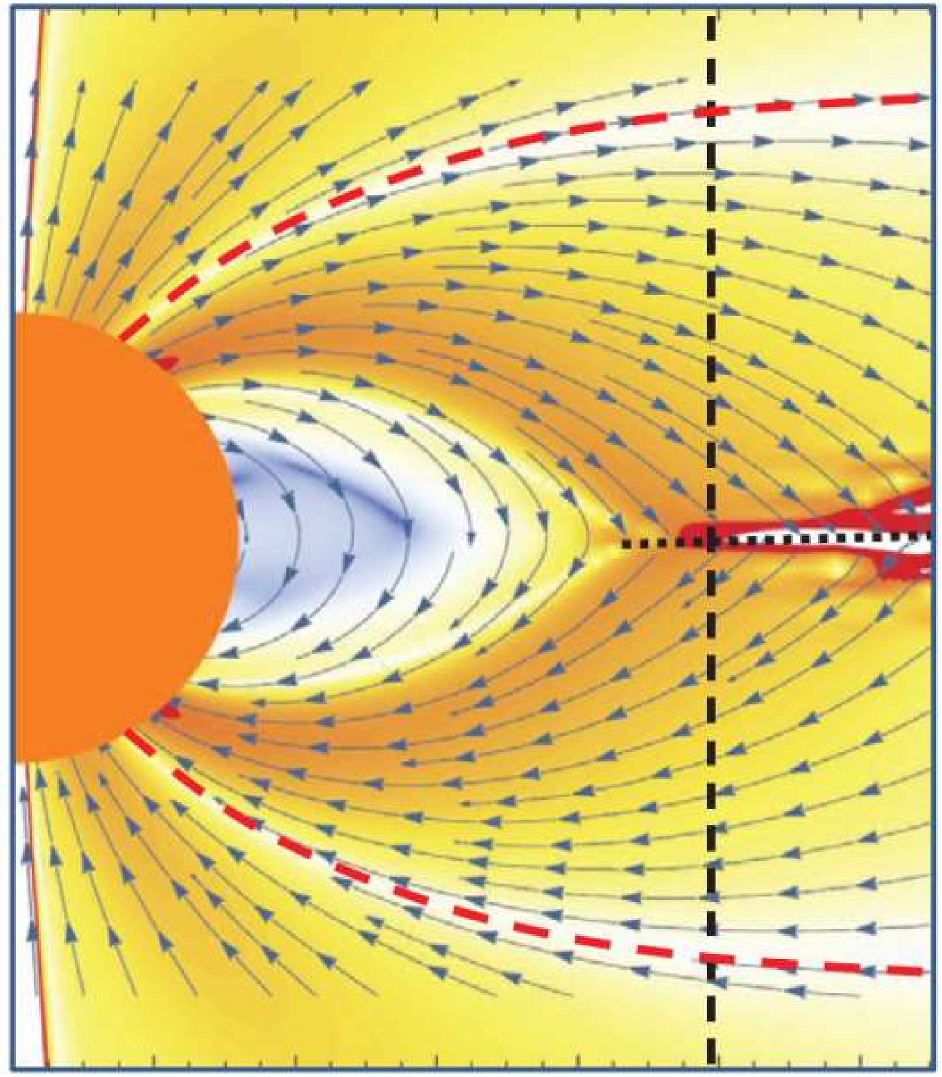
- Lego tiles:
  - Light cylinder position:







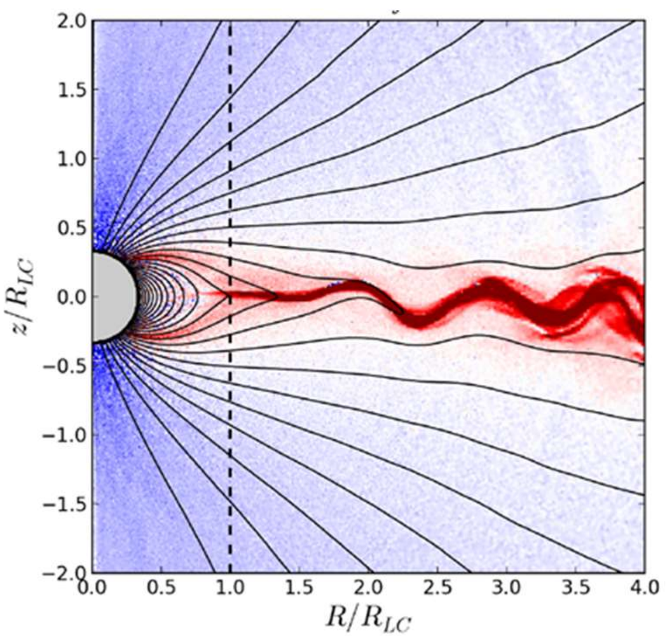
Cerutti et al. 2015



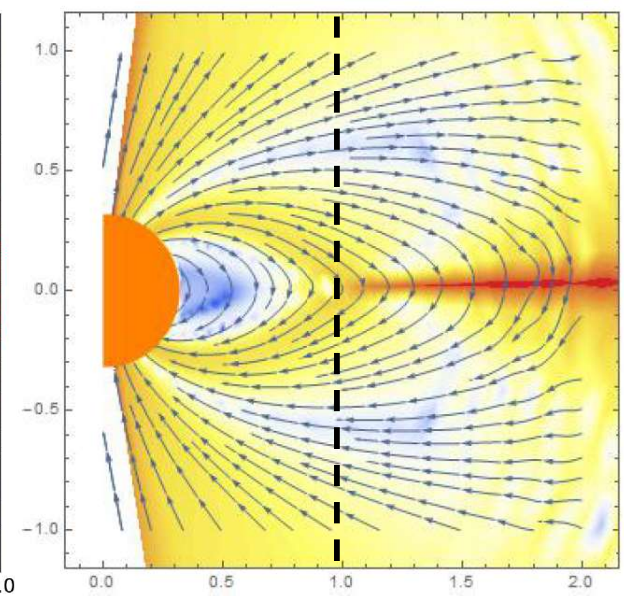
Contopoulos 2016

Limitations of numerical simulations

- Lego tiles:
  - Light cylinder position:



Cerutti et al. 2015



Contopoulos 2016

Limitations of numerical simulations

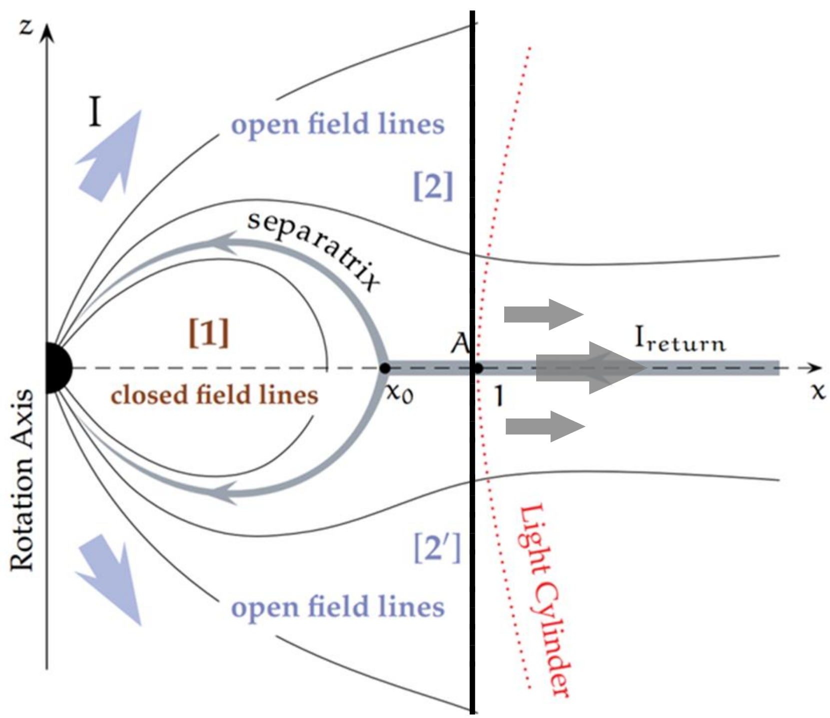
- Death stars:
  - ρ_{GJ} , $J_{GJ} = \rho_{GJ}\, c$
  - J_{CKF} is a global quantity (nothing to do with J_{GJ})

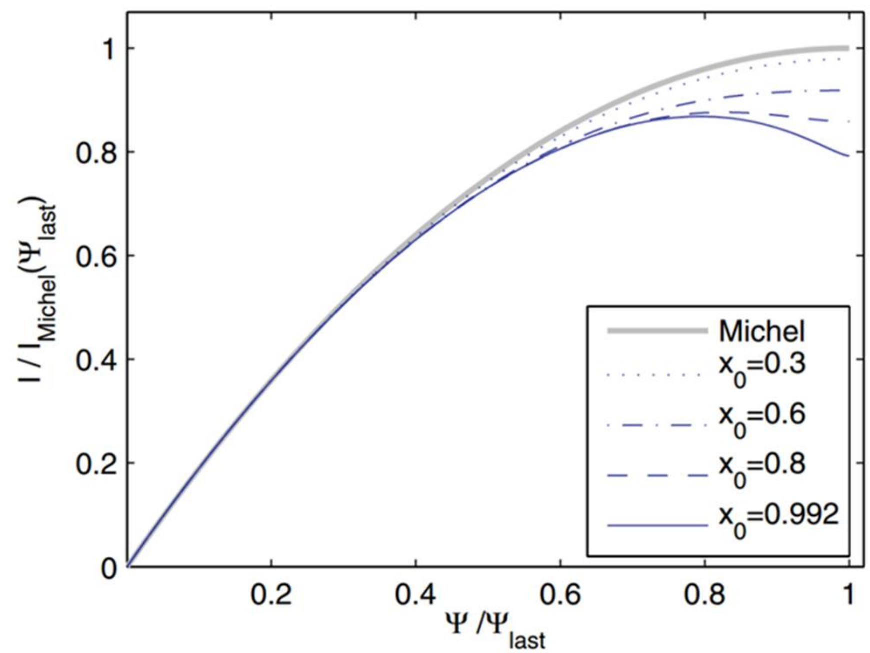
Limitations of numerical simulations

- Death stars:
  - ρ_{GJ}, $J_{GJ} = \rho_{GJ}\, c$
  - J_{CKF} is a global quantity (nothing to do with J_{GJ})
- Density floors
- PIC simulations: "billiard balls"
- Numerical treatment of CS: "trade secrets"

I needed to return to the drawing board and reconsider the global picture

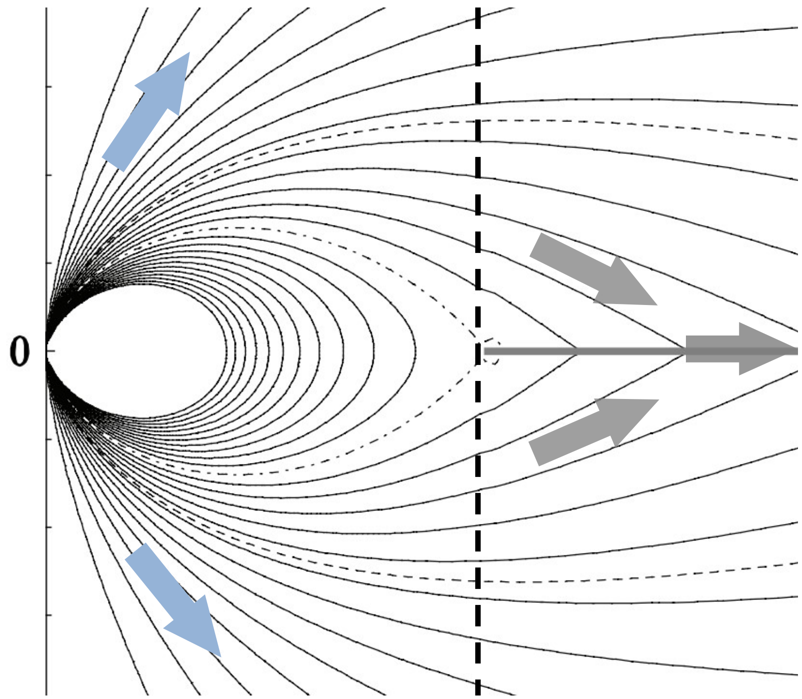
What drives dissipation?

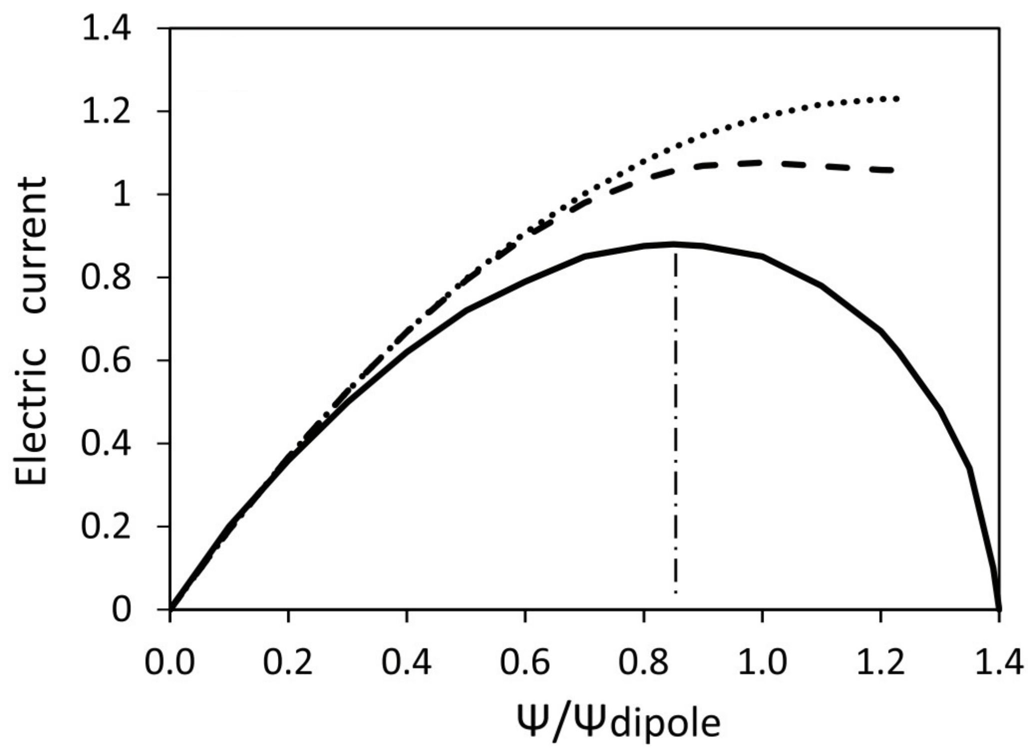




1999, 2005; 2006

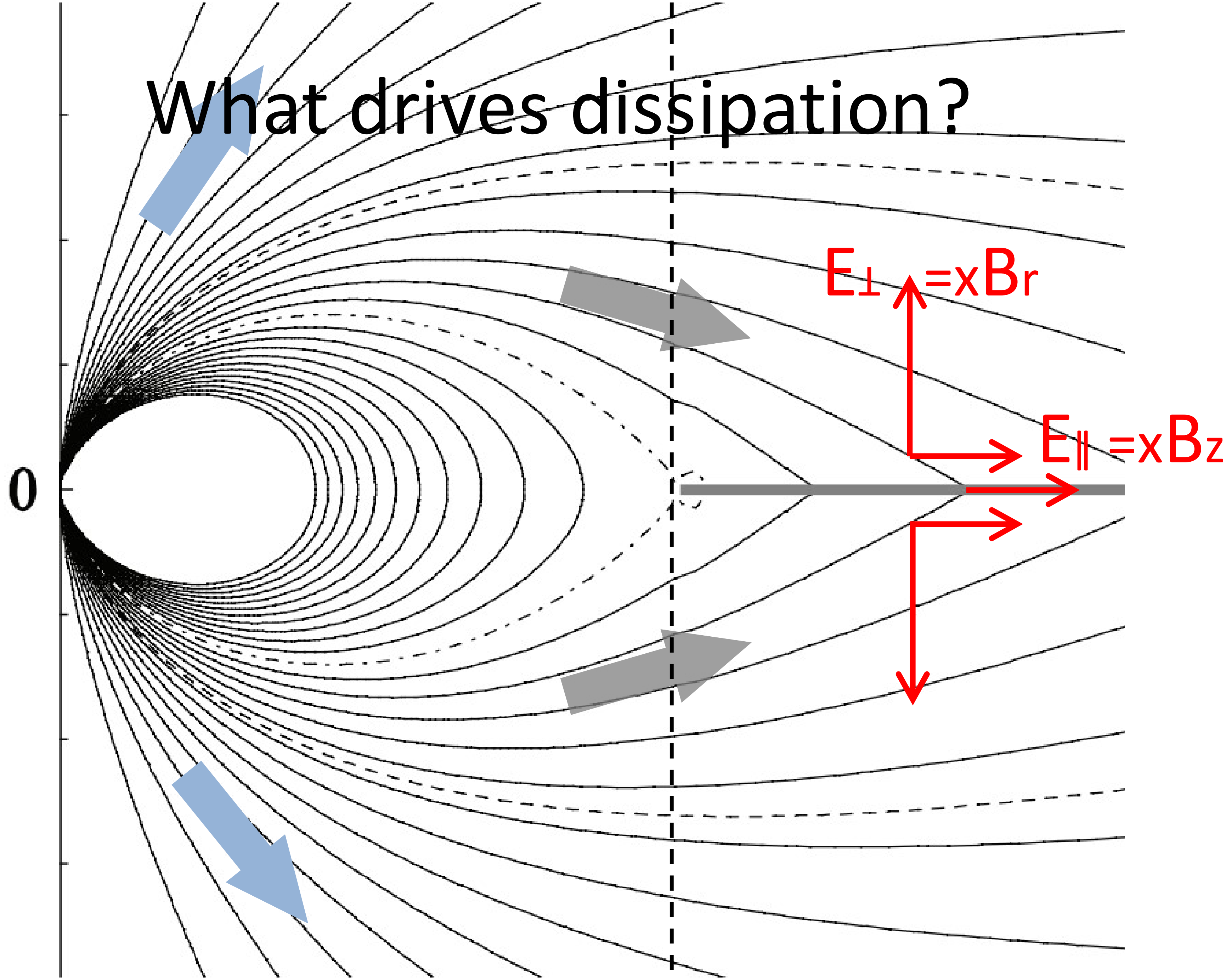
What drives dissipation?





2007, 2014

What drives dissipation?



What drives dissipation?

$$v_{converge} \equiv \frac{\boldsymbol{E}_{\parallel CS} \times \boldsymbol{B}_{\parallel CS}}{B^2} c\,.$$

$$E_{\parallel CS} = \frac{2\eta}{lc} B_{\parallel CS} \equiv \frac{2}{\mathcal{R}_m} B_{\parallel CS}$$

What drives dissipation?

$$v_{converge} \equiv \frac{\boldsymbol{E}_{\|CS} \times \boldsymbol{B}_{\|CS}}{B^2} c$$

$$E_{\|CS} = \frac{2\eta}{lc} B_{\|CS} \equiv \frac{2}{\mathcal{R}_m} B_{\|CS}$$

Spontaneous dissipation?

$$v_{converge} \sim 0.1c$$

Sironi, Spitkovsky, Arons 2013

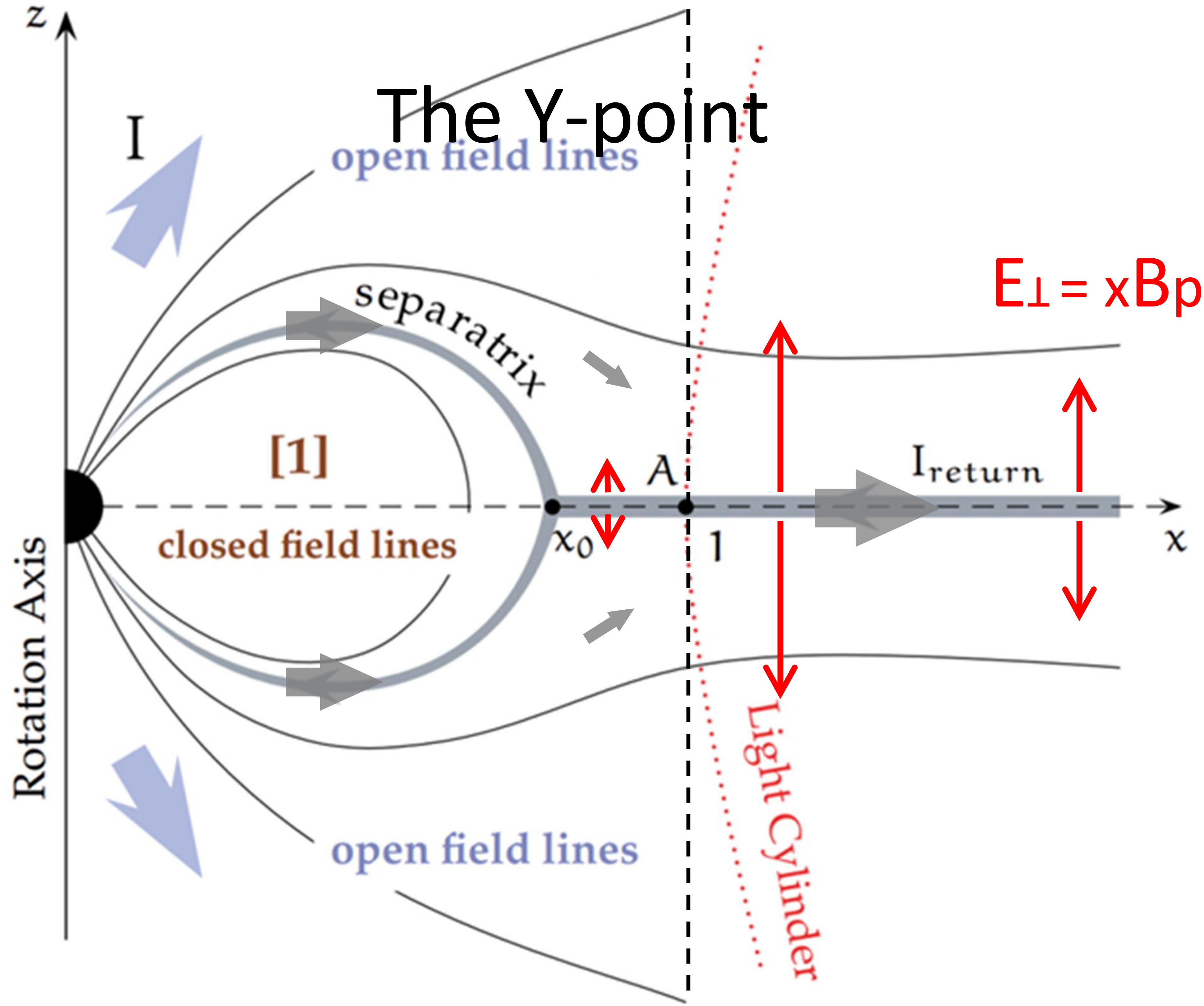
$$v_{maxPetschek} \approx (\pi/8 \ln \mathcal{R}_m)c$$

Cowley 1985

$$v^2_{converge} + v^2_{\parallel CS} \approx c^2$$

$$B_r/B_z \sim 9.95$$

The Y-point

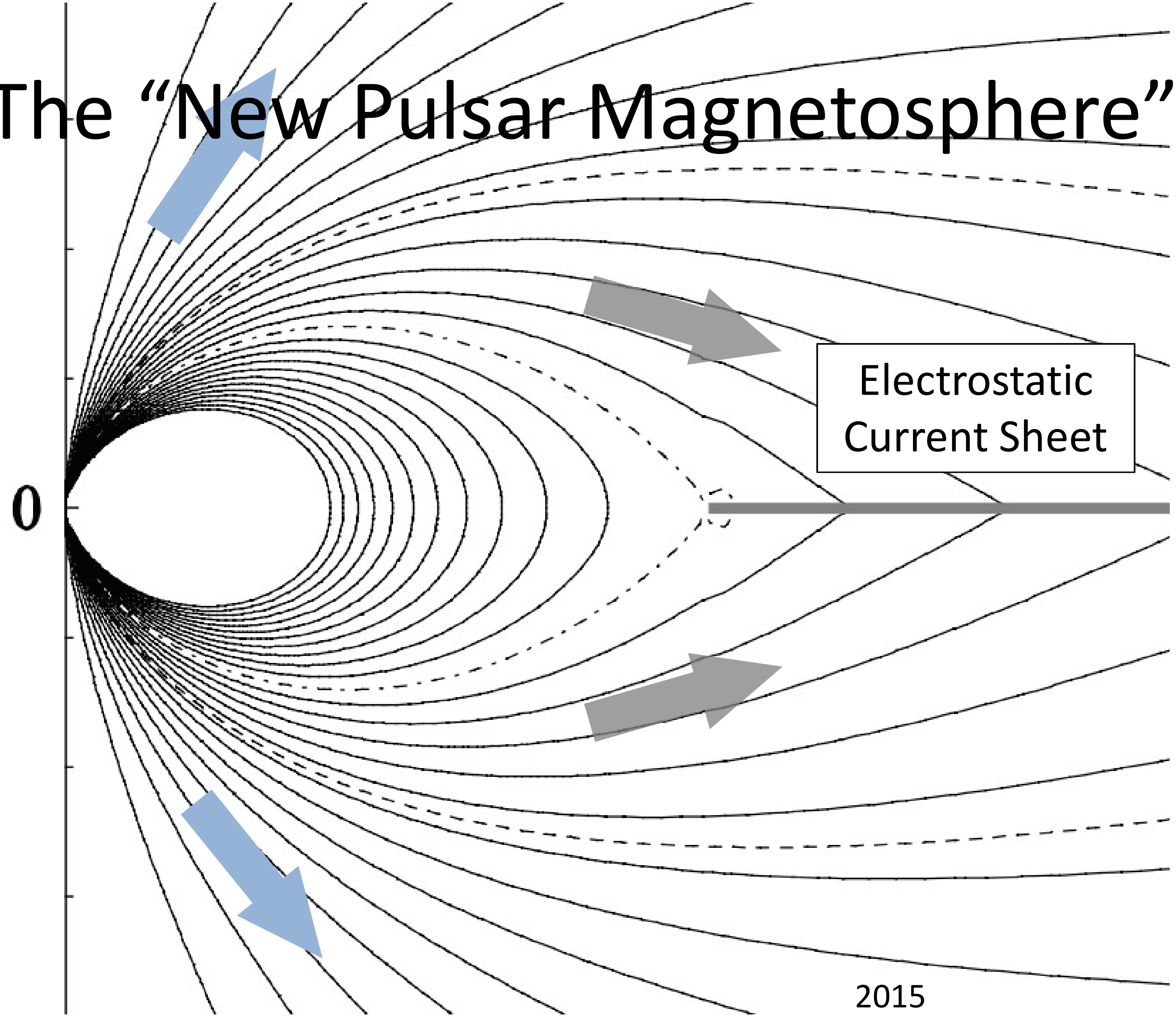


z
I
open field lines
separatrix
[1]
closed field lines
x0
A
1
Ireturn
x
E⊥ = xBp
Light Cylinder
open field lines
Rotation Axis

The Y-point

- B_p, E_p, σ, all three vanish right outside the Y-point
- It becomes problematic to support a current sheet through the Y-point, unless B_ϕ also vanishes there
- There is no current sheet that returns to the star
- CKF "proved" that the solution that is dissipationless everywhere is unique and it does contain a separatrix current sheet
- The CKF-type solution cannot be valid anymore, and the magnetosphere must find a new very different global equilibrium that is strongly dissipative

The “New Pulsar Magnetosphere”



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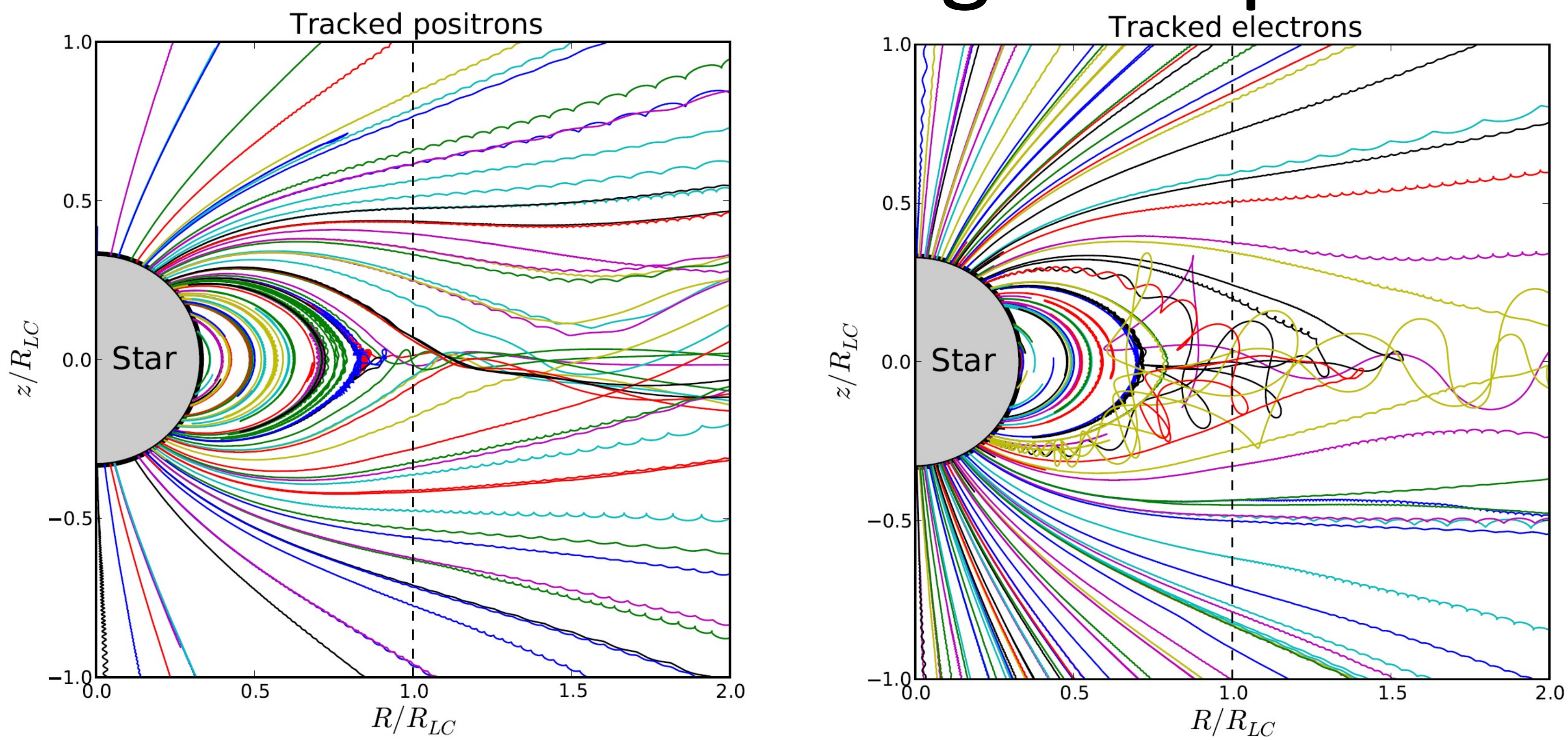
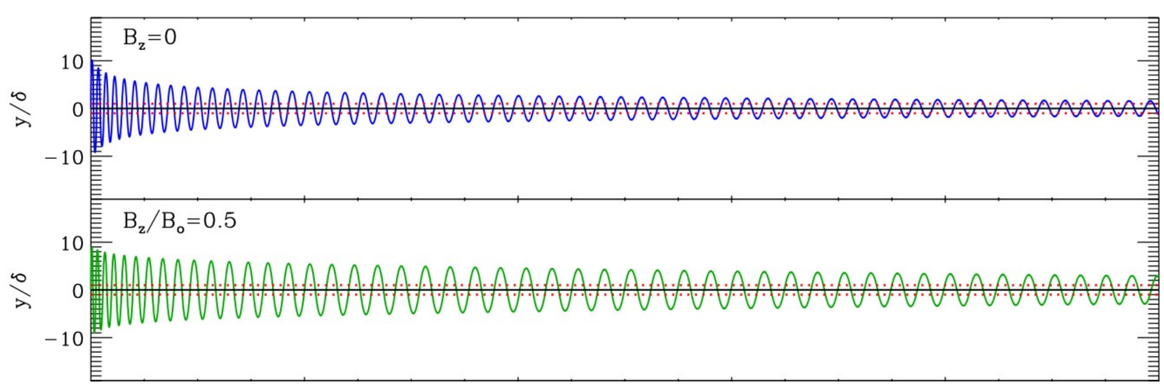




Cerutti et al. 2012; 2015

It is very hard to support an electric current sheet through the Y-point

unless

there is pair production at the Y-point

The “Aristotelian” current sheet

$$\mathbf{J}_{\mathrm{FFE}} = \rho_e \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\mathbf{B}\cdot(\nabla\times\mathbf{B}) + \mathbf{E}\cdot(\nabla\times\mathbf{E})}{B^2}\mathbf{B}$$

Force-Free Electrodynamics

$$\mathbf{v}^{\pm} = \frac{\mathbf{E}\times\mathbf{B} \pm (E_0\mathbf{E} + B_0\mathbf{B})}{B^2 + E_0^2}$$

$$\mathbf{J}_{\mathrm{AE}} = \frac{\rho_e\mathbf{E}\times\mathbf{B} + |\rho_e|(E_0\mathbf{E} + B_0\mathbf{B})}{B^2 + E_0^2}$$

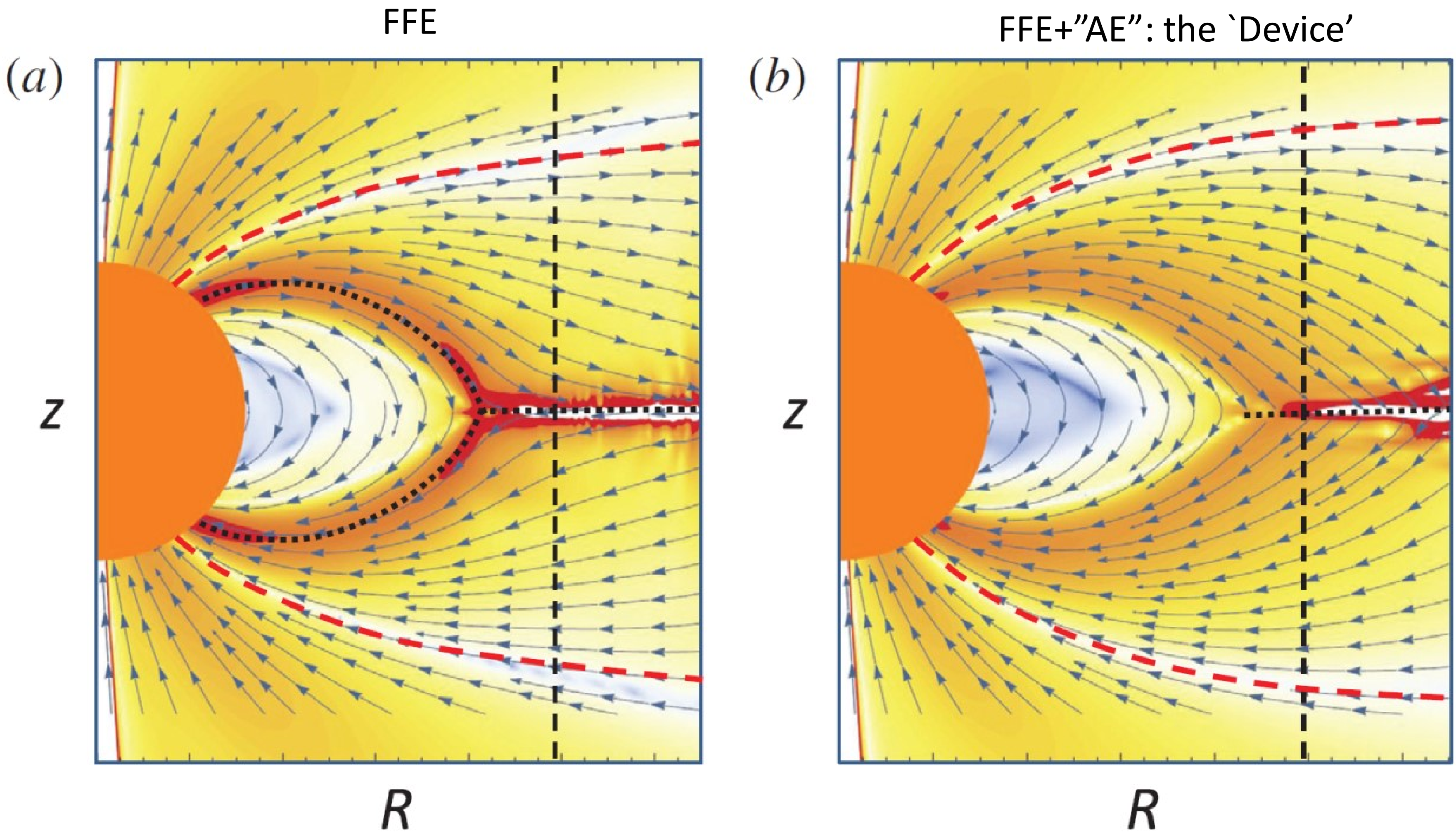
“Aristotelian” Electrodynamics

E ⊥ B everywhere

\+ zero multiplicity in “AE”

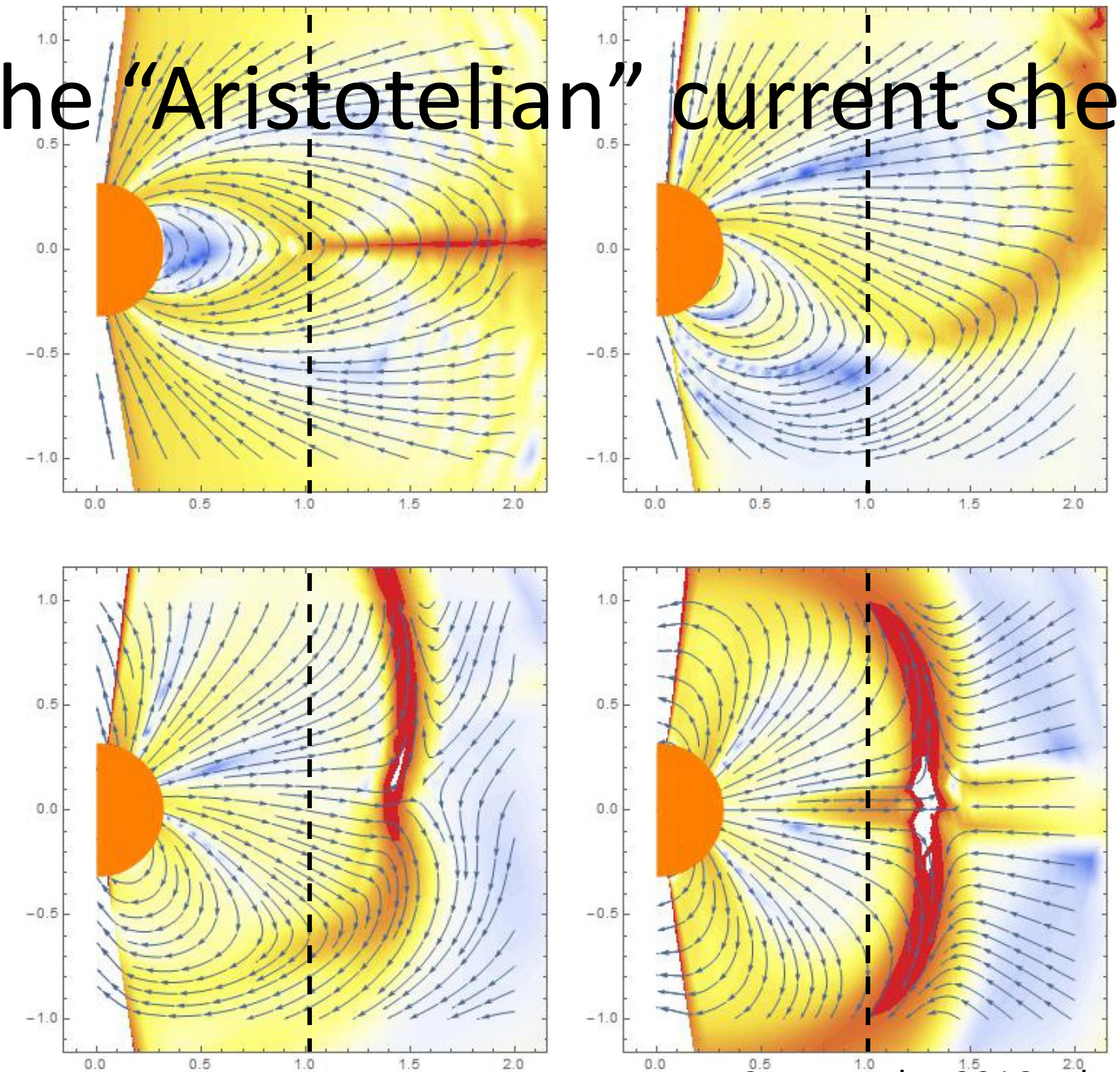
Contopoulos 2016

The “Aristotelian” current sheet



Contopoulos 2016

The “Aristotelian” current sheet

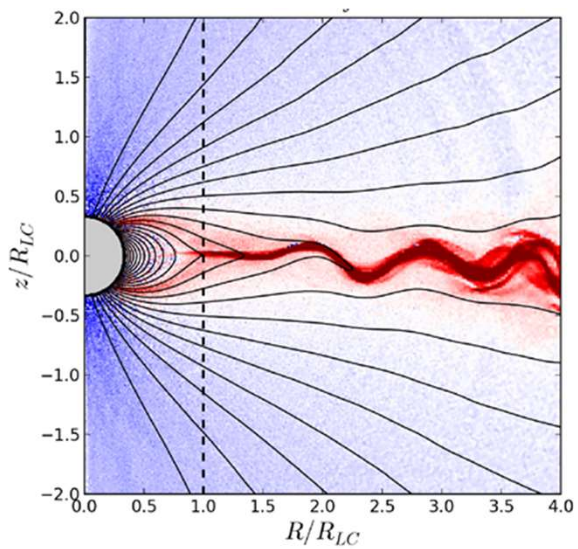


FFE+”AE”

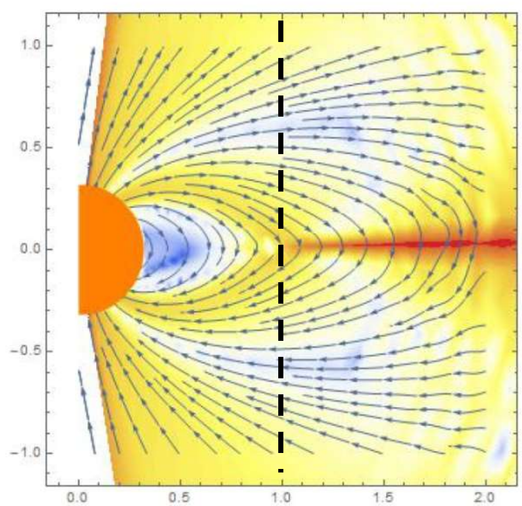
Contopoulos 2016 submitted

`Weak' pulsars?

- No pair production at the Y-point
  - All particles are provided by the star
- No electric current through the Y-point
- Strongly dissipative



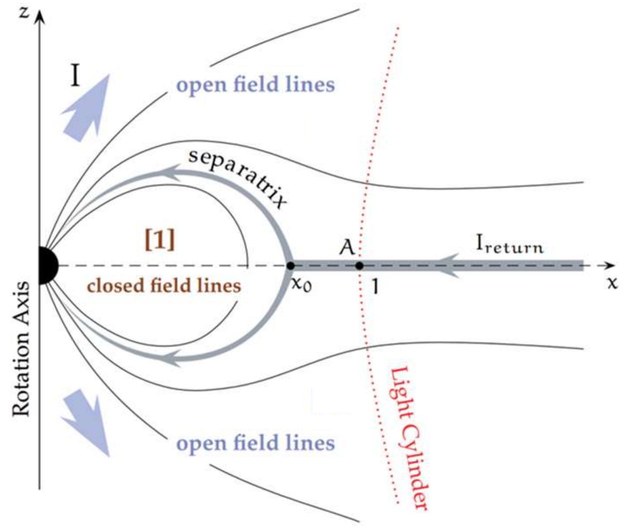
Cerutti et al. 2015



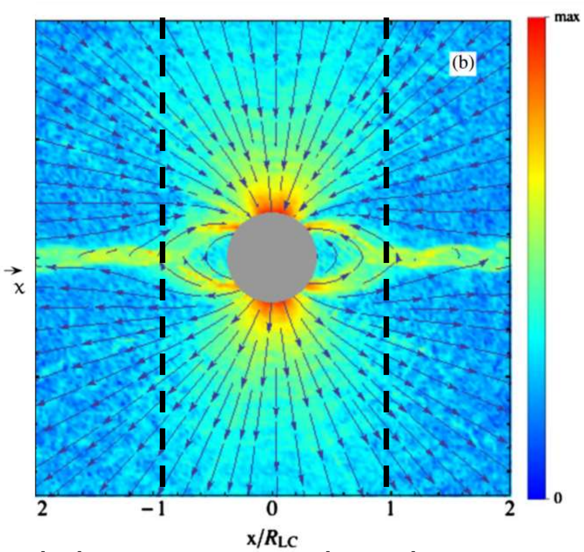
Contopoulos 2016

`Strong' pulsars?

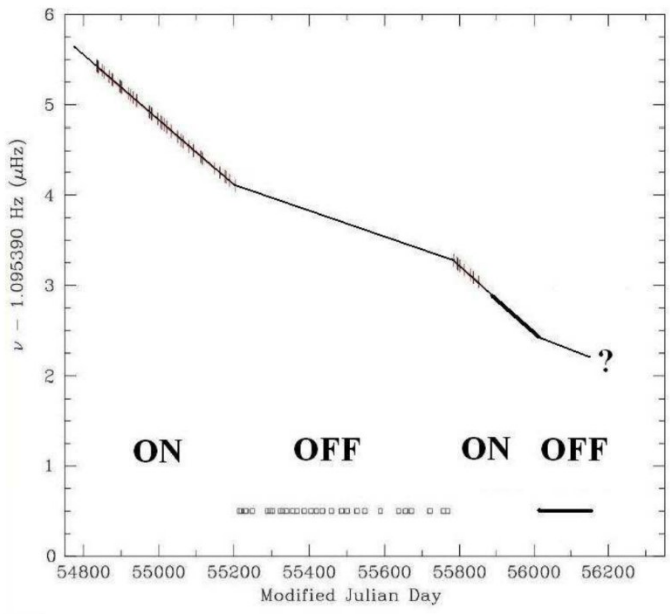
- `Free' pair production everywhere
  - In particular at the Y-point
- CKF-type ideal solution
  - Electric current sheet through Y-point
- Weakly dissipative (FFE)



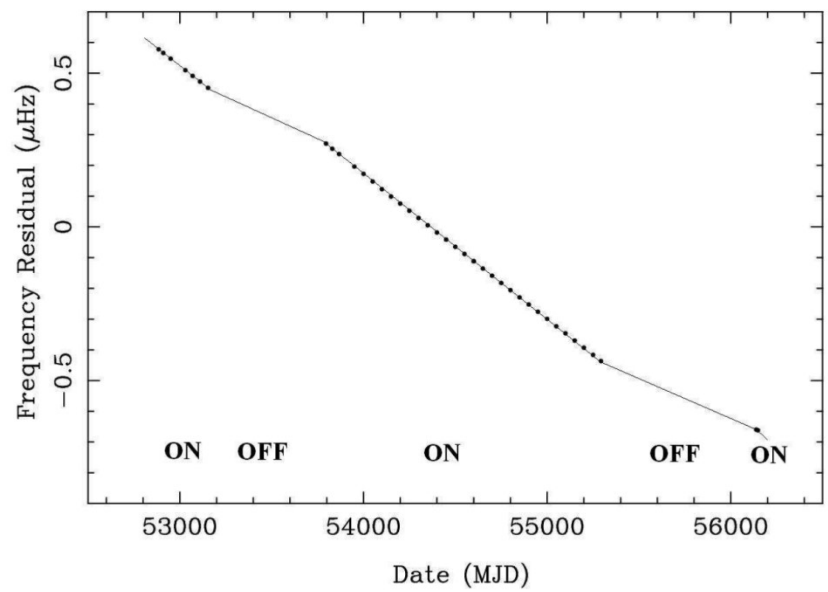
CKF 1999 and others



Philippov & Spitkovsky 2014



The rotational frequency evolution of PSR J1841−0500 (Camilo et al. 2012 and Lyne, priv. comm.).



The rotational frequency evolution of PSR J1832+0029 (Lorimer et al. 2012)

Final remarks

- It is early for global “ab initio” PIC simulations
- Our proposal:

Combine ideal MHD/FFE global simulations with focused PIC simulations of the equatorial current sheet and the Y-point