Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών
της Ακαδημίας Αθηνών

# Hybrid Modeling of Pulsar Magnetospheres: a personal view

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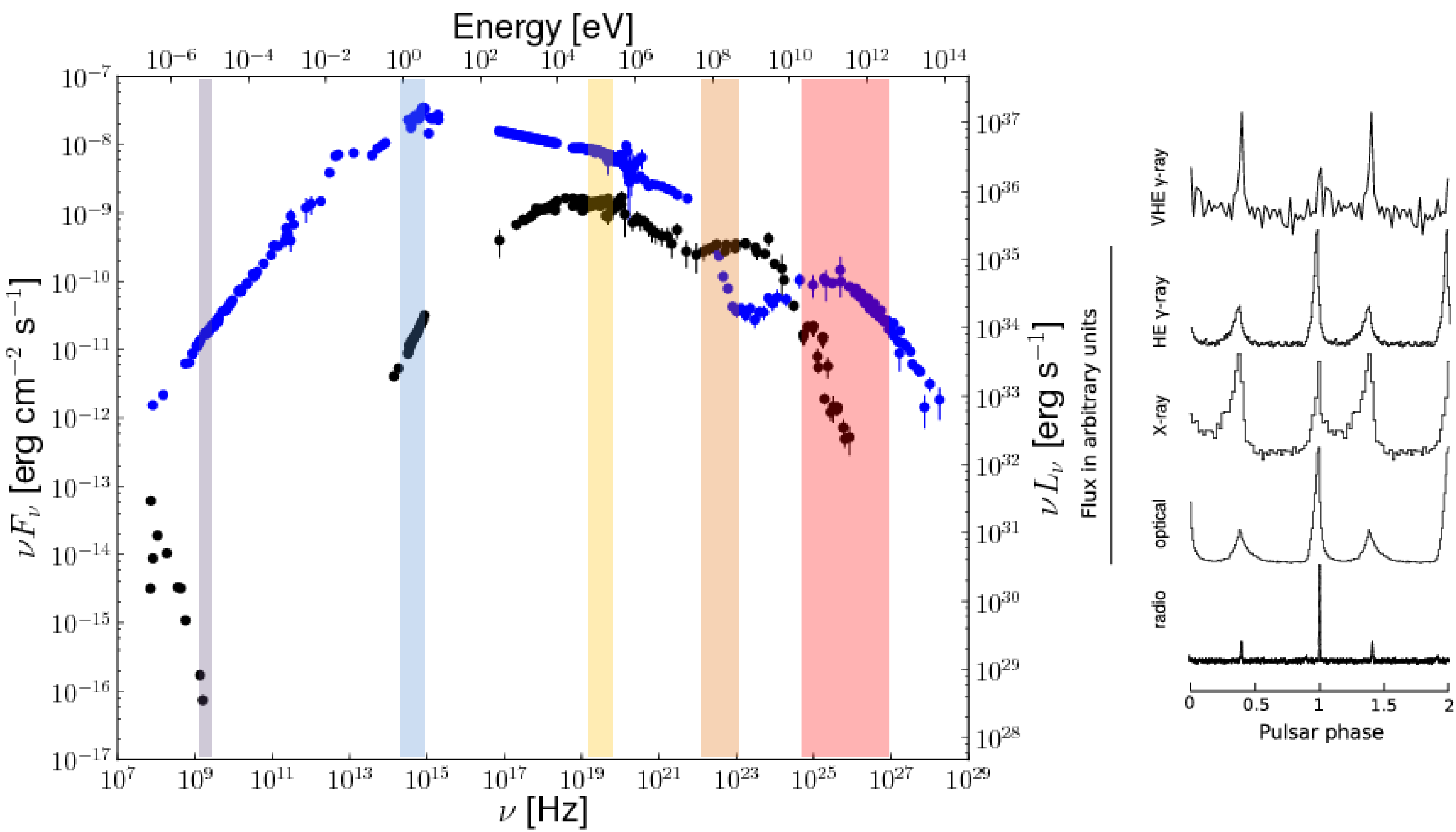
1st Meeting of ISSI International Team, Bern, Tuesday, December 10 2019

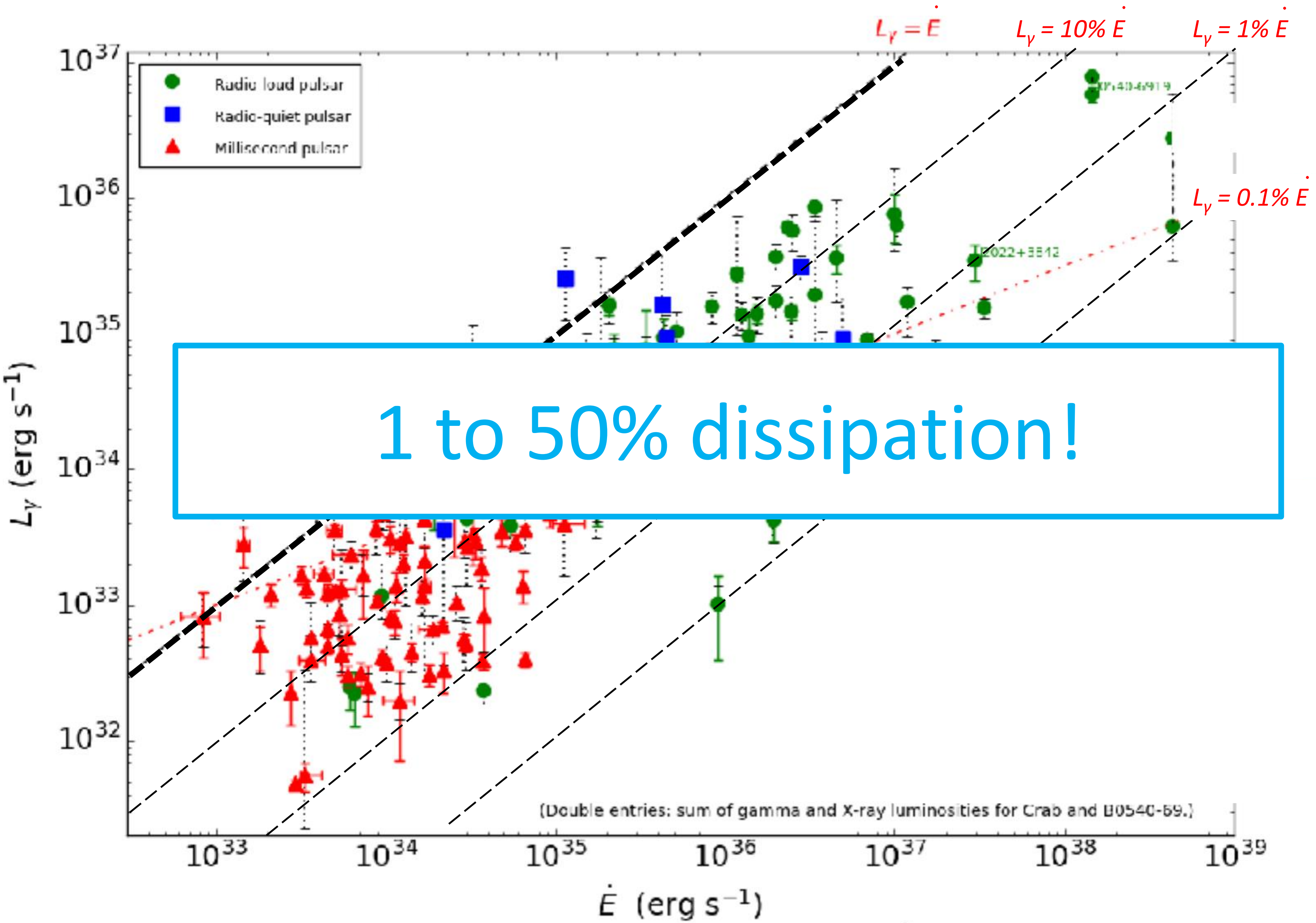
# A little bit of…

- History
- Critique
- FFE everywhere + AE equatorial CS
- Particle trajectories
- (VHE γ-ray spectra)

Current collaborators:
Jérôme Pétri (Strasbourg), Petros Stefanou (Athens→Alicante)



Energy [eV]
$\nu F_\nu$ [erg cm$^{-2}$ s$^{-1}$]
$\nu$ [Hz]
$\nu L_\nu$ [erg s$^{-1}$]
Flux in arbitrary units
VHE γ-ray
HE γ-ray
X-ray
optical
radio
Pulsar phase

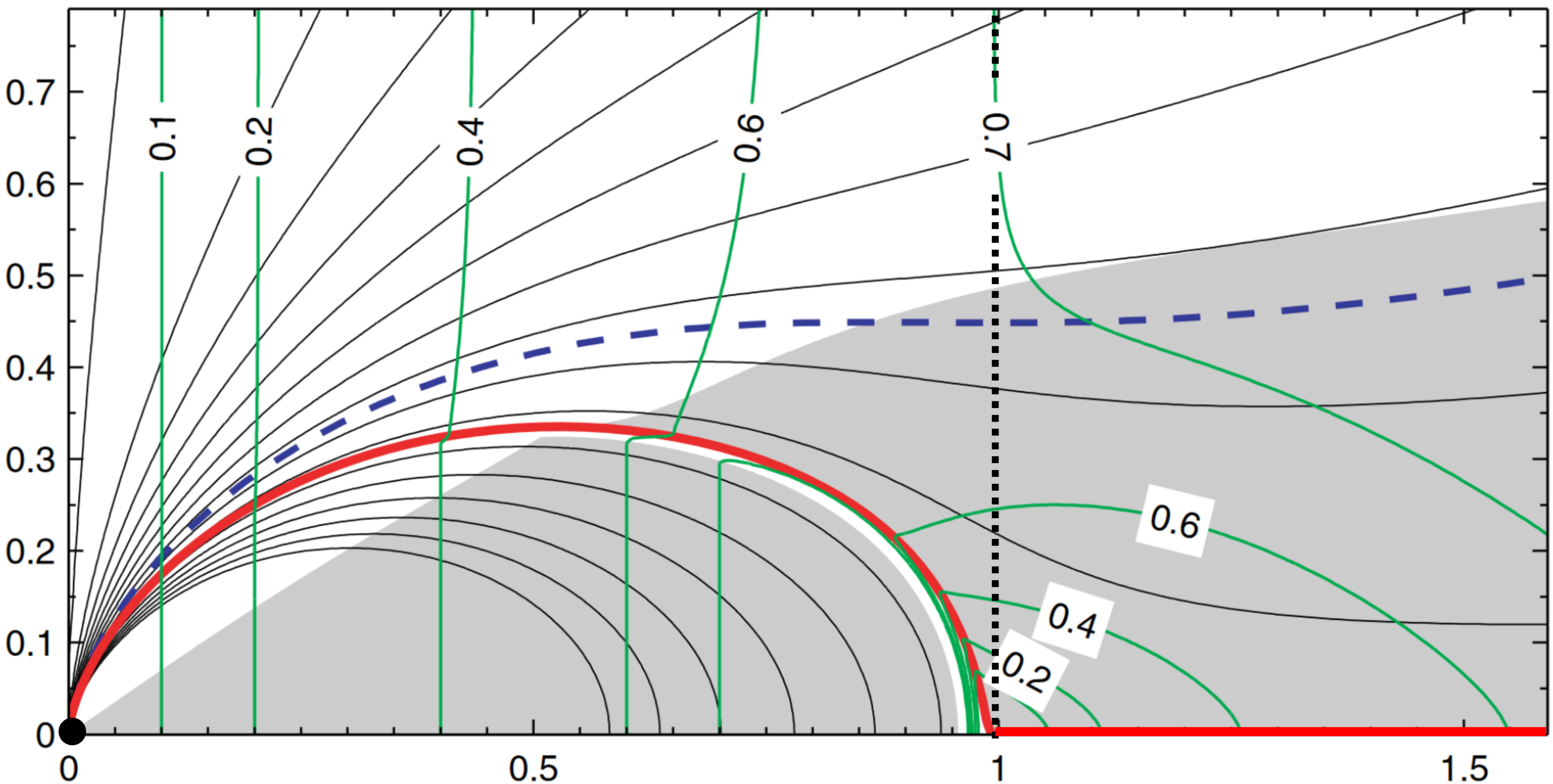


1 to 50% dissipation!
$L_\gamma = \dot{E}$
$L_\gamma$ = 10% $\dot{E}$
$L_\gamma$ = 1% $\dot{E}$
$L_\gamma$ = 0.1% $\dot{E}$
Radio loud pulsar
Radio-quiet pulsar
Millisecond pulsar
(Double entries: sum of gamma and X-ray luminosities for Crab and B0540-69.)
$L_\gamma$ (erg s$^{-1}$)
$\dot{E}$ (erg s$^{-1}$)
$10^{32}$
$10^{33}$
$10^{34}$
$10^{35}$
$10^{36}$
$10^{37}$
$10^{38}$
$10^{39}$

# A little bit of history…

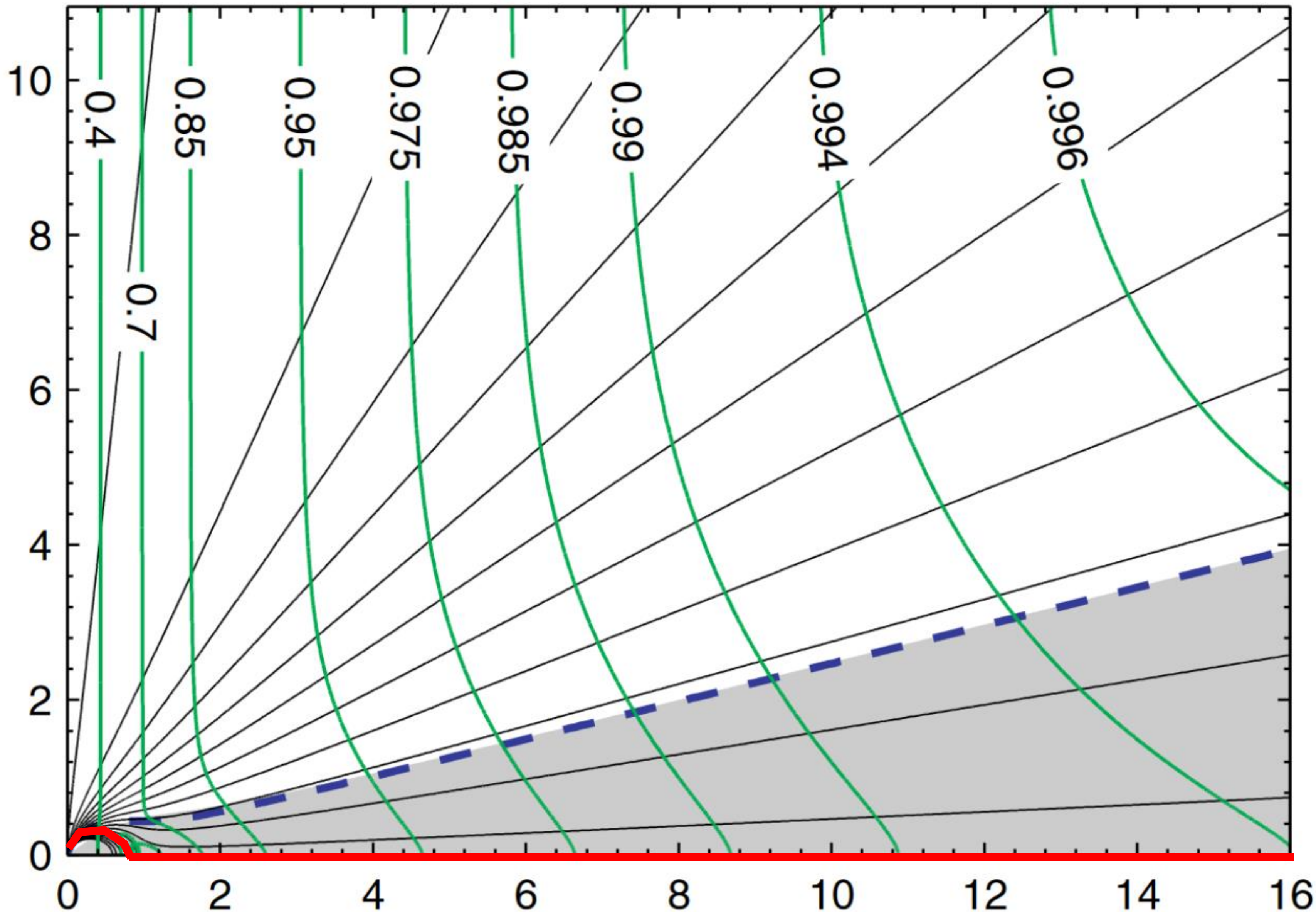
## 2D steady-state ideal (force-free→pulsar equation)

1967 (Pulsar discovery: Jocelyn Bell)
1969 (Ideal force-free: Goldreich & Julian)
1999 (Contopoulos, Kazanas & Fendt)




the “light cylinder”

Timokhin 2006




Timokhin 2006

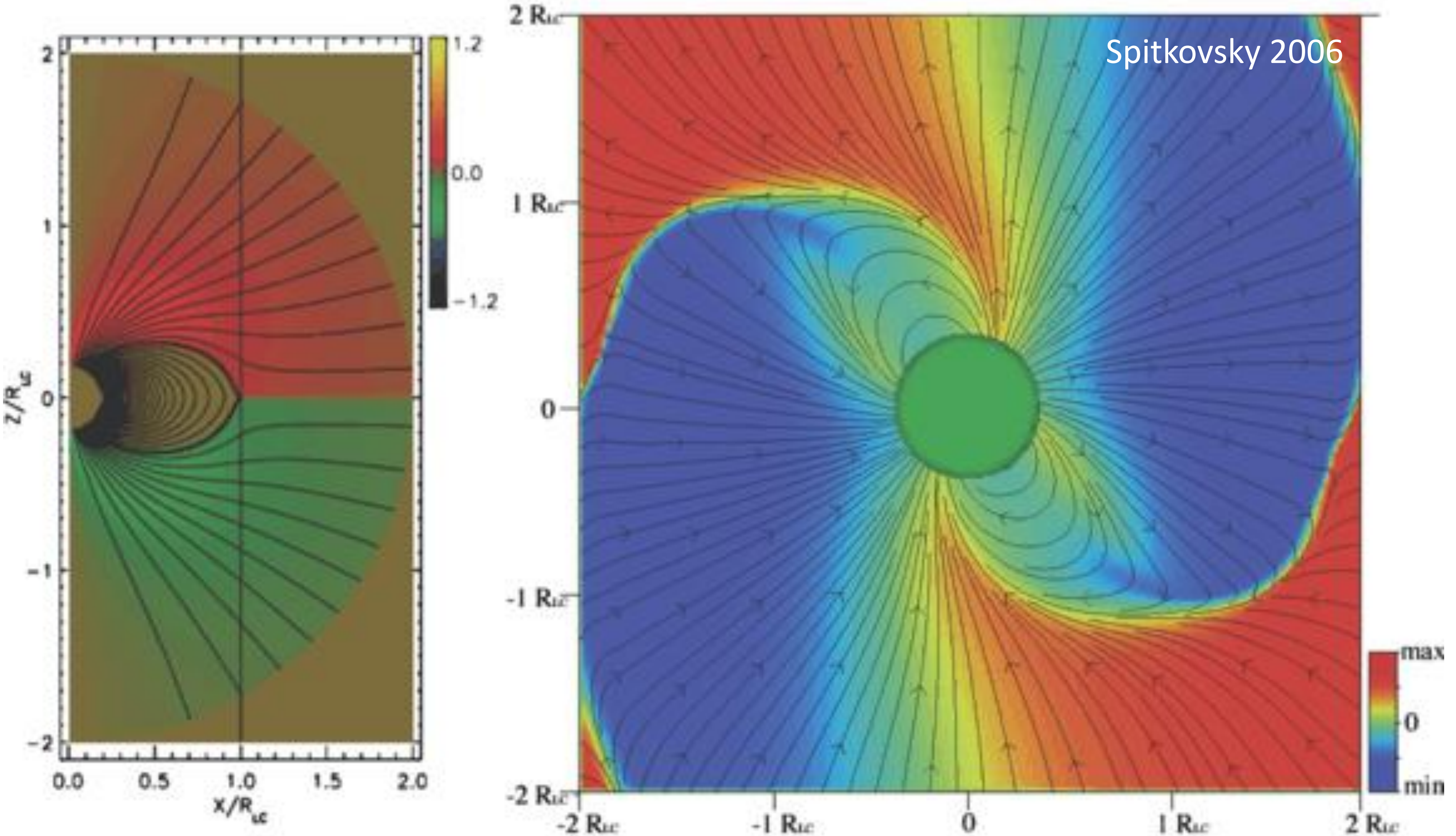
# A little bit of history…

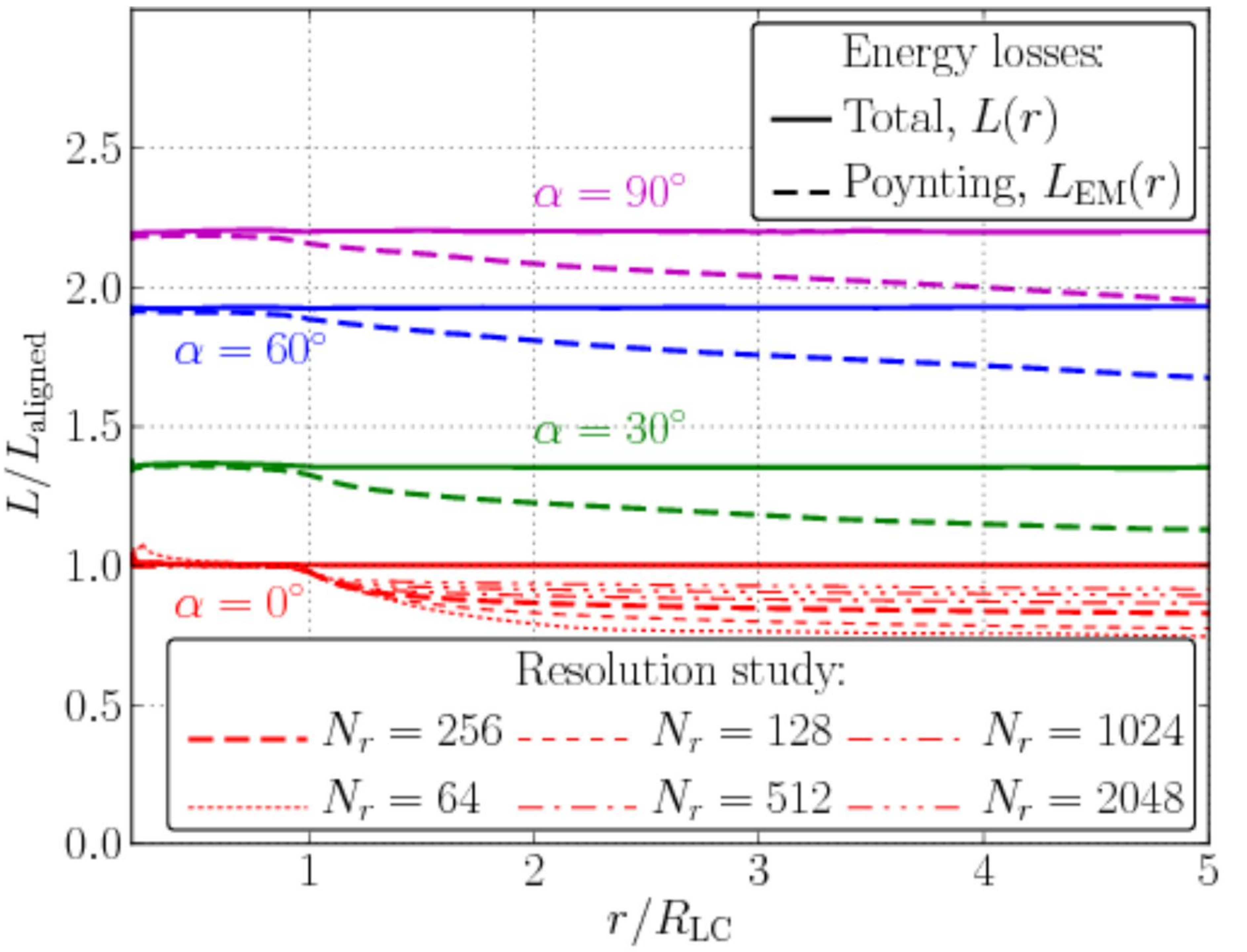
Current Closure is key!

# A little bit of history…

## 3D steady-state ideal (FFE, MHD)

2006 (FFE, Spitkovsky)
2009 (FFE, Contopoulos & Kalapotharakos)
2013 (MHD, Spitkovsky, Tchekhovskoy & Li)


Spitkovsky 2006
Z/R_LC
X/R_LC
1.2
0.0
−1.2
2 R_LC
1 R_LC
0
-1 R_LC
-2 R_LC
max
0
min



Energy losses:
Total, $L(r)$
Poynting, $L_{\rm EM}(r)$
$\alpha = 90°$
$\alpha = 60°$
$\alpha = 30°$
$\alpha = 0°$
Resolution study:
$N_r = 256$
$N_r = 128$
$N_r = 1024$
$N_r = 64$
$N_r = 512$
$N_r = 2048$
$L/L_{\rm aligned}$
$r/R_{\rm LC}$
0.0
0.5
1.0
1.5
2.0
2.5
1
2
3
4
5

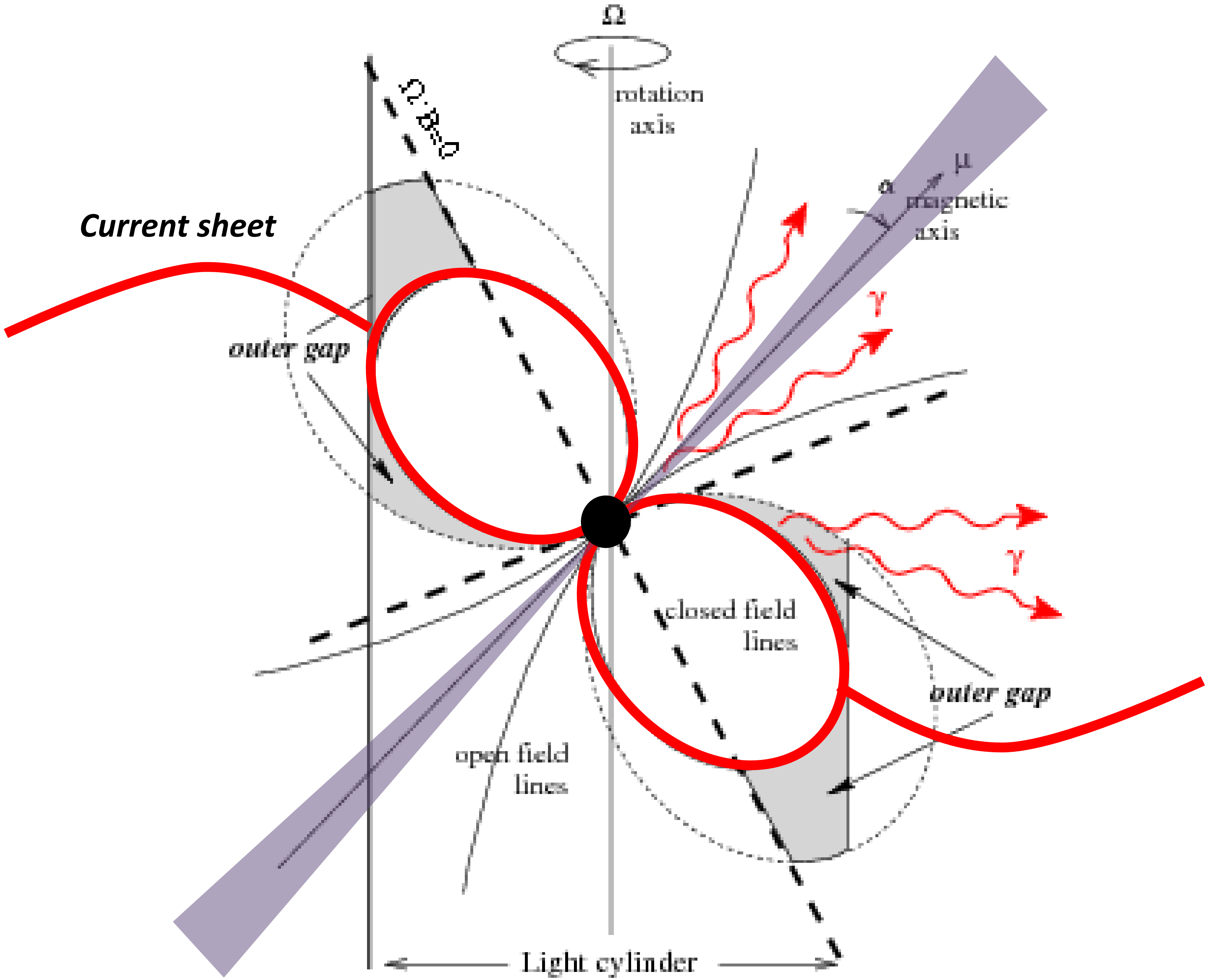
# A little bit of critique…

Ideal simulations are
non-ideal numerically…

# A little bit of history…

# Non-ideal magnetospheres (non-ideal prescriptions…)

2012 (Spitkovsky et al.)
2012 (Contopoulos, Kalapotharakos et al.)



Ω
rotation axis
Ω·B=0
μ
α
magnetic axis
Current sheet
γ
outer gap
γ
closed field lines
outer gap
open field lines
Light cylinder

## 2. NON-IDEAL PRESCRIPTIONS

In the FFE description of pulsar magnetospheres, Spitkovsky (2006) and Kalapotharakos & Contopoulos (2009) solved numerically the time-dependent Maxwell equations

$$\frac{\partial \mathbf{B}}{\partial t} = -c\boldsymbol{\nabla} \times \mathbf{E} \tag{1}$$

$$\frac{\partial \mathbf{E}}{\partial t} = c\boldsymbol{\nabla} \times \mathbf{B} - 4\pi \mathbf{J} \tag{2}$$

under ideal force-free conditions

$$\mathbf{E} \cdot \mathbf{B} = 0, \quad \rho \mathbf{E} + \frac{\mathbf{1}}{\mathbf{c}} \mathbf{J} \times \mathbf{B} = 0,$$

where $\rho = \nabla \cdot \mathbf{E}/(4\pi)$. The evolution of these equations in time requires in addition an expression for the current density $\mathbf{J}$ as a function of $\mathbf{E}$ and $\mathbf{B}$. This is given by

$$\mathbf{J} = c\rho \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{c}{4\pi} \frac{\mathbf{B} \cdot \nabla \times \mathbf{B} - \mathbf{E} \cdot \nabla \times \mathbf{E}}{B^2} \mathbf{B} \tag{3}$$

(A) The above implementation of the ideal condition hints at an easy generalization that leads to non-ideal solutions: one can evolve Equations (1) and (2), using only the first term of the FFE current density (Equation (3)), and at each time step keep only a certain fraction $b$ of the $\mathbf{E}_{||}$ developed during this time instead of forcing it to be zero. In general, the portion $b$ of the remaining $\mathbf{E}_{||}$ can be either the same everywhere or variable (locally) depending on some other quantity (e.g., $\rho$, $J$). As $b$ goes from 0 to 1, the corresponding solution goes from FFE to vacuum. In this case, an expression for the electric current density is not given a priori, and $\mathbf{J}$ can be obtained indirectly from the expression

$$\mathbf{J} = \frac{1}{4\pi}\left(c\boldsymbol{\nabla} \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t}\right). \tag{4}$$

(B) Another way of controlling $\mathbf{E}_{||}$ is to introduce a finite conductivity $\sigma$. In this case, we replace the second term in Equation (3) by $\sigma \mathbf{E}_{||}$ and the current density reads

$$\mathbf{J} = c\rho \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \sigma \mathbf{E}_{||}. \tag{5}$$

Note that Equation (5) is related to but is not quite equivalent to Ohm's law, which is defined in the frame of the fluid. Others

non-dissipative. The current density expression in the so-called strong field electrodynamics (hereafter SFE) reads

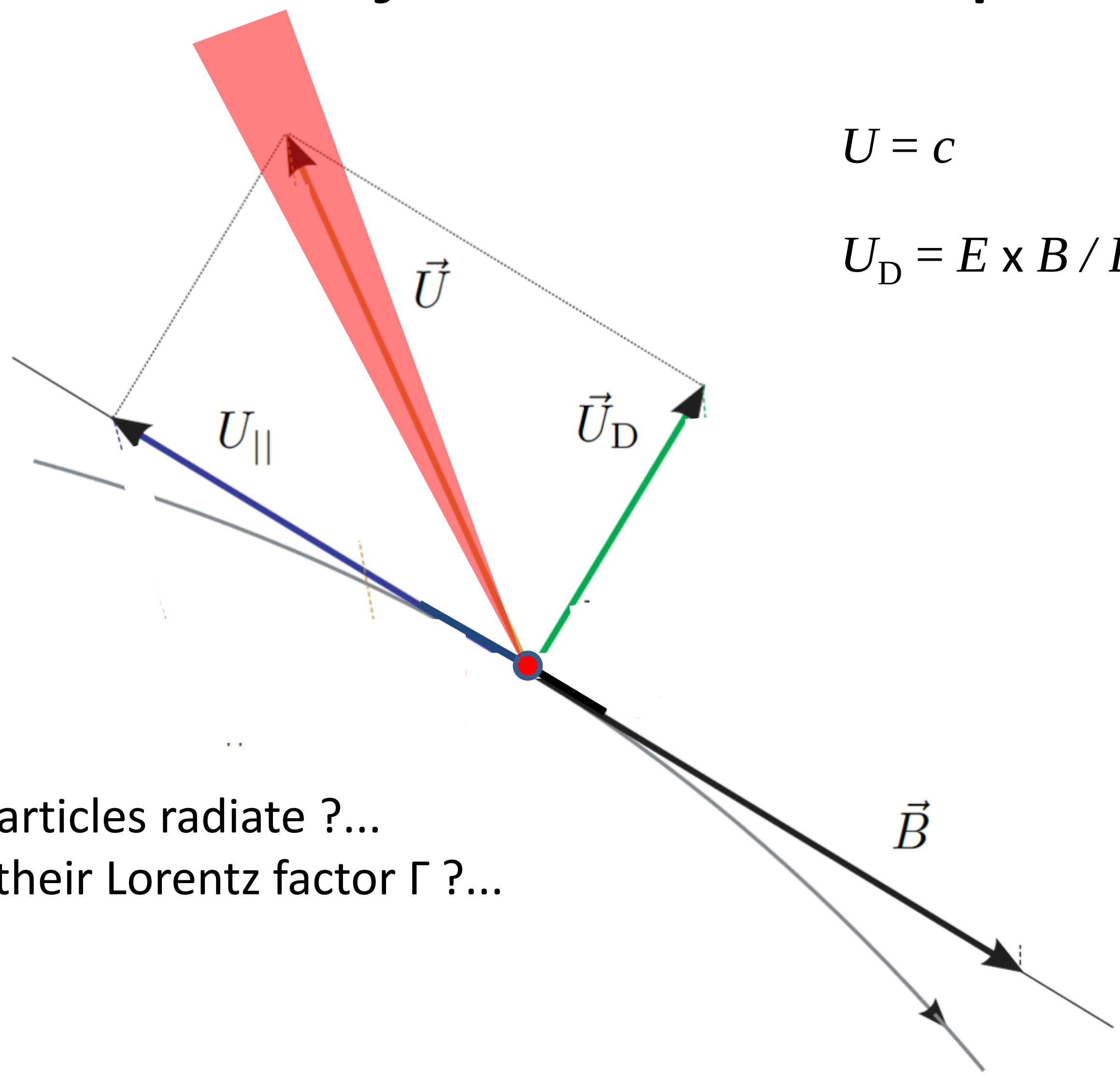
$$\mathbf{J} = \frac{c\rho \mathbf{E} \times \mathbf{B} + (c^2\rho^2 + \gamma^2\sigma^2 E_0^2)^{1/2}(B_0\mathbf{B} + E_0\mathbf{E})}{B^2 + E_0^2}, \tag{6}$$

where

$$B_0^2 - E_0^2 = \mathbf{B^2} - \mathbf{E^2}, \;\; B_0 E_0 = \mathbf{E} \cdot \mathbf{B}, \;\; E_0 \geqslant 0, \tag{7}$$

$$\gamma^2 = \frac{B^2 + E_0^2}{B_0^2 + E_0^2}, \tag{8}$$

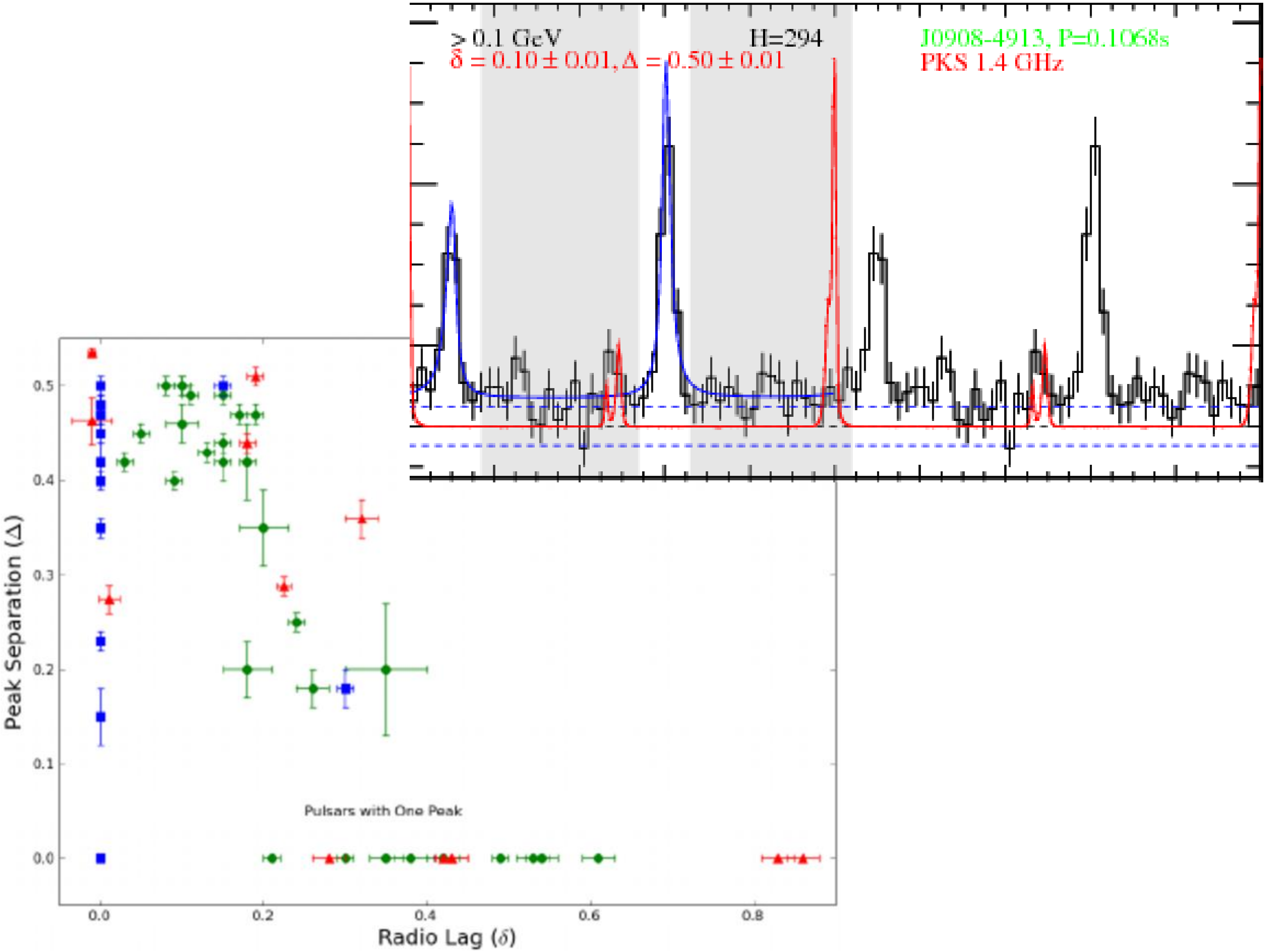
# Radiation from particle trajectories with β=1...

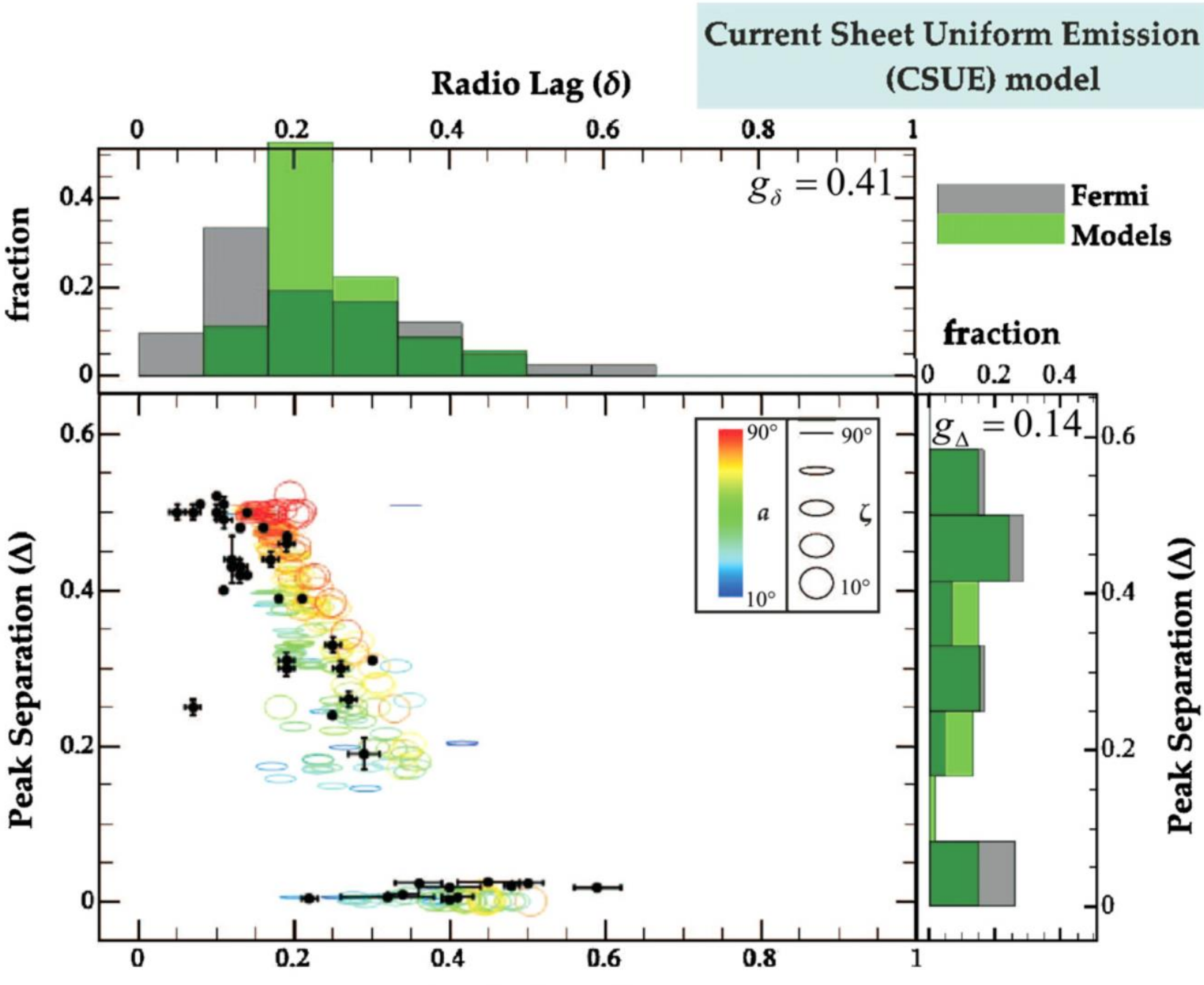



$U = c$

$U_{\mathrm{D}} = E \times B / B^2$

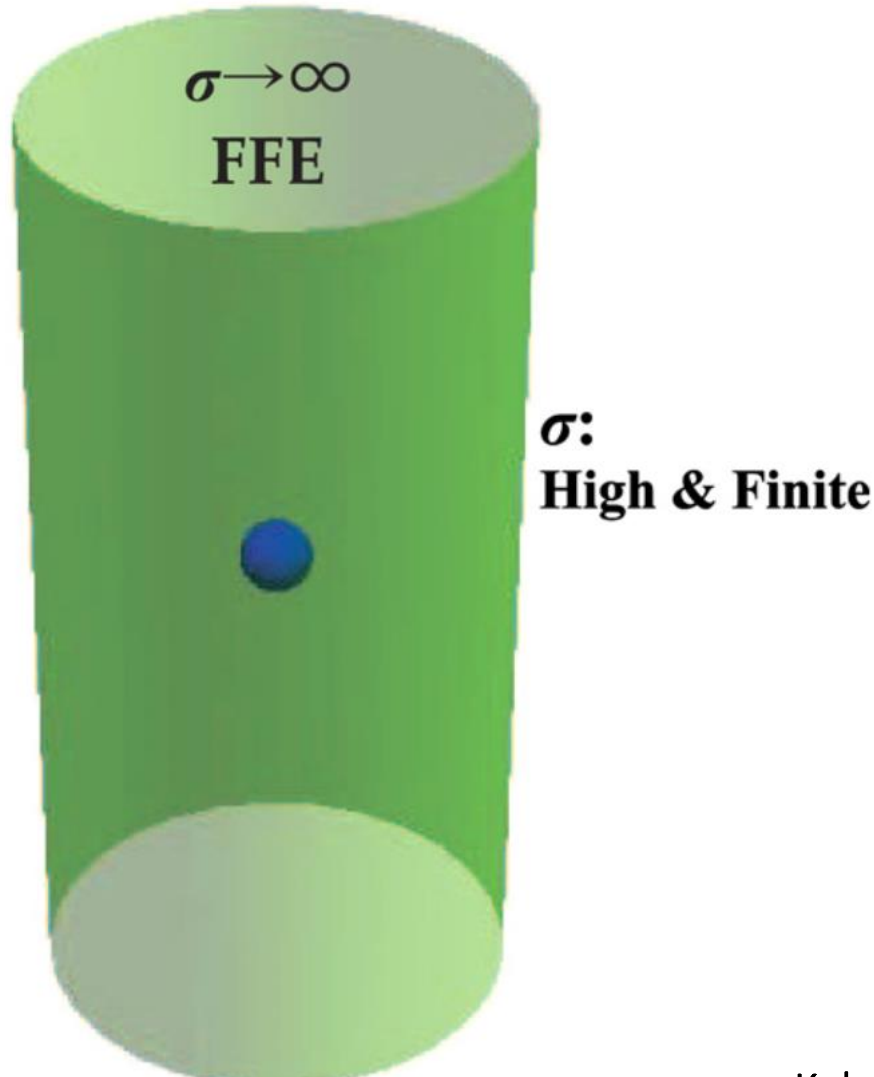
Which particles radiate ?...
What is their Lorentz factor Γ ?...


> 0.1 GeV
H=294
J0908-4913, P=0.1068s
δ = 0.10 ± 0.01, Δ = 0.50 ± 0.01
PKS 1.4 GHz
Peak Separation (Δ)
Radio Lag (δ)
Pulsars with One Peak
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.2
0.4
0.6
0.8



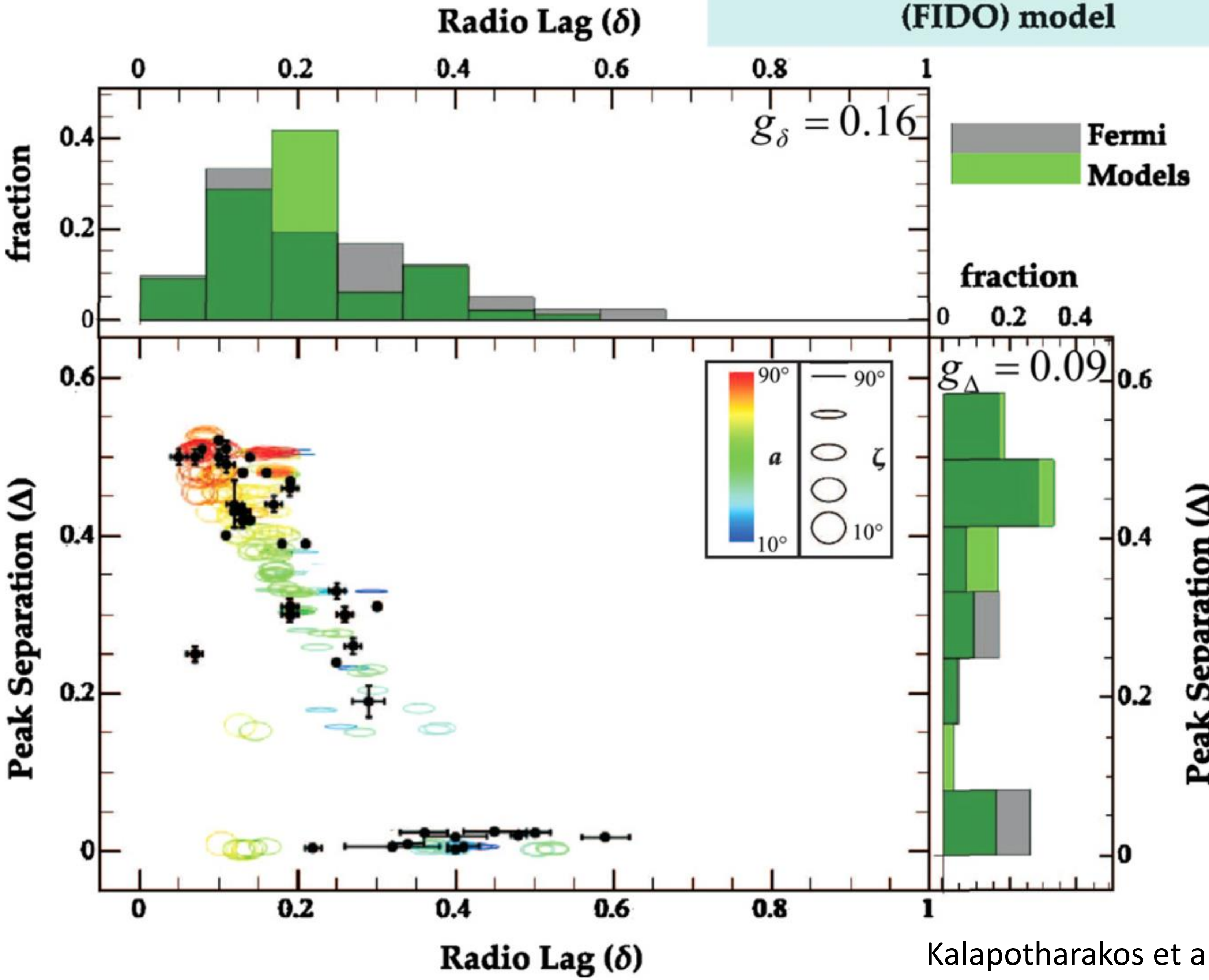

Kalapotharakos et al. 2015

# Force-Free Inside, Dissipative Outside




Kalapotharakos et al. 2015

## FFE Inside Dissipative Outside (FIDO) model

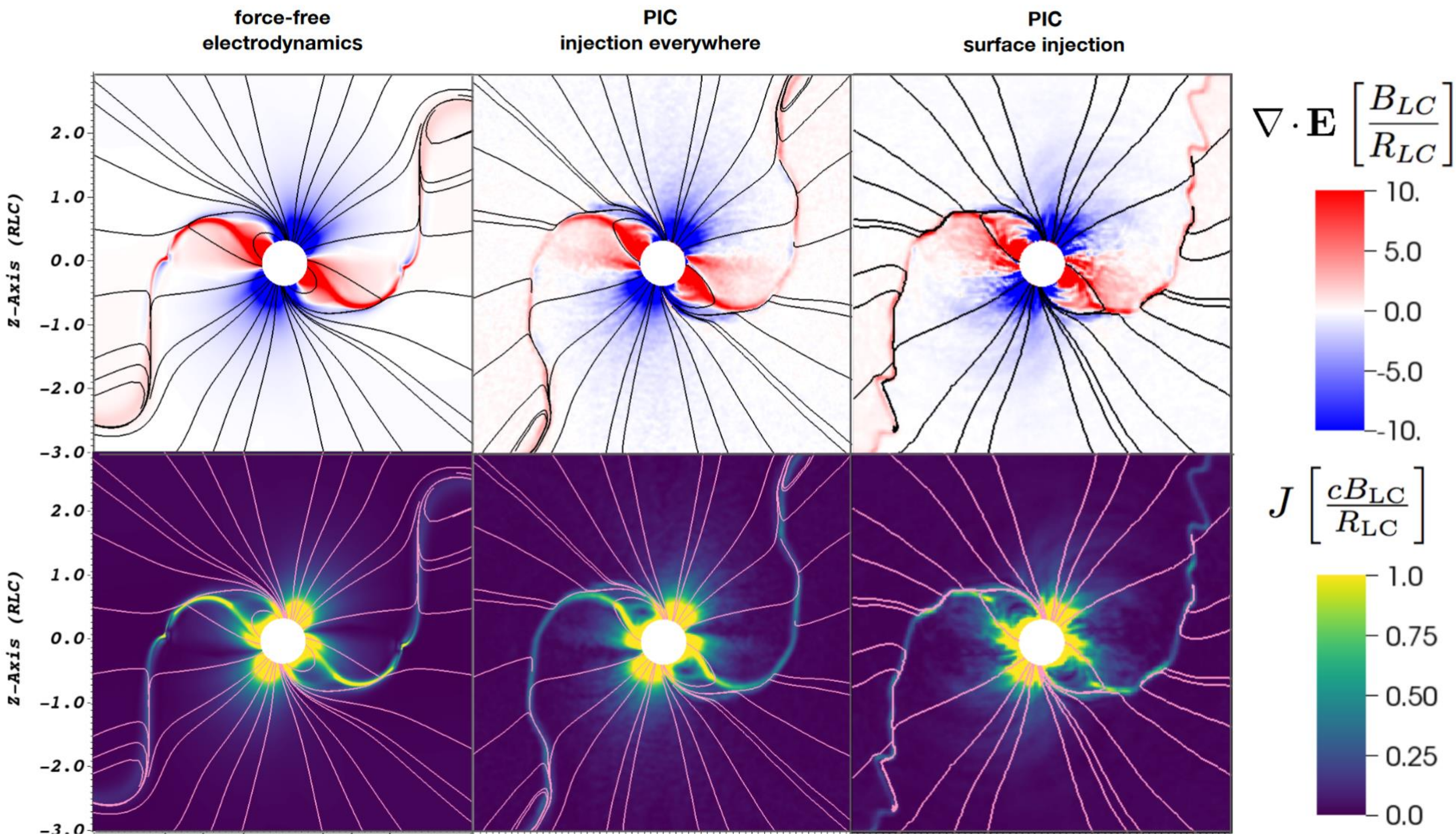



Kalapotharakos et al. 2015

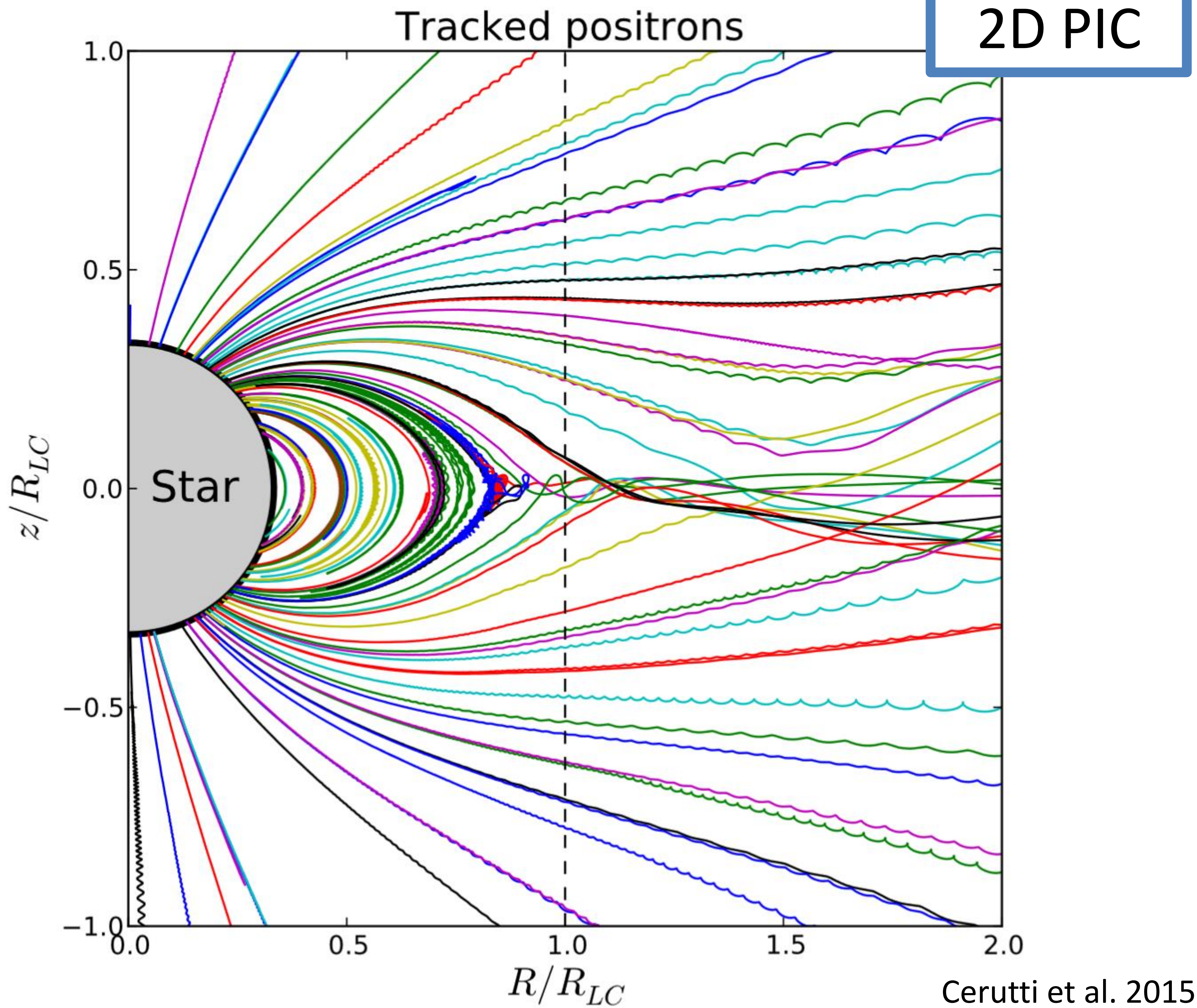
# A little bit of history…

# “Ab initio” numerical simulations (global PIC)

2014 (Spitkovsky, Sironi, Cerutti et al.)
2016 (Kalapotharakos)

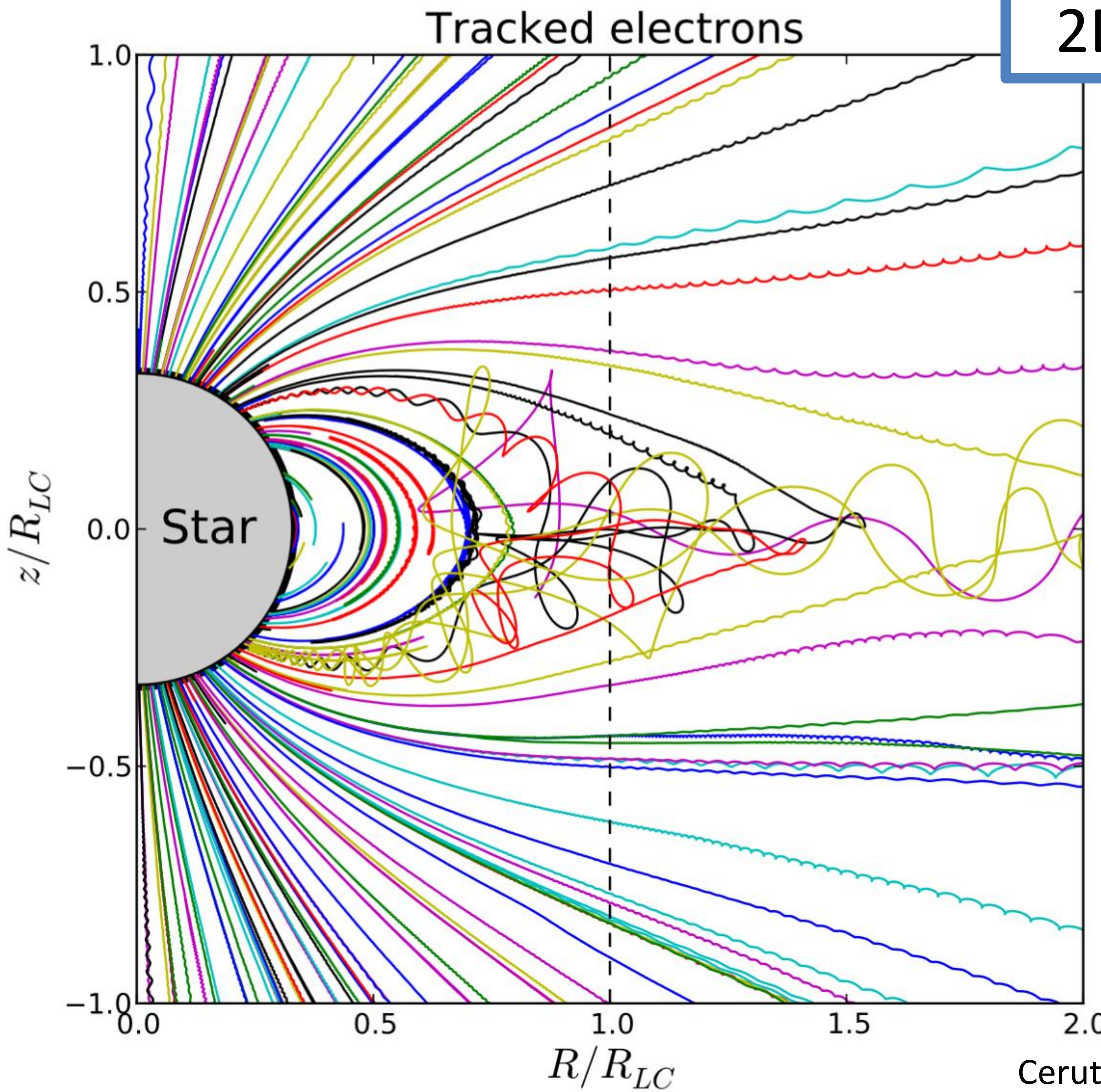



Brambilla, Kalapotharakos et al. 2018



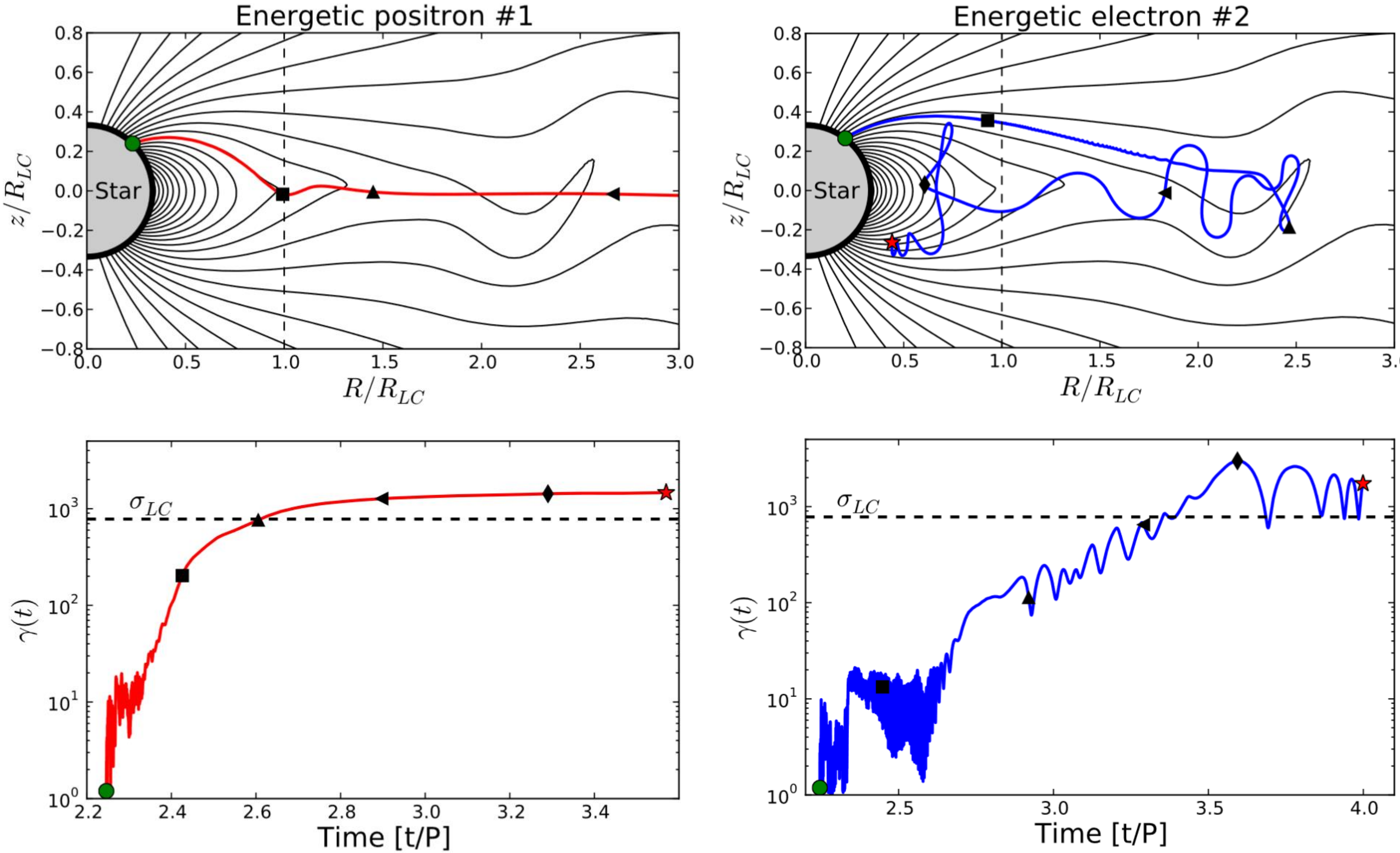

Cerutti et al. 2015

# 2D PIC



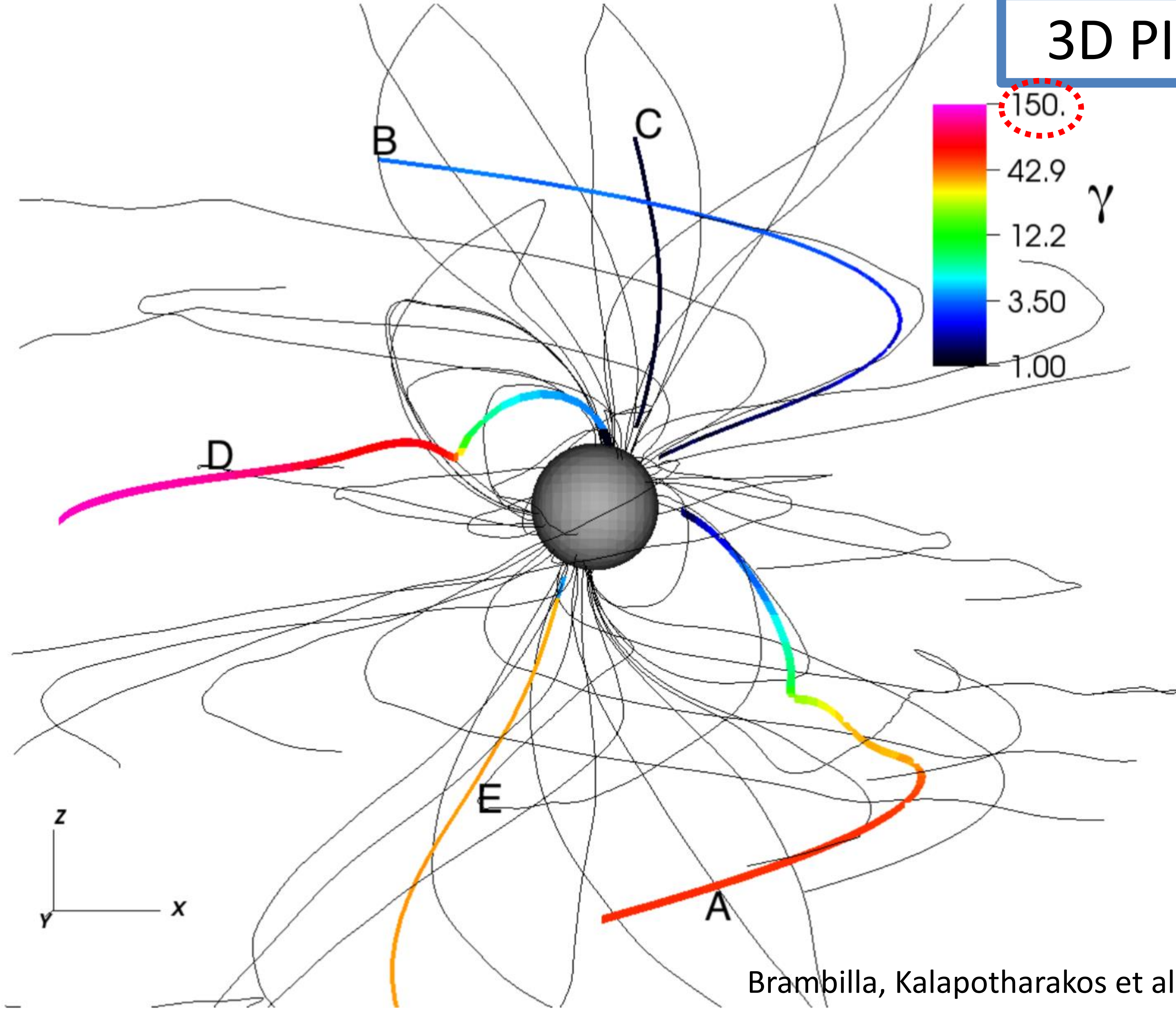

Cerutti et al. 2015

# 2D PIC




Cerutti et al. 2015

# 3D PIC




Brambilla, Kalapotharakos et al. 2018

# A little bit of critique…

"Ab initio" is too ambitious!
(is it hopeless?...)

# A little bit of critique…

The key is Current Closure

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# Ideal Force-Free everywhere, non-ideal non-force-free ECS

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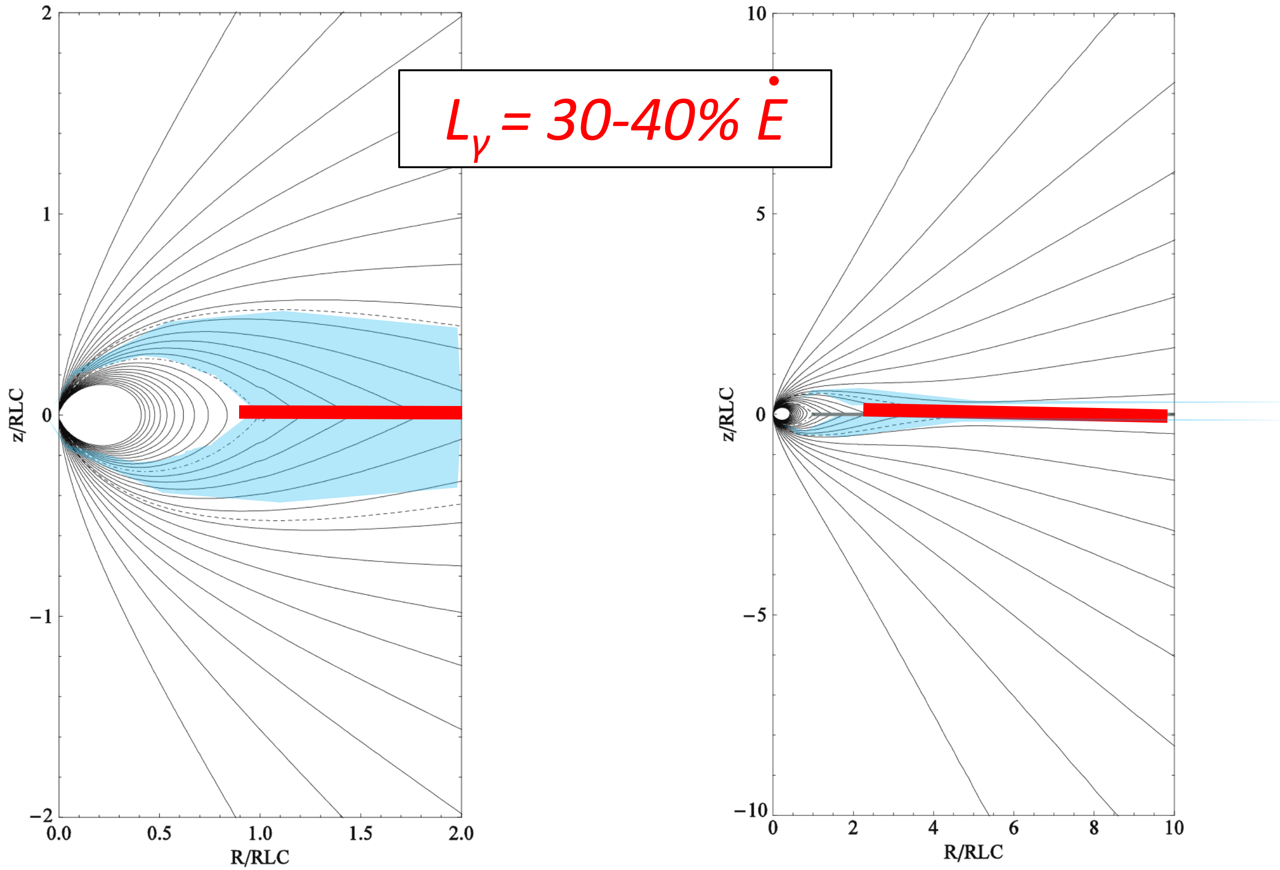
1st Meeting of ISSI International Team, Bern, Tuesday, December 10 2019

# FFE everywhere + electrostatic CS

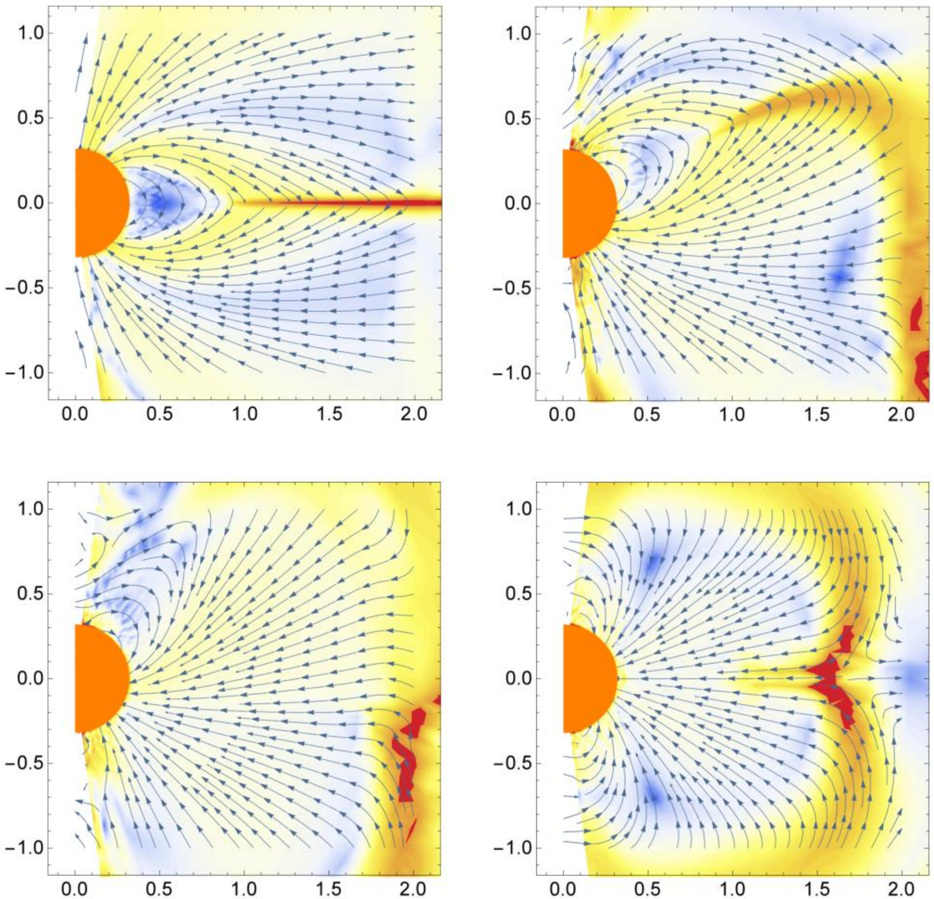
The Astrophysical Journal, 781:46 (5pp), 2014 January 20
doi:10.1088/0004-637X/781/1/46

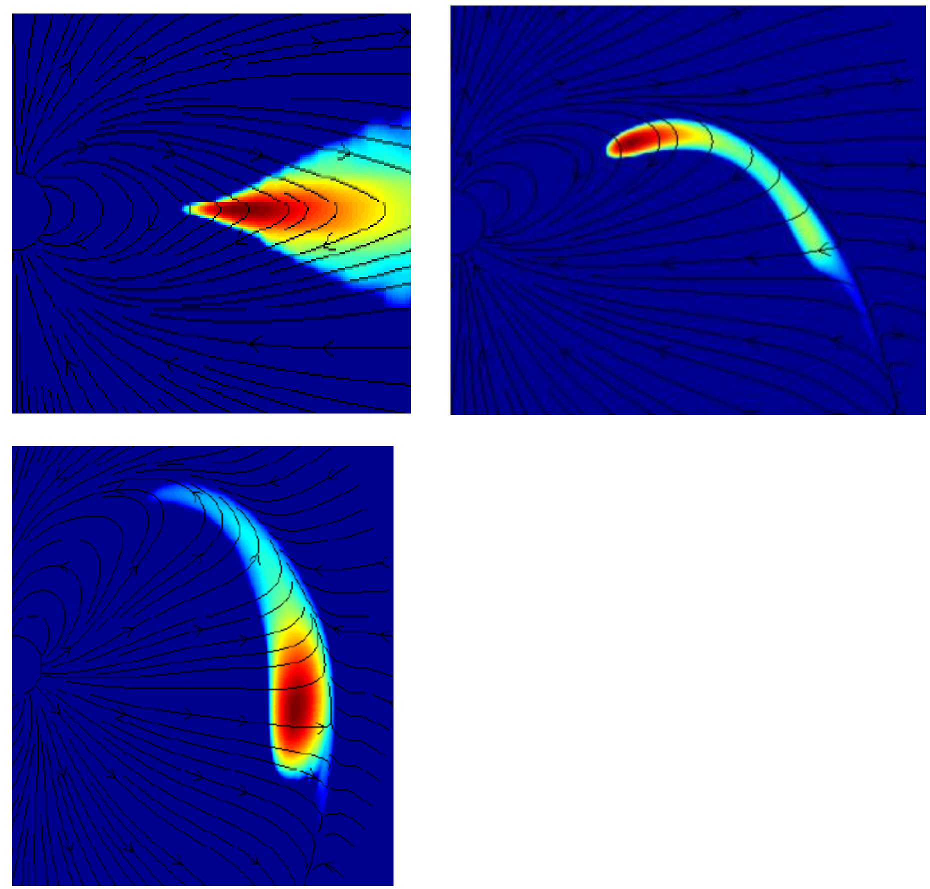

## A NEW STANDARD PULSAR MAGNETOSPHERE

Ioannis Contopoulos[1], Constantinos Kalapotharakos[2,3], and Demosthenes Kazanas[3]



# FFE everywhere + Aristotelian CS

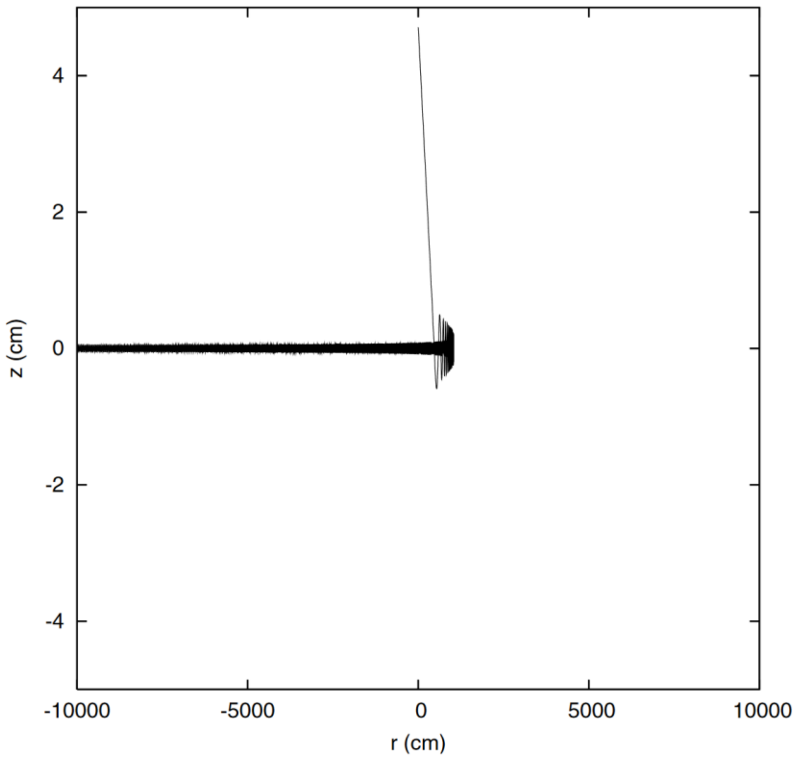


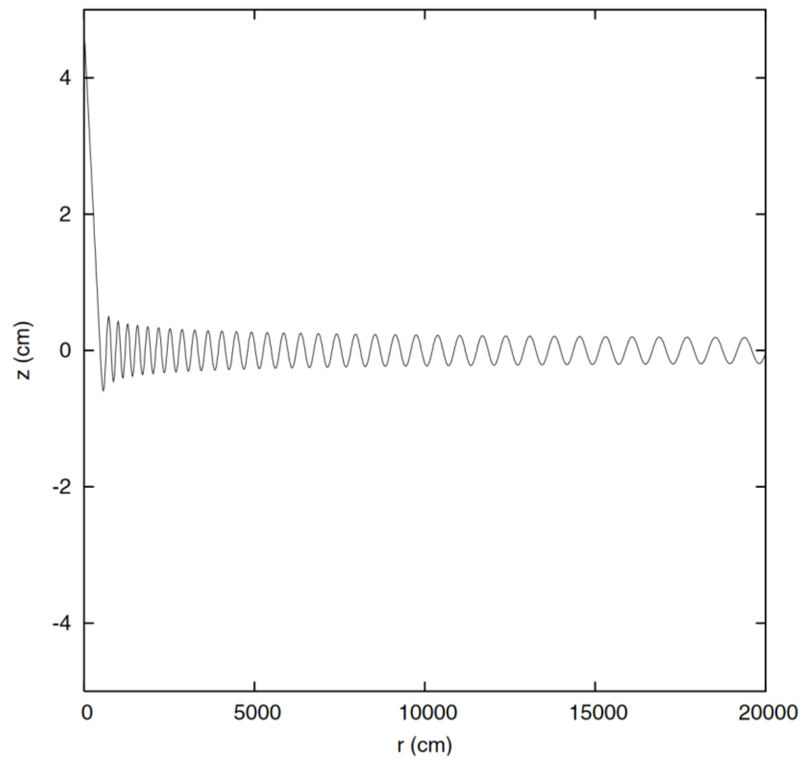



Aristotelian → Electrostatic for κ=0

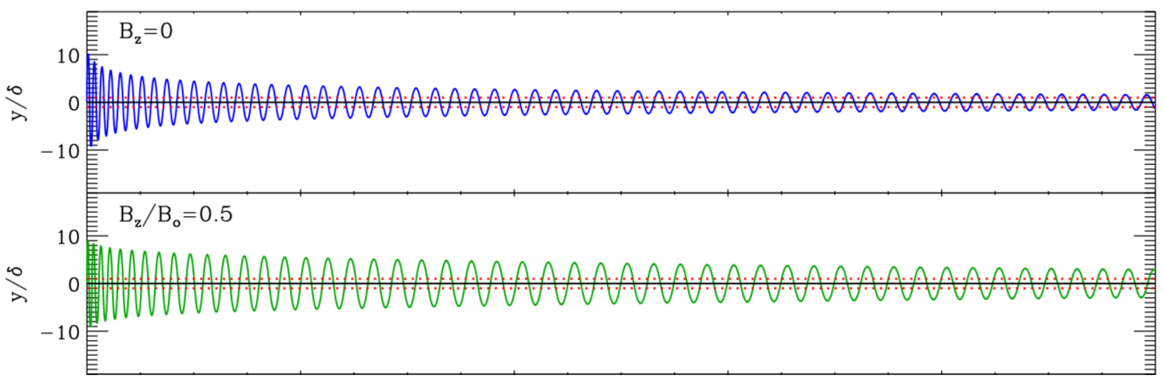
Contopoulos 2016

Cao & Yang 2019

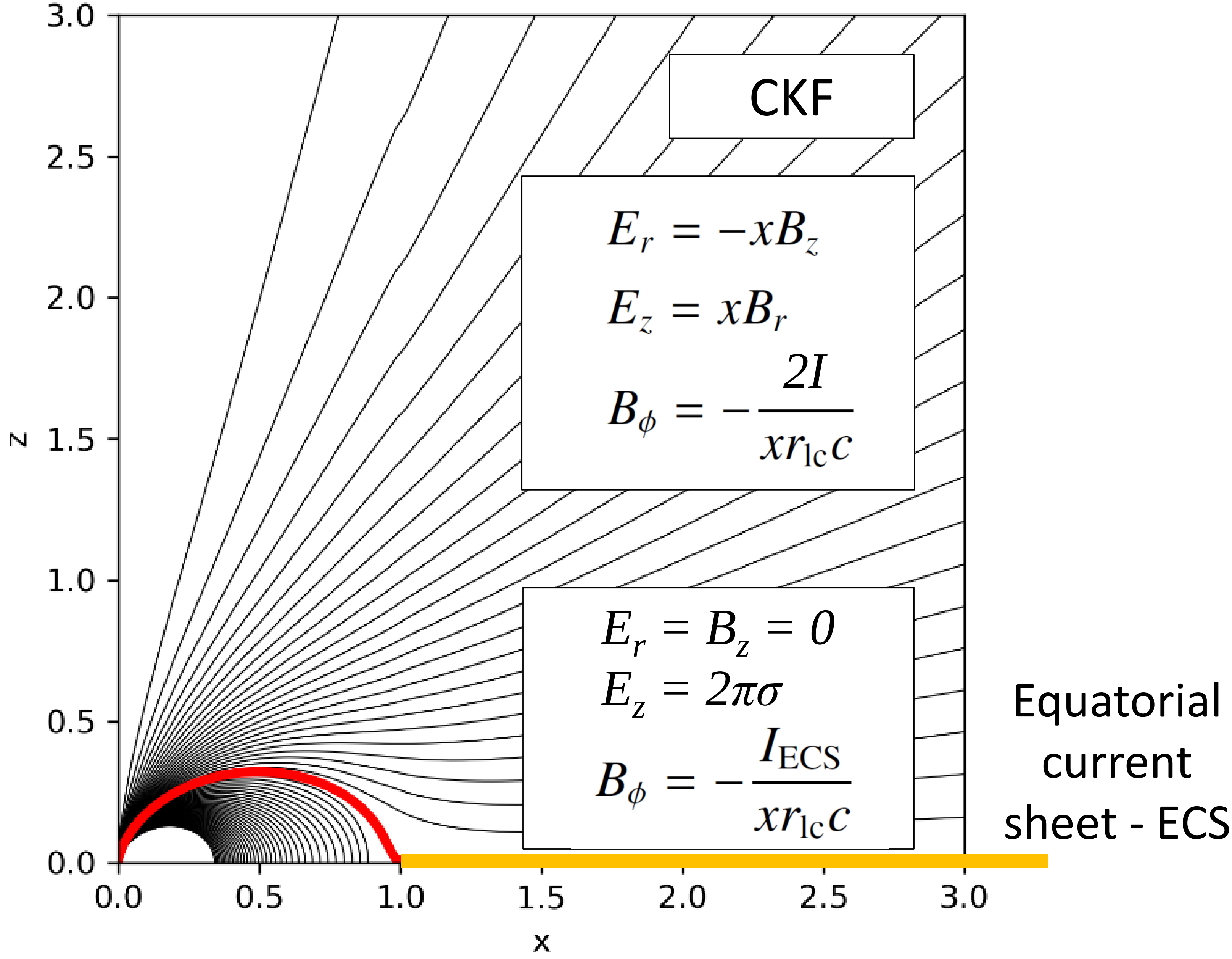


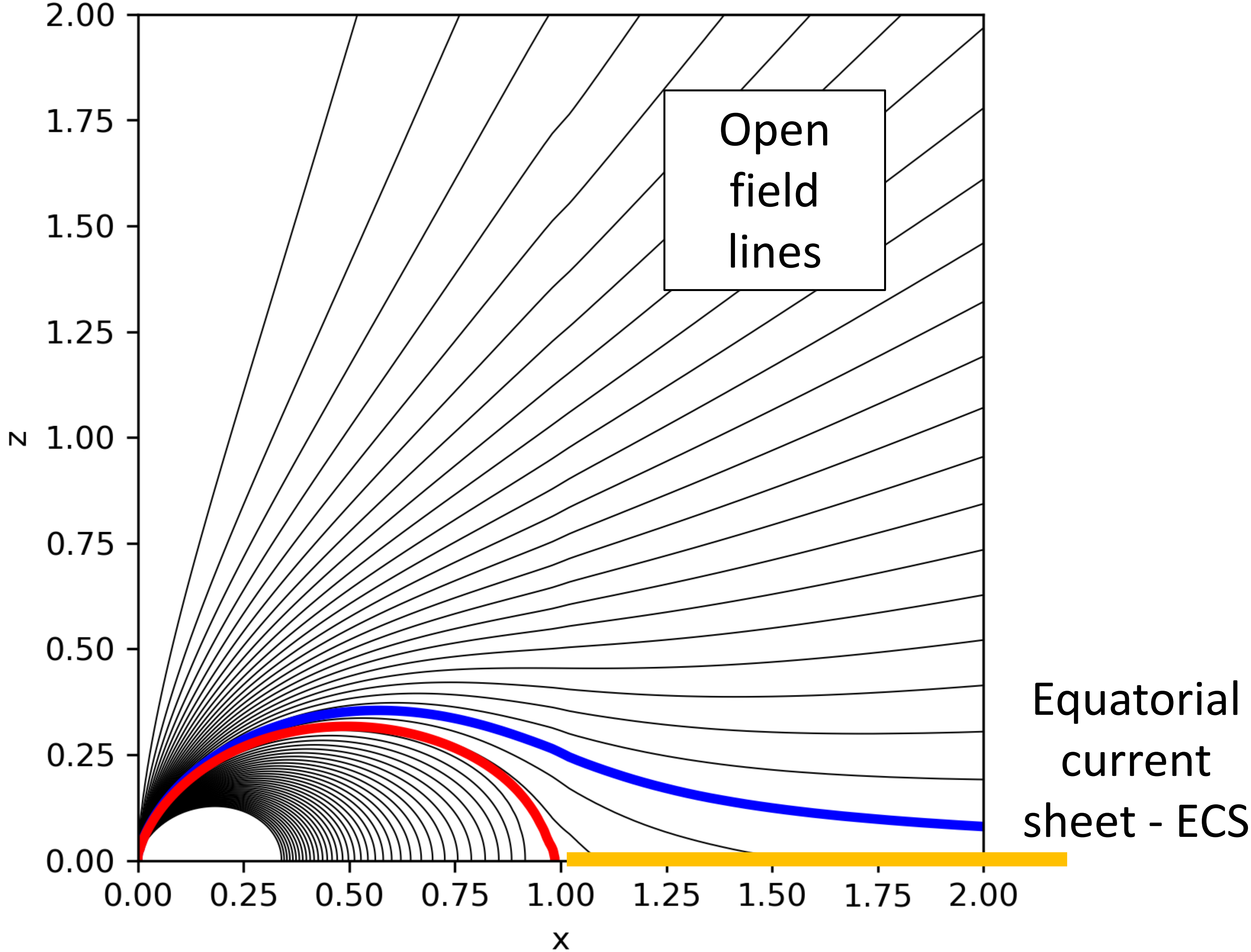




# Speiser orbits

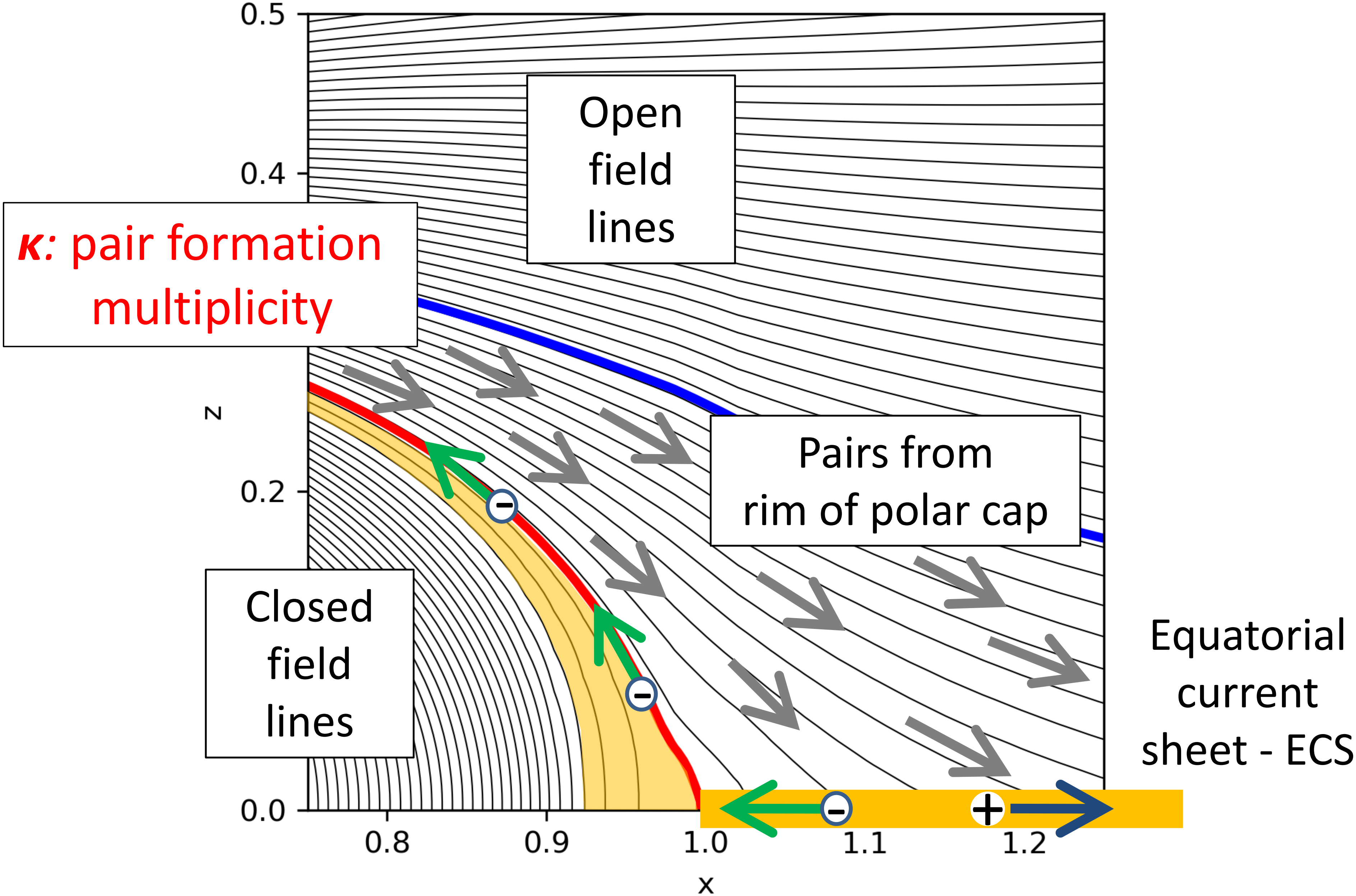



Contopoulos 2007; Cerutti et al. 2012, 2015


CKF
$E_r = -xB_z$
$E_z = xB_r$
$B_\phi = -\frac{2I}{x r_{\rm lc} c}$
$E_r = B_z = 0$
$E_z = 2\pi\sigma$
$B_\phi = -\frac{I_{\rm ECS}}{x r_{\rm lc} c}$
Equatorial current sheet - ECS
z
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0



Open field lines
Equatorial current sheet - ECS
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
z
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
x



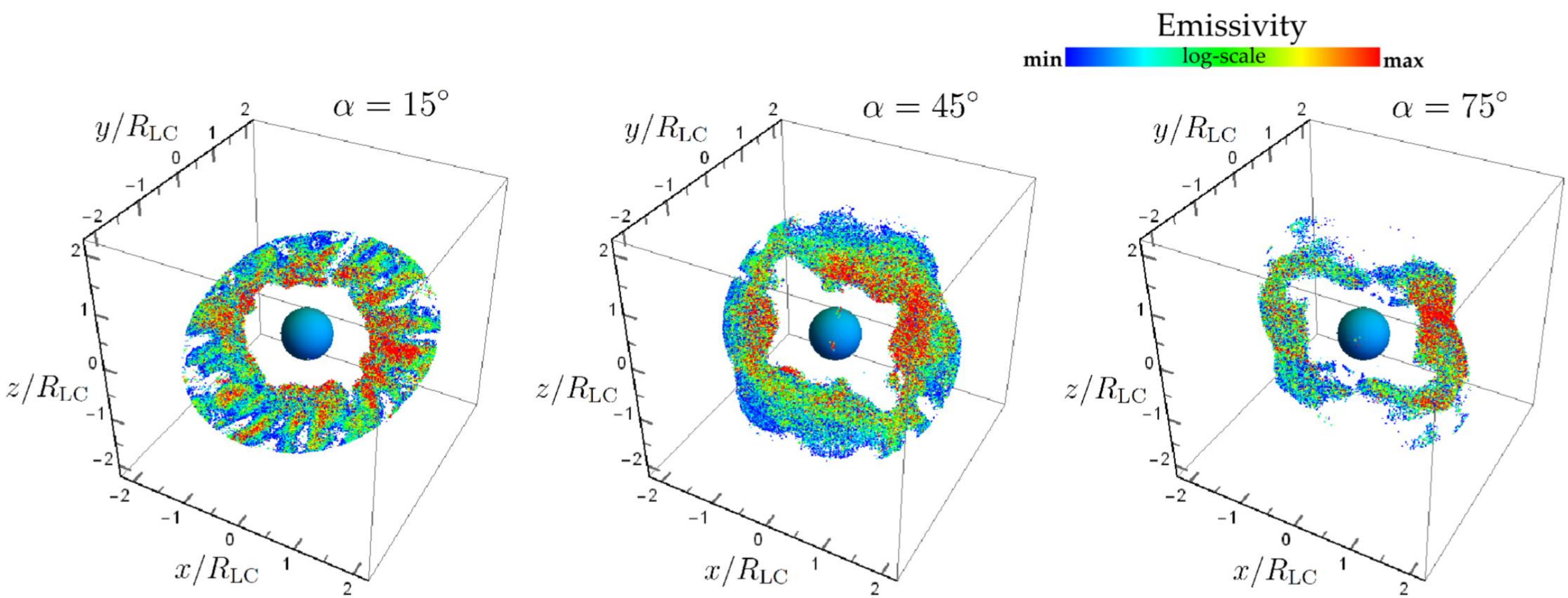
0.5
0.4
0.2
0.0
z
0.8
0.9
1.0
1.1
1.2
x
Open field lines
κ: pair formation multiplicity
Pairs from rim of polar cap
Closed field lines
Equatorial current sheet - ECS

# A ”ring of fire” in the pulsar magnetosphere

Contopoulos 2019

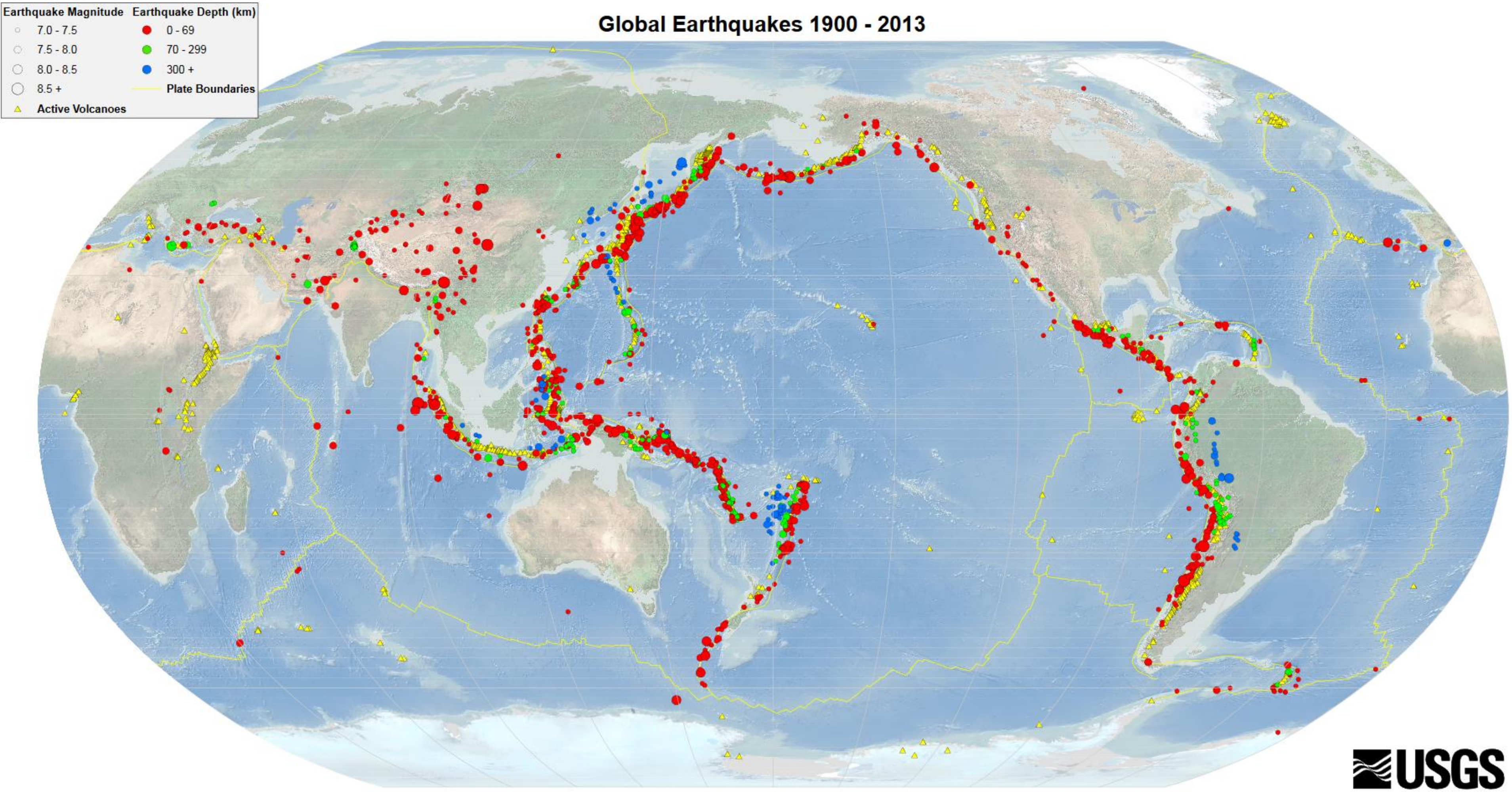
Contopoulos & Stefanou 2019

Contopoulos, Petri & Stefanou 2019

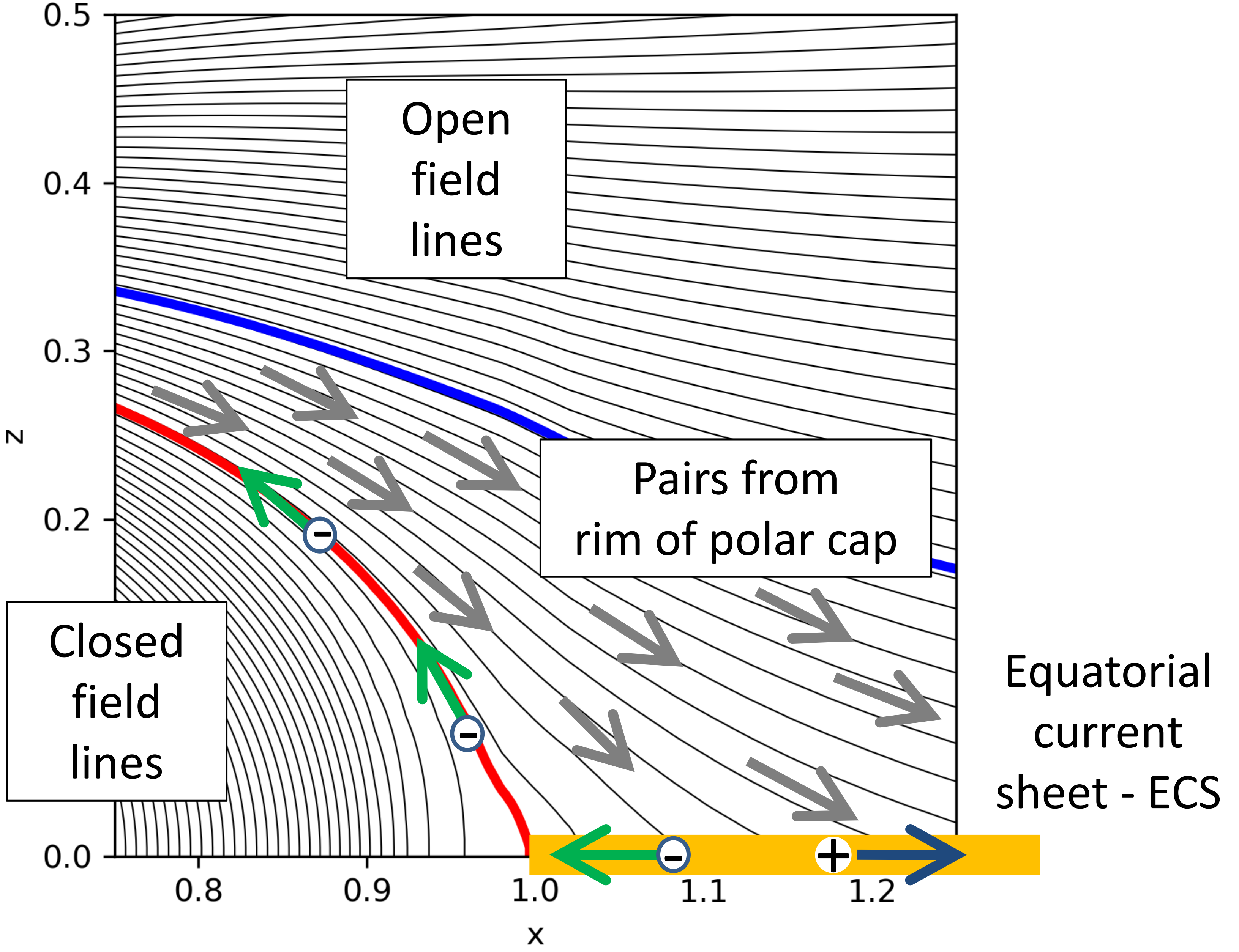



κ = 28

Kalapotharakos et al. 2018


Global Earthquakes 1900 - 2013
Earthquake Magnitude
7.0 - 7.5
7.5 - 8.0
8.0 - 8.5
8.5 +
Active Volcanoes
Earthquake Depth (km)
0 - 69
70 - 299
300 +
Plate Boundaries

$$
\begin{aligned}
\sigma &= \sigma_+ + \sigma_- \\
&= 2\mathrm{e}\left\{\frac{\int_{r_{\mathrm{lc}}}^{r} 2\pi r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z|}{2\pi r v_{r+}} + \frac{-\int_{r}^{\infty} 2\pi r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z|}{-2\pi r v_{r-}}\right\} \\
&\approx \frac{2\mathrm{e}}{r|v_r|}\left\{\int_{r_{\mathrm{lc}}}^{r} r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z| - \int_{r}^{\infty} r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z|\right\} \\
&= \frac{2\mathrm{e}}{r|v_r|}\left\{2\int_{r_{\mathrm{lc}}}^{r} r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z| - \int_{r_{\mathrm{lc}}}^{\infty} r'\,\mathrm{d}r'\, n_{\mathrm{pairs}}|v_z|\right\} .
\end{aligned}
$$


0.5
0.4
0.3
0.2
0.0
z
0.8
0.9
1.0
1.1
1.2
x
Open field lines
Pairs from rim of polar cap
Closed field lines
Equatorial current sheet - ECS

$$\begin{aligned}
\sigma &= \sigma_+ + \sigma_+ + \frac{I_{\mathrm{ECS\ separatrix}}}{2\pi r|v_r|} \\
&= \frac{4\mathrm{e}}{r|v_r|}\int_{r_{\mathrm{lc}}}^{r} r'\mathrm{d}r' n_{\mathrm{pairs}}|v_z|\,, \\
I_{\mathrm{ECS}} &\approx 2\pi r|v_r|(\sigma_+ - \sigma_-) + I_{\mathrm{ECS\ separatrix}} \\
&= 4\mathrm{e}\int_{r_{\mathrm{lc}}}^{\infty} 2\pi r'\mathrm{d}r' n_{\mathrm{pairs}}|v_z| \\
&= 4\mathrm{e}\int_{r_{\mathrm{lc}}}^{\infty} 2\pi r'\mathrm{d}r' \left(\frac{n_{\mathrm{pairs}} v_p}{B_p}\right)|B_z| \\
&= 4\mathrm{e}\frac{\kappa\Omega}{2\pi \mathrm{e}}\int_{r_{\mathrm{lc}}}^{\infty} 2\pi r'\mathrm{d}r' B_z \\
&\equiv \frac{2\kappa\Omega}{\pi}\Psi_{\mathrm{ECS}}\,.
\end{aligned}$$

*$\kappa$:* pair formation multiplicity

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}r}(r|v_r|\sigma) &= \\
\frac{\mathrm{d}}{\mathrm{d}x}(\sigma\sqrt{x^2-1}c) &= 4ern_{\mathrm{pairs}}|v_z| = 4ern_{\mathrm{pairs}}v_p(|B_z|/B_p) \\
&= \frac{2\kappa\Omega r}{\pi}|B_z| \,. \qquad (19)
\end{aligned}
$$

Solving for the distribution of $B_z$ along the dissipation layer, and remembering that $\sigma = E_z/(2\pi) = xB_r/(2\pi)$ yields

$$
B_z = -\frac{1}{4\kappa x}\frac{\mathrm{d}}{\mathrm{d}x}(x\sqrt{x^2-1}B_r) \,. \qquad (20)
$$

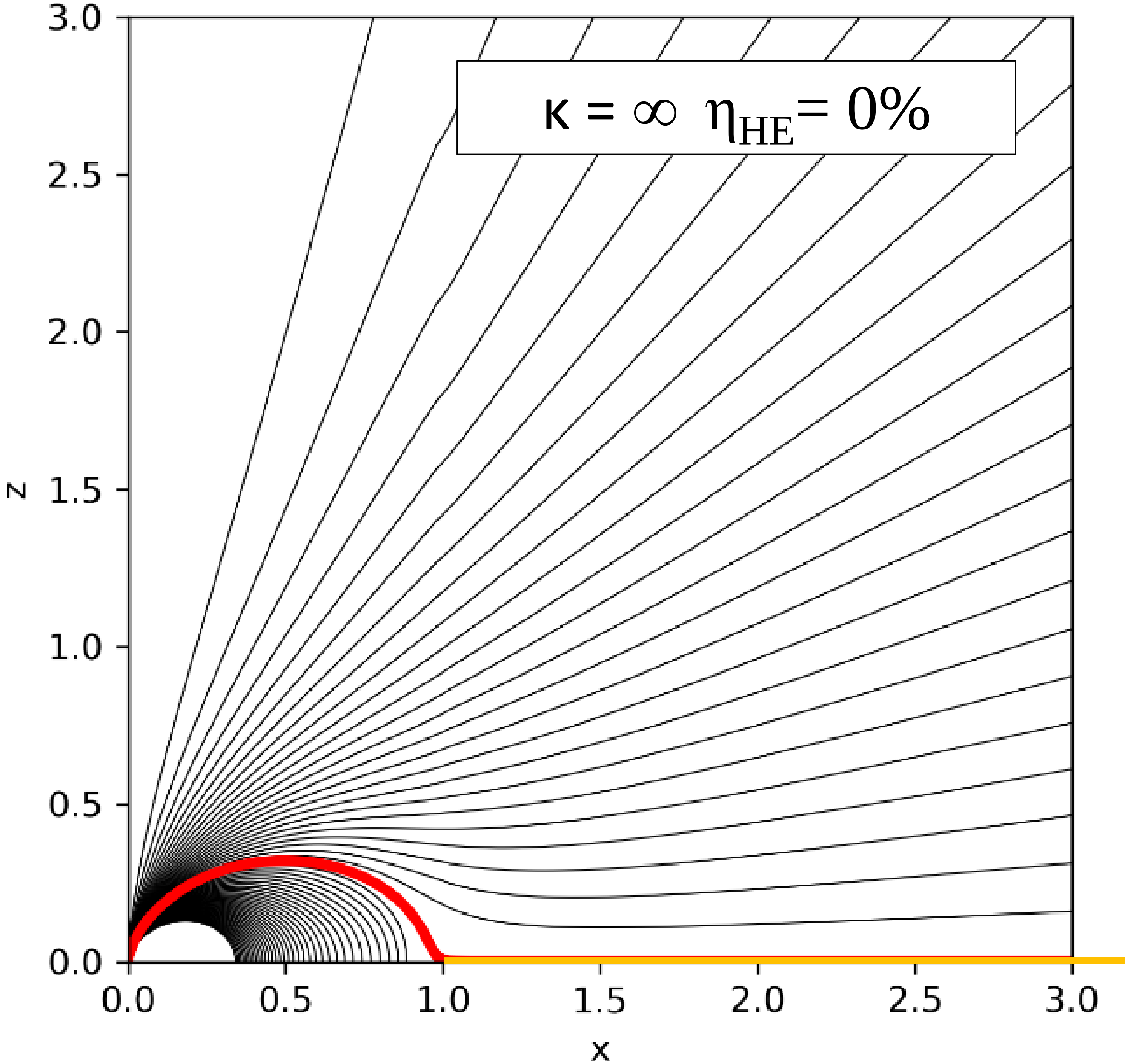
$$\sigma = \sigma_+ + \sigma_+ + \frac{I_{\rm ECS\ separatrix}}{2\pi r|v_r|} + 2\frac{(I(r) - I(r_{\rm lc}))}{2\pi r|v_r|}$$
$$= \frac{2\kappa\Omega}{\pi r|v_r|}\int_{r_{\rm lc}}^{r} r'{\rm d}r'|B_z| + \frac{2}{r|v_r|}\int_{r_{\rm lc}}^{r} r'{\rm d}r'|B_z|\left|\frac{{\rm d}I}{{\rm d}\Psi}\right| , \quad (29)$$

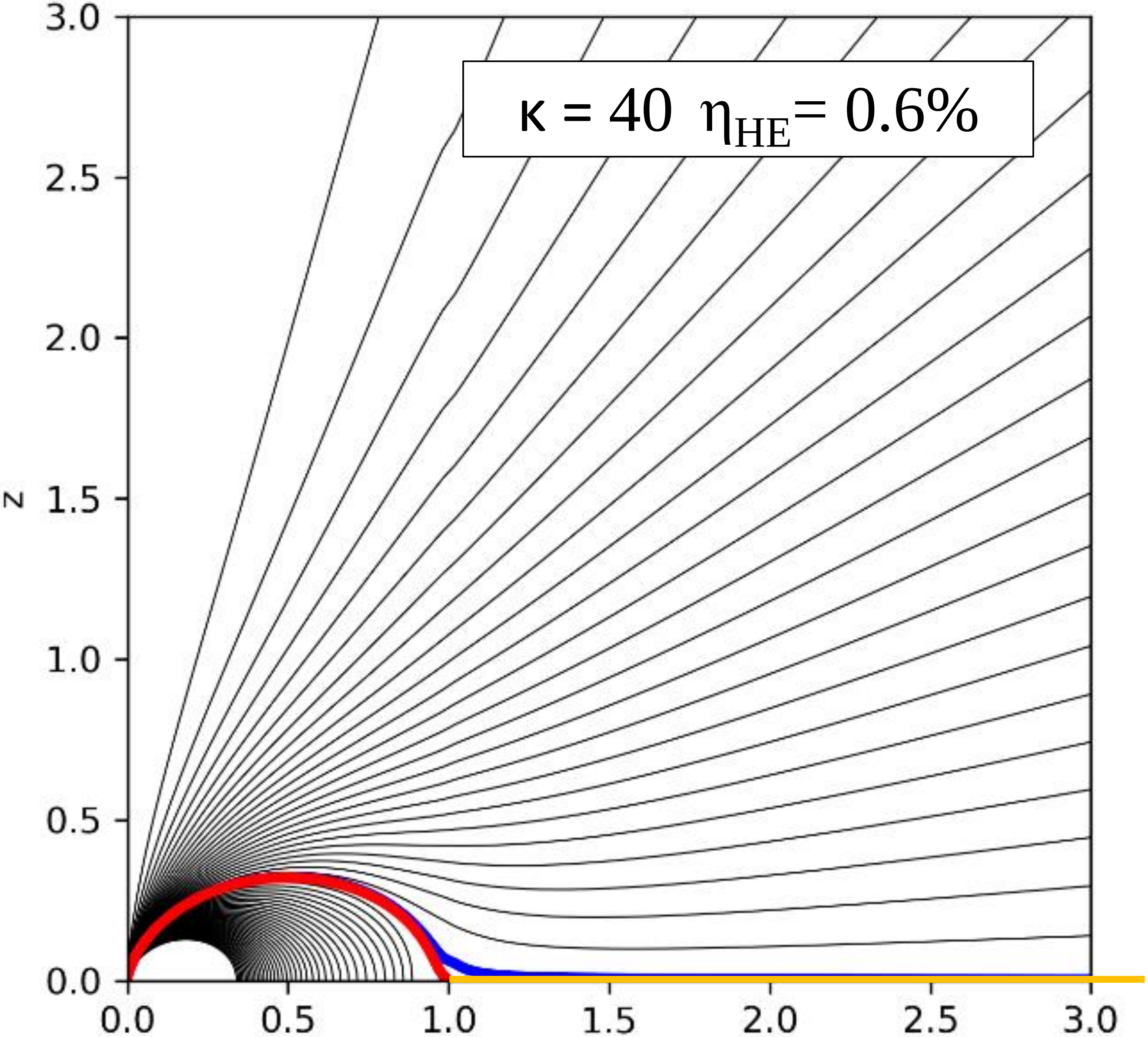
and consequently, the equatorial boundary condition of eq. (20) becomes

$$B_z = -\left(4\kappa + \frac{4\pi}{\Omega}\left|\frac{{\rm d}I}{{\rm d}\Psi}\right|\right)^{-1}\frac{1}{x}\frac{\rm d}{{\rm d}x}(x\sqrt{x^2-1}B_r) . \quad (30)$$

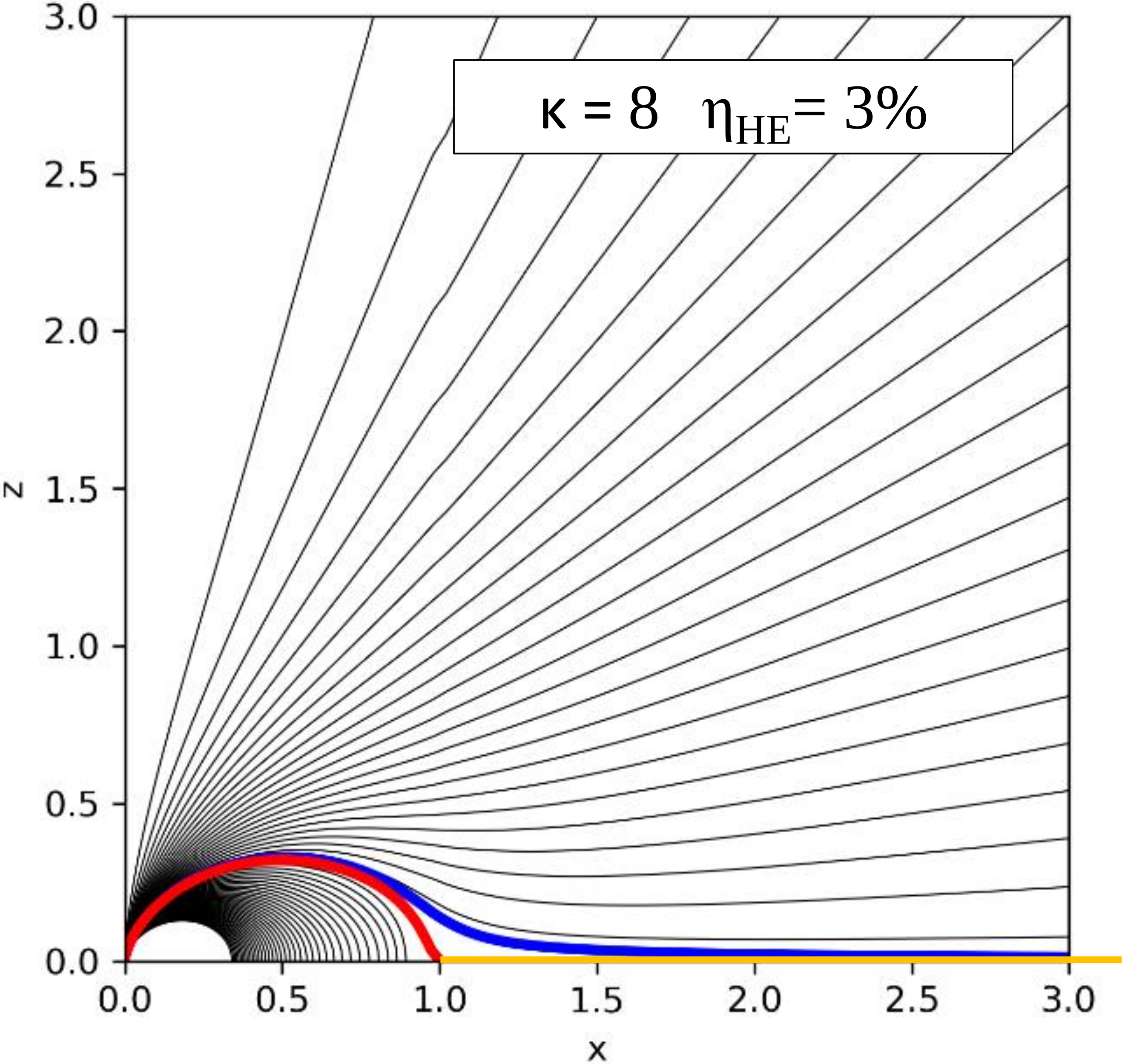
Here, $I(r)$ is the magnetospheric electric current contained inside radius $r$ of the ECS. Eq. (30) allows us to extend figure 4 to very low $\kappa$ values.

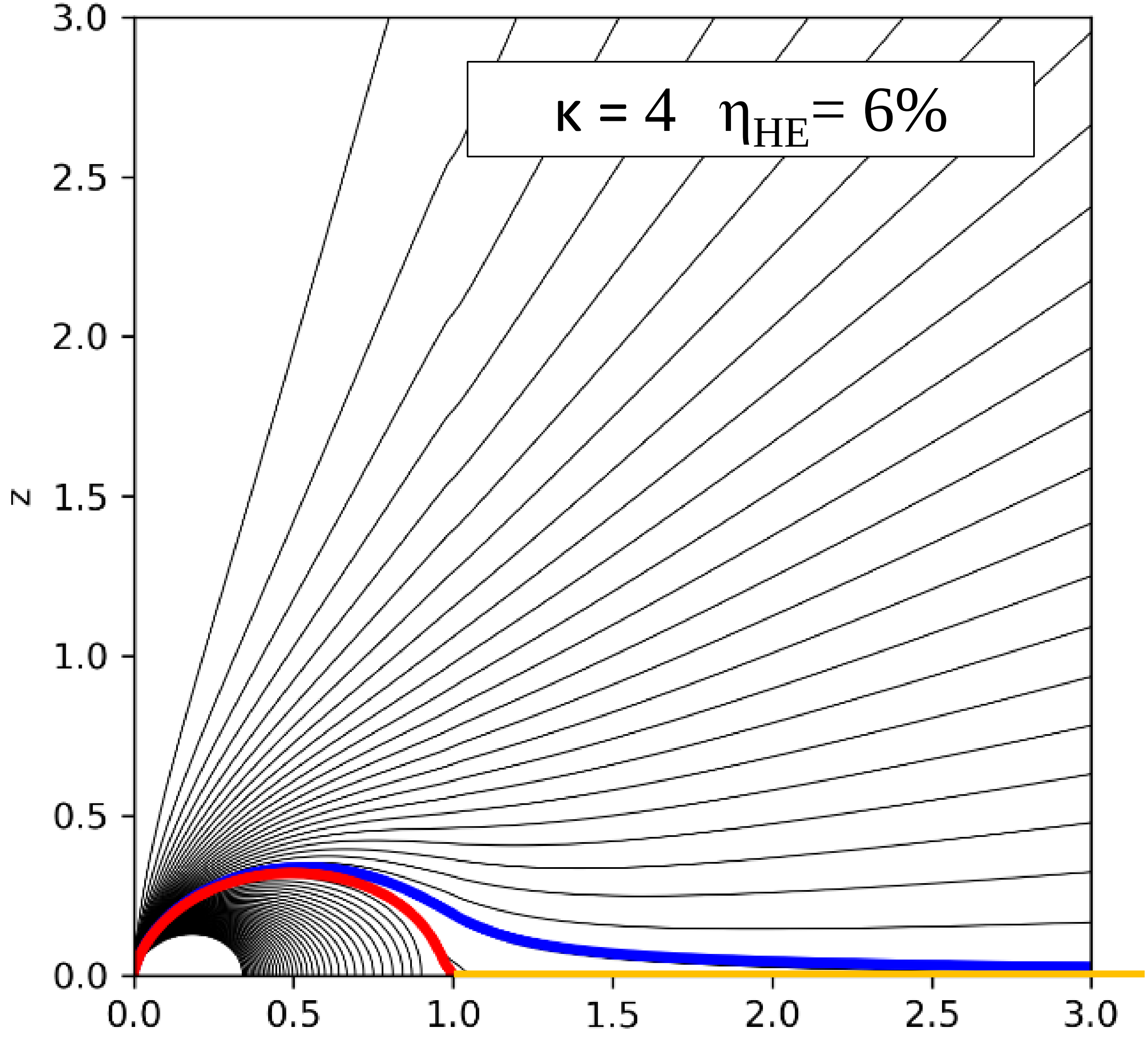
Aristotelian → Electrostatic for $\kappa$=0

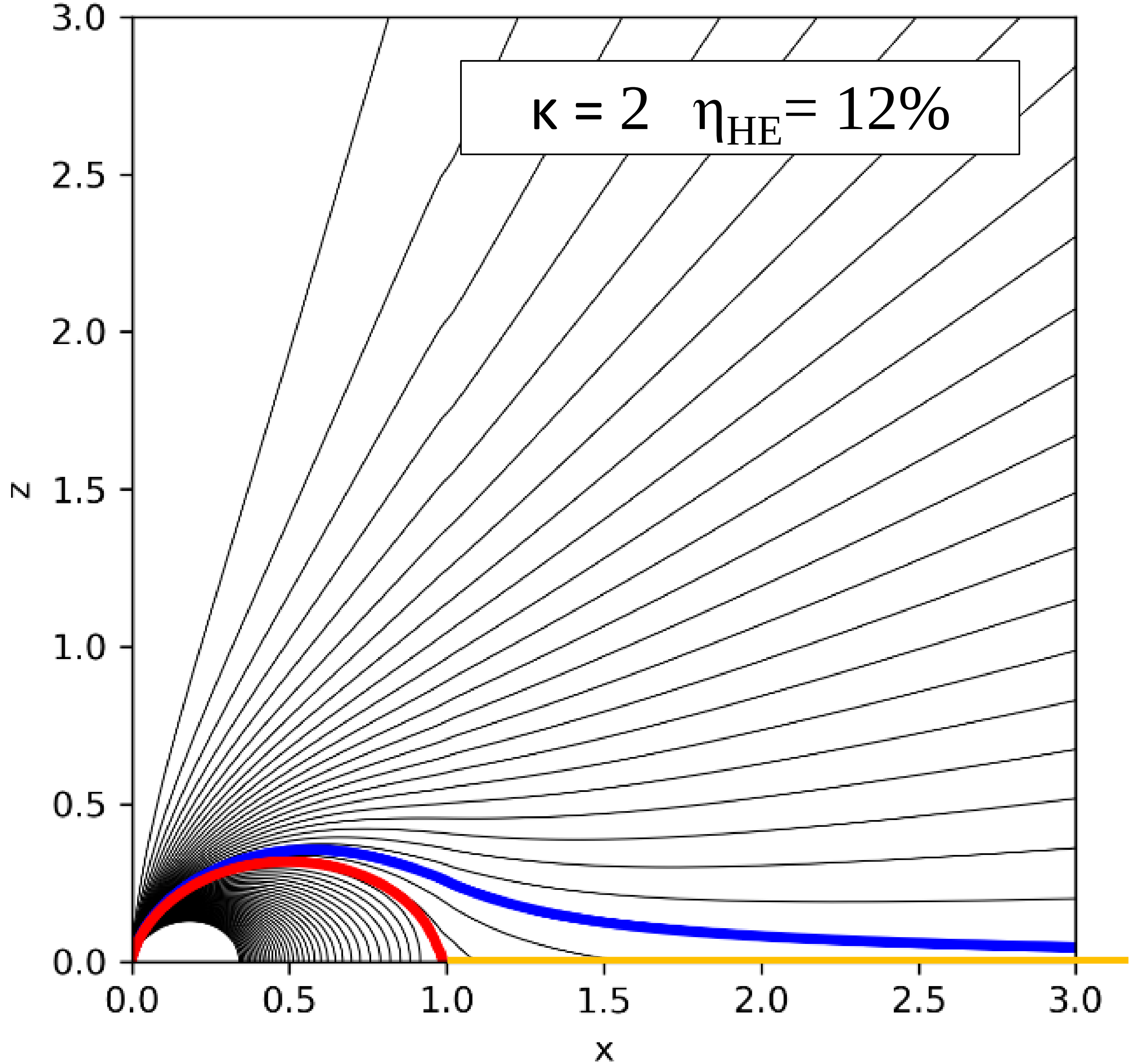

κ = ∞ η_HE= 0%
z
x
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0



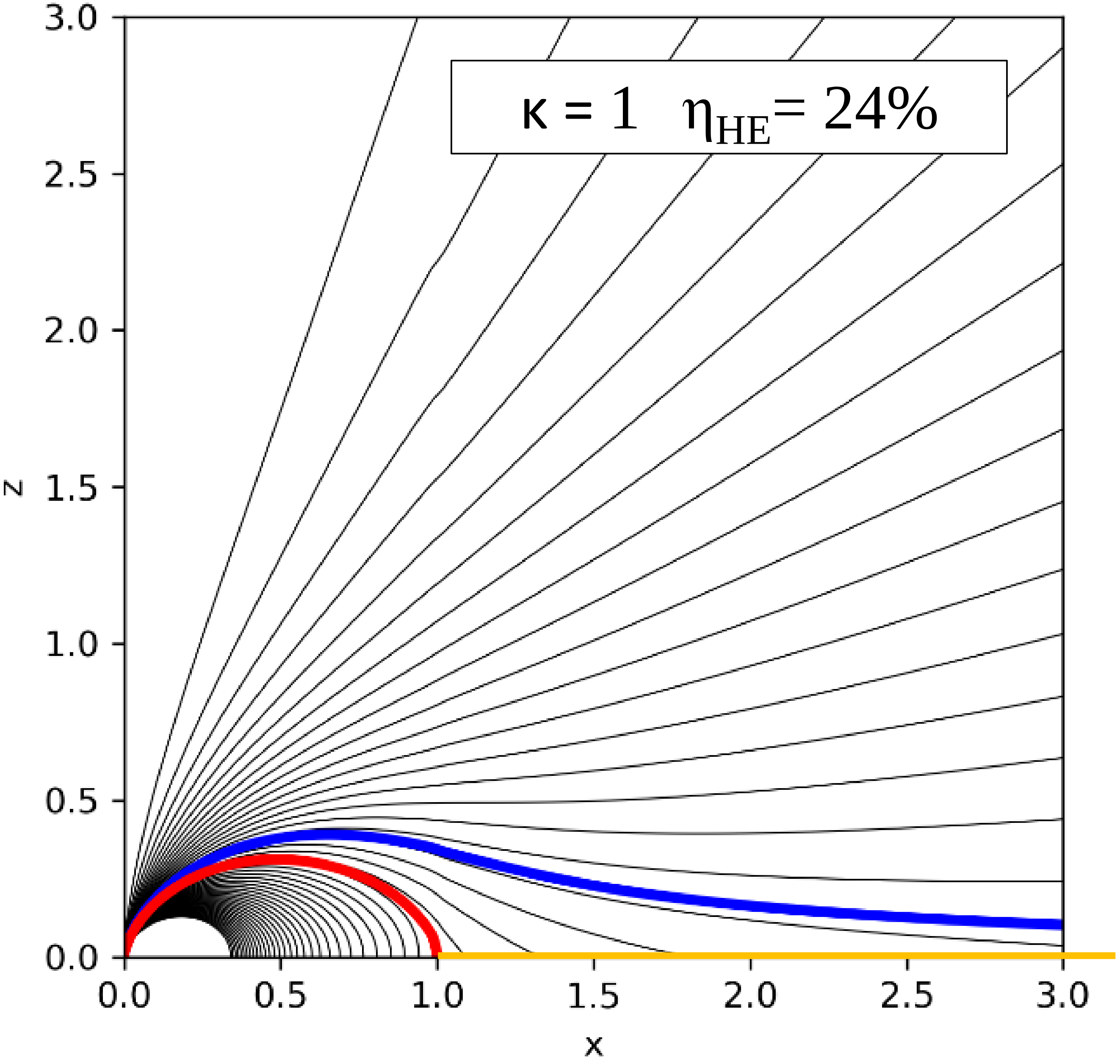
κ = 40 η_HE = 0.6%
z
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0


κ = 8 η_HE = 3%
z
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0

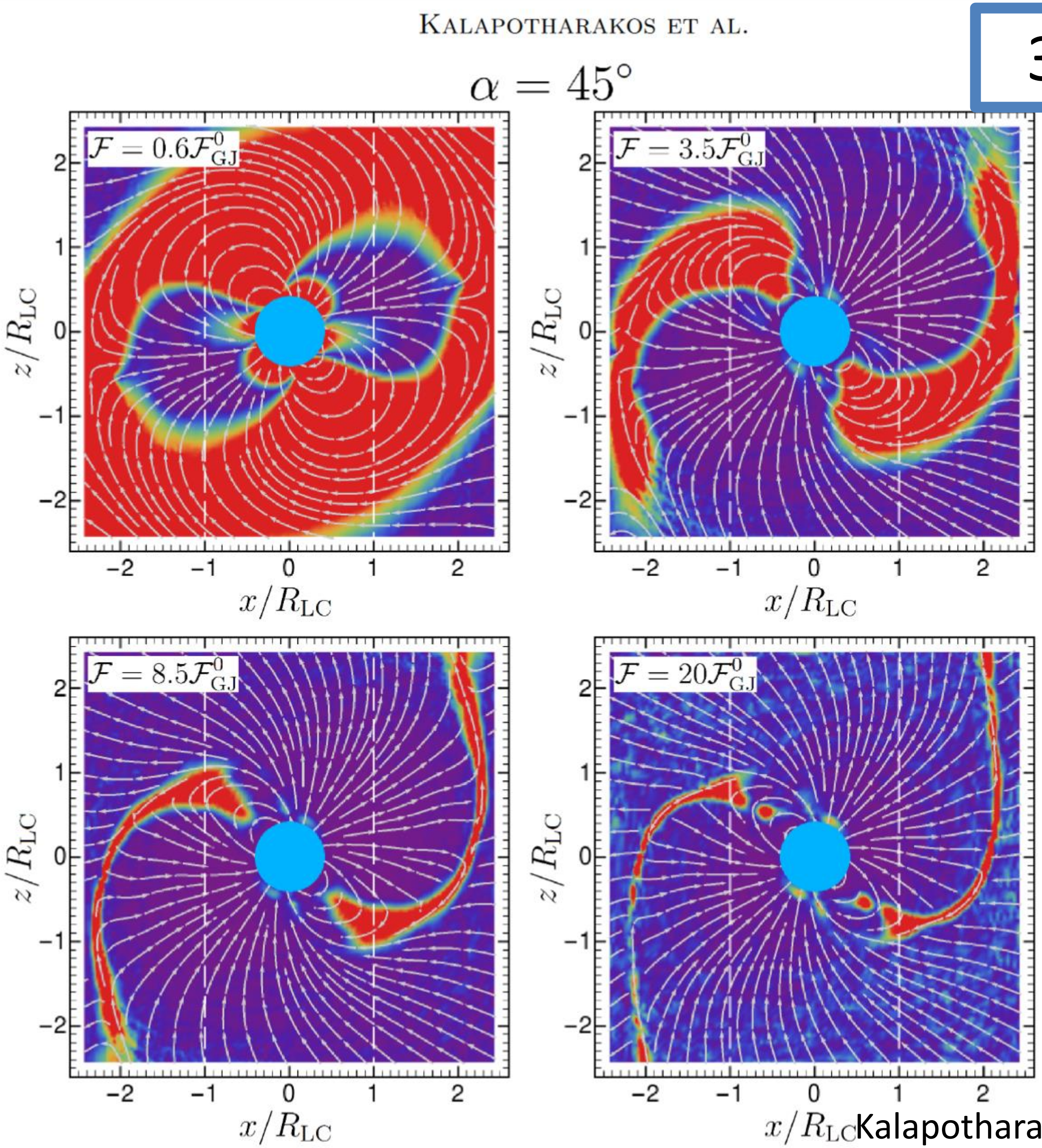

κ = 4   η_HE = 6%
3.0
2.5
2.0
1.5
1.0
0.5
0.0
z
0.0
0.5
1.0
1.5
2.0
2.5
3.0
x



κ = 2 η_HE = 12%
z
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0



κ = 1 η_HE = 24%
z
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0




3D PIC

Kalapotharakos et al. 2018

$$B_r \approx \frac{1}{x^2}\left(1-\frac{1}{x^2}\right)^{0.7} B_{\rm lc\ dipole}\ . \tag{22}$$

Here, $B_{\rm lc\ dipole} \equiv B_* r_*^3/(2r_{\rm lc}^3)$ is the equatorial value of the vacuum dipole magnetic field at the light cylinder. Therefore, according to eqs. (2) and (20)

$$B_z \approx -\frac{3}{5\kappa x^4}\left(1-\frac{1}{x^2}\right)^{0.2} B_{\rm lc\ dipole}\ , \tag{23}$$

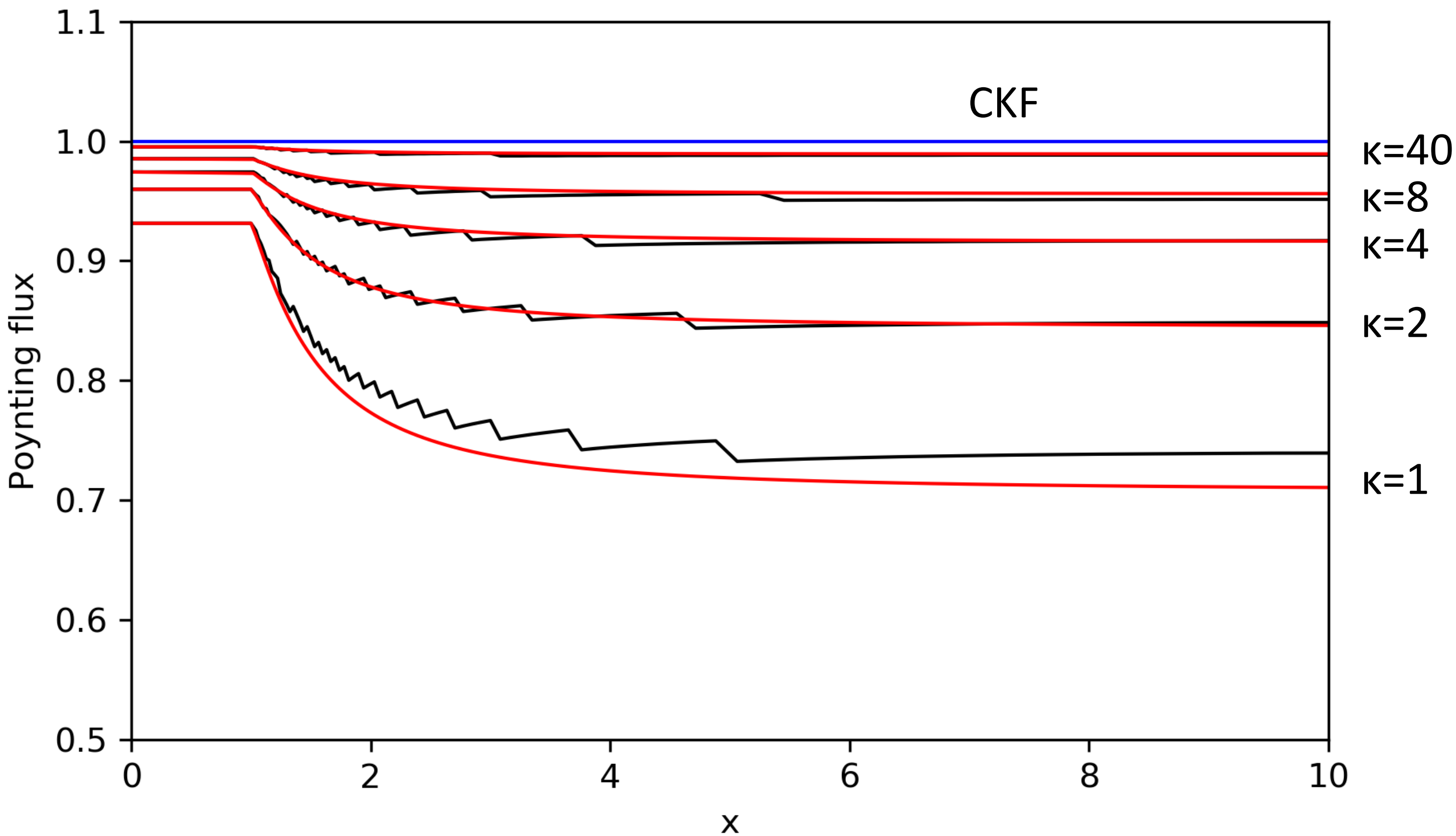
$$E_r \approx \frac{3}{5\kappa x^3}\left(1-\frac{1}{x^2}\right)^{0.2} B_{\rm lc\ dipole}\ . \tag{24}$$

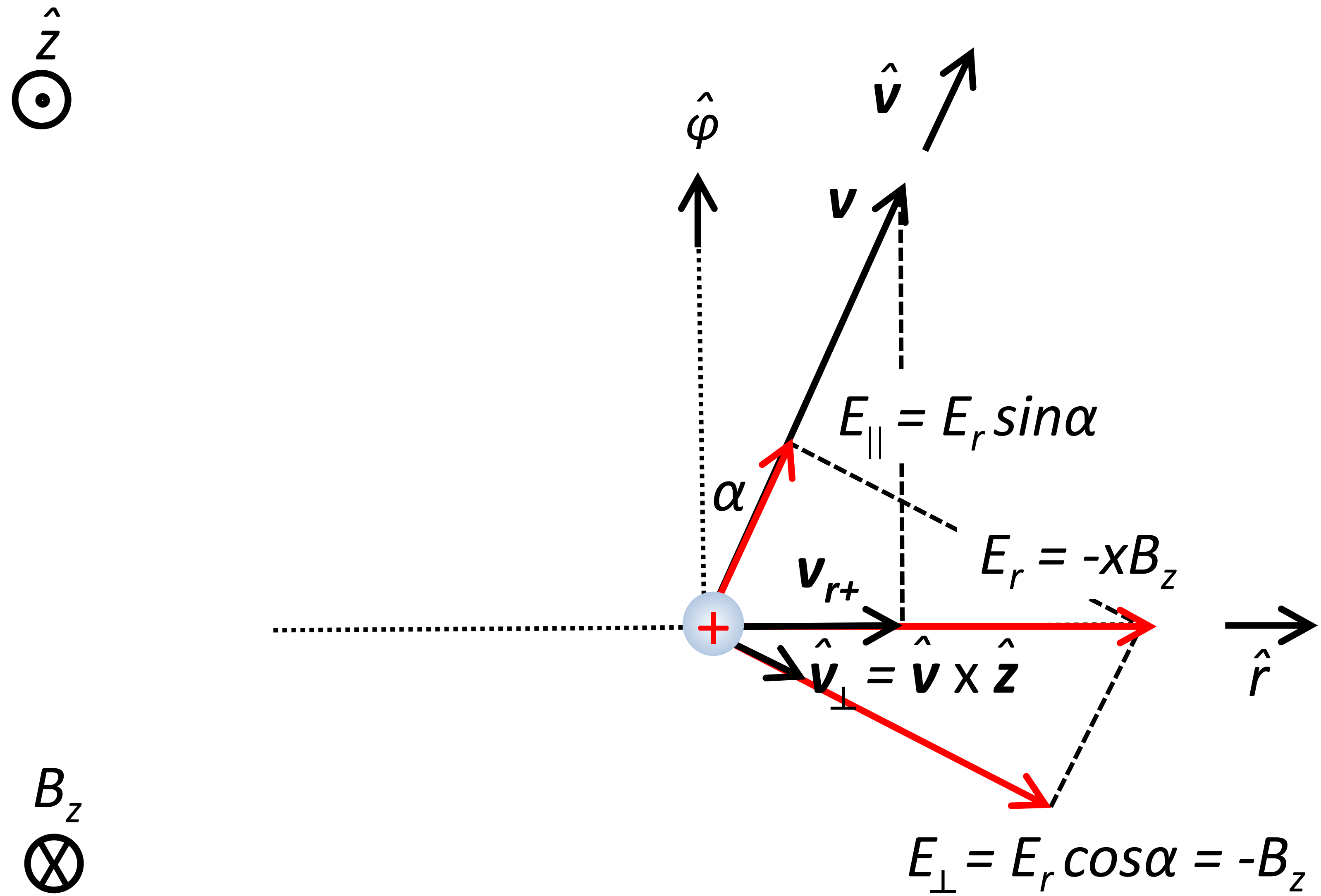
Notice the very sharp decrease of $B_z$ and $E_r$ with distance. Finally, let us also introduce

$$B_\phi = -\frac{I_{\rm ECS}}{x r_{\rm lc} c} = -\frac{\Omega r^2_{\rm pc\ dipole} B_*}{2 x r_{\rm lc} c} = -\frac{B_{\rm lc\ dipole}}{x}\ . \tag{25}$$

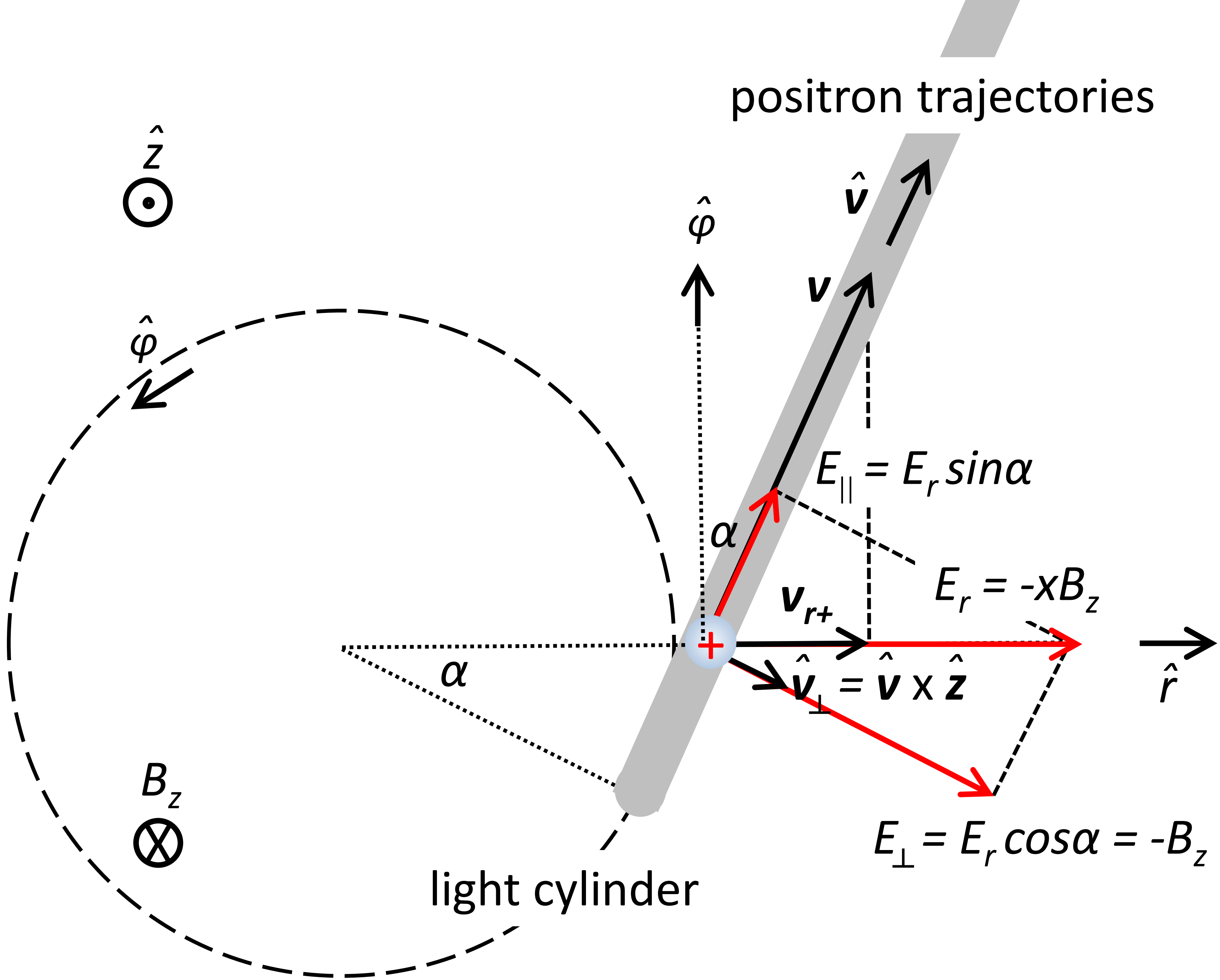
$$\dot{E}_{\mathrm{Poynting}}(x) = \dot{E} - \dot{E}_{\mathrm{ECS}}(x)$$

$$\approx \begin{cases} \dot{E}\left(1 - \frac{6}{25\kappa}\left(1 - \frac{1}{x^2}\right)^{1.2}\right) & \text{if } x \geq 1 \\ \dot{E} & \text{otherwise} \end{cases}$$

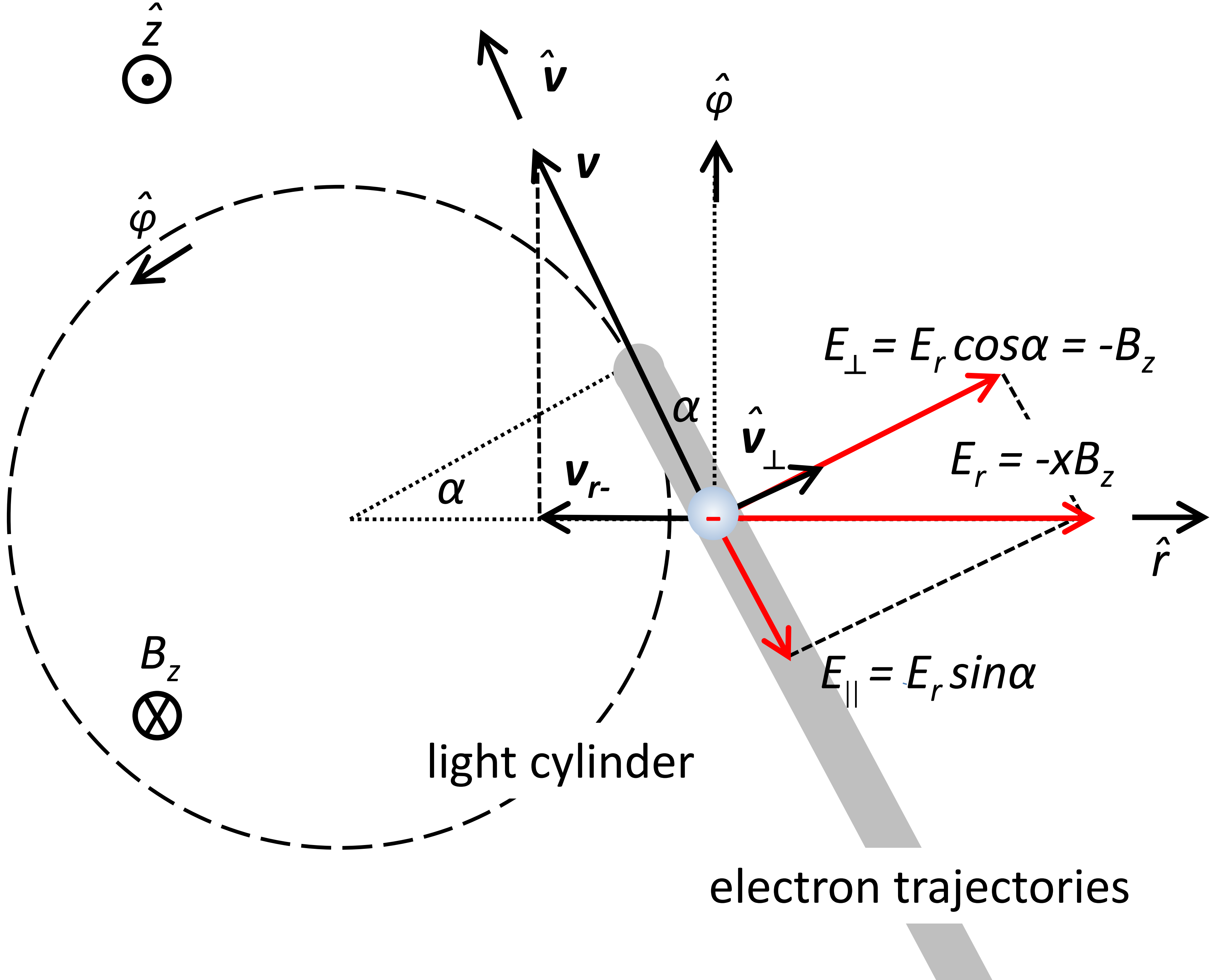




$\hat{z}$
$\hat{\varphi}$
$\hat{\boldsymbol{v}}$
$\boldsymbol{v}$
$E_{||} = E_r sin\alpha$
$\alpha$
$E_r = -xB_z$
$\boldsymbol{v}_{r+}$
$\hat{\boldsymbol{v}}_{\perp} = \hat{\boldsymbol{v}} \times \hat{\boldsymbol{z}}$
$\hat{r}$
$B_z$
$E_{\perp} = E_r cos\alpha = -B_z$



positron trajectories
$\hat{z}$
$\hat{\varphi}$
$\hat{\boldsymbol{v}}$
$\hat{\varphi}$
$\boldsymbol{v}$
$E_{||} = E_r sin\alpha$
$\alpha$
$E_r = -xB_z$
$\boldsymbol{v}_{r+}$
$\alpha$
$\hat{\boldsymbol{v}}_{\perp} = \hat{\boldsymbol{v}} \times \hat{\boldsymbol{z}}$
$\hat{r}$
$B_z$
$E_{\perp} = E_r cos\alpha = -B_z$
light cylinder

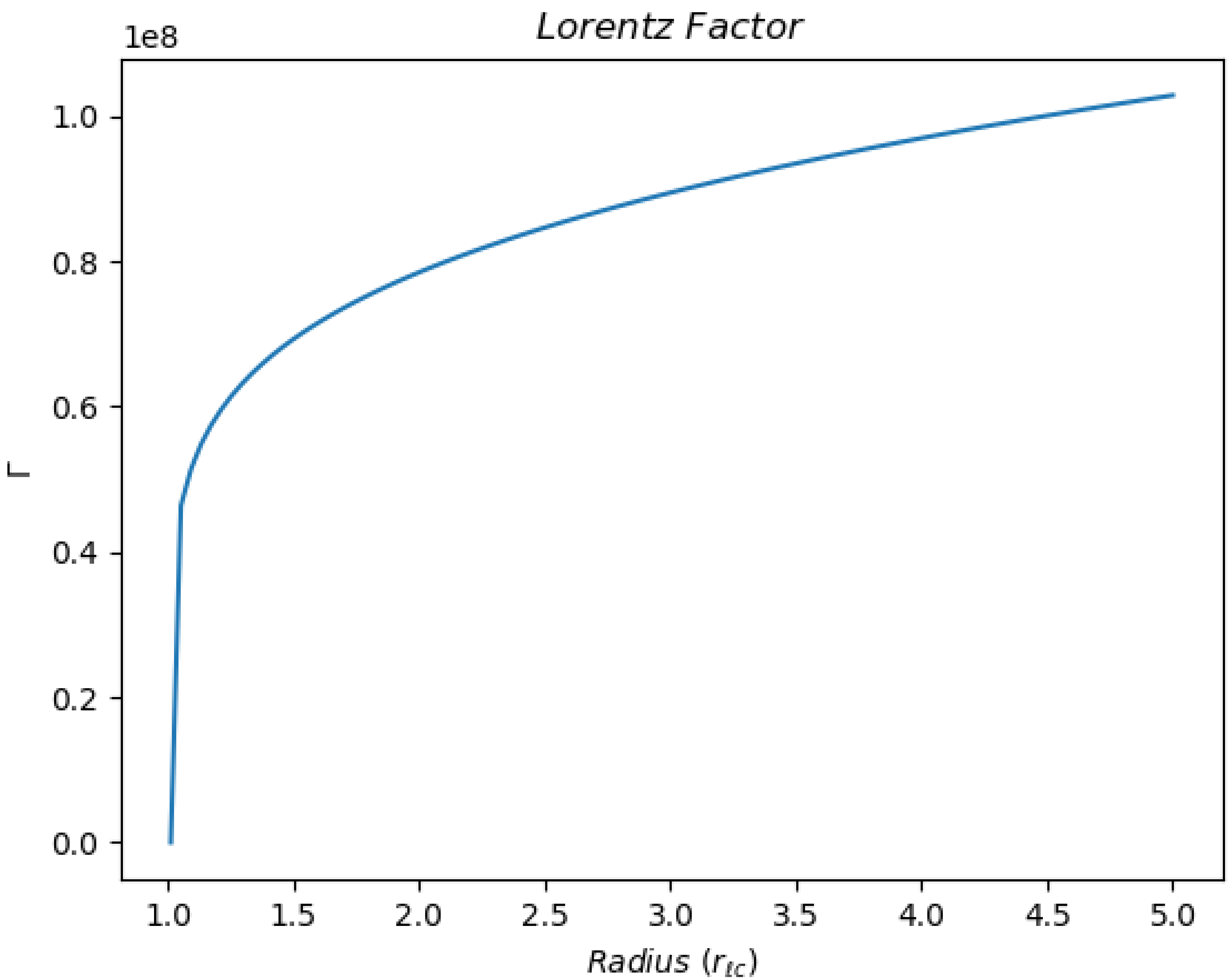


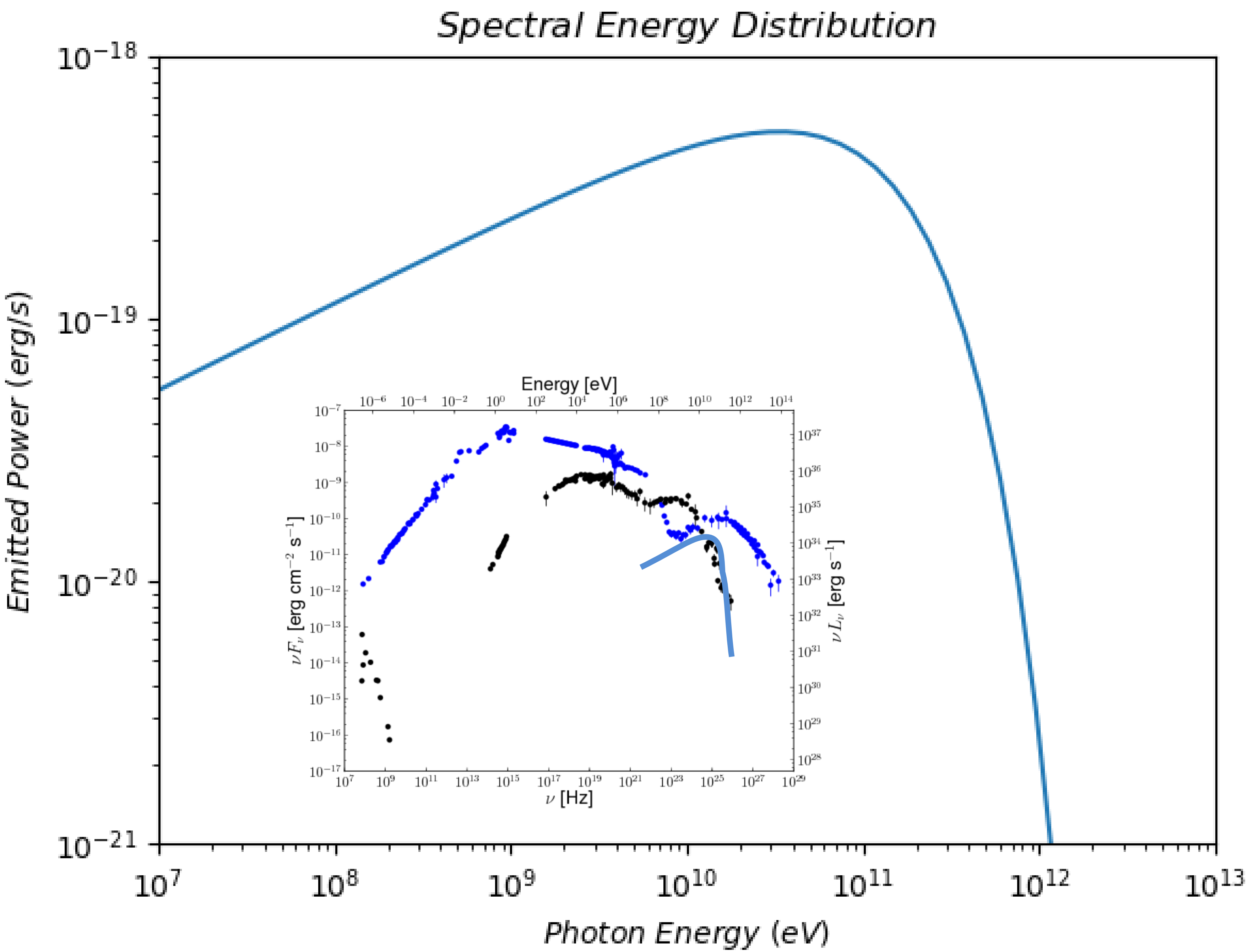
$\hat{z}$
$\hat{v}$
$v$
$\hat{\varphi}$
$\hat{\varphi}$
$E_\perp = E_r \cos\alpha = -B_z$
$\alpha$
$\hat{v}_\perp$
$E_r = -xB_z$
$\alpha$
$v_{r-}$
$\hat{r}$
$E_{||} = E_r \sin\alpha$
$B_z$
light cylinder
electron trajectories

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}t} = \frac{ecE_{\mathrm{acc}}}{m_e c^2} - \frac{2e^2\Gamma^4}{3r_{\mathrm{lc}}^2 m_e c}$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = \frac{\mathrm{e}B_{\mathrm{lc}}r_{\mathrm{lc}}}{m_{\mathrm{e}}c^2}\left\{\frac{3}{5\kappa x^3}\left(1-\frac{1}{x^2}\right)^{0.2} - \frac{\Gamma^4/\Gamma_{\mathrm{rrl}}^4}{(R_{\mathrm{c}}/r_{\mathrm{lc}})^4}\left(1-\frac{1}{x^2}\right)^{-0.5}\right\}$$

$$\Gamma_{\mathrm{rrl}} = \left(\frac{3r_{\mathrm{lc}}^2 E_{\mathrm{acc}}}{2e}\right)^{1/4} = 4\times 10^7\left(\frac{B_*}{10^{13}\mathrm{G}}\right)^{1/4}\left(\frac{P}{1\ \mathrm{s}}\right)^{-1/4}$$


Lorentz Factor
1e8
1.0
0.8
0.6
0.4
0.2
0.0
Γ
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radius ($r_{lc}$)



Spectral Energy Distribution
Emitted Power (erg/s)
Photon Energy (eV)
$10^{-18}$
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{10}$
$10^{11}$
$10^{12}$
$10^{13}$
Energy [eV]
$\nu F_\nu$ [erg cm$^{-2}$ s$^{-1}$]
$\nu L_\nu$ [erg s$^{-1}$]
$\nu$ [Hz]

# Conclusions

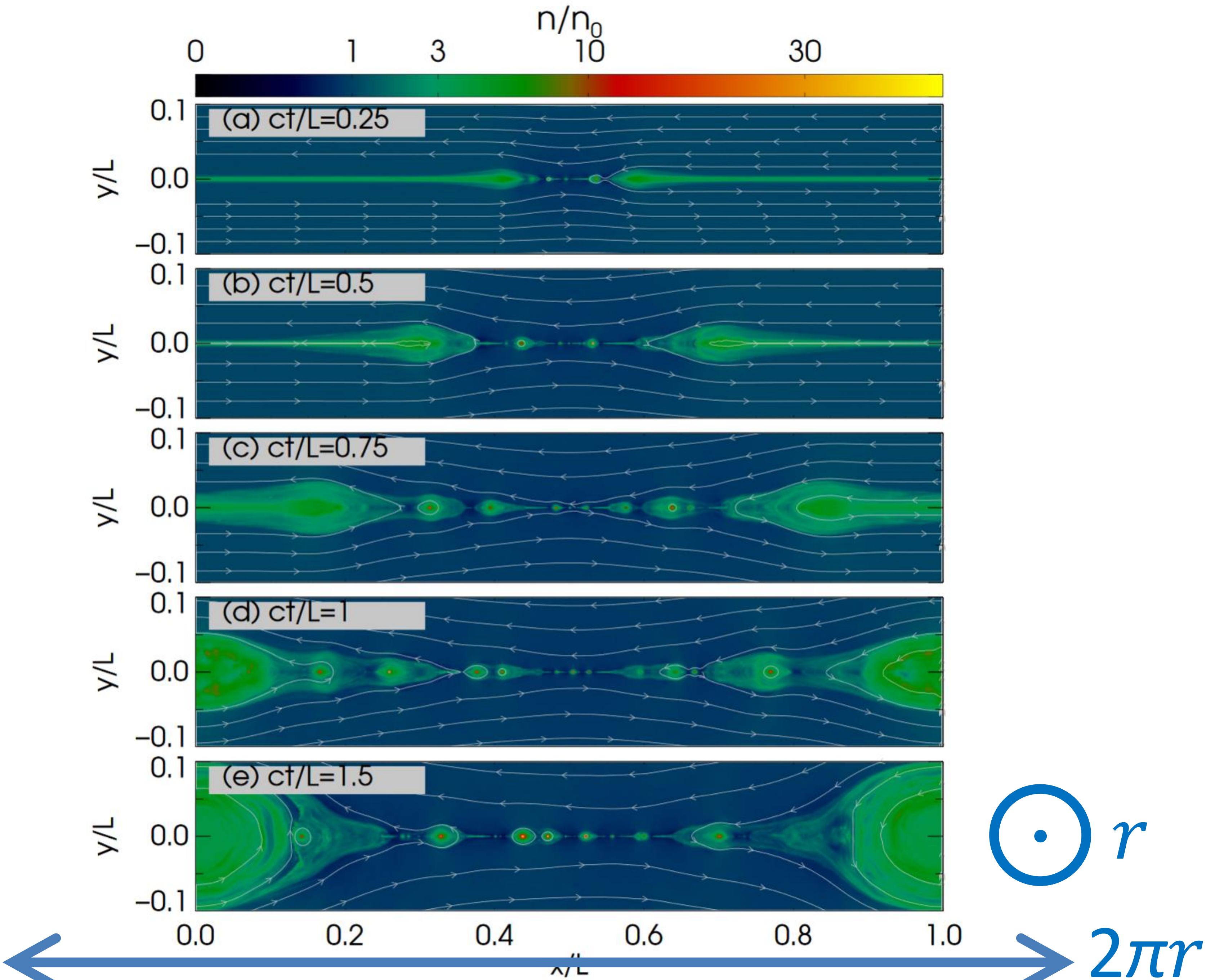
- "Ab initio" PIC simulations are very ambitious
- Current closure and charge replenishment

  → Ring of fire
- "Aristotelian" particle orbits when E>B in the CS
- We can perform calculations with realistic parameters (Γ, magnetic field)
  - High energy spectra
  - Different spectra for $e^-$ and $e^+$

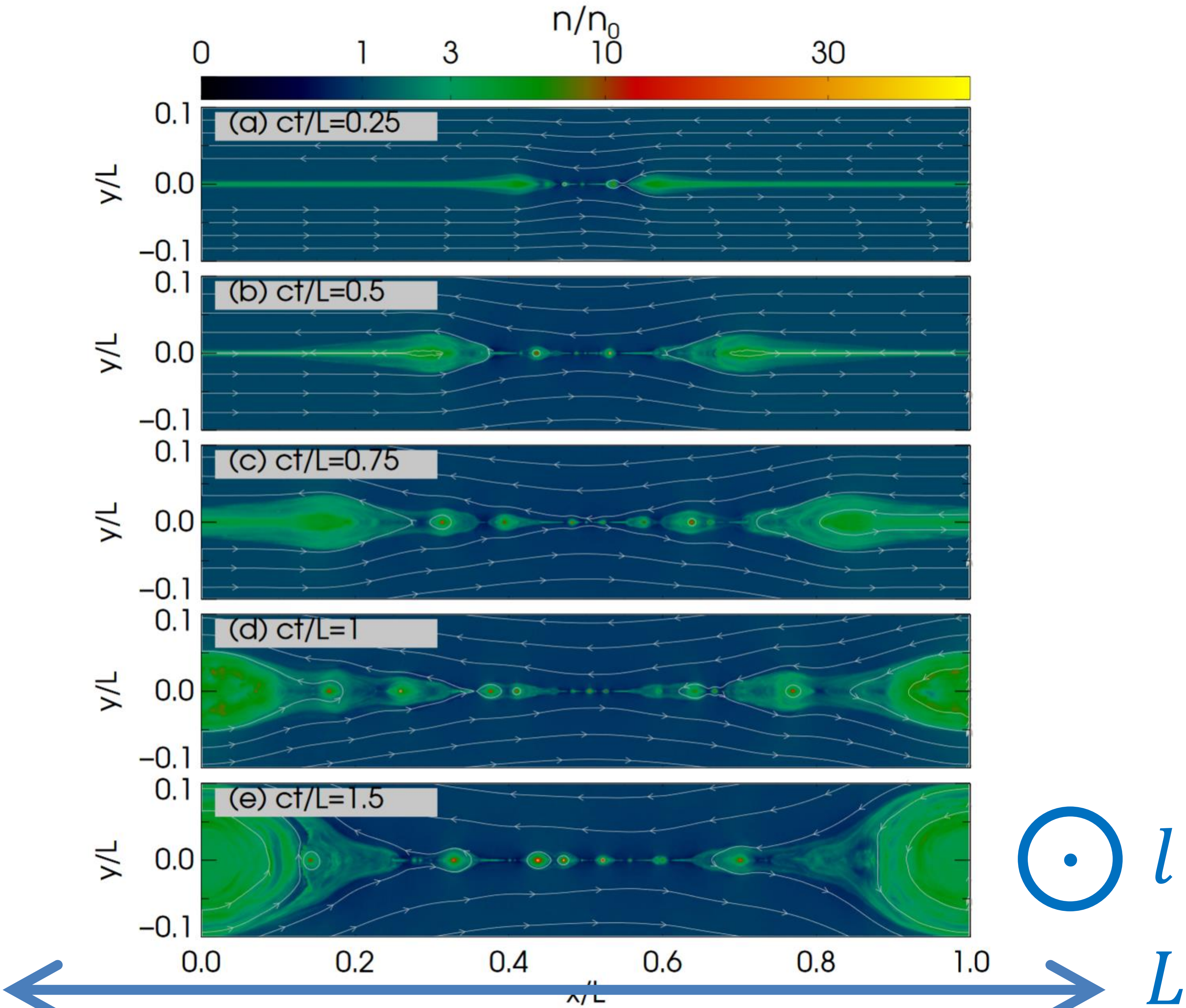
# Conclusions

- Pair-formation multiplicities near the rim of the polar cap may be very low ($\kappa \rightarrow 0$ ?!)
- Highly dissipative magnetospheres ?!
  - very different from CKF
- New type of global current sheet simulations:
  - $I \sim B_\varphi 2\pi r c \sim \rho_e v_z 2\pi r \cdot r$

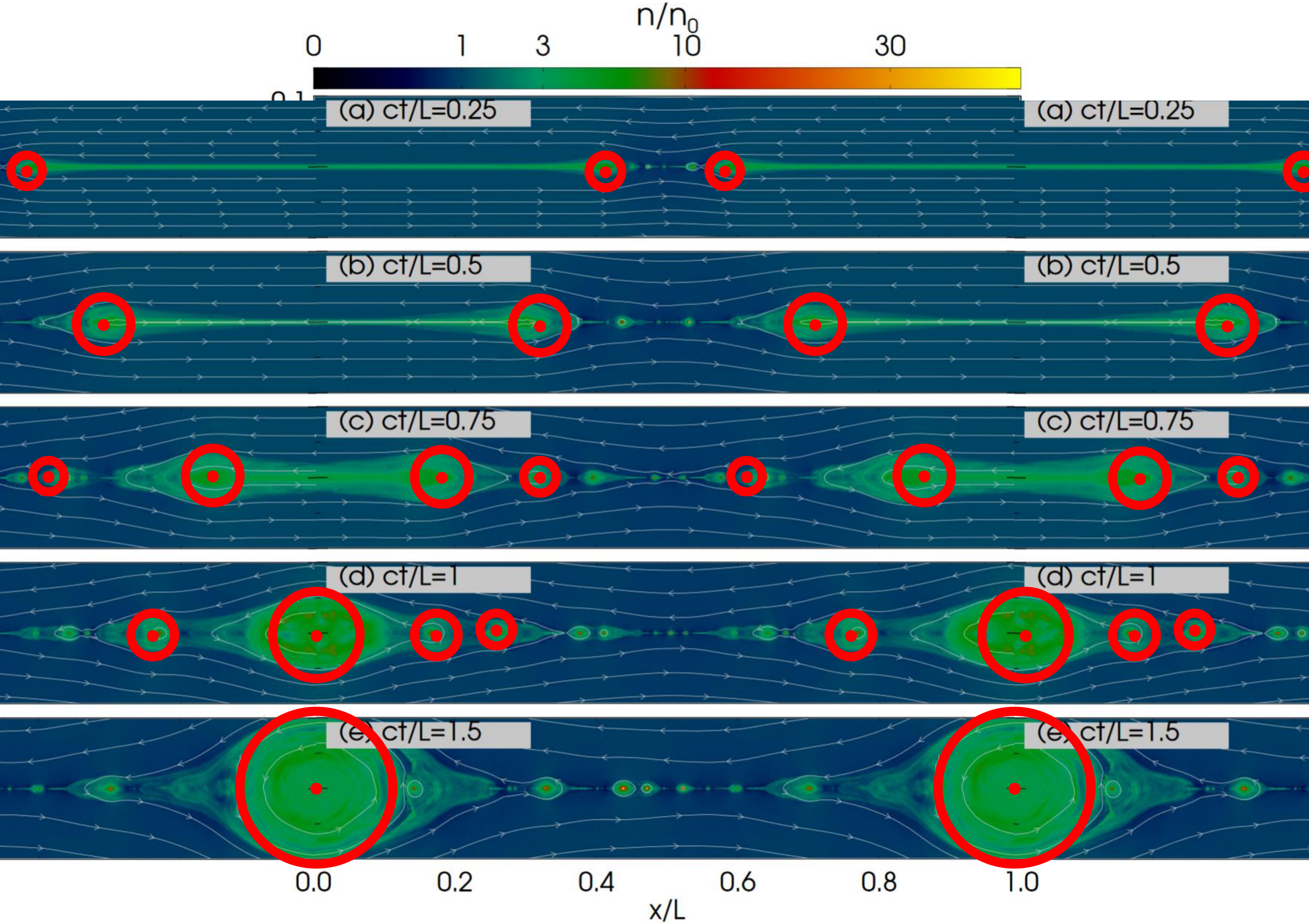
$$\sim \kappa\, \rho_{\mathrm{GJ}} \frac{E_r}{B_\varphi} cL \cdot l \rightarrow E_r \sim \frac{1}{\kappa}$$



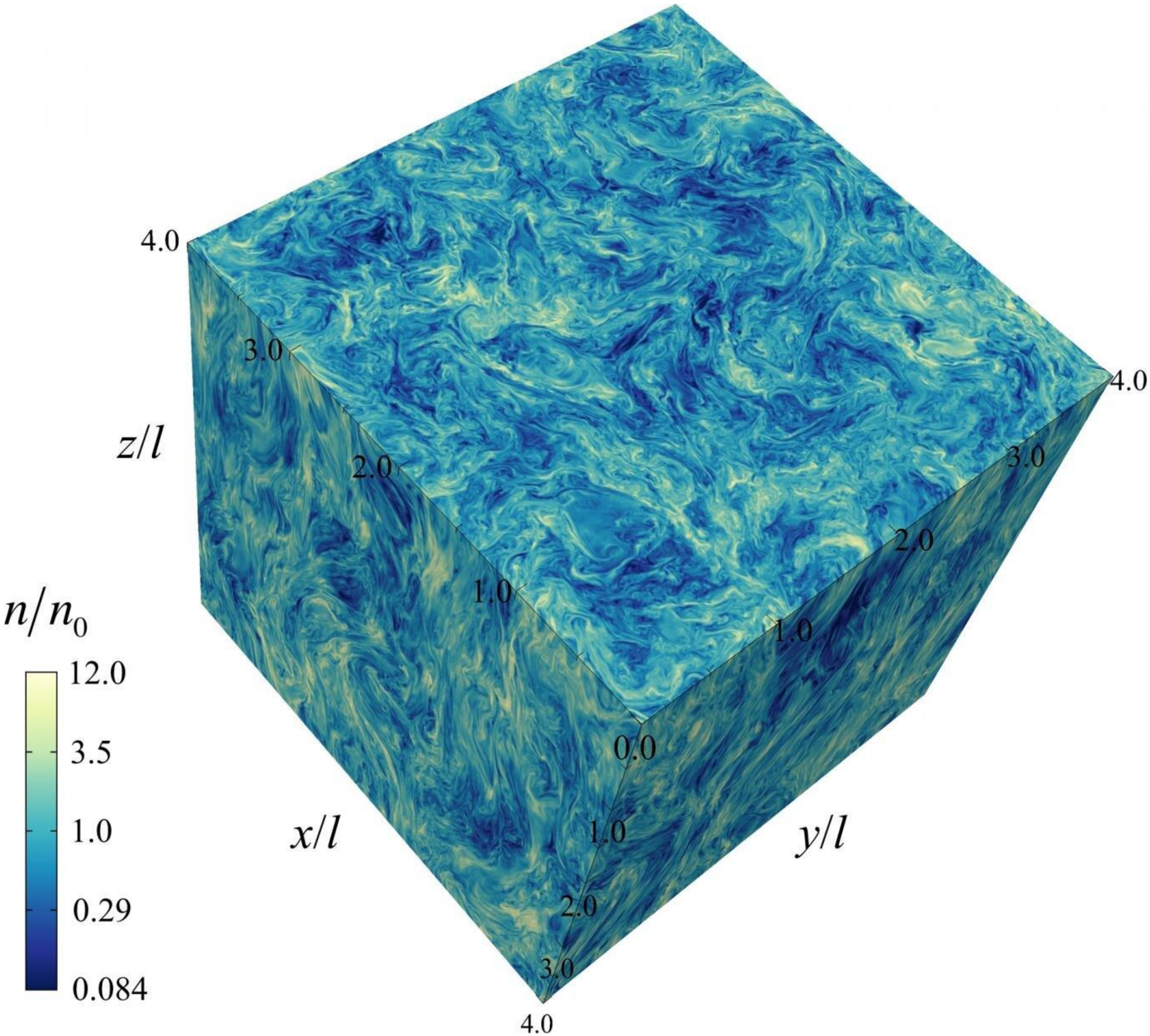

Petropoulou, Sironi, Spitkovsky, Giannios 2019




Petropoulou, Sironi, Spitkovsky, Giannios 2019




Petropoulou, Sironi, Spitkovsky, Giannios 2019




Comisso & Sironi 2019

# Conclusions

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    $\sim \kappa\, \rho_{\mathrm{GJ}} \frac{E_r}{B_\varphi} cL \cdot l \rightarrow E_r \sim \frac{1}{\kappa}$
- More questions…
- Need hybrid simulations!

# The multi-messenger physics and astrophysics of neutron stars

PHAROS Conference
30 March - 3 April, 2020
Porto Rio Hotel, Patras, Greece

## S.O.C.

Felix Aharonian
Sergei Bogovalov
Marta Burgay
Ioannis Contopoulos
Daniela Doneva
Morgane Fortin
Ersin Gogus
Kostas Gourgouliatos
Vanessa Graber
Alice Harding
Bryn Haskell
Yuri Lyubarsky
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Nanda Rea
Luciano Rezzolla
David Smith
Ben Stappers
Anna Watts

## L.O.C.

Ioannis Contopoulos
Kostas Gourgouliatos
Vasileios Karageorgopoulos

## Thematic Areas

-Dense matter: equations of state, superfluidity and superconductivity
-Magnetic field formation, structure and evolution
-Neutron star observations: from radio to gamma-rays
-Neutron stars in the multimessenger era
-Magnetospheric high-energy emission
-Population studies
-Fast Radio Bursts

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

UNIVERSITY OF PATRAS
ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ

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