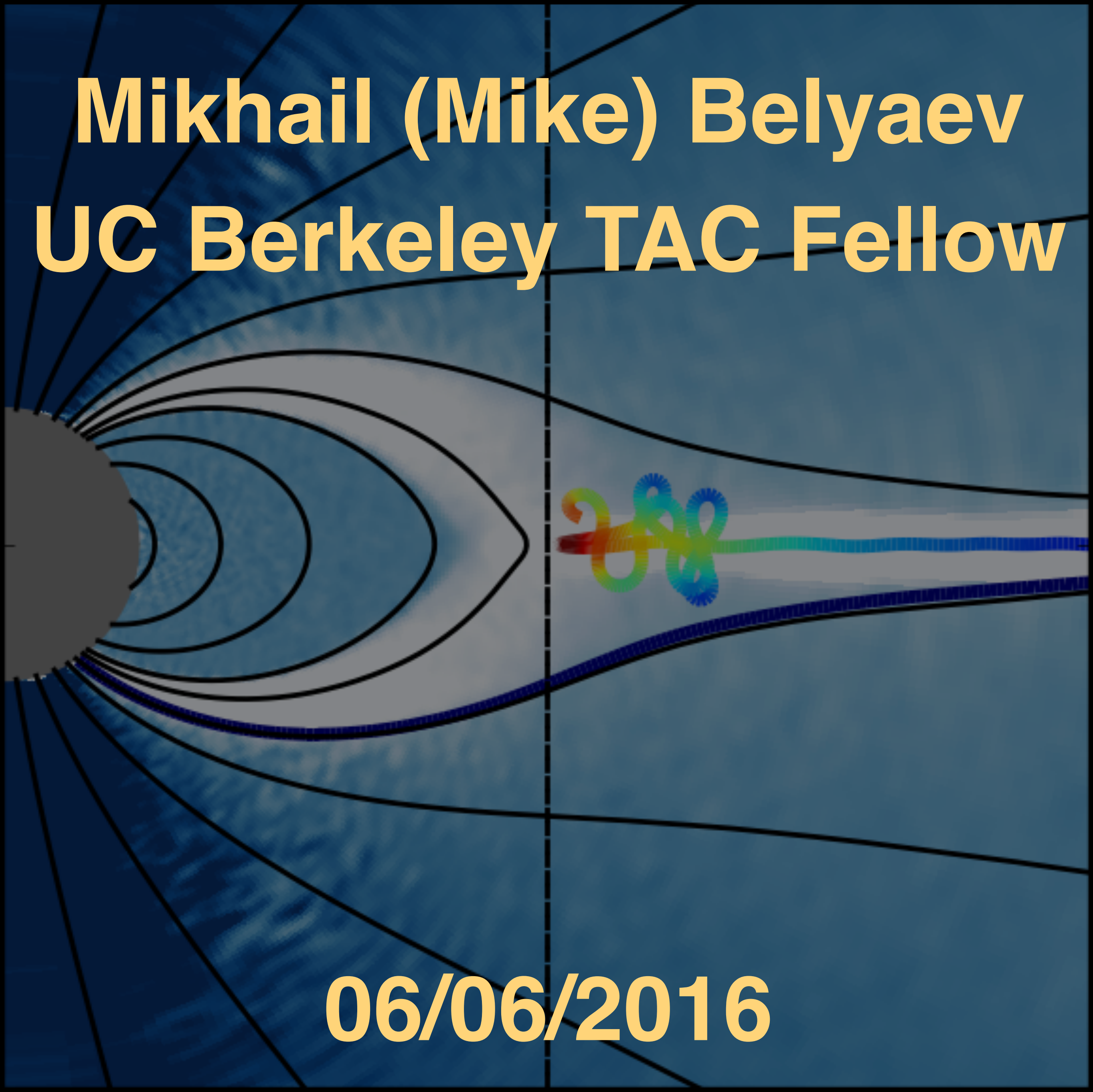
Polar Cap & Y-Point

Theory & PIC Simulation



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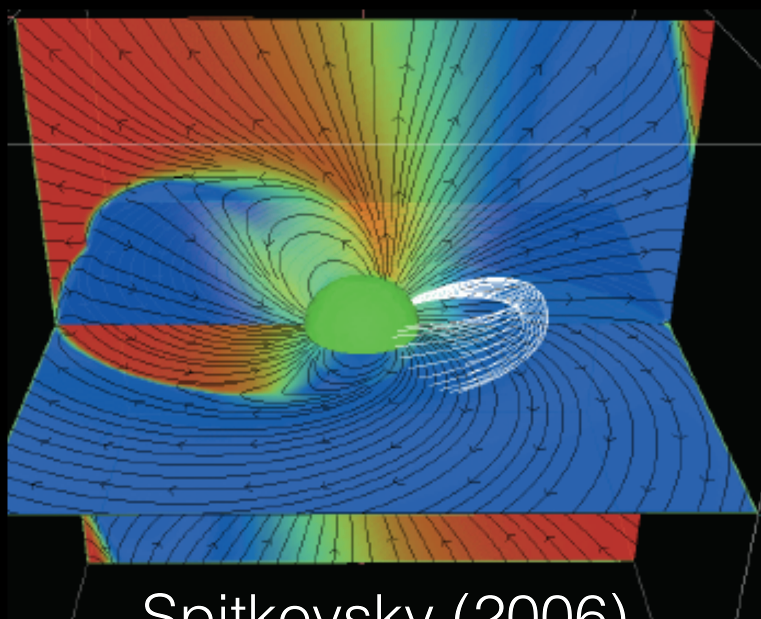
Theoretical Backgr

We need to go beyond force-free to understand the emission and connect to observations!

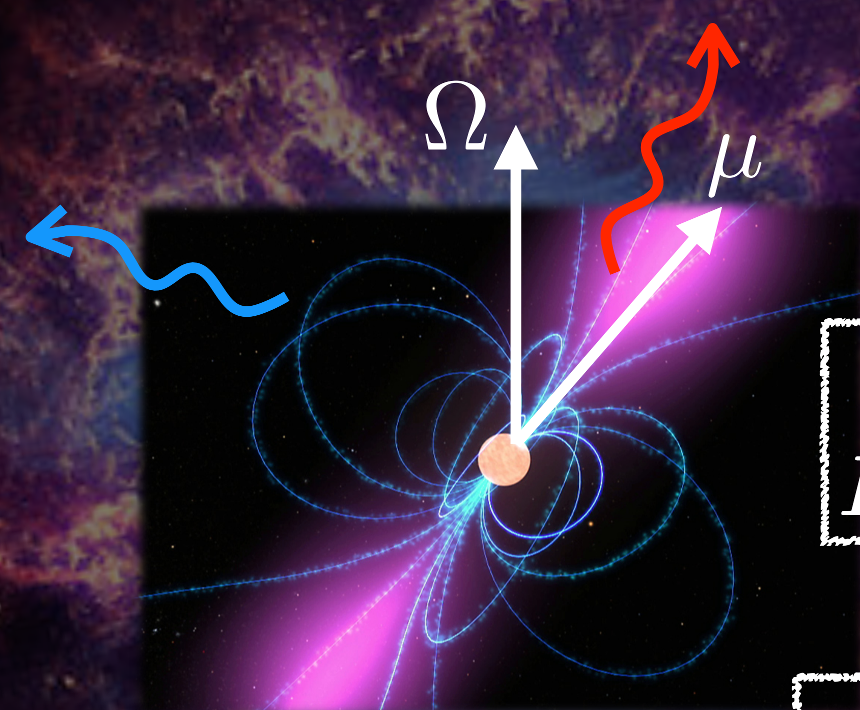


Spitkovsky (2006)

Magnetosphere approximated as force-free due to a high plasma density.

$$\rho \boldsymbol{E} + c^{-1} \boldsymbol{J} \times \boldsymbol{B} = 0 \implies \boldsymbol{E} \cdot \boldsymbol{B} = 0$$

$$B^2 - E^2 > 0 \implies \boldsymbol{V}_d = c\boldsymbol{E} \times \boldsymbol{B}/B^2$$



Gaps
$\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$

Instabilities

Current sheets
$B^2 - E^2 < 0$

Emission in the magnetosphere requires non-force-free effects.

$$\frac{\partial u}{\partial t} + \frac{c}{4\pi} \nabla \cdot (\boldsymbol{E} \times \boldsymbol{B}) = -\boldsymbol{E} \cdot \boldsymbol{J}$$

Part I: Polar Cap

Goals:

- Analytically determine distribution of current over the polar cap for a force-free magnetosphere with aligned spin and magnetic axes.

- Relate spatial distribution of current to spatial distribution of polar cap pair production.

Results:

- Pair production occurs at the inner and outer edges of the polar cap when general-relativity taken into account.

- No pair production at mid-latitudes on polar cap for simple surface field structure (e.g. dipole).

Polar Cap Pair Production

$$J^\mu J_\mu \equiv -(\rho c)^2 + J^2$$

$\gamma - B$ **pair production**

Pairs generated when there is backflow of particles onto the polar cap.

Pairs produced locally:

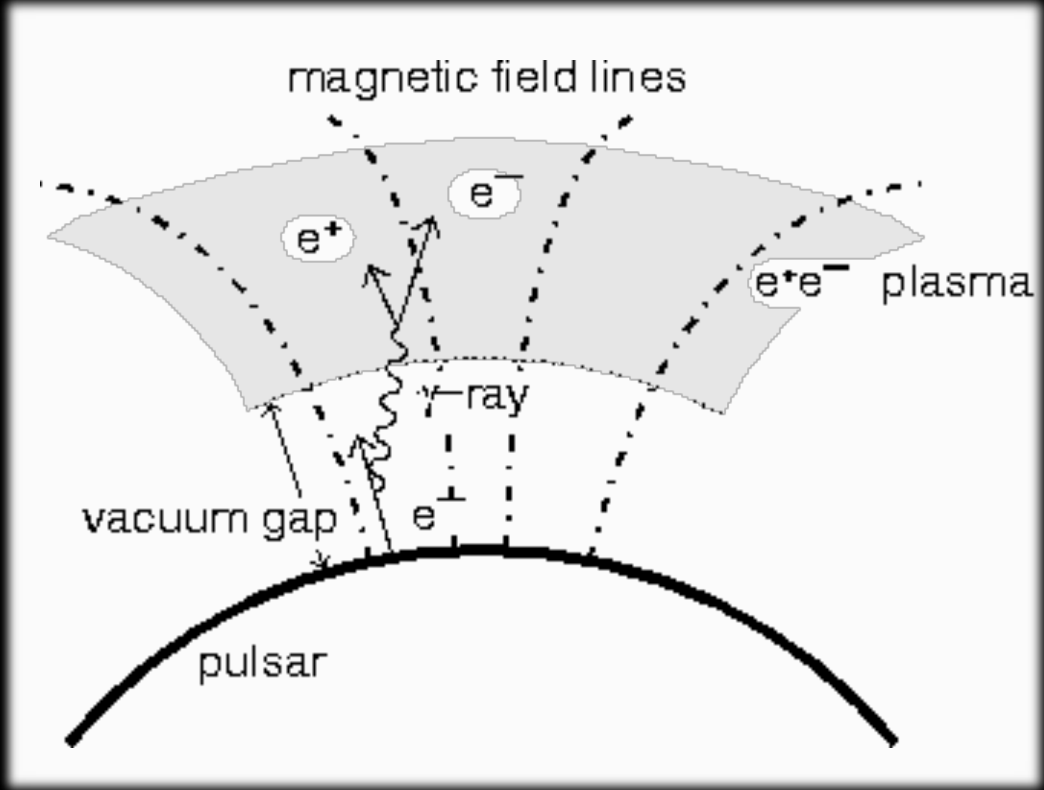
Field line by field line basis

Beloborodov (2008)

Timokhin & Arons (2013)

$$J^\mu J_\mu < 0 \begin{cases} \boldsymbol{J} \cdot \hat{\boldsymbol{r}}/\rho_{GJ} > 0 : \text{no pairs} \\ \boldsymbol{J} \cdot \hat{\boldsymbol{r}}/\rho_{GJ} < 0 : \text{pairs} \end{cases}$$

$$J^\mu J_\mu > 0 : \text{pairs}$$



General Solution Method

Density is determined ***locally*** as GJ density

$$\boldsymbol{V}_0 \equiv \begin{cases} \boldsymbol{\Omega} \times \boldsymbol{r}, & \text{flat} \\ \alpha^{-1}\left(\boldsymbol{\Omega} - \boldsymbol{\omega}_{LT}\right) \times \boldsymbol{r}, & \text{Kerr} \end{cases}$$

$$\rho_G = -\frac{(\boldsymbol{\Omega} - \boldsymbol{\omega}_{LT}) \cdot \boldsymbol{B}}{2\pi c \alpha} + \frac{\boldsymbol{V}_0 \cdot (\boldsymbol{\nabla} \times \boldsymbol{B})}{4\pi c}$$

Current is set by ***global*** magnetospheric structure

Poloidal current flows along magnetic flux surfaces

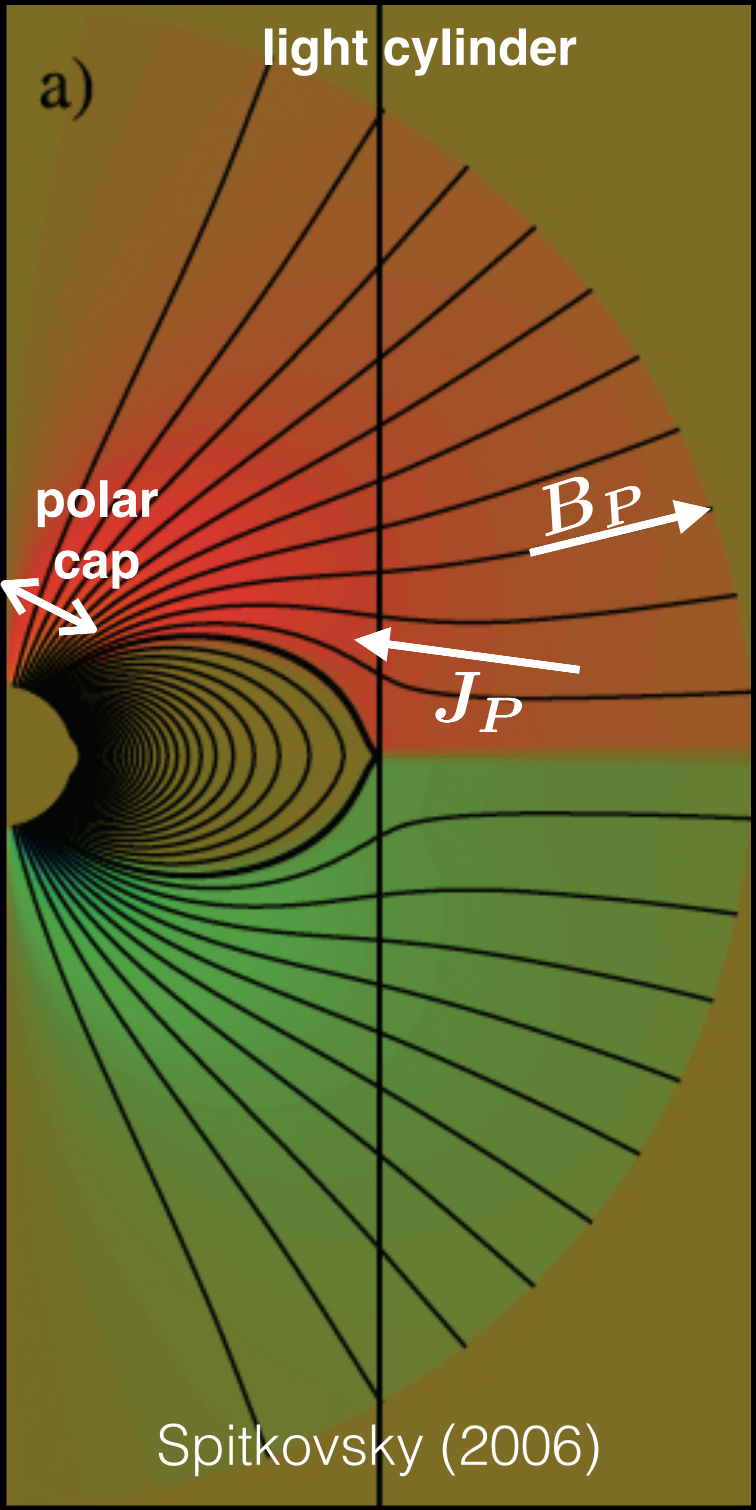
$$\boldsymbol{J}_P \times \boldsymbol{B}_P = 0$$

$$\boldsymbol{\nabla} \cdot (\alpha \boldsymbol{J}) = 0$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

→ flux surface invariant

$$\alpha \boldsymbol{J}_P \propto \boldsymbol{B}_P$$



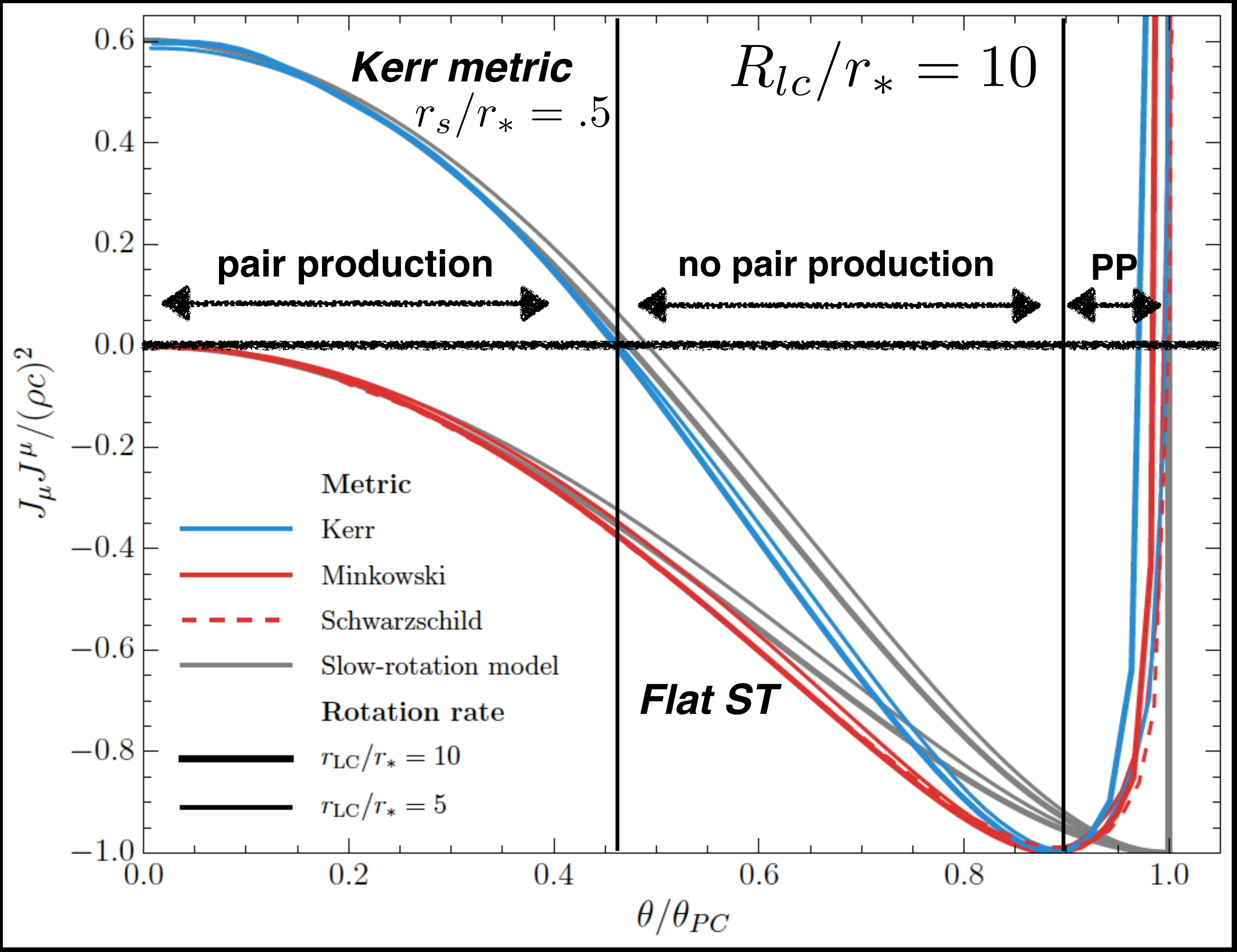
Trace back current on open B field lines from beyond light cylinder (simple current distribution) to the polar cap (complicated distribution)

Dipole: Computational Results

Difference between GR and flat ST due exclusively to frame dragging.

With GR, ***two PP regions.*** *Second region due to distributed return current.*

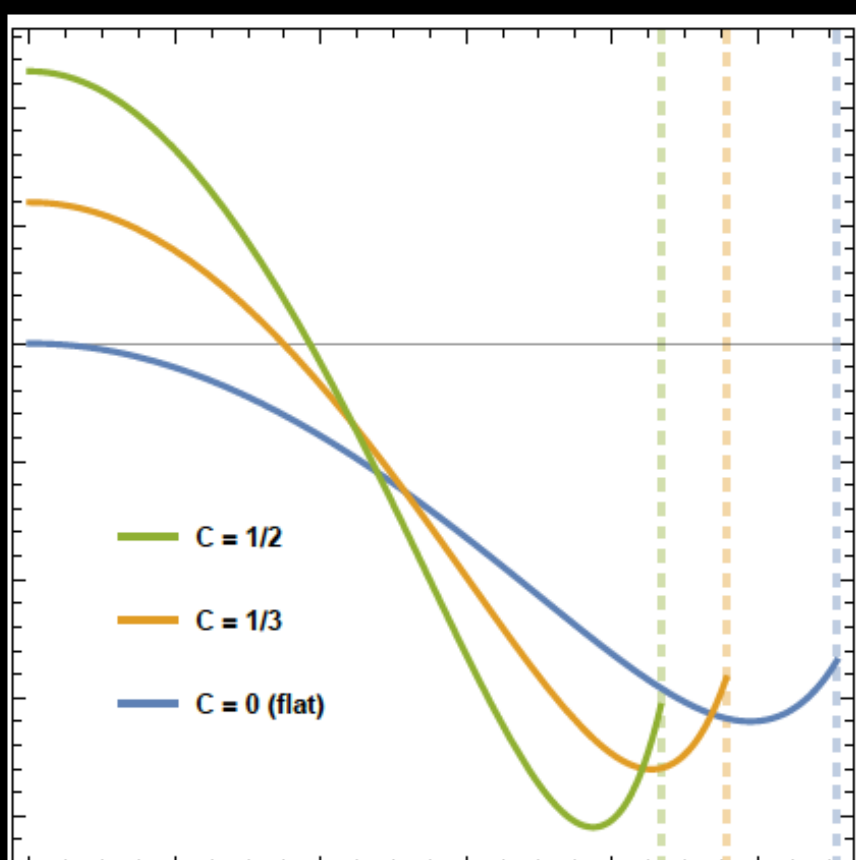
No PP region ***always*** exists, because poloidal current changes sign.



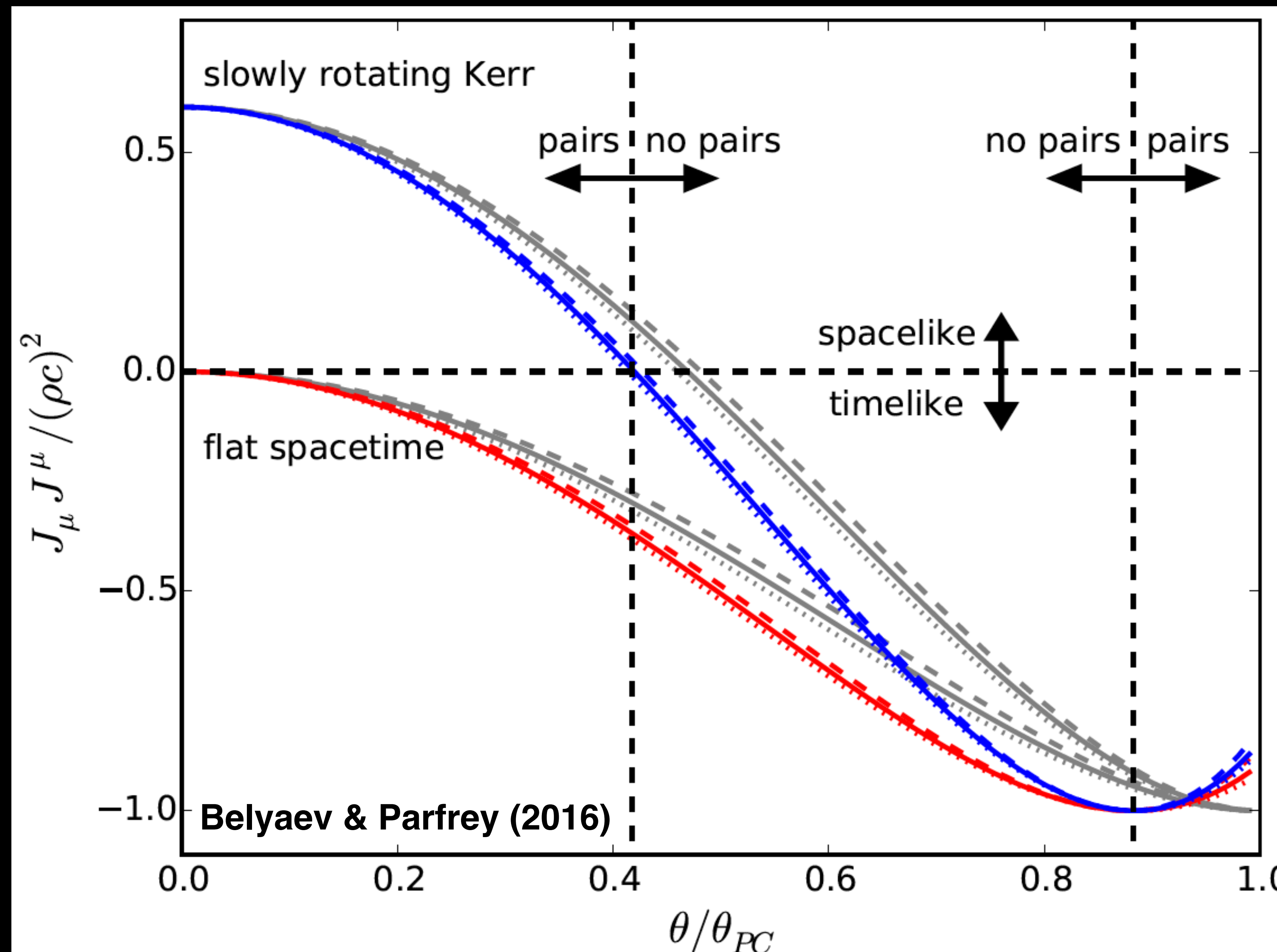
Belyaev & Parfrey (2016)

Dipole: Analytical Results

- Gray curves — split monopole
- Color curves — SM + 1st correction
- Different linetypes — different amounts of open flux and different ratios of R_lc/r_*.



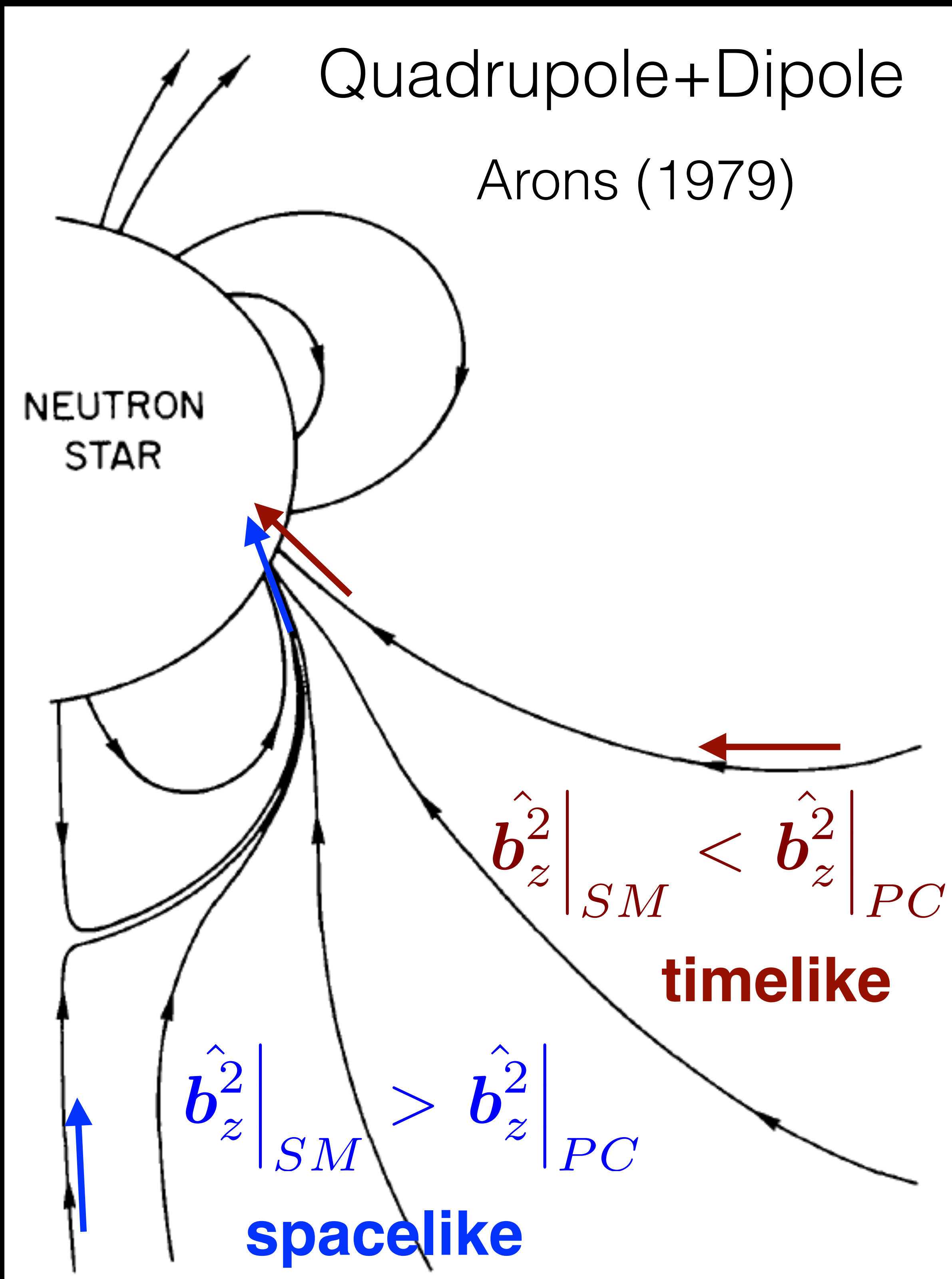
Gralla, Lupsascu, Philippov (2016)



$$B_r^{(1)}(\theta) = B_0(r/r_0)^{-2}[1 + 0.02\sin\theta + 0.22(\cos\theta - 1) - 0.07(\cos\theta - 1)^4] \times \text{sign}\cos\theta.$$

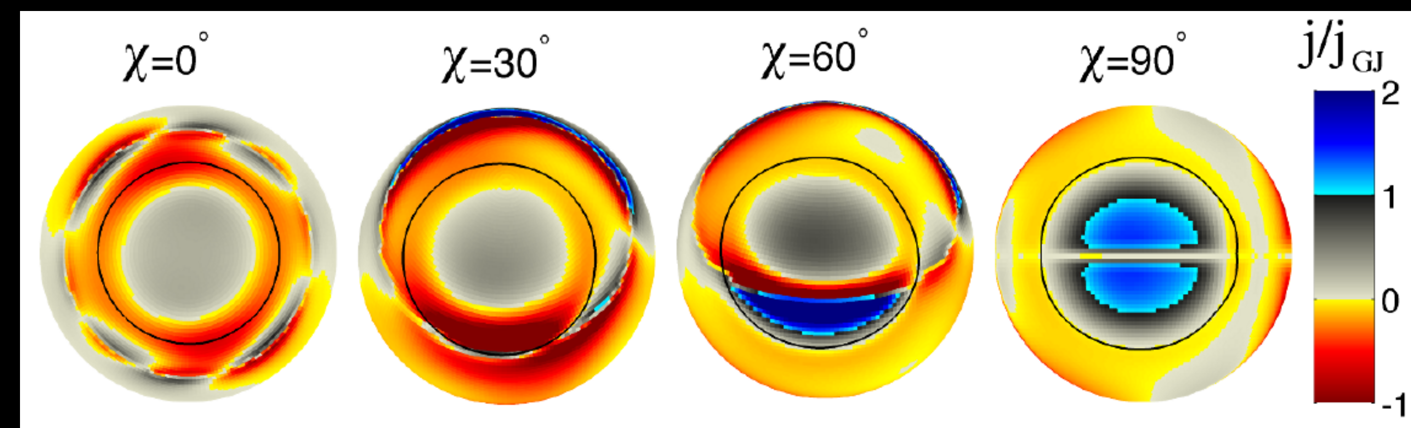
Tchekhovskoy, Philippov & Spitkovsky (2016)

More General Surface Field



Extension to 3D

Bai & Spitkovsky (2010)



Gruzinov (2005)

$$\boldsymbol{B} \times \left[\boldsymbol{\nabla} \times \left(\boldsymbol{B} + \frac{\boldsymbol{V}_0}{c} \times \left(\frac{\boldsymbol{V}_0}{c} \times \boldsymbol{B} \right) \right) \right] = 0$$

Current-like 3D vector invariant along magnetic field lines.

Part II: Pulsar Y-Point

Goals:

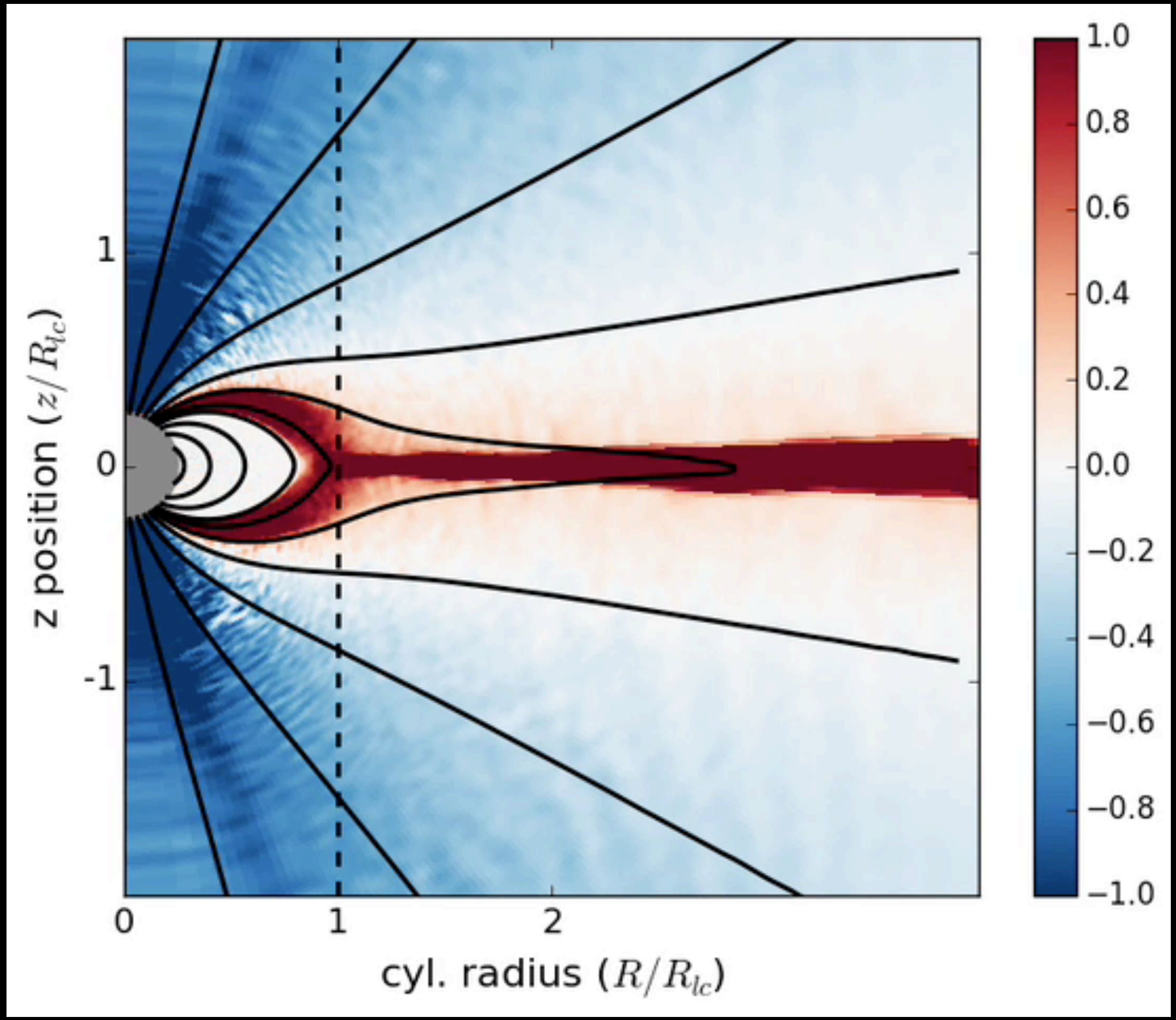
- Understand particle trajectories at the Y-point and in the current sheet beyond it.
- Understand dissipation at the pulsar Y-point, i.e. the role of pair multiplicity on dissipation and kink instability.

Results:

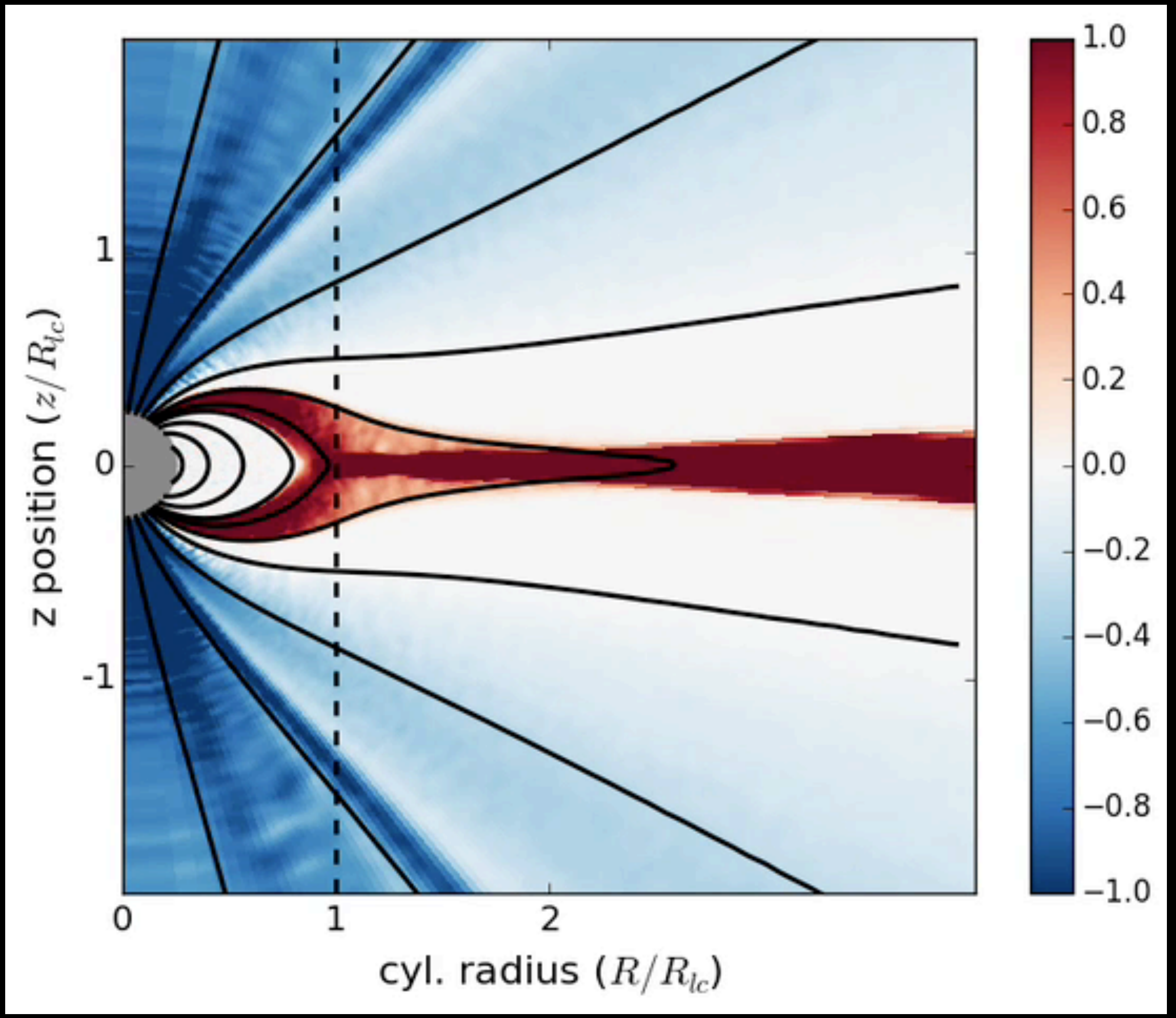
- Axisymmetric magnetosphere is inherently dissipative.
- Y-point can extend inside light cylinder with PIC due to finite Larmor radius effect.
- Radiation reaction likely to be important for particle trajectories at the Y-point.

Magnetospheric Current

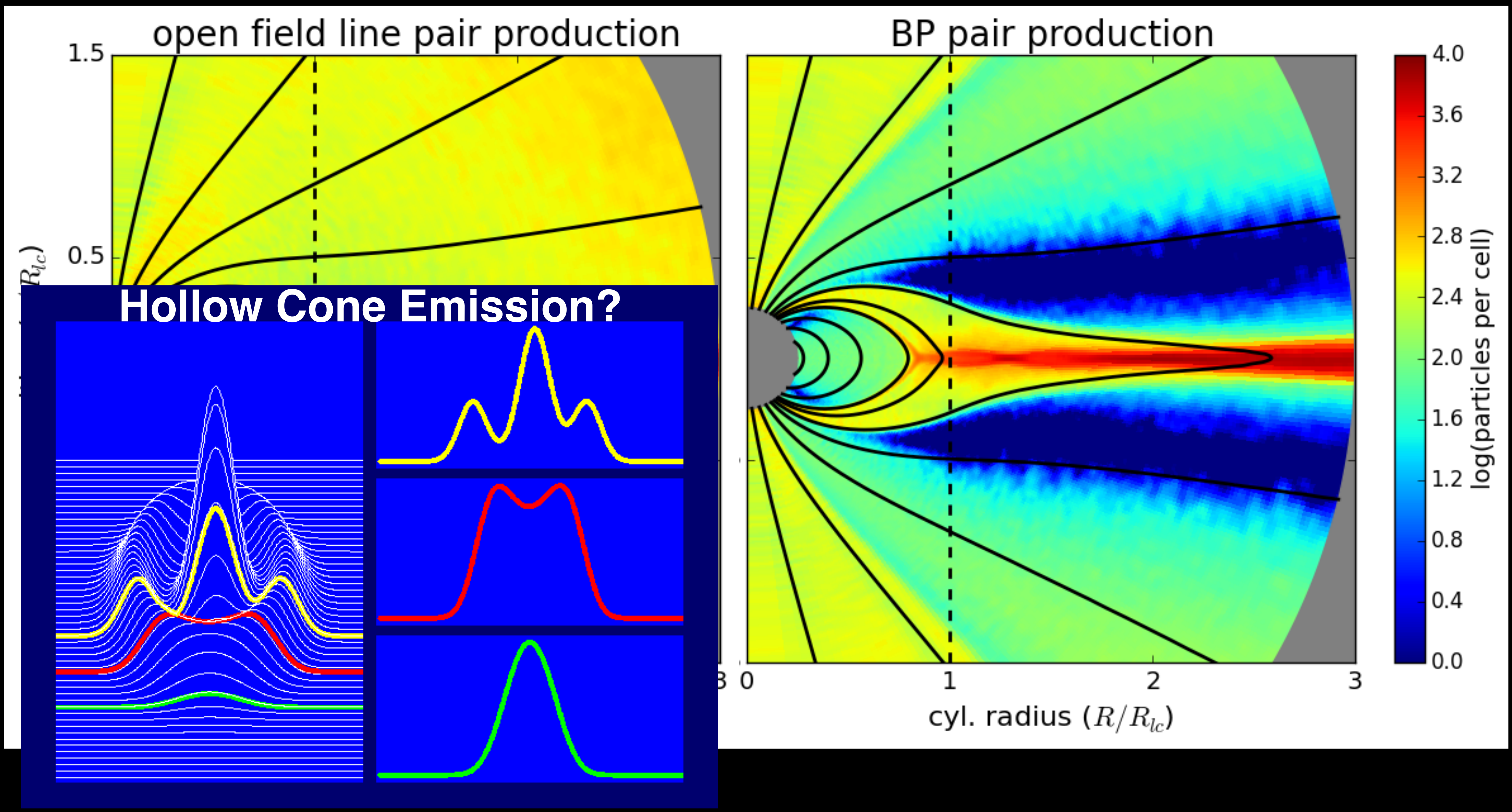
PP Open Field lines



BP Model

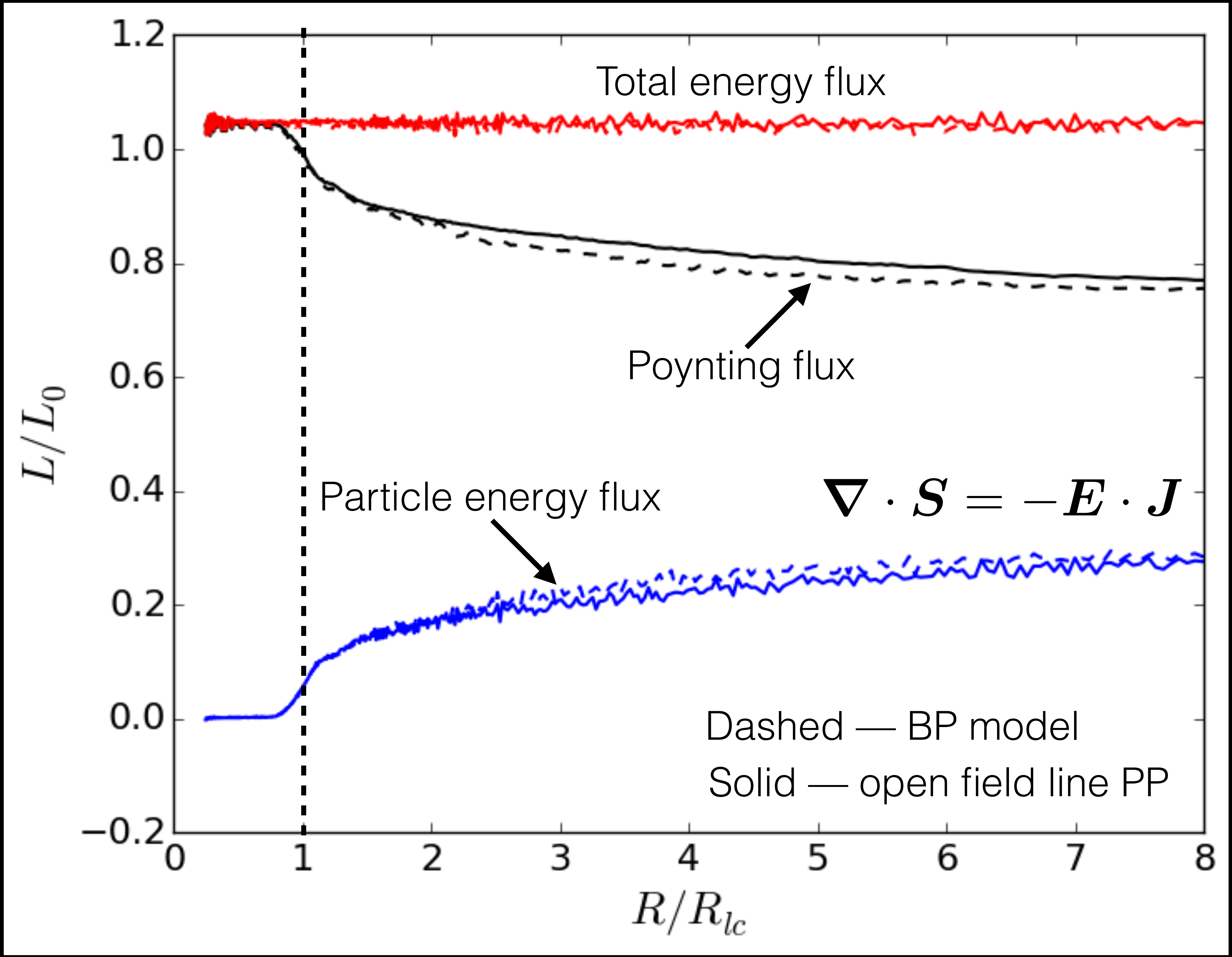


Mind the Gap!

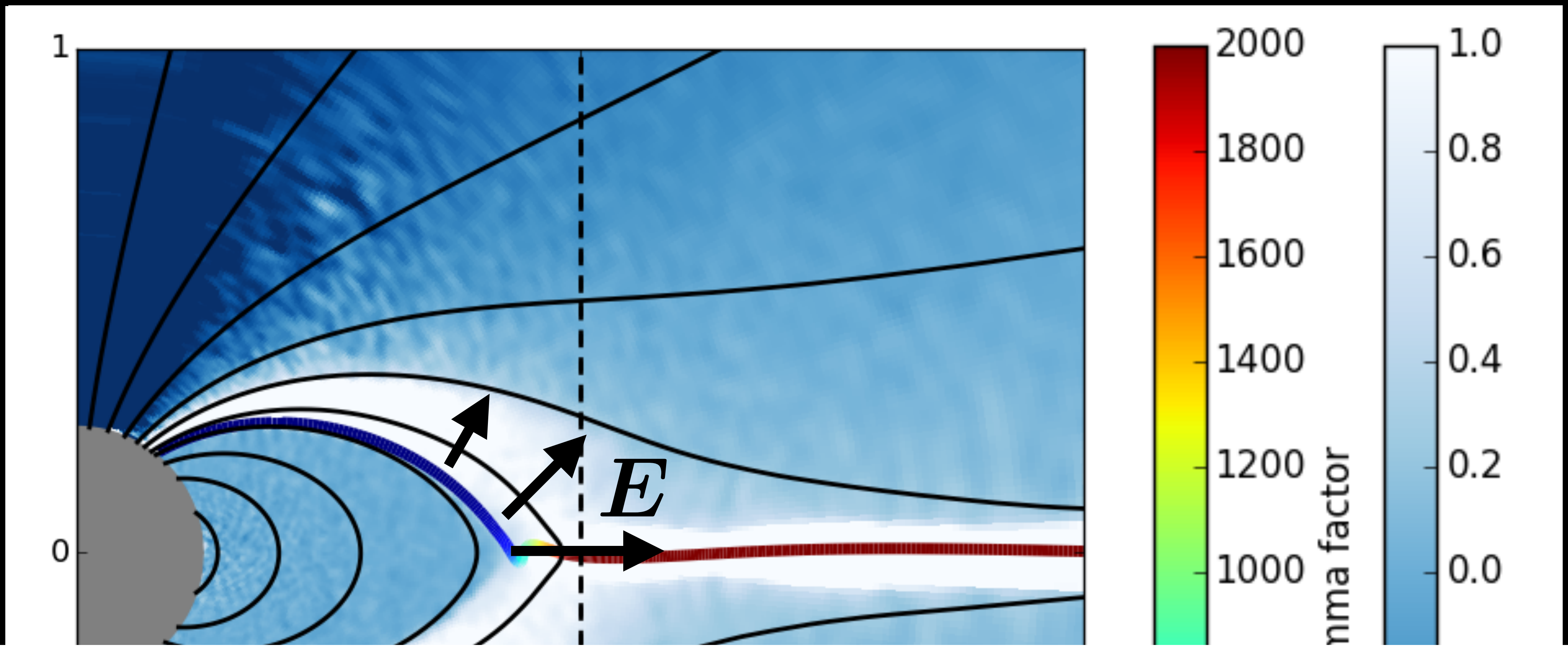


BP PP model has a large outer gap above the current sheet.

Luminosity & Dissipation



Positron Trajectory

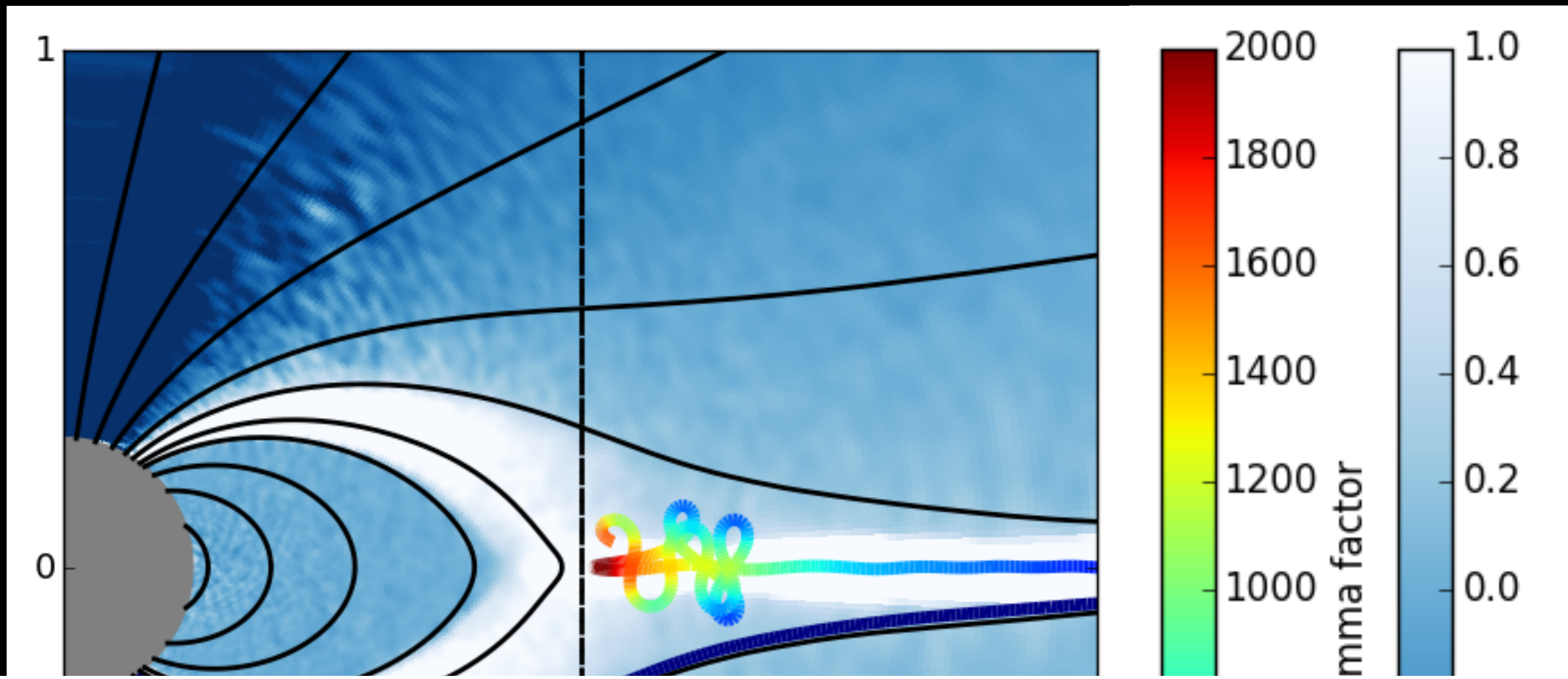


Drift velocity close to speed of light near Y-point:

$$v_{D,\phi} = -E_r/B_z \lesssim c, \quad B'_z = B_z/\gamma_D$$

Particles in closed region accelerate radially across field lines (voltage drop). They cross light cylinder before turning around and escape to infinity in current sheet.

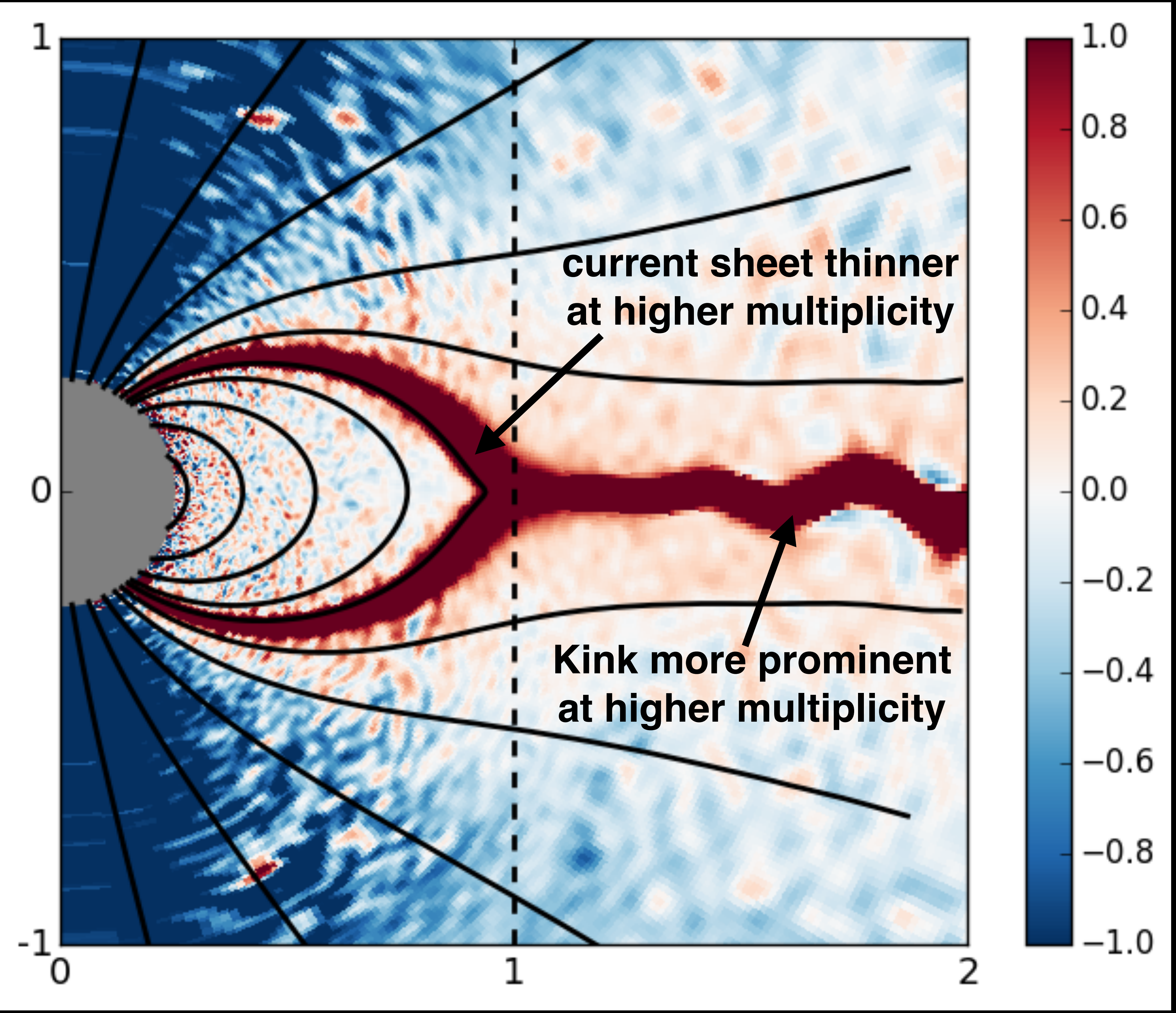
Electron Trajectory



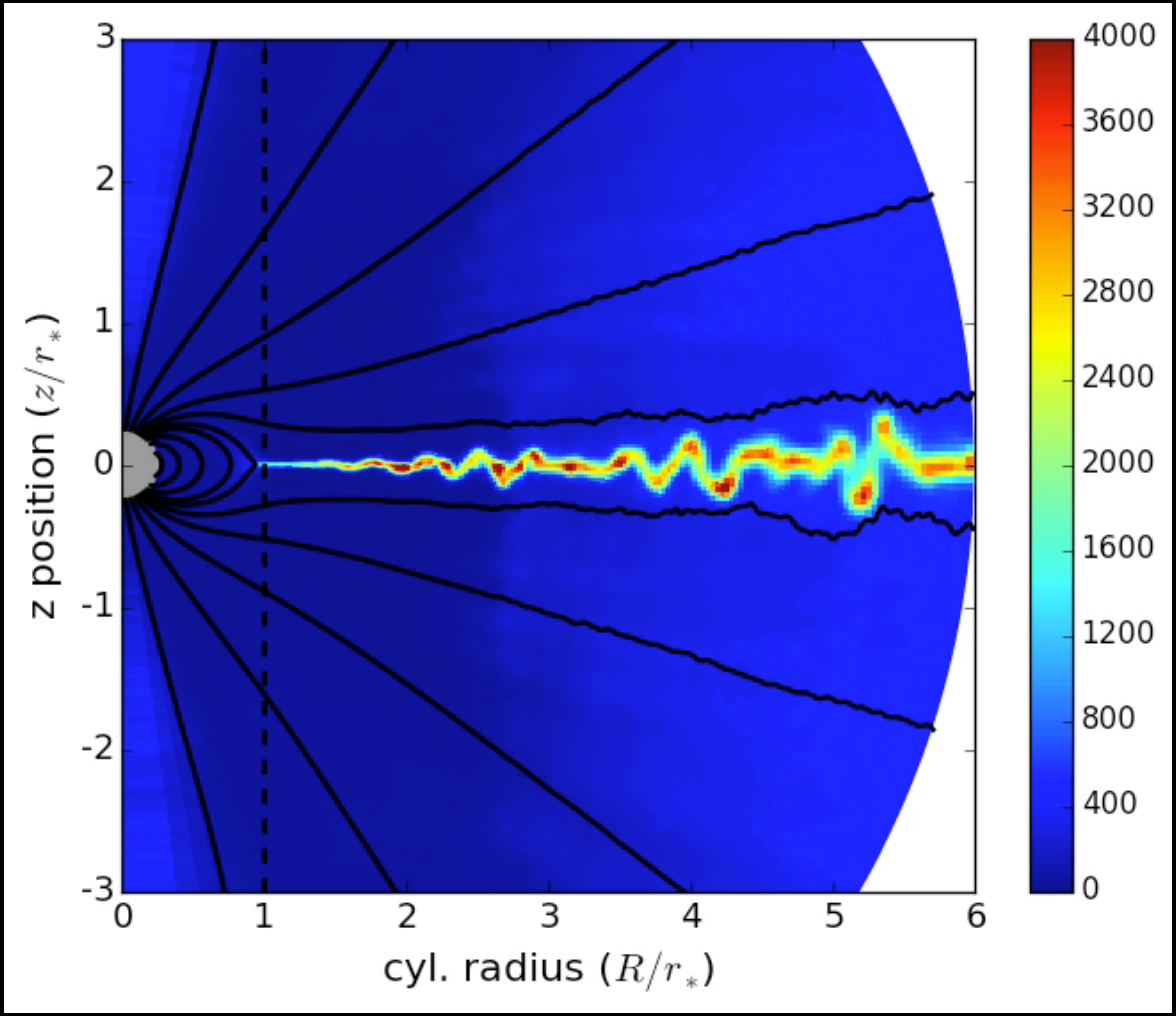
Electrons entering current sheet are sent back towards Y-point —> current sheet mostly positive charges

Backflowing electrons cannot cross Y-point due to magnetic mirror effect. With radiation reaction it should be possible for electrons to flow back through Y-point.

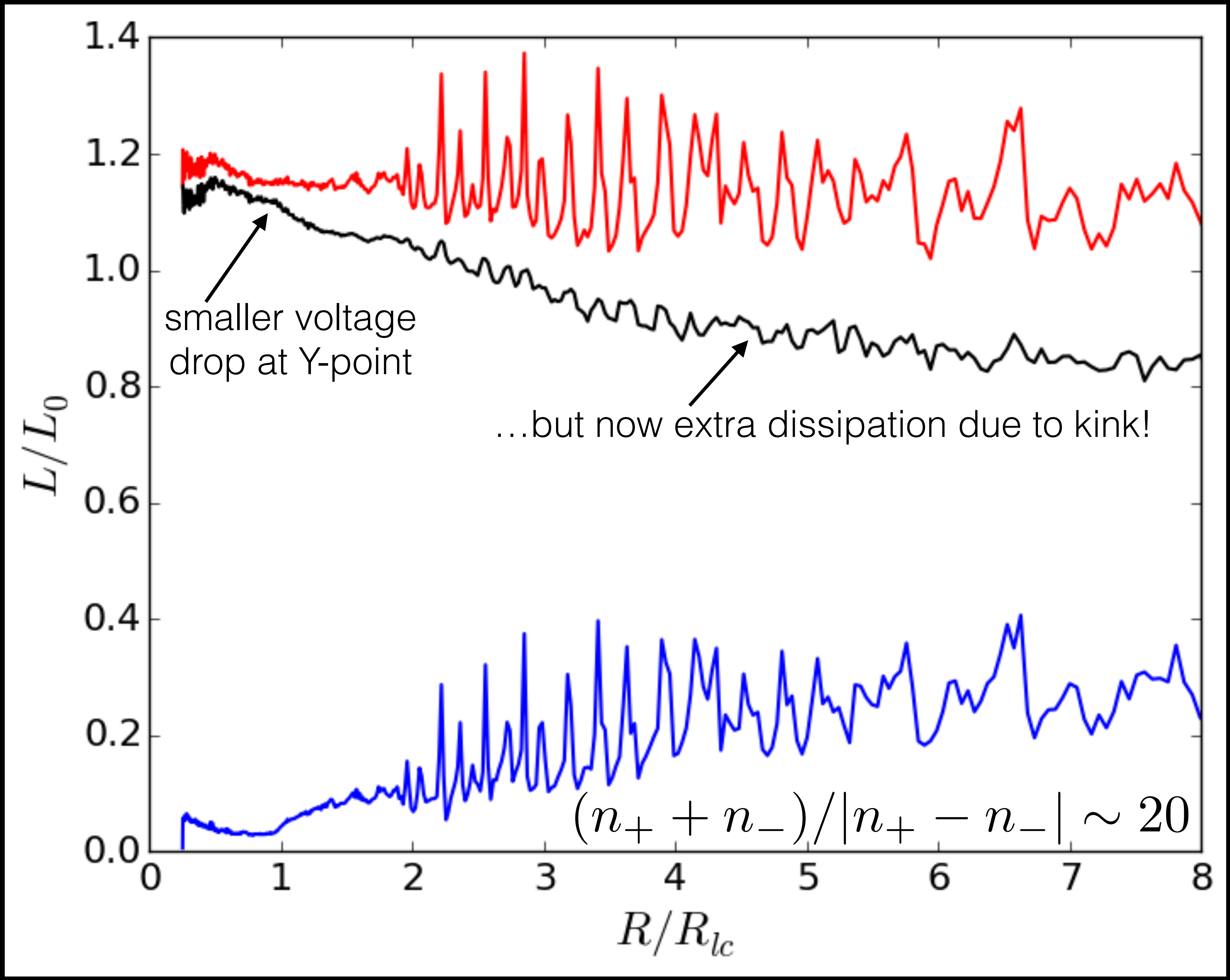
Y-Point at Higher Pair Multiplicity



Current Sheet Kink Instability



Dissipation due to Kink



Conclusions

1. **Targeted studies** of polar cap and Y-point beyond force-free limit.

2. **Polar cap** — computed spatial distribution of pair production with implications for radio & high energy emission as well as for gaps.

3. **Y-point** — studying particle trajectories and dissipation. Around 20% of FF luminosity dissipated in current sheet. Dissipation is inherent to aligned rotator.