Global Particle Simulation of Pulsar Magnetospheres

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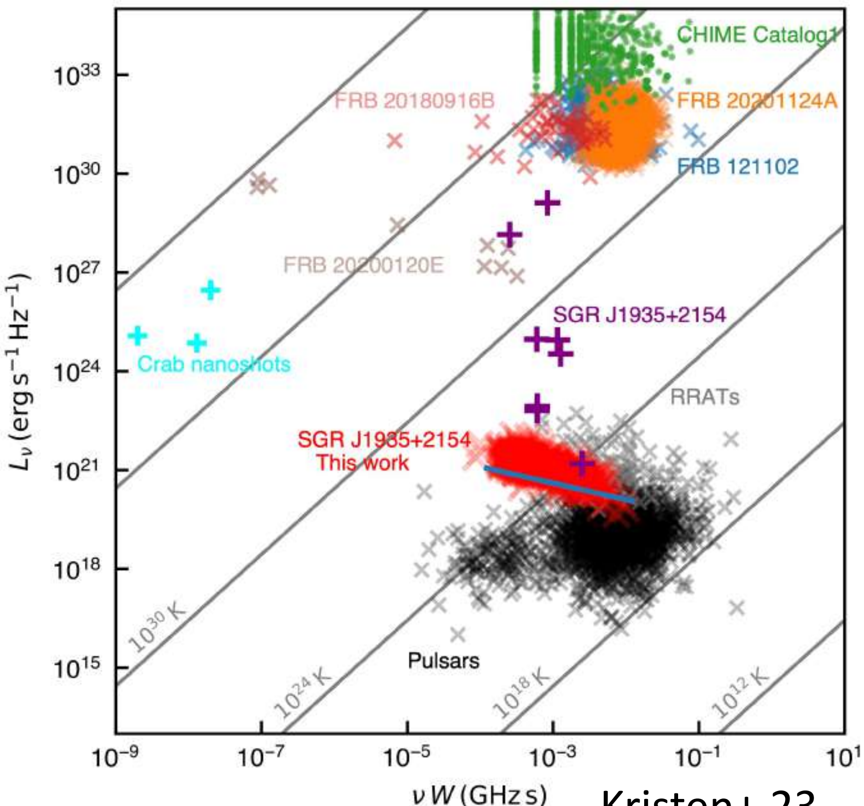
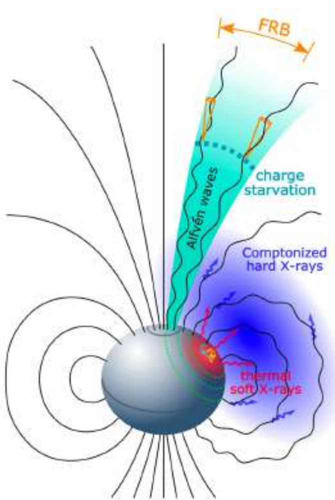
FRB and Pulsar Magnetosphere

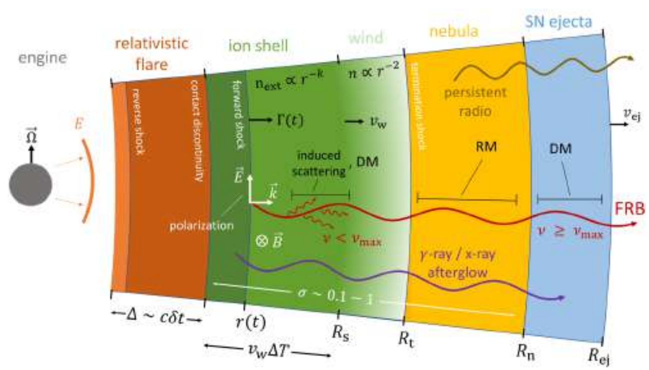


Kristen+ 23

- Pulsar emit coherent radio pulse.
- Progenitor of Galactic FRB is SGR J1935+2154, a strongly magnetized neutron star.
- Most proposed FRB models consider the phenomena in the magnetosphere or the plasma wind from the magnetosphere.



Lu+ 20



Metzger+ 19

Plasma properties in the pulsar magnetosphere is important to consider the generation and Propagation of FRBs.

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2. Global particle simulation of magnetosphere

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Pulsar Physics

Rotation energy

Dipole B-field ⟶ ↓

Electromagnetic energy (Poynting flux)

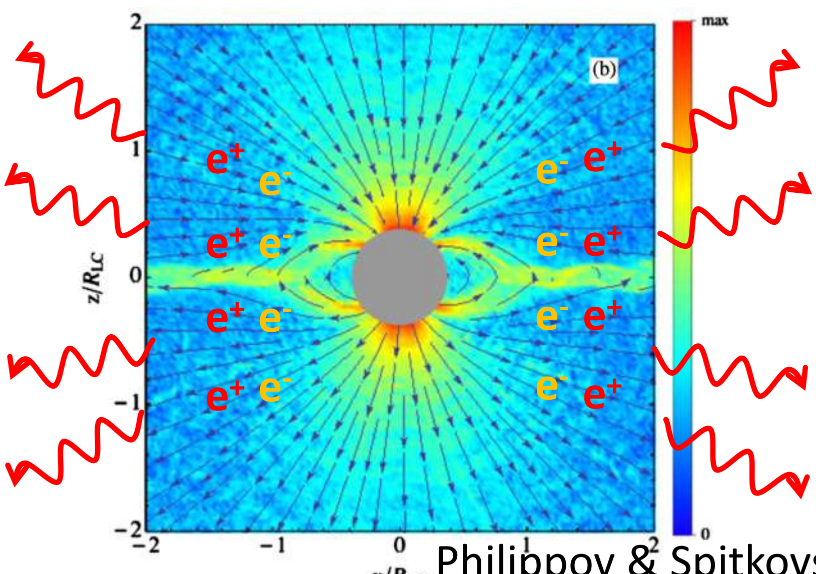
Acceleration, creation ⟶ ↓

Particle energy

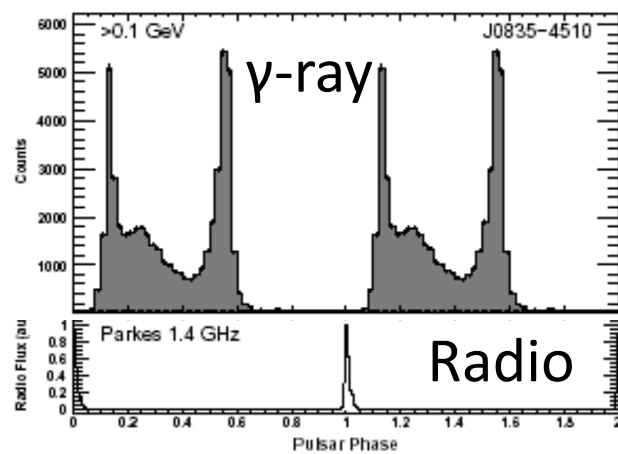
B-field, environment ⟶ ↓

Radiation, cosmic ray, heat

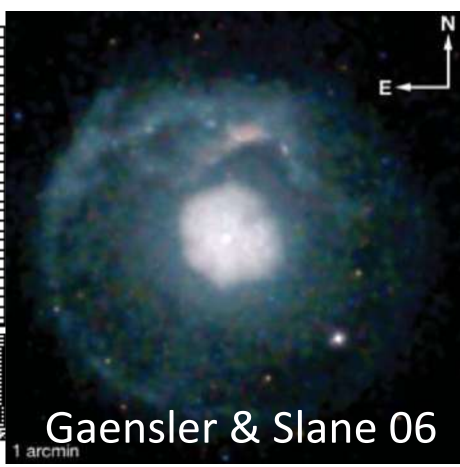
- Where?
- How efficient?



Philippov & Spitkovsky 14



Abdo+ 10



Gaensler & Slane 06

Energy Conversion in Magnetosphere

EM cascade

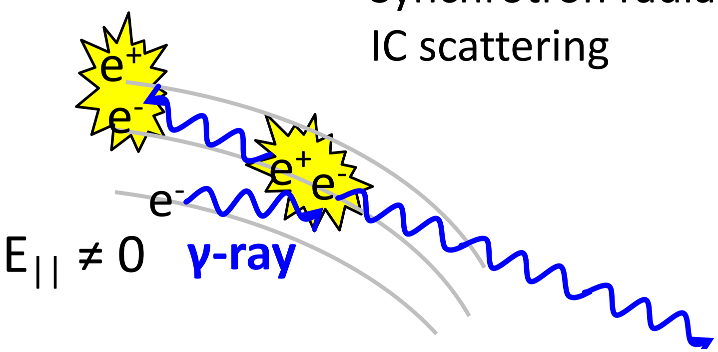
Acceleration

$F = qE_{||}$

Creation ← Radiation

Creation:
- Photon - Photon
- Photon - B-field

Radiation:
- Curvature radiation
- Synchrotron radiation
- IC scattering



High energy particles emit γ-ray photons ↑

↓ ↑

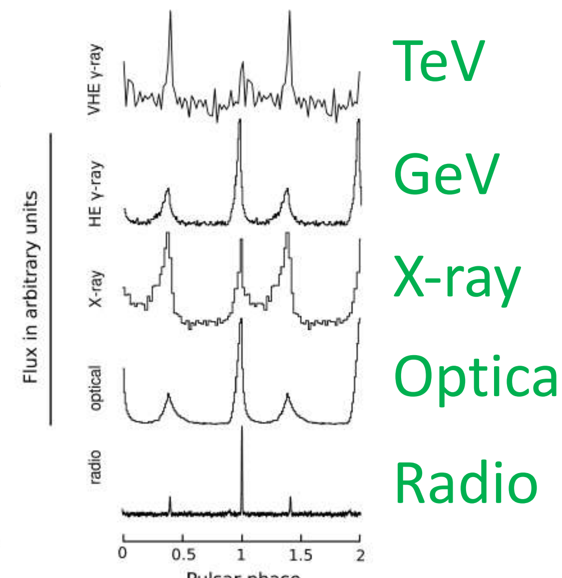
γ-ray photons convert to $e^{\pm}$ pairs → ↑

↓ ↑

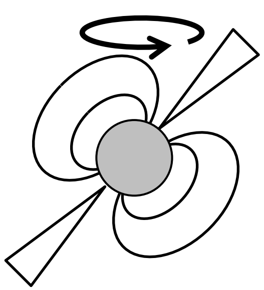
Created $e^{\pm}$ pairs are accelerated → ↑

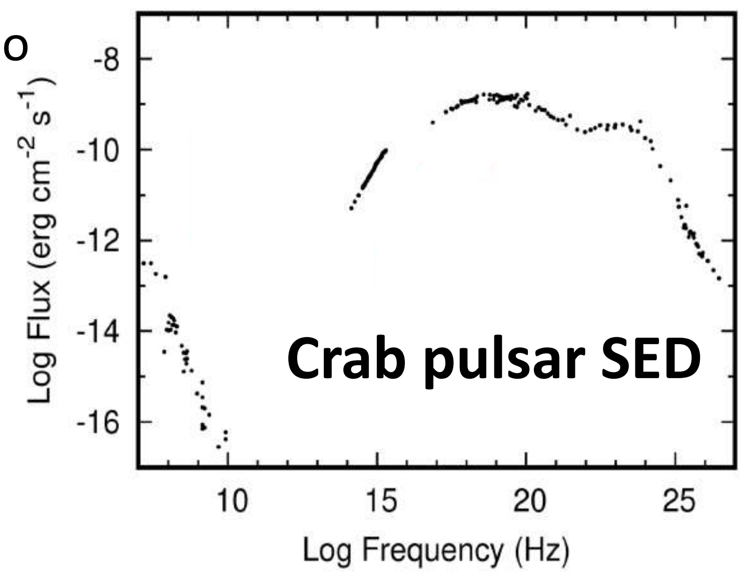
↓

A part of γ-ray and low-energy photons can escape from the magnetosphere and be observed. → **Pulsed emission**



Although the coherent radio emission mechanism is uncertain, it would be related to the EM cascade.





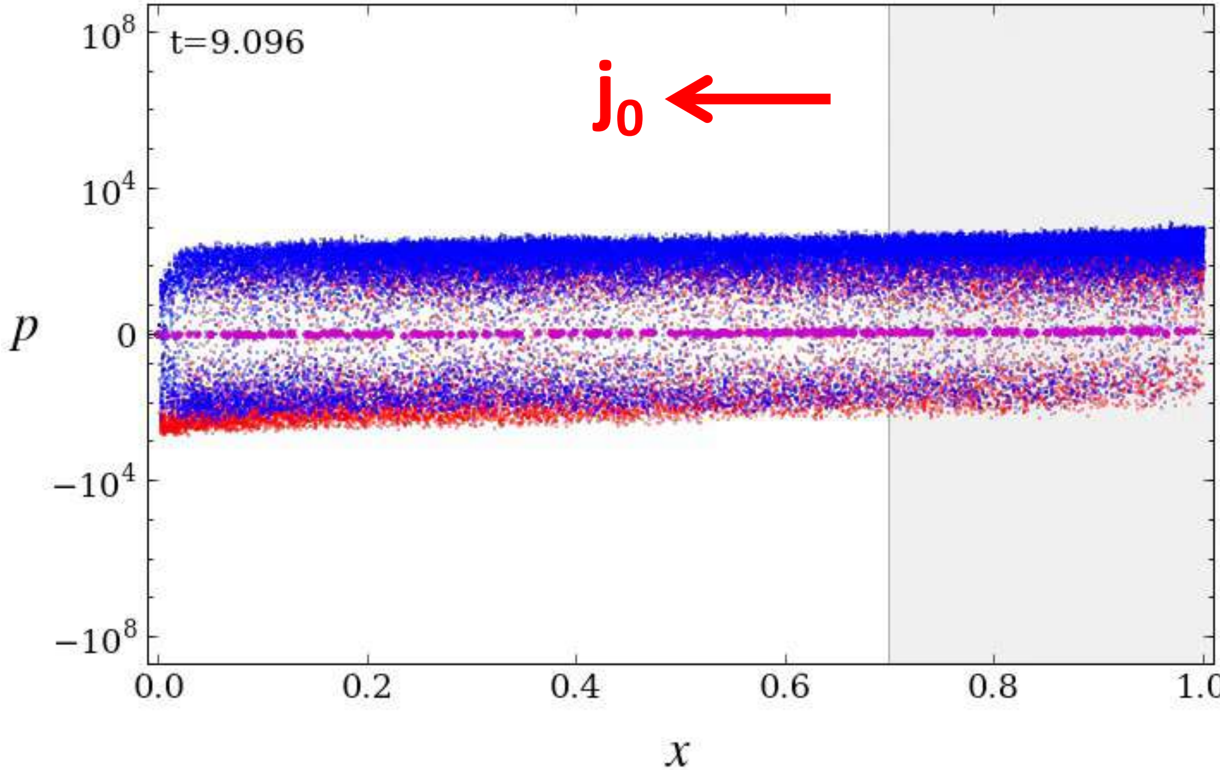
Bühler & Blandford 14

Local Particle Simulations

Local kinetic simulation of electromagnetic cascade.

→ Time -dependent

Timokhin 10
Timokhin & Arons 13
Timokhin & Harding 15, 19
Philippov+ 20, Cruz+ 21



See also
Chen & Yuan 20
SK+ 20, 22
Crinquand+ 21
Niv+23
Kin, SK+ 23

Plasma deficiency → E-field development → Acceleration

↑ ↓

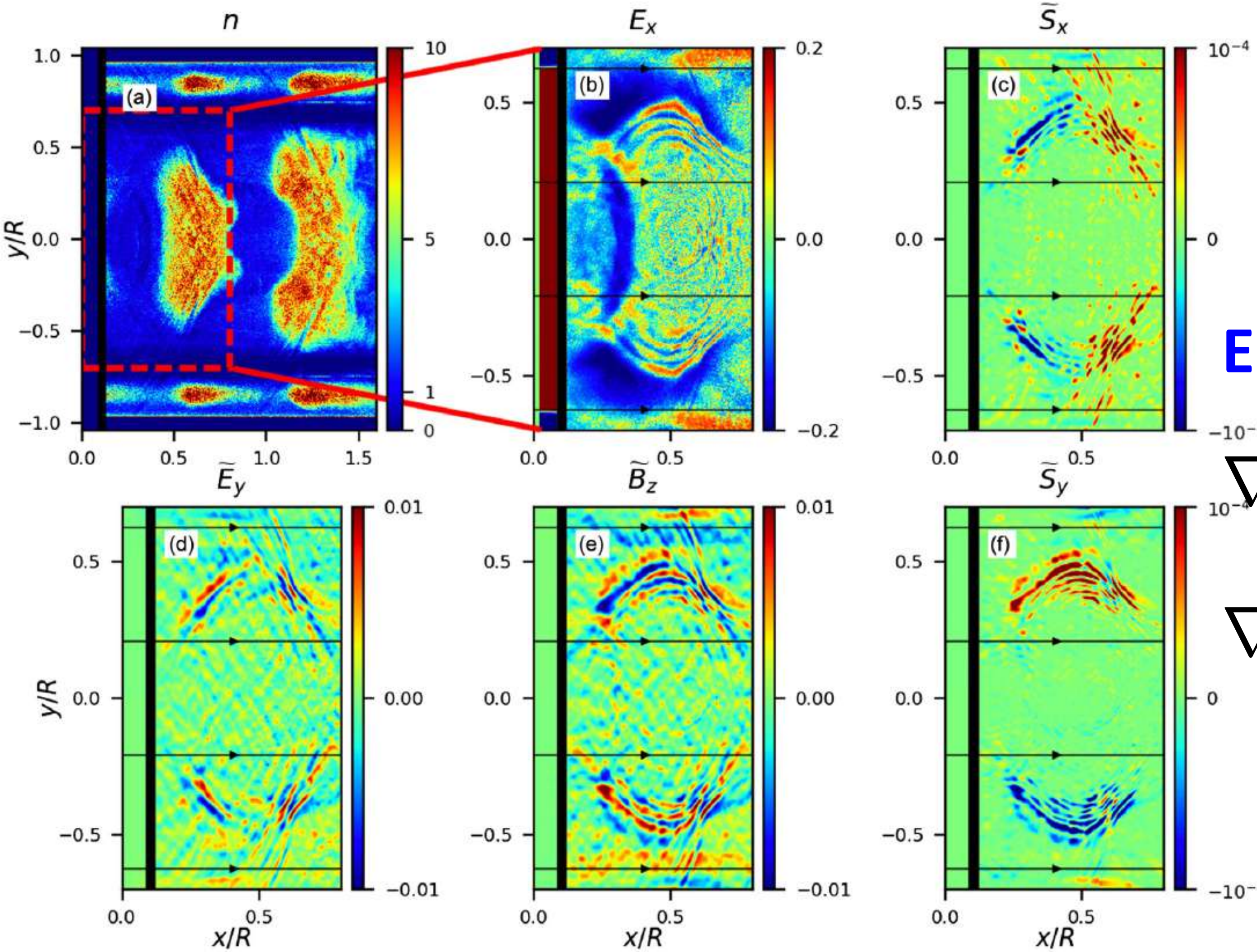
E-field screening ← Particle creation ← γ-ray emission

$$\partial \mathbf{E}/\partial t = 4\pi(\mathbf{j}_0 - \mathbf{j})$$

Excitation of EM mode

Excitation of the EM wave during the dynamic E-field screening.
→ Origin of coherent emission?

Philippov, Timokhin & Spitkovsky 20
Melrose, Rafat & Mastrano 21
Cruz+ 21

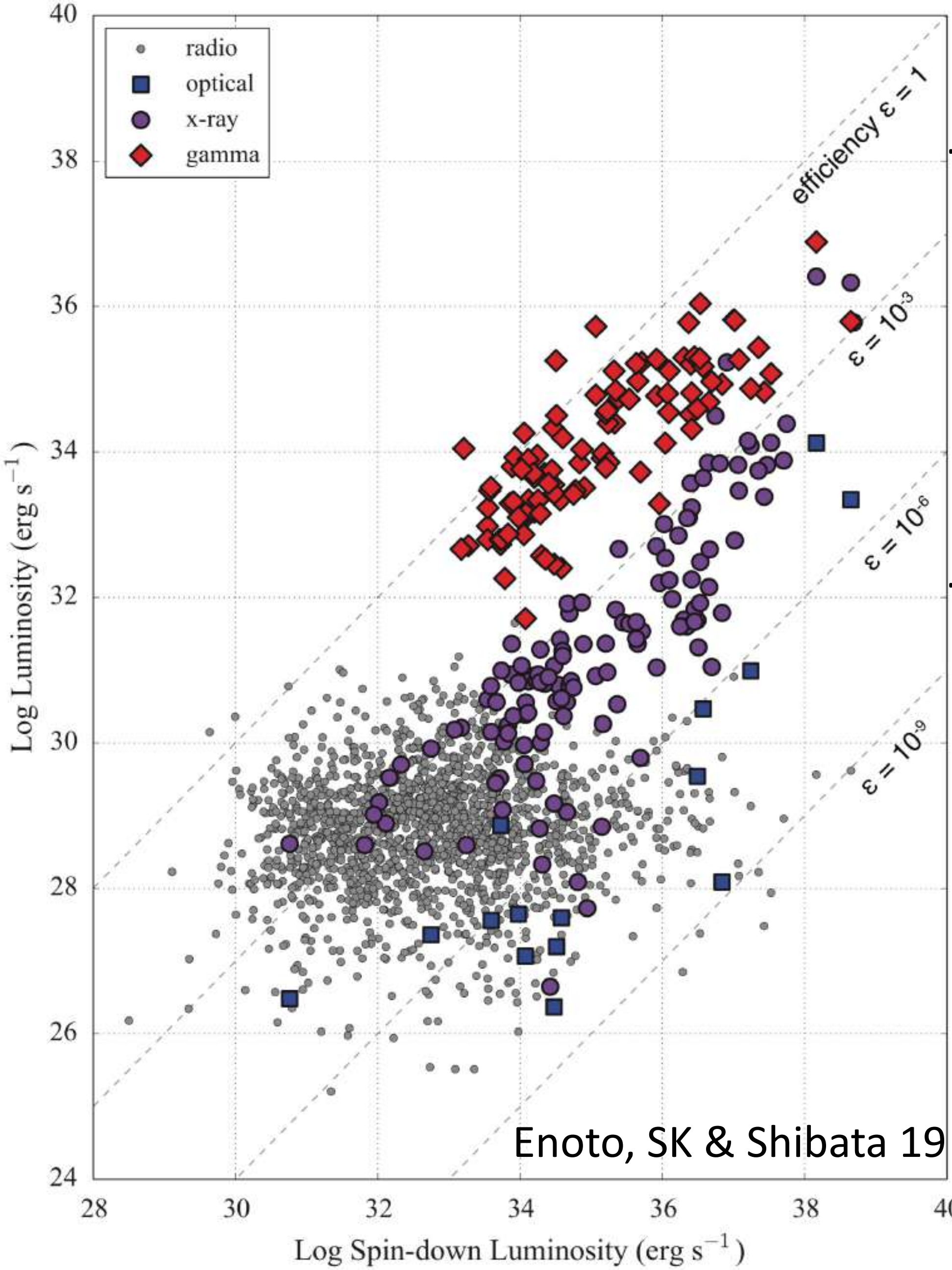


EM mode

$$\nabla_y \times E_x \rightarrow B_z$$

$$\nabla_x \times B_z \rightarrow E_y$$

Dissipation at Outer Region

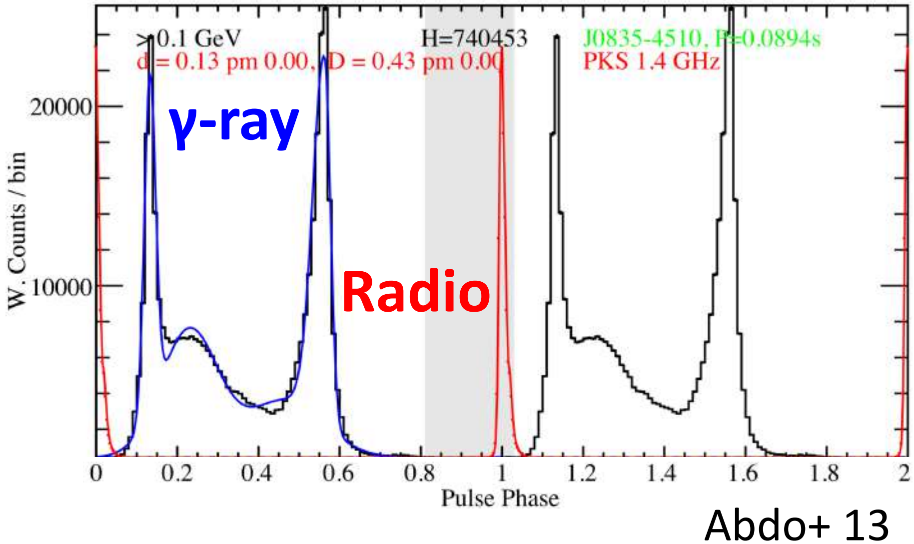


- **γ-ray efficiency : ~10%**

→ More than ~ 10 % of total energy converts to particle kinetic energy in the magnetosphere.

- **γ-ray and radio peaks are not aligned.**

→ Global structure should be solved.



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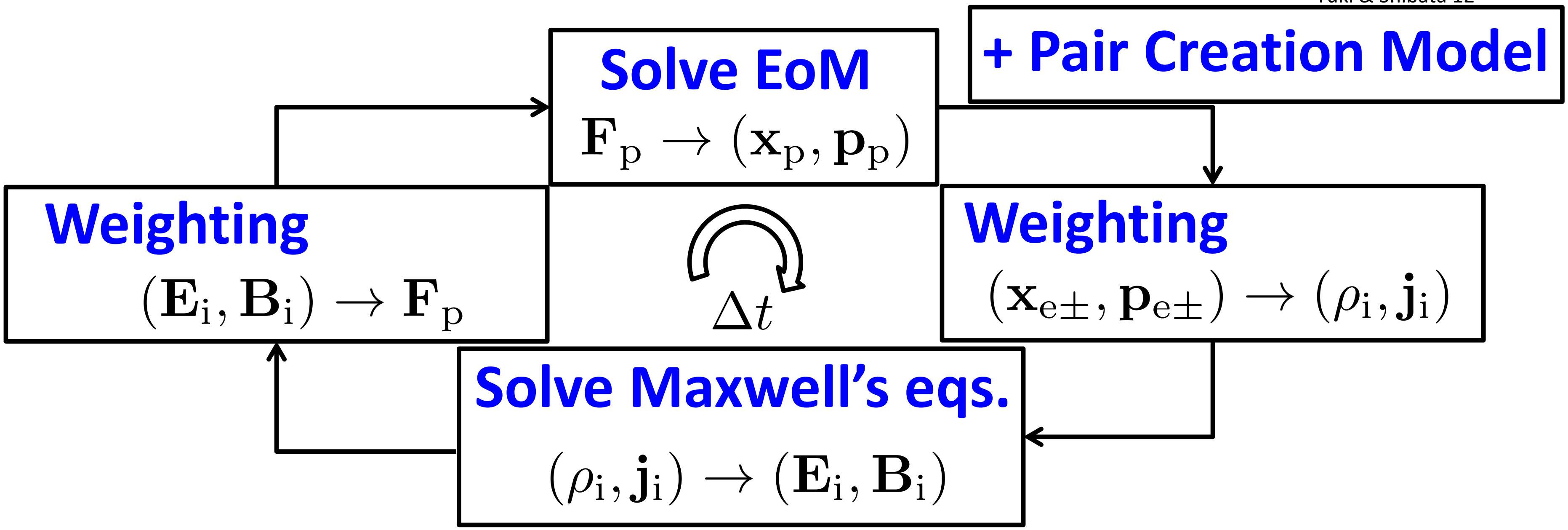
Global Particle Simulations

Spitkovsky & Arons 02
Philippov & Spitkovsky 14, 18
Chen & Beloborodov 14
Philippov+ 14, 15a, 15b
Belyaev 15a, 15b
Cerutti+ 15, 16a, 16b, 17
Karapothalakos+ 18, 23
Brambilla+ 18, Chen+ 20
Guépin et al. 20
Hu & Beroborodov 22
Bransgrove+ 23
Hakobyan+ 23, Cruz+ 23
cf. Krauss-Polstroff & Michel 85
Wada & Shibata 07, 11
Yuki & Shibata 12

Solving particle EoM and EM field simultaneously (+ simplified pair creation model).

→ Acceleration site, Conversion efficiency

Particle-in-Cell method

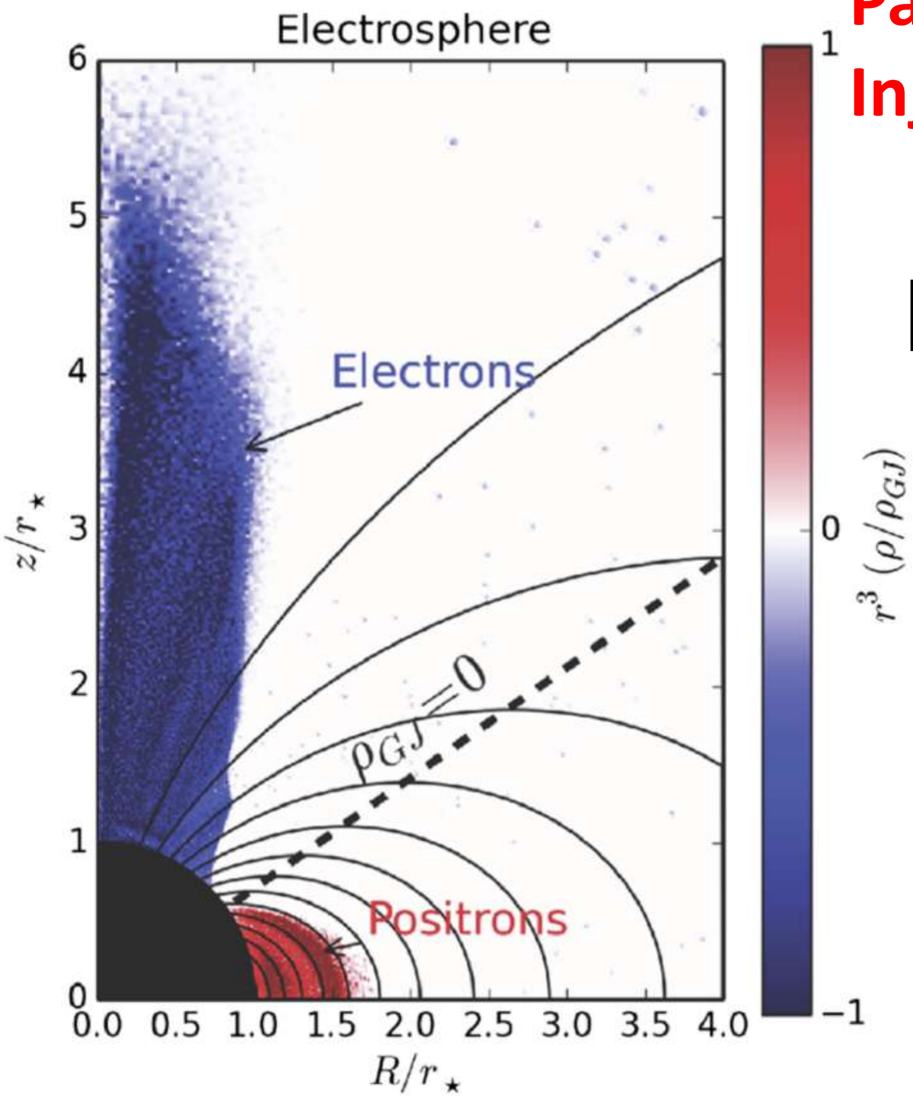


$$\partial \mathbf{E}/\partial t = c(\nabla \times \mathbf{B}) - 4\pi \mathbf{j}, \quad \nabla \cdot \mathbf{E} = 4\pi \rho_{\rm e}, \quad \nabla \cdot \mathbf{B} = 0$$

$$\partial \mathbf{B}/\partial t = -c(\nabla \times \mathbf{E}), \quad d(\gamma m \mathbf{v})/dt = q(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})$$

Particle Injection

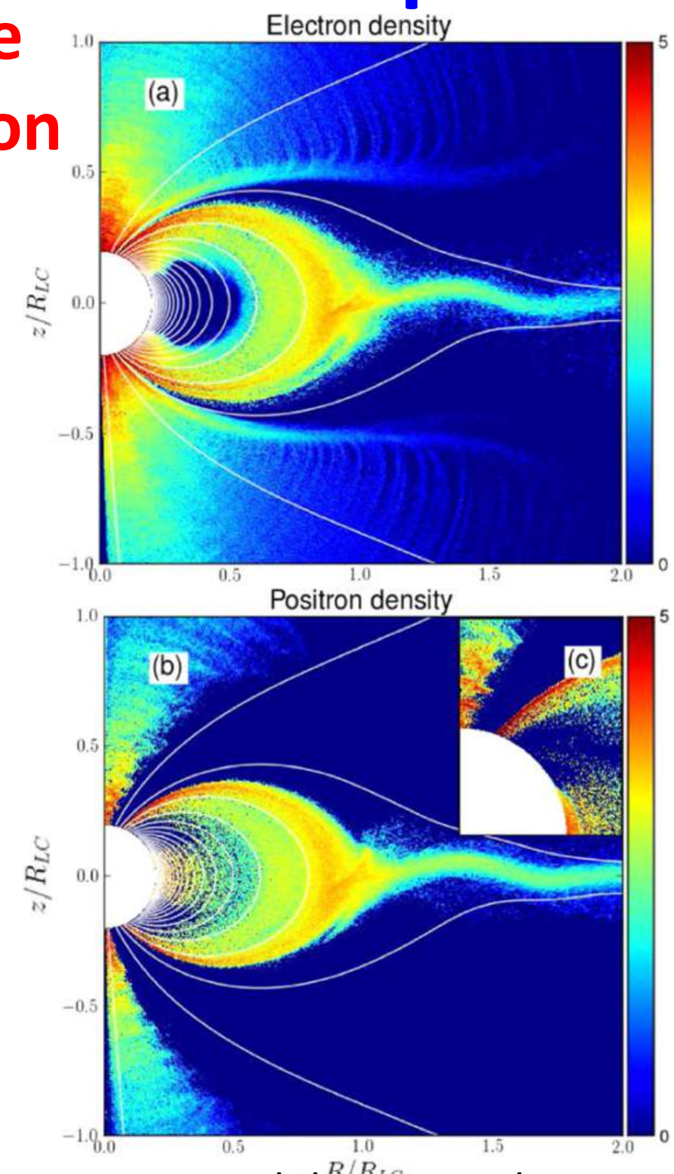
Dead pulsar



Cerutti & Beloborodov 17

Particle Injection

Active pulsar

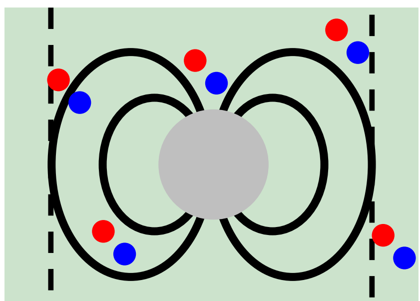


Philippov et al. 15

Particle Injection Models

Philippov & Spitkovsky 14
Kalapothelakos+ 18, 23
Brambillia+ 18

σ > σ_th



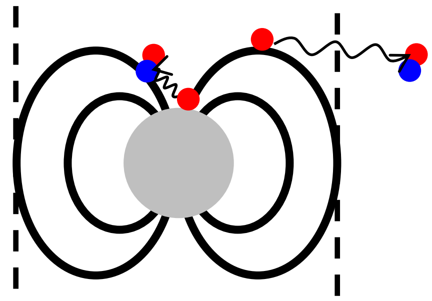
$$\sigma = \frac{B^2}{4\pi n m_e c^2}$$

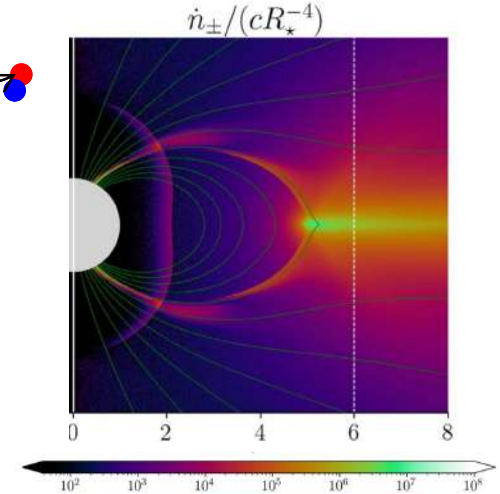
Cerutti+ 15, 16a, 16b, 17, Hakobyan+ 23
Kalapothelakos+ 18, Brambillia+ 18

Chen & Beloborodov 14, Philillov+ 15a, 15b,
Philippov & Spitkovsky 18, Hu & Beloborodov 22
Bransgrove+ 22

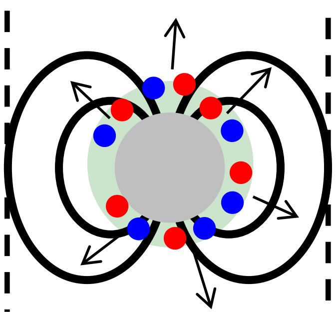
γ > γ_th

$$l = \begin{cases} 0.2R_{\rm ns} & (r < 2R_{\rm ns}) \\ 5R_{\rm ns} & (r > 2R_{\rm ns}) \end{cases}$$





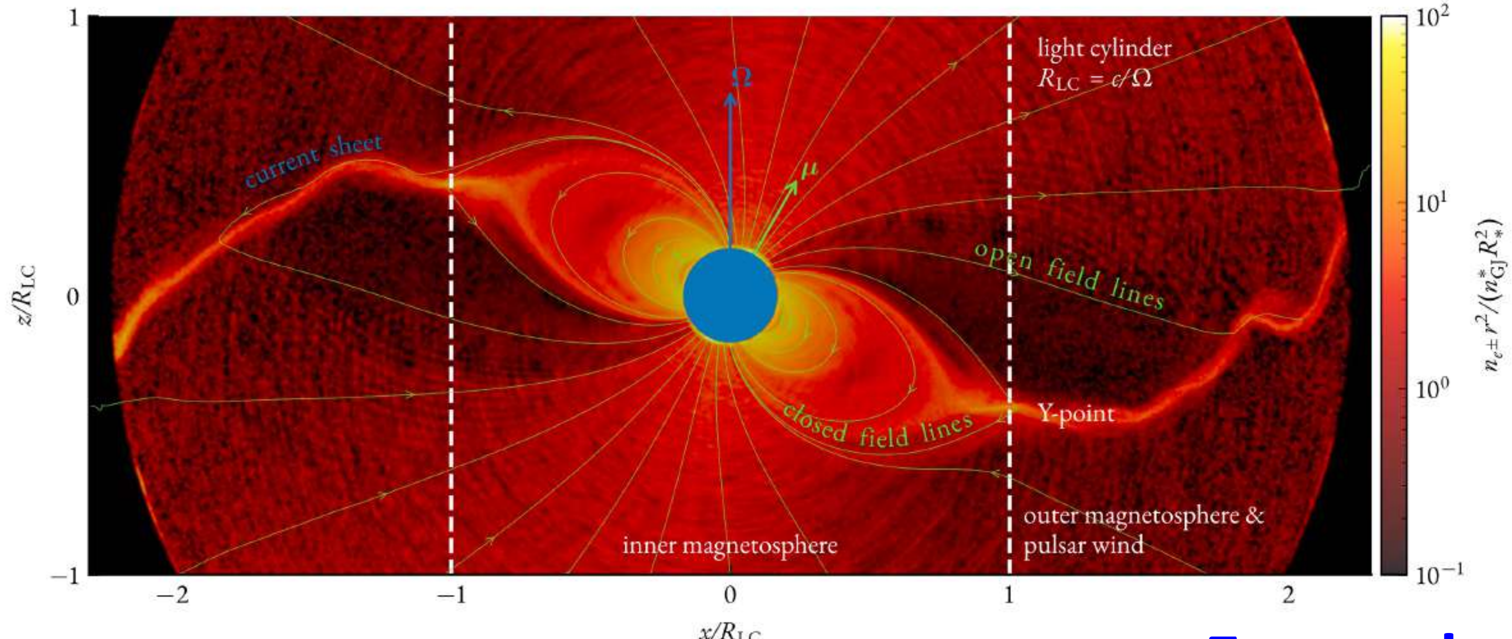
Surface injection



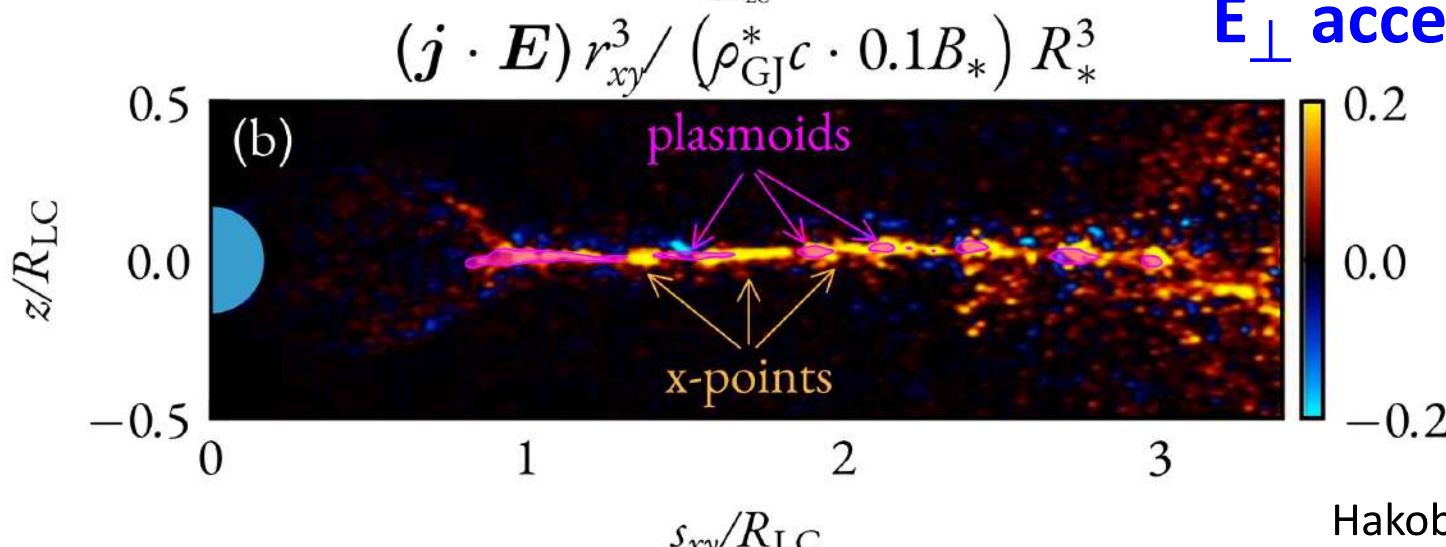
These models can supply particles throughout the magnetospheres.

Surface Injection

Dissipation region (=Emission region) : Current sheet



E$_\perp$ acceleration

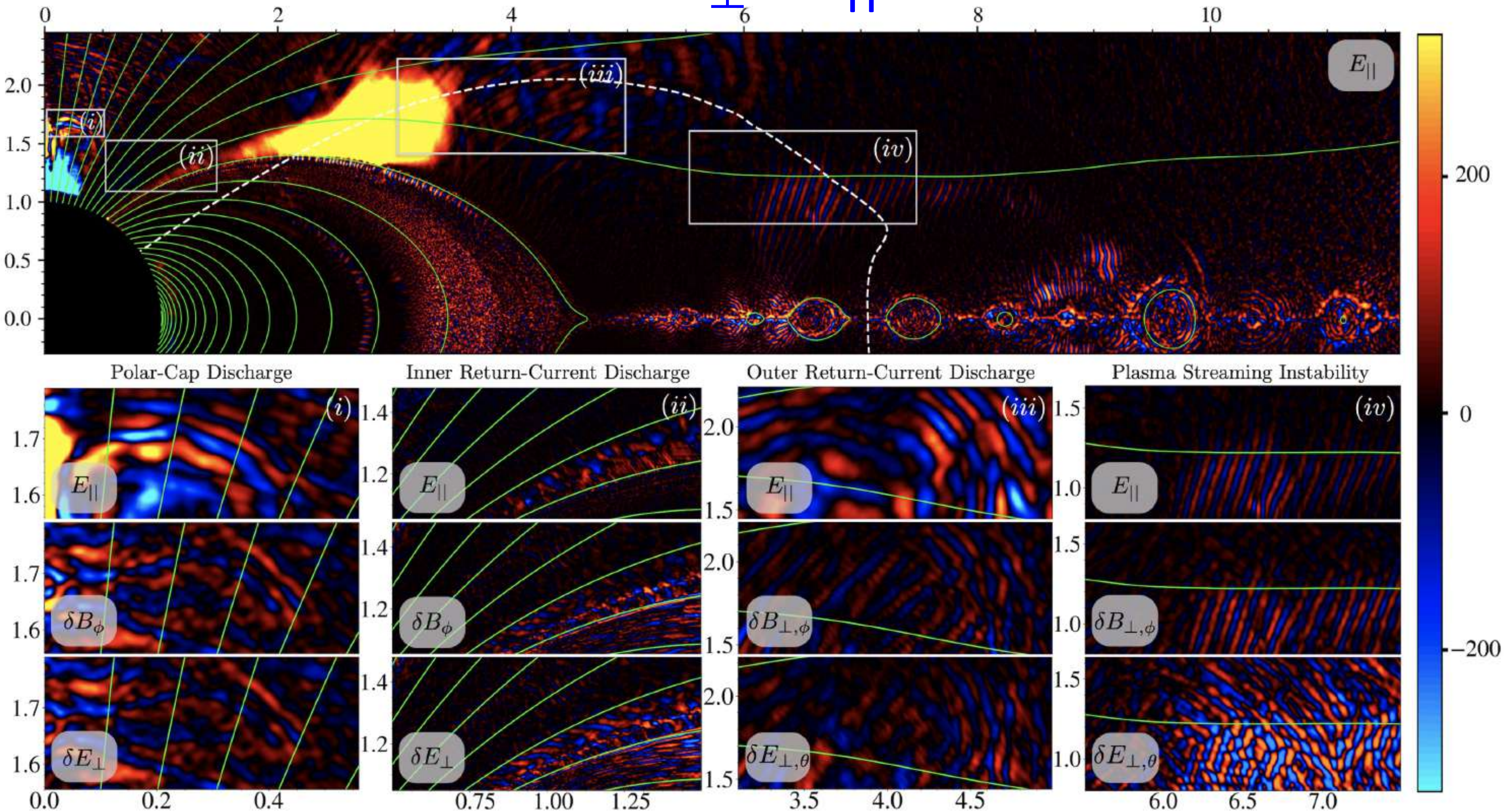


Hakobyan+ 23

γ-threshold Model

Gap opens at the return current region.

$E_\perp$ & $E_{||}$ accelerations



Bransgrove+ 22

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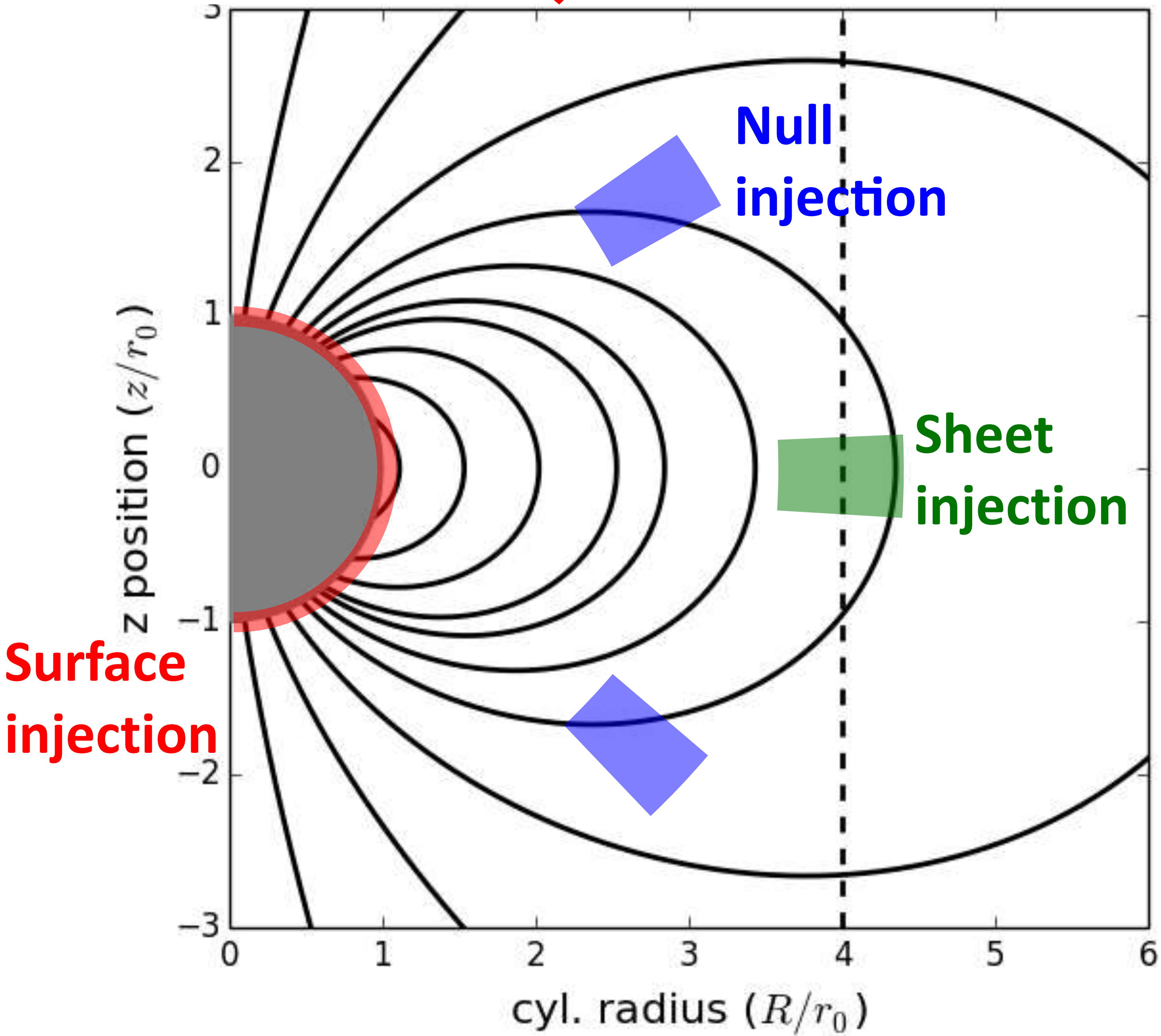
Particle Injection Models

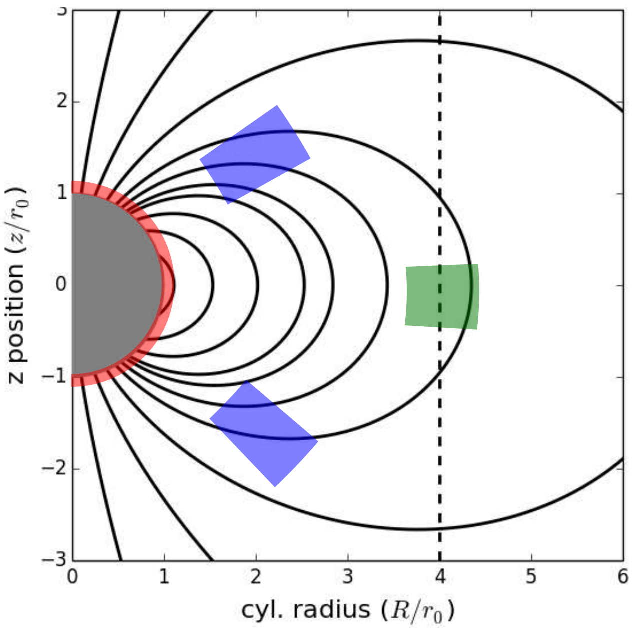


PICsar2D

Belyaev 15a, 15b, 17

Axisymmetric aligned rotator

Cell number : 4096 (log r) × 2048 (cos θ)
Light cylinder radius : $R_{lc}/R_{ns} = 4$
Particle per cell : 10000 (surface)
Surface B-field : $B_0 = 10^4$ G



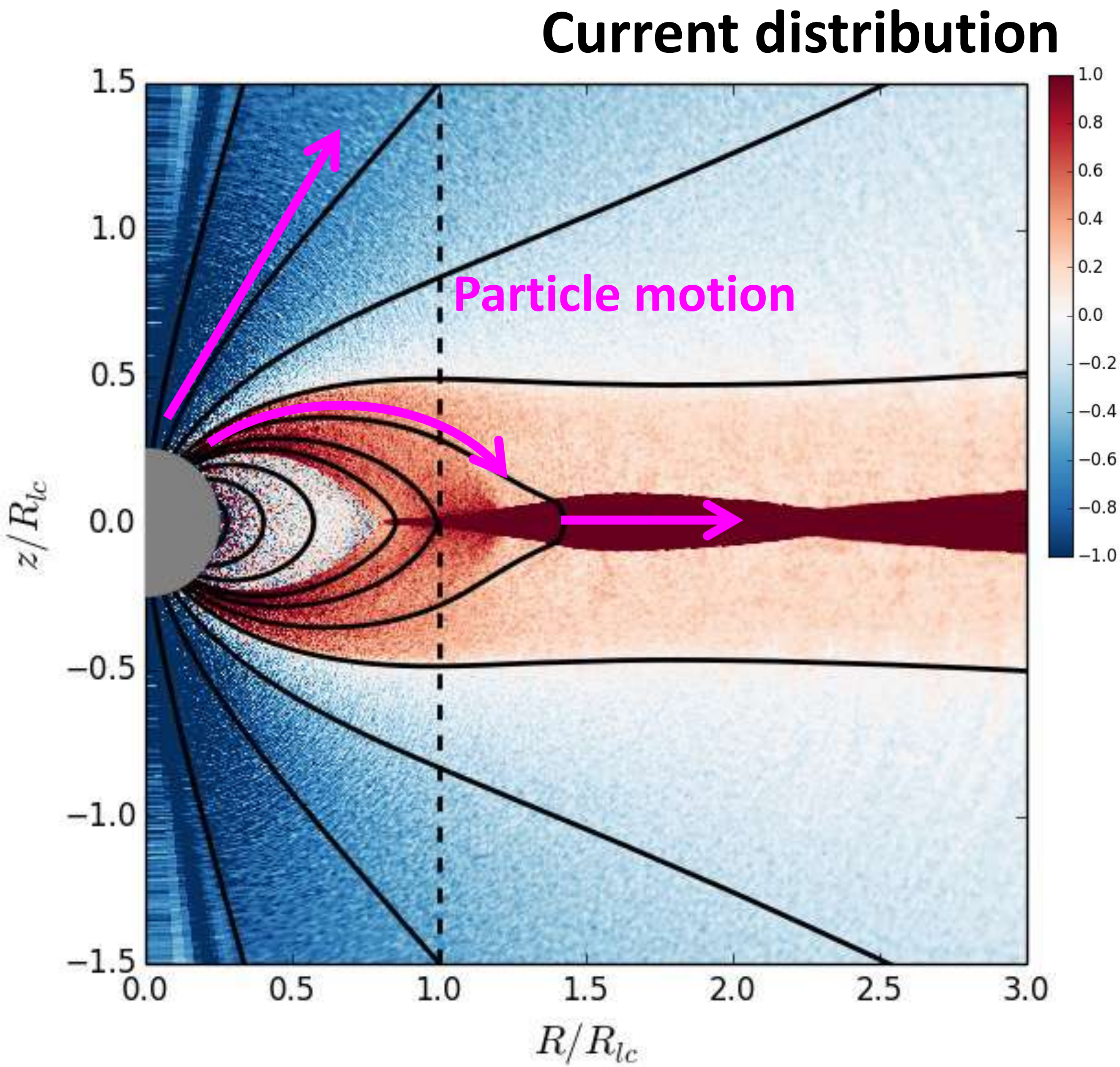
Initial B-field : Vacuum dipole
Particles : Electrons and Positrons

Particle injection

- Surface plasma injection : $\dot{n} \propto |E \cdot B|$
- Pair injection :
  - Surface ($r_{inj} = R_{ns}$, $0^\circ < \theta_{inj} < 180^\circ$)
  - Null ($0.64 < r_{inj}/R_{lc} < 0.69$, $53^\circ < \theta_{inj} < 57^\circ$, $123^\circ < \theta_{inj} < 127^\circ$)
  - Sheet ($0.95 < r_{inj}/R_{lc} < 1.05$, $85^\circ < \theta_{inj} < 95^\circ$)

Injection rate : ~ 10 n_{GJ} in each step

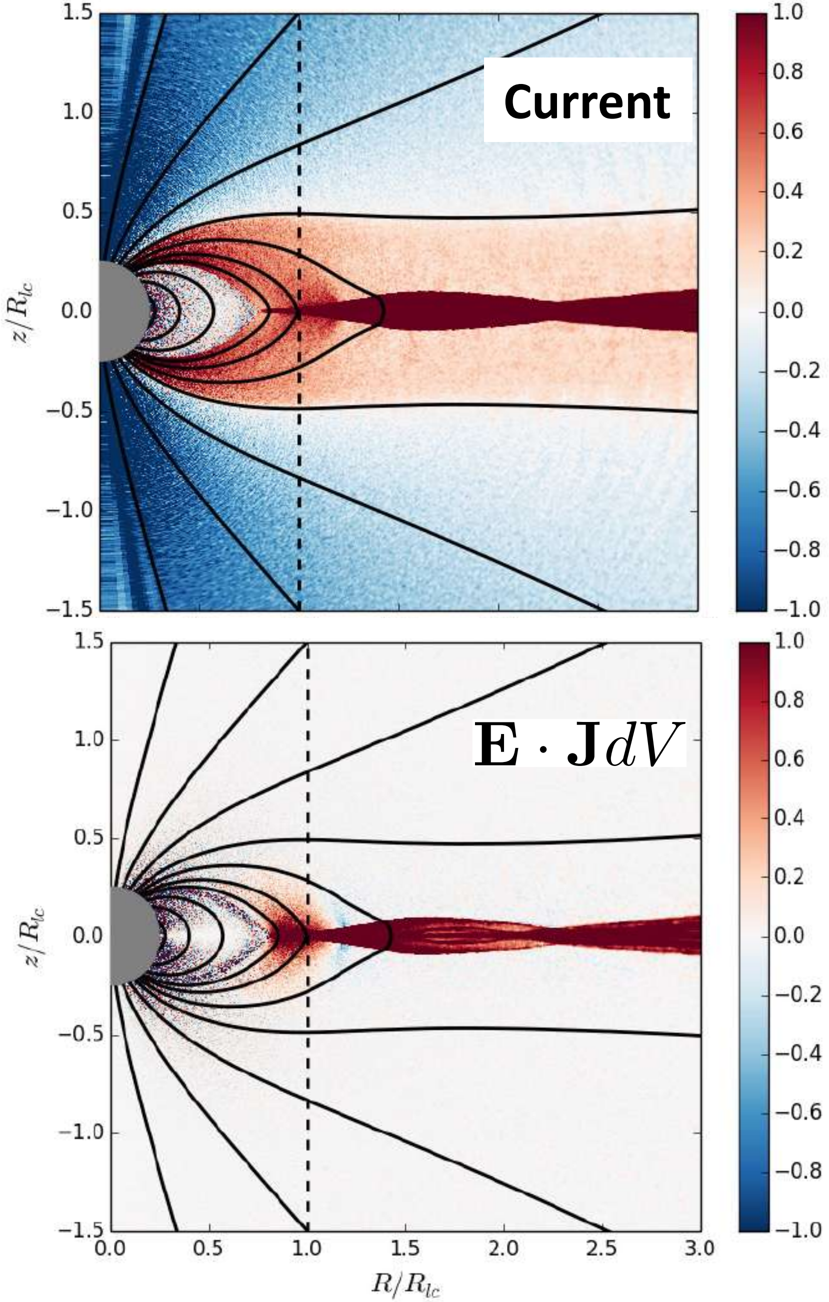
Surface Injection

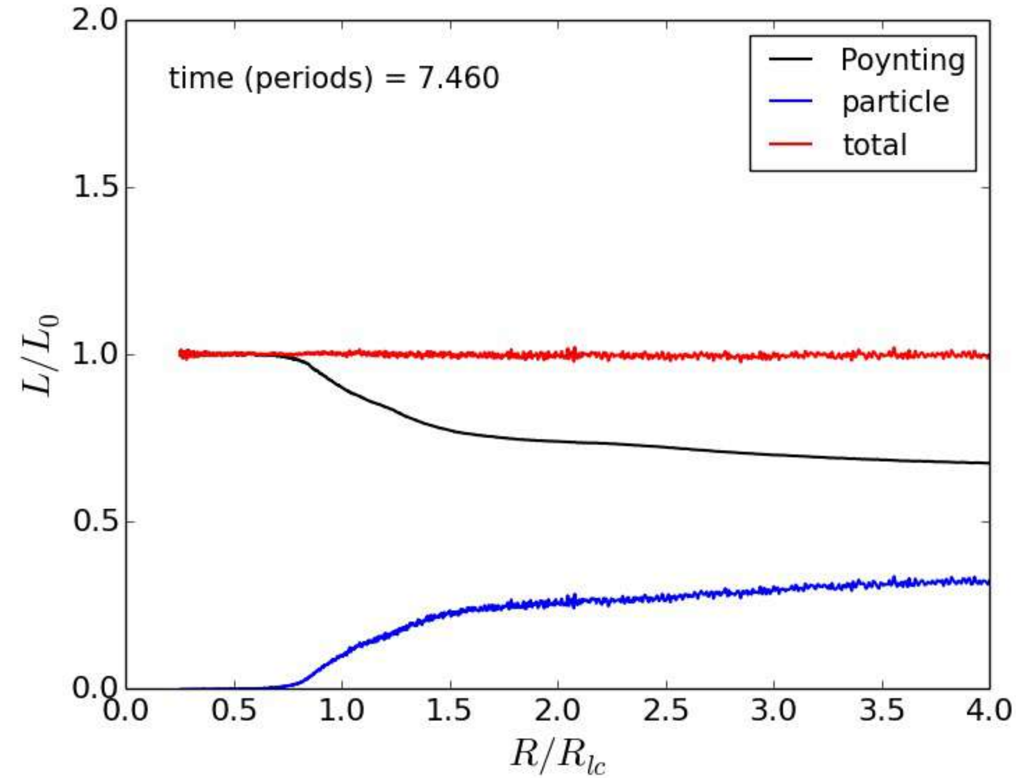


Particles are supplied throughout the magnetosphere.

B-field lines open when enough current is supplied to the equatorial current sheet.

Surface Injection

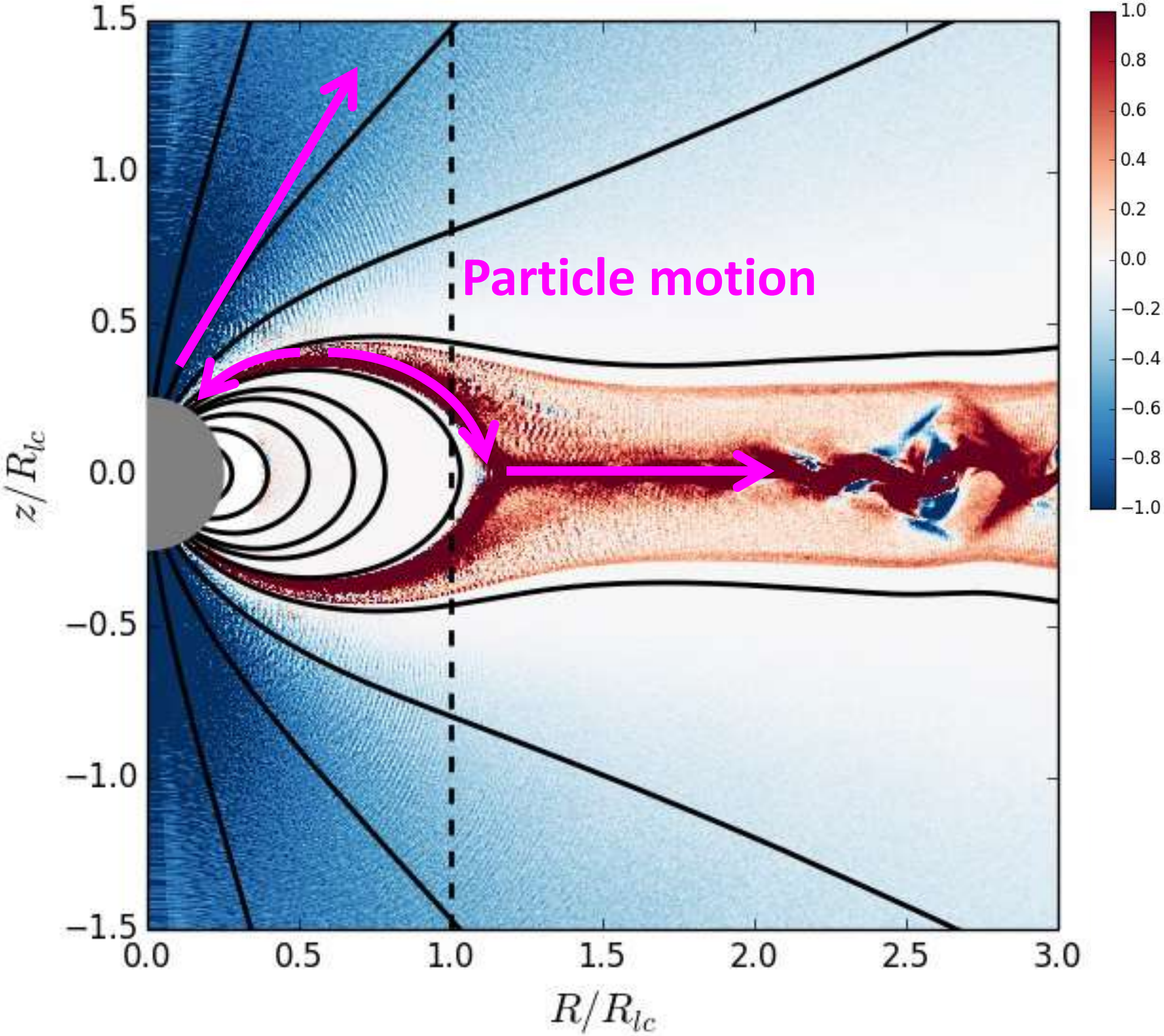




- **Dissipation region : Current sheet**
- **$E_{\perp}$ acceleration**

Null Injection

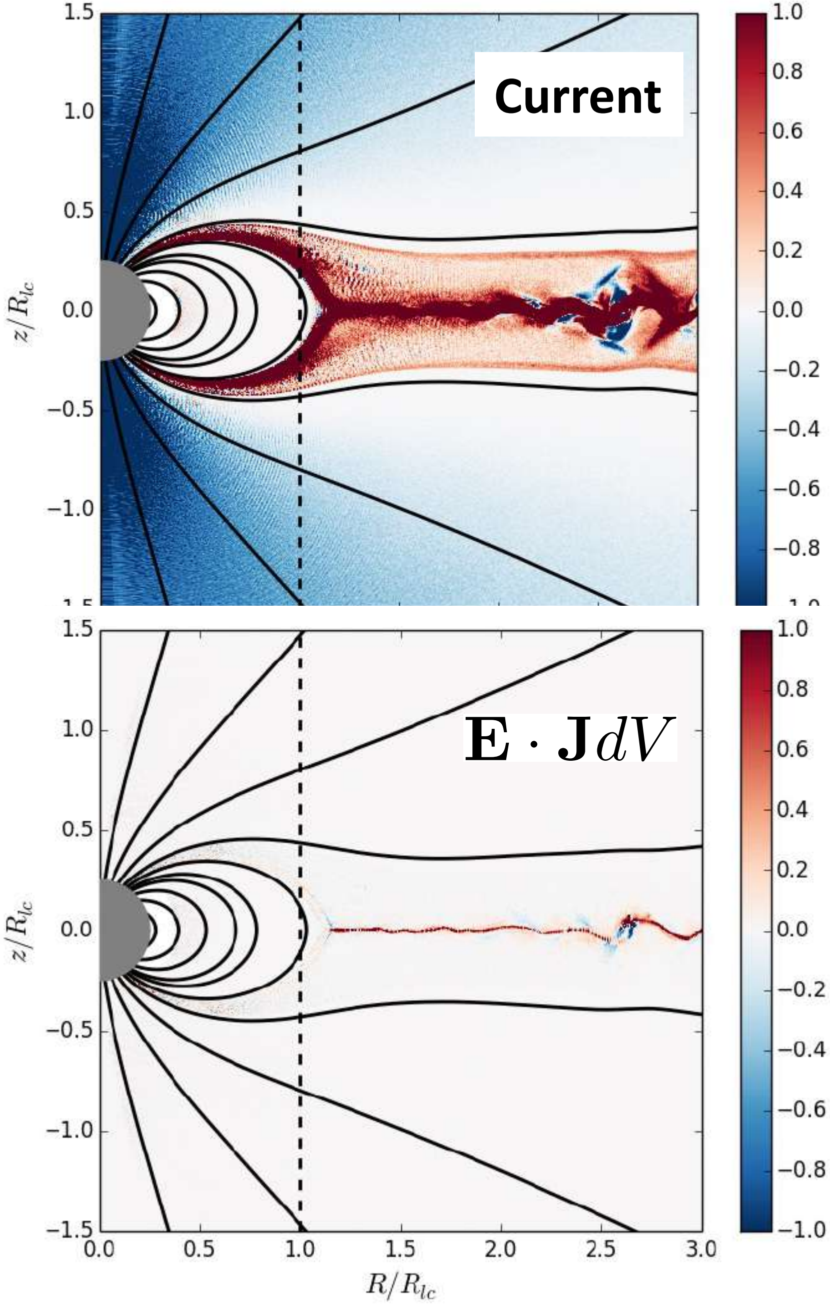
Current distribution

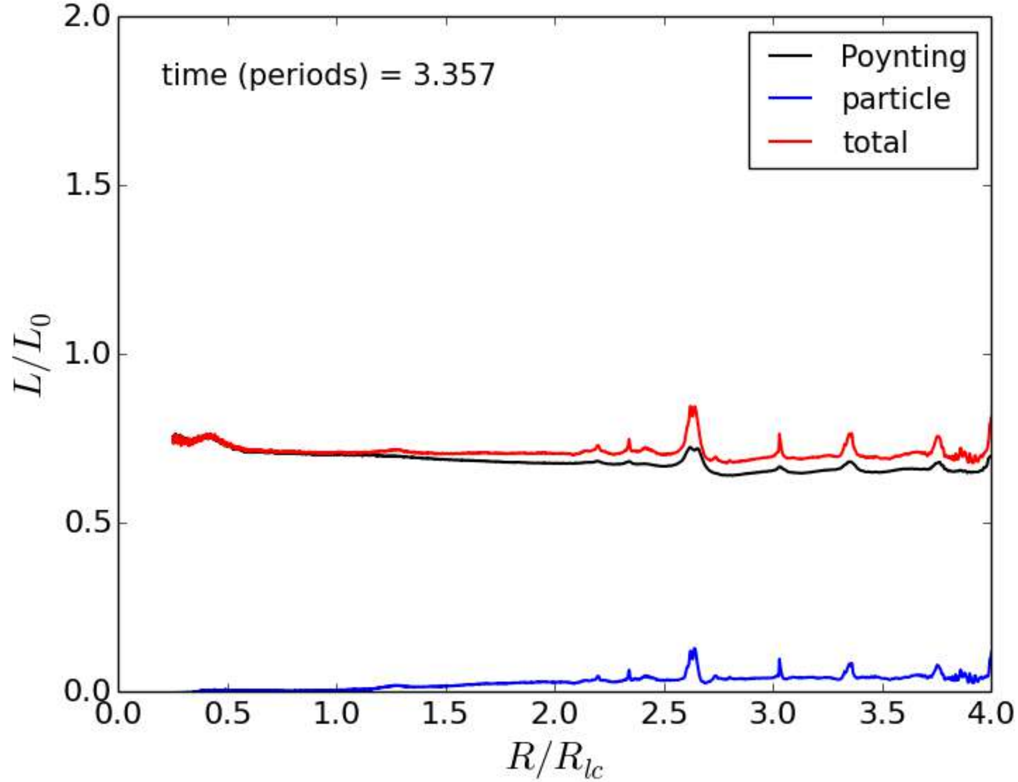


No particle in middle altitude
→ **Small current**

Pairs are separated by weak E-field at the injection region.
→ **Weak $E_{||}$ acc.**

Null Injection

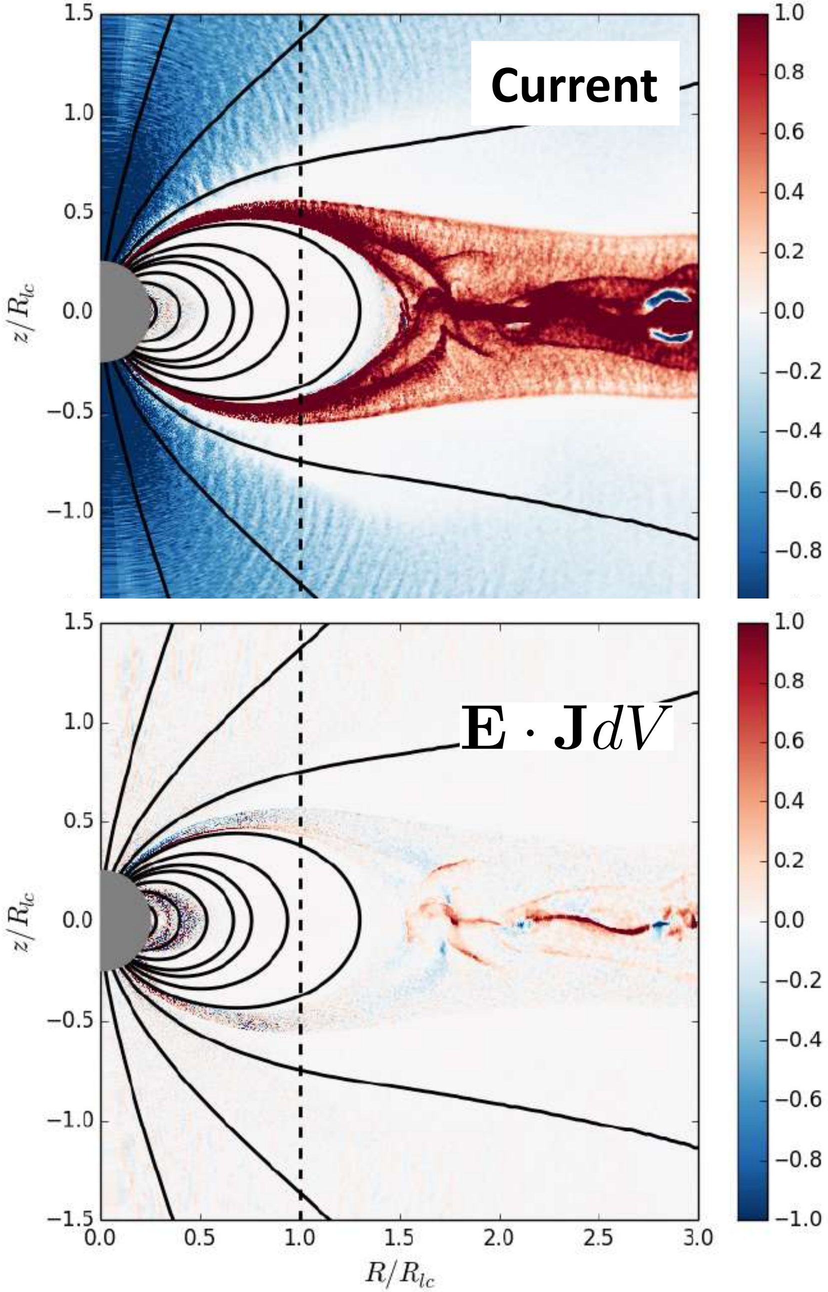


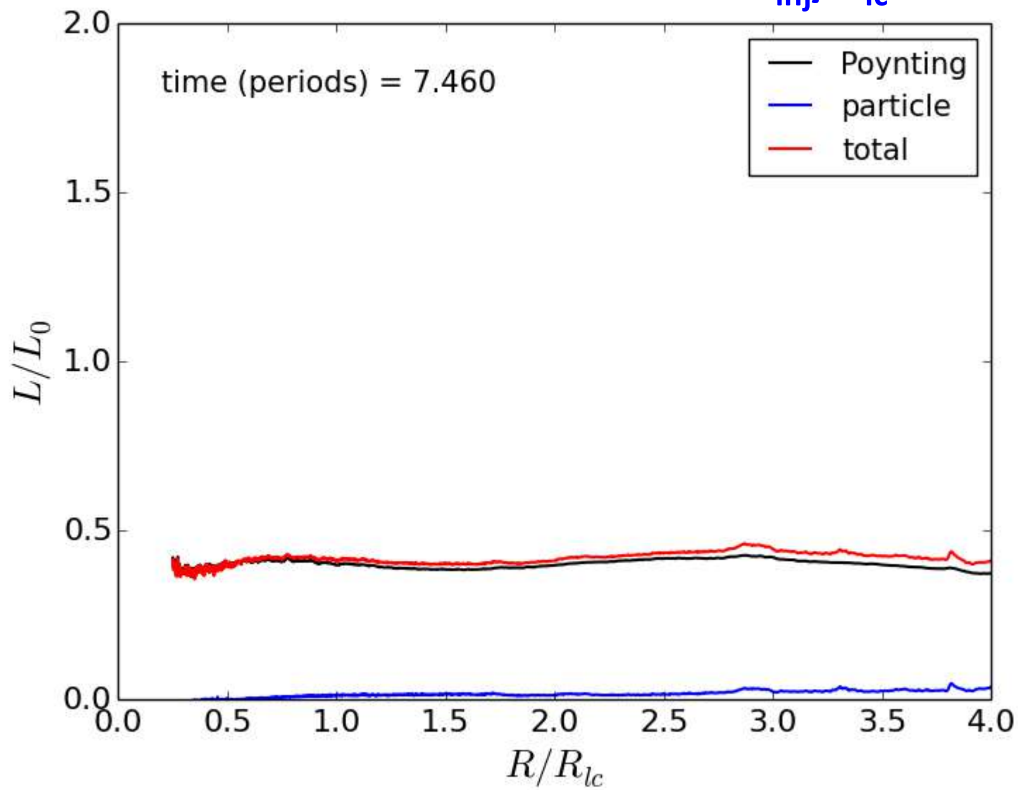


- $E_\perp$ acceleration
- No significant dissipation

Null Injection

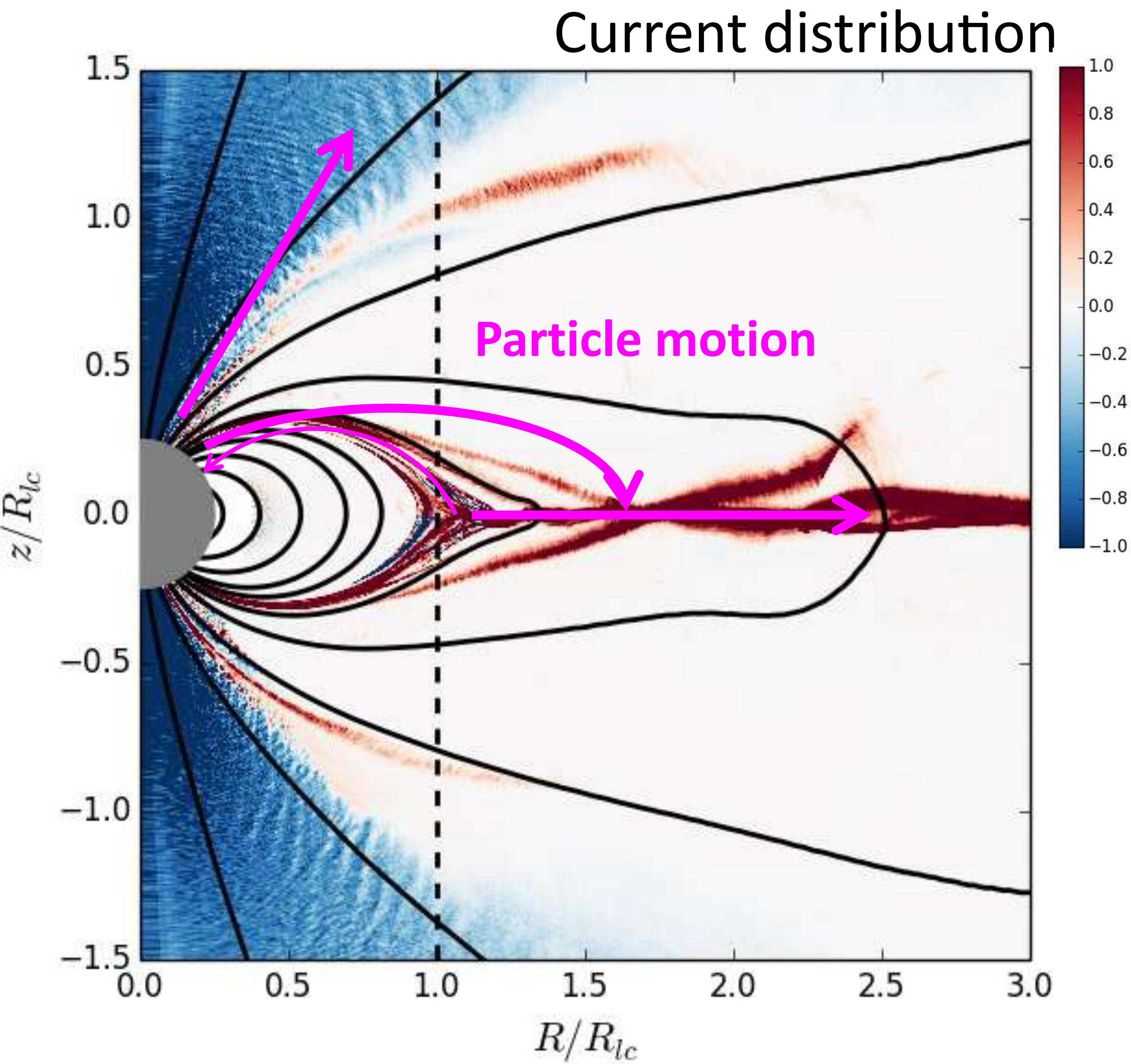
$0.64 < r_{inj}/R_{lc} < 0.69$
$\rightarrow 0.84 < r_{inj}/R_{lc} < 0.89$





- $E_\perp$ acceleration
- No significant dissipation
- Injection at higher altitude
  - → Extended closed zone
  - → Low Poynting flux

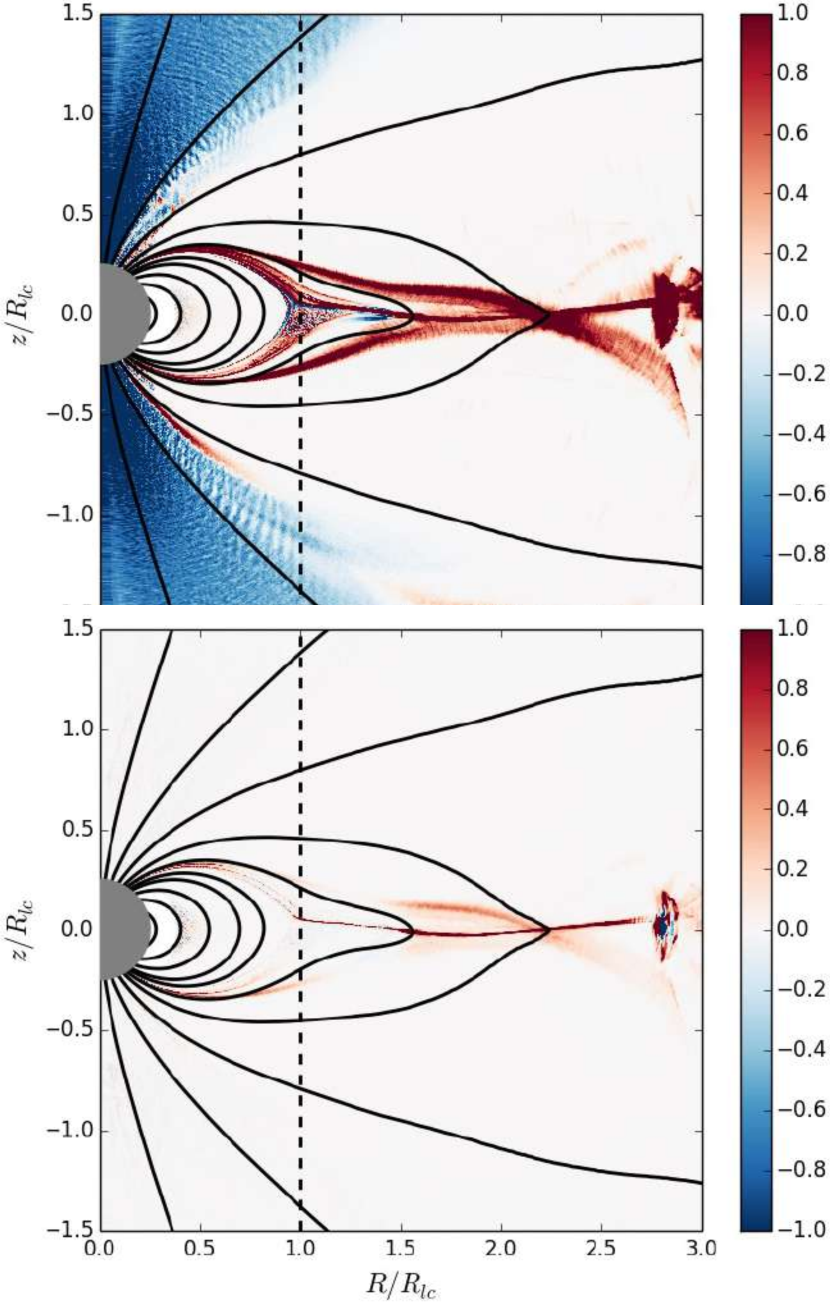
Sheet Injection

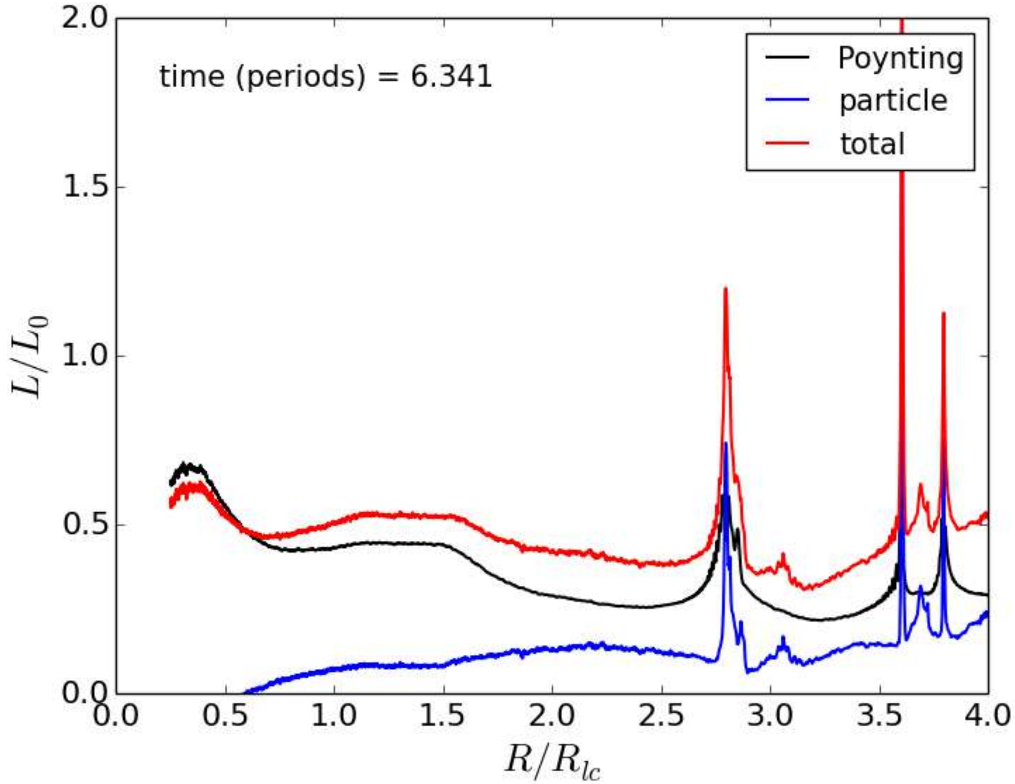


No particle in middle altitude → **small current**

Pairs are not easily separated because of large inertia.
→ **Particles are extracted from the NS to connect the current circuit.**

Sheet Injection

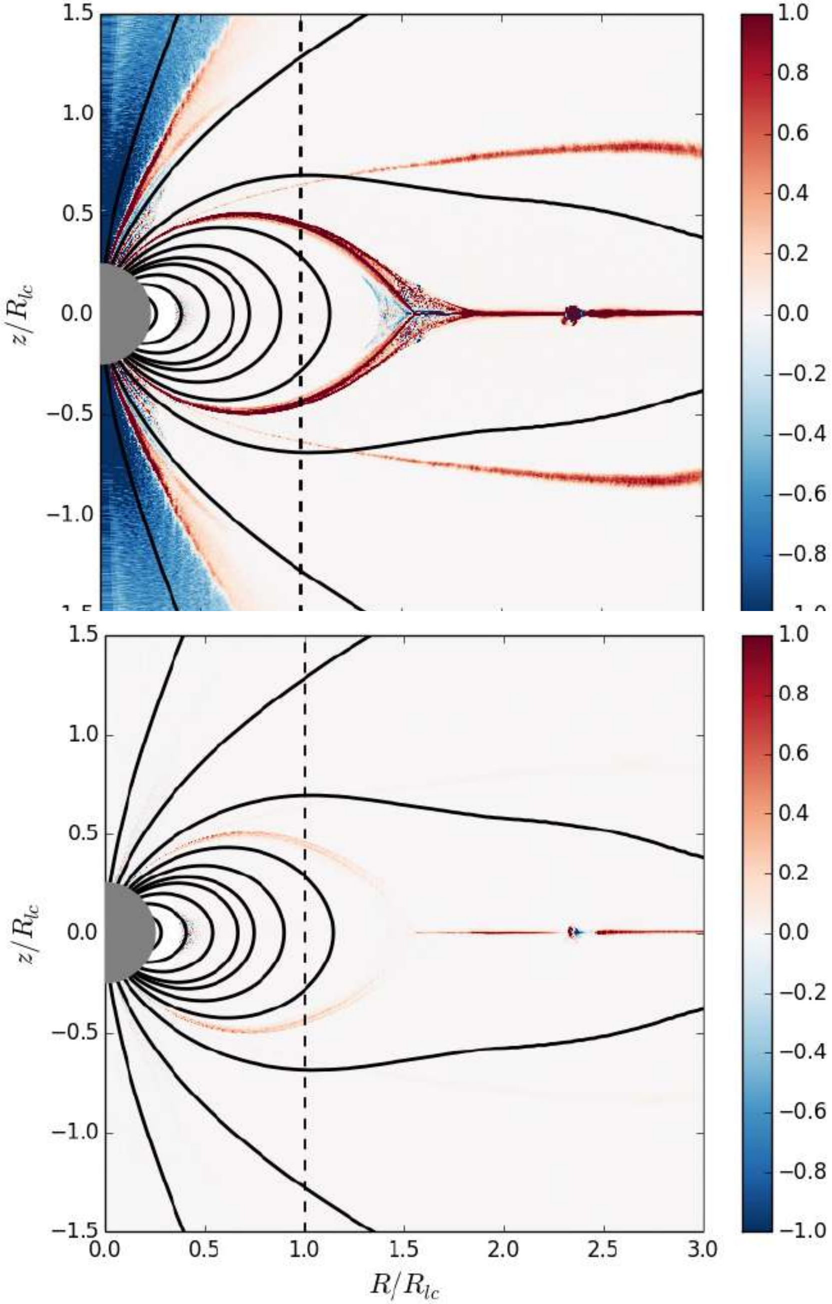


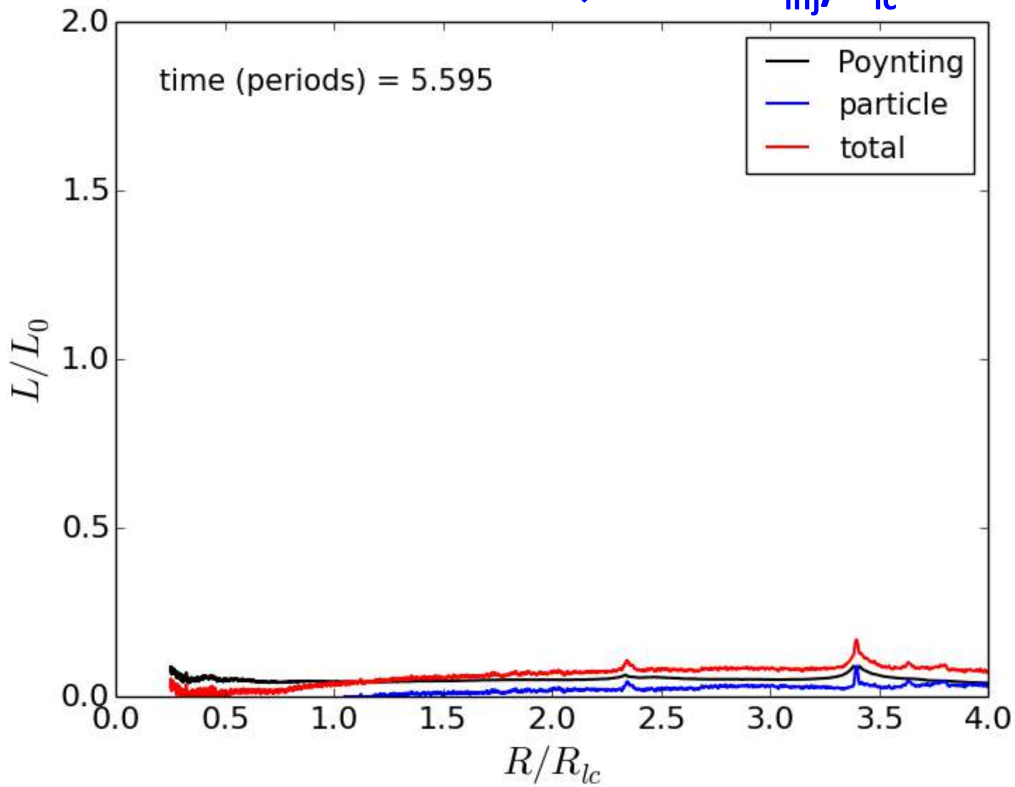


- $E_\perp$ and $E_{||}$ accelerations
  → Null or Surface injection due to $E_{||}$ acceleration?
- Thin current sheet
  → Formation of plasmoids

Sheet Injection

$0.95 < r_{inj}/R_{lc} < 1.05$
→ $1.50 < r_{inj}/R_{lc} < 1.60$





- **Injection at larger distance**
  - **→ Extended closed zone**
  - **→ Low Poynting flux**

Summary

We performed 2D PIC simulation for a global pulsar magnetosphere with the localized pair injection models.

Local injection → Localized current → Low Poynting flux

Injection at large r → extended closed region

→ Low Poynting flux

Injection at r < R_{lc} → Low dissipation

$E_{\perp}$ acceleration

Injection at r > R_{lc} → High dissipation

$E_{\perp}$ & $E_{||}$ accelerations

→ Null or surface injection?

Localized sheet injection model is unrealistic?