Coherence of Multi-Dimensional Pair Production Discharges in Polar Caps of Pulsars

Chernoglazov A., Philippov A., Timokhin A. 2024
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Reporter: 曹顺顺 (Shunshun Cao)

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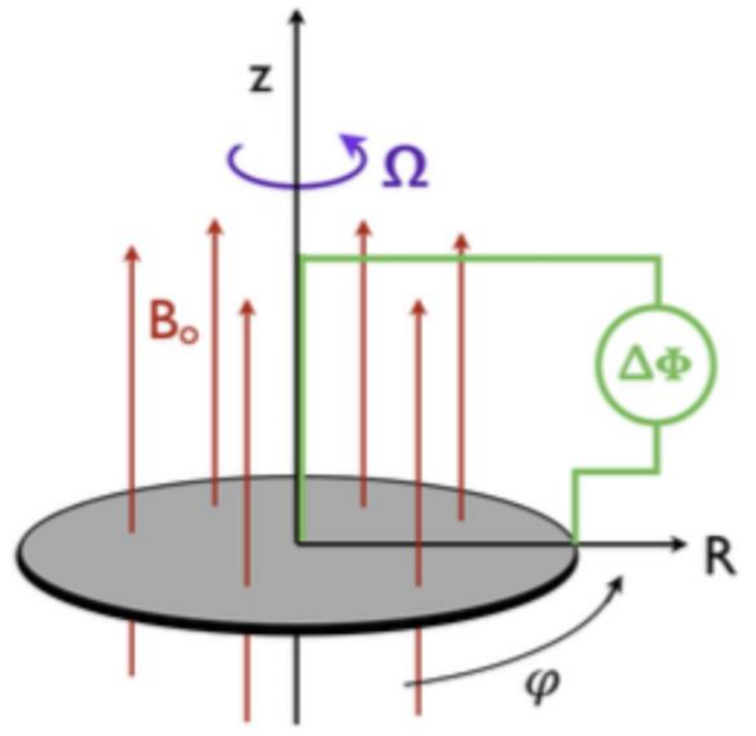
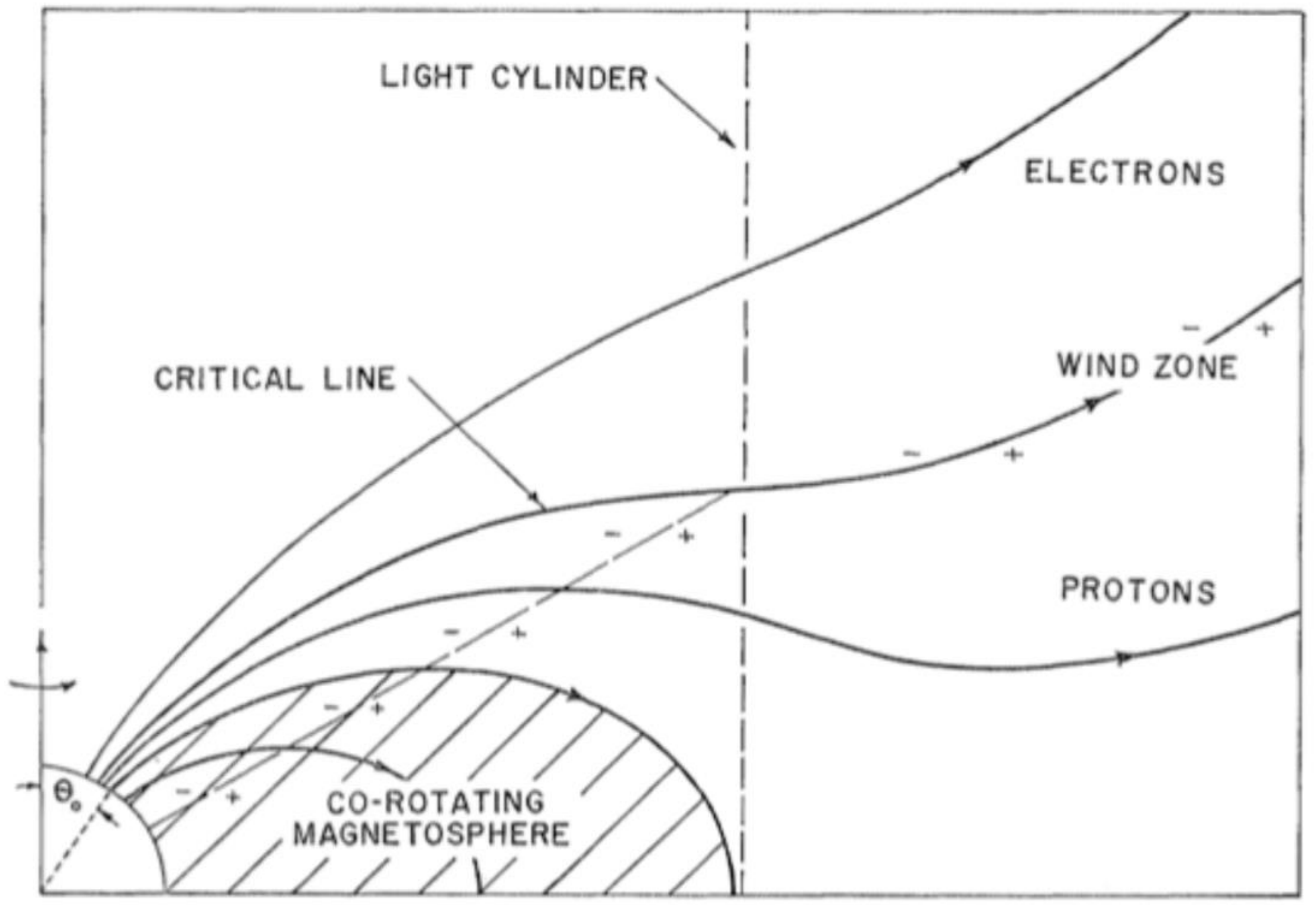
27 pages in total

I. Introduction

(i) Pulsar magnetosphere and polar cap

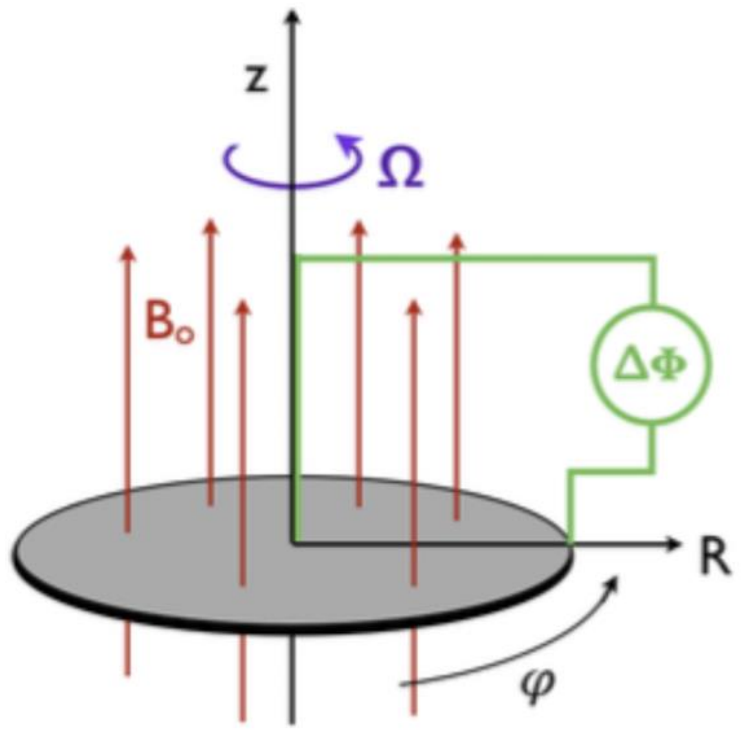
A note in Zhihu
for Amato’s paper.

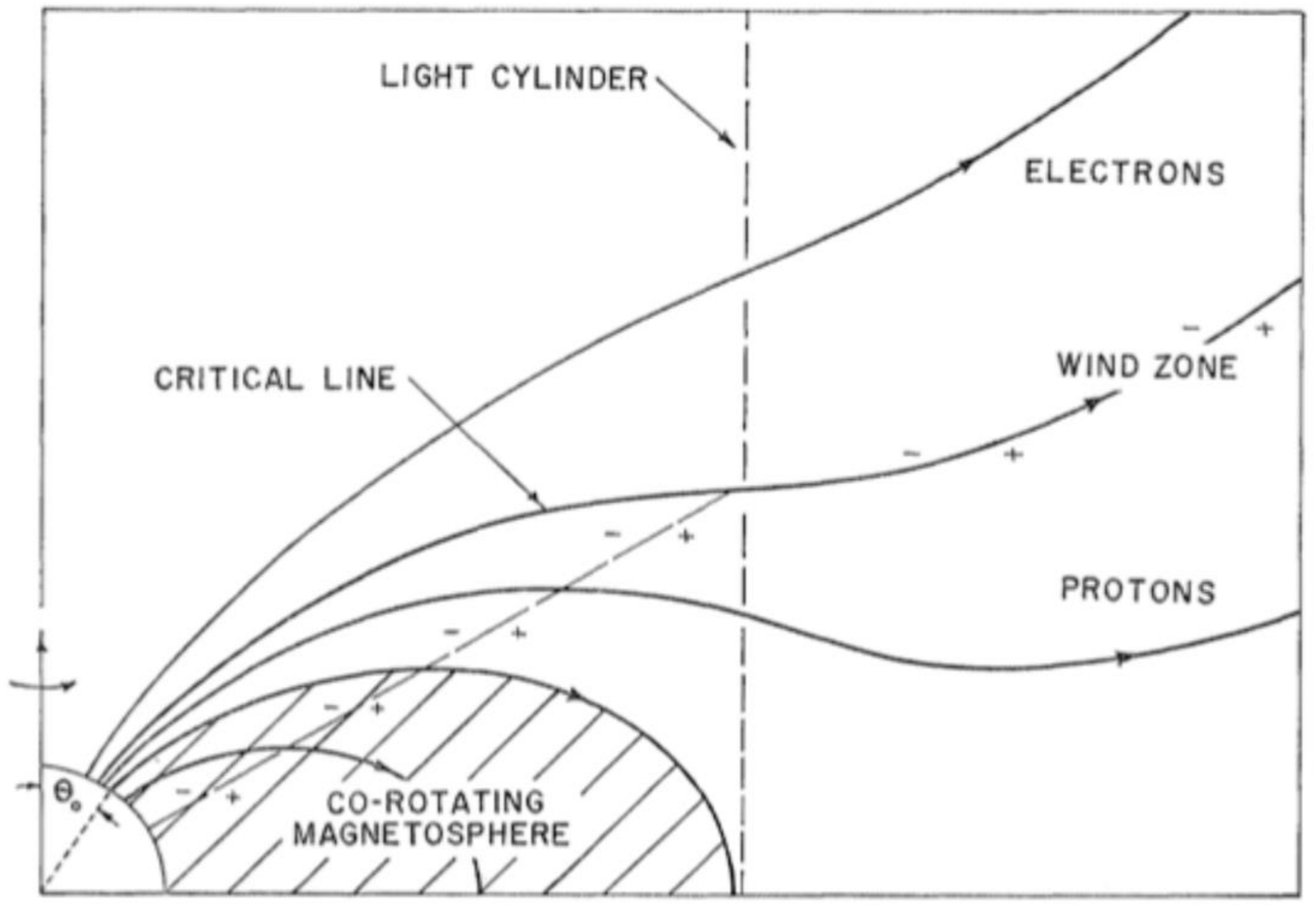


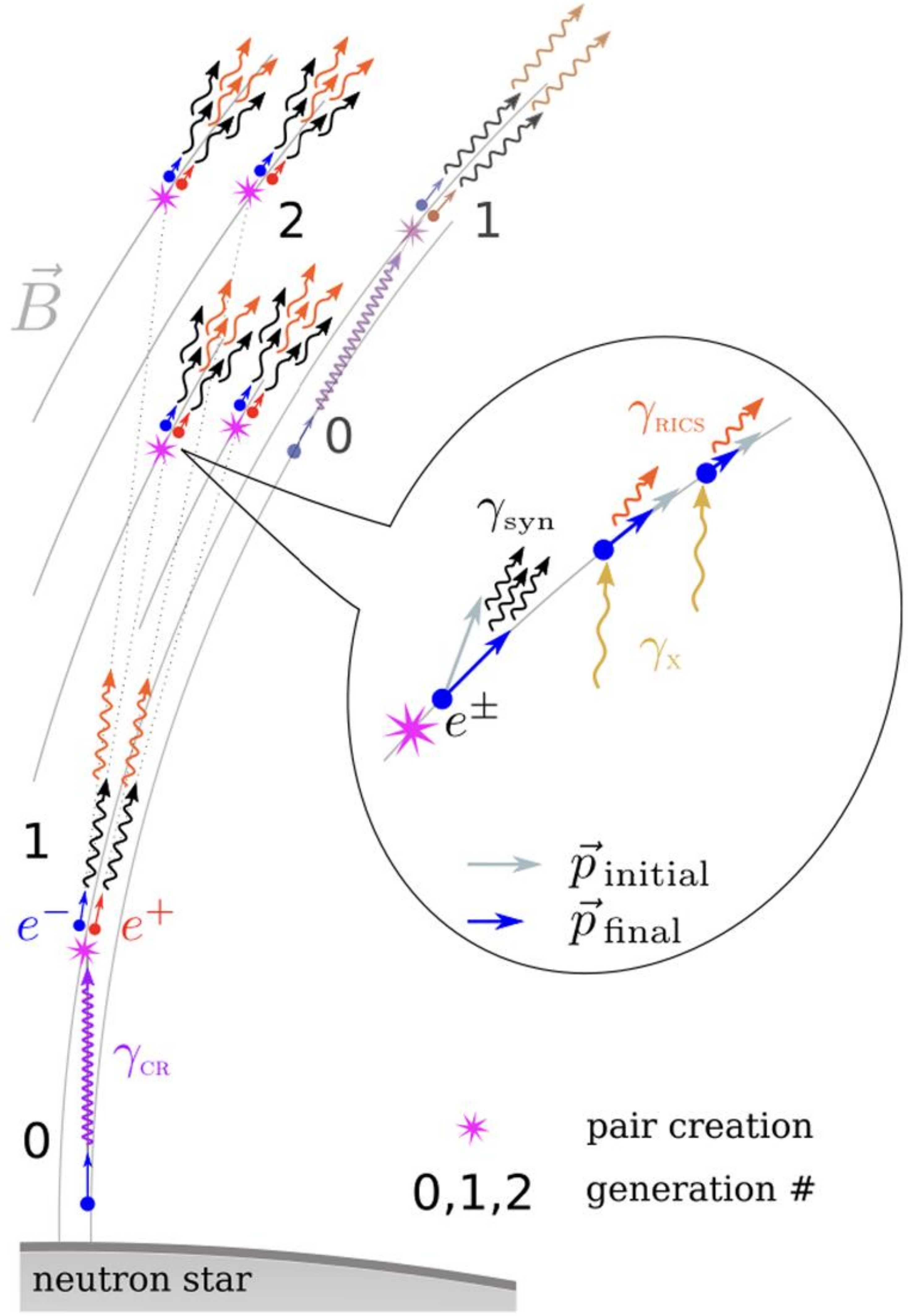


Pulsar ≈ Faraday Disk
Rotating compact object in magnetic field
➔Electric field distribution
➔➔ Provide acceleration regions

Amato 2024 arxiv.







A note in Zhihu
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Initial particles in ***E*** field
➔Accelerated particles
➔➔ Emitted photons
(curvature or ICS)
➔➔➔ Pair (e±) creation
➔➔➔➔ Charge separation
screen original ***E*** field

(**Discharge** process)

Amato 2024 arxiv.

Charged particles fill the pulsar surroundings ➔ magnetized plasma ➔ magnetosphere

Static magnetosphere:

$$q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = 0$$

Corotation condition:

$$\mathbf{E} + (\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B} = 0$$

Charge density satisfies:

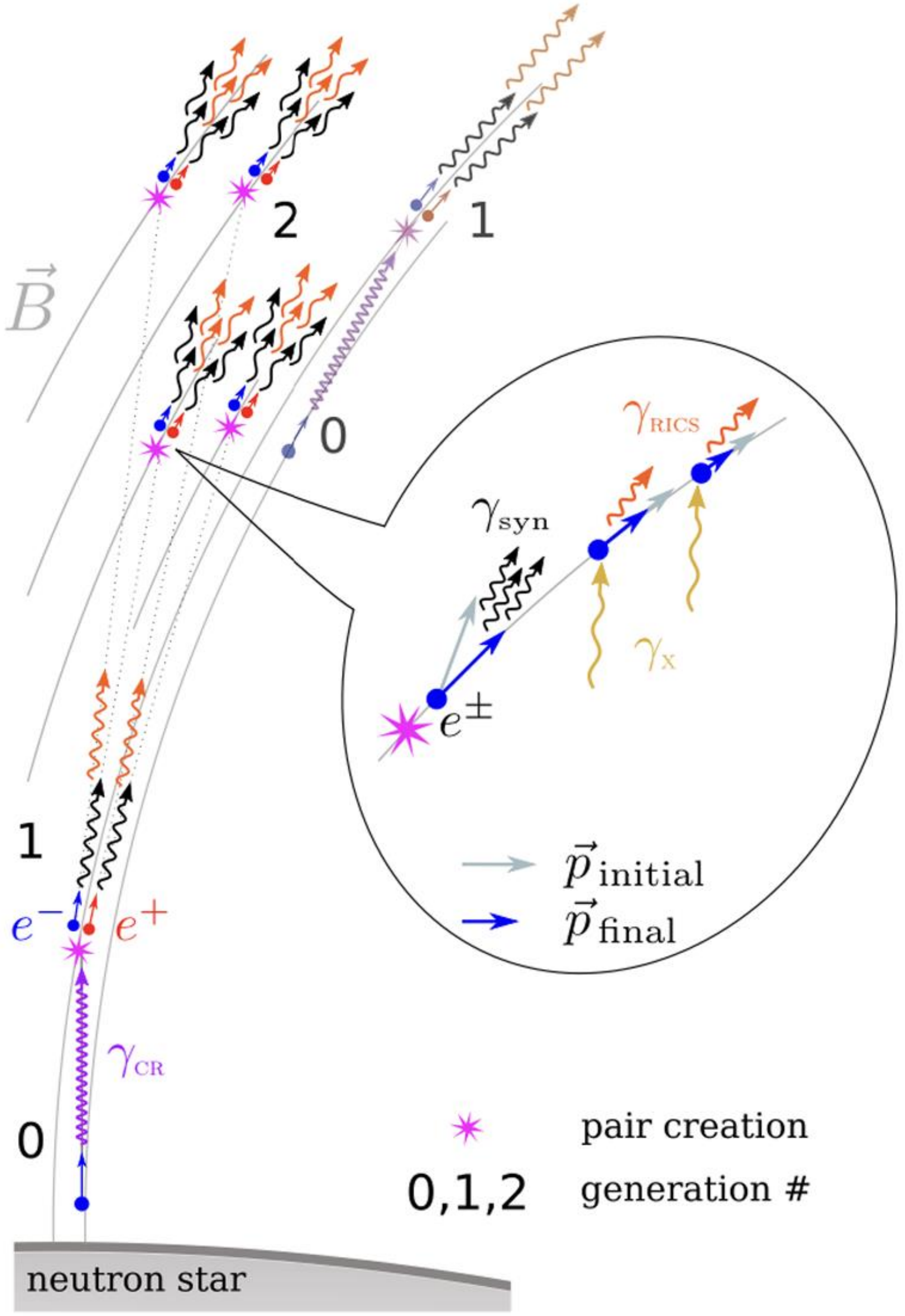
$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

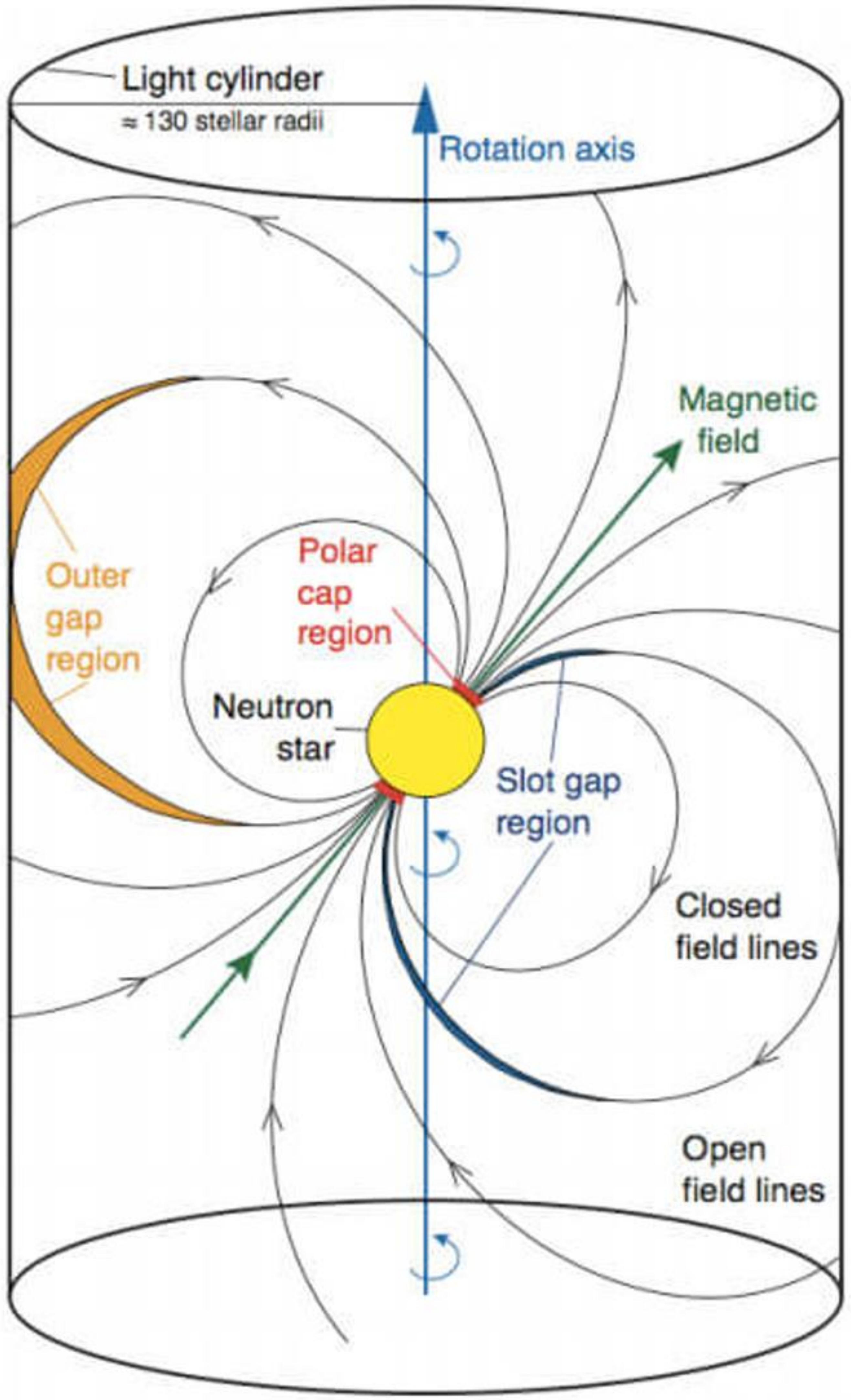
➔

$$\rho_{\rm GJ} = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c} \frac{1}{1 - (\Omega r/c)^2 \sin^2 \theta}$$

$$n_{\rm GJ} \equiv \rho_{\rm GJ}/e \approx 7 \times 10^{10} \times \left(\frac{B_z}{10^{12} G}\right) \left(\frac{P}{1s}\right)^{-1} {\rm cm}^{-3}$$

Goldreich-Julian density (Goldreich & Julian 1969)





Amato 2024 arxiv.

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Goldreich-Julian density (Goldreich & Julian 1969)

Corotation: limited because

$$|\mathbf{\Omega} \times \mathbf{r}| < c$$

➔Light cylinder (LC):

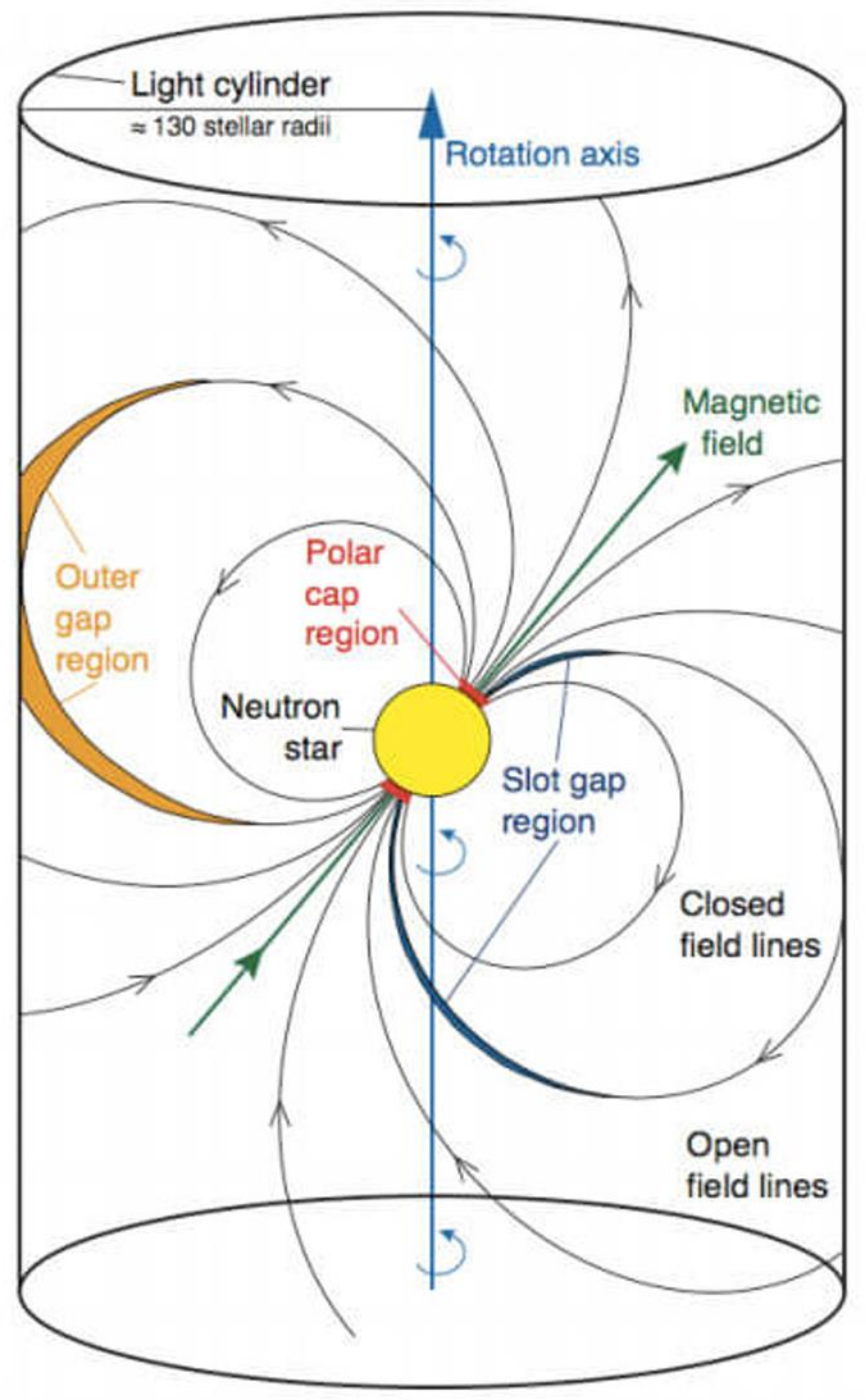
$$R_{\rm LC} = c/\Omega$$

Magnetic field lines
- ➢ Closed within LC:

Closed field lines
- ➢ Not closed within LC:

Open field lines

Feet of open field lines on pulsar surface: **Polar cap.**



Amato 2024 arxiv.

(ii) Introduction to models

(1) From Charge density driven to Current density driven:

From previous pages, we know when $\rho \neq \rho_{GJ}$ at somewhere, the magnetosphere is no longer static (non-force-free, non-FFE).

But for open field lines region, the magnetosphere is naturally "non-static":
Open field lines **twist** at light cylinder ➔ always requires magnetospheric currents.

Use current density as indication for acceleration's happening.

Introduce $\alpha = j_{\parallel}/(\rho_{\mathrm{GJ}} c)$

$0 < \alpha < 1$: (mild relativistic $\rho = \rho_{GJ}$ flow) or (ultra-relativistic $\rho < \rho_{GJ}$ flow) ➔ no lack for charge
$\alpha > 1$: $|\rho| > |\rho_{GJ}|$ flow ➔ charge starvation ➔ parallel electric field arises
$\alpha < 0$: net charge decrease ➔ charge starvation ➔ parallel electric field arises

(2) Ruderman-Sutherland (RS) model v.s. Space-Charge-Limited-Flow (SCLF) model:

RS model (Ruderman & Sutherland 1975): no supplement of plasma from pulsar surface.
(With isolated "sparks" ➔ can explain subpulse drifting)

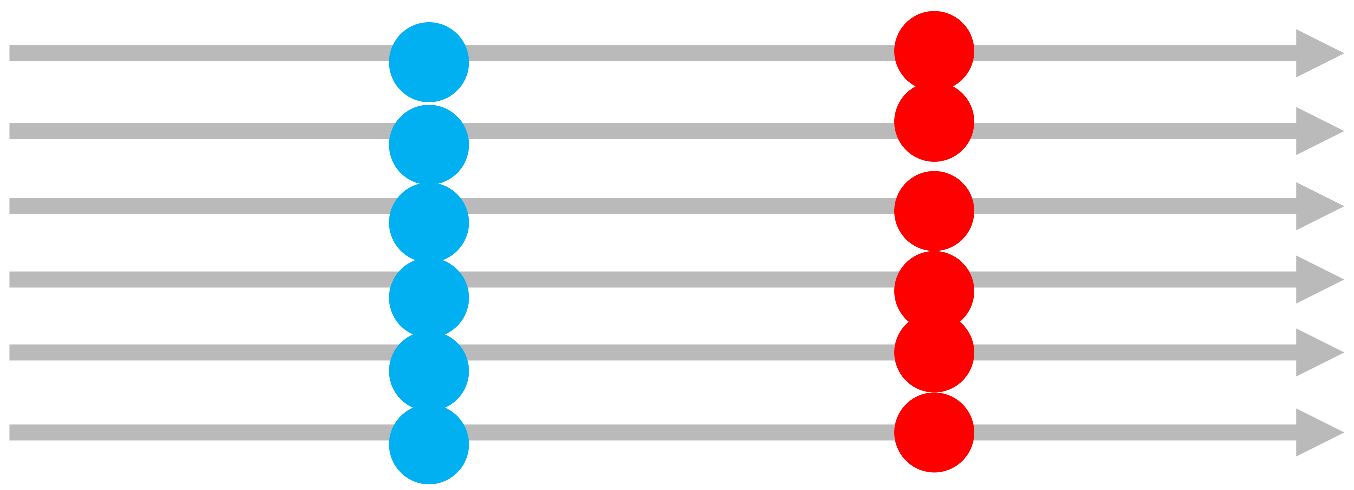
SCLF mode (Arons & Scharlemann 1979…): ions & electrons supplied by pulsar surface/atmosphere.

(Different in binding energy at pulsar surface)

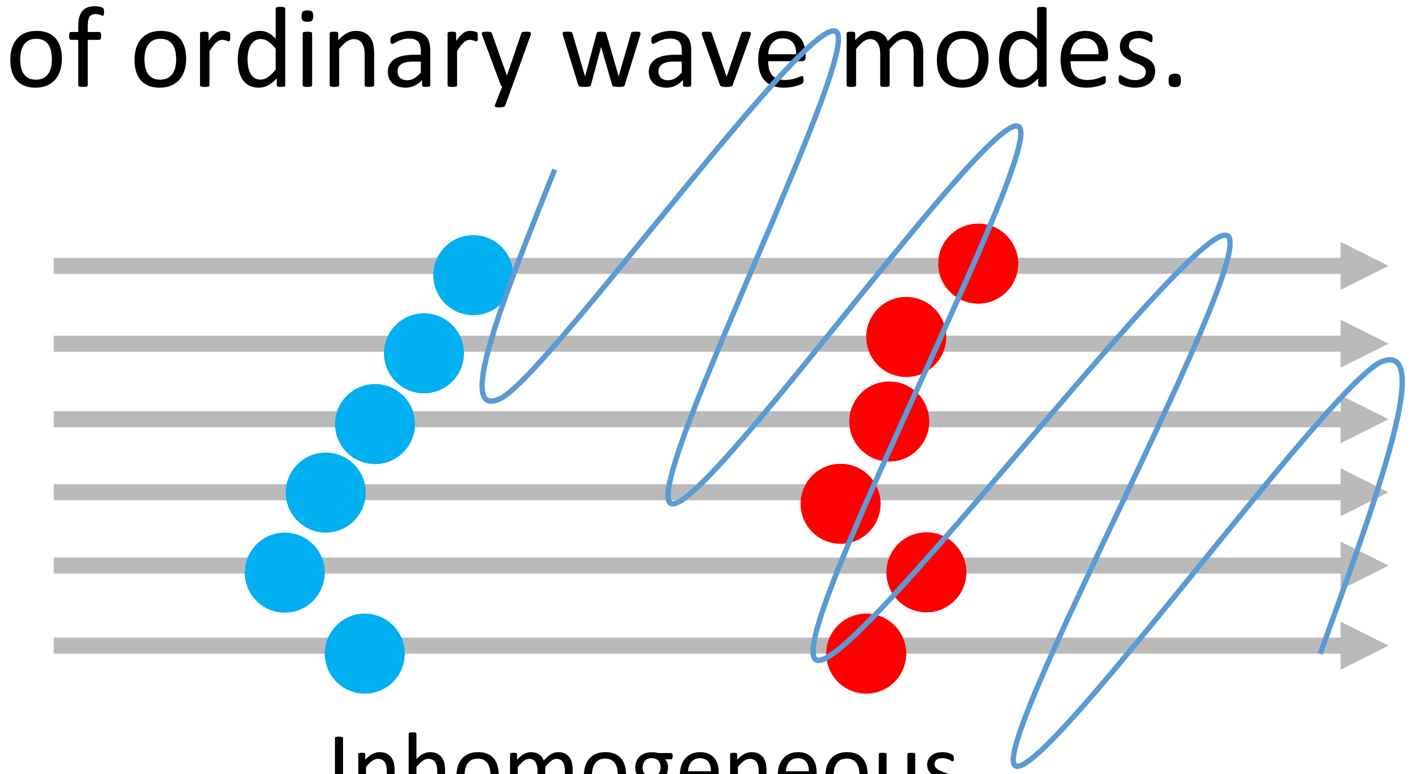
This paper:
2D & 3D simulations
On discharge processes

(3) Coherent radio emission mechanism:

Simulation by Philippov, Timokhin & Spitkovsky 2020:
Spatial inhomogenous discharge causes excitation of ordinary wave modes.



Homogeneous: Oscillation // Magnetic field



Inhomogeneous

II. Simulation setups

(1) EM dynamics

Unperturbed (Force-Free, FFE): $\boldsymbol{B}_{\mathrm{FFE}} = \boldsymbol{B}_0 + \boldsymbol{B}_\varphi,\ \boldsymbol{E}_{\mathrm{FFE}} = -\boldsymbol{\Omega} \times \boldsymbol{r} \times \boldsymbol{B}_0/c$ $\rho_{\mathrm{GJ}} = \nabla \cdot \boldsymbol{E}_{\mathrm{FFE}}/4\pi$

Corrections:

$$\frac{\partial}{\partial t}\delta\boldsymbol{E} = c\nabla \times \delta\boldsymbol{B} - 4\pi(\boldsymbol{j} - \boldsymbol{j}_{\mathrm{mag}}),$$

$$\frac{\partial}{\partial t}\delta\boldsymbol{B} = -c\nabla \times \delta\boldsymbol{E}.$$

$$\nabla \cdot \delta\boldsymbol{E} = 4\pi(\rho - \rho_{\mathrm{GJ}})$$

Polar cap: $R_{\mathrm{PC}} = R_\star\sqrt{R_\star/R_{\mathrm{LC}}}$ $R_{\mathrm{LC}} = cP/2\pi$

Two stationary solutions:

(i) δE = δB = 0, fully force free, $j = j_{\mathrm{mag}}$ ← Abundant plasma everywhere

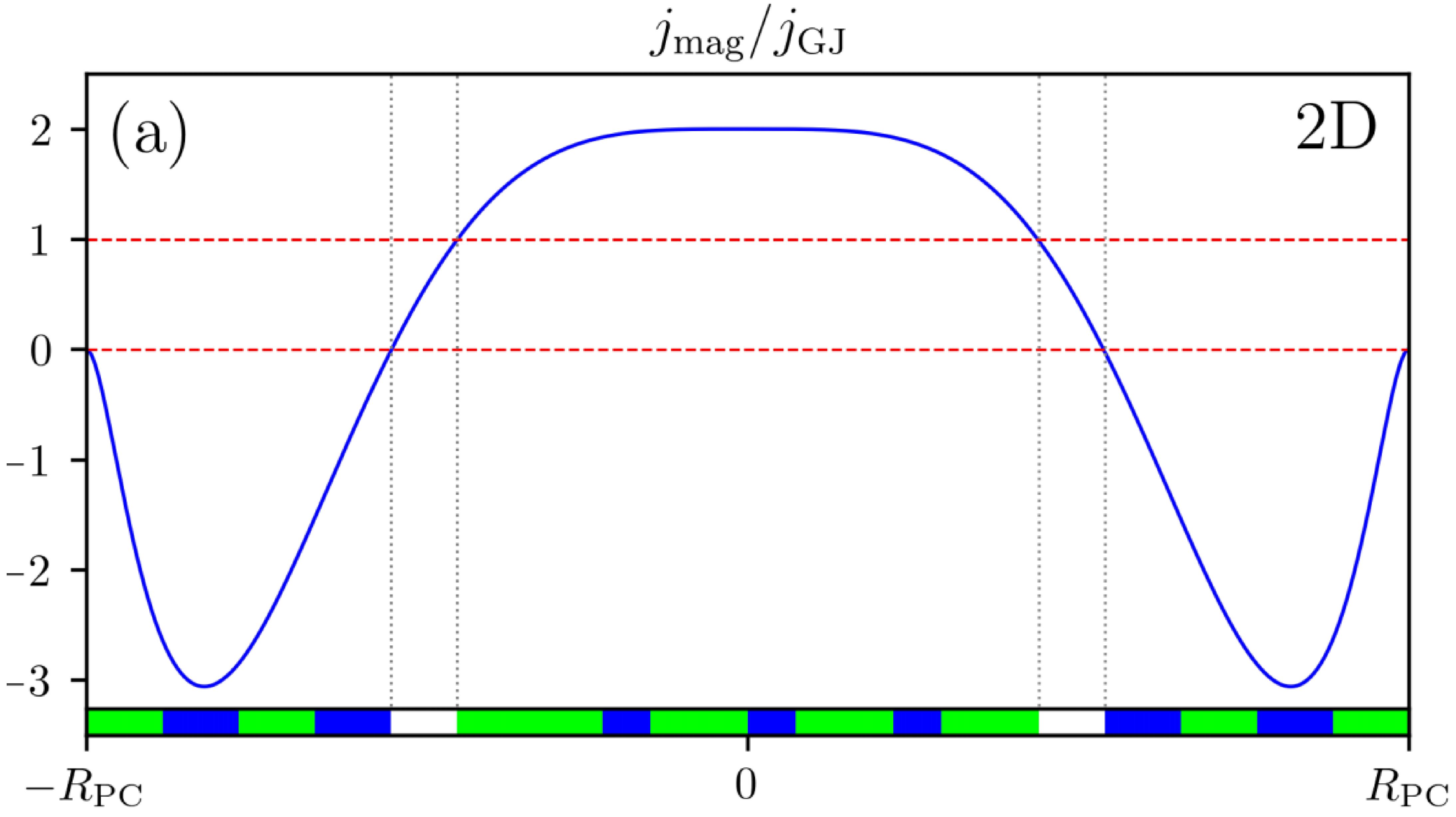
(ii) j = 0, $\delta B = -B_\varphi$, no magnetic field twist ← No plasma loading

(2) Magnetospheric current distribution: follow Gralla et al. 2016, 2017

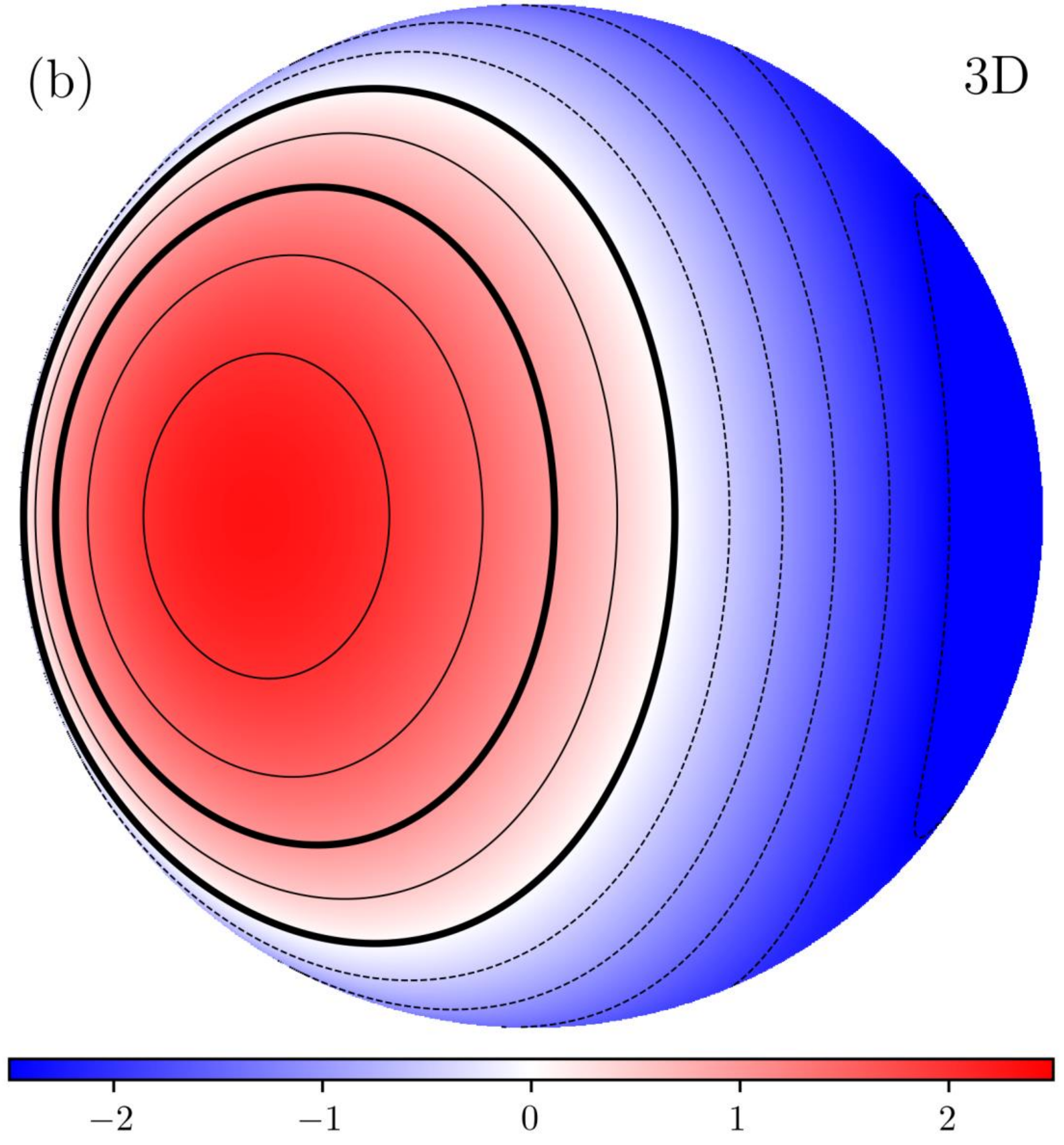
2D: $$j^{2D}_{mag}(x) = 2 - C_1 x^4 + C_2 x^6 + C_3 x^{40}$$

$$\int_0^{R_{PC}} j^{2D}_{mag} dx = 0, \quad j^{2D}_{mag}(1) = 0, \quad \frac{d}{dx} j^{2D}_{mag}\Big|_{x=1} = 0$$

$$x = r_\perp / R_{PC}$$



3D: $$\frac{j^{3D}_{mag}}{\rho_{GJ} c}(\theta, \phi) \approx \frac{1}{(1 - \Omega_Z/\Omega)} [J_0 (\arcsin(\theta/\sqrt{\alpha_0})) - -J_1 (\arcsin(\theta/\sqrt{\alpha_0})) \tan i \cos\phi].$$



(3) QED pair creation ➔ leads to large multiplicity $\mathcal{M} = n_{\pm}/n_{\rm GJ} \gg 1$

Emission in polar cap: synchrotron curvature radiation.

$$\frac{dN_{\rm ph}}{dtd\varepsilon} = \frac{1}{\sqrt{3}\pi}\frac{e^2}{\hbar^2 c}\frac{1}{\gamma_{\rm b}^2}\int_{\frac{\varepsilon}{\varepsilon^*_{\rm ph}}}^{\infty} K_{5/3}(x)dx, \qquad \varepsilon^*_{\rm ph} = \frac{3}{2}\hbar\frac{c}{\rho_{\rm c}}\gamma_{\rm b}^3.$$

Cross section for pair creation:

$$\frac{{\rm d}\sigma}{{\rm d}z} = 0.23\frac{B}{B_q}\sin\psi\frac{\alpha_{\rm F}}{\lambda_c}\exp\left(-\frac{8}{3\chi}\right)\Theta(\tilde{\varepsilon}_{\rm ph}\sin\psi - 2),$$

$$\chi = (B/B_q)\tilde{\varepsilon}_{\rm ph}\sin\psi \qquad \tilde{\varepsilon}_{\rm ph} = \varepsilon_{\rm ph}/m_e c^2$$

$$B_q = m_e^2 c^3/e\hbar \approx 4.41\times 10^{13}{\rm G}$$

Secondary particles' velocity:

$$u_{||} = \frac{|\cos\psi_a|(\tilde{\varepsilon}_{\rm ph}^2 - 4)^{1/2}}{\left(\tilde{\varepsilon}_{\rm ph}^2\sin^2\psi_a + 4\cos^2\psi_a\right)^{1/2}} \sim \frac{1}{\sin\psi_a} \sim 10^2 - 10^3,$$

Pair creation & emission energy scales described in 3 gamma parameters:

$$\gamma_{\rm PC} = 0.5(R_{\rm PC}/d_{\rm e}^{\rm GJ})^2 \qquad eE_{\rm PC} = (2/3)e^2\gamma_{\rm rad}^4/\rho_{\rm c}^2 \qquad (3/2)\hbar(c/\rho_{\rm c})\gamma_{\rm emit}^3 = m_e c^2$$

$$d_{\rm e}^{\rm GJ} = c/\sqrt{4\pi|\rho_{\rm GJ}e|/m_e} \qquad \tilde{\varepsilon}_{\rm ph} = (\gamma/\gamma_{\rm emit})^3$$

Generally, γ_PC >> γ_rad >> γ_emit.

(4) Atmosphere

SCLF model: thin electron-ion atmosphere ➔ reservoir of charged particles.
≈ A hot plasma layer at simulation boundary. $n = n_{\rm peak} \exp(-z/h)$
(This T is about 2.5×10^4 K.)

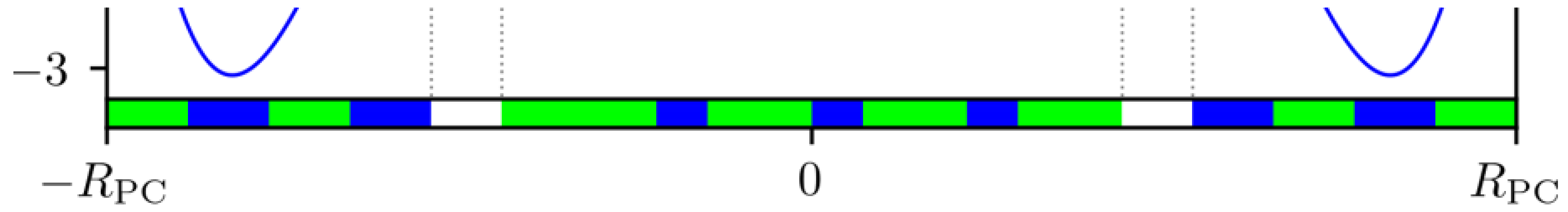
$h = kT/(m_e g) \approx 10 d_{\rm e}^{\rm GJ}$
$n_{\rm peak} \approx 10 n_{\rm GJ}$

RS model: no atmosphere.

(5) Initial plasma state

Multiplicity ~ a few. $j = j_{\rm mag}$ $\delta \boldsymbol{E} = 0$ $\rho_{\rm GJ} = \rho^0_{\rm GJ}(1 + 0.8z/L_z)$

Initial inhomogeneity: divide polar cap into different patches.



stop injecting initial plasma at different times on neighboring patches.

(6) Numerical details

Tristan-v2: multi-species radiative PIC code (Hakobyan et al. 2024).
Initial magnetic field: uniform. Curvature of field lines: prescribed. Multiplicity < 50...

III. Results

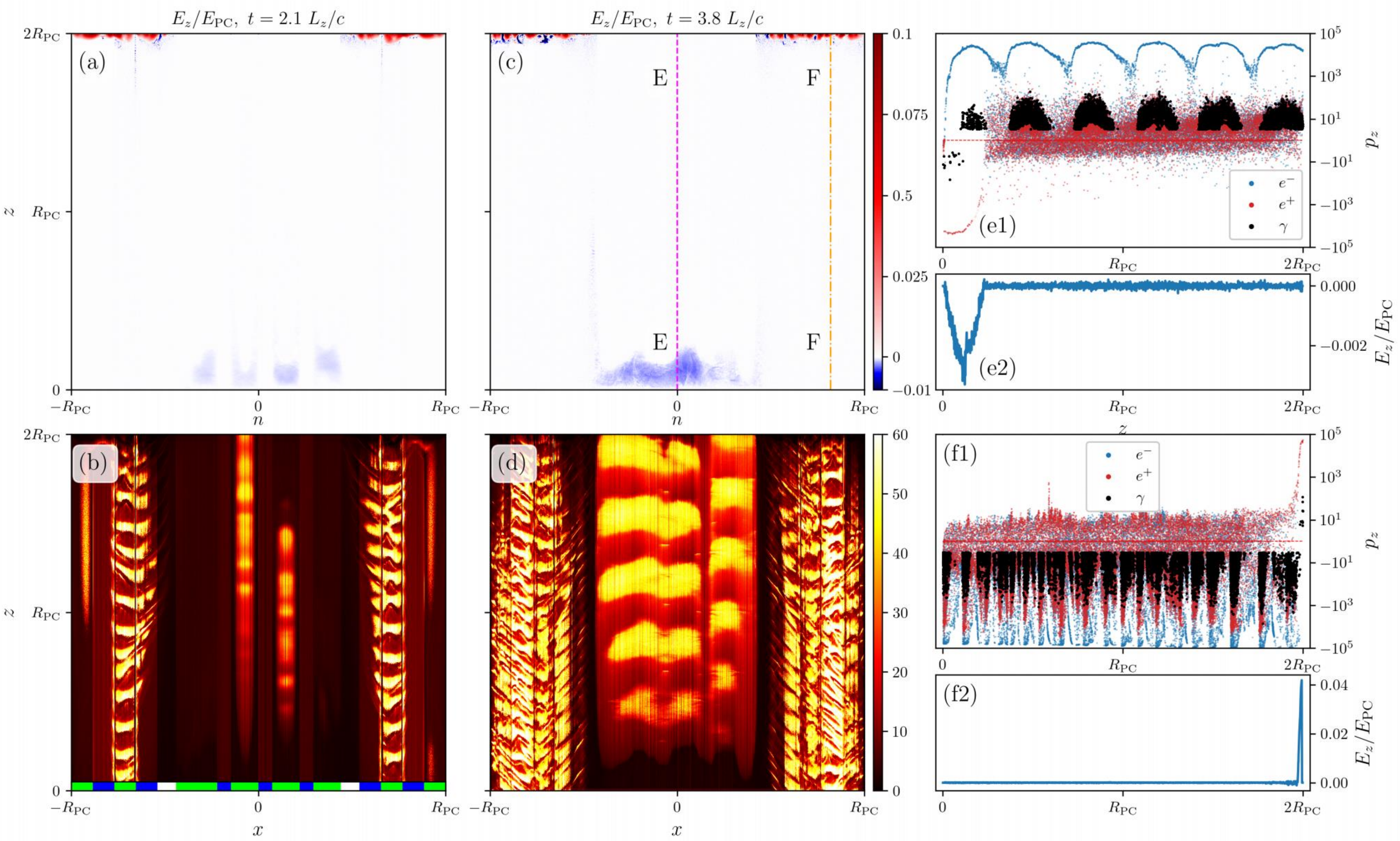
(1) SCLF

(1.1) Small gap & Constant field lines' curvature

Dipolar field with multipolar components?

$E_{//}$ field:

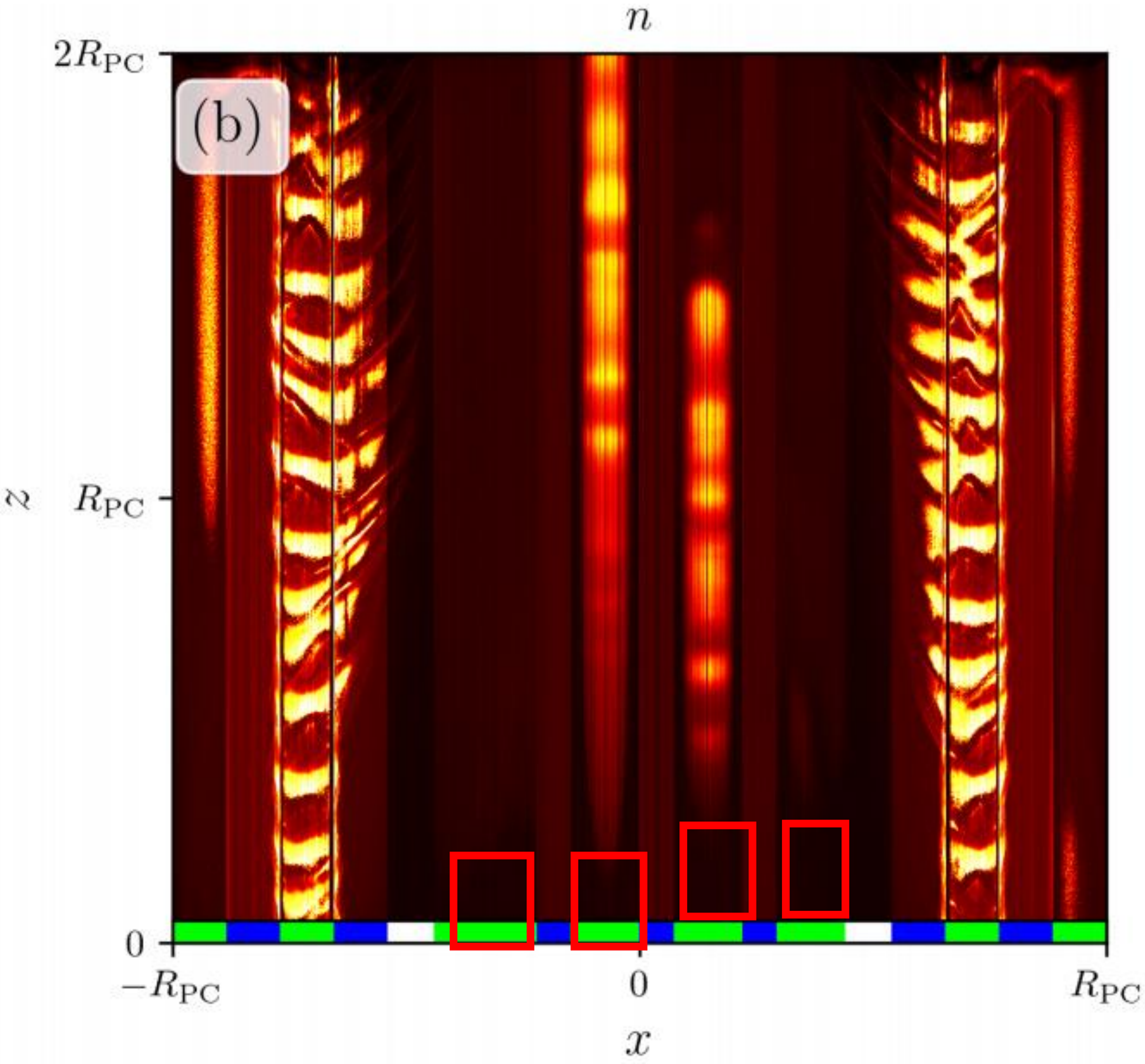
Particle number density:

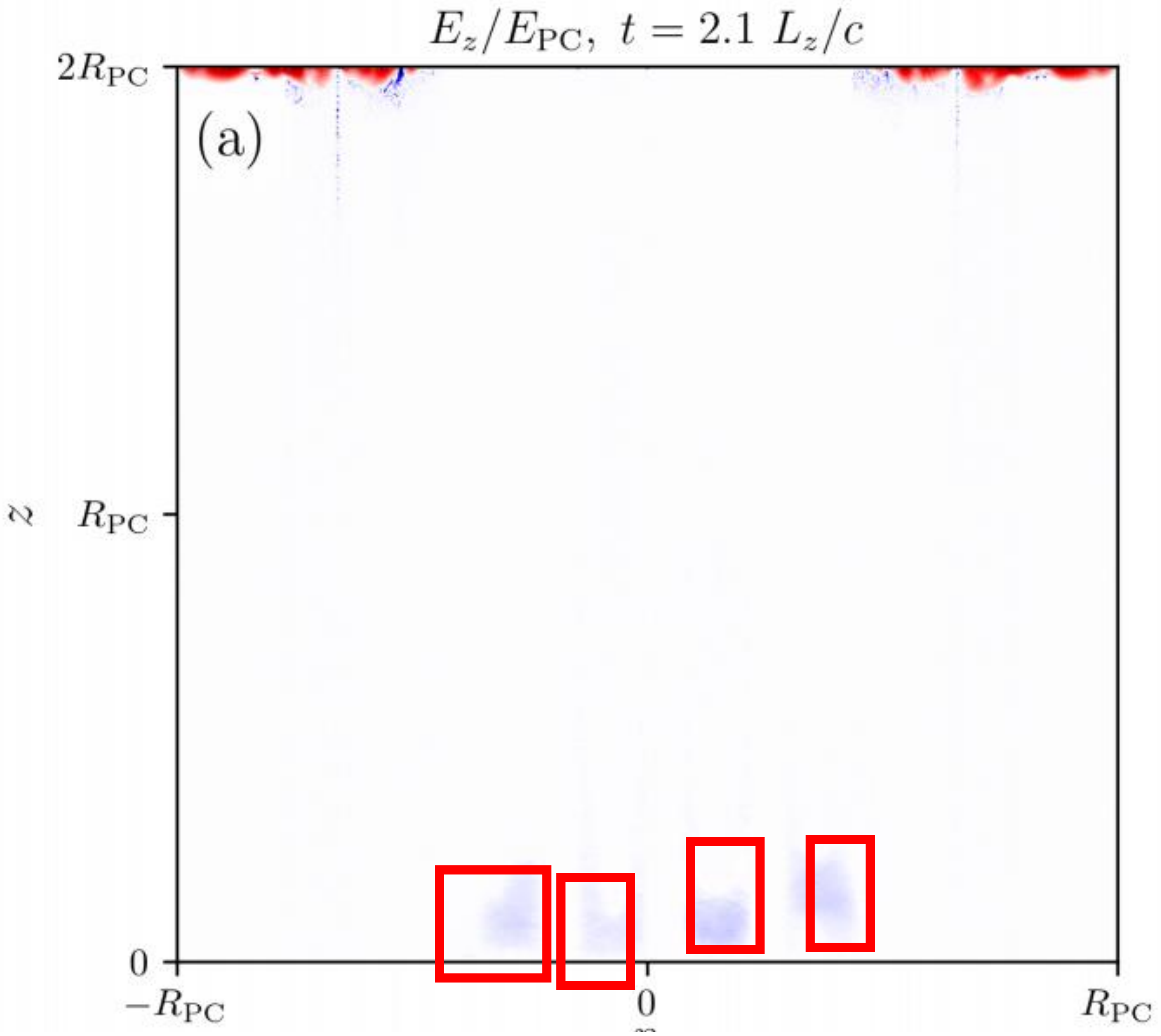


Super-GJ region (j/j_GJ>1): gap close to surface.

Early time: due to initial inhomogeneity sets, some patches have cleared plasma region, while some have not.

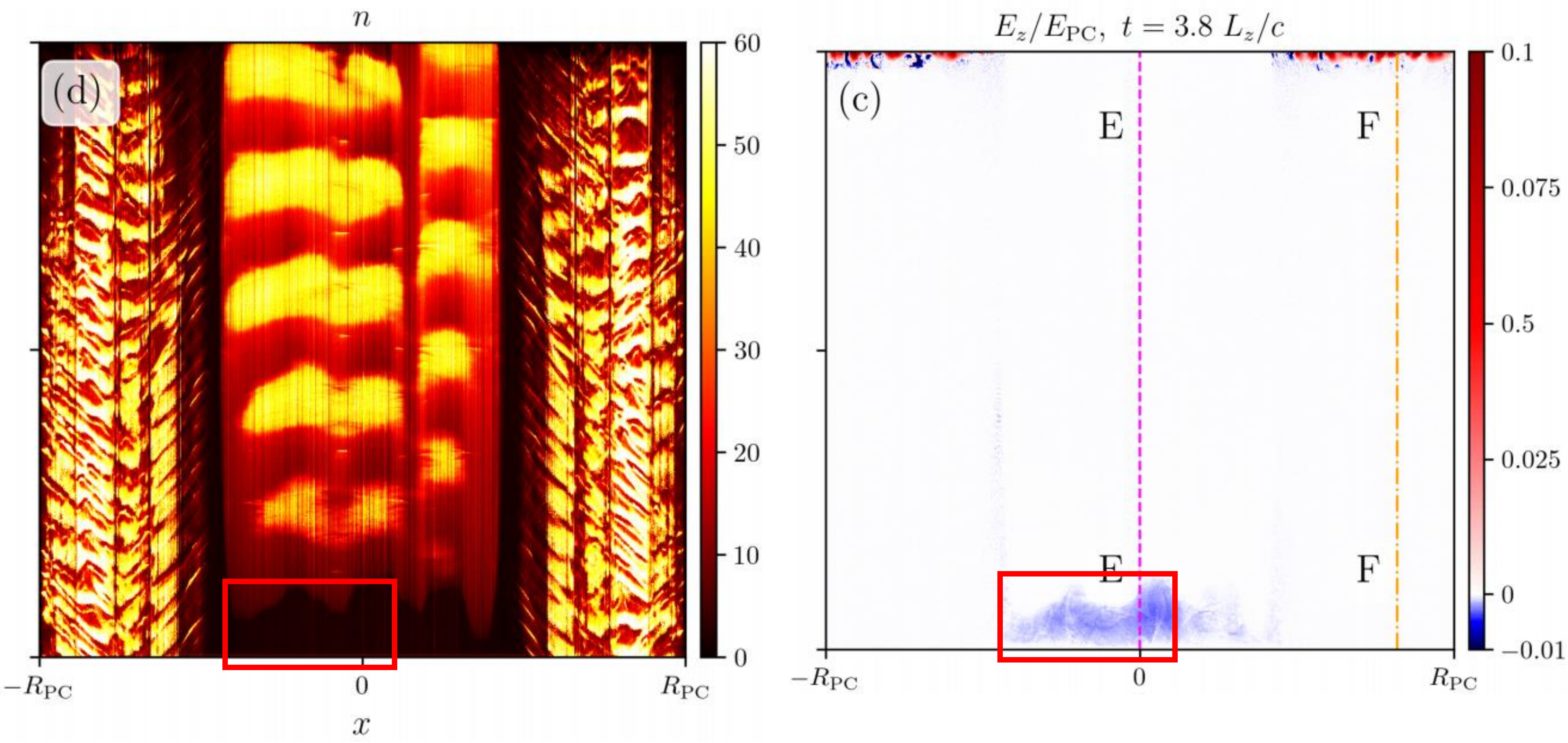
➔➔ Gaps are also in patches. And they are quasi-stationary.





Super-GJ region (j/j_GJ>1): gap close to surface.

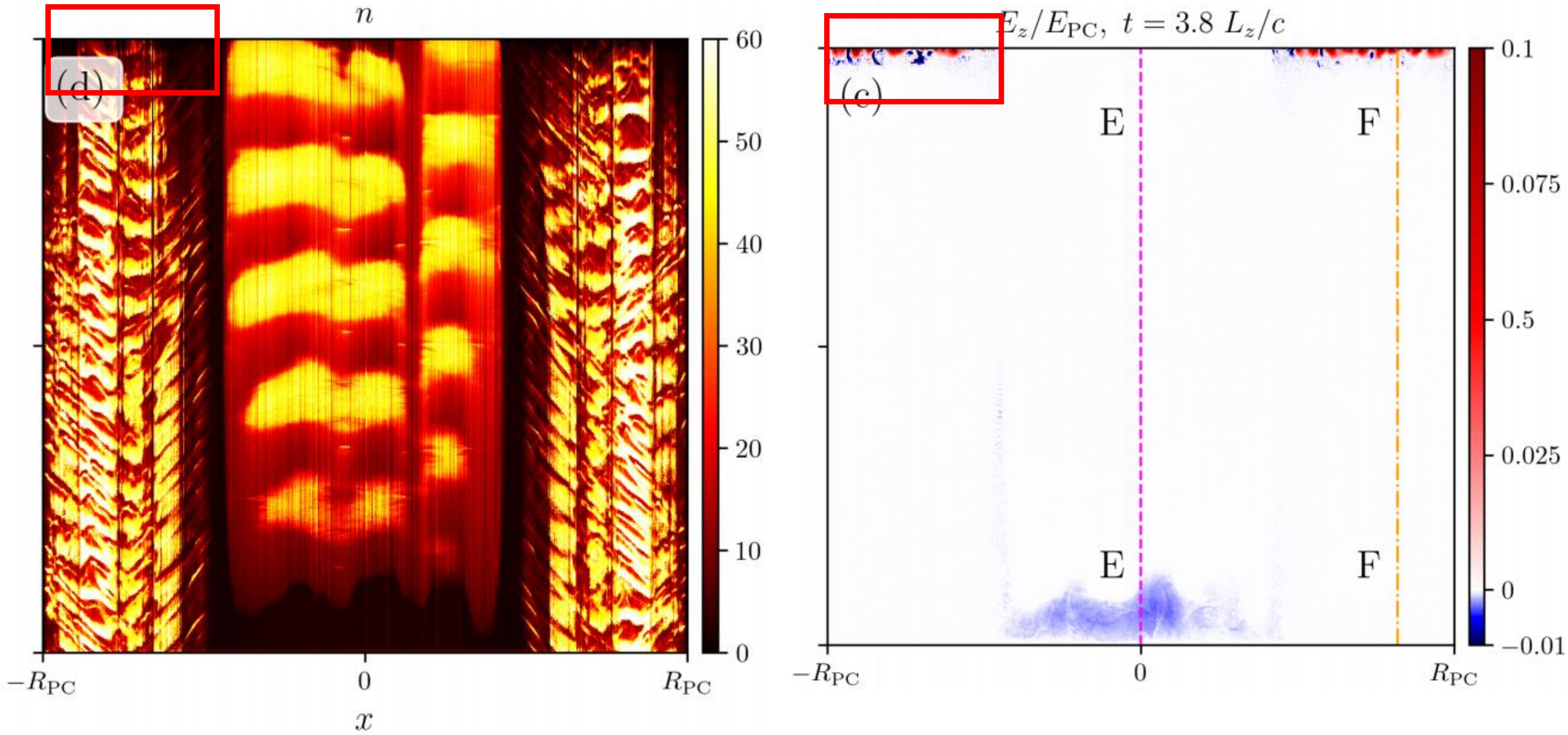
Late time: more patches clear plasma ➔ gaps are connected to **larger pieces**.



Cyclic screening happens ➔ Discharges are intermittent.

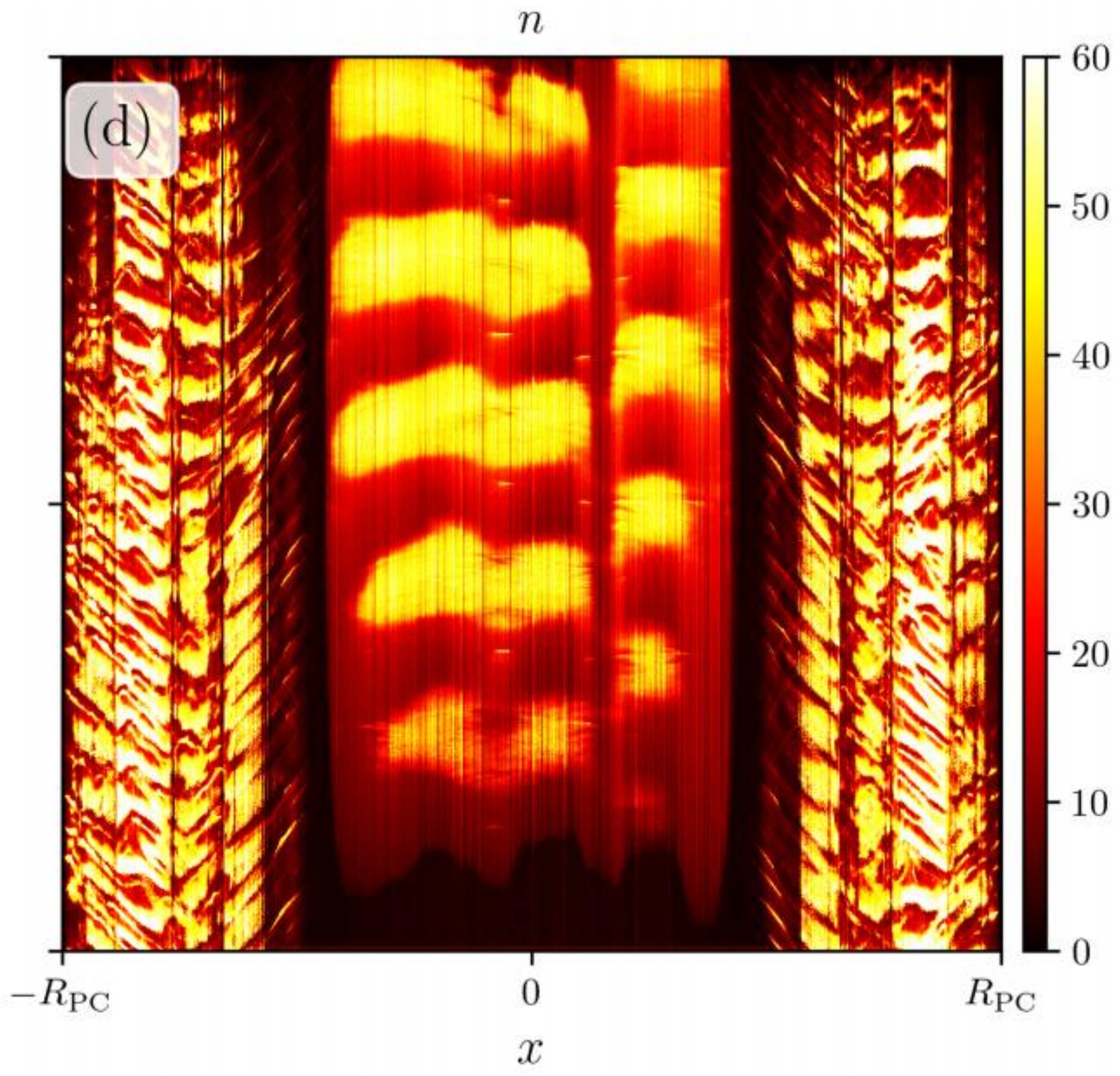
Return current region (j/j_GJ<0): higher gap.

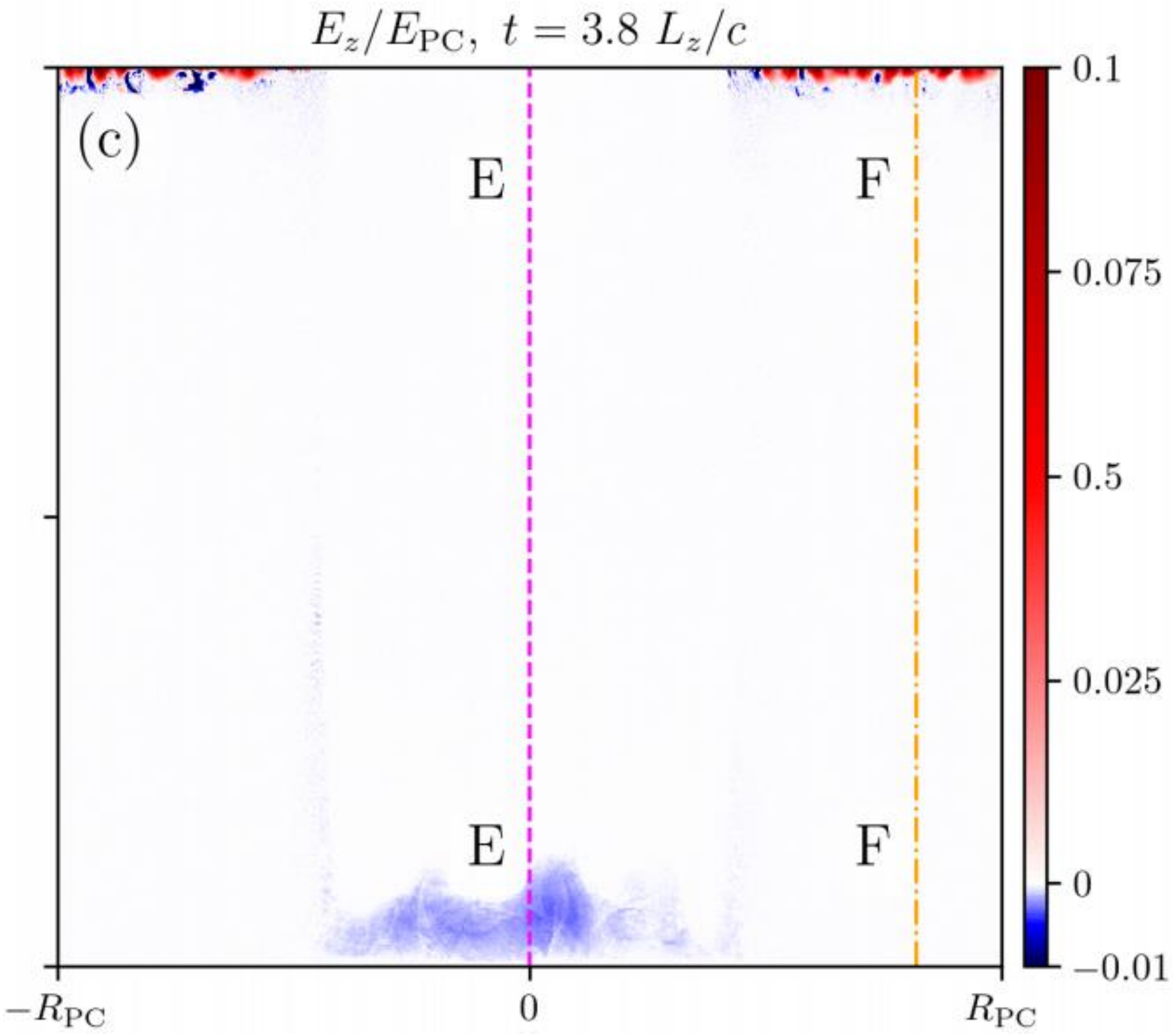
Larger difference in motions of positrons & electrons ➔ stronger electric field ➔ smaller gaps



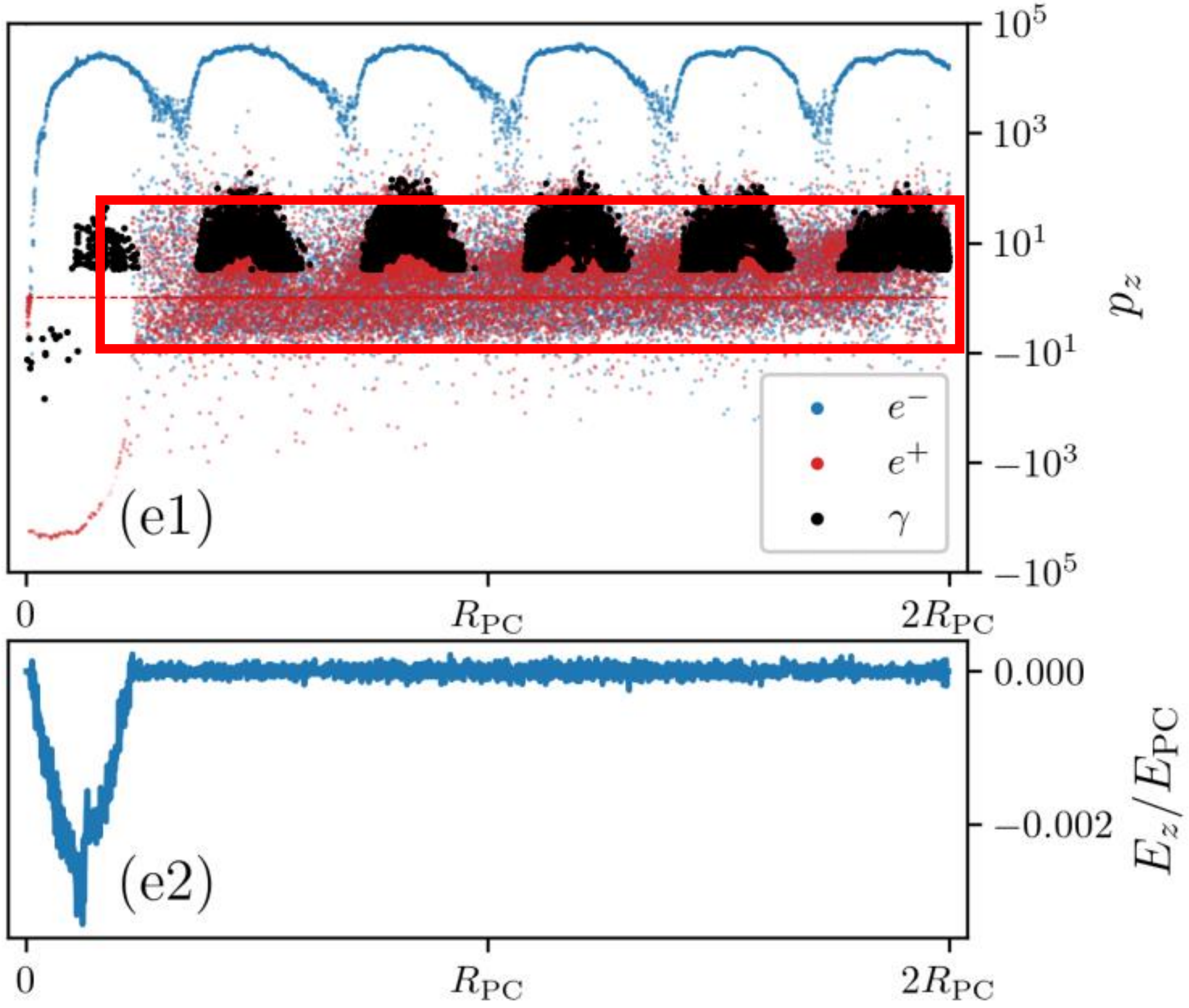
Cyclic screening happens ➔ Discharges are intermittent.

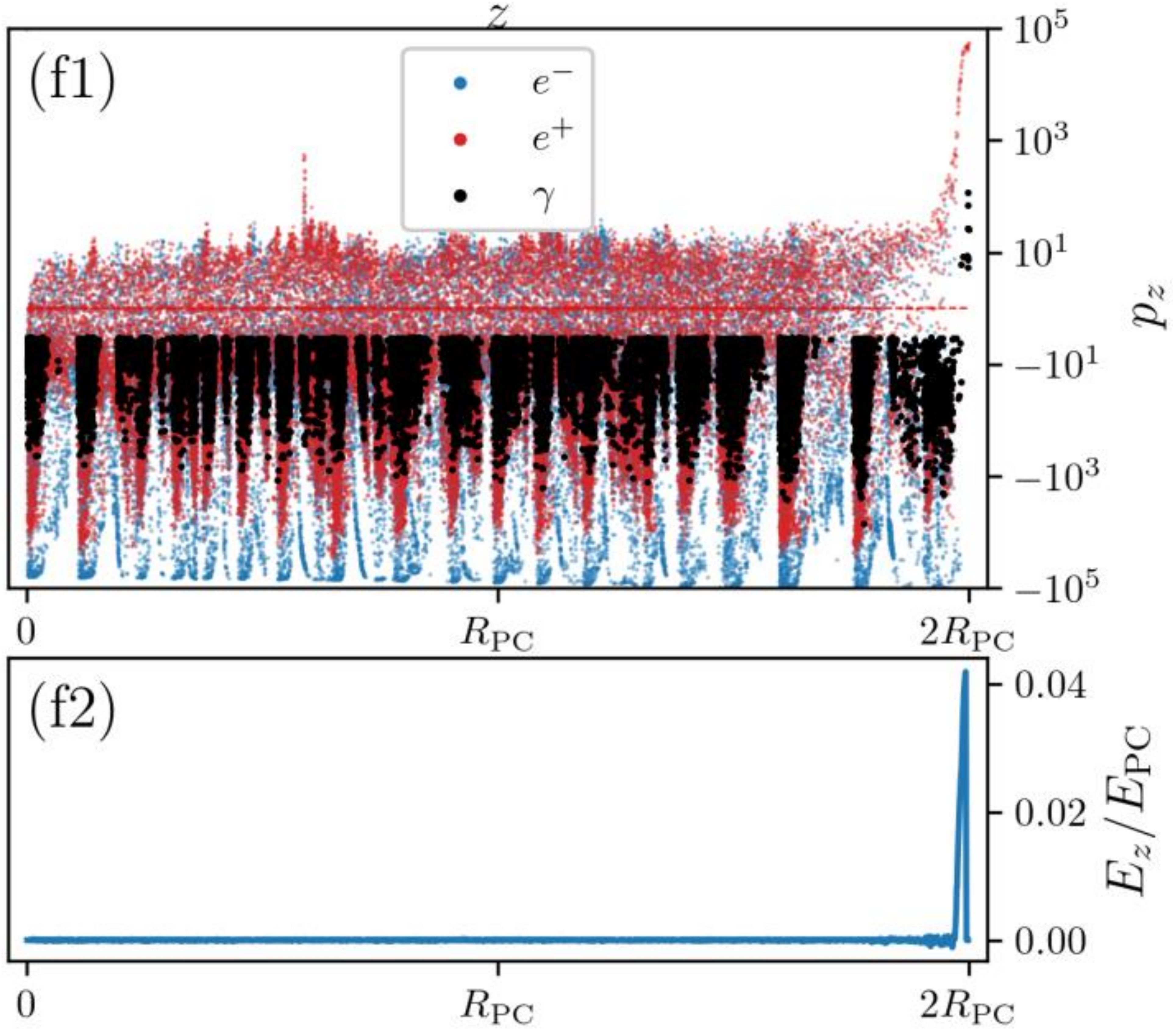
Transverse coherence scale of gaps < 2*l_gap ➔ Desynchronization of discharges.

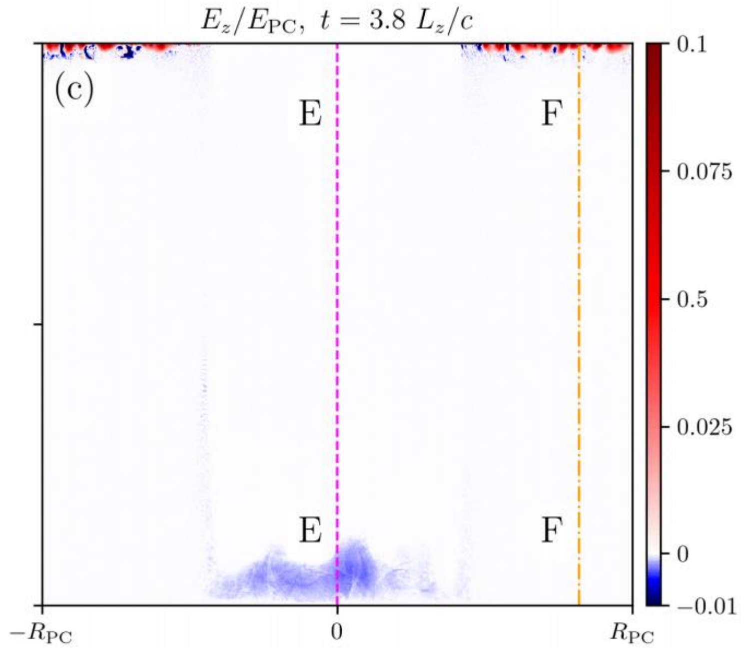




Difference in particle momentums and electric field for two kinds of gaps:







j/j_GJ>1

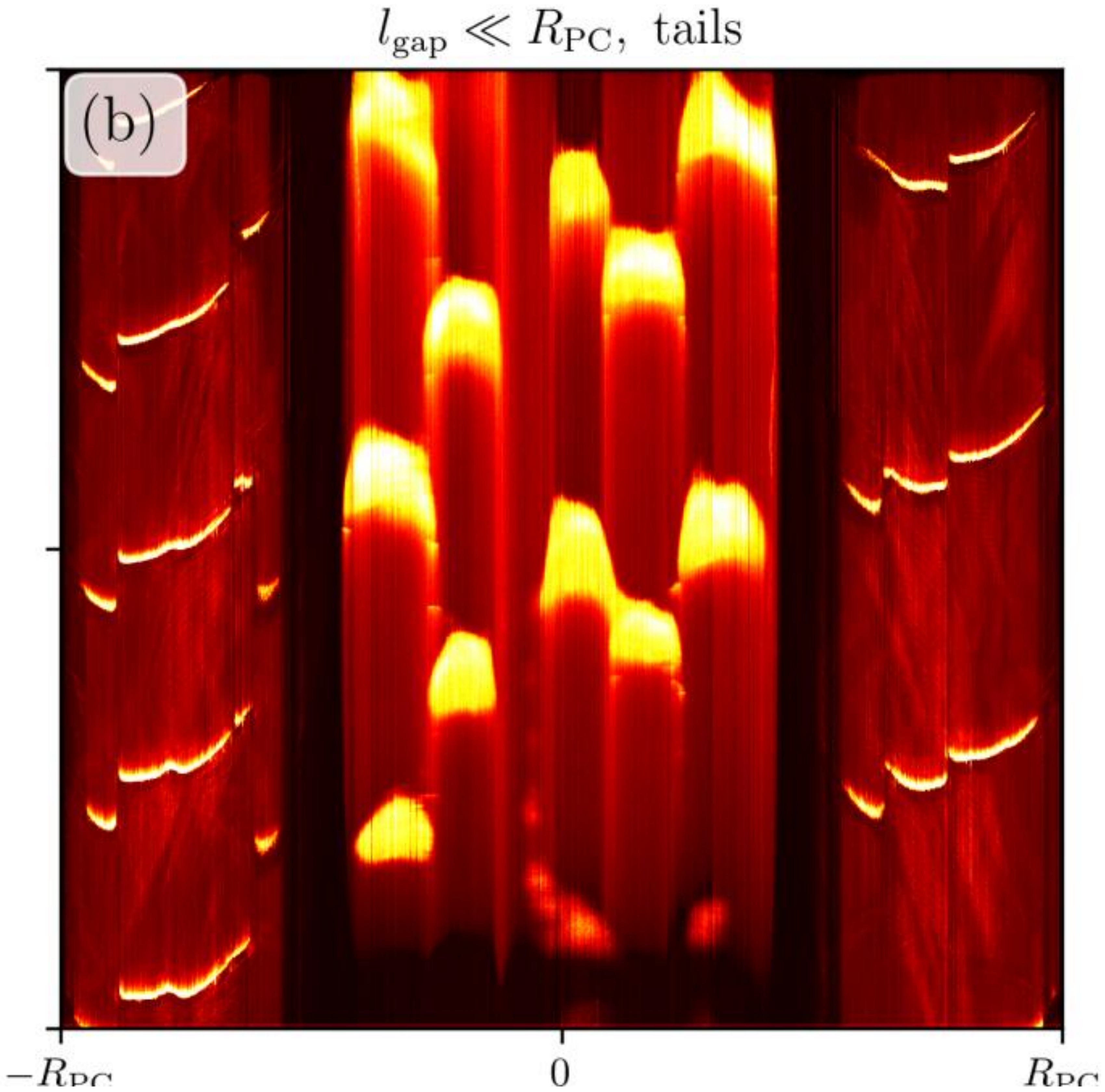
j/j_GJ<0

(1.2) Small gap & Strong Desynchronization (more plasma)

Discharge cyclic period too short ➔ reverse bombardment too strong ➔ surface too hot
➔ can't fit X-ray observation

Actually caused by too low plasma density in simulation.
➔ To fix it, the authors inject **additional** extended tails behind escaping clouds of secondary plasma

Particle number density:



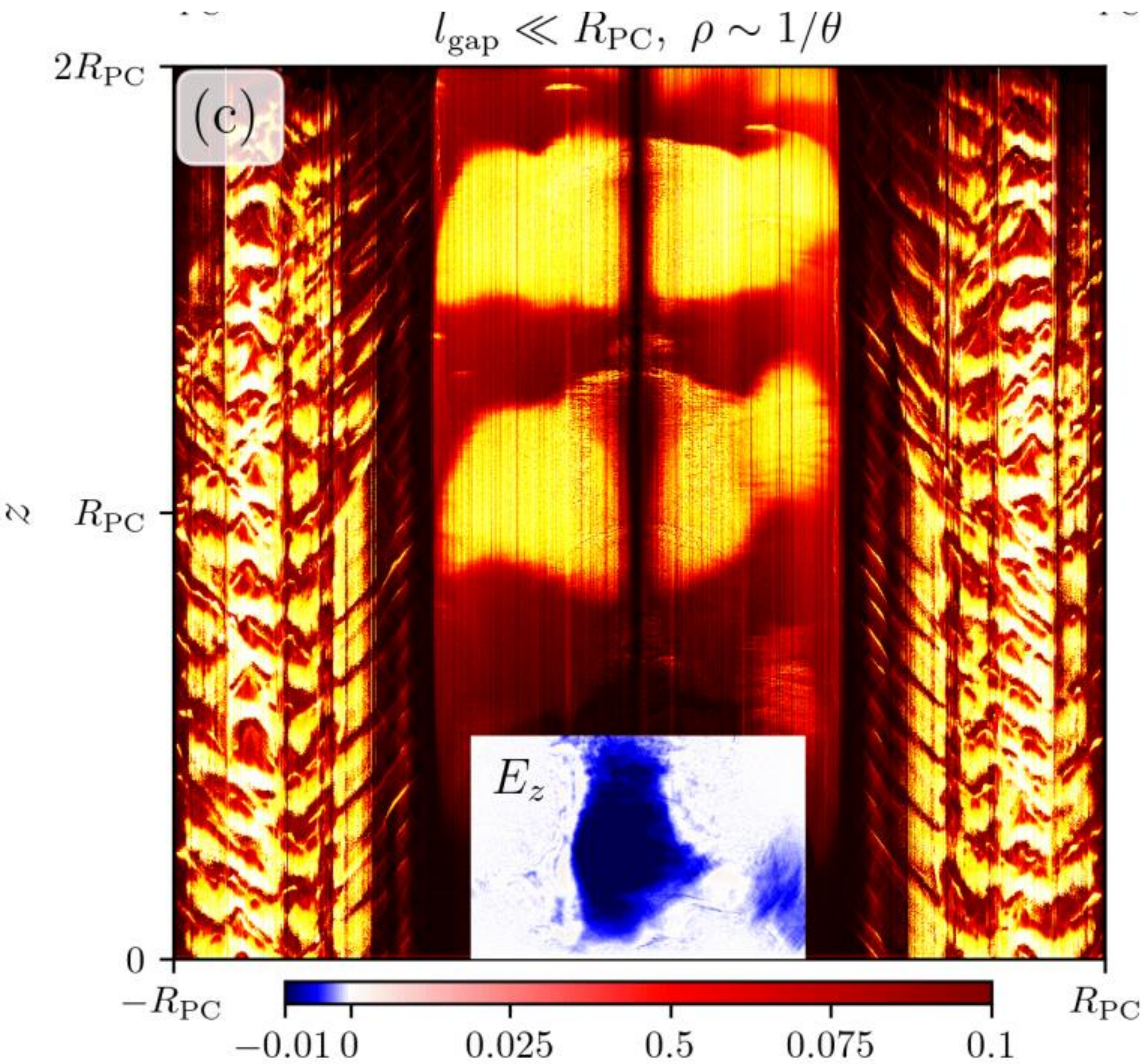
Longer cyclic period
& Stronger desynchronization

(1.3) Small gap & Quasi dipolar field

$$\rho_c = \rho_{c,0}(R_{PC}/x)$$

When x → 0, ρ → ∞ ➔ discharge is absent at the center.

Particle number density:



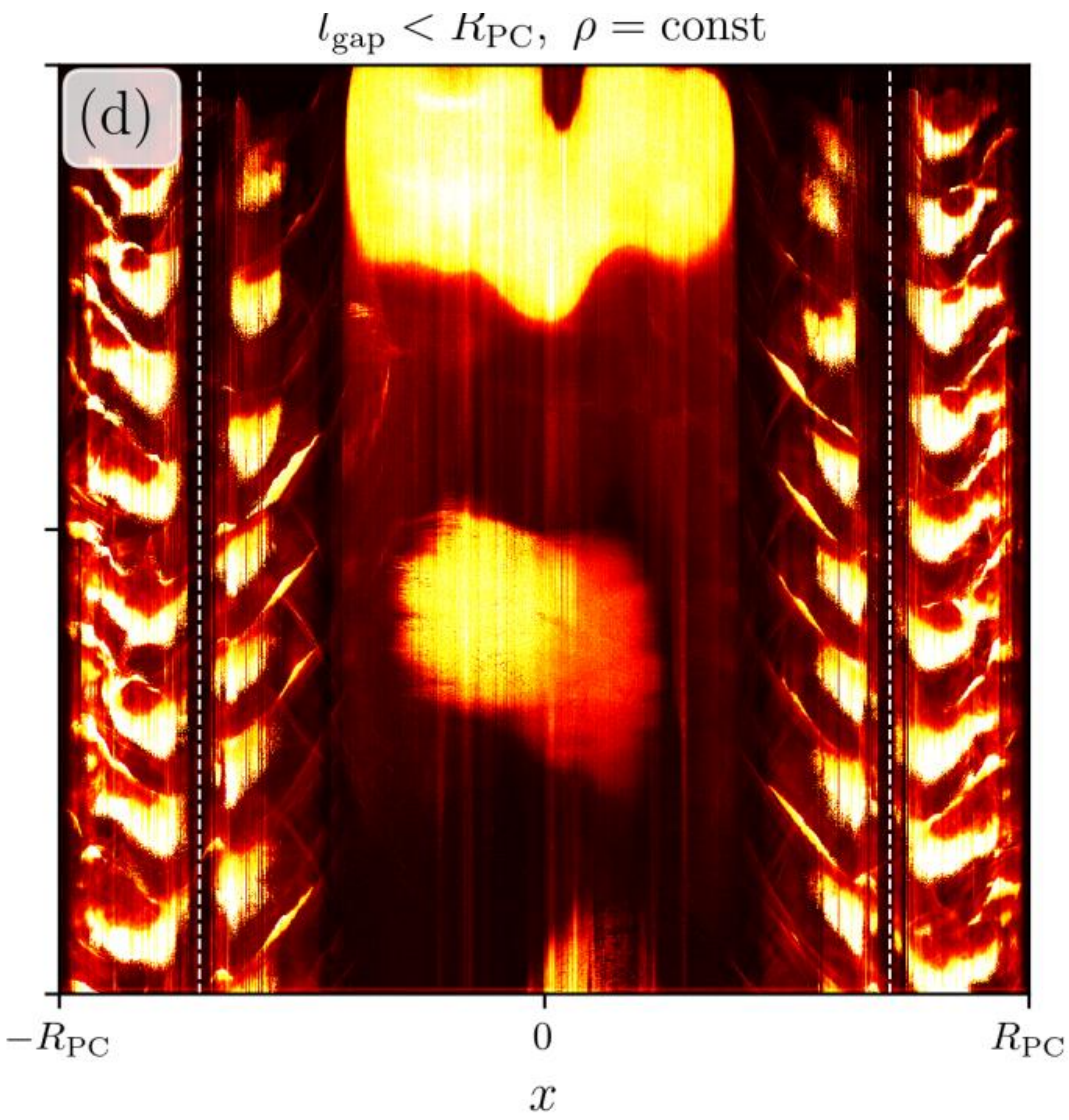
Larger gap.

Front of screening inclined
➔ benefit emission
(See page 7)

(1.4) Large gap 🡐 less energetic pulsars

Smaller electric field for acceleration.

Particle number density:

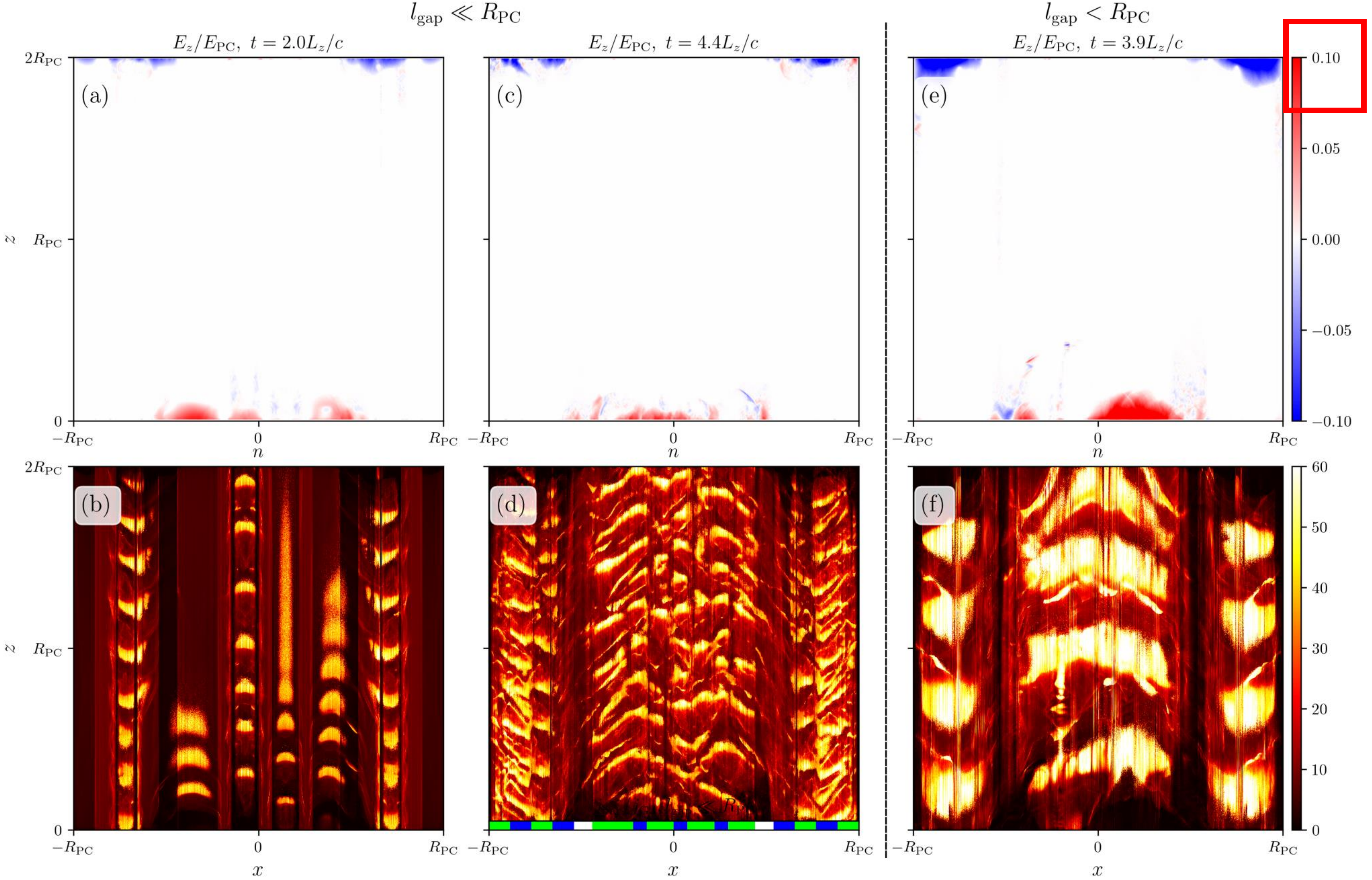


Longer cyclic period.

(2) RS model: generally similar to SCLF, but with larger electric field for j/j_GJ>1

E// field:

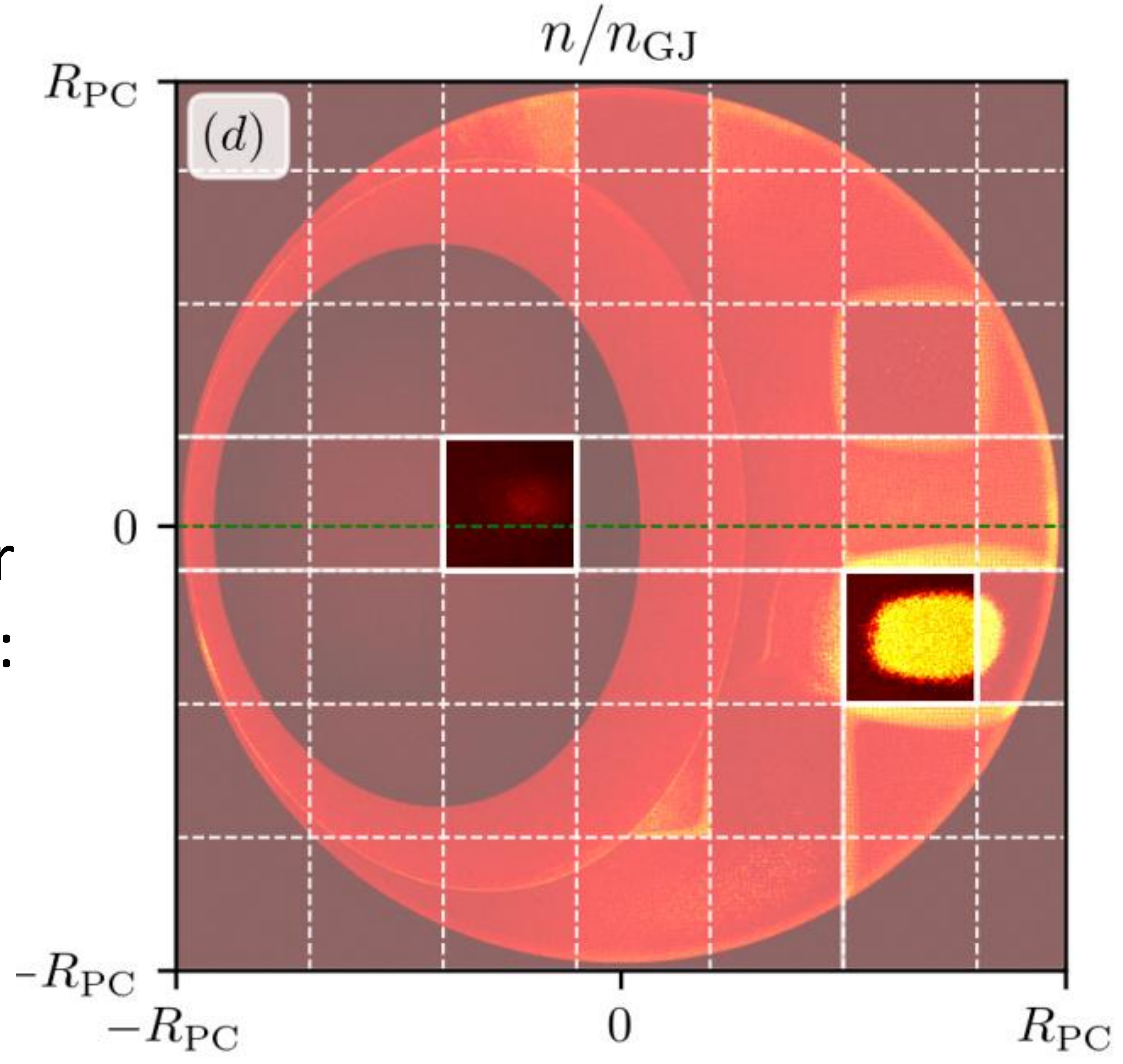
Particle number density:

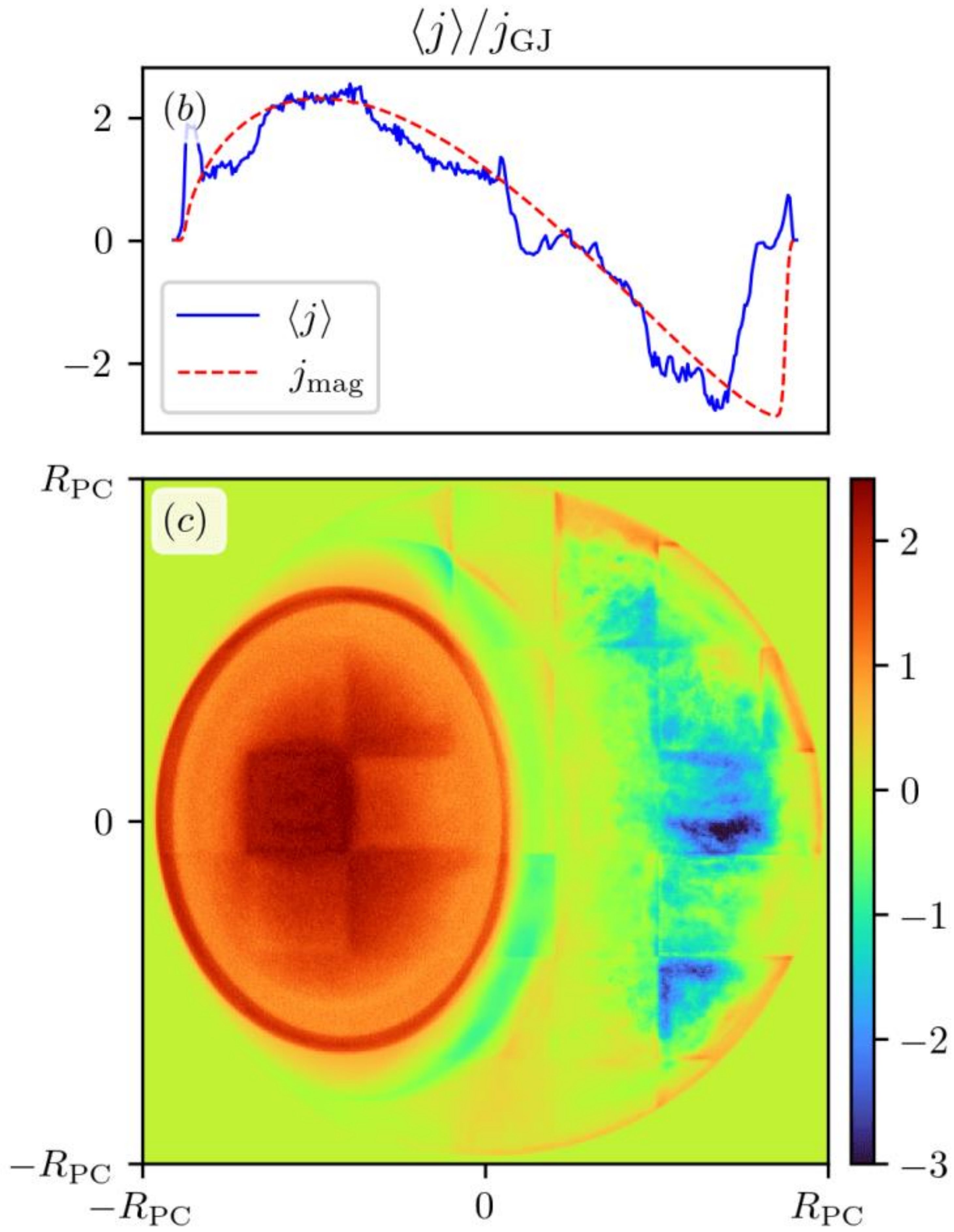


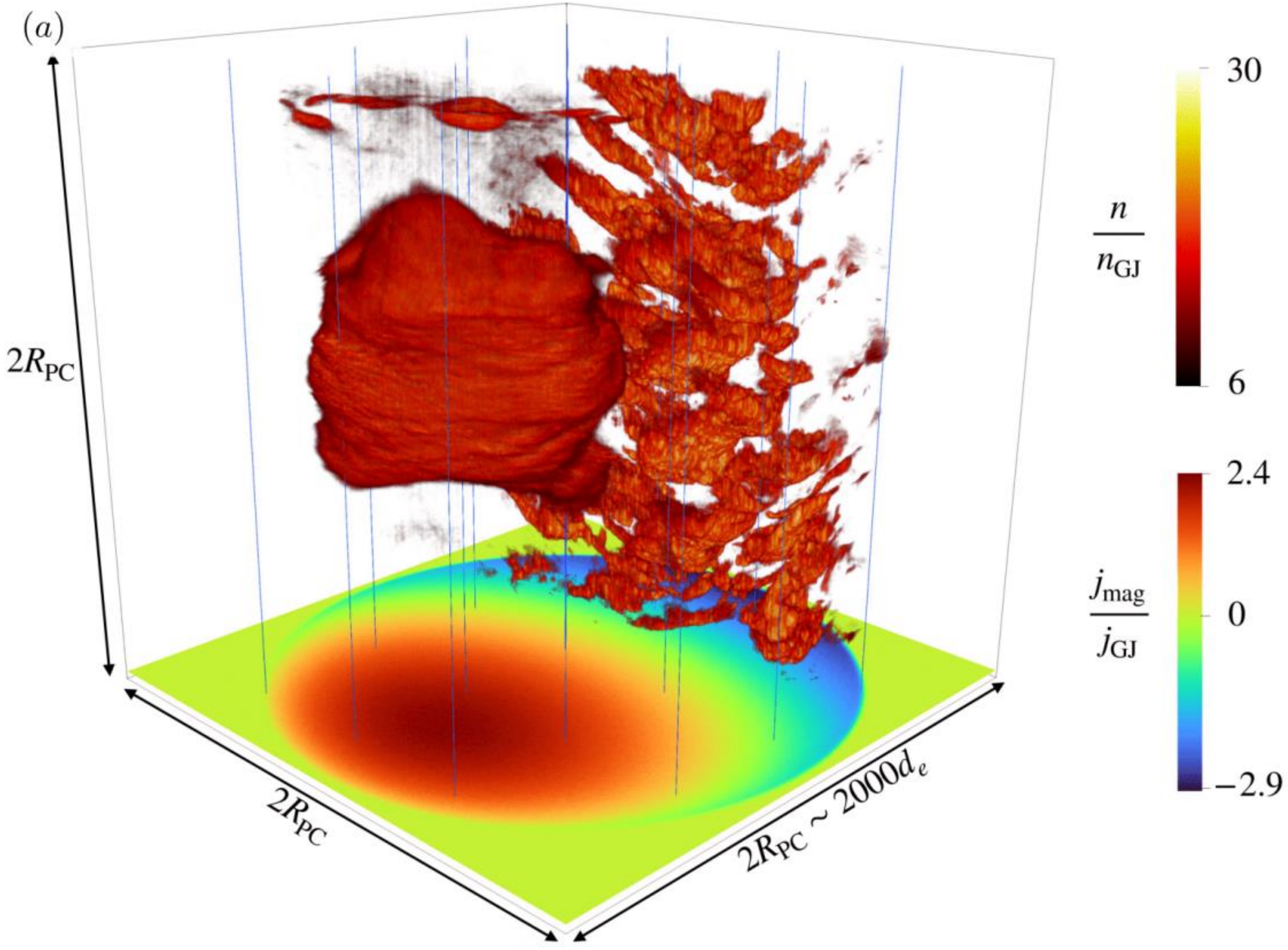
(3) 3D, SCLF

60° inclined rotator. Small gap for j/j_GJ<0, larger gap for j/j_GJ>1.
Divide polar cap into 6×6 square patches. Two patches with initial plasma injection.

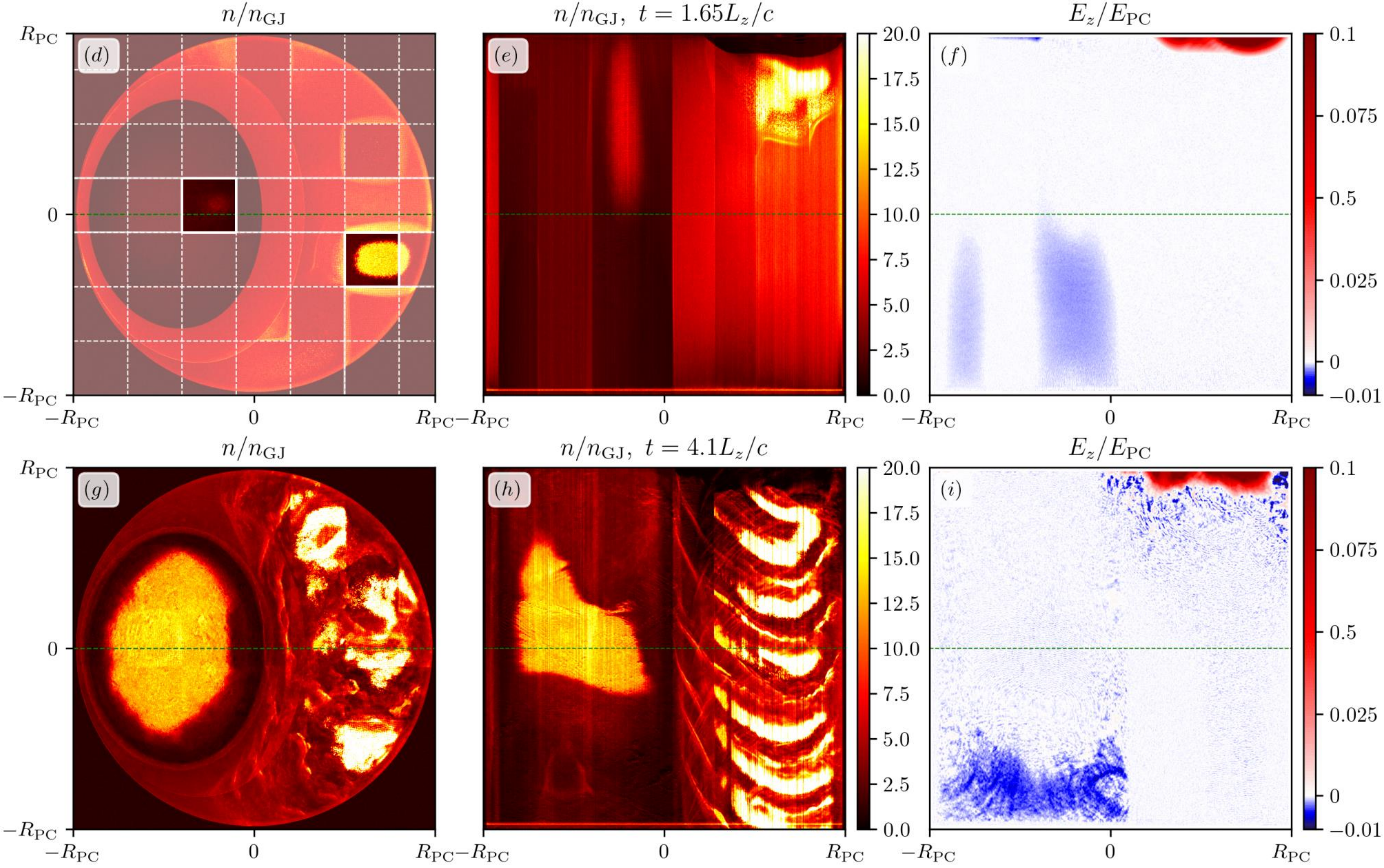
Particle number density:







(a)
$2R_{PC}$
$2R_{PC}$
$2R_{PC} \sim 2000 d_e$
$\frac{n}{n_{GJ}}$
30
6
$\frac{j_{mag}}{j_{GJ}}$
2.4
0
−2.9

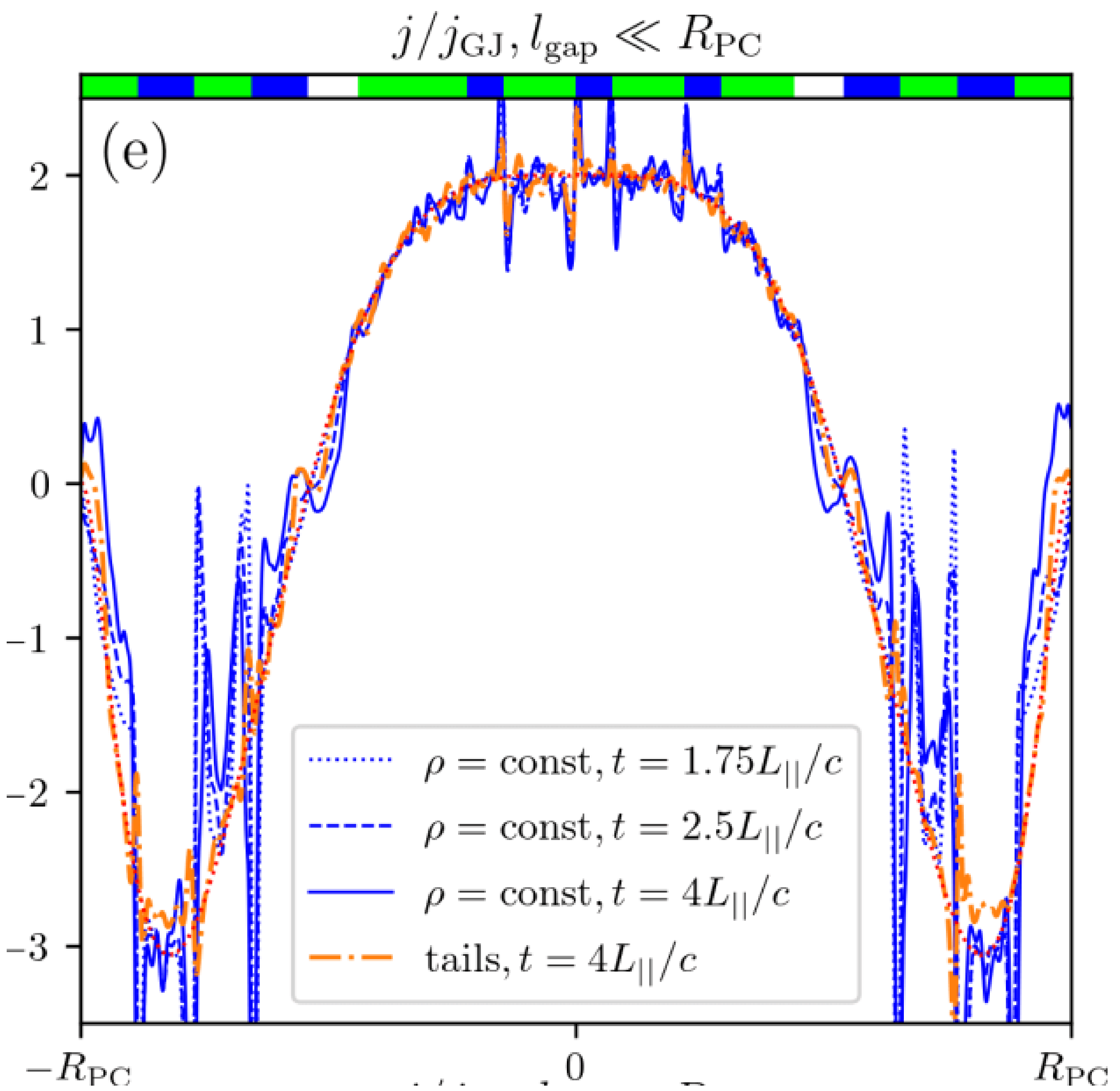


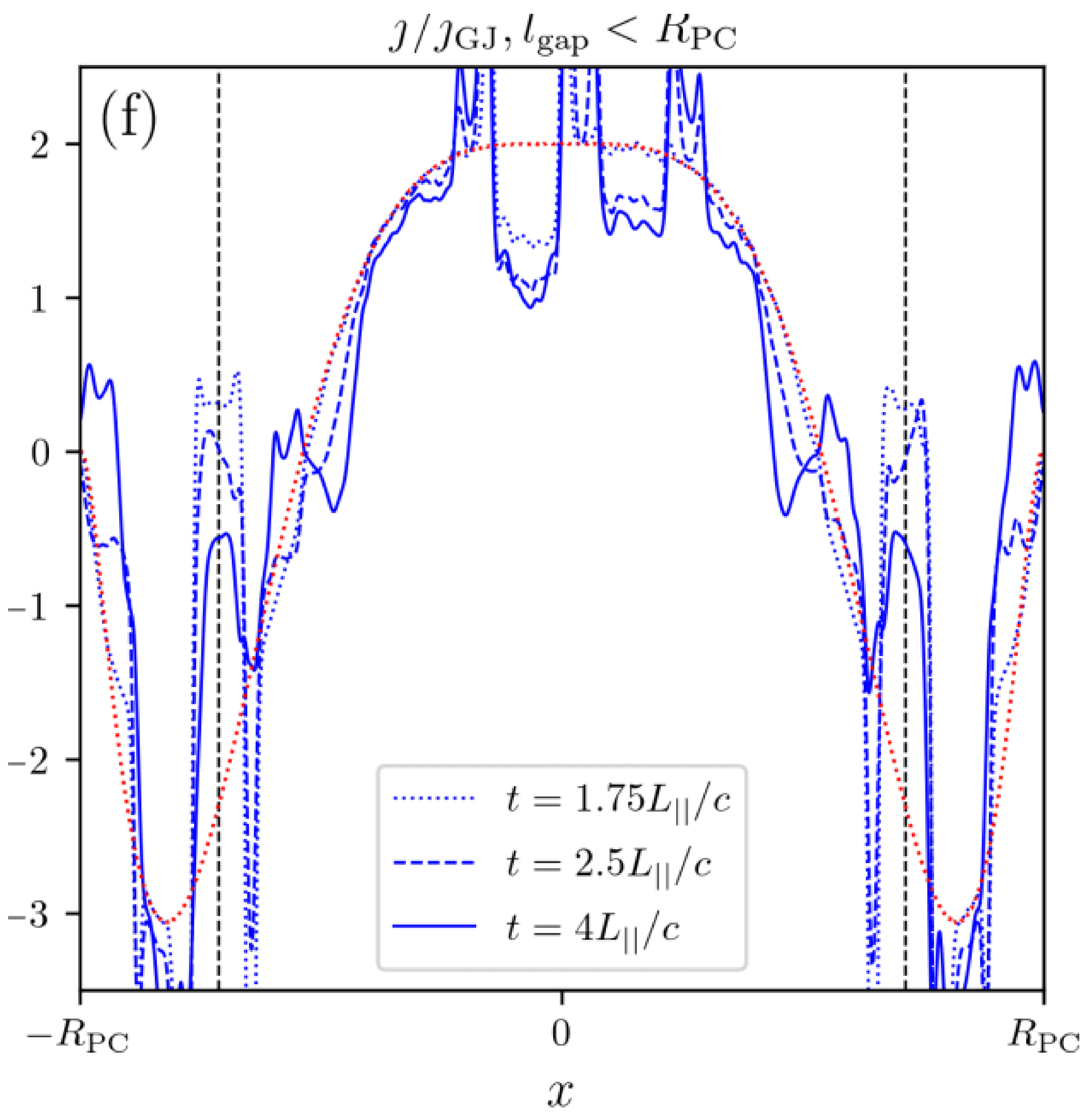
Early time

Late time

(4) Check for the model validity: evolution of magnetic field twist ↔ evolution of magnetospheric current

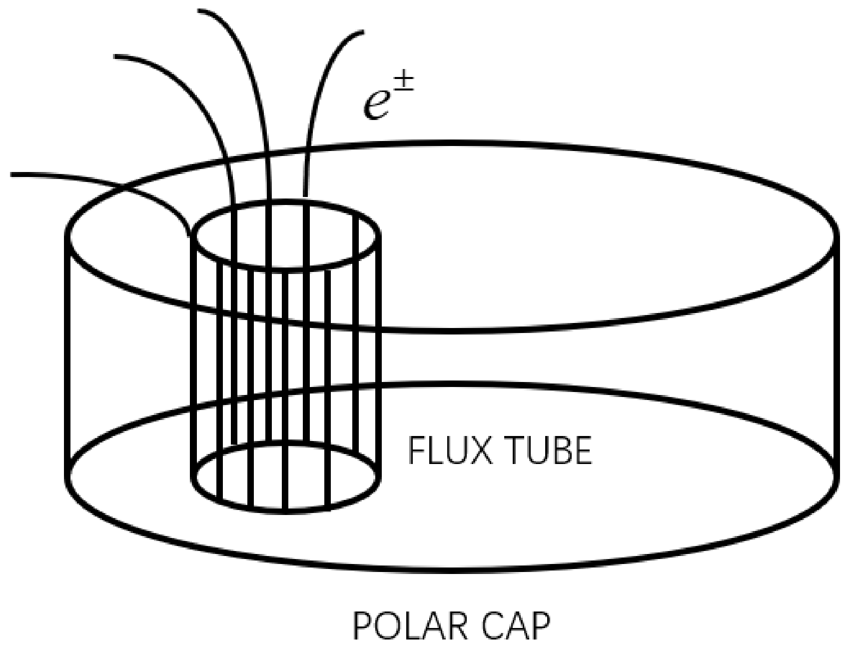
Large gaps lead to a noticeable untwist of the field lines.





IV. Conclusion & Discussion

Main conclusion: transverse coherence scale of a discharge zone ~ longitudinal gap size



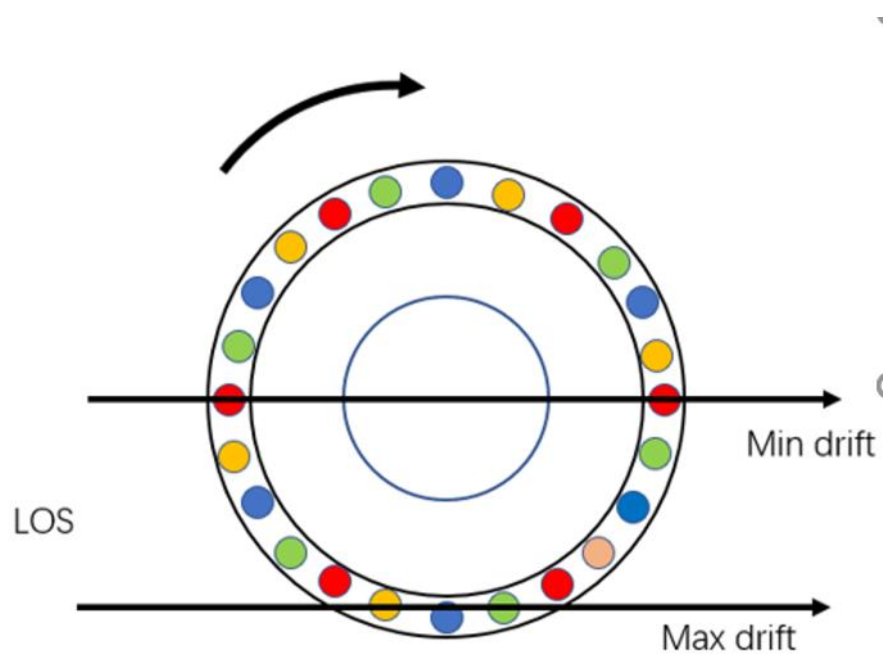
Discussion point 1: **NO spark**.

Polar caps are filled with discharge regions.

NO noticeable plasma drifting.

Single pulse timescale >> discharge timescale

Single pulse modulation 🡐 Radiation happens at discharge boundaries?



Discussion point 2: for old pulsars, plasma density may be smaller ➔ deviate from FFE.
➔ may have different properties from this paper's simulation.
Larger gap ➔ significant twist (at light cylinder) evolution
➔ larger timescale evolutions
➔ nulling… in old pulsars?

Discussion point 3: repetition rate of discharge… too artificial?

感谢大家 Thanks for your attention.