Radiation-reaction-limited particle acceleration during the relaxation of force-free equilibria

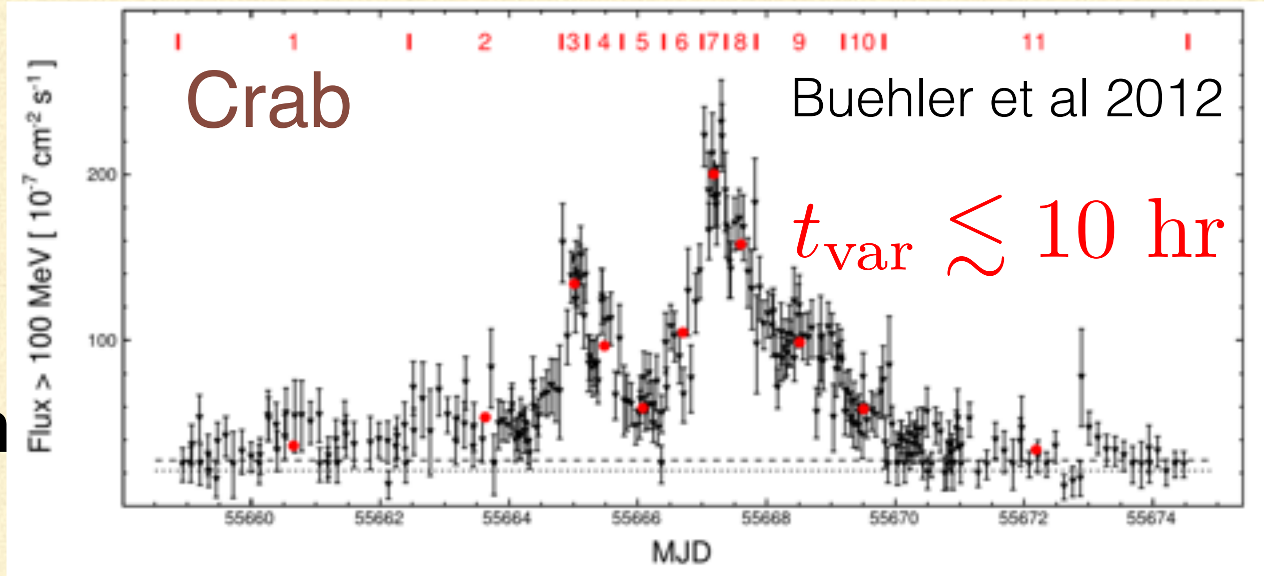
Yajie Yuan

with Roger Blandford, William East,
Krzysztof Nalewajko and Jonathan Zrake

Observational puzzles

- Crab gamma-ray flares
  - $t_{\rm var} \lesssim 10\ {\rm hr}, L_\gamma \sim 10^{36}\ {\rm erg\,s^{-1}}$ (isotropic)
  - Above synchrotron radiation reaction limit
  - If B~1 mG,

$$\epsilon \equiv \frac{L_\gamma t_{\rm var}}{(c t_{\rm var})^3 B^2/8\pi} \sim 10^3$$



- AGN flares
  - e.g. 3C 279 (FSRQ), GeV t_{var}~5 min, isotropic L_γ~10^{49} erg s^{-1} (Hayashida et al)
  - Polarization angle swing
- GRB

These might be results of efficient particle acceleration and electromagnetic dissipation in a highly magnetized outflow.

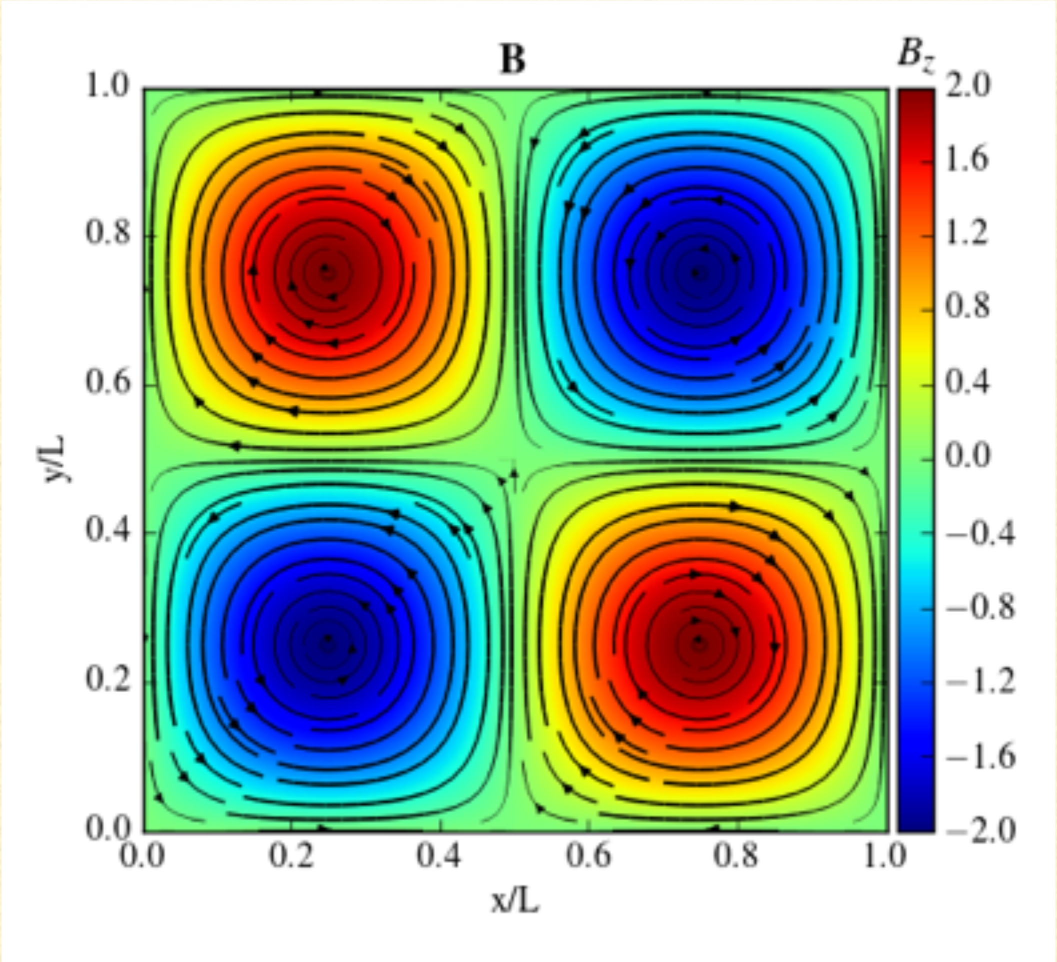
A toy model—the unstable force-free equilibria

- Use the relativistic Particle-In-Cell code Zeltron* (Cerutti et al 2013)
- Include radiation reaction force

$$\mathbf{F}_{\rm syn} = -\frac{2e^2}{3c^5} a_{L\perp}^2 \gamma^2 \mathbf{v}$$

$$\eta \equiv \frac{1}{\omega_g t_{\rm cool}} = \frac{4\alpha_F \hbar\omega}{9mc^2}$$

- Collect spectrum-resolved radiation power for each observer in real time



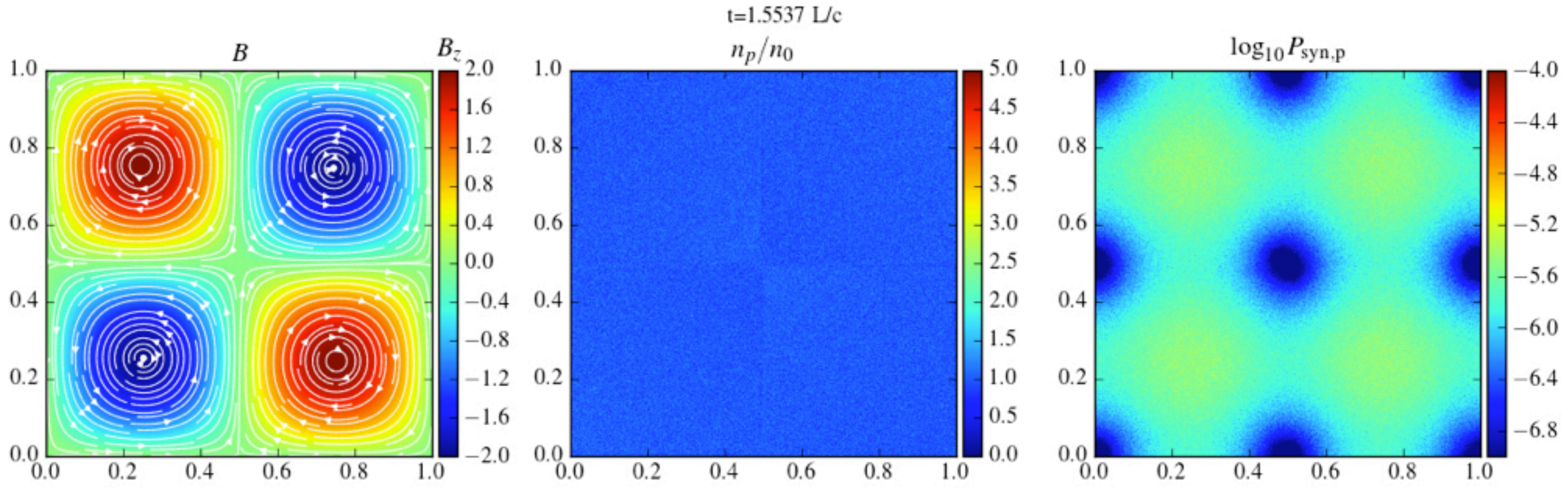
See Nalewajko et al 2016 (arXiv: 1603.04850) for a study without radiation; this talk: Yuan et al 2016 (arXiv: 1604.03179)

*http://benoit.cerutti.free.fr/Zeltron/index.html

Passive radiation

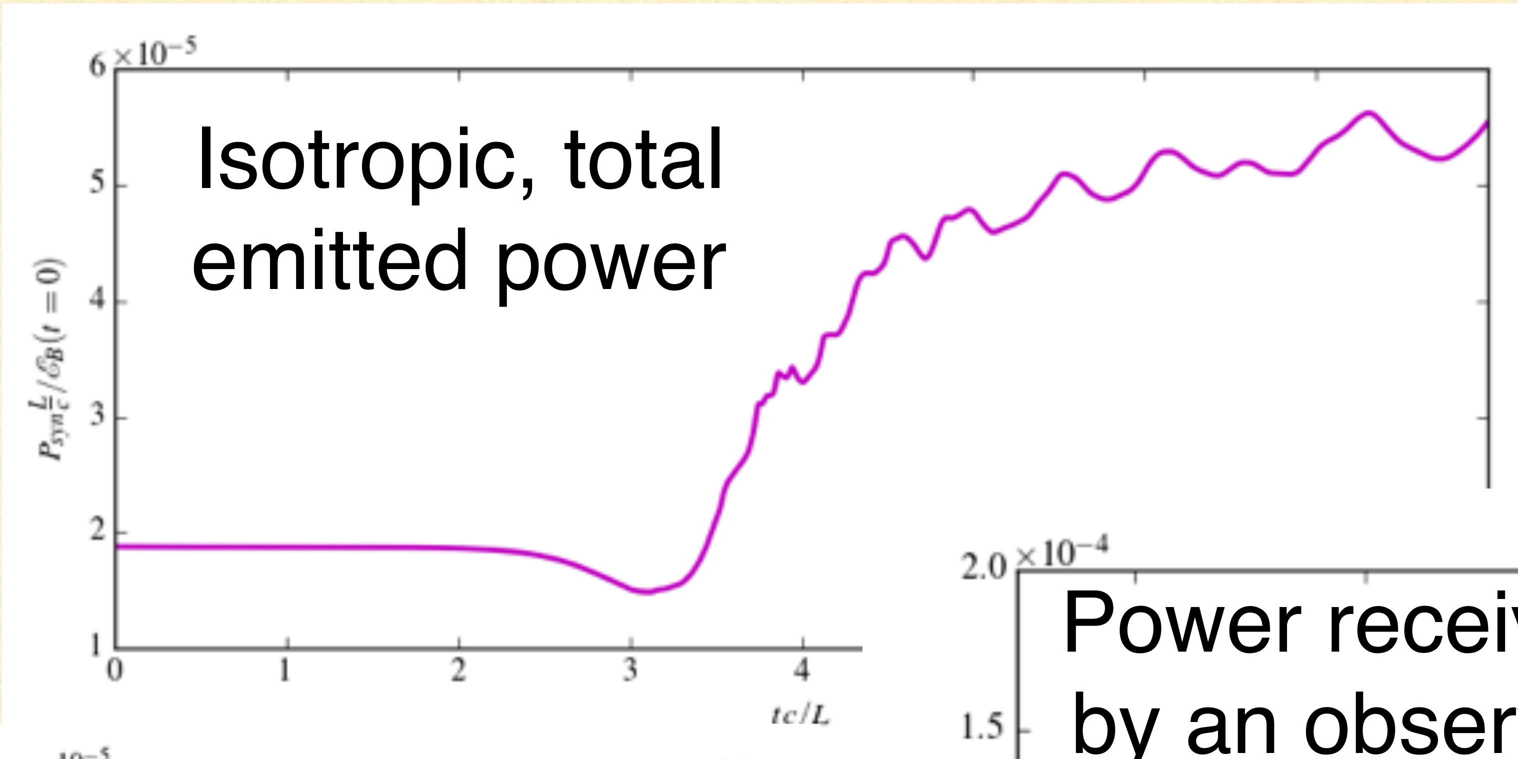
—when radiation is *not* significant enough to affect particle dynamics

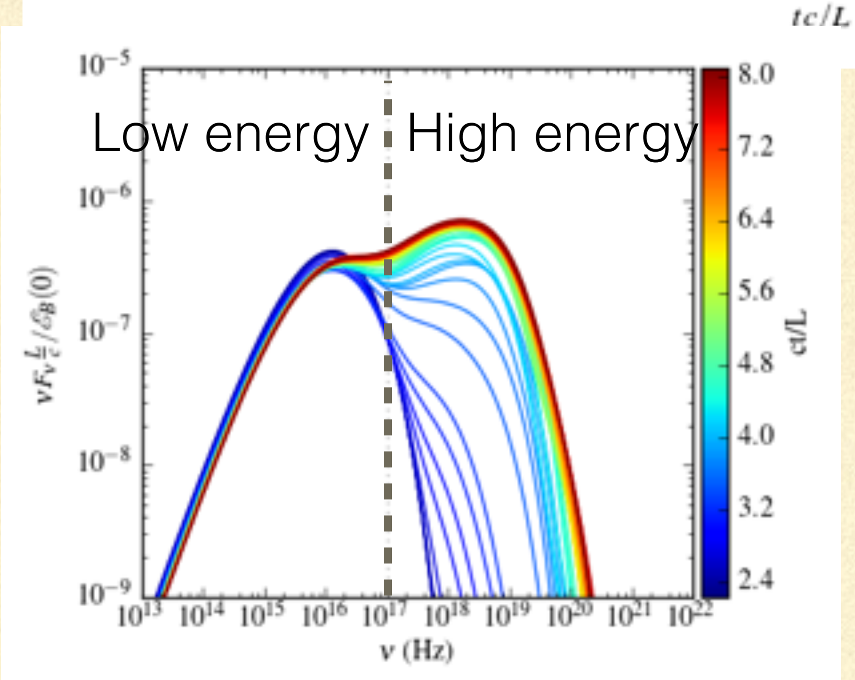
Example: σ=3.76, L/r_L=800, η=1.1e-8



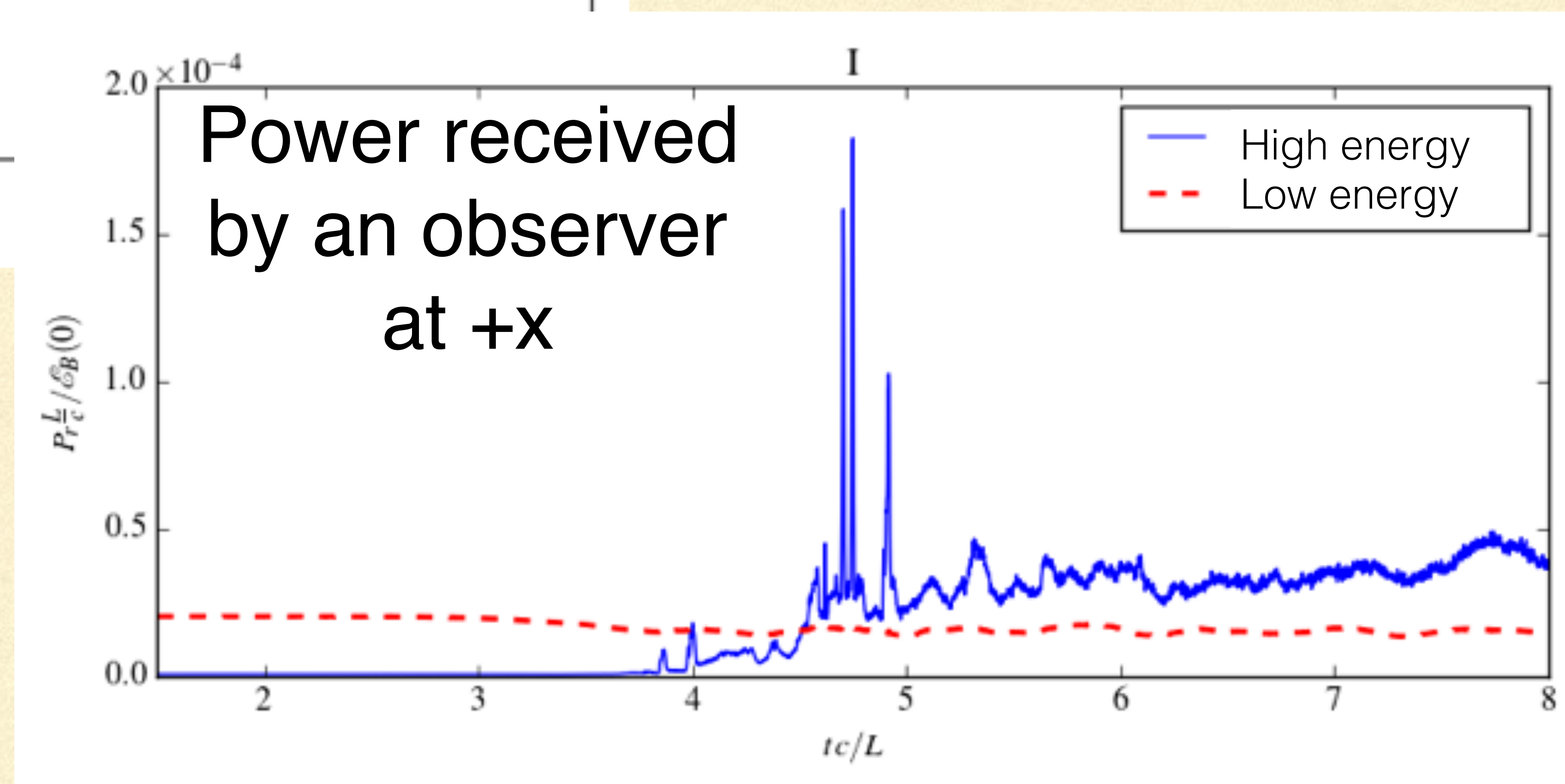
- Complex structures develop self-consistently from an initially smooth configuration!
- Lifetime of the current layers is ~ one dynamic time scale.
- Most intensive radiation is produced by plasmoids and current layer ejecta.

Variability of observed radiation



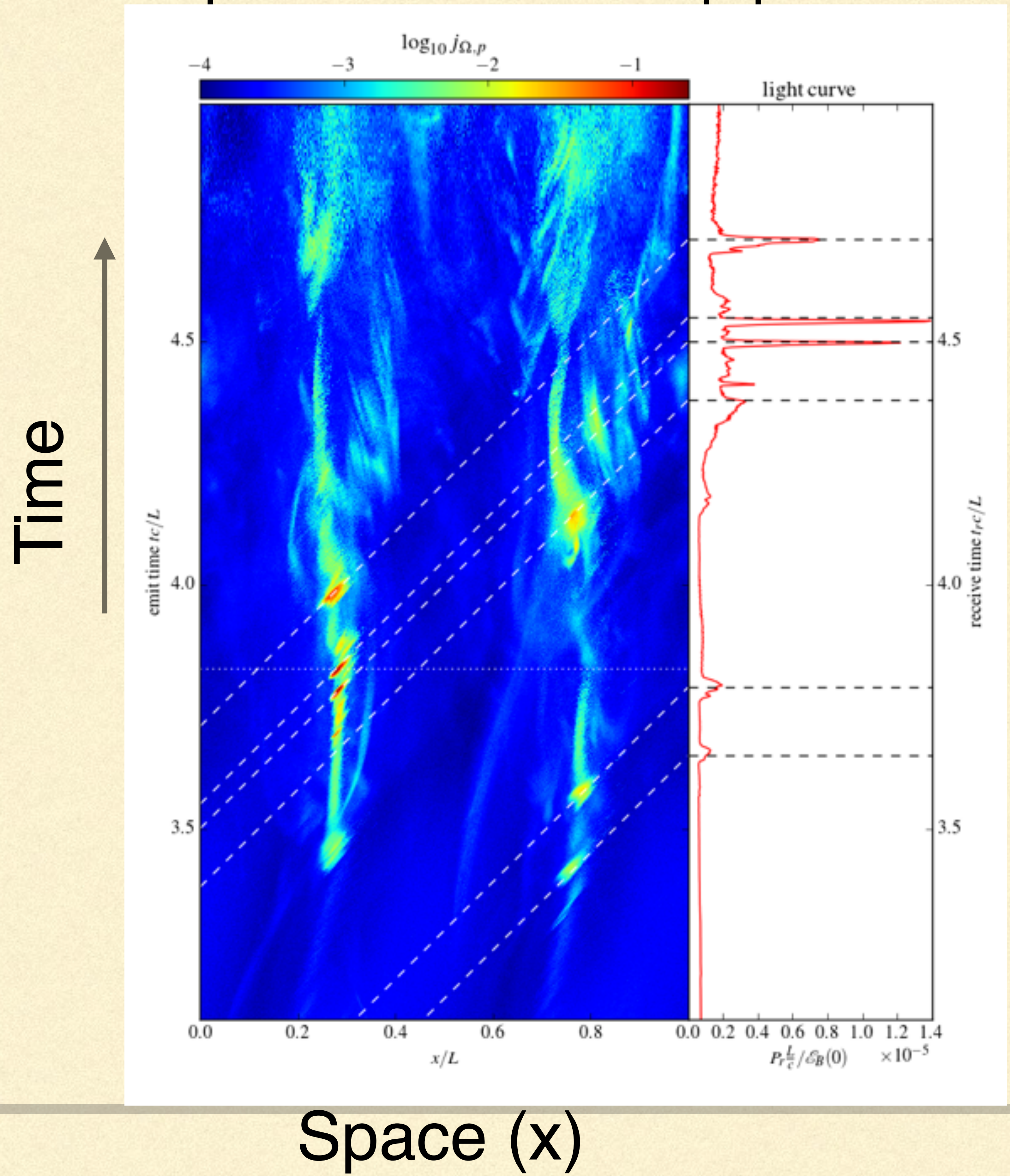


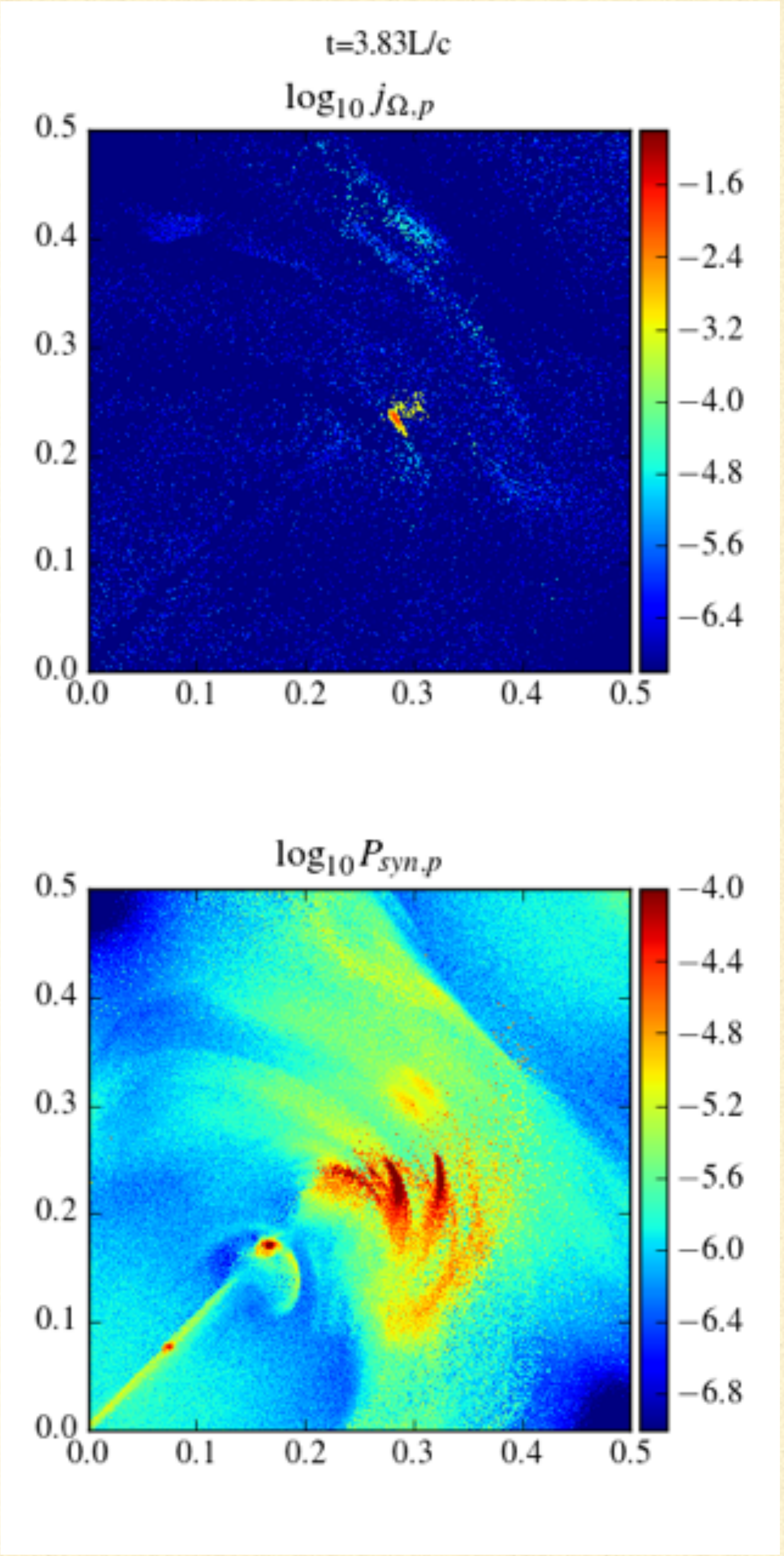
Isotropic emitted spectrum



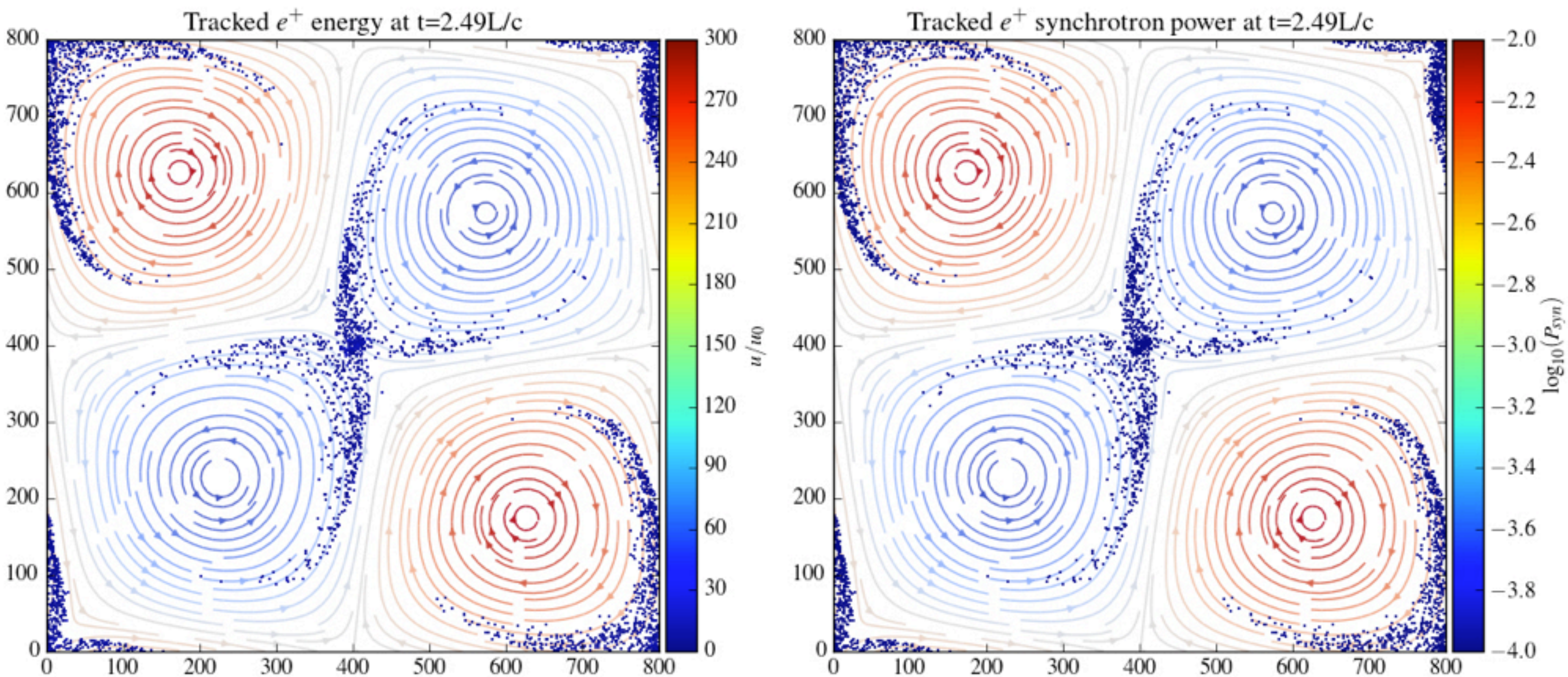
$$t_{\mathrm{var}} \sim 0.01 L/c, \quad \epsilon \equiv \frac{L_\gamma t_{\mathrm{var}}}{(c t_{\mathrm{var}})^3 B^2/8\pi} \sim \frac{4\pi}{\Delta\theta}\eta\left(\frac{\langle\gamma\rangle}{\gamma_0}\right)^2 \sim 0.01$$

What produces the sharp peaks in the light curve?



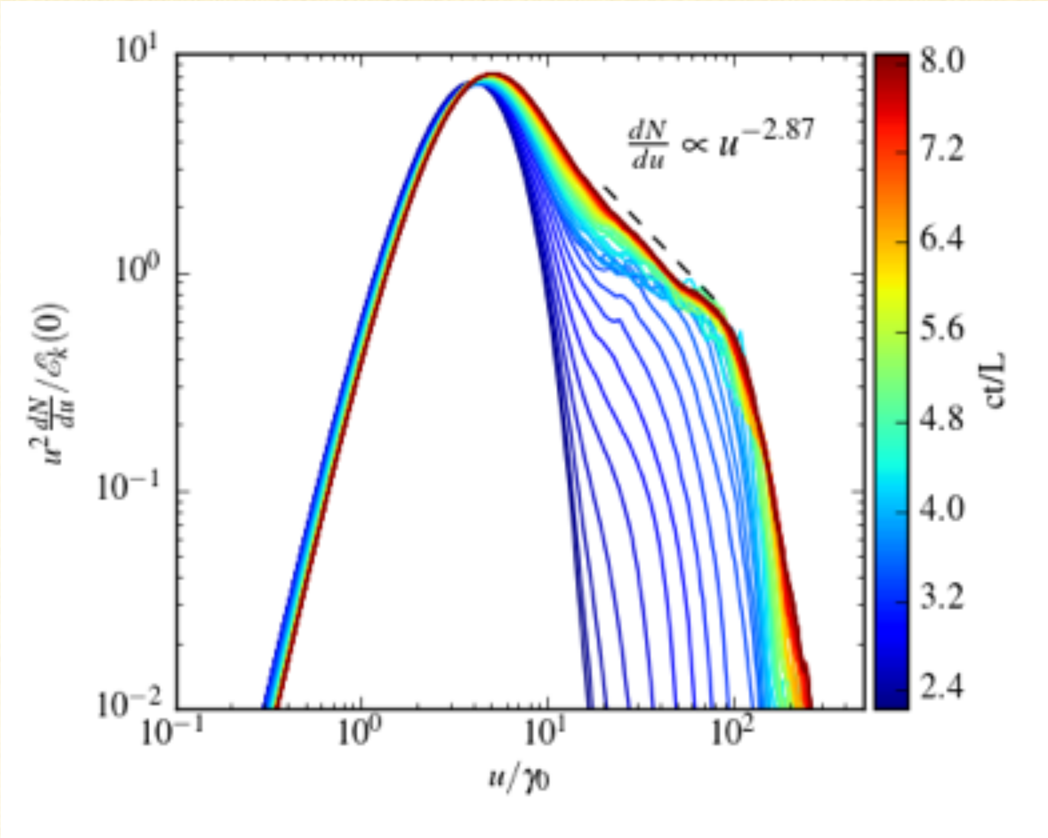


Where does most of the high energy radiation come from?

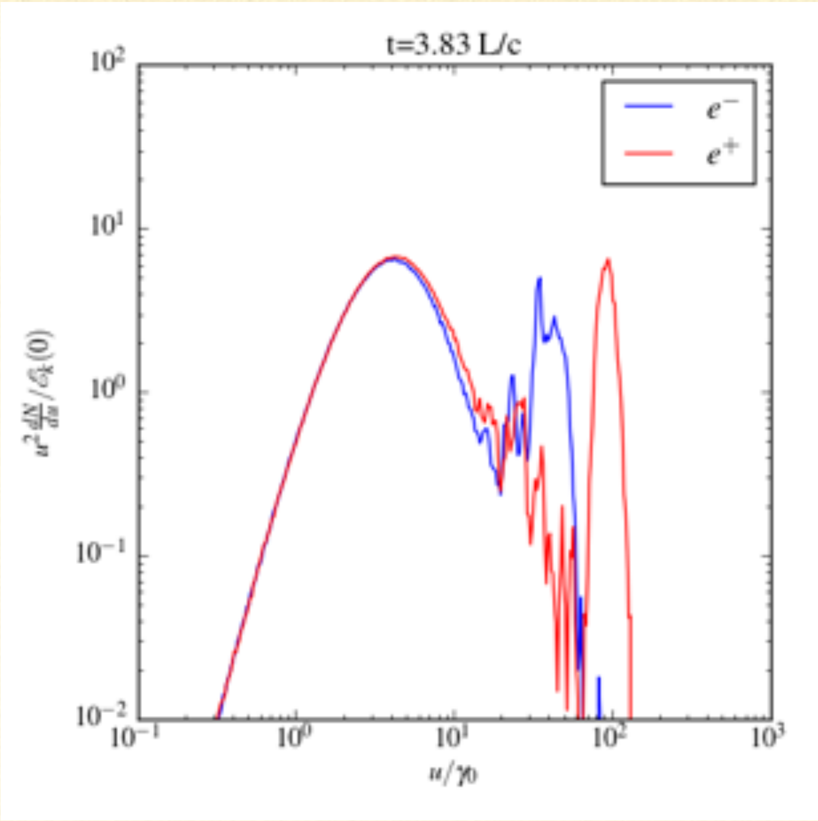


- In current layers: $E_{||}$ acceleration, small radiative loss; high energy particles are bunched by tearing modes
- Exiting current layers: B direction change —> increased trajectory curvature, strong synchrotron radiation

Particle spectrum



Isotropic



along +x, at t=3.83L/c

Particle distribution can be quite anisotropic!

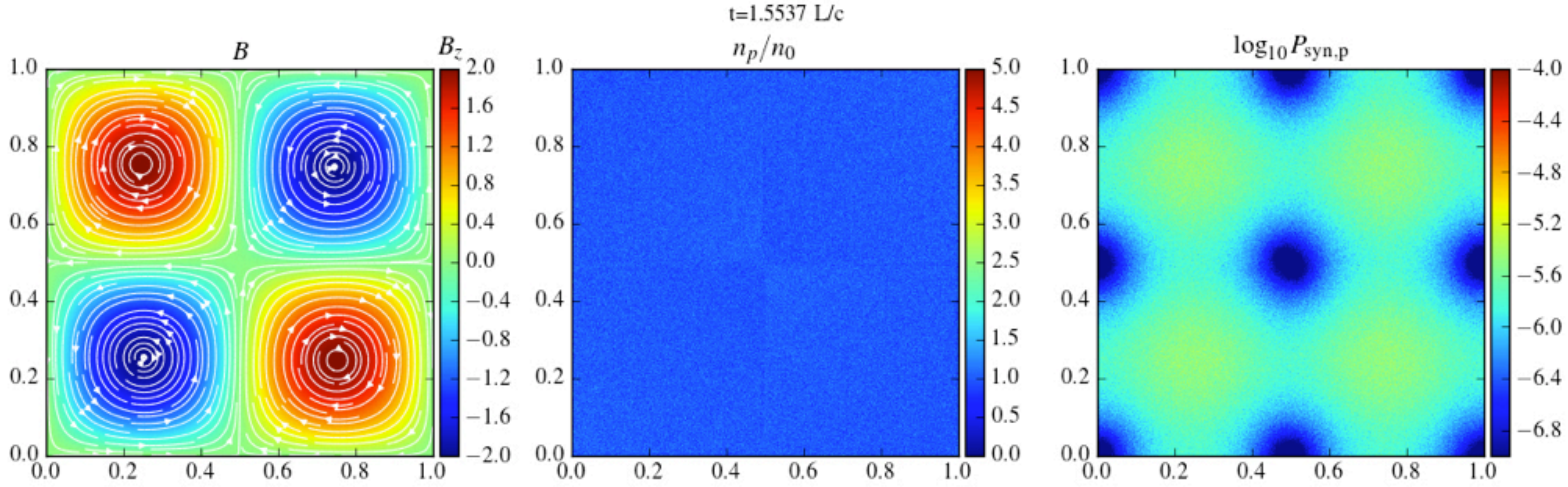
Fast variability results from…

- Anisotropy of accelerated particles (kinetic beaming)
- Spatial bunching of particle beams due to tearing modes

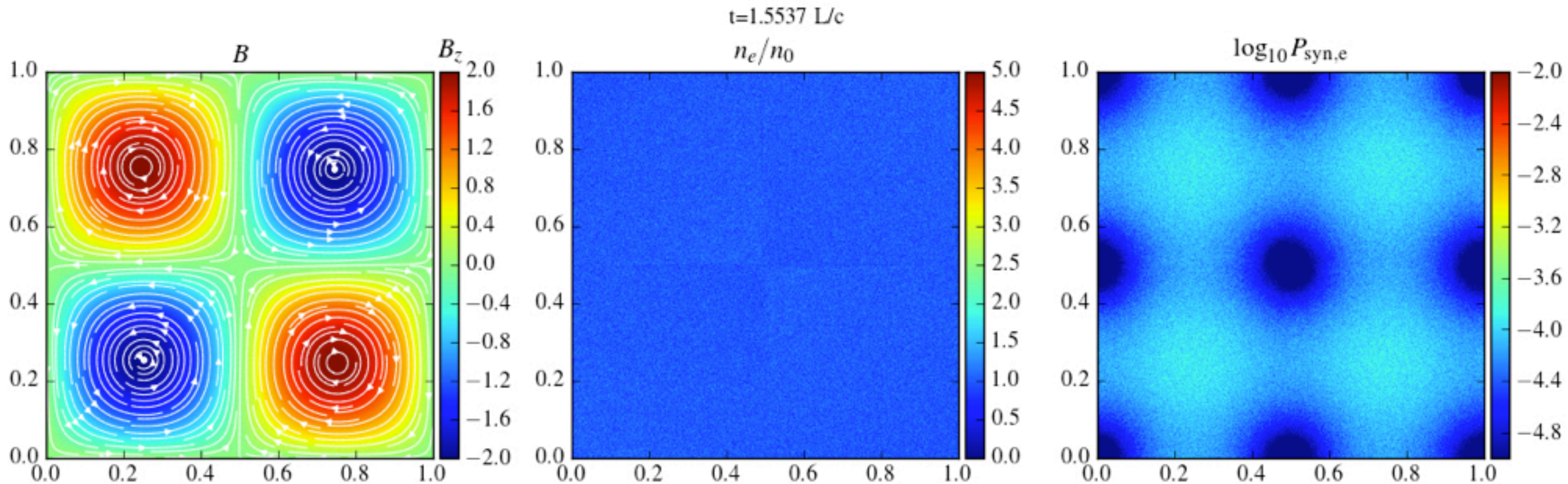
Active radiation

—when radiation *is significant* enough to affect particle dynamics

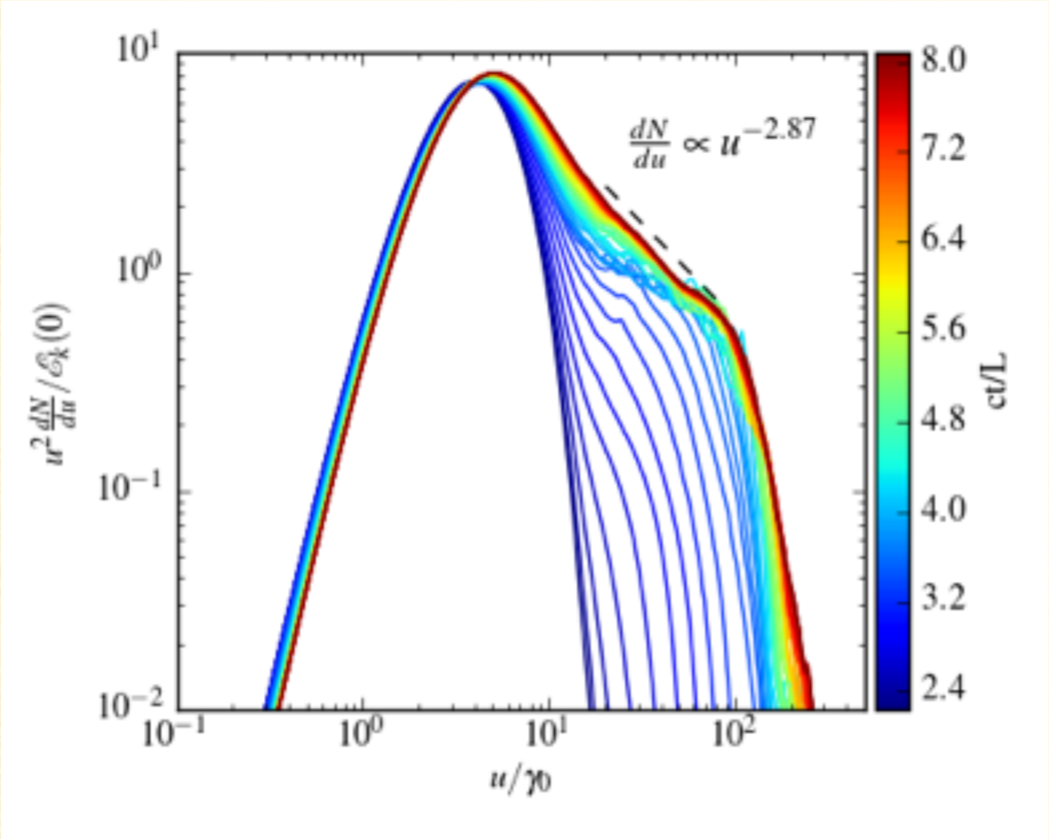
Insignificant cooling (η=1.1e-8)



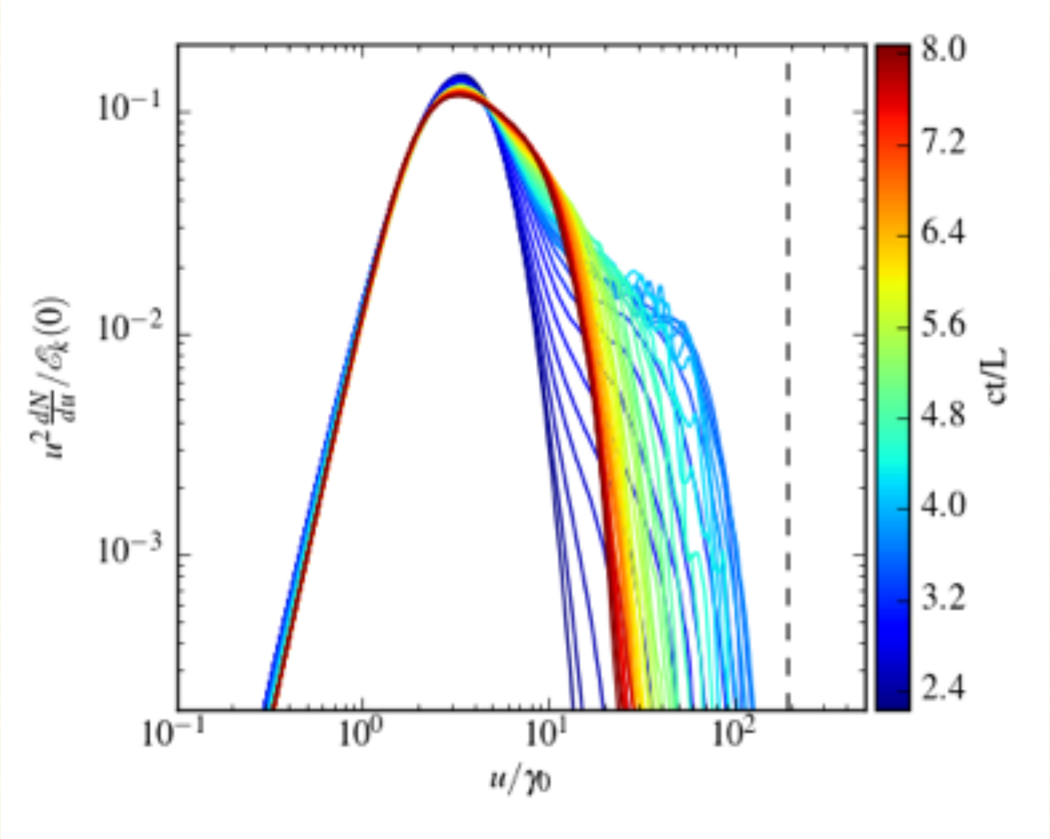
Strong cooling (η=2.75e-5)



Insignificant cooling (η=1.1e-8)



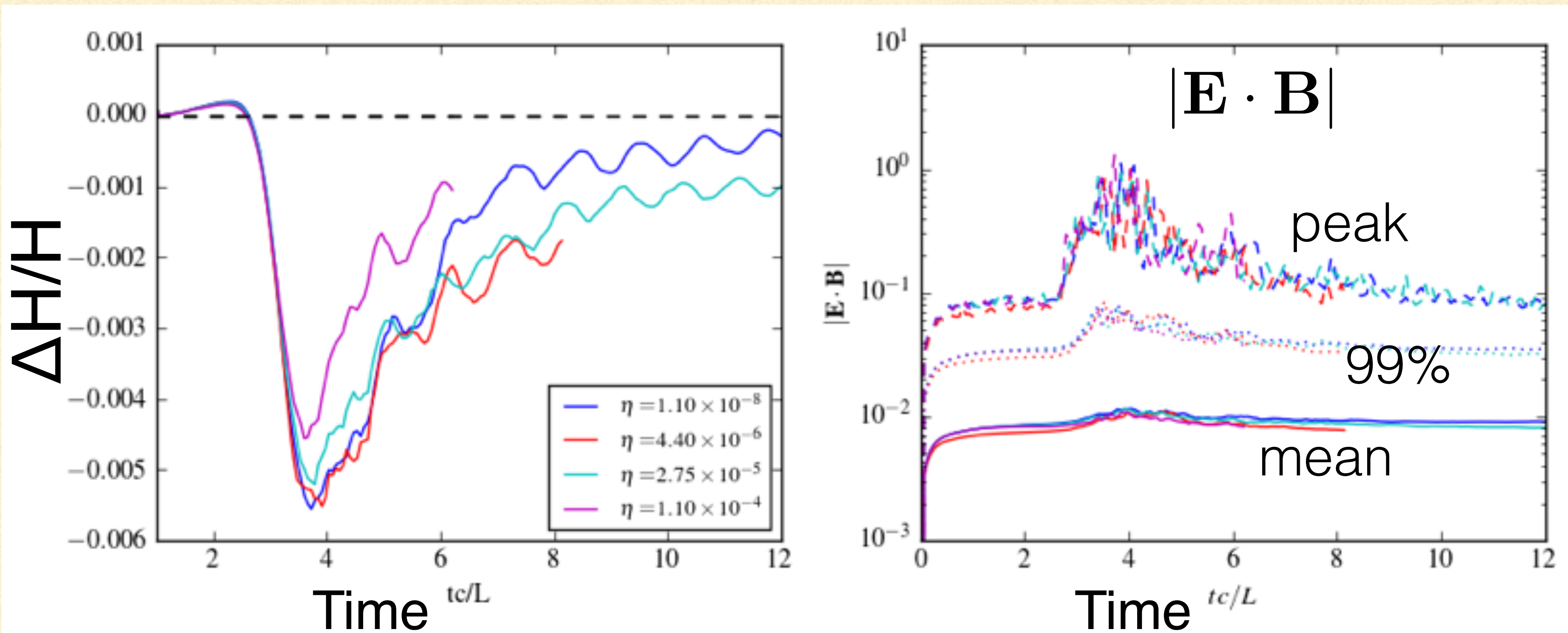
Strong cooling (η=2.75e-5)



- Similar dynamics
- $E_{||}$ acceleration within the current layer is still efficient
- Later stochastic acceleration process is unable to compete with radiative loss

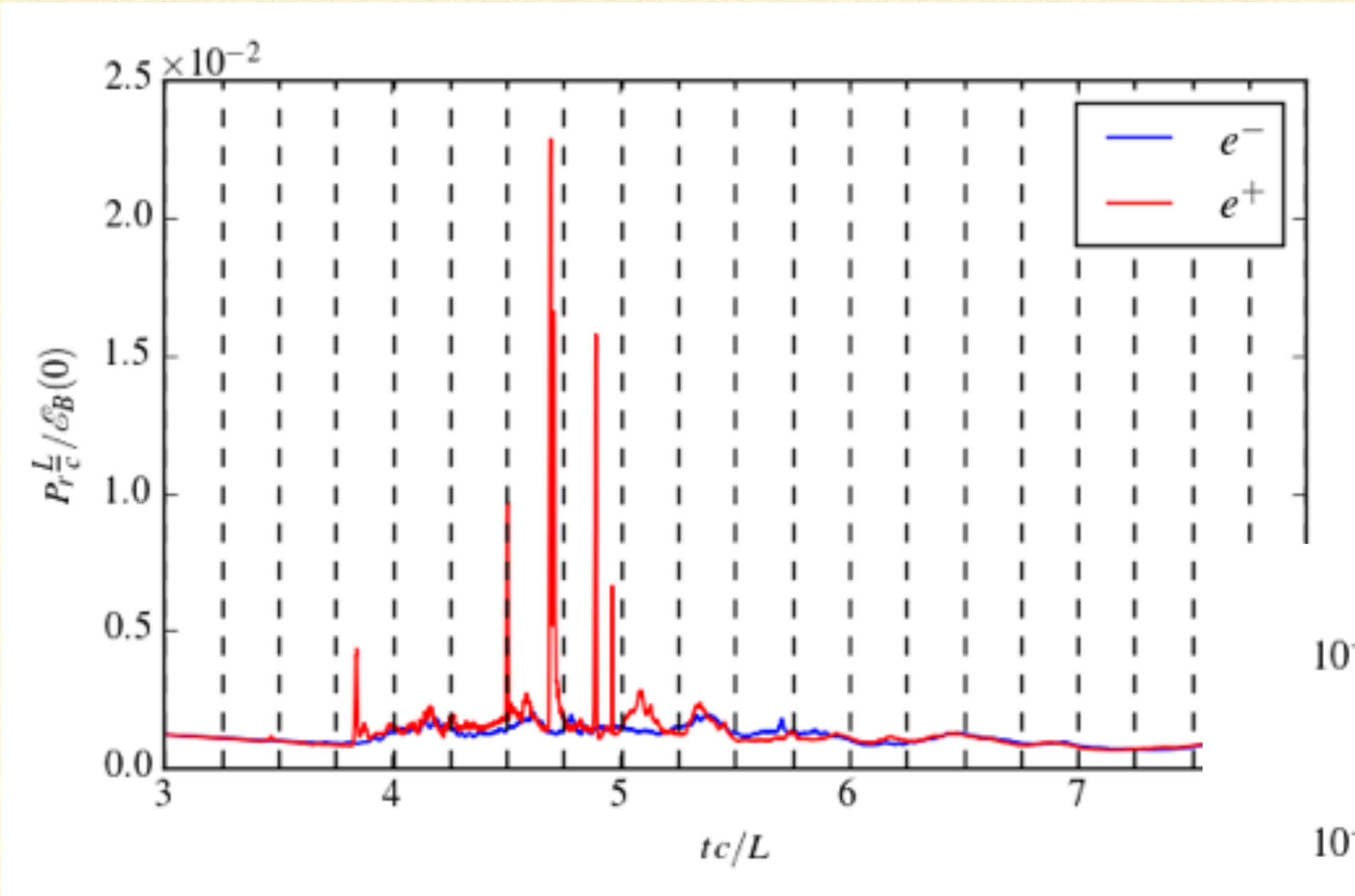
Effect of radiation reaction on global dynamics

Helicity change $\frac{dH}{dt} = -2\int \mathbf{E}\cdot\mathbf{B}\,dV$

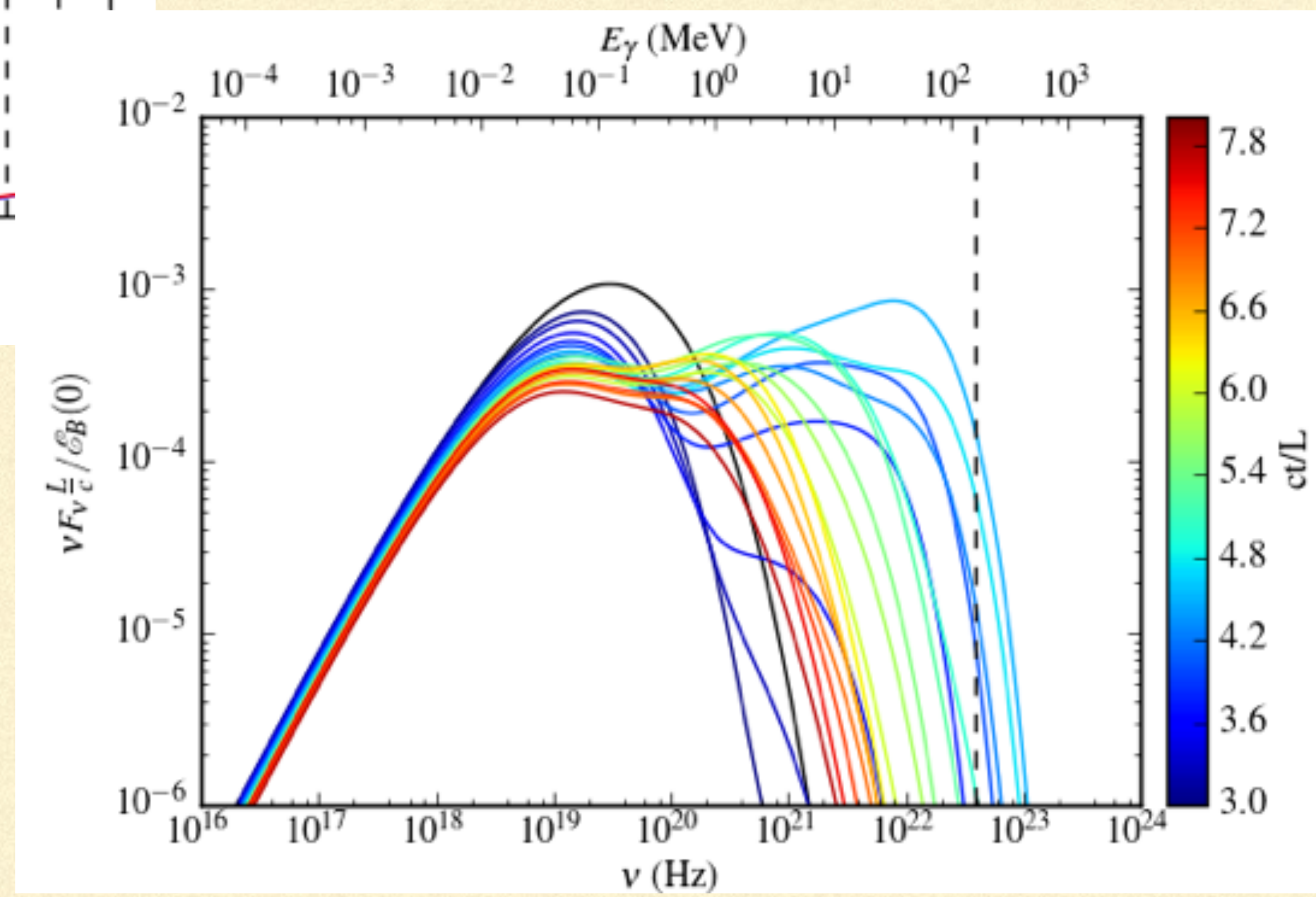


In our simulations so far, synchrotron radiation reaction does not help to support volumetric non-ideal E.

Variability, radiation efficiency, and time dependent spectrum



Example: η=2.75e-5, light curve and spectrum seen at +x



$$t_{\rm var} \sim 0.01 L/c,$$

$$\epsilon \equiv \frac{L_\gamma t_{\rm var}}{(ct_{\rm var})^3 B^2/8\pi} \sim \frac{4\pi}{\Delta\theta}\eta\left(\frac{\langle\gamma\rangle}{\gamma_0}\right)^2 \sim 10$$

Summary

- We observe:
  - Fast variability in high energy synchrotron radiation (key ingredients: kinetic beaming, spatial bunching)
  - Modest apparent radiation efficiency
  - Separation between the acceleration sites and synchrotron radiation sites for the highest energy particles
- Our current simulations are not yet able to reproduce Crab flares but higher σ runs may be promising.

Back up

Ideal instability—linear analysis

- Force-free evolution

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mathbf{j}$$

$$\nabla \cdot \mathbf{E} = \rho, \quad \mathbf{E} \cdot \mathbf{B} = 0, \quad \rho \mathbf{E} + \mathbf{j} \times \mathbf{B} = 0$$

$$\mathbf{j} = \frac{1}{B^2}[(\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mathbf{E} \cdot (\nabla \times \mathbf{E}))\mathbf{B} + (\nabla \cdot \mathbf{E})\mathbf{E} \times \mathbf{B}]$$

- Linearized equations

$$\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2 \qquad \mathbf{v} = \partial \vec{\xi}/\partial t$$

$$\mathbf{B}_1 = \nabla \times (\vec{\xi} \times \mathbf{B}_0),$$

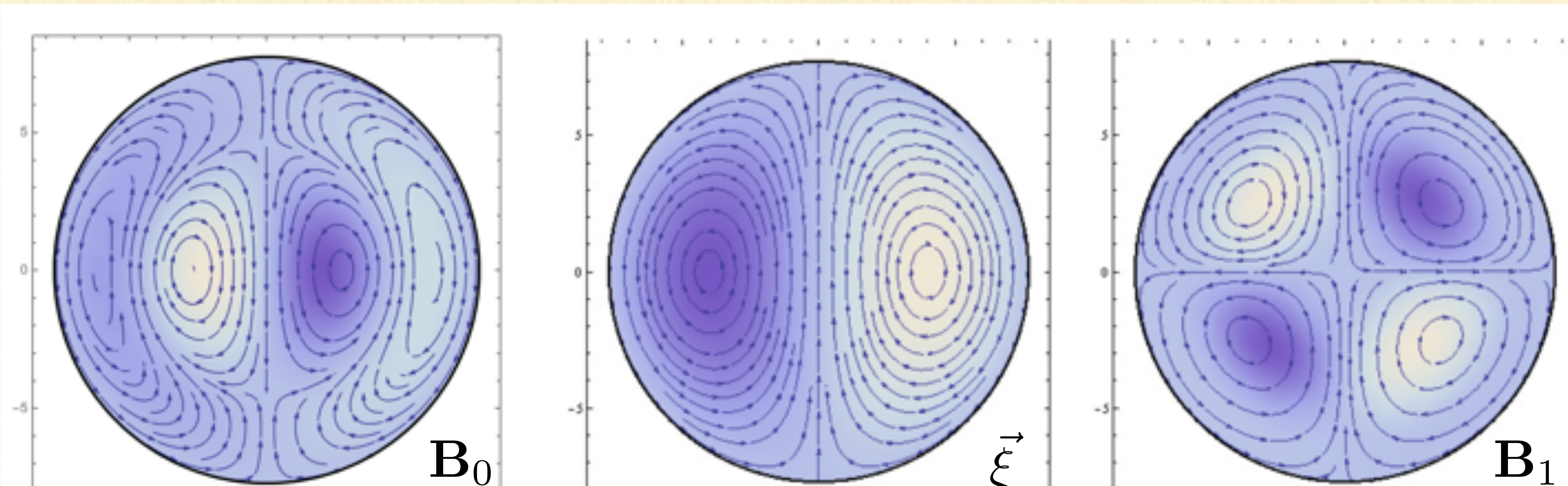
$$B^2 \frac{\partial^2 \vec{\xi}}{\partial t^2} = (\nabla \times \mathbf{B}_0) \times (\nabla \times (\vec{\xi} \times \mathbf{B}_0)) + [\nabla \times (\nabla \times (\vec{\xi} \times \mathbf{B}_0))] \times \mathbf{B}_0$$

- Variational principle

$$V = \int dV (\nabla \times (\vec{\xi} \times \mathbf{B}_0)) \cdot [(\nabla \times (\vec{\xi} \times \mathbf{B}_0)) - \vec{\xi} \times (\nabla \times \mathbf{B}_0)]$$

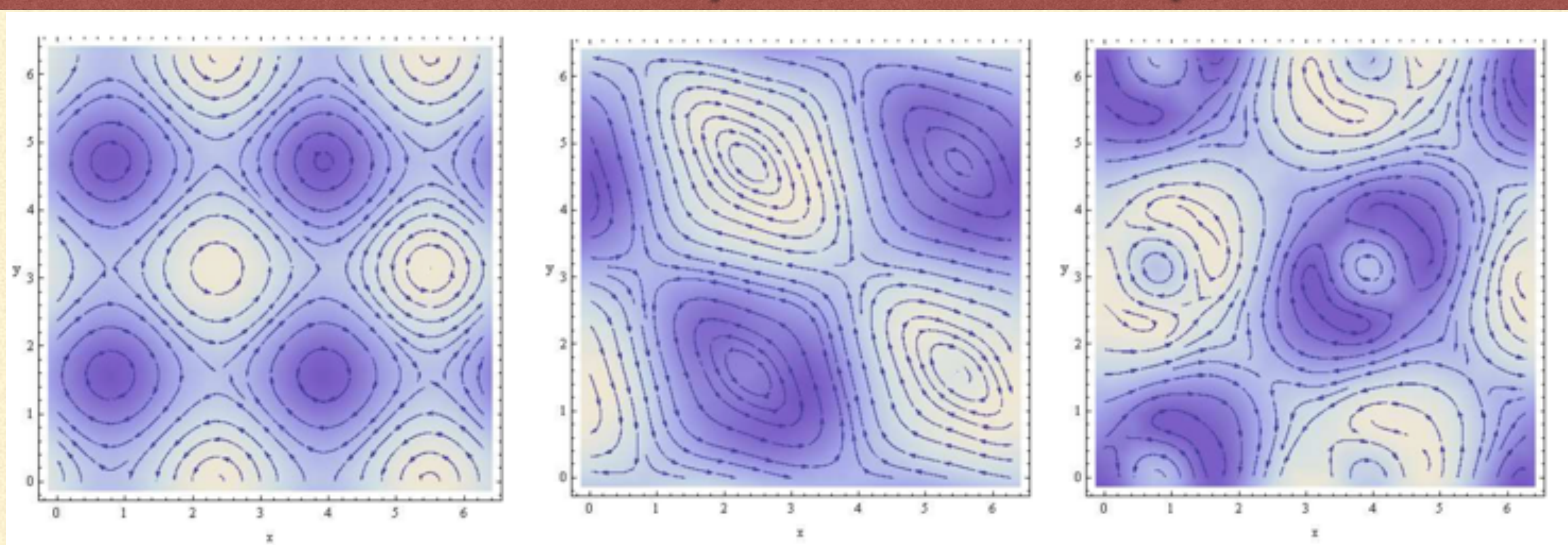
$$\omega^2 = \frac{V}{\frac{1}{2}\int dV B^2 (\vec{\xi}_\perp)^2}$$

Two examples in 2D



Linear force-free equilibrium within a spherical wall, l=1, m=0, n=2

Unstable to even incompressible ideal perturbations!

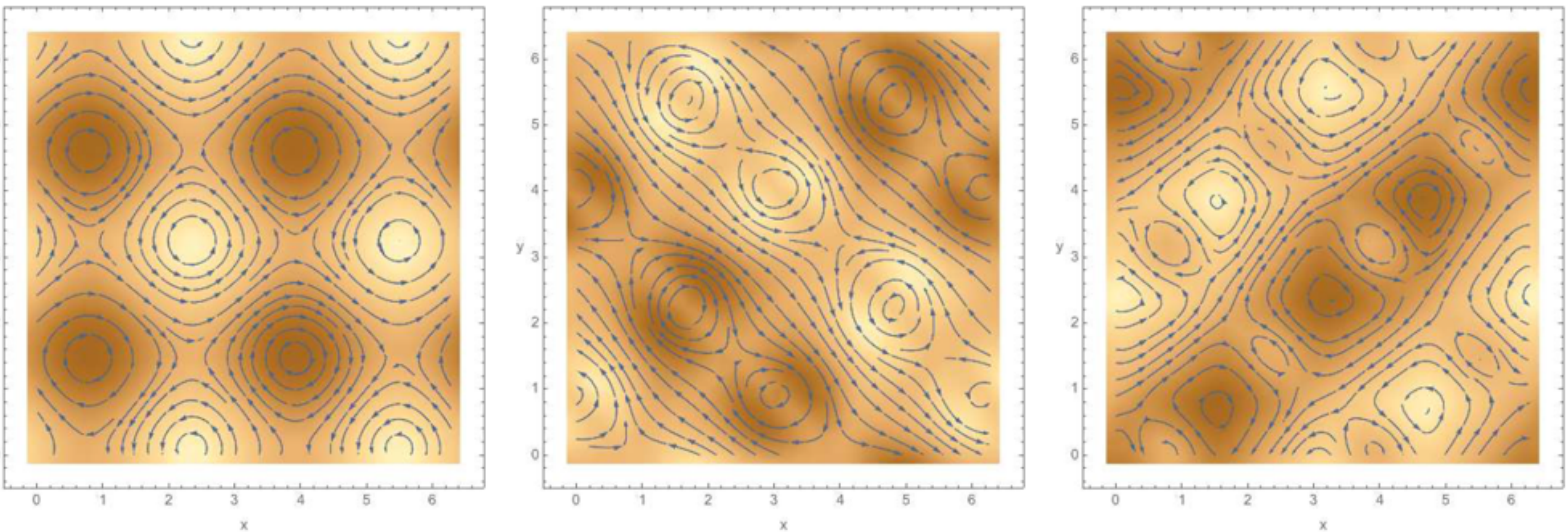


$\mathbf{B}_0$ $\vec{\xi}$ $\mathbf{B}_1$

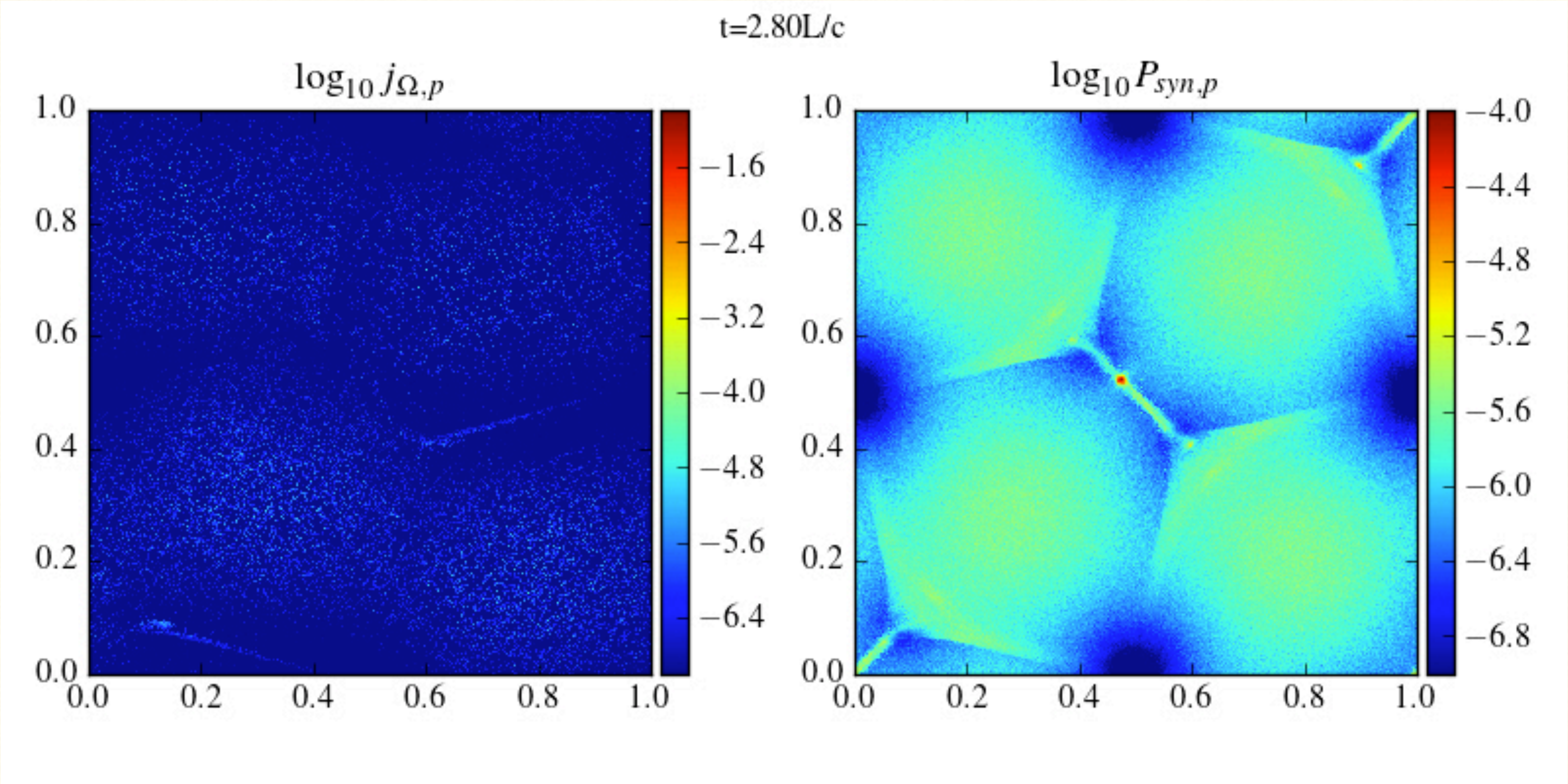
A particular ABC field

$$\mathbf{B}_0 = (0, \cos\alpha x, -\sin\alpha x) + (-\sin\alpha y, 0, \cos\alpha y)$$

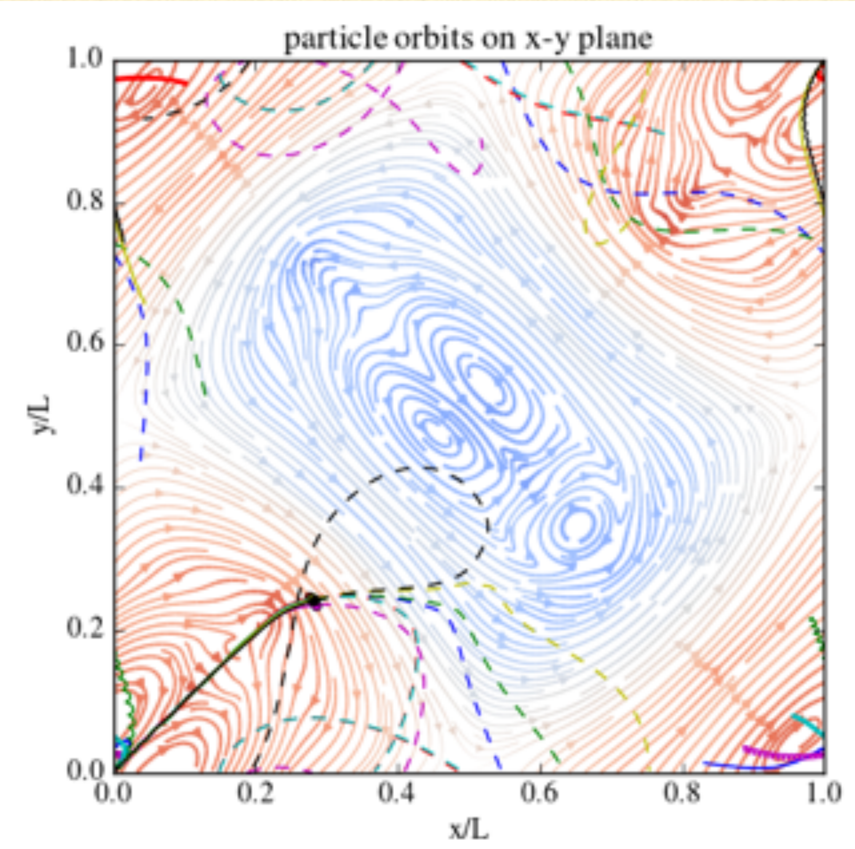
A 3D example

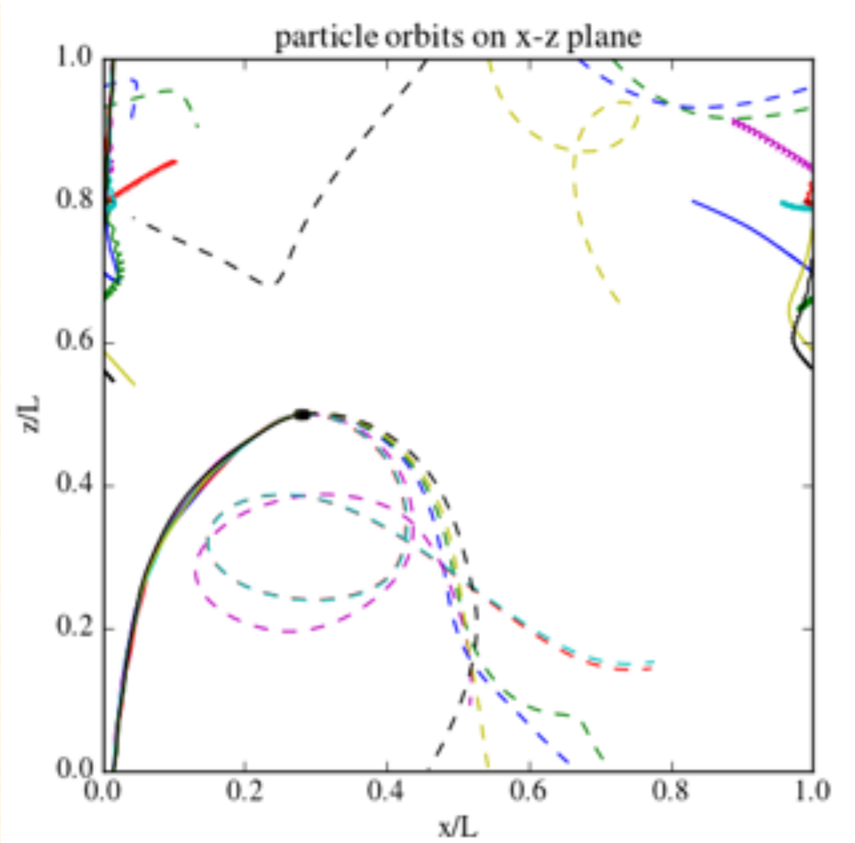


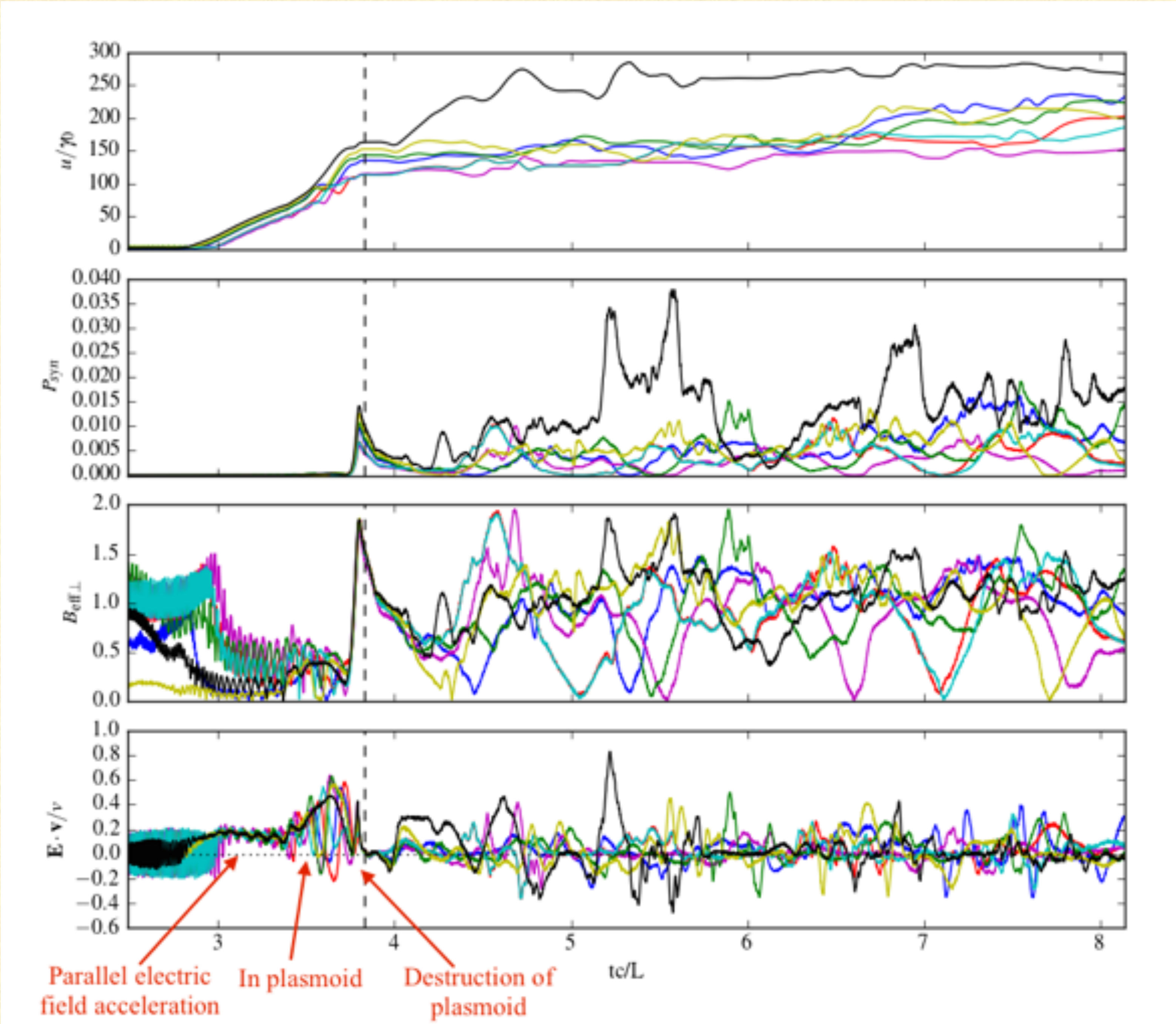
$\mathbf{B}_0$ $\vec{\xi}$ $\mathbf{B}_1$



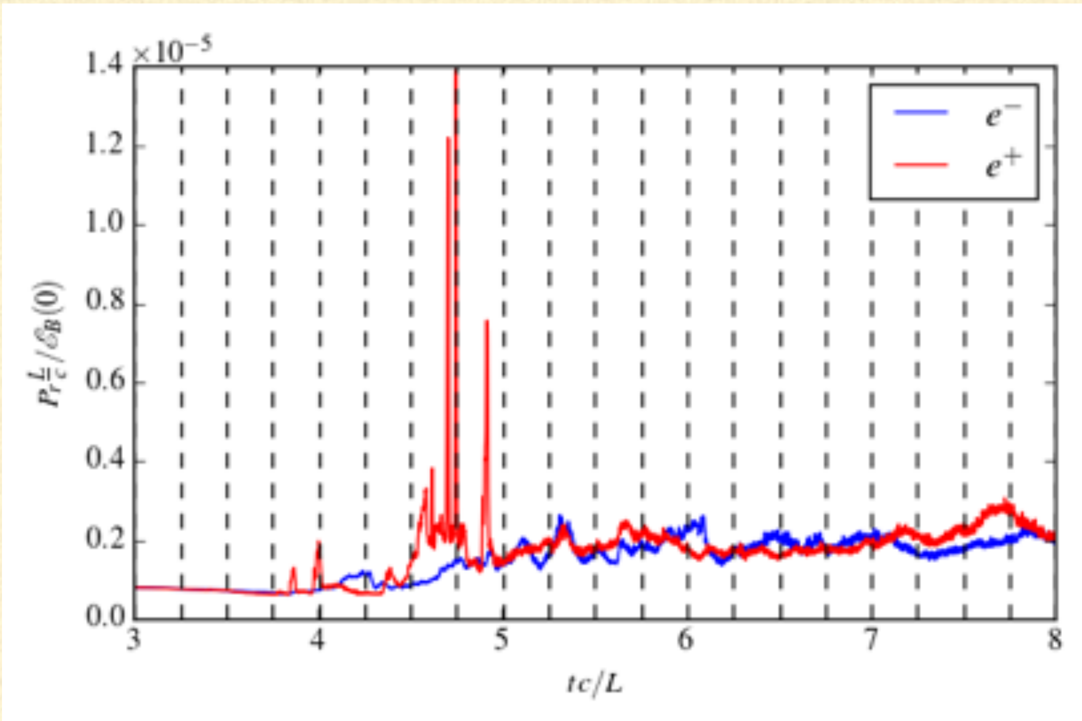
t=2.80L/c
$\log_{10} j_{\Omega,p}$
$\log_{10} P_{syn,p}$

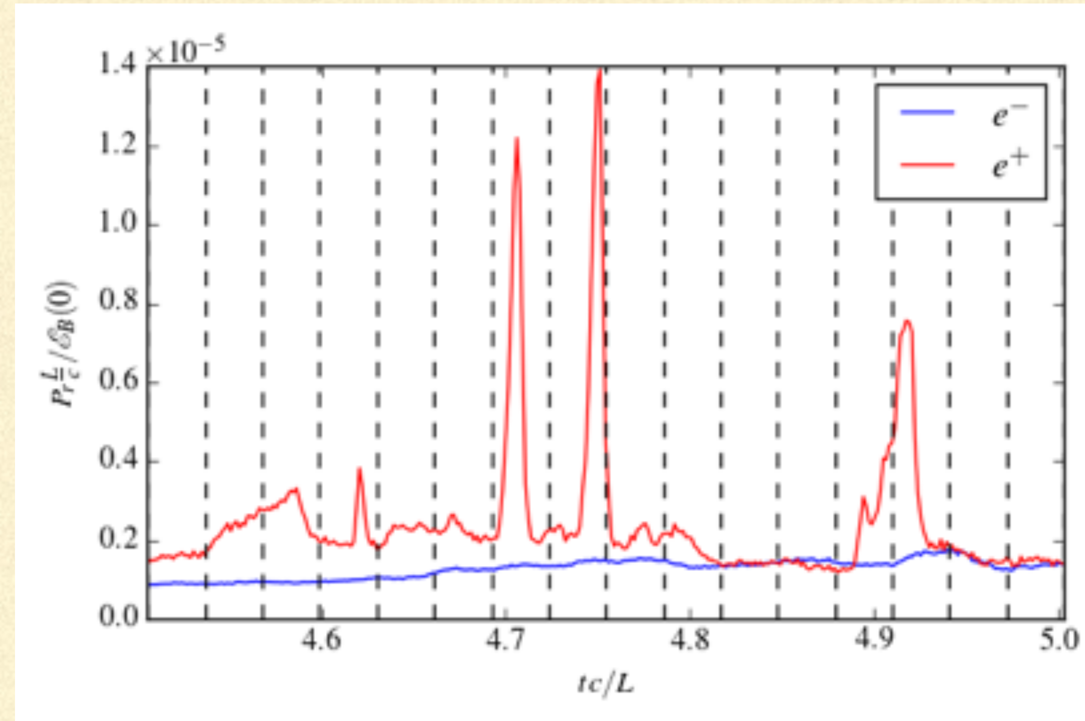

particle orbits on x-y plane
y/L
x/L
0.0
0.2
0.4
0.6
0.8
1.0

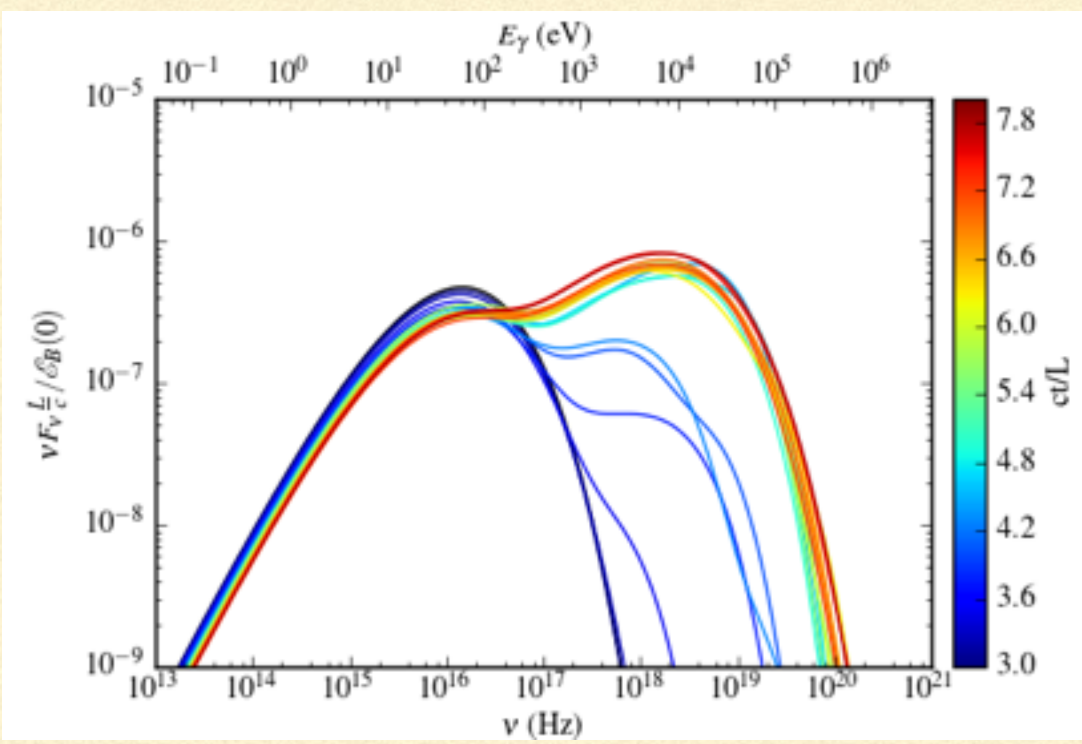

particle orbits on x-z plane
z/L
x/L
0.0
0.2
0.4
0.6
0.8
1.0

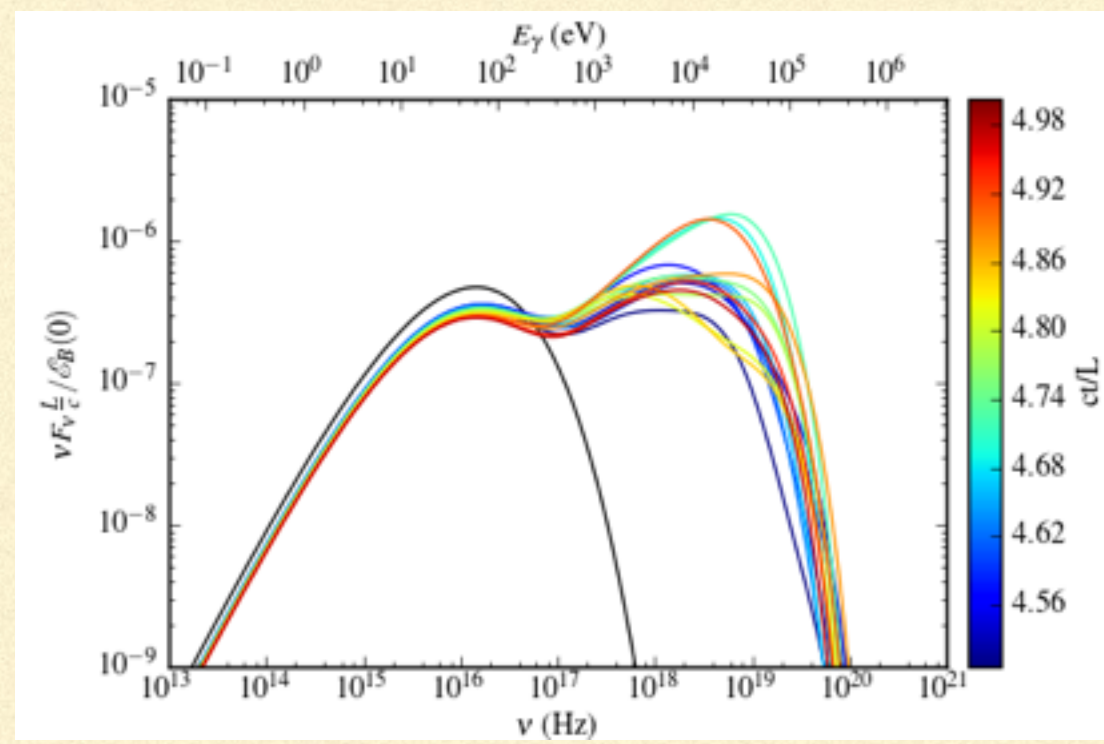

u/γ_0
P_{syn}
$B_{\mathrm{eff}\perp}$
$\mathbf{E}\cdot\mathbf{v}/v$
tc/L
Parallel electric field acceleration
In plasmoid
Destruction of plasmoid

Radiation spectrum

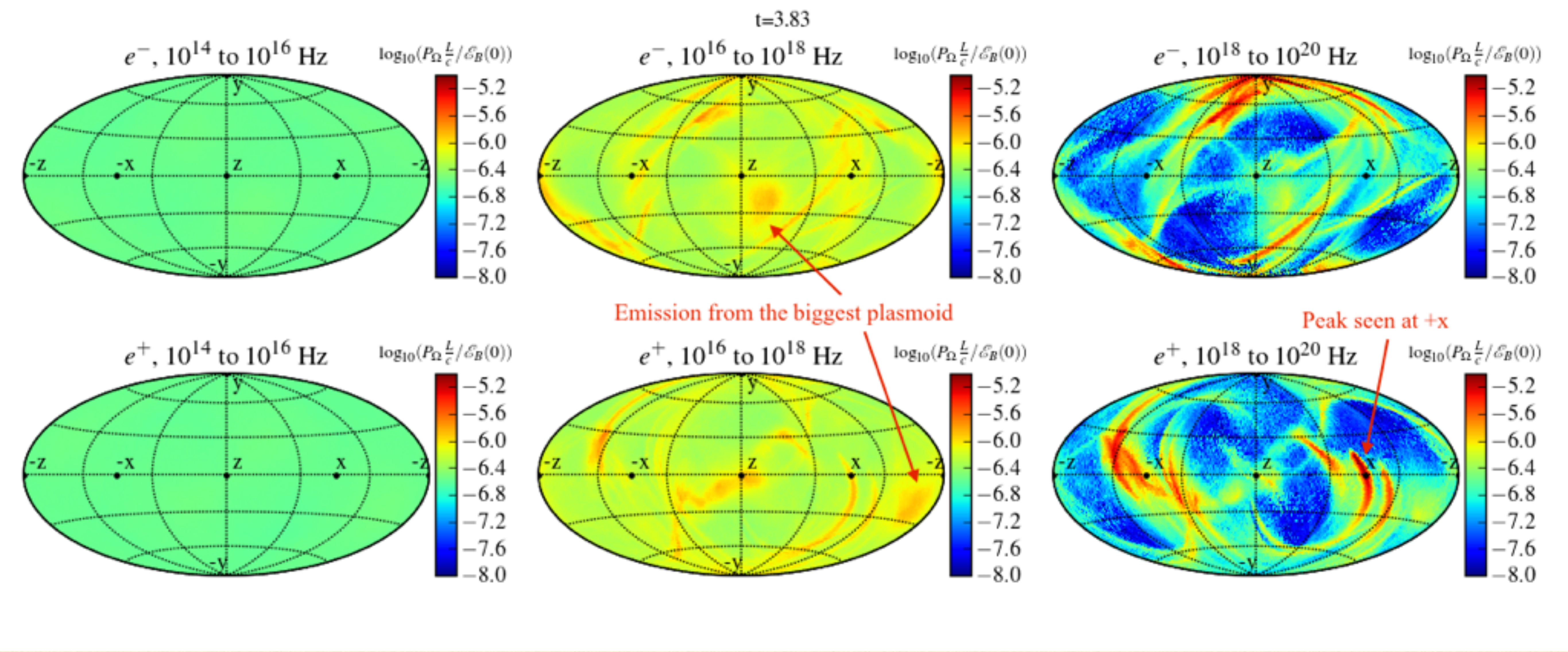




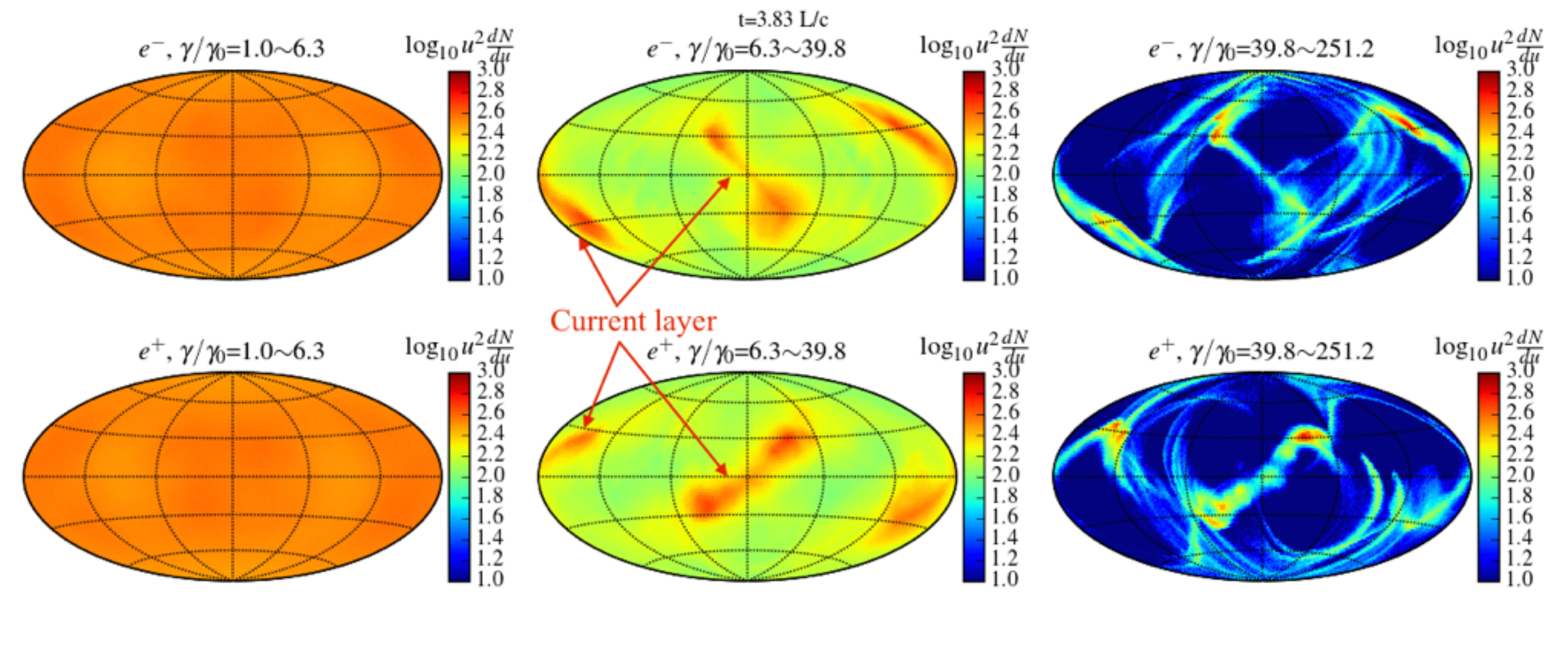




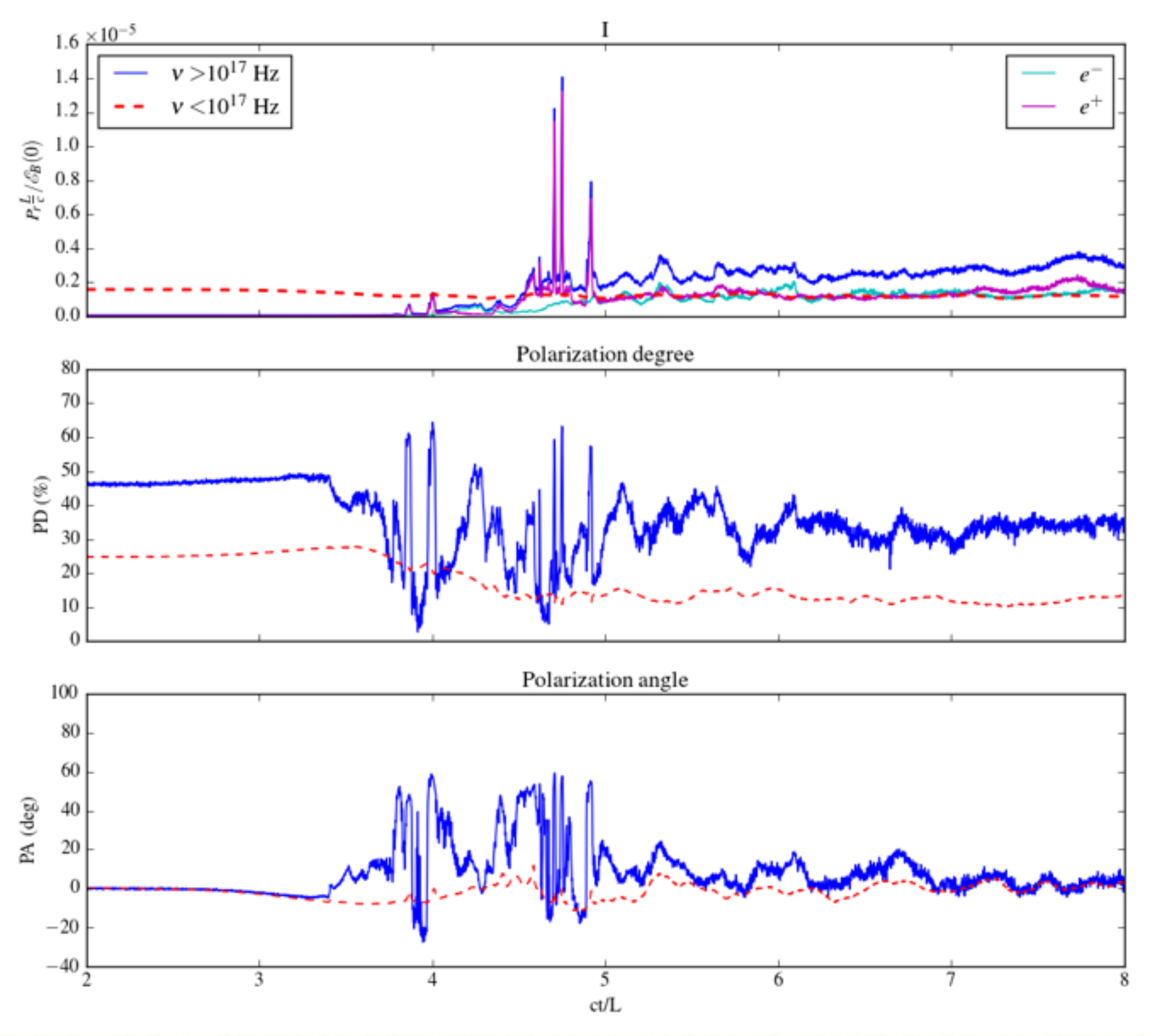
angular distribution of radiation



angular distribution of particles

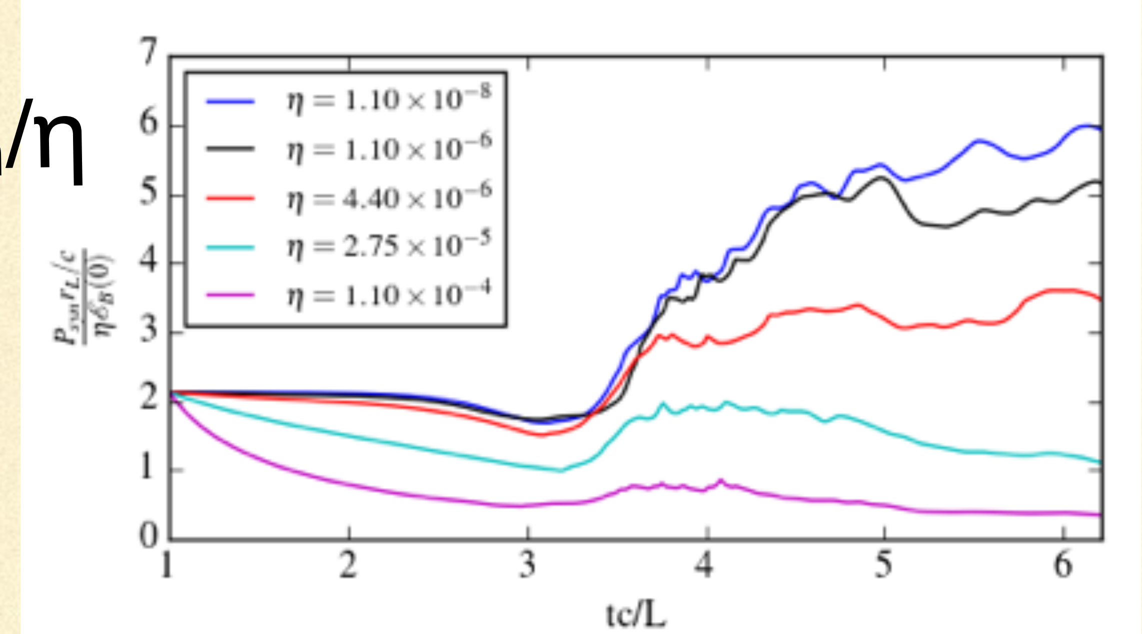


Polarization signal



Effects of radiation reaction

P_{syn}/η

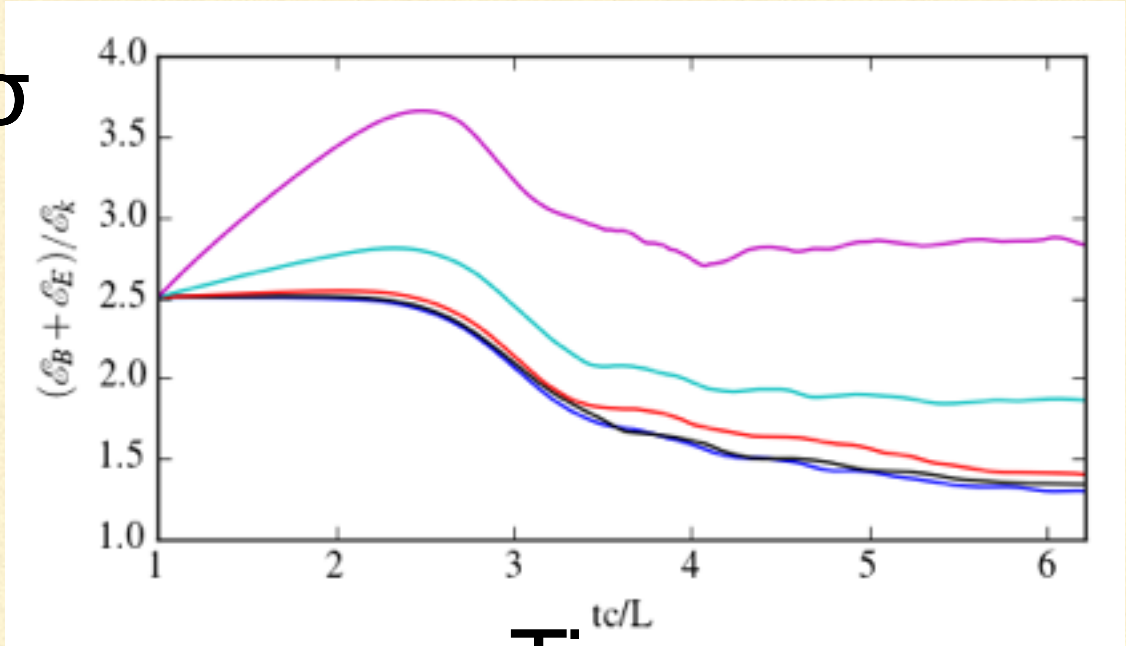


Time

Suppression of P_{syn}/η near the radiation reaction limit.

In strong cooling regime, the magnetization is kept high.

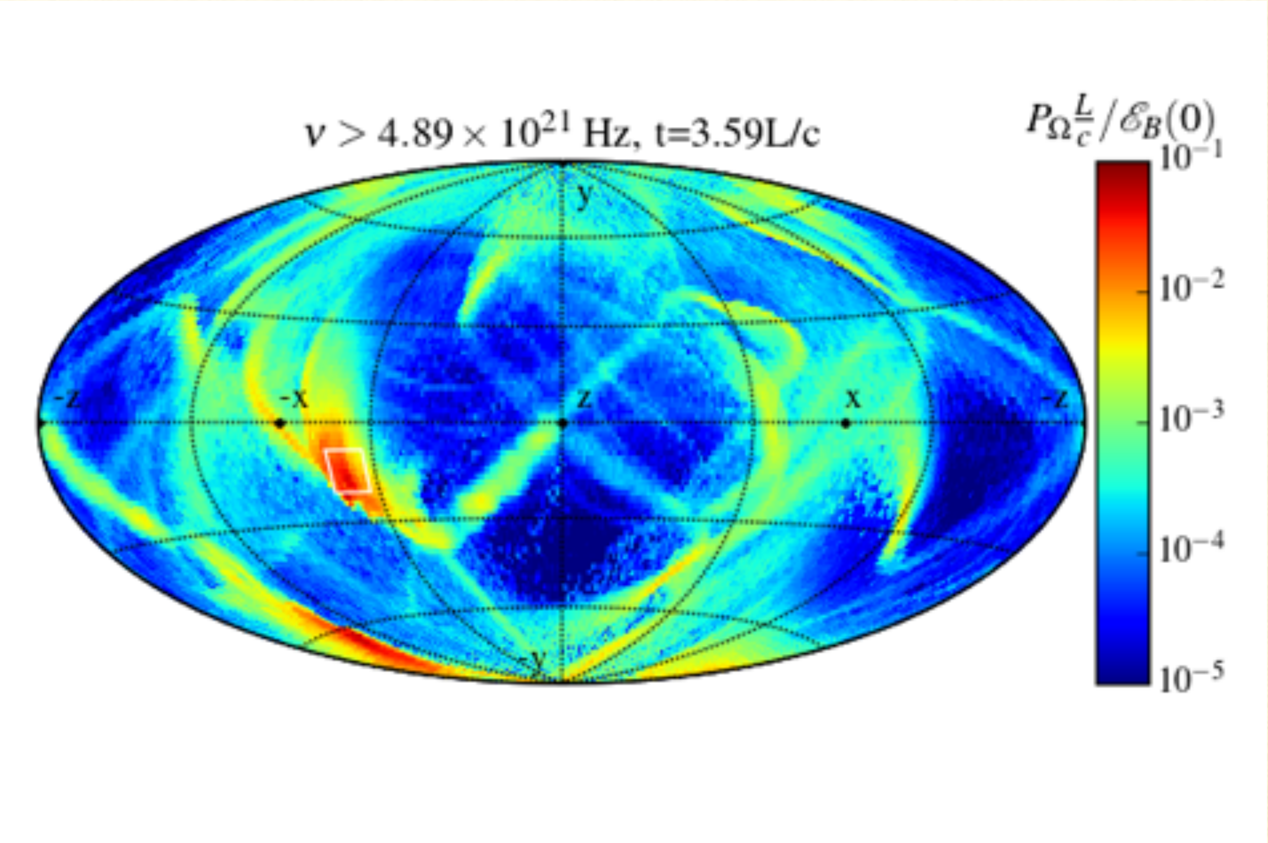
σ

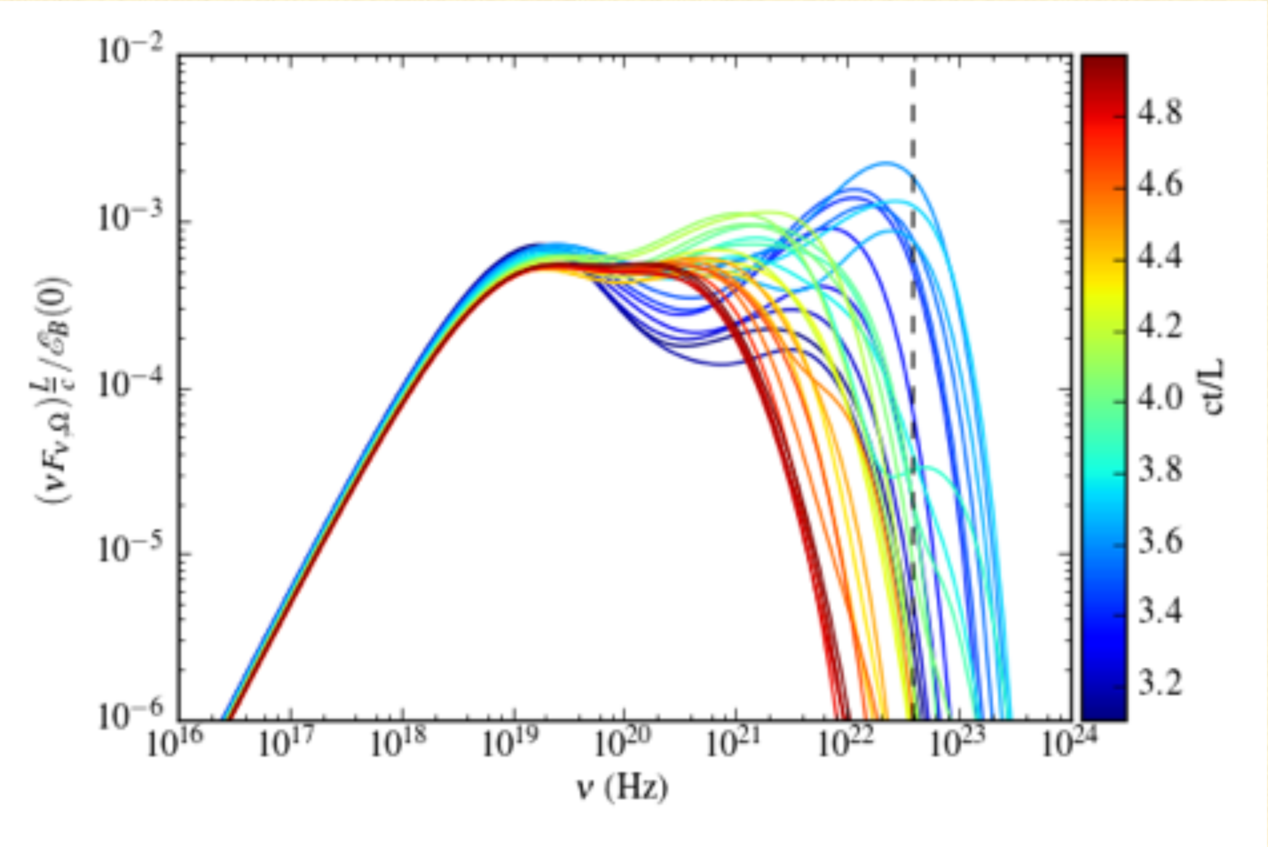


Time

Getting beyond radiation reaction limit?

- Large enough potential
- Possibility of accessing this potential quickly
- Separation between the acceleration region and the radiation region





Example: η=1.1e-4

Next Steps

- Full 3D simulations
- Higher magnetization and strong radiation reaction regime
- Inverse Compton as dominant radiation mechanism
- Electron-ion plasma