RECONNECTION AND RADIATION IN OUTER MAGNETOSPHERES OF PULSARS

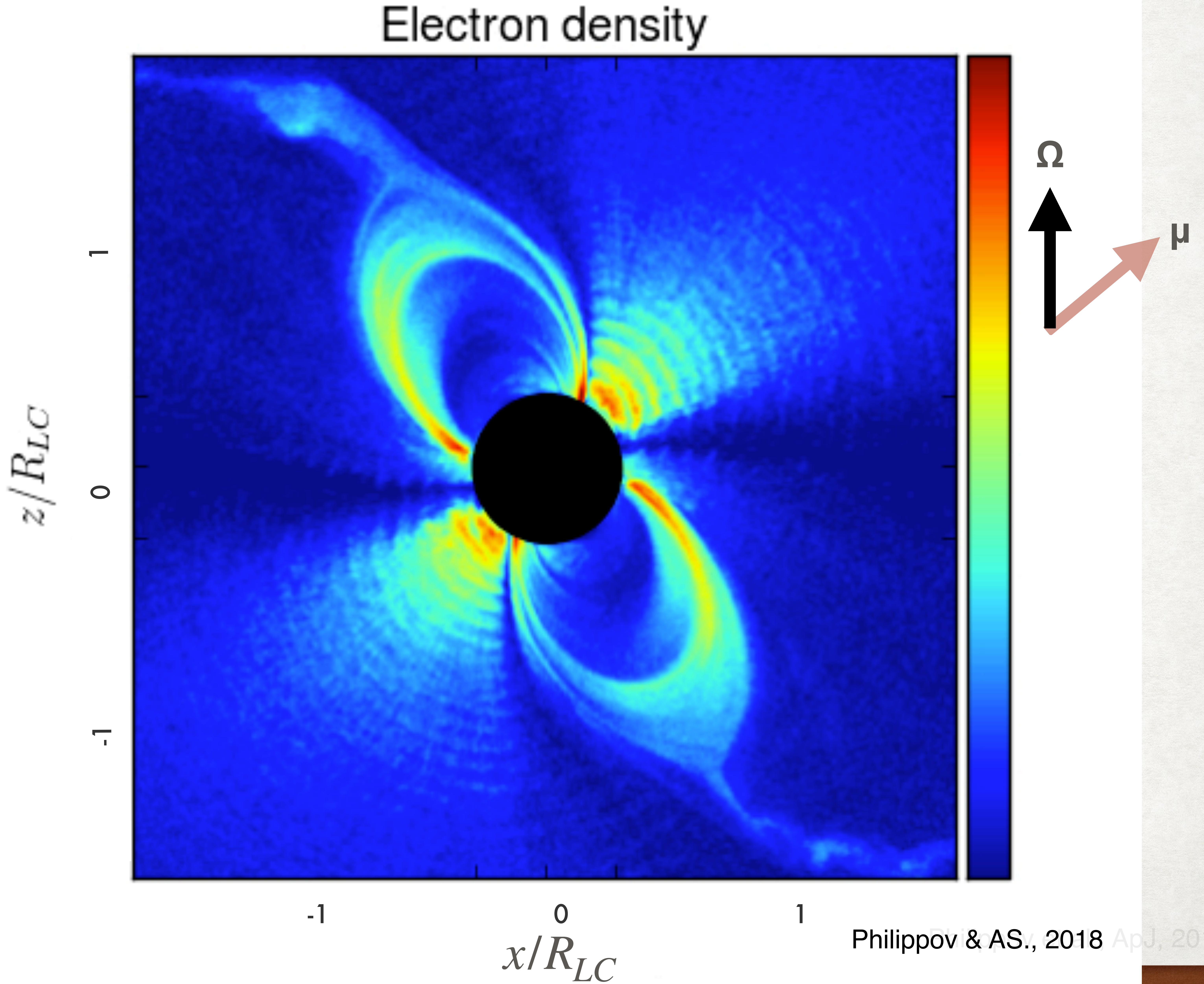
ANATOLY SPITKOVSKY
WITH H. HAKOBYAN, A. CHEN, A. PHILIPPOV, B. CERUTTI

OBLIQUE ROTATOR WITH GR AND PAIRS

- Pair production happens on the polar cap, in return current layers and in the current sheet beyond LC

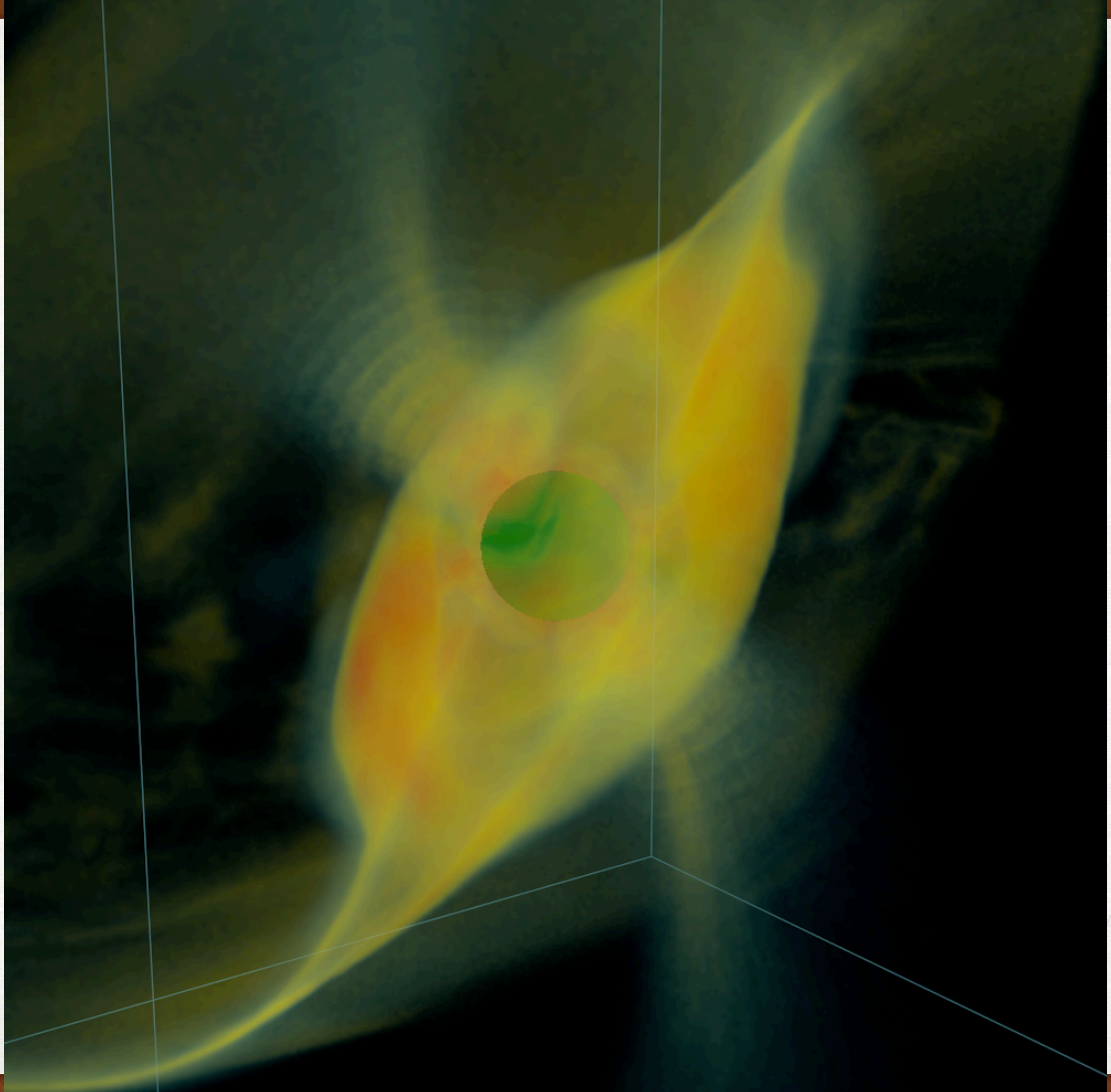
- Polar discharge is non-stationary. Electric field screening by advecting plasma clouds generates waves. The plasma motions are collective and coherent — implications for radio emission (see Beloborodov 2008, Timokhin & Arons 2013)

- Reconnection in current sheet



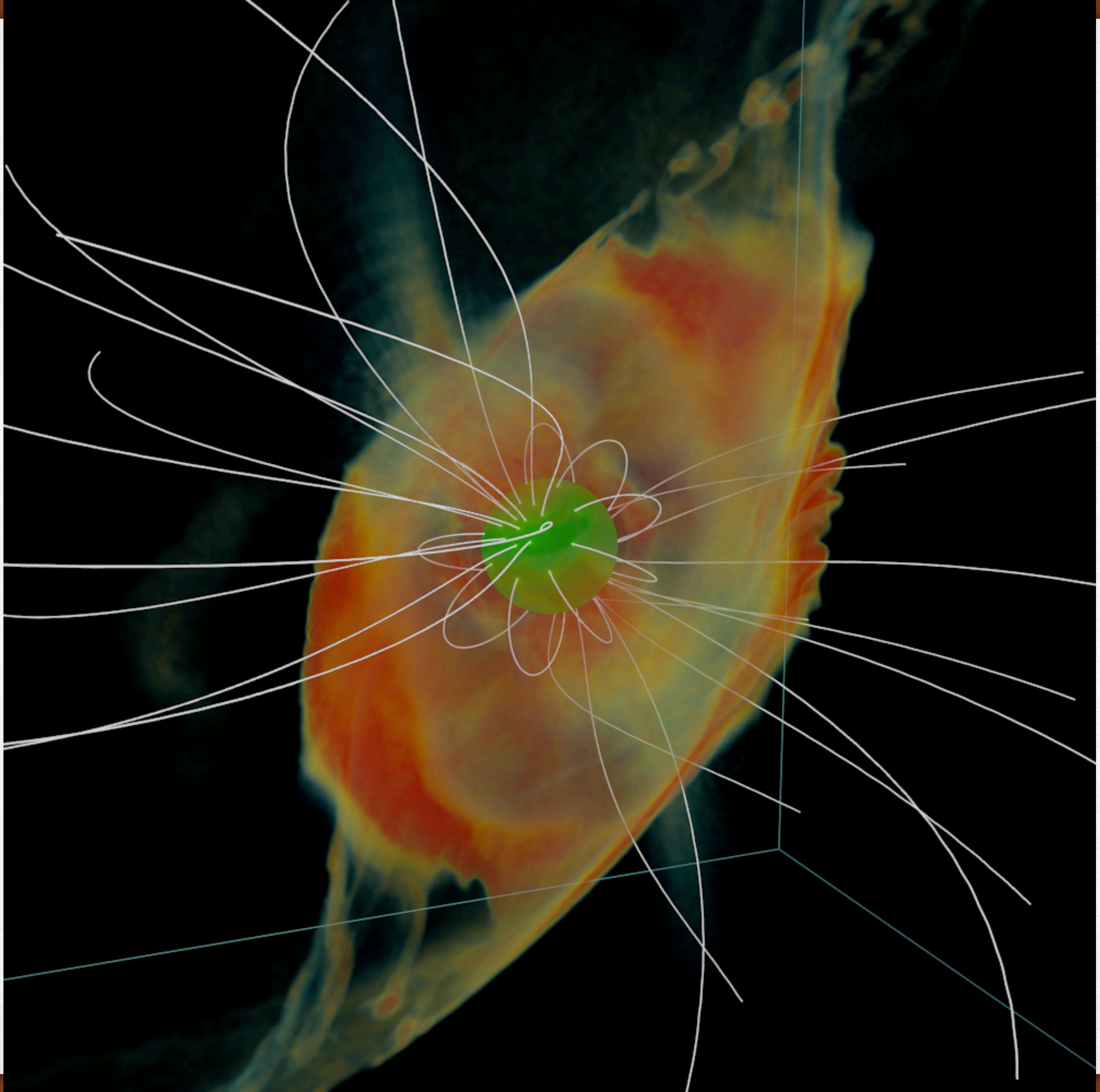
Philippov & AS., 2018

OBLIQUE ROTATOR WITH GR AND PAIRS: PLASMA DENSITY



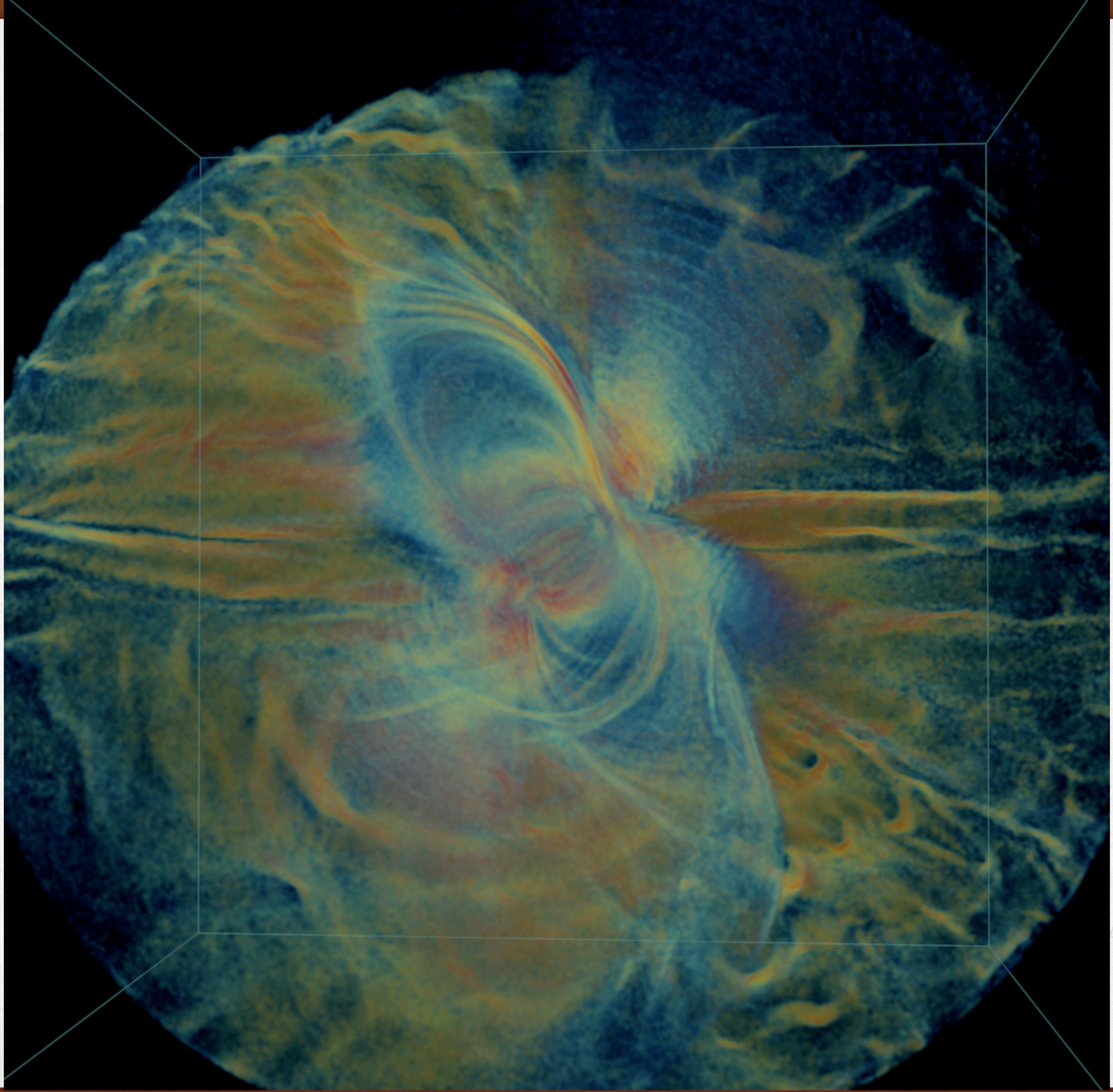
ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS: PLASMA DENSITY



ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS: CURRENT DENSITY

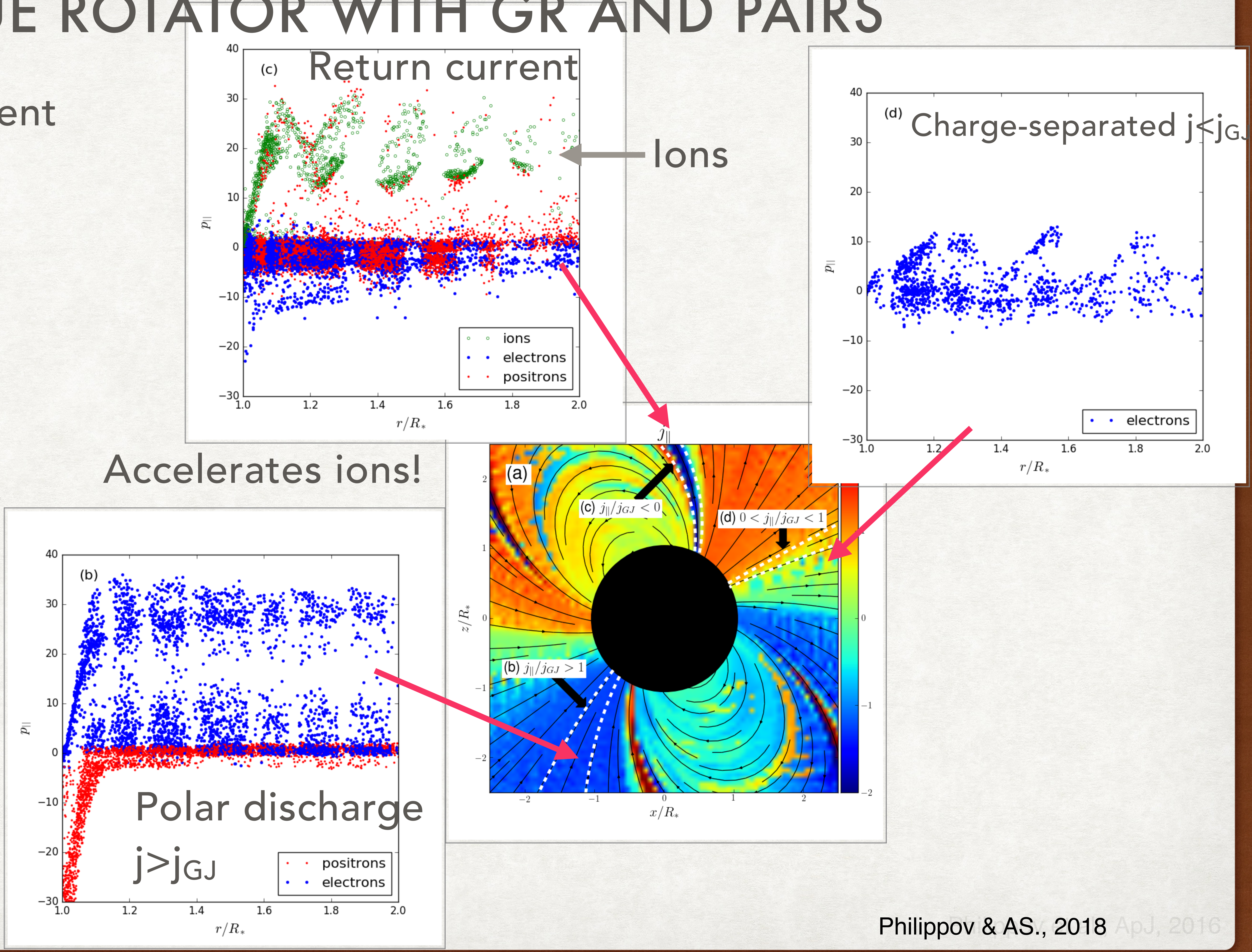


ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS

- Counterstreaming is present in polar discharge and in return current
- Opportunities for maser emission from collective instabilities of counterstreaming distributions.
- High energy ions in the sheet!

Momentum space

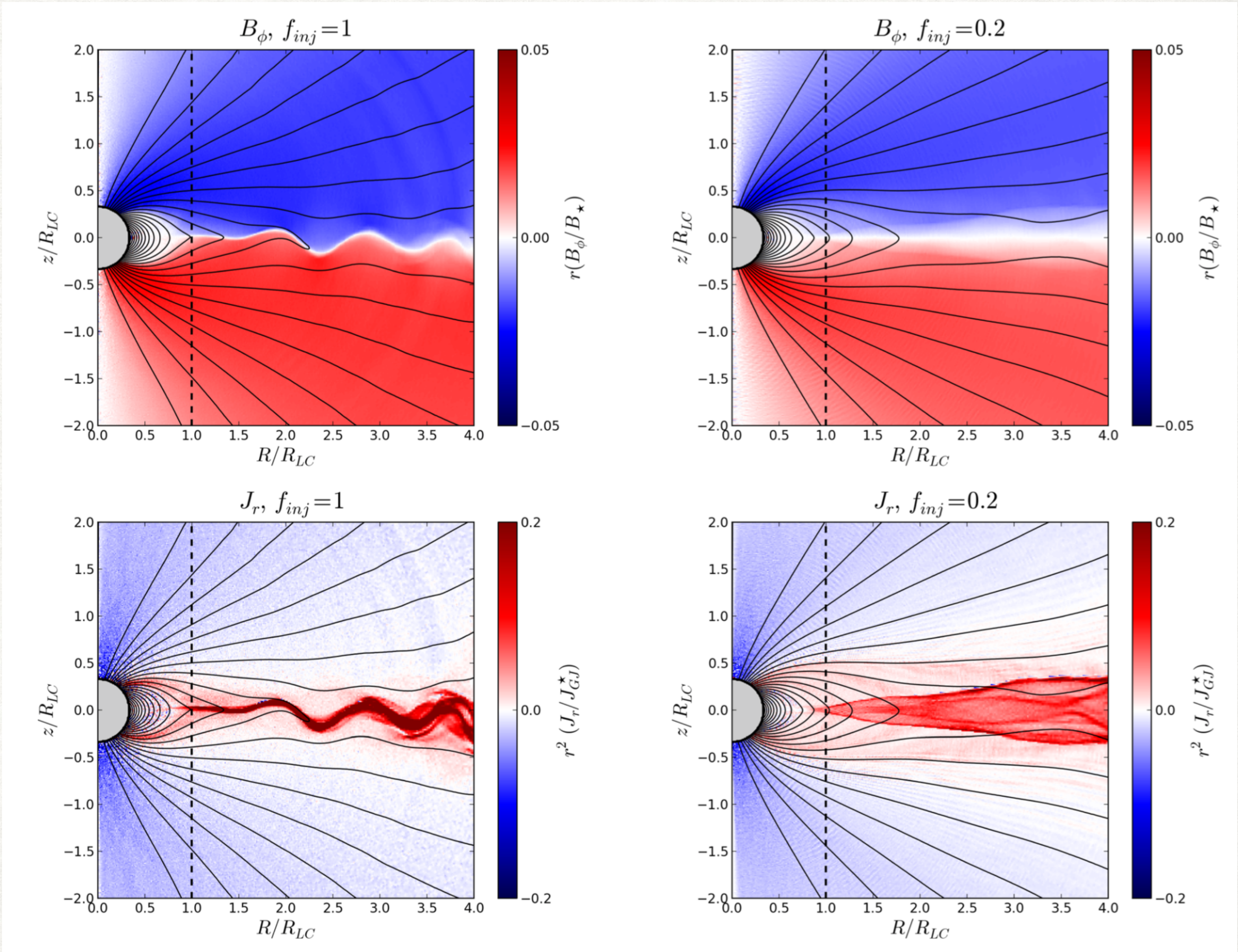


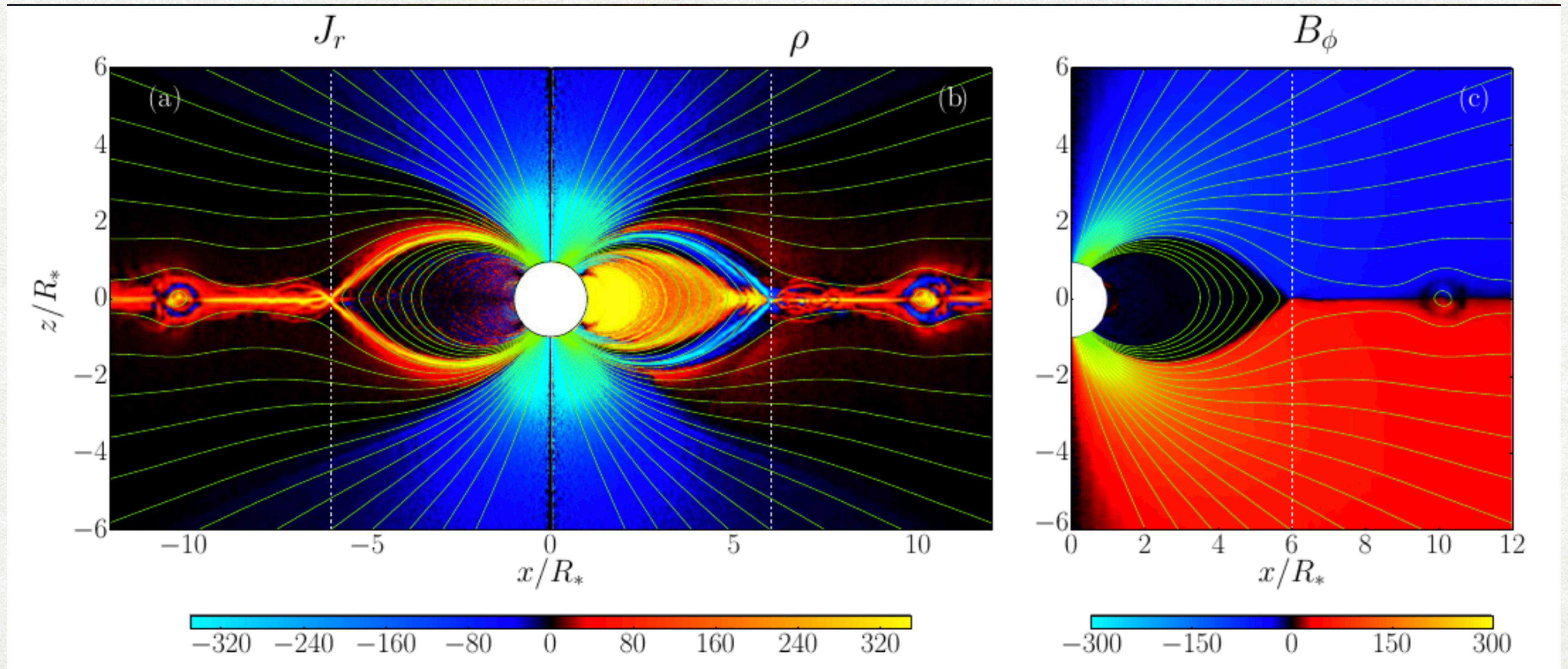
Philippov & AS., 2018

WEAK PULSARS?

- Is existence of pair production beyond the LC necessary for active magnetosphere?
- In many pulsars acceleration at LC is not enough to create pairs.
- Is pair injection near the star enough to jump start the magnetosphere?
- Are there E>B regions (Gruzinov '13)?

Cerutti et al 2014





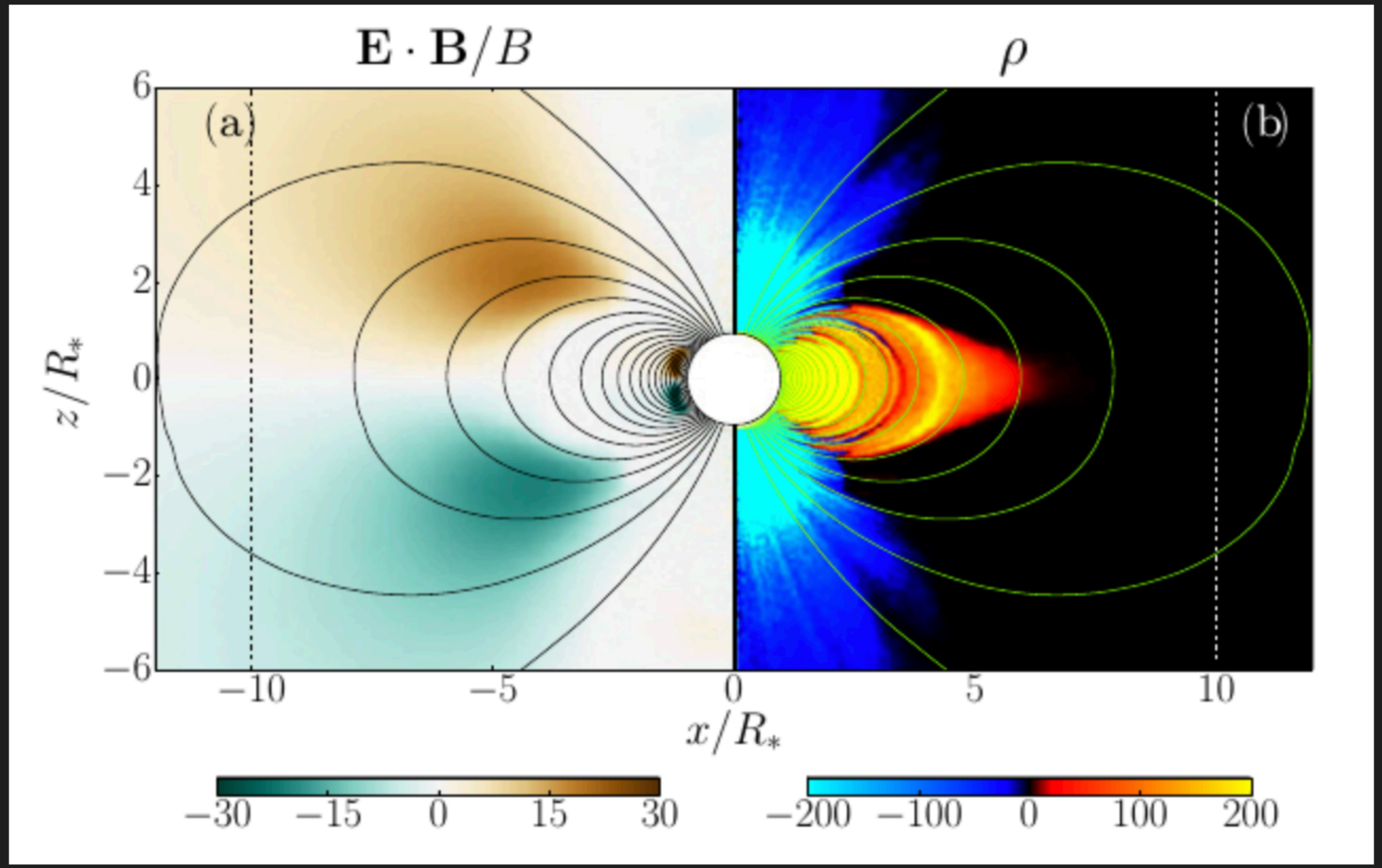
Chen & Beloborodov 2014

WEAK PULSARS?

- Is existence of pair production beyond the LC necessary for active magnetosphere?

Define $\eta = \gamma_{\max}/\gamma_{\text{thr}}$.

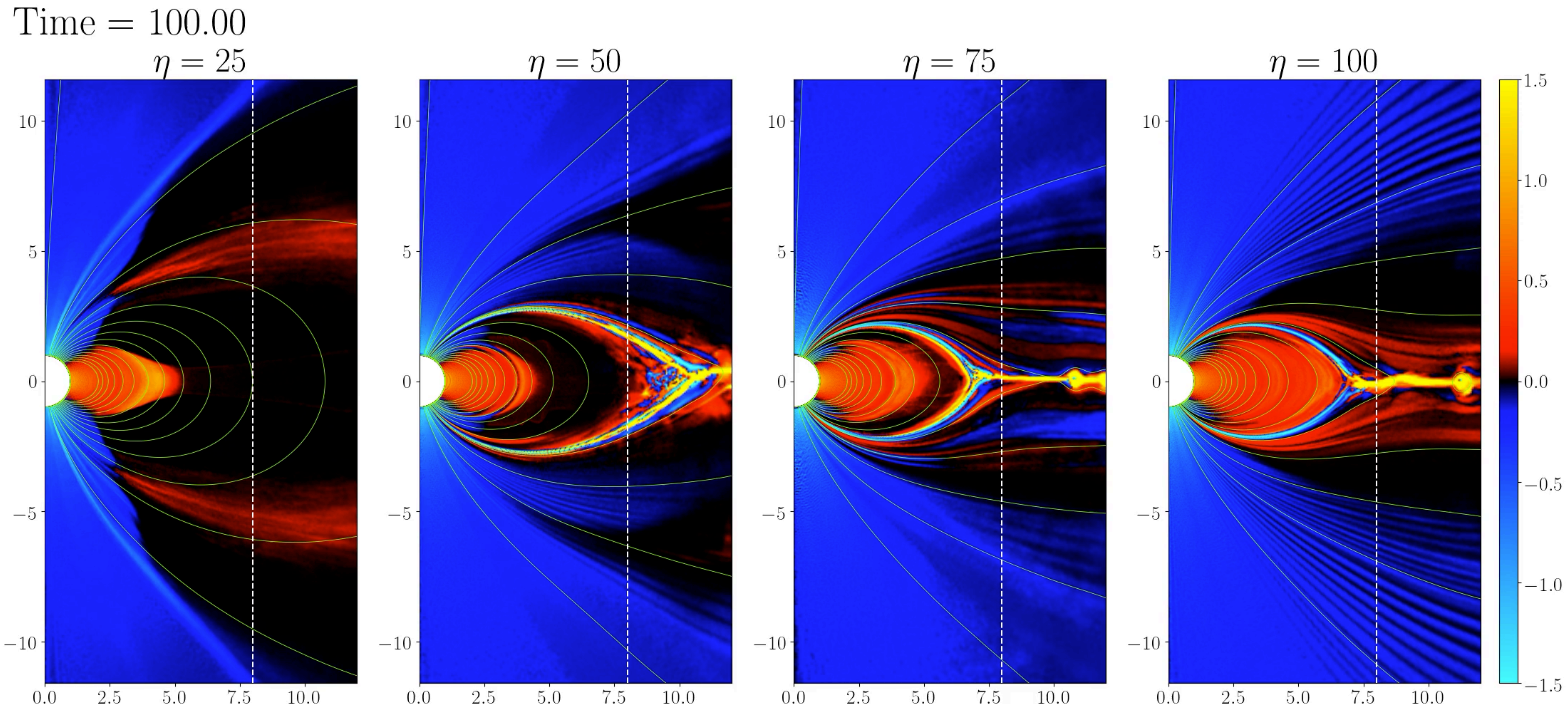
- Threshold pair creation
- $R_{\text{LC}}/R_* = 8$
- $r_{\text{cutoff}}/R_* = 3$
- Vary η from 10 to 150



(Chen & Beloborodov 2014)
$\eta \sim 10$

- Push to larger separation of scales, while limiting pair production to near the star

WEAK PULSARS?



Pair production confined to small radius. Filled solutions possible at high polar cap potentials! Multiplicity in the sheet is ~1.

IMPLICATIONS OF WEAK PULSAR SOLUTIONS

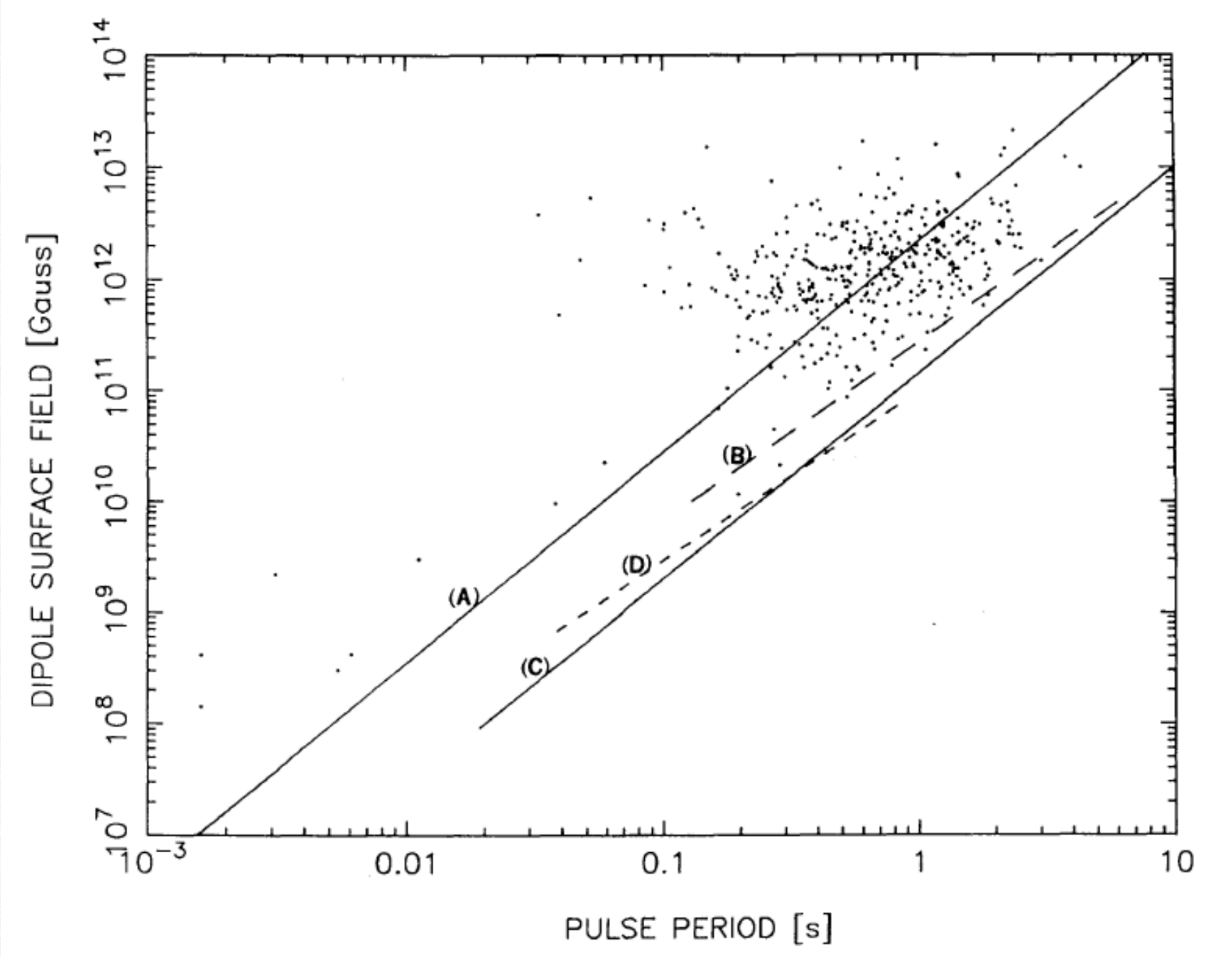
- When pair supply is low, the pulsar magnetosphere undergoes global oscillations, on a time scale comparable to the spin period.

- This kind of oscillations periodically open up vacuum electric fields that can have total voltage higher than the ordinary polar cap voltage, closer to the vacuum dipole voltage.

- Many observed old pulsars are below the threshold to produce pairs with their polar cap voltage. These pulsars can in principle produce pairs through the global magnetospheric oscillations, without requiring higher multipolar components.

- The pair production sites through this mechanism are only along the return (separatrix) current sheet. This suggests that radio emission is likely constrained along the return current sheet as well.

- These old pulsars typically have a cone-like radio emission pattern, while exhibiting subpulse drifts. The drifting period may be connected to the global magnetospheric oscillations, while the cone-like pattern natura radio-emitting pairs are only injected in the
return current sheet.

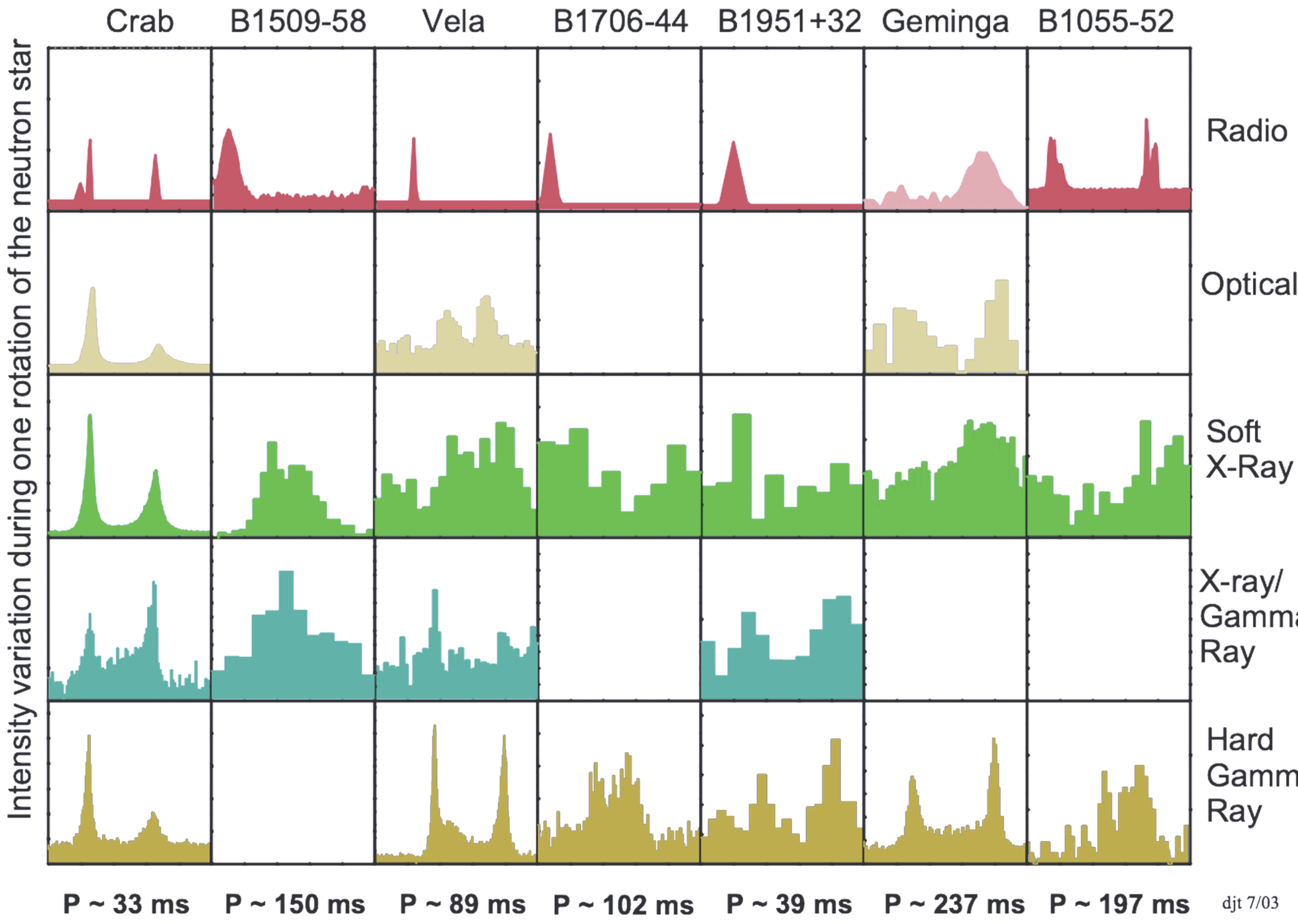


(Chen & Ruderman 1993)

Philippov et al., ApJ, 2016

ɣ-ray emission from pulsars

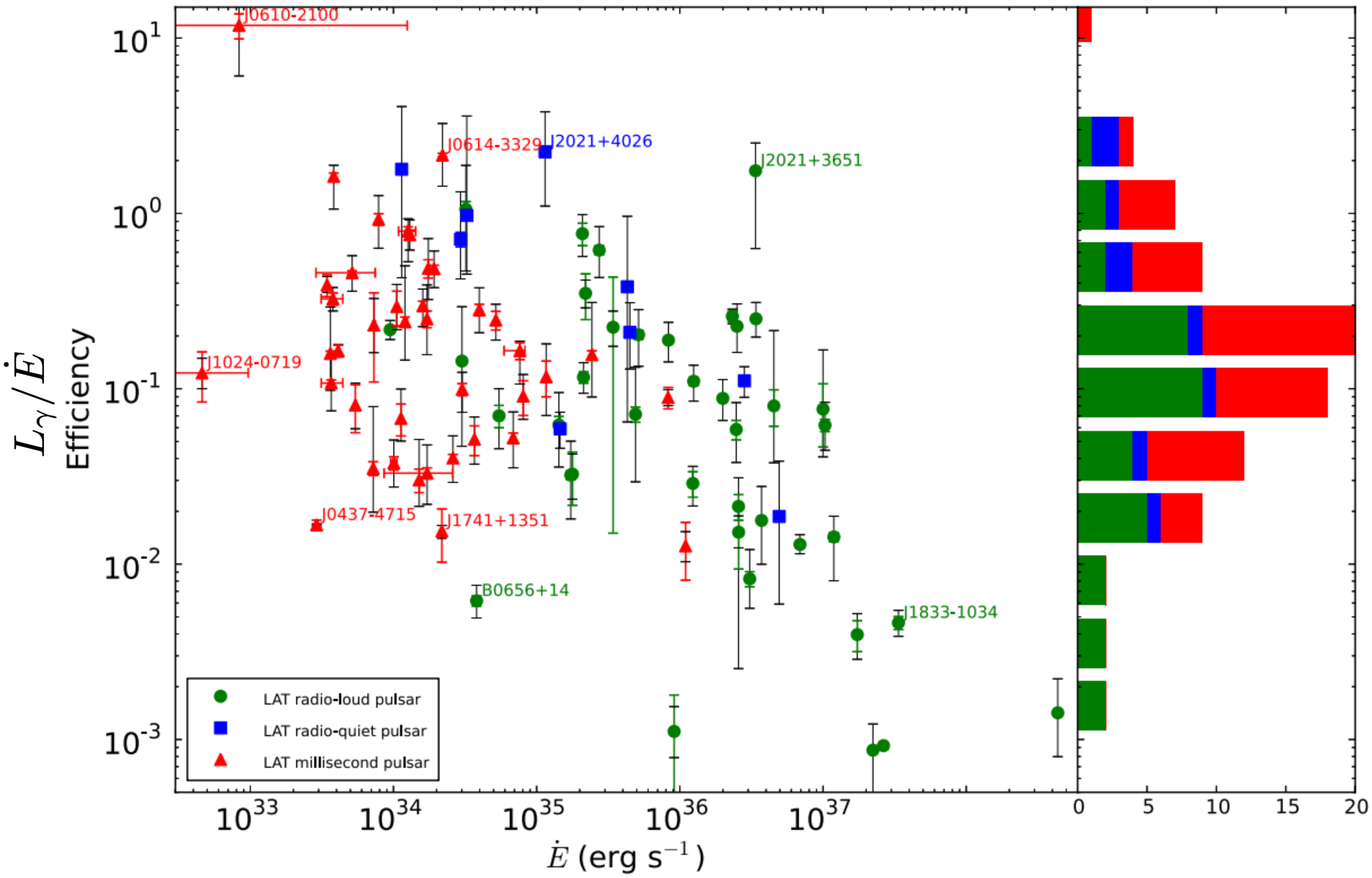
- 1970's: ɣ from Crab & Vela
- EGRET on CGRO: 6 pulsars
- Fermi: ~100 pulsars



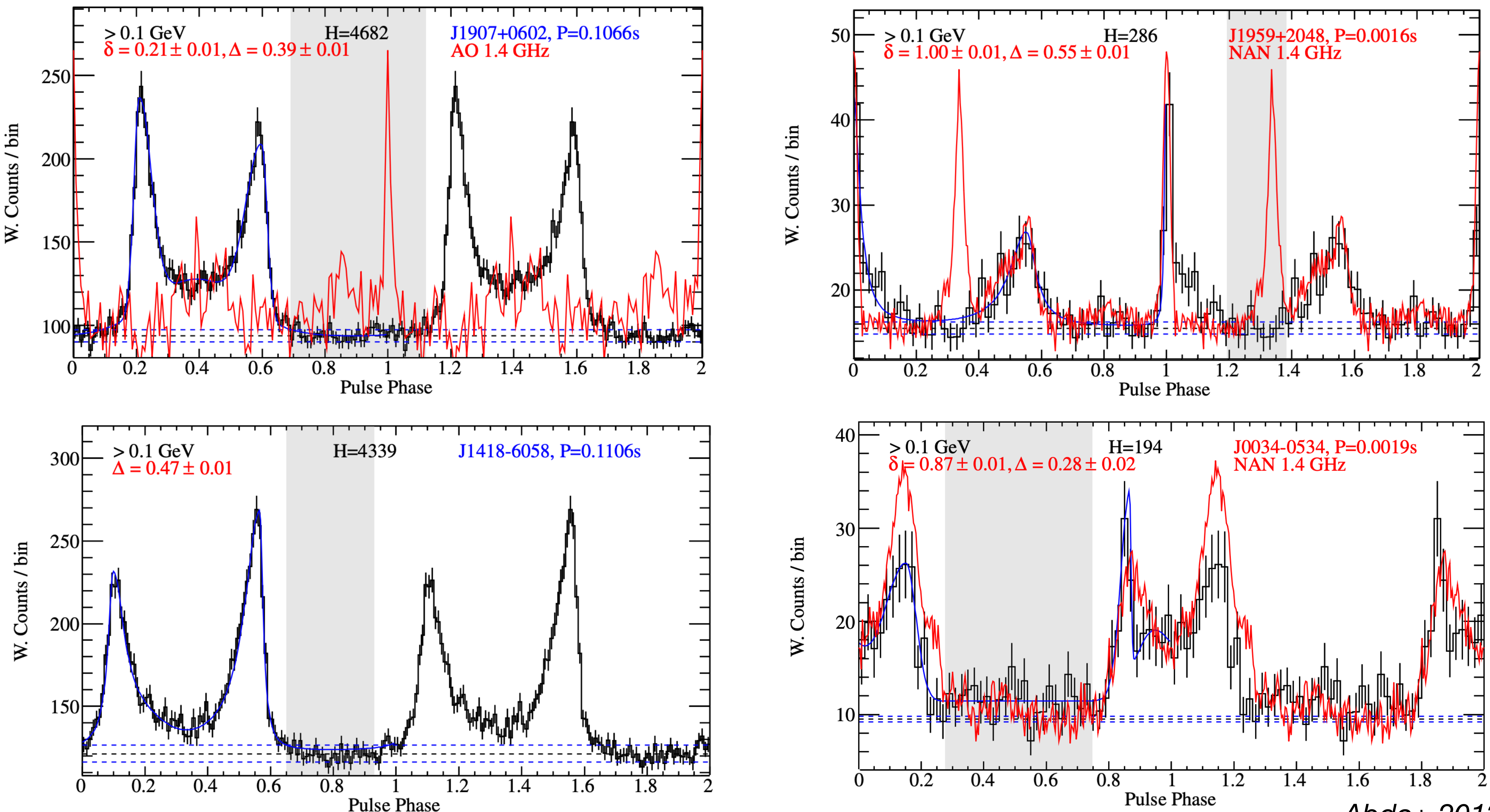
Thompson 2003

ɣ-ray emission from pulsars

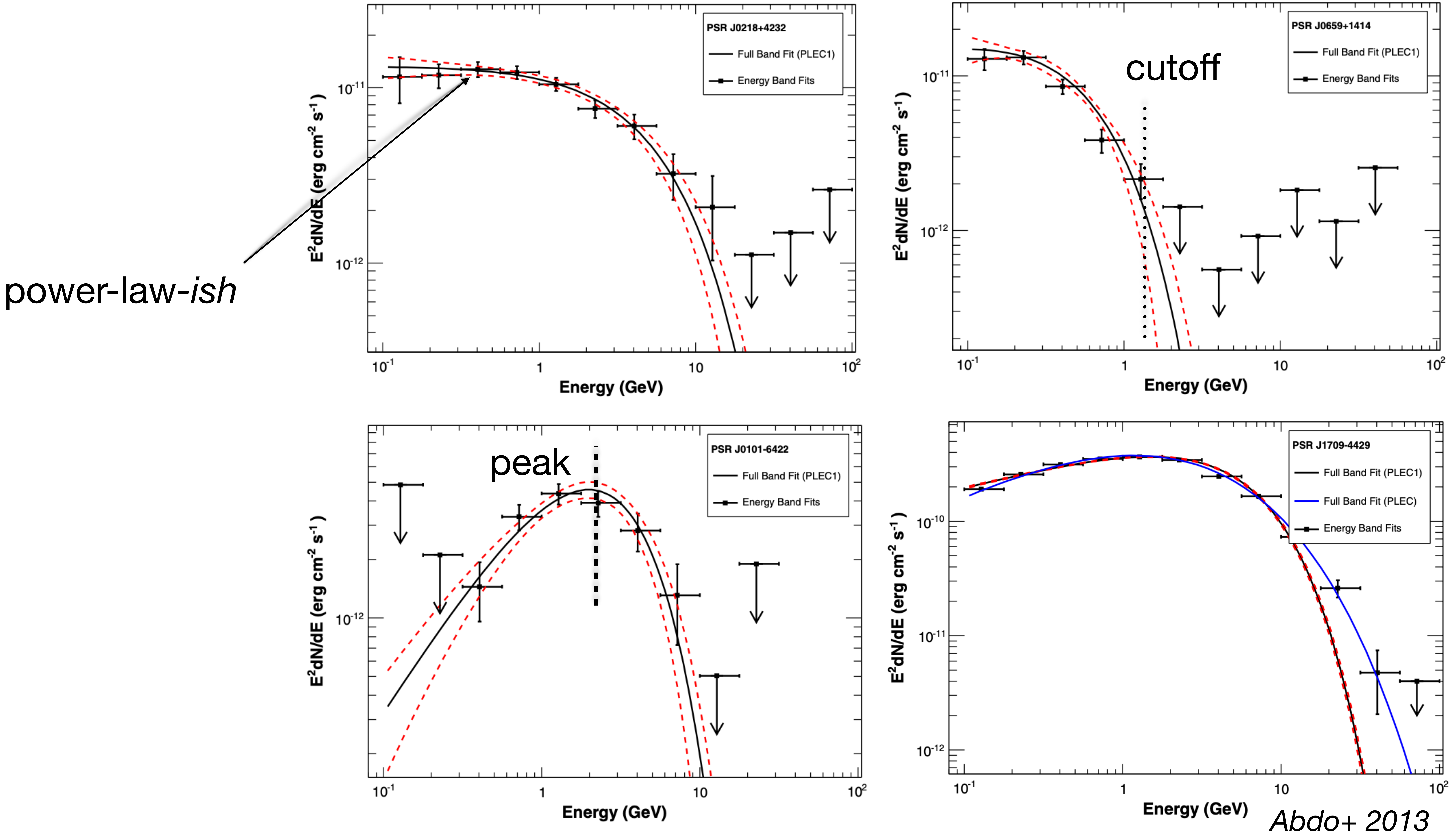
$\dot{E}$ = spin-down power



Abdo+ 2013


> 0.1 GeV
H=4682
J1907+0602, P=0.1066s
δ = 0.21 ± 0.01, Δ = 0.39 ± 0.01
AO 1.4 GHz
W. Counts / bin
Pulse Phase
> 0.1 GeV
H=286
J1959+2048, P=0.0016s
δ = 1.00 ± 0.01, Δ = 0.55 ± 0.01
NAN 1.4 GHz
W. Counts / bin
Pulse Phase
> 0.1 GeV
H=4339
J1418-6058, P=0.1106s
Δ = 0.47 ± 0.01
W. Counts / bin
Pulse Phase
> 0.1 GeV
H=194
J0034-0534, P=0.0019s
δ = 0.87 ± 0.01, Δ = 0.28 ± 0.02
NAN 1.4 GHz
W. Counts / bin
Pulse Phase

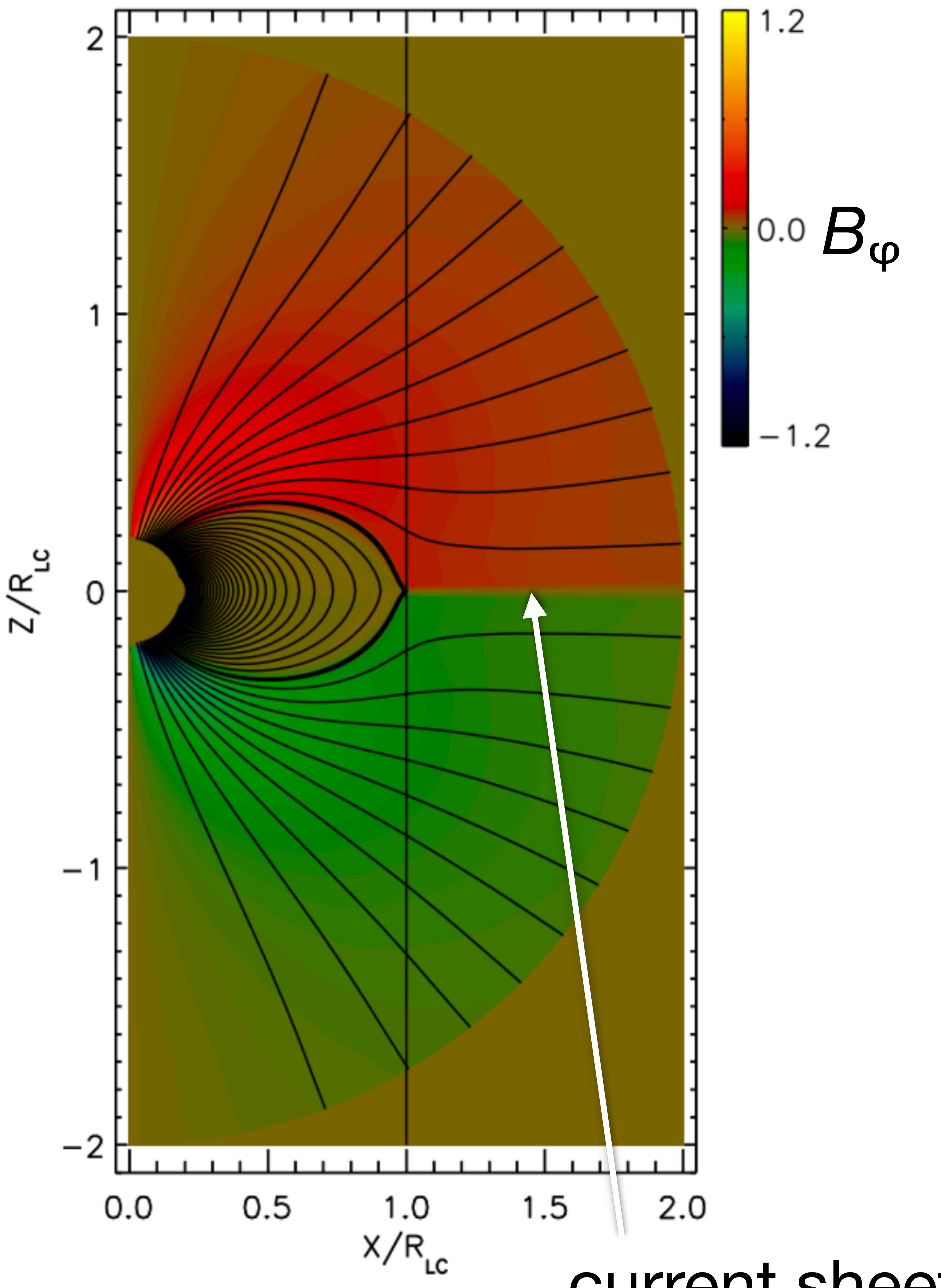
Abdo+ 2013

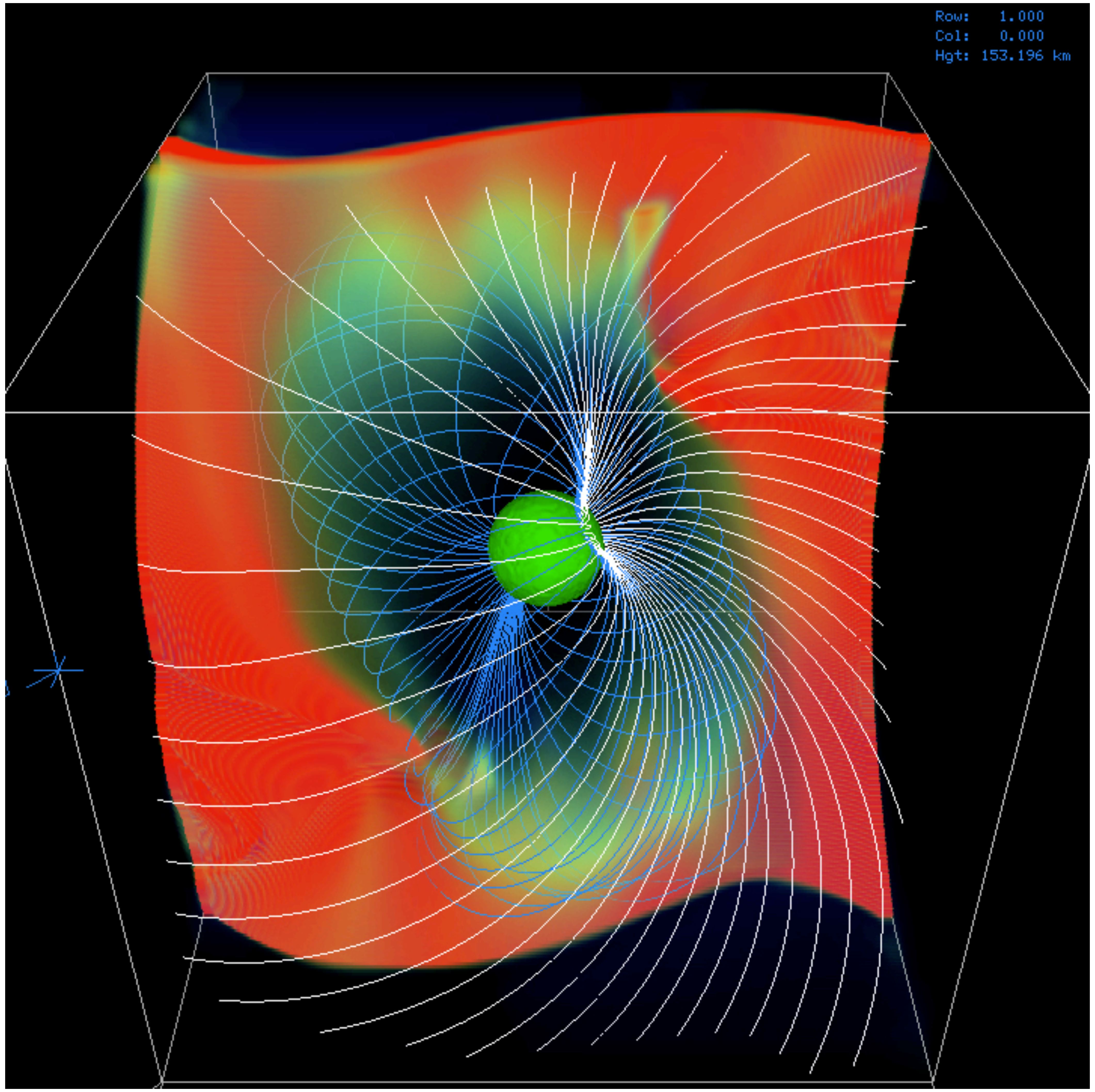

power-law-ish
cutoff
peak
PSR J0218+4232
PSR J0659+1414
PSR J0101-6422
PSR J1709-4429
Full Band Fit (PLEC1)
Full Band Fit (PLEC)
Energy Band Fits
Energy (GeV)
E²dN/dE (erg cm⁻² s⁻¹)
Abdo+ 2013

Origin of radiation

Force-free magnetosphere

Contopoulos+ 1999
Gurevich+ 1993
Spitkovsky 2006





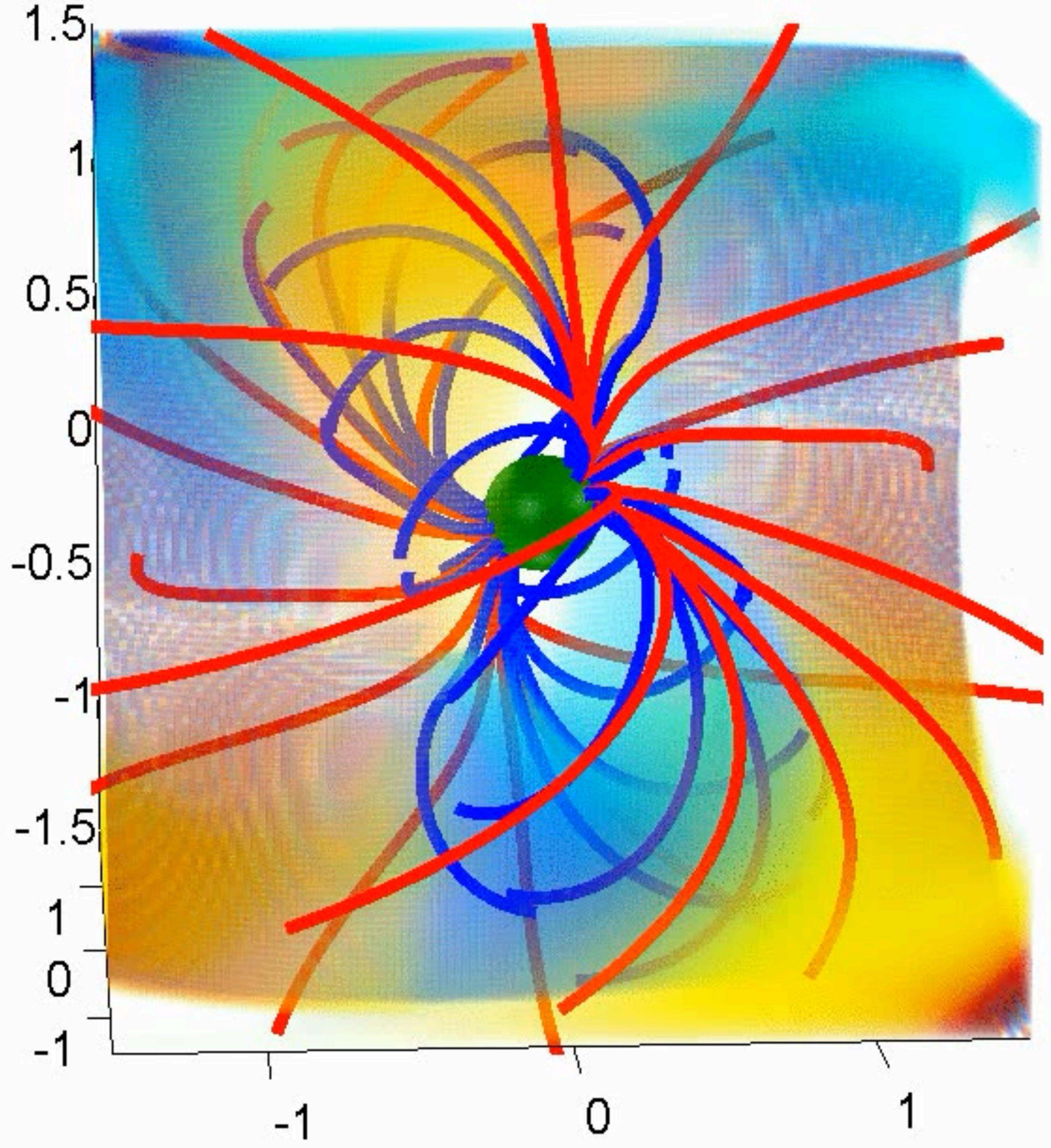
current sheet [jump of B_φ]

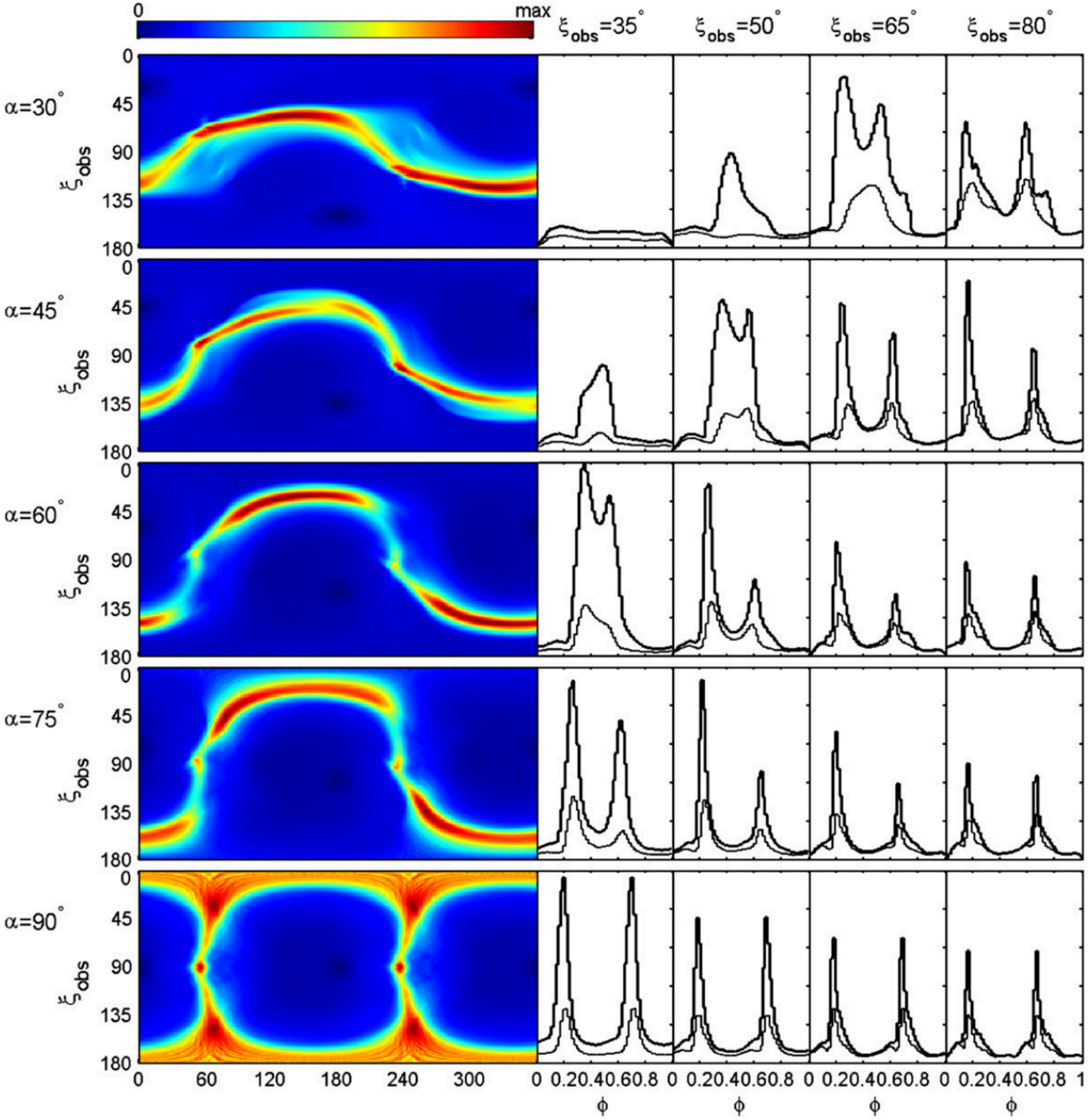
Origin of radiation

Force-free magnetosphere

Bai & Spitkovsky 2010

Radiation
from (force-free) current sheet

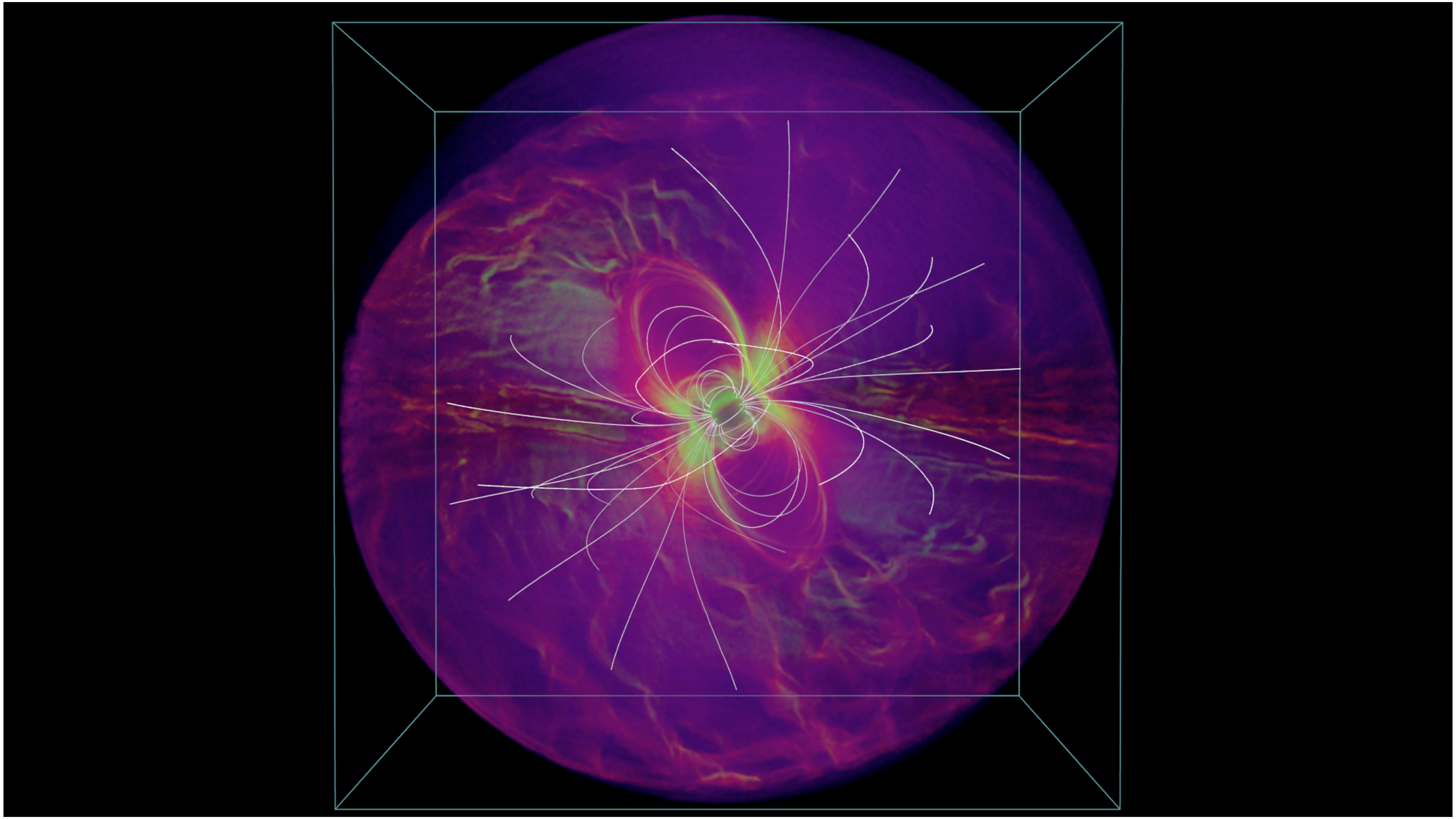




Origin of radiation

PIC magnetosphere

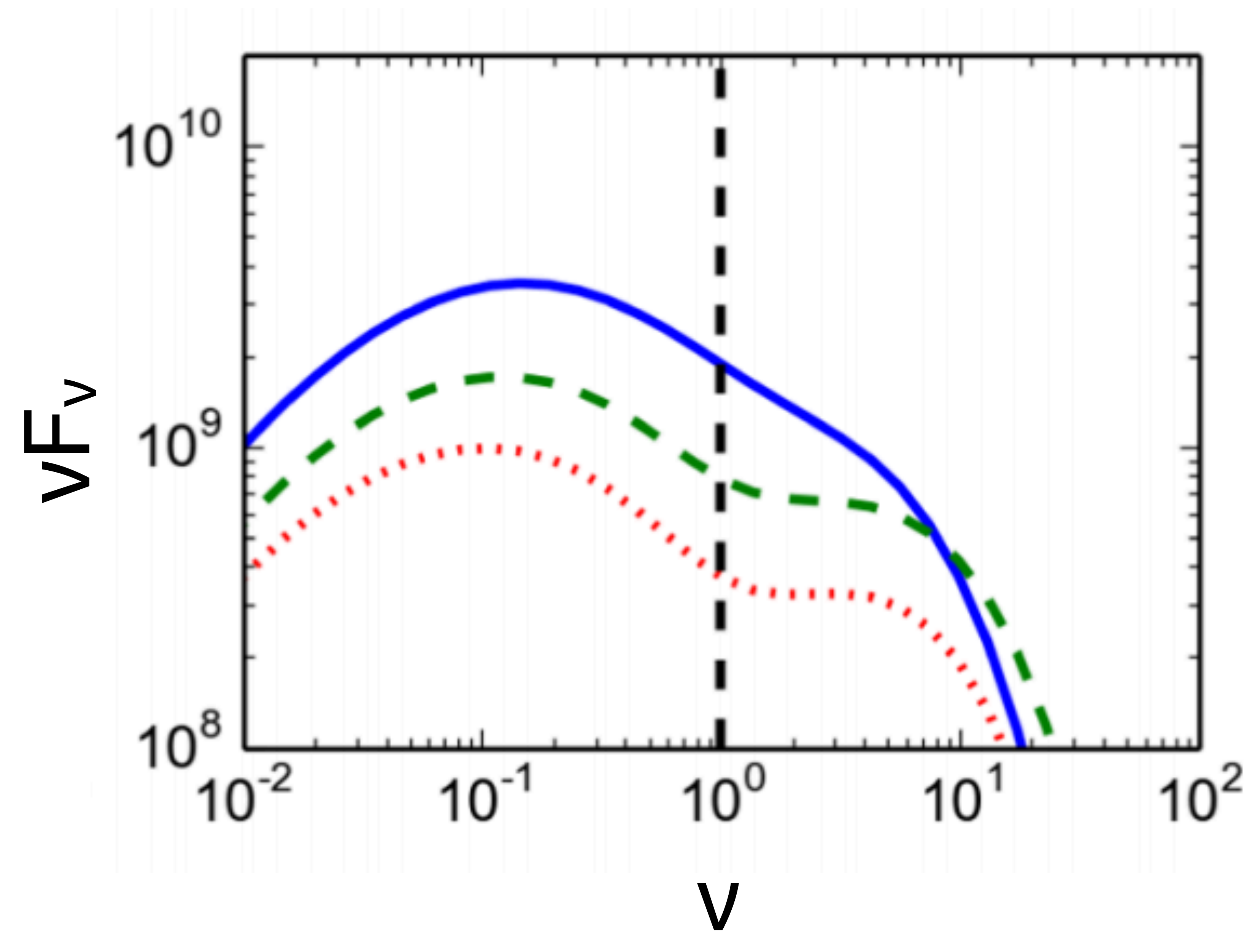
Philippov & Spitkovsky 2014-2018

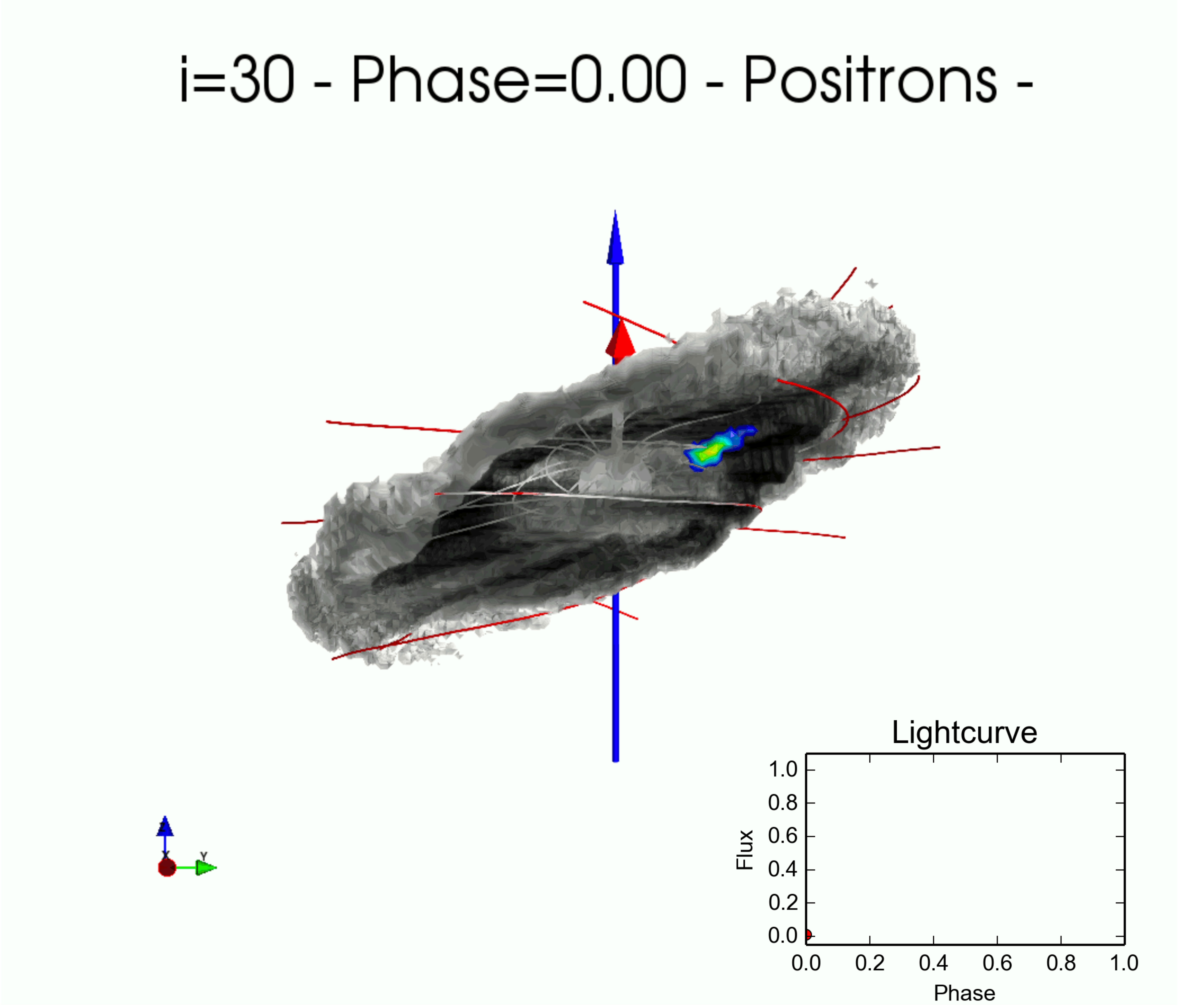


Origin of radiation

PIC magnetosphere

Philippov & Spitkovsky 2014-2018
Cerutti+ 2016





Origin of radiation

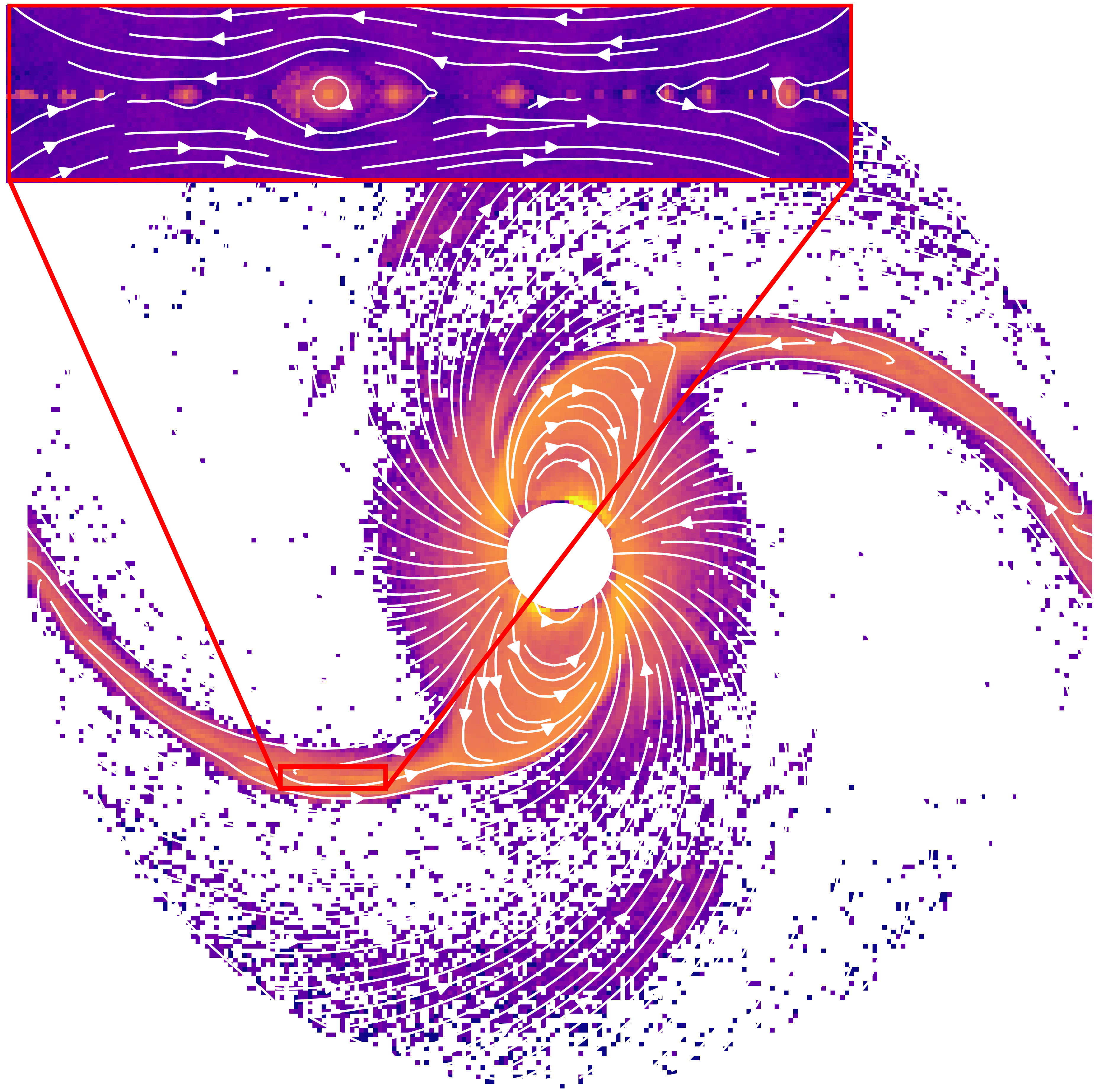
PIC magnetosphere

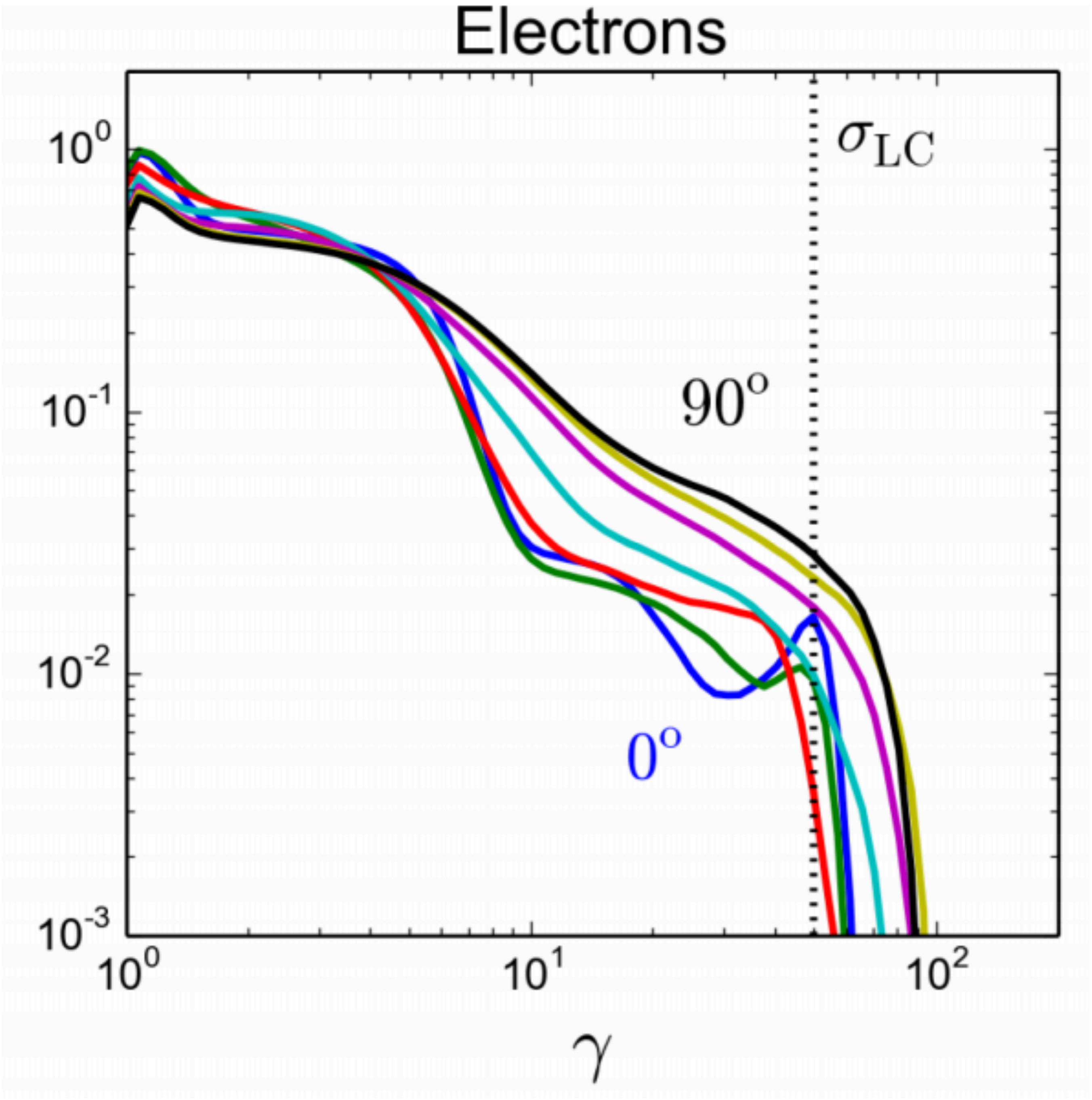
Philippov & Spitkovsky 2014-2018
Cerutti+ 2016

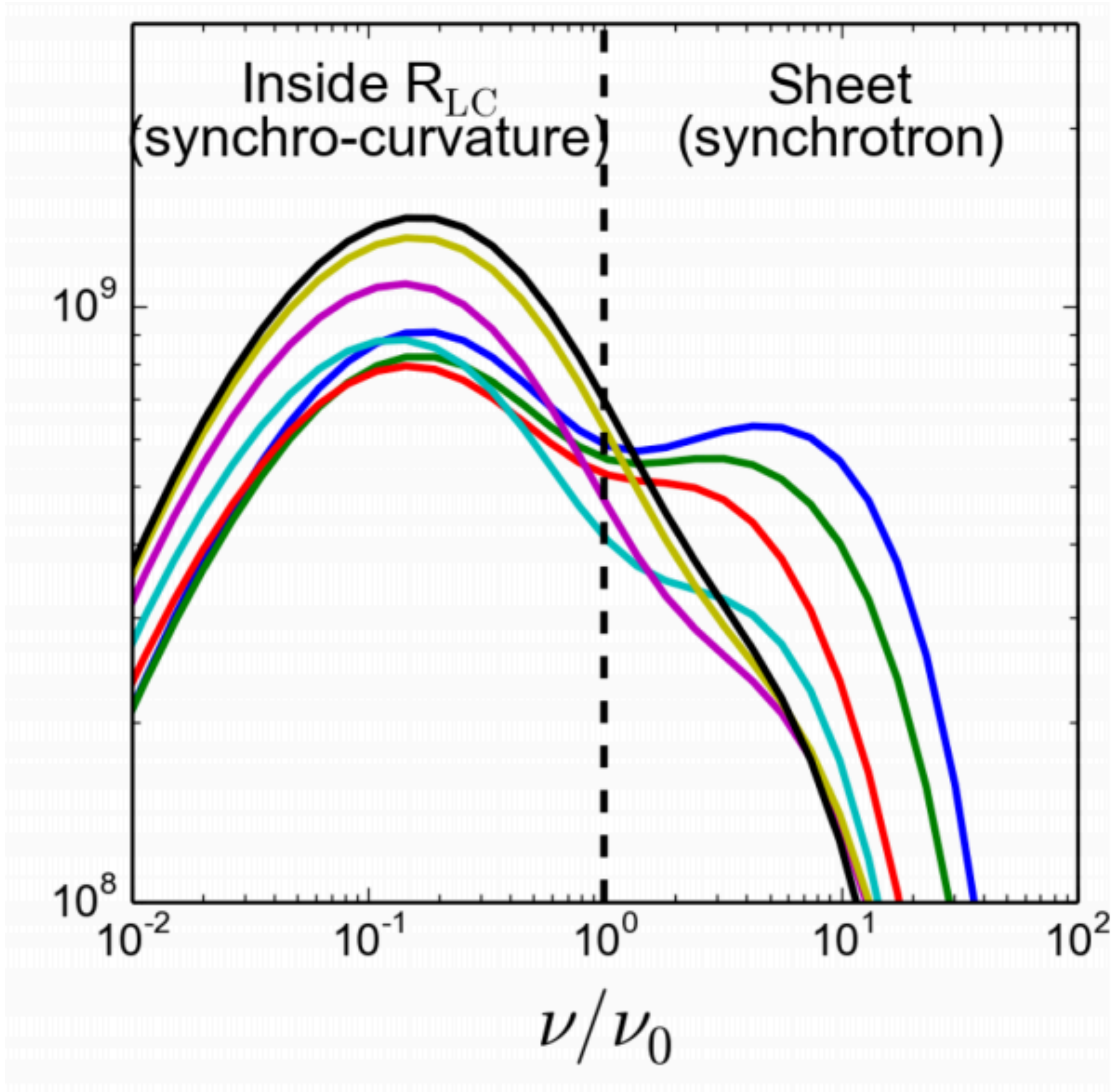
Synchrotron emission from particles accelerated in the reconnecting current sheet!

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

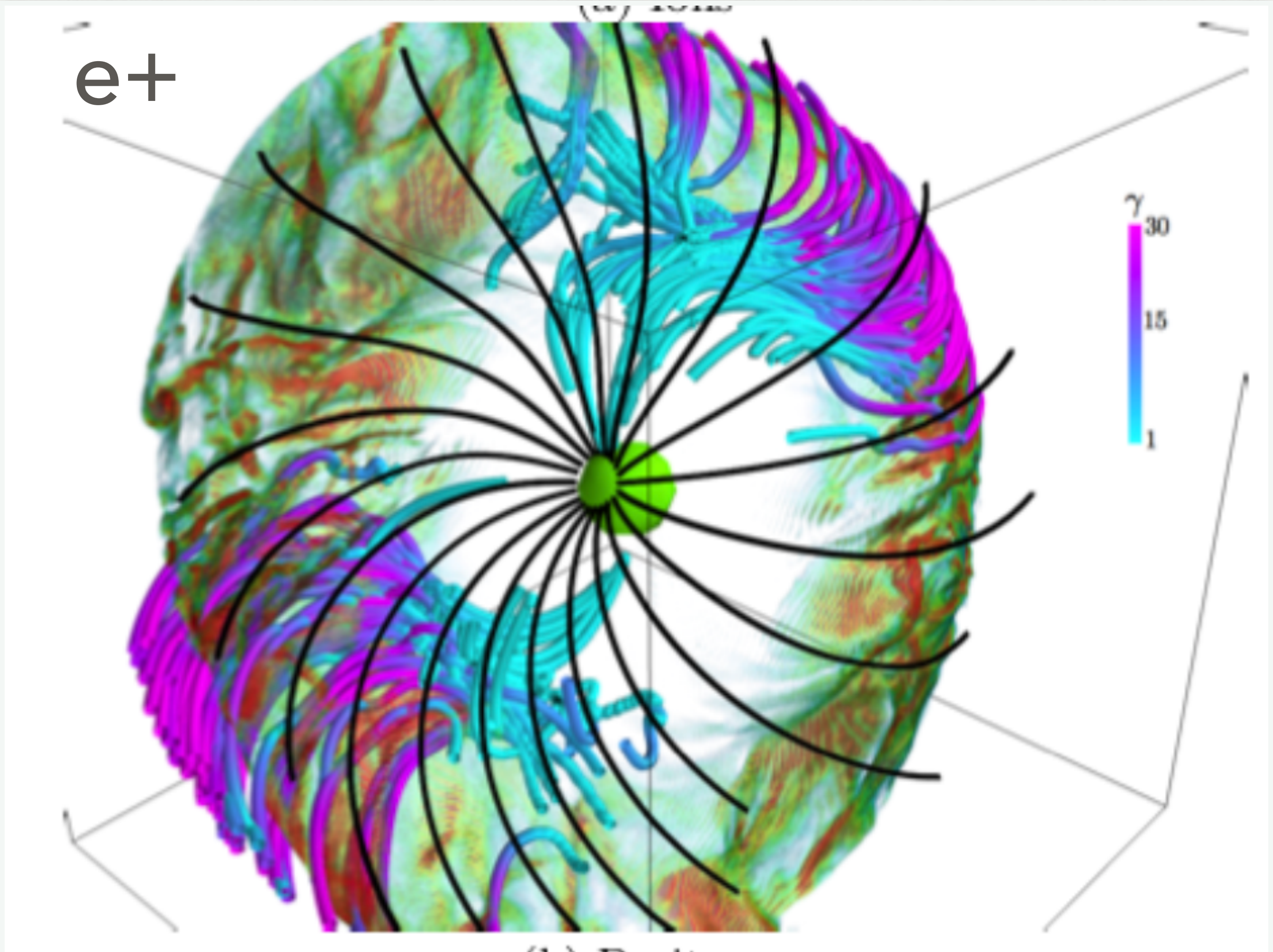
$$\gamma_{\max} \sim \text{few } \sigma$$



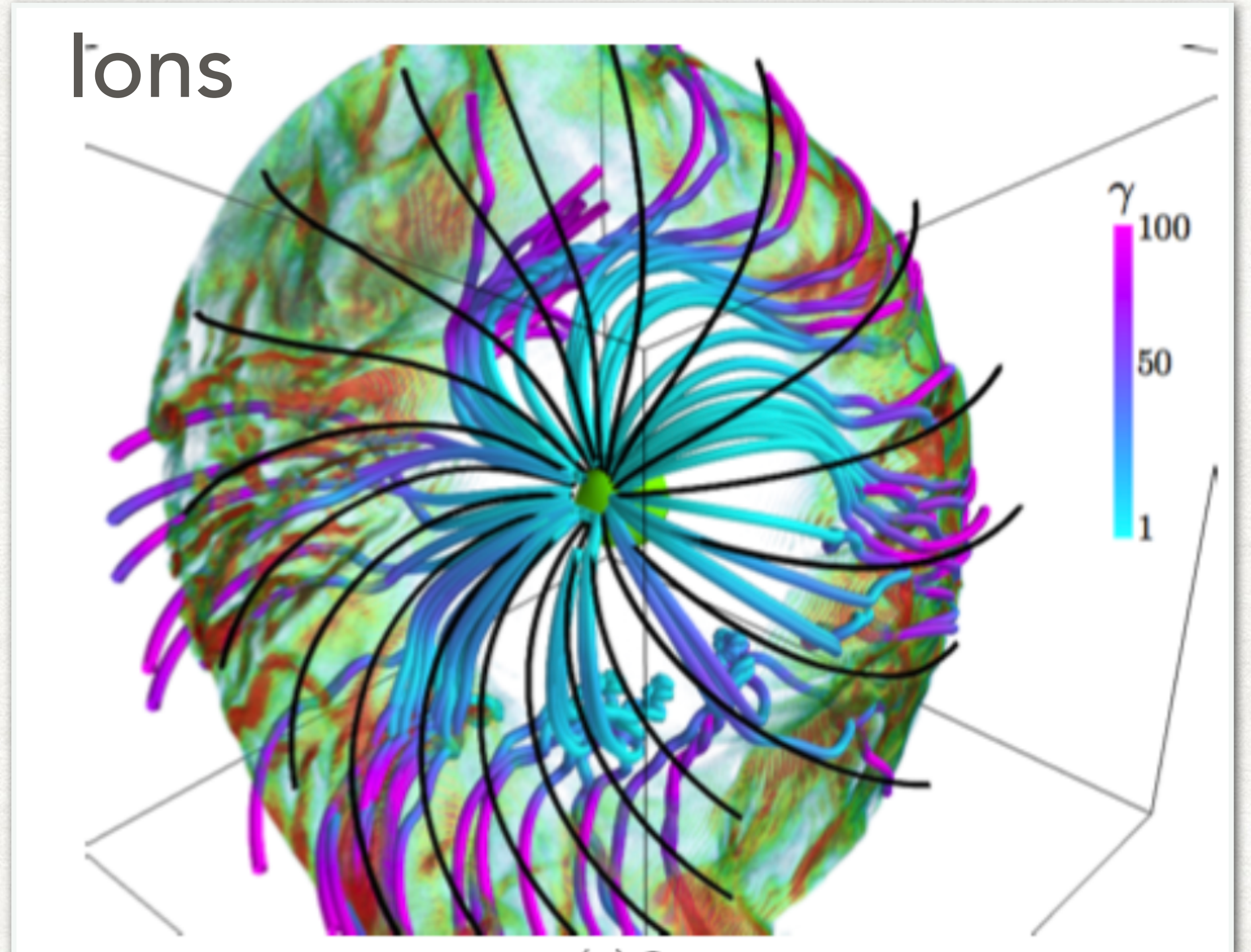




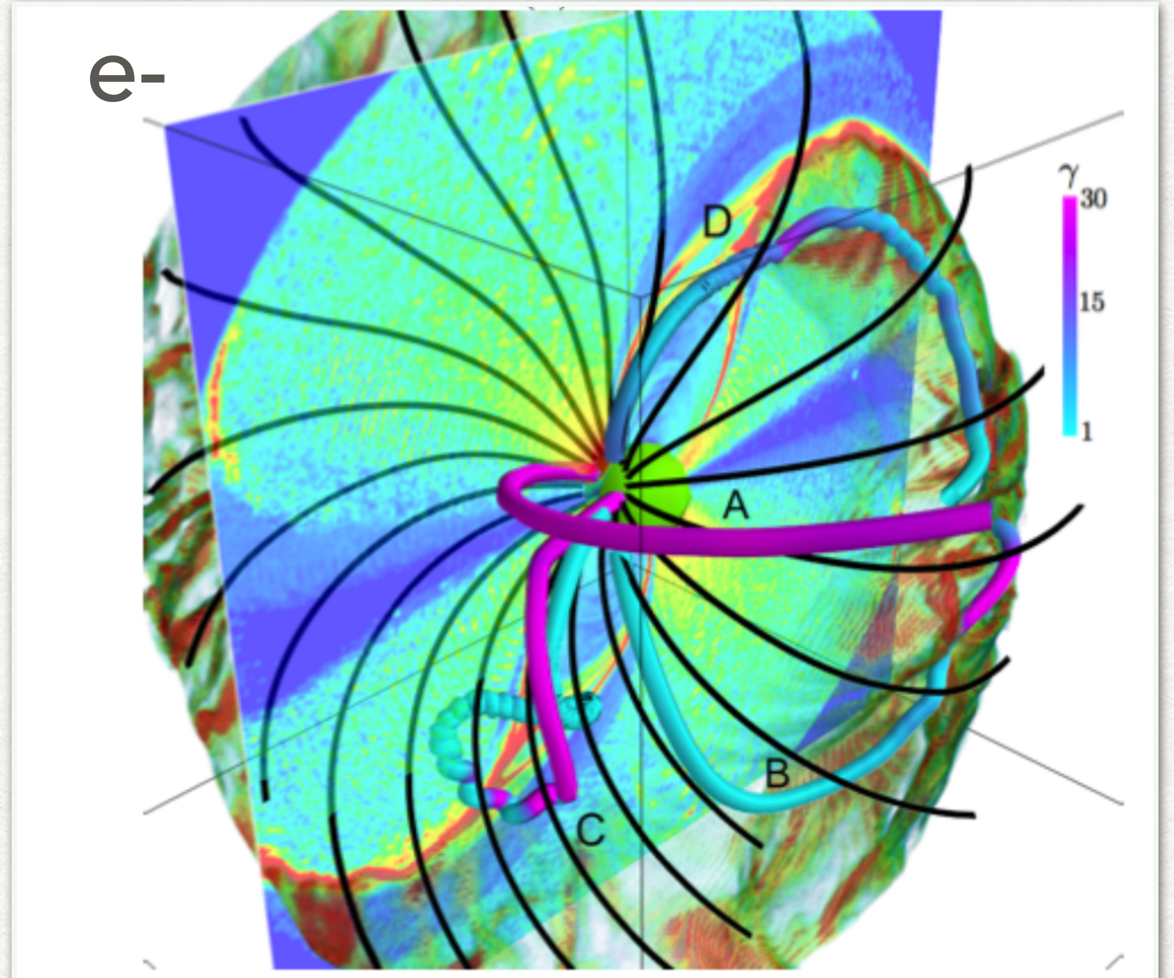
PARTICLE ACCELERATION AND SPECTRA



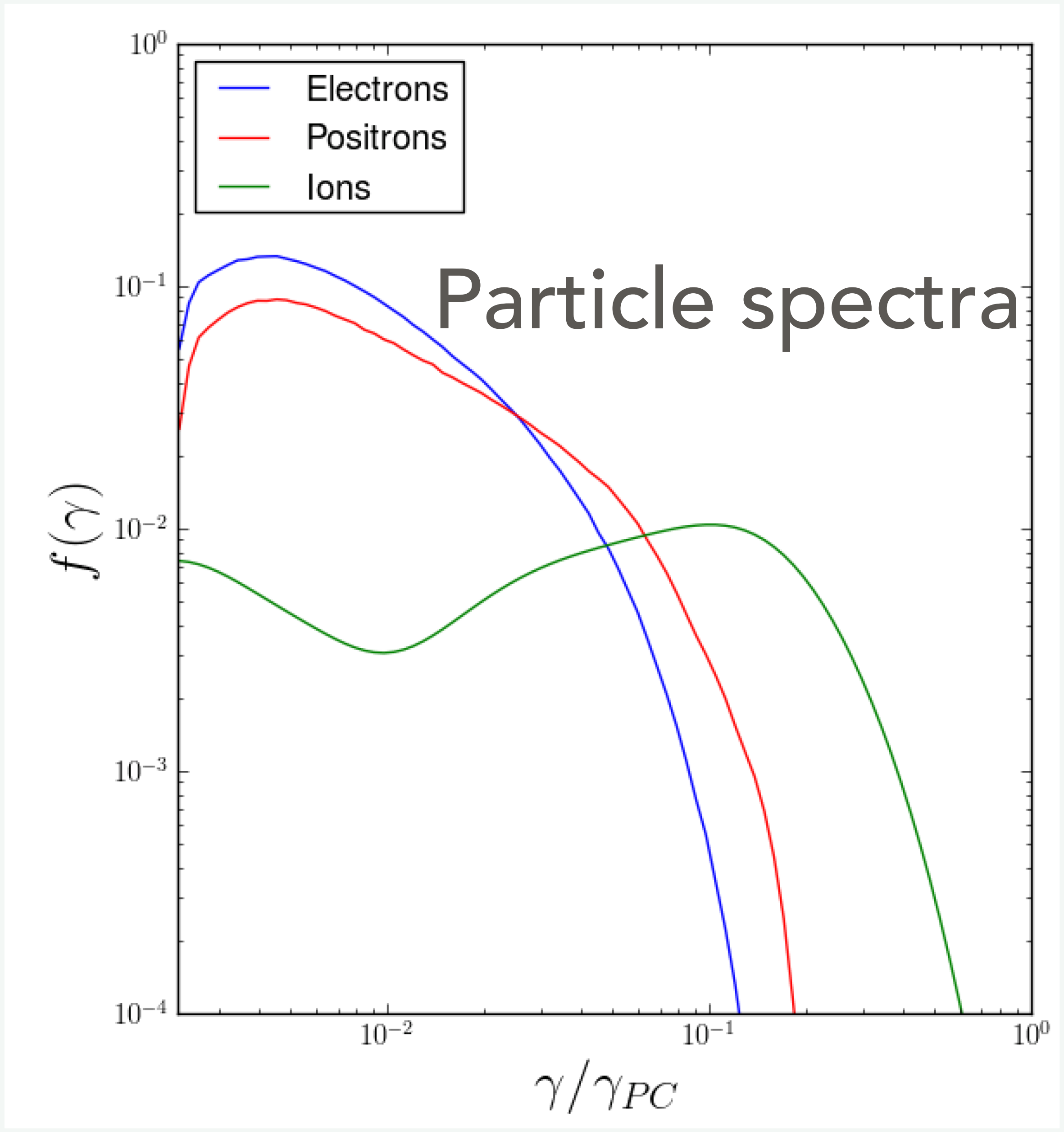
(b) Positrons

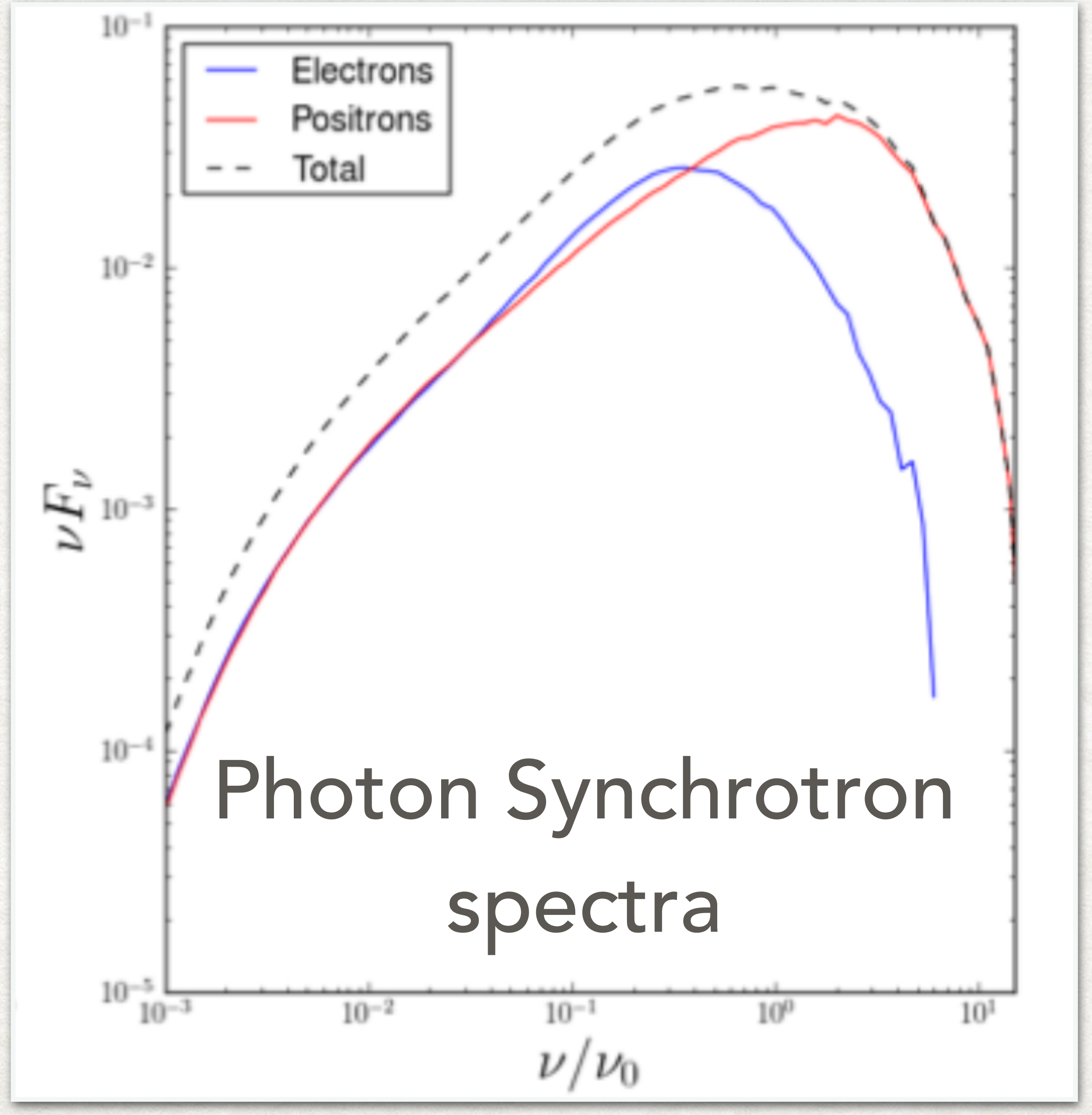


(a) Ions



(c) Electrons





Particles are accelerated in the current sheet during reconnection.

Radiation appears as broad spectral peak.

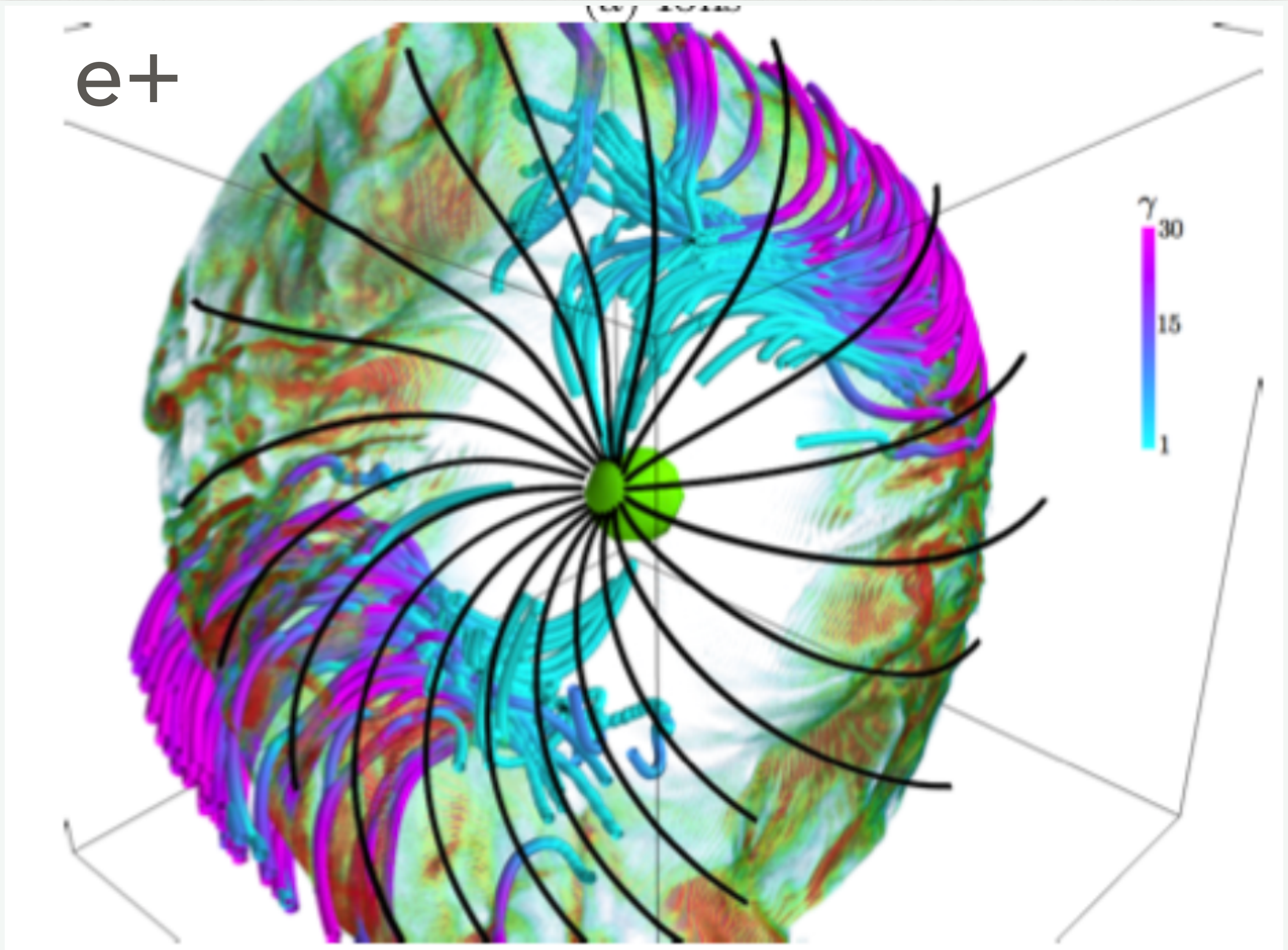
The max frequency is set by magnetization σ_{LC}:

$$\nu_{\max} \approx 3e\,(0.1B_{\rm LC})\,\sigma_{\rm LC}^2/4\pi m_e c$$

Pair production in sheet sets the sigma parameter. Ions gain good fraction of Φ_{pc}

Philippov & AS., 2018

PARTICLE ACCELERATION AND SPECTRA



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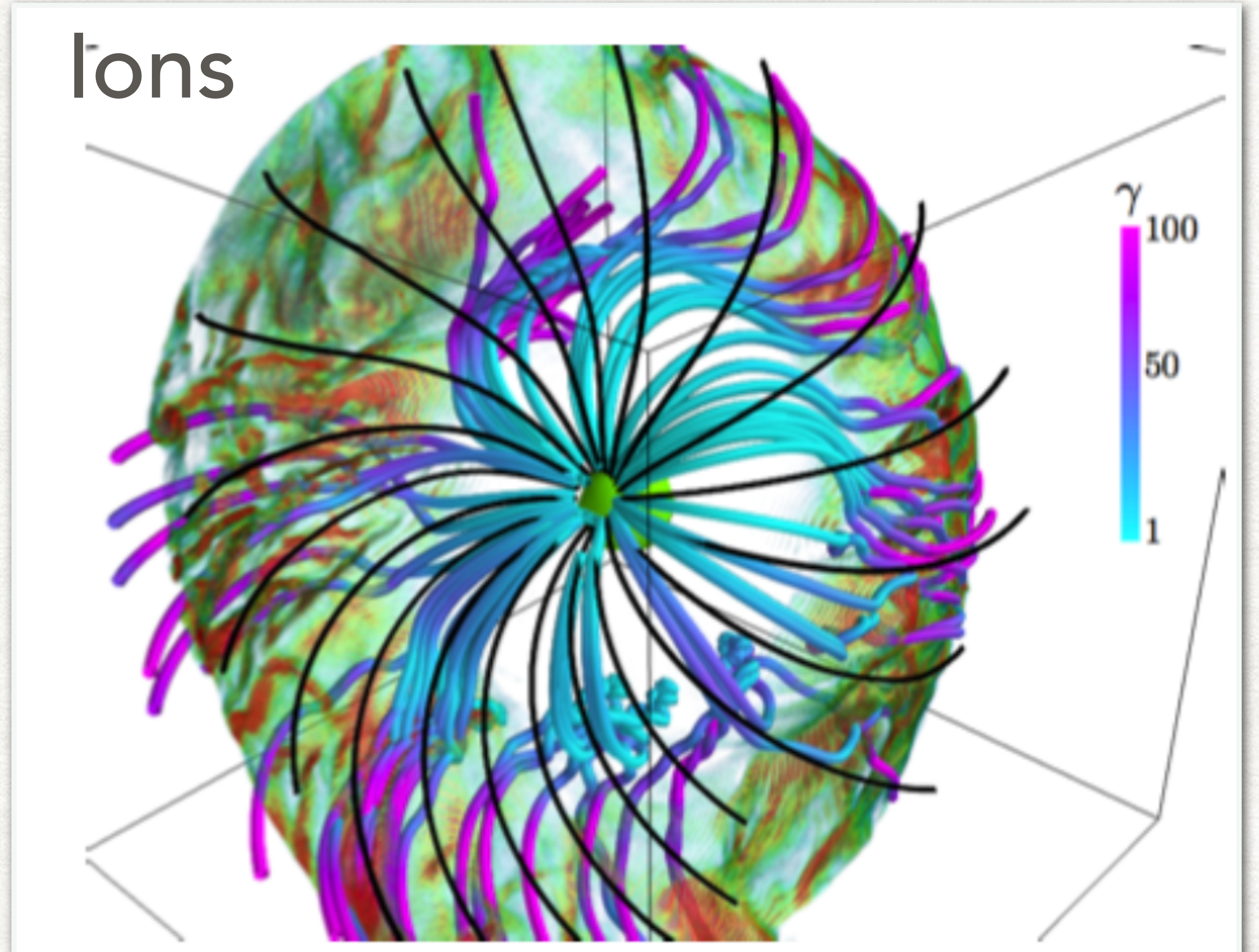

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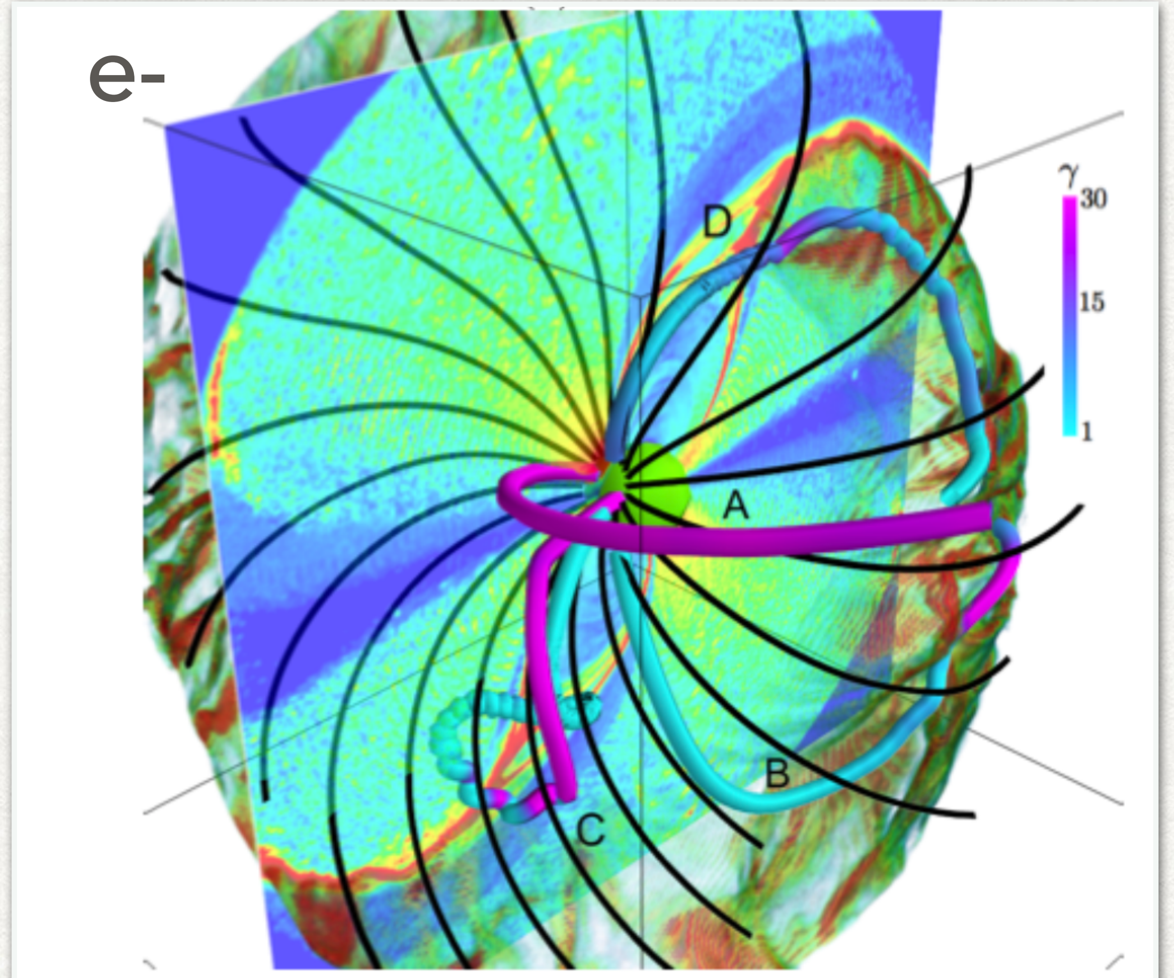
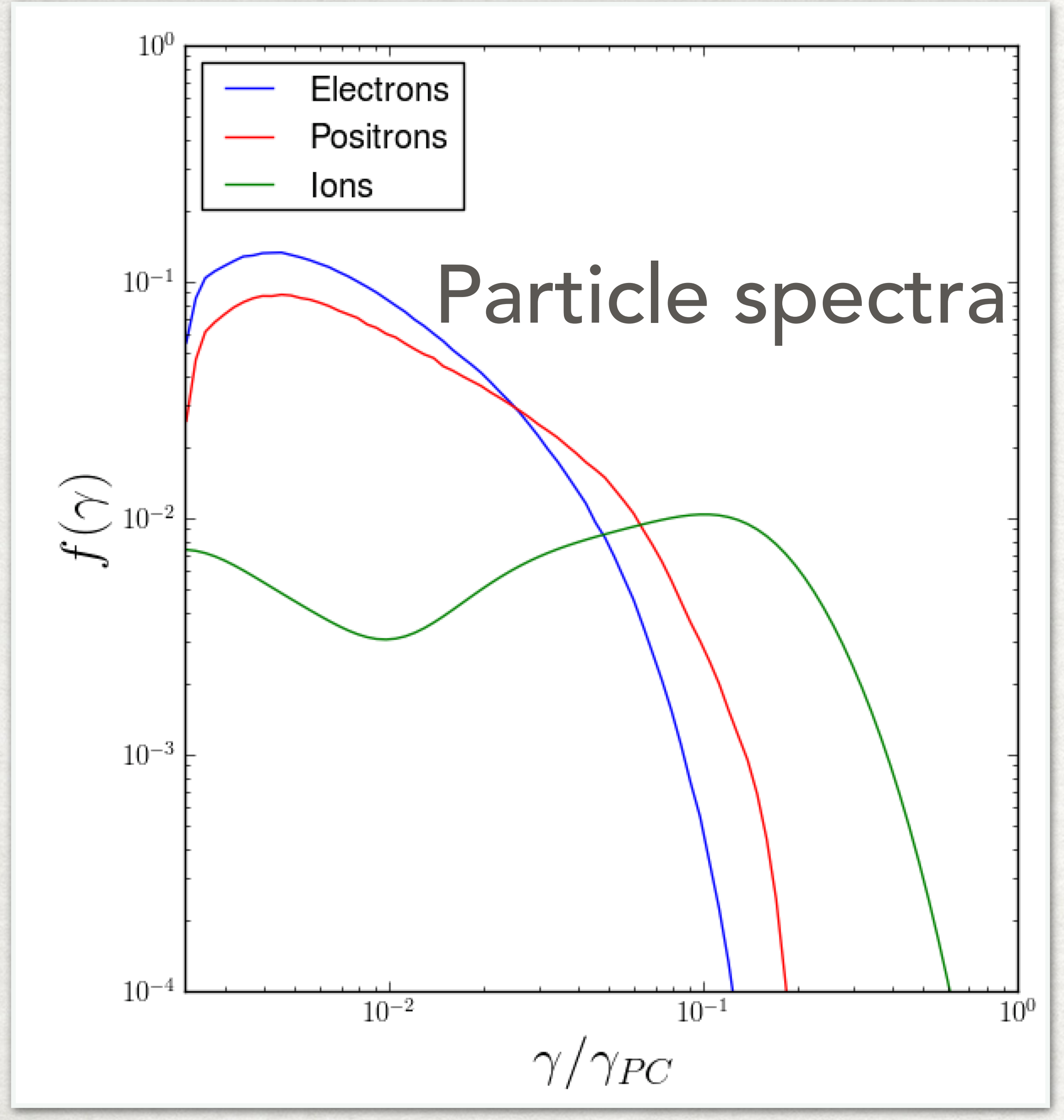
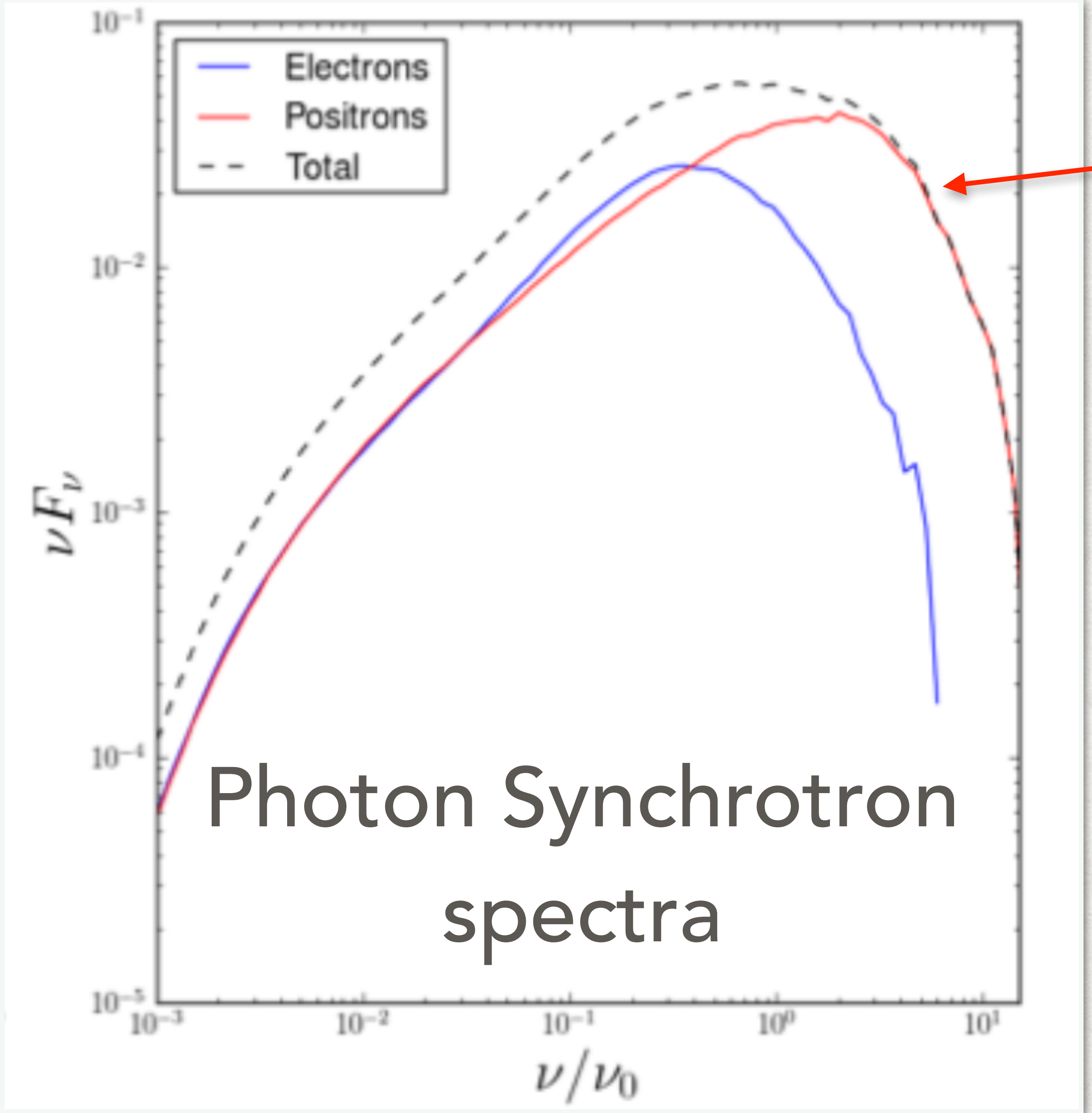
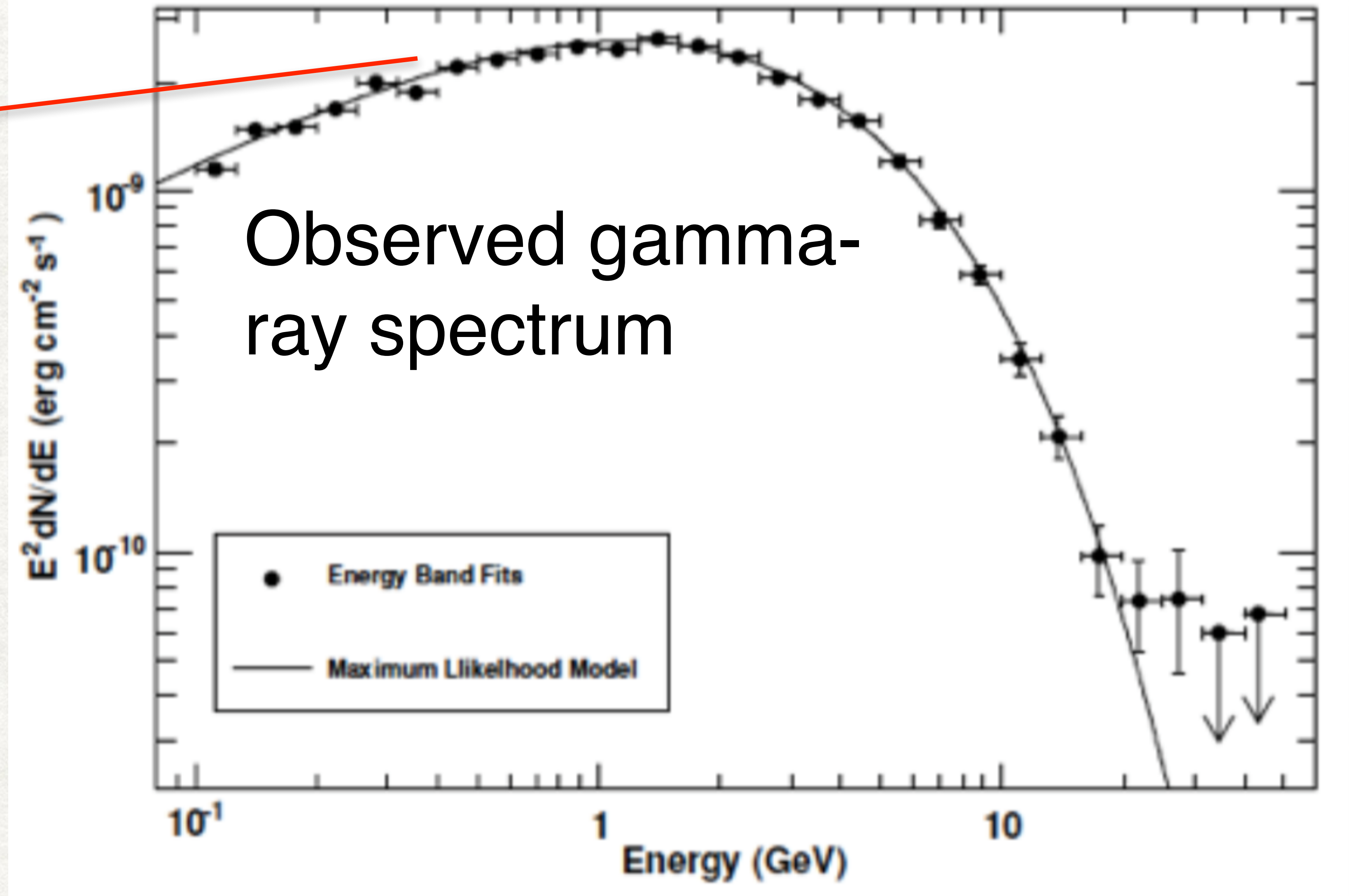


(c) Electrons







$m_e c$

Pair production at LC sets the peak emission frequency

Philippov et al., ApJ, 2016

ɣ-ray emission from pulsars

$$\gamma_{\max} \propto \sigma_{\mathrm{LC}} \propto B_{\mathrm{LC}}^2/n_{\mathrm{LC}} \propto B_{\mathrm{LC}}$$

*because of the reconnection

$$E_{\mathrm{cut}} \propto B_{\mathrm{LC}}\gamma_{\max}^2 \propto B_{\mathrm{LC}}^3$$

*because it's a synchrotron emission

$$L_\gamma \propto \dot{E}$$

ɣ-ray emission from pulsars

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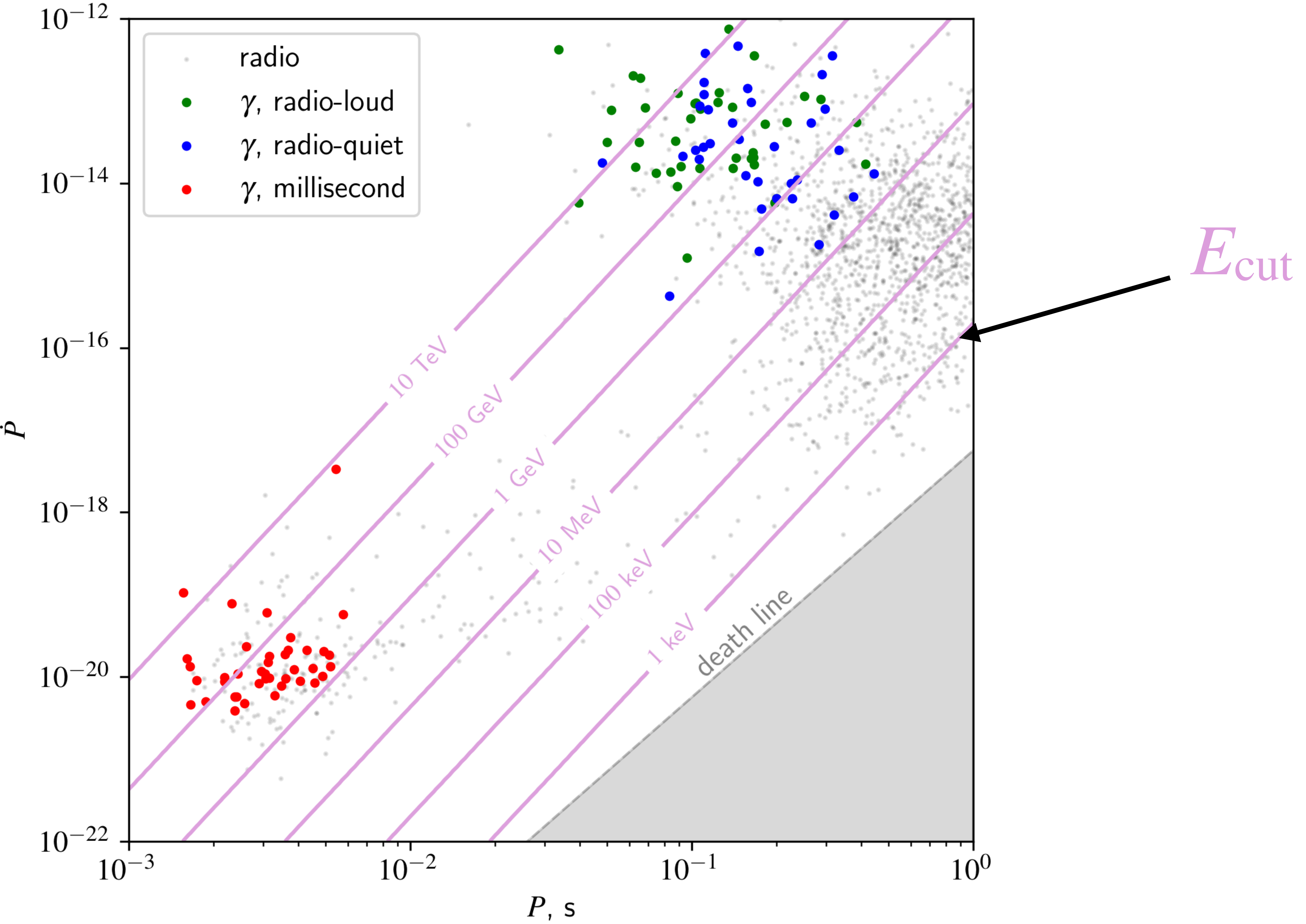

Abdo+ 2013

γ-ray emission from pulsars

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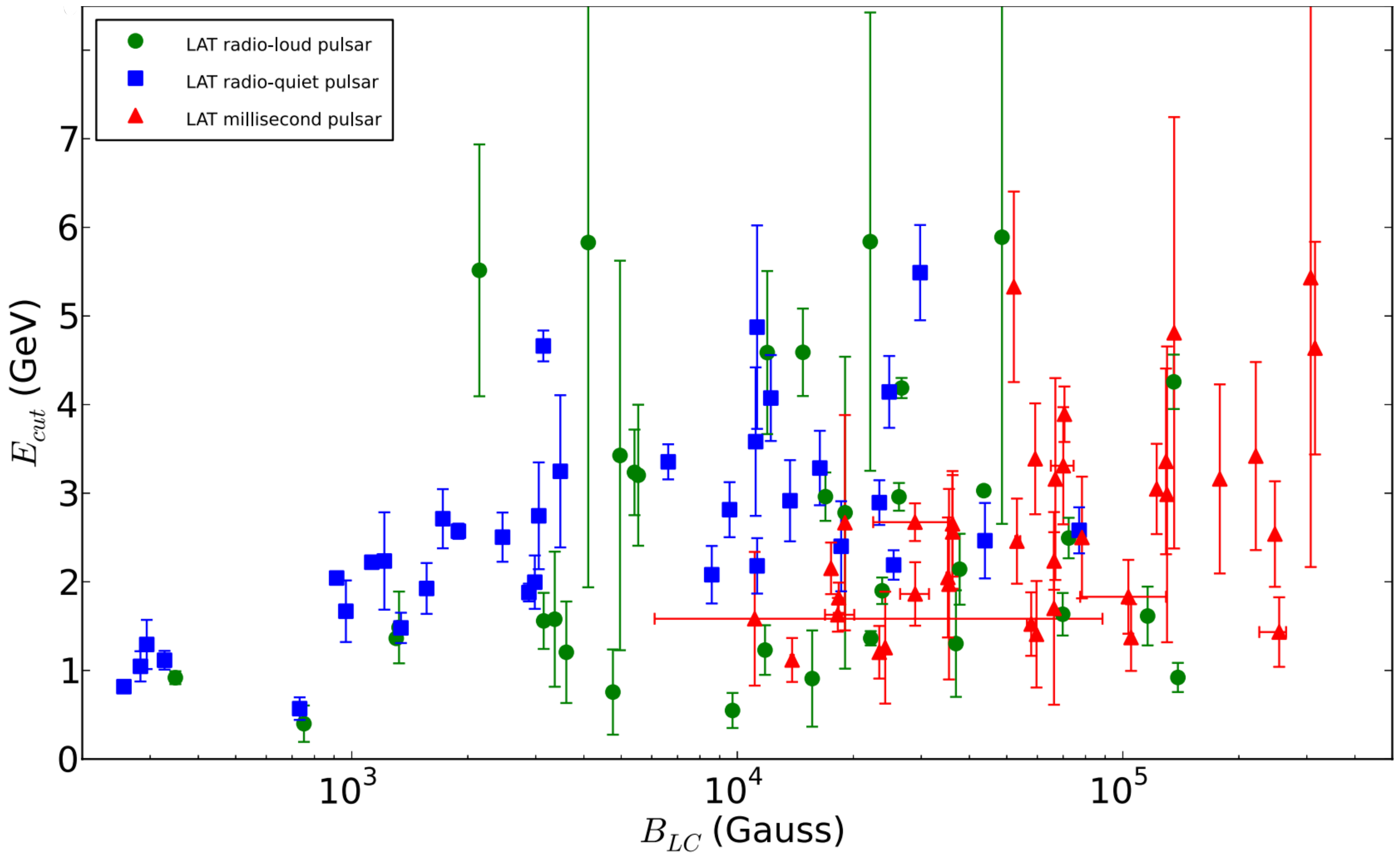

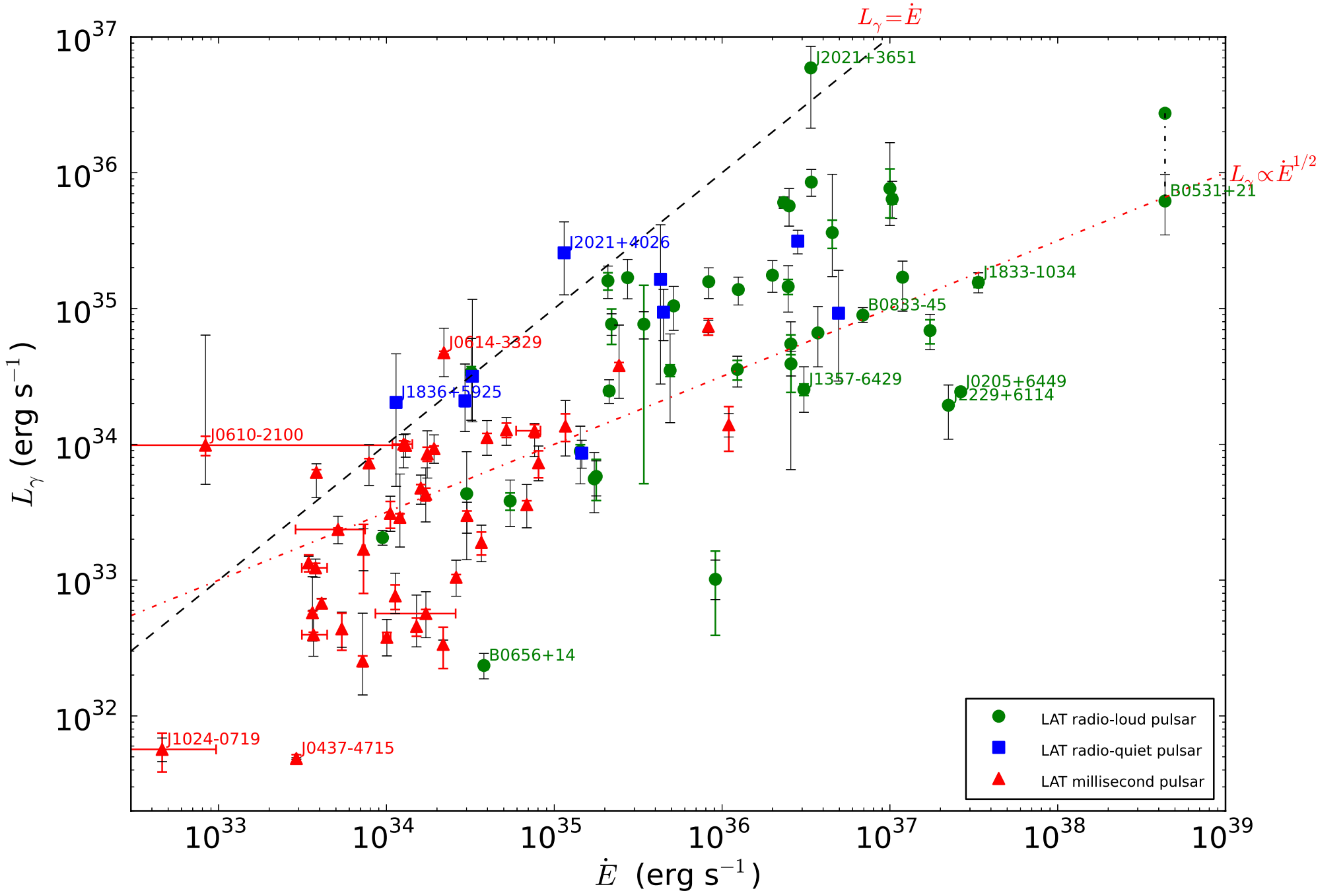

Abdo+ 2013

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$$\gamma_{\max} \propto \sigma_{\rm LC} \propto B_{\rm LC}^2/n_{\rm LC} \propto B_{\rm LC}$$

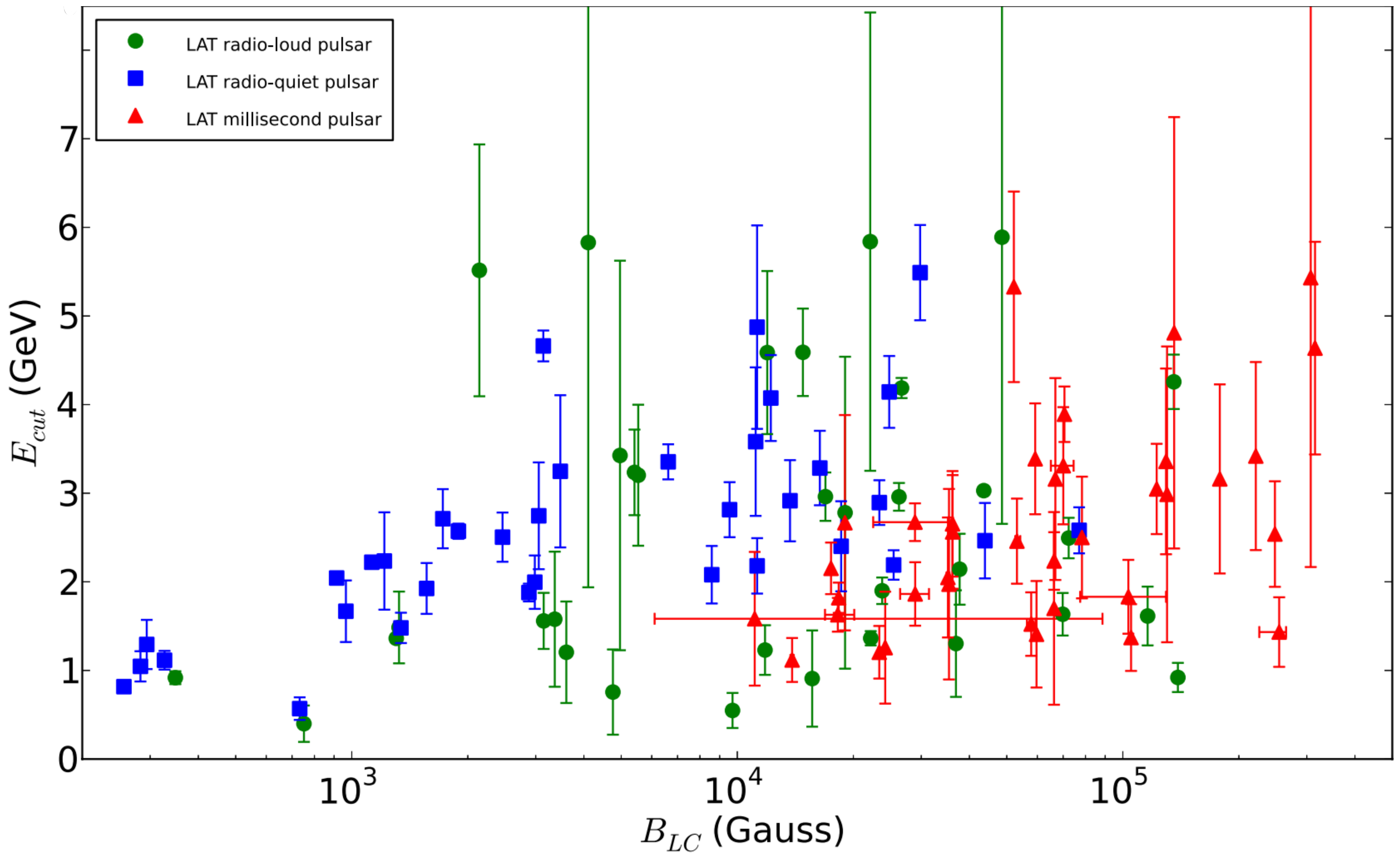
*because of the reconnection

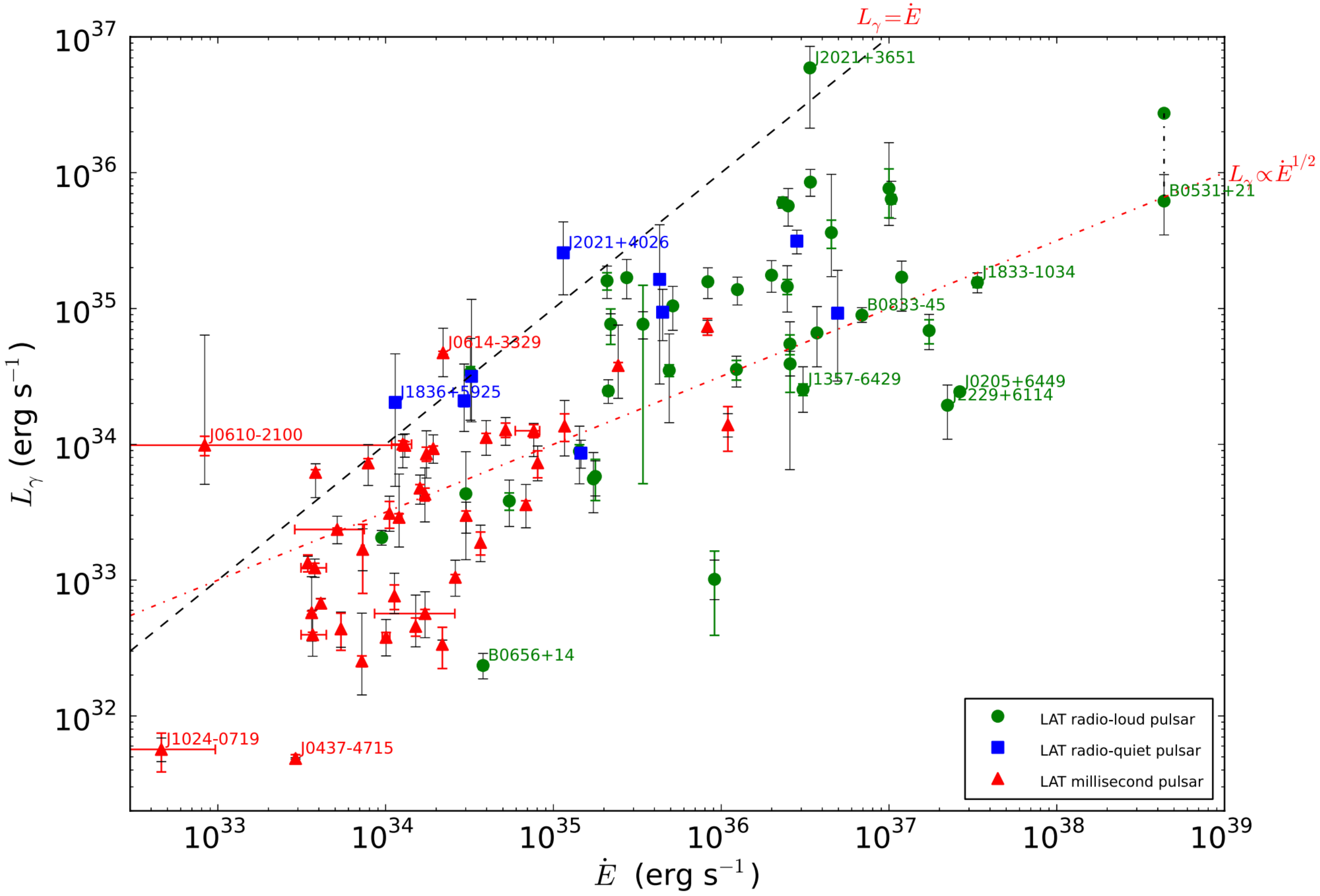
$$L_\gamma \propto \dot{E}$$

additional pair loading?

$$E_{\rm cut} \propto B_{\rm LC}\gamma_{\max}^2 \propto B_{\rm LC}^3$$

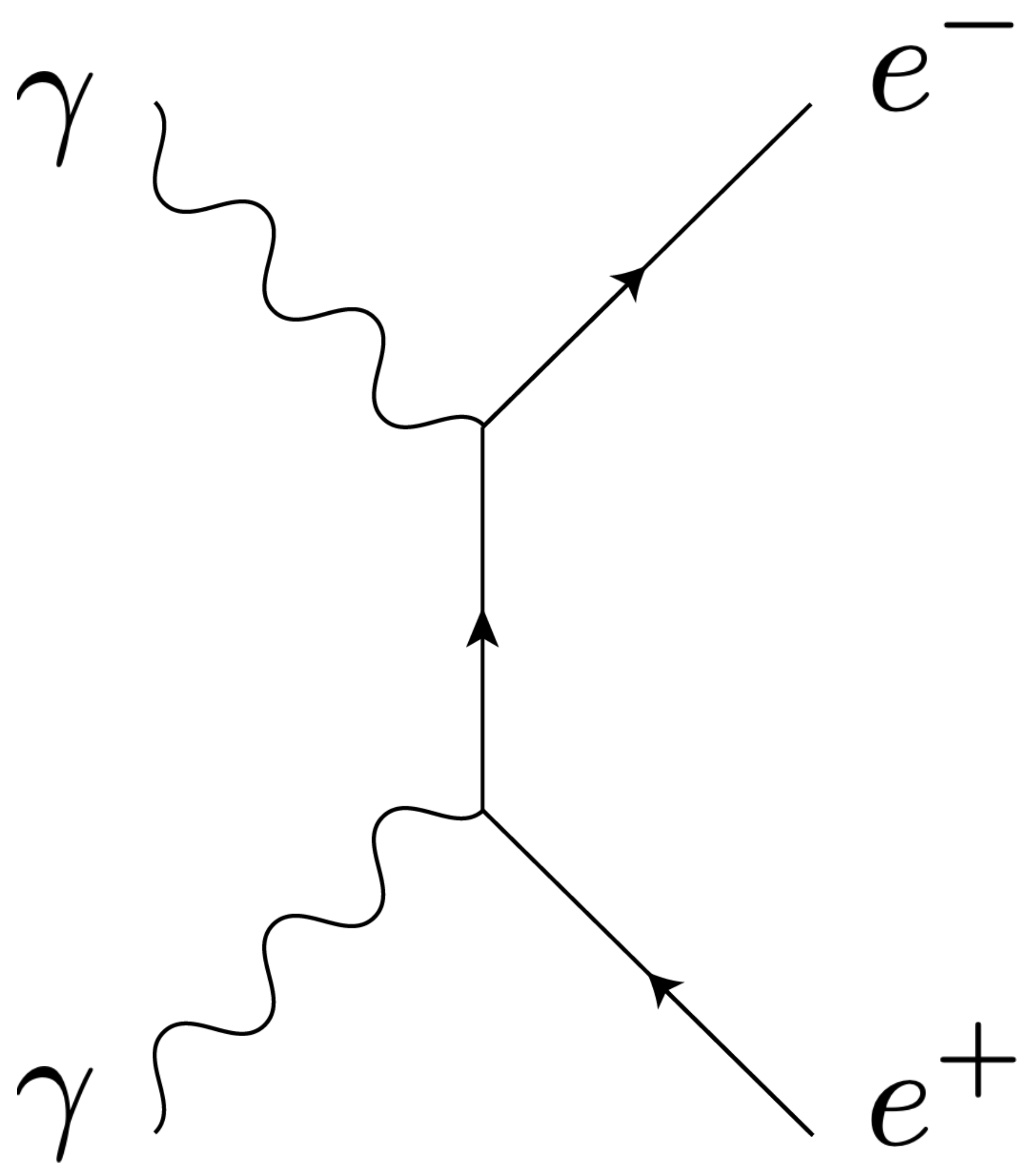
*because it's a synchrotron emission





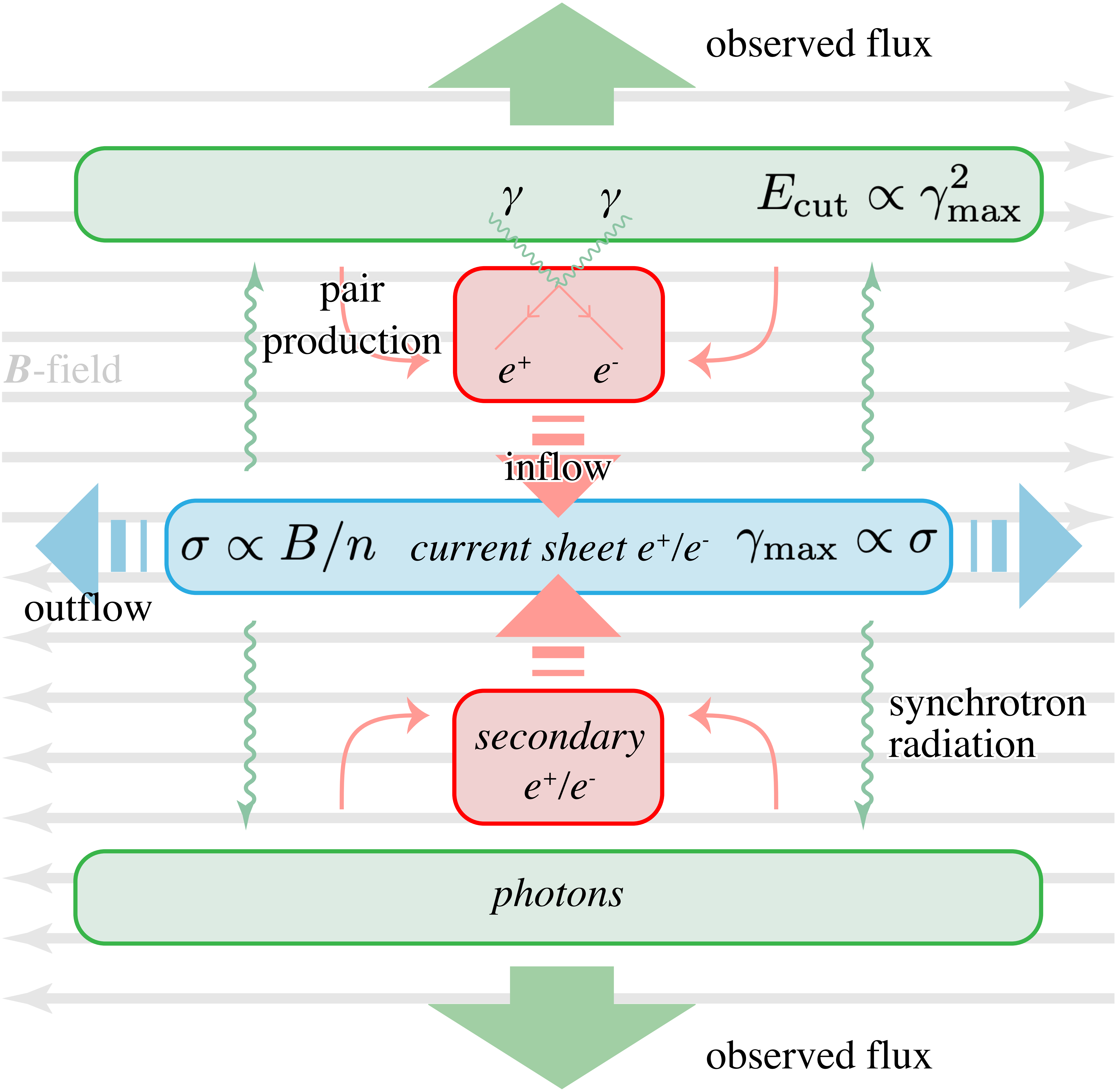
Abdo+ 2013

Pair production



Breit-Wheeler process

first proposed by ***Lyubarskii (1996)***!



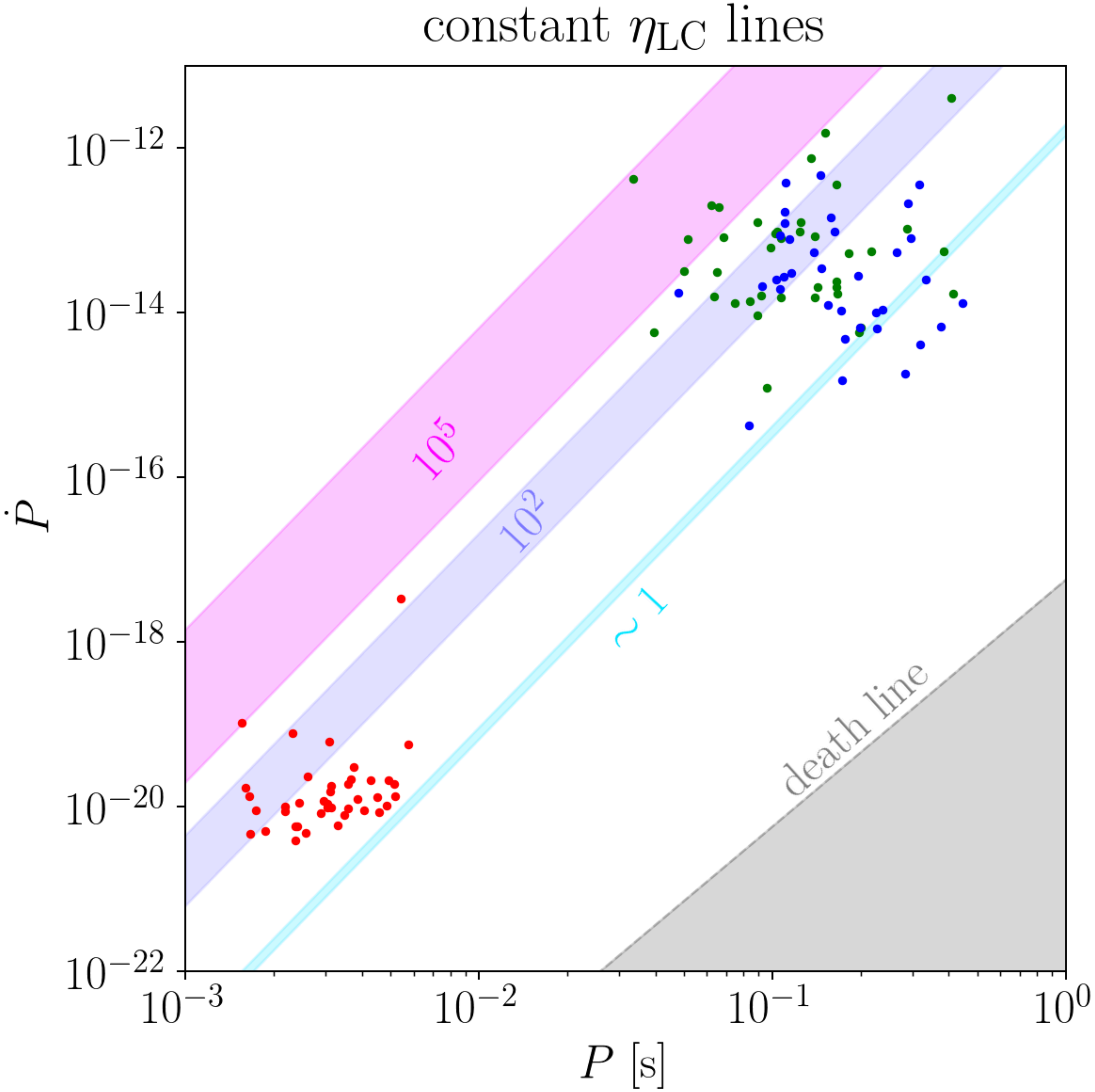
Pair production

- Simple 1D steady-state model
- Photon index *Γ~1.5-2.5*
- Radiation/pp region ~ *0.1* R_{LC}
- Inflow to LC with: $n \sim 10^4 n_{\rm GJ}$
- Pair-production feedback: $\sigma = \sigma_0/\eta_{\rm LC}$

$$\eta = \frac{n_{\rm sec}}{n_{\rm prim}}$$

multiplicity of secondary pairs

$$\eta_{\rm LC} \sim 2\times 10^4 \left(\frac{B_{\rm LC}}{10^5\ {\rm G}}\right)^3 \left(\frac{P}{100\ {\rm ms}}\right)^2$$

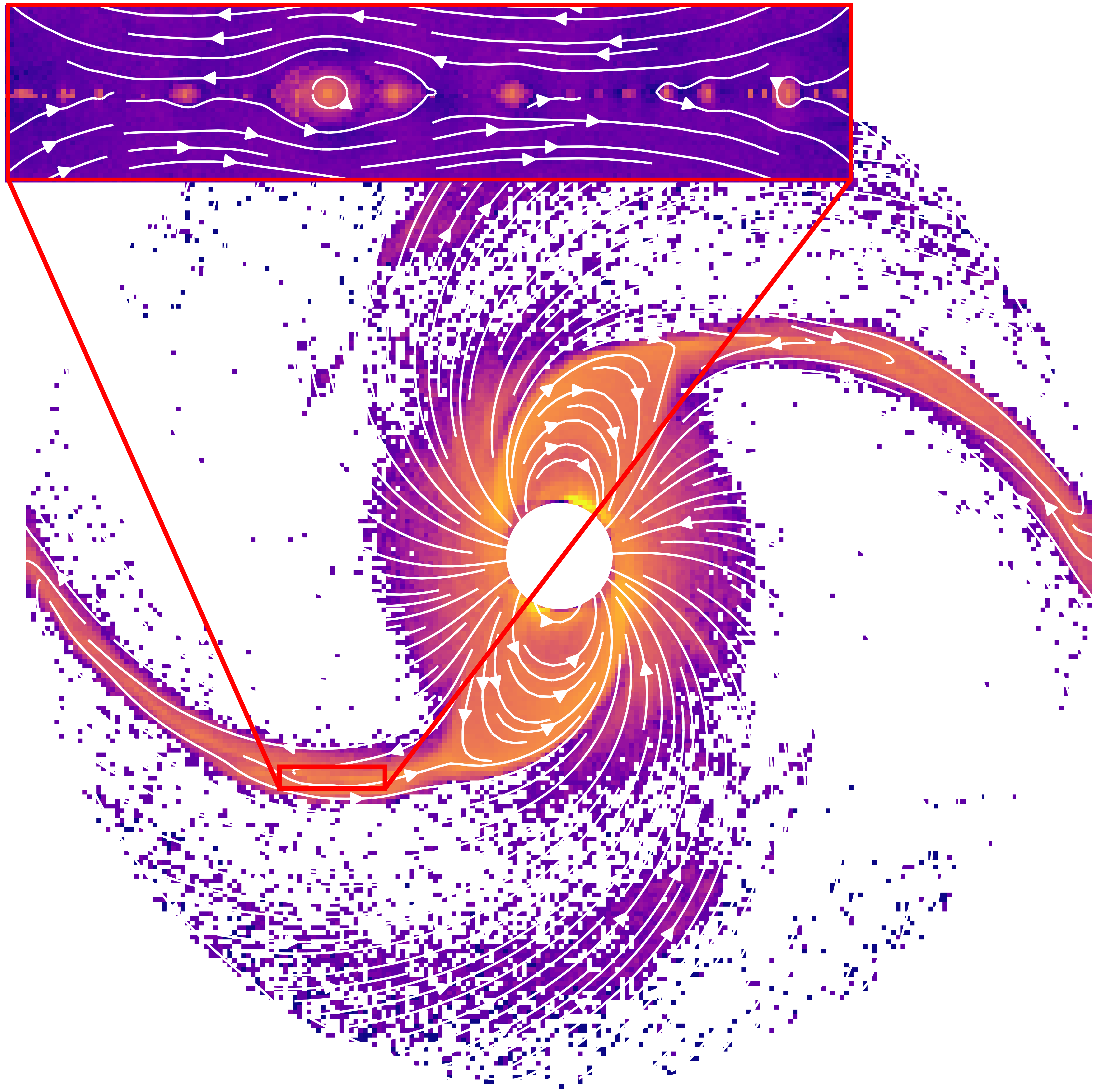


for details see *HH, Philippov, Spitkovsky (2019)*

Pair production

Can we simulate this?

- pair production is a binary process:
  - ✳ complexity $\sim N_{ph}^2$
- low optical thickness to pp:
  - ✳ to produce any reasonable amount of plasma $N_{ph} >> N_{part}$
- want to resolve reconnection in it’s full power:
  - ✳ need large aspect ratio of the current sheet
  - ✳ need ~100 ϱ_G in the box



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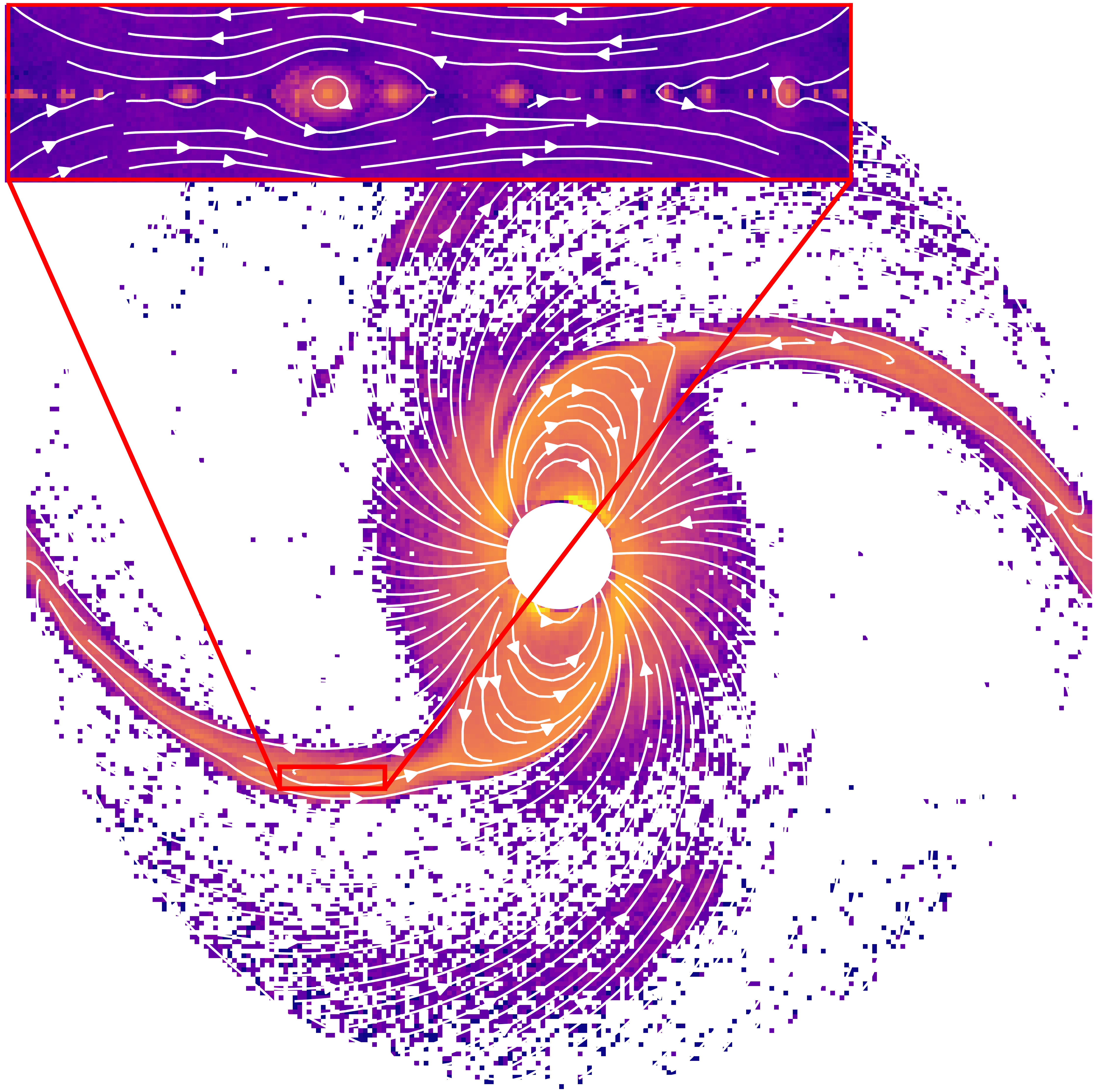
$\Downarrow$

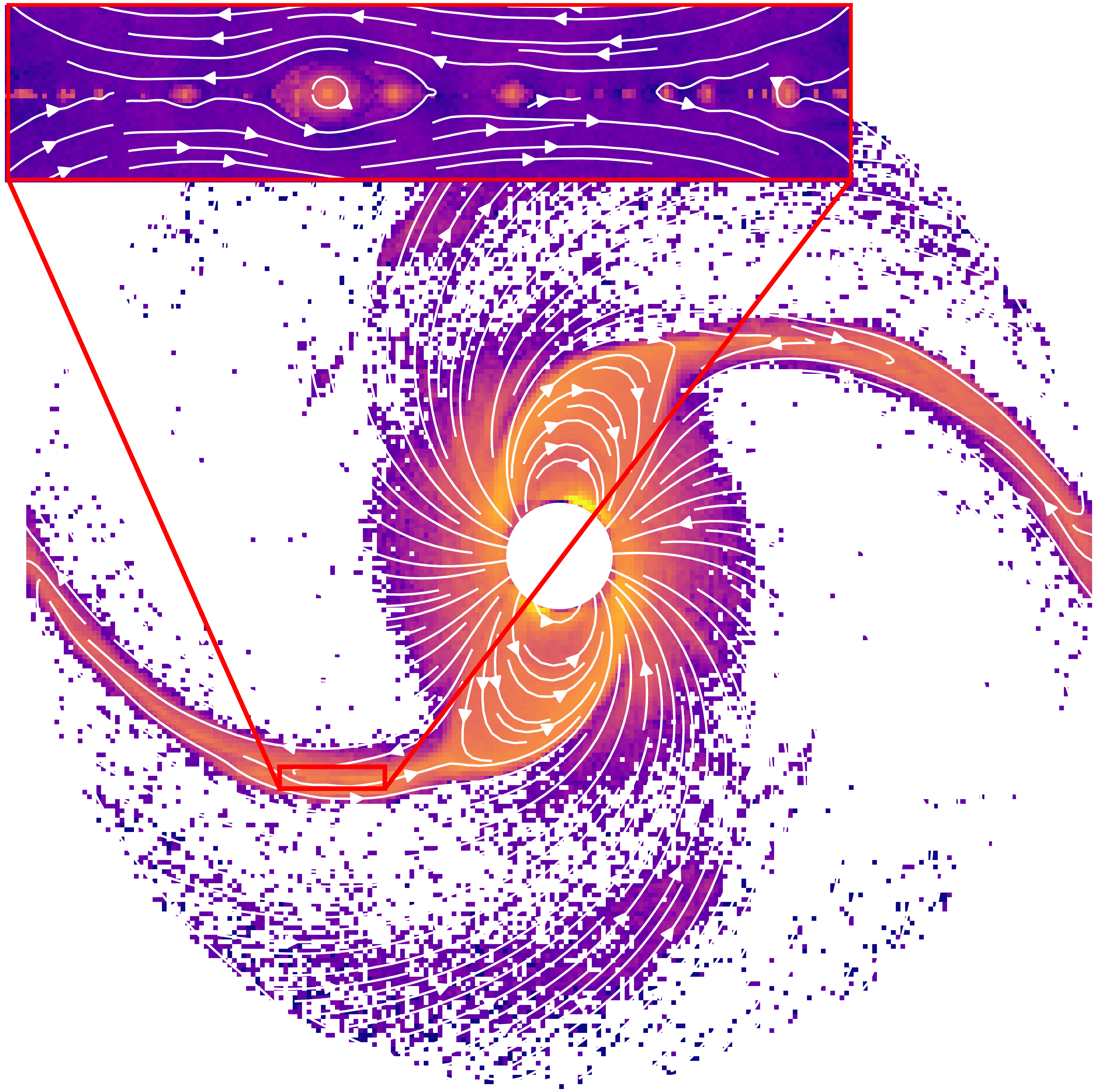
local 2D box



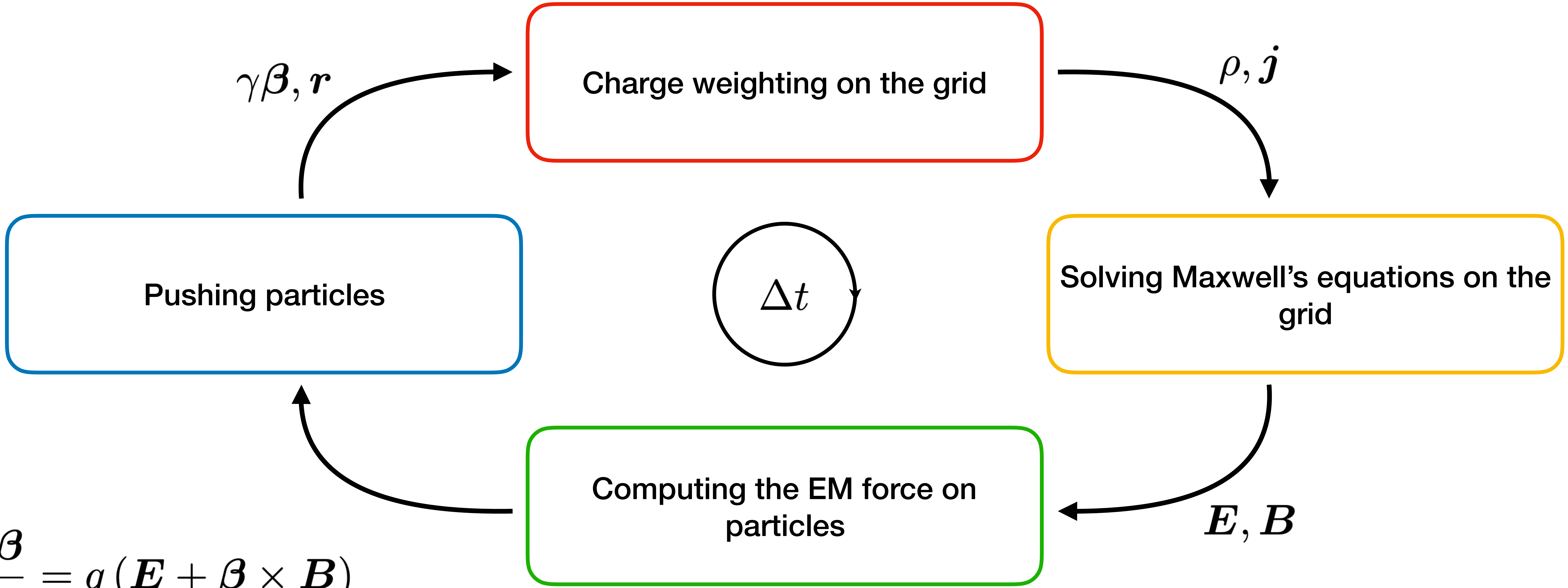
Pair production

What do we lose in 2D localized box?

- field geometry
- background outflow
- have to assume the inflow rate from inner magnetosphere
- large scale behavior

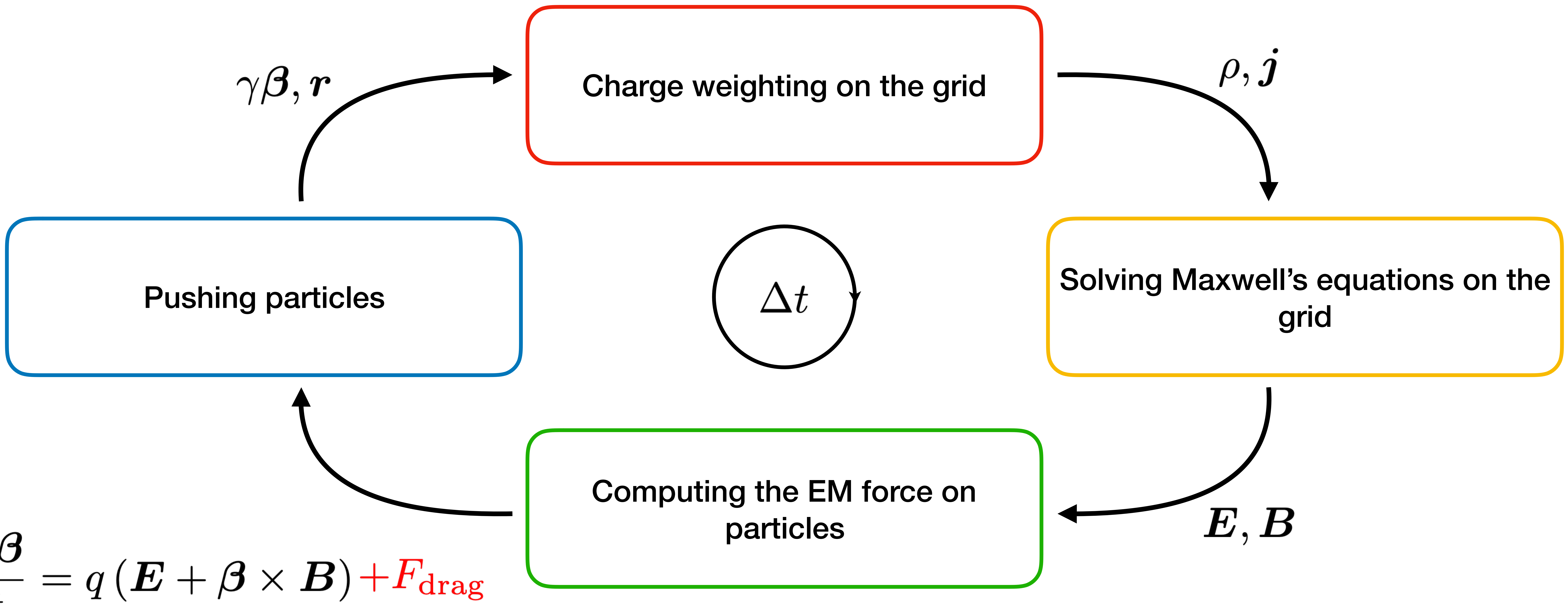


PIC algorithm



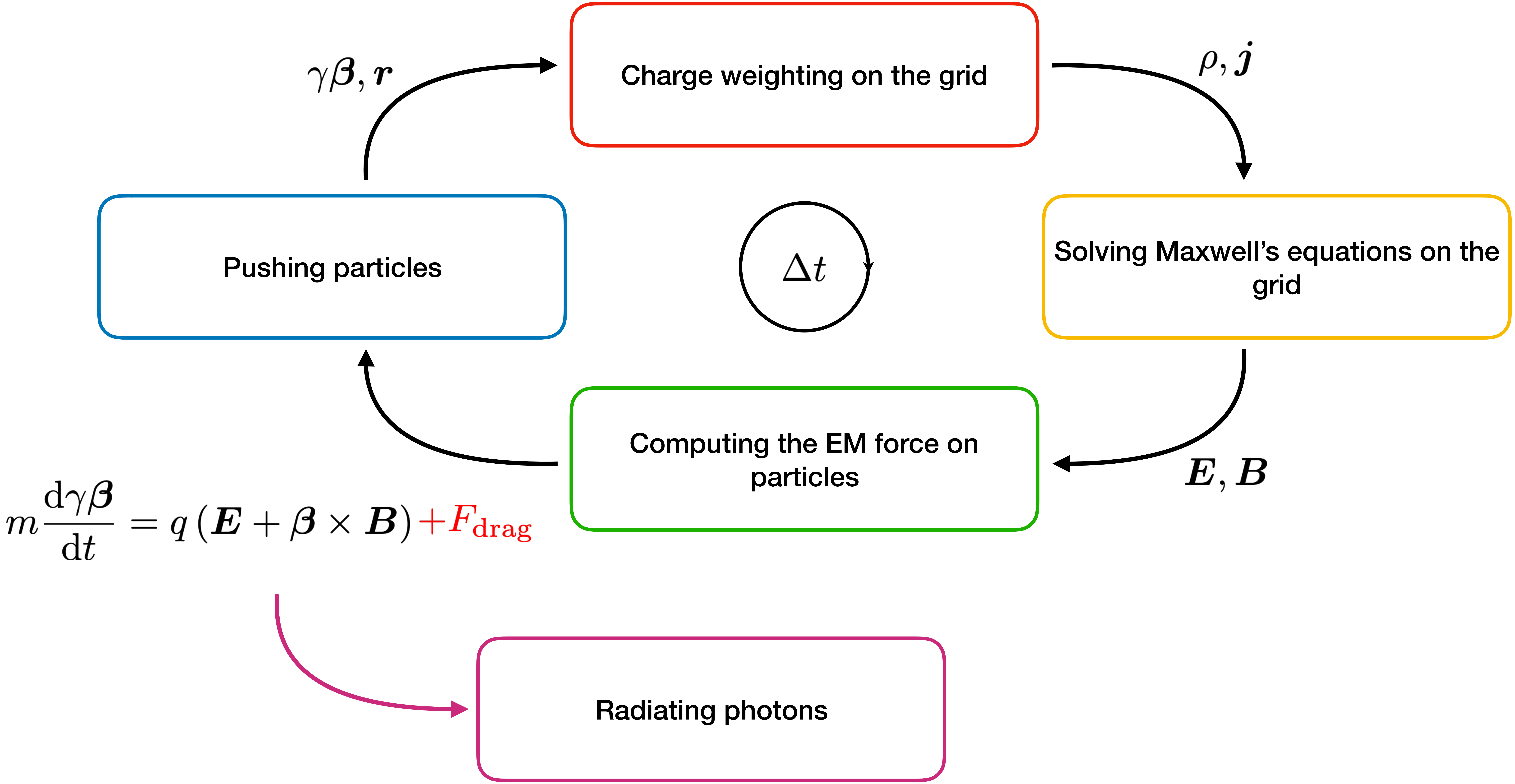
$$m\frac{\mathrm{d}\gamma\boldsymbol{\beta}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \boldsymbol{\beta}\times\boldsymbol{B}\right)$$

PIC algorithm + cooling



$$m\frac{\mathrm{d}\gamma\boldsymbol{\beta}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}\right) + F_{\mathrm{drag}}$$

PIC algorithm + cooling + photons



PIC algorithm

+ cooling + photons

$$\dot{\epsilon} = -\frac{2}{3} r_e^2 c \gamma^2 \beta^2 \tilde{B}_\perp^2$$

$$\varepsilon_\gamma = \frac{3}{2} \frac{\hbar e \beta \tilde{B}_\perp \gamma^2}{m_e c}$$

PIC algorithm + cooling + photons

$$\dot{\epsilon} = -\frac{2}{3} r_e^2 c \gamma^2 \beta^2 \tilde{B}_\perp^2$$

$$\varepsilon_\gamma = \frac{3}{2} \frac{\hbar e \beta \tilde{B}_\perp \gamma^2}{m_e c}$$

$$\dot{\epsilon}\big|_{B_0} = -eE_{\rm rec} c = -e\beta_{\rm in} B_0 c$$

$\gamma_{\rm rad}$ — energy of particles that have drag force equal to Lorentz force **in the upstream field**

PIC algorithm + cooling + photons

$$\dot{\epsilon} = -\frac{2}{3} r_e^2 c \gamma^2 \beta^2 \tilde{B}_\perp^2$$

$$\varepsilon_\gamma = \frac{3}{2} \frac{\hbar e \beta \tilde{B}_\perp \gamma^2}{m_e c}$$

$$\dot{\epsilon}\big|_{B_0} = -eE_{\mathrm{rec}}c = -e\beta_{\mathrm{in}} B_0 c$$

γ_{rad} — energy of particles that have drag force equal to Lorentz force **in the upstream field**

$$\varepsilon_\gamma = m_e c^2 \left(\frac{\gamma}{\gamma_c}\right)^2 \frac{\tilde{B}_\perp}{B_0}$$

γ_c — energy of particles that radiate 0.51 MeV photon **in the upstream magnetic field**

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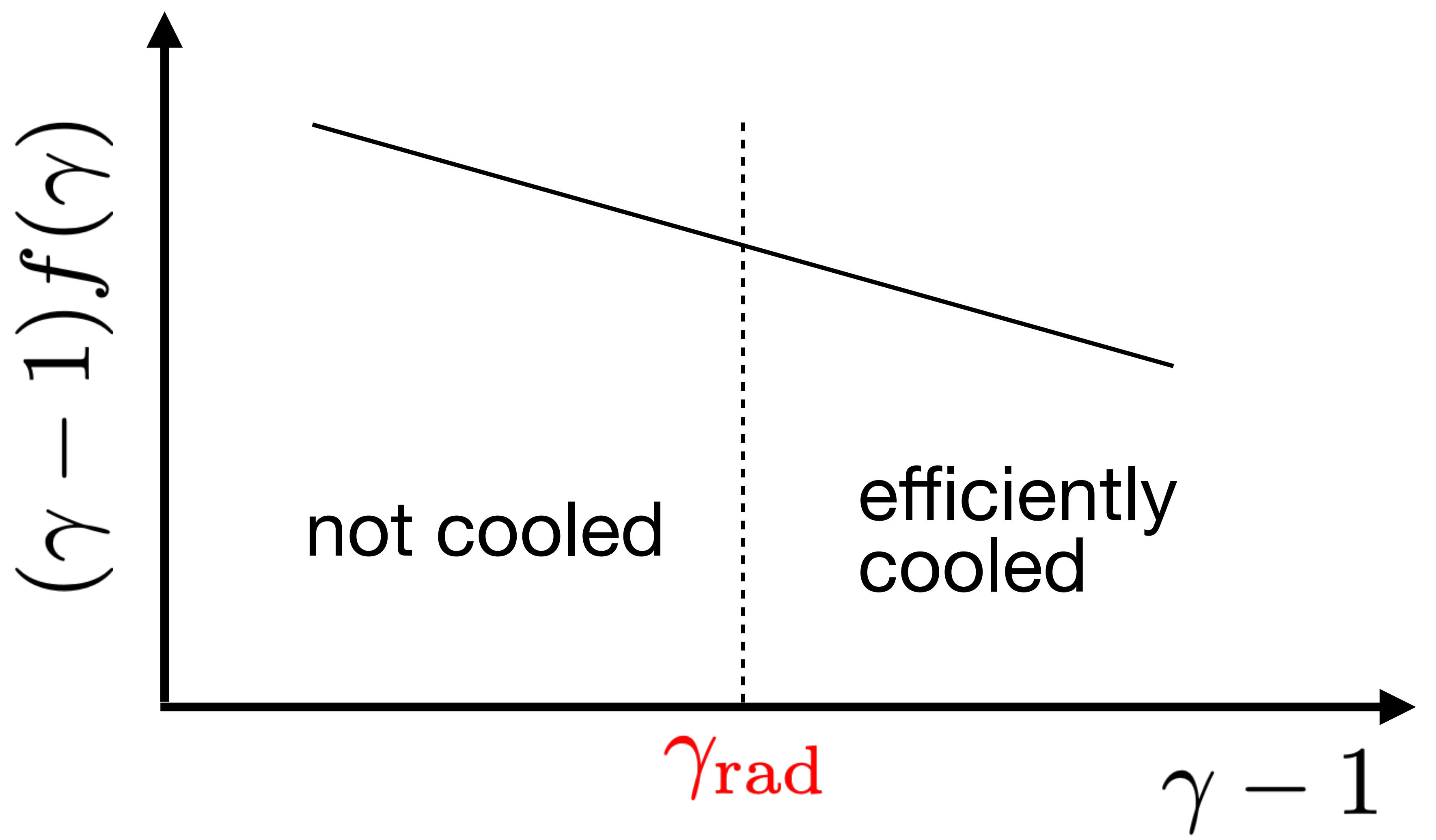

in the upstream magnetic field!

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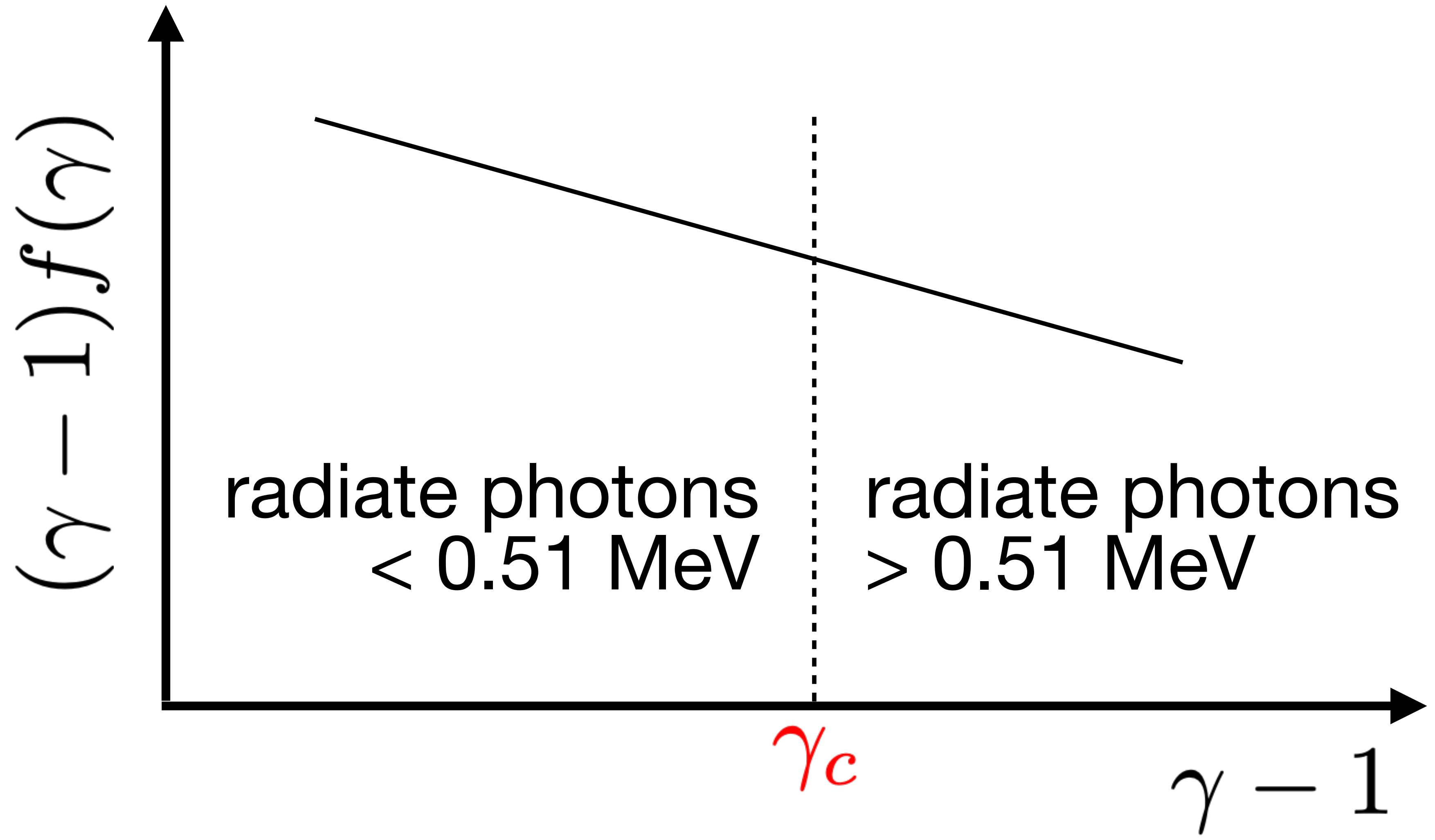

in the upstream magnetic field!

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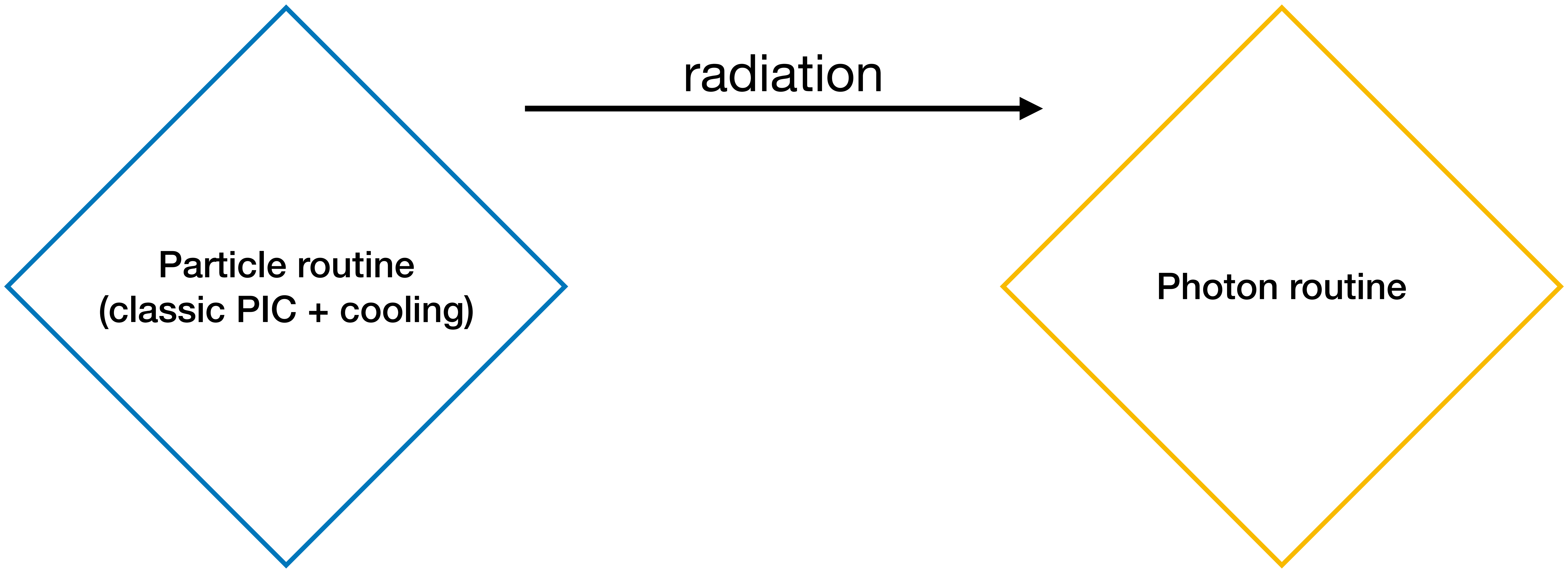
γ_c — energy of particles that radiate 0.51 MeV photon **in the upstream magnetic field**

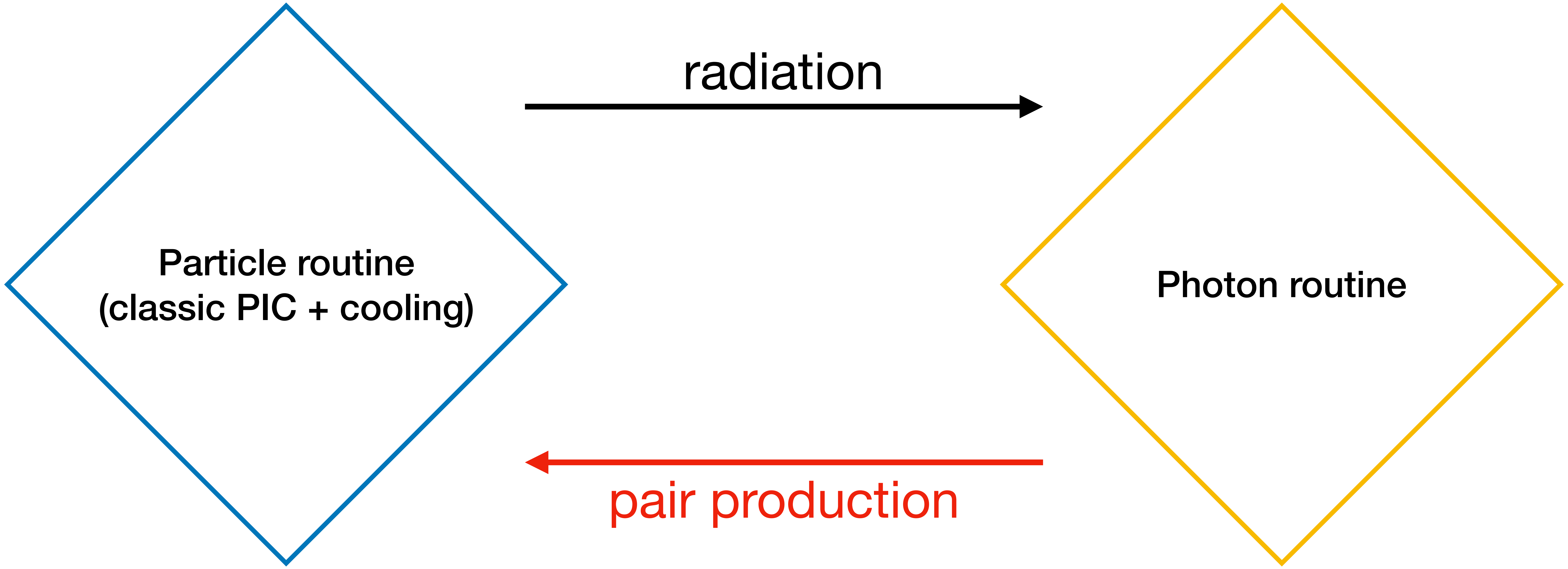
$$\gamma_{\rm rad} \sim 10^5 \left(\frac{B_0}{10^5\ \mathrm{G}}\right)^{-1/2} \qquad \gamma_c \sim 2 \times 10^4 \left(\frac{B_0}{10^5\ \mathrm{G}}\right)^{-1/2}$$

in pulsars $\sigma \gtrsim 10^5$ there are plenty of particles with $\gamma \gtrsim \gamma_{\rm rad}, \gamma_c$

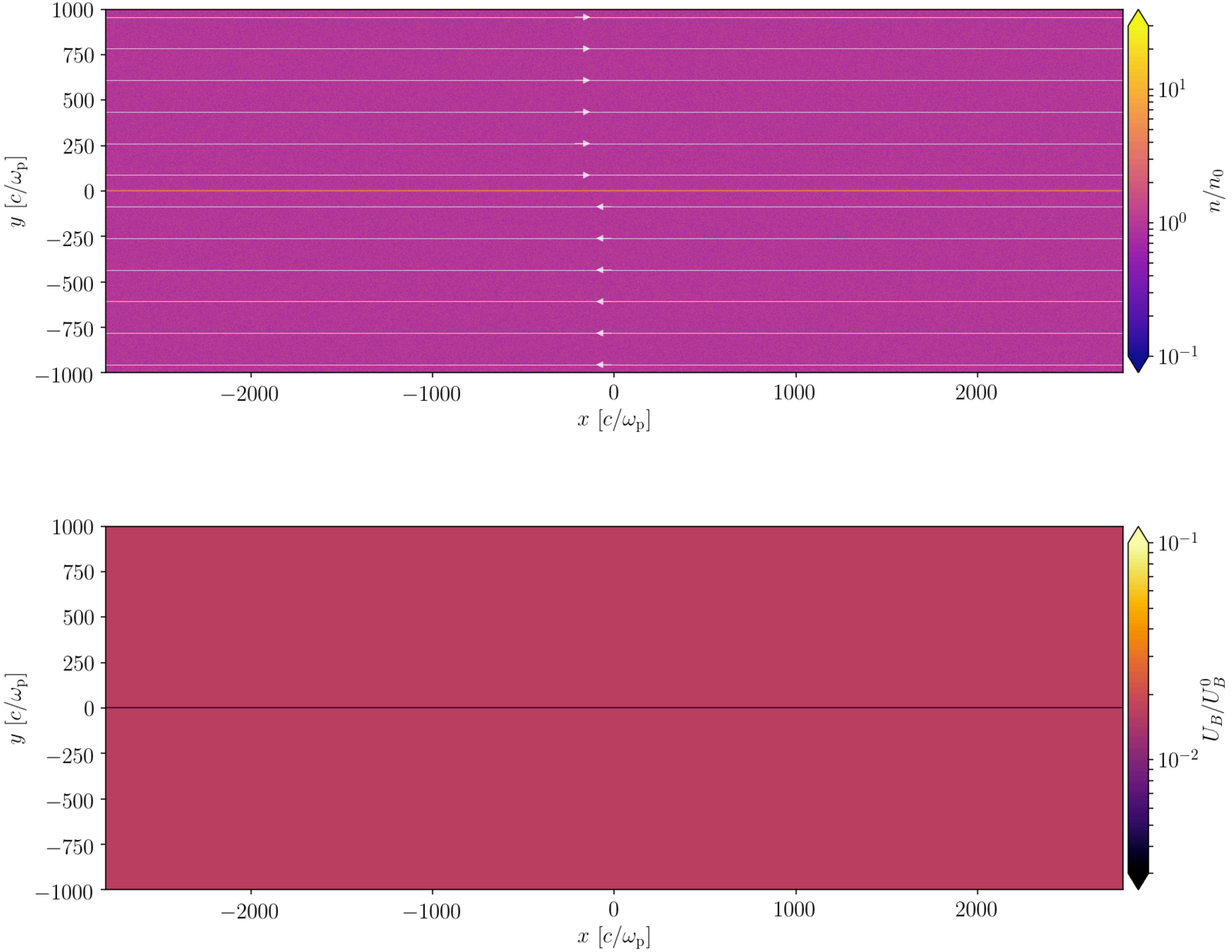
PIC algorithm + cooling + photons



PIC algorithm + cooling + photons + pair production

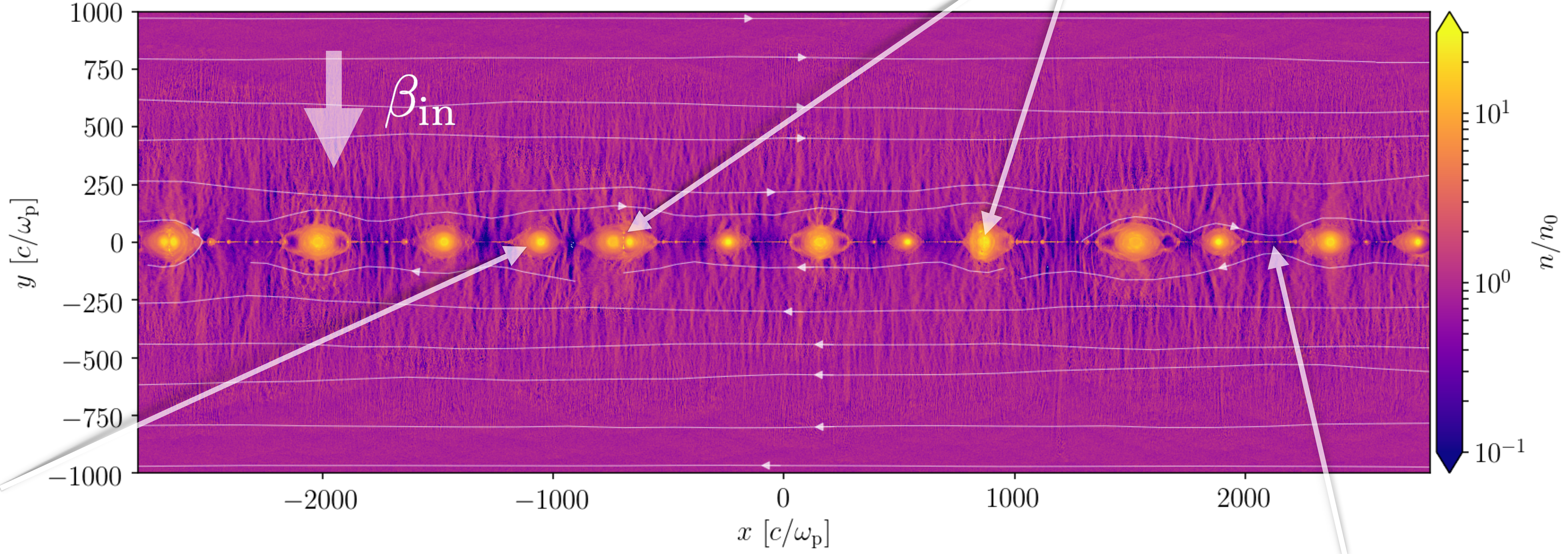


Reconnection



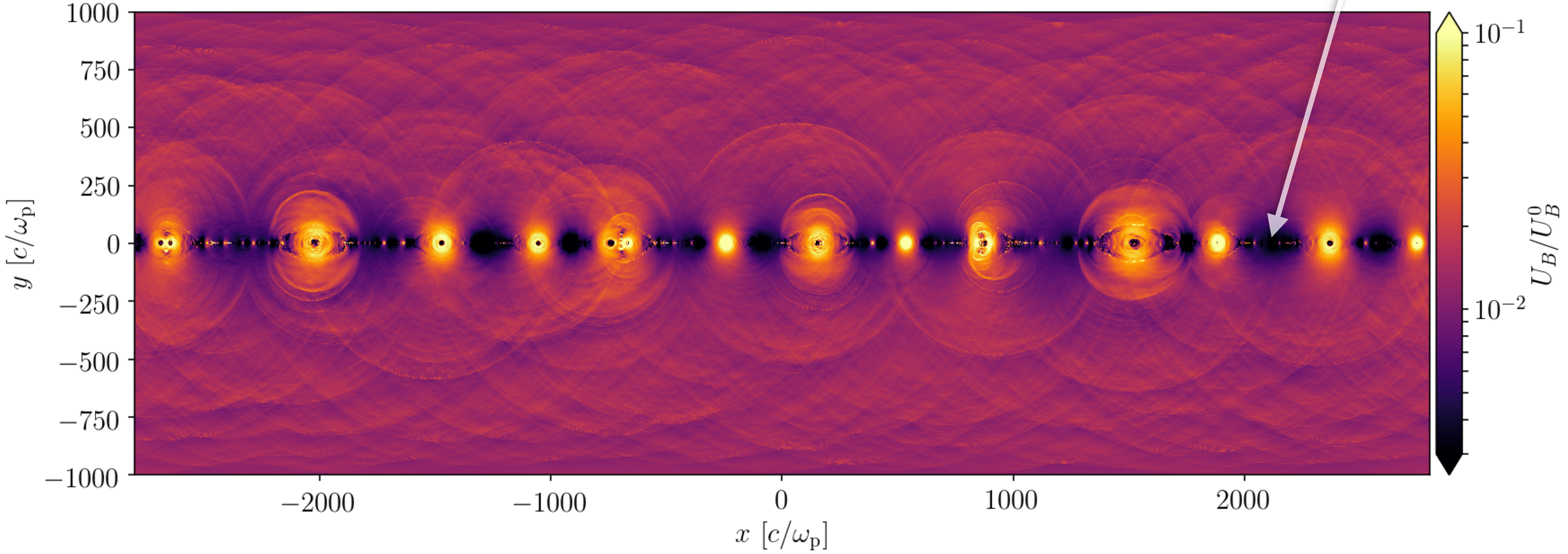
Reconnection

2. magnetic loops with dense plasma are formed (a.k.a. islands/plasmoids)

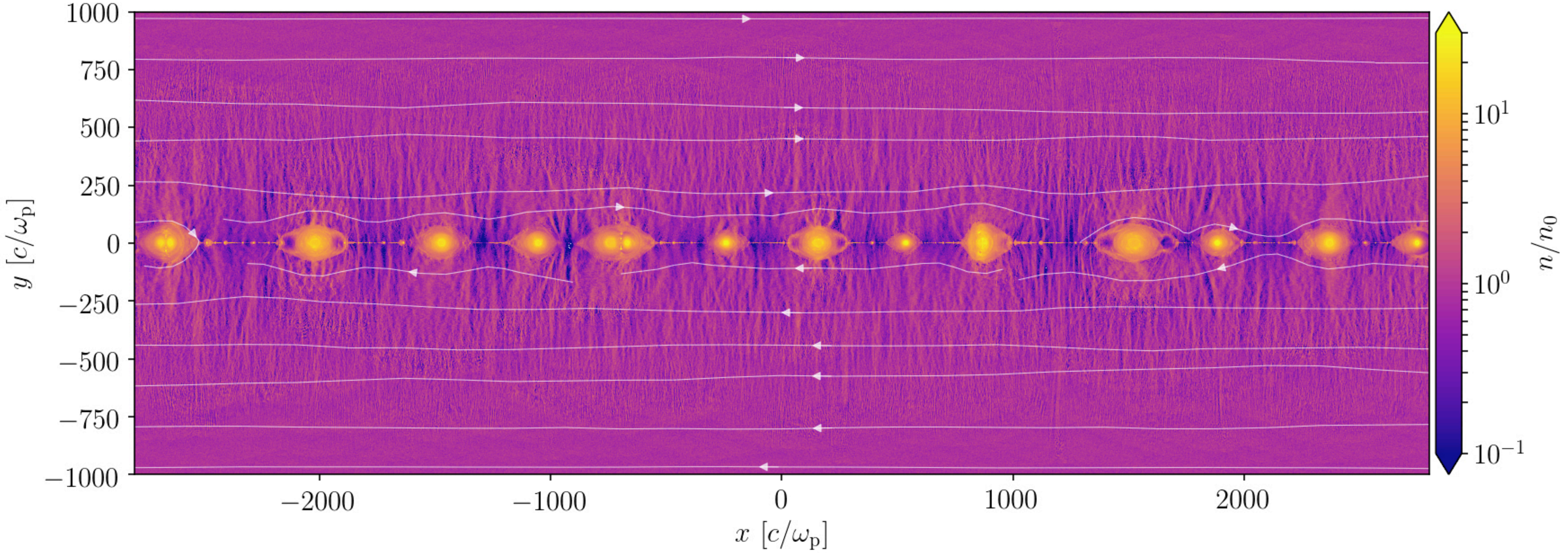


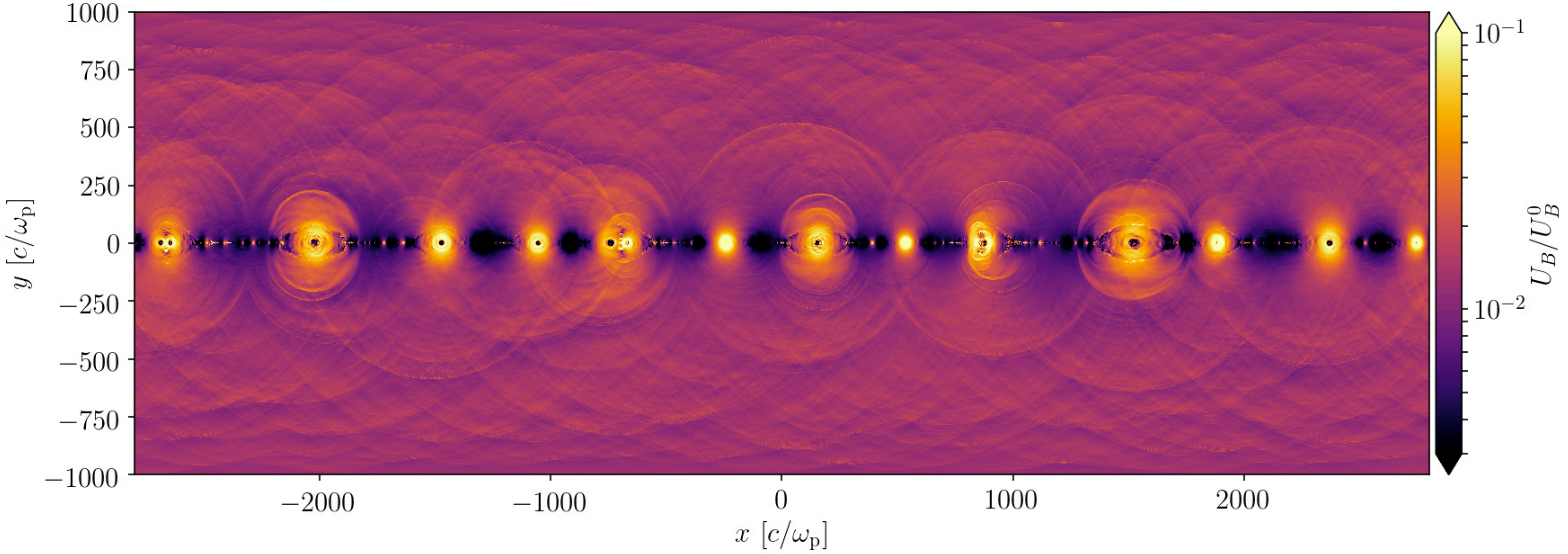
1. tearing instability breaks the current sheet

3. ***E***-field in so-called x-points accelerates particles



Reconnection



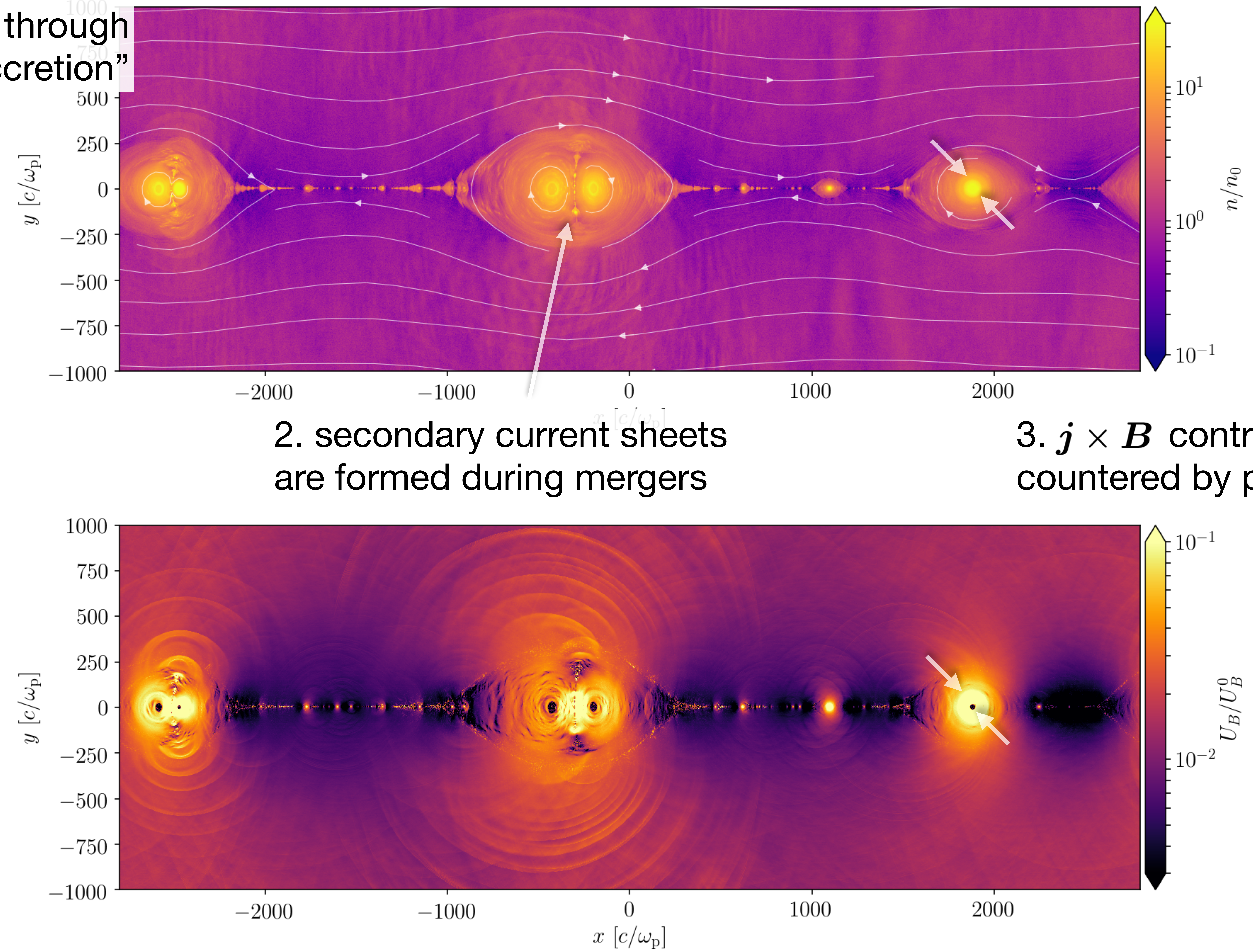


Reconnection

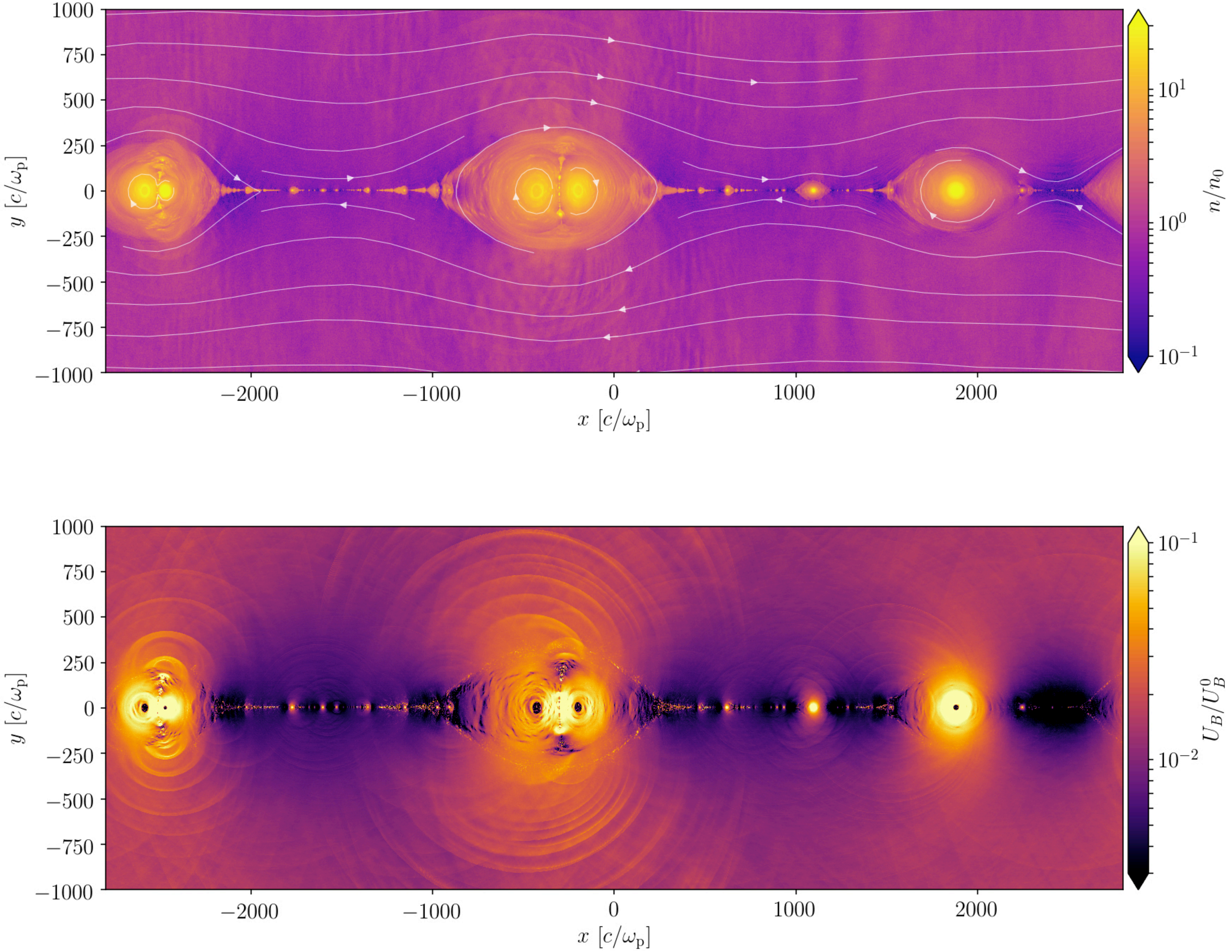
1. plasmoids grow through mergers + “accretion”

2. secondary current sheets are formed during mergers

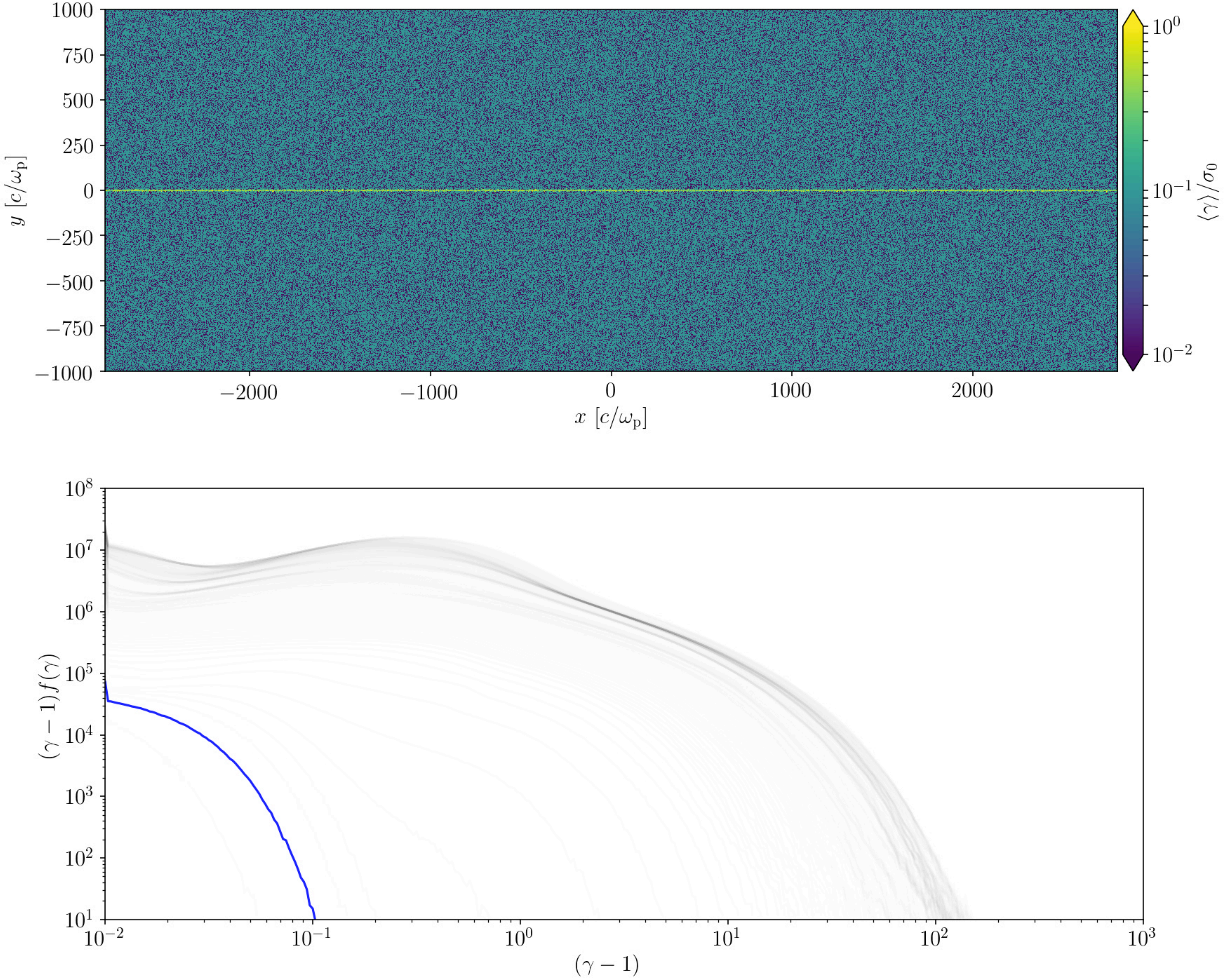
3. $\boldsymbol{j} \times \boldsymbol{B}$ contraction is countered by plasma pressure



Reconnection



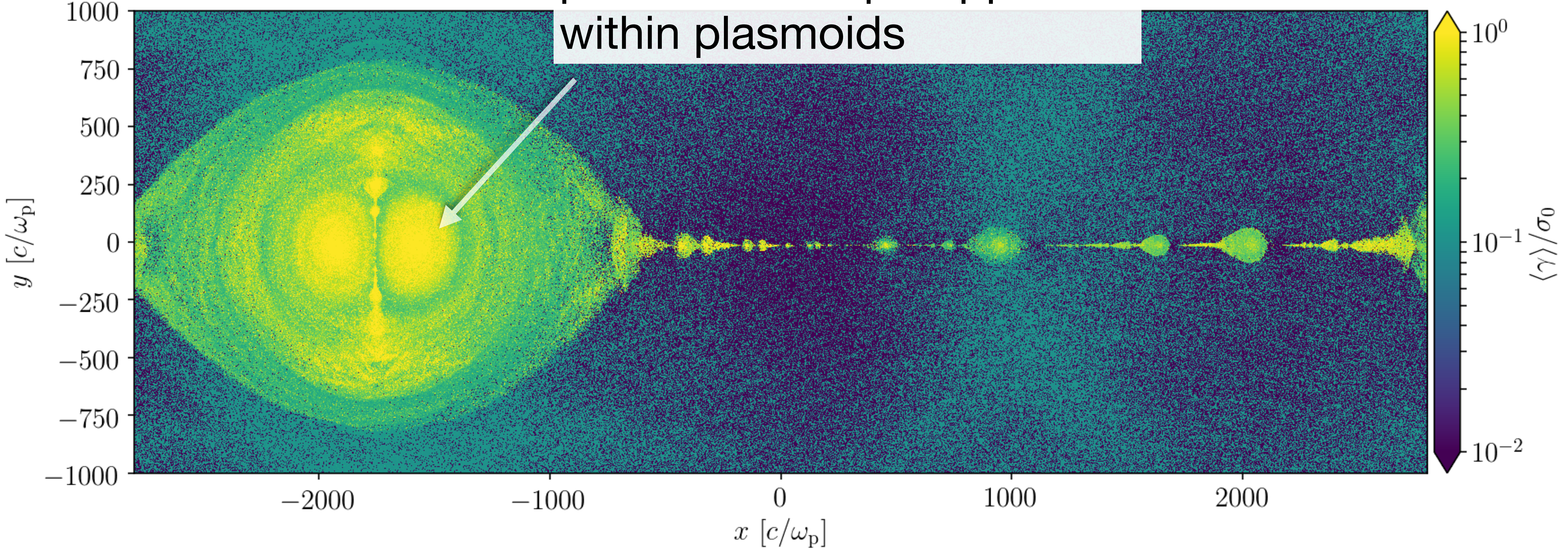
Reconnection



Reconnection

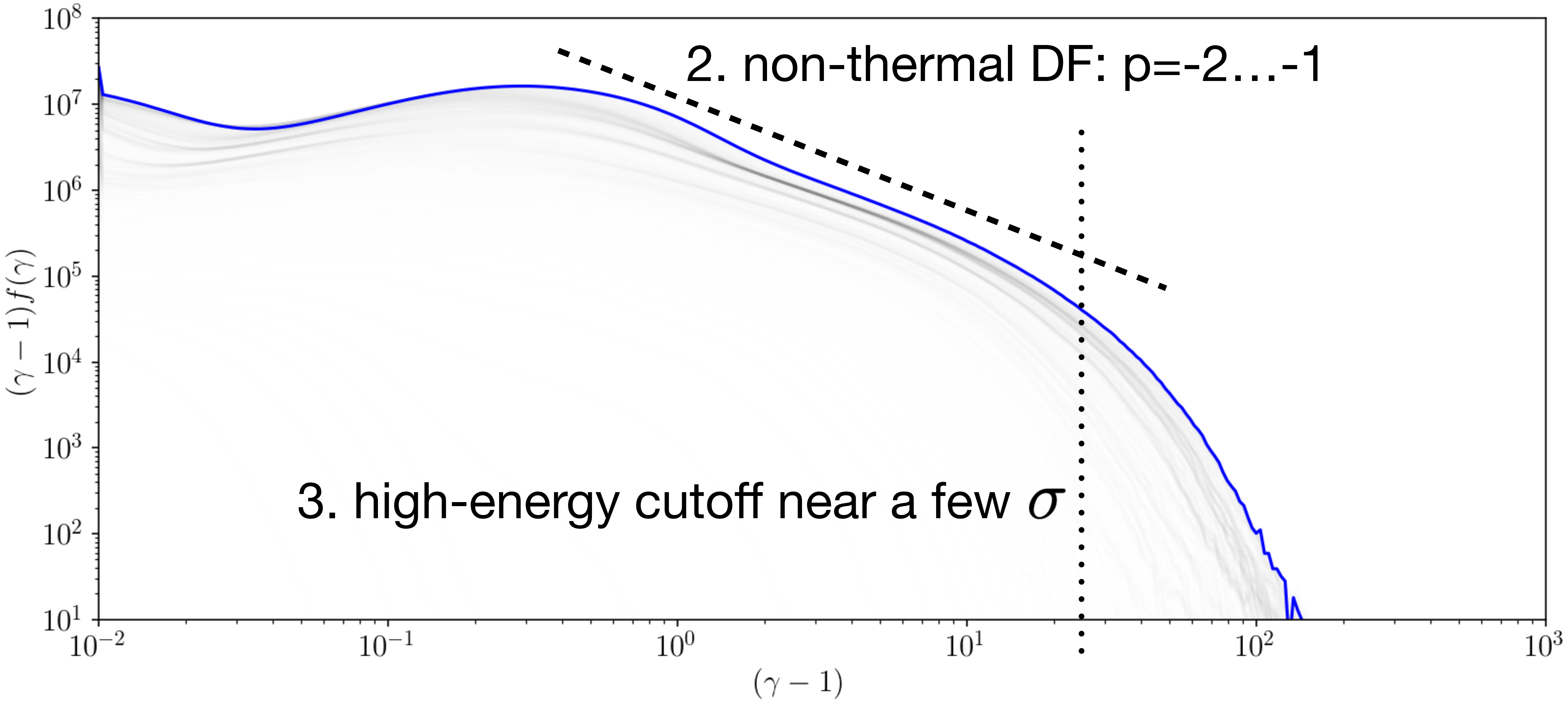
Sironi & Spitkovsky 2014
Werner+ 2016

1. most of high energy particles end up trapped within plasmoids

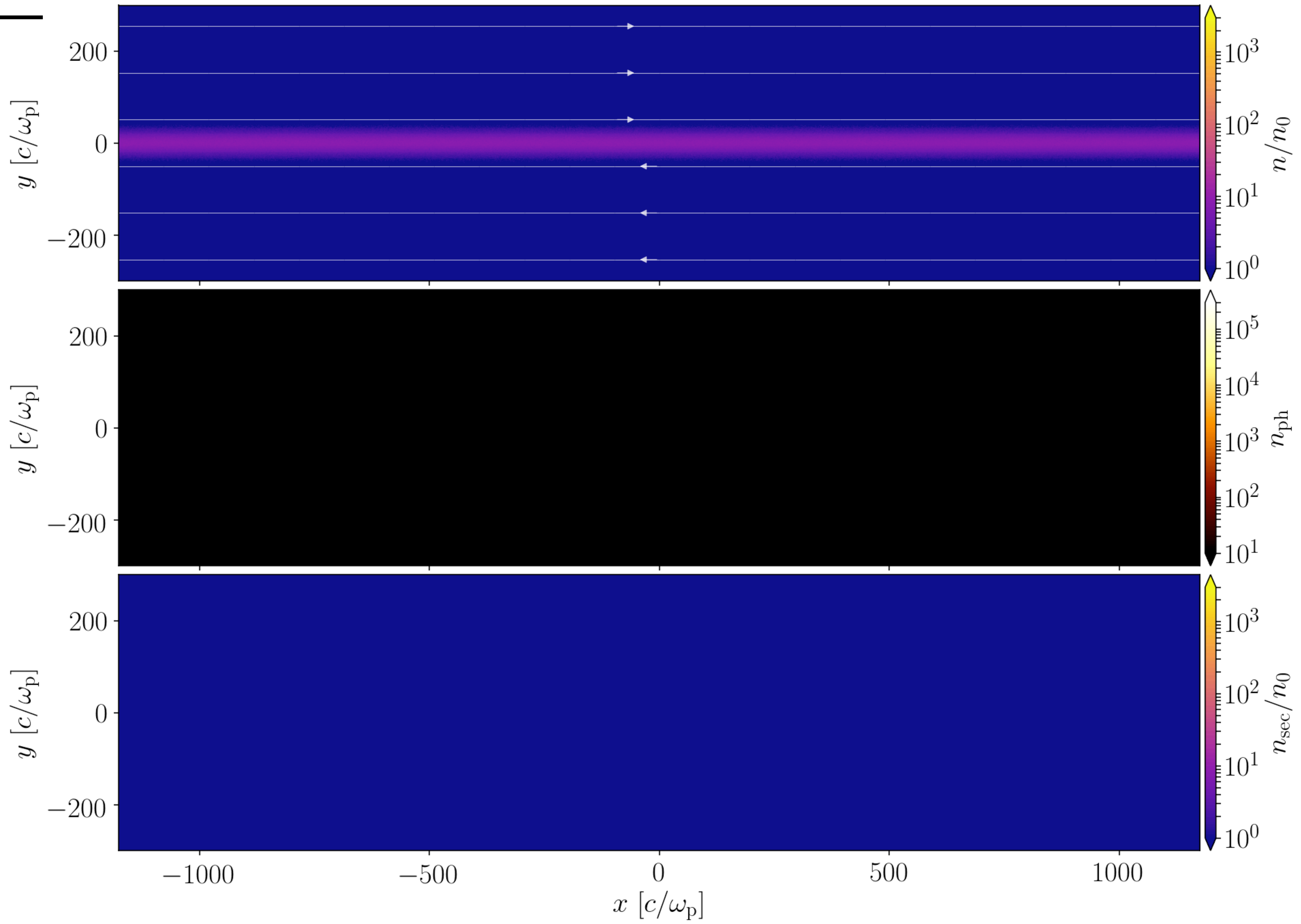


2. non-thermal DF: p=-2…-1

3. high-energy cutoff near a few σ



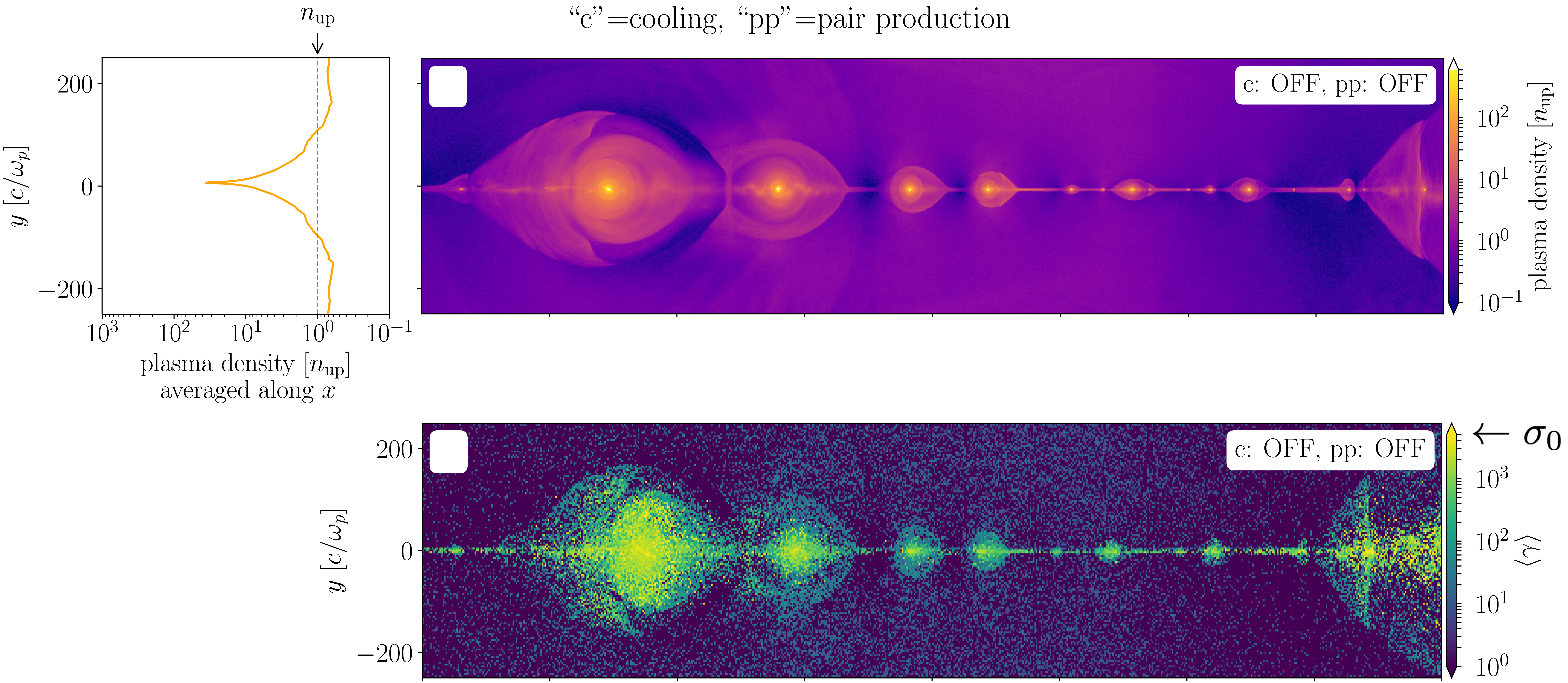
Our setup



$y\ [c/\omega_\mathrm{p}]$
200
0
−200
n/n_0
10^0
10^1
10^2
10^3
n_ph
10^1
10^2
10^3
10^4
10^5
n_sec/n_0
−1000
−500
0
500
1000
$x\ [c/\omega_\mathrm{p}]$

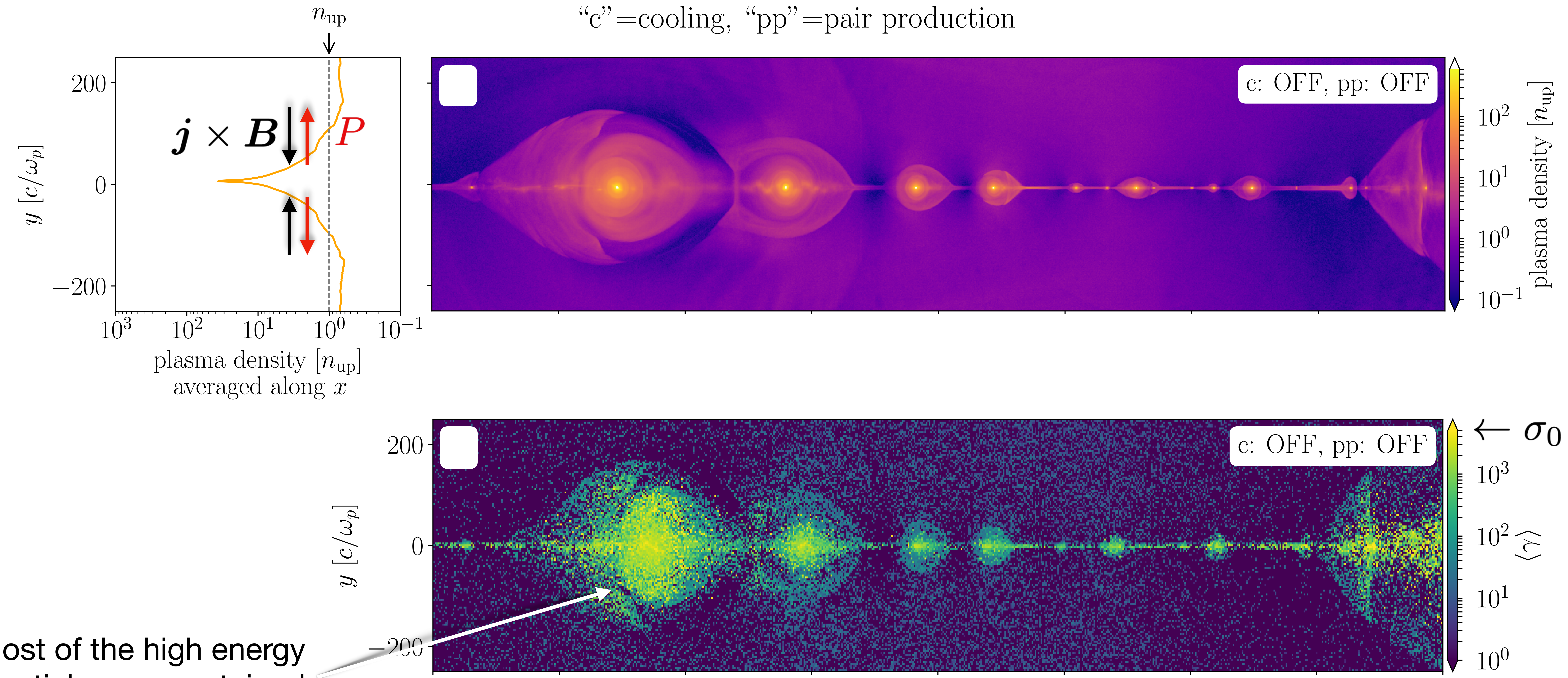
Results

no cooling



Results

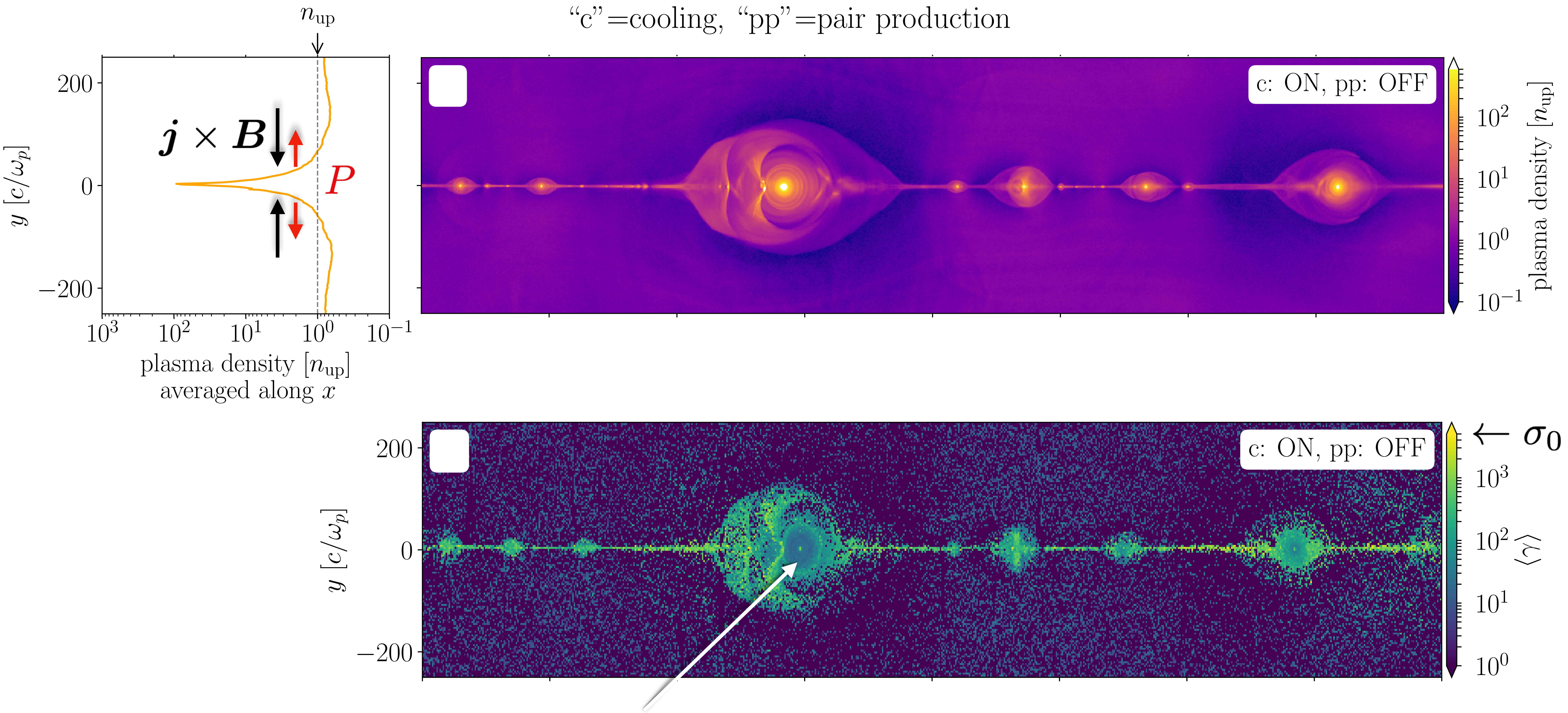
no cooling



most of the high energy particles are contained within the plasmoids (high ***B***-field)

Results

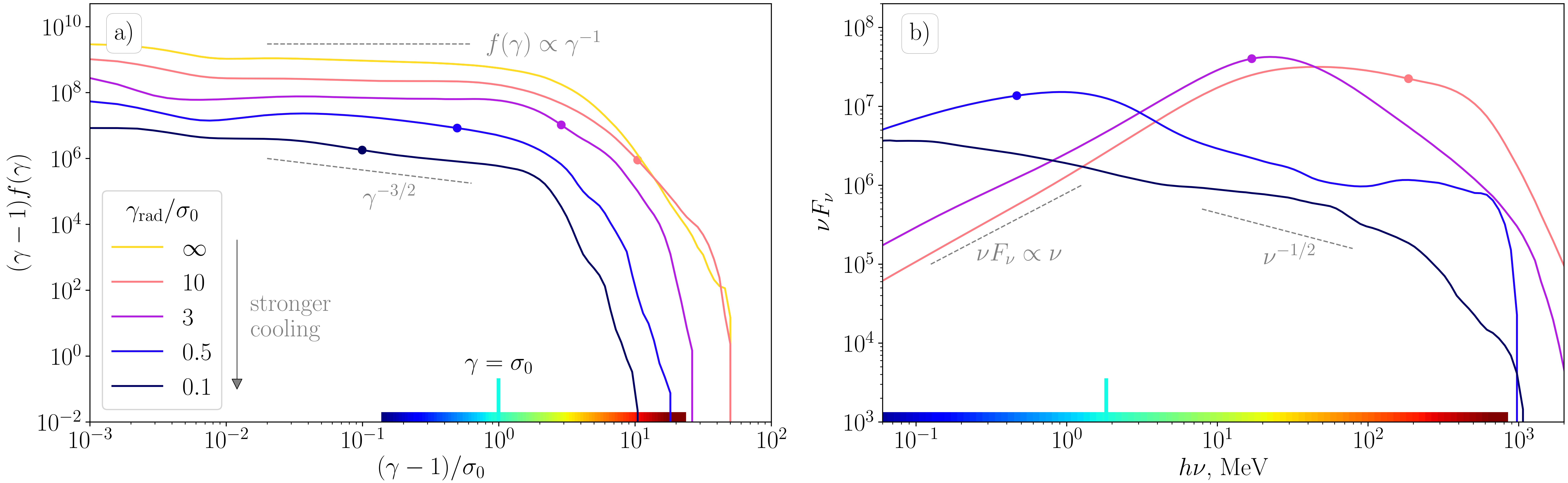
cooling ON



no high energy particles
inside the plasmoids

Results

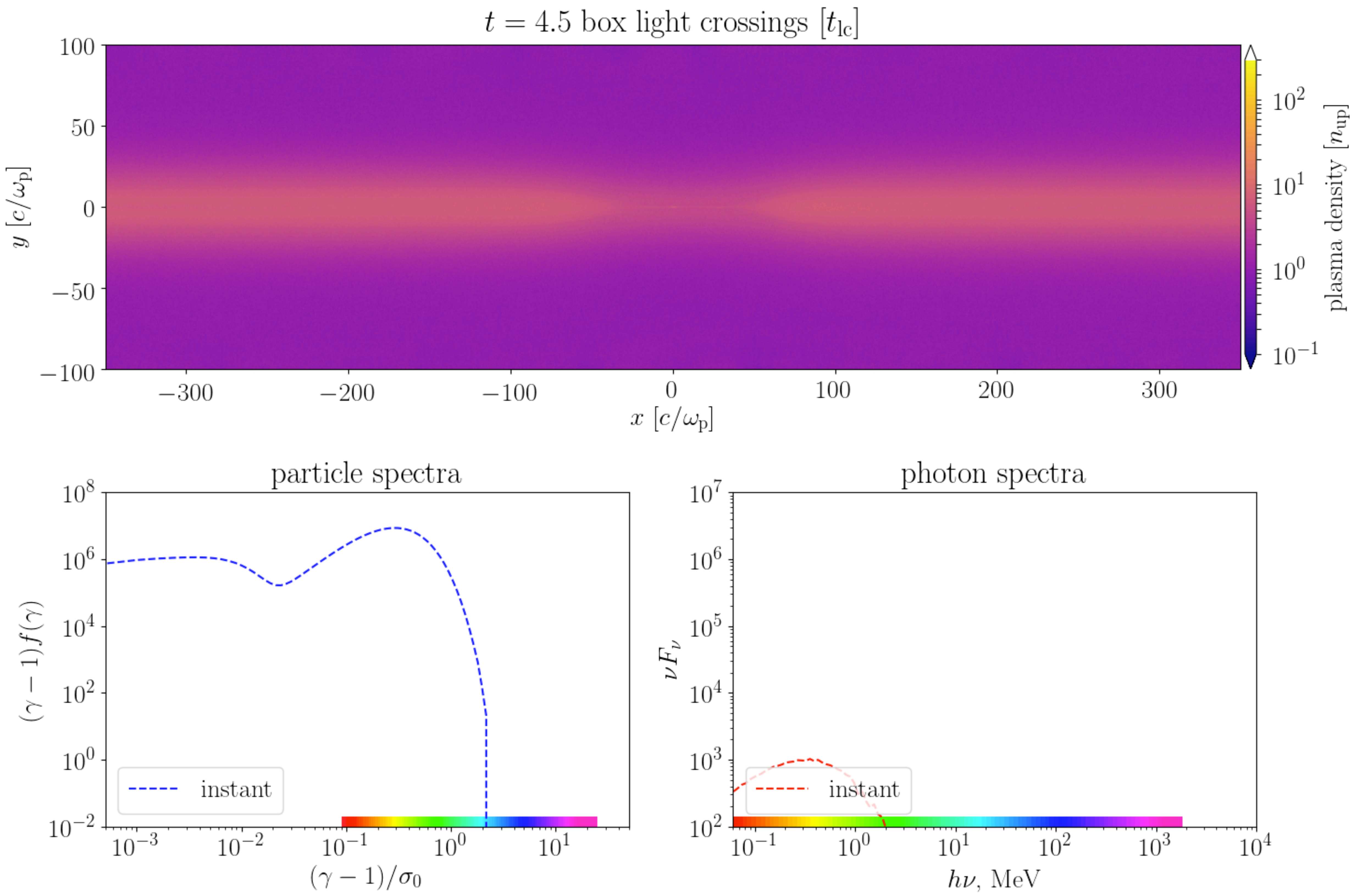
cooling ON



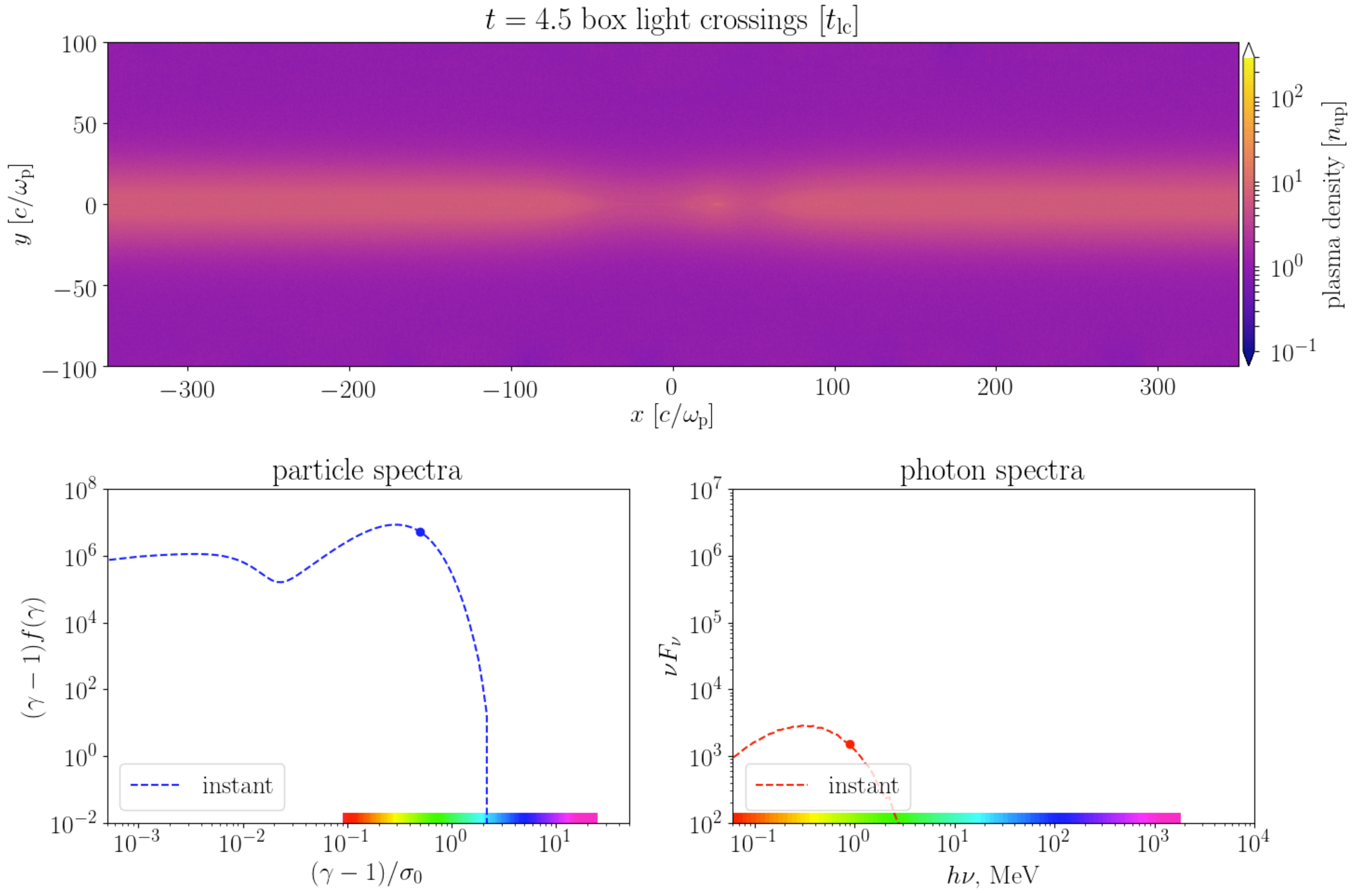
Results

cooling ON

weak cooling

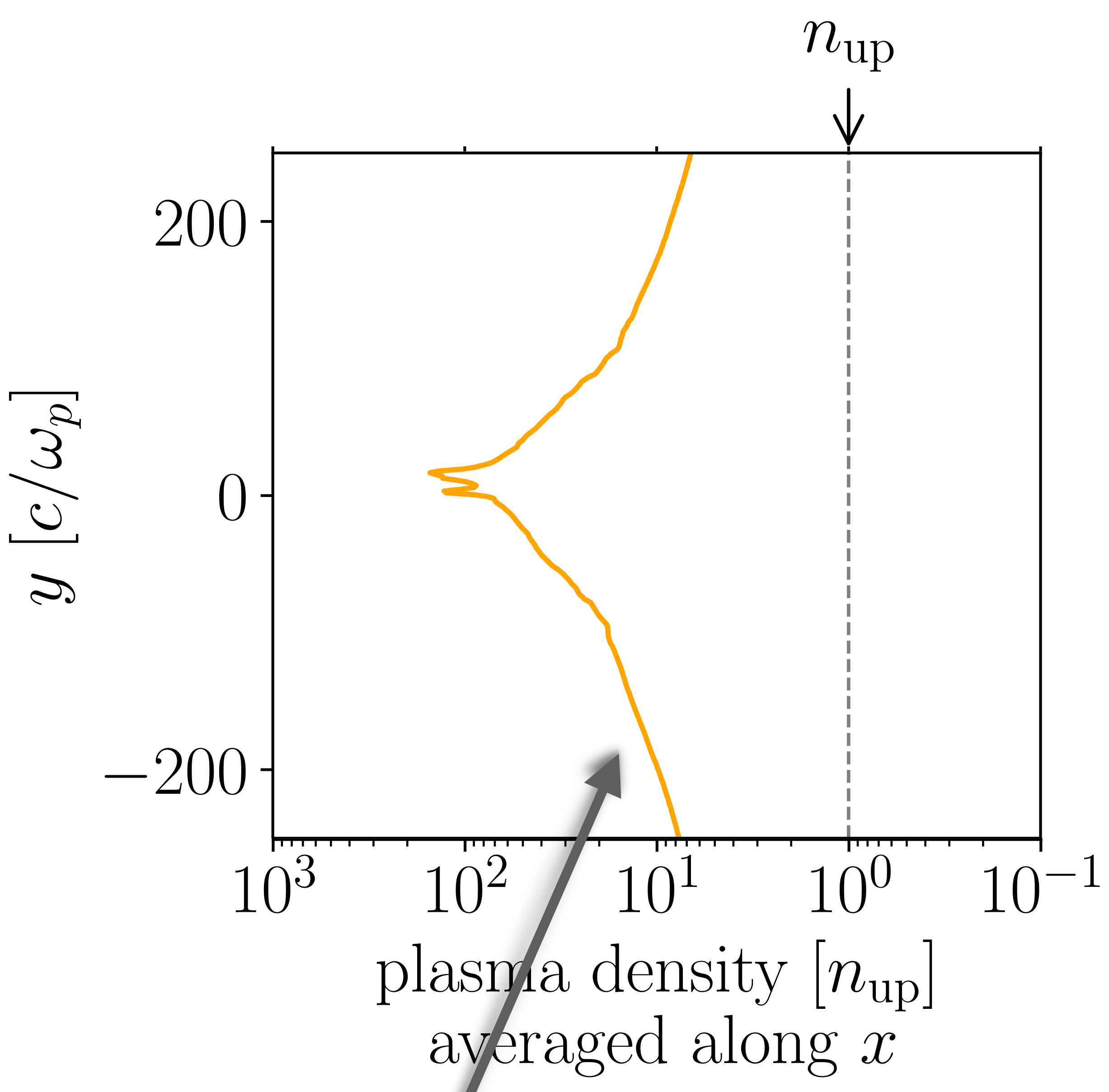


strong cooling



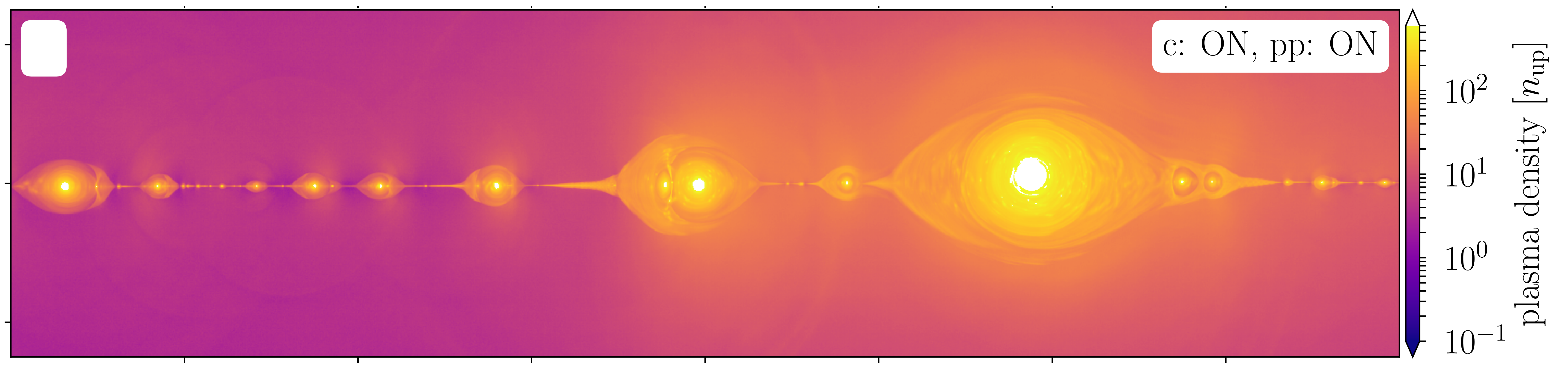
Results

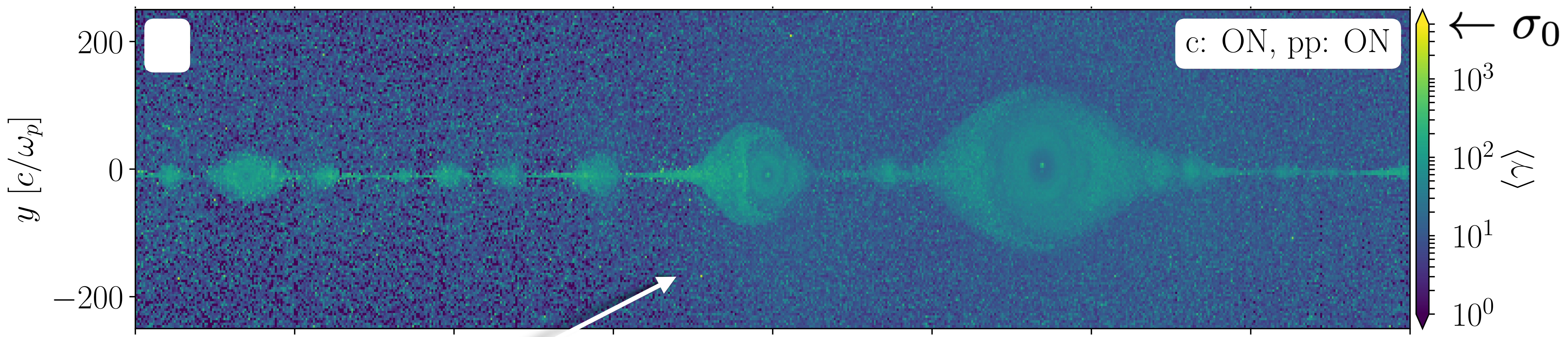
pair production ON



upstream is populated by secondaries

“c”=cooling, “pp”=pair production





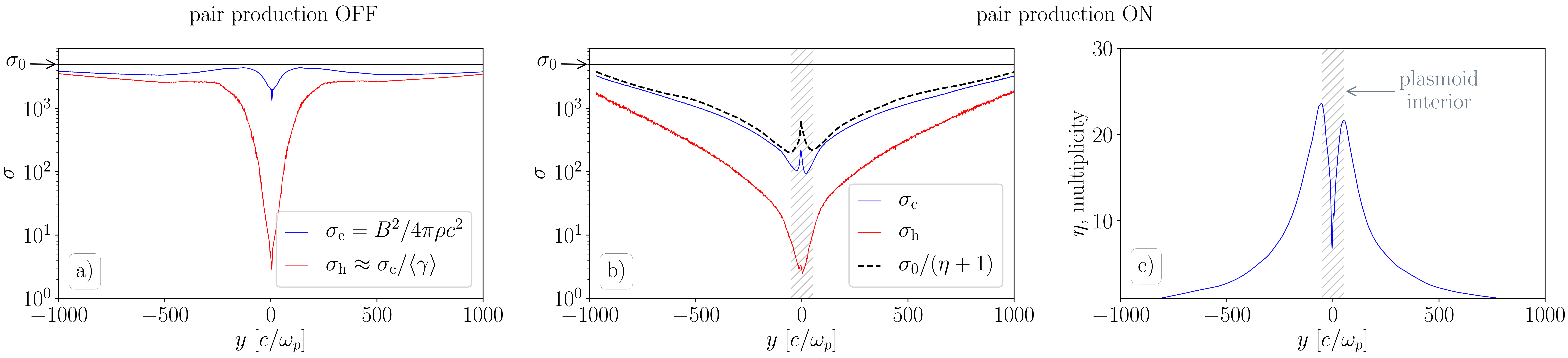
upstream is “hot”: particles inherit DF from photons

Results

pair production ON

1. suppression of σ (acceleration) due to pair loading
2. “hot” upstream (no single power-law)

$$\sigma_{\mathrm{eff}} = \frac{B^2/4\pi}{\langle\gamma\rangle\eta\,(n_0 m_e c^2)}$$



Results

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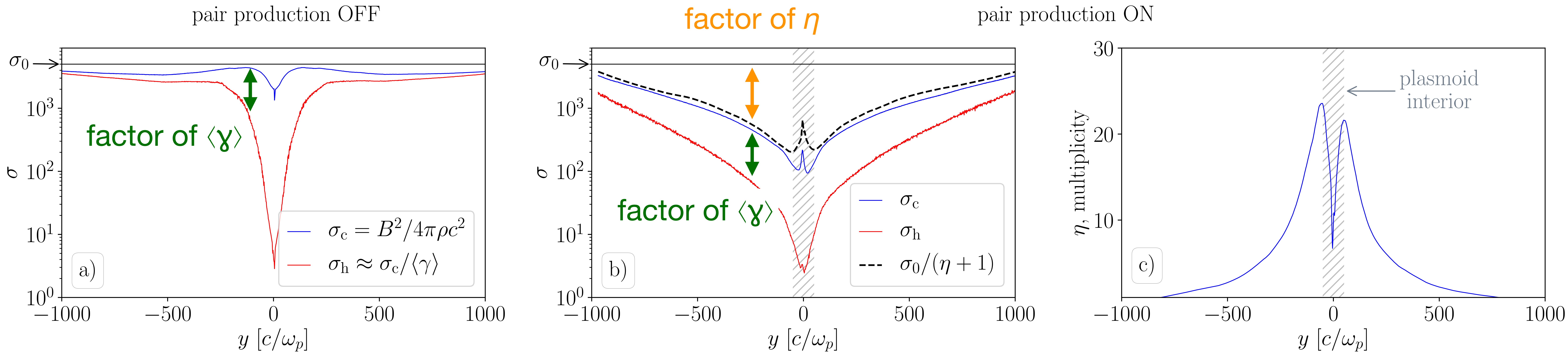
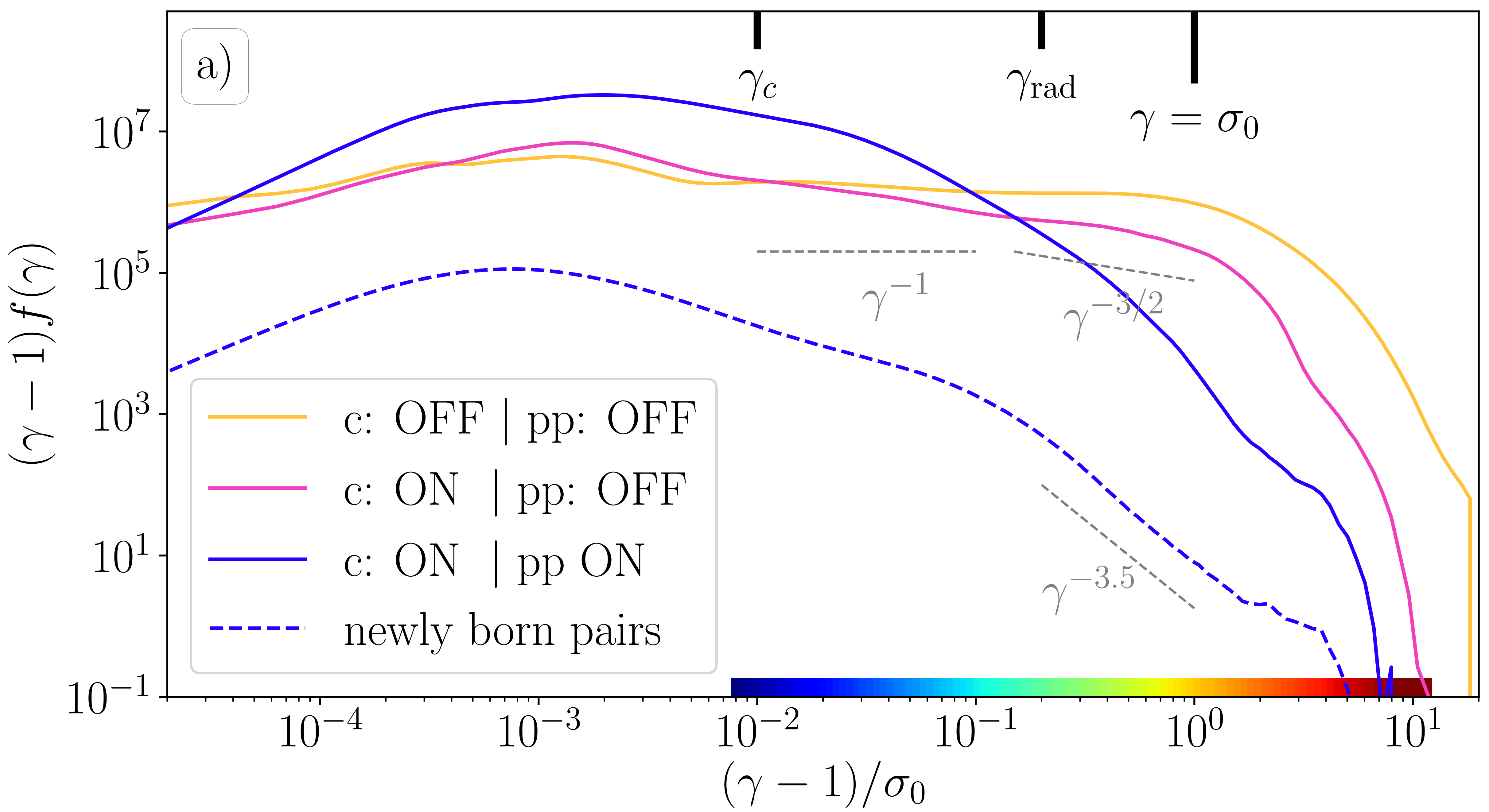
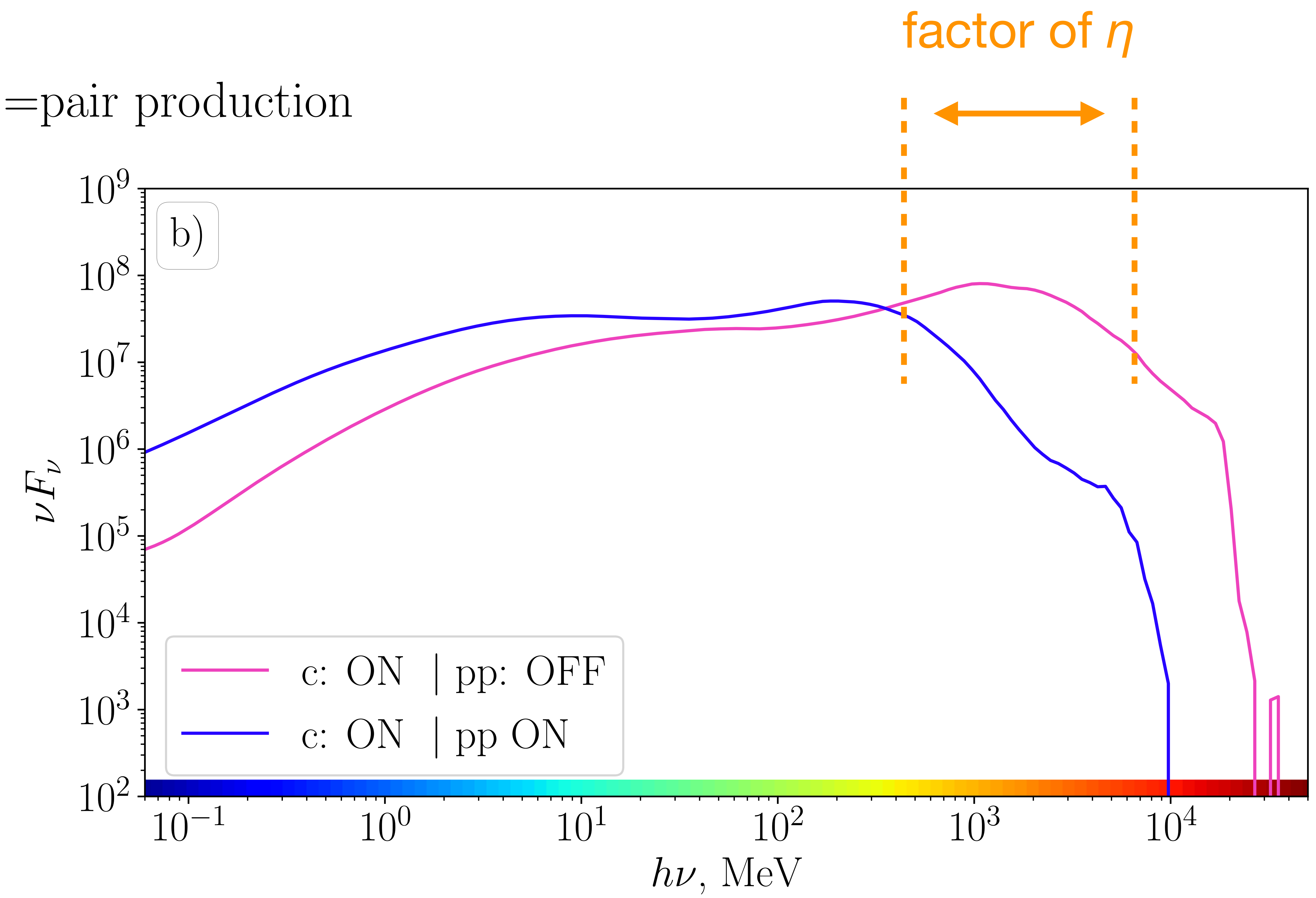


Results

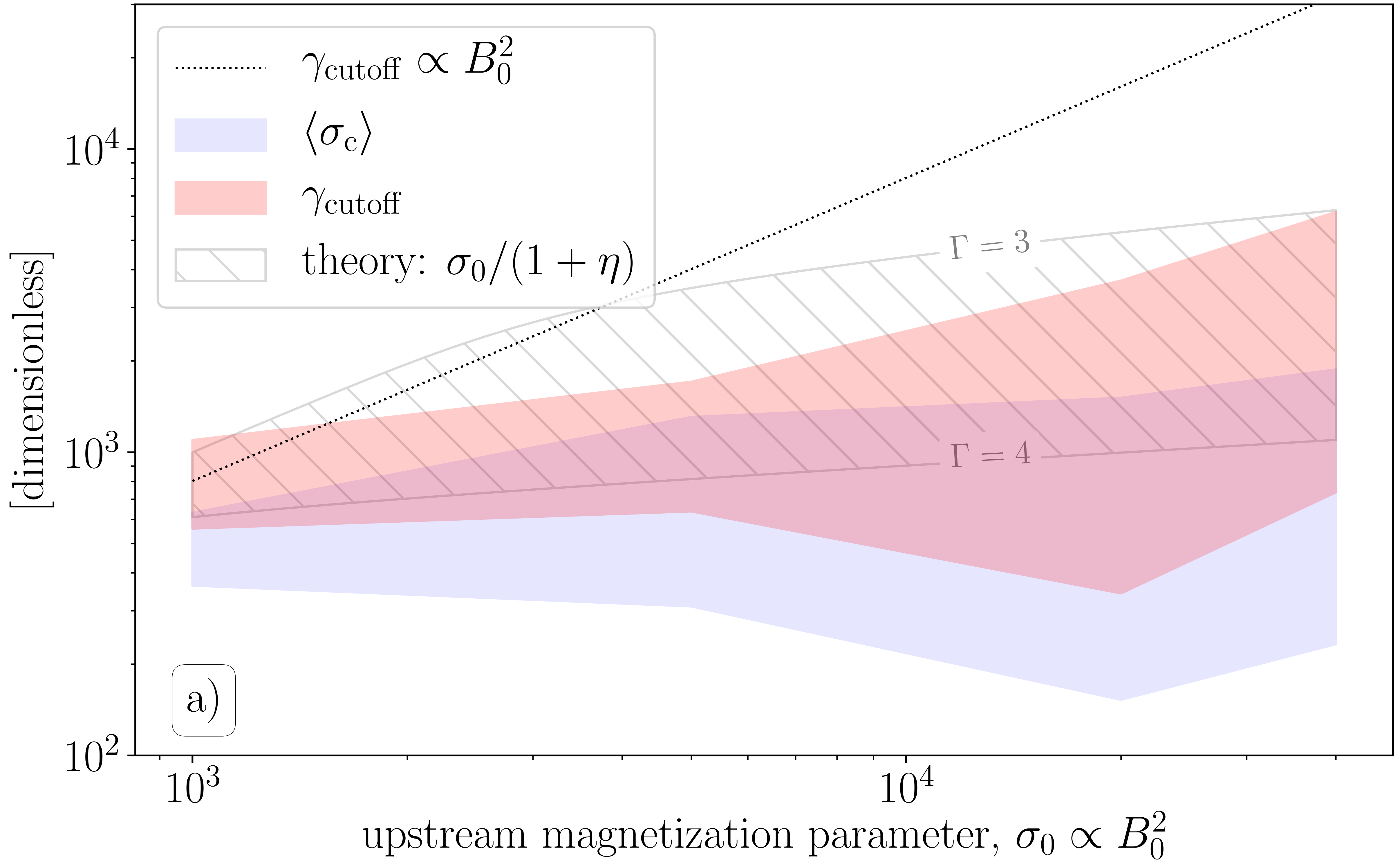
pair production ON

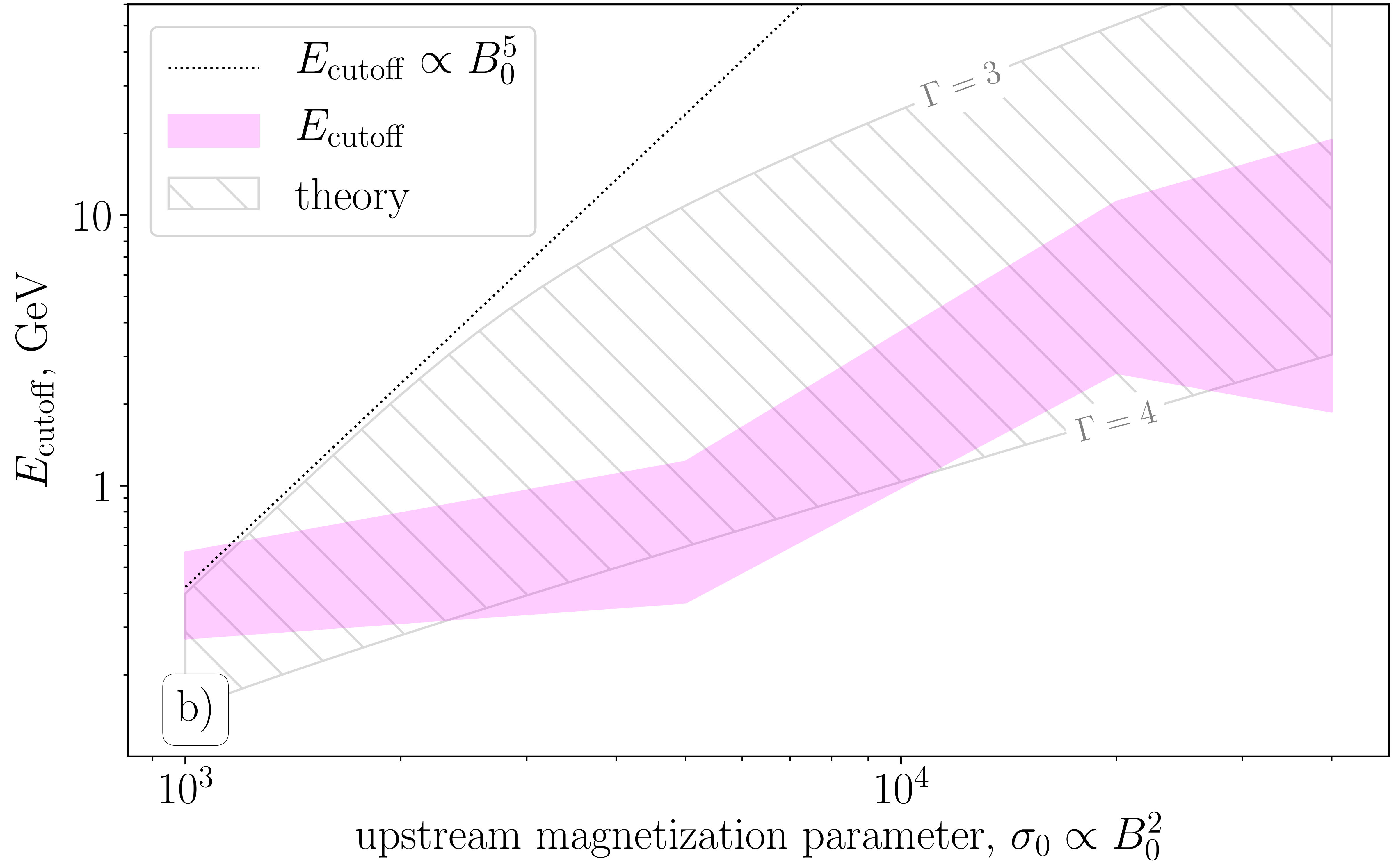
“c”=cooling, “pp”=pair production





Results



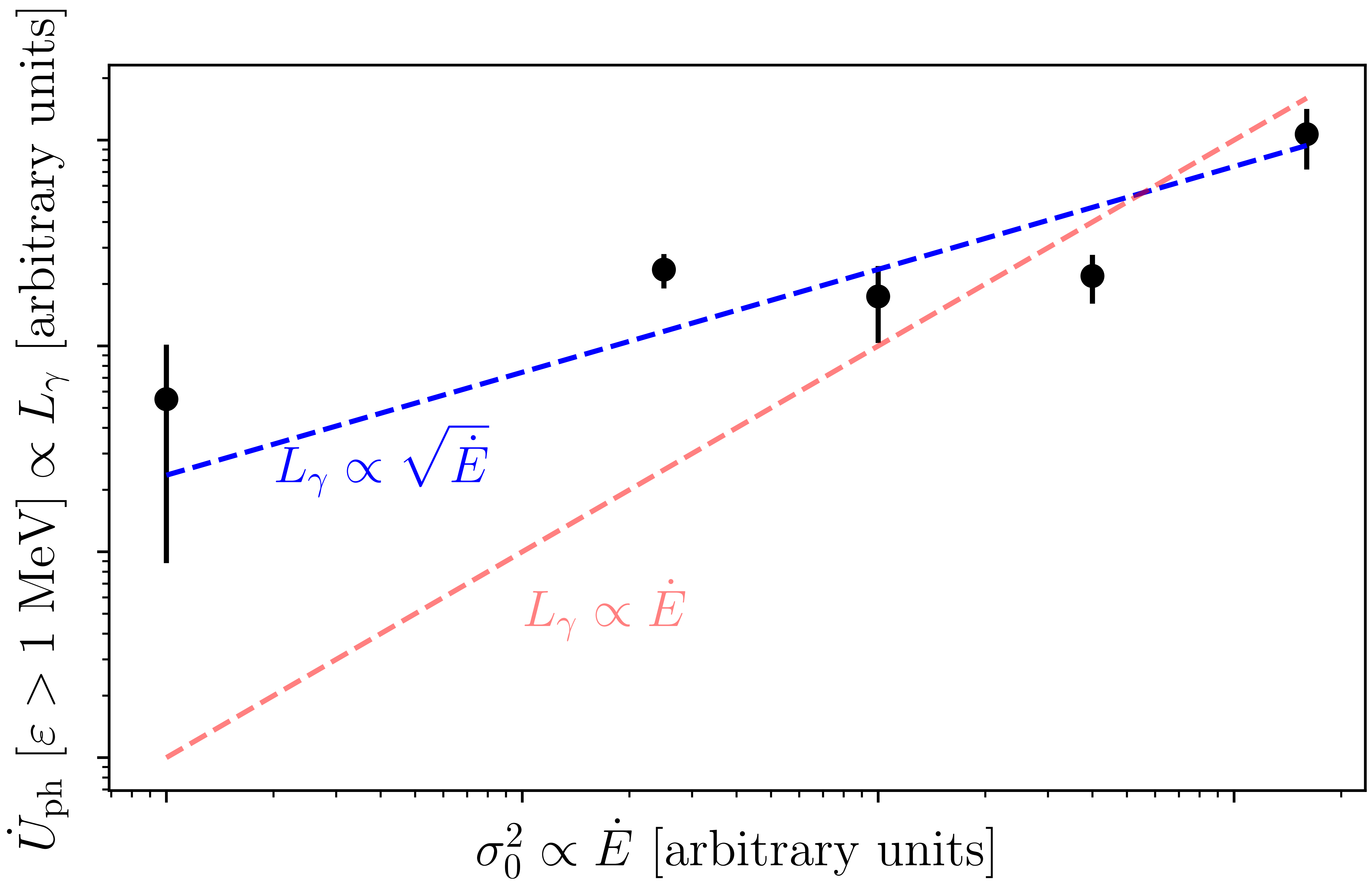


(roughly)

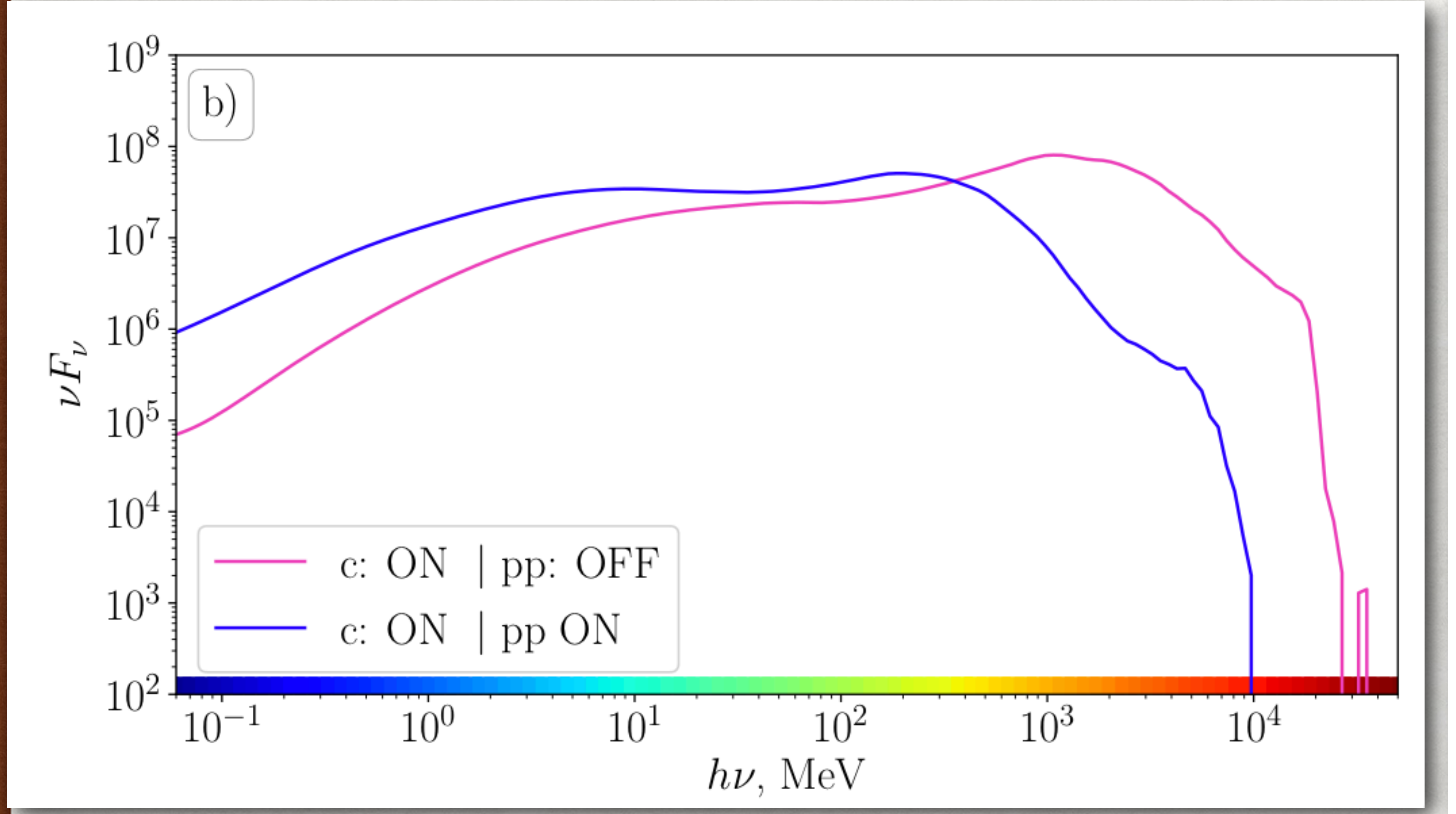
$$\eta \propto \sigma_0$$

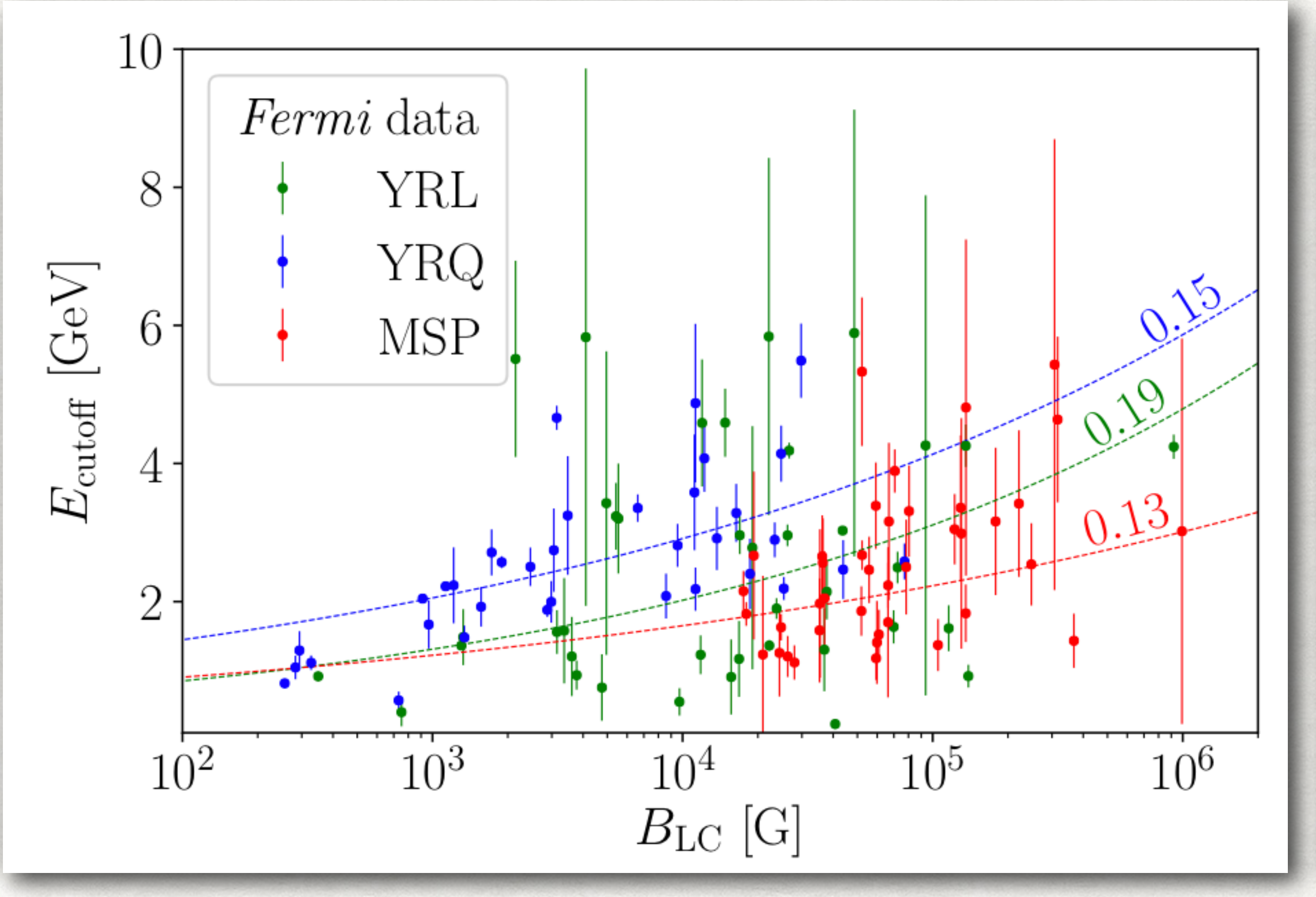
Results

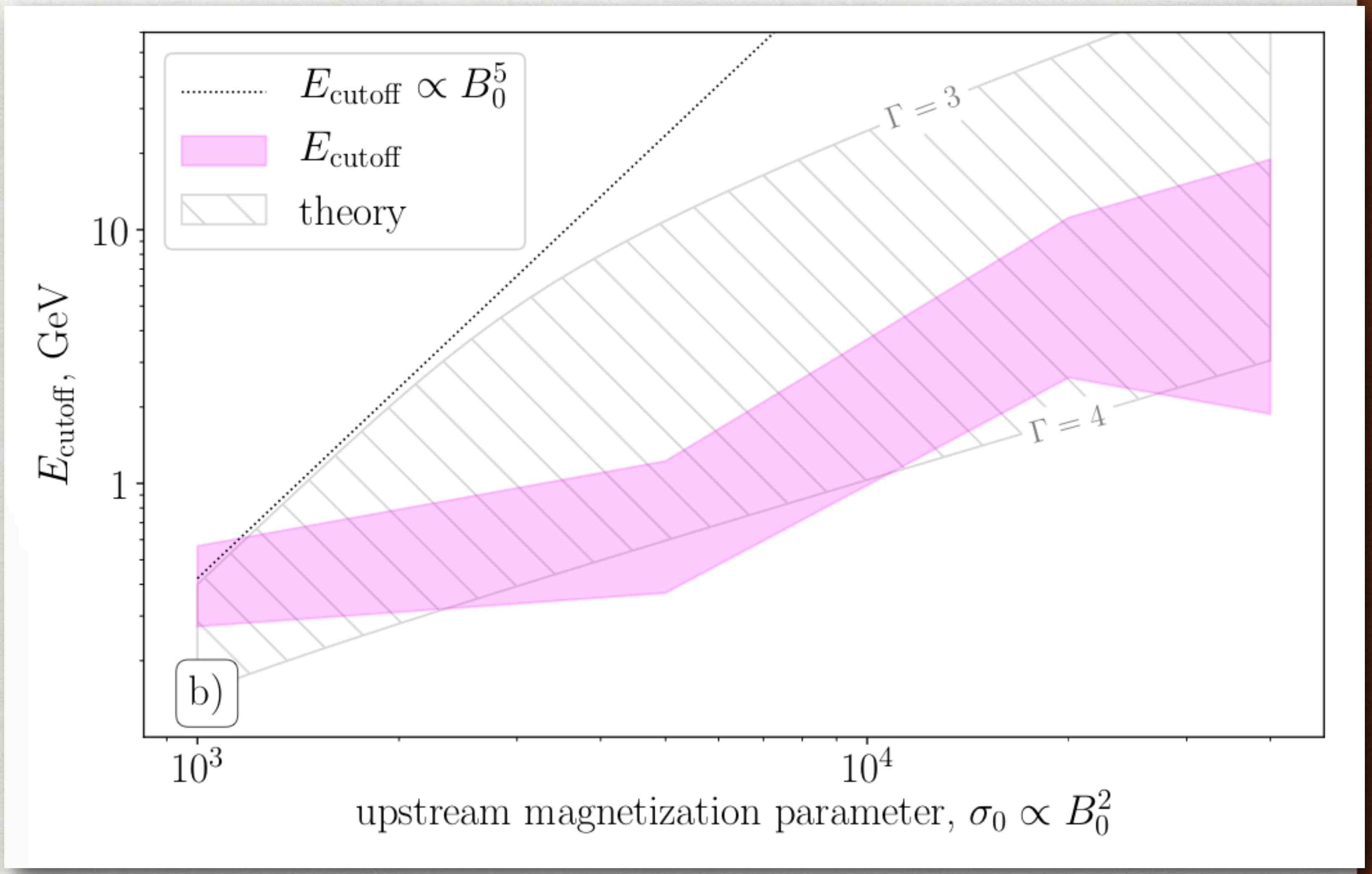
- L_γ is computed in the simulation box by taking all the tracked photons
- $\dot{E}$ is (by definition) proportional to our upstream σ_0



THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY







Pair formation increases the pair loading above the sheet, and lowers effective magnetization in the sheet.
Particle acceleration follows magnetization, max particle energy is reduced. Synchrotron emission.
Naively, cutoff energy should be a strong function of B at the LC.

$$\gamma_{\rm cuttoff} \propto \sigma_0 \propto B_0^2, \quad E_{\rm cutoff} \propto \gamma_{\rm cuttoff}^2 B_0 \propto B_0^5$$

Pair loading softens the dependence

$$\gamma_{\rm cutoff} \sim \sigma_{\rm LC} \propto B_{\rm LC}^2/\eta n_{\rm GJ}$$

Expect cutoff energy dependence to be between $E_{\rm cutoff} \propto B_{\rm LC}^{1.2}\text{-}B_{\rm LC}^{1.8}$ and $E_{\rm cutoff} \propto B_{\rm LC}^{-0.8}\text{-}B_{\rm LC}^{-0.2}$

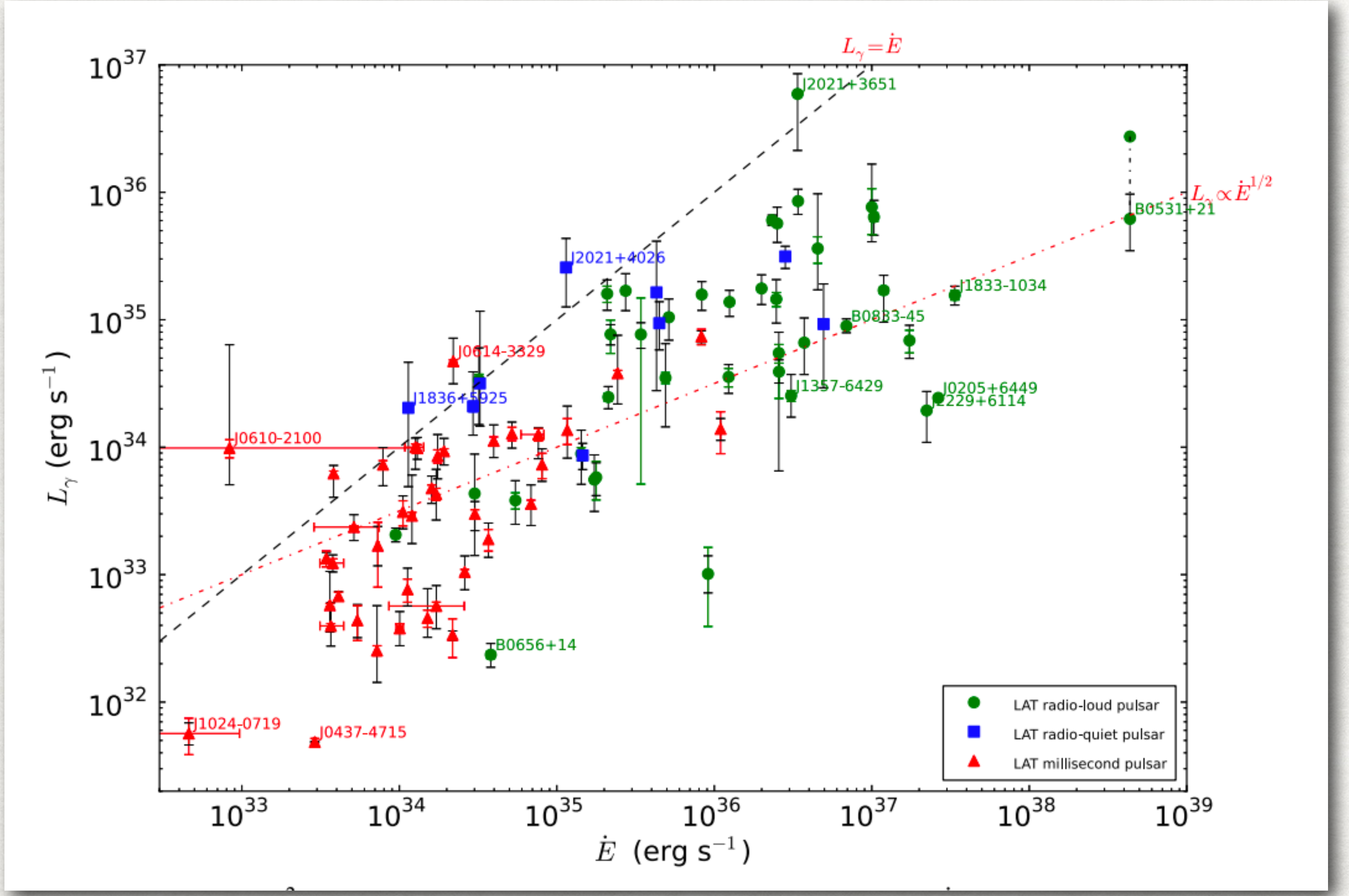
Observed dependence: $E_{\rm cutoff} \propto B_{\rm LC}^{0.1}\text{-}B_{\rm LC}^{0.2}$

Hakobyan, Philippov, AS 2018

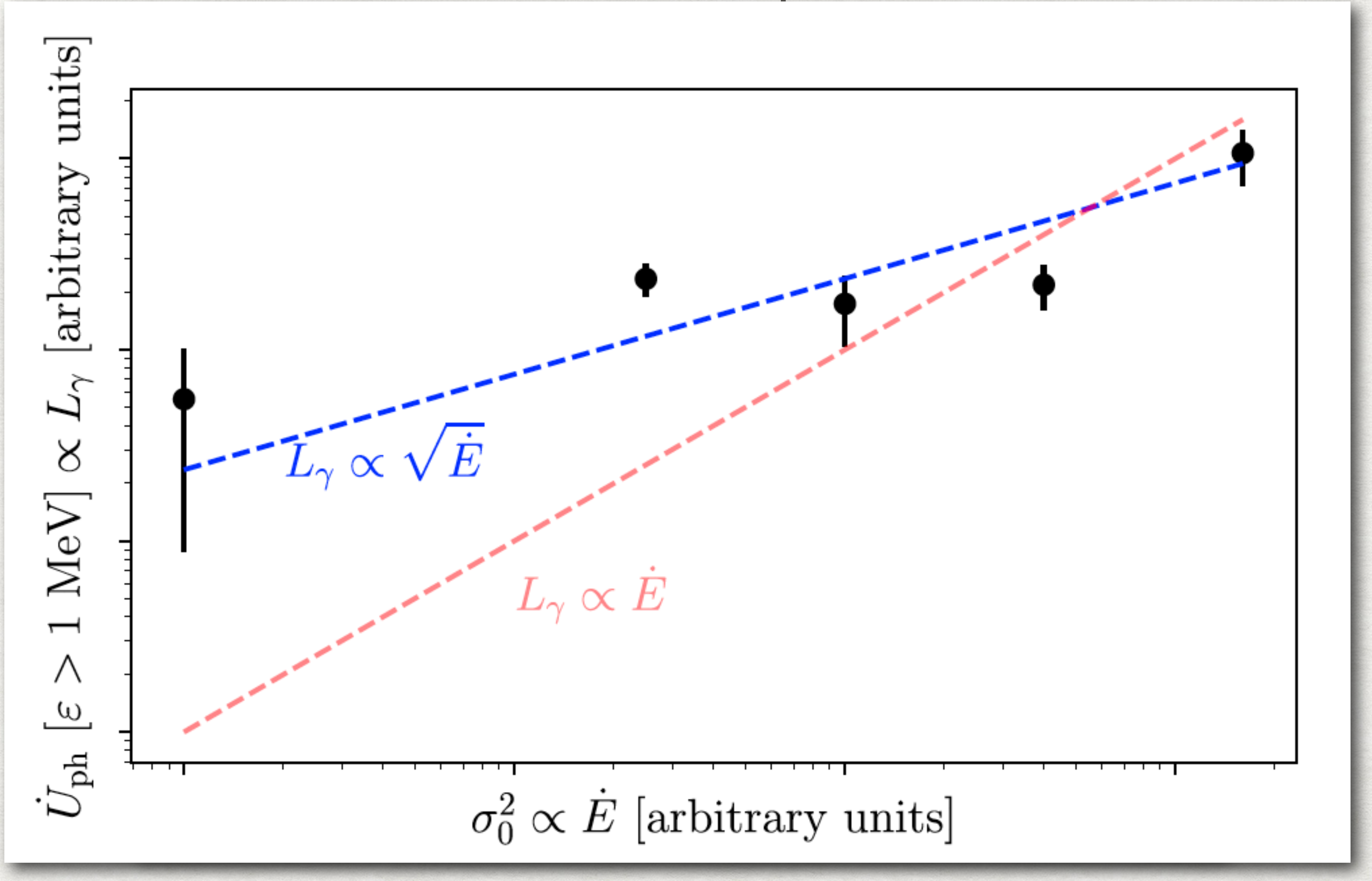
THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING L_γ

Gamma luminosity is larger for aligned rotators than for oblique ones. $L_\gamma/\dot{E}$ varies from 1% for orthogonal rotator to 10% for near aligned. Obliqueness effects can explain the spread in observed values of L_γ . In this regime $L_\gamma \propto \dot{E}$. Another model: curvature emission cf: Kalapotharakos et al 2019

Pair formation in the current sheet decreases magnetization and lowers maximum particle energy, and radiative efficiency decreases. Also, reconnection slows down. This leads to slower Edot dependence.



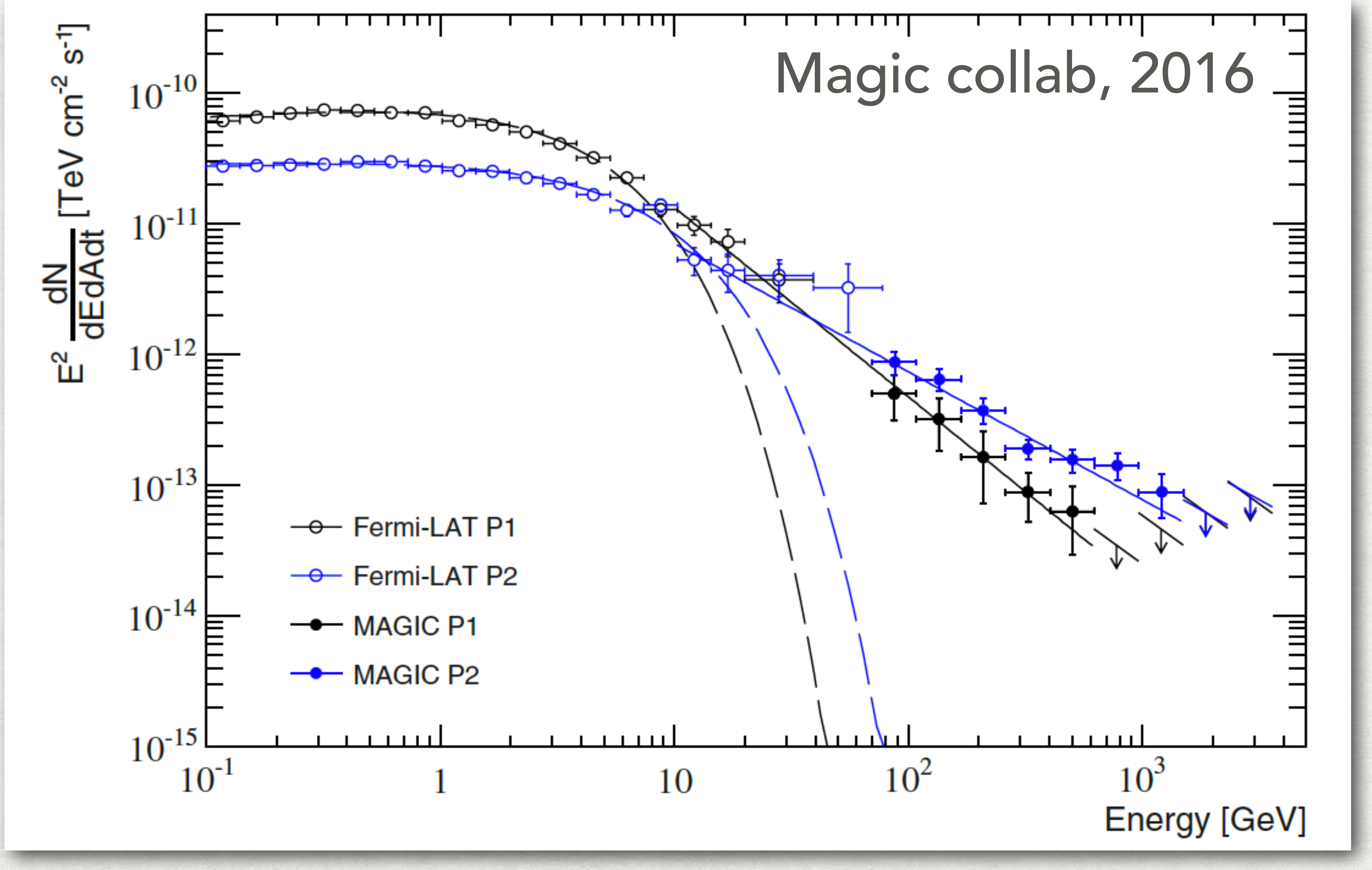
Abdo et al 2013

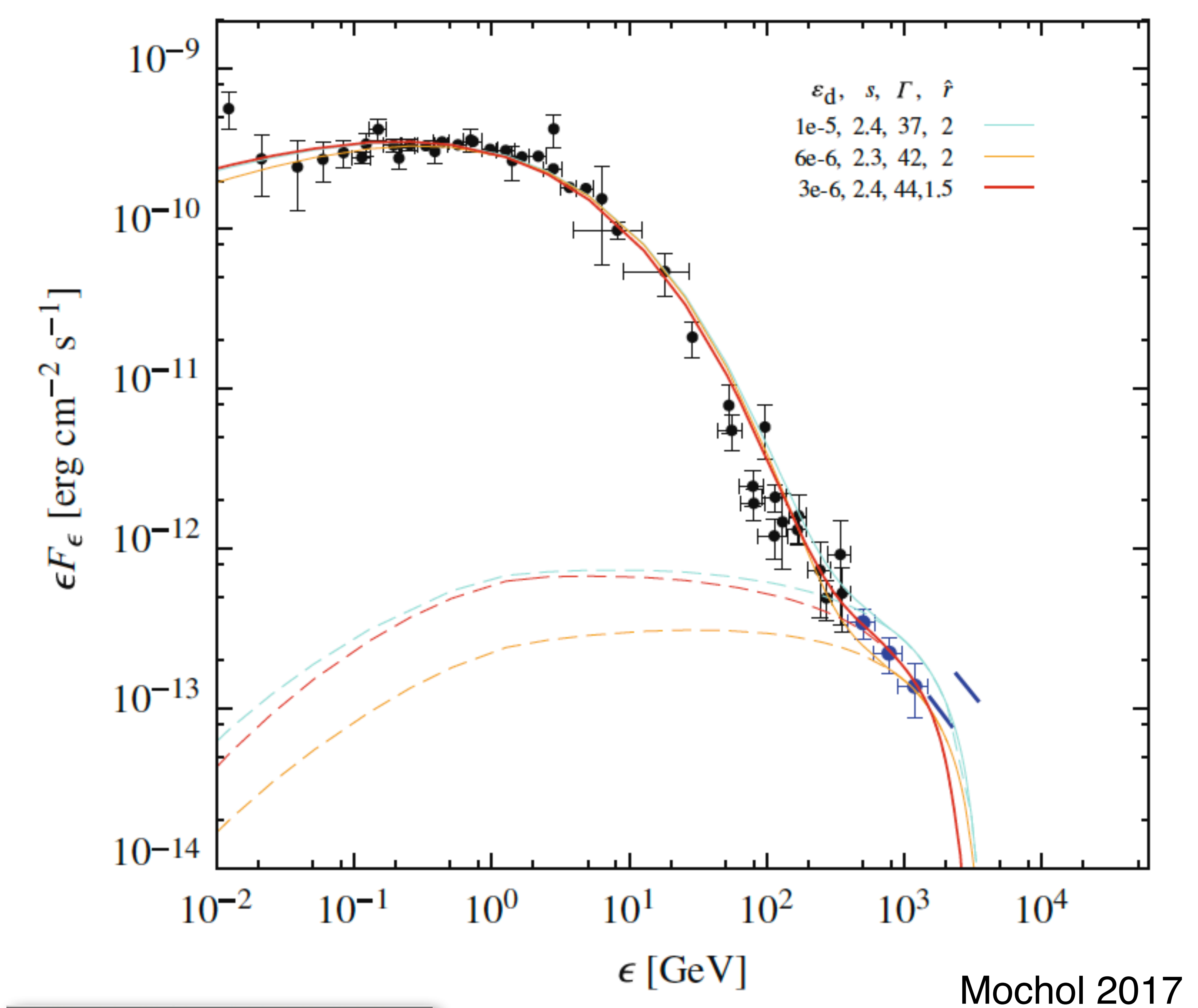


Hakobyan, Philippov, AS 2018

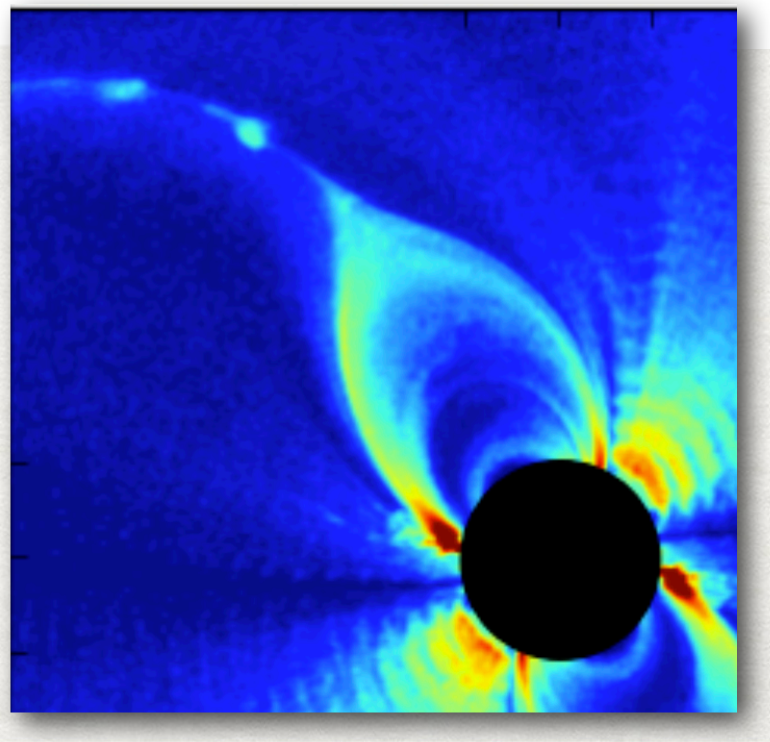
PULSED TEV EMISSION

- IACT detection of pulsed TeV: new component or IC?
- Direct IC would imply particles with gamma~10^7 in the current sheet — hard to obtain in reconnection without direct Ell acceleration (Harding et al 18).
- SSC of current-sheet accelerated particles +doppler boost due to bulk wind motion (Mochol 17) is more natural. More modeling needs to be done!



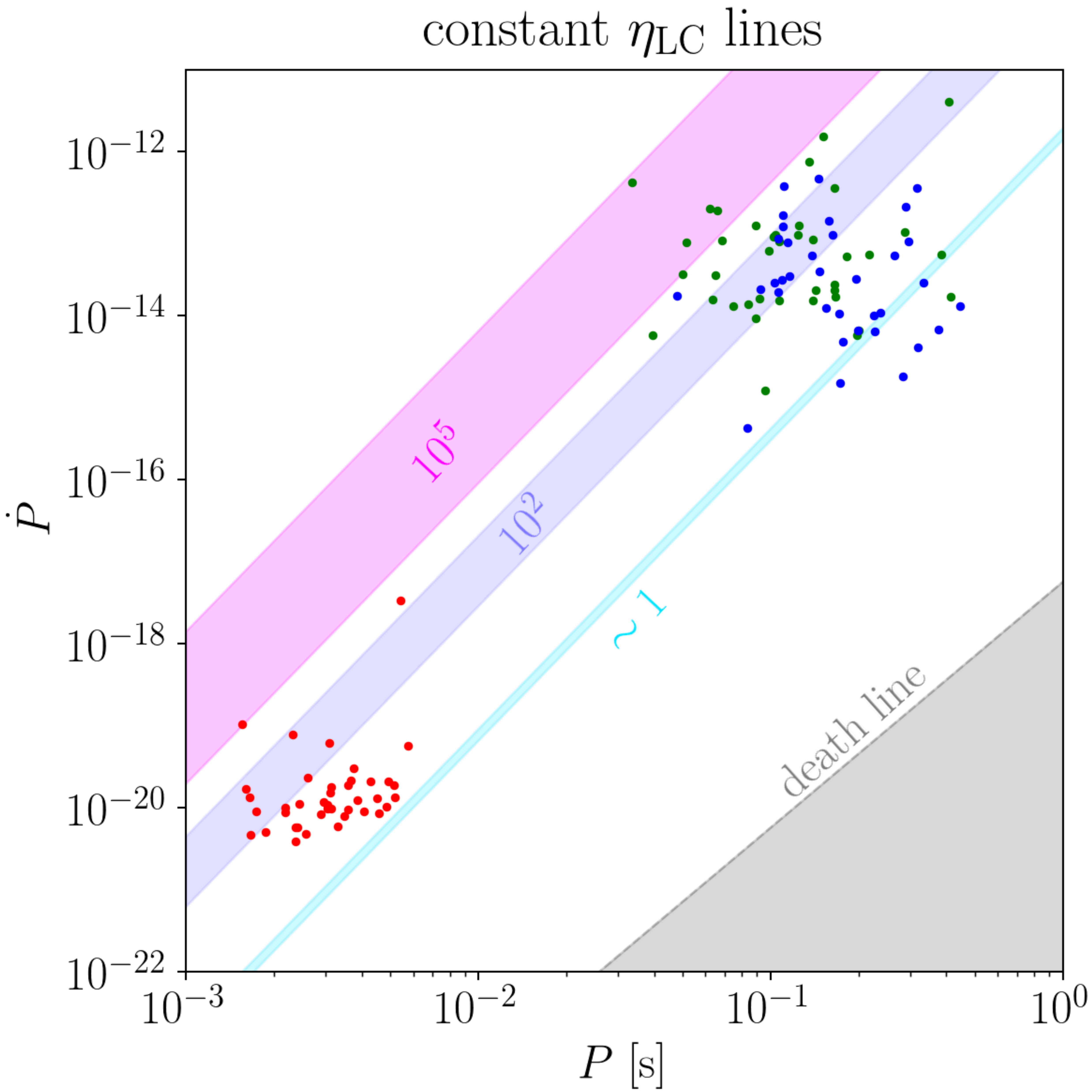


Mochol 2017



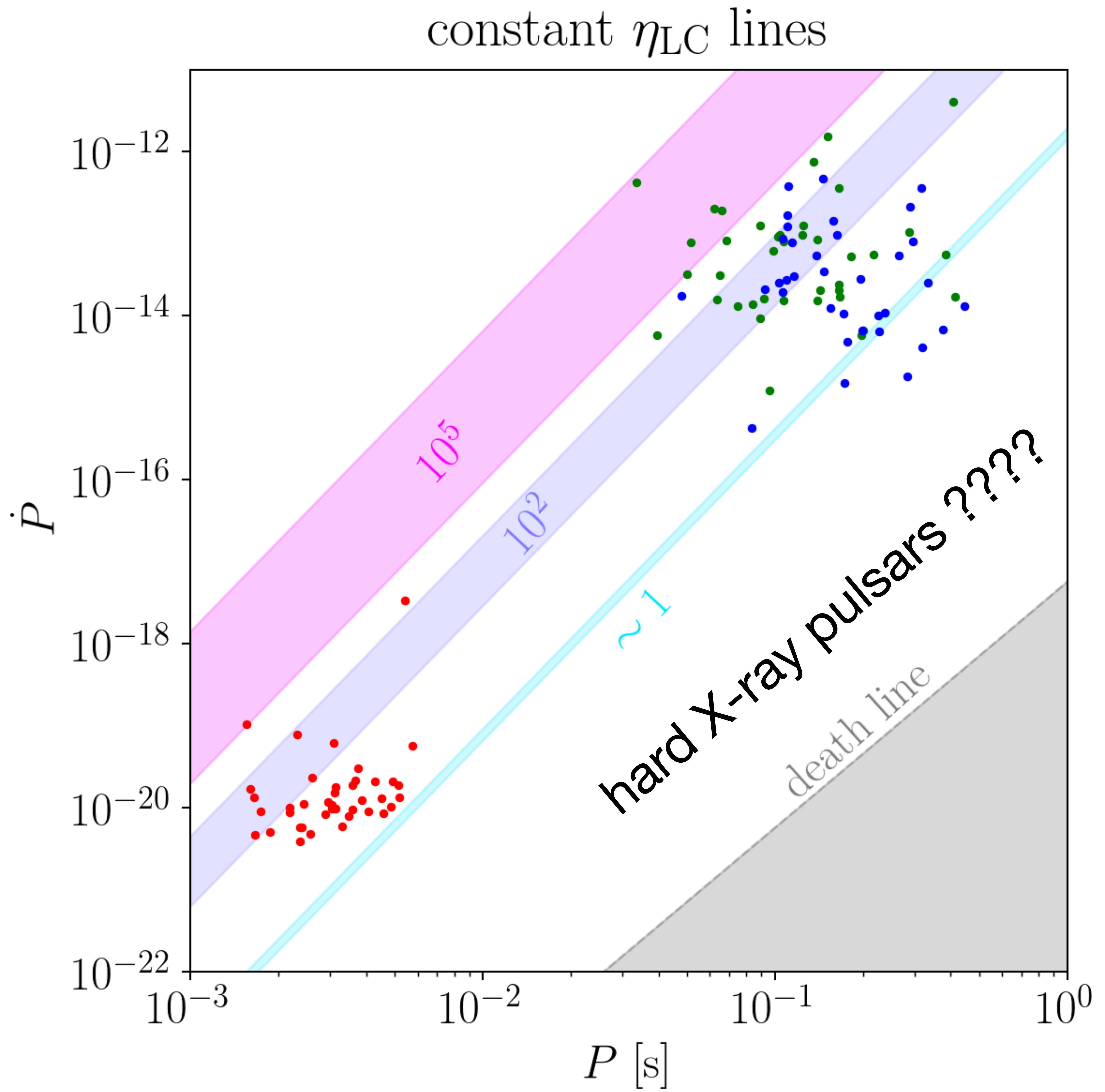
Recap

- ɣ-ray emission in pulsars is most likely generated by particles accelerated in the reconnecting current sheet
- Two-photon pair production must be a very efficient source of pair loading in most of the ɣ-ray pulsars
- Acceleration is self-consistently controlled by the amount of secondary plasma produced
- Weak scaling of E_{cut} on B_{LC} and the scaling of $L_ɣ$ on $\dot{E}$ can be explained by this effect

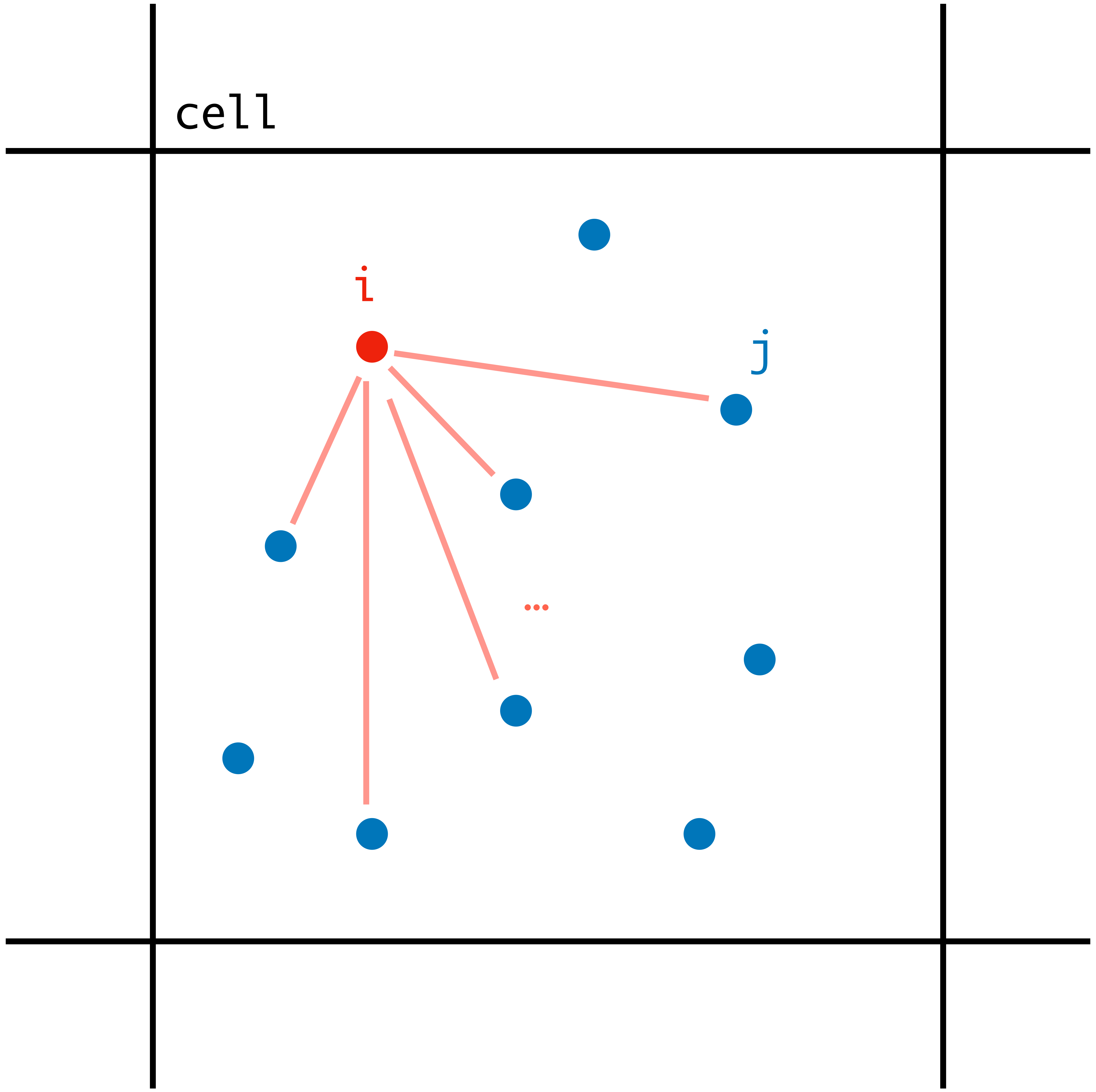


Future…

- What's going on in the global 3D pulsar magnetosphere with this effect turned on?
- Does this plasma escape to the wind (i.e., enrich PWN)? What fraction returns back to the inner magnetosphere?
- Are there any hard X-ray pulsars? If they don't have pair-production, what does the scaling of E_{cut} on B_{LC} look like for them?
- Other objects? (coronae, blazar jet flares, magnetar flares, etc)



Binary pair production



> Sort particles and find all the particles in a given cell : $O(N^2)$

> Pair production : $O(N^2)$

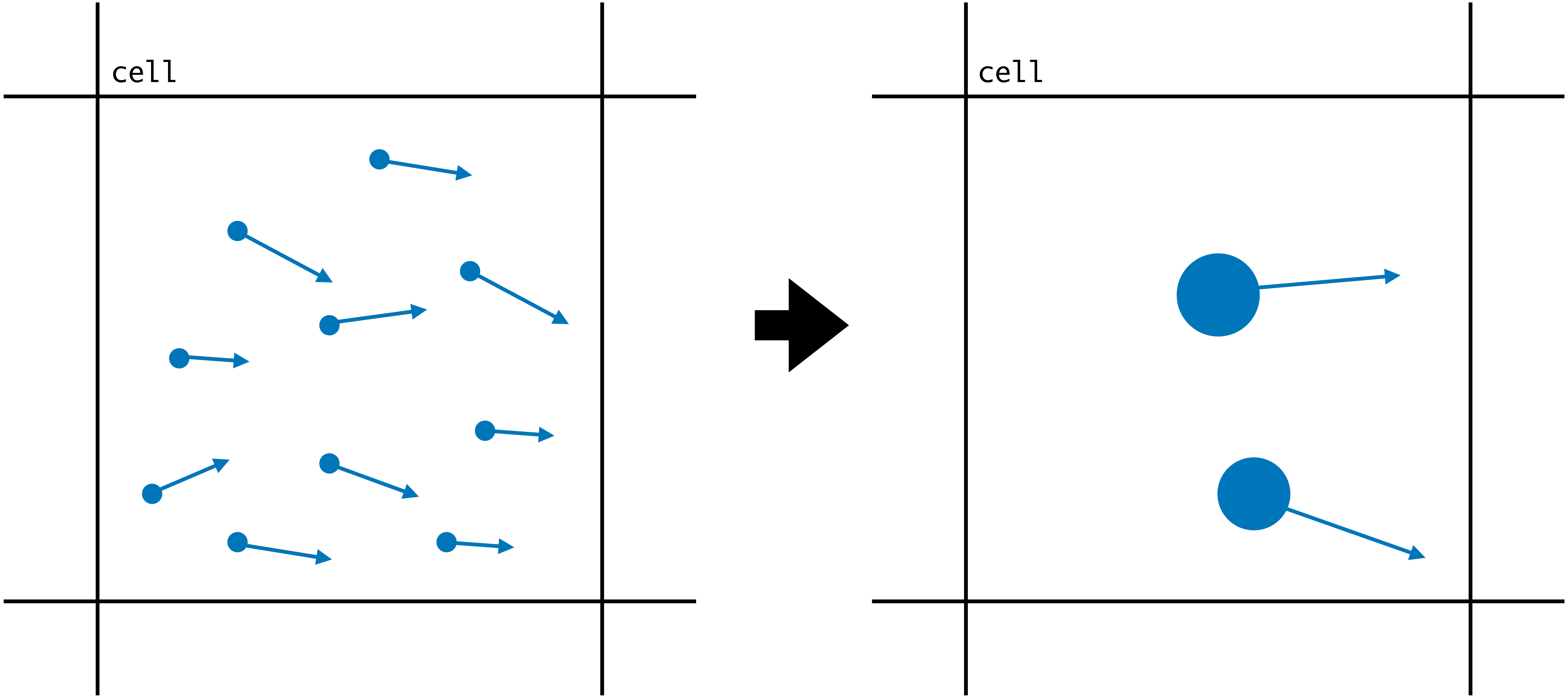
1. Loop over all particles i
2. For each i find all pairs ij, and compute the cross sections σ_{ij}
3. Generate a random number and pair produce according to the cross sections
4. Repeat 1-3 for all particles i

Problems:

1. Expensive computationally $O(N^2)$
2. High memory usage (some problems require too many photons/pairs)

Improving the efficiency

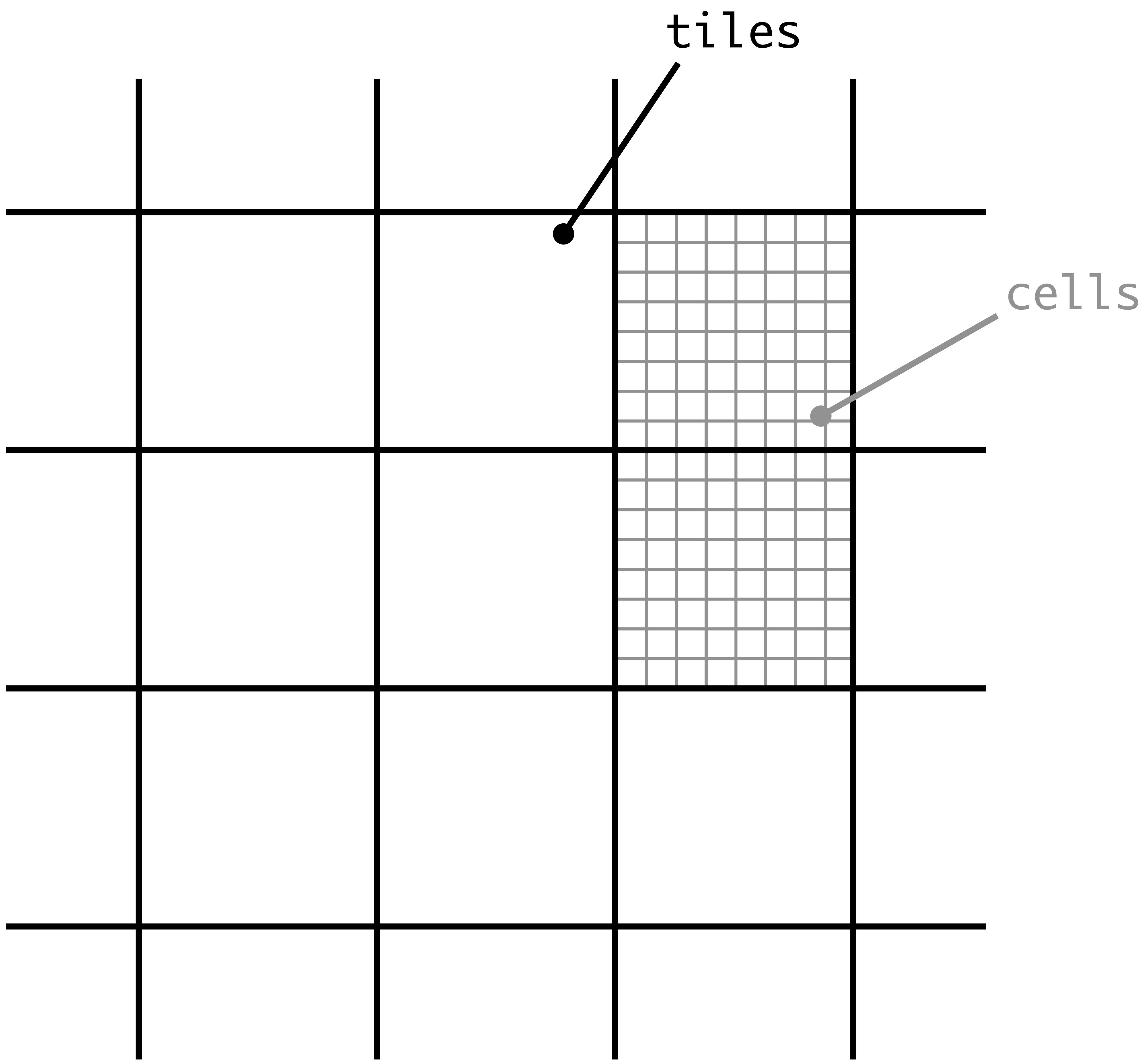
1. particle downsampling



> downsampling conserves both energy and momentum

Improving the efficiency

2. usage of particle tiles



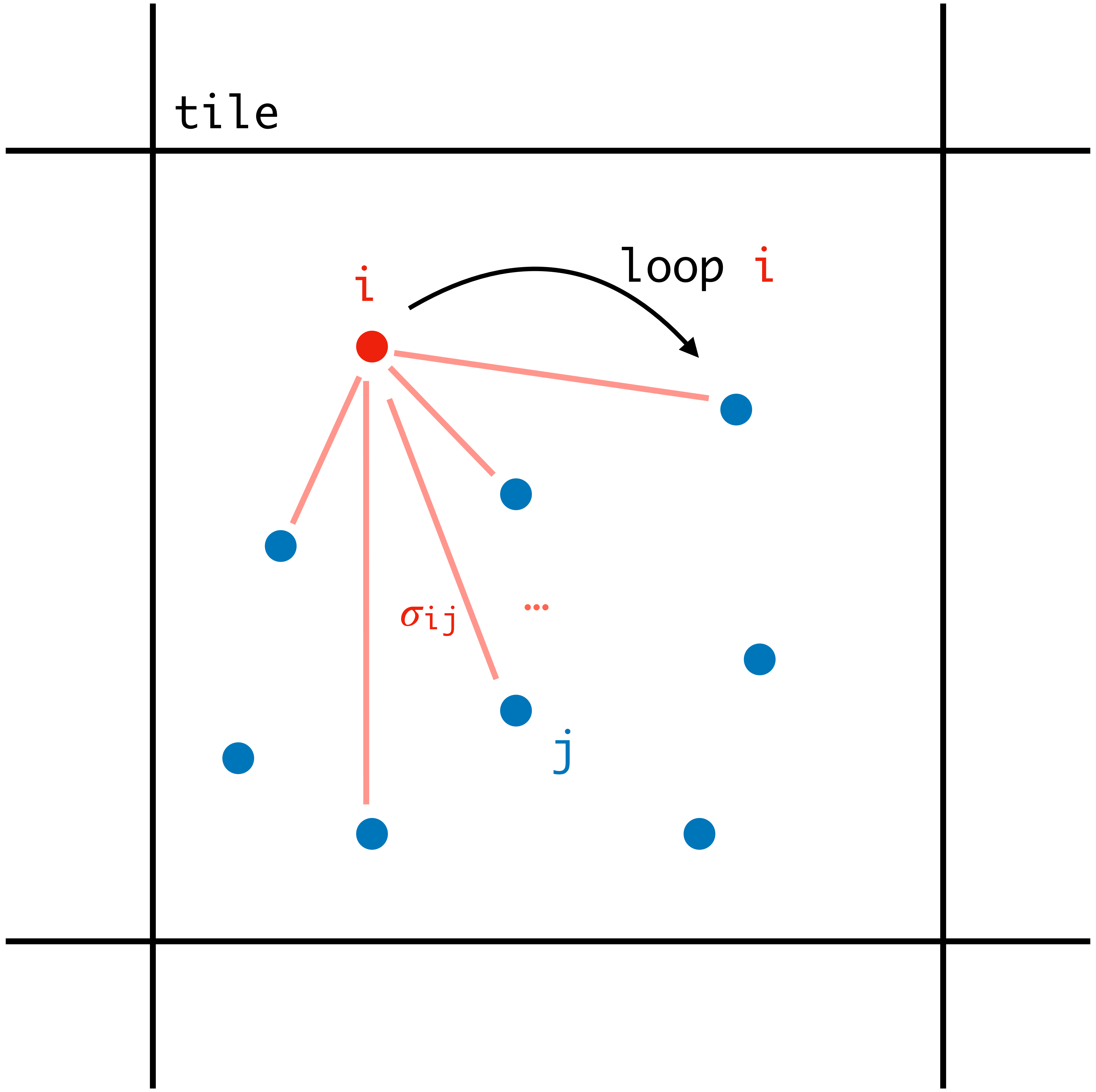
> particles are stored on tiles, so no need to find neighbors

> sizes of these tiles (in cells) can be varied

Improving the efficiency

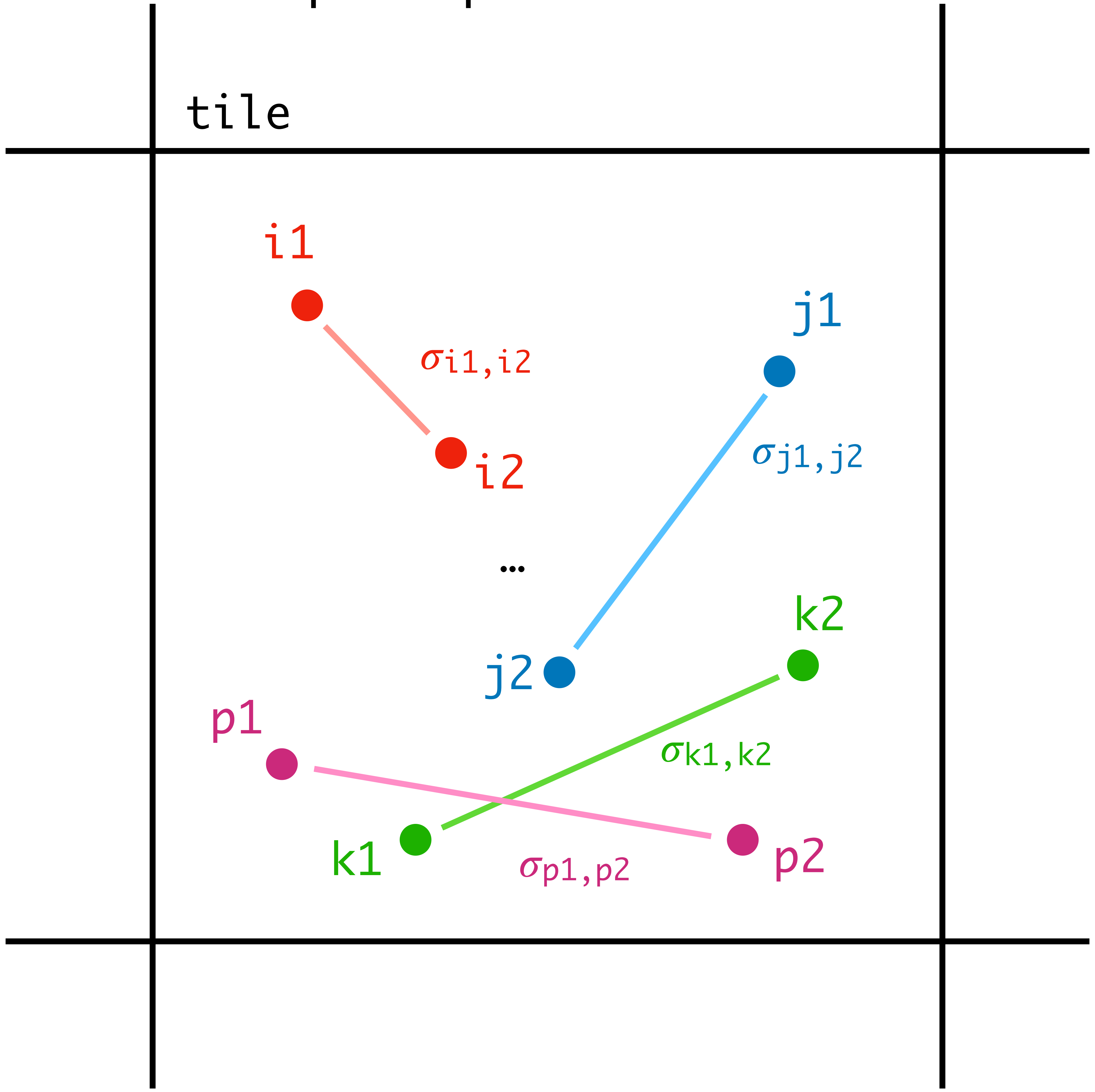
3. Monte Carlo pairing

> randomly pair photons
> compute cross sections, and multiply by N
> pair produce



binary pairing : O(N²)

vs



MC pairing : O(N)