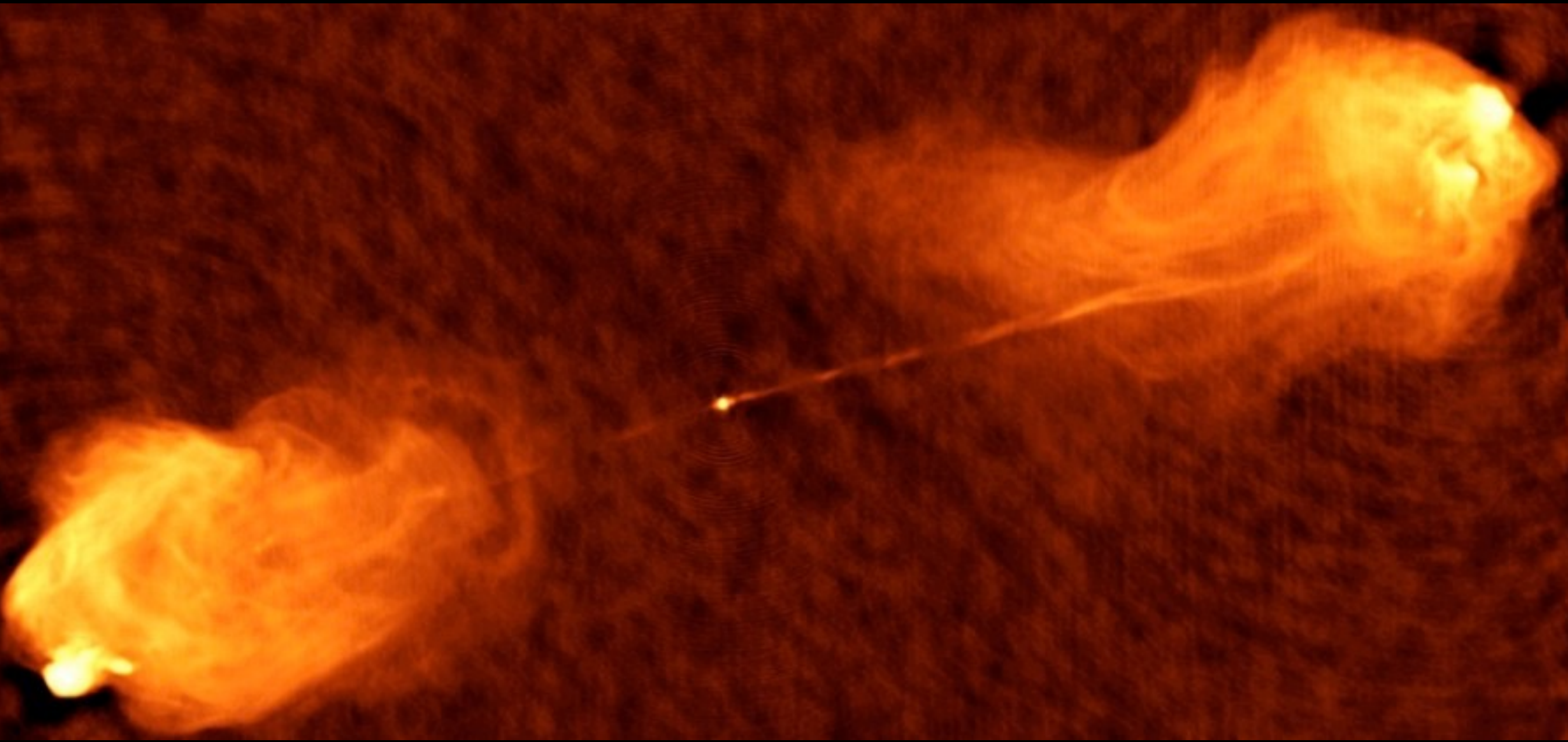
The journey of high-energy photons from blazar jets to the *Fermi* telescope

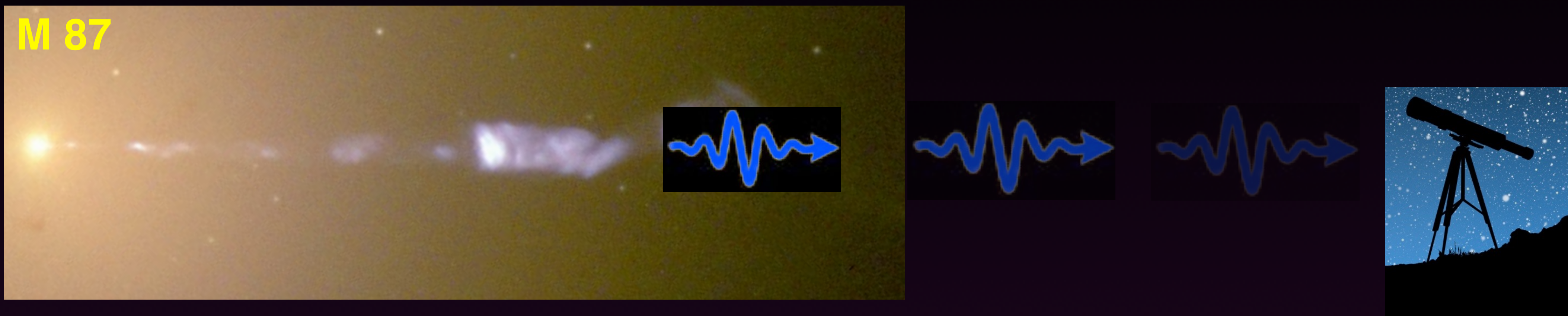


Lorenzo Sironi (ITC-Harvard → Assistant Prof. at Columbia U.)

Sixth International Fermi Symposium, November 12^{th} 2015

with: D. Giannios, M. Petropoulou, A. Spitkovsky

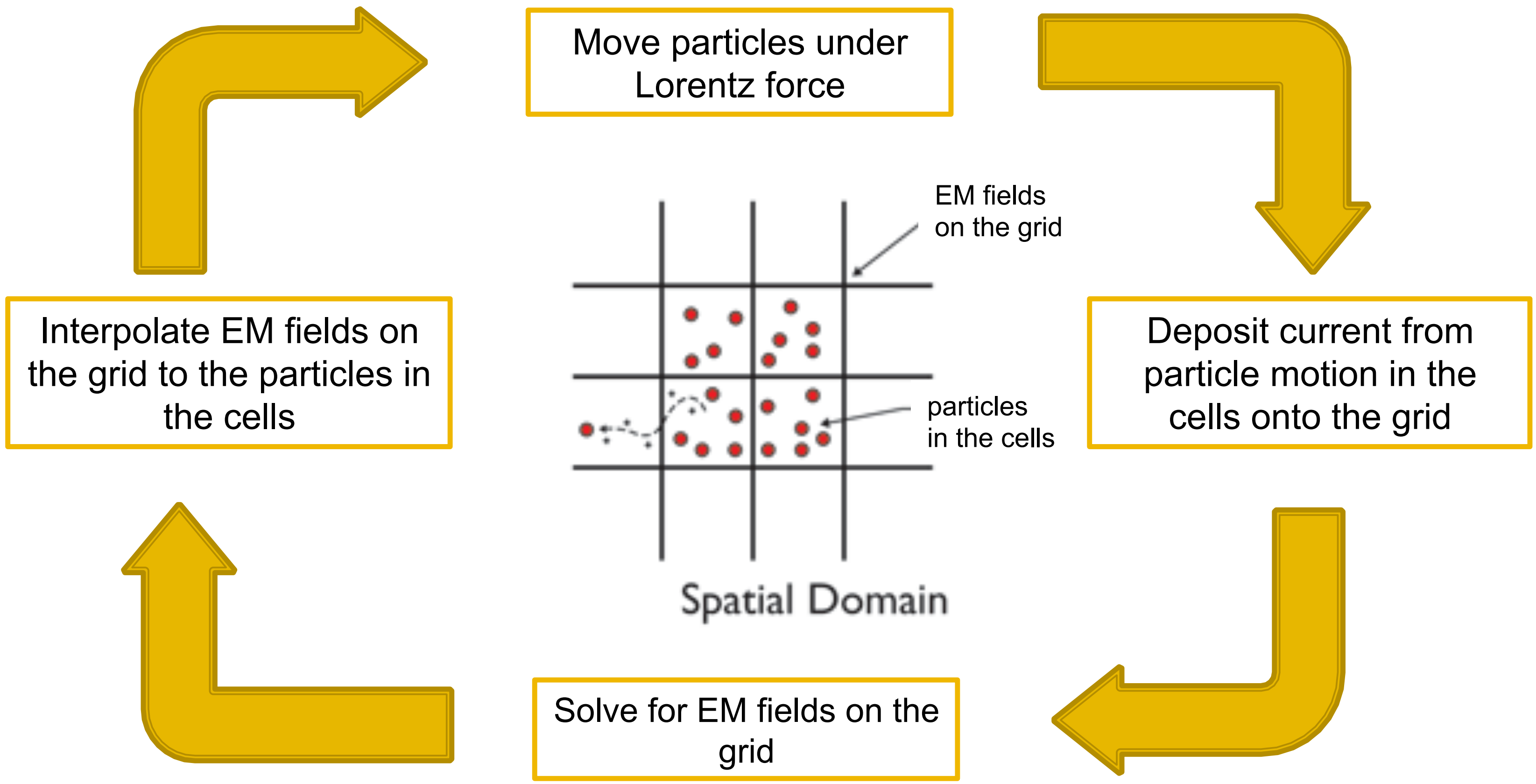
Outline



- The Dawn (i.e., the origin of non-thermal emission in blazar jets): magnetic reconnection as the accelerator of non-thermal particles

- The Sunset (i.e., the fate of TeV photons from distant blazars): blazar-induced plasma instabilities in the intergalactic medium

The PIC method



No approximations, full plasma physics of ions and electrons

Tiny length-scales (c/ω_p) and time-scales (ω_p^{-1}) need to be resolved: $\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$

➔ huge simulations, limited time coverage

- Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 93, Spitkovsky 05, LS+ 13,14)


The dawn of blazar photons

Powerful emission and hard spectra

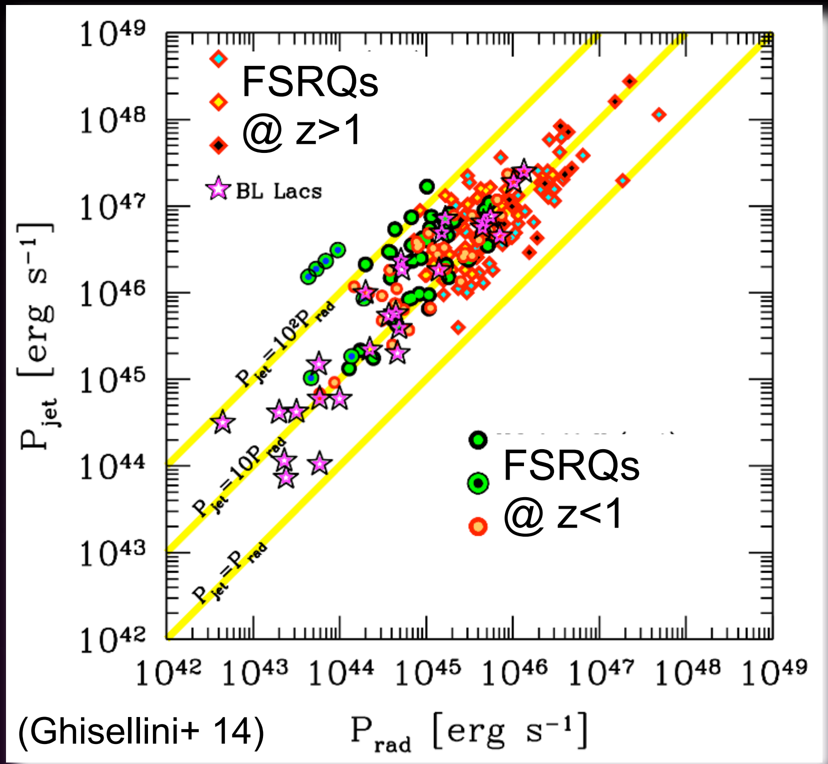
Blazar phenomenology:

(1) blazars are efficient emitters (radiated power ~ 10% of jet power)

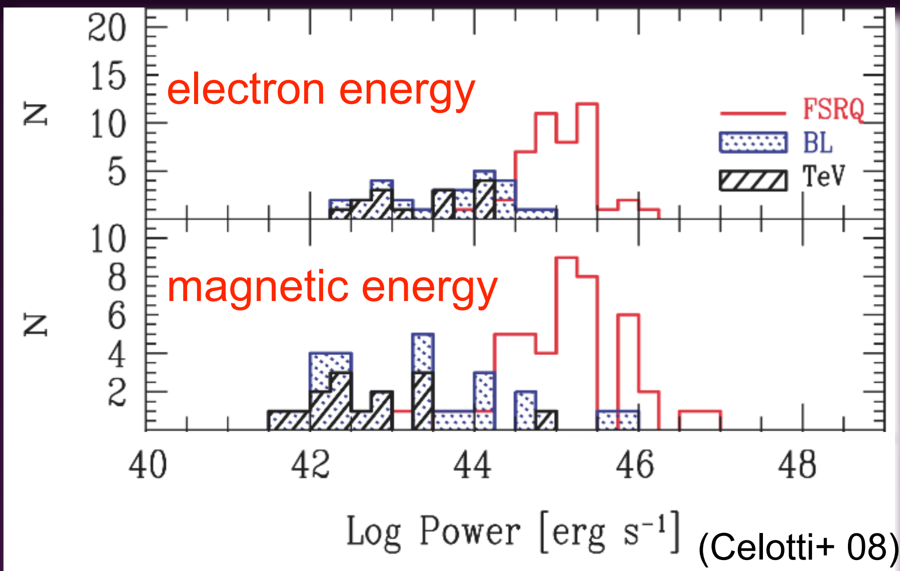
(2) rough energy equipartition between emitting particles and magnetic field

(3) extended power-law distributions of the emitting particles, with hard slope

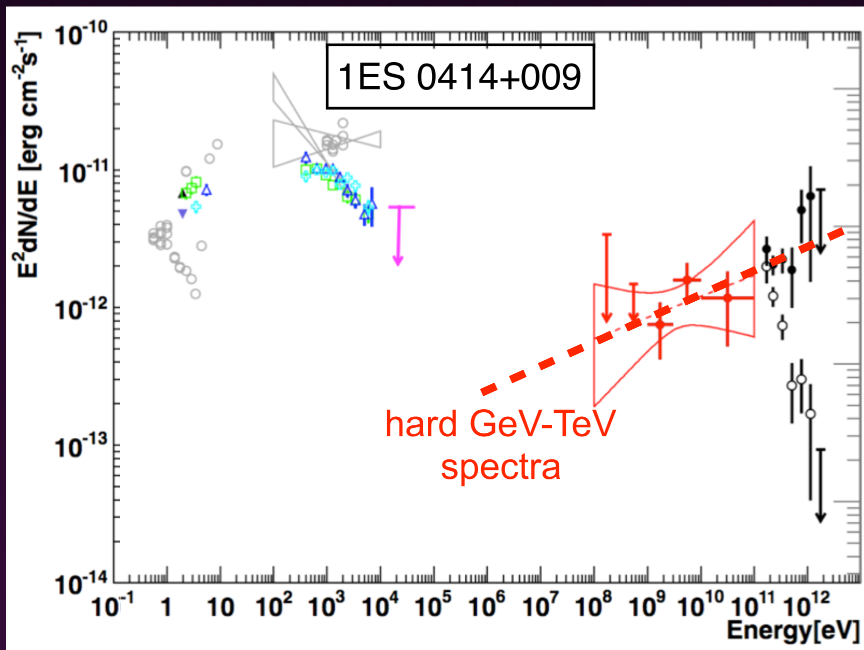
$$\frac{dn}{d\gamma} \propto \gamma^{-p} \quad p \lesssim 2$$



(Ghisellini+ 14)

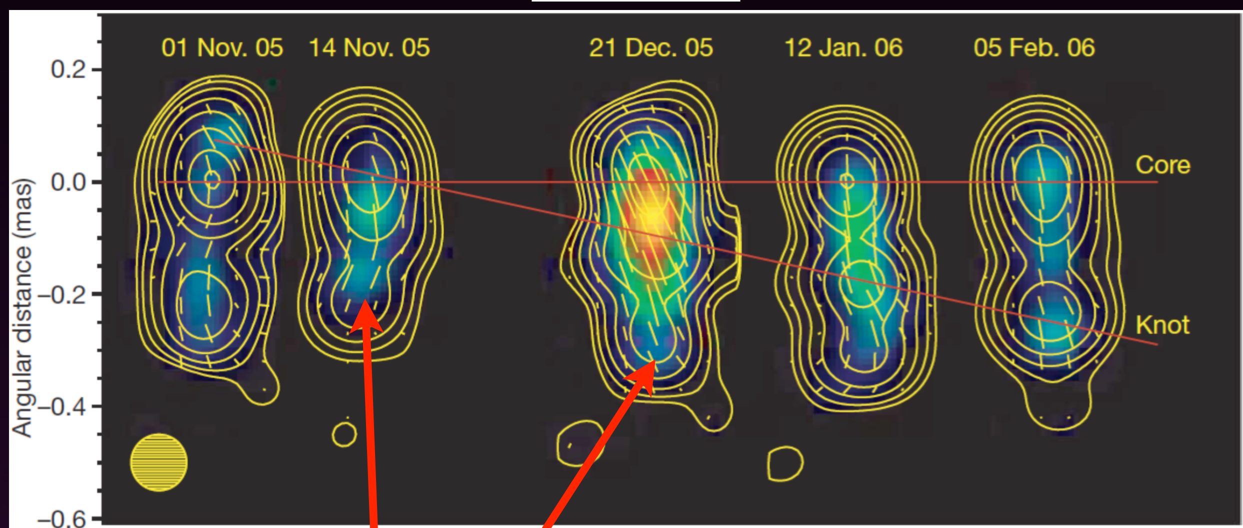


(Celotti+ 08)



Internal dissipation in blazar jets

BL Lac



(Marscher et al. 08)

Internal Dissipation:
Shocks or Reconnection?

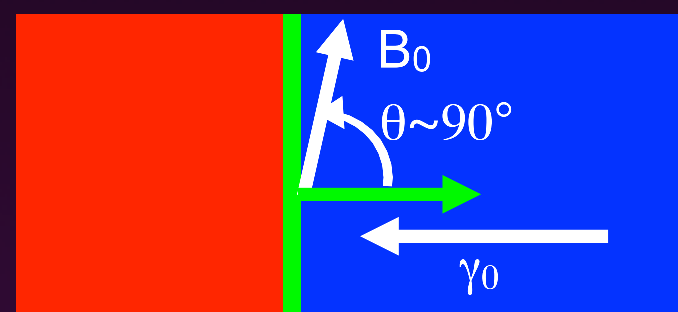
Internal shocks in blazars:

- trans-relativistic (γ_0~a few)
- magnetized (σ>0.01)

$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$

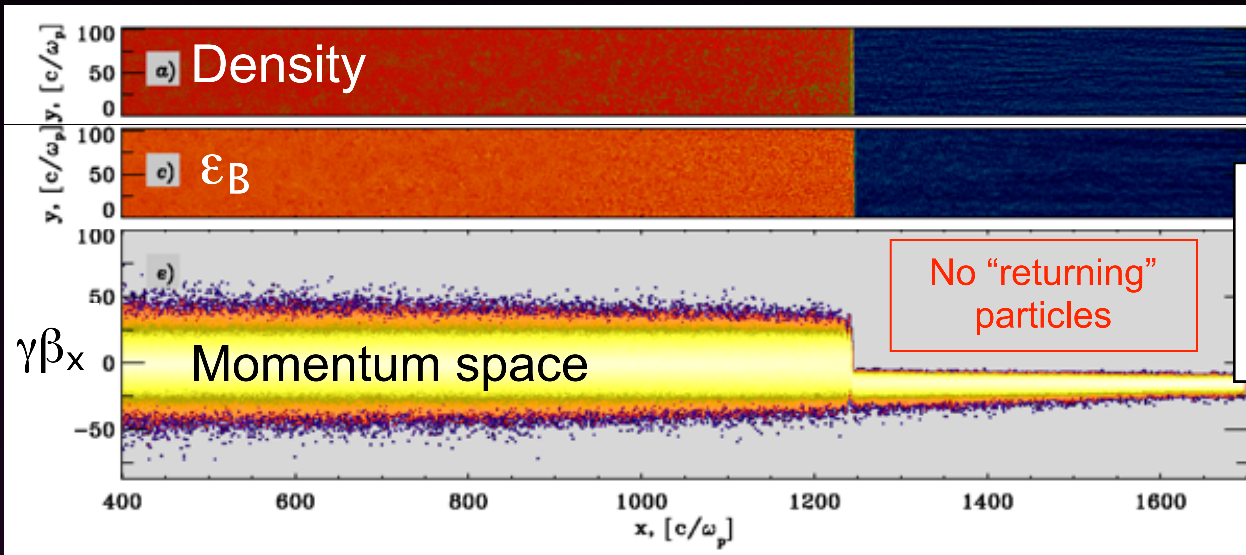
- toroidal field around the jet

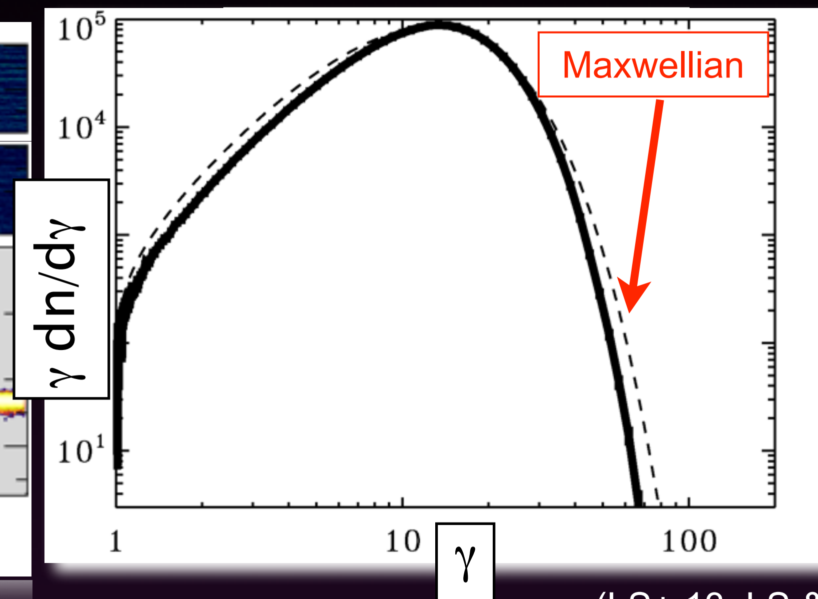
→ field ⊥ to the shock normal



Shocks: no turbulence → no acceleration

$\sigma=0.1$ $\theta=90°$ $\gamma_0=15$ e^--e^+ shock



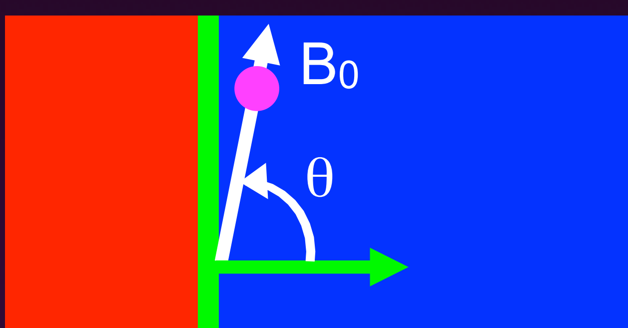


(LS+ 13, LS & Spitkovsky 09,11)

No “returning” particles → No self-generated turbulence

No self-generated turbulence → No particle acceleration

Strongly magnetized ($\sigma>10^{-3}$) quasi-perp $\gamma_0 \gg 1$ shocks are poor particle accelerators:



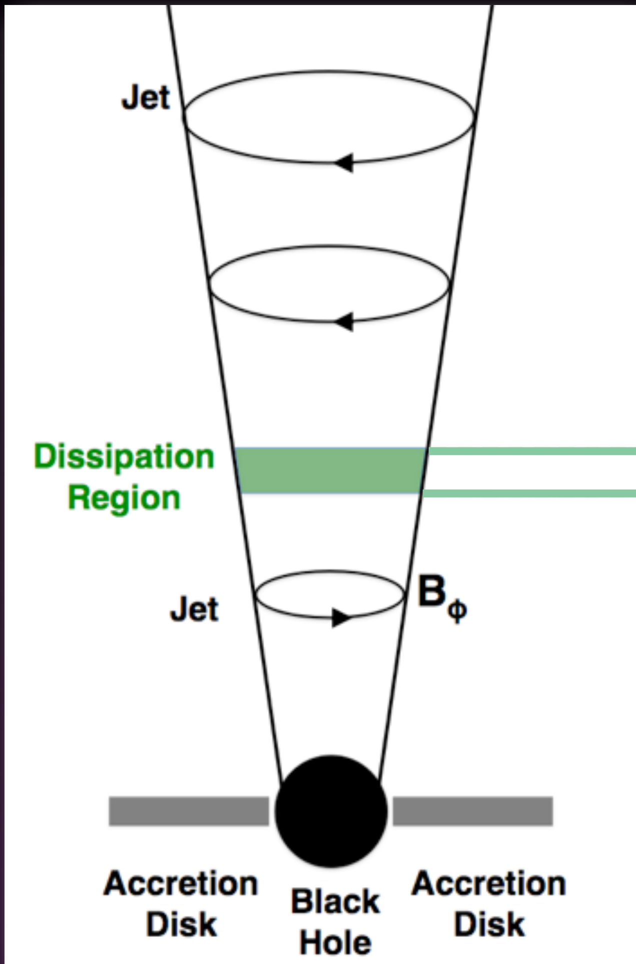
σ is large → particles slide along field lines

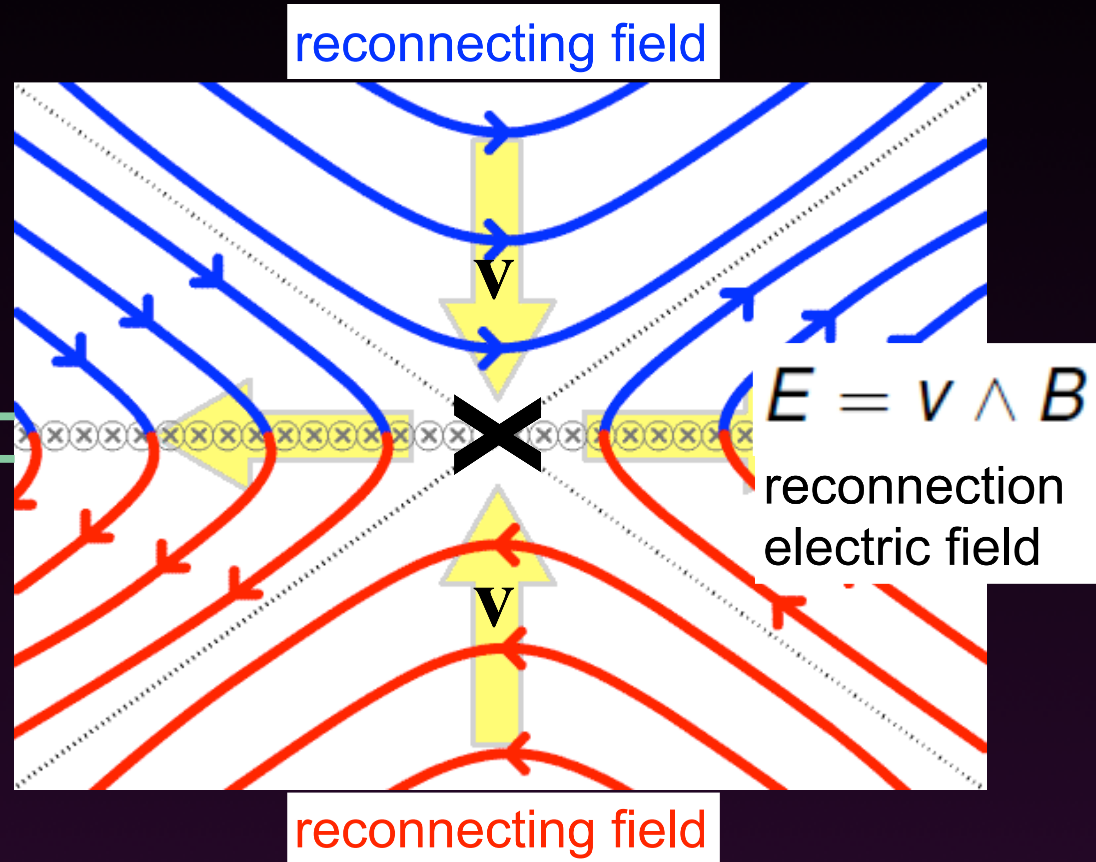
θ is large → particles cannot outrun the shock

unless v>c (“superluminal” shock)

→ Fermi acceleration is generally suppressed

Relativistic magnetic reconnection





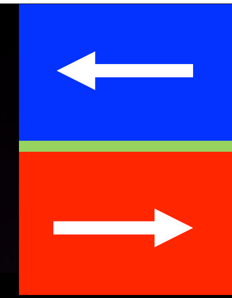
Relativistic Reconnection

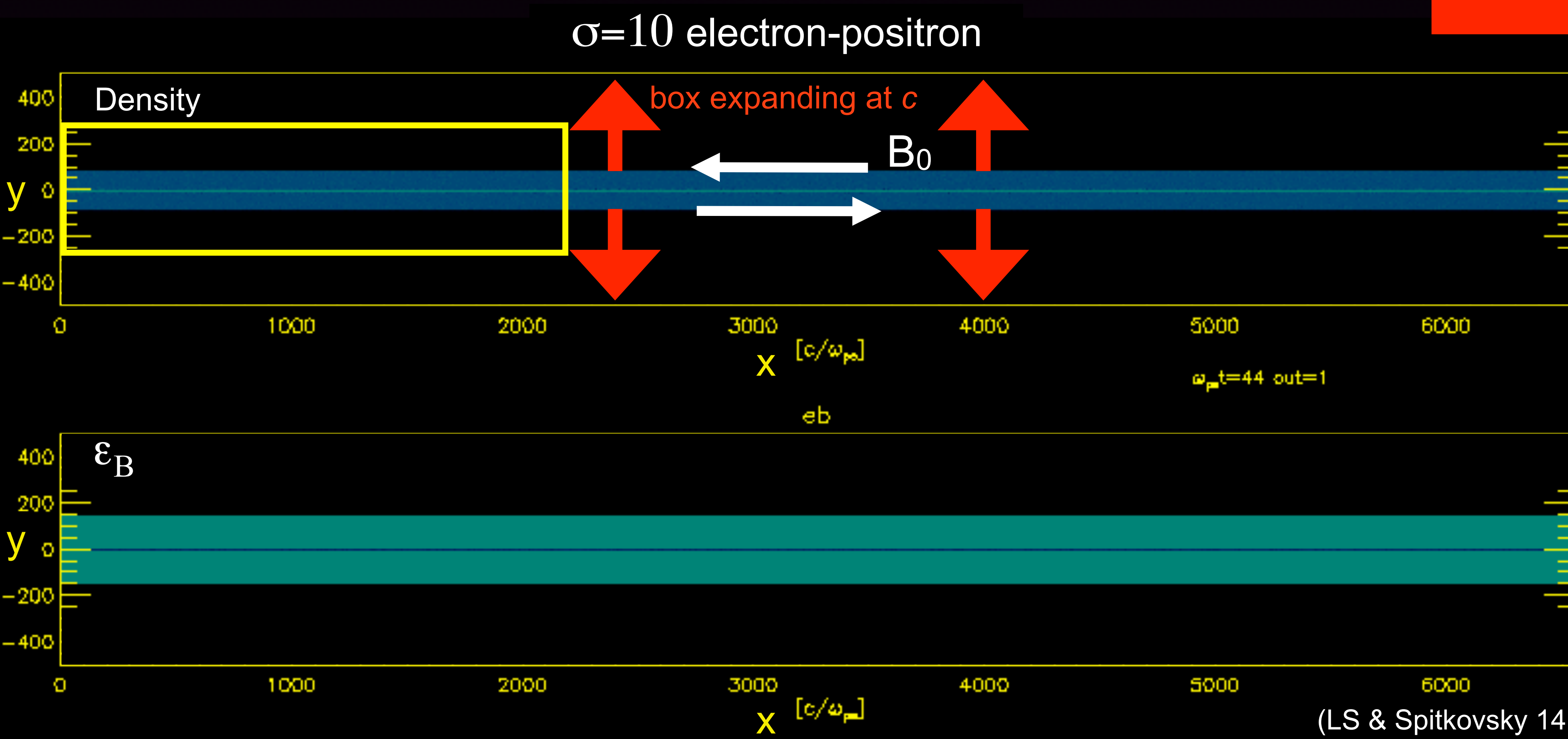
$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \gg 1 \qquad v_A \sim c$$

Can relativistic reconnection self-consistently produce non-thermal particles?

Dynamics and particle spectrum

Hierarchical reconnection

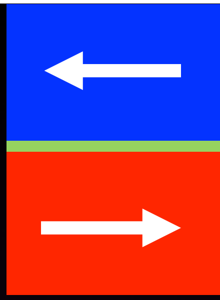




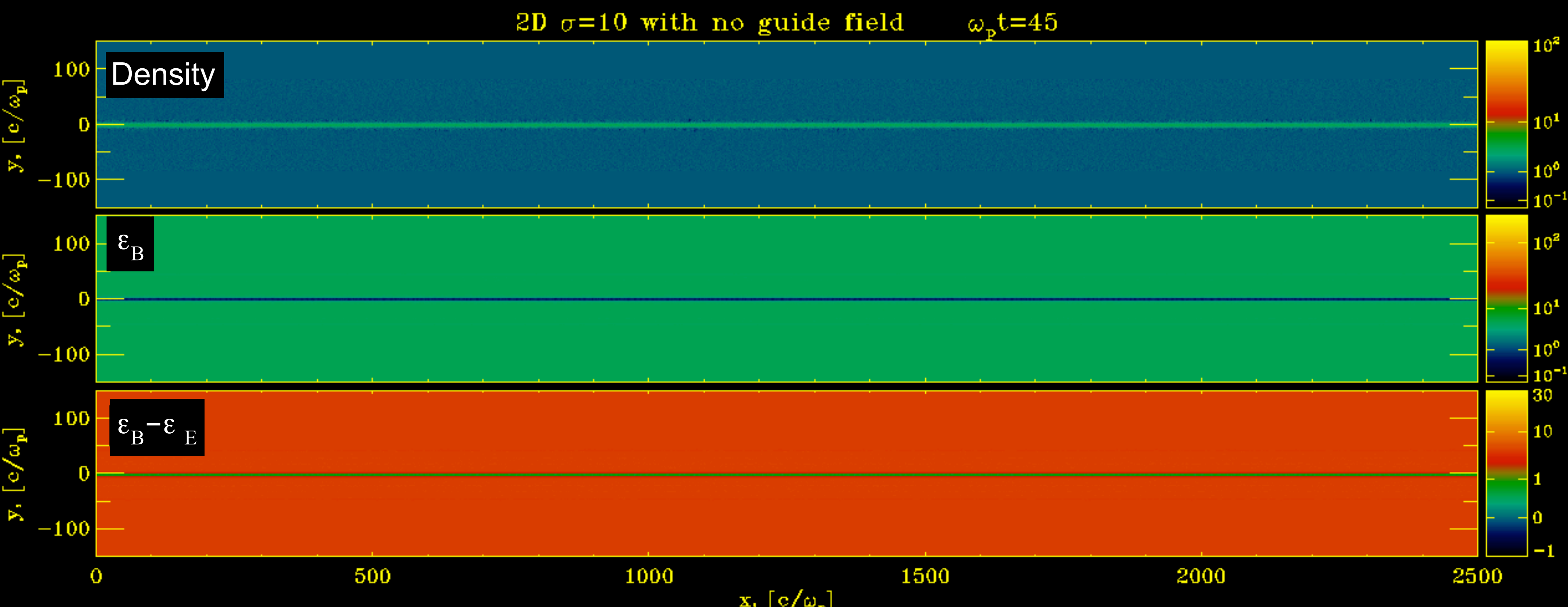
(LS & Spitkovsky 14)

- Reconnection is a hierarchical process of island formation and merging (e.g., Uzdensky 10).
- The field energy is transferred to the particles at the X-points, in between the magnetic islands.

Hierarchical reconnection

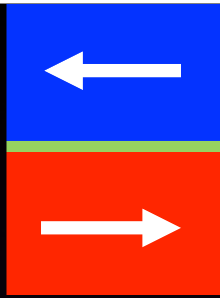


σ=10 electron-positron



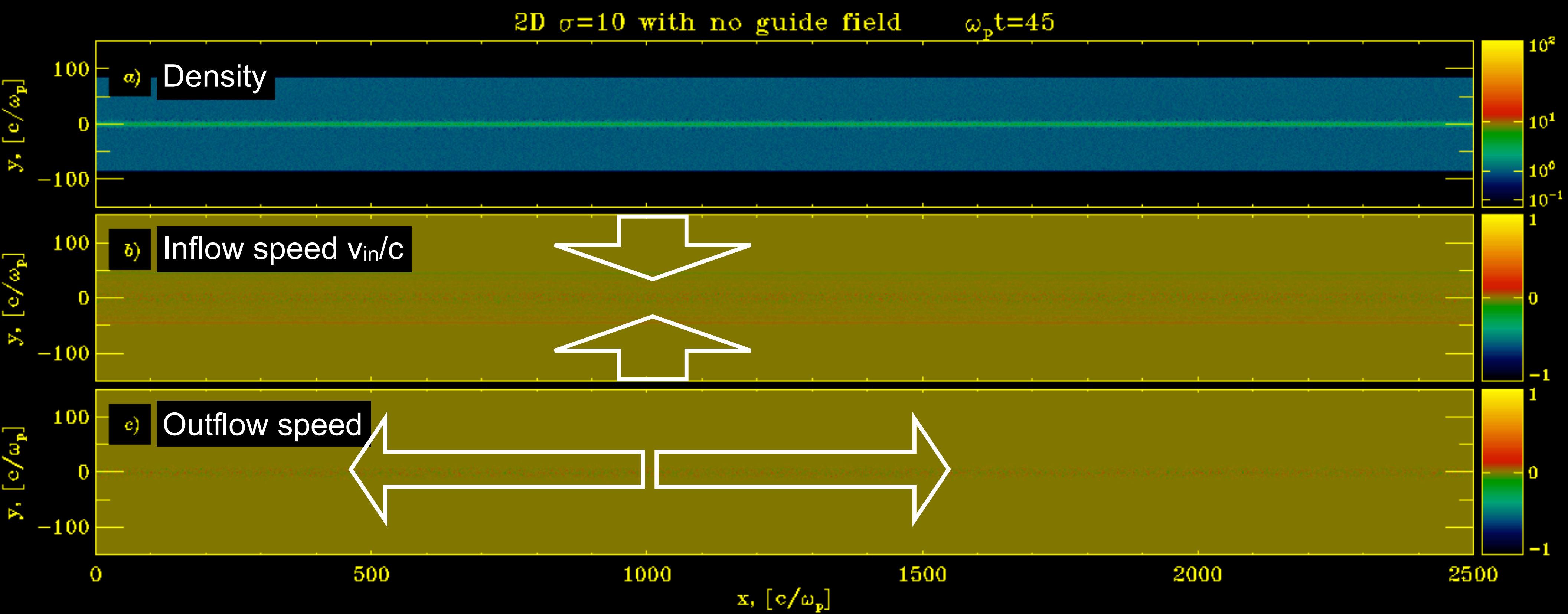
(LS & Spitkovsky 14)

- The current sheet breaks into a series of secondary islands (e.g., Loureiro+ 07, Bhattacharjee+ 09, Uzdensky+ 10, Huang & Bhattacharjee 12, Takamoto 13).
- The field energy is transferred to the particles at the X-points, in between the magnetic islands.
- Localized regions exist at the X-points where E>B.



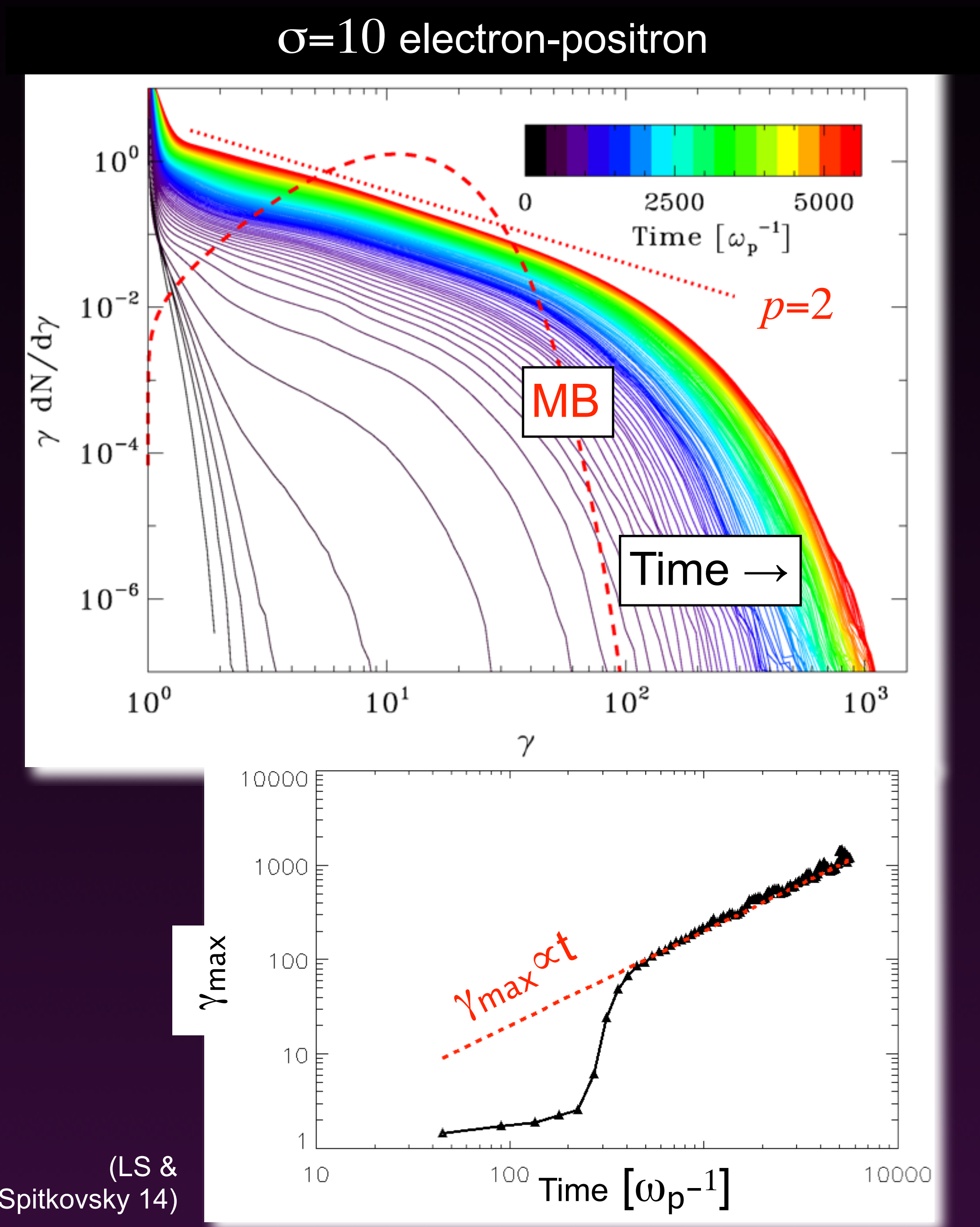
Inflows and outflows

σ=10 electron-positron



- Inflow into the X-line is non-relativistic, at v_{in} ~ 0.1 c (Lyutikov & Uzdensky 03, Lyubarsky 05)
- Outflow from the X-points is ultra-relativistic, reaching the Alfven speed $v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$

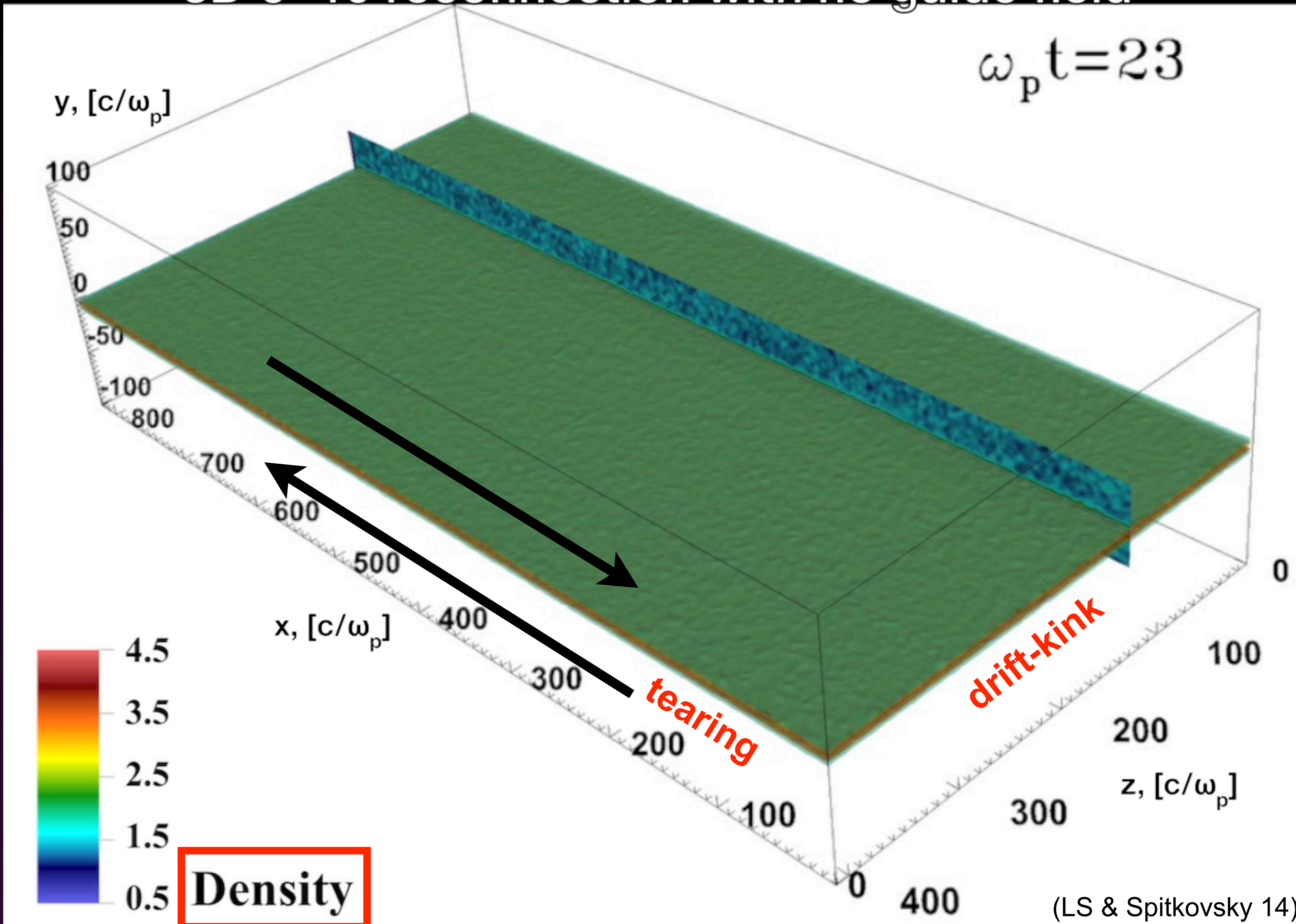
The particle energy spectrum



(LS & Spitkovsky 14)

- At late times, the particle spectrum in the current sheet approaches a power law $dn/d\gamma \propto \gamma^{-p}$ of slope $p\sim2$.
- The normalization increases, as more and more particles enter the current sheet.
- The mean particle energy in the current sheet reaches $\sim\sigma/4$ → rough energy equipartition
- The max energy grows as $\gamma_{max} \propto t$ (compare to $\gamma_{max} \propto t^{1/2}$ in shocks).

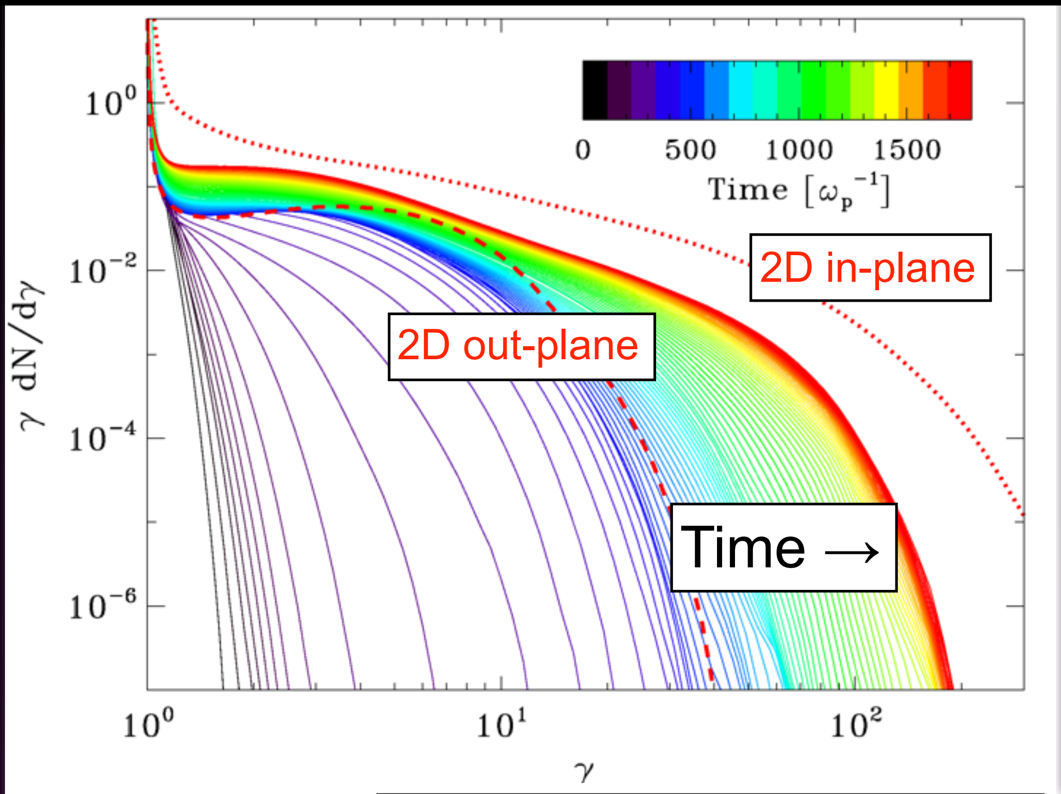
3D σ=10 reconnection with no guide field

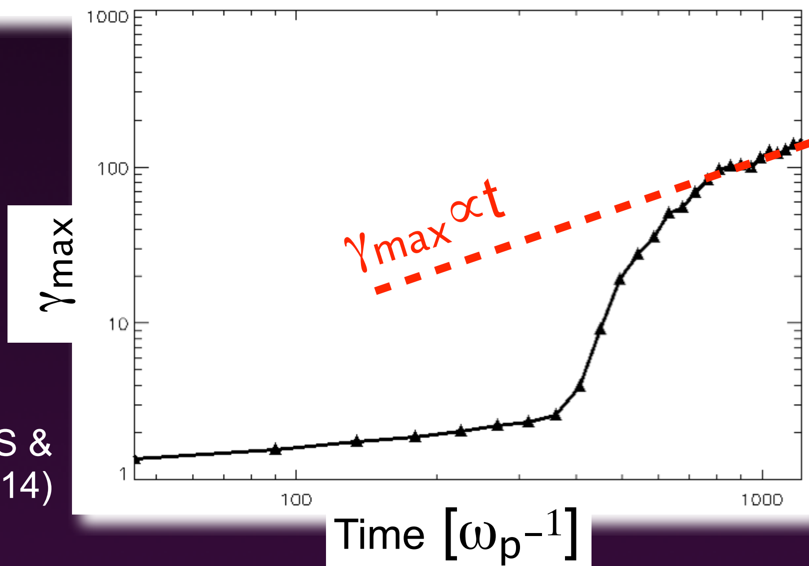


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

3D: particle spectrum

σ=10 electron-positron



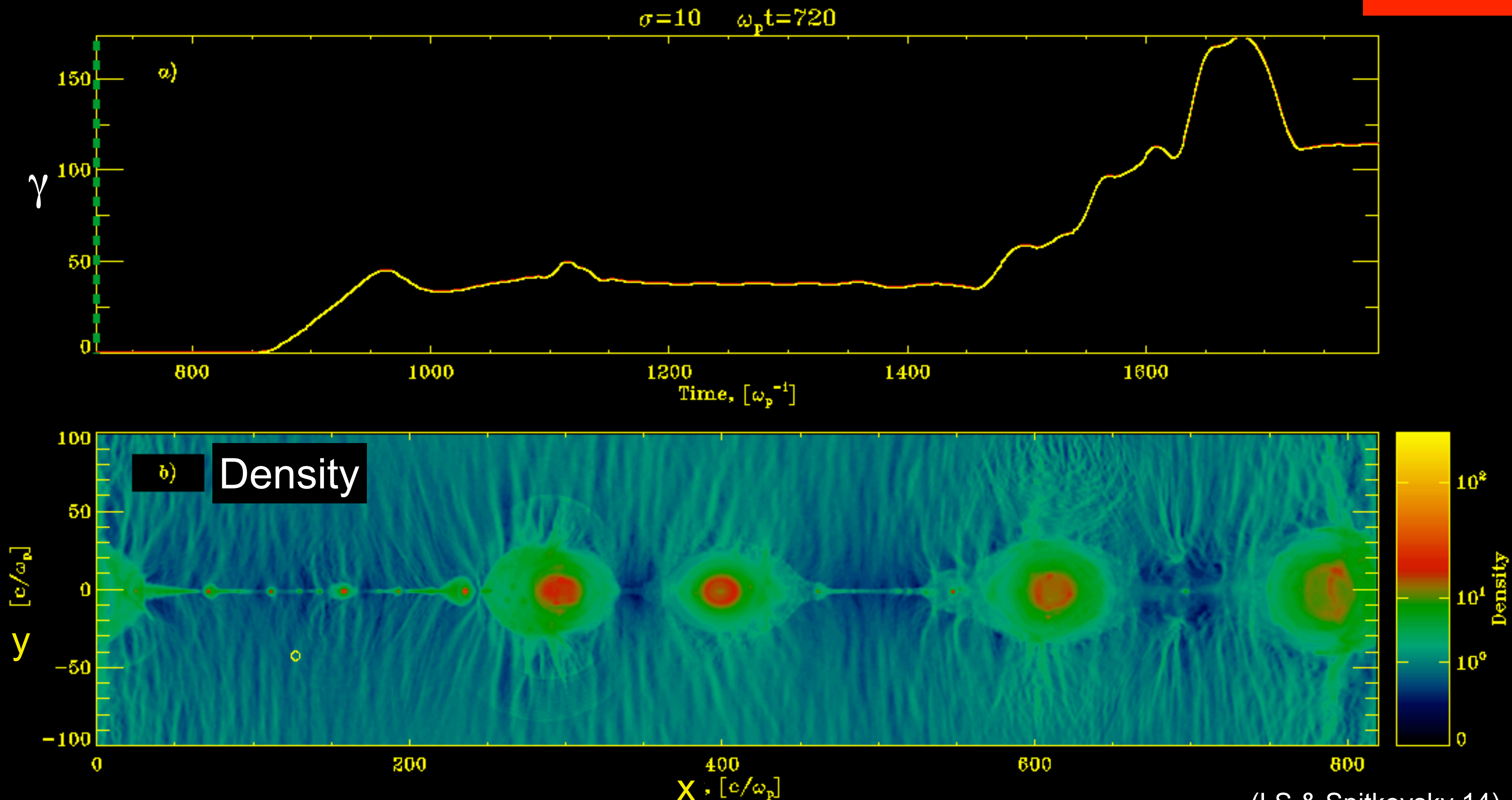


(LS & Spitkovsky 14)

- At late times, the particle spectrum approaches a power-law tail of slope *p*~2, extending in time to higher and higher energies. The same as in 2D.

- The maximum energy grows as $\gamma_{max} \propto t$. The inflow speed / reconnection rate is v_{in}/c~ 0.02 in 3D (vs v_{in}/c ~ 0.1 in 2D).

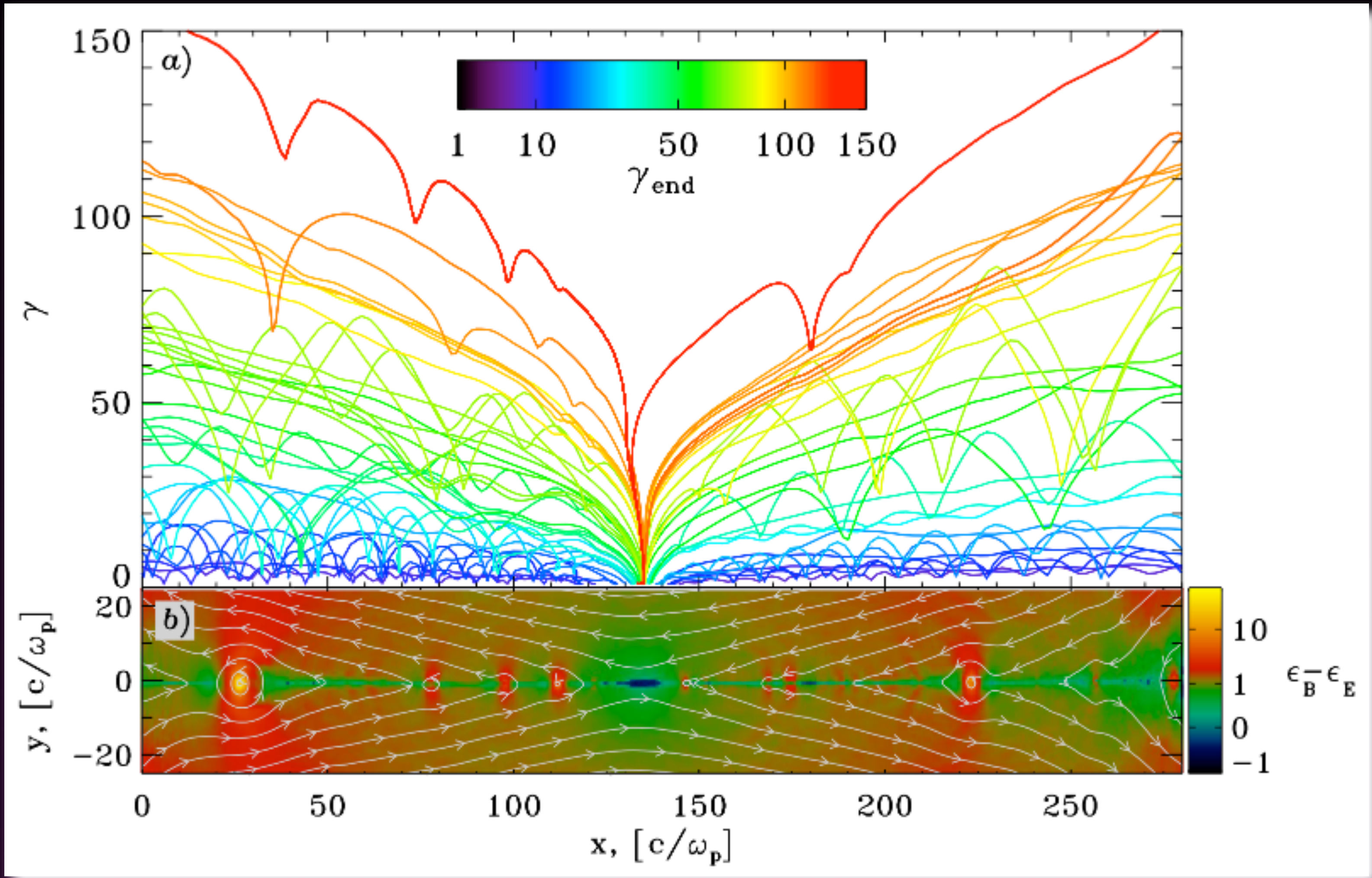
The highest energy particles



(LS & Spitkovsky 14)

Two acceleration phases: (1) at the X-point; (2) in between merging islands

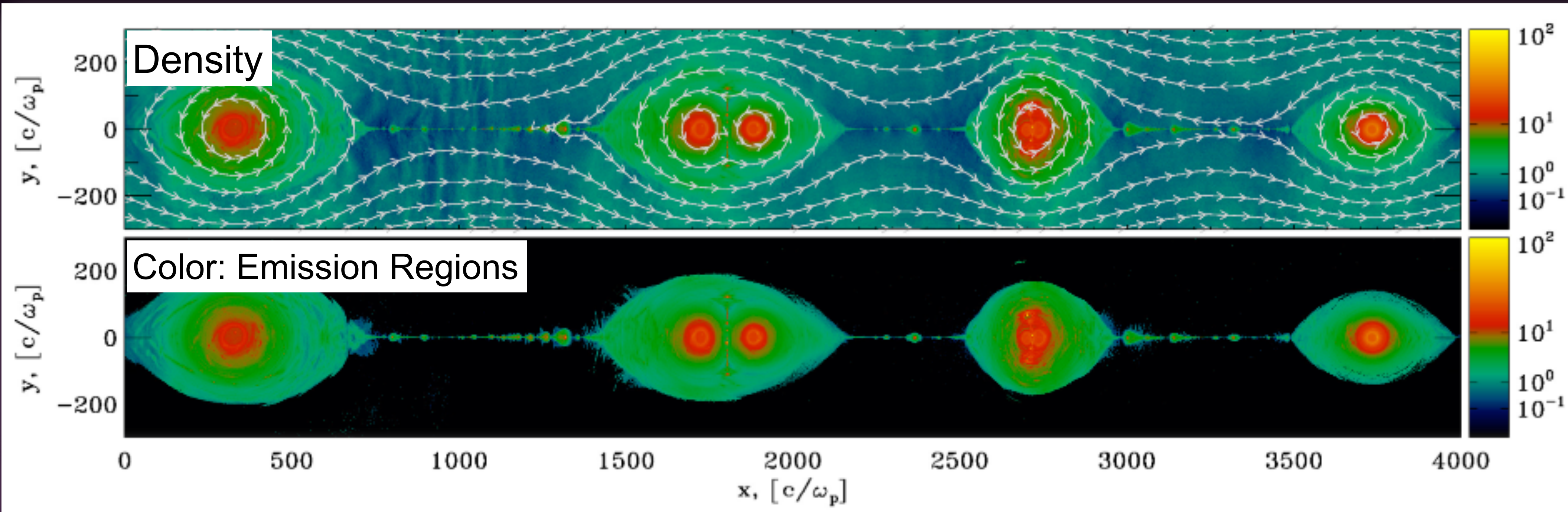
(1) Acceleration at X-points



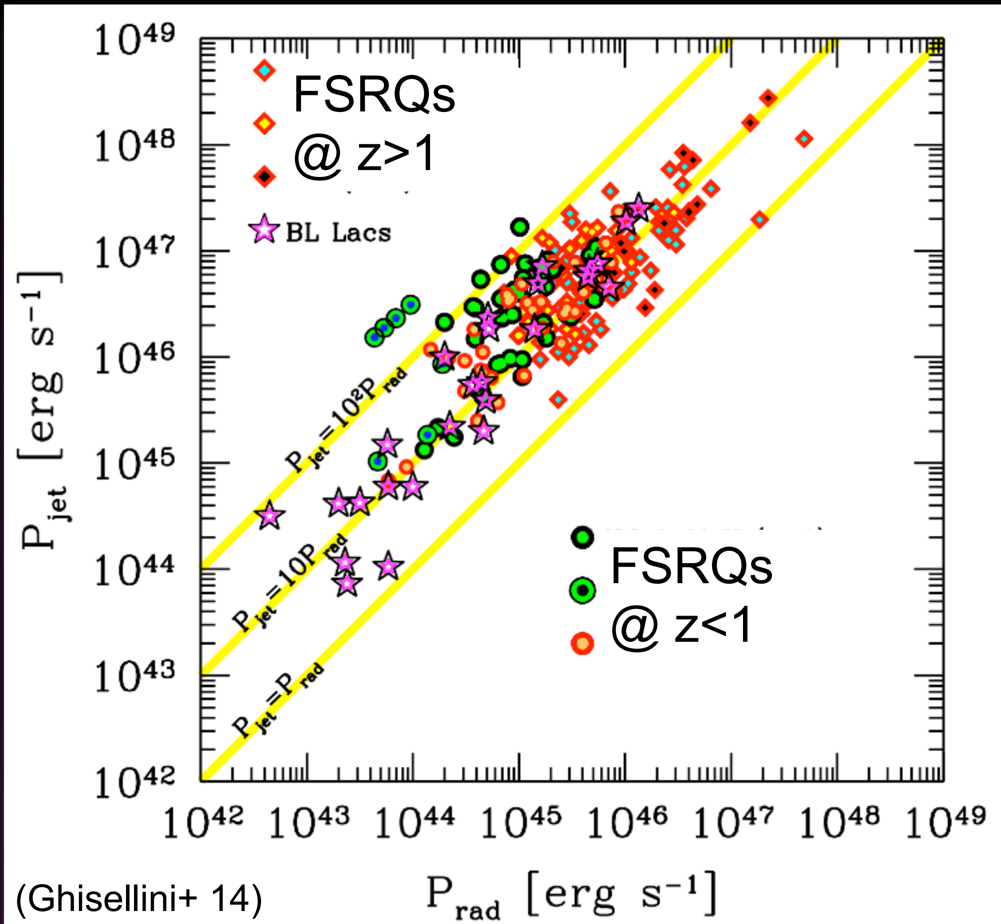
(LS & Spitkovsky 14)

- In cold plasmas, the particles are tied to field lines and they go through X-points.
- The particles are accelerated by the reconnection electric field at the X-points, and then advected into the nearest magnetic island.
- The energy gain can vary, depending on where the particles interact with the sheet.

Implications for blazar emission



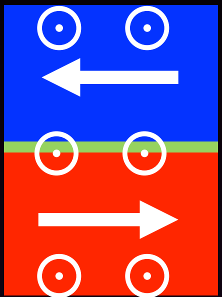
(1) Relativistic reconnection is efficient

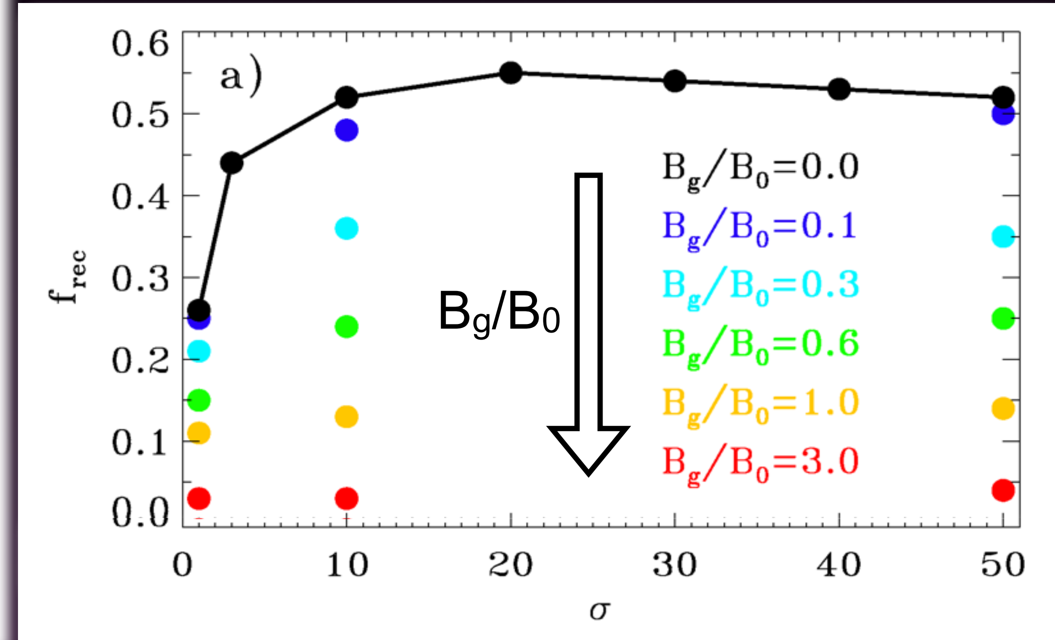


(Ghisellini+ 14)

Efficiency

$$f_{rec} \equiv \frac{\sum_i \int_{V_i} U_e dV_i}{\sum_i \int_{V_i} (e + \rho c^2 + U_B)\, dV_i}$$





(Sironi+ 15)

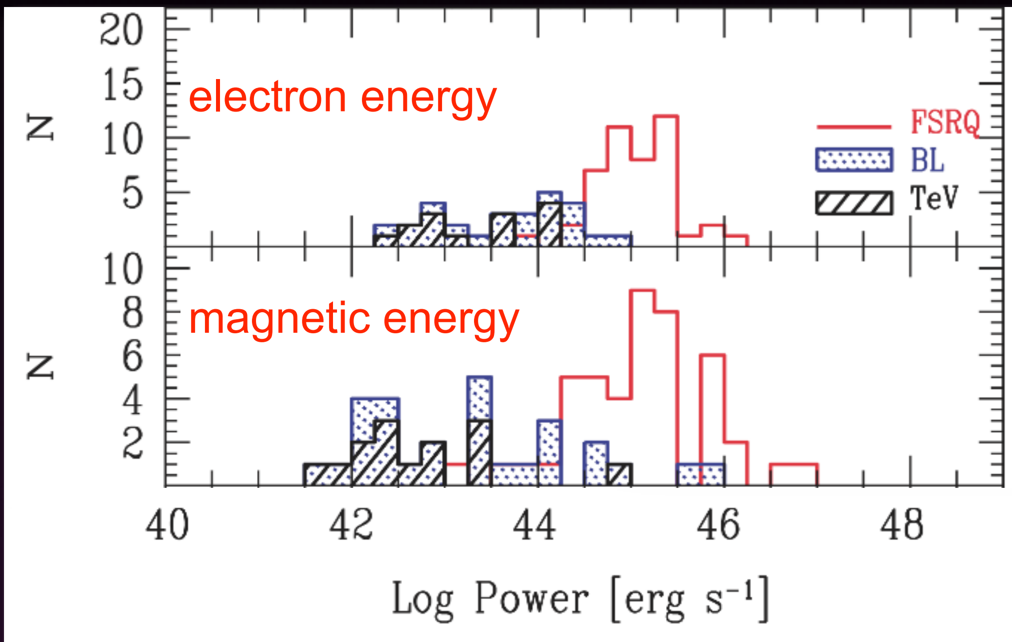
Blazar phenomenology:

- blazars are efficient emitters (radiated power ~ 10% of jet power)

Relativistic reconnection:

✓ it transfers up to ~ 50% of flow energy (electron-positron plasmas) or up to ~ 25% (electron-proton) to the emitting particles

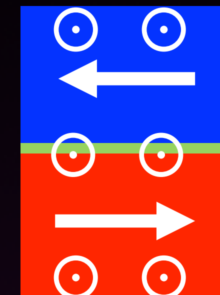
(2) Equipartition of particles and fields

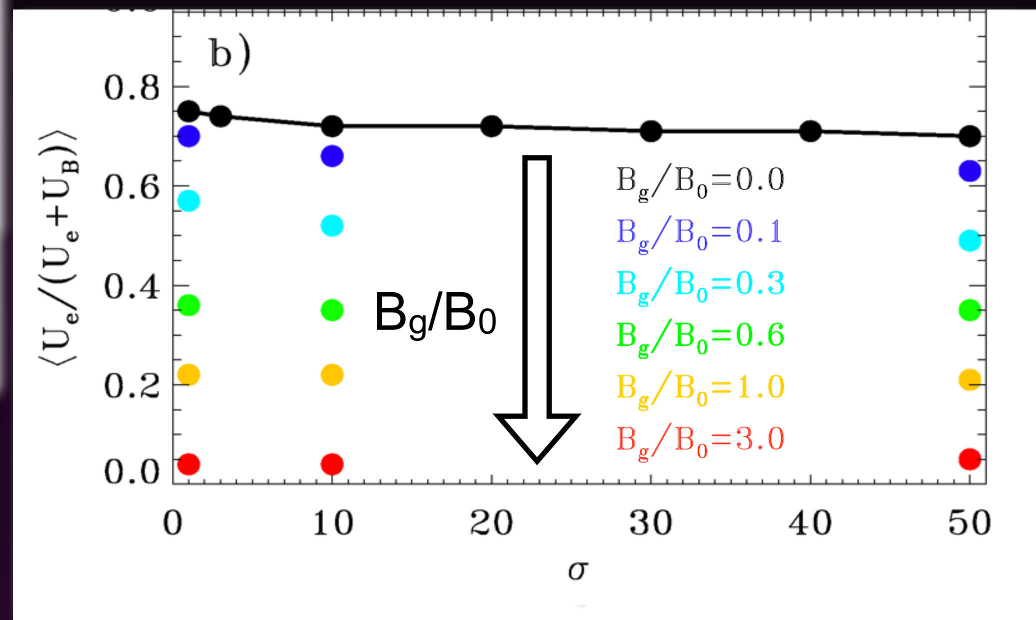


(Celotti+ 08)

Equipartition parameter

$$\left\langle \frac{U_e}{U_e + U_B} \right\rangle$$





(Sironi+ 15)

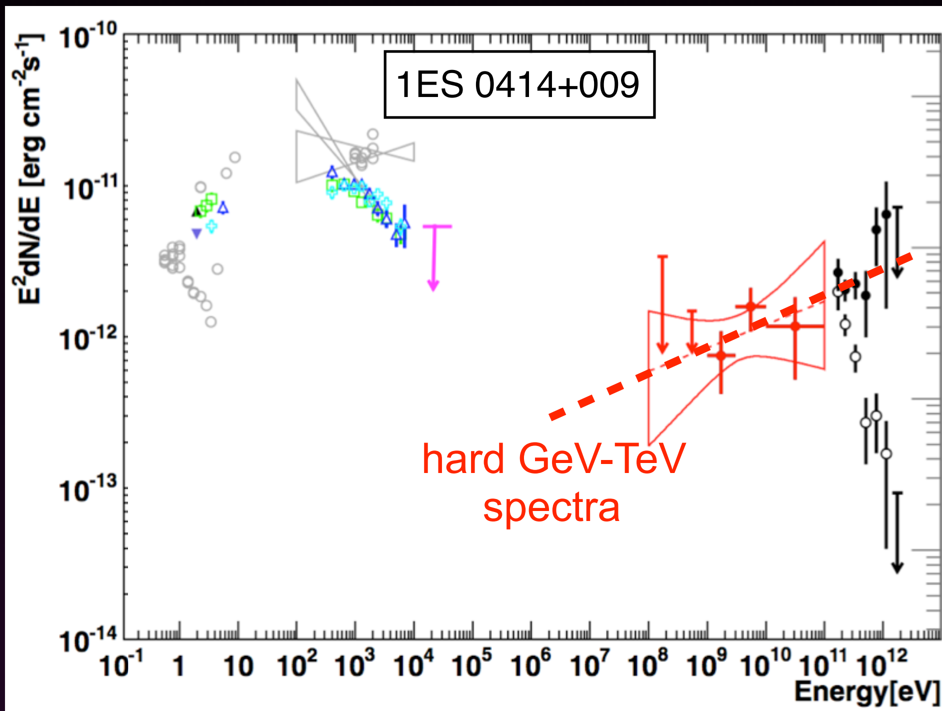
Blazar phenomenology:

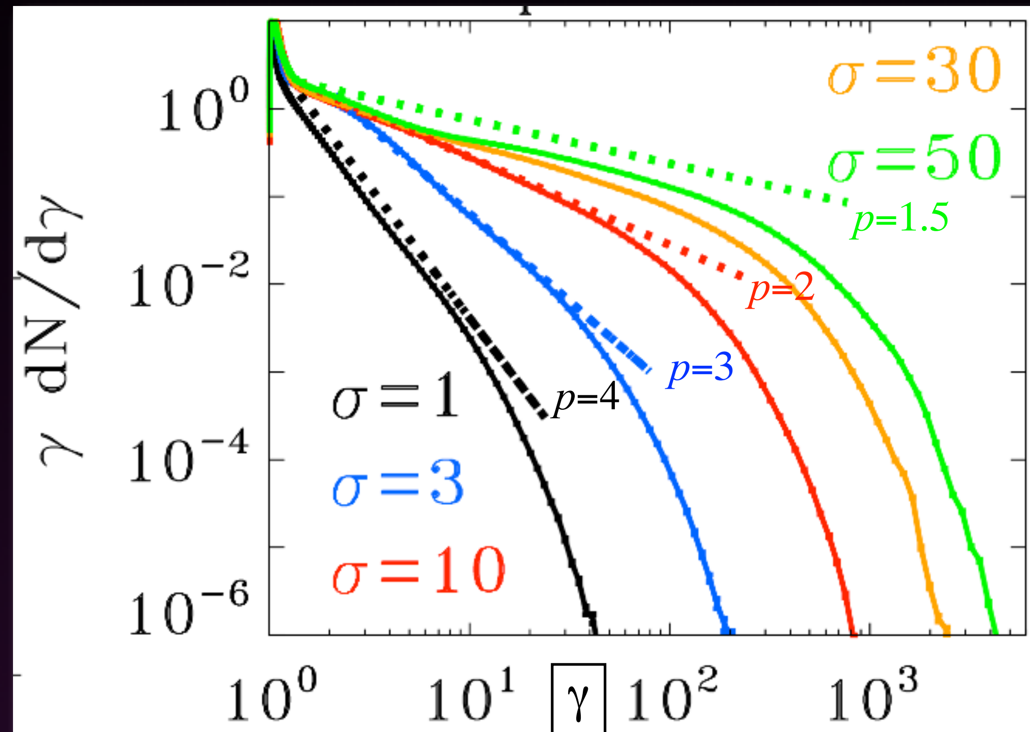
- rough energy equipartition between emitting particles and magnetic field

Relativistic reconnection:

✓ in the magnetic islands, it naturally results in rough energy equipartition between particles and magnetic field

(3) Extended non-thermal distributions





(LS & Spitkovsky 14, confirmed by Guo+ 14,15, Werner+ 14)

Blazar phenomenology:

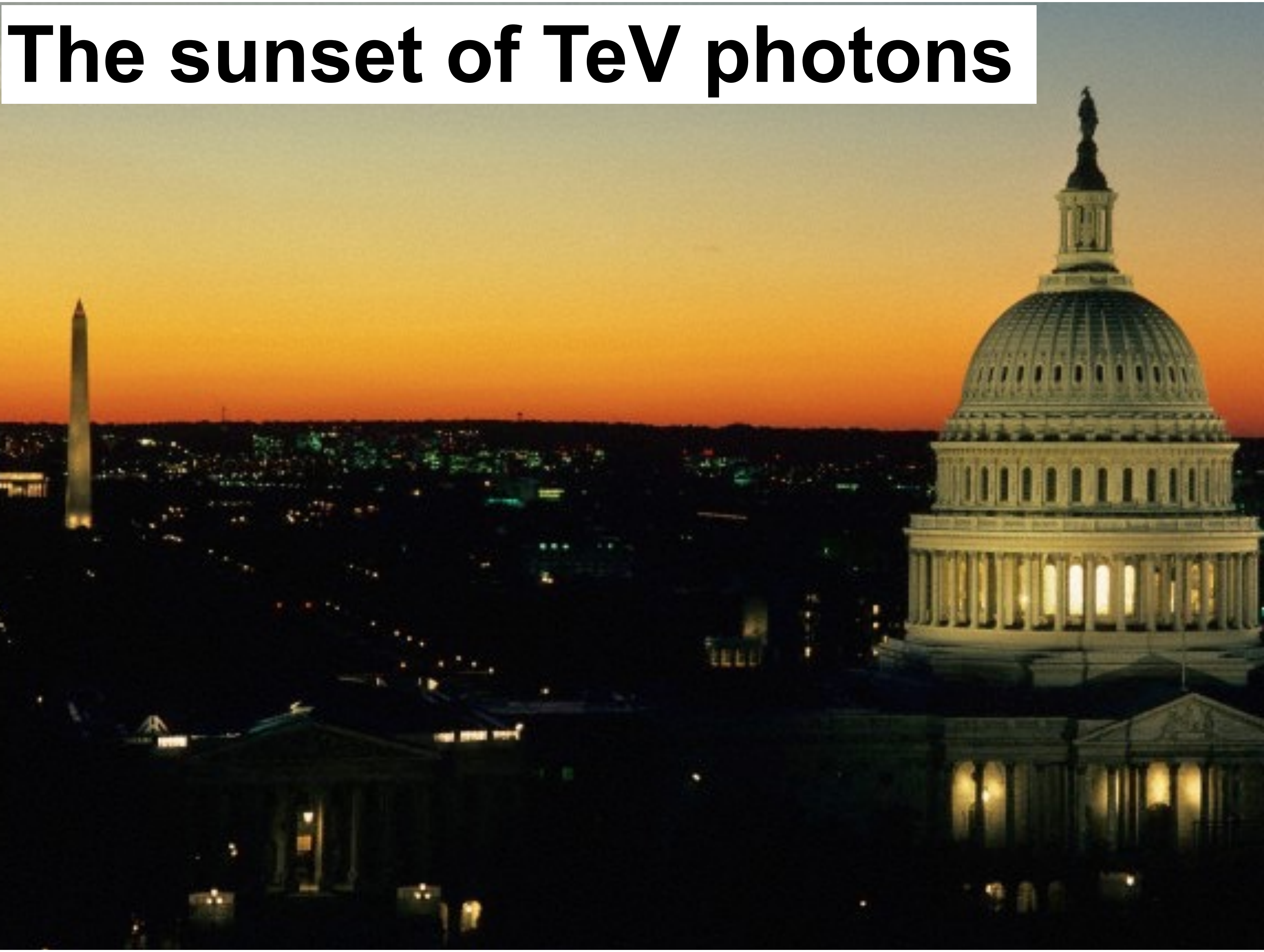
• extended power-law distributions of the emitting particles, with hard slope

$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$

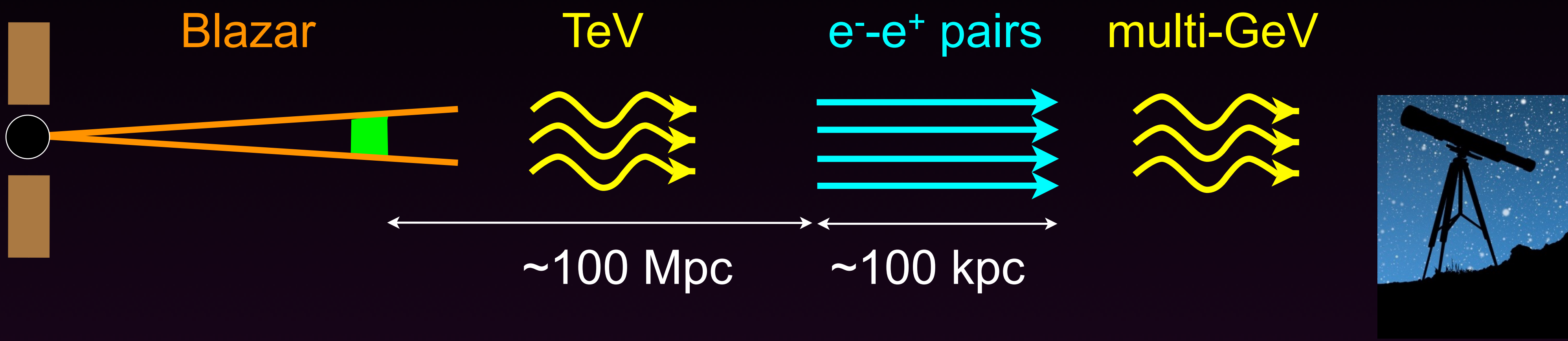
Relativistic reconnection:

✓ it produces extended non-thermal tails of accelerated particles, whose power-law slope is harder than *p*=2 for high magnetizations (σ>10)

The sunset of TeV photons



TeV photons are absorbed in the IGM



TeV photons from blazars pair-produce in the IGM by interacting with ~ eV EBL photons.

- mean free path is ~100 Mpc

$$\gamma_{\rm TeV} + \gamma_{\rm eV} \rightarrow e^+ + e^-$$

The beam of electron-positron pairs has:

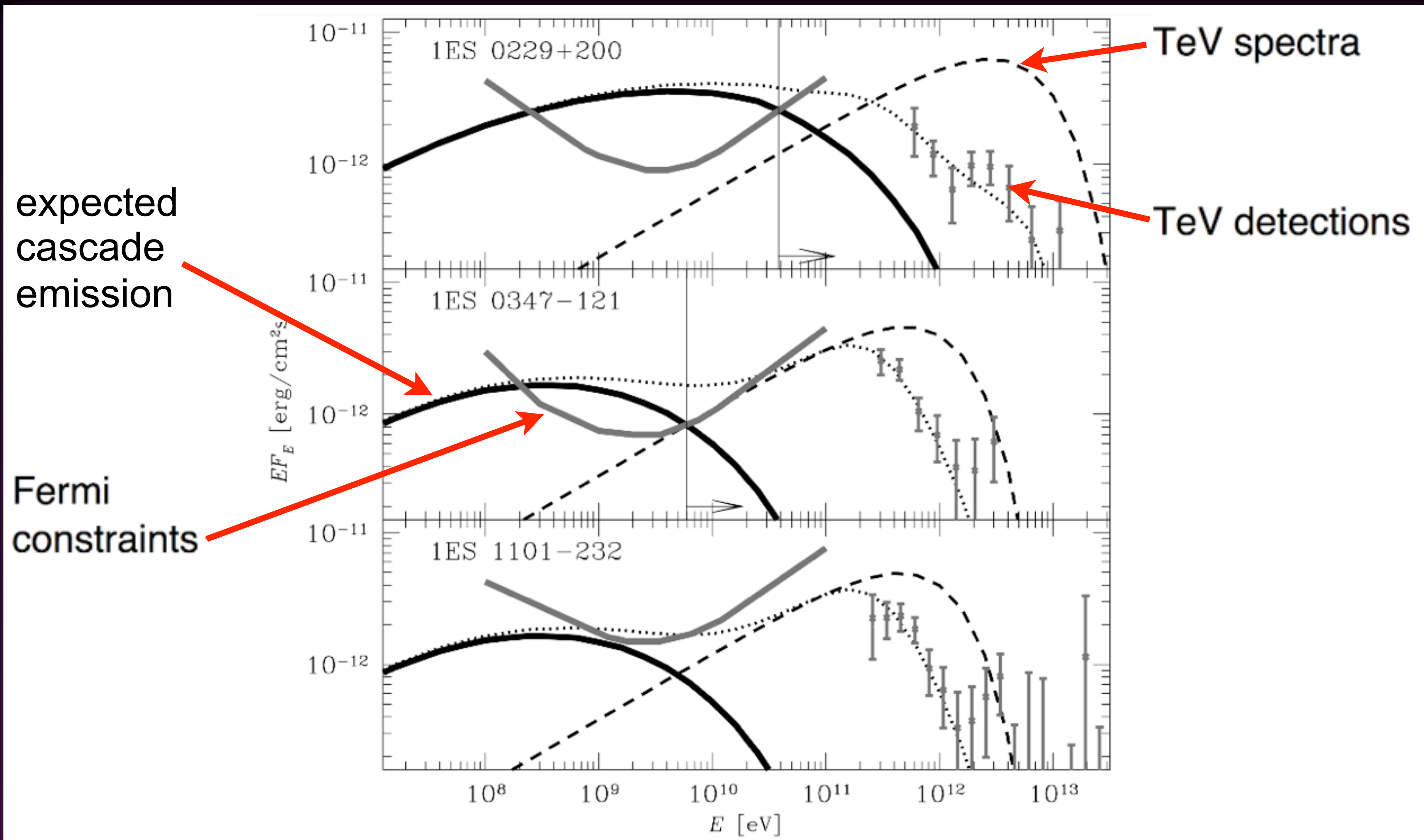
Lorentz factor $\gamma=10^6-10^7$ and density ratio $\alpha=10^{-15}-10^{-18}$ (wrt the IGM plasma)

These pairs should IC scatter off the CMB, producing ~ GeV photons.

- mean free path is ~ 100 kpc (IC cooling length)

No excess GeV emission from blazars

Every TeV blazar should have a GeV halo of reprocessed light. However, not seen!

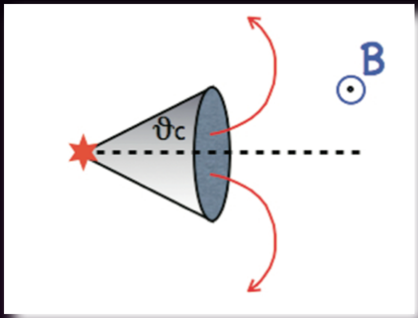


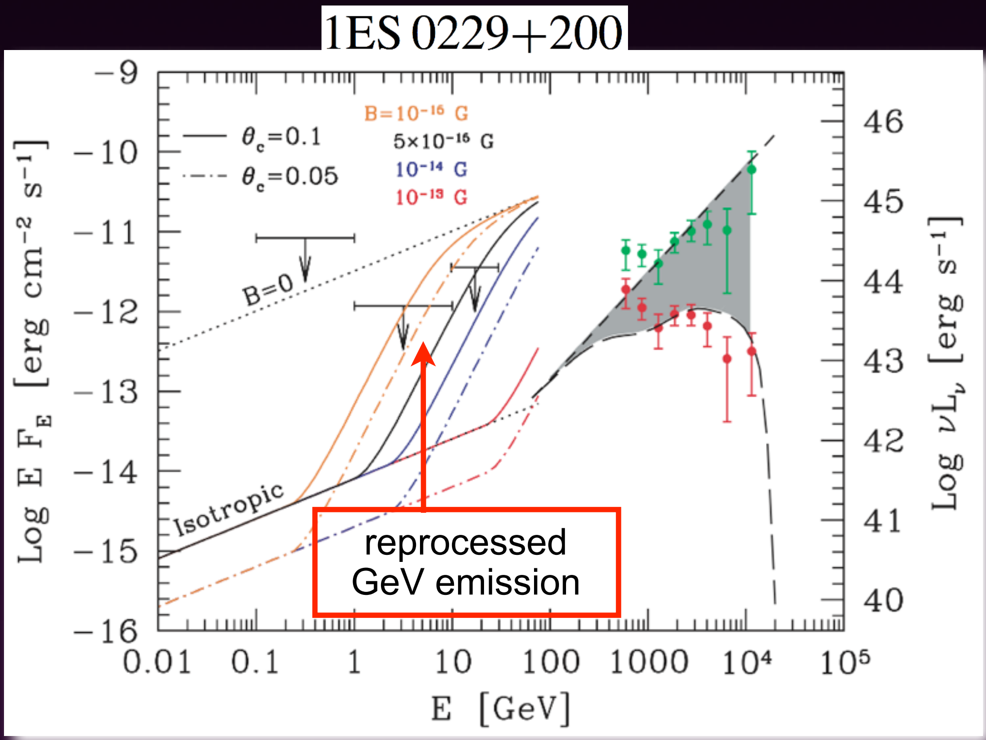
(Neronov & Vovk 10)

IGM fields or plasma instabilities

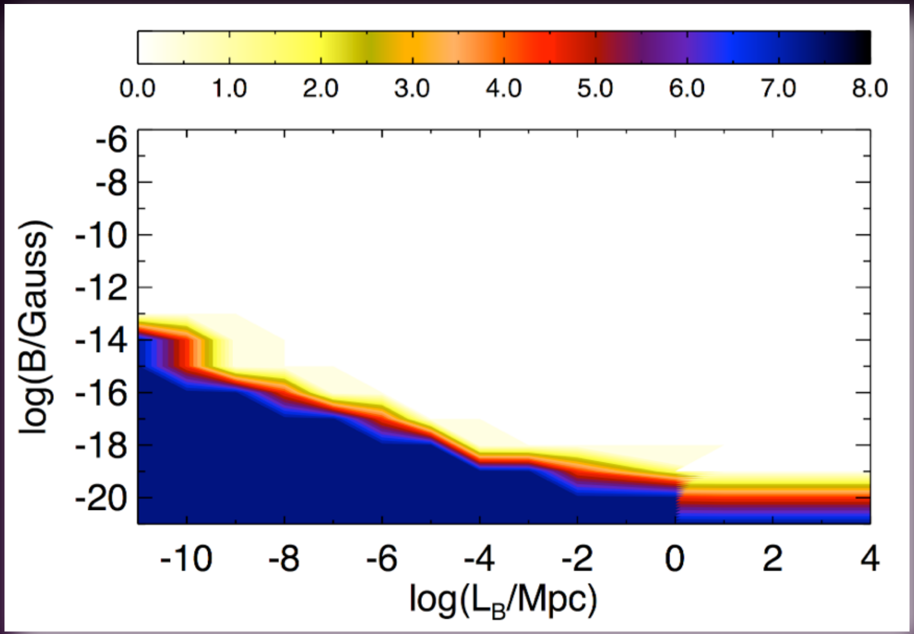
Every TeV blazar should have a GeV halo of reprocessed light. However, not seen!
Two possibilities:

1) IGM magnetic fields deflect the streaming pairs
(Neronov & Vovk 10, Tavecchio+ 11, Finke+15)





(Tavecchio+ 11)

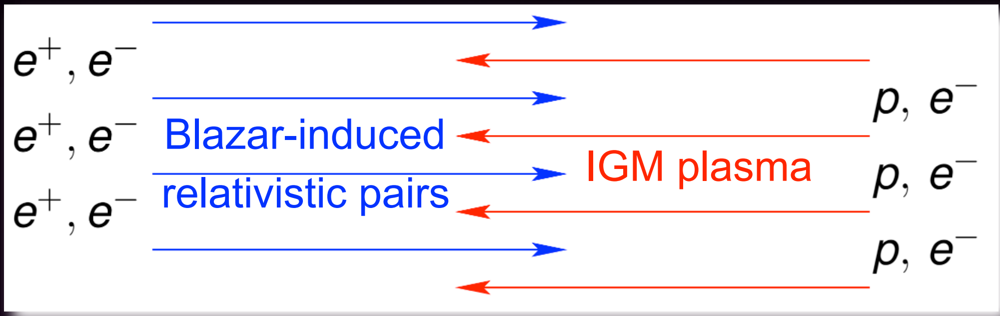


(Finke+ 15)

2) The pair energy is deposited into the IGM as heat, via collective plasma instabilities
(Broderick, Chang & Pfrommer 12, 13, 14)

Plasma instabilities in the IGM

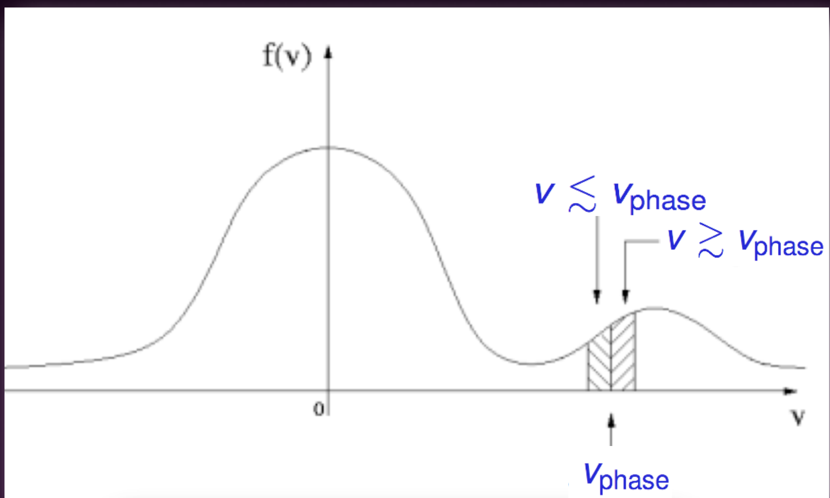
Interpenetrating beams of charged particles are unstable (beam-plasma instabilities)



microscopic scales!

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \qquad \lambda_p = \frac{c}{\omega_p}\bigg|_{\bar{\rho}(z=0)} \sim 10^8\ \mathrm{cm}$$

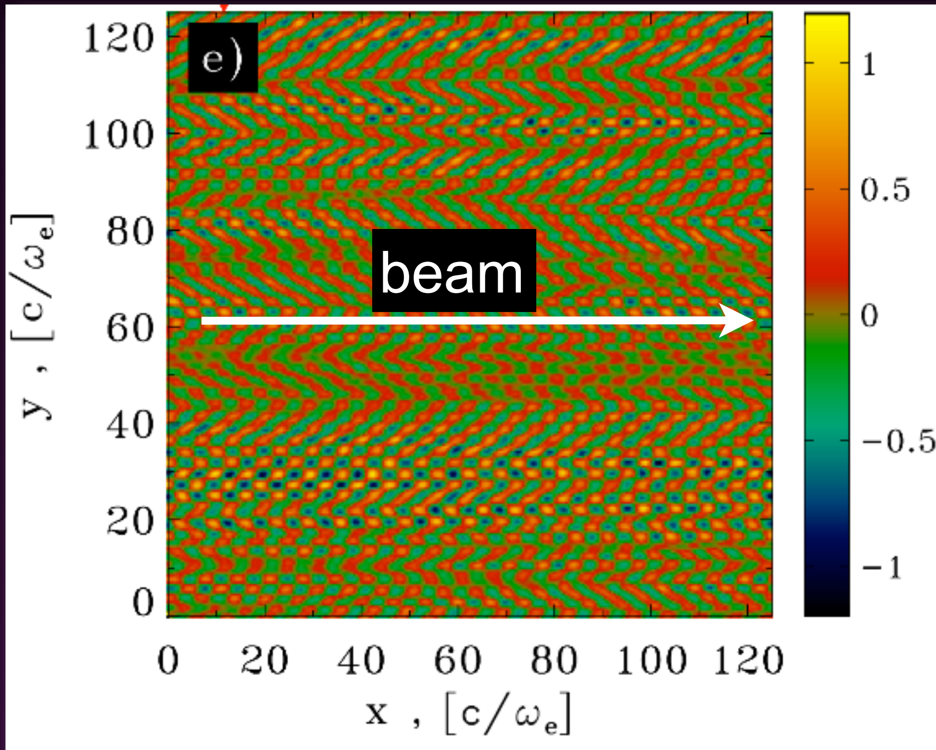
Two-stream (bump on tail) instability



$v \gtrsim v_{\rm phase}$ energy from particles to waves: → instability

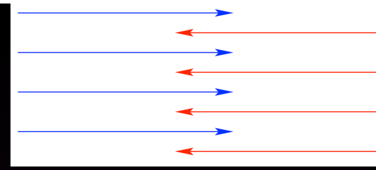
$v \lesssim v_{\rm phase}$ energy from waves to particles: → damping

Oblique instability

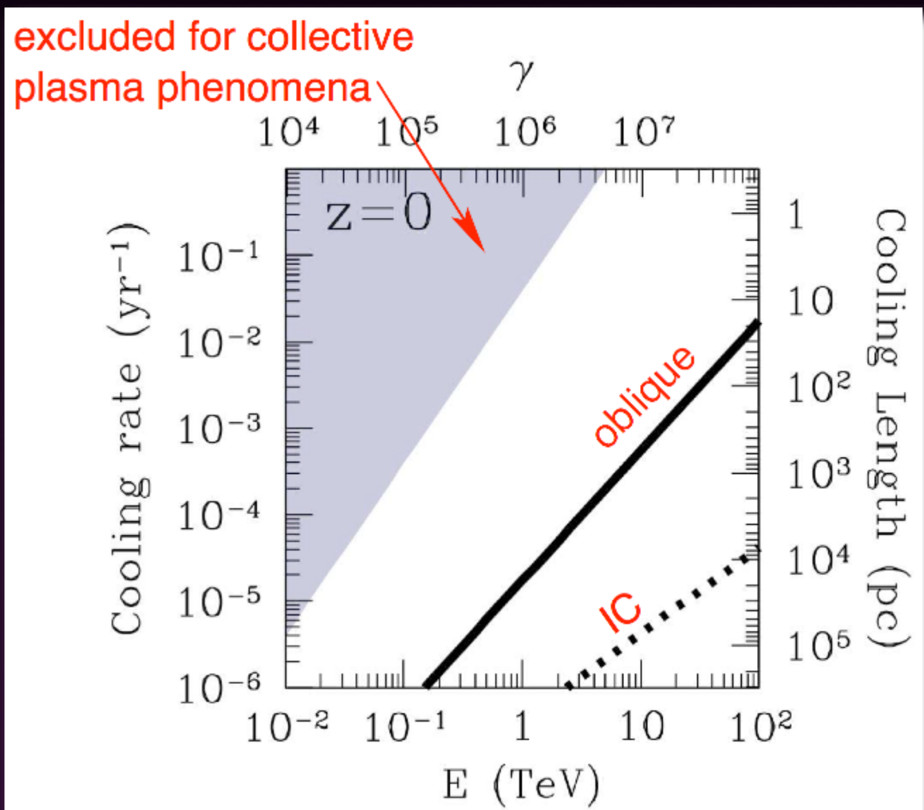


(LS & Giannios 14)

Beam-plasma linear evolution



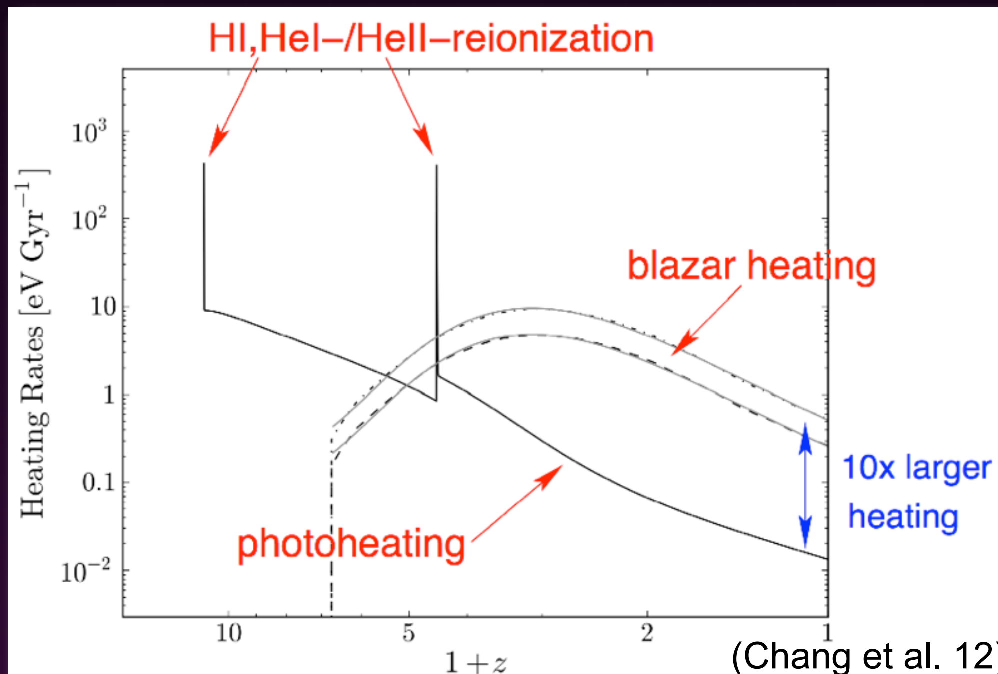
Linear analysis:
the oblique instability grows 10-100 times faster than the IC cooling losses.



(Broderick et al. 12)

If all the beam energy is deposited into the IGM via plasma instabilities:

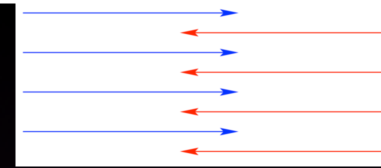
- No reprocessed blazar GeV emission
- IGM field estimates are invalid
- IGM heating from blazars will have important cosmological implications



(Chang et al. 12)

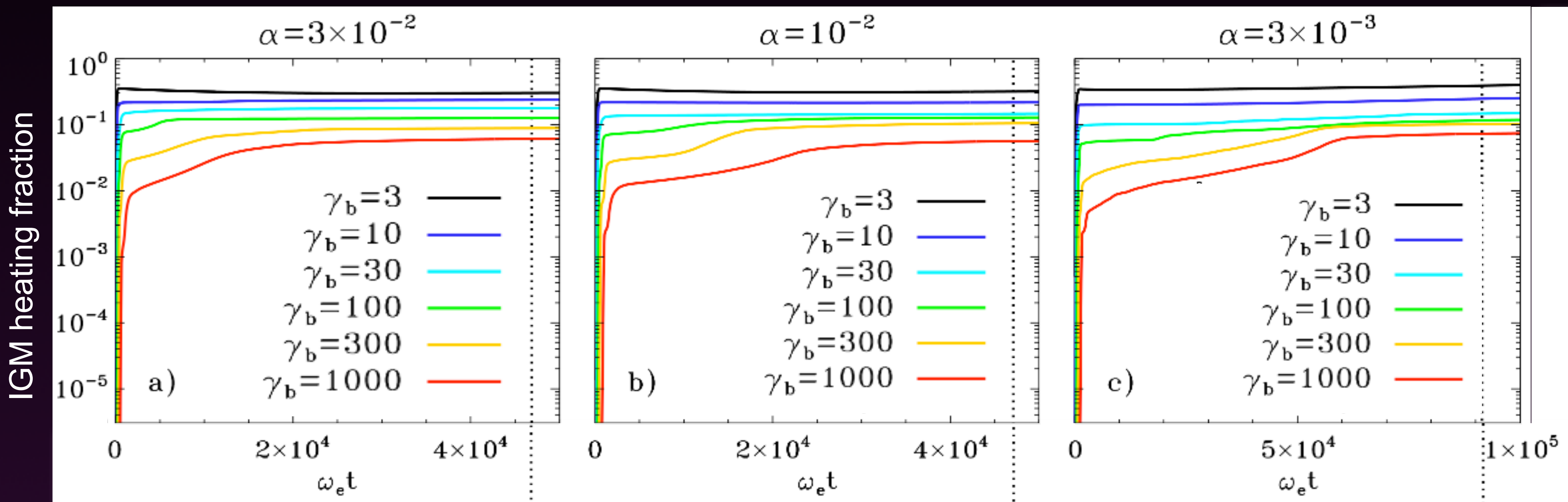
The non-linear evolution of the beam-plasma system requires PIC simulations.

10% in heat, 90% in GeV emission



Blazar-induced beams: Lorentz factor $\gamma=10^6-10^7$ and density ratio $\alpha=10^{-15}-10^{-18}$

Numerically tractable: Lorentz factor $\gamma=10^1-10^3$ and density ratio $\alpha=10^{-1}-10^{-3}$



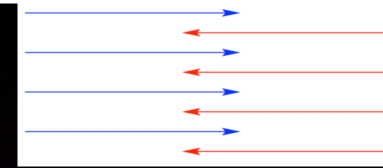
(LS & Giannios 14)

COLD (i.e., monoenergetic) beams:

- Regardless of the beam γ or α, the beam longitudinal momentum dispersion at the end of the evolution reaches ~ 0.2 γ, and the IGM heating fraction reaches ~10%.

→ 90% is still available to power the reprocessed GeV emission.

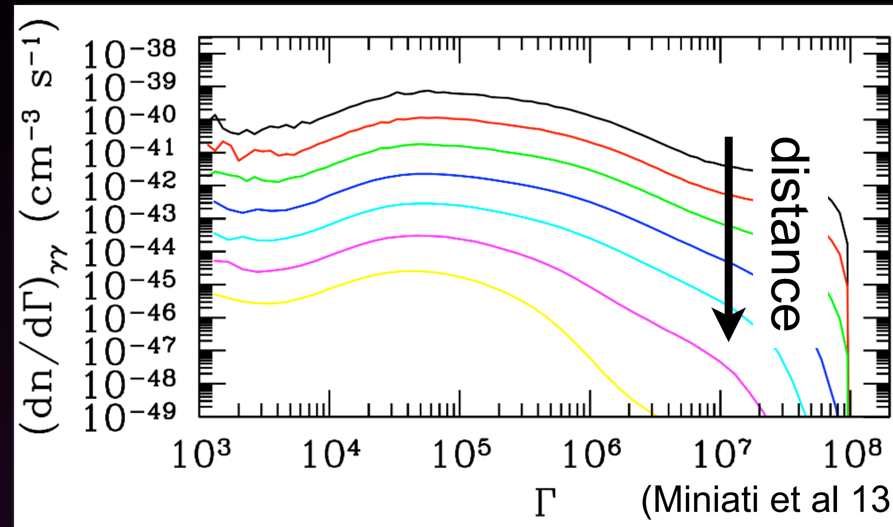
Blazars beams are not cold



Blazar beams are born WARM:

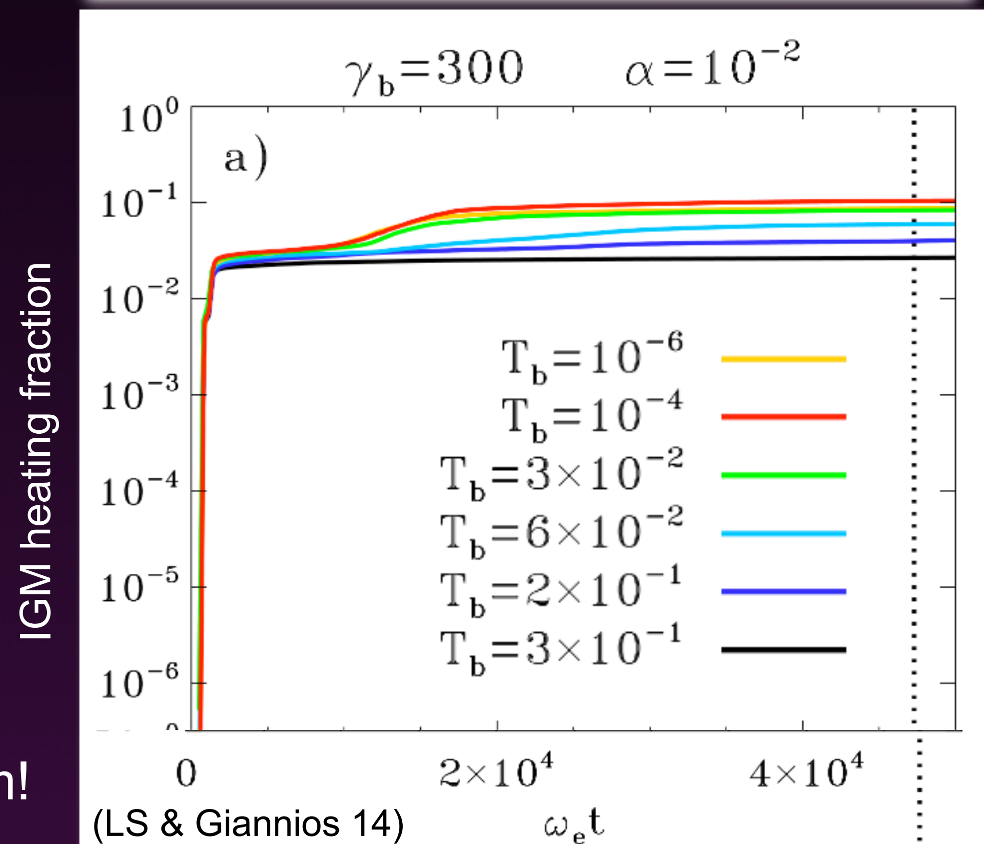
• the pair production cross section peaks at ~ few $m_e c^2$.

• the TeV blazar spectrum and the EBL spectrum are broad.



The heating fraction will be ≪10%:

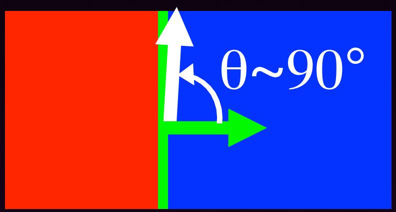
• if the initial longitudinal beam dispersion is already > 0.2 γ, as expected for blazar beams.



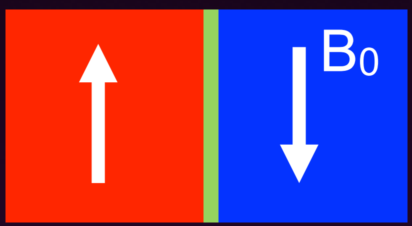
So, nearly all of the energy stays in the beam!

Summary

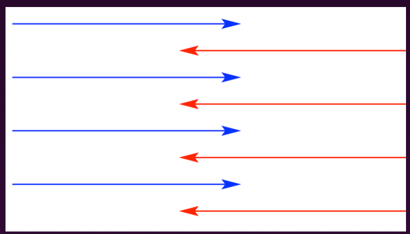
High-energy emission from blazars:



• The (failed) dawn: internal shocks, if significantly magnetized ($\sigma > 10^{-3}$) and quasi-perpendicular, are poor particle accelerators.

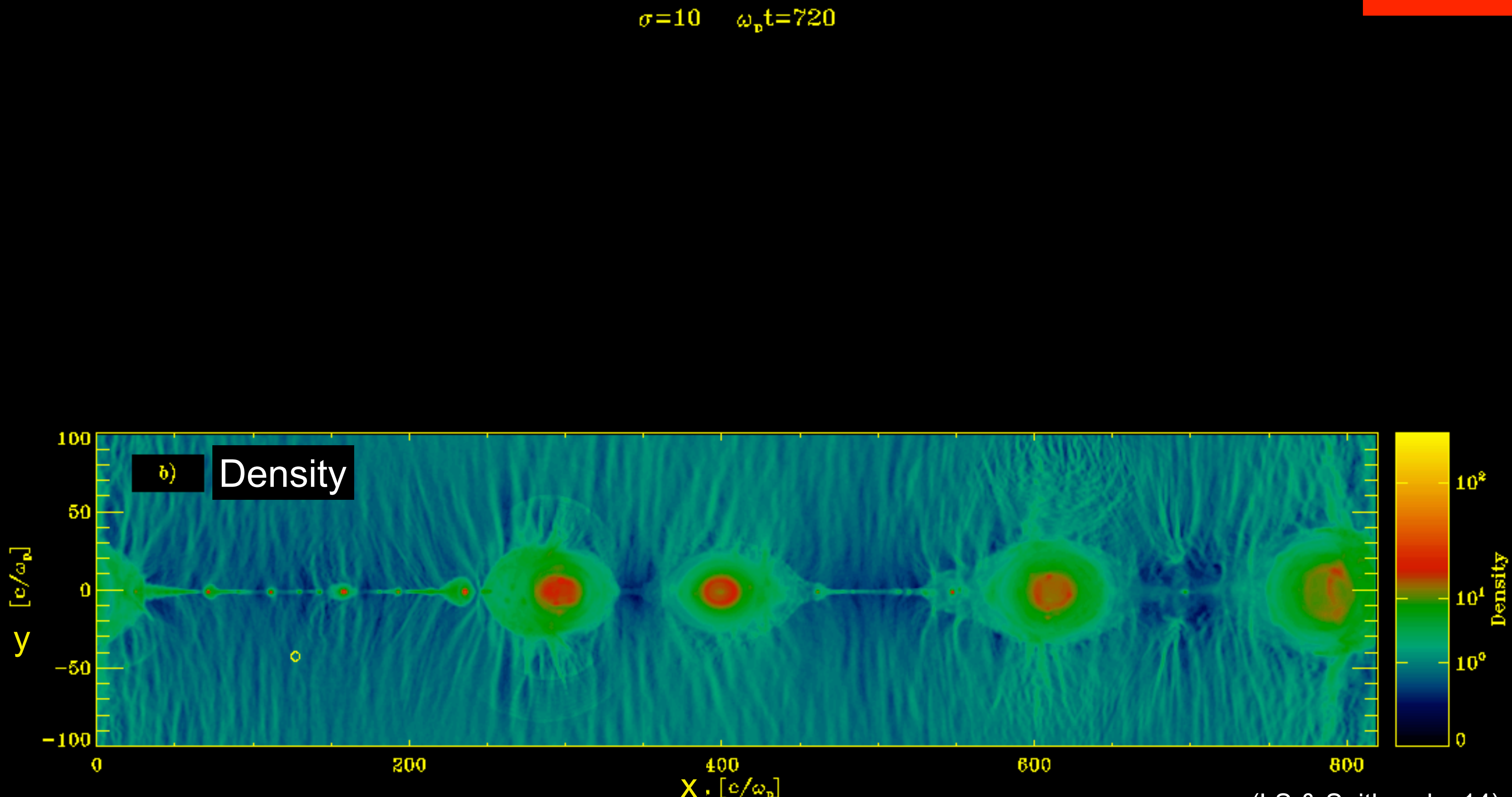


• The (likely) dawn: magnetic reconnection in magnetically-dominated flows ($\sigma \gg 1$) is fast and efficient, can produce non-thermal populations with a power-law slope $p \sim 1 \div 2$, and results in rough energy equipartition between particles and fields.



• The sunset: TeV photons will pair-produce in the IGM. The resulting beam will deposit $\ll 10\%$ of the its energy into the IGM. Most of the beam energy will result in multi-GeV emission by IC scattering off the CMB.

The highest energy particles



(LS & Spitkovsky 14)

Two acceleration phases: (1) at the X-point; (2) in between merging islands