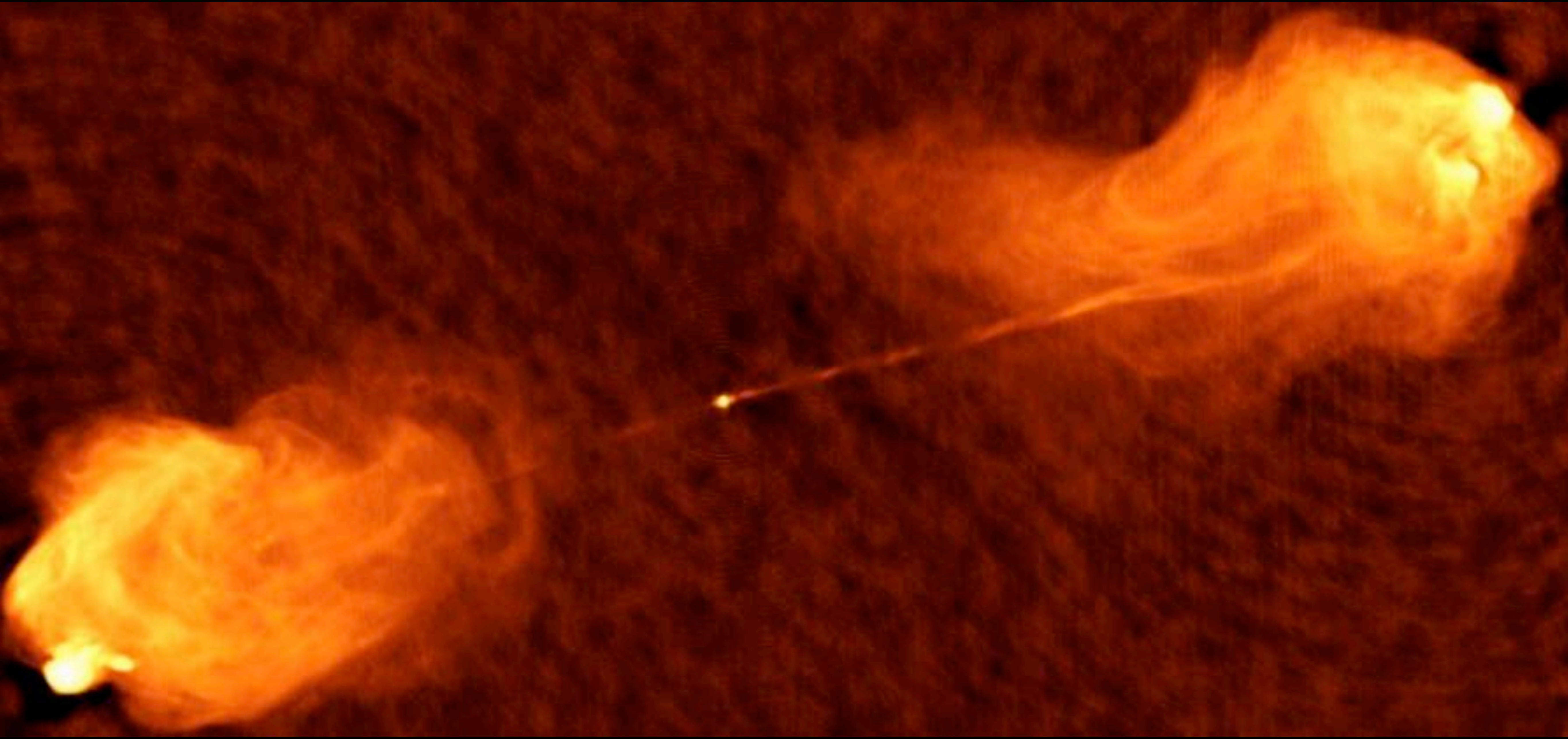
Particle Acceleration via Shocks and Reconnection in Relativistic Jets



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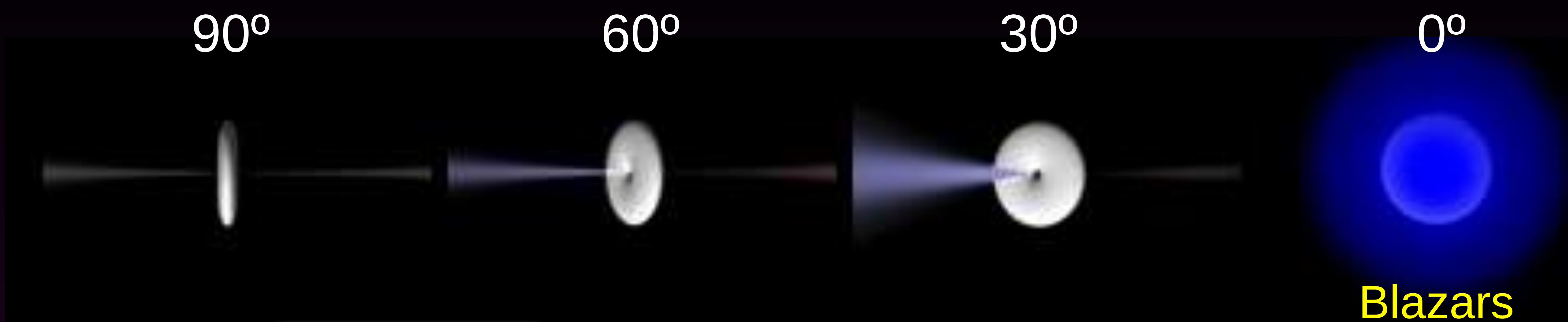
MFU V, Cargèse, October 6th 2015

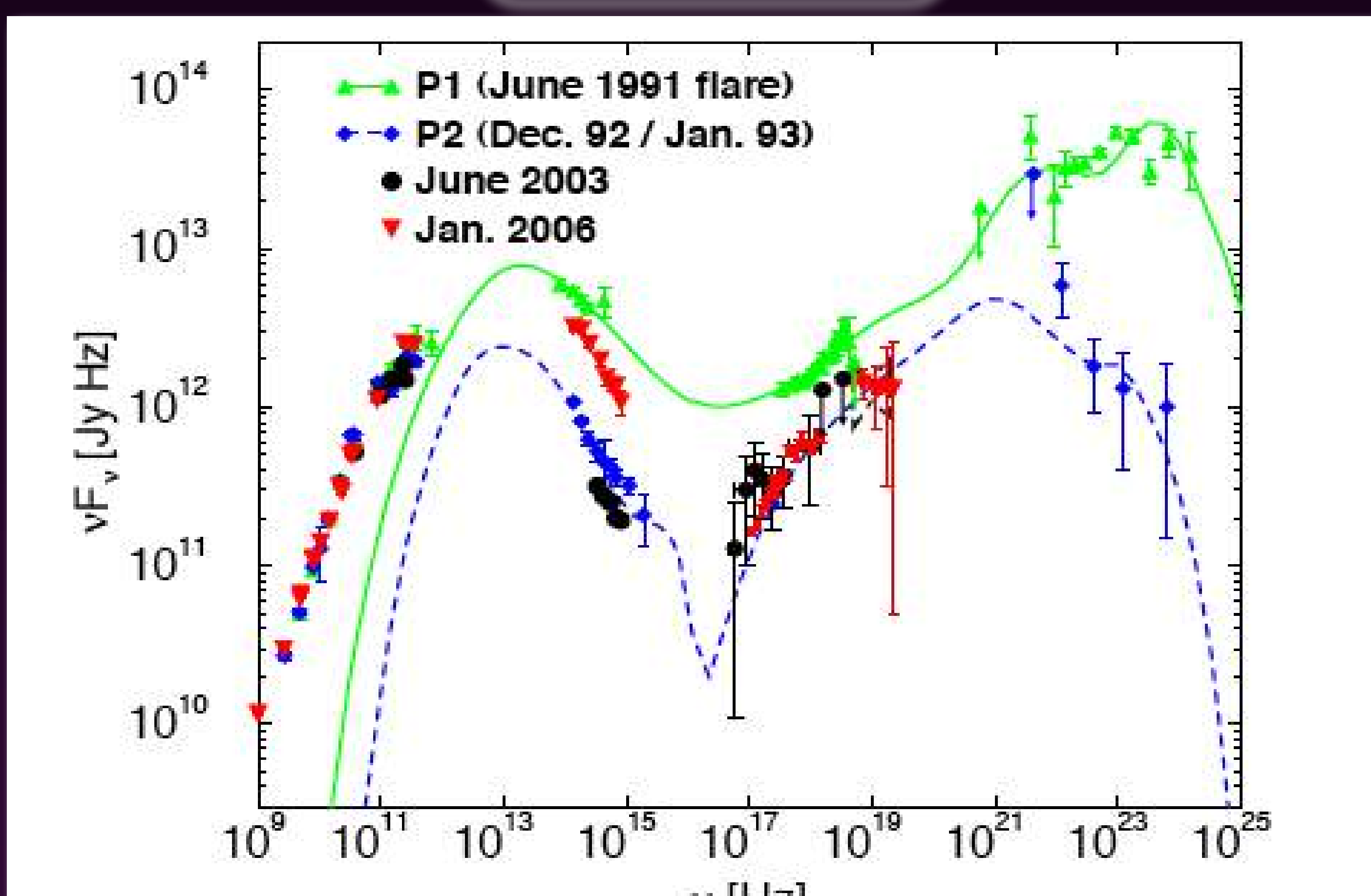
with: J. Arons, D. Giannios, M. Petropoulou, A. Spitkovsky

Non-thermal emission from blazars

Blazars: jets from Active Galactic Nuclei pointing along our line of sight



3C 279



(Boettcher 07)

- broadband spectrum, from radio to γ-rays (and even TeV energies)
- low-energy synchrotron + high-energy inverse Compton (IC) from non-thermal particles
- high degree of radio and optical polarization → magnetic fields

Powerful emission and hard TeV spectra

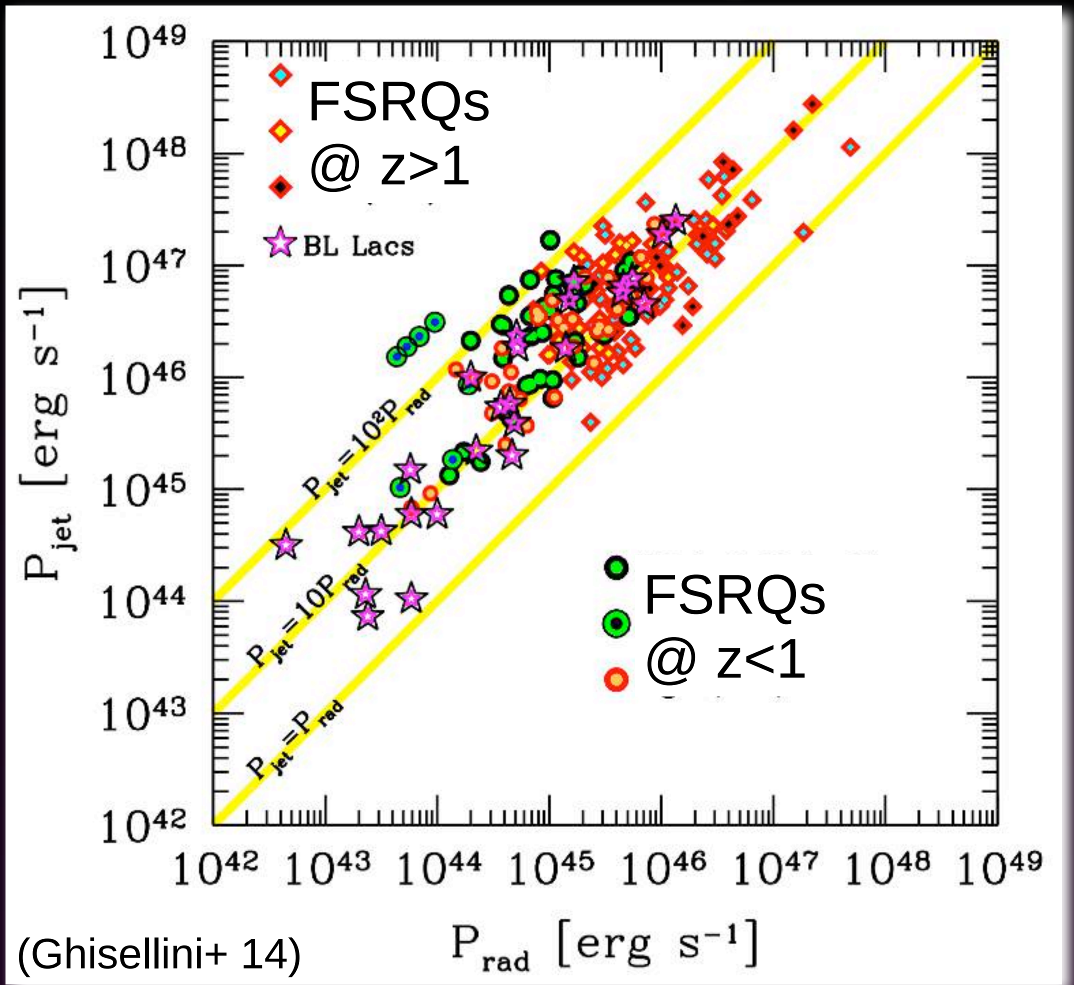
Blazar phenomenology:

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

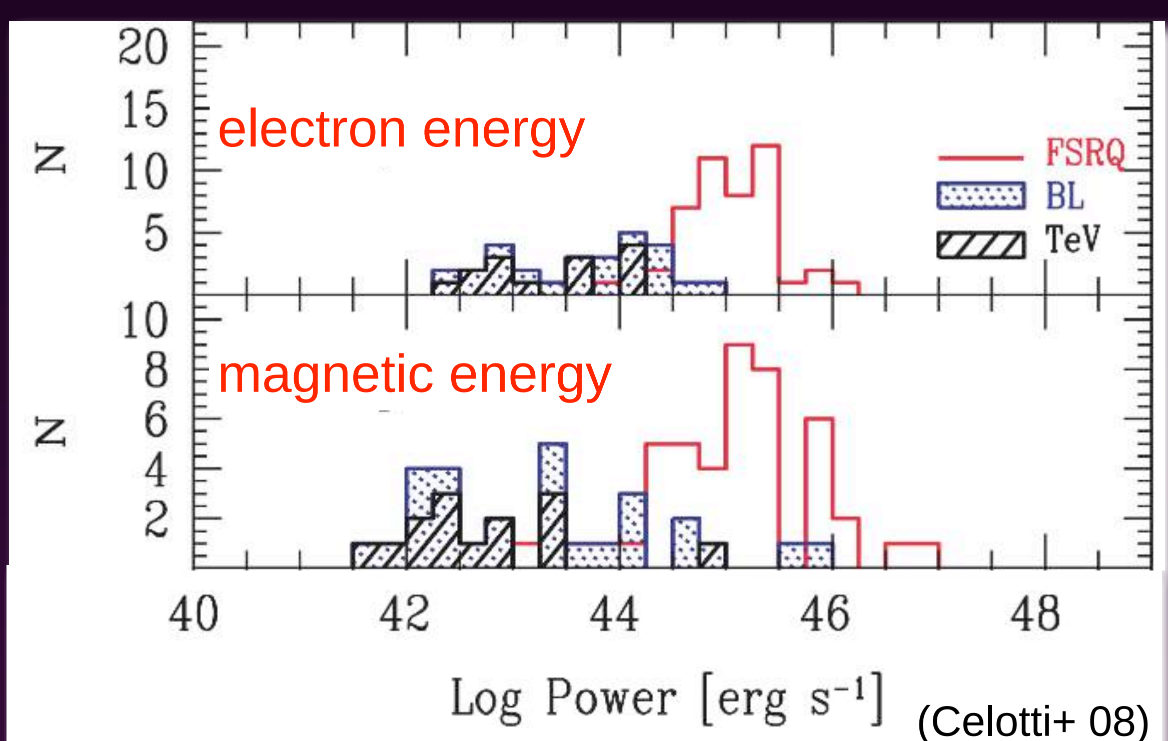
(2) rough energy equipartition between emitting particles and magnetic field

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

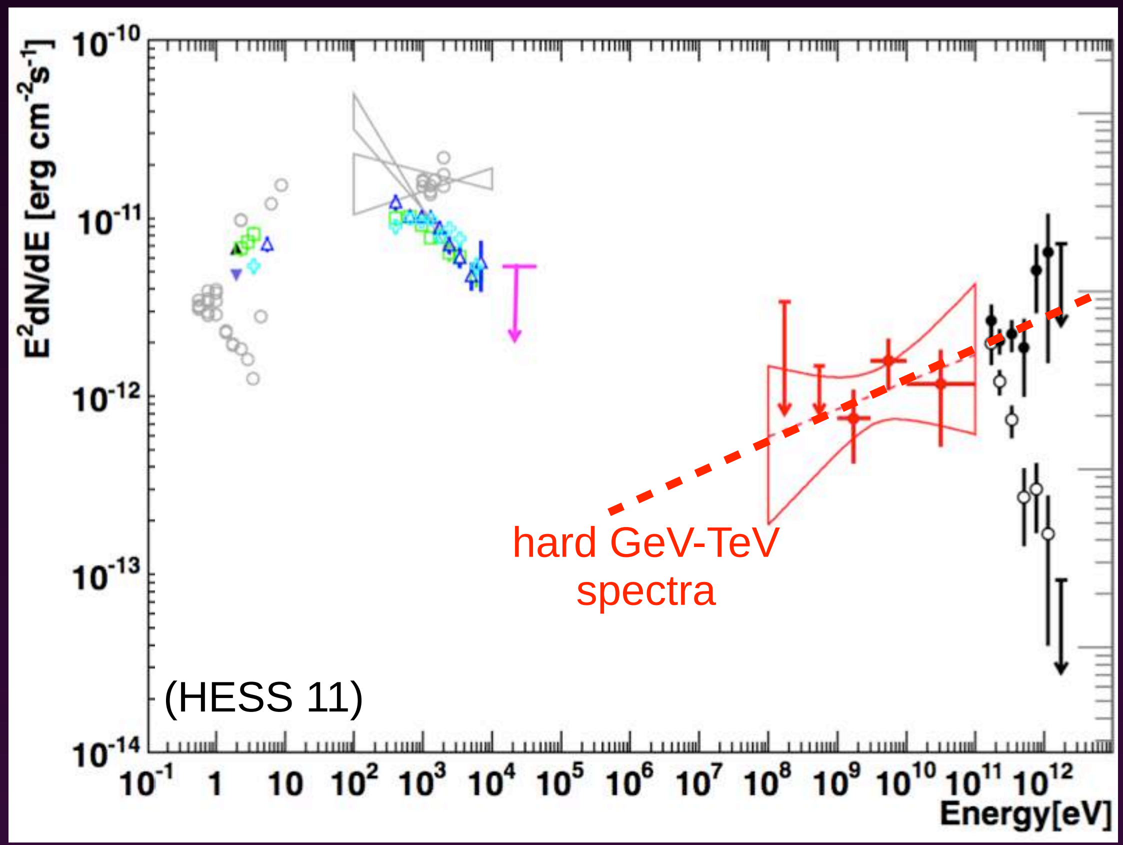
$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$



(Ghisellini+ 14)

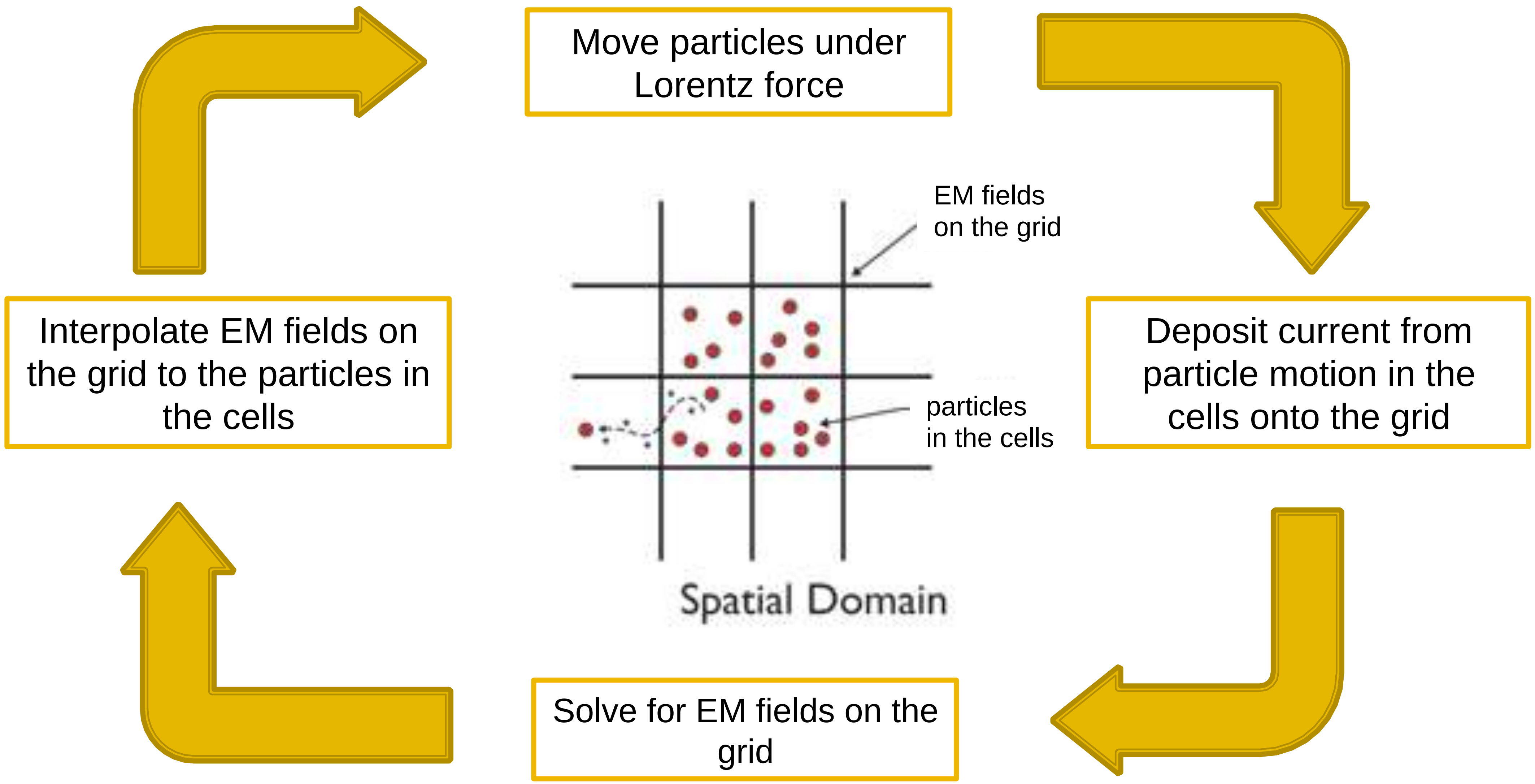


(Celotti+ 08)



(HESS 11)

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)

Internal dissipation in blazar jets

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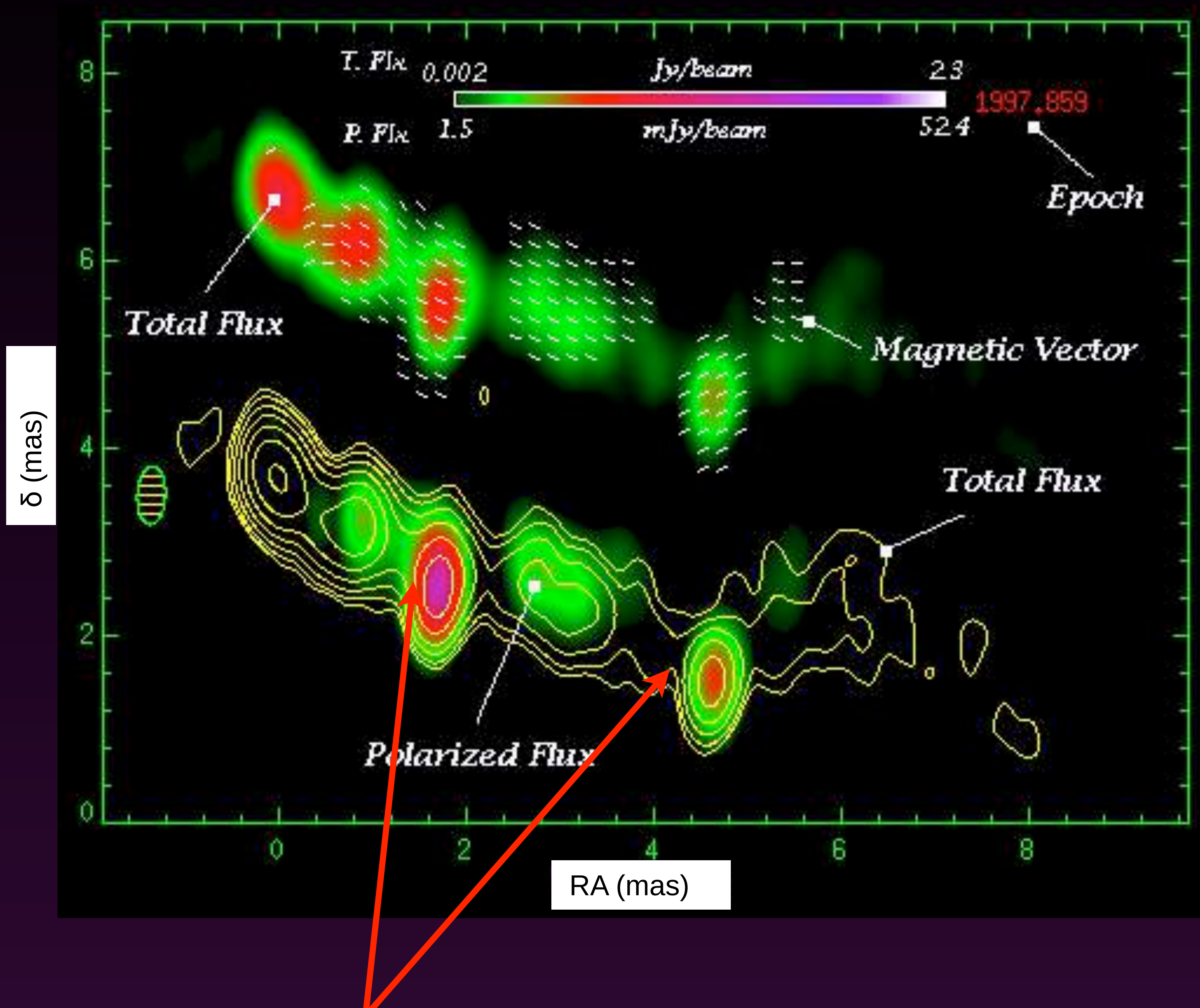


Internal Dissipation:

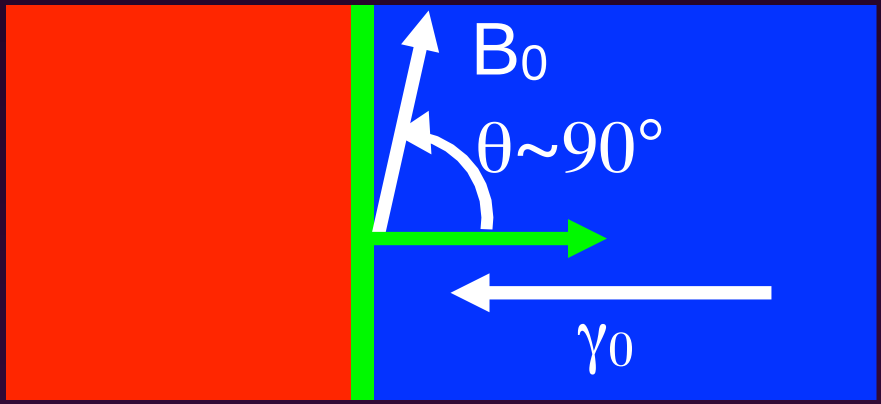
Shocks or Reconnection?

Internal shocks in blazars and gamma-ray burst jets:

- trans-relativistic (γ_0~a few)
- magnetized ($\sigma>0.01$)

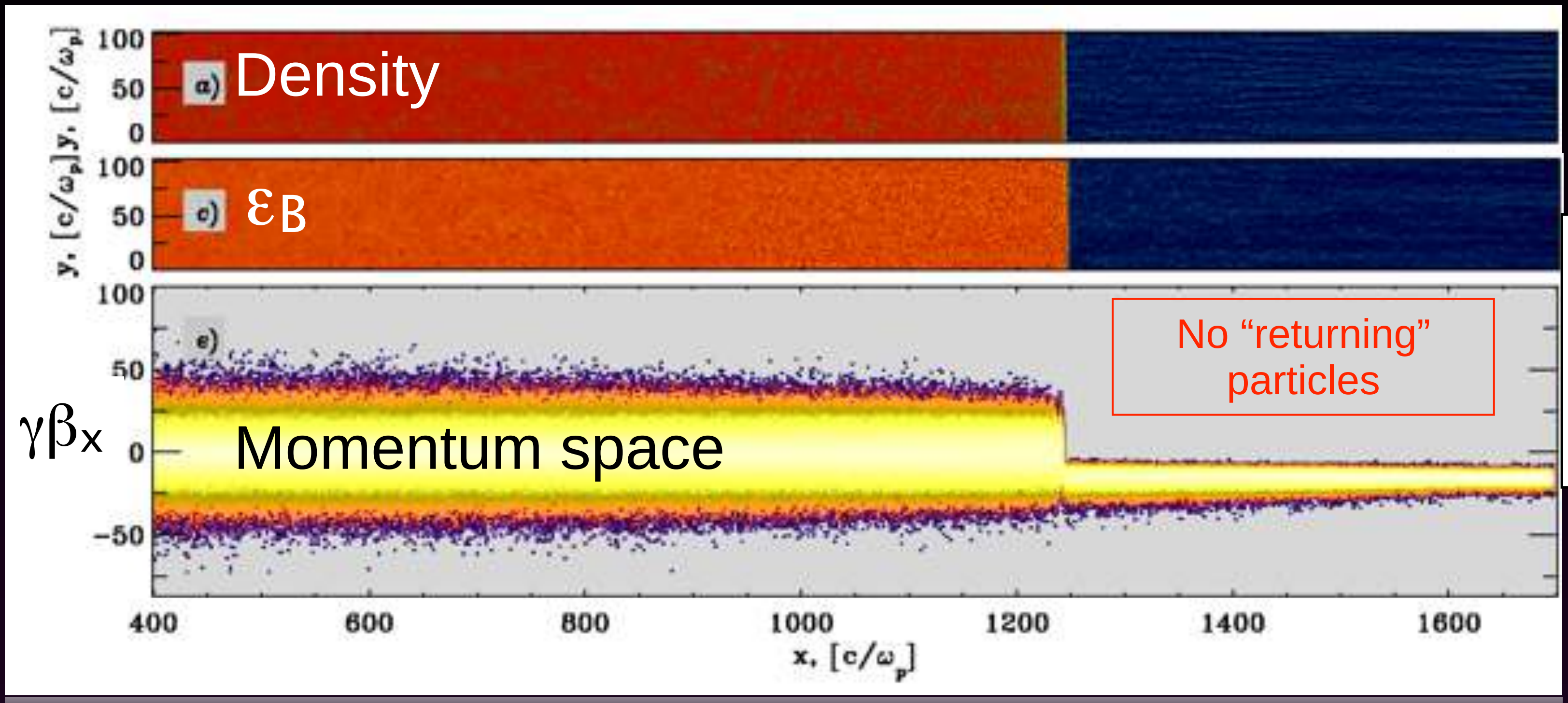
$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$

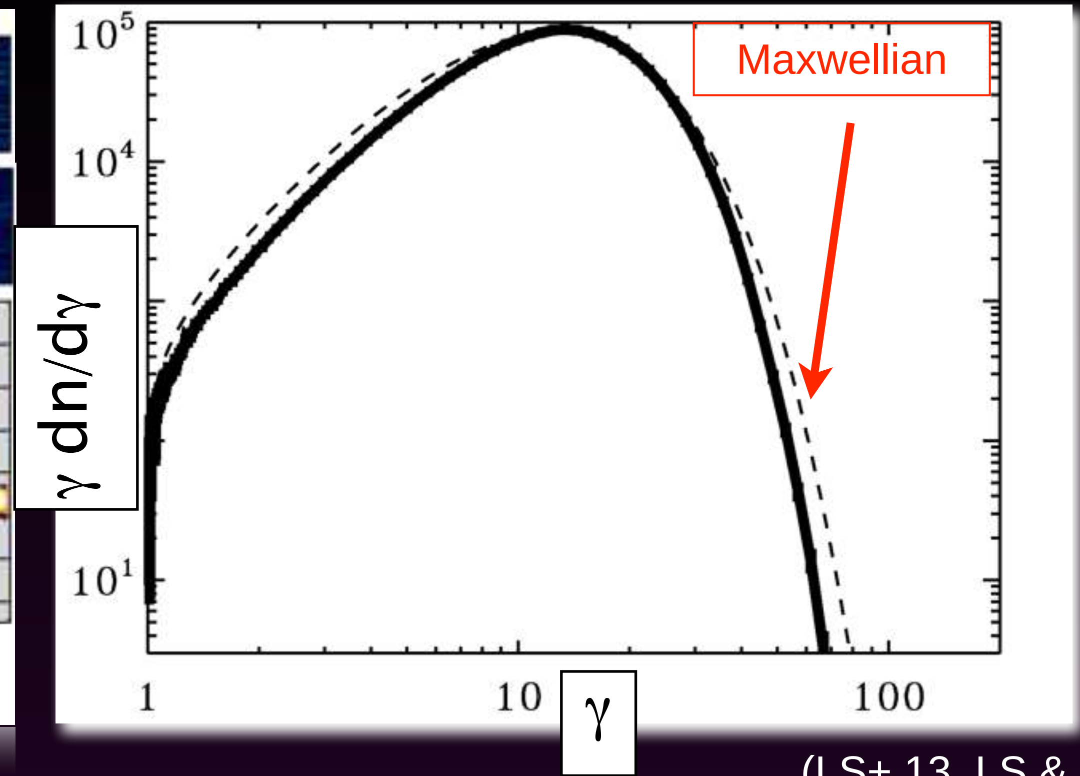
- toroidal field around the jet → field ⊥ to the shock normal



Shocks: no turbulence → no acceleration

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



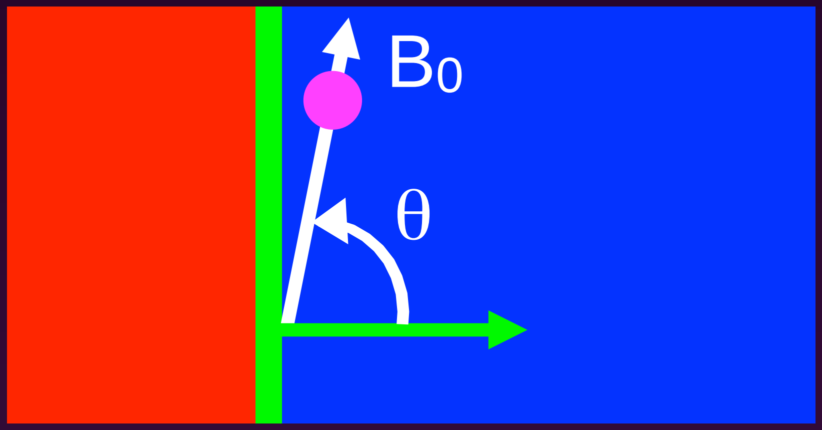


(LS+ 13, LS & Spitkovsky 09,11)

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

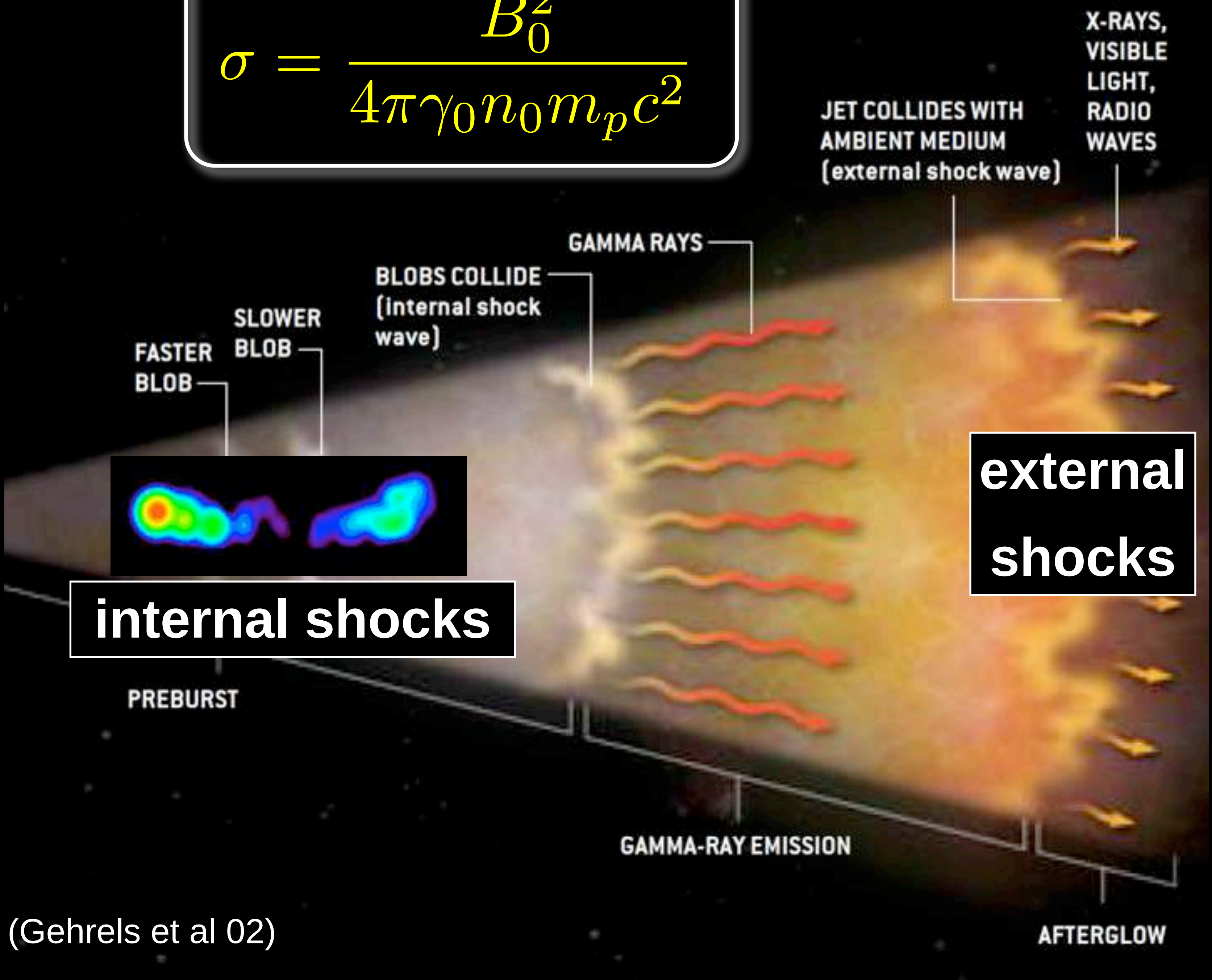
θ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

→ Fermi acceleration is generally suppressed

Are relativistic shocks always inefficient?

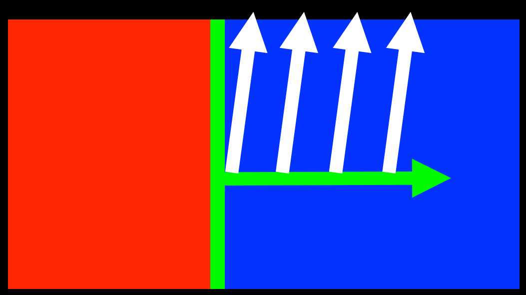
$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$



(Gehrels et al 02)

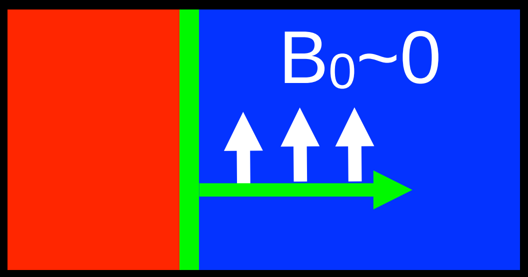
Internal shocks in blazars and gamma-ray burst jets:

- γ_0~a few
- quasi-perpendicular shocks
- σ~0.01−0.1

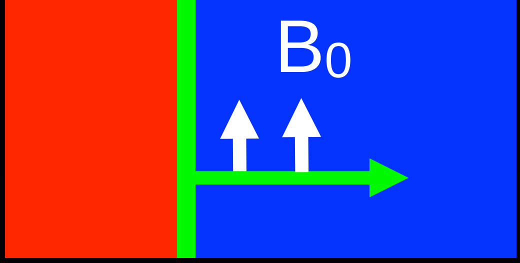


Gamma-ray burst external shocks:

- γ_0~a few hundreds
- perpendicular shocks
- $\sigma \sim 10^{-9}$



High-σ vs low-σ shocks



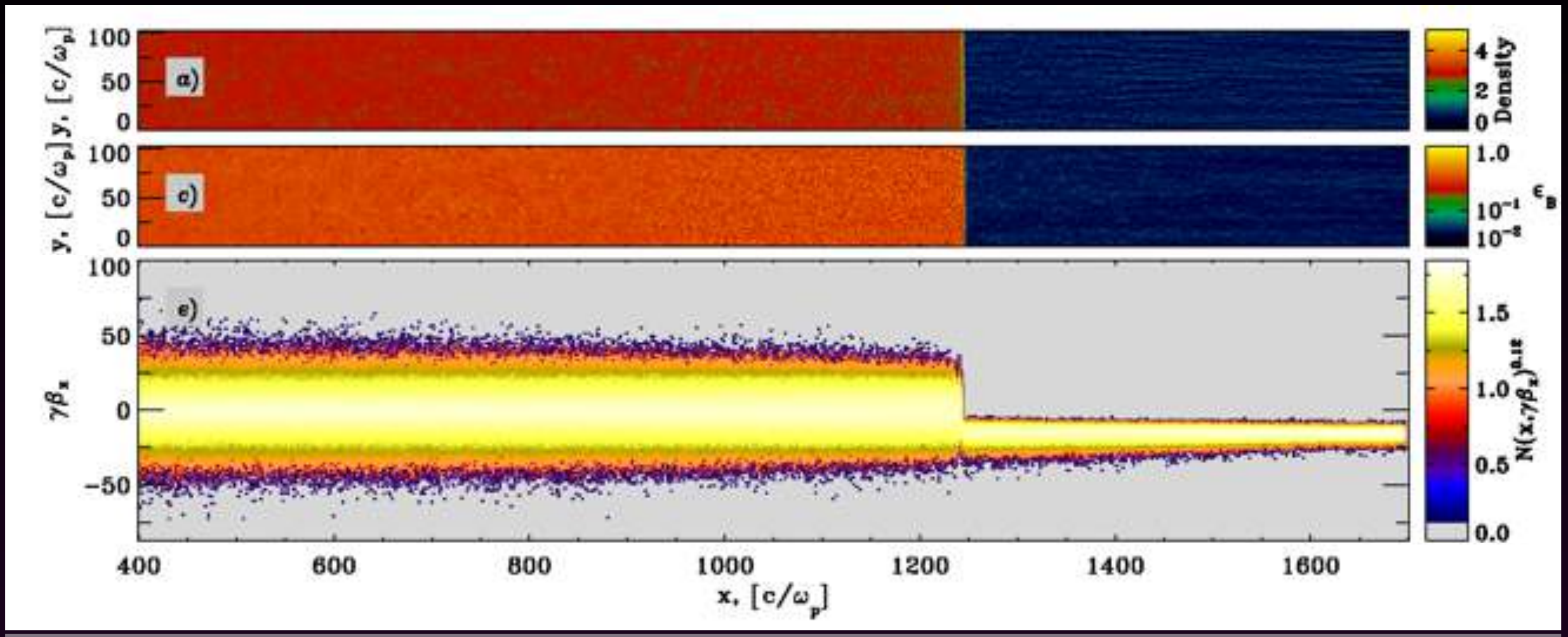
- High-σ shocks: no returning particles → no turbulence

σ=0.1

perp shock

γ_0=15

e^--e^+



Density

ϵ_B

$\gamma\beta_x$

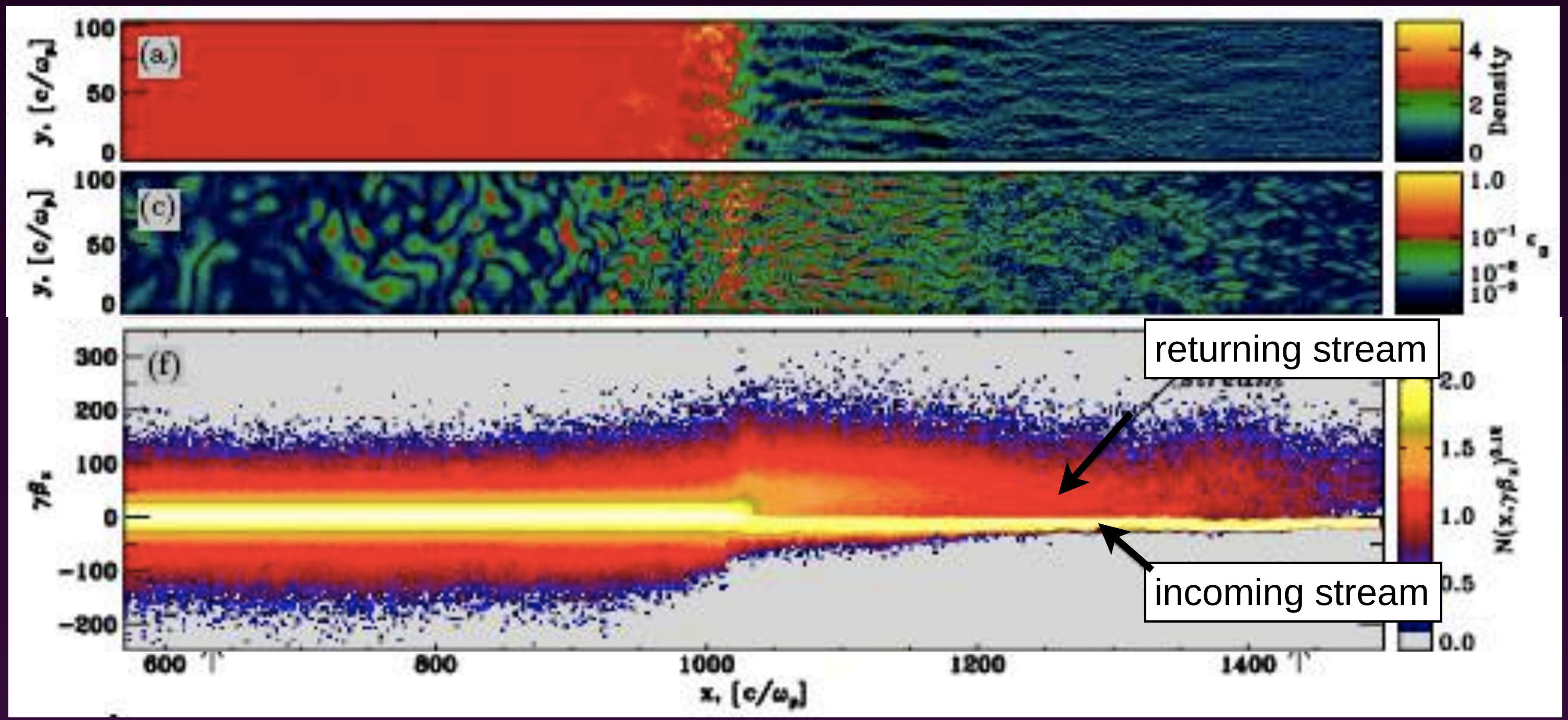
(LS & Spitkovsky 11)

- Low-σ shocks: returning particles → oblique & filamentation instabilities

σ=0

γ_0=15

e^--e^+



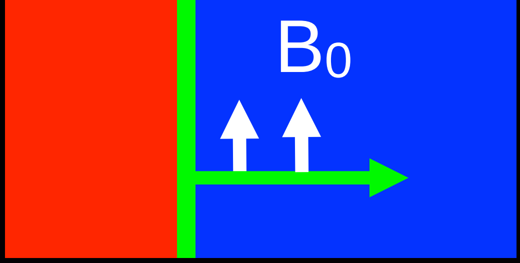
Density

ϵ_B

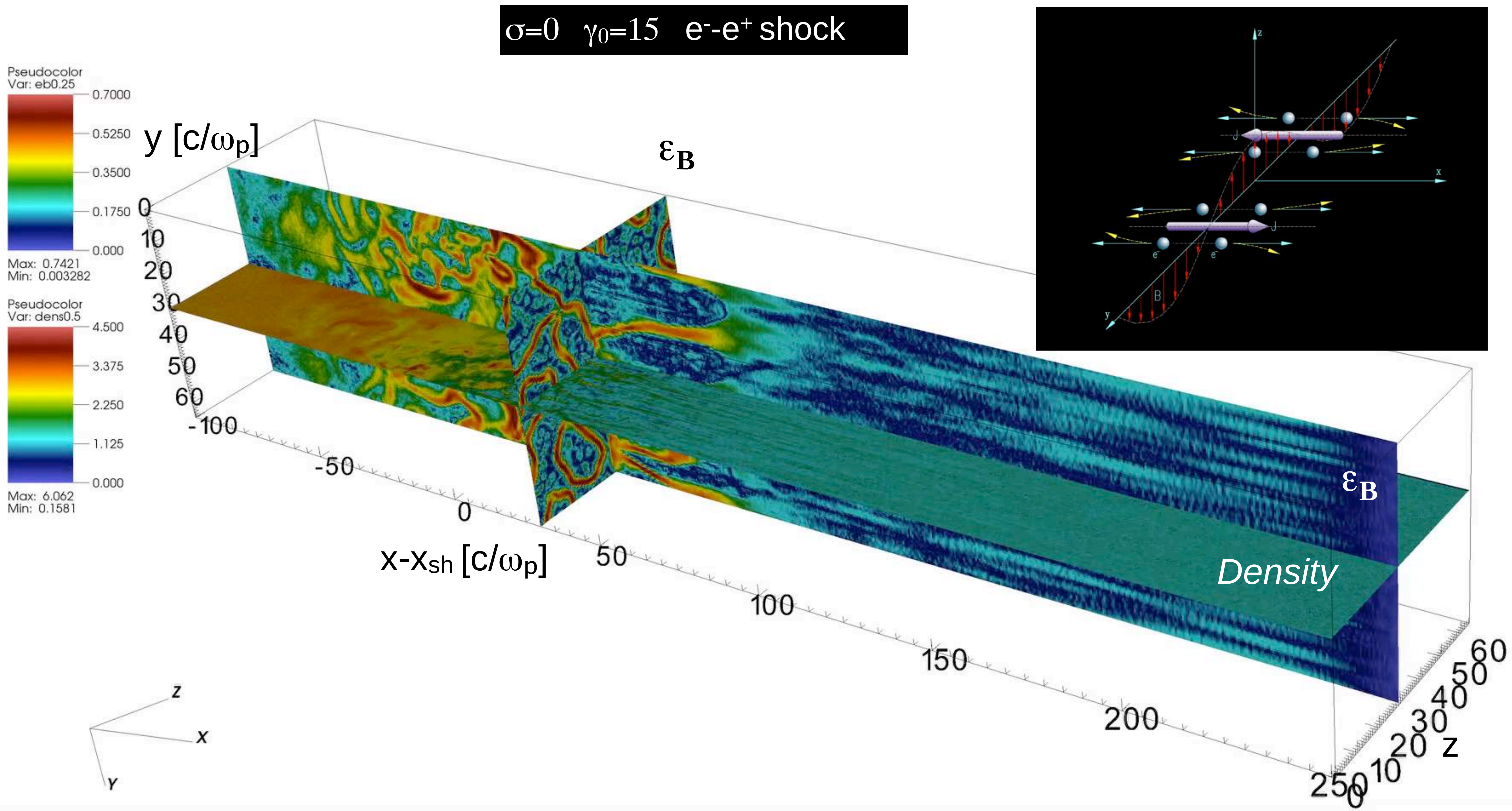
$\gamma\beta_x$

(LS et al 13)

Low-σ shocks are filamentary

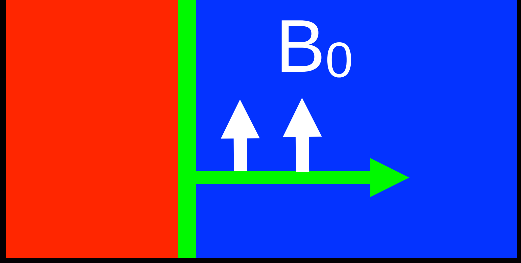


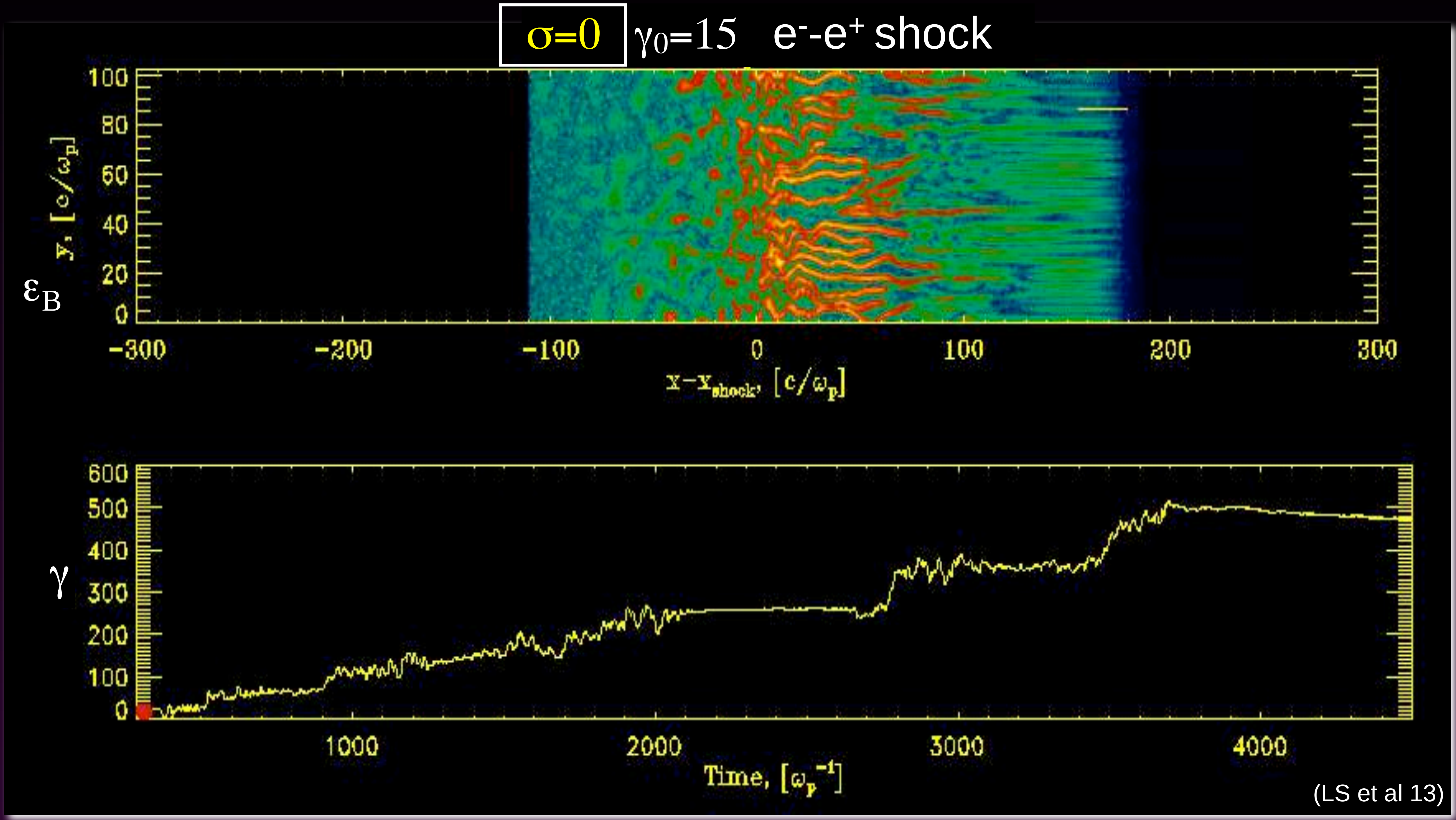
Mediated by the filamentation (Weibel) instability, which generates small-scale sub-equipartition magnetic fields.



(LS et al. 13)

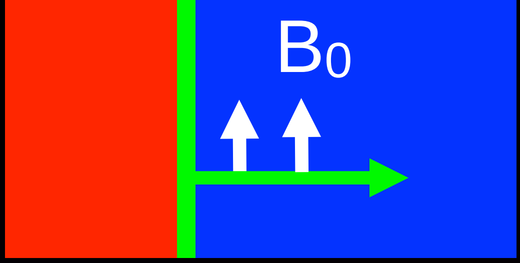
The Fermi process in low-σ shocks





Particle acceleration via the Fermi process in self-generated turbulence, for initially unmagnetized (i.e., $\sigma=0$) or weakly magnetized flows.

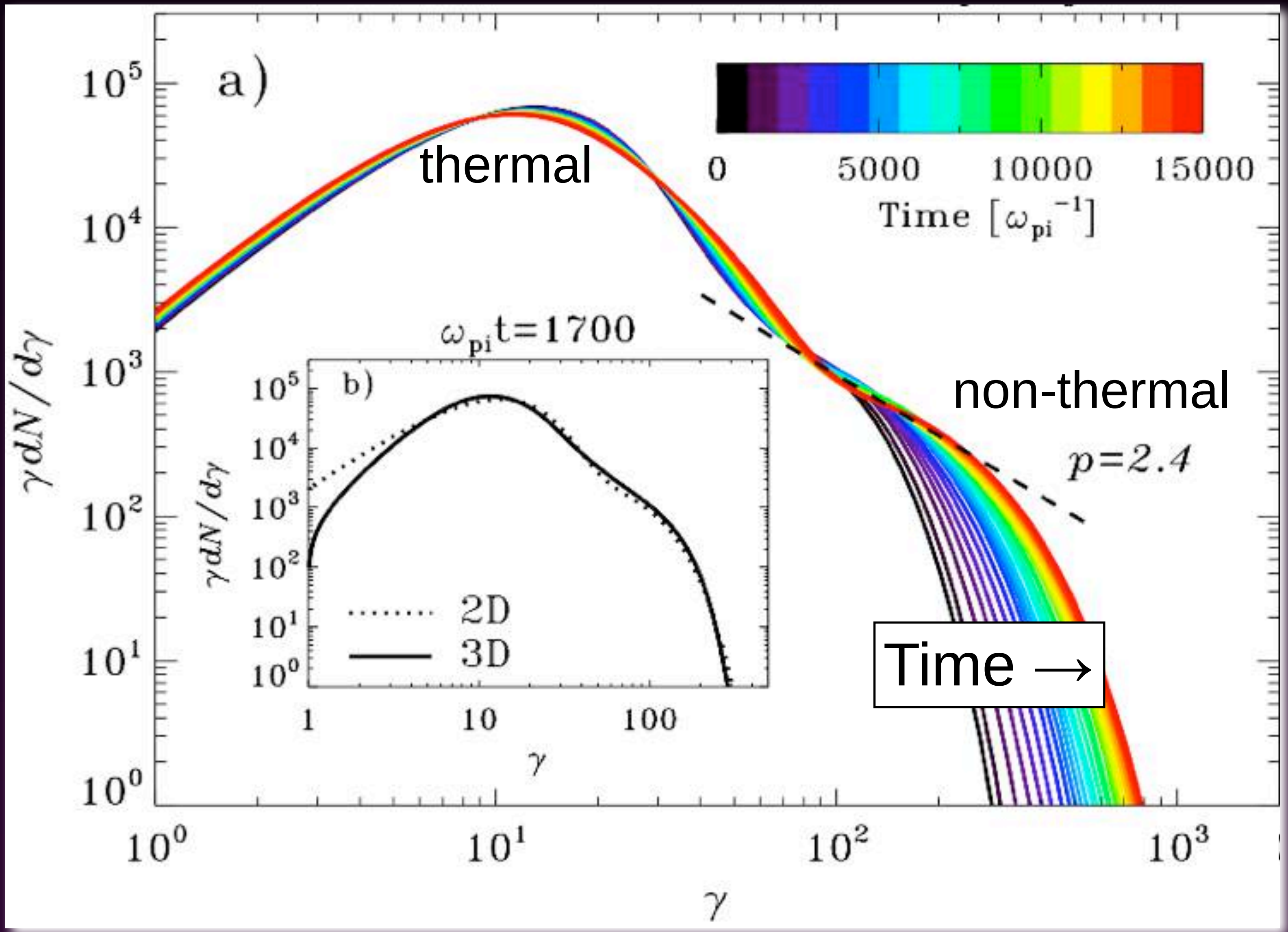
Low-σ shocks are efficient but slow



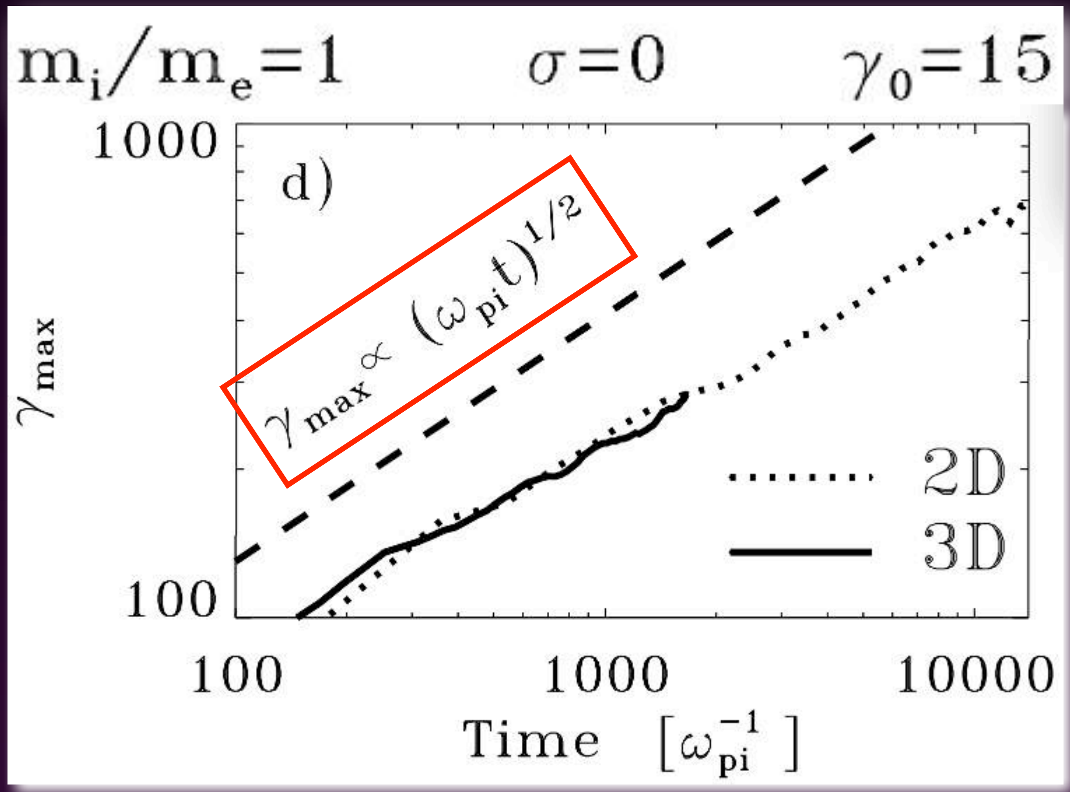
The nonthermal tail has slope *p*=2.4±0.1 and contains ~1% of particles and ~10% of energy.

By scattering off small-scale Weibel turbulence, the maximum energy grows as $\gamma_{max} \propto t^{1/2}$.

Instead, most models of particle acceleration in shocks assume $\gamma_{max} \propto t$ (Bohm scaling).



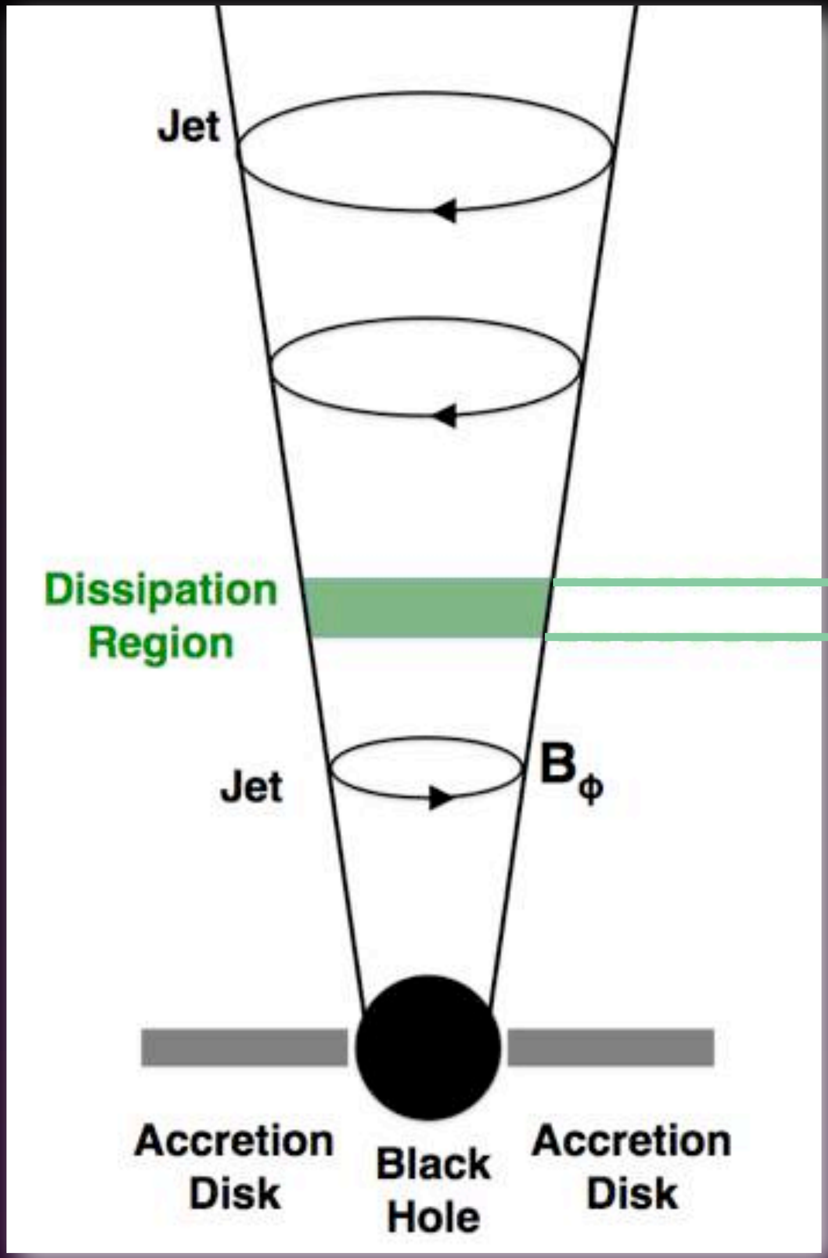
$$\gamma_{max} \simeq 0.5\,\gamma_0\,(\omega_{pi}t)^{1/2}$$

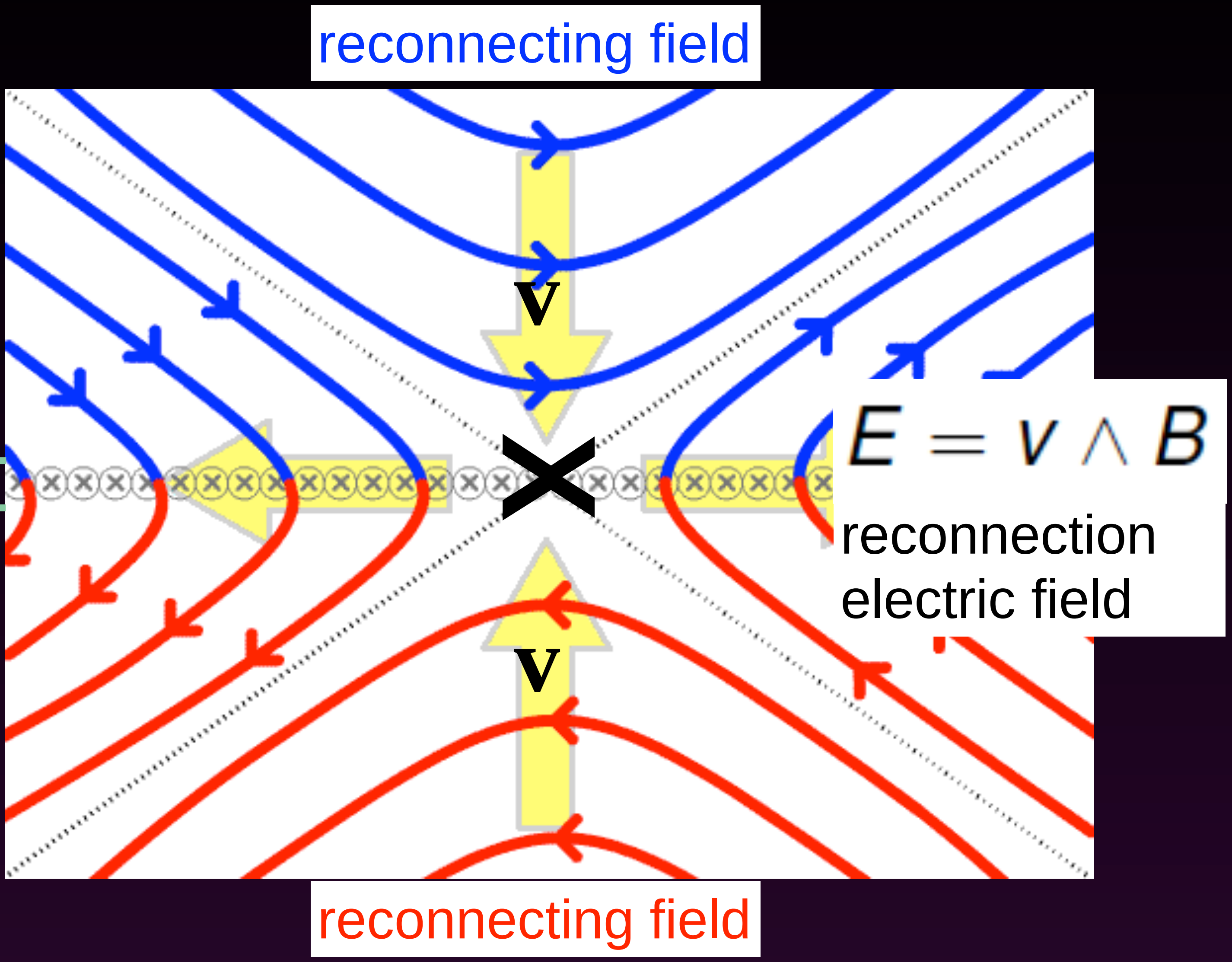


(LS et al. 13, Martins et al. 09, Haugbolle 10)

Conclusions are the same in 2D and 3D

Relativistic reconnection within jets





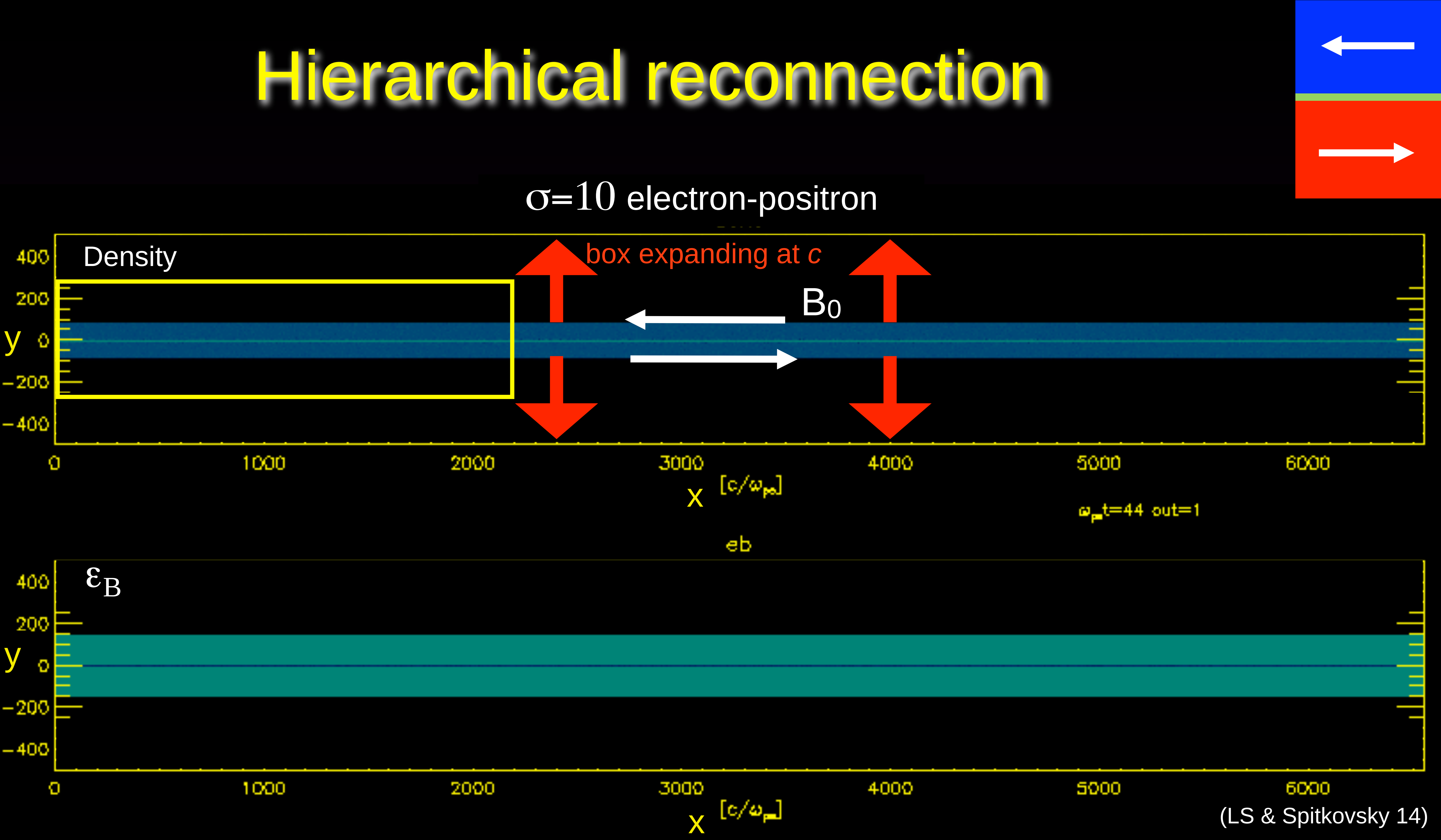
Relativistic Reconnection

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

Refs: Bessho, Bhattacharjee, Cerutti, Drake, Egedal, Giannios, de Gouveia dal Pino, Hesse, Hoshino, Huang, Jaroschek, Kagan, Karimabadi, Kulsrud, Liu, Li, Lyubarsky, Lyutikov, Oka, Takamoto, Uzdensky, Yin, Zenitani

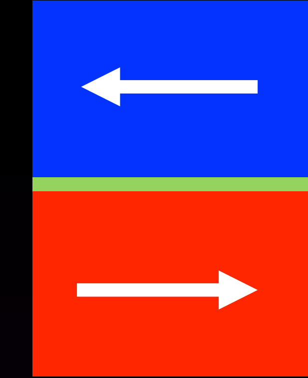
Dynamics and particle spectrum

Hierarchical reconnection

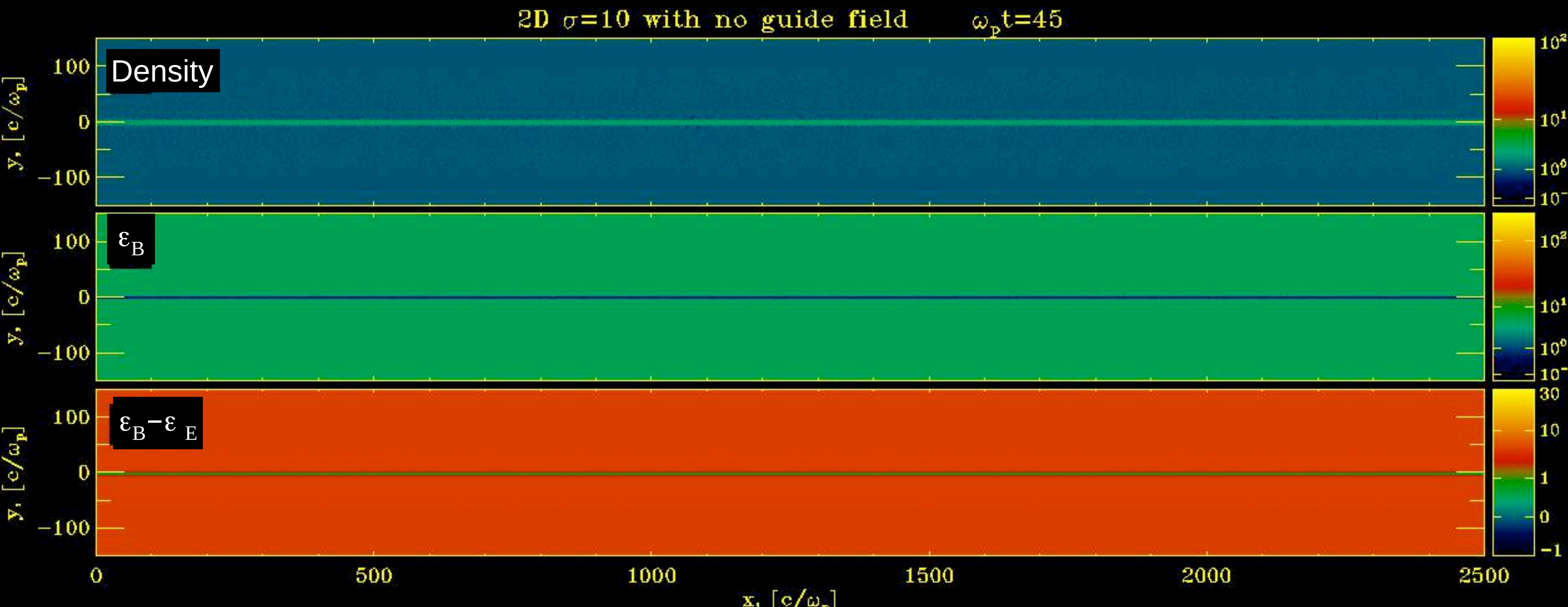


- Reconnection is a hierarchical process of island formation and merging.
- The field energy is transferred to the particles at the X-points, in between the magnetic islands.

Hierarchical reconnection



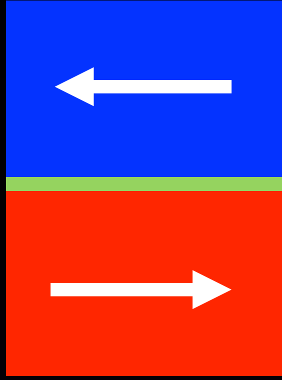
$\sigma=10$ electron-positron



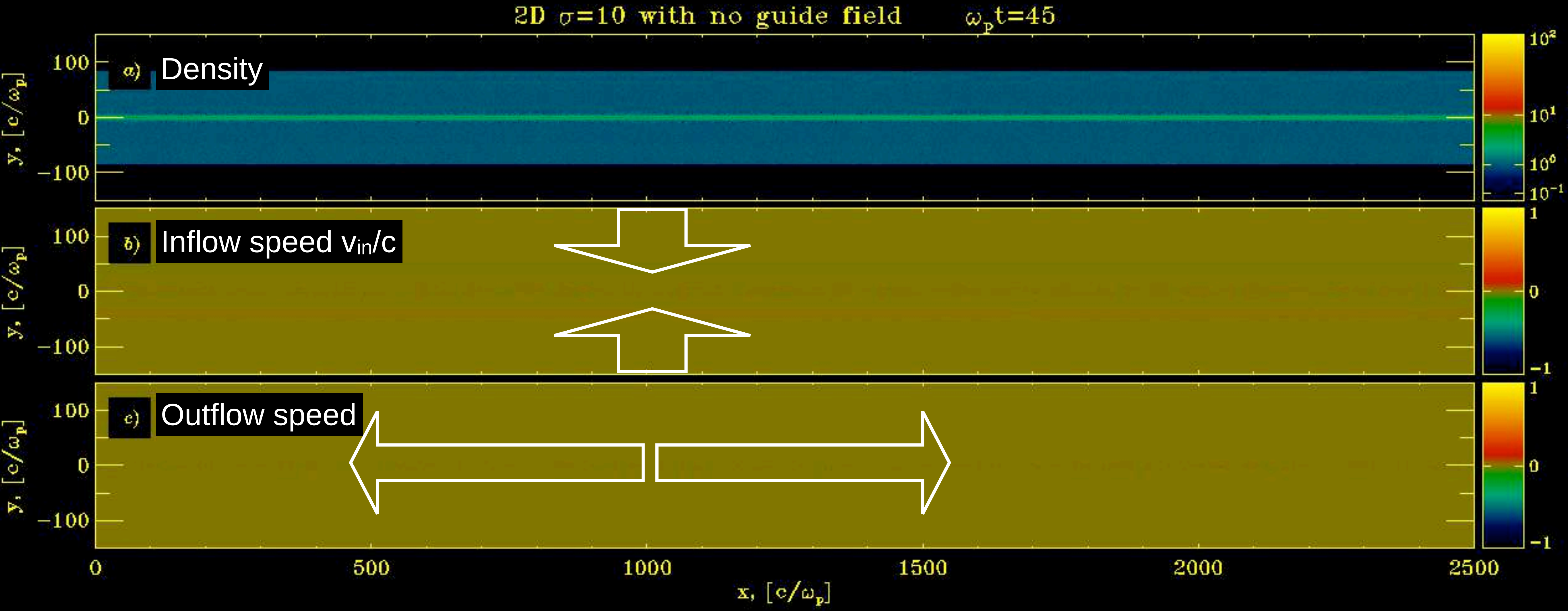
(LS & Spitkovsky 14)

- 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

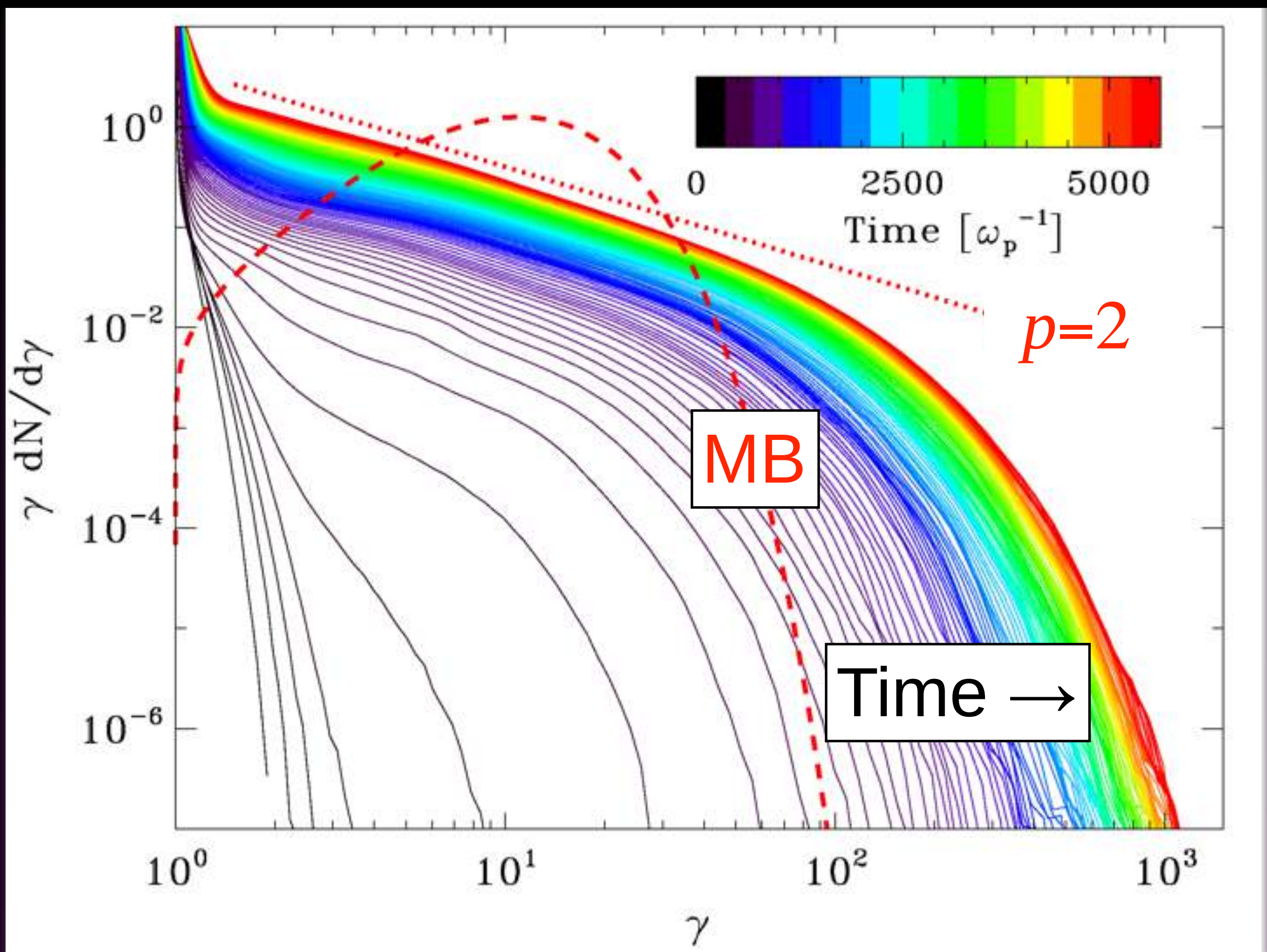


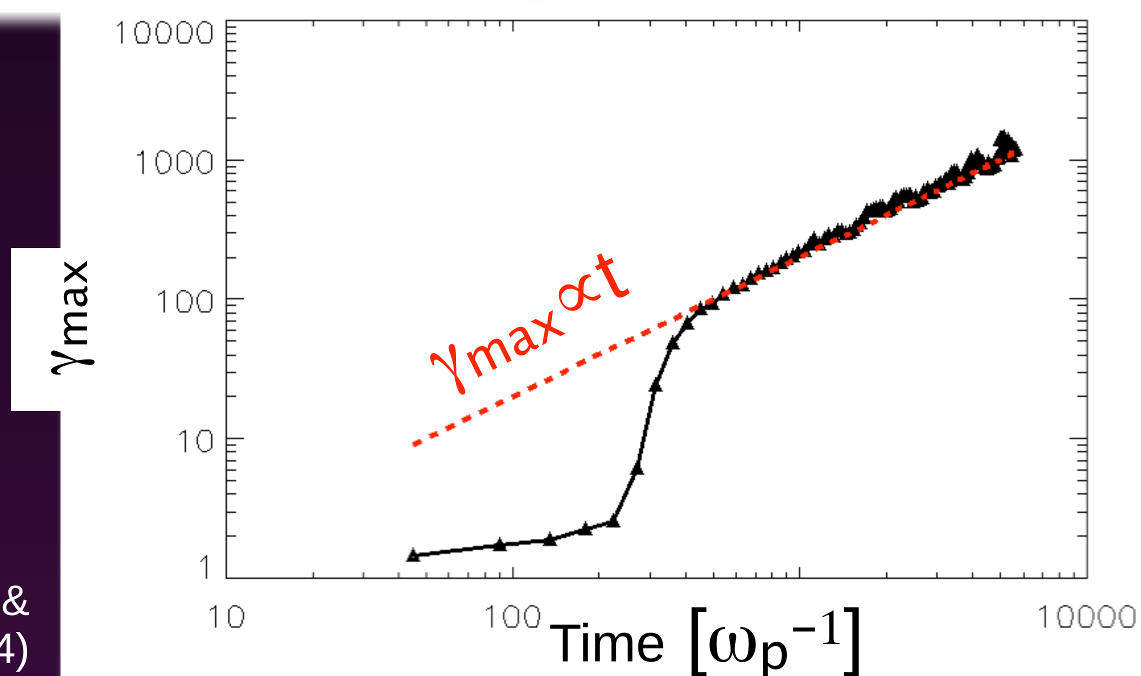
- Inflow into the X-line is non-relativistic, at v_{in} ~ 0.1 c (Lyutikov & Uzdensky 03, Lyubarsky 05)
- Outflow from the X-points is ultra-relativistic, reaching the Alfven speed

$$v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$$

The particle energy spectrum

σ=10 electron-positron





(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~2.

- The normalization increases, as more and more particles enter the current sheet.

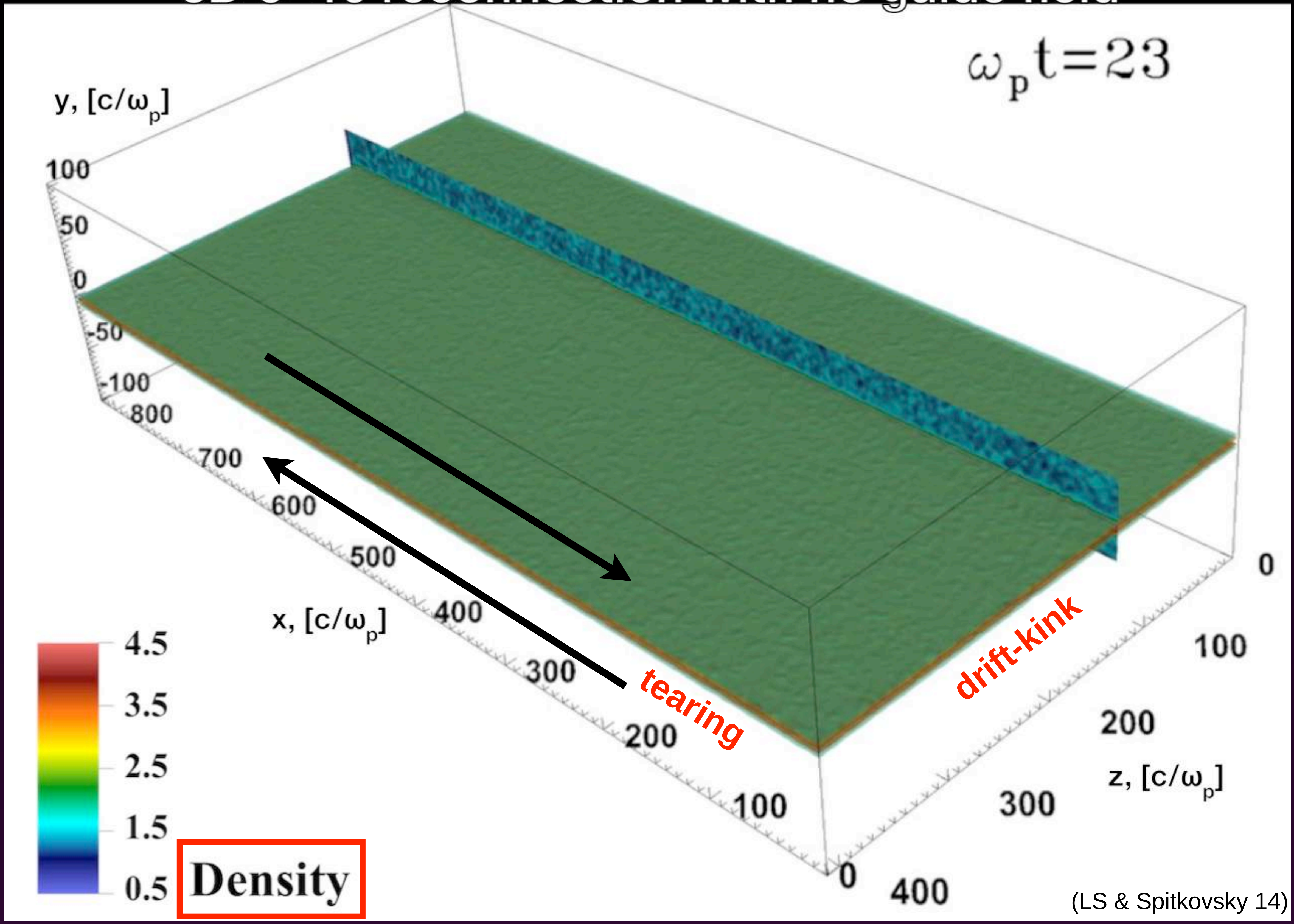
- The mean particle energy in the current sheet reaches ~σ/4

→ rough energy equipartition

- The max energy grows as $\gamma_{max} \propto t$

(compare to $\gamma_{max} \propto t^{1/2}$ in shocks).

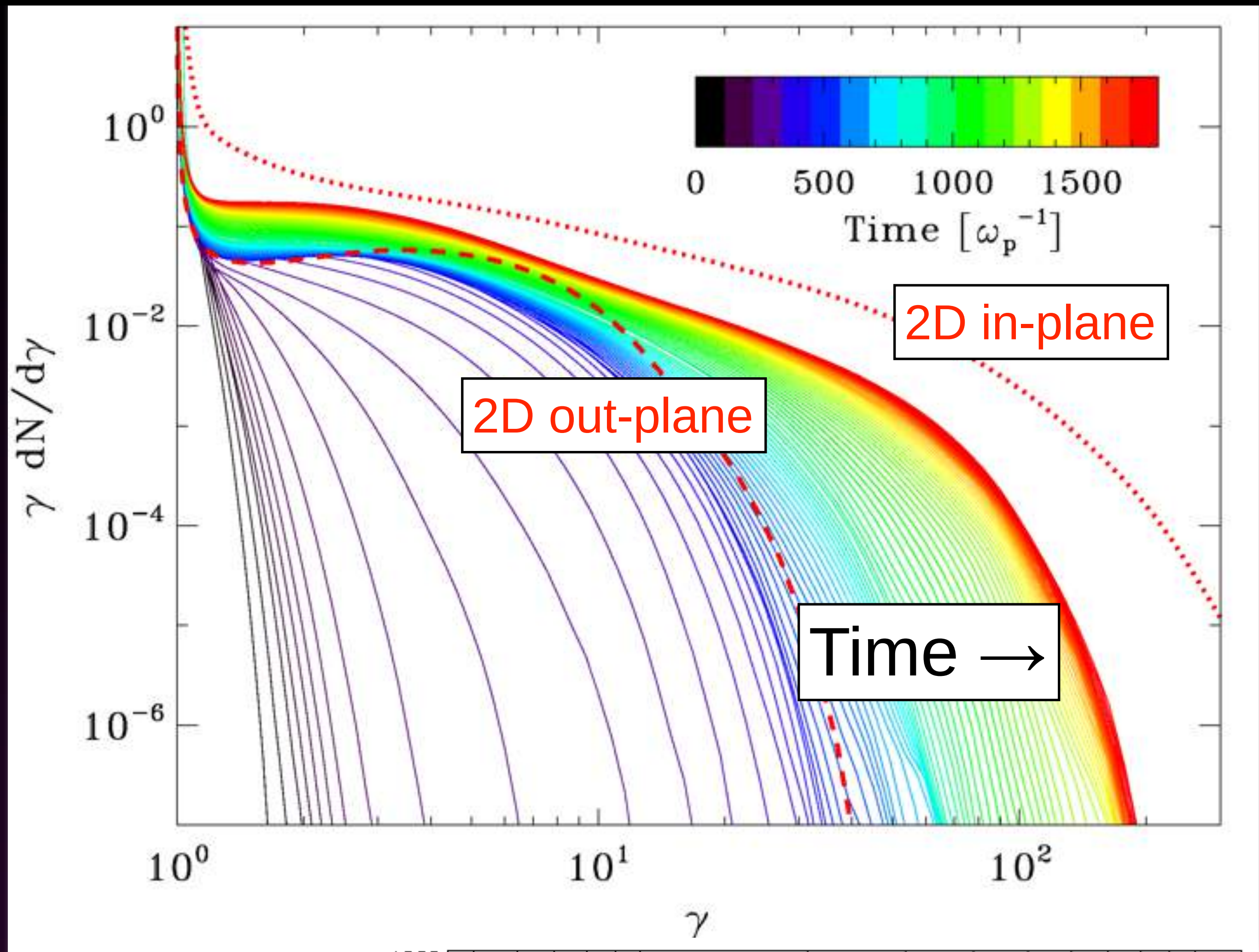
3D σ=10 reconnection with no guide field

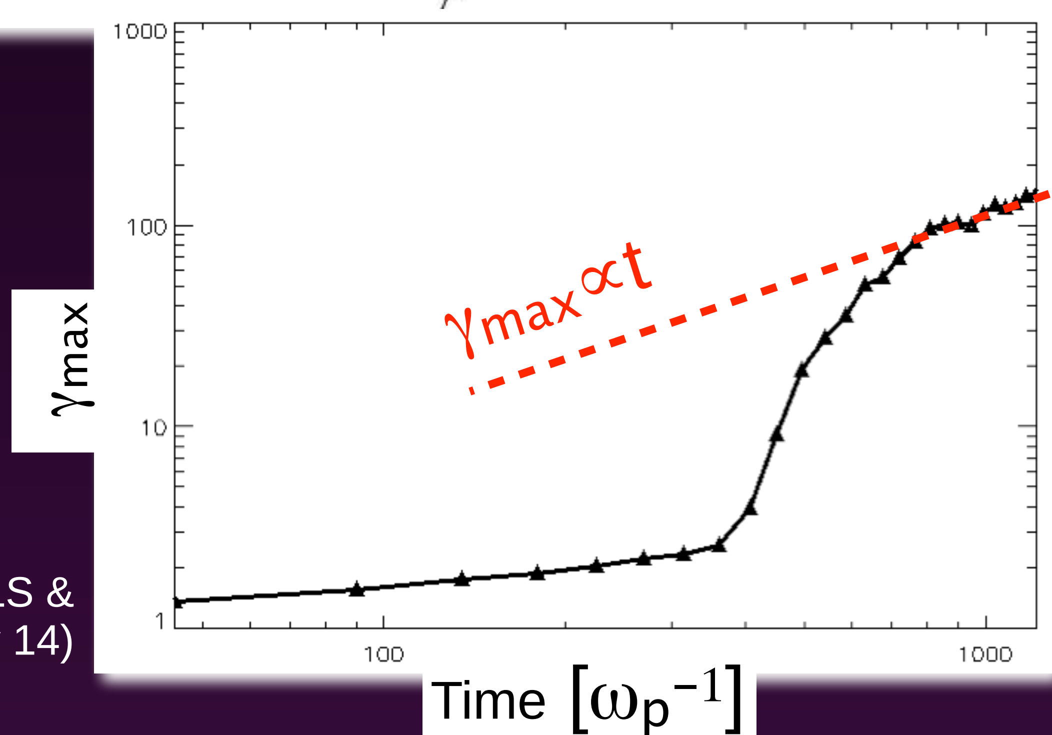


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

3D: particle spectrum

$\sigma=10$ electron-positron





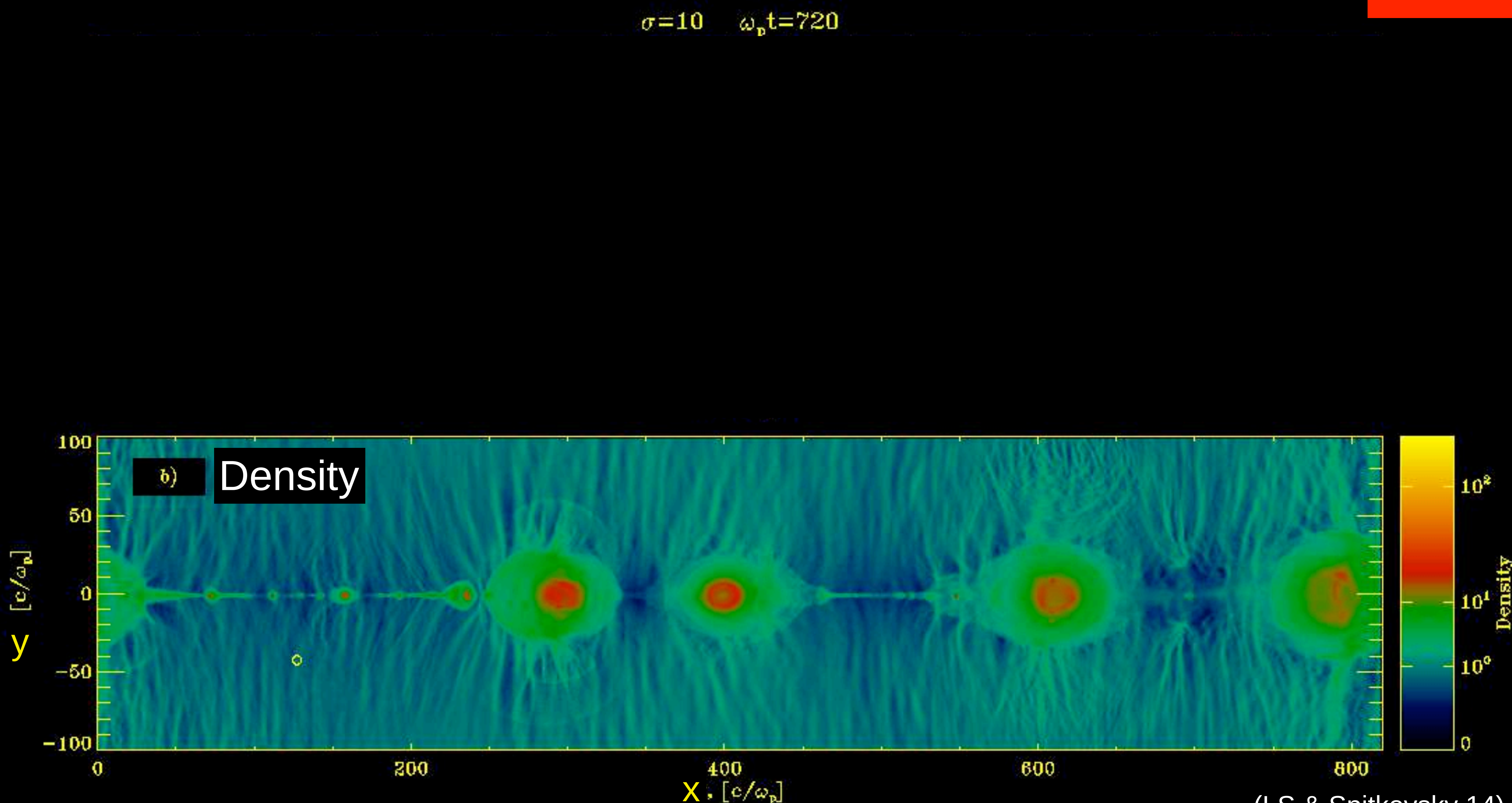
(LS & Spitkovsky 14)

- 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 $\gamma_{max} \propto t$ (compare to $\gamma_{max} \propto t^{1/2}$ in shocks). The reconnection rate is v_{in}/c~ 0.02 in 3D (compare to v_{in}/c ~ 0.1 in 2D).

Particle acceleration mechanism

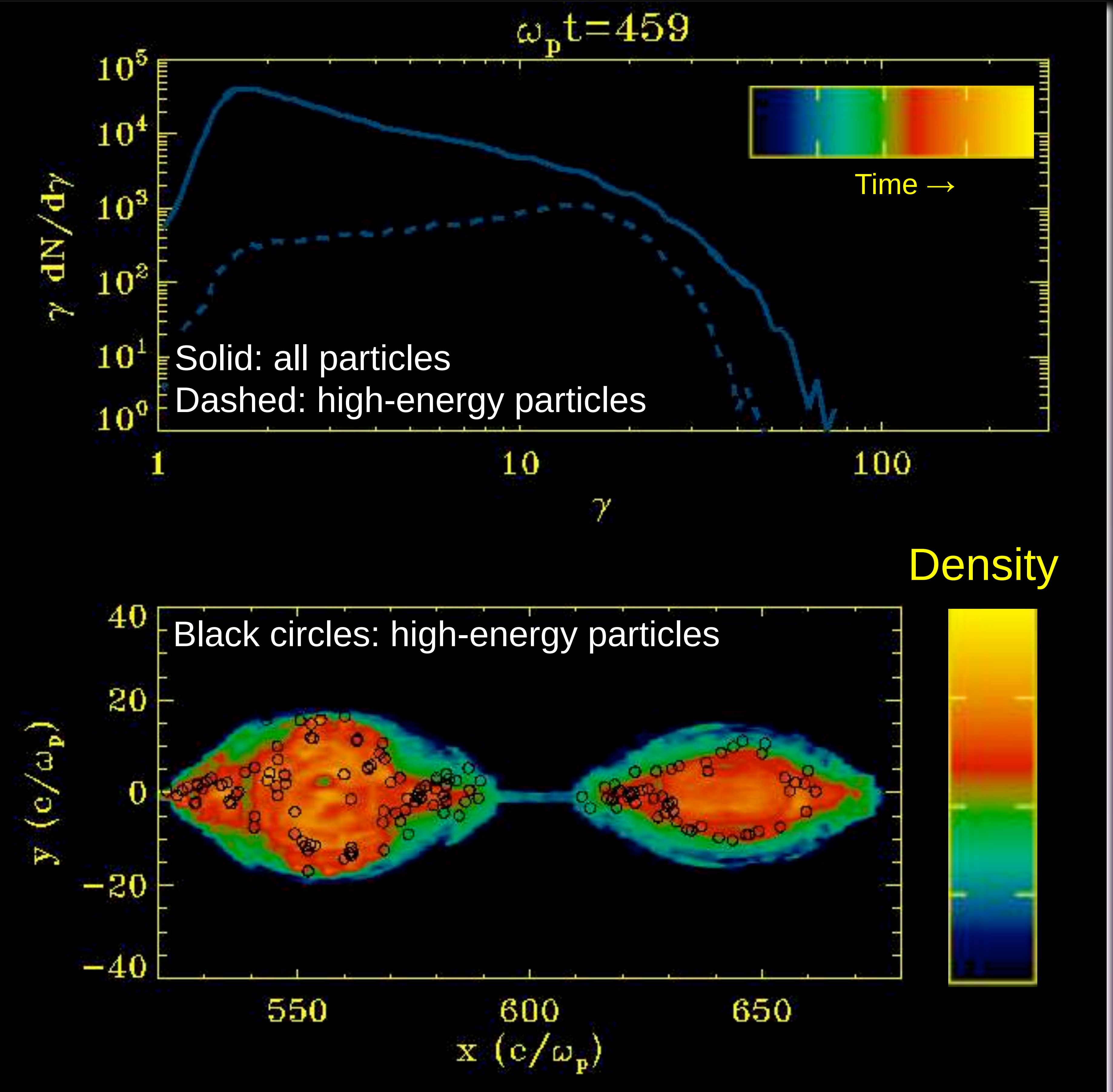
The highest energy particles



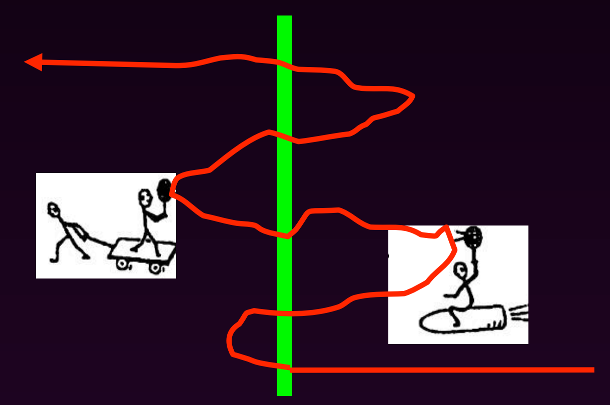
(LS & Spitkovsky 14)

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

(2) Fermi process in between islands



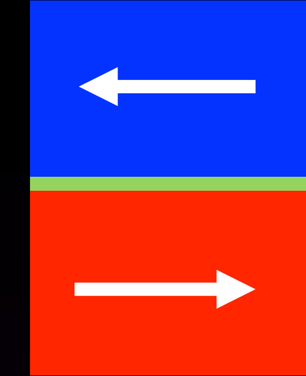
- The particles are accelerated by a Fermi-like process in between merging islands.

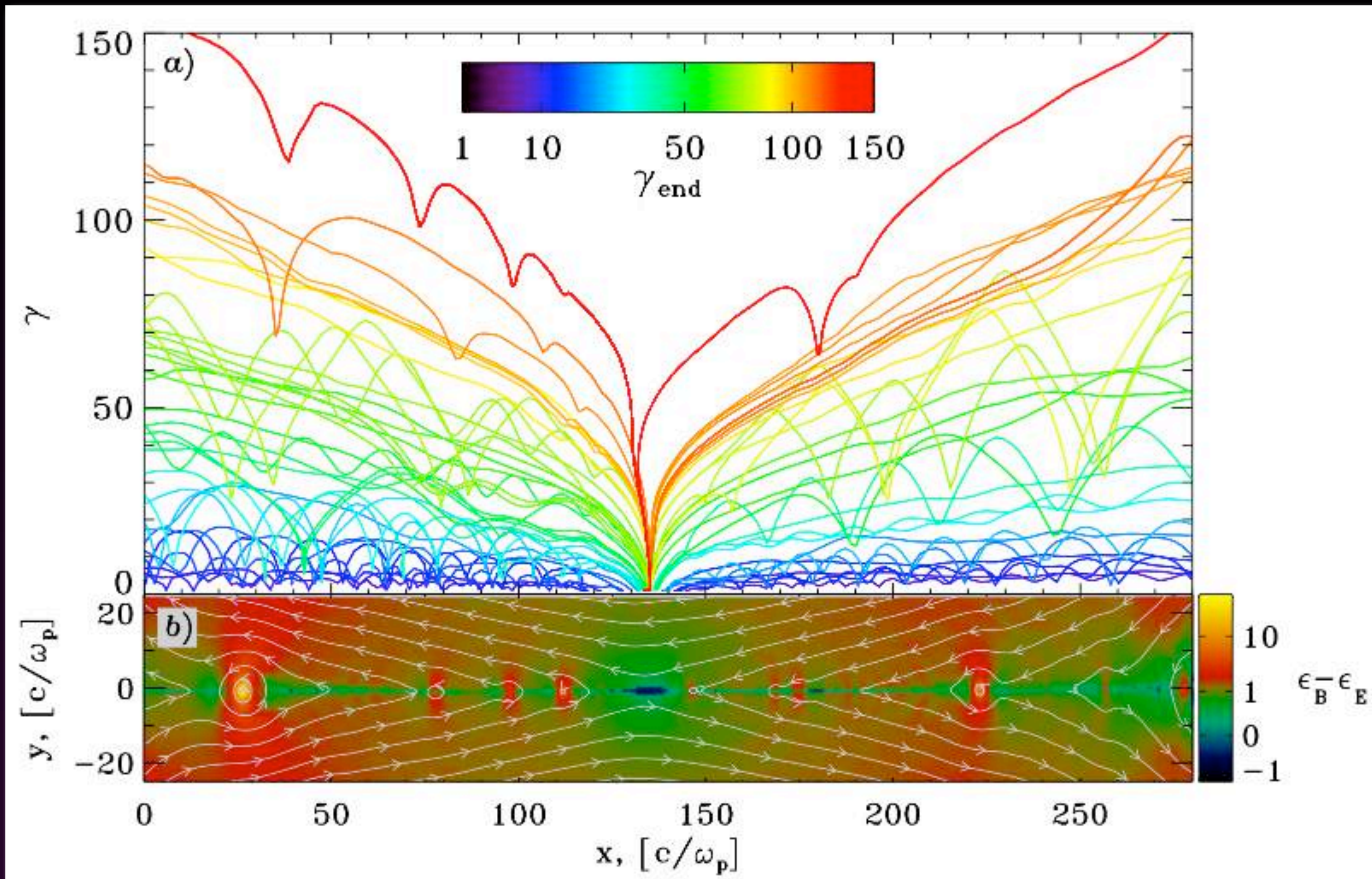


- Island merging is essential to shift up the spectral cutoff energy.

- In the Fermi process, the rich get richer. But how do they get rich in the first place?

(1) Acceleration at X-points



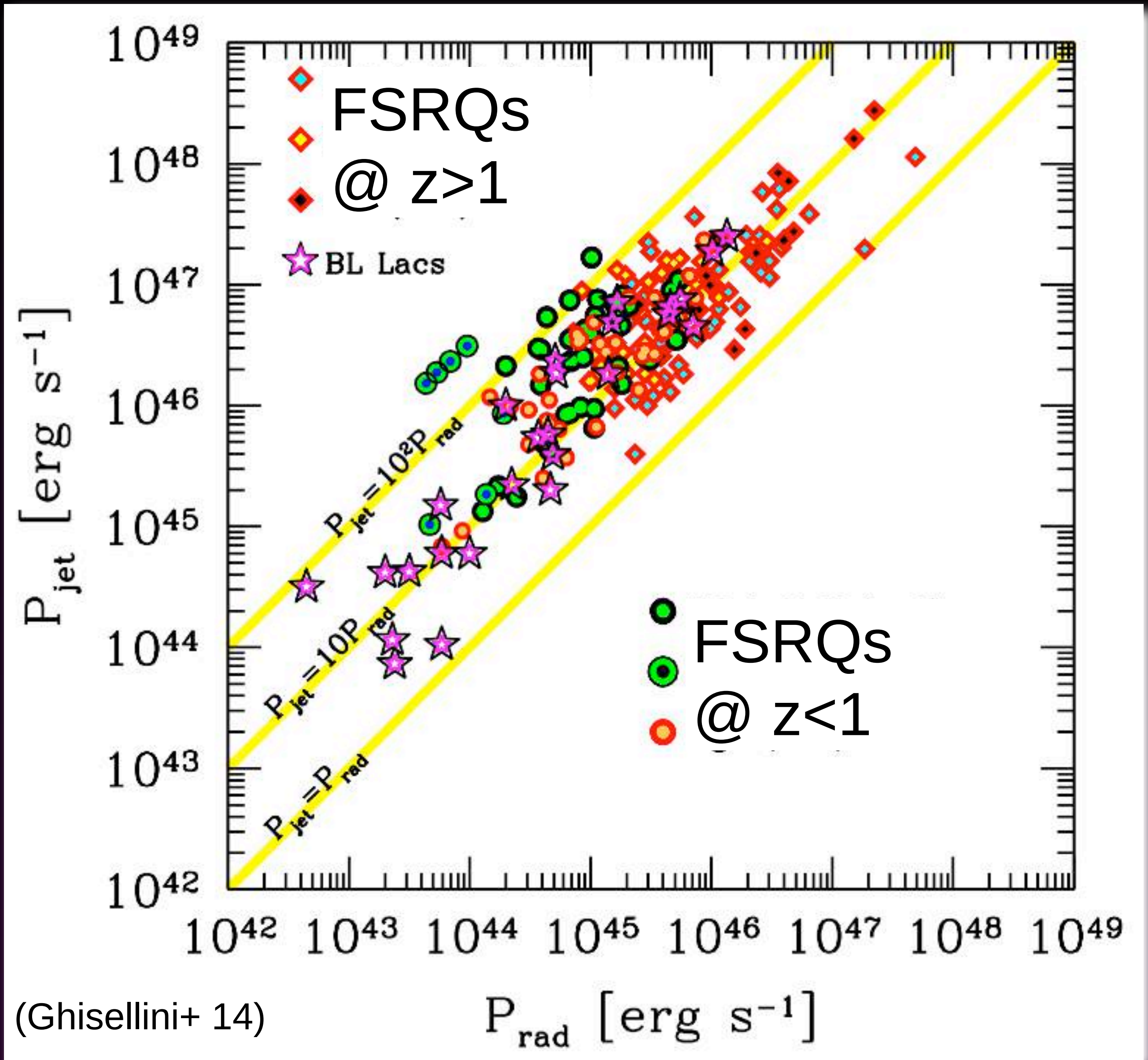


(LS & Spitkovsky 14)

- 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

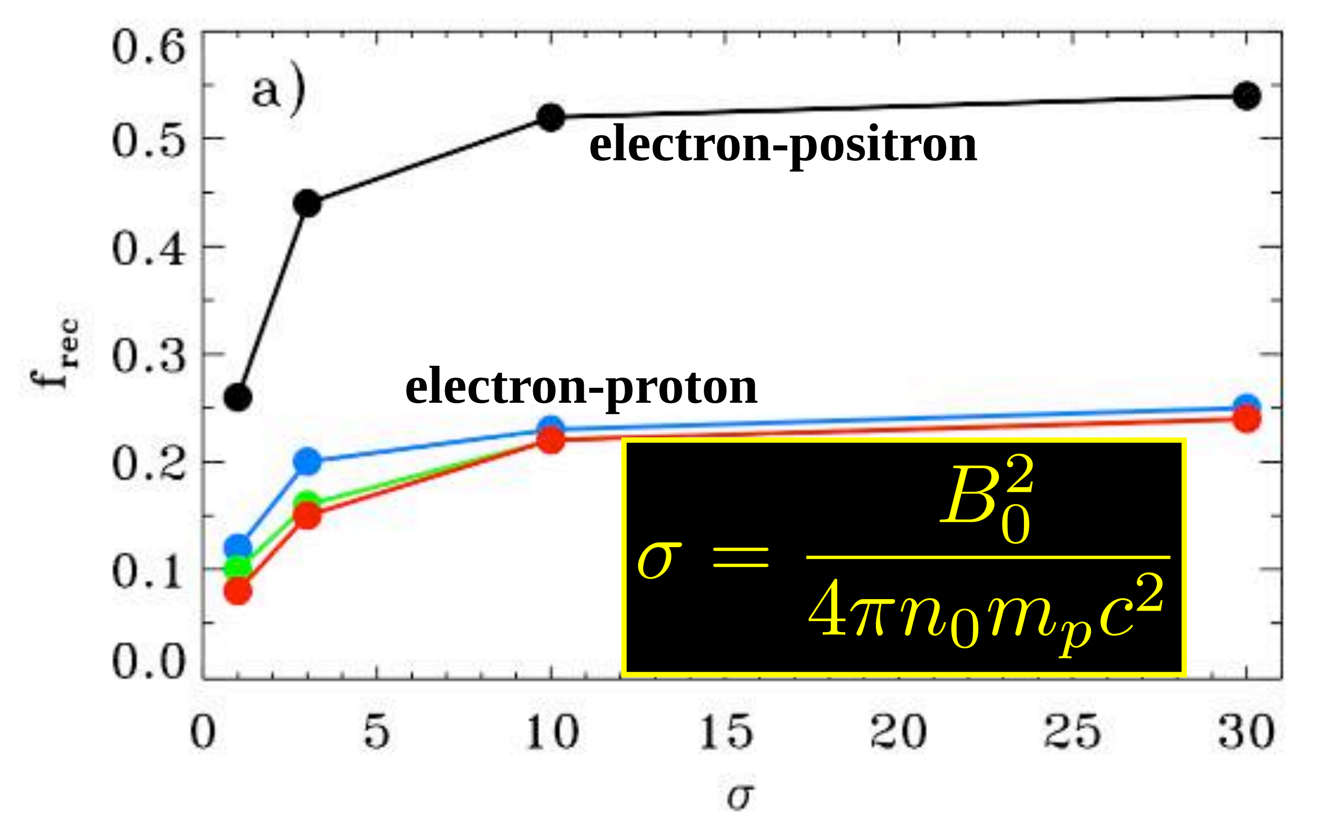
(1) Relativistic reconnection is efficient



(Ghisellini+ 14)

Efficiency

$$f_{\rm rec} \equiv \frac{\sum_i \int_{V_i} U_{\rm e} {\rm d}V_i}{\sum_i \int_{V_i} (e+\rho c^2 + U_{\rm B})\,{\rm d}V_i}$$



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

(Sironi+ 15)

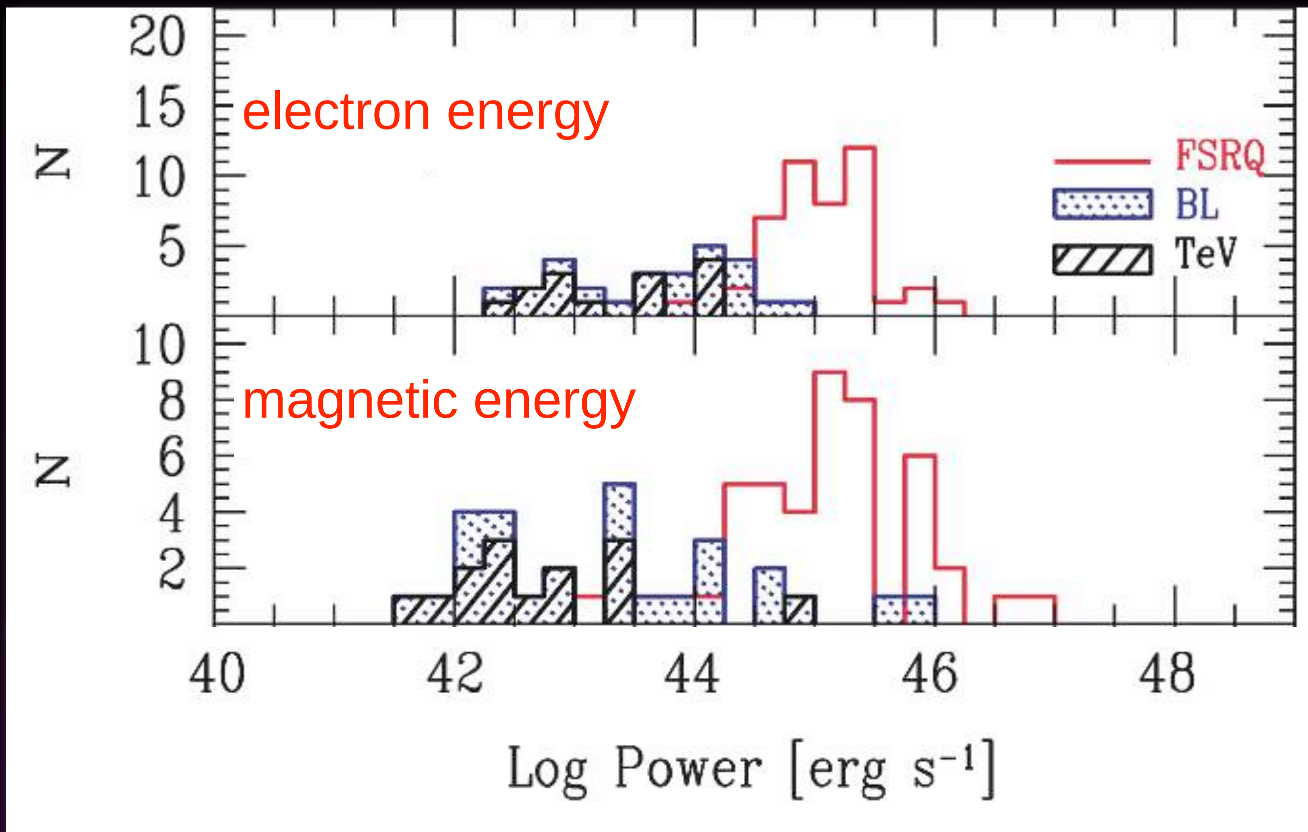
Blazar phenomenology:

- 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

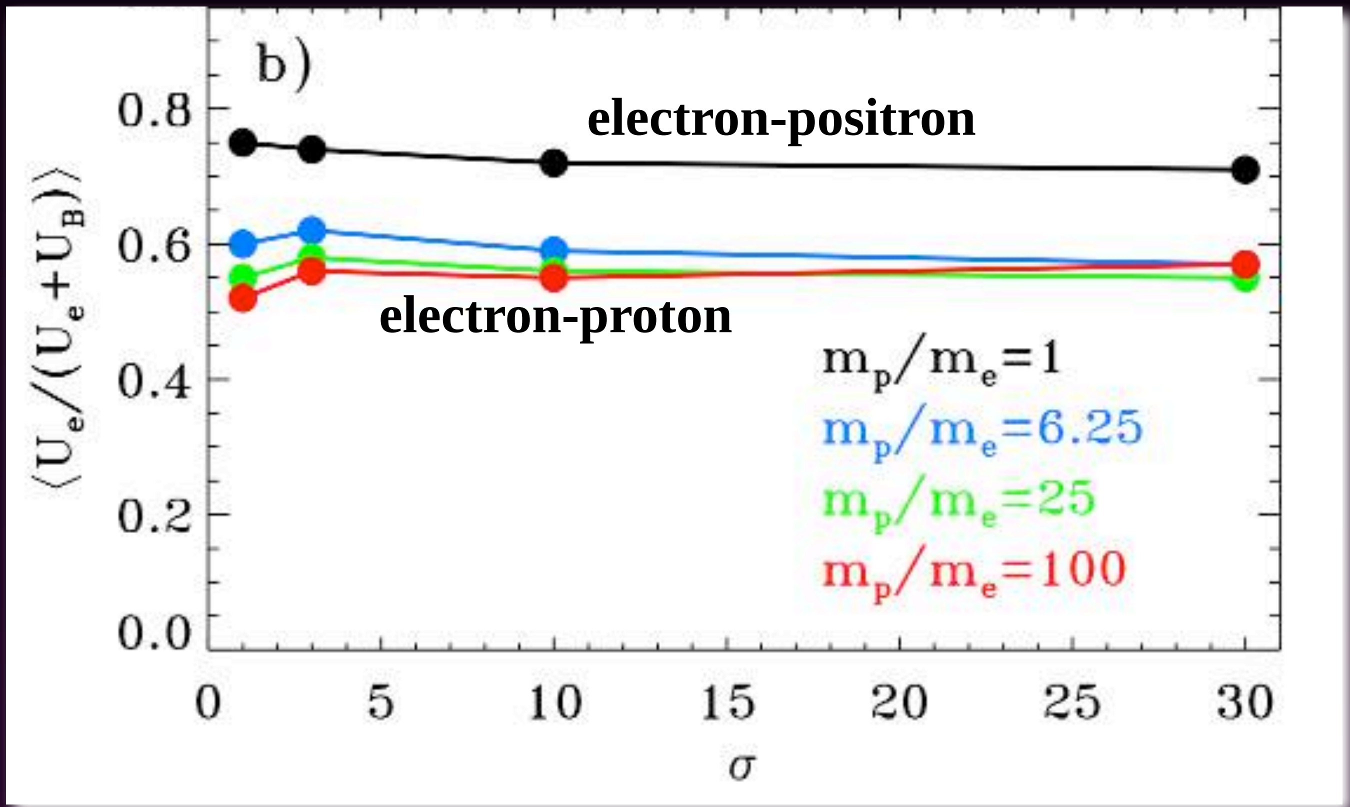
(2) Equipartition of particles and fields



(Celotti+ 08)

Equipartition parameter

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



(Sironi+ 15)

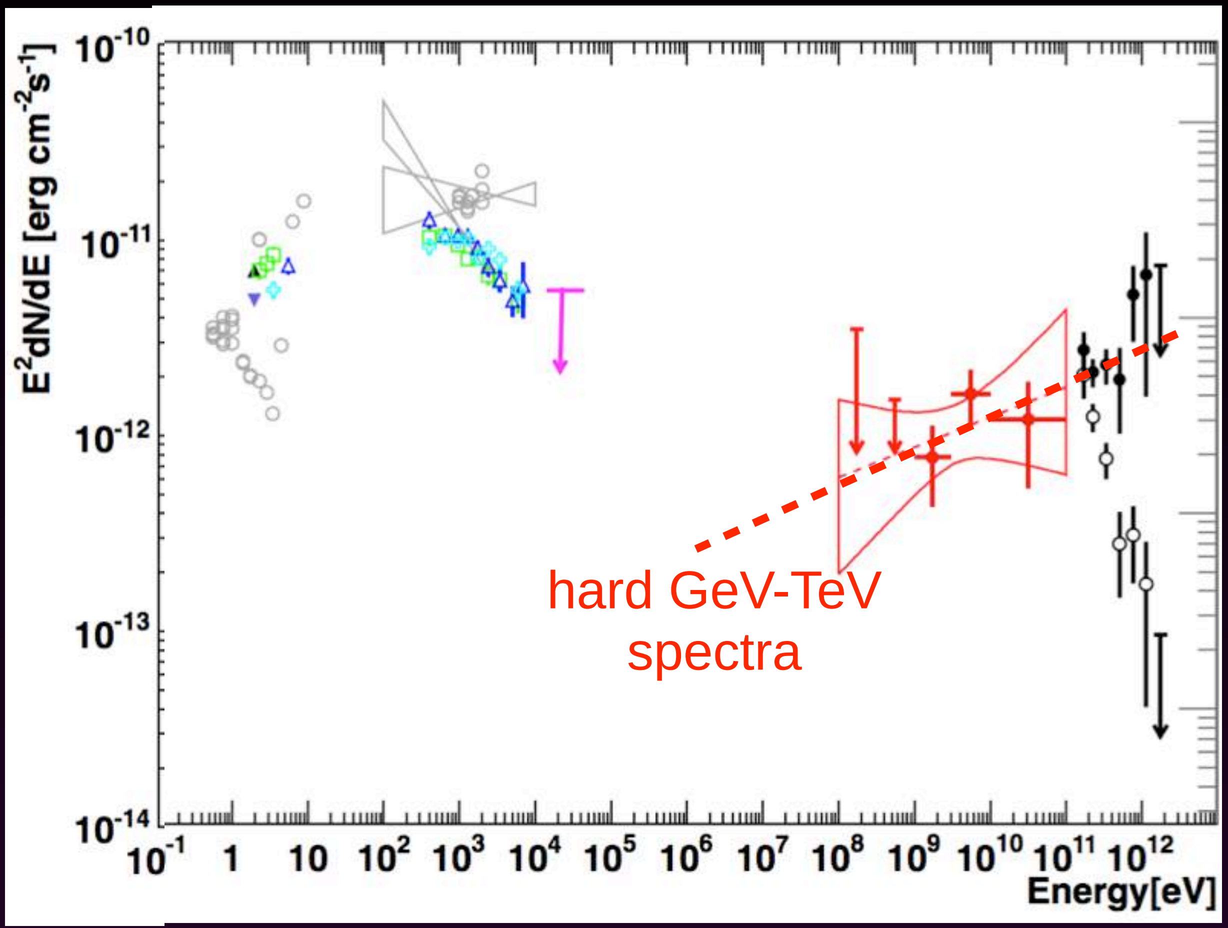
Blazar phenomenology:

- rough energy equipartition between emitting particles and magnetic field

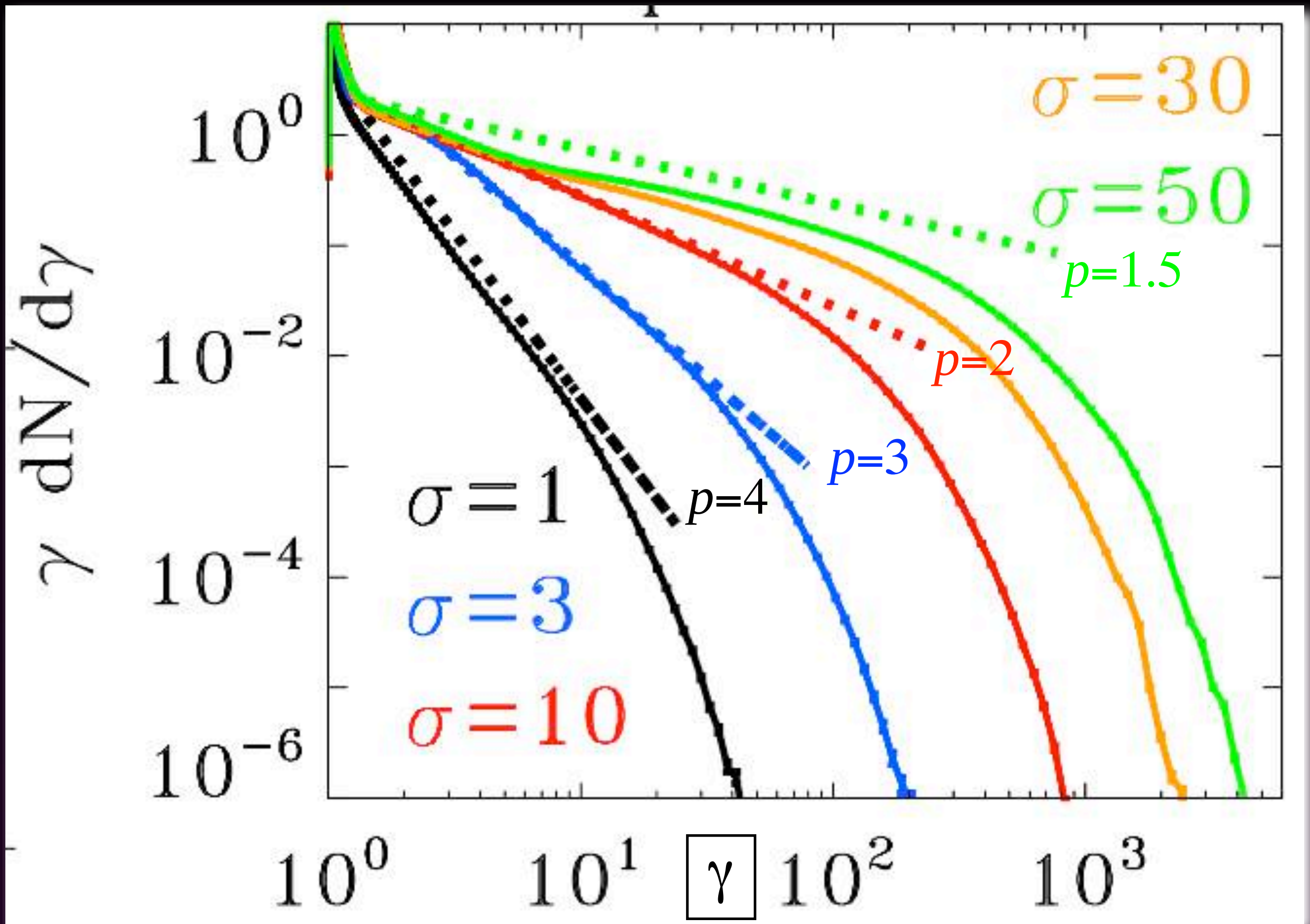
Relativistic reconnection:

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

(3) Extended non-thermal distributions



(HESS 11)



(LS & Spitkovsky 14, confirmed by Guo et al. 14, Werner et al. 14)

Blazar phenomenology:

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

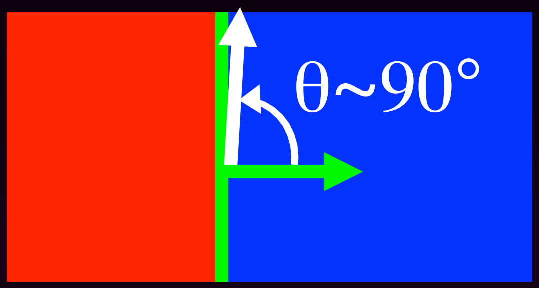
$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$

Relativistic reconnection:

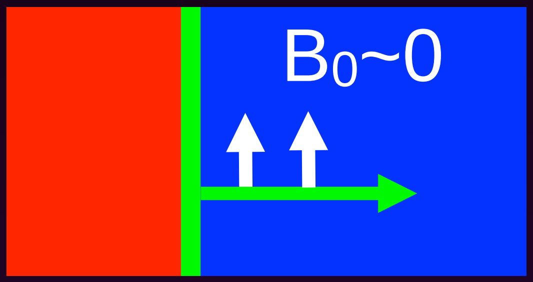
✓ it produces extended non-thermal tails of accelerated particles, whose power-law slope is harder than *p*=2 for high magnetizations (σ>10)

Summary

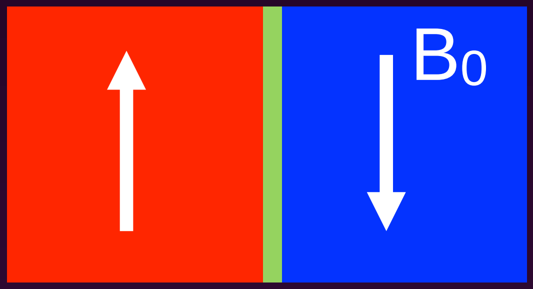
High-energy emission from relativistic jets:



• Internal shocks in blazars and GRB jets: Since they are significantly magnetized ($\sigma > 10^{-3}$) and quasi-perpendicular, they are poor particle accelerators.



• External shocks in GRBs: Weakly magnetized ($\sigma < 10^{-3}$) shocks can be efficient particle accelerators (~1% by number, ~10% by energy). The maximum energy grows slowly, as $\gamma_{max} \propto t^{1/2}$.



• Magnetic reconnection in magnetically-dominated flows ($\sigma \gg 1$) satisfies all the basic conditions for the emission: it 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.