Particle Acceleration by Relativistic Magnetic Reconnection in Blazar Jets

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Krakow Jet Meeting, April 22nd 2015

LS & Spitkovsky, A. 2014, ApJL, 783, L21

LS, Petropoulou, M. & Giannios, D. 2015, arXiv:1502.0102

Powerful emission and hard TeV spectra

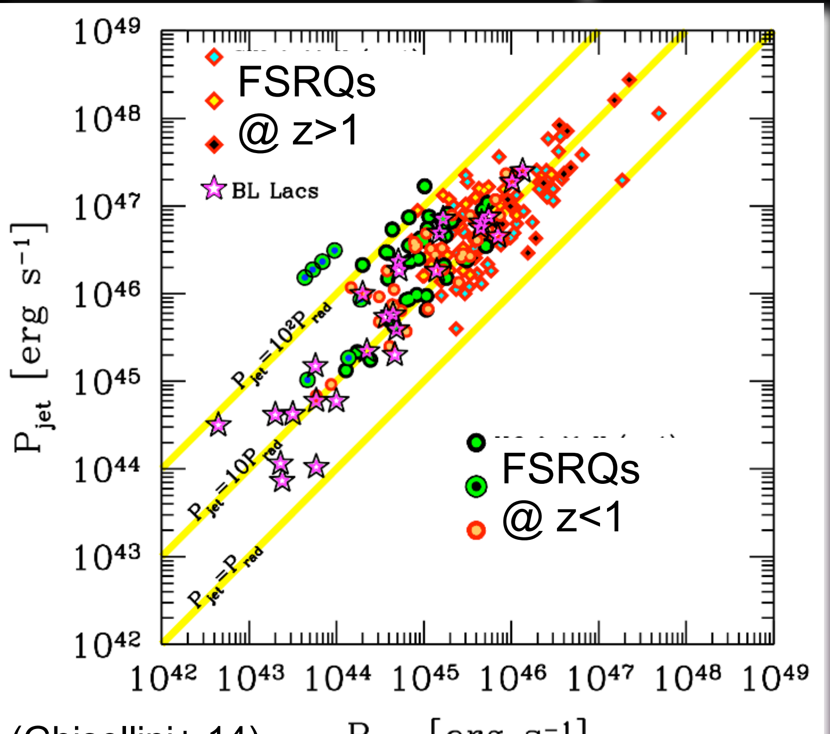
Blazar phenomenology:

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

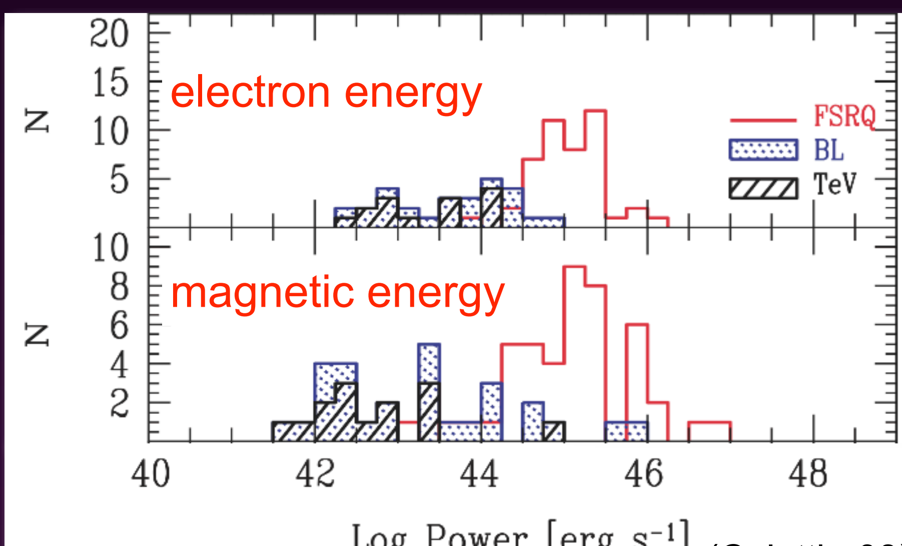
(2) rough energy equipartition between emitting particles and magnetic field

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

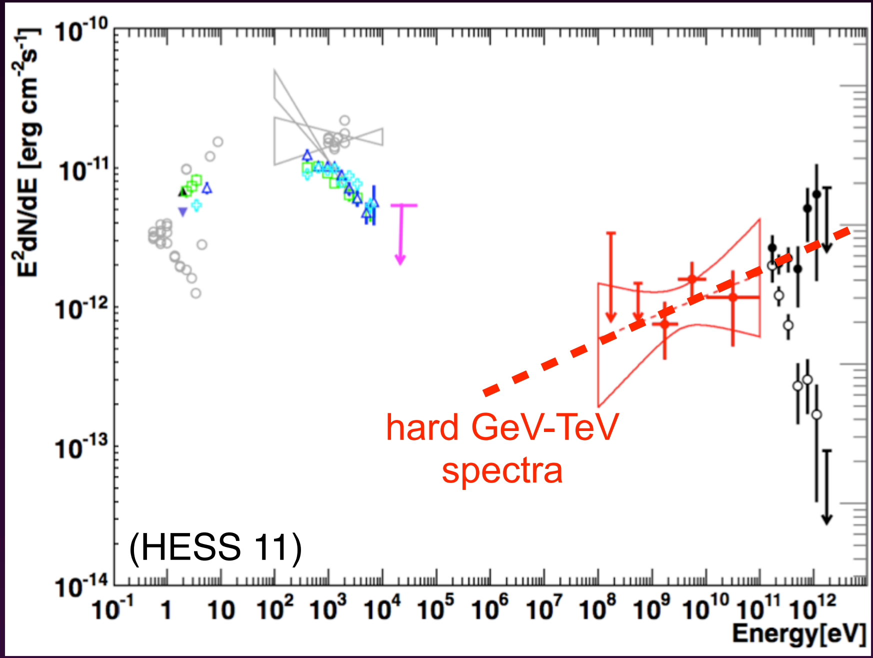
$$\frac{dn}{d\gamma} \propto \gamma^{-p} \quad p \lesssim 2$$



(Ghisellini+ 14)



(Celotti+ 08)

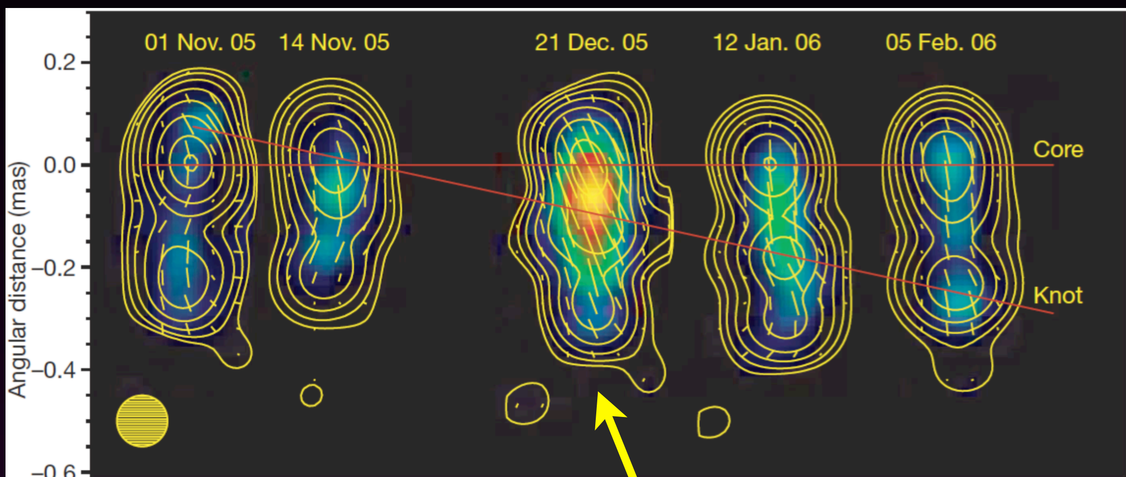


(HESS 11)

Internal dissipation in blazar jets

BL Lac

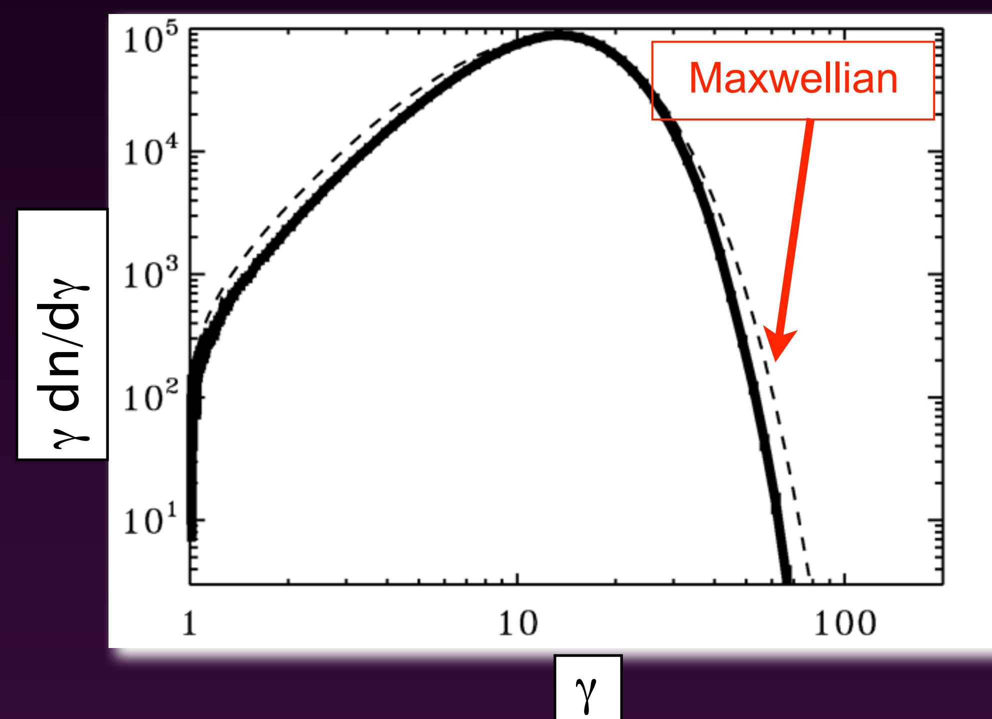
(Marscher et al. 08)



Shocks or Reconnection?

Internal shocks in jets are likely to be poor non-thermal accelerators. (Giannios' and Spitkovsky's talks)

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



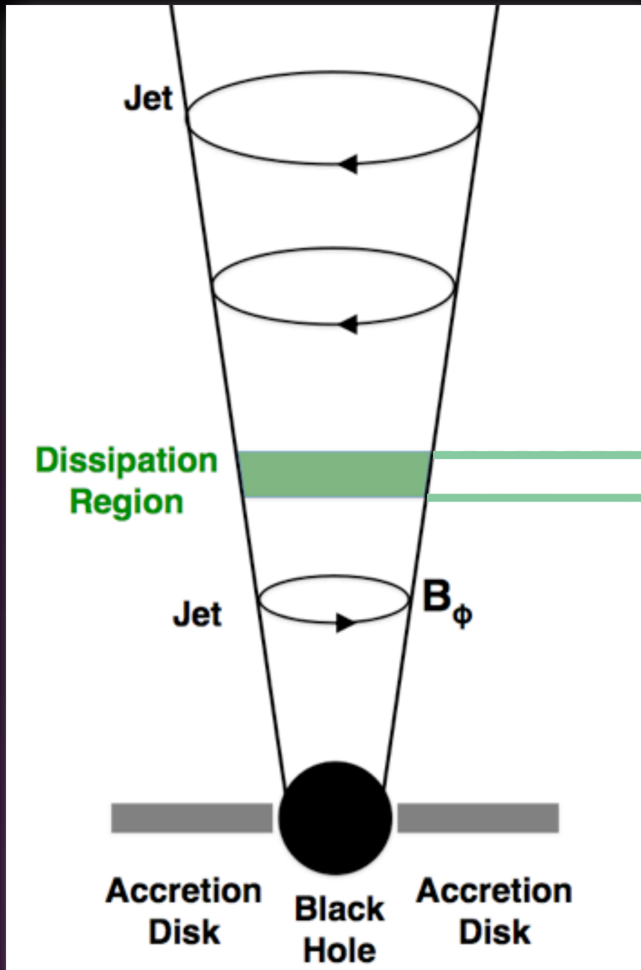
Internal shocks in blazars:

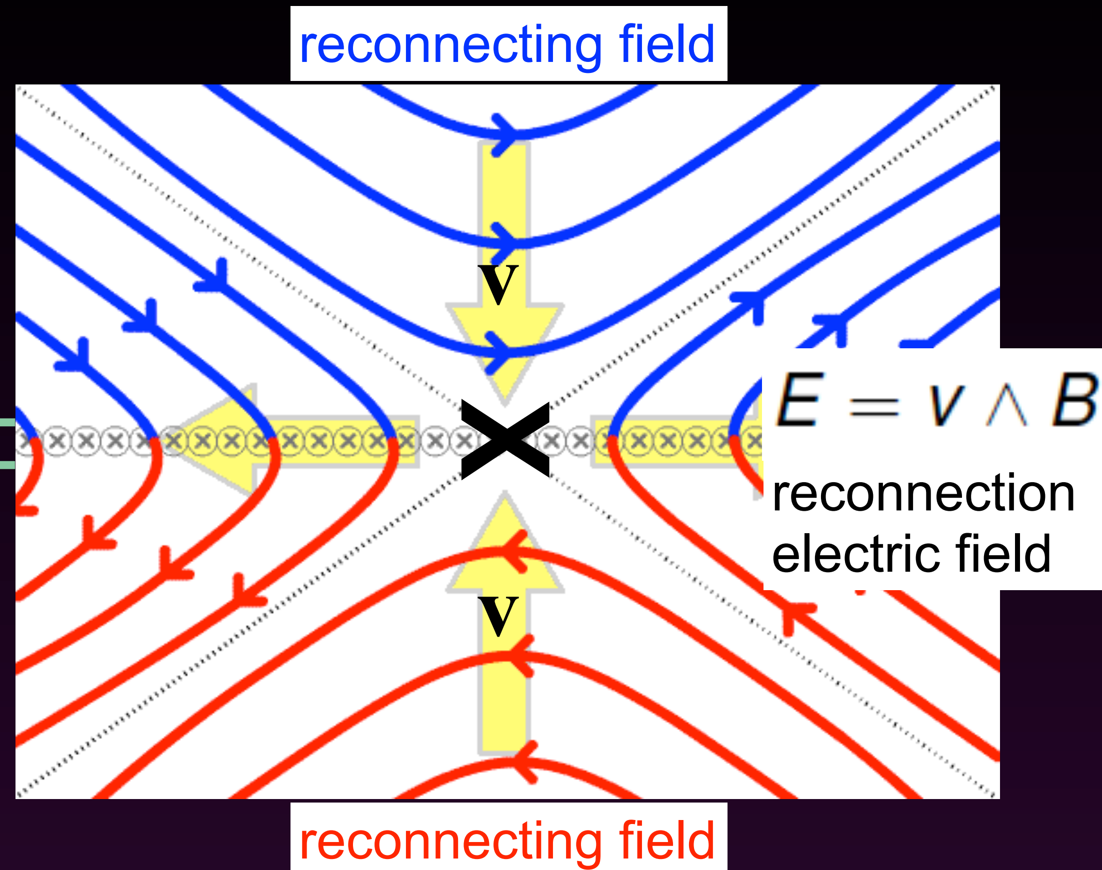
- electron-proton or pair plasma
- trans-relativistic (γ_0~a few)
- magnetized (σ>0.01)

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

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

Relativistic magnetic reconnection



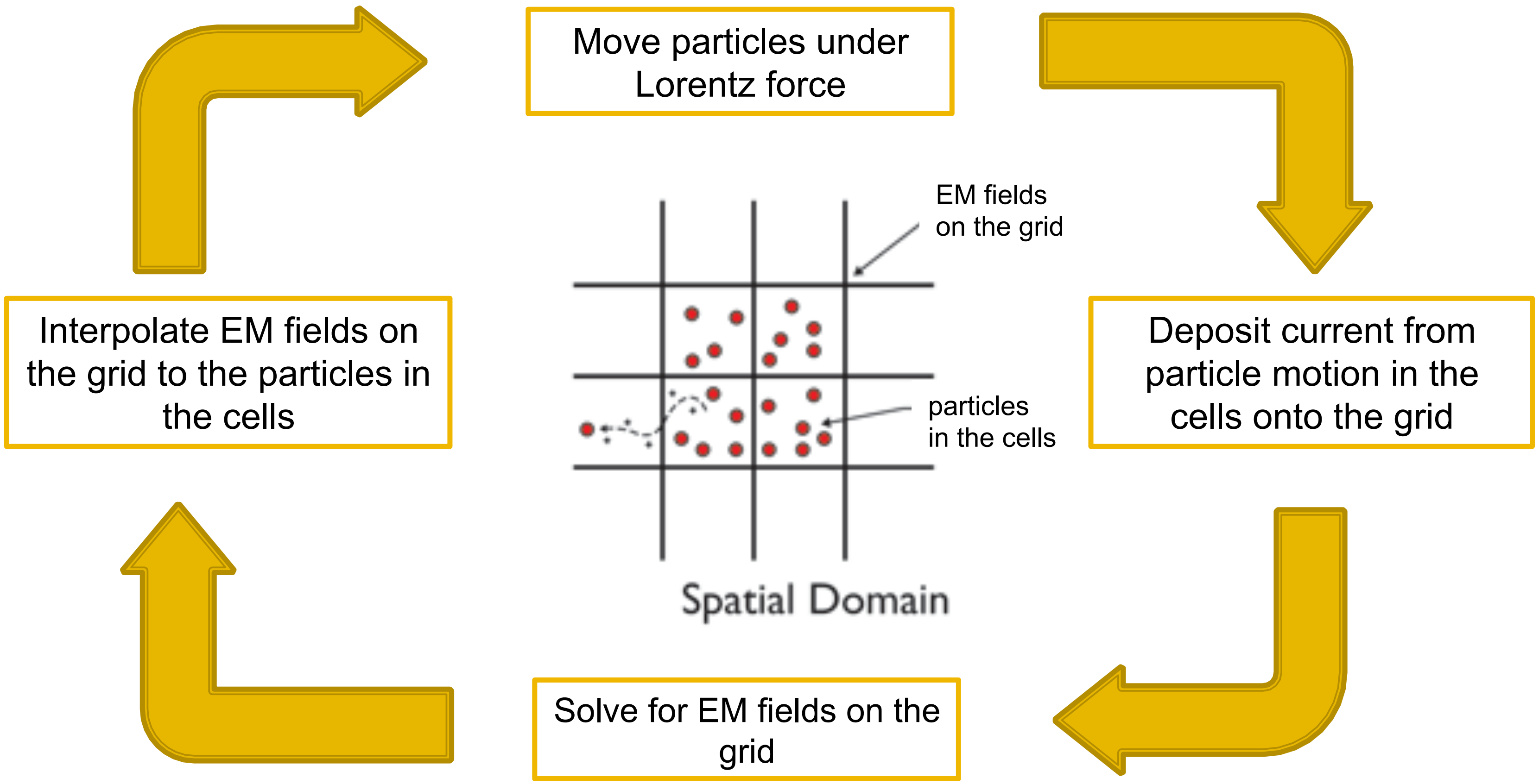


Relativistic Reconnection

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

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

The PIC method



No approximations, full plasma physics of ions and electrons

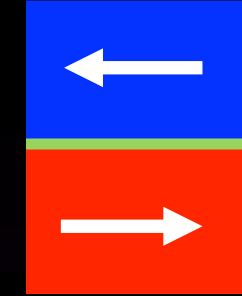
Tiny length and time scales (electron scales) need to be resolved

➔ huge simulations, limited time coverage

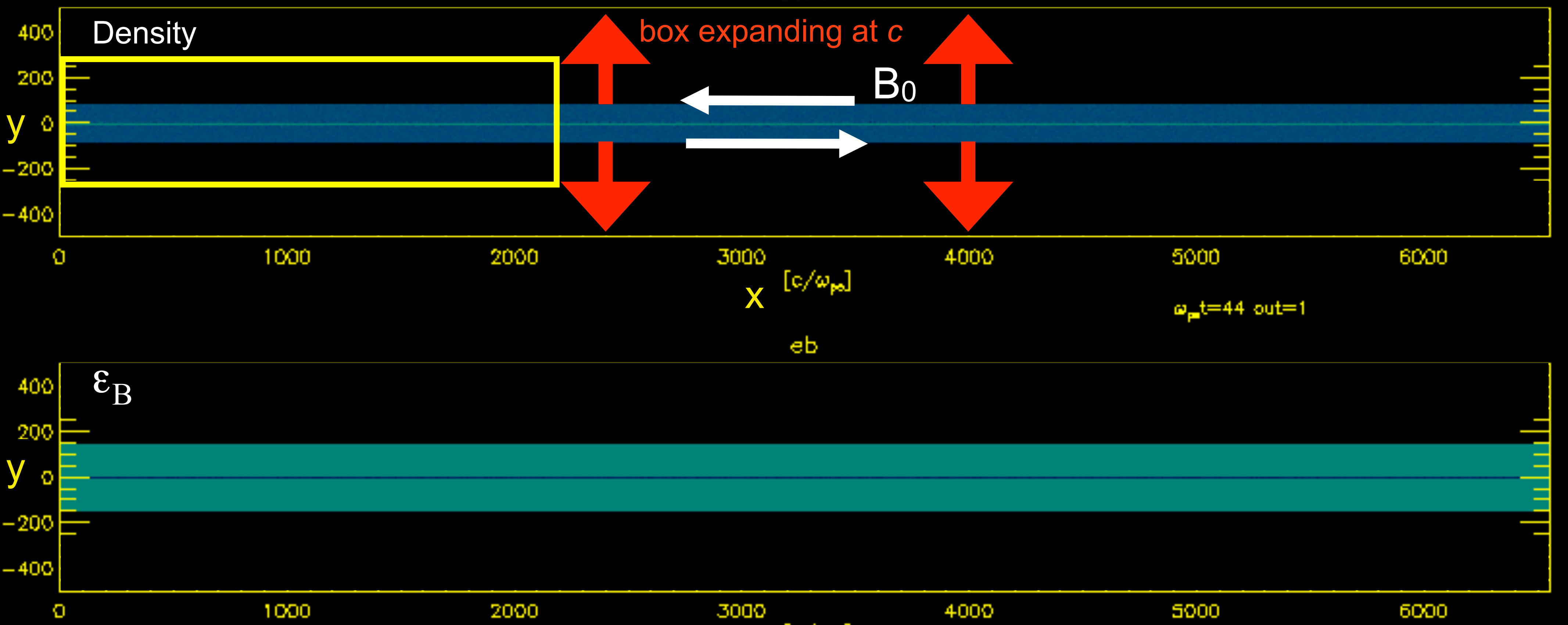
- Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 93, Spitkovsky 05, LS+ 13,14)

Dynamics and particle spectrum

Hierarchical reconnection



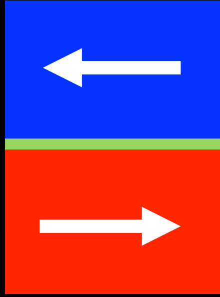
σ=10 electron-positron



(LS & Spitkovsky 14)

- 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



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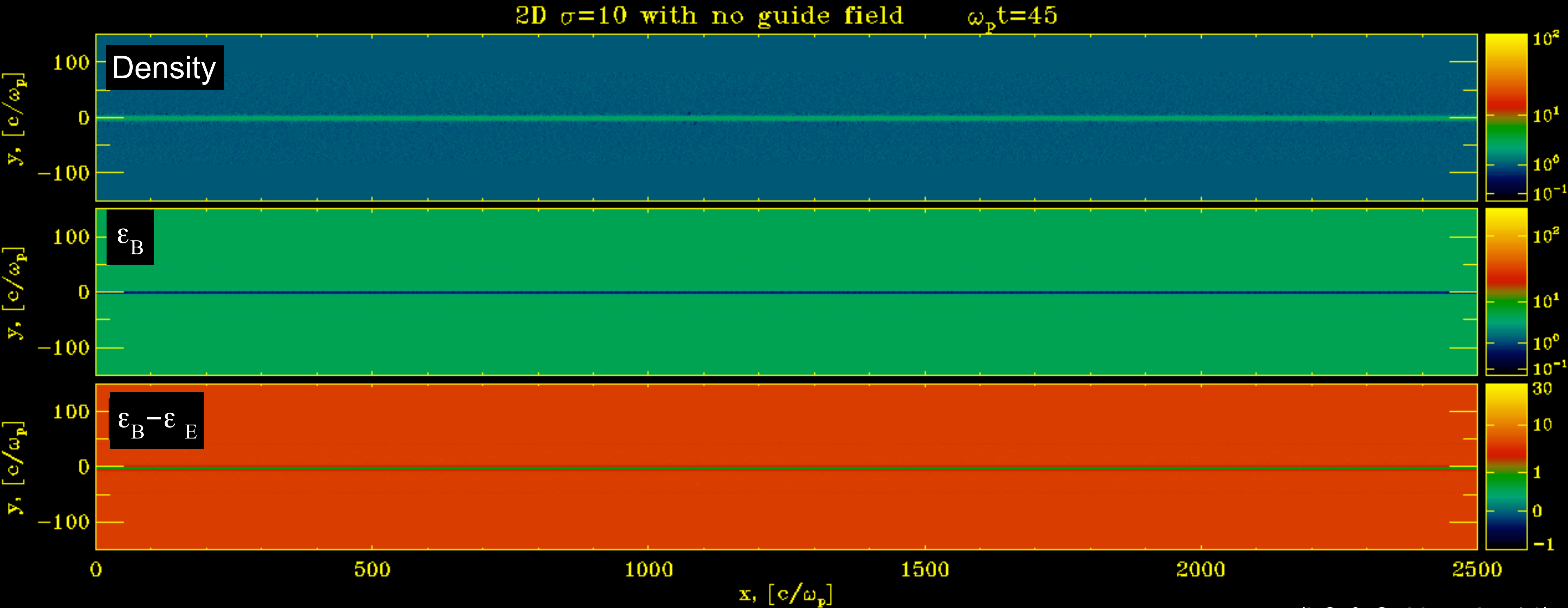
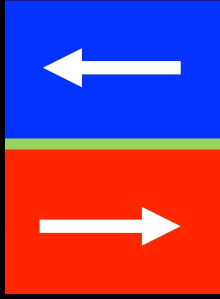


(LS & Spitkovsky 14)

- 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.
- Localized regions exist at the X-points where E>B.

Inflows and outflows



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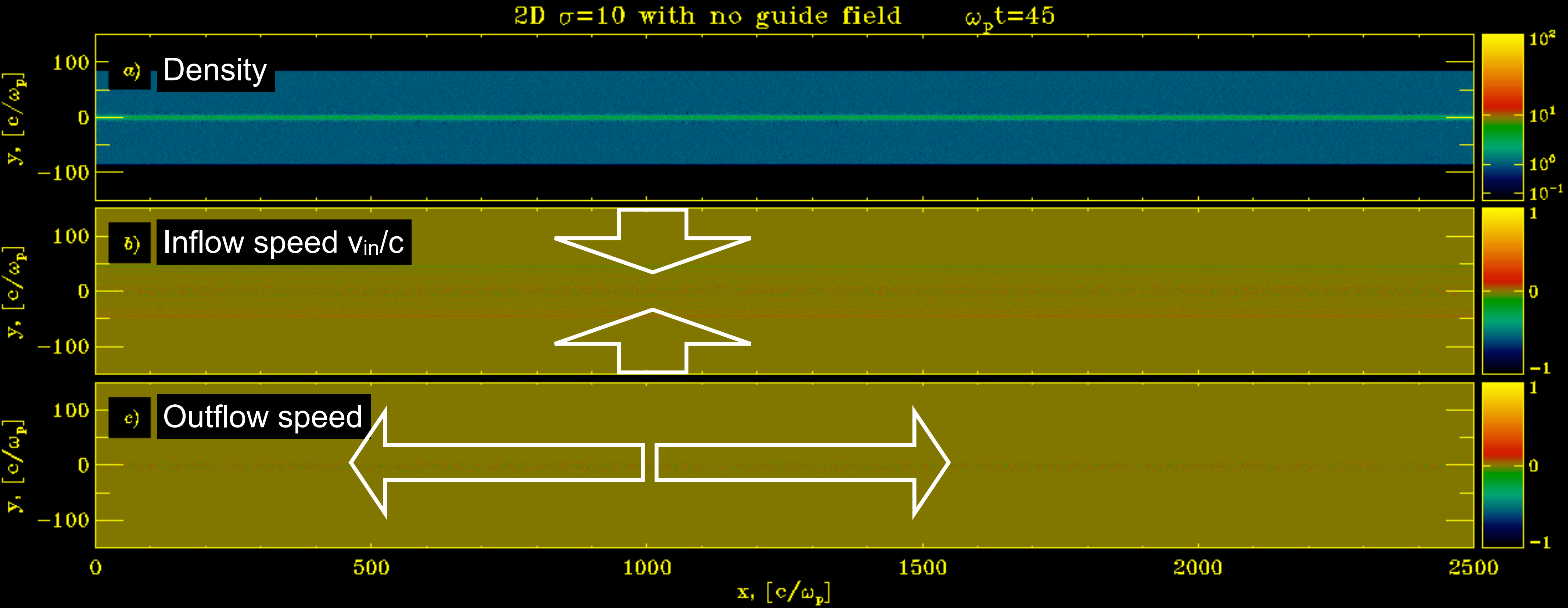
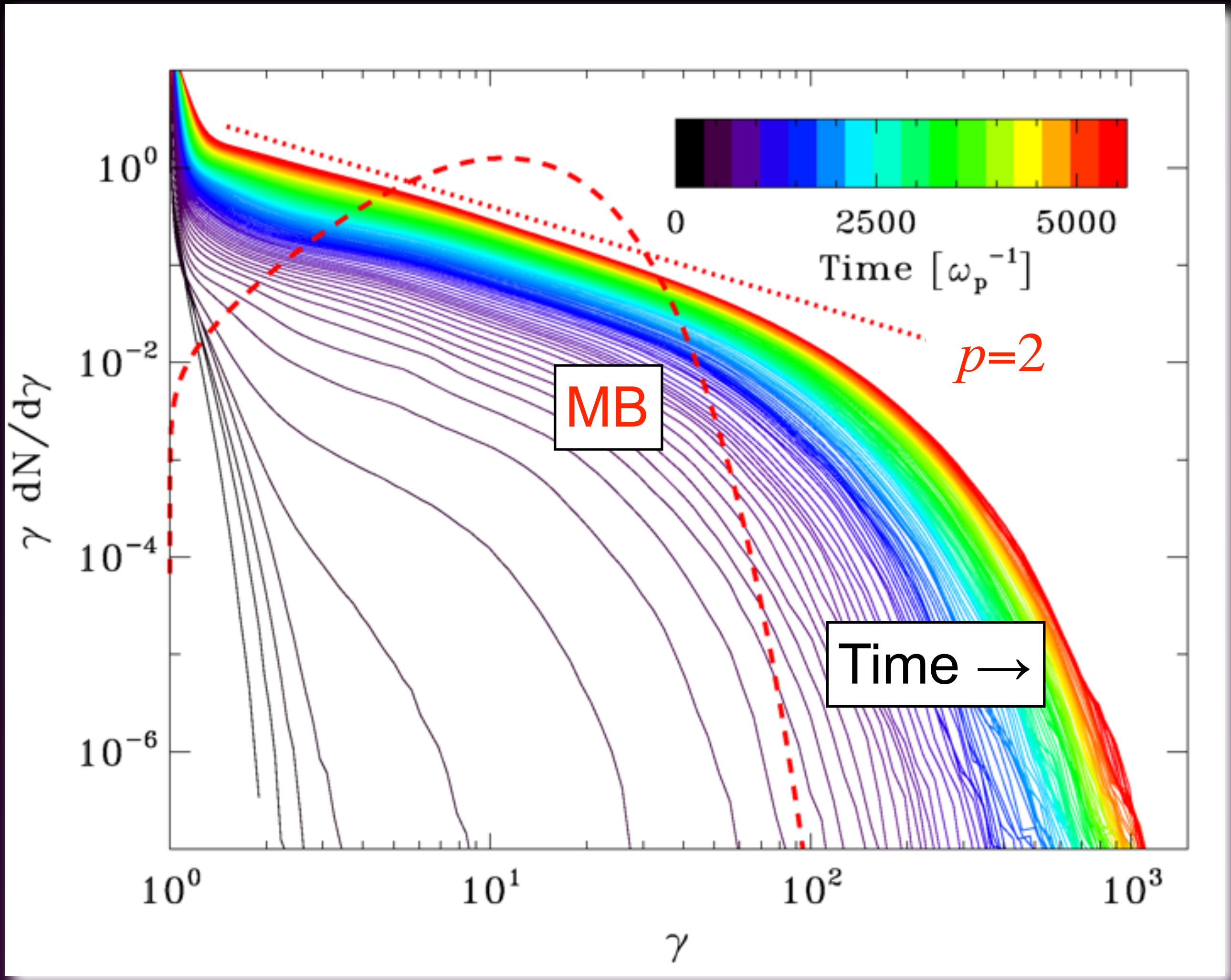


- Inflow into the X-line is non-relativistic, with speed v_{in} ~ 0.1 c.
- Outflow from the X-points is ultra-relativistic, reaching the Alfven speed $v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$

The particle energy spectrum

σ=10 electron-positron

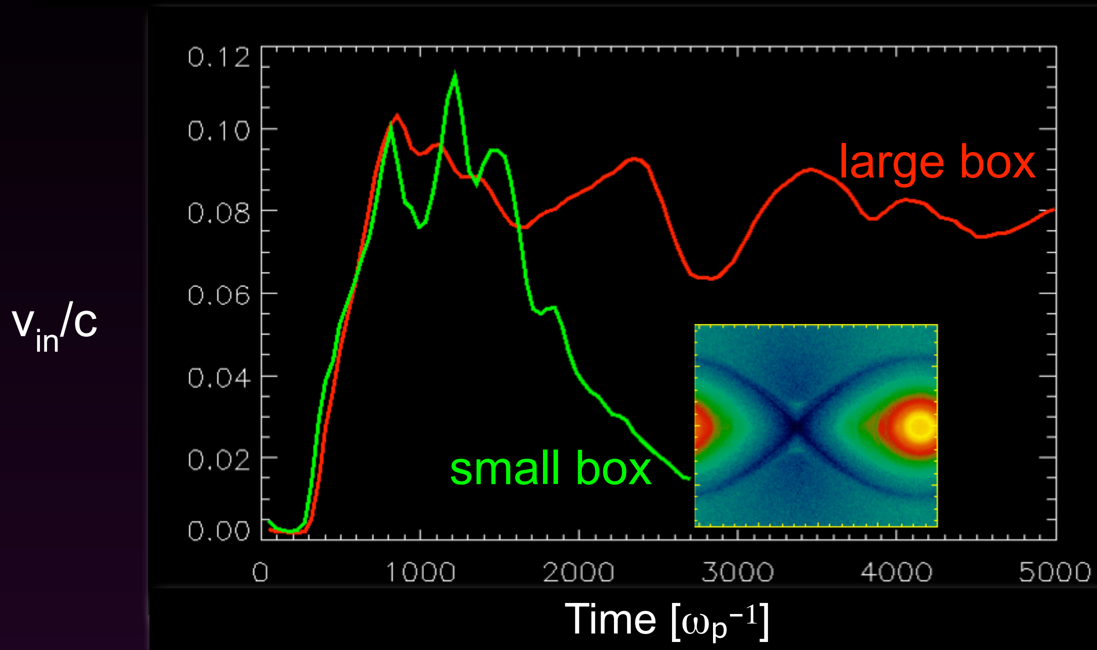


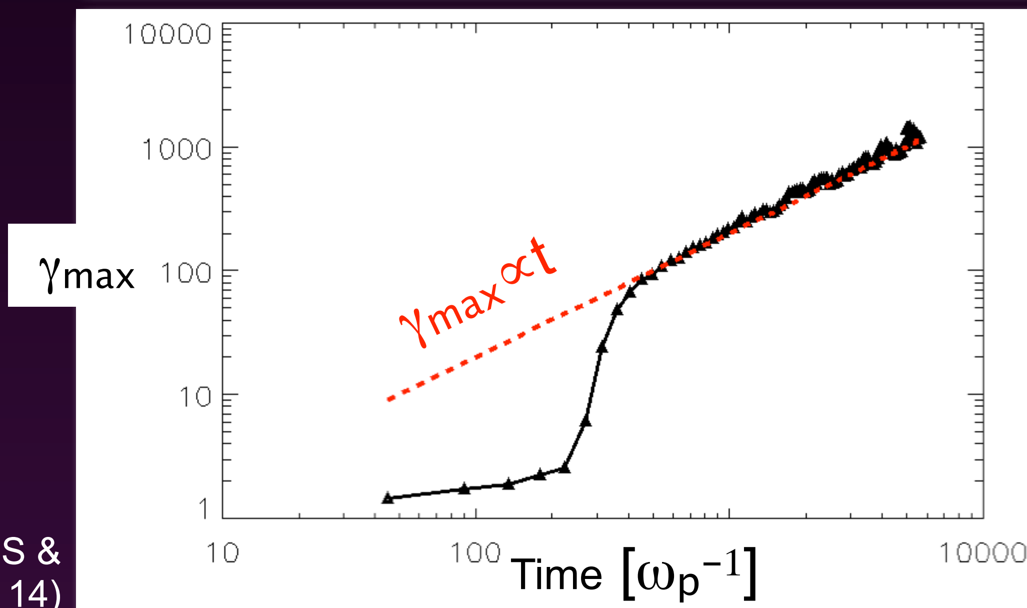
(LS & Spitkovsky 14)

- At late times, the particle spectrum in the current sheet approaches a broad power-law tail $dn/d\gamma \propto \gamma^{-p}$ 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 $\sim\sigma/2$ → energy equipartition

The maximum particle energy

$\sigma=10$ electron-positron



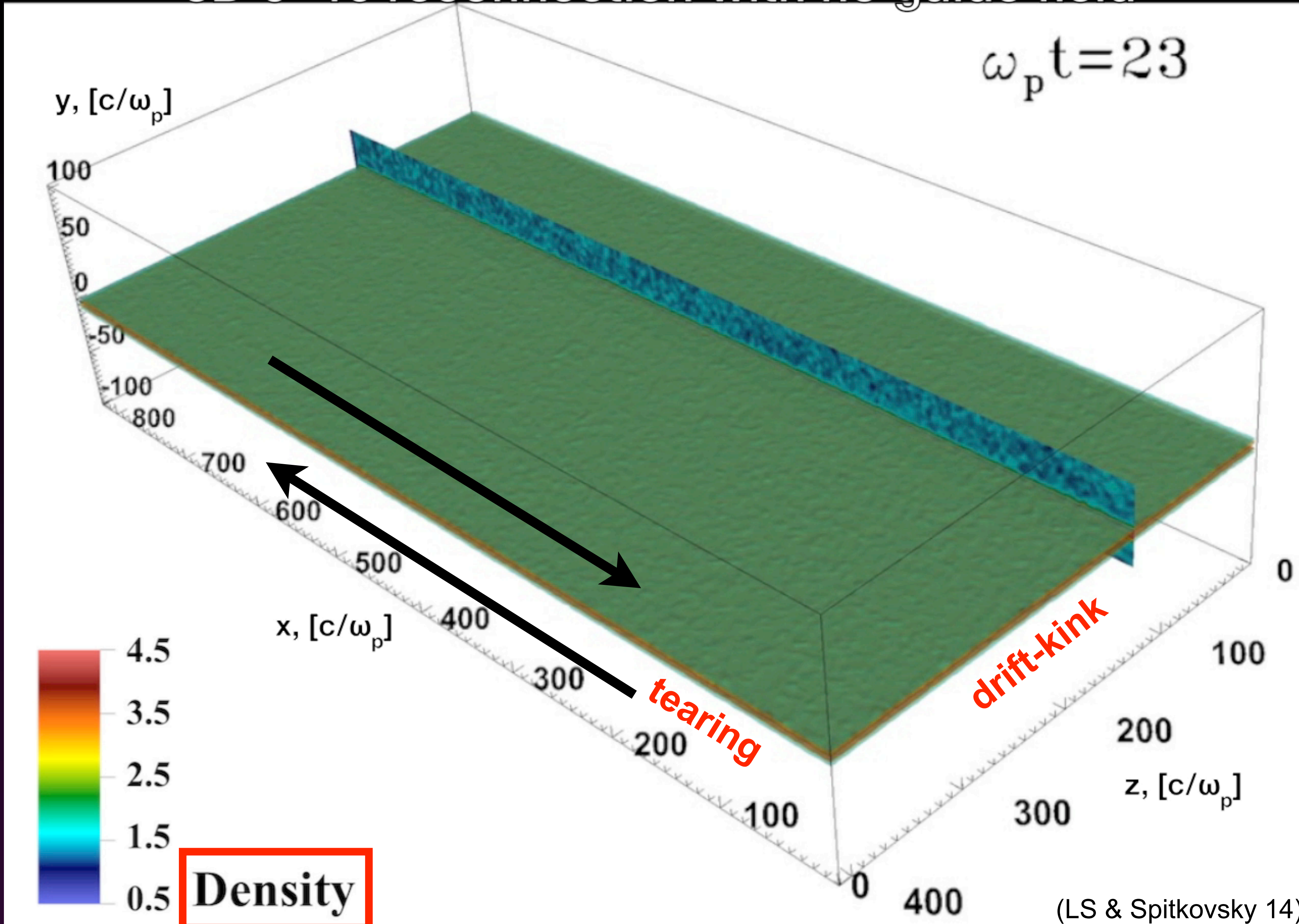


(LS & Spitkovsky 14)

- The reconnection rate stays nearly constant in time, if the evolution is not artificially inhibited by the boundaries.

- The maximum energy grows at a rate proportional to the reconnection rate v_{in}, so that $\gamma_{max} \propto t$ (compare to $\gamma_{max} \propto t^{1/2}$ in relativistic shocks).

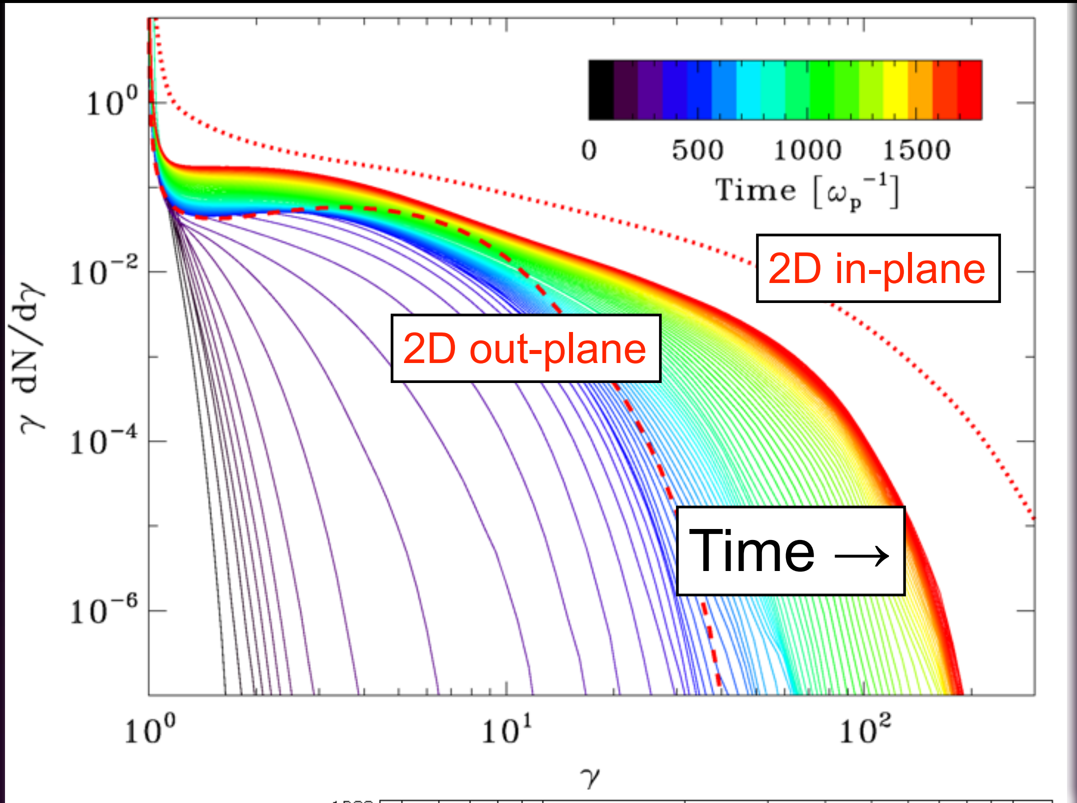
3D σ=10 reconnection with no guide field

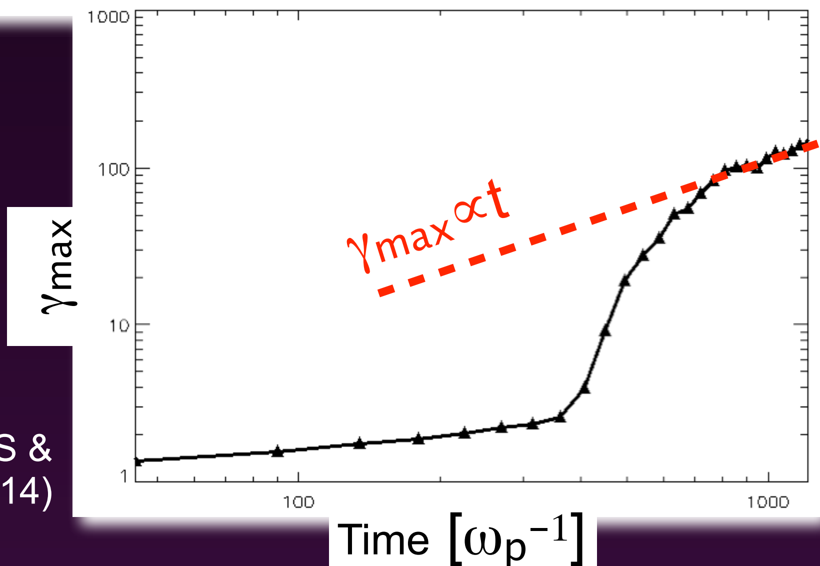


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

3D: particle spectrum

$\sigma=10$ electron-positron



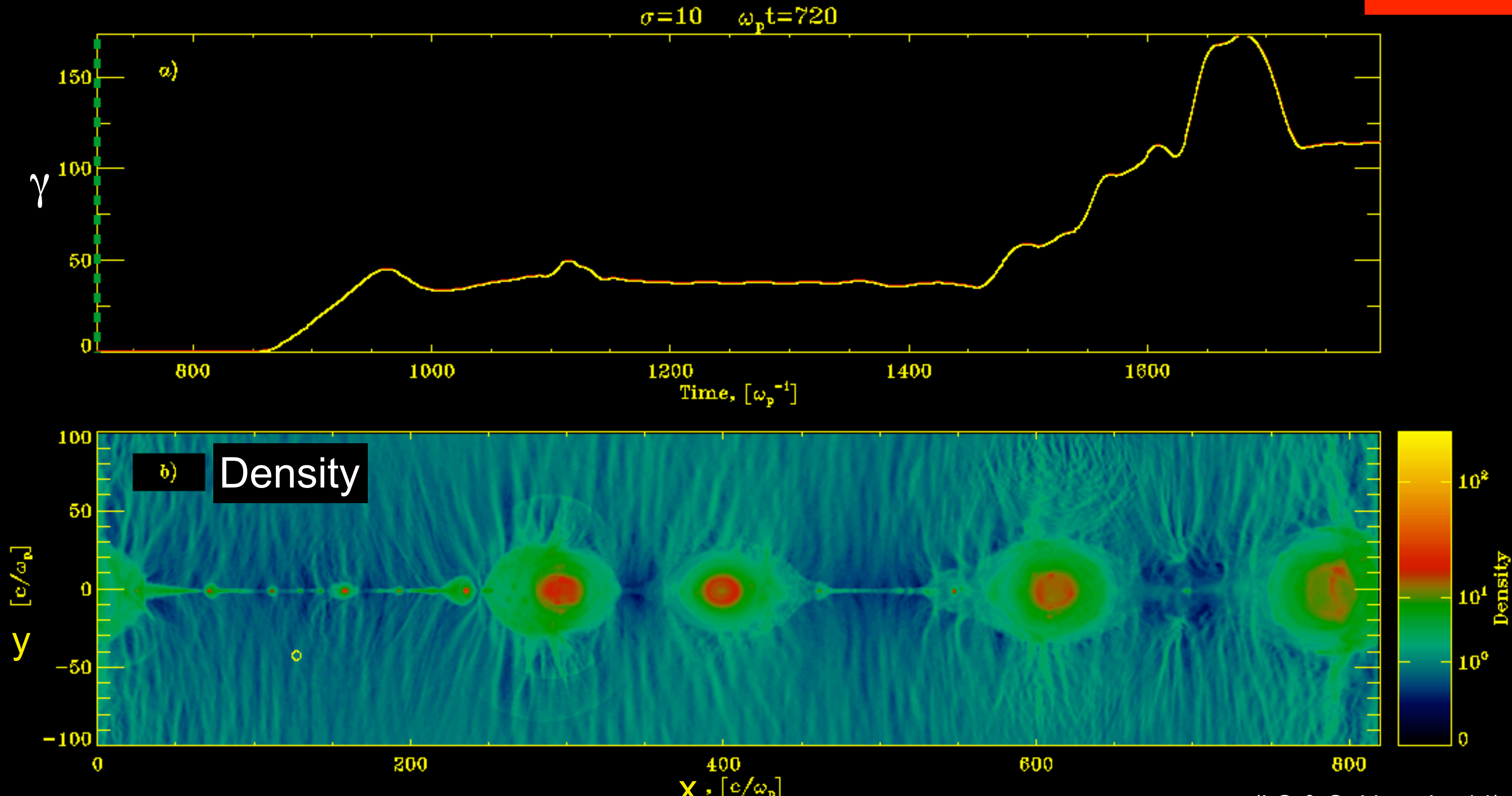


(LS & Spitkovsky 14)

- 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 (vs v_{in}/c ~ 0.1 in 2D).

Particle acceleration mechanism

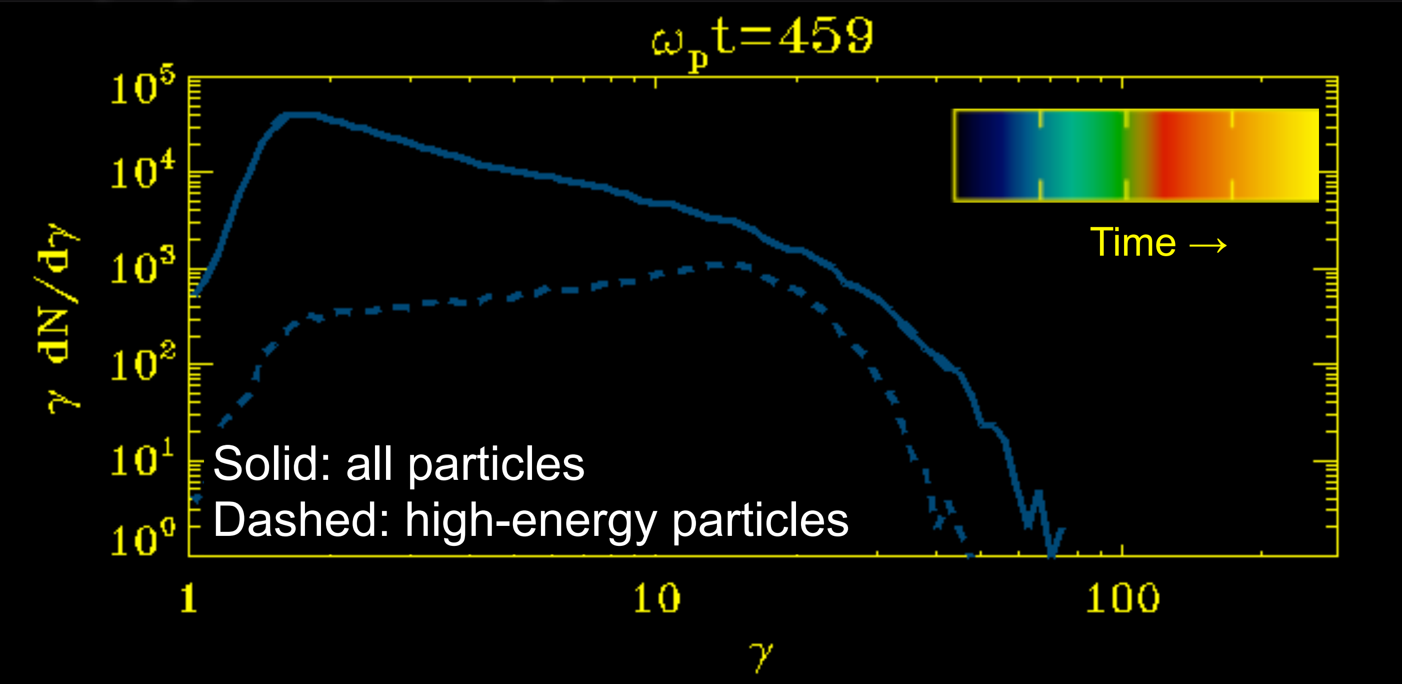
The highest energy particles

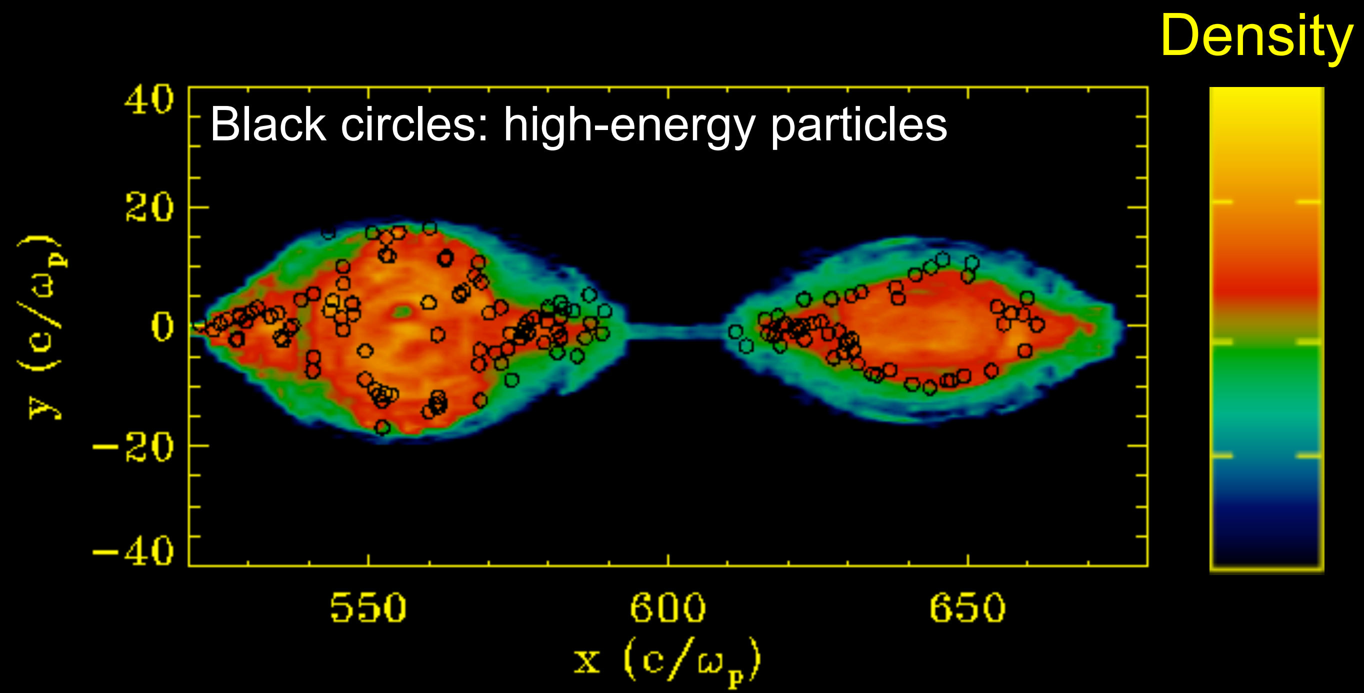


(LS & Spitkovsky 14)

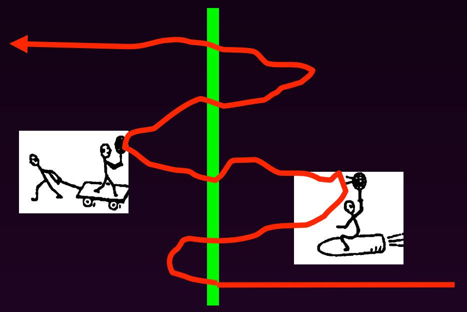
Two acceleration phases: (1) at the X-point; (2) in between merging islands

(2) Fermi process in between islands



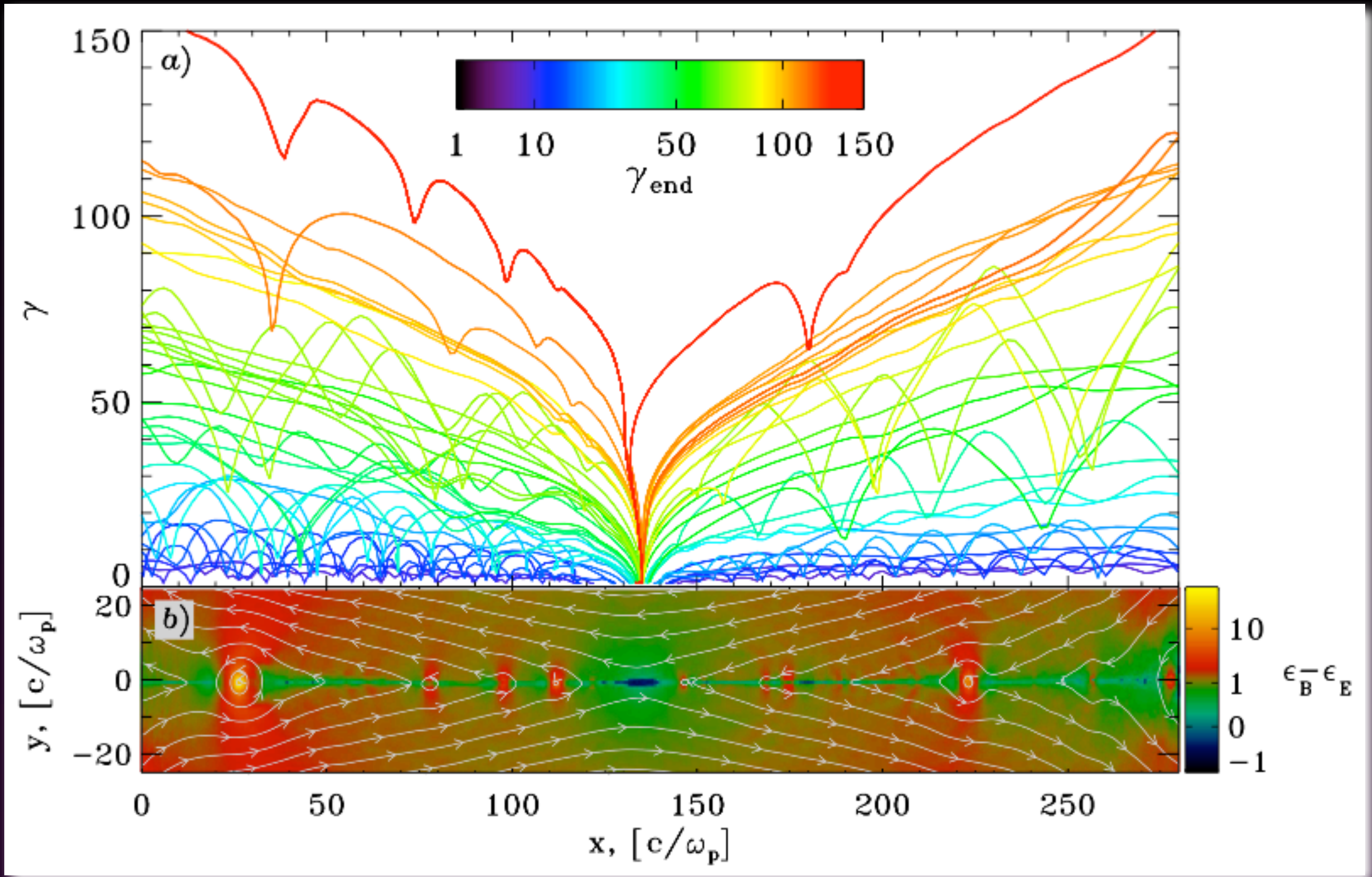


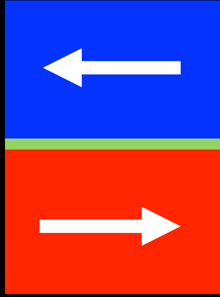
- The particles are accelerated by a Fermi-like process in between merging islands.



- 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





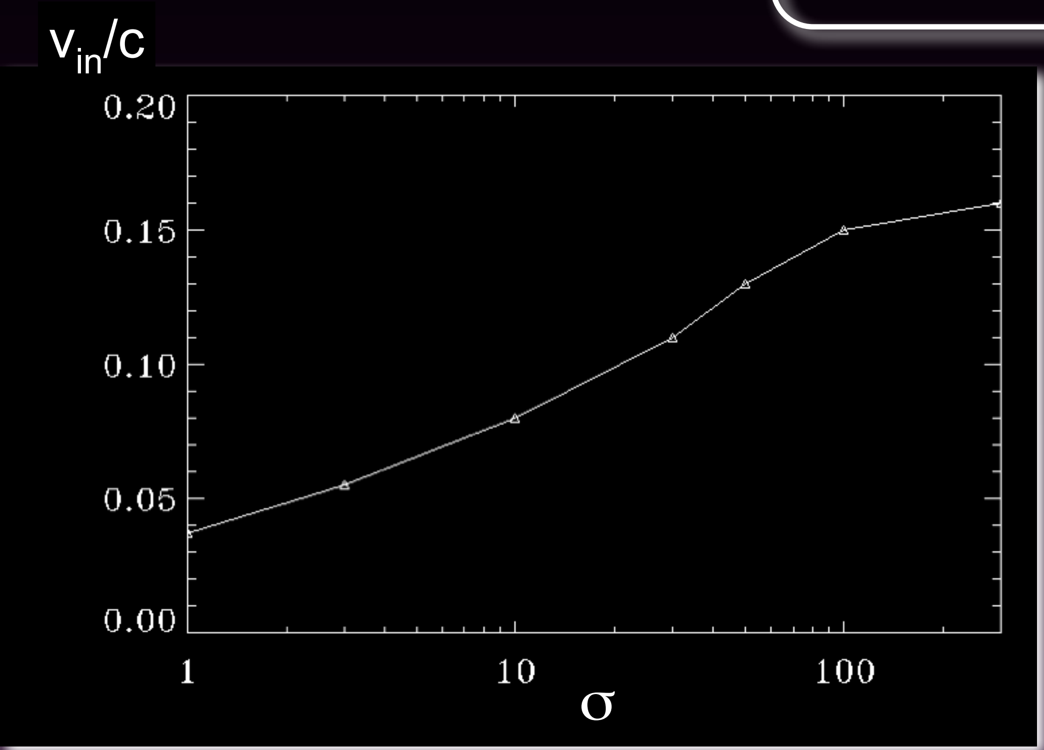
(LS & Spitkovsky 14)

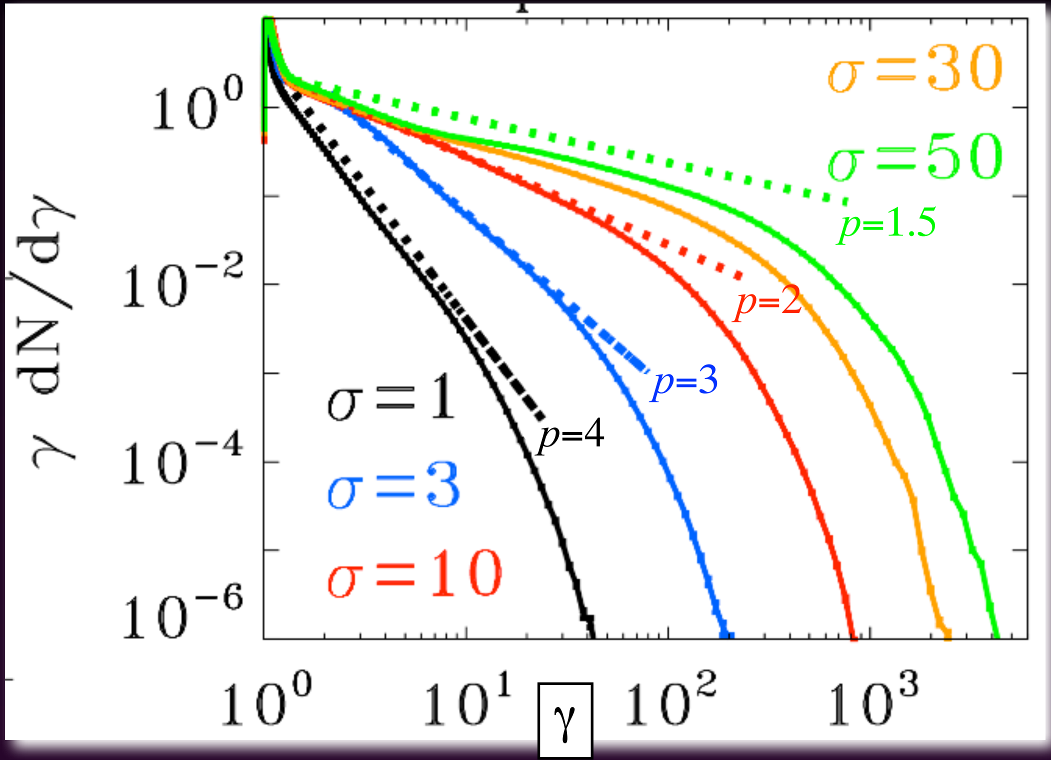
- In cold plasmas, the particles are tied to field lines and they go through X-points.
- The particles are accelerated by the reconnection electric field at the X-points, and then advected into the nearest magnetic island.
- The energy gain can vary, depending on where the particles interact with the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

Dependence on the flow conditions

Dependence on the magnetization

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





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

As σ increases:

- the reconnection rate v_{in}/c increases with magnetization and it saturates at ~ 0.2 for σ»1

As σ increases:

- the power-law slope becomes harder

⇒ a probe of the flow magnetization?

Implications for blazar emission

Powerful emission and hard TeV spectra

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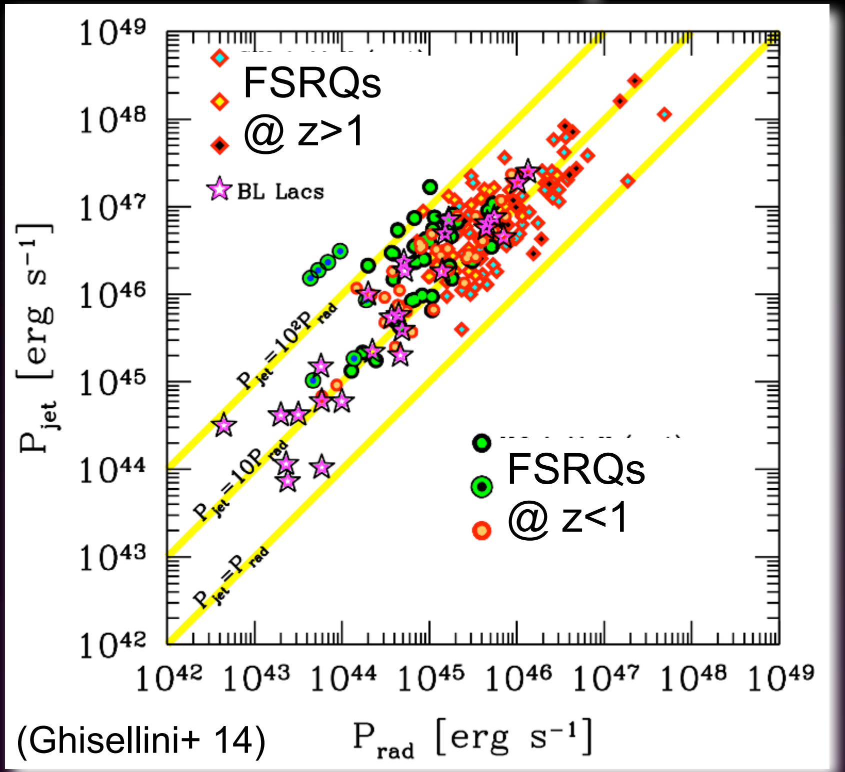
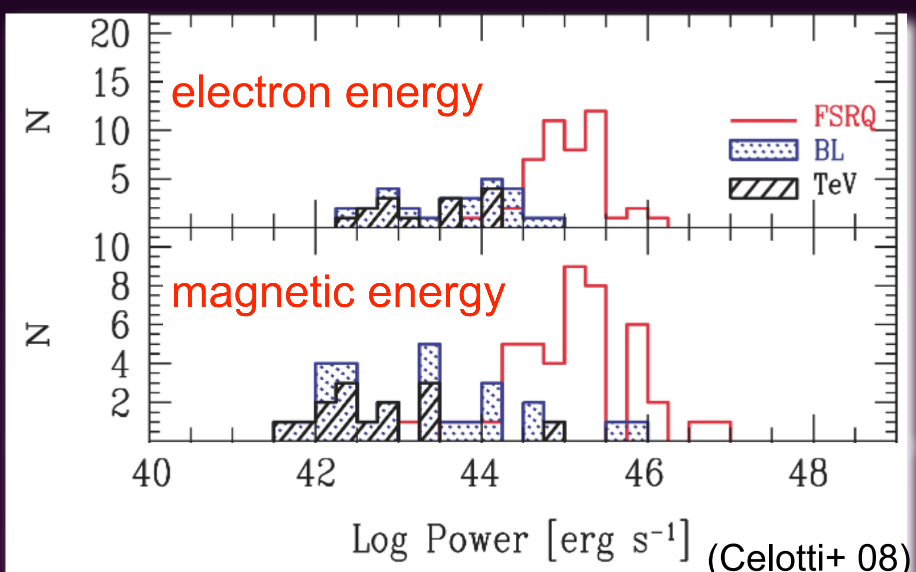
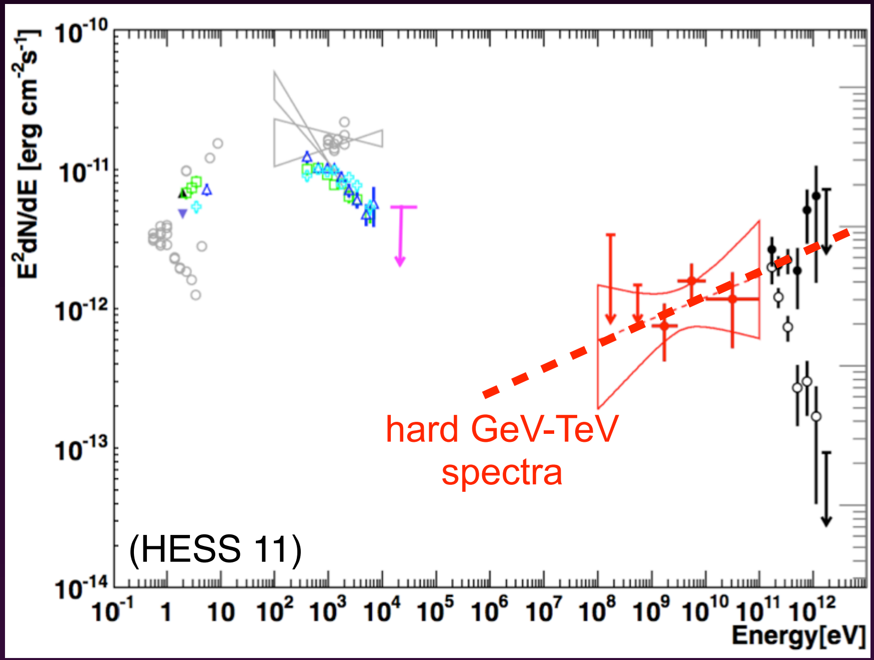






Implications for blazar emission

Relativistic reconnection in blazars:

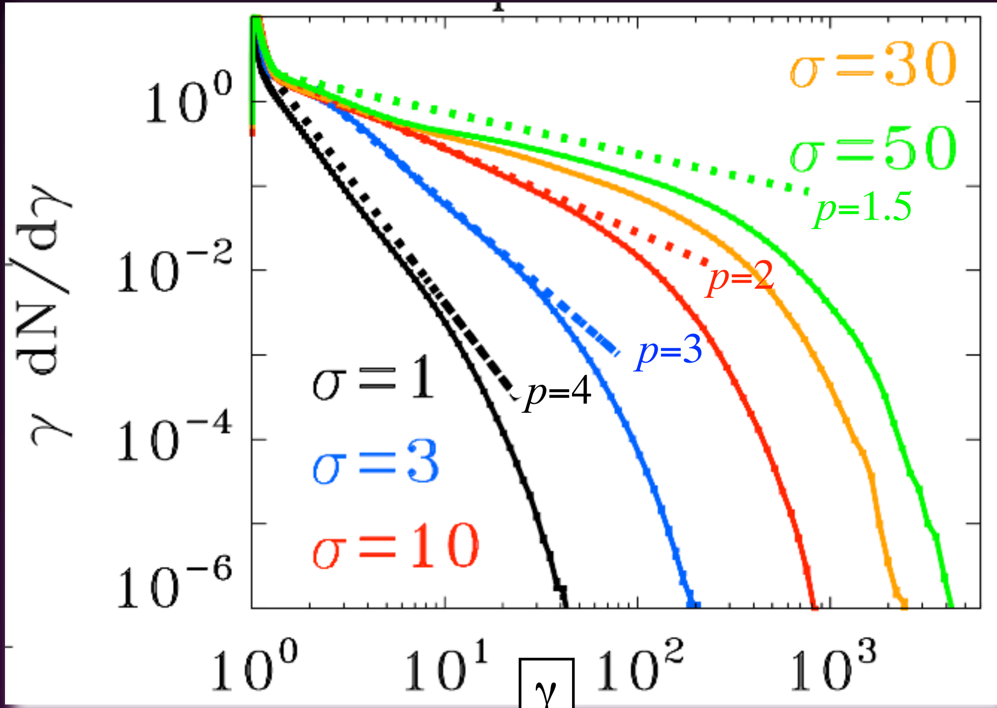
(1) it transfers up to 50% of the flow energy (in pair plasmas) to the emitting particles.

(2) results in rough energy equipartition between particles and magnetic field.

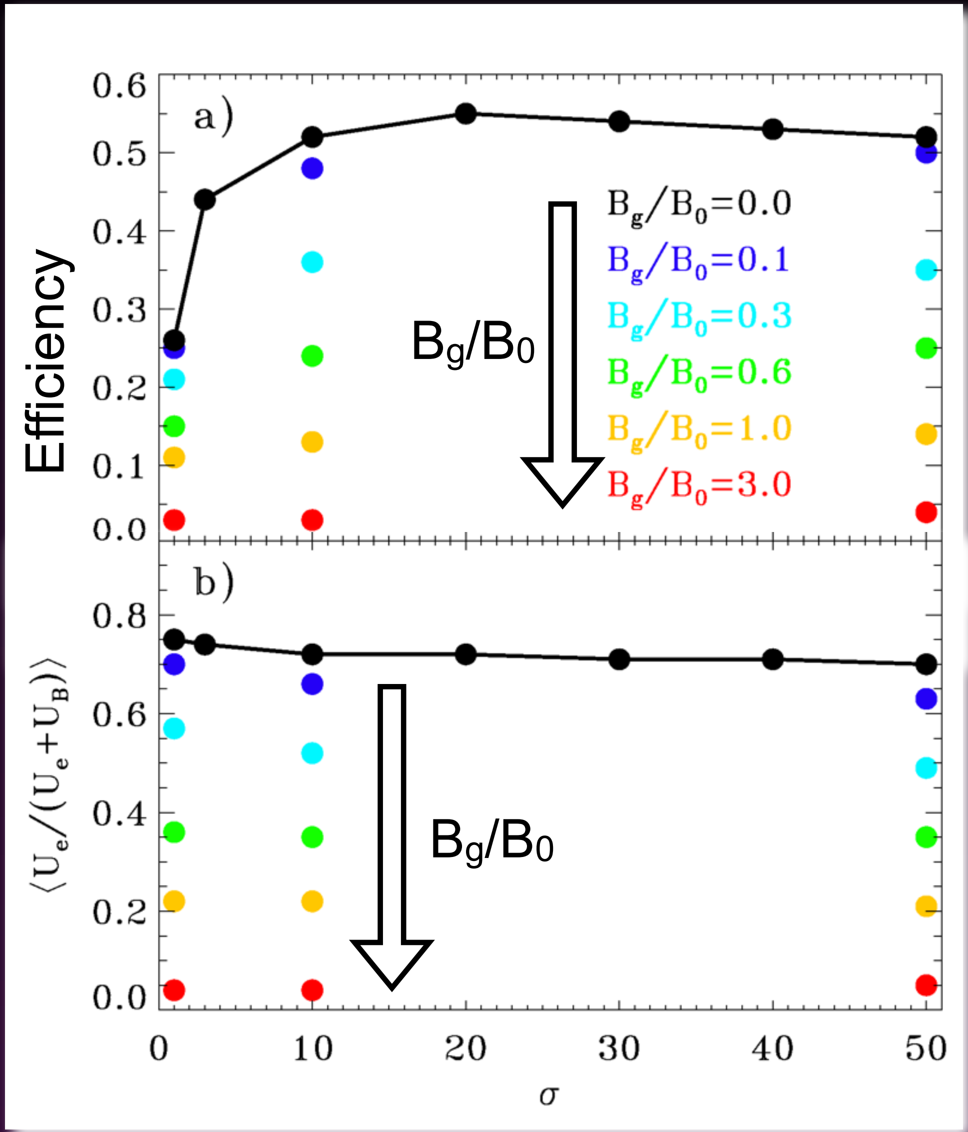
(3) it produces power-law distributions, with slope harder than *p*=2 for σ≳10.

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

(Sironi+ 15)



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



(Sironi+ 15)

Summary

• Relativistic magnetic reconnection in magnetically-dominated blazar jets is an efficient particle accelerator, in 2D and 3D.

• Relativistic reconnection ($\sigma \gtrsim 1$) can accelerate particles into a power-law tail with slope between -4 and -1 (harder for higher magnetizations), and max energy growing linearly with time, if slope is less than -2.

• The reconnection rate (and so, the rate of growth of the max energy) is around 0.1 - 0.2 *c* in 2D and ~ 0.02 *c* in 3D for the case of zero guide field. In 3D, the drift-kink mode is unimportant for the long-term evolution. The reconnection rate decreases with the strength of the guide field, in both 2D and 3D.

• Magnetic reconnection satisfies all the basic requirements for blazar emission (Giannios' talk): it is fast and efficient, produces non-thermal particles with hard slopes, and results in rough energy equipartition between particles and fields. With increasing guide field strength, the efficiency drops and the islands become more magnetically-dominated.