Magnetic reconnection in relativistic astrophysical jets

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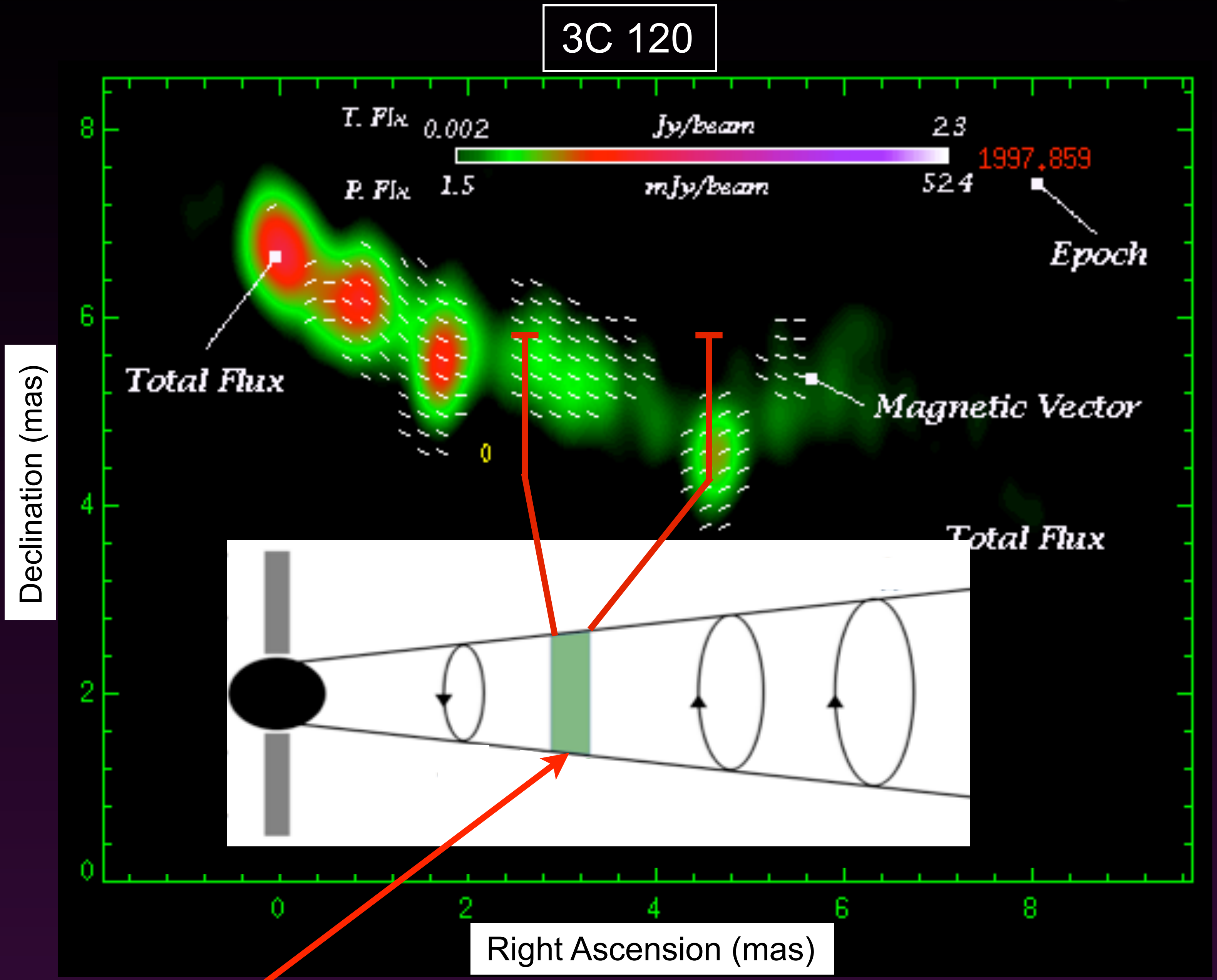
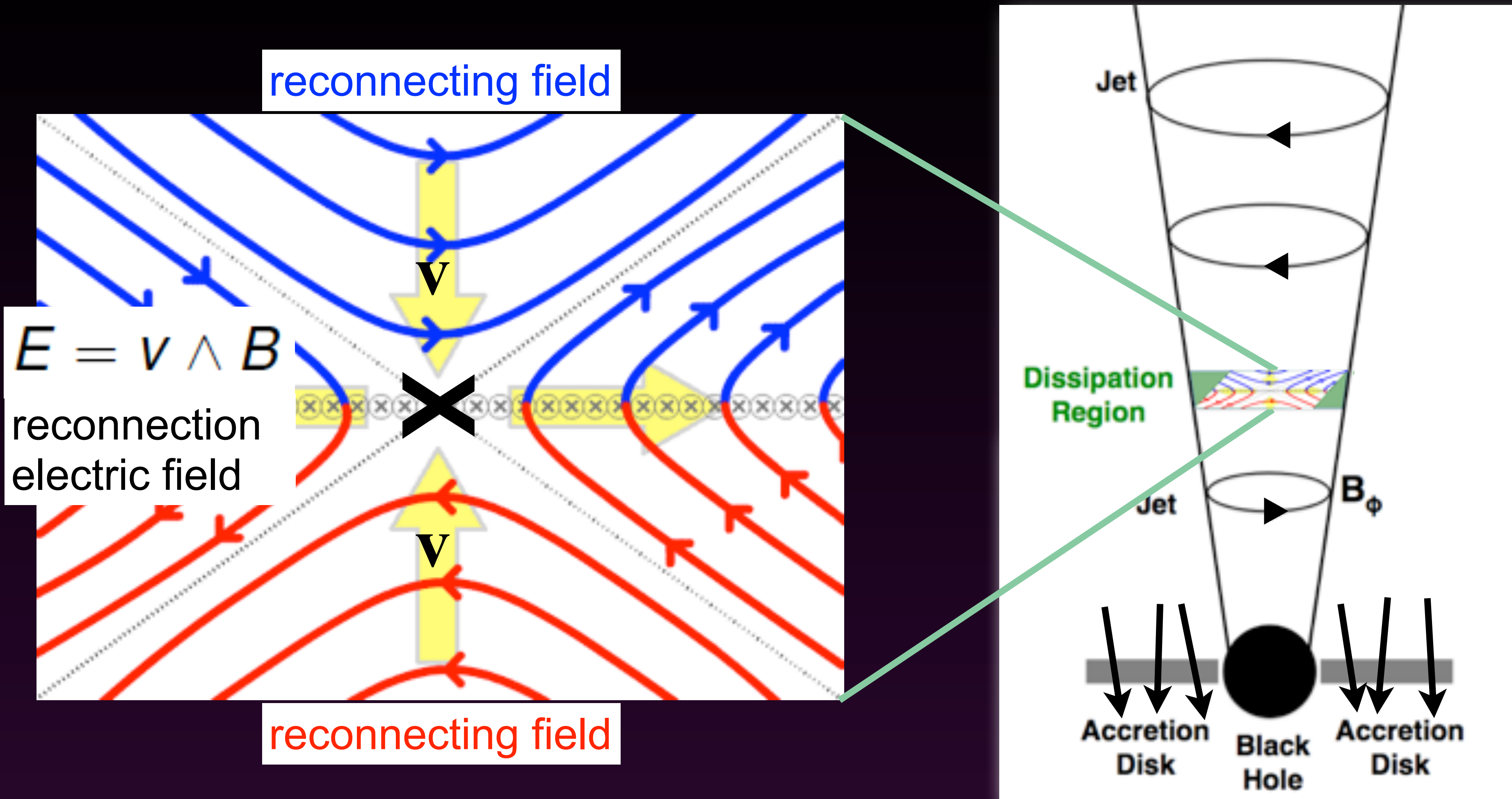
Internal dissipation in blazar jets



Internal dissipation: shocks or magnetic reconnection?

Relativistic magnetic reconnection



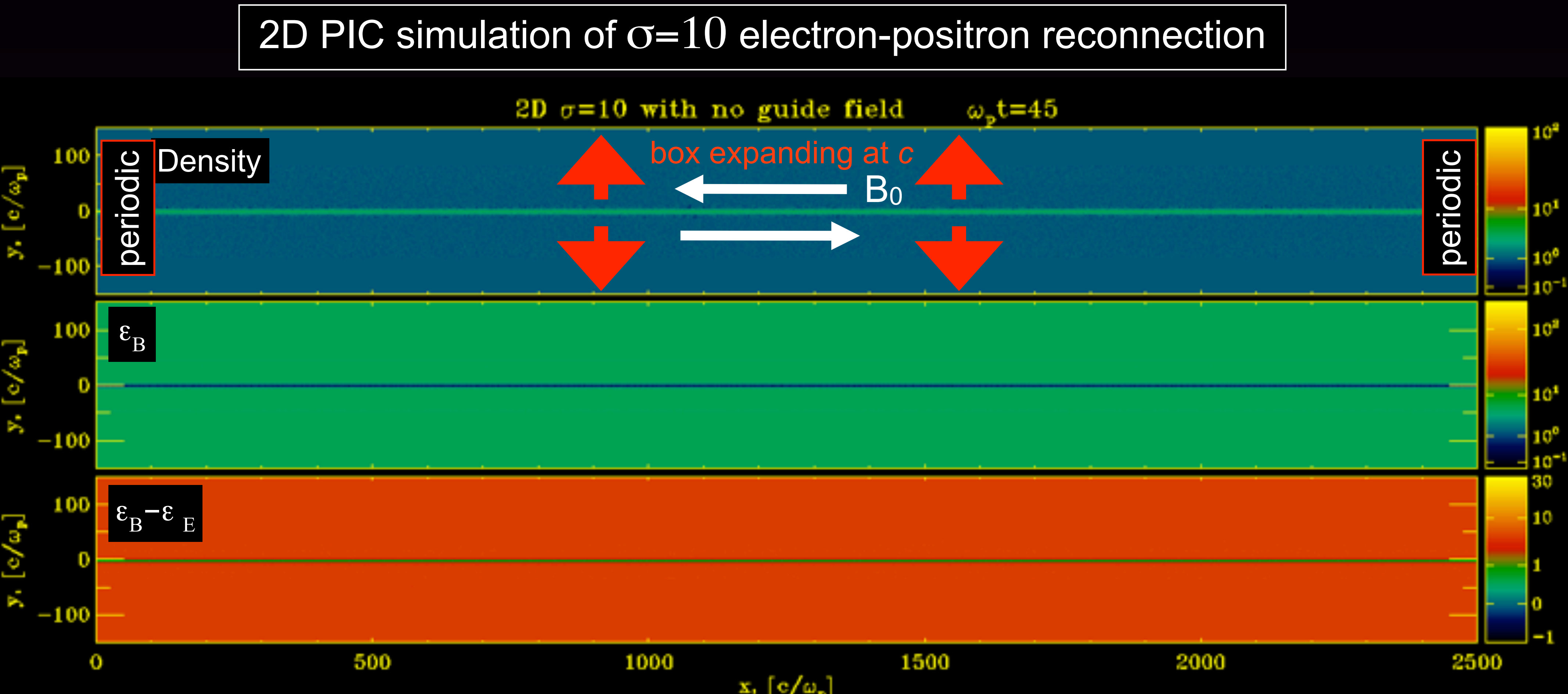
Relativistic Reconnection

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

What is the long-term evolution of relativistic magnetic reconnection?

Dynamics and particle spectrum

Hierarchical reconnection

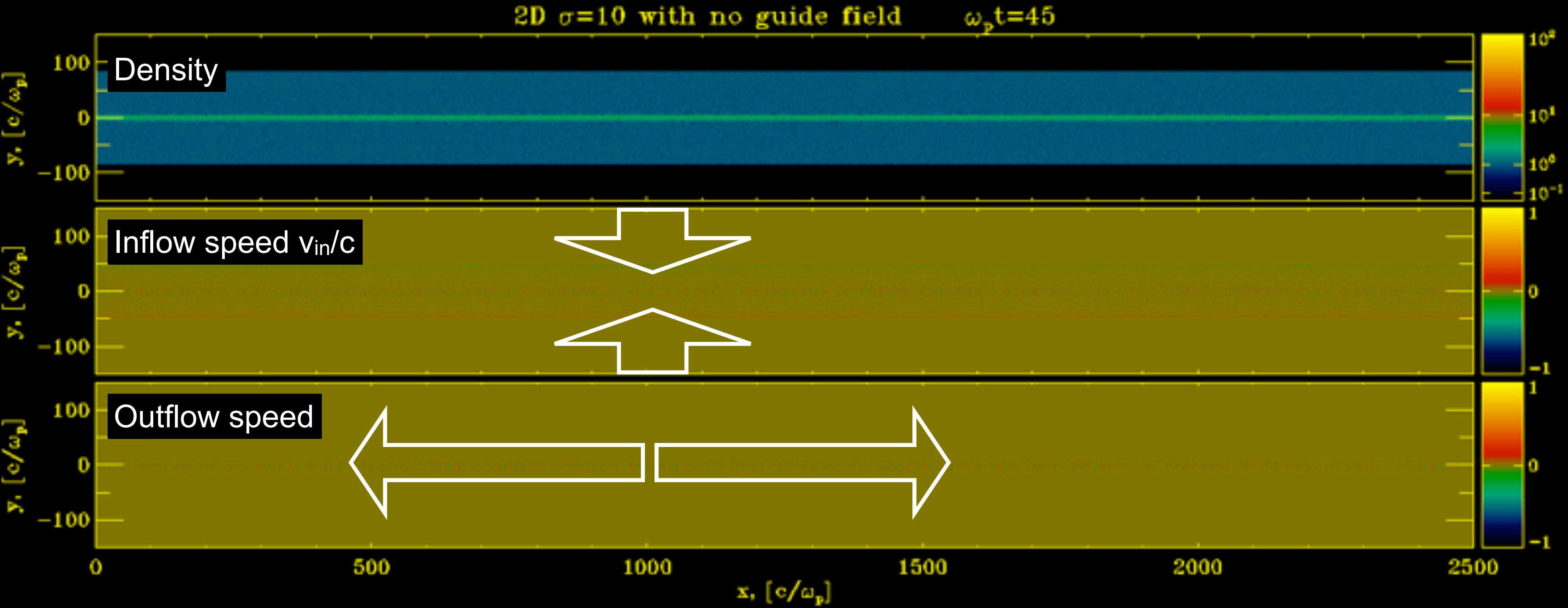


(LS & Spitkovsky 14)

- 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.

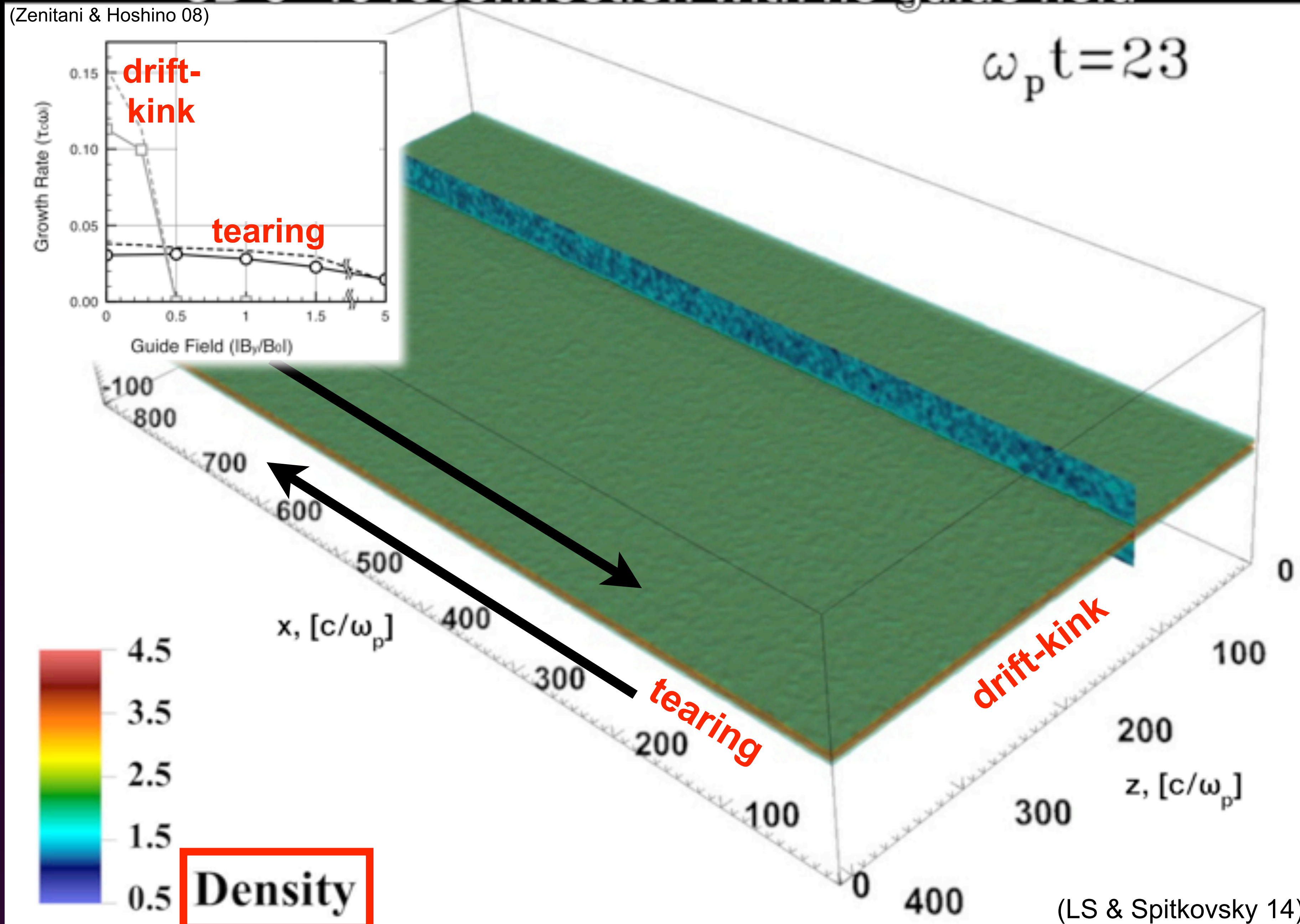
Inflows and outflows

2D PIC simulation of σ=10 electron-positron reconnection



- Inflow into the layer 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 $v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$

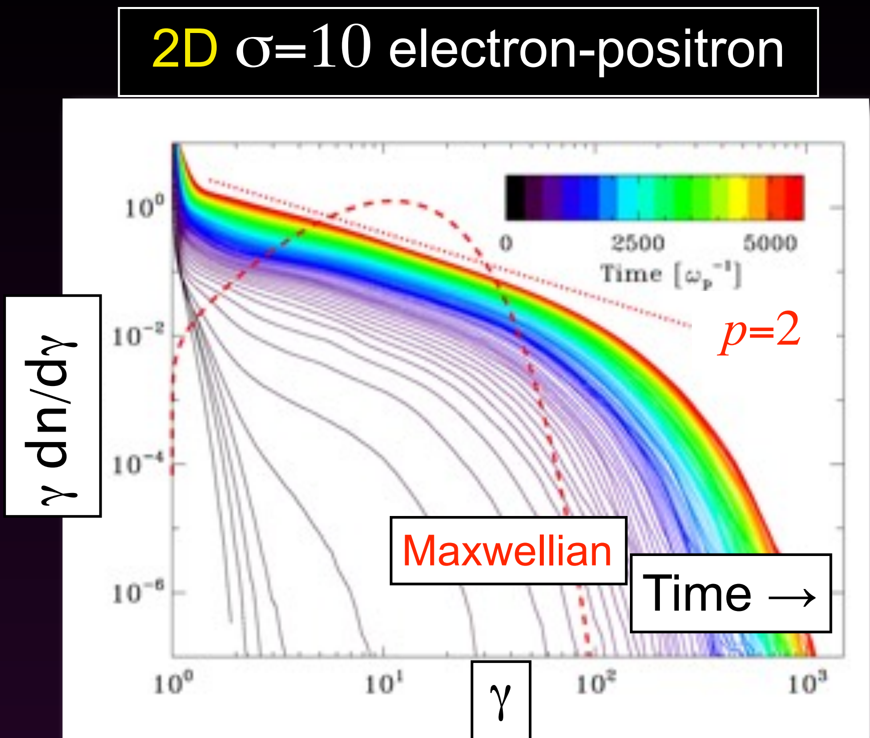
3D σ=10 reconnection with no guide field

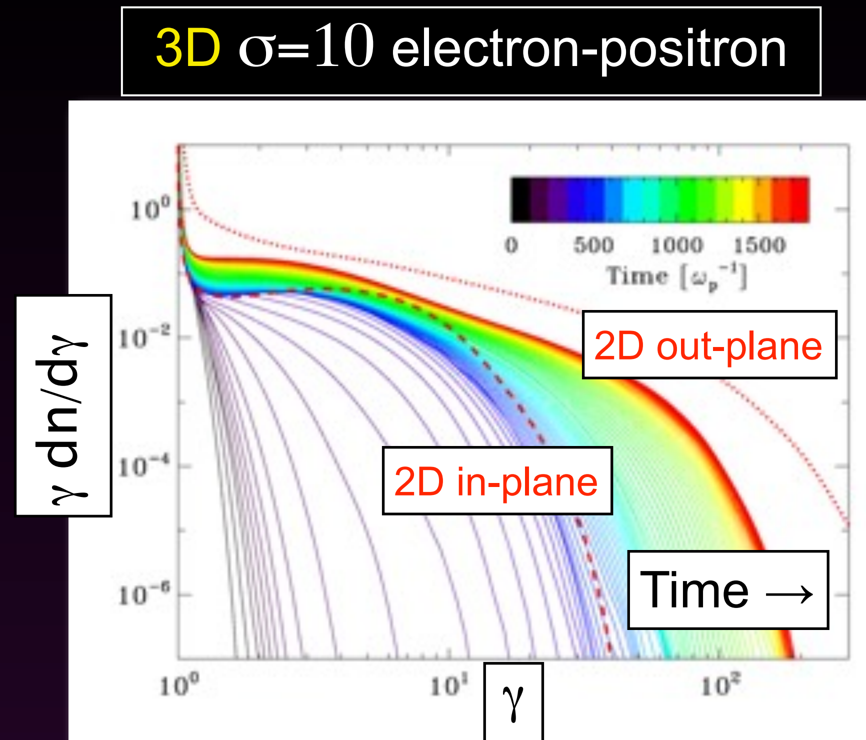


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

The particle energy spectrum

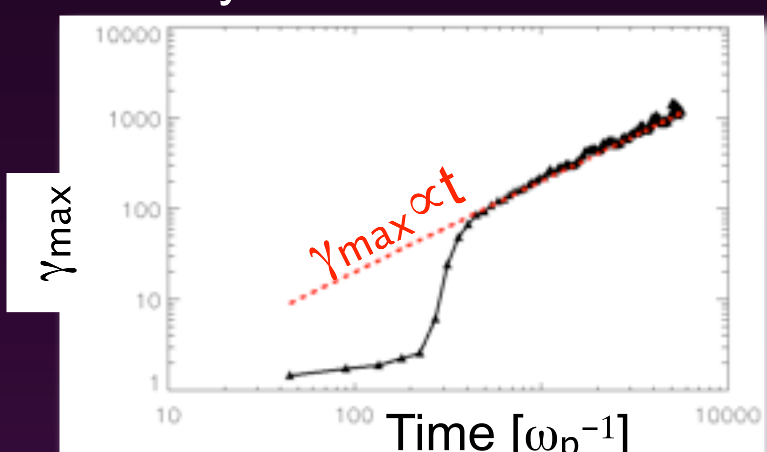
- At late times, the particle spectrum approaches a power law $dn/d\gamma \propto \gamma^{-p}$

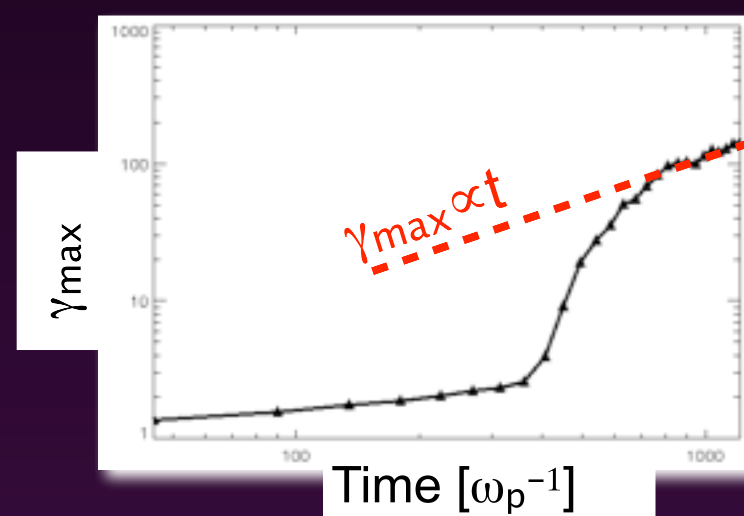




(LS & Spitkovsky 14)

- The max energy grows linearly with time, if the evolution is not artificially inhibited by the boundaries.

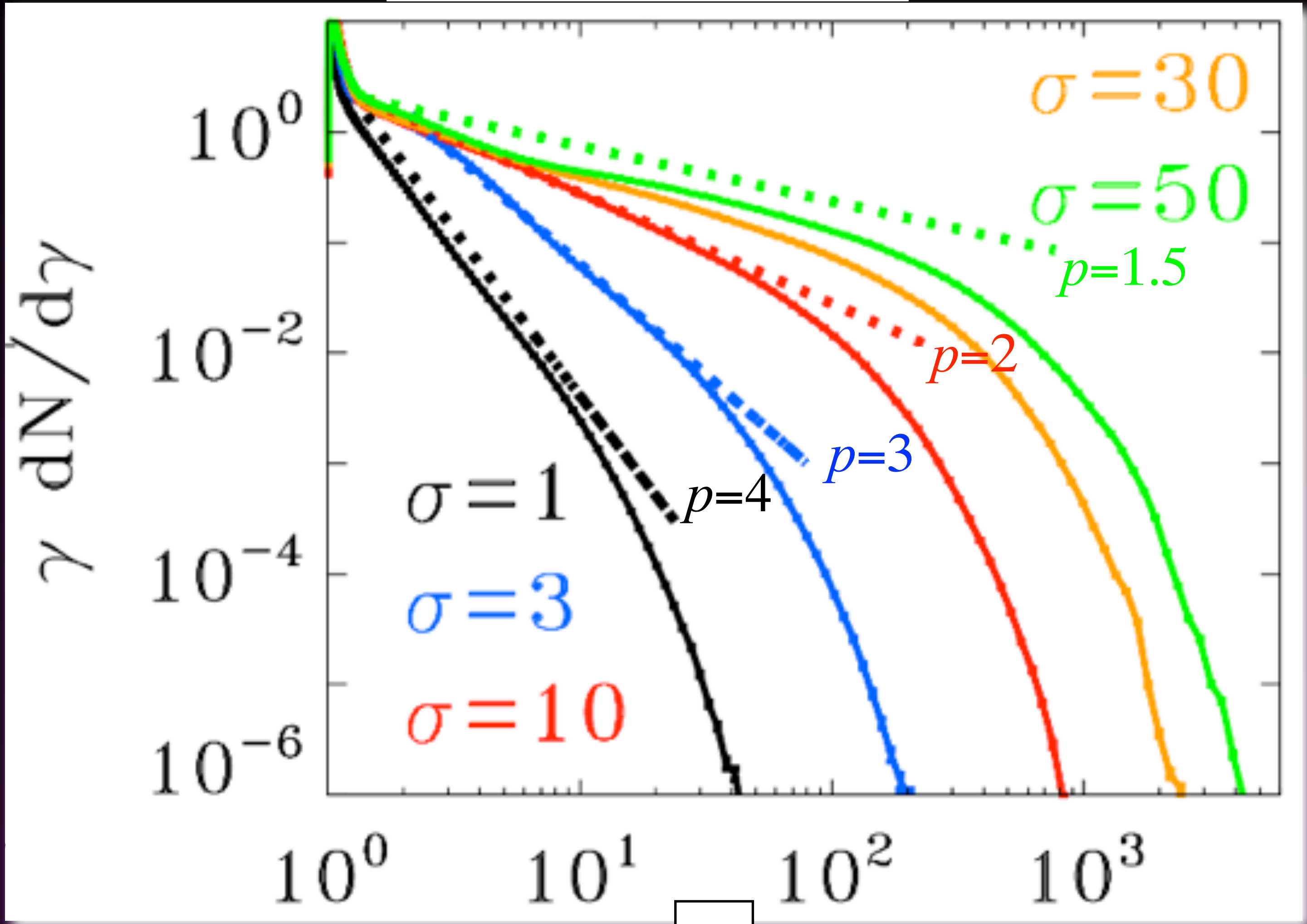




(LS & Spitkovsky 14)

The power-law slope

2D electron-positron



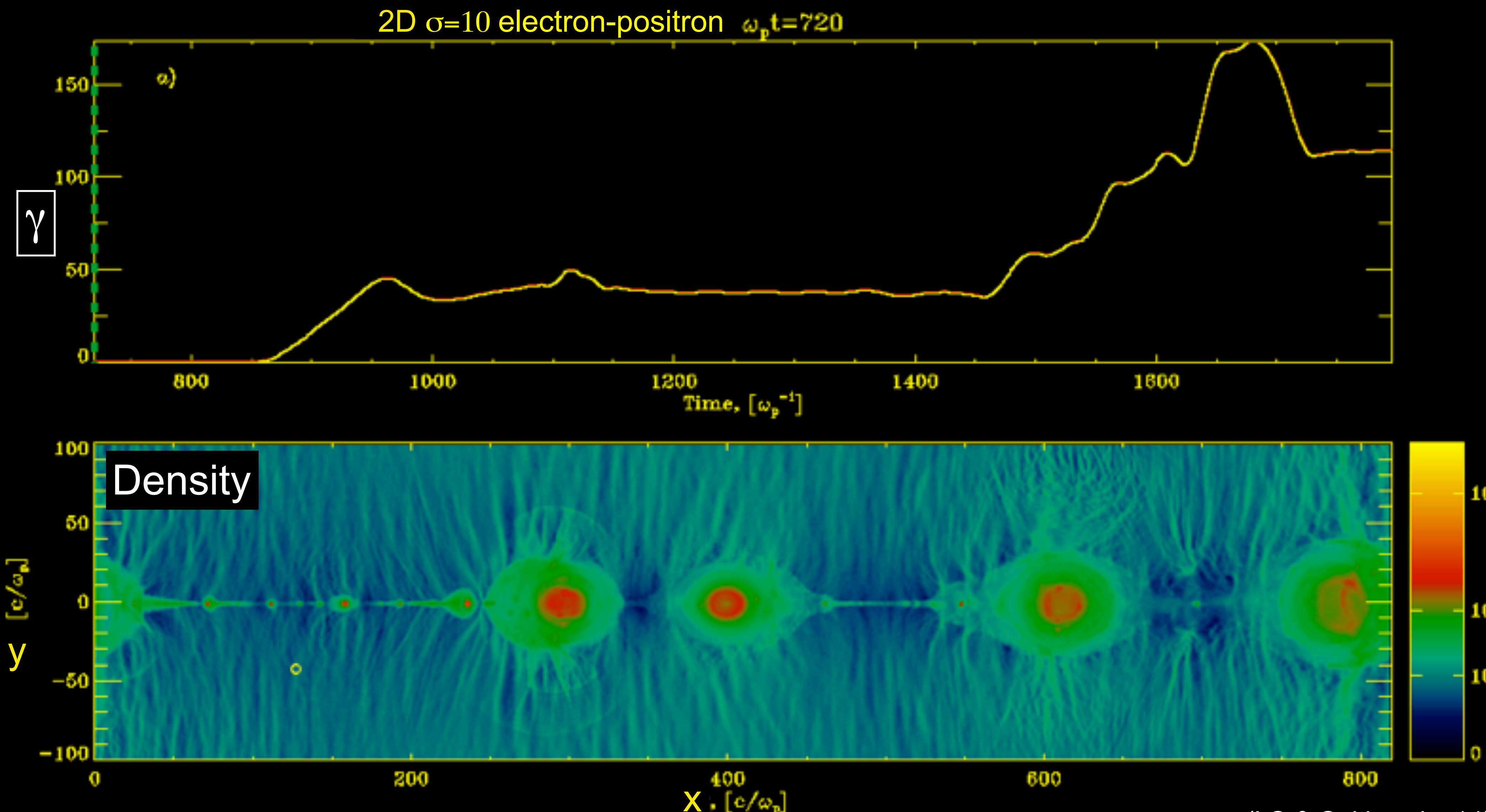
γ

(LS & Spitkovsky 14, see also Melzani+14, Guo+14,15, Werner+16)

The power-law slope is harder for higher magnetizations.

Particle acceleration mechanisms

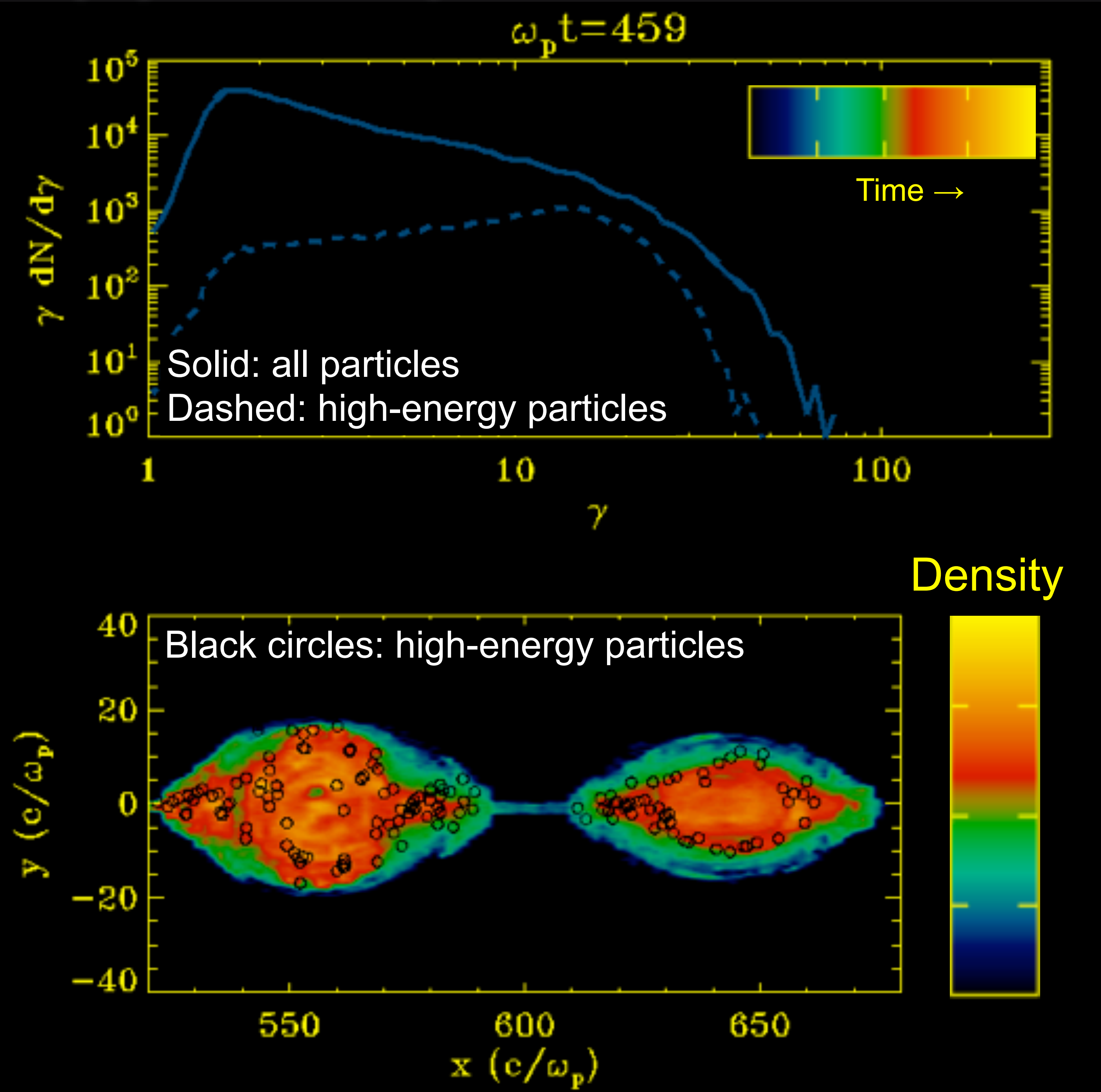
The highest energy particles



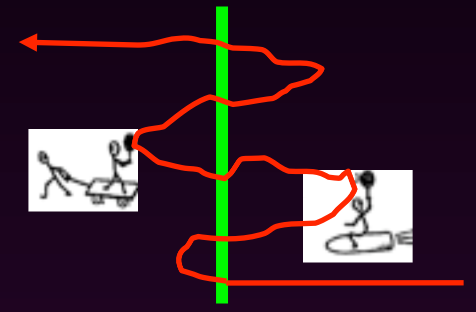
(LS & Spitkovsky 14)

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

(2) Fermi process in between islands

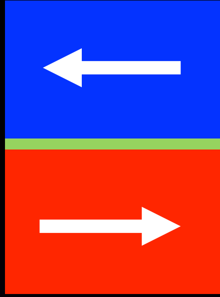


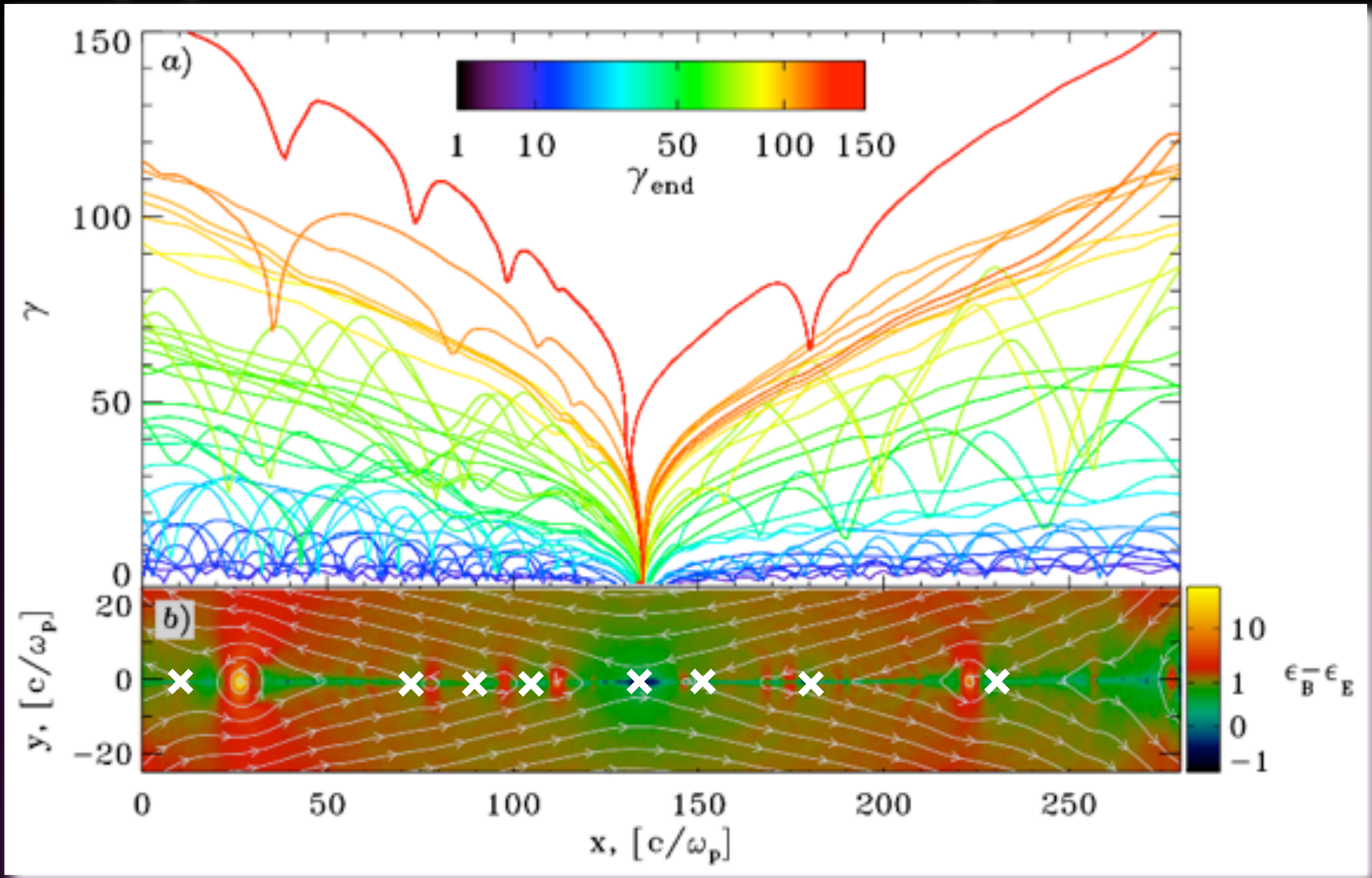
- The particles are accelerated by a Fermi-like process in between merging islands (Guo+14, Nalewajko+15).



- 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



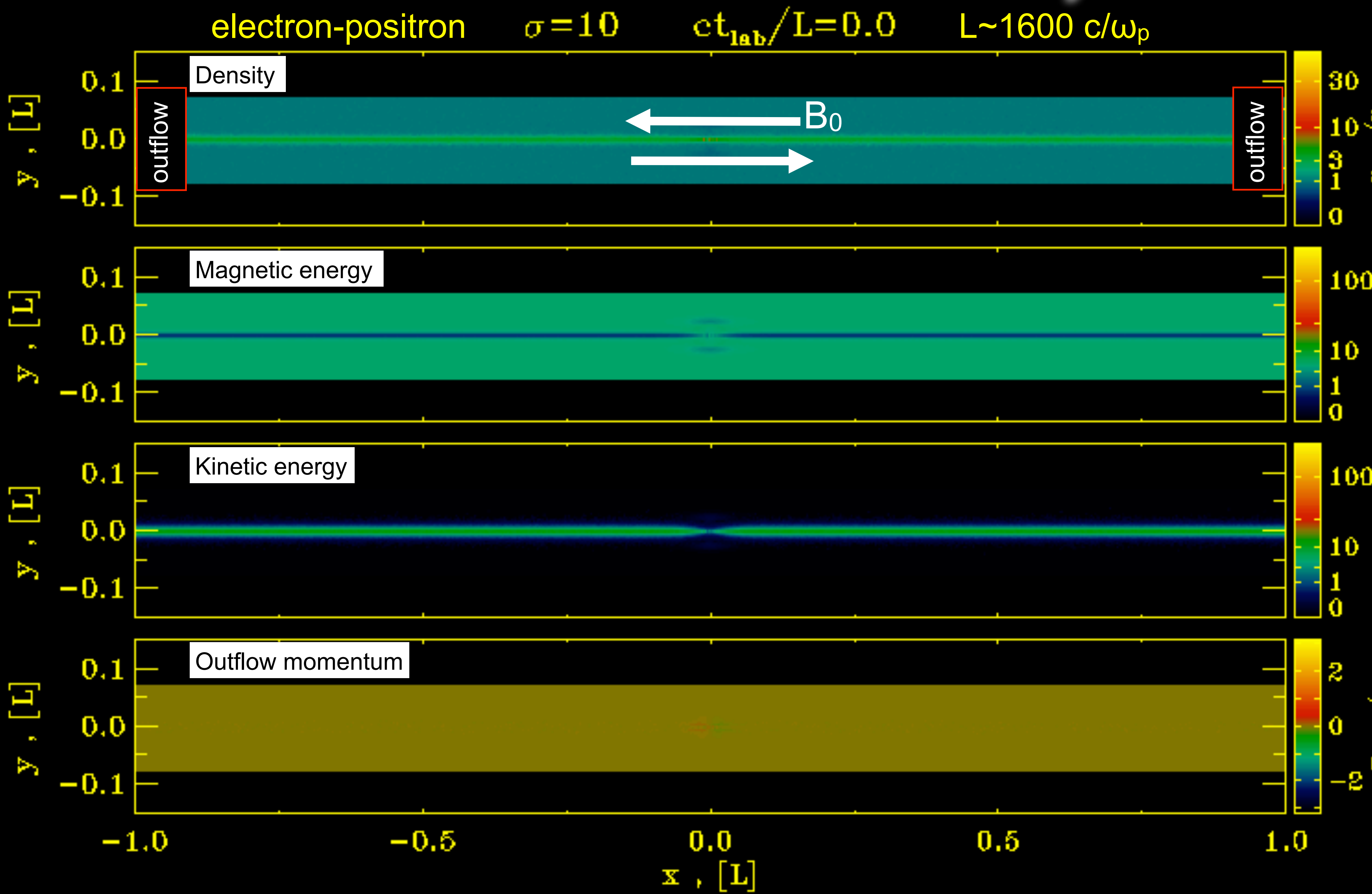


(LS & Spitkovsky 14)

- 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 (Zenitani & Hoshino 01). The energy gain can vary, depending on where the particles interact with the sheet.
- The same physics operates at the main X-point and in secondary X-points.

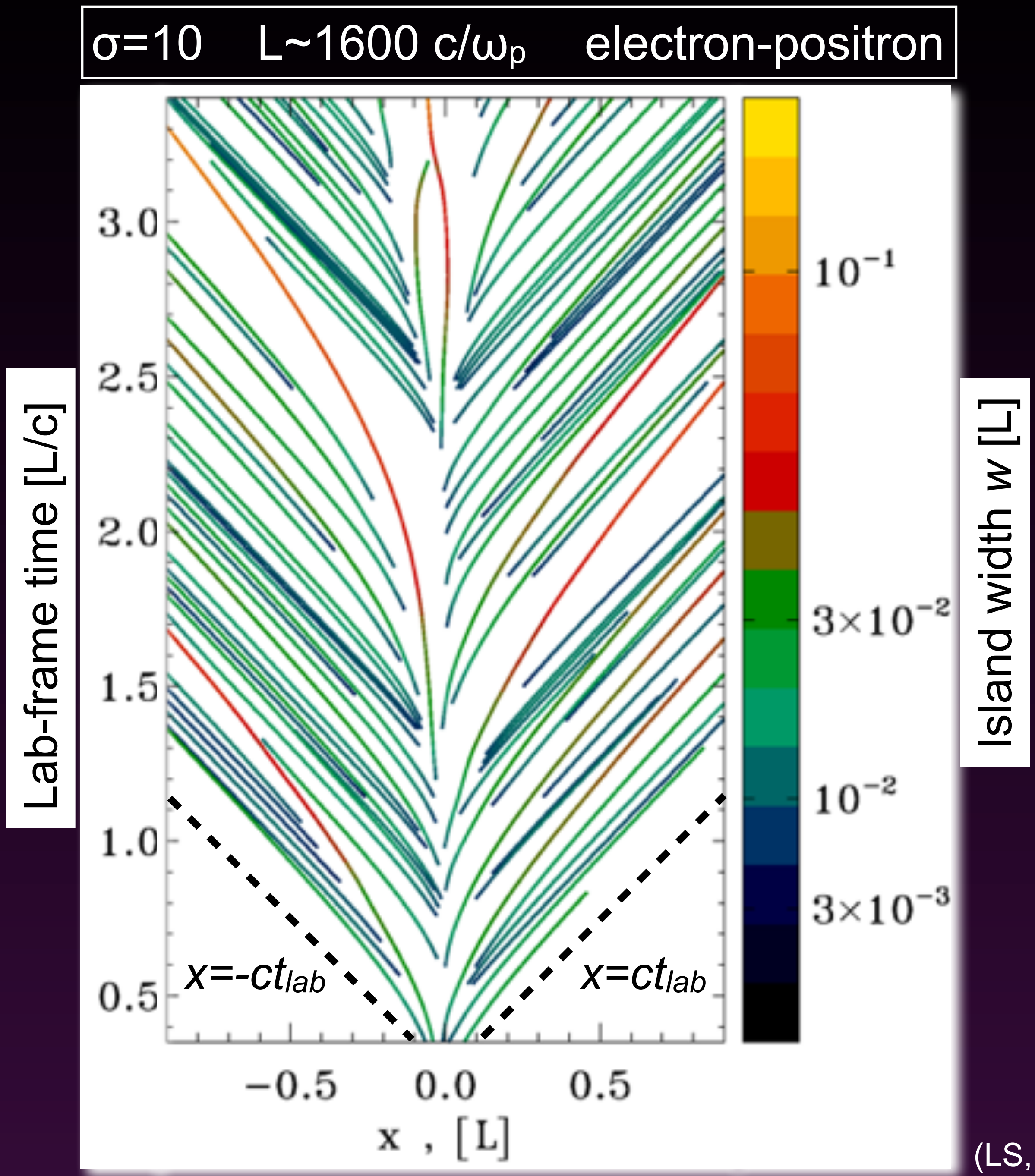
Plasmoids in relativistic reconnection

Plasmoids in reconnection layers



(LS, Giannios & Petropoulou 16)

Plasmoid space-time tracks



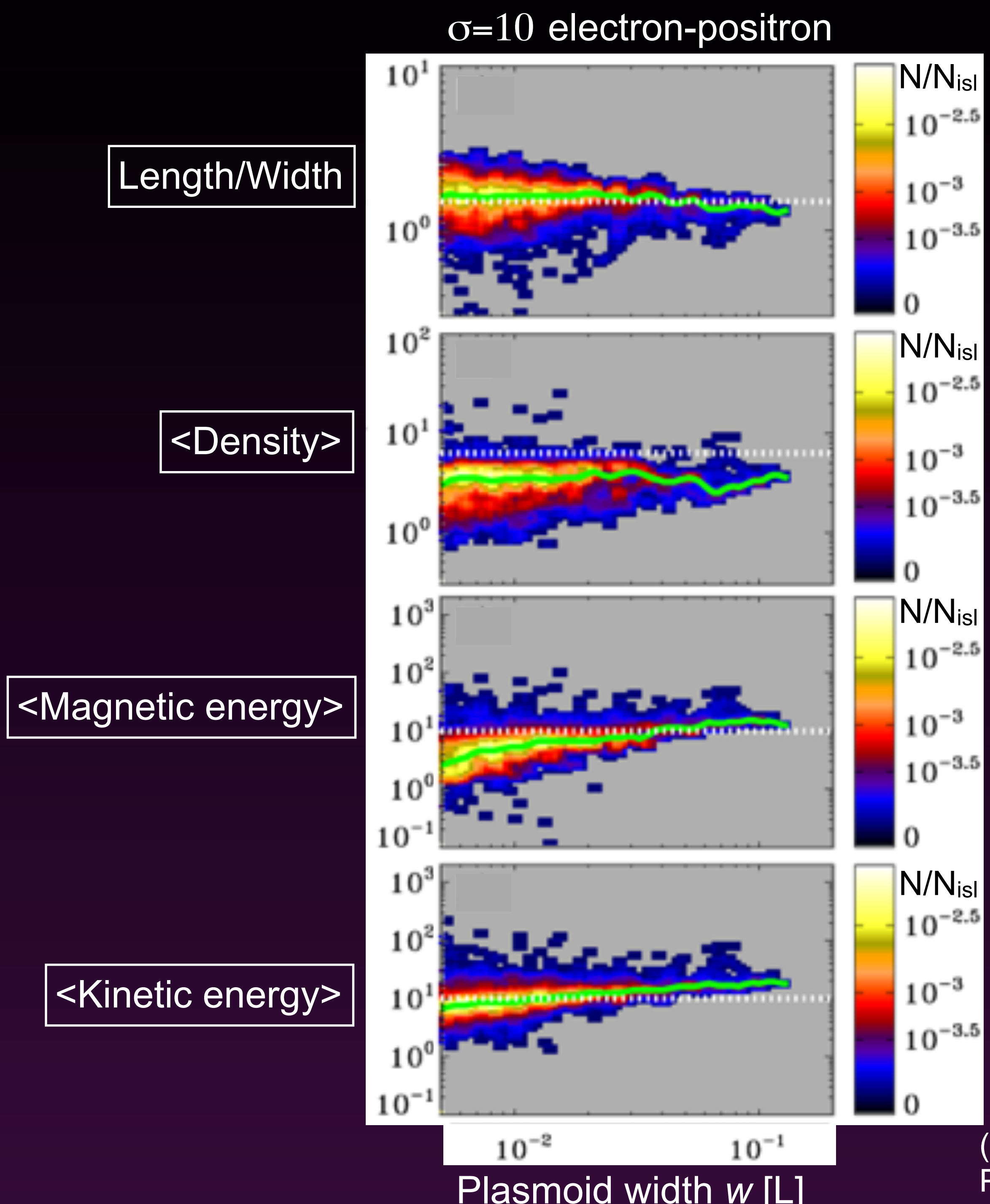
We can follow individual plasmoids in space and time.

First they grow, then they go:

- First, they grow in the center at non-relativistic speeds.
- Then, they accelerate outwards approaching the Alfven speed ~ *c*.

(LS, Giannios & Petropoulou 16)

Plasmoid fluid properties



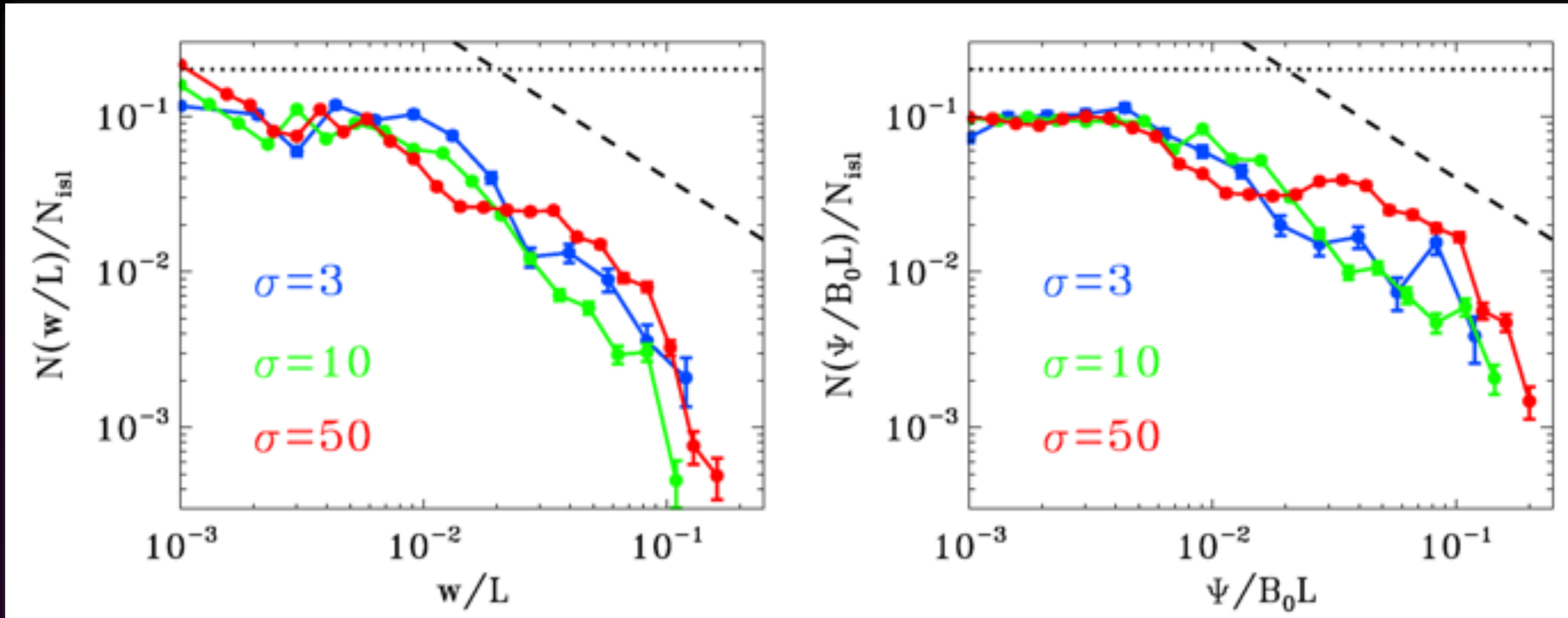
Plasmoids fluid properties:

- they are nearly spherical, with Length/Width~1.5 (regardless of the plasmoid width *w*).
- they are over-dense by ~ a few with respect to the inflow region (regardless of *w*).
- $\varepsilon_B \sim \sigma$, corresponding to a magnetic field compressed by $\sim\sqrt{2}$ (regardless of *w*).
- $\varepsilon_{kin} \sim \varepsilon_B \sim \sigma \longrightarrow$ equipartition (regardless of *w*).

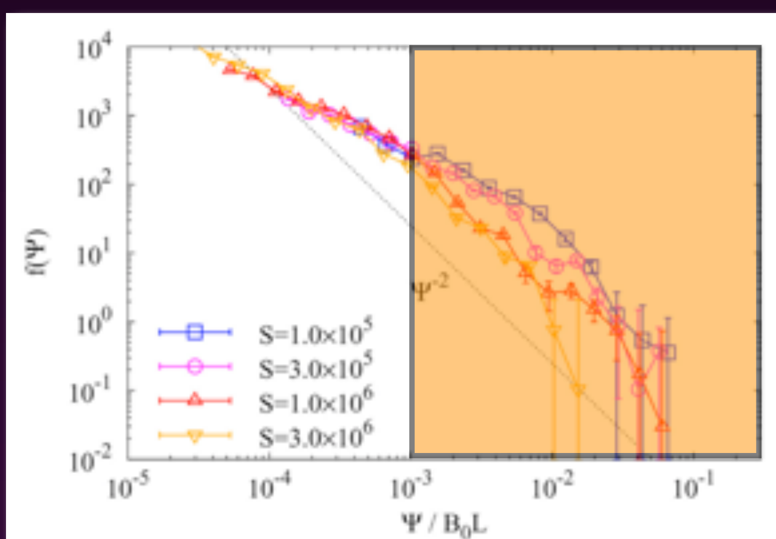
(LS, Giannios & Petropoulou 16)

Plasmoid statistics

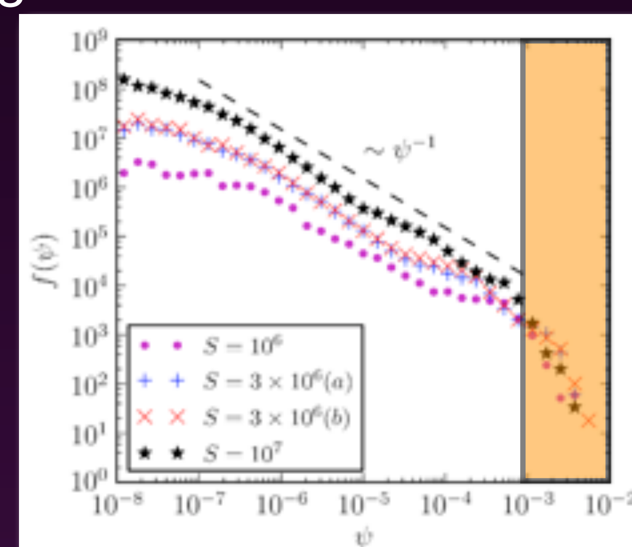
Cumulative distribution of size   Cumulative distribution of magnetic flux



Differential distributions of magnetic flux



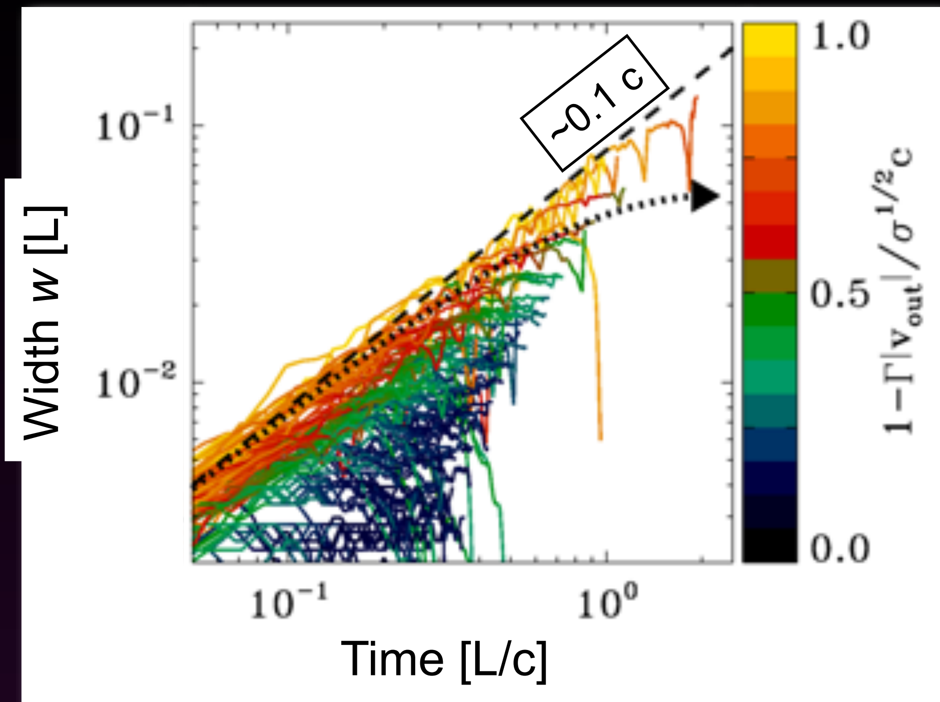
(Loureiro+12)



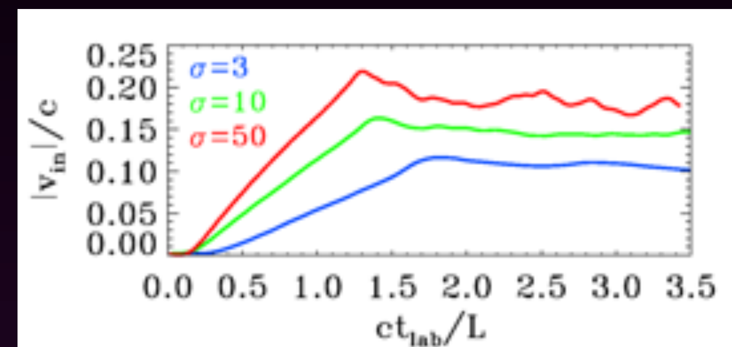
(Huang+12)

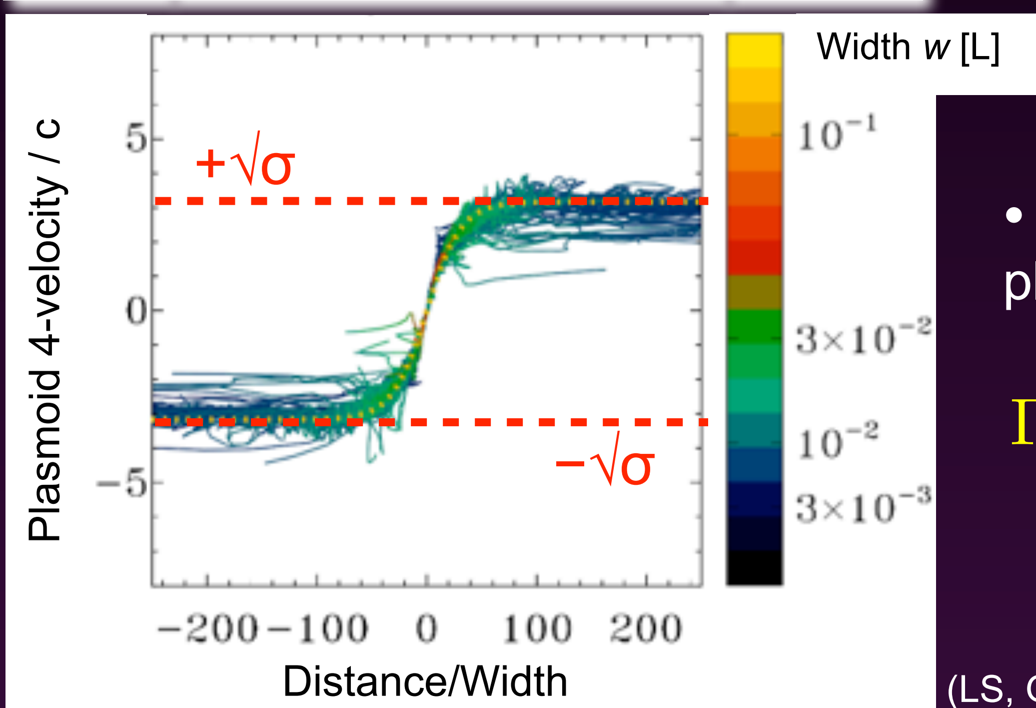
First they grow, then they go

σ=10 electron-positron



- The plasmoid width *w* grows in the plasmoid rest-frame at a constant rate of ~0.1 c (~ reconnection inflow speed), weakly dependent on the magnetization.



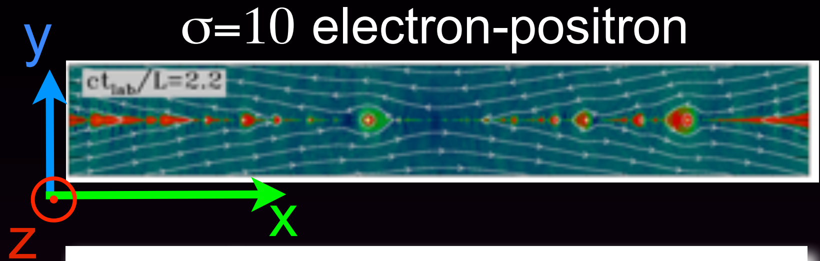


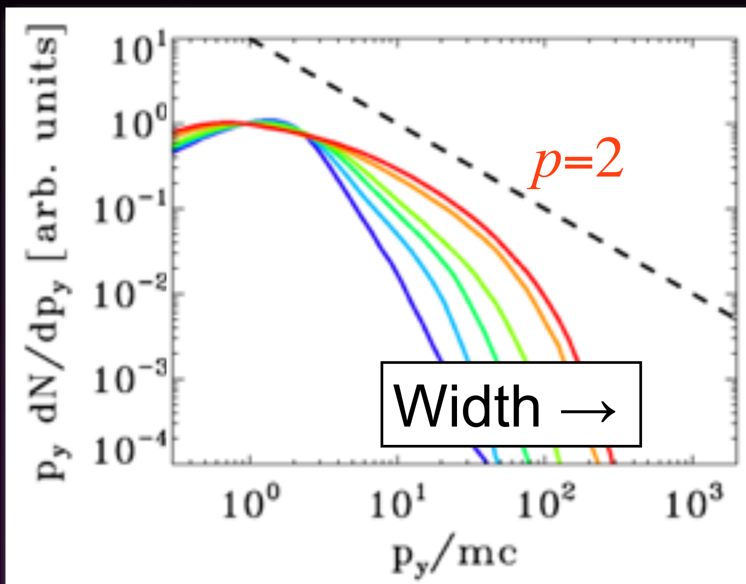
- Universal relation for the plasmoid acceleration:

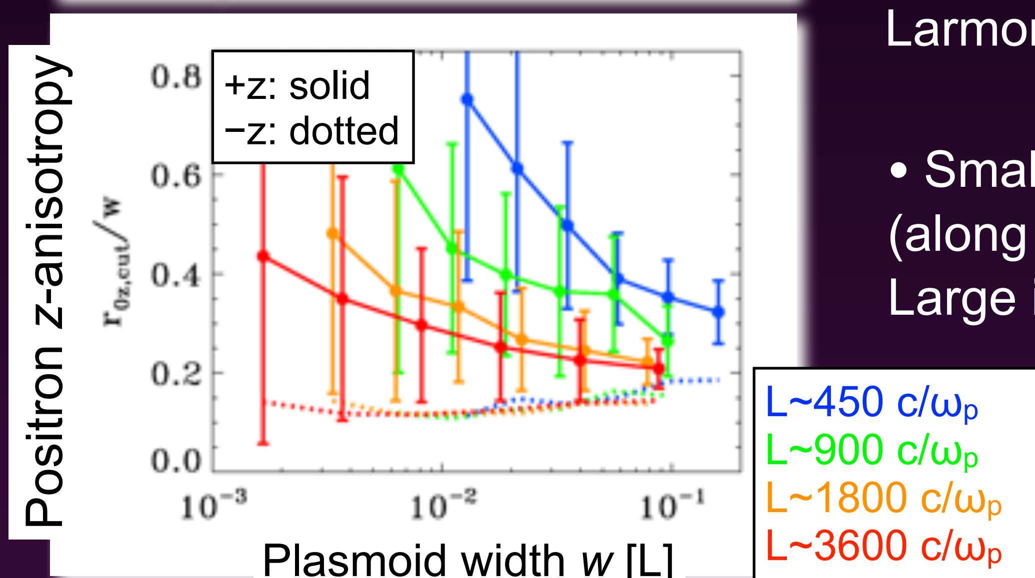
$$\Gamma \frac{v_{\rm out}}{c} \simeq \sqrt{\sigma} \tanh\left(\frac{0.1}{\sqrt{\sigma}} \frac{x}{w}\right)$$

(LS, Giannios & Petropoulou 16)

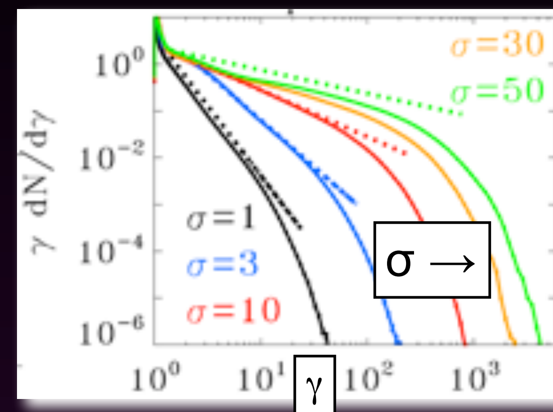
Non-thermal particles in plasmoids







- The *comoving* particle spectrum of large islands is a power law, with the same slope as the overall spectrum from the layer (so, harder for higher σ).



Text

- The low-energy cutoff scales as ∝√σ, the high-energy cutoff scales as ∝*w*, corresponding to a Larmor radius ~0.2 *w* (a *confinement criterion*).

- Small islands show anisotropy along *z* (along the reconnection electric field). Large islands are nearly isotropic.

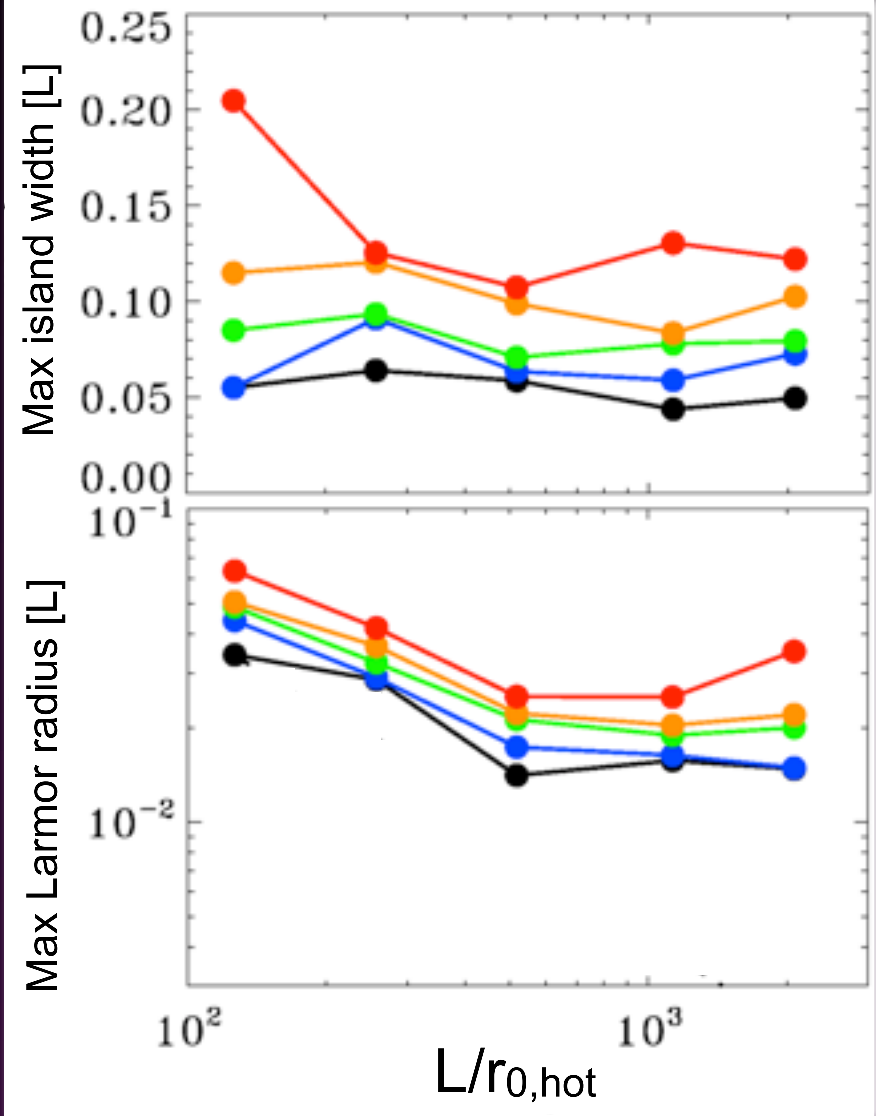
(LS, Giannios & Petropoulou 16)

From microscoPIC scales to blazars

Let us measure the system length *L* in units of the post-reconnection Larmor radius:

$$r_{0,\mathrm{hot}} = \sigma \frac{mc^2}{eB_0}$$

σ=10 electron-positron



Relativistic reconnection is a self-similar process, in the limit $L \gg r_{0,hot}$:

- The width of the biggest ("monster") islands is a fixed fraction of the system length L (~0.1-0.2 L), regardless of $L/r_{0,hot}$.

- At large L ($L/r_{0,hot} \gtrsim 300$), the Larmor radius of the highest energy particles is a fixed fraction of the system length L (~0.03-0.05 L), regardless of $L/r_{0,hot}$.

→ Hillas criterion of relativistic reconnection (e.g., for UHECRs).

(LS, Giannios & Petropoulou 16)

Summary

• Relativistic magnetic reconnection ($\sigma \gtrsim 1$) is an efficient particle accelerator, in 2D and 3D. In 3D, the drift-kink mode is unimportant for the long-term evolution.

• Relativistic reconnection can efficiently produce non-thermal particles, in the form of a power-law tail with slope between -4 and -1 (harder for higher magnetizations), and maximum energy growing linearly with time.

• Plasmoids generated in the reconnection layer are in rough energy equipartition between particle and magnetic energy. They grow in size near the center at a rate ~0.1 *c*, and then accelerate outwards up to a four-velocity $\sim\sqrt{\sigma}$.

• "Monster" plasmoids of size ~0.2 L are generated once every ~2.5 L/c, their particle distribution is quasi-isotropic and they contain the highest energy particles, whose Larmor radius is ~0.05 L (*Hillas criterion of relativistic reconnection*).

• Explosive reconnection driven by large-scale stresses is fast (~ few dynamical times), efficient and can produce hard spectra, in both 2D and 3D.