Relativistic reconnection in astroplasmas, from plasma scales to astro scales: the computational perspective

Lorenzo Sironi (Harvard → Columbia)

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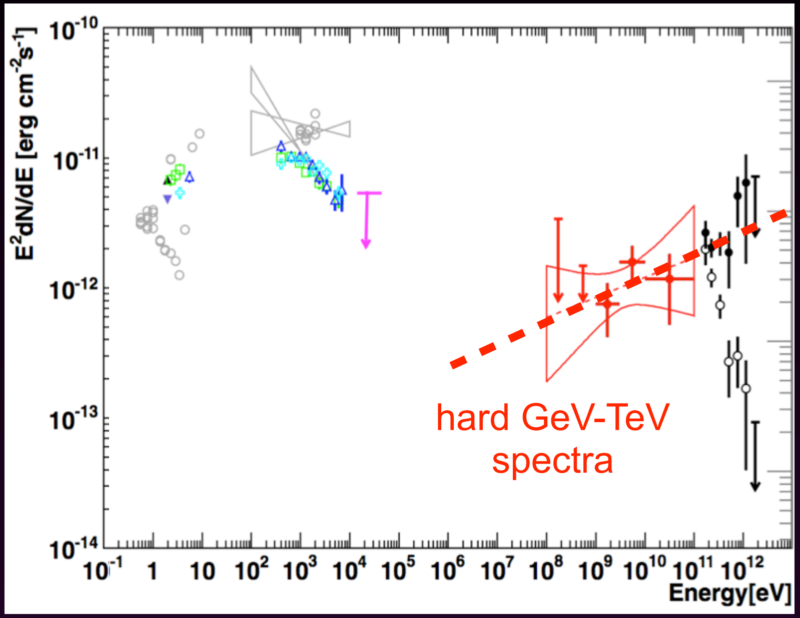
with: Giannios, Komissarov, Lyutikov, Petropoulou, Porth, Spitkovsky

Hard and fast flares from relativistic flows

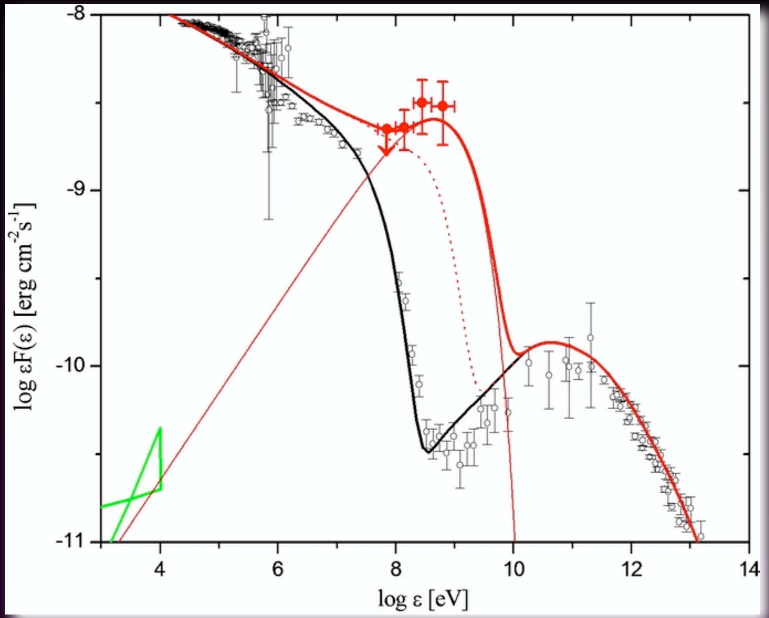
(1) extended power-law distributions of the emitting particles, often with hard slope

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

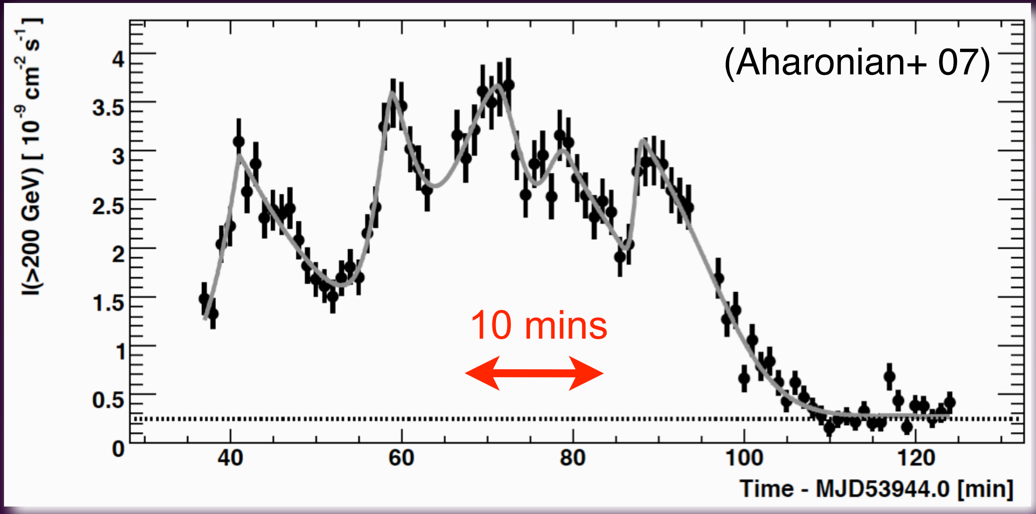
TeV blazars

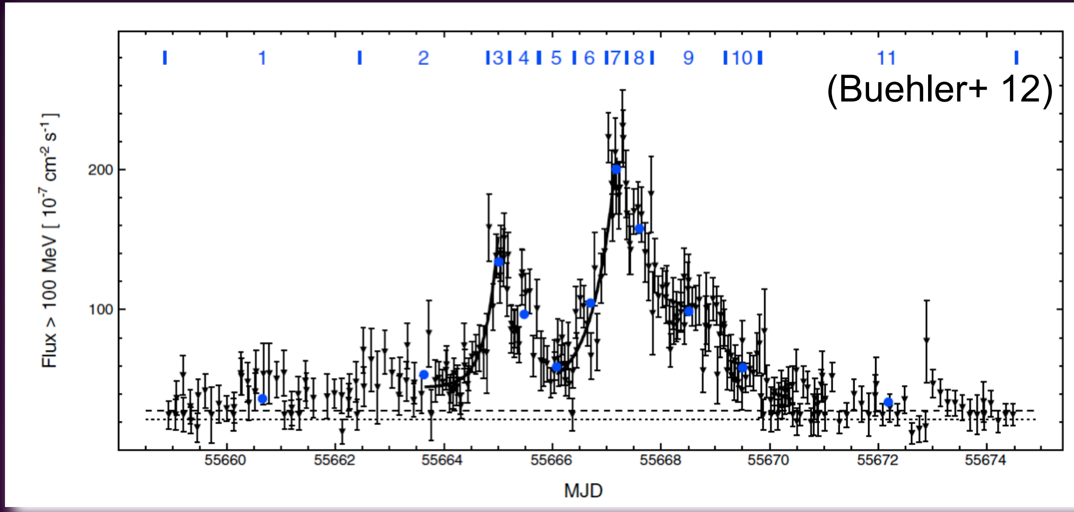


Crab Nebula

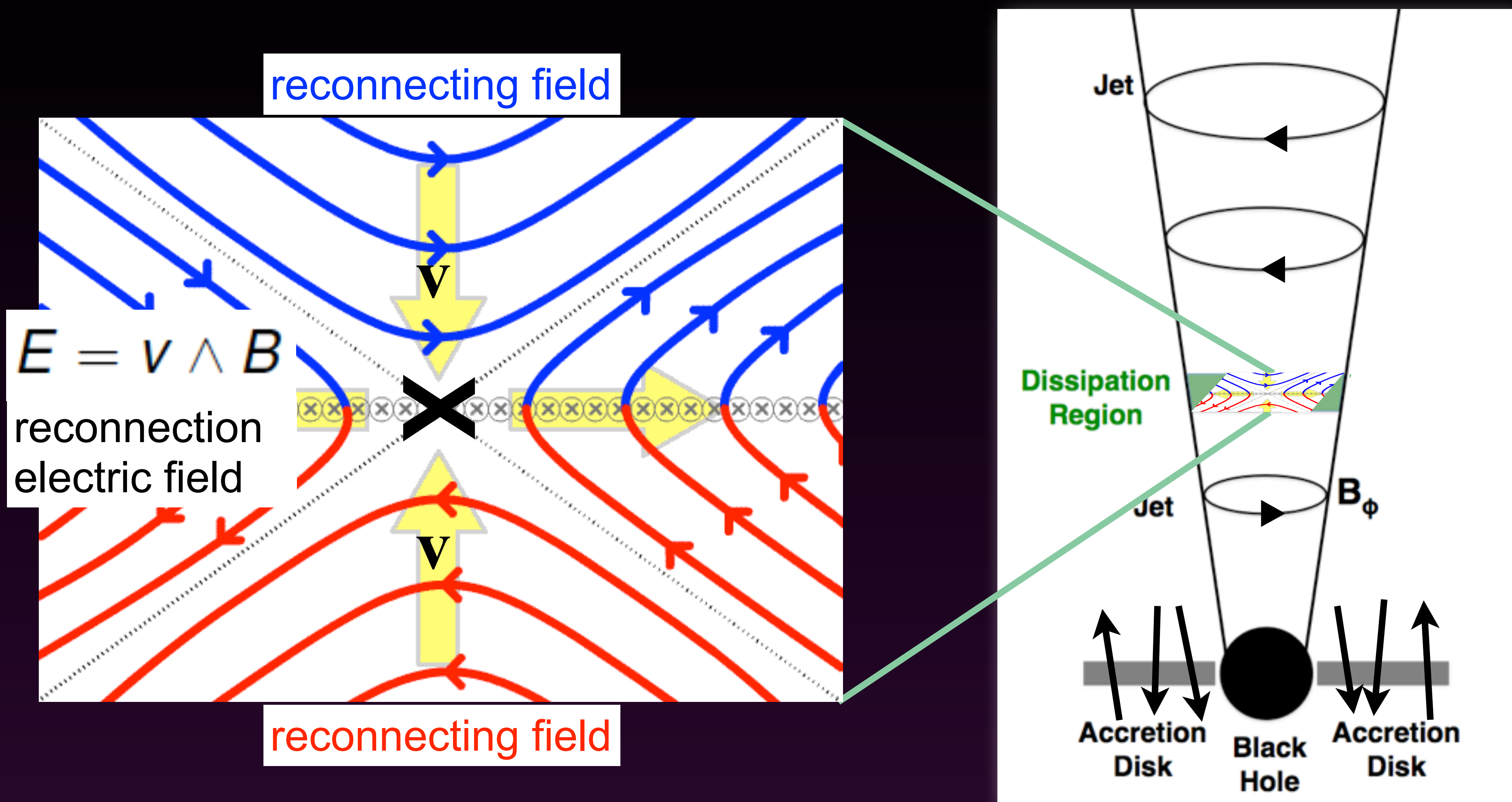


(2) fast time variability





Relativistic magnetic reconnection



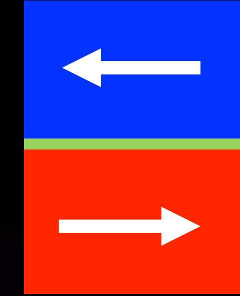
Relativistic Reconnection

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

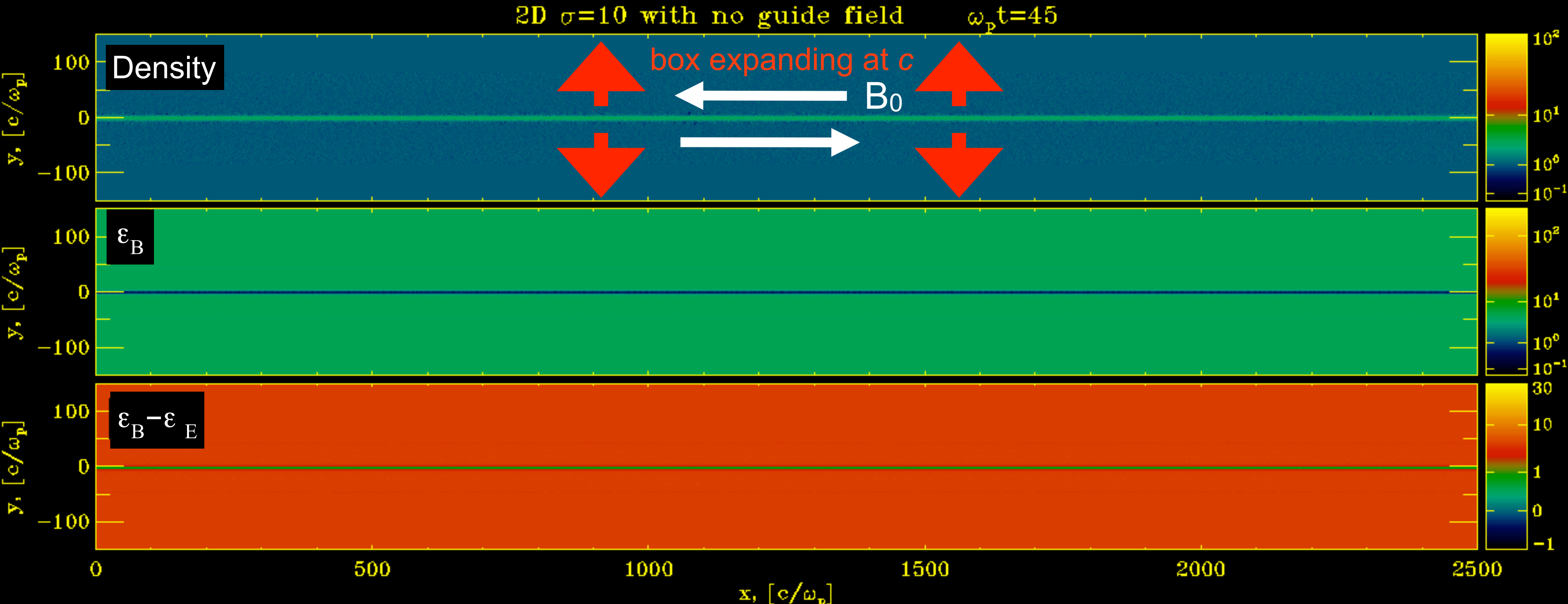
What is the long-term evolution of relativistic magnetic reconnection?

Dynamics and particle spectrum

Hierarchical reconnection



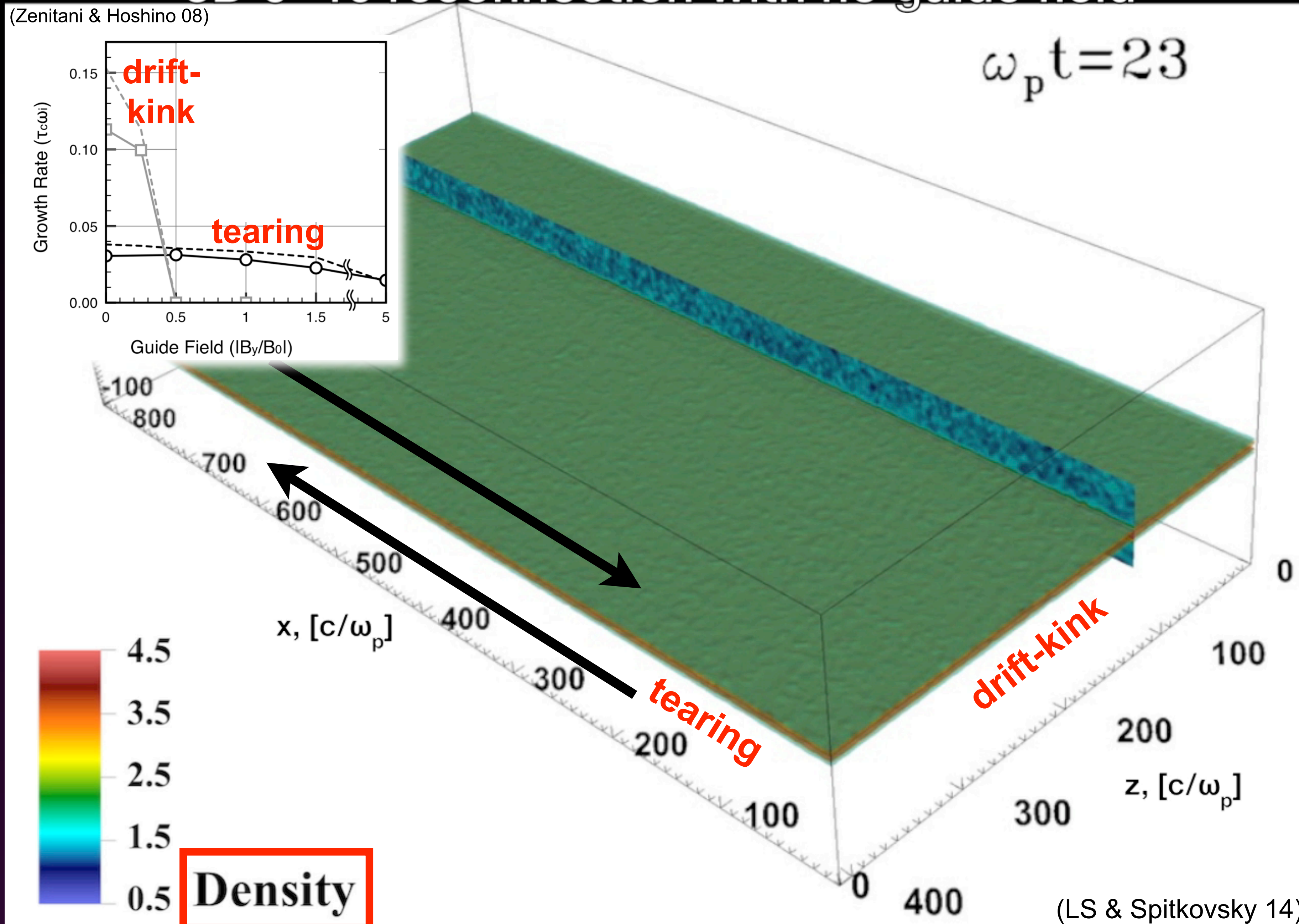
2D PIC simulation of $\sigma=10$ electron-positron reconnection



(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.

3D σ=10 reconnection with no guide field

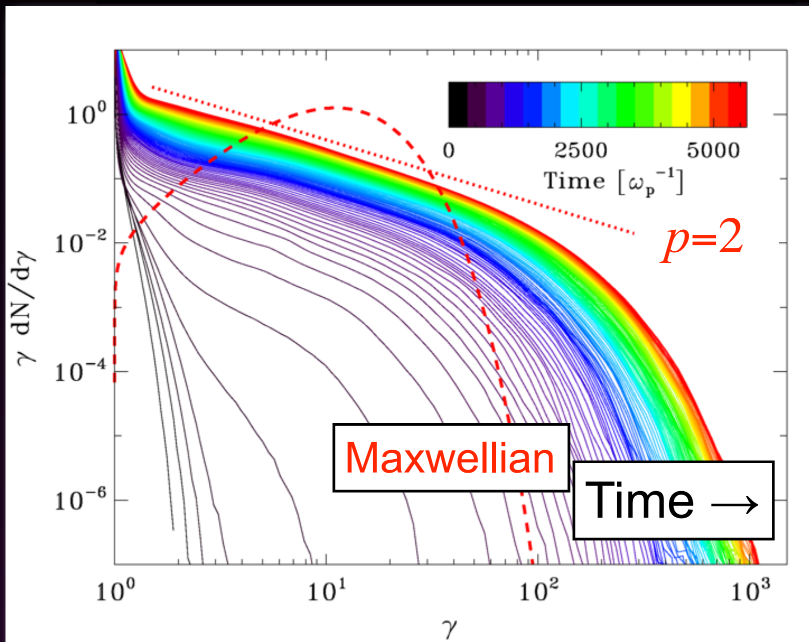


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

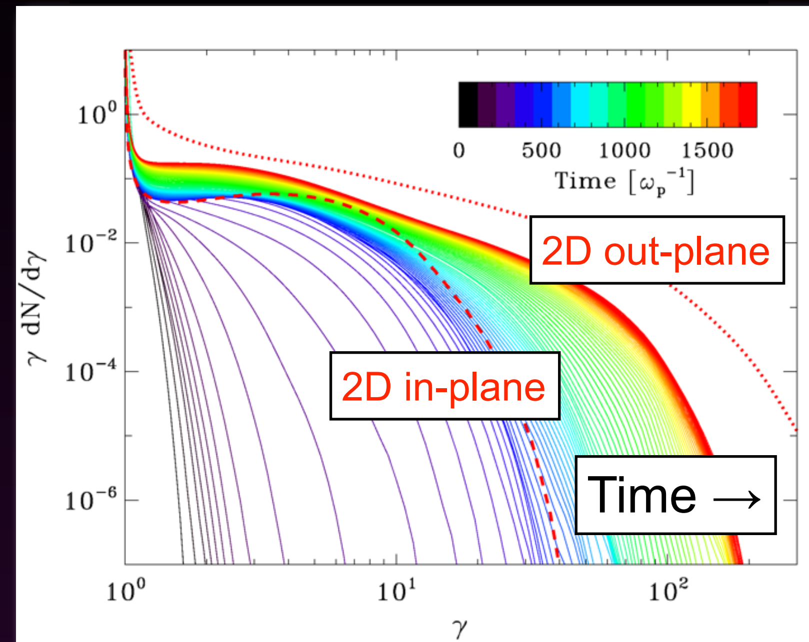
The particle energy spectrum

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

2D σ=10 electron-positron

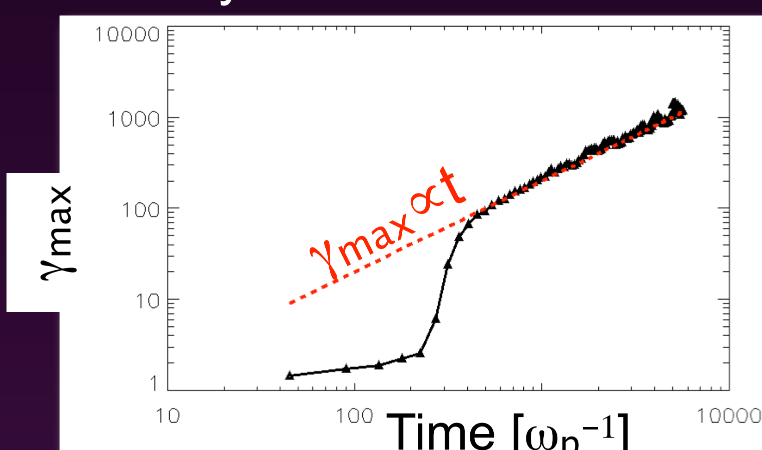


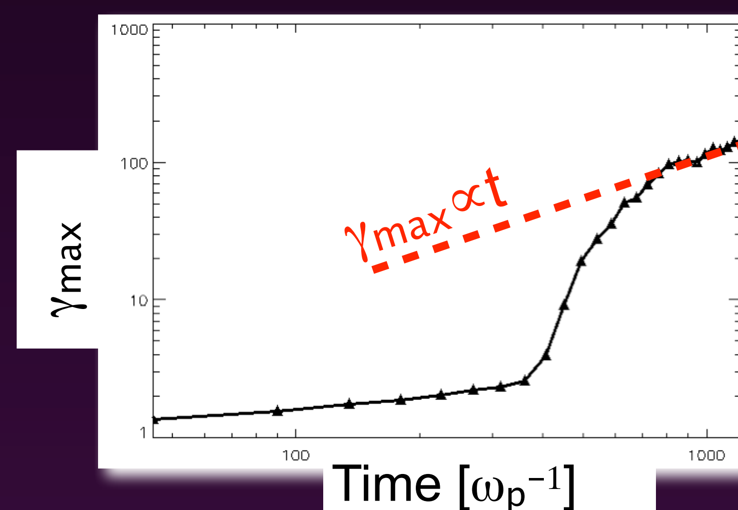
3D σ=10 electron-positron



(LS & Spitkovsky 14)

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

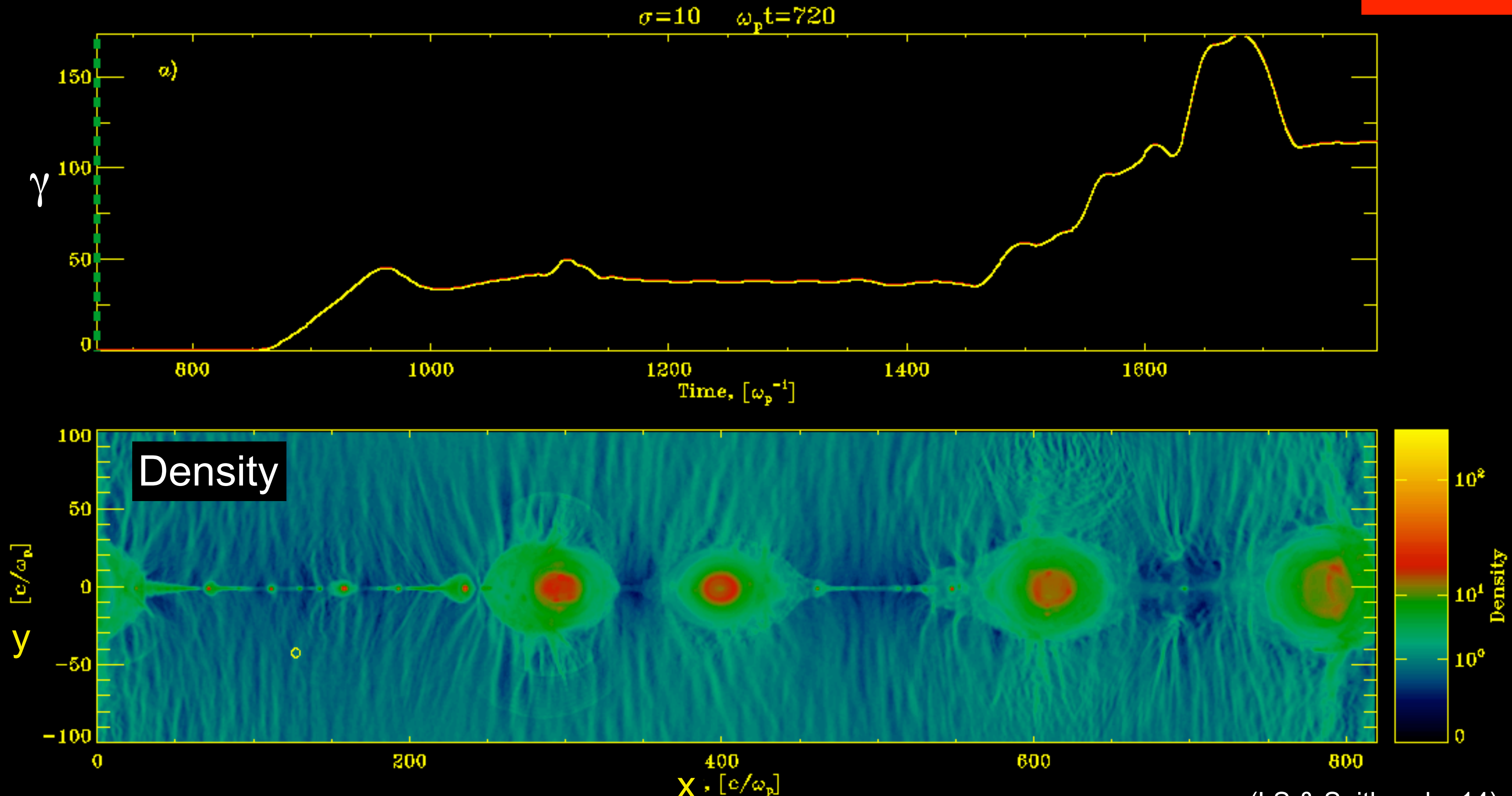




(LS & Spitkovsky 14)

Particle acceleration mechanisms

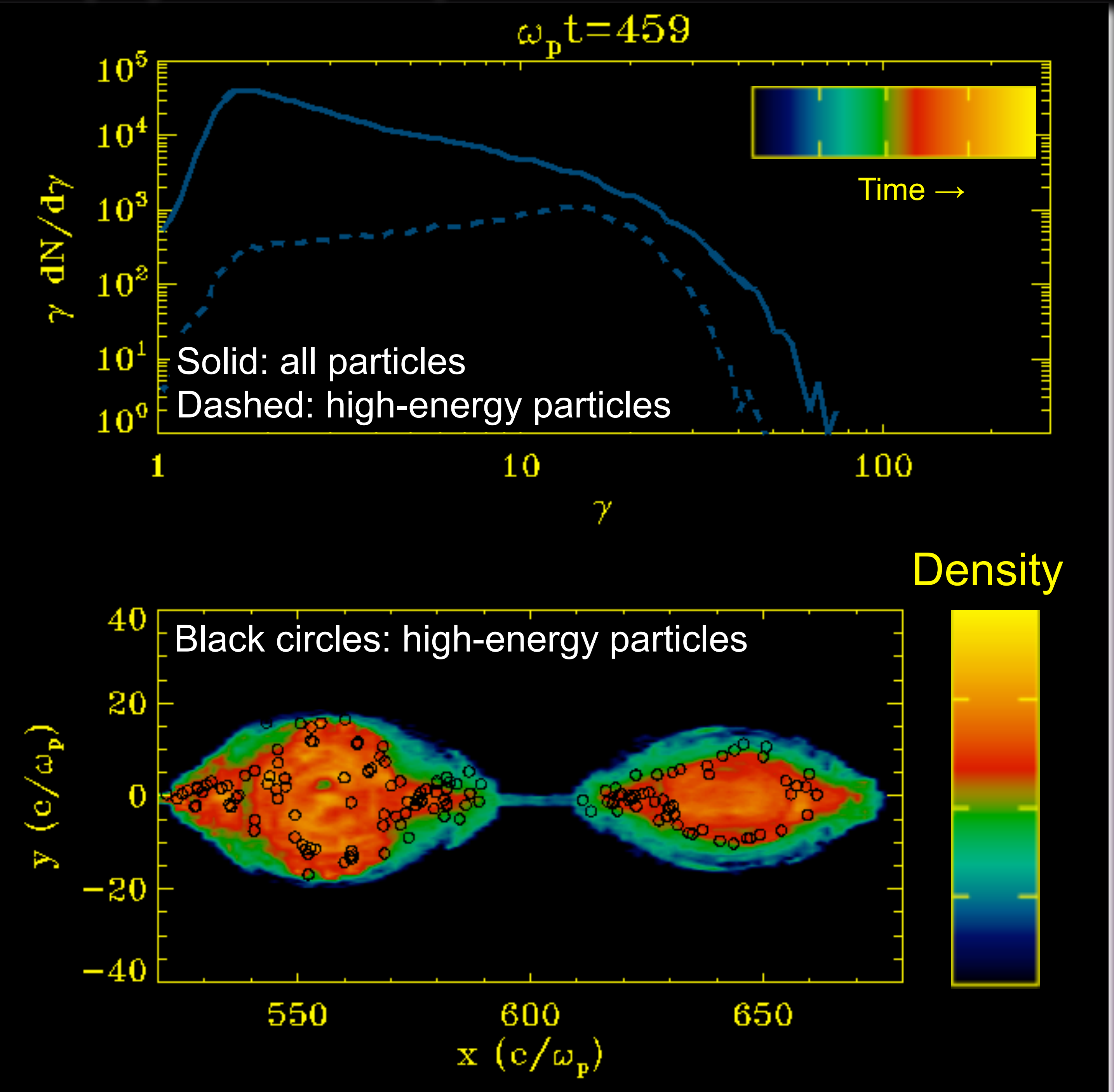
The highest energy particles



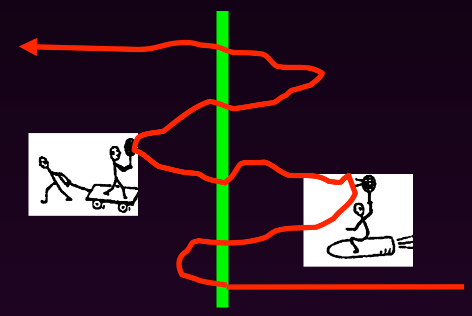
(LS & Spitkovsky 14)

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

(2) Fermi process in between islands



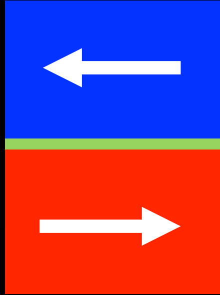
- The particles are accelerated by a Fermi-like process in between merging islands (Guo+14, Nalewajko+15).

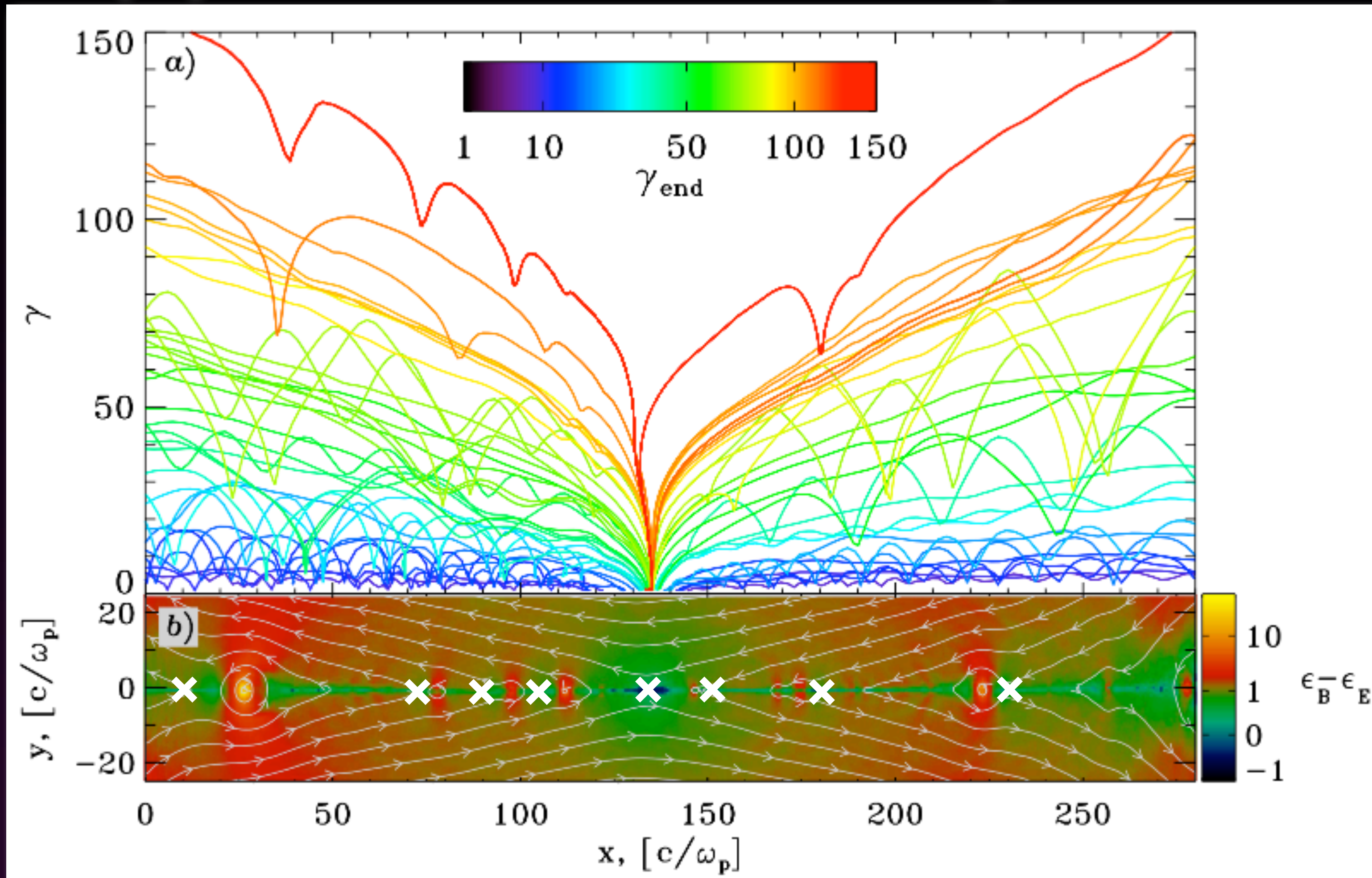


- Island merging is essential to shift up the spectral cutoff energy.

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

(1) Acceleration at X-points



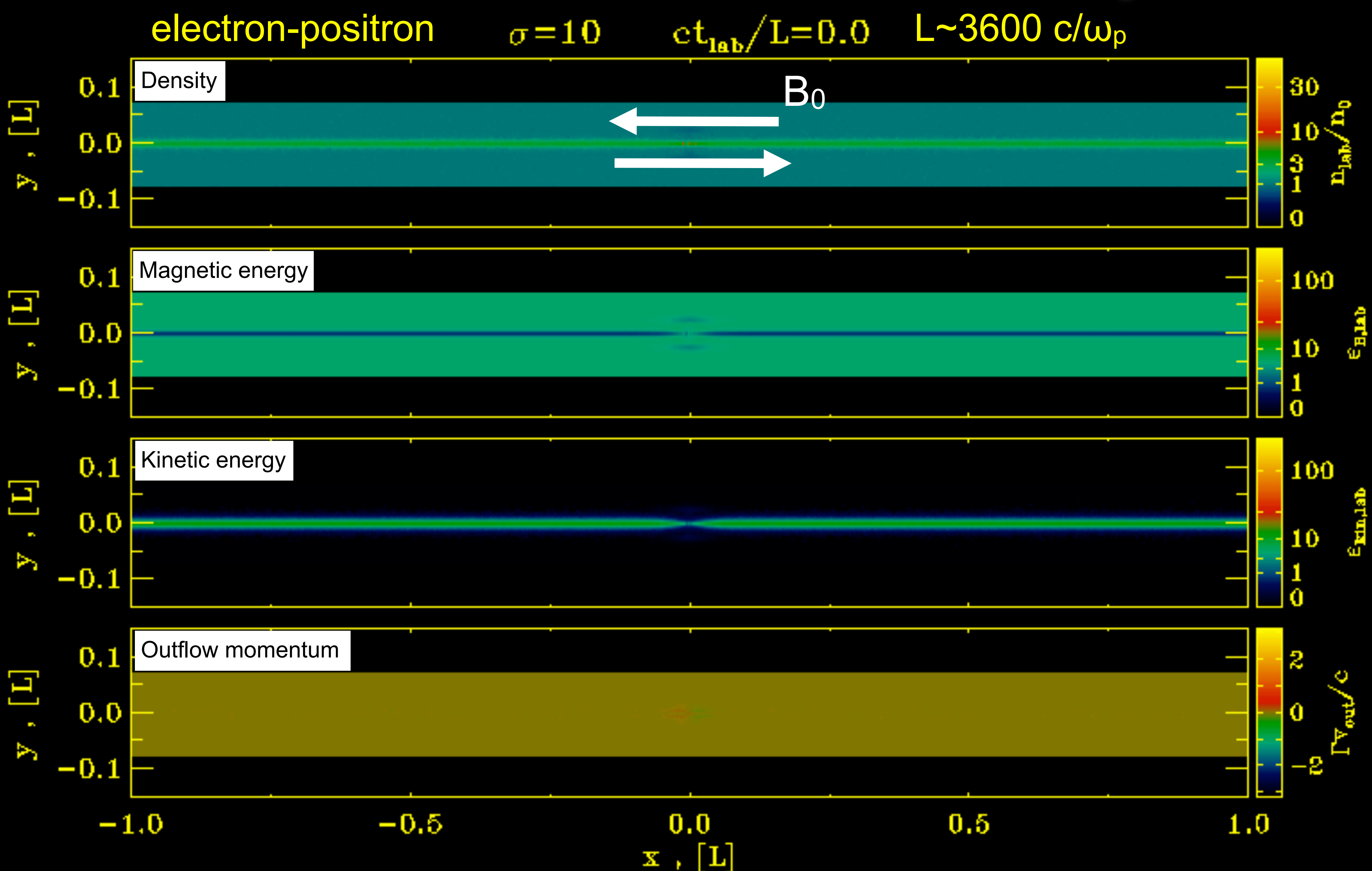


(LS & Spitkovsky 14)

- 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

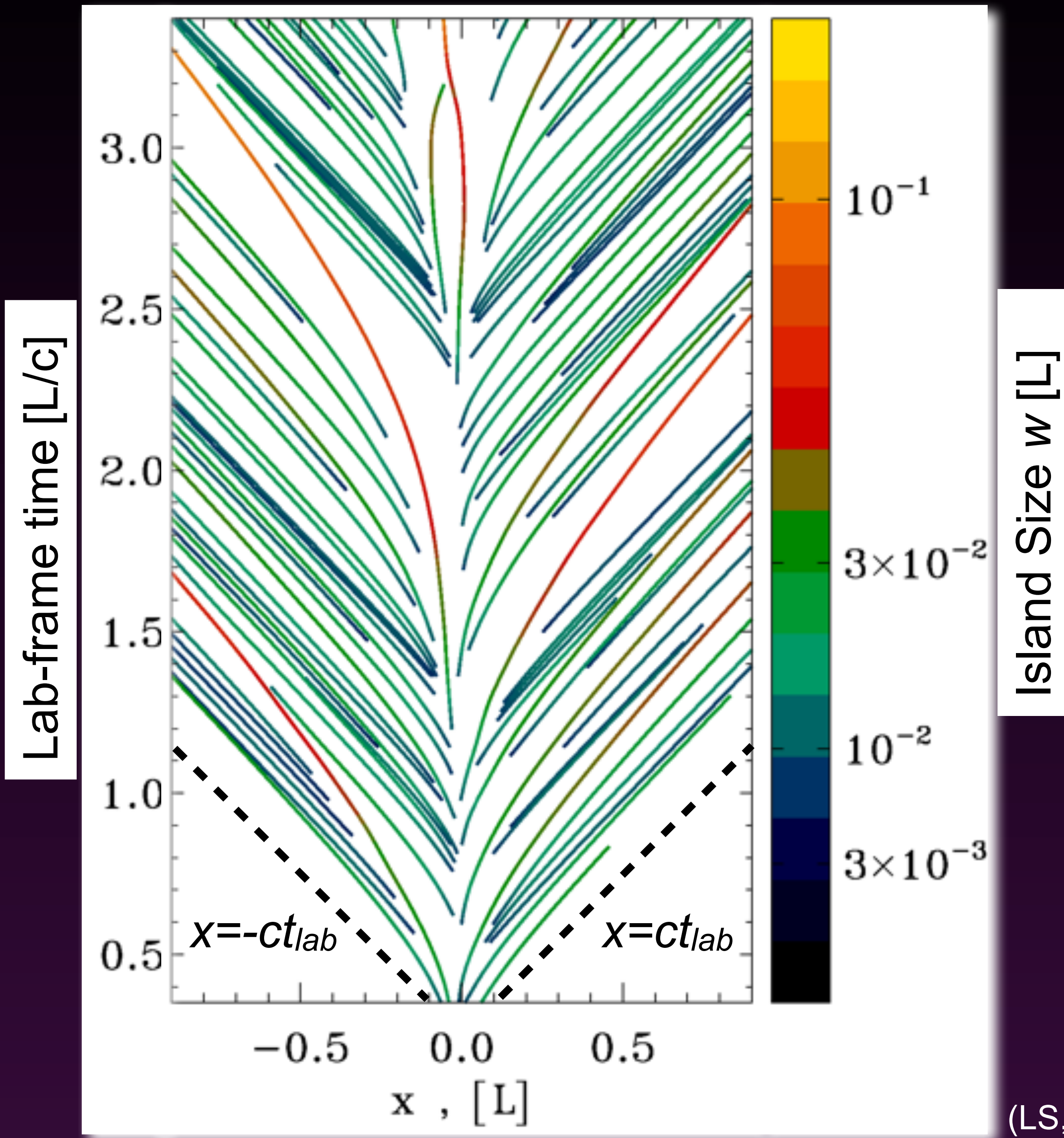


- the plasmoids/magnetic islands are over-dense, by a factor of a few.
- they are in rough equipartition of magnetic and kinetic energy.
- they move outwards at ultra-relativistic speeds.

(LS, Giannios & Petropoulou, on arXiv tonight)

Plasmoid space-time tracks

σ=10   L~3600 c/ω_p electron-positron



We can follow individual plasmoids in space and time.

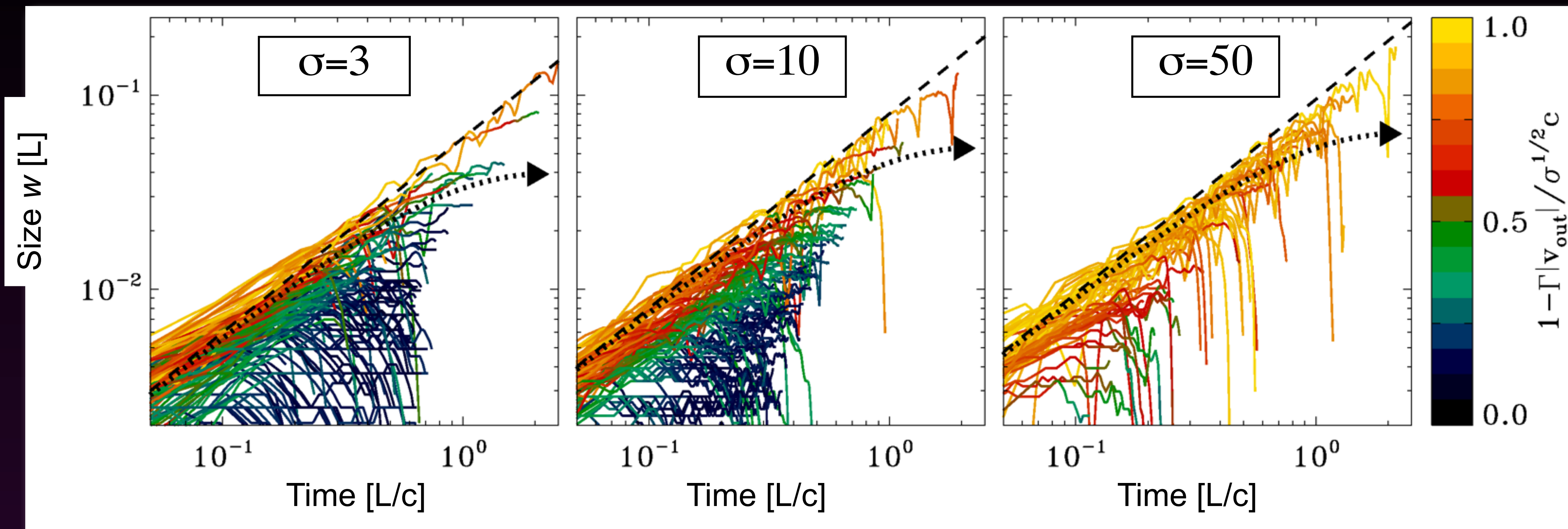
First they grow, then they go:

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

(LS, Giannios & Petropoulou, on arXiv tonight)

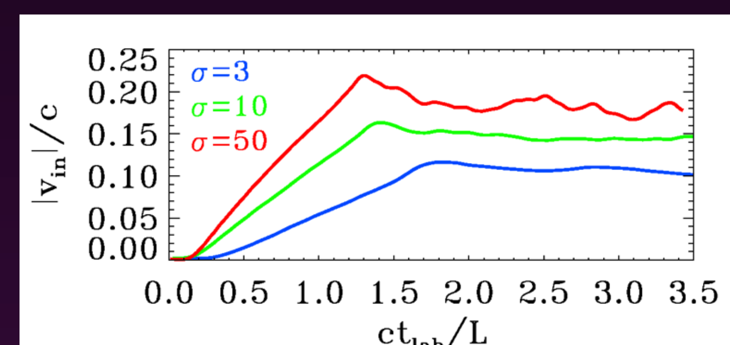
First they grow

• The plasmoid size *w* grows in the plasmoid rest-frame at a constant rate of ~0.1 c (dashed black lines), with weak dependence on magnetization.



(LS, Giannios & Petropoulou 16)

• The weak dependence of the growth rate on σ is consistent with the weak dependence on σ of the reconnection rate/inflow speed.

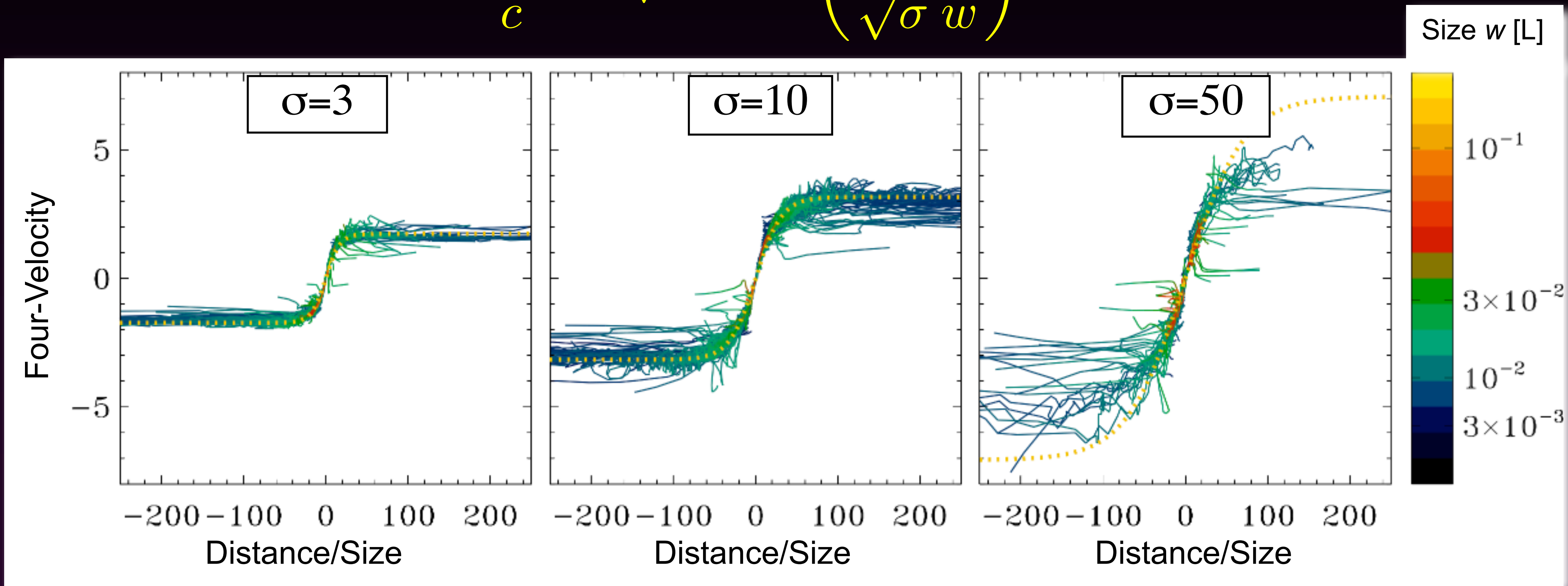


• The growth terminates when the plasmoid approaches the Alfven speed (or equivalently, its four-velocity approaches ~$\sqrt{\sigma}\,c$).

Then they go

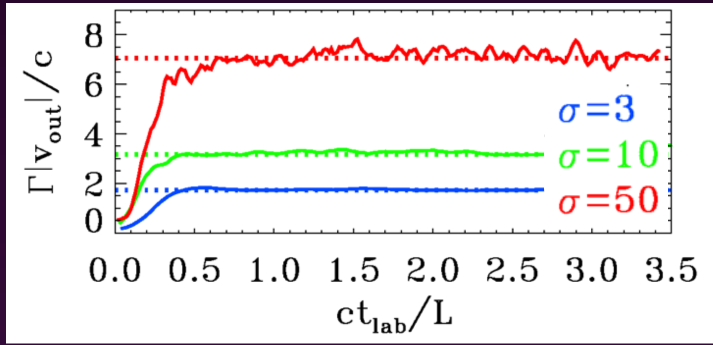
• After growing, the plasmoids are accelerated by the field line tension with a universal acceleration profile (dotted yellow lines):

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



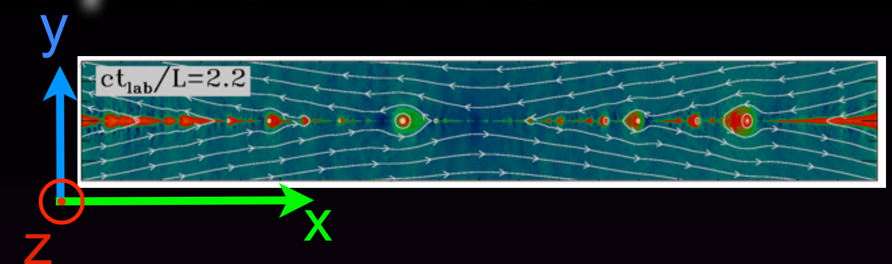
(LS, Giannios & Petropoulou 16)

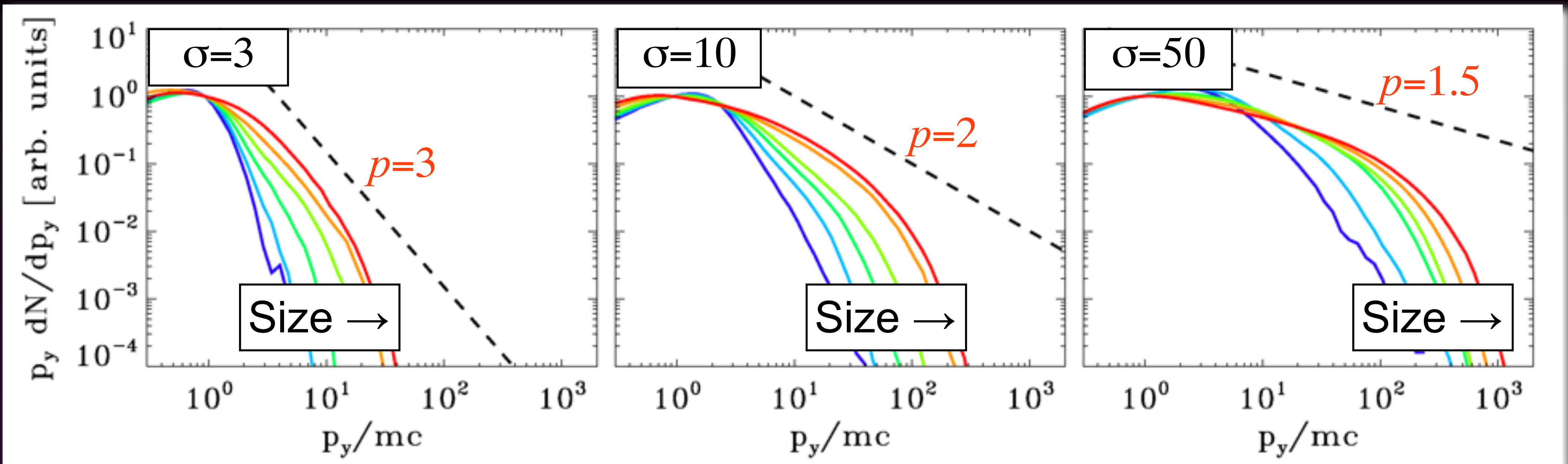
• The "target" four-velocity is always ~√σ c, as expected for the fastest regions of the outflow (Lyubarsky 2005).



Particle spectrum in plasmoids

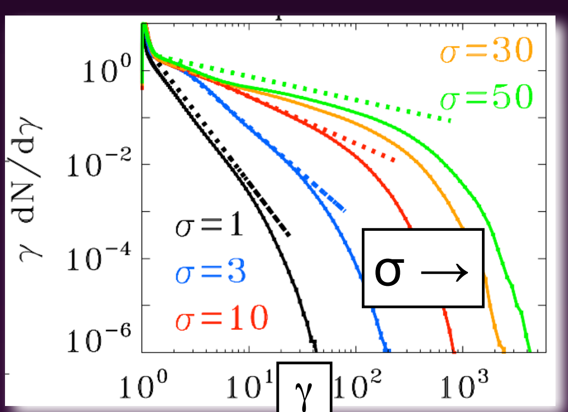
Comoving momentum spectrum in the *y* direction
(i.e., transverse to the current sheet)





• The upper cutoff in momentum corresponds to a Larmor radius $r_{0y,\mathrm{cut}} \sim 0.2\, w$ regardless of the magnetization (a *confinement criterion*)

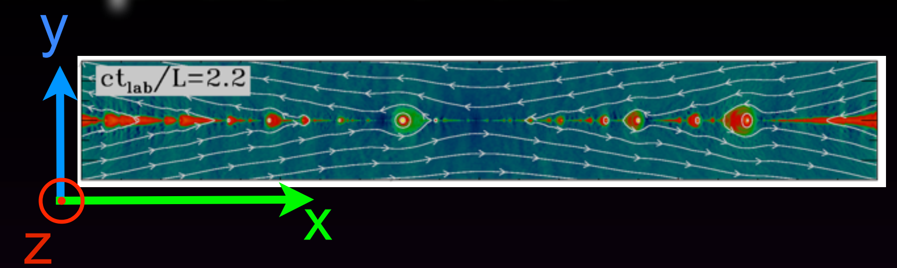
• The spectrum of large islands has the same slope as the overall spectrum from the layer.

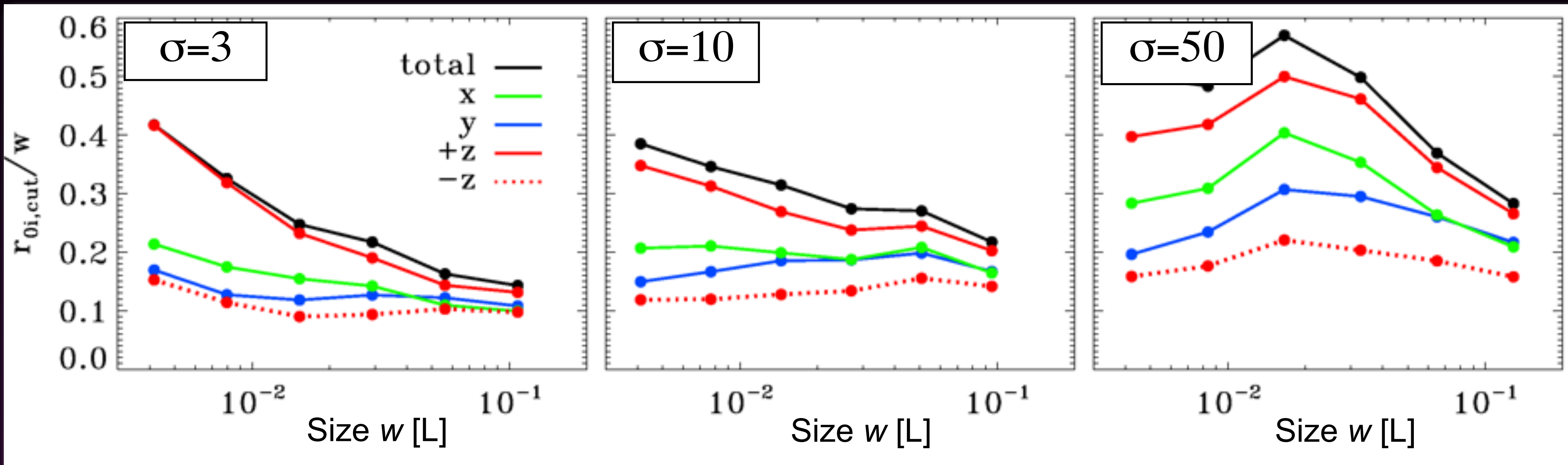


(LS & Spitkovsky 14, see also Guo+ 14,15, Werner+ 16)

Particle anisotropy in plasmoids

Larmor radius at the comoving positron cutoff momentum in different directions

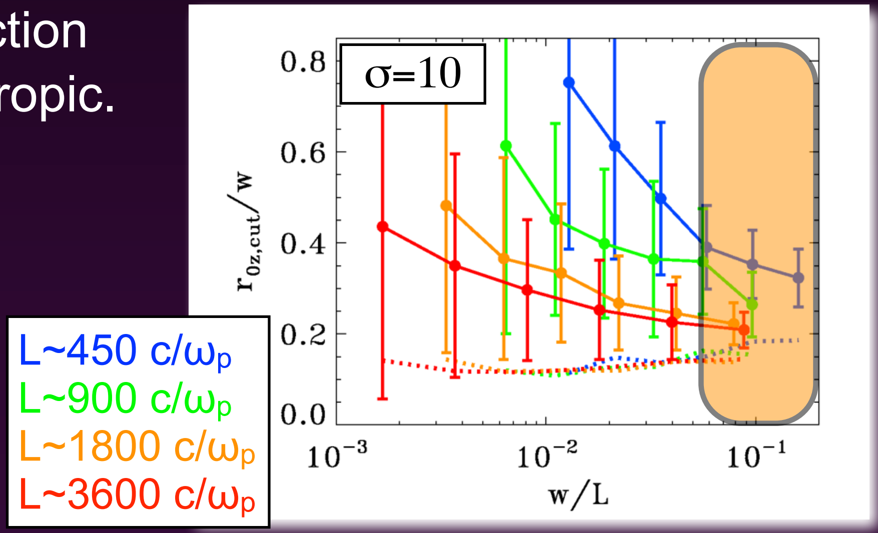




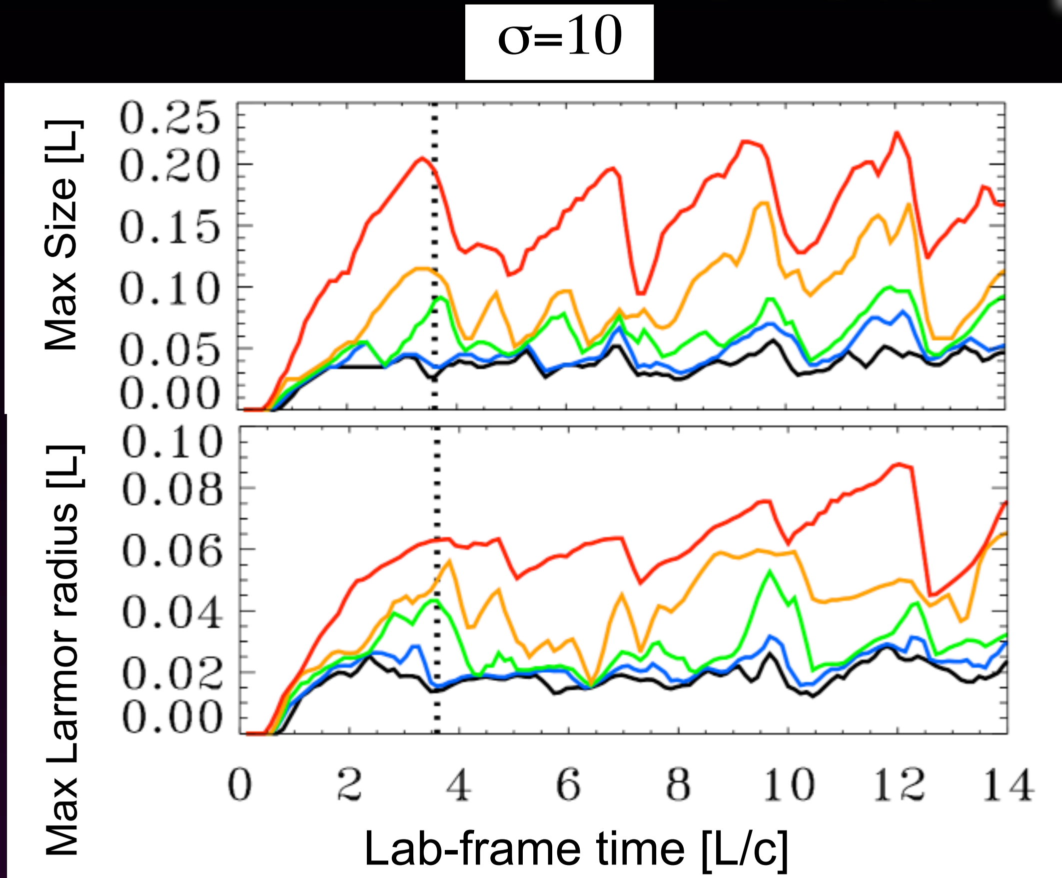
- Small islands show *z* anisotropy along the reconnection electric field at X-points. Large islands are nearly isotropic.

- By balancing the max energy from X-point acceleration with the max energy from island mergers, the transition should occur at

$$w \sim 50\sqrt{\sigma}\, c/\omega_p$$



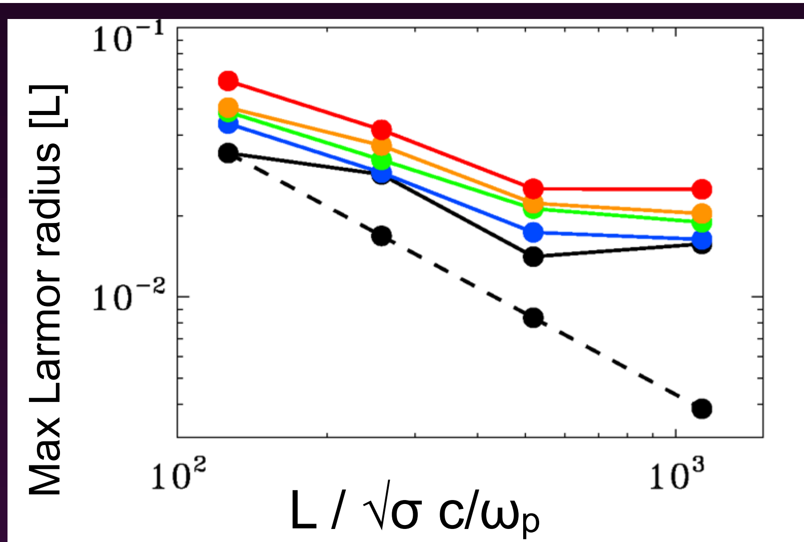
“Monster” plasmoids



“Monster” plasmoids (Uzdensky+10):

- they can reach a size of ~ 0.2 L (regardless of L) and their typical recurrence time is ~ 2.5 L/c.

- the monster plasmoids contain the highest energy particles, with a Larmor radius approaching ~ 0.05 L (Hillas criterion for relativistic reconnection).



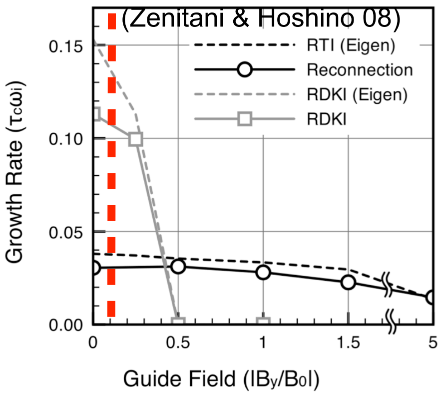
- the linear scaling between max energy and system length L can be probed only with simulations having $L \gtrsim 300\sqrt{\sigma}\, c/\omega_p$.

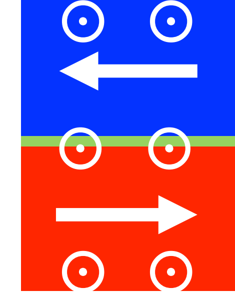
(LS, Giannios & Petropoulou 16)

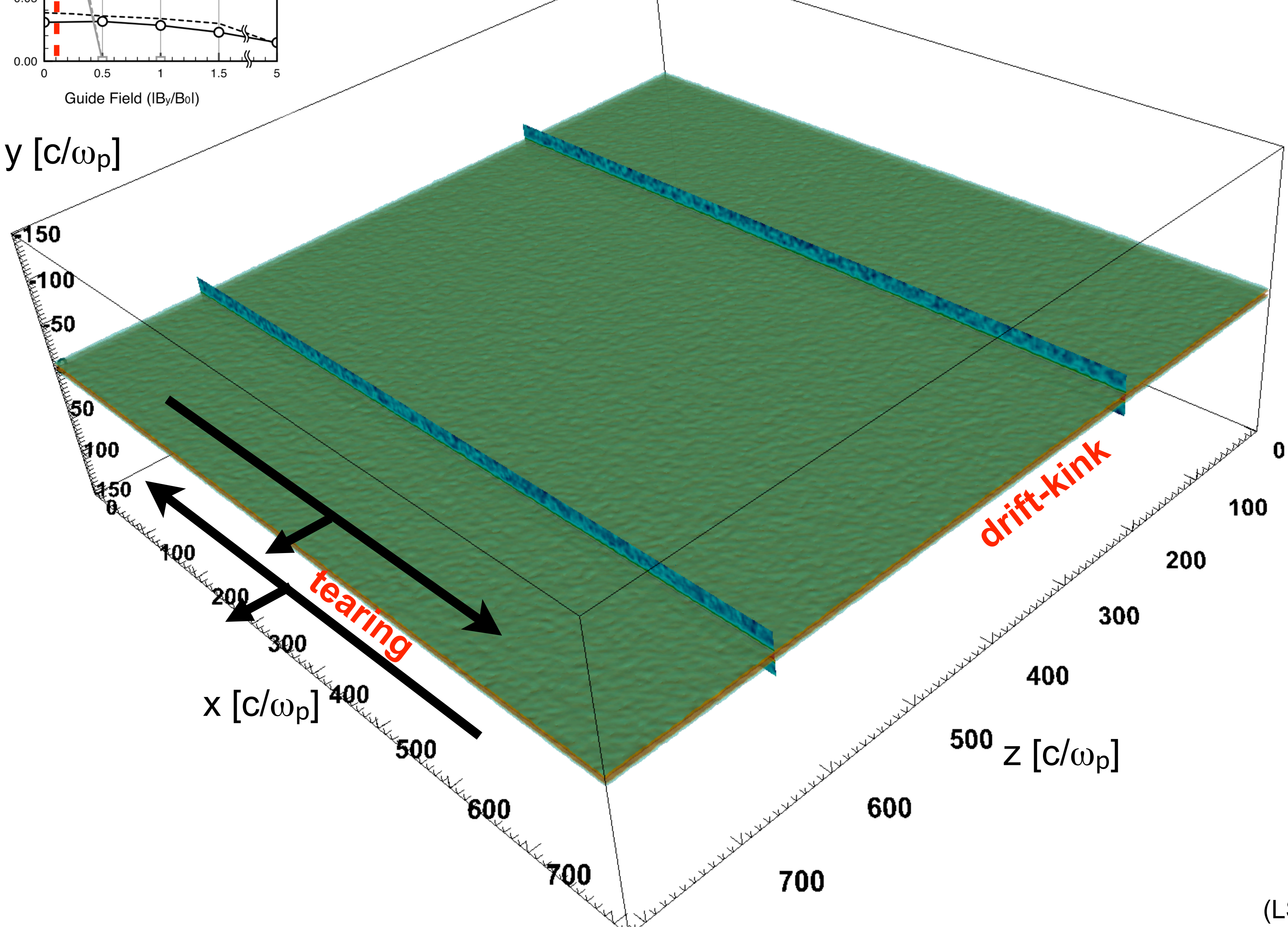
Dependence on the guide field

$\sigma=10 \quad B_g/B_0=0.1$

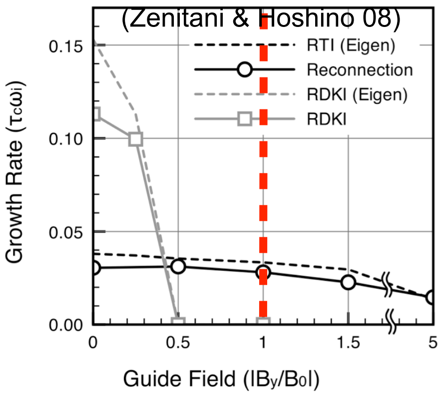
Density





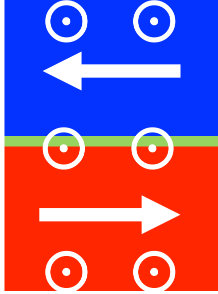


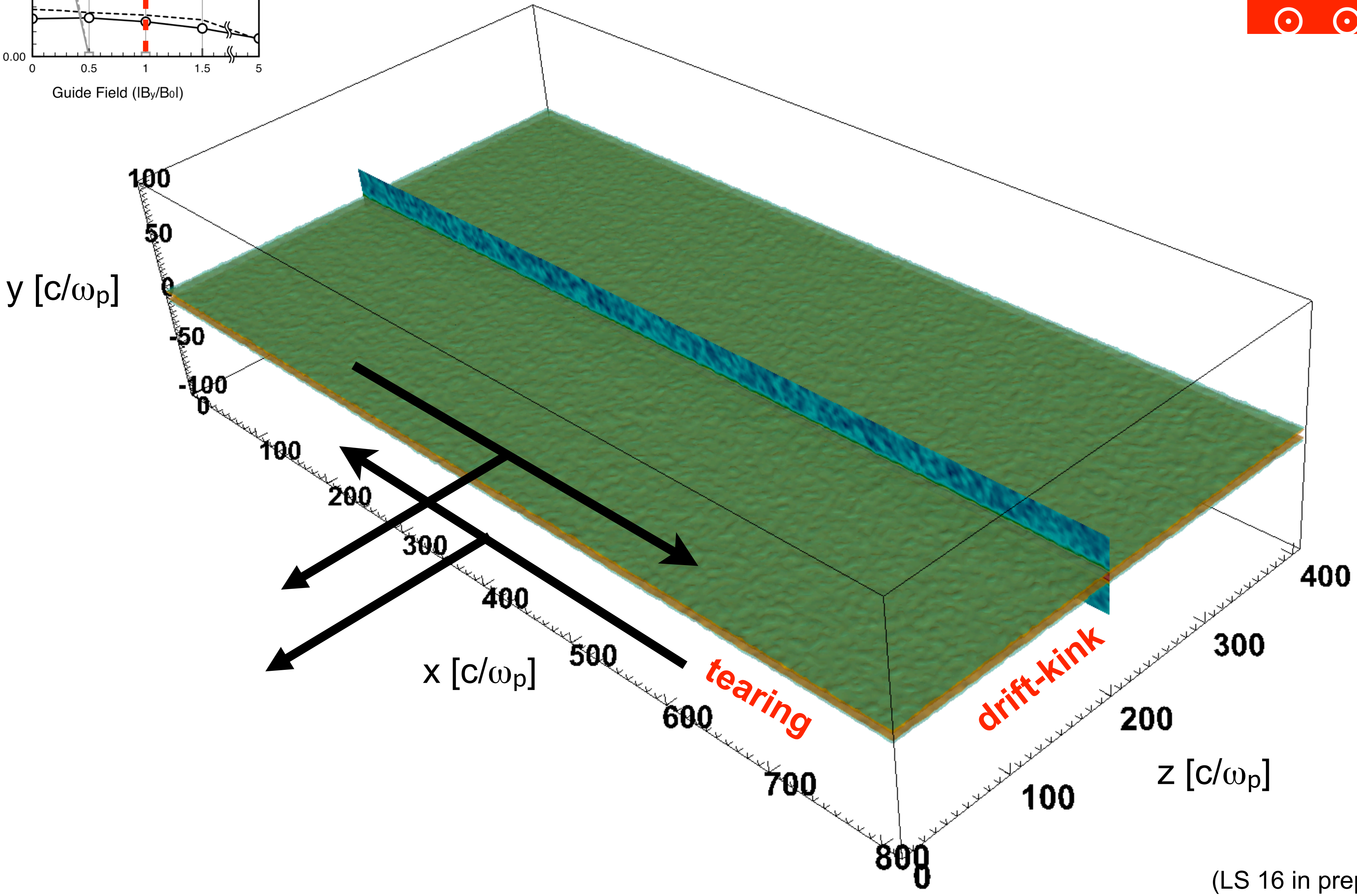
(LS 16 in prep)



σ=10 B_g/B_0=1.0

Density





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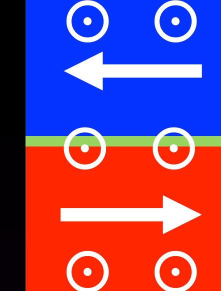
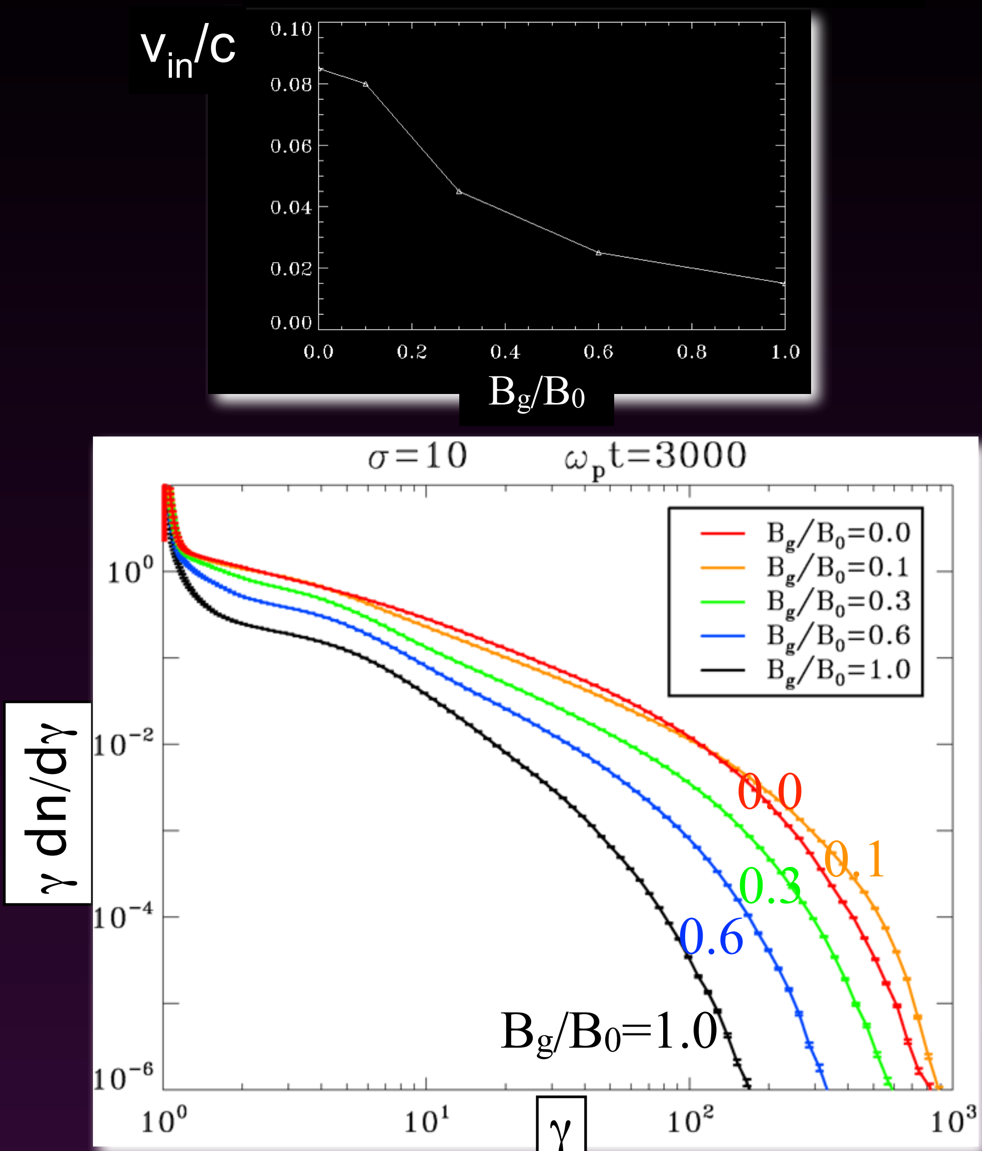
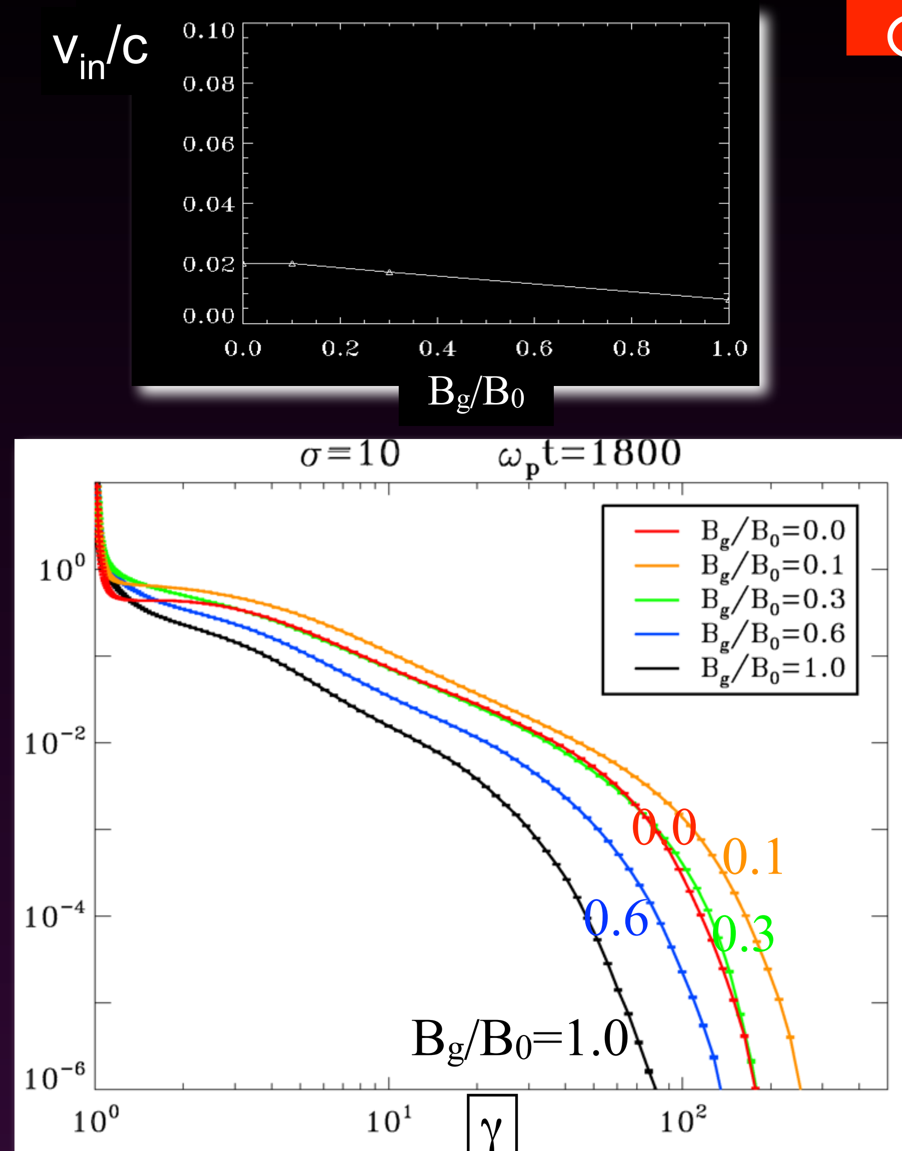


2D $\sigma=10$ electron-positron

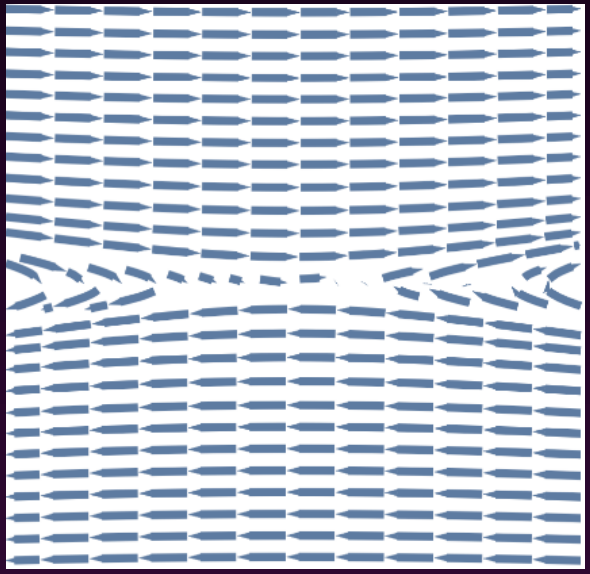


3D $\sigma=10$ electron-positron



For stronger guide fields, the normalization and the maximum energy are smaller, because the reconnection electric field (and so, the reconnection rate) are smaller.

Explosive relativistic reconnection



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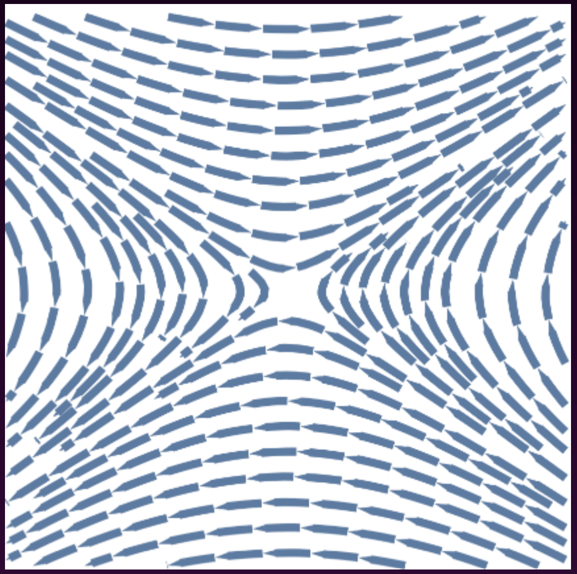
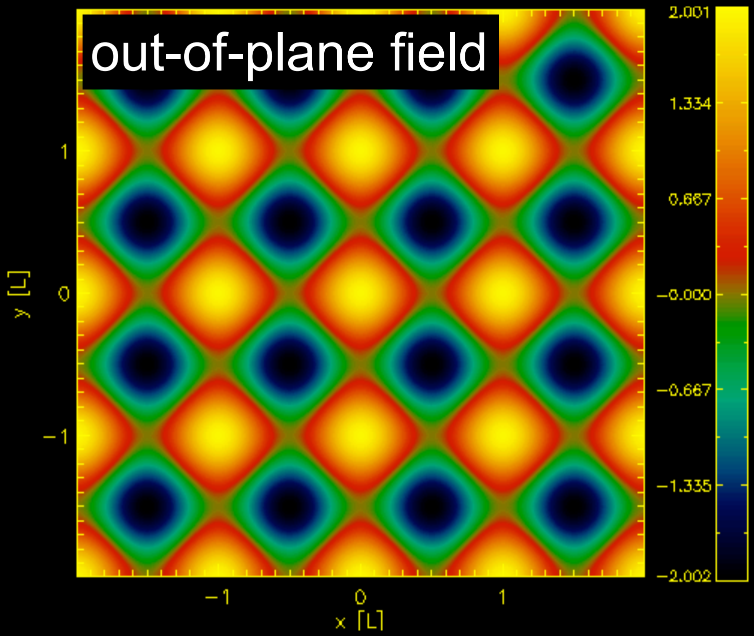


The ABC of explosive particle acceleration

σ_{in}=42 L=800 c/ω_p kT/mc^2=100



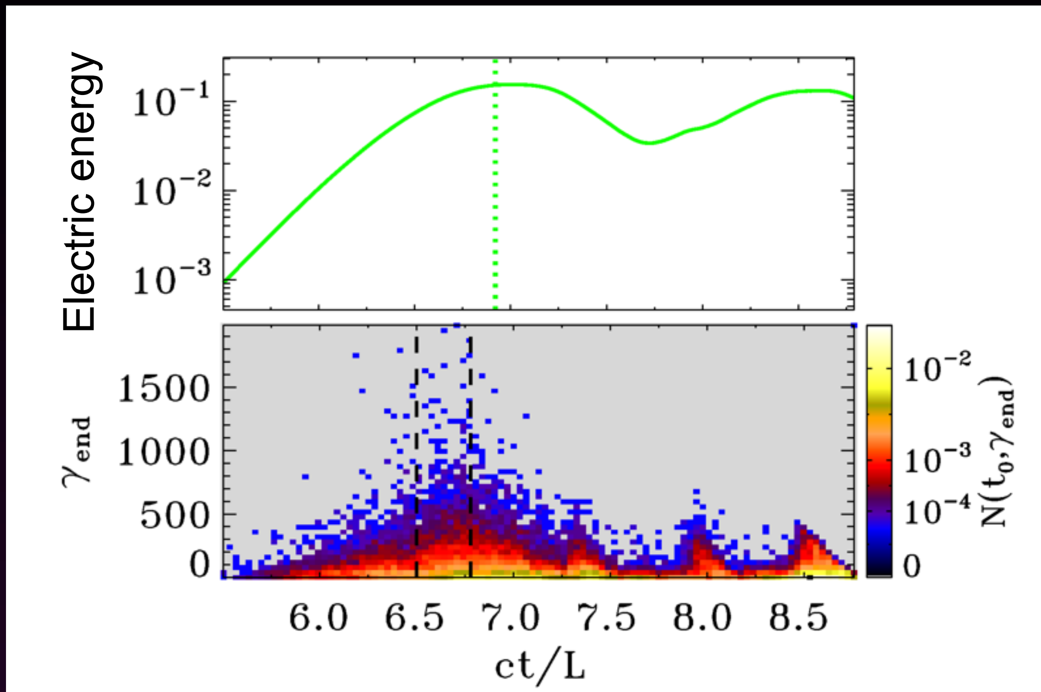
ABC structures: idealized force-free geometries

- Stable for ~ 5 L/c, where L is the island size.
- Explosive evolution on dynamical timescales (~ L/c).

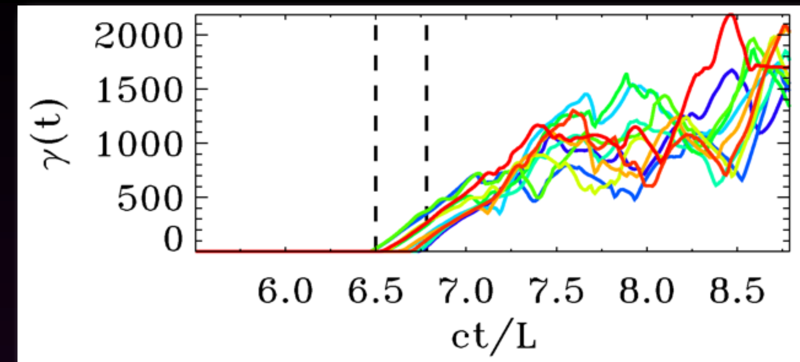
(Lyutikov, LS, Komissarov & Porth 16)

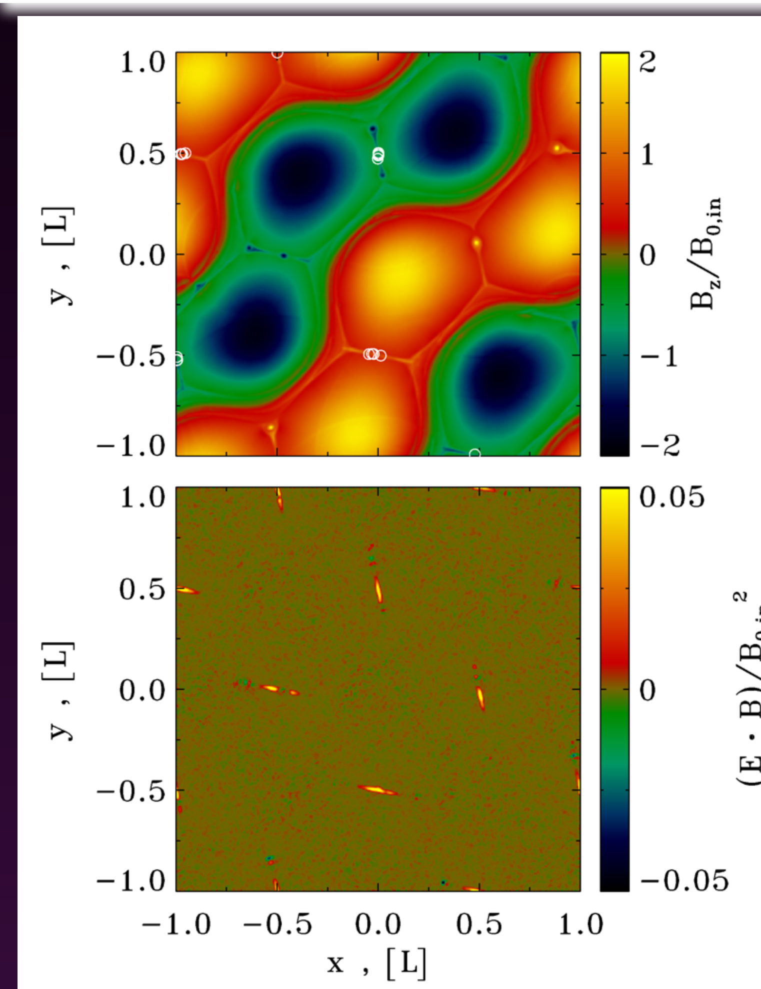
Mechanism of particle acceleration

σ_{in}=42 L=800 c/ω_p kT/mc^2=cold



(Lyutikov, LS, Komissarov & Porth 16)





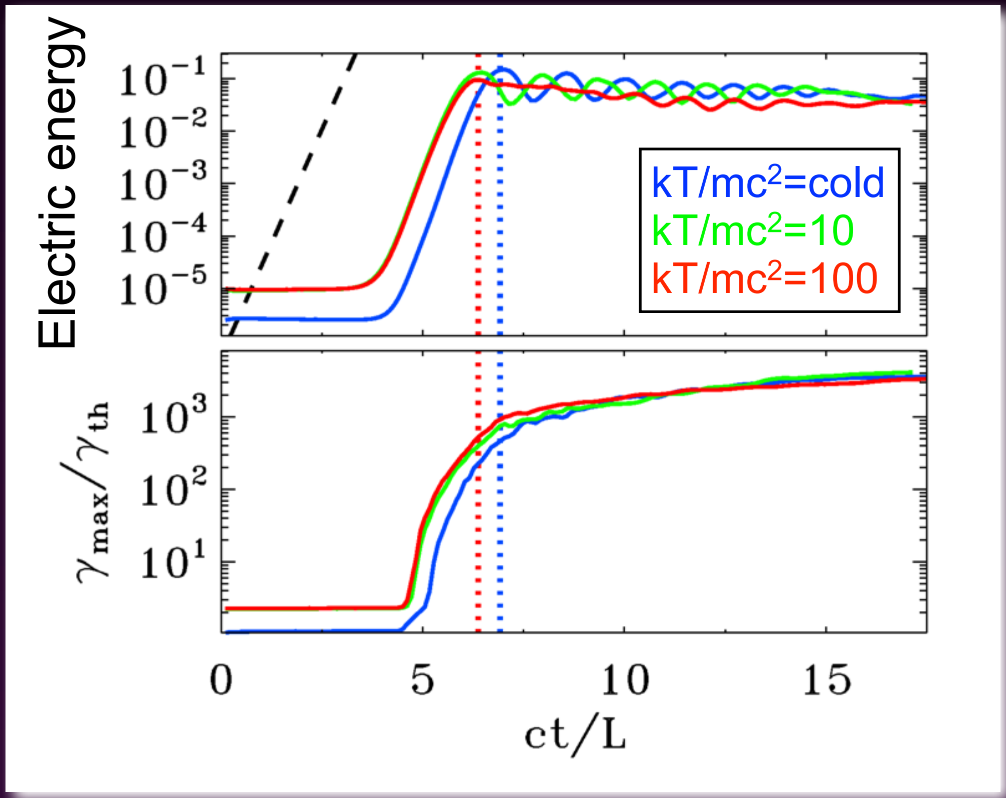
- Most of the particles that will reach high energies are injected near the most violent phase of evolution.

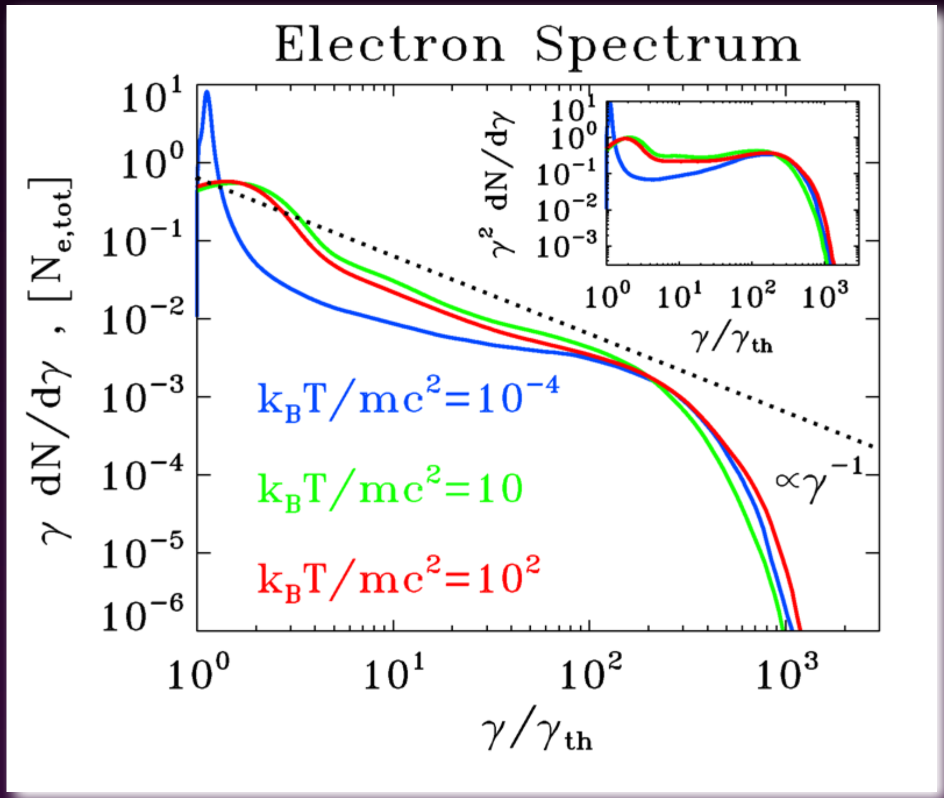
- Particle injection happens in regions where E·B≠0, and particle acceleration is governed by the reconnection electric field.

Dependence on the ABC parameters

- The onset of the instability always happens at ~ 5 L/c.
- The shape of the particle spectrum is independent of kT/mc^2, provided σ is defined with the enthalpy and L is the same in units of the plasma skin depths.

$\sigma_{in}=42$ $L=800\ c/\omega_p$





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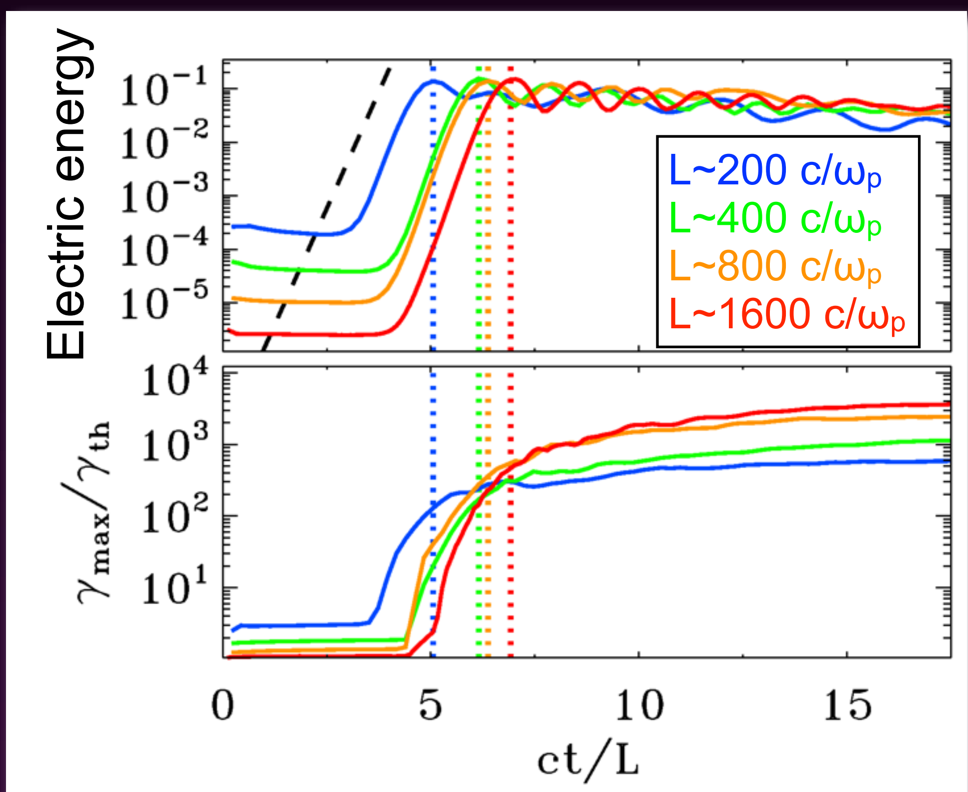
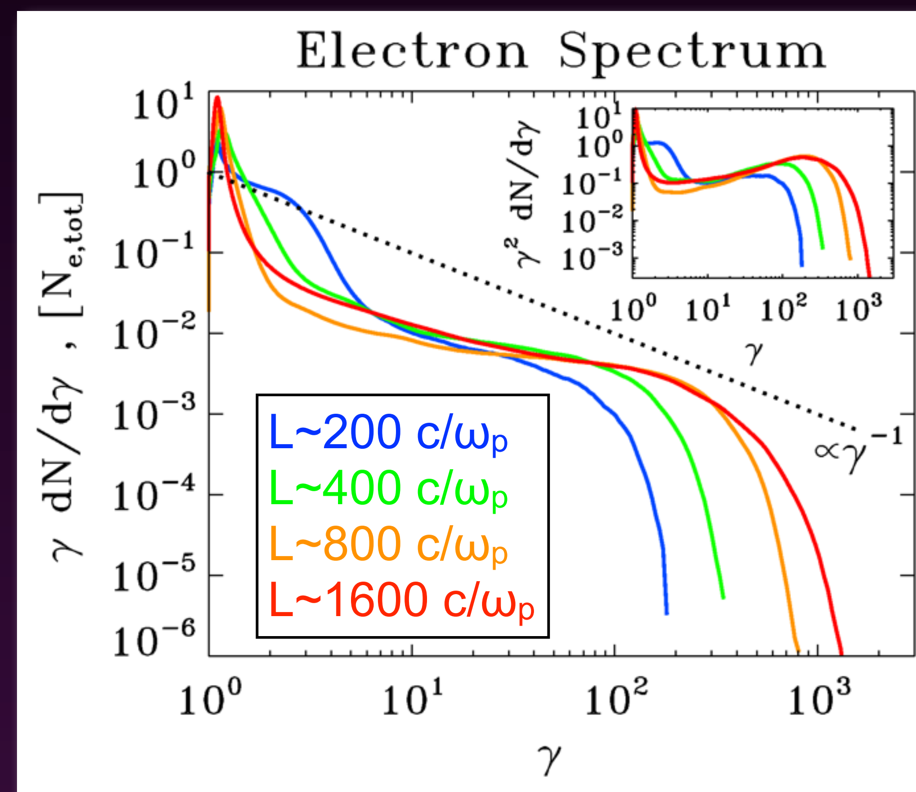
- The shape of the particle spectrum is independent of kT/mc^2, provided σ is defined with the enthalpy and L is the same in units of the plasma skin depths.
- High energy cutoff grows linearly with L, if kT/mc^2 and σ are fixed.

σ_{in}=42 kT/mc^2=cold

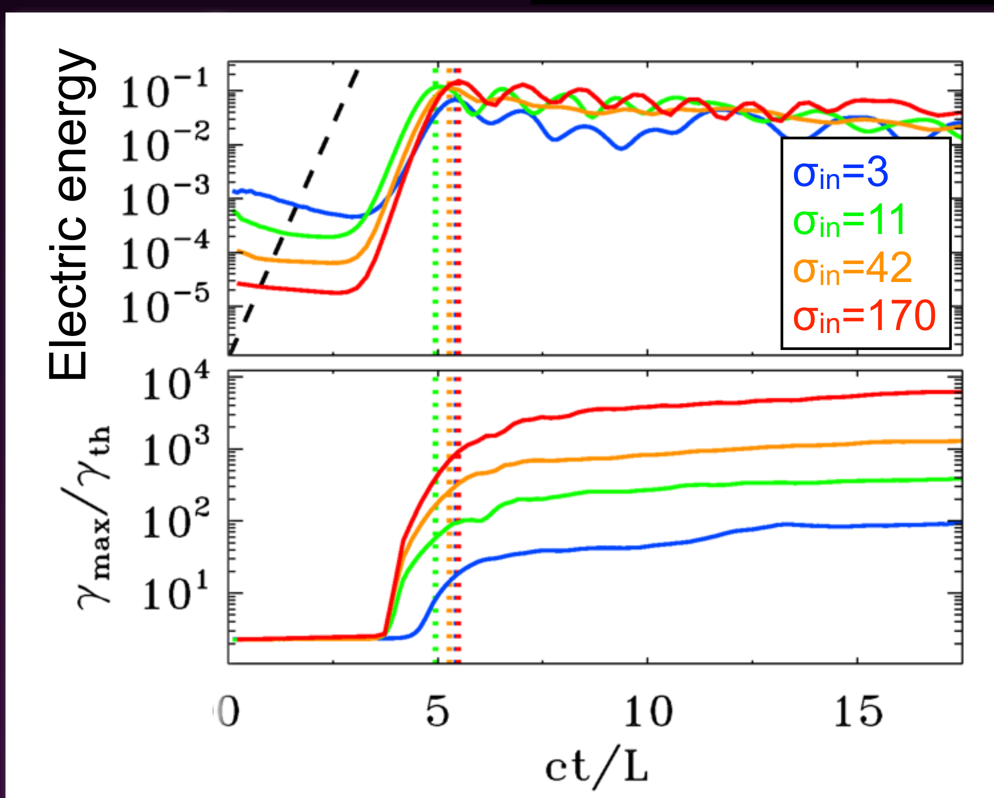


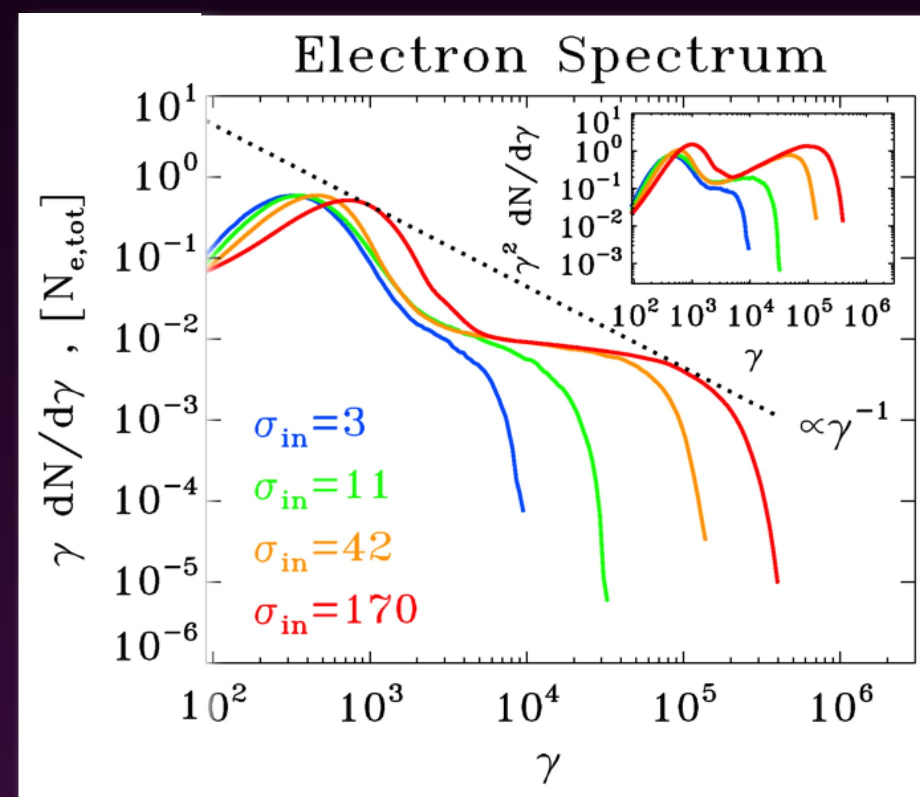


Dependence on the ABC parameters

- The onset of the instability always happens at ~ 5 L/c.
- The shape of the particle spectrum is independent of kT/mc^2, provided σ is defined with the enthalpy and L is the same in units of the plasma skin depths.
- High energy cutoff grows linearly with L, if kT/mc^2 and σ are fixed.
- Harder spectra for higher σ, if kT/mc^2 and $L/\sigma^{1/2}$ are fixed.

$L/\sigma_{in}^{1/2}=63\ c/\omega_p$ $kT/mc^2=100$

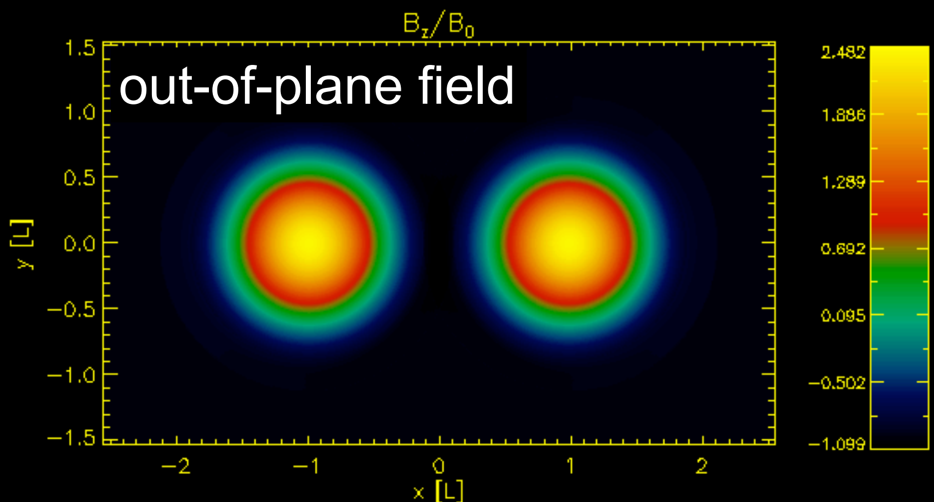


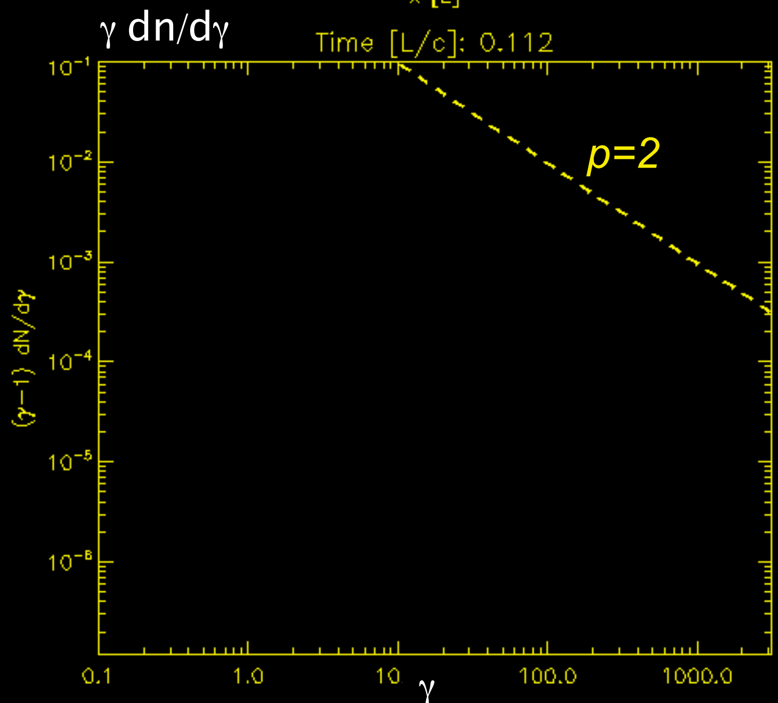


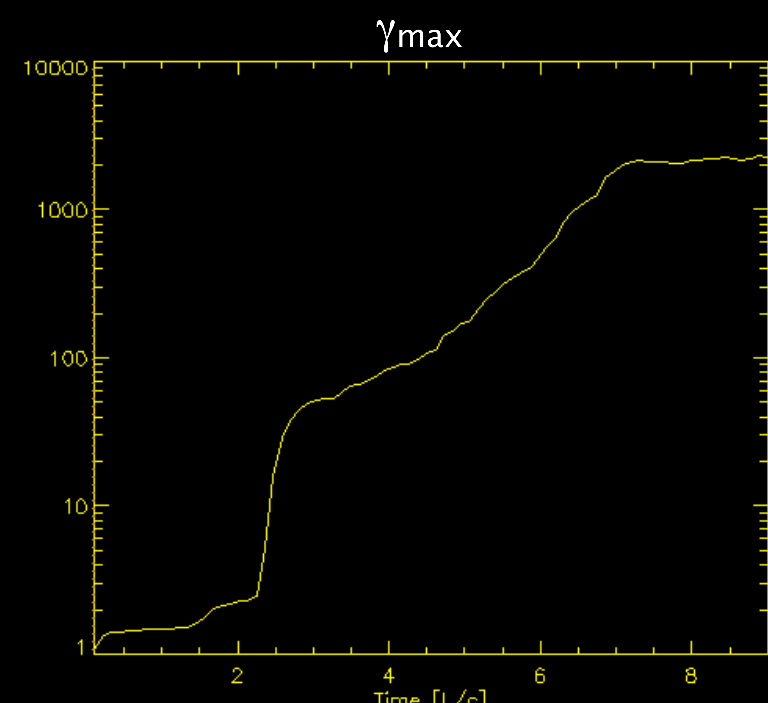
Merger of zero-current flux ropes

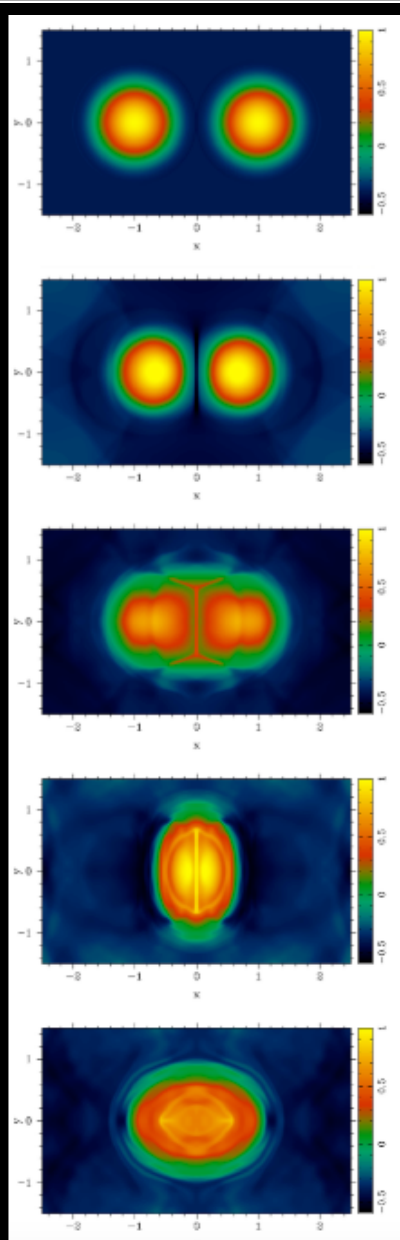
- Flux ropes are pushed together by hand, “eroding” the envelopes.
- Then, parallel currents are exposed, and they attract explosively.

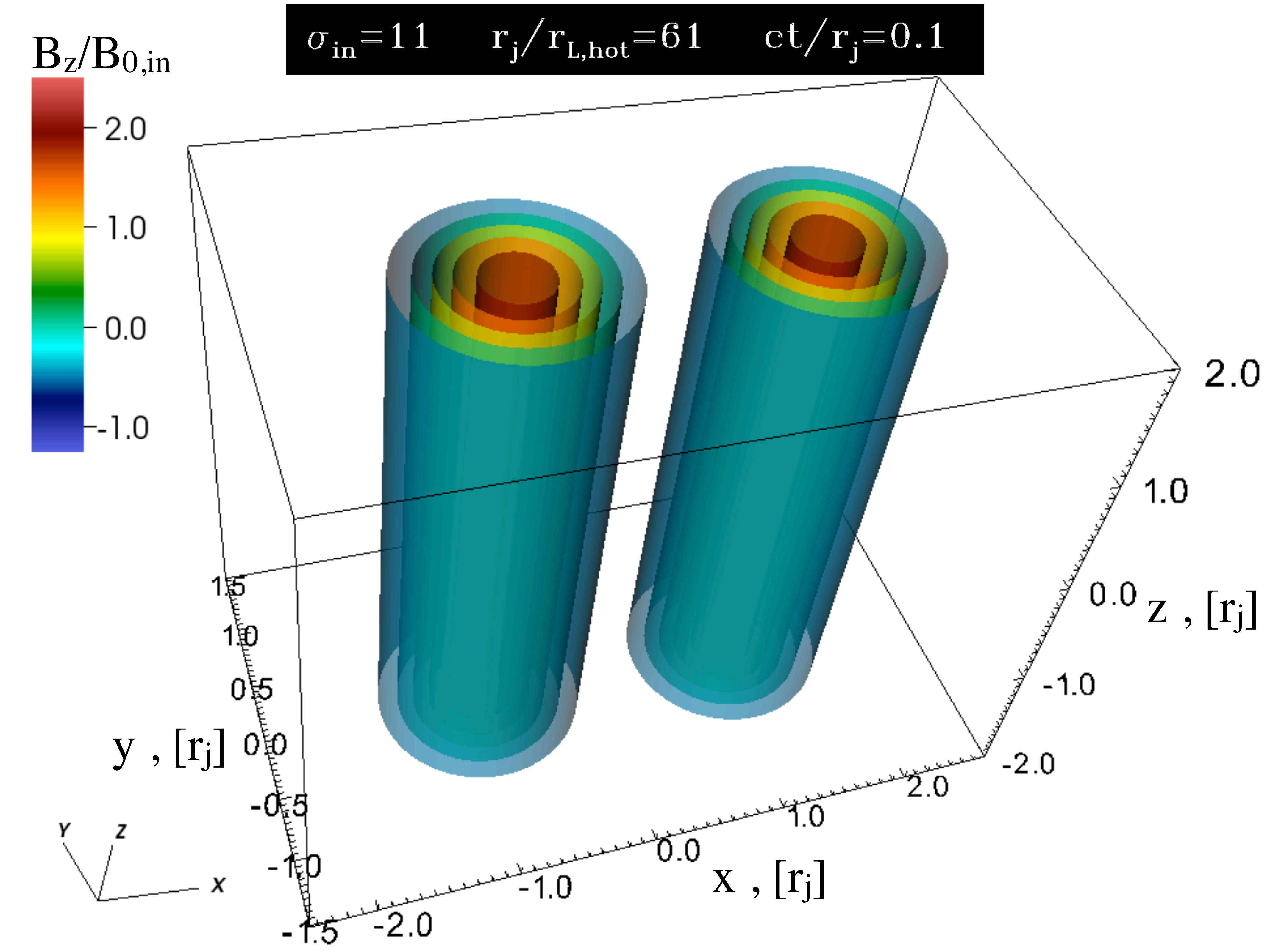
force-free simulation at time=0, 2, 4, 6, 9





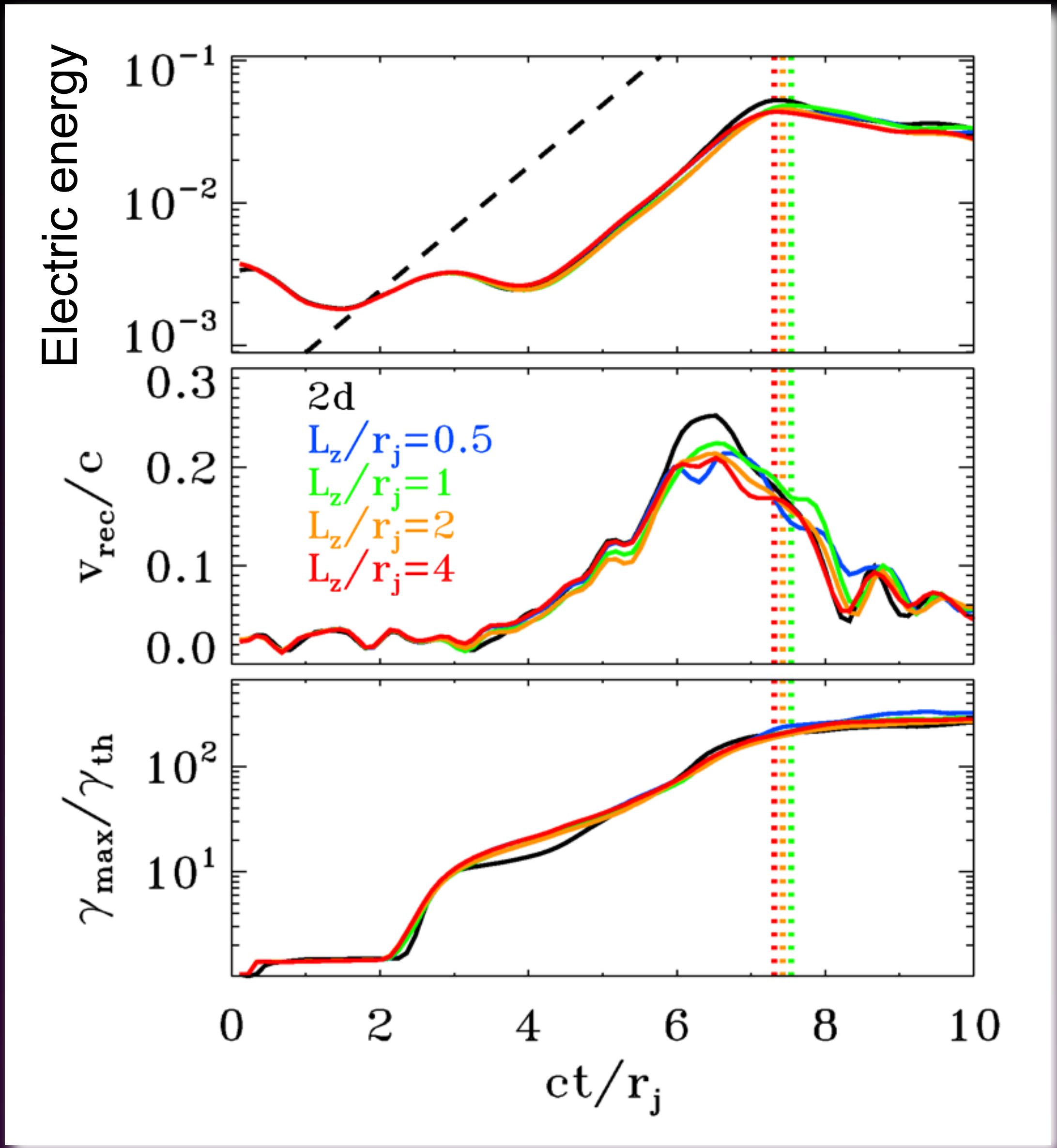


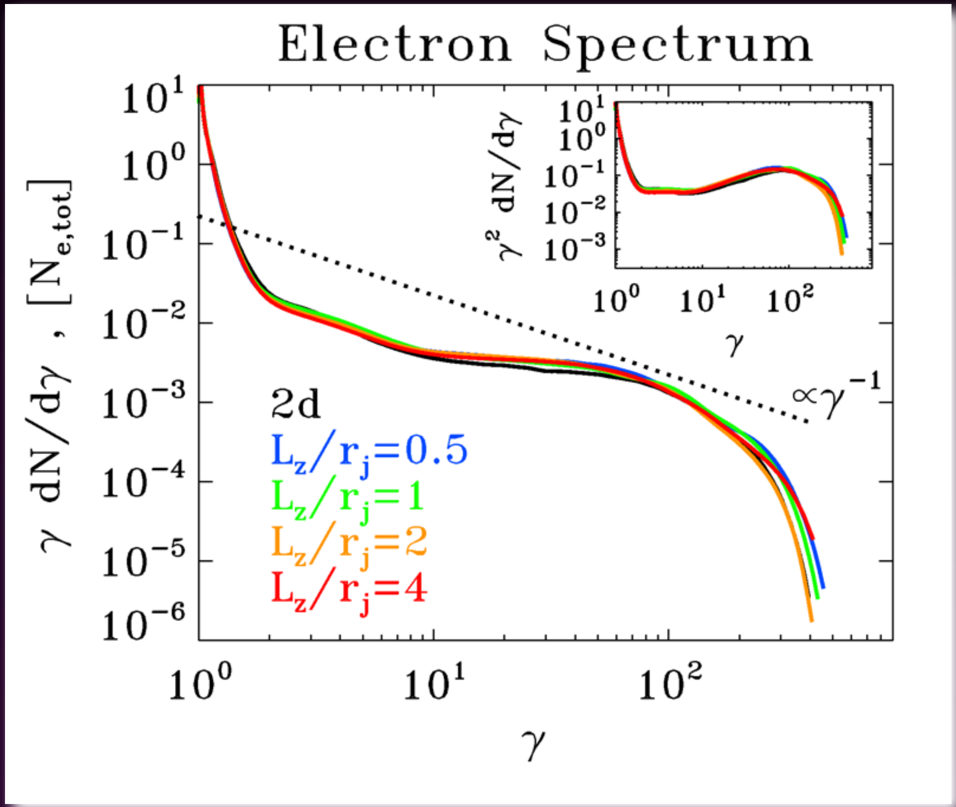




σ_{in}=11 $r_j/r_{L,hot}$=61 ct/r_j=0.1
$B_z/B_{0,in}$
2.0
1.0
0.0
-1.0
x , [r_j]
y , [r_j]
z , [r_j]
-2.0
-1.0
0.0
1.0
2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
-2.0
-1.0
0.0
1.0
2.0

Comparison of 2D and 3D





- The 3D evolution parallels closely the 2D evolution.

Is reconnection the source of high-energy emission in relativistic astrophysical flows?

- Relativistic magnetic reconnection ($\sigma \gtrsim 1$) in pulsar winds and relativistic astrophysical jets 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.

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