Particle Acceleration in Relativistic Magnetic Reconnection

Lorenzo Sironi (Columbia)

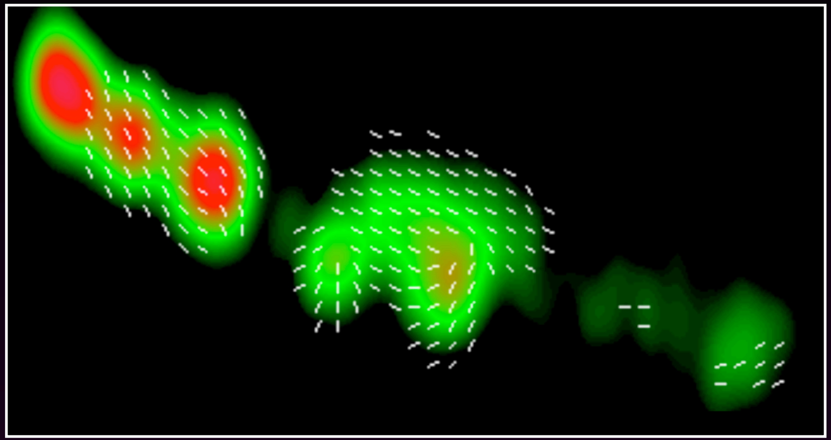
Workshop "Beyond a PeV", IAP, September 14th 2016

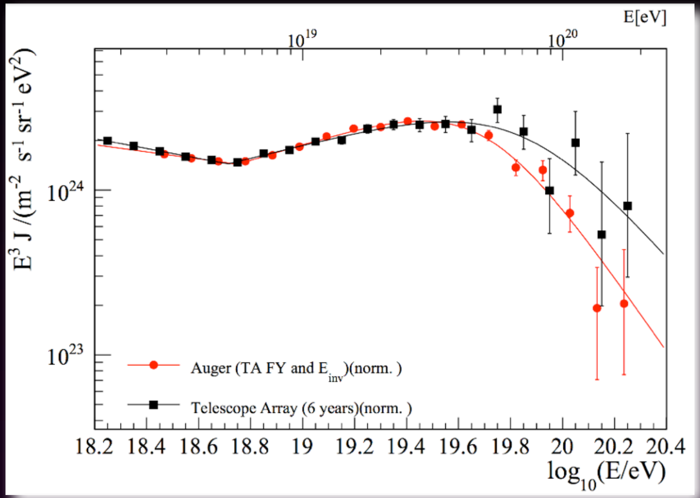
with: Giannios, Komissarov, Lyutikov, Petropoulou, Porth, Spitkovsky

Outline

- Well beyond a PeV:

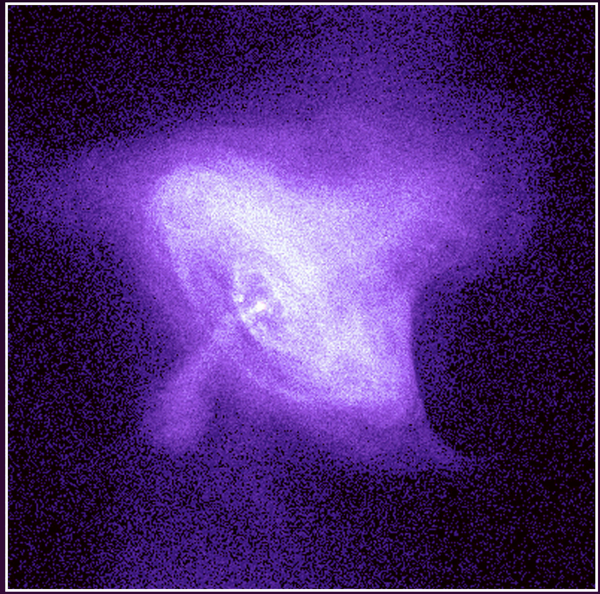
  UHECRs from magnetic reconnection events in blazars.

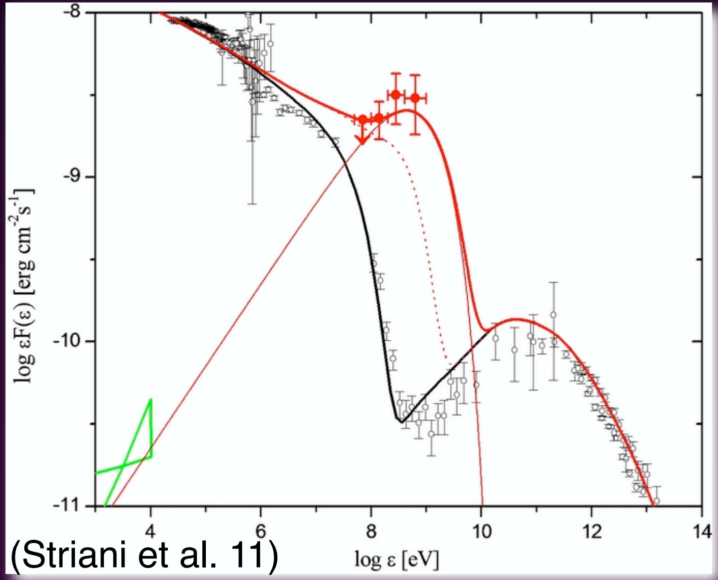




- Slightly above a PeV:

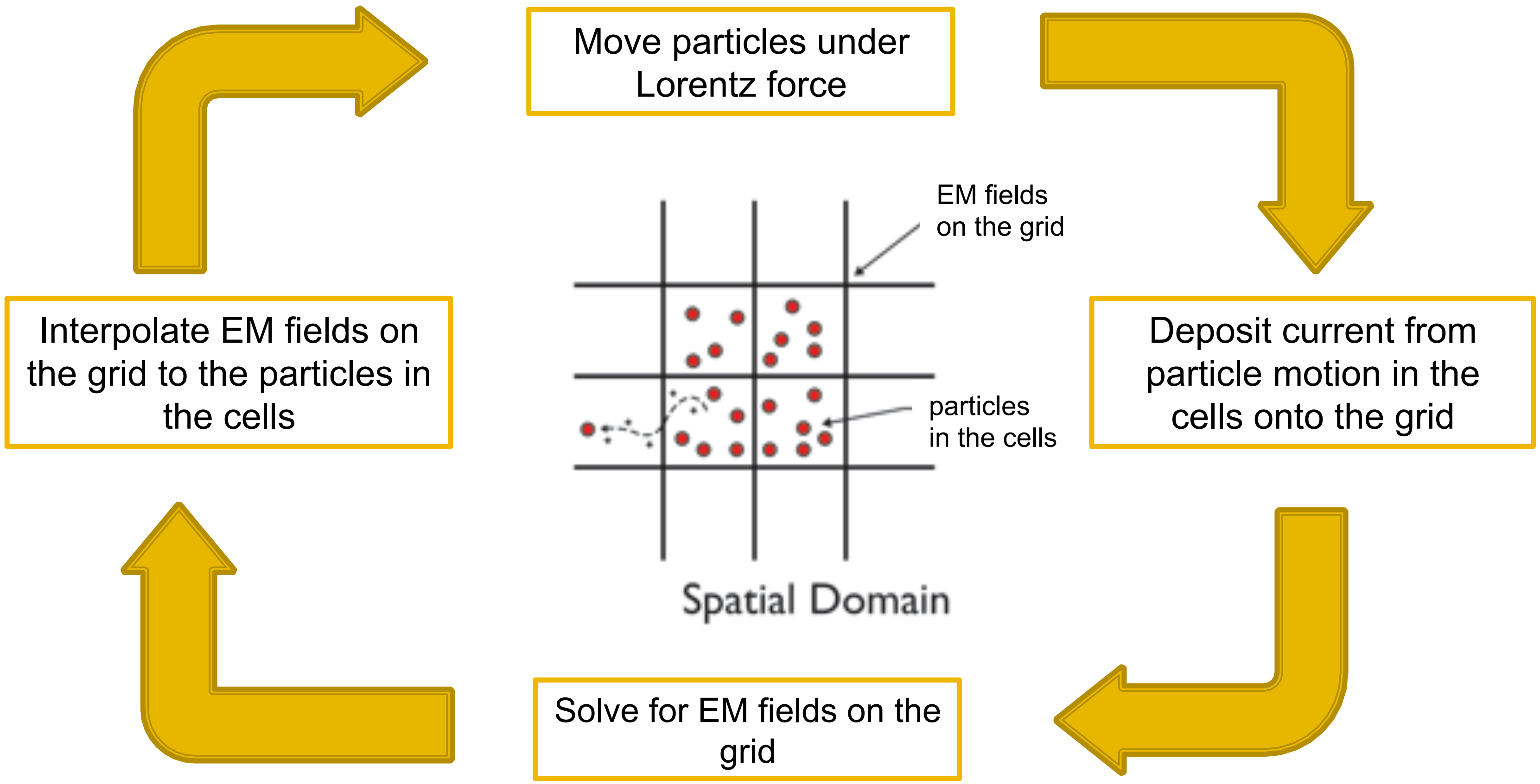
  Explosive reconnection in PWNe and the Crab Nebula gamma-ray flares.





(Striani et al. 11)

The PIC method



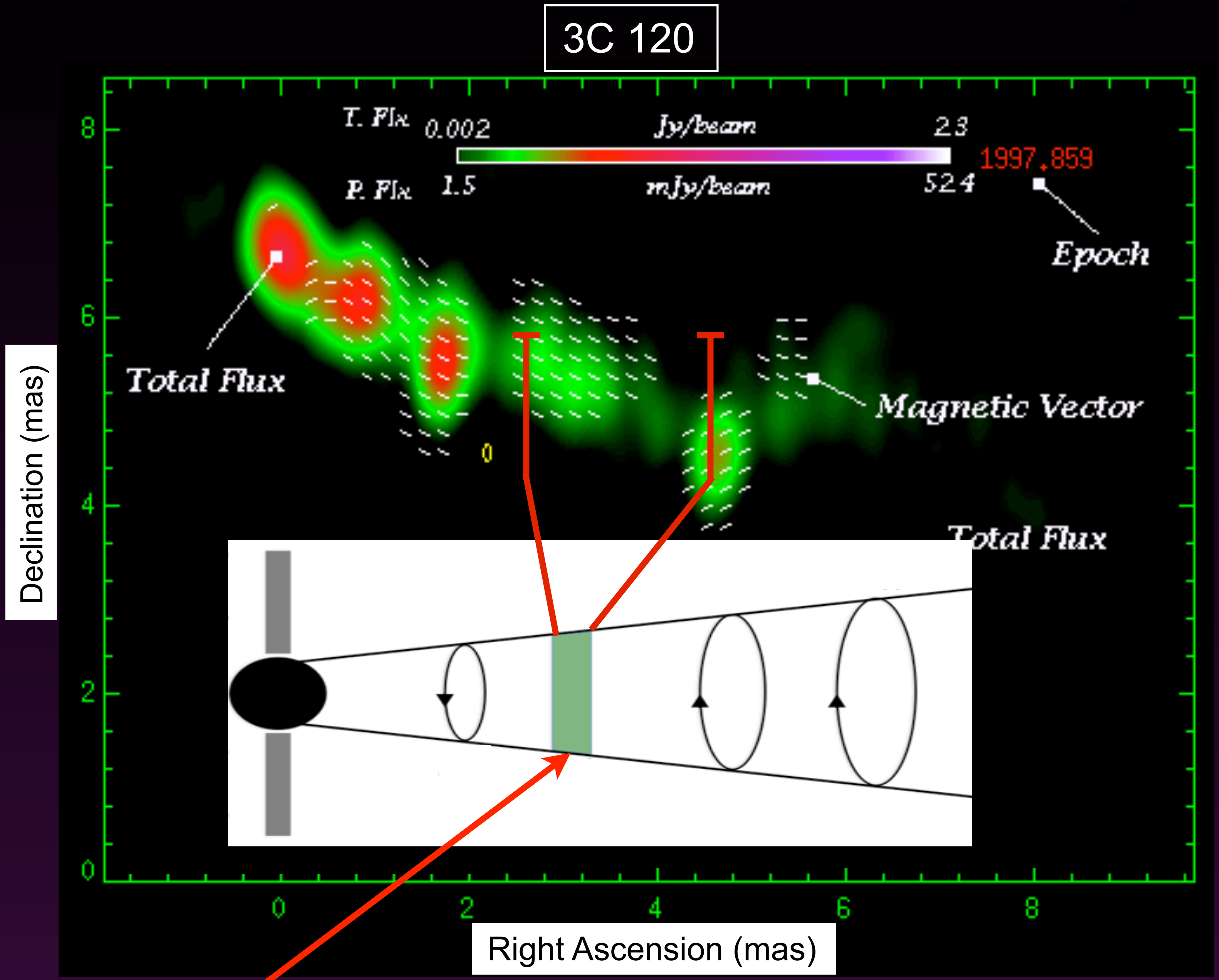
No approximations, full plasma physics of ions and electrons

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

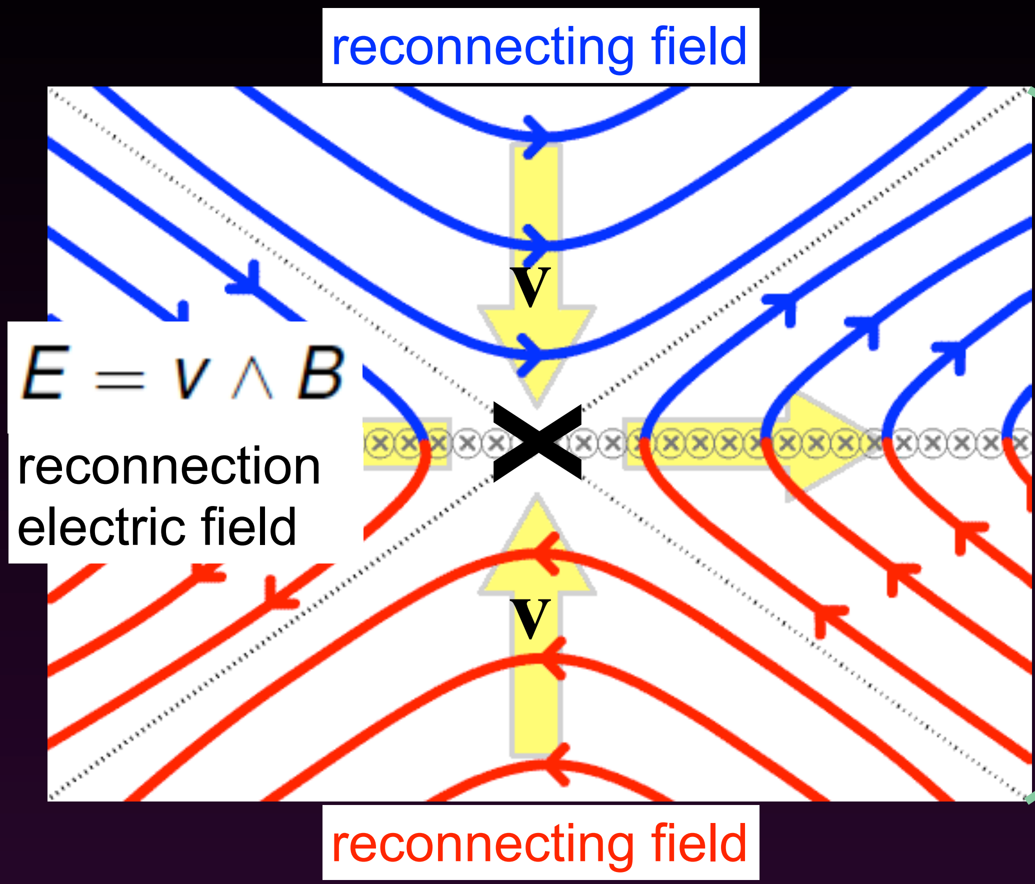
- Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 93, Spitkovsky 05, LS+ 13,14)

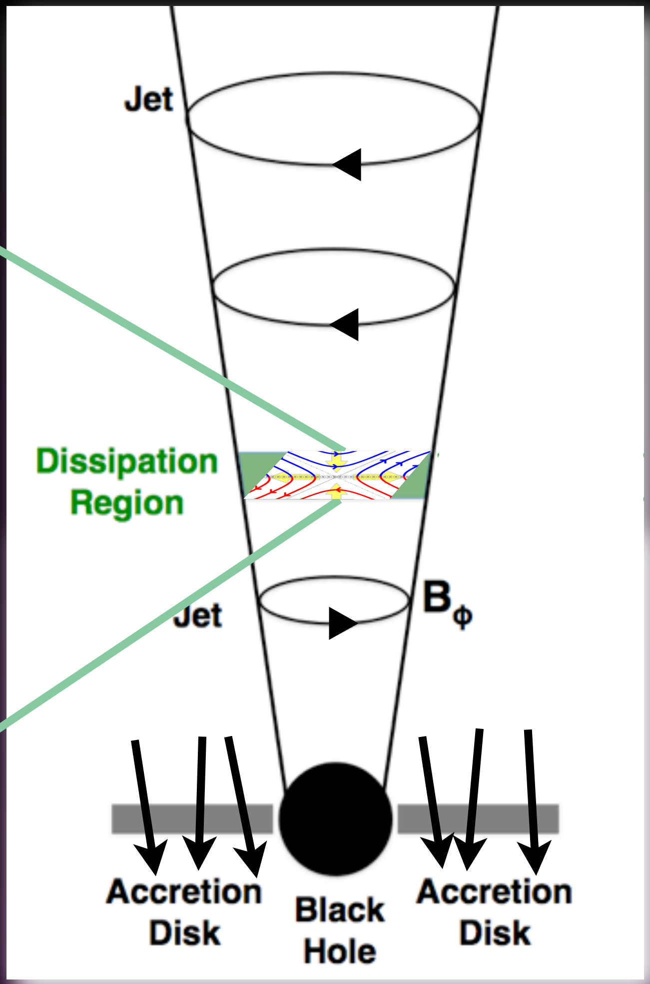
Internal dissipation in blazar jets



Internal dissipation: magnetic reconnection?

Relativistic magnetic reconnection





Relativistic Reconnection

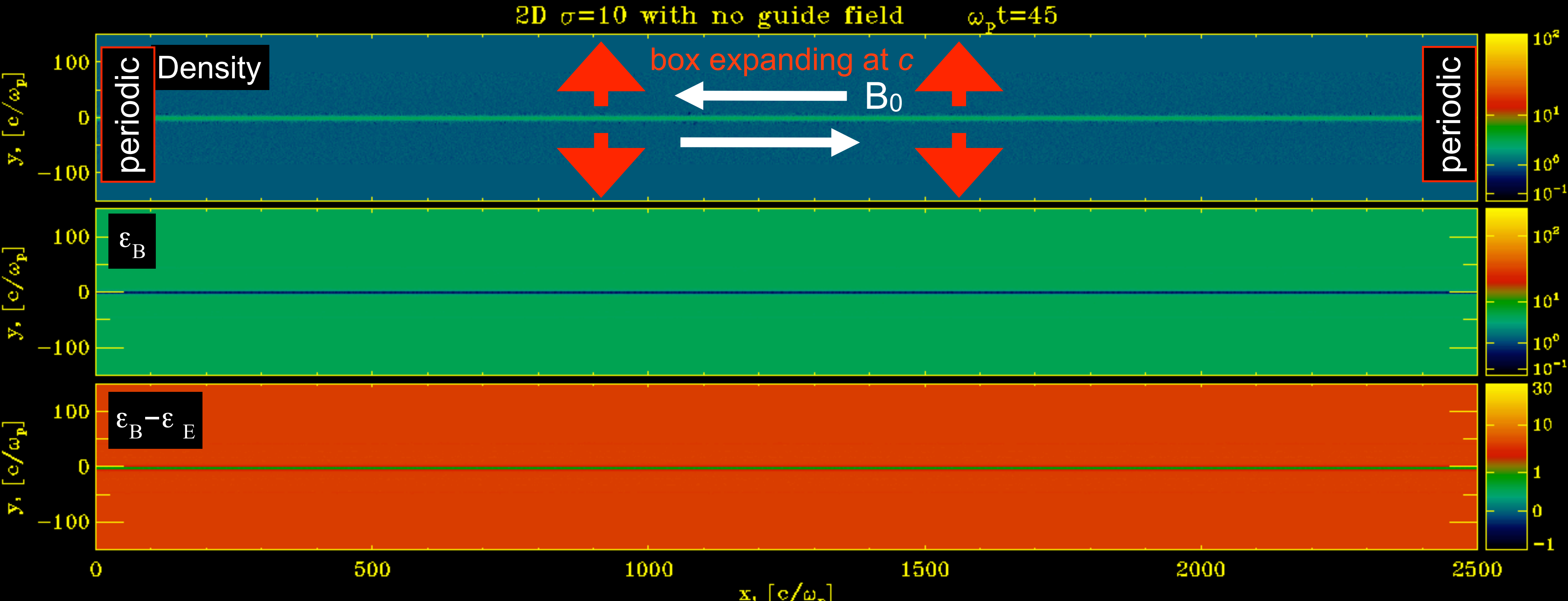
$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \gg 1 \qquad v_A \sim c$$

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

Dynamics and particle spectrum

Hierarchical reconnection

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

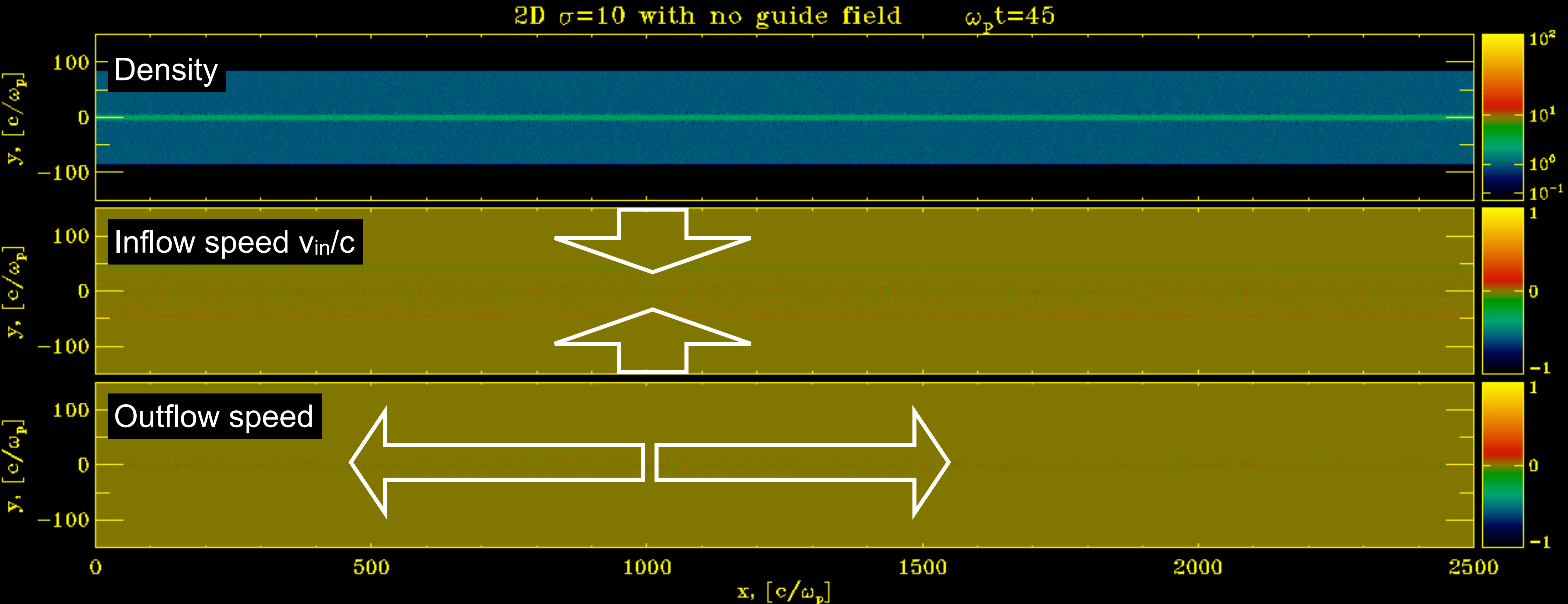


(LS & Spitkovsky 14)

- 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.

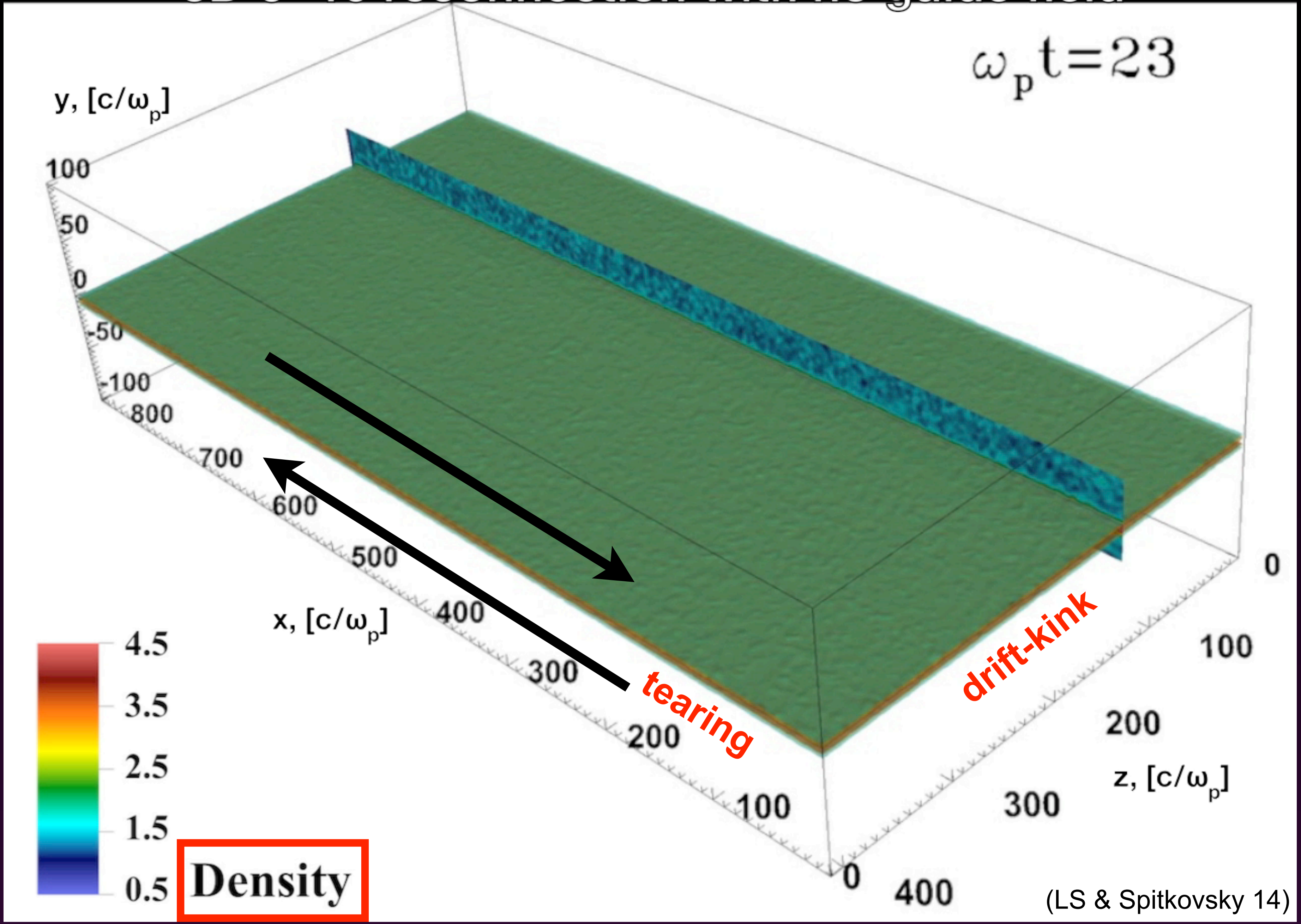
Inflows and outflows

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



- Inflow into the layer is non-relativistic, at $v_{in} \sim 0.1$ 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

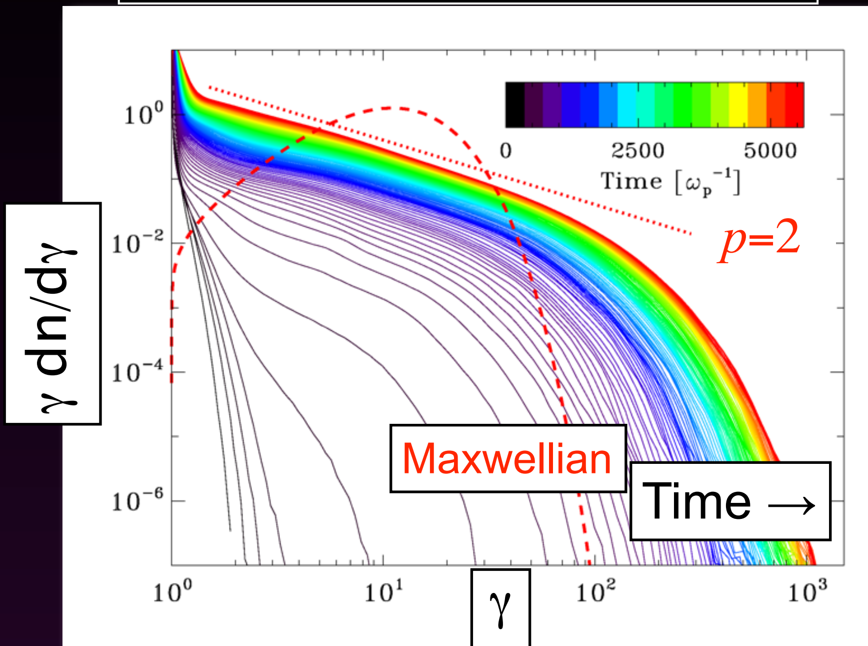


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

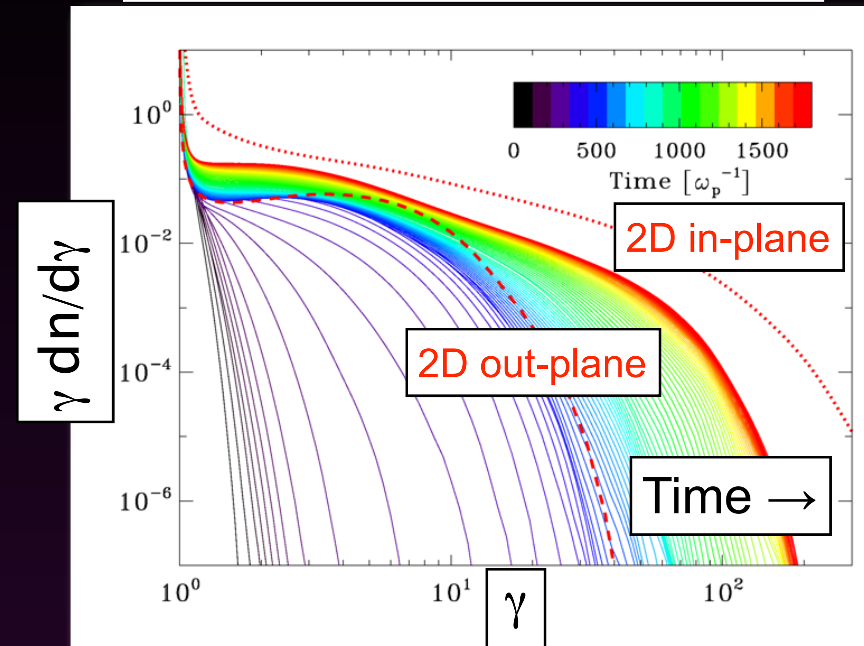
The particle energy spectrum

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

2D $\sigma=10$ electron-positron

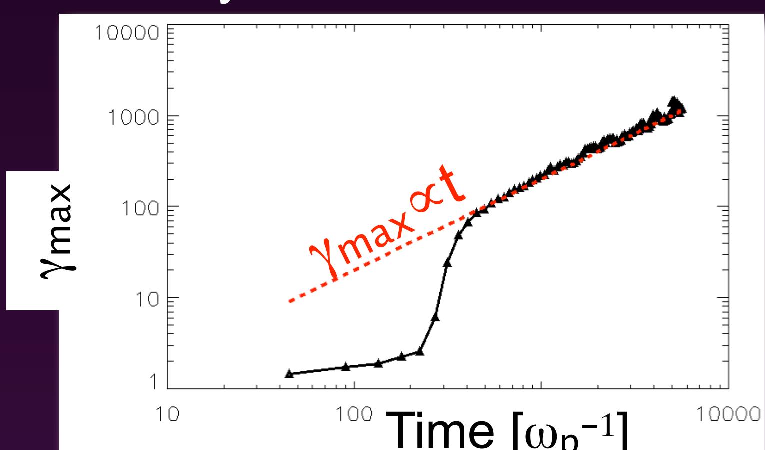


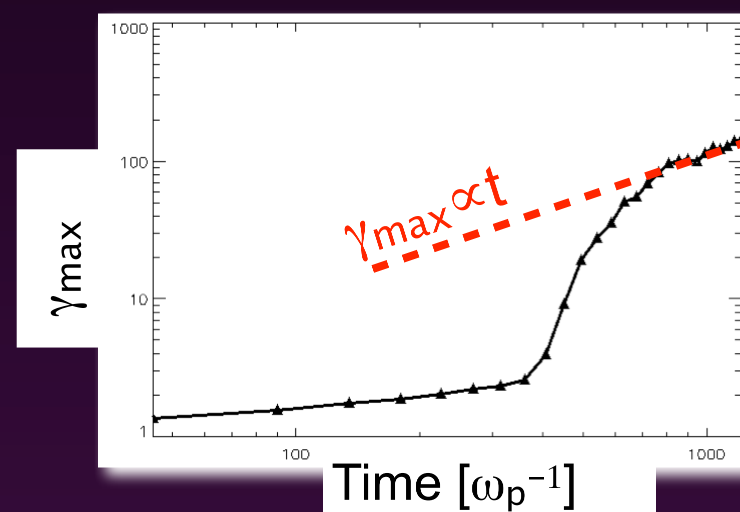
3D $\sigma=10$ electron-positron



(LS & Spitkovsky 14)

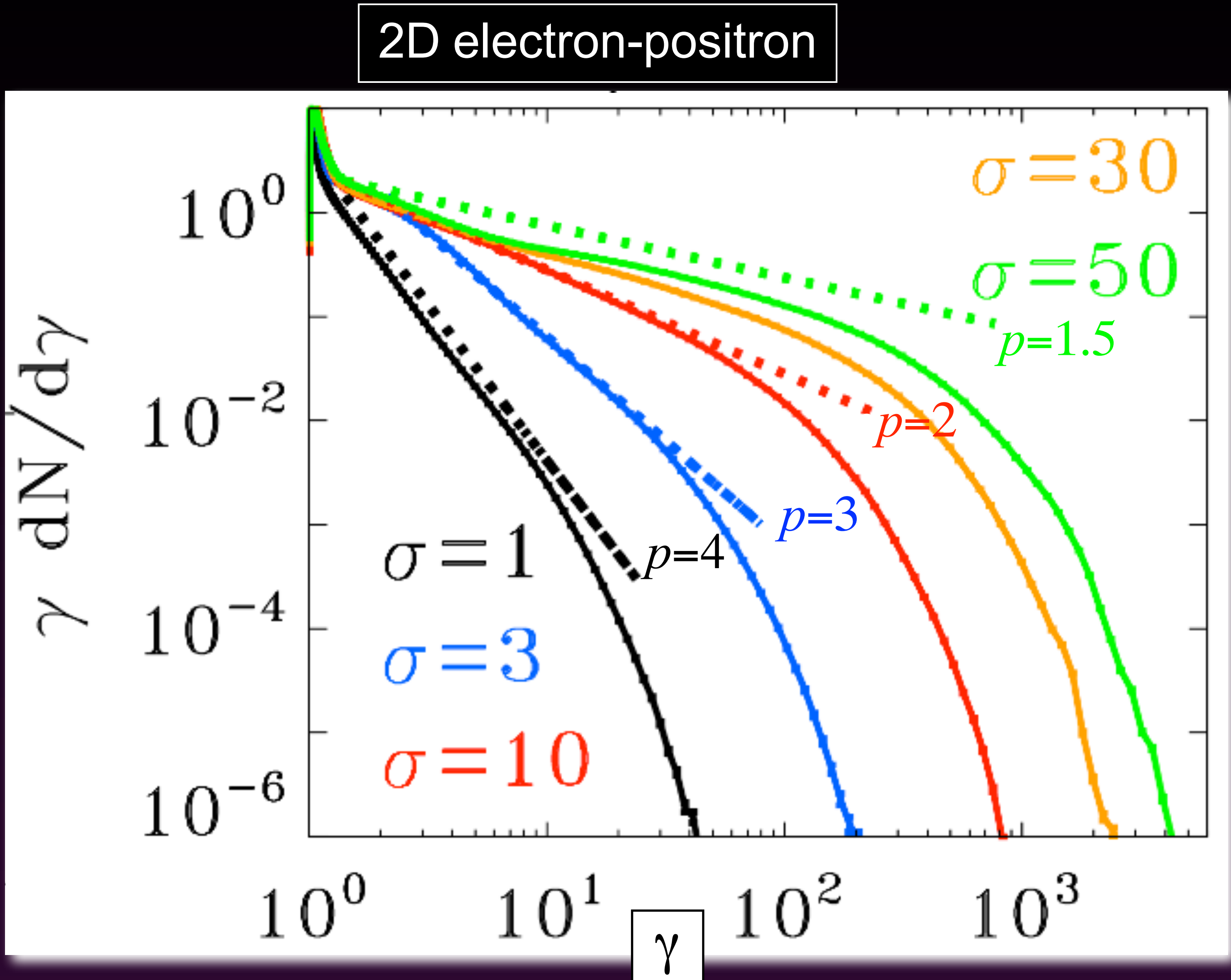
- The max energy grows linearly with time, if the evolution is not artificially inhibited by the boundaries.





(LS & Spitkovsky 14)

The power-law slope

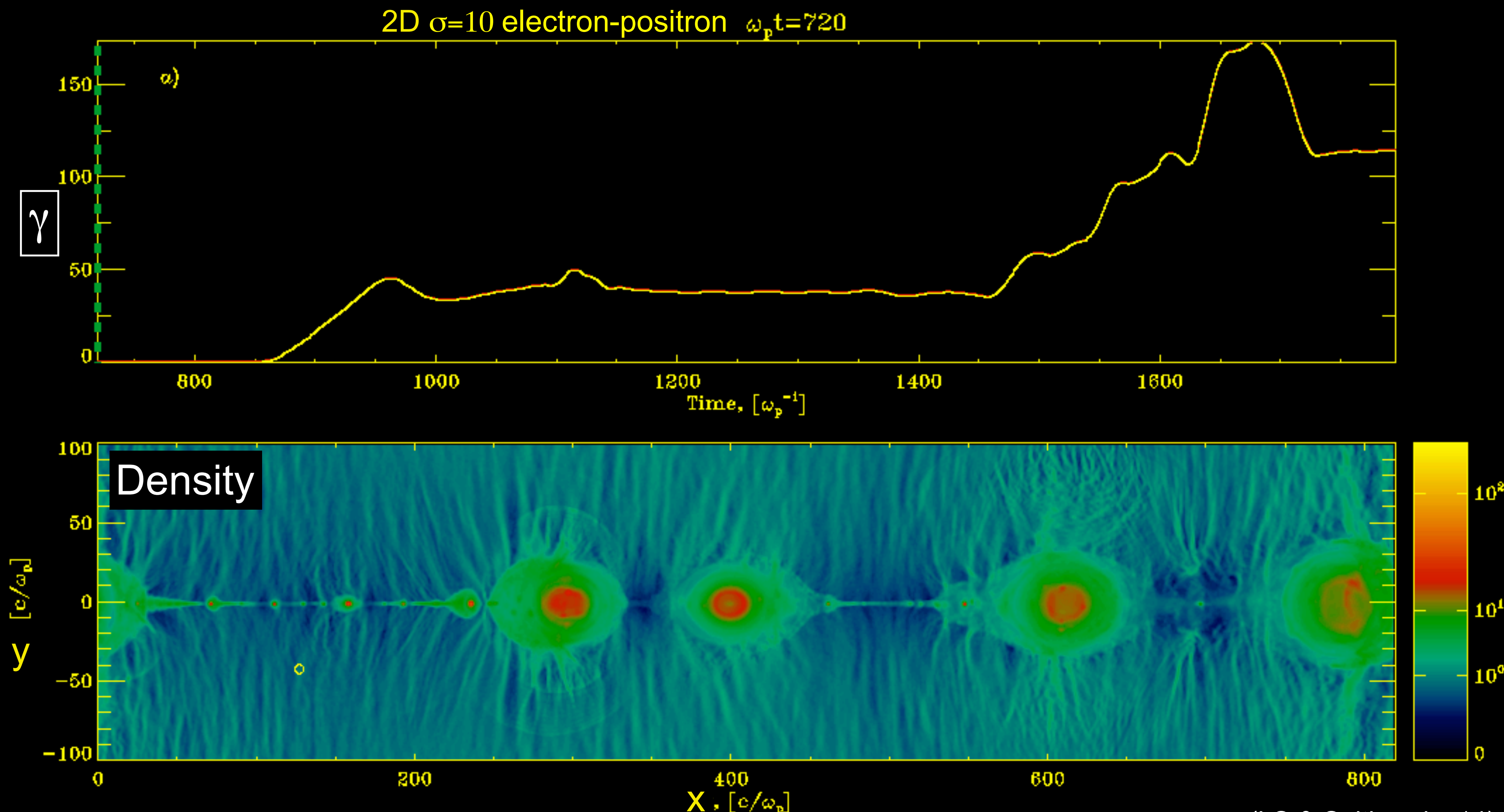


(LS & Spitkovsky 14, see also Melzani+14, Guo+14,15, Werner+16)

The power-law slope is harder for higher magnetizations.

Particle acceleration mechanisms

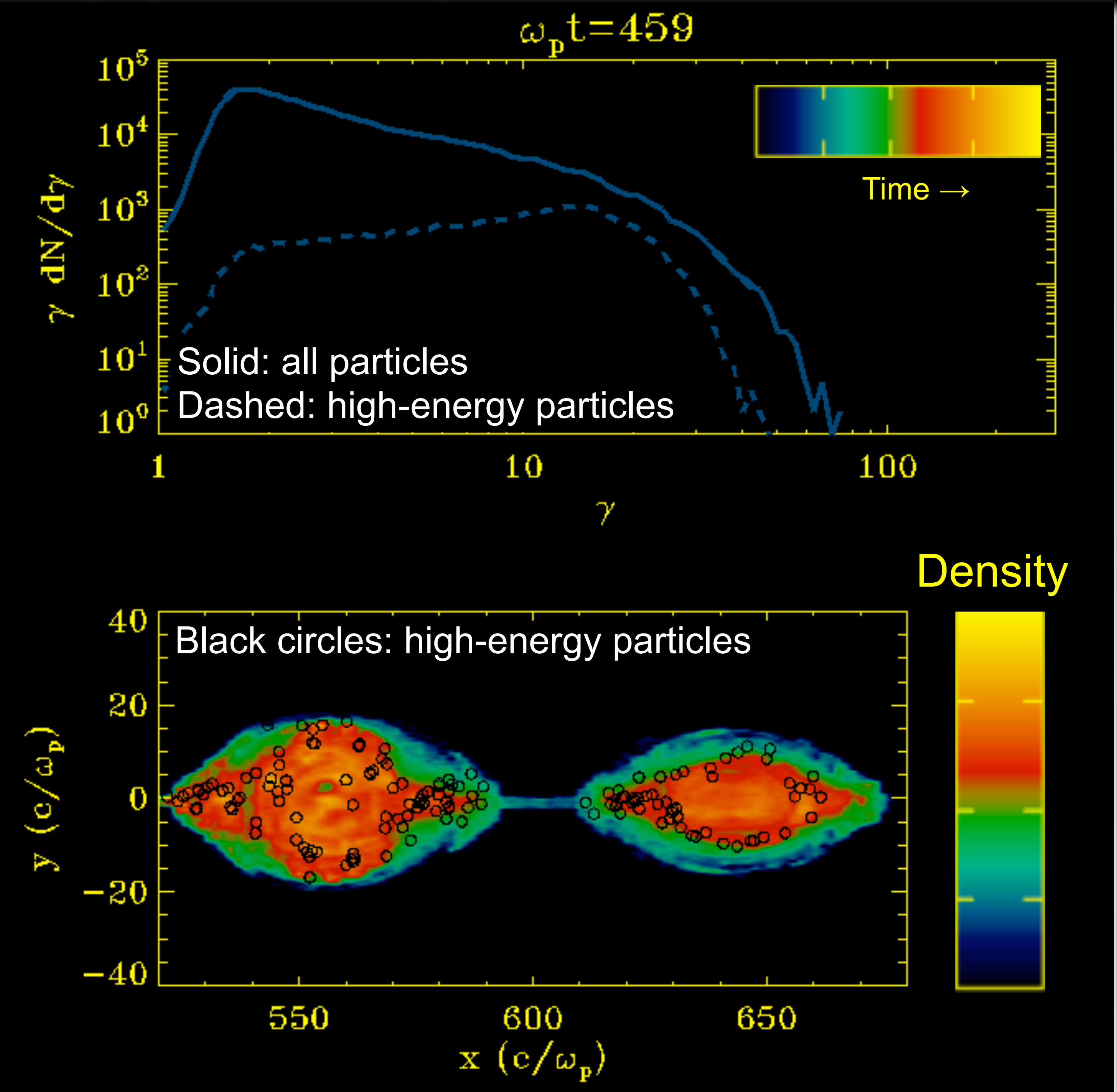
The highest energy particles



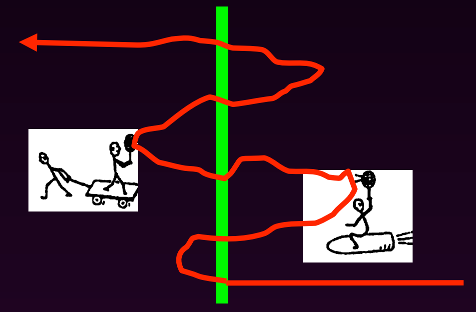
(LS & Spitkovsky 14)

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

(2) Fermi process in between islands



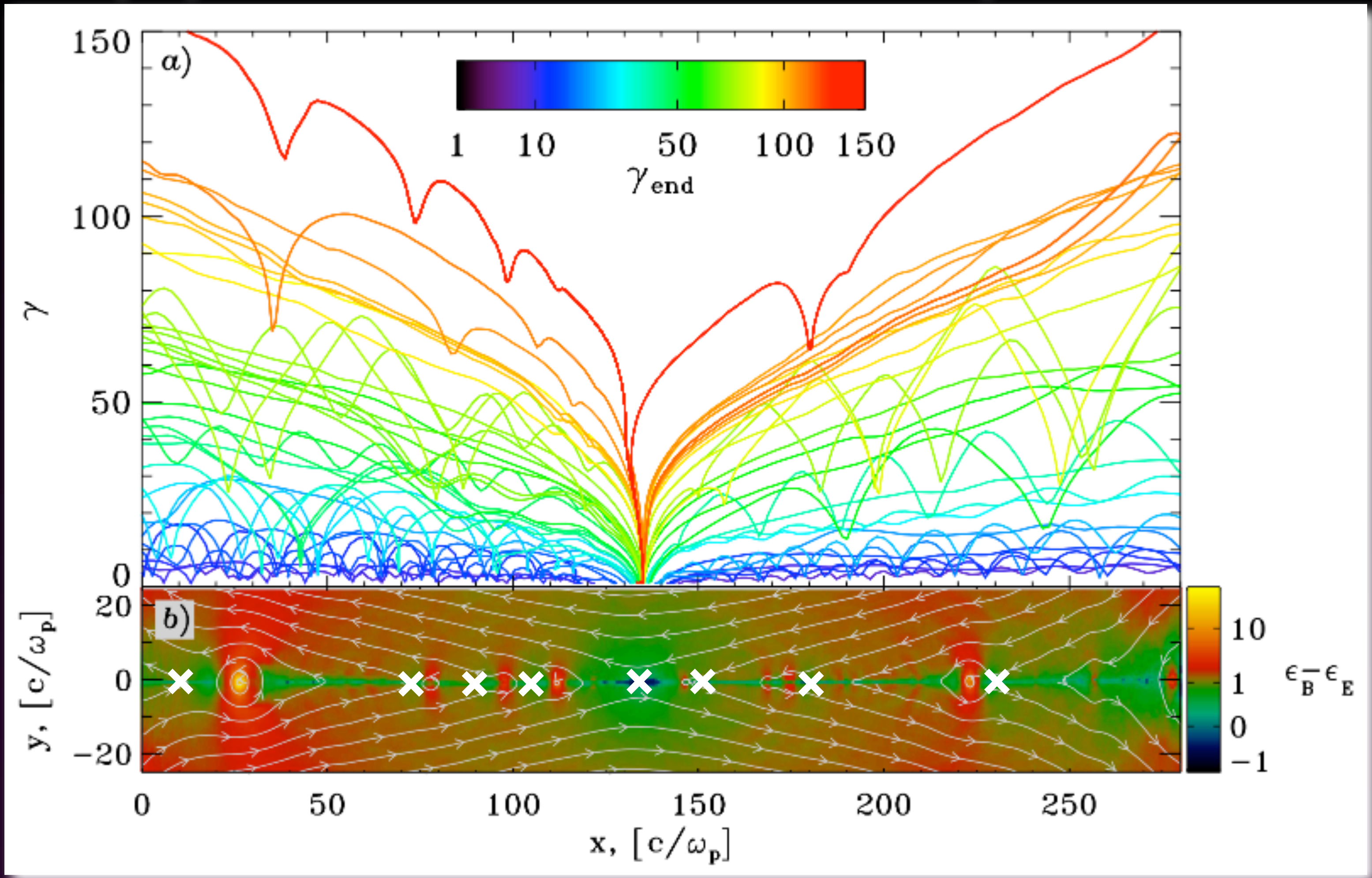
- The particles are accelerated by a Fermi-like process in between merging islands (Guo+14, Nalewajko+15).



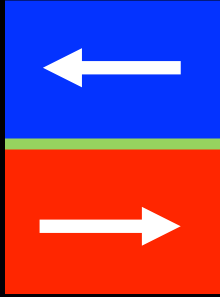
- Island merging is essential to shift up the spectral cutoff energy.

- 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)

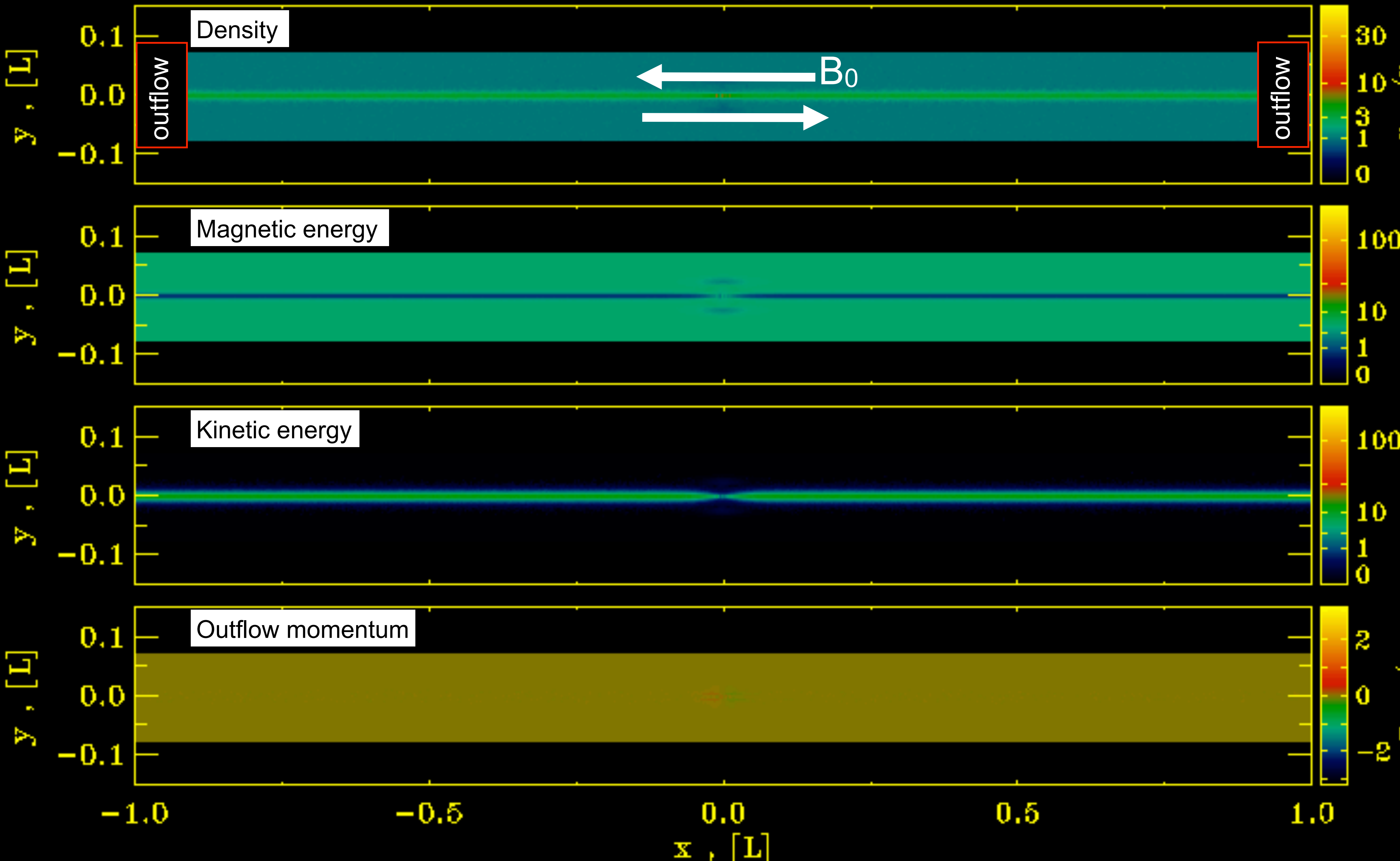


- In cold plasmas, the particles are tied to field lines and they go through X-points.
- The particles are accelerated by the reconnection electric field at the X-points (Zenitani & Hoshino 01). The energy gain can vary, depending on where the particles interact with the sheet.
- The same physics operates at the main X-point and in secondary X-points.

Plasmoids in relativistic reconnection

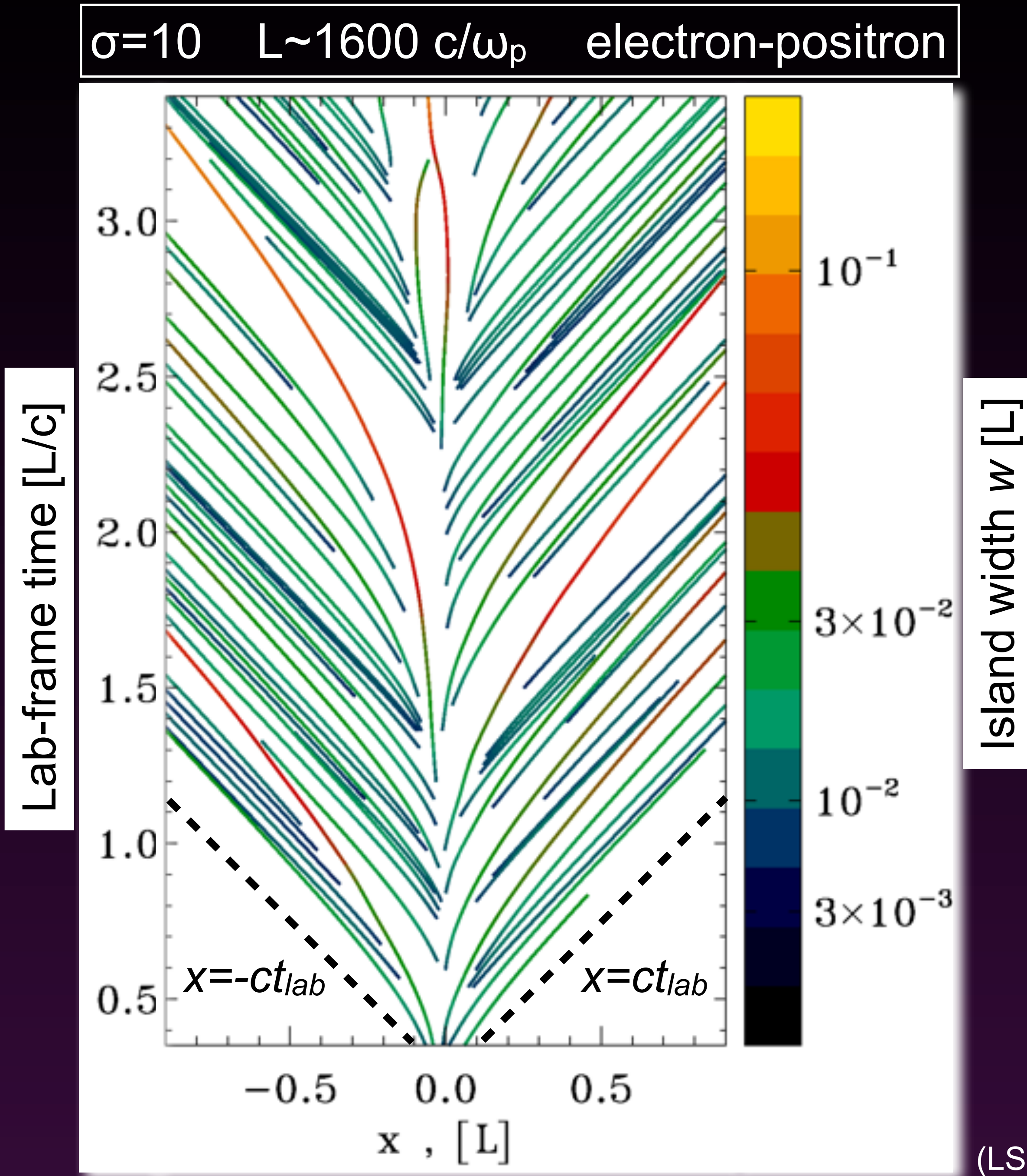
Plasmoids in reconnection layers

electron-positron $\sigma=10$ $ct_{lab}/L=0.0$ $L\sim1600\ c/\omega_p$



(LS, Giannios & Petropoulou 16)

Plasmoid space-time tracks



We can follow individual plasmoids in space and time.

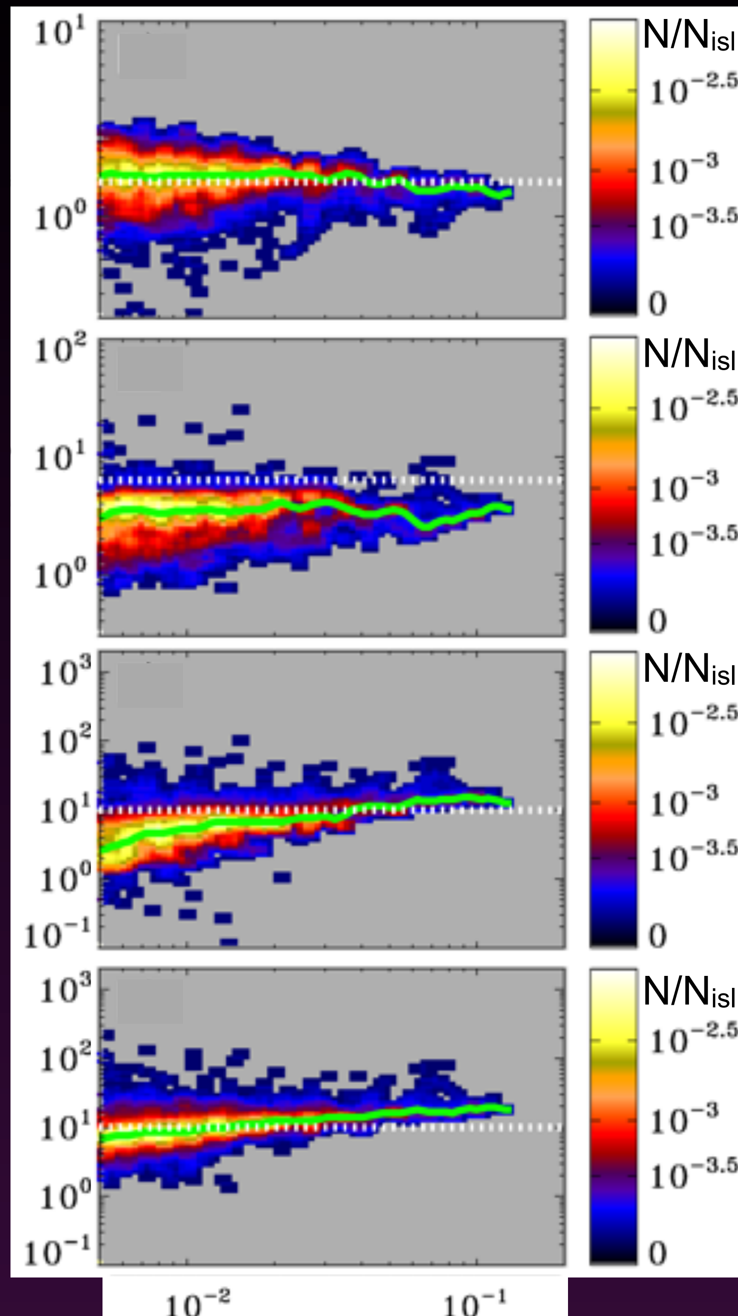
First they grow, then they go:

- 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

σ=10 electron-positron



Plasmoid width *w* [L]

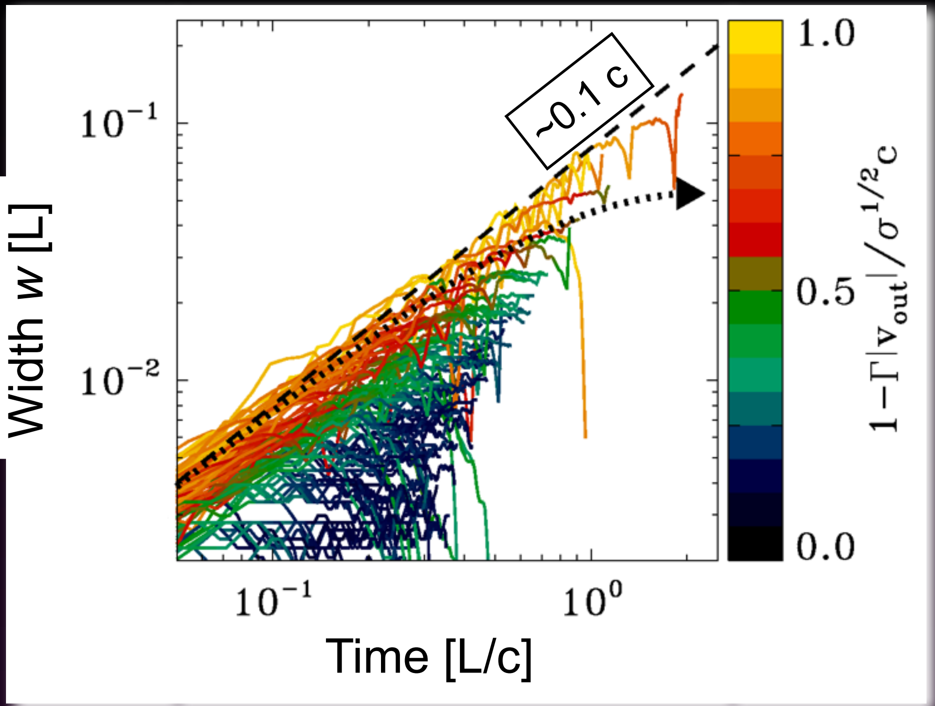
Plasmoids fluid properties:

- 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 ~√2 (regardless of *w*).
- $\varepsilon_{kin} \sim \varepsilon_B \sim \sigma \rightarrow$ equipartition (regardless of *w*).

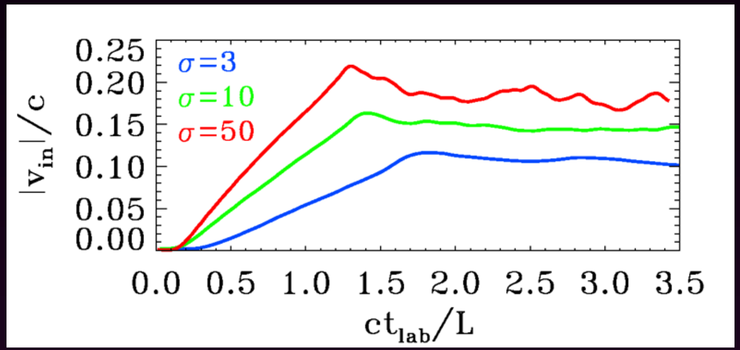
(LS, Giannios & Petropoulou 16)

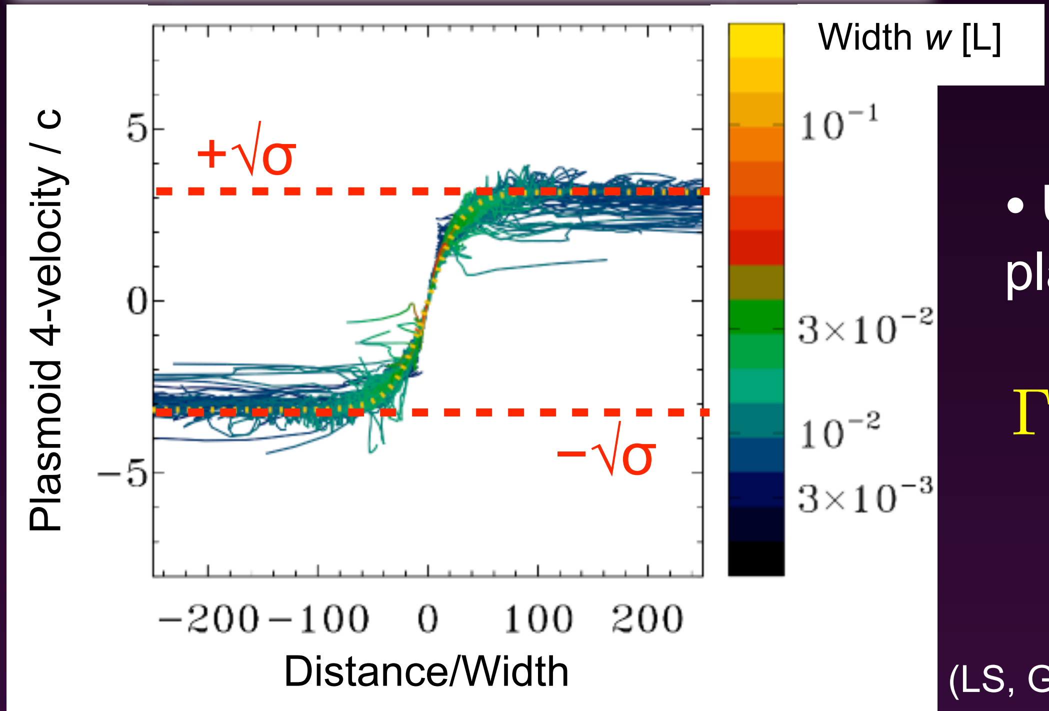
First they grow, then they go

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.





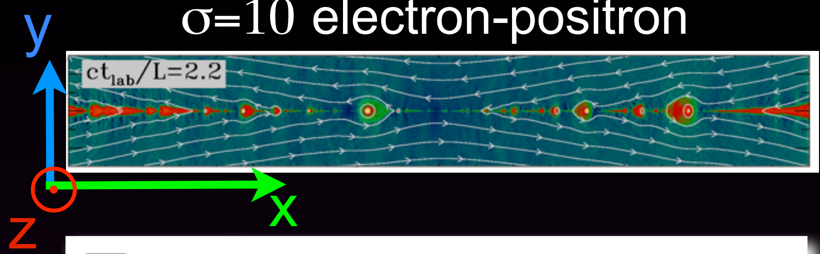
- Universal relation for the plasmoid acceleration:

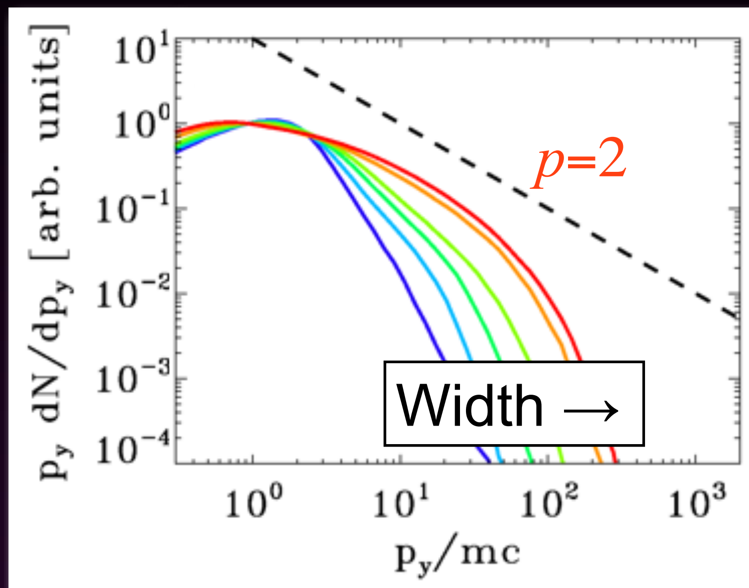
$$\Gamma\frac{v_{\rm out}}{c} \simeq \sqrt{\sigma}\tanh\left(\frac{0.1}{\sqrt{\sigma}}\frac{x}{w}\right)$$

(LS, Giannios & Petropoulou 16)

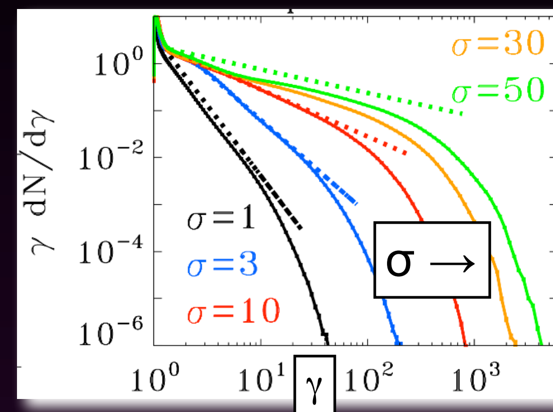
Non-thermal particles in plasmoids

σ=10 electron-positron



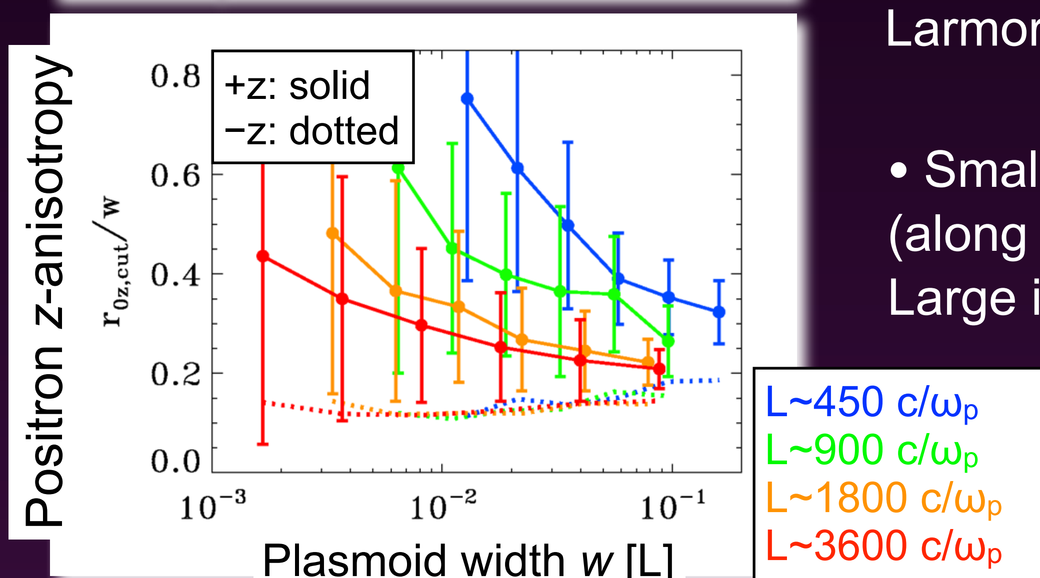


- The *comoving* particle spectrum of large islands is a power law, with the same slope as the overall spectrum from the layer (so, harder for higher σ).



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.

The transition happens at

$$w \sim 50\,\sqrt{\sigma}\,c/\omega_{\rm p}$$

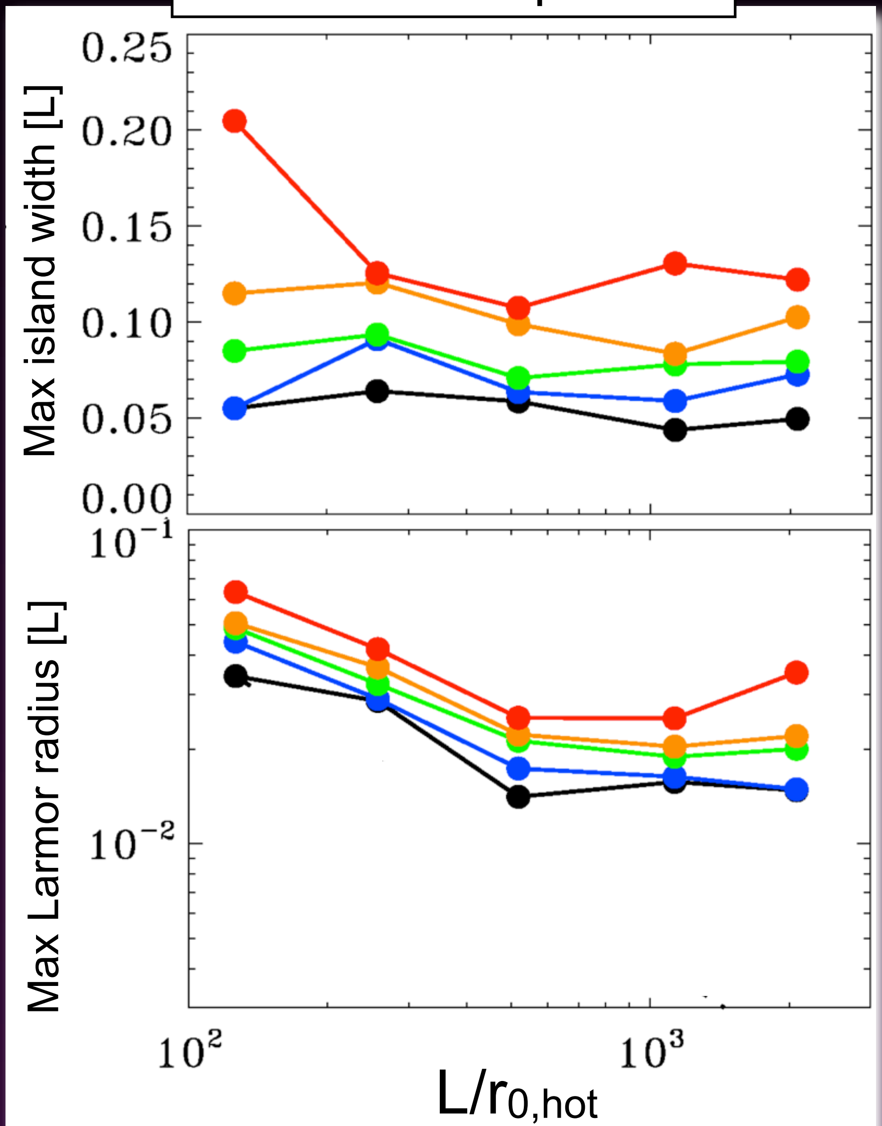
(LS, Giannios & Petropoulou 16)

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 $L \gg r_{0,hot}$:

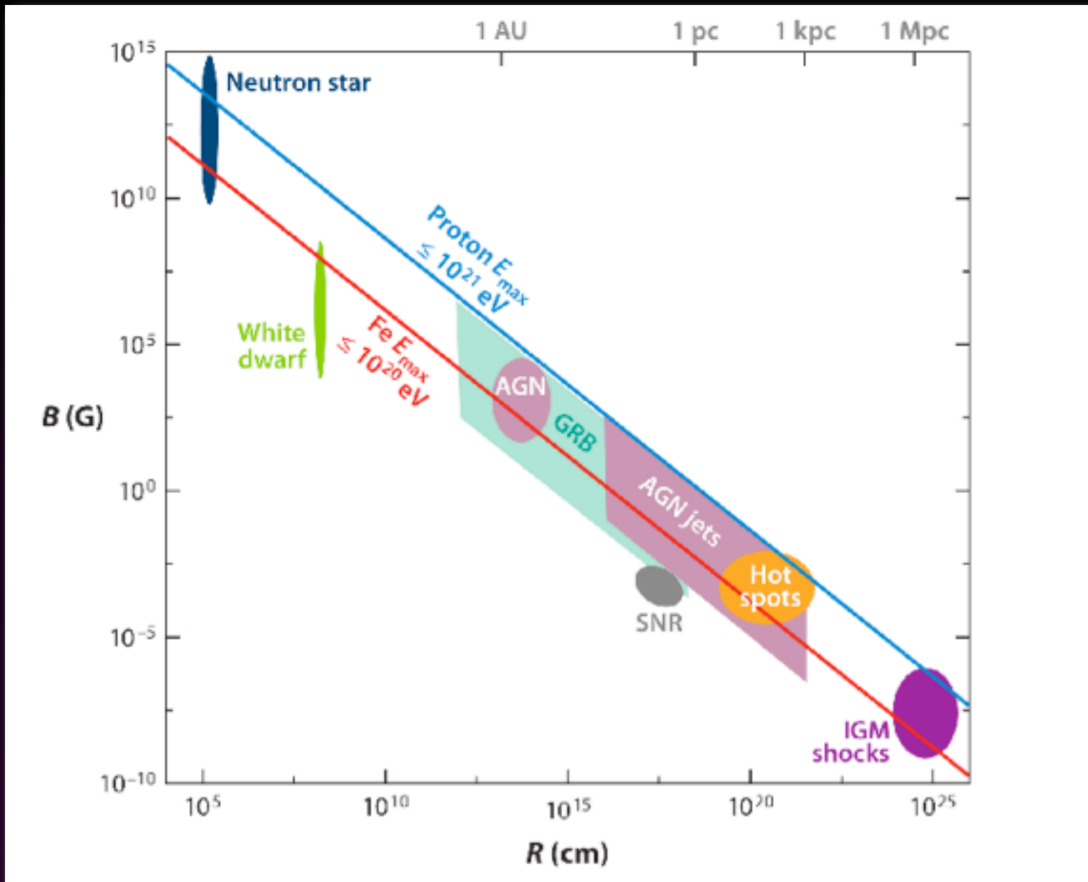
- The width of the biggest ("monster") islands is a fixed fraction of the system length L (~0.1-0.2 L), regardless of $L/r_{0,hot}$.

- 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

(LS, Giannios & Petropoulou 16)

UHECRs from reconnection in blazars?



From PIC simulations of relativistic reconnection in blazars:

- the max energy particles have Larmor radius

$$r_{L,\mathrm{max}} \sim 0.04\, L$$

$$r_{L,\mathrm{max}} \sim 0.2\, w_{\mathrm{max}}$$

- From the typical timescale $t_f \sim 10^5$ s of blazar major flares, one can infer the size w_{max} of the largest plasmoids, and so $r_{L,max}$.

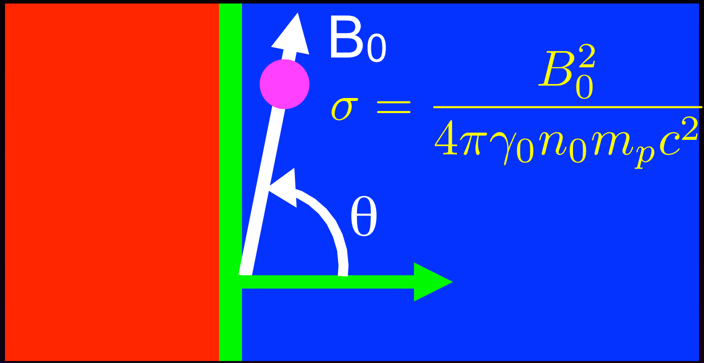
- The highest energy ions will have (if the jet Doppler factor δ~10)

$$\boxed{E_{\mathrm{UHECR}} \sim 5 \times 10^{18}\, Z\, \Gamma_1 \delta_1 B_0 t_{\mathrm{f},5}\ \mathrm{eV}}$$

Alternatives?

Internal shocks in relativistic jets

Magnetized ($\sigma > 10^{-3}$) quasi-perp relativistic shocks are poor particle accelerators:

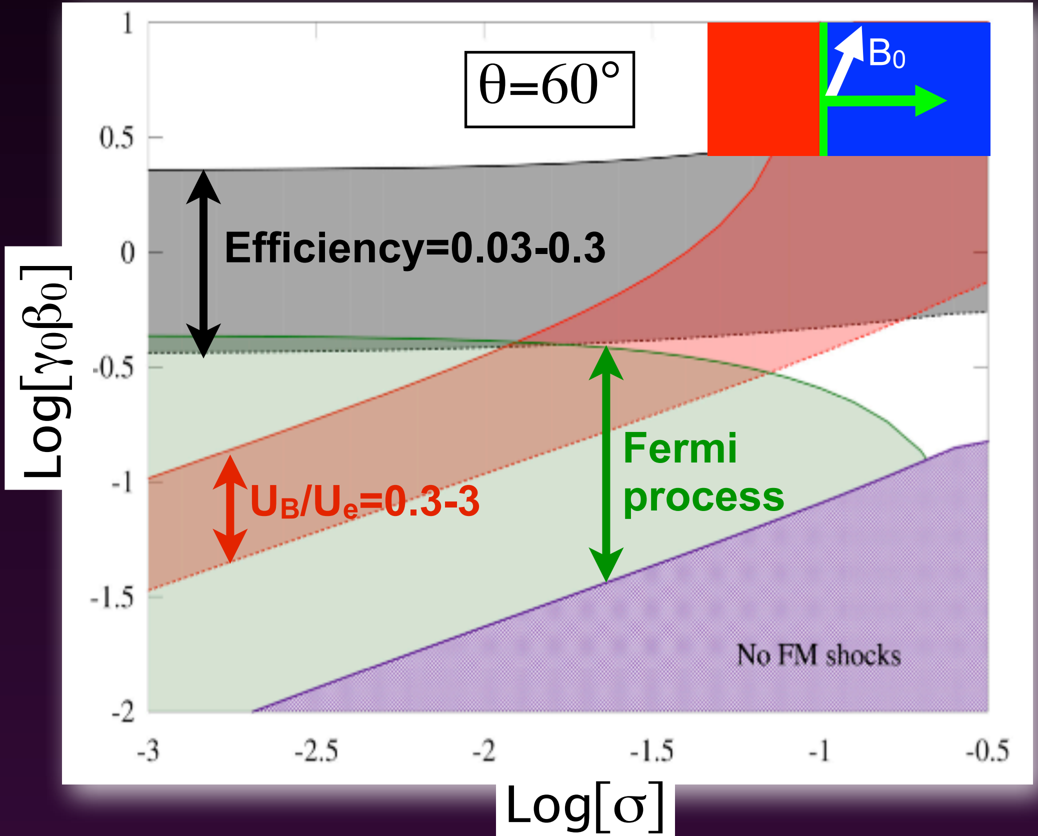


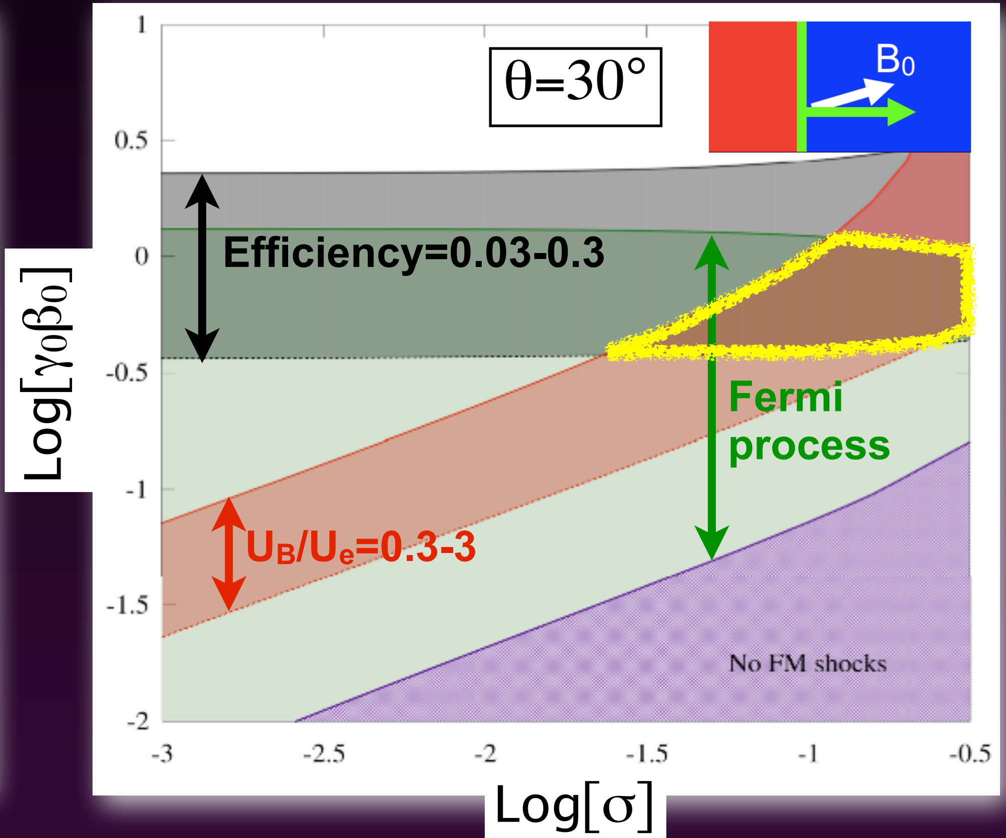
σ is large → particles slide along field lines

θ is large → particles cannot outrun the shock
unless v>c ("superluminal" shock)

→ Fermi acceleration is generally suppressed

(LS, Petropoulou & Giannios 15)

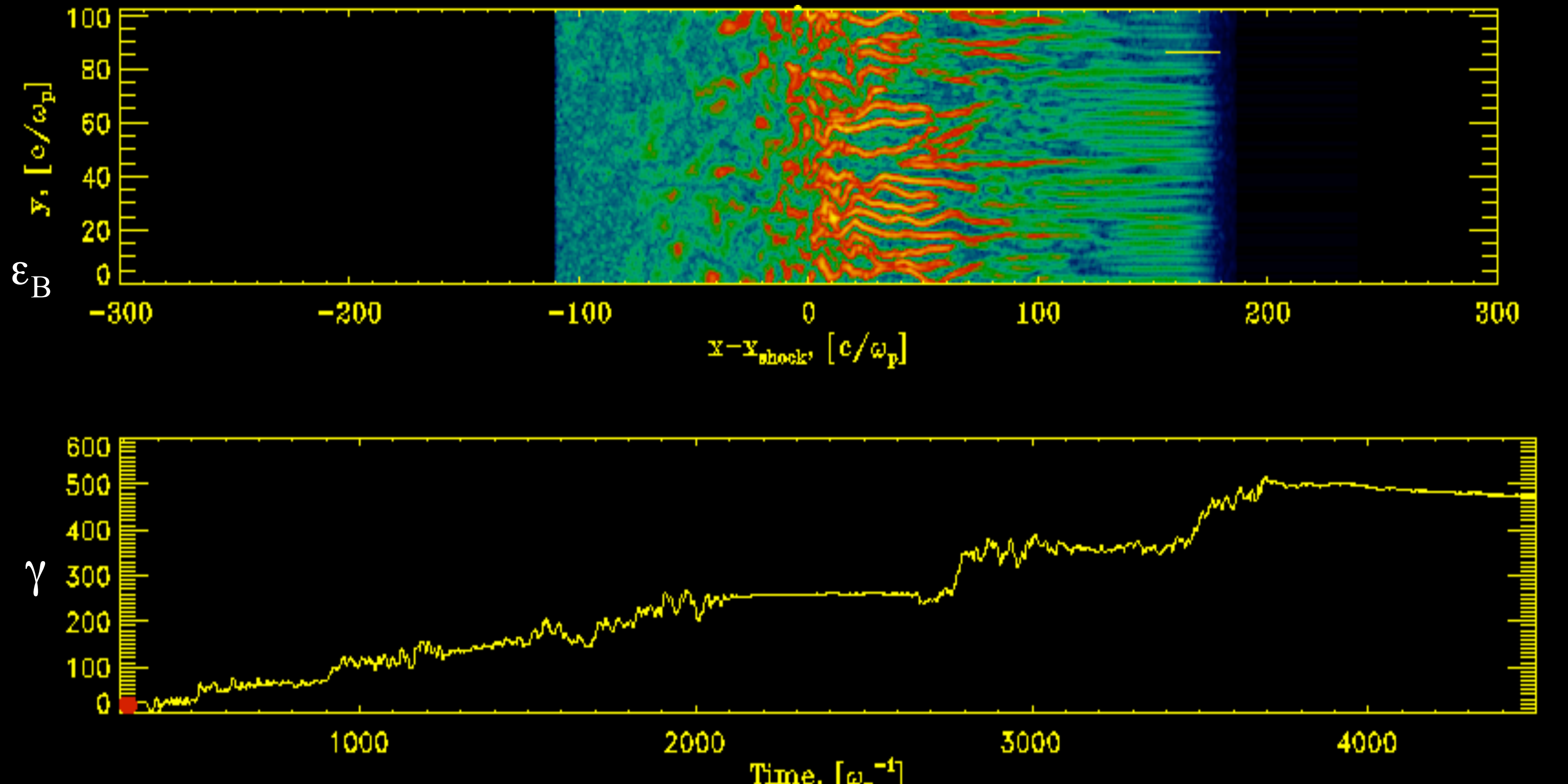




Only trans-relativistic (γ_0~a few) magnetized ($\sigma > 0.03$) quasi-parallel shocks satisfy the constraints.

External shocks in GRBs

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



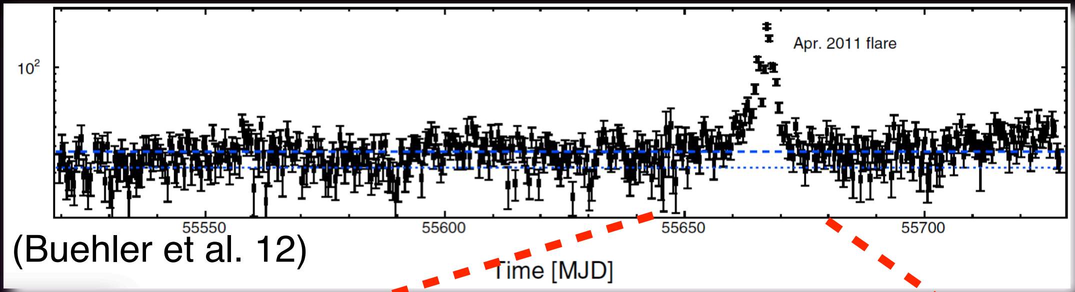
(LS et al 13)

By scattering off the small-scale Weibel turbulence, the acceleration rate is slow: $\gamma \propto t^{1/2}$

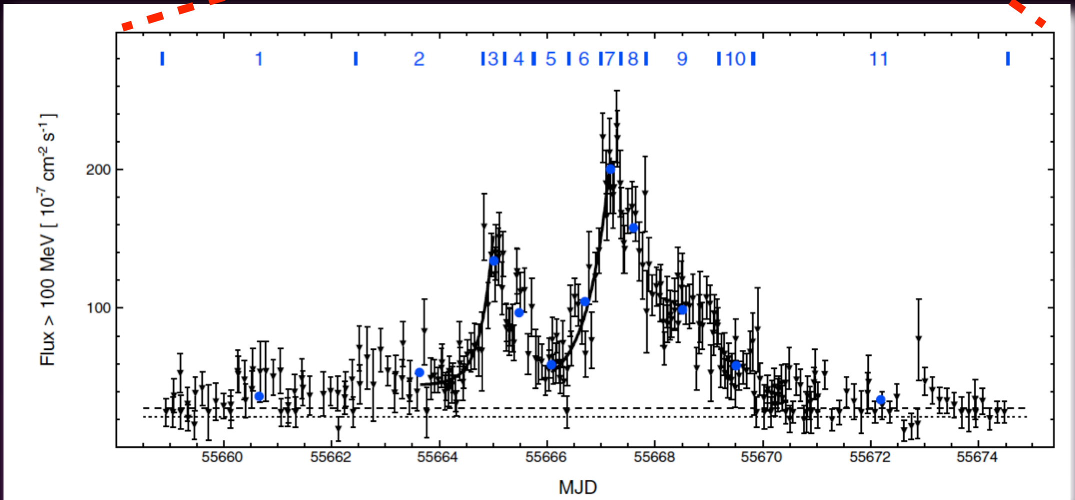
→ Maximum proton Lorentz factor: $\gamma^{\rm up}_{{\rm age},i} \simeq 1.7 \times 10^8 E_{0,54}^{3/4} n_0^{-1/2} R_{17}^{-7/4}.$ (Plotnikov, Pelletier & Lemoine 12, LS et al 13, Reville & Bell 14)

The Pevatron in our backyard

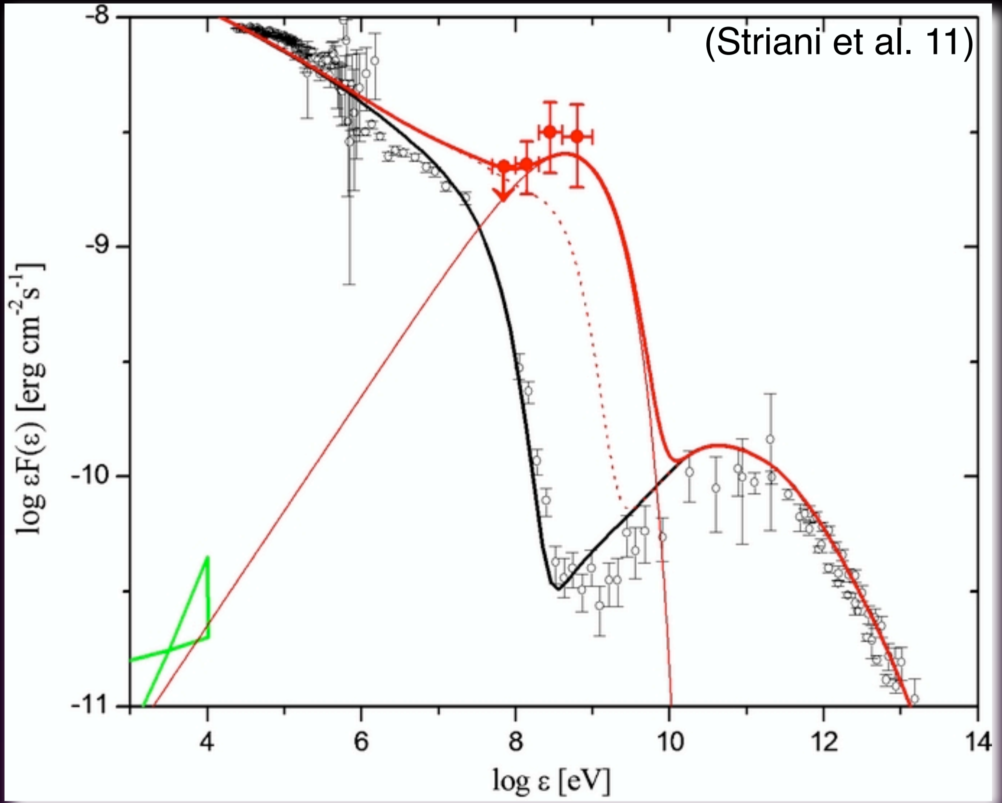
Lightcurve



(Buehler et al. 12)



Spectrum



Doubling time of ~8 hrs, with peak photon flux ~30 times larger than the average.

The flare spectrum below the GeV peak and the lack of X-ray detections require *p*<2.

Flux decay of ~ 10 hrs is controlled by synchrotron cooling + GeV peak frequency

➔ PeV electrons radiating in ~ mG magnetic fields

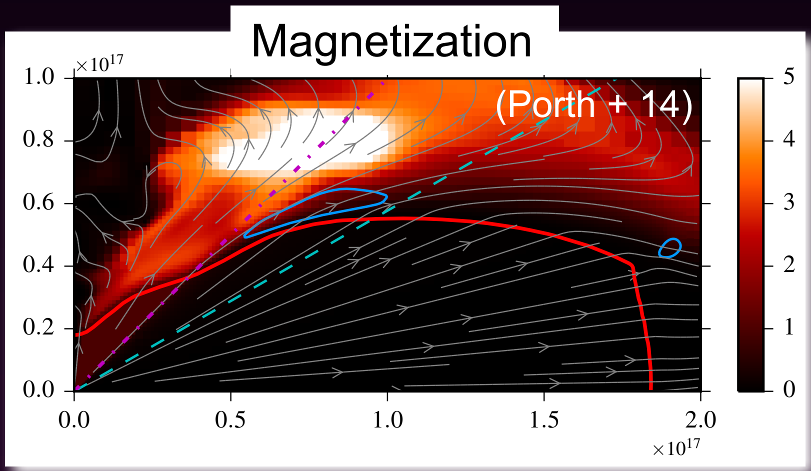
The GeV flares in the Crab Nebula

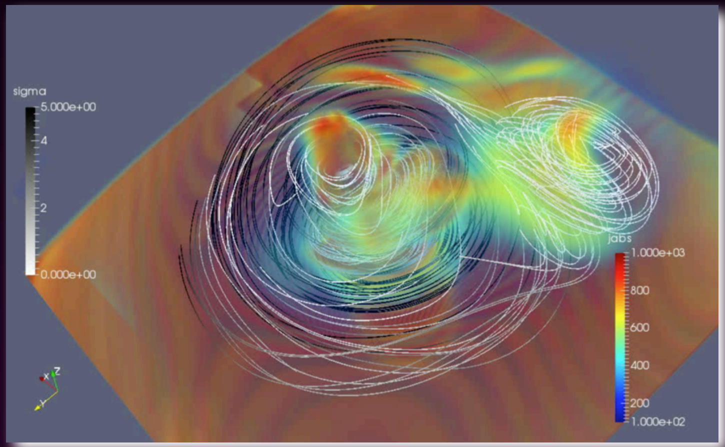
Constraints:

- Particle acceleration by E~B (energy gain and losses on Larmor radius scale).
- Particle acceleration on macroscopic scales » skin depth. Evolution on ~ dynamical time.
- Few particles are accelerated (with hard spectrum) beyond the synchrotron burnoff limit.

Where?

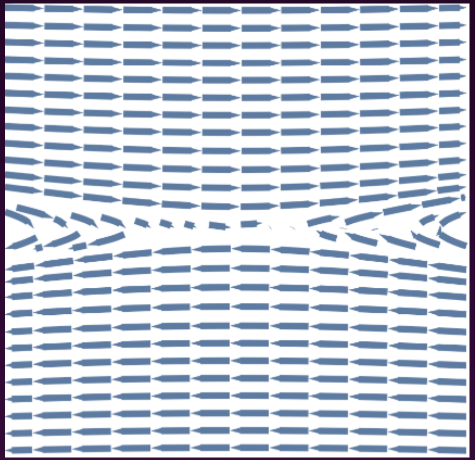
High-sigma regions → intermediate latitudes.



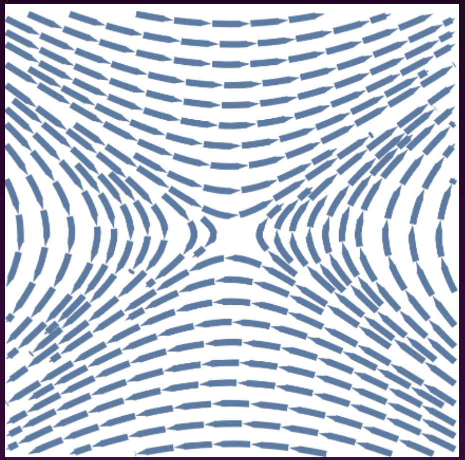


What process?

Plane-parallel reconnection



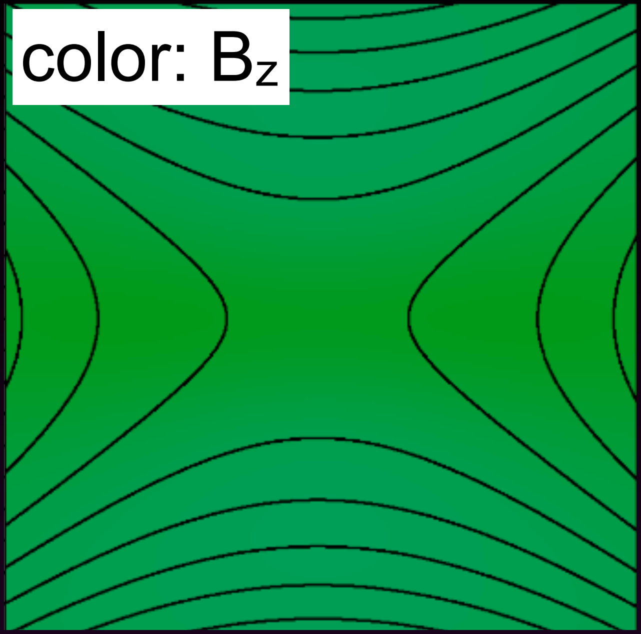
vs



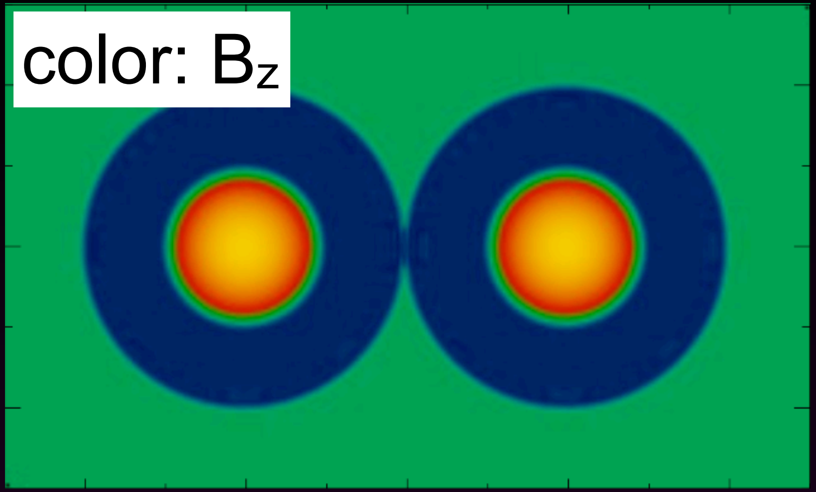
Explosive reconnection

Force-free magnetic field configurations

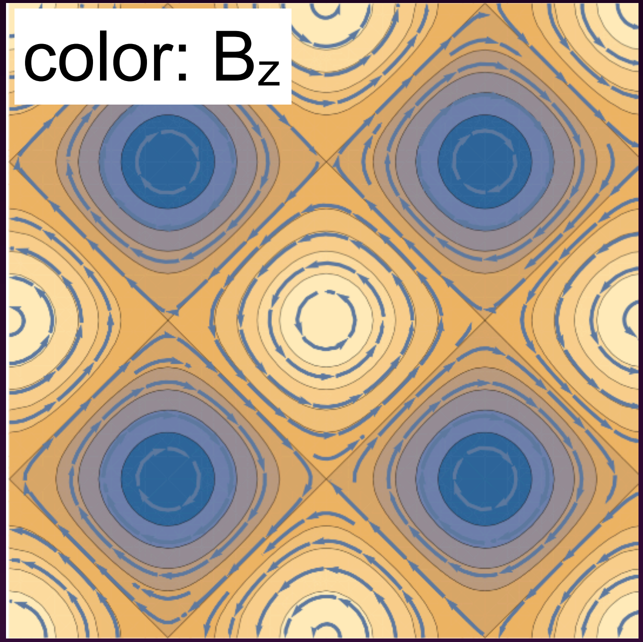
X-point collapse



Core-envelope flux tubes

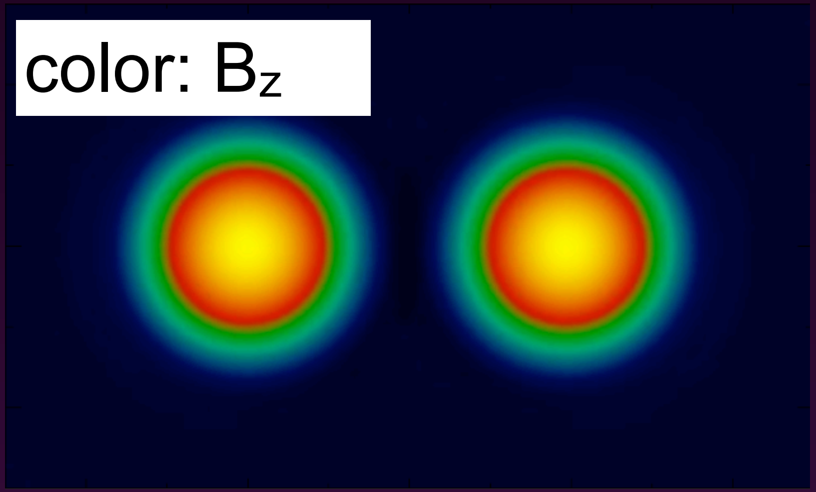


ABC structures



Lundquist flux tubes

$$\mathbf{B}_L(r \le r_\mathrm{j}) = J_1(r\alpha)\mathbf{e}_\phi + J_0(r\alpha)\mathbf{e}_z$$

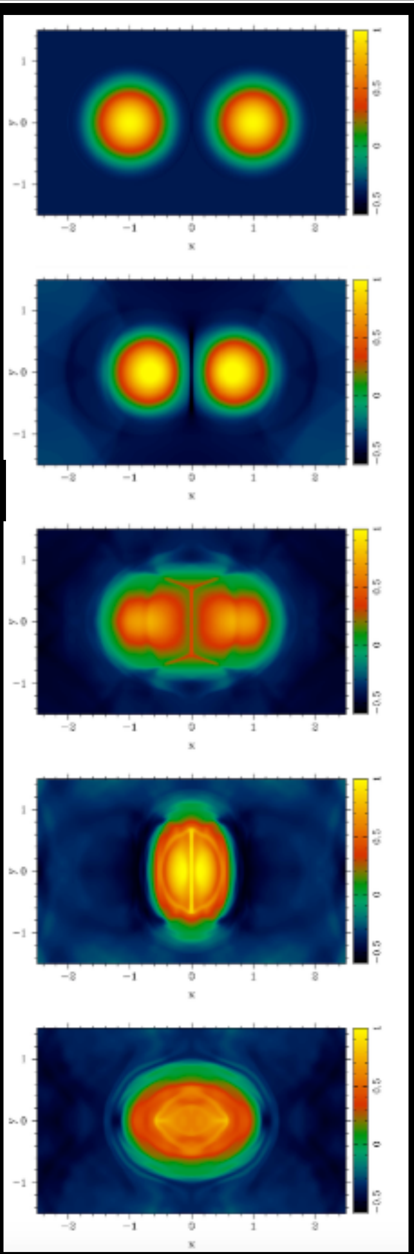


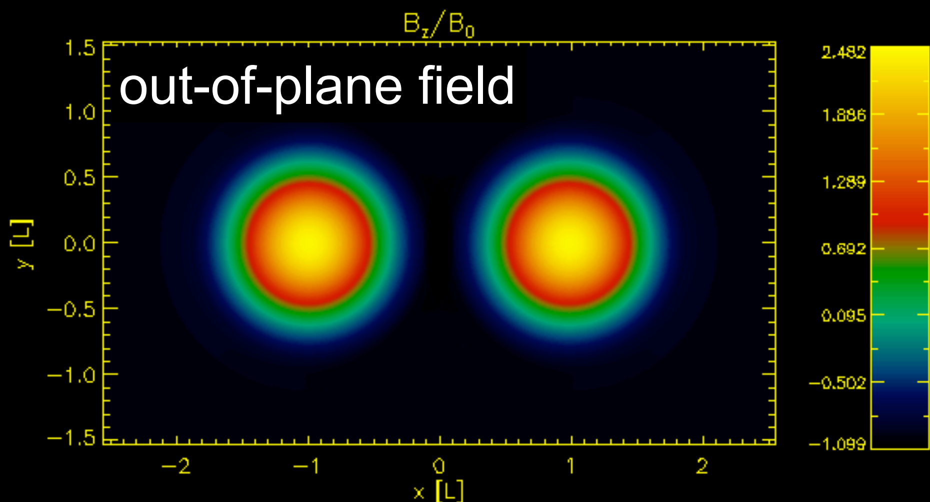
(Lyutikov, Sironi, Komissarov & Porth 16, submitted to a special issue of JPP)

Merger of magnetized flux ropes

- Flux ropes are pushed together by hand, “eroding” the envelopes → first episode of particle acceleration, dependent on the initial push.

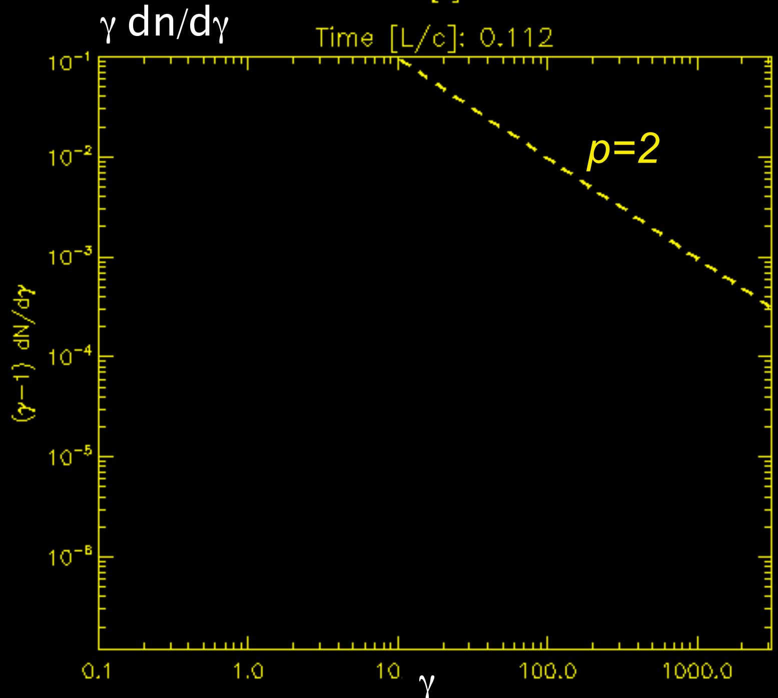
force-free simulation at time=0, 2, 4, 6, 9

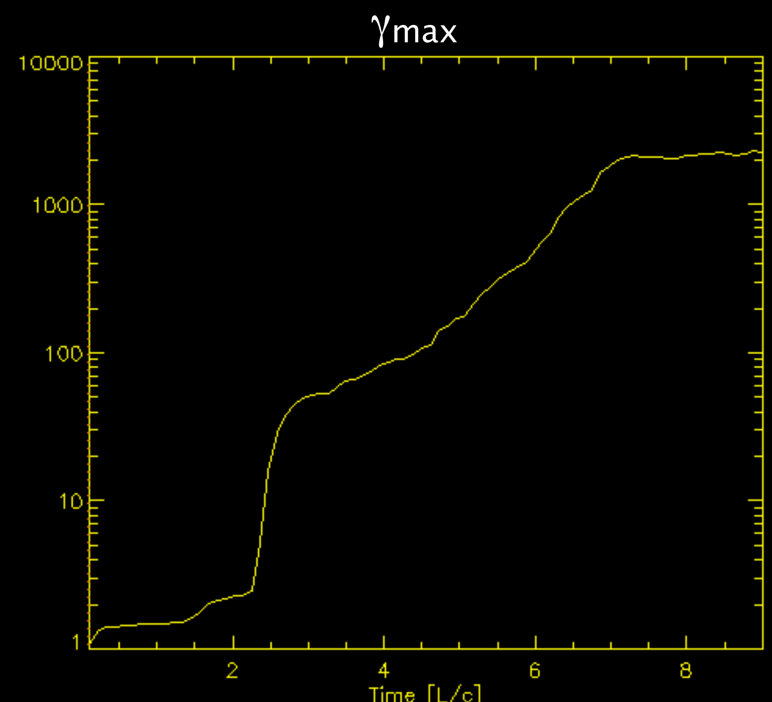


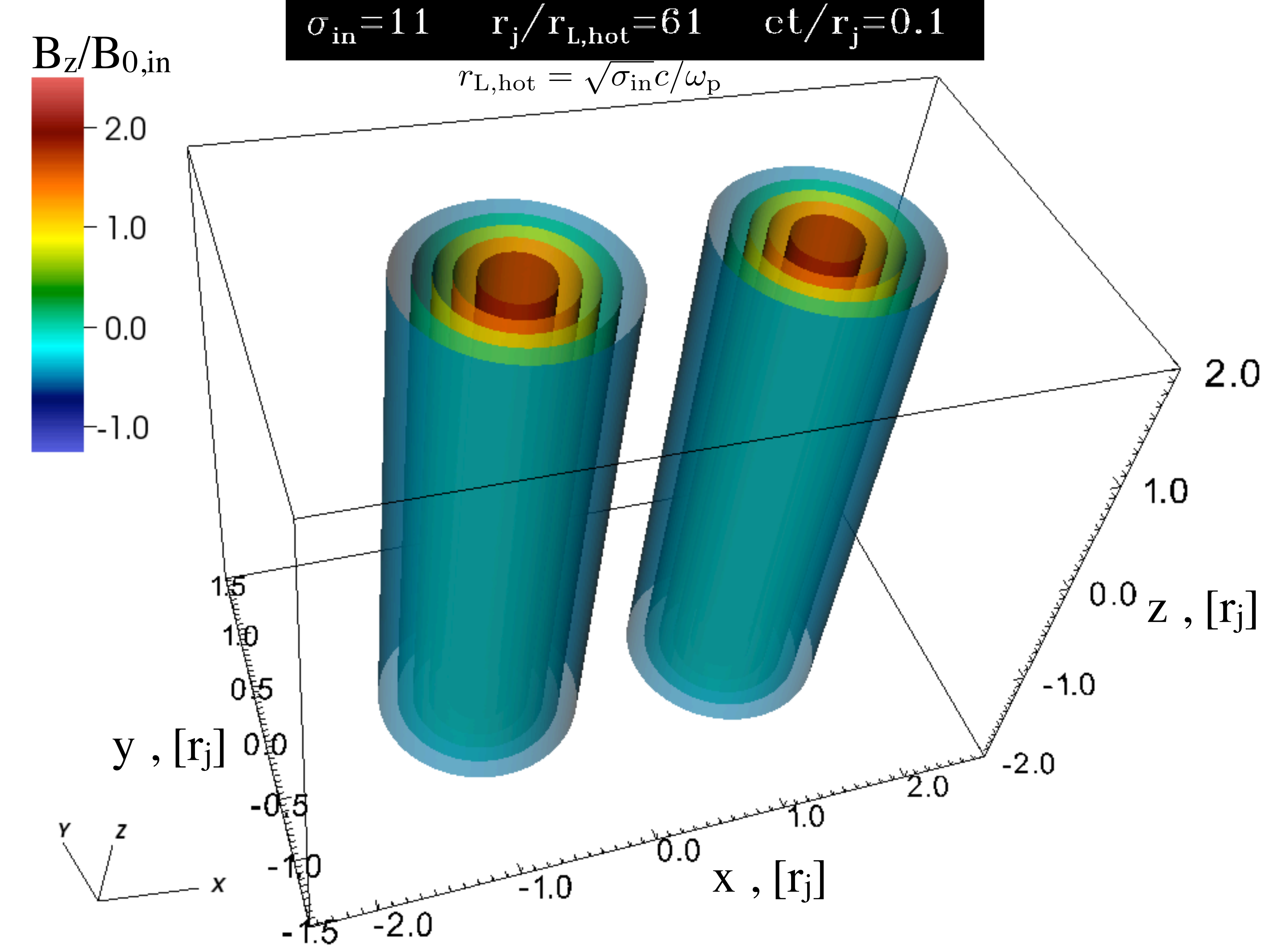


- Then, parallel currents are exposed, and they attract explosively, merging on a dynamical timescale → explosive particle acceleration.

(Lyutikov, LS, Komissarov & Porth 16)



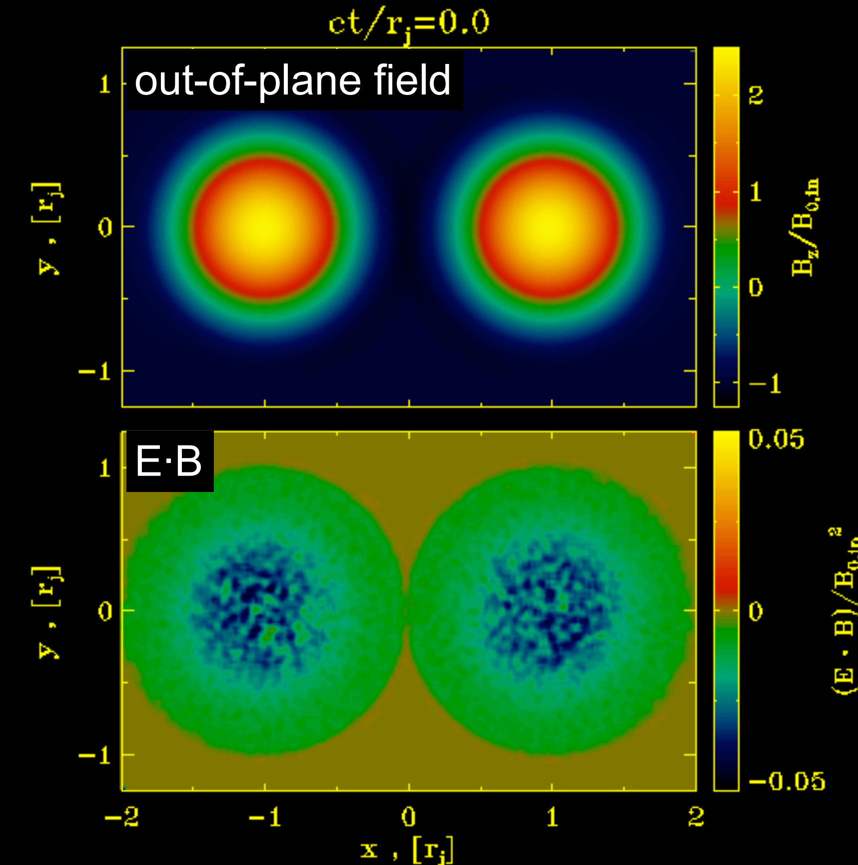


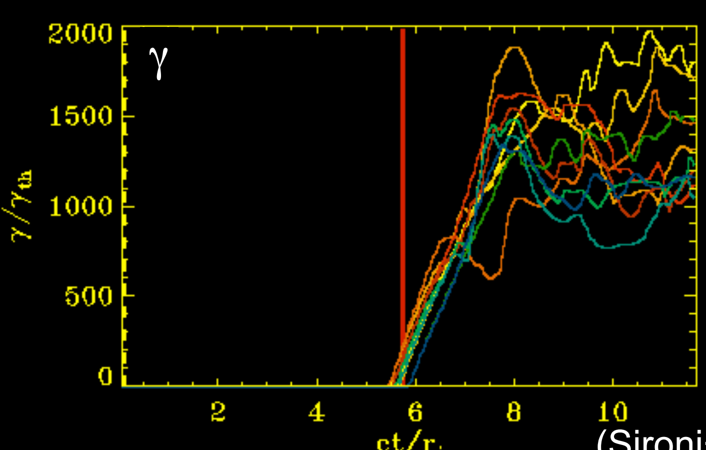


$\sigma_{\rm in}$=11 $\rm r_j/r_{L,hot}$=61 $\rm ct/r_j$=0.1
$r_{\rm L,hot} = \sqrt{\sigma_{\rm in}} c/\omega_{\rm p}$
$\rm B_z/B_{0,in}$
2.0
1.0
0.0
-1.0
y , [$\rm r_j$]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
x , [$\rm r_j$]
-2.0
-1.0
0.0
1.0
2.0
z , [$\rm r_j$]
2.0
1.0
0.0
-1.0
-2.0
Y
Z
X

Mechanism of particle acceleration

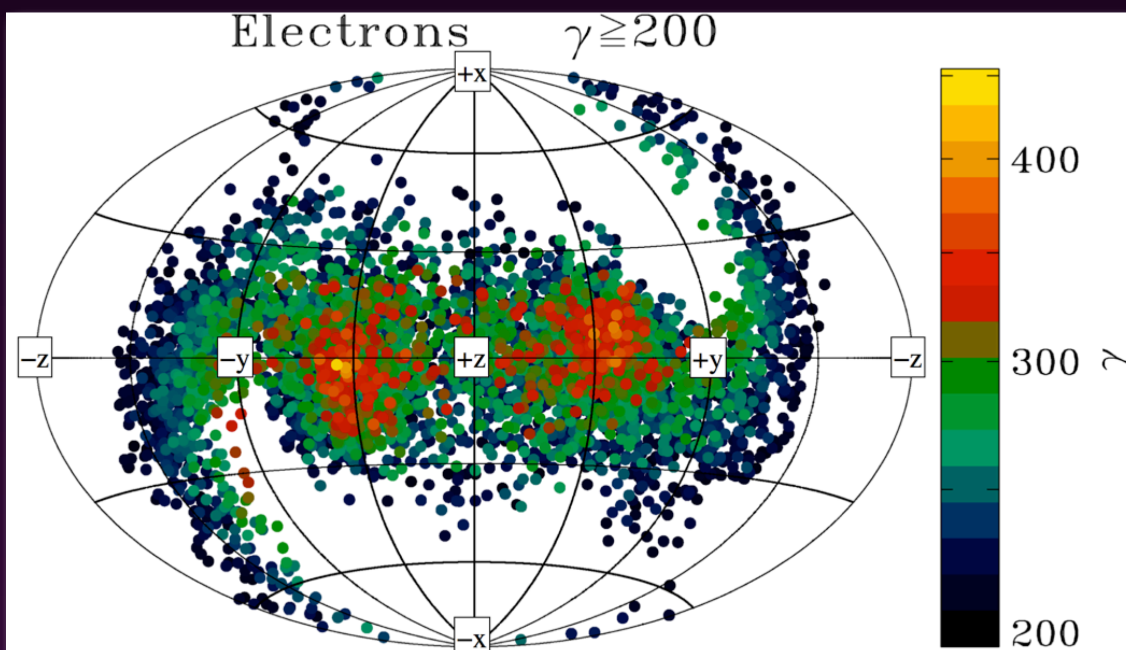
σ_{in}=42 $L/\sigma_{in}^{1/2}$=62 c/ω_p kT/mc^2=cold





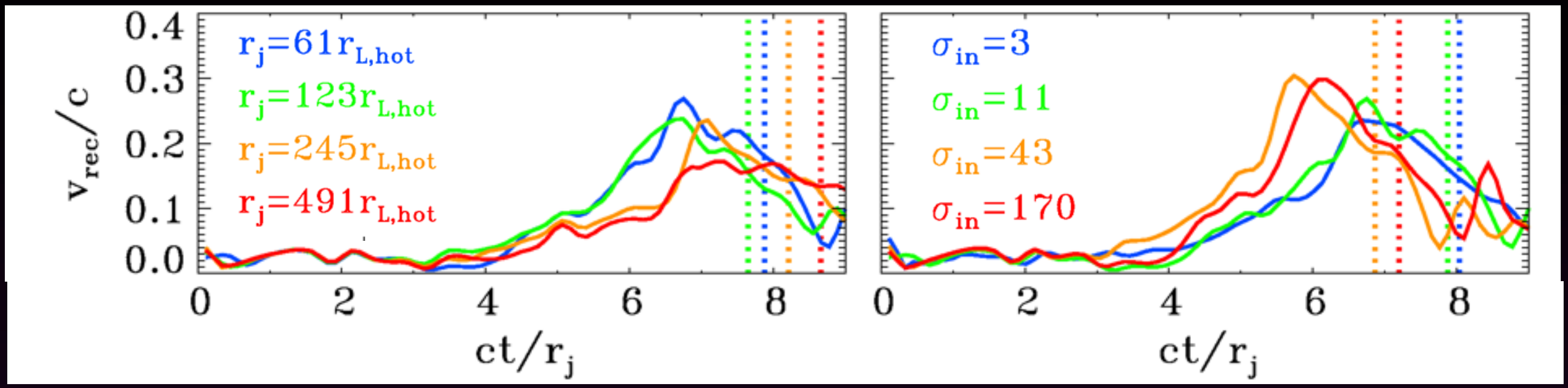
(Sironi+ 16, in prep)

- 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.
- The highest energy particles are highly anisotropic (see also Cerutti+ 12, 13).

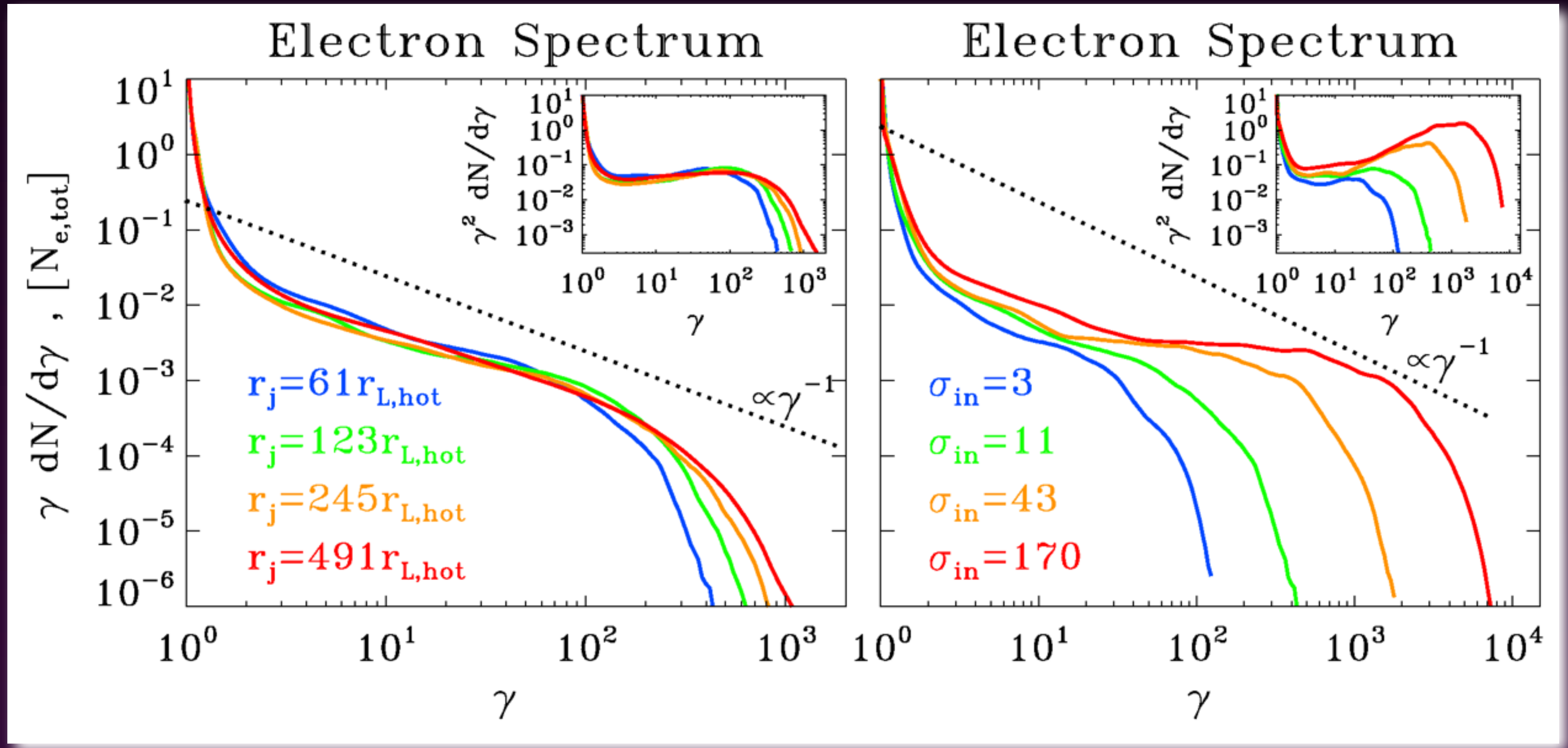


Dependence on the flow parameters

- The reconnection rate is ~0.3 → E/B~0.3.



- For $\sigma_{in}\gtrsim10$, the power-law slope is hard: $p\lesssim2$.
- The high energy cutoff grows linearly with the flux rope radius r_j and with the magnetization σ_{in} → acceleration on dynamical ($\sim r_j$) length scales.



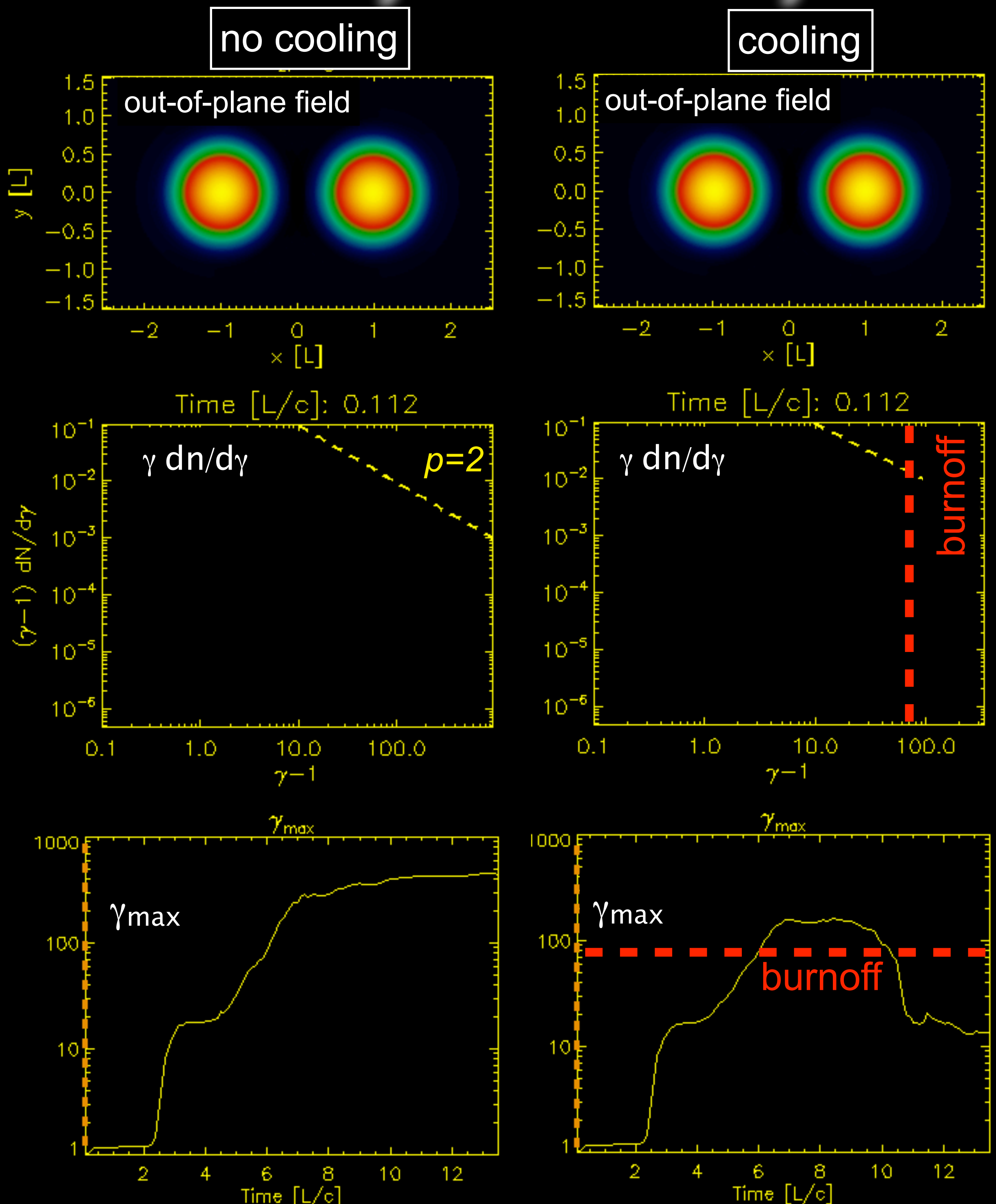
Beyond the synchrotron burnoff

Synchrotron burnoff limit: balance of acceleration by E~B with synchrotron cooling gives

$$\gamma_{\rm max} \propto B^{-1/2}$$

$$h\nu_{\rm sync,max} \sim 150 \ {\rm MeV}$$

Beyond the synchrotron burnoff



Synchrotron burnoff limit: balance of acceleration by E~B with synchrotron cooling gives

$$\gamma_{\rm max} \propto B^{-1/2}$$

$$h\nu_{\rm sync,max} \sim 150\ {\rm MeV}$$

- Particles are accelerated in the (macroscopic) current sheet, where B is small, and they can be accelerated beyond the synchrotron burnoff limit.

(see also Cerutti+ 12,13 for plane-parallel reconnection).

(Sironi+ 16, in prep)

Summary

• Relativistic magnetic reconnection ($\sigma \gtrsim 1$) is an efficient particle accelerator, in 2D and 3D. It produces 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 ~0.04 L (*Hillas criterion of relativistic reconnection*). In blazar jets, reconnection can accelerate UHECRs.

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