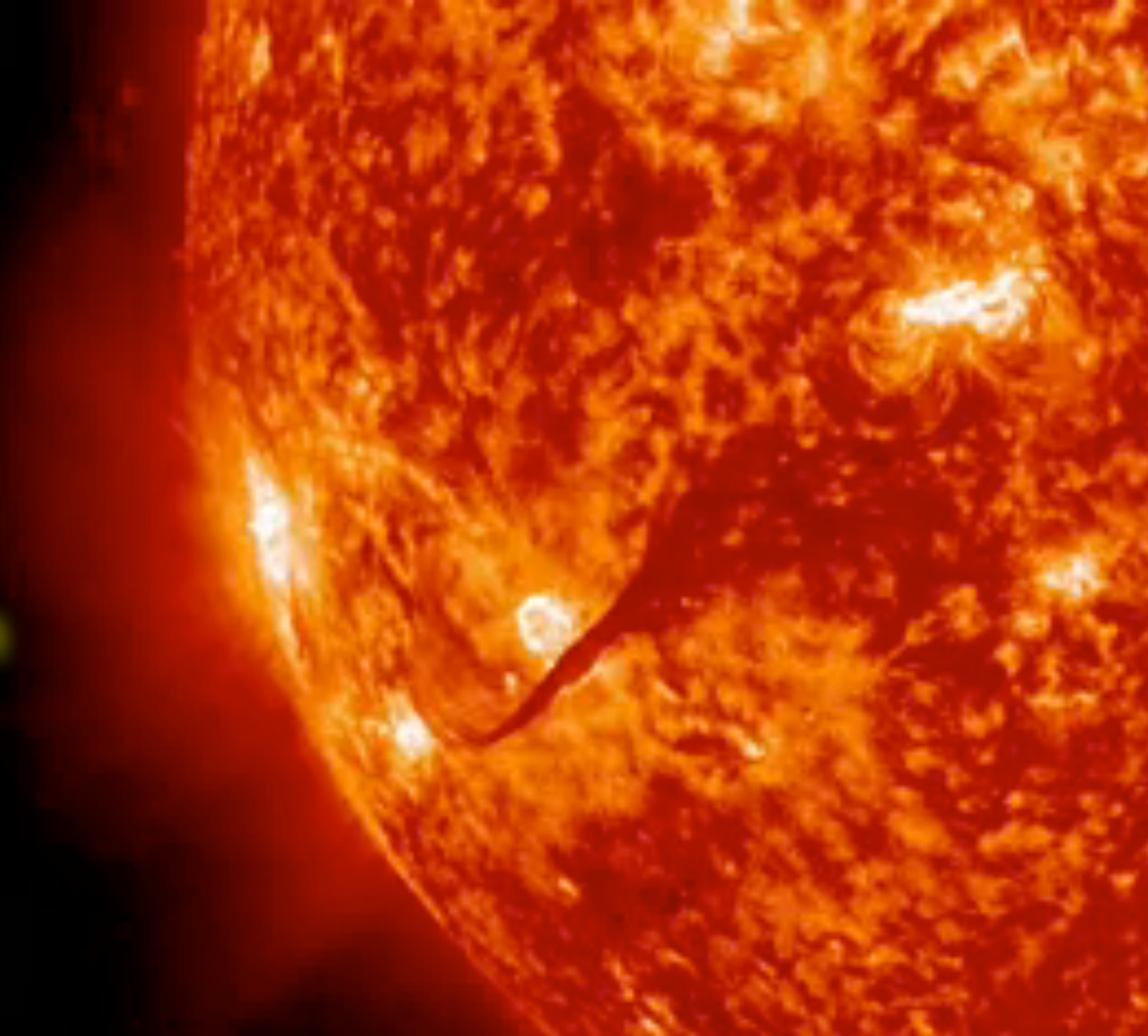
# Particle Acceleration by Relativistic Magnetic Reconnection



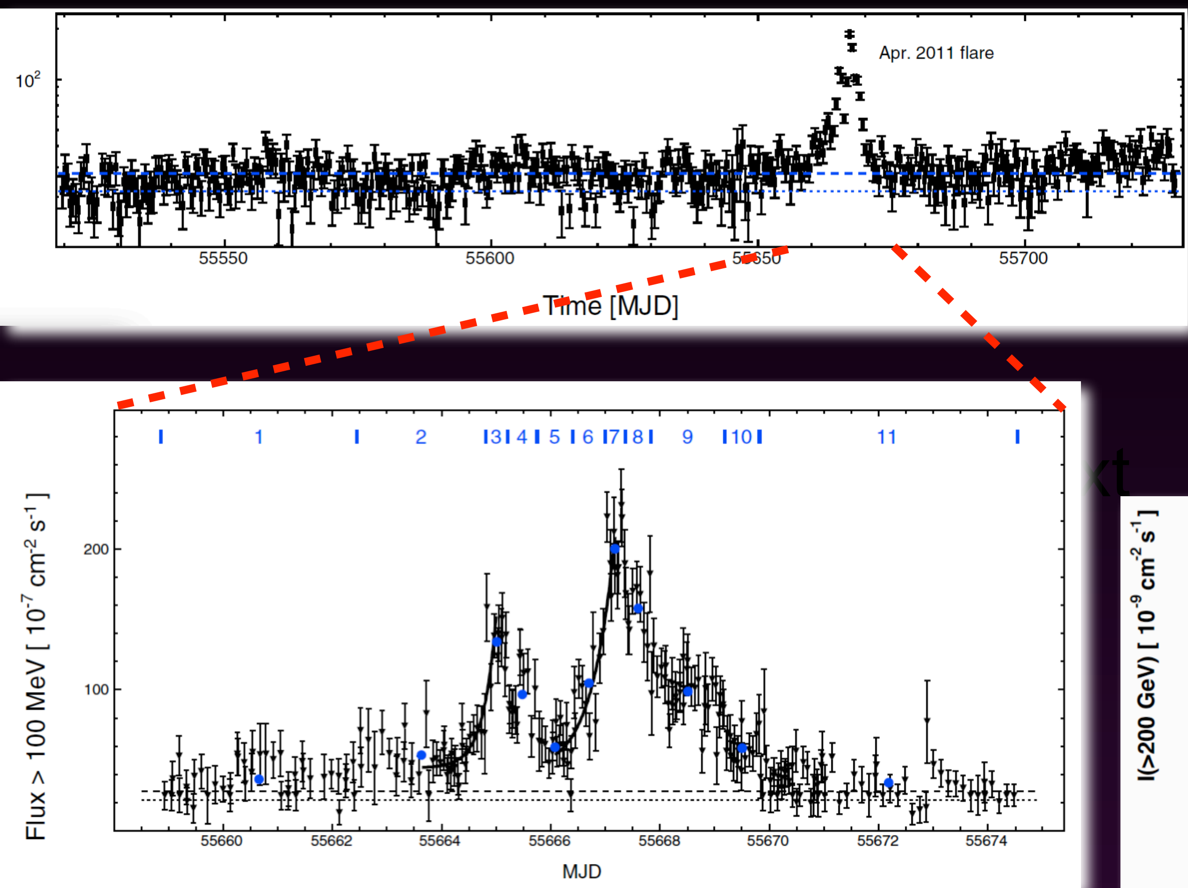
Lorenzo Sironi (ITC-Harvard), Einstein Fellow

“Relativistic Plasma Astro”, Purdue, May 13th 2014

LS 2014, in prep.; LS & Spitkovsky, A. 2014, ApJL, 783, L21

# Fast flares in relativistic flows

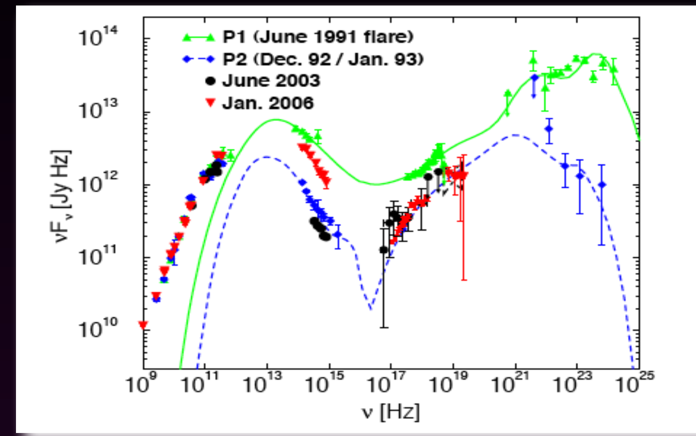
## Crab Nebula

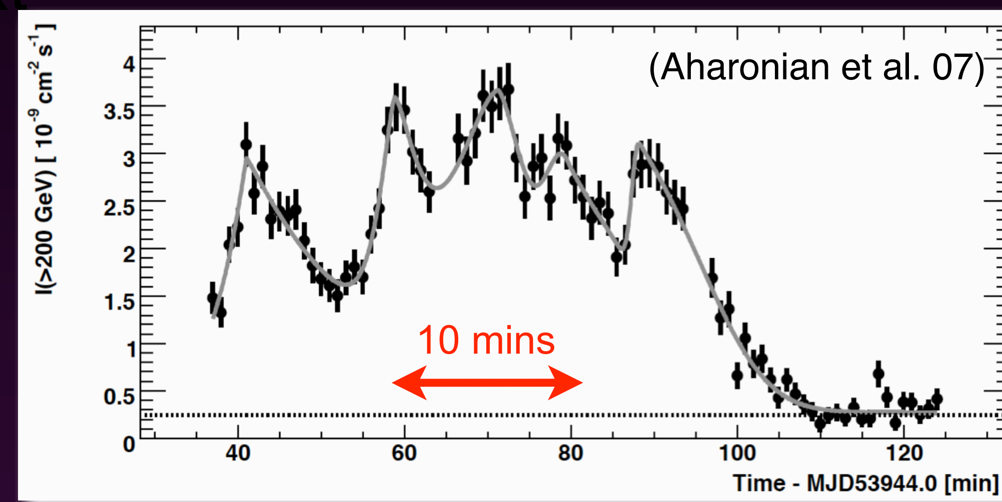



(Buehler et al. 12)

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

## TeV blazars

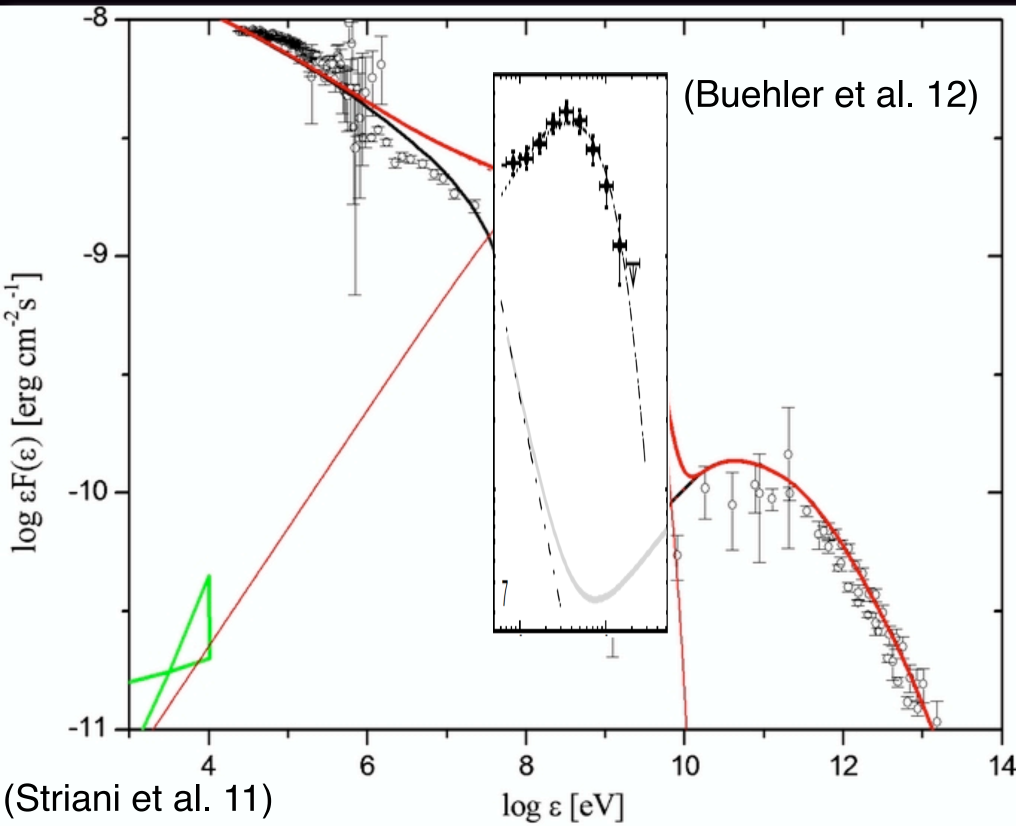



~10 minutes flares on top of a high-state “envelope” that lasts for ~days

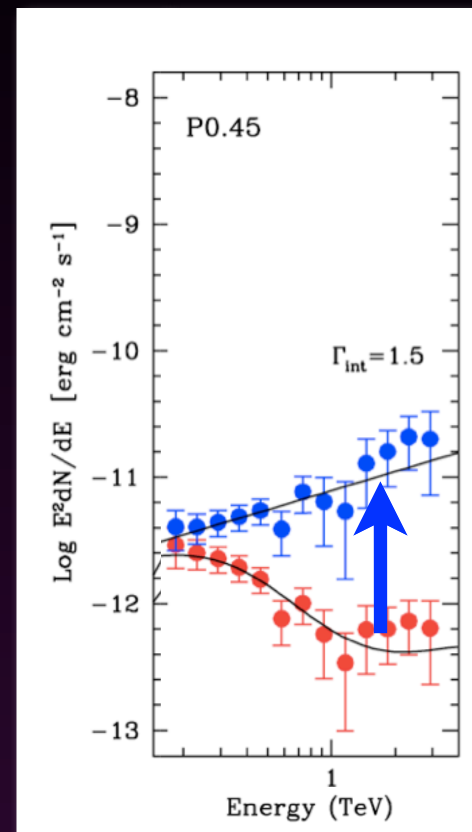
# Hard spectra in relativistic flows

**Crab Nebula**

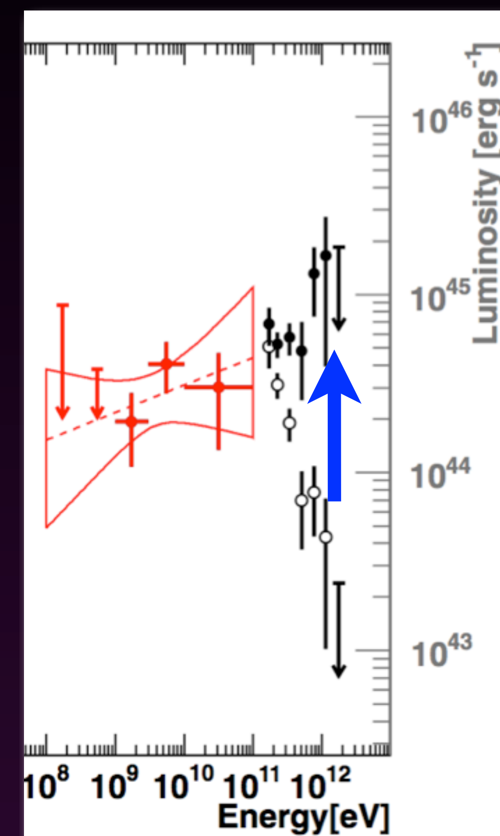



The flare spectrum below the peak requires $p$<2. $\frac{dn}{d\gamma} \propto \gamma^{-p}$

**TeV blazars**




(Aharonian et al. 06)



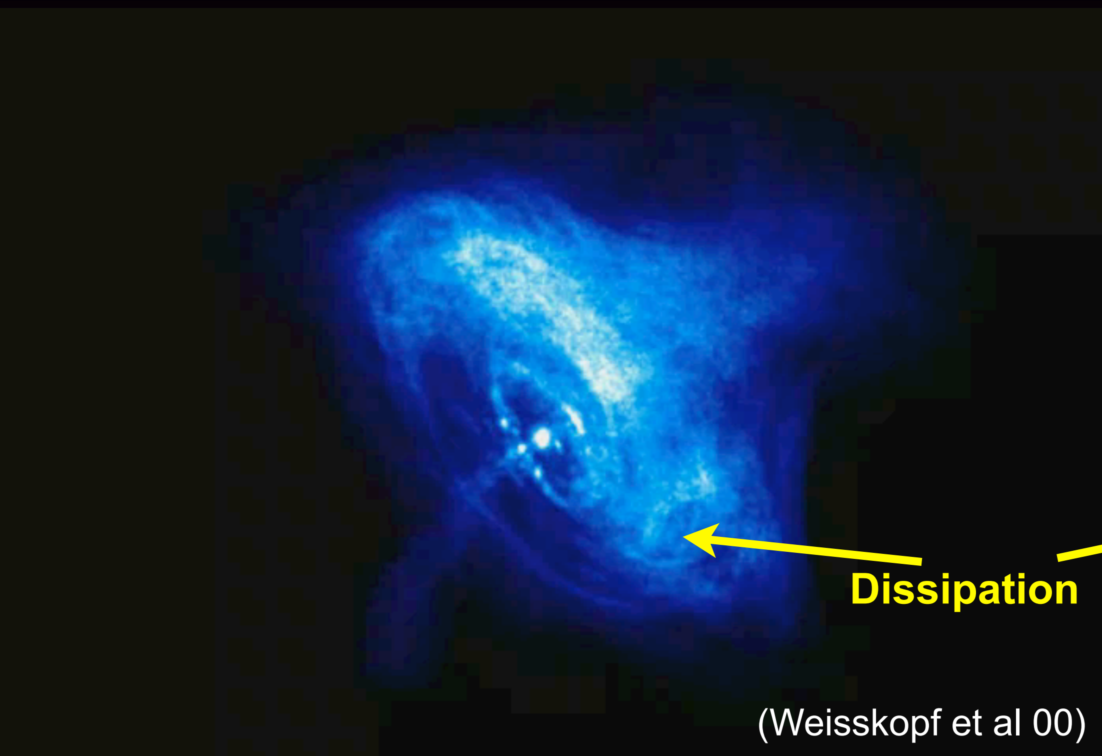

(HESS 11)

After correcting for EBL absorption, the inferred TeV spectra are extremely hard (requiring $p$<2).

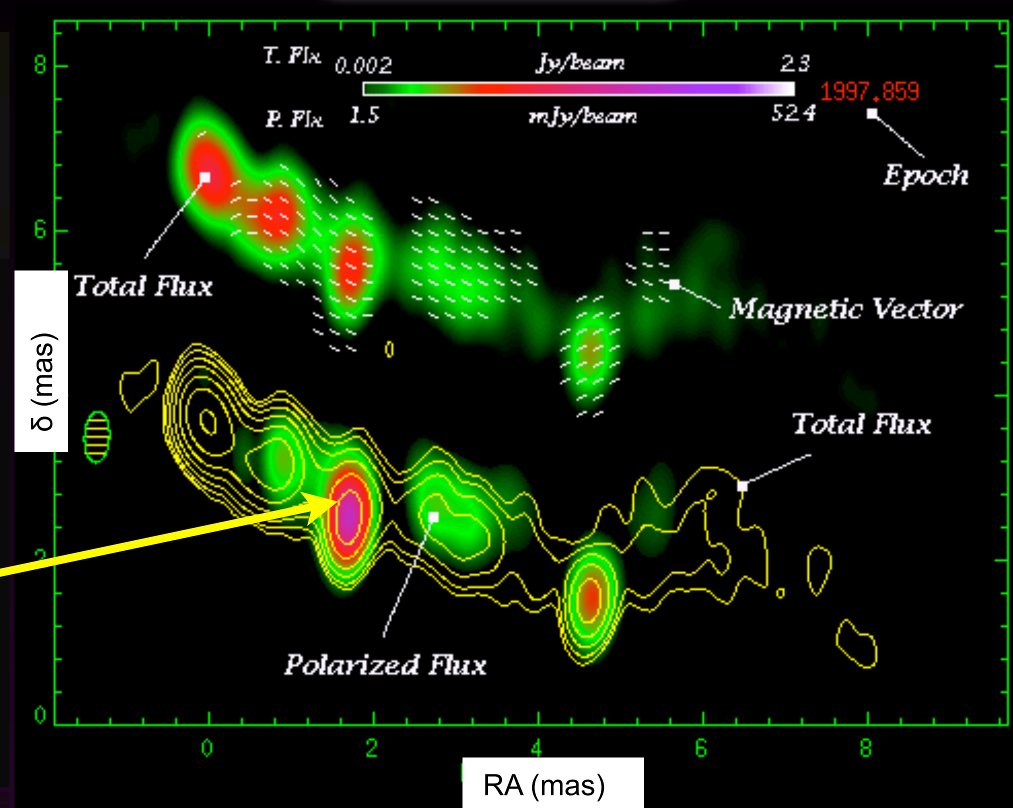
# Dissipation in relativistic outflows

Crab Nebula

3C 120




**Dissipation**

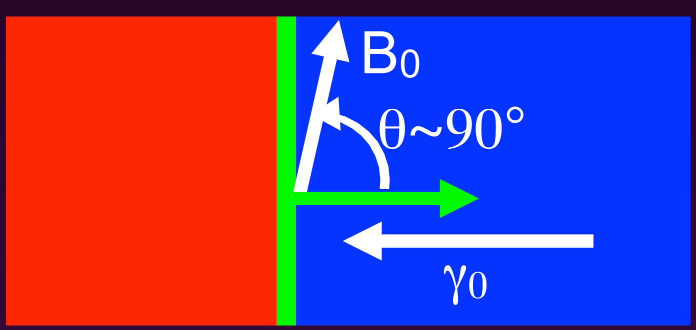



Relativistic outflows: $\gamma_0 >> 1$

Magnetized: $\sigma > 0.01$

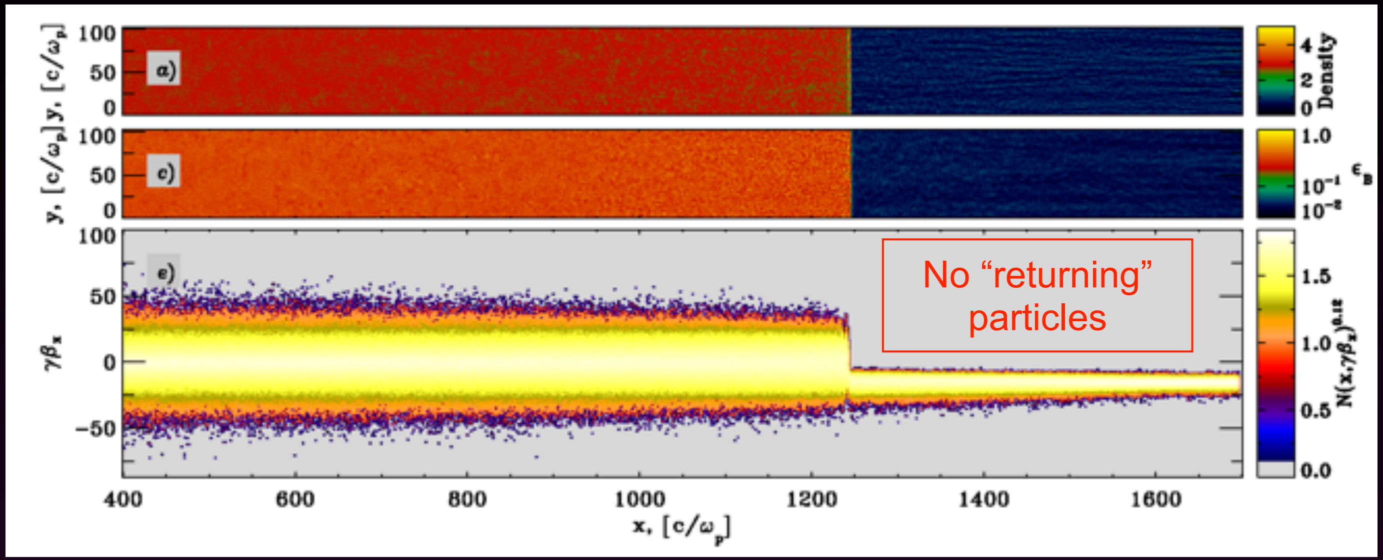
If shocks, then the field is $\perp$ to the shock normal

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



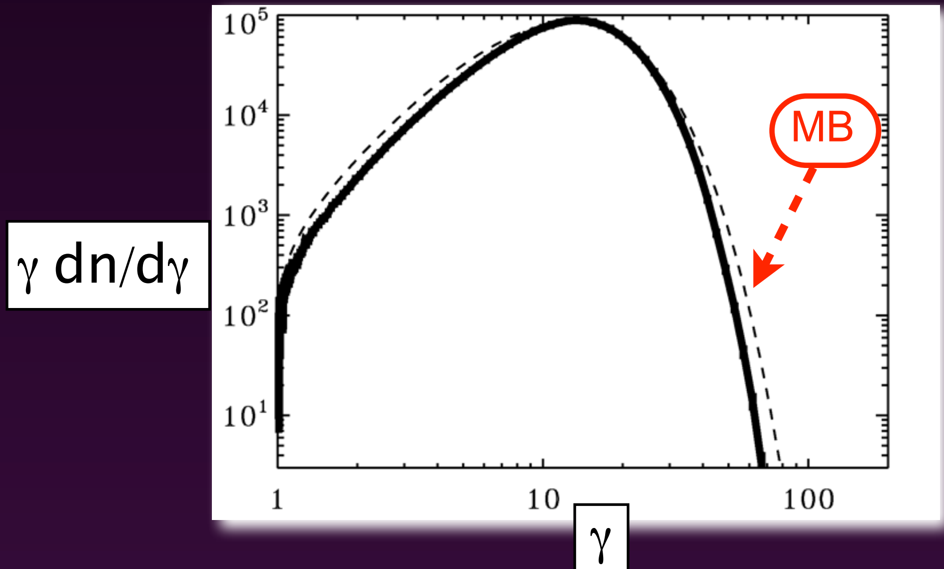
# Shocks: no turbulence → no acceleration

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




No "returning" particles → No self-generated turbulence

No self-generated turbulence → No particle acceleration

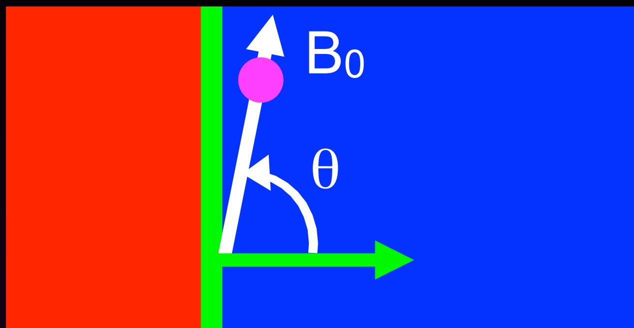



Spectrum fitted by a Maxwellian

(LS & Spitkovsky 11a)

# The shock(ing) puzzle

Strongly magnetized ($\sigma > 10^{-3}$) quasi-perp $\gamma_0 \gg 1$ shocks are poor particle accelerators

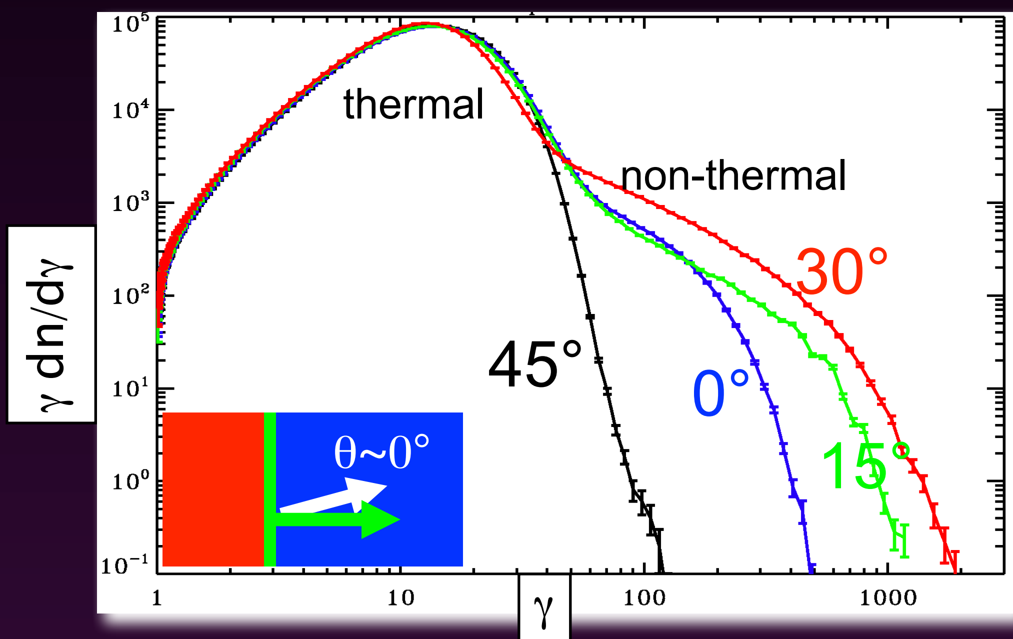


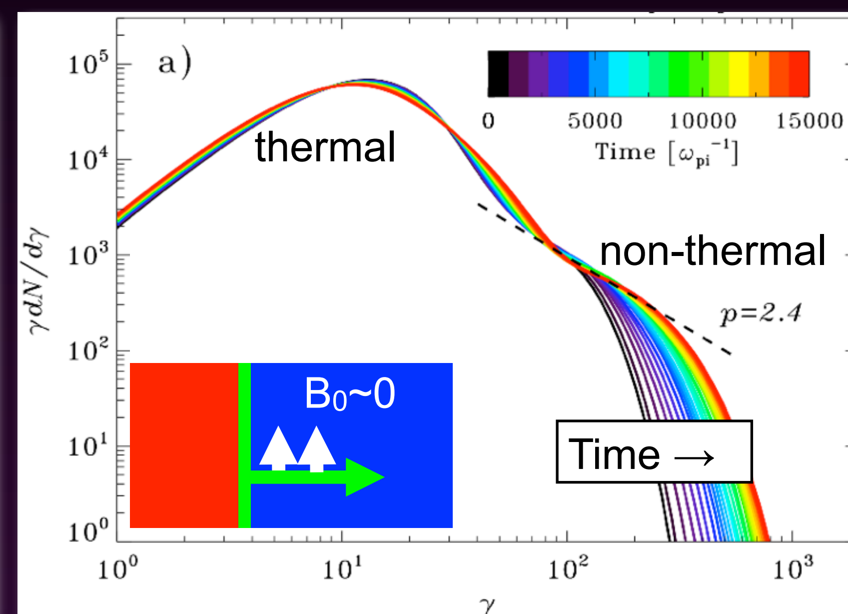

σ is large → particles slide along field lines

θ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

→ Fermi acceleration is generally suppressed

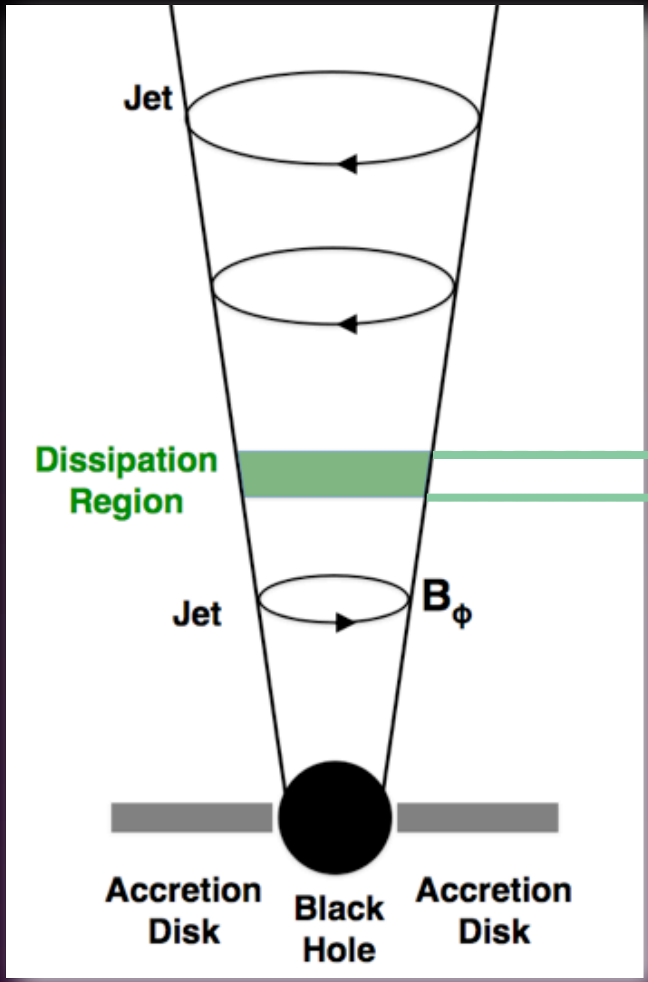


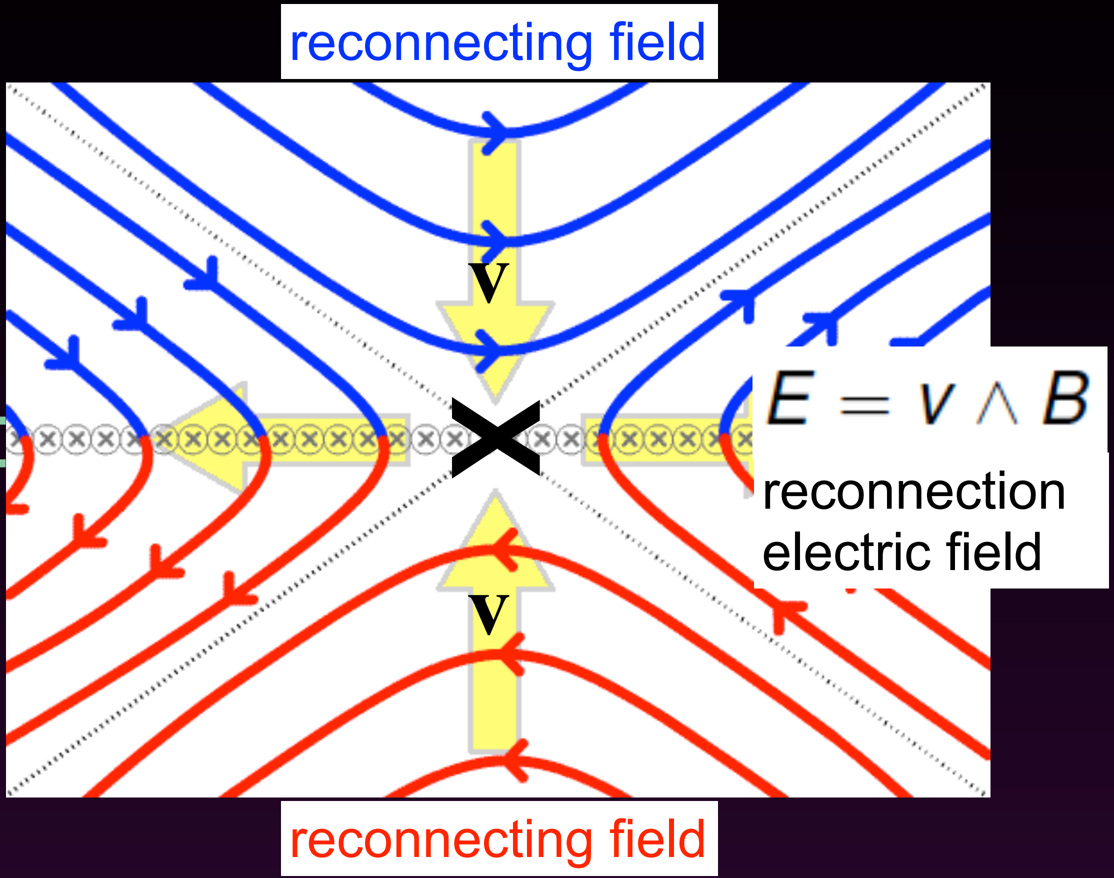




(LS et al. 13)

- Non-thermal energy spectra from shocks are steep (*p*>2).
- Shocks are not a natural explanation for the fast time variability.

# Relativistic magnetic reconnection



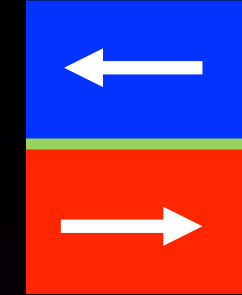

Relativistic Reconnection

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

*References: most of the people in this room*

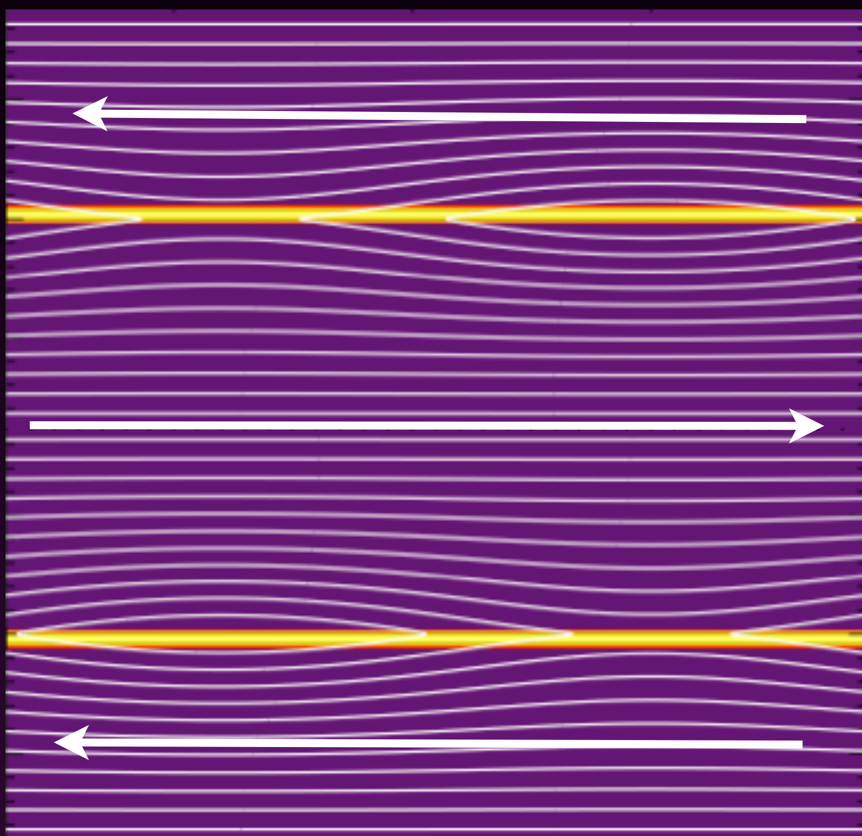
Can relativistic magnetic reconnection self-consistently produce non-thermal particles?

# Simulation setup

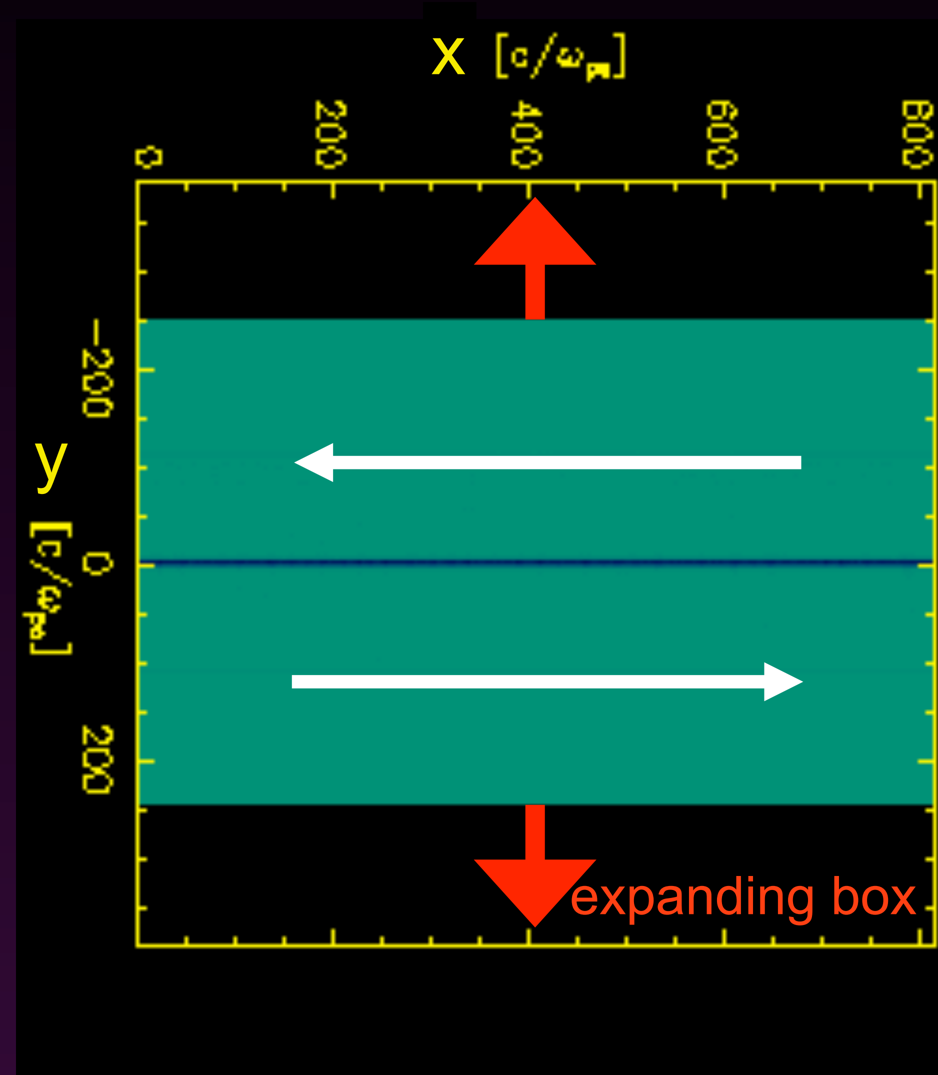


Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman '93, Spitkovsky '05)

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



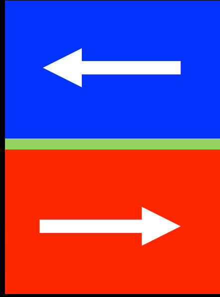
double-periodic boundary conditions



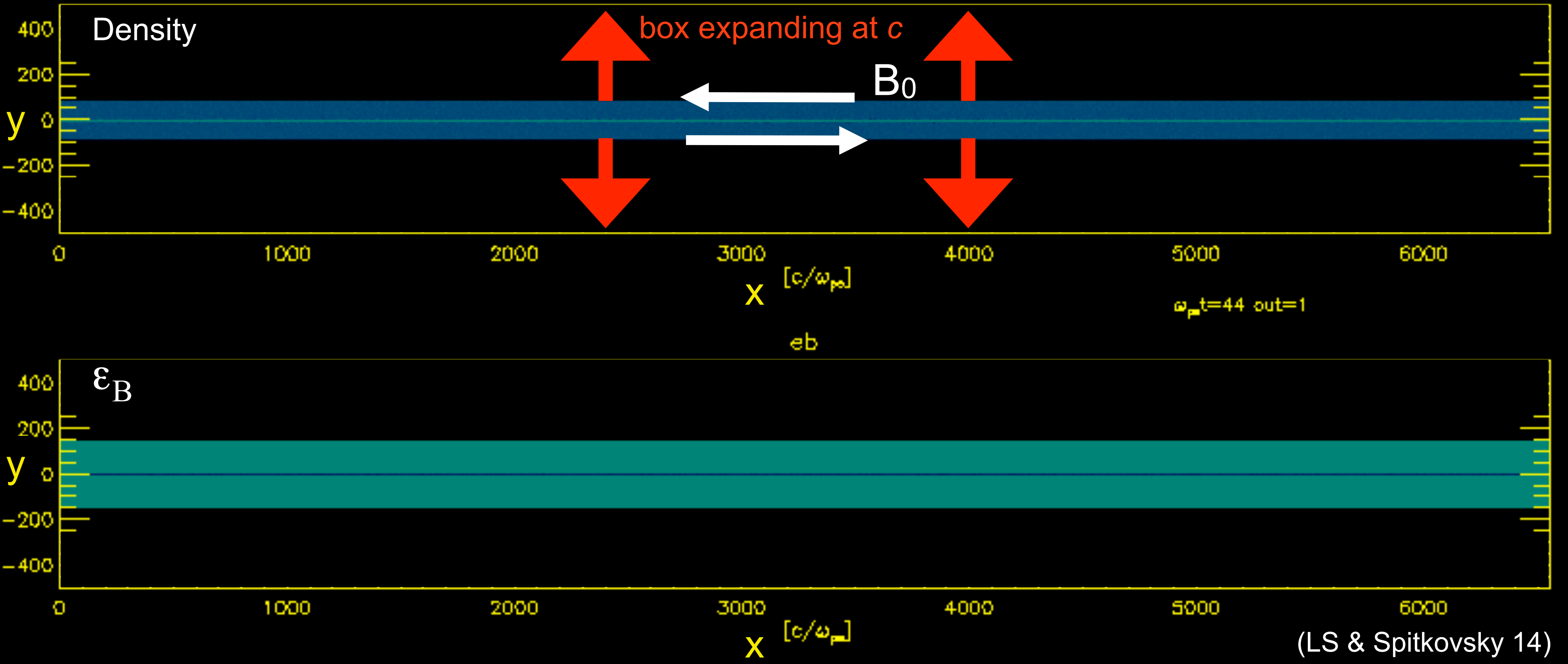

periodic in x, expanding along y at *c*

# Dynamics and particle spectrum

# Hierarchical reconnection



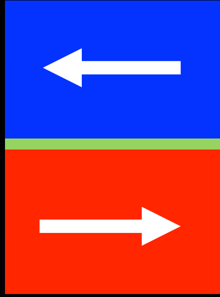
$\sigma$=10 electron-positron

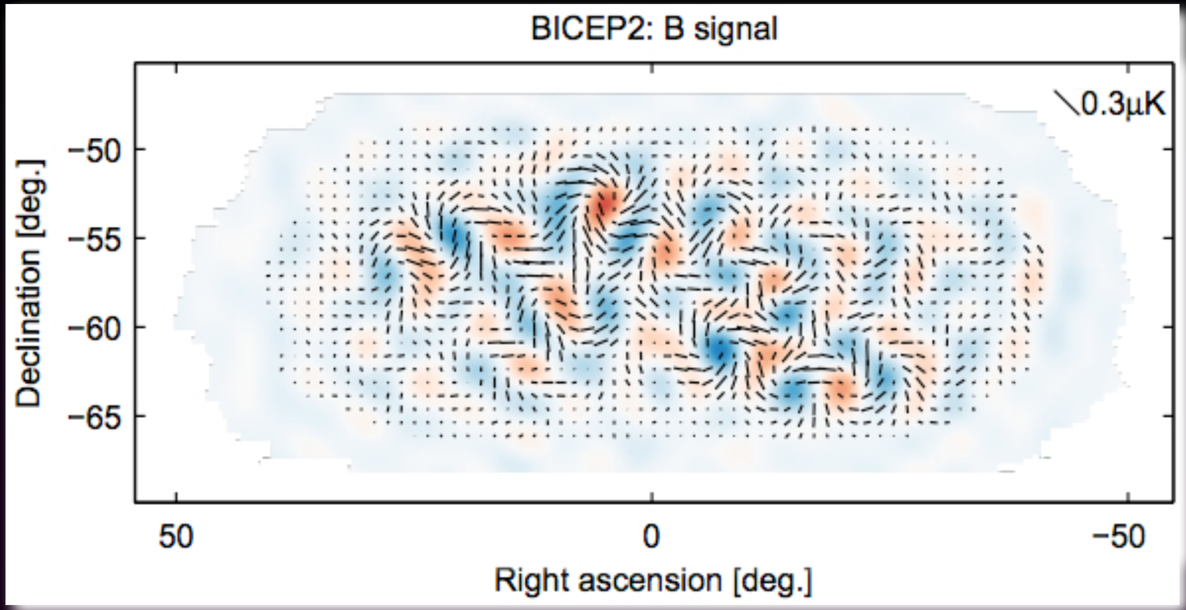


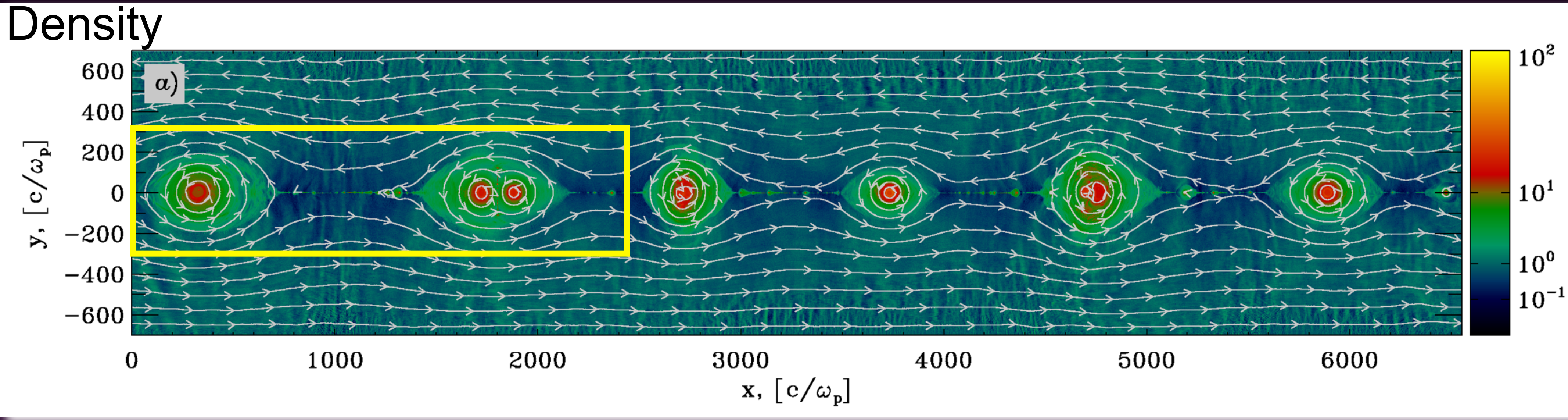

(LS & Spitkovsky 14)

- 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.

# Structure of the reconnection layer

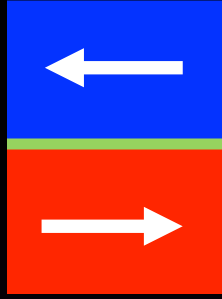




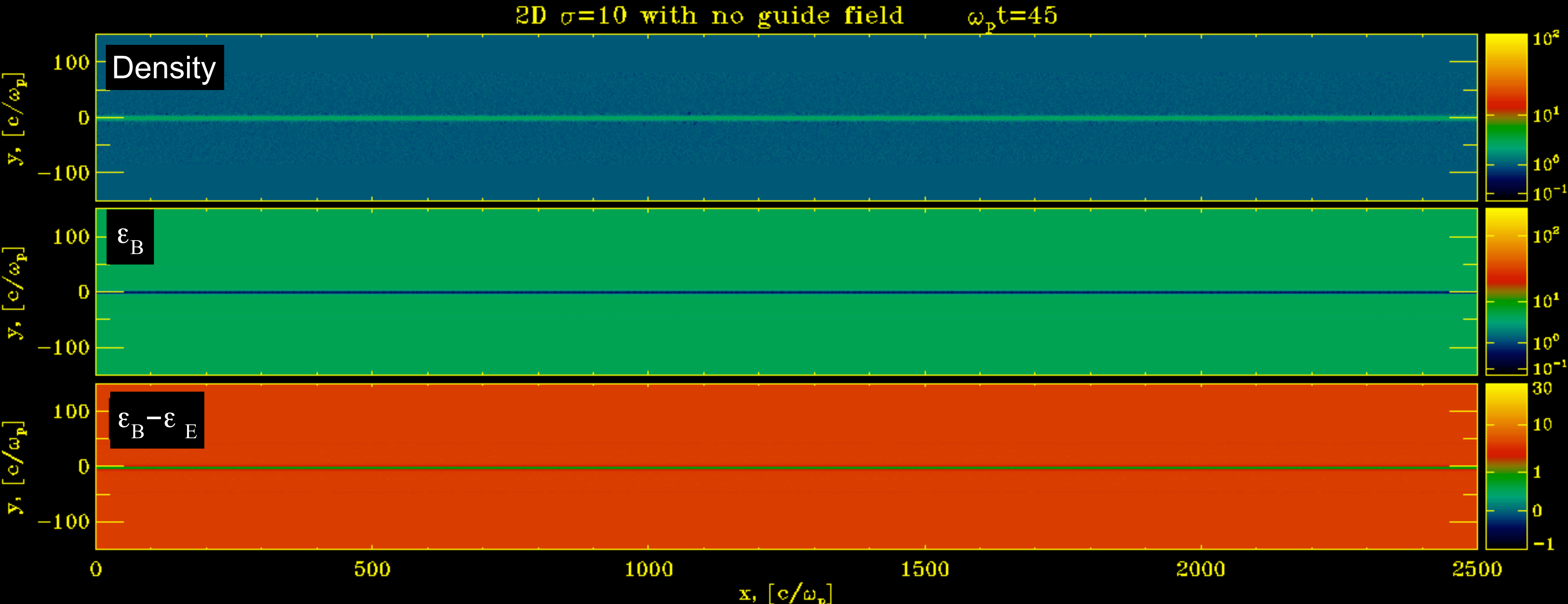




Reconnection rate: $r = \dfrac{v_{\rm in}}{v_A}$ $\qquad v_A = c\sqrt{\dfrac{\sigma}{1+\sigma}} \sim c$

# Hierarchical reconnection



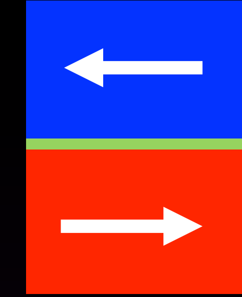
$\sigma=10$ electron-positron



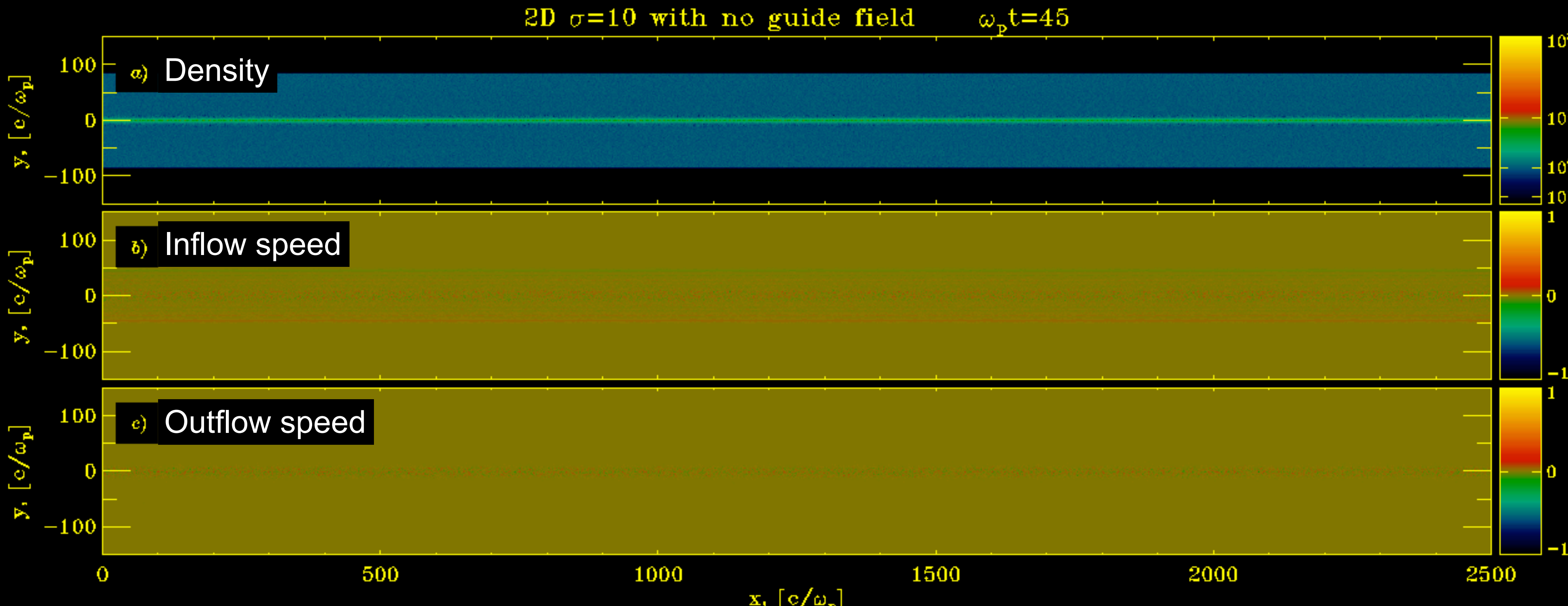

(LS & Spitkovsky 14)

- 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.
- Anti-reconnection occurs at the interface between two merging islands.

# Inflows and outflows



σ=10 electron-positron

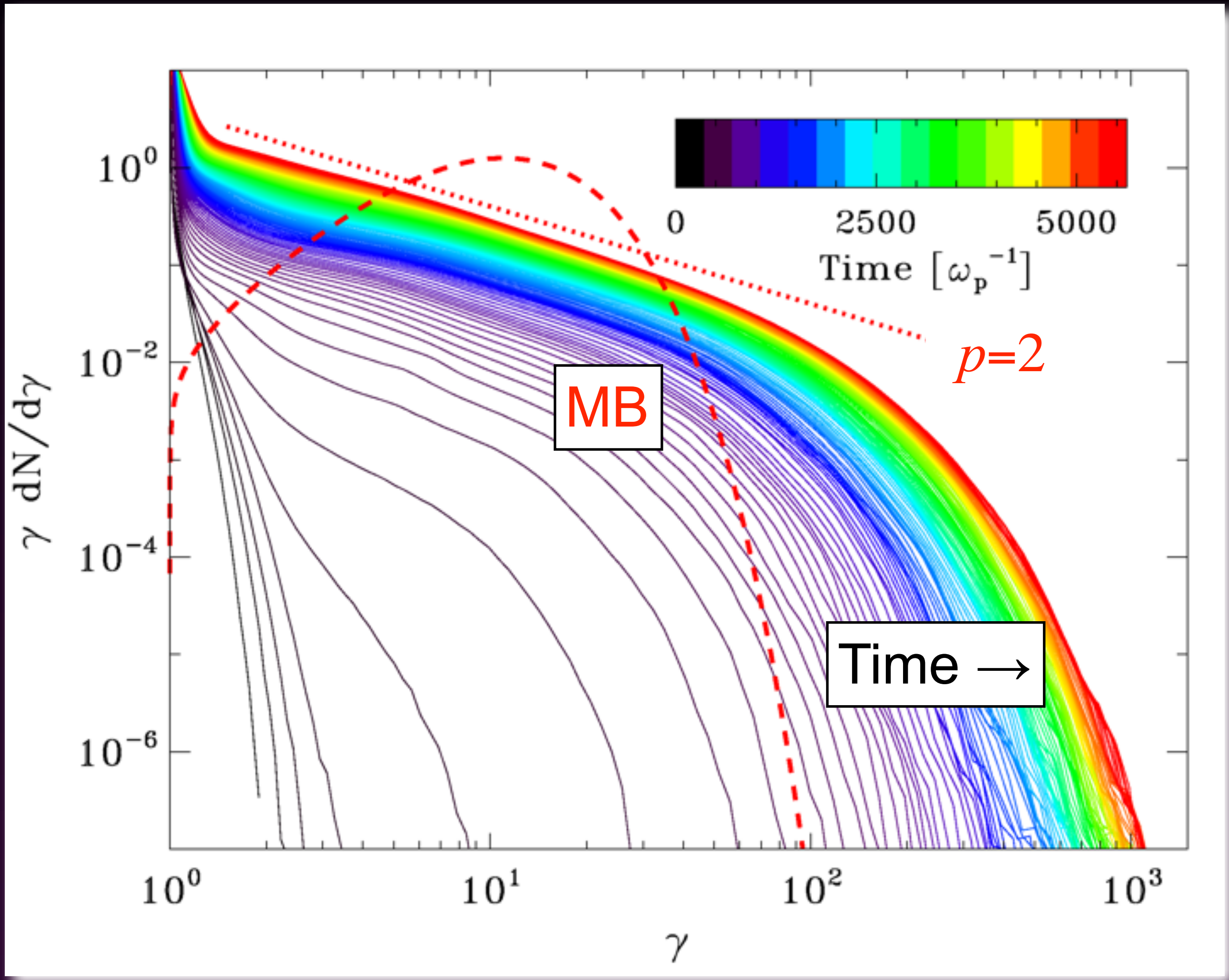



(LS 14, in prep)

- Inflow into the X-line is non-relativistic, $v_{in}$ ~ 0.1 c (so, the reconnection rate *r* ~ 0.1).
- Outflow into the islands is ultra-relativistic, at the Alfven speed $v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$

# The particle energy spectrum

σ=10 electron-positron

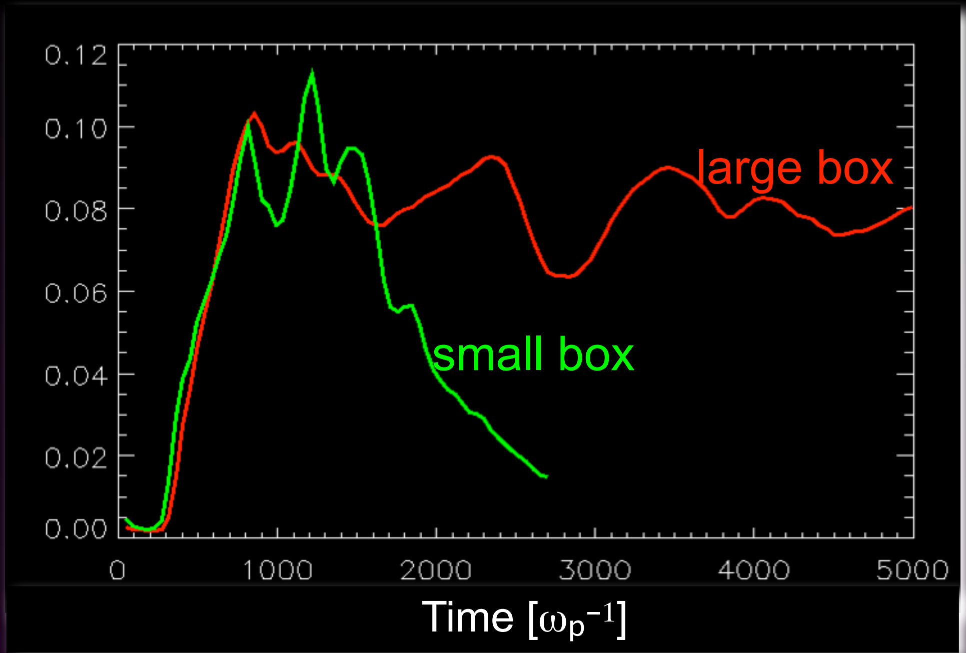



(LS & Spitkovsky 14)

- At late times, the particle spectrum in the current sheet approaches a power-law tail $dn/d\gamma \propto \gamma^{-p}$ of slope $p$~2.
- The normalization increases, as more and more particles enter the current sheet.
- The mean particle energy in the current sheet is ~σ/2 → energy equipartition

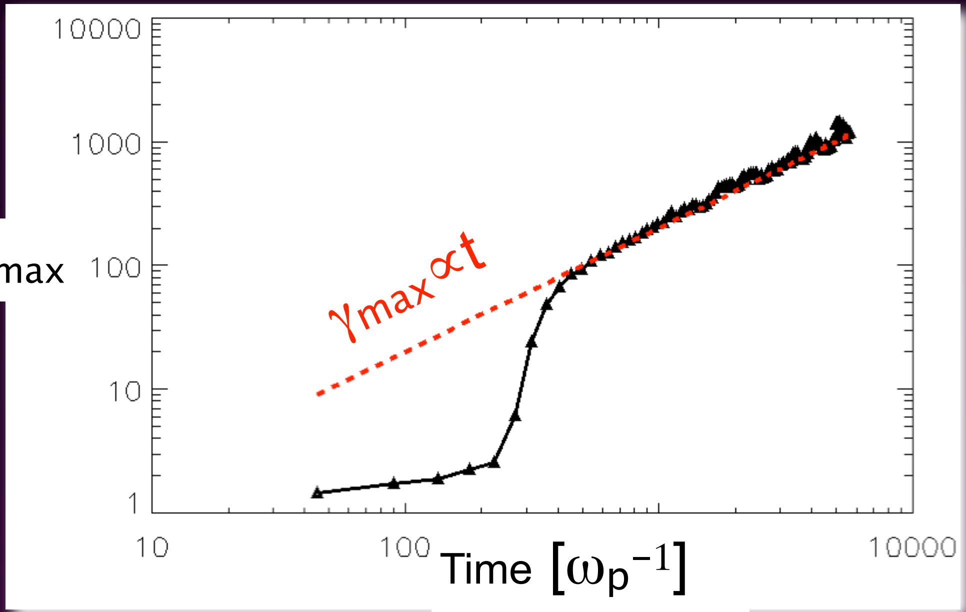
# The maximum particle energy

σ=10 electron-positron




$r \sim v_{in}/c$

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

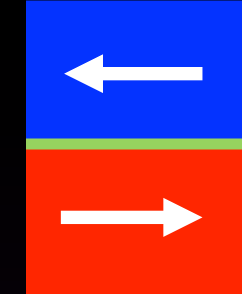



$\gamma_{max}$

- The maximum energy grows at a rate ~*r* so that $\gamma_{max} \propto t$ (compare to $\gamma_{max} \propto t^{1/2}$ in relativistic shocks).

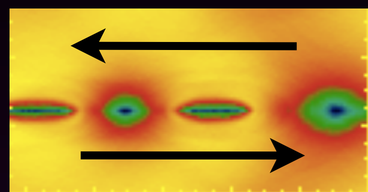
(LS & Spitkovsky 14)

# Tearing mode vs drift-kink mode



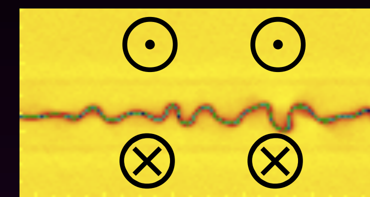
TEARING mode in the plane of alternating fields

$B_0$

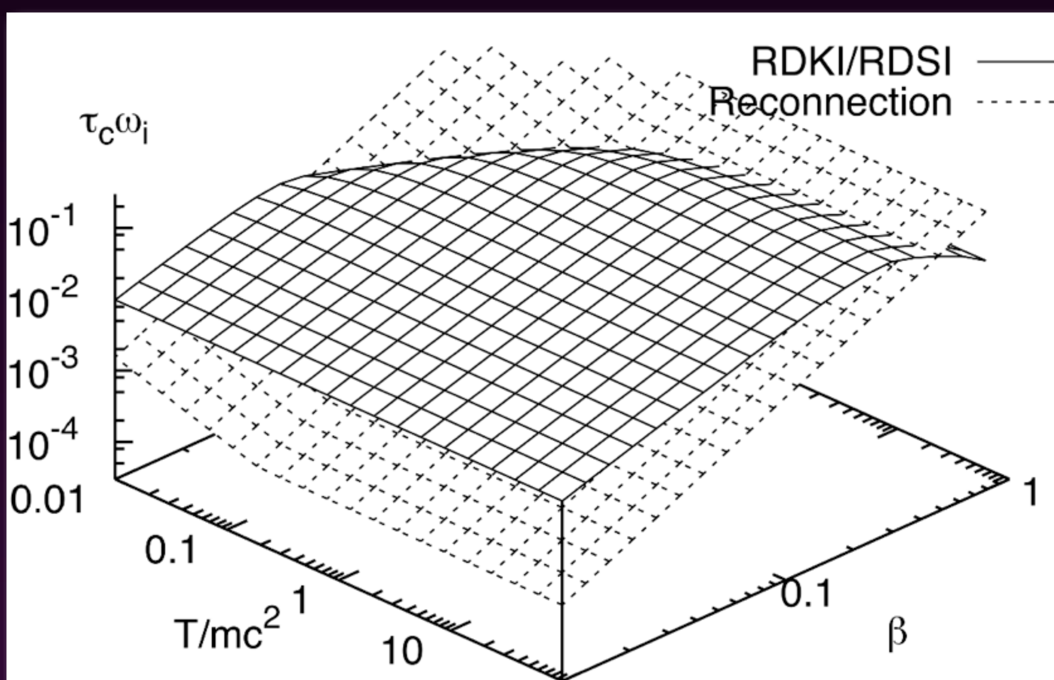


DRIFT-KINK mode perp to the plane of alternating fields

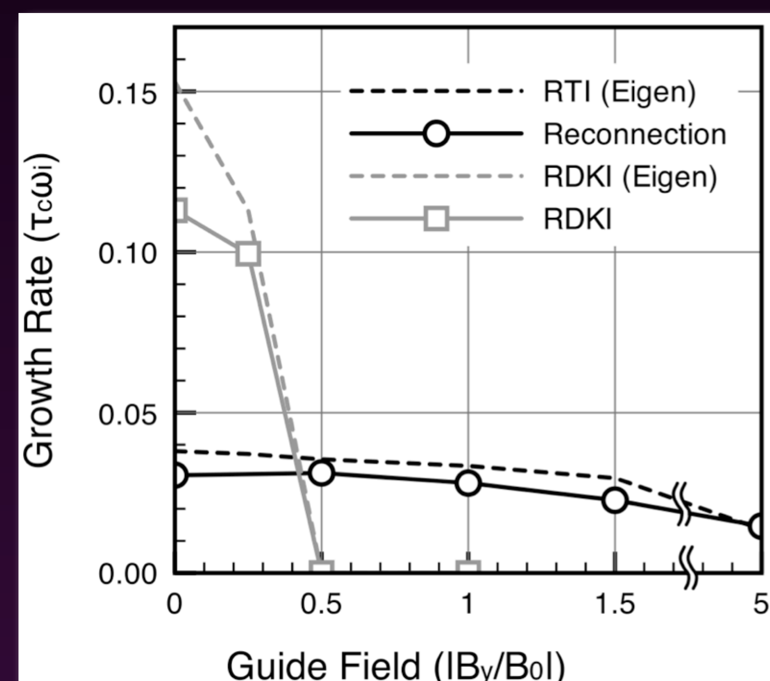
$B_0$



Which mode dominates in 3D?

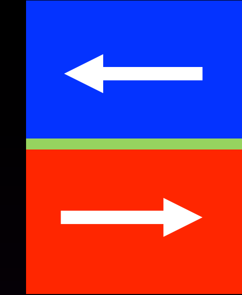


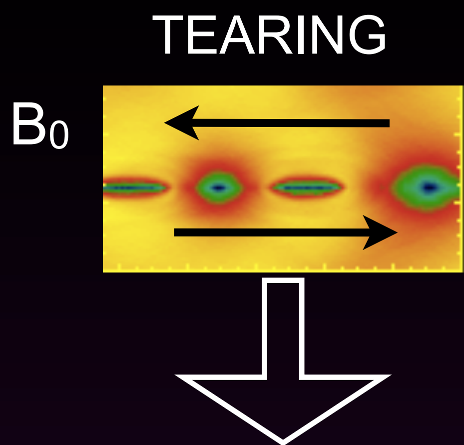

(Zenitani & Hoshino 07)

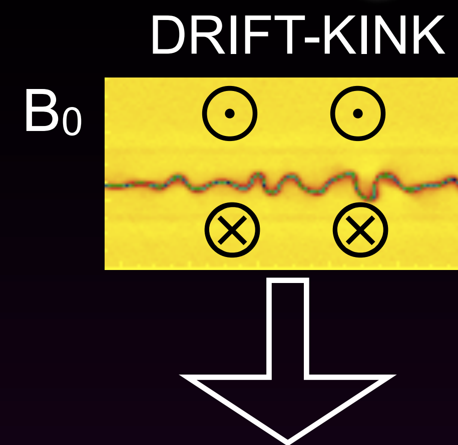


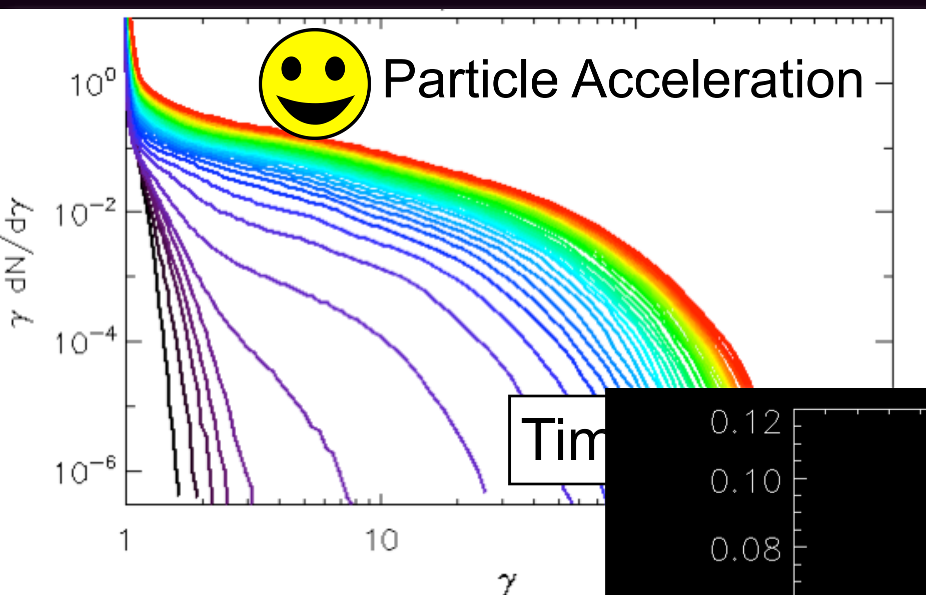

(Zenitani & Hoshino 08)

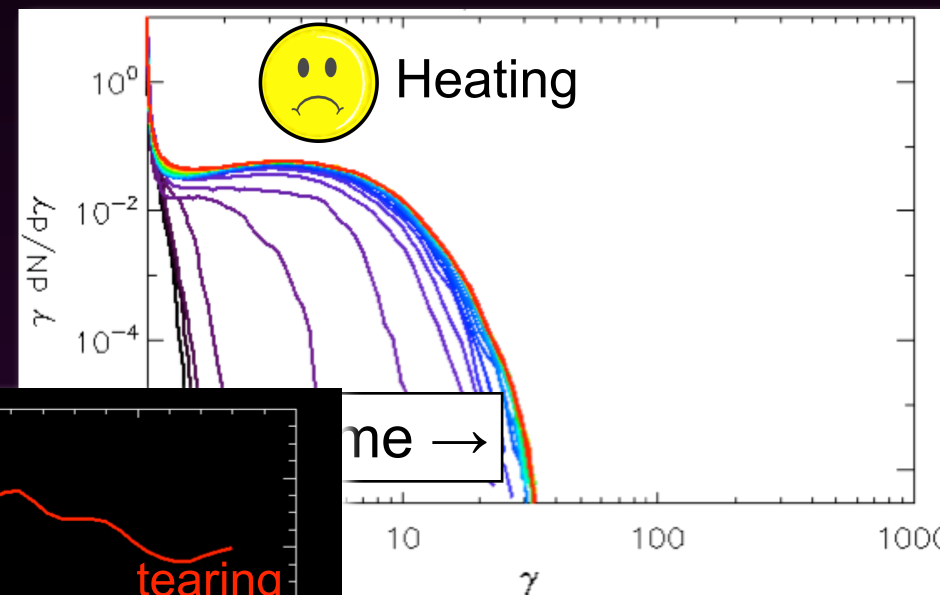
# Particle acceleration vs heating

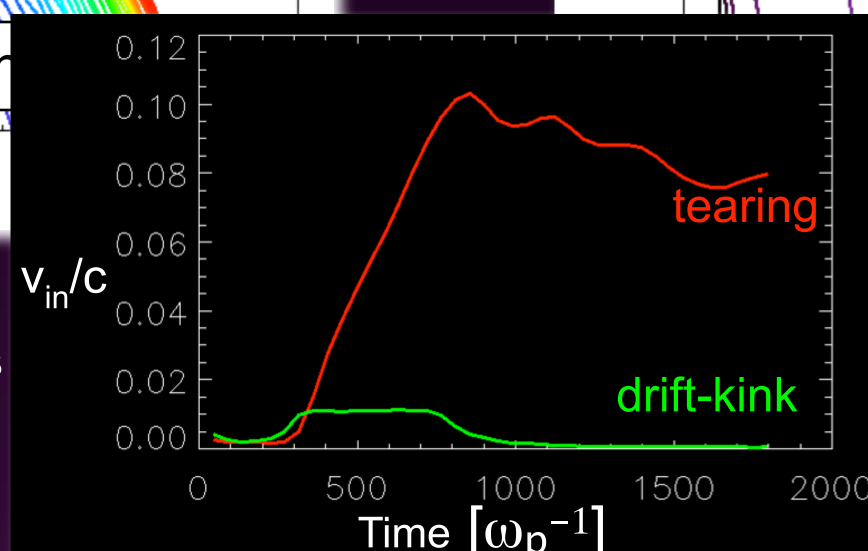




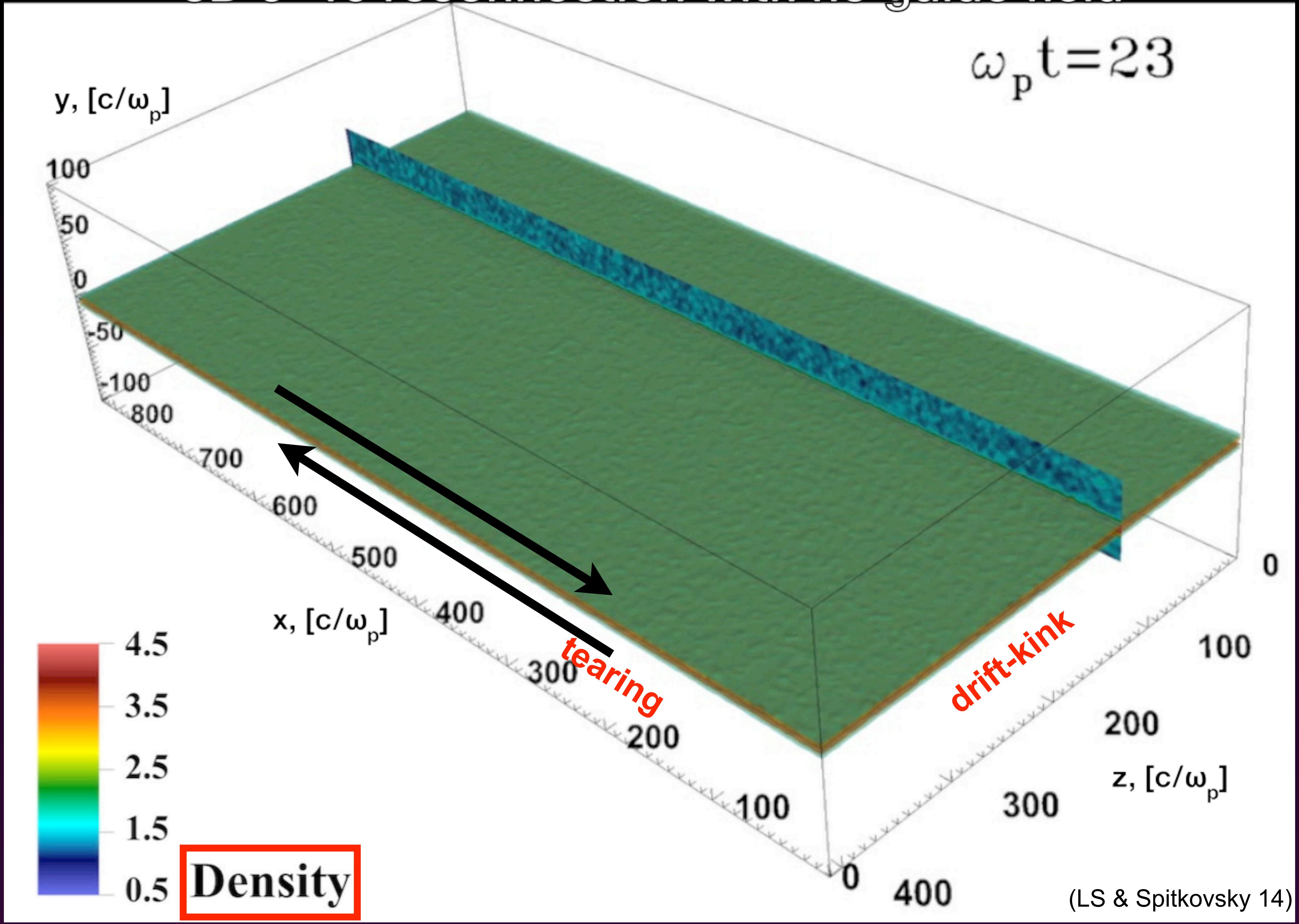




The DK mode saturates by broadening the current sheet.

esop, 600 BC)

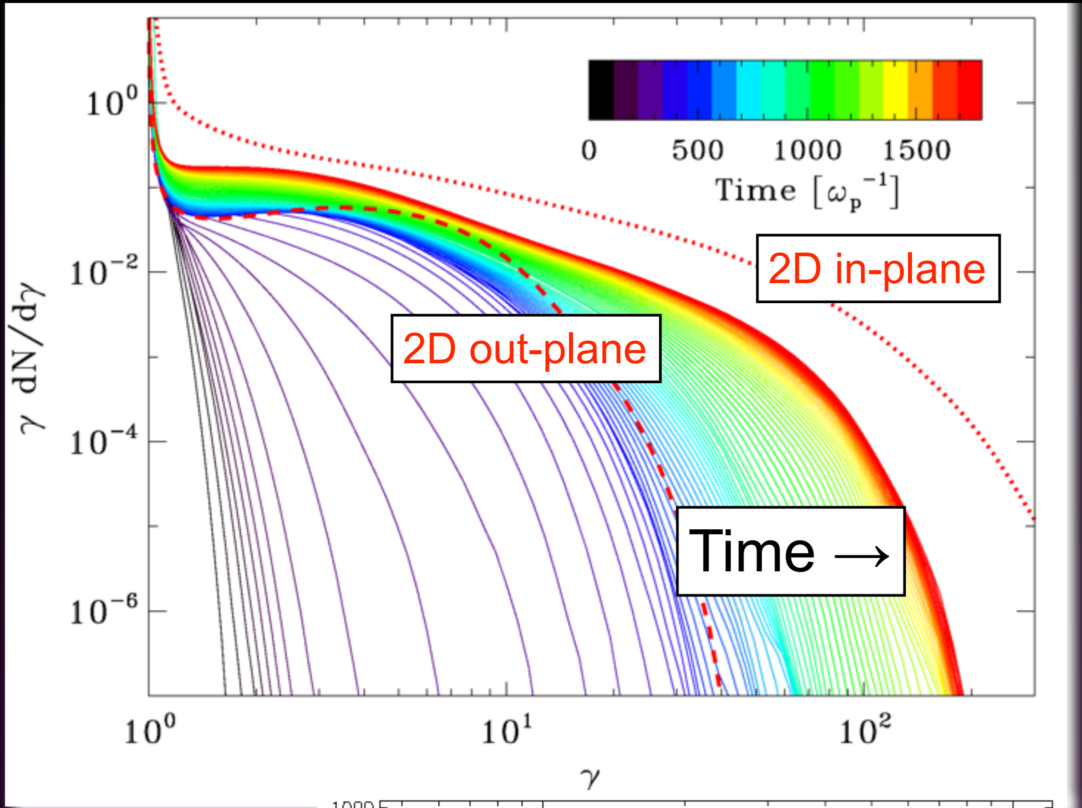
# 3D σ=10 reconnection with no guide field

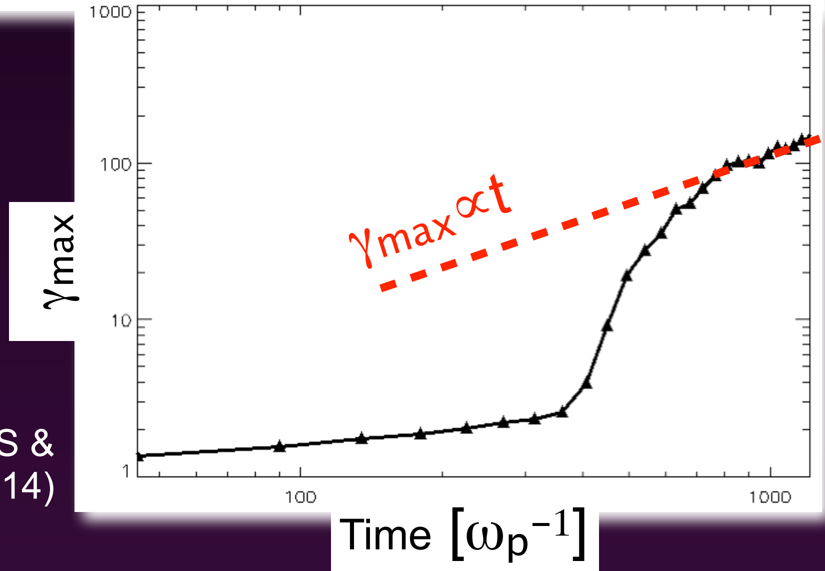



In 3D, the in-plane tearing mode controls the evolution at late times.

# 3D: particle spectrum

σ=10 electron-positron



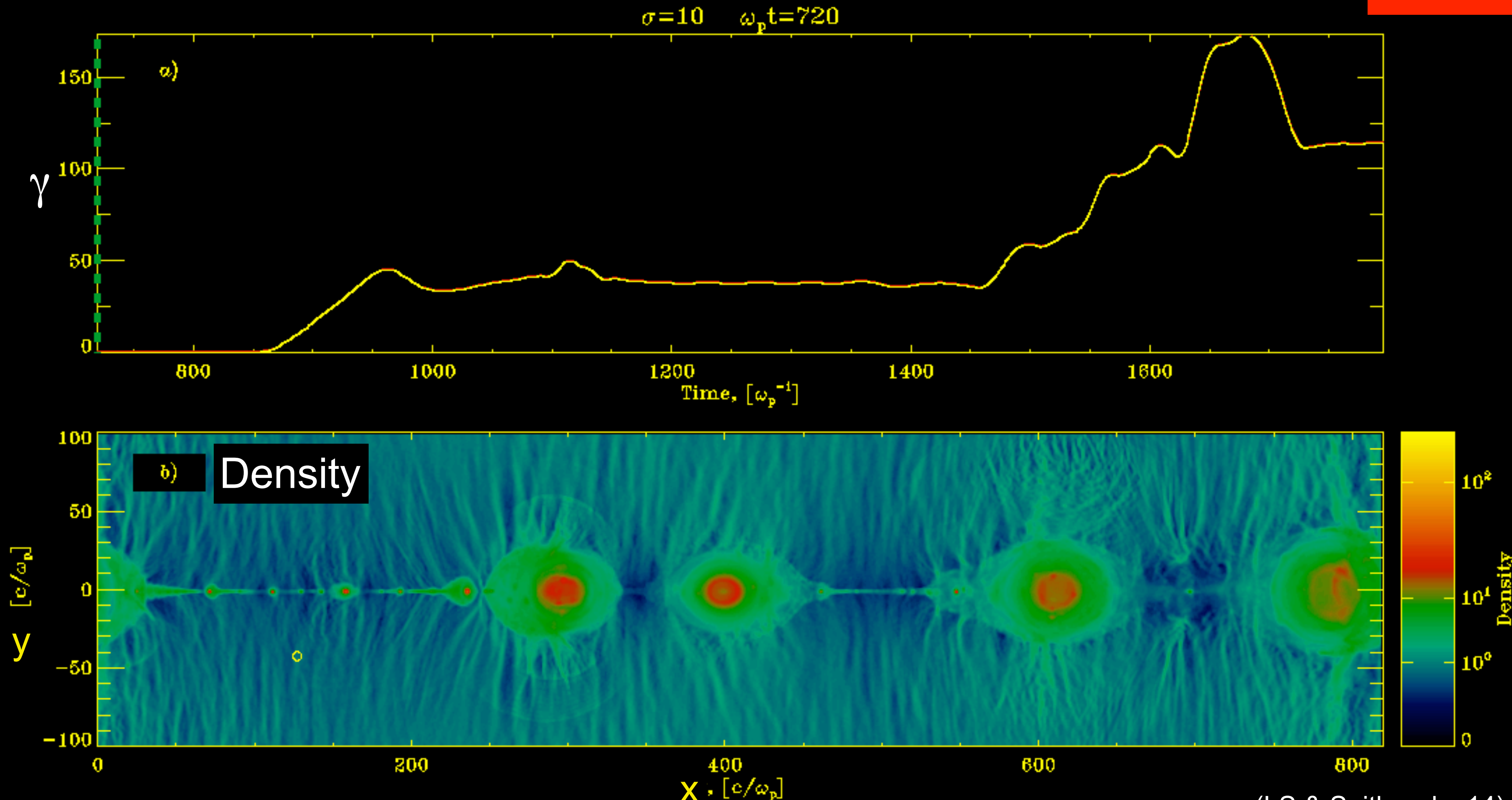

(LS & Spitkovsky 14)

- 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 *r* ~ 0.02 in 3D (vs *r* ~ 0.1 in 2D).

# The acceleration mechanism

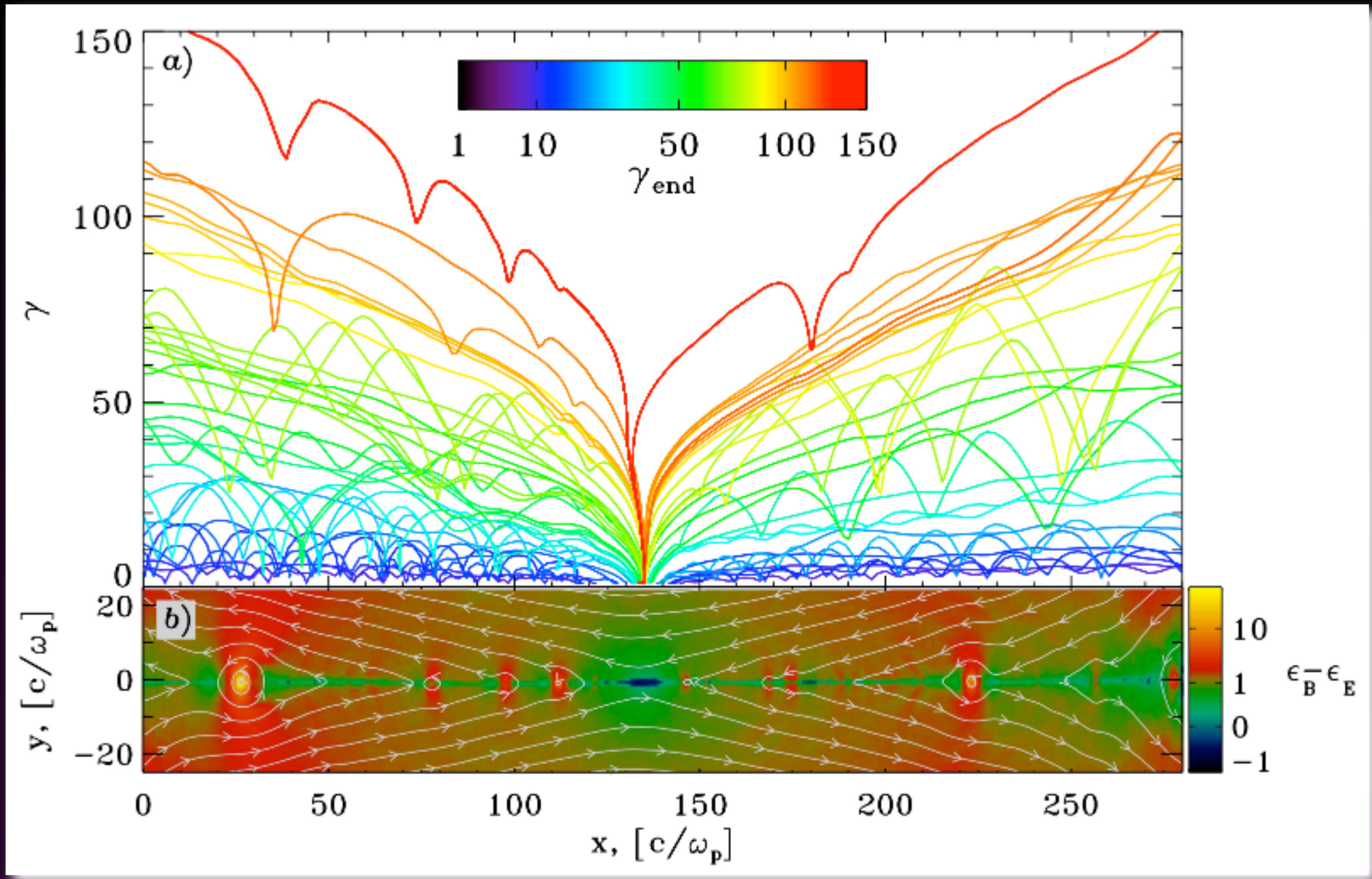
# The highest energy particles




(LS & Spitkovsky 14)

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

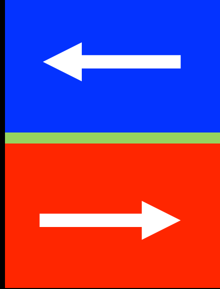
# Acceleration at X-points

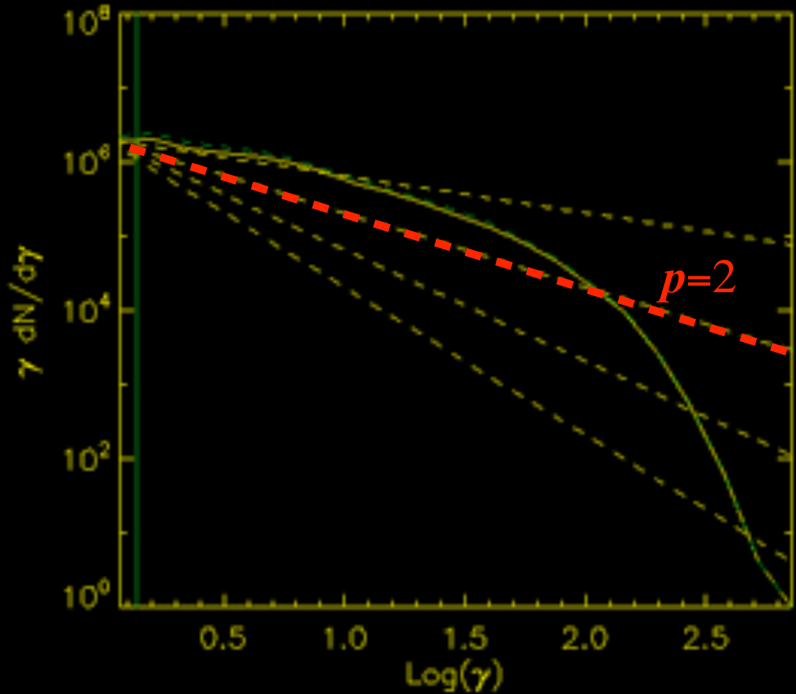


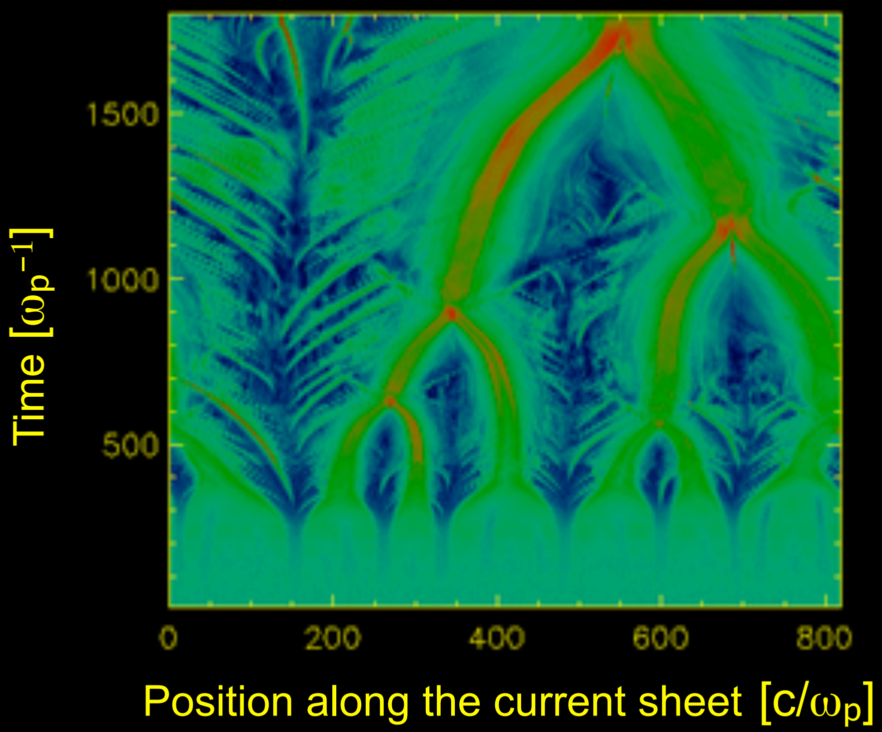

(LS & Spitkovsky 14)

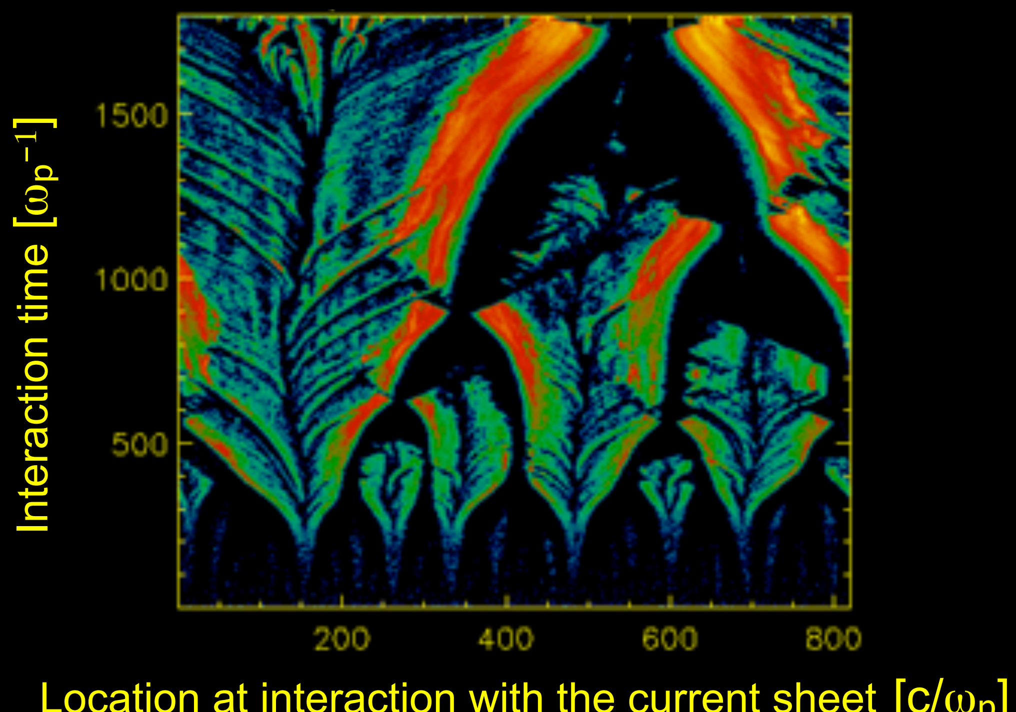
- The particles are accelerated by the reconnection electric field at the X-points, and then advected into the nearest magnetic island.
- The energy gain can vary, depending on where the particle interacts with the sheet.

# Primary & secondary X-points

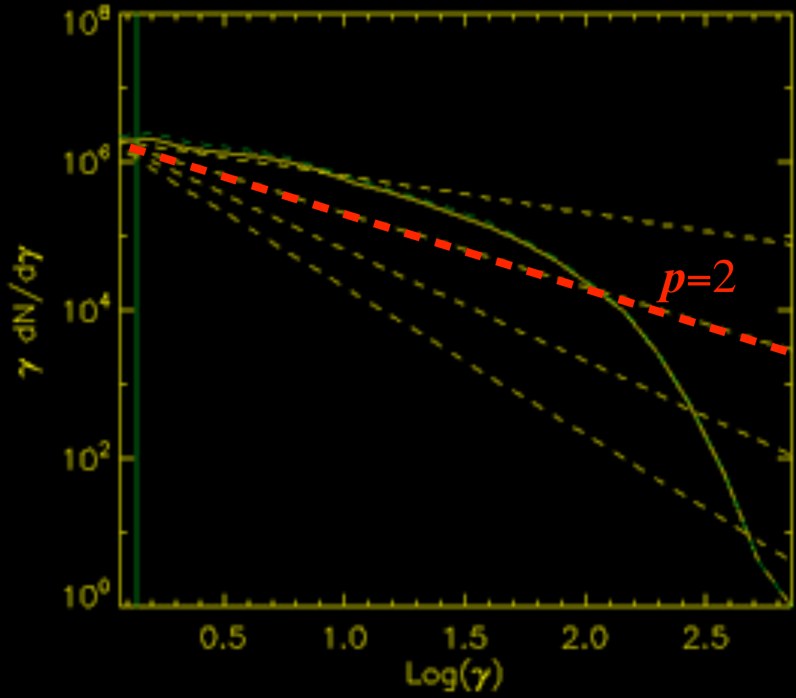


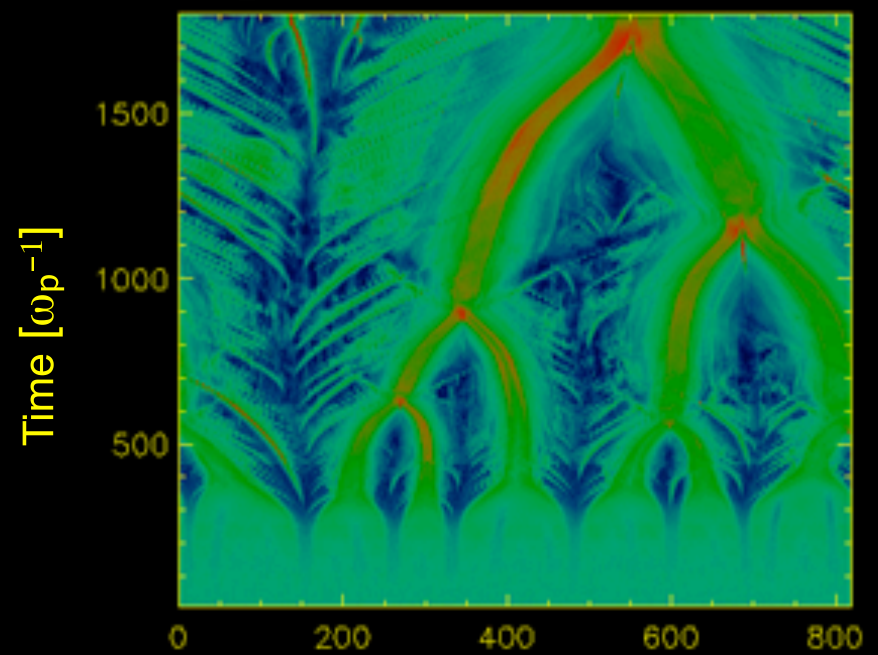


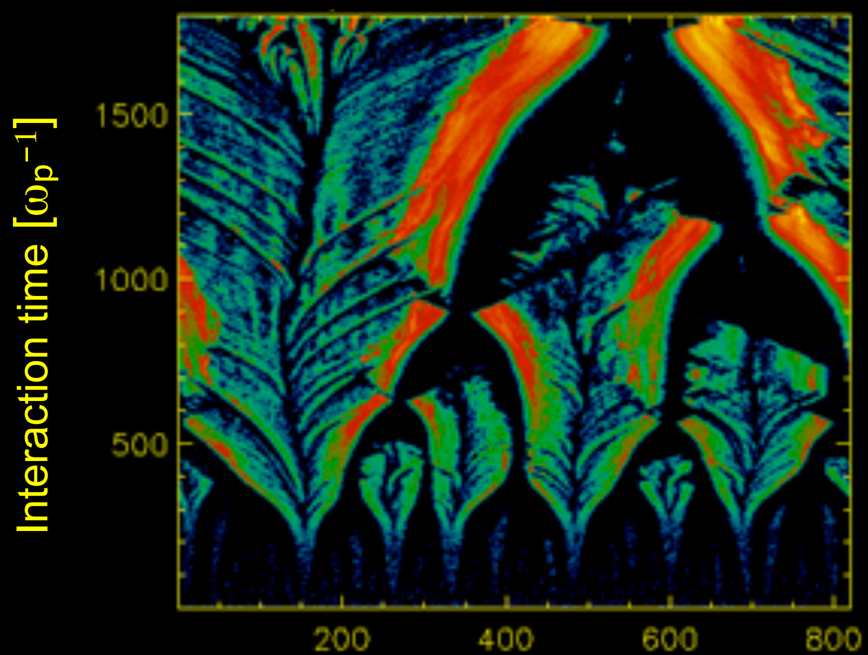



# Primary & secondary X-points



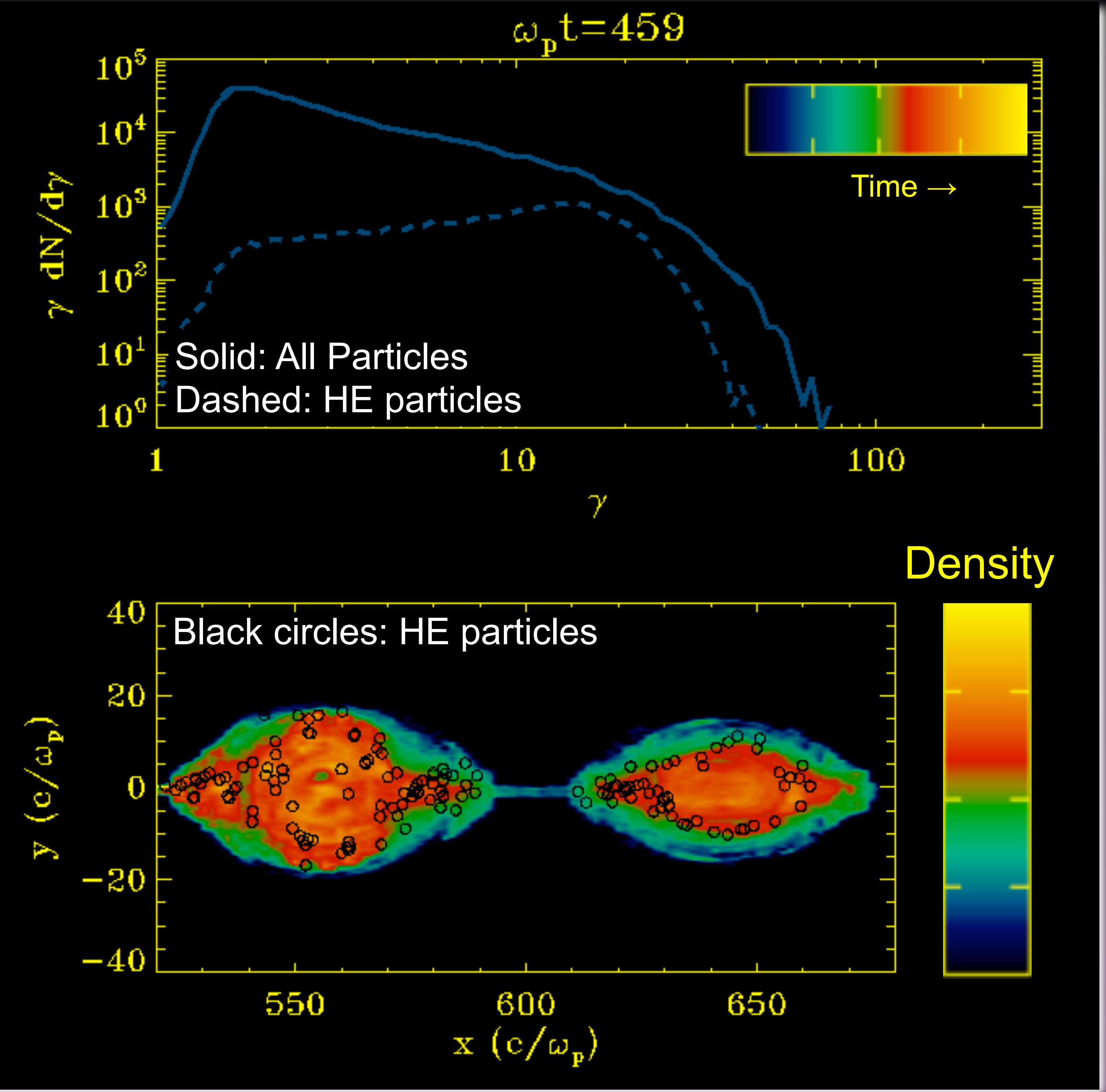

Position along the current sheet [$c/\omega_p$]




Location at interaction with the current sheet [$c/\omega_p$]

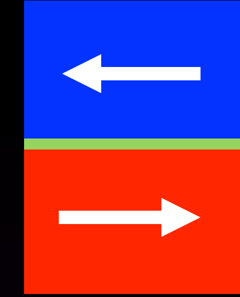
- High-energy particles start their acceleration at both primary and secondary X-points.
- The highest energy particles are injected in a small fraction of the volume.

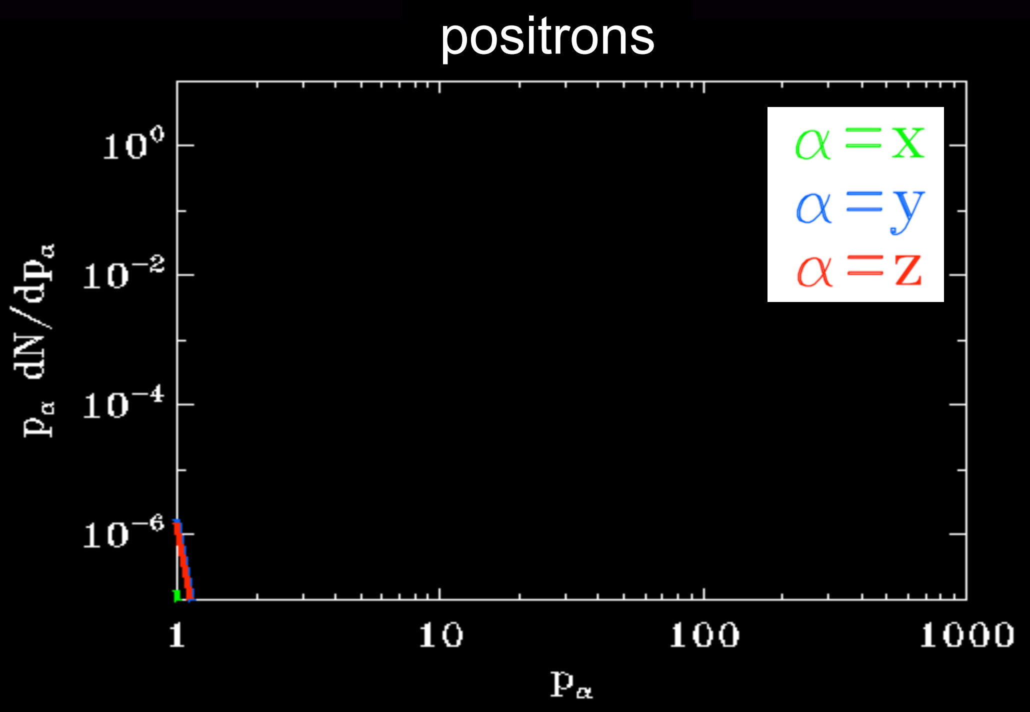
# Fermi acceleration in between islands

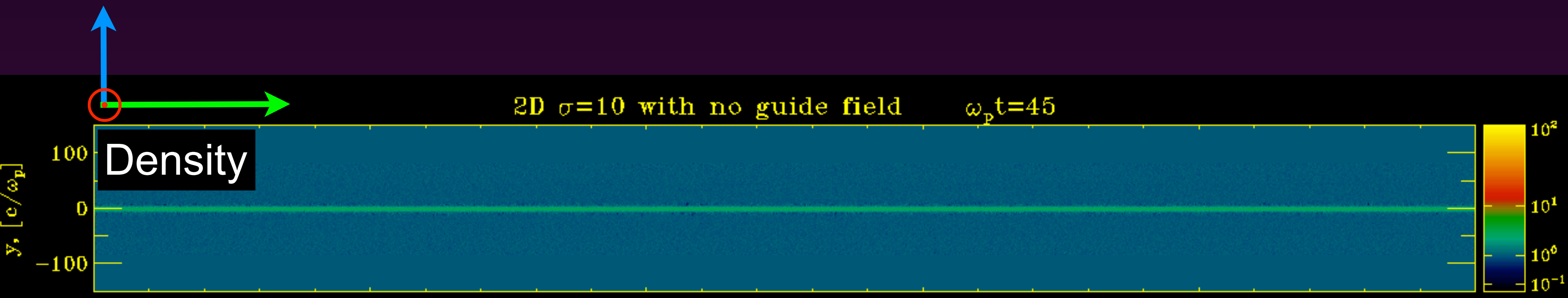



- The particles are accelerated by a Fermi-like process in between merging islands.
- Island merging is essential to shift up the spectral cutoff energy.

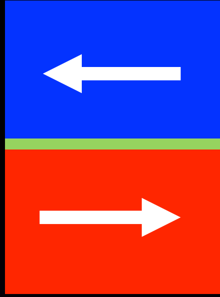
# Anisotropy of the accelerated particles

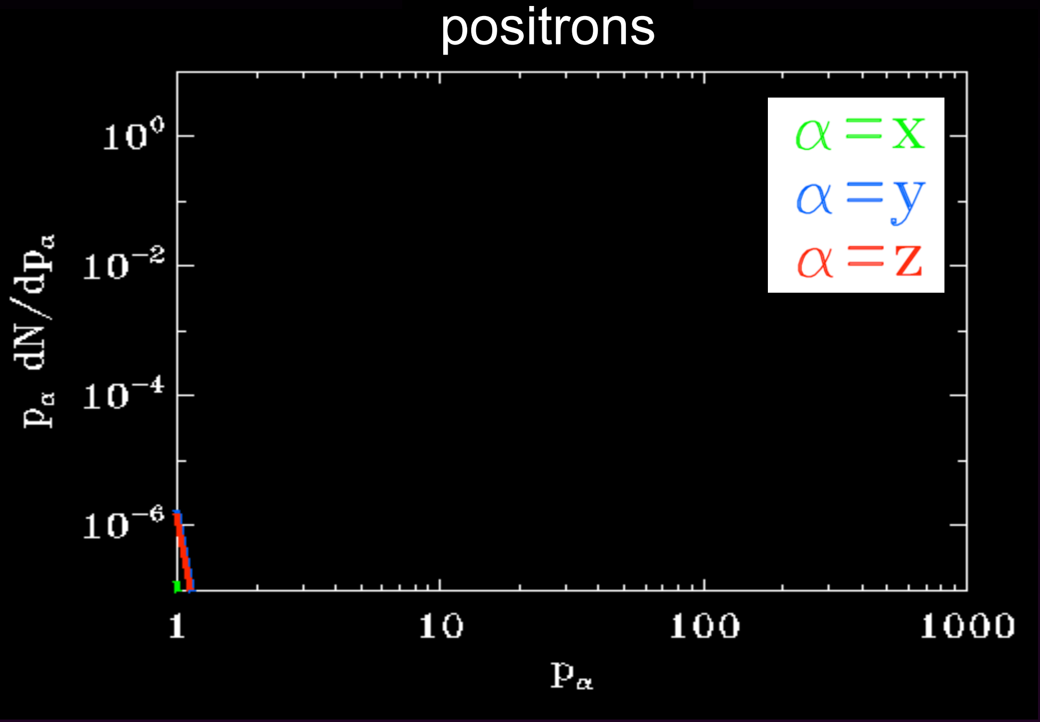


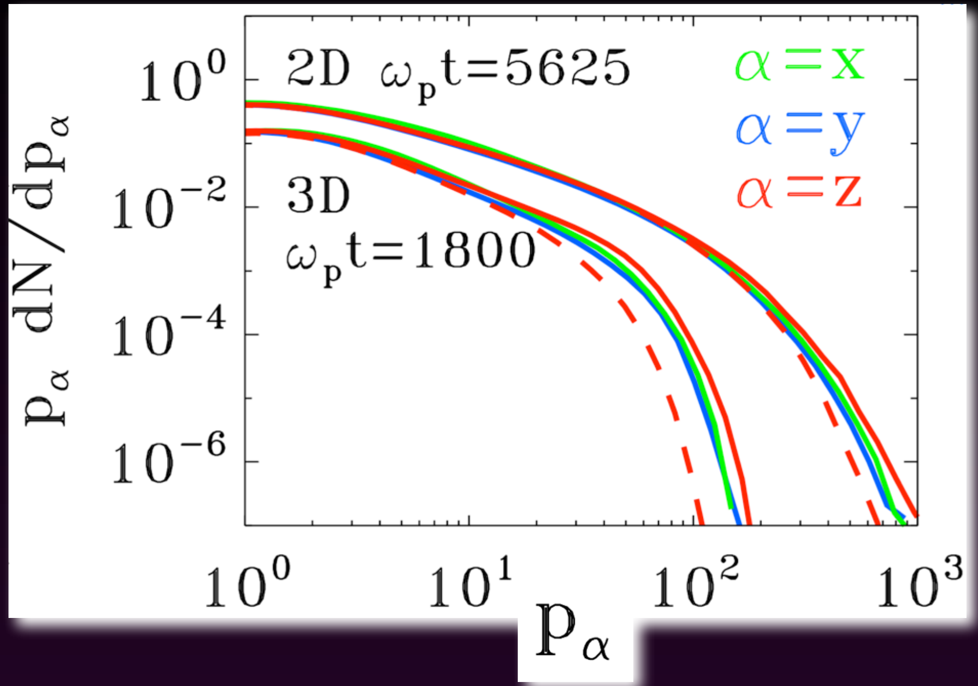


# Anisotropy of the accelerated particles

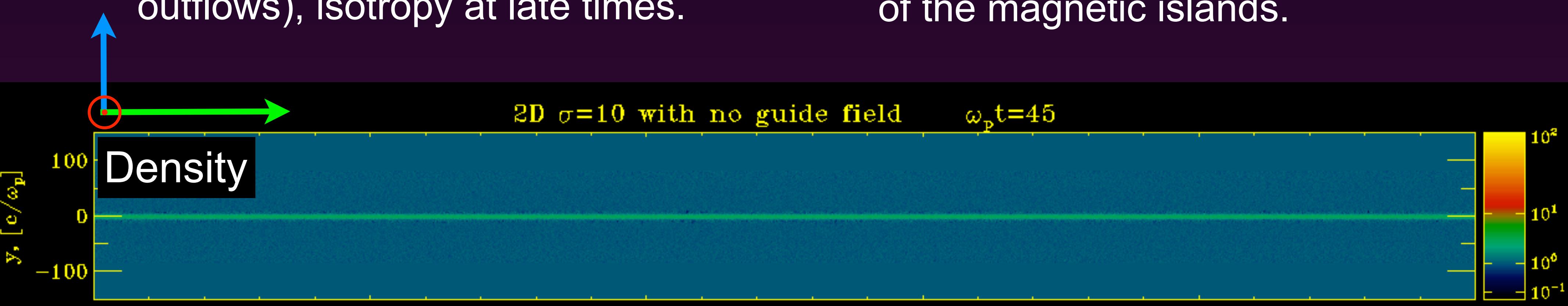




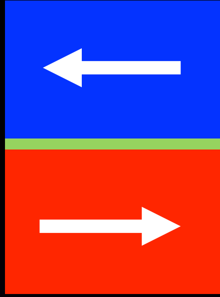

Anisotropy at early times (first along the reconnection E field, and then along the outflows), isotropy at late times.

The residual anisotropy at late times comes from ∇B drift in the outskirts of the magnetic islands.

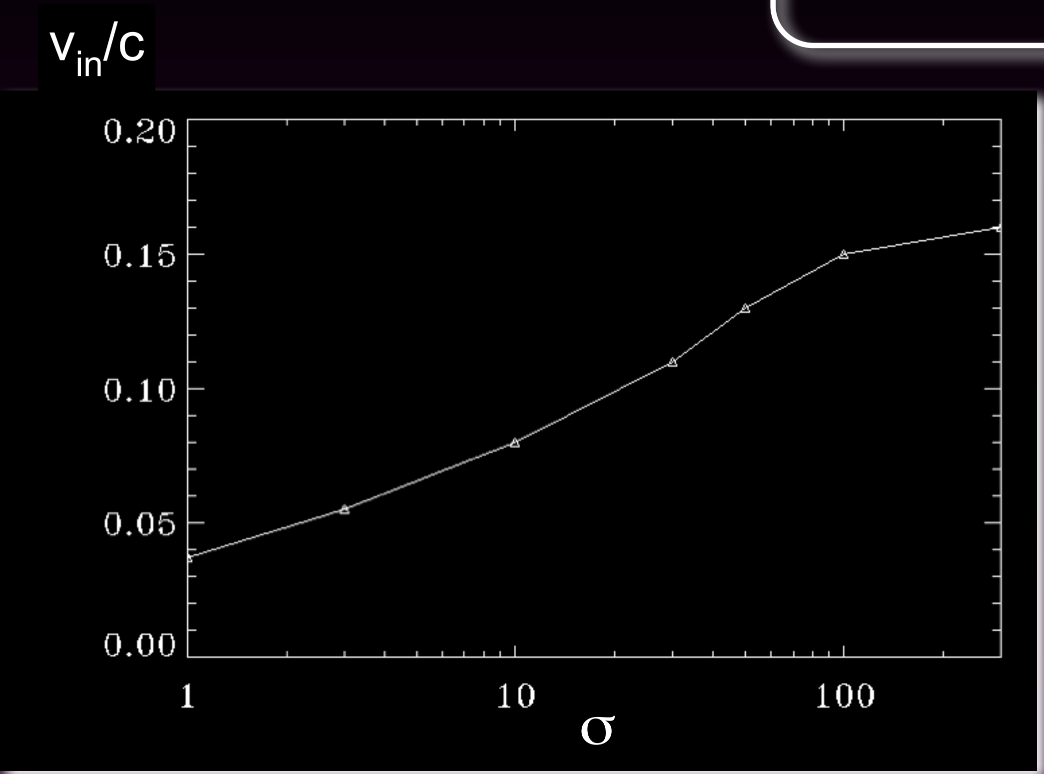


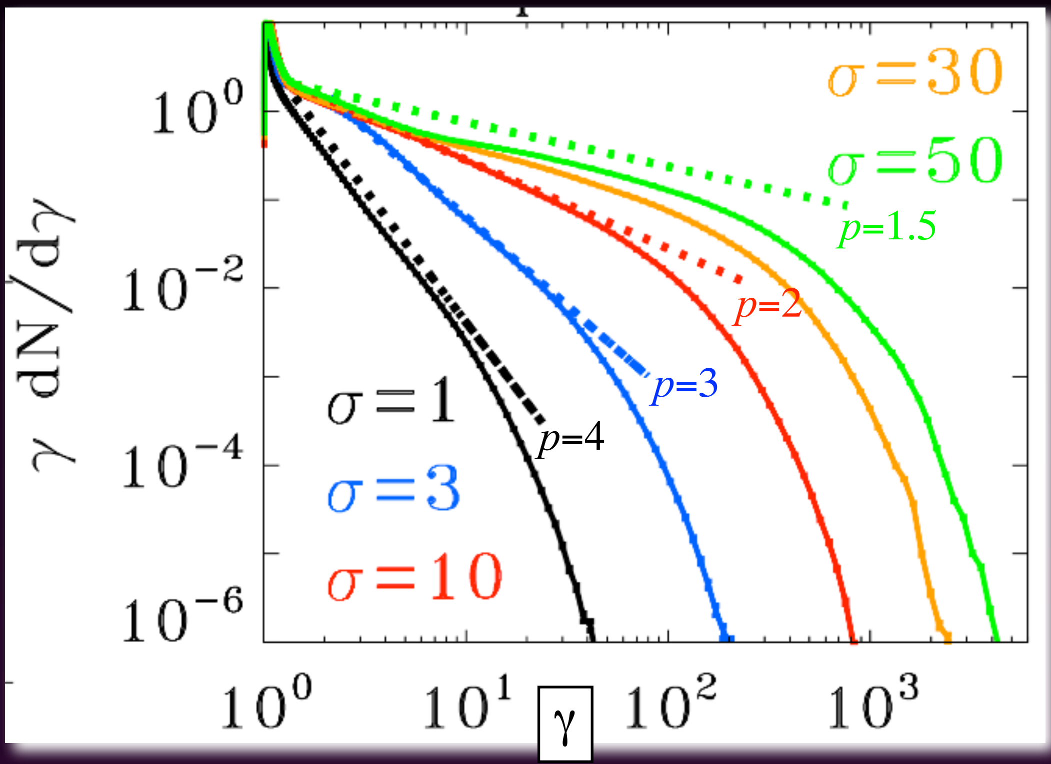
# Dependence on the flow conditions

# Dependence on the magnetization



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




(LS 14, in prep)

As σ increases:

• the reconnection rate saturates at ~ 0.15 *c*

As σ increases:

• the power-law slope becomes harder

⇒ a probe of the flow magnetization?

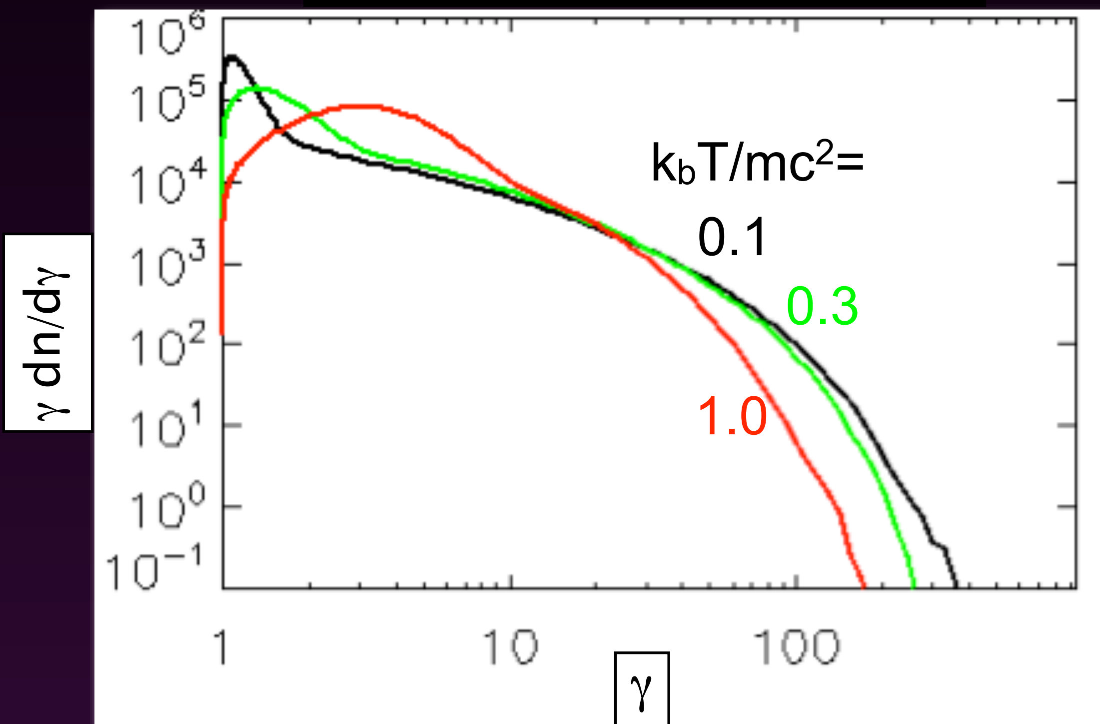
# Dependence on the temperature

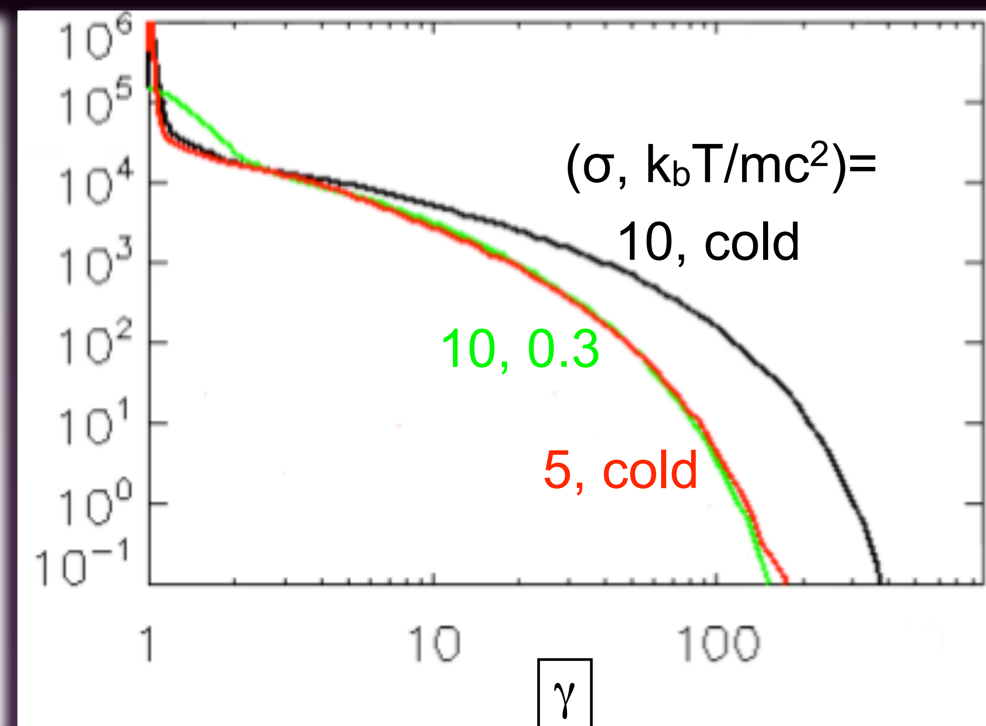
$$\sigma_w = \frac{B_0^2}{4\pi w}$$

*w*=enthalpy

$$w = e + p = nmc^2 + [\Gamma/(\Gamma - 1)]p$$

σ=10 electron-positron

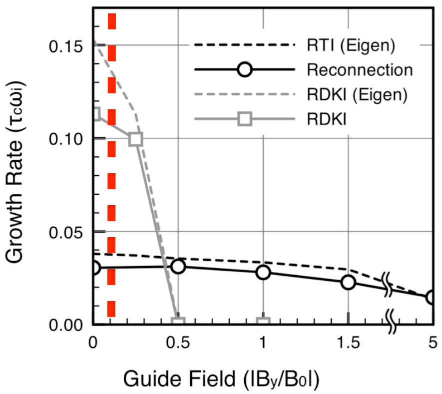


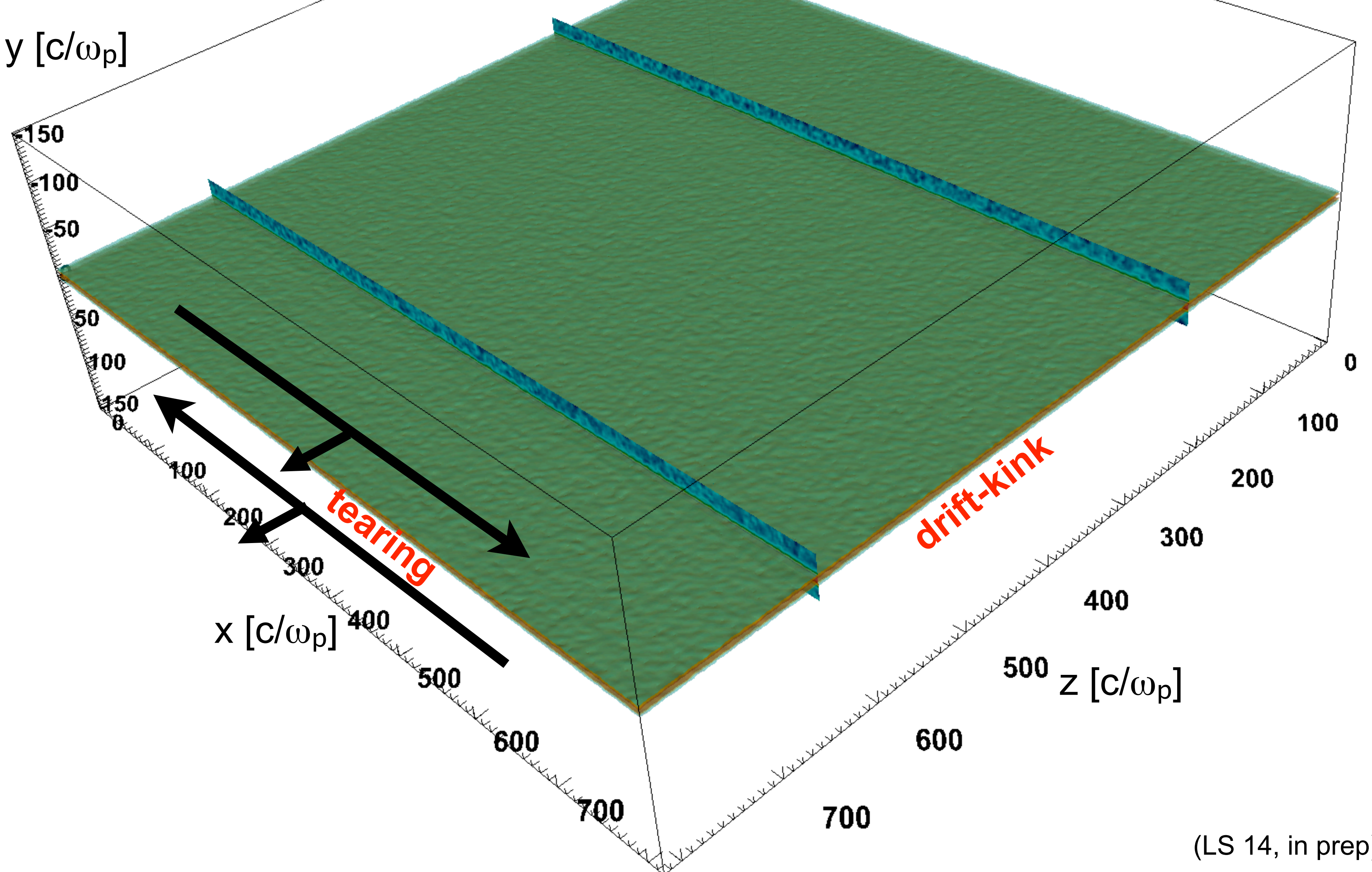

(LS 14, in prep)

The temperature dependence is encoded in $\sigma_w$

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

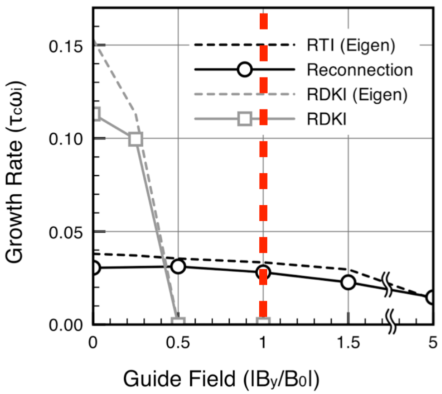


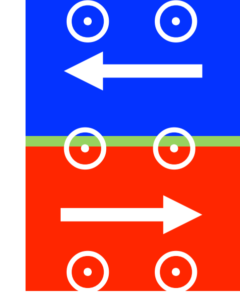

Density



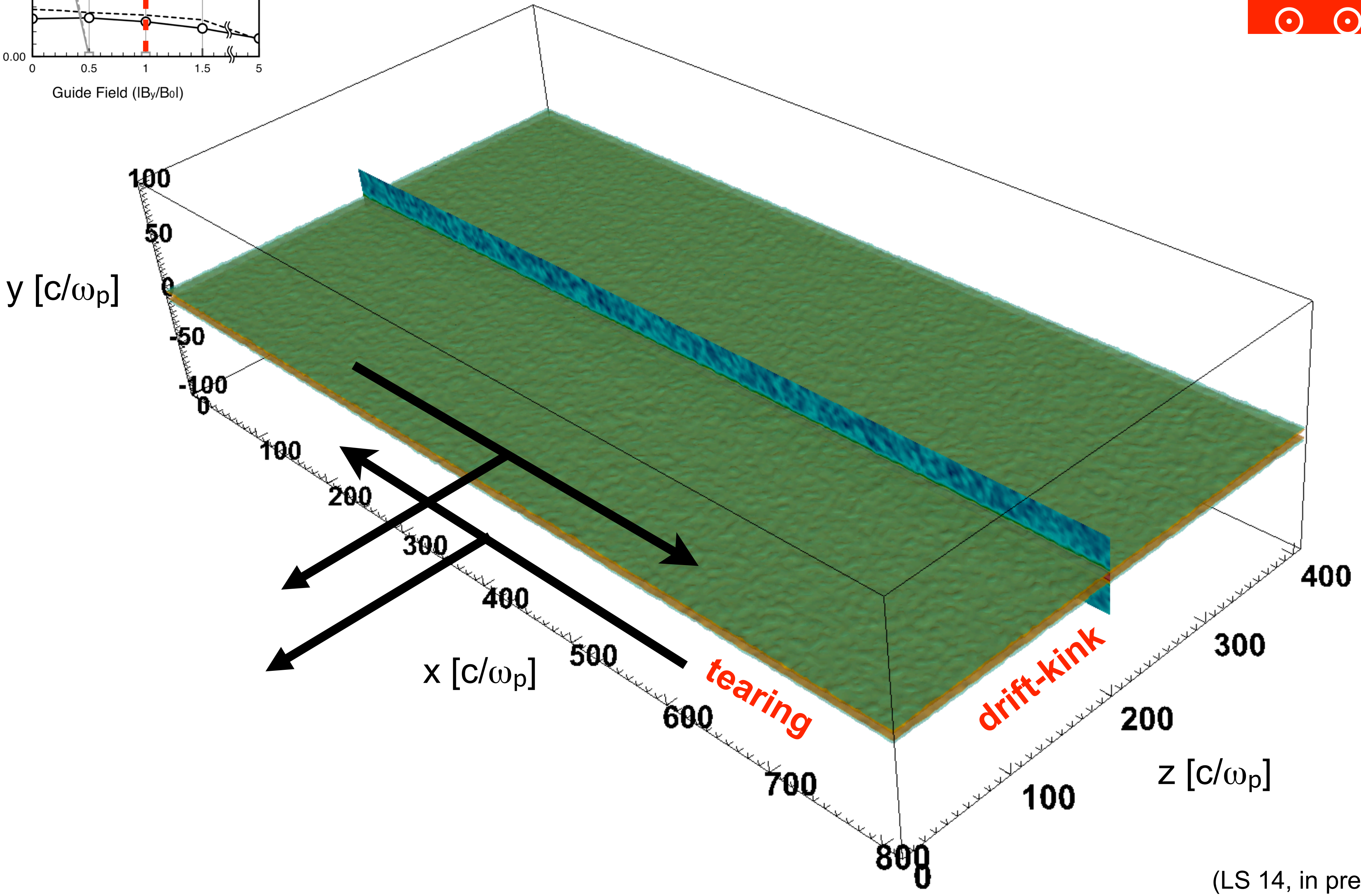

(LS 14, in prep)

$\sigma=10 \quad B_g/B_0=1.0$



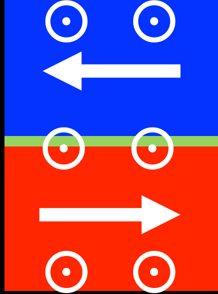



Density

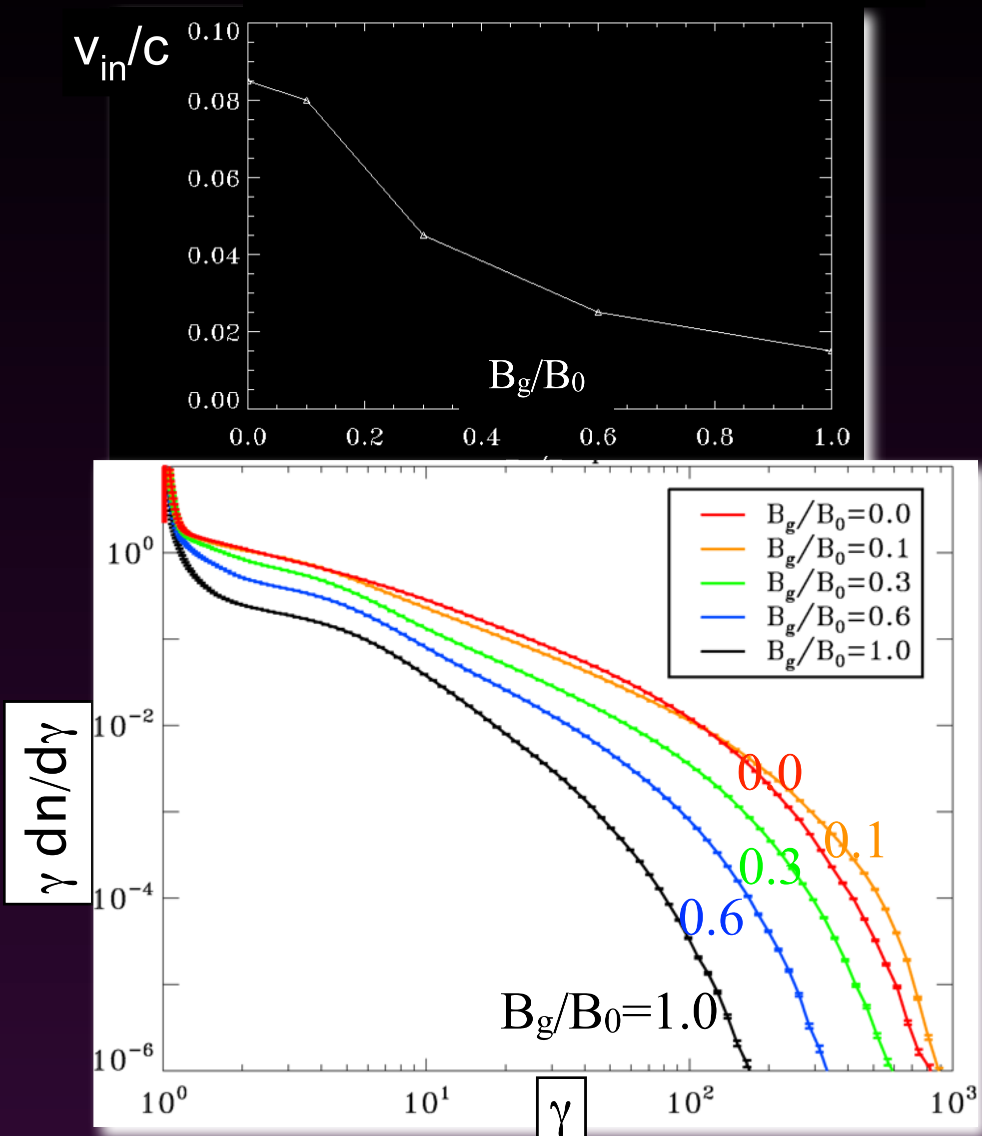



(LS 14, in prep)

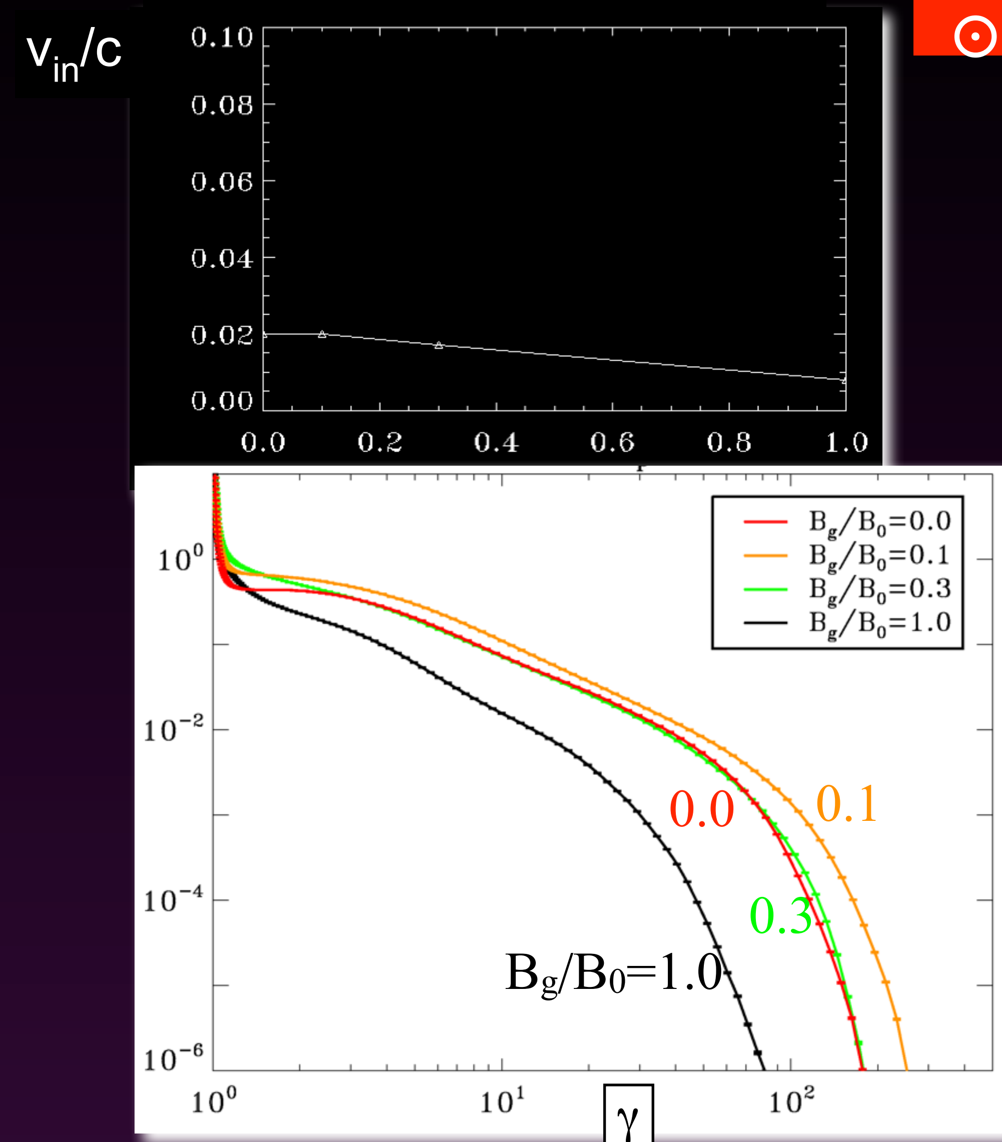
# Dependence on the guide field



2D $\sigma$=10 electron-positron



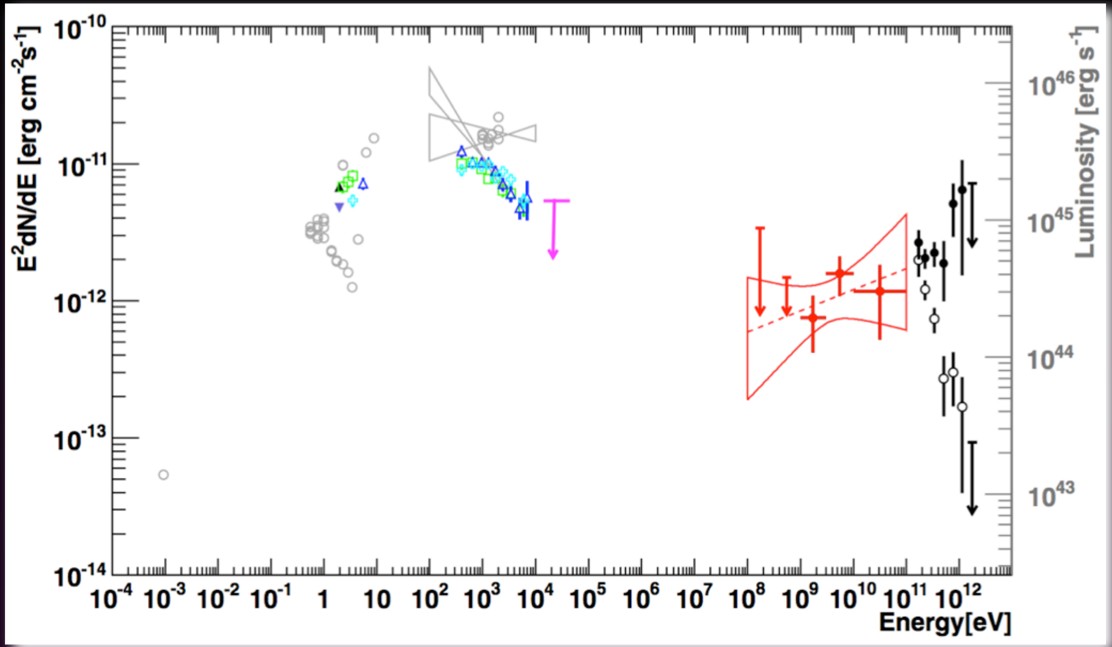

3D $\sigma$=10 electron-positron




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

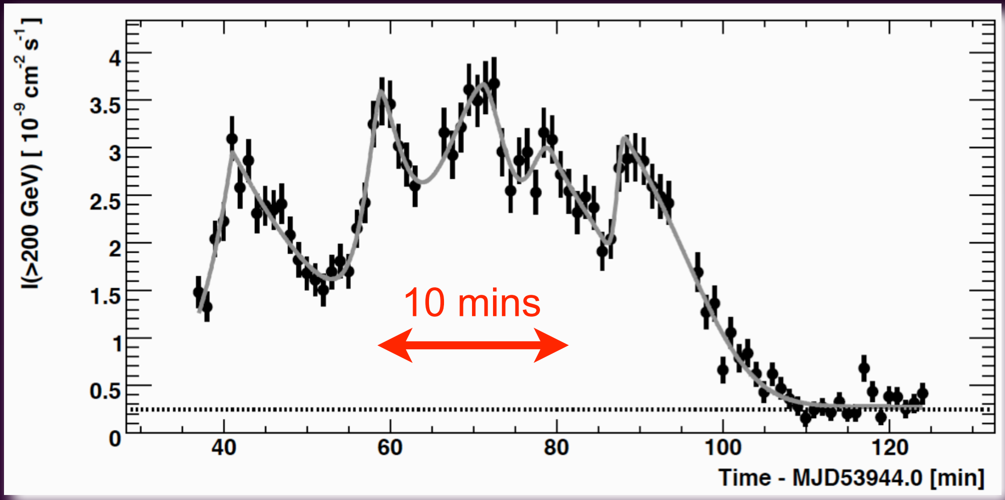
# Astrophysical implications

- For high magnetizations, the non-thermal slope can be *p*<2, as needed to explain the de-absorbed TeV spectra in blazars and the spectrum of the Crab GeV flares.




(HESS 11)

- Small-scale islands in reconnection might explain the fast (~ 10 minutes) variability in TeV blazars and the Crab flares.




(Aharonian et al. 07)

# Summary

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

• Relativistic reconnection can efficiently produce non-thermal particles, in the form of a power-law tail with slope between -2 and -1 (harder for higher magnetizations), and max energy growing linearly in time (promising for UHECRs).

• The reconnection rate (and so, the rate of growth of the max energy) is ~ 0.1 *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 increases with magnetization up to ~ 0.15 *c* (in 2D).
It decreases with the strength of the guide field.