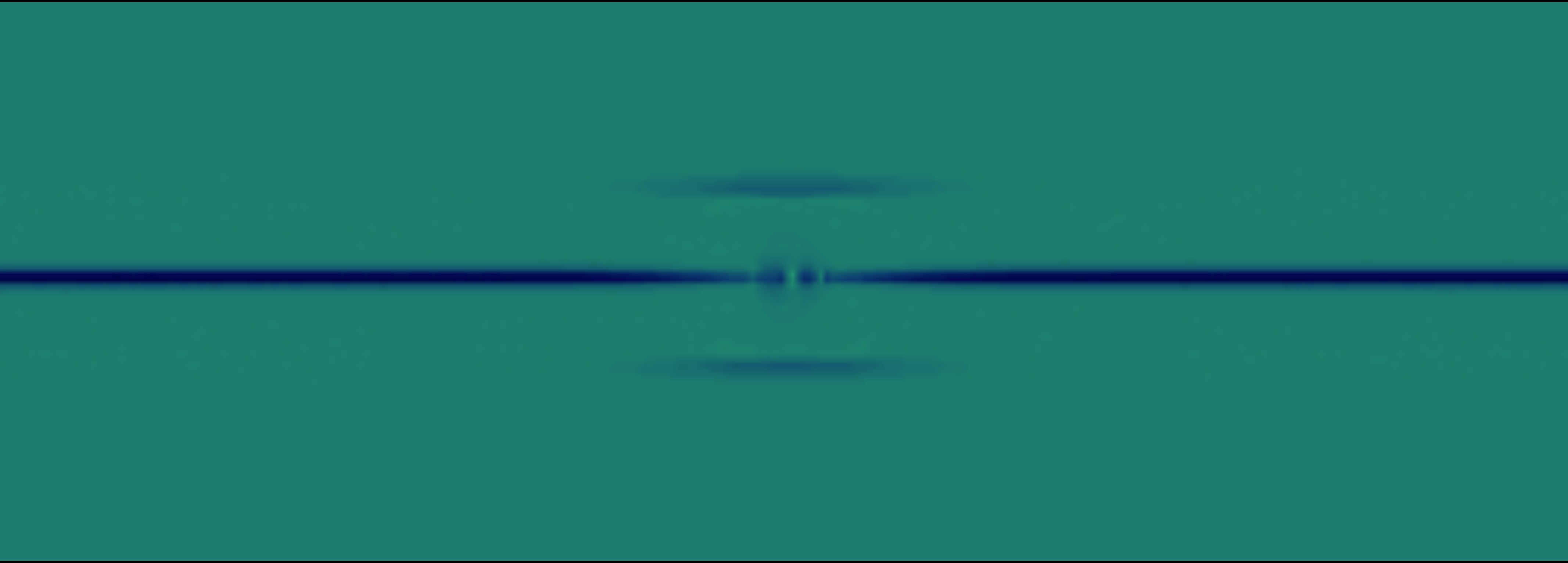
Magnetic Reconnection



Lorenzo Sironi (Columbia)

Foundations of CR Astrophysics, Varenna 2022

Reconnection blah blah blah

Reconnection blah blah blah

What is magnetic reconnection?

- The Sweet-Parker model of magnetic reconnection.
- The regime of relativistic reconnection.
- The physics of particle acceleration in relativistic reconnection.

What can magnetic reconnection do?

- Where/How do reconnection layers form?
- UHECRs from relativistic reconnection.
- Hard and fast flares from relativistic reconnection.
- It allows you to build a career in plasma astrophysics.

What is magnetic reconnection?

R. Kulsrud at his 90th birthday party:
"Enrico Fermi told me to study reconnection for my PhD thesis, nearly 70 years ago.
We have yet to understand it."

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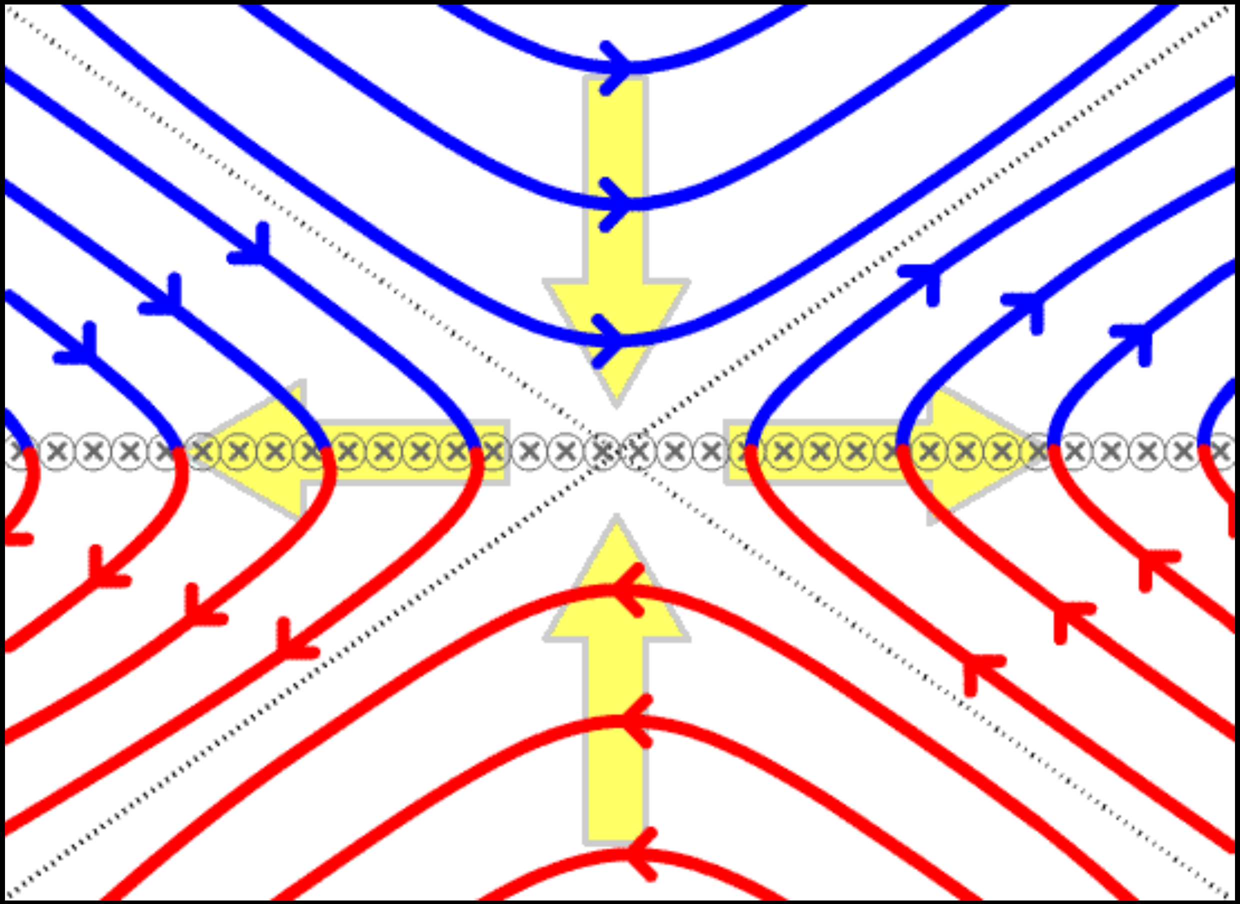
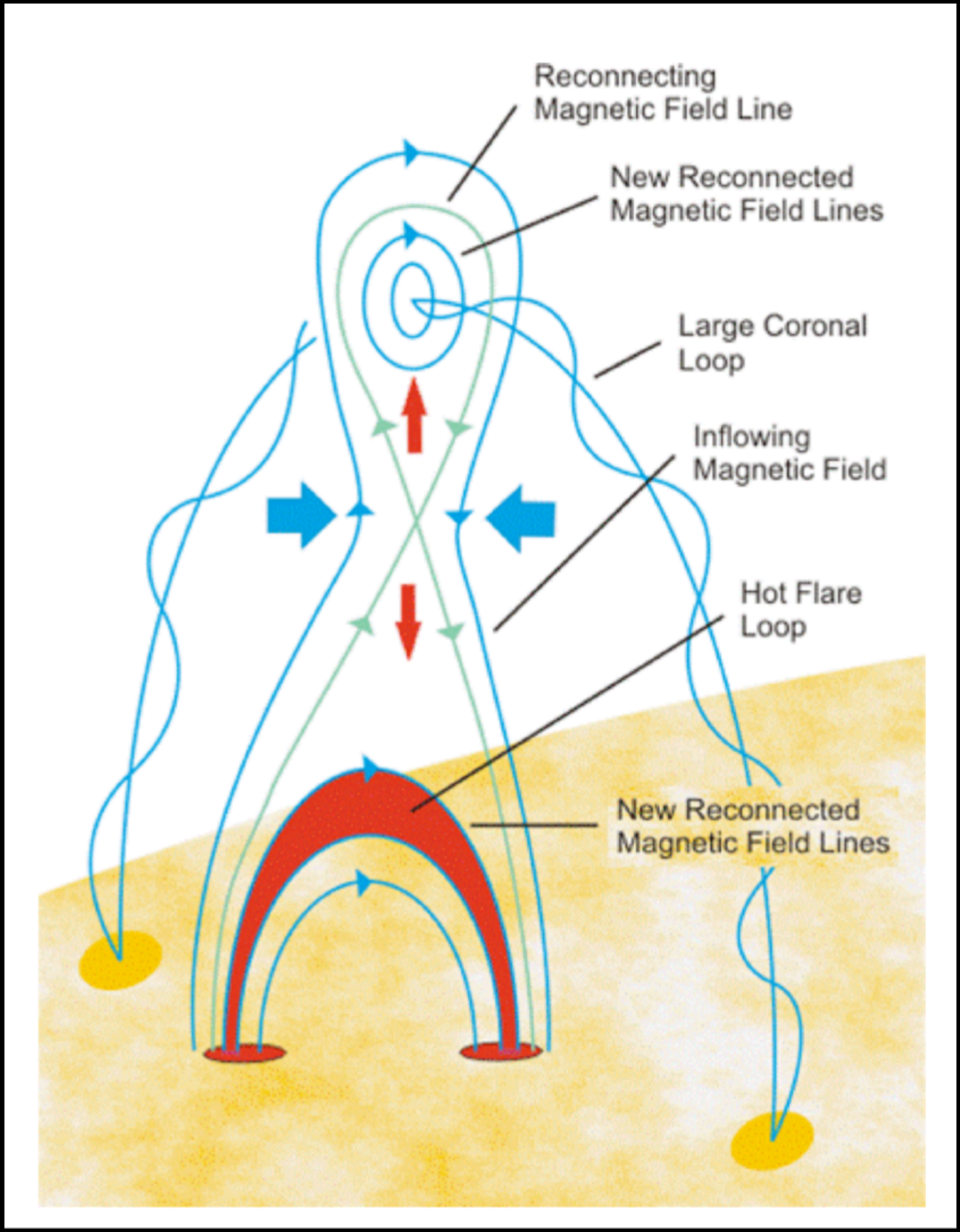


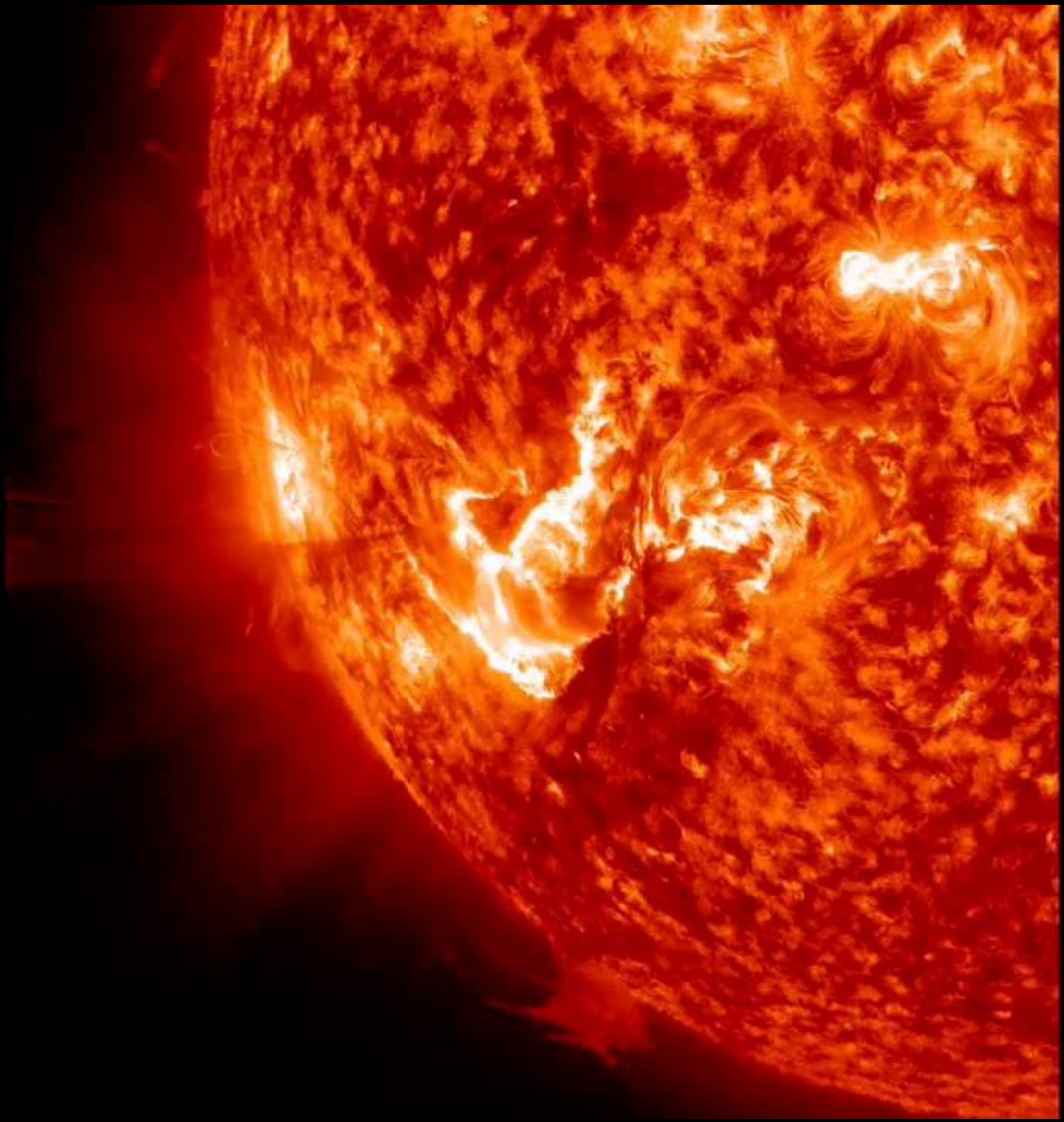
What is magnetic reconnection?

<u>What is magnetic reconnection?</u>

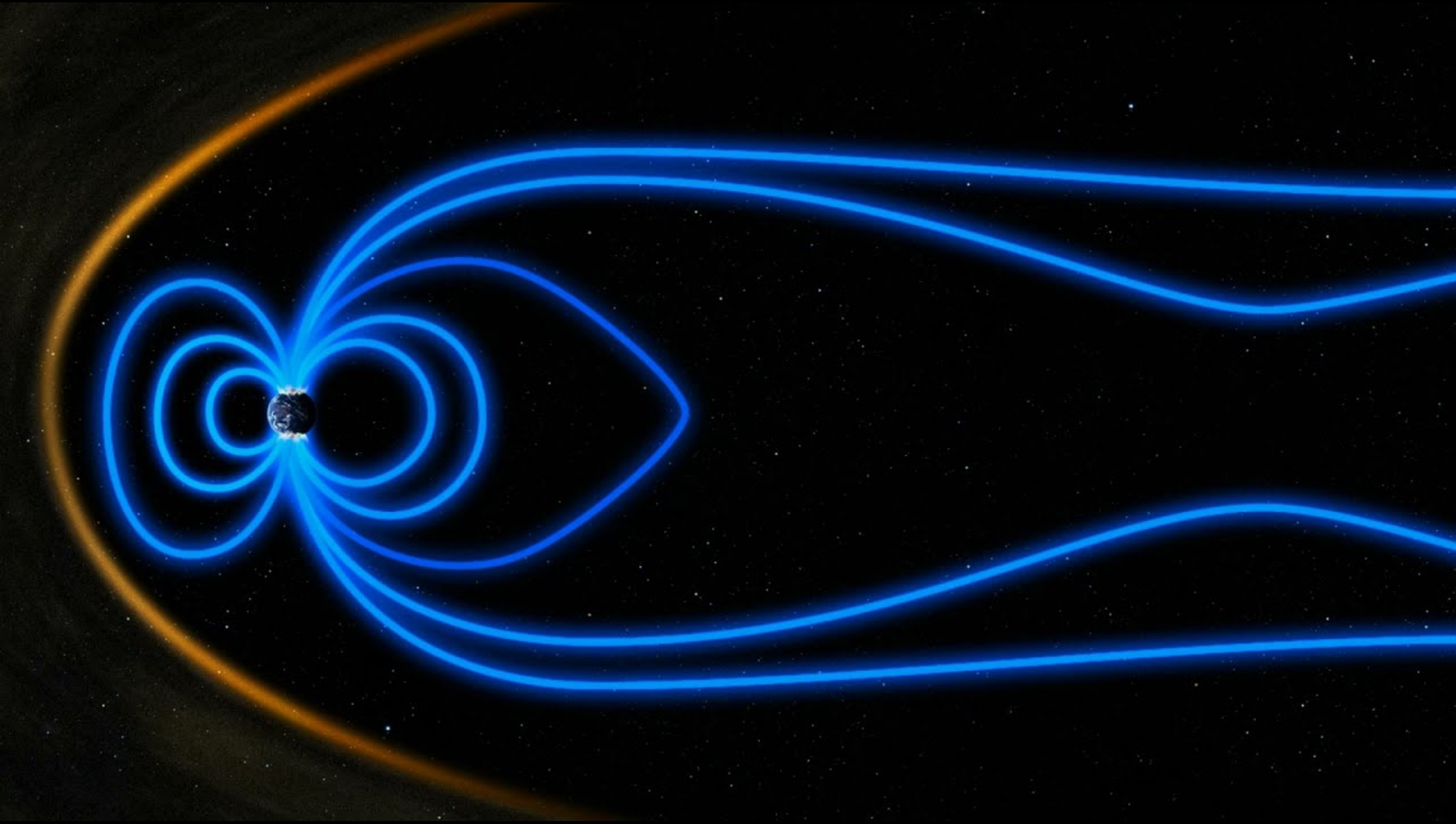
- A change in the macroscopic topology of the B field due to microscopic plasma effects.
- This is often accompanied by explosive energy release.



Reconnection in the Sun



Reconnection in Earth's magnetosphere



Three million-dollar questions

What is magnetic reconnection?

- A change in the macroscopic topology of the B field due to microscopic plasma effects.
- This is often accompanied by explosive energy release.

Three key questions:

- The *rate* problem: how fast does the field dissipation proceed?
- The *particle acceleration* problem: how does reconnection partition energy between B field, ions and electrons (thermal and non-thermal)?
- The *onset* problem: how does the system evolve towards reconnection?

Why does the field topology change?

From Maxwell to ideal MHD

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

Induction equation

in ideal MHD

What did I use? Ohm's law in ideal MHD:

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = 0$$

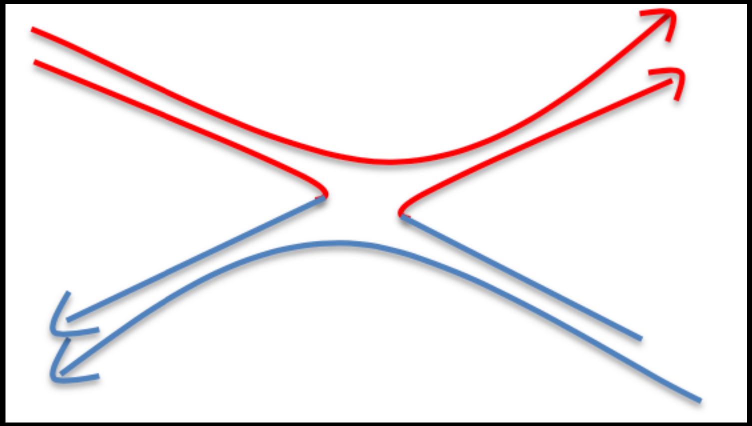
Resistive MHD

Ohm's law in ideal MHD:

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = 0$$

Ideal Ohm's law leads to *flux freezing* (Alfven theorem):
magnetic field lines must move with (are *frozen* into) the plasma.

BUT: Reconnection implies *breaking* the frozen-field constraint,
i.e., we need to go beyond ideal MHD.



Ohm's law in resistive MHD:

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J}$$

Resistive MHD

Ohm's law in resistive MHD:

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J}$$

Induction equation in resistive MHD (for uniform resistivity):

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{V} \times \mathbf{B})}_{\text{advection}} + \underbrace{D_\eta \nabla^2 \mathbf{B}}_{\text{diffusion}}$$

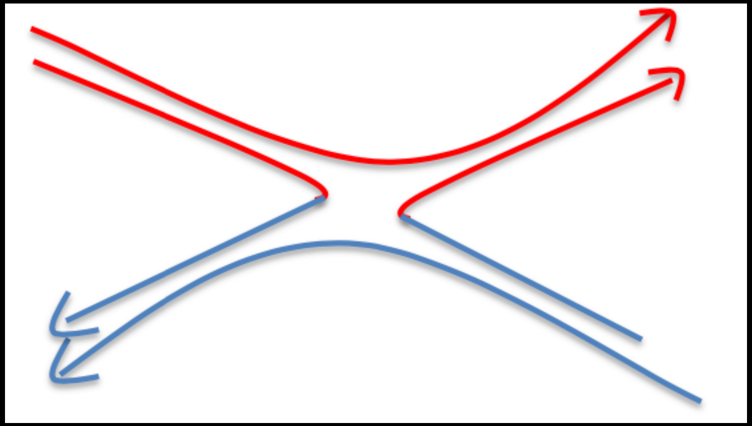
$$D_\eta \equiv \frac{\eta c^2}{4\pi}$$

Lundquist number: $$S \equiv \frac{L_0 V_A}{D_\eta}$$

Alfven speed: $$V_A \equiv \frac{B}{\sqrt{4\pi\rho}}$$

Resistive MHD and reconnection

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{V} \times \mathbf{B})}_{\text{advection}} + \underbrace{D_\eta \nabla^2 \mathbf{B}}_{\text{diffusion}}$$



The last term becomes important not because the resistivity is large, but because B gradients (i.e., currents) are large → *current sheets*

Ideal MHD is ok in most of the volume, but not in current sheets

In astro, the mean free path to collisions is enormous: ~kpc in supernova remnants, ~Mpc in galaxy clusters. So, the plasma is ~ *collisionless.*

What can violate the frozen-in condition and mediate reconnection?

The generalized Ohm's law

The generalized Ohm's law:

$$\mathbf{E} + \frac{\mathbf{V}\times\mathbf{B}}{c} = \eta\mathbf{J} + \underbrace{\frac{\mathbf{J}\times\mathbf{B}}{en_e c}}_{\text{Hall}} - \underbrace{\frac{\nabla\cdot\mathbf{P}_e}{n_e ec}}_{\text{elec. pressure}} + \underbrace{\frac{m_e}{n_e e^2}\frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}}_{\text{elec. inertia}}$$

This introduces new (microscopic) length scales:

$$d_i \equiv \frac{c}{\omega_{pi}} = \sqrt{\frac{c^2 m_i}{4\pi n_i Z^2 e^2}}$$

$$d_e \equiv \frac{c}{\omega_{pe}} = \sqrt{\frac{c^2 m_e}{4\pi n_e e^2}}.$$

- ISM: $n \sim 1\ \mathrm{cm}^{-3} \Rightarrow d_i \sim 200\ \mathrm{km},\ d_e \sim 5\ \mathrm{km}$
- Solar corona: $n \sim 10^9\ \mathrm{cm}^{-3} \Rightarrow d_i \sim 7\ \mathrm{m},\ d_e \sim 20\ \mathrm{cm}$
- Solar wind : $n \sim 10\ \mathrm{cm}^{-3} \Rightarrow d_i \sim 70\ \mathrm{km},\ d_e \sim 2\ \mathrm{km}$

(credit: Murphy)

The Sweet-Parker model in resistive MHD

Lundquist number: $$S \equiv \frac{L_0 V_A}{D_\eta}$$

The SP model: the rec rate

- The dimensionless reconnection rate scales as

$$\frac{V_{in}}{V_A} \sim \frac{1}{S^{1/2}} \qquad (7)$$

- The Lundquist number S is the ratio of the resistive diffusion time scale to the Alfvén wave crossing time scale:

$$S \equiv \frac{LV_A}{D_\eta} = \frac{\tau_{res}}{\tau_{Alf}} \qquad (8)$$

Typically S is somewhere between 10^9 and 10^{20} in astrophysics

- The Sweet-Parker model predicts **slow** reconnection

(credit: Murphy)

Lab		**Galaxy**	
Basic plasma experiments	$10 - 10^4$	Protostellar disks	10^4
Fusion exper			10^{16}
			10^{20}
Solar system			
Geomagnetic tail	10^{15}	AGN disks	10^{13}
Solar wind	10^{12}	AGN disk coronae	10^{23}
Solar corona	10^{14}	Jets	10^{29}

S tends to be large

Note: S here is computed using the collisional (Spitzer) resistivity

The SP model: issues

It predicts solar flares should last ~ months. Instead, they last ~ minutes.

So?

1. Most astro plasmas are *collisionless*, so we need to include kinetic effects, which may generate a higher *effective* resistivity.

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = \eta \mathbf{J} + \underbrace{\frac{\mathbf{J} \times \mathbf{B}}{e n_e c}}_{\text{Hall}} - \underbrace{\frac{\nabla \cdot \mathbf{P}_e}{n_e e c}}_{\text{elec. pressure}} + \underbrace{\frac{m_e}{n_e e^2} \frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t}}_{\text{elec. inertia}}$$

Kinetic effects can be studied with particle-in-cell (PIC) simulations.
[much more on this later]

The SP model: issues

It predicts solar flares should last ~ months. Instead, they last ~ minutes.

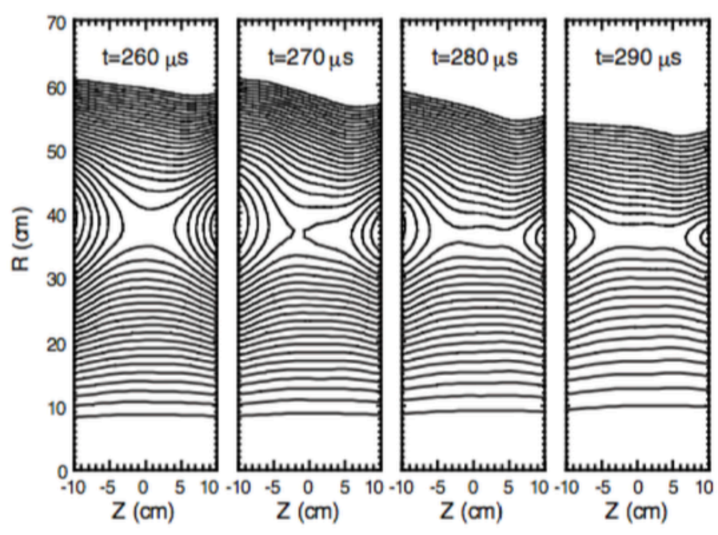
So?

1. Most astro plasmas are *collisionless*, so we need to include kinetic effects, which may generate a higher *effective* resistivity.
2. Still, some systems (interiors of stars and accretion disks, solar chromosphere) should be collisional enough, that resistive MHD applies.

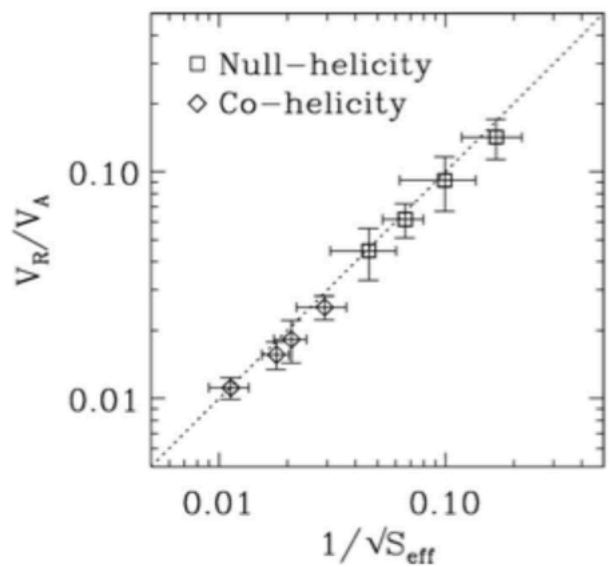
Is the SP model actually correct?

Is the SP model actually correct?

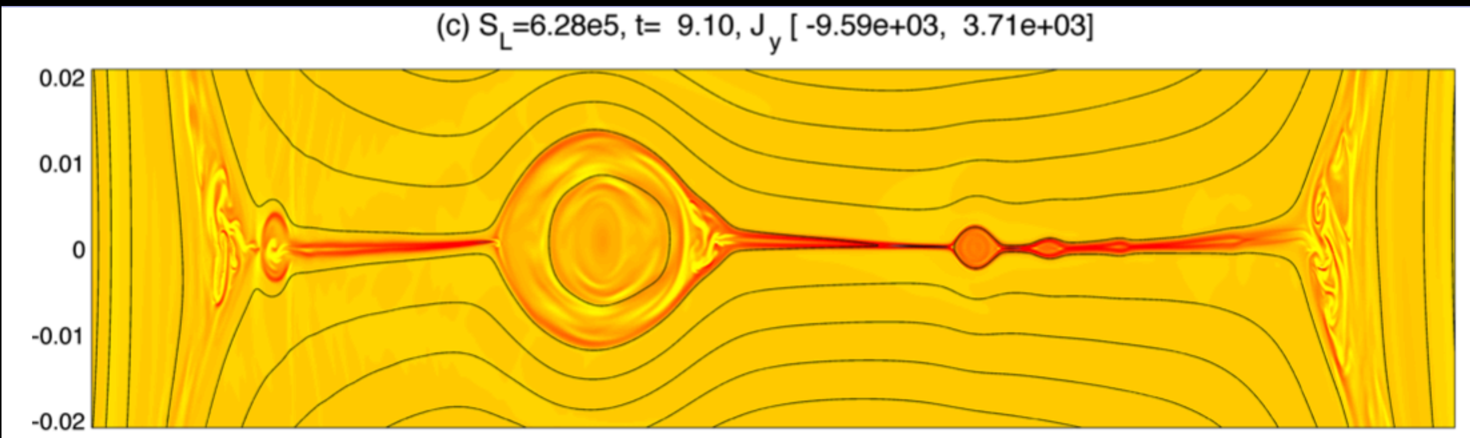
It seemed so for a long time…



Ji '99, Yamada '00



until…

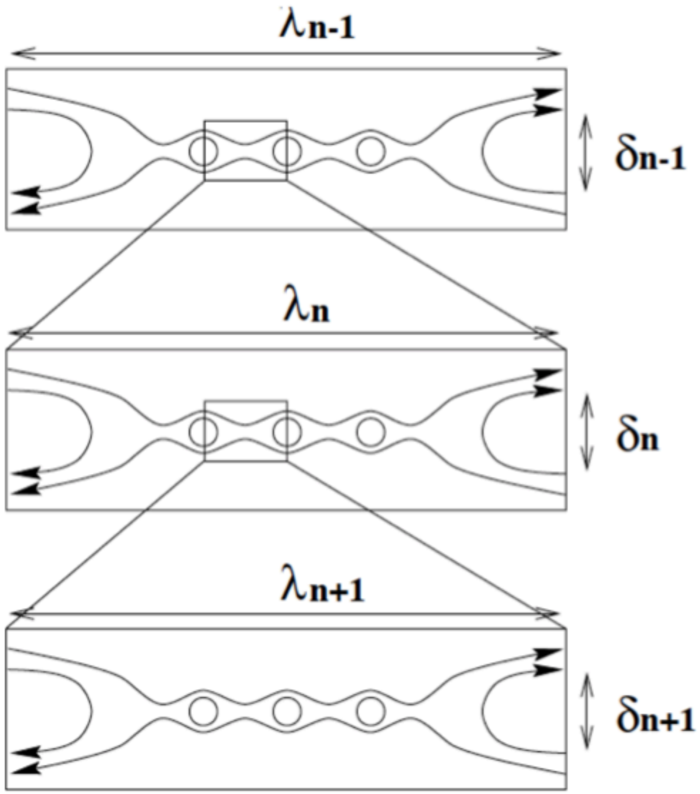


Bhattacharjee et al. (2009); simulations by Y.-M. Huang

Elongated current sheets are susceptible to the plasmoid instability!

The plasmoid instability

Long current sheets ($S > S_c \sim 10^4$) are violently unstable to multiple plasmoid formation.



(Shibata & Tanuma '01)

- Current layers between any two plasmoids are themselves unstable to the same instability if

$$S_n = L_n V_A / D_\eta > S_c$$

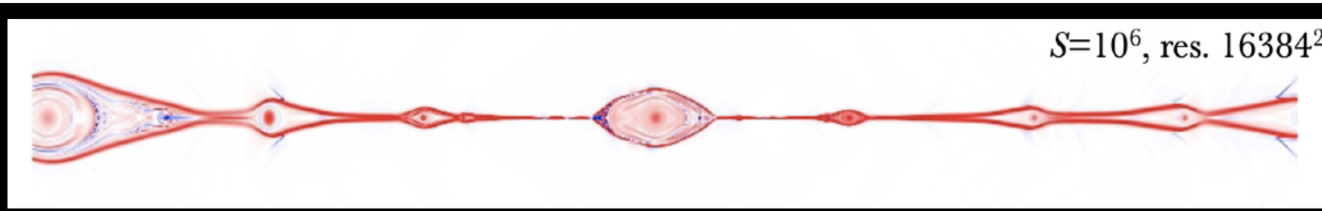
- Plasmoid hierarchy ends at *the critical layer*:

$$L_c = S_c D_\eta / V_A \; ; \; \delta_c = L_c S_c^{-1/2}$$

$$cE_c = B_0 V_A S_c^{-1/2}$$

- $N \sim L / L_c$ plasmoids separated by near-critical current sheets.

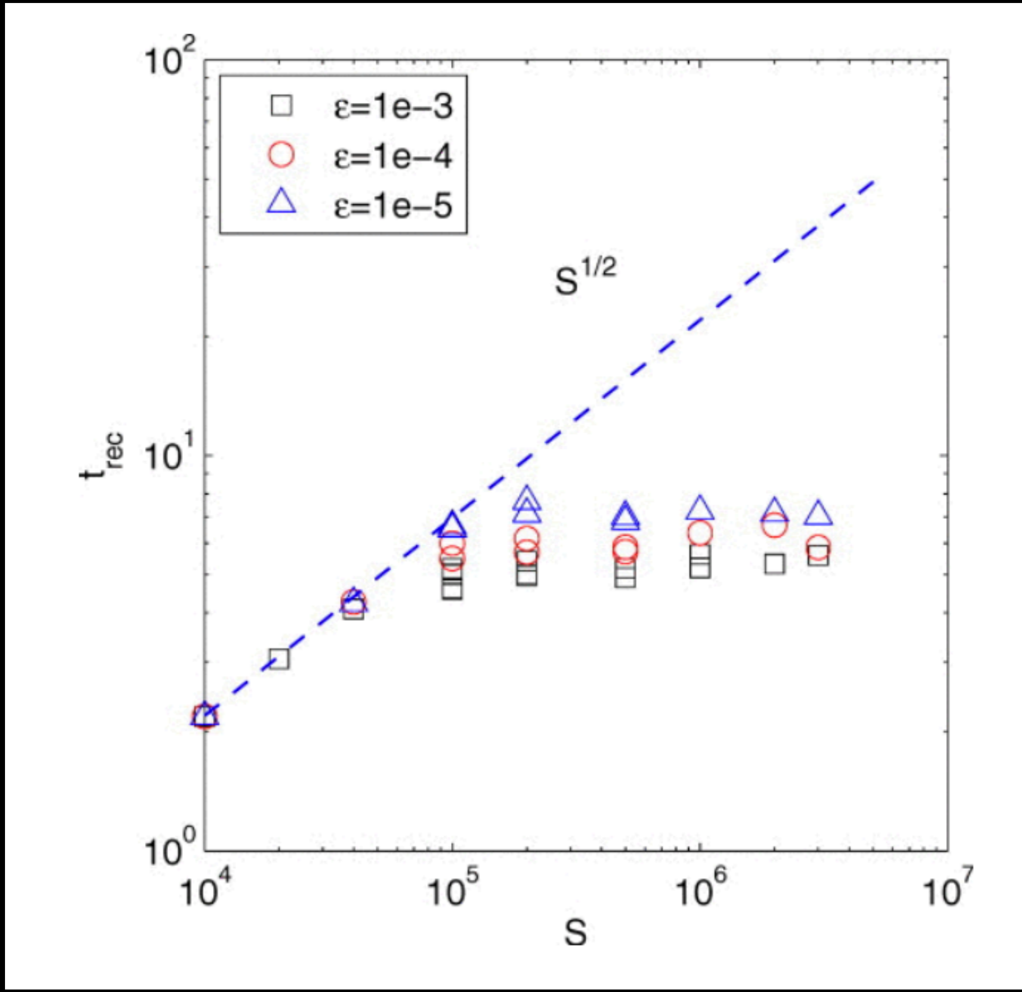
(credit: Loureiro)



The plasmoid instability: rec rate

The reconnection rate levels off at $\frac{V_{in}}{V_A} \sim 0.01$ for $S \gtrsim 10^4$

The Sweet-Parker model is not applicable to astrophysical reconnection!

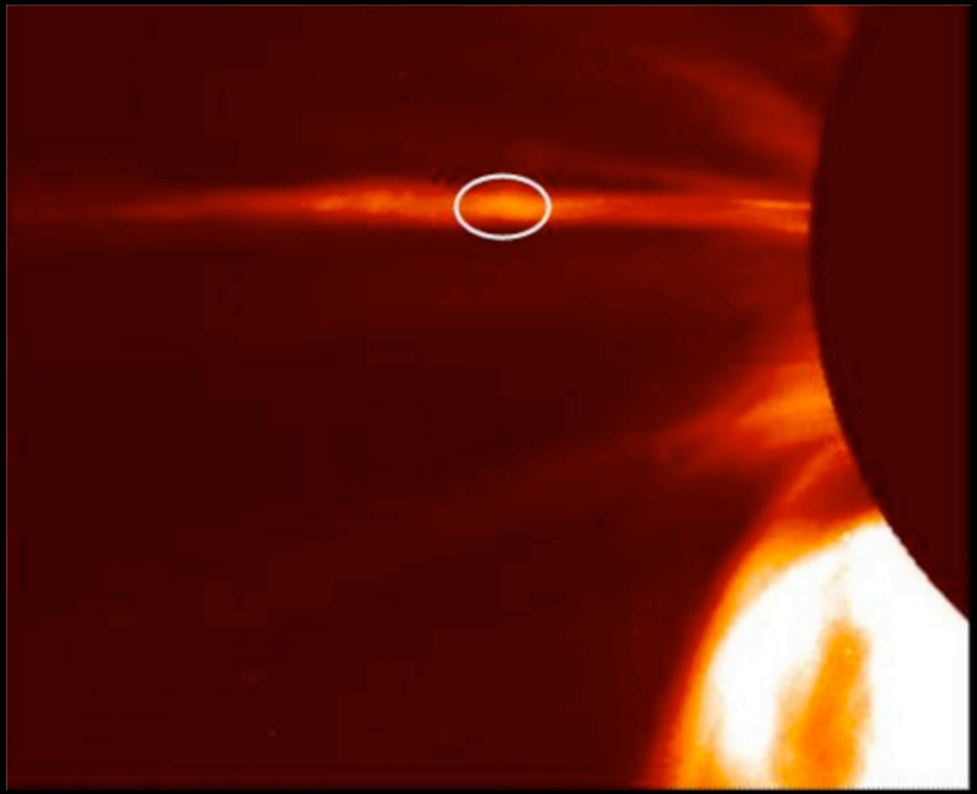


$$v_{\rm in} \sim v_A/\sqrt{S_c} \sim 0.01 v_A$$

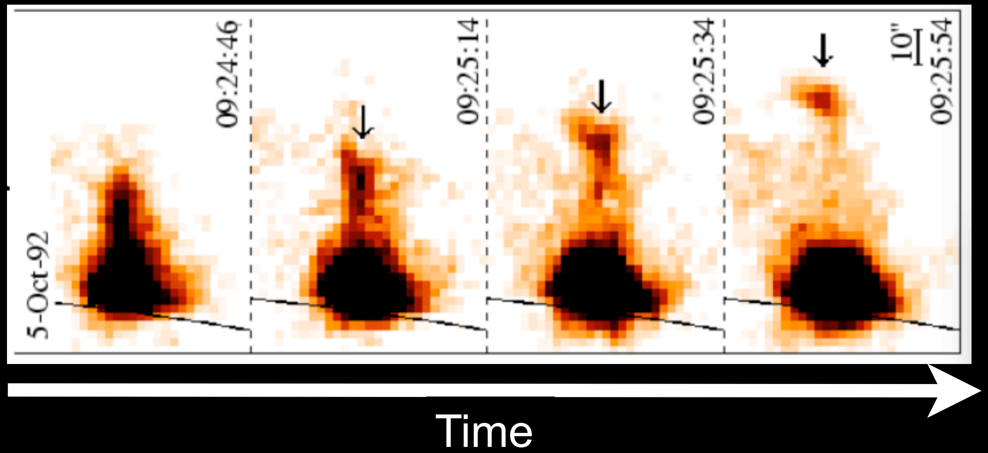
$$t_{\rm rec} = L/v_{\rm in}$$

Plasmoids: solar flares

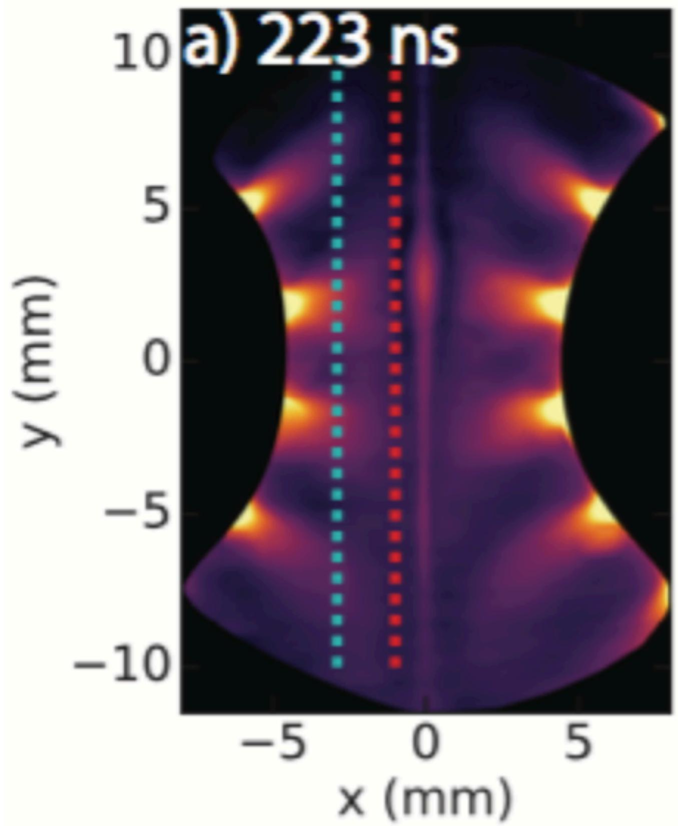
LASCO



Yohkoh/SXT



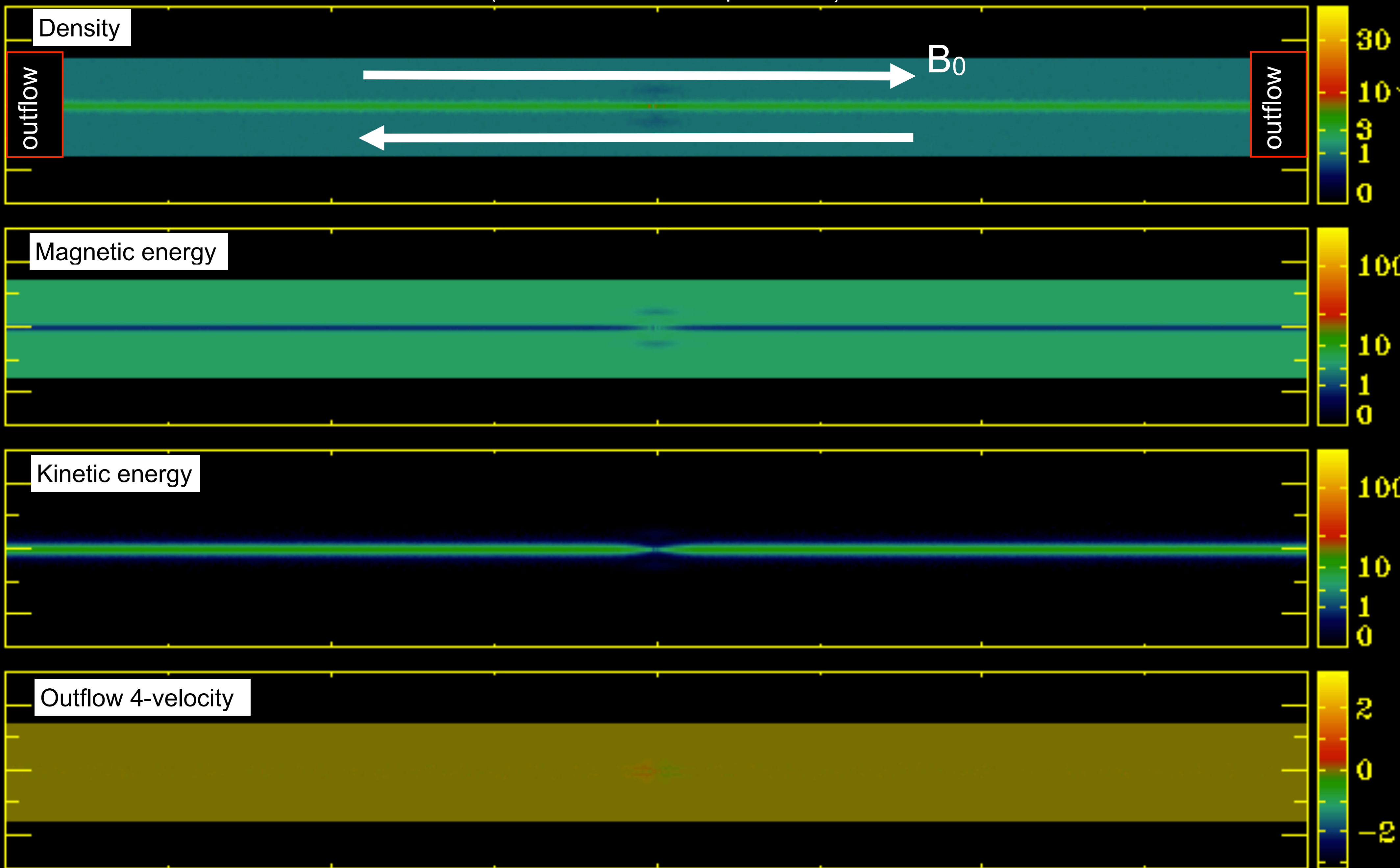
Plasmoids: lab experiments



(Hare *et al.*, PRL ‘17)

Plasmoids in reconnection: PIC sims

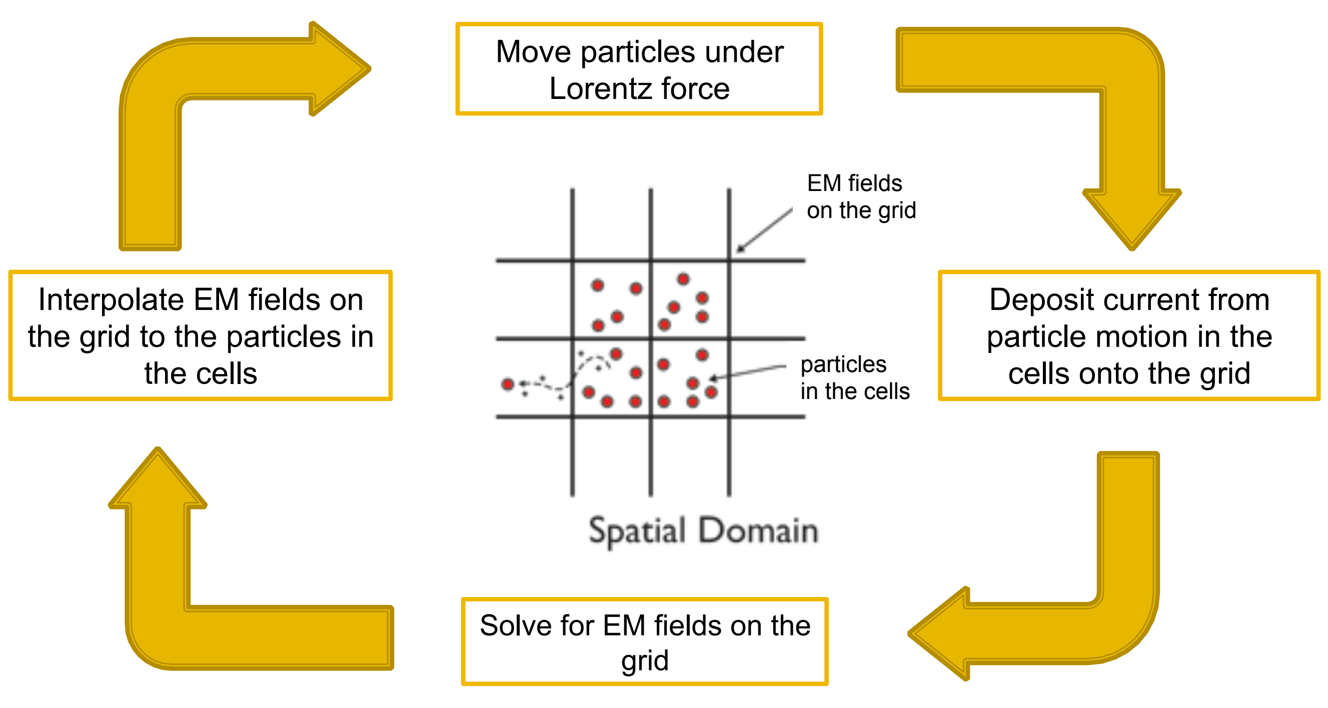
(LS, Giannios & Petropoulou 16)



The PIC method

Particle-in-Cell (PIC) method:

It is the <u>most fundamental way</u> of capturing the interplay of charged particles and e.m. fields.



The computational challenge:

The *microscopic* scales resolved by PIC simulations are much smaller than *astronomical* scales.

Typical length (c/ω_p) and time ($1/\omega_p$) scales are:

$$\frac{c}{\omega_p} \simeq 5.5 \times 10^5 \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm} \qquad \frac{1}{\omega_p} \simeq 1.8 \times 10^{-5} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

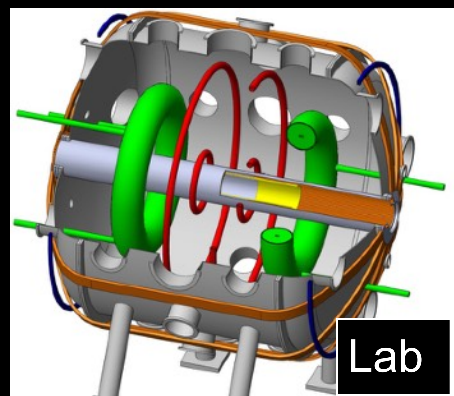
$$\omega_p = \omega_{pe} \quad ; \quad \omega_{pi} = \omega_{pe}\sqrt{m_e/m_i}$$

Hereafter:
relativistic kinetic reconnection in collisionless plasmas

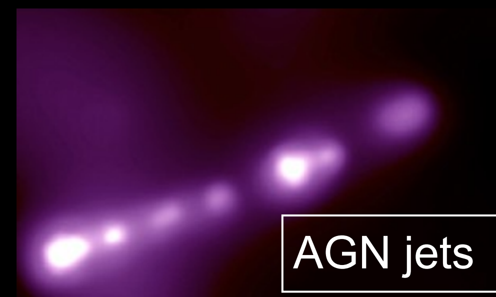
The regime of “relativistic plasmas”

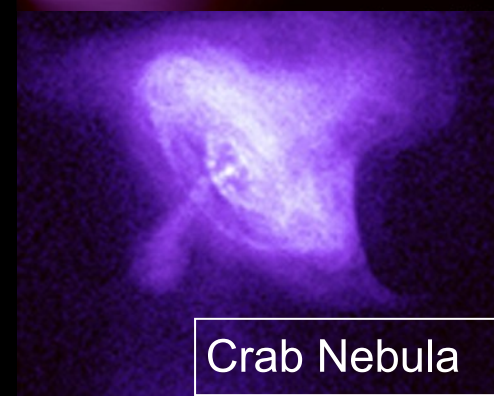
$$\sigma = \frac{B_0^2}{4\pi\rho c^2}$$

σ≪1



σ≫1

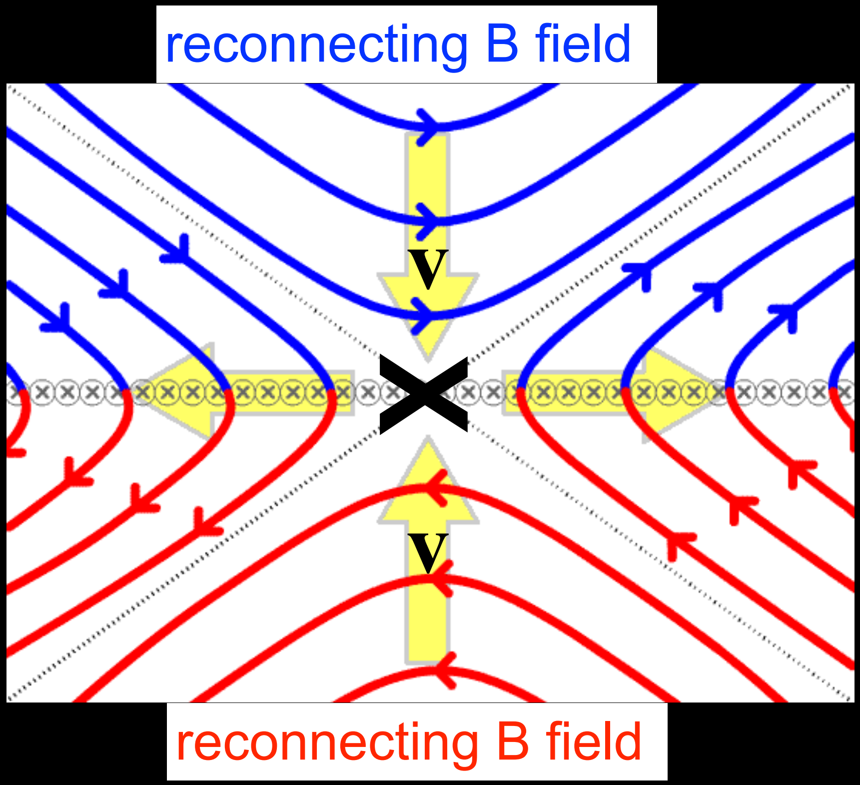




Magnetically-dominated plasmas: $\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$ $\quad v_A \sim c$

High-energy astro sources are our best “laboratories” of relativistic plasma physics

Relativistic reconnection



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

- Reconnection electric field (out-of-plane): $E_{\rm rec} \simeq 0.1 B_0$ $\rightarrow$ $\dfrac{v_{\rm in}}{v_A} = \dfrac{E_{\rm rec}}{B_0} \sim 0.1$
- "Guide" (out-of-plane) uniform magnetic field B_g

The physics of particle acceleration in relativistic reconnection

LS 2022, PRL, 128, 145102

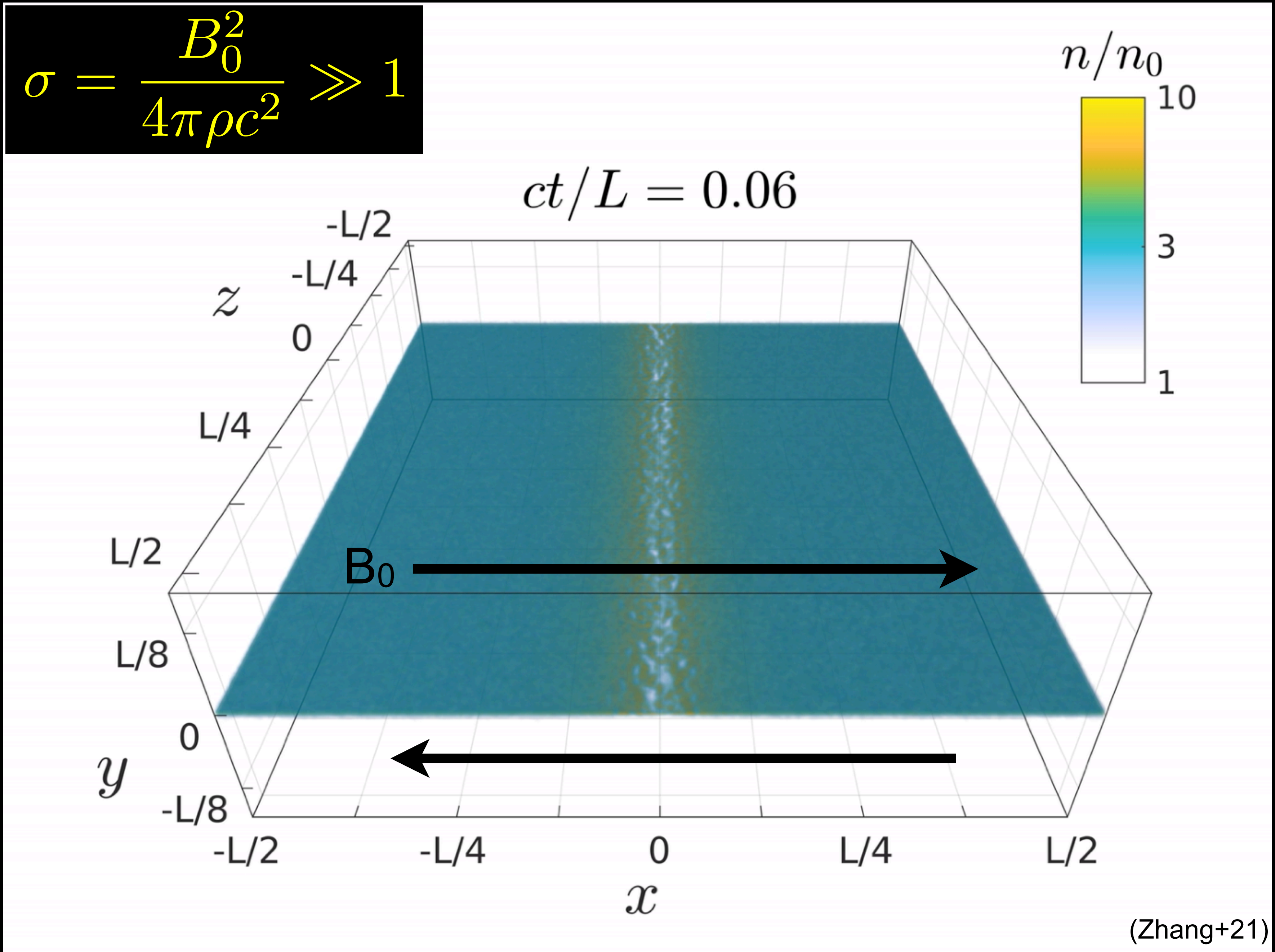
Zhang, LS & Giannios 2021, ApJ, 922, 261

The physics of particle acceleration in relativistic reconnection

LS 2022, PRL, 128, 145102

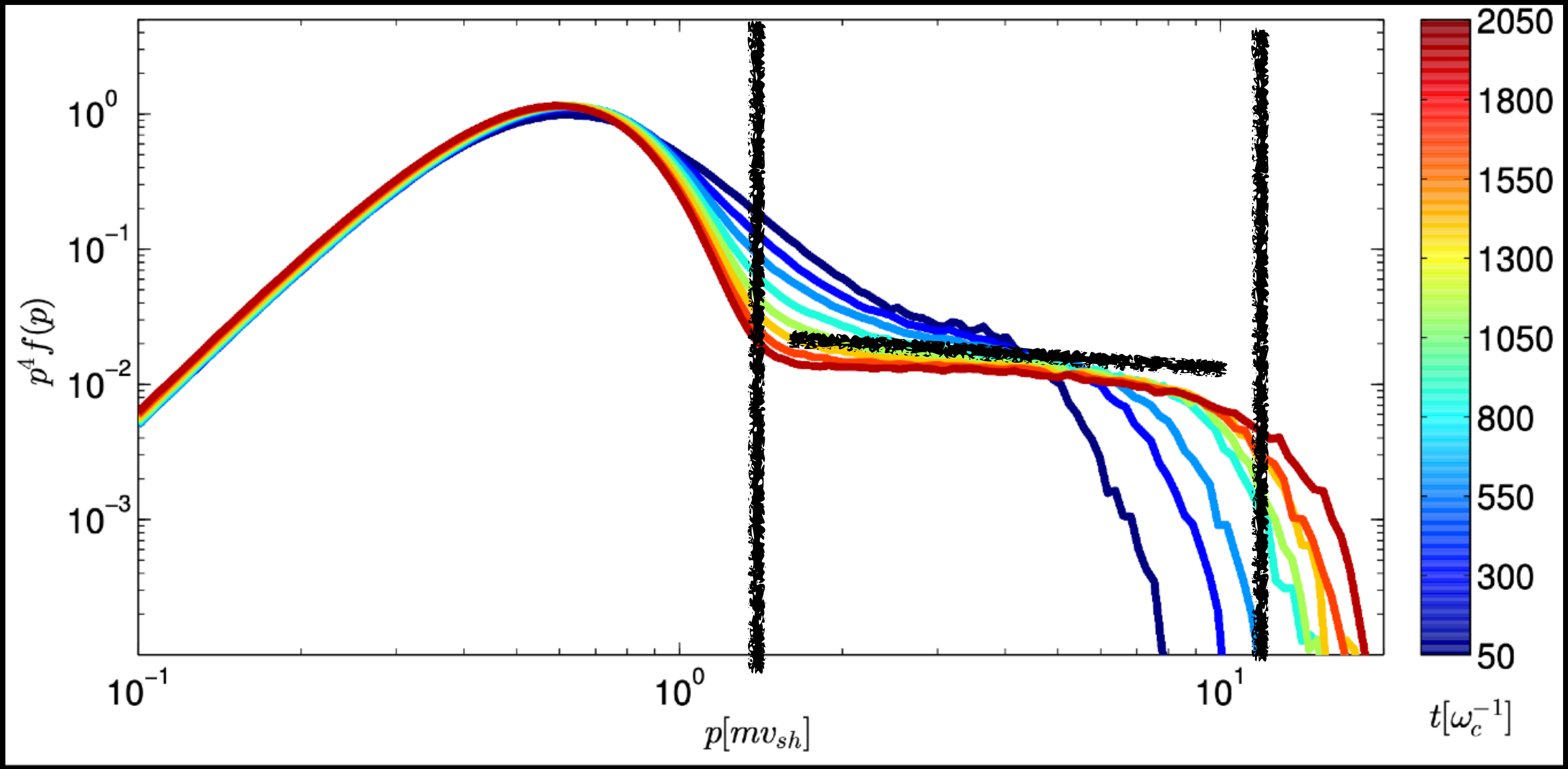
Zhang, LS & Giannios 2021, ApJ, 922, 261

PIC simulation of σ=10 (relativistic) reconnection



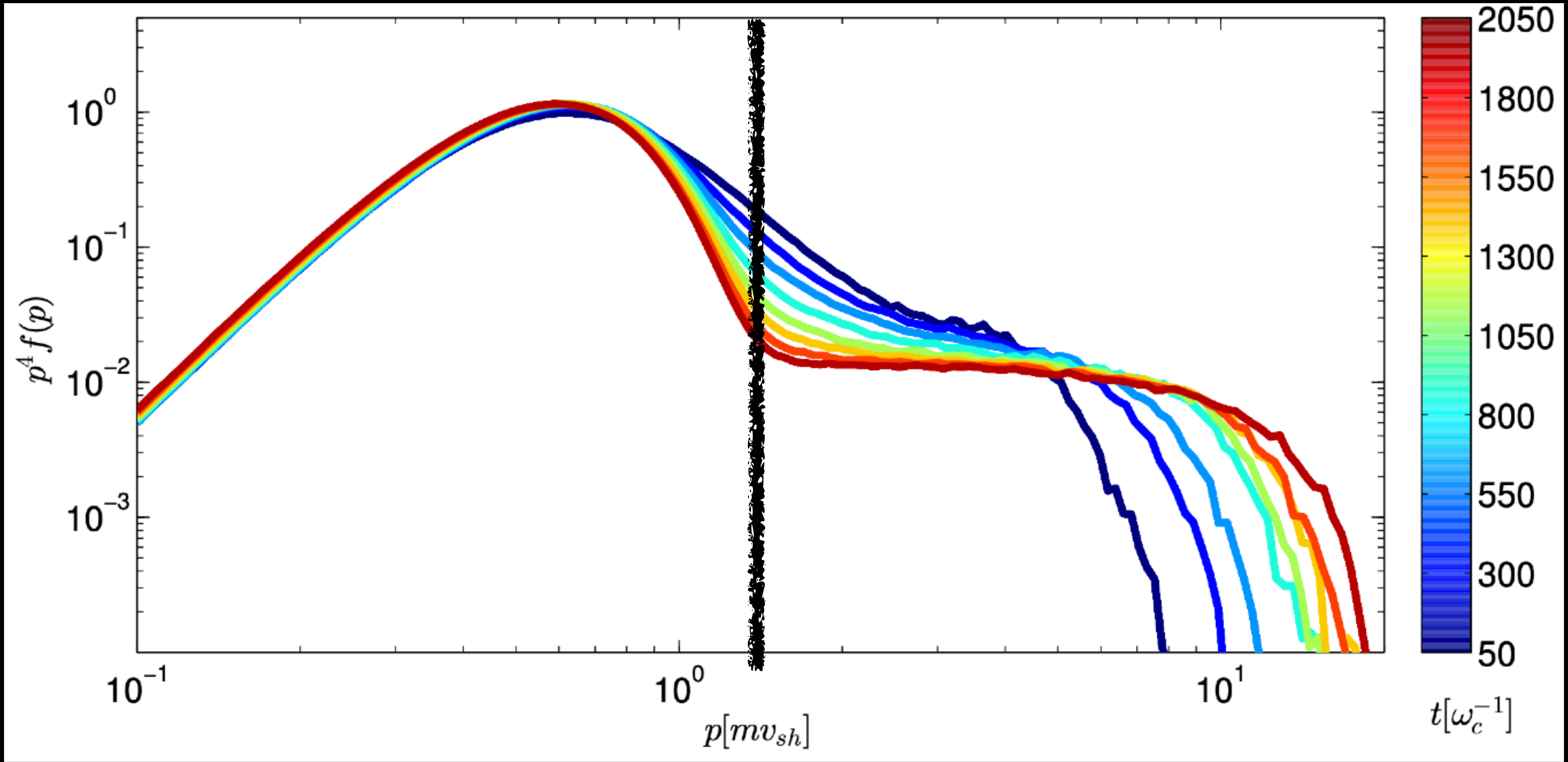
The reconnection layer breaks into a chain of magnetic islands / plasmoids

The three stages of any accelerator



(Caprioli & Spitkovsky 14)

- Injection
- Power-Law Formation
- Maximum Energy (cutoff)



10^0
10^{-1}
10^{-2}
10^{-3}
$p^4 f(p)$
10^{-1}
10^0
10^1
$p[mv_{sh}]$
2050
1800
1550
1300
1050
800
550
300
50
$t[\omega_c^{-1}]$

- Injection

Particle injection

How can the inflowing cold particles be promoted to $\gamma \sim \sigma/2$ and above?

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

They need to be in the right place at the right time!

where they interact with non-ideal fields $\mathbf{E} \neq -\frac{\mathbf{v}}{c} \times \mathbf{B}$

$$E > B \text{ for } B_g/B_0 \lesssim \eta_{\rm rec}$$

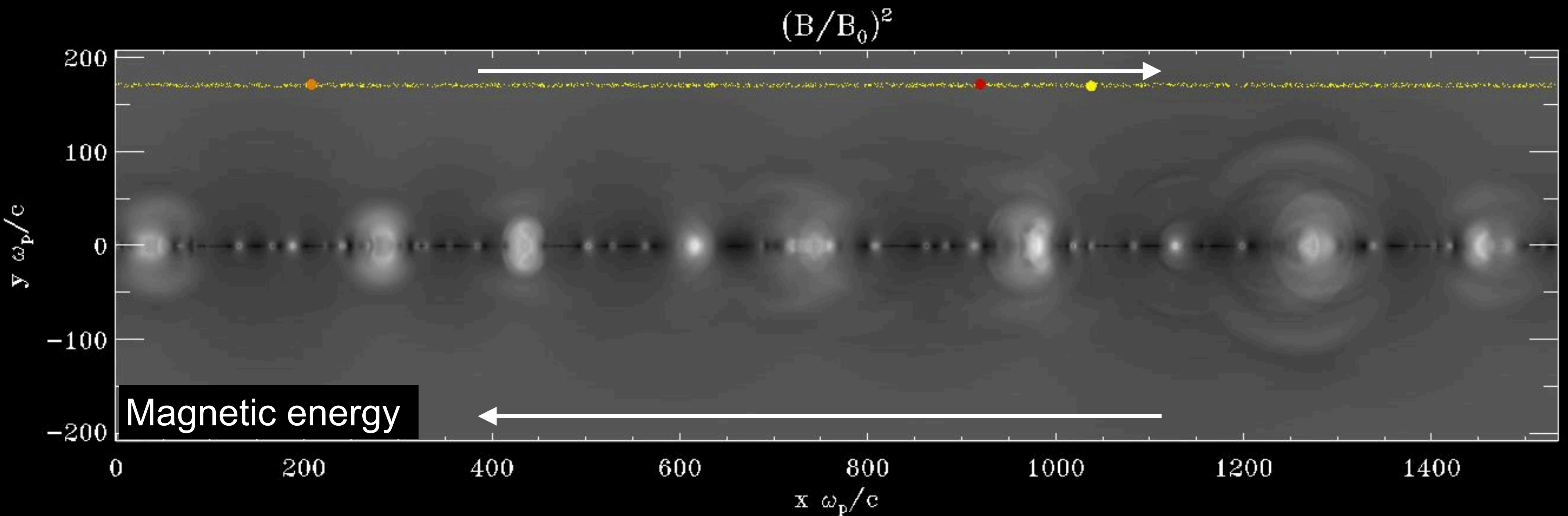
$$E_{||} \text{ for } B_g/B_0 \gtrsim \eta_{\rm rec}$$

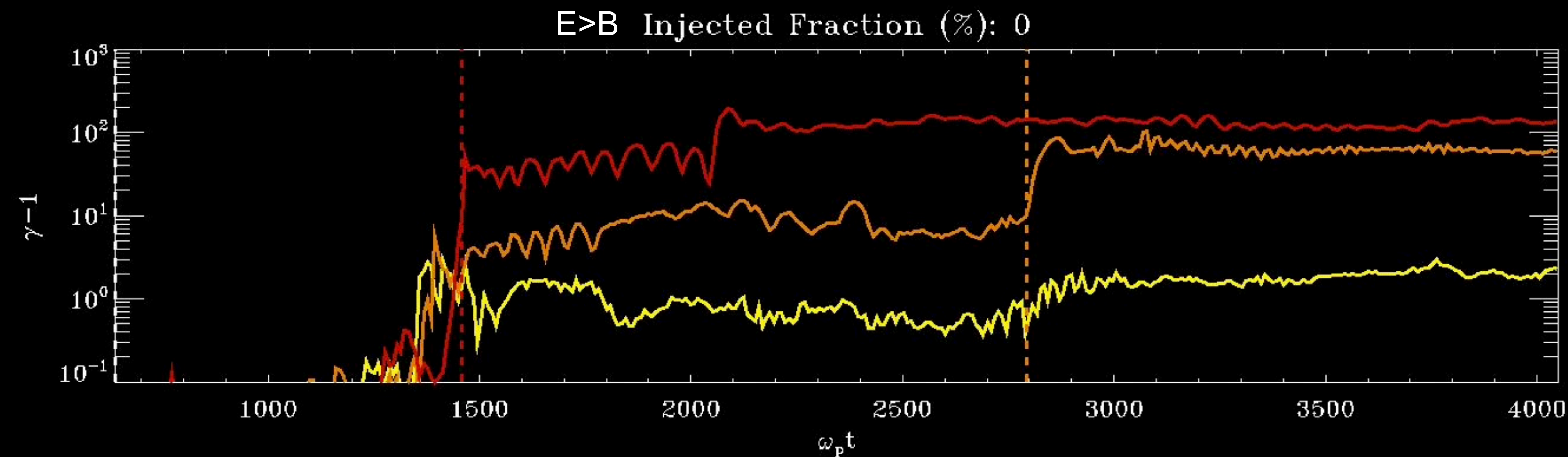
$$E_{||} = \mathbf{E} \cdot \mathbf{B}/B$$

$\eta_{\rm rec} \sim 0.1$ reconnection rate

B_g guide field (along electric current)

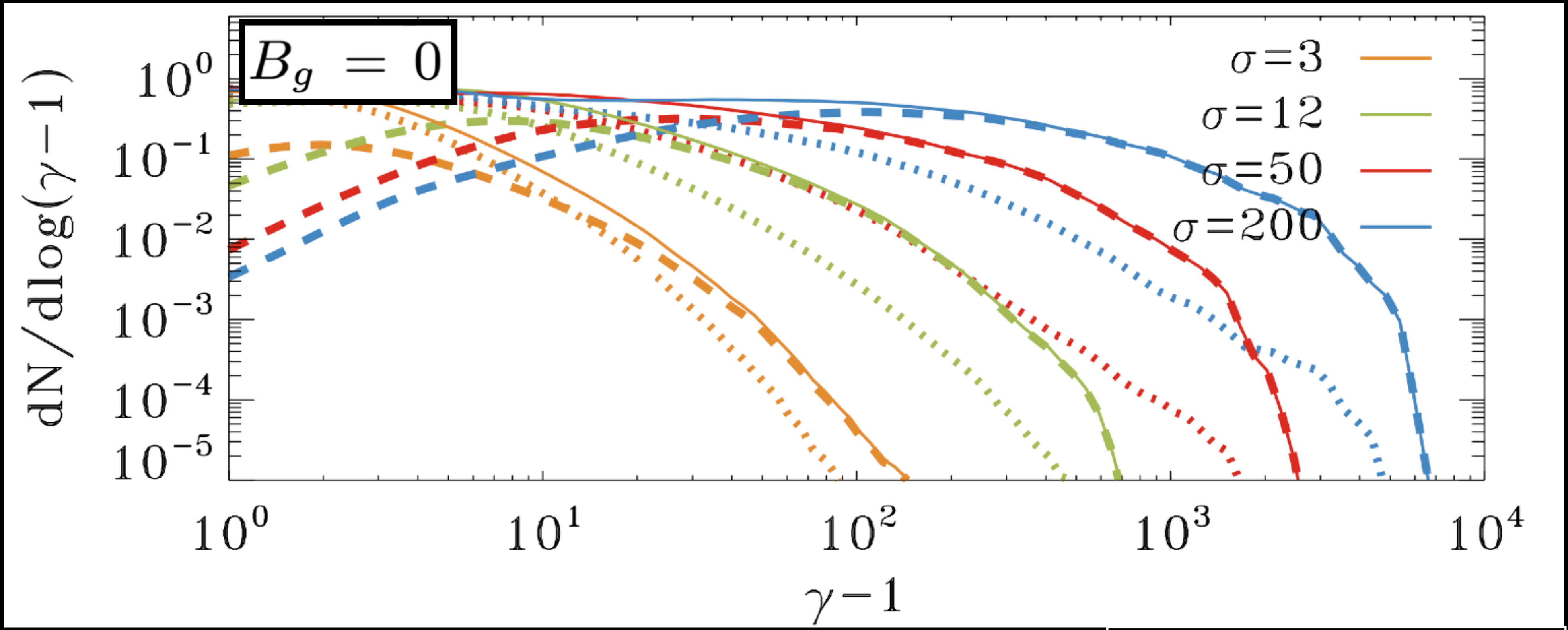
Particle injection





(LS 22, PRL)

Particle injection



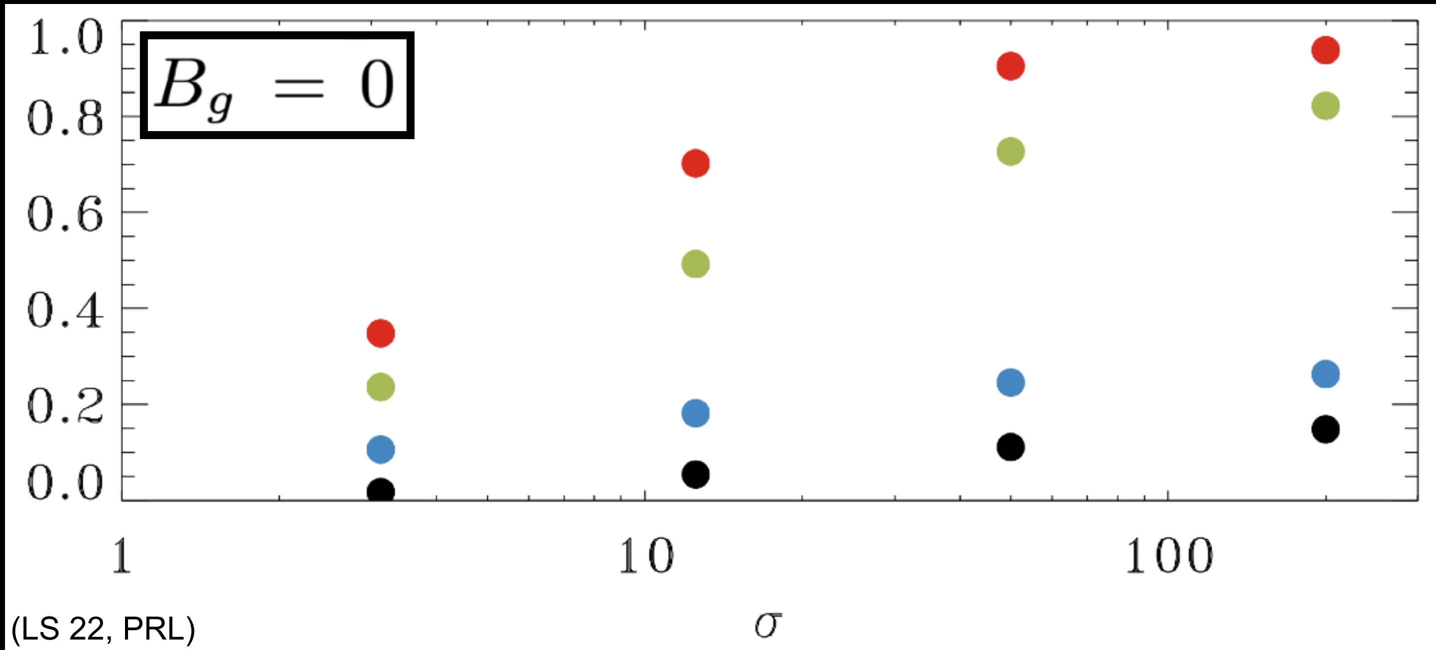
(LS 22, PRL)

Solid: total spectrum
Dashed: E>B particles
Dotted: E<B particles

- The spectrum of E<B particles peaks at $\gamma\sim1$
- The spectrum of E>B particles peaks at $\gamma\sim\sigma$

⇒ The high-energy end is dominated by E>B particles.

Particle injection fraction

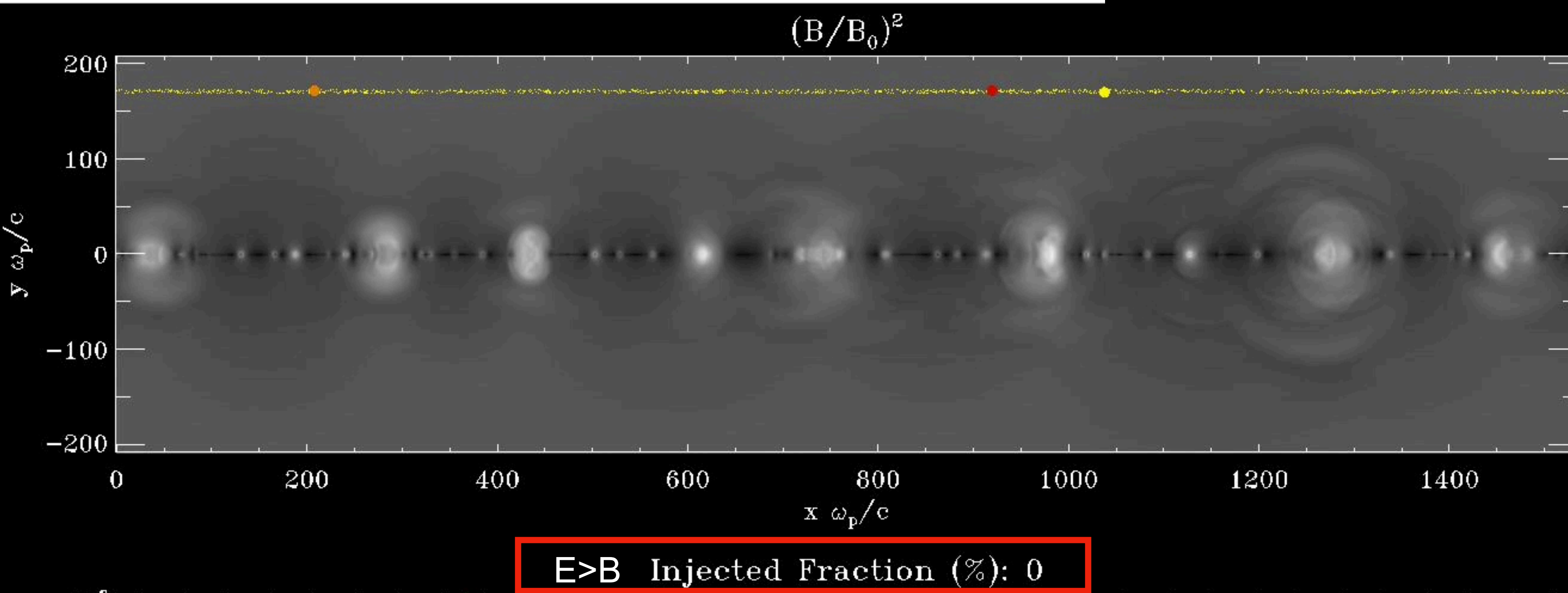


E>B fraction at $\gamma > \sigma$

E>B fraction at $\gamma > \sigma/4$

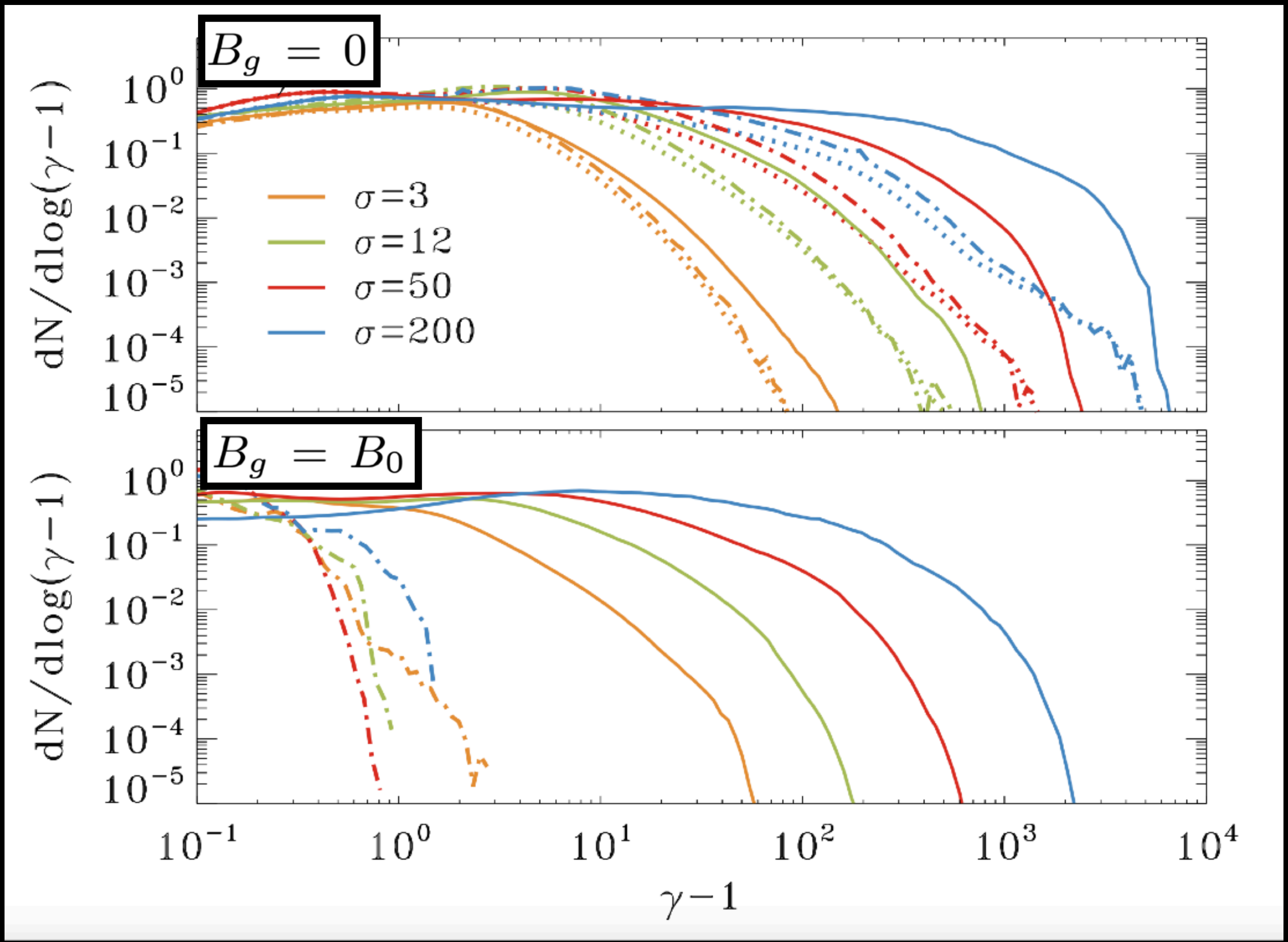
Overall E>B fraction

Fraction of length along y=0 with E>B regions



How to kill particle injection?

Testparticles: like regular particles, but they do not contribute to the current.



Dot-dashed: testparticles whose energy is fixed at γ~few while in E>B regions.

Dotted: E<B particles.

Dot-dashed: testparticles evolved without $E_{//}$

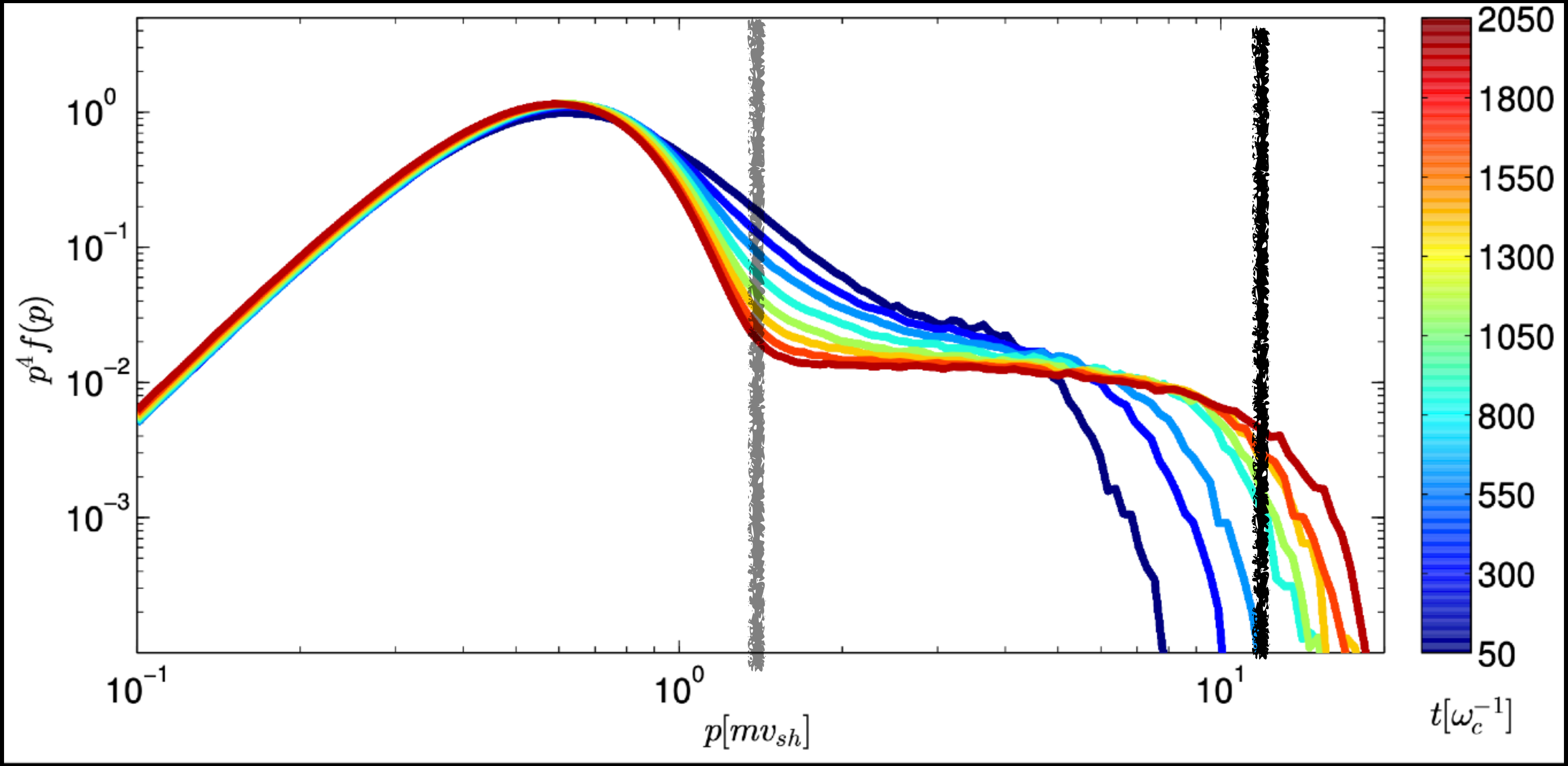
(LS 22, PRL)

⇒ Injection by non-ideal fields is a <u>necessary prerequisite</u> for further acceleration.

Why should we care about injection?

- To emphasize that studies of test-particle acceleration in MHD simulations need to properly include non-ideal effects.

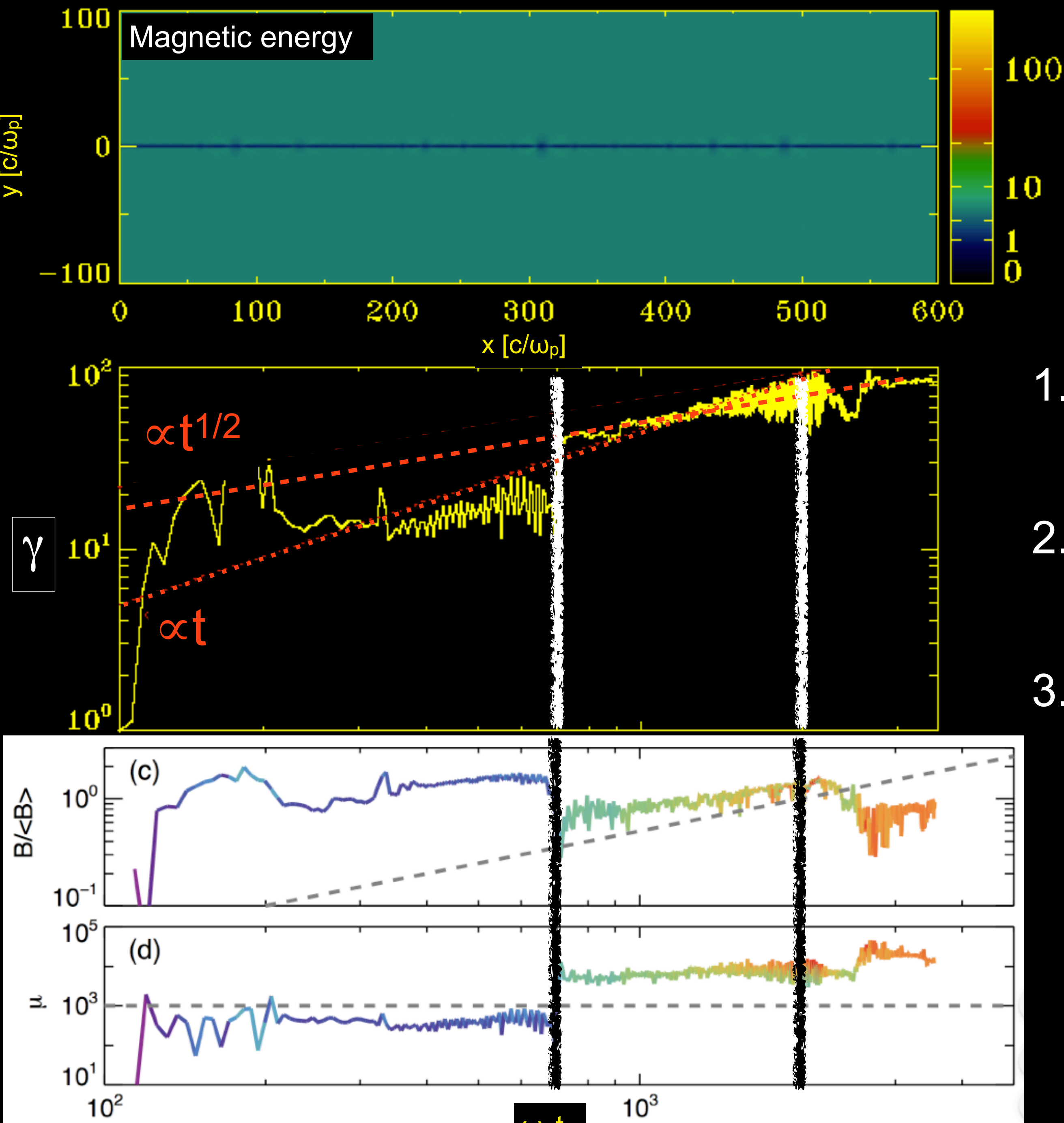
- Because reconnection-accelerated particles may not get much beyond the injection stage.



- Injection

- Maximum Energy (cutoff)

The spectral cutoff in 2D

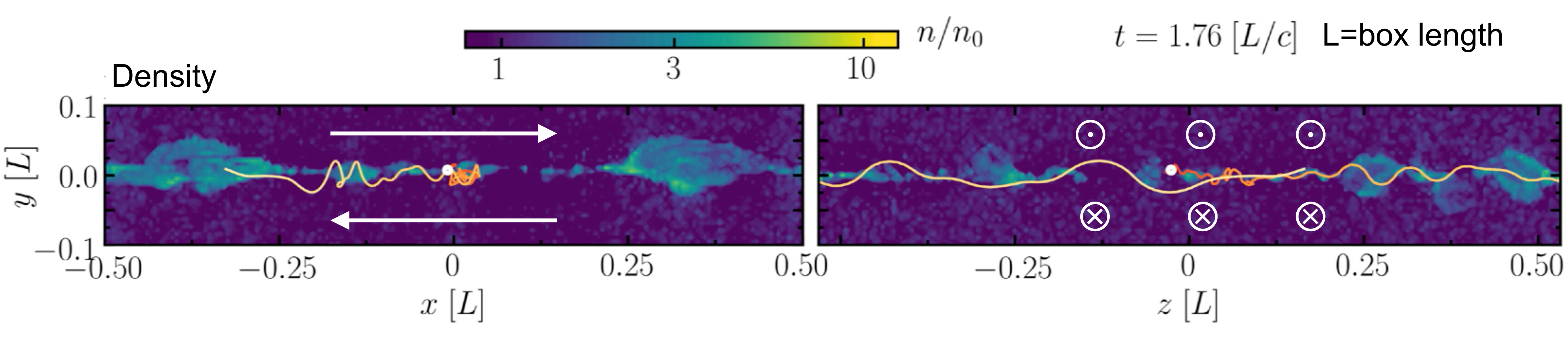


(Petropoulou & LS 18, Hakobyan+ 21)

1. B increases linearly in compressing plasmoids.
2. Magnetic moment $\mu \propto \frac{\gamma^2}{B}$ is conserved.
3. This gives $\gamma \propto t^{1/2}$

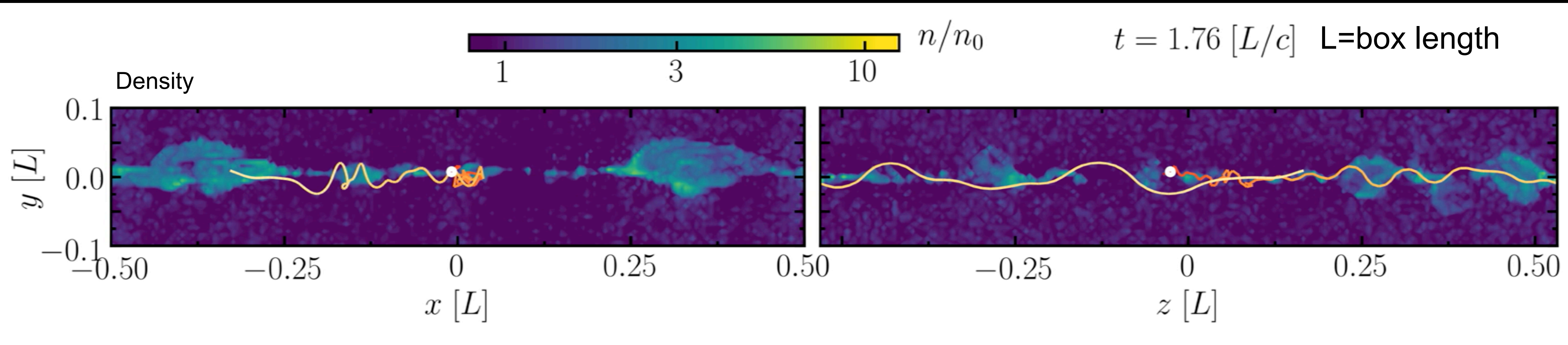
2D reconnection is slow!

The highest energy particles in 3D



• In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle "free" around the layer.

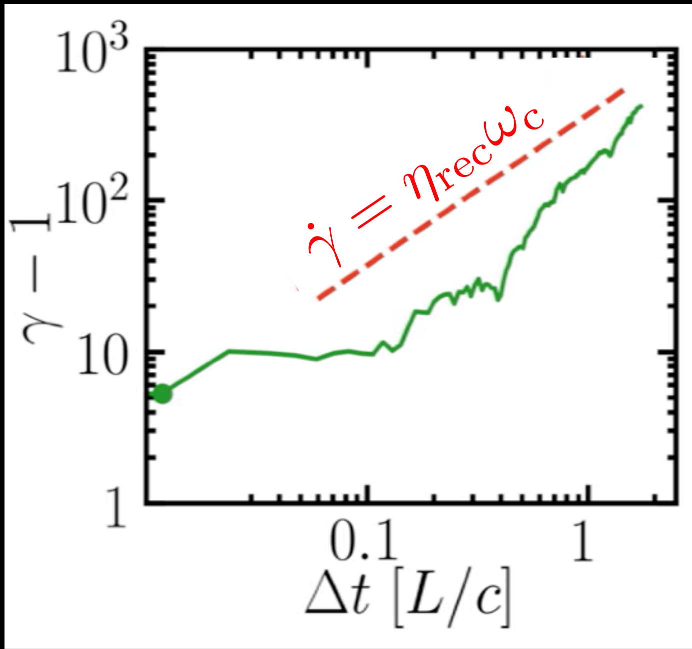
The highest energy particles in 3D



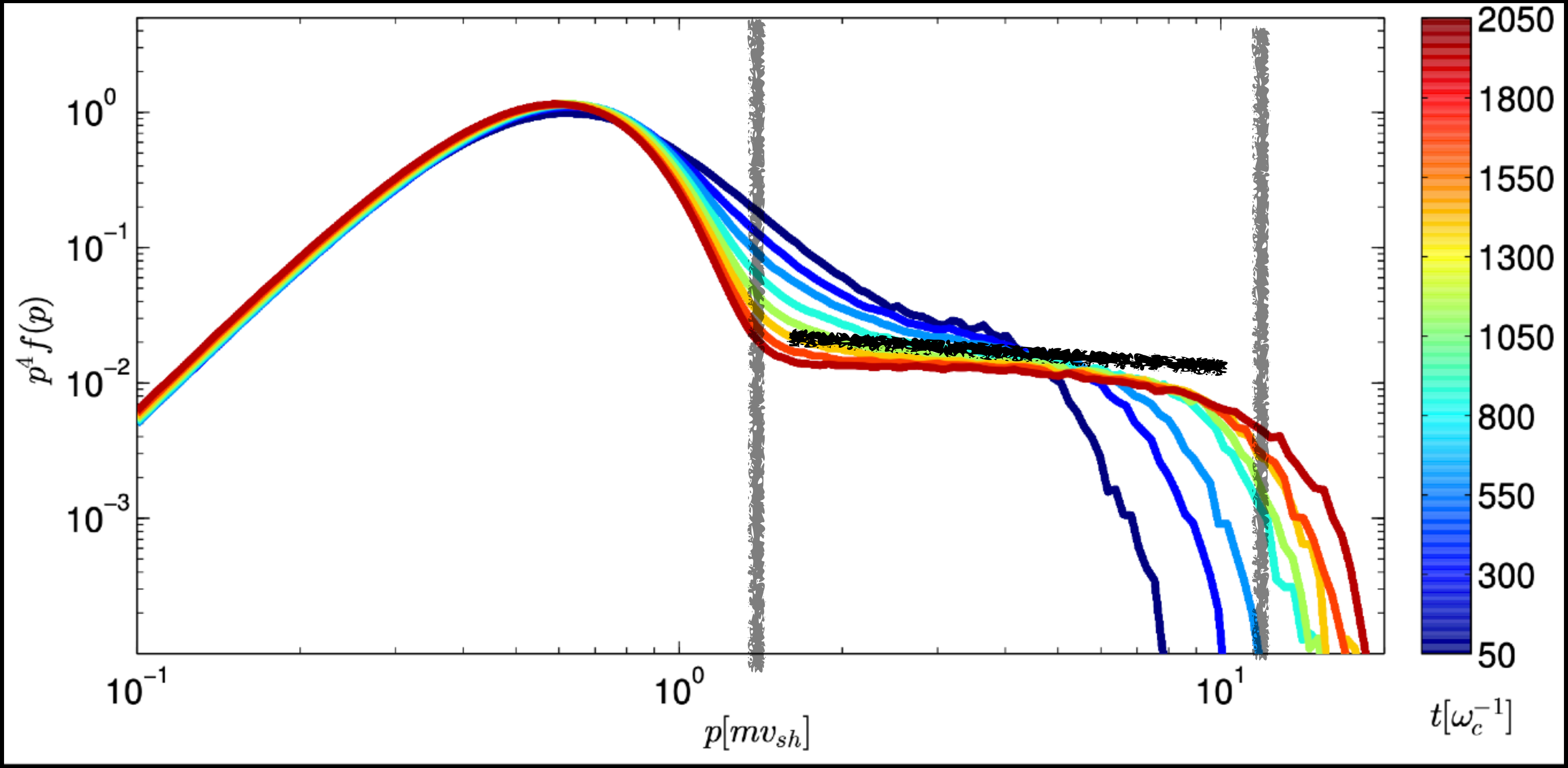
- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle "free" around the layer.
- They get accelerated linearly in time, $\gamma \propto t$, by the large-scale (ideal) electric field in the upstream.
- The energy gain rate approaches $\sim eE_{\rm rec}c$,

$$E_{\rm rec} \simeq 0.1 B_0$$

- AGN jets are able to accelerate UHECRs.



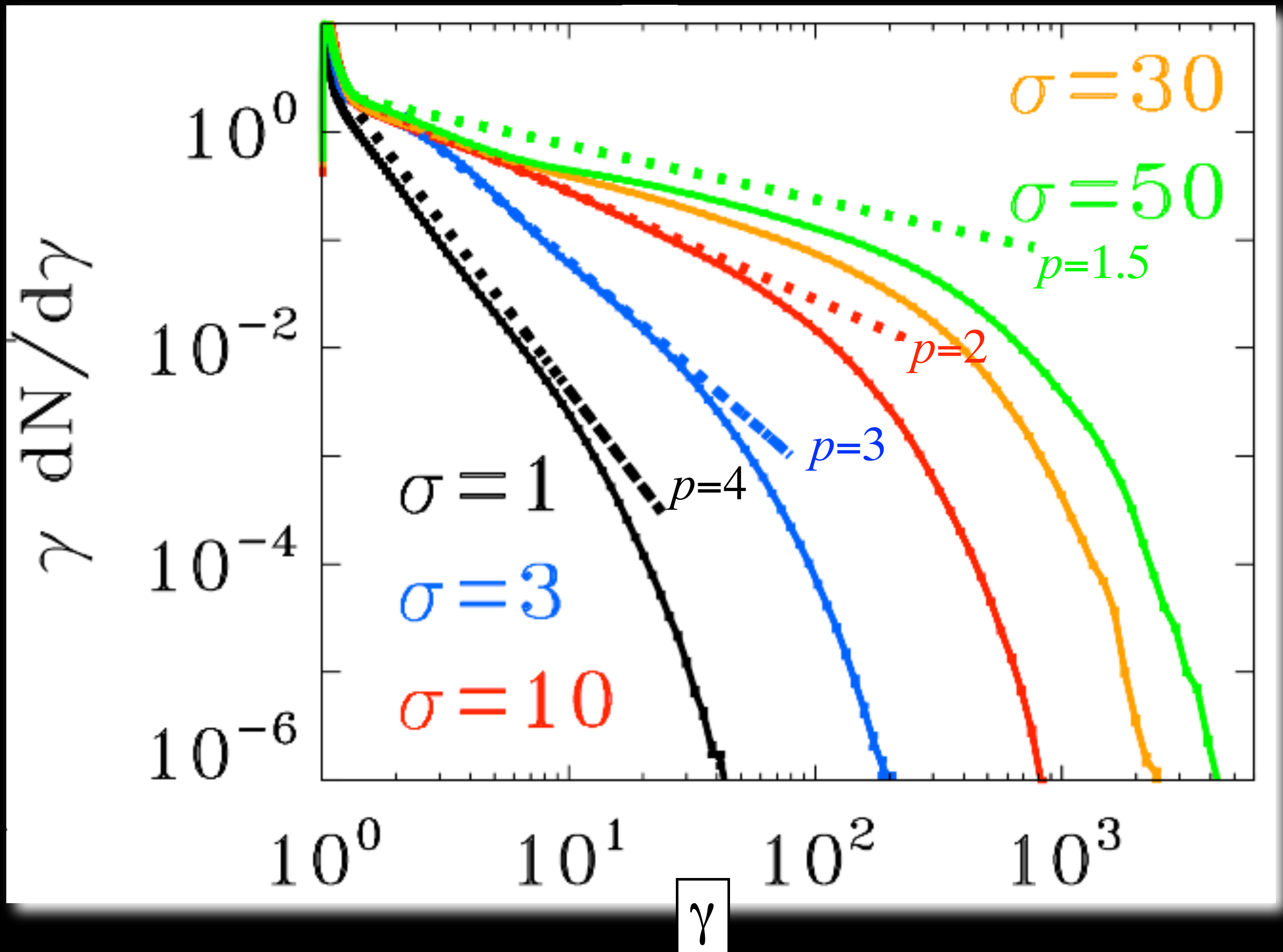
(Zhang, LS, Giannios 21)



- Injection
- Power-Law Formation
- Maximum Energy (cutoff)

The injection stage gives hard spectra

2D and 3D electron-positron



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

(LS & Spitkovsky 14, see also Melzani+14, Guo+14,15, Werner+16,17)

The injection stage produces power laws at $\gamma \lesssim 3\sigma$, with slope as hard as *p=1* for high magnetizations.

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

This holds in electron-positron, electron-proton and electron-positron-proton plasmas.

Theory of post-injection power-law

- In steady state,

$$\frac{\partial}{\partial\gamma}\left(\frac{\gamma}{t_{\rm acc}}f\right)+\frac{f}{t_{\rm esc}}=Q_0\delta(\gamma-3\sigma)$$

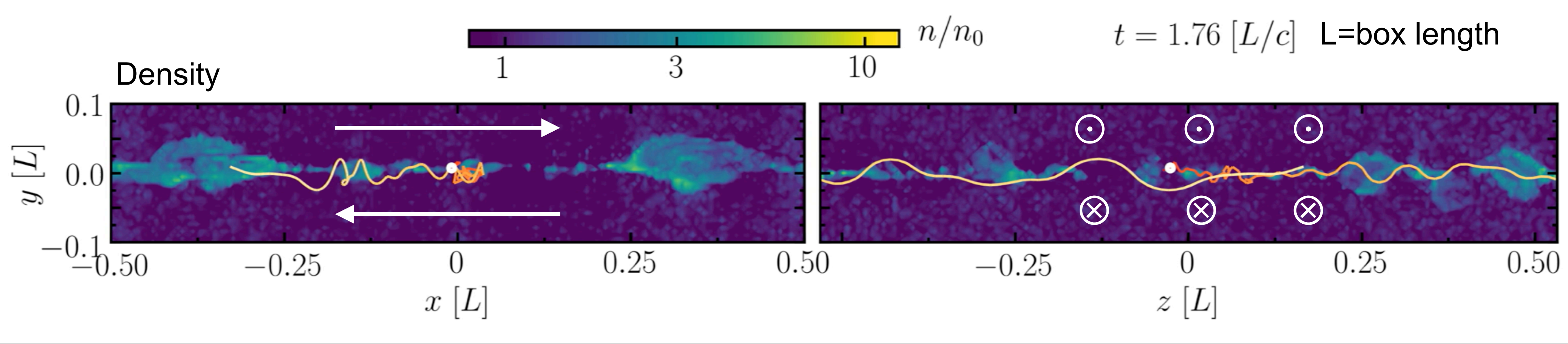
assuming injection at $\gamma = 3\sigma$.

- If t_{acc} and t_{esc} depend linearly on γ, the solution is

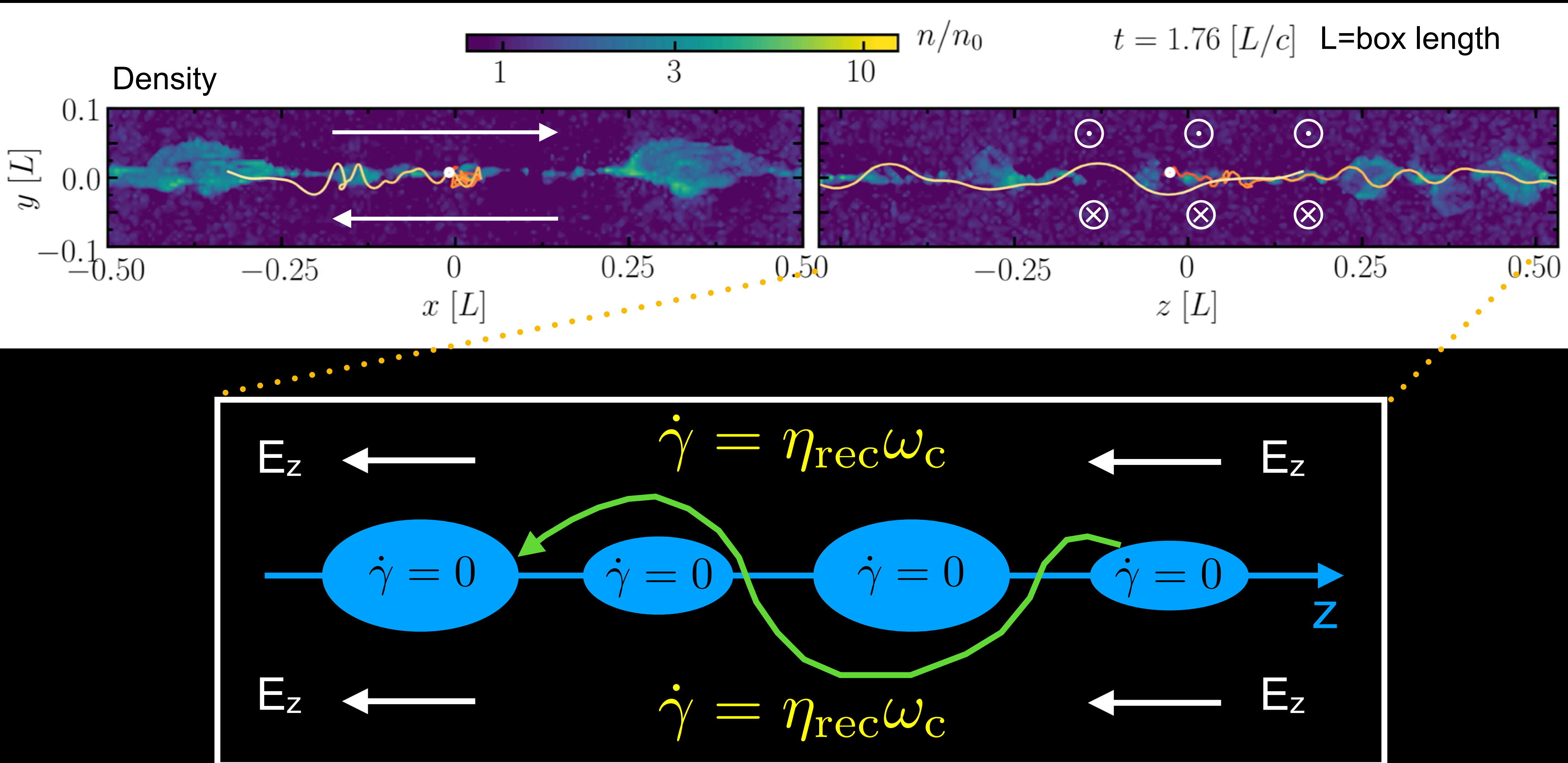
$$f \propto \gamma^{-t_{\rm acc}/t_{\rm esc}}$$

- What is the acceleration time $t_{acc} = \gamma/\dot{\gamma}$?
- What is the escape time t_{esc} ?

A new 3D theory of power-law formation

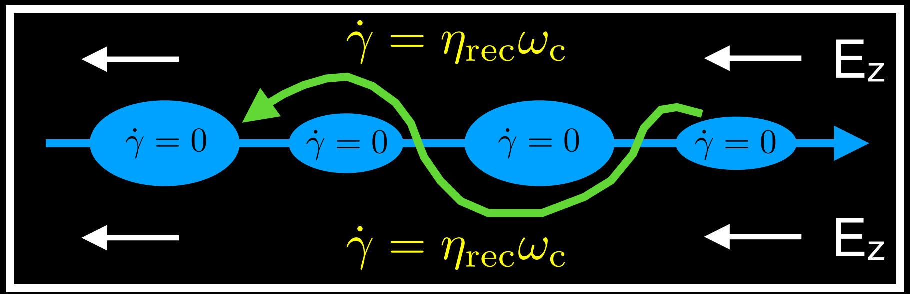


A new 3D theory of power-law formation

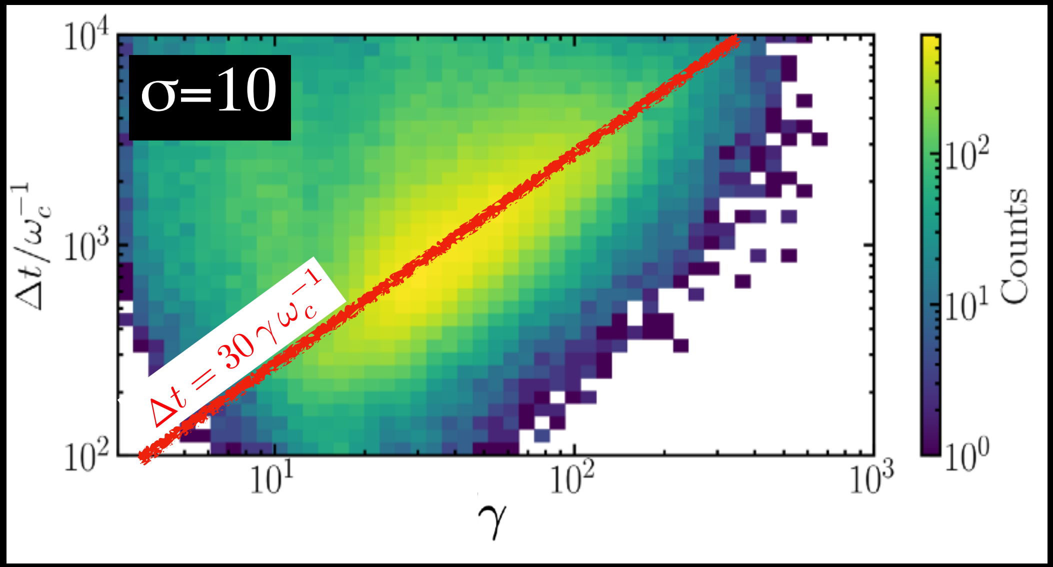


- Active acceleration only in the “free” state while particles are in the upstream.
- Acceleration ceases when particles are captured by plasmoids (escape term).

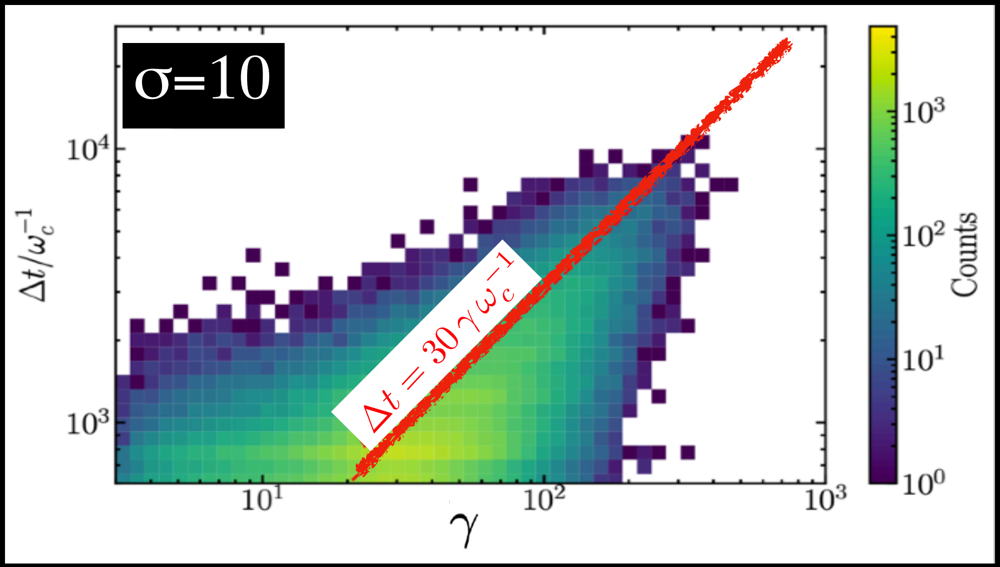
Acceleration and escape times



Acceleration time $t_{acc} = \gamma/\dot{\gamma}$



Escape/trapping time t_{esc}

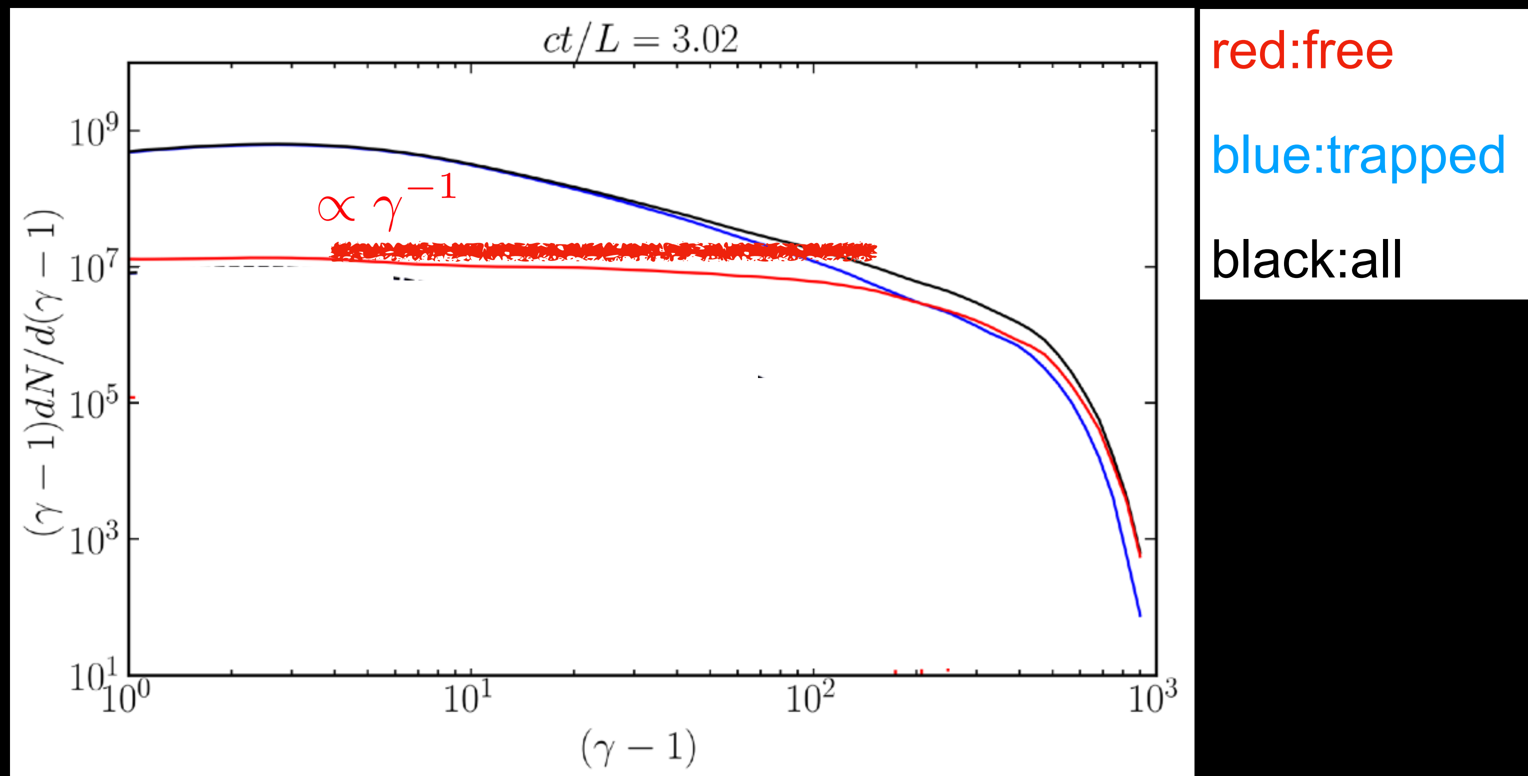


The two timescales are comparable, so

$$f_{\rm free} = \frac{dN_{\rm free}}{d\gamma} \propto \gamma^{-t_{\rm acc}/t_{\rm esc}} \propto \gamma^{-1}$$

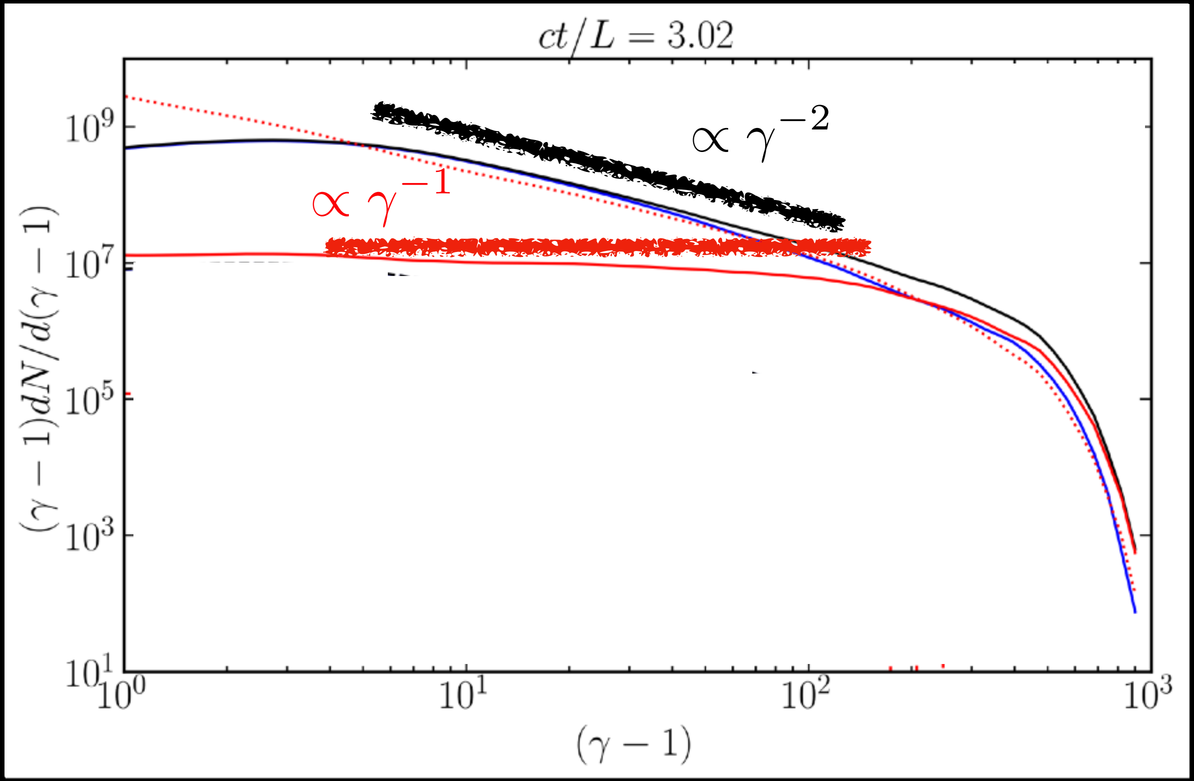
Free vs trapped vs all

σ=10



Free vs trapped vs all

σ=10



red:free

blue:trapped

black:all

In steady state:

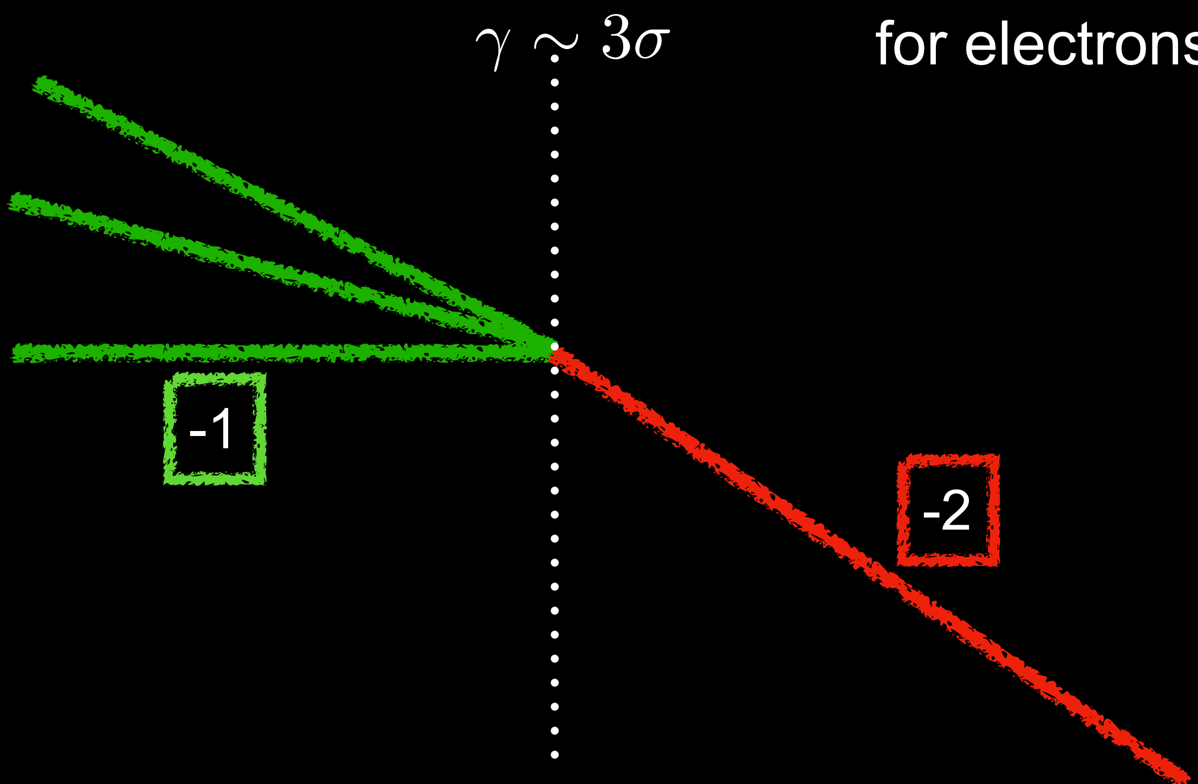
rate of free particles getting trapped = rate of trapped particles being advected out

$$f_{\rm trap} = f_{\rm free}\frac{t_{\rm adv}}{t_{\rm esc}} \propto f_{\rm free}\gamma^{-1} \propto \gamma^{-2}$$

At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (σ-independent) slope of *p*=2.

The outcome: a broken power law

for electrons: $\sigma_e = \frac{m_p}{m_e}\sigma$

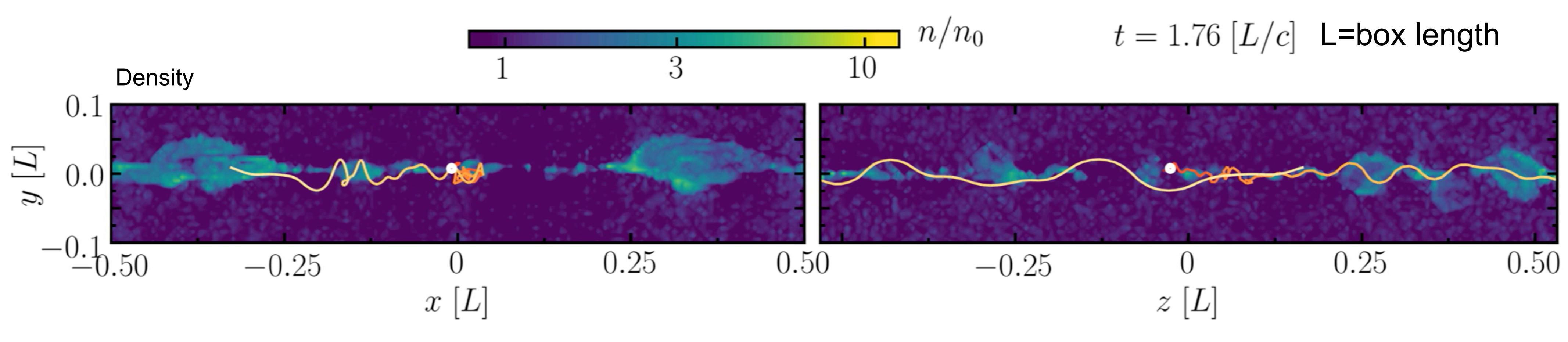


At $\gamma \lesssim 3\sigma$ injection in reconnection leads to σ-dependent slopes, as hard as *p=1*.

At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (σ-independent) slope of *p*=2.

Relativistic reconnection vs relativistic shocks (as UHECRs accelerators)

The highest energy particles in 3D



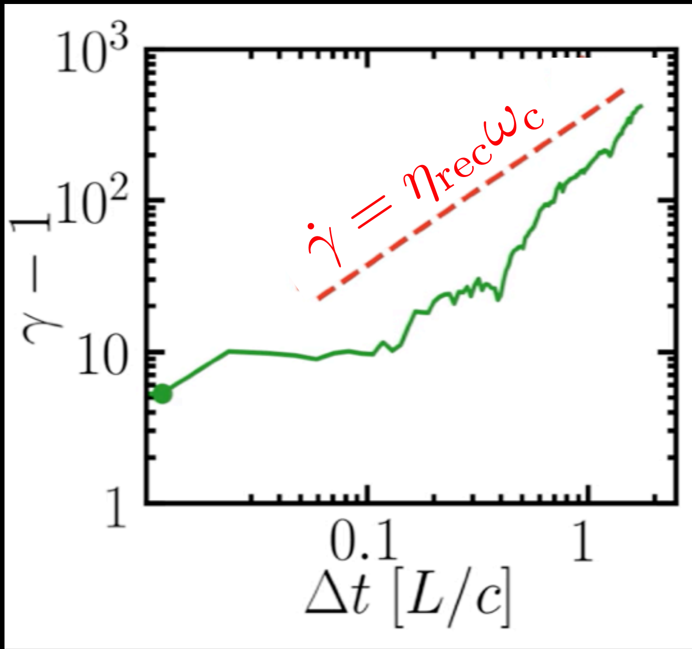
- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle “free” around the layer.

- They get accelerated linearly in time, $\gamma \propto t$, by the large-scale (ideal) electric field in the upstream.

- The energy gain rate approaches $\sim eE_{\rm rec}c$

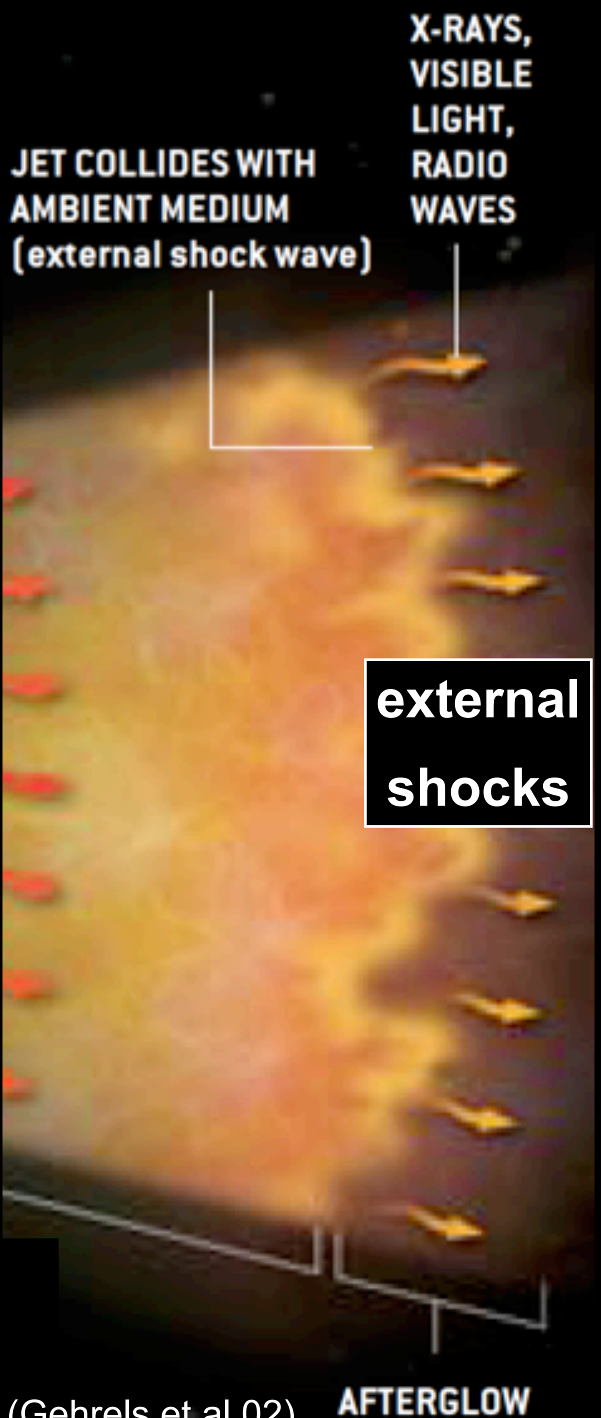
$$E_{\rm rec} \simeq 0.1 B_0$$

- AGN jets are able to accelerate UHECRs.



(Zhang, LS, Giannios 21)

Relativistic shocks in GRBs



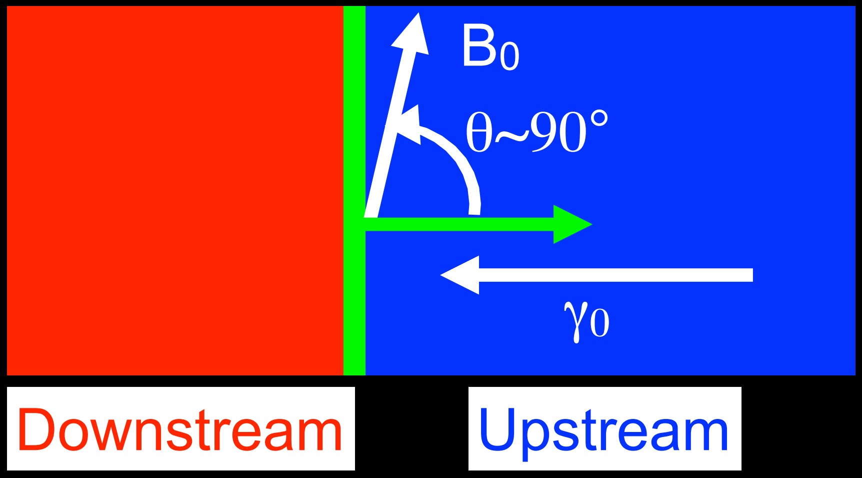
(Gehrels et al 02)

Gamma-ray burst external shocks:

- γ_0~a few hundreds
- weakly magnetized: $\sigma \sim 10^{-9}$

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

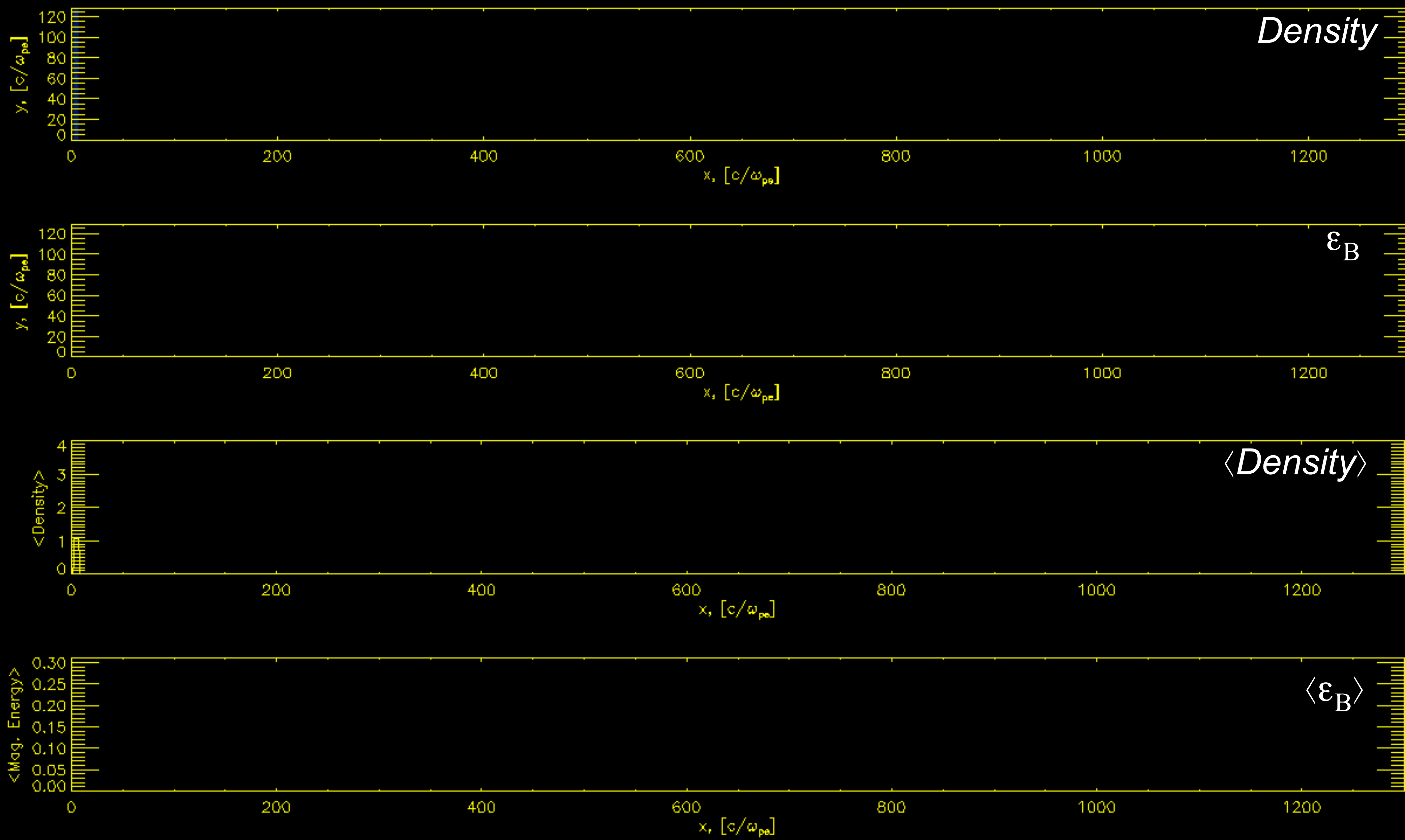
- quasi-perpendicular shocks



Weakly magnetized shocks

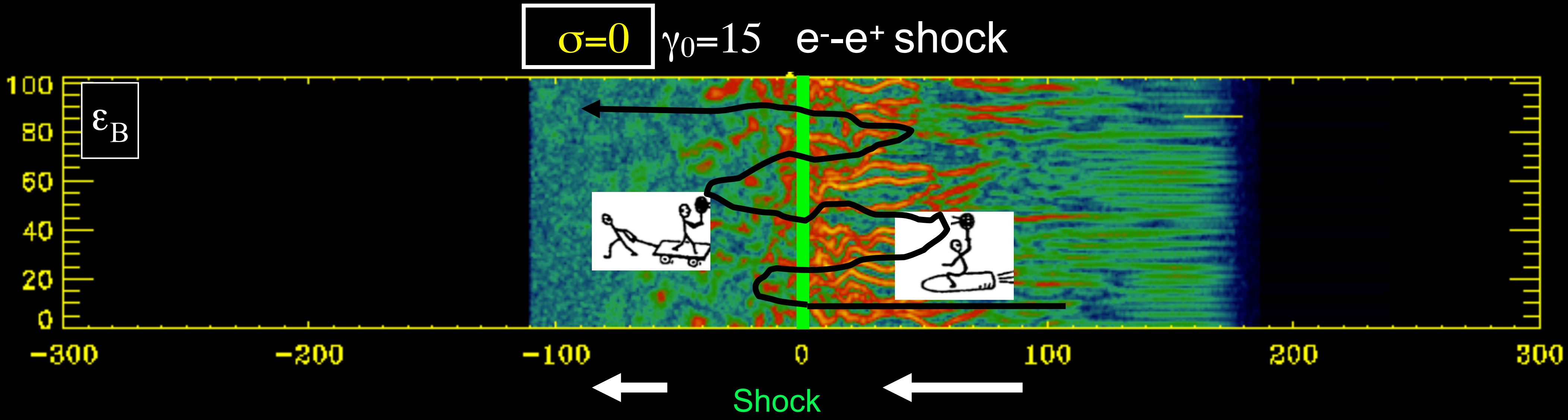
Mediated by the Weibel instability, that generates small-scale sub-equipartition magnetic fields.

2D PIC simulation of $\sigma=0$ $\gamma_0=15$ $e^- - e^+$ shock



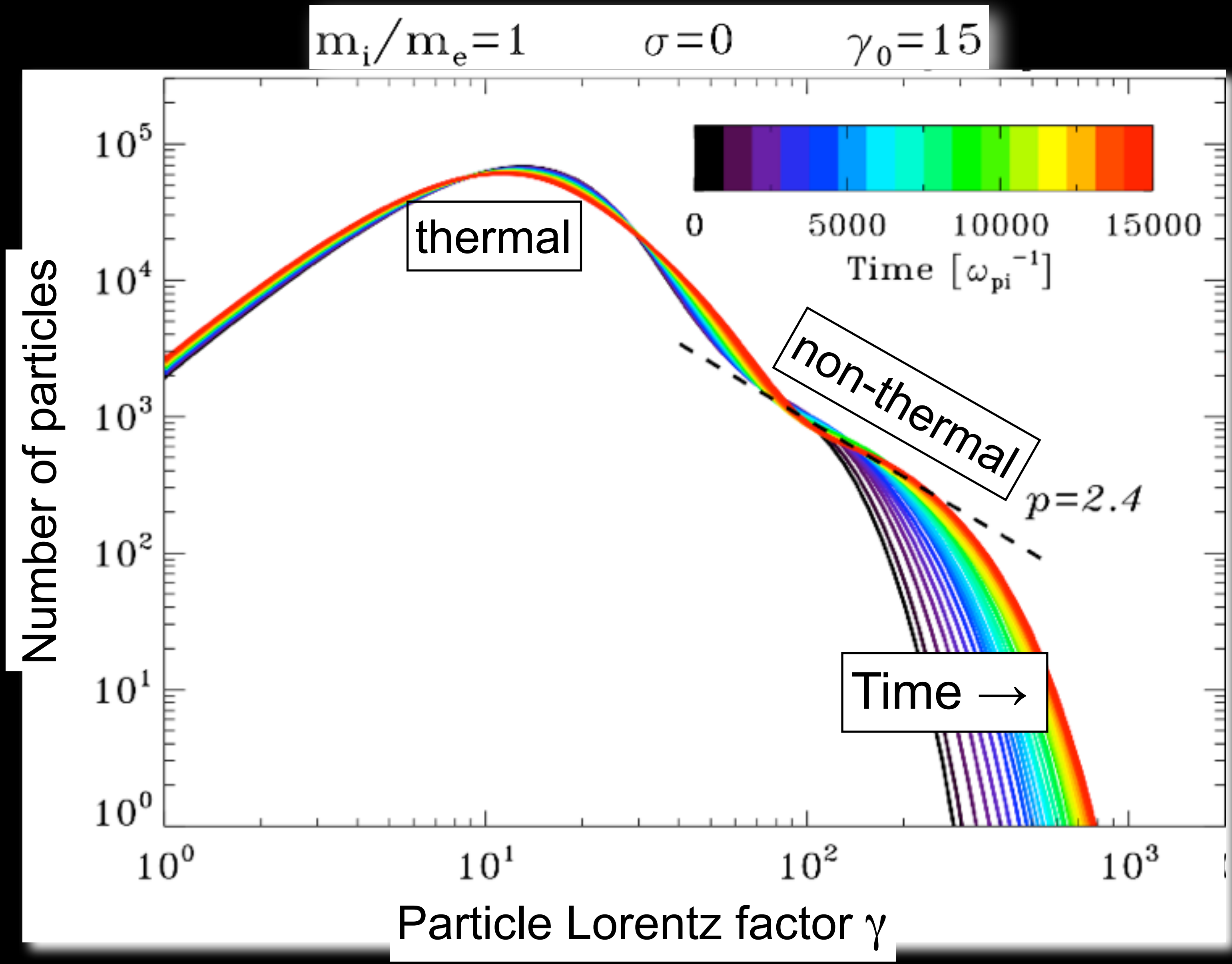
The Fermi process in low-σ shocks

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



(LS et al 13)

GRB shocks accelerate non-thermal particles



(LS et al. 13, Martins et al. 09, Haugbolle 10)

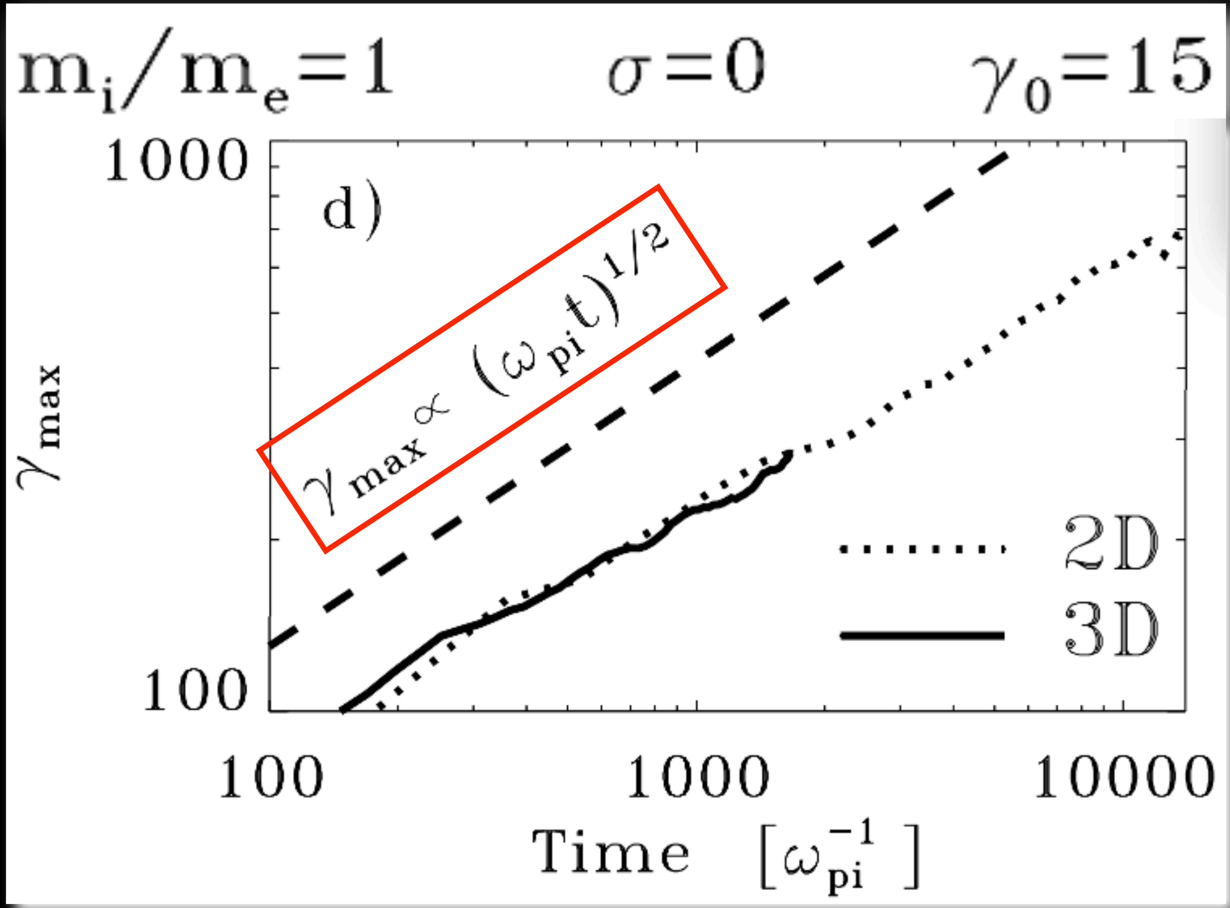
Conclusions are the same in 2D and 3D, for electron-positron and electron-ion plasmas

GRB shocks are slow accelerators

By scattering off small-scale Weibel turbulence, the maximum energy grows as $\gamma_{max} \propto t^{1/2}$.

Instead, most models of particle acceleration in shocks assume $\gamma_{max} \propto t$ (Bohm scaling).

$$\gamma_{max} \simeq 0.5\,\gamma_0\,(\omega_{pi} t)^{1/2}$$



(LS et al. 13)