Energy Dissipation, Plasma Dynamics, and Particle Acceleration in Two- & Three-dimensional Magnetic Reconnection

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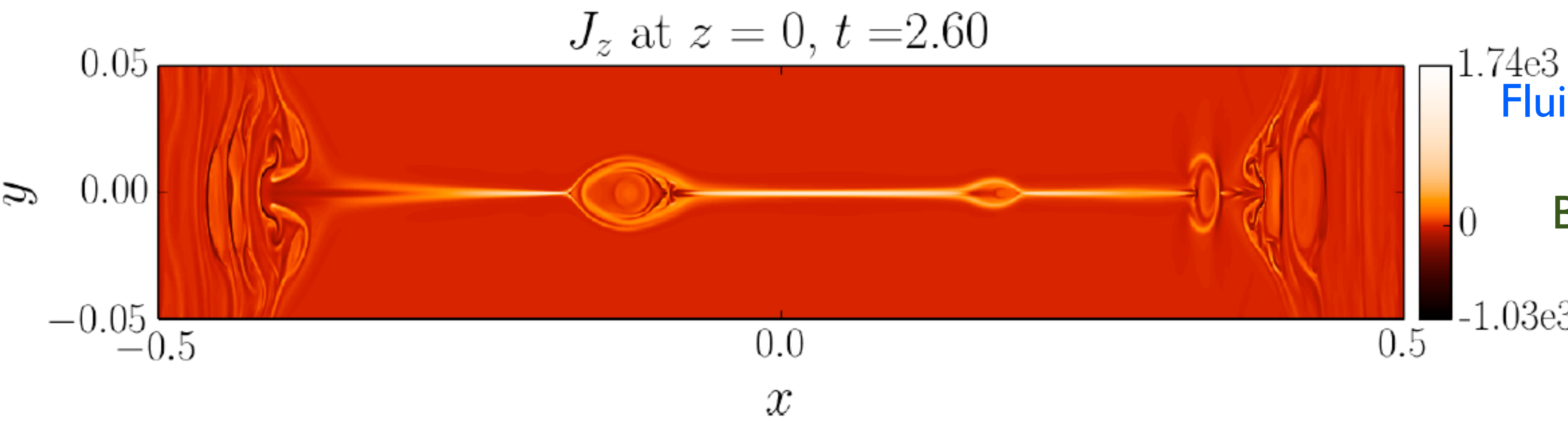
Our Understanding about 2D Magnetic Reconnection



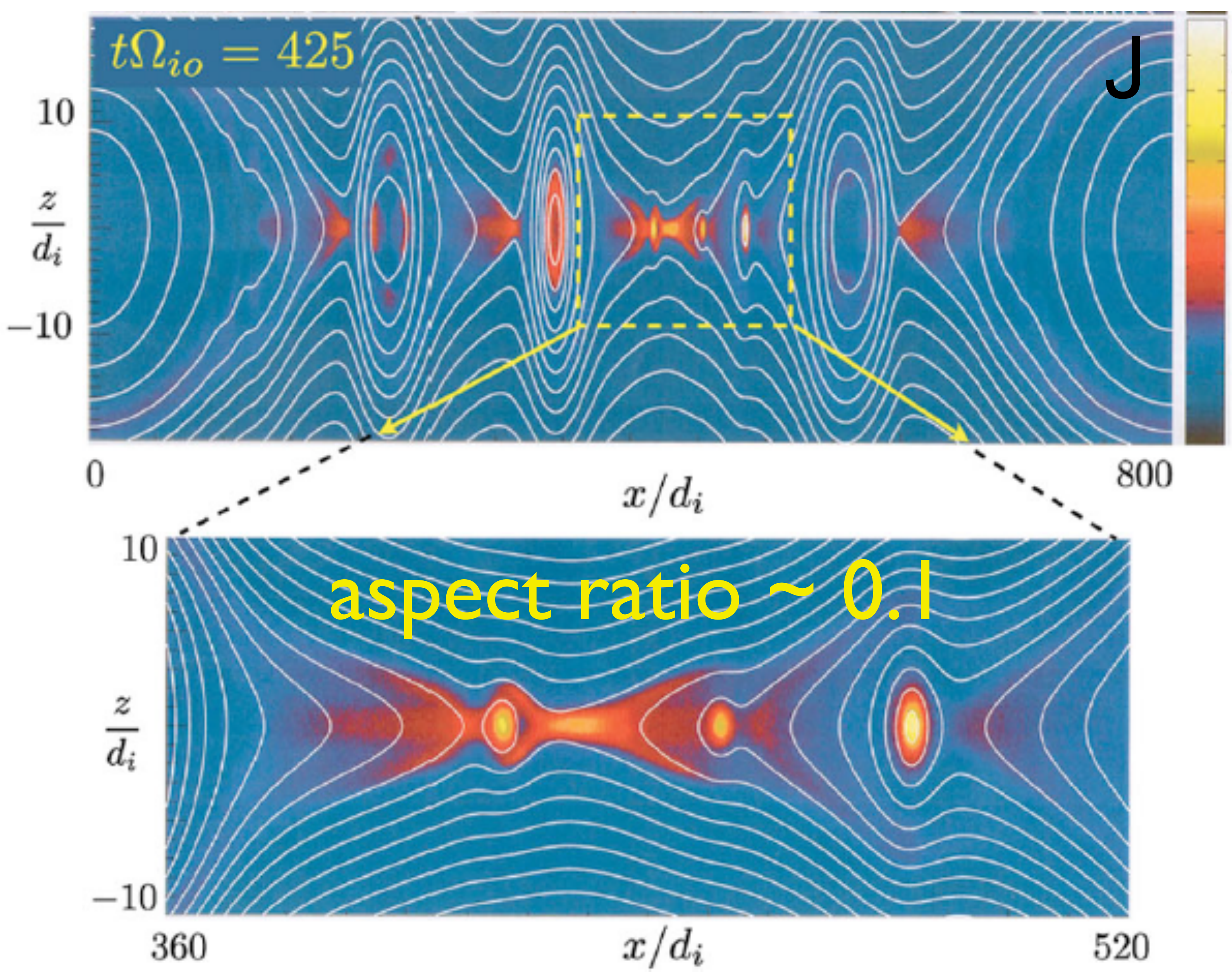
Fluid approach (MHD eqn.)

Loureiro et al. 07

Bhattacharjee et al. 09

Uzdensky et al. 10

$R \sim 0.01$



Fully kinetic approach

Daughton et al. (2009)

Liu et al. (2017)

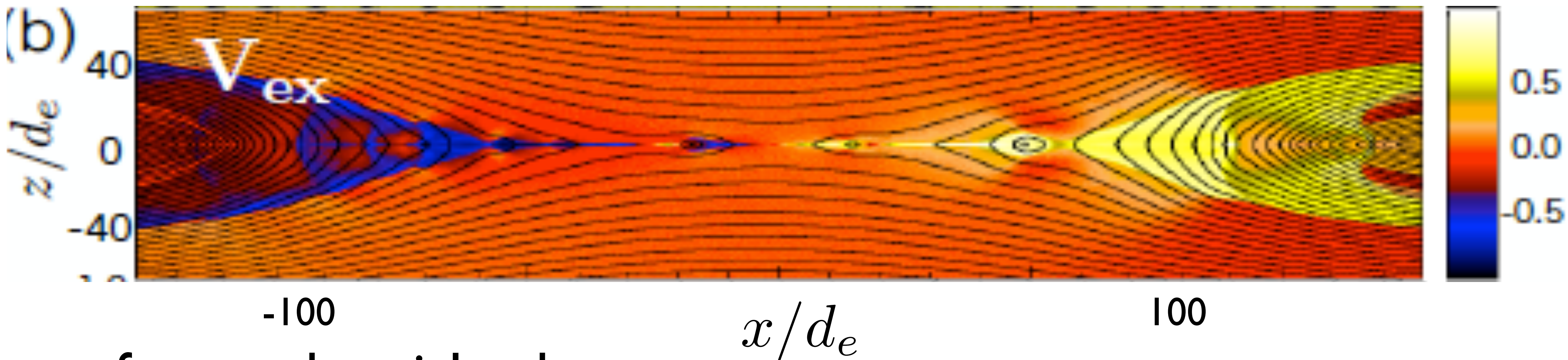
$R \sim 0.1$

Main findings:

Fast magnetic reconnection

$$\tau = 10 - 100\tau_A$$

Magnetic Reconnection Rate (local)

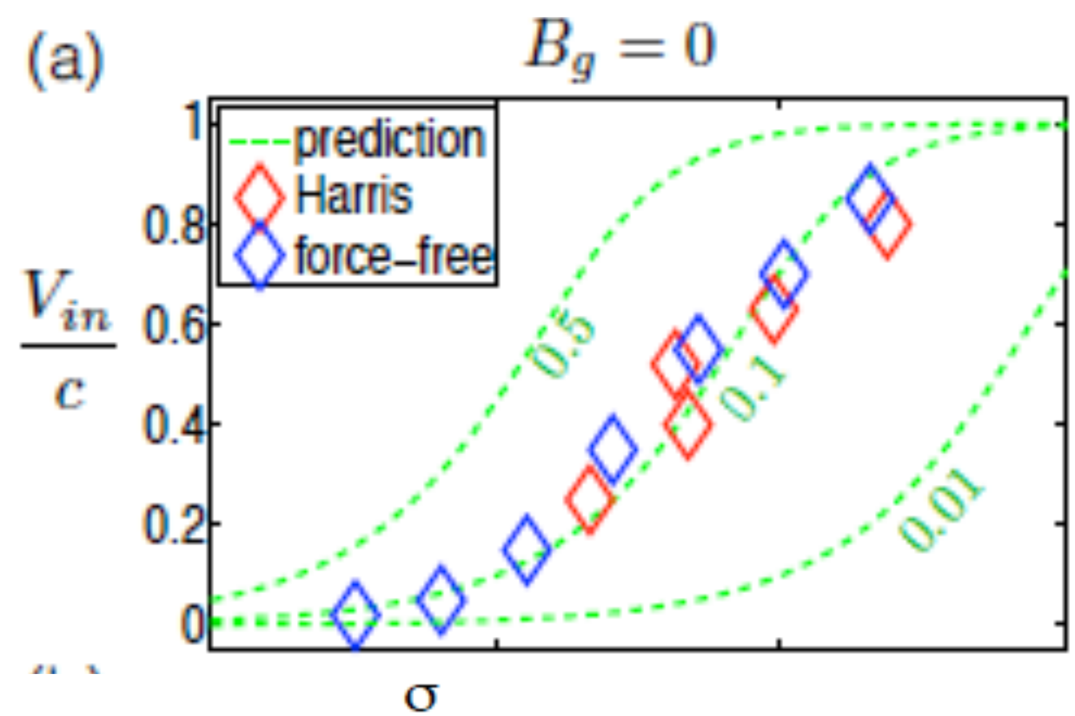


- Lots of secondary islands
- The local rate is enhanced due to relativistic inflow/outflow.
- Current sheet aspect ratio remains ~0.1

$$\Gamma_{in} v_{in} n_{in} L = \Gamma_{out} v_{out} n_{out} \delta$$

nonrelativistic $R \sim \frac{\delta_i}{L_i}\frac{v_{i,out}}{V_{Ax}} \sim \frac{\delta_i}{L_i} \sim 0.1$

relativistic $R = \frac{\delta}{L}\sqrt{\frac{1+\sigma}{1+(\delta/L)^2\sigma}}$



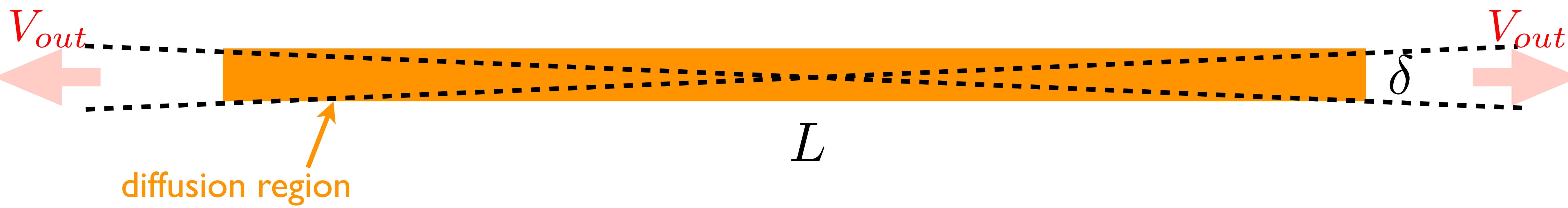
Liu et al. 2015 PRL

Guide field dependence, Γ_{out} is suppressed when Bg is considered $\Gamma_{out} < B_0/B_g$

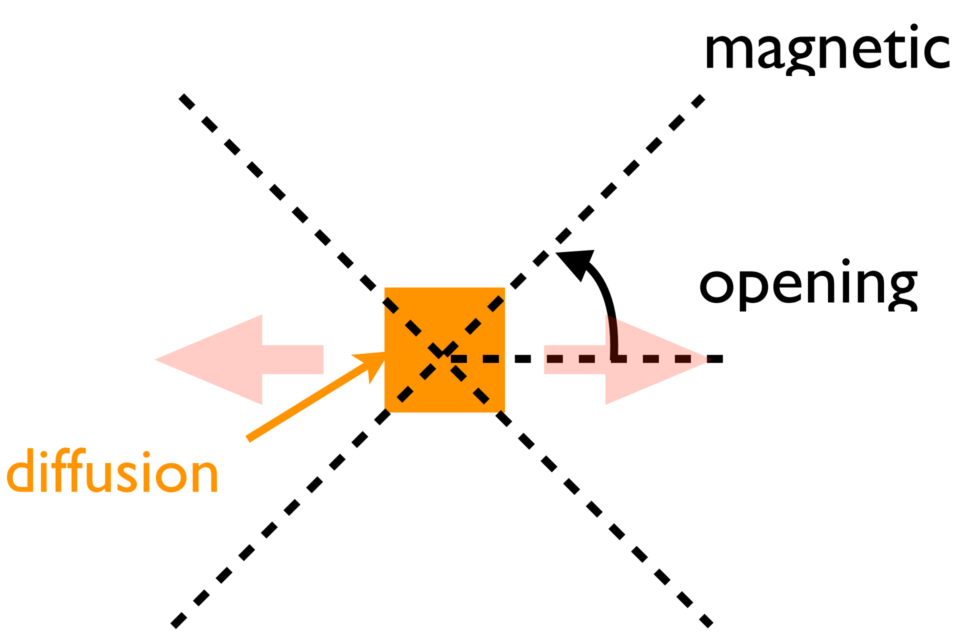
Explanation of global rate ~ 0.1

-- Geometrical consideration

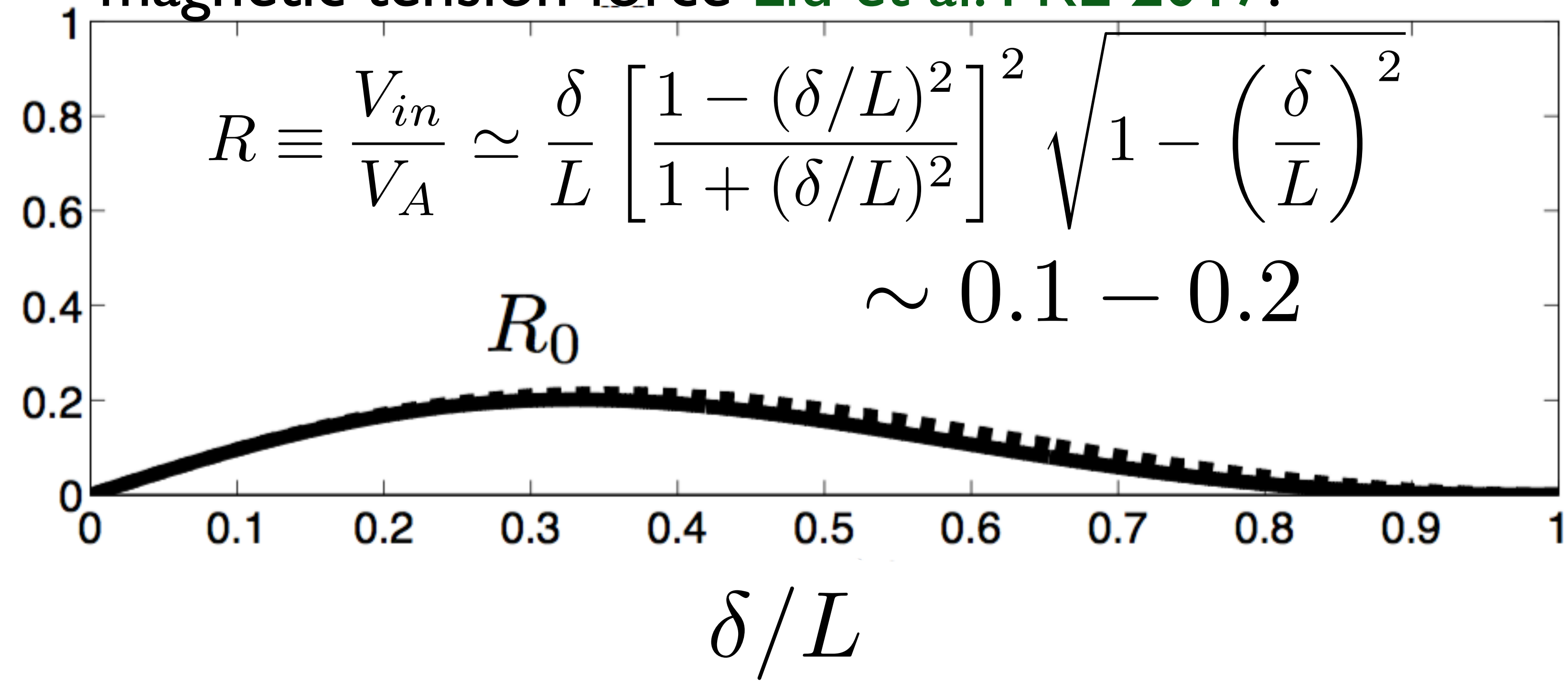
In the small δ/L limit, $R \sim \delta/L \rightarrow 0$ (Sweet & Parker 1957)



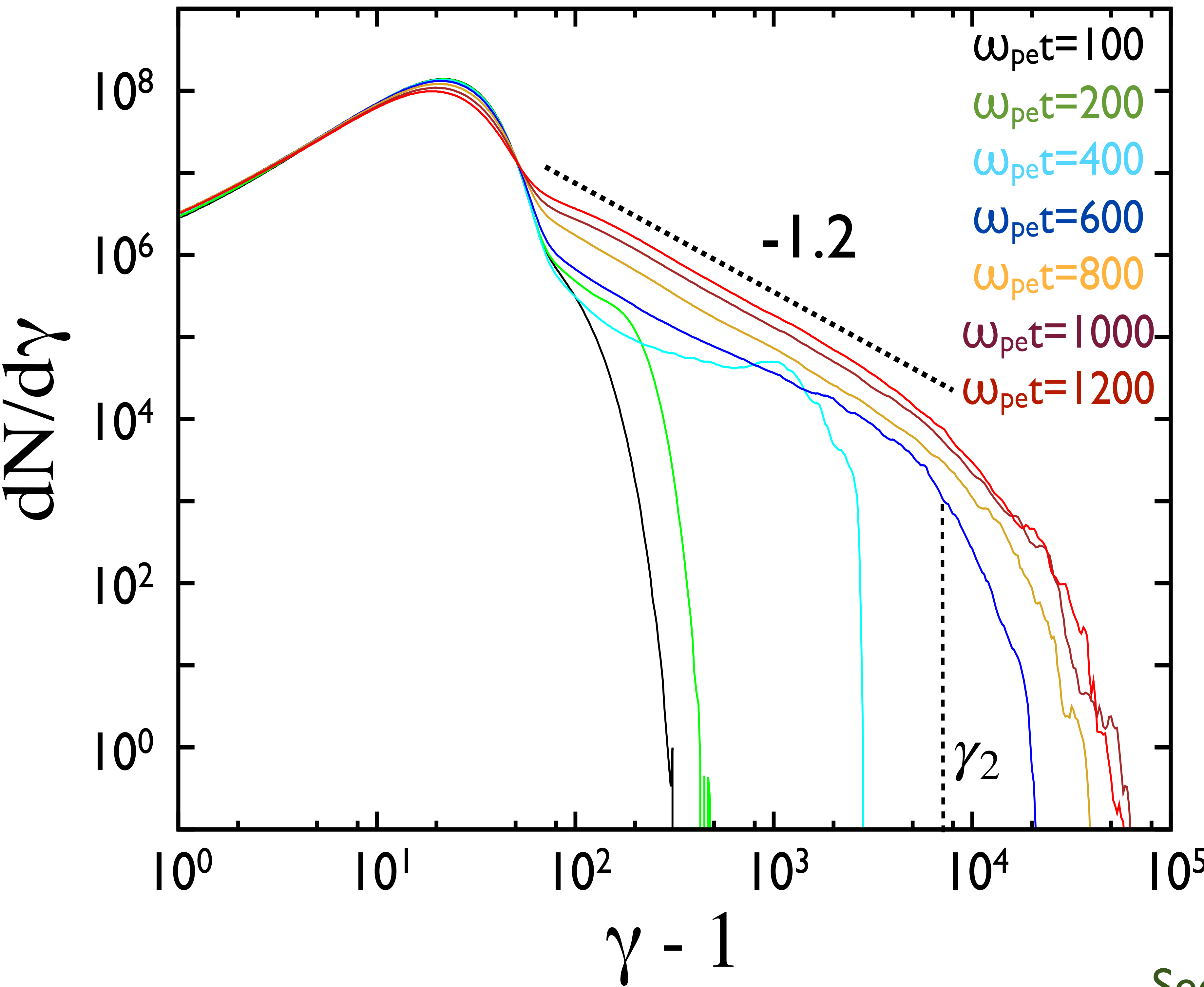
How about the large δ/L limit? It turns out that when $\delta/L \rightarrow 1$, $R \rightarrow 0$



Evaluate the balance between inward-directed magnetic pressure force and outward directed magnetic tension force Liu et al. PRL 2017.



A relativistic run with σ = 6400, γ_0 = 16



Spectral index p ~ 1

Fast variability ~ Lx/c

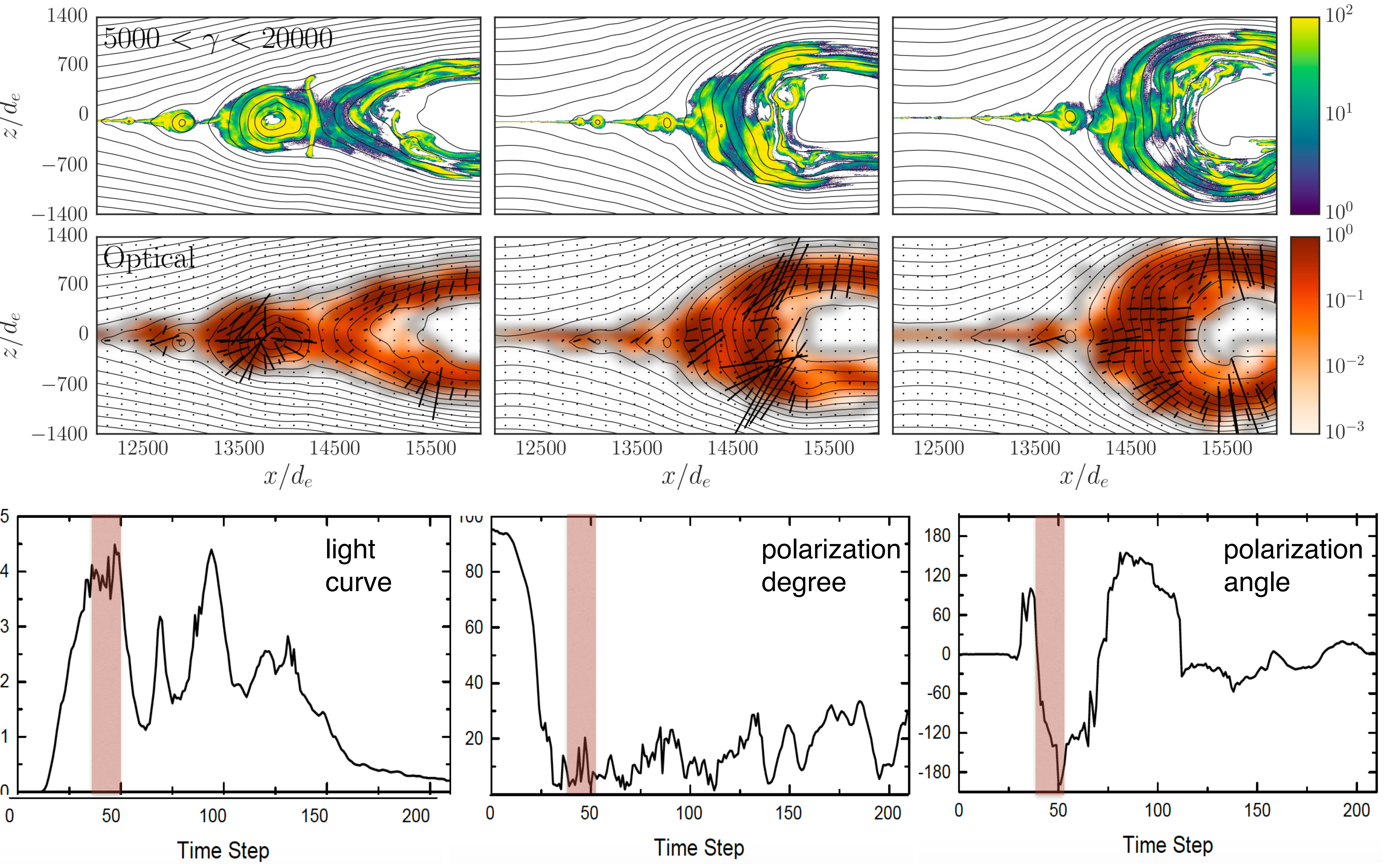
Power-law range

$\gamma_2 \sim \sigma$

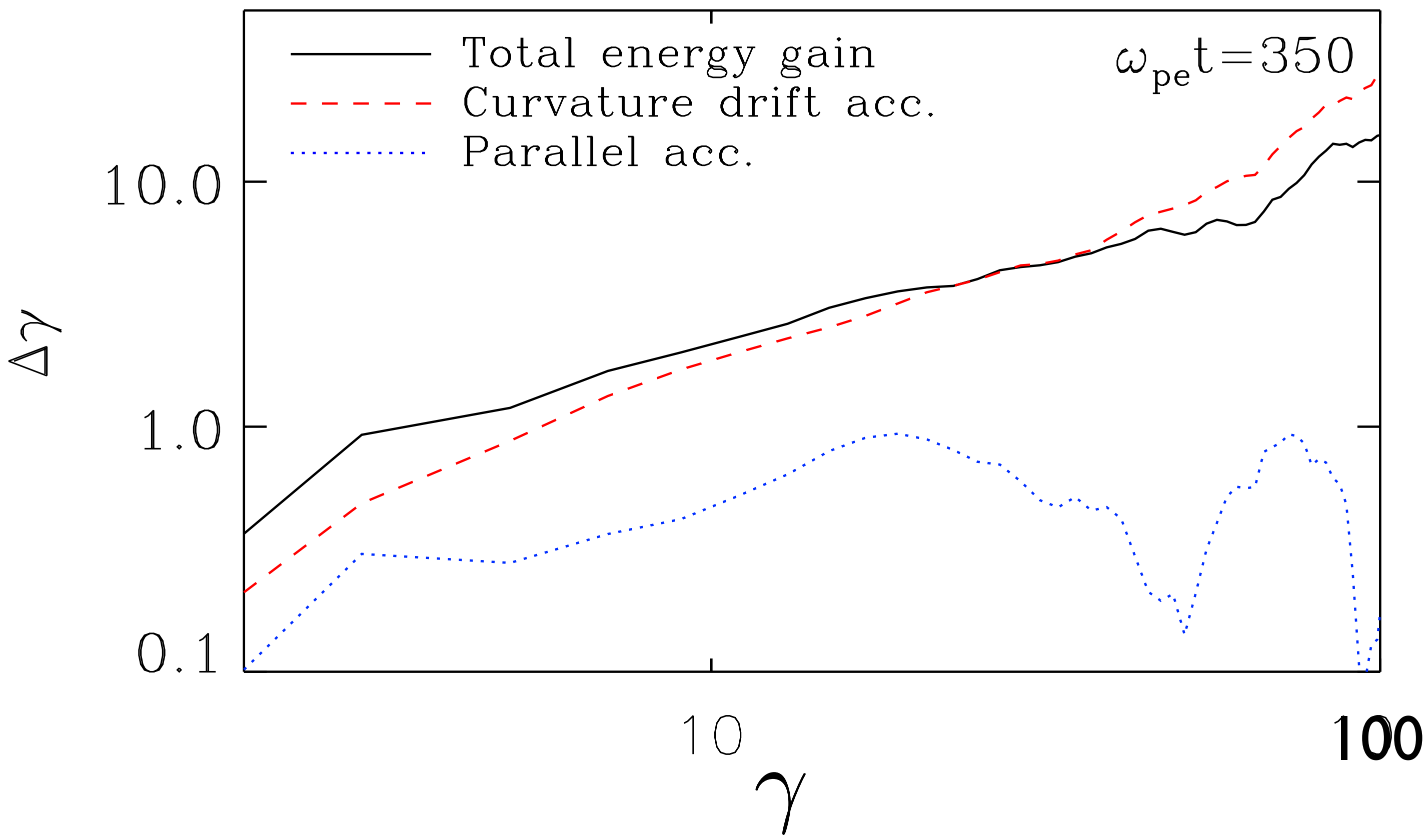
$$\varepsilon_{max} = \int |qE_{rec}|cdt$$

Guo et al. 2016 ApJL
See also Sironi, Guo, Werner…

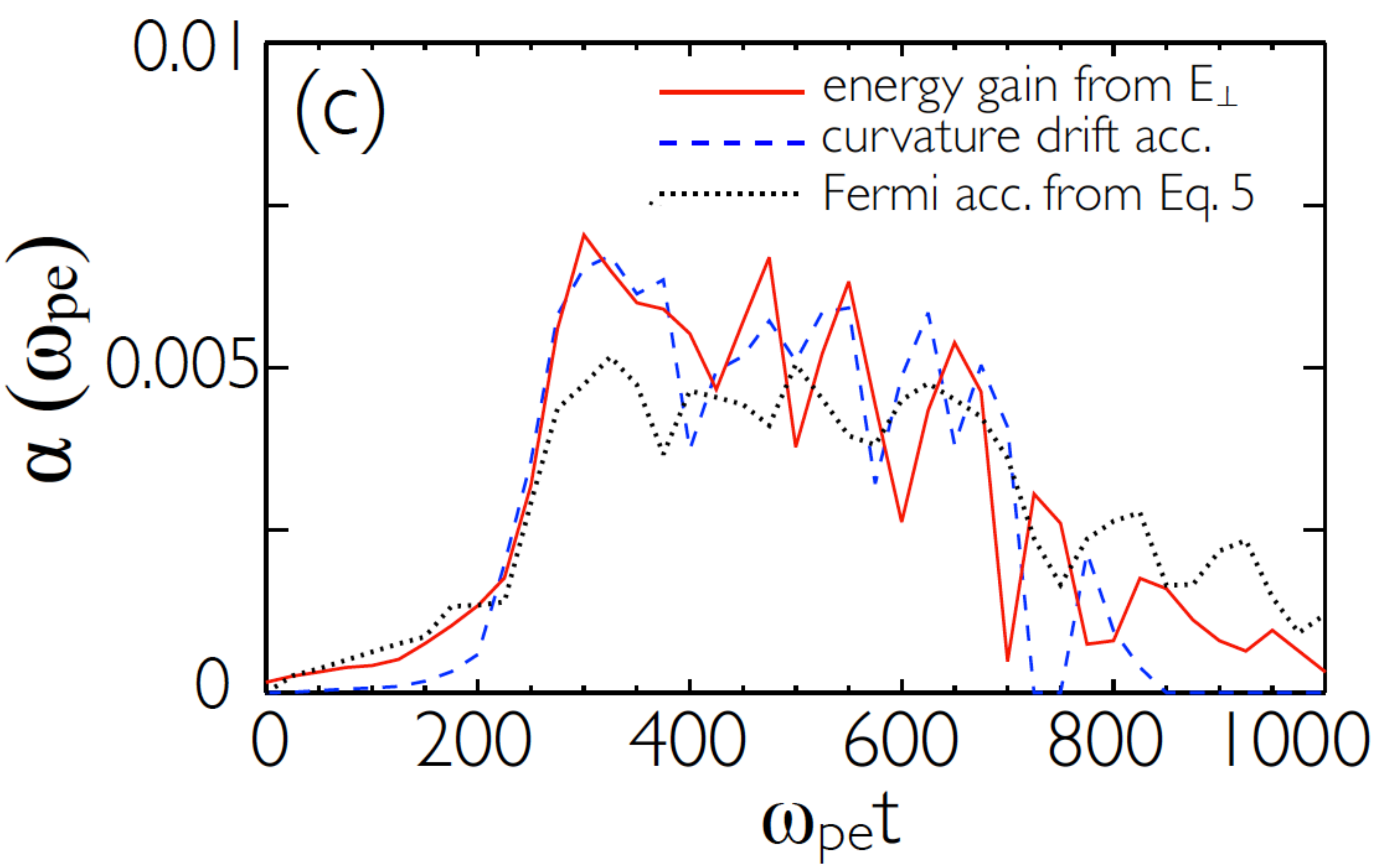
Radiative effects in Relativistic Reconnection



Zhang et al. in preparation



The acceleration is dominated by energy gain through curvature drift motion



Fermi acceleration formula agrees with the acceleration by curvature drift motion.

$$\Delta\gamma = \left(\Gamma^2(1 + \frac{2Vv_x}{c^2} + \frac{V^2}{c^2}) - 1\right)\gamma$$

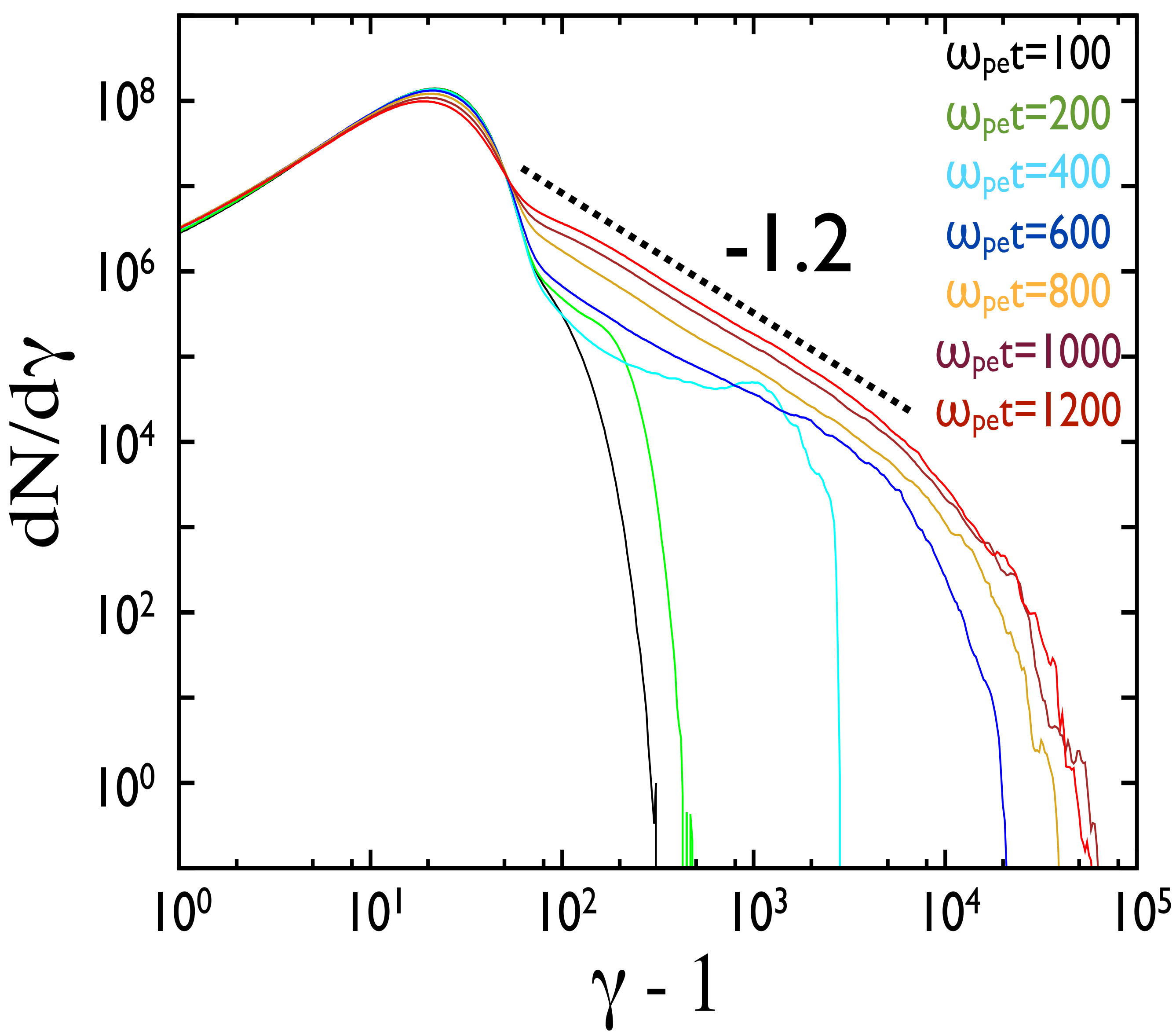
$$\Delta t = L_x/v_x$$

$$\alpha = \Delta\gamma/(\gamma\Delta t)$$

Guo et al. 2014, 2015

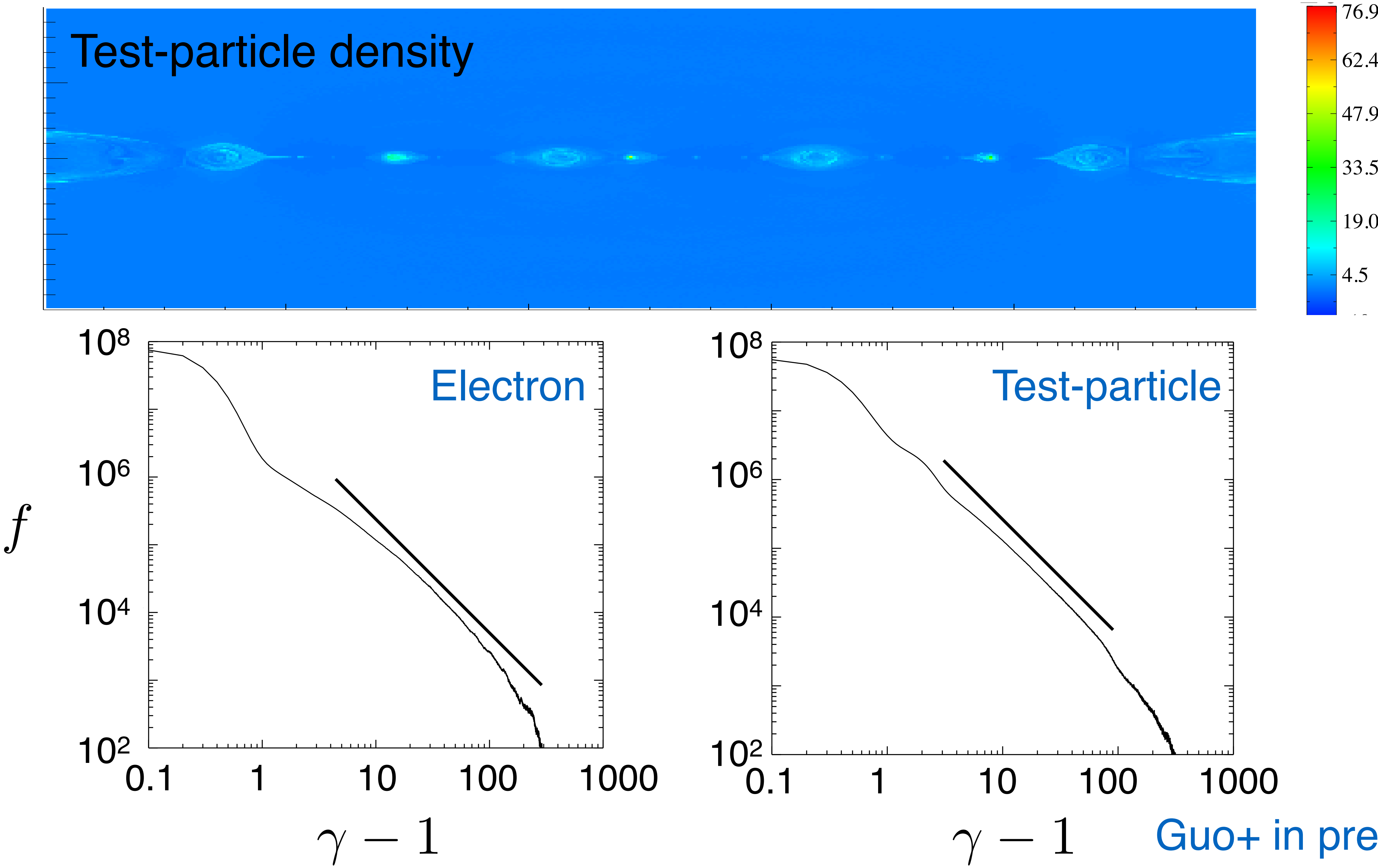
A few extra comments

- Parallel electric field at X-points allows the development of nonthermal spectrum as well (Zenitani & Hoshino 2001, Bessho+,Sironi & Spitkovsky 2014, Larrabee 2003).
- My view: the two mechanisms can operate independently. In large-scale relativistic reconnection simulations, parallel electric field can generate spectrum harder than "-1".
- Parallel electric field acceleration can be an important injection mechanism for "compression" acceleration in reconnection layer.



New simulation and analysis for power-law formation

In a 2D PIC simulation, Add a test-particle component without feedback. The component only experience E_{ideal}=-uxB field.



Guo+ in prep

Slide from Roger Blandford, also see Parker (1957)

Particle drifts and current

Normal approach is to analyze particle orbits and deduce currents
Can also start from static equilibrium and understand what is happening

$$\rho \vec{E} + \vec{j} \times \vec{B} = \nabla \cdot \mathrm{P}, \qquad \mathrm{P} = \mathrm{P}_\perp \mathrm{I} + (\mathrm{P}_\parallel - \mathrm{P}_\perp)\frac{\vec{B} \otimes \vec{B}}{B^2}.$$

$$\vec{j}_\perp = \mathrm{P}_\parallel \frac{\vec{B} \times (\vec{B} \cdot \nabla)\vec{B}}{B^4} - \left[\nabla \times \left(\frac{\mathrm{P}_\perp \vec{B}}{B^2}\right)\right]_\perp + \mathrm{P}_\perp \left(\frac{\vec{B}}{B^3}\right) \times \nabla B + \rho \frac{\vec{E} \times \vec{B}}{B^2}$$

Curvature perpendicular magnetization gradient ExB

Orbit, fluid approaches to Ohm's law perpendicular to field are identical
Parallel current requires additional physics eg wave-particle scattering
A closely related approach is double adiabatic theory

$$P_\perp = \tfrac{1}{2}\int dp p_\perp v_\perp f \propto \rho p_\perp^2 \propto \rho B \quad (NR)$$ Complete?

$$P_\parallel = \int dp p_\parallel v_\parallel f \propto \rho p_\parallel^2 \propto \rho^3 B^{-2} \quad (NR)$$ Incomplete?

Go back to the original derivation of diffusive-convective transport equation (Parker 1965)

Ensemble averaging particle drift motions

drift velocity $= \underbrace{P_{\|} \frac{\boldsymbol{B} \times (\boldsymbol{B} \cdot \nabla) \boldsymbol{B}}{B^4}}_{\text{curvature drift}} + \underbrace{P_{\perp} \left(\frac{\boldsymbol{B}}{B^3} \right) \times \nabla B}_{\text{gradient drift}} - \underbrace{\left[\nabla \times \frac{P_{\perp} \boldsymbol{B}}{B^2} \right]_{\perp}}_{\text{magnetization}}$

Li et al. 2015 ApJL
Parker 1957

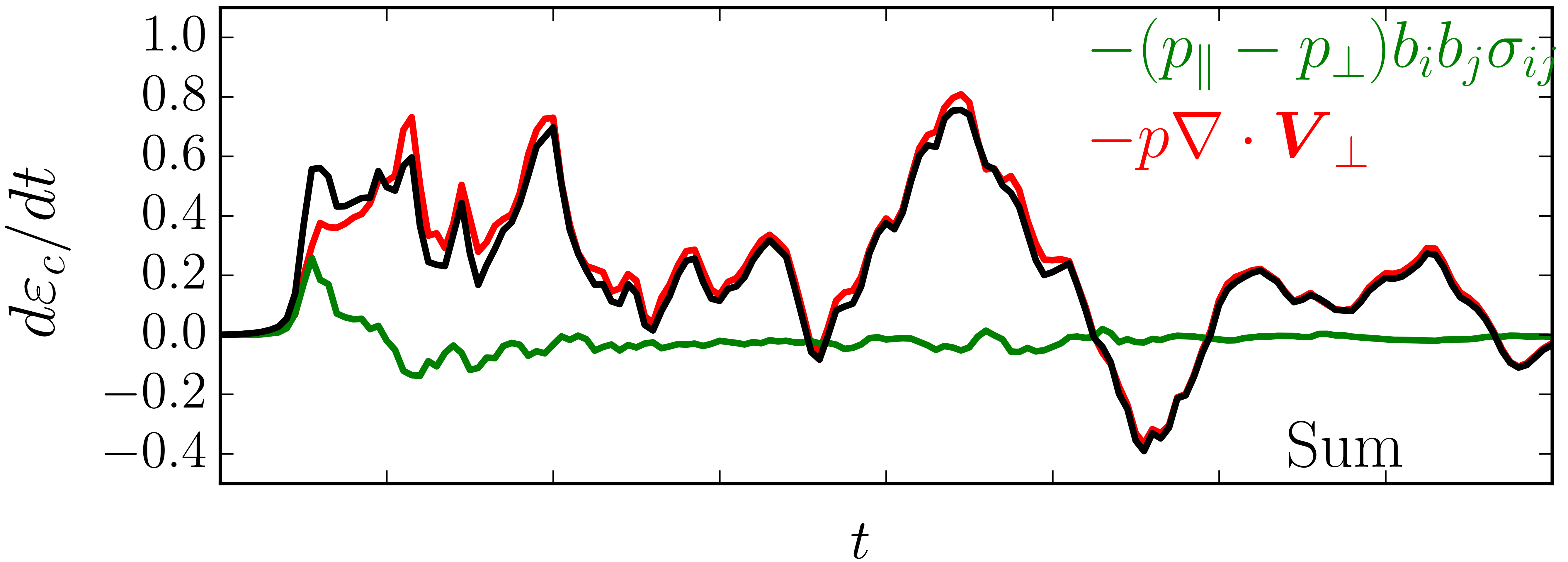
Fluid description $E = -V \times B/c$

Total energy change $= -p \nabla \cdot \boldsymbol{V}_{\perp} - (p_{\|} - p_{\perp}) b_i b_j \sigma_{ij}$

Jones 1990
Parker 1965

This leads to the main acceleration term in the standard advection-diffusion transport equation (Parker 1965). This compression can be described by MHD!

Test with a 2D kinetic simulation



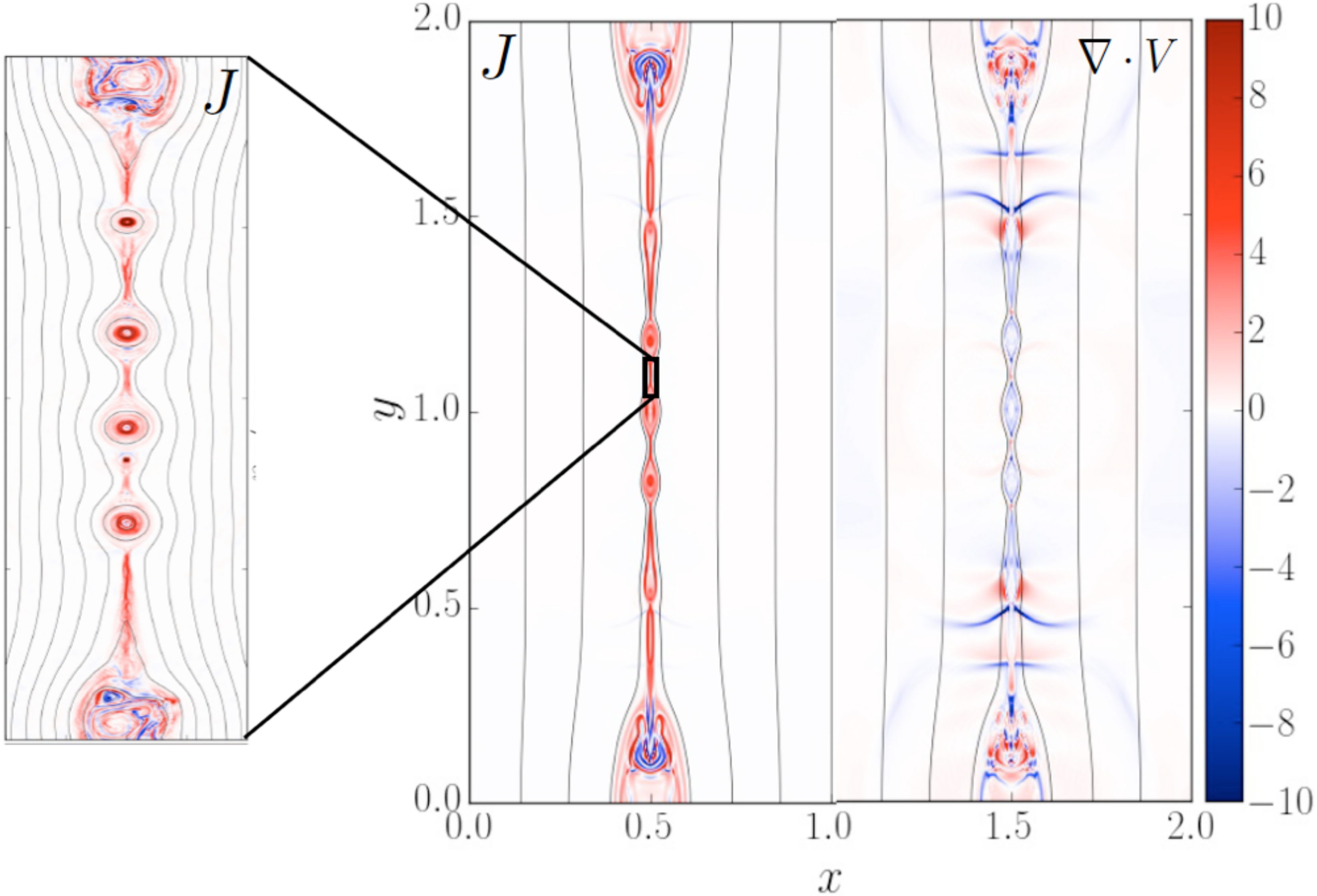
Compression term is the dominant term!

Li et al. 2018
ApJ, 855, 80

A new approach for studying particle acceleration in magnetic reconnection

L~1 km

Kinetic



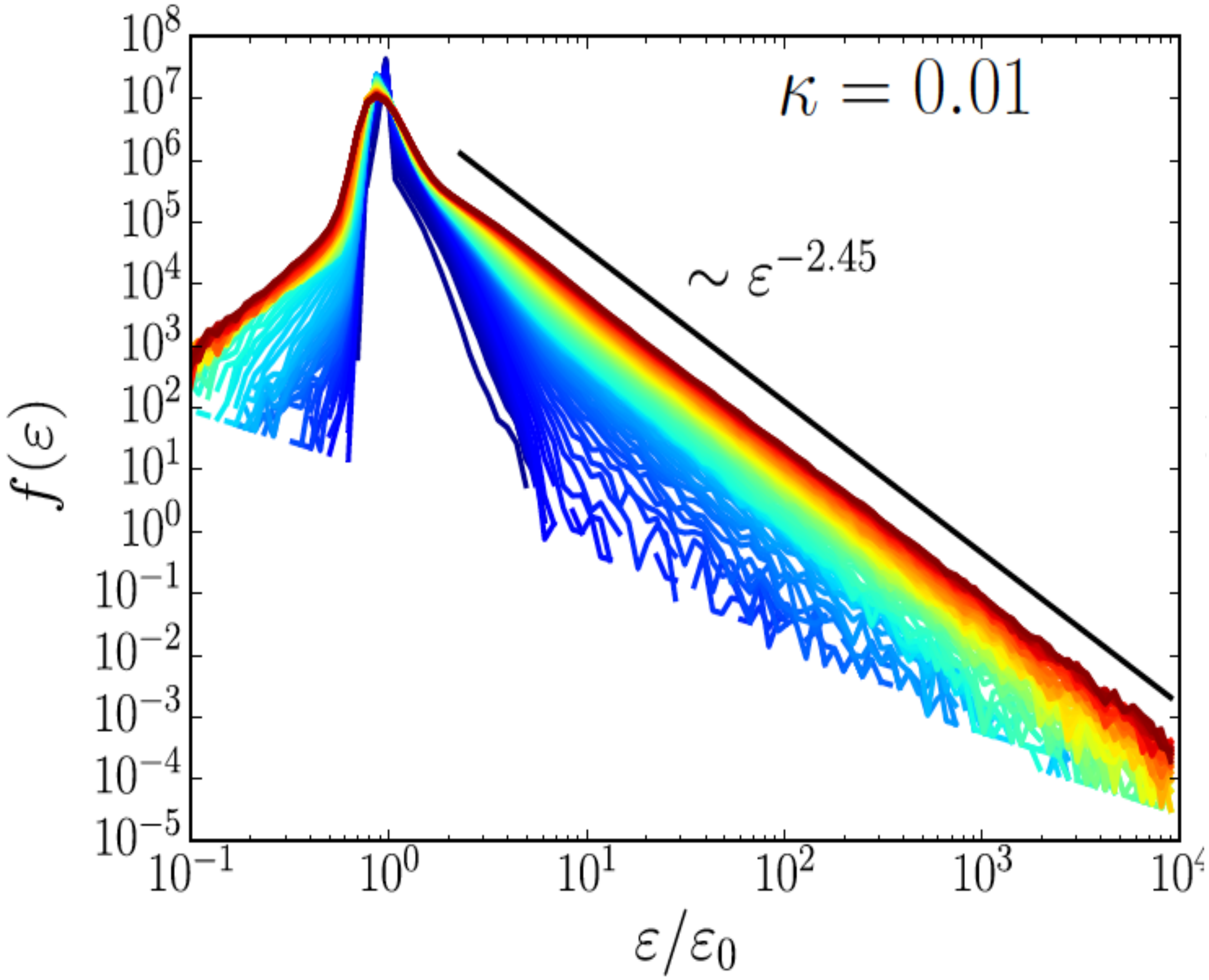
L~10^5 km

MHD

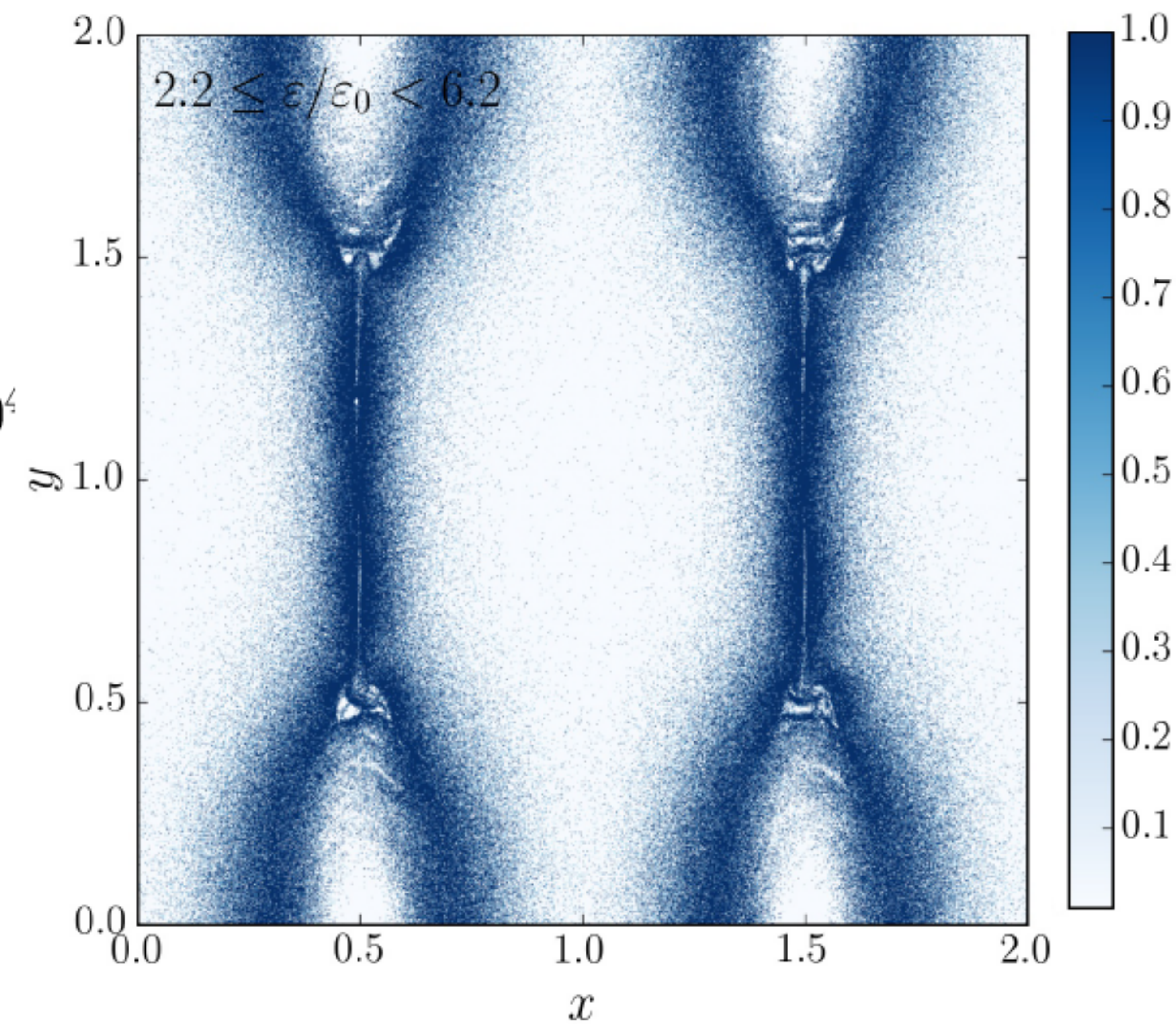
Solve the Parker equation in a background field provided by MHD simulations

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} - V_{d,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\left[\frac{\partial f}{\partial \ln p}\right] + Q.$$

Li+, in preparation



New simulations solving ***advection-diffusion*** transport equation in reconnection fields provided by MHD simulations

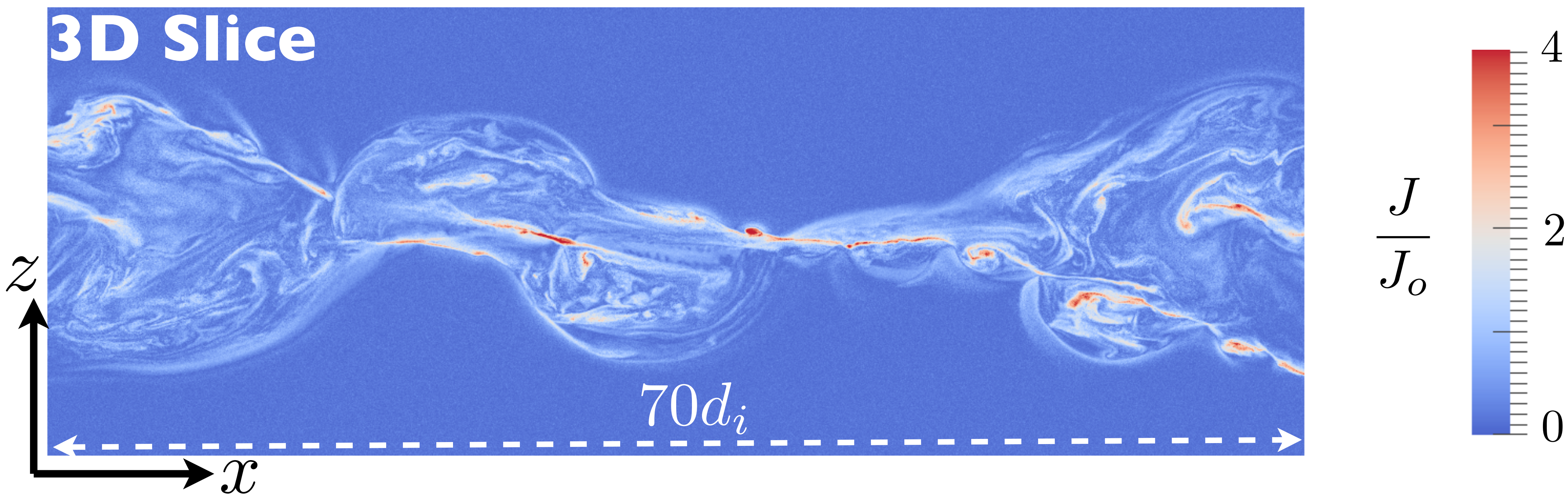


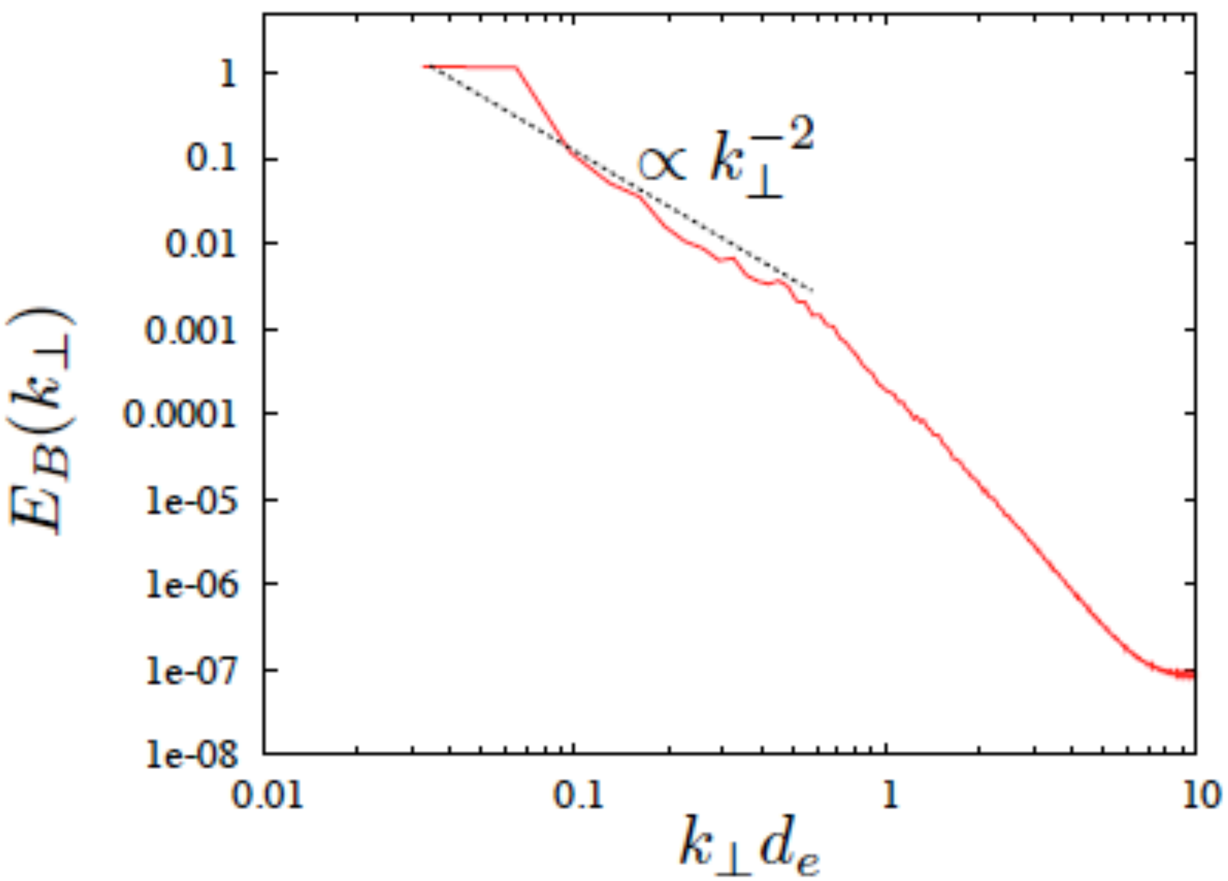
In Parker's transport equation, the acceleration term is associated with compression effect

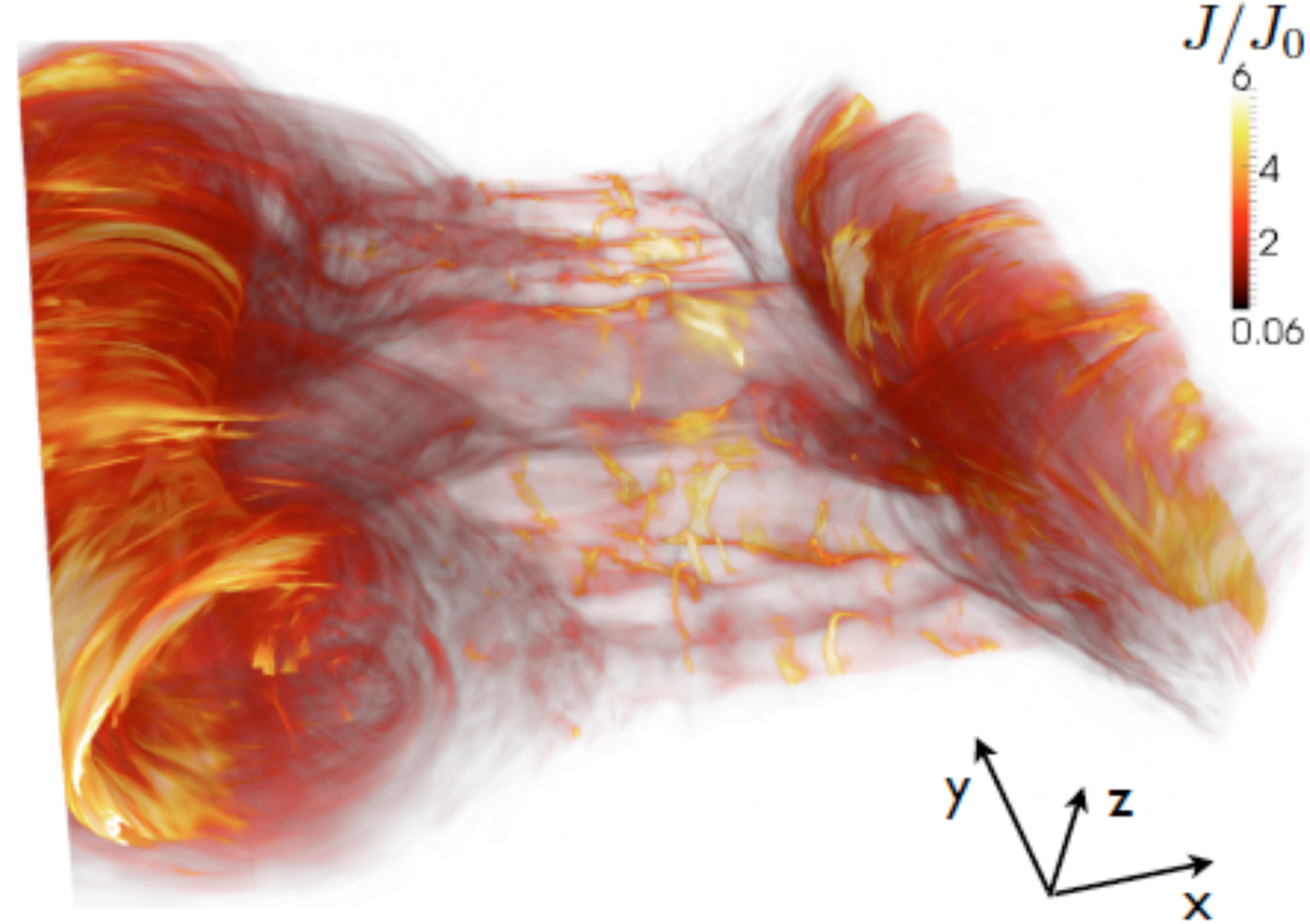
$$\frac{\partial f}{\partial t} = \frac{p}{3} \nabla \cdot \mathbf{V} \frac{\partial f}{\partial p}$$

Li+, in preparation

Recent development: 3D Magnetic Reconnection

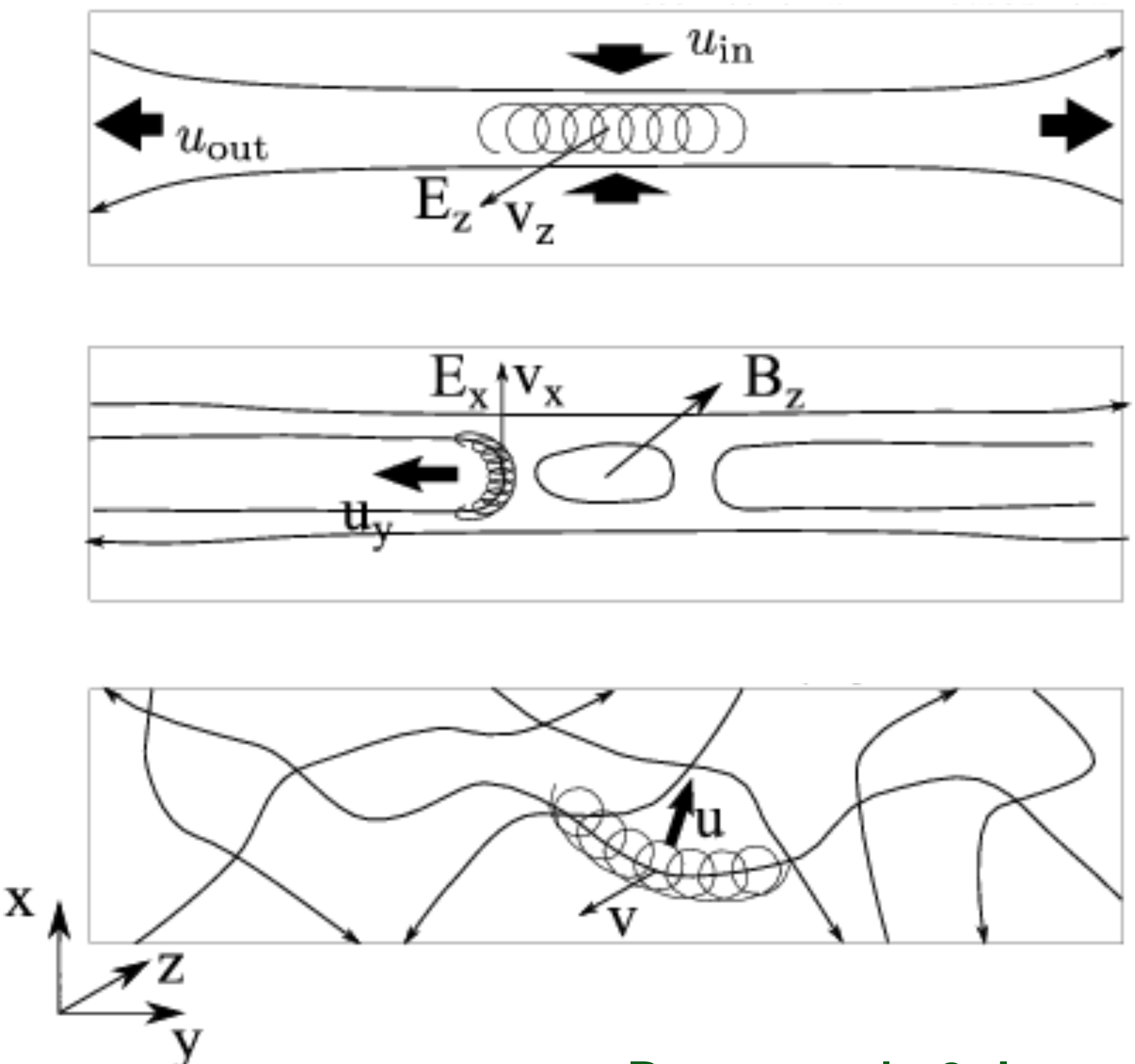






Daughton et al, Nature Physics, 2011, Guo et al. 2014 PRL, 2015 ApJ

Particle acceleration/energization during reconnection



Beresnyak & Li

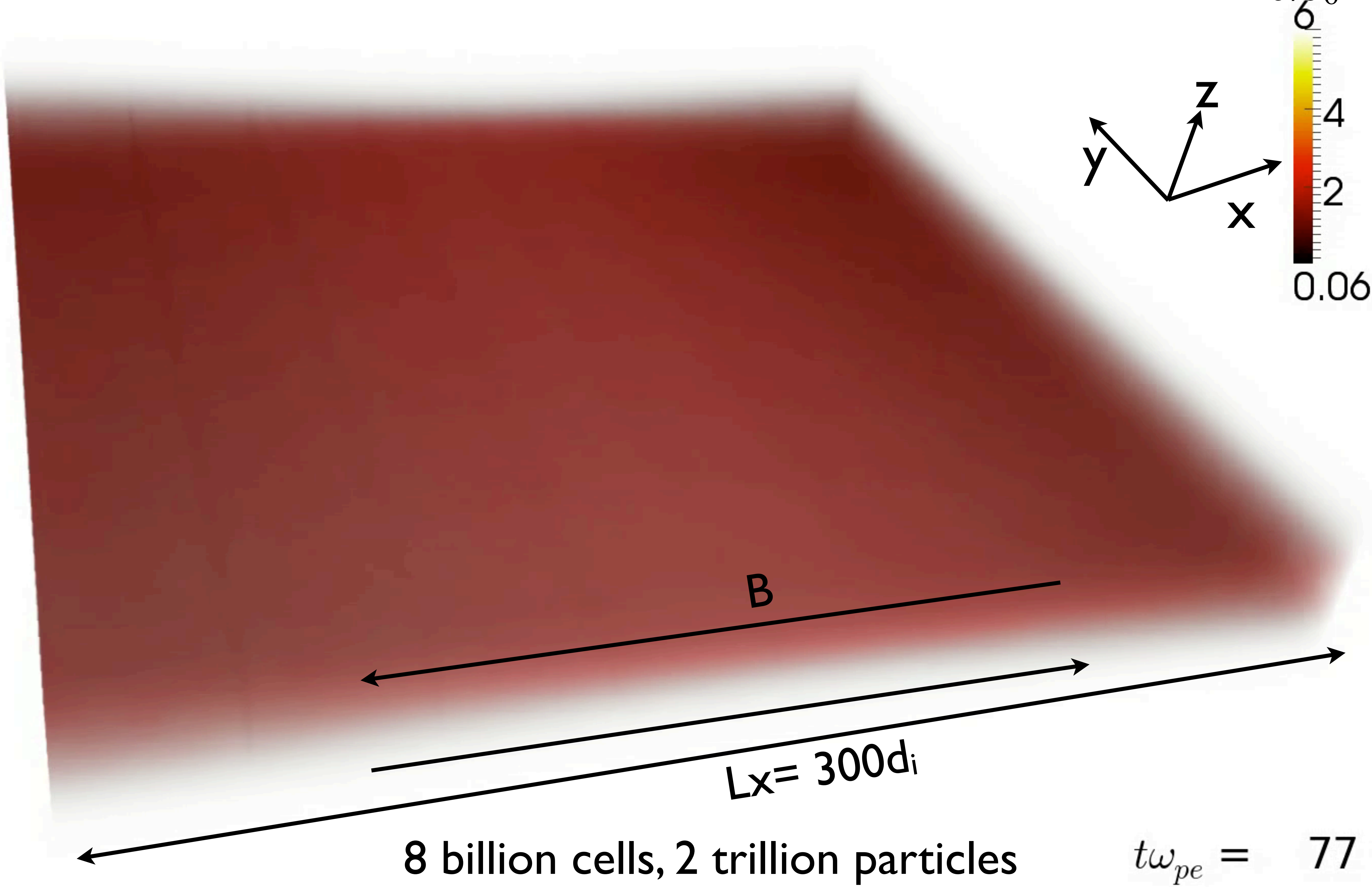
Key unknowns

- Primary acceleration mechanism
- Resulting energy spectra and maximum energy
- The role of 3D Physics

  3D instabilities (self-generated turbulence)

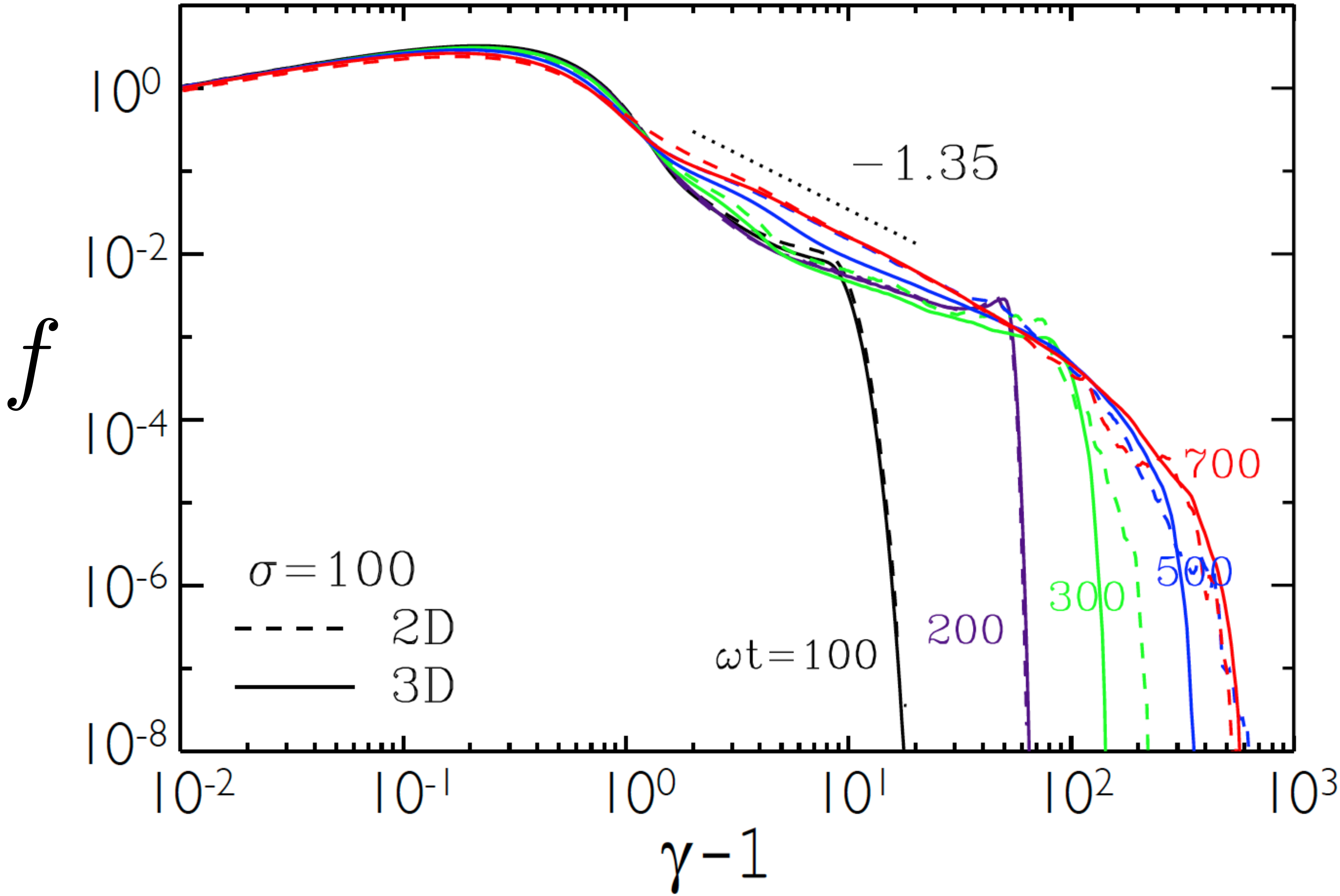
  external turbulence
- The role of different boundary conditions

$\sigma = 100$



8 billion cells, 2 trillion particles
using 100k cores on blue waters

Energy spectra from 2D and 3D PIC simulations



Guo et al. 2014 PRL, 2015 ApJ, 2016 PoP

Simulations on Trinity machine

- Typical 3D runs

$$4096 \times 2048 \times 2048 \ \text{cells} \qquad \sim 5.2 \times 10^{12} \ \text{particles}$$

- Particle acceleration

$$\text{track} \ \sim 10^{8} \ \text{particles}$$

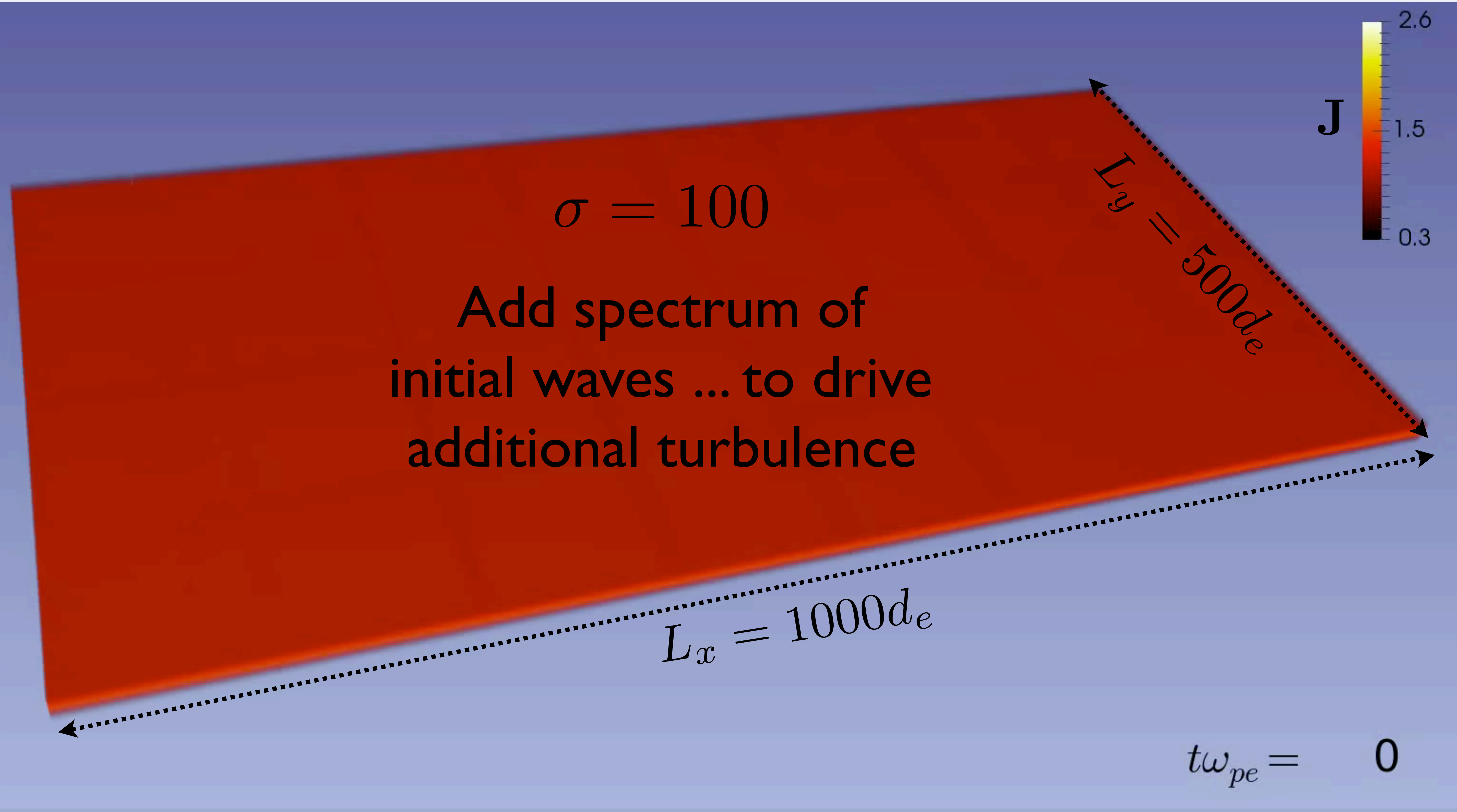
- Examine the effect of pre-existing turbulence

Add spectrum of waves to drive turbulence $\delta B^2/B_0^2$ up to 0.4

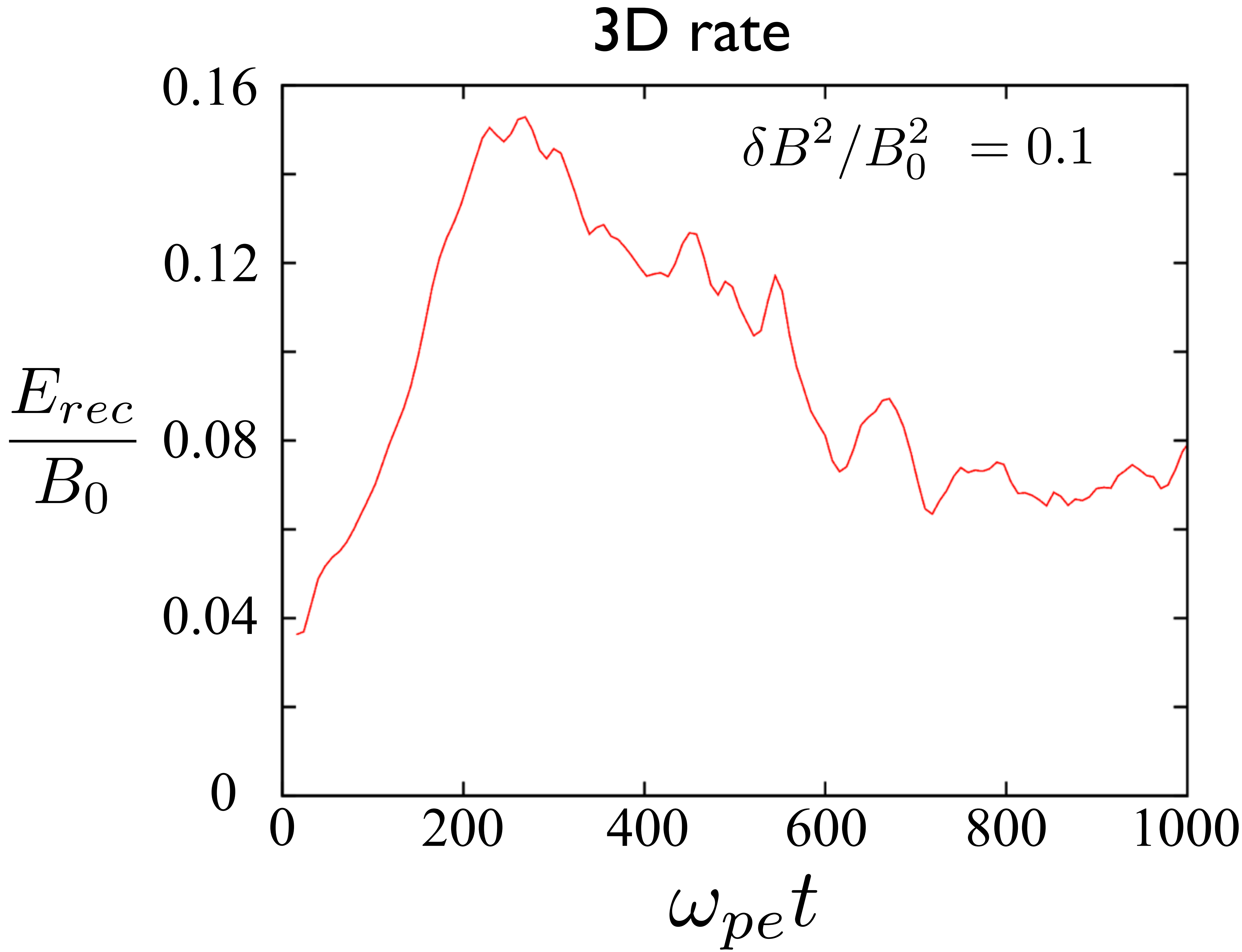
Trinity runs

$4096 \times 2048 \times 2048$ cells

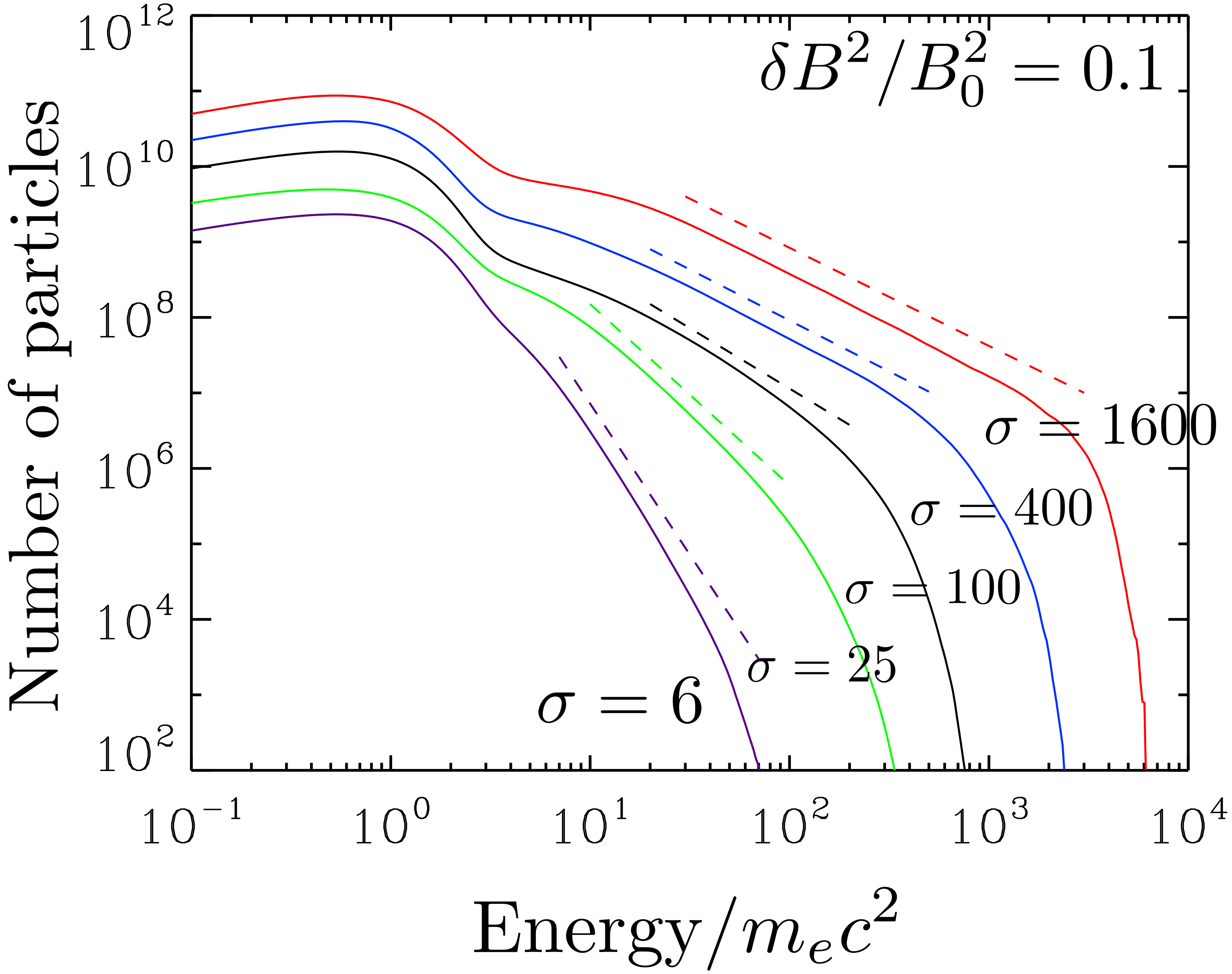
$\sim 5.2 \times 10^{12}$ particles track $\sim 10^{8}$ particles



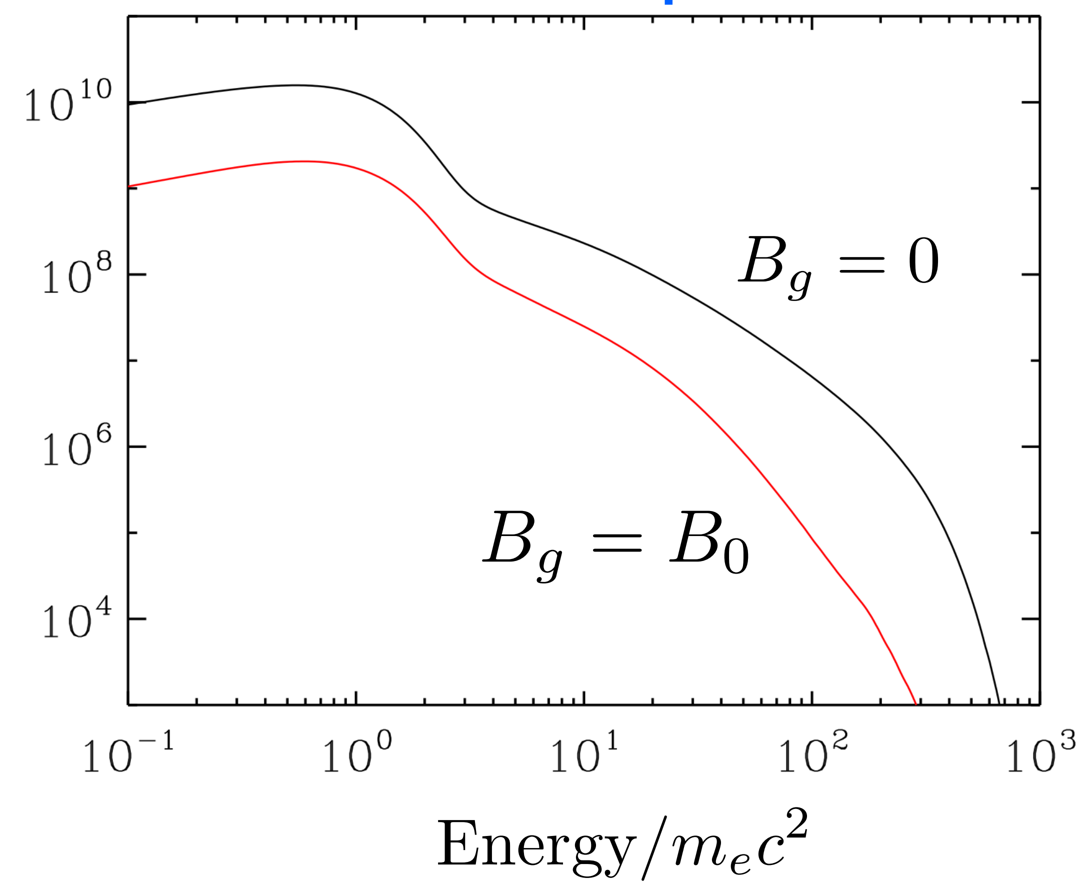
Reconnection Rate from Trinity Run Similar to 2D Evolution



Energy distribution for different magnetization

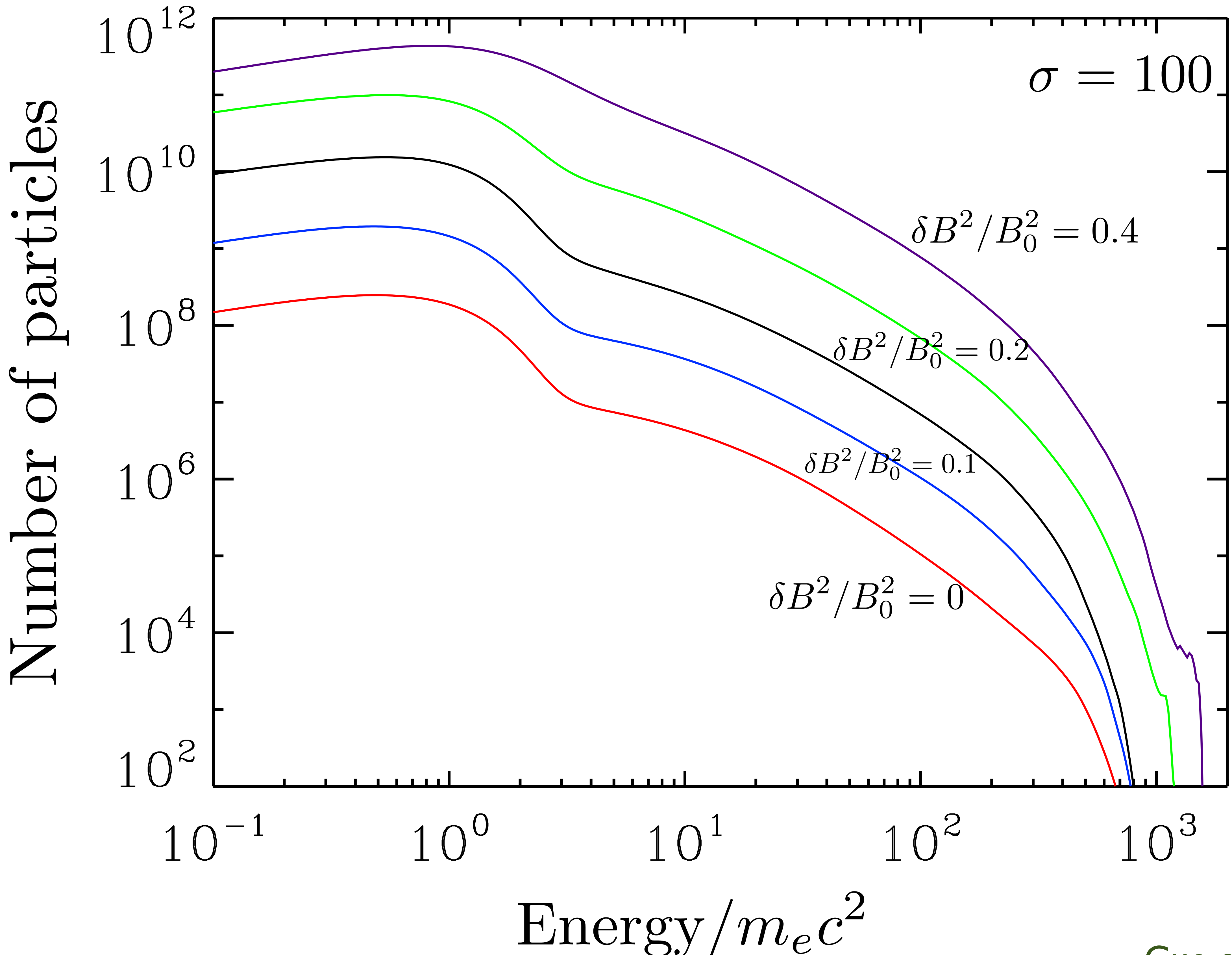


Guide field dependence



The additional turbulence does not strongly modify nonthermal acceleration.

Energy distribution for different turbulence amplitude



Guo et al. in prep.

Acceleration mechanism

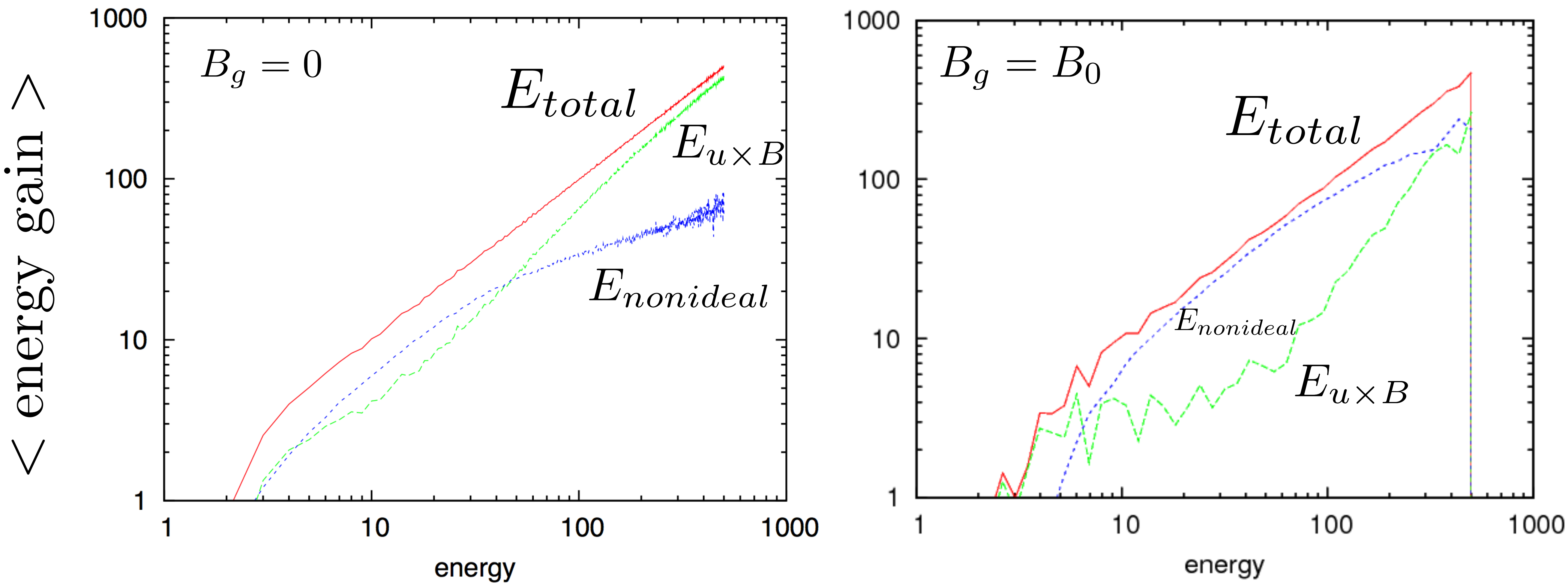
Fermi/Betatron accelerations

$$\mathbf{E}_{motional} = -\mathbf{u} \times \mathbf{B}/c$$

Direct acceleration

$$\mathbf{E}_{nonideal} = \mathbf{E} + \mathbf{u} \times \mathbf{B}/c$$

Evaluating $\int qv \cdot E$ from different electric fields



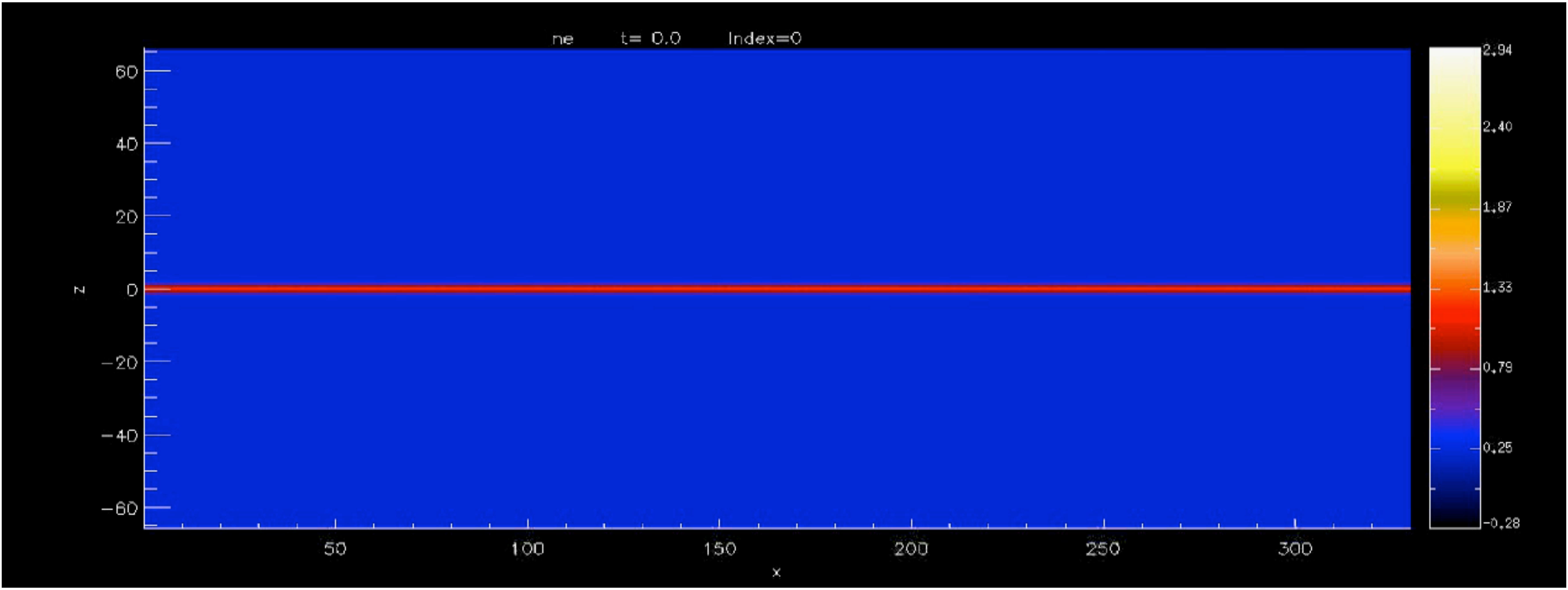
Fermi acceleration dominates for antiparallel reconnection.

Direct acceleration is important for strong guide field case.

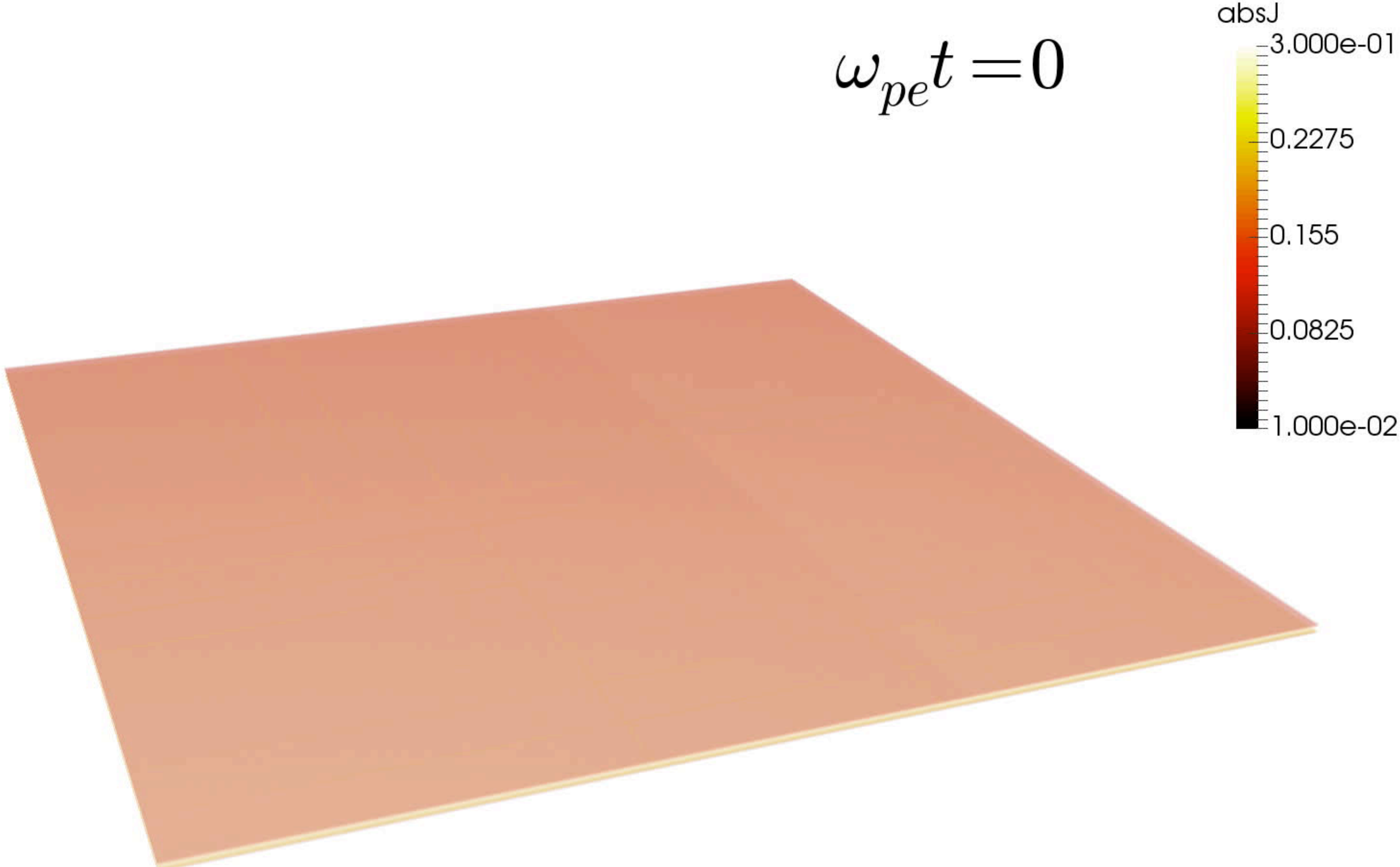
2D and 3D simulations show similar features

Open boundary simulations

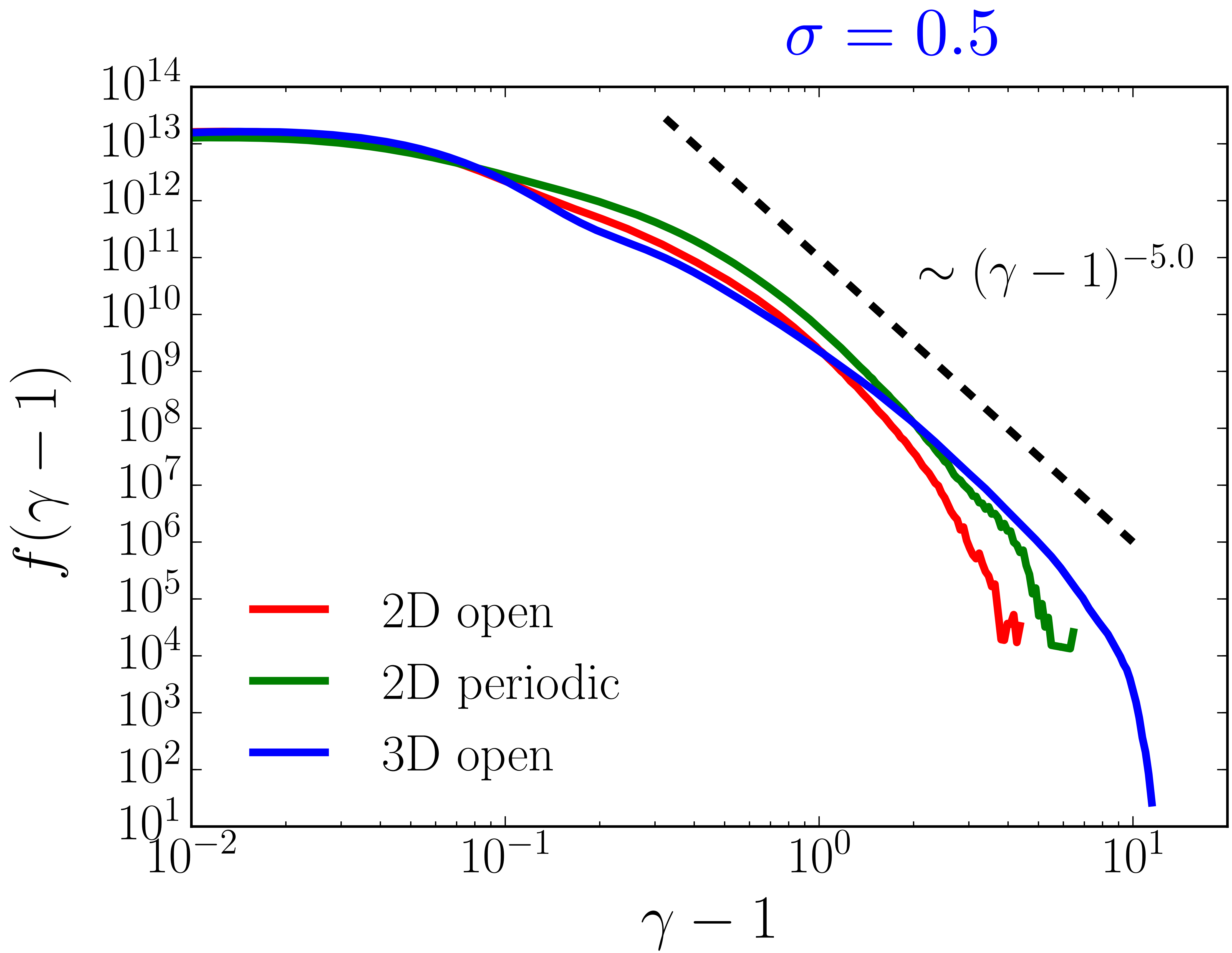
Only a small chance of island coalescence in 2D open boundary simulations



Li, X. et al. in prep.

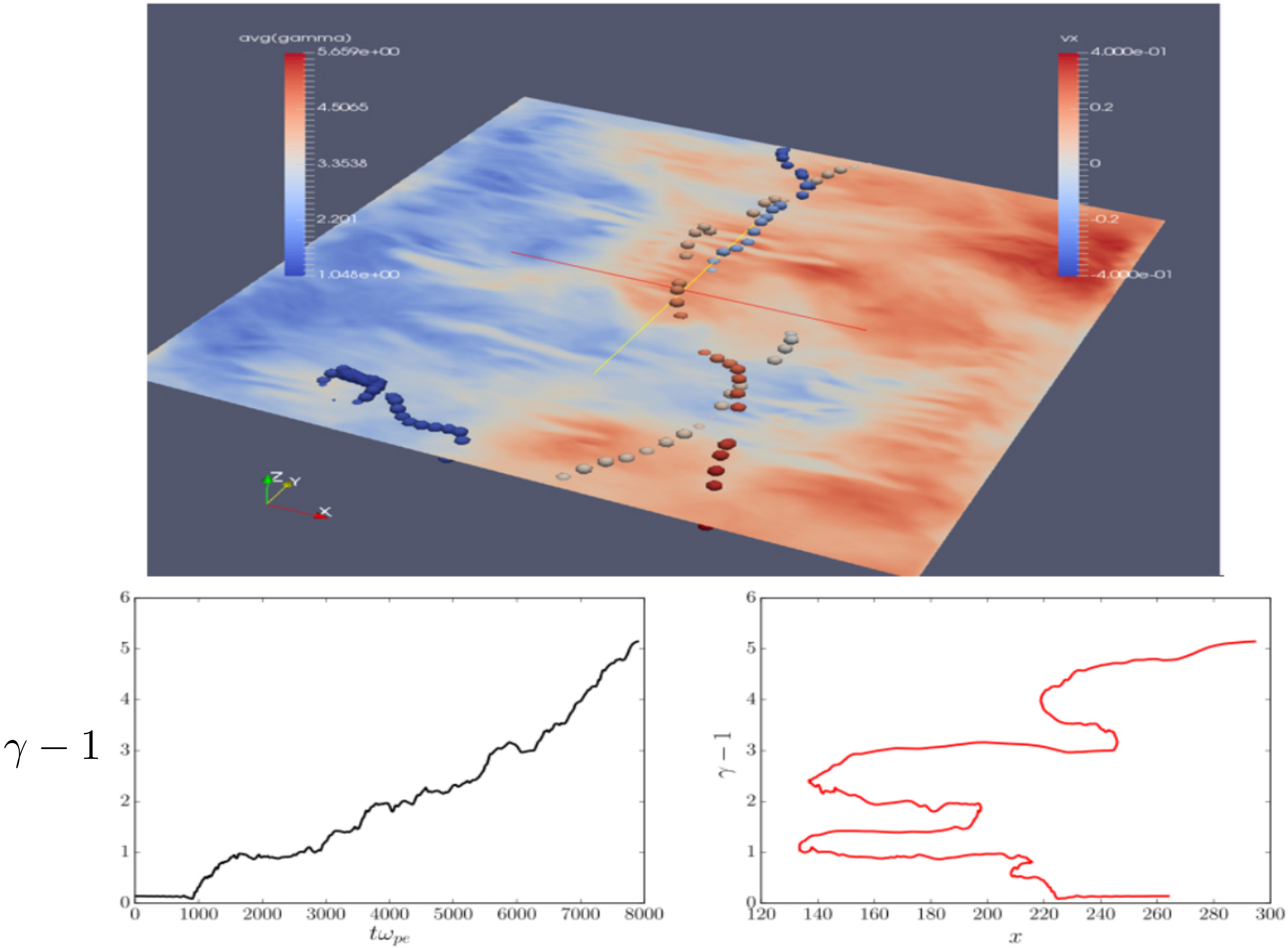


$\omega_{pe} t = 0$
absJ
3.000e-01
0.2275
0.155
0.0825
1.000e-02



$\sigma = 0.5$
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
$f(\gamma - 1)$
$\sim (\gamma - 1)^{-5.0}$
2D open
2D periodic
3D open
10^{-2}
10^{-1}
10^{0}
10^{1}
$\gamma - 1$

New particle acceleration pattern in 3D runs



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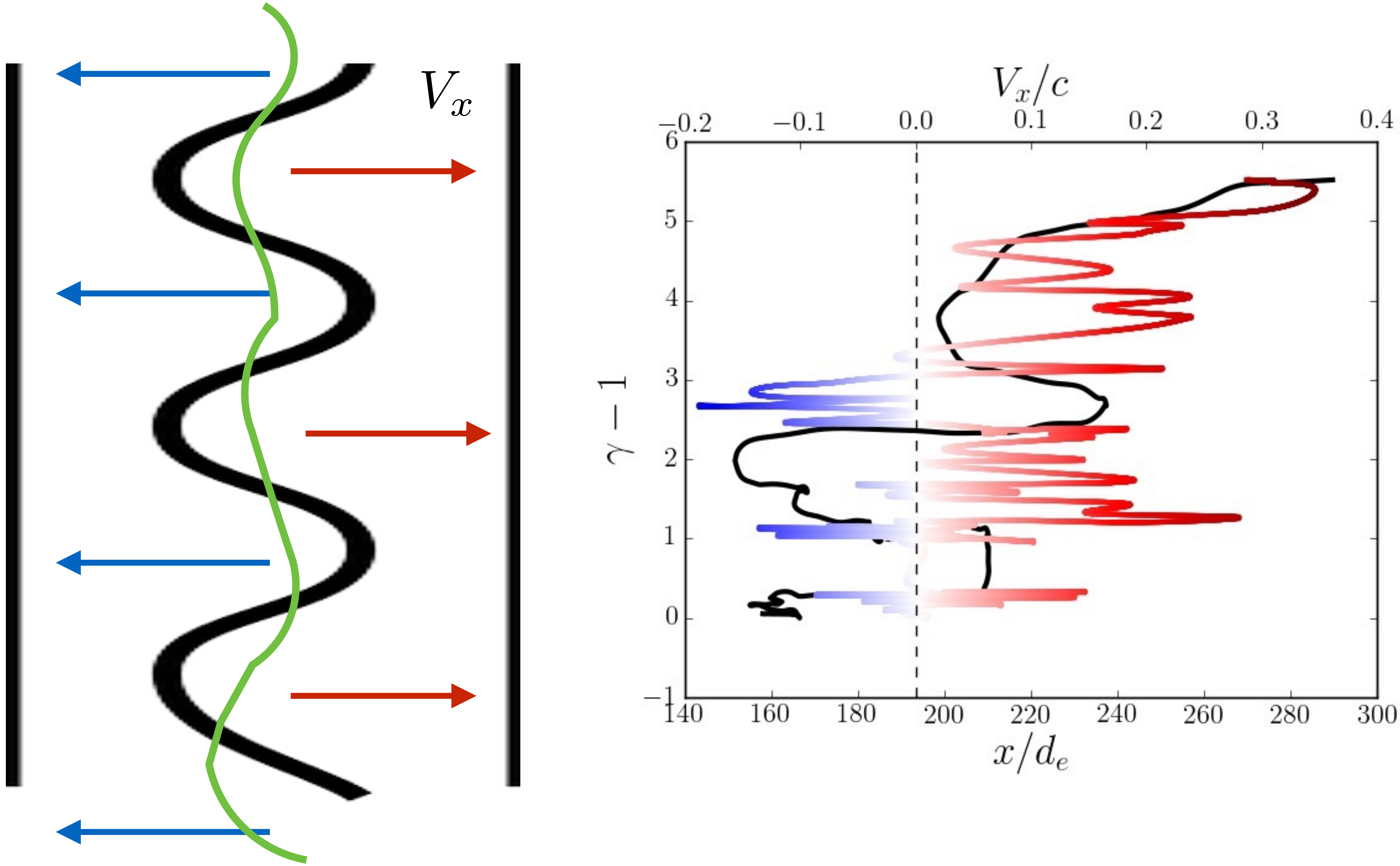


There are claims that island acceleration is not efficient in open systems, but 3D effects need to be considered for a real system

Summary and Several take-aways

- 2D and 3D kinetic simulations for relativistic magnetic reconnection show that the reconnection layer is dominated by development of flux ropes, and generates strong particle acceleration.

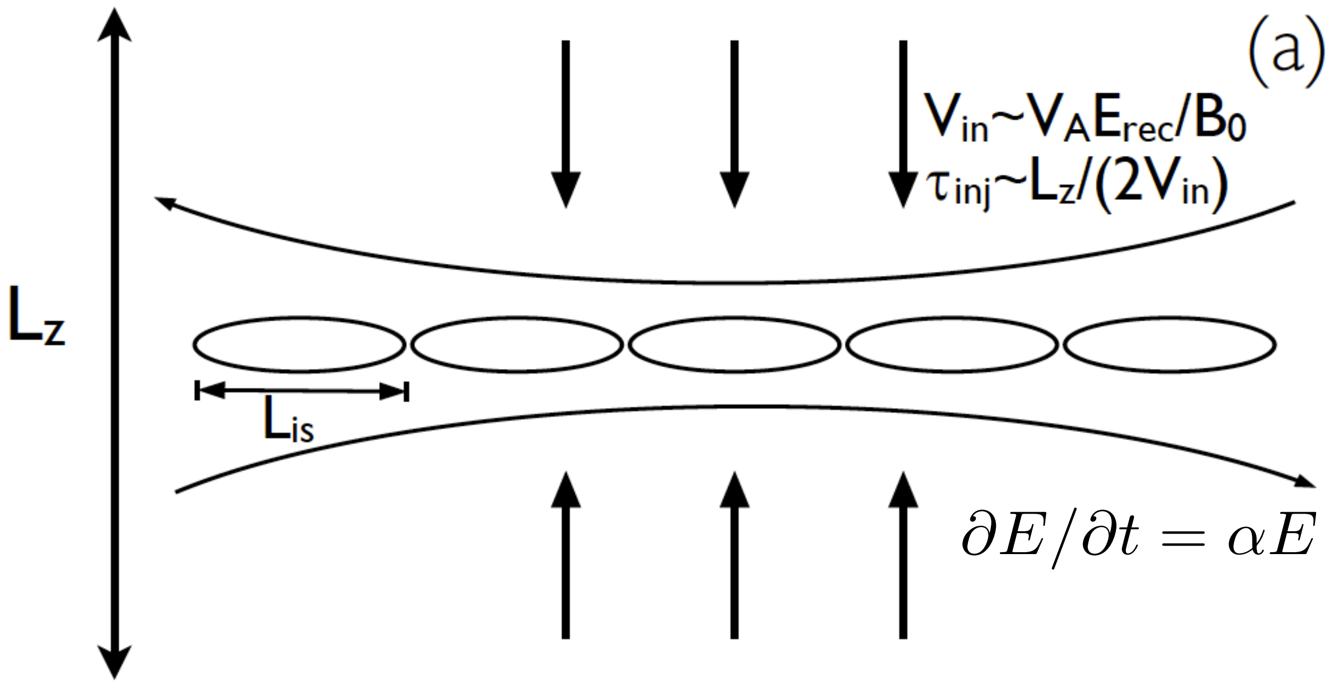
- Despite turbulence in the reconnection layer, nonthermal particles are efficiently generated and form power-law distributions.

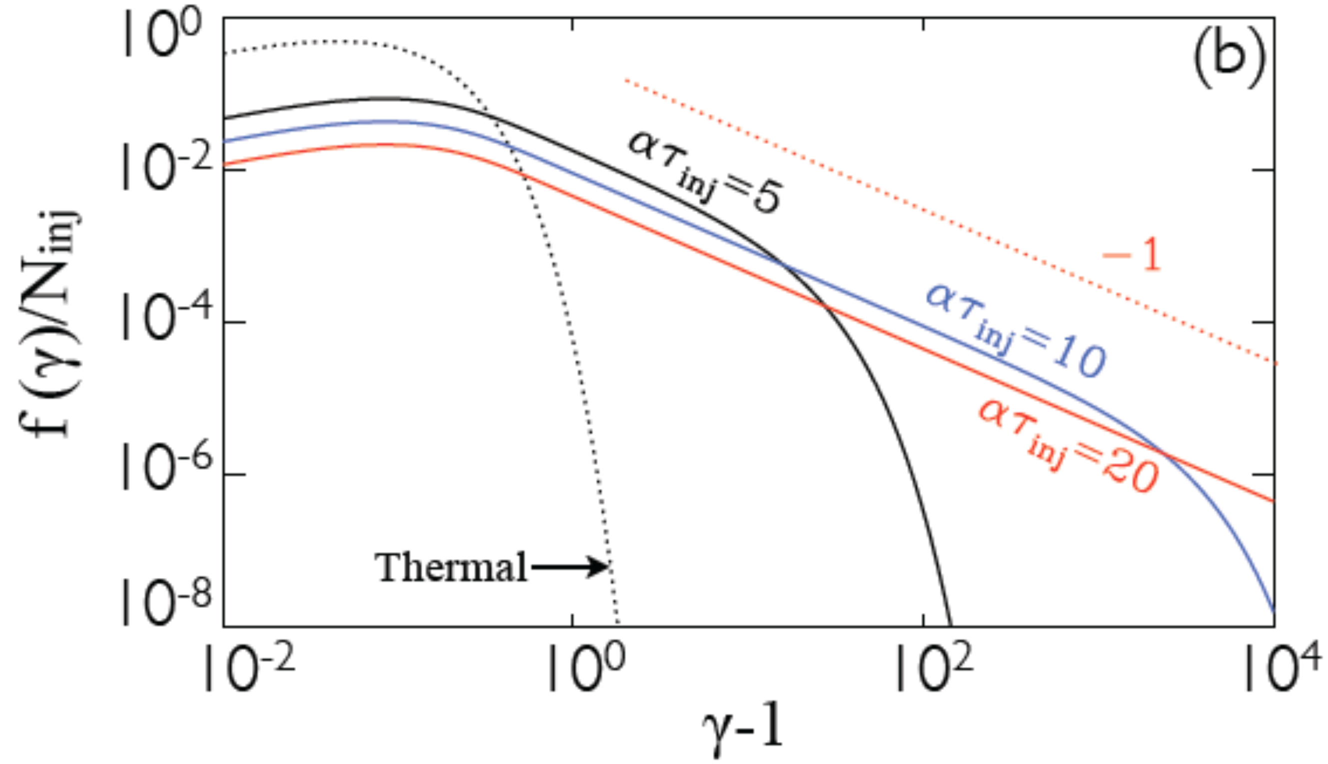
- Using a number of diagnostics, we show the contributions from different acceleration mechanism. For anti-parallel case, the acceleration is dominated by Fermi acceleration, and this leads to power-law distribution. Acceleration by parallel electric field is important for reconnection with a strong guide field.

- The acceleration mechanism and power-law formation are quite robust and general.

- We solve Parker's transport equation on MHD background fluid and show efficient particle acceleration, which is a promising new way to study the large-scale acceleration during astrophysical flares.

Power-law formation





$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = \frac{f_{inj}}{\tau_{inj}} - \frac{f}{\tau_{esc}}$$

$$f \propto \varepsilon^{-(1+\frac{1}{\alpha\tau_{esc}})}$$

$$\begin{aligned} f(\varepsilon, t) &= \frac{2N_0}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-(3/2+\beta)\alpha t}\exp(-\varepsilon e^{-\alpha t}) \\ &+ \frac{2N_{inj}}{\sqrt{\pi}(\alpha\tau_{inj})\varepsilon^{1+\beta}}\left[\Gamma_{(3/2+\beta)}(\varepsilon e^{-\alpha t}) - \Gamma_{(3/2+\beta)}(\varepsilon)\right], \end{aligned}$$

Guo et al. 2014, 2015

Averaging particle motions to get averaged fluid quantities (starting from the single particle motion)

Evaluate exact expression for energy gain of all particles:

$$\text{energy change} = q_j \mathbf{v} \cdot \mathbf{E} = q_j v_{\|} E_{\|} + q_j \mathbf{v}_{\perp} \cdot \mathbf{E}_{\perp}$$

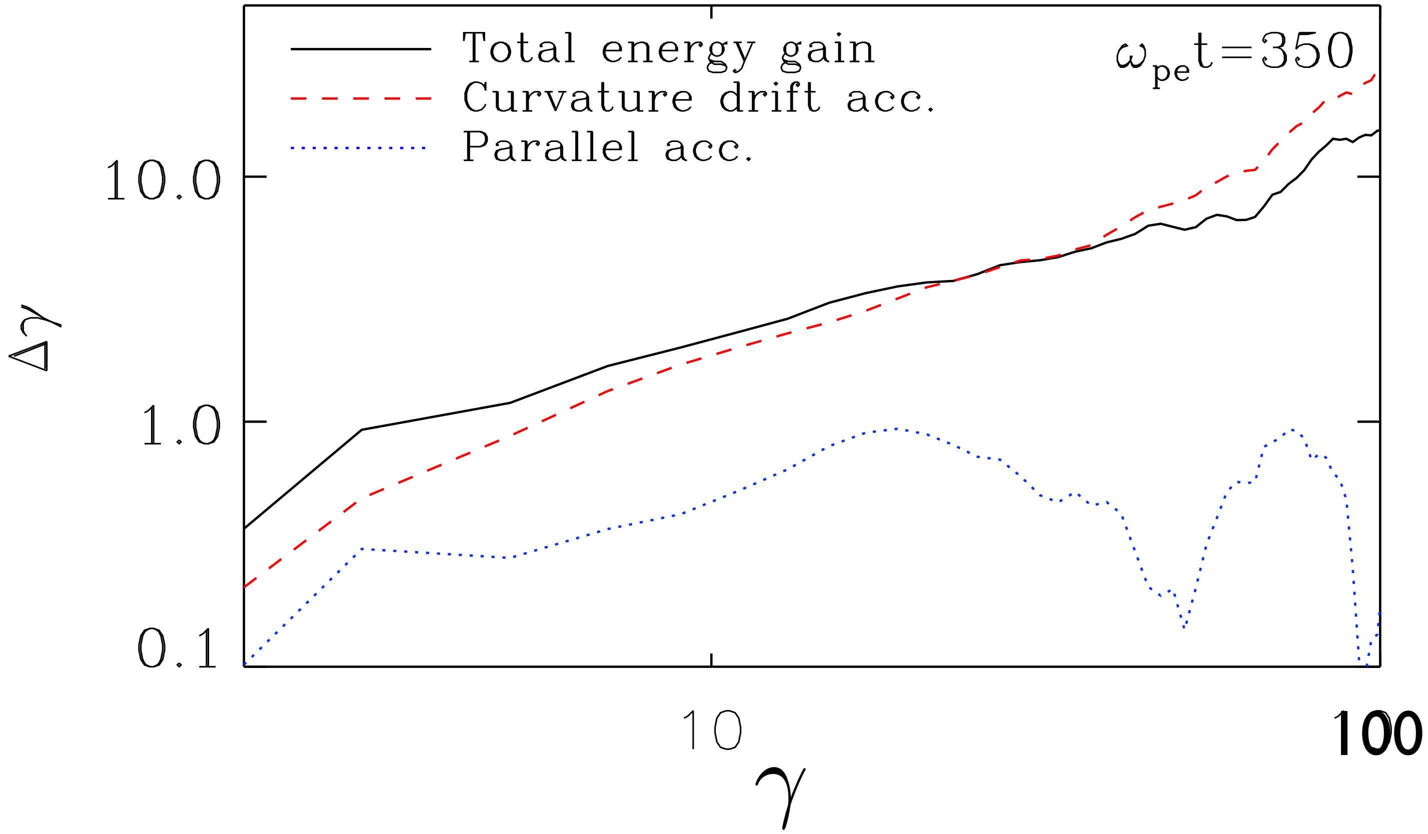
Also evaluate energy gain from guiding center approximation

$$\mathbf{v} = \mathbf{v}_D + \cancel{\mathbf{v}_g}$$

$$\text{energy change} = q_j \int (\mathbf{v}_{curv} + \mathbf{v}_{\nabla B}) \cdot \mathbf{E} \, dt$$

Dominant acceleration term is from the curvature drift

$$\mathbf{v}_{curv} = \frac{\gamma v_{\|}^2}{\Omega_{ce}} \left[\mathbf{b} \times (\mathbf{b} \cdot \nabla) \, \mathbf{b} \right]$$



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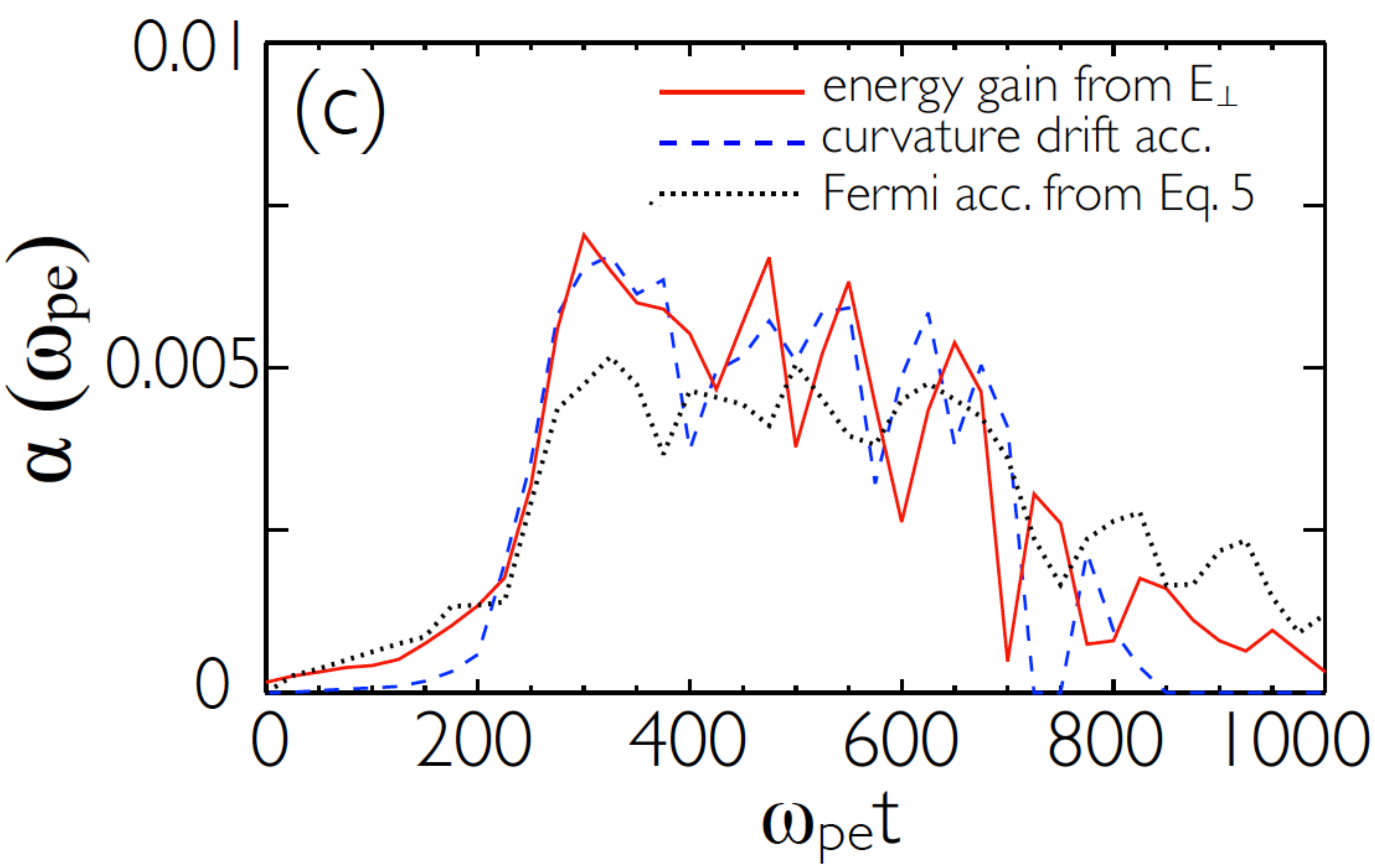


Fermi acceleration formula agrees with the acceleration by curvature drift motion.

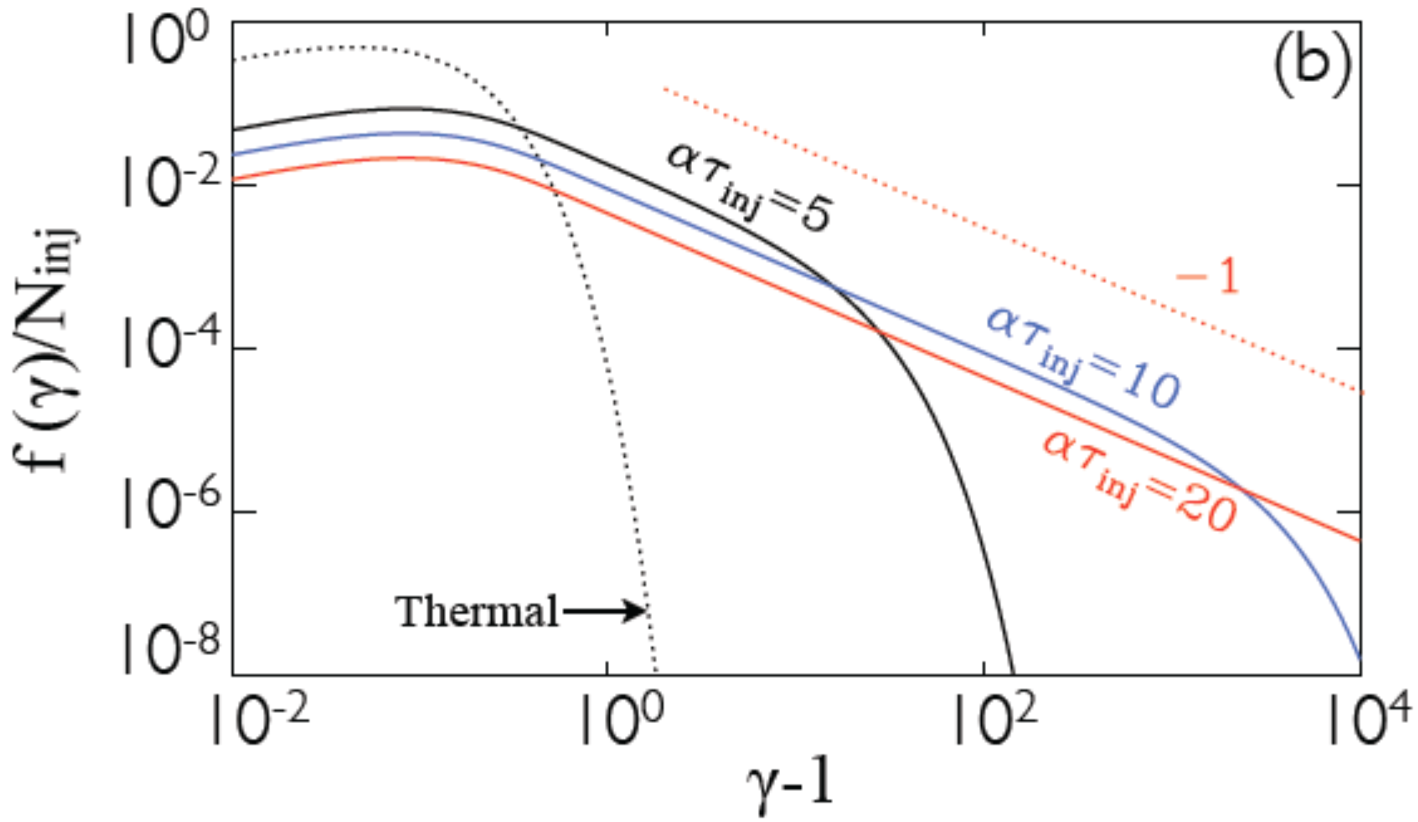
$$\Delta\gamma = \left(\Gamma^2(1 + \frac{2Vv_x}{c^2} + \frac{V^2}{c^2}) - 1\right)\gamma$$

$$\Delta t = L_x/v_x$$

$$\alpha = \Delta\gamma/(\gamma\Delta t)$$

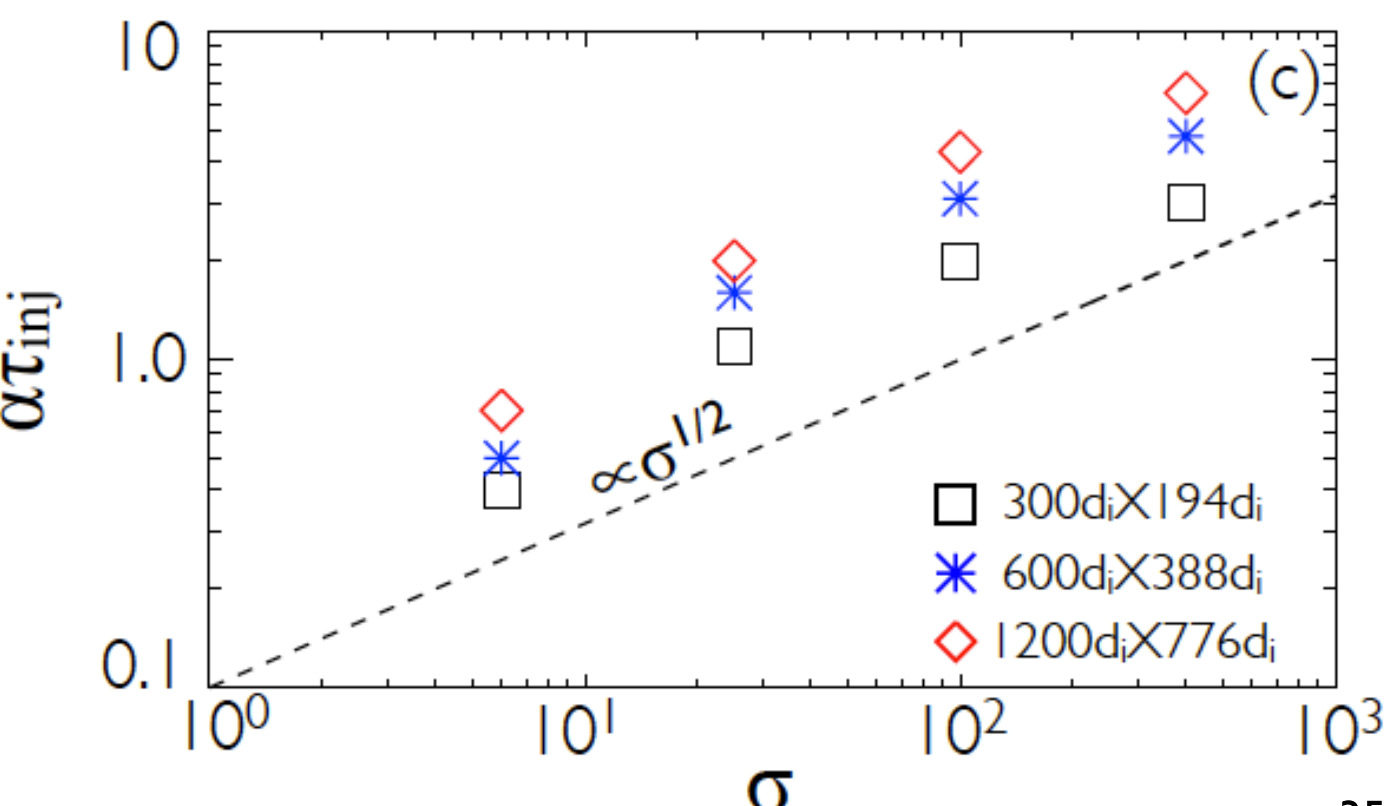
Guo et al. 2014, 2015

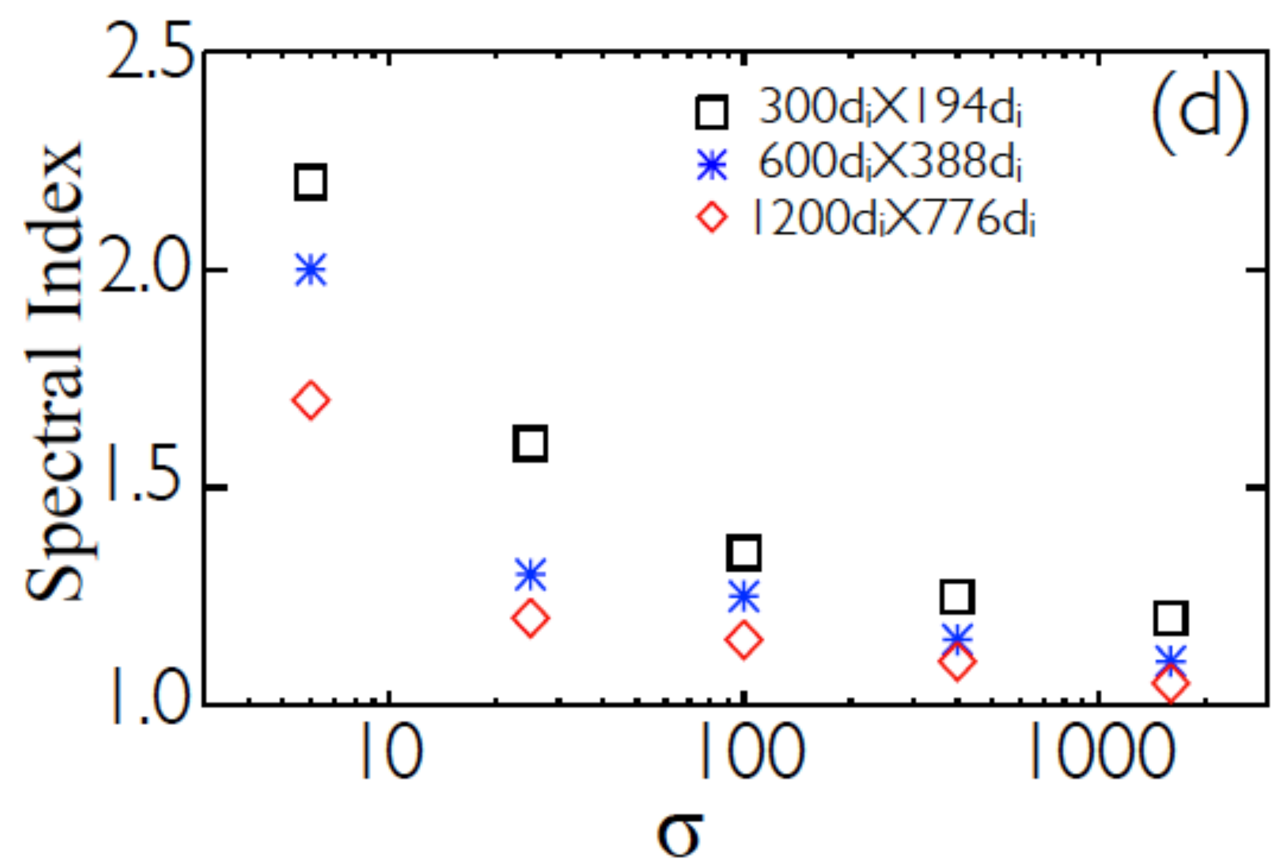
Power-law formation condition



$$\alpha\tau_{inj} > 1$$

This can easily be satisfied in relativistic reconnection, even in kinetic scales.





Acceleration mechanism

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Direct acceleration

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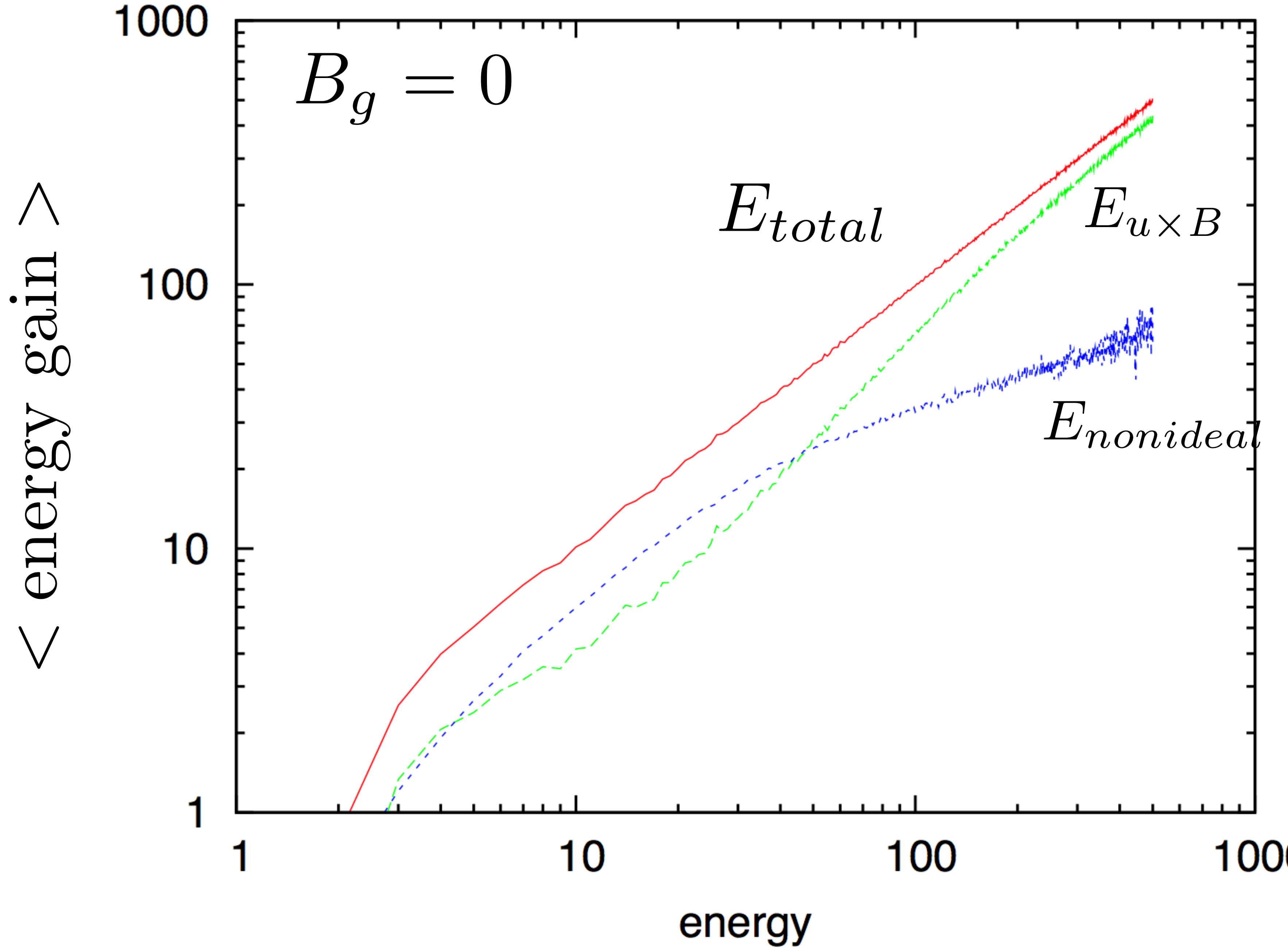
Evaluating $\int qv \cdot E$ from different electric fields



Fermi acceleration dominates for antiparallel reconnection.

Direct acceleration is important for strong guide field case.

2D and 3D simulations show similar features

Power law solution (Fermi 1949)

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = -\frac{f}{\tau_{esc}}$$

$$\varepsilon = m_e c^2 (\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

Power law solution (Fermi 1949)

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$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f \propto \varepsilon^{-(1+\frac{1}{\alpha \tau_{esc}})}$$

Consider evolution of f in a closed system

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$

$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

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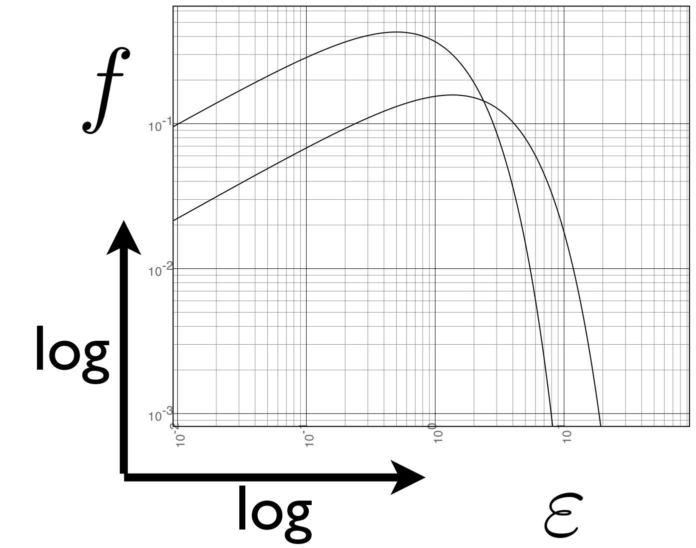
$$f = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-3\alpha t/2}\exp(-\varepsilon e^{-\alpha t})$$



The distribution is heated up $T \longrightarrow Te^{\alpha t}$

Consider escape

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}(\frac{\partial \varepsilon}{\partial t} f) = -\frac{f}{\tau_{esc}}$$

$$\varepsilon = m_e c^2 (\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

↓

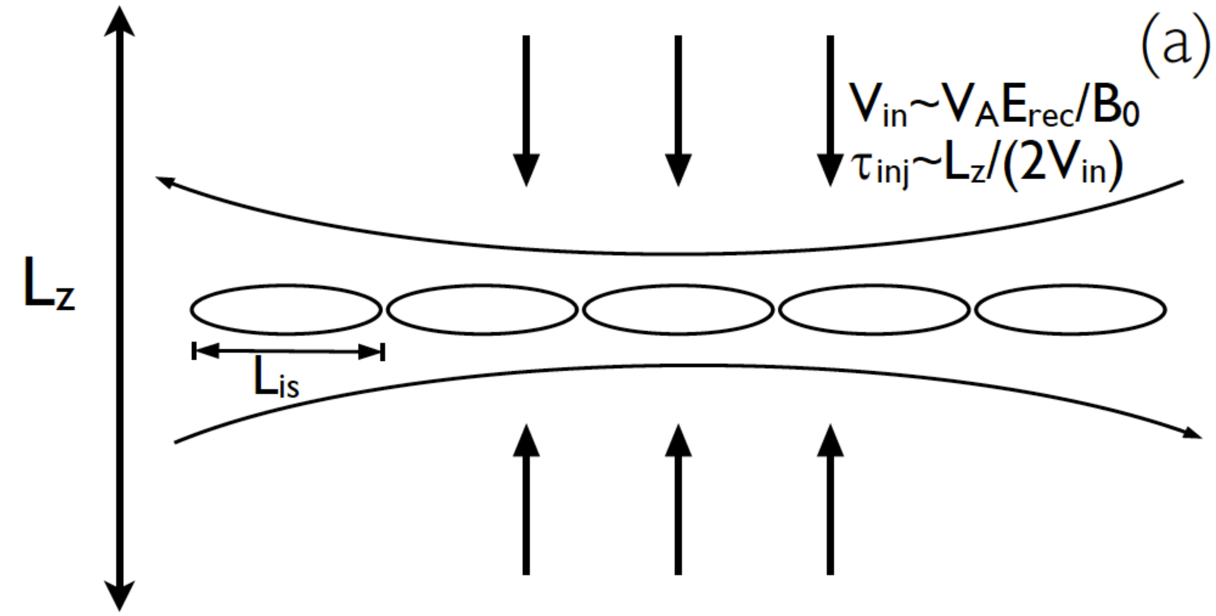
$$\frac{df}{dt} + (\alpha + \frac{1}{\tau_{esc}})f = 0$$

The distribution is heated up. No power-laws

Escape does not give a power law.

Injection is the key! Consider continuous injection

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$



- Total injection $N_{inj} = LV_{inj}T_{inj}$
- Divide the whole process into N groups.
- Release Nth group at t=N dt.
- Evolution of each group is described by

$$f = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-3\alpha t/2}\exp(-\varepsilon e^{-\alpha t})$$

$$T \longrightarrow Te^{\alpha t}$$