Particle Acceleration in Two- and Three-dimensional Magnetically-dominated Reconnection

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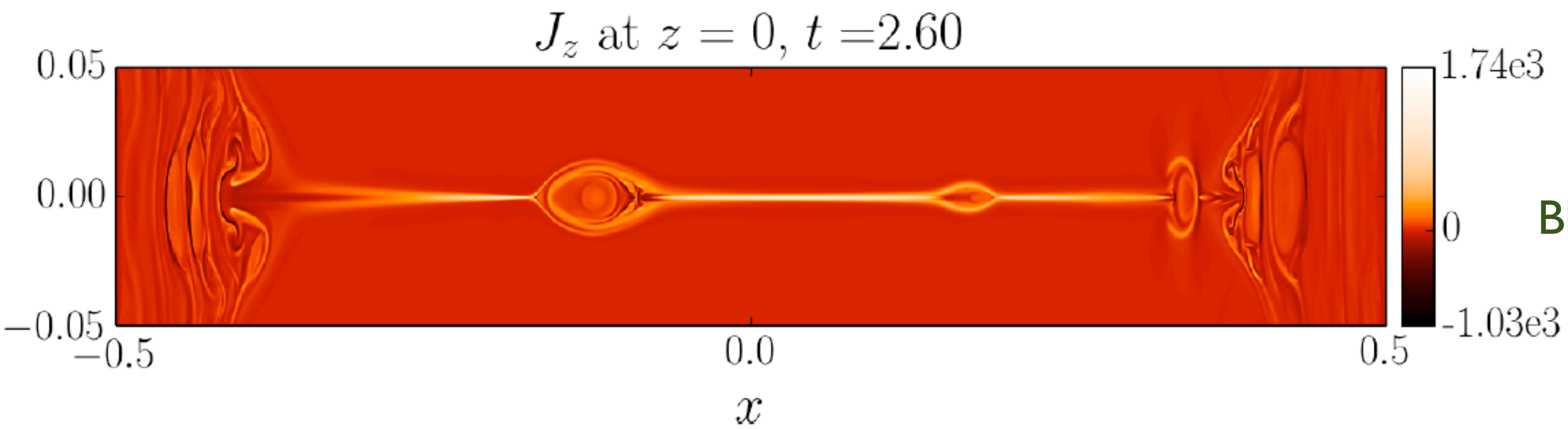
Outline

Particle Acceleration in Magnetic Reconnection Layers

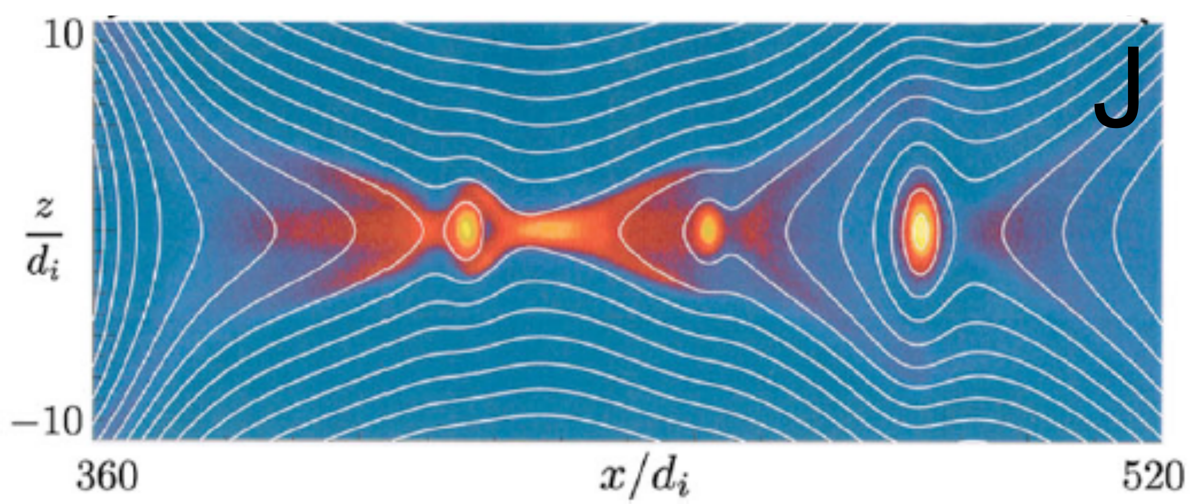
We focus on understanding the primary acceleration mechanism and formation of power-law distributions in kinetic simulations

- Plasma dynamics in 2D and 3D reconnection
- Features of energetic particle distribution
- Diagnostics for understanding particle acceleration
- Analysis for formation of power-law distributions
- Summary

2D Magnetic Reconnection

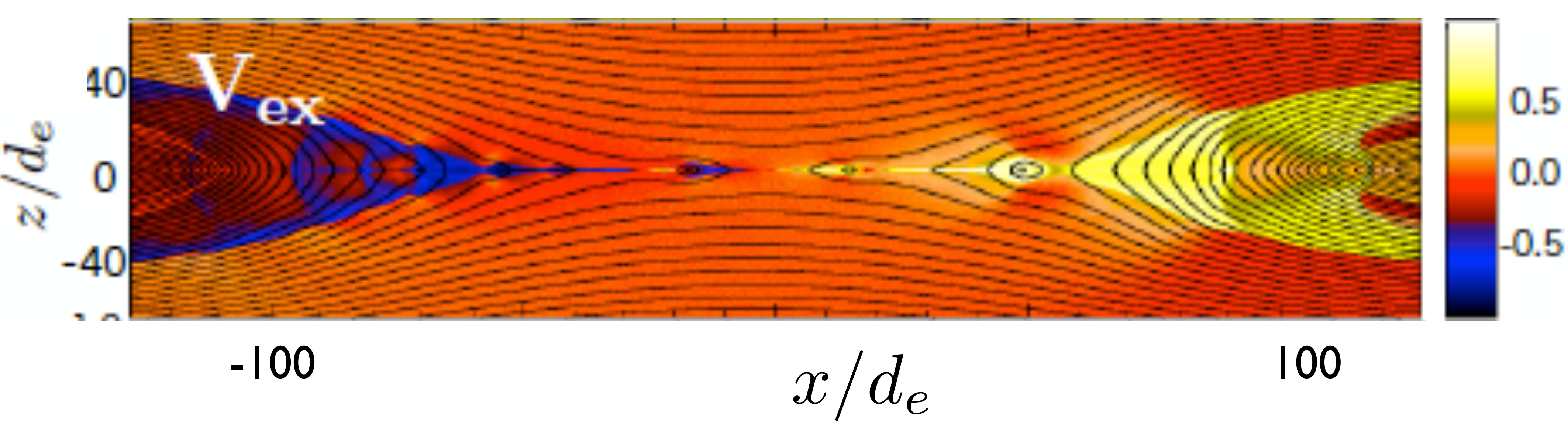


MHD simulations
Loureiro et al. 07
Bhattacharjee et al. 09
Uzdensky+ 10



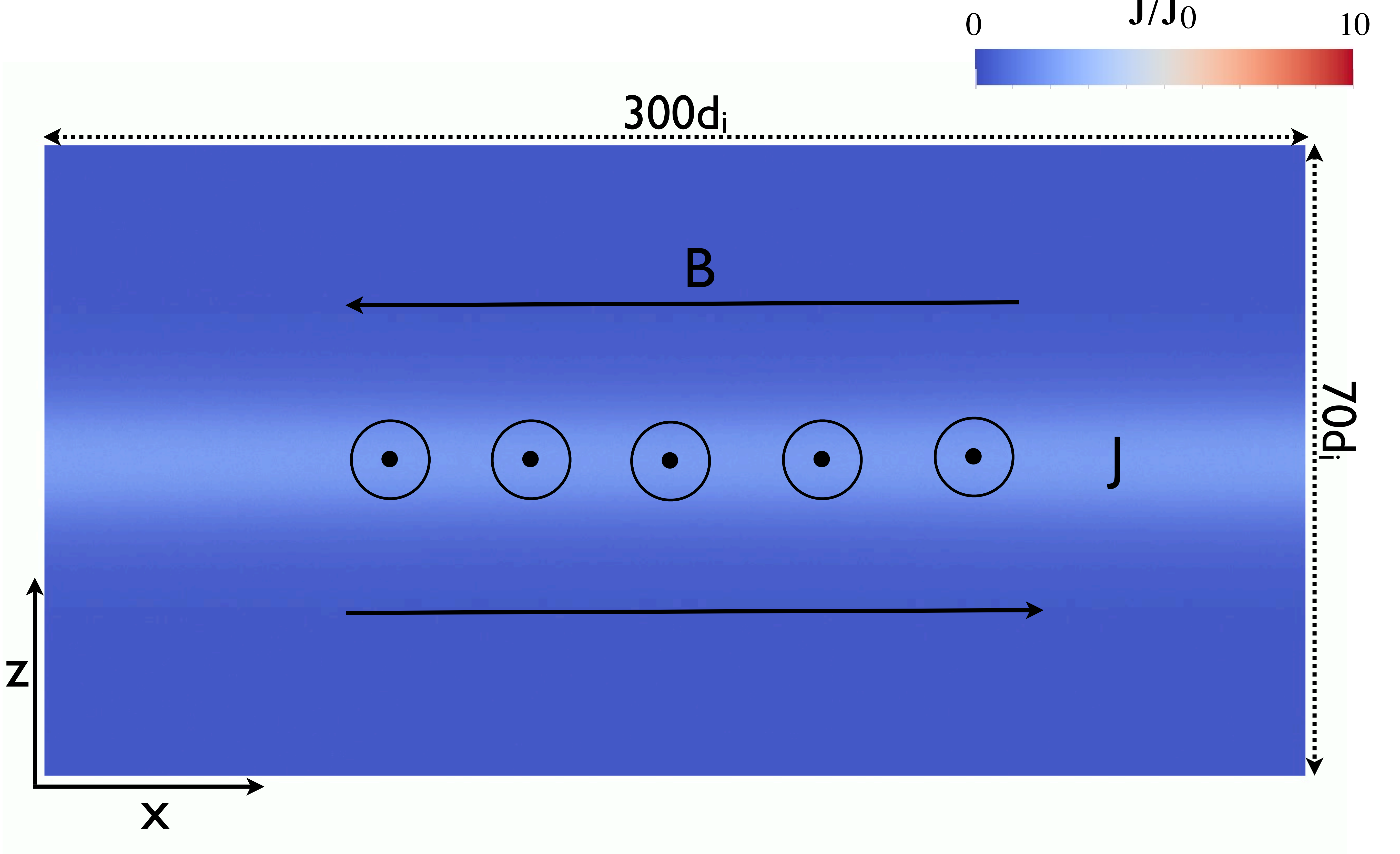
Fully kinetic approach
Daughton et al. (2009)

$$\sigma = \frac{B^2}{4\pi n m_e c^2} \gg 1$$

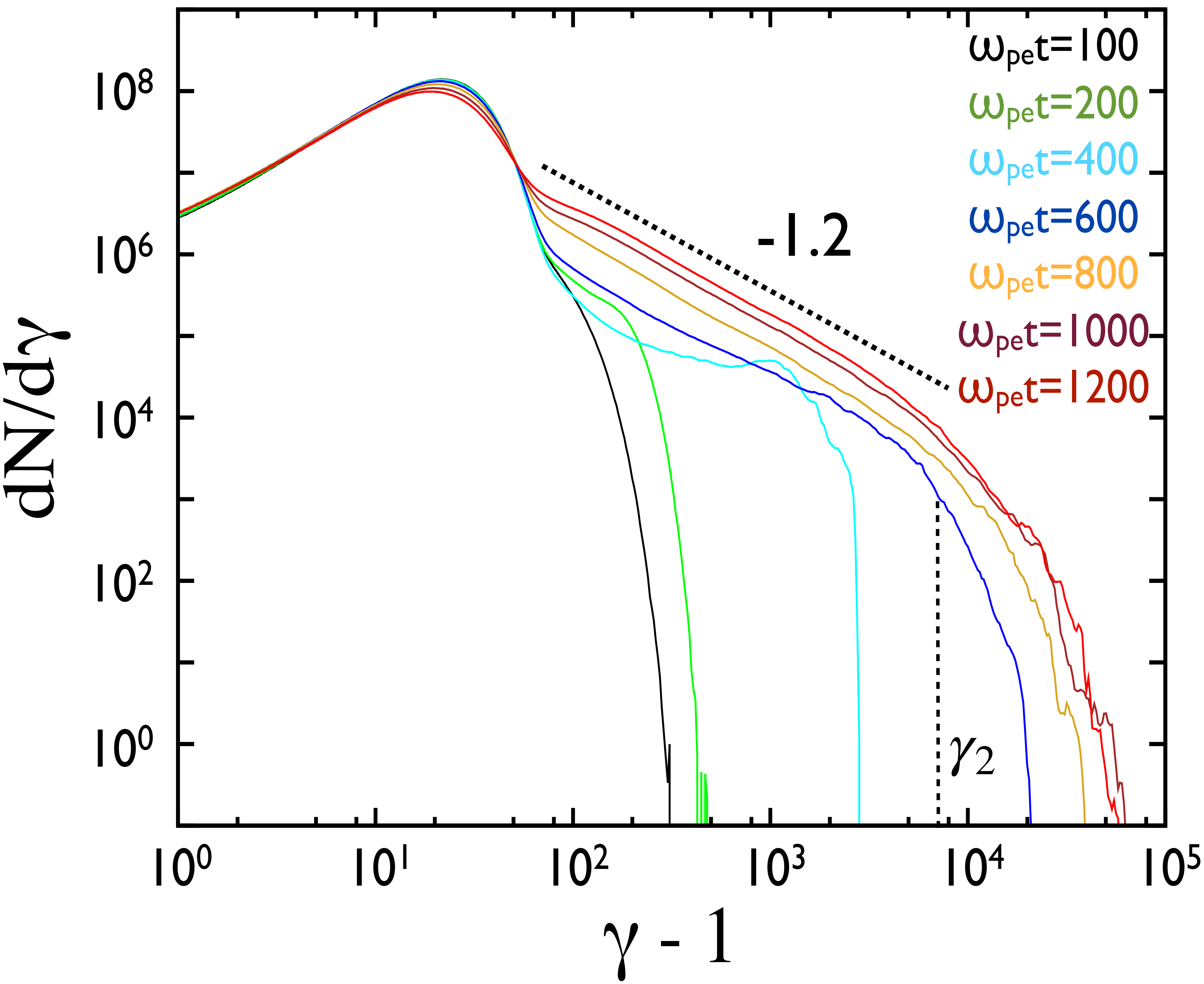


Relativistic flows
in relativistic case
Liu et al. 15 PRL

2D current density $\sigma = 100$ $\omega_{pe}t$=0 - 700



A relativistic run with σ = 6400, γ_0 = 16



Spectral index p ~ 1

Fast variability ~ Lx/c

Power-law range

$\gamma_2 \sim \sigma$

$$\varepsilon_{max} = \int |qE_{rec}| c dt$$

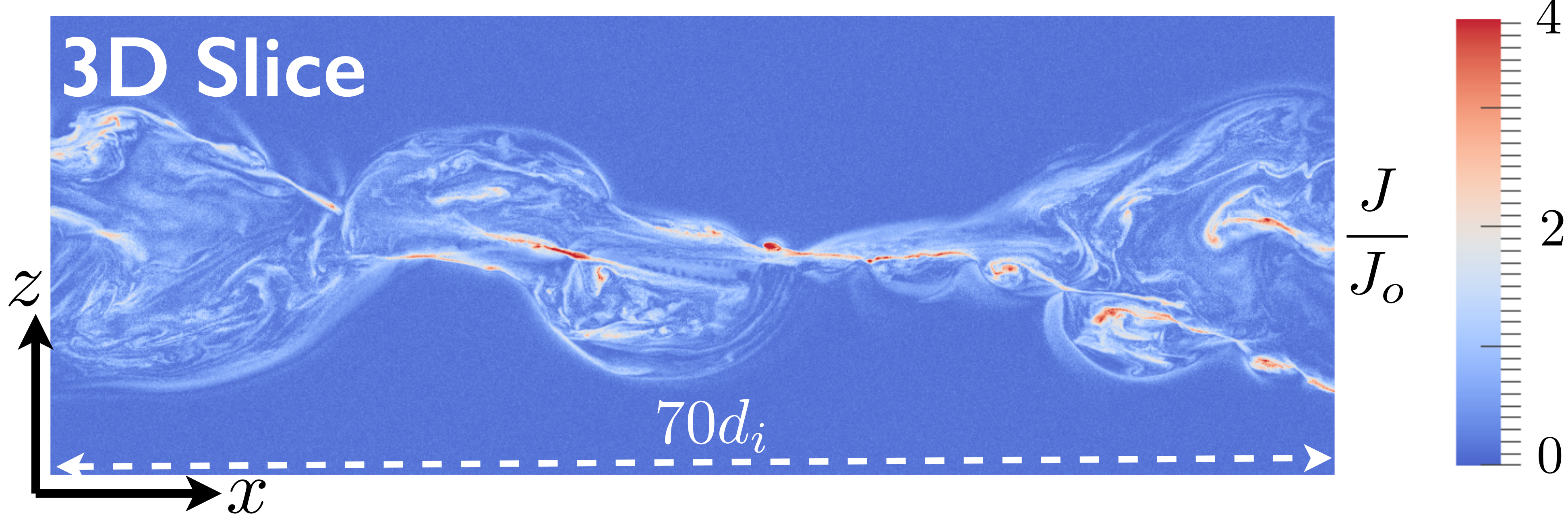
E_{rec} up to ~ $0.2B_0$ for σ>>1

Guo et al. 2016 ApJL

3D Magnetic Reconnection

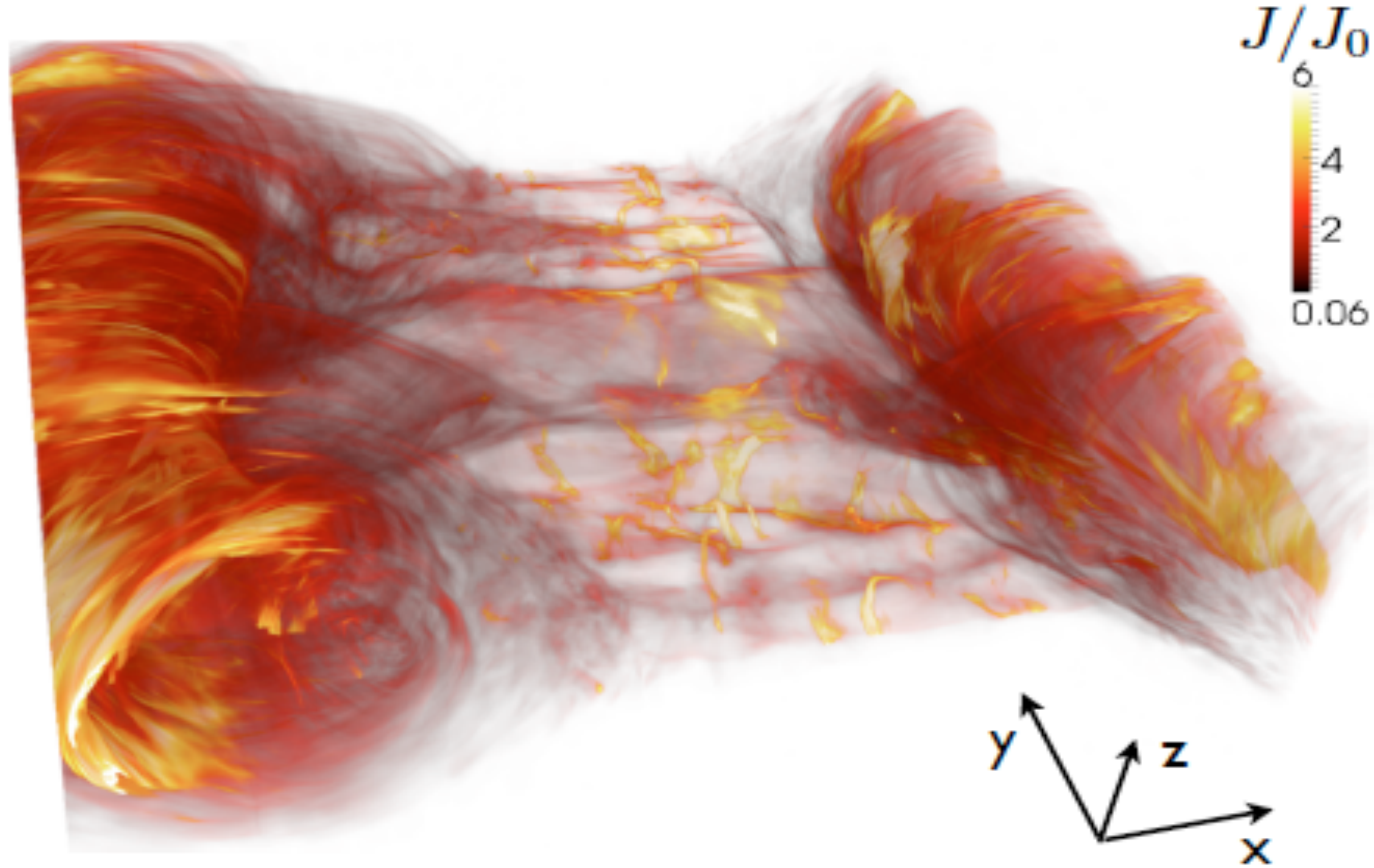
Nonrelativistic Reconnection
m_i/m_e=100

Daughton et al, 2011

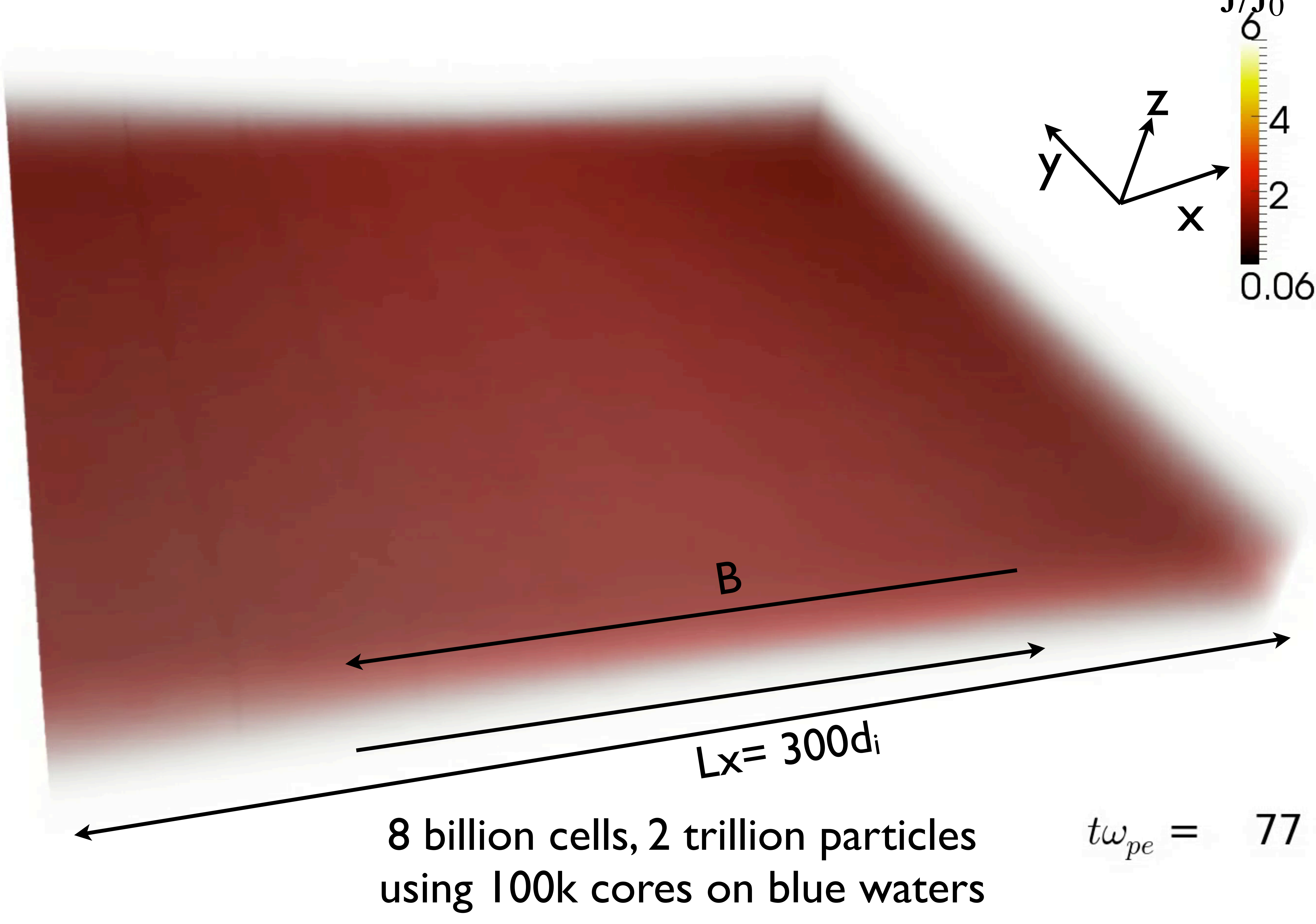


Relativistic reconnection
σ = 100, m_i/m_e=1

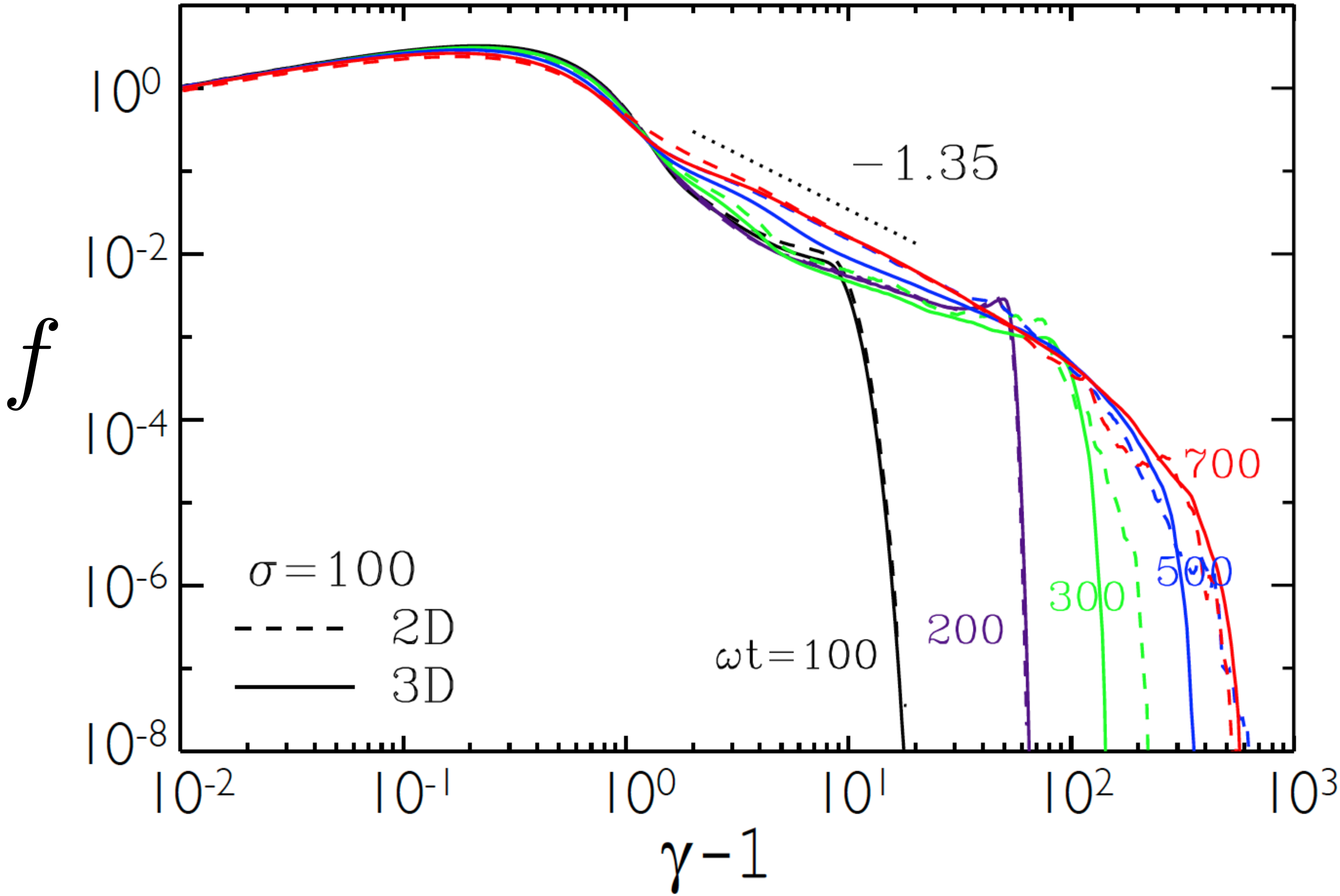
Guo et al. 2014 2015



$\sigma = 100$


J/J$_0$
6
4
2
0.06
z
y
x
B
Lx= 300d$_i$
8 billion cells, 2 trillion particles
using 100k cores on blue waters
$t\omega_{pe}$ = 77

Energy spectra from 2D and 3D PIC simulations

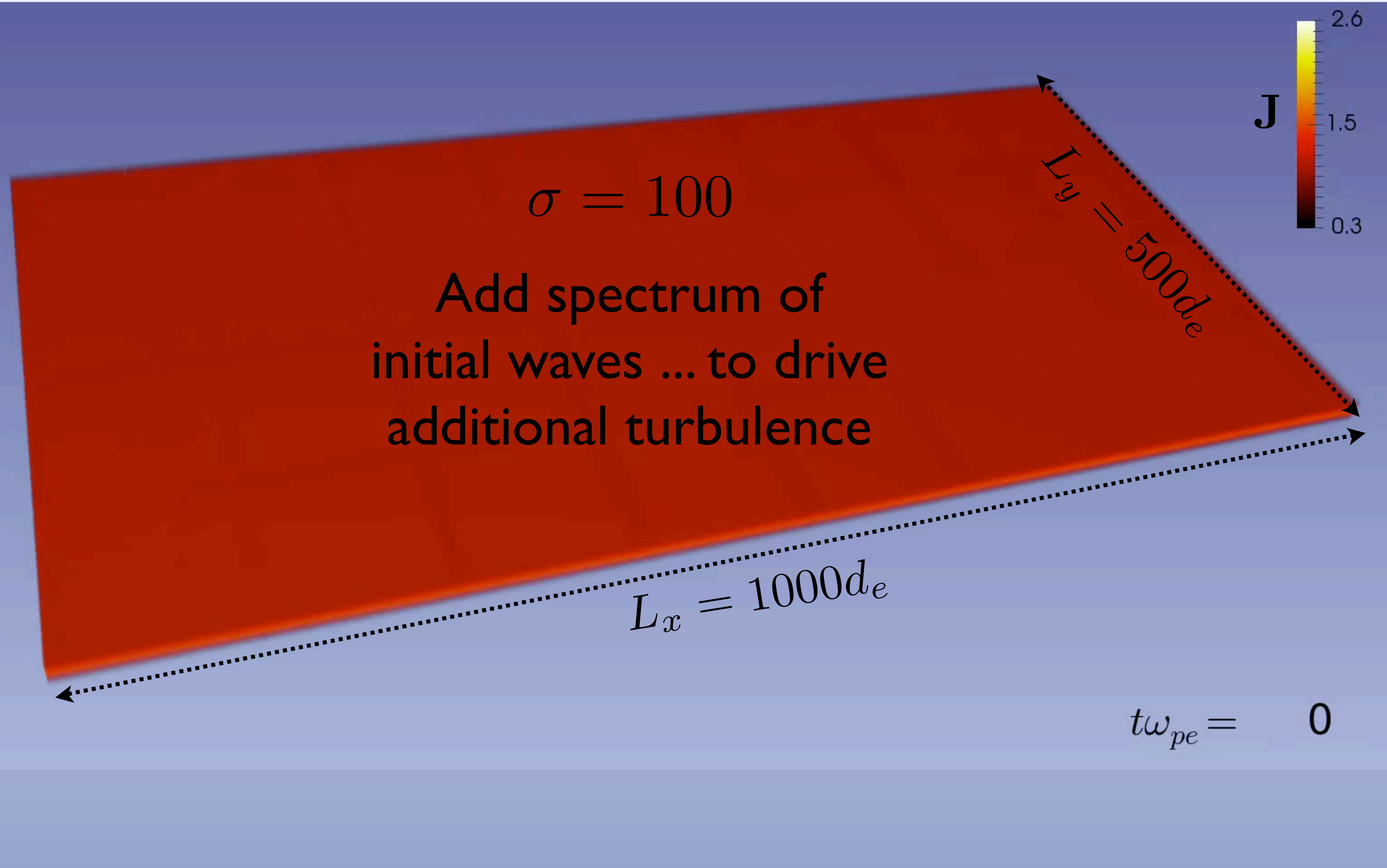


Guo et al. 2014 PRL, 2015 ApJ, 2016 PoP

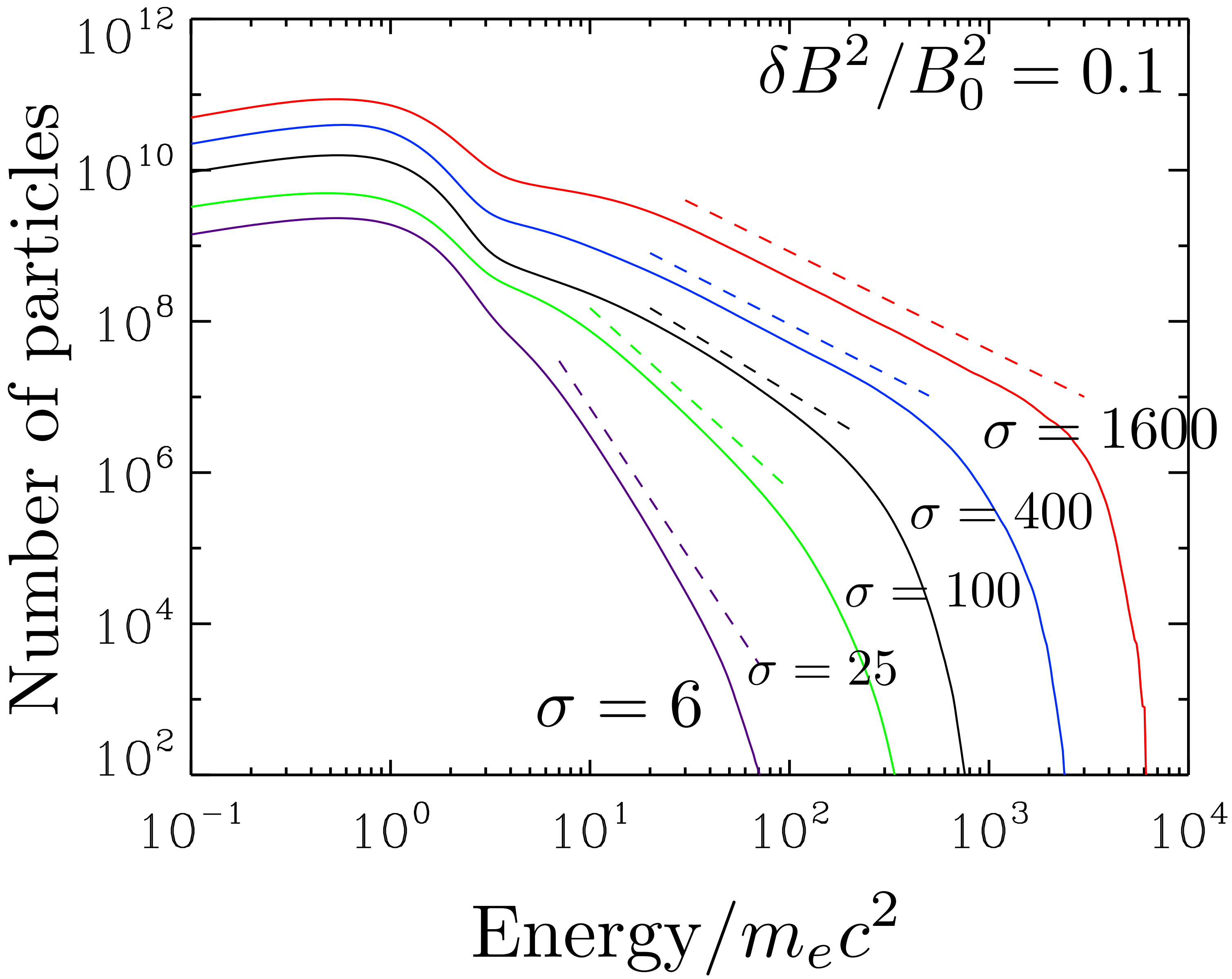
Trinity runs

$4096 \times 2048 \times 2048$ cells

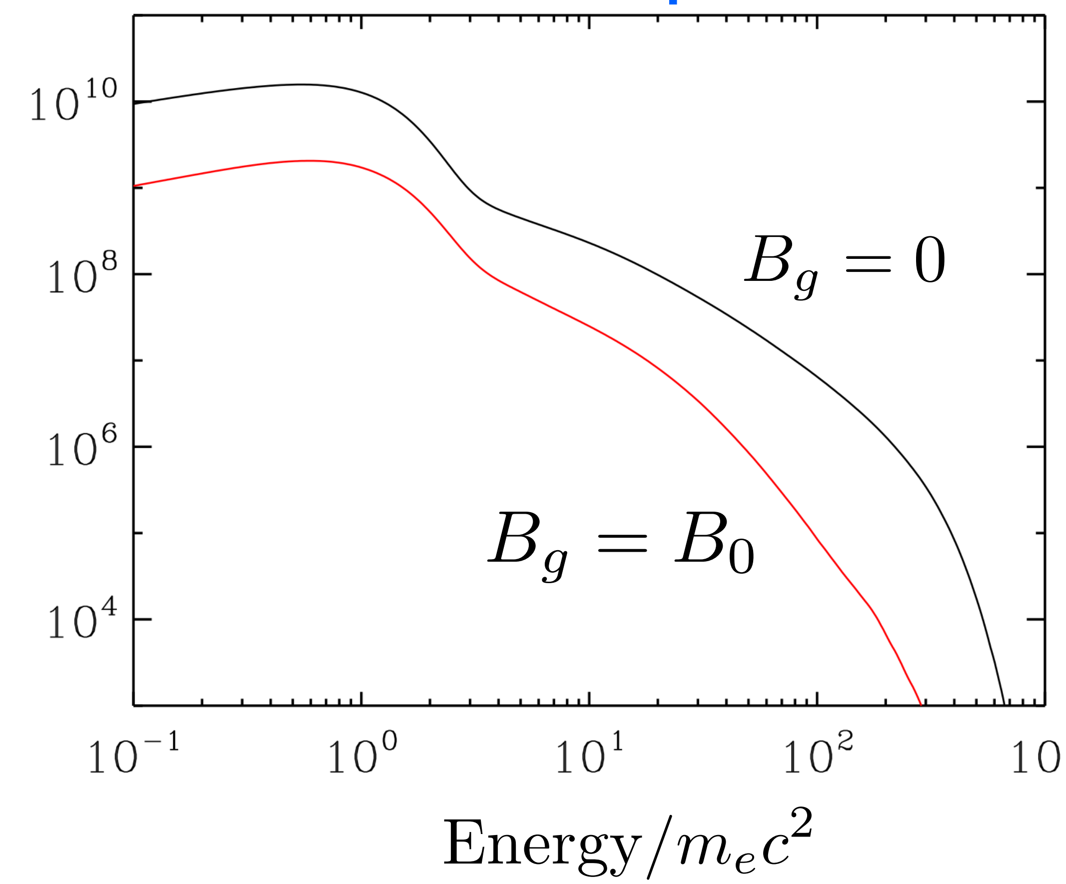
$\sim 5.2 \times 10^{12}$ particles track $\sim 10^{8}$ particles



Energy distribution for different magnetization

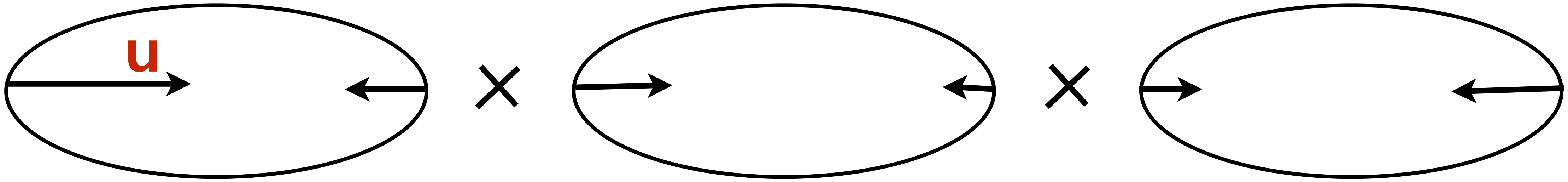


Guide field dependence



The additional turbulence does not strongly modify nonthermal acceleration.

Acceleration mechanism & Power law distribution



Many 2D studies ...

Fermi/Betatron accelerations

Curvature/grad-B drift
motion transverse to B

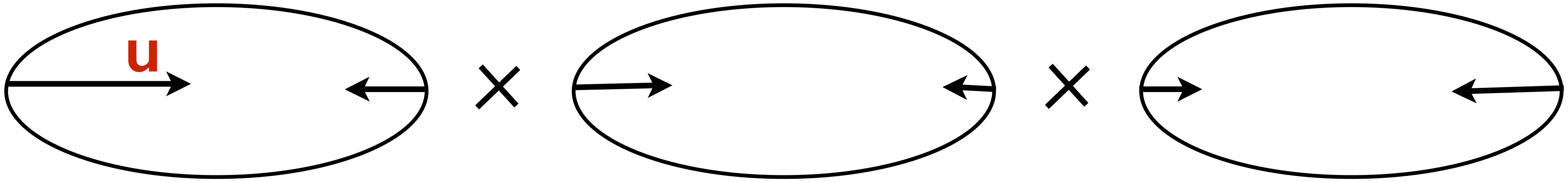
$$\mathbf{E}_{motional} = -\mathbf{u} \times \mathbf{B}/c$$

Direct acceleration

Particle move along B
or in weak B

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

Acceleration mechanism & Power law distribution



Many 2D & 3D studies ...

We track a large number of particle trajectories, and

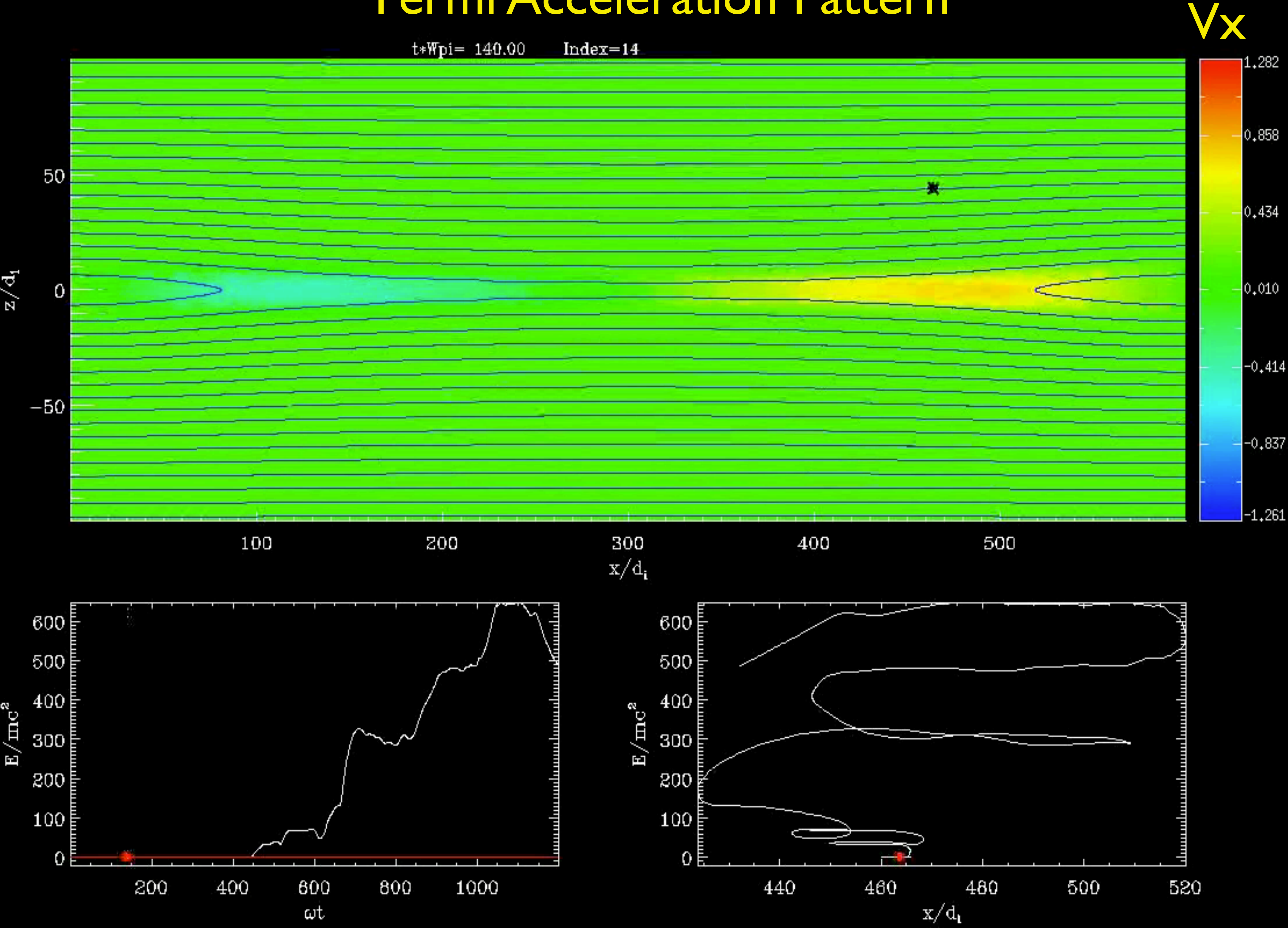
- Identify their acceleration pattern
- Statistically calculate several important quantities
  - acceleration rate $< d\varepsilon > /dt$
  - drift motion, v_D and contribution to acceleration $\int q v_D \cdot E$
  - magnetic field and electric fields at particle positions

$$B_l,\ E_{l,u\times B},\ E_{l,nonideal}$$

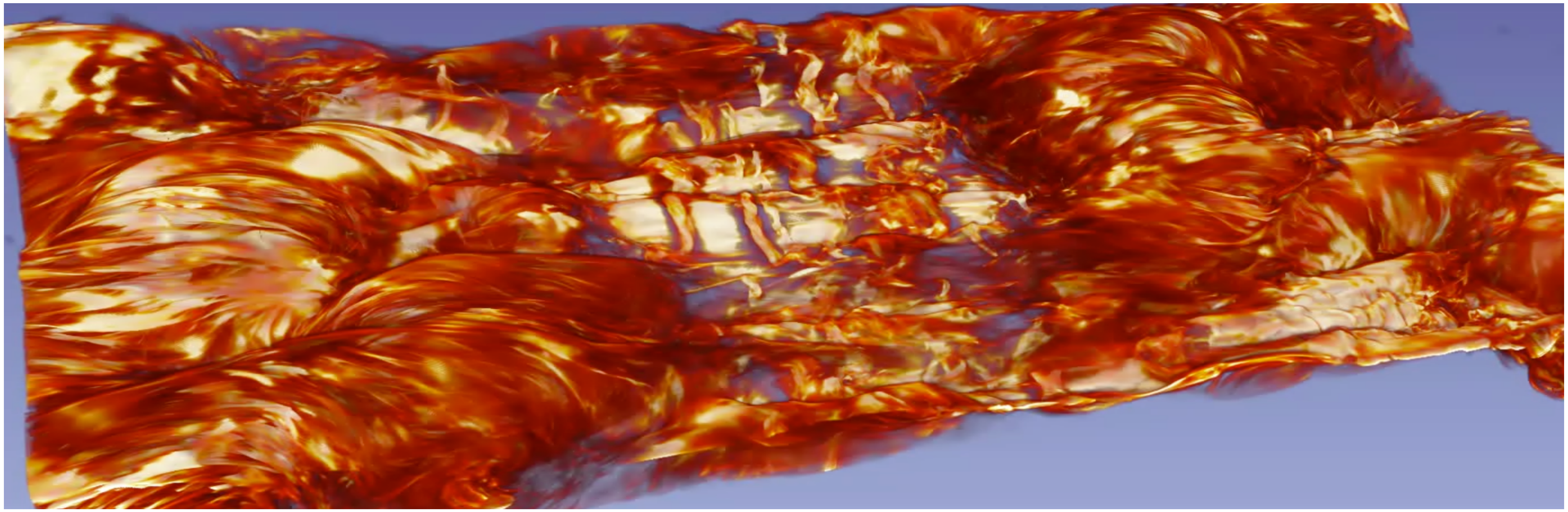
- Add additional test-particle to probe acceleration mechanism

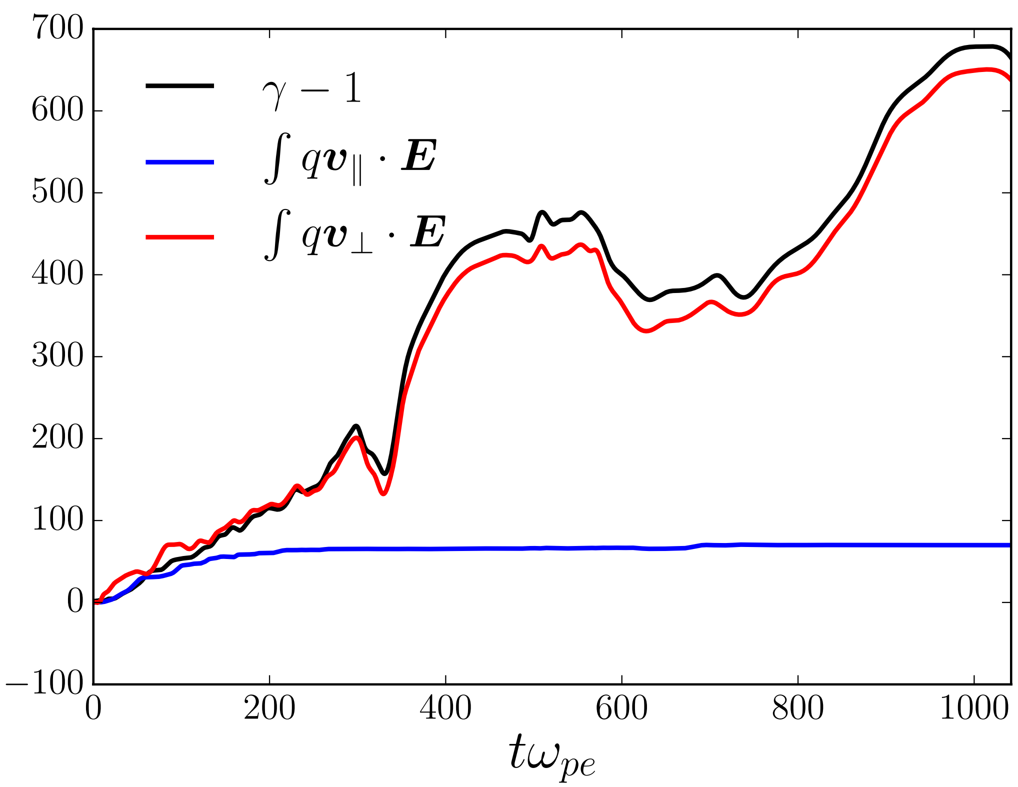
$$only\ experience\ E_{l,u\times B}$$

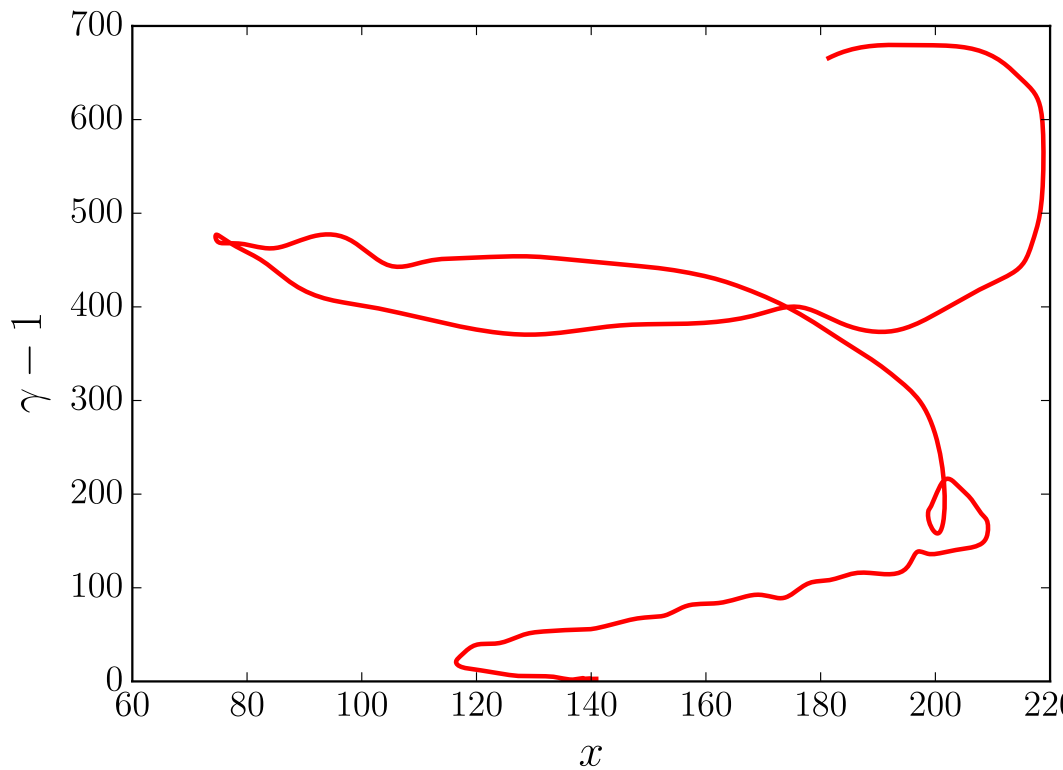
Fermi Acceleration Pattern



Fermi acceleration is still operating in 3D simulation







Diagnostics for understanding primary acceleration

Evaluate exact expression for energy gain of all particles:

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

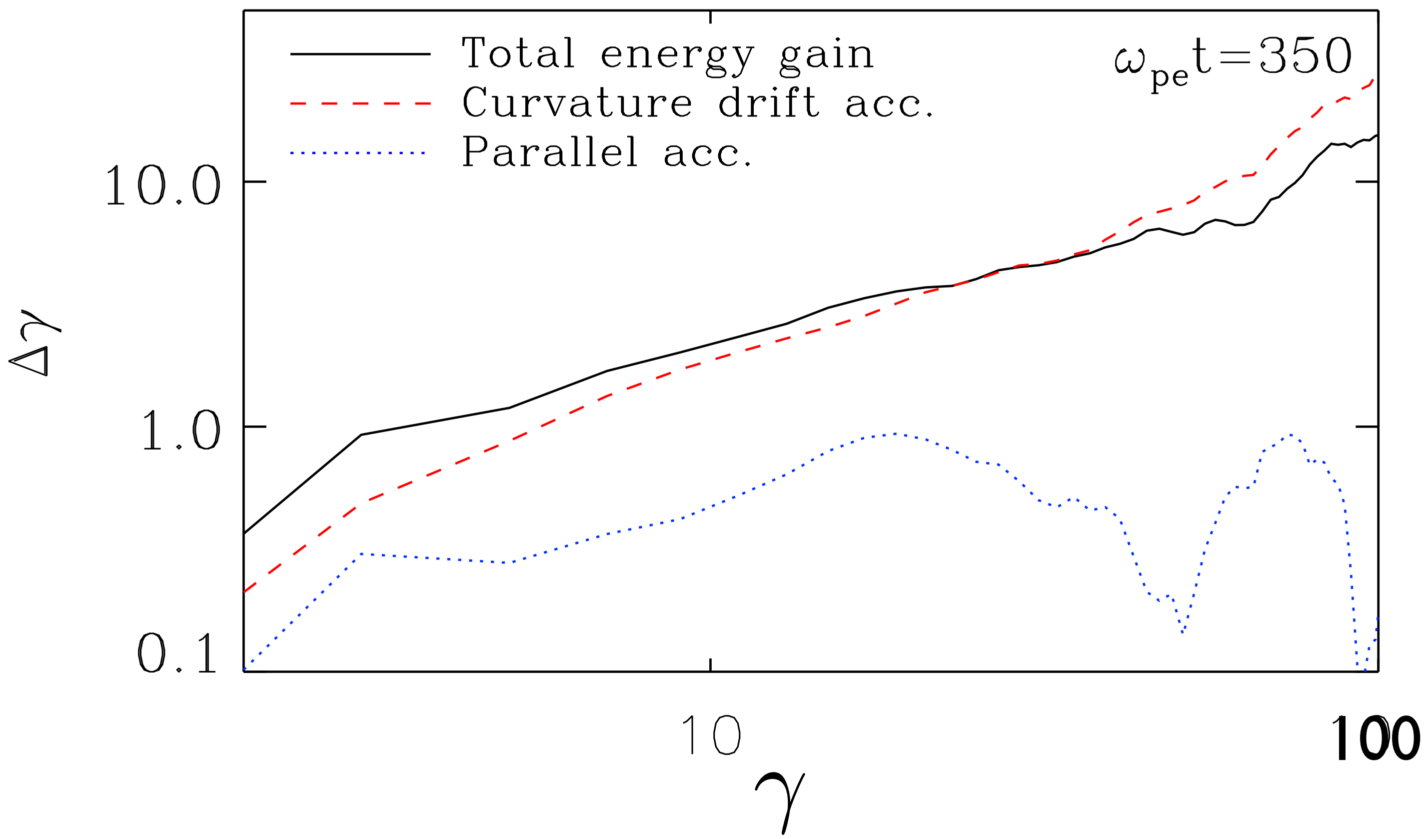
Also evaluate energy gain from guiding center approximation

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

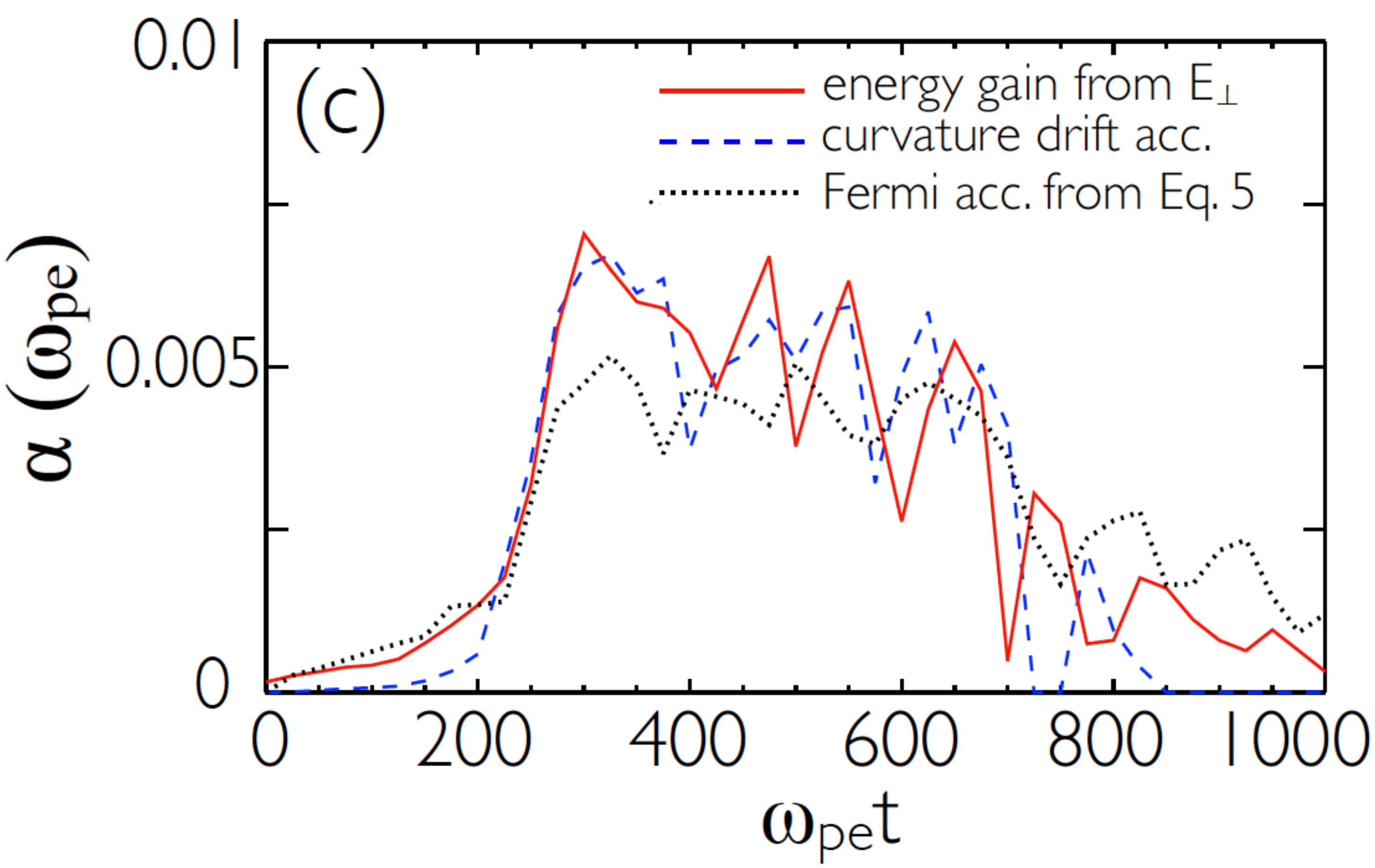
energy change $= q_j \int \left(\mathbf{v}_{curv} + \mathbf{v}_{\nabla B}\right) \cdot \mathbf{E}\, dt$

Dominant acceleration term is from the curvature drift for anti parallel reconnection

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



The acceleration is dominated by energy gain through curvature drift motion



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

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

$$\Delta t = L_x/v_x$$

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

Acceleration mechanism

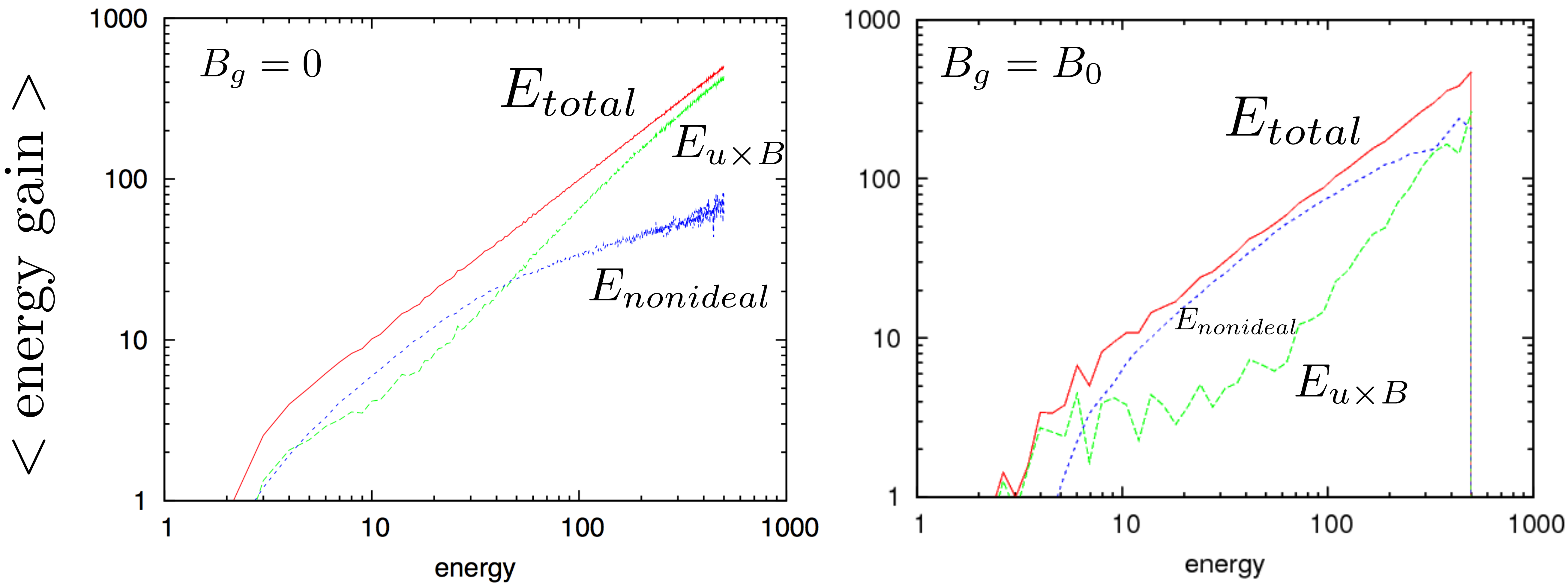
Fermi/Betatron accelerations

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

Direct acceleration

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

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

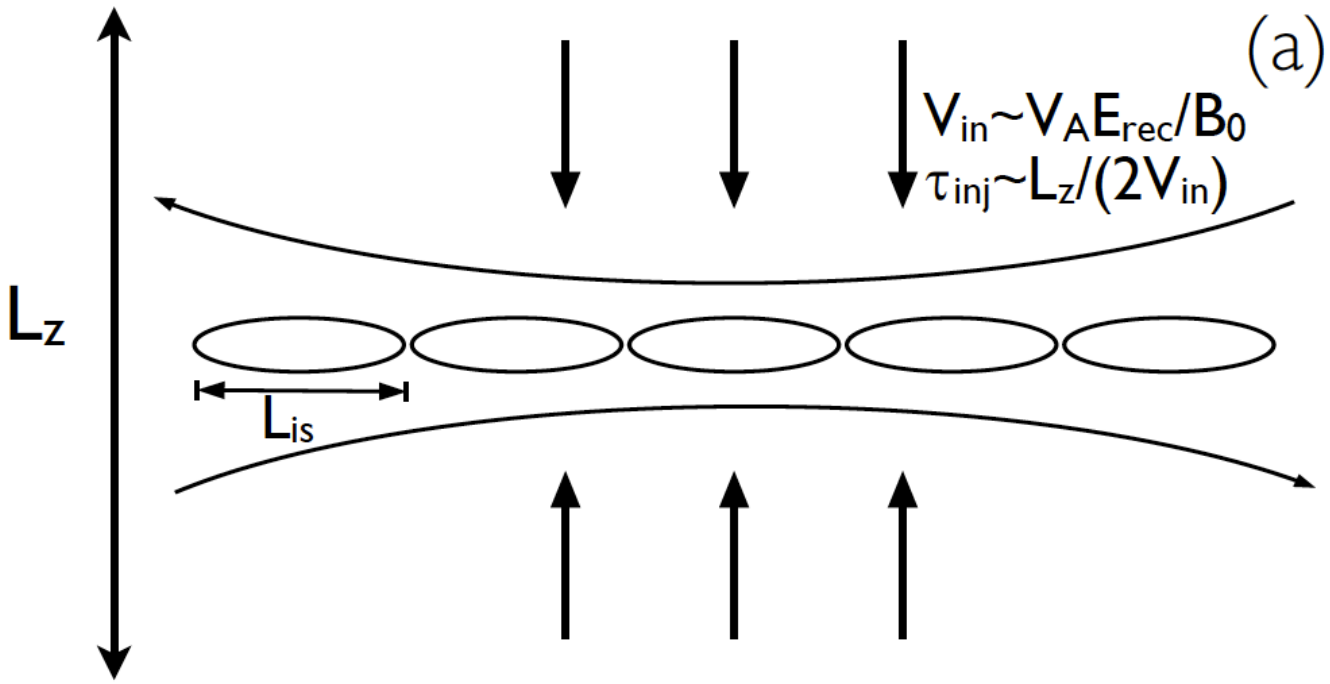


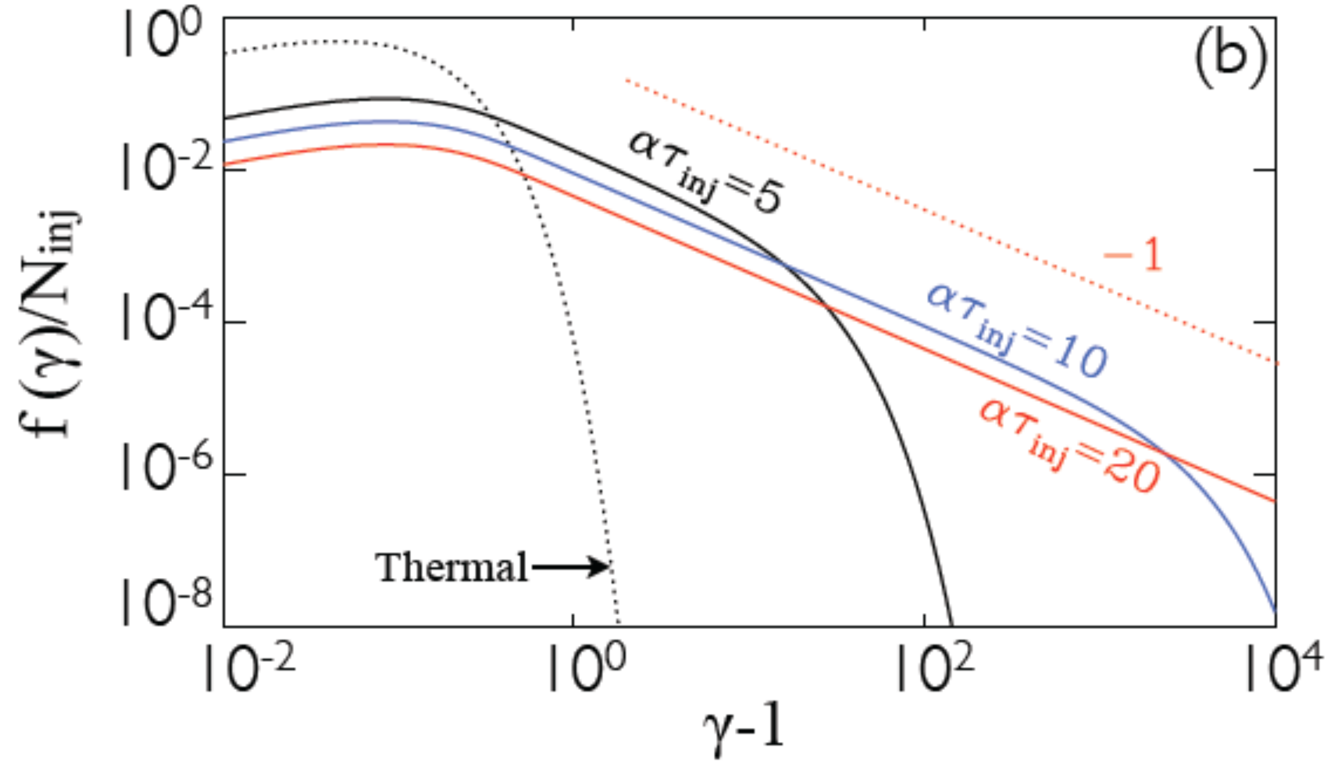
Fermi acceleration dominates for antiparallel reconnection.

Direct acceleration is important for strong guide field case.

2D and 3D simulations show similar features

Power-law formation

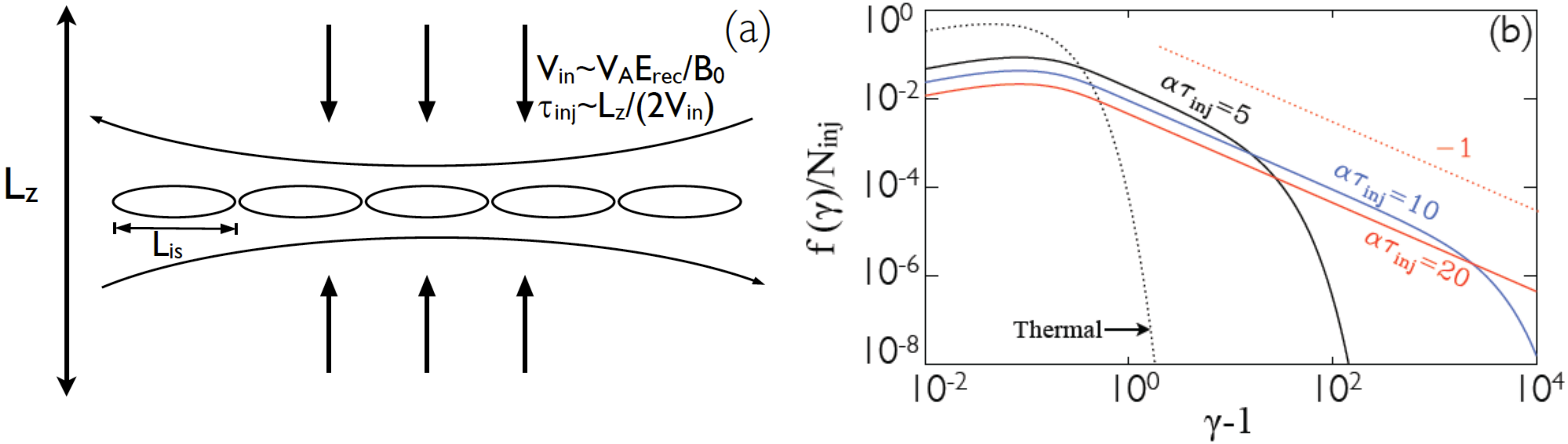




Fokker-Planck Equation for understanding nonthermal distribution

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

Power-law formation

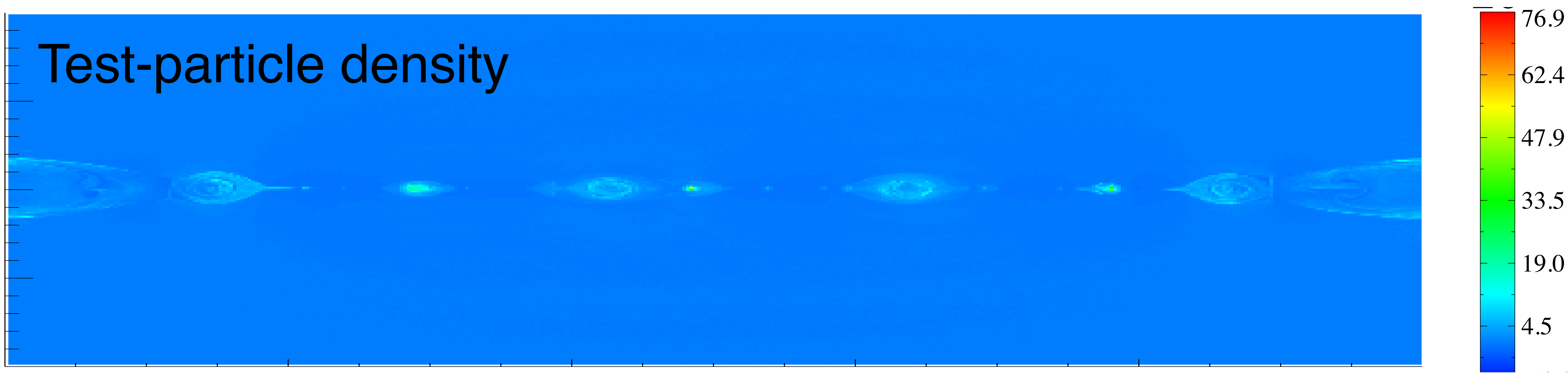


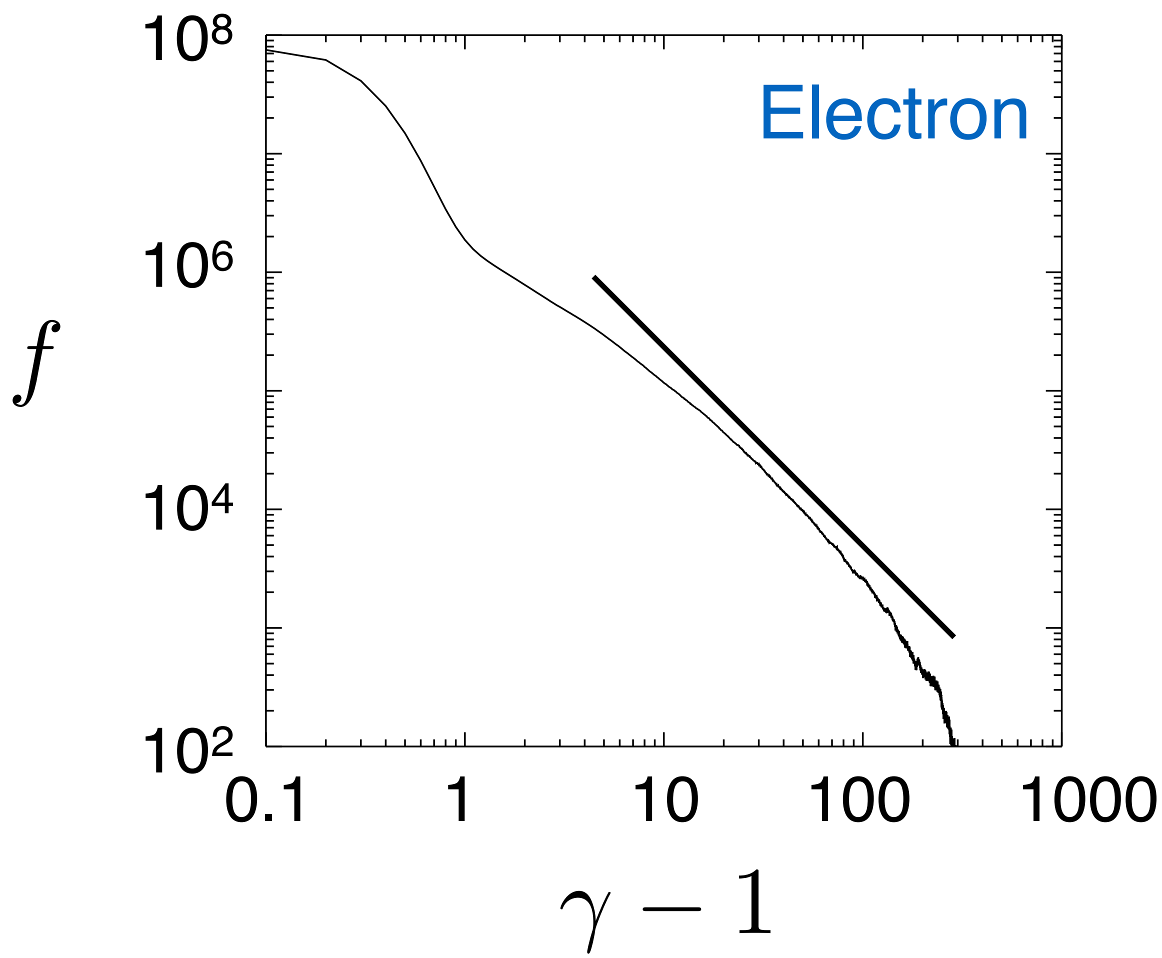
$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = \frac{f_{inj}}{\tau_{inj}} - \frac{f}{\tau_{esc}} \qquad \frac{\partial \varepsilon}{\partial t} = \alpha\varepsilon \qquad f \propto \varepsilon^{-(1+\frac{1}{\alpha\tau_{esc}})}$$

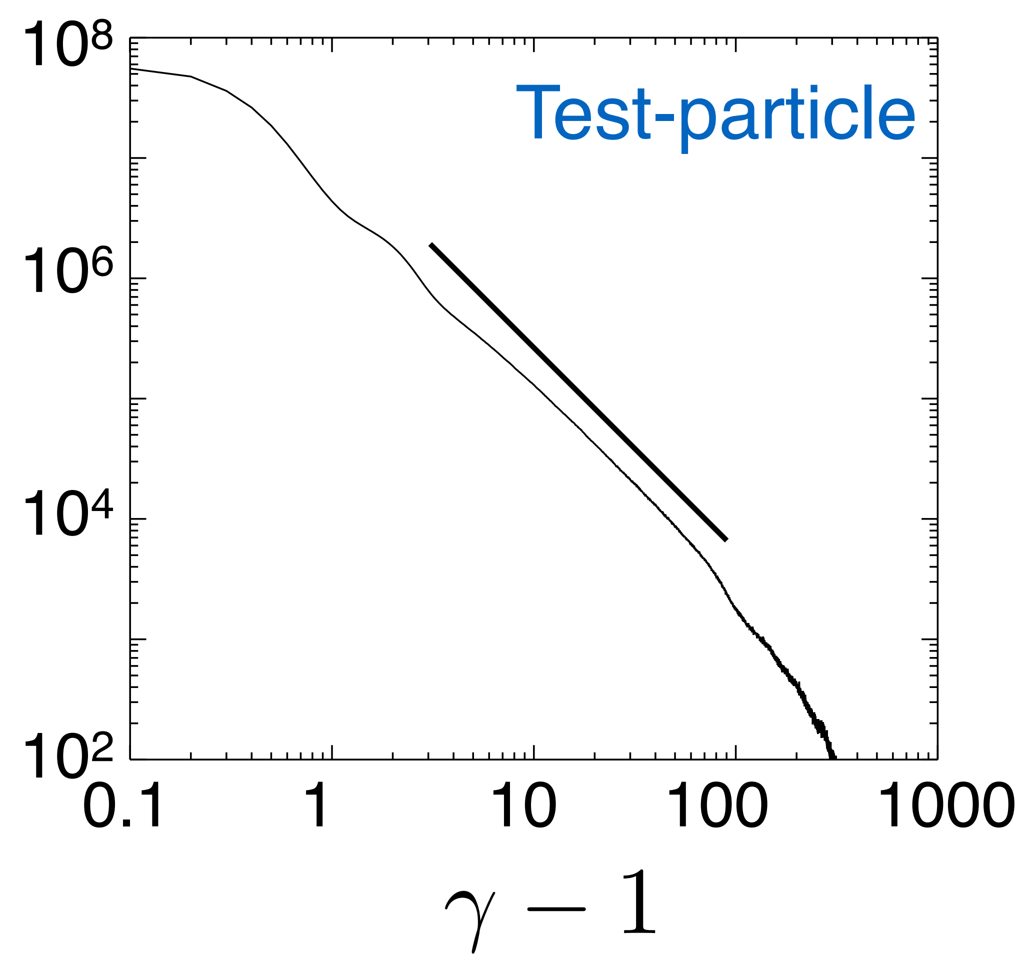
$$\begin{aligned} f(\varepsilon,t) &= \frac{2N_0}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-(3/2+\beta)\alpha t}\exp(-\varepsilon e^{-\alpha t}) \\ &+ \frac{2N_{inj}}{\sqrt{\pi}(\alpha\tau_{inj})\varepsilon^{1+\beta}}\left[\Gamma_{(3/2+\beta)}(\varepsilon e^{-\alpha t}) - \Gamma_{(3/2+\beta)}(\varepsilon)\right],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

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.







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.
- 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 can lead 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.