Efficient Nonthermal Particle Acceleration during Magnetic Reconnection in Magnetically-dominated Flows

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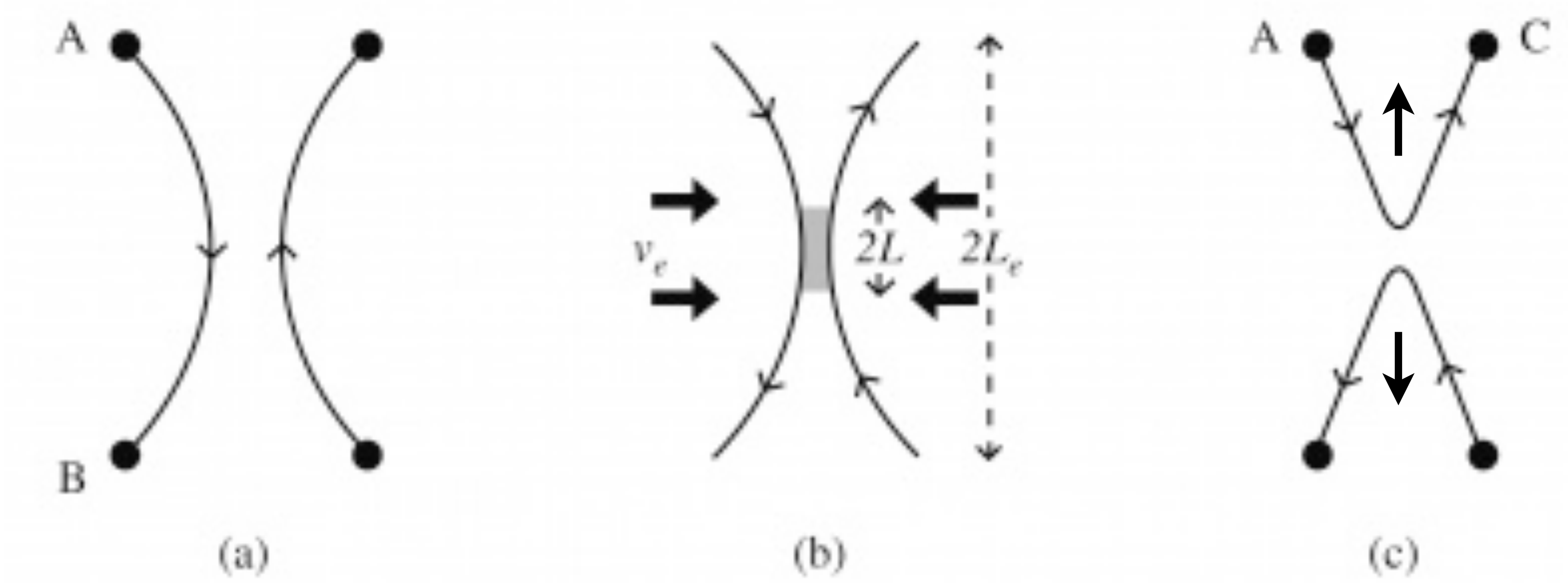
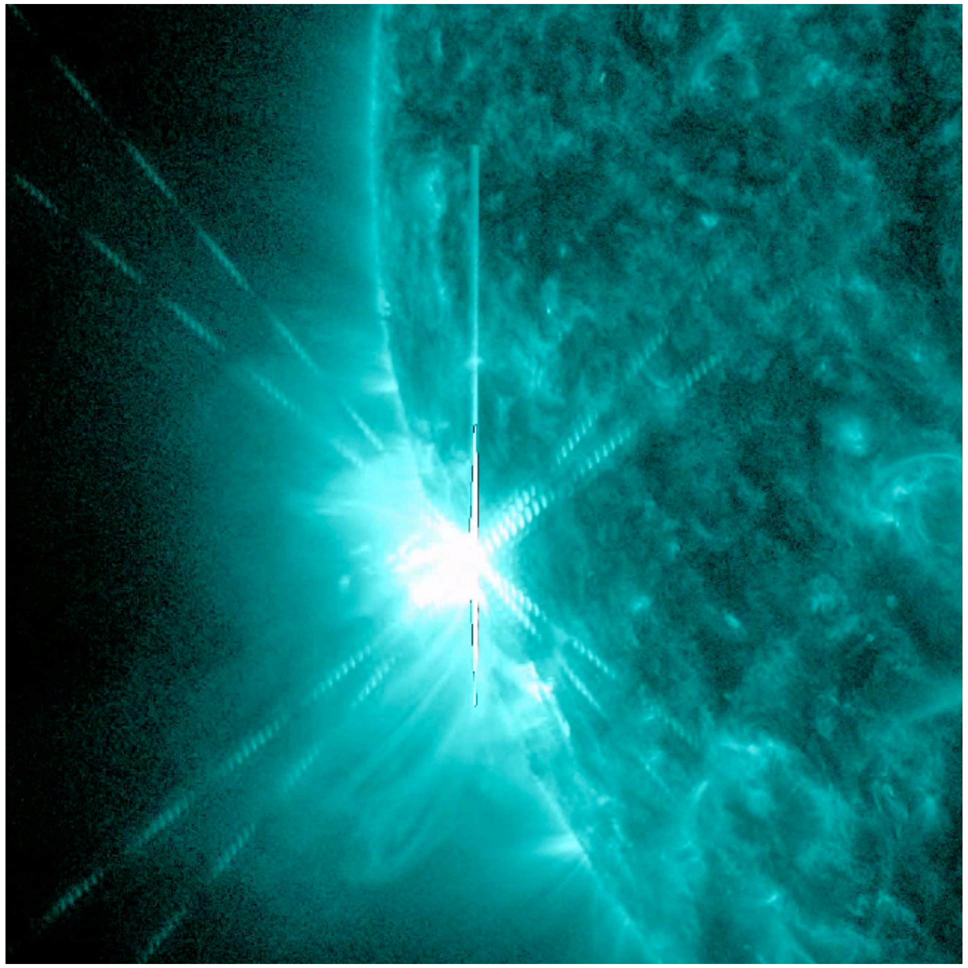
Magnetic Reconnection & Associated Particle Acceleration



Where does reconnection occur?

- Planetary magnetosphere, solar flares
- Active galactic nuclei (AGN), Gamma-ray bursts (GRBs), Pulsar wind nebulae (PWNs)



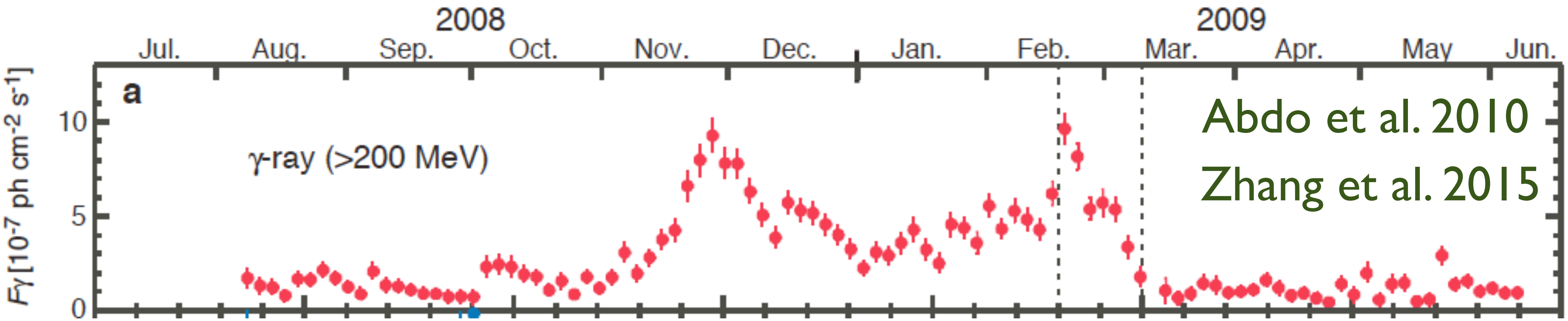
Particle Acceleration: Hints from solar flares

- Power-law distribution
- A large fraction of electrons are accelerated

$N_{nonthermal} > N_{thermal}$ (e.g., Krucker et al. 2010)

This is not well understood.

Extreme Acceleration/Radiation in AGNs, GRBs, and PWNe

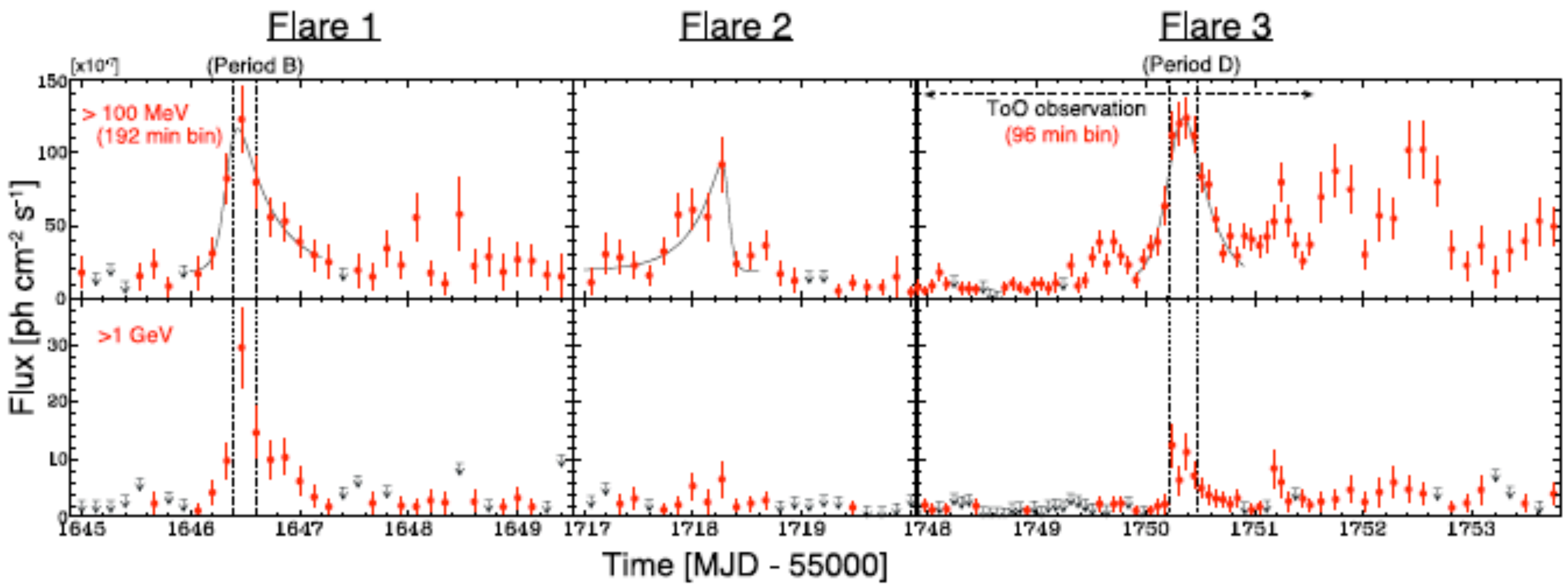


Abdo et al. 2010

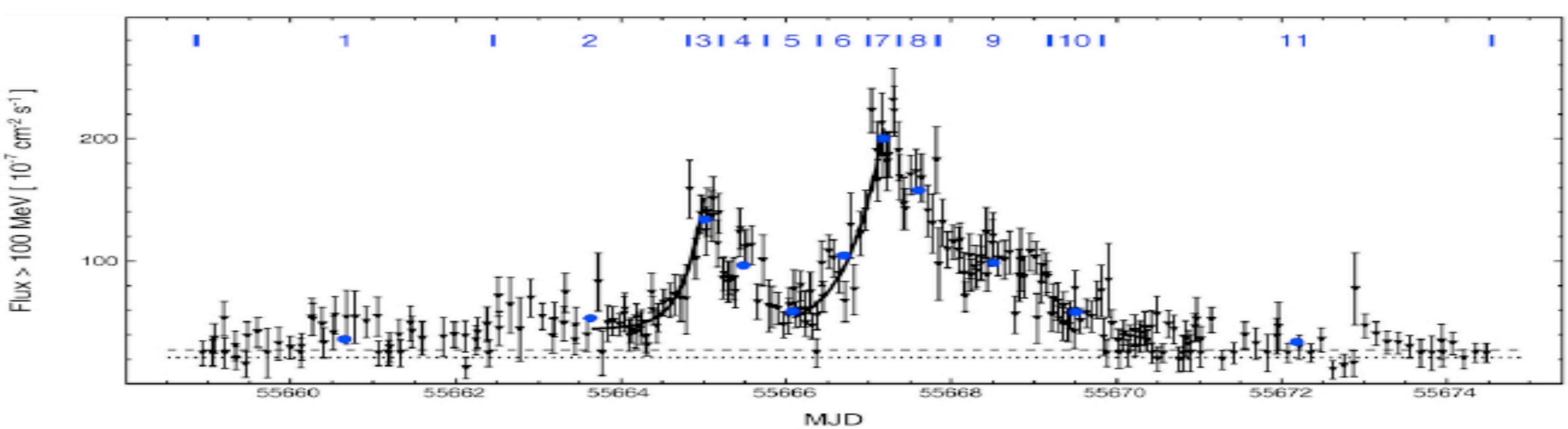
Zhang et al. 2015

Polarization reveals active participation of magnetic field

See talk by Haocheng Zhang in Session 11A

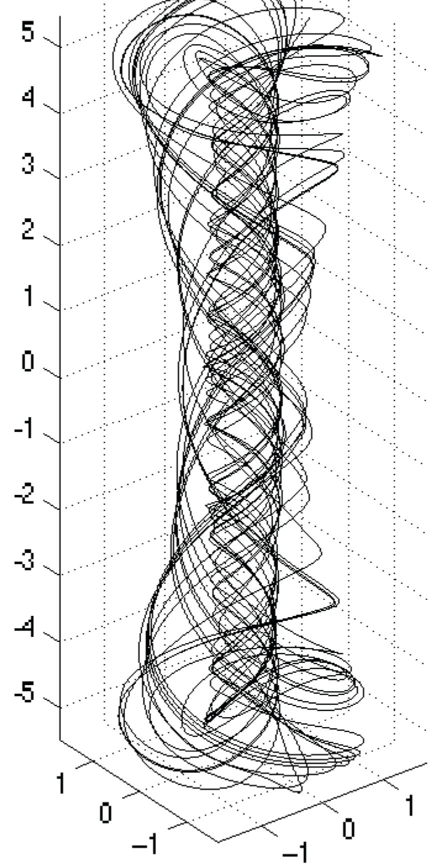


Hayashida et al. 2015

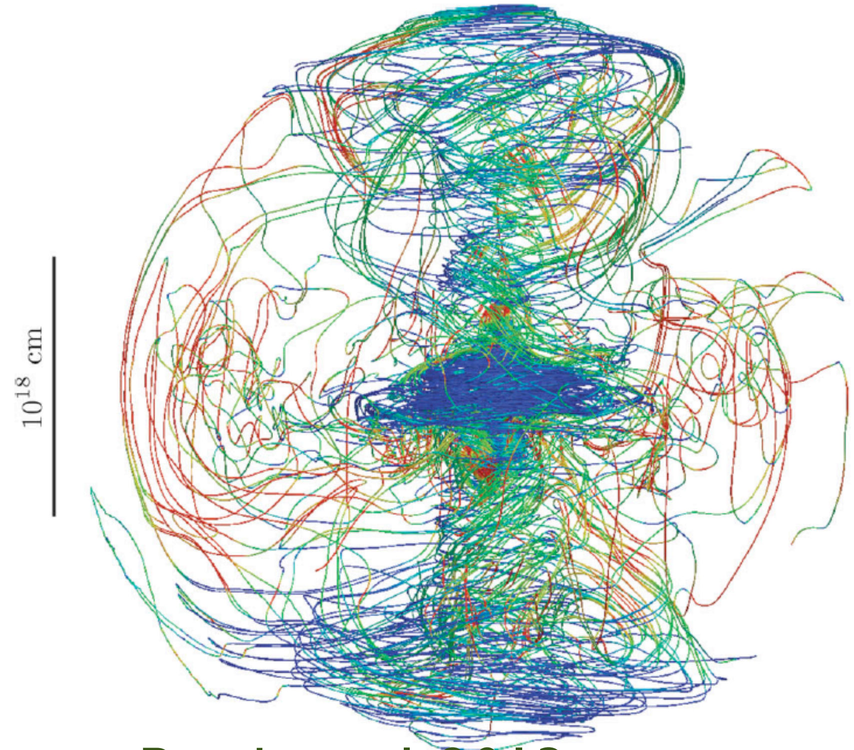


Abdo et al. 2011

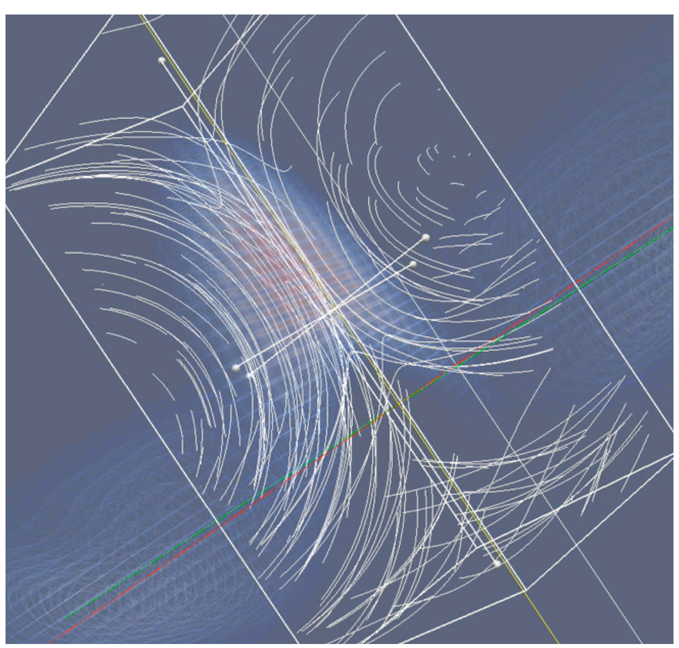
Tavani et al. 2011



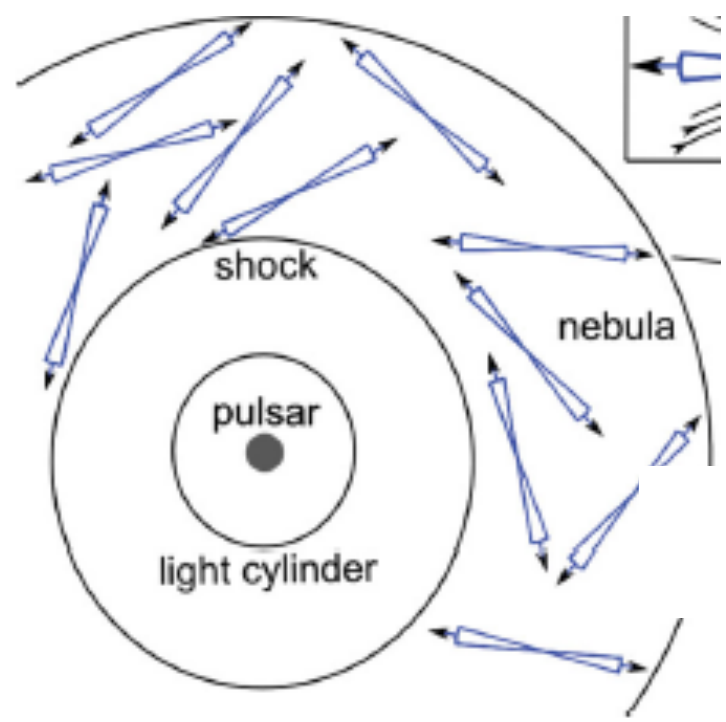
Large-scale field reversal
Lynden-Bell et al. 96
Li et al. 06



Porth et al. 2013

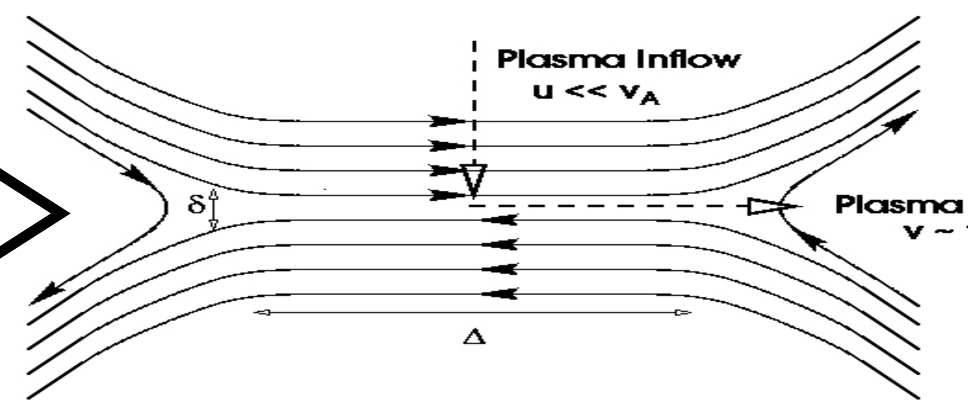


Blob collision
Deng et al. 2015



Clausen-Brown & Lyutikov

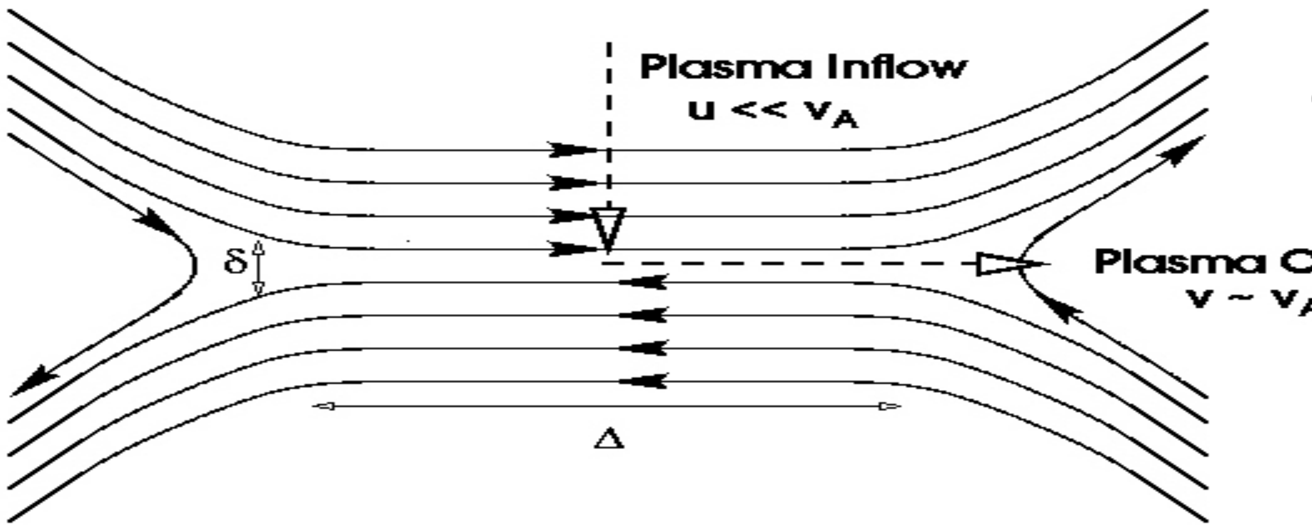
A general local geometry: current sheets

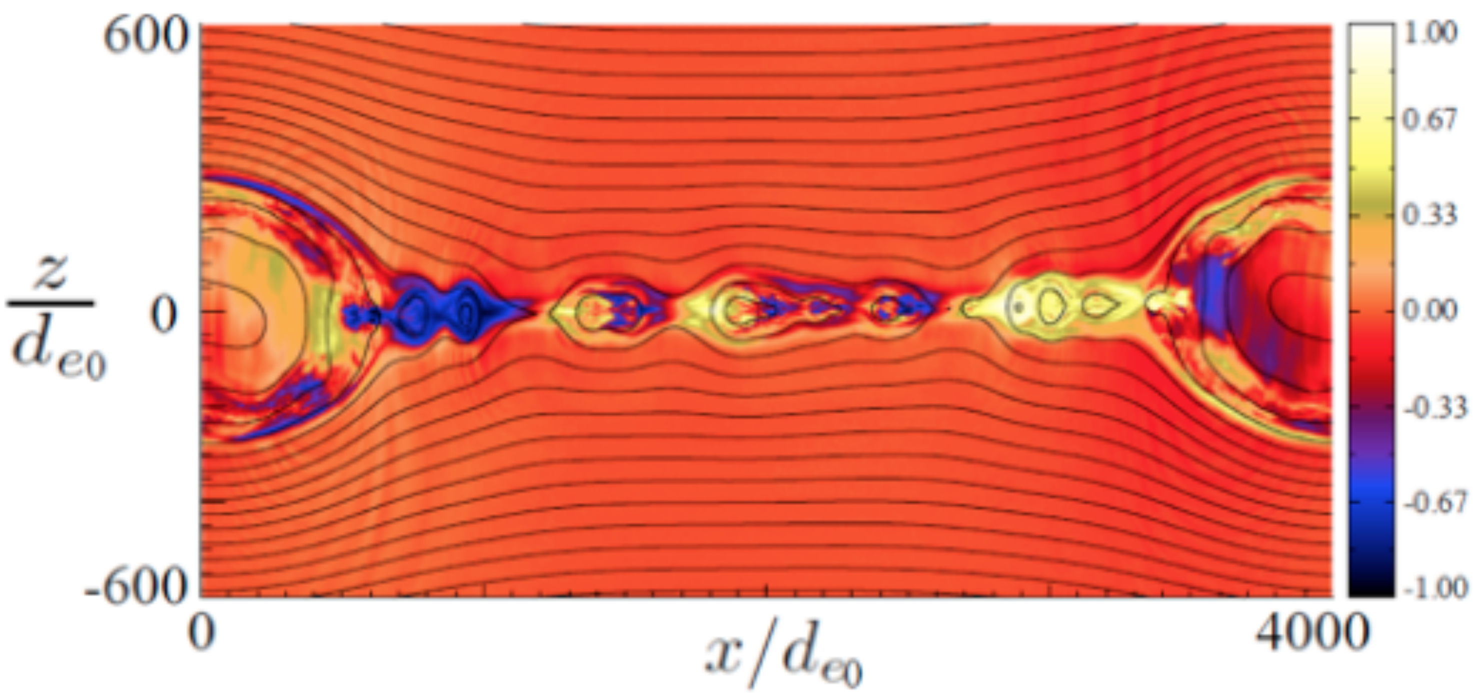


$$\sigma = \frac{B^2}{4\pi n m c^2} \gg 1$$

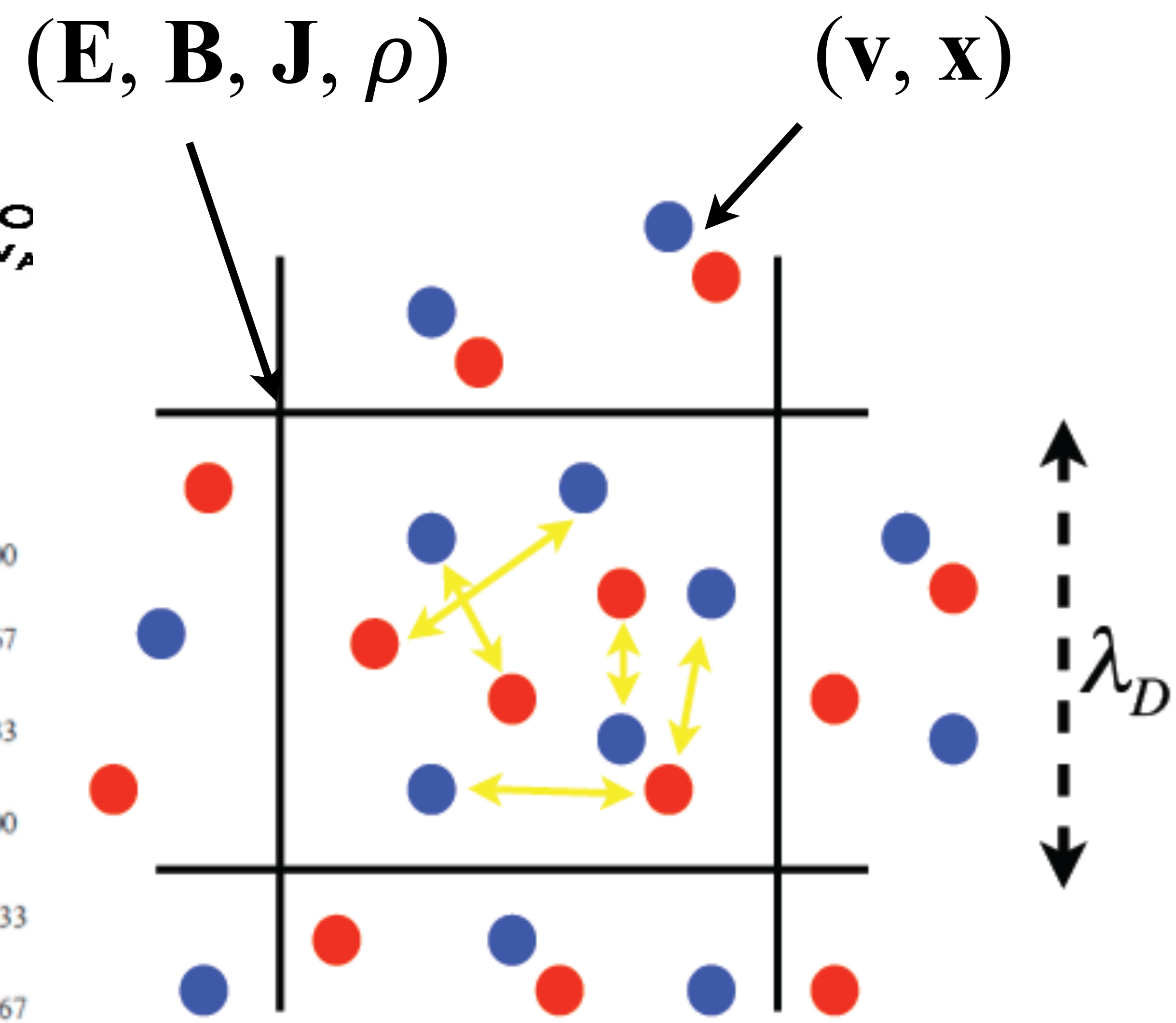
$$v_A \sim c$$

Focusing on a local reconnection site with σ>>1





Particle-in-Cell simulation



GF et al. 2014 PRL, 2015a ApJ (pair, particle acc.)
2015b arxiv 1511.01434 (ion-electron, particle acc.)
Liu, GF, Daughton, Li, Hesse 2015 PRL (fast outflow/dissipation)
Li, GF, Li et al. 2015 ApJL - nonrelativistic reconnection

Focusing on a local reconnection site with σ>>1
Key results:

- Efficient particle acceleration and formation of power laws dN/d$\gamma = \gamma^{-p}$, and extending to $\gamma_i = \sigma,\ \gamma_e = (m_i/m_e)\sigma$
- Main Acceleration mechanism: first-order relativistic Fermi process
- Power-law model and formation condition (τ_{acc} < τ_{inj}).
- Properties of relativistic magnetic reconnection:
  Relativistic inflow and outflow
  Reconnection rate is enhanced because of relativistic effect
  2D & 3D rates are similar

GF et al. 2014 PRL, 2015a ApJ (pair, particle acc.)
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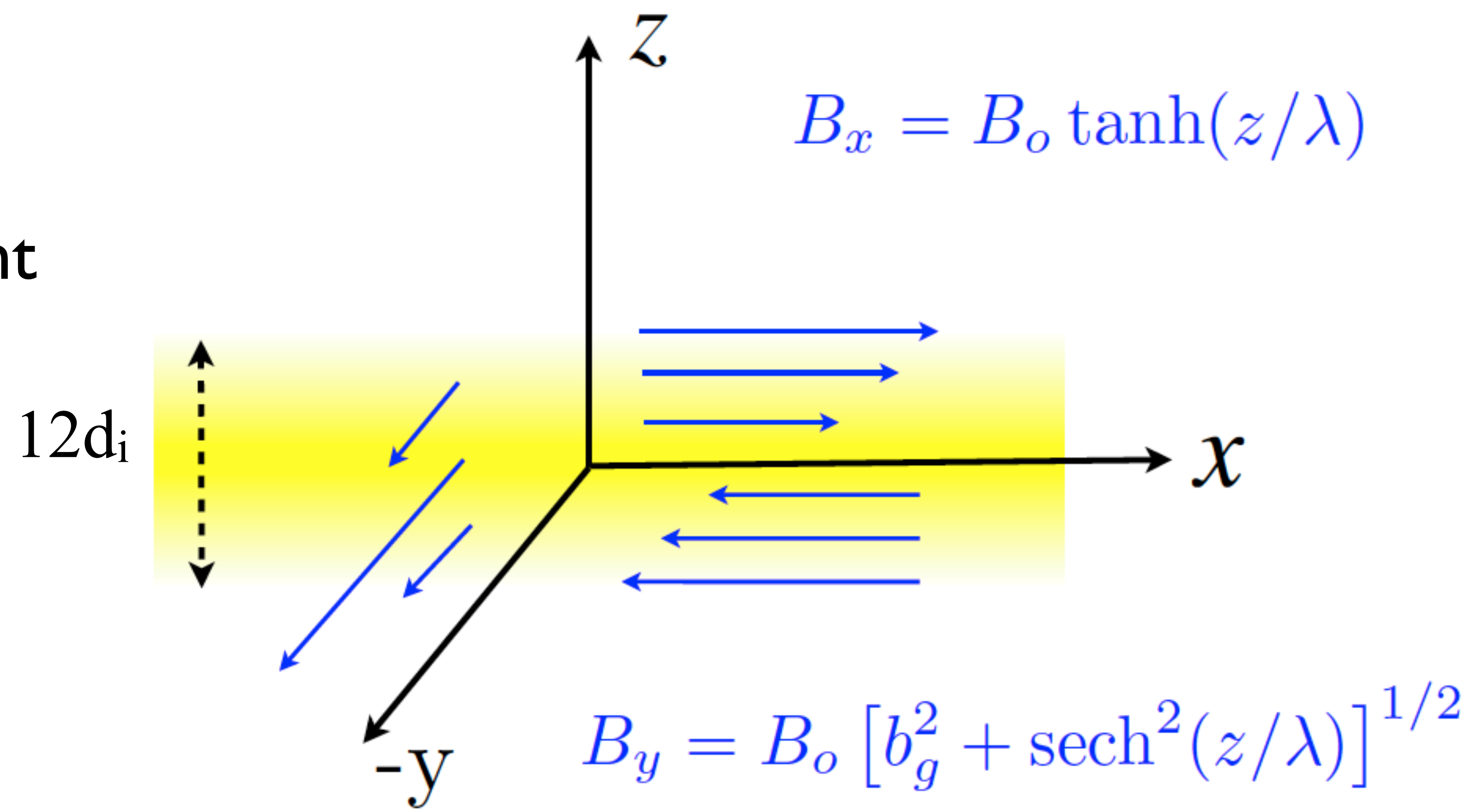
Initial Setup & Parameters

- Force-free current sheet

- Magnetic energy dominant initially $E_B >> E_k$

- Pair plasma ($m_i/m_e = 1$)
- Proton-electron plasma (m_i/m_e up to 1836)



2D: σ = 1-1600

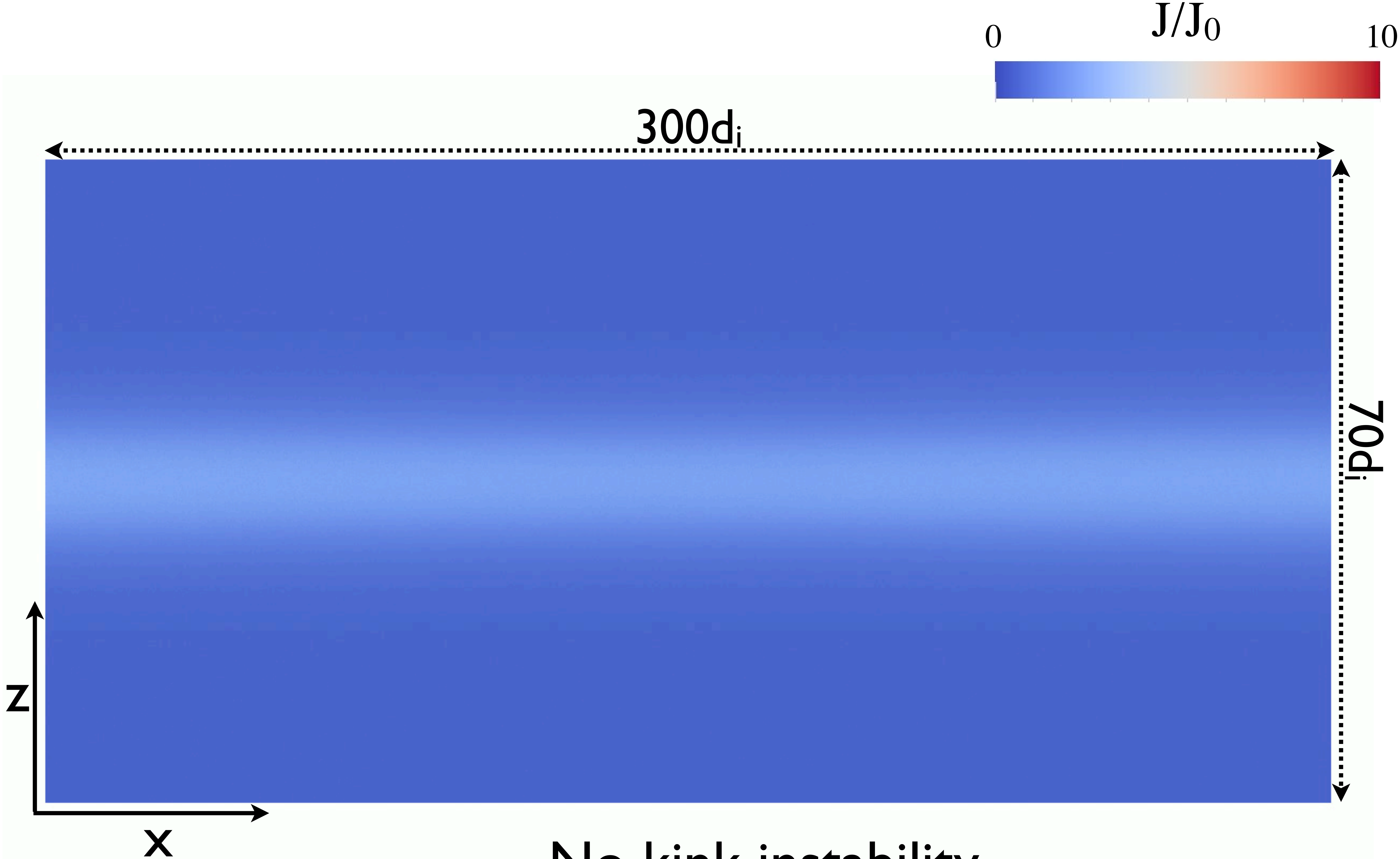
Boundary conditions: mainly periodic currently exploring open boundary cases

3D: σ up to 100

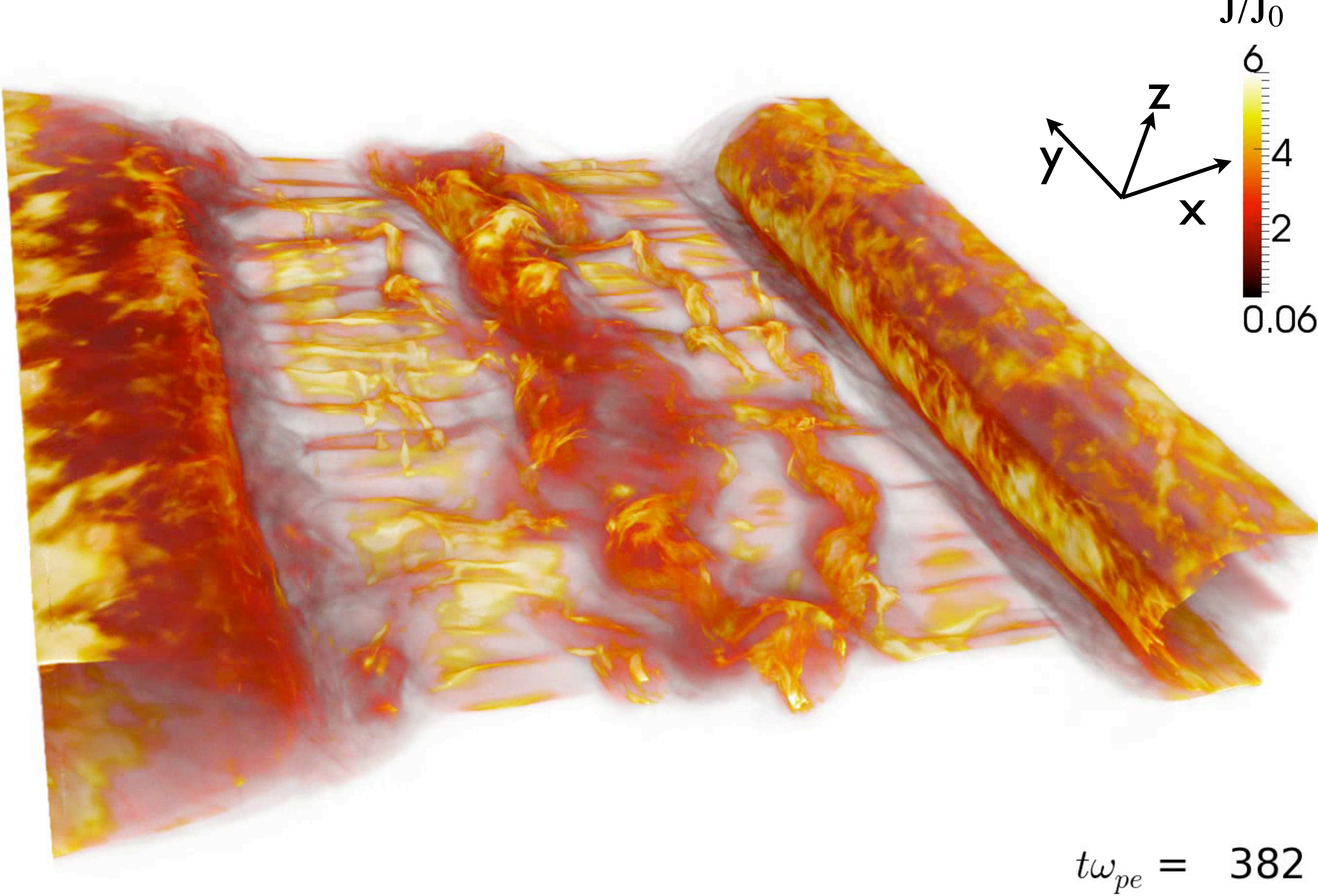
$$L_x \times L_z \times L_y = 300d_i \times 194d_i \times 300d_i$$

~1.4 trillion particles and 2048^3 grids, using 10^5 CPU-cores on Blue Waters

2D current density (σ=100, m_i/m_e = 1) $\omega_{pe}t$=0 - 700



No kink instability



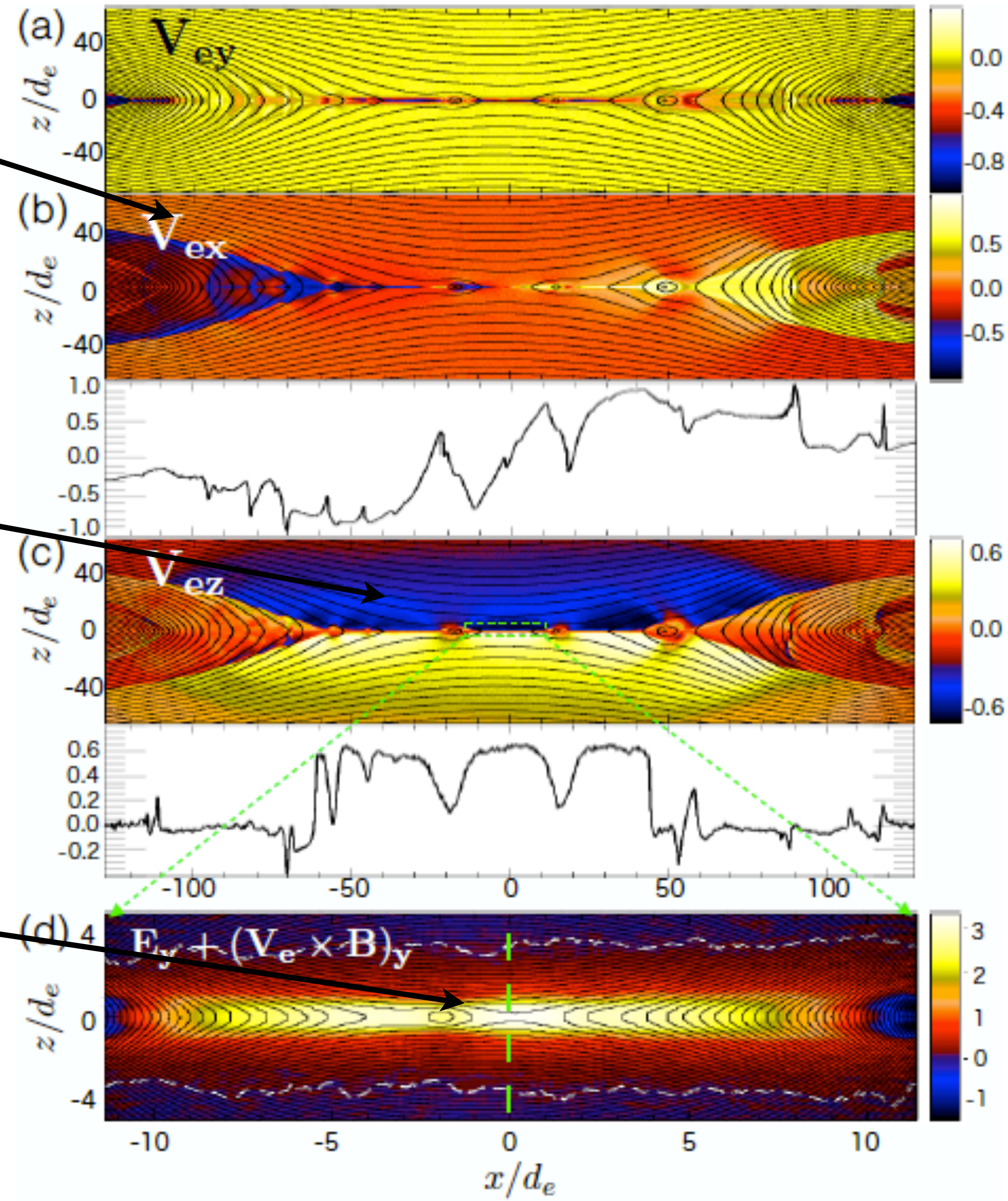
J/J0
6
4
2
0.06
z
y
x
$t\omega_{pe}$ = 382

Plasma flows associated with reconnection

Relativistic outflow speed

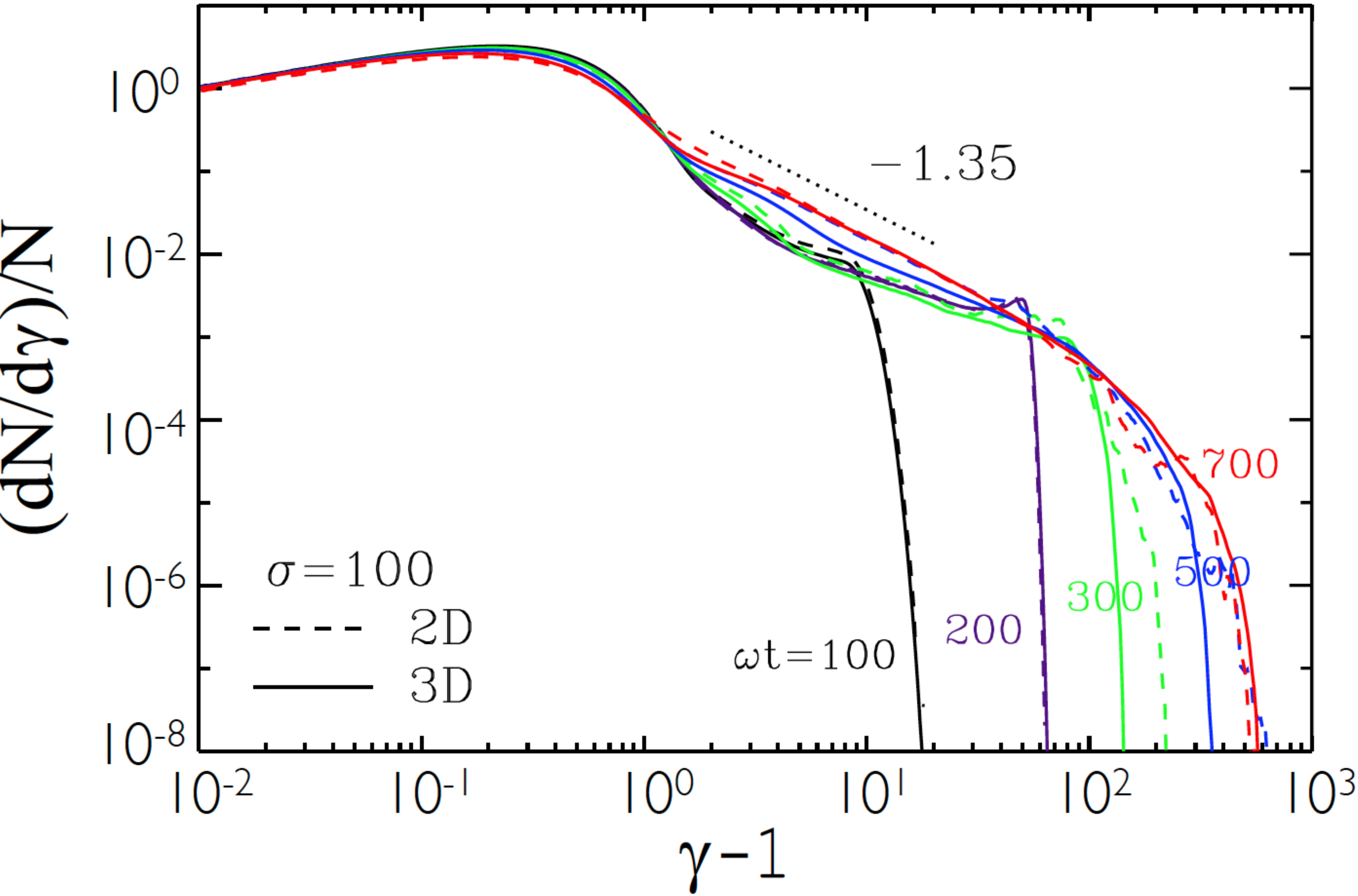
enhanced inflow speed

current structure aspect ratio ~ 0.1

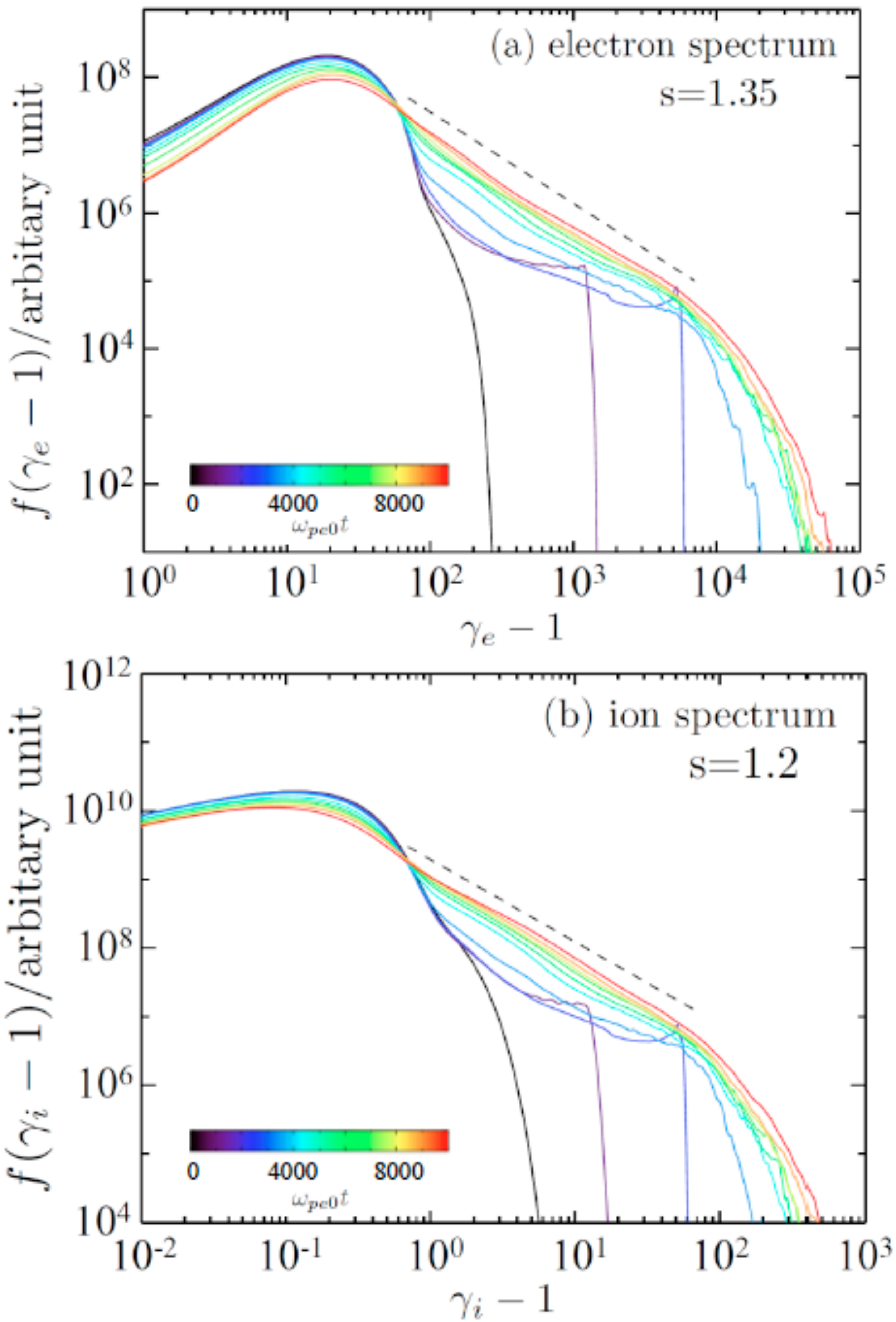


(Liu, Y., GF et al. 14 PRL, Guo et al. 2015)

Energy spectra from 2D and 3D PIC simulations



A relativistic run with σ = 100, mi/me=100



Spectral index s ~ 1

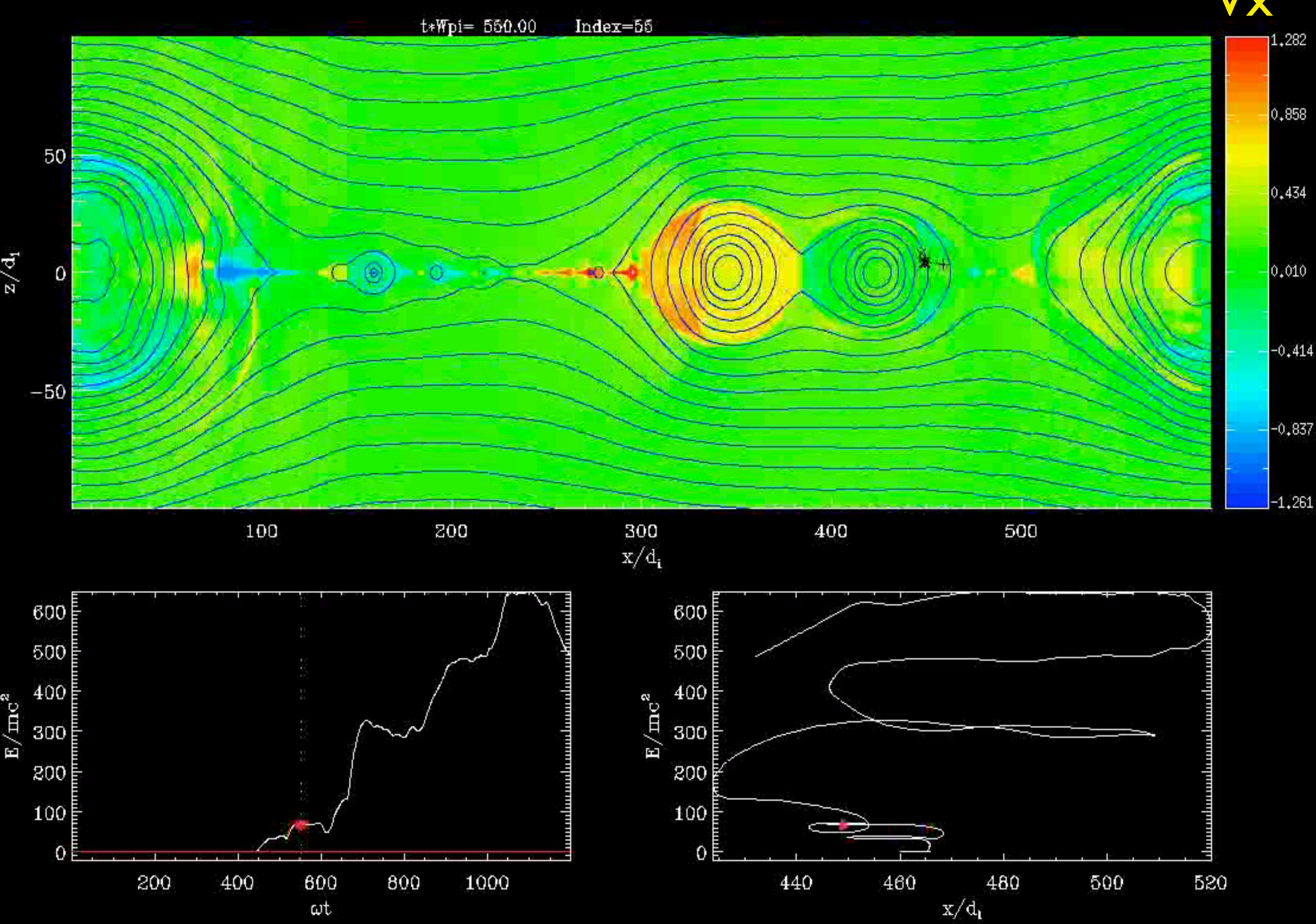
Fast variability ~ Lx/c

$$\gamma_i = \sigma, \ \gamma_e = (m_i/m_e)\sigma$$

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

slopes are identical in momentum space

Fermi Acceleration Pattern



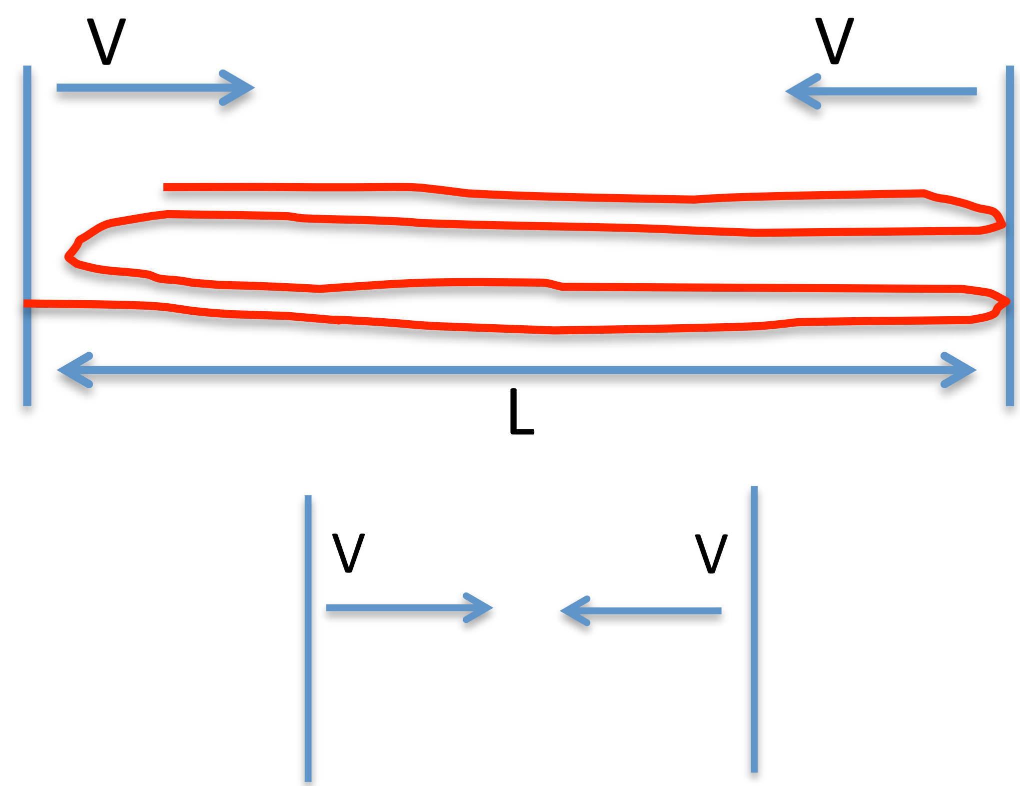
1st order Fermi mechanism

- Acceleration by "collision" in between moving magnetic clouds (Fermi 1949)

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

$$\Delta t = L_{is}/v_x$$

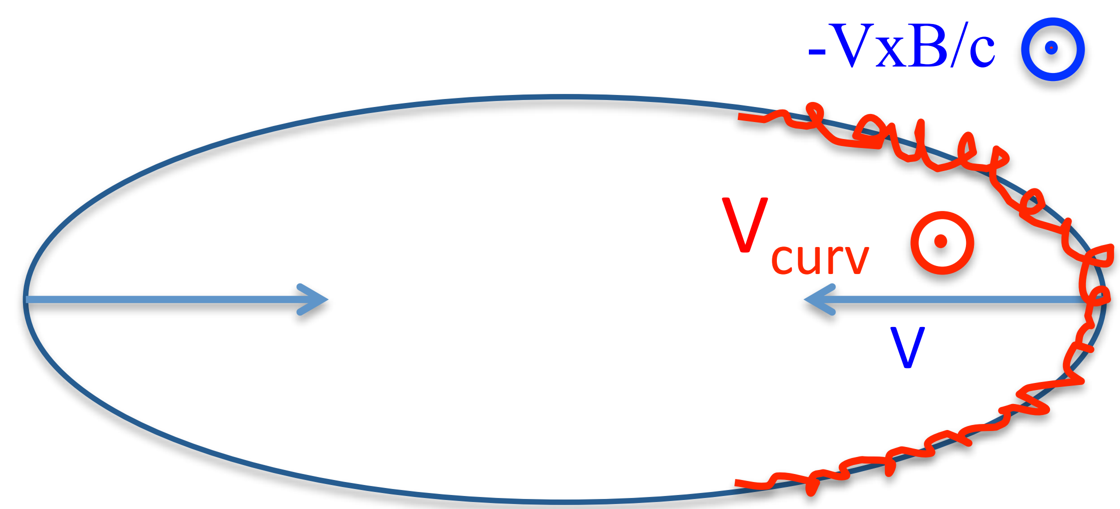
$$\alpha = \Delta\gamma/(\gamma\Delta t)$$



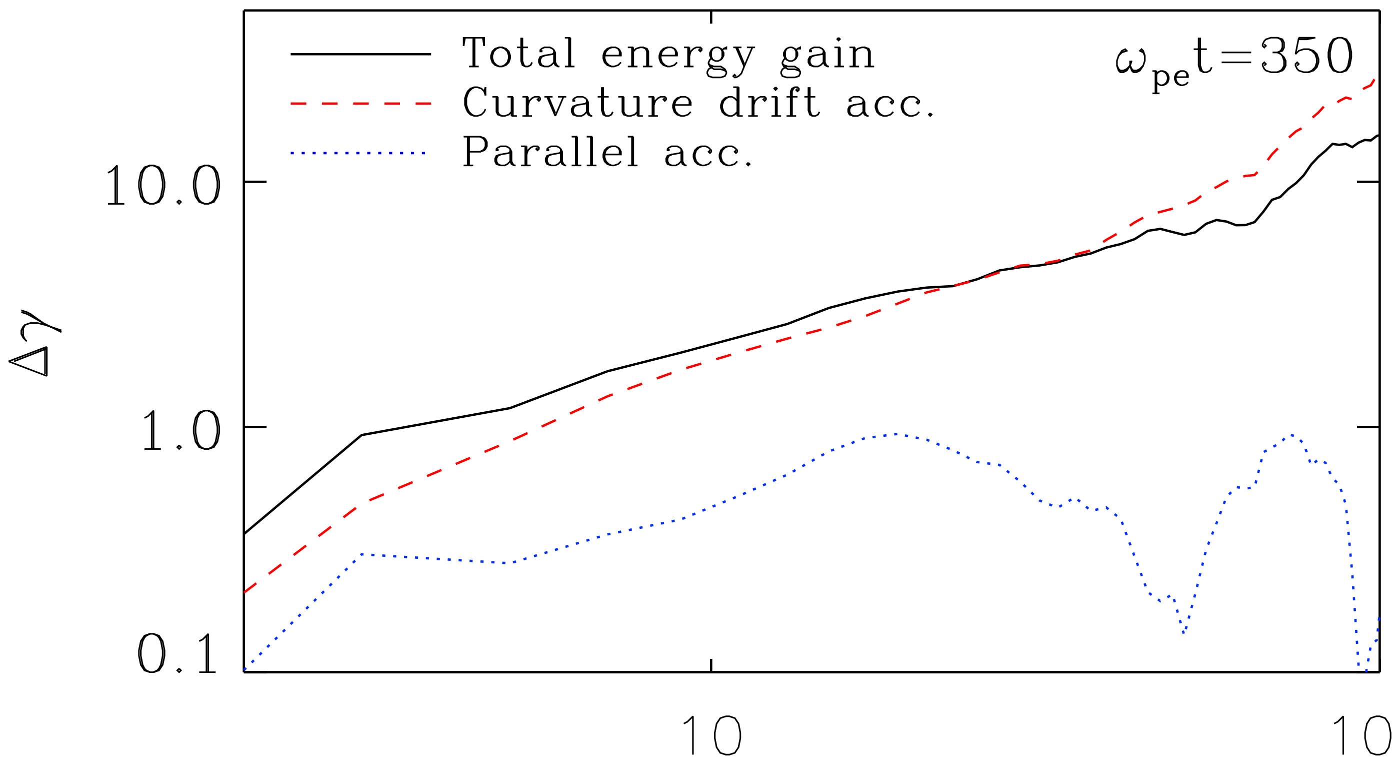
- In large-scale simulations, the dominant electric field for energy release

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

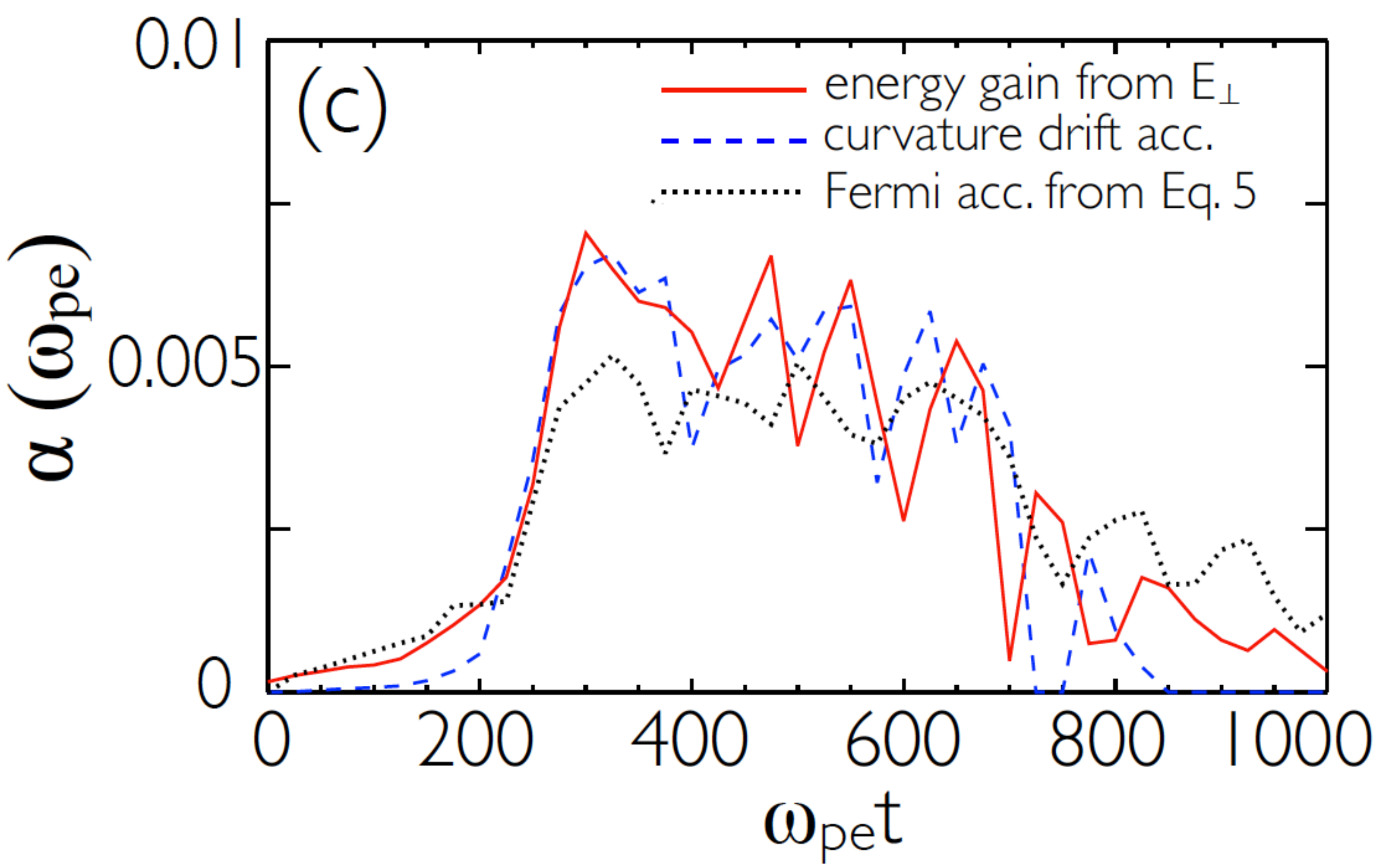
- In reconnection region, the Fermi process is accomplished by curvature drift motion in plasmoids along the motional electric field.



Type-B Fermi process (Fermi 1949)
Drake et al. 2006, 2010; Birn et al. 2012
Guo et al. 2014



The acceleration is dominated by energy gain through curvature drift motion



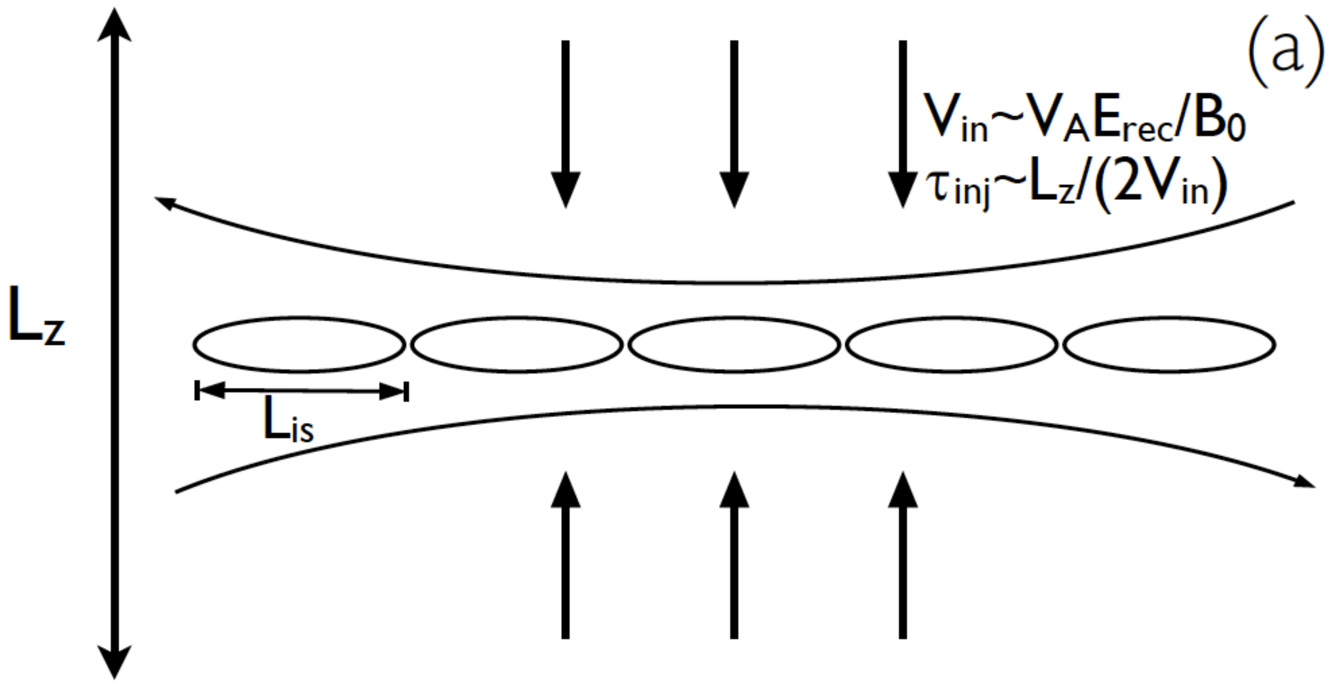
Fermi acceleration formula agrees with the acceleration by curvature drift motion.

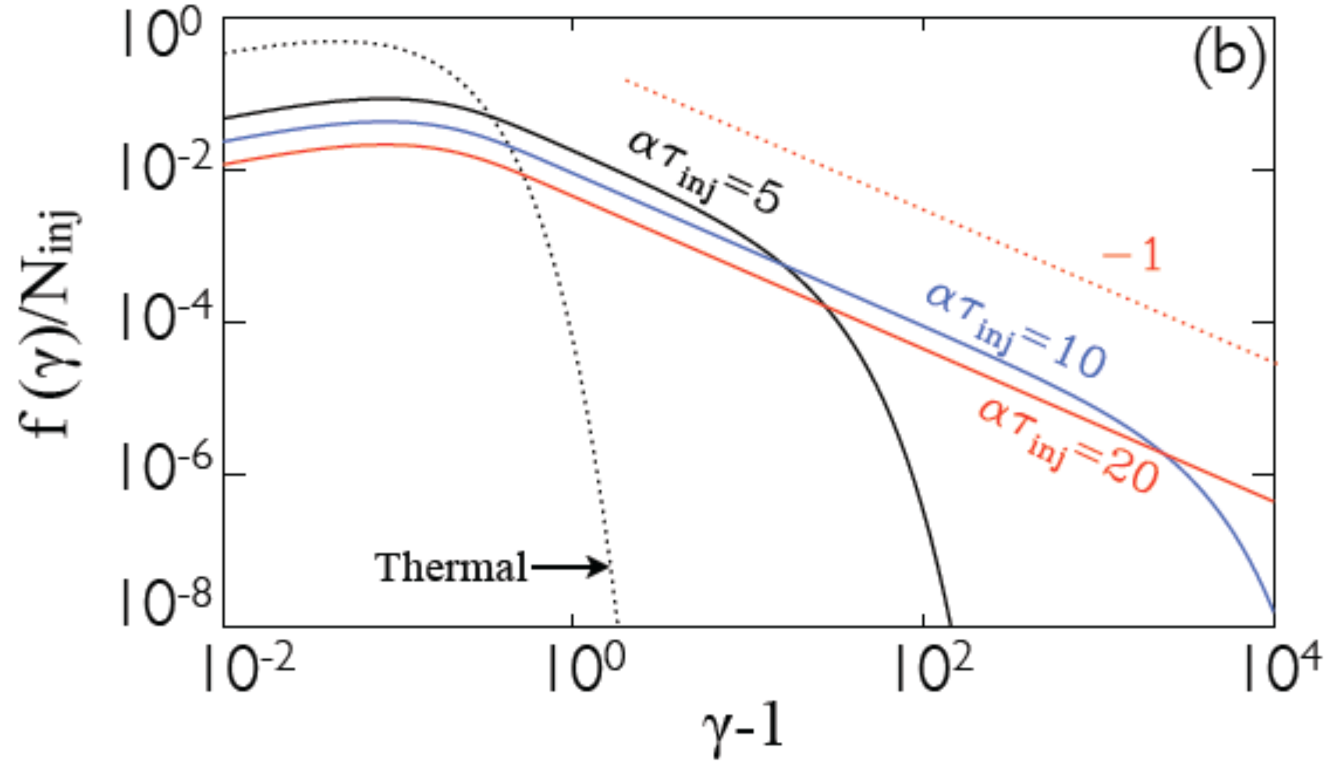
$$\Delta\gamma = \left(\Gamma^2(1+\frac{2Vv_x}{c^2}+\frac{V^2}{c^2})-1\right)\gamma$$

$$\Delta t = L_x/v_x$$

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

Power-law formation





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

Two parts in the final solution:

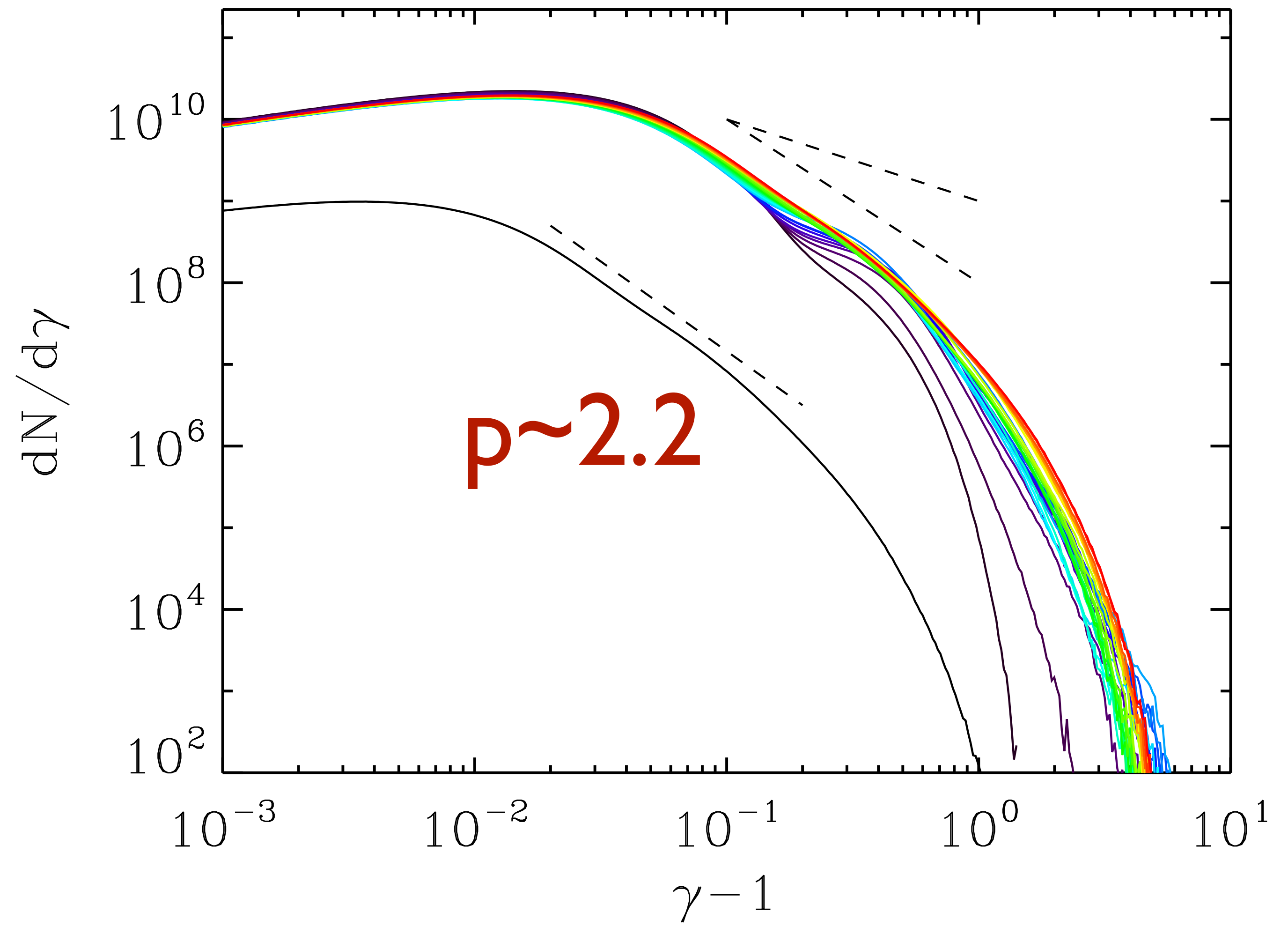
1) Particles initially in the current layer: heated thermal distribution

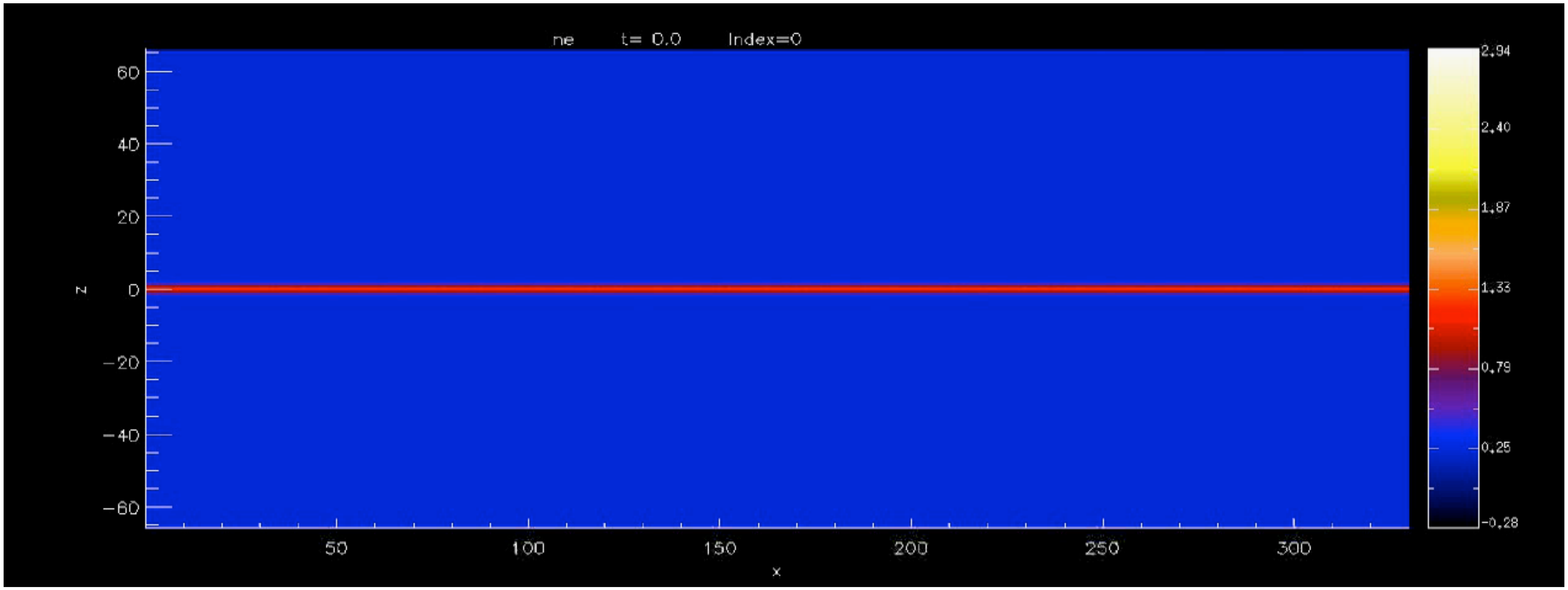
2) Particles injected from upstream: power-law distribution

This explains a number of previous simulation results.

Both periodic (closed) and open boundary systems give spectral index p~1 for high-σ case.

Open boundary simulations with sigma=0.25





The property of relativistic reconnection ($\sigma >> 1$)

- Efficient nonthermal particle acceleration and formation of hard power laws.
- Relativistic inflow and outflow Γ up to 10.
- Reconnection rate is enhanced (locally R~1).
- 2D & 3D are similar. Why?
- Effect of boundary conditions: Periodic, Open, Line-tied...
- What's the implication to large-scale system (AGN, GRB, PWN, etc.)