Dissipation Mechanism in 3D Collisionless Magnetic Reconnection

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Outline

- Introduction

  -- Importance of reconnection, Multi-scale nature

- Dissipation Mechanism in Magnetic Reconnection, comparing 2D and 3D reconnections

  -- Results from particle-in-cell simulations

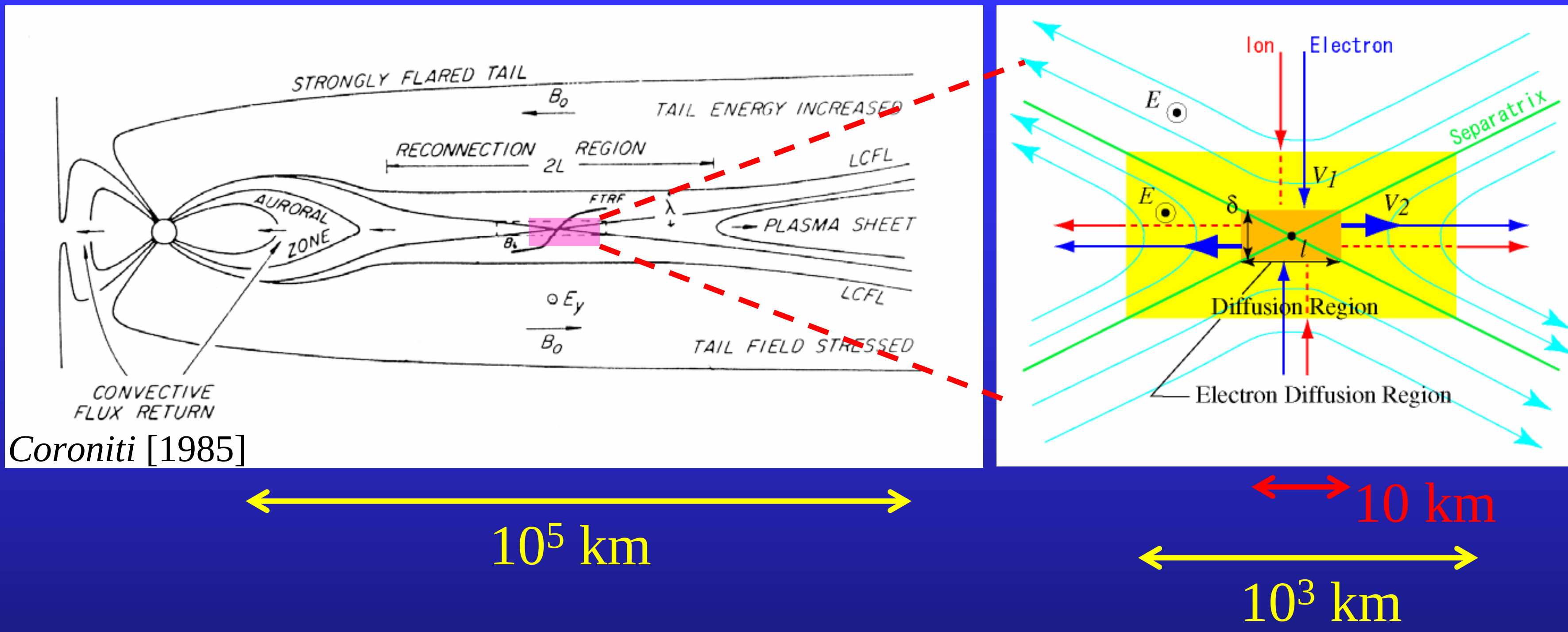
- Summary & Conclusions

Introduction

-- Why is reconnection important?

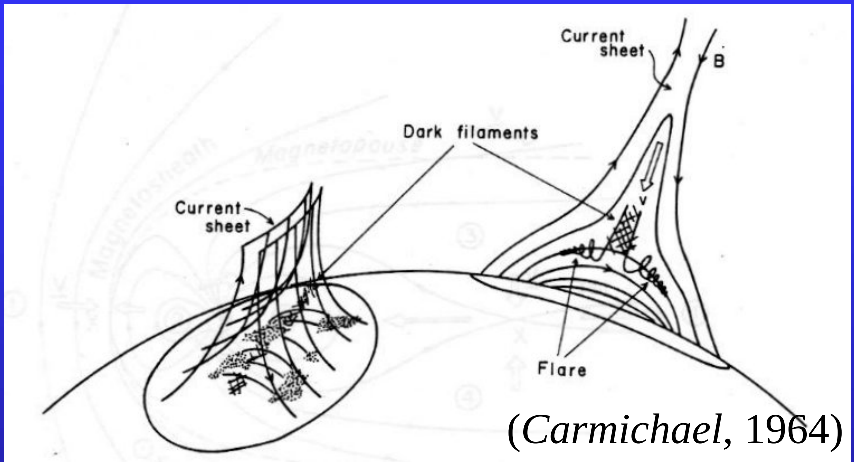
-- Why do we need to study the dissipation mechanism?

Reconnection (in the Earth Magnetosphere)

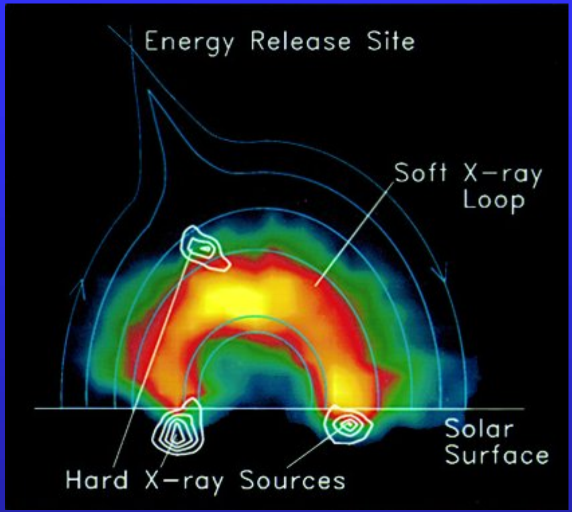


- Can induce global-scale convection causing change in the field line topology,
- Is inherently multi-scale process.

Reconnection (in Solar Flares)



(*Carmichael*, 1964)



(NASA)

- Leads to rapid energy release,
- Strongly accelerates the electrons and protons.

Why is the dissipation mechanism important?

Our goal is to understand macroscopic dynamics in a variety of systems.

Diffusion equation: $$\frac{\partial \vec{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \vec{B}$$

η: Electric resistivity → Macroscopic parameter resulting from microscopic (kinetic) processes

We need to know the **microscopic physics** to model the **macroscopic dynamics**.

In the MHD framework…

The reconnection rate depends on the resistivity model.

(Biskamp,1986; Ugai, 1995)

Global responses in substorm and flares are sensitive to the parameterization of the resistivity.

(Raeder et al.,2001; Kuznetsova et al., 2007)

Dissipation Mechanism in Magnetic Reconnection, comparing 2D and 3D reconnections

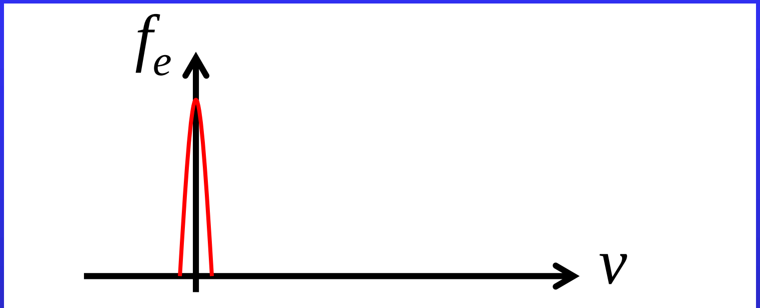
-- Results from particle-in-cell simulations

How is the resistivity generated?

The motion of charged particles supporting the current must be disturbed by "collision".

Collision with other particles

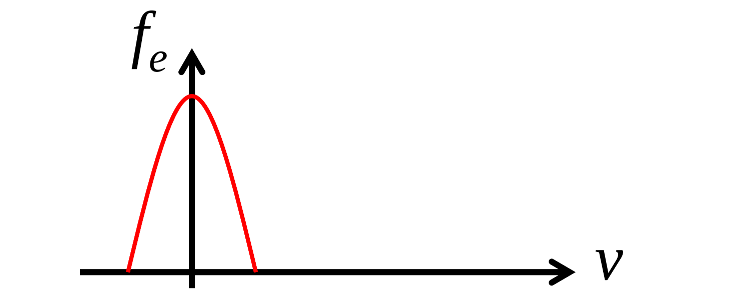
$$\eta = \frac{m_e \nu_c}{n_e e^2}, \qquad \nu_c = \frac{1}{\tau_c}$$



➢ ***How does the "collision" occur in collisionless plasmas?***
= How does the momentum transport occur?

Inertia resistivity

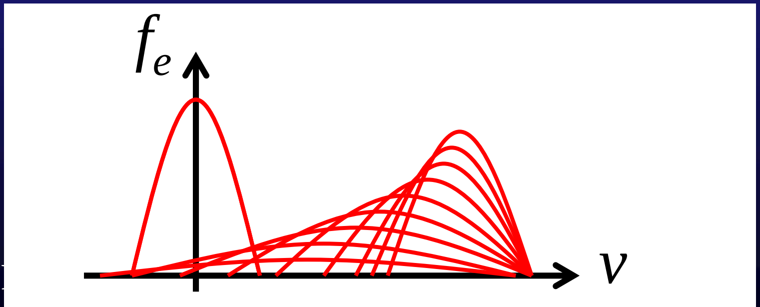
$$\eta = \frac{m_e \nu_T}{n_e e^2}, \qquad \nu_T = \frac{1}{\tau_T} \sim \frac{V}{L}$$



Anomalous resistivity
(Wave-particle interaction)

$$\eta = \frac{m_e \nu_w}{n_e e^2}, \qquad \nu_w \approx \frac{R_e^{an}}{n_e m_e V_e}$$

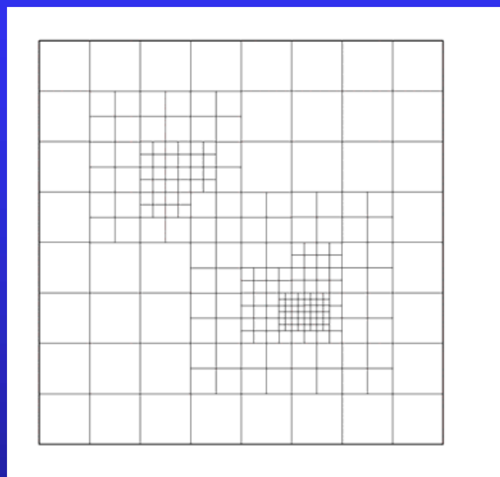
$$R_e^{an} = -e \left(\left\langle \delta n_e \delta \vec{E} \right\rangle + \left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle \right)$$

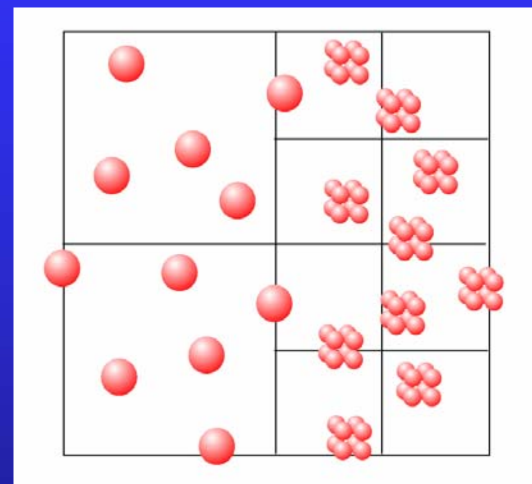


Simulation Model

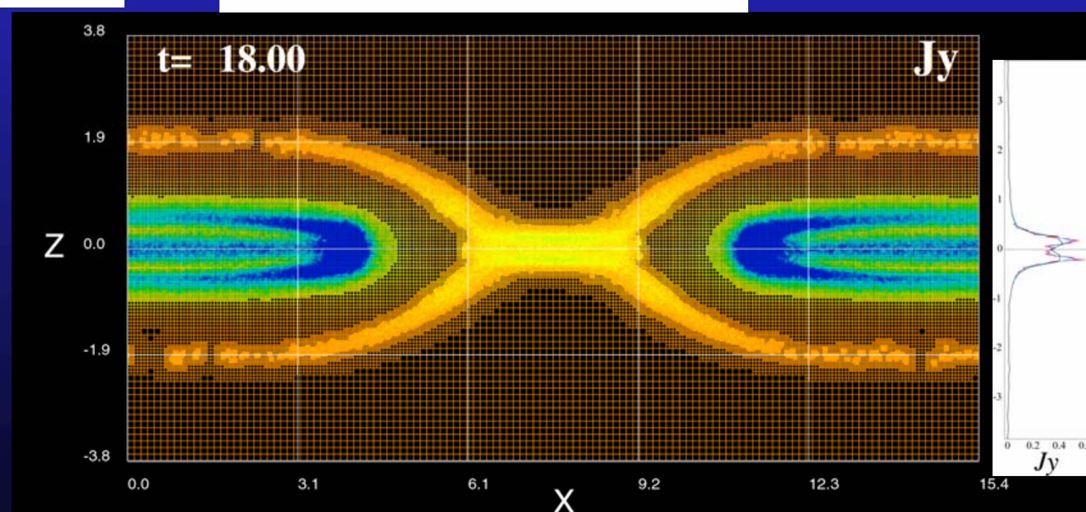
PIC + Adaptive Mesh Refinement (AMR)

[Fujimoto & Machida, 2006; Fujimoto & Sydora, 2008]

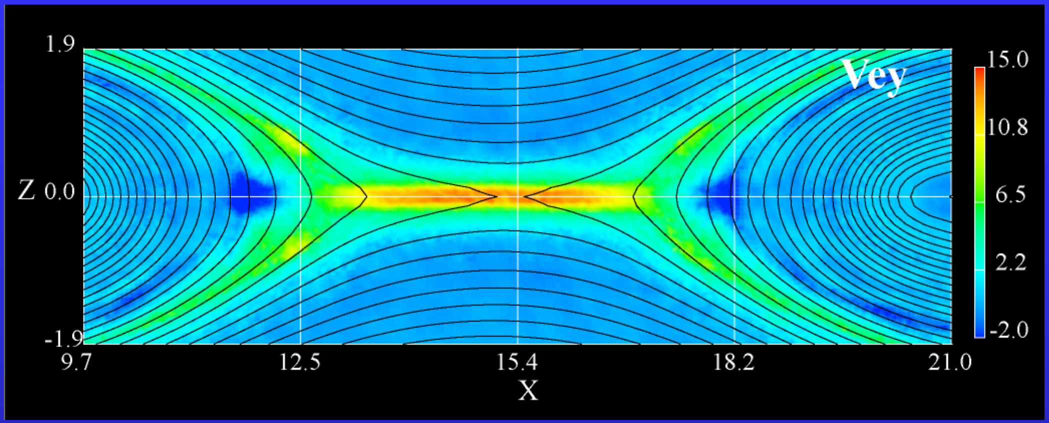


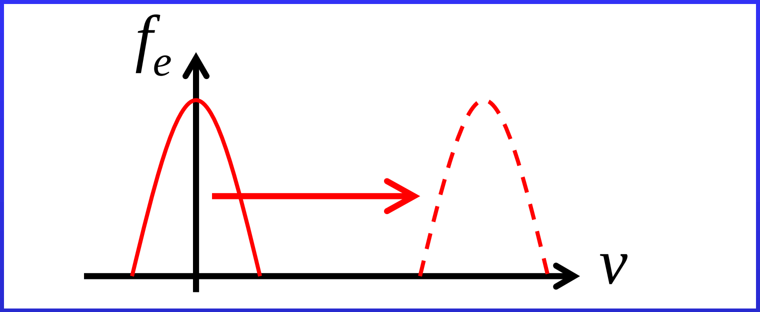


Refinement cells are selectively allocated around the X-line and separatrices.



2D Reconnection

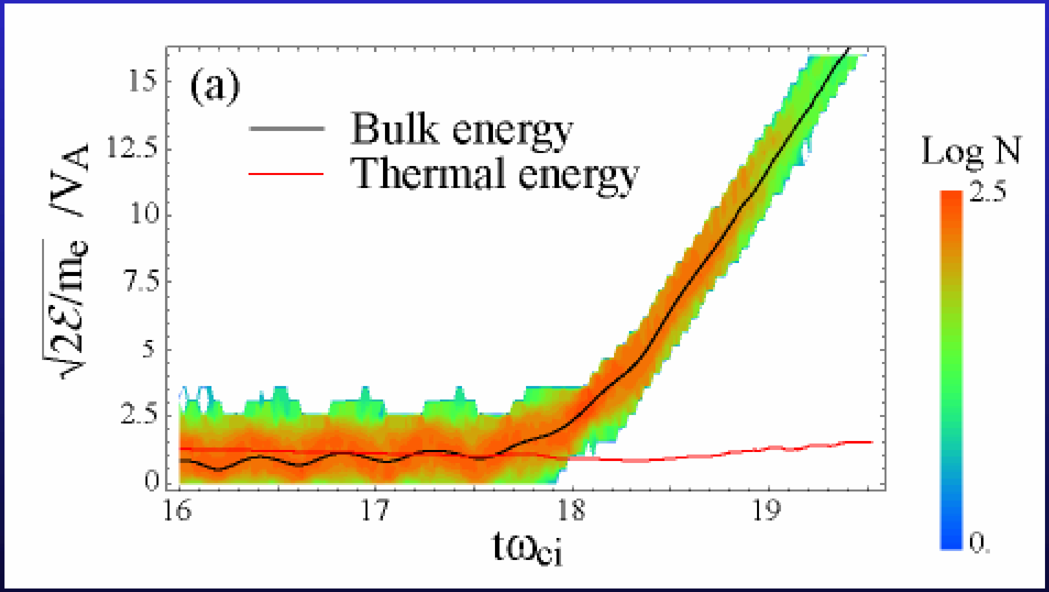




Electrons are…

- Coherently accelerated in the diffusion region,
- Not thermalized.

➡ Inertia resistivity



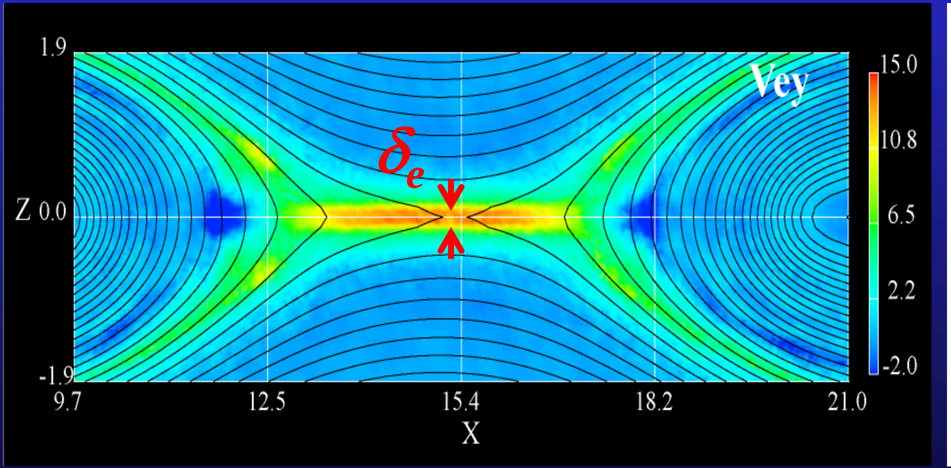
Electron Inertia Resistivity

[Speiser, 1970; Tanaka, 1995; Fujimoto & Sydora, 2009]

$$\eta_{in} = \frac{m_e \nu}{n_e e^2}, \qquad \nu = \frac{1}{\tau_{tr}}$$

$$E_R = \eta_{in} j \approx \frac{m_e}{e} \frac{V_{ey}}{\tau_{tr}}$$

The electrons must be accelerated quickly up to a high velocity.



$$\delta_e \approx \lambda_e \, (= c/\omega_{pe})$$

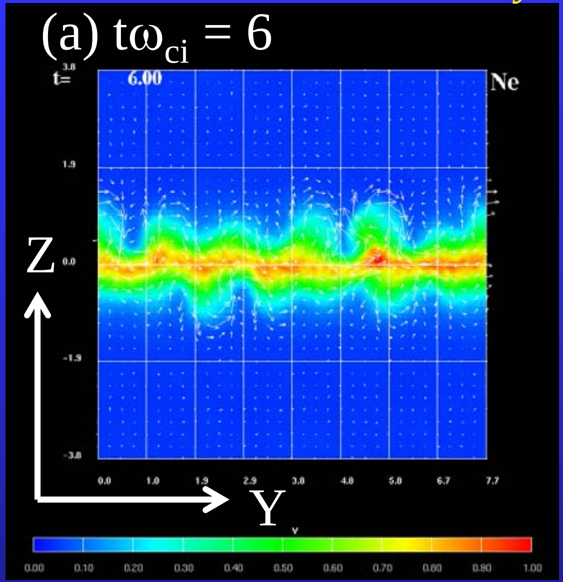
Magnetotail : ~ 10km ($\Leftrightarrow 10^5$km)

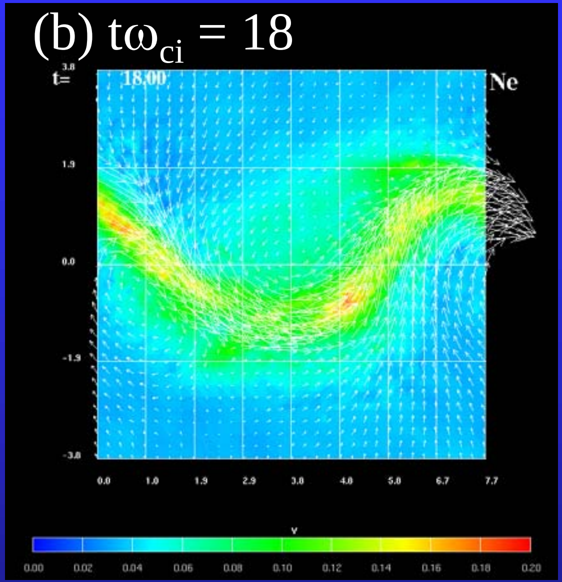
Solar Flare : ~ 10^{-5}km ($\Leftrightarrow 10^4$km)

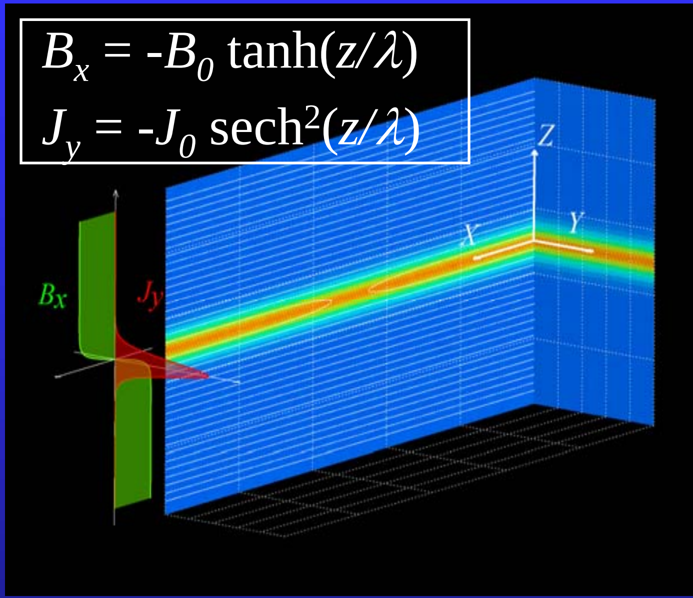
Is such a thin current sheet really stable in 3D system?

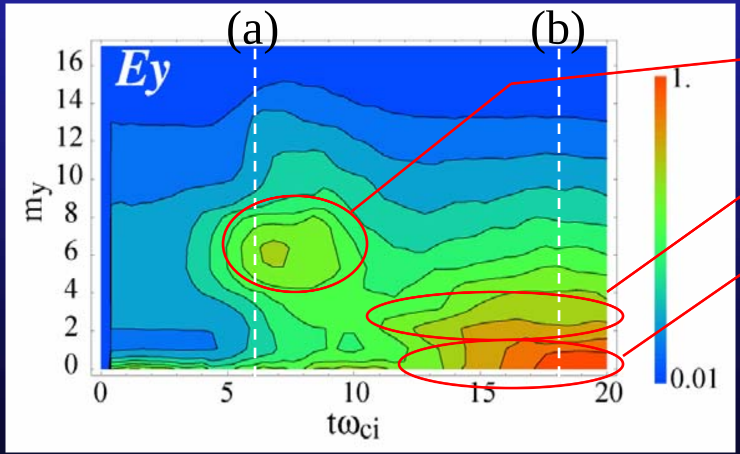
Time Evolution of the Current Sheet in 3D system

$m_i/m_e = 25,\ L_x \times L_y \times L_z = 31 \times 7.7 \times 31$









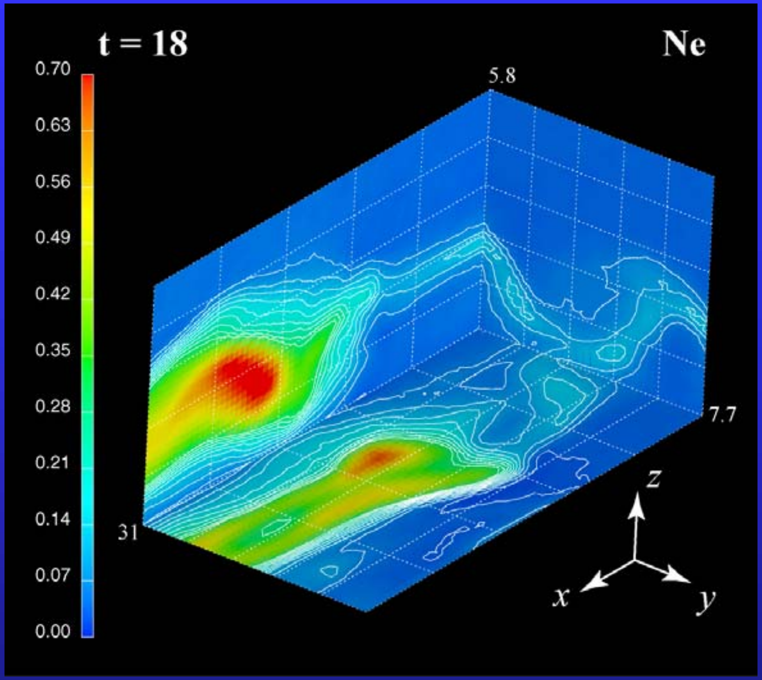
Lower hybrid drift instability (LHDI)

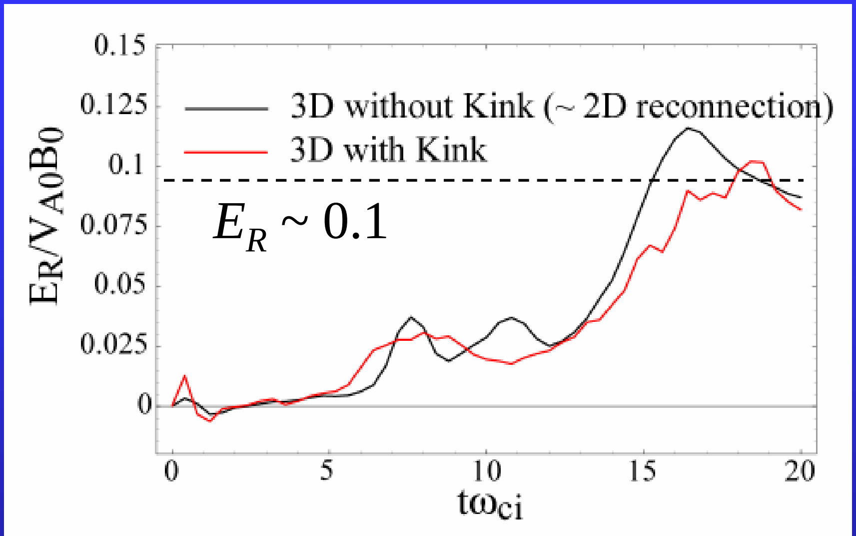
Kink-type instability

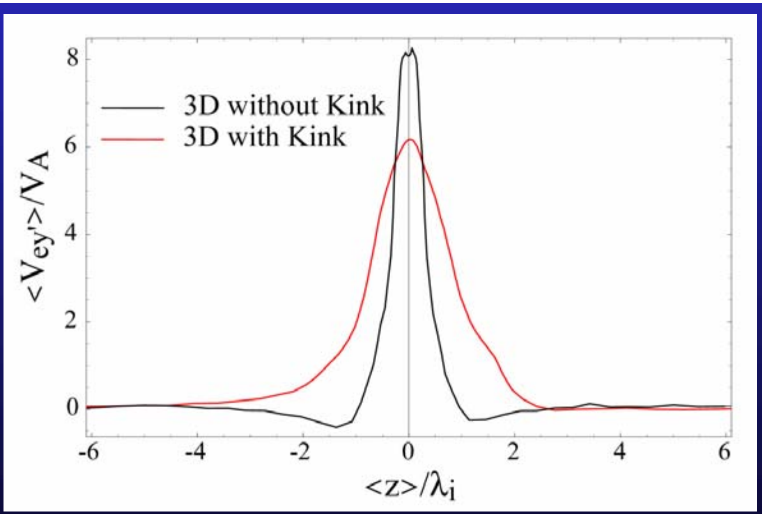
Induction field due to tearing instability

Kink instability coexists with the tearing mode.

Reconnection Rate & Current Sheet Width





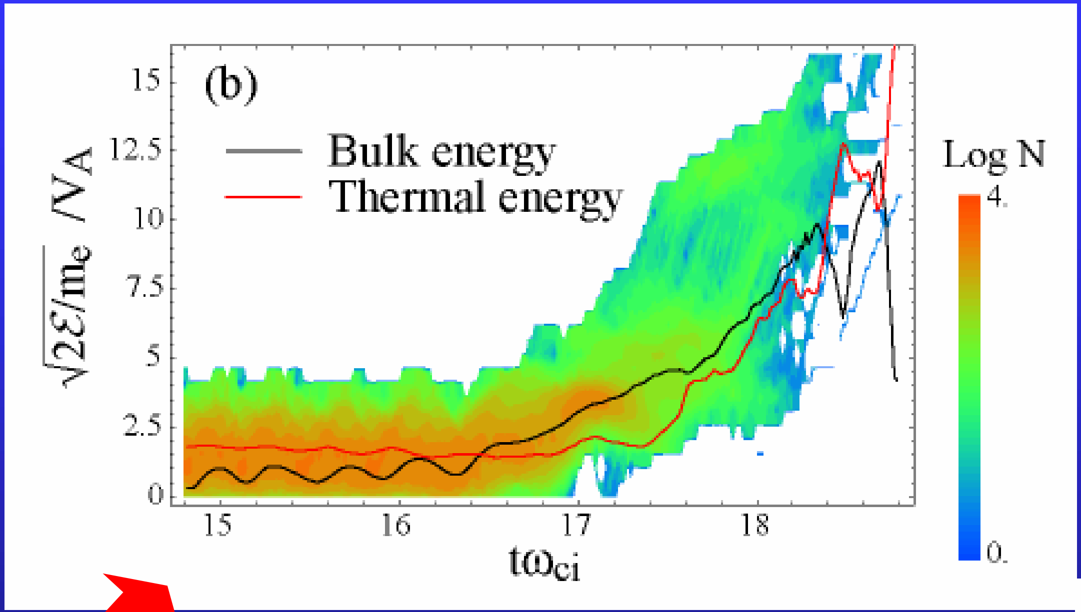


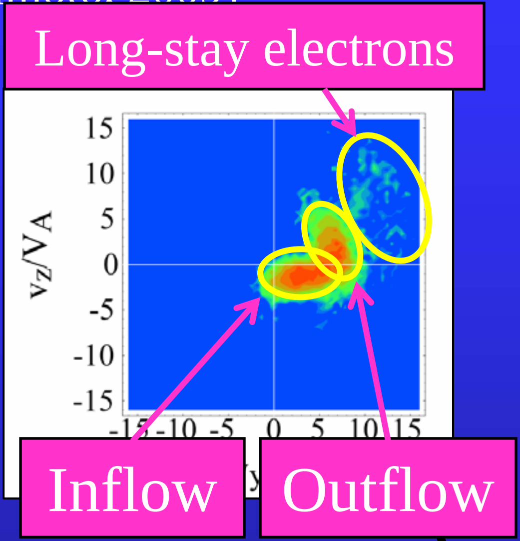
If the inertia resistivity alone supported the dissipation, the E_R would be significantly reduced.

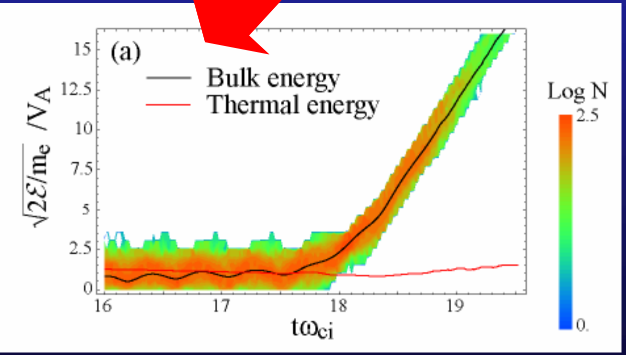
$$\frac{E_{R,kink}}{E_{R,nokink}} \propto \left(\frac{V_{e,kink}}{V_{e,nokink}}\right)^2 \approx 0.56$$

Dissipation Mechanism in 3D Reconnection

[Fujimoto, 2009]

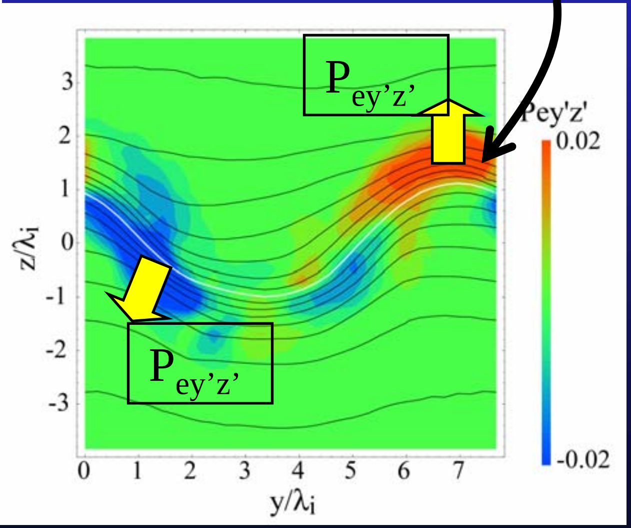




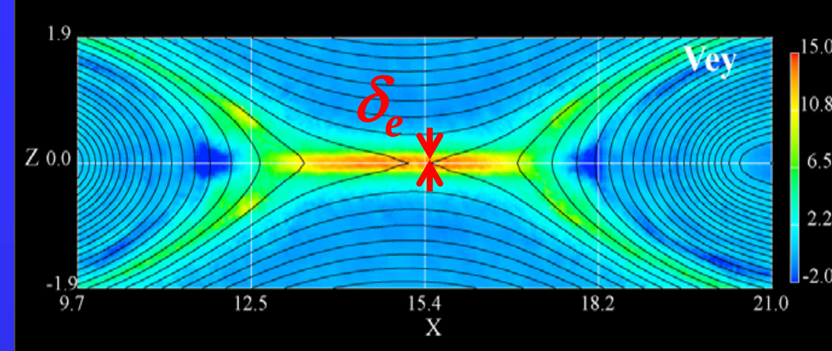


(2D reconnection case)

The electrons are intensely thermalized as well as accelerated in bulk.

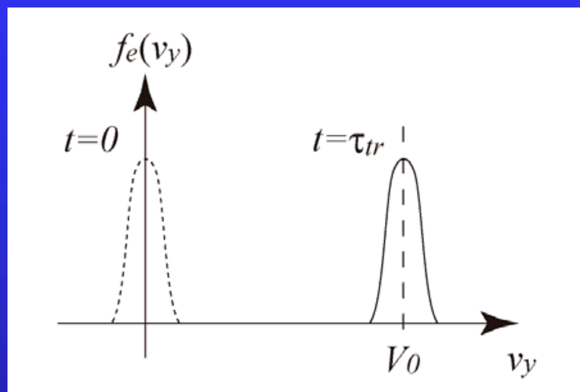


Current Sheet Width (δ_e)



2D case

Inertia resistivity

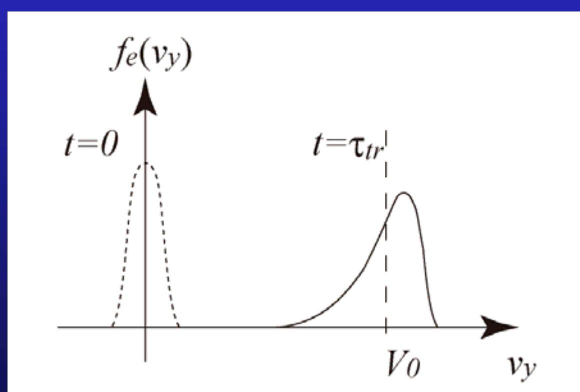


$$\frac{e|E_y|}{m_e}\tau_{tr} = V_0 \qquad \tau_{tr} \sim \frac{\delta_e}{V_{in}}$$

$$\Rightarrow \quad \delta_e \sim c/\omega_{pe}$$

3D case

Inertia + anomalous resistivity



$$\frac{e|E_y|}{m_e}\tau_{tr} > V_0 \qquad \tau_{tr} \sim \frac{\delta_e}{V_{in}}$$

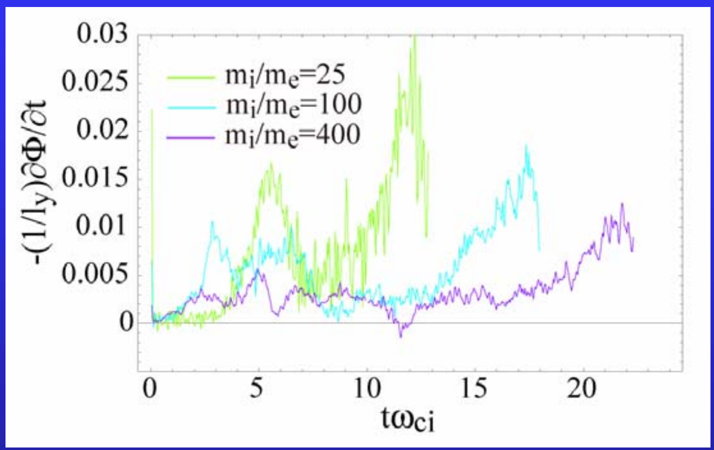
$$\Rightarrow \quad \delta_e > c/\omega_{pe}$$

Broader current sheets have been observed in the Earth magnetotail [*Wygant et al.*, 2005] and laboratory experiment [*Ji et al.*, 2008].

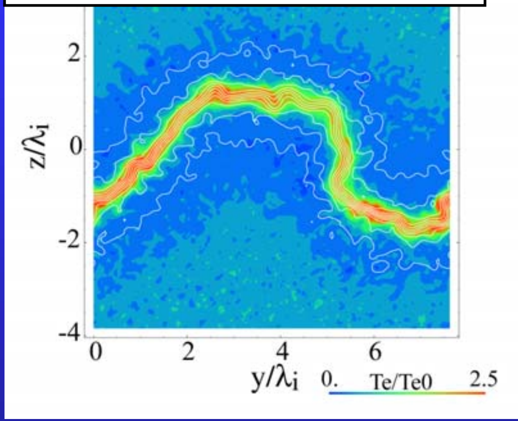
In the Cases with Lager m_i/m_e (> 100)

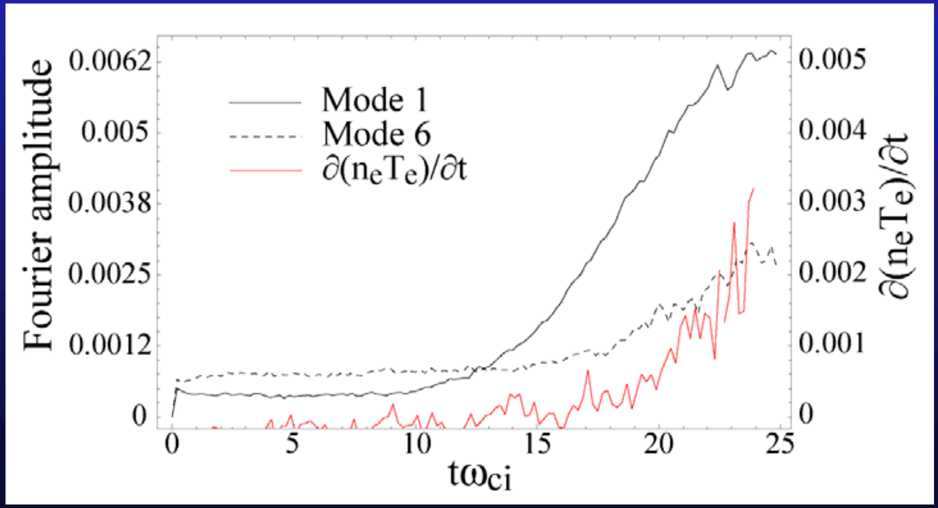
- 2D simulations in the YZ plane

$$y_m \approx 3\pi\lambda_e\left(1 + \frac{3\pi}{2}\frac{\lambda_e}{V_{ey'}\tau}\right)$$



Temparature: m_i/m_e=400





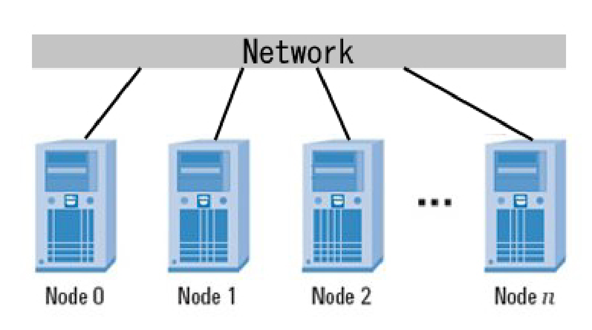
Hybrid-scale kink mode

$\lambda \sim (\lambda_i\lambda_e)^{1/2}$

Electron Heating

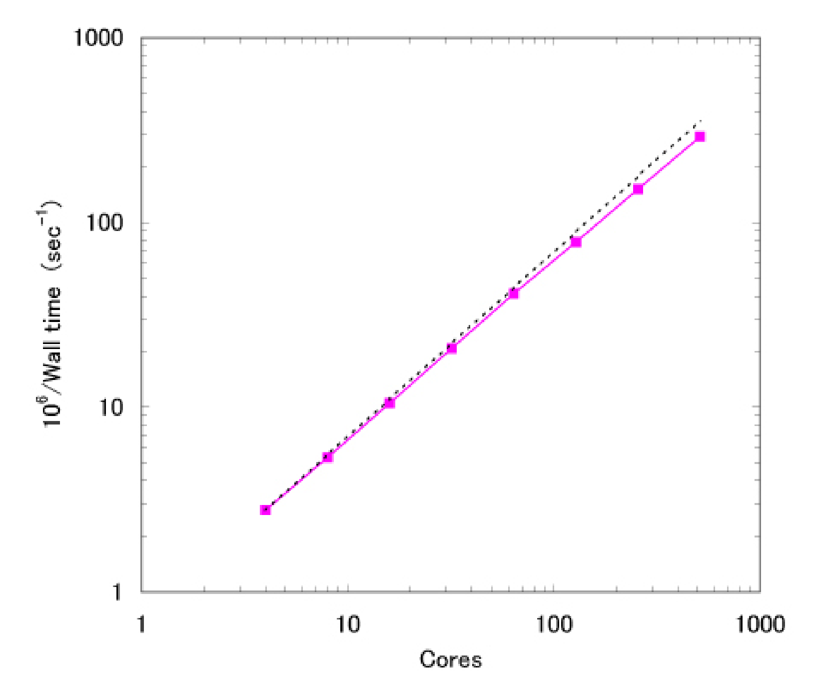
Toward Larger-Scale Simulations with Larger m_i/m_e

Massively parallel computing of 3D AMR-PIC model



Larger computer resources including more memory capacity and CPUs.

The present code has achieved very good scalability.



Summary and Conclusions

The present study has investigated the dissipation mechanism in 3D magnetic reconnection in comparison with 2D reconnection, using a large-scale PIC simulations.

- Reconnection rate

  E_R ~ 0.1 both the cases of 2D and 3D reconnections

- Dissipation mechanism

  2D reconnection → Inertia resistivity

  3D reconnection → Inertia resistivity +
  Anomalous resistivity (Electron heating due to wave-particle interaction)

  → Current sheet width larger than c/ω_{pe}

Both the 3D simulation and observation studies indicate the existence of some wave-particle interaction at the X-line.

Toward the better understanding of the dissipation mechanism

The current sheet thicker than c/ω_{pe} → Wave-particle interaction

- Which unstable modes are responsible for the resistivity?
- How much does the wave-particle interaction contribute to the total resistivity?

➢ Observations

Better space and time resolutions.

➢ Numerical simulations

More realistic parameters and boundary conditions (Higher mass ratio and larger system size)