Dissipation Mechanism in 3D Magnetic Reconnection

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Outline

- Introduction

  -- Importance of reconnection, Multi-scale nature

- Dissipation Mechanism in Magnetic Reconnection

  in 2D system & in 3D system

  -- Results from particle-in-cell simulations

- Observational Facts

  -- In the Earth magnetotail and laboratory experiment

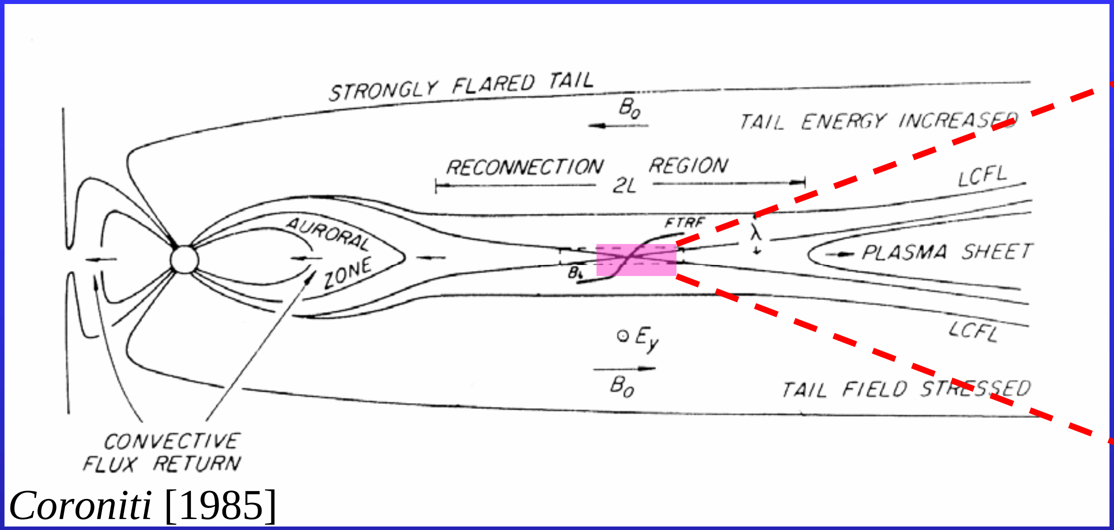
- Summary & Conclusions

Introduction

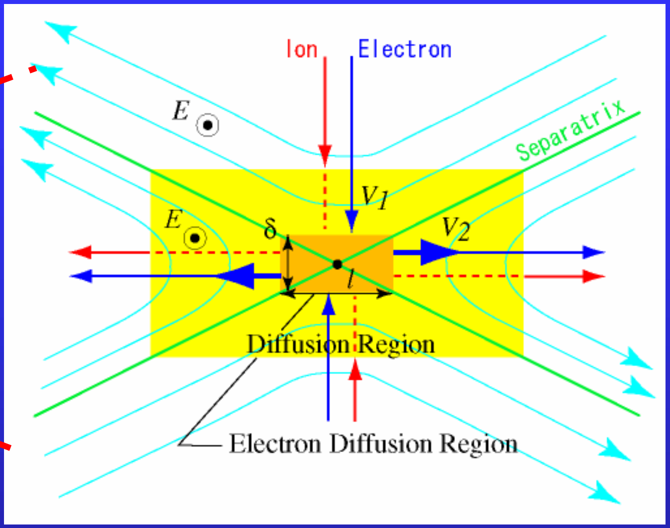
-- Why is reconnection important?

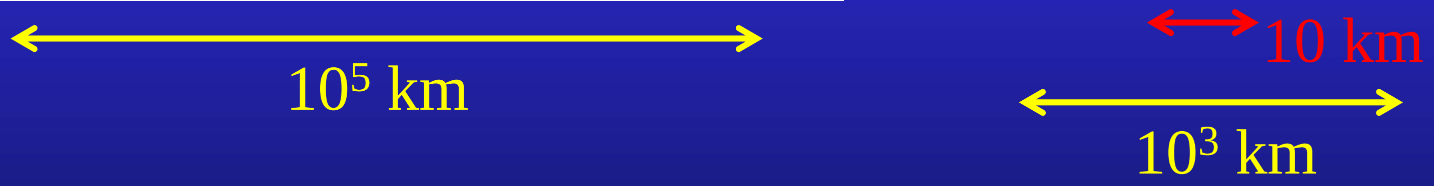
-- Why do we need to study the dissipation mechanism?

Reconnection (in the Earth Magnetoshere)



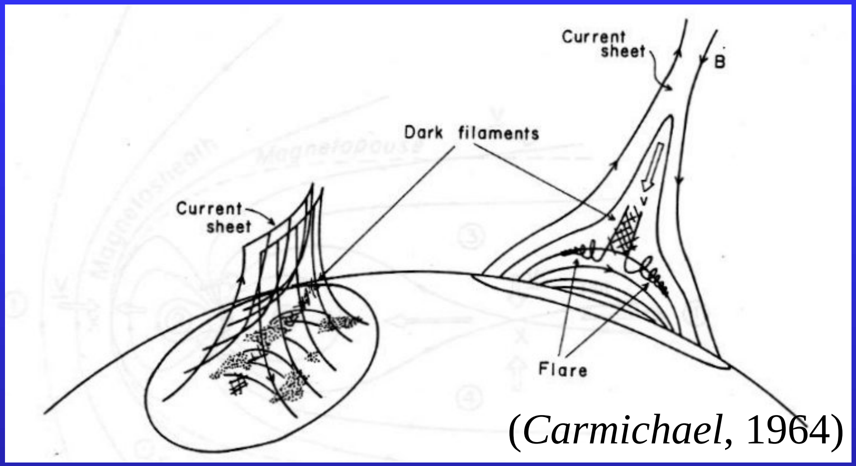
Coroniti [1985]



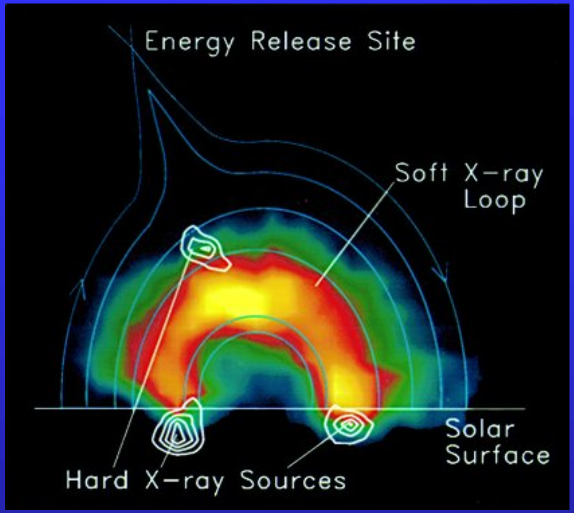


- Can induce global-scale convection causing change in the field line topology,
- Is inherently multi-scale process.

Reconnection (in Solar Flares)

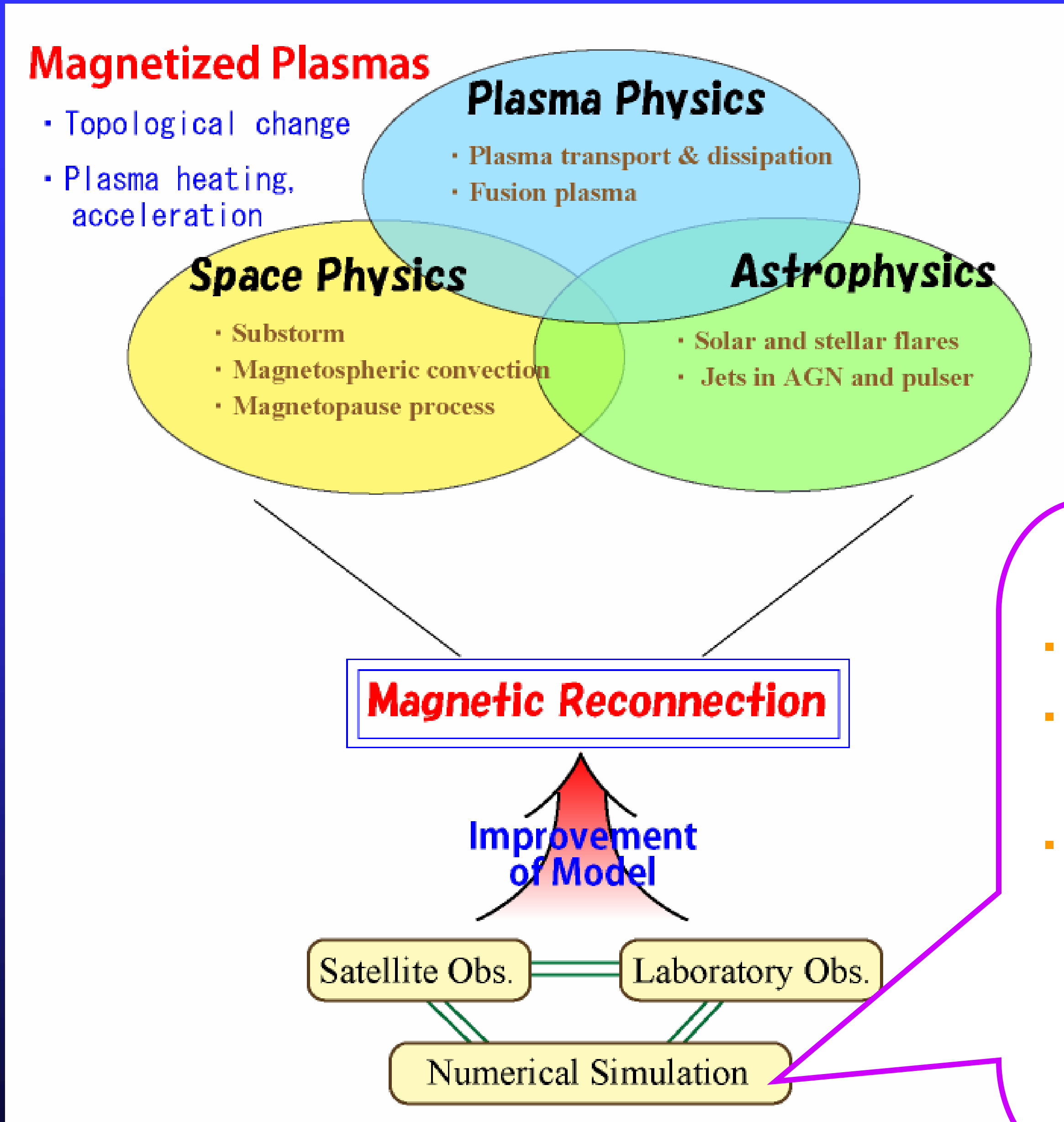


(*Carmichael*, 1964)



(NASA)

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



Advantage

- Repeatability
- Flexibility in initial & boundary conditions
- Low cost relatively

⬇

Model Proposal

Open Questions on Magnetic Reconnection

- How is the fast reconnection triggered?
- What is the sufficient condition for the fast and steady reconnection?
  - Which of macro-scale ($L >> \lambda_i$) or micro-scale ($L < \lambda_i$) physics controls the reconnection rate?
  - What is the dissipation mechanism at the X-line? (Inertia or anomalous resistivity?)
  - Is reconnection inherently steady or intermittent?
  - Is it possible to incorporate correctly the kinetic effects into fluid simulation models?
- How are the electrons and protons accelerated by reconnection?

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.

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)

We need to know what is happening in the microscopic region in order to model the macroscopic dynamics.

Dissipation Mechanism in Magnetic Reconnection in 2D system & in 3D system

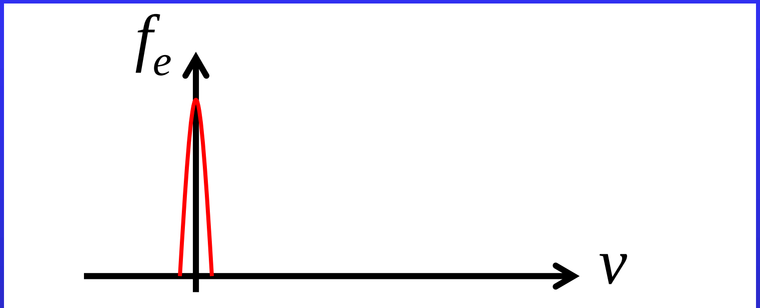
-- Results from particle-in-cell simulations

How is the resistivity generated?

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

Collision with other particles

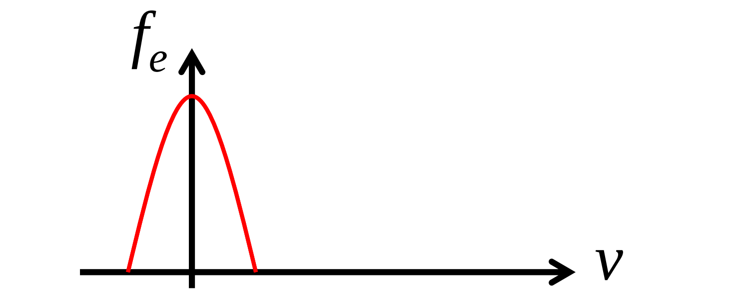
$$\eta = \frac{m_e \nu_c}{n_e e^2}, \qquad \nu_c = \frac{1}{\tau_c}$$



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

Inertia resistivity

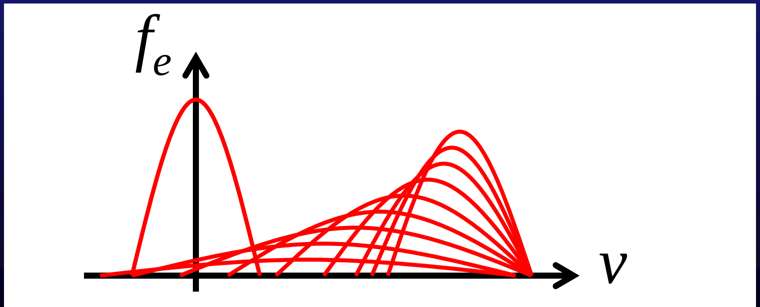
$$\eta = \frac{m_e \nu_T}{n_e e^2}, \qquad \nu_T = \frac{1}{\tau_T} \sim \frac{V}{L}$$



Anomalous resistivity
(Wave-particle interaction)

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

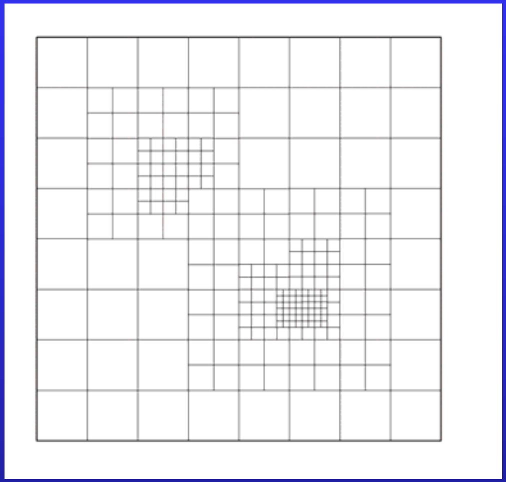
$$R_e^{an} = -e\left(\left\langle \delta n_e \delta \vec{E} \right\rangle + \left\langle \delta(n_e \vec{V}_e) \times \delta \vec{B} \right\rangle\right)$$

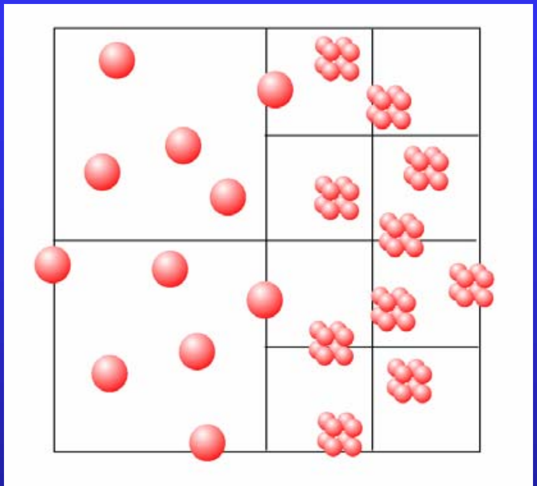


Simulation Model

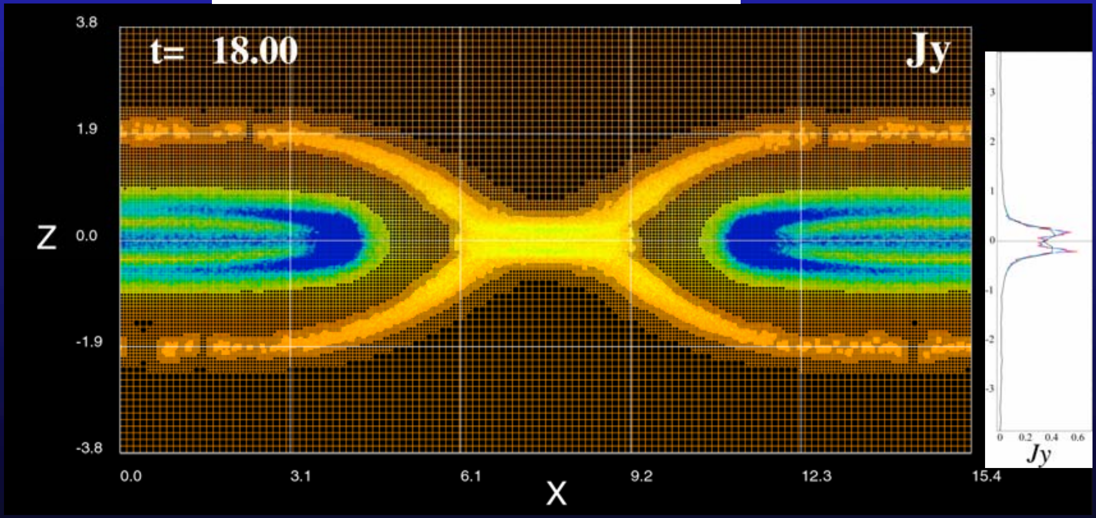
PIC + Adaptive Mesh Refinement (AMR)

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

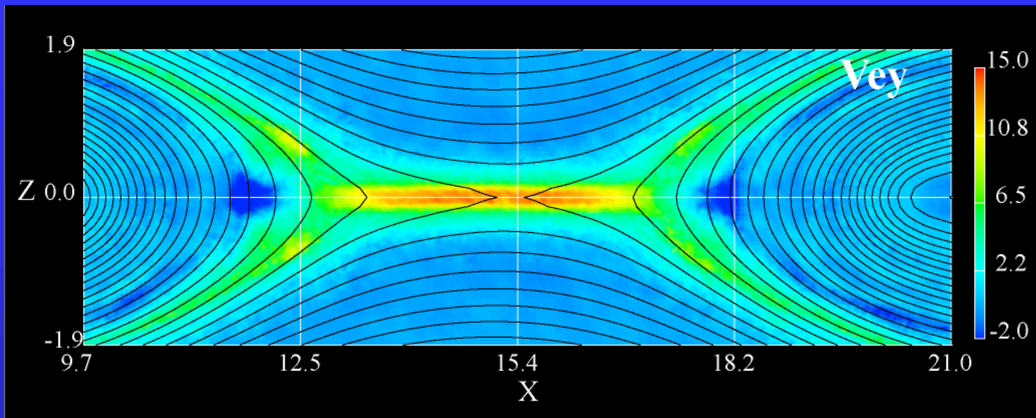


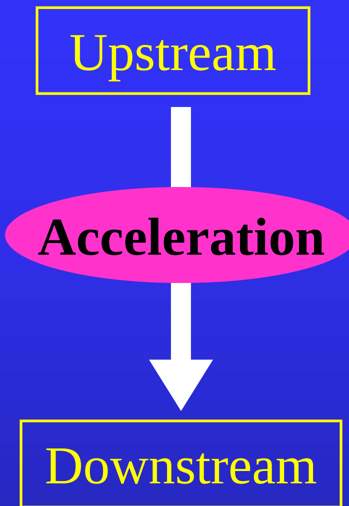


Refinement cells are selectively allocated around the X-line and separatrices.



2D Reconnection

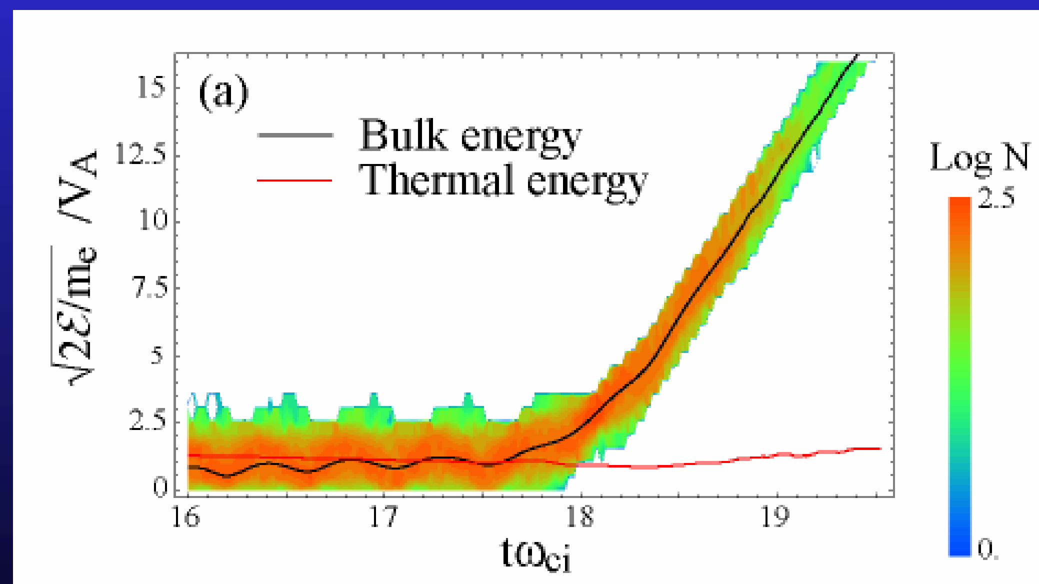




Electrons are…

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

→ Inertia resistivity



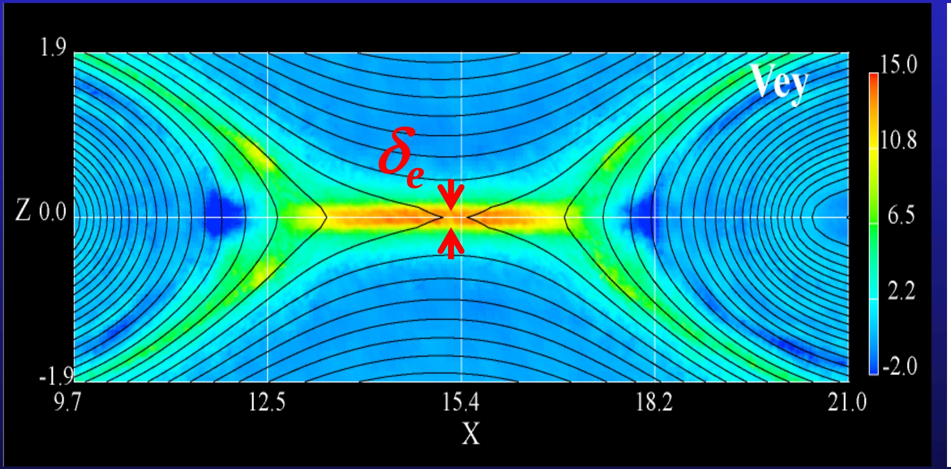
Electron Inertia Resistivity

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

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

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

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



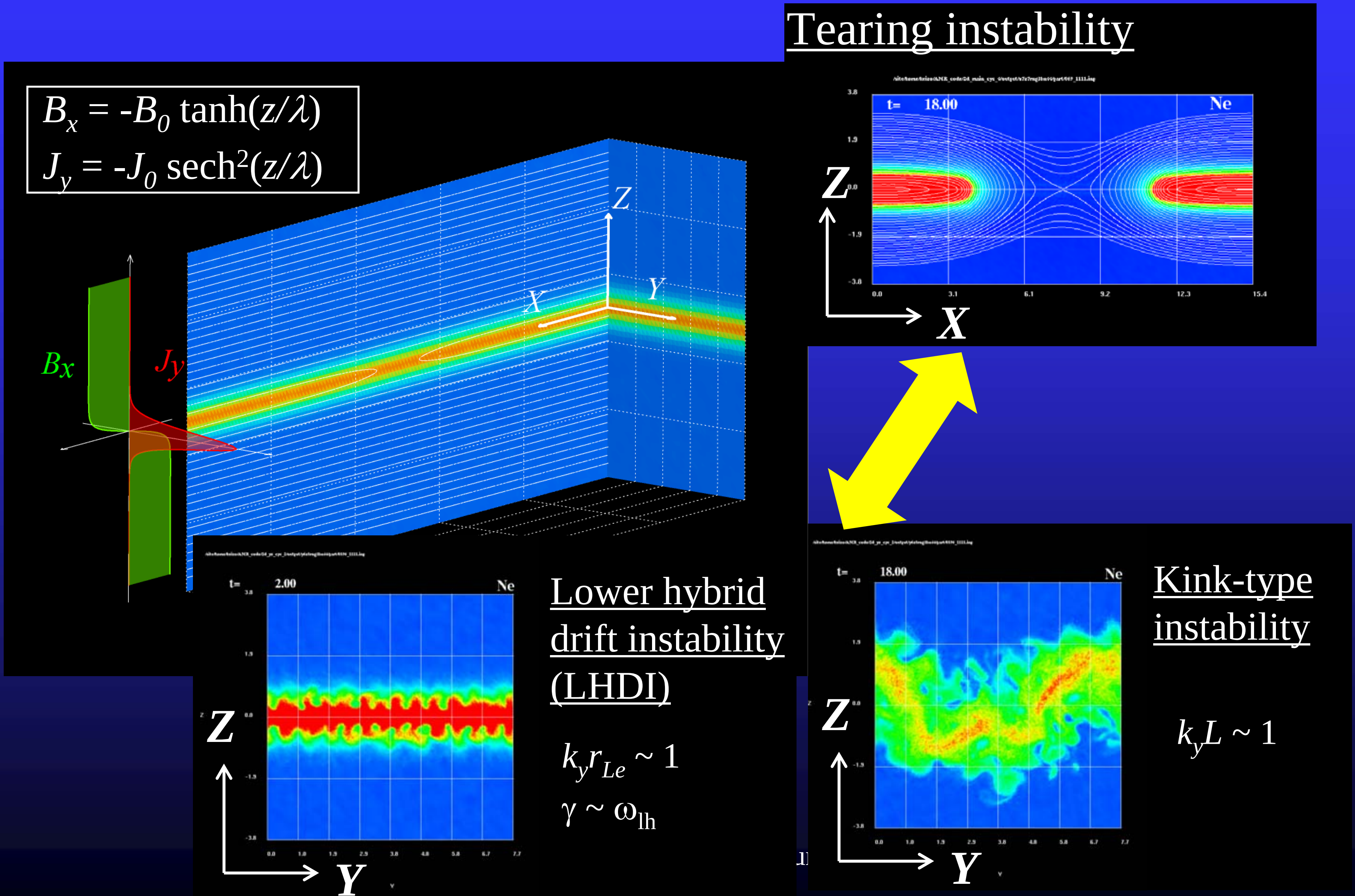
$$\delta_e \approx \lambda_e \, (= c/\omega_{pe})$$

Magnetotail : ~ 10km (⇔10^5km)

Solar Flare : ~ 10^{-5}km (⇔10^4km)

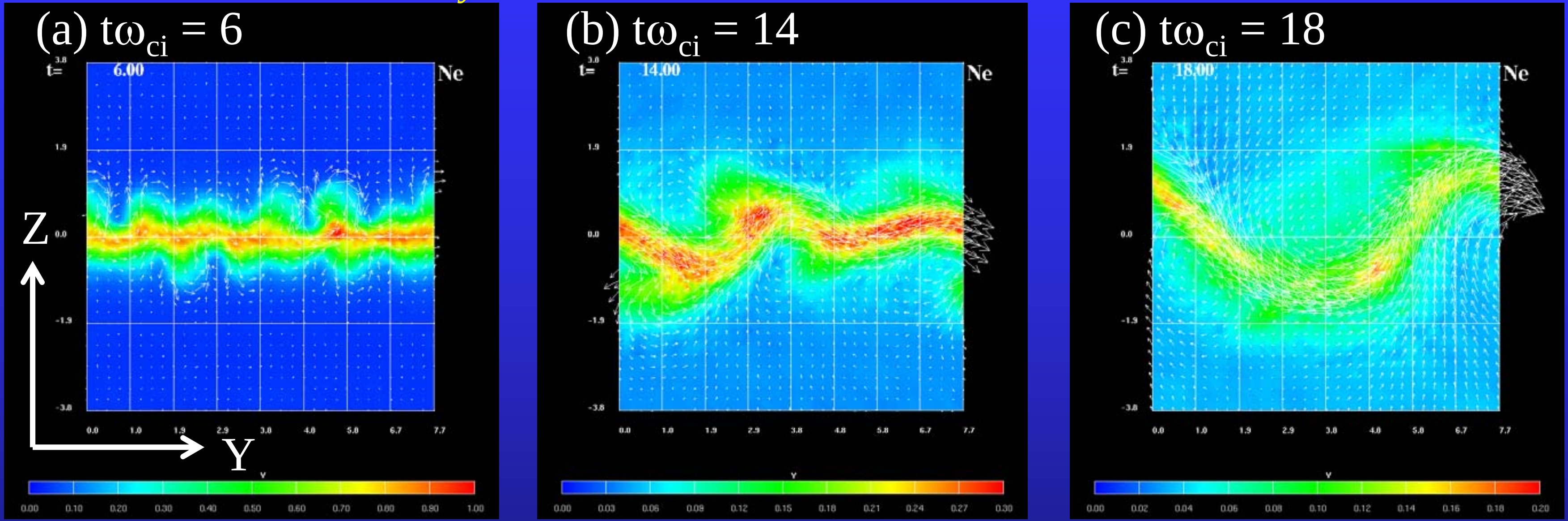
→ Is such a thin current sheet really stable in 3D system?

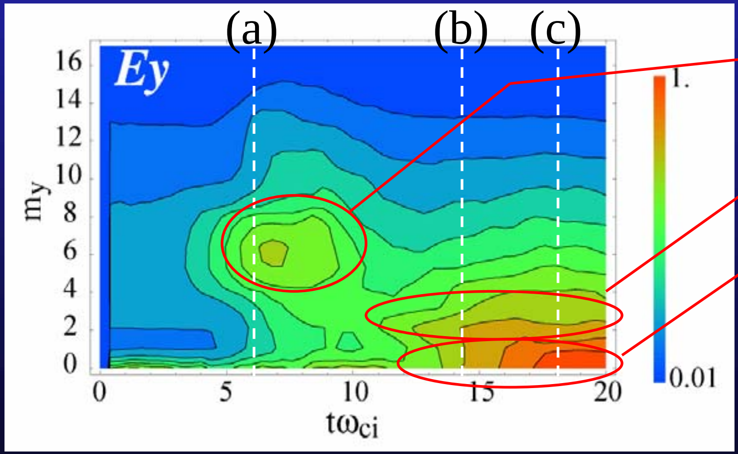
Unstable Modes Expected in the Current Sheet



Time Evolution of the Current Sheet in the YZ Plane

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





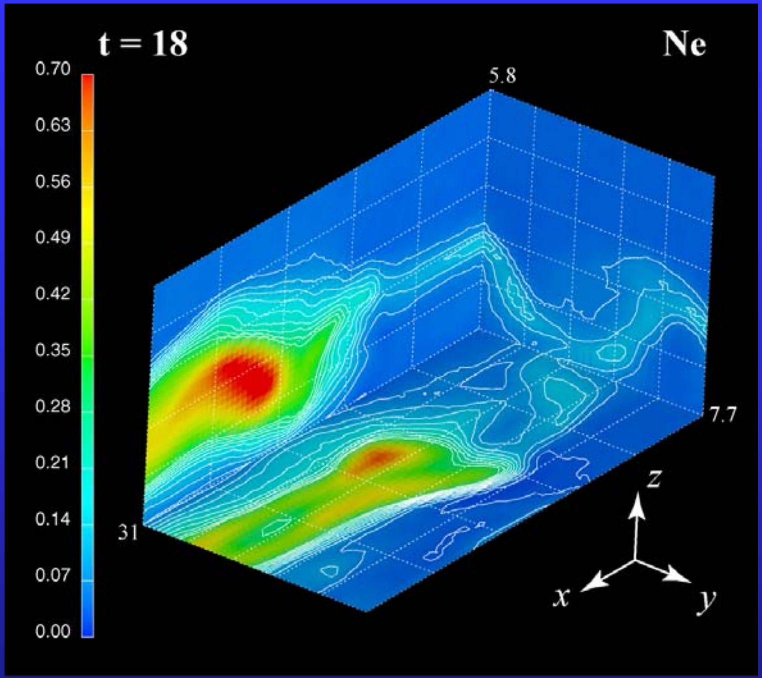
Lower hybrid drift instability (LHDI)

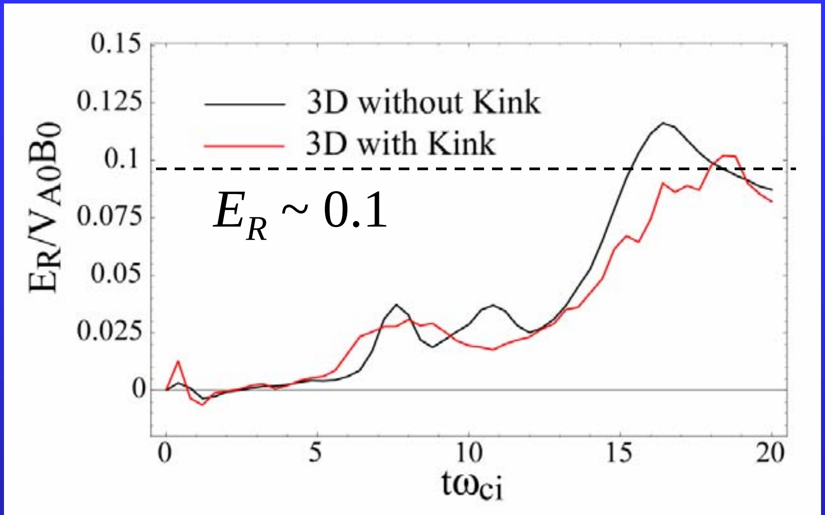
Kink-type instability

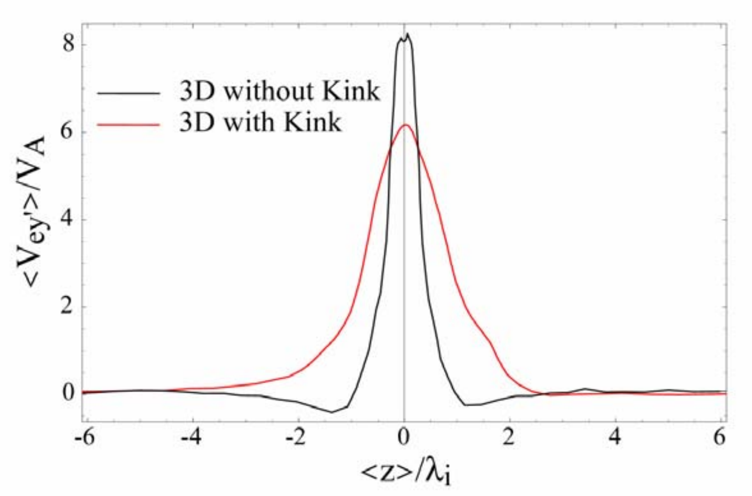
Induction field due to tearing instability

Kink instability coexists with the tearing mode.

Reconnection Rate & Current Sheet Width





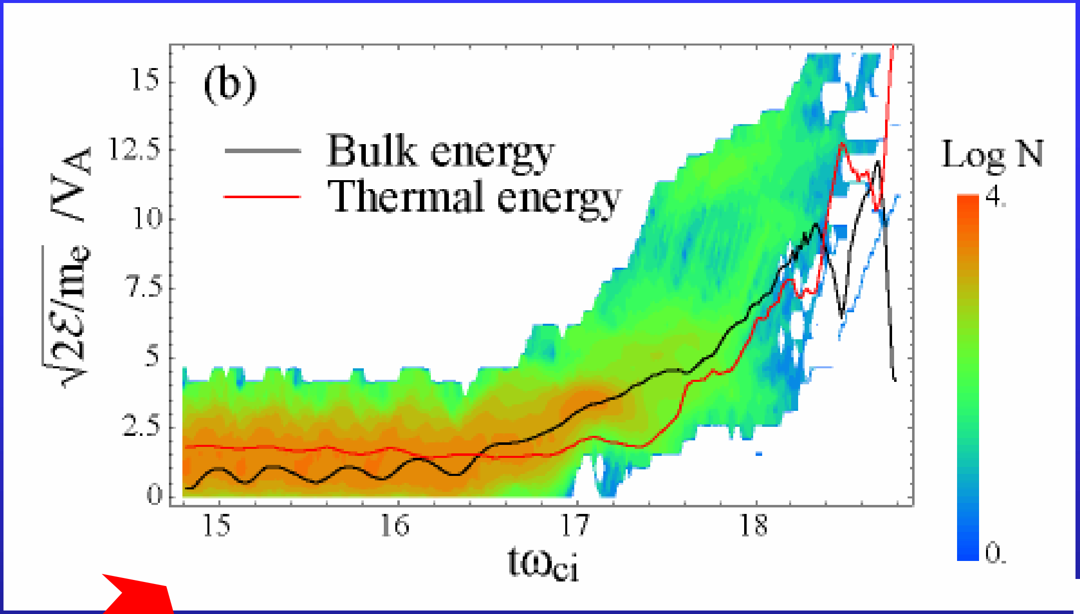


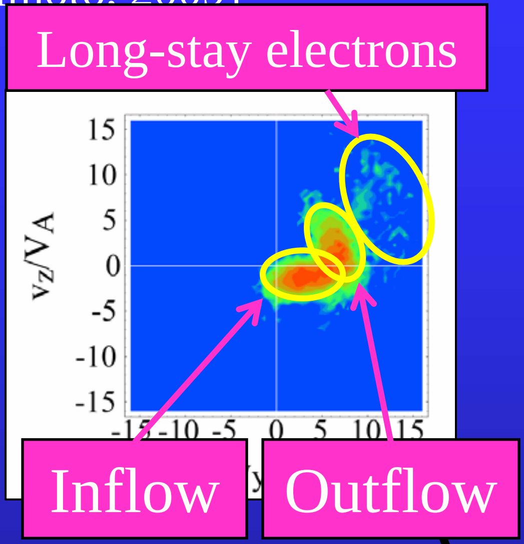
If the inertia resistivity alone supported the dissipation, the E_R would be significantly reduced.

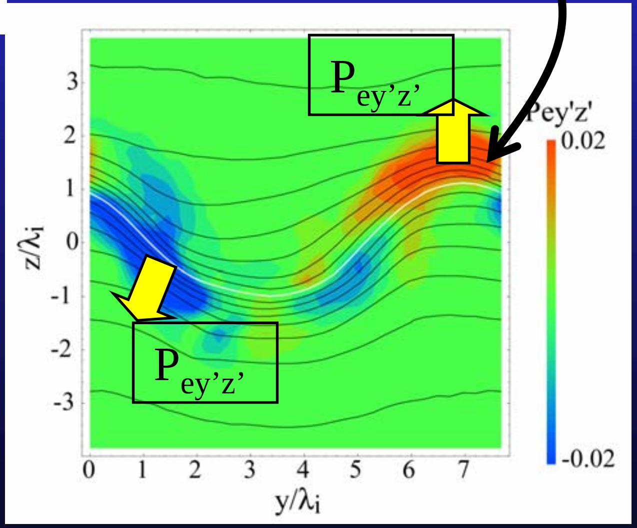
$$\frac{E_{R,kink}}{E_{R,nokink}} \propto \left(\frac{V_{e,kink}}{V_{e,nokink}}\right)^2 \approx 0.56$$

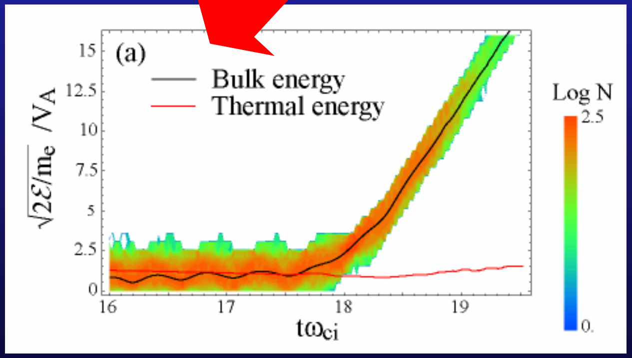
Dissipation Mechanism in 3D Reconnection

[Fujimoto, 2009]









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

(2D reconnection case)

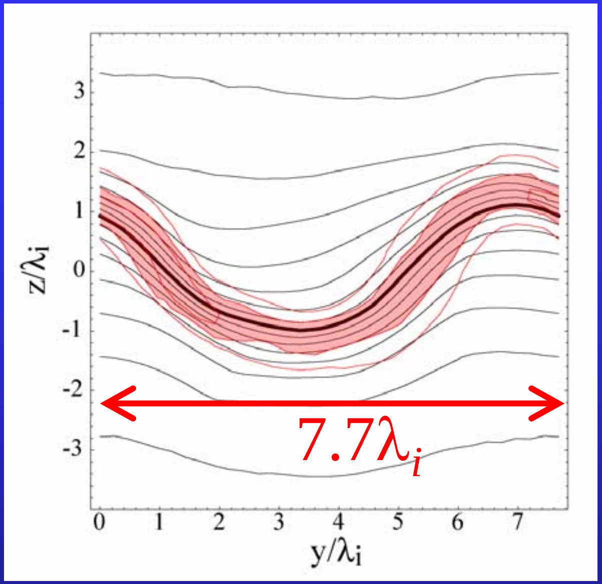
Meandering Scale & Wavelength

- Electron meandering scale

$$\omega \approx \frac{2}{3}\frac{V_{ey'}}{c}\omega_{pe} \quad [\textit{Speiser}, 1965]$$

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

$$\approx 9\lambda_i$$



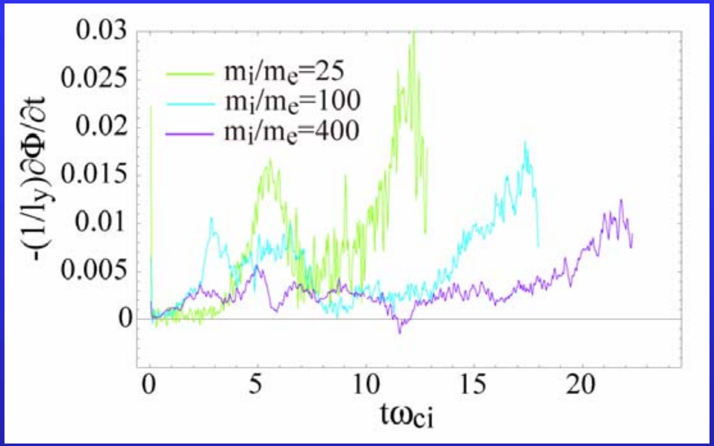
Meandering scale ~ Wavelength of the kink mode

Does the wave-particle interaction still occur in higher mass ratio cases?

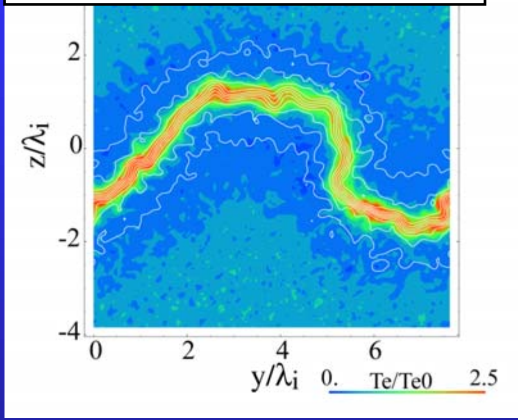
In the Cases with Lager m_i/m_e (> 100)

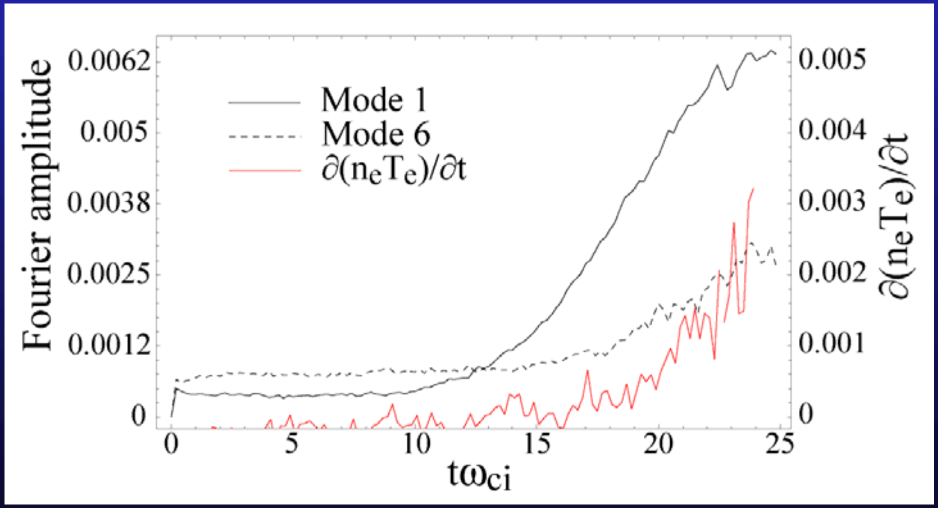
- 2D simulations in the YZ plane

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



Temparature: m_i/m_e=400





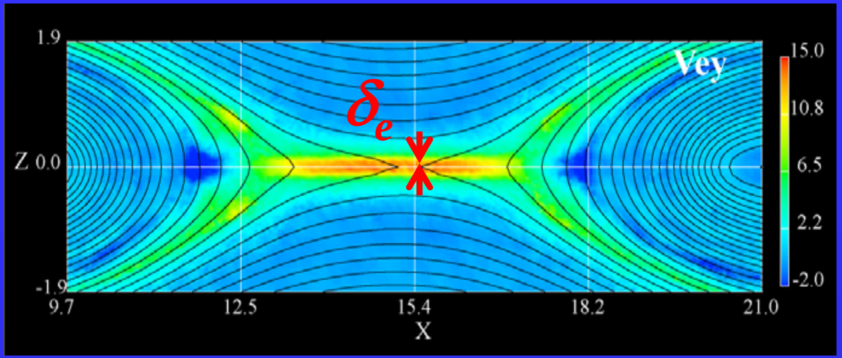
Hybrid-scale kink mode

[*Shinohara et al.*, 2001;*Daughton*, 2003]:

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

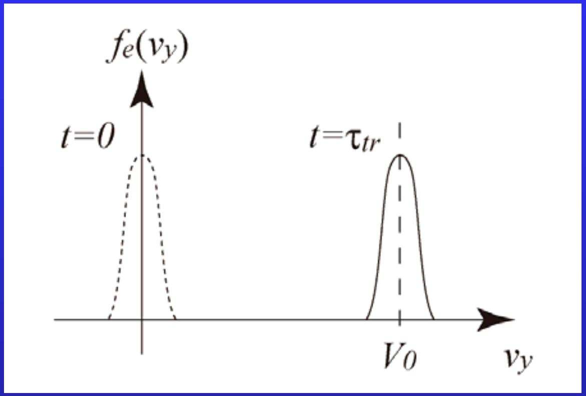
Electron Heating

Current Sheet Width (δ_e)



2D case

(Inertia resistivity)

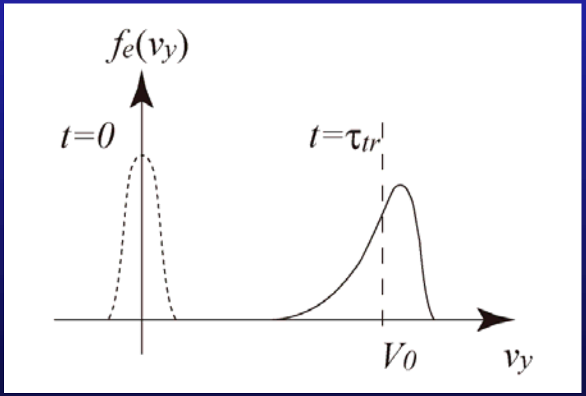


$$\frac{e|E_y|}{m_e}\tau_{tr} = V_0 \qquad \tau_{tr} \sim \frac{\delta_e}{V_{in}}$$

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

3D case

(Inertia + anomalous resistivity)



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

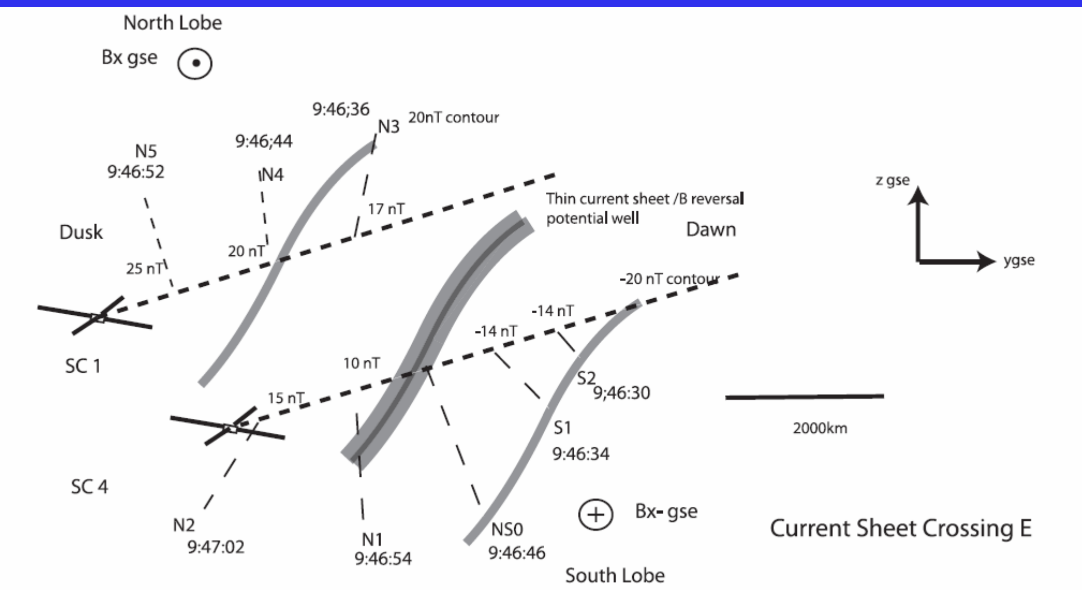
$$\Rightarrow \delta_e > c/\omega_{pe}$$

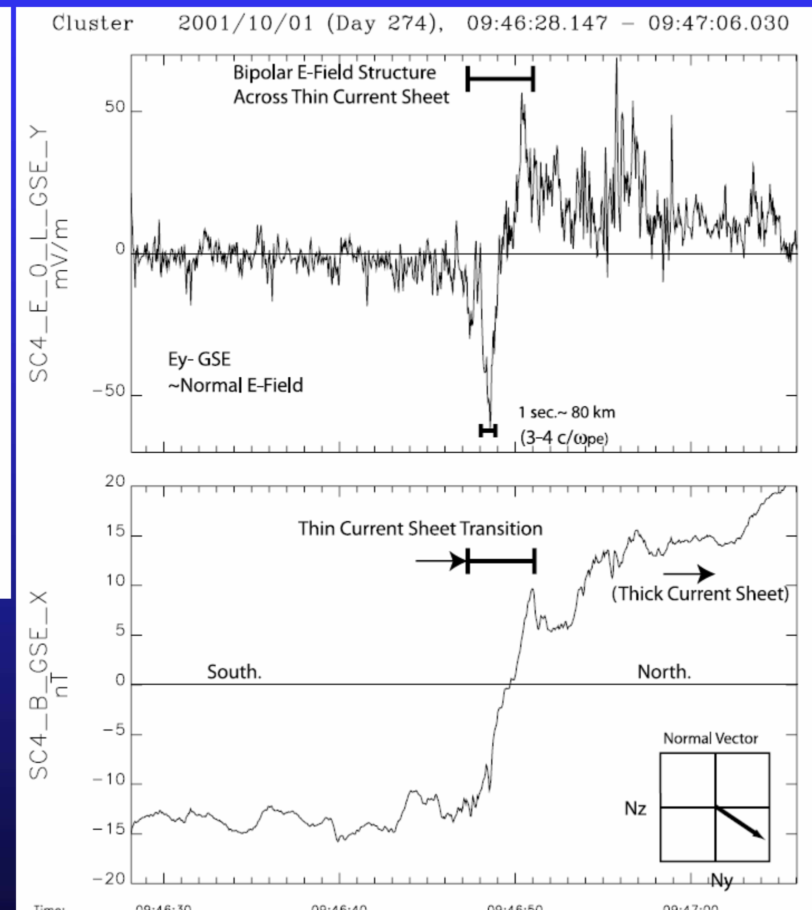
Observational Facts

-- Current sheet width in the Earth magnetotail and laboratory experiment

In the Earth Magnetotail

Cluster observation of normal electric field in the kinked current sheet [Wygant et al., 2005]





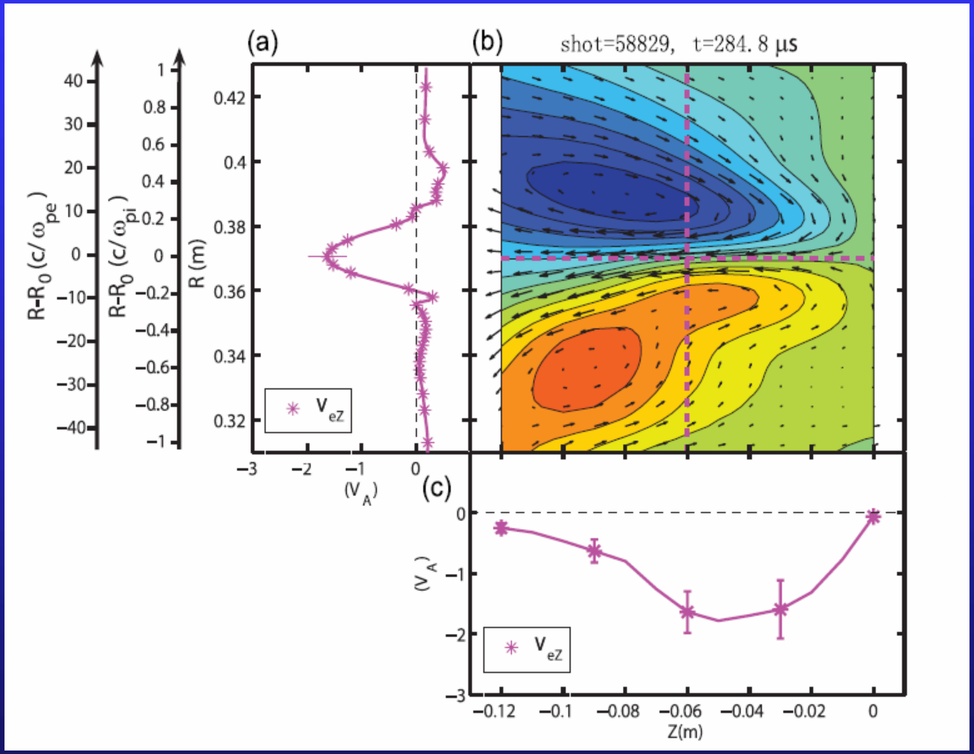
Spiky normal electric field

- Duration = 1 sec ~ 80 km
- $3 – 4\ c/\omega_{pe} > c/\omega_{pe}$

In the Laboratory Experiment

Laboratory measurement performed on the MRX

[Ji et al., 2008]



Current sheet width

$\sim 8\ c/\omega_{pe} \gg c/\omega_{pe}$

with electromagnetic waves

Toward the better understanding of the dissipation mechanism

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

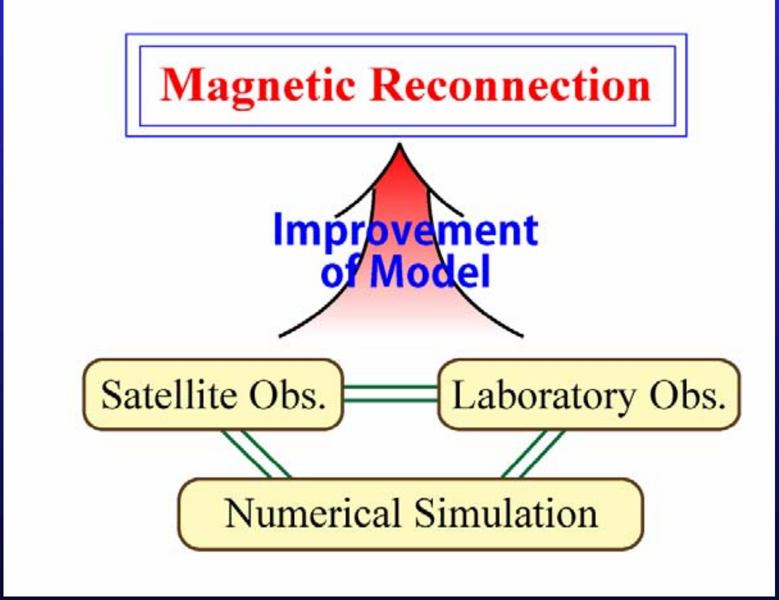
- Which unstable modes are responsible for the resistivity?
- How much does the wave-particle interaction contribute to the total resistivity?

➢ Observations

Better space and time resolutions.

➢ Numerical simulations

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



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.

Future Study

1. 3D PIC simulations with higher mass ratio and larger system size.
2. Application to the MHD-scale system.

MHD code

- Flexible boundary and initial conditions

Global Modeling

$$\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} = \eta \boldsymbol{J}$$

PIC code

Kinetic effects with microscopic structure