磁気リコネクションの大規模粒子シミュレーション

Large-Scale Particle-in-Cell Simulation of Magnetic Reconnection

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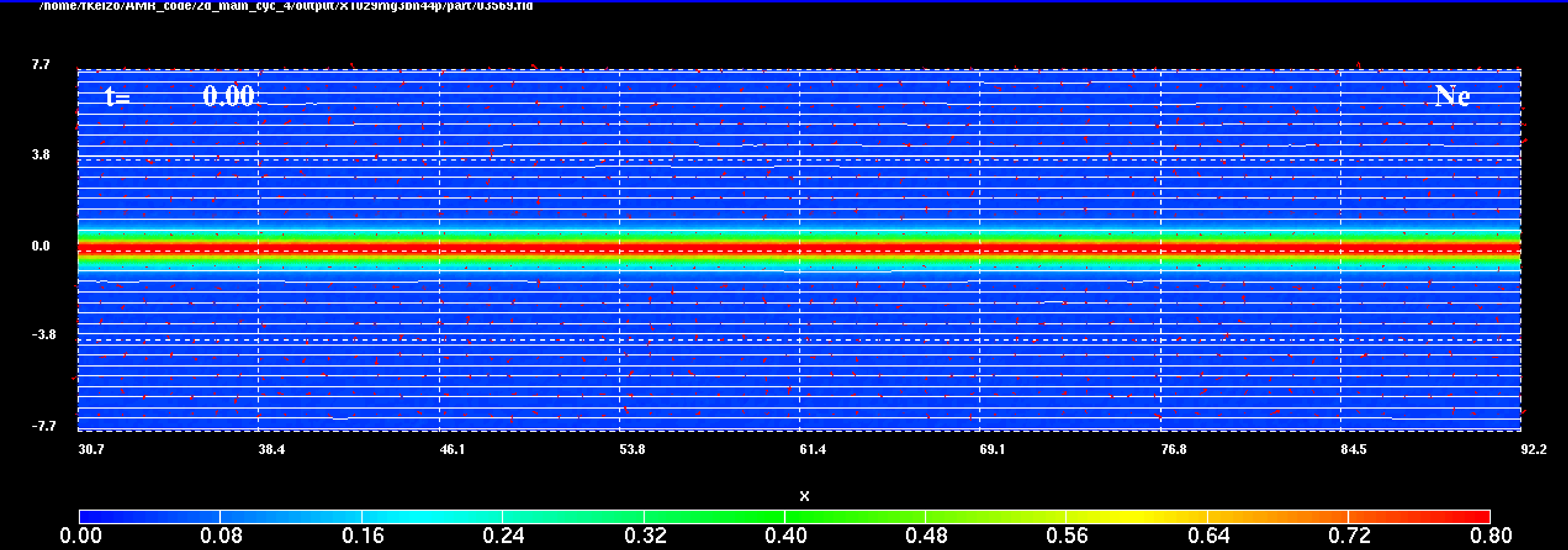
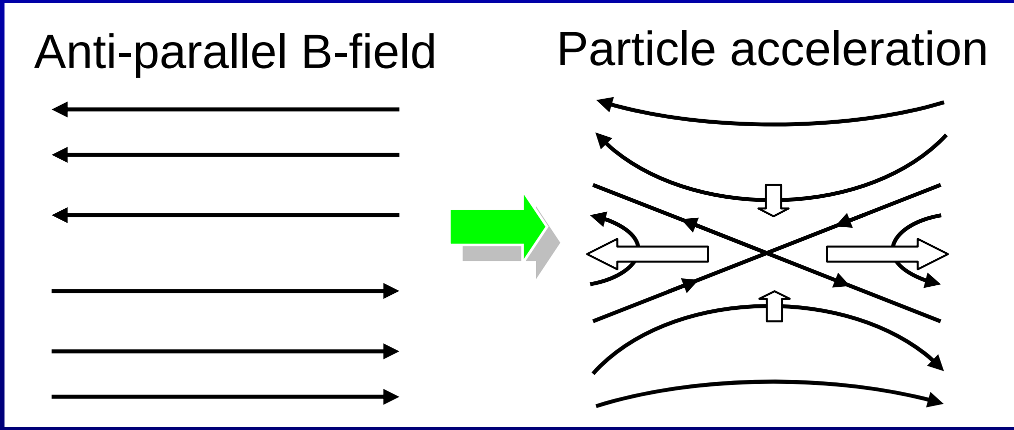
Magnetic Reconnection

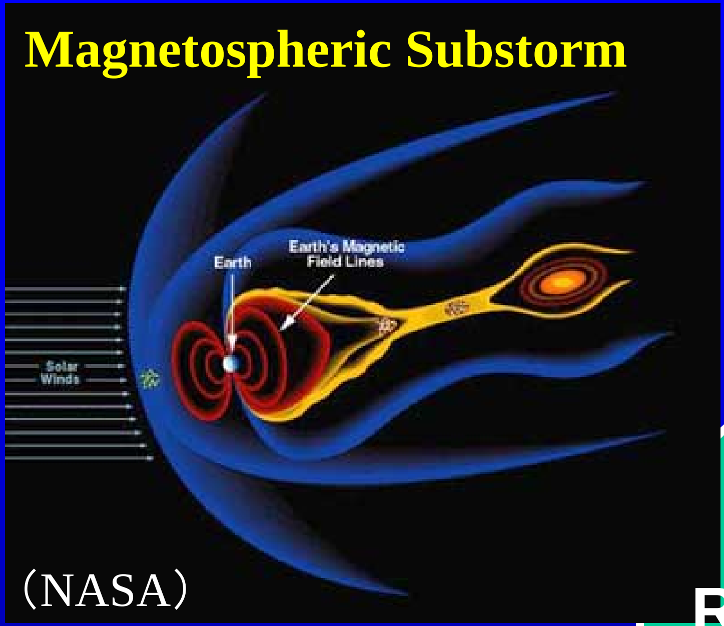
Line : Field line, Contour : n_e
Arrow : V_e

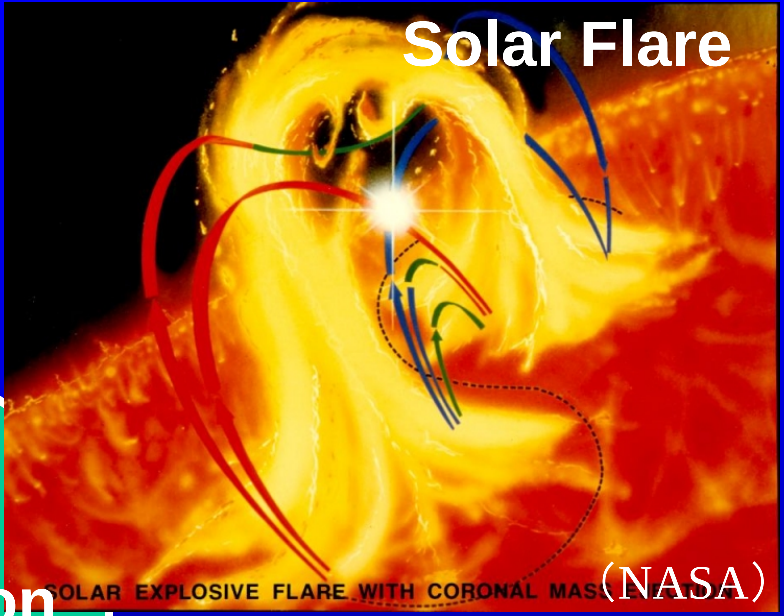




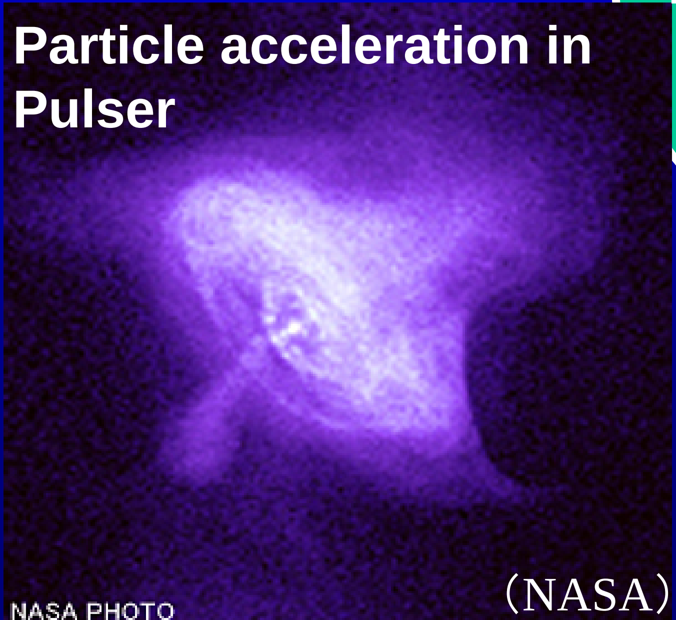
- Change in field line topology
- Plasma acceleration and heating

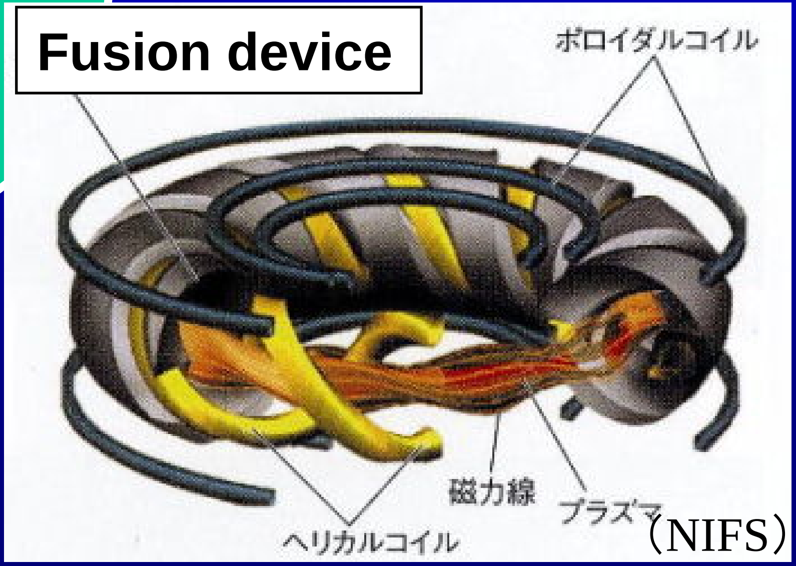
Impact of Magnetic Reconnection





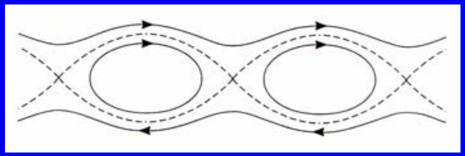
Magnetic Reconnection





Main Issues of Magnetic Reconnection

- Triggering mechanism



How can reconnection be triggered *quickly*?

Tearing mode is not sufficient.

$\tau_g \sim 2\pi(\lambda/V_A)R_m^{3/5}$ = 5.6 *months* >> a few *min*

- Quasi-steady process of fast reconnection

$$\frac{\partial B}{\partial t} = \eta \nabla^2 B/\mu_0$$

η : Electric Resistivity → Very small in collisionless plasmas

Fluid (MHD) model : **Sweet-Parker $E_R = R_m^{-1/2} \propto \eta^{1/2}$? or**

Petschek $E_R = (\pi/4)(\ln R_m)^{-1} \propto \ln\eta$?

(E_R: Reconnection rate, R_m: Magnetic Reynolds number)

- Plasma acceleration and heating mechanism

MagnetoHydroDynamic (MHD) Model(1950s-60s)

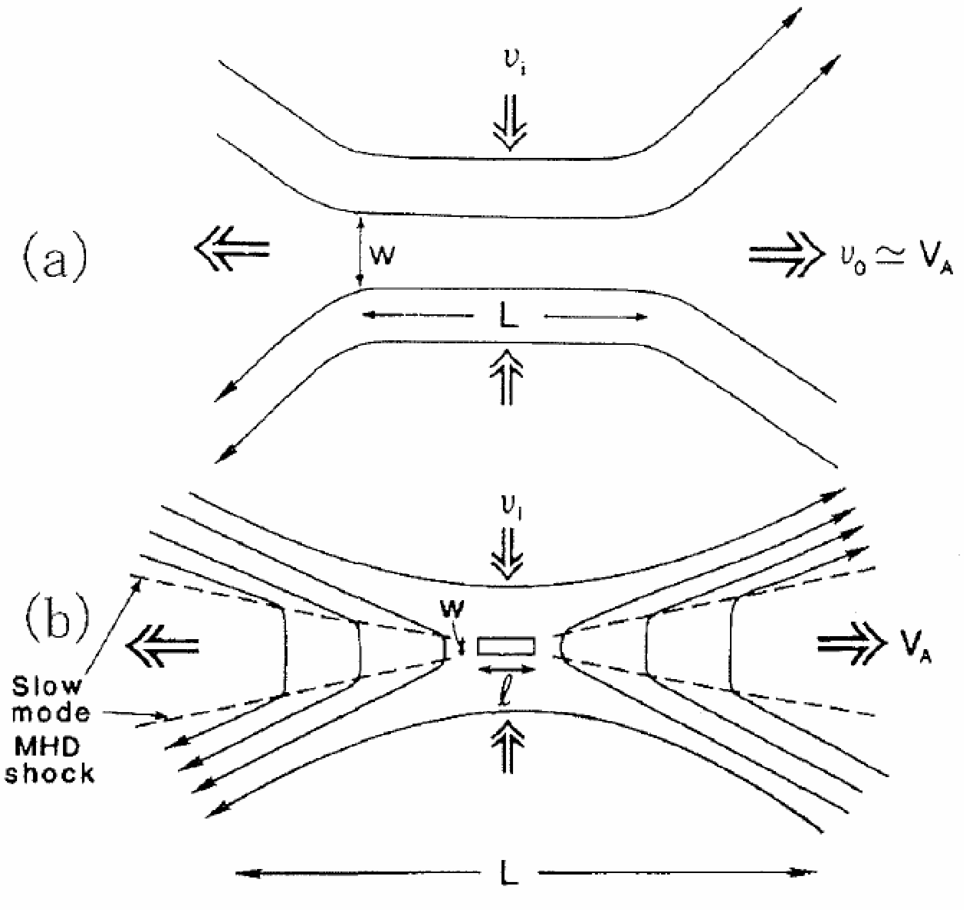


Fig. 4 (a) Sweet-Parker model and (b) Petschek model.

[*Ono et al.*, JSPF, 2001]

Sweet-Parker model [1957, 1958]

$$E_R \sim R_m^{-1/2}$$

($R_m = \mu_0 L V_A / \eta$:
Magnetic Reynolds number)

➡ ***Slow reconnection***

Petschek model [1964]

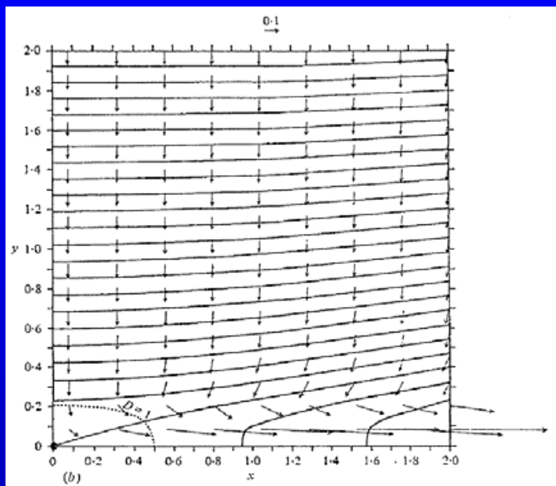
$$E_R \sim (\pi/4)\,(\ln R_m)^{-1}$$

➡ ***Fast reconnection***

Exact solution of the MHD equations?

MagnetoHydroDynamic (MHD) Simulations

[Ugai & Tsuda, 1977; Sato & Hayashi, 1979; Biskamp, 1986;…] **(1970s – 80s)**



[after *Ugai & Tsuda*, 1977]

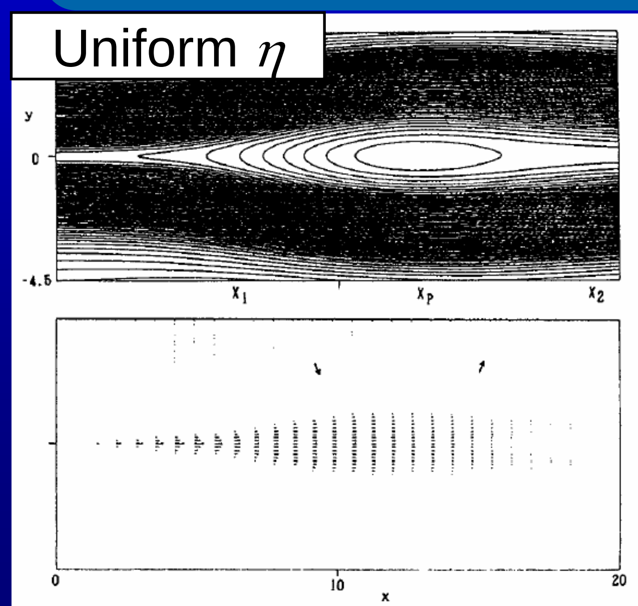
What is the condition for Petschek reconnection to evolve?

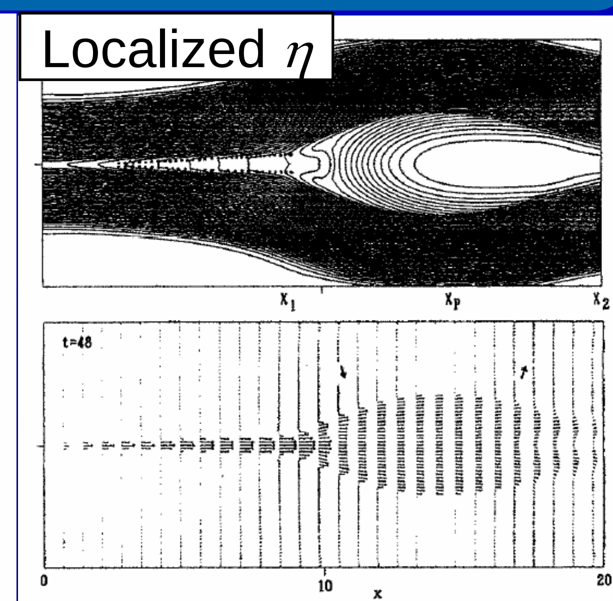
$$E = \eta J$$

Depending on the resistivity model.

Uniform $\eta \Rightarrow$ Sweet-Parker reconnection

Localized $\eta \Rightarrow$ Petschek reconnection





[*Ugai*, 1995]

Plasma Particle Simulations (1990s – early 2000s)

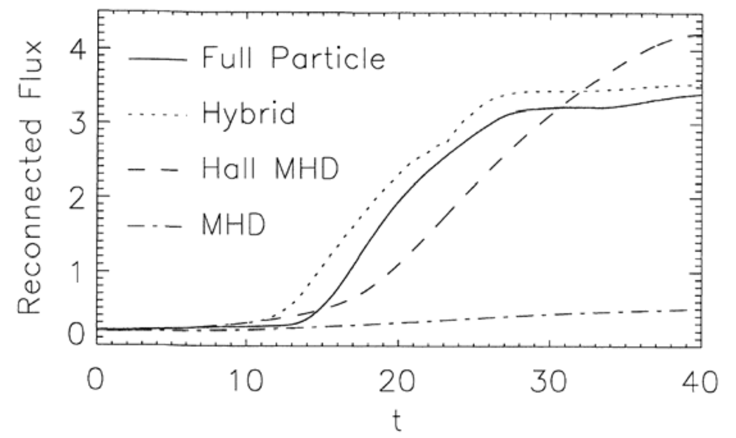
What is the condition for localized resistivity to arise?

What is the mechanism for generating the resistiviy in collisionless plasmas?

GEM (Geospace Environment Modeling) Magnetic Reconnection Challenge

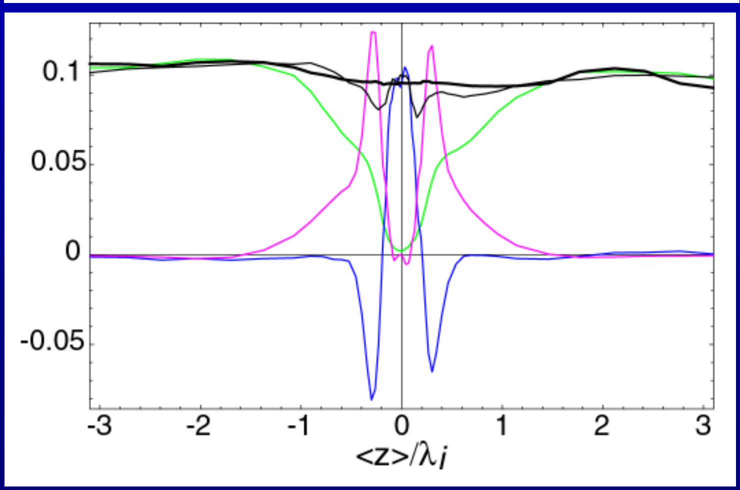
Inclusion of the Hall effect is sufficient condition for the fast reconnection!

[*Birn et al*., 2001]



$$\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} = \eta \boldsymbol{j} + \underbrace{\frac{1}{ne}\boldsymbol{j} \times \boldsymbol{B}}_{\text{Hall}} - \underbrace{\frac{1}{ne}\nabla \cdot \boldsymbol{P}_e}_{\text{Viscosity}}$$

Electron viscosity is dominant at the x-line. [*Cai & Lee*, 1997; *Hesse et al*., 1999]



After GEM Challenge

The Hall reconnection has not been accepted.

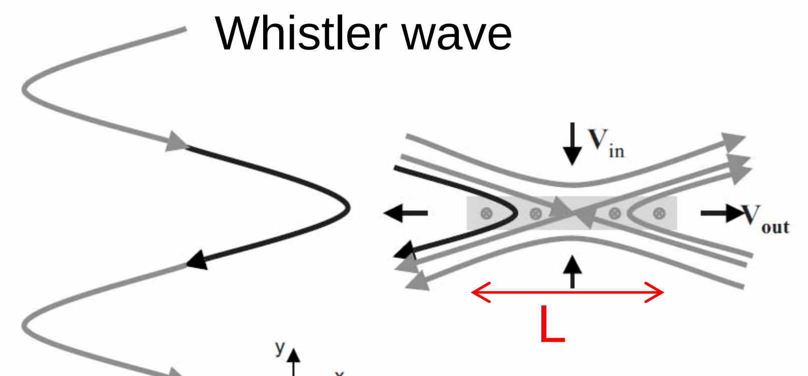
- **Unclear theoretical background**

  $\omega = k^2 \omega_{ce} \lambda_e^2$, $V_{out} \sim V_{Ae}$, $E_R \propto 1/L$

- **Fast reconnection in electron-positron plasmas**

  [*Bessho & Bhatacharjee*, 2005]

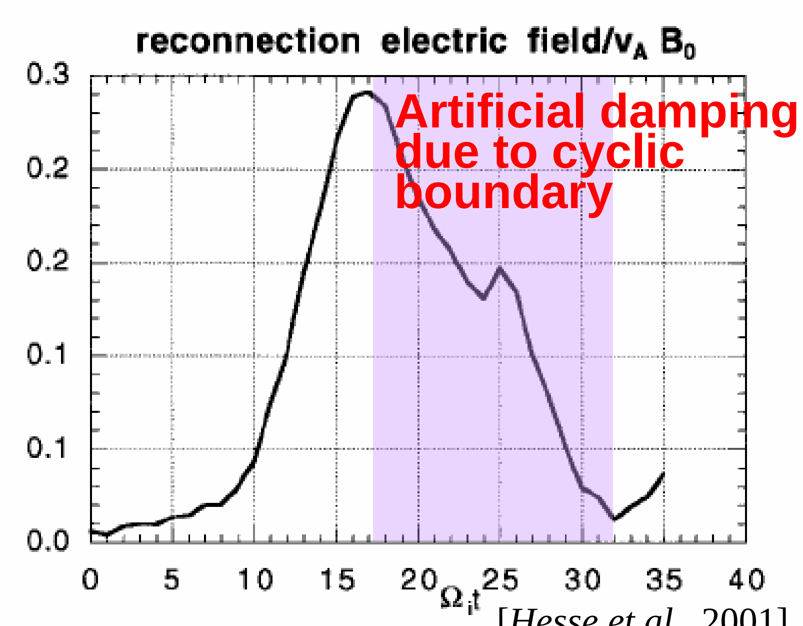
- **No evidence for the steady-state fast reconnection**



[*Drake et al.*, 2008]

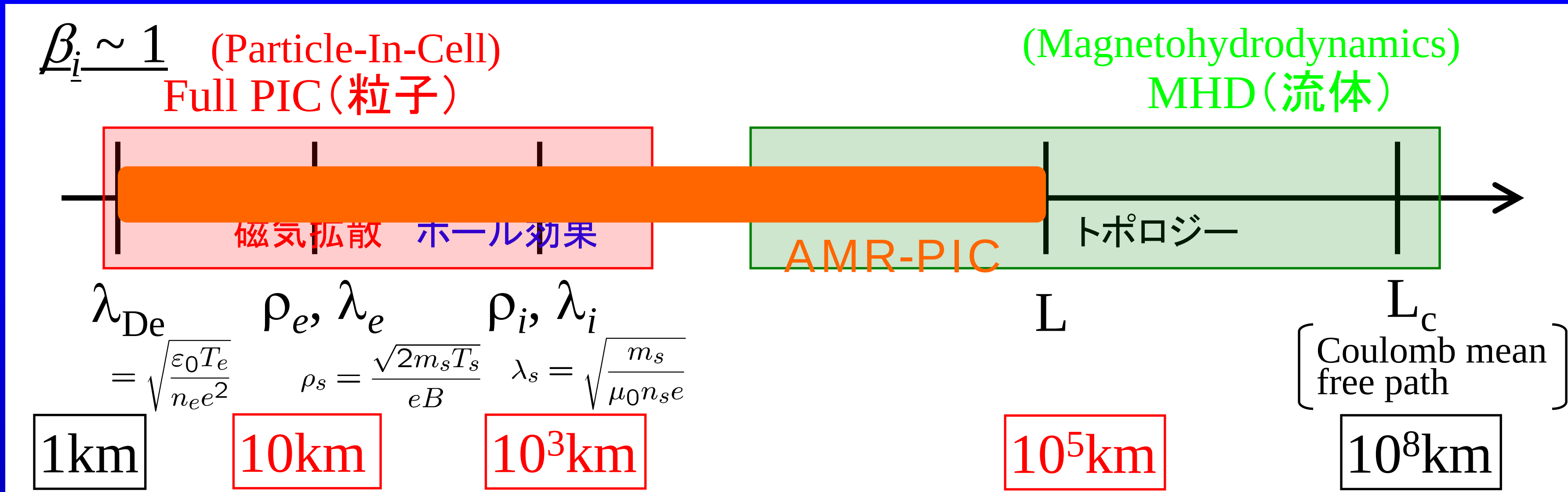
Dissipation mechanism is not consistent with observations.

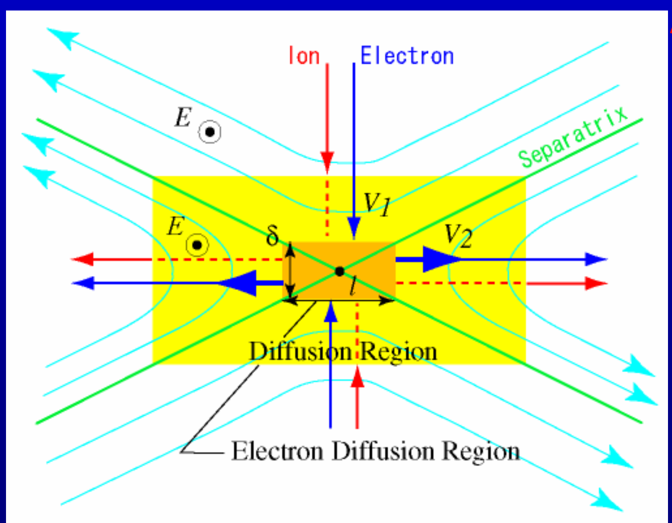
- **3D effects must be important.**

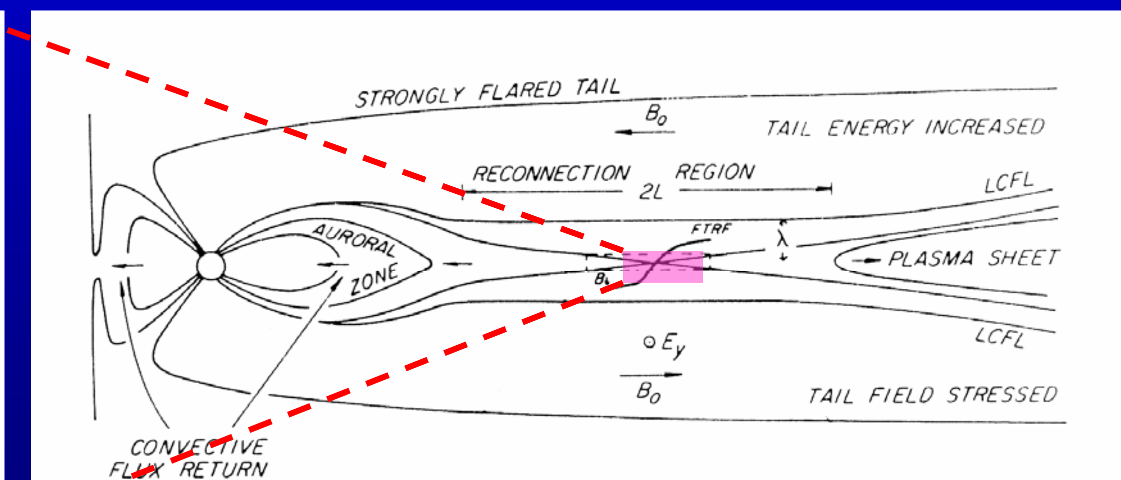


[*Hesse et al.*, 2001]

Multi-Scale & 3D Kinetic Simulations (later 2000s~)







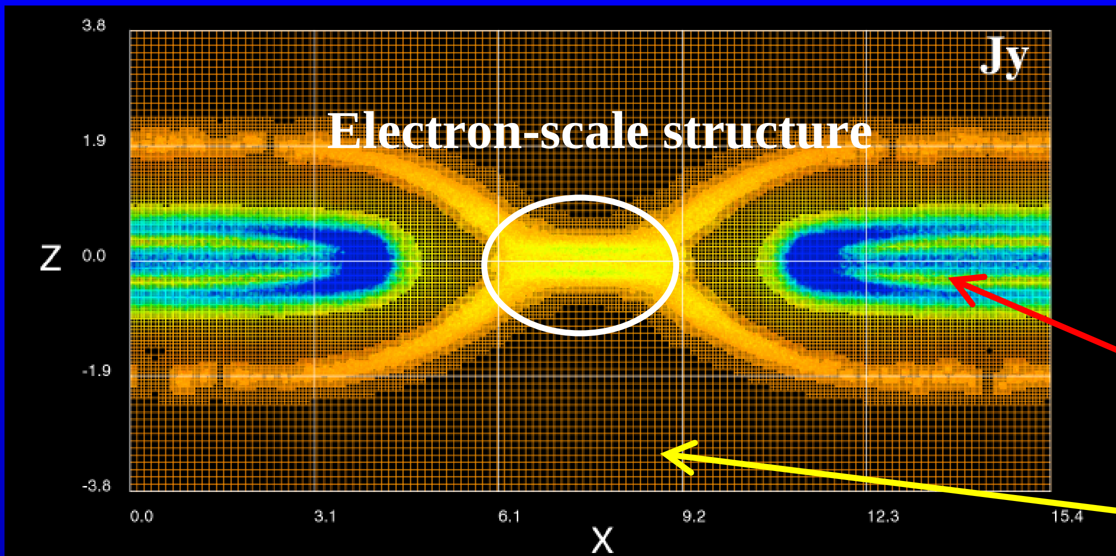
Coroniti [1985]

2. Development of AMR-PIC code

AMR-PIC Code

(Adaptive Mesh Refinement – Particle-in-Cell)

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 T_e}{n_e e^2}}$$



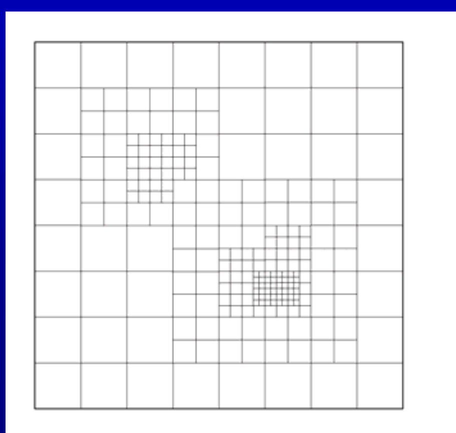
Restrictions in PIC code

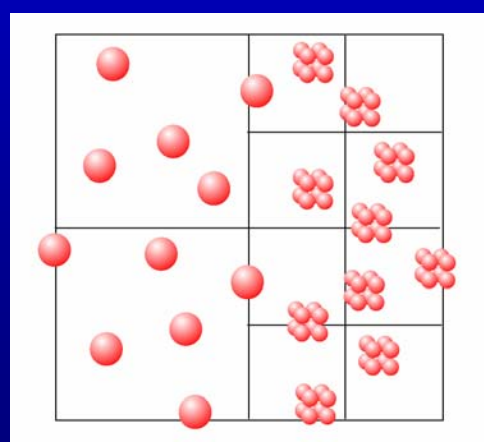
$\Delta x \leq \lambda_{De}$, $\omega_{pe}\Delta t < 1$

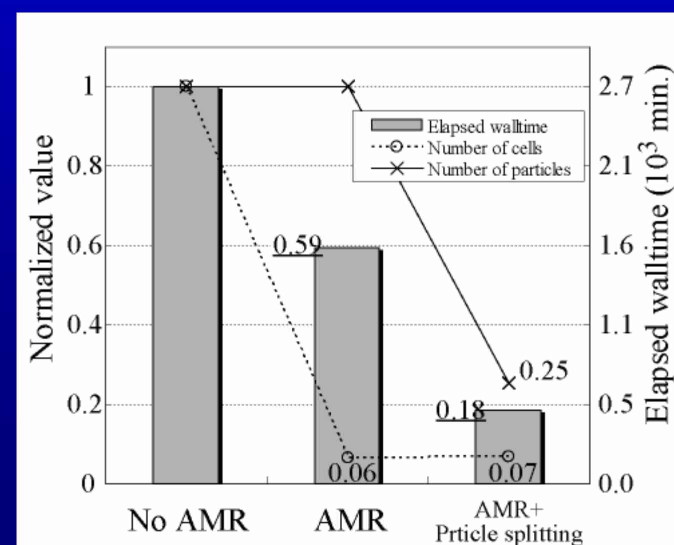
$\Delta x/\Delta t > c$

$\lambda_{De,ps} \sim 3 \times 10^2$ m

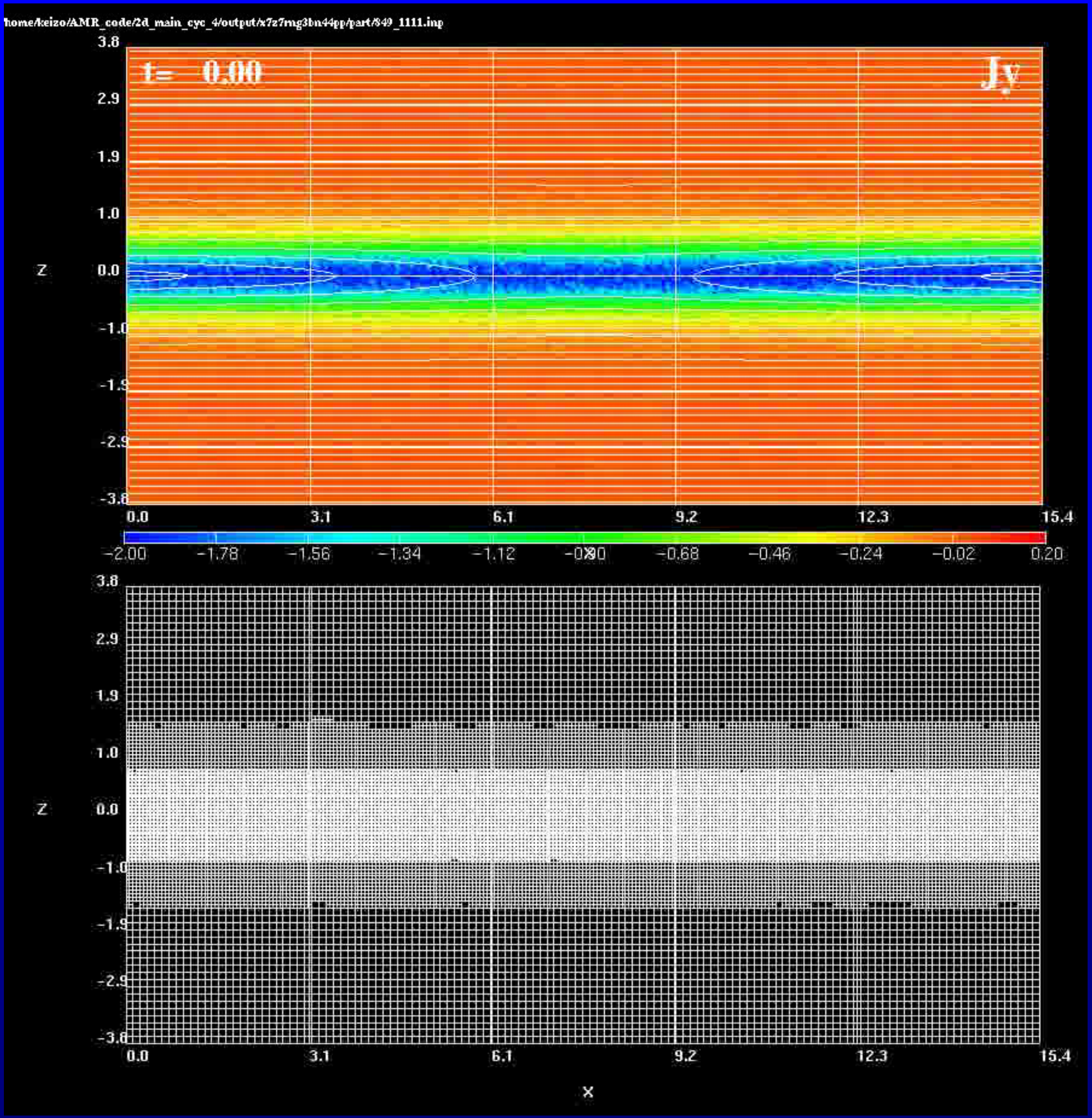
$\lambda_{De,lobe} \sim 6 \times 10^3$ m

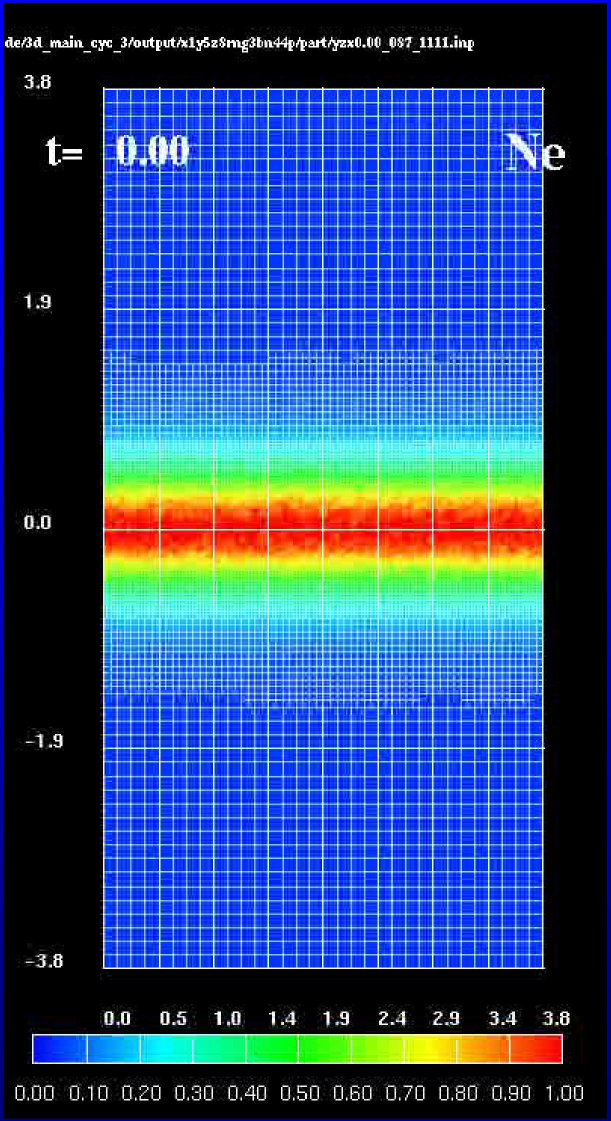






AMR-PIC Simulation

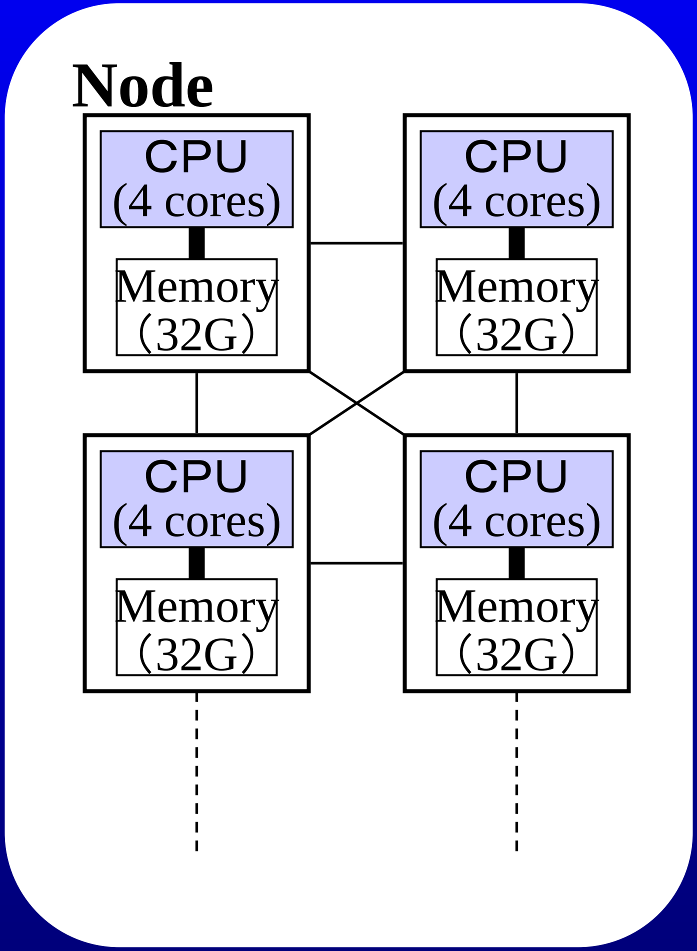


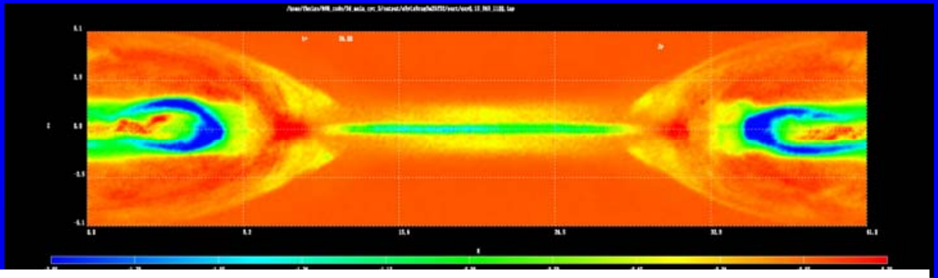


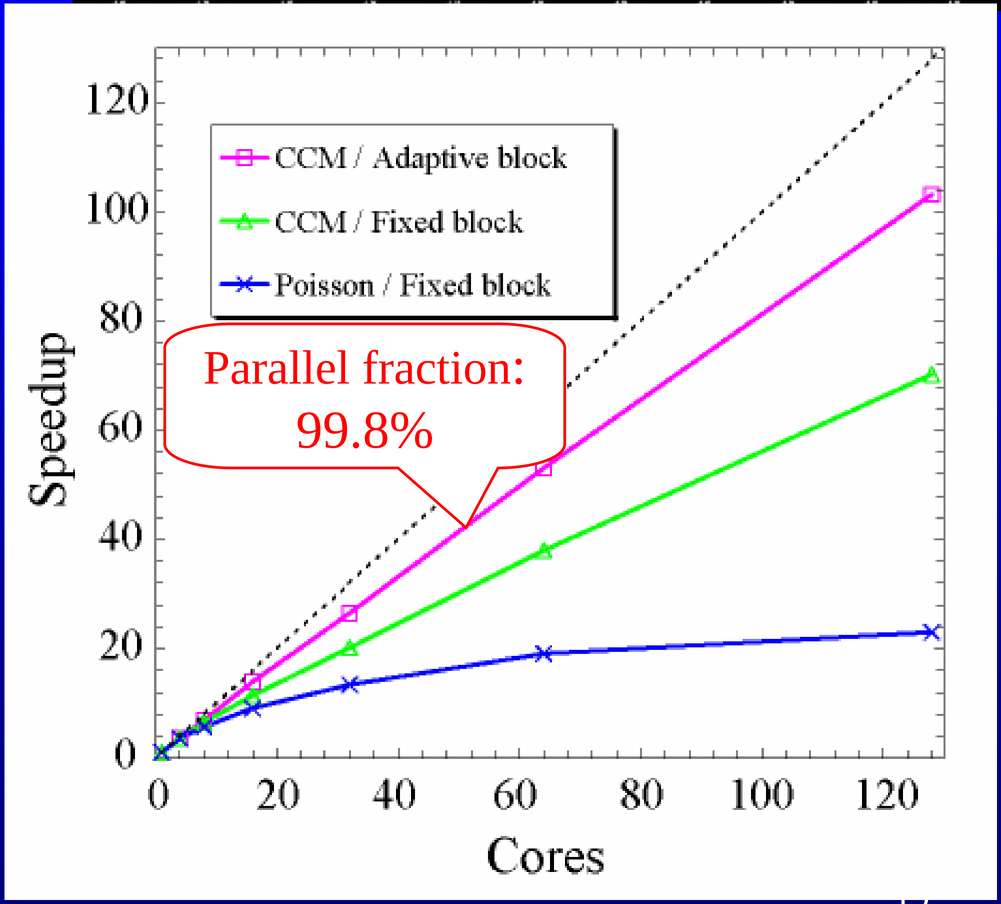
Massively Parallelized AMR-PIC Code

[*Fujimoto*, JCP, 2011]

Fujitsu FX1 *@Nagaya Univ.*

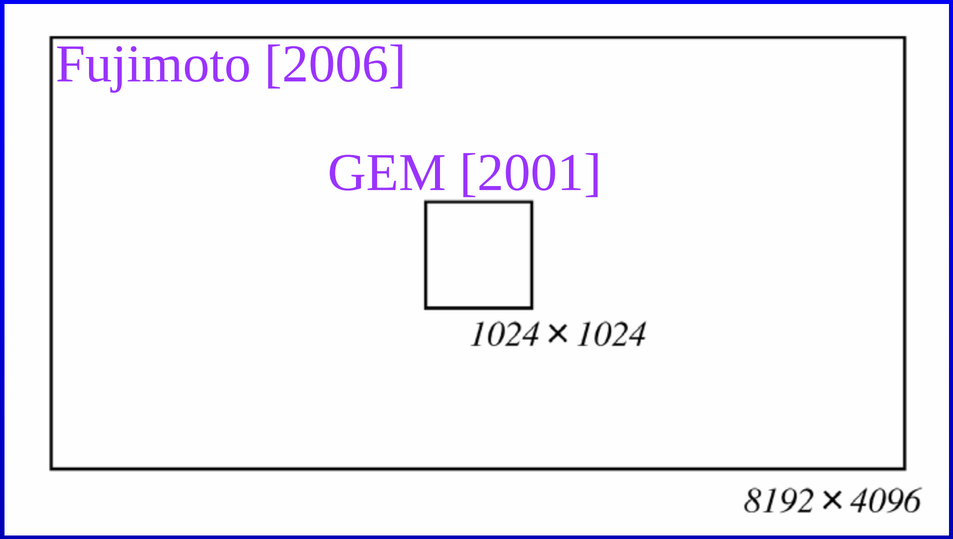


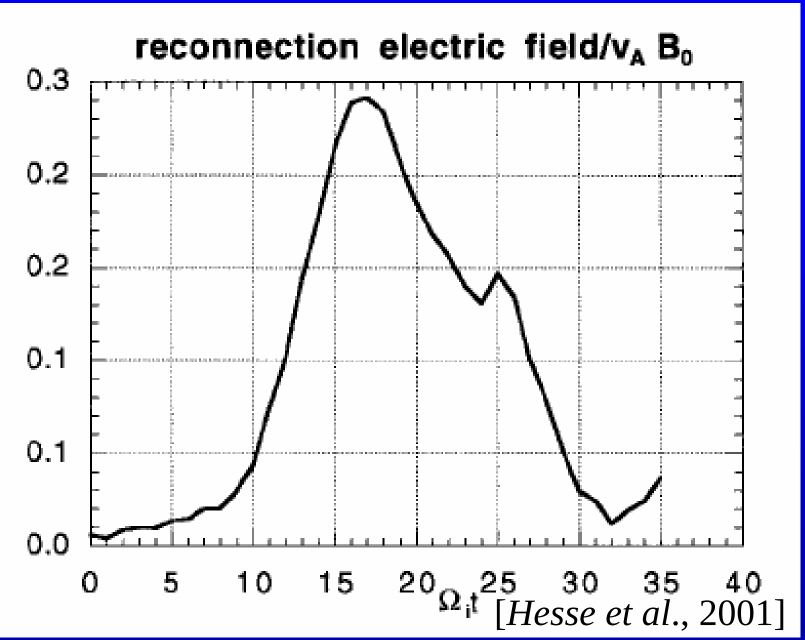




3. Large-Scale 2D Simulation

Target of This Study



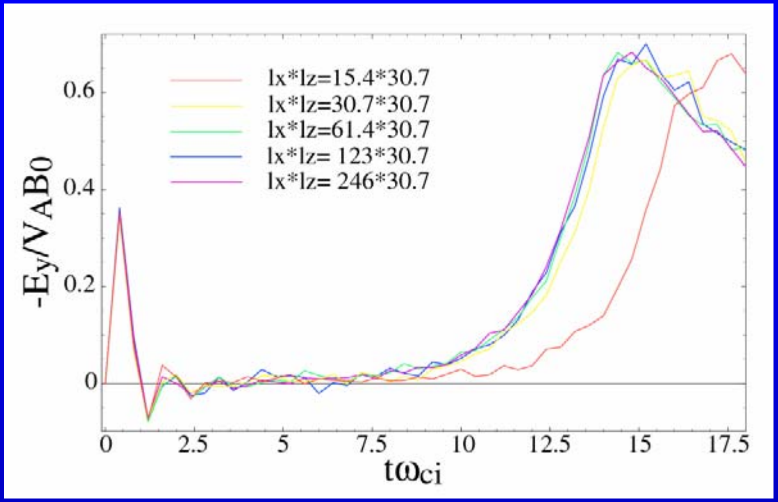


[*Hesse et al.*, 2001]

Does the inclusion of the Hall effect really lead to the fast reconnection?

→ **Large-scale simulations to exclude the boundary condition effects.**

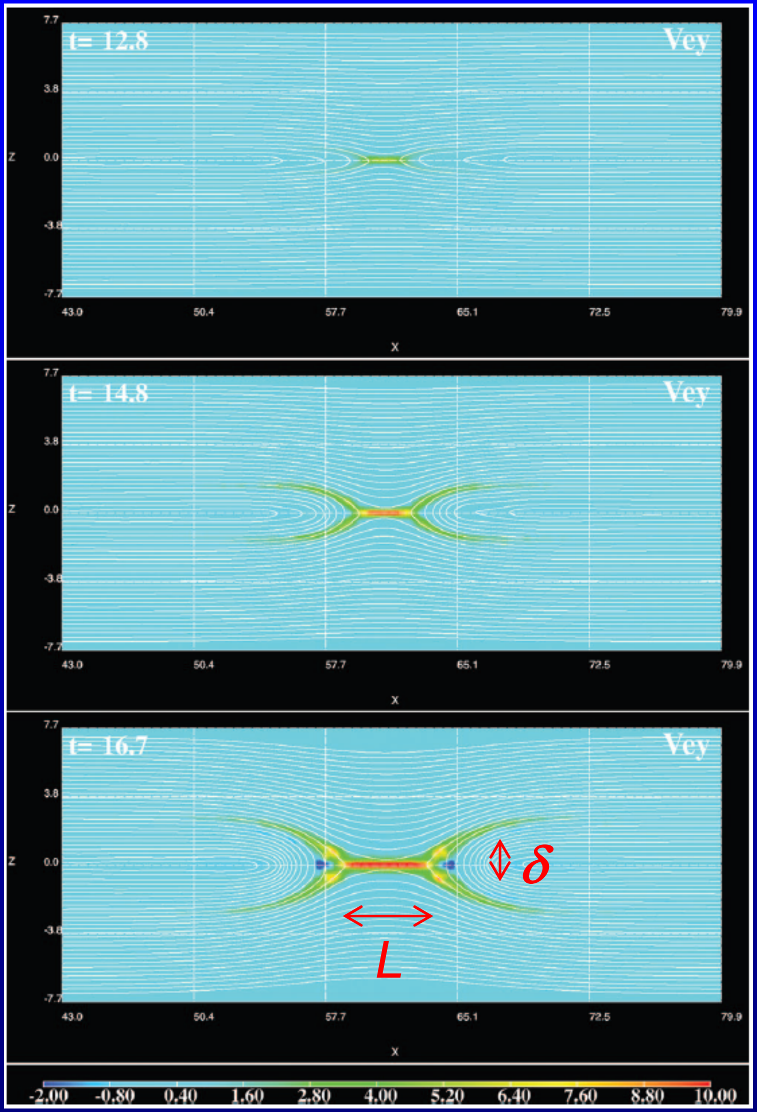
Simulation Results [*Fujimoto*, 2006]



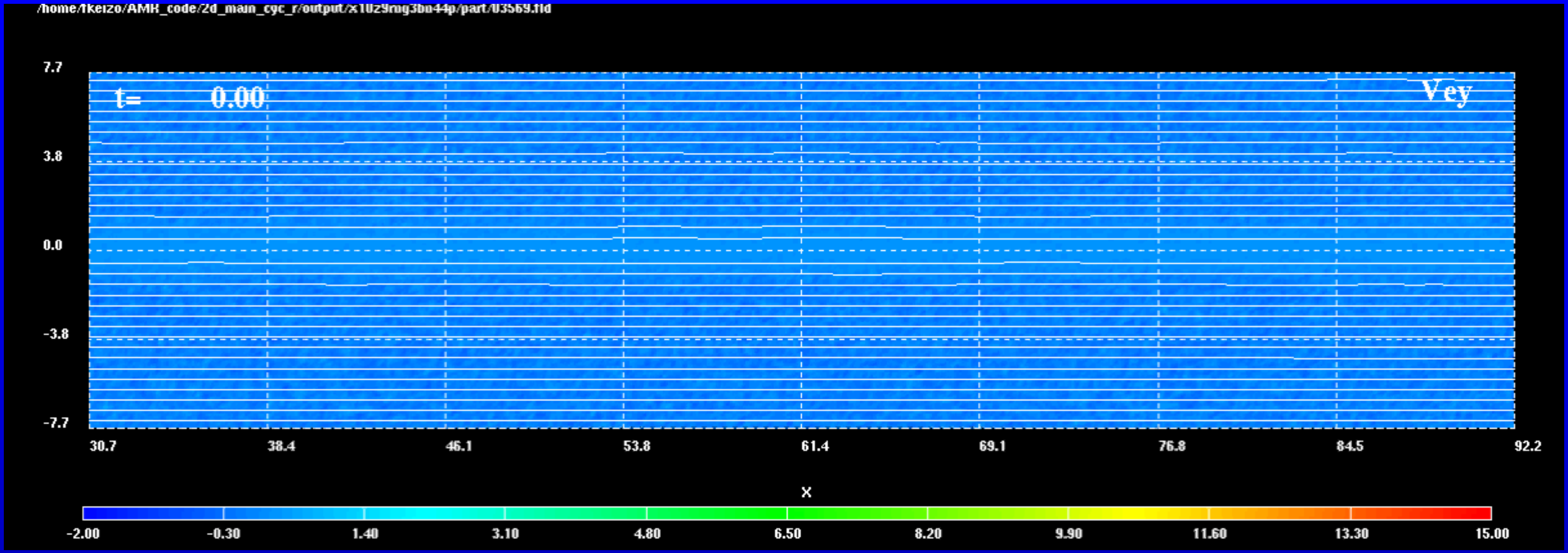
$$E_R \sim \frac{\delta}{L}$$

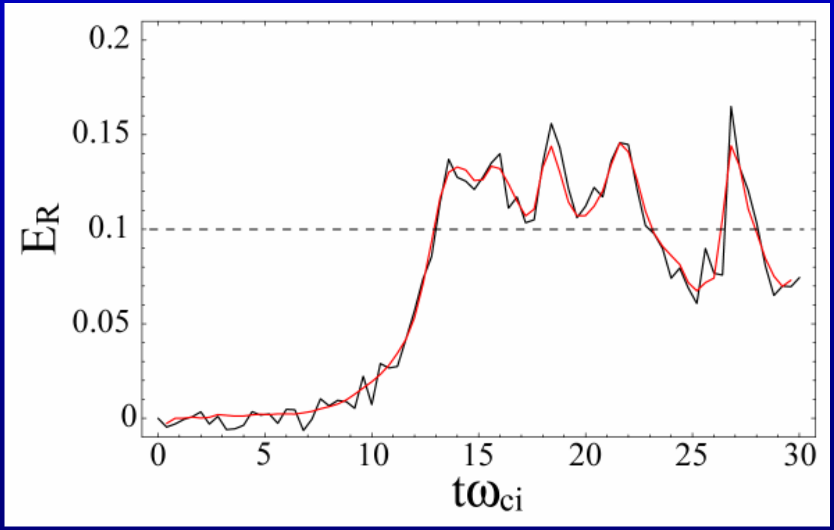
Elongation of the electron diffusion region

➡ Reduces the reconnection rate.



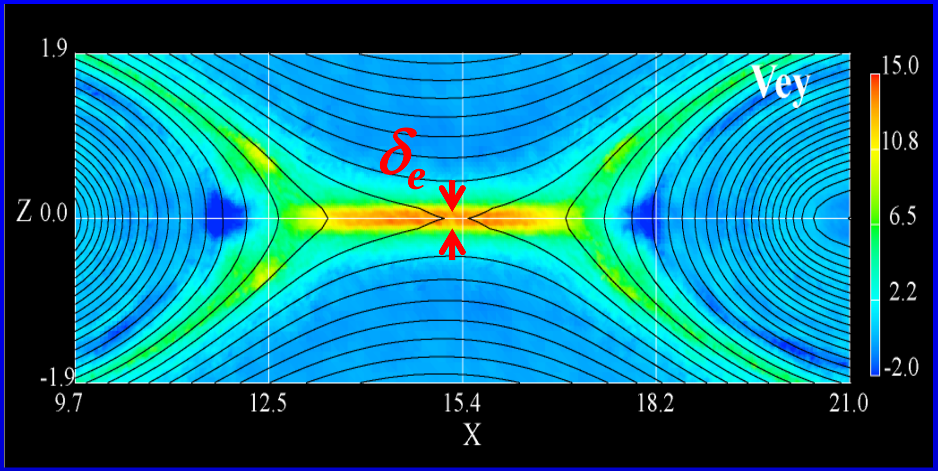
Plasmoid Ejection [*Daughton et al.*, 2006: *Klimas et al.*, 2008]

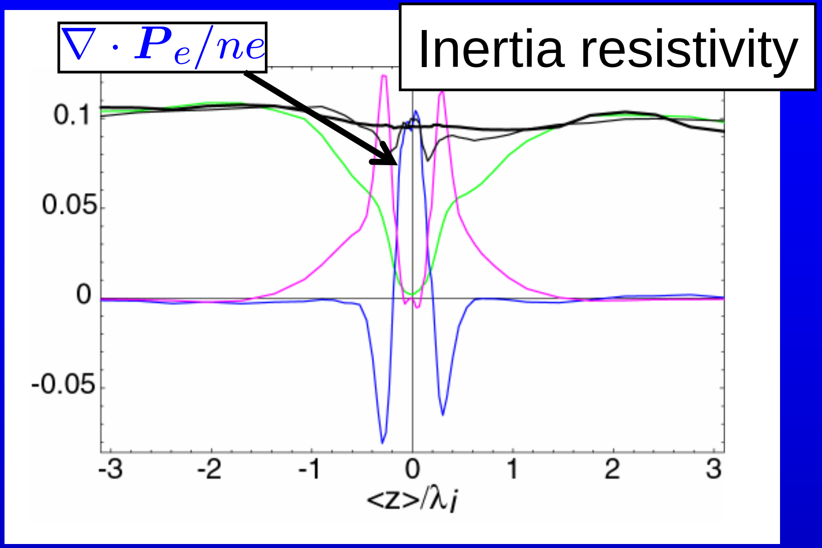




- The reconnection rate is enhanced associated with the plasmoid ejections.
- $E_R \sim 0.1$ on average.
- Mechanism of the plasmoid ejection and determining the reconnection rate is not clear.

Dissipation Mechanism in 2D Reconnection



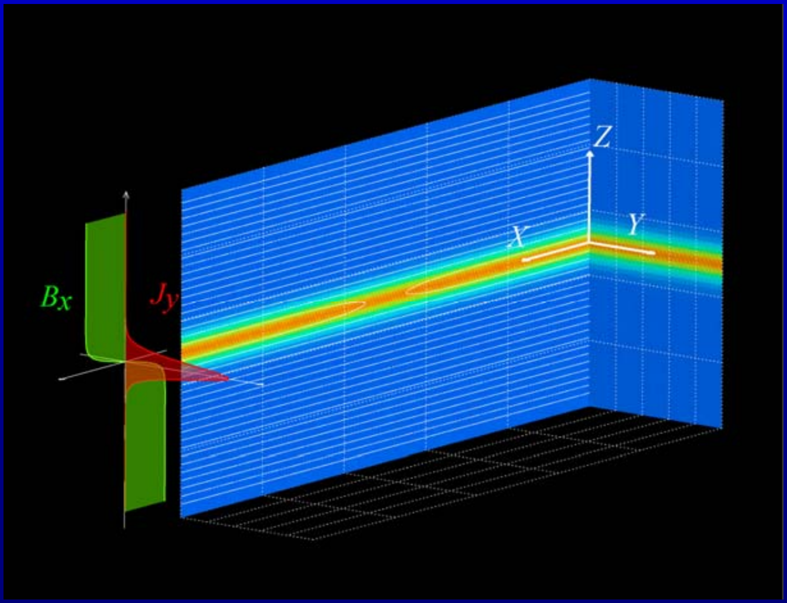


Intense current
Narrow current sheet

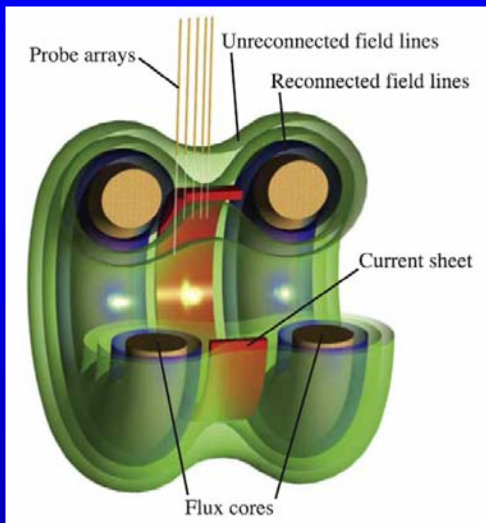
$\delta_e \sim \lambda_e = c/\omega_{pe}$

$V_d = V_e - V_i > 2\, v_{th,e}$

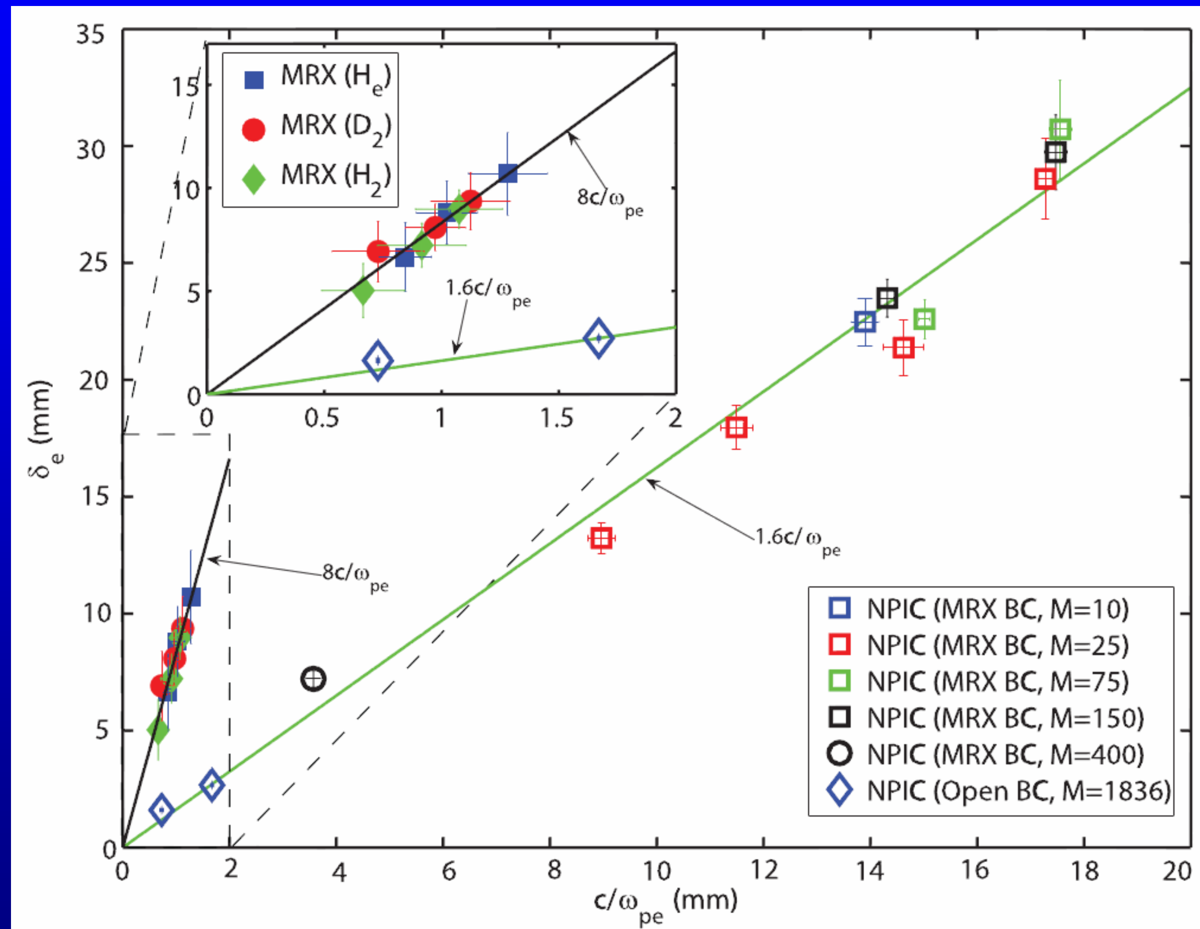
→ **Two-stream instabilities are expected.**



Implication of Anomalous Effects: Lab. Experiment

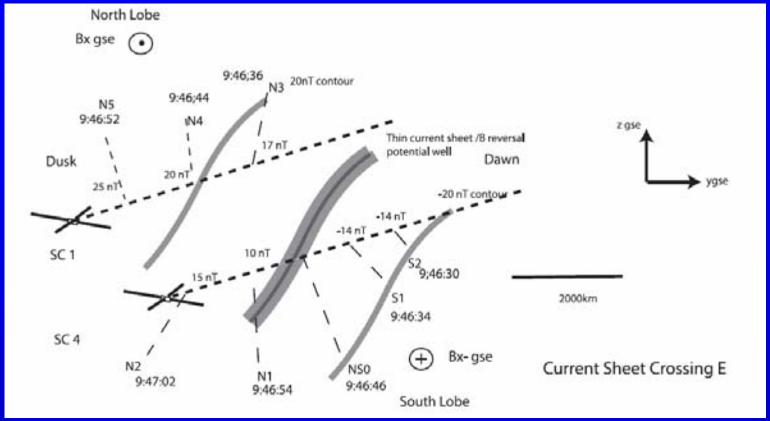


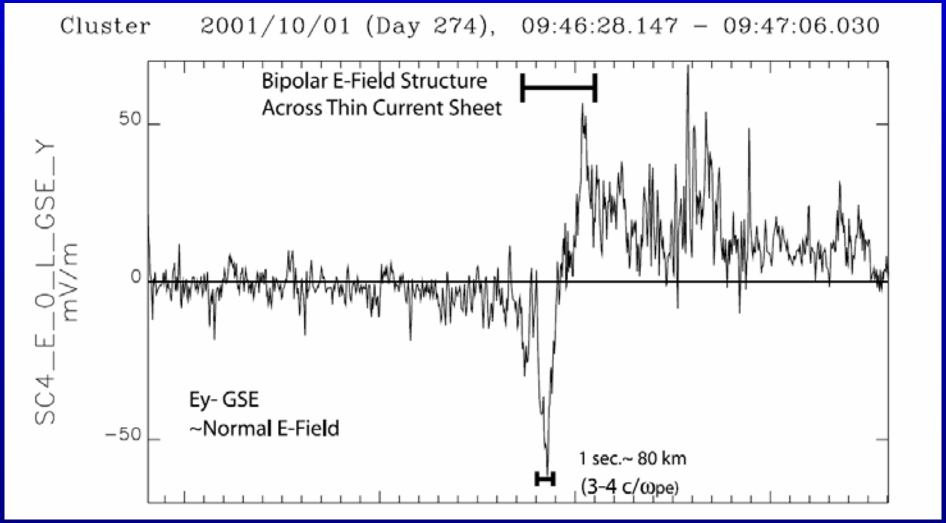
$\delta \gg c/\omega_{pe}$



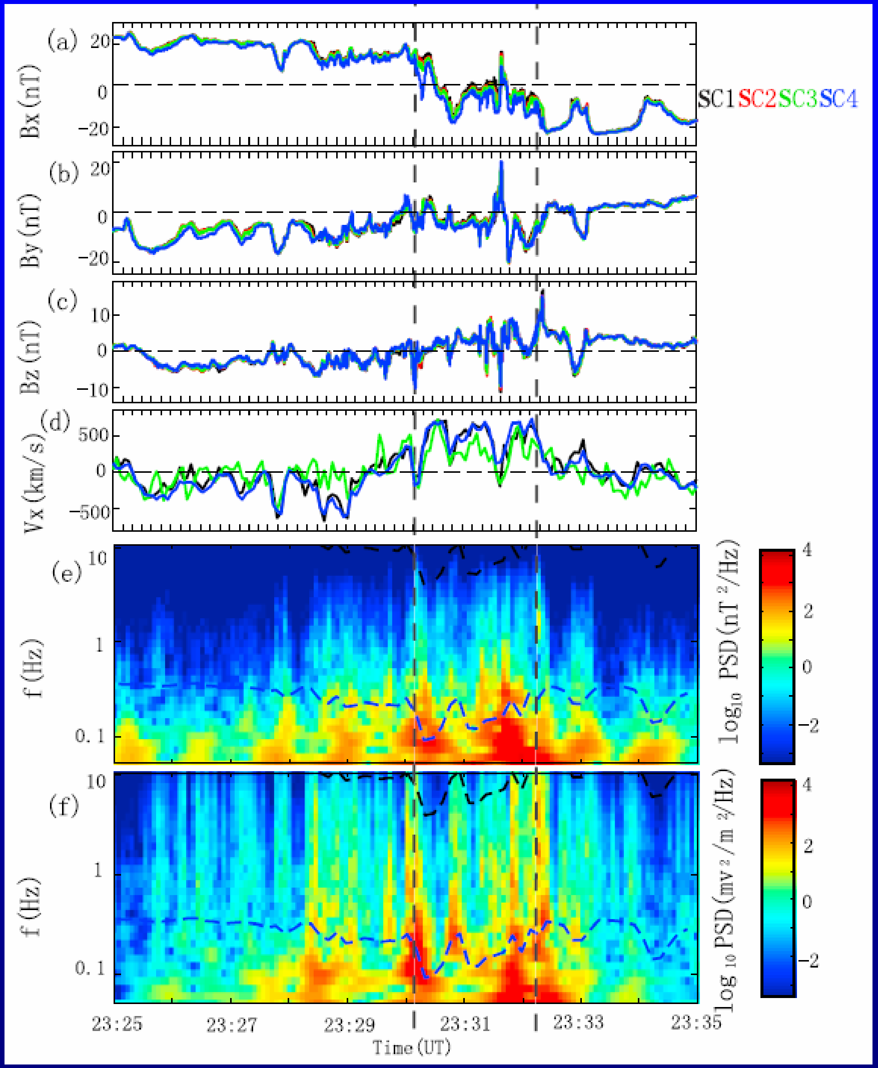
[*Ji et al.*, GRL, 2008]

Implication of Anomalous Effects: Satellite Observation





[*Wygant et al*, JGR, 2005]



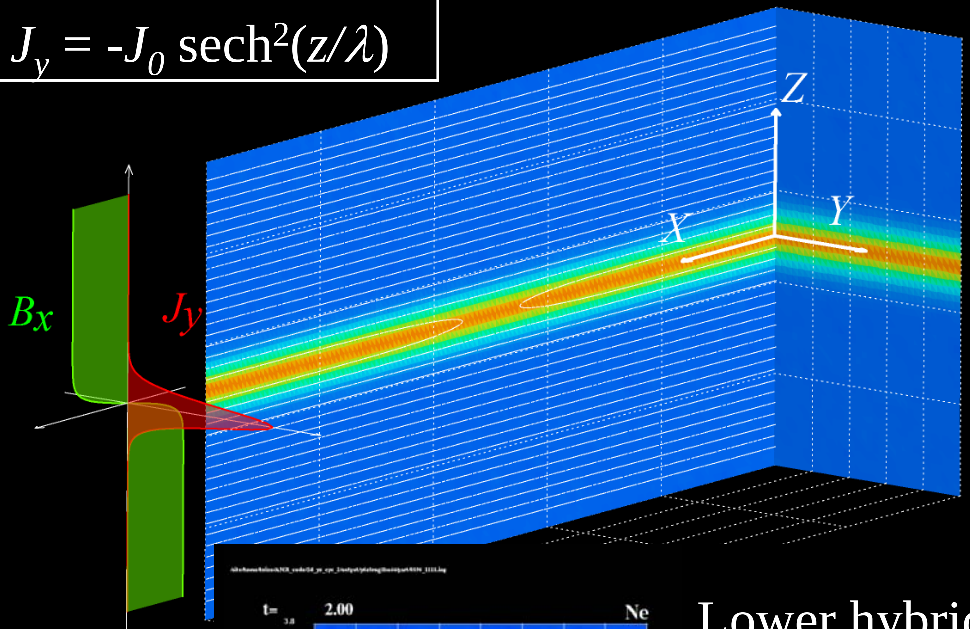
[*Zhou et al*, JGR, 2009]

4. Recent 3D Simulation Results

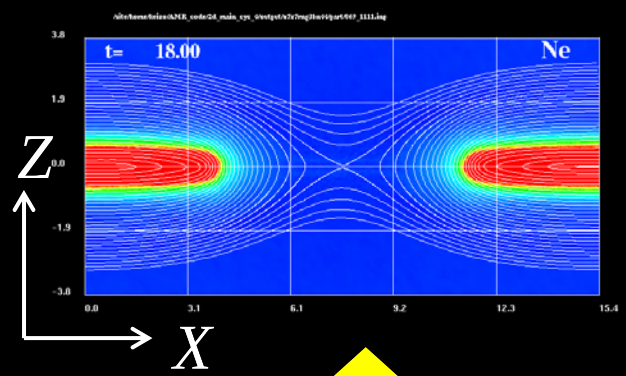
Instabilities in the Harris Current Sheet

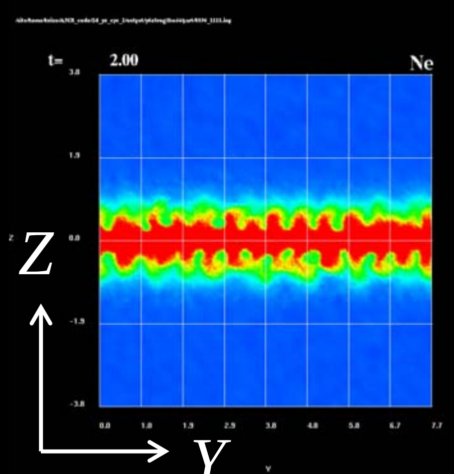
$B_x = -B_0 \tanh(z/\lambda)$

$J_y = -J_0 \,\mathrm{sech}^2(z/\lambda)$



Tearing instability

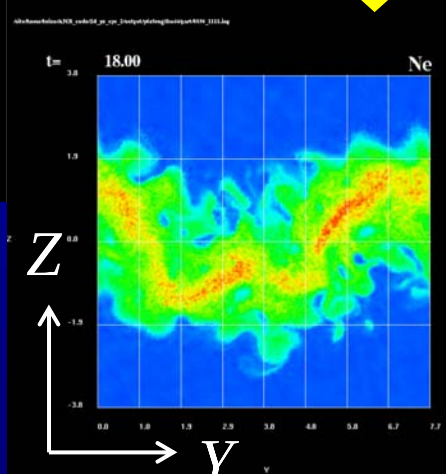




Lower hybrid drift instability (LHDI)

$k_y r_{Le} \sim 1$

$\gamma \sim \omega_{lh}$



Kink-type instability

$k_y L \sim 1$

3D Reconnection Research

- **LHDI and magnetic reconnection**

  Enhances the tearing mode growth rate [*Scholer et al.* (2003), *Ricci et al.* (2004)],

  No impact on the quasi-steady process [*Zeiler et al.*, (2002), *Fujimoto* (2009)].

- **Kink-type instability and magnetic reconnection**

Drift mode:

- Drift kink ($k\delta \sim 1$, $\omega \sim \omega_{ci}$) [*Pritchett & Coroniti*, 1996]
- Current sheet kink instability ($k(\lambda_i\lambda_e)^{1/2} \sim 1$) [*Suzuki et al.*, 2002]
- Electromagnetic LHDI ($k(\rho_i\rho_e)^{1/2} \sim 1$) [*Daughton*, 2003]

Triggers magnetic reconnection [*Horiuchi & Sato* (1999), *Scholer et al.* (2003)],

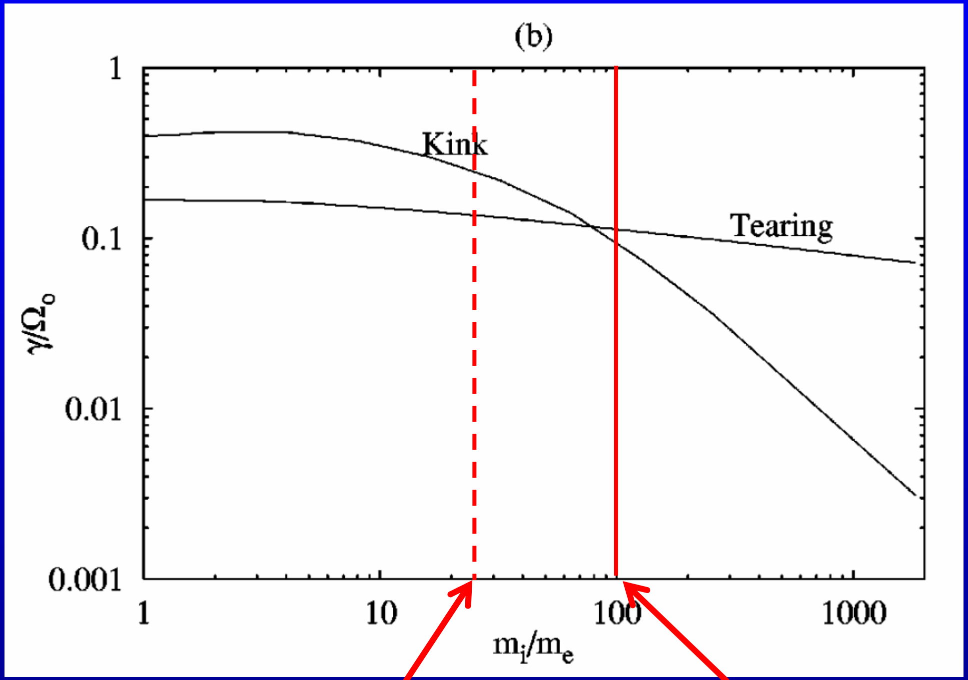
No impact on the quasi-steady process [*Pritchett & Coroniti* (2001), *Karimabadi et al.* (2003)],

Gives anomalous dissipation during the quasi-steady reconnection [*Fujimoto* (2009, 2011)].

Mass Ratio Dependence of Kink Mode

$k\delta = 1$ (δ: Half width of the current sheet)

[*Daughton*, POP, 1999]



Particle simulation

Cost $\propto (m_i/m_e)^{5/2}$

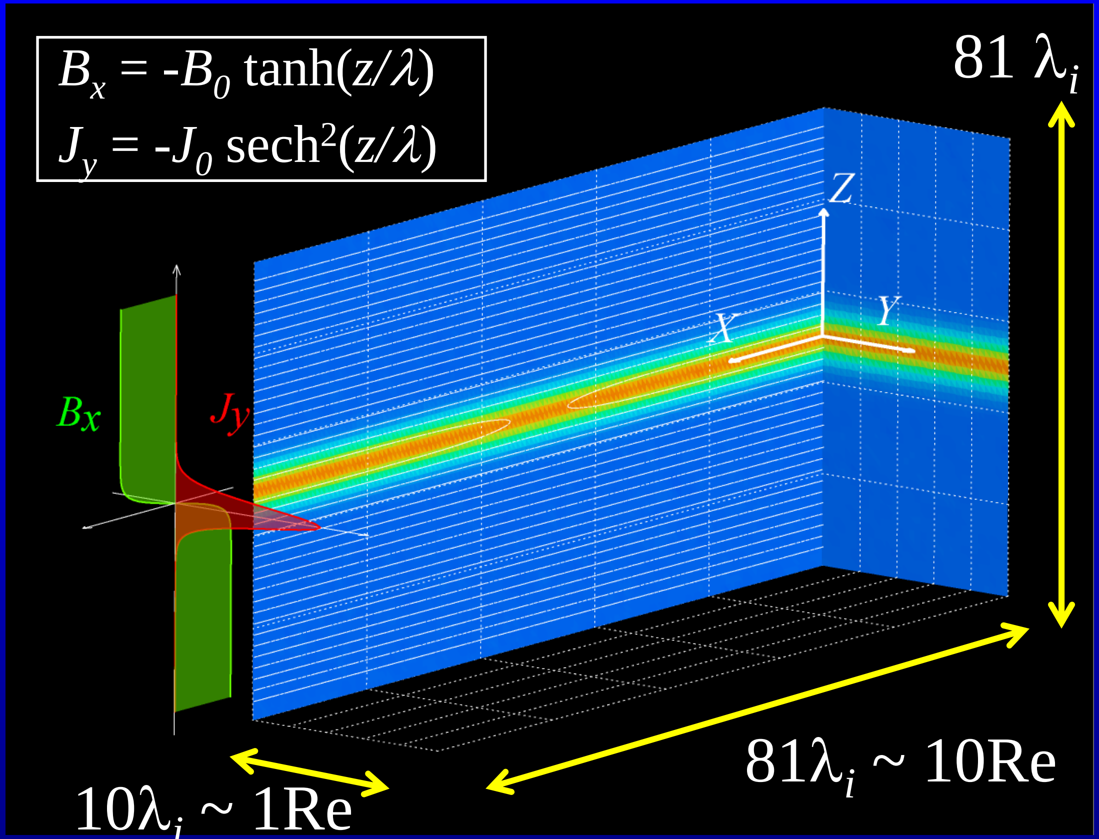
Fujimoto (2009; 2011)

$m_i/m_e = 25$

Target in this study

$m_i/m_e = 100$

Simulation Setup



$m_i/m_e = 100$

Max resolution:
$4096 \times 512 \times 4096 \sim 10^{10}$

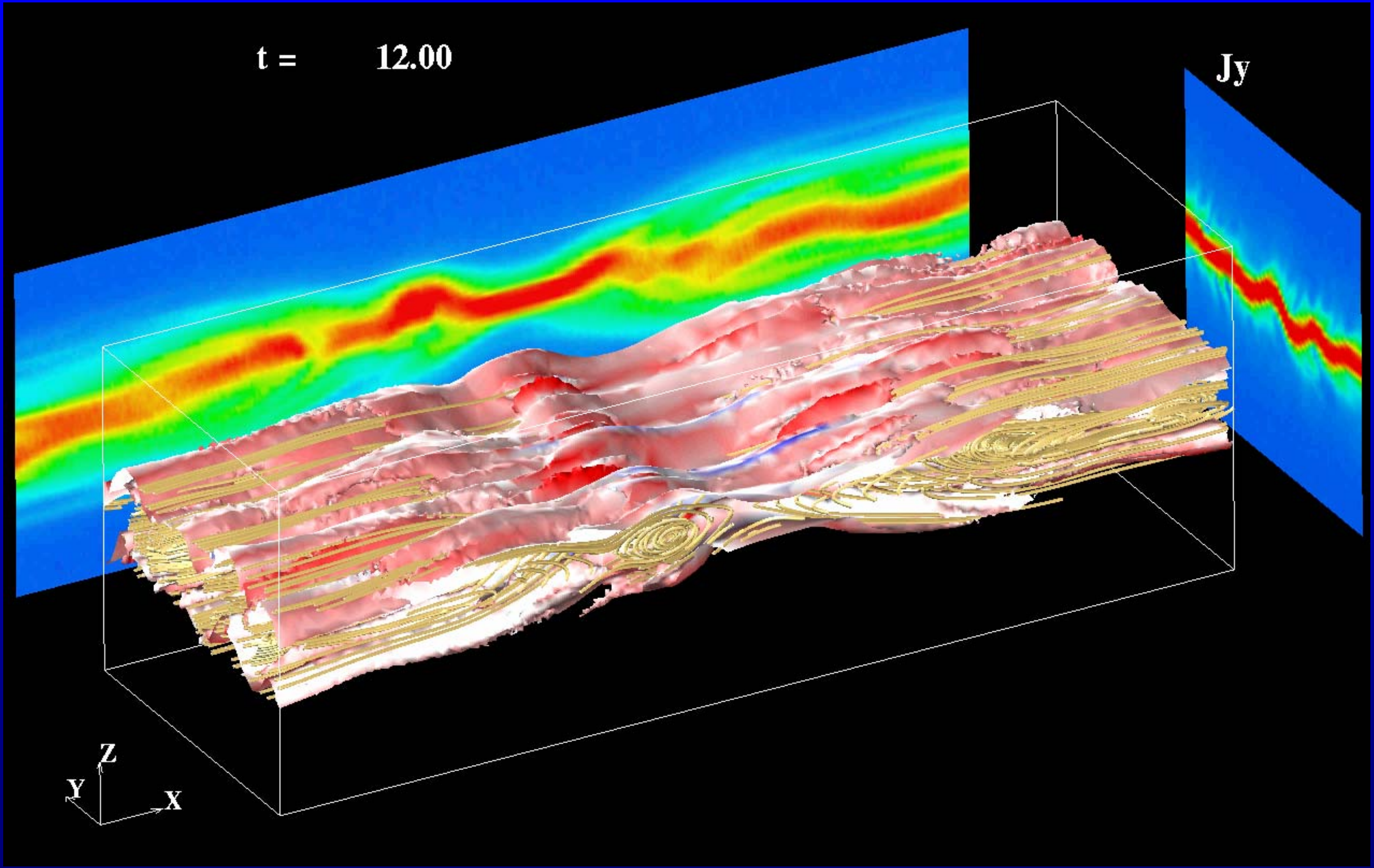
Max number of particles
Ion + Electron ~ 10^{11}

Max memory used ~ 6TB

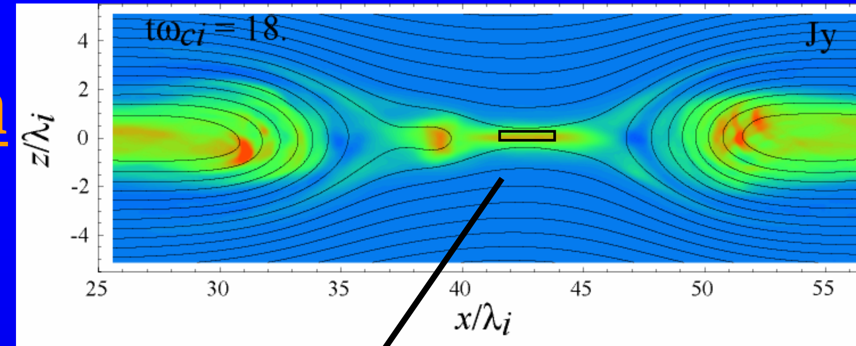
Time Evolution of the Current Sheet

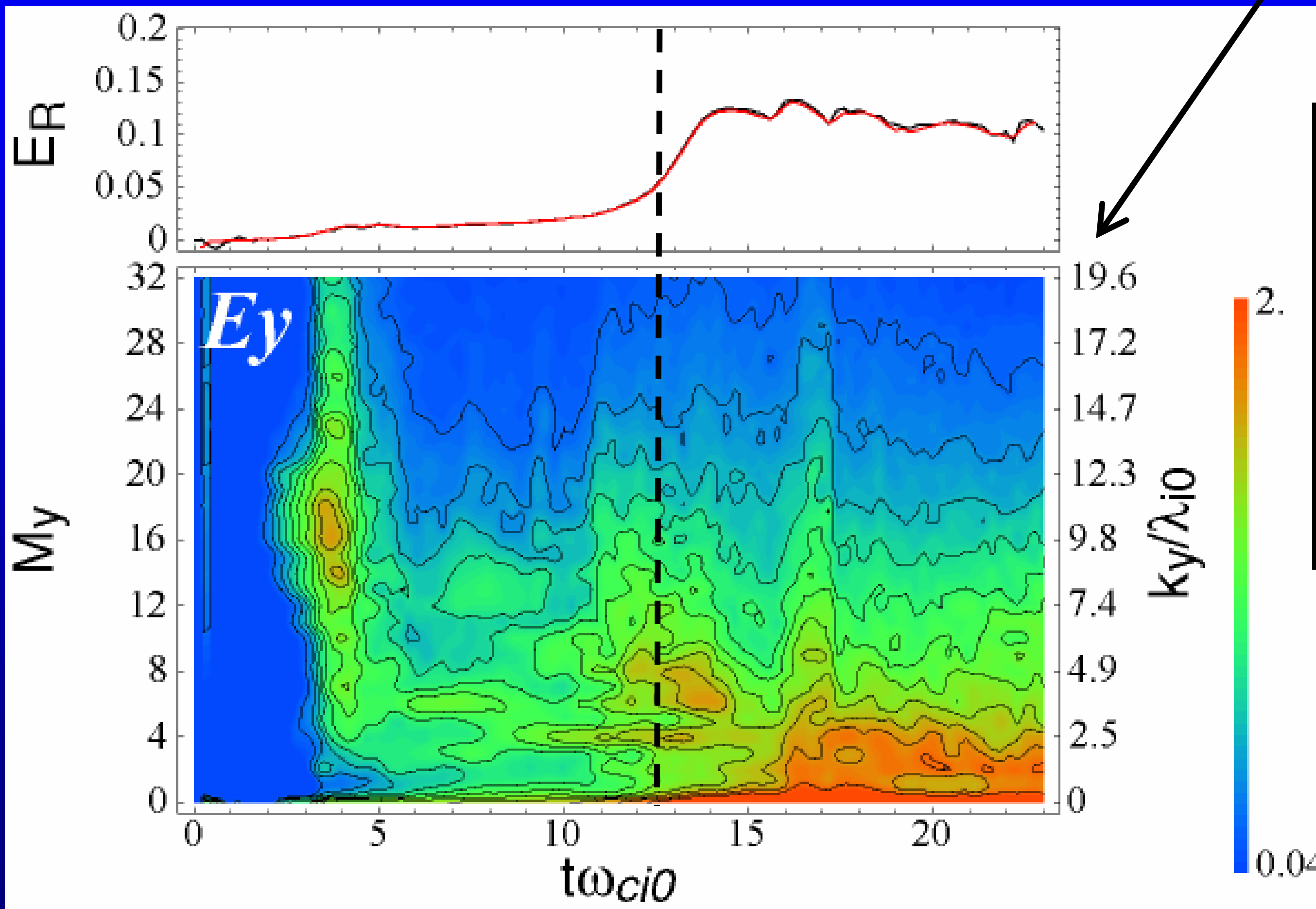
Surface: |J|, Line: Field line

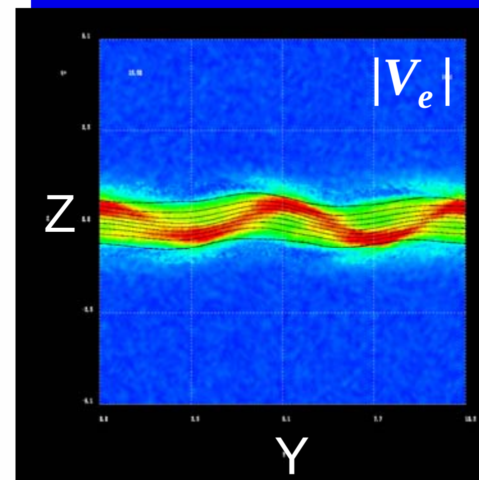
Color on the surface: Ey, Cut plane：Jy



Wave Number Spectrum







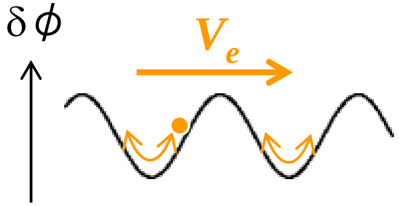
Wave-Particle Interactions

$$A = \langle A \rangle + \delta A \qquad \left(\langle \cdot \rangle = \frac{1}{L_y} \int_0^{L_y} \cdot \, dy \right)$$

$$\langle -E_y \rangle = \frac{1}{\langle n_e \rangle} \left(\langle n_e \vec{V}_e \rangle \times \langle \vec{B} \rangle \right)_y + \frac{1}{e \langle n_e \rangle} \left\langle \nabla \cdot \vec{P}_e \right\rangle_y + \frac{m_e}{e \langle n_e \rangle} \left\langle \frac{\partial V_{ey}}{\partial t} + \vec{V}_e \cdot \nabla V_{ey} \right\rangle + \frac{1}{\langle n_e \rangle} \langle \delta n_e \delta E_y \rangle + \frac{1}{\langle n_e \rangle} \left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle_y$$

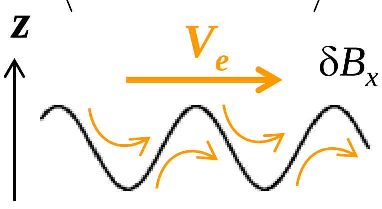
Anomalous effects

$\langle \delta n_e \delta E_y \rangle$

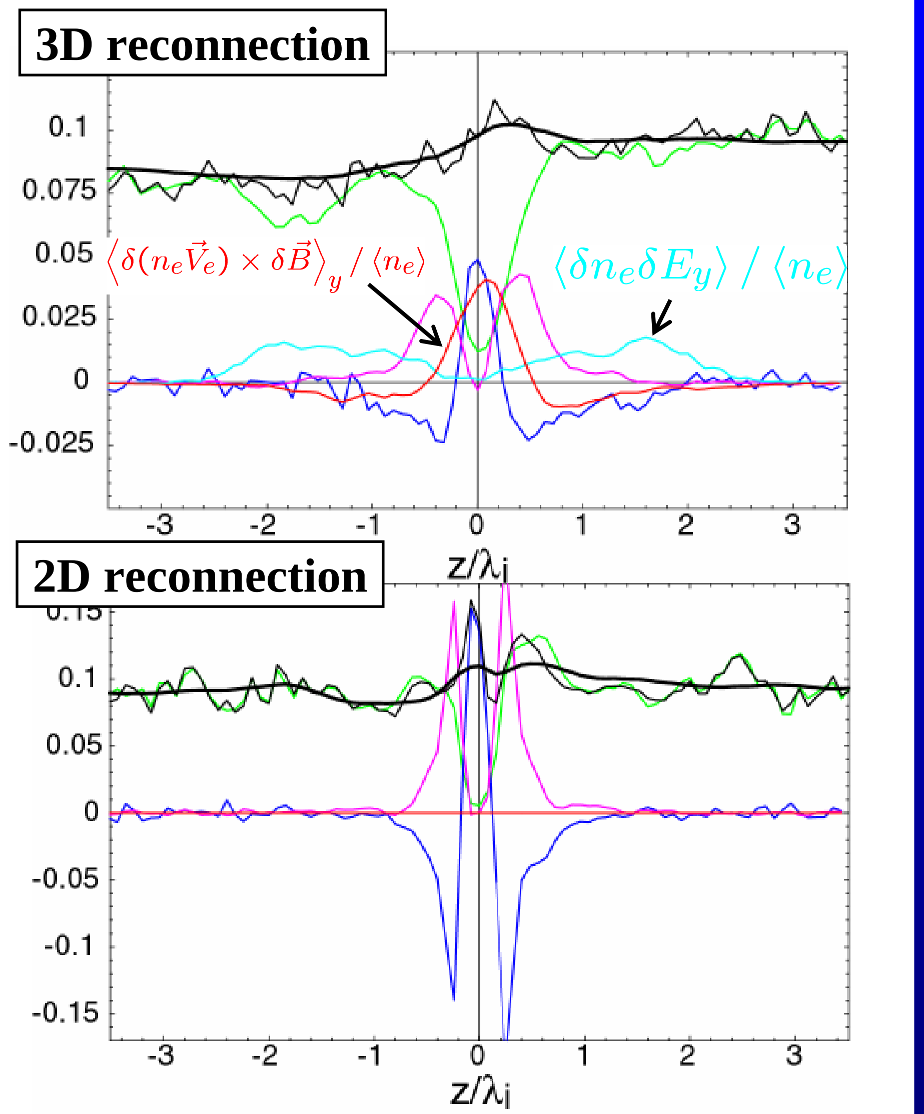


ES turb.

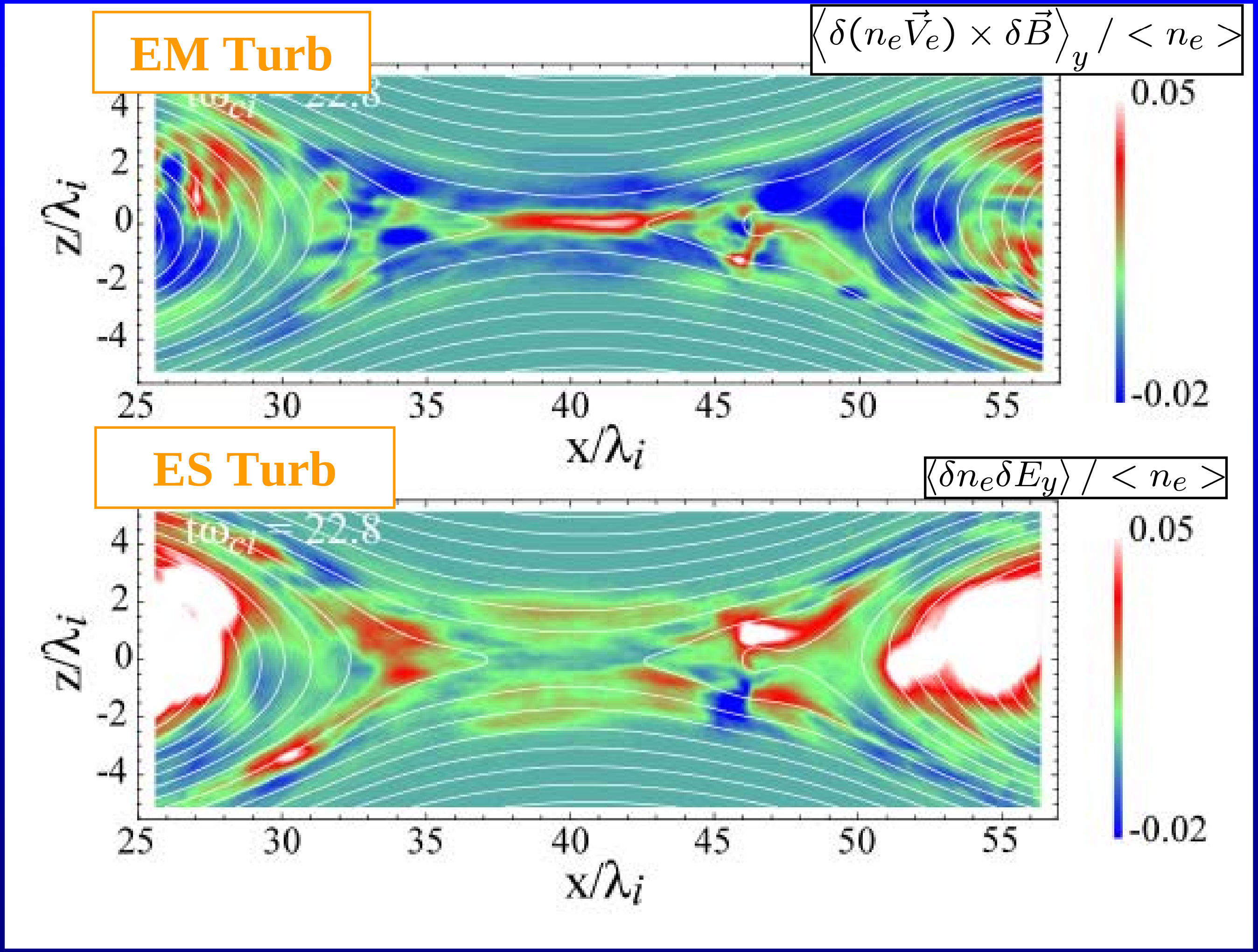
$\left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle$



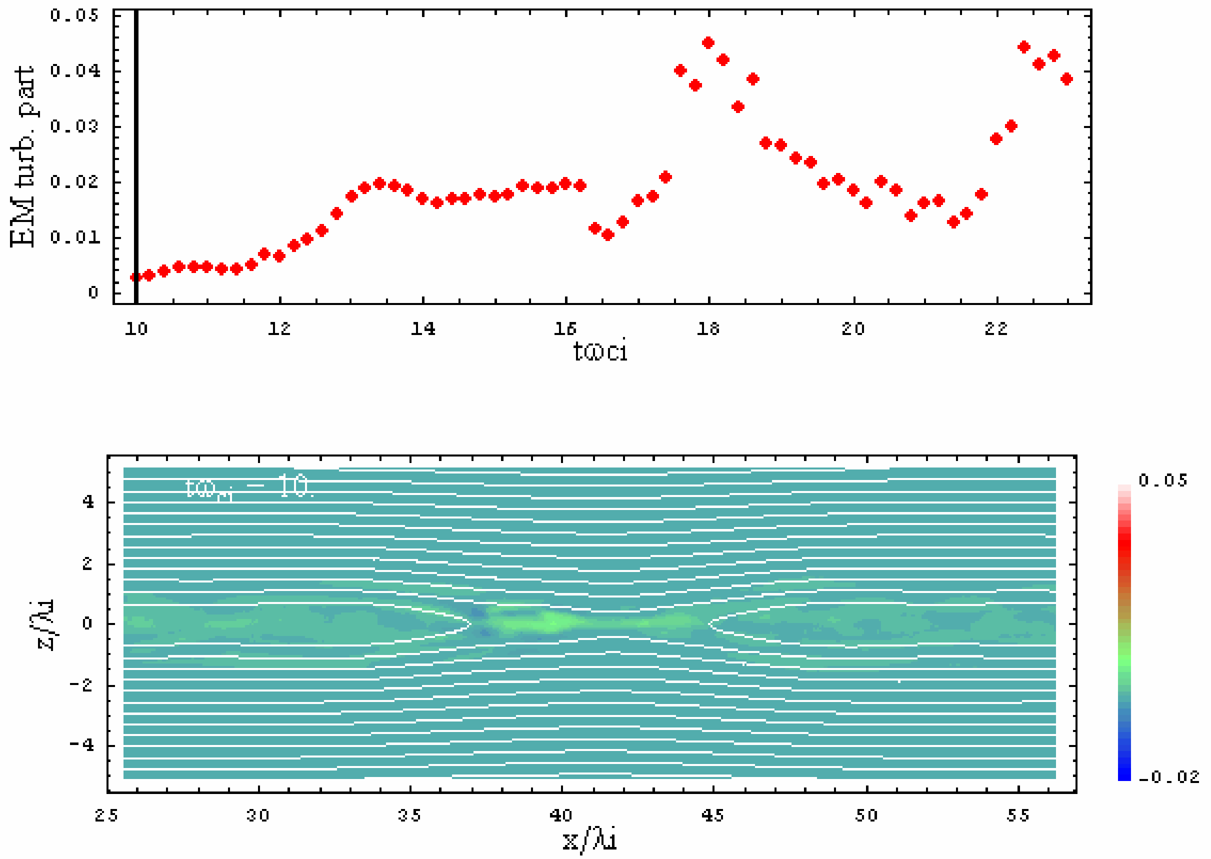
EM turb.



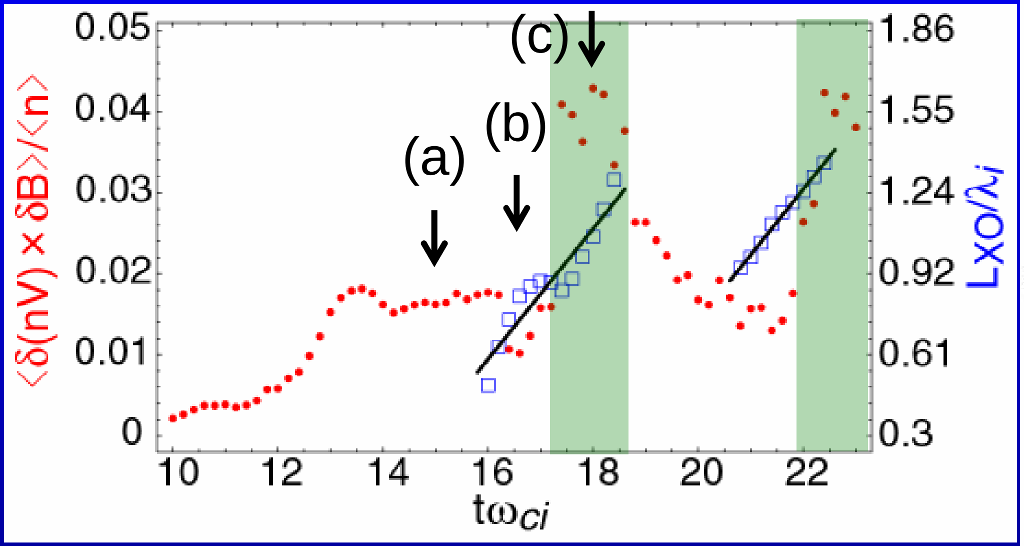
EM vs. ES Turbulence Effects

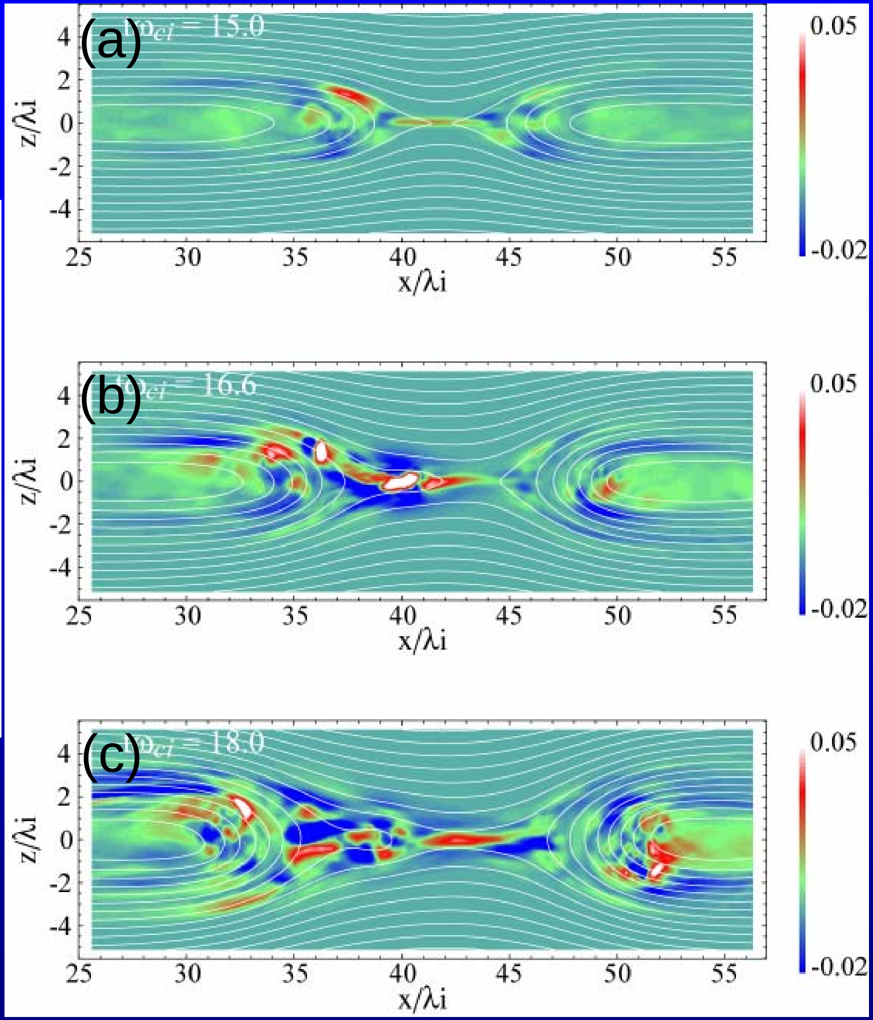


EM Turbulence Effect at the X-line

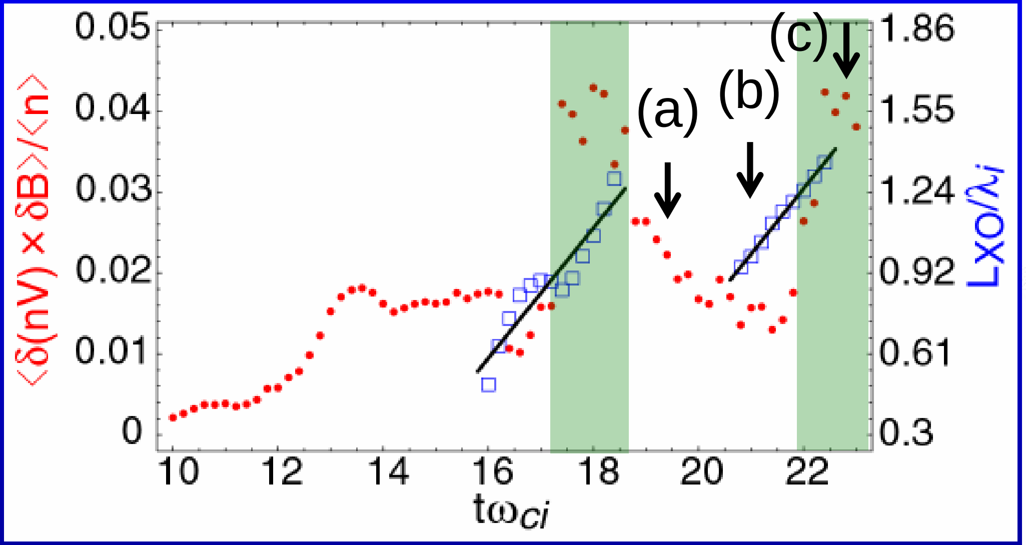


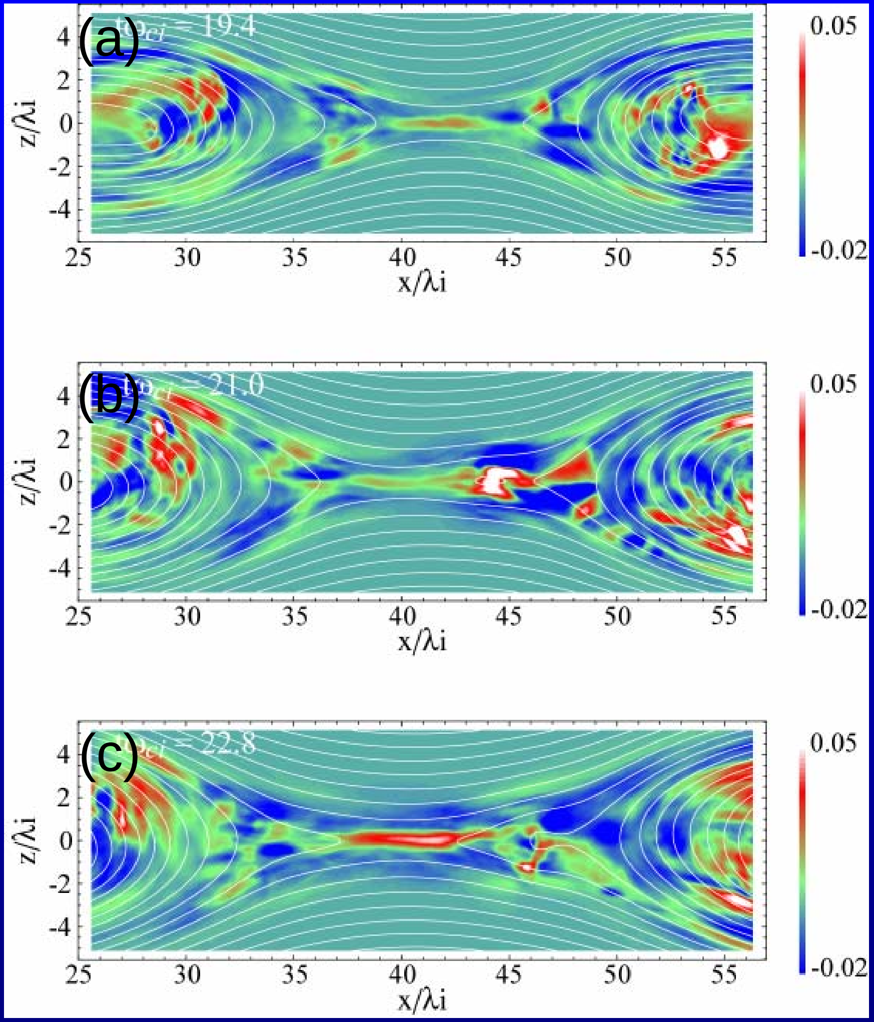
Plasmoid-Induced Turbulence I





Plasmoid-Induced Turbulence II

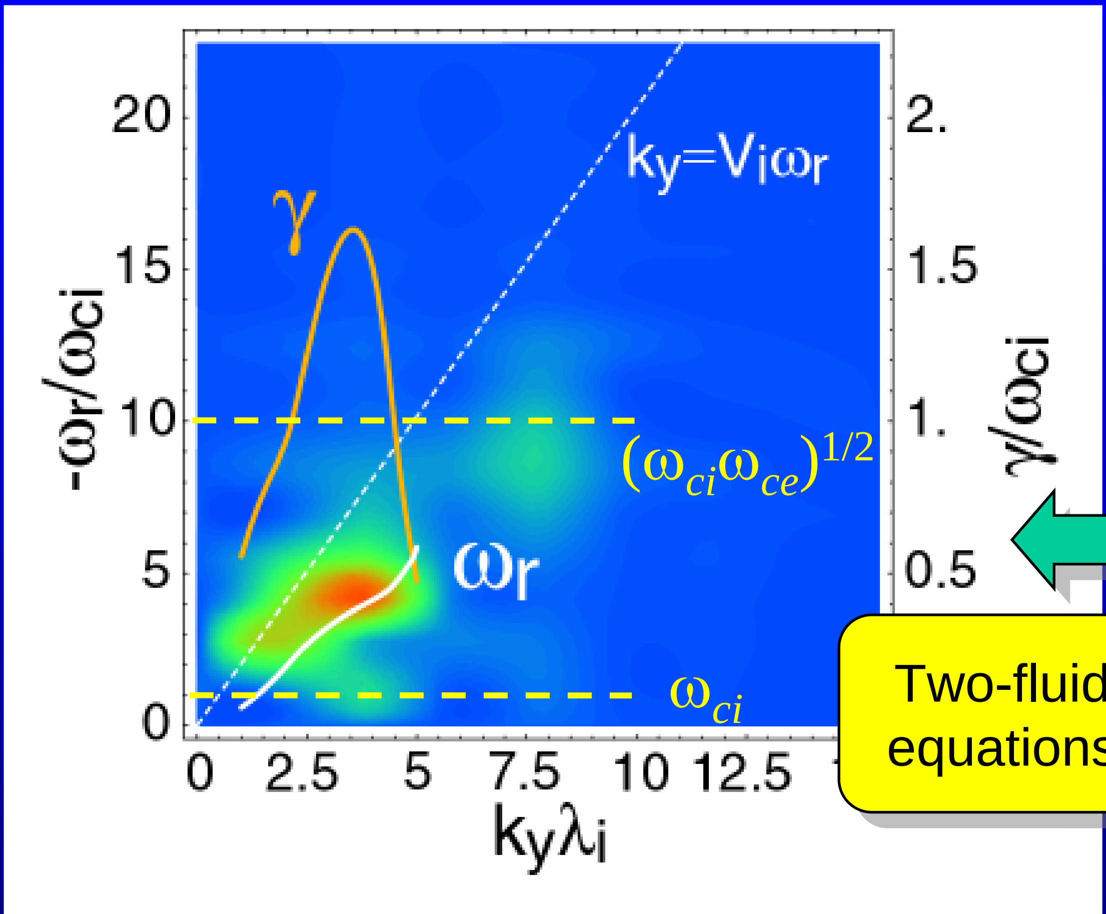




Wave Properties

In collaboration with R. Sydora (U. Alberta)

$\omega = \omega_r + i\gamma$



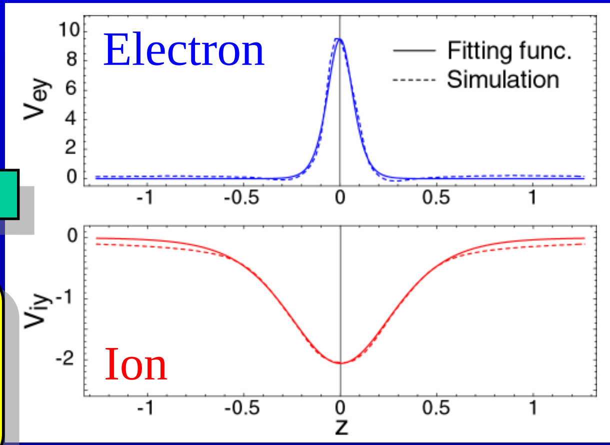
Two-fluid equations

Simulation results

$$\omega_{ci} < |\omega_r| < (\omega_{ci}\omega_{ce})^{1/2}$$

$$V_{ph} \approx V_A$$

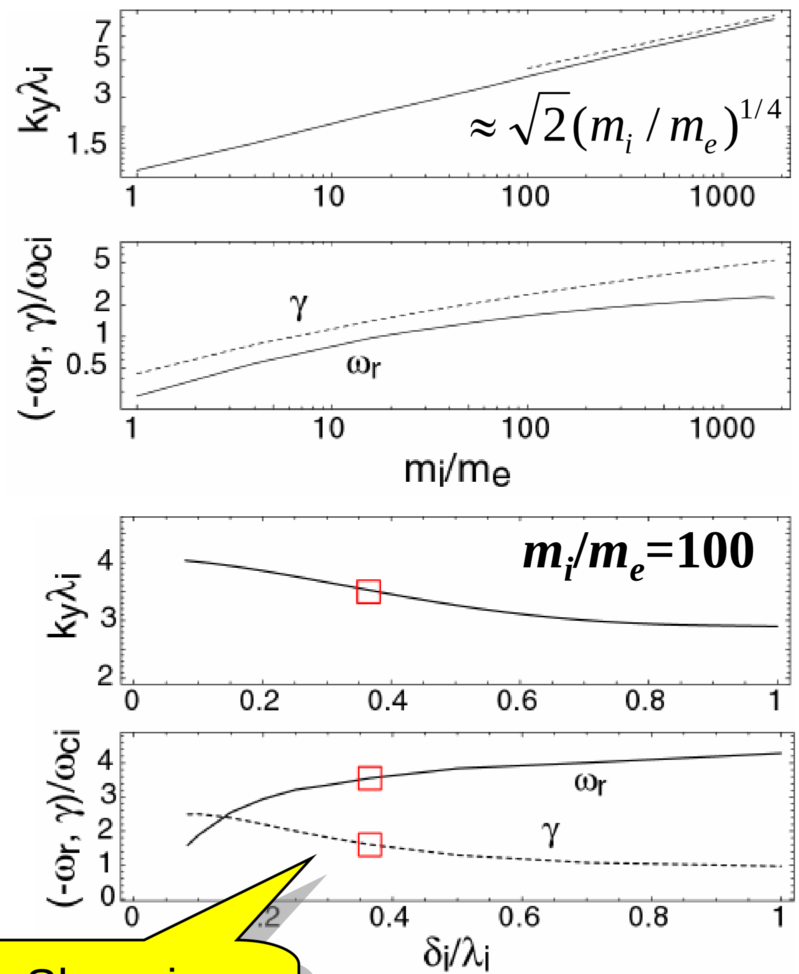
Linear analyses

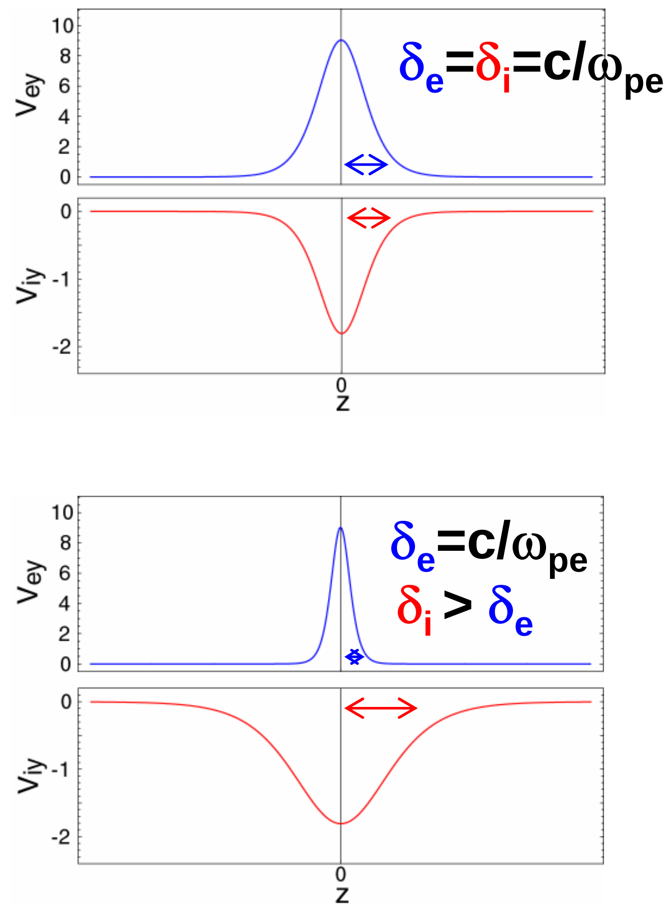


Inconsistent with drift mode property

$$V_{ph} \neq \frac{m_iV_i + m_eV_e}{m_i + m_e}$$

Wave Properties: Linear Analyses





Shear is important factor.

The wave is expected to arise for m_i/m_e=1836.

Summary

The present study has investigated the steady-state process of the fast magnetic reconnection using the newly developed AMR-PIC code.

- **2D reconnection**

  The electron diffusion region is elongated in the outflow direction, which throttles the reconnection process. The plasmoid ejection plays a key role in enhancing the reconnection rate.

- **3D reconnection**

  A low-frequency EM mode arises in the current density direction, which causes the anomalous force around the x-line. The plasmoid ejection is again important in enhancing the turbulence.

  Further investigation is needed to understand the nature of the EM mode