3Dリコネクション：プラズモイドによって誘発された乱流効果

3D Reconnection: Plasmoid-Induced Turbulence Effect

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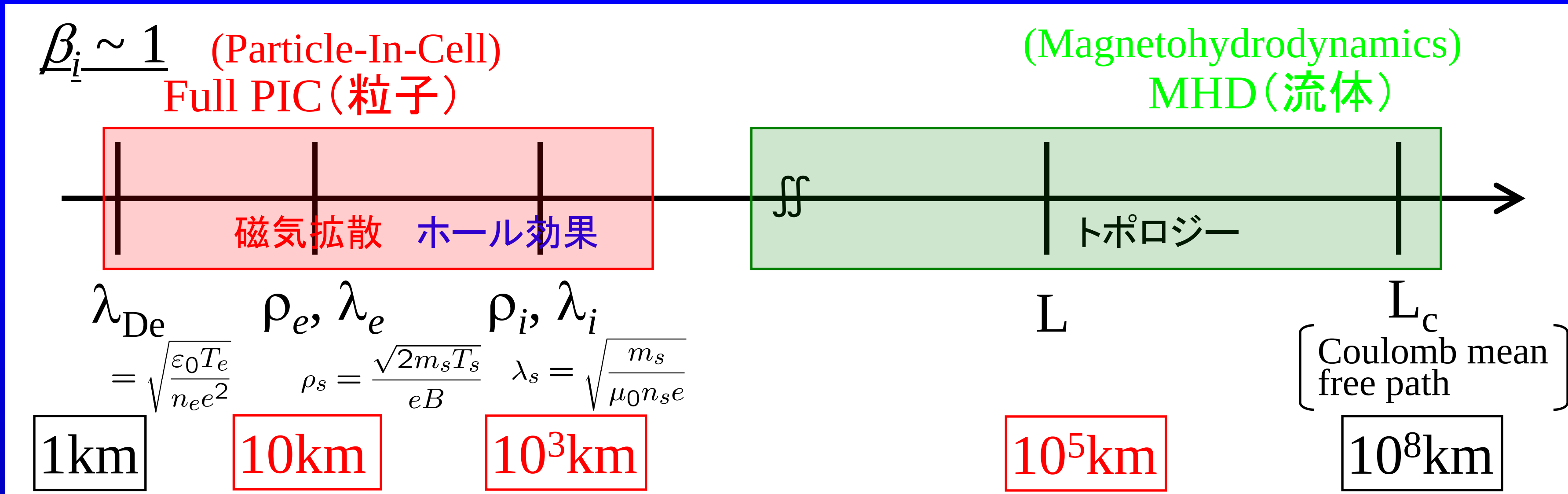
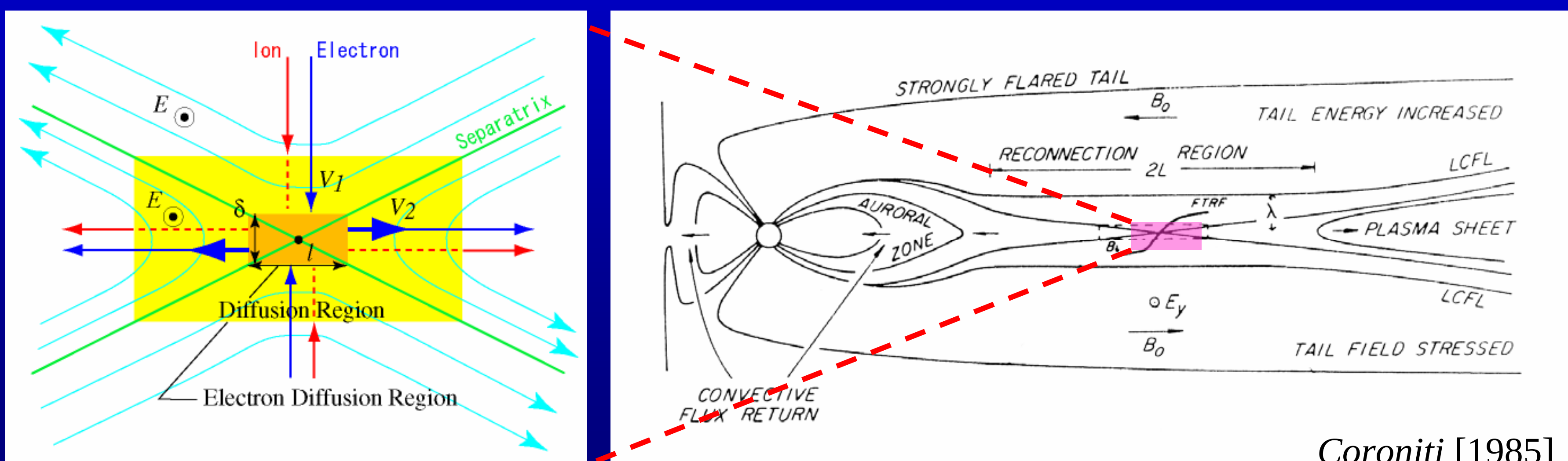
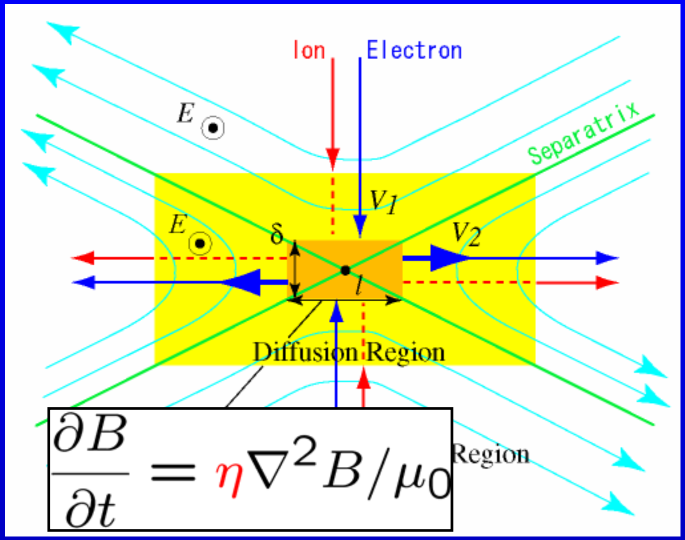
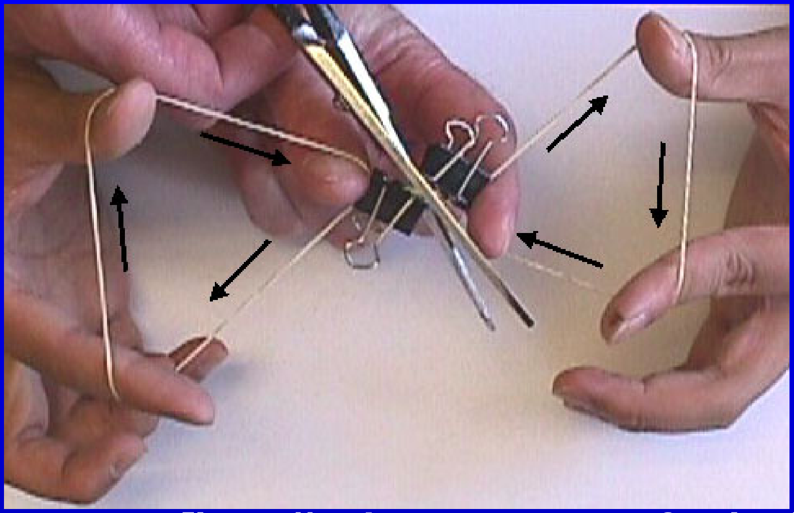
Multi-Scale Nature of Magnetic Reconnection





Impact of Dissipation Mechanism





[http://solar-center.stanford.edu/]

The reconnection rate depends on the resistivity model.

(Biskamp,1986; Ugai, 1995)

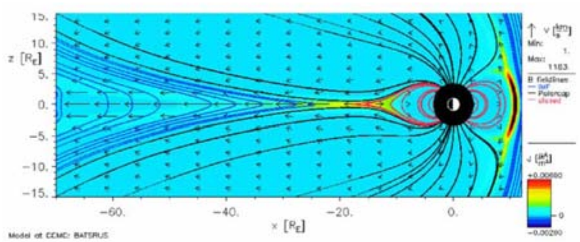
Global responses in substorm and flares are sensitive to the parameterization of the resistivity.

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

Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

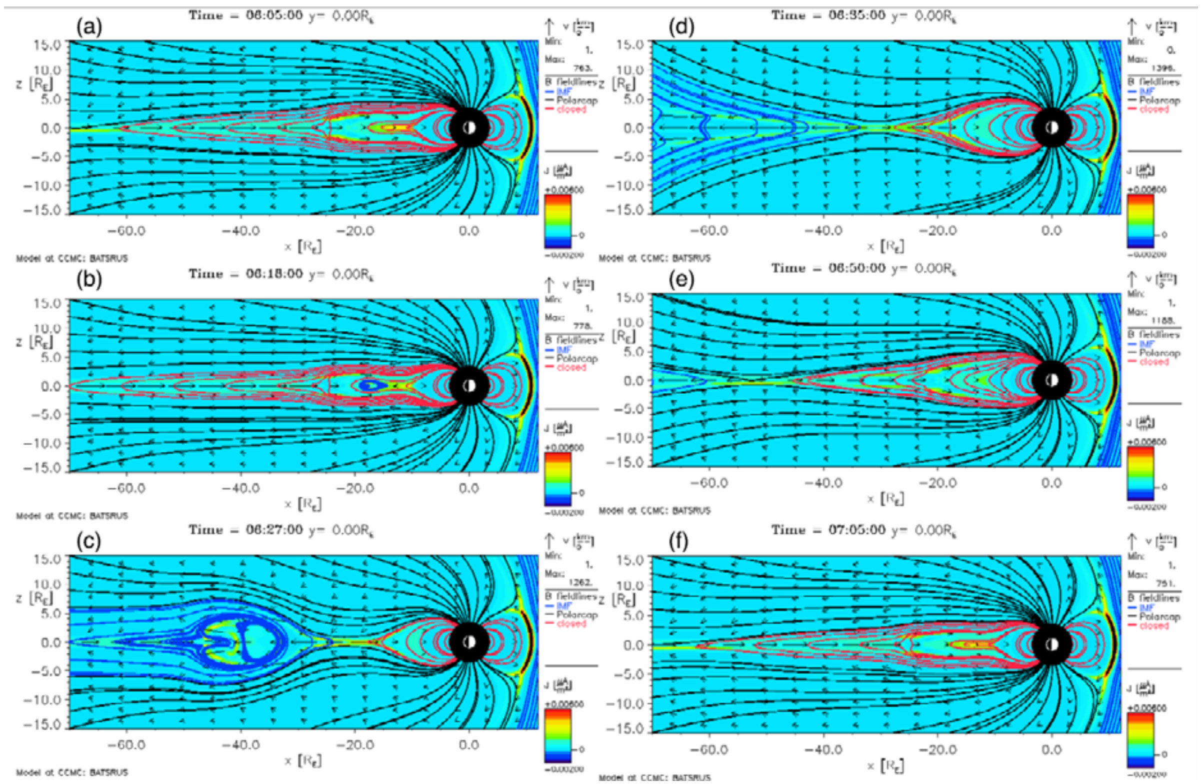


- Slow reconnection
- Quasi-steady configuration

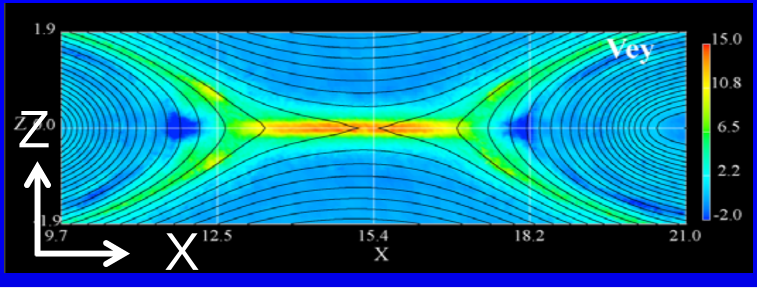
- Fast reconnection
- Quasi-periodic process

Nongyrotropic correction case

$$E^{ng} = \frac{1}{ne}\left(\frac{\partial P_{ixy}}{\partial x} + \frac{\partial P_{ixz}}{\partial z}\right) = \frac{m_i}{e}\sqrt{\frac{2P}{\rho}}\frac{\partial V_x}{\partial x}$$



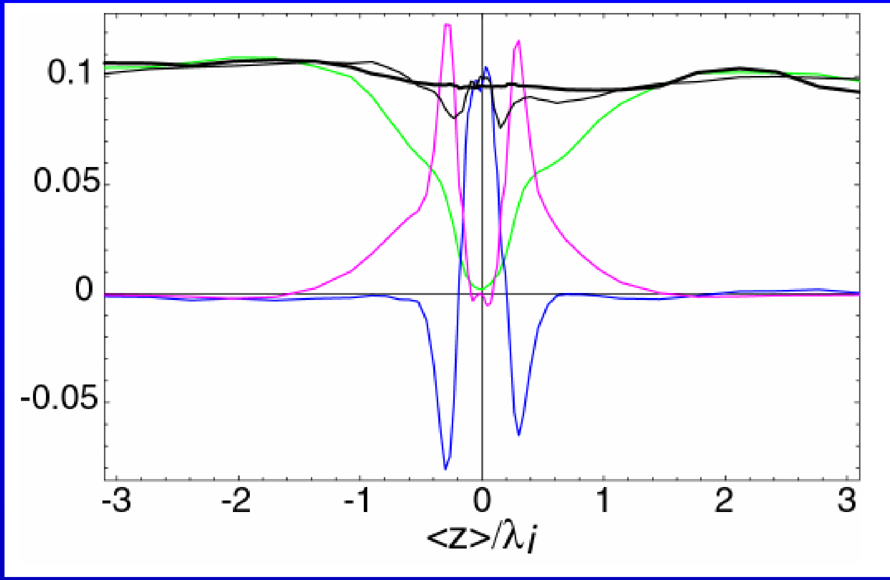
Dissipation Mechanism in 2D Reconnection



$$E = \eta j - V \times B - \frac{m_e}{ne} V \cdot \nabla V - \frac{1}{ne} \nabla \cdot P_e$$

$$E_{\text{xline}} = -\frac{1}{ne}\left(\frac{\partial P_{exy}}{\partial x} + \frac{\partial P_{eyz}}{\partial z}\right)$$

[*Cai & Lee*, 1997; *Hesse et al.*, 1999]

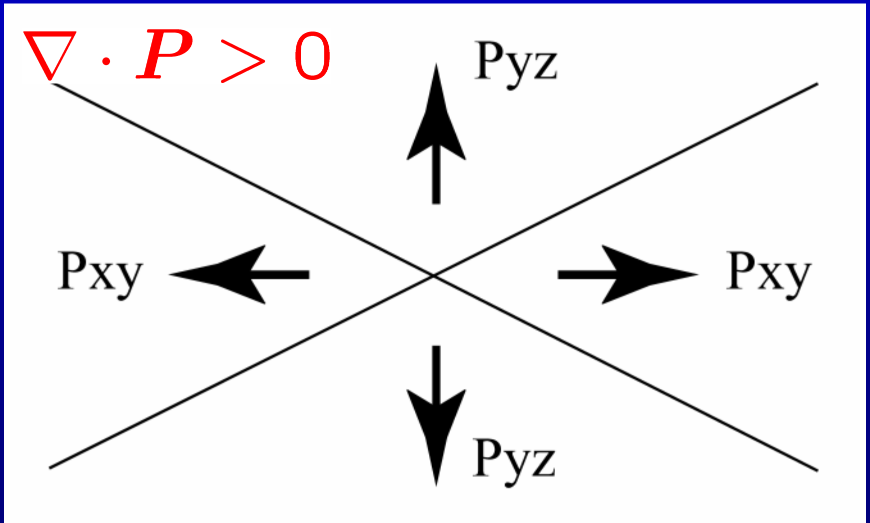


$$P_{exy} = \int m_e (v_x - V_{ex})(v_y - V_{ey}) f \, d^3 v$$

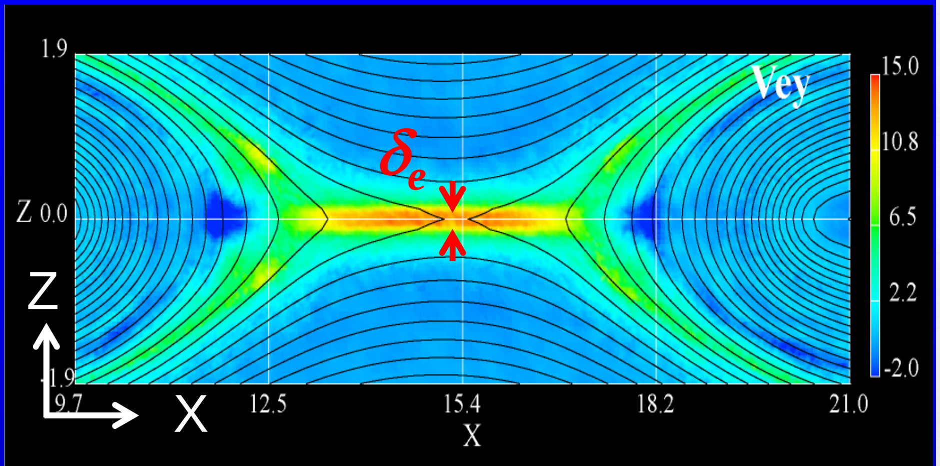
$V_{ex} \approx 0$ near the x-line.

$$P_{exy} \approx \int m_e v_y v_x f \, d^3 v$$

$$P_{eyz} \approx \int m_e v_y v_z f \, d^3 v$$



Dissipation Mechanism in 2D Reconnection

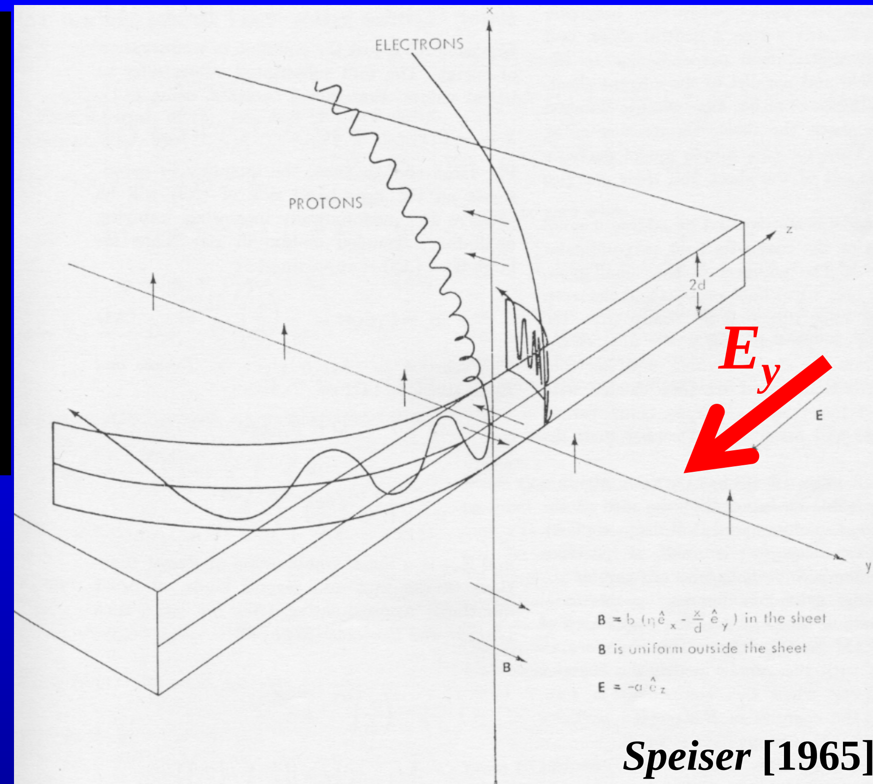


$$-\frac{1}{n_e e}\nabla\cdot\boldsymbol{P}_e \approx E_y\left[1-\frac{5}{2}\left(\frac{z}{\delta_e}\right)^2\right] = E_y$$

Fluid

Particle

[*Fujimoto & Sydora*, 2009]



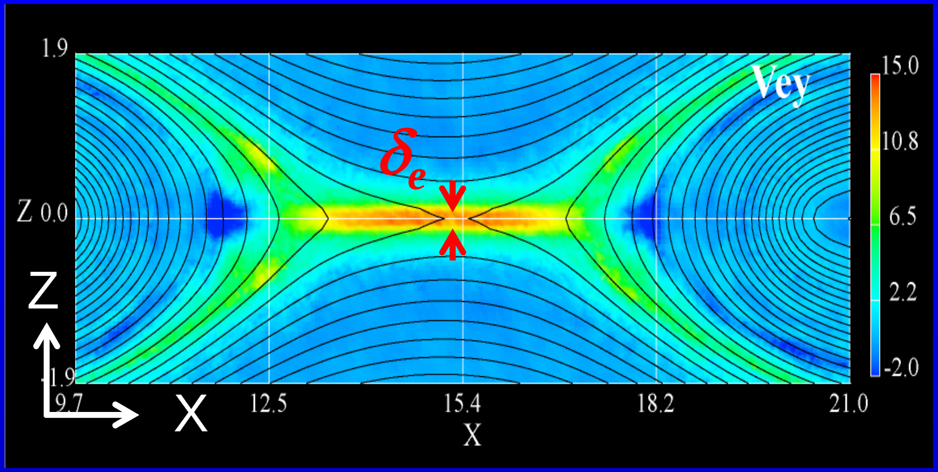
Speiser [1965]

Electron inertia resistivity

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

τ_{tr}: Transit time through the electron diffusion region

Dissipation Mechanism in 2D Reconnection



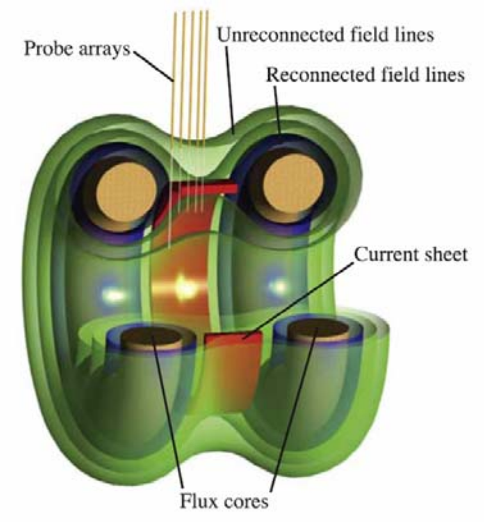
$$E_y = \eta_{in} j_y \qquad \eta_{in} = \frac{m_e}{n_e e^2}\frac{1}{\tau_{tr}} \approx \frac{m_e}{n_e e^2}\frac{V_{in}}{\delta_e}$$

$$E_y = -V_{in} B_{in} \qquad j_y \approx -\frac{1}{\mu_0}\frac{B_{in}}{\delta_e}$$

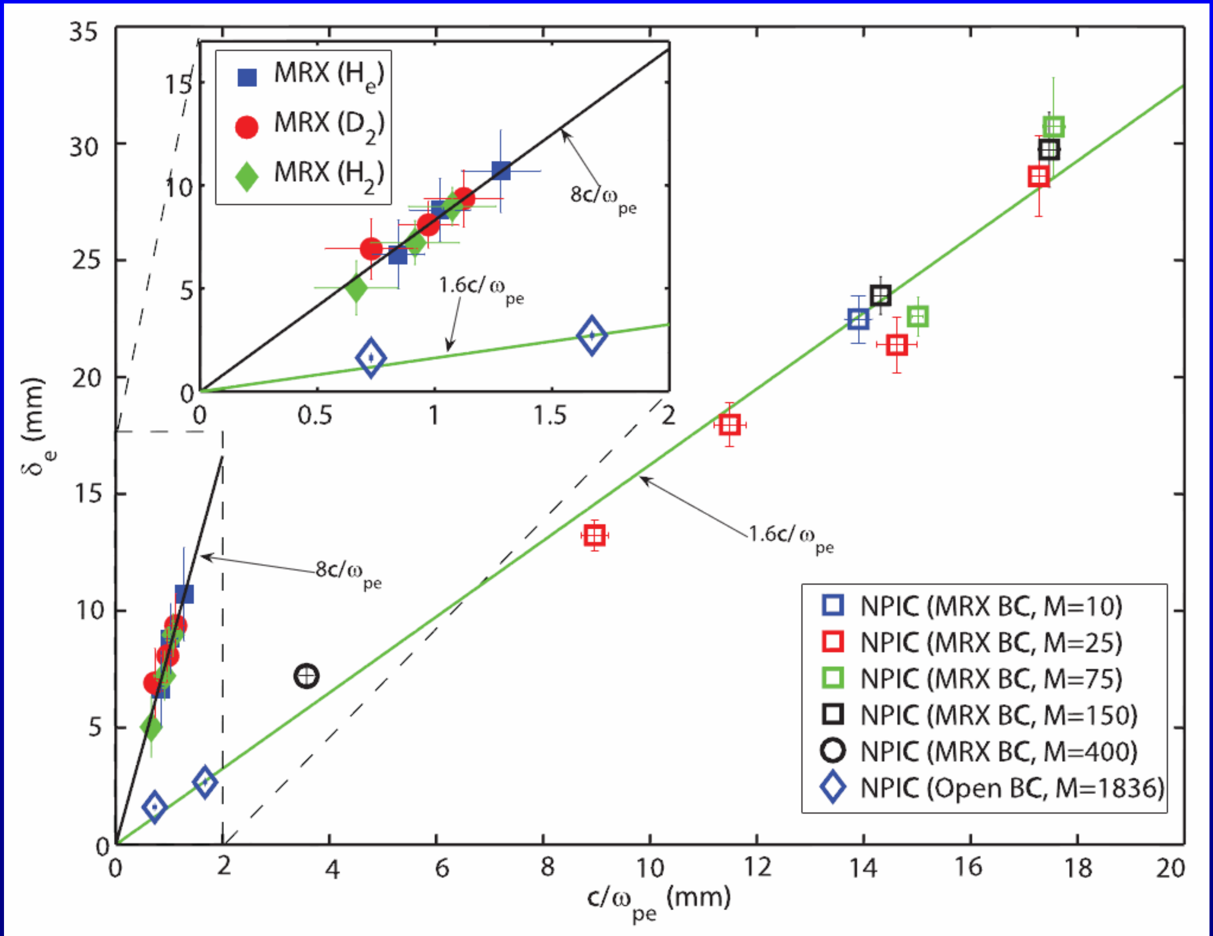
$$\Rightarrow \qquad \delta_e \approx \frac{c}{\omega_{pe}} = \lambda_e$$

Very thin current layer!

Implication of Anomalous Effects: Lab. Experiment

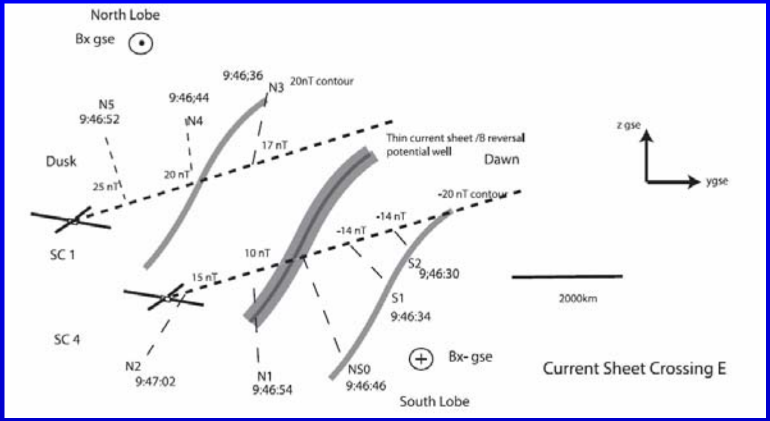


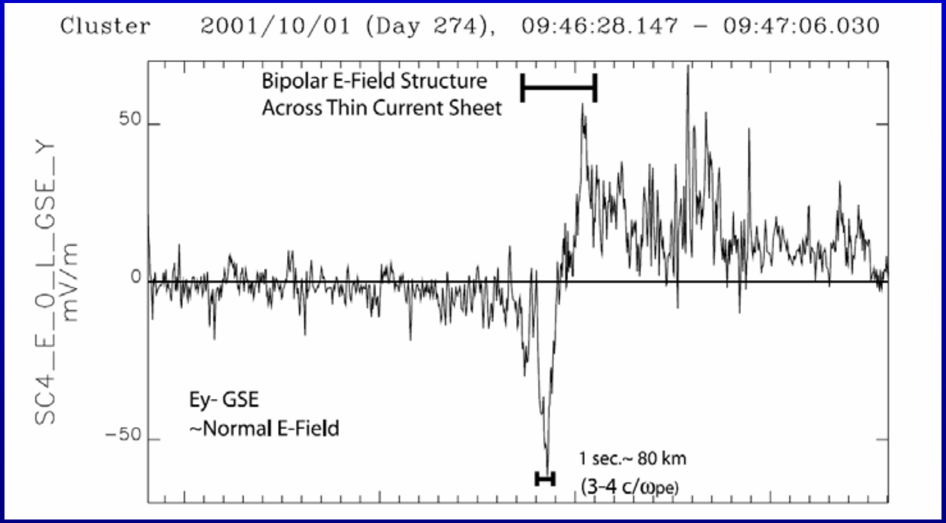
$\delta_e >> c/\omega_{pe}$



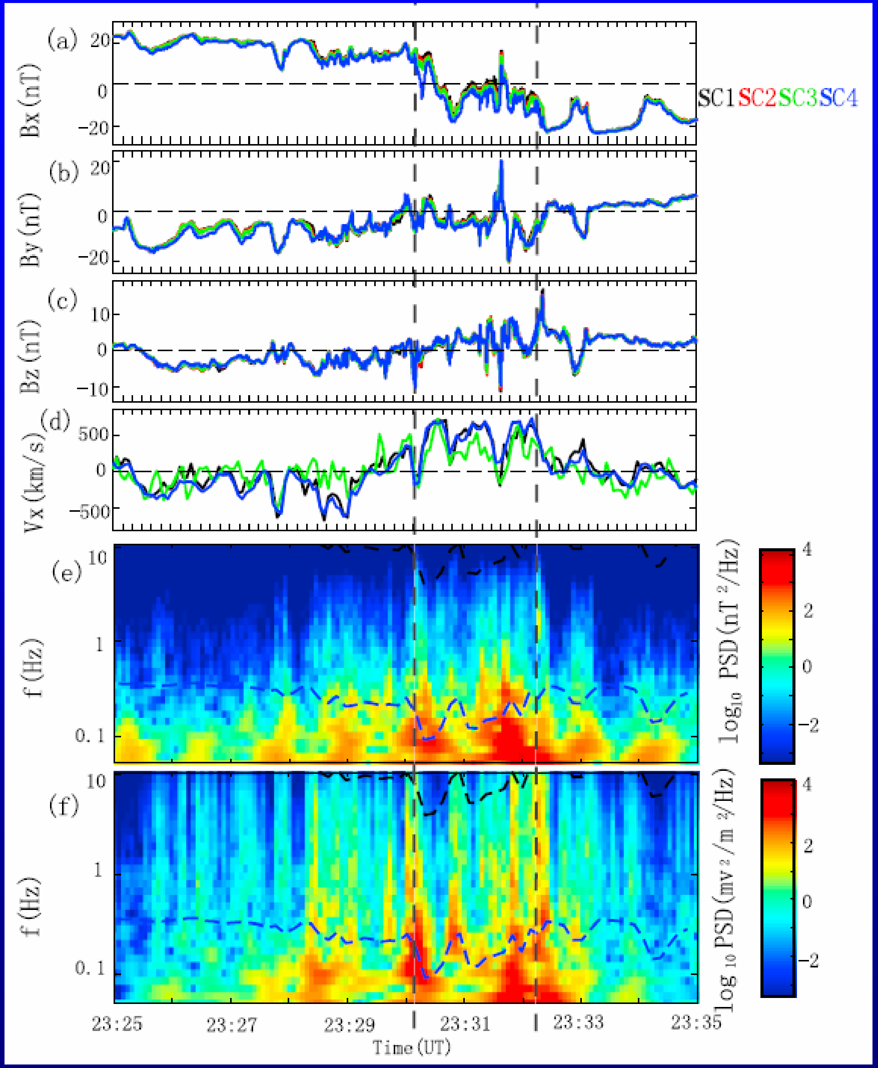
[*Ji et al.*, GRL, 2008]

Implication of Anomalous Effects: Satellite Observation





[*Wygant et al*, JGR, 2005]



[*Zhou et al*, JGR, 2009]

Implication of Anomalous Effects

$$E_y = (\eta_{in} + \eta)\, j_y$$

$$\eta_{in} = \frac{m_e}{n_e e^2}\frac{1}{\tau_{tr}} \approx \frac{m_e}{n_e e^2}\frac{V_{in}}{\delta_e}$$

$$E_y = -V_{in} B_{in} \qquad j_y \approx -\frac{1}{\mu_0}\frac{B_{in}}{\delta_e}$$

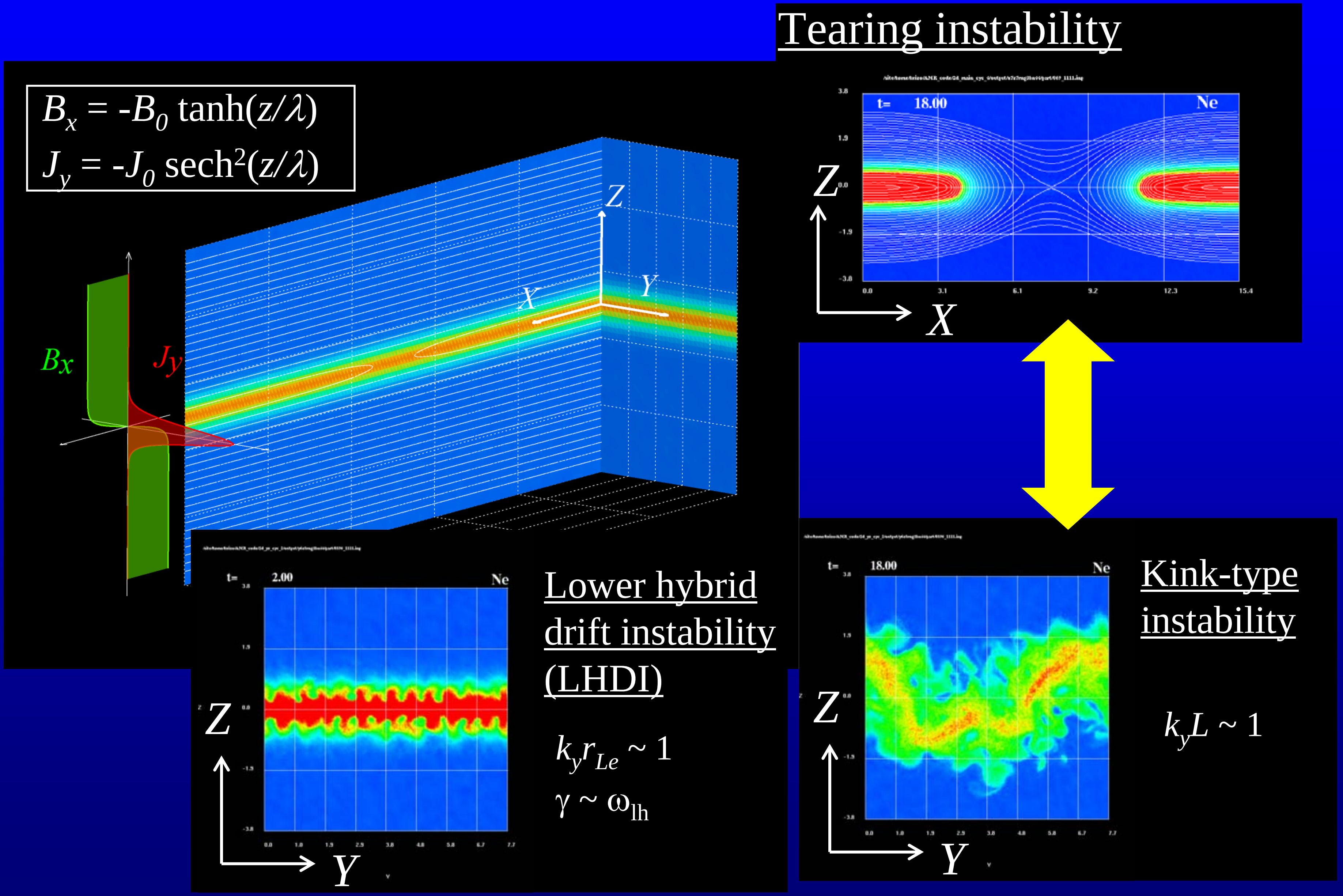
$$\delta_e \approx \frac{\lambda}{2} + \sqrt{\left(\frac{\lambda}{2}\right)^2 + \lambda_e^2} > \lambda_e = \frac{c}{\omega_{pe}}$$

[*Vasyliunas*, 1975]

$$\lambda \equiv \frac{\eta}{\mu_0 V_{in}}$$

(Resistive length)
Could be caused by wave-particle interactions.

Instabilities in the Harris Current Sheet



3D Reconnection Researches ($\beta \sim 1$)

➢ 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)],

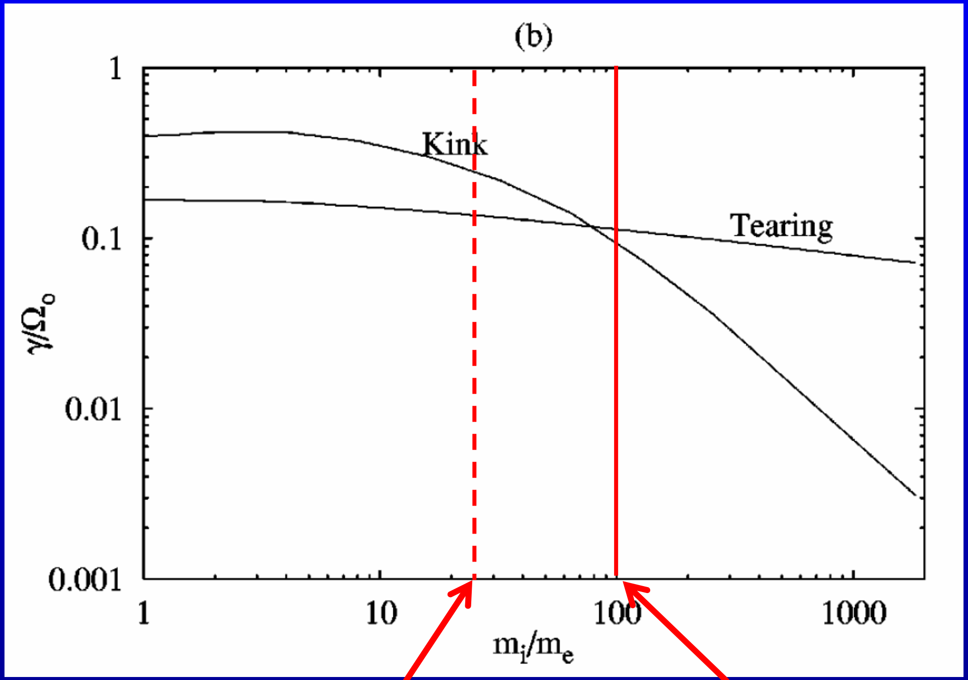
No impact on the quasi-steady process
[*Pritchett & Coroniti* (2001), *Karimabadi et al.* (2003)],

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)

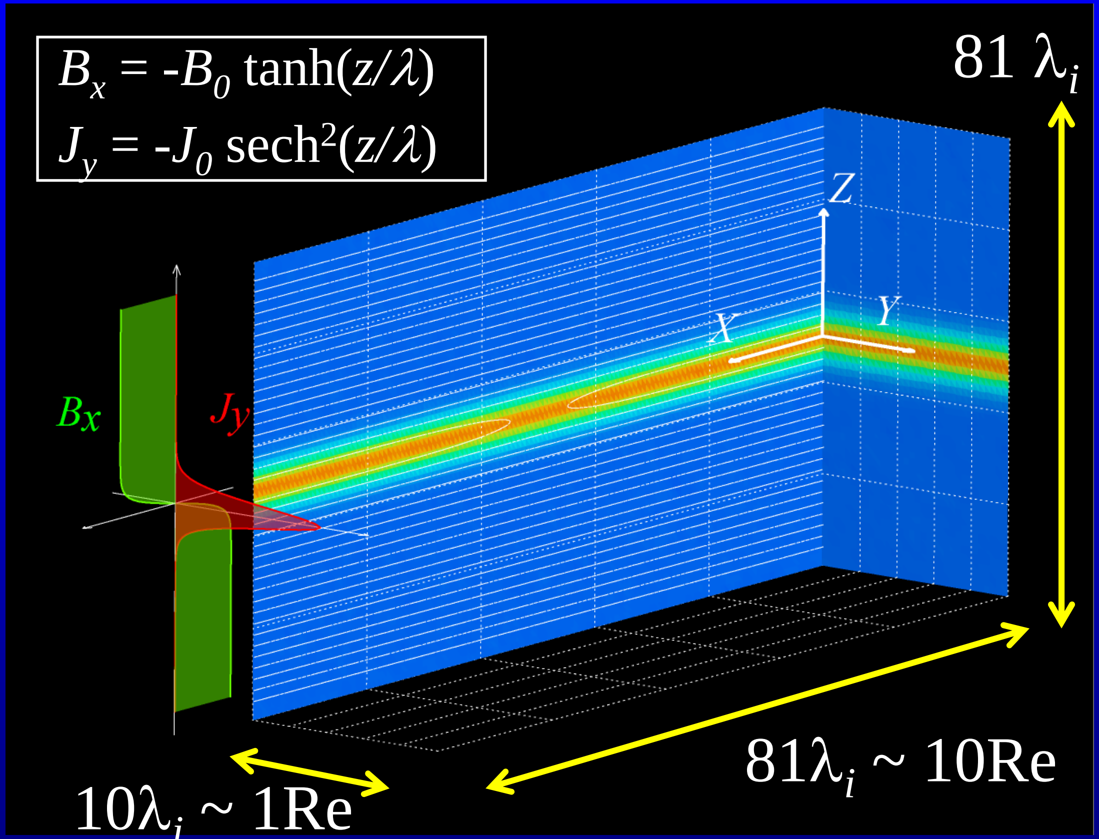
$m_i/m_e = 25$

Target in this study

$m_i/m_e = 100$

Simulation Setup

Massively parallel AMR-PIC code [Fujimoto, JCP, 2011]



$m_i/m_e = 100$

Max resolution:

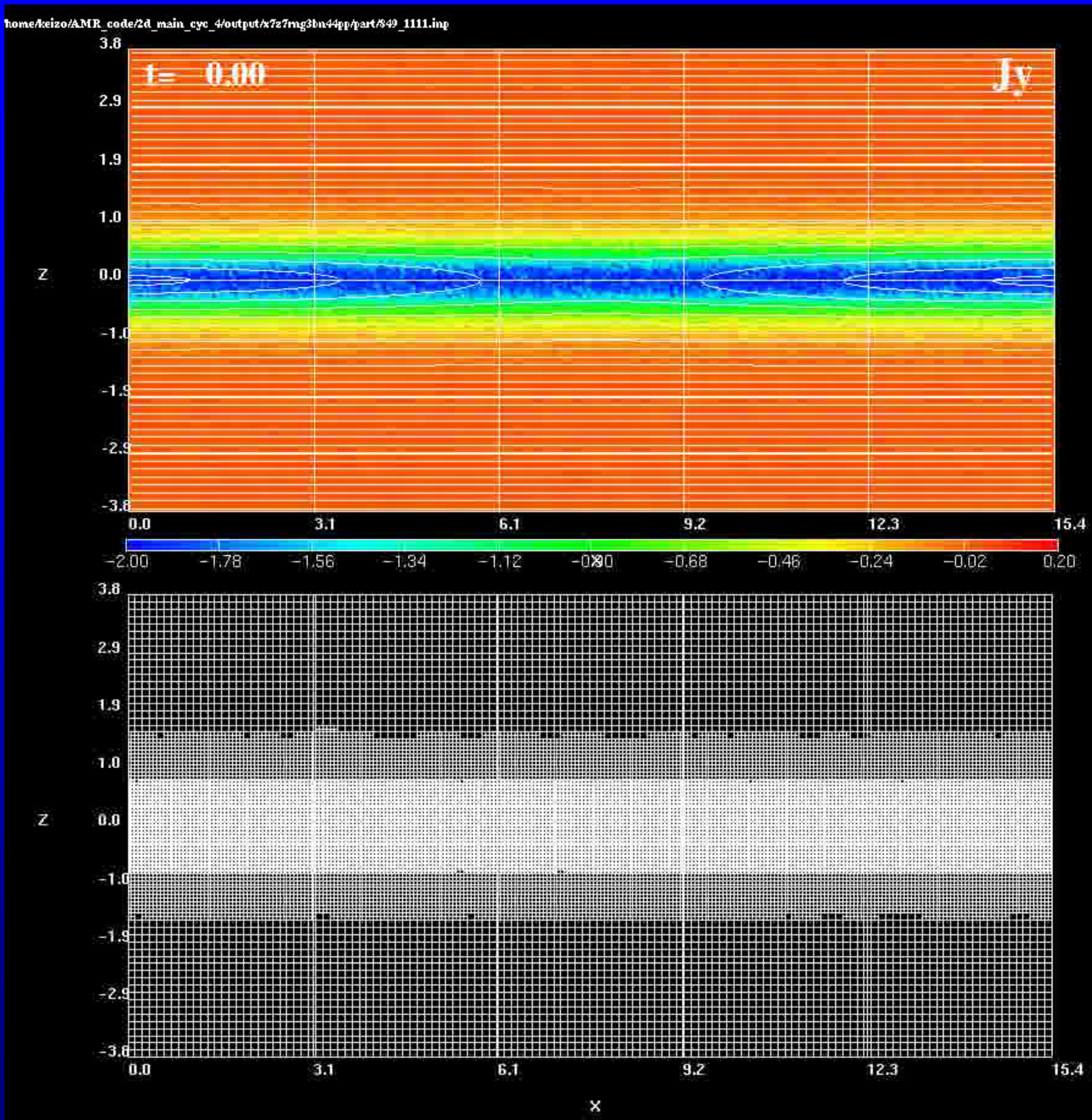
$4096 \times 512 \times 4096 \sim 10^{10}$

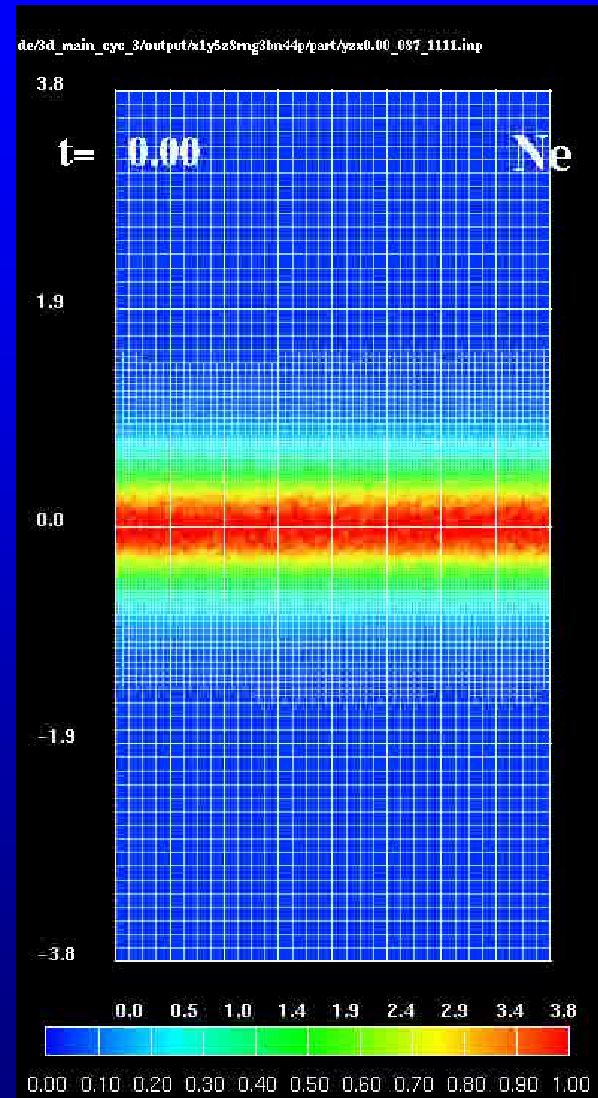
Max number of particles

Ion + Electron $\sim 10^{11}$

Max memory used ~ 6TB

AMR-PIC Simulation

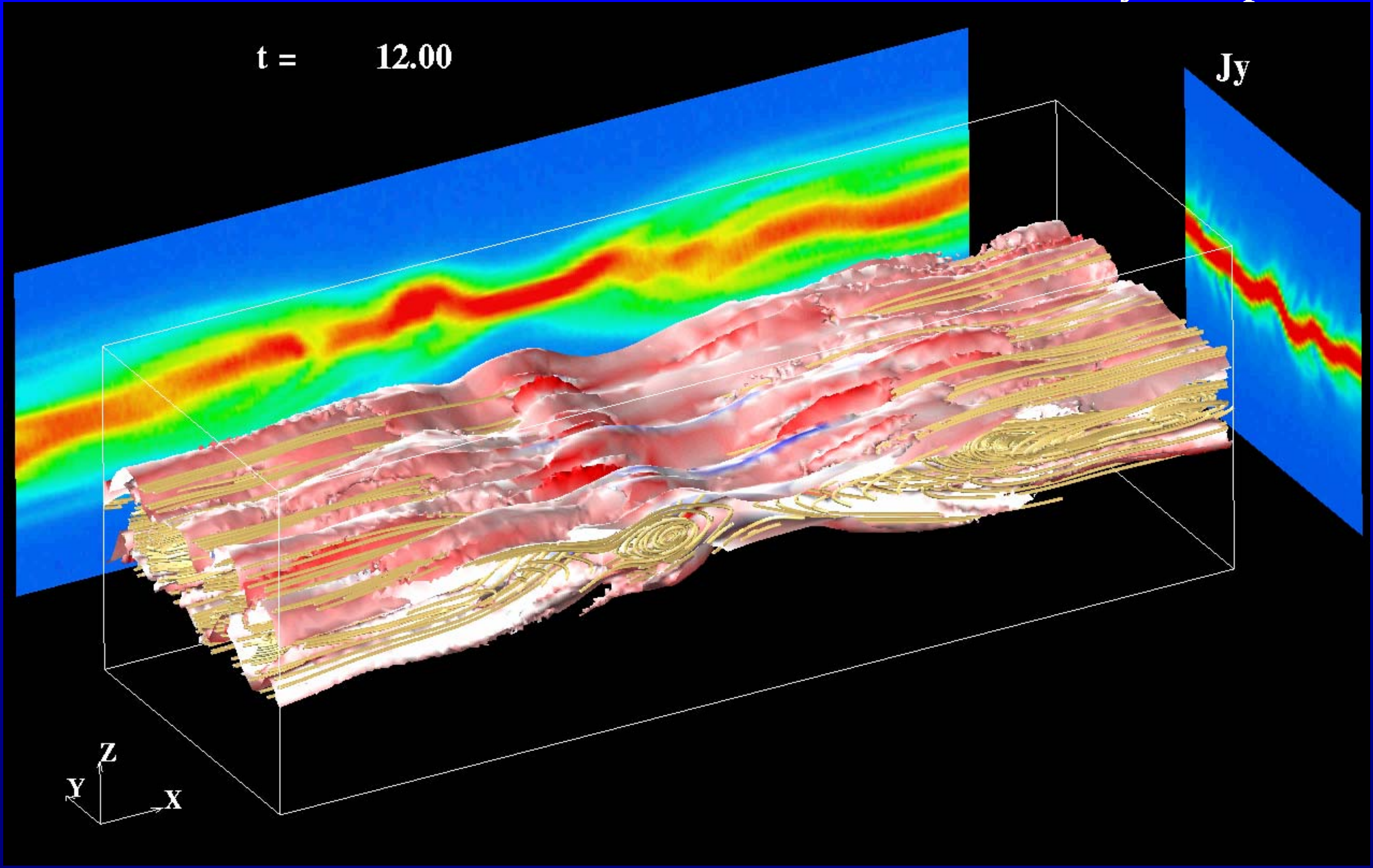




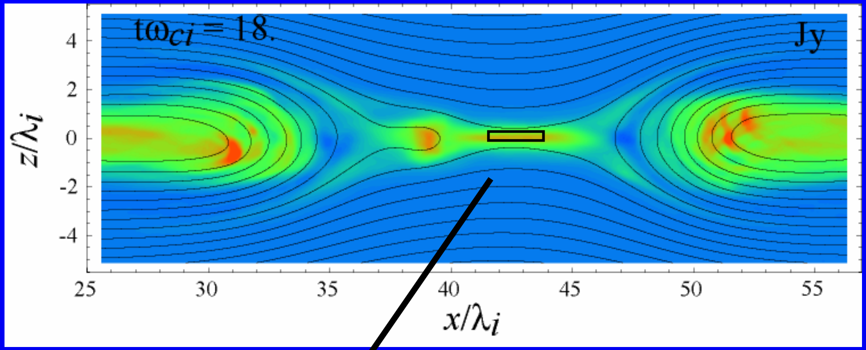
Time Evolution of the Current Sheet

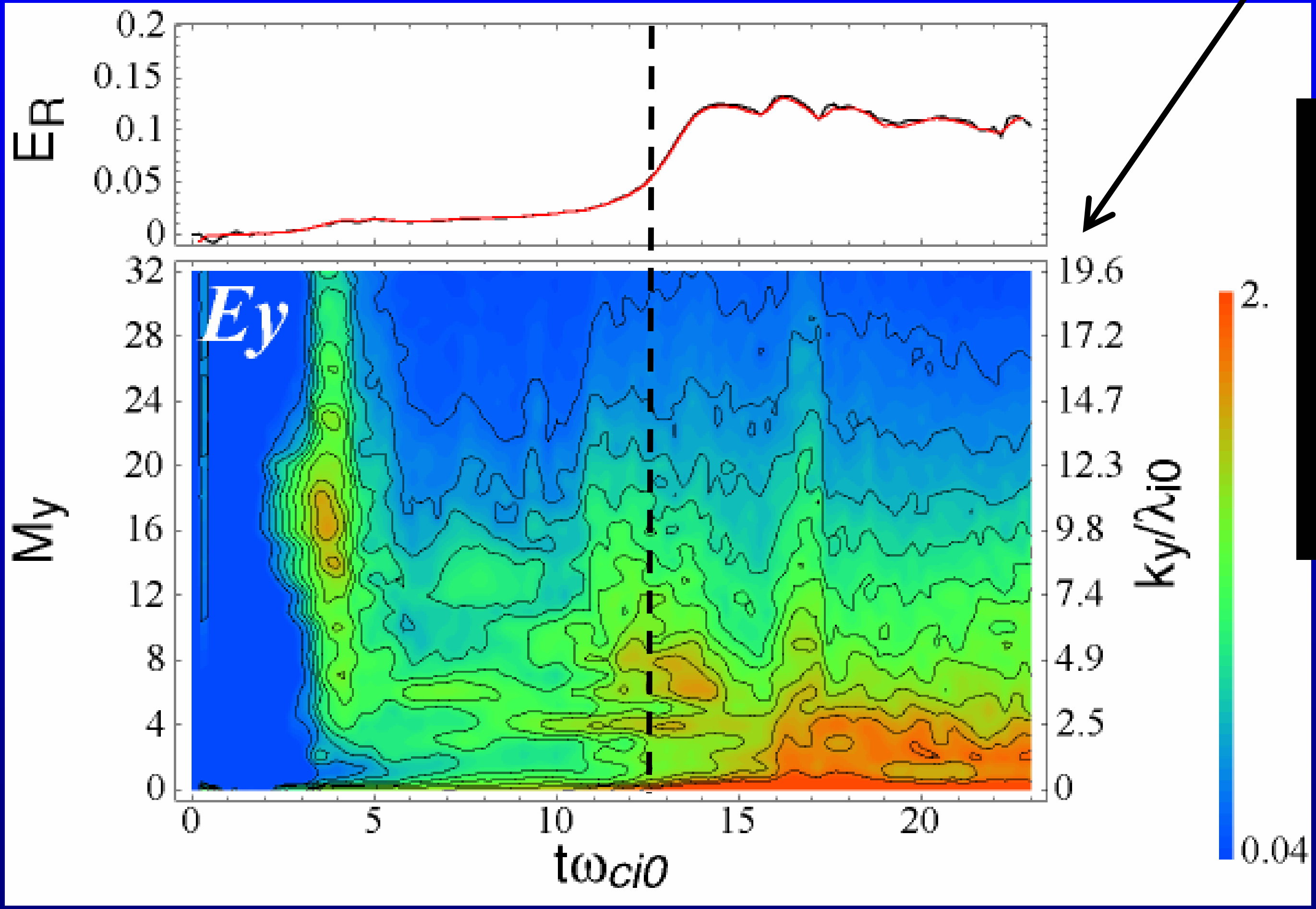
Surface: |J|, Line: Field line

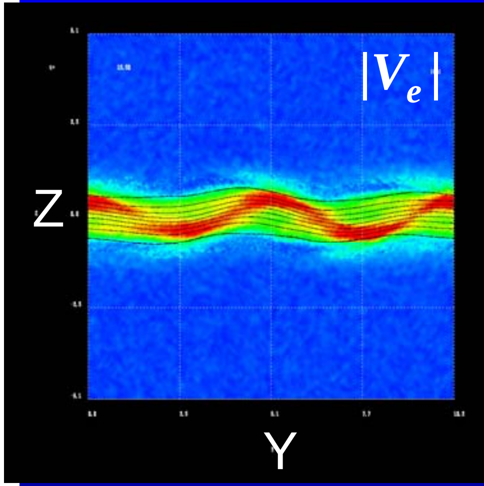
Color on the surface: Ey, Cut plane：Jy



Wave Number Spectrum







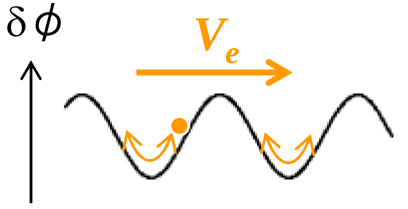
Wave-Particle Interactions

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

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

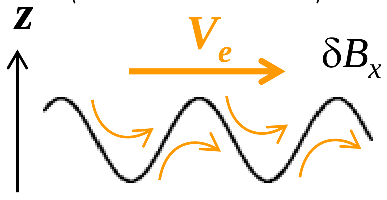
Anomalous effects

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

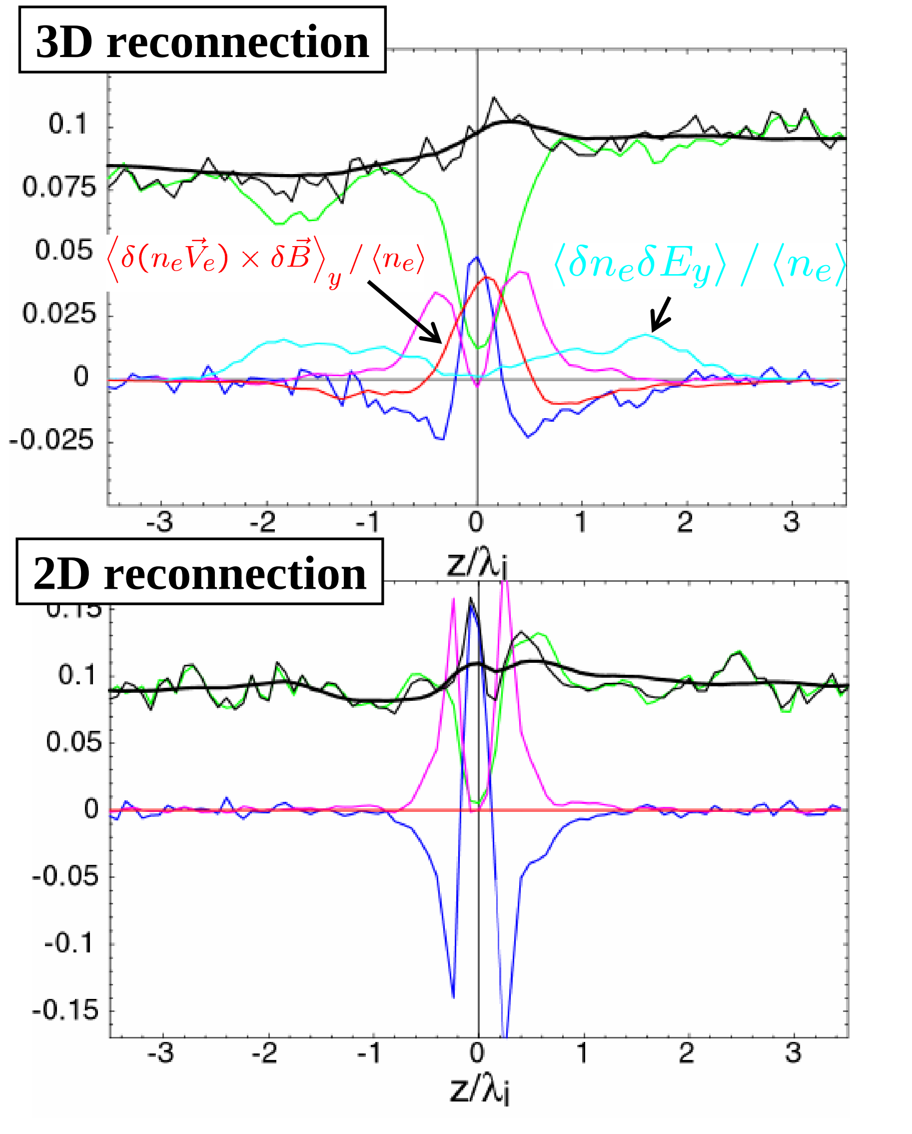


ES turb.

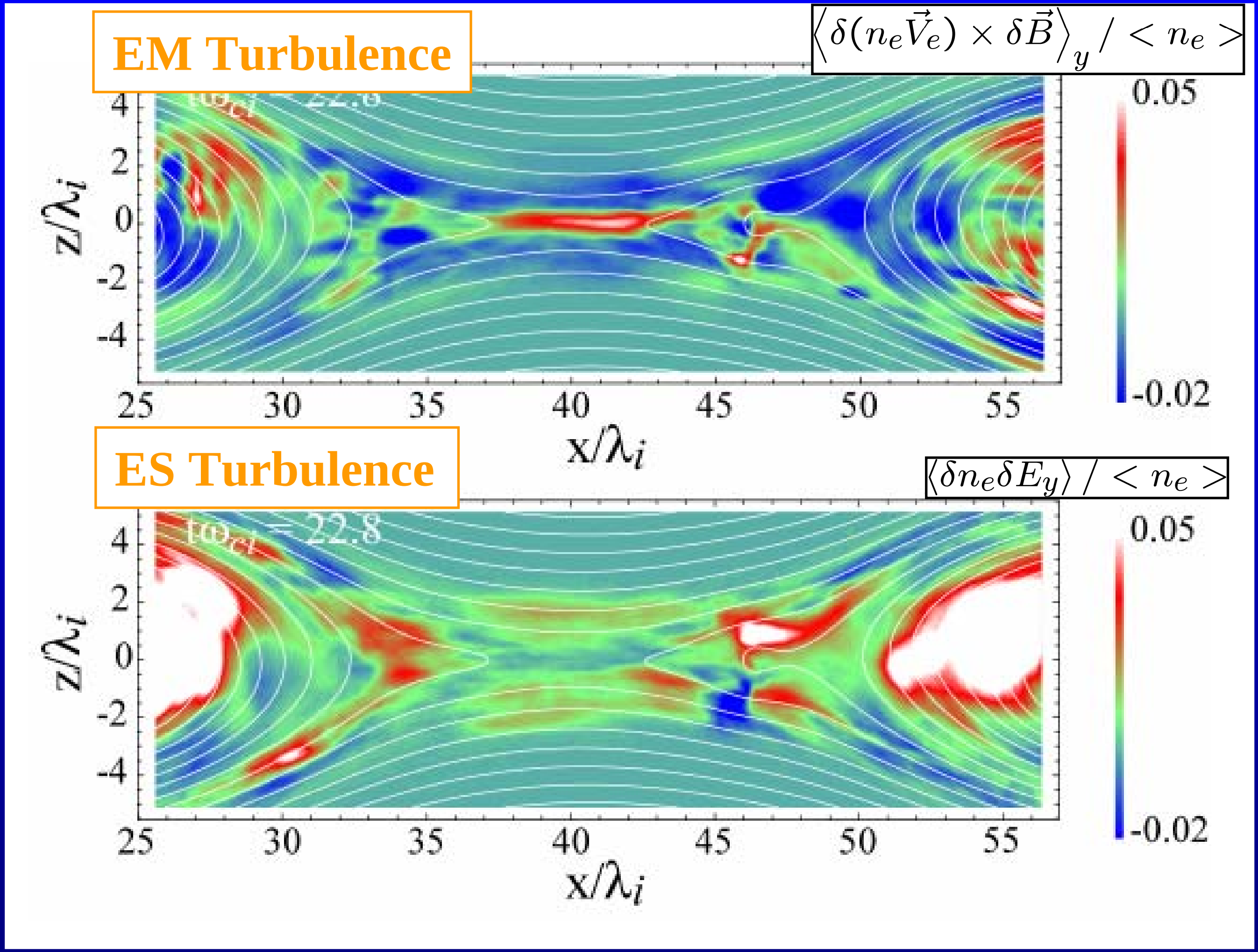
$\left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle$



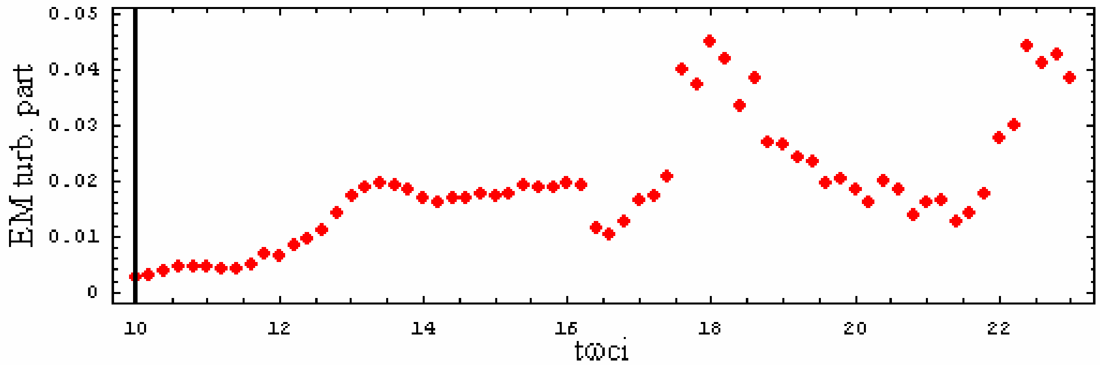
EM turb.

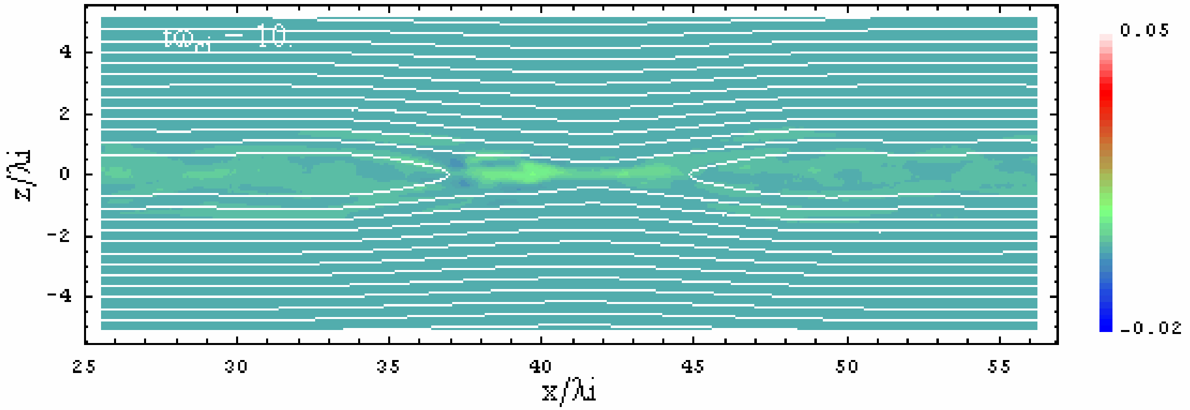


EM vs. ES Turbulence Effects

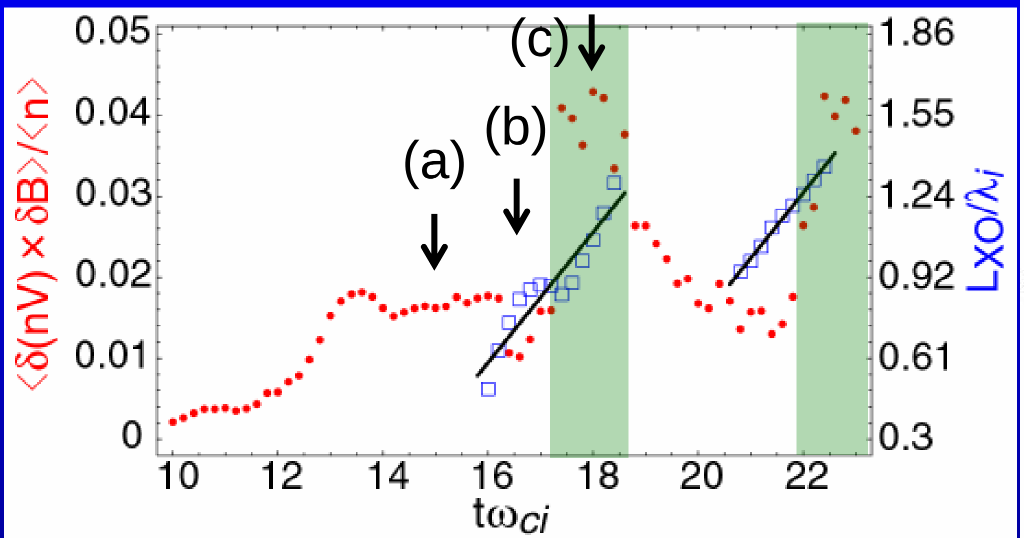


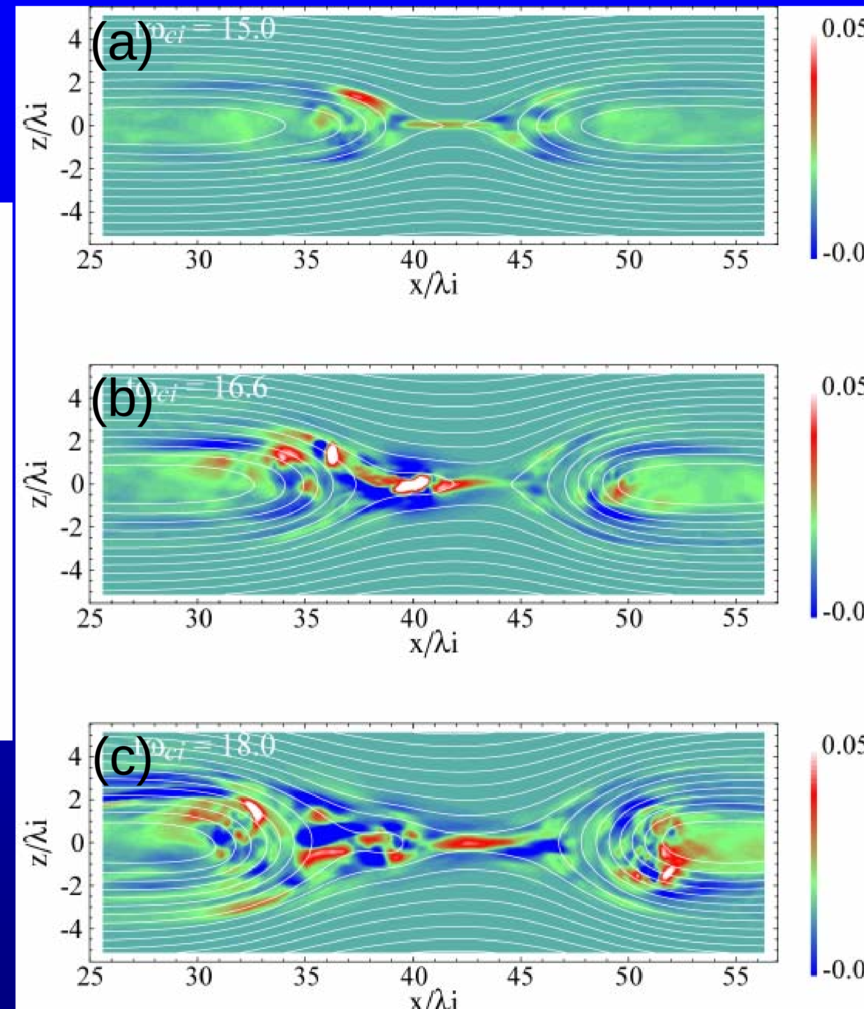
EM Turbulence Effect at the X-line



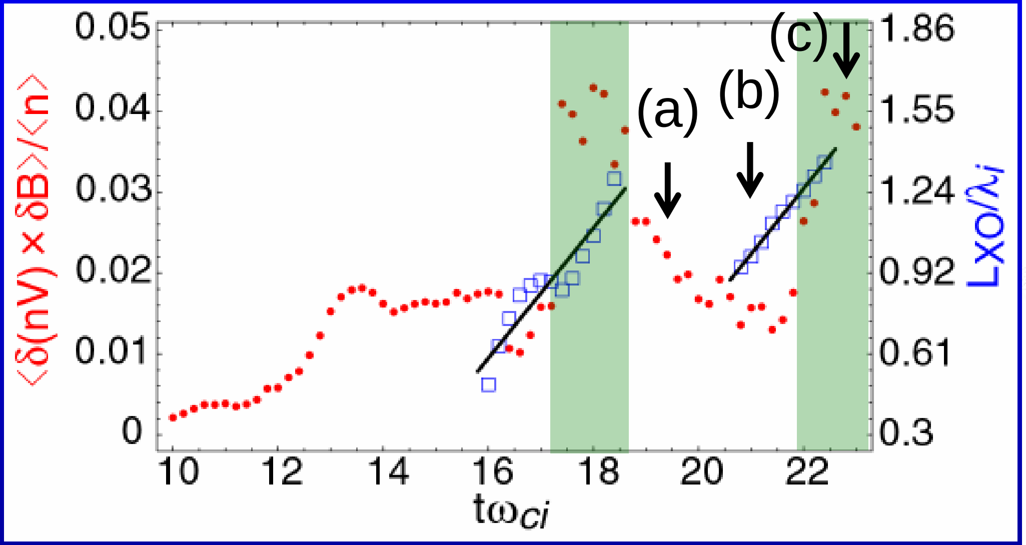


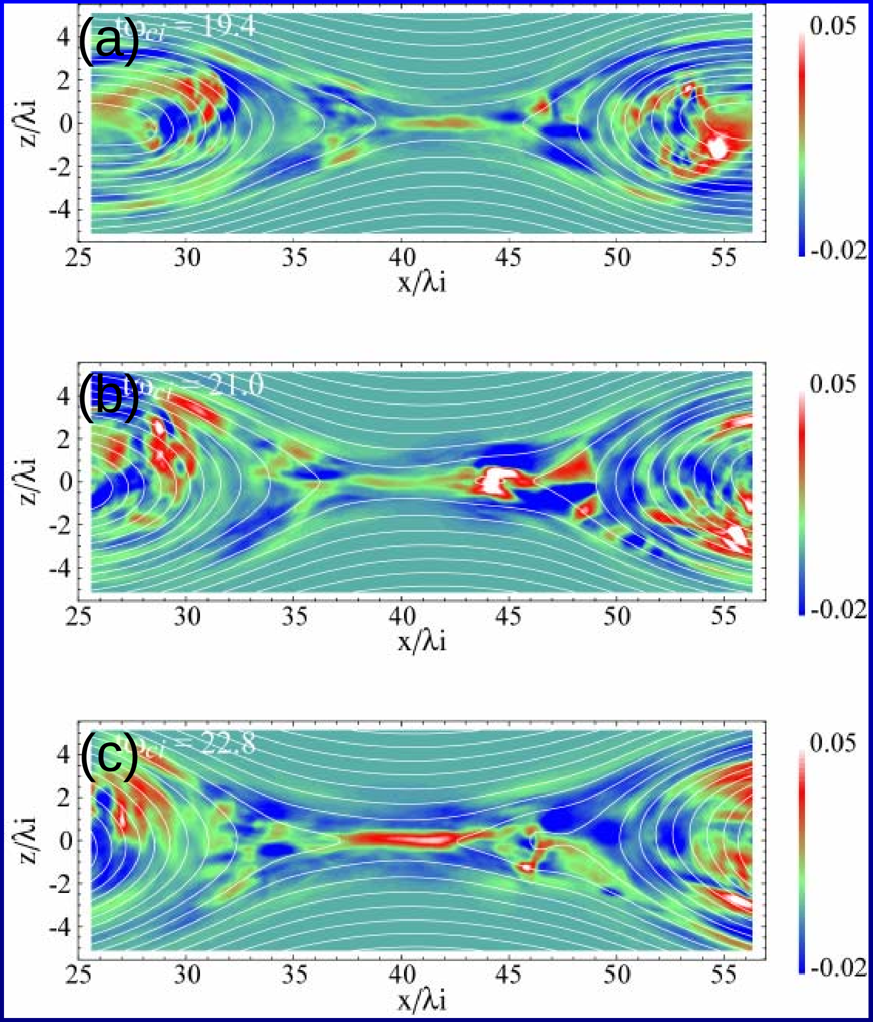
Plasmoid-Induced Turbulence I



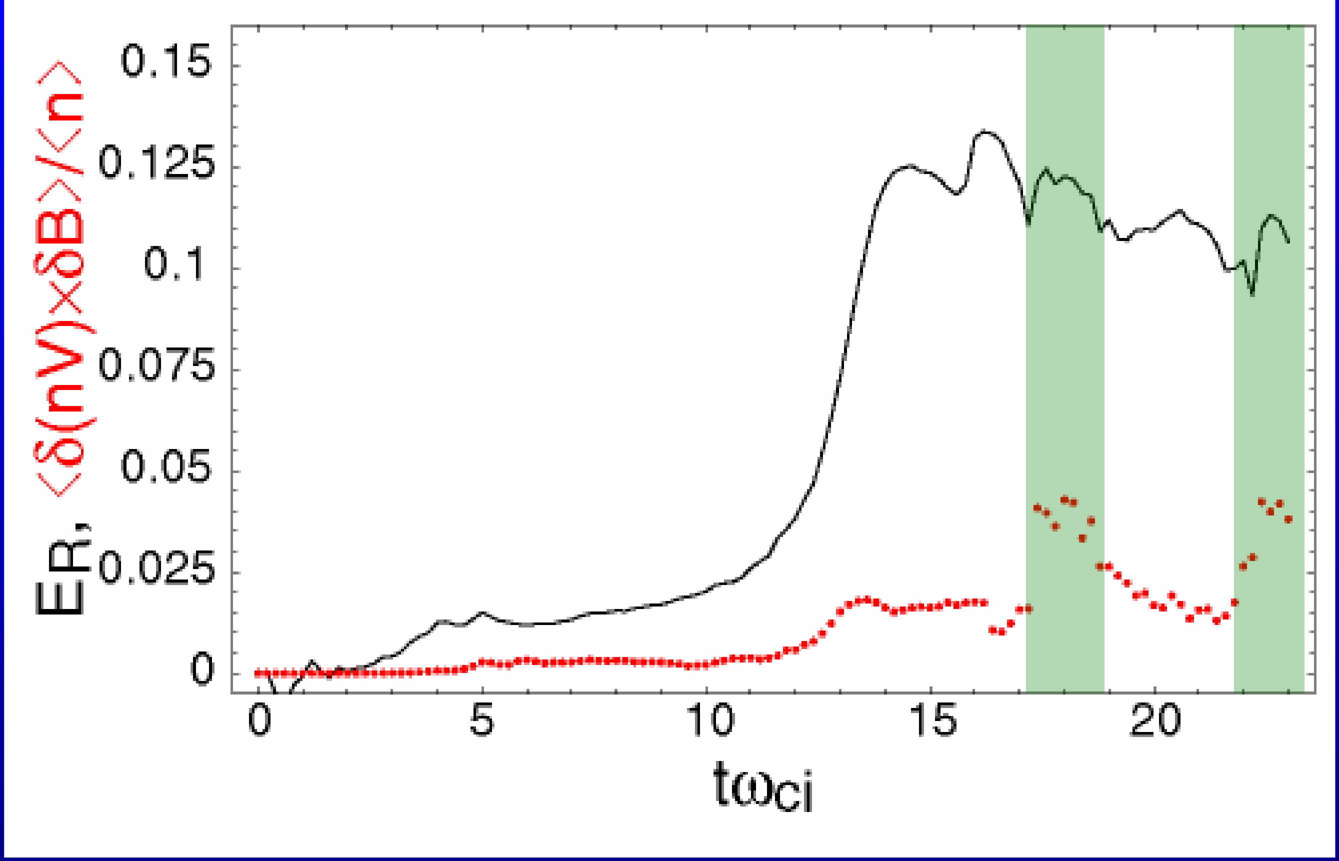


Plasmoid-Induced Turbulence II





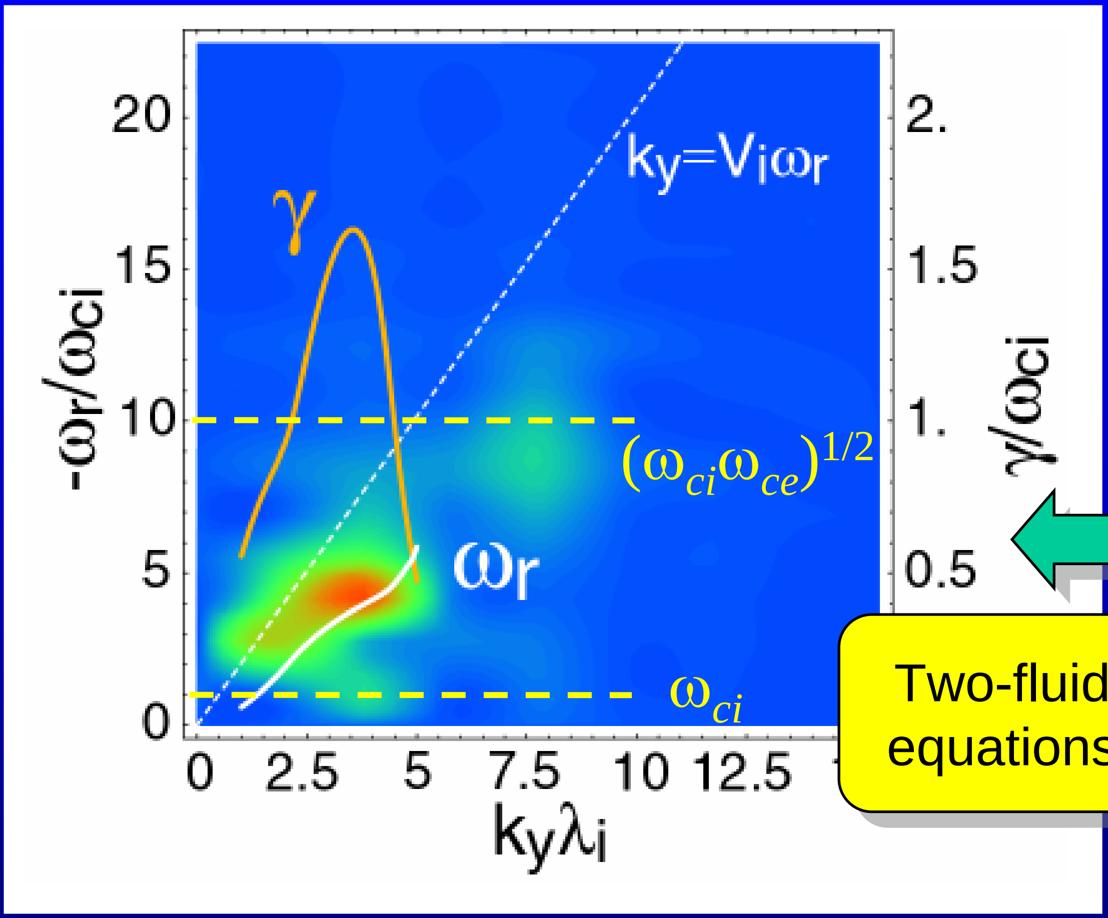
Enhancement of the Reconnection Rate



Wave Properties

In collaboration with R. Sydora (U. Alberta)

$$\omega = \omega_r + i\gamma$$



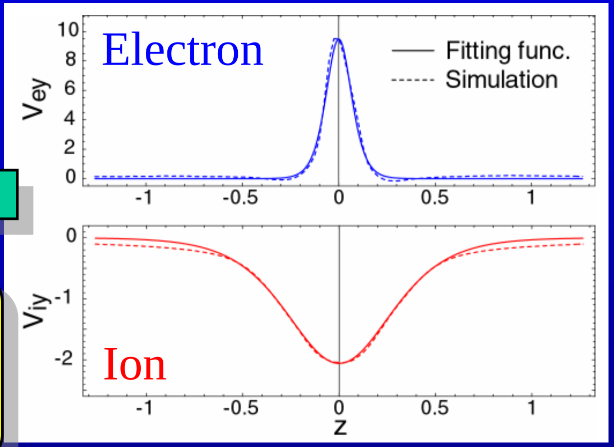
Two-fluid equations

Simulation results

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

$$V_{ph} \approx V_A$$

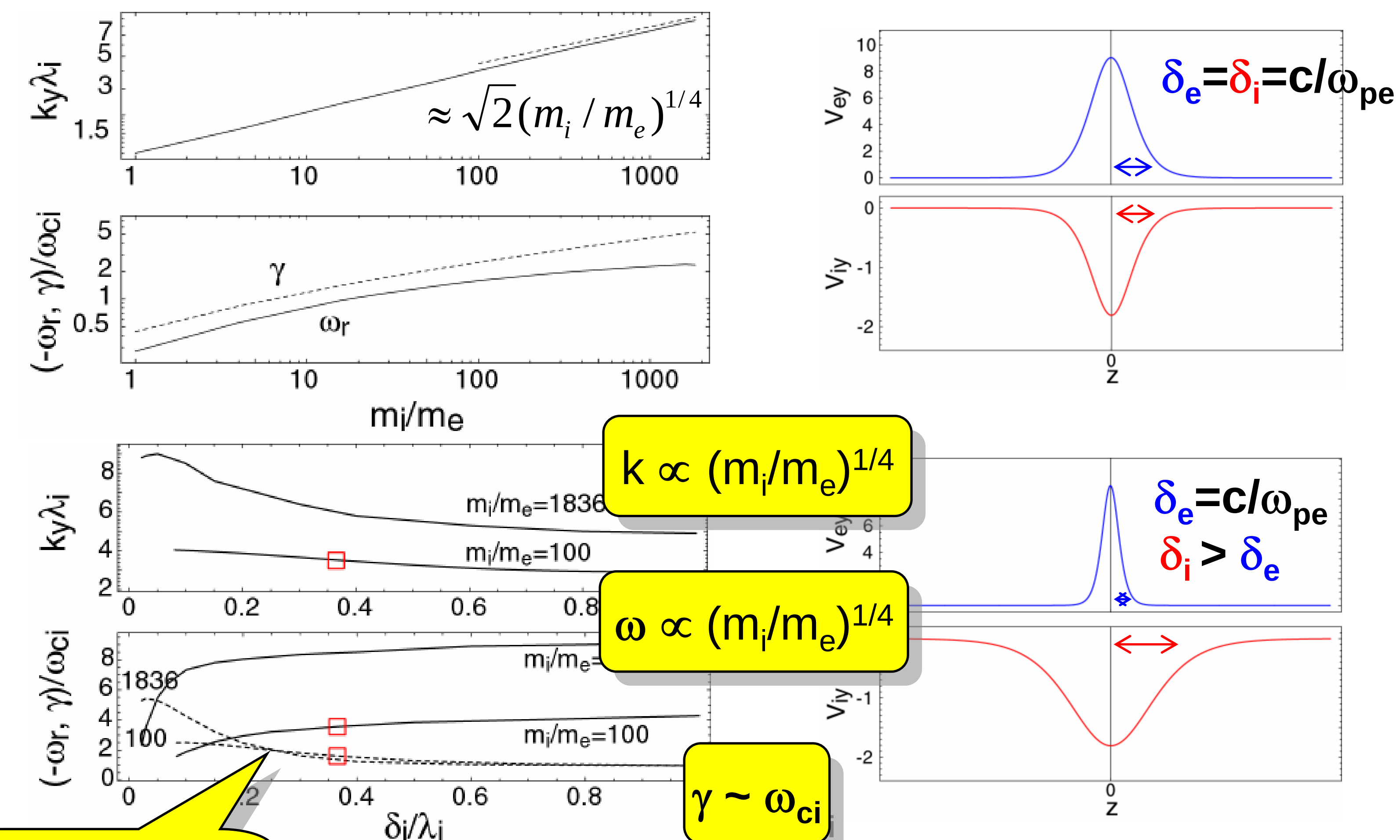
Linear analyses



Inconsistent with drift mode property

$$V_{ph} \neq \frac{m_i V_i + m_e V_e}{m_i + m_e}$$

Wave Properties: Linear Analyses



$k \propto (m_i/m_e)^{1/4}$

$\omega \propto (m_i/m_e)^{1/4}$

$\gamma \sim \omega_{ci}$

Shear is important factor.

The wave survives even for m_i/m_e=1836.

Conclusion

Large-scale 3D PIC simulations using AMR-PIC code

The EM turbulence effect is enhanced in association with the plasmoid ejections, which coincides with enhancement of the reconnection rate.

Further investigations are needed to understand the nature of the EM mode.

Perspective in Near Future

磁気リコネクションのマクロシステムへの適用

MHDコード

- スケールフリー
- 自由な境界条件・初期設定

グローバル構造のモデリング

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

プラズマ運動論効果

PICコード

- 完全な運動論効果
- 詳細なミクロ構造

物理的考察