無衝突磁気リコネクションにおける磁気拡散機構

藤本桂三

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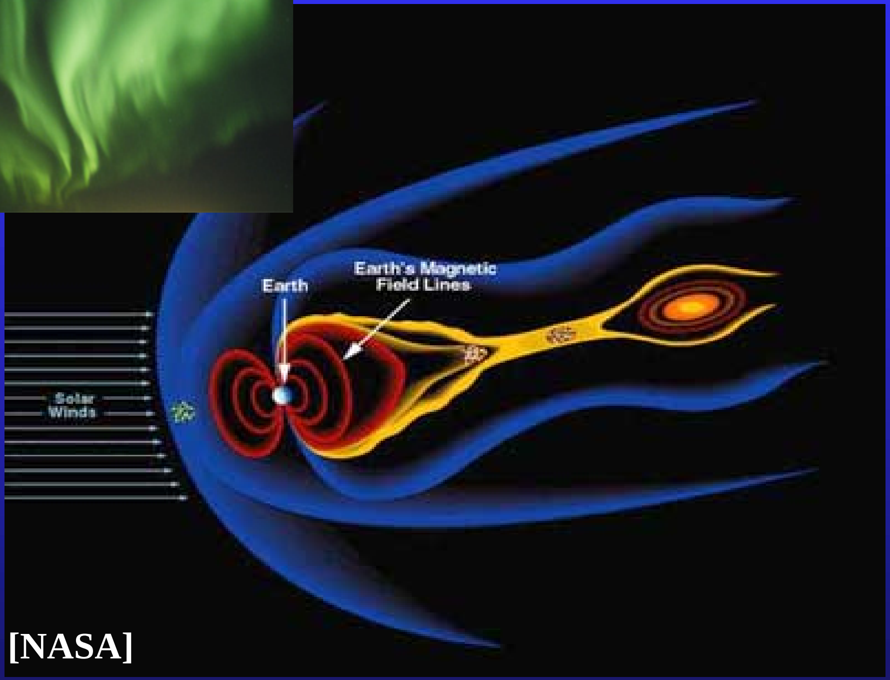
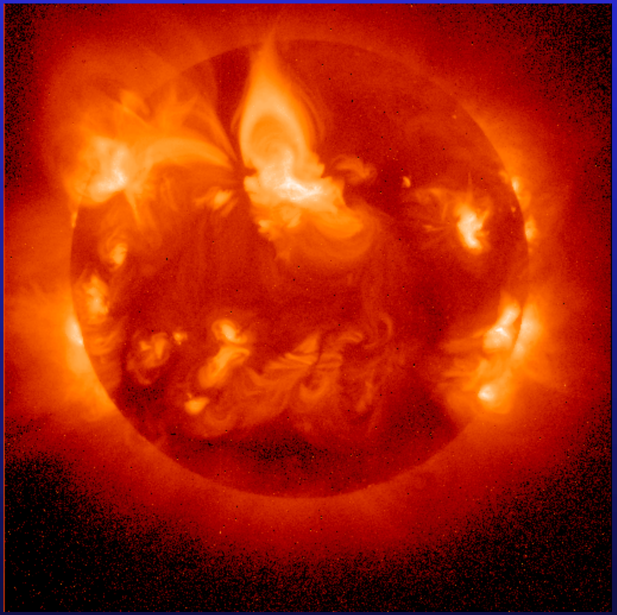
宇宙空間における磁気リコネクション

地球磁気圏(オーロラ)サブストーム



太陽フレア



地球磁気圏におけるスケール

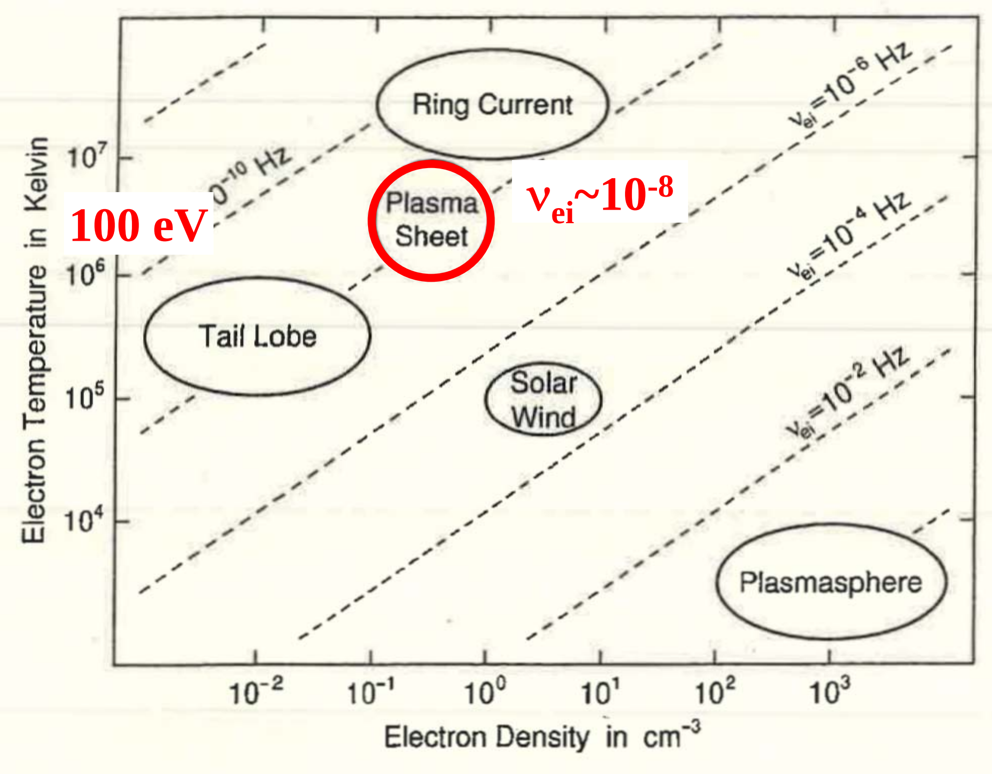
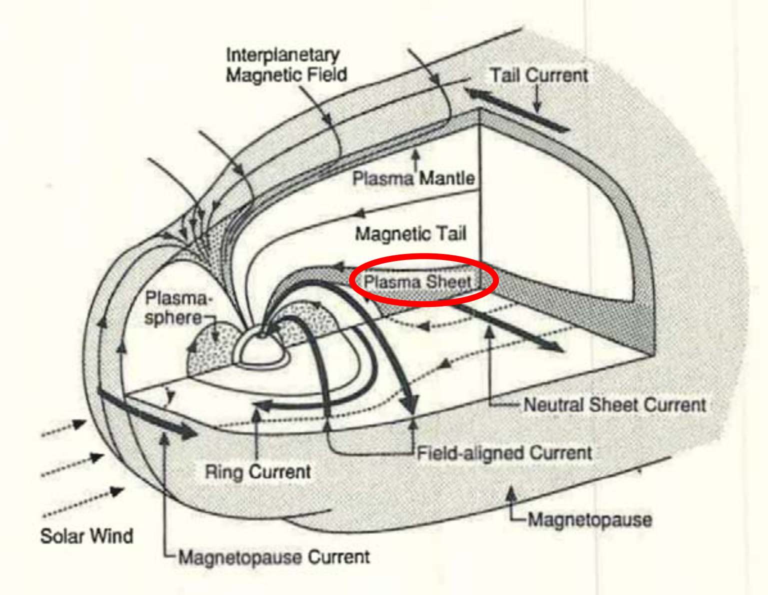


Fig. 4.2. Typical Coulomb collision frequencies for geophysical plasmas.

[Baumjohann & Treumann, 1997]

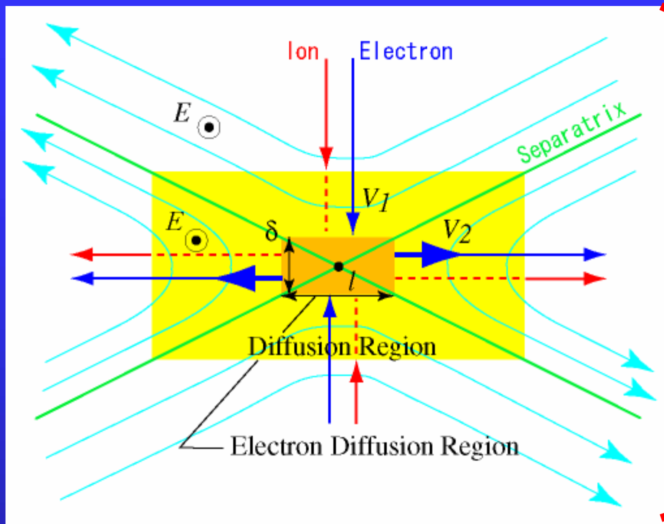


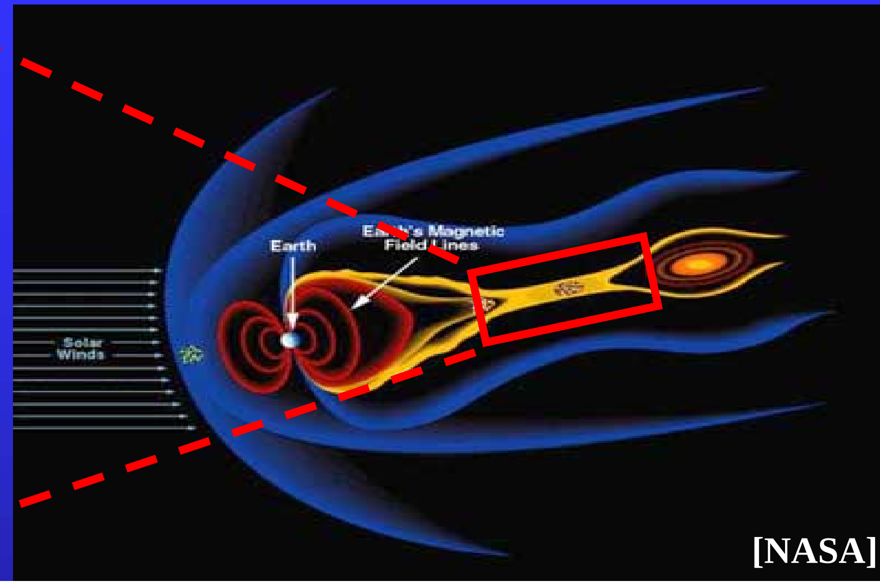
[Kivelson & Russell, 1995]

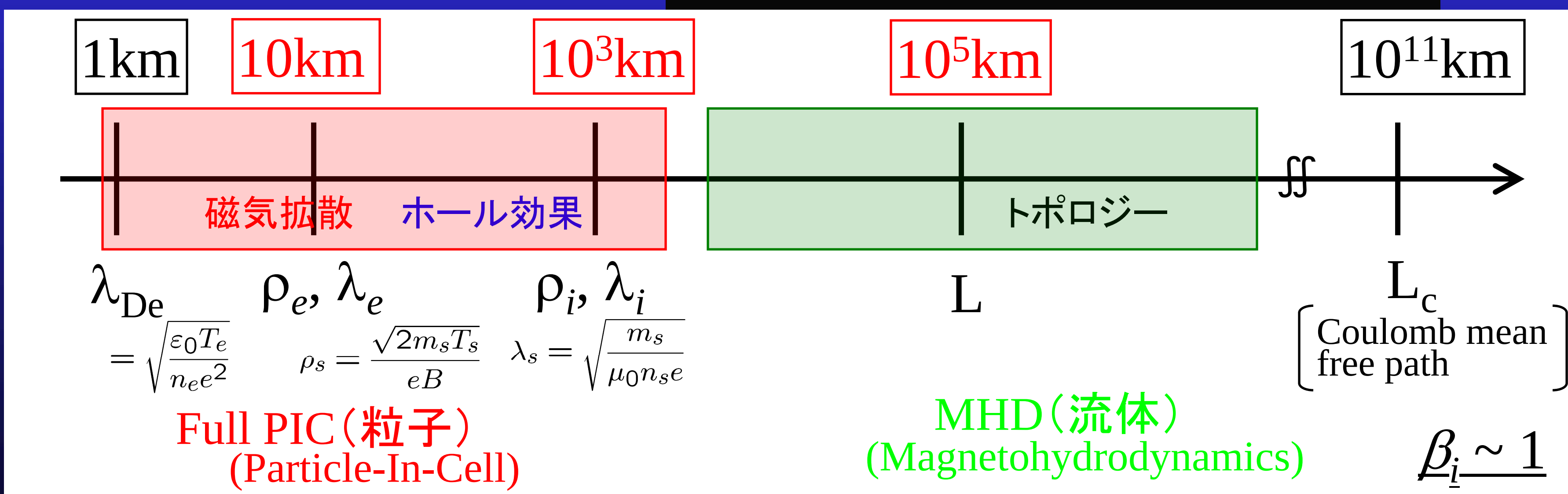
衝突頻度：3年に1回くらい

平均自由行程：1000AU

磁気リコネクションと磁気圏ダイナミクス



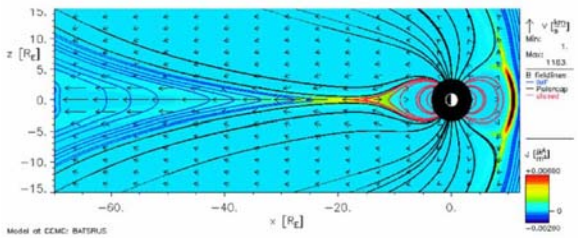




Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

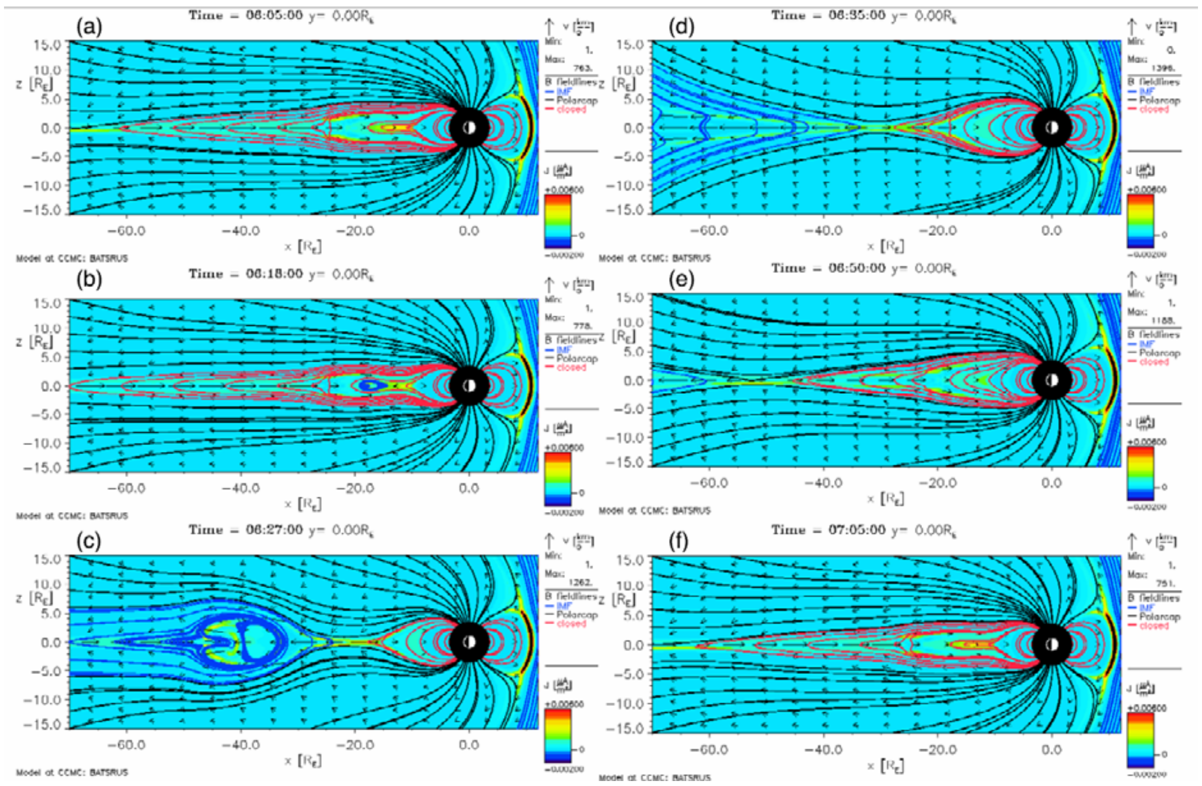


- Slow reconnection
- Quasi-steady configuration

- Fast reconnection
- Quasi-periodic process

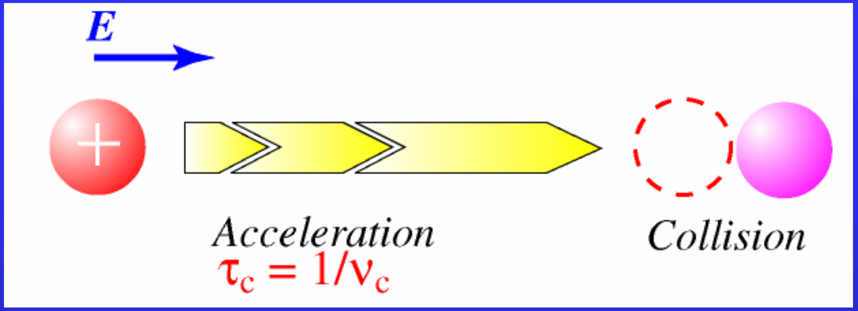
Nongyrotropic correction case

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



電気抵抗とは？

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



単位時間に受取る運動量

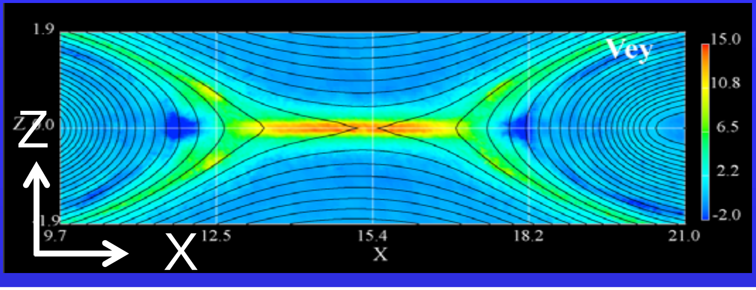
$$n_i e E = n_i m_i V_i \nu_c$$

単位時間に失う運動量

$$j = e n_i V_i$$

$$E = \frac{m_i \nu_c}{e^2 n_i} j = \eta j$$

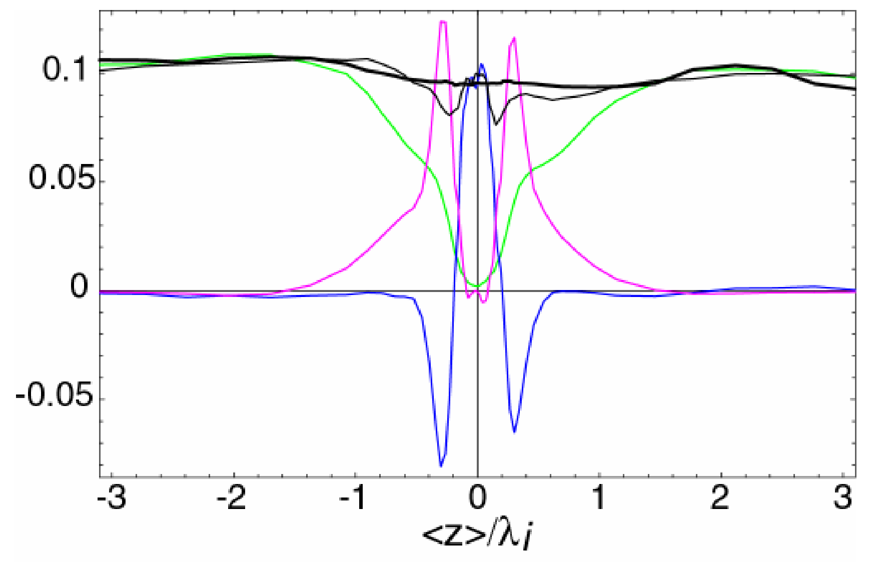
Dissipation Mechanism in 2D Reconnection



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

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

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

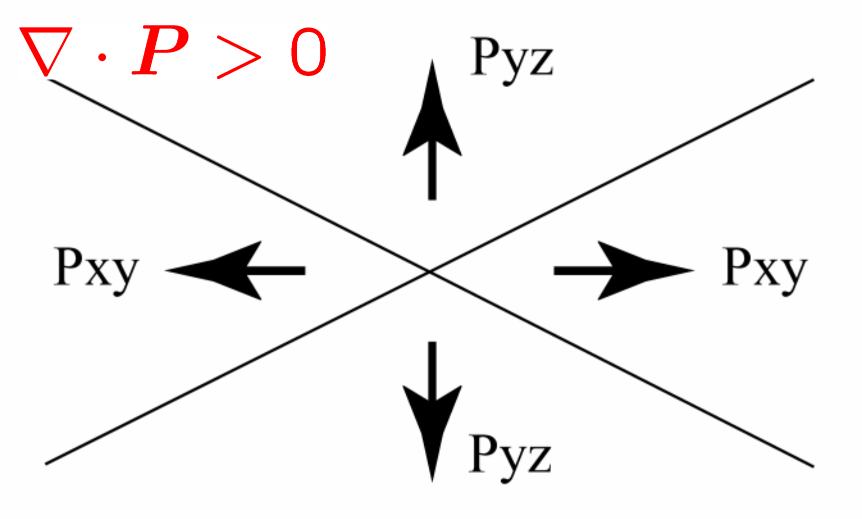


$$P_{exy} = \int m_e (v_x - V_{ex})(v_y - V_{ey}) f \, d^3 v$$

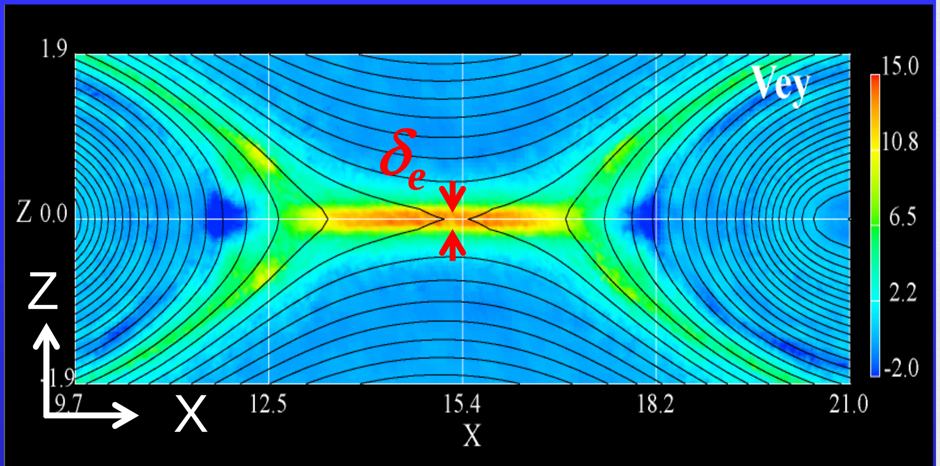
$V_{ex} \approx 0$ near the x-line.

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

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



Dissipation Mechanism in 2D Reconnection

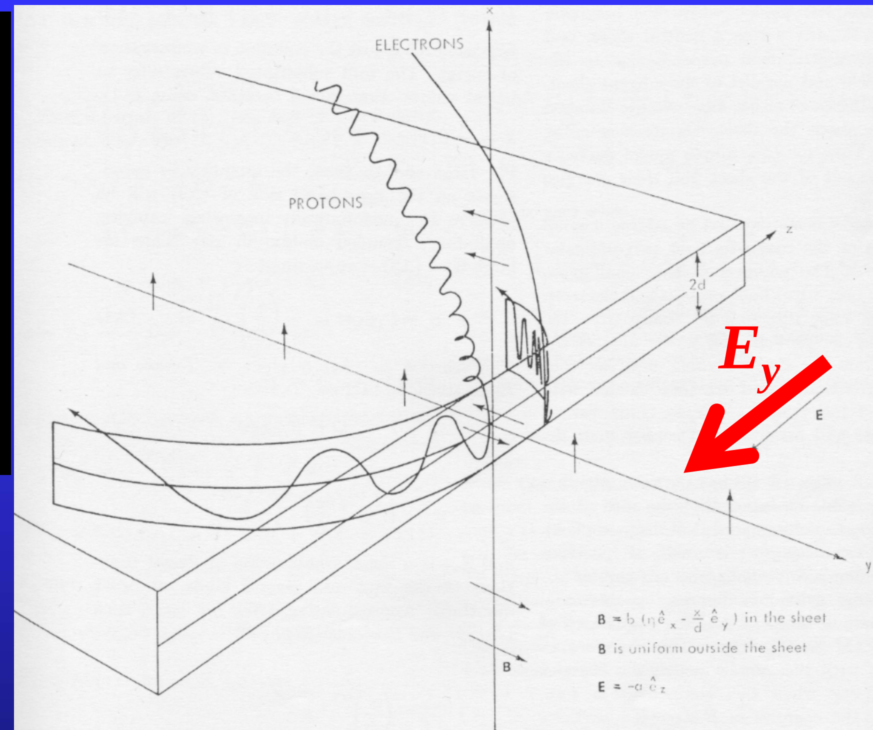


$$-\frac{1}{n_e e}\nabla\cdot\boldsymbol{P}_e \approx E_y\left[1-\frac{5}{2}\left(\frac{z}{\delta_e}\right)^2\right] = E_y$$

Fluid

Particle

[*Fujimoto & Sydora*, 2009]



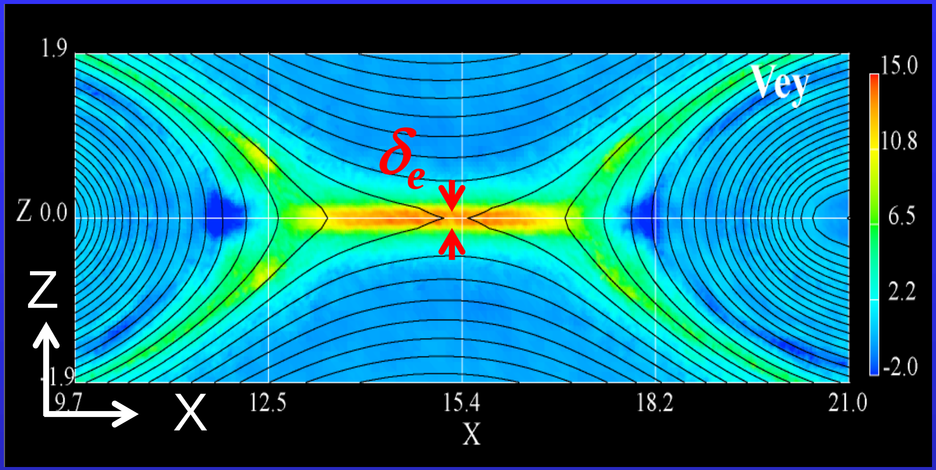
Speiser [1965]

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



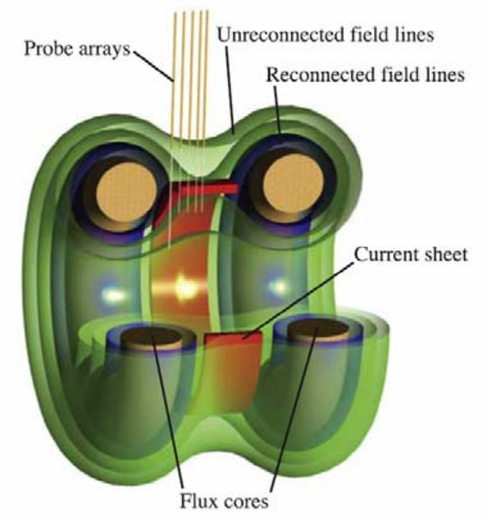
$$E_y = \eta_{in} j_y \qquad \eta_{in} = \frac{m_e}{n_e e^2}\frac{1}{\tau_{tr}} \approx \frac{m_e}{n_e e^2}\frac{V_{in}}{\delta_e}$$

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

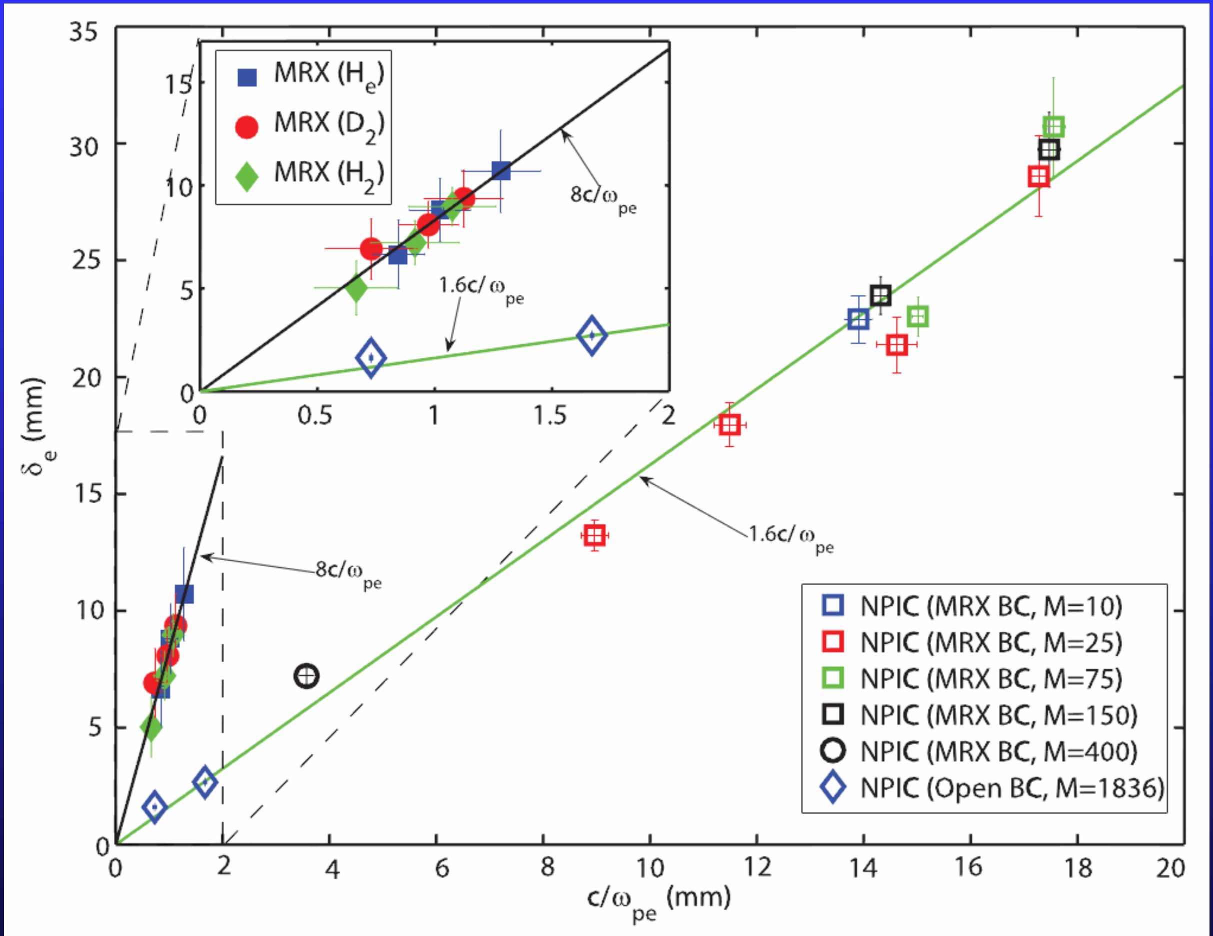
$$\Rightarrow \qquad \delta_e \approx \frac{c}{\omega_{pe}} = \lambda_e$$

Very thin current layer!

Implication of Anomalous Effects: Lab Experiment

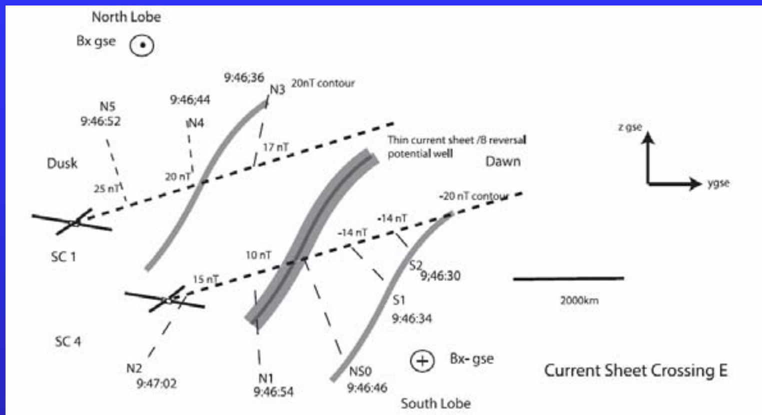


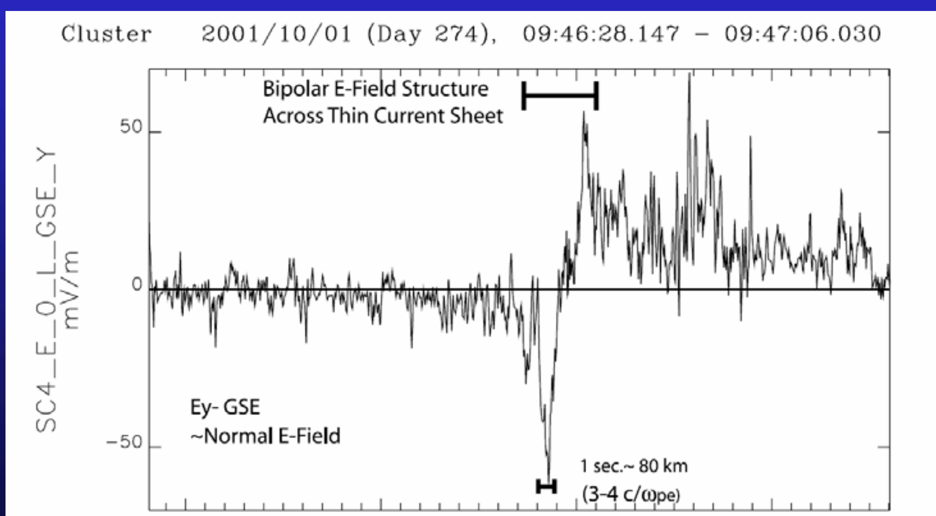
$\delta_e >> c/\omega_{pe}$



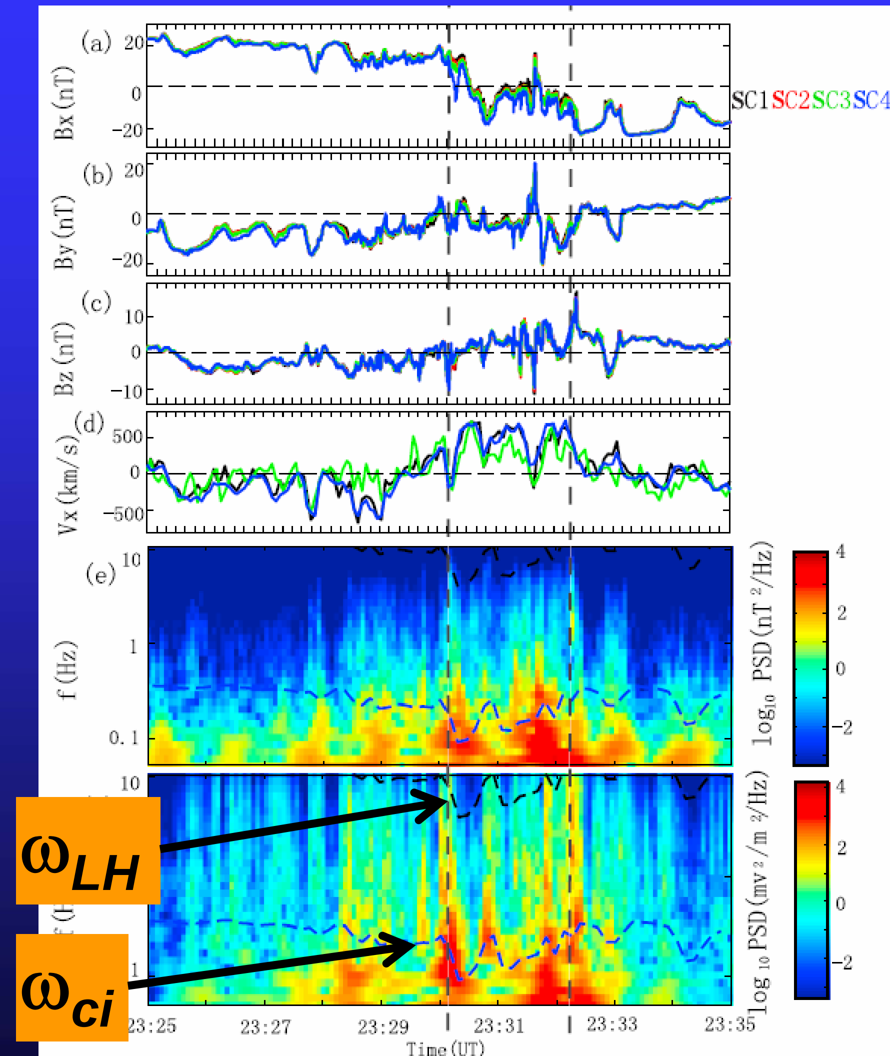
[*Ji et al.*, GRL, 2008]

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]

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

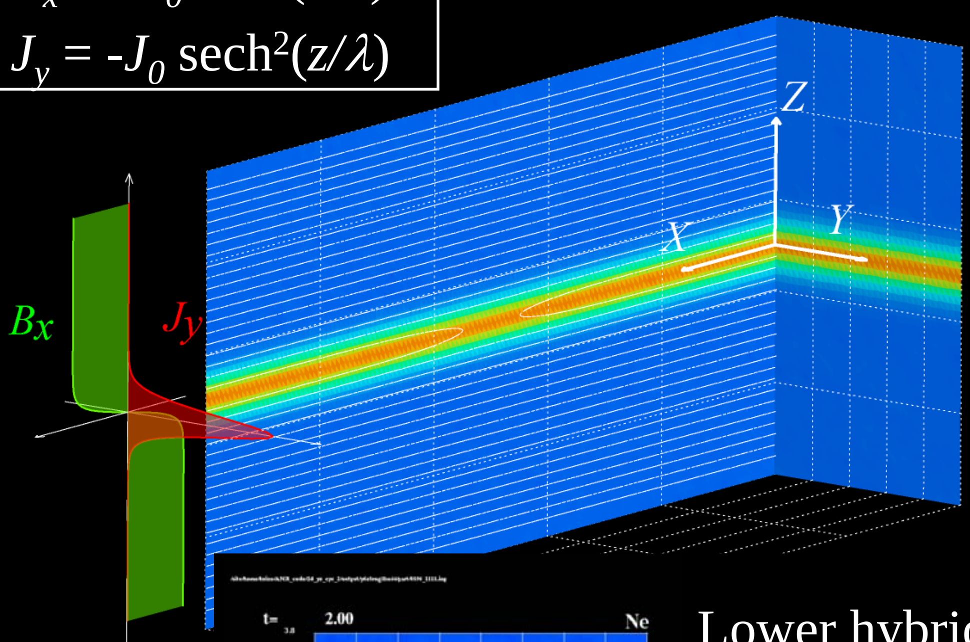
(Resistive length)

Could be caused by wave-particle interactions.

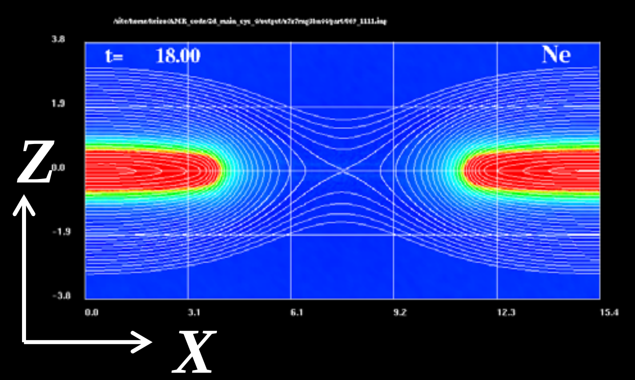
３次元電流層における不安定モード

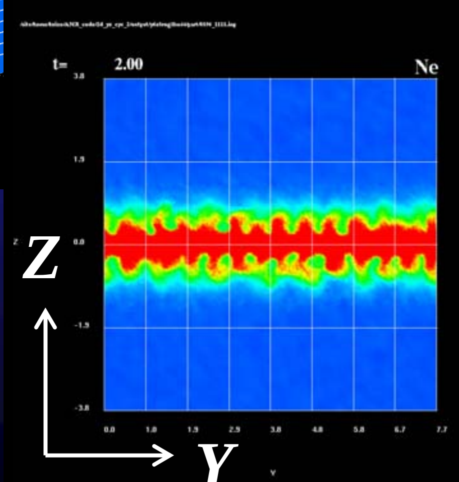
$B_x = -B_0 \tanh(z/\lambda)$

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



Tearing instability

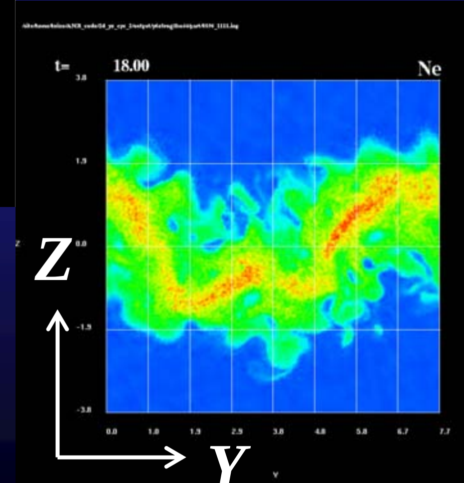




Lower hybrid drift instability (LHDI)

$k_y \rho_e \sim 1$

$\gamma \sim \omega_{lh}$



Kink-type instability

$k_y L \sim 1$

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)],

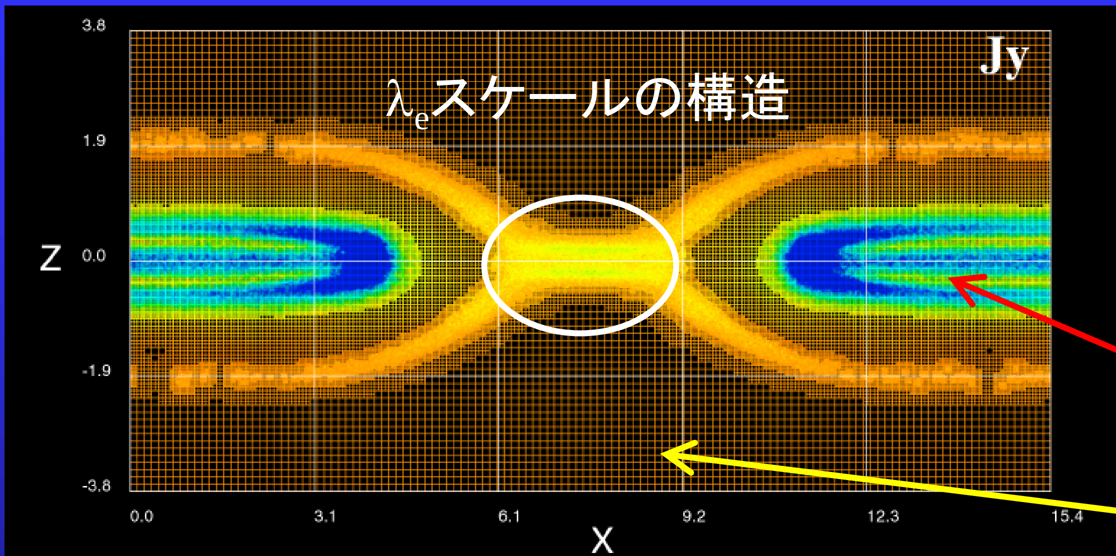
No impact on the quasi-steady process
[*Pritchett & Coroniti* (2001), *Karimabadi et al.* (2003)],

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

AMR-PICコード

[Fujimoto & Machida, JCP, 2006;
Fujimoto, JCP, 2011]

(Adaptive Mesh Refinement – Particle-in-Cell)



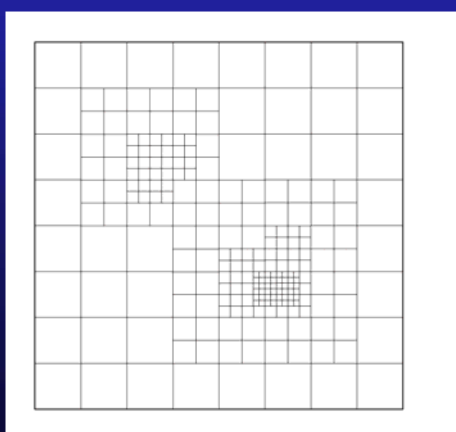
陽解法の制約

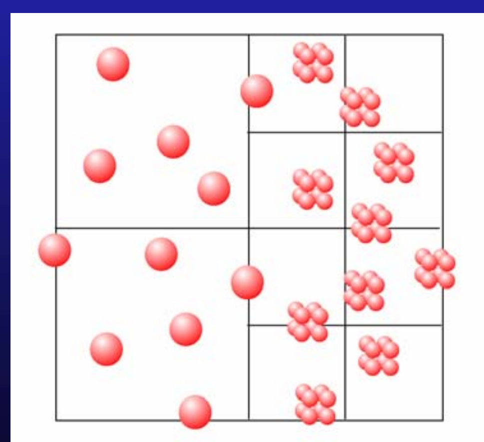
$\Delta x < \lambda_{De}, \quad \omega_{pe}\Delta t < 1$

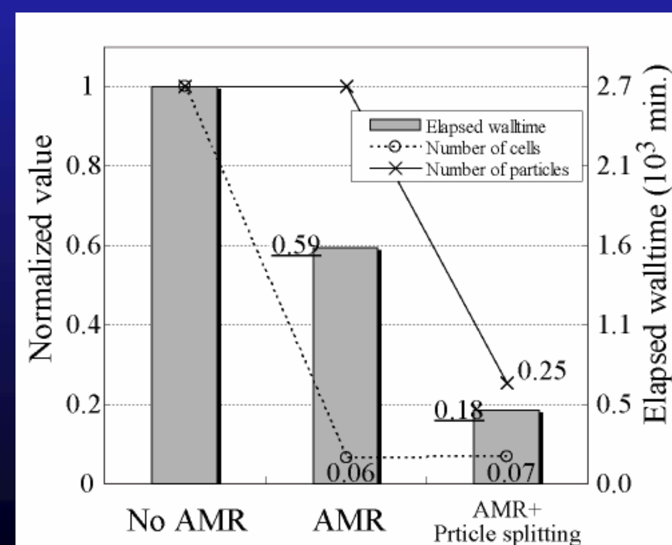
$\Delta x/\Delta t > c$

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

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

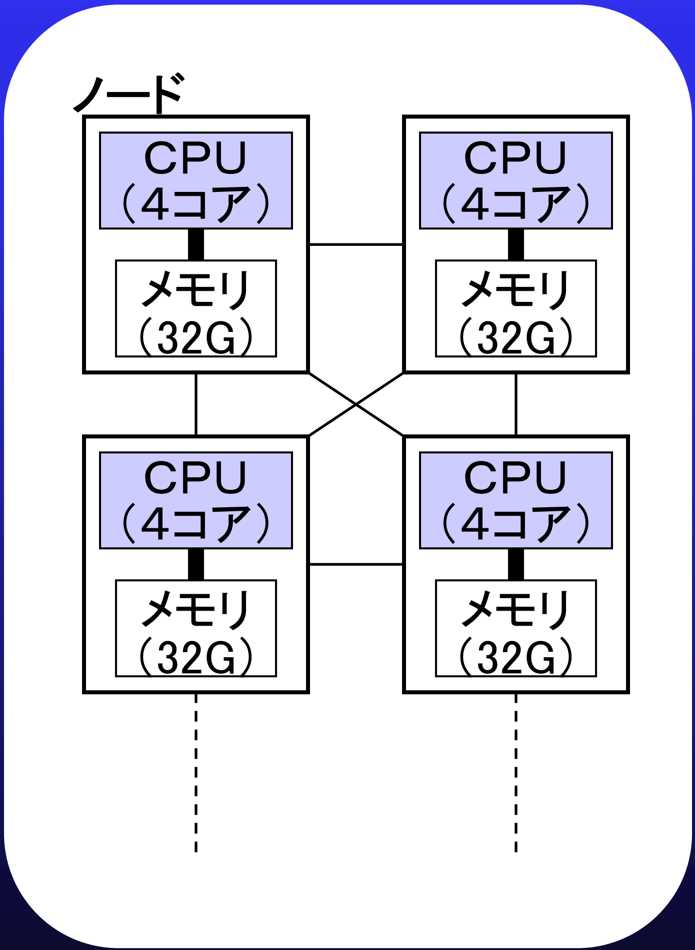


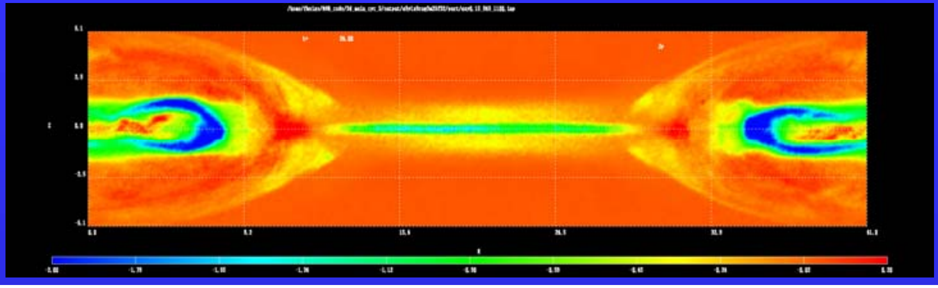


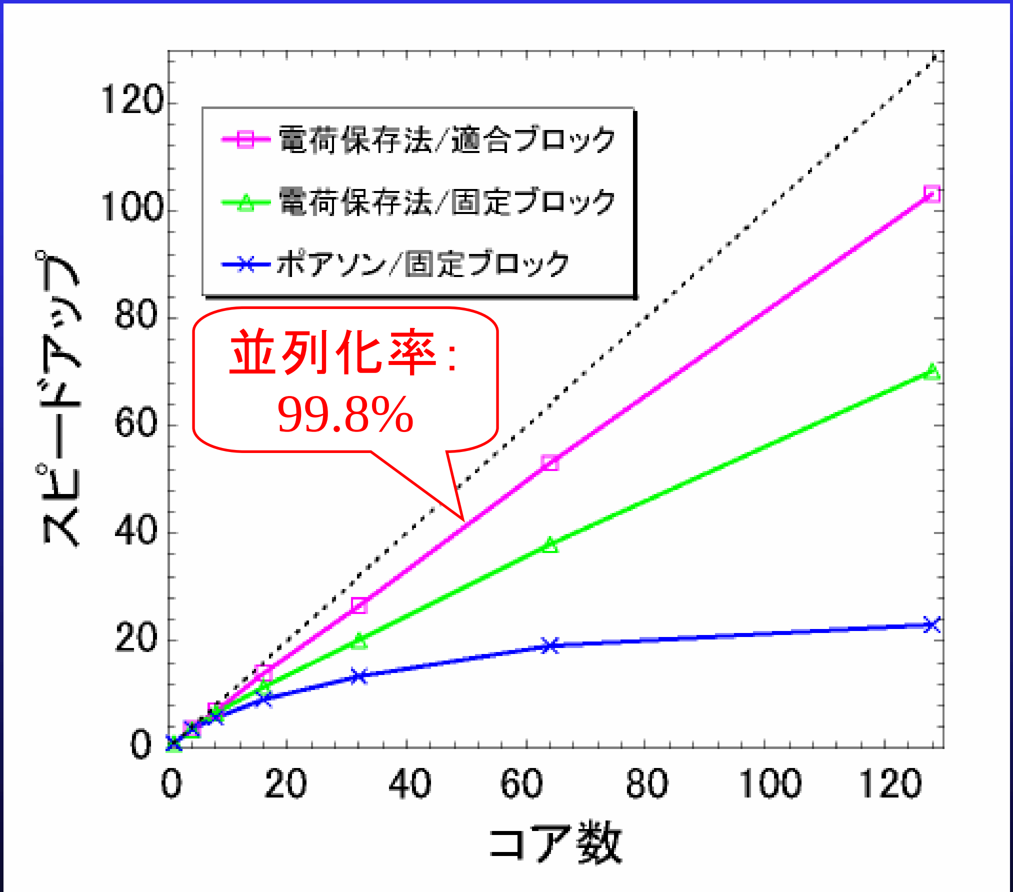


超並列AMR-PICコードの性能

Fujitsu FX1
（名大情報基盤センター）

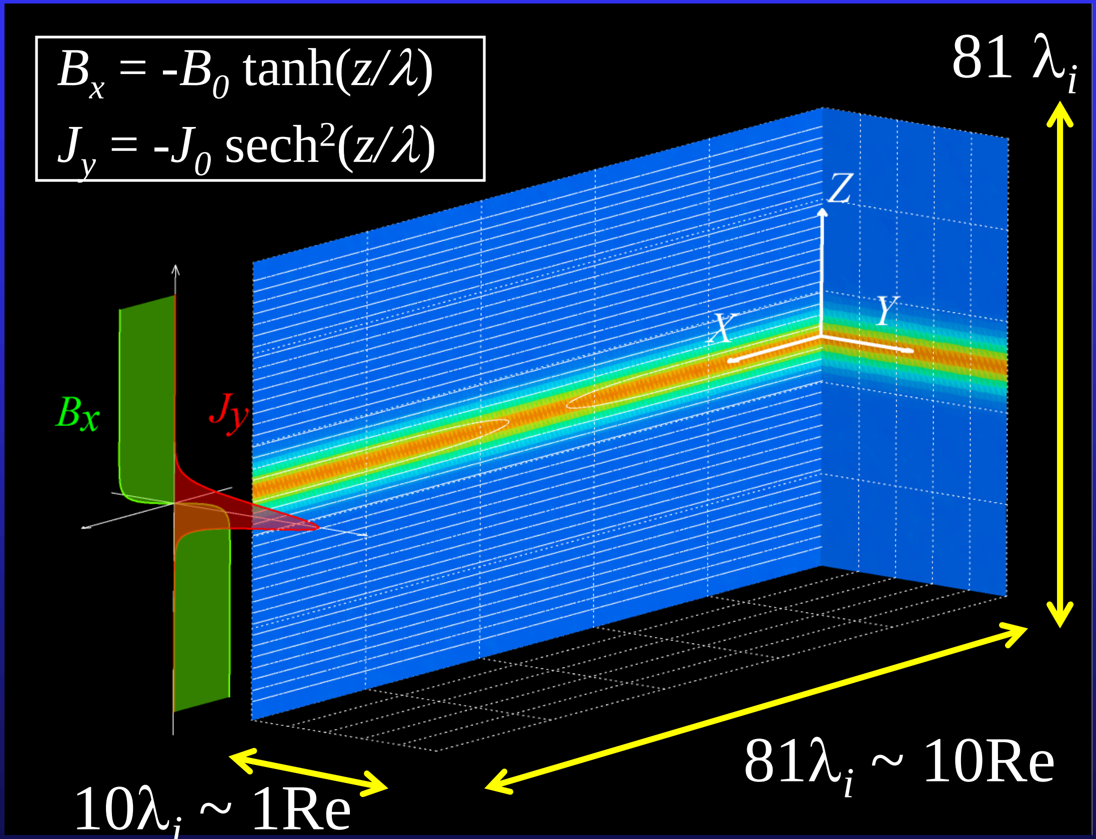






Simulation Setup

AMR-PIC-3D code on Fujitsu FX1 (1024 cores)



$m_i/m_e = 100$

Max resolution:

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

Max number of particles

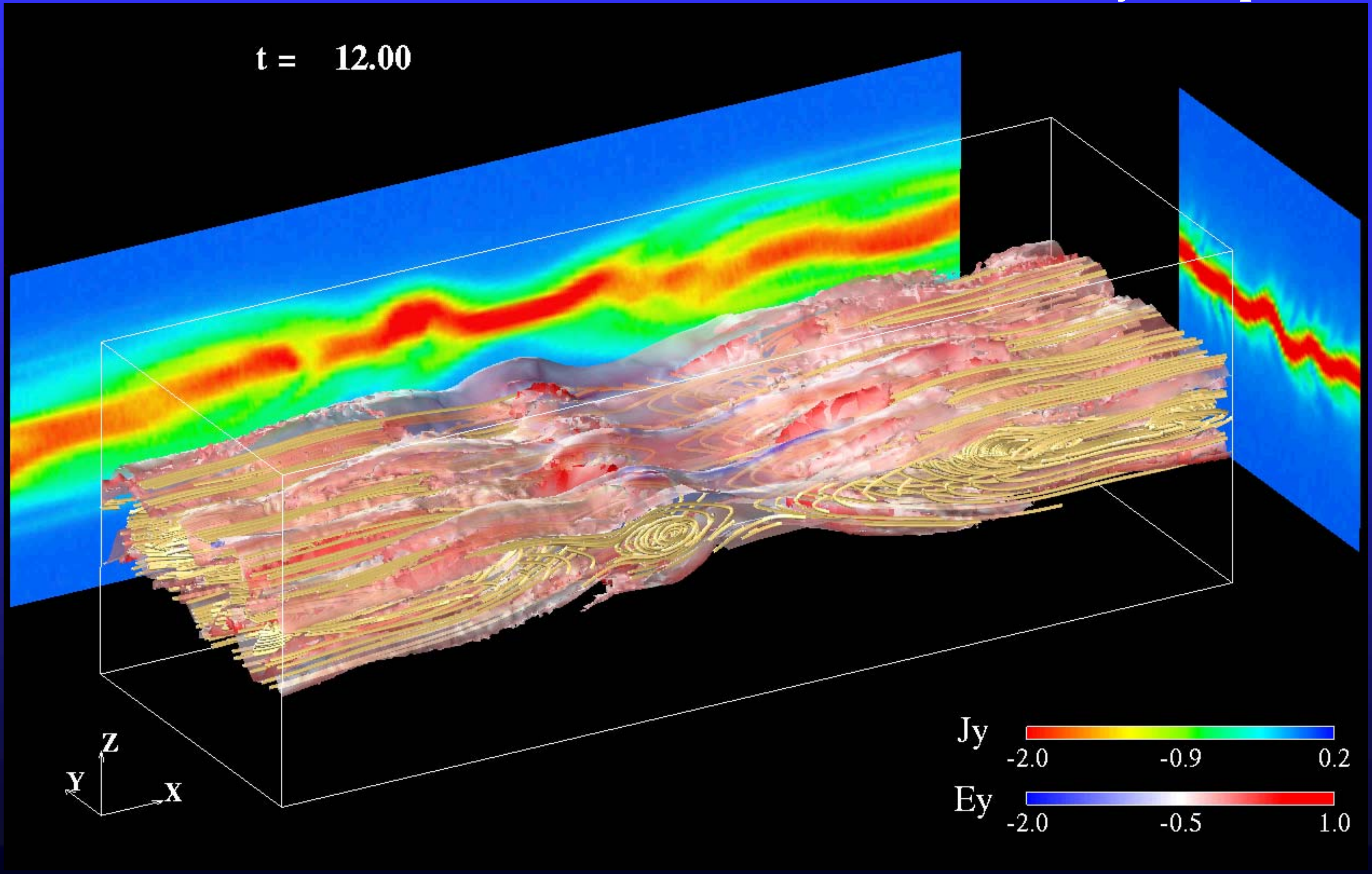
Ion + Electron $\sim 10^{11}$

Max memory used ~ 6TB

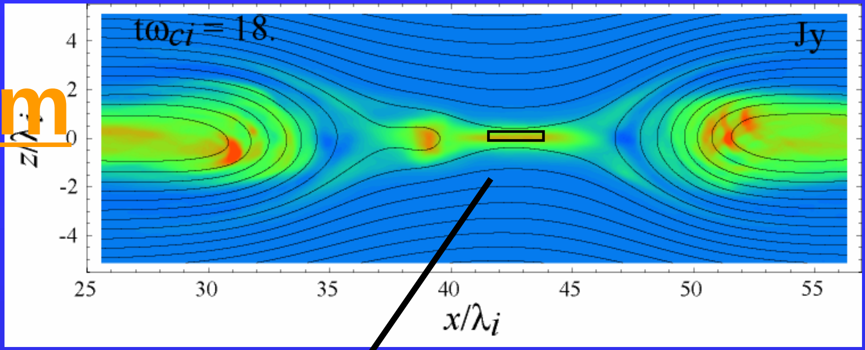
Time Evolution of the Current Sheet

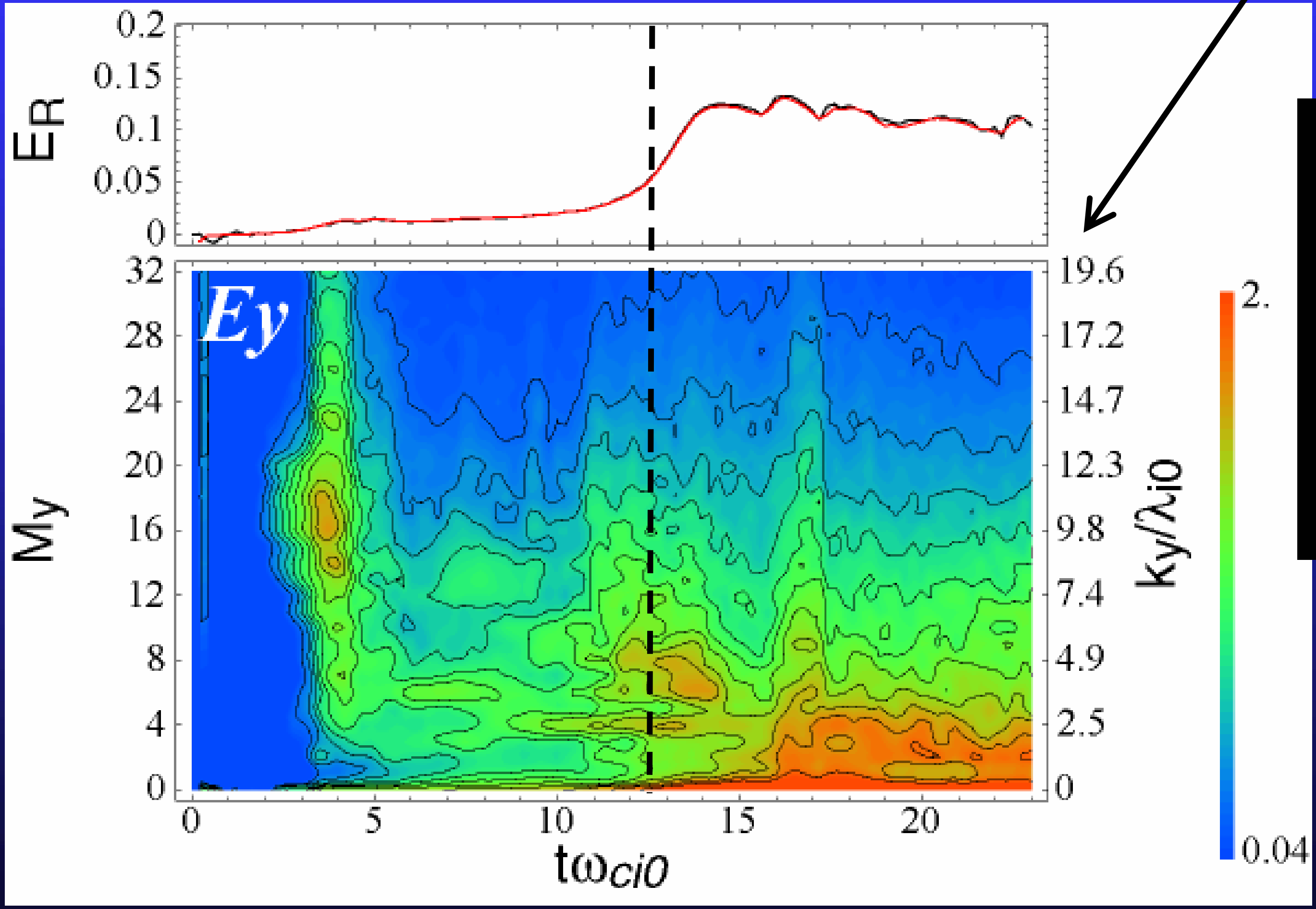
Surface: |J|, Line: Field line

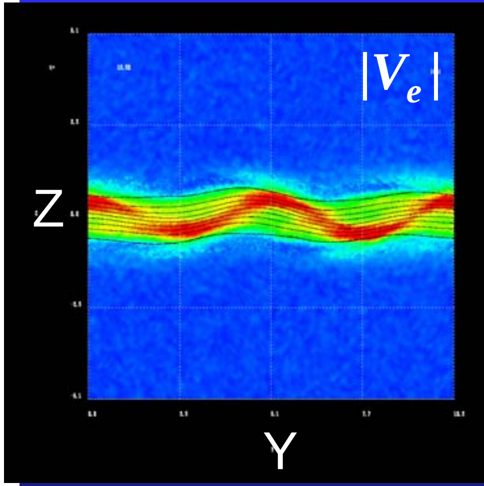
Color on the surface: Ey, Cut plane：Jy



Wave Number Spectrum







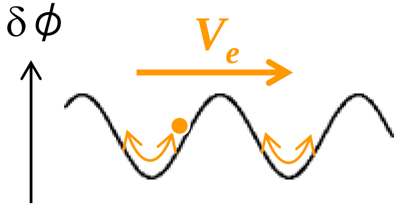
Wave-Particle Interactions

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

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

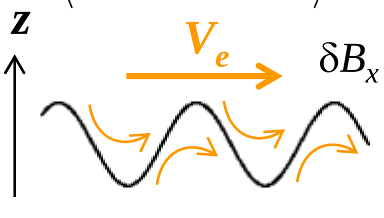
Anomalous effects

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

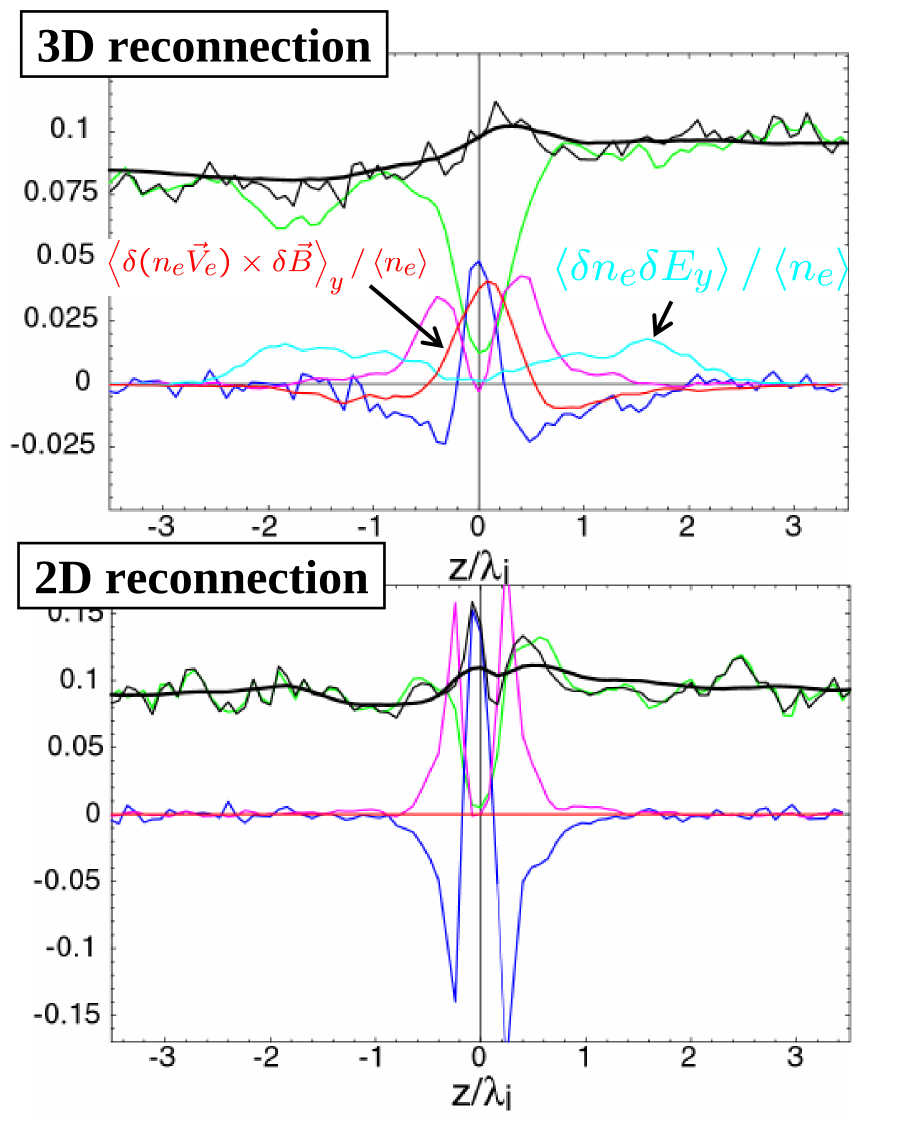


ES turb.

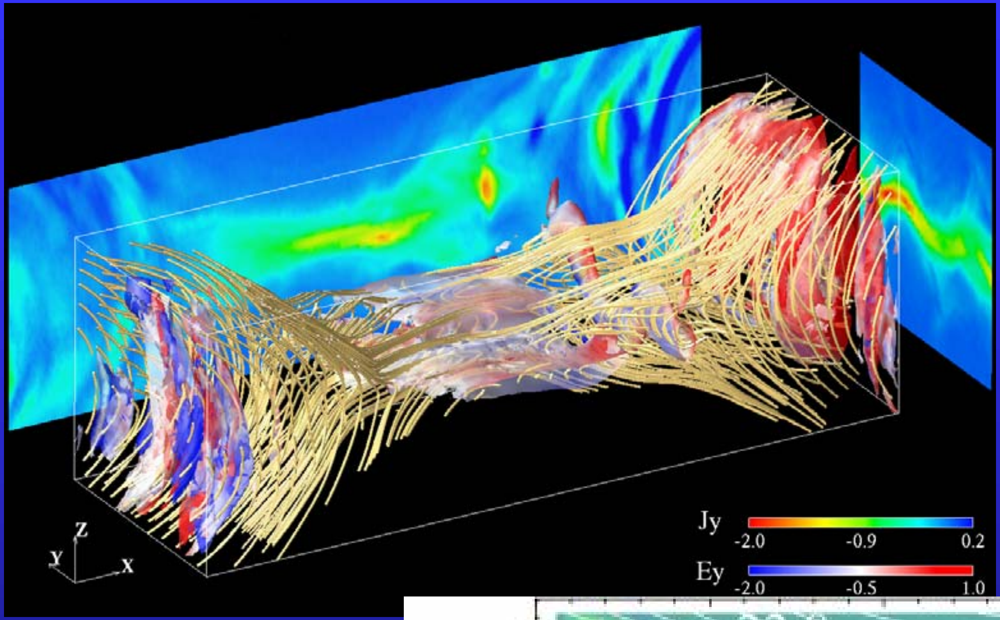
$\left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle$

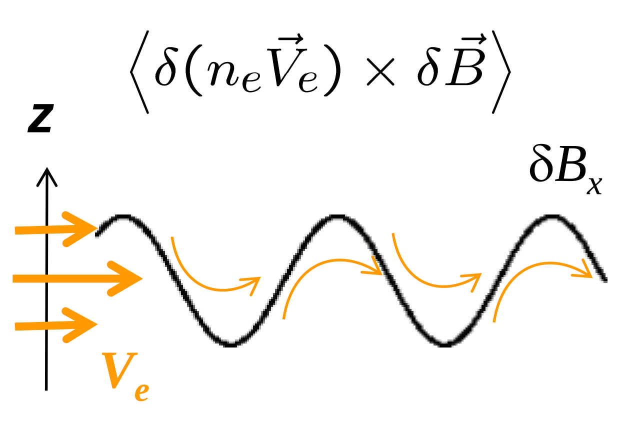


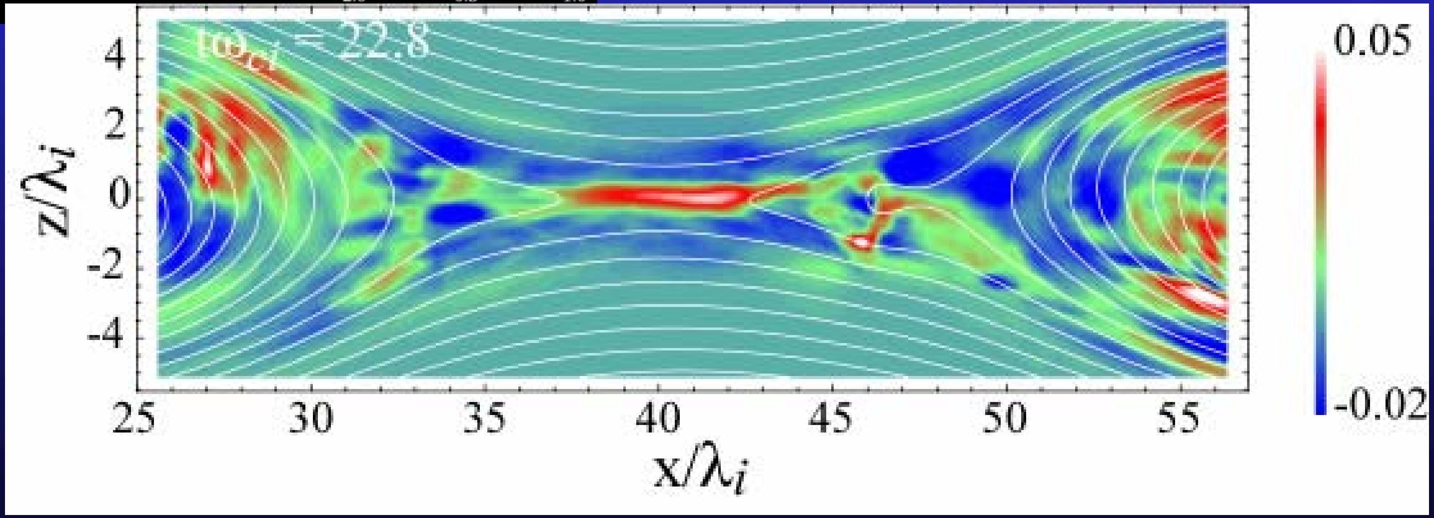
EM turb.



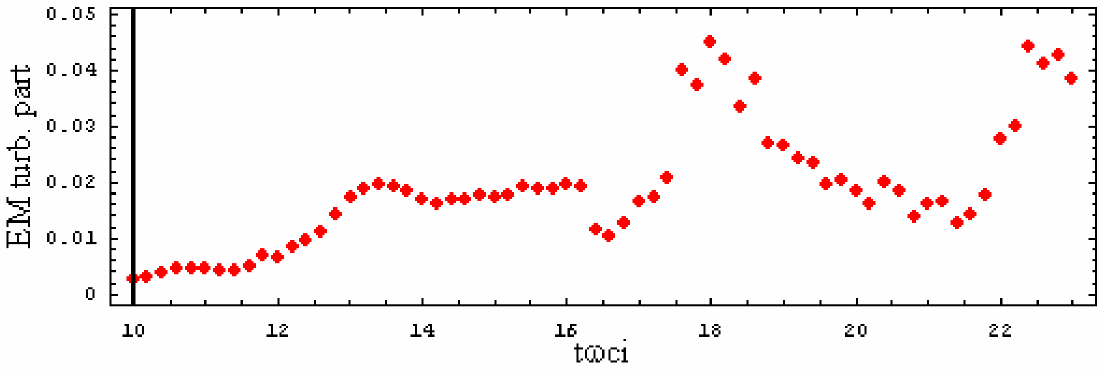
電磁波動による運動量異常輸送(異常磁気拡散)

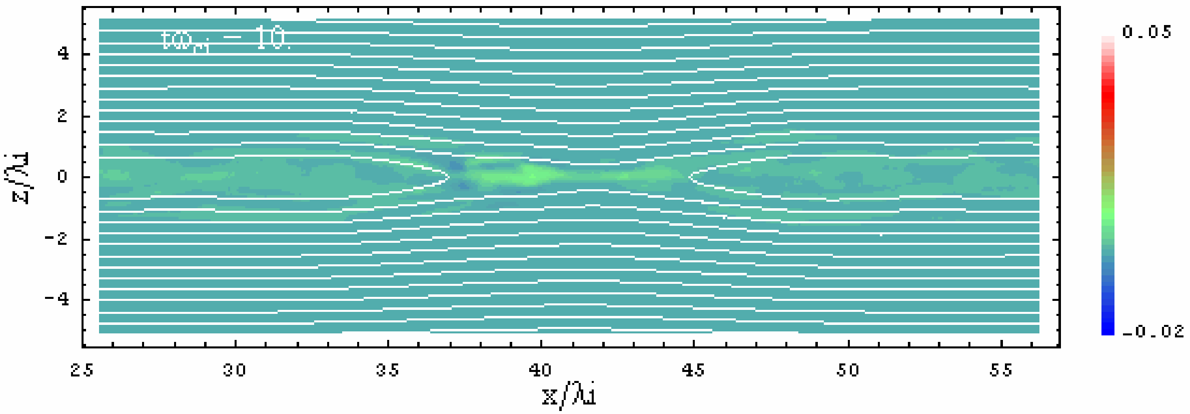




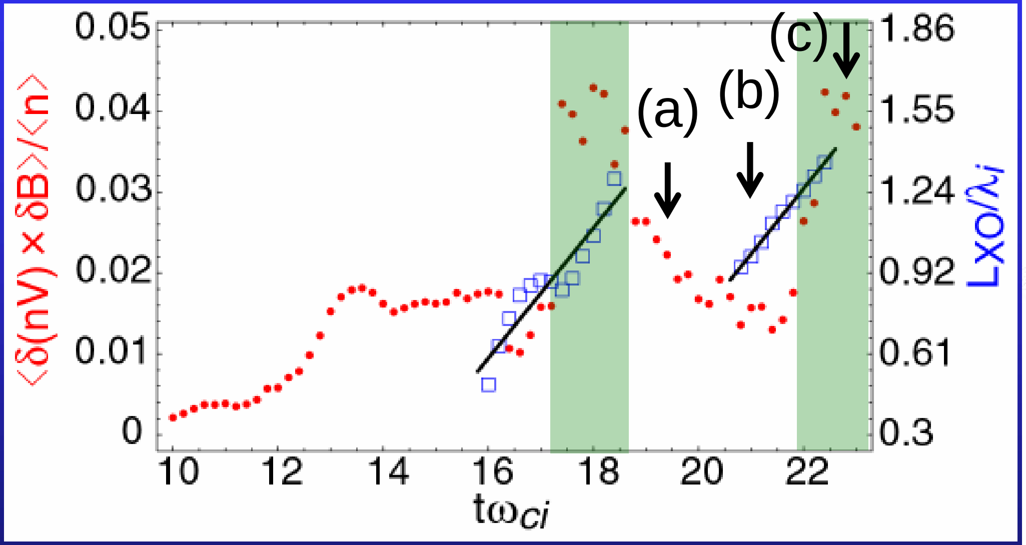


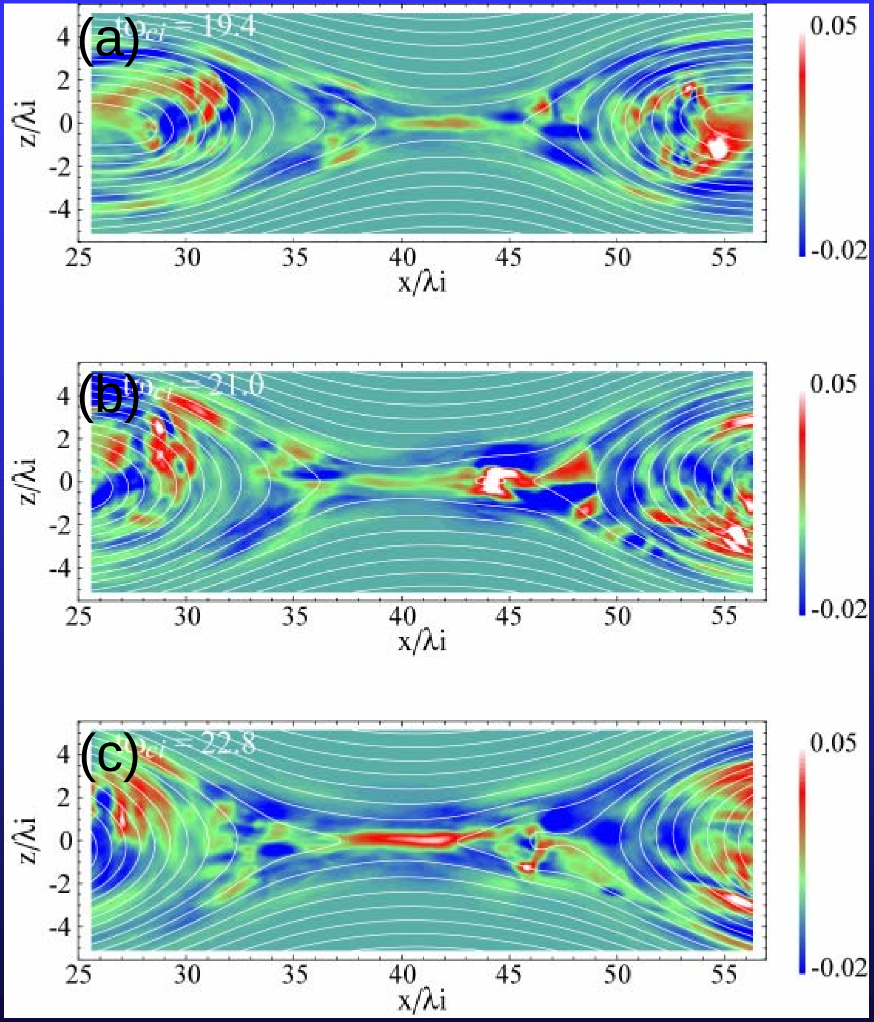
プラズモイドにともなう電磁擾乱の強化





Plasmoid-Induced Turbulence II

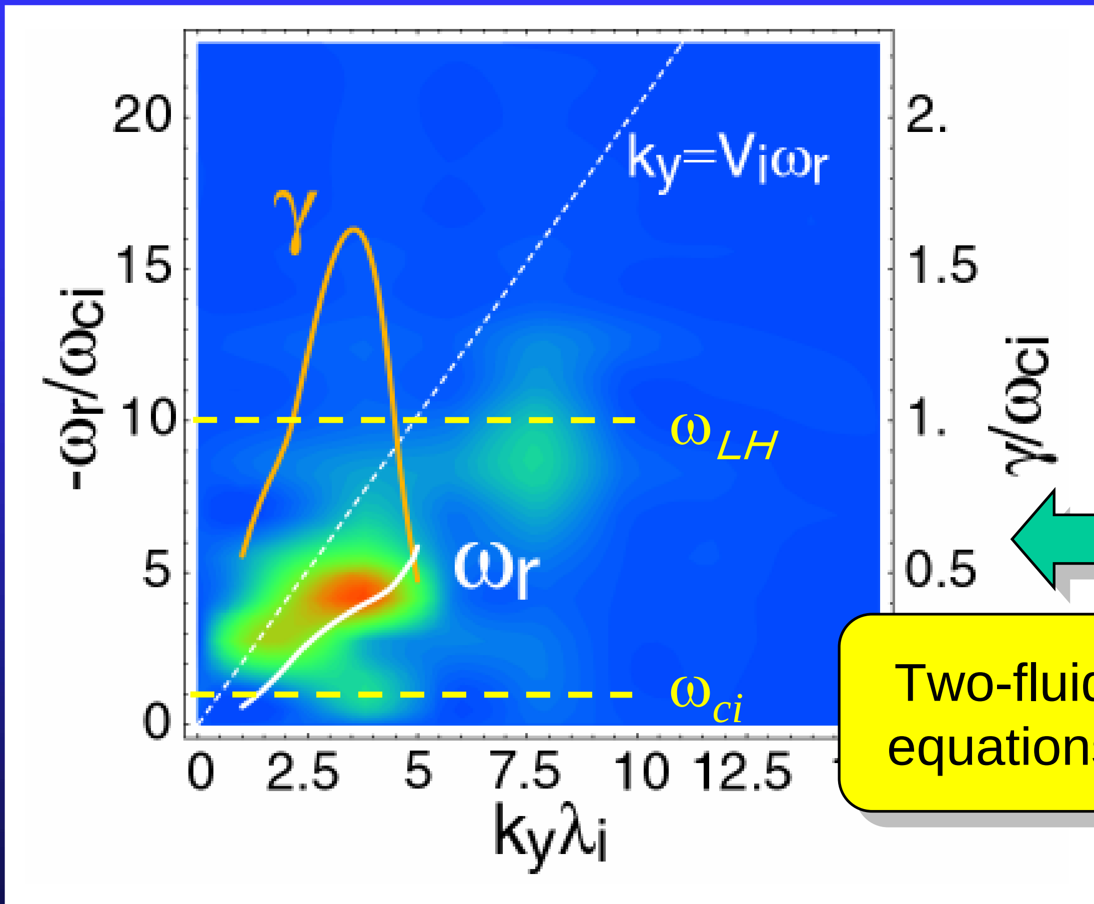




Wave Properties

In collaboration with R. Sydora (U. Alberta)

$\omega = \omega_r + i\gamma$



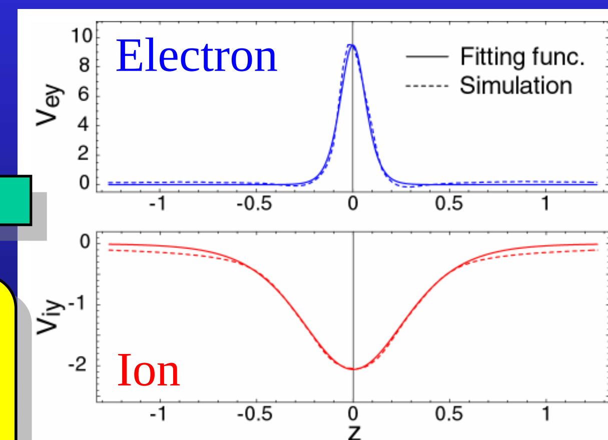
Two-fluid equations

Simulation results

$\omega_{ci} < |\omega_r| < \omega_{LH}$

$V_{ph} \approx V_A$

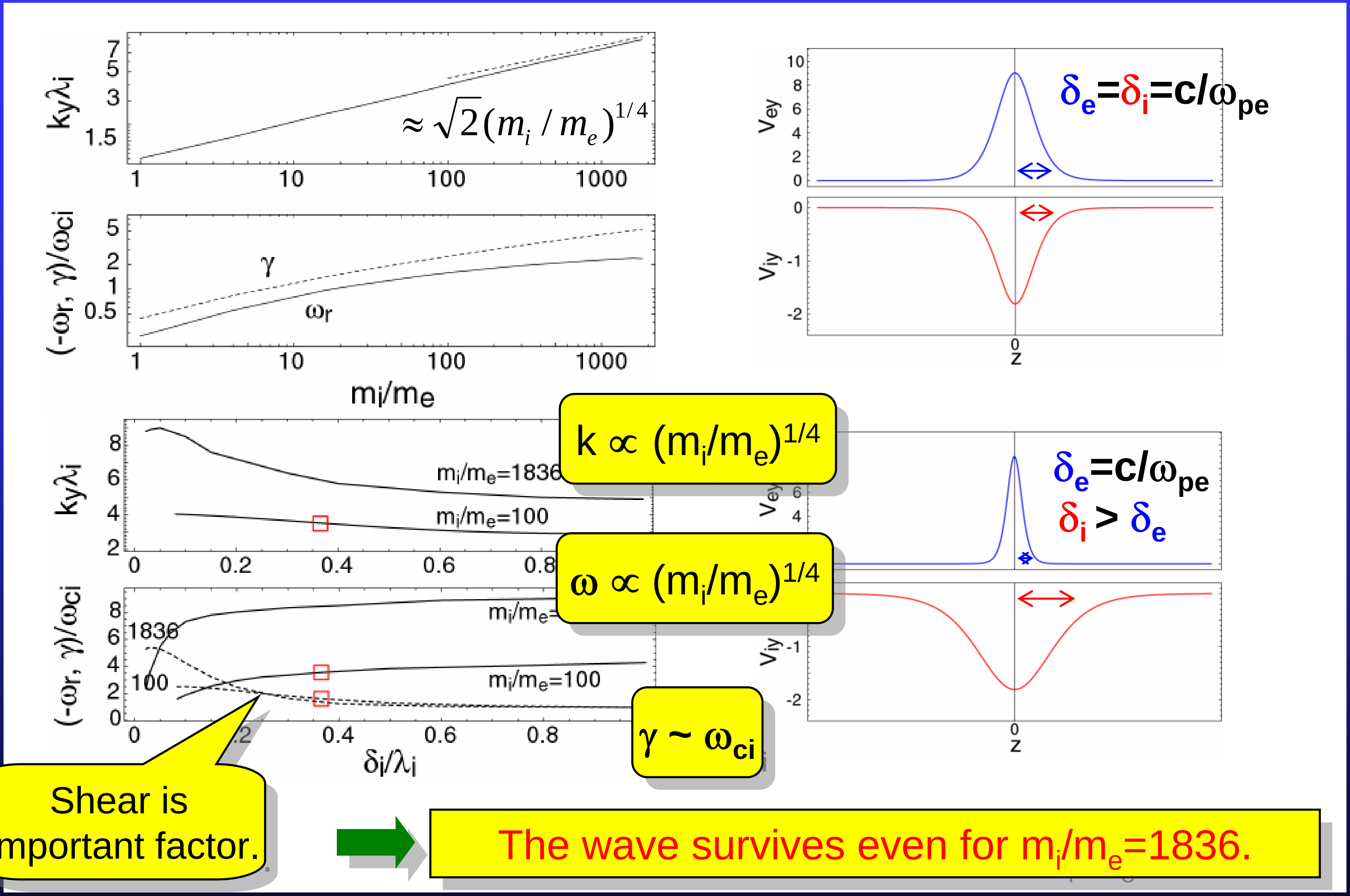
Linear analyses



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.

まとめ

AMR-PICコードを用いて、磁気リコネクションの大規模な3次元粒子シミュレーションを実施し、3次元的な磁気拡散機構を調べた。

- 電流層に沿って電磁波動が発生　⇒　運動量の異常輸送（異常磁気拡散）
- プラズモイドの発生　⇒　電磁擾乱を強化
- 線形波動解析　⇒　$\omega_{ci} < \omega_r < \omega_{LH}$
  シアー駆動型不安定性
  $m_i/m_e = 1834$ でも大きな成長率

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