３次元磁気リコネクションにおけるプラズモイド誘導乱流
(Plasmoid-induced turbulence in 3D magnetic reconnection)

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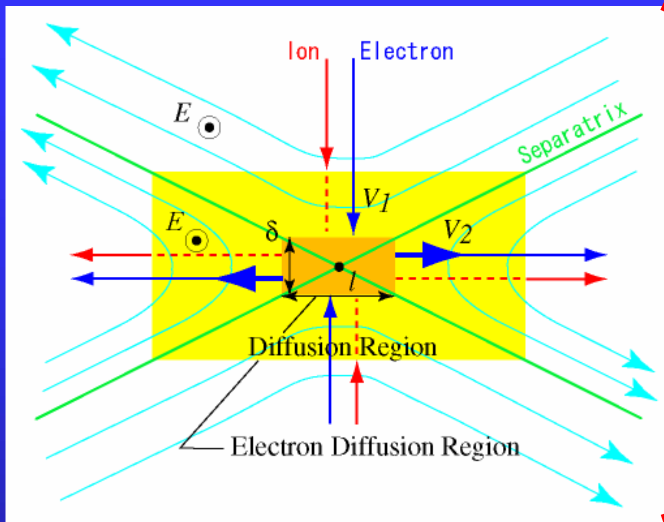
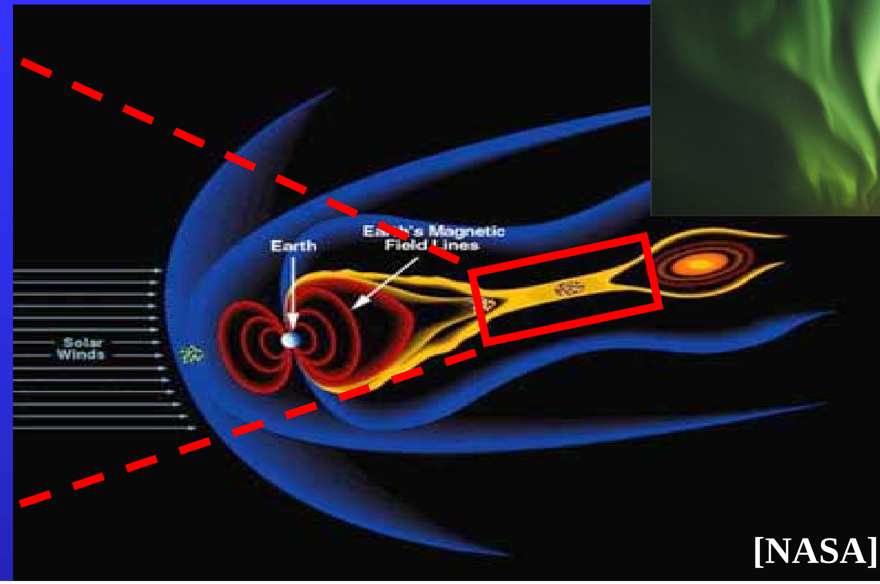
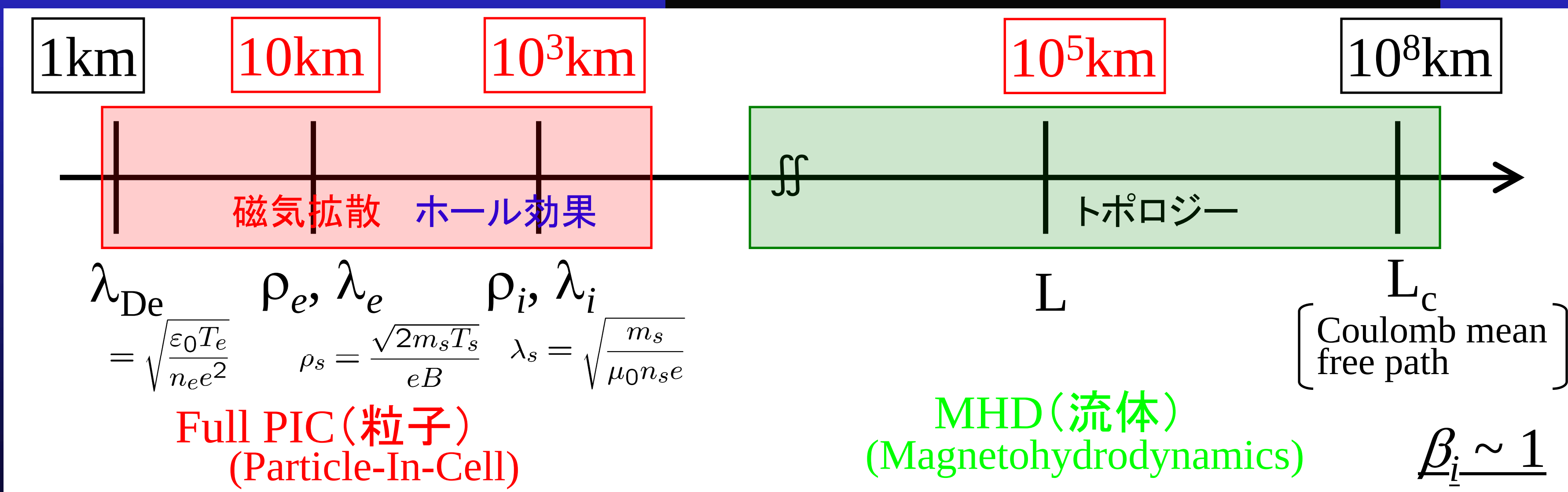
磁気リコネクションと磁気圏ダイナミクス



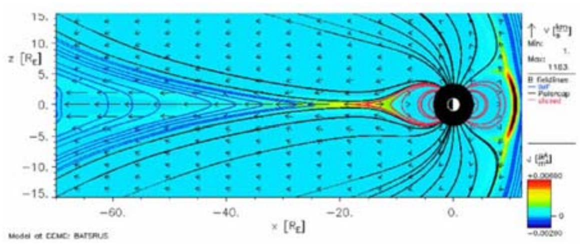




Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

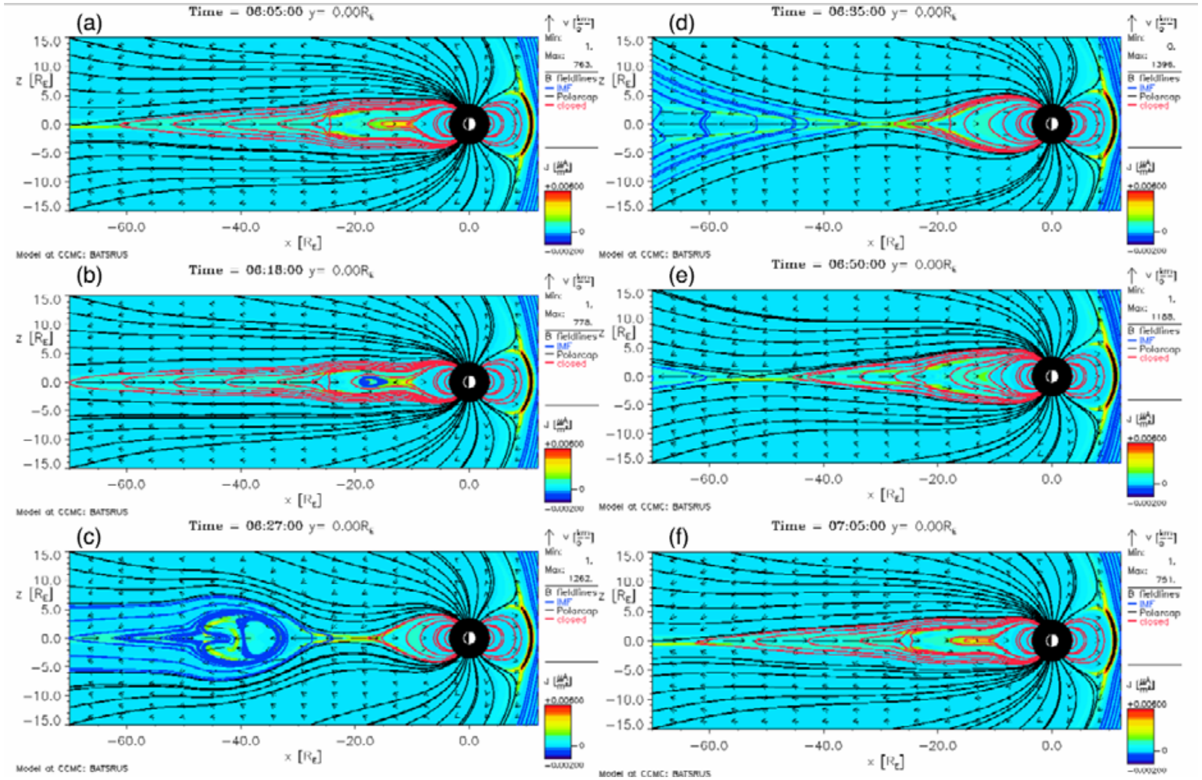


- Slow reconnection
- Quasi-steady configuration

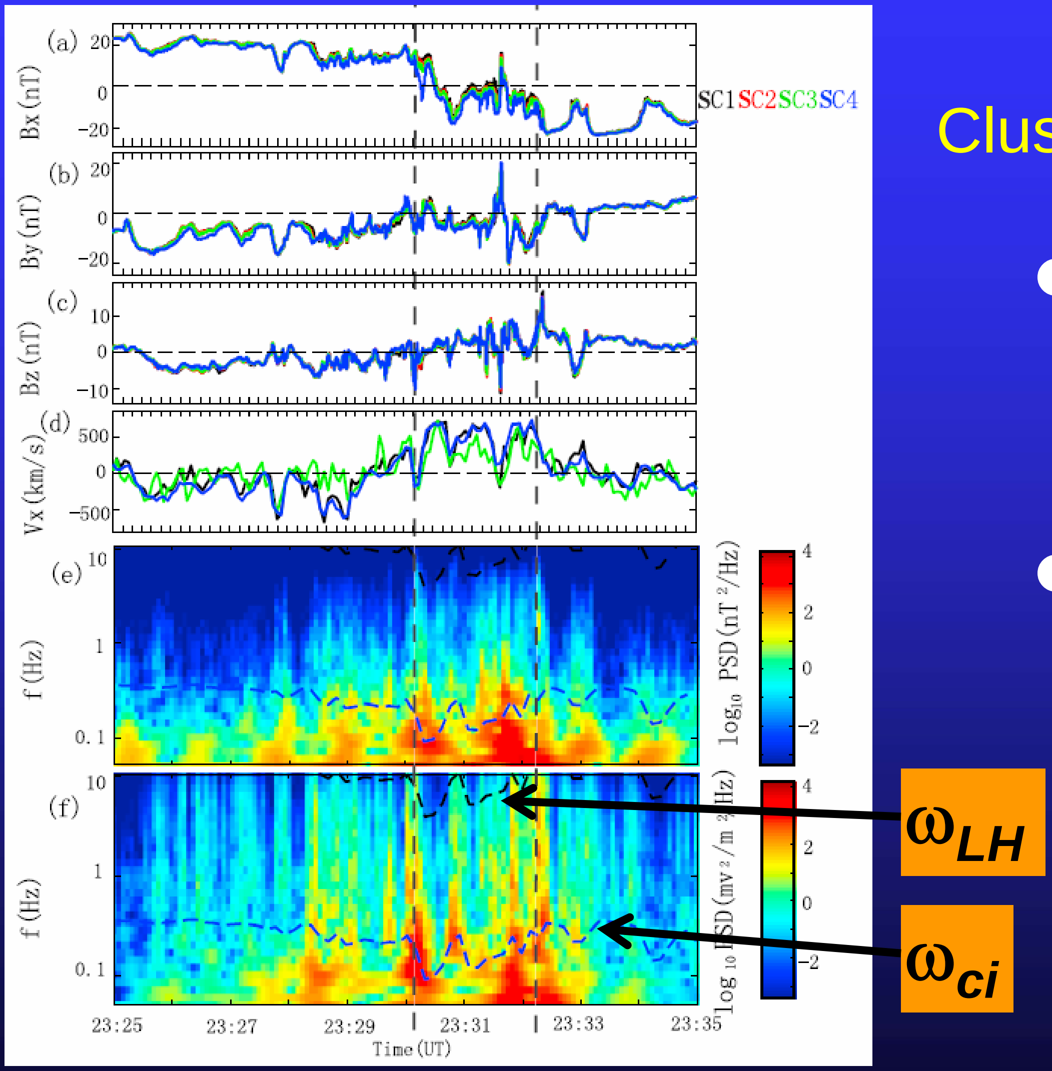
- Fast reconnection
- Quasi-periodic process

Nongyrotropic correction case

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



Wave Observations in the Magnetotail



[*Zhou et al*, JGR, 2009]

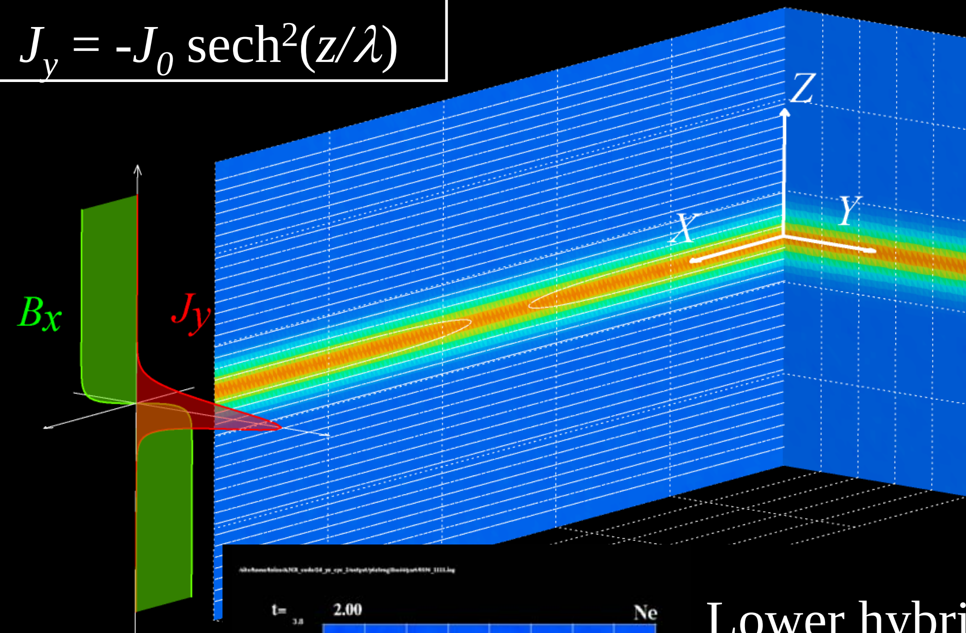
Cluster衛星による観測

- 電流層中心付近で $\omega_{ci} < \omega < \omega_{LH}$ の電磁波
- 波長 $\lambda \sim 352$km $\sim (\lambda_i \lambda_e)^{1/2}$

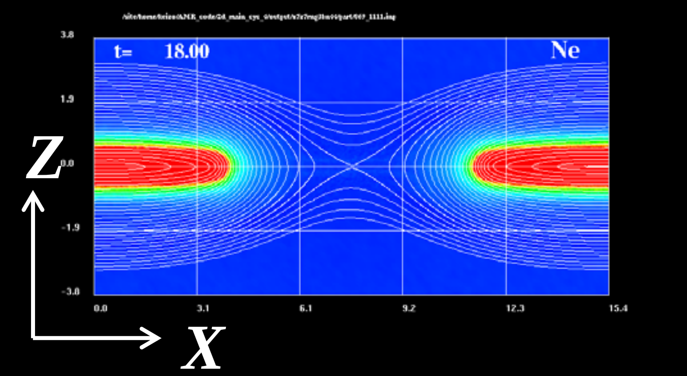
３次元電流層における不安定モード

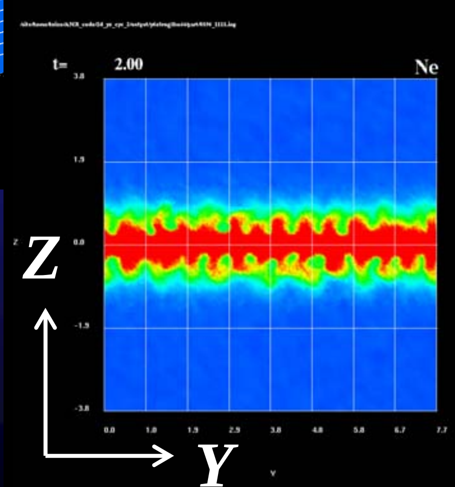
$B_x = -B_0 \tanh(z/\lambda)$

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



Tearing instability

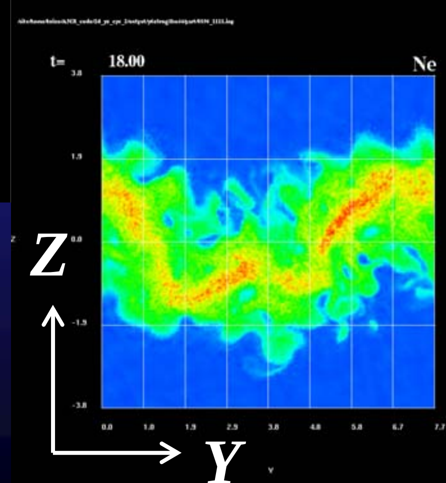




Lower hybrid drift instability (LHDI)

$k_y \rho_e \sim 1$

$\gamma \sim \omega_{lh}$



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]

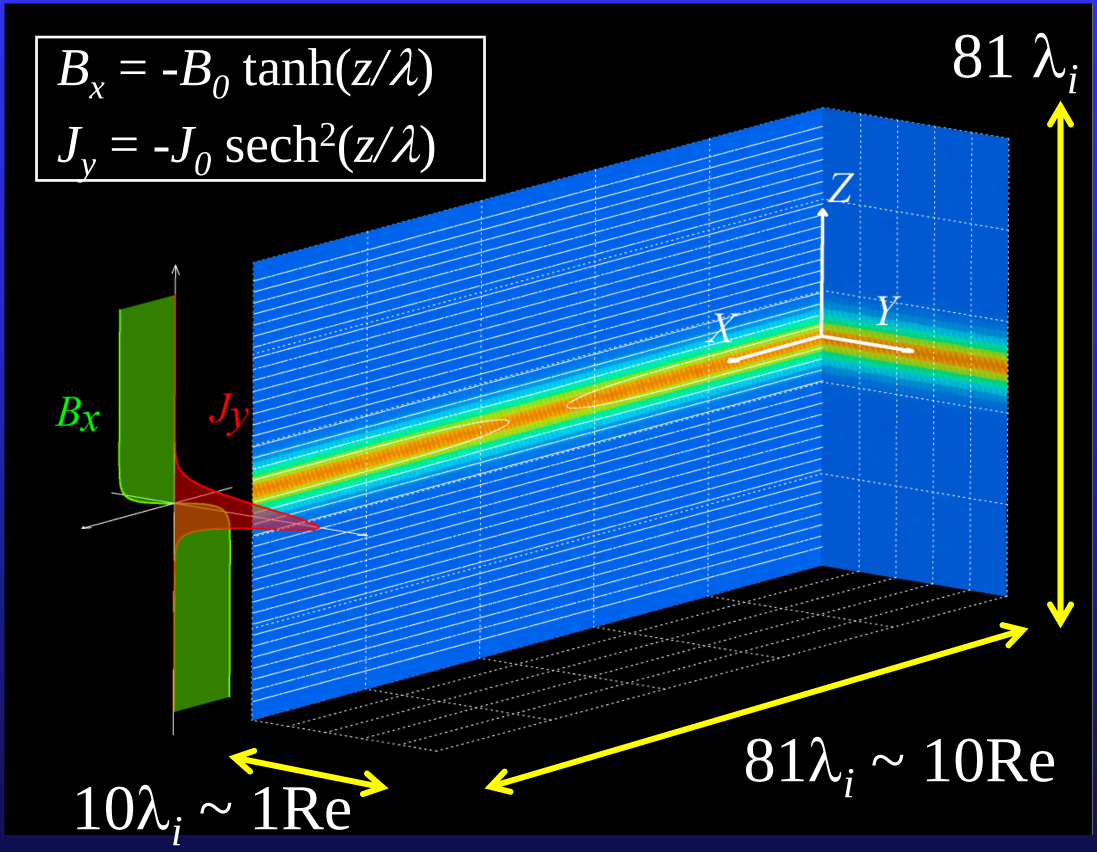
Triggers magnetic reconnection [*Horiuchi & Sato* (1999), *Scholer et al.* (2003)],

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)].

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

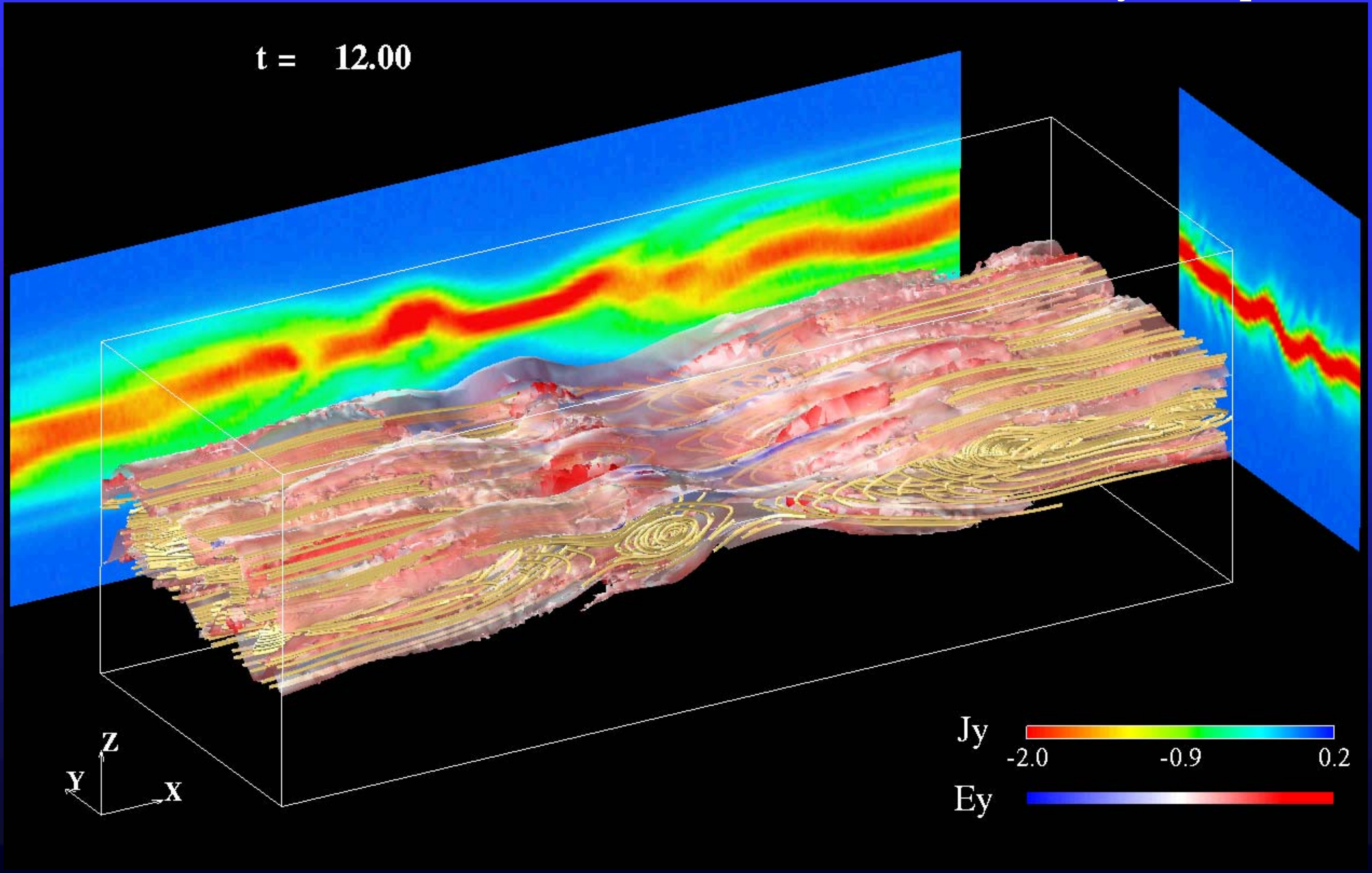
Ion + Electron ~ 10^{11}

Max memory used ~ 6TB

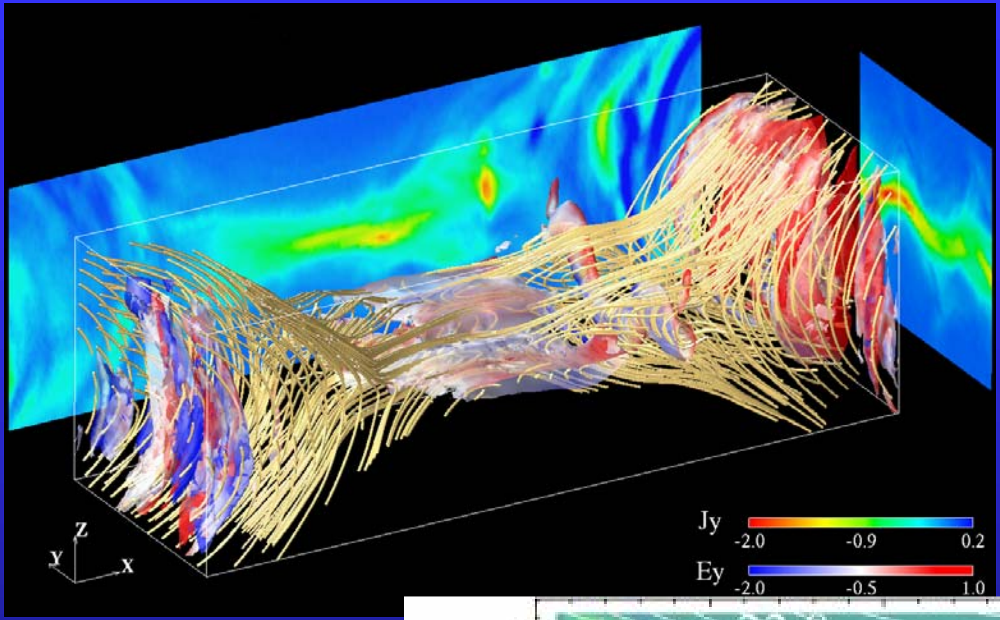
Time Evolution of the Current Sheet

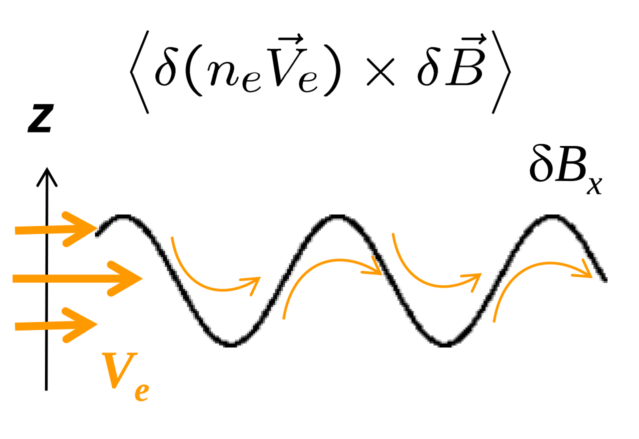
Surface: |J|, Line: Field line

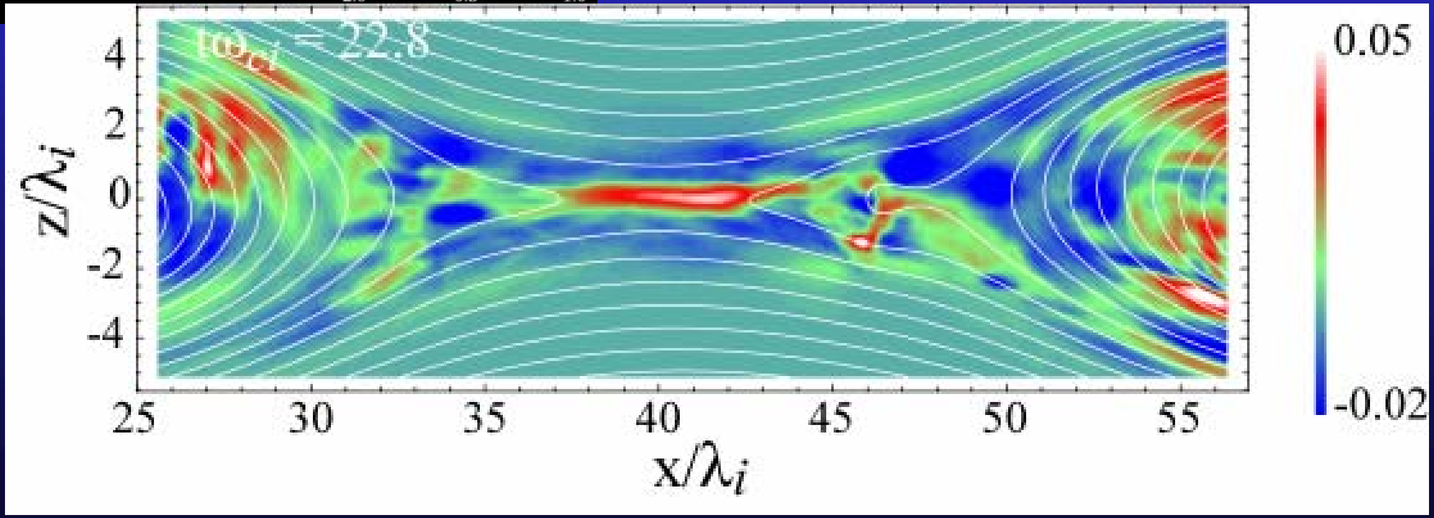
Color on the surface: Ey, Cut plane：Jy



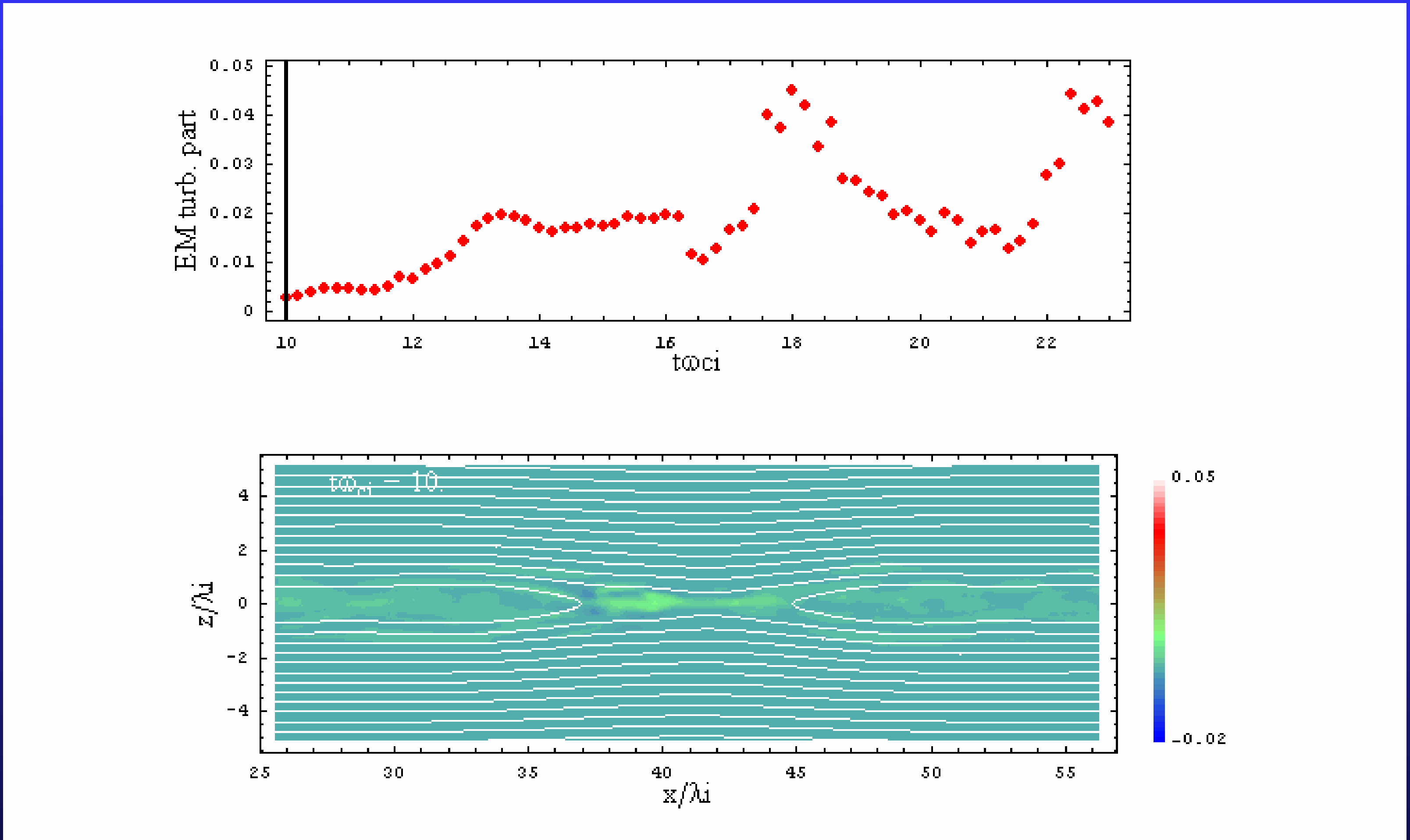
電磁波動による運動量異常輸送(異常磁気拡散)



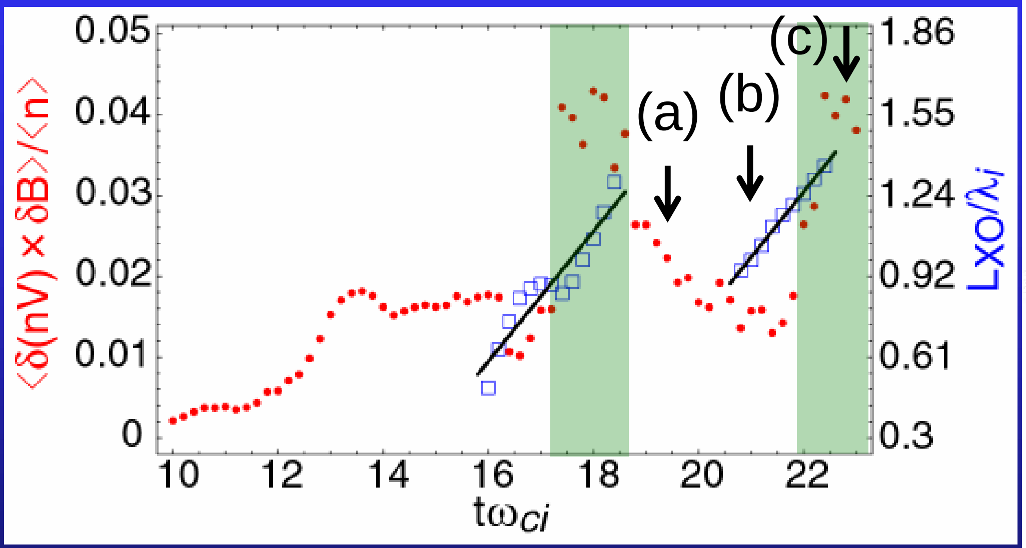


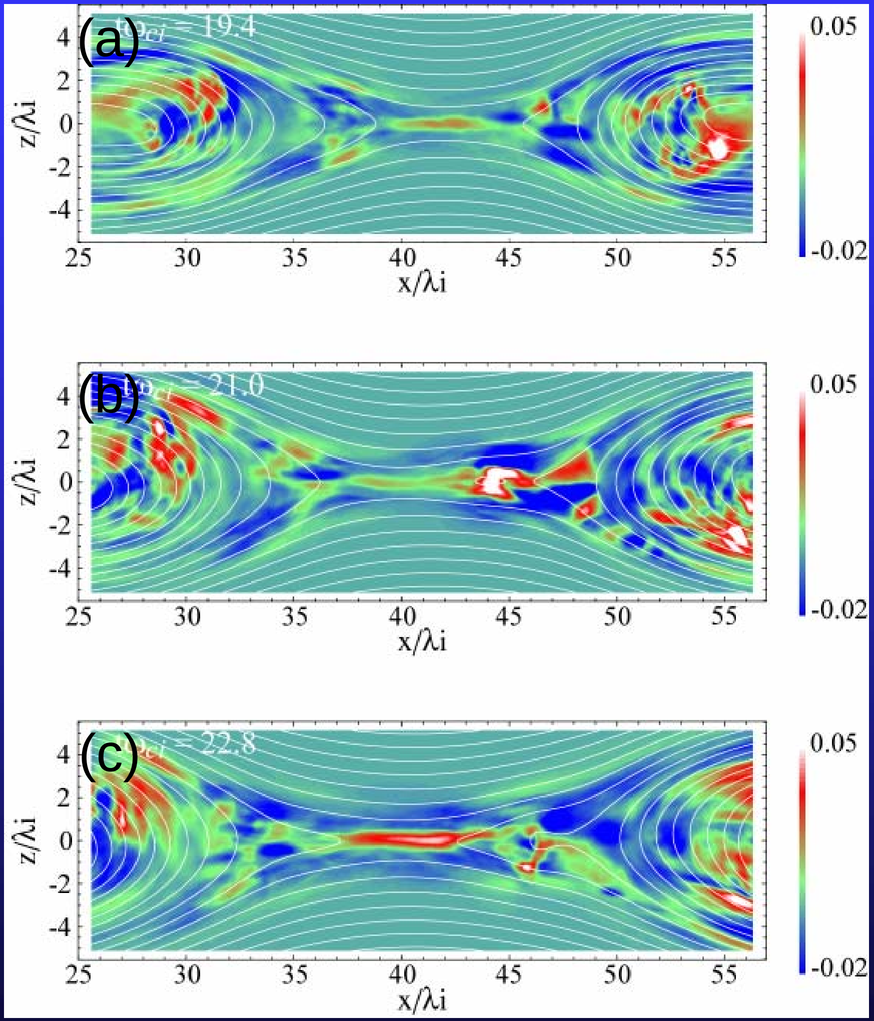


プラズモイドにともなう電磁擾乱の強化



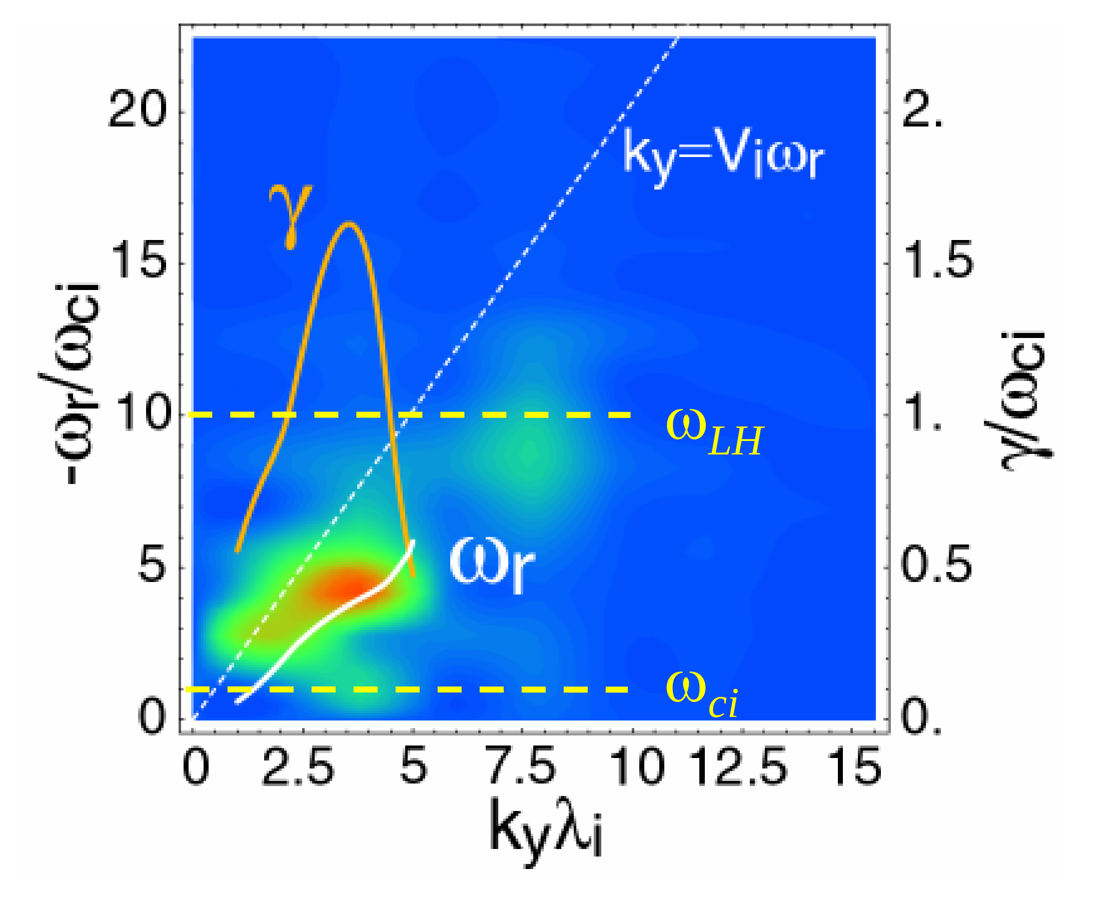
Plasmoid-Induced Turbulence II





Wave Properties (Linear Analyses)

$\omega = \omega_r + i\gamma$



Simulation results

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

$V_{ph} \approx V_A$

Linear analyses

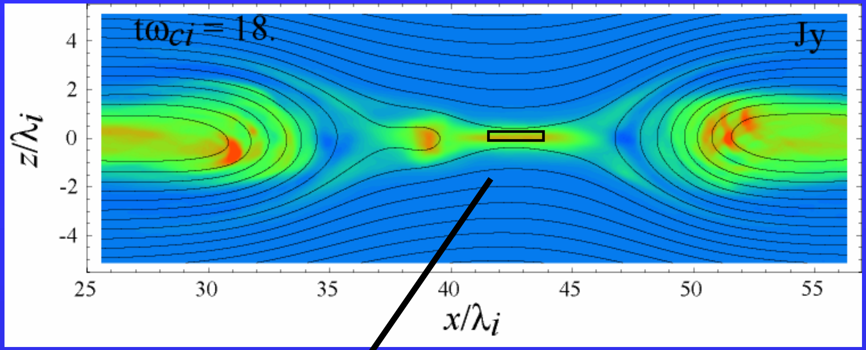
- ドリフト波ではない
- シアー駆動型モード
- ω_rとk_yはm_i/m_eに依存
- $m_i/m_e = 1834$ でも大きな成長率

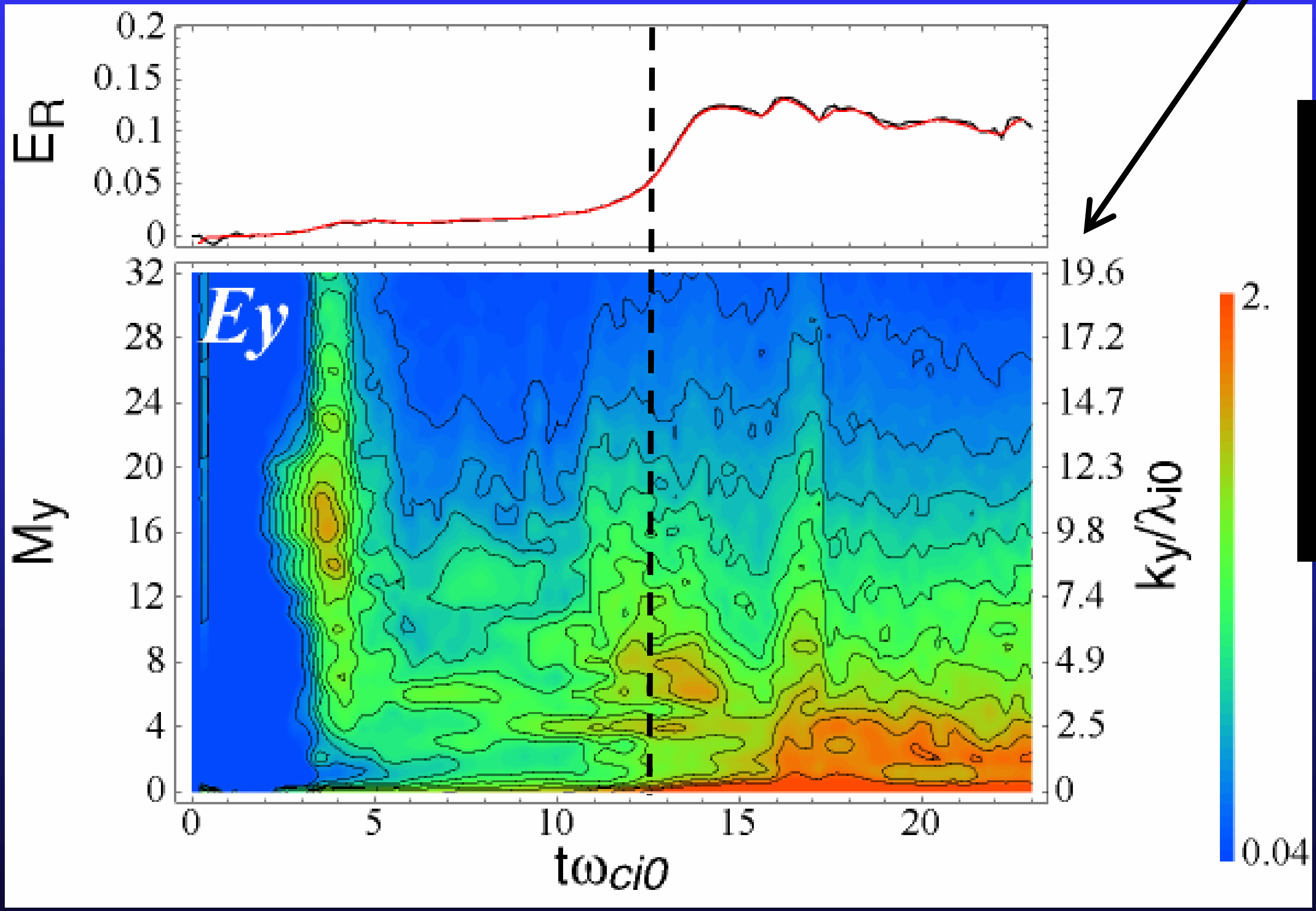
まとめ

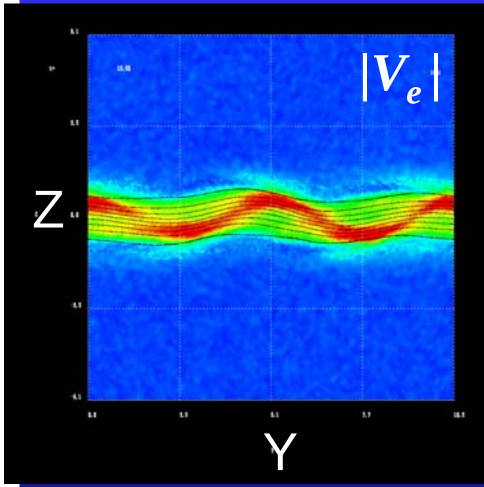
AMR-PICコードを用いて、磁気リコネクションの大規模な3次元粒子シミュレーションを実施し、3次元的な磁気拡散機構を調べた。

- 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

Wave Number Spectrum







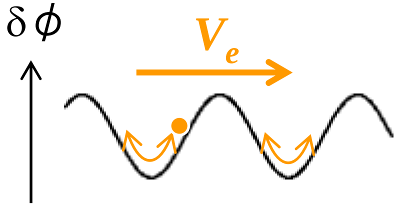
Wave-Particle Interactions

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

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

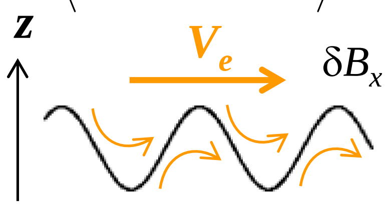
Anomalous effects

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

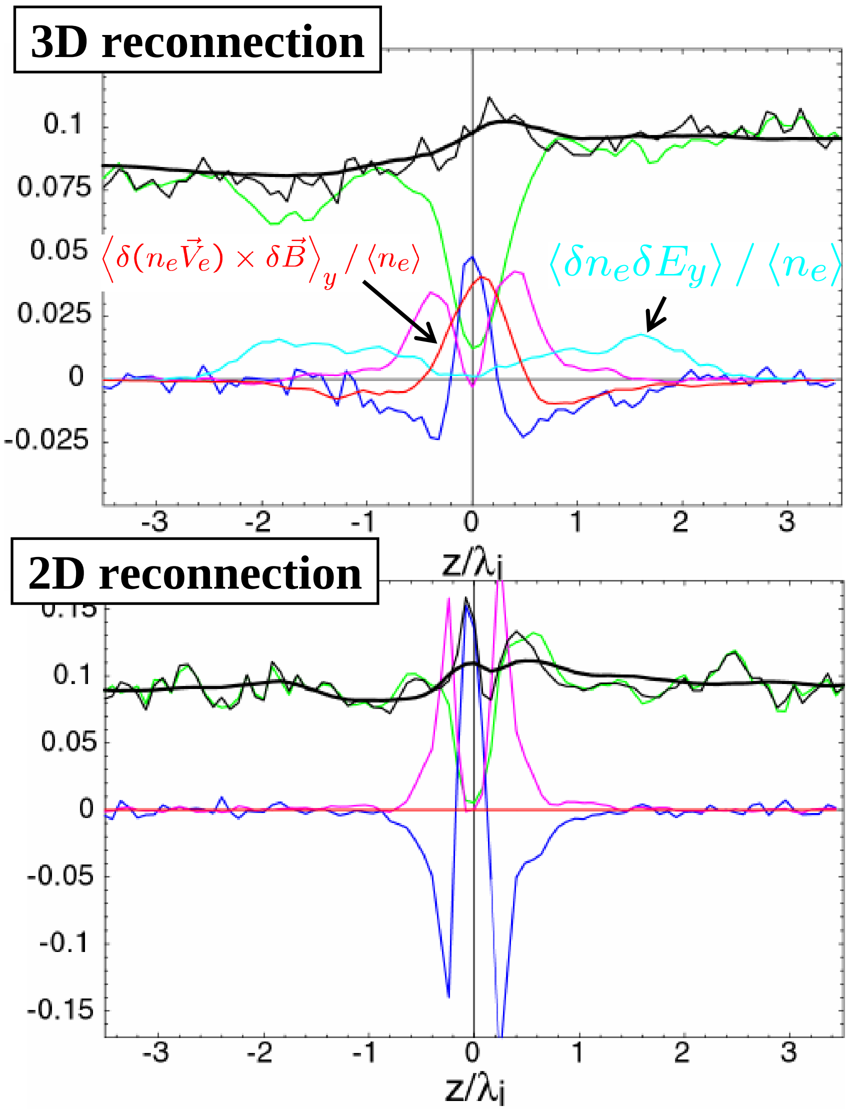


ES turb.

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



EM turb.



Wave Properties: Linear Analyses