高速磁気リコネクションにおける プラズモイド誘導乱流

藤本桂三

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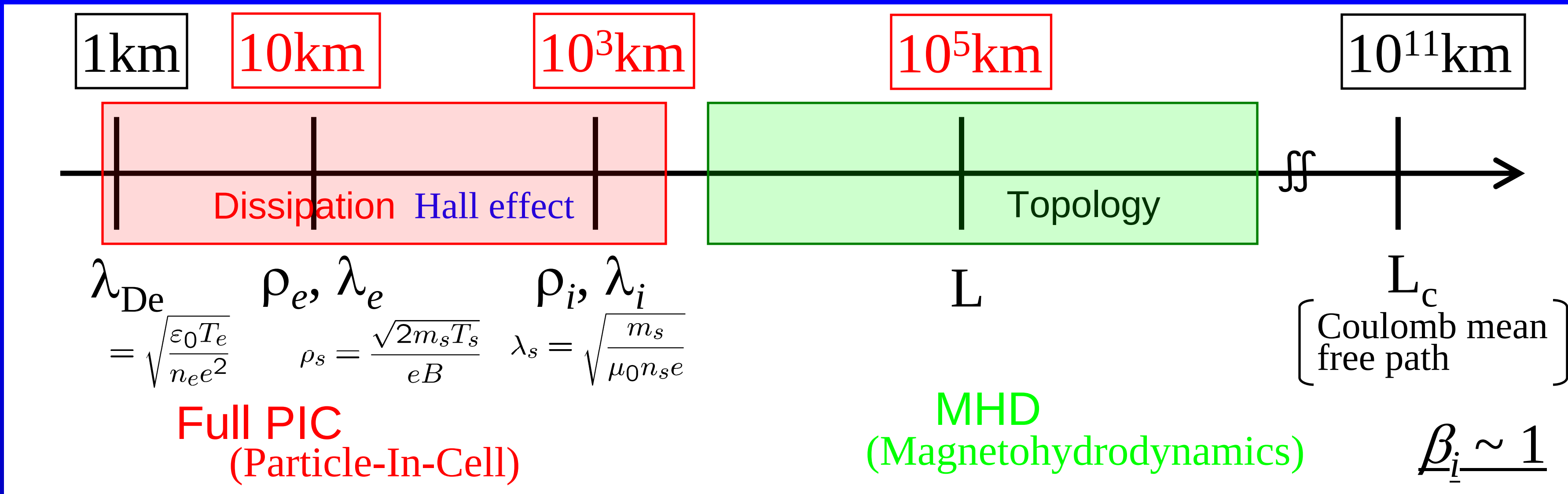
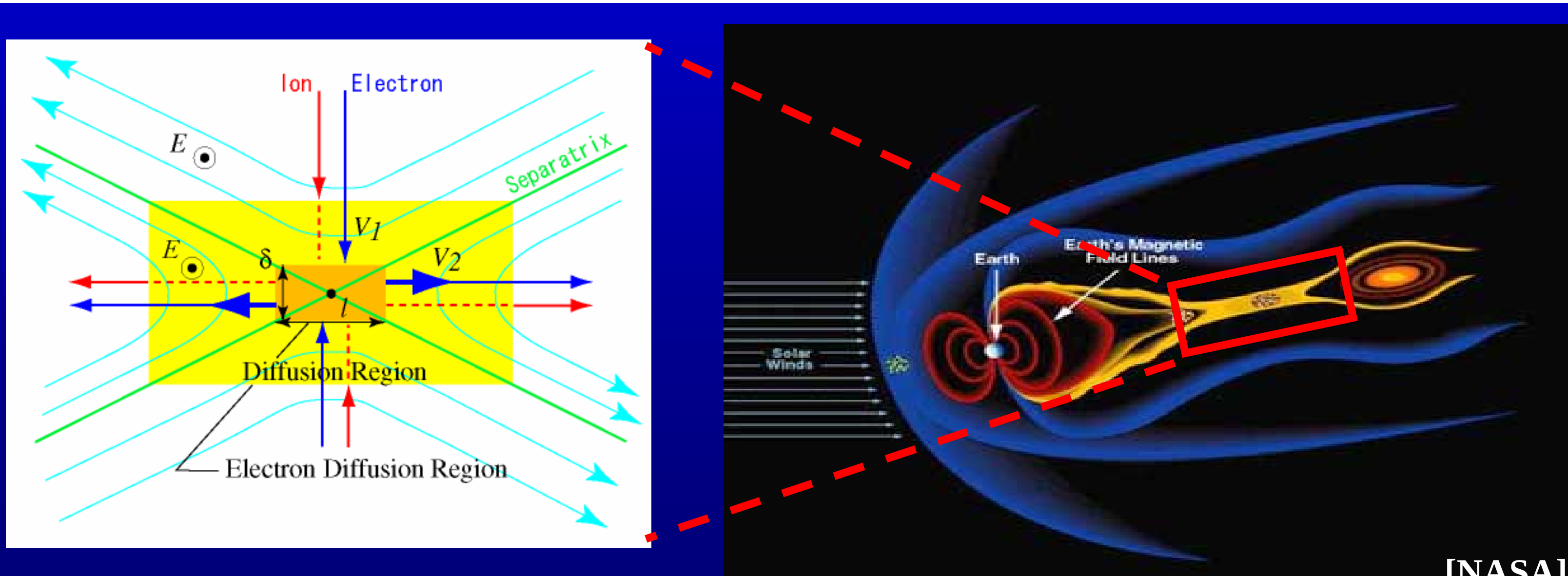
Multi-Scale Nature of Reconnection





Impact of Dissipation Mechanism

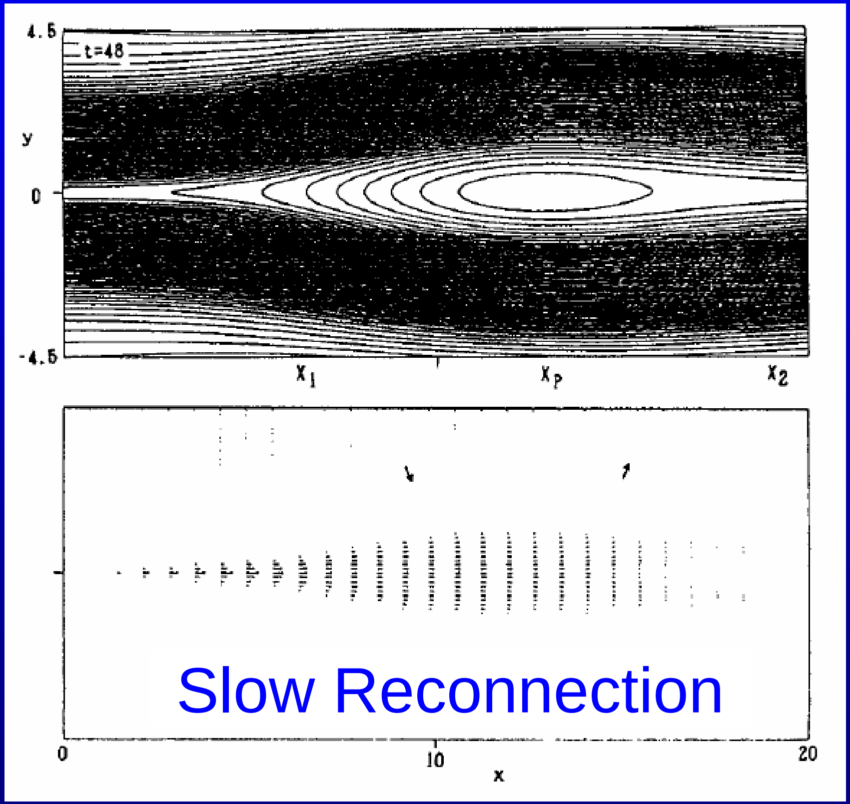
Ugai, PoP, 1995

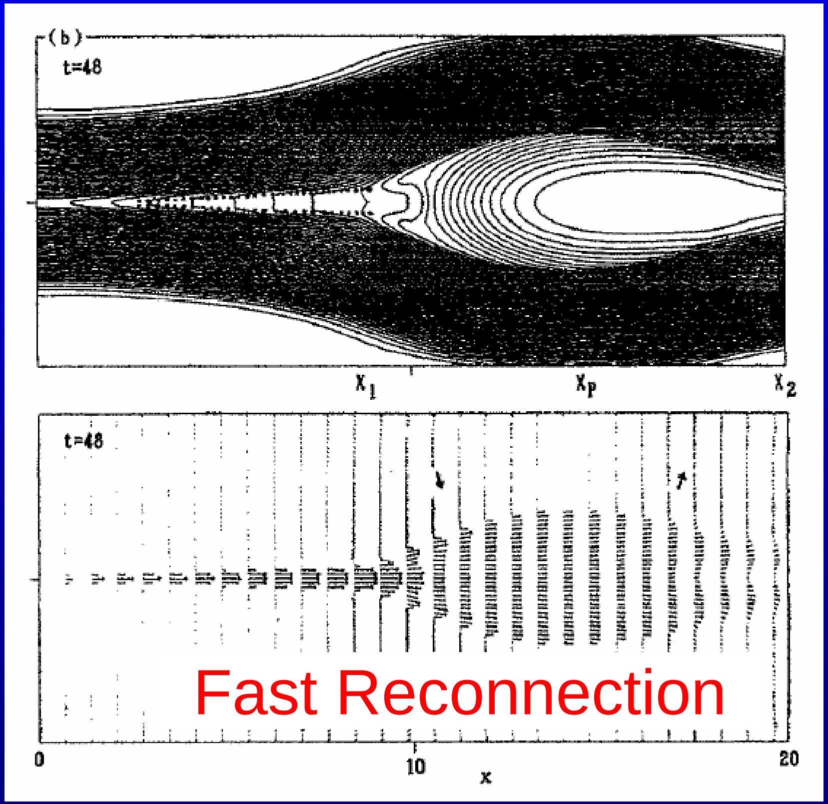
MHD simulations

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

Uniform η

Localized η

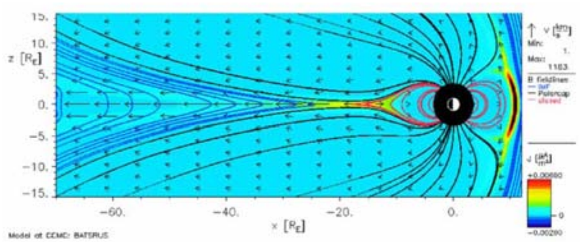




Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

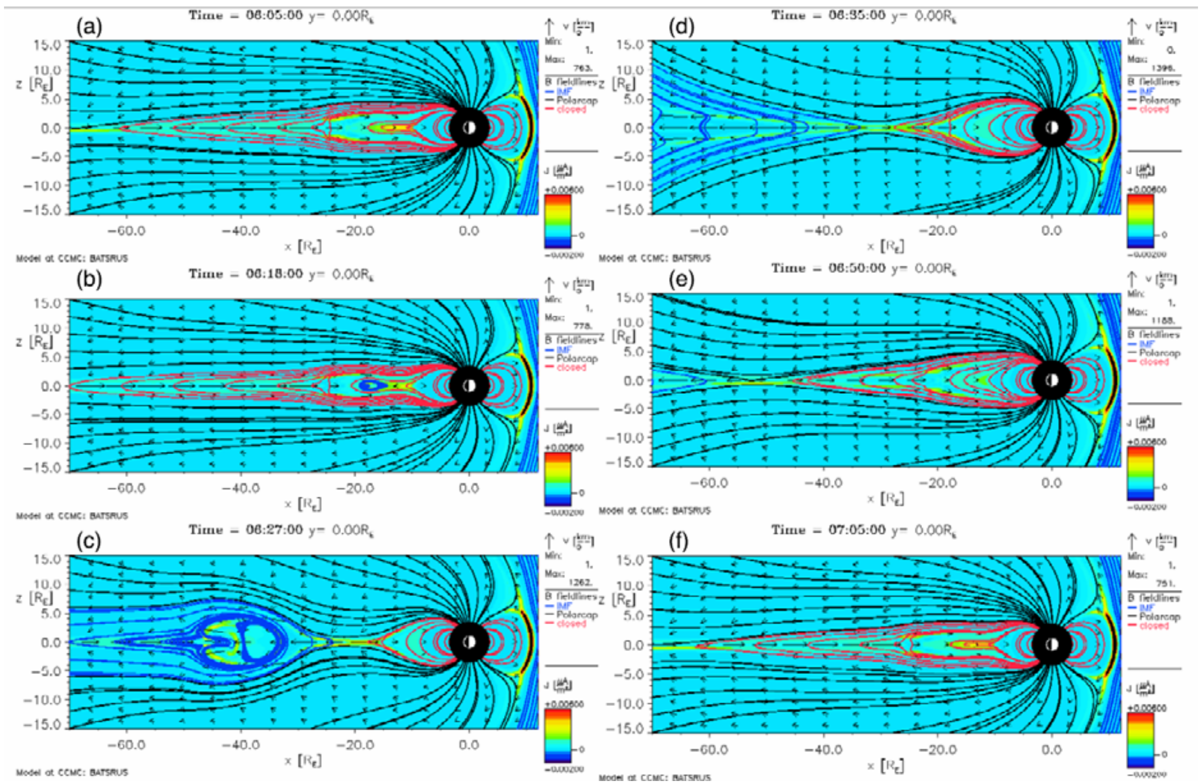


- Slow reconnection
- Quasi-steady configuration

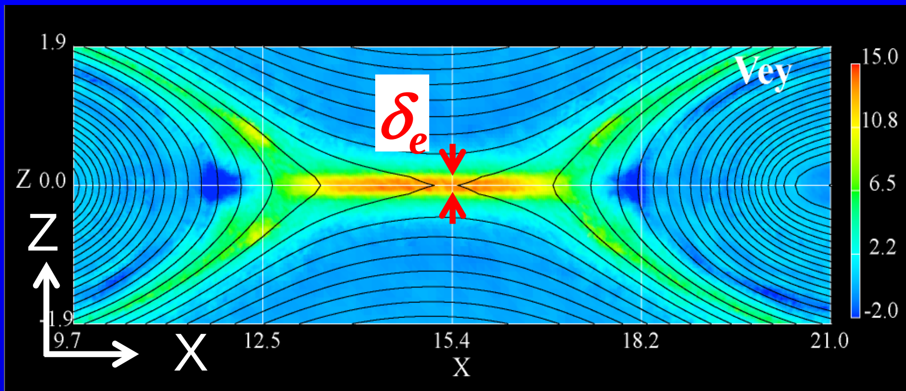
- Fast reconnection
- Quasi-periodic process

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 in 2D Kinetic Reconnection

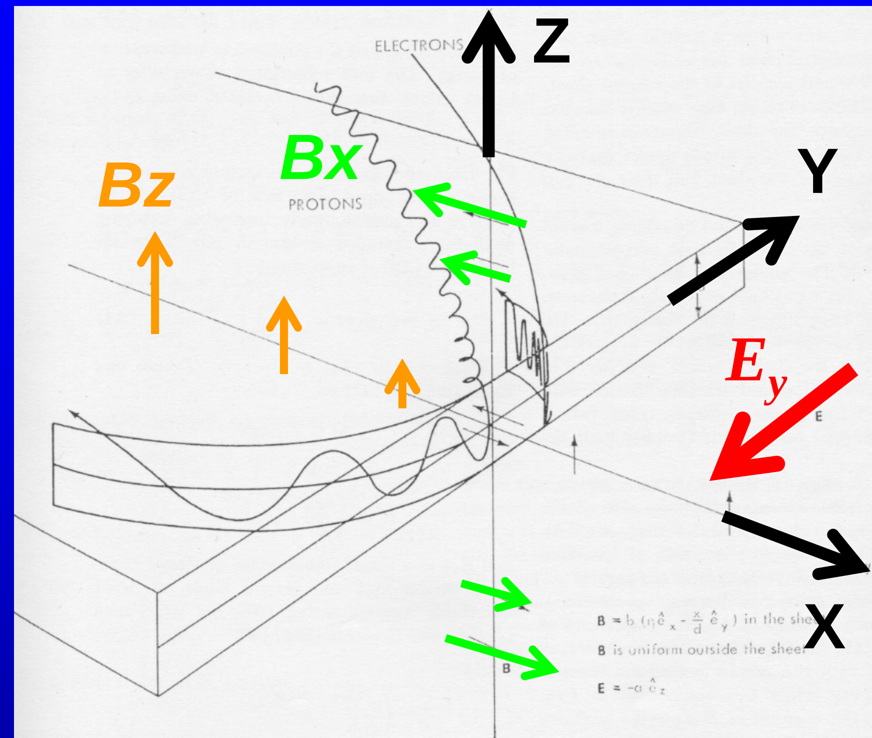


PIC simulations

$$-E_y \approx \frac{1}{ne}(\nabla \cdot \boldsymbol{P}_e)_y \quad \text{at x-line}$$

Electron viscosity

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



Speiser [1965]

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

Fluid — Particle

[*Fujimoto & Sydora*, PoP, 2009]

Inertia resistivity

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

τ_{tr}: Transit time through the diffusion region

Inertia Resistivity & Current Sheet Width

X-line

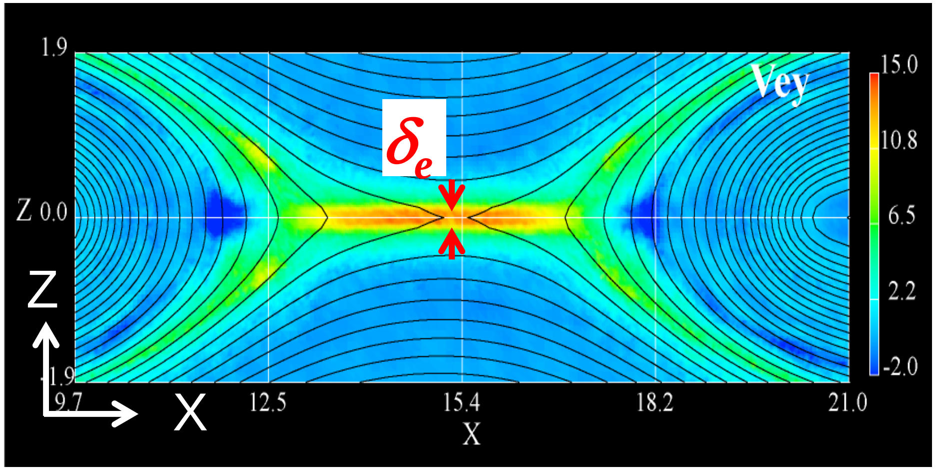
$$E_{y,xline} = \eta_{in} j_y$$

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

$$j_y \approx -\frac{1}{\mu_0} \frac{B_{inflow}}{\delta_e}$$

Inflow region

$$E_{y,inflow} = -V_{inflow} B_{inflow}$$



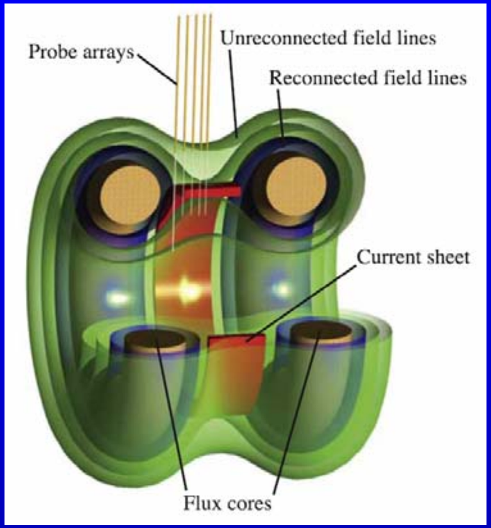
$$\underline{E_{y,xline} = E_{y,inflow}}$$

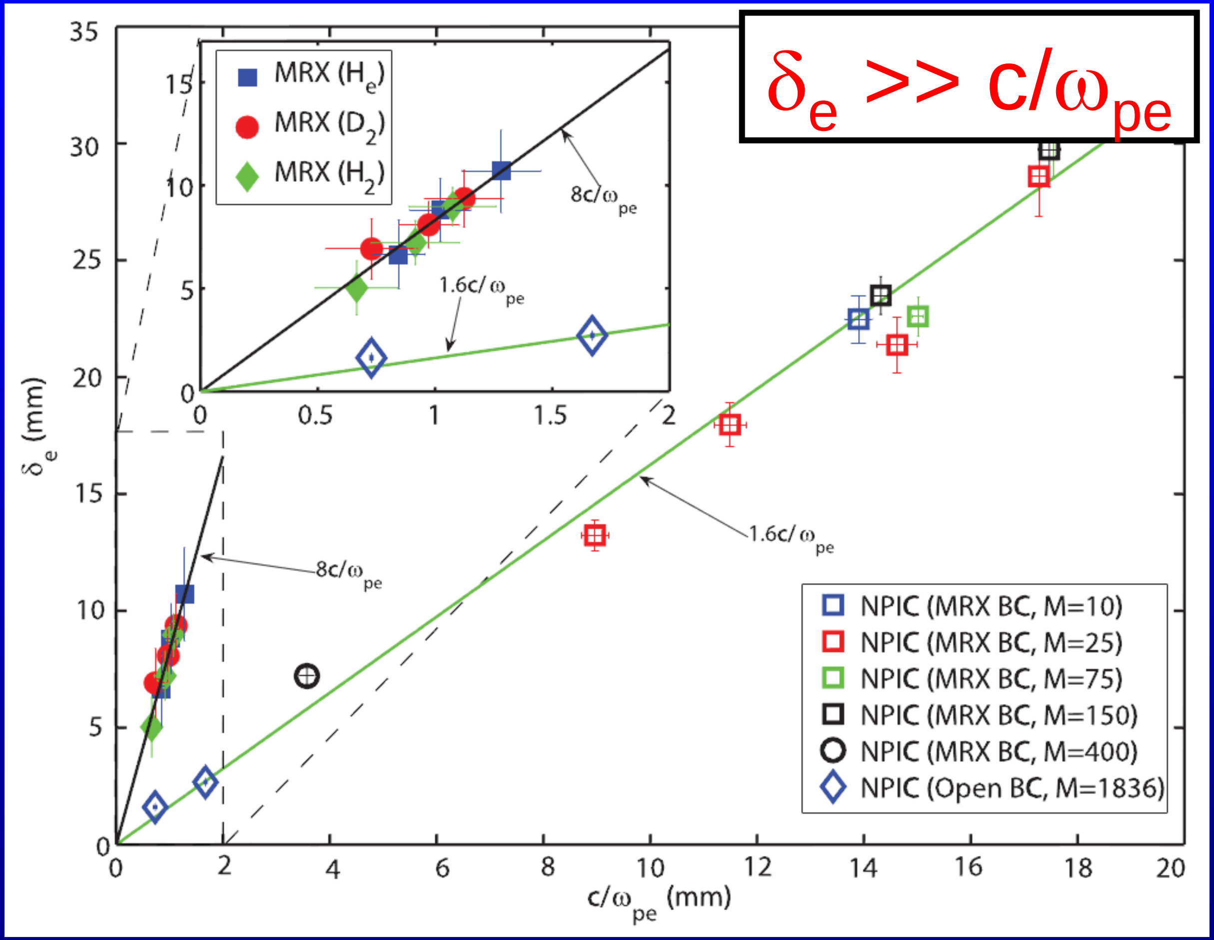
$$\Downarrow$$

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

Very thin current layer!

Implication of Anomalous Effects: Lab. Experiment

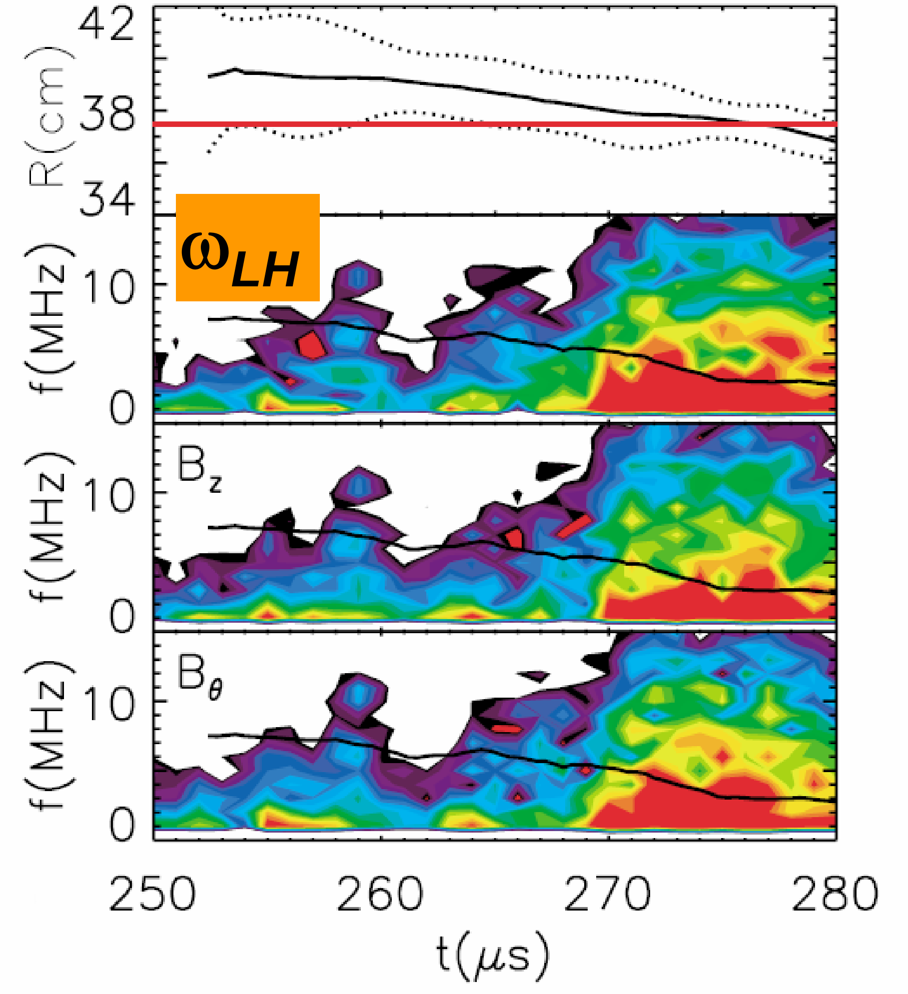


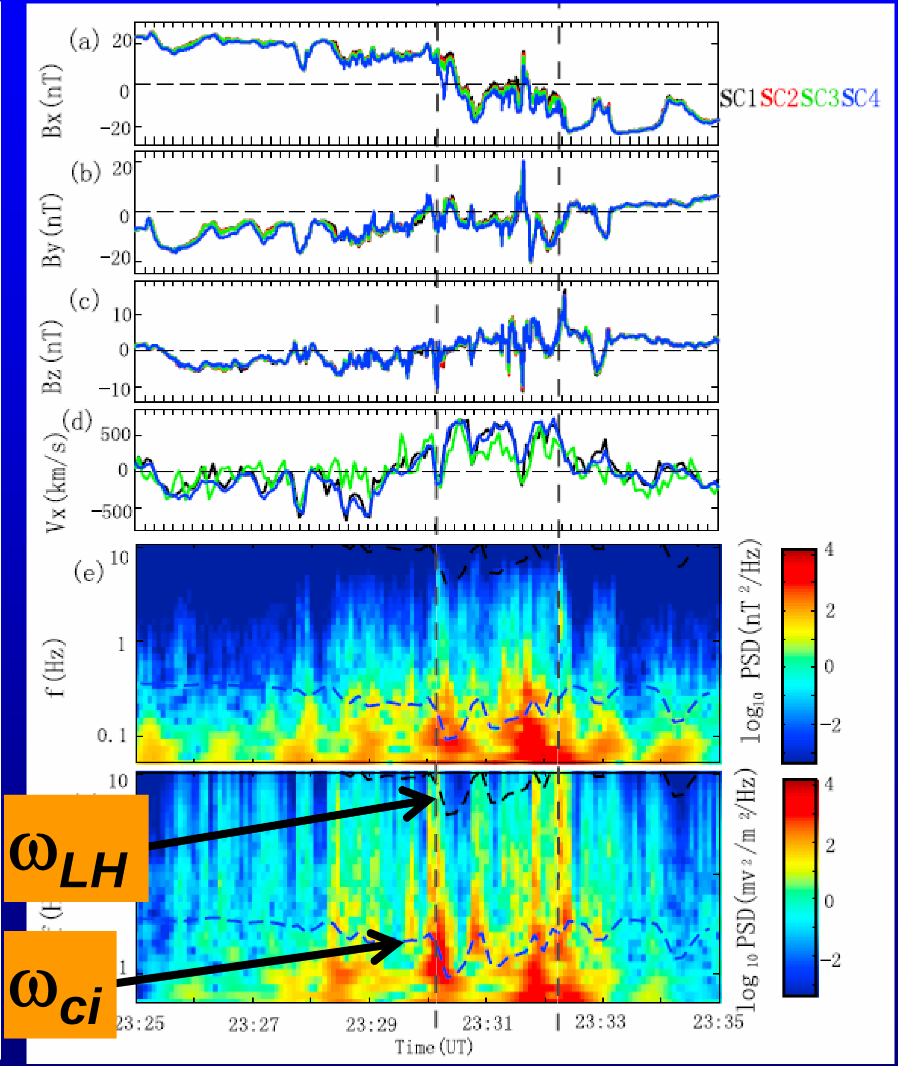


[*Ji et al.*, GRL, 2008]

Implication of Anomalous Effects: Wave Activities

[Zhou et al, JGR, 2009]





Implication of Anomalous Effects

X-line

$$E_{y,xline} = (\eta_{in} + \eta)\, j_y$$

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

$$j_y \approx -\frac{1}{\mu_0}\frac{B_{inflow}}{\delta_e}$$

Inflow region

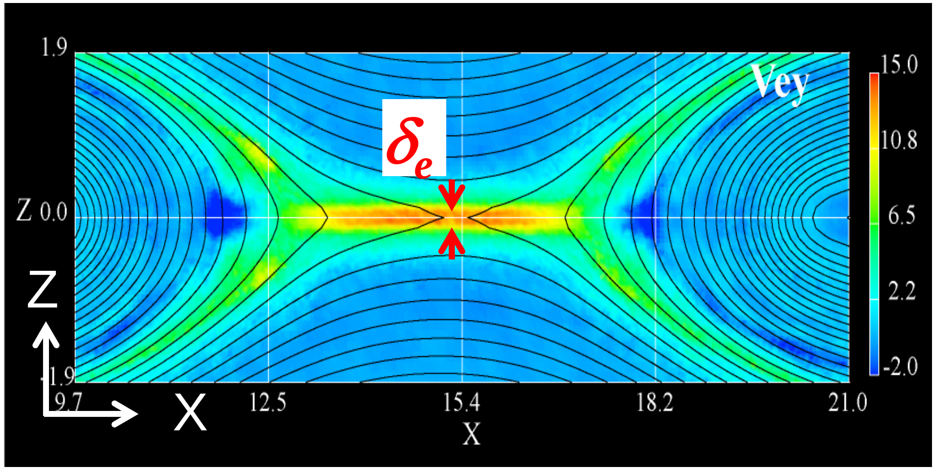
$$E_{y,inflow} = -V_{inflow} B_{inflow}$$

$$E_{y,xline} = E_{y,inflow}$$

$$\Downarrow$$

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

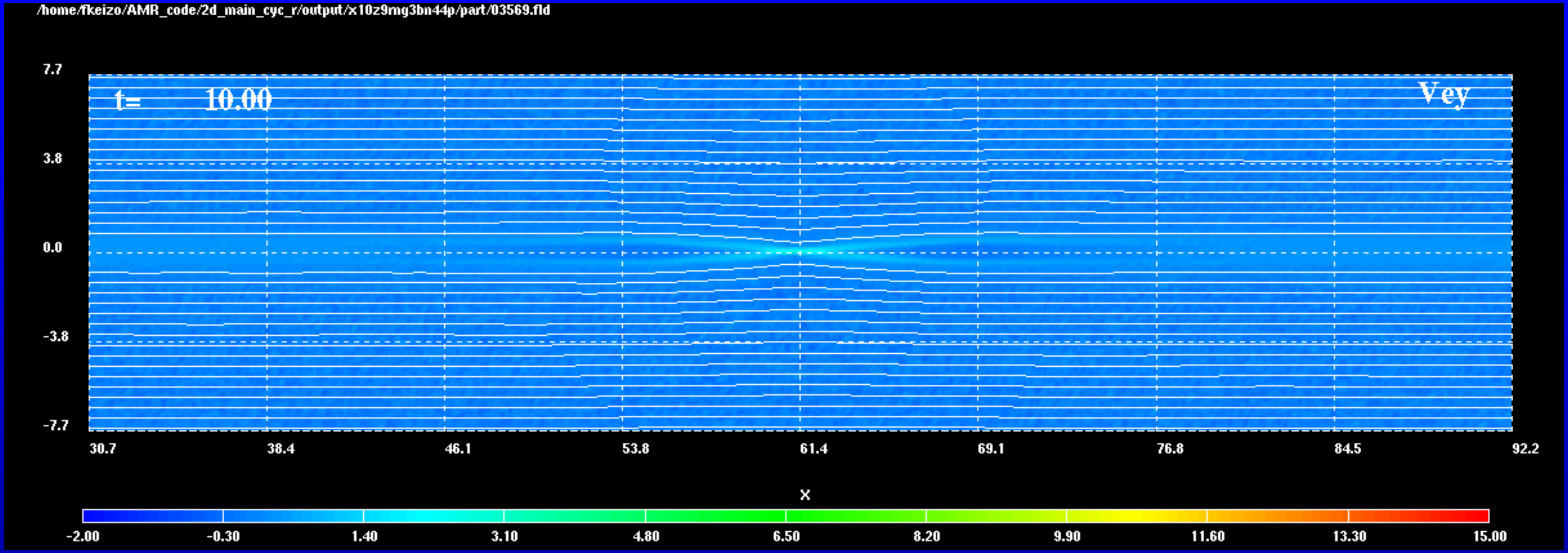
$$\lambda \equiv \eta/\mu_0 V_{inflow}$$



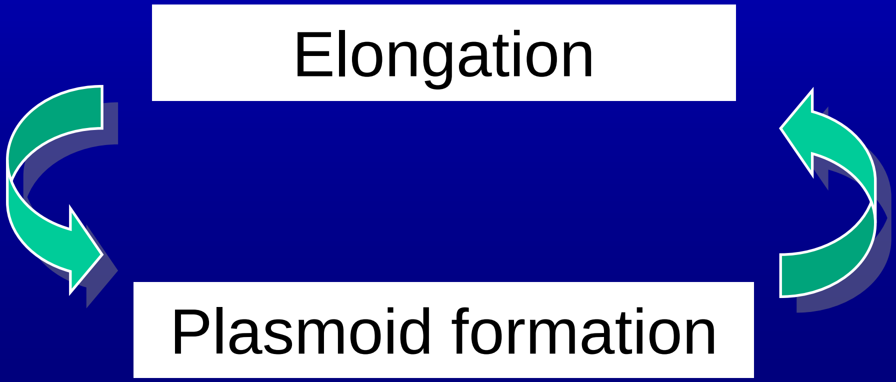
Dynamical Current Sheet

[Fujimoto, PoP, 2006;
Daughton et al., PoP, 2006]

2D PIC simulation



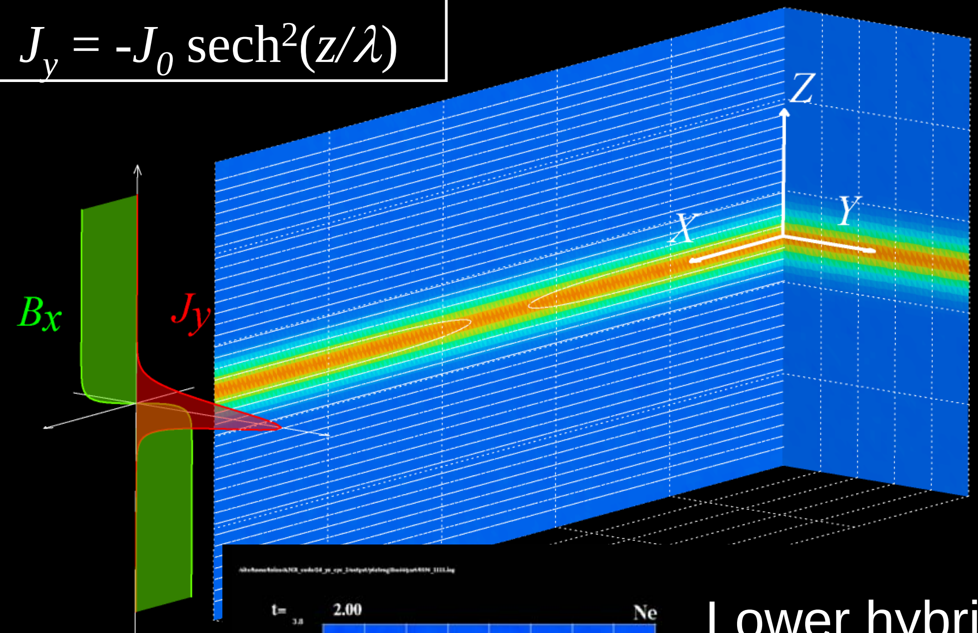
Thin current layer:



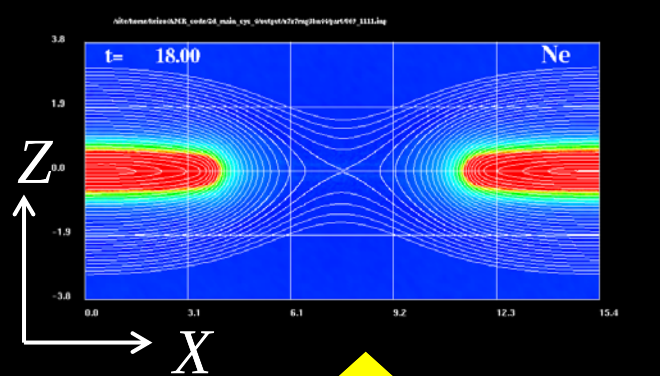
Instabilities in the Harris Current Sheet

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

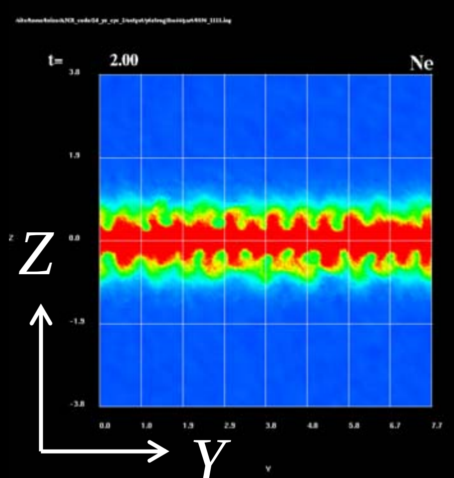
$J_y = -J_0 \,\mathrm{sech}^2(z/\lambda)$



Tearing instability



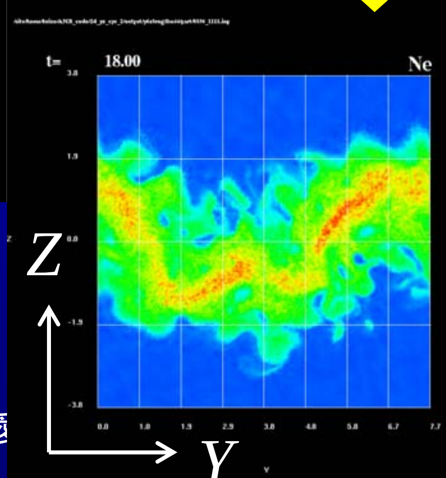
Lower hybrid drift instability (LHDI)



$k_y r_{Le} \sim 1$

$\gamma \sim \omega_{lh}$

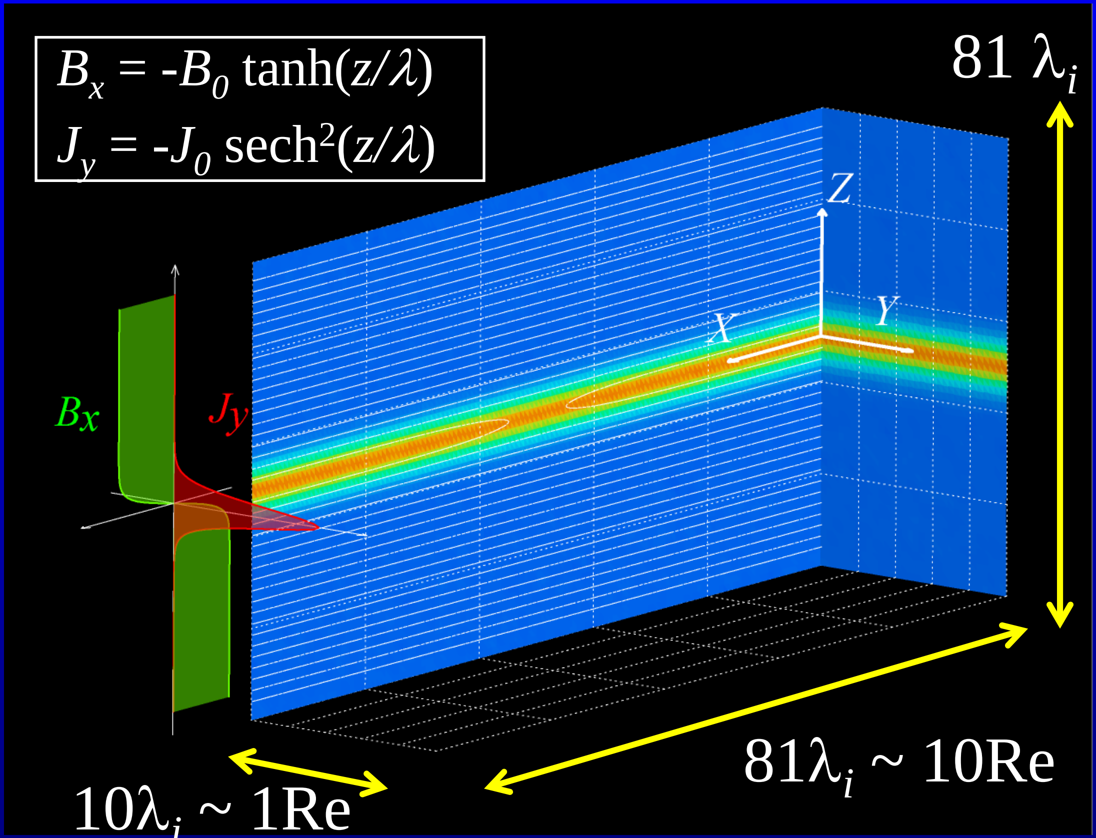
Kink-type instability



$k_y L \sim 1$

Simulation Setup

AMR-PIC-3D code [Fujimoto, JCP, 2011]
on Fujitsu FX1 (1024 cores)



$m_i/m_e = 100$

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

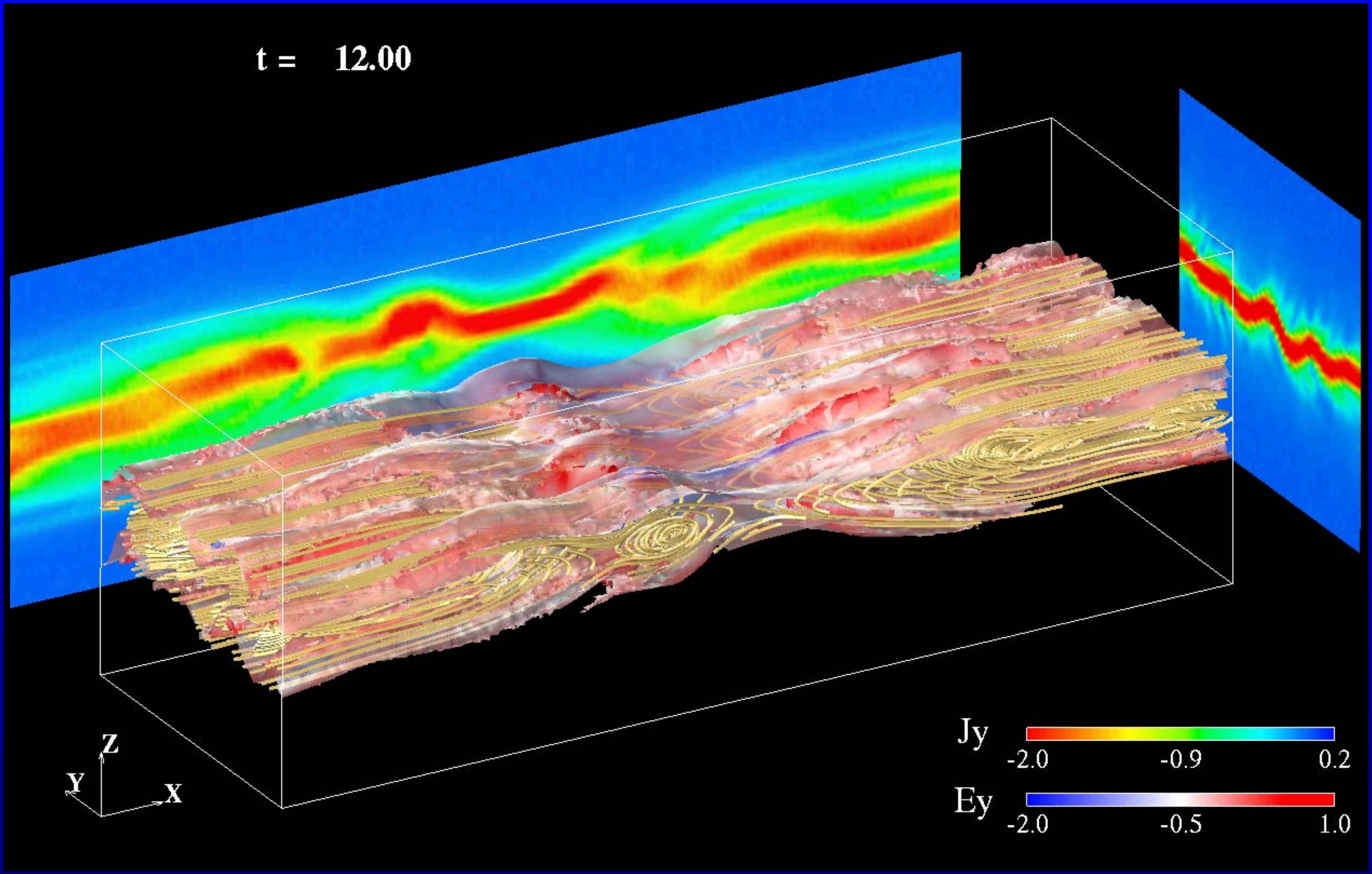
Max number of particles
Ion + Electron $\sim 10^{11}$

Max memory used ~ 6TB

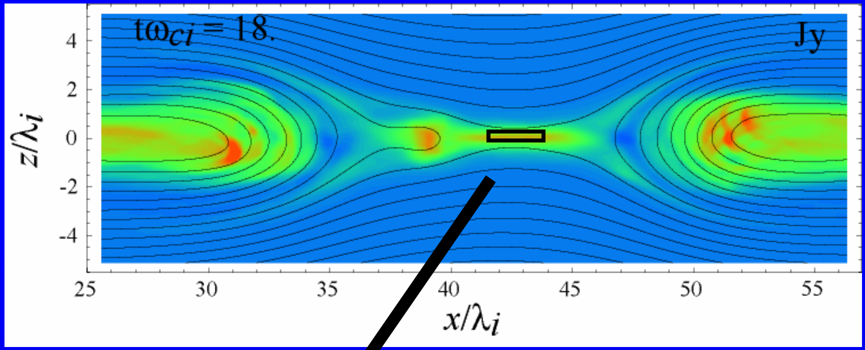
Time Evolution of the Current Sheet

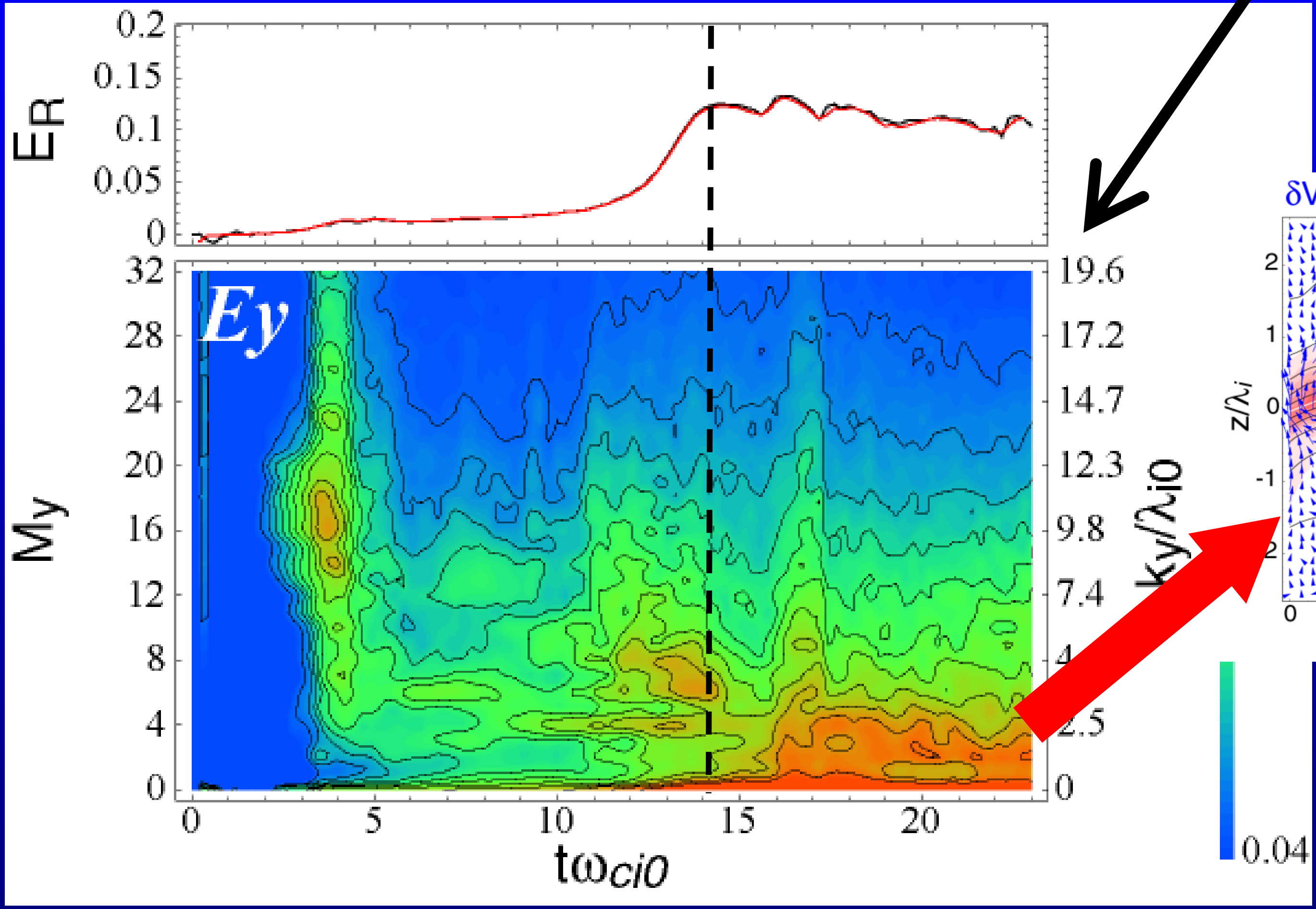
Surface: |J|, Line: Field line

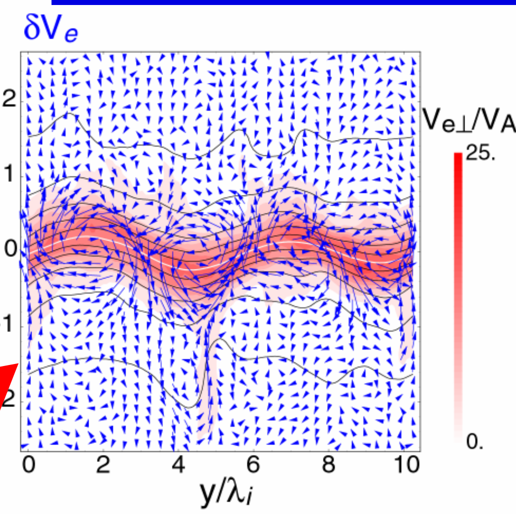
Color on the surface: Ey, Cut plane：Jy



Wave Activity







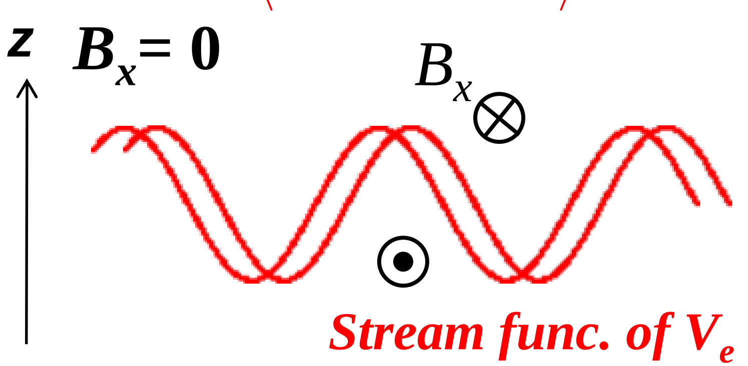
Wave-Particle Interactions

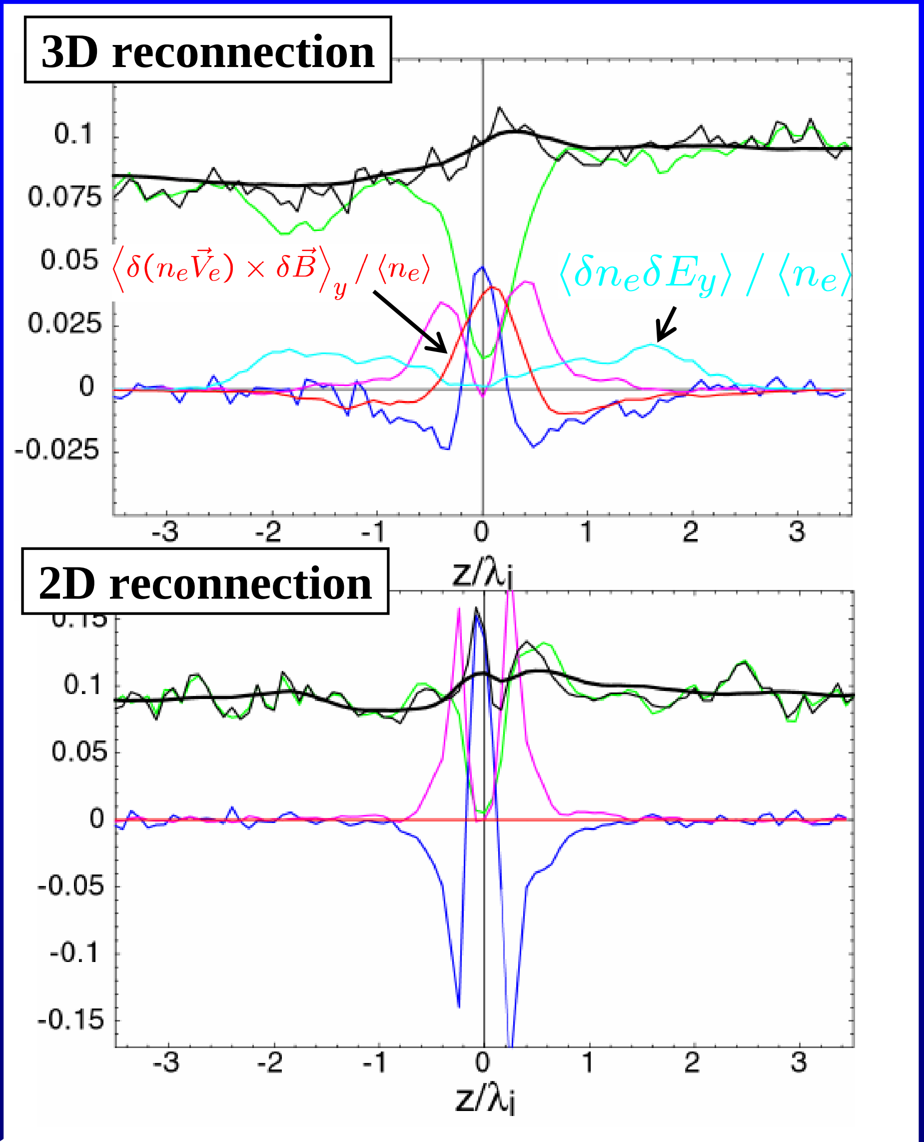
$$A = \langle A \rangle + \delta A \qquad \left(\langle \cdot \rangle = \frac{1}{L_y} \int_0^{L_y} \cdot \, dy \right)$$

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

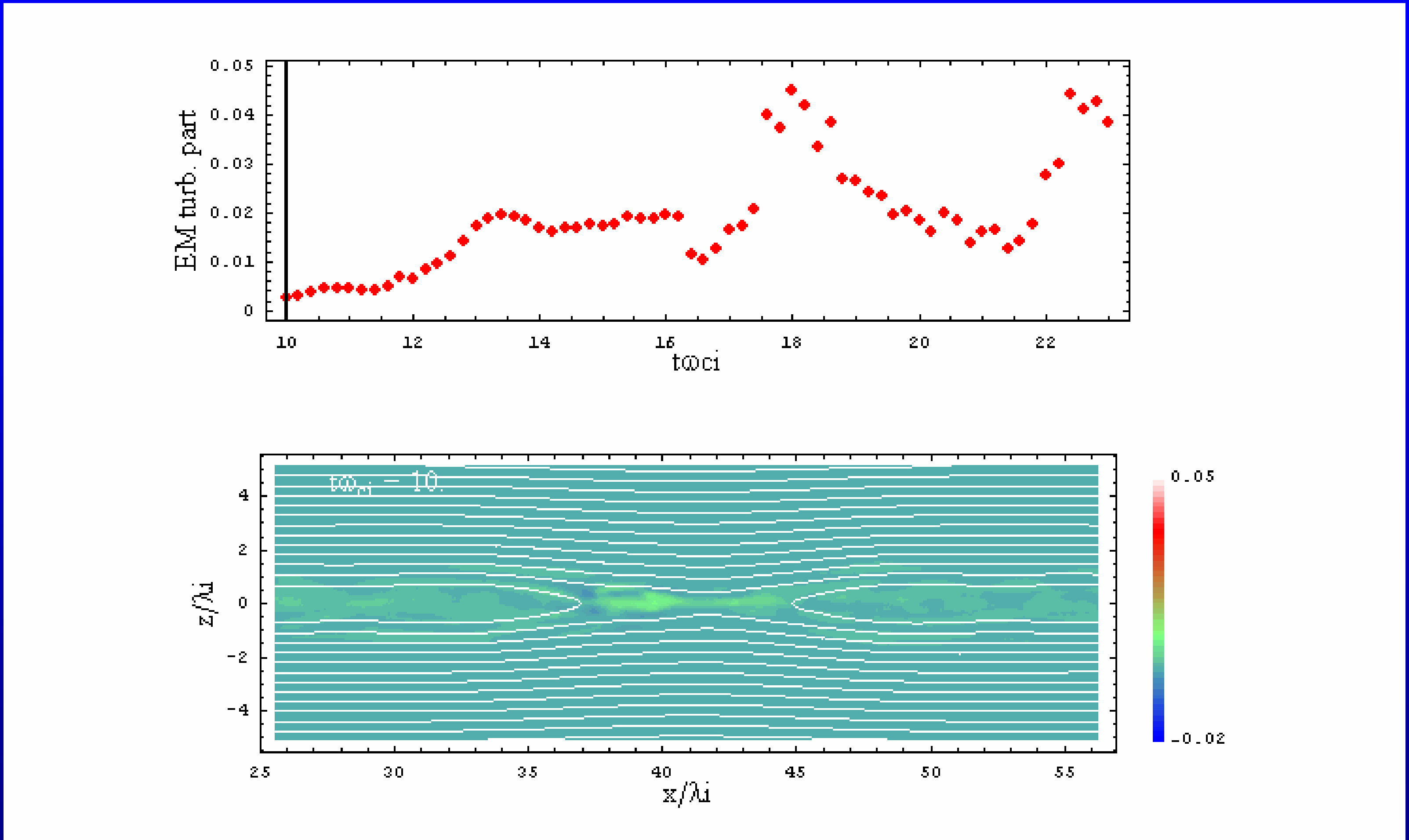
Anomalous effects

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

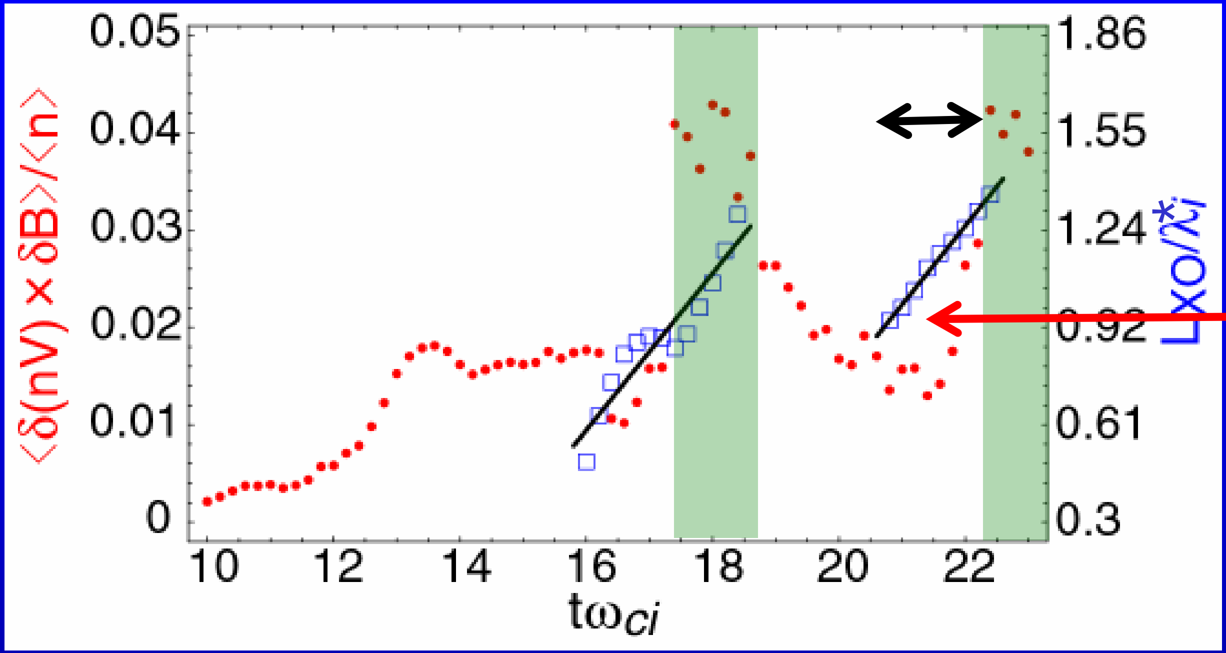




Anomalous Transport at the X-line

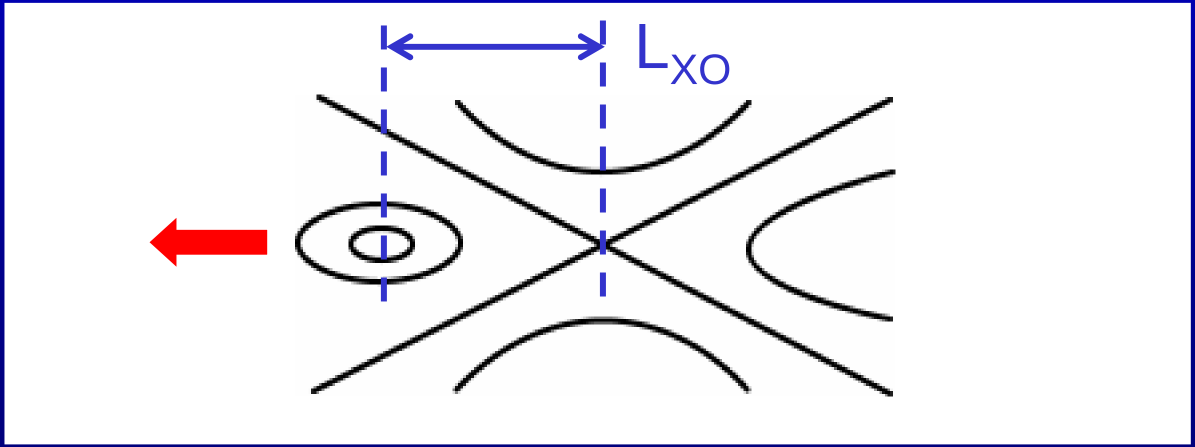


Plasmoid-Induced Turbulence



$\Delta t = 1.6\ \omega_{ci}^{-1}$

$L_{XO} = 0.95\ \lambda_i^*$

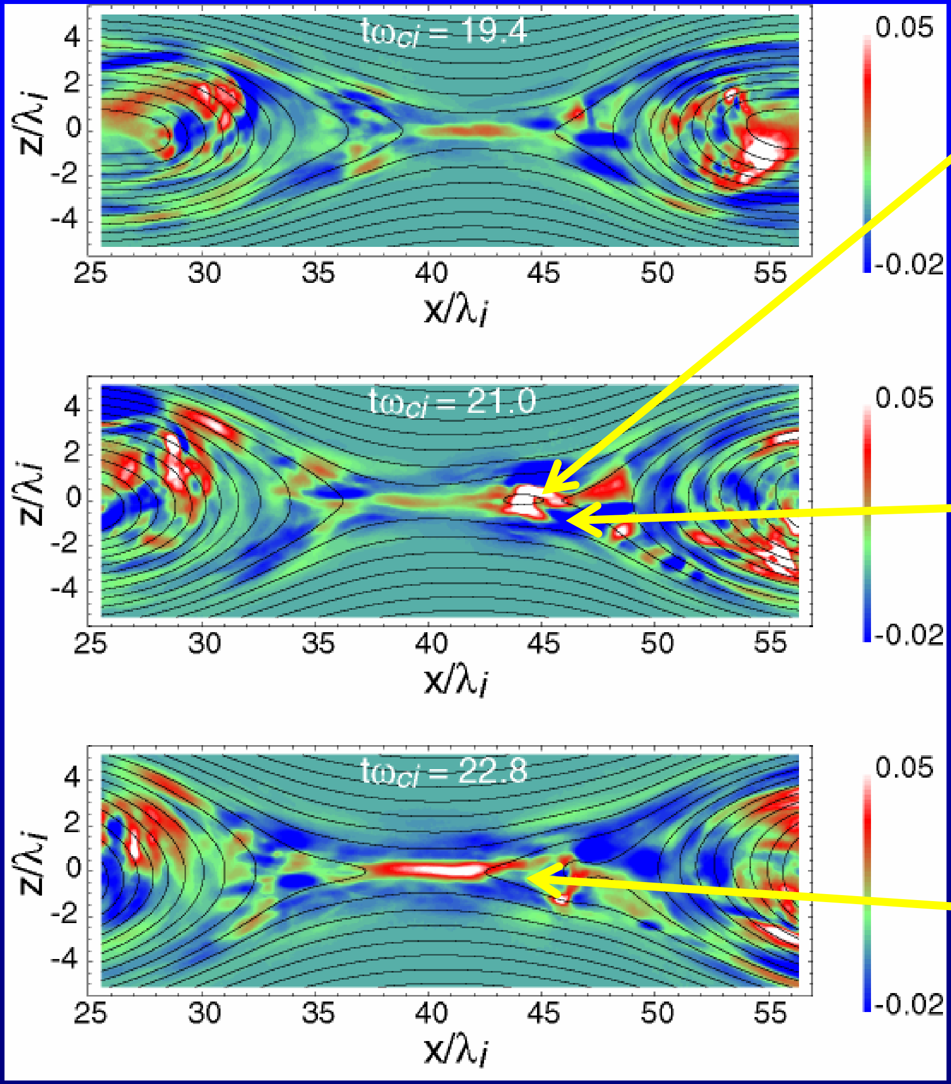


Information propagates at

$V_p \sim V_A^*$

$(B^* = 0.5B_0)$

Plasmoid-Induced Turbulence



Plasmoid formation

Wave amplification

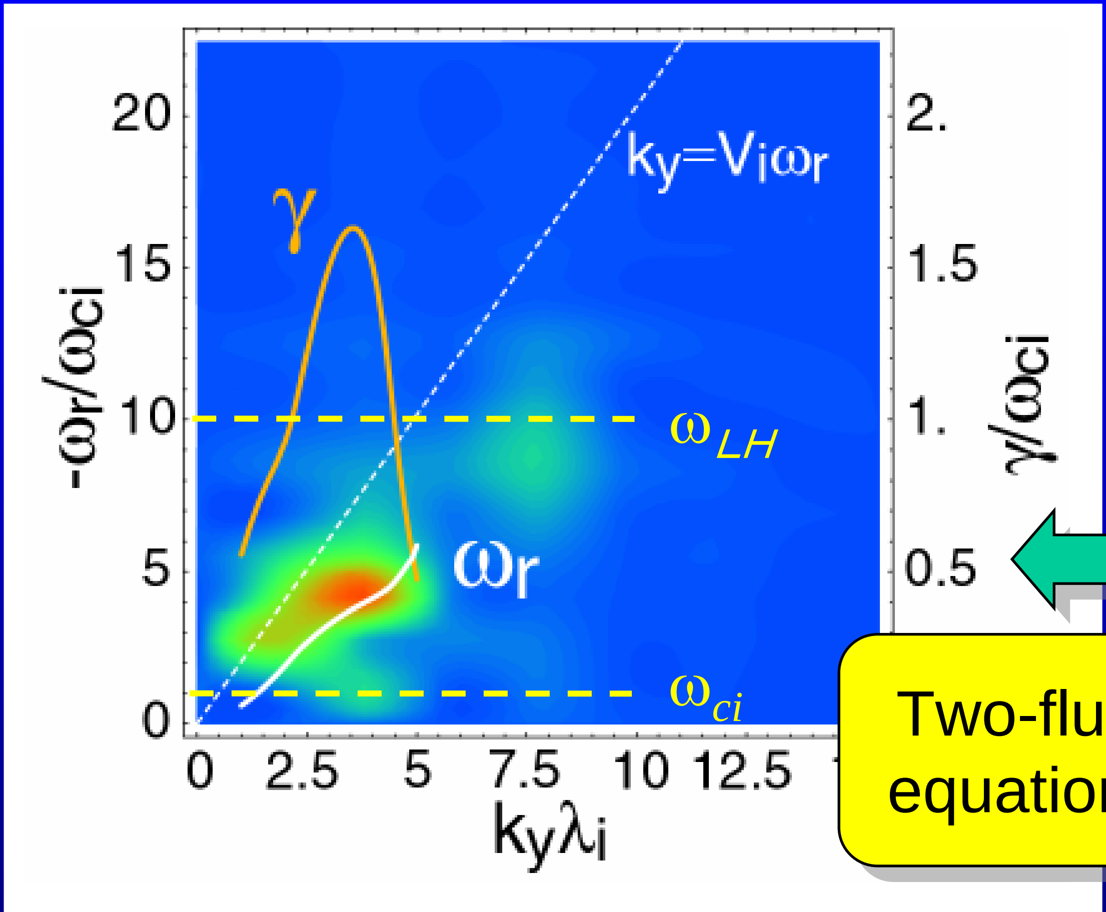
Local turbulence enhancement

Propagation along the field line

Intensified turbulence at the x-line

Wave Properties

$\omega = \omega_r + i\gamma$



Simulation results

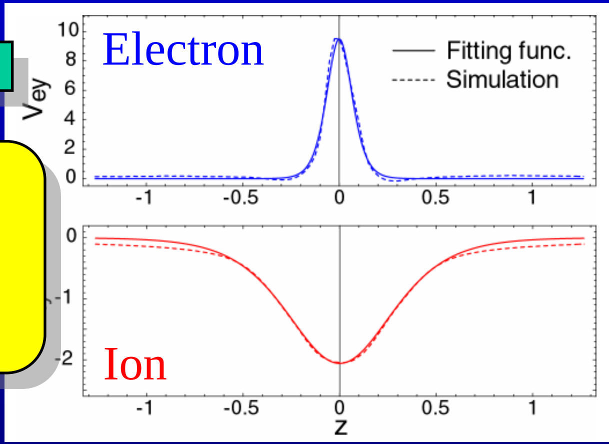
$\omega_{ci} < |\omega_r| < \omega_{LH}$

$V_{ph} \approx V_A$

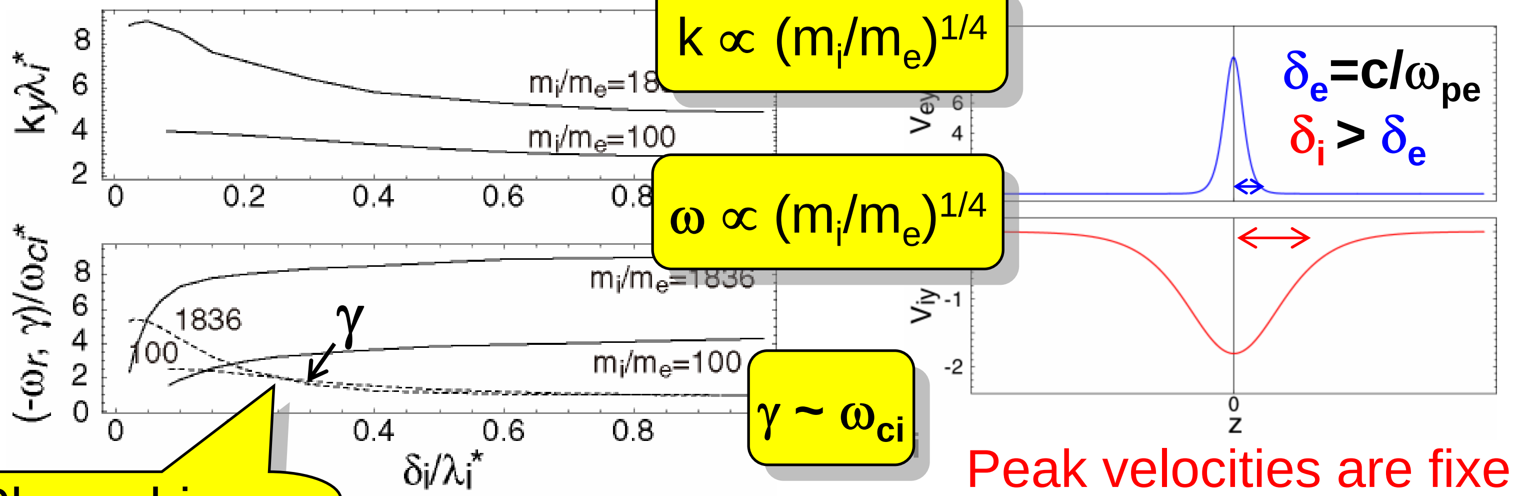
Linear analyses

Profiles taken from simulation

Two-fluid equations



Wave Properties: Linear Analyses

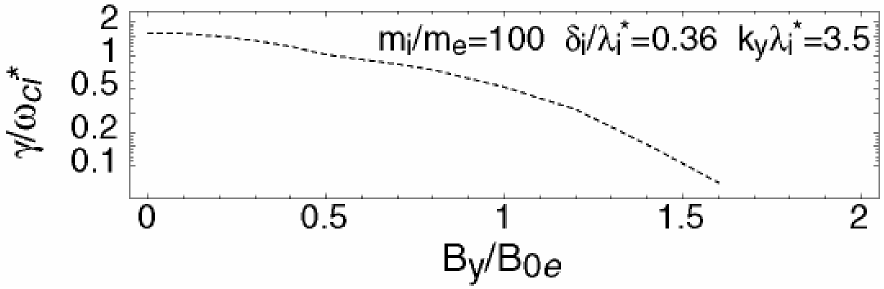


Peak velocities are fixed.

Shear driven mode rather than the drift mode

$\gamma \propto \partial V_d/\partial z$

The wave survives even for m_i/m_e=1836.

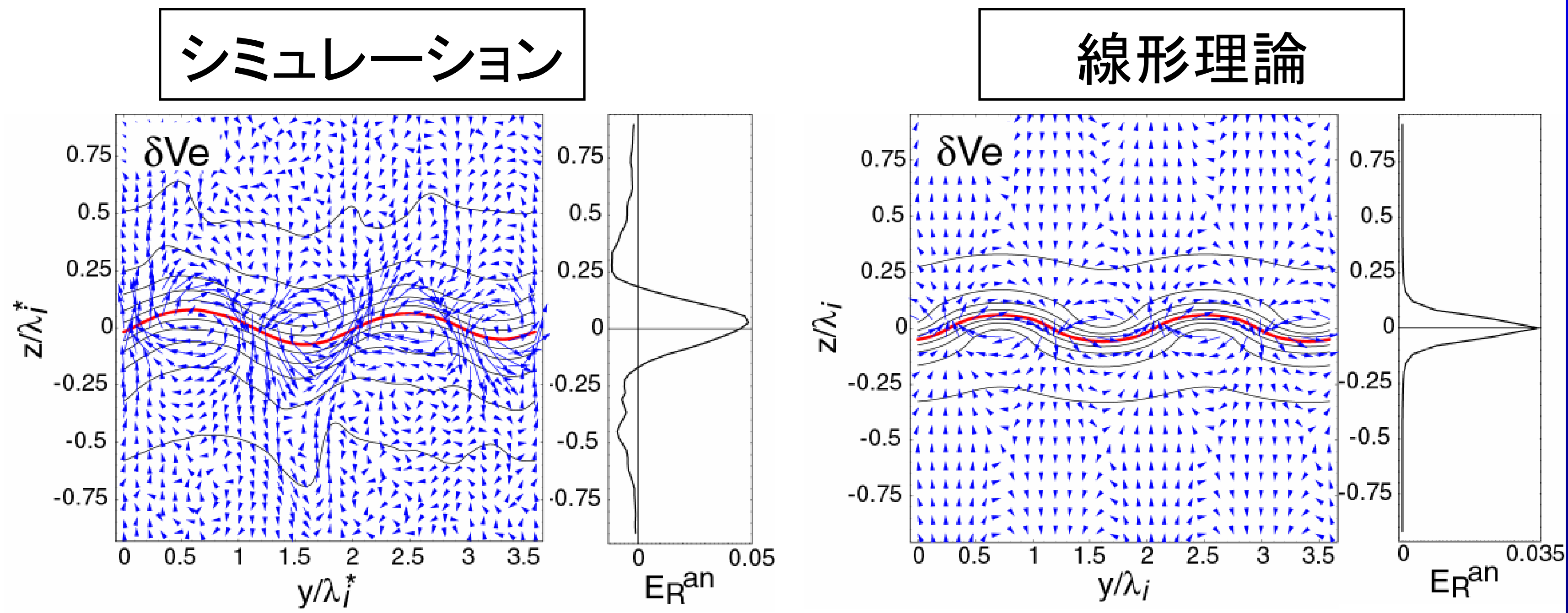


Dependence on the guide field (*By*)

運動量の異常輸送 [Fujimoto & Sydora, in prep.]

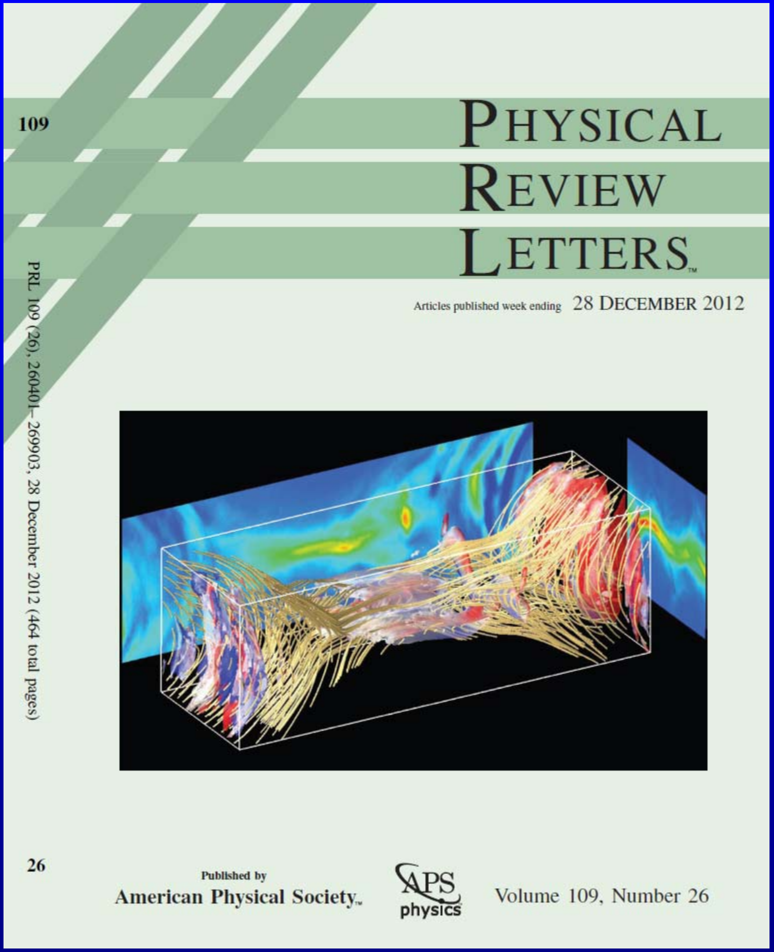
電磁波動による電子運動量の異常輸送

$$E_R^{an} = \frac{1}{\langle n_e \rangle} \left\langle \delta(n_e \vec{V}_e) \times \delta \vec{B} \right\rangle_y \qquad \left(\langle \cdot \rangle = \frac{1}{L_y} \int_0^{L_y} \cdot \, dy \right)$$



Summary

[Fujimoto & Sydora, PRL, 2012]



大規模な3次元粒子シミュレーションを実施して、高速磁気リコネクション時における磁気拡散機構を調べた。

プラズモイドによって誘発される電磁的乱流が磁気拡散過程において重要な役割を果たすことがわかった。

線形波動解析を実施することによって、乱流を引き起こす電磁波動の特性を調べた。

- $\omega_{ci} < \omega_r < \omega_{LH}$
- シアー駆動型不安定性
- m_i/m_e=1836 でも大きな成長率