Plasmoid-Induced Turbulence in 3D Kinetic Reconnection

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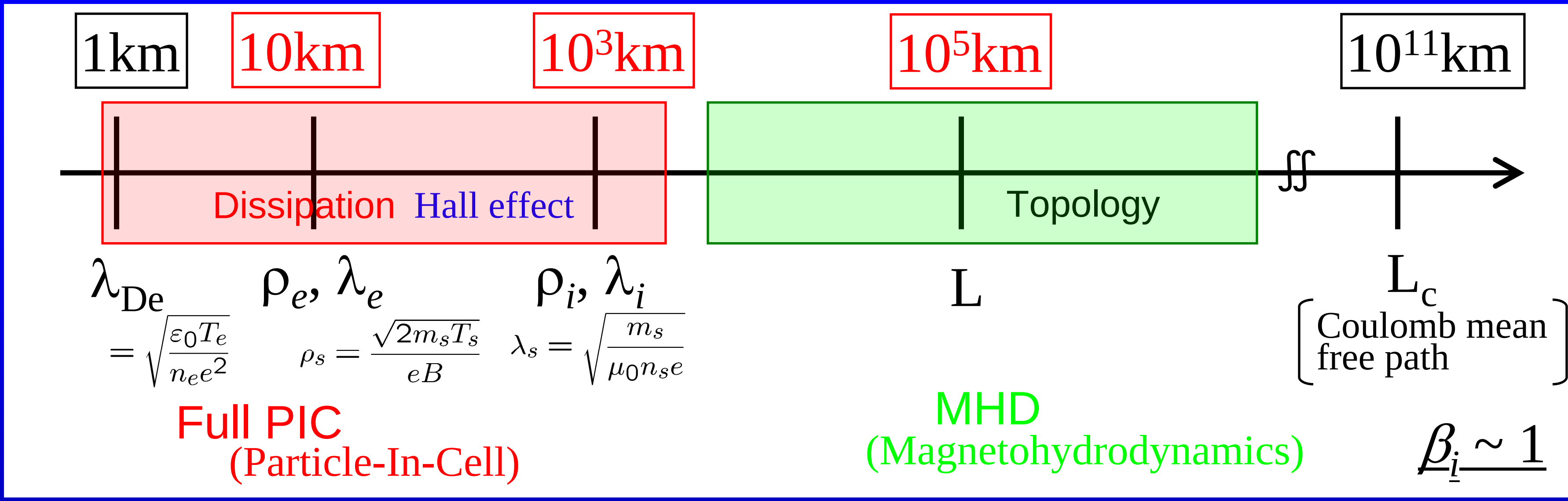
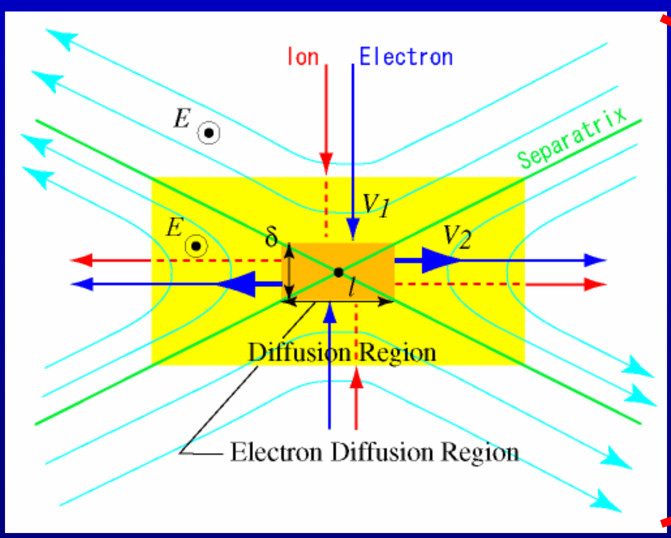
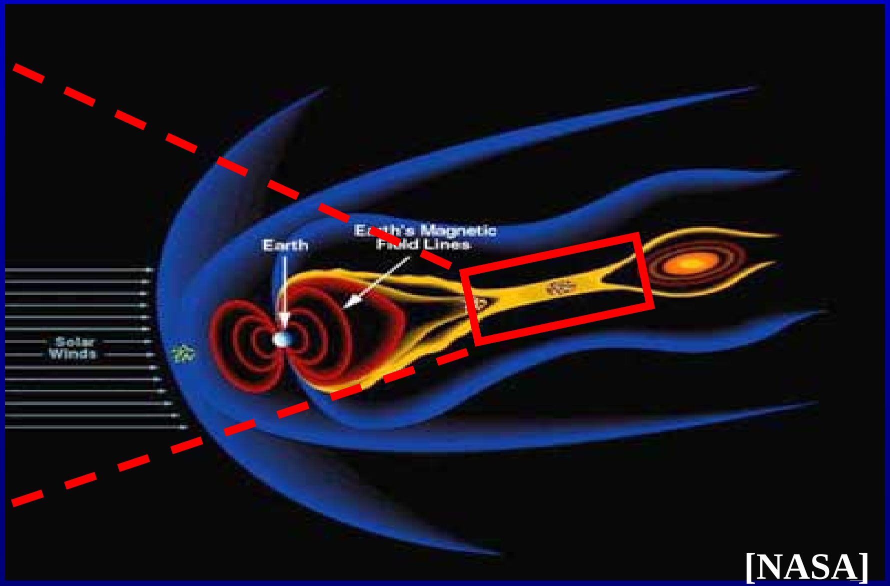
Multi-Scale Nature of Reconnection







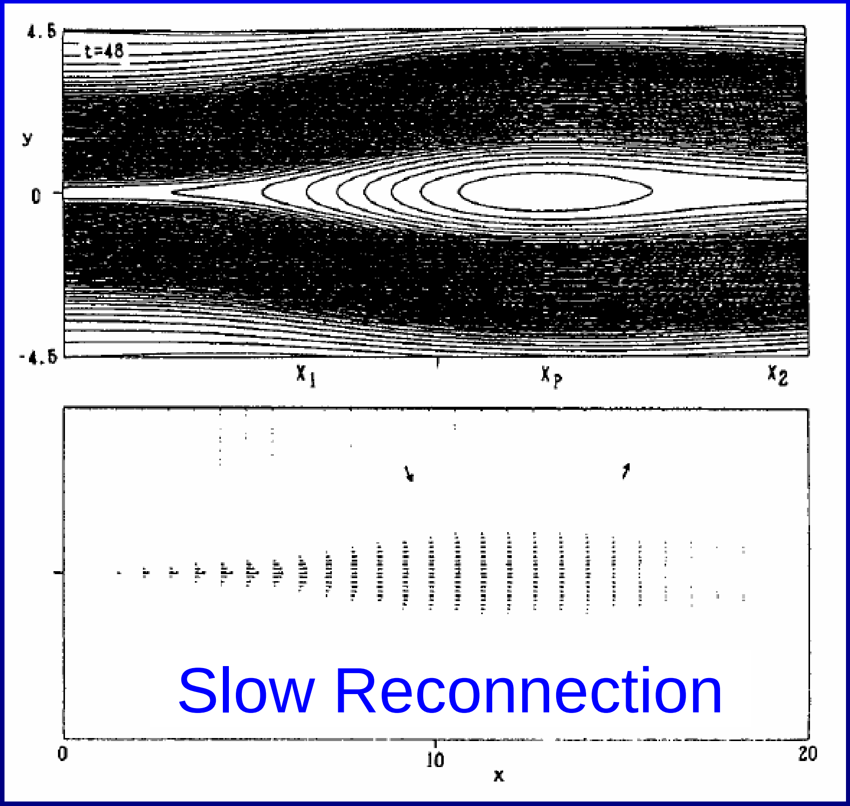
Impact of Dissipation Mechanism

Ugai, Phys. Plasmas, 1995

MHD simulations

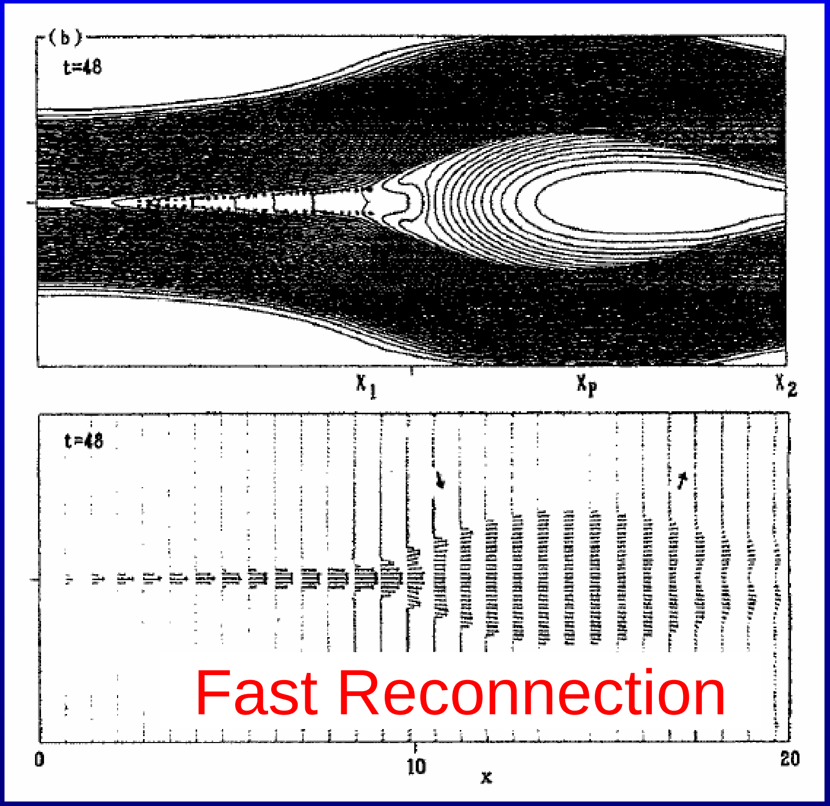
$$\frac{\partial B}{\partial t} = \eta \nabla^2 B / \mu_0$$

Uniform η



Slow Reconnection

Localized η

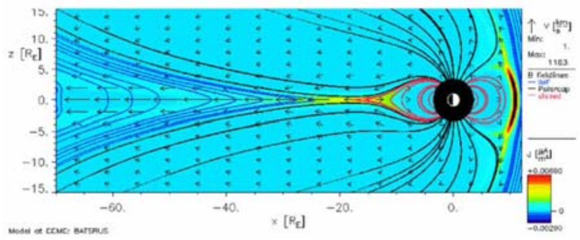


Fast Reconnection

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

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

Numerical resistivity only

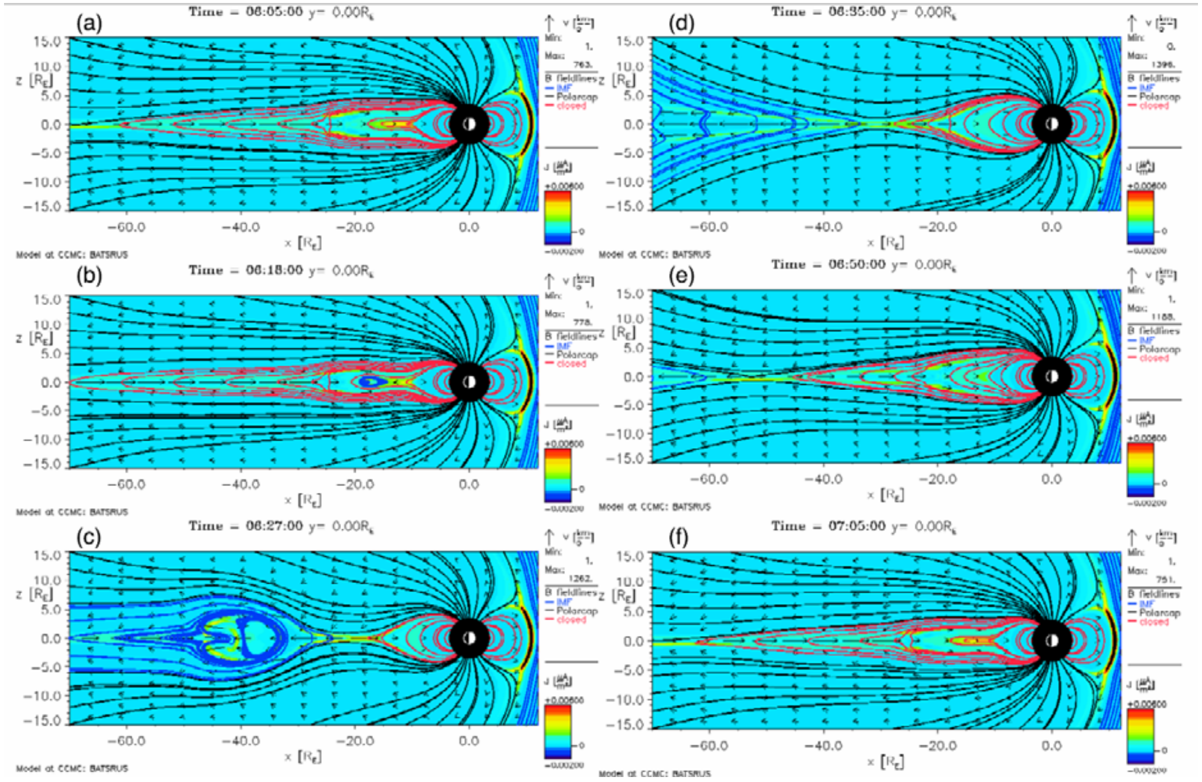


- Slow reconnection
- Quasi-steady configuration

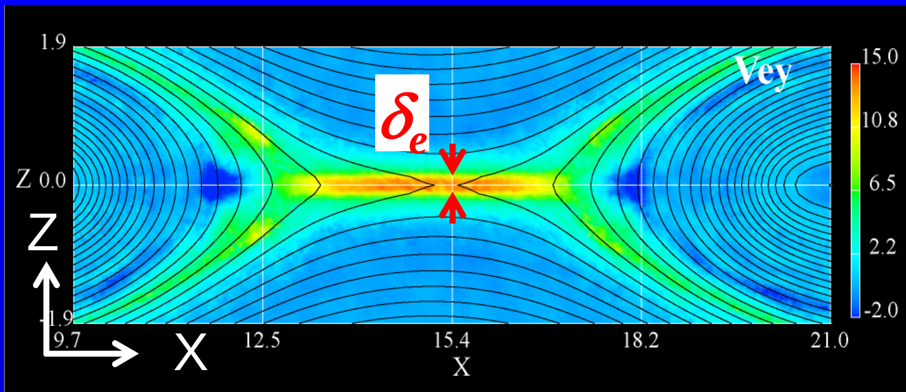
- Fast reconnection
- Quasi-periodic process

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

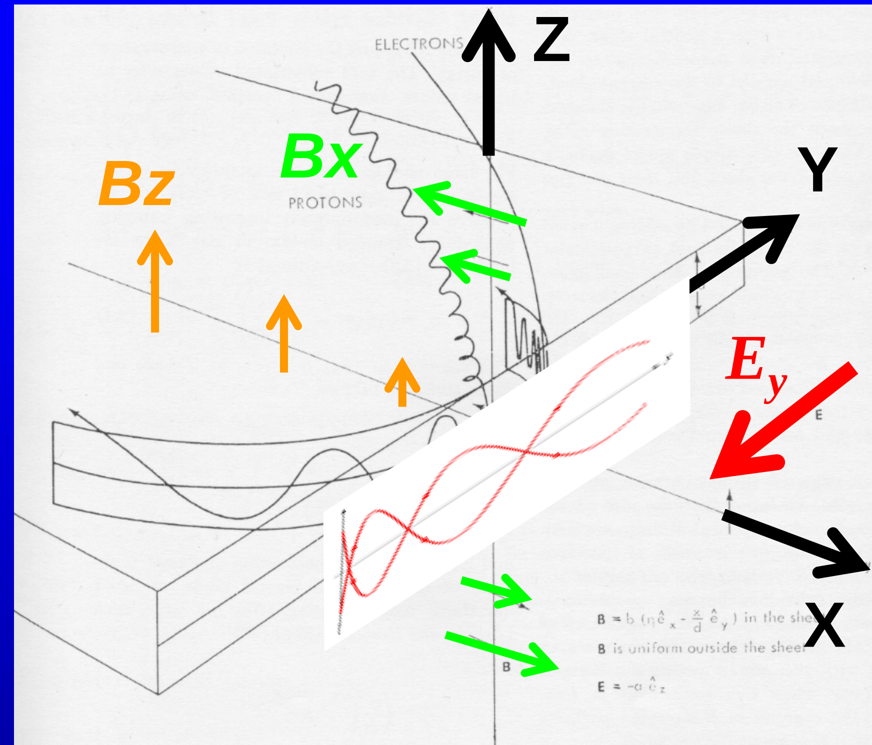


PIC simulations

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

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*, 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

$E_y = \eta_{in} j_y$ at the x-line

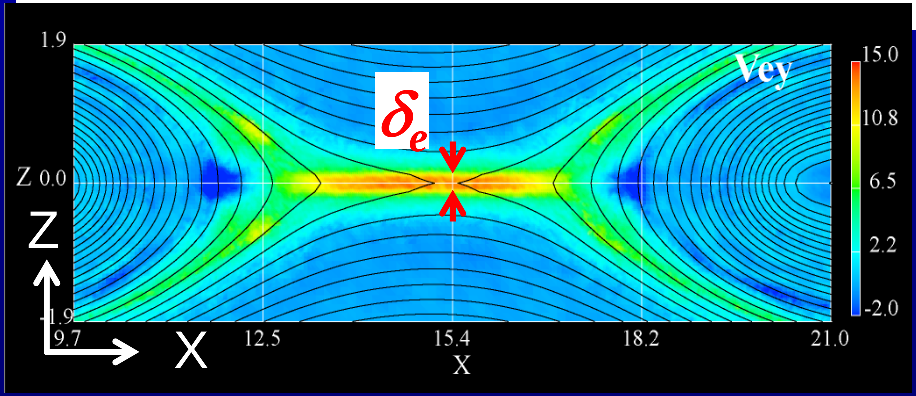
$E_y = -V_{in} B_{in}$ outside the current layer

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

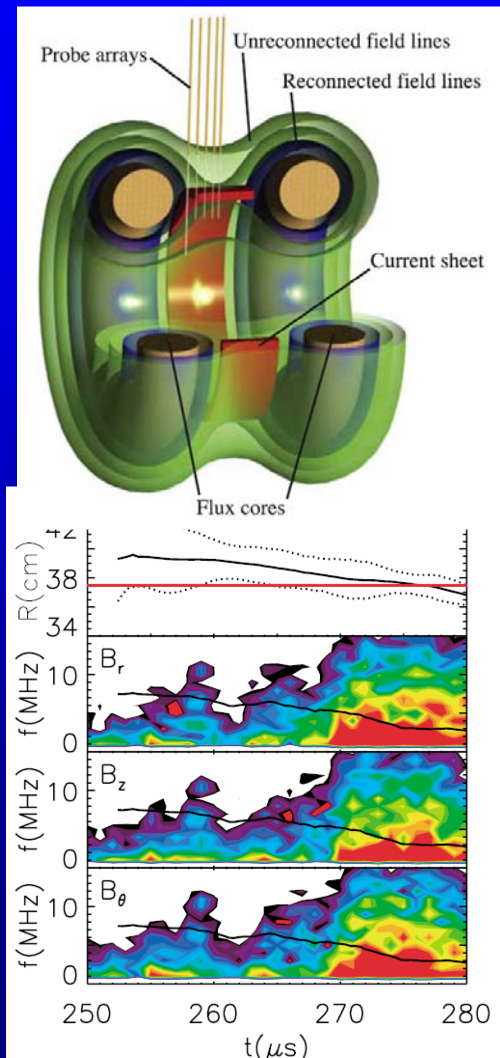
$$j_y \approx -\frac{1}{\mu_0} \frac{B_{in}}{\delta_e}$$

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

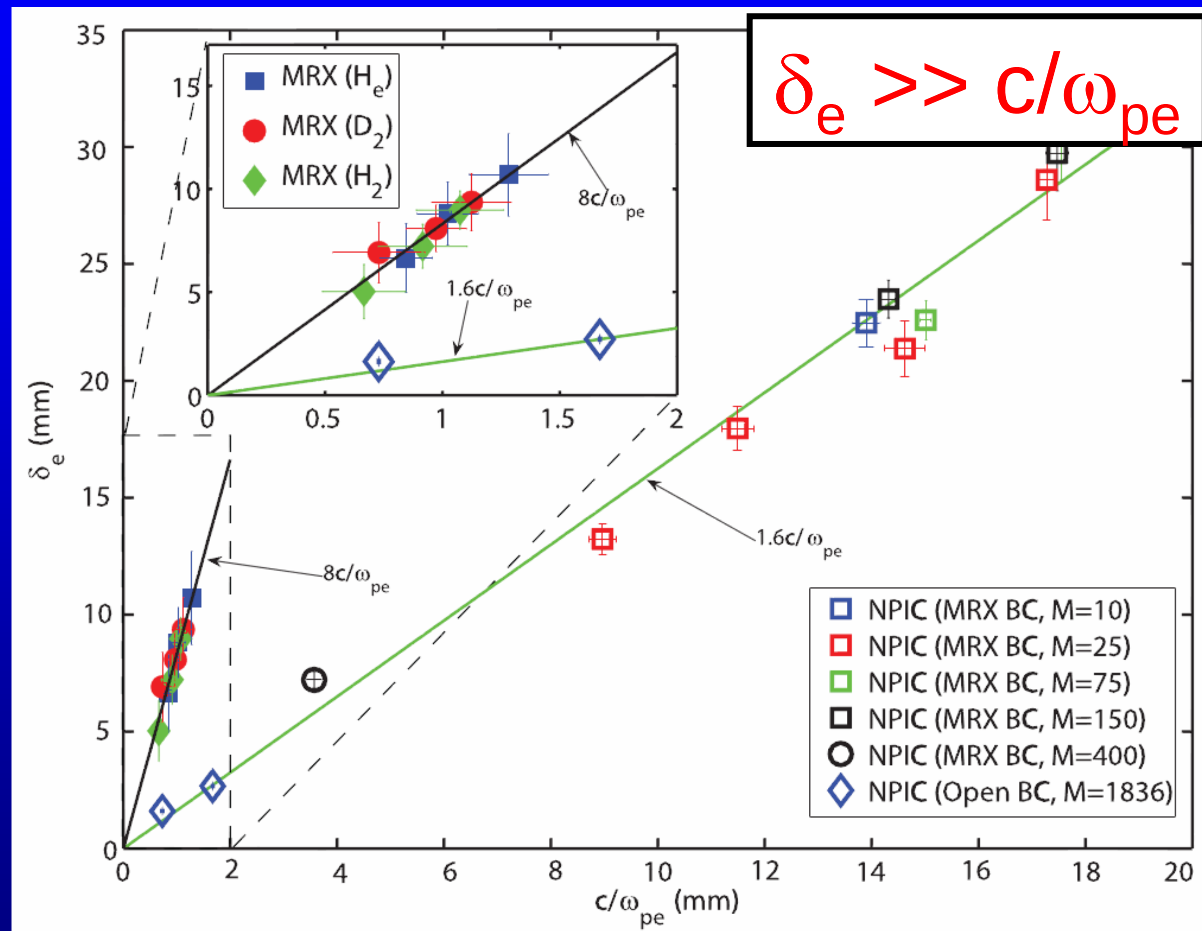
Very thin current layer!



Implication of Anomalous Effects: Lab. Experiment



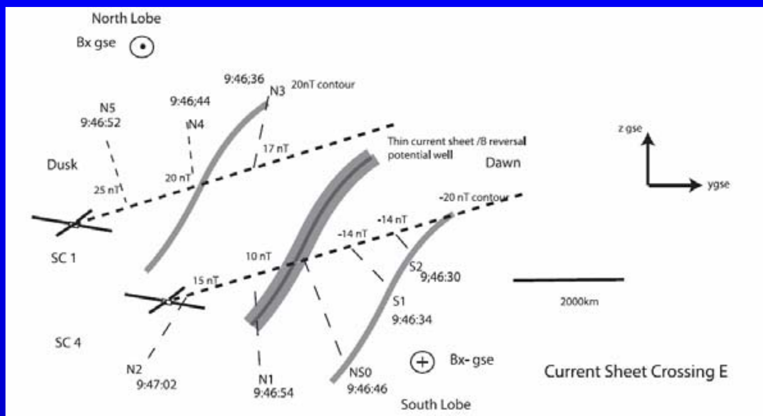
[*Ji et al.*, PRL, 2004]

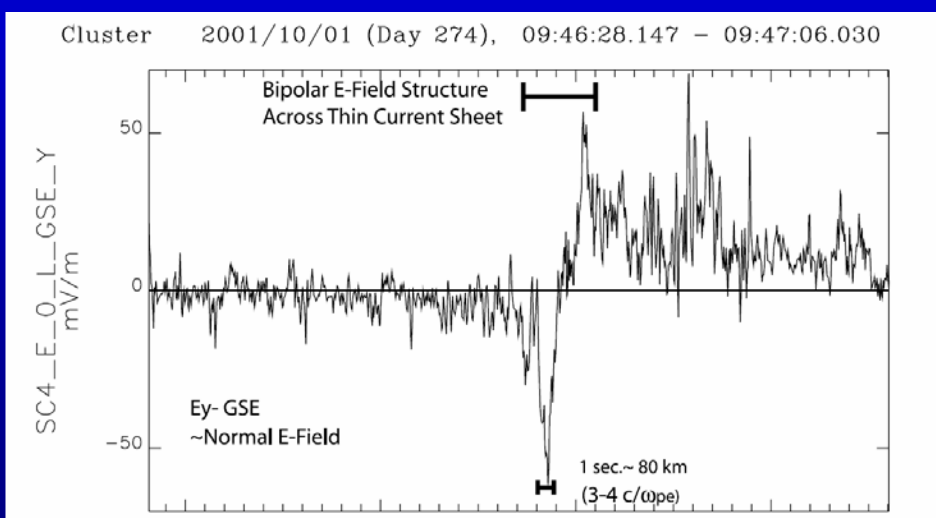


$\delta_e >> c/\omega_{pe}$

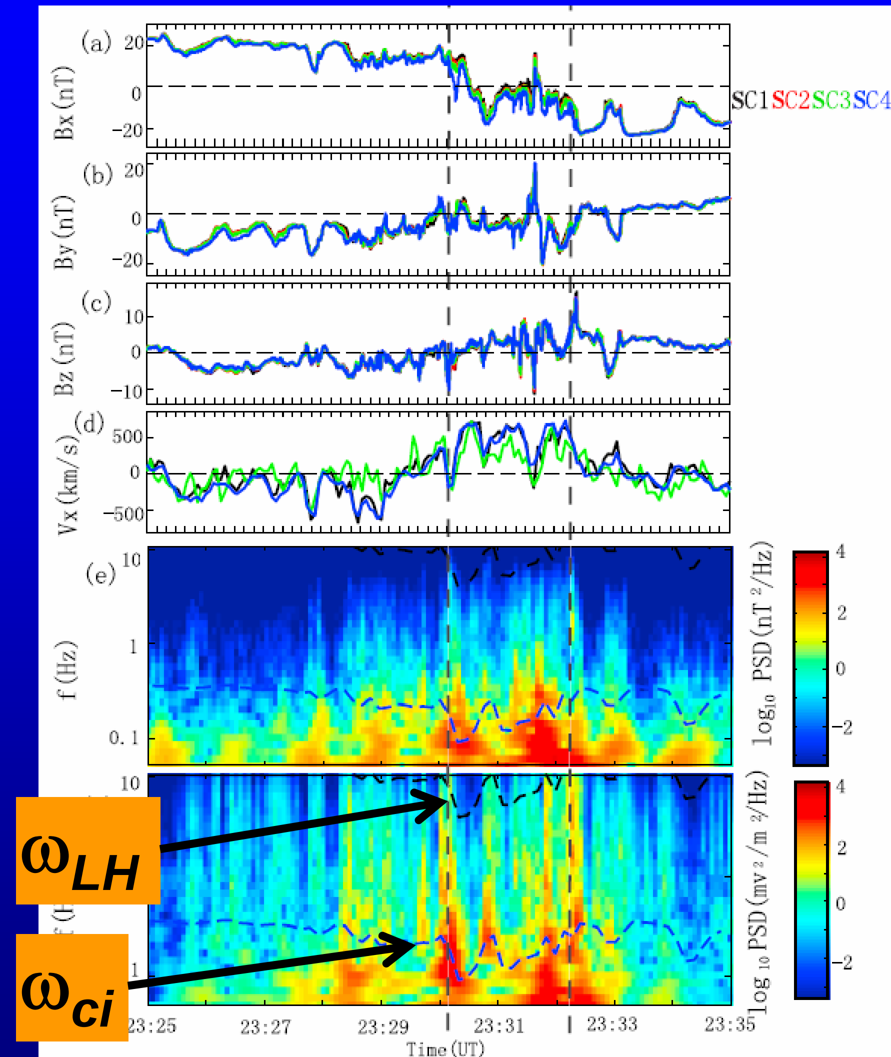
[*Ji et al.*, GRL, 2008]

Implication of Anomalous Effects: Satellite Observation





[Wygant et al, JGR, 2005]



[Zhou et al, JGR, 2009]

Implication of Anomalous Effects

$$E_y = (\eta_{in} + \eta)\, j_y$$ at the x-line

$$E_y = -V_{in} B_{in}$$ outside the current layer

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

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

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

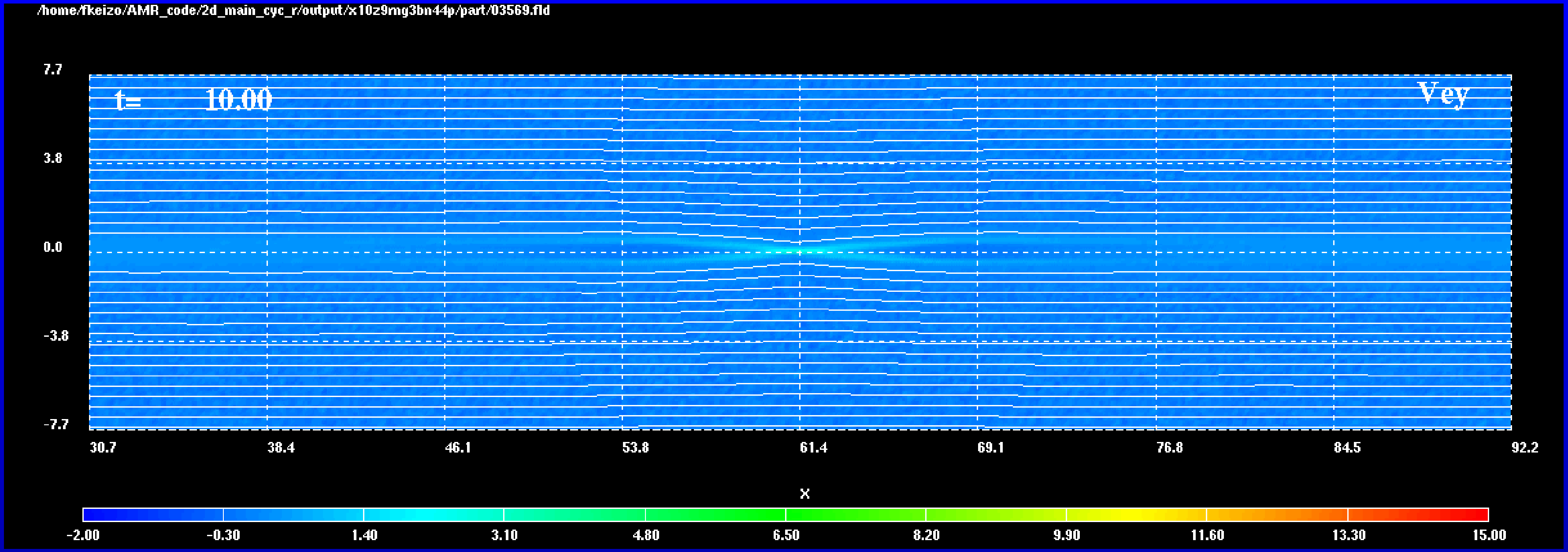
[*Vasyliunas*, 1975]

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

(Resistive length)

Could be caused by wave-particle interactions.

Dynamical Current Sheet (2D PIC simulation)



Thin current layer:

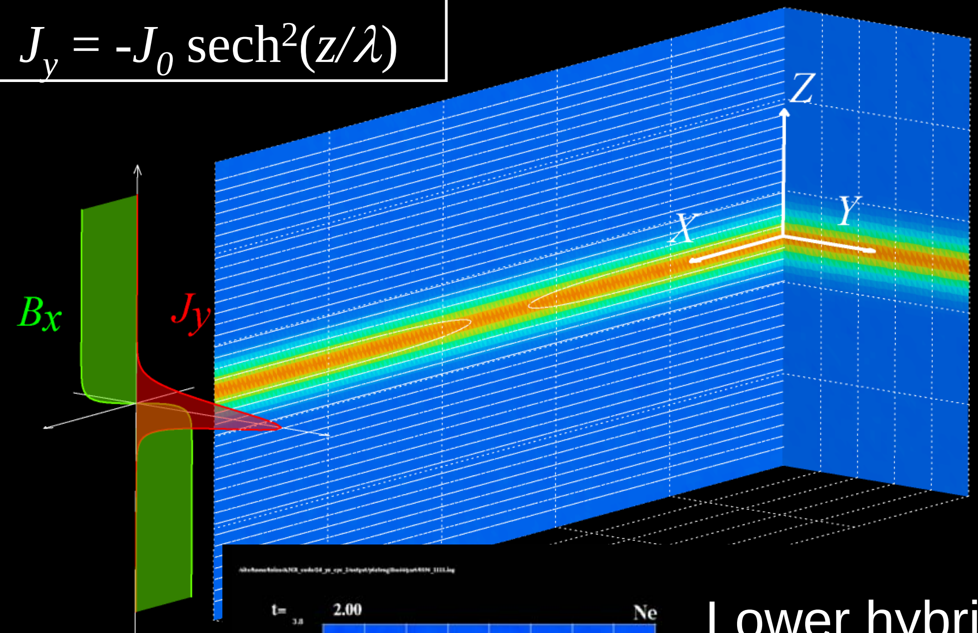
Elongation

Plasmoid formation

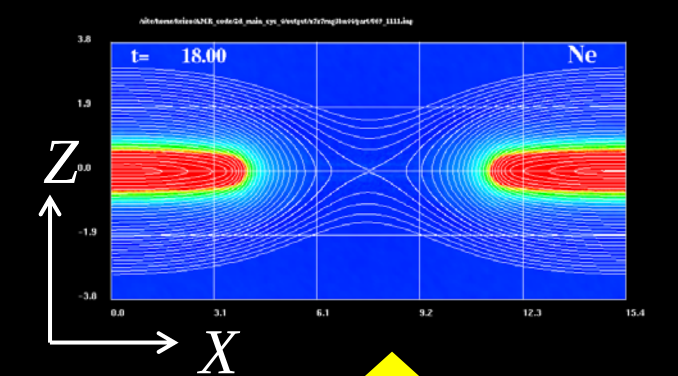
Instabilities in the Harris Current Sheet

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

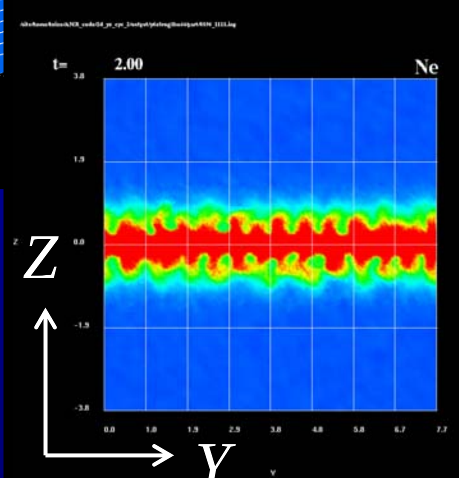
$J_y = -J_0\, \mathrm{sech}^2(z/\lambda)$



Tearing instability



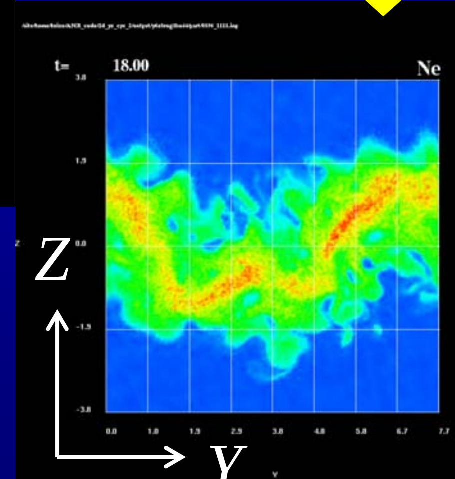
Lower hybrid drift instability (LHDI)



$k_y r_{Le} \sim 1$

$\gamma \sim \omega_{lh}$

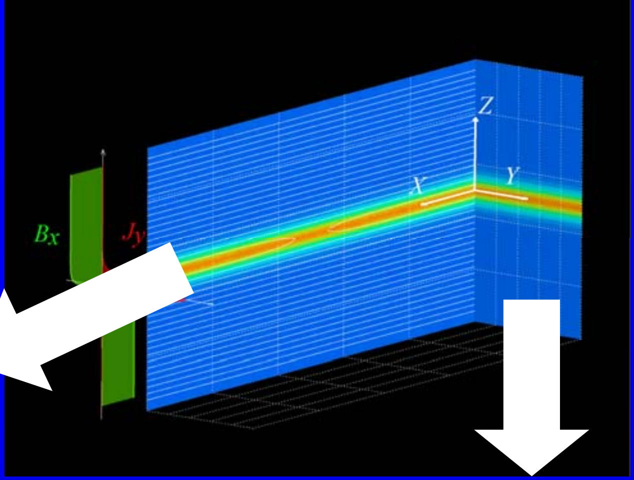
Kink-type instability

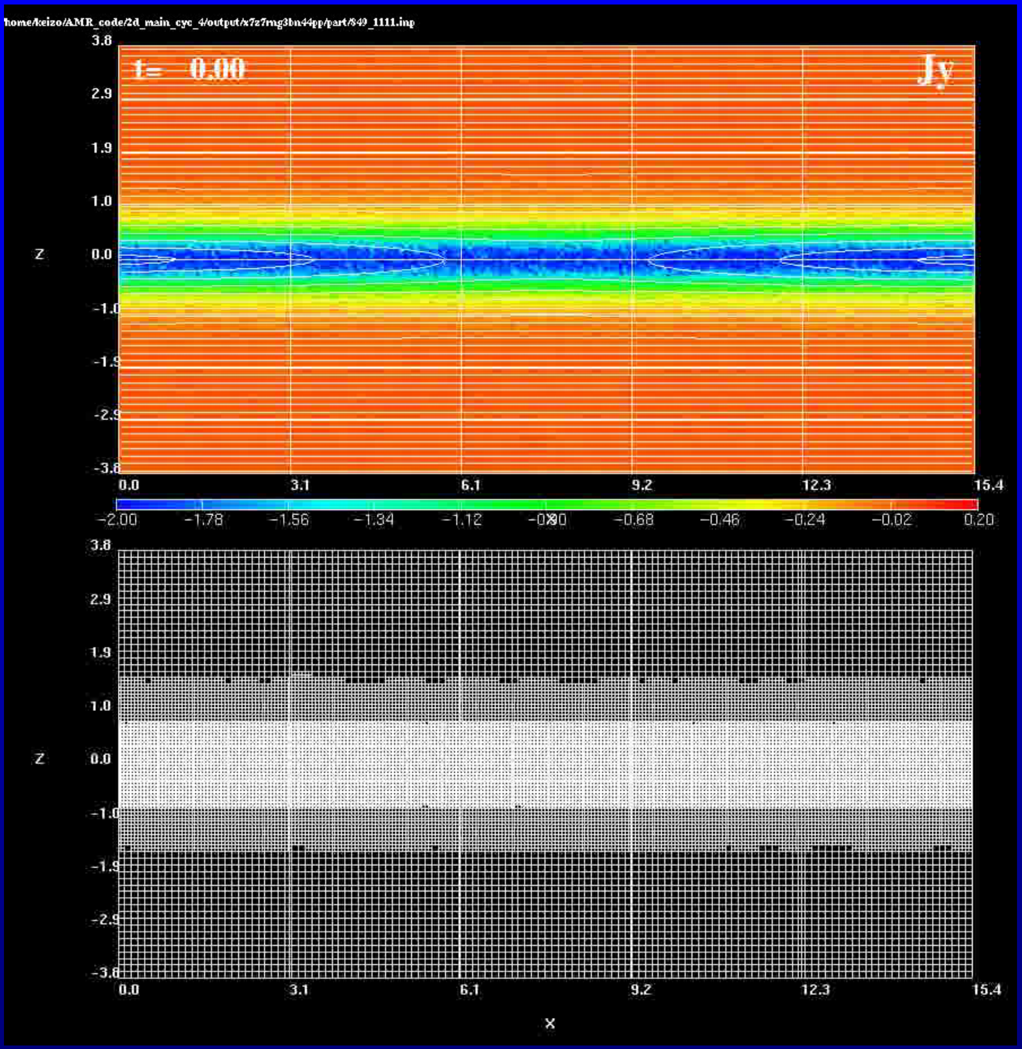


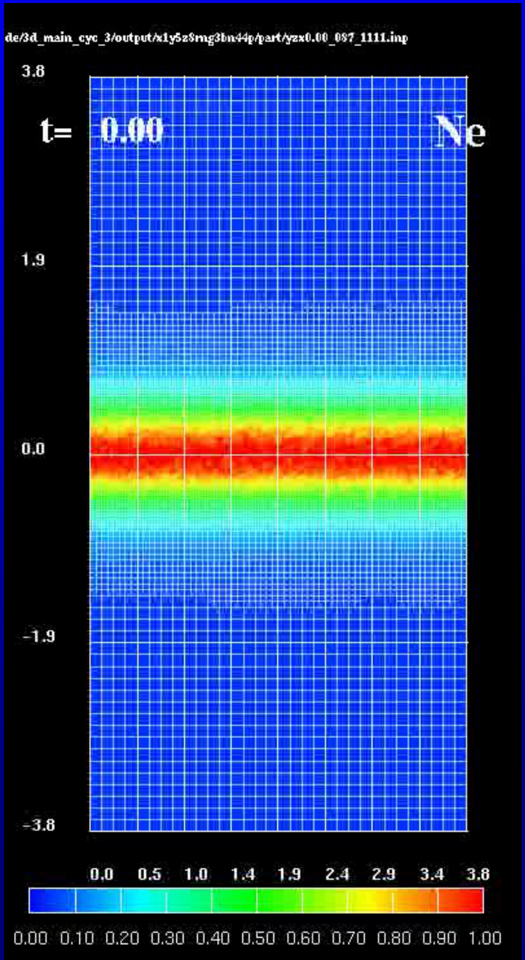
$k_y L \sim 1$

AMR-PIC Simulations

[Fujimoto, JCP, 2011]

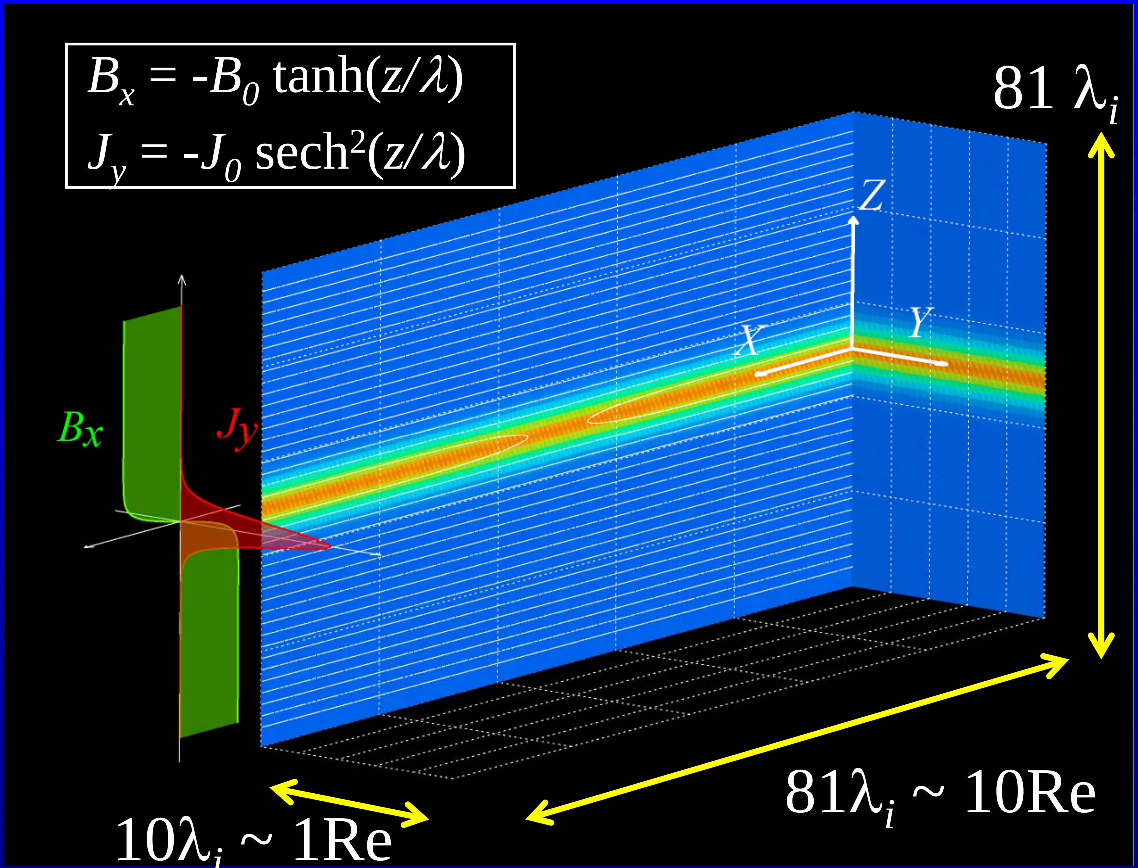






Simulation Setup

Fujitsu FX1



$m_i/m_e = 100$

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

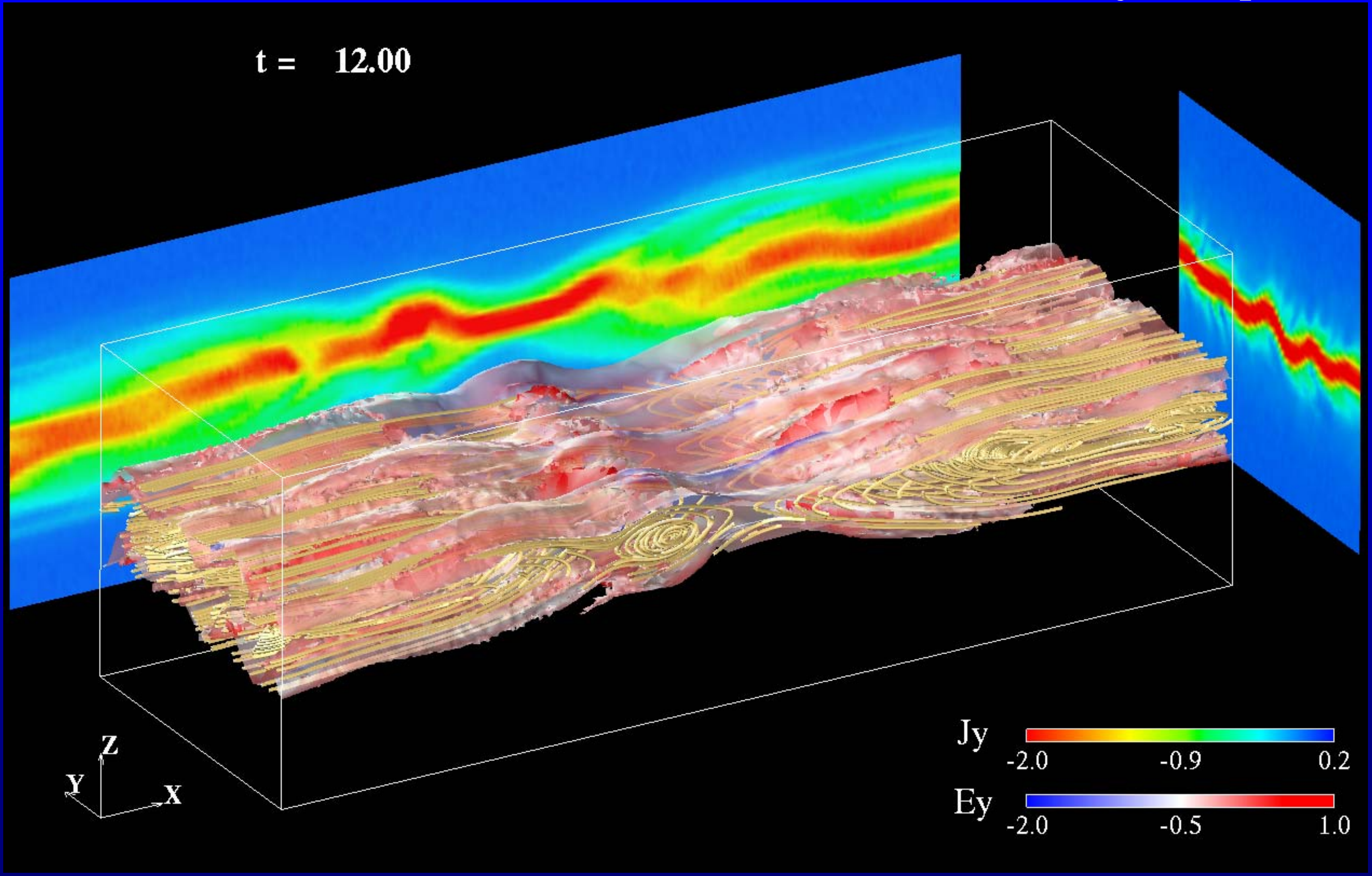
Max number of particles
Ion + Electron $\sim 10^{11}$

Max memory used
~ 6TB

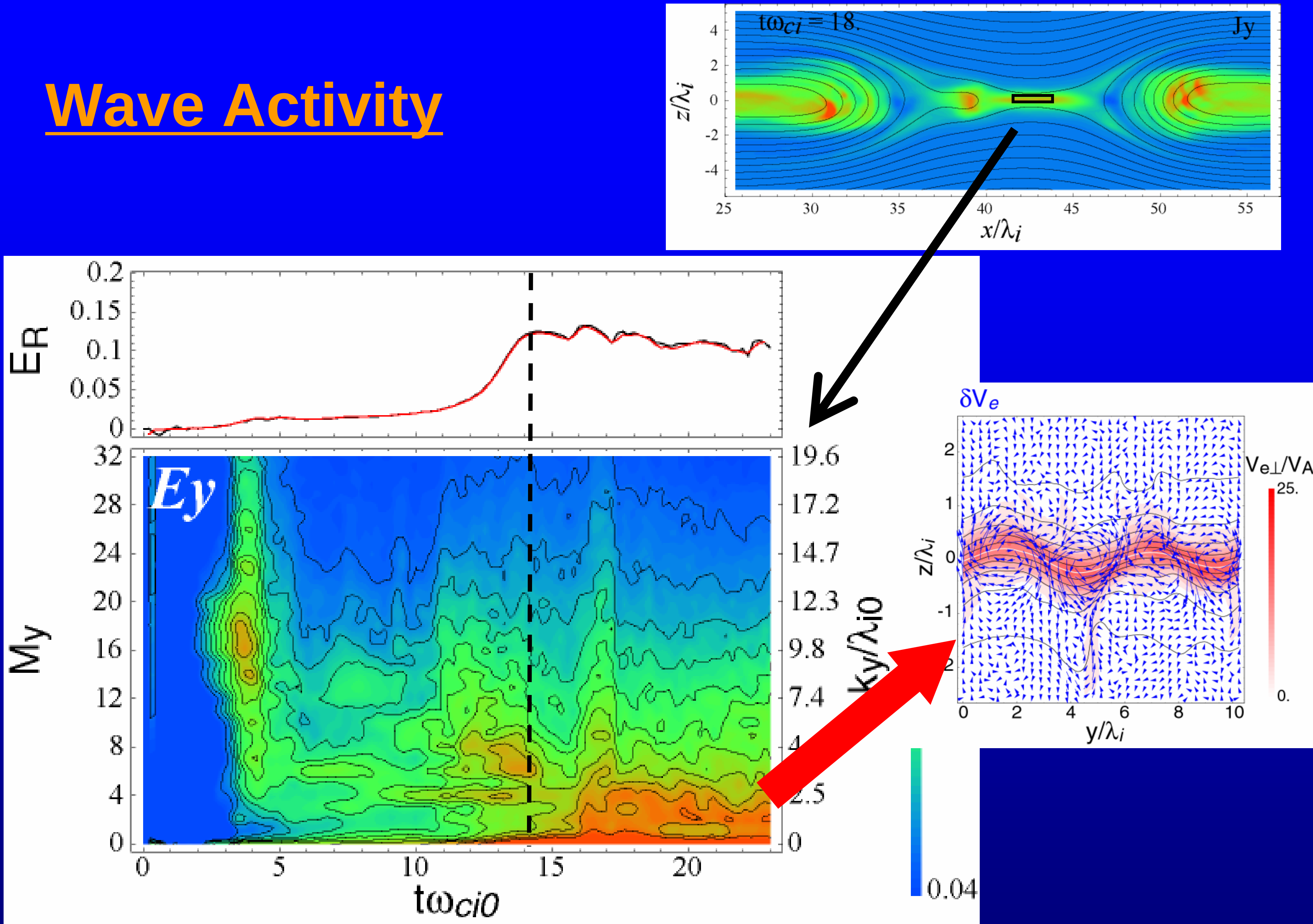
Time Evolution of the Current Sheet

Surface: |J|, Line: Field line

Color on the surface: Ey, Cut plane：Jy



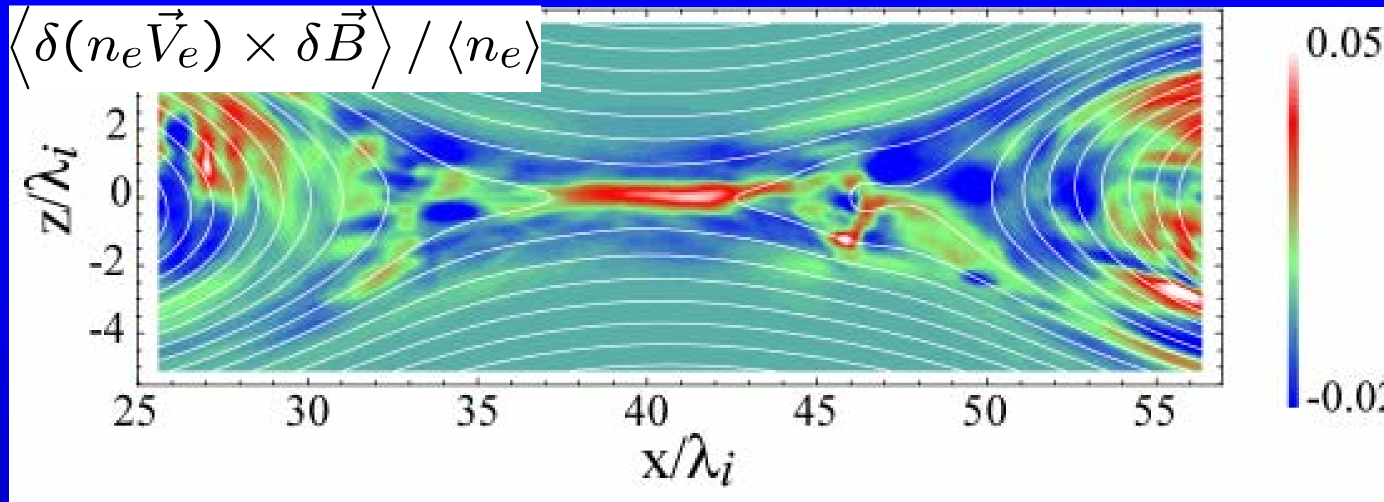
Wave Activity



Anomalous Momentum Transport

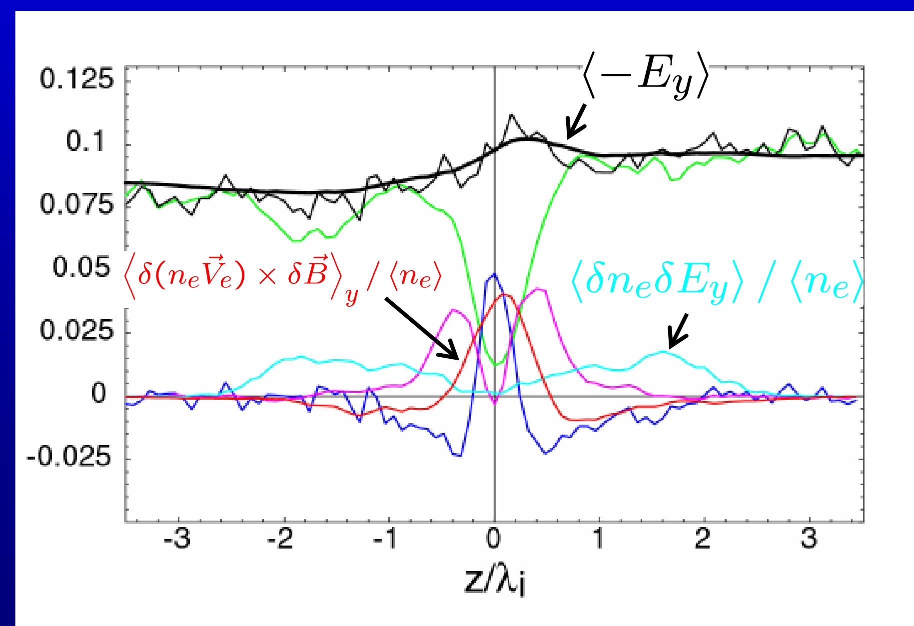
$$A = \langle A \rangle + \delta A$$

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

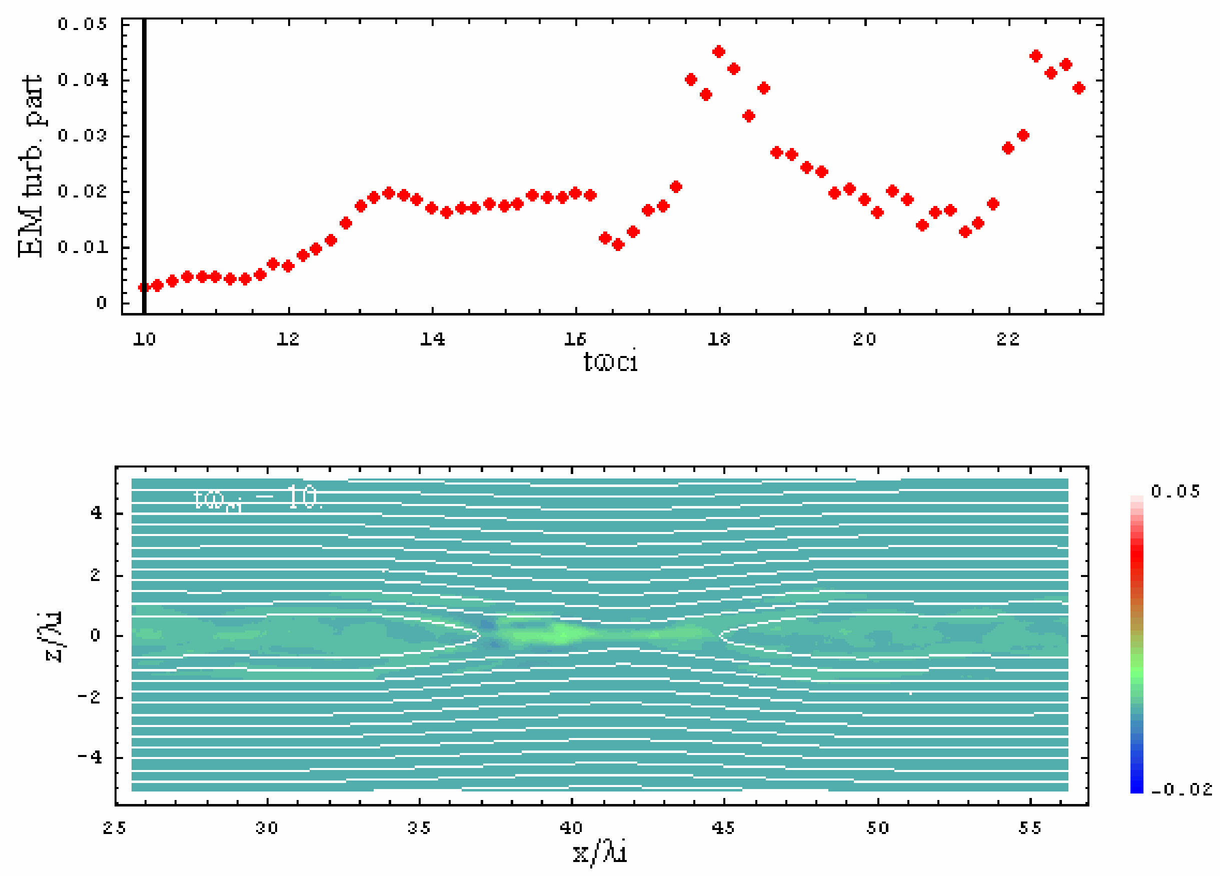


$$\langle -E_y \rangle = \frac{1}{\langle n_e \rangle} \left(\left\langle n_e \vec{V}_e \right\rangle \times \left\langle \vec{B} \right\rangle \right)_y + \frac{1}{e \langle n_e \rangle} \left\langle \nabla \cdot \vec{P}_e \right\rangle_y + \frac{m_e}{e \langle n_e \rangle} \left\langle \frac{\partial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

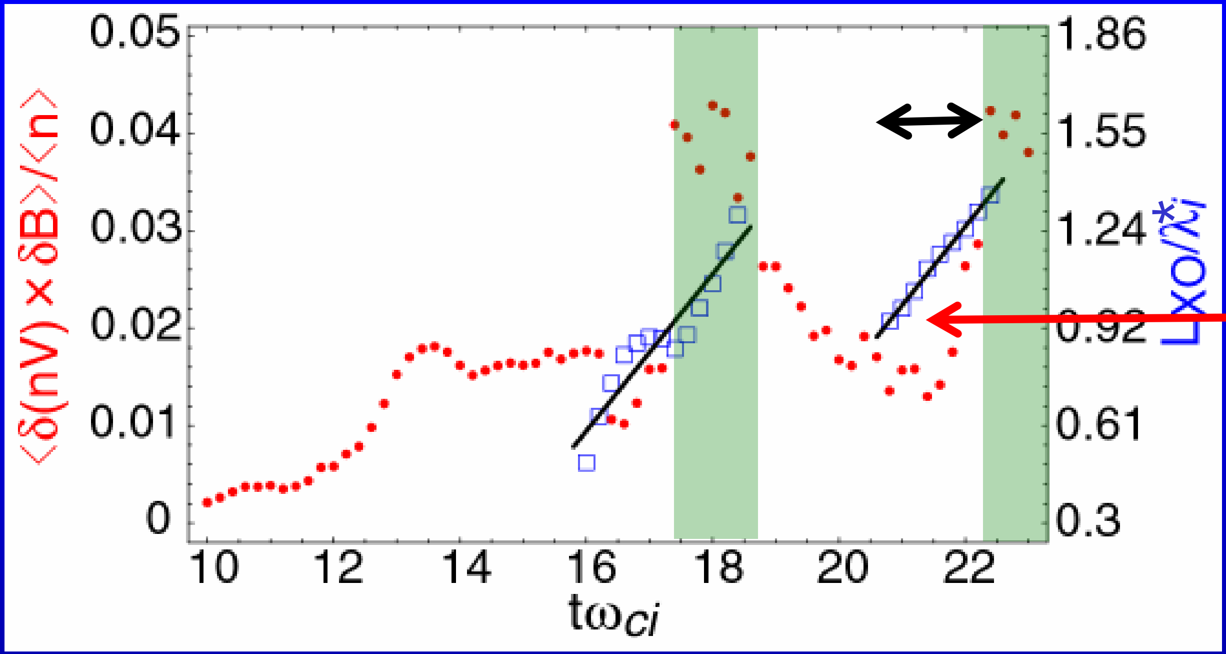
Anomalous effects



Anomalous Transport at the X-line

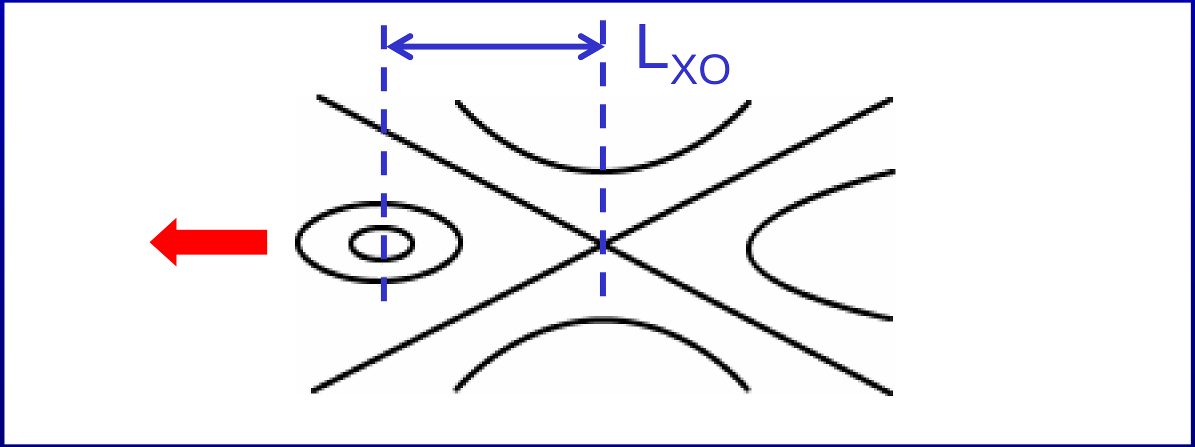


Plasmoid-Induced Turbulence



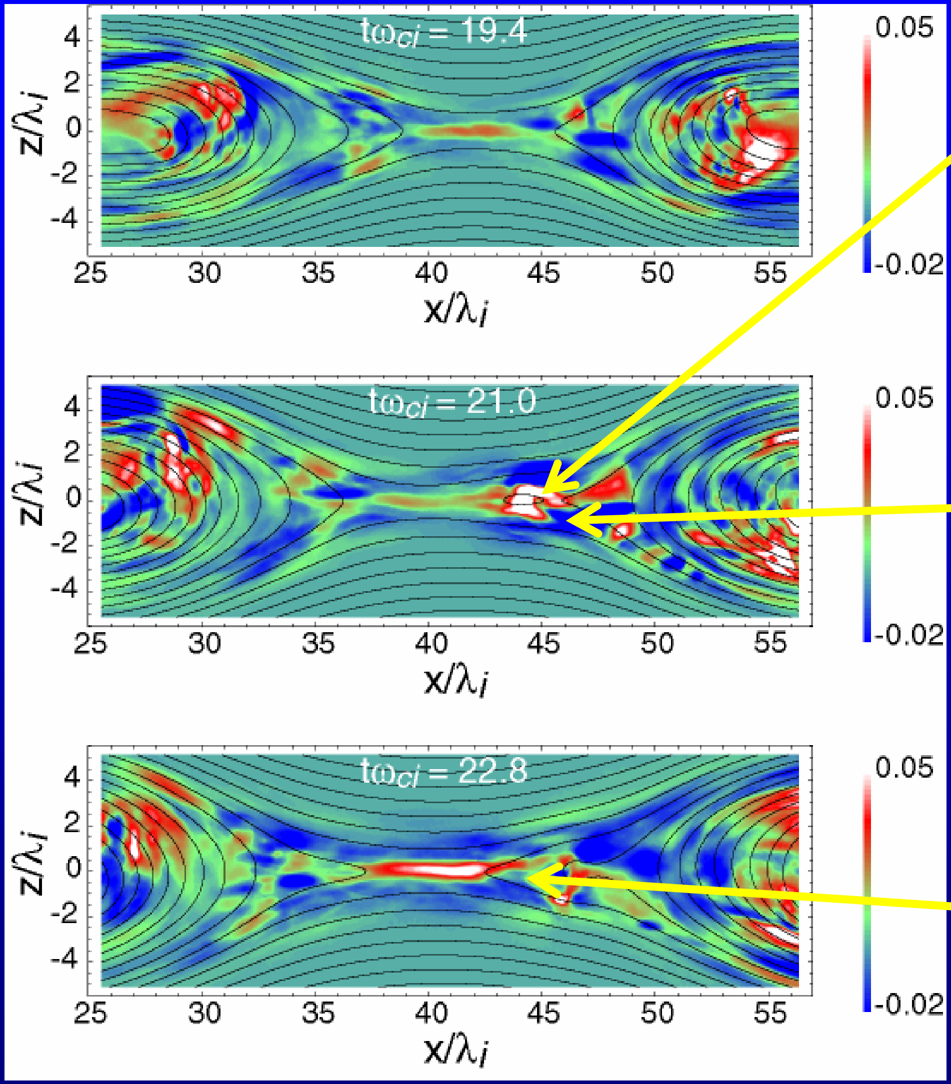
$\Delta t = 1.6\ \omega_{ci}^{-1}$

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



Information propagates at $V_p \sim V_A^*$ $(B^* = 0.5B_0)$

Plasmoid-Induced Turbulence



Plasmoid formation

Wave amplification

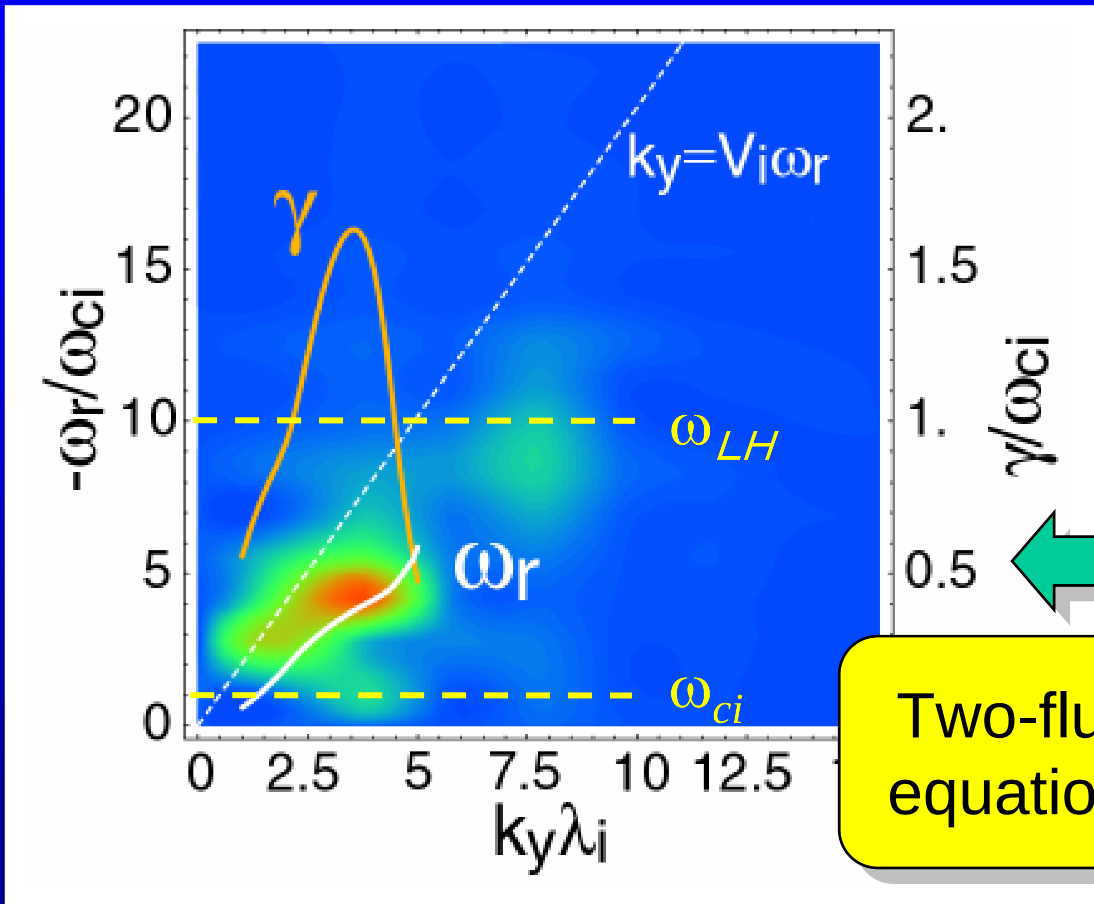
Local turbulence enhancement

Propagation along the field line

Intensified turbulence at the x-line

Wave Properties

$\omega = \omega_r + i\gamma$



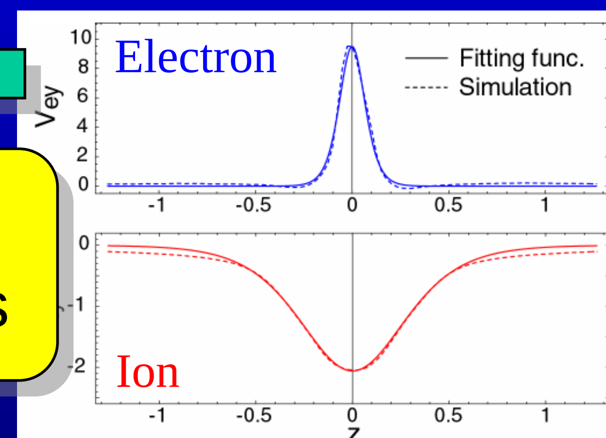
Simulation results

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

$$V_{ph} \approx V_A$$

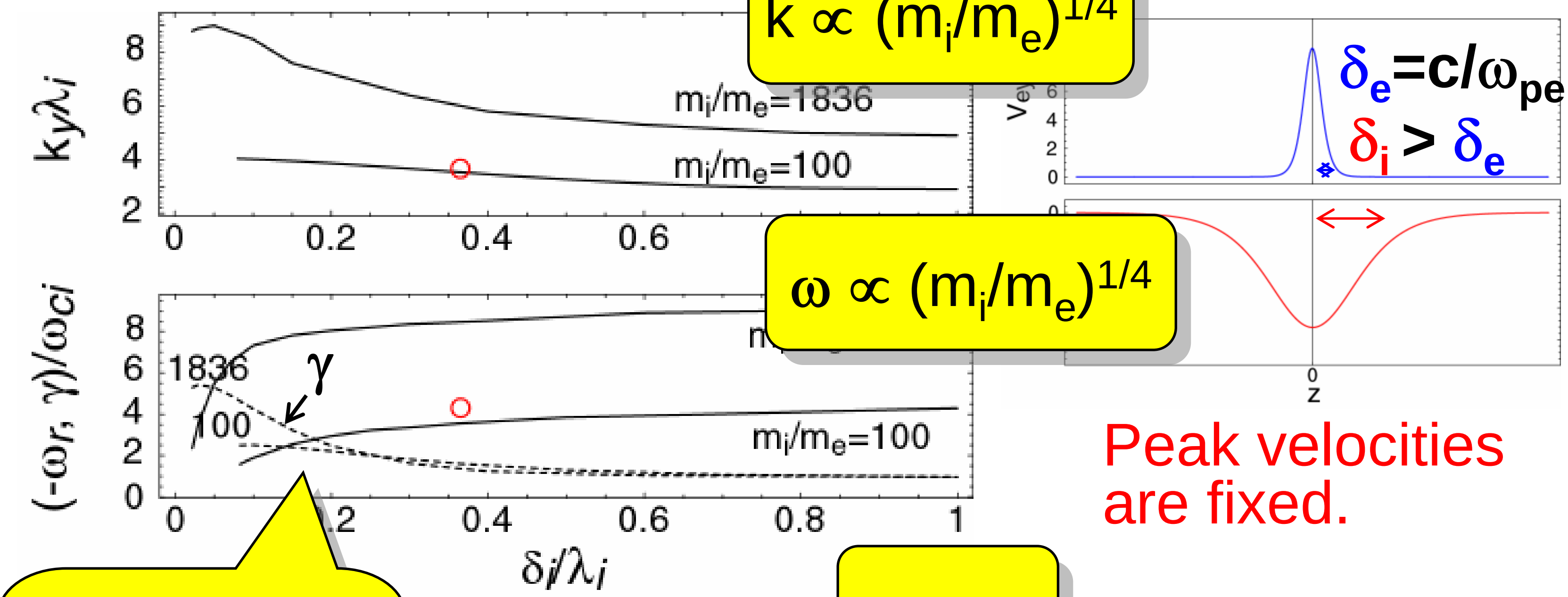
Linear analyses

Profiles taken from simulation



Two-fluid equations

Linear Analyses



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

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

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

$\delta_i > \delta_e$

Peak velocities are fixed.

$\gamma \sim \omega_{ci}$

Shear driven mode rather than drift mode

The wave survives even for m_i/m_e=1836.

Summary

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

The EM turbulence has a significant impact on the dissipation mechanism during the fast reconnection, in association with plasmoid formations.

The properties of the EM mode responsible for the turbulent electron flow.

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

Shear driven instability

Large growth rate even for $m_i/m_e=1836$