Kinetic Modeling of Collisionless Magnetic Reconnection in Three Dimension

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Outline

- Introduction
- Particle-in-Cell (PIC) model with adaptive mesh refinement (AMR)
- 3D kinetic modeling of reconnection (*Instabilities, turbulence, and anomalous transport at the x-line*)
- Summary

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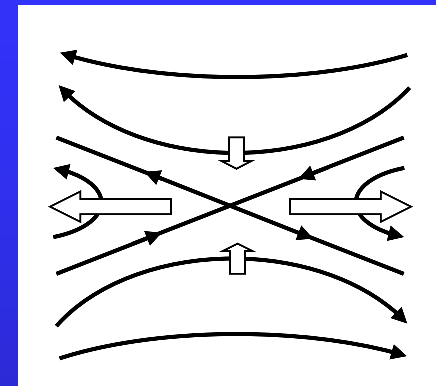
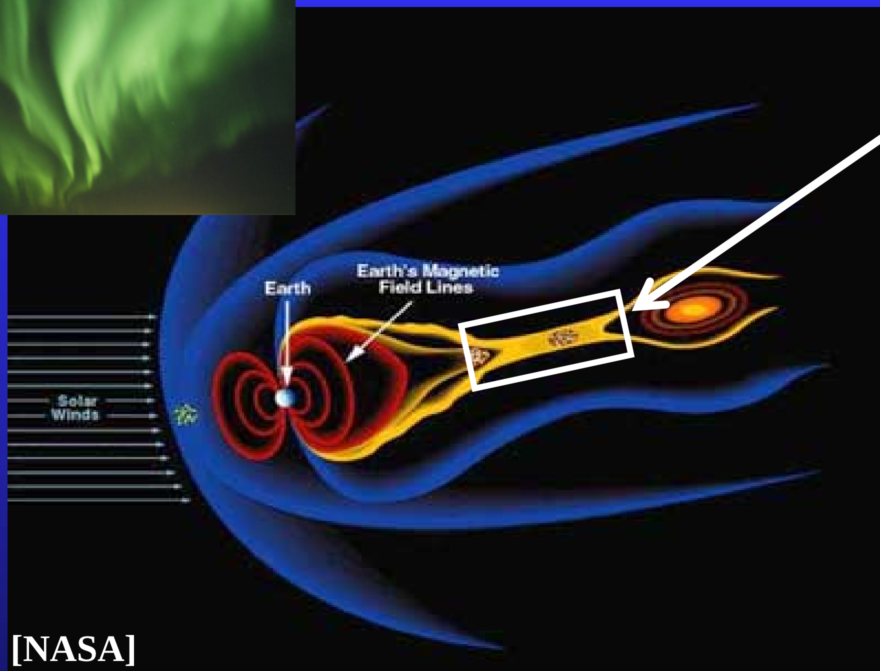
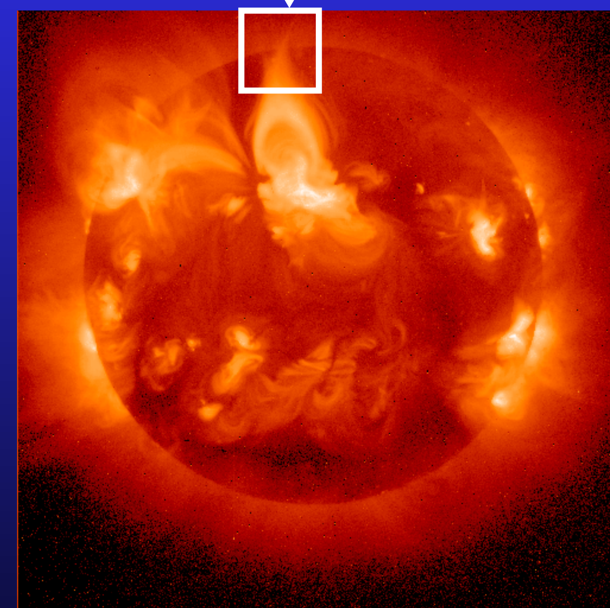
Magnetic Reconnection in Space

Auroral Substorms

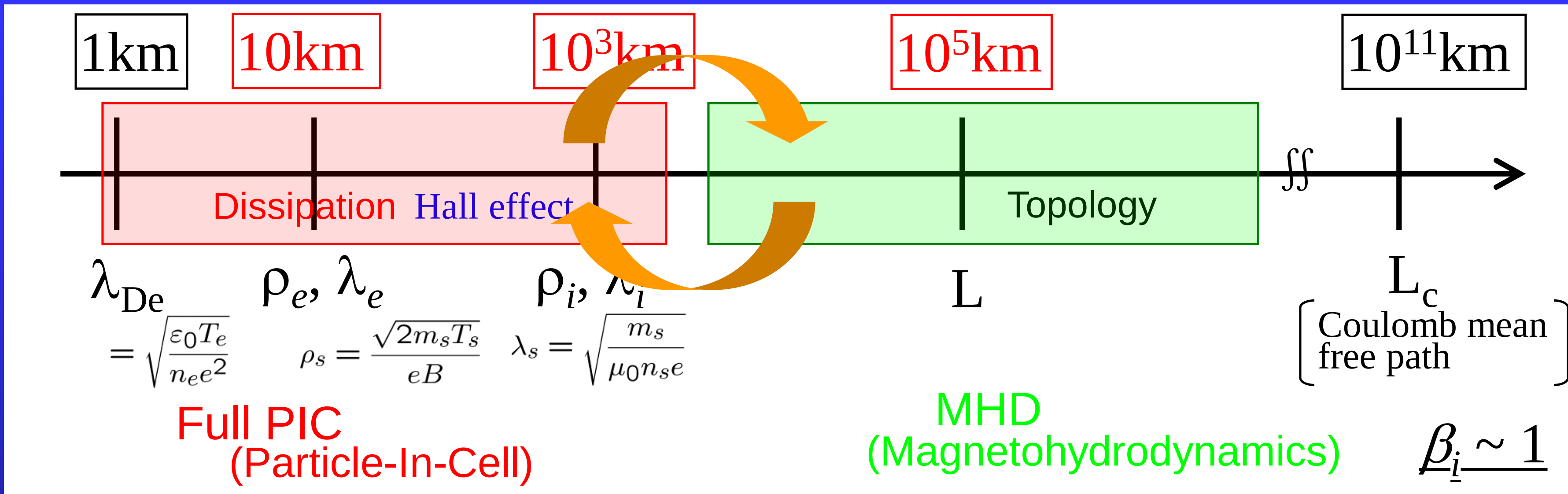


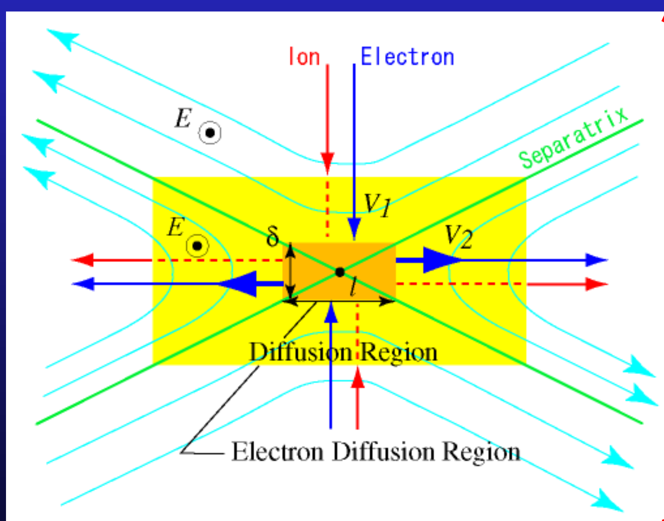


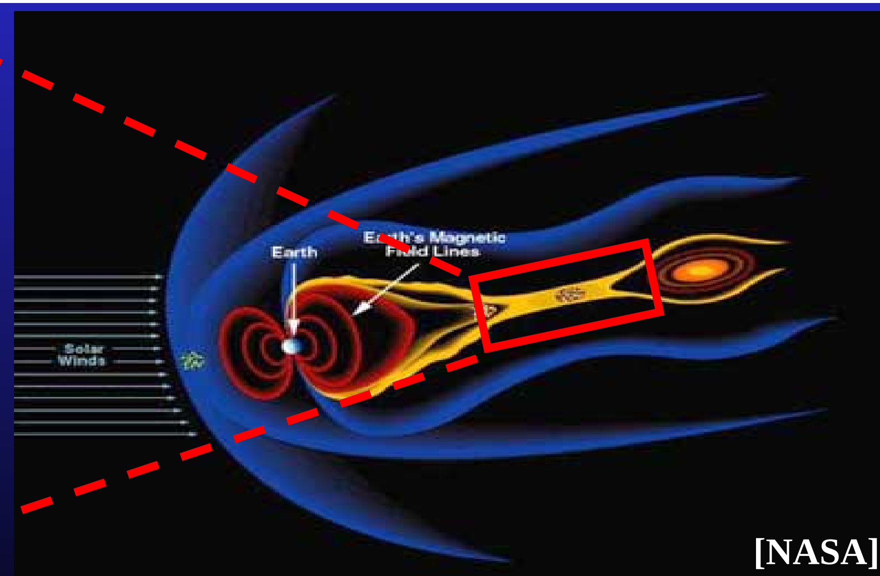


Solar Flares

Multi-Scale Nature of Reconnection



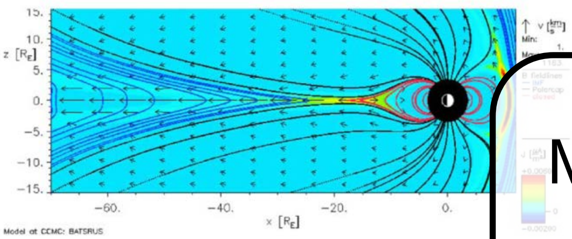




Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

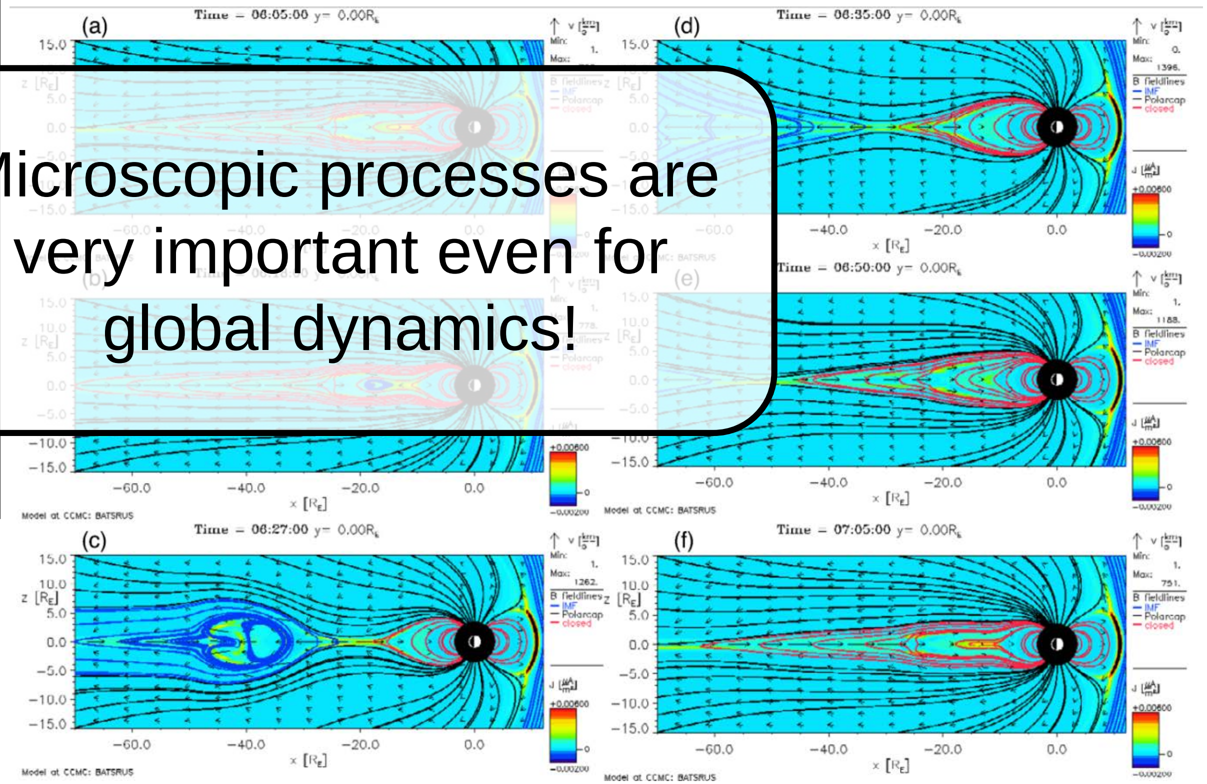


- Slow reconnection
- Quasi-steady configuration

- Fast reconnection
- Quasi-periodic process

Nongyrotropic correction case

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



Microscopic processes are very important even for global dynamics!

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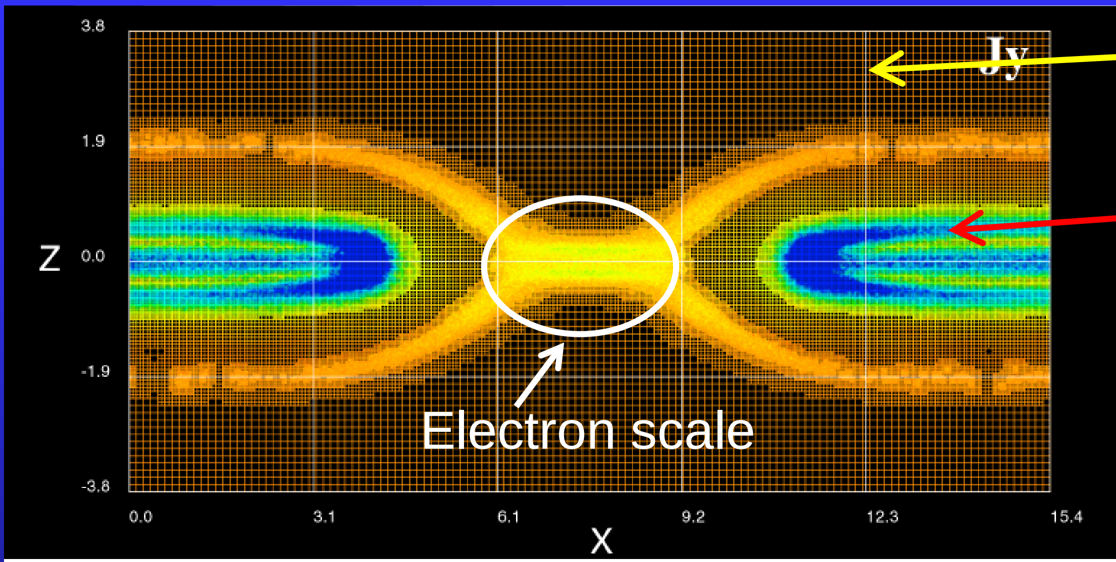
AMR-PIC Model [Fujimoto, JCP, 2011]

(Adaptive Mesh Refinement – Particle-in-Cell)

$$\Delta x \lesssim 3\lambda_{De} \propto n_e^{-1/2}$$

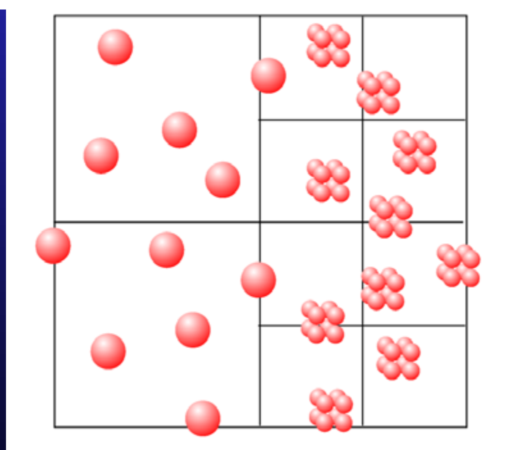


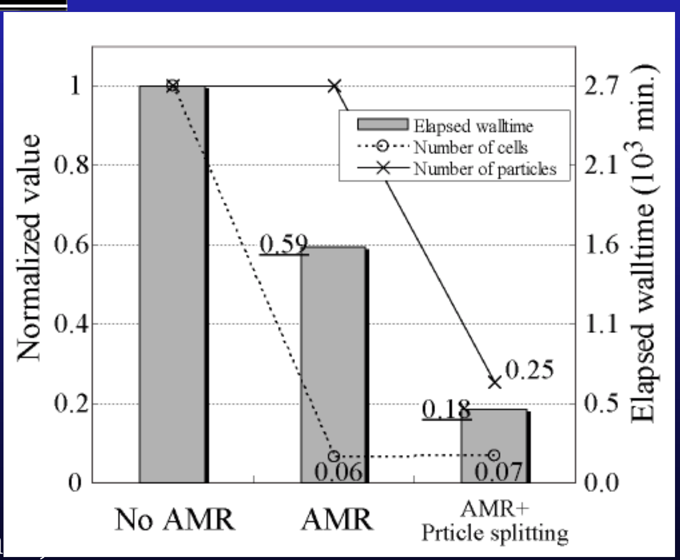
$$\lambda_{De,lobe} \sim 6 \times 10^3 \text{ m}$$

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

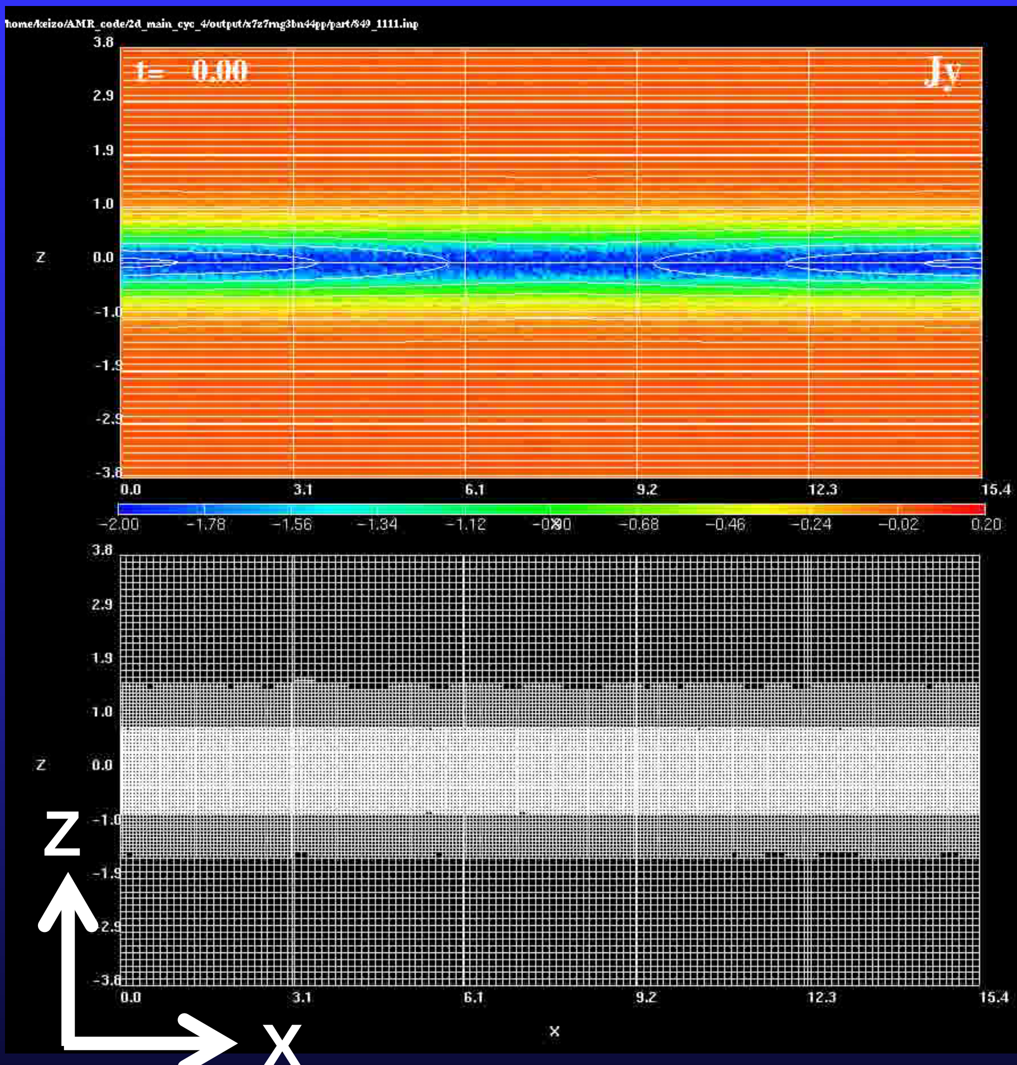
Removing unnecessary cells.

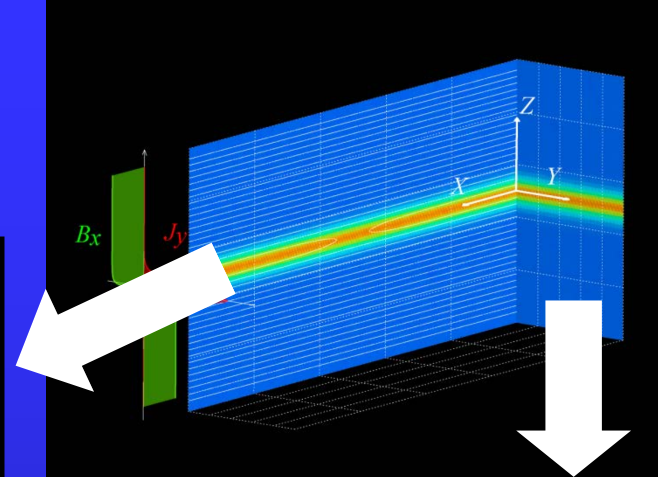
Particle splitting-coalescence

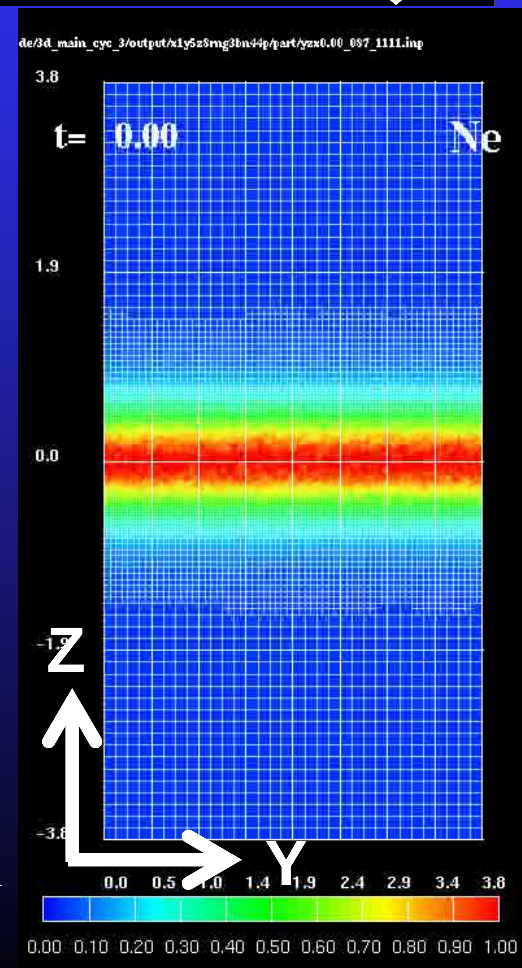




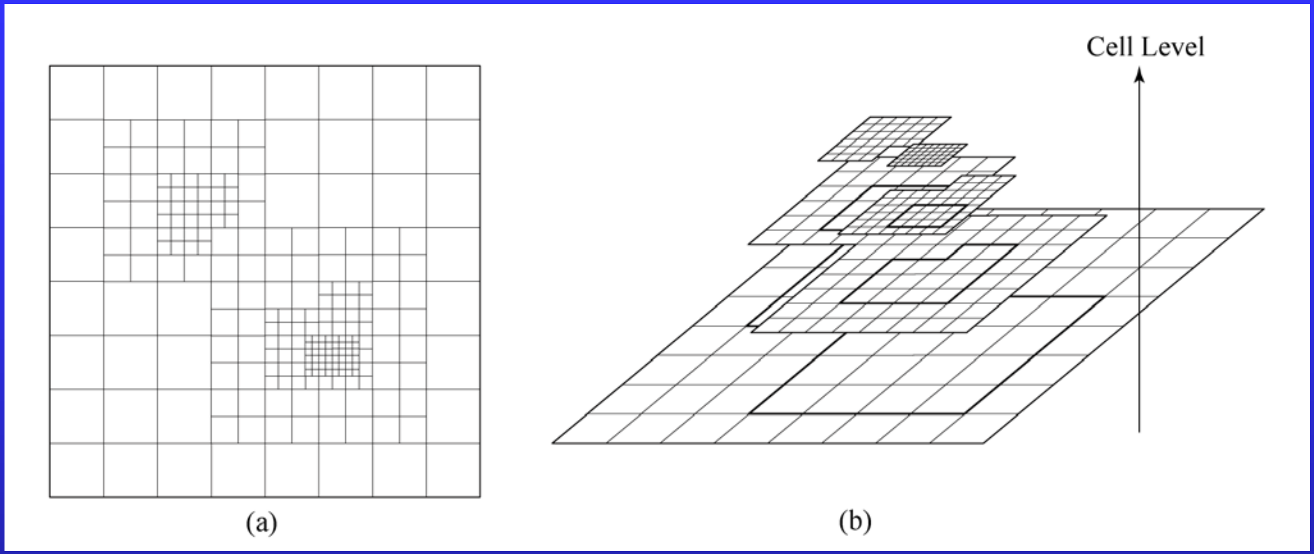
AMR-PIC Simulations





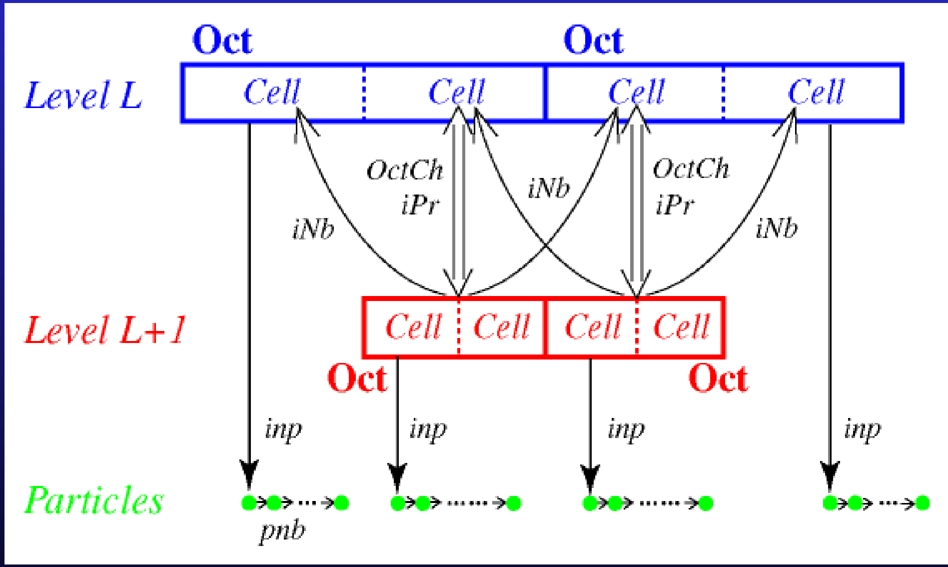


Data Structure



Similar to a fully threaded tree (FTT) structure (Khokhlov, 1998).

[Fujimoto & Machida, JCP, 2006]



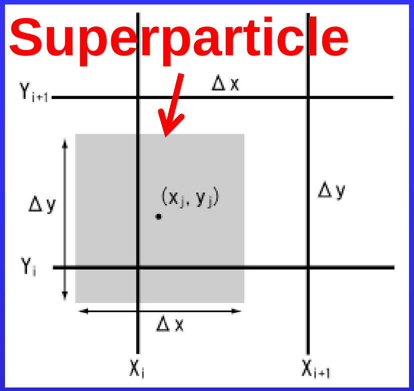
Basic Equations

The same as usual PIC

$$\rho_{l,m,n} = \sum_s \sum_j q_{sj} S(\vec{x}_{sj} - \vec{X}_{l,m,n})$$

$$A(\vec{x}_{sj}) = \sum_l \sum_m \sum_n A_{l,m,n} S(\vec{x}_{sj} - \vec{X}_{l,m,n})$$

S: Shape function



- Superparticles (Buneman-Boris method)

$$\frac{\vec{v}_{sj}^{n+1/2} - \vec{v}_{sj}^{n-1/2}}{\Delta t} = \frac{q_{sj}}{m_{sj}} \left[\vec{E}^n(\vec{x}_{sj}^n) + \frac{\vec{v}_{sj}^{n-1/2} + \vec{v}_{sj}^{n+1/2}}{2} \times \vec{B}^n(\vec{x}_{sj}^n) \right]$$

$$\frac{\vec{x}_{sj}^{n+1} - \vec{x}_{sj}^{n}}{\Delta t} = \vec{v}_{sj}^{n+1/2}$$

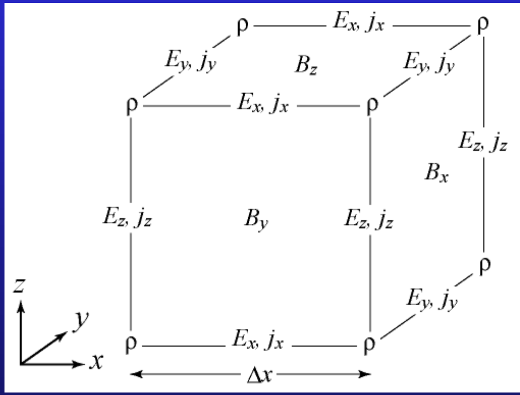
- EM Field (Yee-Buneman scheme)

$$\frac{\vec{B}^{n+1/2} - \vec{B}^{n-1/2}}{\Delta t} = -\nabla \times \vec{E}^n$$

$$\frac{\vec{E}^{n+1} - \vec{E}^{n}}{\Delta t} = c^2 \nabla \times \vec{B}^{n+1/2} - \frac{1}{\varepsilon_0} \vec{j}^{n+1/2}$$

Charge Conservation Method

[Villasenor & Buneman, 1992]

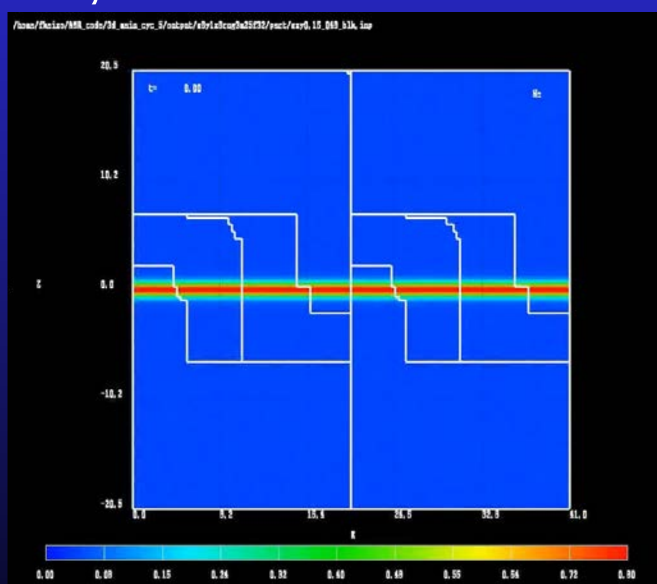


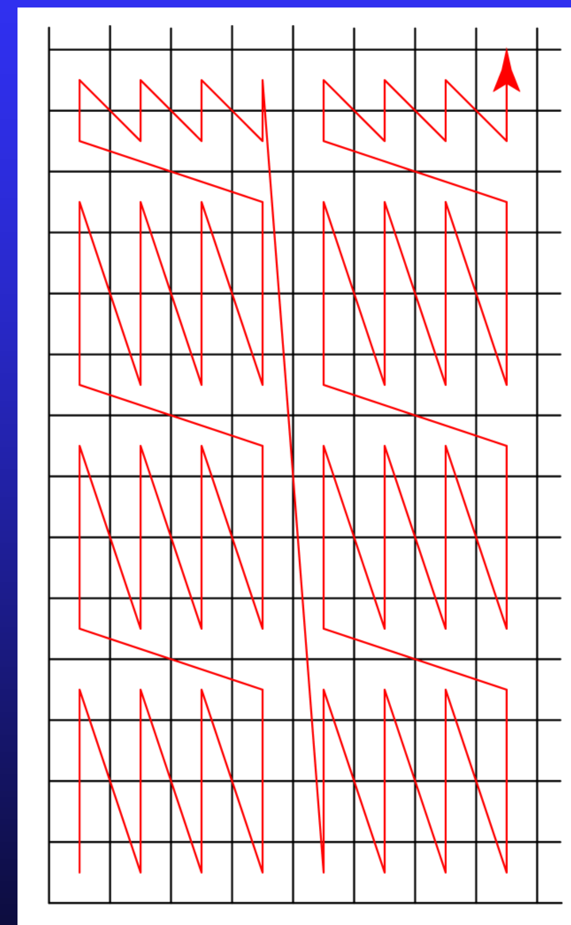
○ Local operations → Facilitate parallel computation

Adaptive Block Technique [Fujimoto, JCP, 2011]

Base-level cells in the entire domain are sorted in an appropriate order:

- That is similar to Morton order,
- So that the block surface is as small as possible,
- Especially in the central current sheet, the surface must be small.



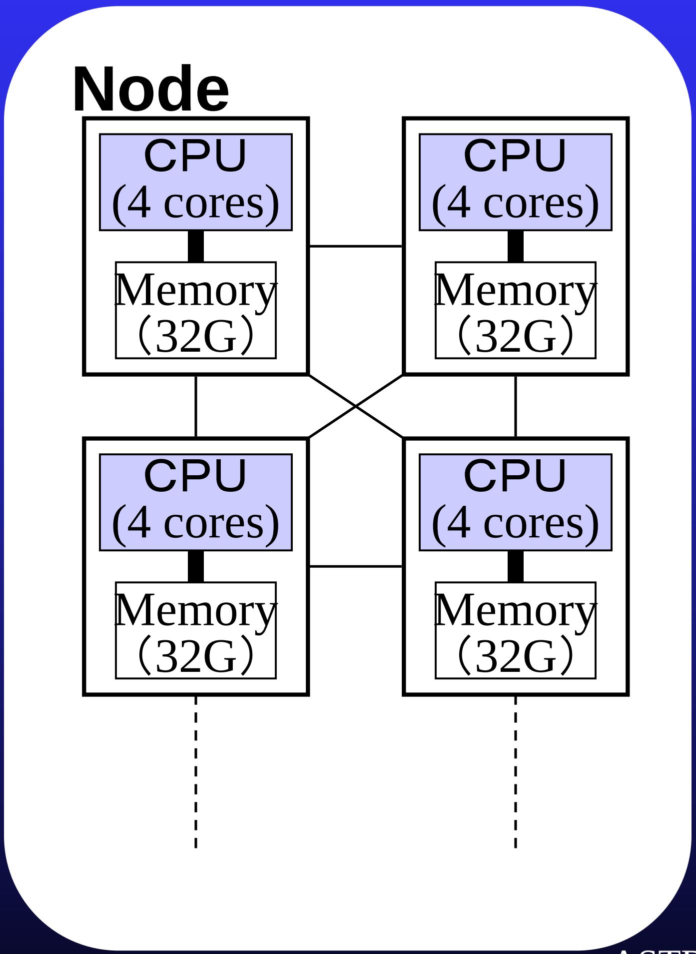


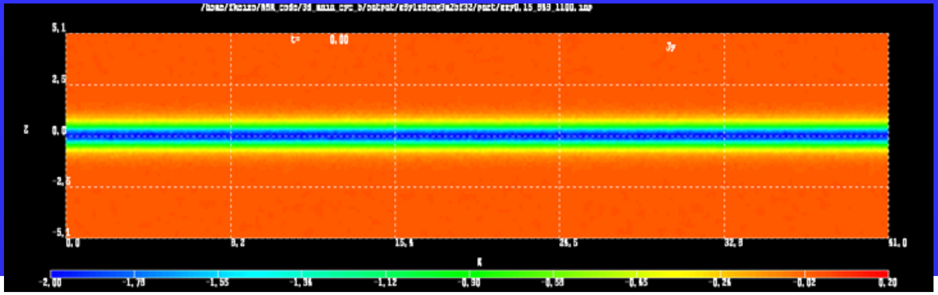
Performance of the AMR-PIC Model

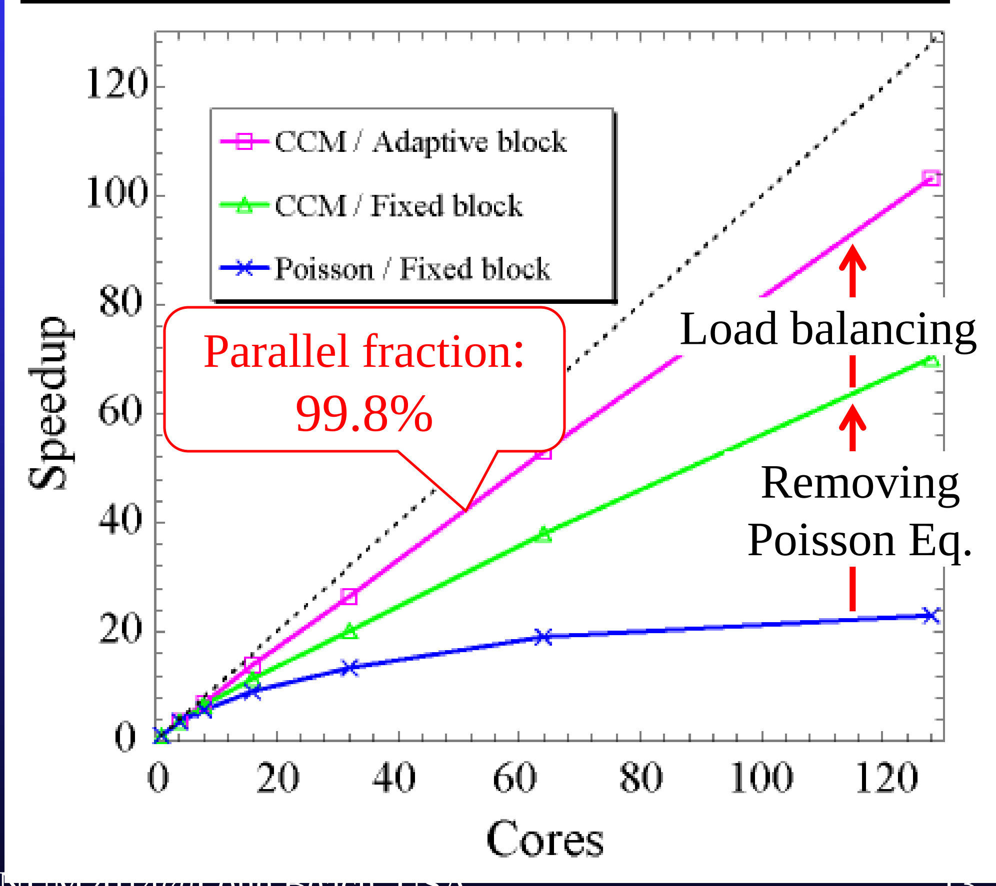
[Fujimoto, JCP, 2011]

Fujitsu FX1

@Nagaya Univ.







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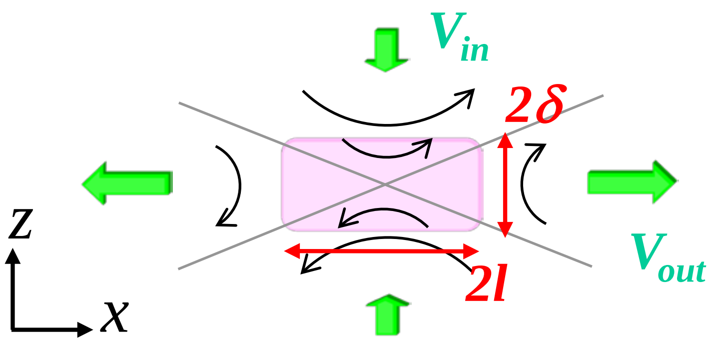
Origin of resistivity…

- Summary

Reconnection Rate and Resistivity η



Reconnection rate

$$E_R \equiv -\frac{\partial \Phi_m^*}{\partial t} \approx \frac{V_{in}}{V_{out}} \approx \frac{\delta}{l}$$

$$\Phi_m^* = \int_0^{L_z} B_x^* \, dz$$

[Vasyliunas, 1975]

Depending on width and length of the dissipation region.

$$\delta \approx \eta / \mu_0 V_{in}$$

2D case

$\rightarrow c/\omega_{pe}$

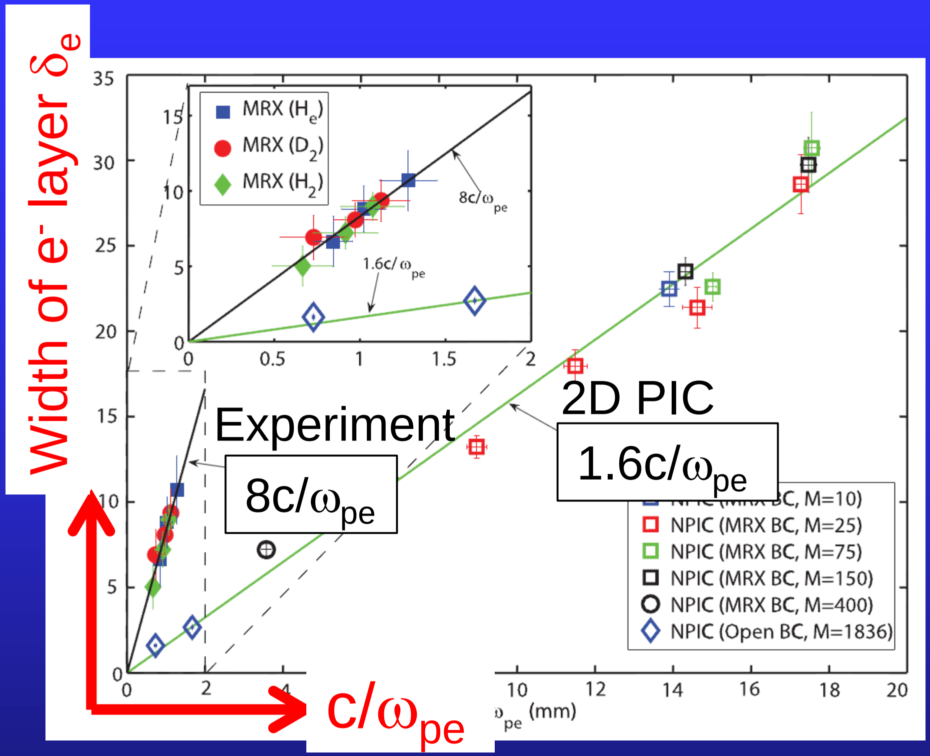
Inertia resistivity limit

Inconsistent with Observations

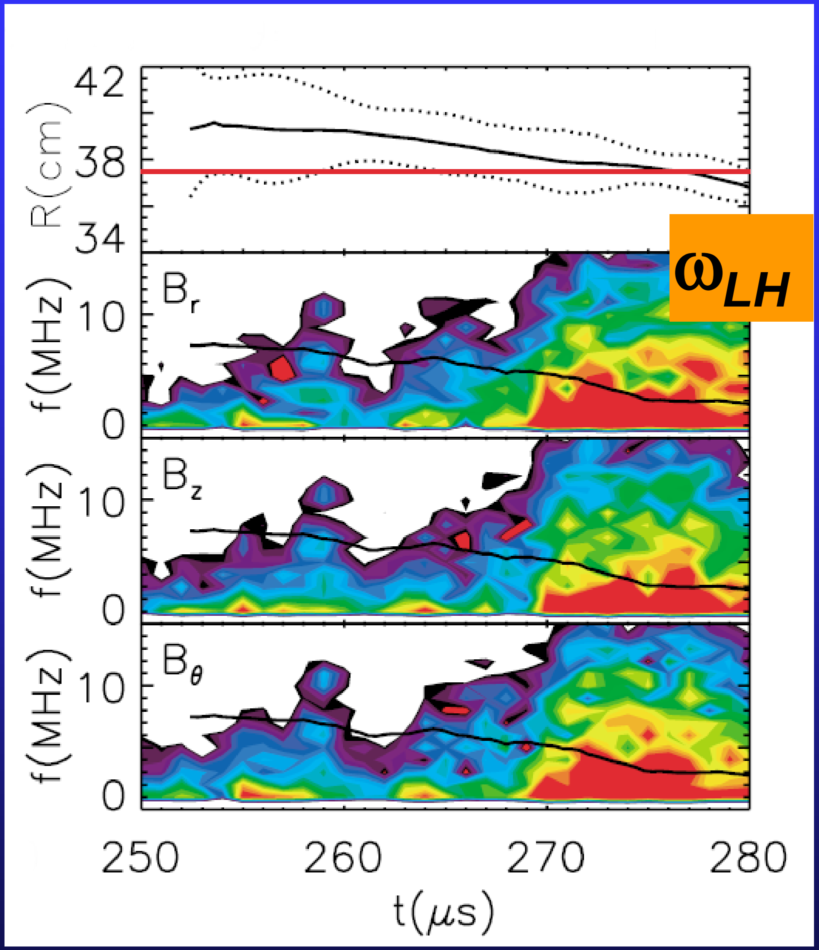
Anomalous dissipation?

3D, Multi scale, Nonlinear, Kinetic ⇒ Large-scale PIC

Laboratory Experiment



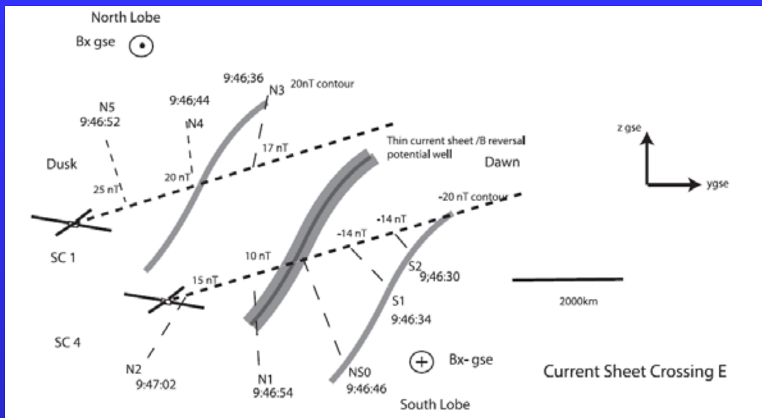
[Ji et al, GRL, 2008]

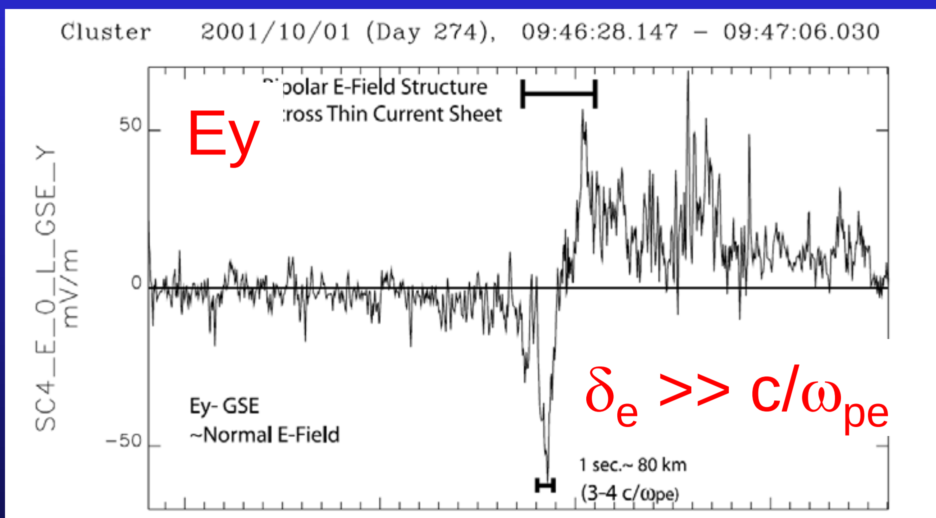


[Ji et al, PRL, 2004]

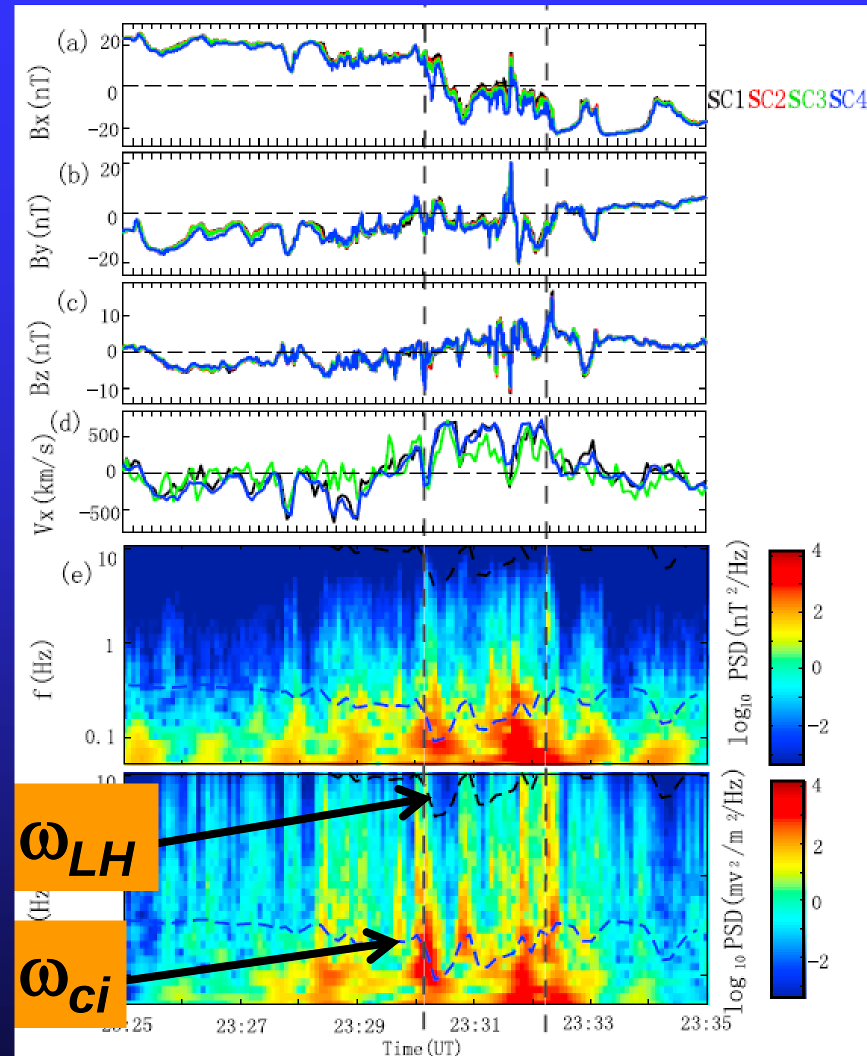
- $\delta_e \gg c/\omega_{pe}$
- Active ω_{LH} waves

Satellite Obs. in Earth's Magnetotail





[Wygant et al, JGR, 2005]



[Zhou et al, JGR, 2009]

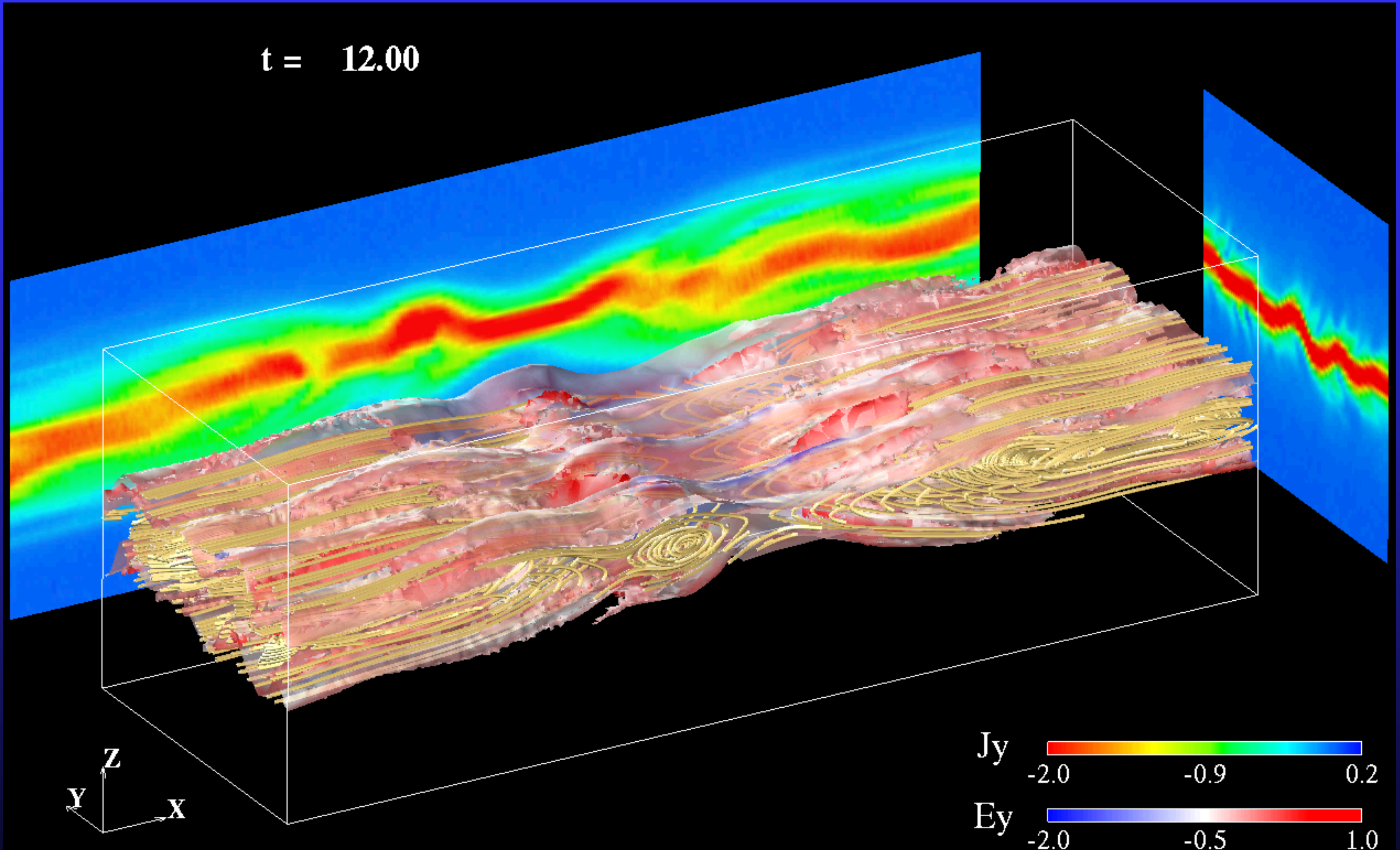
3D AMR-PIC of Anti-Parallel Reconnection

$m_i/m_e = 100$ ~ 10^{11} particles

~ 6 TB memory

Surface: |J|, Line: Field line

Color on the surface: Ey, Cut plane : Jy



[Fujimoto & Sydora, PRL, 2012]

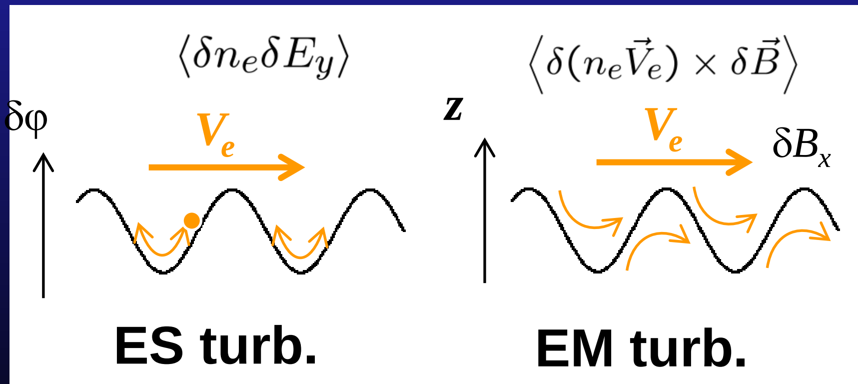
Generalized Ohm's Law

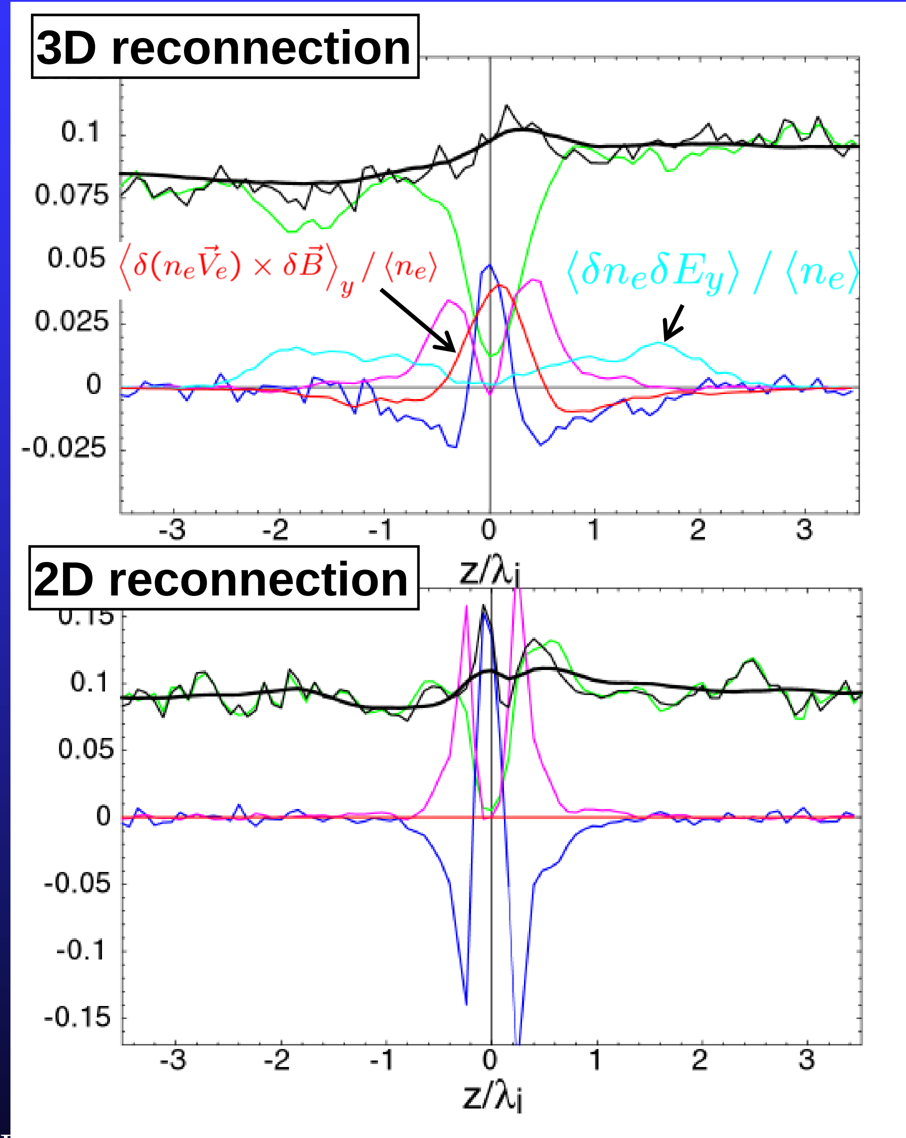
[Fujimoto & Sydora, PRL, 2012]

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

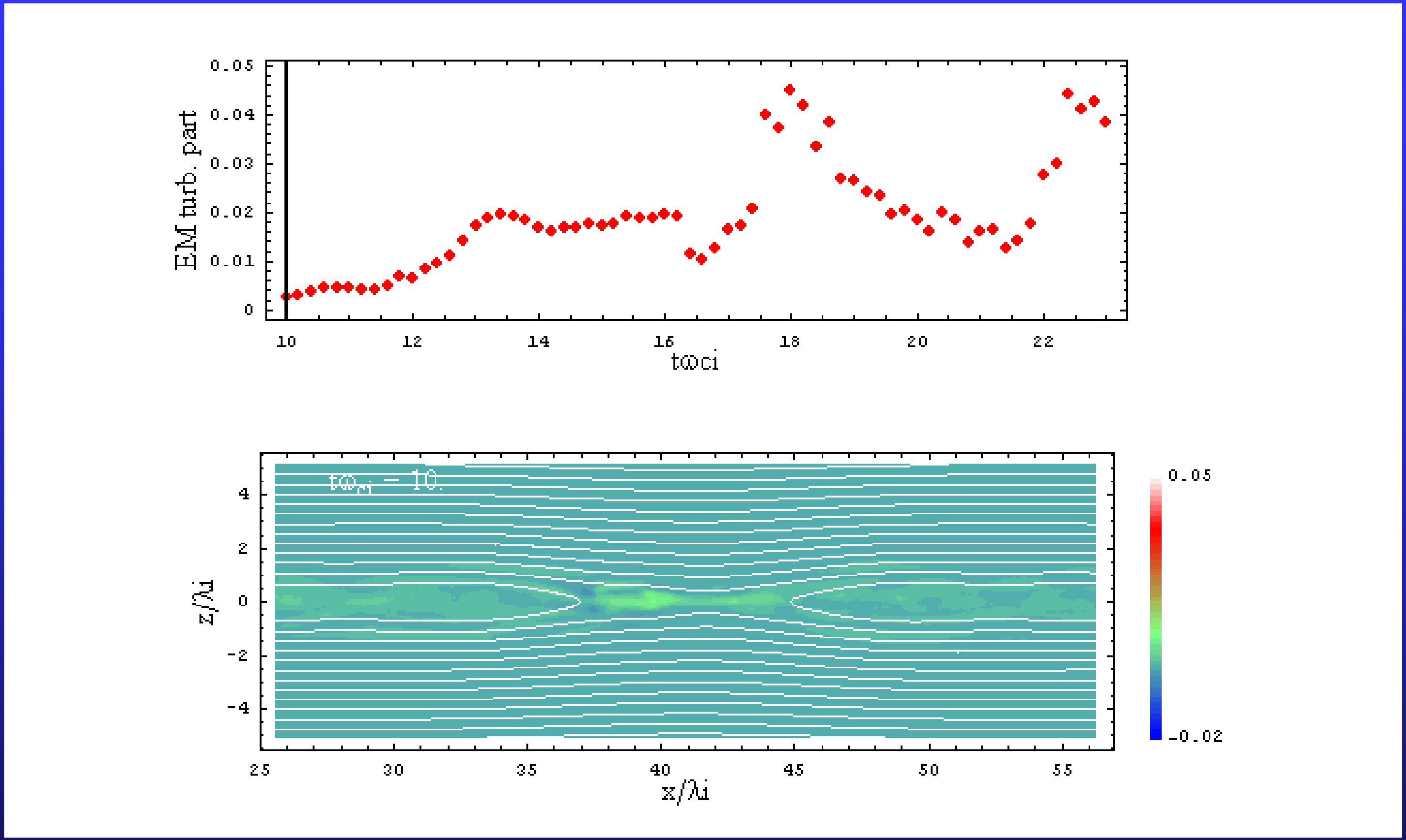
$$\langle -E_y \rangle = \frac{1}{\langle n_e \rangle} \left(\langle n_e \vec{V}_e \rangle \times \langle \vec{B} \rangle \right)_y + \frac{1}{e \langle n_e \rangle} \left\langle \nabla \cdot \vec{P}_e \right\rangle_y + \frac{m_e}{e \langle n_e \rangle} \left\langle \frac{\partial V_{ey}}{\partial t}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

Anomalous effects





Anomalous Transport at the X-line

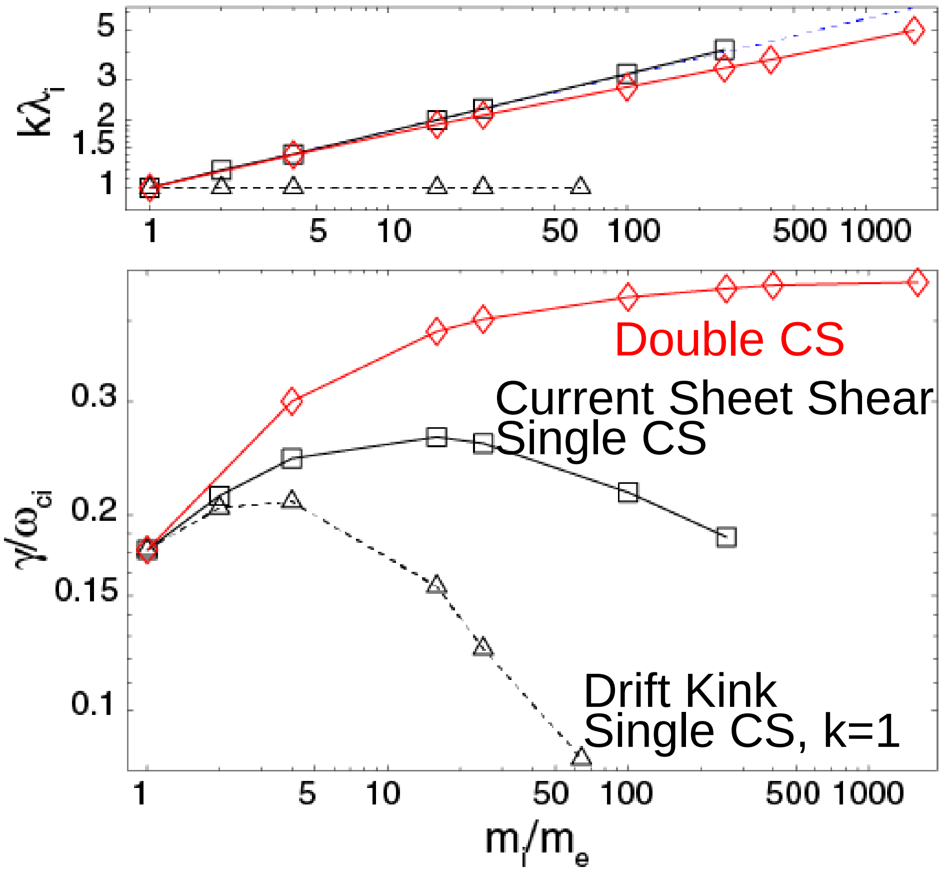


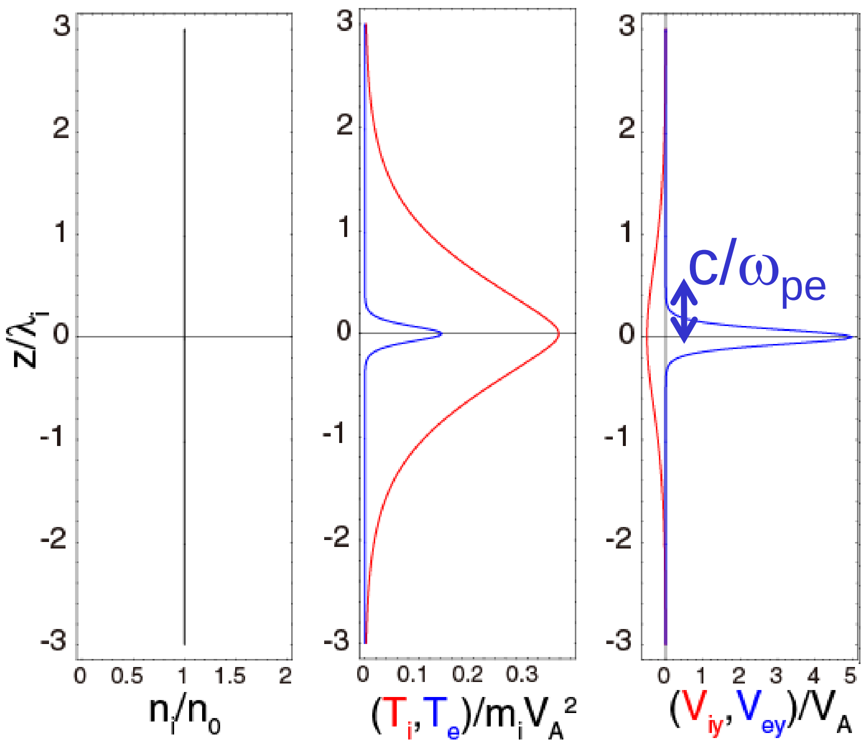
Turbulence is enhanced by plasmoid ejections.

Linear Analyses of the Wave [Fujimoto & Sydora, in prep]

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

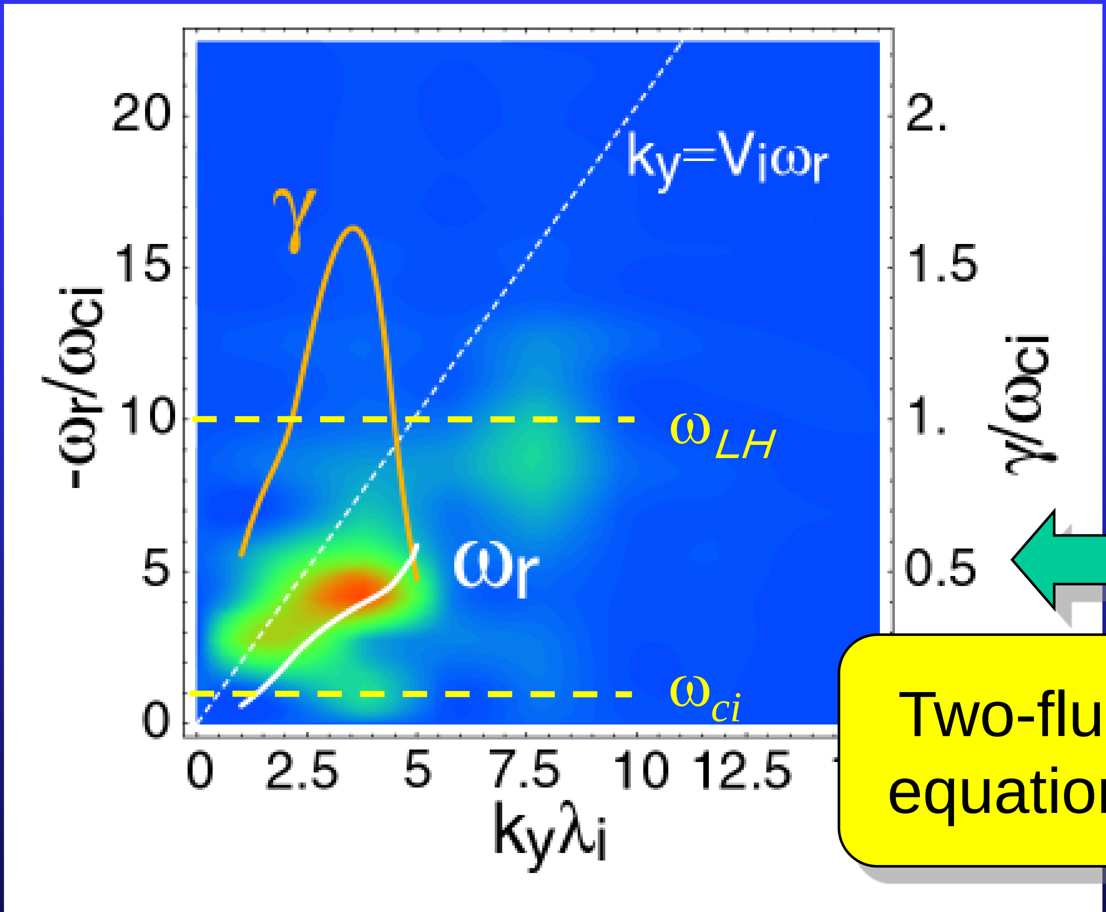
The mode is not the Drift Kink,
not the LHDI,
but the *Current Sheet Shear Inst*.





Comparison with 3D Simulations

$\omega = \omega_r + i\gamma$



Two-fluid equations

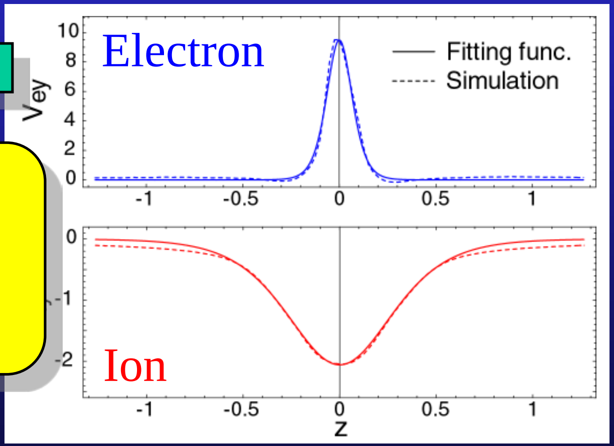
Simulation results

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

$$V_{ph} \approx V_A$$

Linear analyses

Profiles taken from simulation



Summary

- Adaptive mesh refinement (AMR) has been implemented in the electromagnetic particle-in-cell (PIC) model to achieve large-scale simulations of magnetic reconnection.

- The AMR-PIC simulations indicate that the dissipation process of collisionless reconnection is three dimensional. The current sheet shear instability is dominant around the x-line. The turbulence is enhanced by the plasmoid ejections.