PIC Simulation of Magnetic Reconnection with Adaptive Mesh Refinement

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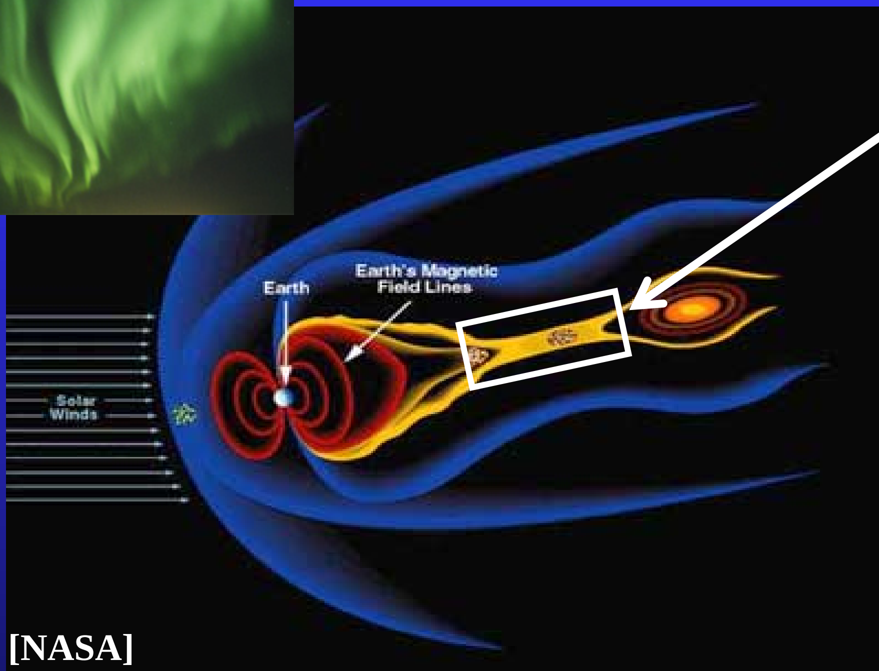
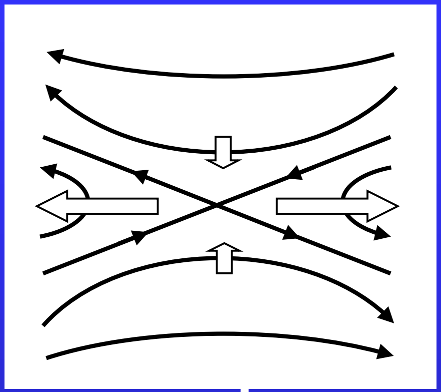
Overview

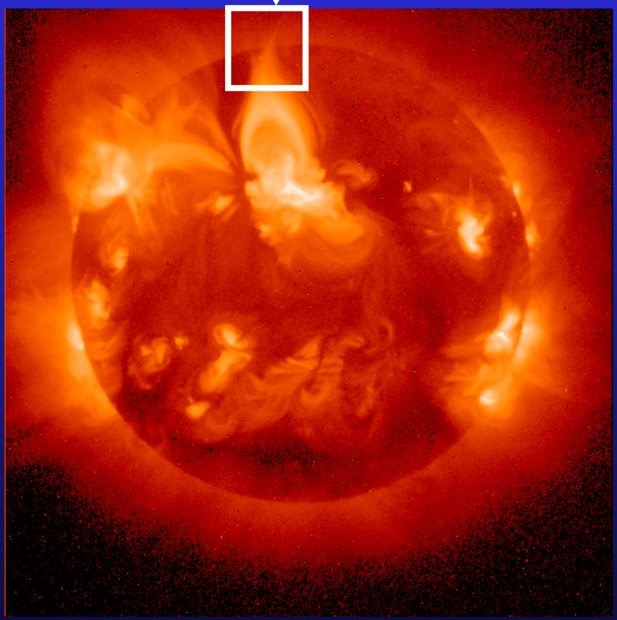
- Introduction
- Particle-in-Cell (PIC) model with adaptive mesh refinement (AMR)
- Wave activities in the reconnection region
    - Electrostatic solitary waves (ESWs)
    - Whistler waves
    - EM waves around the x-line
- Summary

Magnetic Reconnection in Space

Auroral Substorms

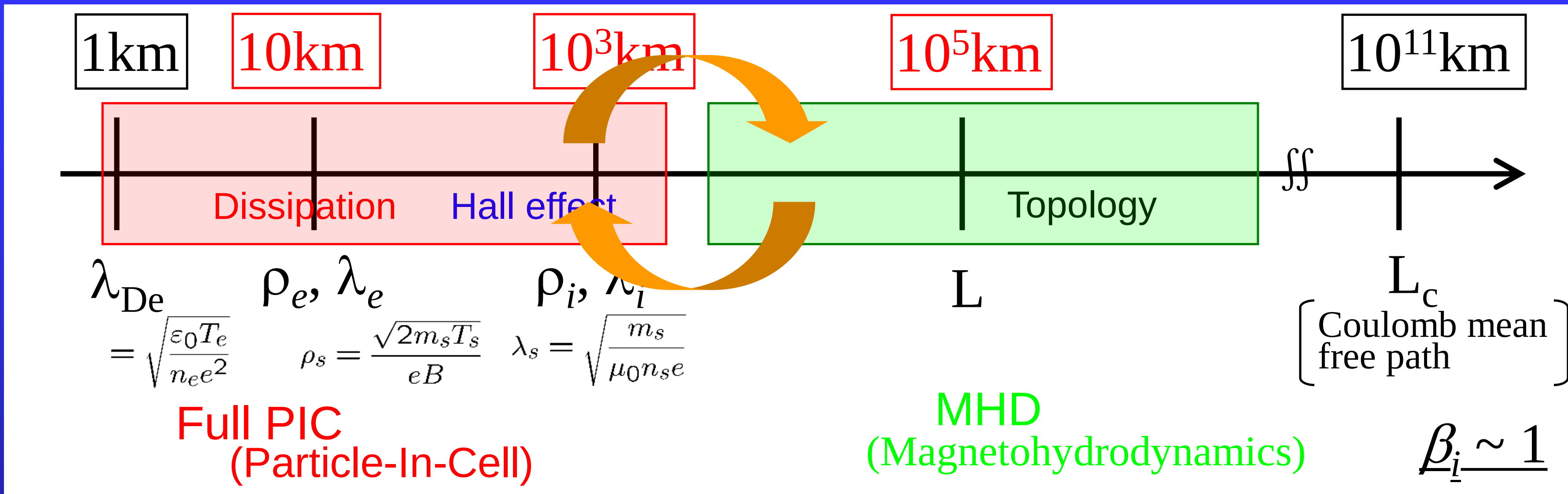


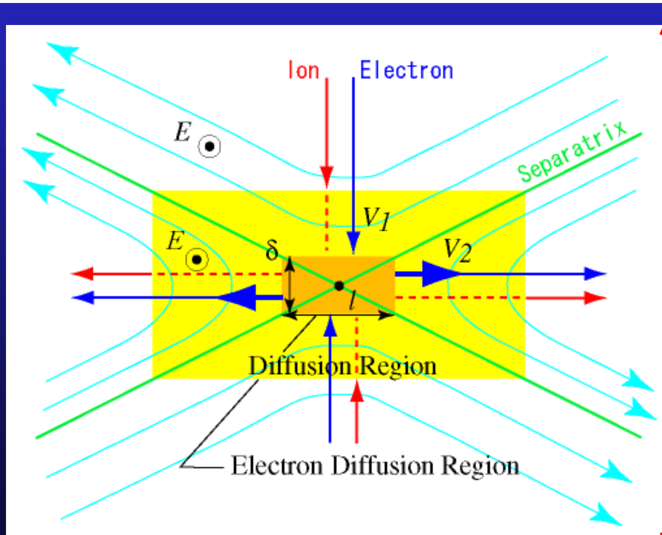


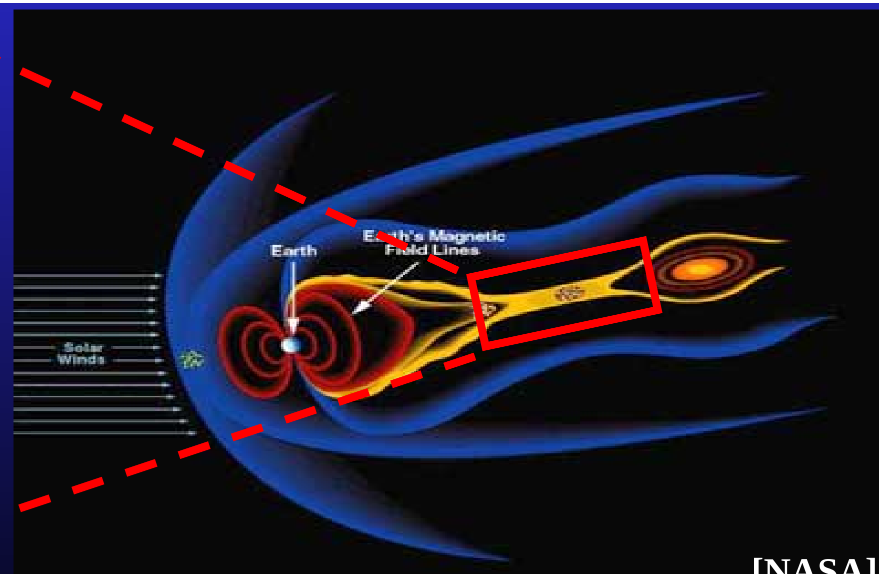


Solar Flares

Multi-Scale Nature of Reconnection

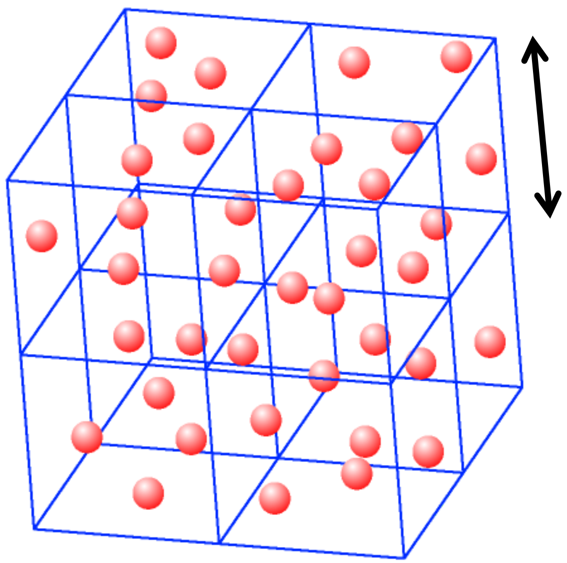






[NASA]

Restrictions of Explicit PIC Model



Cell size

$\Delta x \lesssim 3\lambda_{De}$ $\quad \lambda_{D_e} = \sqrt{\frac{\varepsilon_0 T_e}{n_e e^2}}$

Num of particles per cell

$N_p \gtrsim 10^2$

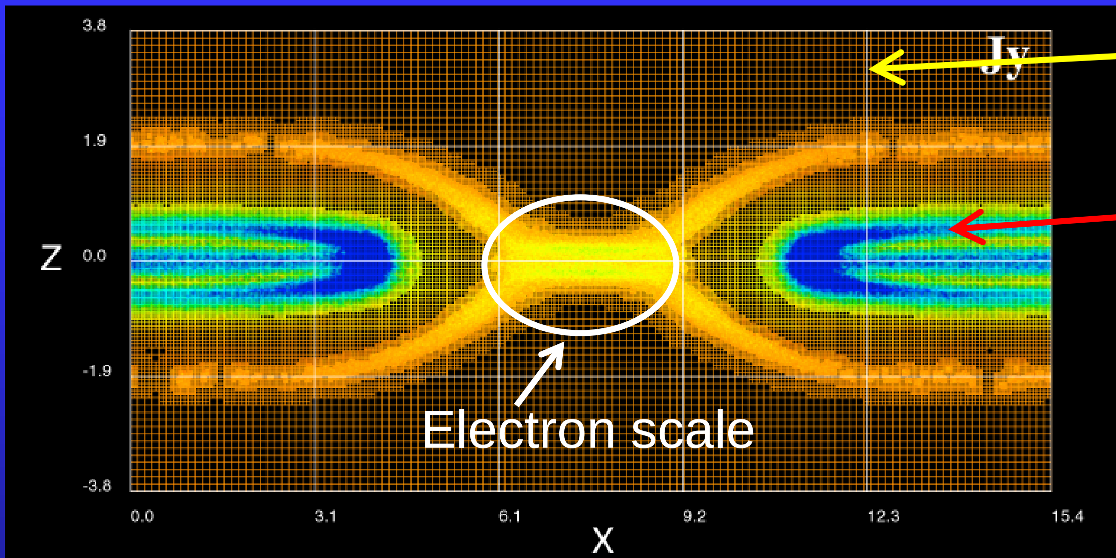
Memory requirement per cell

Field (n_s, J_s, E, B) 14×4 Byte	<<	Particle (x_s, v_s) $(12 \times 4$ Byte$) \times 10^2$

AMR-PIC Model [Fujimoto, JCP, 2011]

(Adaptive Mesh Refinement – Particle-in-Cell)

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

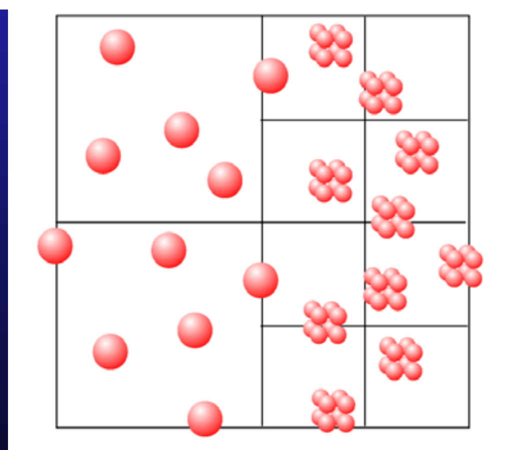


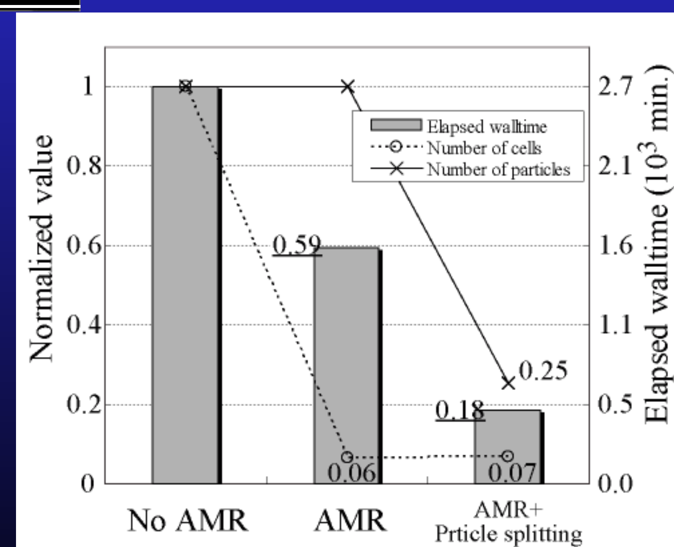
$\lambda_{De,lobe} \sim 6 \times 10^3$ m

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

Removing unnecessary cells.

Particle splitting-coalescence





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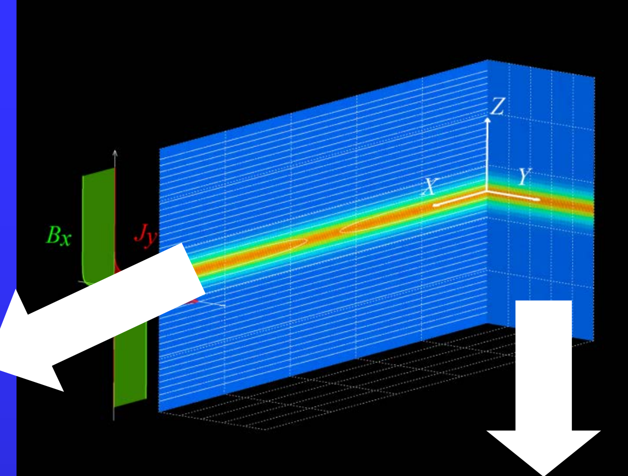
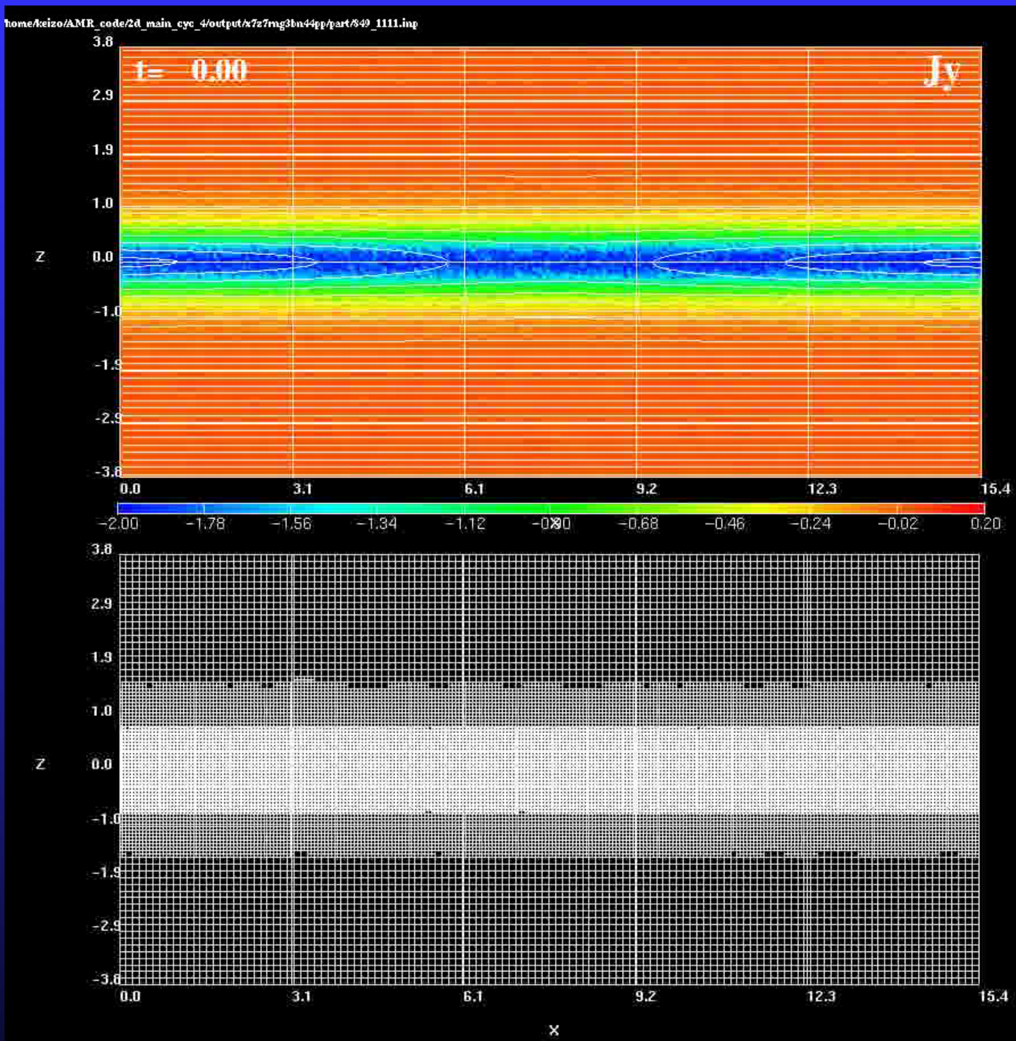
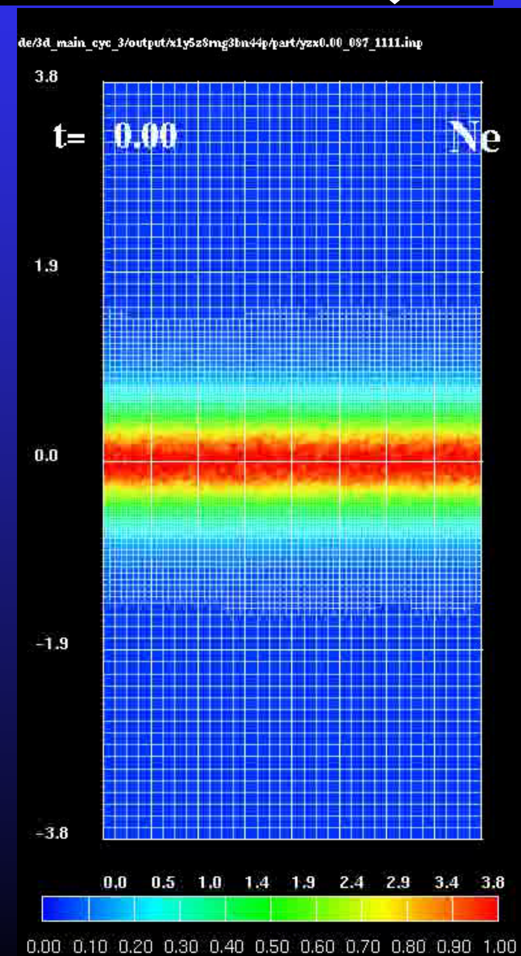
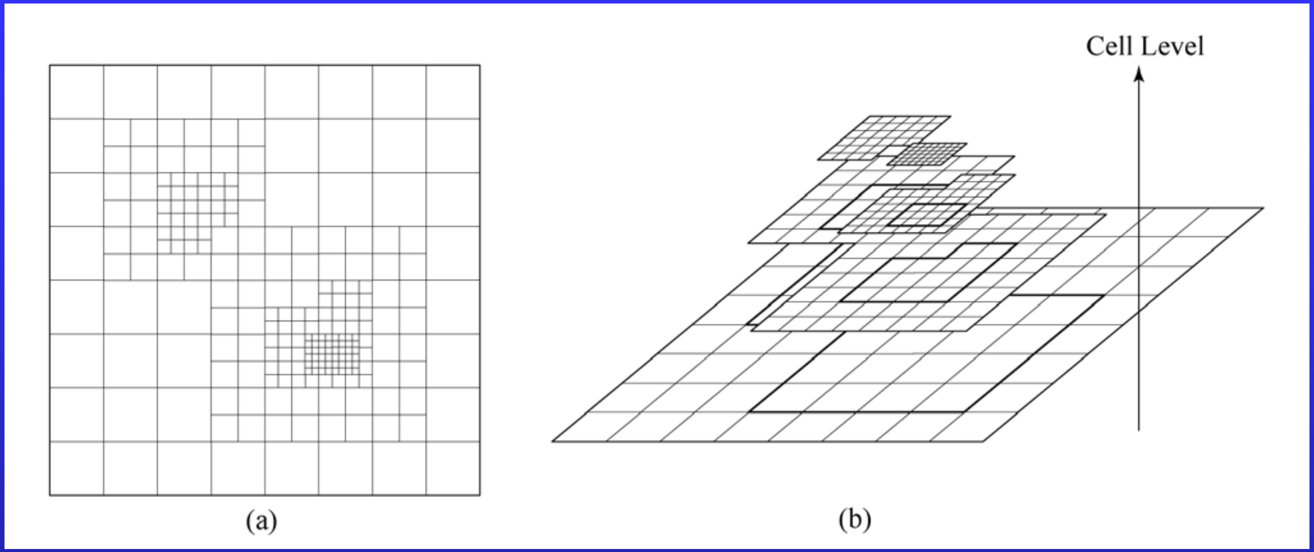
AMR-PIC Simulations





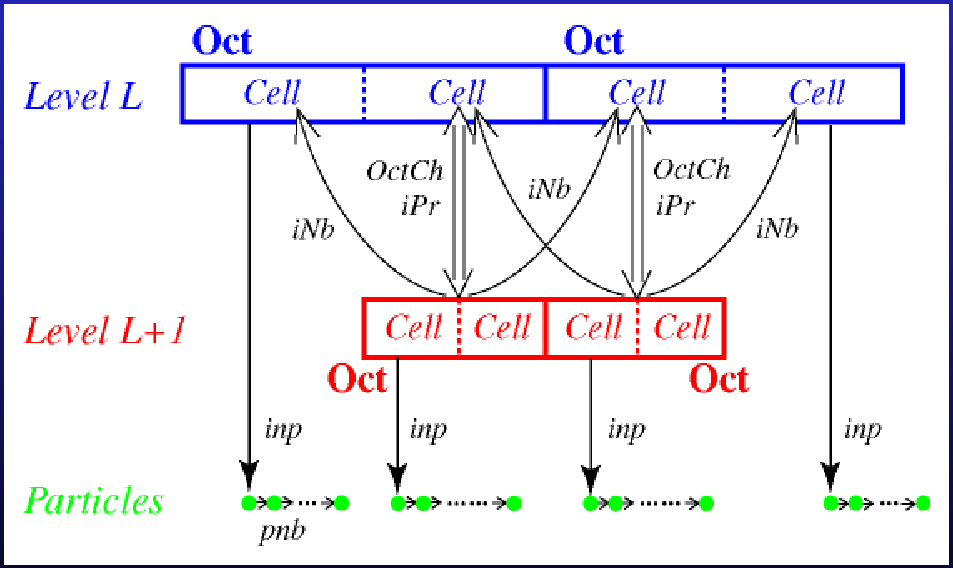


Data Structure



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

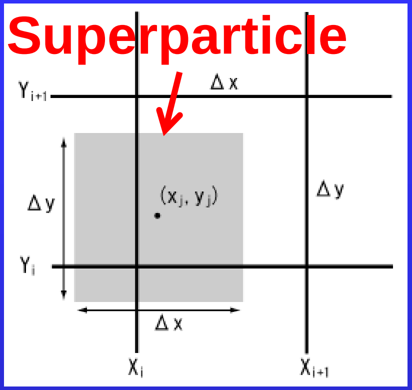
[Fujimoto & Machida, JCP, 2006]



Basic Equations

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

S: Shape function



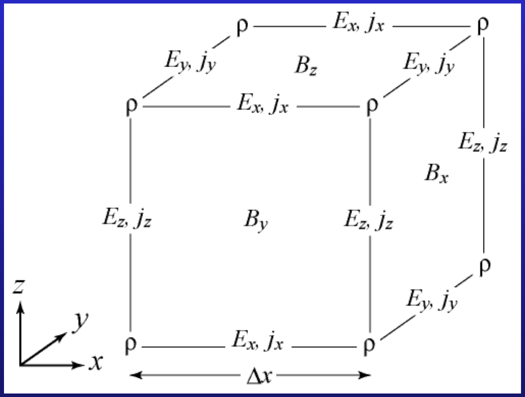
- Superparticles (Buneman-Boris method)

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

- EM Field (Yee-Buneman scheme)

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

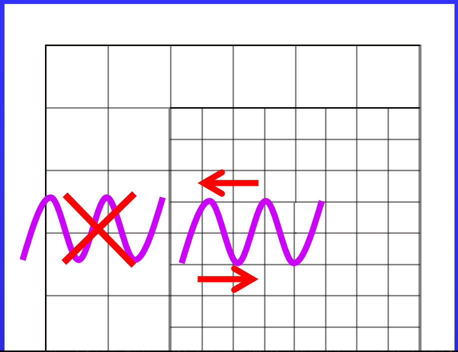
Charge Conservation Method
[Villasenor & Buneman, 1992]



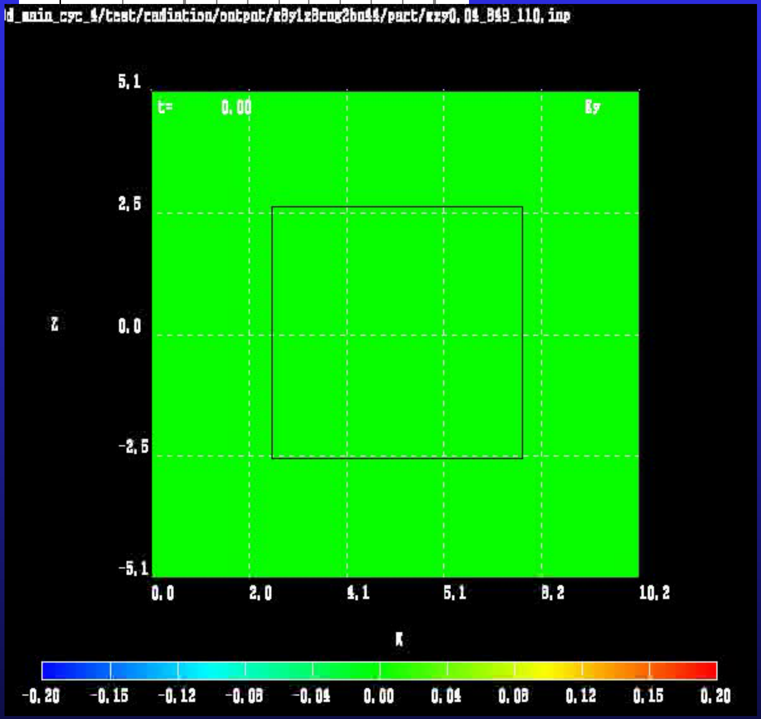
○ Local operations ➡ Facilitate parallel computing

× No numerical damping for any wave numbers!

Radiation of EM Waves

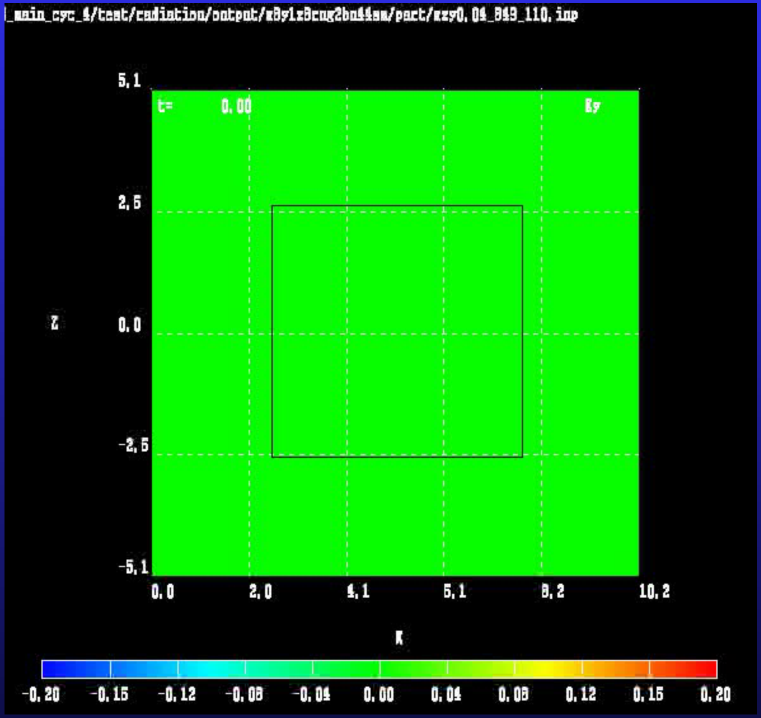


$$A_{SM,j} = f_{SM}(A_j) = \frac{\alpha A_{j-1} + A_j + \alpha A_{j+1}}{1+2\alpha}$$
$$(\alpha = 0.002)$$



$E_{SM}=f_{SM}(E)$

$B_{SM}=f_{SM}(B)$



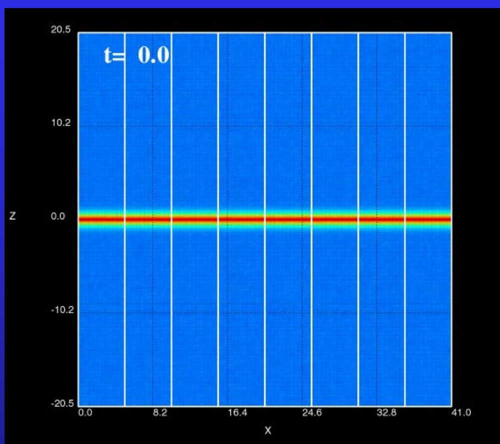
Load Balancing

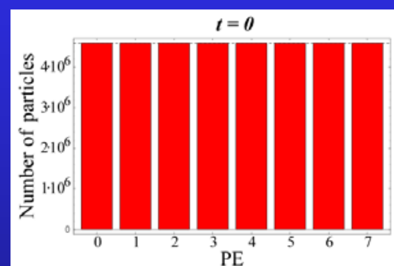
* Block = Decomposition domain

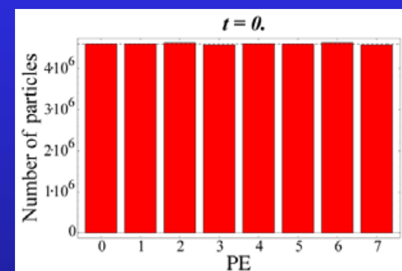
Example using 8 nodes

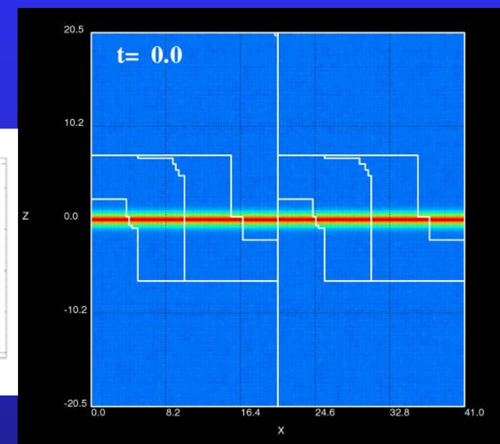
Fixed block case

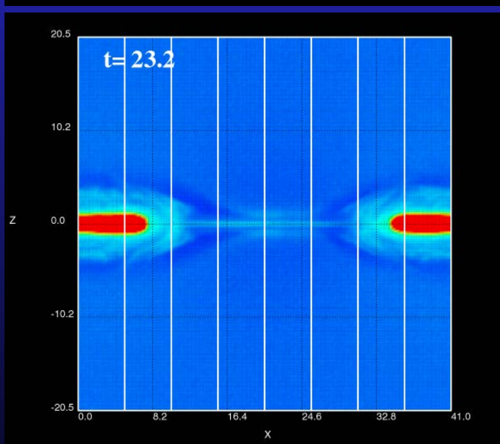
Adaptive block case

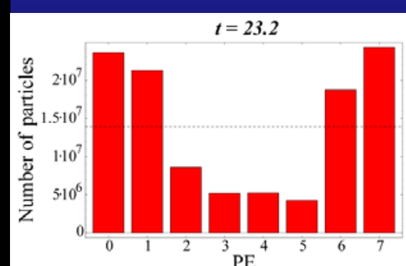


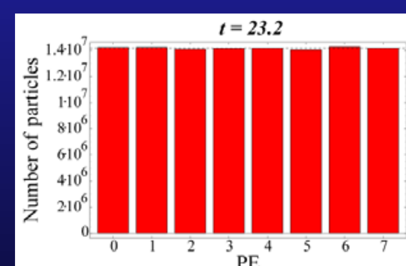


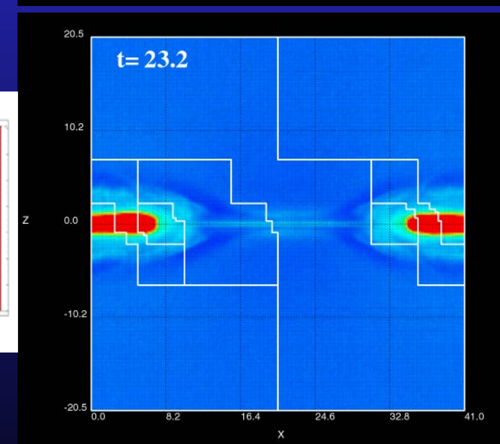








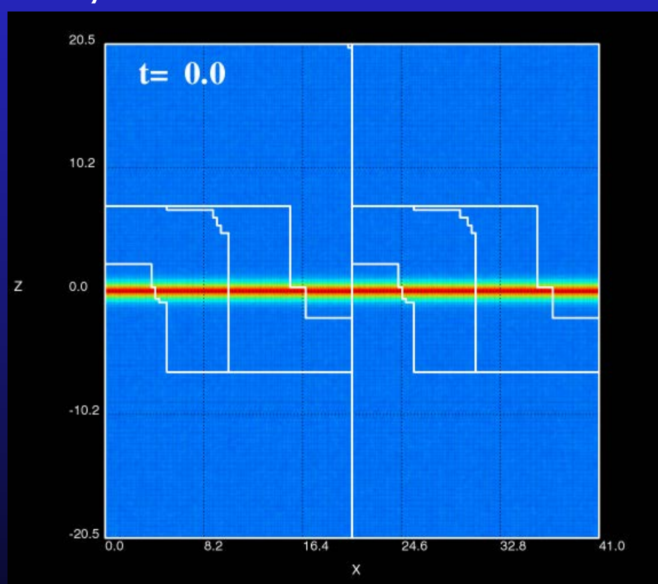


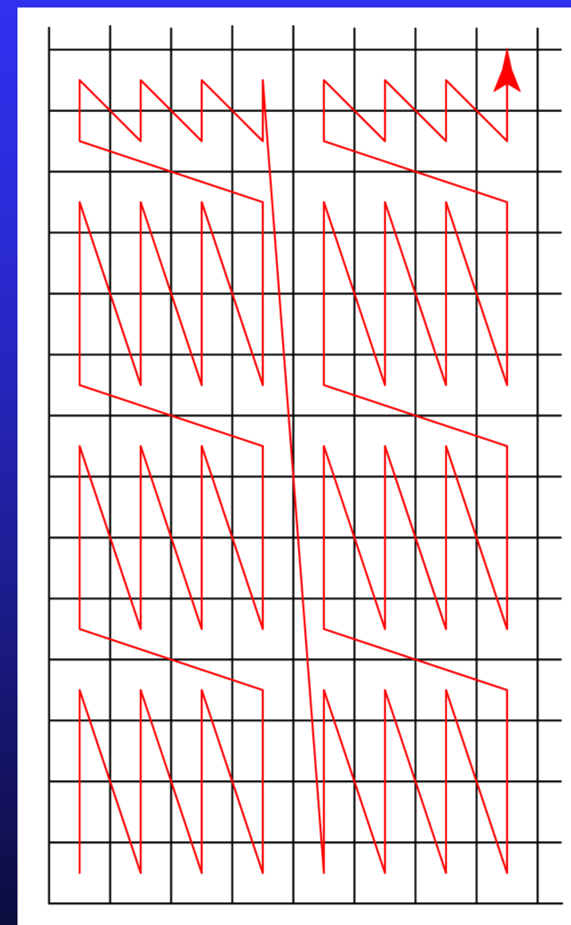


Adaptive Block Technique [Fujimoto, JCP, 2011]

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]

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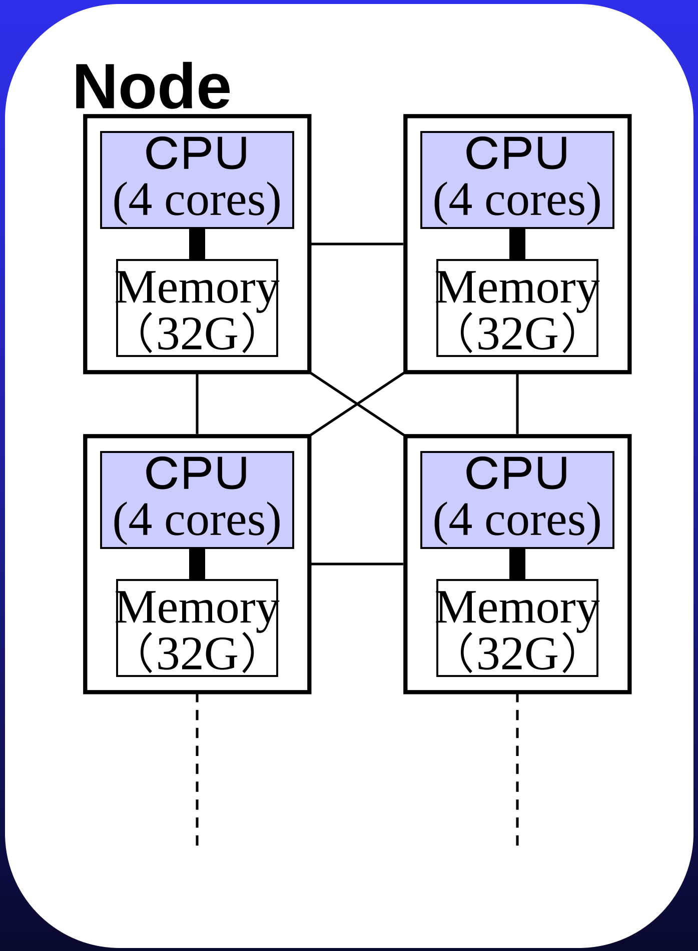
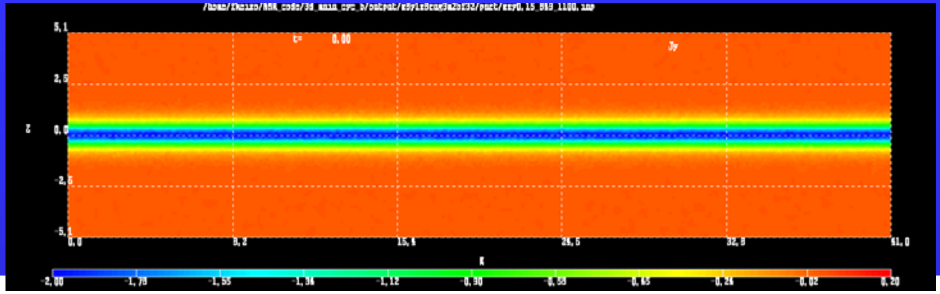
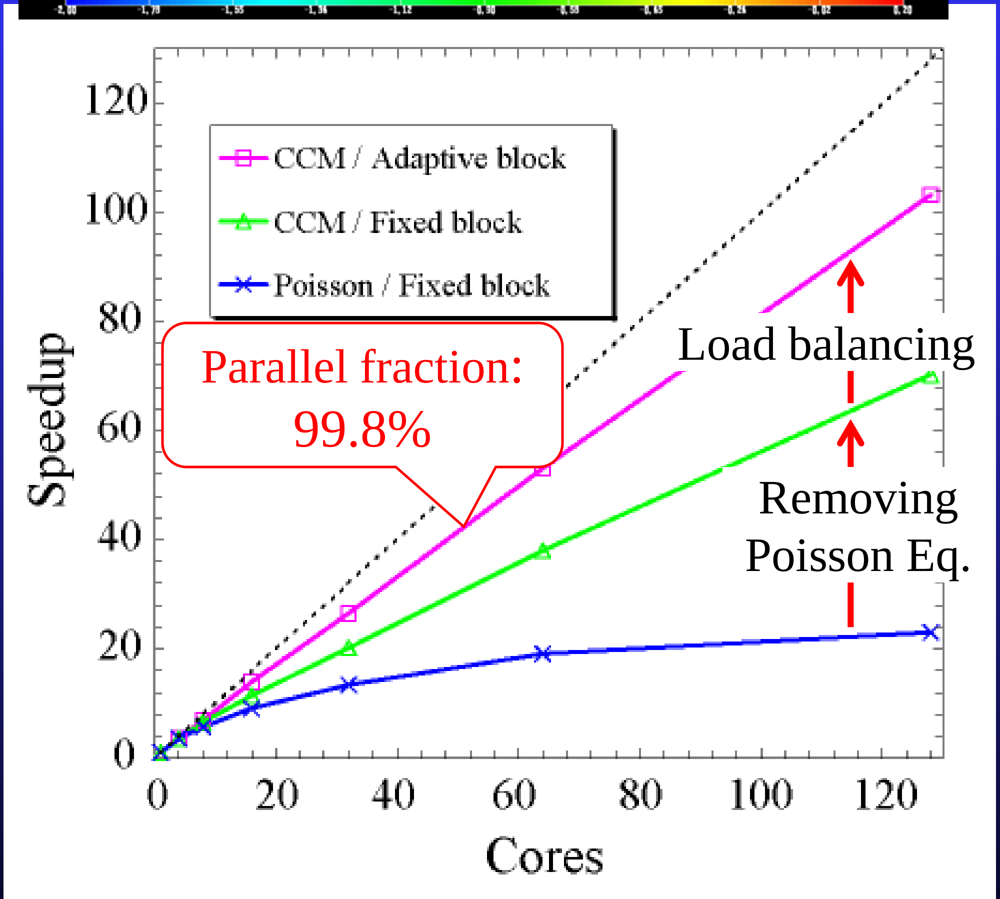
@Nagaya Univ.

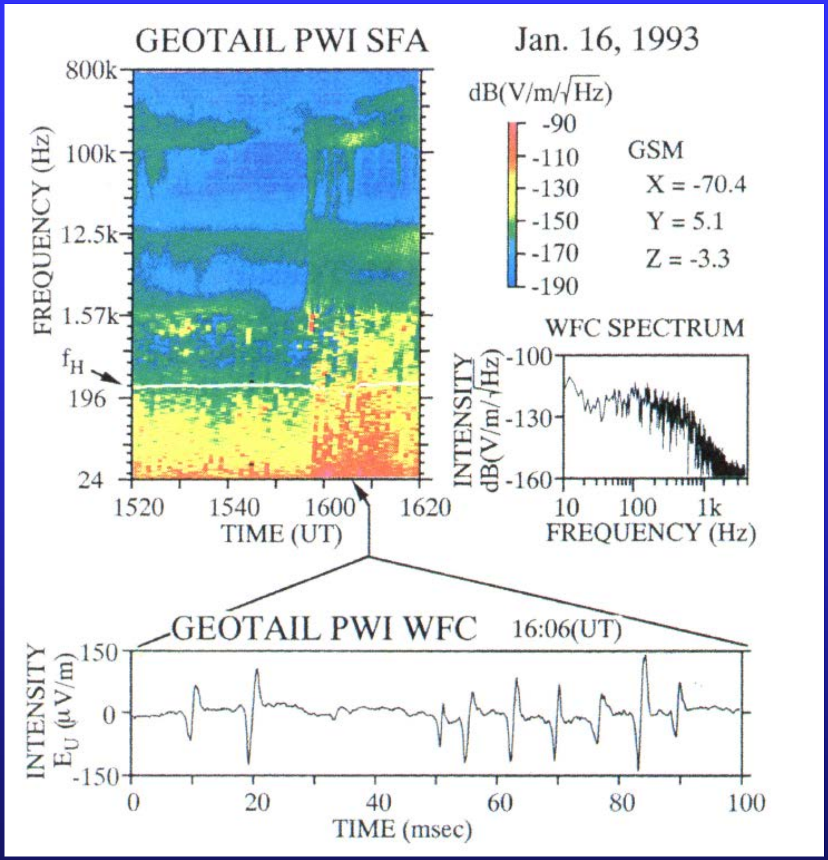






Examples of the AMR-PIC simulation:
Wave activities in the reconnection region

Electrostatic Solitary Wave (ESW)

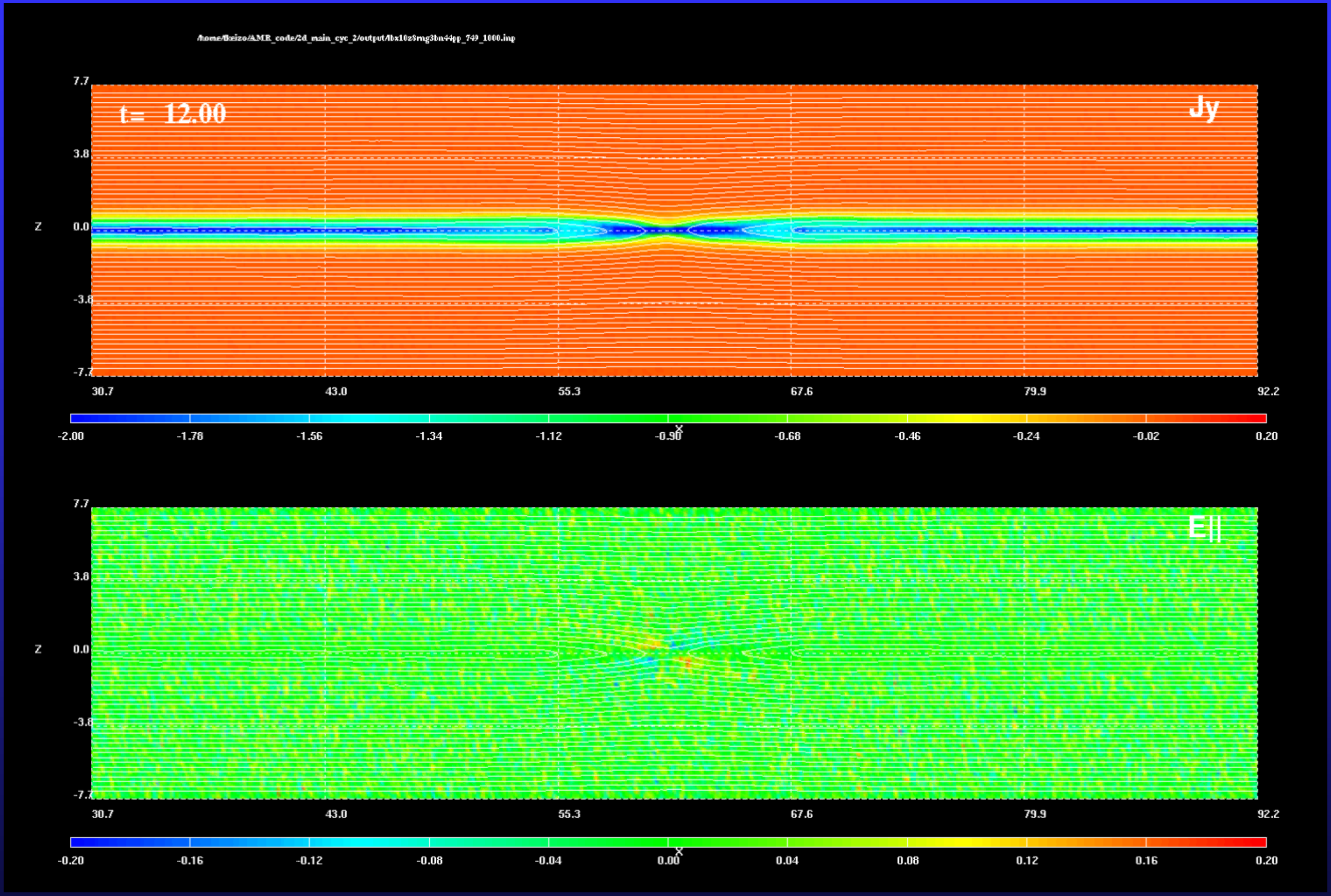


[Matsumoto et al., GRL, 1994]

- ESWs are often observed in the PSBL in the Earth magnetotail (Matsumoto et al., 1994).
- Magnetic reconnection is closely related to the generation of the ESWs (Deng et al, 2004; Cattell et al., 2005; Viberg et al., 2013).

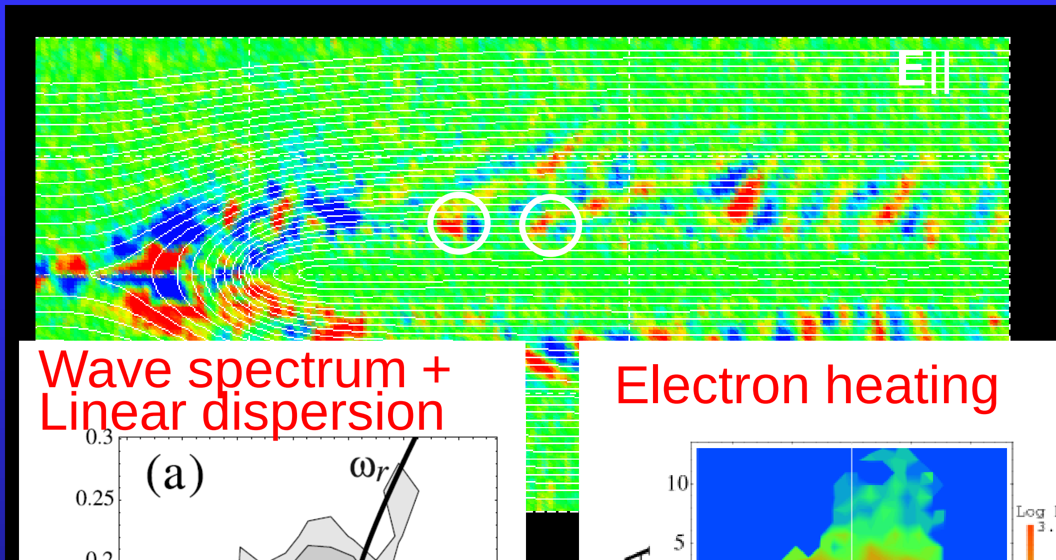
Electrostatic Solitary Wave (ESW)

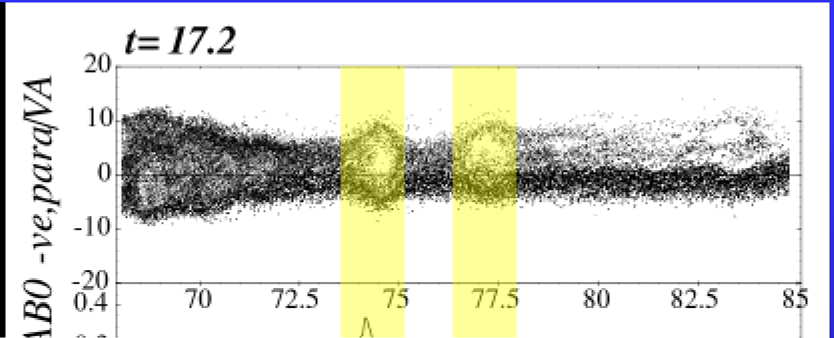
[Fujimoto & Machida, JGR, 2006]



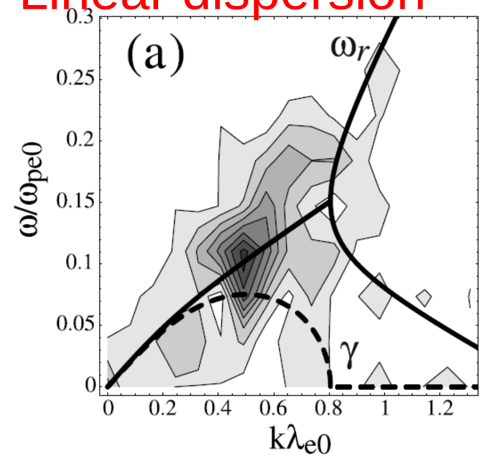
Electrostatic Solitary Wave (ESW)

[Fujimoto & Machida, JGR, 2006]

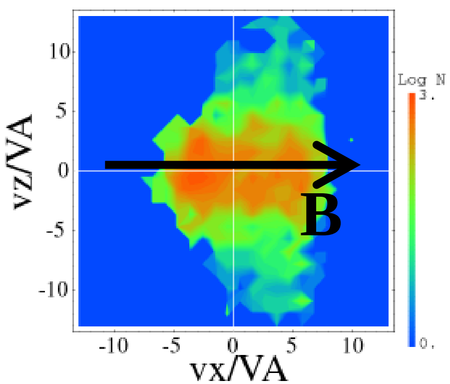


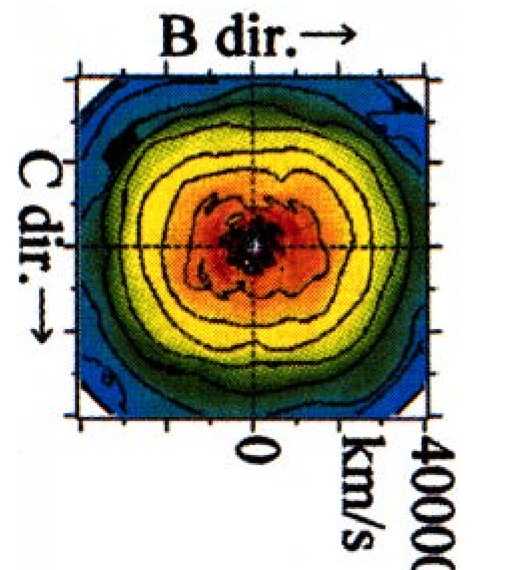


Wave spectrum + Linear dispersion



Electron heating





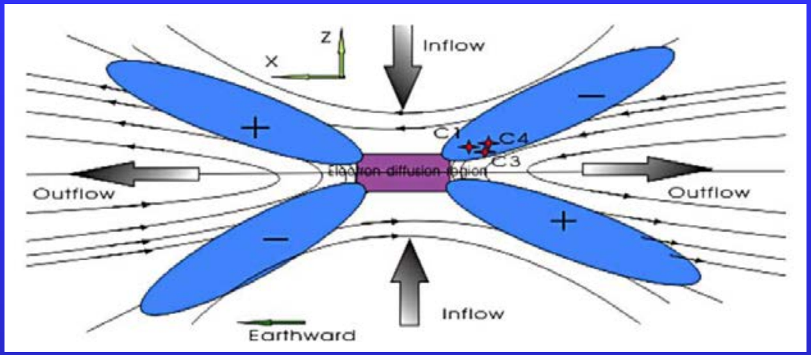
Electron 2-stream instab[...] rather than Buneman.

Consistent with observations.

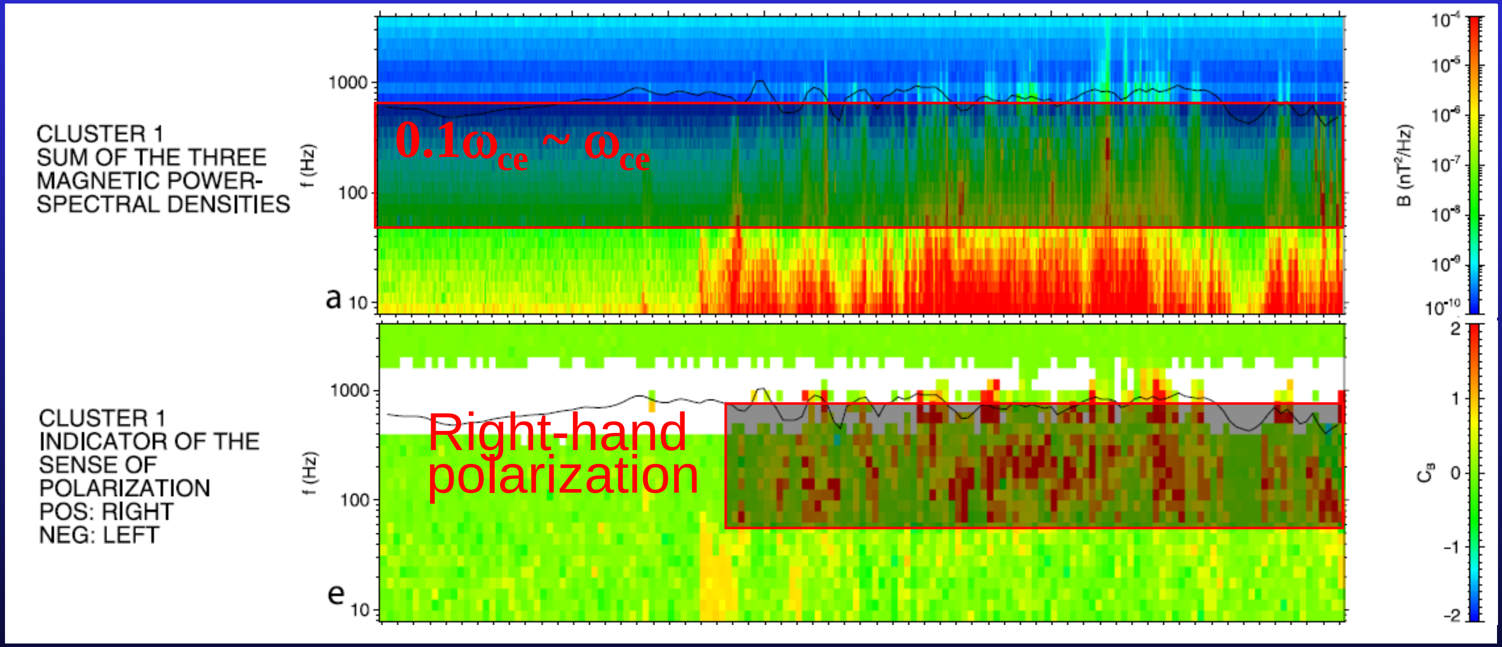
[Shinohara et al., 1998]

Whistler Waves

Cluster observations [Wei et al., JGR, 2007]

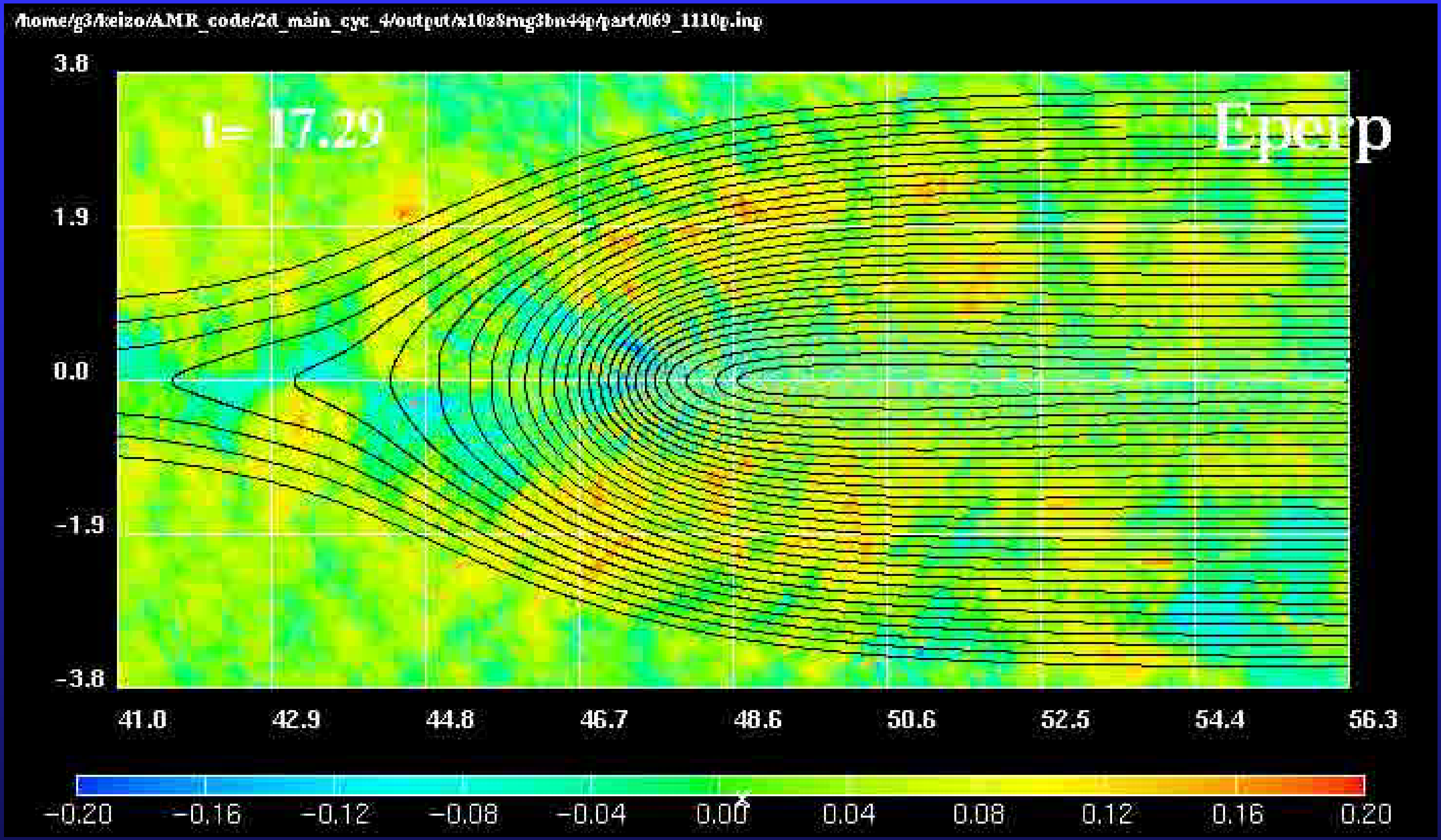


- High frequency waves with $0.1\omega_{ce} \sim \omega_{ce}$.
- Right-hand polarizartion



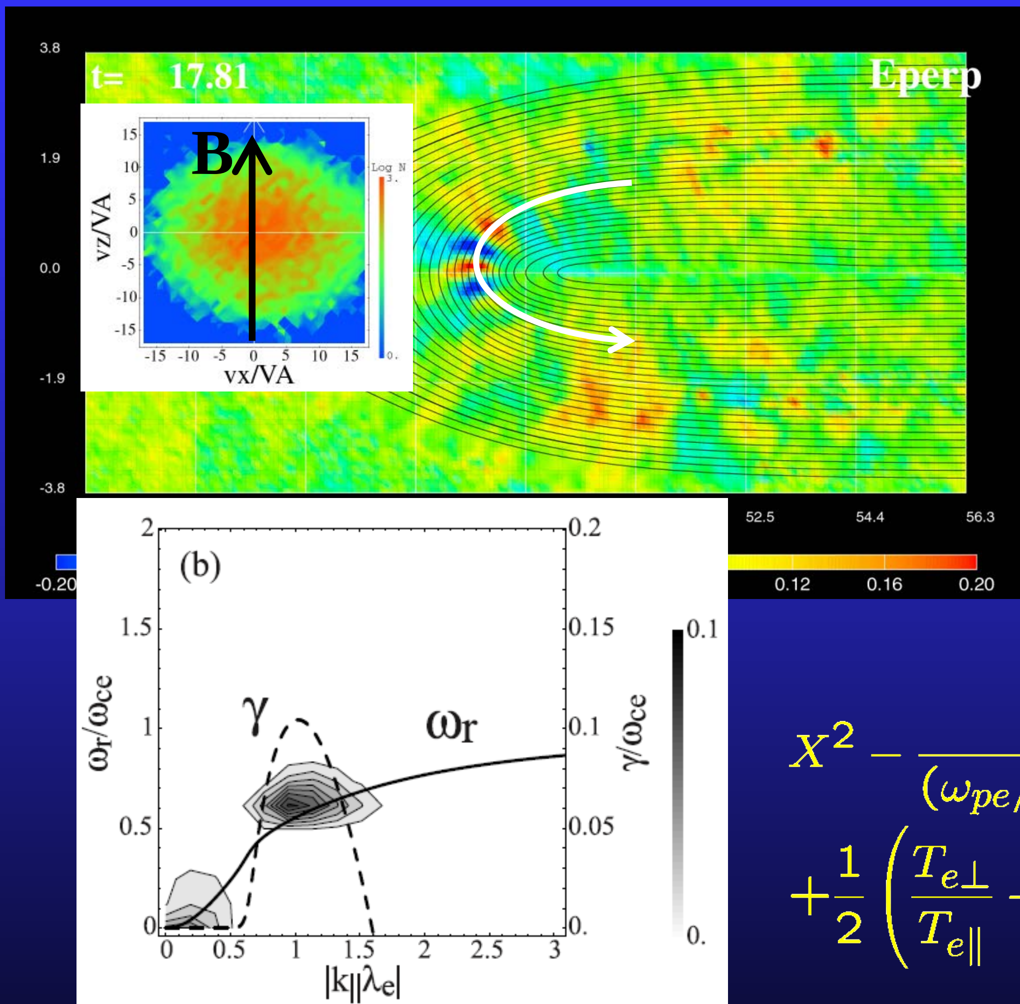
Whistler Waves [Fujimoto & Sydora, GRL, 2008]

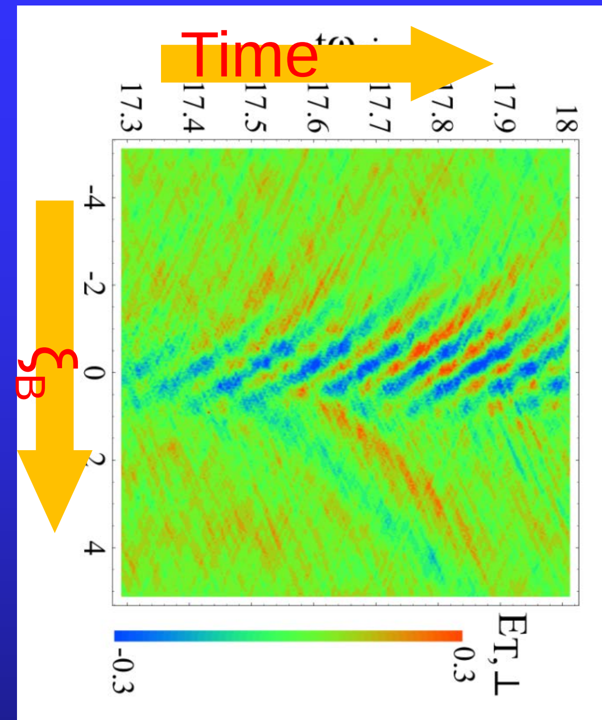
Transverse $E_{||}$



Whistler Waves

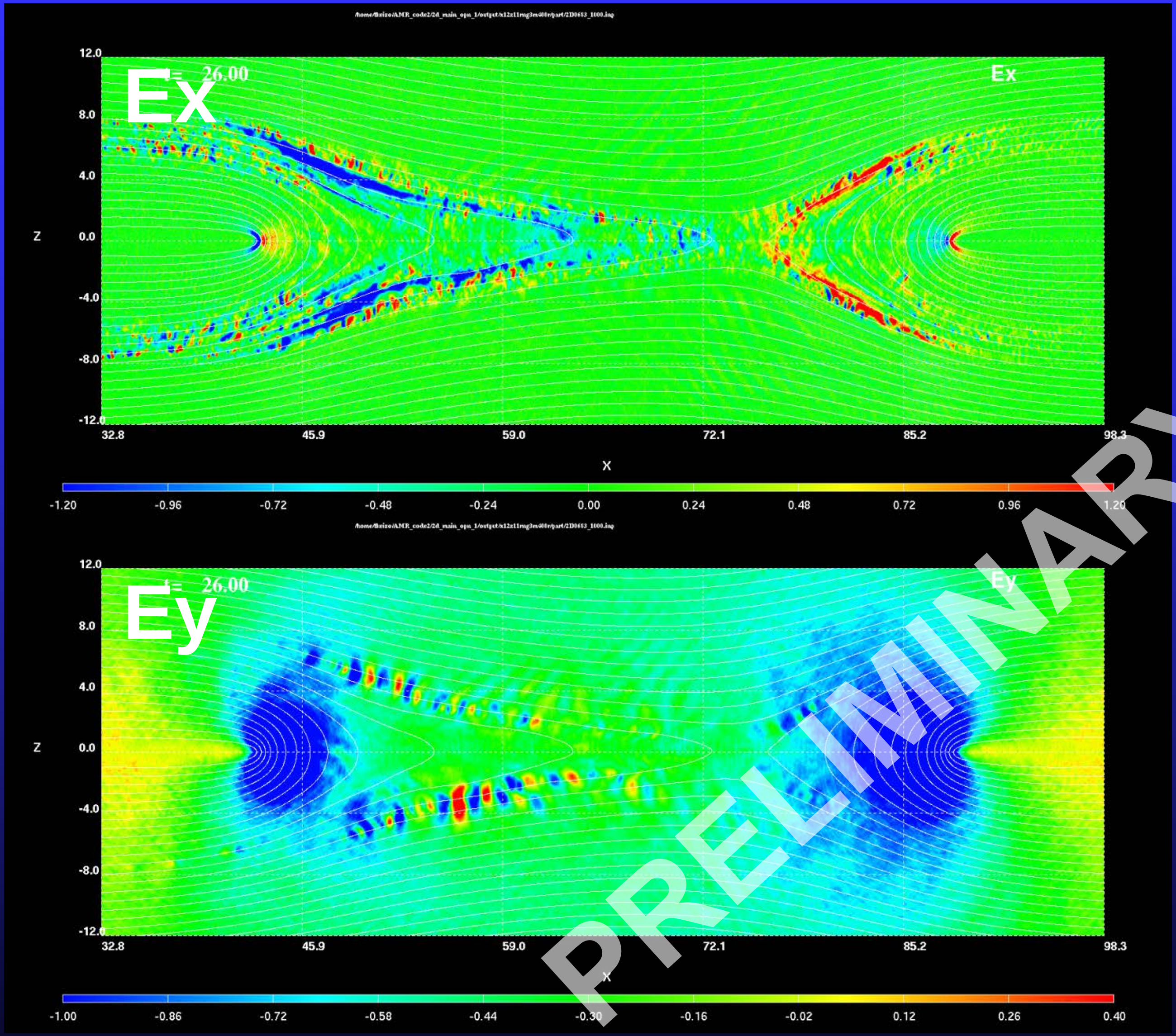
[Fujimoto & Sydora, GRL, 2008]



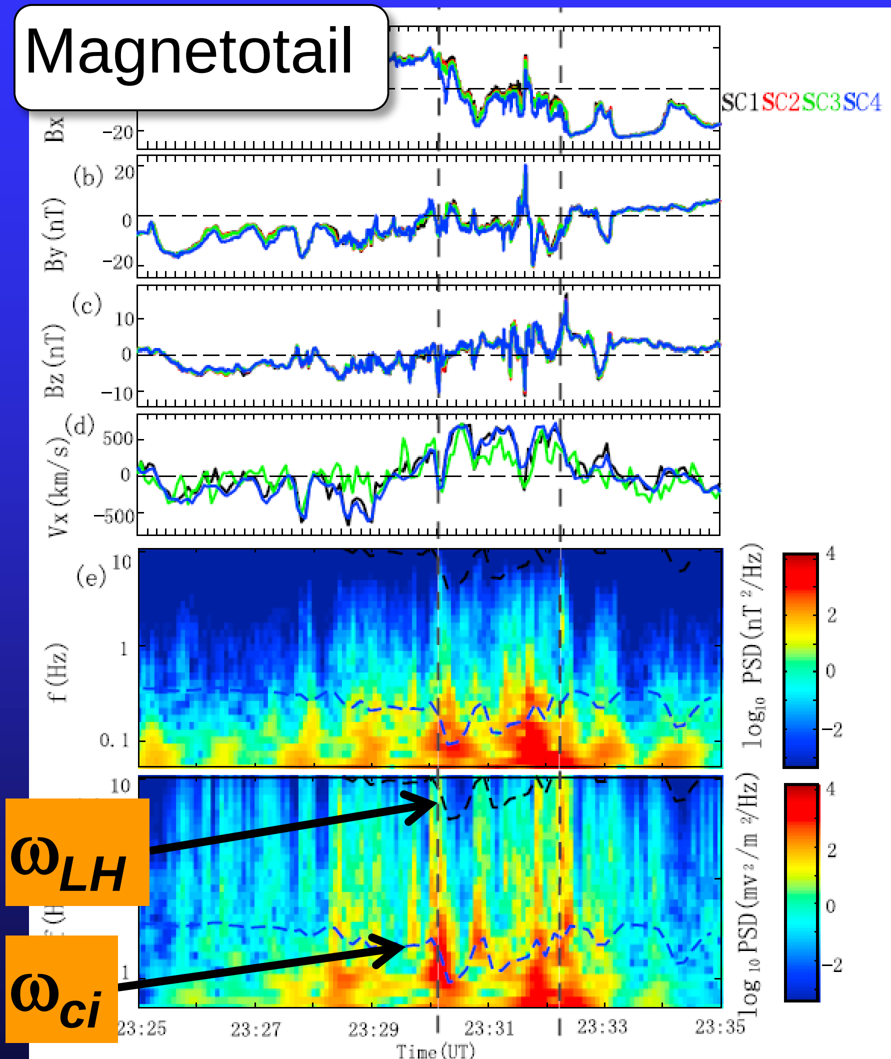


$$X^2 - \frac{1}{(\omega_{pe}/\omega_{ce})^2}Y^2 - \frac{Y}{X\sqrt{\beta_e}}Z(\xi) + \frac{1}{2}\left(\frac{T_{e\perp}}{T_{e\parallel}} - 1\right) Z'(\xi) = 0$$

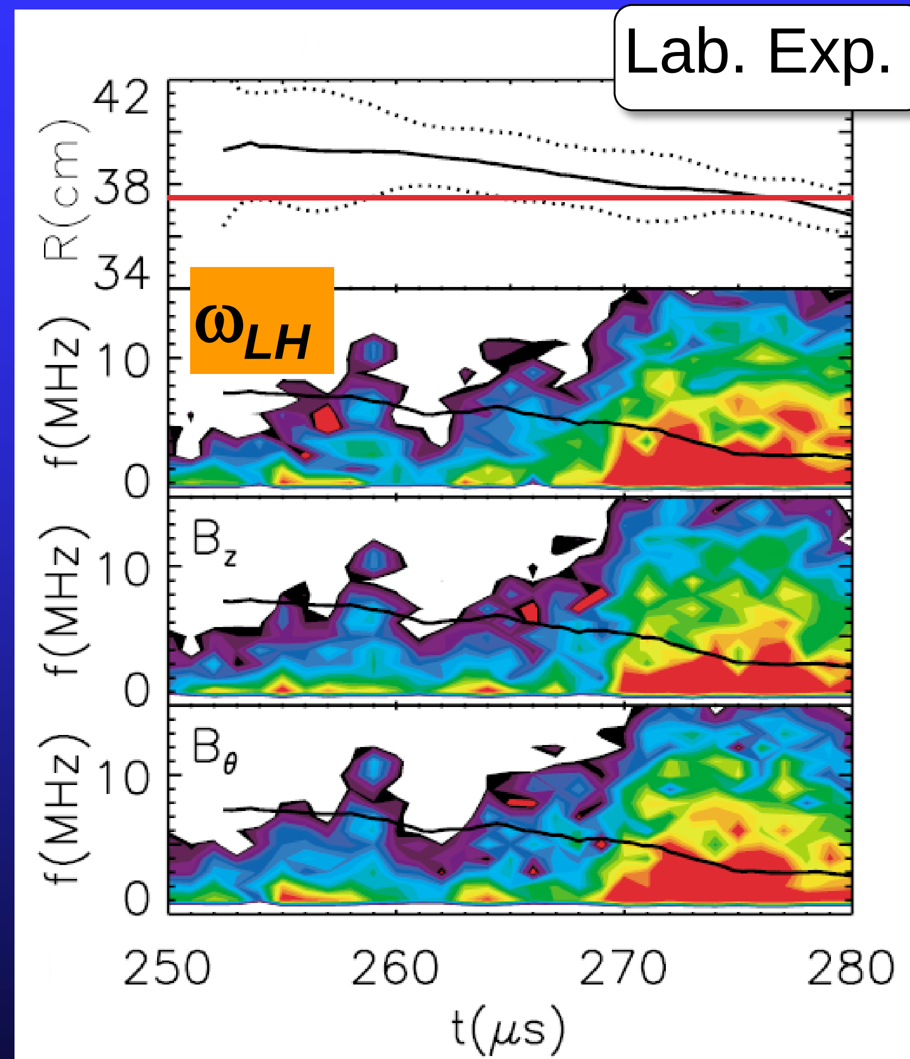
Wave Activities in Separatrix Region



EM Waves near the X-line



[Zhou et al, JGR, 2009]



[Ji et al, PRL, 2004]

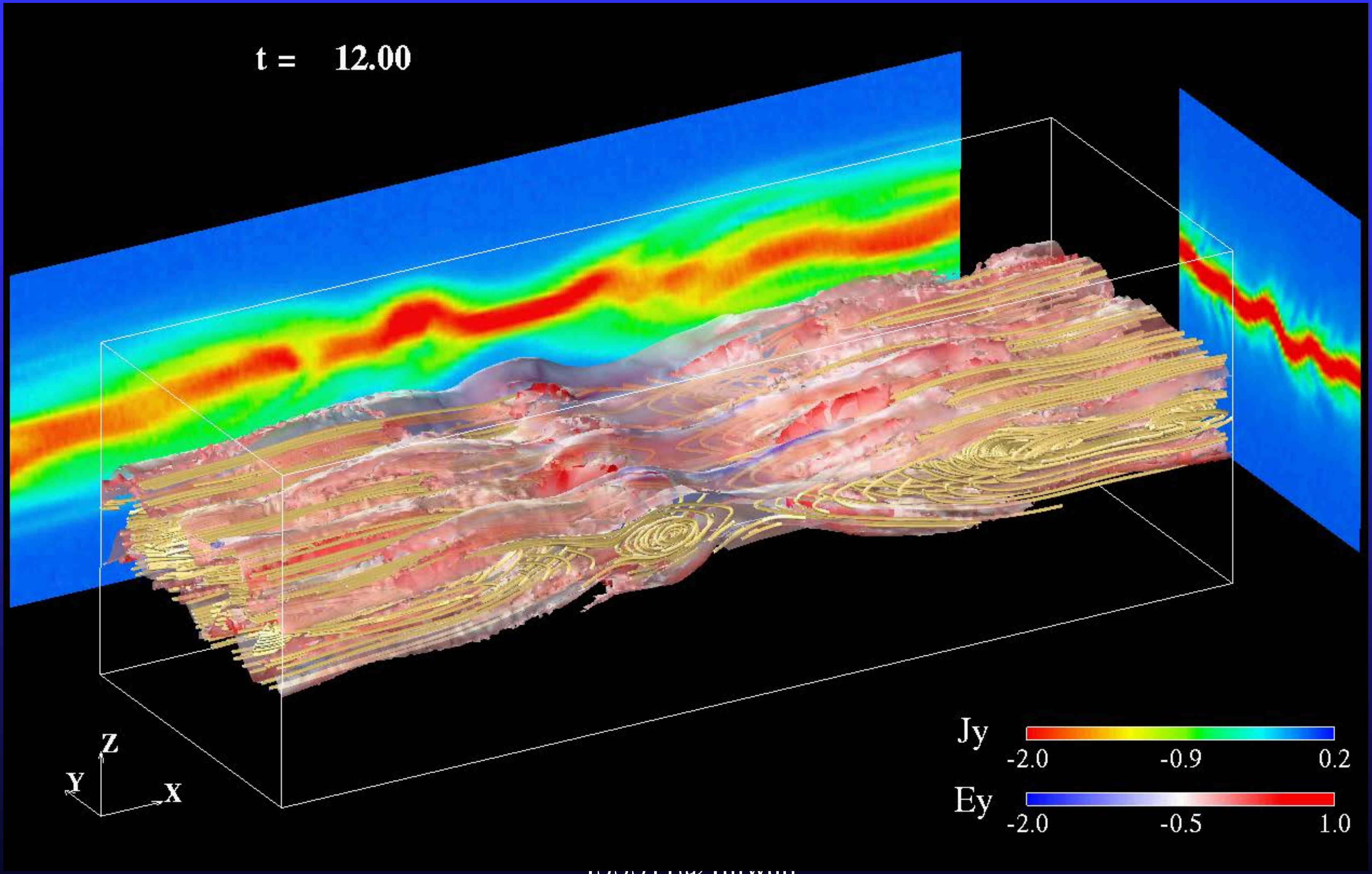
EM Waves in 3D magnetic reconnection

[Fujimoto & Sydora, PRL, 2012]

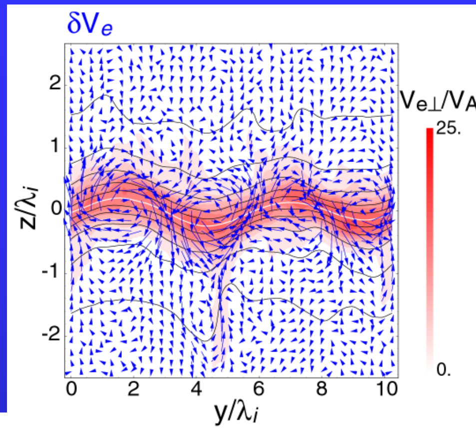
# of particles $\sim 10^{11}$

Surface: |J|, Line: Field line

Color on the surface: Ey, Cut plane：Jy



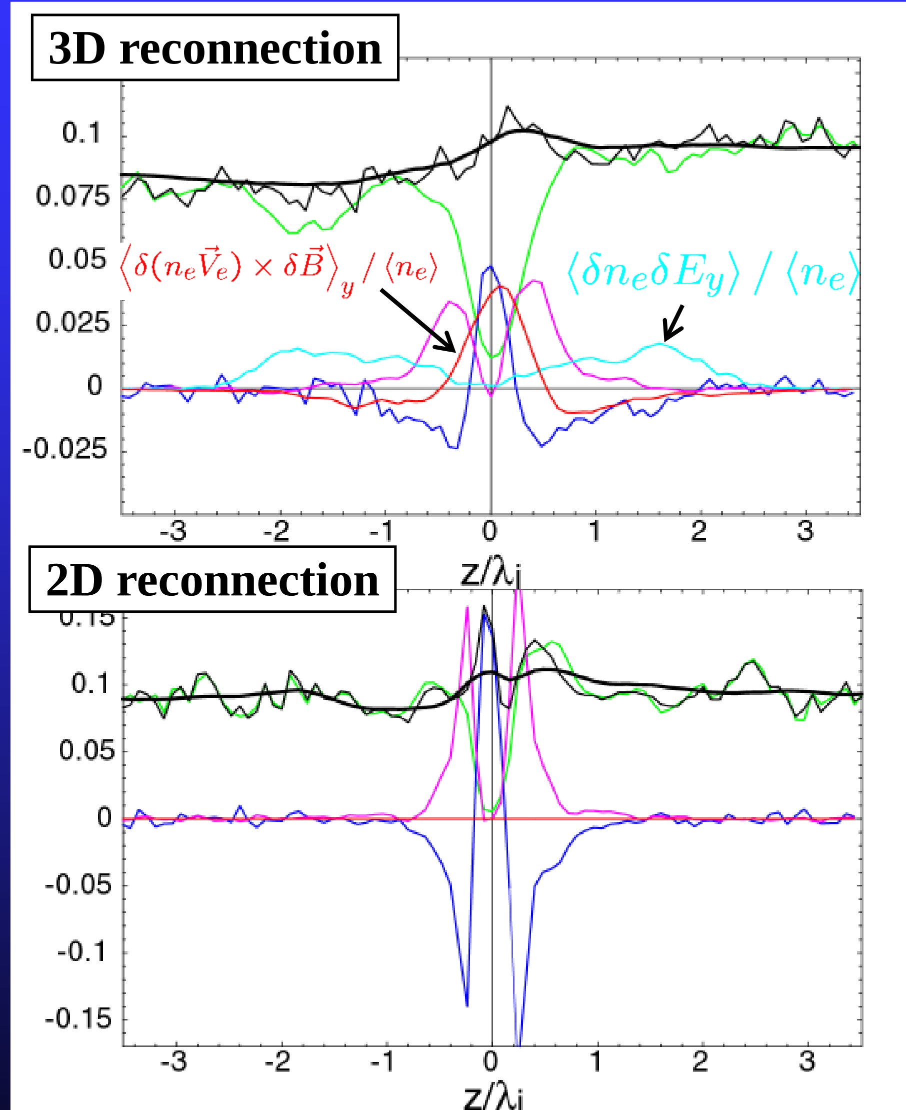
Dissipation Mechanism [Fujimoto & Sydora, PRL, 2012]



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

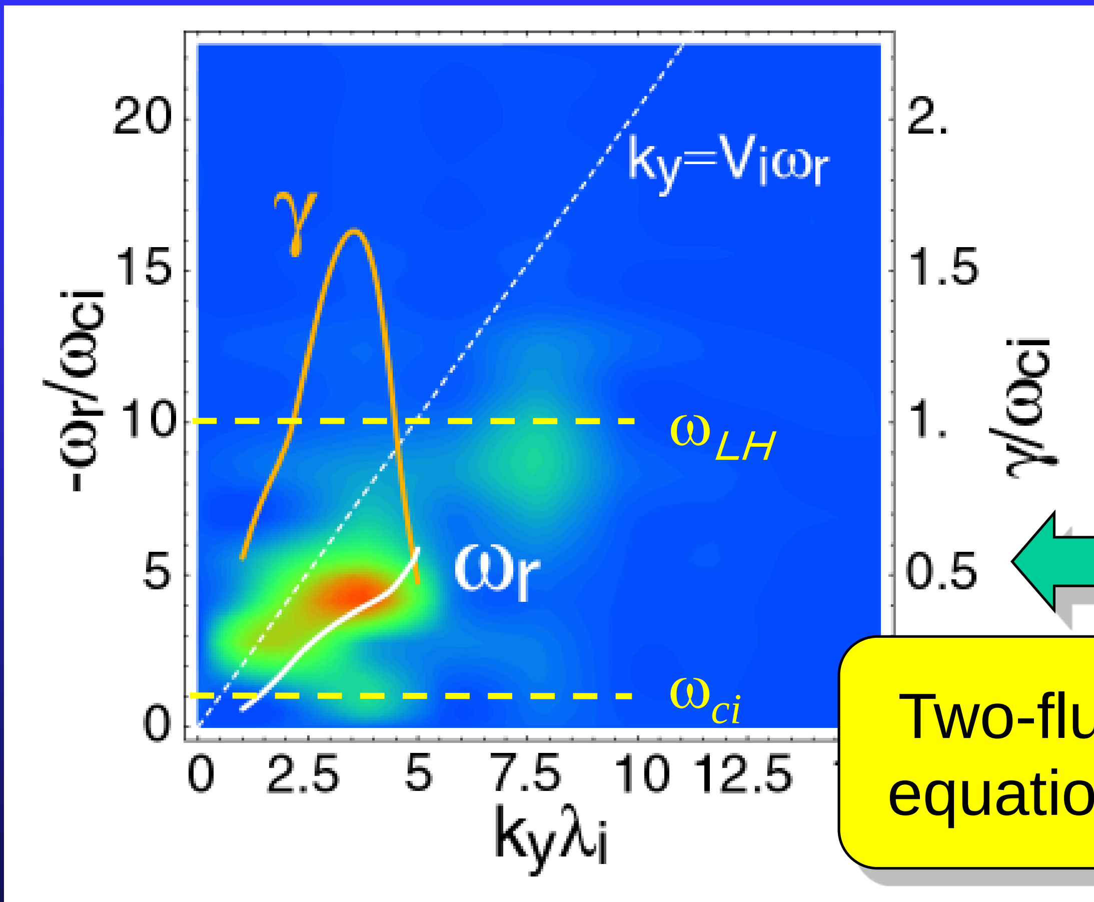
$$\langle -E_y \rangle = \frac{1}{\langle n_e \rangle} \left(\left\langle n_e \vec{V}_e \right\rangle \times \left\langle \vec{B} \right\rangle \right)_y + \frac{1}{e \langle n_e \rangle} \left\langle \nabla \cdot \vec{P}_e \right\rangle_y + \frac{m_e}{e \langle n_e \rangle} \left\langle \frac{\partial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

Anomalous effects



EM Waves in 3D Magnetic Reconnection

$\omega = \omega_r + i\gamma$



[Fujimoto & Sydora, PRL, 2012]

Simulation results

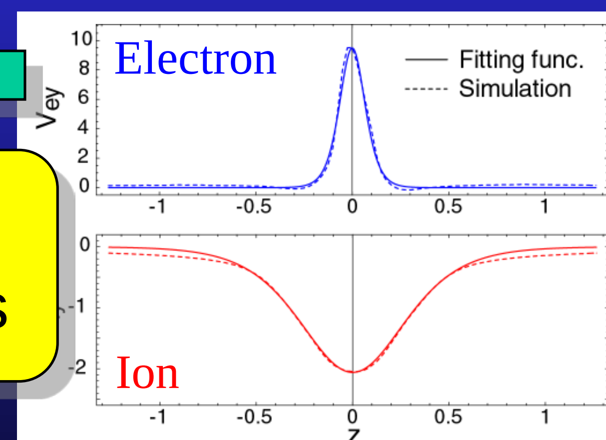
$$\omega_{ci} < |\omega_r| < \omega_{LH}$$

$$V_{ph} \approx V_A$$

Linear analyses

Profiles taken from simulation

Two-fluid equations



Summary

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

Main differences from the usual PIC models are

- Tree-type data structure,
- Smoothing of the EM fields to avoid the wave reflection,
- Particle splitting-coalescence to control the number of particles per cell,
- Adaptive block technique to keep load balancing.

Summary2

We found wave activities in the reconnection region of

- Electrostatic solitary waves (ESWs) generated due to the electron 2-stream instability in the PSBL,
- Whistler waves excited by the temperature anisotropy in the downstream region, and
- EM waves maintained by the velocity shear around the x-line in 3D magnetic reconnection.