

# 適合細分化格子を用いた磁気リコネクショ の大規模粒子シミュレーション

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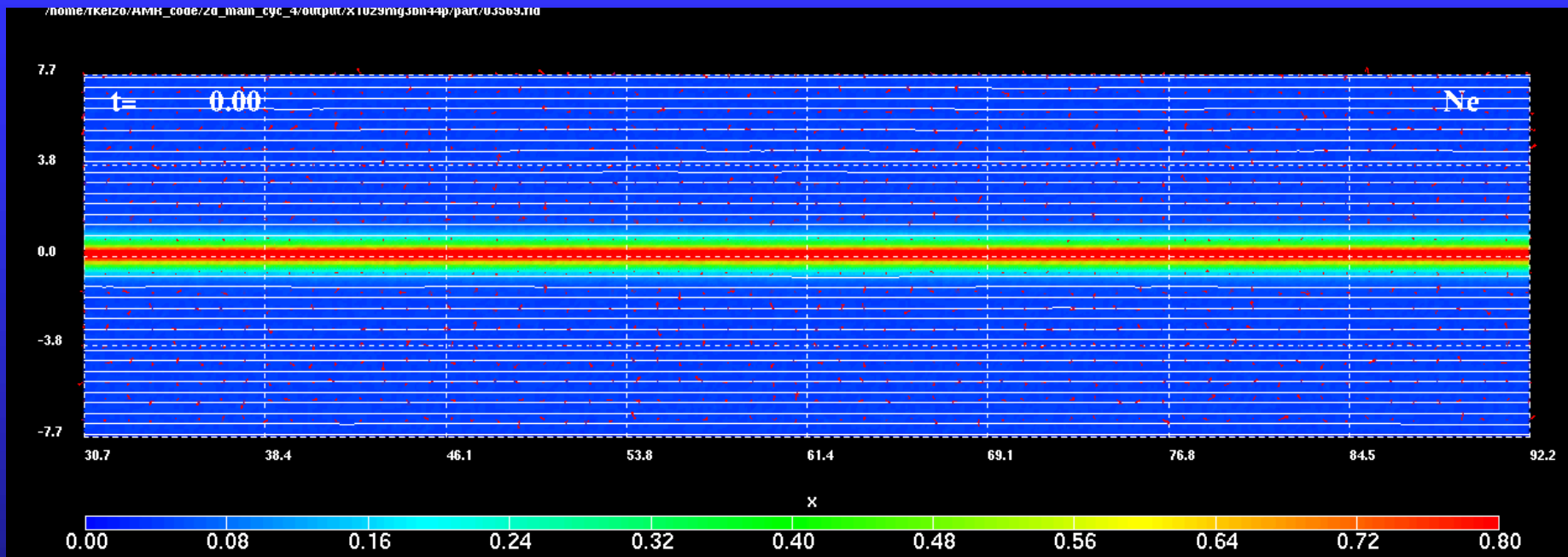
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石井克哉

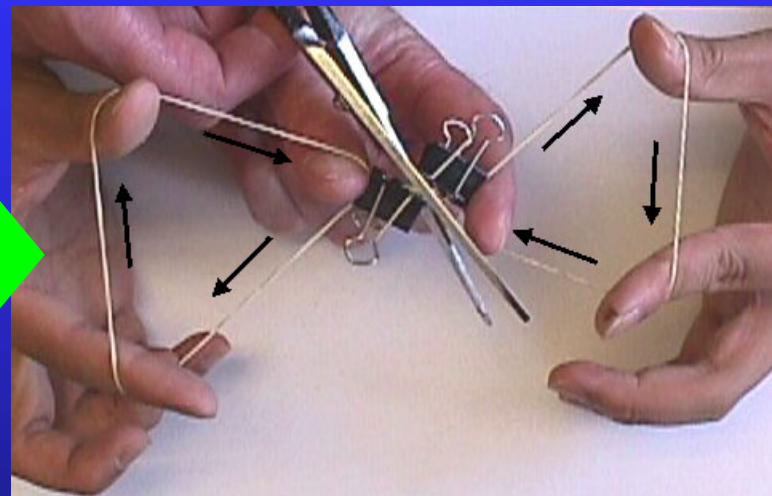
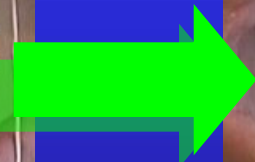
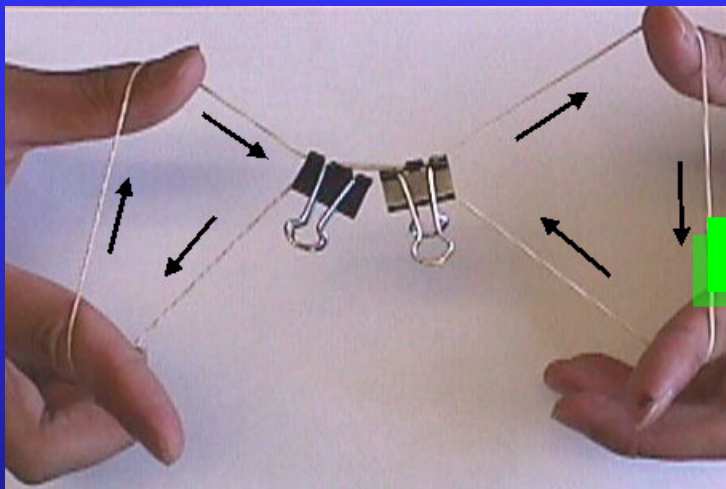
(名古屋大学 情報基盤センター)

# 磁気リコネクション現象

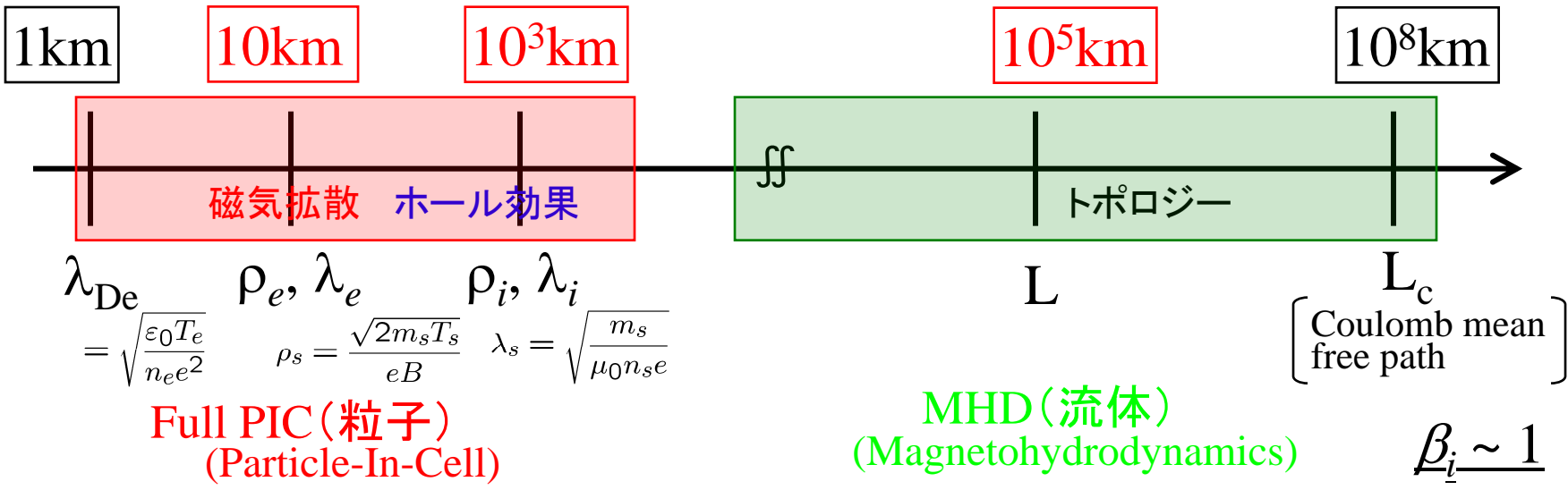
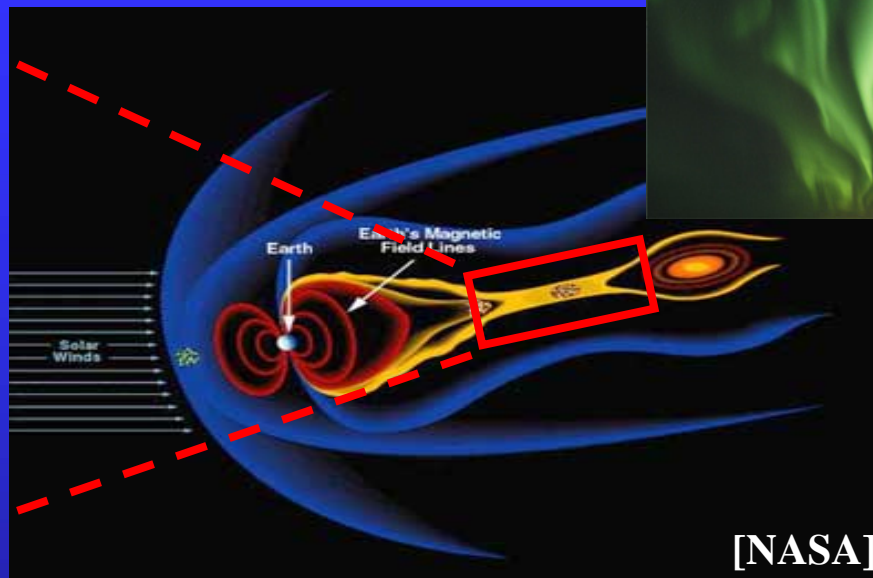
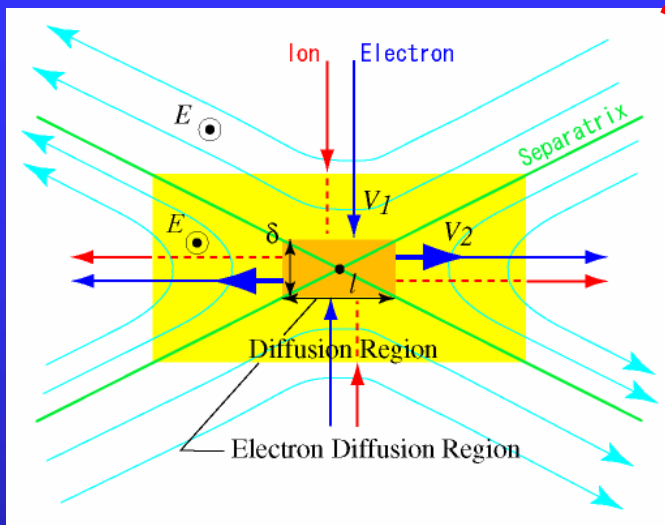


- 磁力線のトポロジーを変える
- プラズマを加速・加熱

# 磁気リコネクション現象

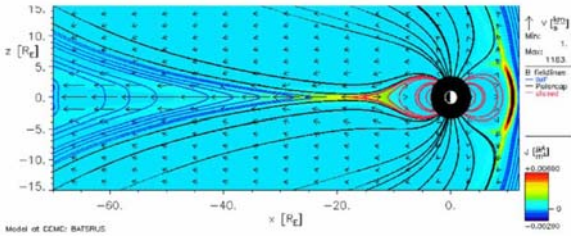


# 磁気リコネクションと磁気圏サブストーム



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

Numerical resistivity only



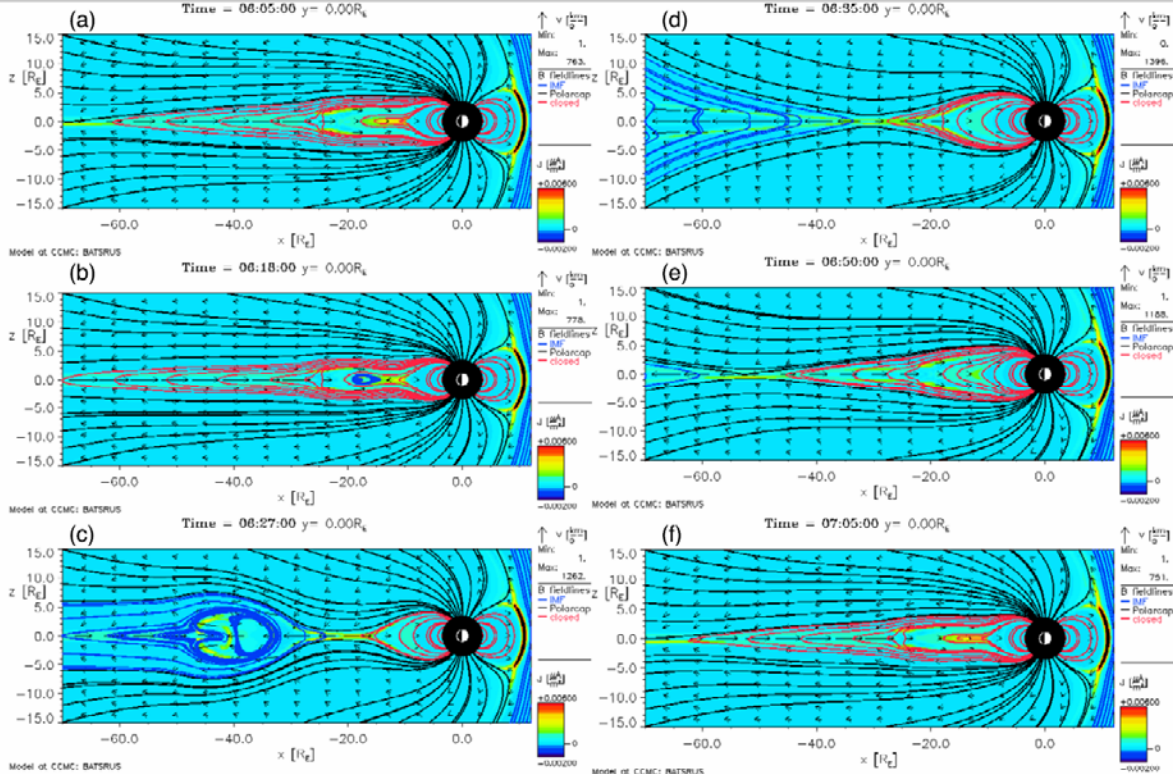
- Slow reconnection
- Quasi-steady configuration

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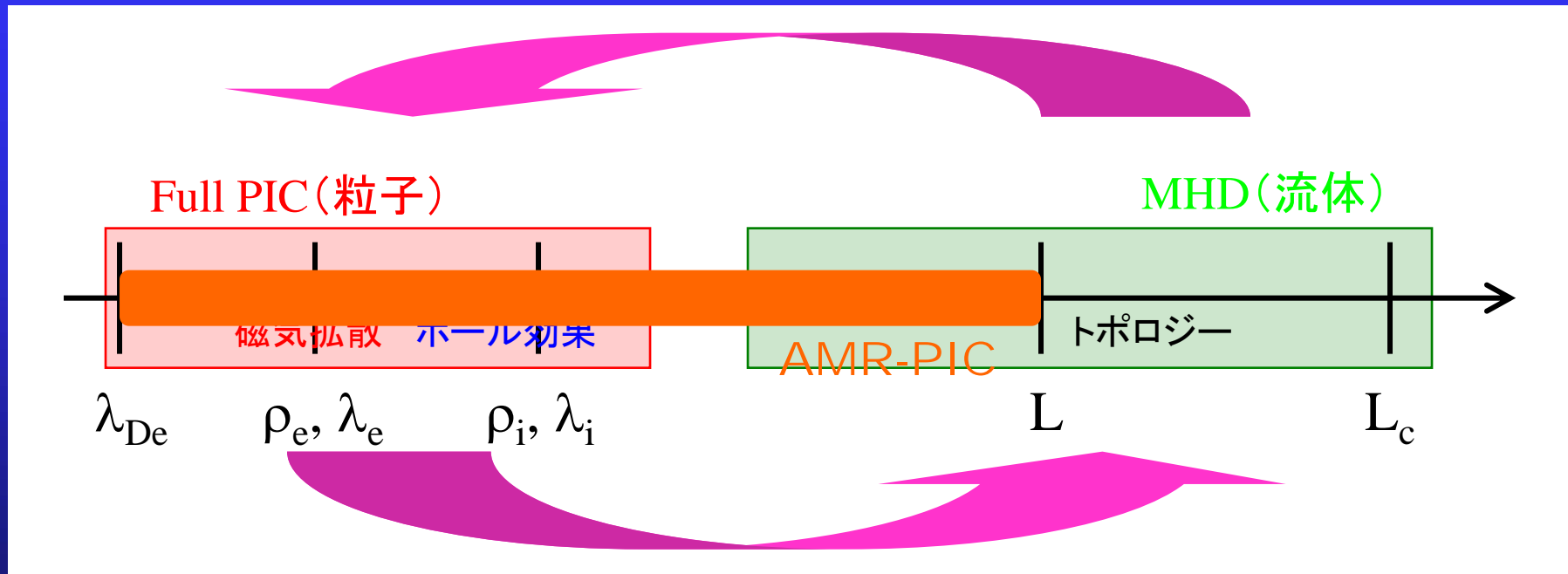
- Fast reconnection
- Quasi-periodic process

Nongyrotropic correction case

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



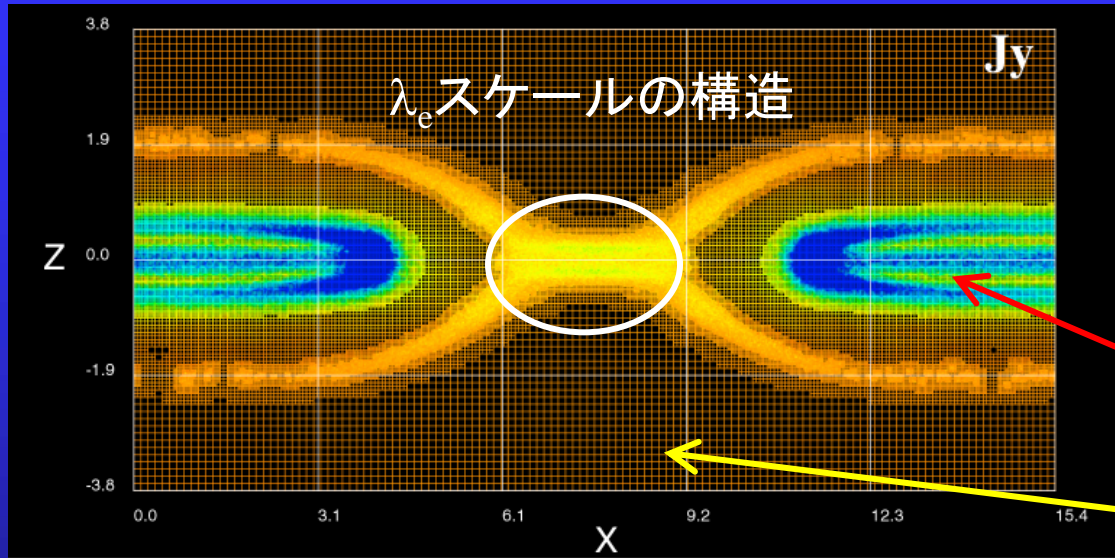
# 磁気リコネクションのマルチスケール性



# AMR-PICコード

[Fujimoto & Machida, JCP, 2006;  
Fujimoto, JCP, 2011]

(Adaptive Mesh Refinement – Particle-in-Cell)



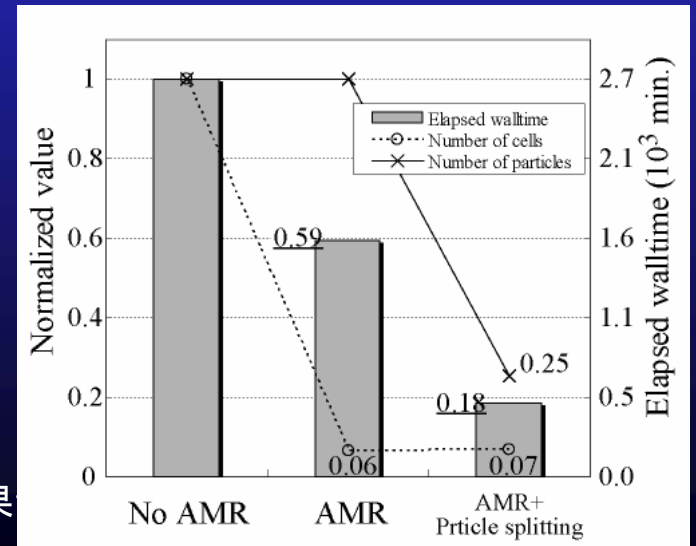
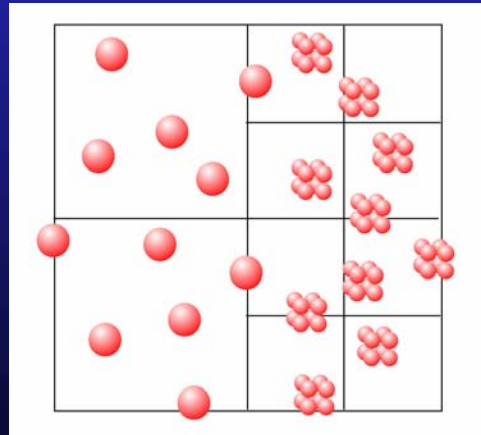
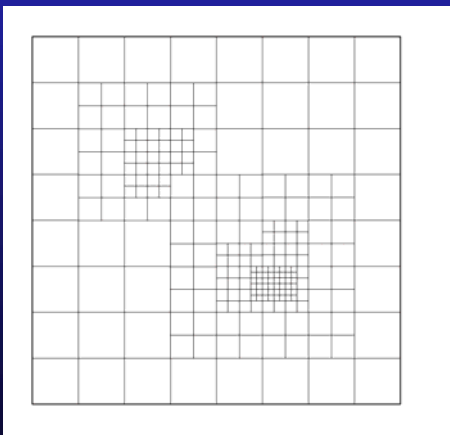
陽解法の制約

$$\Delta x < \lambda_{De}, \quad \omega_{pe} \Delta t < 1$$

$$\Delta x / \Delta t > c$$

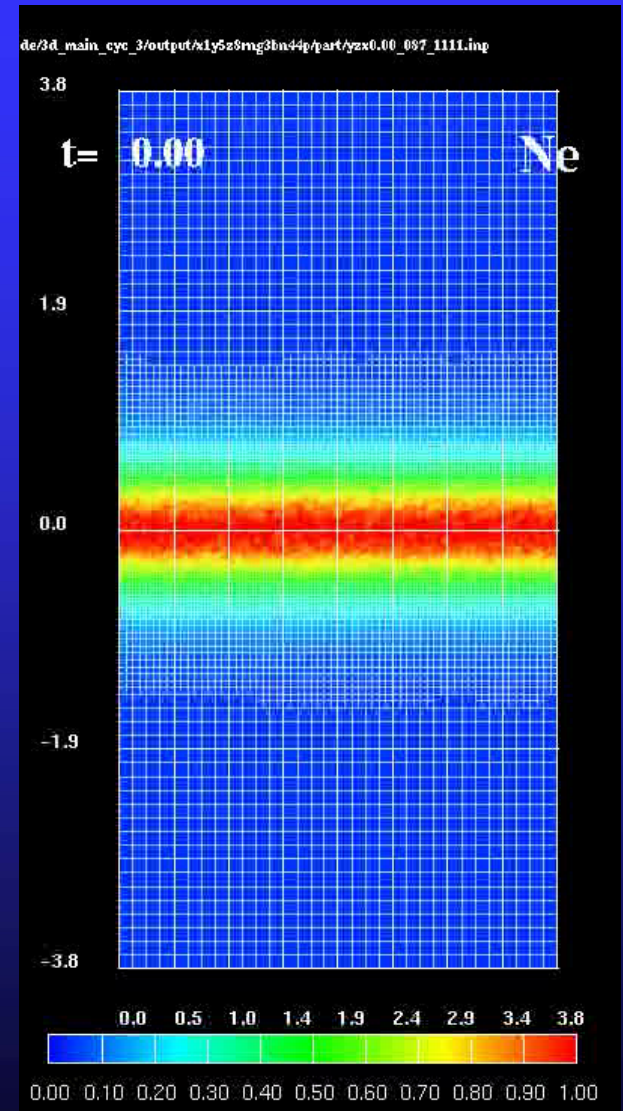
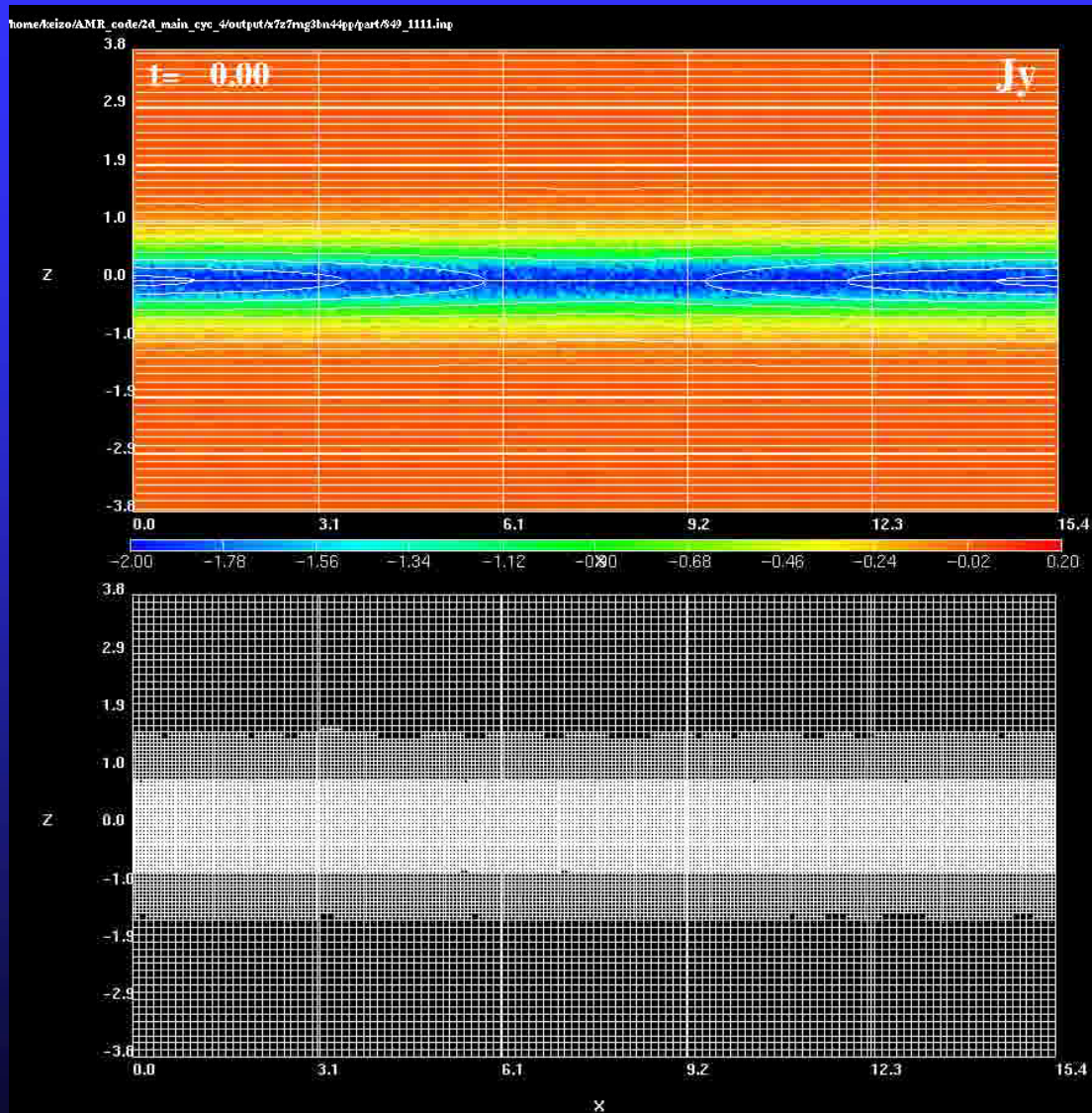
$$\lambda_{De,ps} \sim 3 \times 10^2 \text{ m}$$

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



名大HPCプロジェクト 成果

# AMR-PICシミュレーション





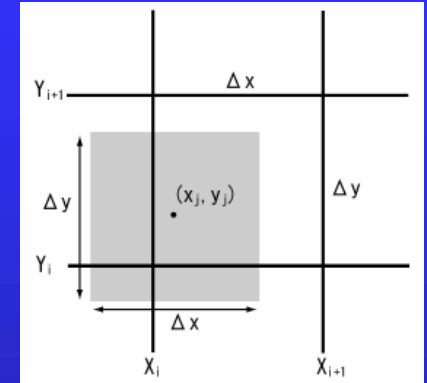
# 電磁粒子(EMPIC)コード

[Birdsall and Langdon, IOP, 1991]

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

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

S: Shape function



## ● 超粒子 (Buneman-Boris法)

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

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

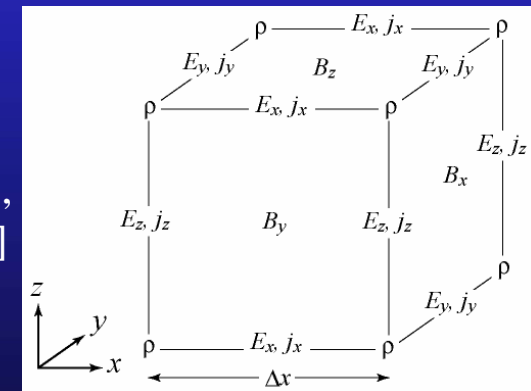
## ● 電磁場 (Yee-Bunemanスキーム)

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

$$\frac{\vec{E}^{n+1} - \vec{E}^n}{\Delta t} = c^2 \nabla \times \vec{B}^{n+1/2} - \frac{1}{\epsilon_0} \vec{j}^{n+1/2}$$

電荷保存法

[Villasenor & Buneman, 1992]



# von Neumannの安定解析

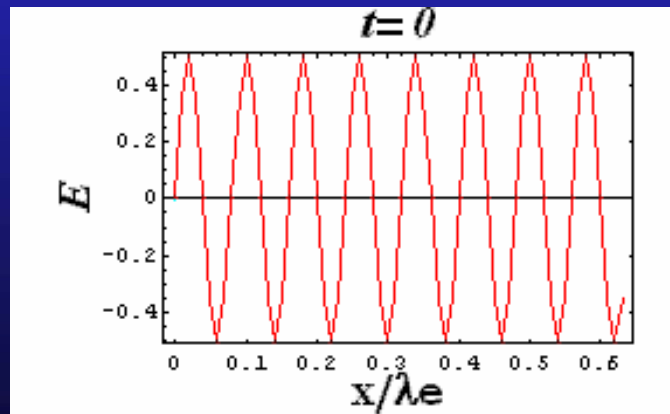
$$E_j^n = g^n \exp[ik(j\Delta x)]$$
$$g = |g| \exp[-i\omega\Delta t]$$



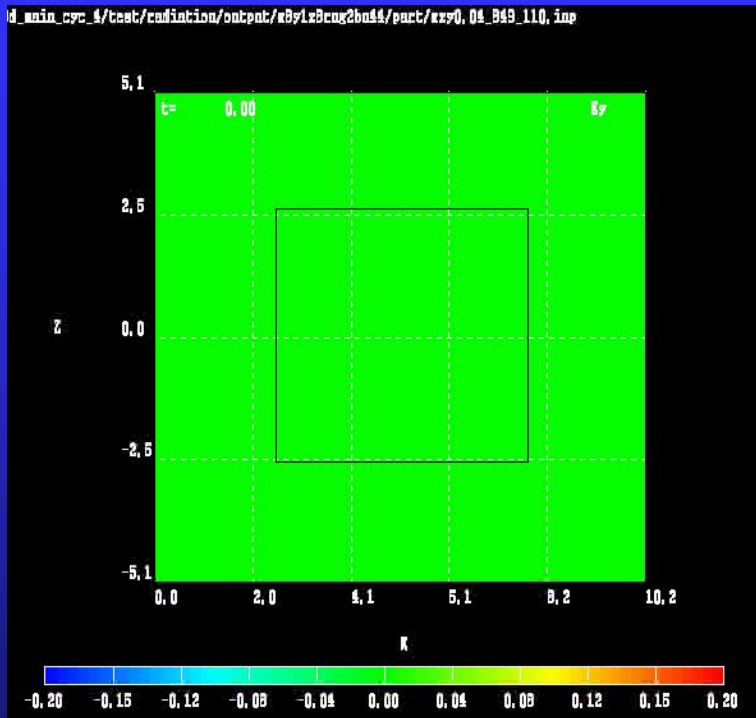
$$\frac{\vec{B}^{n+1/2} - \vec{B}^{n-1/2}}{\Delta t} = -\nabla \times \vec{E}^n$$
$$\frac{\vec{E}^{n+1} - \vec{E}^n}{\Delta t} = c^2 \nabla \times \vec{B}^{n+1/2}$$

$$g = 1 - \frac{(\kappa c \Delta t)^2}{2} \pm i(\kappa c \Delta t) \sqrt{1 - \frac{(\kappa c \Delta t)^2}{4}} \quad (\Delta x / \Delta t > c)$$

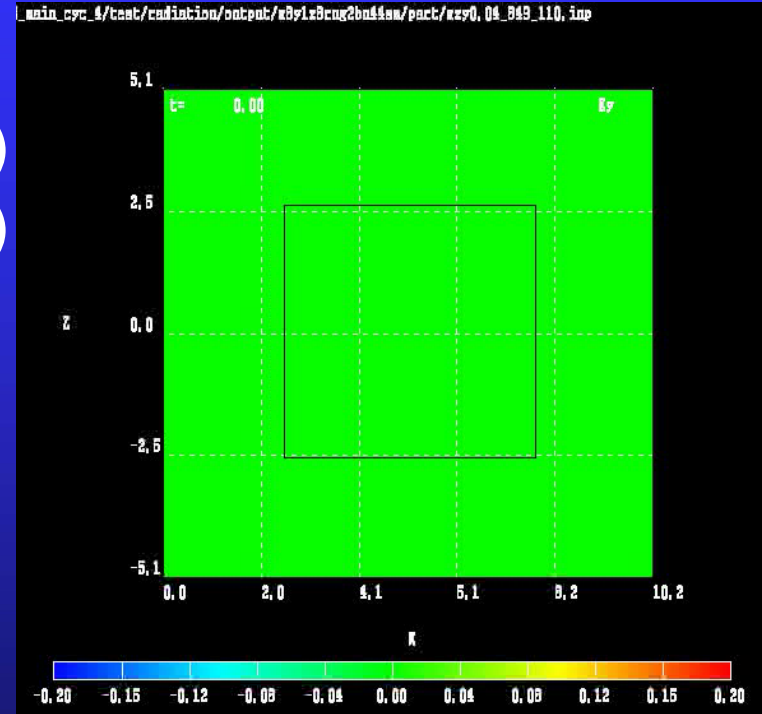
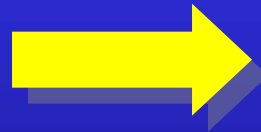
$$|g| = 1$$



# AMRの適用: 電磁場のスムージング

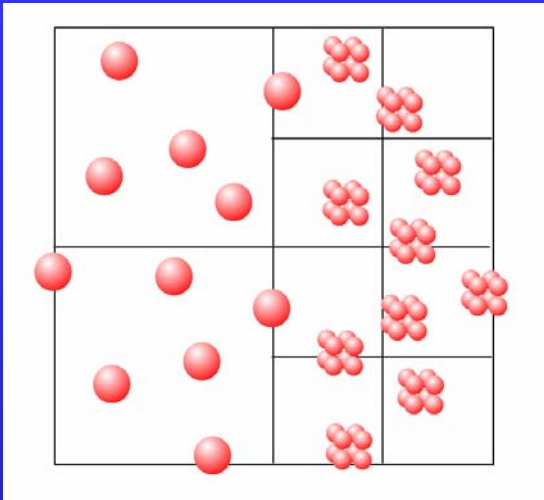


$$E_{SM} = f_{SM}(E)$$
$$B_{SM} = f_{SM}(B)$$



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

# 超粒子の分割・統合 [Lapenta, JCP, 2002]

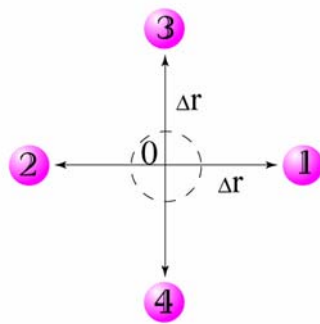


$$\frac{d\vec{v}_s}{dt} = \frac{q_s}{m_s} (\vec{E} + \vec{v}_s \times \vec{B})$$

分割前後で保存させる

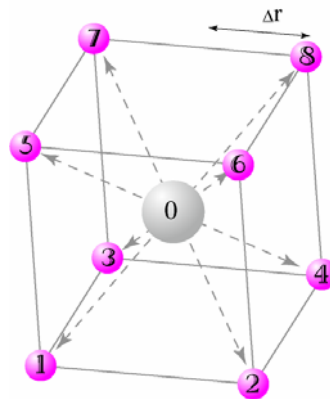
格子点上のモーメント ( $\rho_c, J$ )、全電荷・質量 ( $\Sigma\rho_c, \Sigma m$ )、粒子の全エネルギー ( $\Sigma mv^2/2$ )、粒子の分布関数 ( $f(v)$ )

2次元の場合



$$\vec{v}_j = \vec{v}_0 \quad (j = 1, 2, \dots, 8)$$

3次元の場合

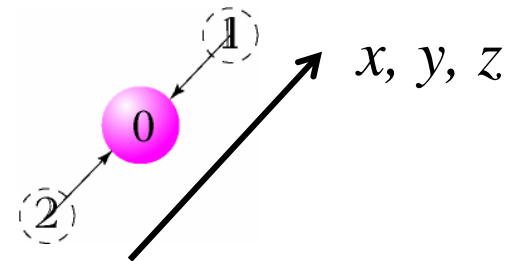


$$q_1 = q_2; m_1 = m_2$$

$$\mathbf{x}_0 = (\mathbf{x}_1 + \mathbf{x}_2)/2$$

$$\mathbf{V}_0 = (\mathbf{V}_1 + \mathbf{V}_2)/2$$

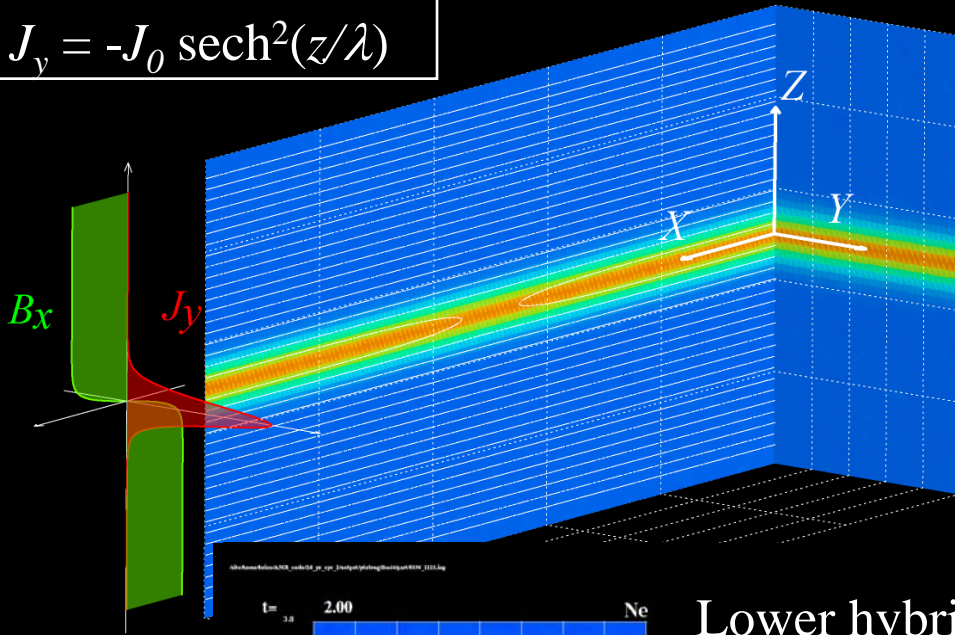
$$q_0 = q_1 + q_2; m_0 = m_1 + m_2$$



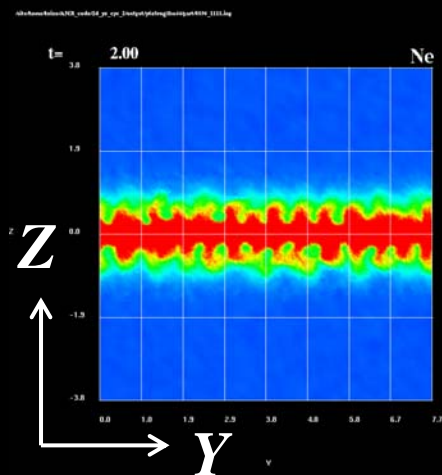
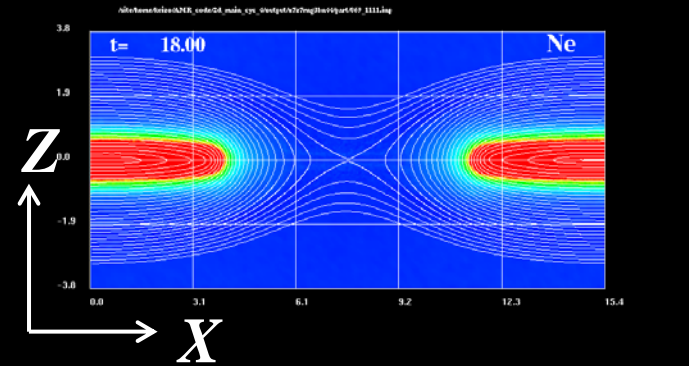
# 3次元電流層における不安定モード

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

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



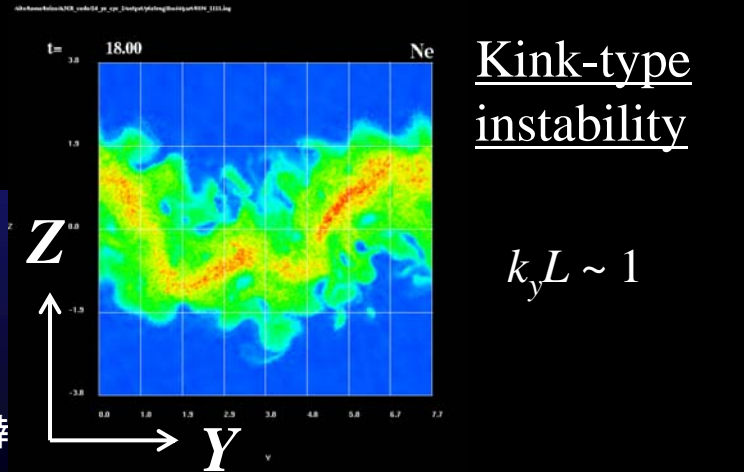
## Tearing instability



Lower hybrid drift instability (LHDI)

$$k_y \rho_e \sim 1$$

$$\gamma \sim \omega_{lh}$$

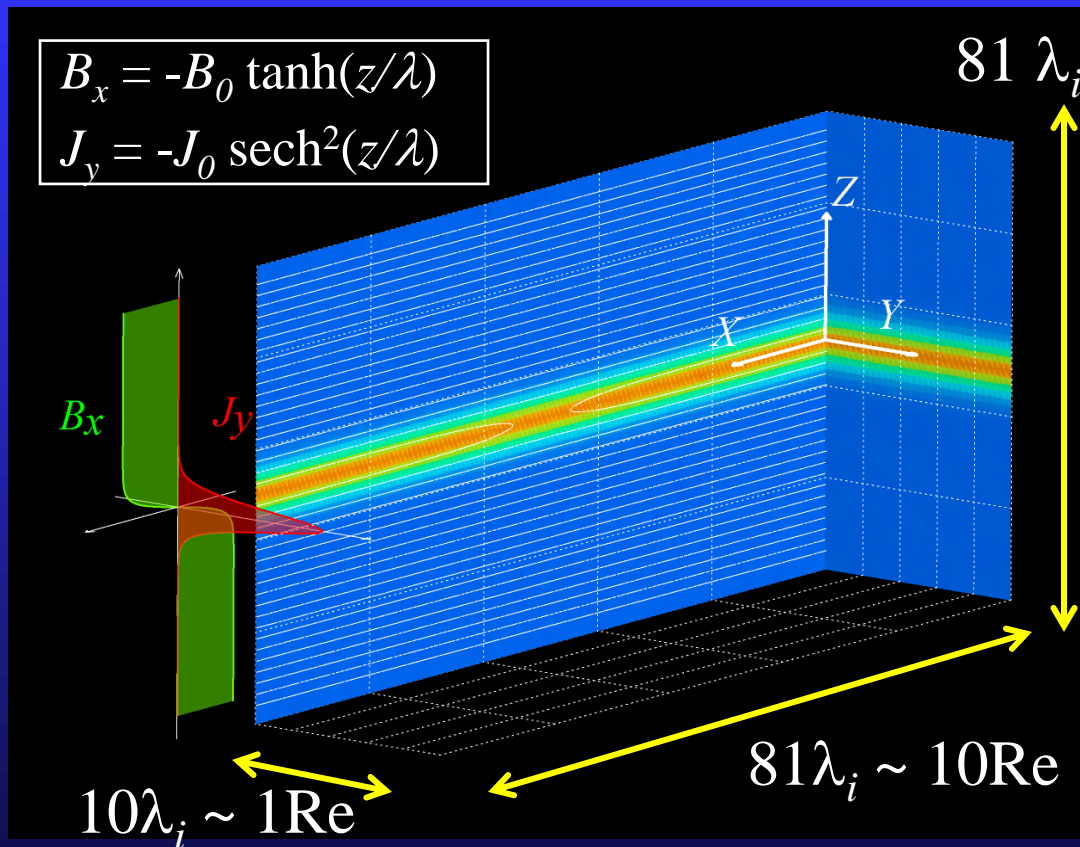


Kink-type instability

$$k_y L \sim 1$$

# Simulation Setup

Fujitsu FX1, 1024 cores



$m_i/m_e = 100$

Max resolution:

$4096 \times 512 \times 4096 \sim 10^{10}$

Max number of particles

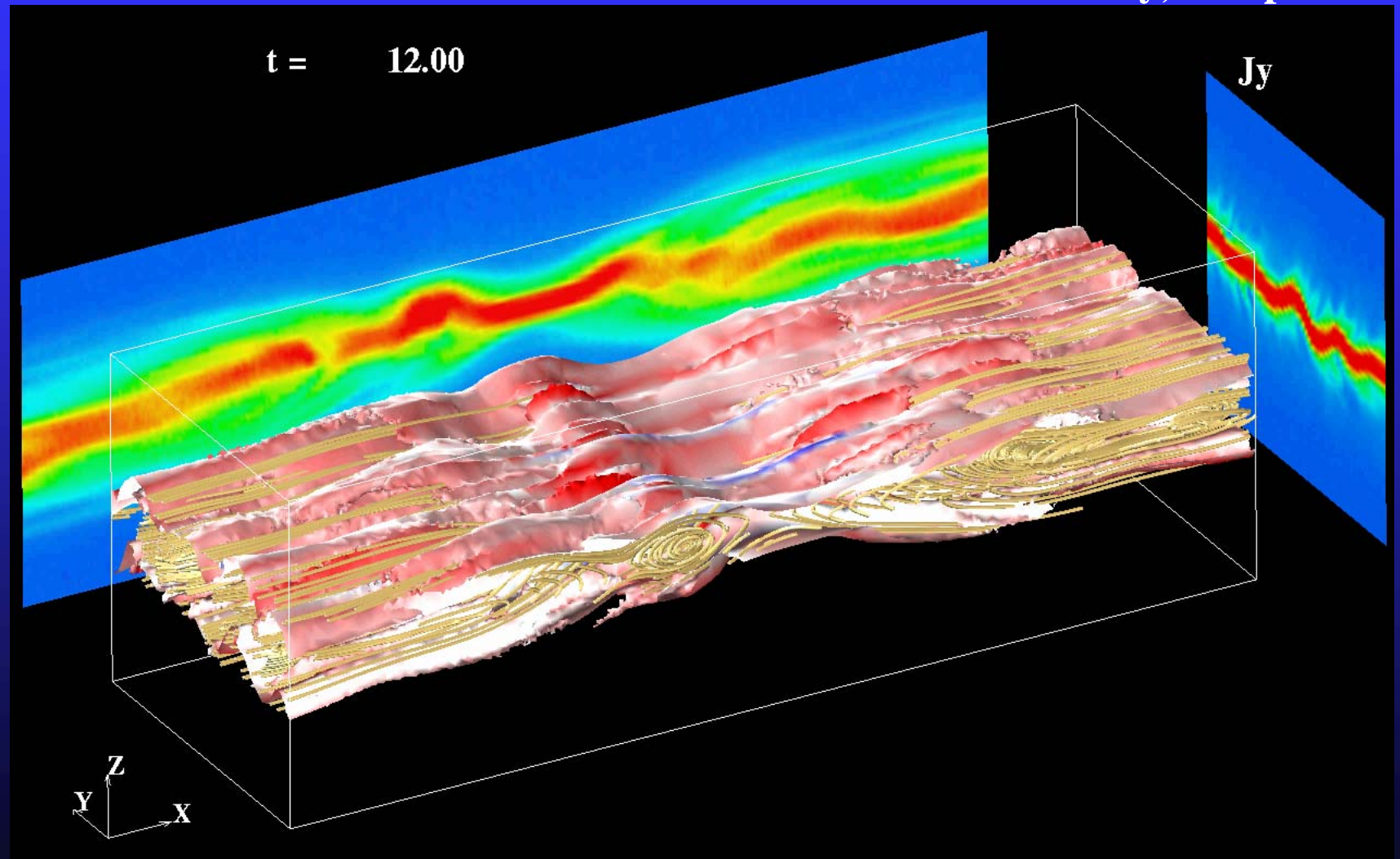
Ion + Electron  $\sim 10^{11}$

Max memory used  $\sim 6\text{TB}$

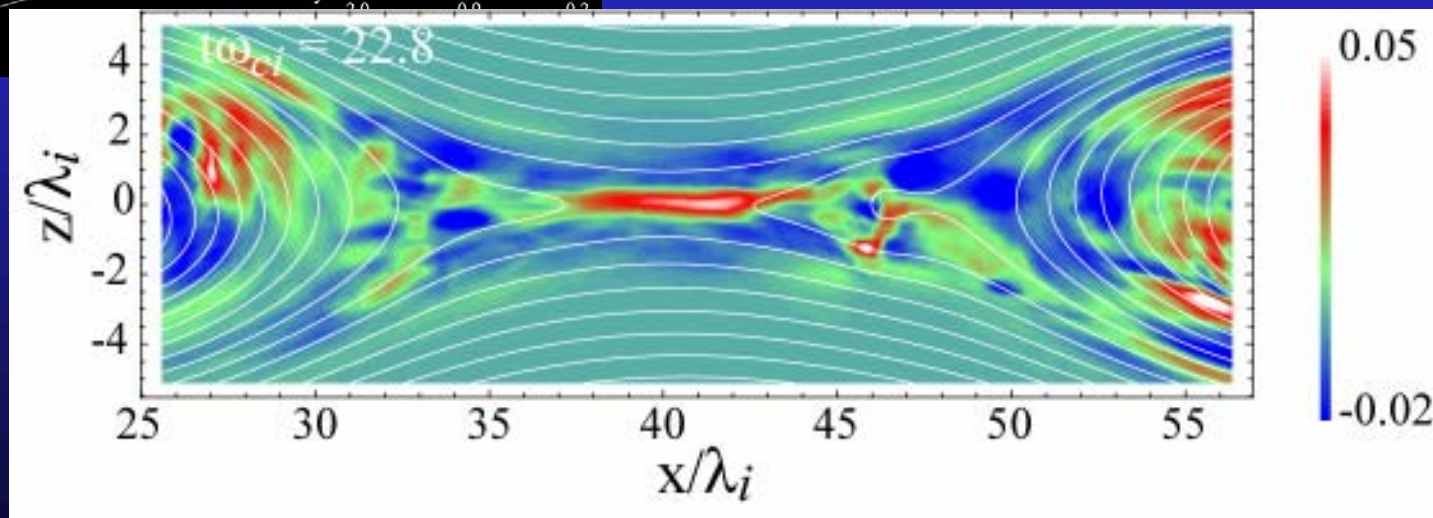
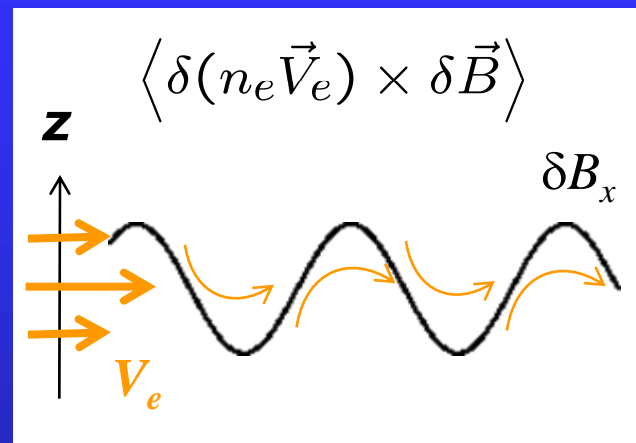
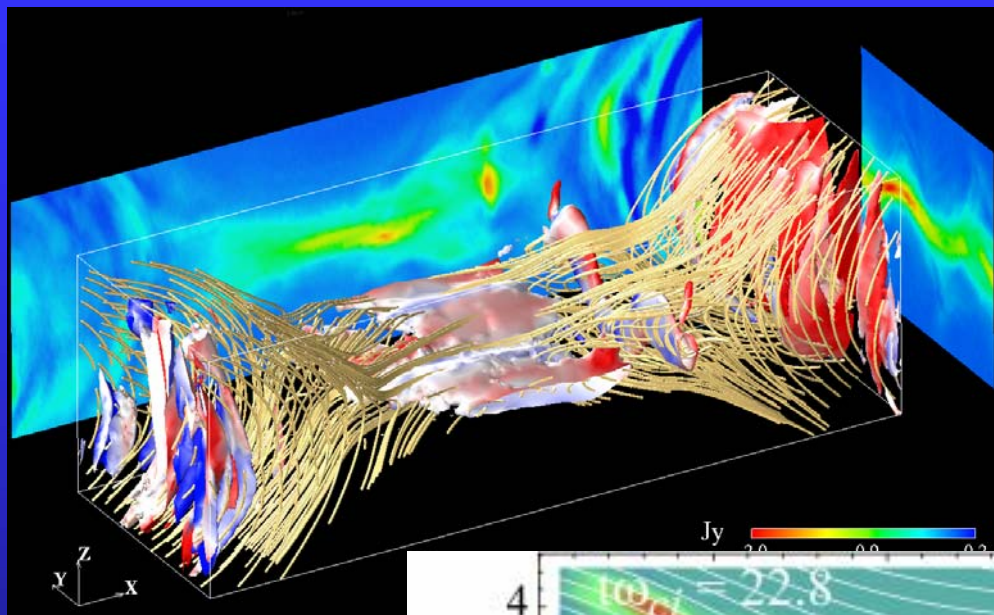
# Time Evolution of the Current Sheet

Surface:  $|J|$ , Line: Field line

Color on the surface:  $E_y$ , Cut plane:  $J_y$

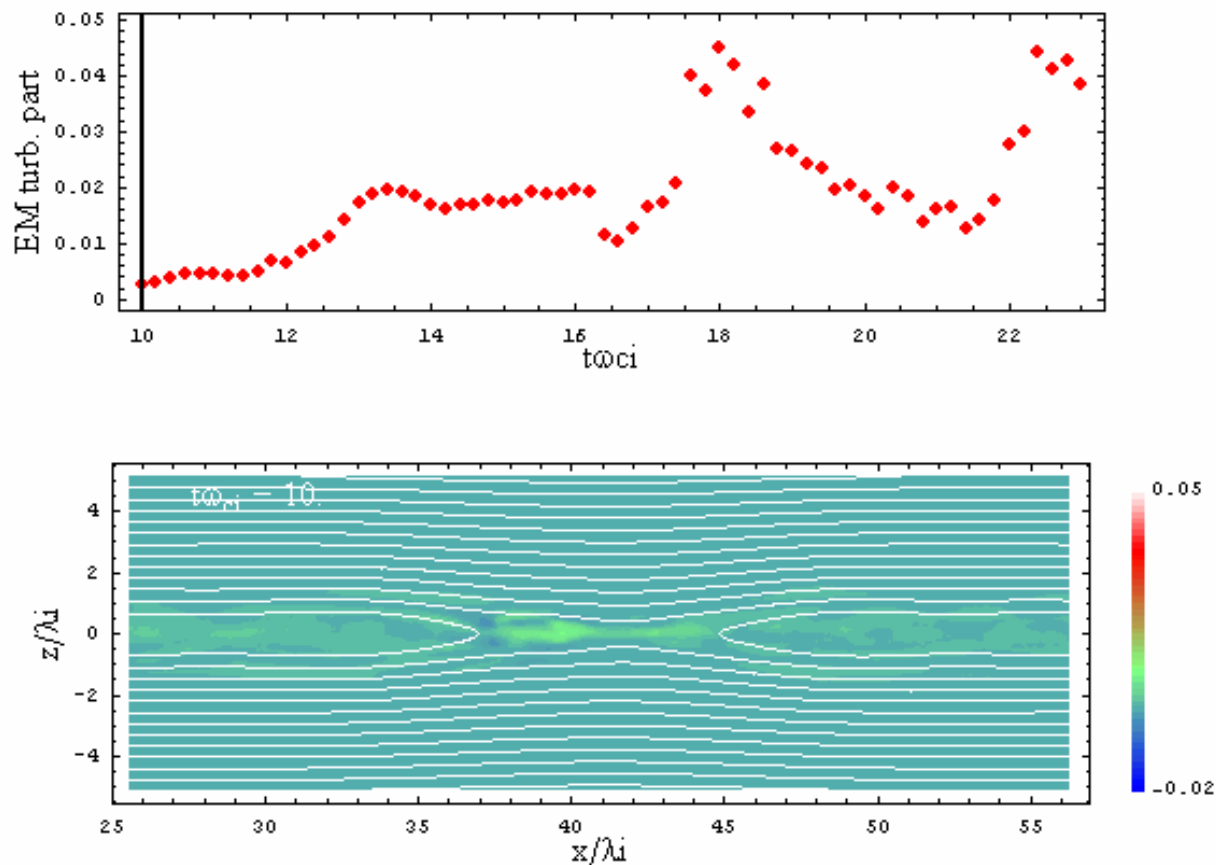


# 電磁波動による運動量異常輸送



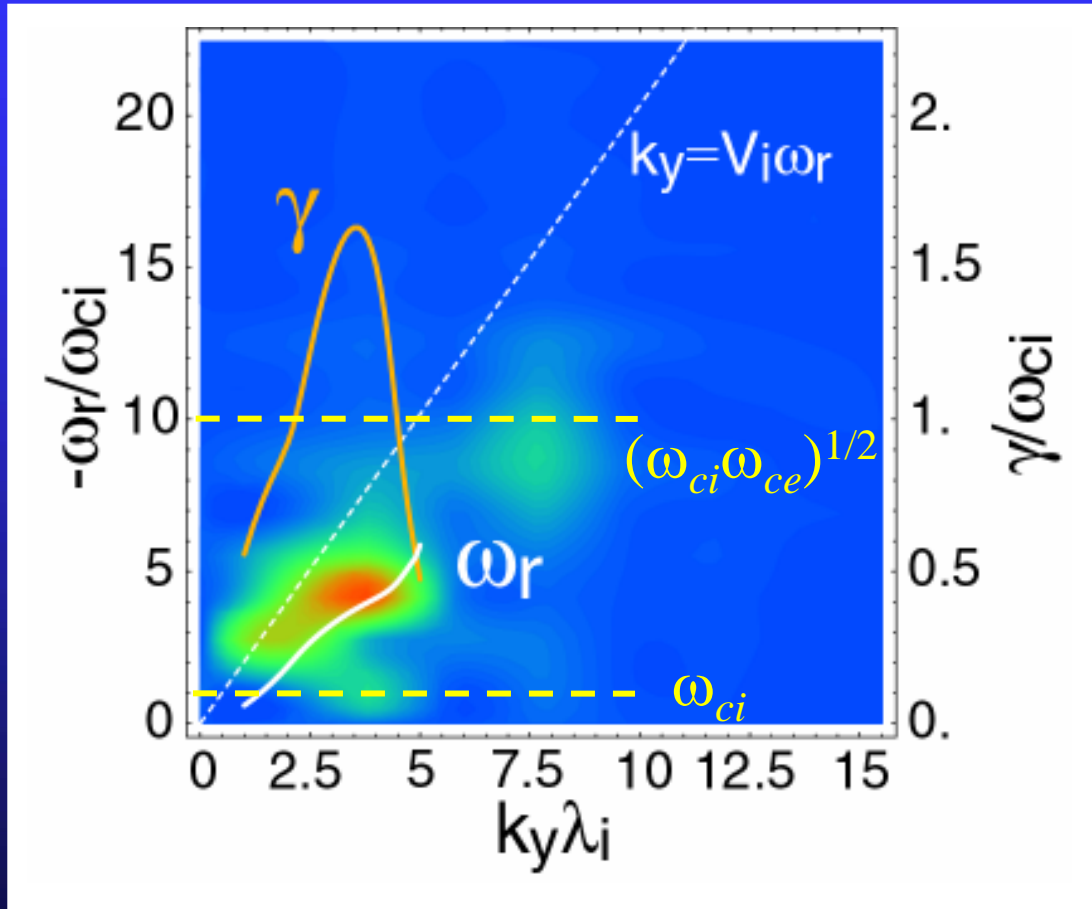


# プラズモイドにともなう電磁擾乱の強化



# Wave Properties

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



## Simulation results

$$\omega_{ci} < |\omega_r| < (\omega_{ci} \omega_{ce})^{1/2}$$

$$V_{ph} \approx V_A$$

## Linear analyses

- ドリフト波ではない
- シア一駆動型モード
- $\omega_r$ 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

電磁粒子コード(PICコード)に適合細分化格子(AMR)を適用した独自のコード(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た。

- 電流層に沿って電磁波動が発生 ⇒ 運動量の異常輸送
- プラズモイドの発生 ⇒ 電磁擾乱を強化
- 線形波動解析 ⇒  $\omega_{ci} < \omega_r < (\omega_{ci}\omega_{ce})^{1/2}$   
シア一駆動型不安定性  
 $m_i/m_e = 1834$  でも大きな成長率

# Perspective in Near Future

磁気リコネクションのマクロシステムへの適用



## MHDコード

- スケールフリー
- 自由な境界条件・初期設定

グローバル構造のモデリング

$$E + V \times B = \eta J$$

プラズマ運動論効果

物理的  
考察

## PICコード

- 完全な運動論効果
- 詳細なマイクロ構造

