開放境界を用いた電磁粒子コードの開発
(Electromagnetic Particle-In-Cell Model with Open Boundary)

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AMR-PICコードの開発

2003 2006 2008 2011 2013

開発スタート

2D AMR-PIC
コード完成

[Fujimoto & Machida, JCP, 2006]

3D AMR-PIC
コード完成

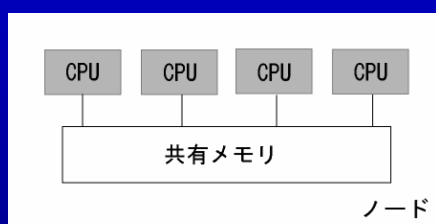
[Fujimoto & Sydora, CPC, 2008]

超並列化完了

[Fujimoto, JCP, 2011]

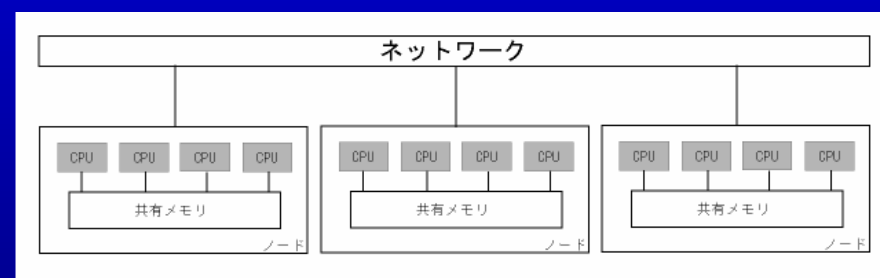
開放境界条件
開発中. . .

- ノード内並列



CPU数、メモリ容量の制約

- 電荷保存法
- 適合ブロック法



より多くの計算機資源が利用可能！

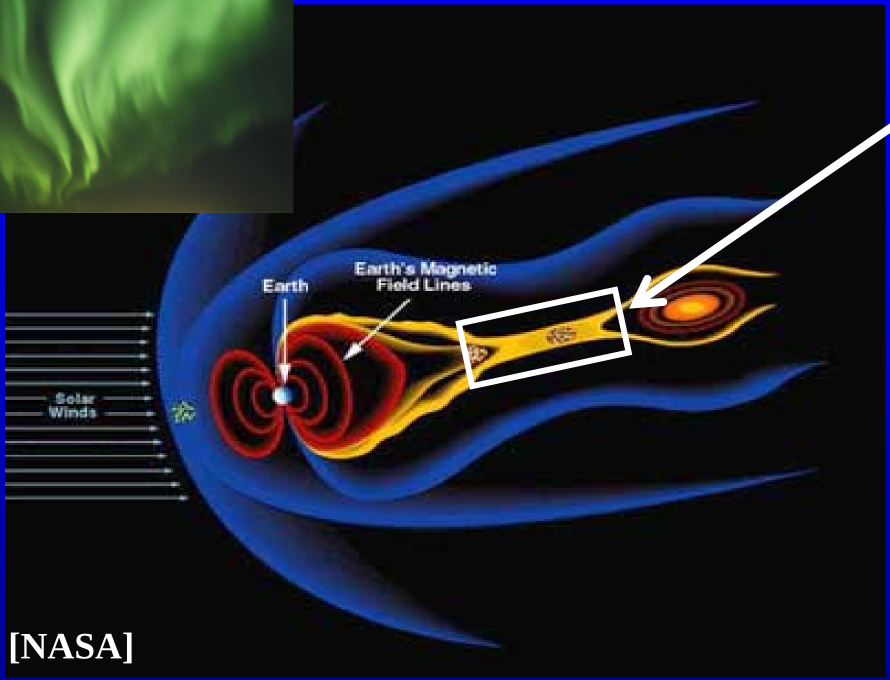
講演内容

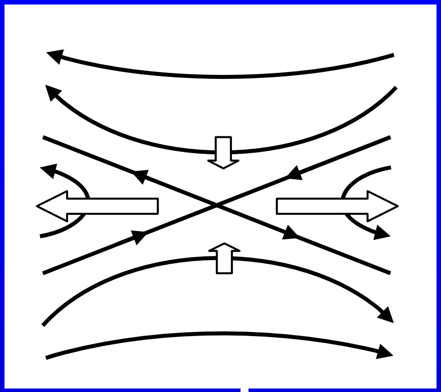
- 開発動機、戦略
  なぜ、敢えて開放境界にするのか？

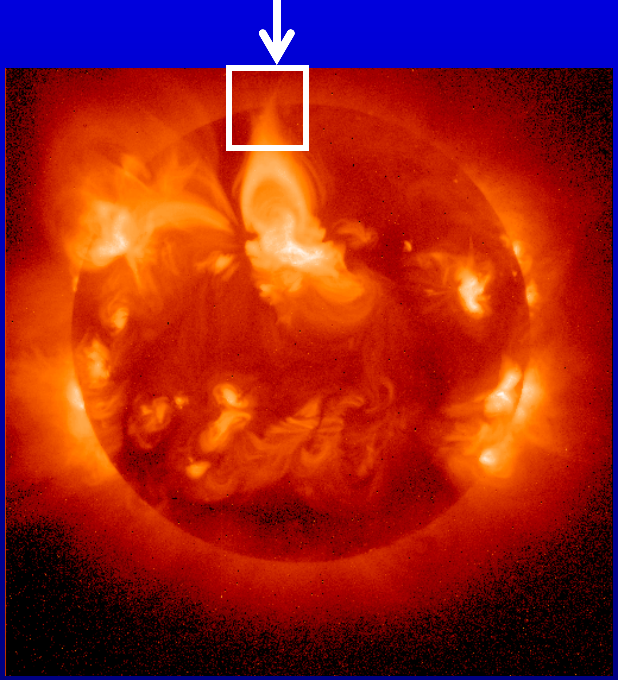
- 簡単なテスト計算

Magnetic Reconnection in Space

Auroral Substorms

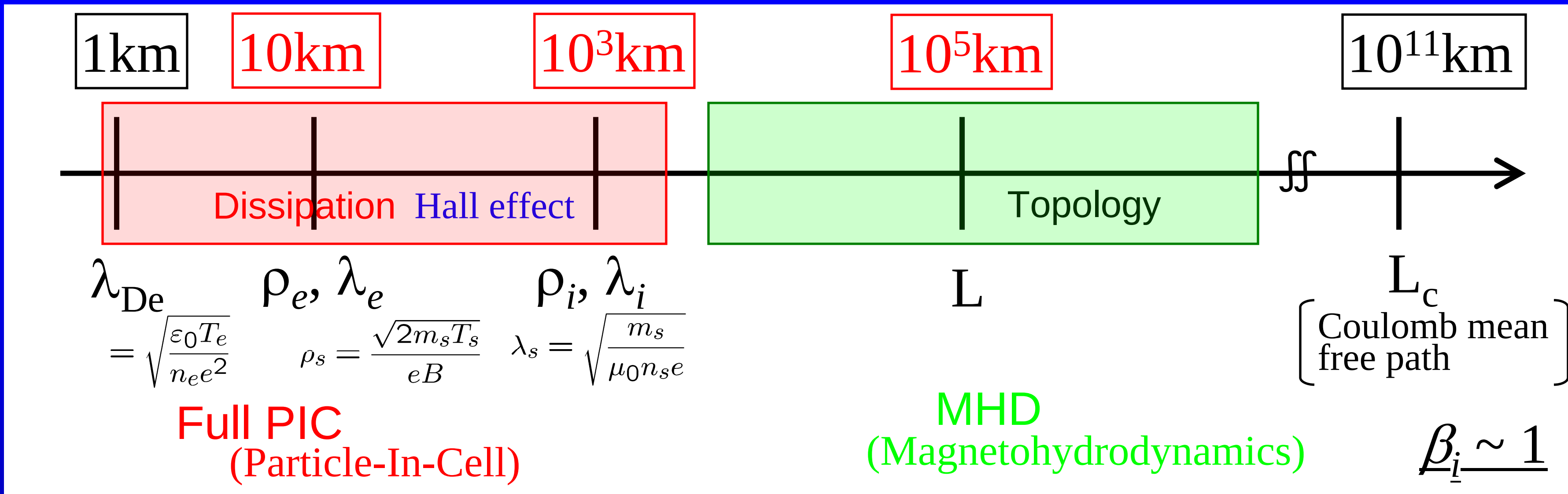


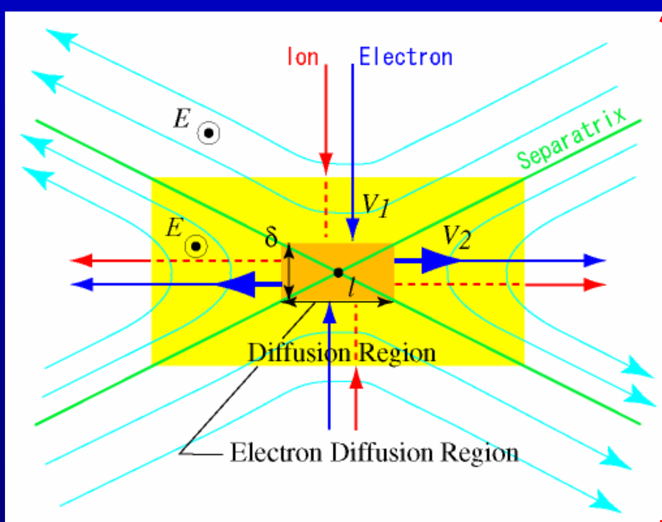


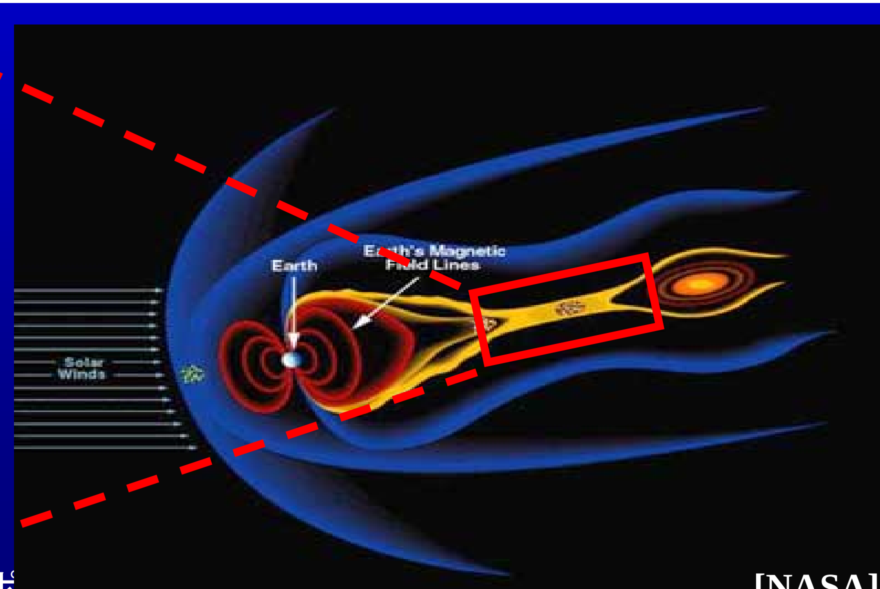


Solar Flares

Multi-Scale Nature of Reconnection



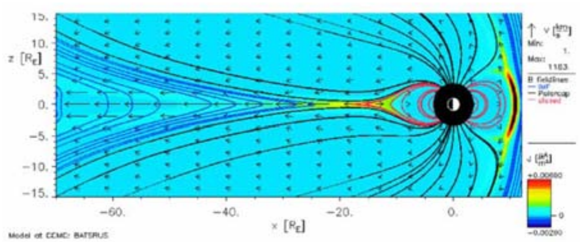




Kuznetsova et al., J. Geophys. Res., 2007

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

Numerical resistivity only

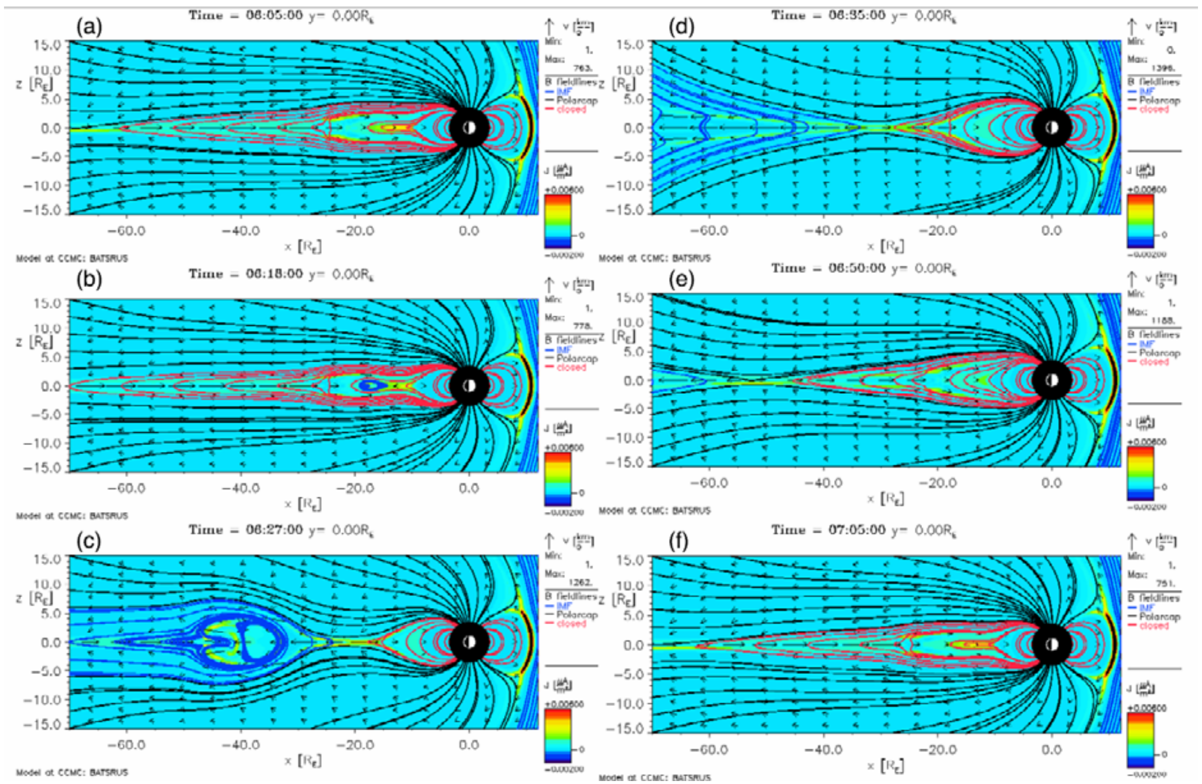


- Slow reconnection
- Quasi-steady configuration

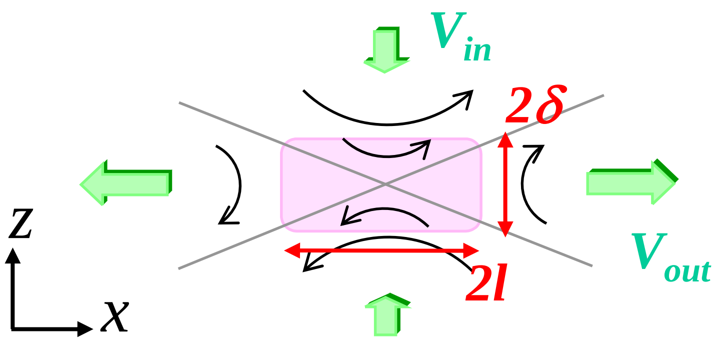
- Fast reconnection
- Quasi-periodic process

Nongyrotropic correction case

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



Reconnection Rate and Resistivity η



リコネクション効率

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

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

磁気散逸領域の縦と横の長さに依存

無衝突プラズマにおいて衝突効果を生む物理は？

$$\delta \approx \eta/\mu_0 V_{in} \quad \rightarrow c/\omega_{pe}$$

Inertia resistivity limit

⇓

観測事実と不一致

⇓

異常磁気散逸の可能性

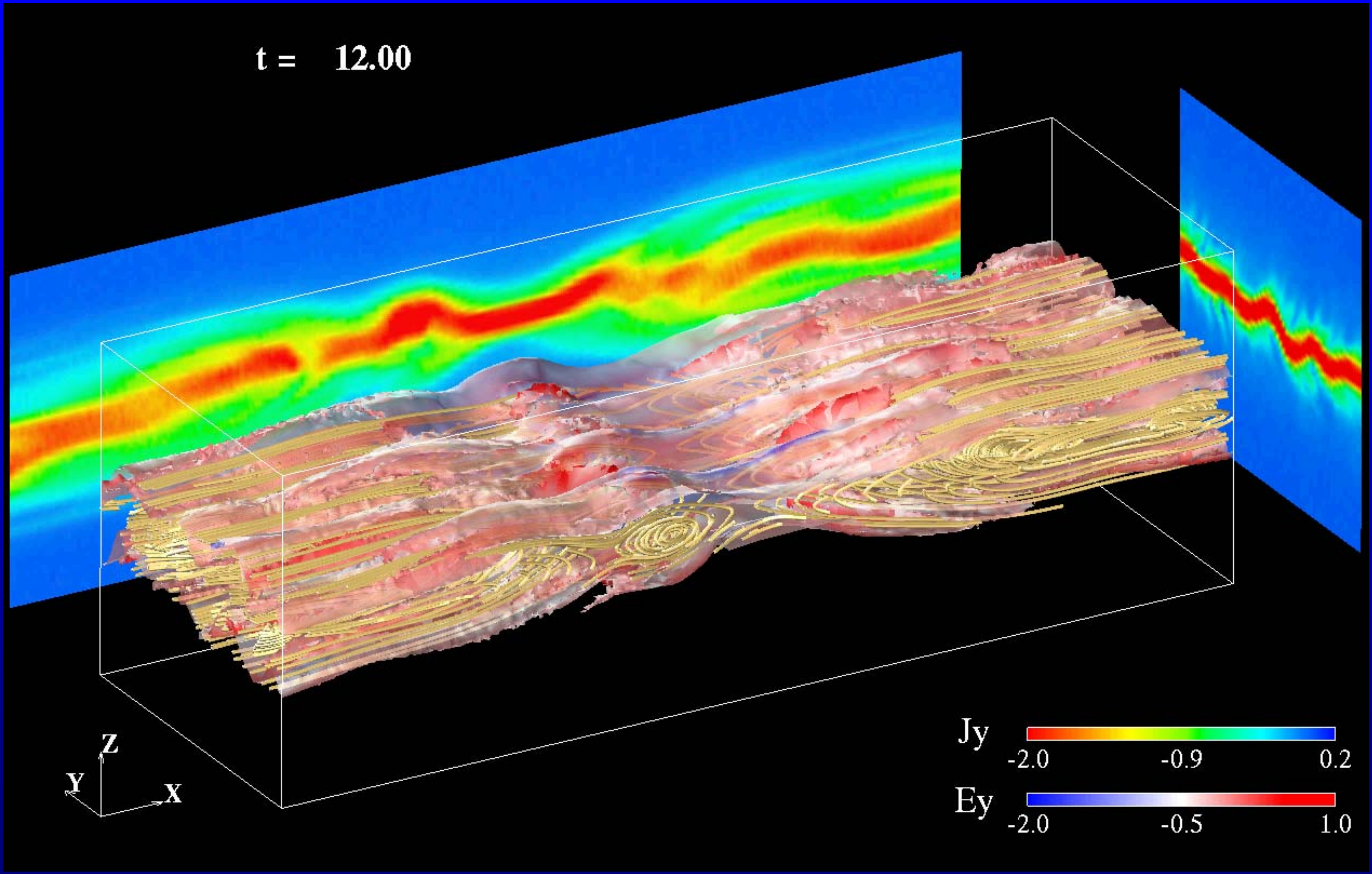
3D過程、マルチスケール、非線形 ⇒ 大規模計算

Time Evolution of the Current Sheet

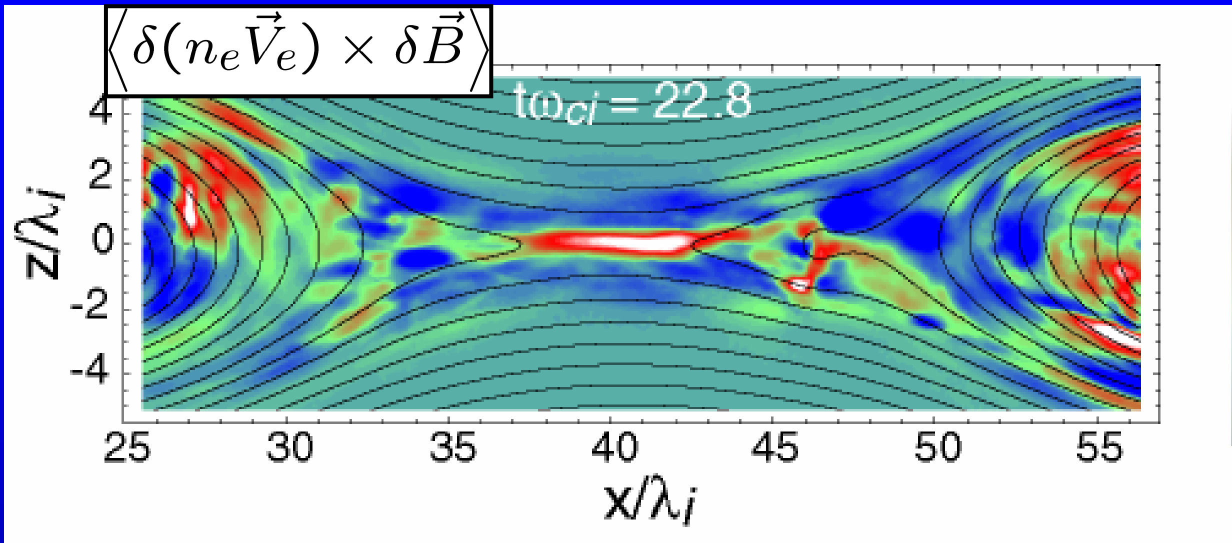
- ~ 10^{11} particles
- ~ 6 TB memory

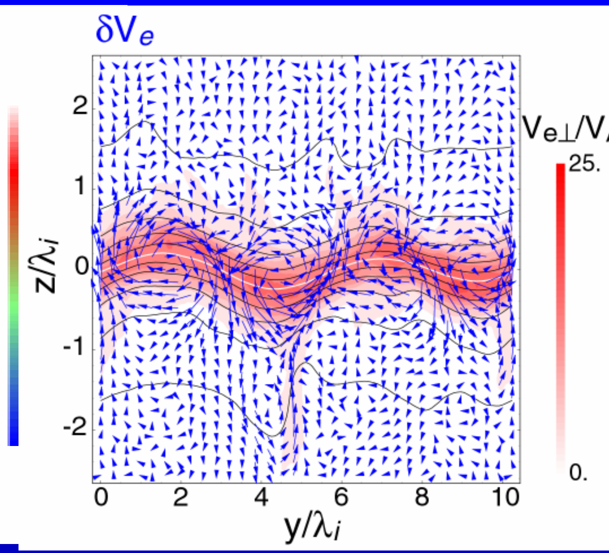
Surface: |J|, Line: Field line

Color on the surface: Ey, Cut plane：Jy



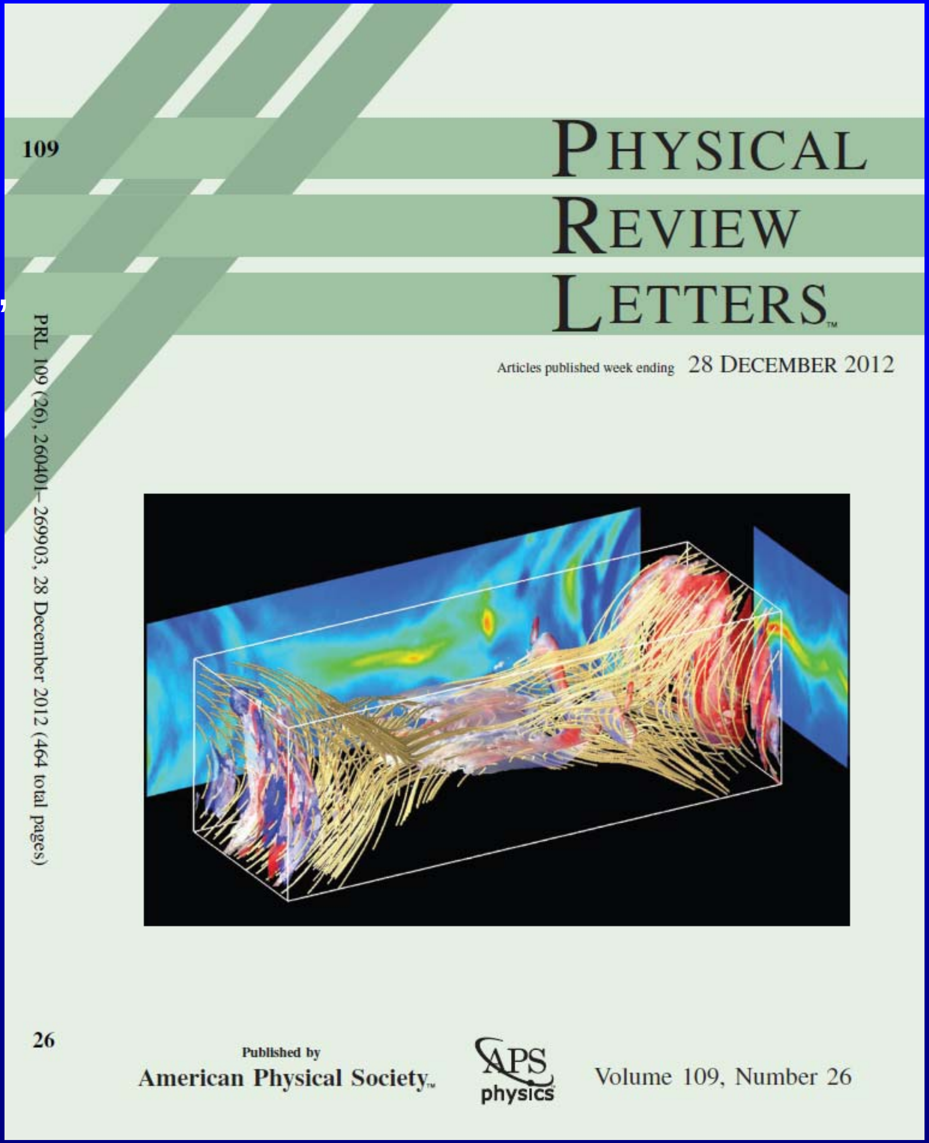
Anomalous Dissipation



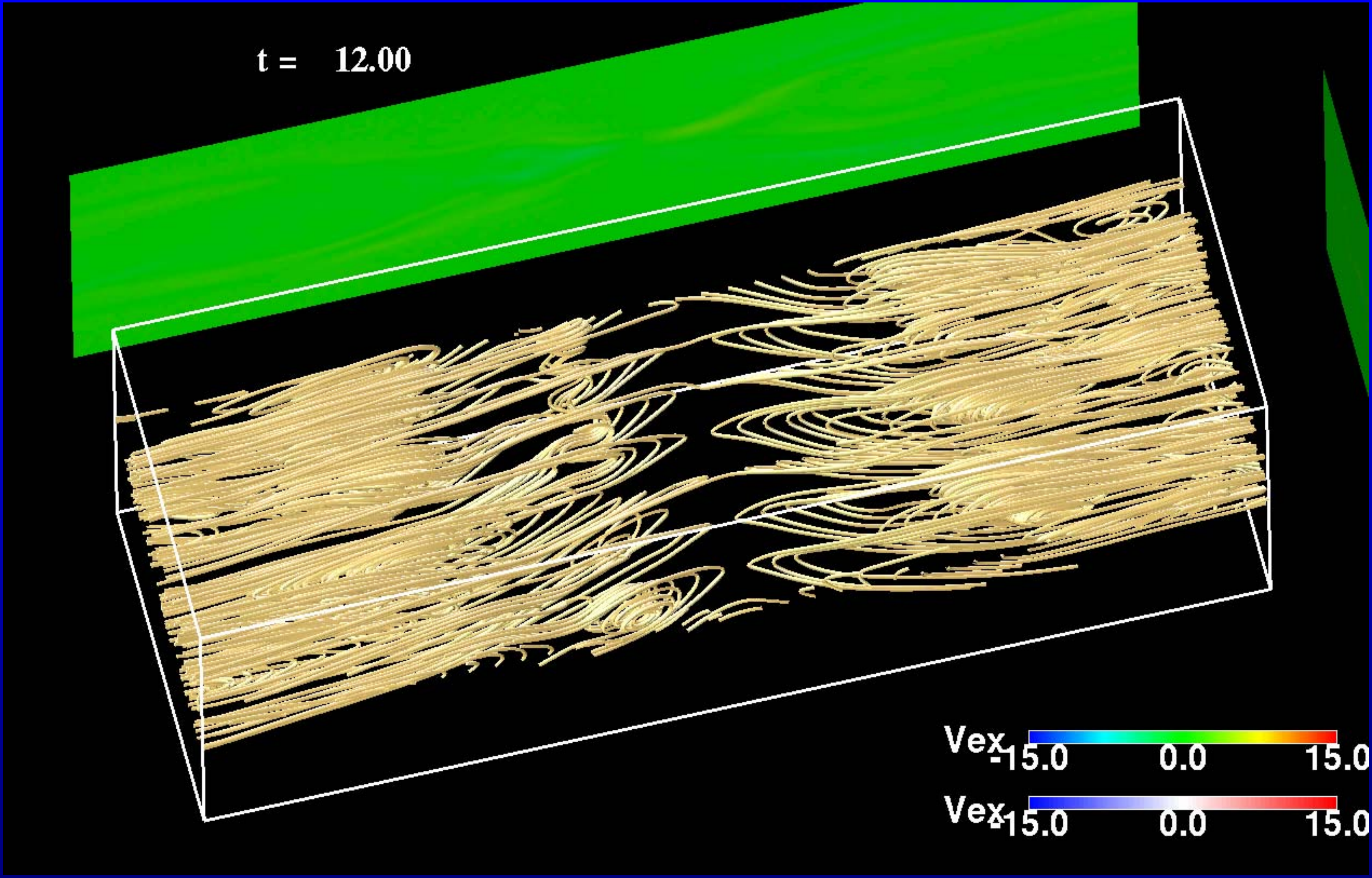


- 電磁波動による異常散逸
- ドリフト不安定性ではなくシア不安定性
- プラズモイドの発生により乱流が強化

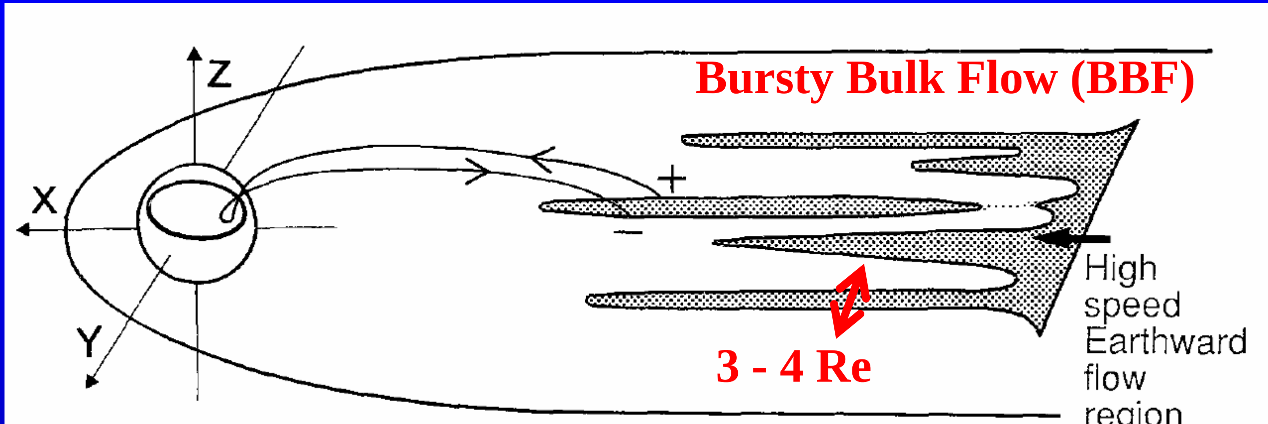
K. Fujimoto & RD. Sydora,
Plasmoid-induced turbulence in collisionless magnetic reconnection,
PRL, **109**, 265004, 2012



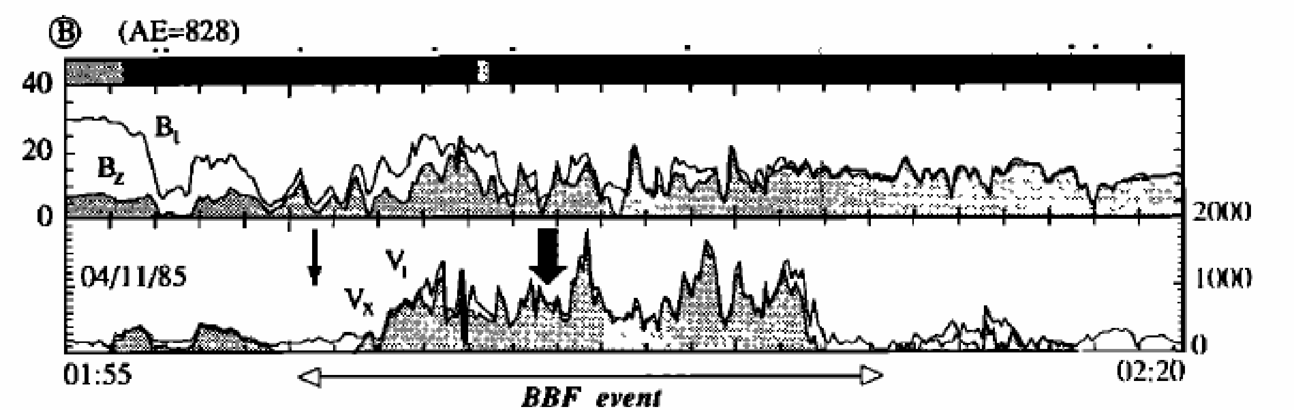
Surface: |Vex|, Line: Field line
Color on the surface:Vex, Cut plane：Vex



Observation in Earth Magnetotail



[Sergeev et al., Space Sci. Rev., 1996]



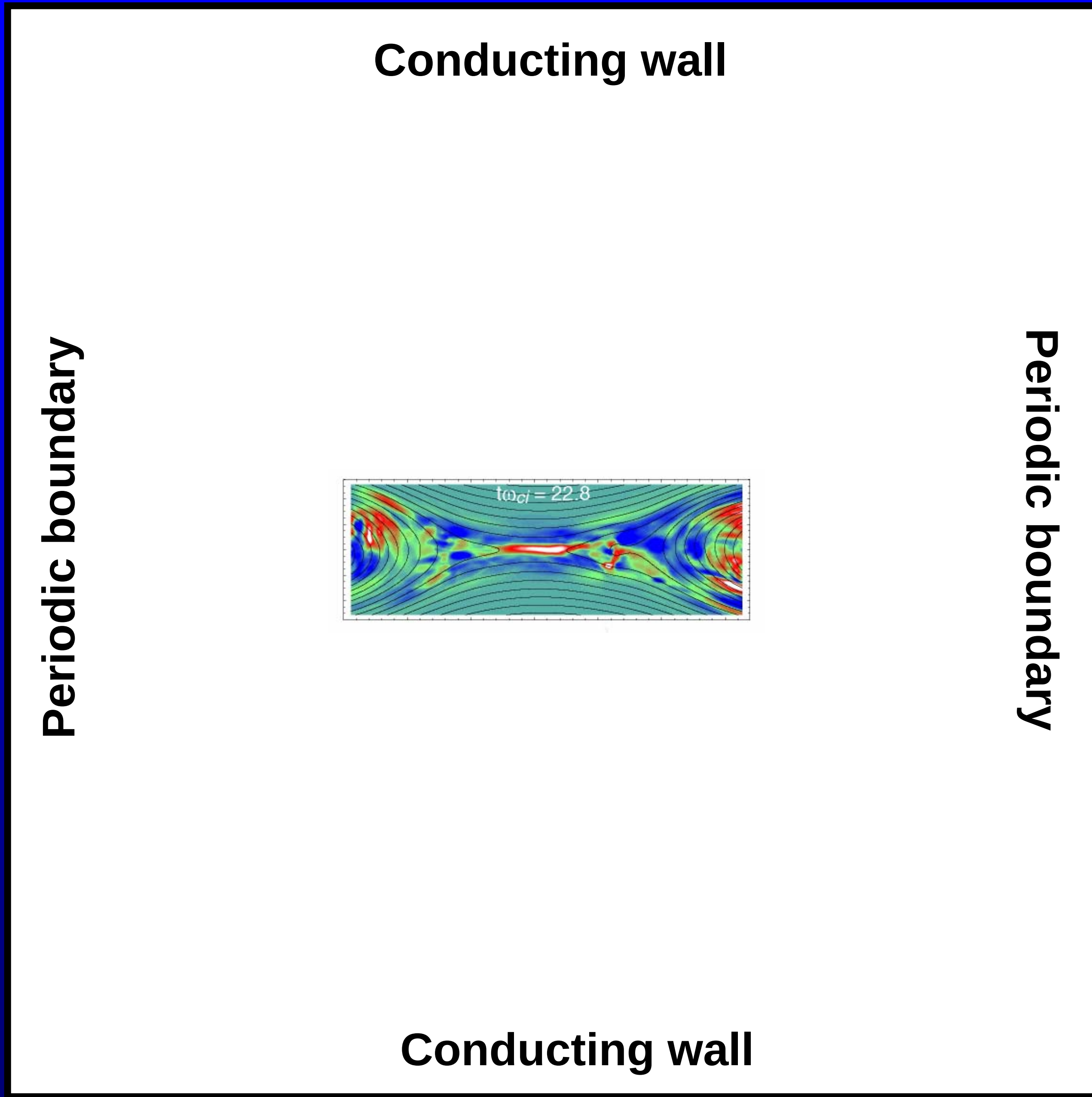
[Angelopoulos et al., 1992]

局所的、間欠的なプラズマ流。

磁気圏尾部におけるエネルギー輸送の大部分。

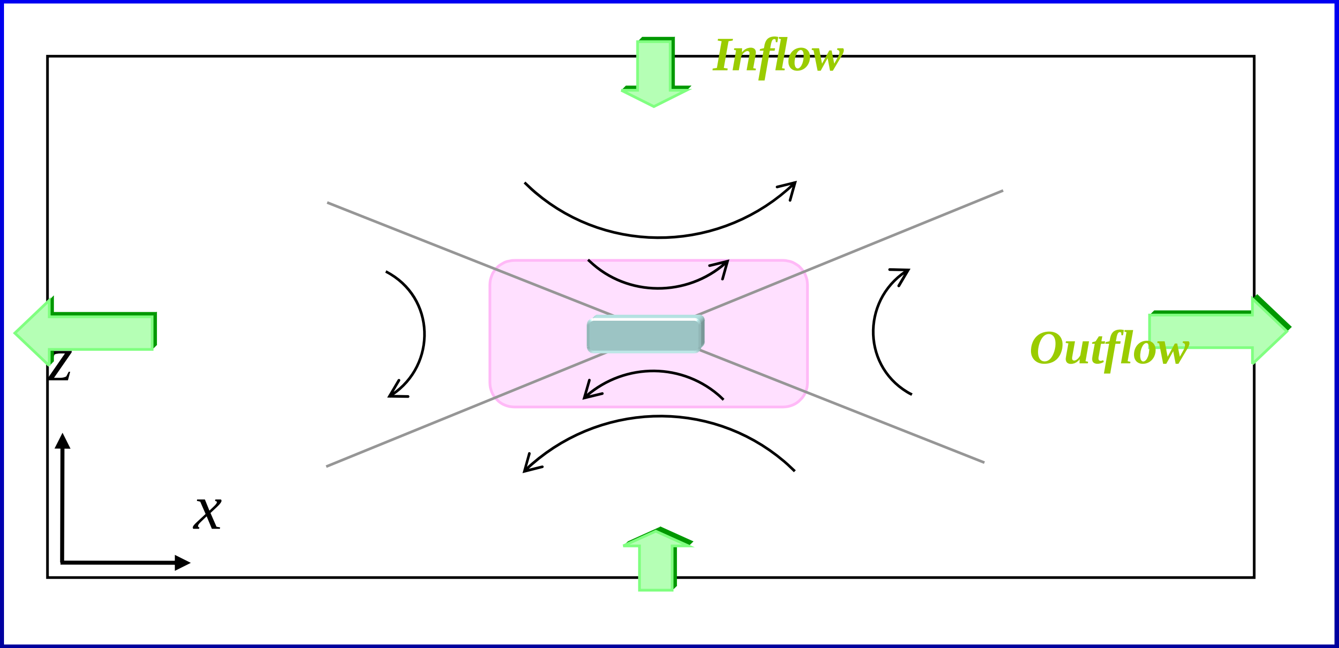
リコネクションとの関係？

System Size in the Current Model



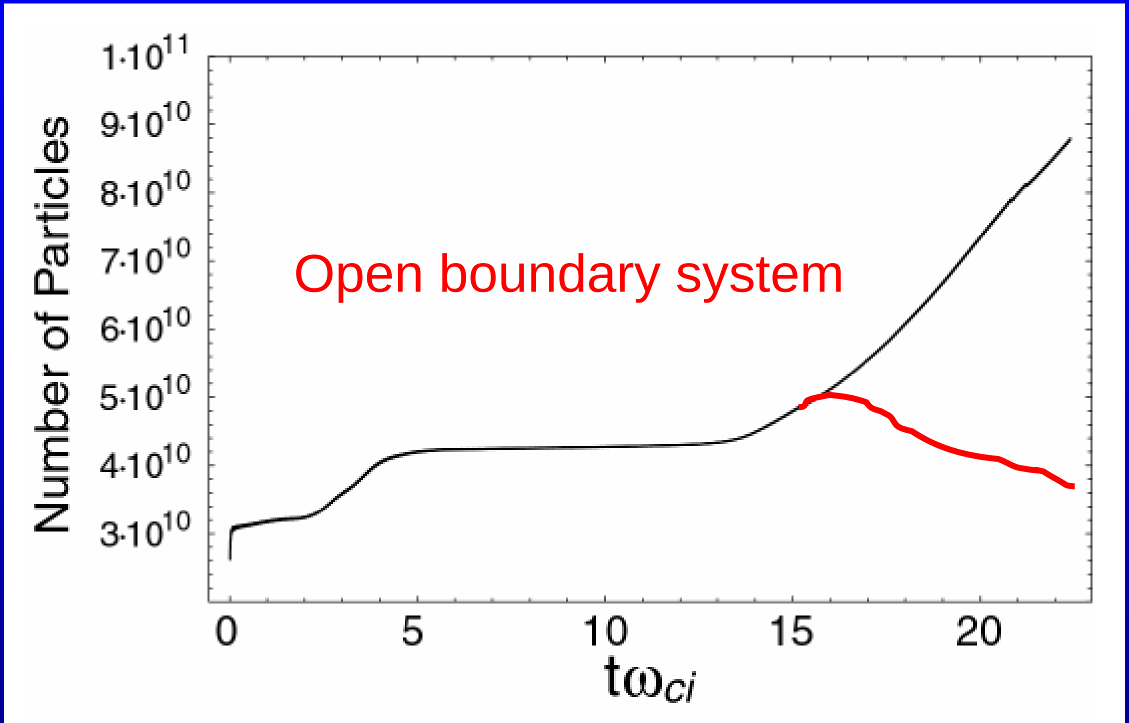
Toward Larger-Scale Simulation

開放境界　⇒　計算領域の縮小



Toward Larger-Scale Simulation

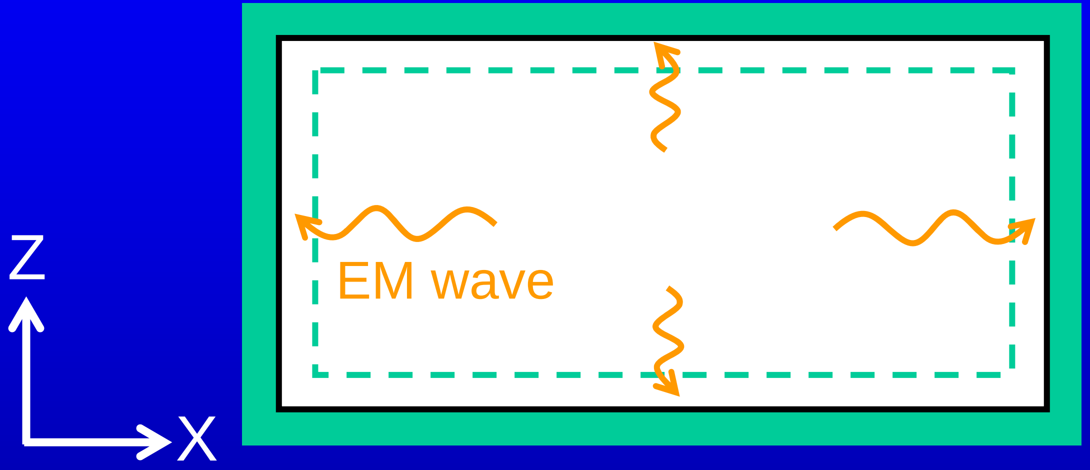
開放境界 ⇒ 粒子数の大幅減少



Open Boundary Condition

粒子・電磁場情報のコピー
（∂ f/∂n = 0）

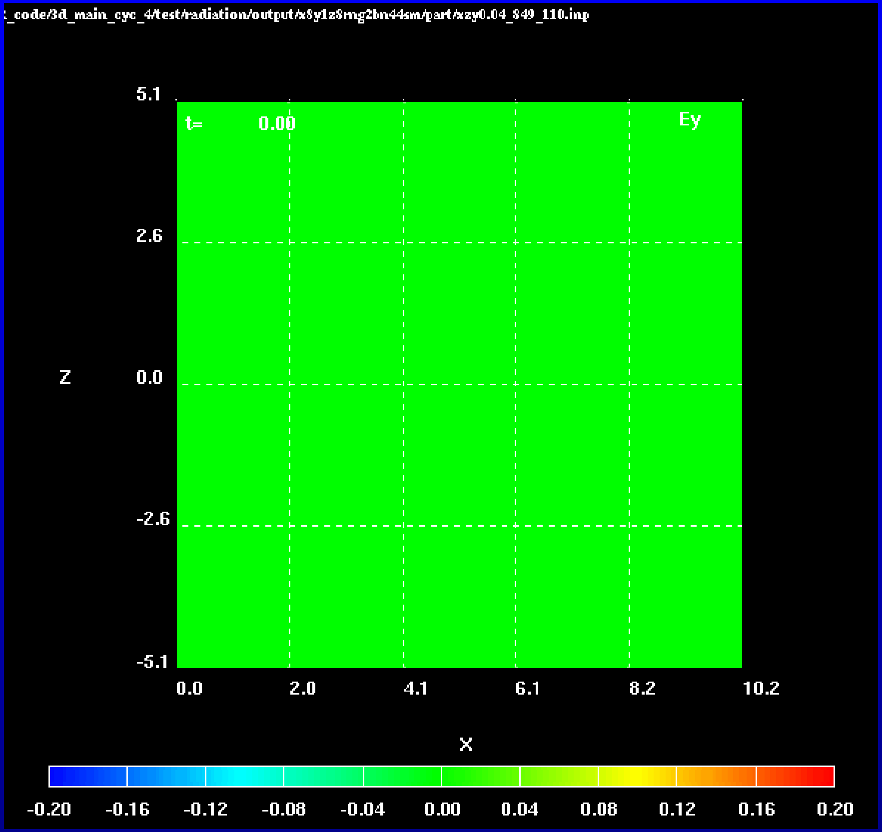
Birdsall & Langdon, IOP, 1995

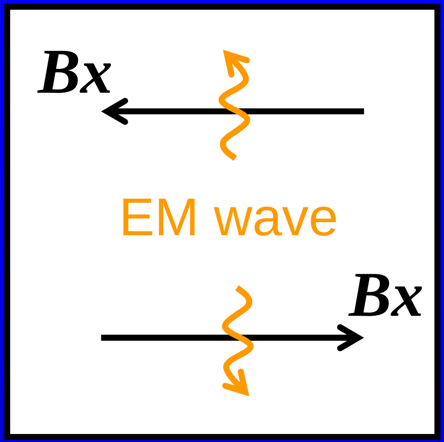


$$E_y = \pm c B_z$$
$$E_z = \mp c B_y$$
$$\frac{\partial E_y}{\partial t} = -c^2 \frac{\partial B_z}{\partial x} + c^2 \left(\frac{\partial B_x}{\partial z} - j_y \right)$$
$$\frac{\partial E_z}{\partial t} = -c^2 \frac{\partial B_y}{\partial x} - c^2 j_z$$

$$E_x = \pm c B_y$$
$$E_y = \mp c B_x$$
$$\frac{\partial E_x}{\partial t} = -c^2 \frac{\partial B_y}{\partial z} - c^2 j_x$$
$$\frac{\partial E_y}{\partial t} = c^2 \frac{\partial B_x}{\partial z} - c^2 \left(\frac{\partial B_z}{\partial x} + j_y \right)$$

Test Simulation





Summary

We have explored a significant frontier of magnetic reconnection using large-scale PIC simulations.

Further larger-scale PIC simulations may reveal the connection between the turbulent x-line model and the bursty flow signature in the downstream region.

Open boundary condition is a key technique to extend the system size in the current density direction.

At this moment, we have confirmed that EM waves propagate successfully cross the boundary.