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Multi-Hierarchy Simulation Bridging Gaps between Macro and Micro Physics of Magnetic Reconnection

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Contents

How to interlock macroscopic and microscopic systems

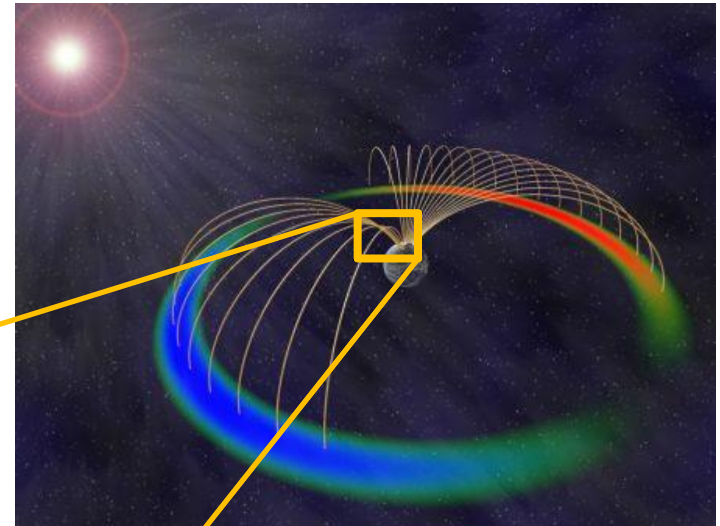
1. The information of micro physics is replaced by/reduced to some macroscopic physical parameters in macro system. ➔ **renormalization method**
2. Divide the phase space into high energy region and low energy region and exchange the information of physics in two different regions at intermediate energy region. ➔ **?**
3. Divide the real space into macroscopic and microscopic (kinetic) regions, and exchange the information at the interface region ➔ **boundary-interlocked method**

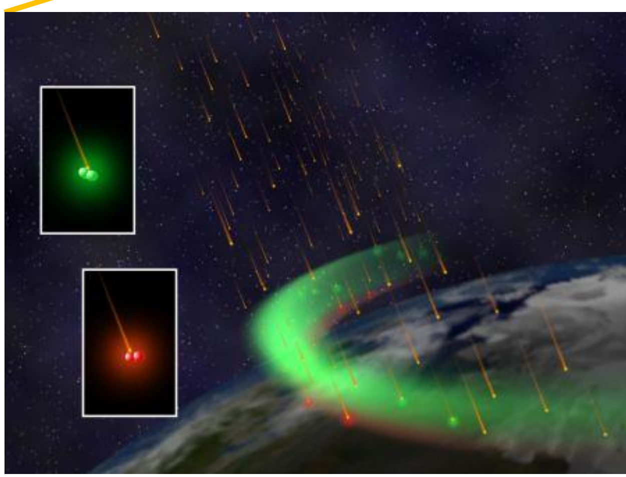
1-A. Macro-Micro Interlocked model for Auroral Arc Formation

[T. Sato, H. Hasegawa, N. Ohno]

The twin plasma convection flow generated in the vicinity of the magnetospheric equator by the solar wind is expected to induce the region 1 current system [2].

[2] T. Iijima and T. A. Potemra, J. Geophys. Res., **81**, 2165, 1976.



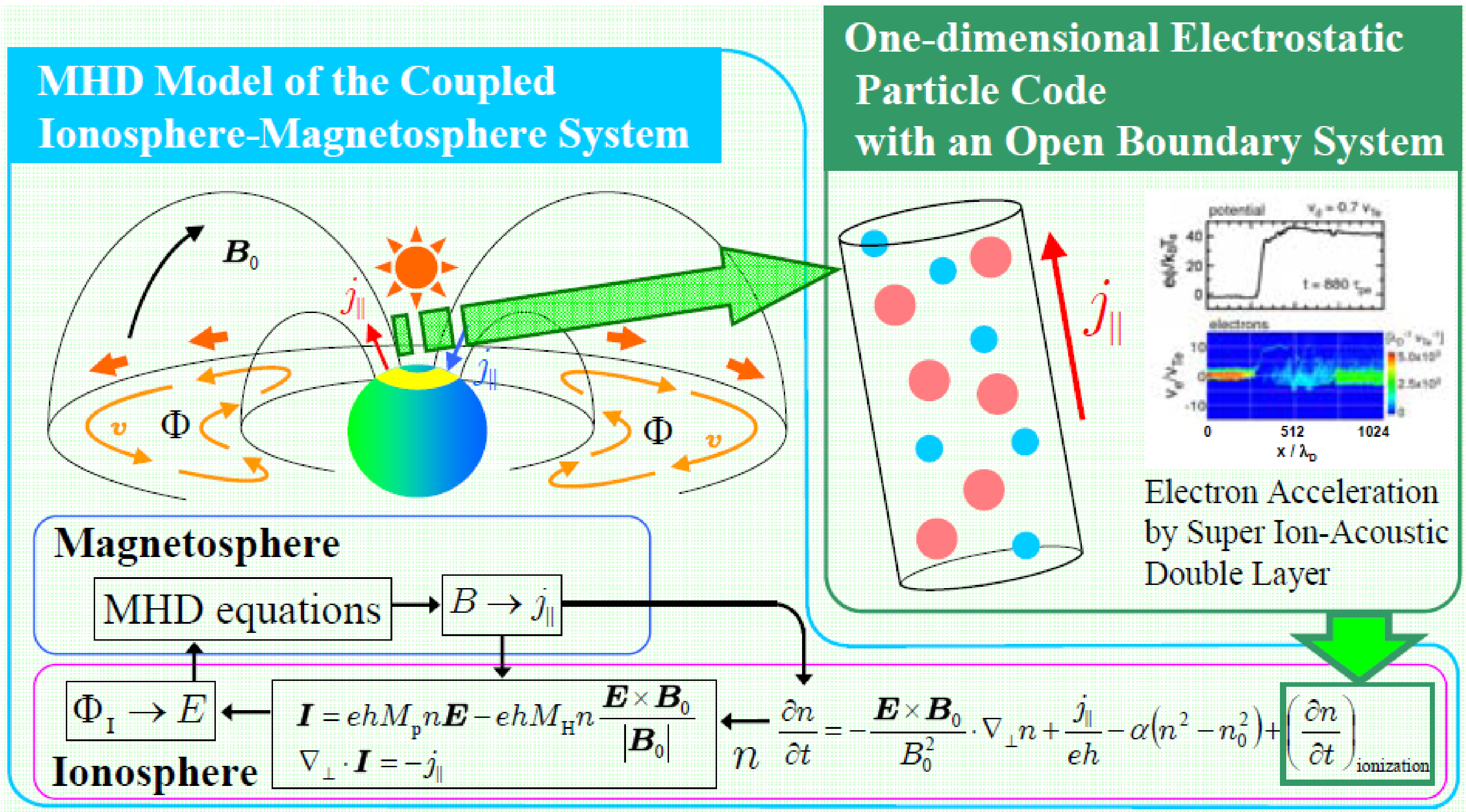


Downward electrons are strongly energized to produce excitation of ionospheric molecules. The ionospheric density is also strongly modulated by the local enhancement of ionization, which in turn changes the evolution of the magnetosphere-ionosphere current system.

➔ The **ion-acoustic double layer** is one of the candidates to explain the production of **auroral energetic electrons**.

These pictures are reprinted from "http://www.jamstec.go.jp/less/space_earth/ja/research-introduction/auroral.html".

Concept of Macro-Micro Interlocked Model



$j_\parallel$: Field aligned current density at ionosphere height

I : Height-integrated ionospheric current, n : Ionospheric plasma density

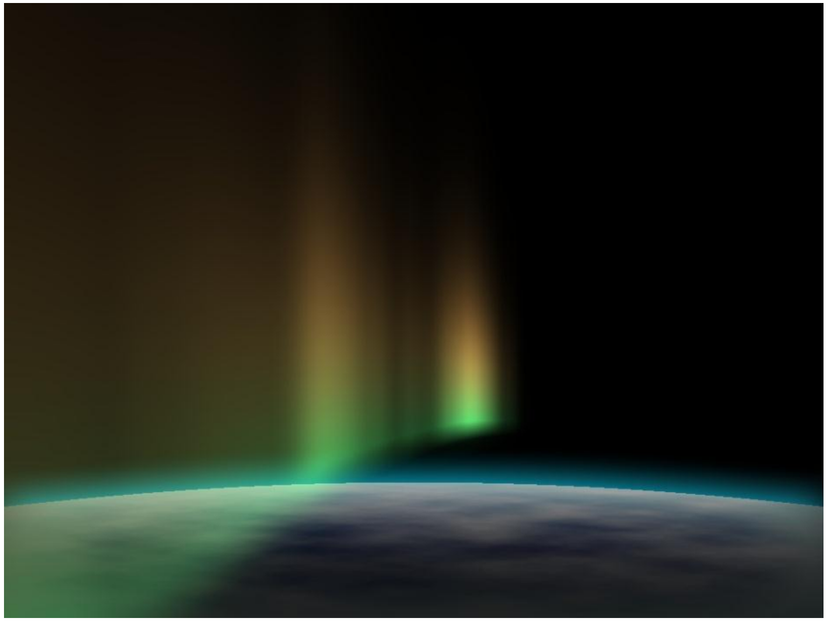
T. Sato, H. Hasegawa, and N. Ohno, Comput. Sci. Disc. **2**, 015007 (2009).
H. Hasegawa, N. Ohno, and T. Sato, Plasma Fusion Res. **6**, 2401128 (2011).
H. Hasegawa, N. Ohno, and T. Sato, NAGARE (J. Jpn. Soc. Fluid Mech.) **30**(5), 401 (2011) (in Japanese).

Auroral Emission

> Using the MMI code, we have been enabled to obtain the 3D-distribution data of the auroral emission intensity.

> Visualize the auroral lights by the special volume rendering method for large-scale.

Sight from the ground.



Sight from the high altitude.

N. Ohno, H. Hasegawa, and T. Sato, IEEE Trans. Plasma Sci. **39**, 2708 (2011).

1-B. Hybrid simulation of Plasma-Wall Interaction

Investigation of dynamics process on the surface of plasma facing materials in fusion device by means of molecular dynamics simulation, and hybrid MD- MC simulation

[A. M. Ito, A. Takayama and H. Nakamura]

MD-BCA hybrid simulation Method :

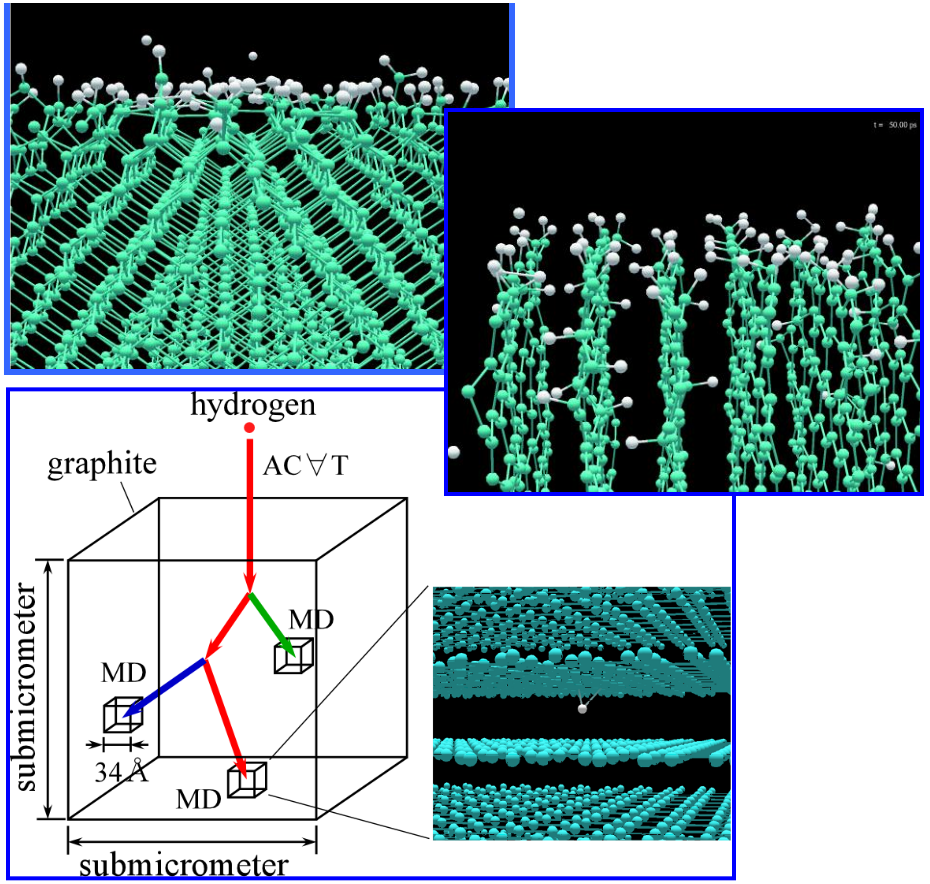
1. **<Low energy and nano-scale physics >**: An original MD-simulation code according to the kinetic equation of motion of hydrogen isotopes and carbon atoms.
2. **<High energy and sub-micrometer physics>:** An extended Binary Collision Approximation (BCA) code, "Atomic Collisions in any structured Target: AC∀T".

Accomplishments:

•Fundamental process of the chemical reactions between hydrogen isotopes and C in the atomic level.

•Mechanism of yielding hydrocarbon for graphite, diamond and amorphous carbon using MD simulation.

•Physical and chemical reactions between H and graphite in sub-micro meter by the MD- AC∀T hybrid code.



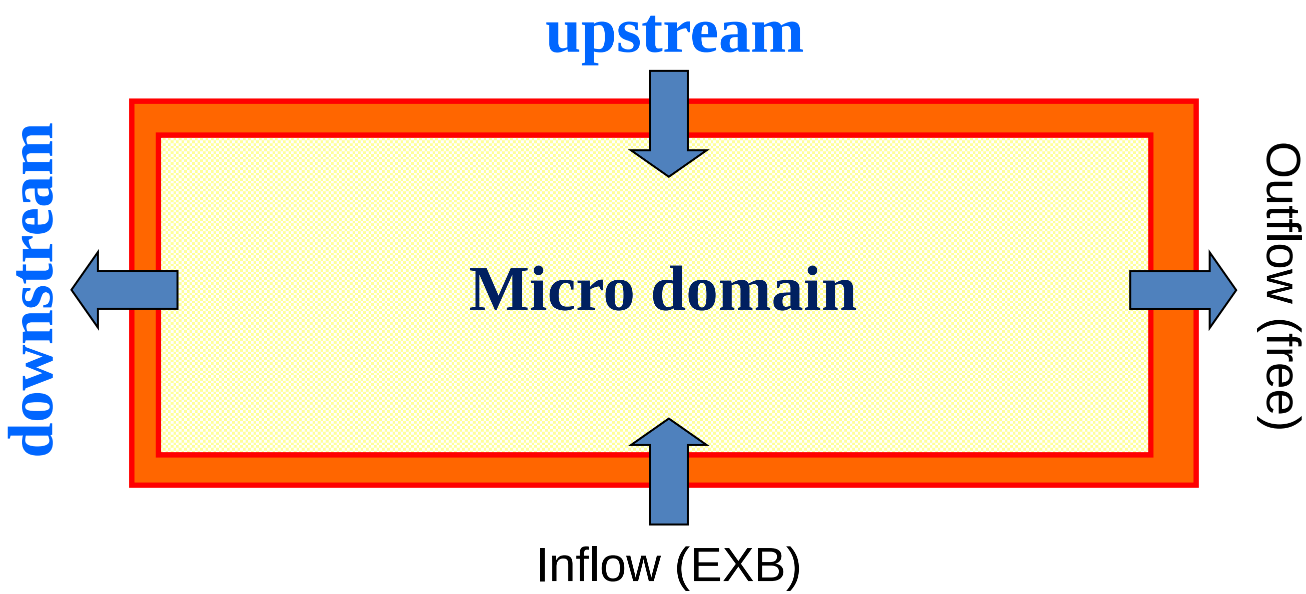
Snapshot of hydrocarbon generation for diamond (left) and graphite (right). Schematic diagram of MD-BCA hybrid simulation (bottom).

1-C. Why is a multi-hierarchy model needed in magnetic reconnection research?

PArticle Simulation code for Magnetic reconnection in an Open system (*PASMO*) :

[H. Ohtani, et al, PFR, 2009]

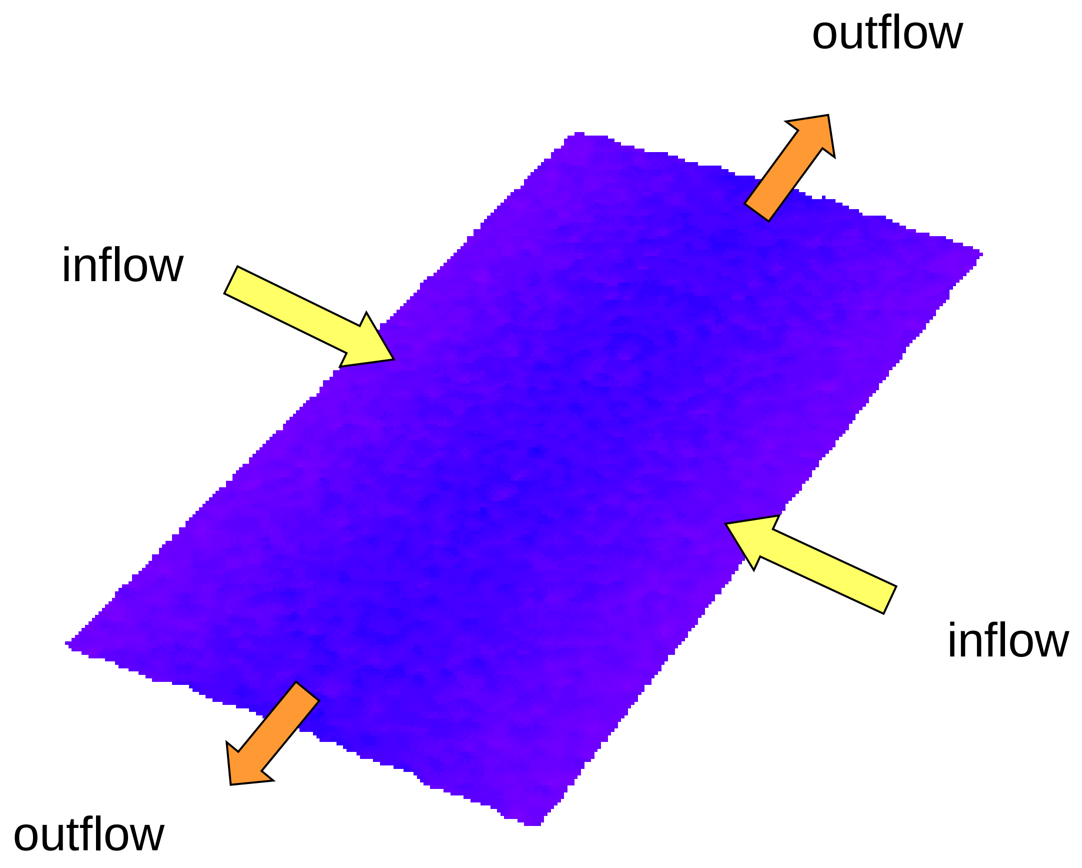
1. Upstream boundary: macroscopic information (T, v, B, E) → microscopic quantities
2. Downstream boundary: floating (free) condition



Steady reconnection is realized under some condition

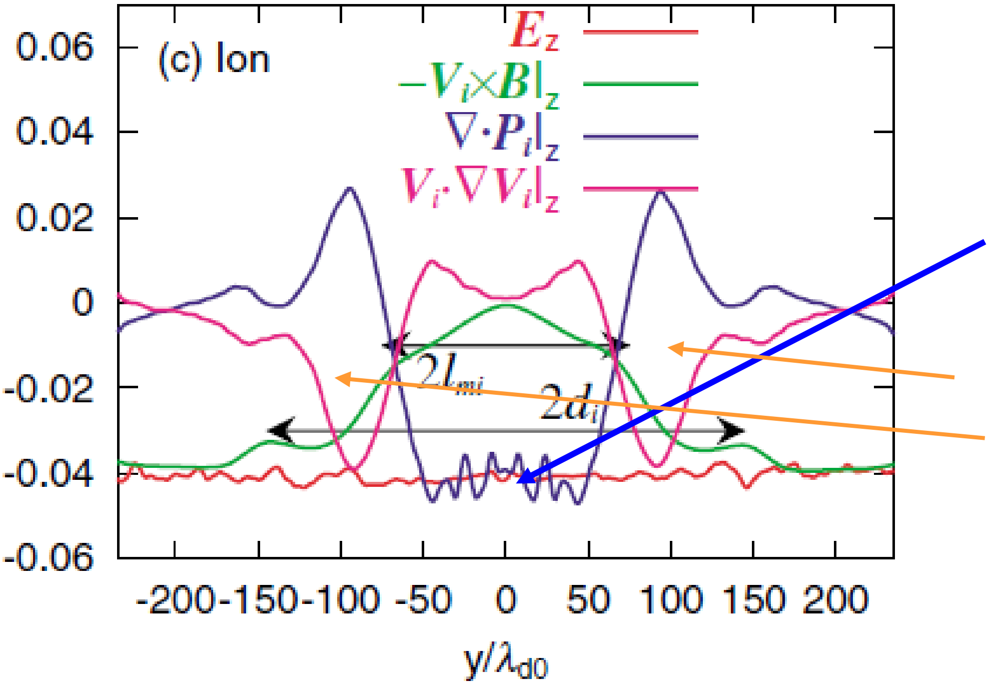
Current density Jz in 2D open system (PASMO code, small input window size)

[W. Pei, et al, PRL, 2001]

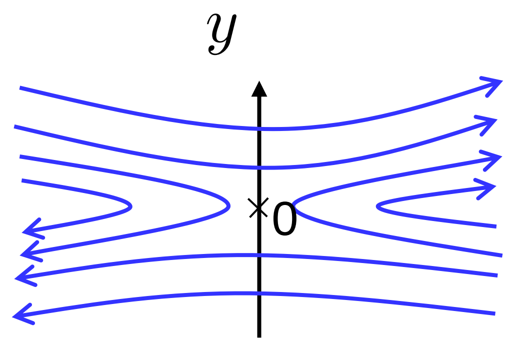


Frozen-in condition is violated due to meandering orbit effect (pressure tensor term) [A. Ishizawa, et al, PRL 2005]

$$\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B} / c \approx \frac{1}{en} \nabla \cdot \overleftrightarrow{\boldsymbol{P}}_i + \frac{m_i}{e} \boldsymbol{v}_i \cdot \nabla \boldsymbol{v}_i$$



Profile of terms along the y axis passing through X point

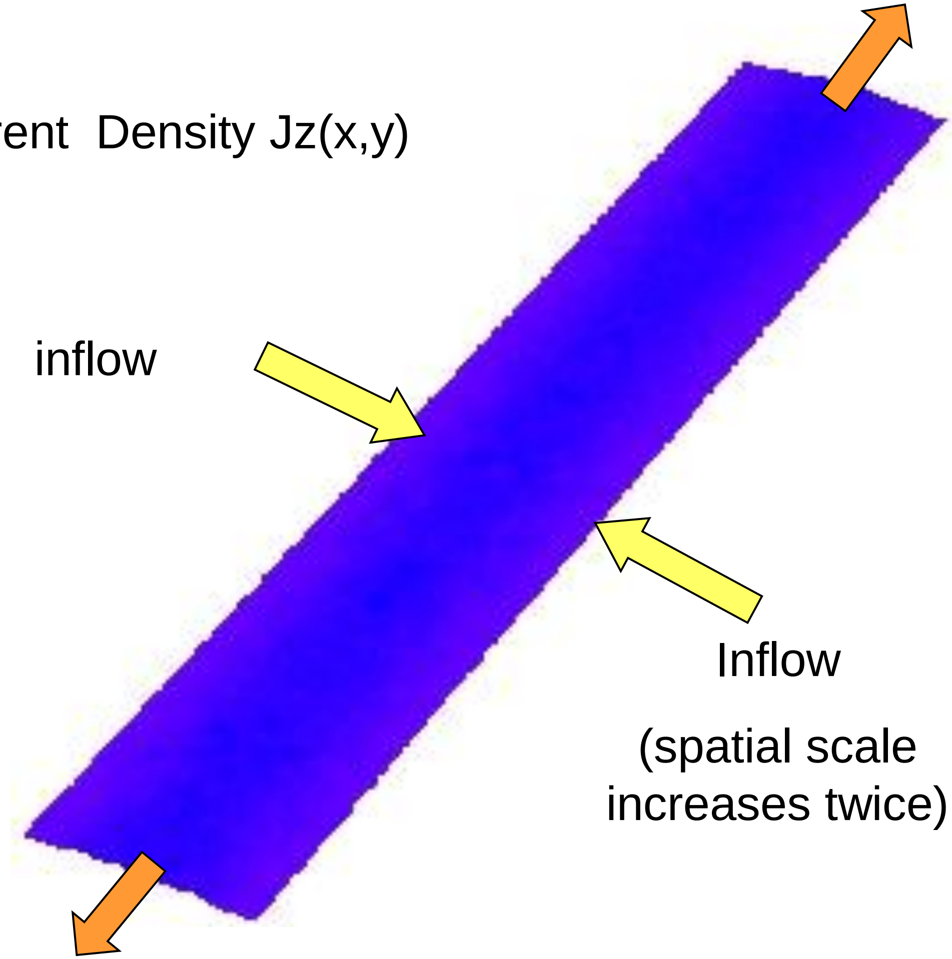


- The pressure tensor term is dominant.
- The pressure tensor term almost cancels out the inertia term.
- $y > d_i$: MHD condition holds.

Intermittent reconnection occurs for upstream boundary condition for a wide inflow window case

Current Density Jz(x,y)

inflow



Inflow

(spatial scale increases twice)

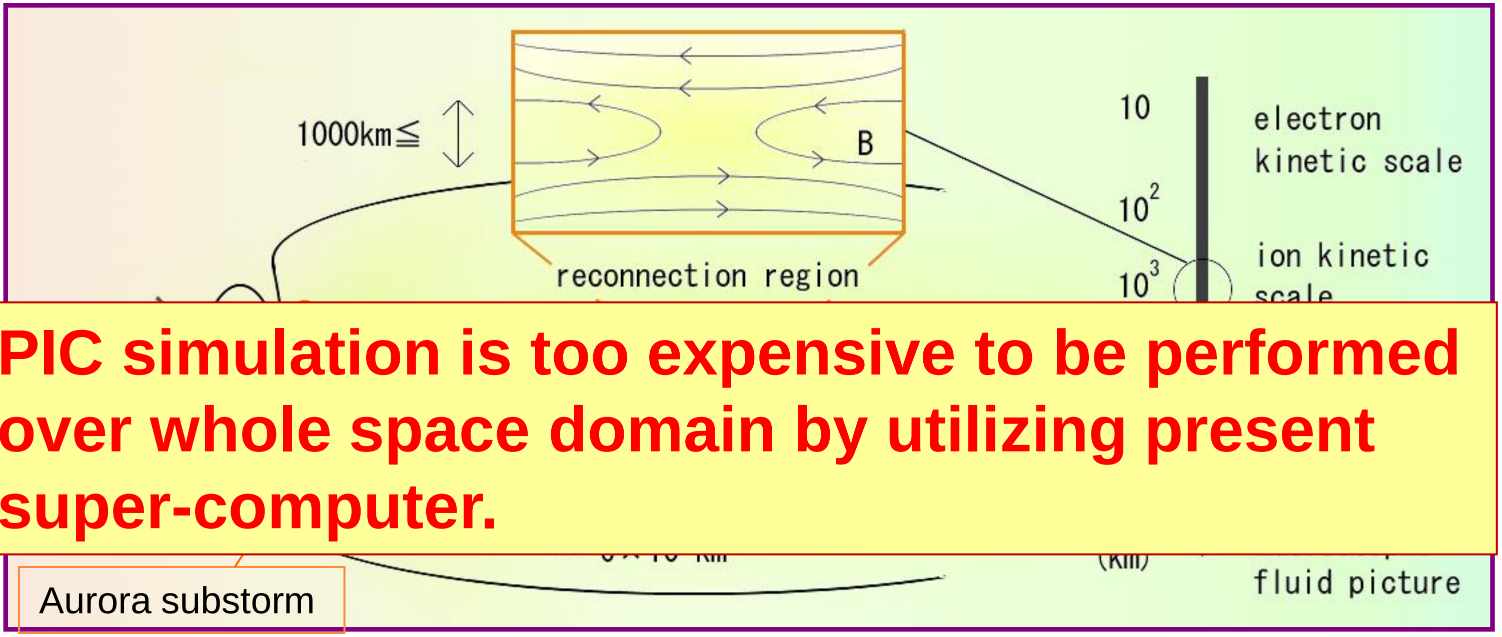
outflow

Microscopic dynamical behavior of the reconnection system is deeply coupled with macroscopic physics, which is described as upstream boundary conditions in this model.

- ➔ **Consistent model is needed**
- ➔ **Simple and straightforward solution is to extend the region of PIC simulation to more wide region covering whole reconnection system.**

Is it possible to simulate magnetic reconnection in earth magnetosphere using PIC model ?

Magnetic substorm in earth magnetosphere



PIC simulation is too expensive to be performed over whole space domain by utilizing present super-computer.

A.T.Y.Lui Tutorial on Geomagnetic Storm and Substorm ,IEEE trans on Plasma Physics ,**28**,1854(2002)

If PIC model with space grids comparable to electron size is applied to this problem, we need➔

$$N_{pt} = 10^5 \times 10^5 \times 10^5 \times 30 = 3 \cdot 10^{16}$$

$$\Rightarrow \text{CPU memory} = 4 \cdot 10^{18} = 4 \cdot 10^3 \,\text{PetaByte}$$

2. Multi-hierarchy simulation for magnetic reconnection phenomena

1. Microscopic physics

Excitation of magnetic reconnection needs a microscopic process, which leads to the generation of electric resistivity, such as wave-particle interaction, a binary collision, etc.

➔ Kinetic model

2. Macroscopic physics

Magnetic reconnection results in global plasma transport and global change of field topology. Dynamical behavior of the reconnection system is strongly coupled with an external system (macroscopic world).

➔ MHD model

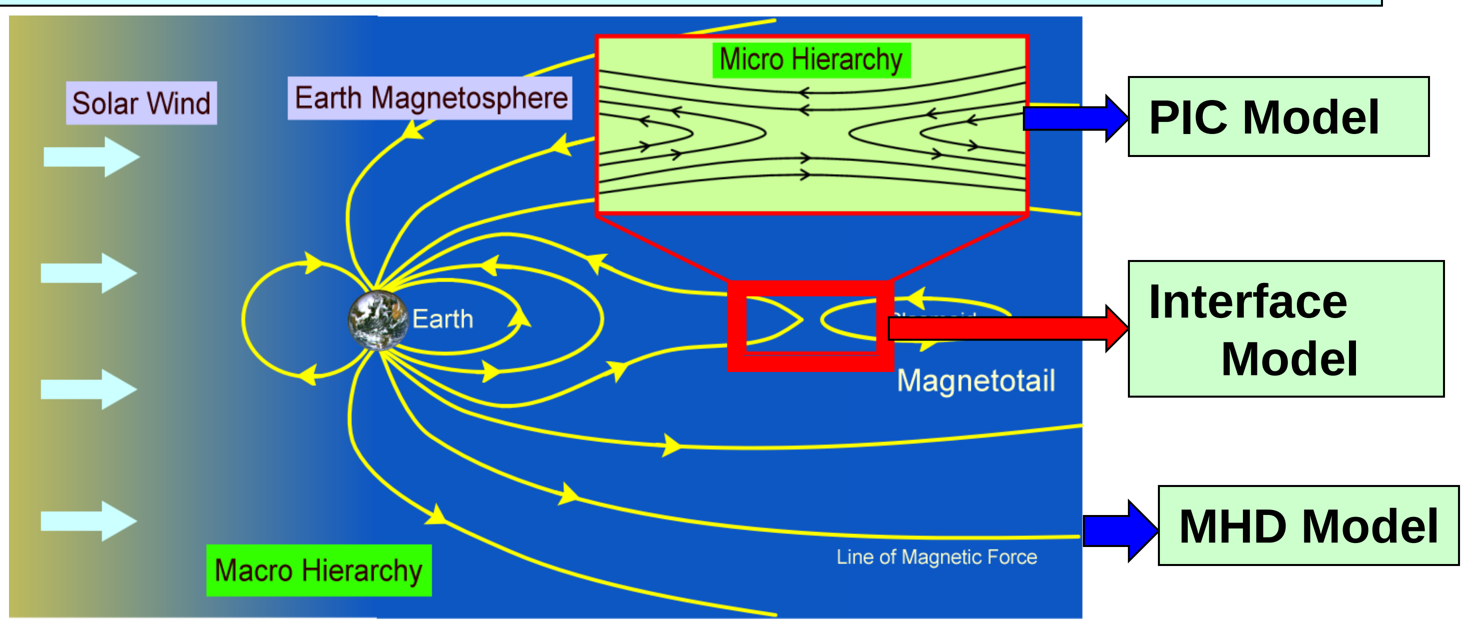
3. Multi-hierarchy simulation model to solve both microscopic physics and macroscopic physics consistently and simultaneously is needed for full understanding of magnetic reconnection.

2.1 Multi-hierarchy model

2.1.A domain decomposition method

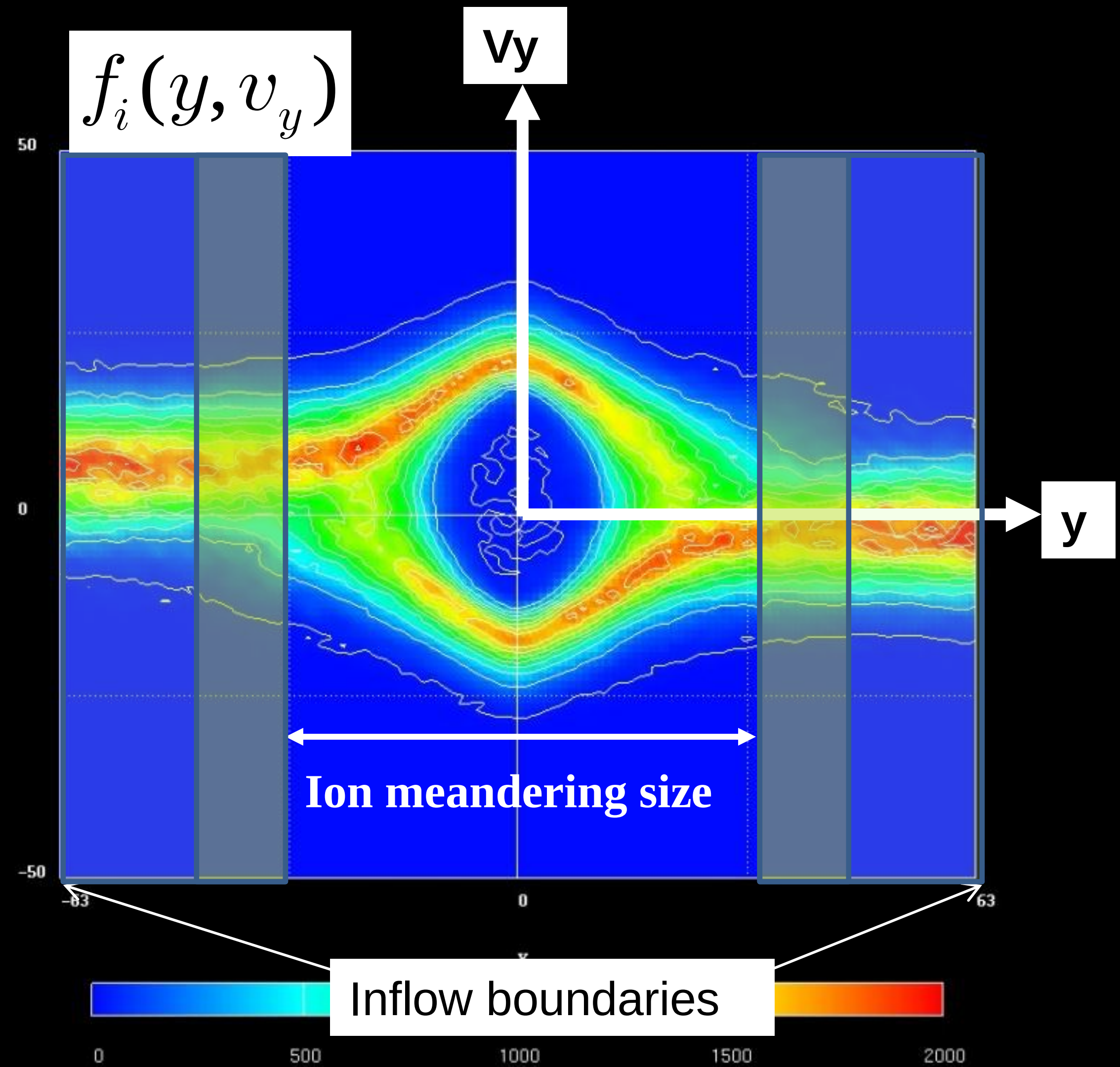
Multi-hierarchy simulation model to interlock three different simulation models based on domain decomposition method

1. **MHD model to describe global dynamics of reconnection phenomena,**
2. **PIC model to describe the microscopic processes in the vicinity of reconnection point, and**
3. **interface model to describe the interaction between micro and macro hierarchies.**



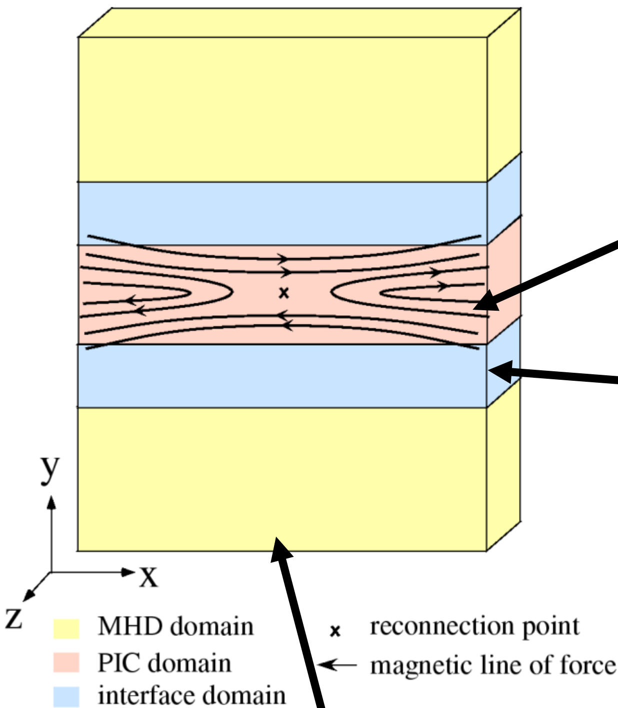
Ion distribution function along inflow direction (y—axis) from PIC simulation data [R. Horiuchi, et al, CiCP 2008]

1. Distribution is largely modified due to meandering effect inside meandering orbit size. ➔ **PIC model**
2. Distribution remains shifted-Maxwellian at outside of meandering orbit size. ➔ **MHD model**
3. **Interface domain** is inserted into PIC-side region of MHD domain for numerical stability.



Simulation domains for multi-hierarchy model

[S. Usami, et al, CiCP 2008.]



PIC domain

$$\boldsymbol{B}, \boldsymbol{E},$$

$$\boldsymbol{v}_j, \boldsymbol{x}_j \text{(particles)}$$

Interface domain

Macroscopic quantity ($\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{u}$, P, ρ) in the interface domain Q is given by a **hand-shake scheme**;

$$Q_{\text{interface}} = aQ_{\text{MHD}} + (1-a)Q_{\text{PIC}}$$

New data for MHD

$$\boldsymbol{B}, P, \rho,$$

$$\boldsymbol{u}\text{(fluid)}$$

New data for PIC

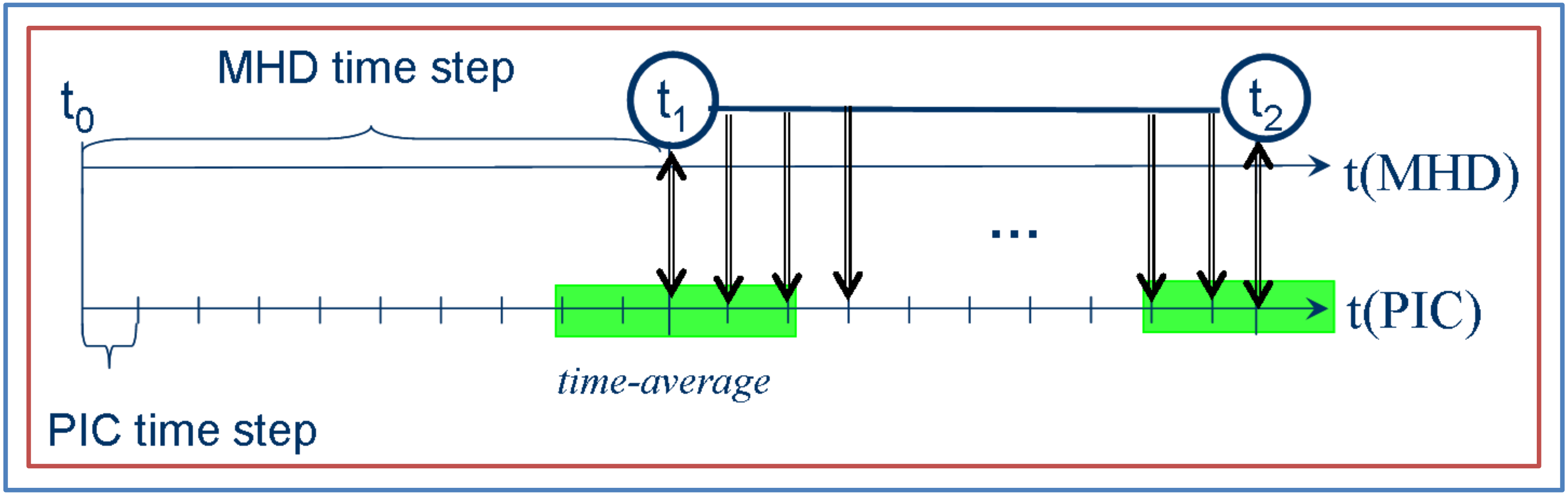
$$\boldsymbol{B}, \boldsymbol{E},$$

$$\boldsymbol{v}_j, \boldsymbol{x}_j$$

MHD domain

$$\boldsymbol{B}, P, \rho, \boldsymbol{u}\text{(fluid)}$$

2.1.B Multi-time step scheme for advancing time

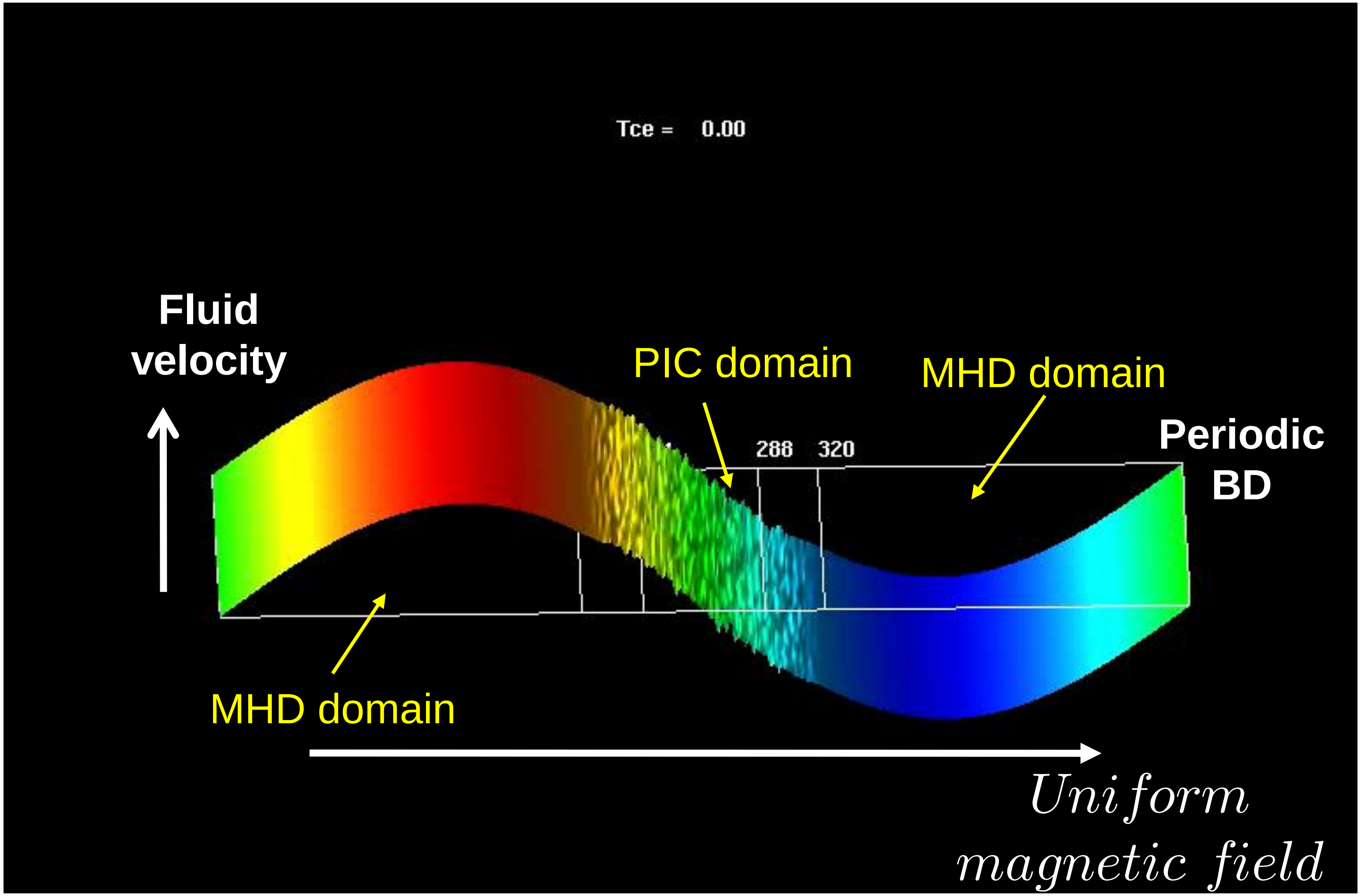


Large time step is for MHD, and small one is for PIC. From t_1 to t_2, PIC receives interpolated data at t_1 and at t_2 from MHD. On the other hand, PIC data averaged over several steps around t_1 is sent to MHD at t_1.

Multi-hierarchy model has been developed step by step by examining numerical applicability

1. **Propagation of 1D Alfven wave**
2. **Plasma inflow from upstream boundary towards reconnection region ➔ upstream interlocking model**
3. **Multi-hierarchy simulation of collisionless reconnection**
4. **Extension to the model with non-uniform space grids ➔ solve gaps in space**
5. **Plasma outflow along downstream direction ➔ towards downstream interlocking model**

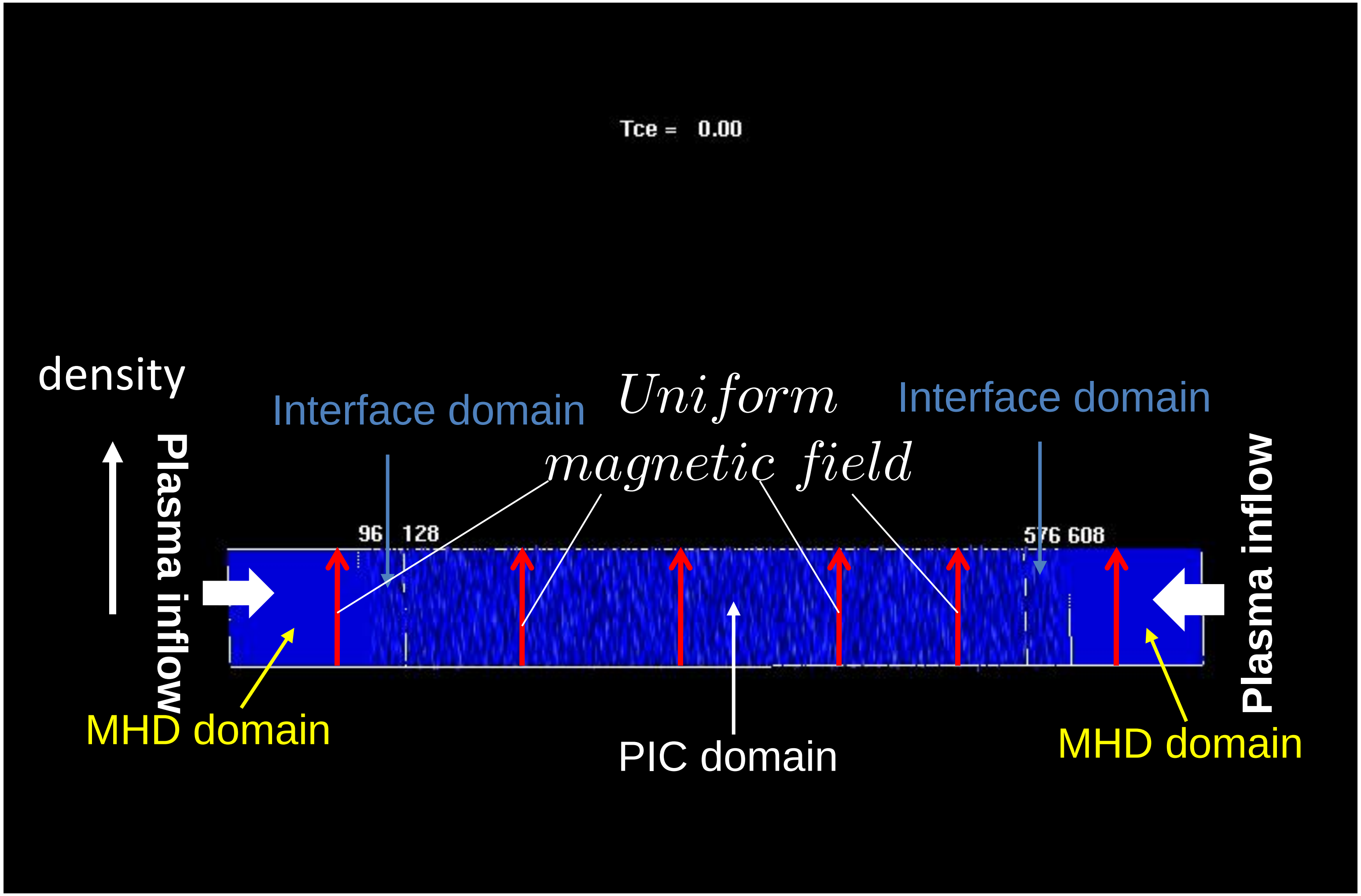
Multi-hierarchy Simulation (1)
- Propagation of 1D Alfven wave -



[Horiuchi et al, PFR 2010]

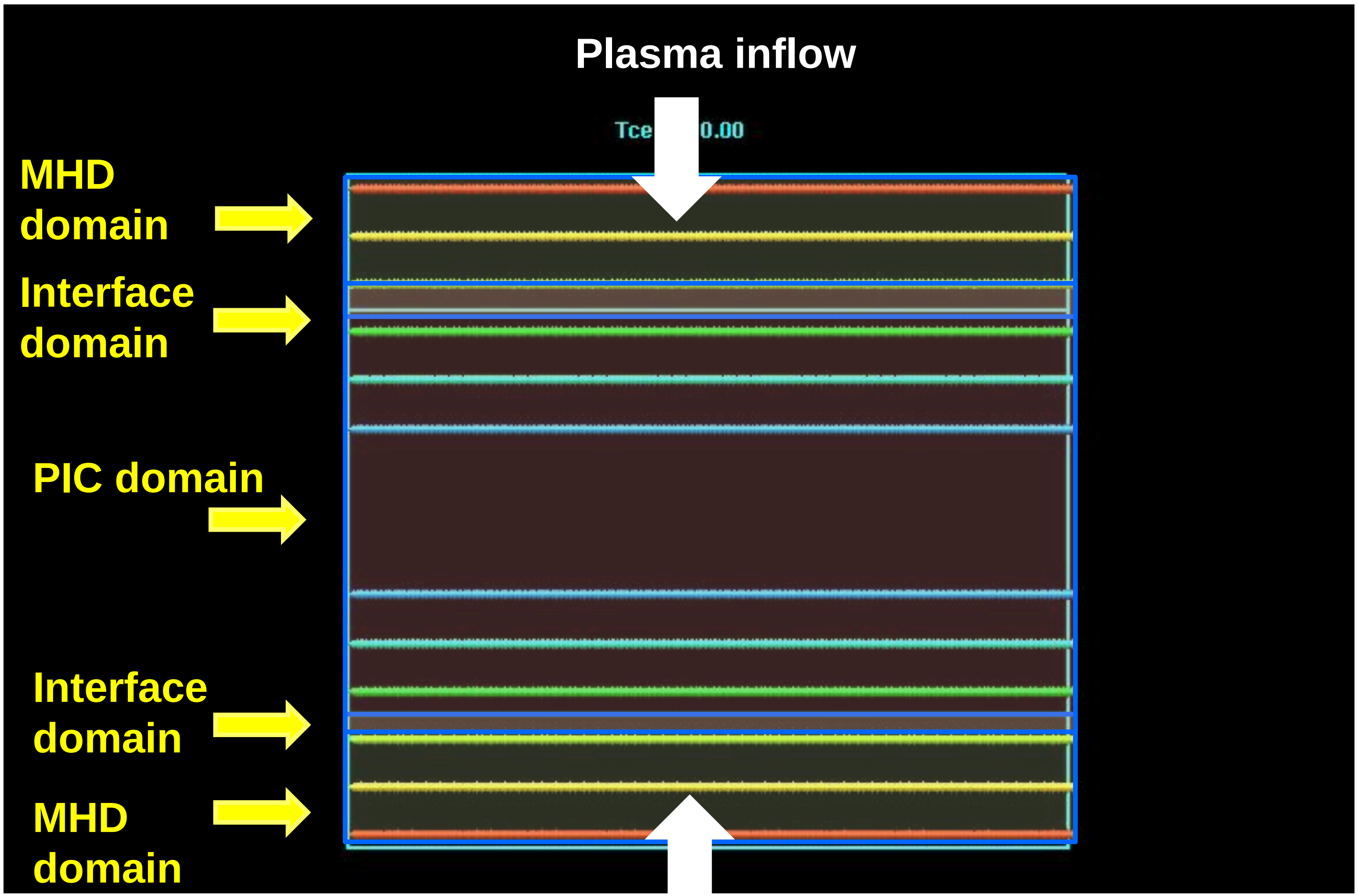
Multi-hierarchy Simulation (2)

- Plasma inflow from upstream boundary towards reconnection region -



[Usami et al, CiCP 2011]

Multi-hierarchy Simulation (3)
- Collisionless Driven Reconnection -



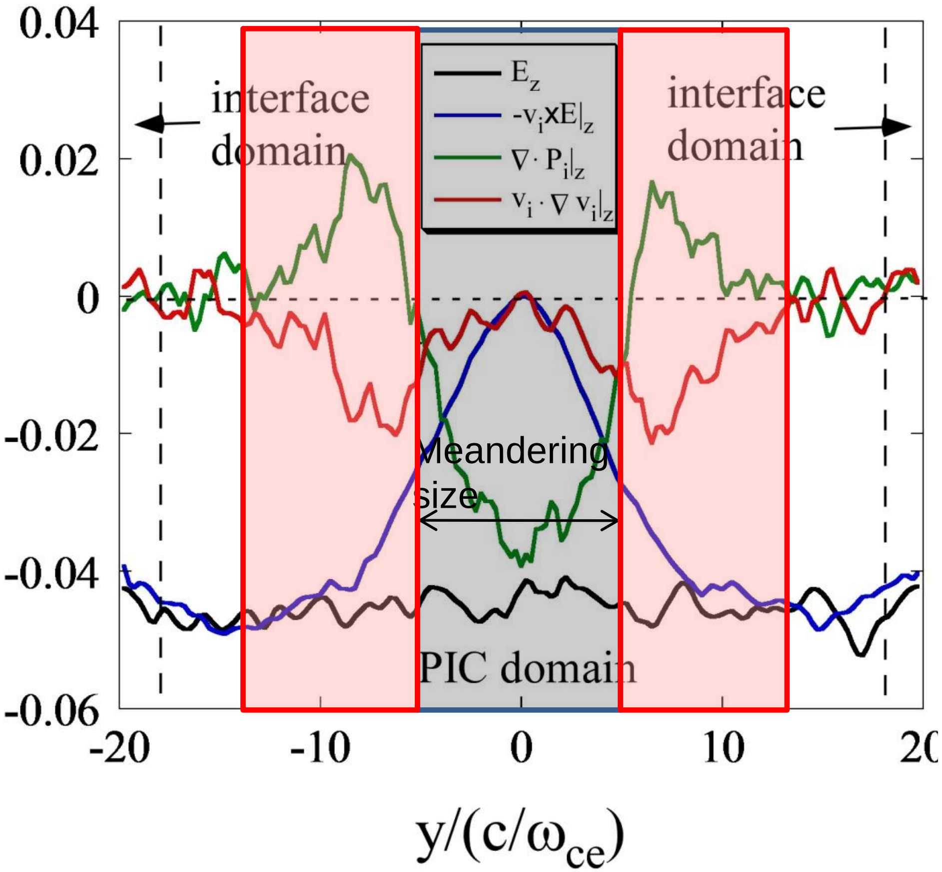
Plasma inflow

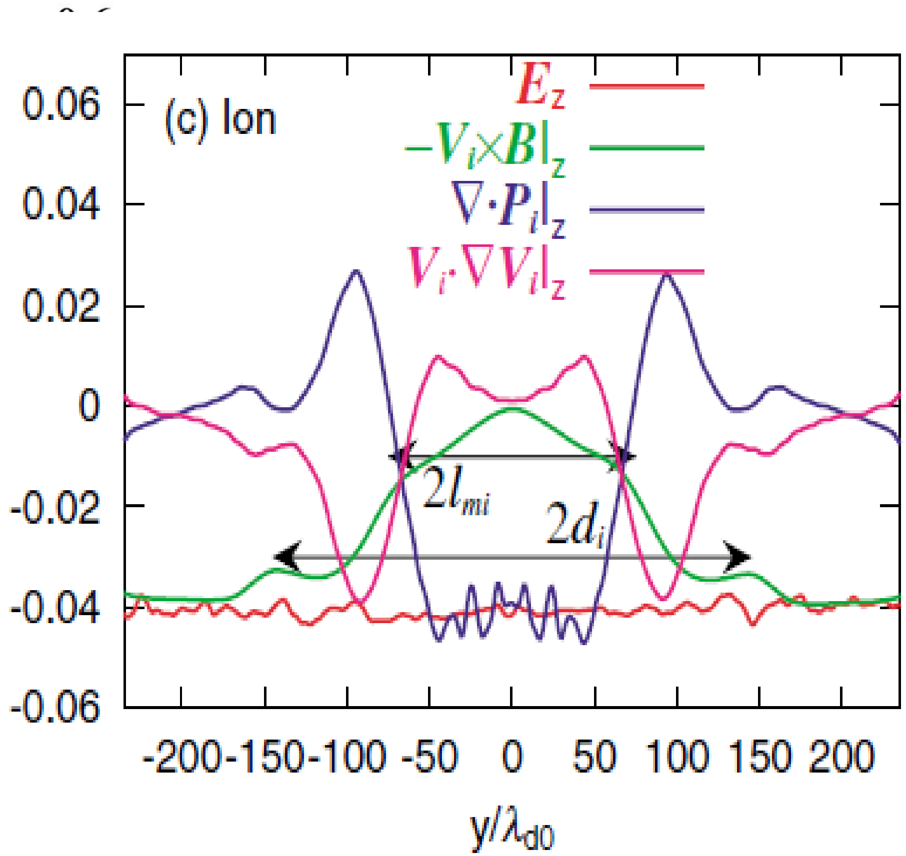
[Usami et al, PFR 2009]

Check of numerical applicability of multi-hierarchy model

Ion force balance

Pure PIC simulation

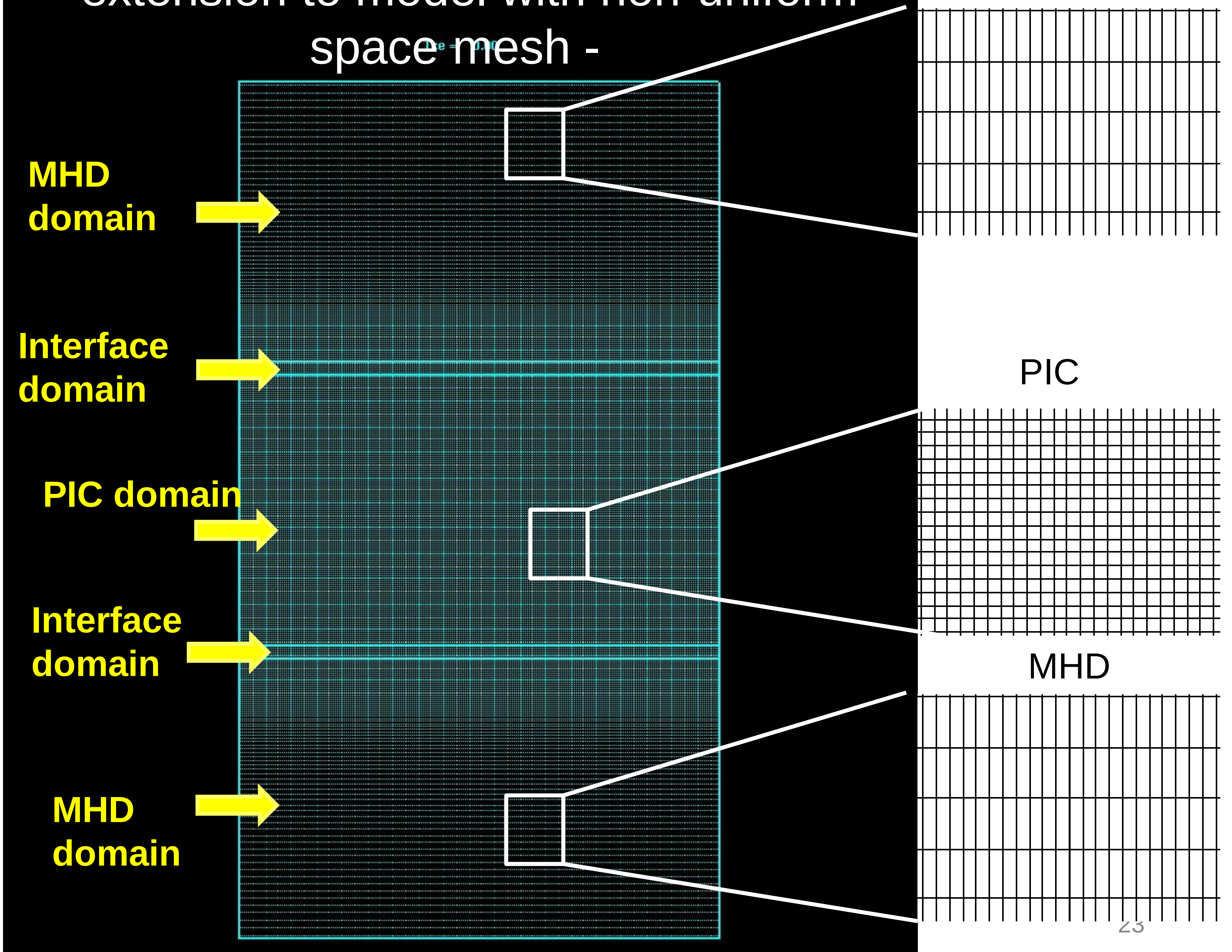




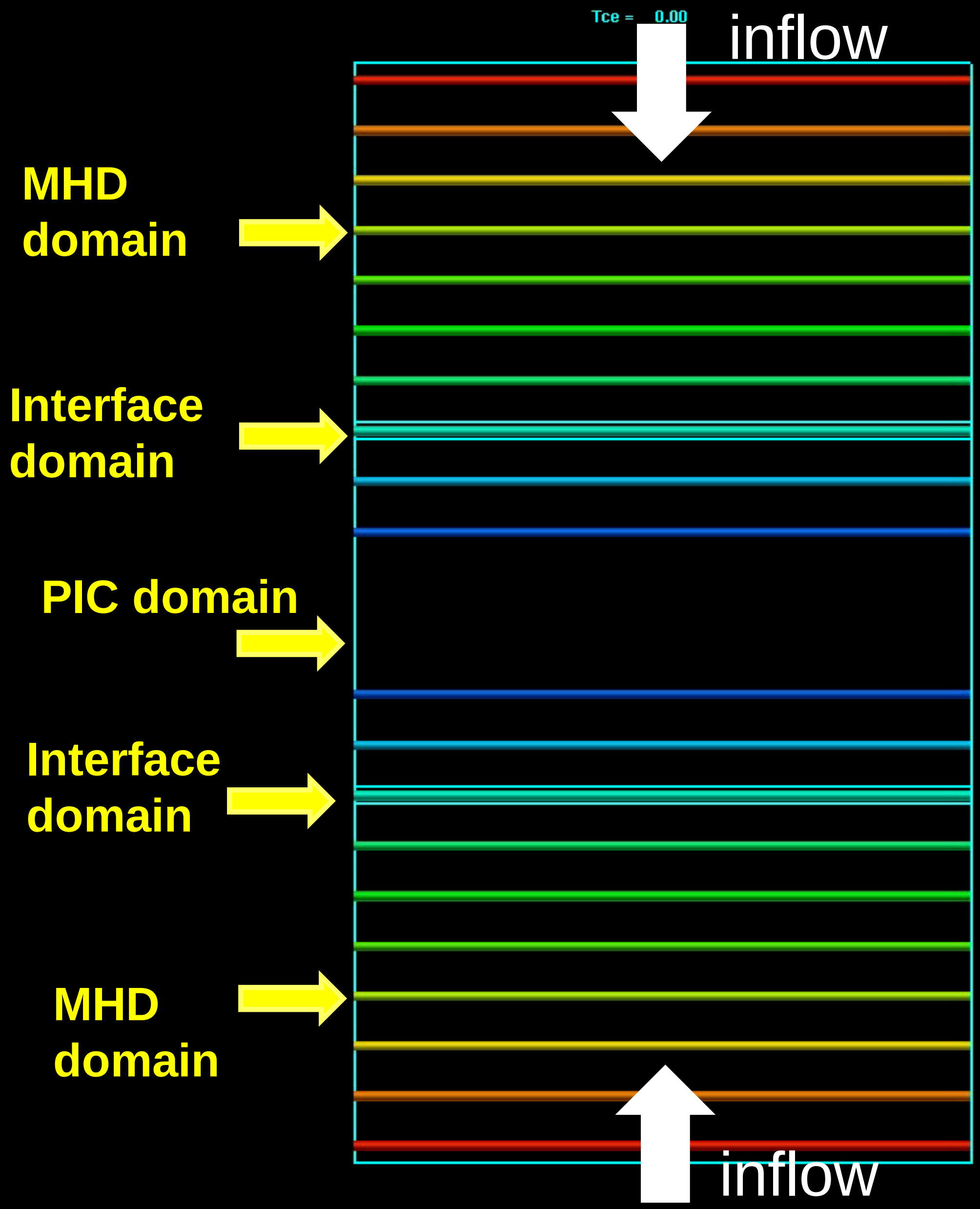
From the comparison with full PIC simulation data it is confirmed that reconnection process is described correctly.

Multi-hierarchy Simulation (4)

- extension to model with non-uniform space mesh -



Multi-hierarchy Simulation of Collisionless Driven Reconnection



Ongoing extensions and future problems

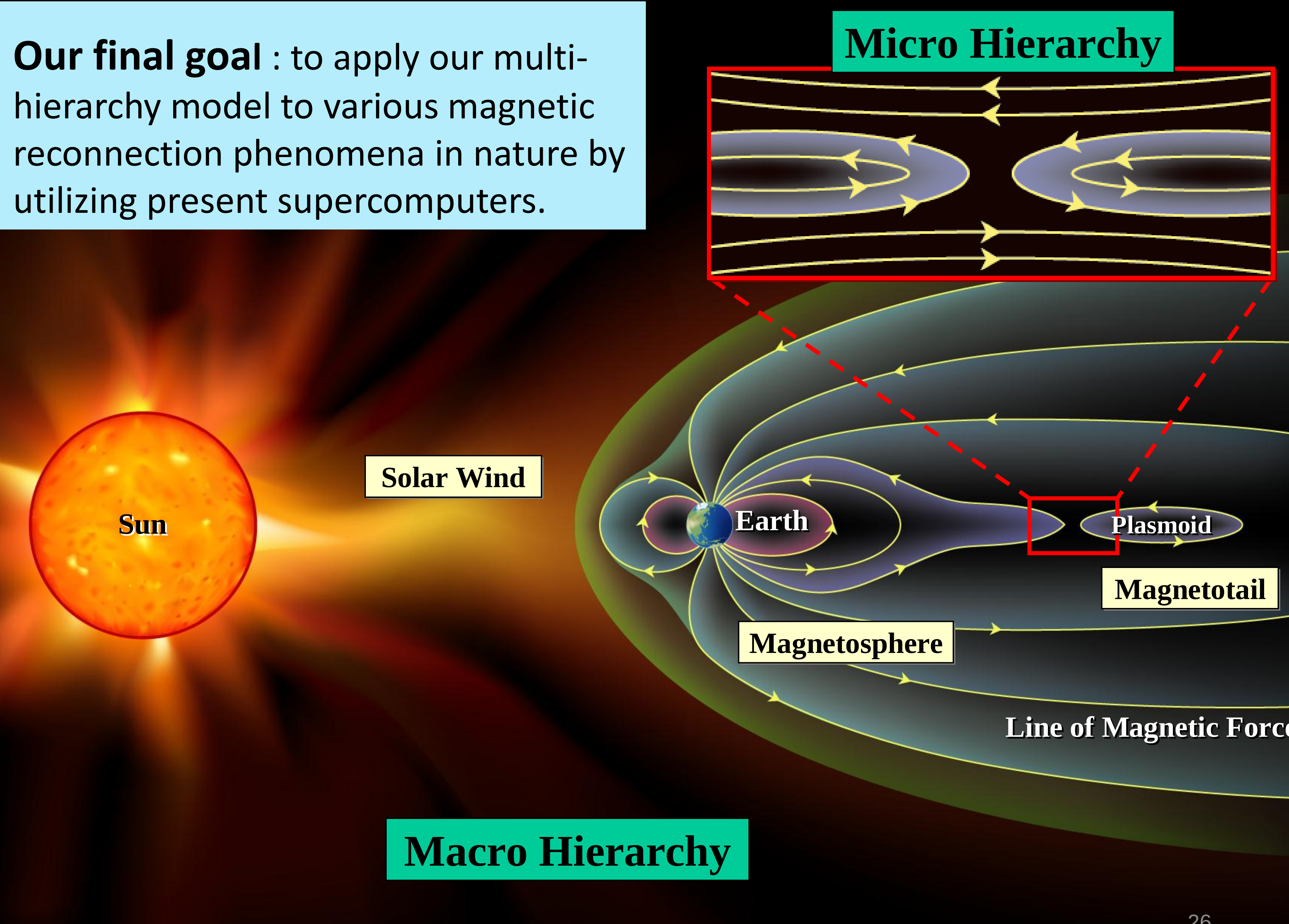
a. **Model to generate moving PIC domains in macro system** 🡐 Micro system appears in macro system according to the evolution of macro system. → developed preliminary model (Poster by S. Usami)

b. **Interlocking model along downstream direction**

🡐 This is very complex problem because particle distribution is modified largely from Maxwllian due to fast plasma outburst as a result of magnetic reconnection. (under consideration)

c. **There remains a huge time gap in applying this model to global phenomena in MHD time scale** 🡒 one of serious problems to be solved in a future

Our final goal : to apply our multi-hierarchy model to various magnetic reconnection phenomena in nature by utilizing present supercomputers.



Summary

We have developed **multi-hierarchy simulation model** for magnetic reconnection in an open system, which can describe macroscopic physics and microscopic physics self-consistently and simultaneously.

① Three models are interconnected based on **domain decomposition method**, i.e., MHD model to describe global dynamics of reconnection phenomena, PIC model (PASMO) to describe the microscopic processes in the vicinity of reconnection point, and interface model with a finite width to describe the interaction between micro and macro hierarchies. [1]

② In order to check **numerical applicability** of multi-hierarchy simulation model, we have applied it to the propagation of linear Alfven wave and plasma inflow from the upstream boundary to PIC region. And we have confirmed that it works well. [1-3]

③ Next, we **applied our multi-hierarchy simulation model to collisionless driven reconnection**. It is confirmed from the comparison with PASMO simulation data that collisionless driven reconnection is described physically correctly. [4,5]

④ Recently we extend the model to more realistic one with non-uniform space grids and plasma outflow problem.

Reference

[1] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Comm. Comput. Phys,Vol.4,* (2008) 537.

[2] R. Horiuchi, S. Usami, H. Ohtani, and M. Den, *J. Plasma Fusion Res. Series* vol. 8 (2009) 184.

[3] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Comm. Comput. Phys.* in press.

[4] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Plasma Fusion Res. Vol. 4* (2009) 049.

[5] R. Horiuchi, S. Usami, H. Ohtani, and T. Moritaka, *Plasma Fusion Res. Vol. 5* , (2010) S2006.