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Development of Magnetic Reconnection Interlocked Simulation Model Based on Domain Decomposition Method

National Institute for Fusion Science

S. Usami, H. Ohtani, R. Horiuchi, and M. Den

U.S. – Japan Workshop
Progress of Multi-Scale Simulation Models

Outline

- Introduction
- MHD-PIC Interlock Method
- Simulation Result(1): Alfvén Wave
- Simulation Result(2): Plasma Flow
- Future Work
- Summary

Background

- Magnetic reconnection is a typical multi-hierarchy phenomenon.
  - Global dynamics of reconnection phenomena is properly described by MHD model.
  - Microscopic kinetic process is needed to trigger magnetic reconnection.

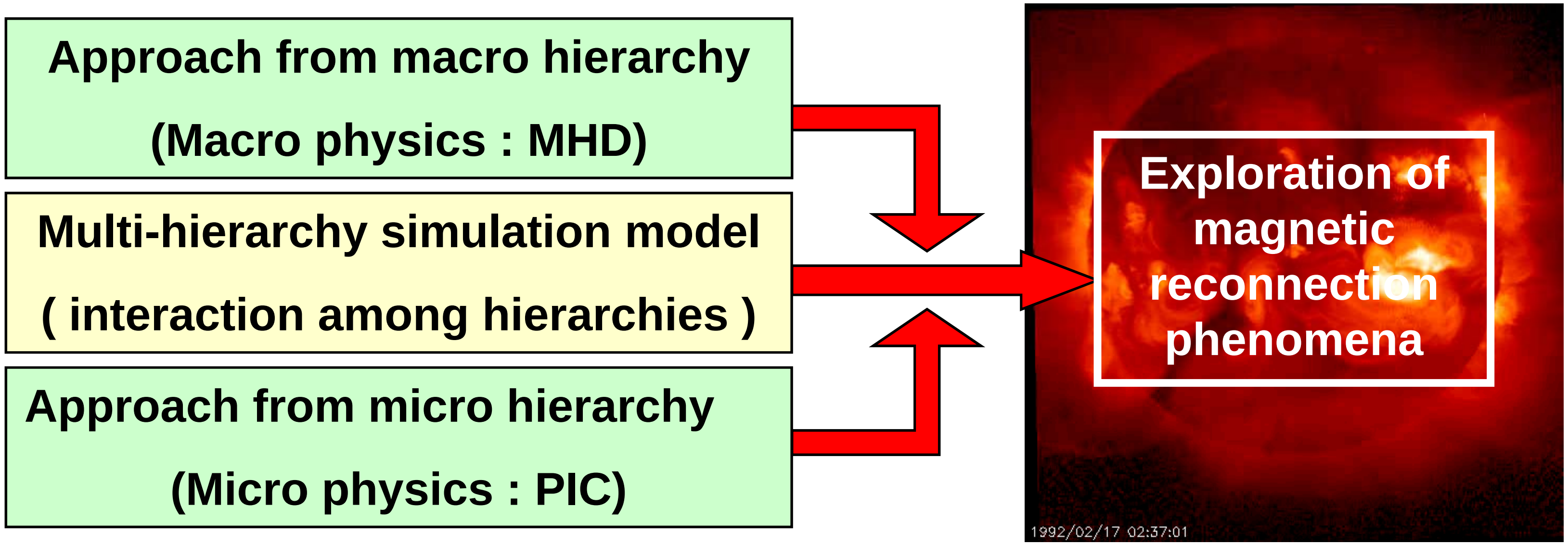
↓

For the full understanding of magnetic reconnection as multi-hierarchy process…

MARIS project

MARIS = **MA**gnetic **R**econnection **I**nterlocked **S**imulation

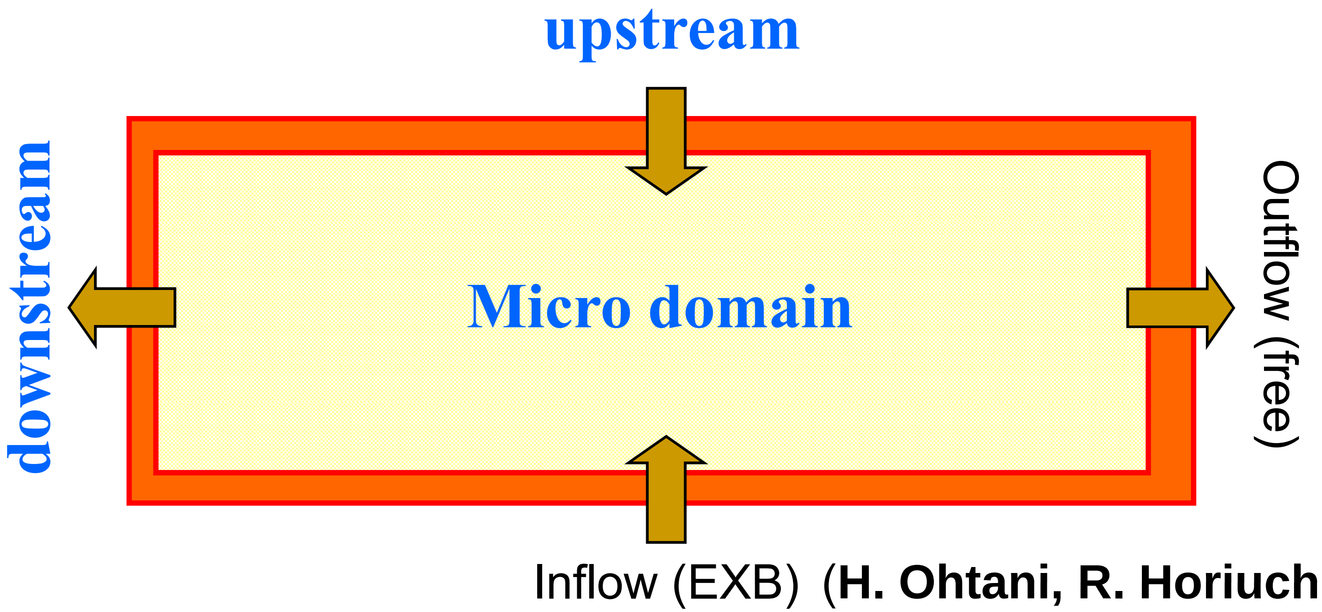
- We develop **multi-hierarchy simulation model** to solve both microscopic and macroscopic physics consistently and simultaneously.
  - Micro: **particle (PIC) code**
  - Macro: **MHD code**



Approach from micro hierarchy

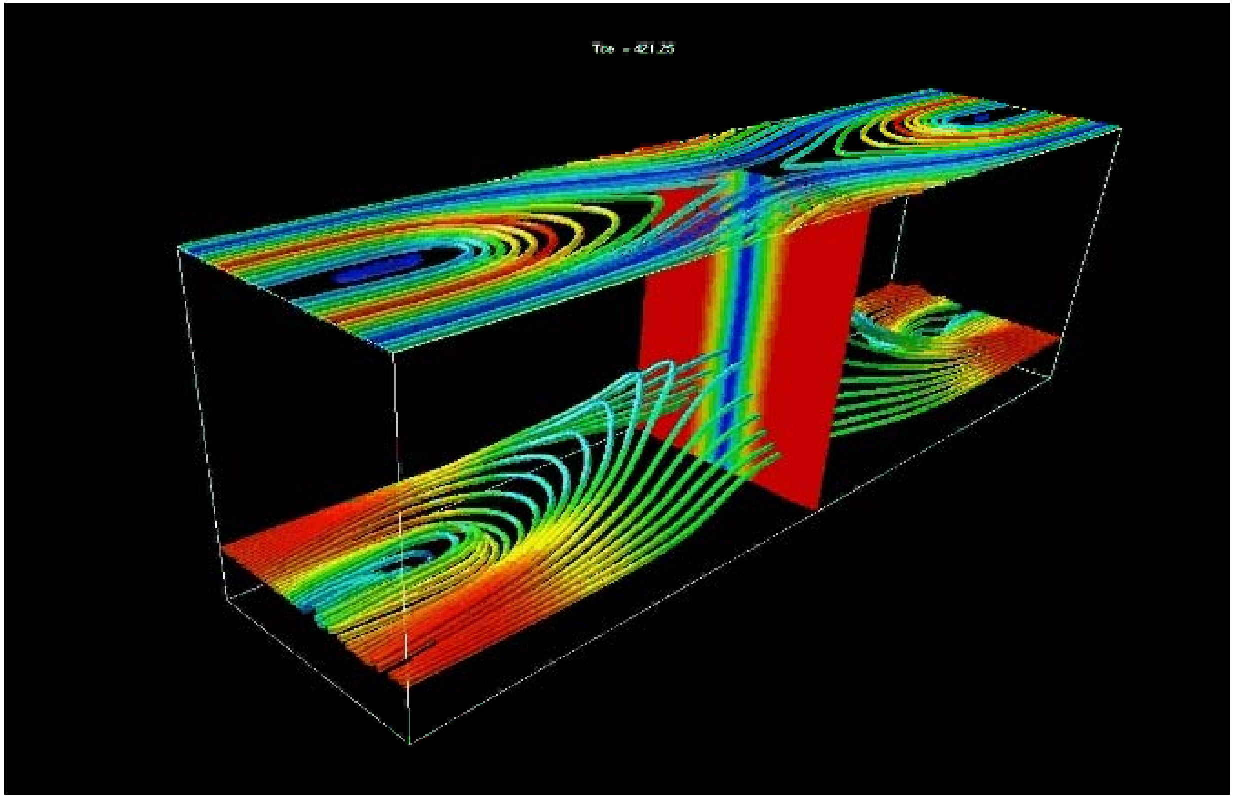
PArticle Simulation code for Magnetic reconnection in an Open system (*PASMO*)

1. Code for microscopic open system, which is designed to connect with code for macroscopic system.
2. Upstream boundary: macroscopic information (T, v, B, E) → microscopic quantities
3. Downstream boundary: floating (free) condition



(**H. Ohtani, R. Horiuchi, W. Pei, et al**)

Approach from micro hierarchy



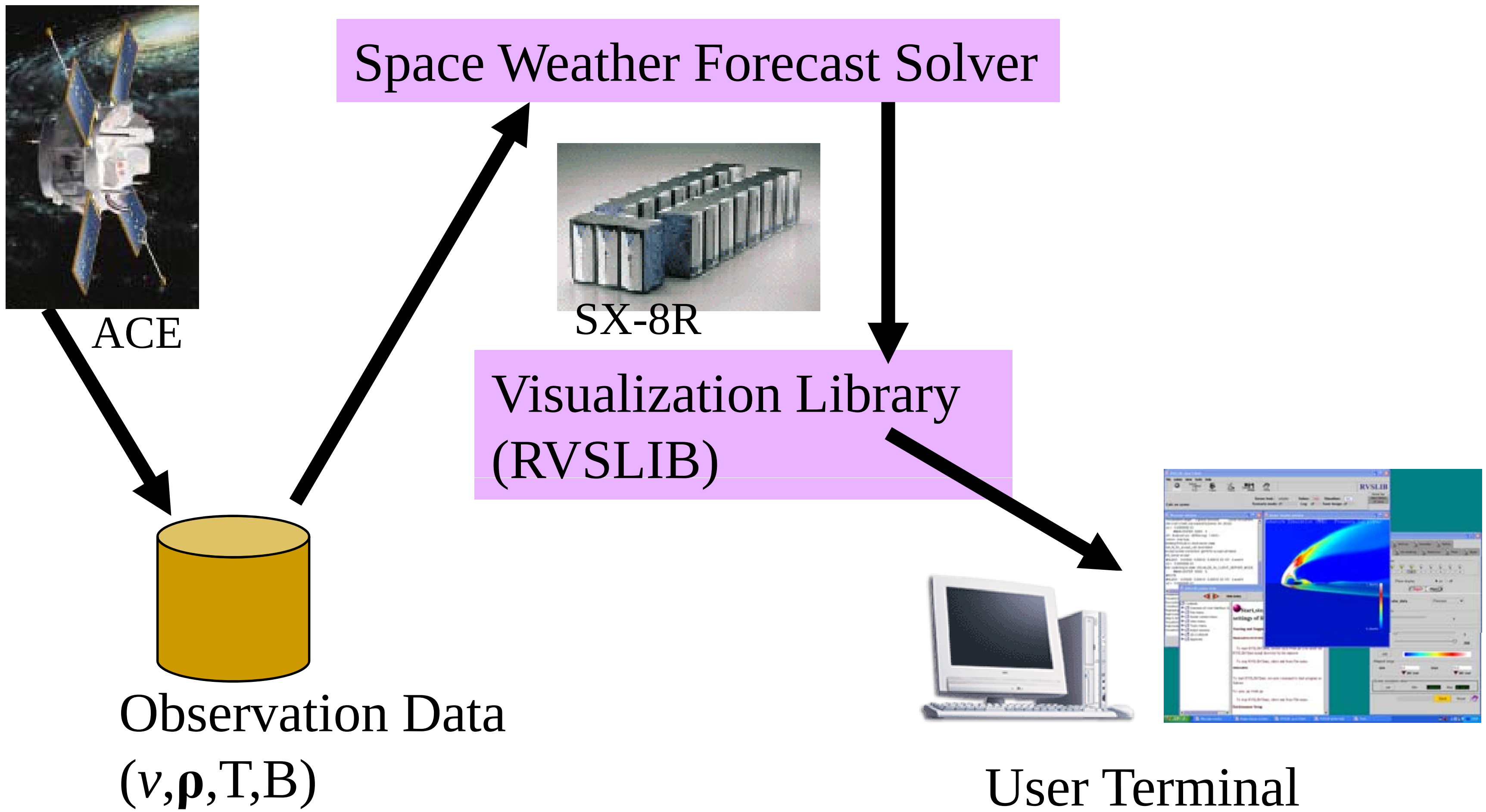
Using PASMO, we successfully investigate magnetic reconnection.
However…

Limitation of PIC

- But, PIC simulation can not calculate wide region, because PIC simulations require many computer resources

Approach from macro hierarchy

Real-time MHD simulation system



Limitation of MHD

- It is based on phenomenological model.
- For magnetic reconnection, resistivity is added to MHD equations. How does resistivity which is a trigger of magnetic reconnection generate? MHD can not explain it.

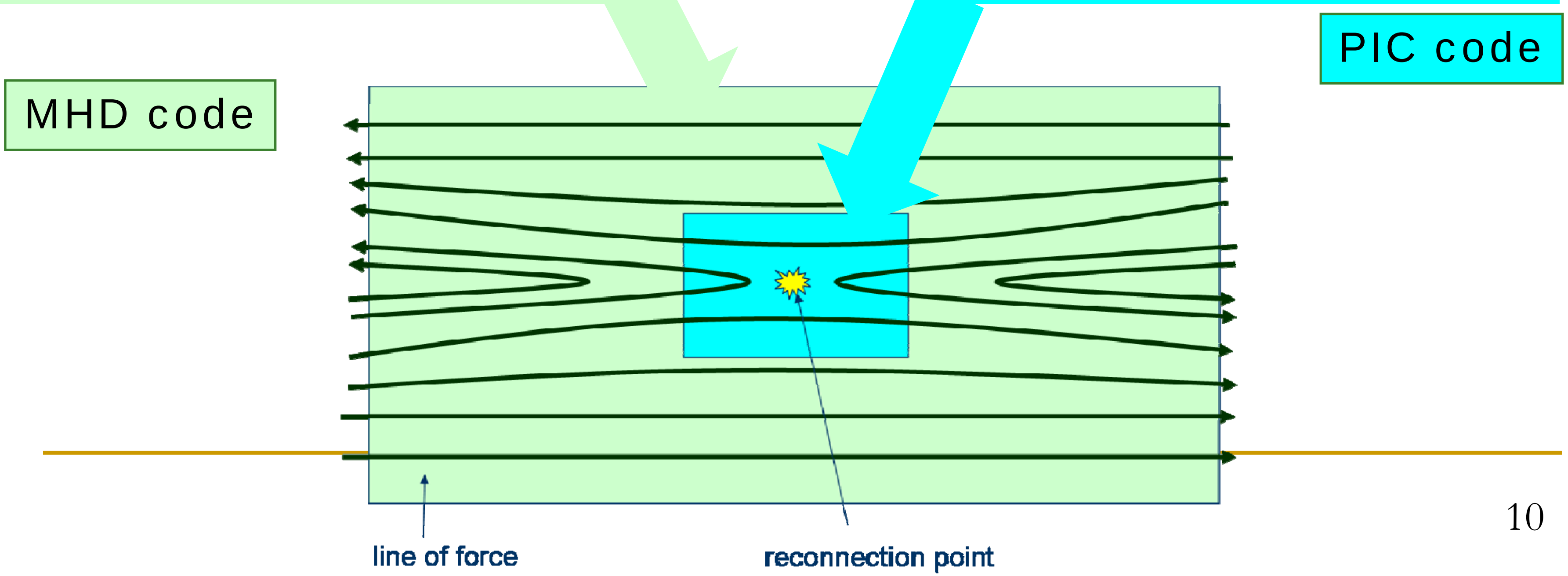
Multi-Hierarchy Simulation Model

Macro hierarchy

The physics in the surrounding of the PIC code is described by MHD code, where ideal MHD equations are applicable, since non-ideal effects leading to the generation of electric resistivity and viscosity are assumed to be generated by microphysics in the vicinity of reconnection point.

Micro hierarchy

The physics in the neighborhood of reconnection point is solved by PIC code, where microscopic kinetic effects play important roles. In this area, frozen-in condition is violated, thus, physics in this area can not be described by MHD code.



Basic equations

MHD

$$\frac{\partial \hat{\rho}}{\partial \hat{t}} = -\hat{\nabla} \cdot (\hat{\rho} \hat{\mathbf{v}})$$

$$\frac{\partial (\hat{\rho} \hat{\mathbf{v}})}{\partial \hat{t}} = -\hat{\nabla} \cdot (\hat{\rho} \hat{\mathbf{v}} \hat{\mathbf{v}}) - \hat{\nabla} \hat{P} + \hat{\mathbf{J}} \times \hat{\mathbf{B}}$$

$$\frac{\partial \hat{\mathbf{B}}}{\partial \hat{t}} = -\hat{\nabla} \times (\hat{\mathbf{B}} \times \hat{\mathbf{v}})$$

$$\frac{\partial \hat{P}}{\partial \hat{t}} = -\hat{\nabla} \cdot (\hat{P} \hat{\mathbf{v}})$$

PIC

$$\frac{d(\gamma_j \hat{\mathbf{v}}_j)}{d\hat{t}} = \frac{\hat{q}_j}{\hat{m}_j} \left(\hat{\mathbf{E}} + \hat{\mathbf{v}}_j \times \hat{\mathbf{B}} \right)$$

$$\frac{d\hat{\mathbf{x}}_j}{d\hat{t}} = \hat{\mathbf{v}}_j$$

$$\frac{\partial \hat{\mathbf{E}}}{\partial \hat{t}} = \hat{\nabla} \times \hat{\mathbf{B}} - C_J \hat{\mathbf{j}}$$

$$\frac{\partial \hat{\mathbf{B}}}{\partial \hat{t}} = -\hat{\nabla} \times \hat{\mathbf{E}}$$

$$\hat{\nabla} \cdot \hat{\mathbf{E}} = C_J \hat{\rho}_q$$

$$\hat{\nabla} \cdot \hat{\mathbf{B}} = 0$$

Interconnection

- We interconnect physical quantities between MHD and PIC.

MHD		PIC
$\mathbf{B}$, P , ρ,	⟺	$\mathbf{B}$, $\mathbf{E}$,
$\mathbf{v}$(fluid)		$\mathbf{v}_j$, $\mathbf{x}_j$ (particles)

From MHD to PIC

MHD		PIC
$\mathbf{B}, \mathbf{v}(\text{fluid})$	B, v →	$\mathbf{E} = -\mathbf{v} \times \mathbf{B}$
P, ρ ⇓ $n, \mathbf{v}_{th}$	v, v_{th} →	$\mathbf{v}_j, \mathbf{x}_j$ (particles)
$\mathbf{J} = \nabla \times \mathbf{B}$	J →	Electron particle velocities $\mathbf{v}_j \rightarrow \mathbf{v}_j - \frac{\mathbf{J}}{ne}$

From PIC to MHD

MHD

E is not necessary.

$\mathbf{B}$

PIC

$\mathbf{B}, \mathbf{E}$

$\langle \mathbf{v} \rangle \Rightarrow \mathbf{v}(\text{fluid})$

$\langle \mathbf{v} \rangle$

$\mathbf{v}_j, \mathbf{x}_j$ (particle)

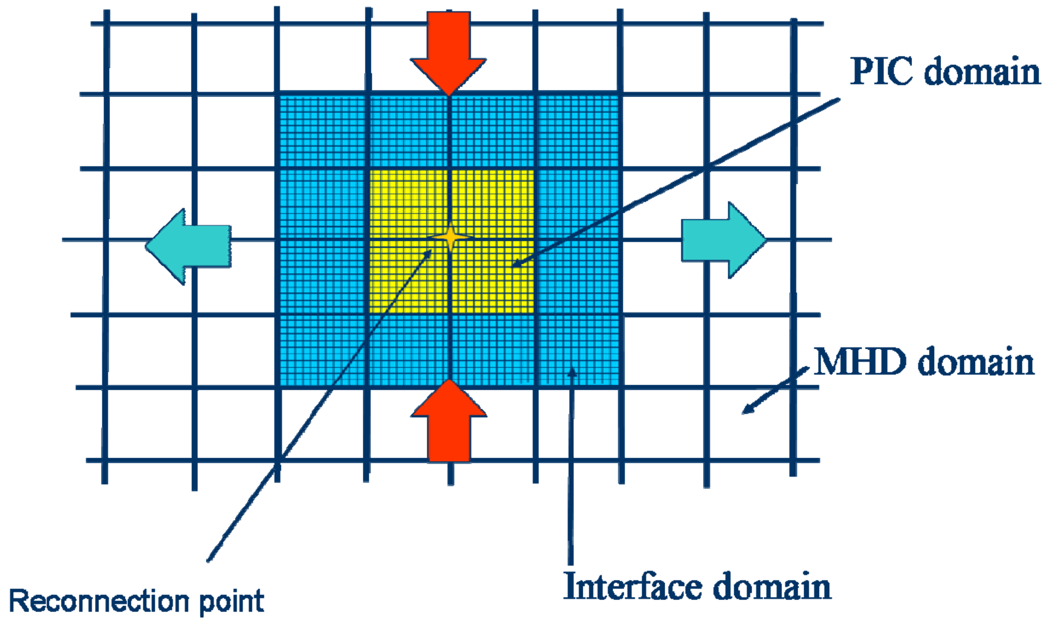
$\langle \mathbf{v} \rangle,$

$\mathbf{v}_{th}, n$

$\mathbf{v}_{th}, n \Rightarrow P, \rho$

$\mathbf{v}_{th}, n$

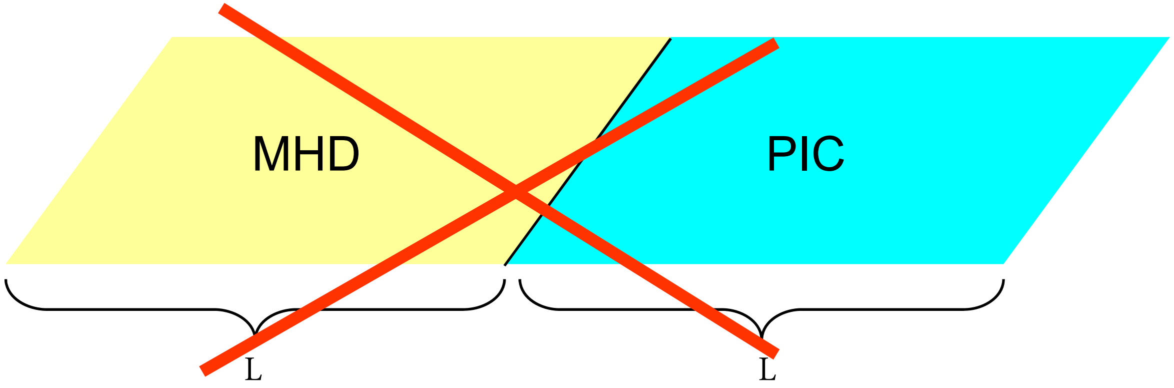
Domain decomposition method

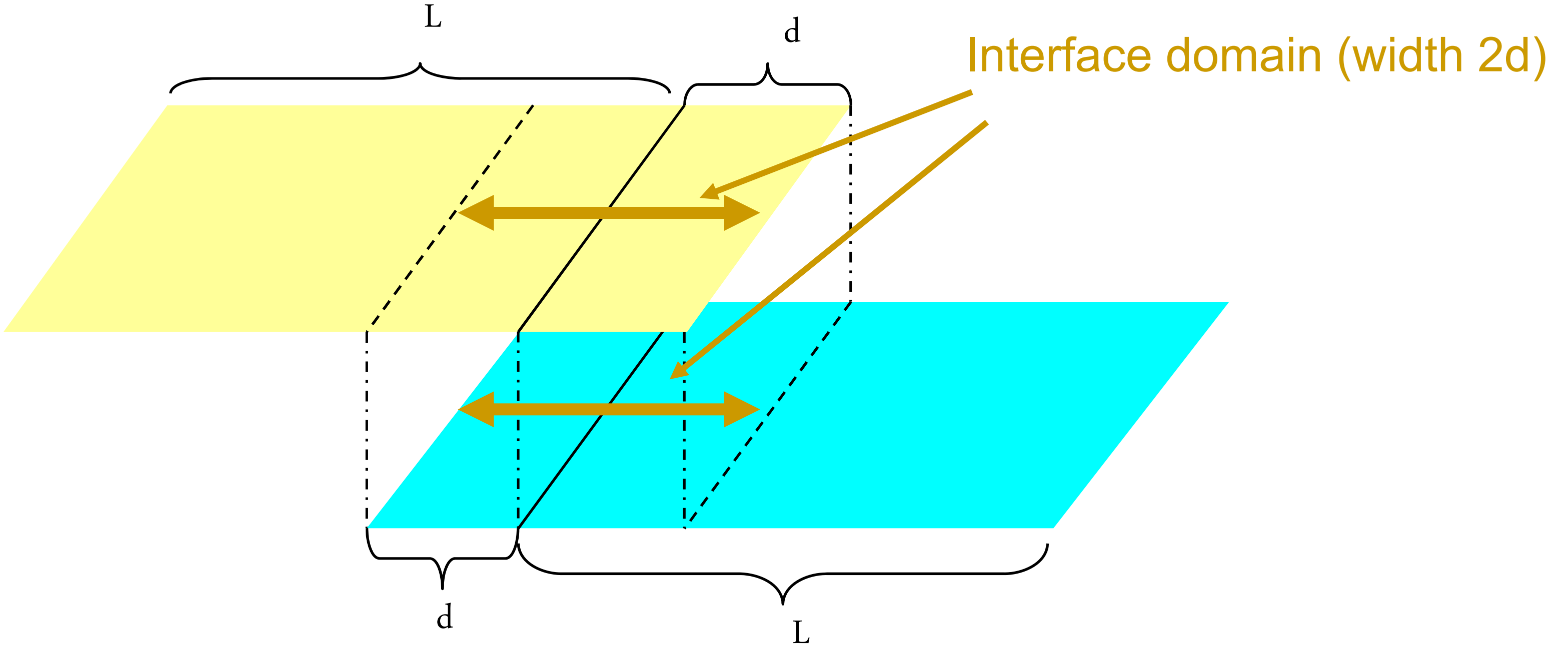


- Three domains
  - PIC domain (micro)
  - MHD domain (macro)
  - Interface domain

- Interface domain is inserted between PIC and MHD domains. Thus, MHD and PIC domains can be smoothly connected each other.

Note: What is Interface domain ?





Shake-hand scheme

- Physical quantity Q in the Interface domain is calculated by each PIC and MHD code.
  - Calculated by PIC: Q_{PIC}
  - Calculated by MHD : Q_{MHD}
- Q in the Interface domain is defined as

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

$$a = a(x, y, z)$$

T.Sugiyama and K.Kusano

near MHD $a \to 1$

near PIC $a \to 0$

Problem div**B**=0

- Before

$$\mathbf{B}_{\text{interface}} = a\mathbf{B}_{\text{MHD}} + (1-a)\mathbf{B}_{\text{PIC}}$$

$$\nabla \cdot \mathbf{B}_{\text{interface}} \neq 0$$

T. Sugiyama: private communication 2008

- After（connection of vector potential）

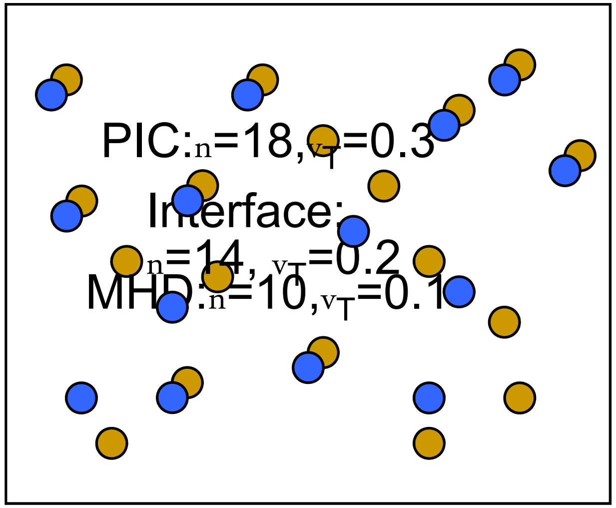
$$\mathbf{A}_{\text{interface}} = a\mathbf{A}_{\text{MHD}} + (1-a)\mathbf{A}_{\text{PIC}}$$

$$\nabla \cdot \mathbf{B}_{\text{interface}} = 0$$

Particle velocity distribution

- The degree of freedom in MHD : 8
- The degree of freedom in PIC : nearly infinity

Maxwellian distribution is assumed

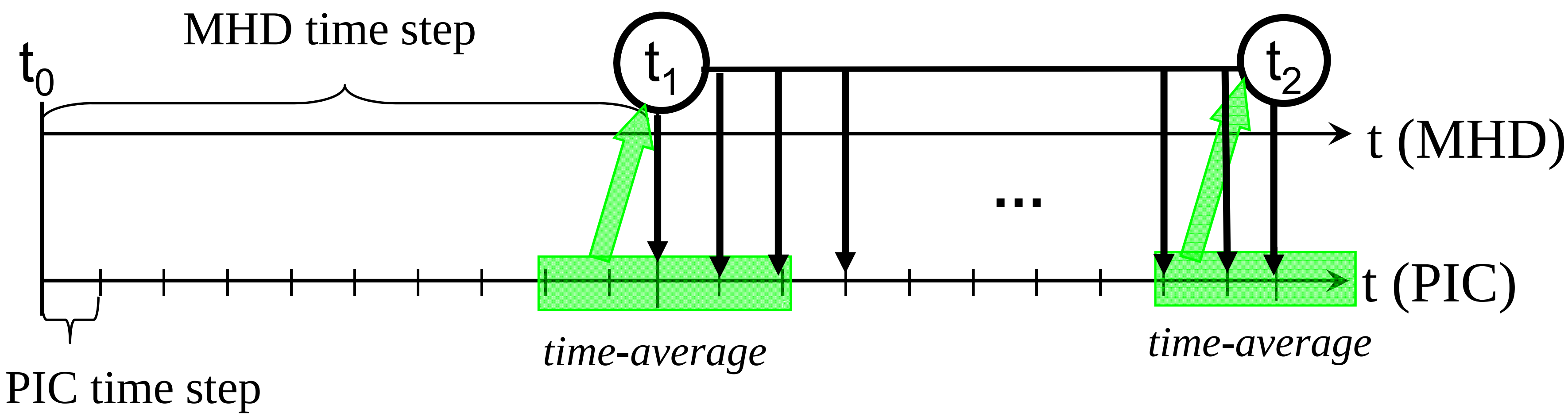


1. All particles are removed.
2. New density n and thermal velocity v_T are decided.
3. New particles are distributed. (Position: random, Velocity: Maxwellian)

Every step, this sequence is done.

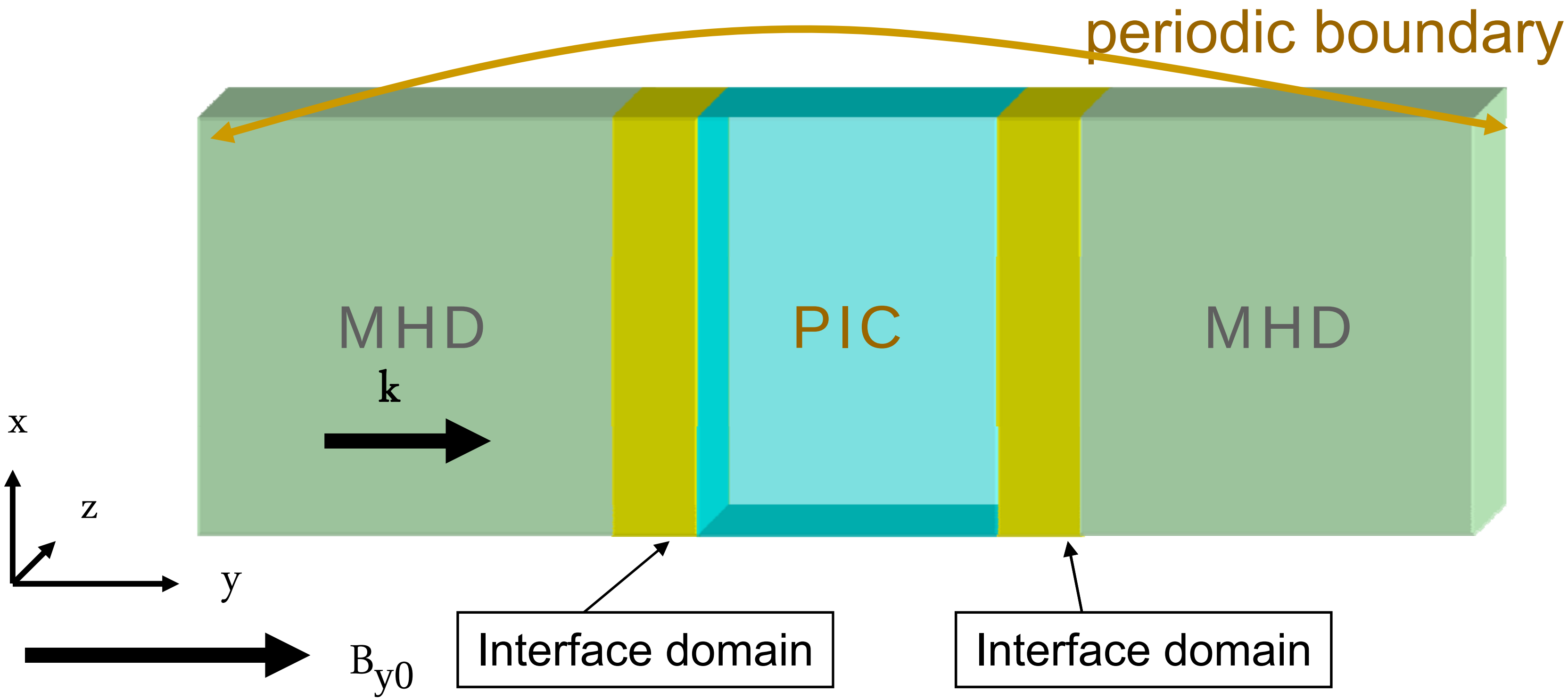
How does time advance ?

multi-time-step method



Large time steps are for MHD, and small ones are 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.

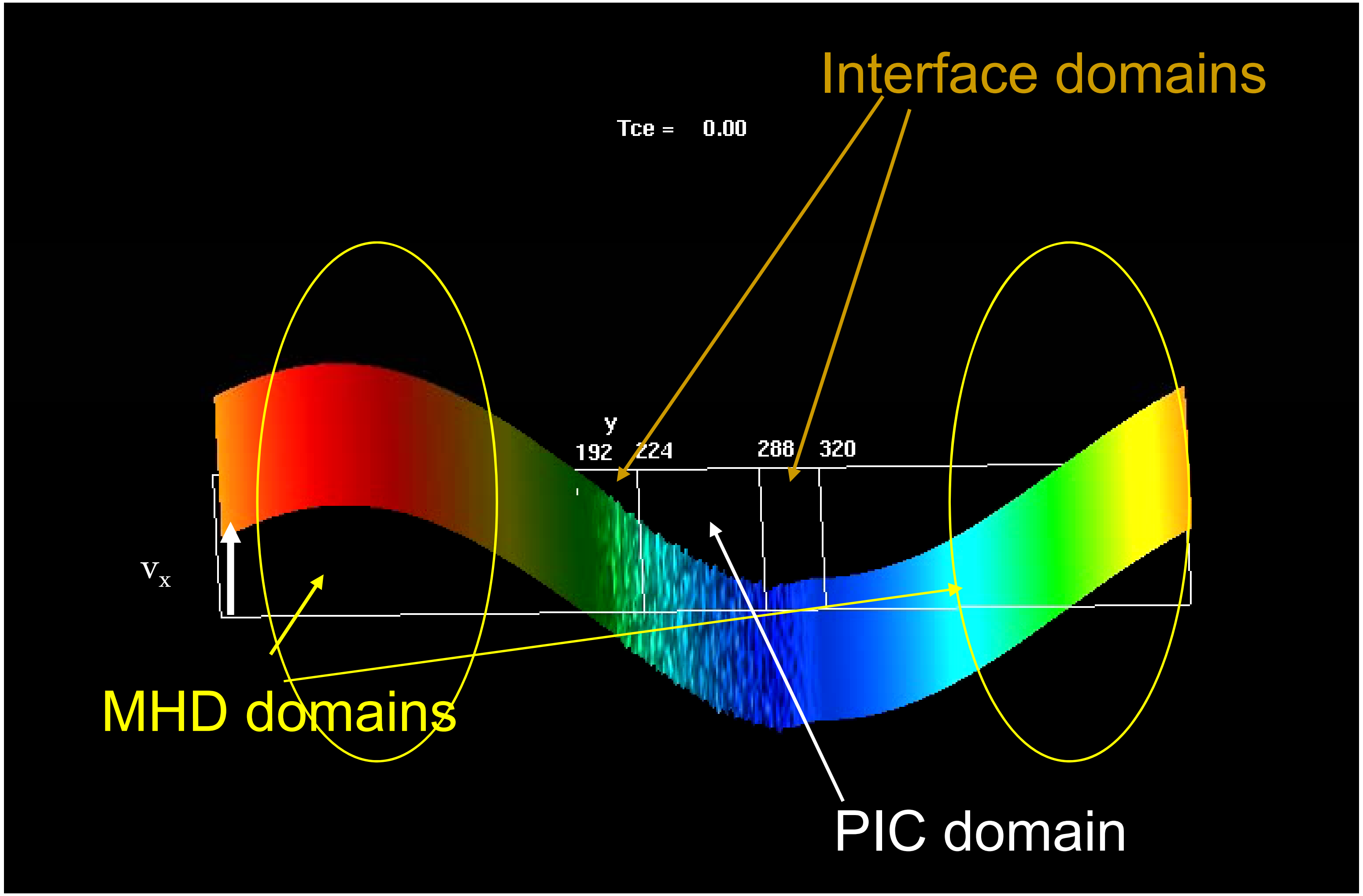
Simulation box for Alfvén wave



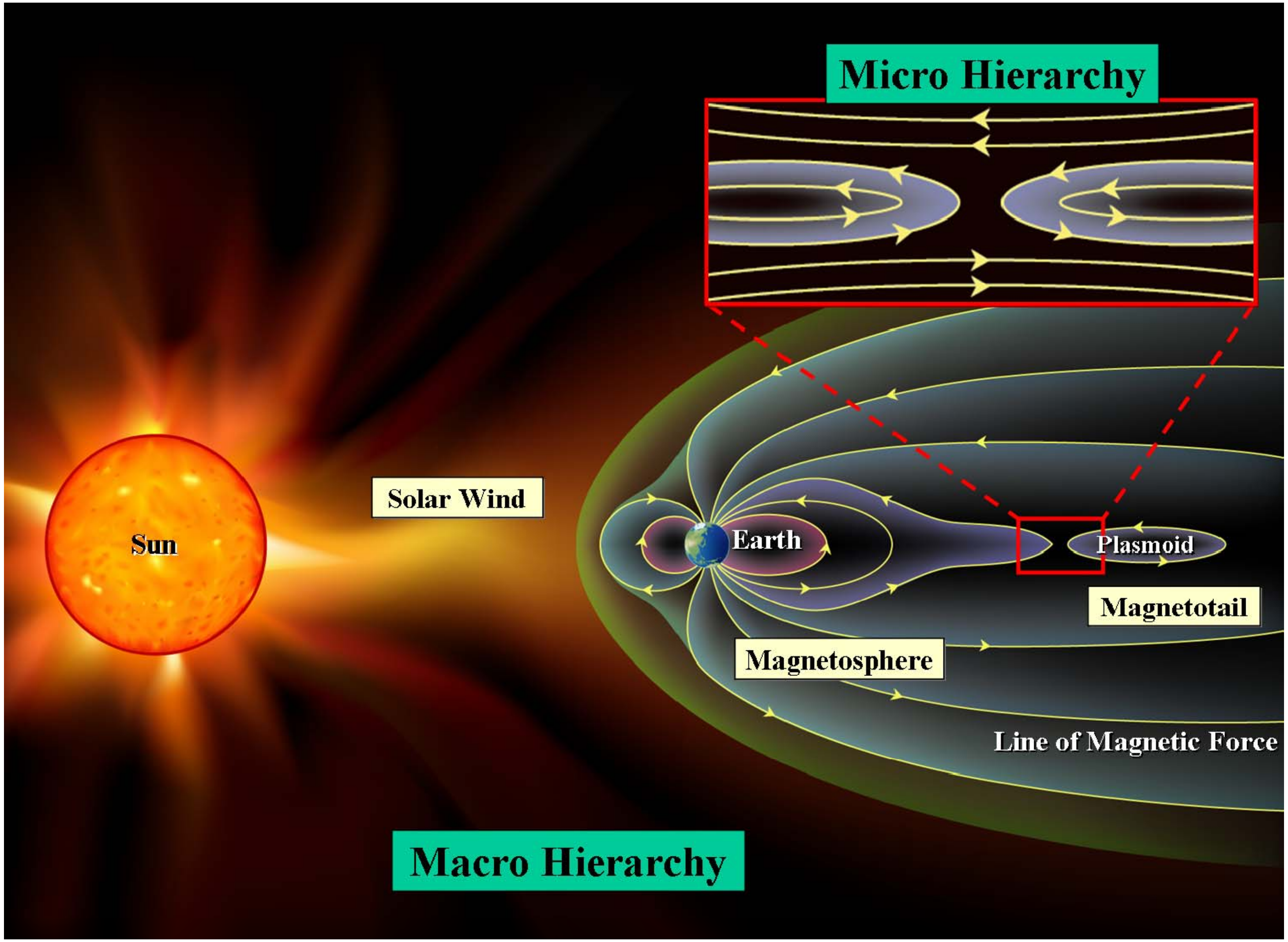
Boundary conditions
x, z: periodic
y: free

The external magnetic field is uniform.

Alfvén wave


Interface domains
Tce = 0.00
y
192
224
288
320
v_x
MHD domains
PIC domain

Final Goal


Micro Hierarchy
Solar Wind
Sun
Earth
Plasmoid
Magnetotail
Magnetosphere
Line of Magnetic Force
Macro Hierarchy

Summary

- Multi-Hierarchy Simulation Model
  - Space: **domain decomposition method**
    - MHD domain (Macro)
    - PIC domain (Micro)
    - Interface domain
  - Time: **multi-time-step method**
- Progress our multi-hierarchy model
  - **Alfvén wave** smoothly propagates in our multi-hierarchy model.
  - **Plasma flow** injects from MHD to PIC domains without large unphysical phenomena.
  - In the near future, we will examine 2D flow injection in anti-parallel B configuration, and then perform multi-hierarchy simulation of magnetic reconnection.