Particle-In-Cell Simulations on the Interactions between Space Plasma and Advanced Propulsion System

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Magneto Plasma Sail (MPS) is proposed as one of the innovative interplanetary flight systems. The propulsion of MPS is obtained as a result of multi-scale kinetic interactions between the solar wind plasma and a small-scale artificial magnetosphere created around the spacecraft. In the investigation of the multi-scale plasma interactions in association with MPS, plasma particle simulation can be a powerful tool. However, it is difficult to handle the multi-scale phenomena with the conventional particle simulation which adopts uniform spatial grid system. To conquer this difficulty we will establish the foundation and the methodology for the multi-scale plasma particle simulations by combining Adaptive Mesh Refinement (AMR) and Particle-In-Cell (PIC) methods. In the new AMR-PIC code, we introduced the fully threaded tree (FTT) structure for the AMR scheme. In the FTT, a hierarchical grid system is maintained all by pointers and each cell is treated as an independent unit organized in a refinement tree structure rather than conventional element of arrays. Each particle also has a pointer for the next particle located in the same cell. In the parallelization of the code, we adopt domain-decomposition and assign each sub-domain to each processor. To keep the load balancing between processors, the partitioning of sub-domains is done by using the Morton ordering method which is one of the space filling curves. We modified the method so that the load of the particle calculation is considered in the sub-domain partitioning.

In parallel to the tool development, we focus on the quantitative evaluation of the MPS thrust by performing Particle-In-Cell(PIC) simulations in which plasma kinetics are included. We will show some preliminary results on the magnetic field inflation by plasma injection from the spacecraft which is necessary to obtain the larger interaction area with the solar wind.

1. Introduction

Magneto Plasma Sail (MPS) is an innovative propulsion system which makes the most use of the multi-scale kinetic interactions between the solar wind plasma and a small-scale artificial magnetosphere created around the spacecraft. The concept of using the interaction between the solar wind and the artificial magnetosphere for interplanetary flight system was originally proposed by Zubrin [1]. To increase the thrust performance, it is necessary to enlarge the size of the magnetosphere because a part of the energy of the solar wind interacting with the magnetosphere will be converted to the thrust. To inflate the artificial magnetosphere, Winglee proposed a concept of introducing a plasma injection from the spacecraft [2].

Inspired by the Winglee's MPS concept, JAXA started to investigate the basic principle of MPS and the thrust performance [3]. The basic concept of MPS is shown in Fig. 1. A magnetosphere is artificially created as

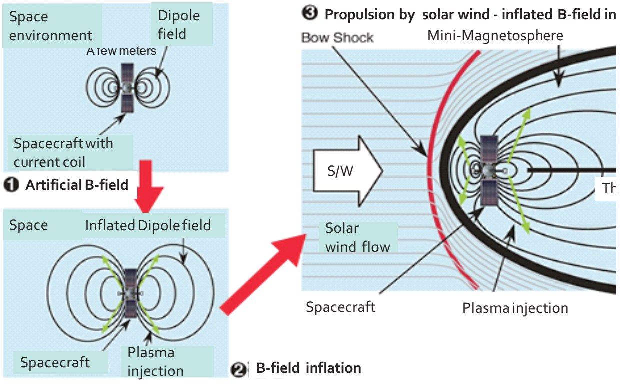

Fig.1. Schematic concept of Magneto Plasma Sail (MPS)

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author's e-mail: h-usui@port.kobe-u.ac.jp a result of the interaction between the solar wind and the dipole magnetic field which is generated by the coil at the spacecraft. To expand the magnetosphere, plasma is injected from the spacecraft so that the interaction region becomes large. In the process of the interaction, current layer structure is induced at the interface between the magnetosphere and the solar wind and it can modulate the original magnetic field at the current coil at the spacecraft. Then the net $\boldsymbol{J} \times \boldsymbol{B}$ force at the spacecraft becomes equivalent to the MPS thrust where $\boldsymbol{J}$ and $\boldsymbol{B}$ denote the current of the coil and the magnetic field at the coil, respectively.

In the previous studies, some MHD simulations were carried out for the understanding of the basic thrust mechanism as well as the dependence of the thrust performance on the plasma injection under the approximation of ideal MHD [4]. However, the fluid treatment of the solar wind as used in the MHD simulations does not seem appropriate when we consider the typical size of the artificial magnetosphere created around the spacecraft is approximately several tens kilometers and it is almost equivalent to the gyroradius of the solar wind ions. In such a situation, kinetic treatment of the solar wind is necessary in the analysis by including the effect of the finite Larmor radius. For this purpose, we started performing hybrid particle simulations in which ions are treated as particle while electrons fluid [5].

In addition to the plasma kinetic effect, we should consider multi-scale phenomena in the MPS analysis. As stated above, the MPS thrust at the local spacecraft is obtained as a result of macro-scale interaction between the magnetosphere and the solar wind. To evaluate the thrust quantitatively, we need a simulation system in which the above-stated macro phenomenon and the local MPS system can be simultaneously included.

With the conventional plasma particle simulations, however, it is difficult to handle the multi-scale phenomena because they adopt uniform spatial grid system. To simulate the multi-scale kinetic phenomena with particle model, we need to introduce non-uniform grid system. For this purpose, we started developing a new plasma simulation code by combining Adaptive Mesh Refinement (AMR) and Particle-In-Cell (PIC) methods. This challenging attempt was selected as a research project of the JST (Japan Science and Technology Agency) CREST (Core Research for Evolutional Science and Technology) in the research area of “high performance computing for multi-scale and multi-physics phenomena” in 2007 fiscal year. The research project which started at October in 2007 will continue for five years.

In parallel to the tool development, we have been examining the inflation of artificial magnetic field by plasma injection from the spacecraft. We already started the analysis by performing hybrid particle simulations in which ions are treated as particles while electrons are fluid. In addition to the hybrid particle simulations, we also started full-PIC simulations to examine the field inflation process including electron kinetics. We will present some of the preliminary results on the magnetic field inflation in the present paper.

2. Development of AMR-PIC Simulation Code

Toward the analysis of multi-scale phenomenon in association with MPS, we started to develop a new electromagnetic particle code with AMR technique. The AMR technique is effective to simulate the phenomena which include local micro-scale processes as well as global macro-scale processes with high-resolution. By using the AMR technique, we can subdivide and remove cells dynamically according to refinement criteria such as the characteristic length, for instance, the local Debye length. In development of the code, we introduced PIC method to the AMR grid system by using fully threaded tree (FTT) structure [6].

The basic concept of FTT is shown in Fig. 2. At the region where high spatial resolution is required, additional spatial grid system (Level L+1 shown in the figure) is locally created with a half size of the cell size used in the upper level (Level L). When the high resolution becomes unnecessary in a simulation run, the fields and particle information obtained in Level L+1 will be stored back to the Level L and the Level L+1 grid system will be automatically eliminated. Each cell consisting of one level of spatial grid system has pointers which indicate neighbors, parent, child cells as well as particles belonging to the corresponding cell. This subdivision of grid system level recursively takes place until the spatial resolution locally meets the refinement criteria.

We have already developed a proto-model of the AMR-PIC simulation code with the FTT method. Fig. 3 shows one example of mesh refinement for a test simulation in which a dense plasma cloud is locally placed at the center of the system. In the present model, we

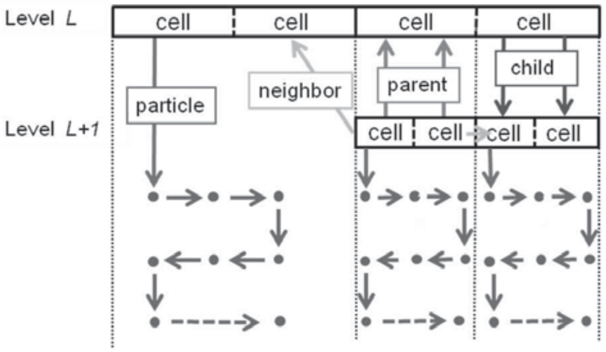

Fig.2. Concept of fully threaded tree (FTT) structure used in the AMR system.

monitored the local Debye length for the refinement criteria. As shown in the figure, three levels of spatial grid system are created and the grid system level with the highest spatial resolution is formed at the center where the plasma density is the maximum. By using this simulation system, we basically confirmed the AMR function with the FTT method including plasma particle.

In terms of memory resource required for simulations, the AMR-PIC method can save a large amount of memories in comparison with the conventional PIC method in which uniform mesh system is used. It is because AMR can set up fine mesh only where micro-scale phenomena take place in the simulation domain. Here is one example showing how much memories can be saved for the AMR-PIC code. When we consider a cubic simulation space consisting of 10^{15} uniform fine meshes, the conventional PIC codes require approximately 5,000 PB memories when we have 100 particles per mesh. If the fine meshes are only used for a region where a microscopic phenomenon occurs in the AMR-PIC simulation, the required memories are much reduced in comparison with the conventional PIC simulation. For example, if the region of the microscopic phenomenon occupies 10% of each spatial direction of the simulation space, namely 0.1% of total volume, then the required fine meshes are much reduced and the total memory size for the simulation become approximately 5 PB. Since the fine mesh region is much reduced, the total calculation time is also decreased. In addition, the spatial resolution for the microscopic phenomenon is maintained with the fine meshes in the AMR-PIC simulation.

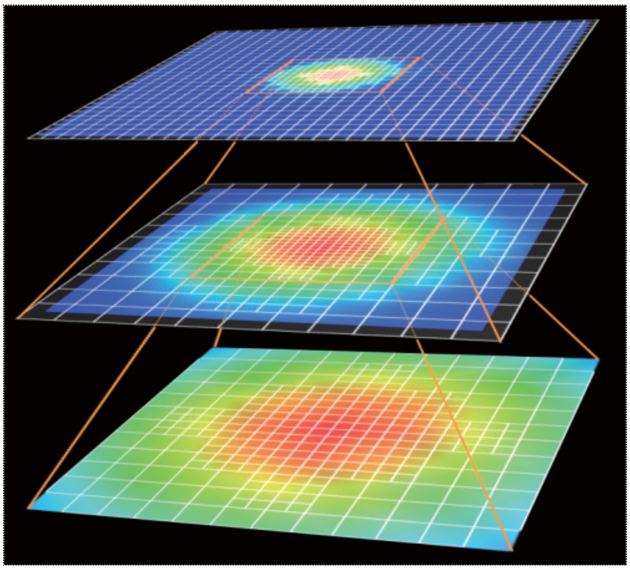

Fig.3. Mesh refinement for a model of dense plasma located at the center.

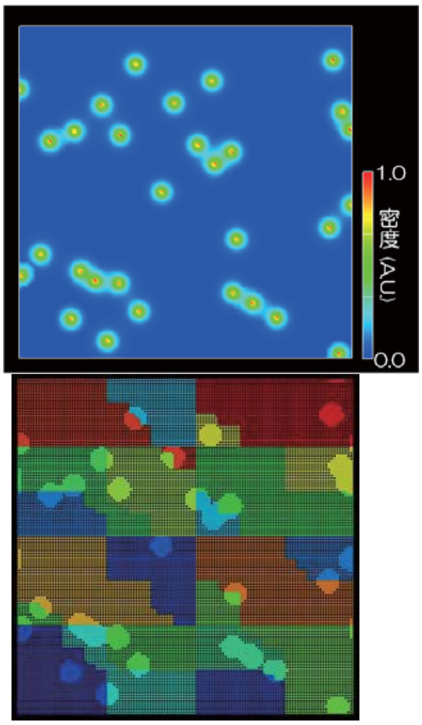

Fig.4. Density profile of plasma cluster simulation (upper panel) and the corresponding sub-domains for the domain-decomposition by using the Morton method to achieve the load balancing between processors (lower panel).

Another important issue in the AMR-PIC code is the parallelization for the high performance computing. As shown in Fig. 4 we use domain decomposition model. In this model, each decomposed region is distributed to a node and plasma simulation is performed in each node by exchanging the fields/particle data at spatial boundaries. In order to obtain the maximum efficiency in the parallel computing, we have to achieve the load balancing among the multi-nodes. To do so, we need to monitor the number of particles in each decomposed region and dynamically change the region in charge of each node so that the number of particle roughly becomes constant. For this purpose, we use the Morton ordering method [7]. The Morton ordering method is one of the space-filling curves which relate the neighboring cells in order. By dividing the order into the number of the processors, we can easily make groups of neighboring cells and assign them to the processors. One example of partitioning of sub-domains is shown in Fig.4 for a case of plasma clusters. At the dense plasma clusters, fine grids are created and the conventional uniform partitioning of sub-domains causes the unbalance loads between processors. To avoid the load unbalance, the sub-domain partitioning is done so that the number of cells assigned to each processor becomes the same. In PIC simulations, however, the particle calculation becomes dominant. Therefore, the load of the particle calculation should be considered in making groups of neighboring cells. By modifying the Morton ordering, we realize the load balancing between processors in consideration of the load of the particle calculation as shown in Fig.5.

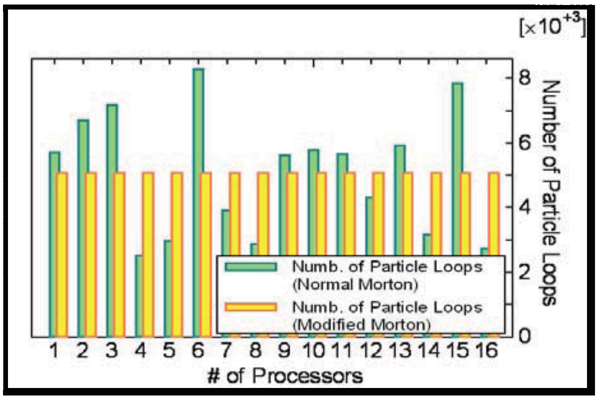

Fig.5. Load balancing using the modified Morton method.

3. Preliminary full-PIC Simulation on the Magnetic Field Inflation

We have examined one case of the magnetic field inflation in which heavy plasma is injected into a dipole magnetic field generated by a current coil at the spacecraft. Plasma is uniformly injected from the spacecraft region in the direction perpendicular to the dipole field. This time we adopted a full-PIC model for the simulation to include the electron dynamics.

Snap shots of density of injected electrons and ions are shown in Fig.6. Ions can propagate farther than electrons because they can be assumed unmagnetized in this spatial scale. The emitted electrons, however, are magnetized and confined in the dipole field and do not propagate much. The distributions between the two species are very different. In the Fig. 7, we show another snap shot of the intensity of the total magnetic field measured along the horizontal direction including the spacecraft position. Spatial structure of the total magnetic field is largely modified by plasma injection along the equatorial direction. A magnetic field cavity is created in the vicinity of the spacecraft. It seems that the magnetized electrons push the local magnetic field to the outer region as shown in red. At the edge and outside of the cavity, magnetic field density is enhanced and this can be associated with the inflation of the original dipole.

4. Summary

We started a research project of multi-scale plasma particle simulation for the development of interplanetary flight system under the support of the JST/CREST. In the present paper, we first overviewed the MPS proposed as one of the innovative interplanetary flight systems. Secondly we briefly stated the development of a new electromagnetic particle code with AMR technique toward the analysis of multi-scale phenomenon in association with MPS. We particularly focused on the fully threaded tree (FTT) structure introduced for the AMR scheme and the Morton ordering for the parallelization needed for the high performance computing. Thirdly, we showed some preliminary results on the inflation of the artificial magnetosphere created around the spacecraft by performing the full-PIC simulations including the electron kinetic effect.. We need the further analysis on the process of the dipole field inflation by plasma injection with different parameters in terms of plasma density and injection velocity as well as the intensity of the original dipole field.

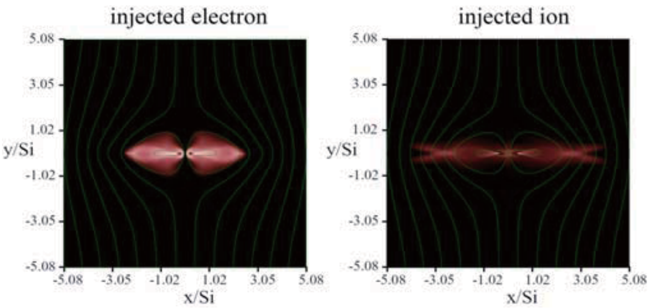

Fig.6. Snap shot of density of electrons and ions injected from the spacecraft located at the center.

Acknowledgement

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[1] R.M. Zubrin and Andrews, D.G., Journal of Spacecraft and Rockets, Vol.28, pp.197-203, (1991).

[2] R.M.Winglee, et al., Journal of Geophysical Research, 105, No.21, 067-078, (2000)

[3] H. Yamakawa et al., Acta Astronautica, Vol. 59, No. 8-11, pp.777-784, (2006).

[4] H. Nishida, et al., Journal of Spacecraft and Rockets, Vol.43, pp.667-672, (2006).

[5] Y. Kajimura, et al., Journal of Plasma Physics, Vol 72(6), pp977-881 (2006).

[6] A. M. Khokhlov, J. Comput. Phys. 143, 519(1998).

[7] S. Warren and J.K. Salmon, Computer Physics Communications, 87, 1-2, 266-290 (1995).

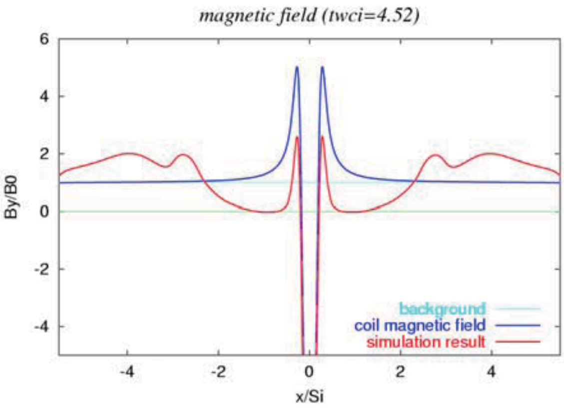

Fig.7. Snap shot of the intensity of the total magnetic field measured along the equatorial direction including the spacecraft position.

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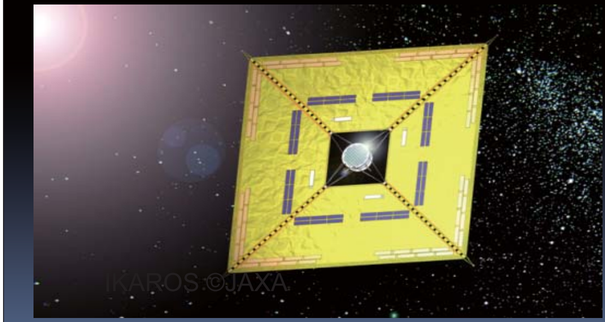
Outline

- Advanced interplanetary flight system using the solar energy (Solar sail and Magneto Plasma Sail(MPS))
- Multi-scale plasma particle simulation using AMR and PIC
- Some results on MPS analysis with PIC simulations
- The next generation supercomputer and the code parallelization
- Summary

Advanced interplanetary flight system

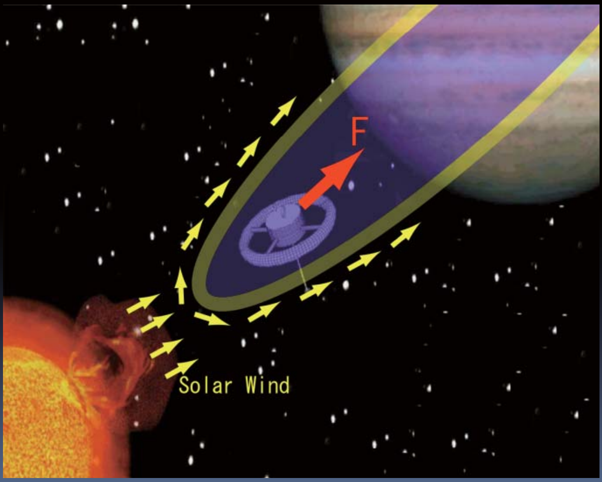
- Fuel-free type propulsion system is necessary for planet exploration
- Some systems using the solar energy have been proposed and planned.

Solar Sail :
IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun)



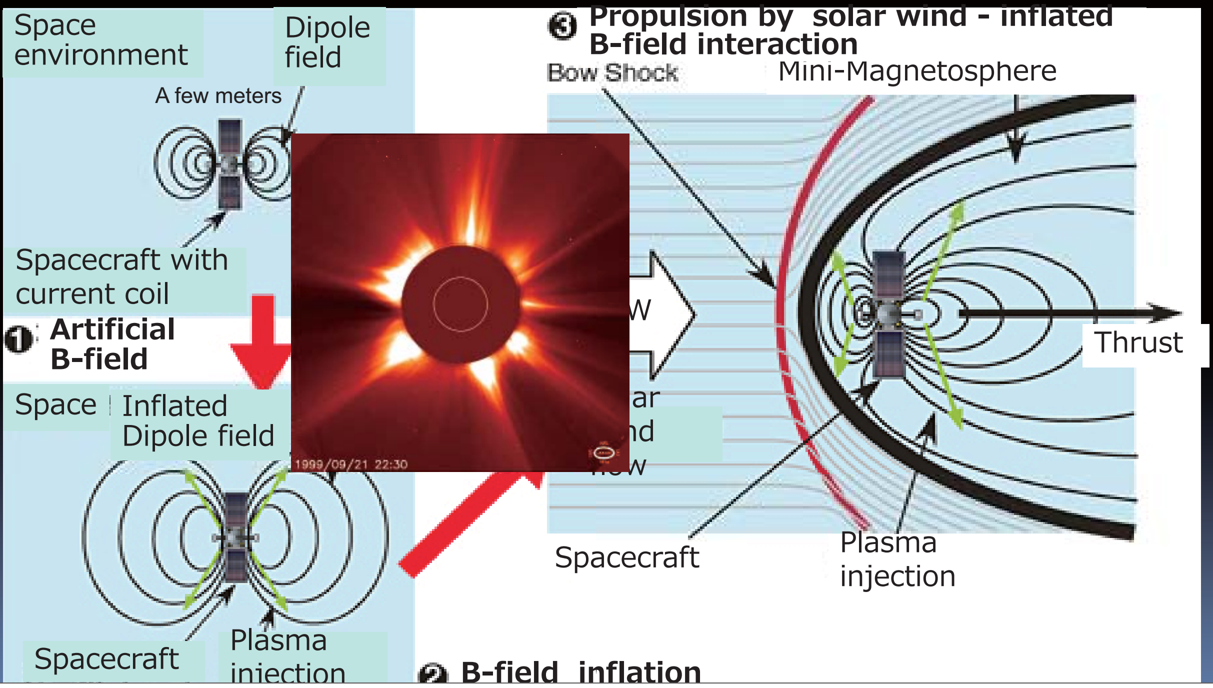
solar power sail: large (14x14 m^2)
thin (<10^{-4}m) sail (JAXA)

Magneto Plasma Sail (MPS)



Magneto Plasma Sail (MPS)

- Magneto sail by Zubrin (1991)
- M2P2 (Mini-Magnetospheric Plasma Propulsion) by Winglee (2000)
- JAXA started the evaluation of the Magneto Plasma Sail (MPS)



Plasma particle simulation toward MPS

Multi-scale characteristics

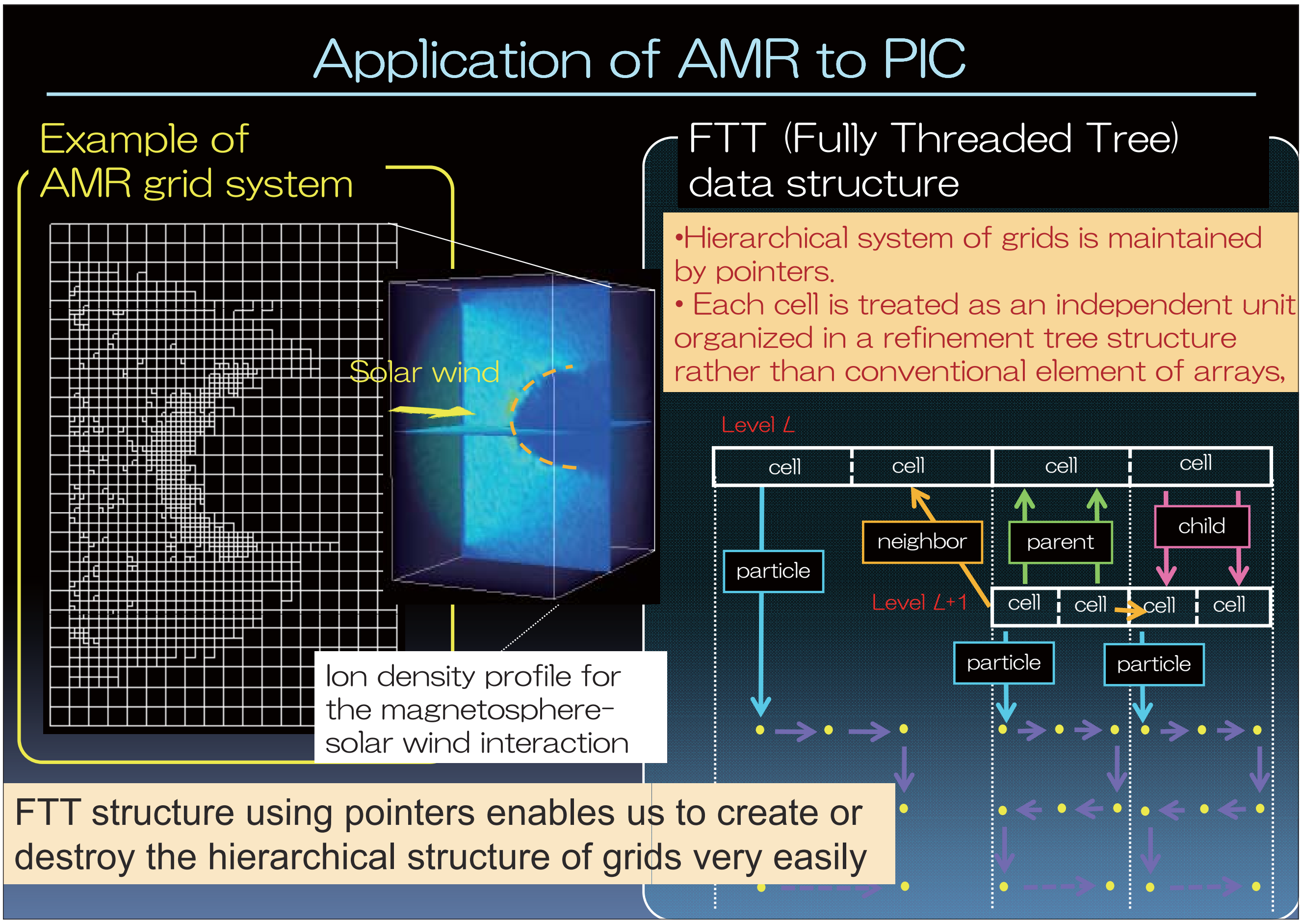
- Plasma injection $\sim \mathcal{O}(10^{-1\sim0}\mathrm{m})$
- Spacecraft $\sim \mathcal{O}(10^{0}\mathrm{m})$
- Inflated dipole field $\sim \mathcal{O}(10^{4}\mathrm{m})$
- Larmor raduis of solar wind ions $\sim \mathcal{O}(10^{4\sim5}\mathrm{m})$

Multi-scale analysis including plasma kinetic effects

- Conventional 3D EM-PIC simulation codes hire uniform and fixed spatial grid system.
- For the multi-scale simulation, it is better that the resolution is adaptively adjusted during a simulation run, depending on local plasma phenomena.

Combination of AMR(Adaptive Mesh Refinement) and PIC

Application of AMR to PIC



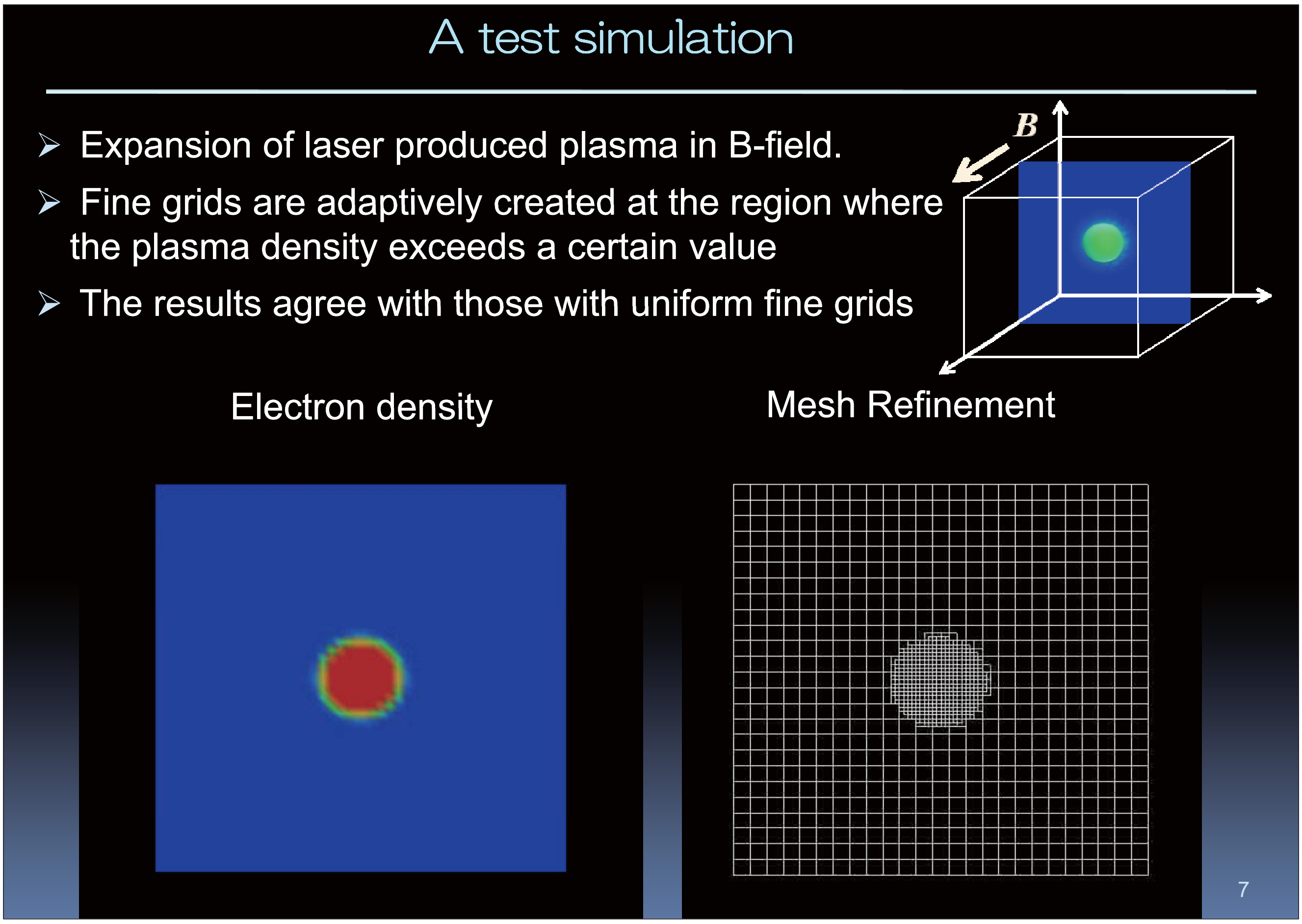
Example of AMR grid system

Ion density profile for the magnetosphere-solar wind interaction

FTT (Fully Threaded Tree) data structure

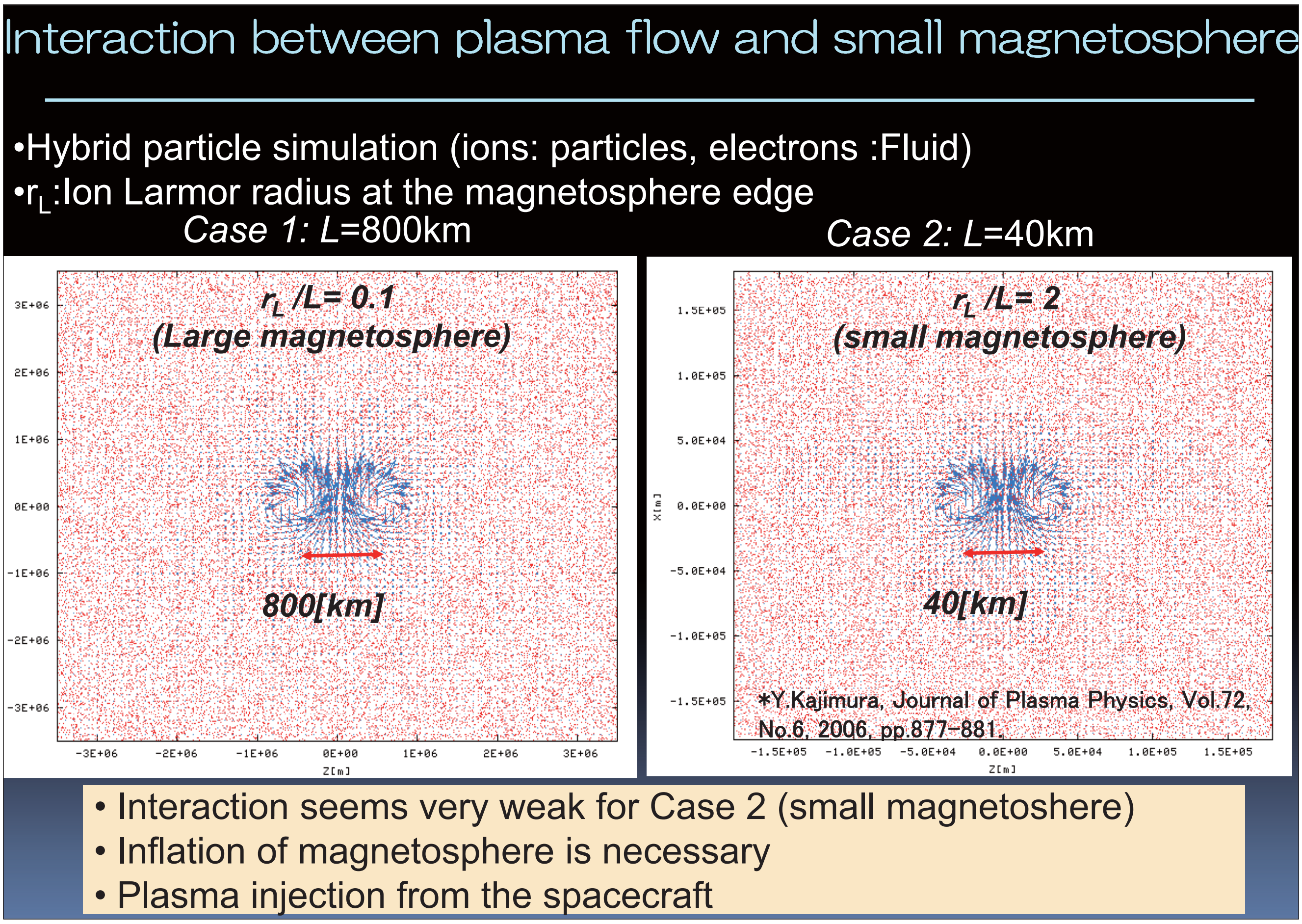
- Hierarchical system of grids is maintained by pointers.
- Each cell is treated as an independent unit organized in a refinement tree structure rather than conventional element of arrays,

FTT structure using pointers enables us to create or destroy the hierarchical structure of grids very easily



A test simulation

- ➢ Expansion of laser produced plasma in B-field.
- ➢ Fine grids are adaptively created at the region where the plasma density exceeds a certain value
- ➢ The results agree with those with uniform fine grids



Interaction between plasma flow and small magnetosphere

•Hybrid particle simulation (ions: particles, electrons :Fluid)

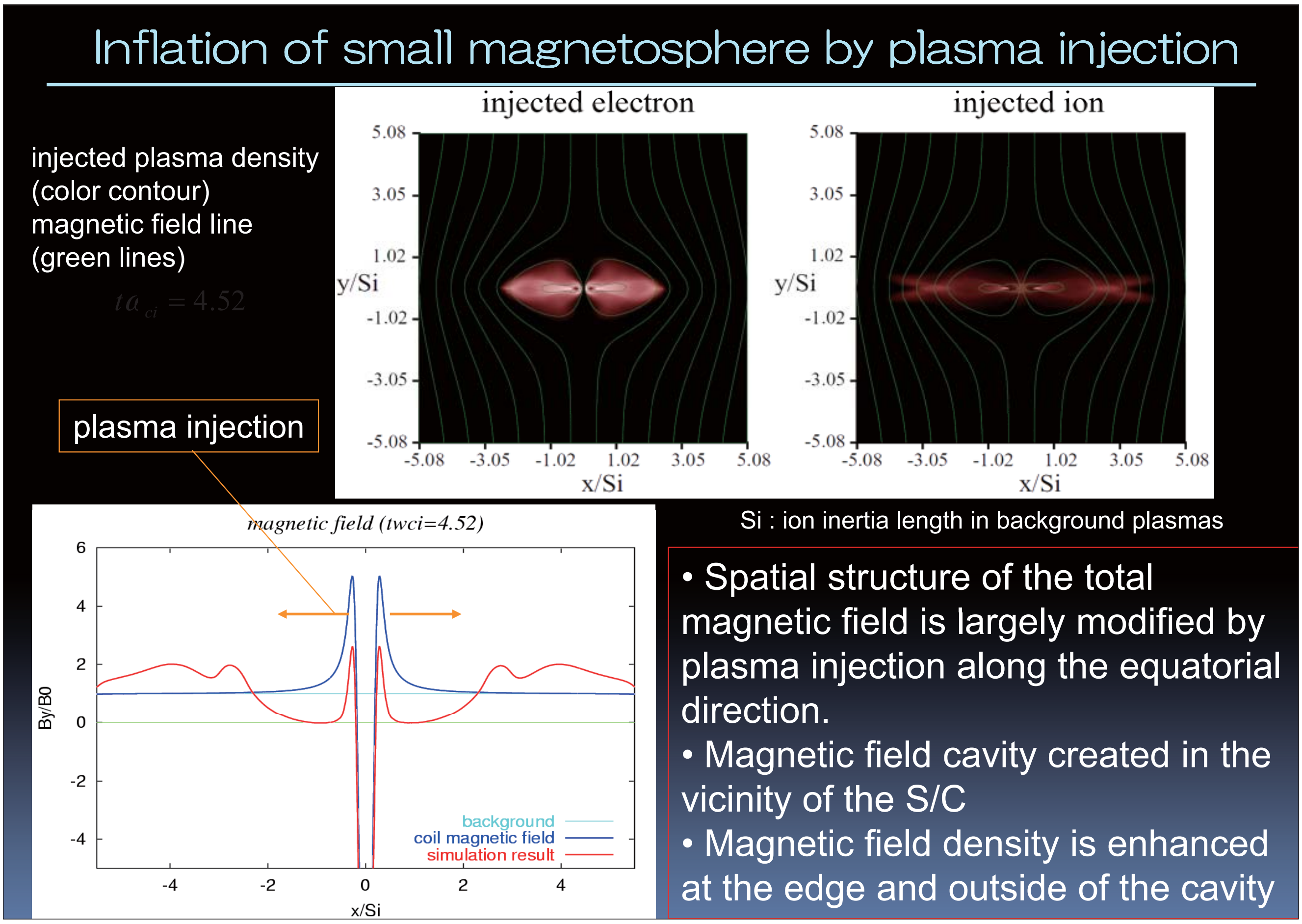
•r_L:Ion Larmor radius at the magnetosphere edge

Case 1: L=800km

Case 2: L=40km

*Y.Kajimura, Journal of Plasma Physics, Vol.72, No.6, 2006, pp.877-881.

- Interaction seems very weak for Case 2 (small magnetoshere)
- Inflation of magnetosphere is necessary
- Plasma injection from the spacecraft



Inflation of small magnetosphere by plasma injection

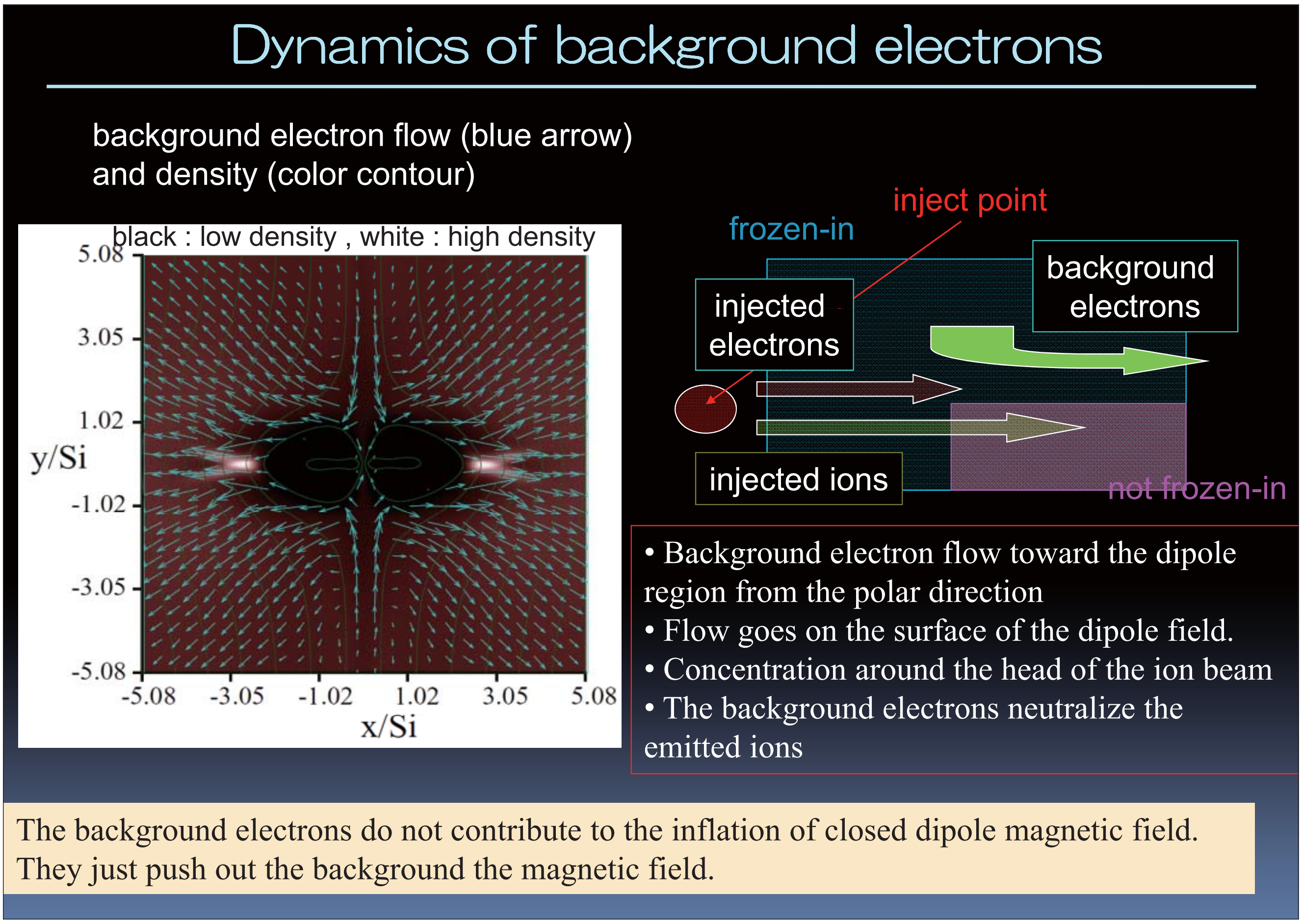
injected plasma density
(color contour)
magnetic field line
(green lines)

$t\omega_{ci} = 4.52$

plasma injection

Si : ion inertia length in background plasmas

- Spatial structure of the total magnetic field is largely modified by plasma injection along the equatorial direction.
- Magnetic field cavity created in the vicinity of the S/C
- Magnetic field density is enhanced at the edge and outside of the cavity



Dynamics of background electrons

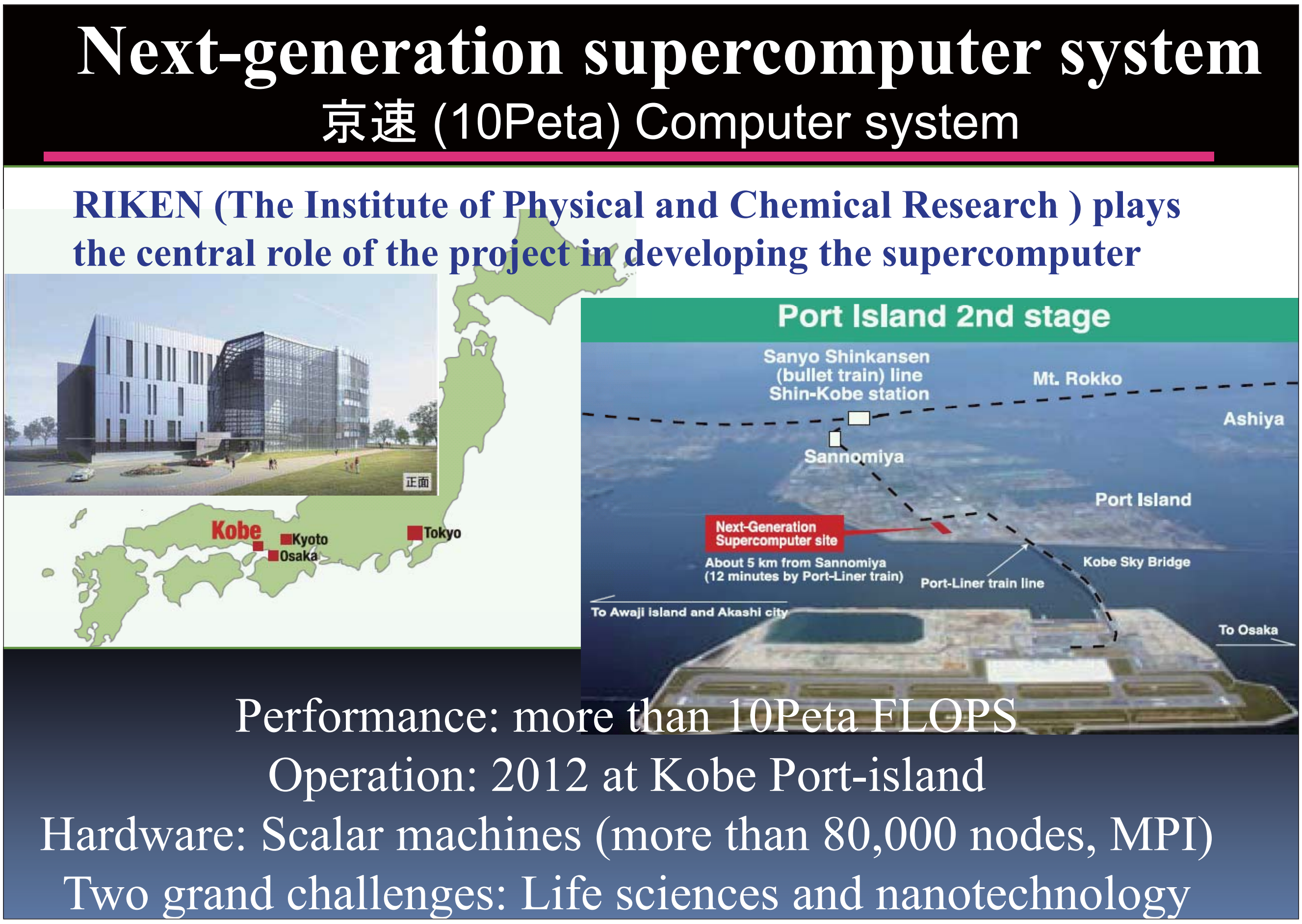
background electron flow (blue arrow)
and density (color contour)

black : low density , white : high density

inject point
frozen-in
background electrons
injected electrons
injected ions
not frozen-in

- Background electron flow toward the dipole region from the polar direction
- Flow goes on the surface of the dipole field.
- Concentration around the head of the ion beam
- The background electrons neutralize the emitted ions

The background electrons do not contribute to the inflation of closed dipole magnetic field. They just push out the background the magnetic field.



Next-generation supercomputer system

京速 (10Peta) Computer system

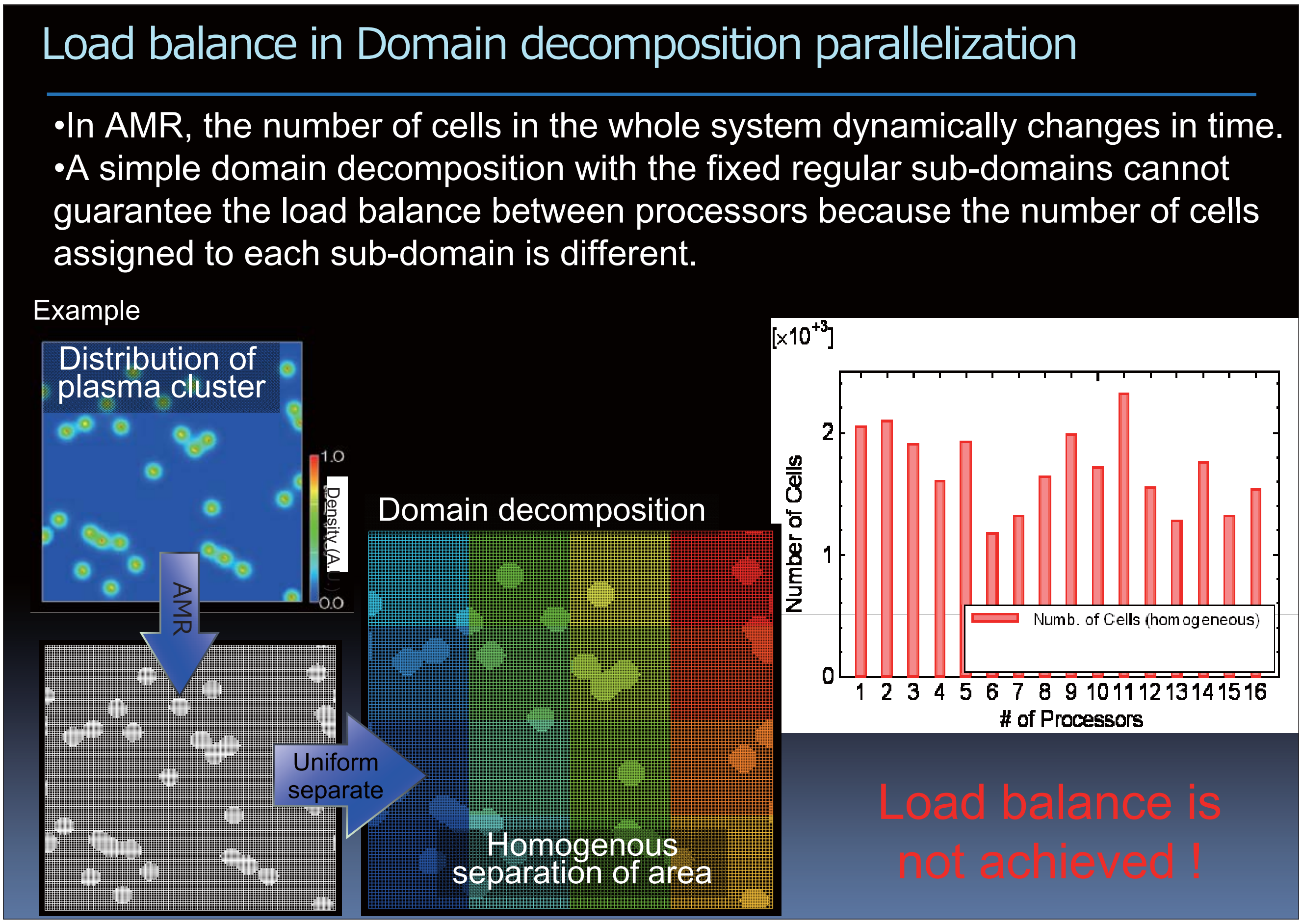
RIKEN (The Institute of Physical and Chemical Research) plays the central role of the project in developing the supercomputer

Performance: more than 10Peta FLOPS

Operation: 2012 at Kobe Port-island

Hardware: Scalar machines (more than 80,000 nodes, MPI)

Two grand challenges: Life sciences and nanotechnology

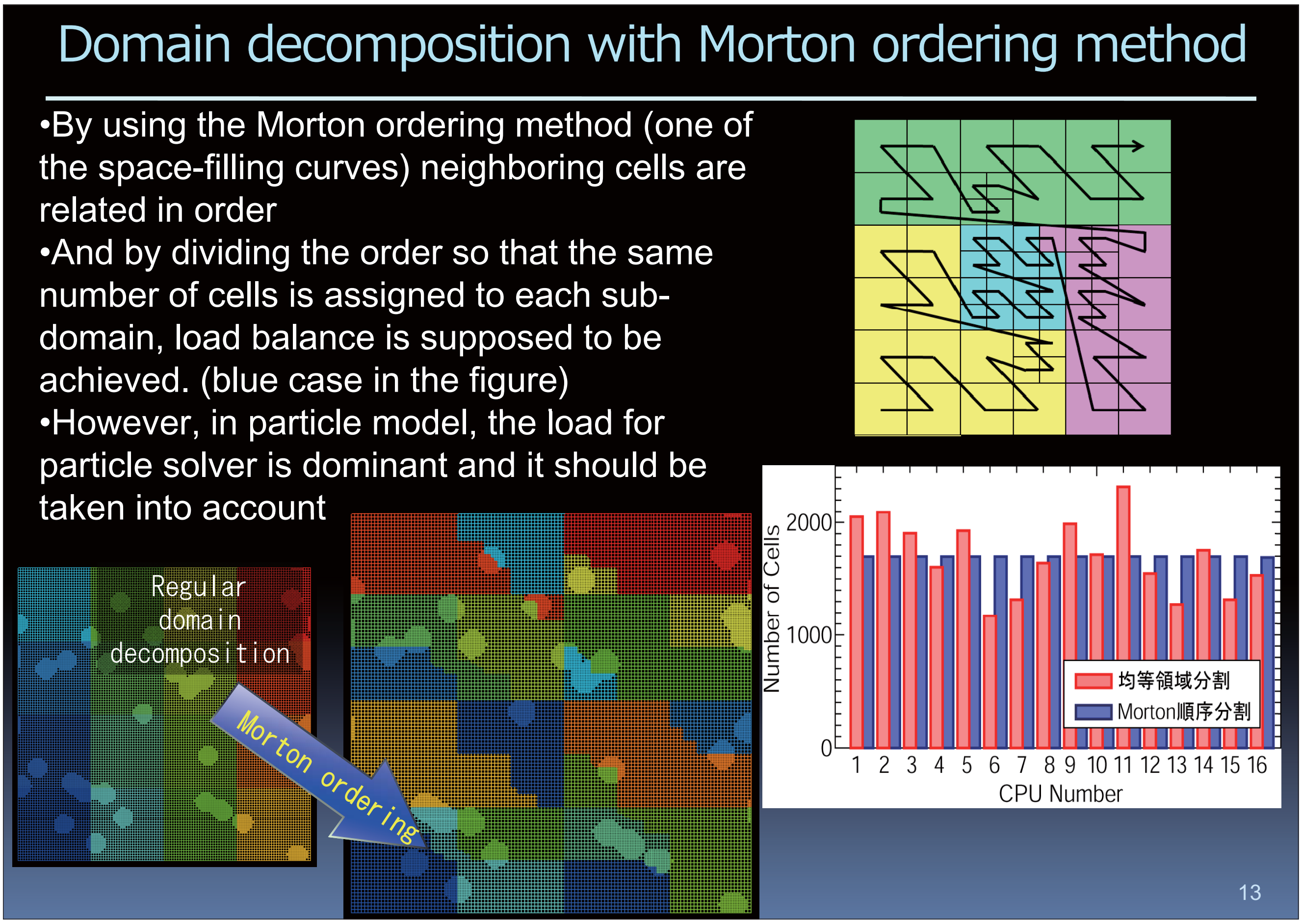


Load balance in Domain decomposition parallelization

- •In AMR, the number of cells in the whole system dynamically changes in time.
- •A simple domain decomposition with the fixed regular sub-domains cannot guarantee the load balance between processors because the number of cells assigned to each sub-domain is different.

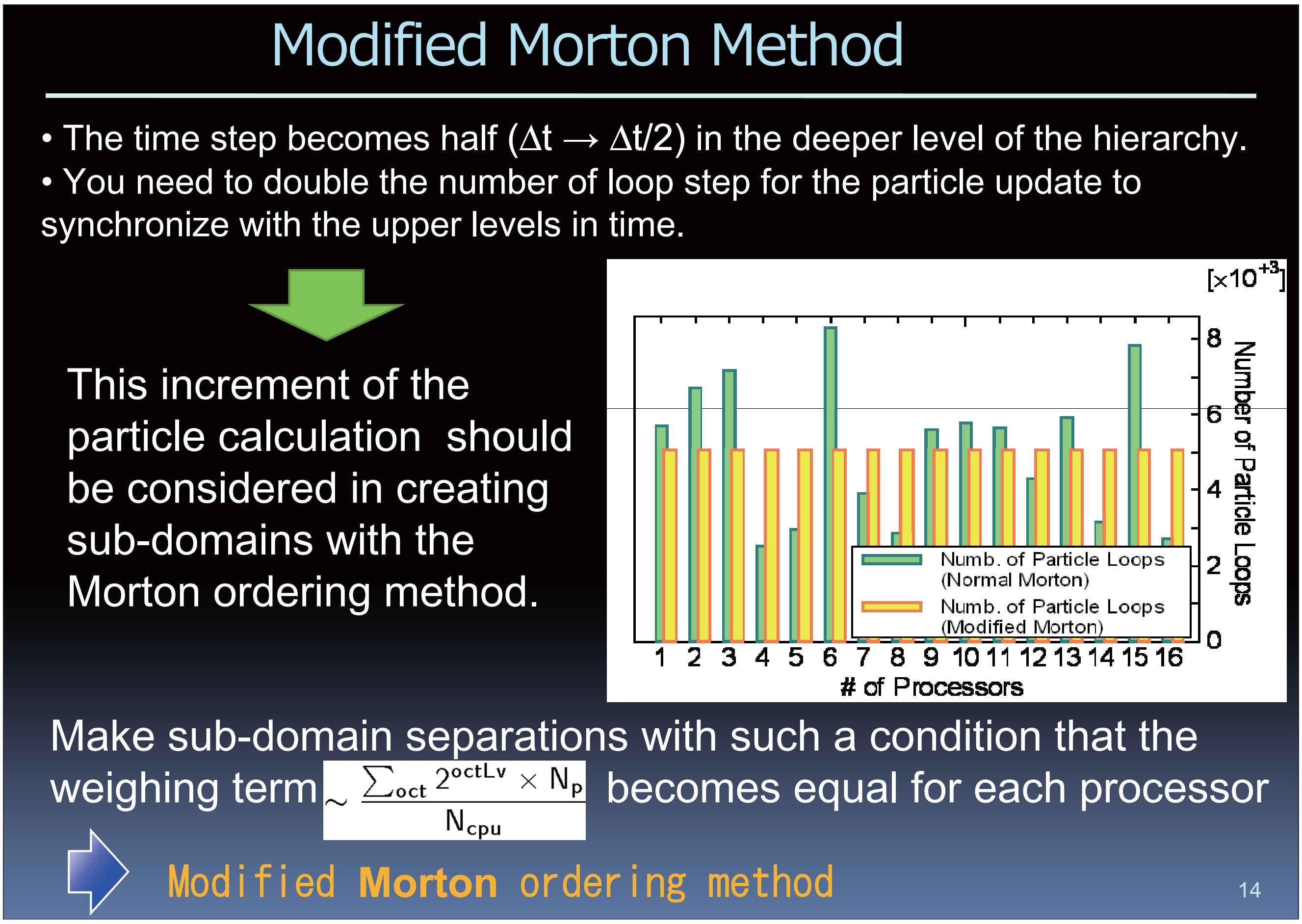
Example

Load balance is not achieved !



Domain decomposition with Morton ordering method

- By using the Morton ordering method (one of the space-filling curves) neighboring cells are related in order
- And by dividing the order so that the same number of cells is assigned to each sub-domain, load balance is supposed to be achieved. (blue case in the figure)
- However, in particle model, the load for particle solver is dominant and it should be taken into account



Modified Morton Method

- The time step becomes half (Δt → Δt/2) in the deeper level of the hierarchy.
- You need to double the number of loop step for the particle update to synchronize with the upper levels in time.

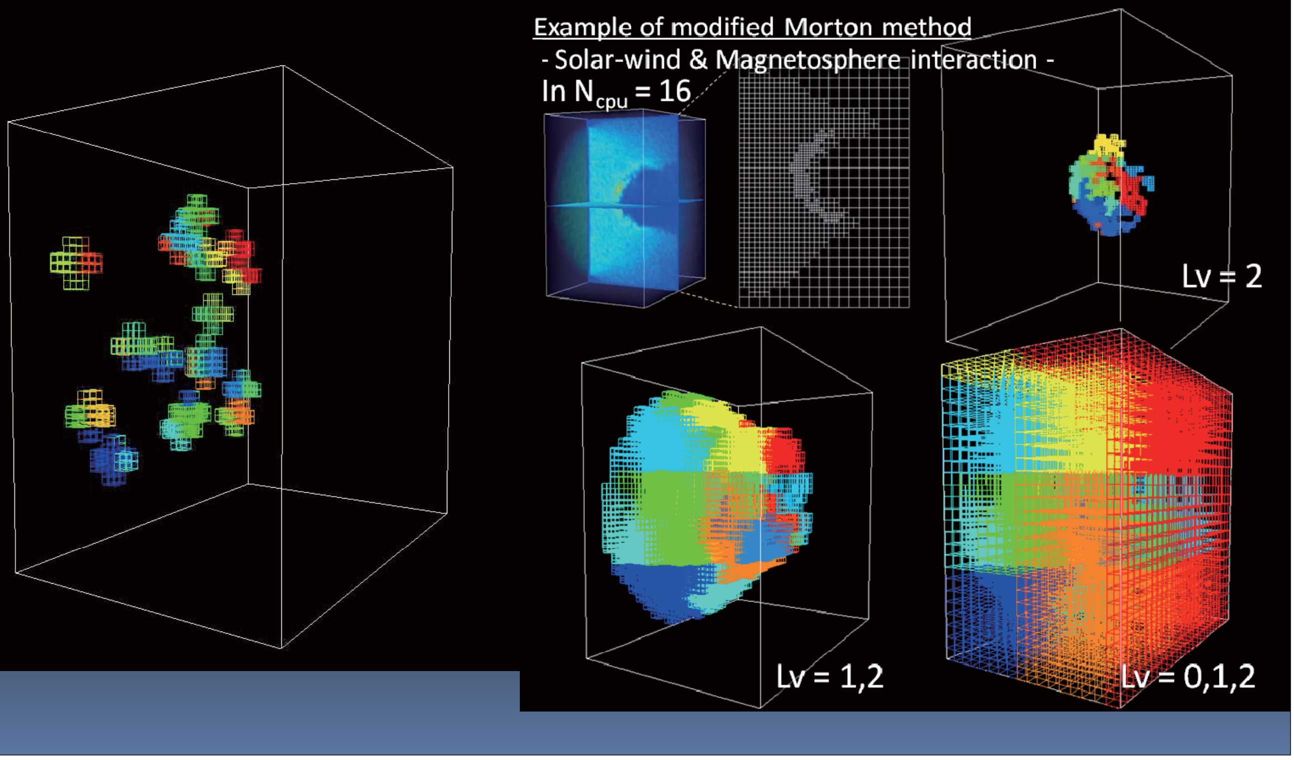
This increment of the particle calculation should be considered in creating sub-domains with the Morton ordering method.

Make sub-domain separations with such a condition that the weighing term $\sim \dfrac{\sum_{oct} 2^{octLv} \times N_p}{N_{cpu}}$ becomes equal for each processor

⇨ Modified **Morton** ordering method

Test of modified Morton ordering

— Plasma flow - magnetosphere interaction —



Example of modified Morton method

- Solar-wind & Magnetosphere interaction -

In N_{cpu} = 16

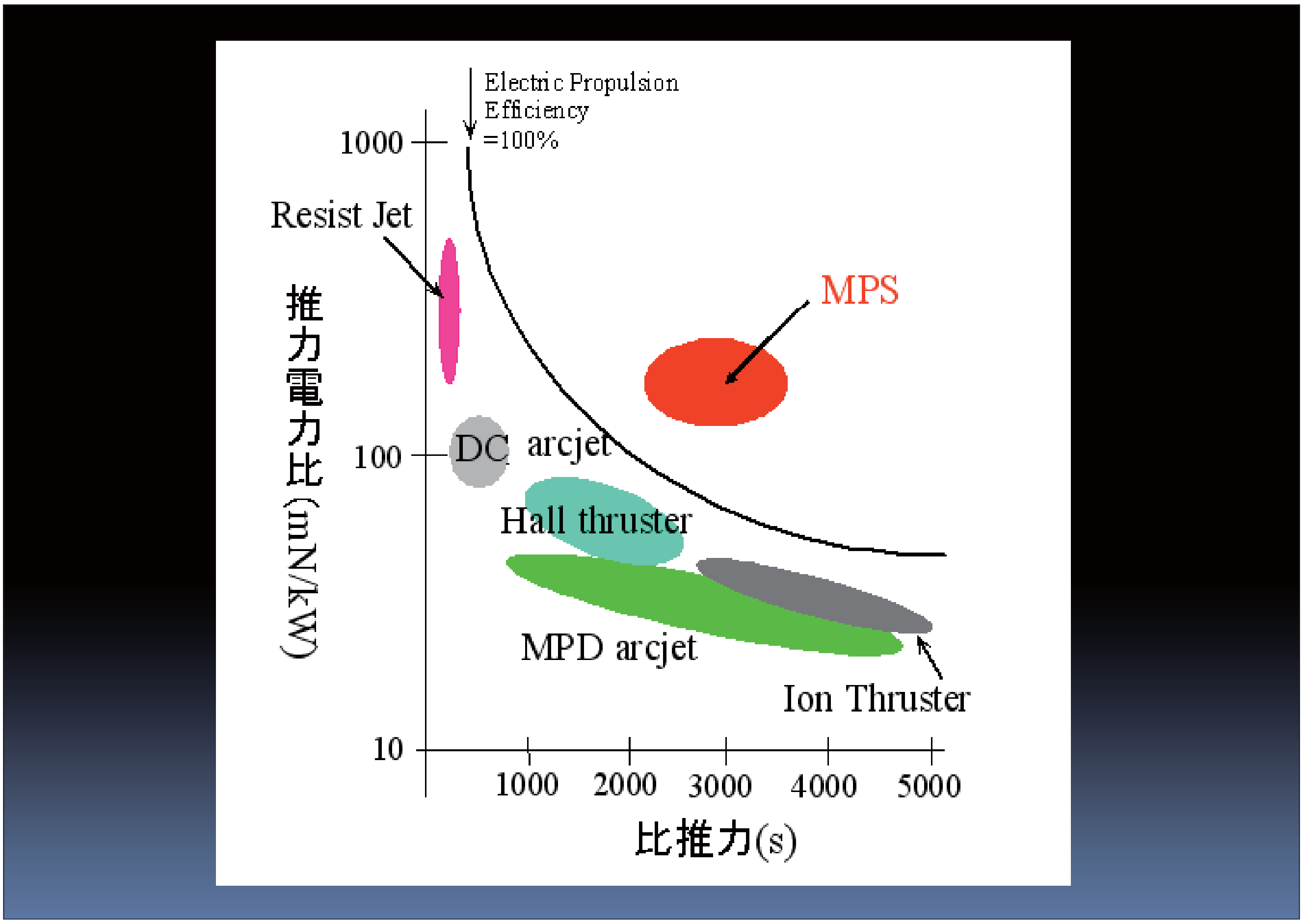
Summary

- We have been investigating MPS interaction with solar wind as well as the inflation of small magnetosphere.

- We started developing a new plasma particle code for multi-scale simulation by incorporating AMR.

- To achieve the load balancing in the domain-decomposition parallelization, we consider the load of the particle loop by modifying the Morton ordering.

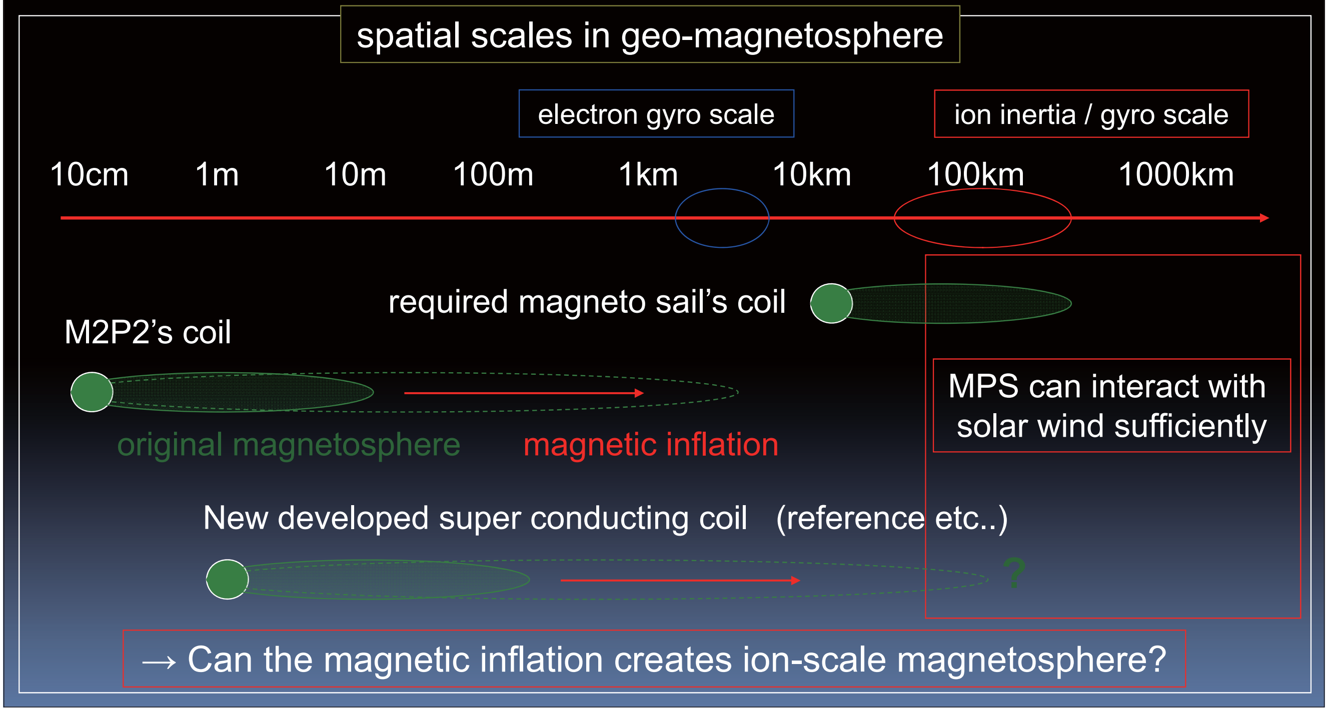
- As a future work, we will complete the parallelization of our AMR-PIC code and apply to the multi-scale particle simulations with the next generation supercomputer (hopefully)



Need for magnetic inflation

In order to interact with solar wind sufficiently, required scale of MPS magnetosphere might be larger than ion inertia length in the solar wind (100 - 1000 km).

G.Khazanov et al, JPP, **21**, 853(1991)


spatial scales in geo-magnetosphere

required magneto sail's coil

M2P2's coil

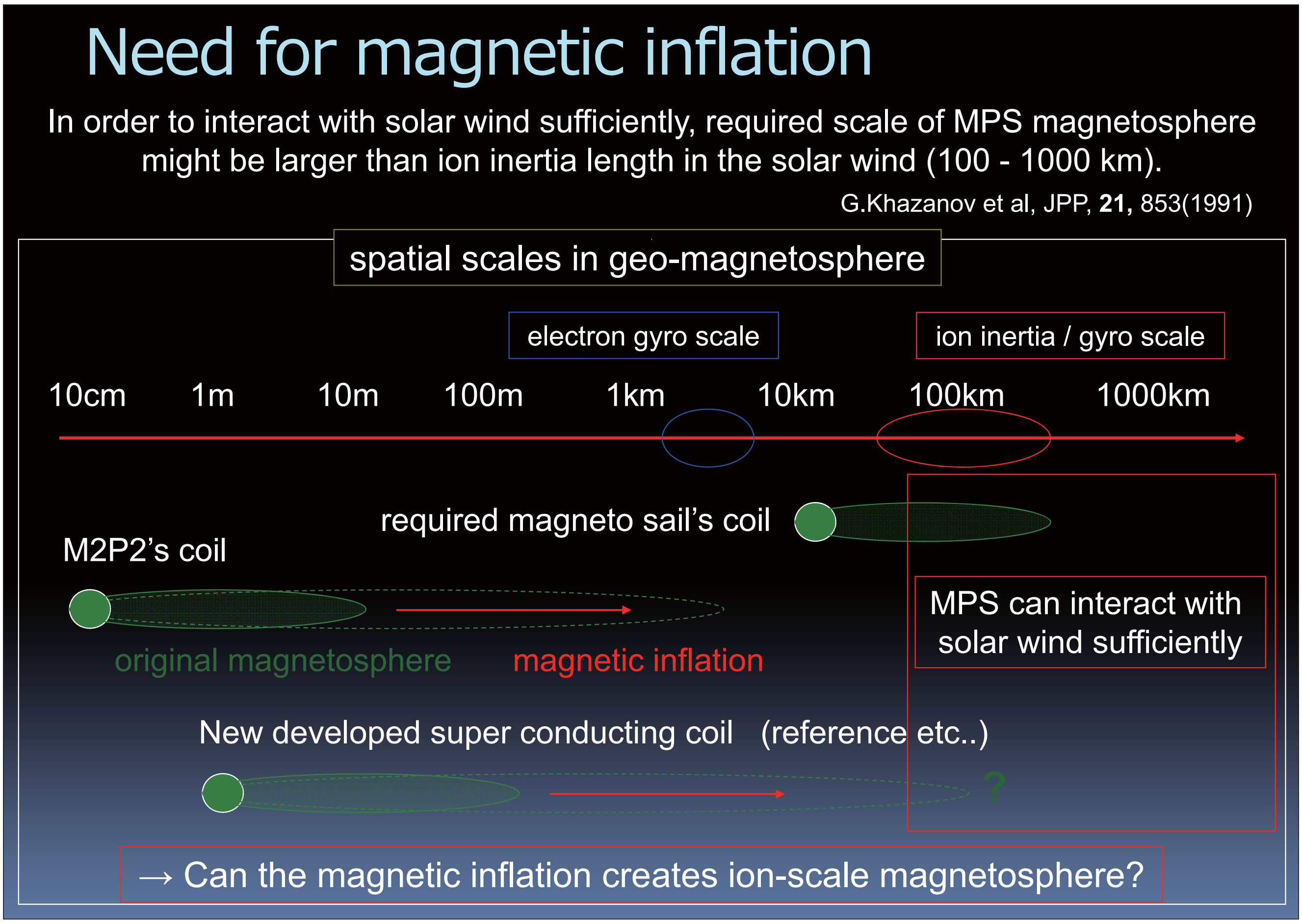
original magnetosphere

magnetic inflation

MPS can interact with solar wind sufficiently

New developed super conducting coil (reference etc..)

→ Can the magnetic inflation creates ion-scale magnetosphere?



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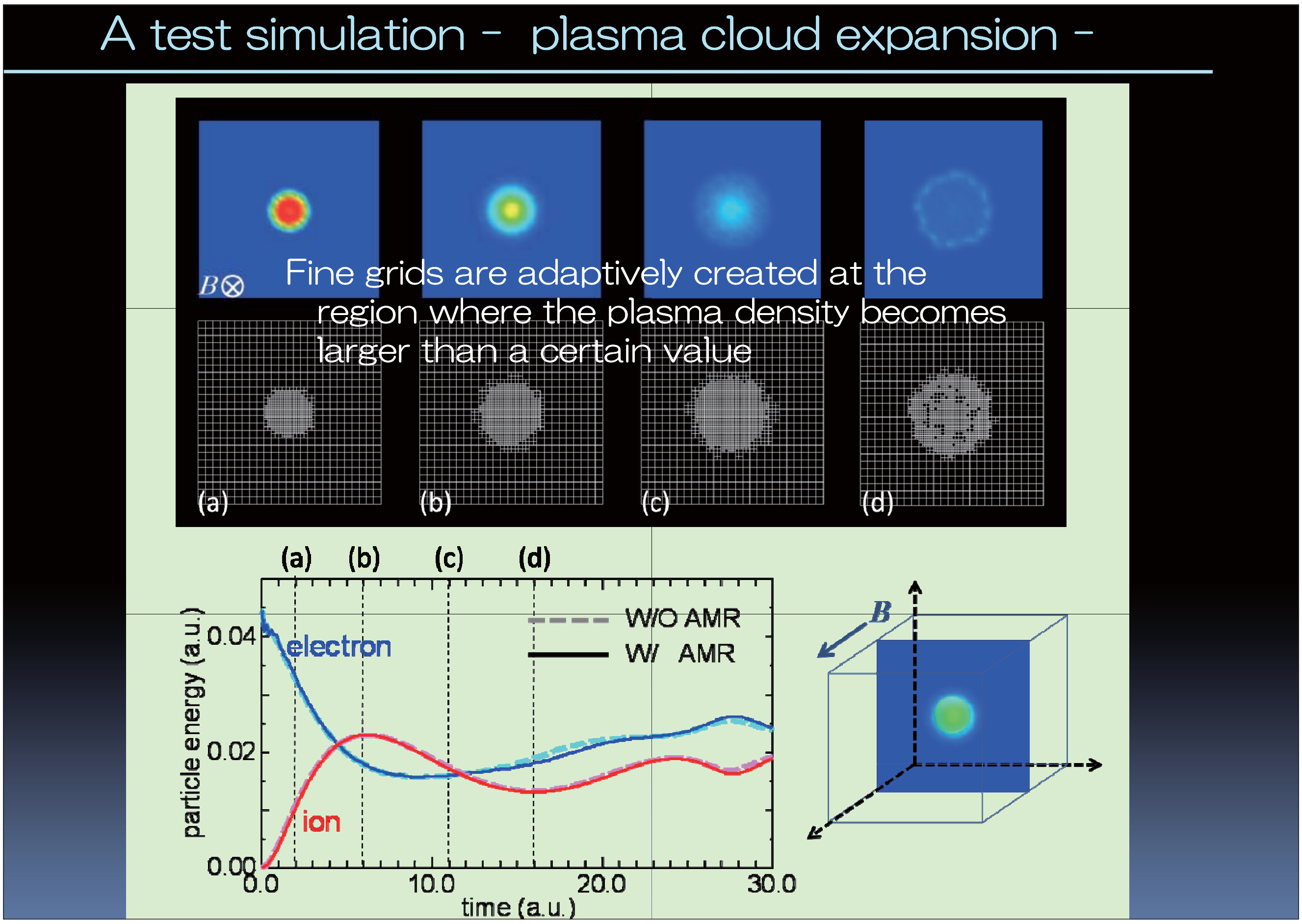
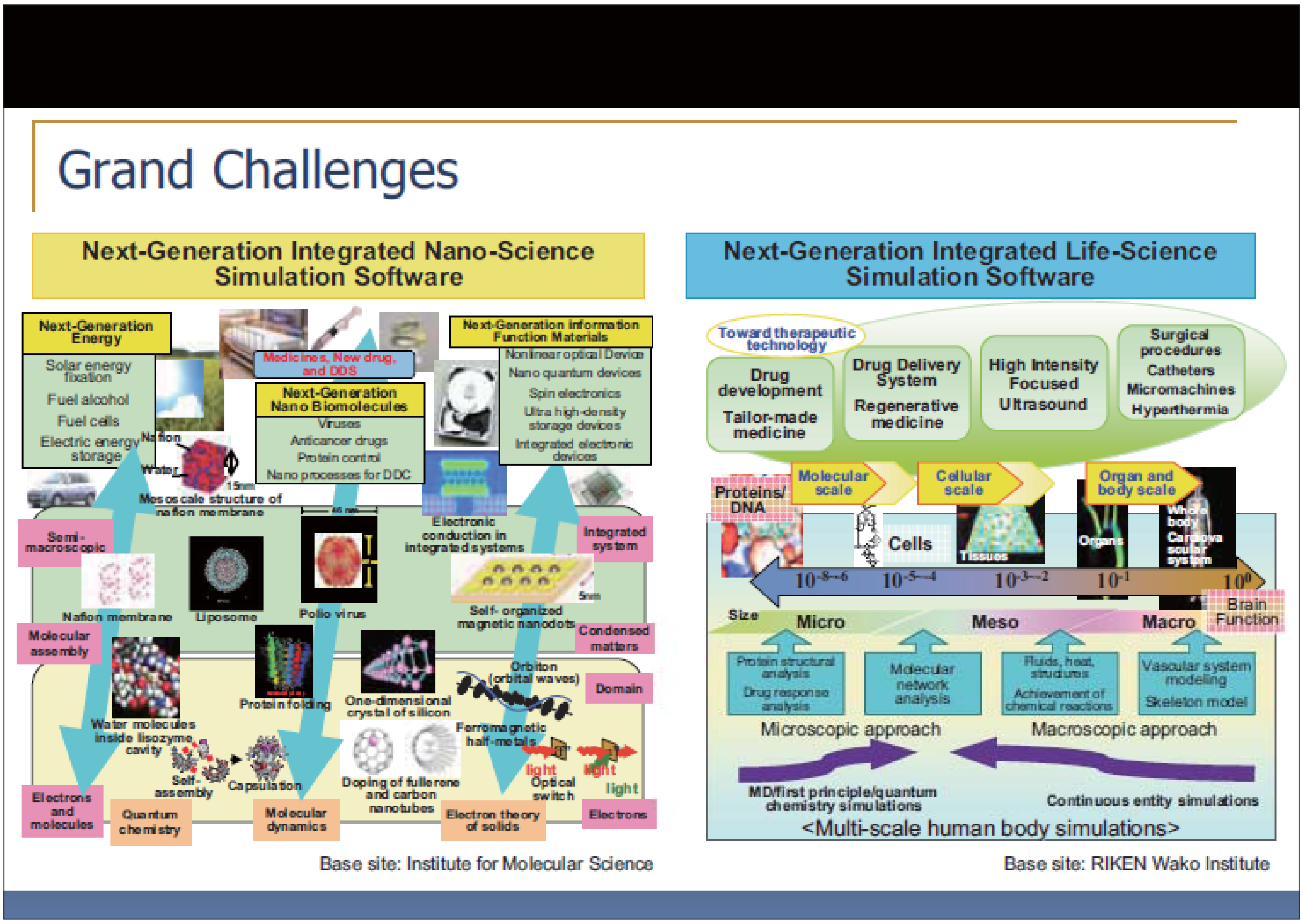


A test simulation － plasma cloud expansion －

Fine grids are adaptively created at the region where the plasma density becomes larger than a certain value



Grand Challenges

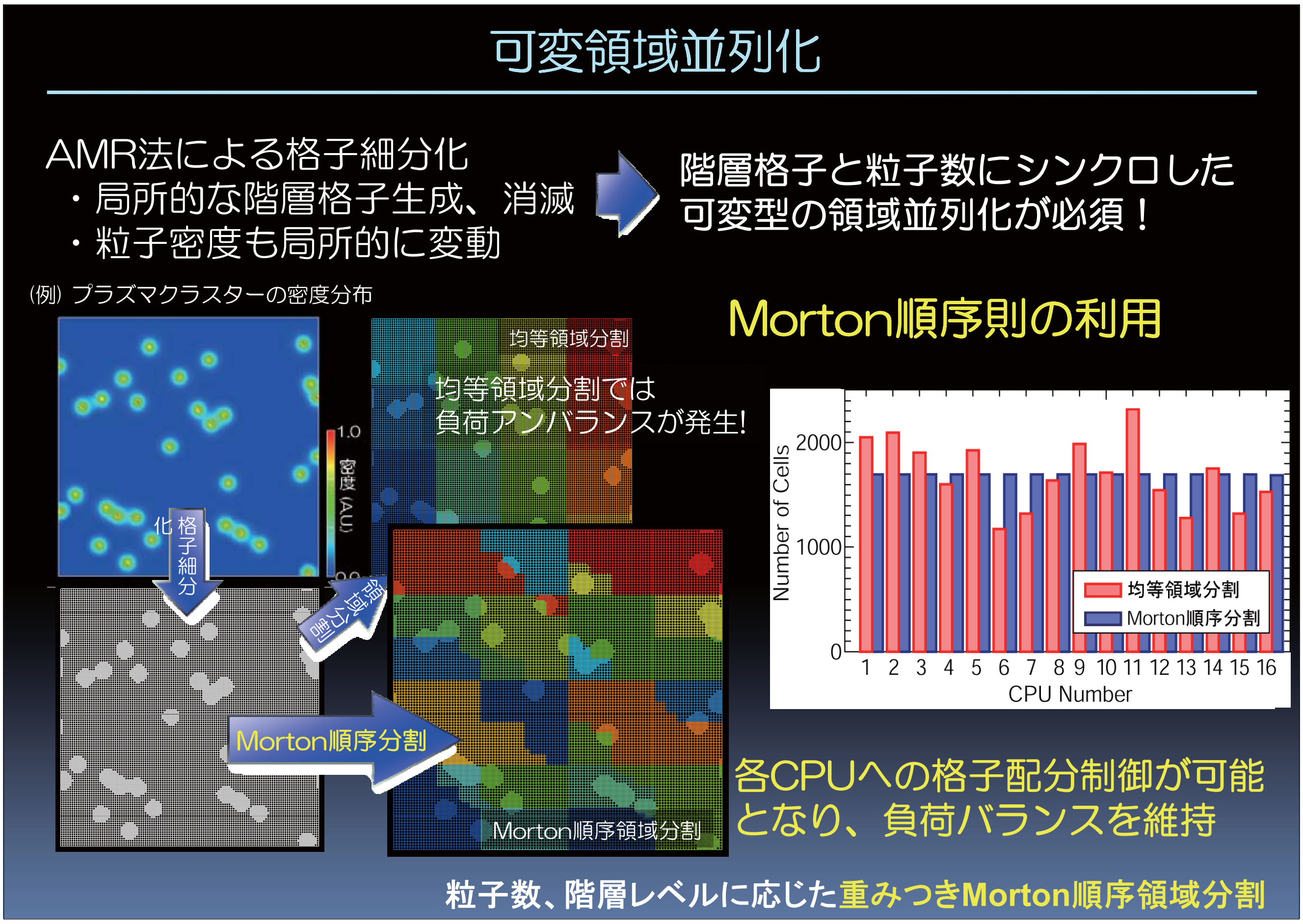
Next-Generation Integrated Nano-Science Simulation Software

Base site: Institute for Molecular Science

Next-Generation Integrated Life-Science Simulation Software

<Multi-scale human body simulations>

Base site: RIKEN Wako Institute



可変領域並列化

AMR法による格子細分化
- 局所的な階層格子生成、消滅
- 粒子密度も局所的に変動

階層格子と粒子数にシンクロした可変型の領域並列化が必須！

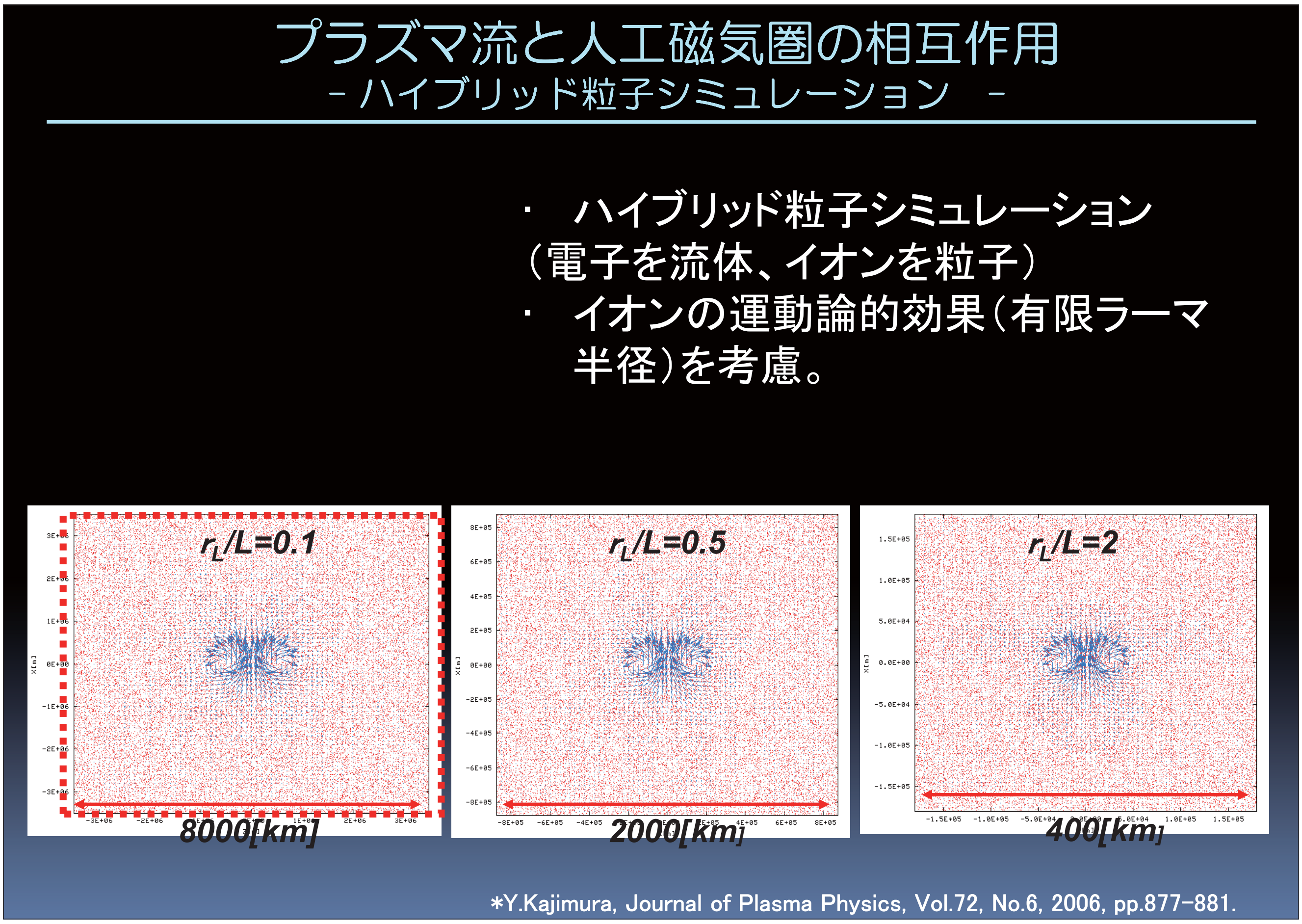
(例) プラズマクラスターの密度分布

均等領域分割では負荷アンバランスが発生!

Morton順序則の利用

各CPUへの格子配分制御が可能となり、負荷バランスを維持

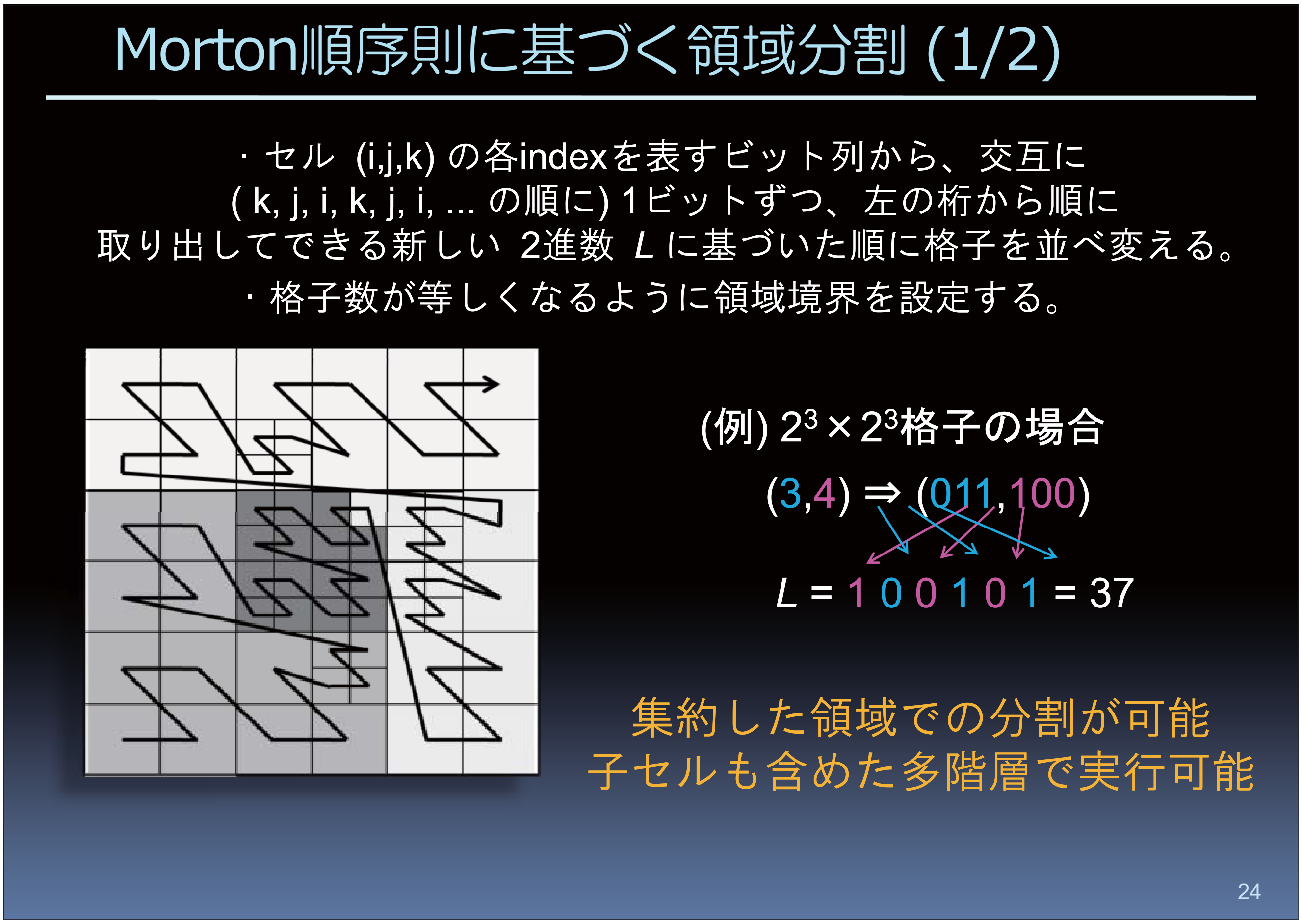
粒子数、階層レベルに応じた重みつきMorton順序領域分割



プラズマ流と人工磁気圏の相互作用
－ハイブリッド粒子シミュレーション　－

- ハイブリッド粒子シミュレーション（電子を流体、イオンを粒子）
- イオンの運動論的効果（有限ラーマ半径）を考慮。

*Y.Kajimura, Journal of Plasma Physics, Vol.72, No.6, 2006, pp.877-881.



Morton順序則に基づく領域分割 (1/2)

・セル (i,j,k) の各indexを表すビット列から、交互に (k, j, i, k, j, i, ... の順に) 1ビットずつ、左の桁から順に取り出してできる新しい 2進数 L に基づいた順に格子を並べ変える。

・格子数が等しくなるように領域境界を設定する。

(例) $2^3 \times 2^3$格子の場合

(3,4) ⇒ (011,100)

L = 1 0 0 1 0 1 = 37

集約した領域での分割が可能
子セルも含めた多階層で実行可能