Magneto-Rotational Instability and Particle Acceleration in a Collisionless Accretion Disk

星野真弘[1]、松本洋介[2]、
白川慶介[1]、平林孝太[1]、天野孝伸[1]、
荻野達樹[3]、石井克哉[4]

[1]東京大学、[2]千葉大学、[3]名古屋大学STEL、[4]名古屋大学情報基盤

ABSTRACT Particle acceleration during the magneto-rotational instability (MRI) in a collisionless accretion disk is investigated by using a particle-in-cell (PIC) simulation. We discuss that magnetic reconnection plays an important role not only on the saturation of MRI but on the relativistic particle generation. This efficient particle acceleration mechanism may be regarded as one of possible models to explain the origin of high energy particles observed around massive black holes such as Sagittarius A*.

Basic Equations

Local, non-inertia frame rotating with angular velocity Ω

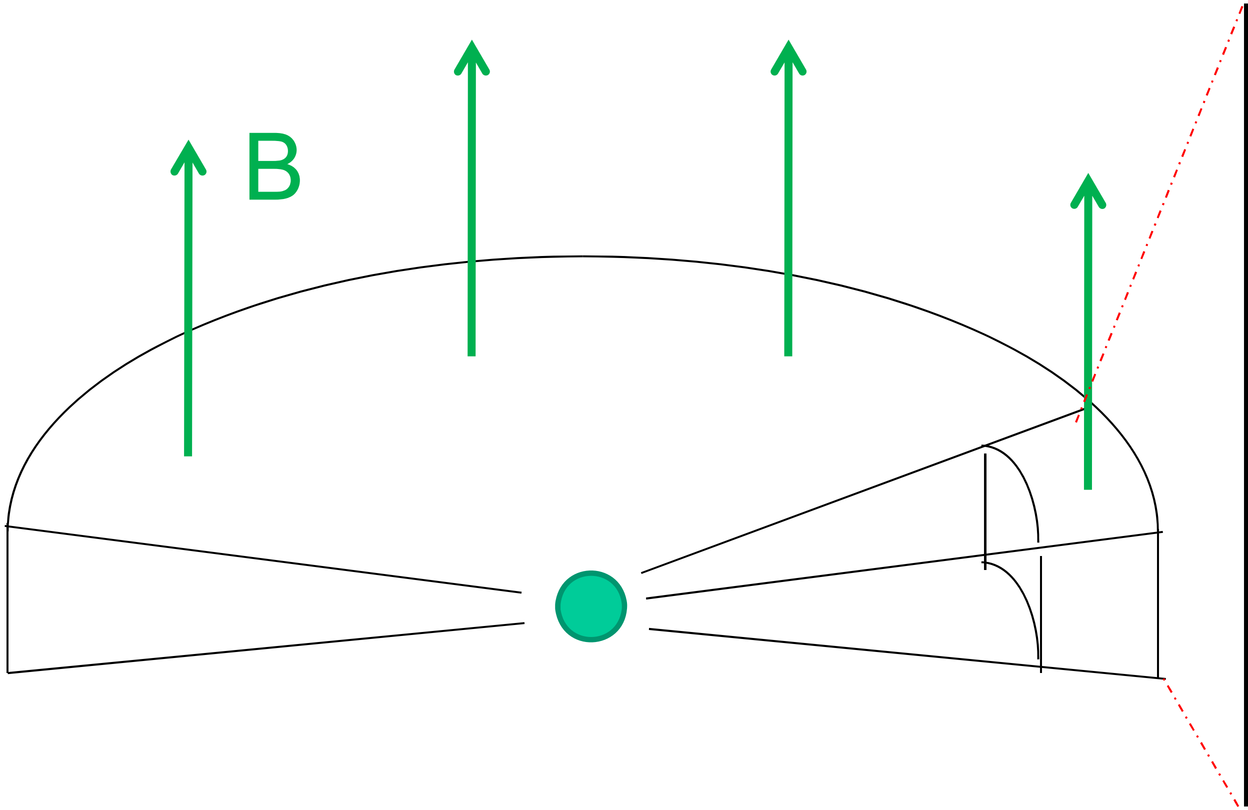
$$
\begin{aligned}
\frac{1}{c}\frac{\partial \vec{B}}{\partial t} &= -\nabla \times \vec{E}, \\
\nabla \cdot \vec{B} &= 0, \\
\frac{1}{c}\frac{\partial}{\partial t}\left(\vec{E} - \frac{\vec{v}_0}{c} \times \vec{B}\right) &= \nabla \times \vec{B}^* - \frac{4\pi}{c}\vec{J}, \\
\nabla \cdot \left(\vec{E} - \frac{\vec{v}_0}{c} \times \vec{B}\right) &= 4\pi\rho_c,
\end{aligned}
$$

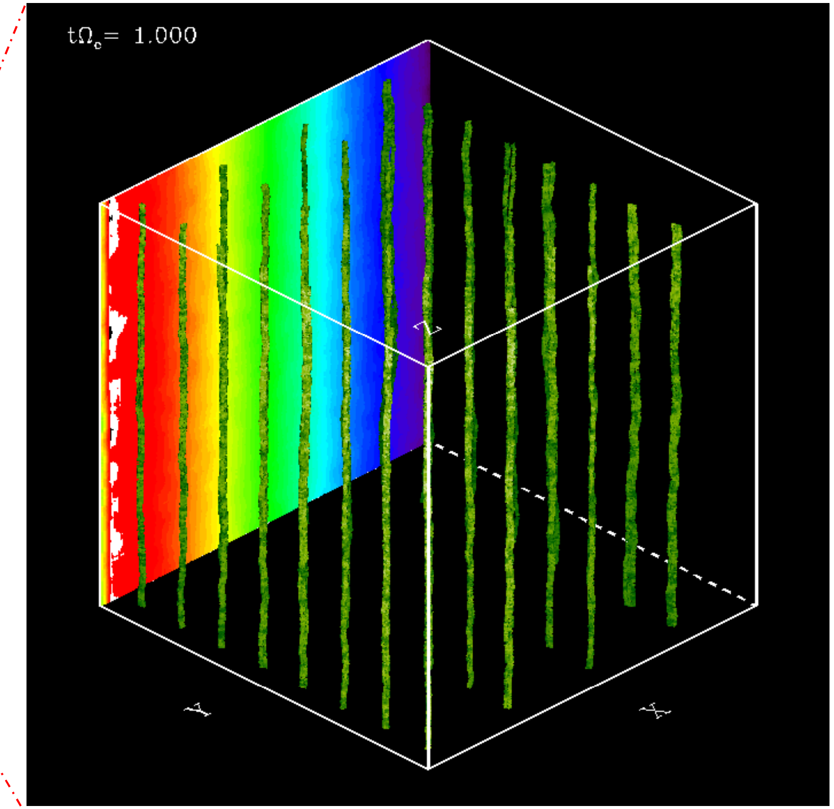
$$\text{where } \vec{v}_0(r) = \Omega_0 \vec{e}_z \times \vec{r}$$

$$
\begin{aligned}
\frac{d\vec{x}}{dt} &= \vec{v}, \\
\frac{d\vec{p}}{dt} &= e(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}) - m\gamma(2\vec{\Omega}_0 \times \vec{v} - 2q\Omega_0^2 x \vec{e}_x).
\end{aligned}
$$

Keplerian disk with a tidal expansion

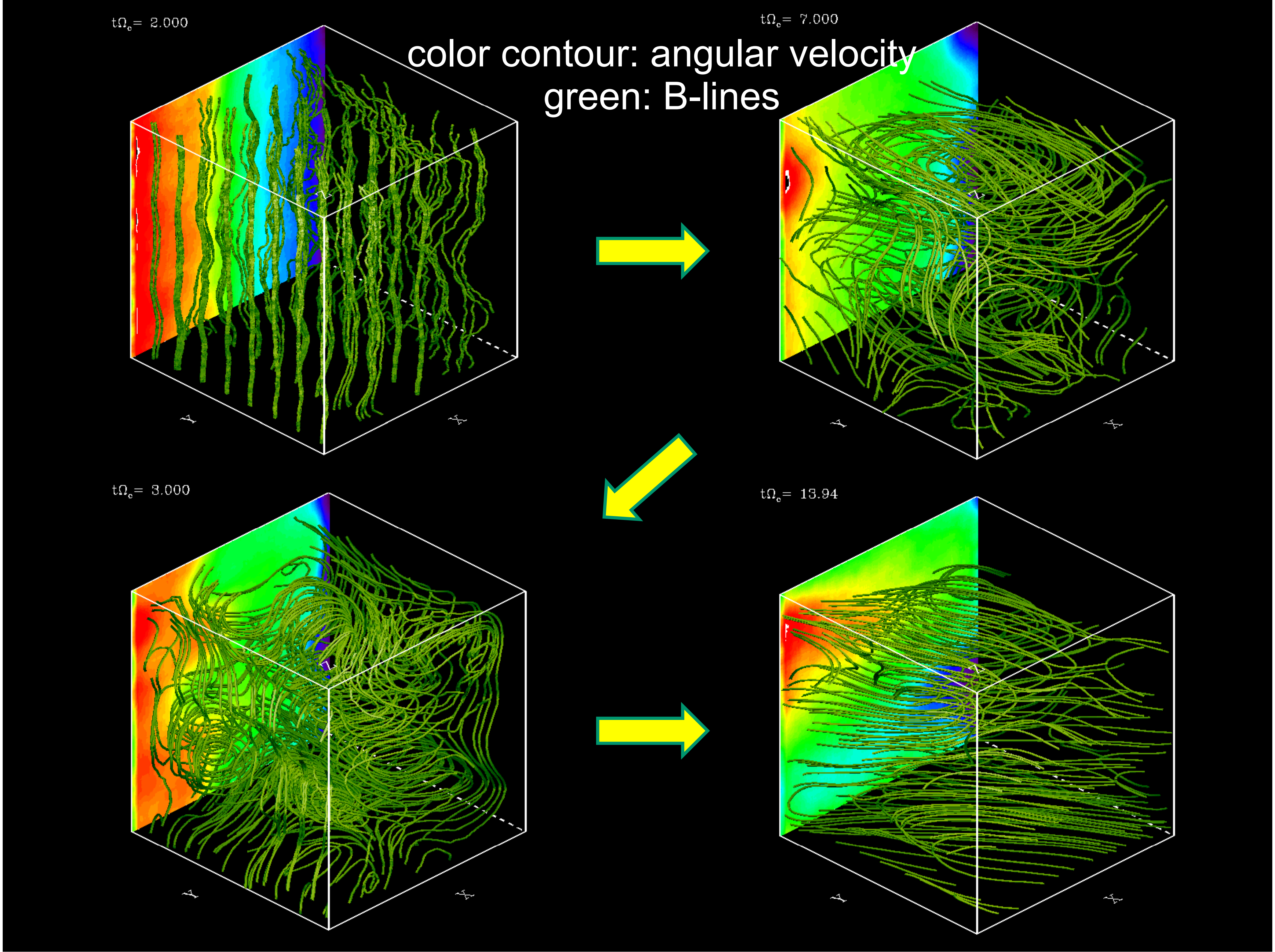
Kinetic MRI in PIC simulation





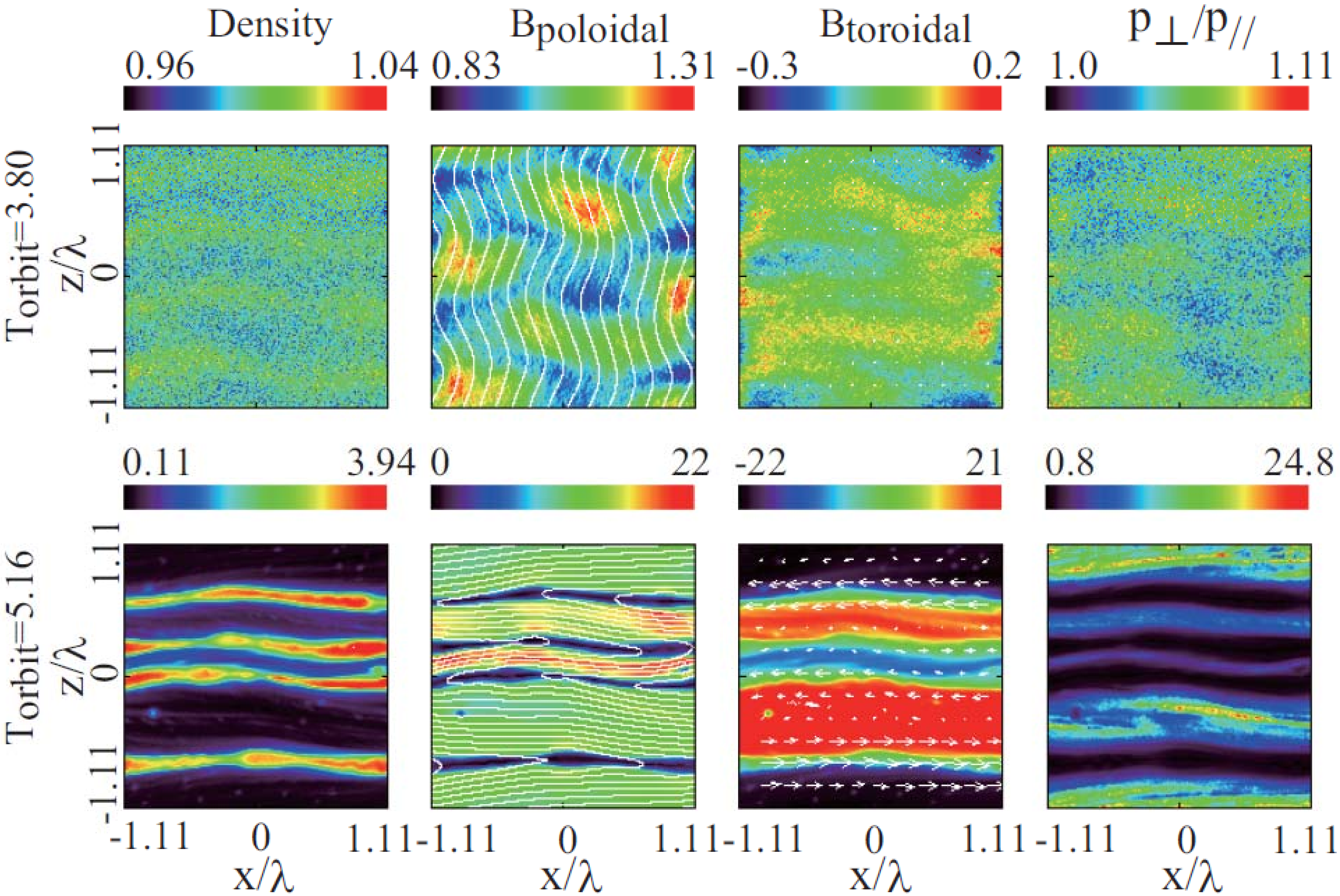
green: magnetic field lines
color contour: angular velocity

β=1000, Kepler rotation Ω
300^3 grids 20 particles/cell,
periodic shearing box, electron-positron plasma

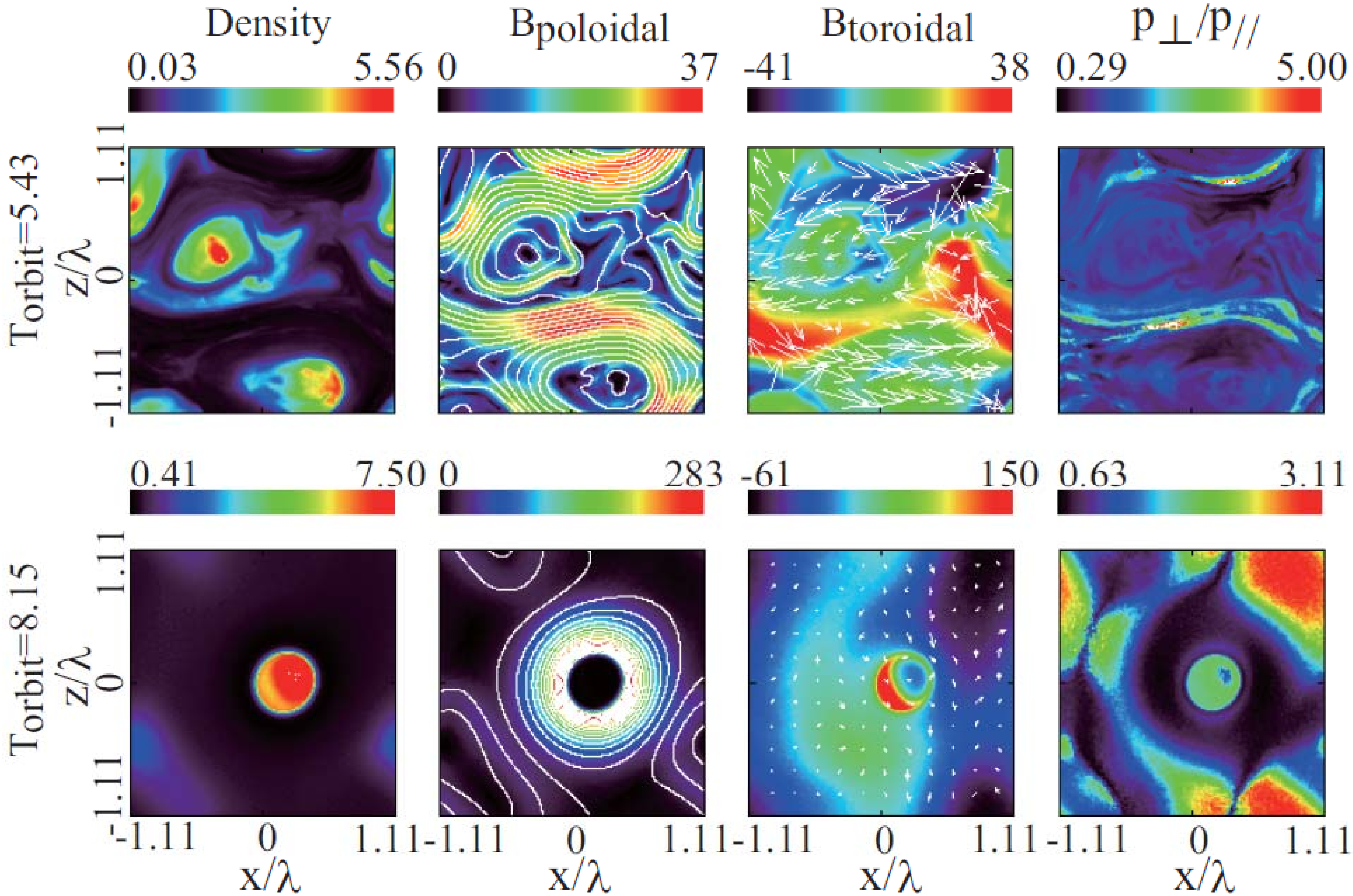


color contour: angular velocity
green: B-lines
tΩc= 2.000
tΩc= 7.000
tΩc= 3.000
tΩc= 13.94

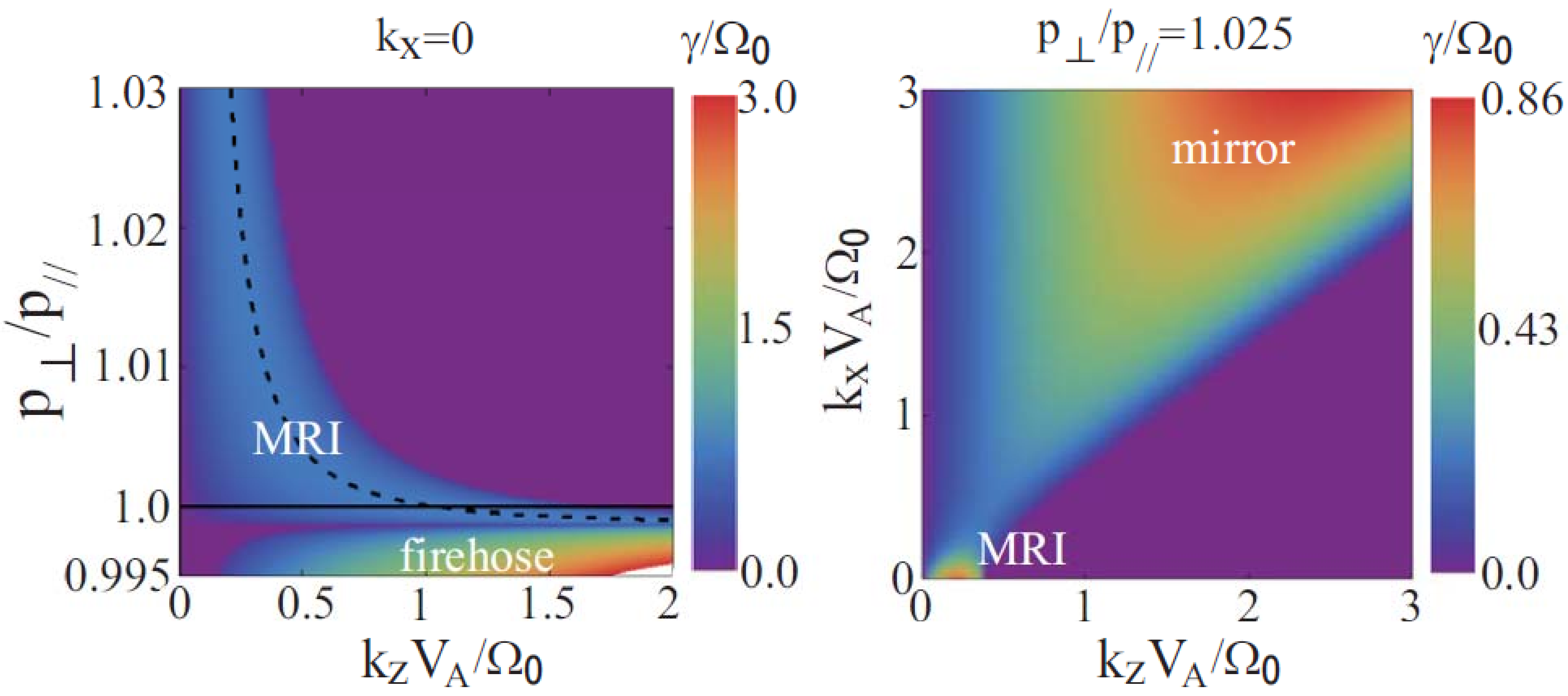
Evolution in Meridional Plane (1)



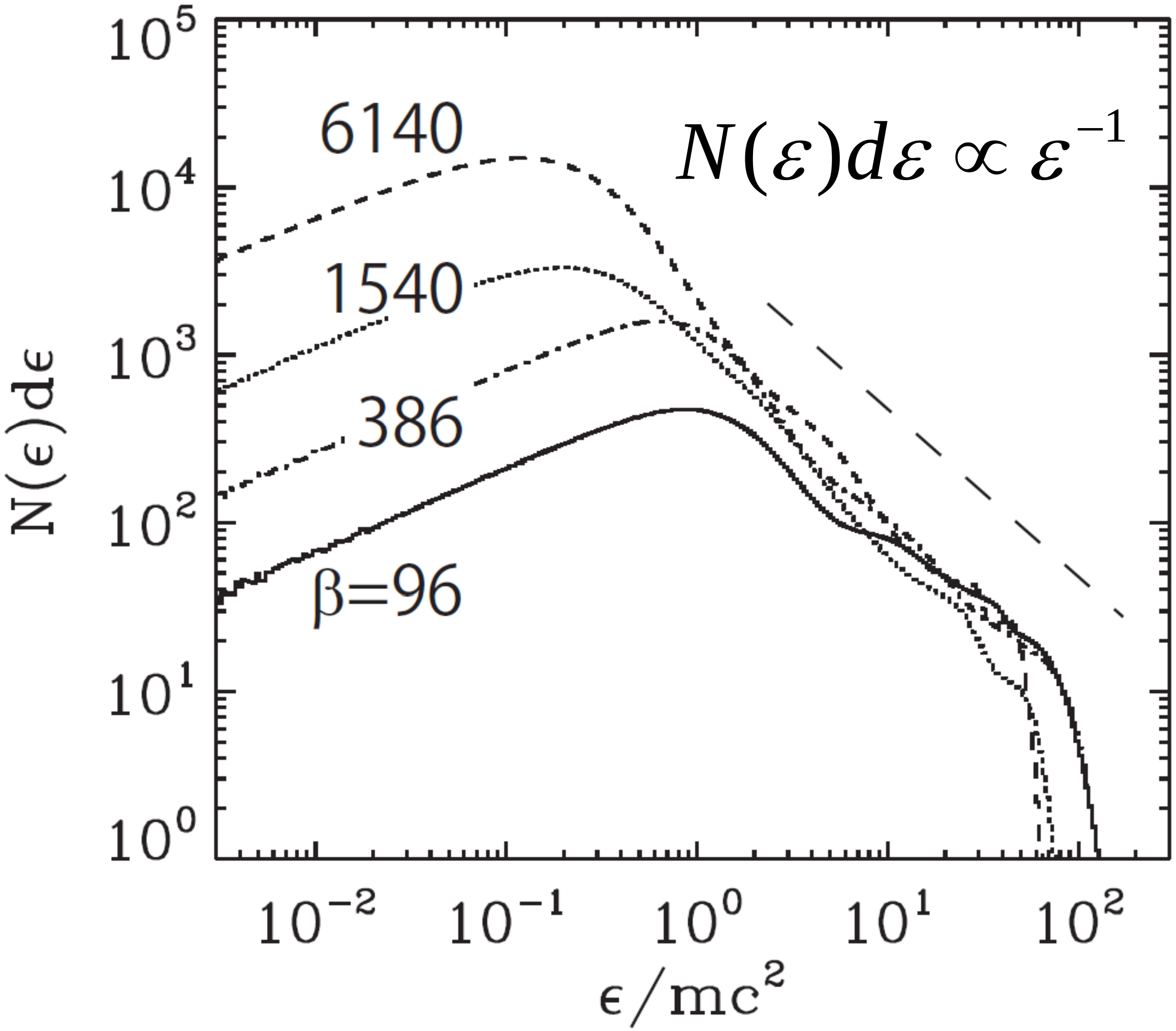
Evolution in Meridional Plane (2)



Linear Theory of Kinetic MRI: Coupling between MRI and Mirror Modes

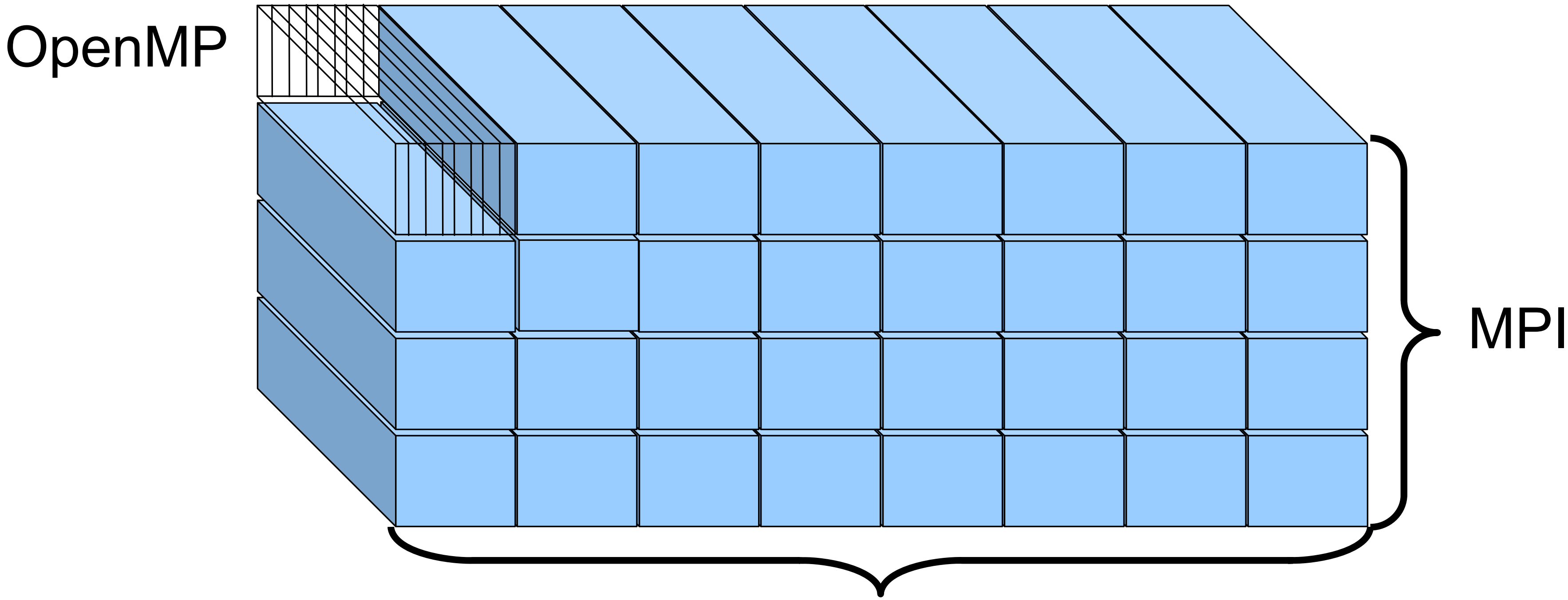


Energy Spectra during MRI-Reconnection



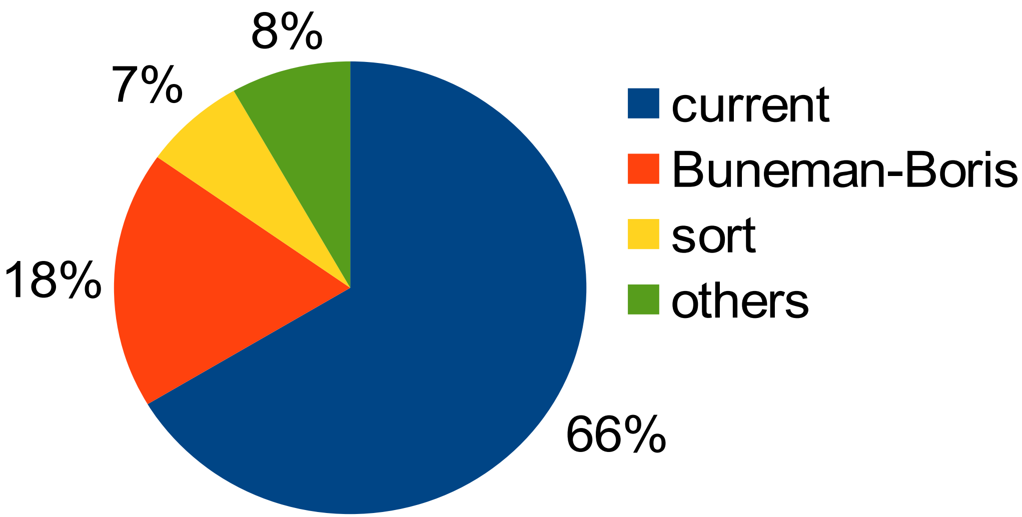
A hard energy spectrum is generated during magnetic reconnection phase. Dependence of initial plasma beta is weak

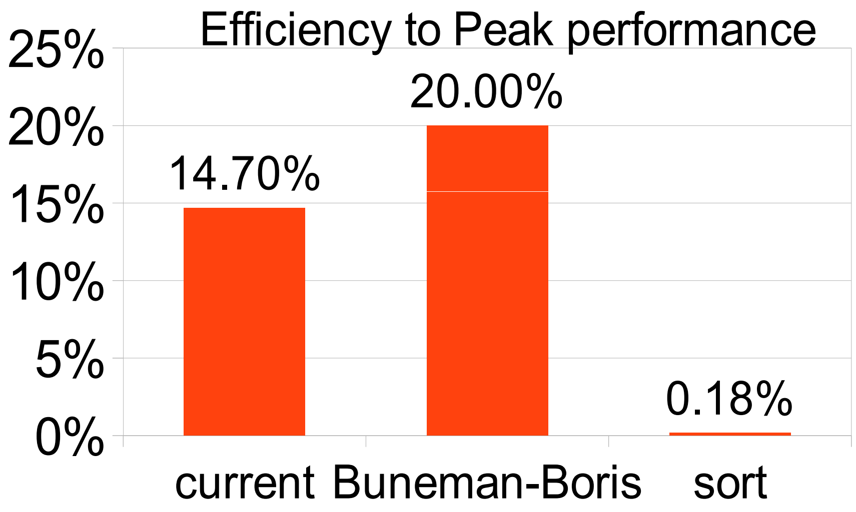
EM PIC code

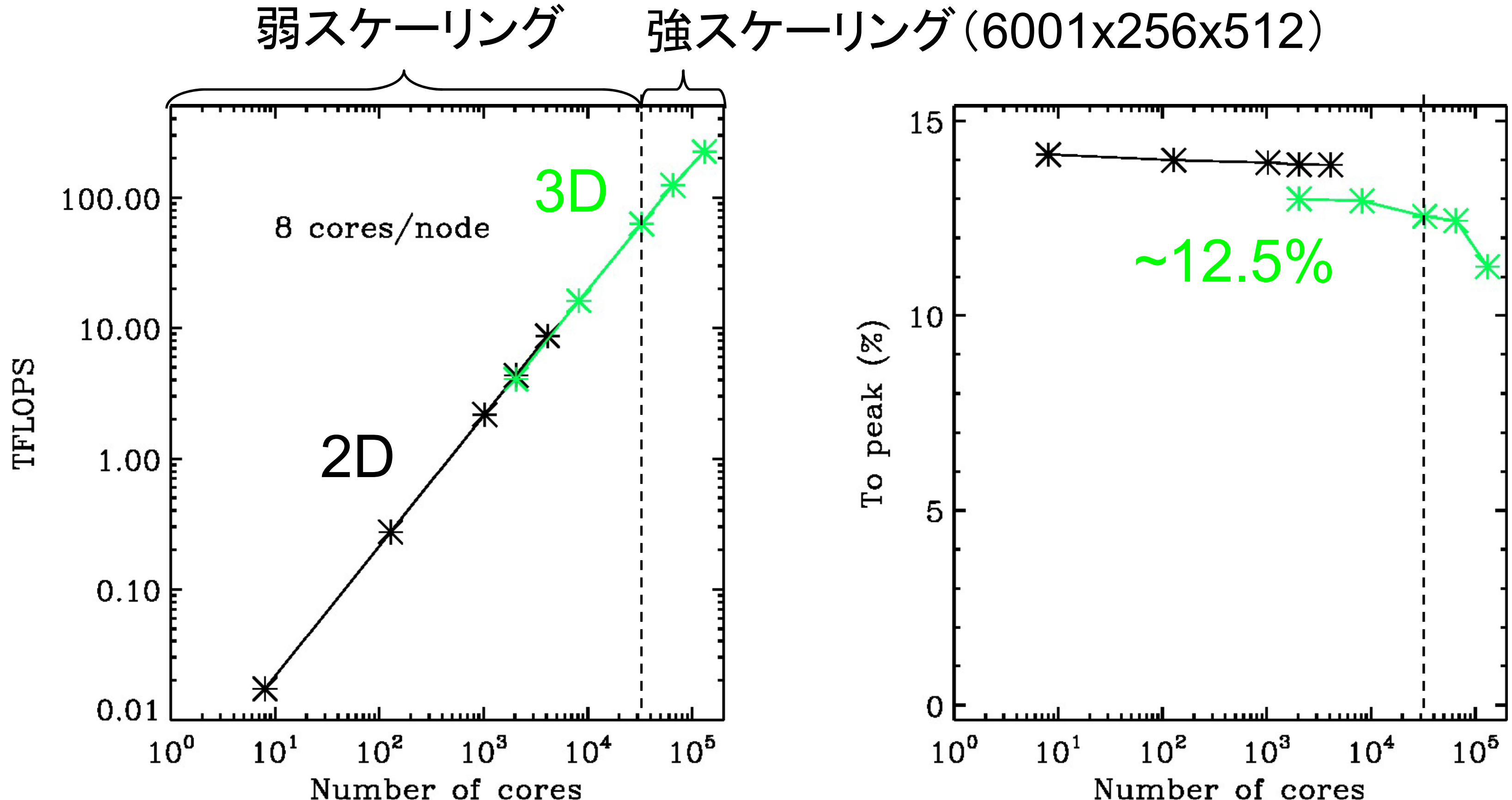


- Fortran 90
- 2-D domain (y-z) decomposition for 3-D code
- MPI+OpenMP hybrid parallelization
- Implicit E-M field solver
- Density decomposition for charge conservation (Esirkepov 03)
- 2nd order shape function

「京」での性能評価


8%
7%
18%
66%
current
Buneman-Boris
sort
others


Efficiency to Peak performance
25%
20%
15%
10%
5%
0%
14.70%
20.00%
0.18%
current
Buneman-Boris
sort


弱スケーリング
強スケーリング（6001x256x512）
TFLOPS
100.00
10.00
1.00
0.10
0.01
8 cores/node
3D
2D
Number of cores
To peak (%)
15
10
5
0
~12.5%
Number of cores

まとめ

- 重力回転系での粒子コードを開発
- 無衝突系降着円盤での磁気回転不安定の3次元および2次元計算を実施
- 磁気リコネクションが粒子加速に重要
- 角運動量輸送の評価には更に大規模計算が必要
- プラズマ$\beta>>1$の領域を計算するため、莫大な粒子数を必要とする。よって粒子コードにおける電流計算アルゴリズムを改良する必要