

冷却効果を考慮した銀河ダイナモの 磁気流体数値実験

Magnetohydrodynamic Simulations of Galactic Dynamo including Cooling Effect

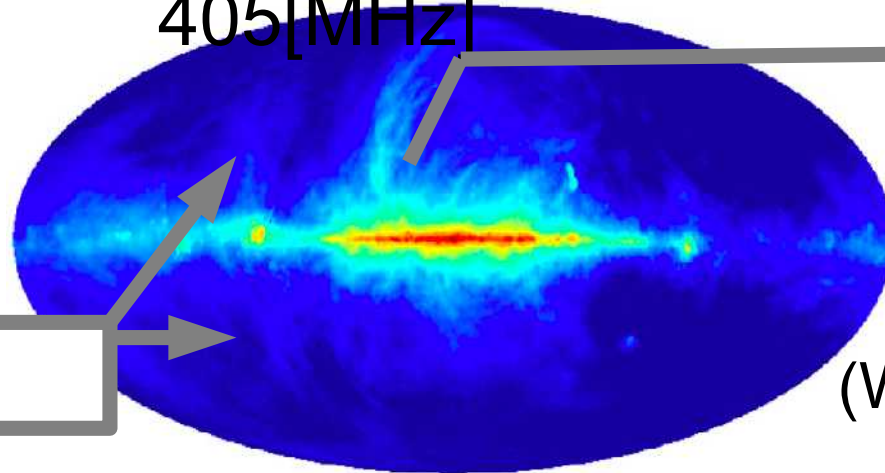
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Magnetic Field of Milky Way

Synchrotron Radiation

405[MHz]



Spar

Filaments

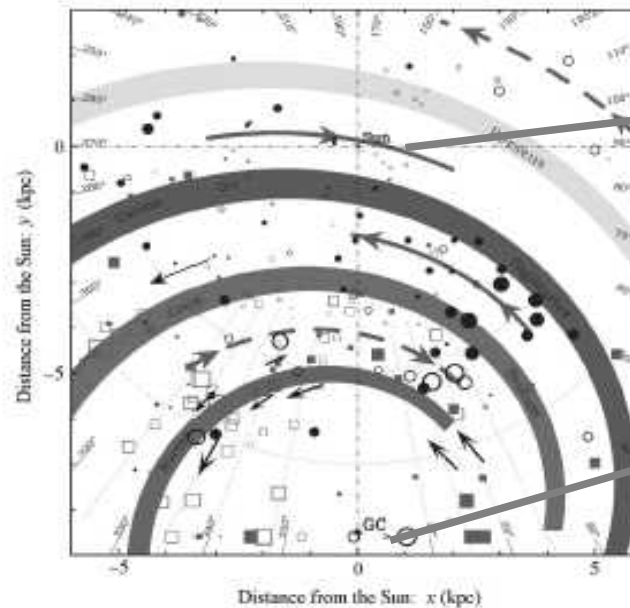
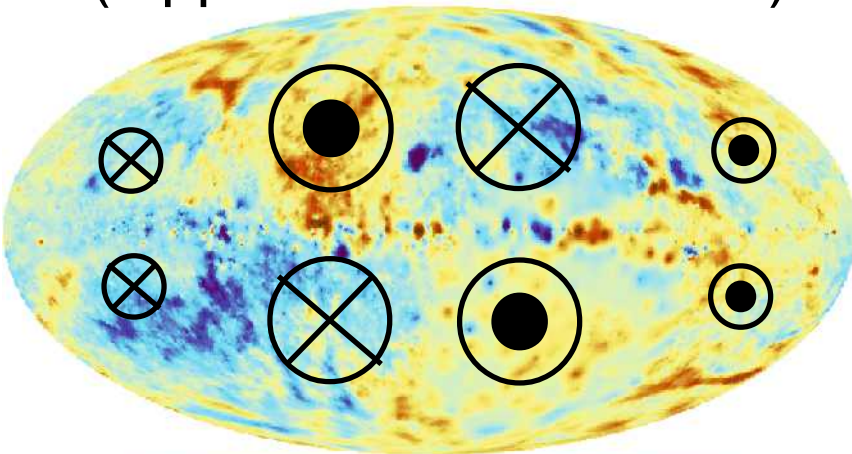
(Waelkens et al. 2009)

1.3 2.8 $\log(\%)$

Rotation Measure

Symmetry

(Oppermann et al. 2012)



Solar System

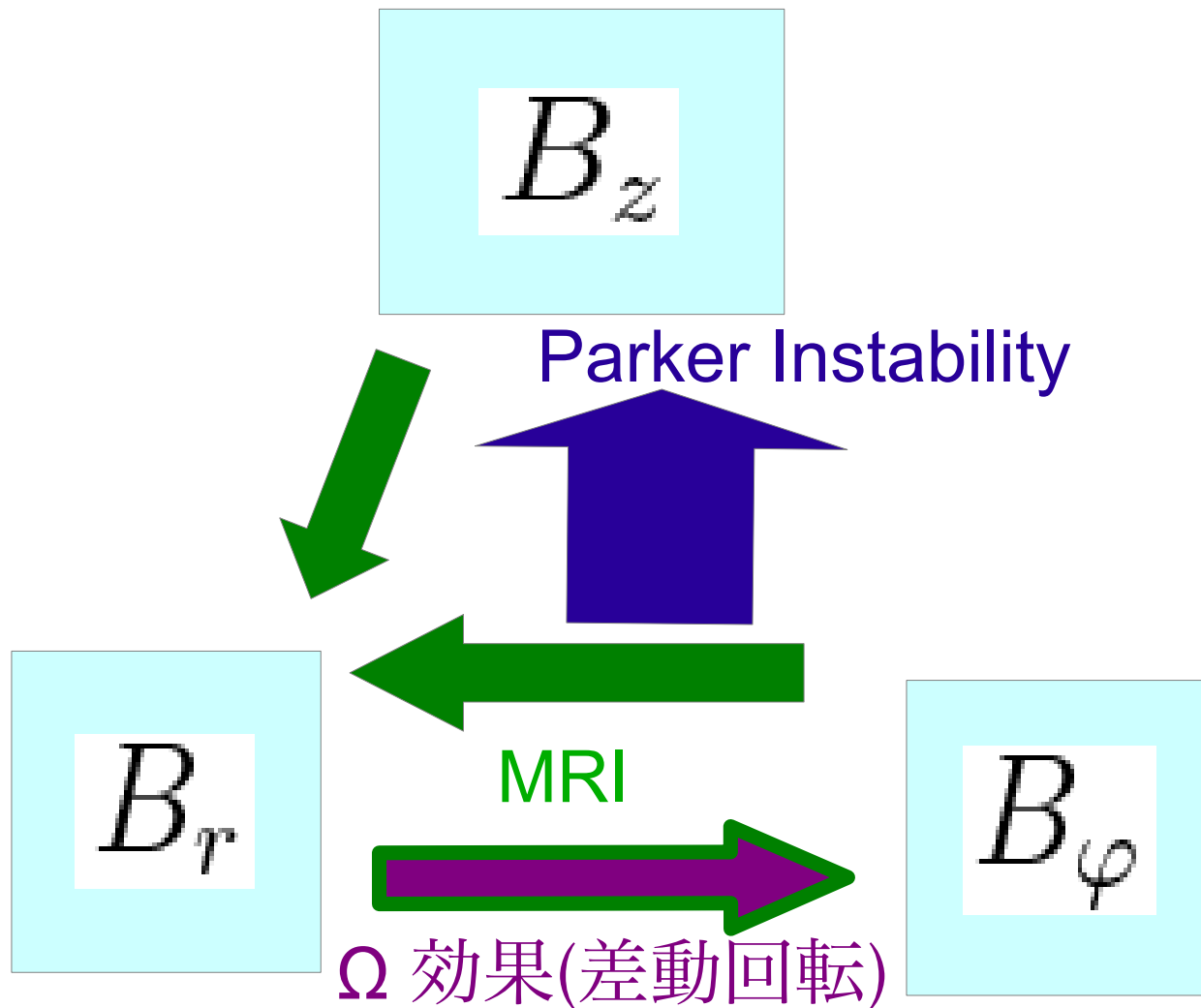
Reversal Structure
(Han et al. 2007)

Galactic Center

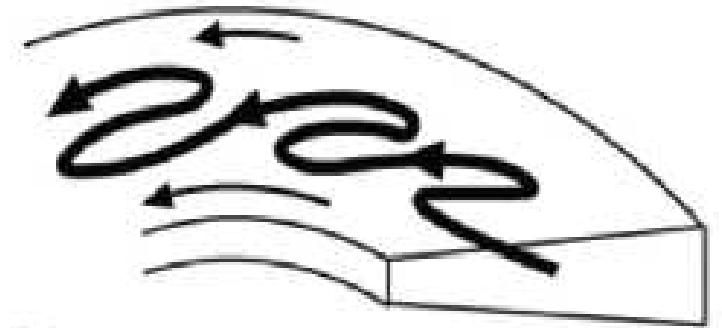
MRI-Parker Dynamo

Nishikori et al. 2006, Machida et al. 2013

- (1) Amplification due to Magneto-Rotational Instability and differential rotation.
- (2) Buoyant escape from disk due to Parker Instability.



(1) MRI
+Differential Rotation

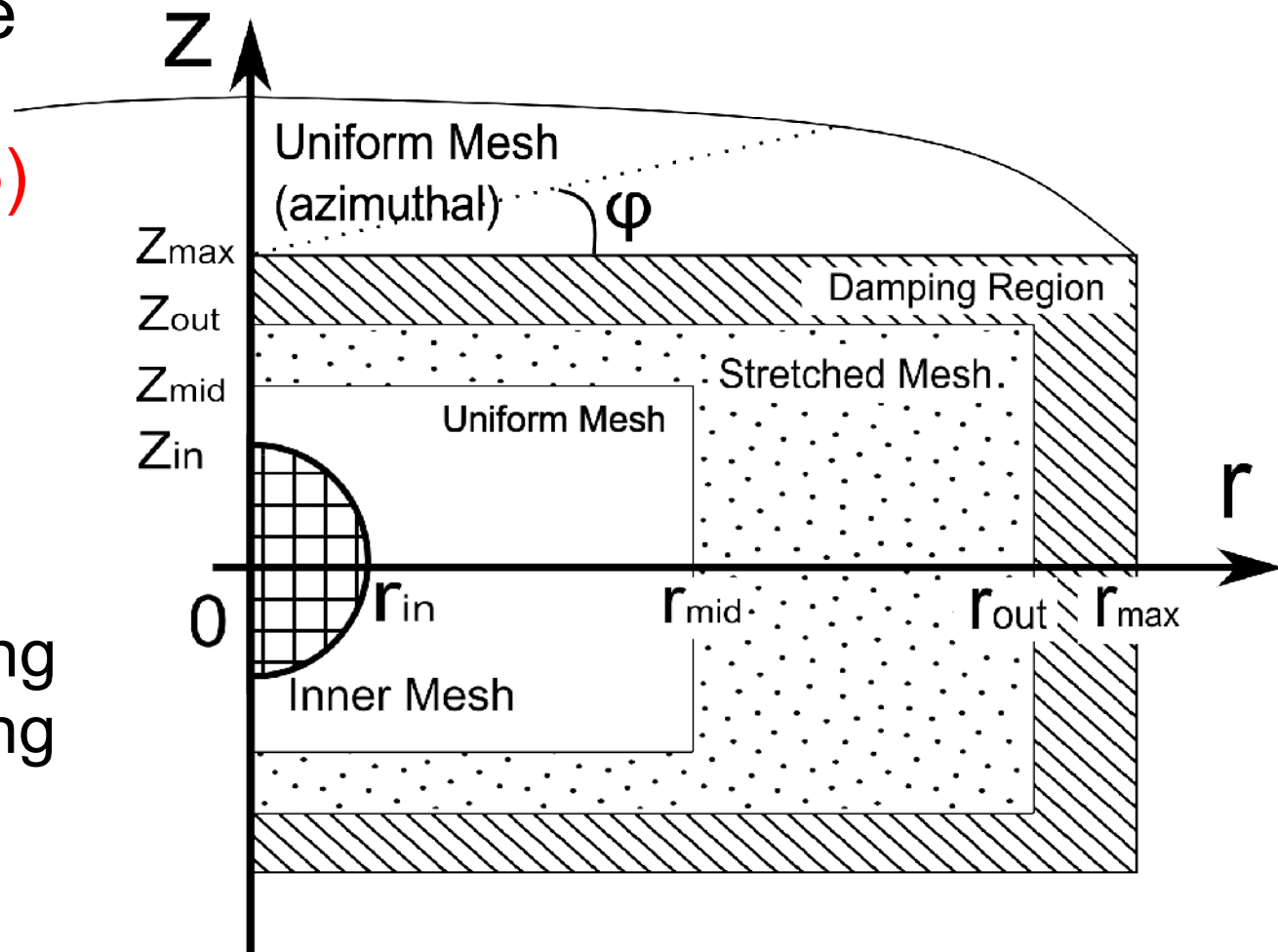


(2) Parker Instability



Simulation Set-Up (Without Cooling)

- Cylindrical Coordinate
(r, φ, z)
- **CANS+ (HLLD + MP5)**
- Domain
 $0 < r < 30$ [kpc]
 $0 < \varphi < 2\pi$
 $-11 < z < 11$ [kpc]
- Boundary Condition
 r - center : wave damping
 r - outer : wave damping
 z : wave damping
 φ : periodic
- Mesh Number
 $(N_r, N_\varphi, N_z) = (384, 64, 760)$
 $\Delta r = 0.04$, $\Delta z = 0.01$
- Non-uniform Mesh
 $r > 8$ [kpc], $|z| < 2.5$ [kpc]



	in	mid	out	max
r [kpc]	0.8	8.28	27.28	29.38
z [kpc]	1.28	2.43	10.13	10.45

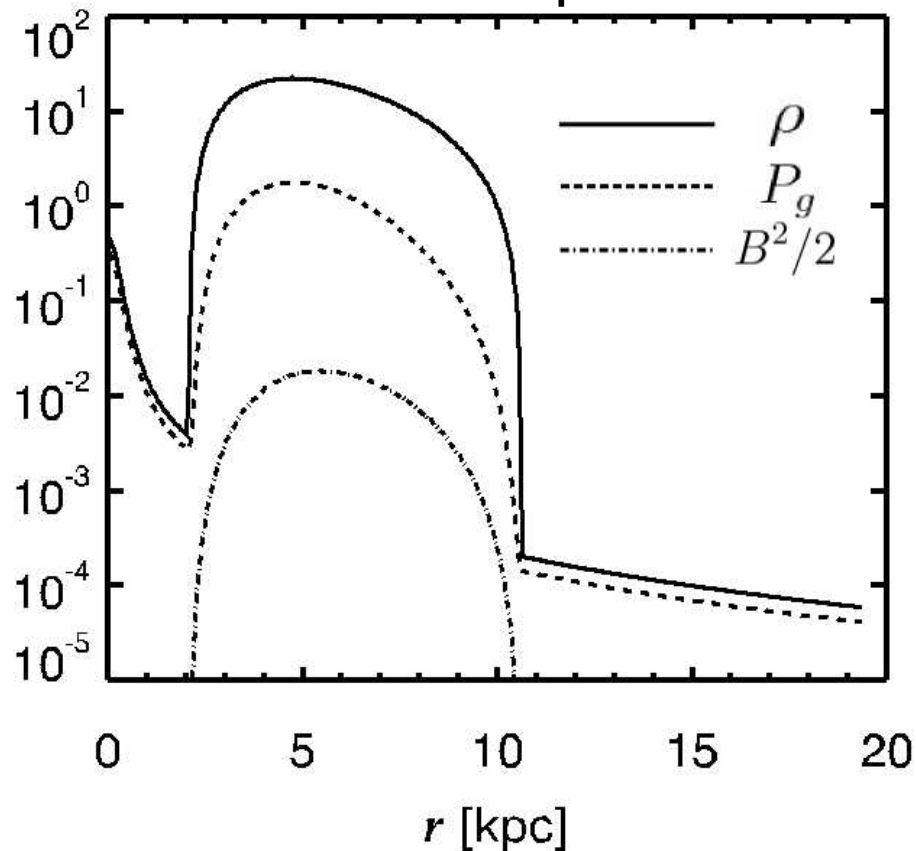
Initial Condition

- Toroidal component B_ϕ (Minimum Plasma $\beta = 100$)
- Axisymmetric gravitational potential (Miyamoto-Nagai)
- Random perturbation of magnetic field

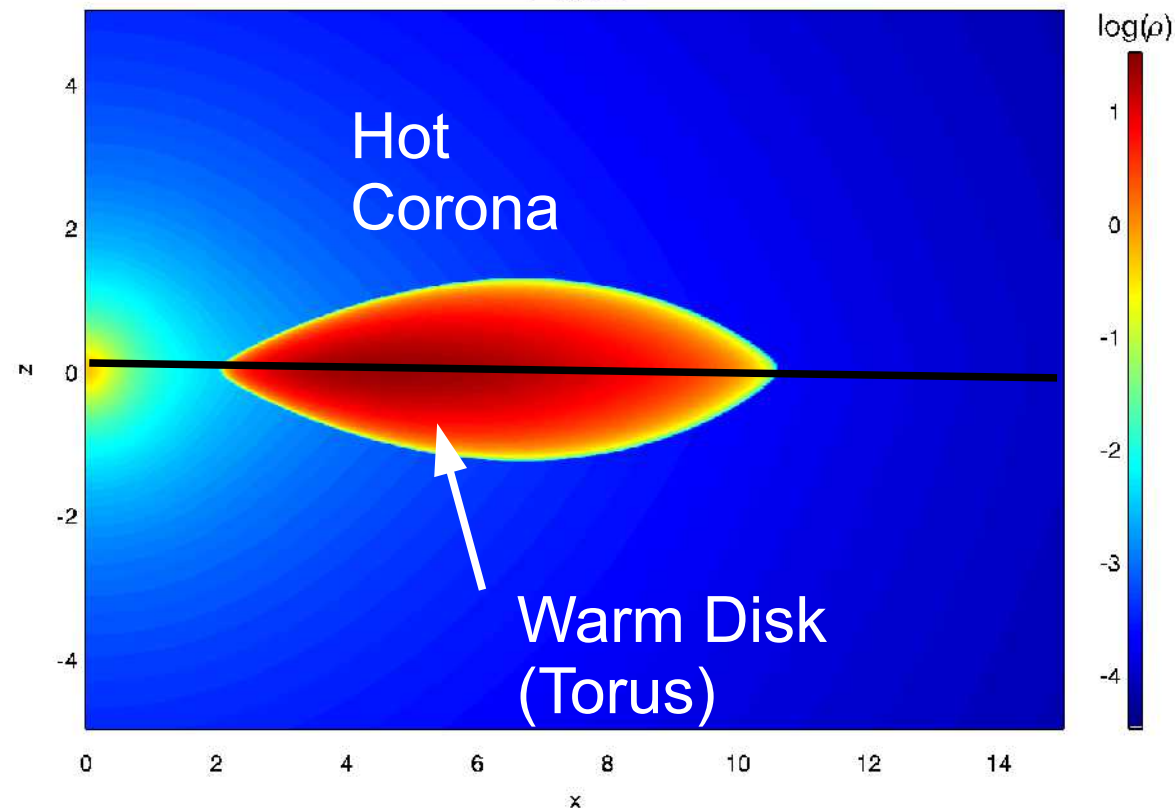
- Angular velocity $\Omega \propto r^{-1.12}$

- Distribution

Galactic plane



r-z plane
 $t=0.000$

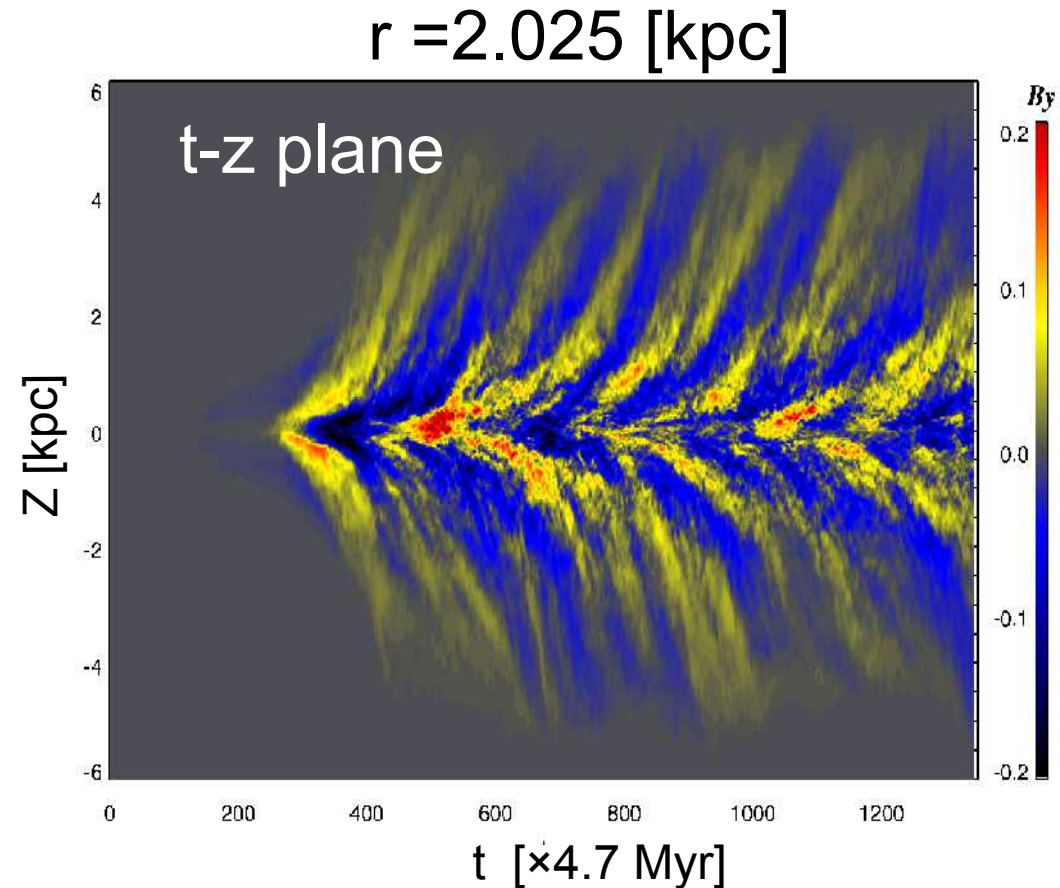
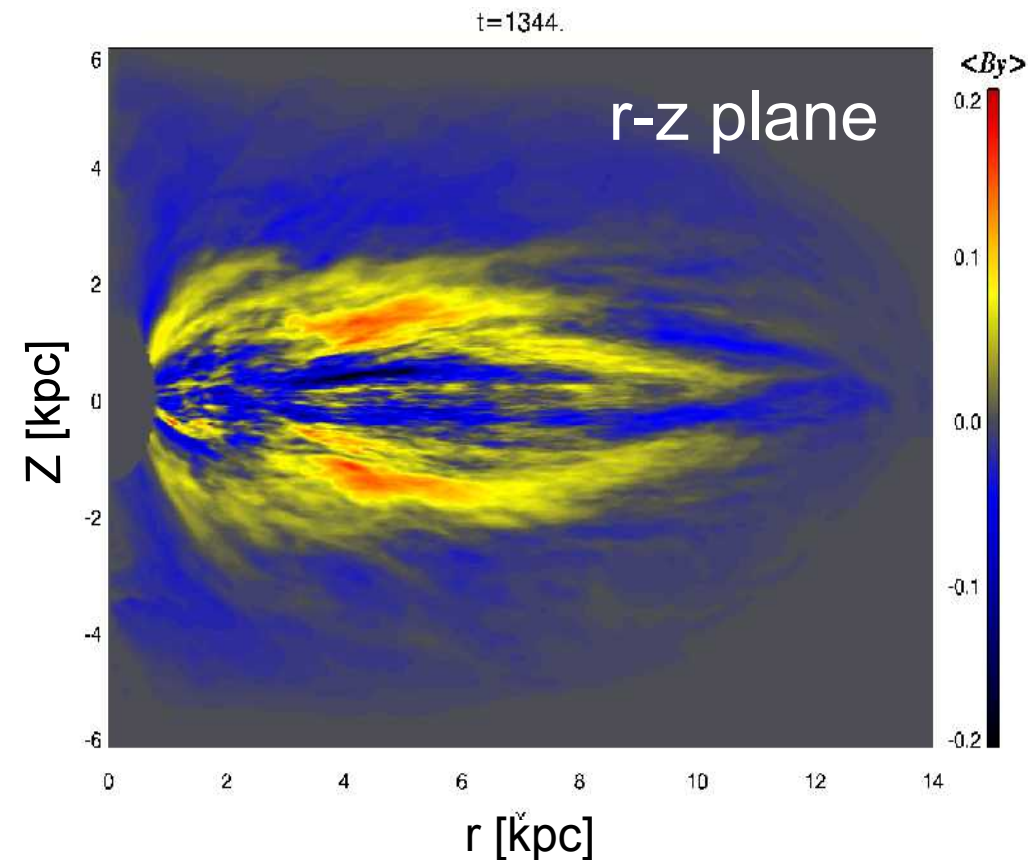


MRI-Parker Dynamo

Pattern of B_ϕ averaged by azimuthal direction

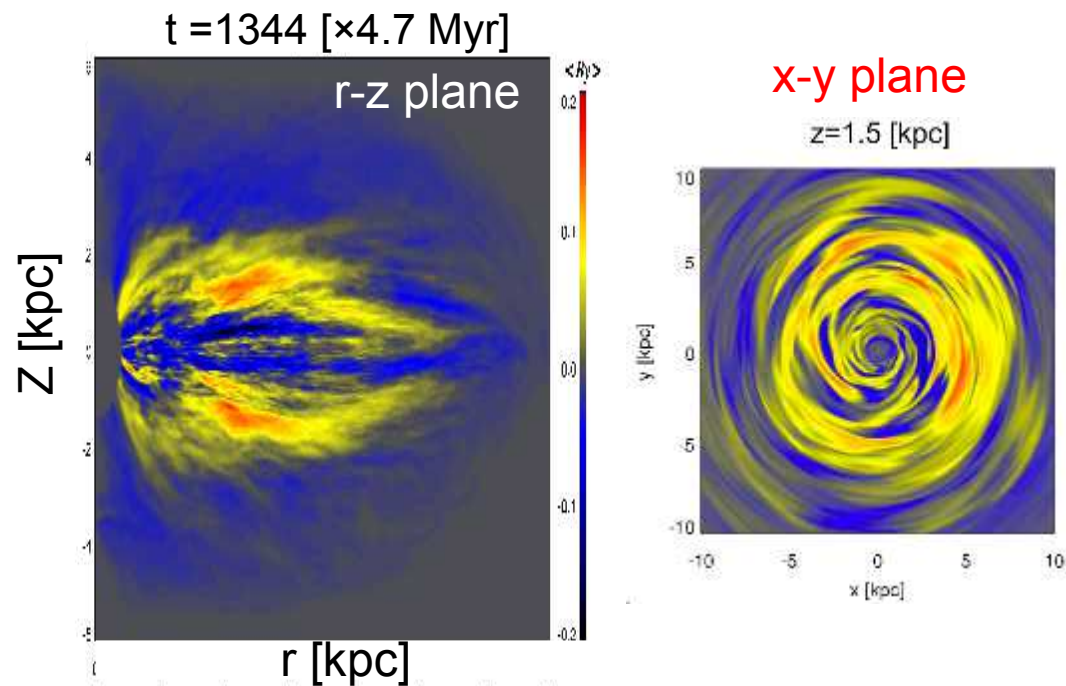
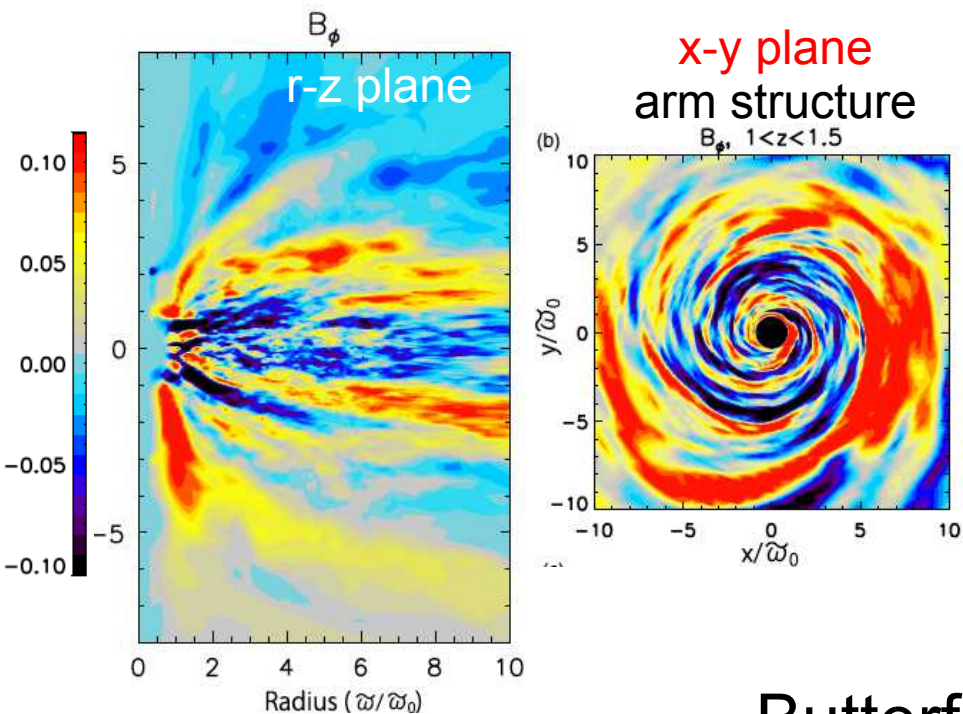
Stripe-patterned Reversal

Quasi-periodic Reversal

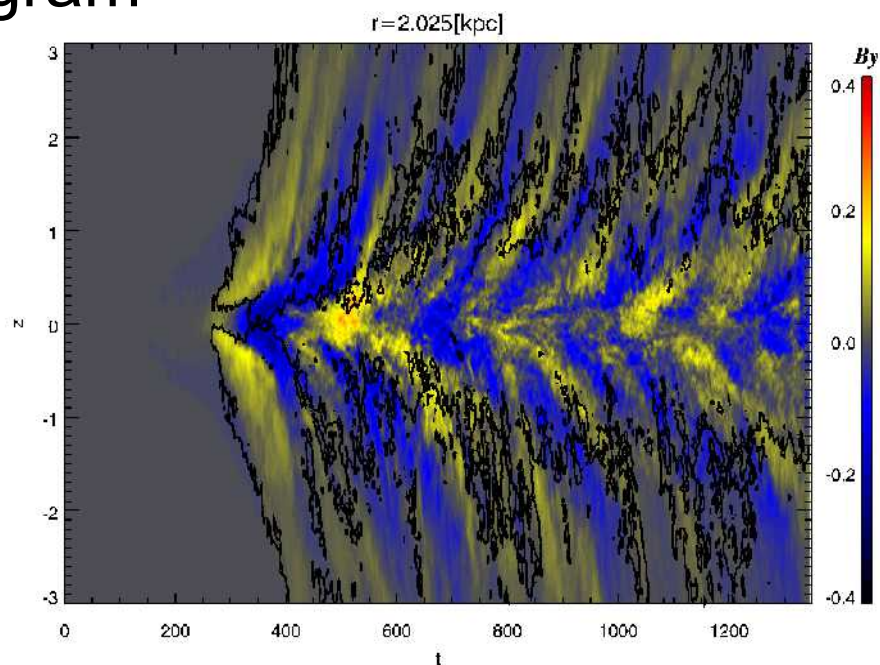
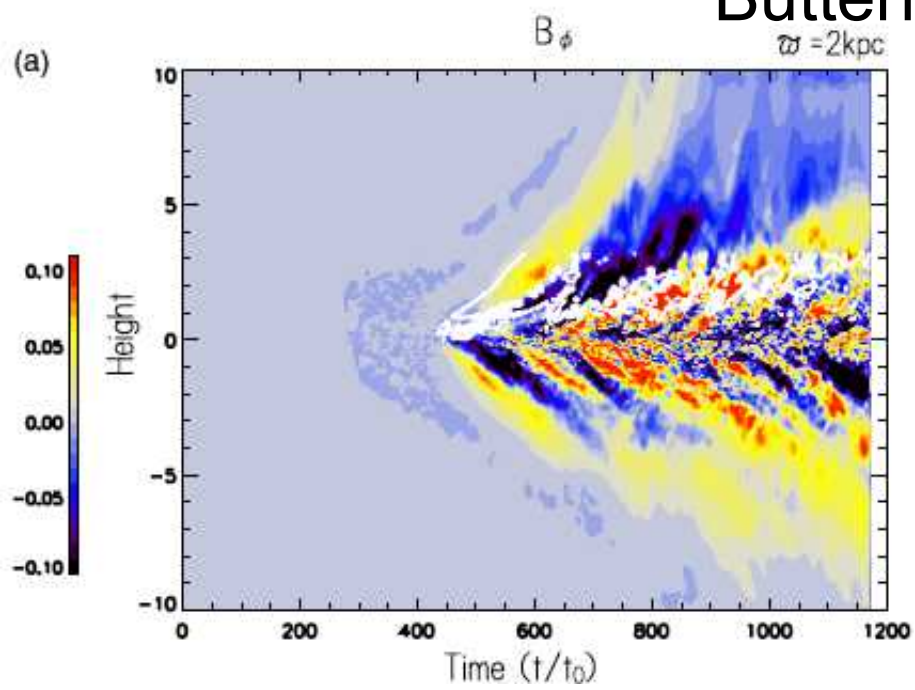


Machida et al. (2013) Modified Lax-Wendroff

v.s. CANS+ HLLD+MP5



Butterfly Diagram

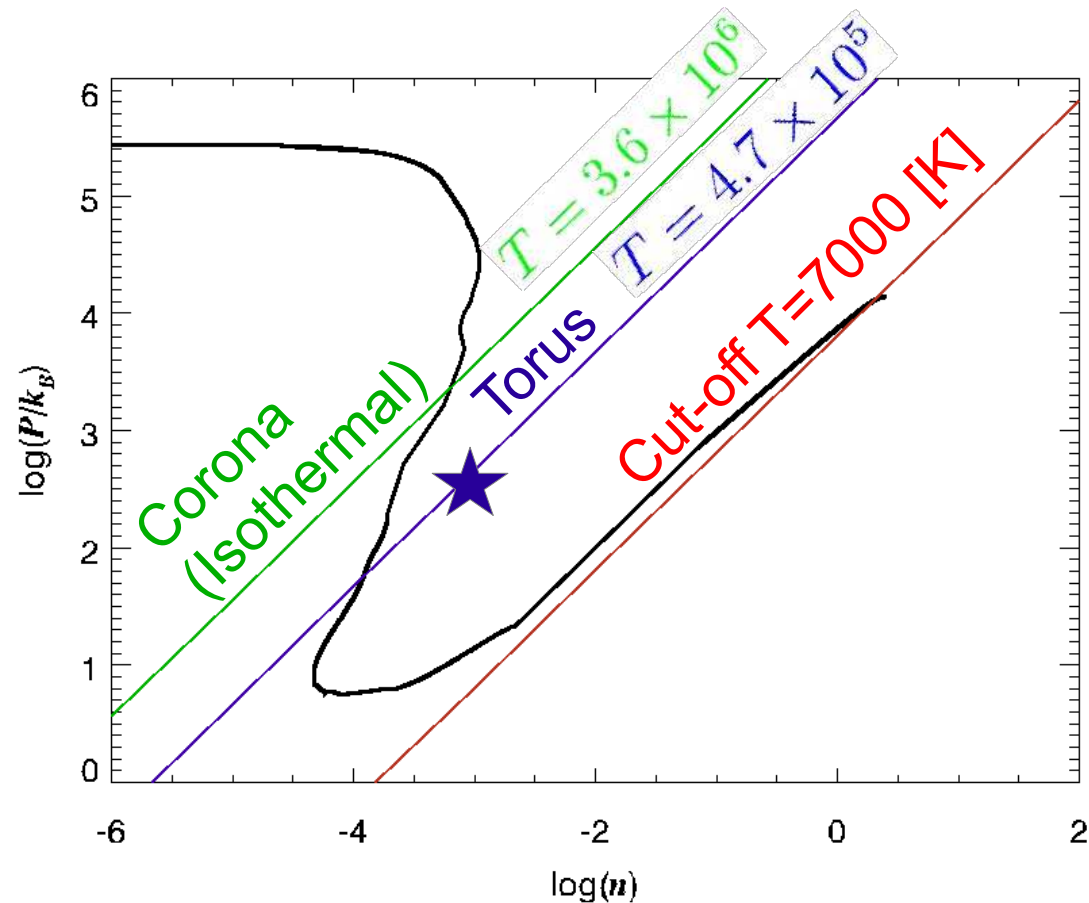


Simulation Set-up (with Cooling)

- CANS+ (Cylindrical Coordinate(r, φ, z), HLLD + MP5)
- Domain $0 < r < 20$ [kpc], $0 < \varphi < 0.5\pi$, $-3 < z < 3$ [kpc]
- Mesh $(N_r, N_\varphi, N_z) = (640, 64, 1024)$, $\Delta r = 0.01$, $\Delta z = 0.001$
- Cooling effect : $t > 170$ [$\times 4.7$ Myr]

- Thermal equilibrium curve
 red : cut-off ($T = 7000$ [K])、
 blue : Initial Temperature
 of the torus center、
 green : Isothermal corona
 $7 \times 10^3 \leq T \leq 1 \times 10^4$ [K]
 : Inoue et al. 2006

$T > 1 \times 10^4$ [K]
 : Sutherland & Dopita 1993



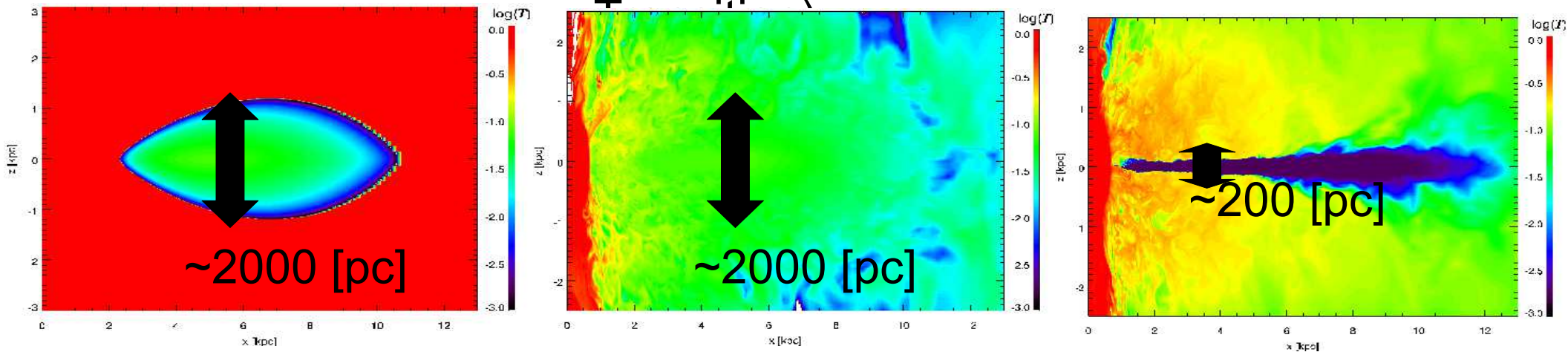
Transition

Initial Condition

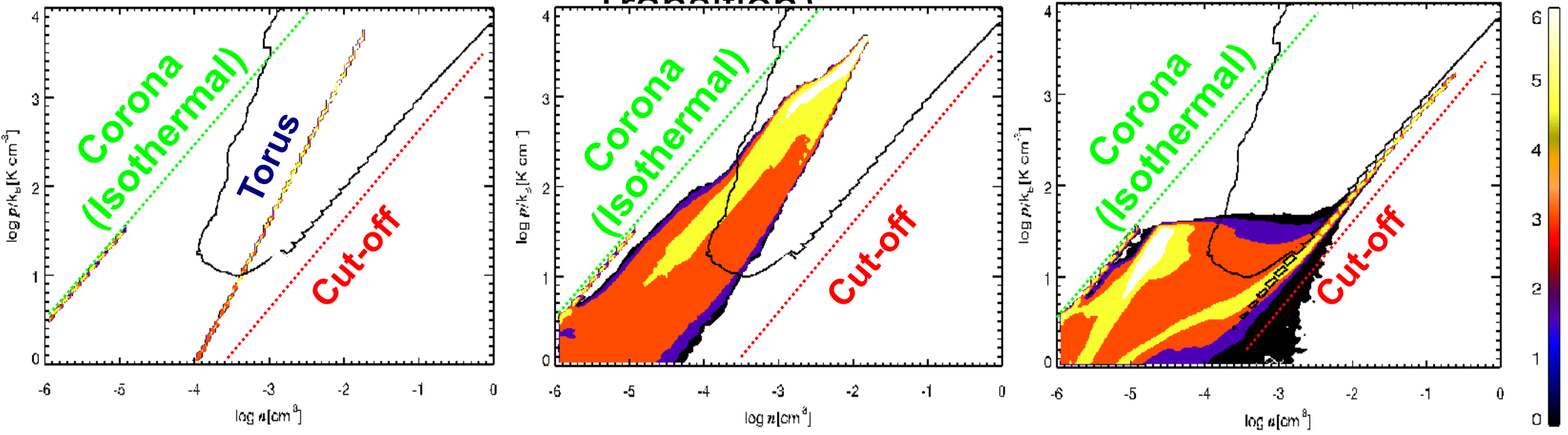
Before $t=427$ [$\times 4.7$ Myr]

After $t=703$ [$\times 4.7$ Myr]

Temperature Distribution [$\times 5.2 \times 10^6$ K] (Structure



Phase Diagram (Phase Transition)

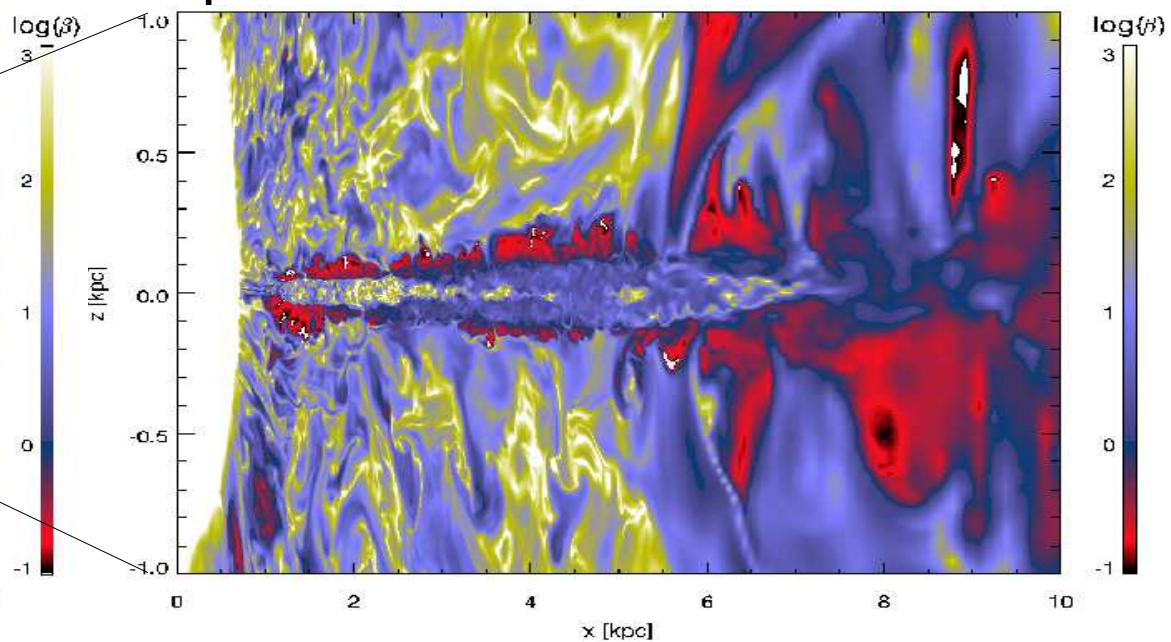
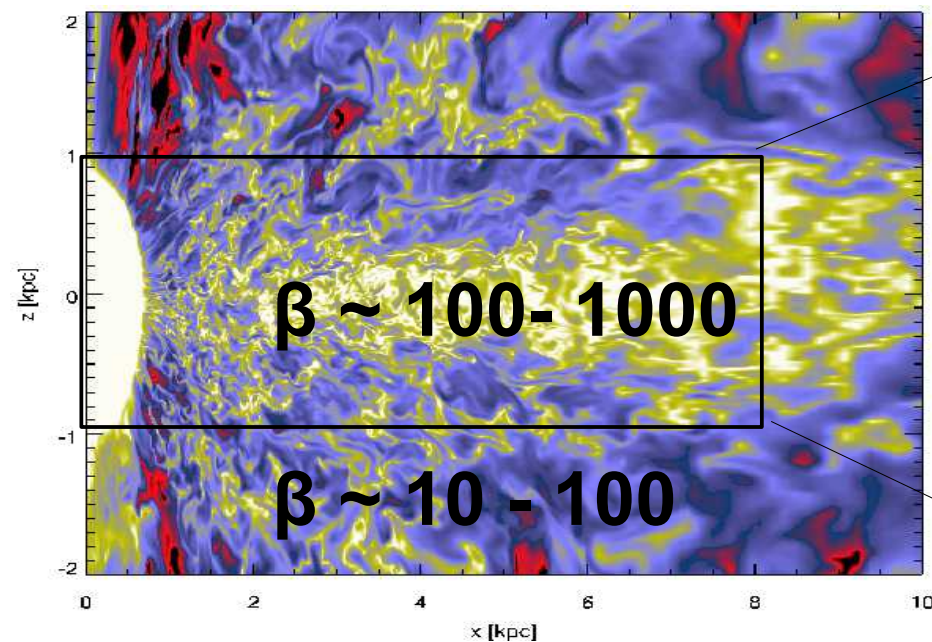


Magnetic Field Structures r-z plane

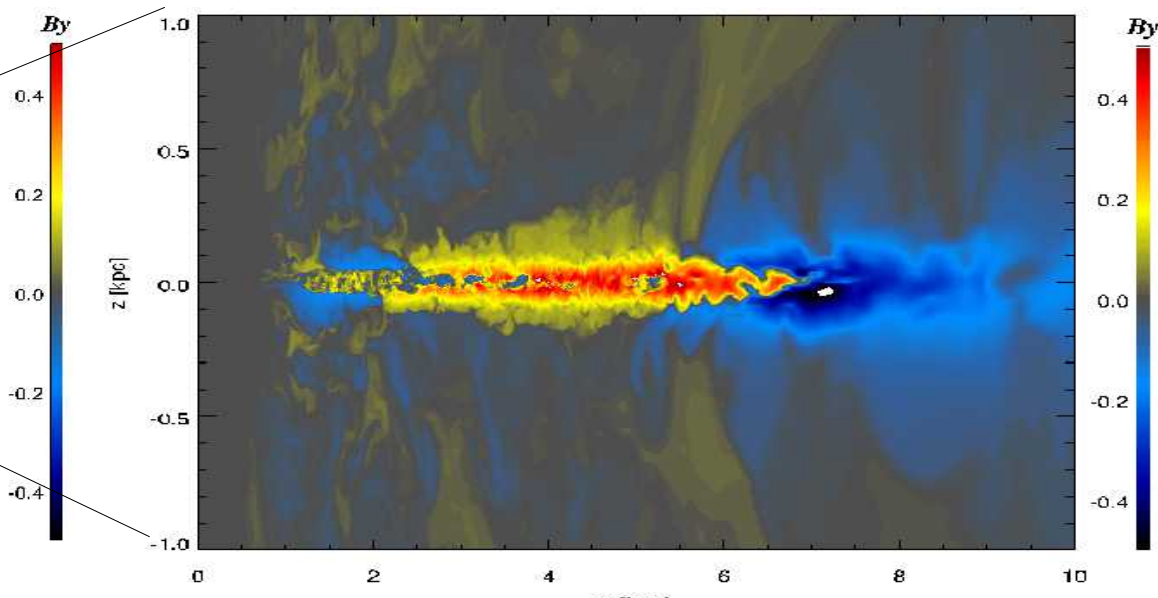
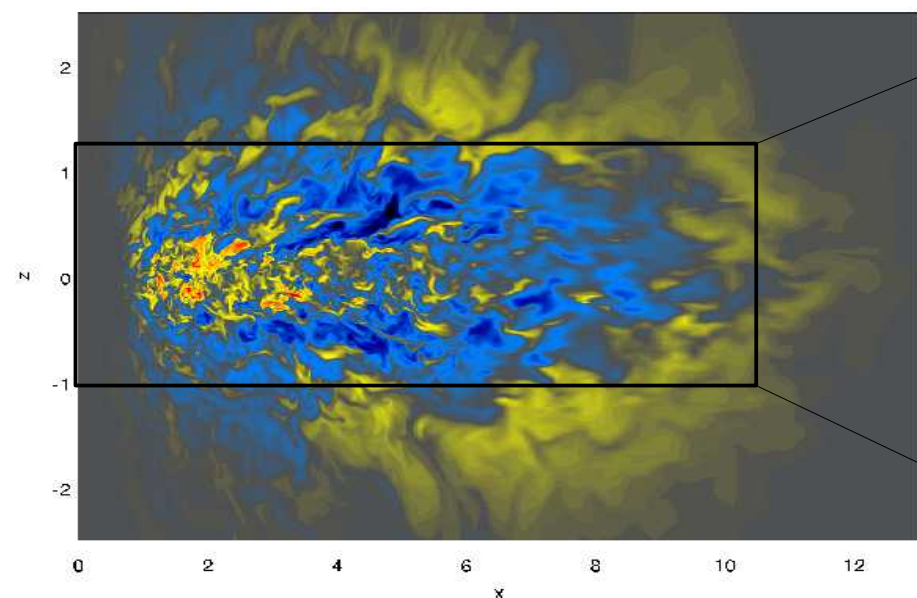
Before $t=427$ [$\times 4.7$ Myr]

After $t=748$ [$\times 4.7$ Myr]

Plasma β

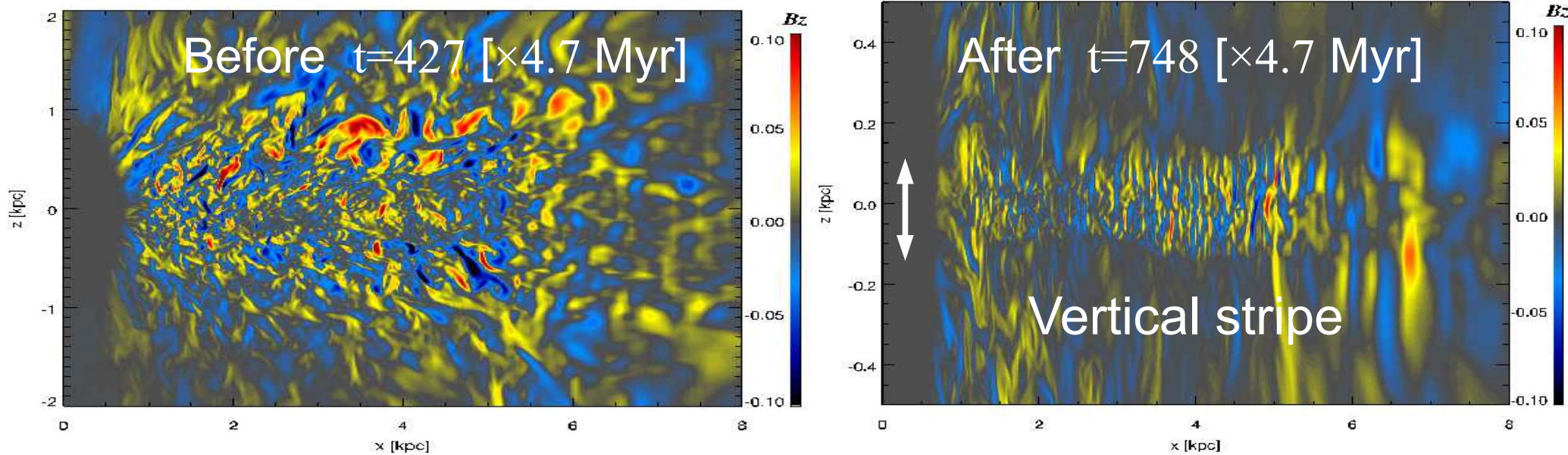


$|B_\phi|$ [$\times 9.3 \mu\text{G}$]

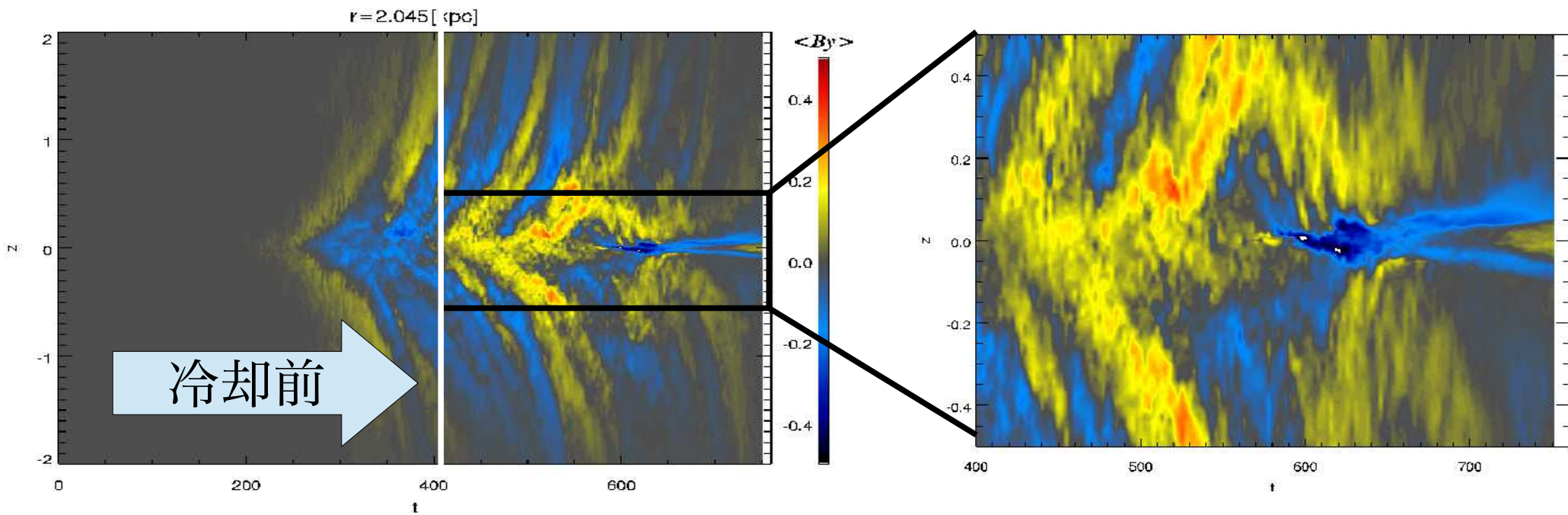


Magnetic Field Structures

B_z [9.3 μG]



Butterfly Diagram $\langle B_\phi \rangle$ [$\times 9.3 \mu\text{G}$]



Summary

- We carried out three-dimensional global MHD simulation of disk galaxies including cooling effect.

➡ Disk Region :

Plasma $\beta \sim 1 - 100$

Quasi-periodic reversal of B_ϕ (?)

Vertical stripe structure of B_z

➡ Coronal Region :

Disappearance of the stripe structure of B_ϕ

Coronal Heating