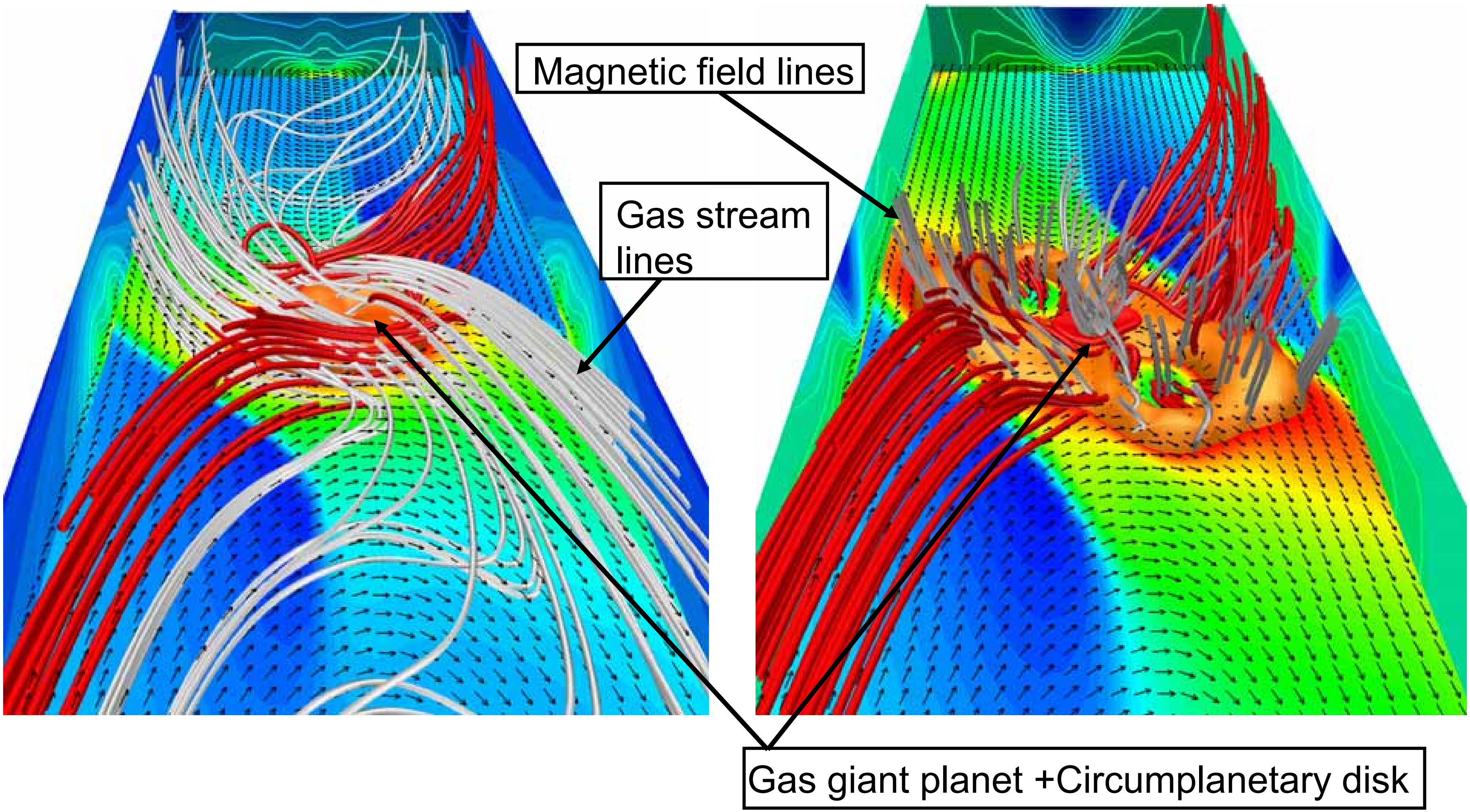
Giant Planet Formation in Magnetized Disk



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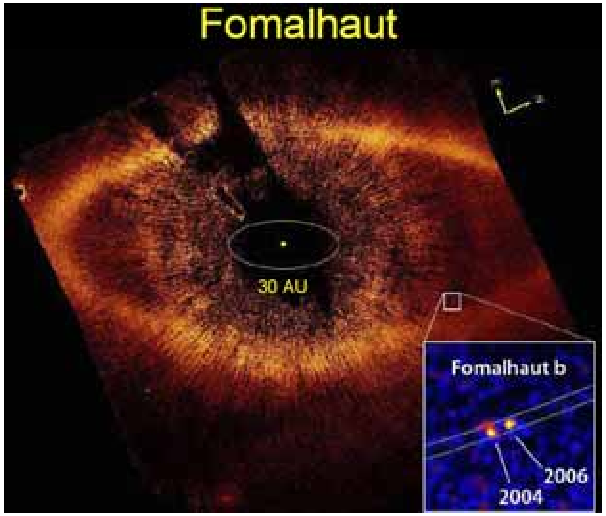
Motivation

- ***350 exoplanets*** ⇒ almost all planets are ***Gas Giant Planets***
- The formation process of gas giant planets is important for understanding the theoretical planet formation
- Gas giant planets are formed in the protoplanetary disk
- Recent Studies: 3D simulations
  - Not resolve (proto) planet (i.e., radius of gas planet)
  - Not include the magnetic effect
- This study
  - ***resolve the gas giant planet with*** $\Delta x < r_{Jup}$ (present Jovian radius)
  - ***include the magnetic effect*** (planet formation in protoplanetary disk with MRI turbulence)



Initial Settings

Local Simulation around Protoplanet

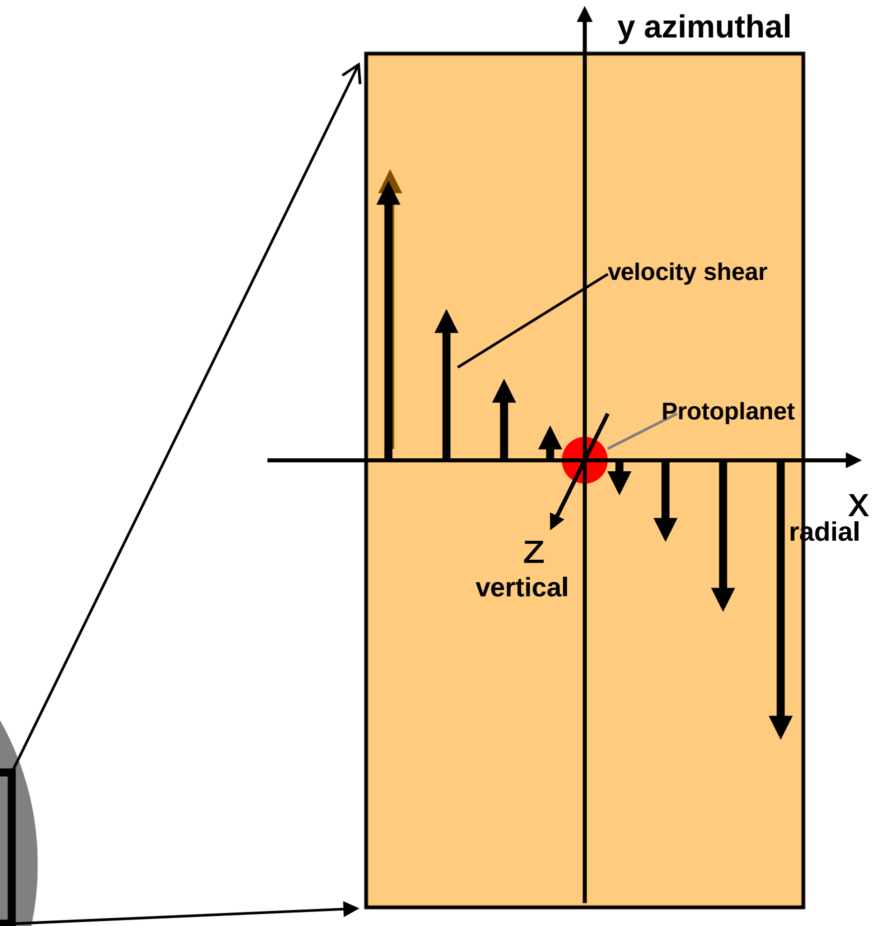
- Basic equations (Resistive MHD eq.)

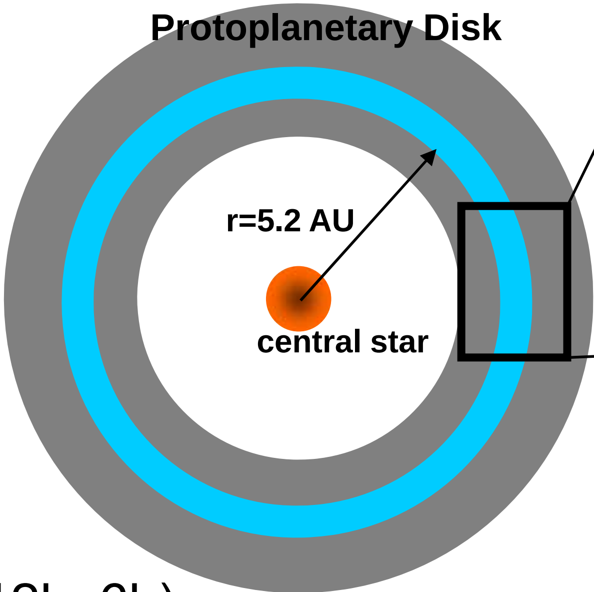
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathrm{v}) = 0$$

$$\frac{\partial \mathrm{v}}{\partial t} + (\mathrm{v} \cdot \nabla)\mathrm{v} = -\frac{1}{\rho}\nabla P - \frac{1}{4\pi}\nabla \times (\mathrm{v} \times B) - \nabla \varphi_{\mathrm{eff}} - 2\Omega_p (z \times \mathrm{v})$$

$$\frac{\partial B}{\partial t} = \nabla \times (\mathrm{v} \times B) + \eta \Delta B$$

$$P = P(\rho)$$





- Boundary Condition
  - x- fixed boundary
  - y- periodic boundary
  - z- fixed boundary

x: radial direction
y: azimuthal direction
z: vertical direction

- Size

  (x, y, z) = (12h, 12h, 6h)

Initial Settings

- **Density Distribution**

$$\rho = \frac{\sigma_0}{\sqrt{2\pi}h} \exp\left(-\frac{z^2}{2h^2}\right)$$

- **Shear Velocity**

$$\boldsymbol{v_0} = (0, -\frac{3}{2}\Omega_p\, x, 0)$$

- **Gravitational Potential**

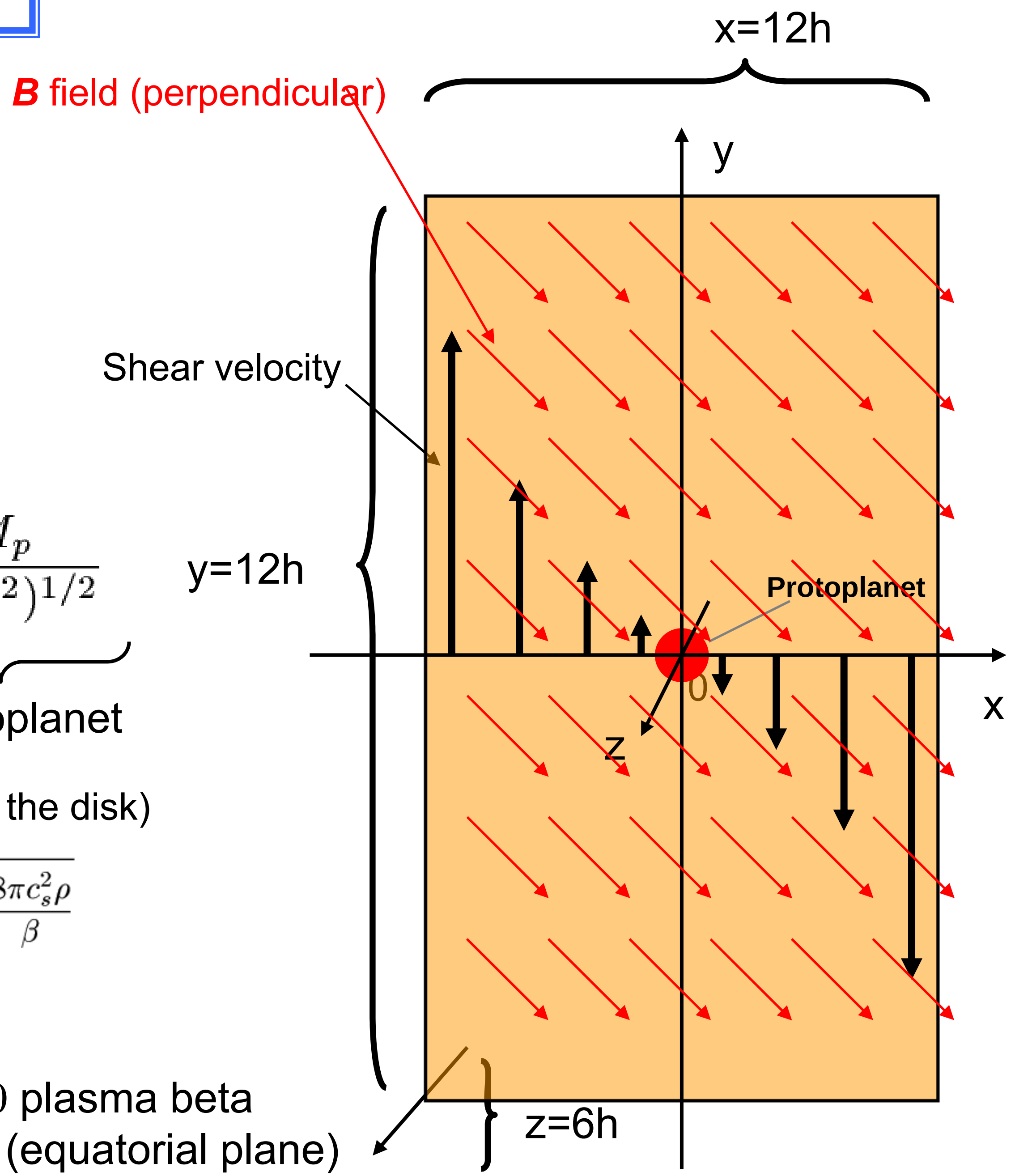
$$\psi = -\frac{\Omega_p^2}{2}(3x^2 - z^2) - \frac{GM_p}{(r^2+\epsilon^2)^{1/2}}$$

Central star — Protoplanet

- **Magnetic Field** (perpendicular to the disk)

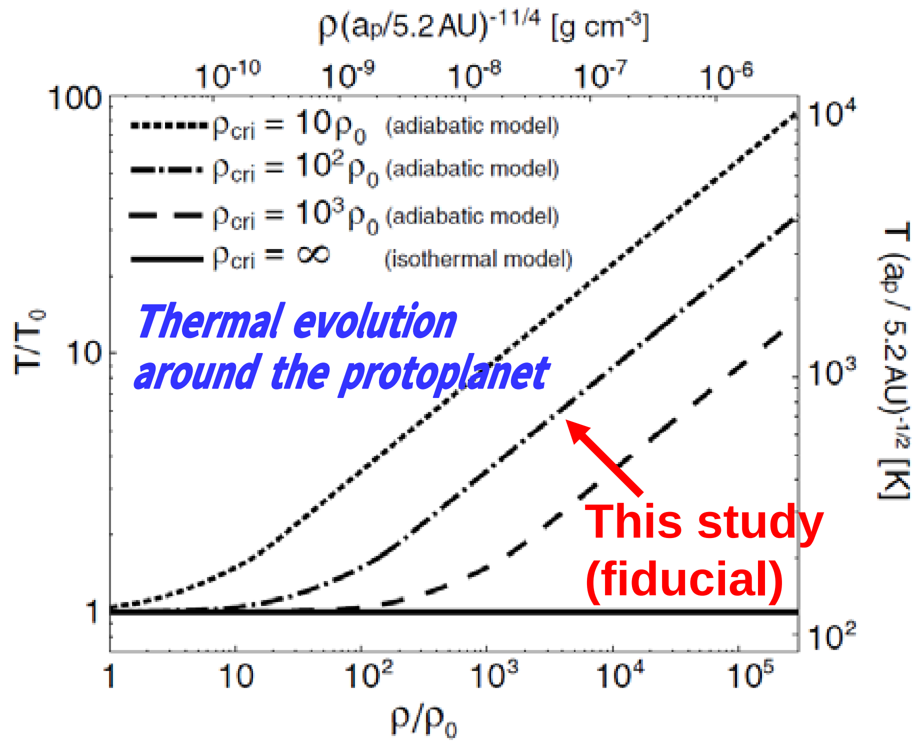
$$\boldsymbol{B} = [0, 0, B_c] \qquad B_c = \sqrt{\frac{8\pi c_s^2 \rho}{\beta}}$$

- **Parameters**
  - $M_p = 0.6\, M_{Jup}$@5.2AU
  - $\beta=100$ plasma beta (equatorial plane)



Thermal evolution and Resistivity

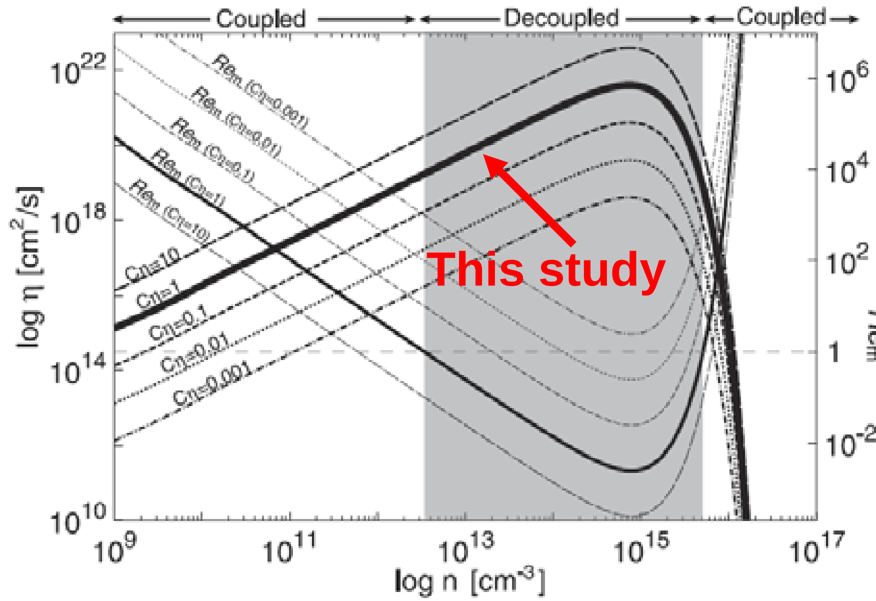
Thermal evolution



Barotropic EOS (Mizuno 1978, Machida 2009)

- ***isothermal*** far from the protoplanet
- ***adiabatic*** near the protoplanet
- depends on the dust opacity

Magnetic resistivity

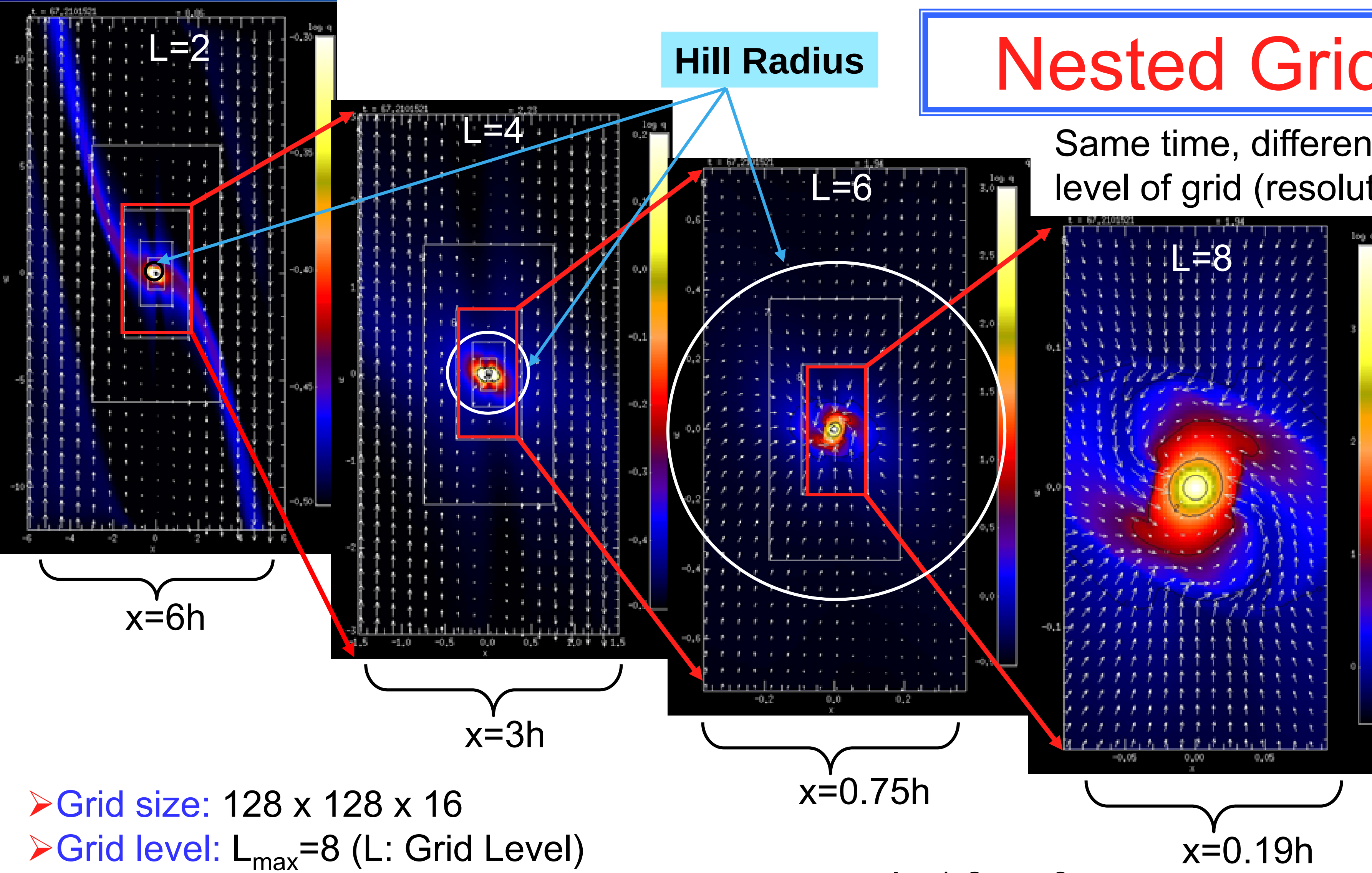


η in the collapsing molecular cloud core (Nakano et al. 2002, Machida et al. 2006)

- $|x|<7h \Rightarrow \eta=0$
- $|x|>7h \Rightarrow \eta=\eta_{fiducial}$
- ***to mimic dead zone (protoplanet exists in the active zone which is enclosed by the dead zone)***

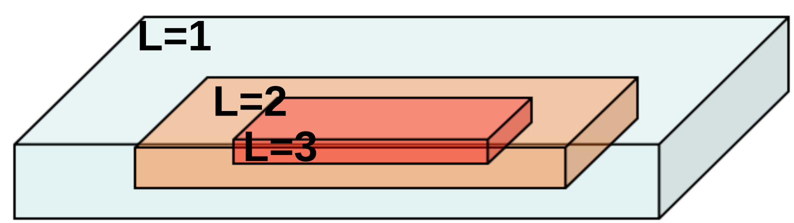
Nested Grid

Same time, different level of grid (resolution)



- Grid size: 128 x 128 x 16
- Grid level: L_{max}=8 (L: Grid Level)
- Total grid number: 128 x128 x 16 x 8
- Scale range： L=12h – 0.008h,
  Δx (L=8) ~0.5 $R_{Jupiter}$ @5.2 AU

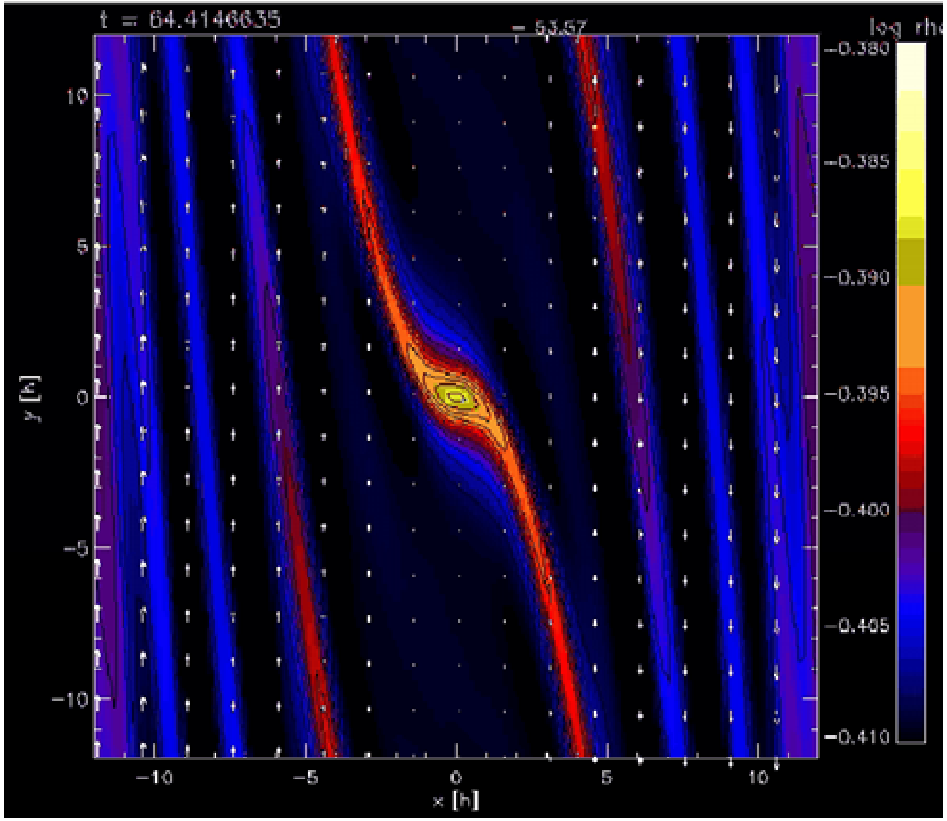
L=1,2,・・・8



Previous Study (unmagnetized case)

(Machida et al. 2008, Machida 2009)

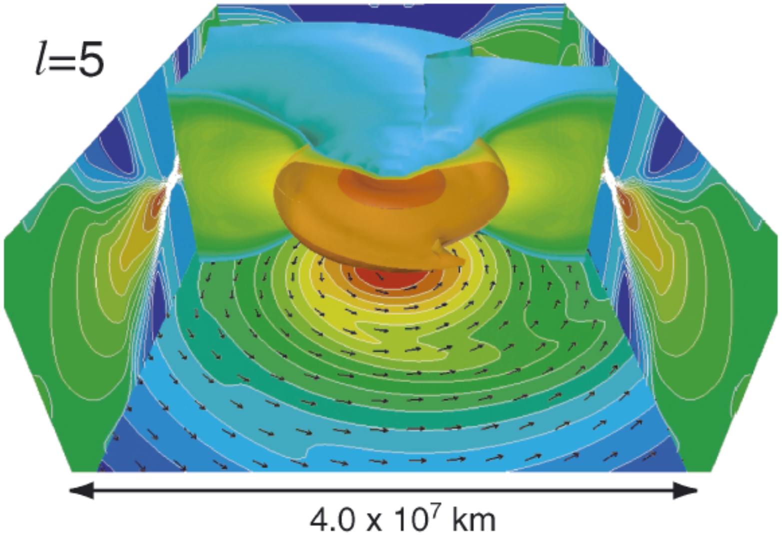
Large scale (l=1)

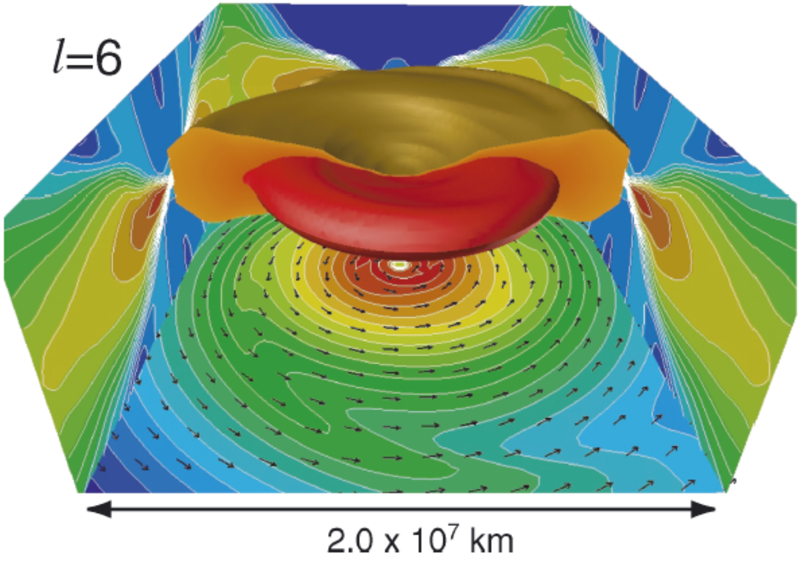


- Spiral arms & Gap formation
- Circum-planetary disk
- *Protoplanet system acquires the angular momentum from shearing motion in the protoplanetary disk*

Small scale

Circum-Jovian Disk





Previous Study (low β case)

(Machida et al. 2006)

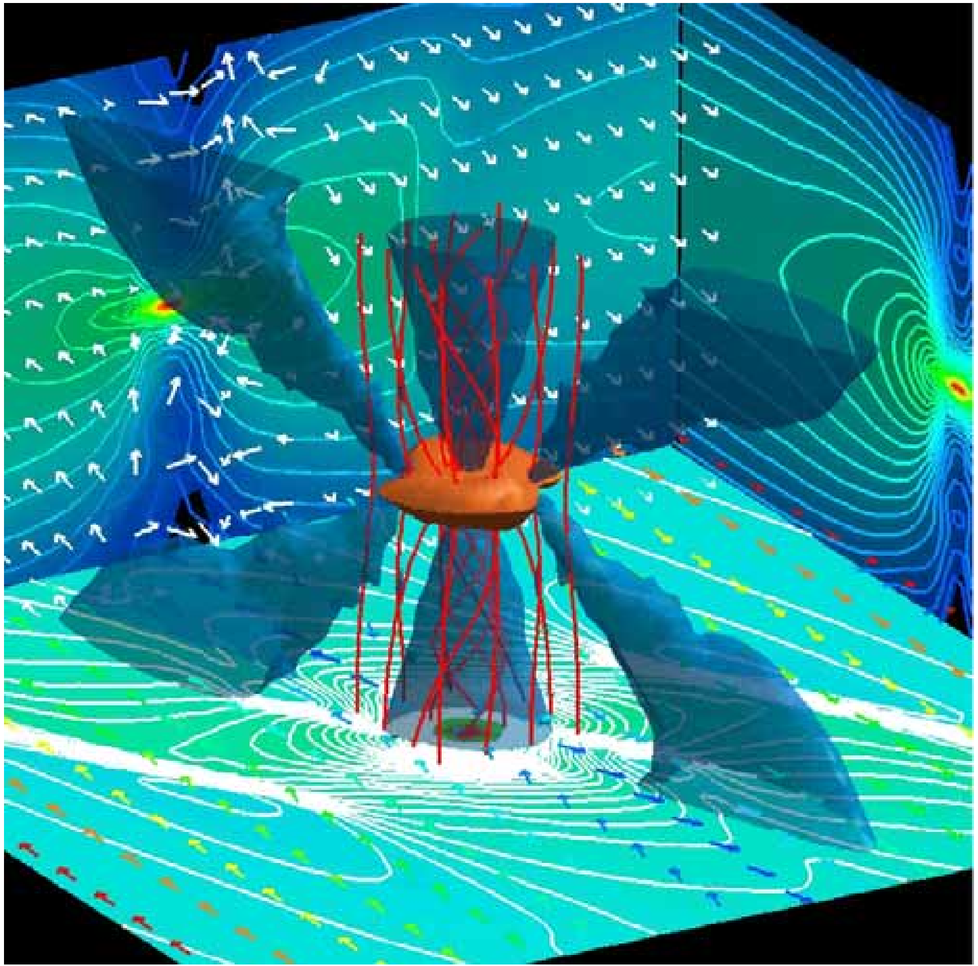
Outflow driven by the proto planet embedded in the protoplanetary disk

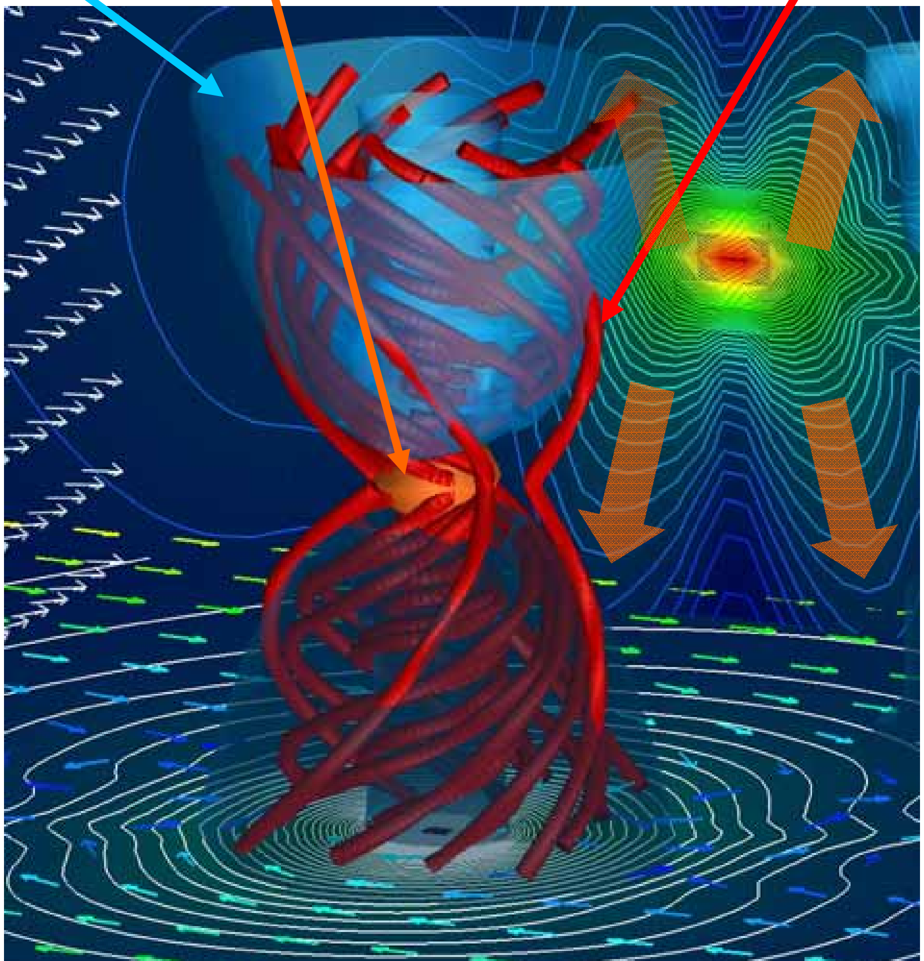
β=1, Ideal MHD, MRI stable

Protoplanet + Circumplanetary disk

Outflow

Magnetic field lines





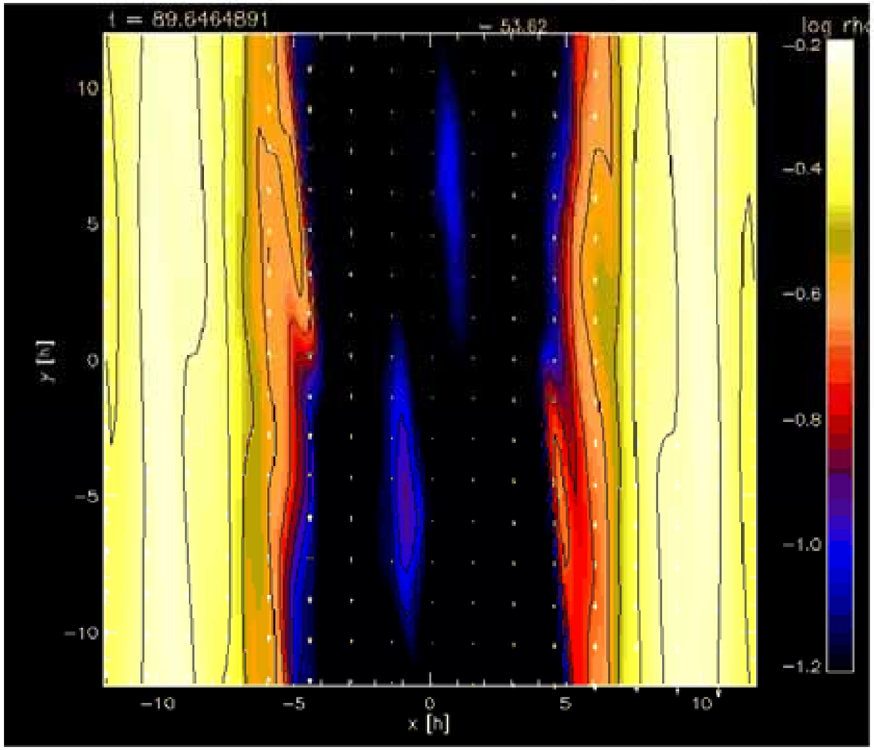
Present Study (high β case)

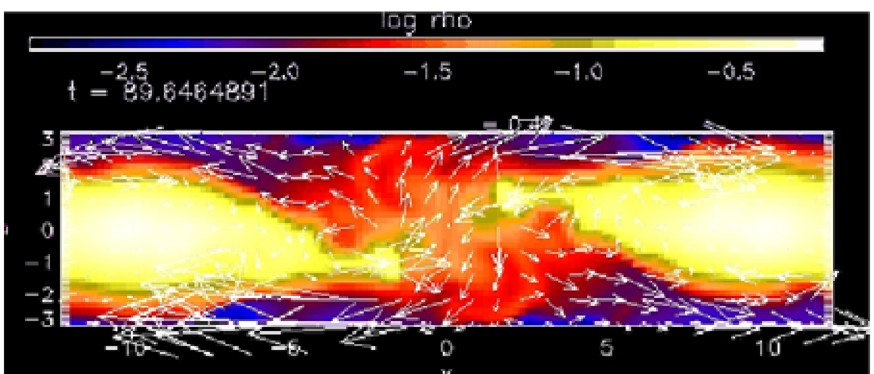
- color: density
- arrows: velocity vector

β_{ini}=100

Resistive MHD model

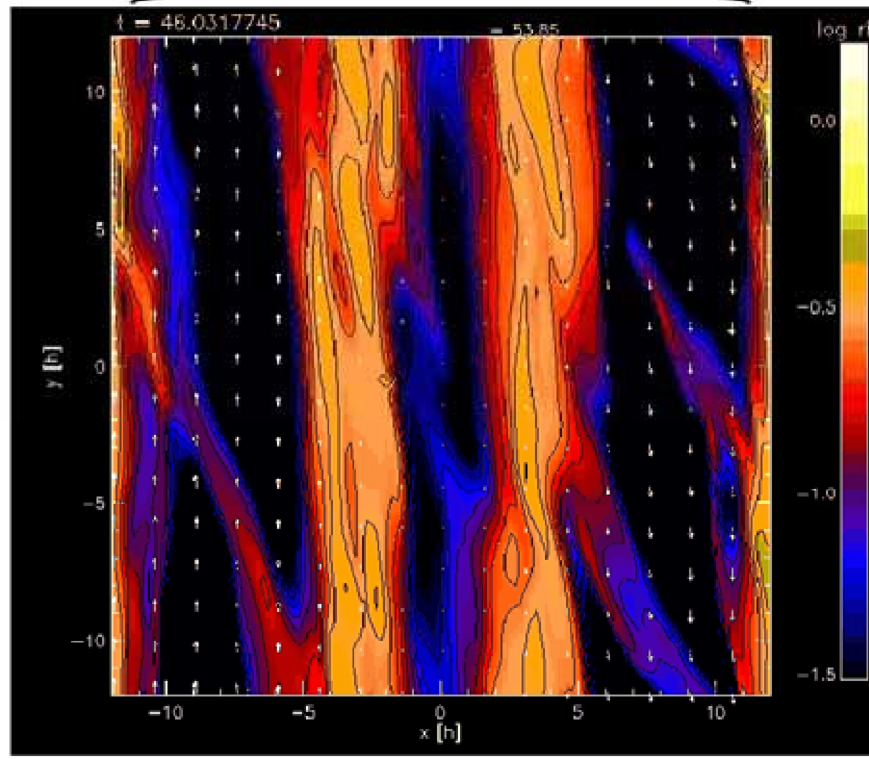
dead zone — active zone — dead zone

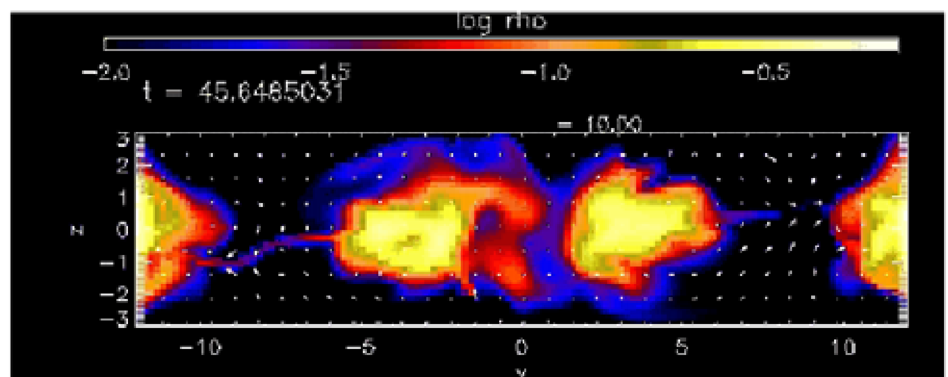




Ideal MHD model

active zone

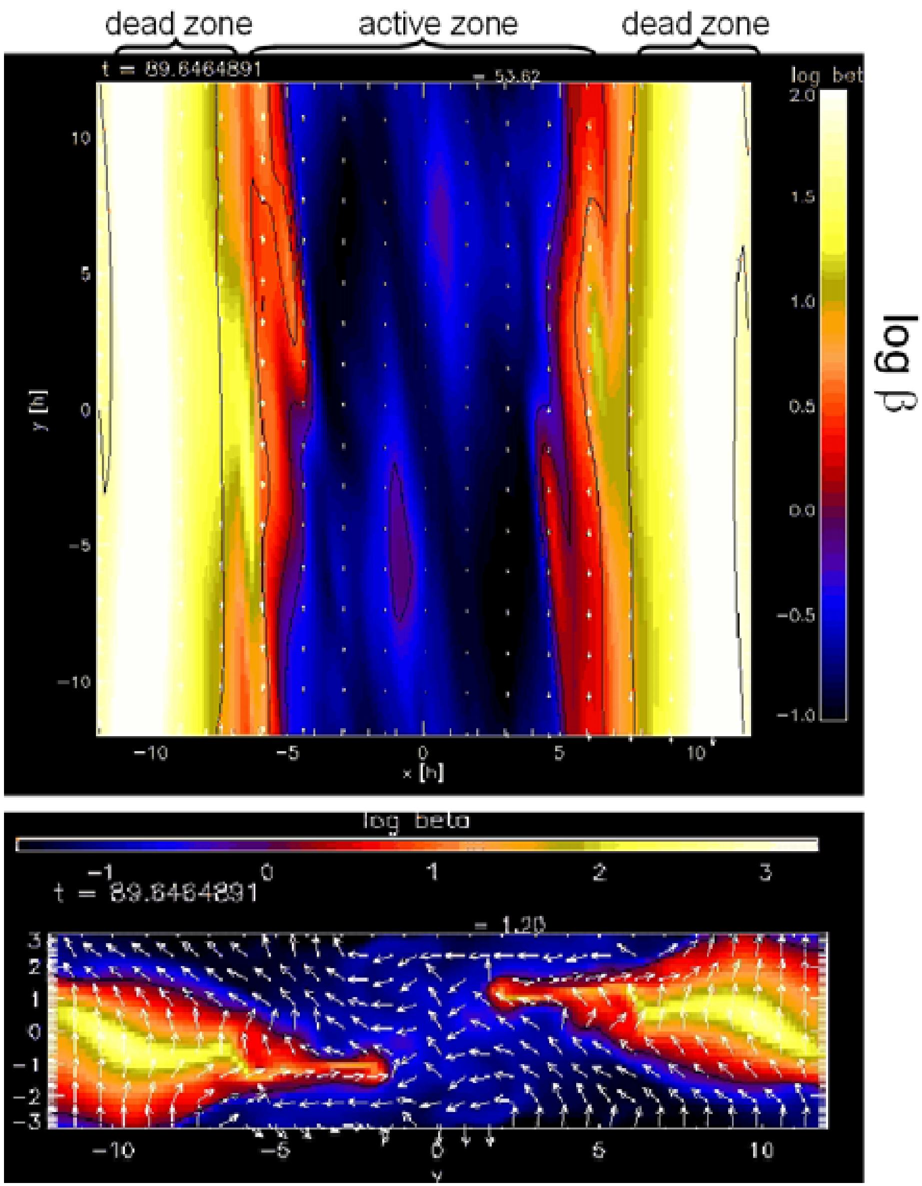




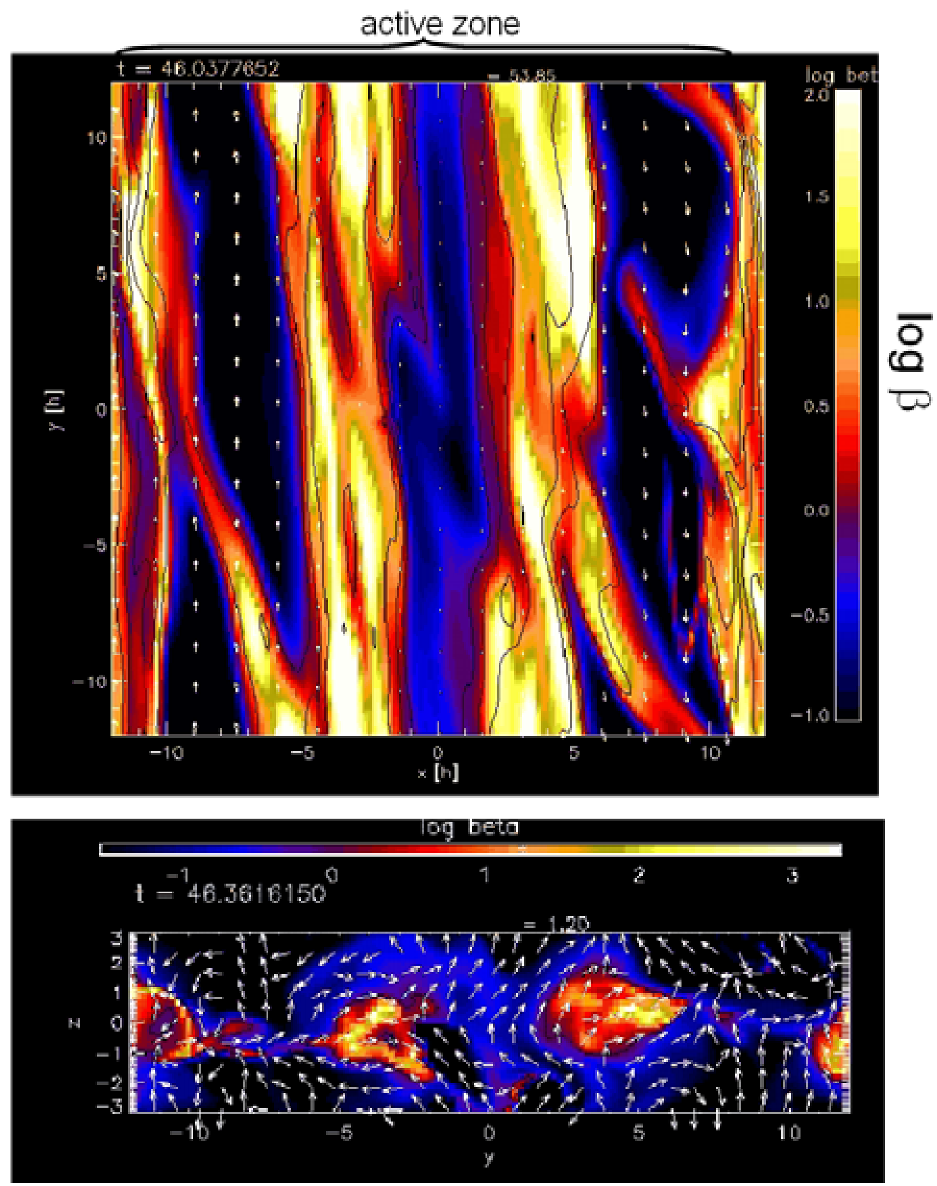
Plasma beta

- color: plasma β
- arrows: magnetic field

Resistive MHD model



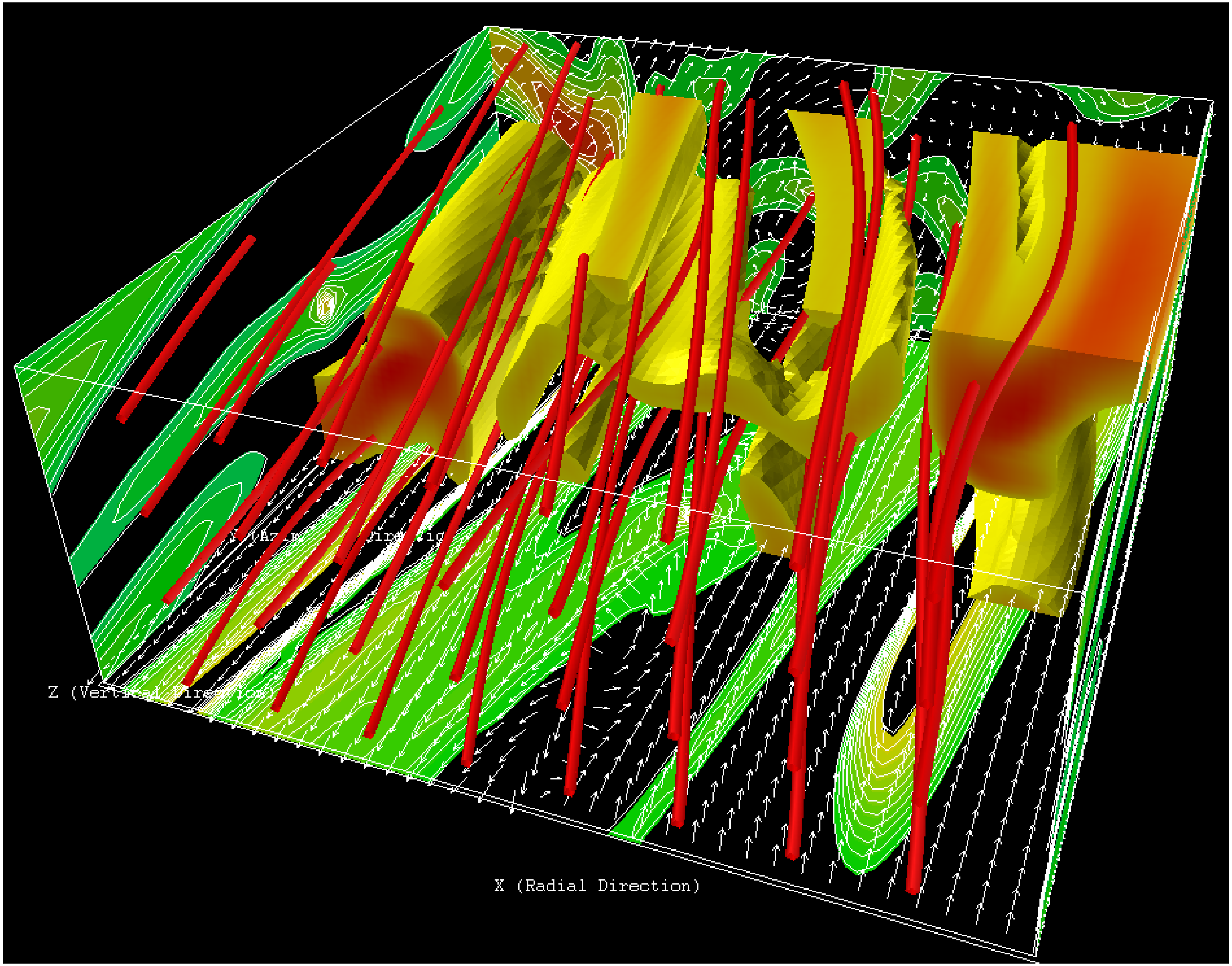
Ideal MHD model



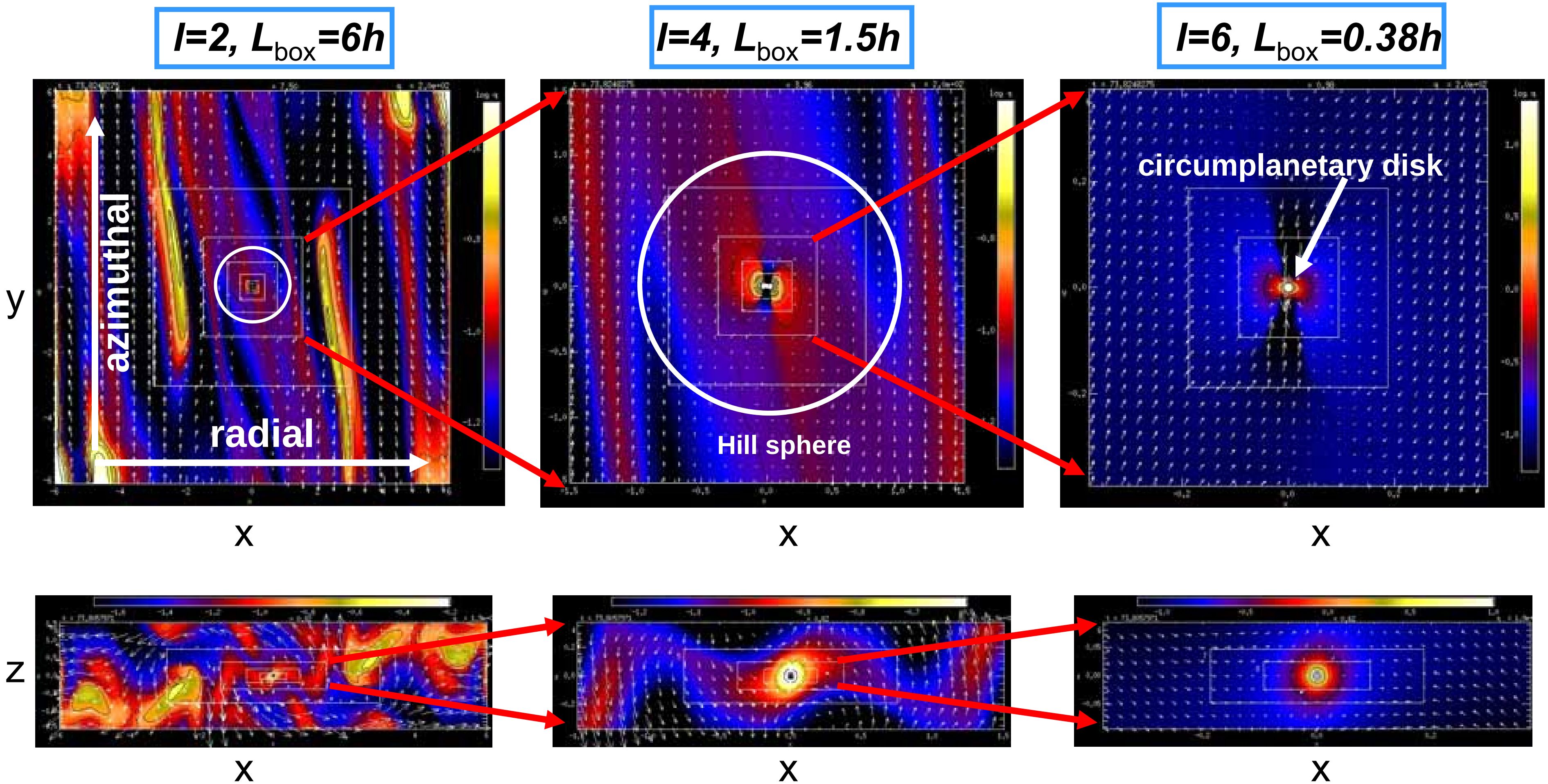
Channel flow in MRI turbulence

Toroidal dominated field lines

Resistive Model, Large scale (l=2, L=6h)



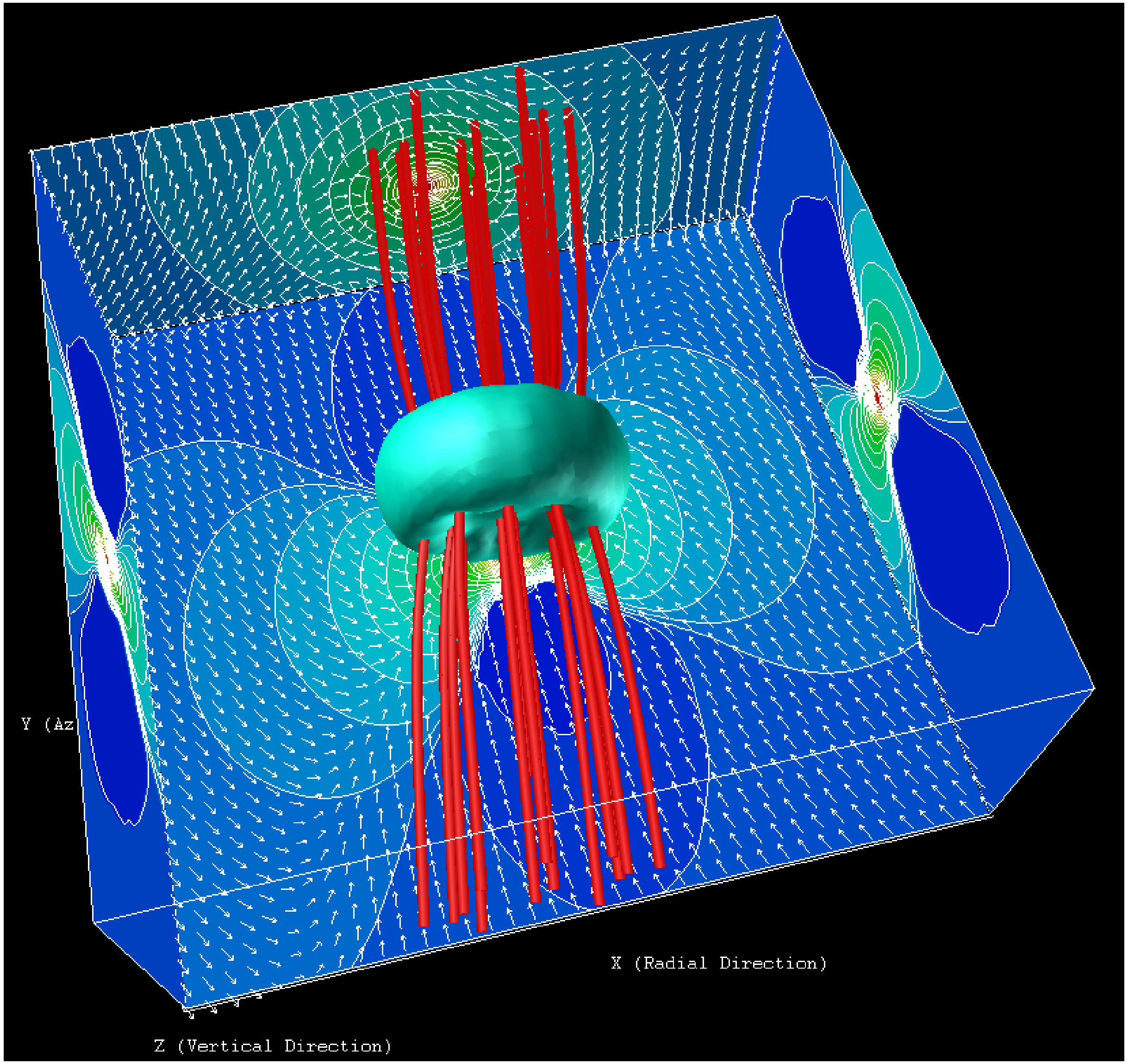
Circumplanetary disk formation in MRI turbulence



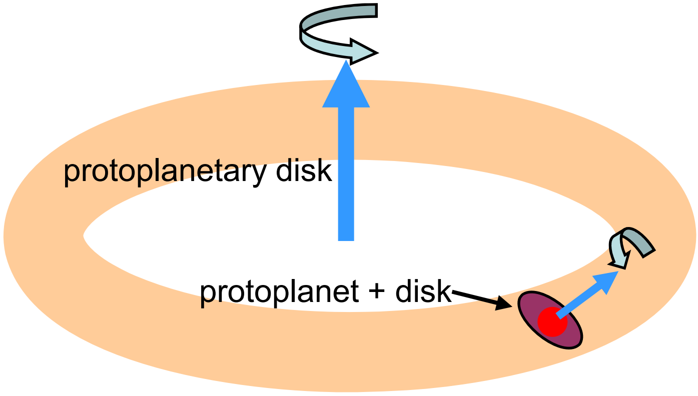
- Protoplanet is located at the center of the simulation box
- Circumplanetary disk formation in the MRI turbulent disk with low β ($\beta \sim 1$)
- The magnetic field significantly affects the circumplanetary disk formation

Circumplanetary disk formation in MRI turbulence

l=6, L_{box}=0.38h, Resistive Model



- Circumplanetary disk *acquires the angular momentum from MRI turbulence*
- Toroidal dominated field
  - ⇒ Gas flows into the Hill sphere along field lines
  - ⇒ Inclined disk formation
  - ⇒ Rotation axis of planetary system (planet and disk) is perpendicular to the protoplanetary disk normal



- Circumplanetary disk has
  - ✓ Ordered & vertical fields
  - ✓ Strong B ⇒ MRI stable

No B *vs.* B

Gas-planet and satellite formation under unmagnetized or magnetized disk

B in disk	No ***B*** Model	Low-β Model	High-β Model
MRI	No	No	Yes
Structure	Spiral	Spiral	Turbulence
Outflow	No	Yes	???
Gap	Deep	Deep	More deep
$M_P/(M_P/dt)$*1	~10^4 yr	~10^5 yr	~10^6 yr?
Satellite disk (acquisition process)	Large (shearing motion)	Compact (transfer by outflow)	Compact (turbulent flow)
B in satellite disk	No	Strong	Strong

*1: $M_P/(M_P/dt)$ is the growth timescale of the protoplanet (gas accretion timescale of the protoplanet)

Summary & Discussion

Giant planet formation in magnetized disks was investigated

- using 3D simulations with higher-spatial resolution
- including the thermal and magnetic effects

MRI in the active zone

- Turbulence and low-β gas near the Hill sphere of protoplanet
- Deeper gap appears in the active zone

The protoplanet formation under low-β (β~1) environment

- Due to the deeper gap and turbulence, the growth timescale of the protoplanet becomes long (~10^6 yr)
- Inclined circumplanetary disk along toroidal field

Satellite formation

- The circumplanetary disk (i.e., the site of the satellite formation) is stable against MRI, because of low-β (β~0.1)
- The circumplanetary disk has a strong, ordered, poloidal field

⇒ Type I migration of satellites may be suppressed by Muto mechanism

(Muto et al. 2008)