3D MHD simulation of primordial star forming cloud

Kenji Eric Sadanari(Tohoku Univ.)

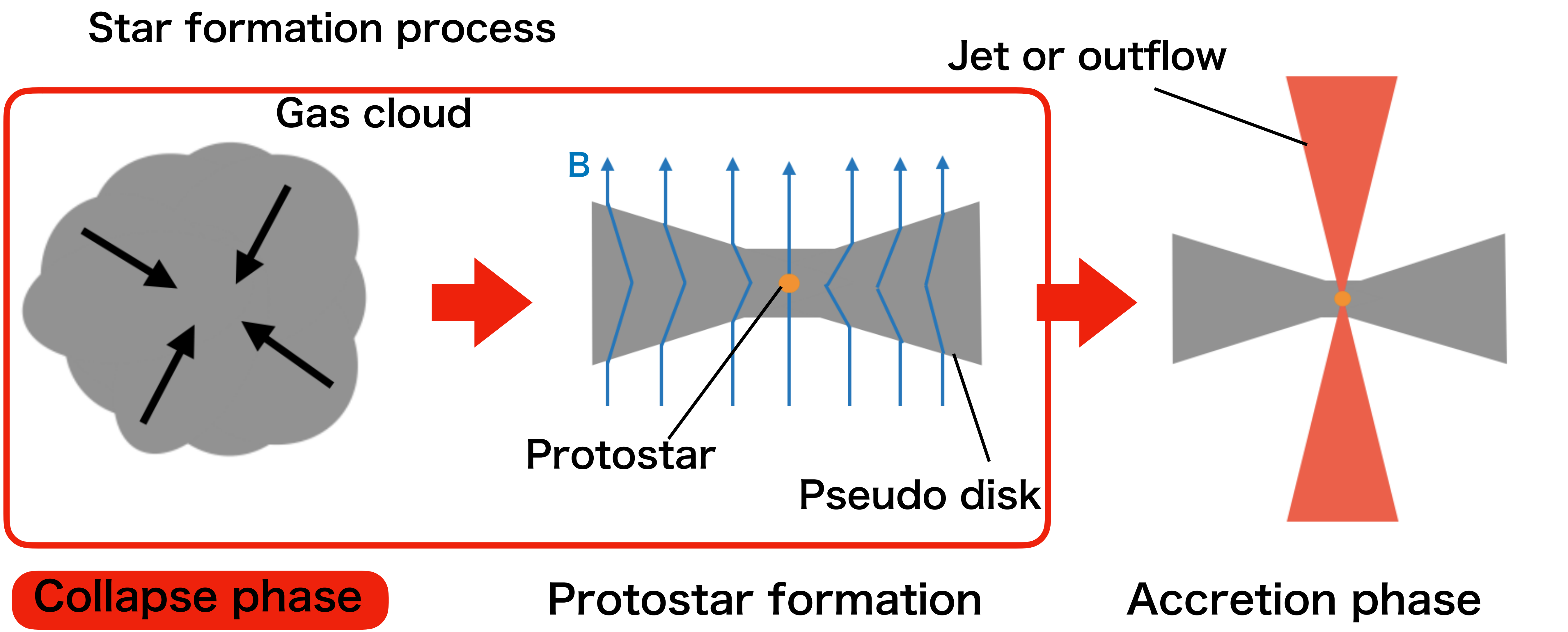
Kazu Omukai(Tohoku Univ.)
Kazu Sugimura(Meryland Univ.)
Tomoaki Matsumoto(Hosei Univ.)

TOHOKU UNIVERSITY

Theoretical Astrophysics
Tohoku University

Introduction

Magnetic field in star-formation



Magnetic effect

- magnetic braking
- magnetic dissipation
- outflow/jet

→

- Formation of circumstellar disk & binary
- Star formation efficiency
- mass of star

Magnetic effect is important for star formation process

Magnetic fields in the Primordial gas

Seed magnetic field

- Observable limitation by CMB → $\mathbf{B} < 1 \times 10^{-9}\mathrm{G}$
- Theoretical model(Biermann battery)→ $\mathbf{B} \sim 10^{-30} - 10^{-20}\mathrm{G}$

→ this B-feld is too small to have influence on star formation

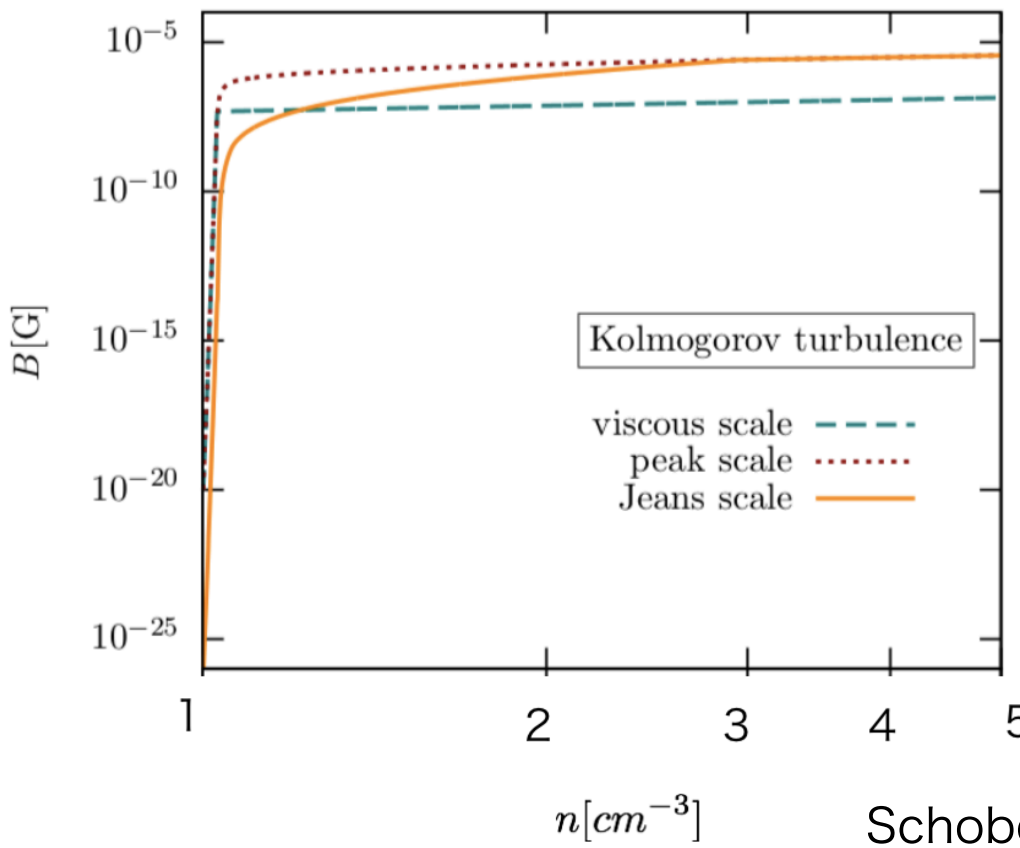
↓

Amplification of B-field
by turbulence
(small scale dynamo)

↓

Strong magnetic fields

there is a possibility to change
first star formation process



Schober et al.2012

B-field is important in primordial gas too

Problem of previous MHD simulation

Machida et al.2008

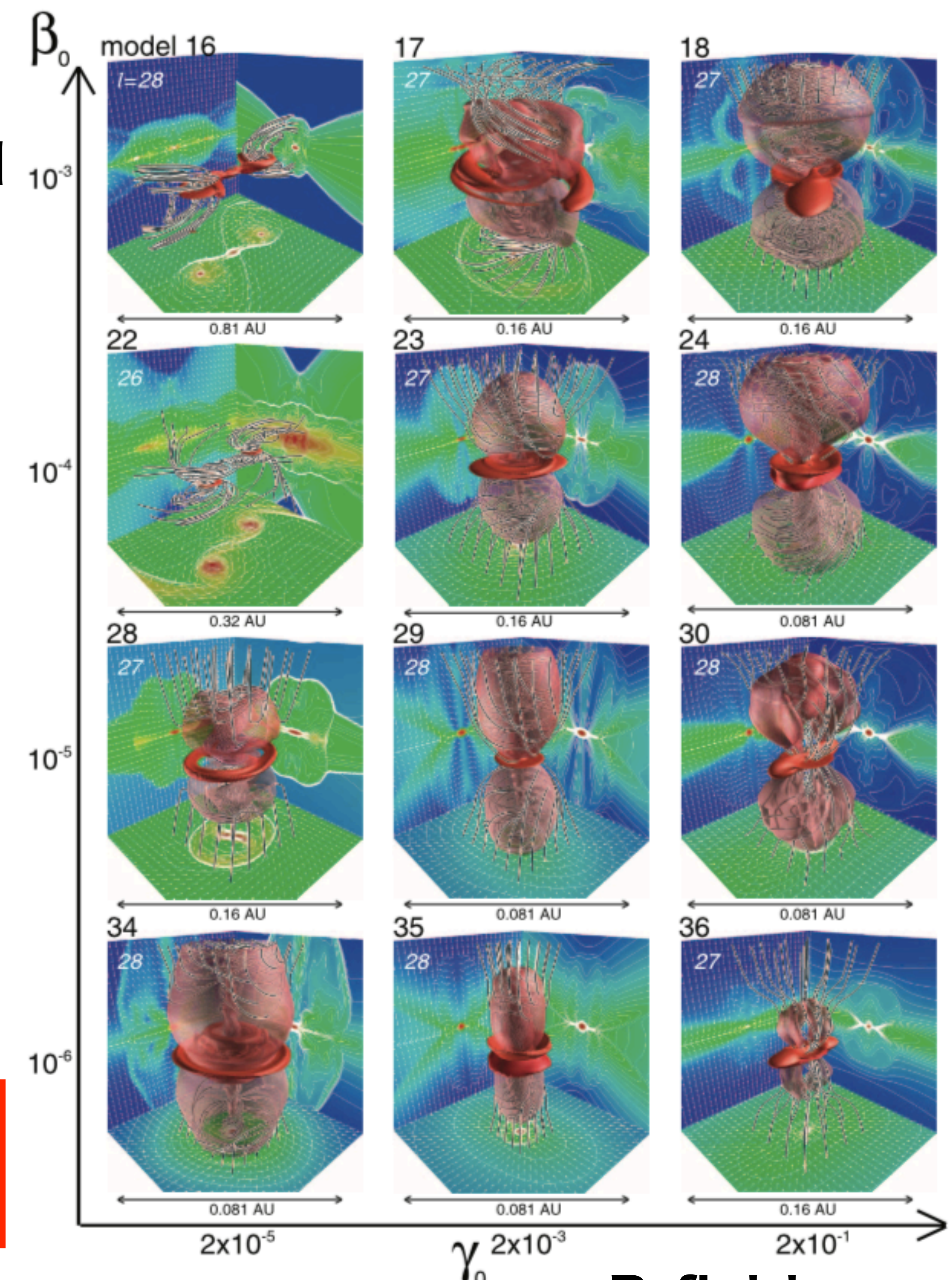
EOS: barotropic relation $P \propto \rho^{\gamma}$ obtained from one-zone model w/o B-field

In reality, T-evolution can deviate from barotropic relation by
shock heating and
magnetic effects:
slow down of collapse by B-field
magnetic dissipation heating

↓

Energy eq & chemistry should be solved consistently in MHD simulation.

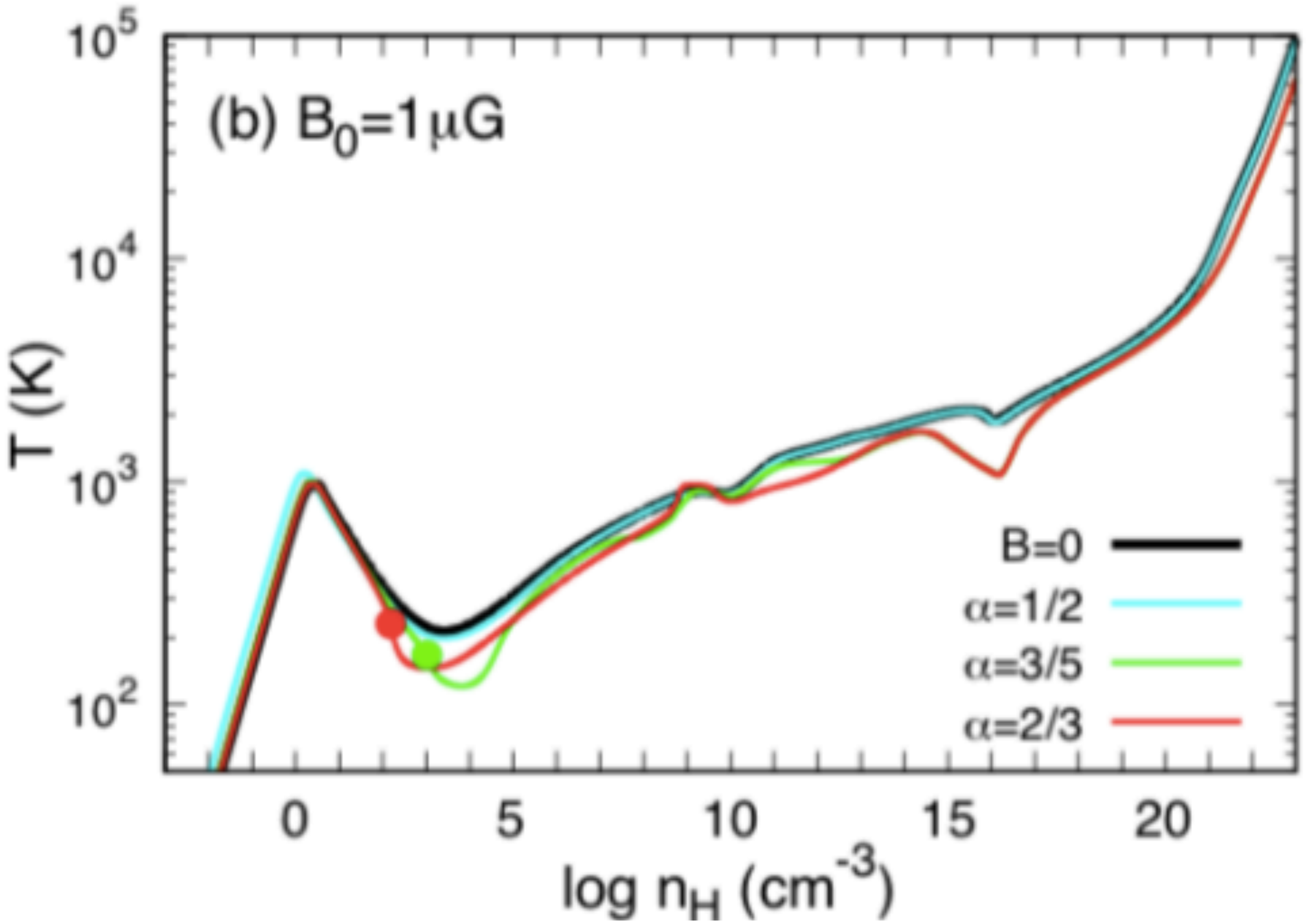
Rotation



B-field

Temperature evolution with magnetic effect

Nakauchi et al .2019(one-zone model)



Effect of Lorentz force

$$\mathbf{t}_{\mathrm{col}} = \frac{\mathbf{t}_{\mathrm{ff}}}{\sqrt{\mathbf{1} - (\mathbf{B}/\mathbf{B}_{\mathrm{cr}})^{\mathbf{2}}}}$$

B ⤴ ➡ $\mathbf{t}_{\mathrm{col}}$ ⤴

➡deviation of T-evolution ⤴

Parameter of cloud structure

$$\mathbf{B} \propto \rho^{\alpha}$$

sphere : $\alpha = \mathbf{2/3}$ sheet-like : $\alpha = \mathbf{1/2}$

T-evolution depends on collapse time($\mathbf{t}_{\mathrm{col}}$) & cloud shape($\alpha$)

➡ 3D MHD simulation is needed

Method

Set-up of 3D MHD simulation

SFUMATO (Matsumoto.2007)

- self-gravitational MHD code
- AMR
- Energy eq(+ cooling/heating)

[Basic equation]

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

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \nabla) = -\nabla P - \frac{1}{4\pi}\vec{B} \times (\nabla \times \vec{B}) - \rho \nabla \phi$$

$$\boxed{\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(e + p + \frac{1}{2}|B|^2 \right) v - B\,(v \cdot B) \right] = \Lambda}$$

$$\nabla^2 \phi = 4\pi G \rho$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$$

Ideal-MHD

Λ: cooling from H2, HD lines, chemical, H2, H- continuum

[chemical reaction: 27 reactions among 9 species]

$\mathrm{H}, \mathrm{H_2}, \mathrm{e}, \mathrm{H^+}, \mathrm{H^-}, \mathrm{H_2^+}, \mathrm{D}, \mathrm{HD}, \mathrm{D^+}$

Set-up of 3D MHD simulation

[Set-up]

- critical Bonnor-Ebert sphere × 1.4

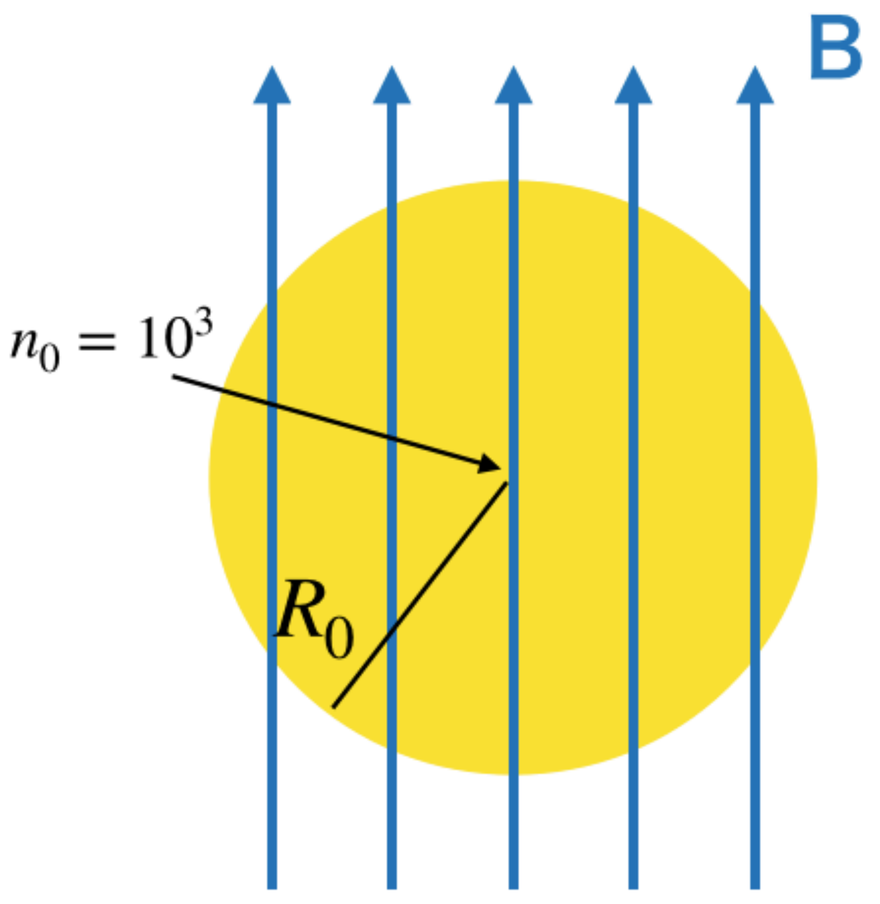
- initial center density $\mathbf{n_0 = 10^3 [cm^{-3}]}$

- using initial Temperature & chemical abundance of one-zone

- no rotation

- uniform magnetic field

$$\gamma = \frac{\mathbf{E_{mag}}}{|\mathbf{E_{grav}}|} = \mathbf{0 \sim 9 \times 10^{-1}}$$



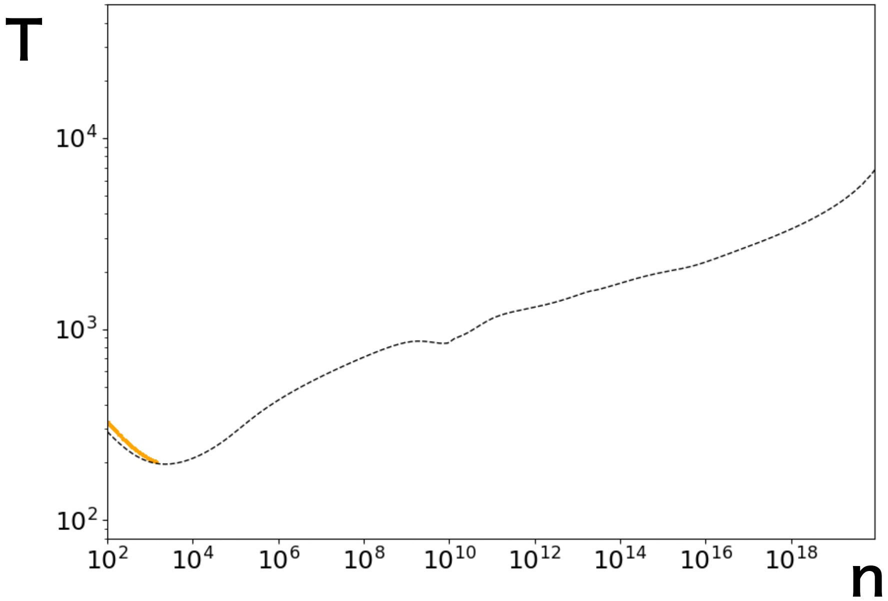
Result

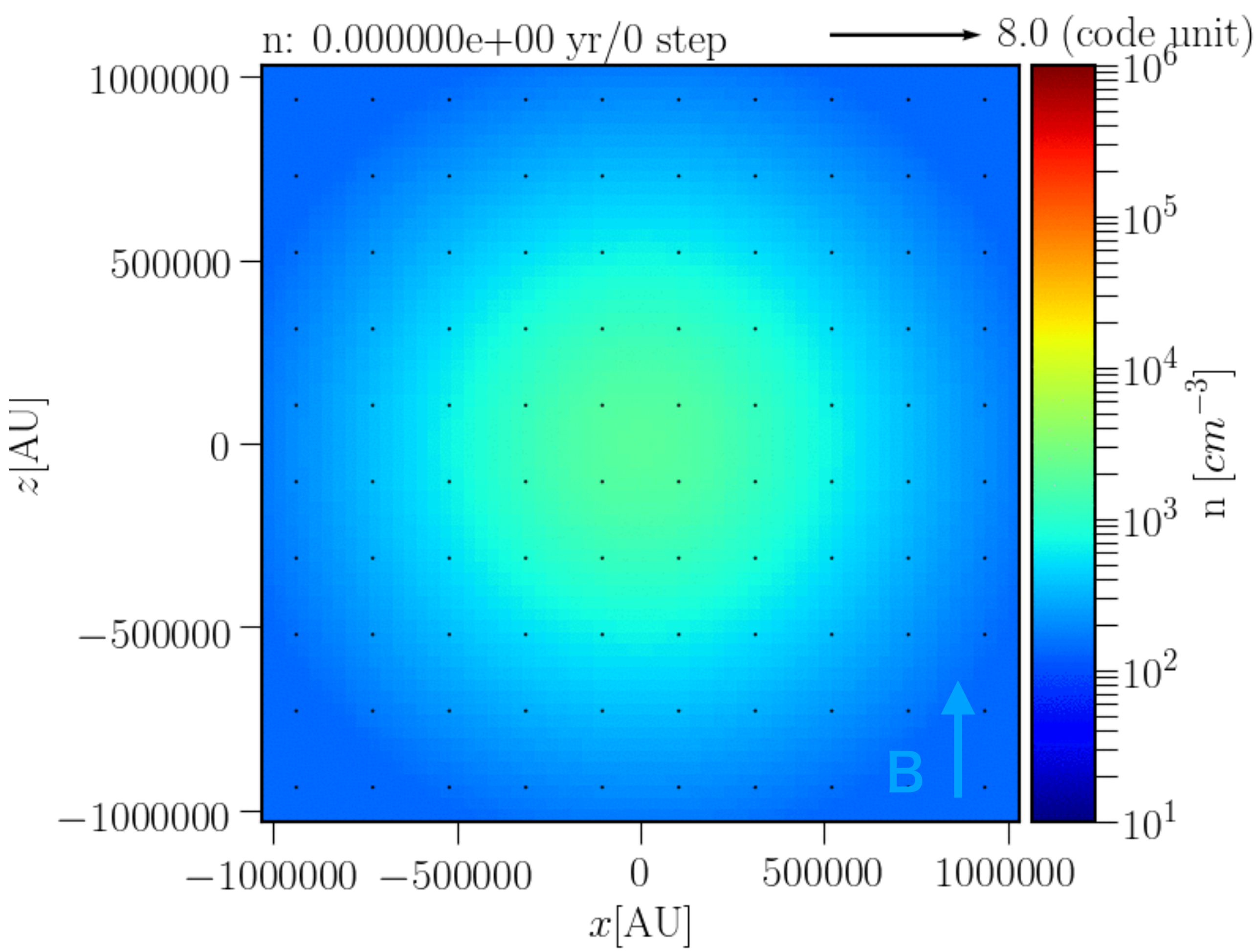
Effect of magnetic fields : case of $\gamma = 4 \times 10^{-2}$

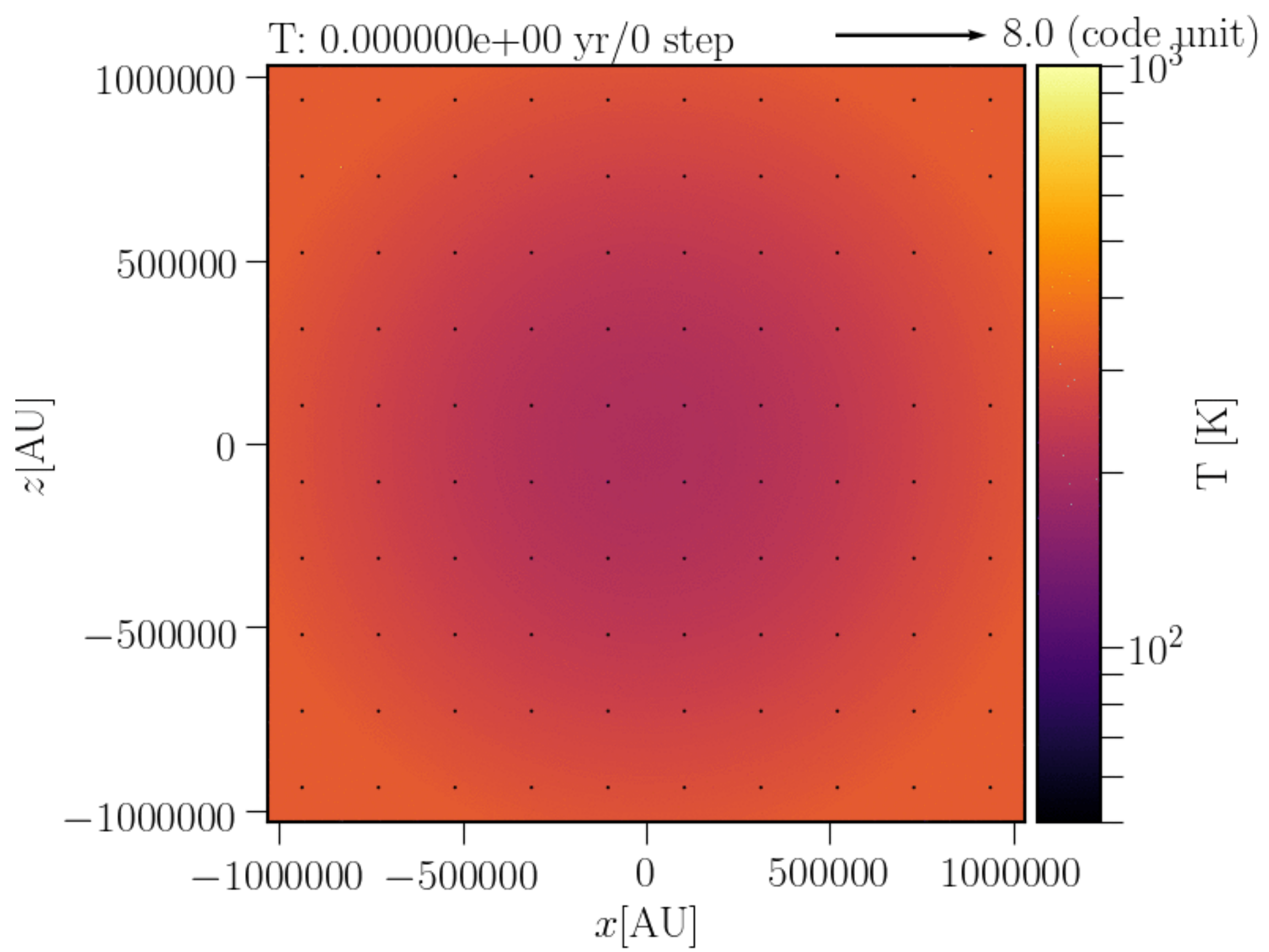
Moderate B-field

$$\gamma = \frac{\mathbf{E}_{\mathrm{mag}}}{|\mathbf{E}_{\mathrm{grav}}|} = 4.0 \times 10^{-2}$$

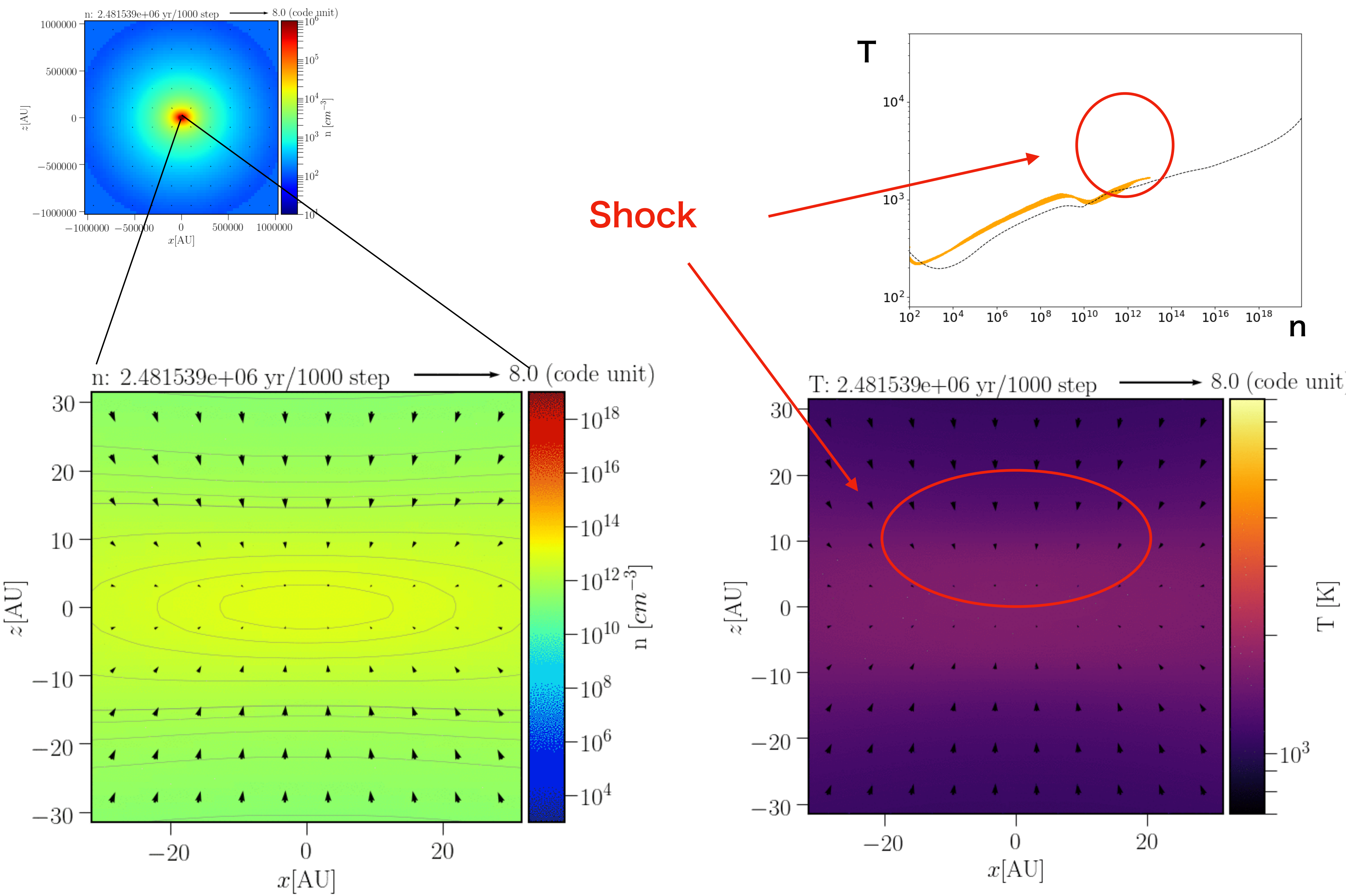
No rotation



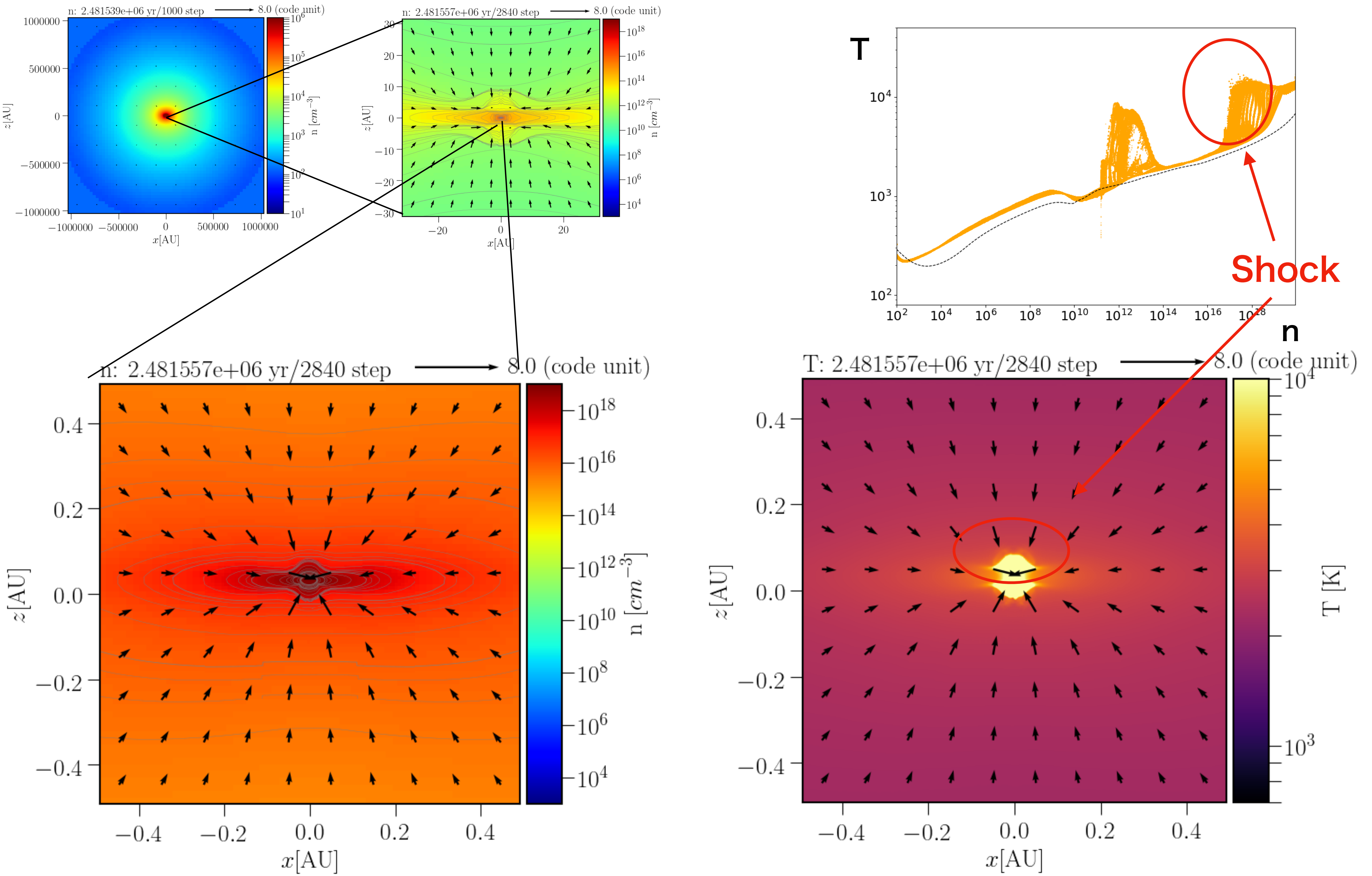




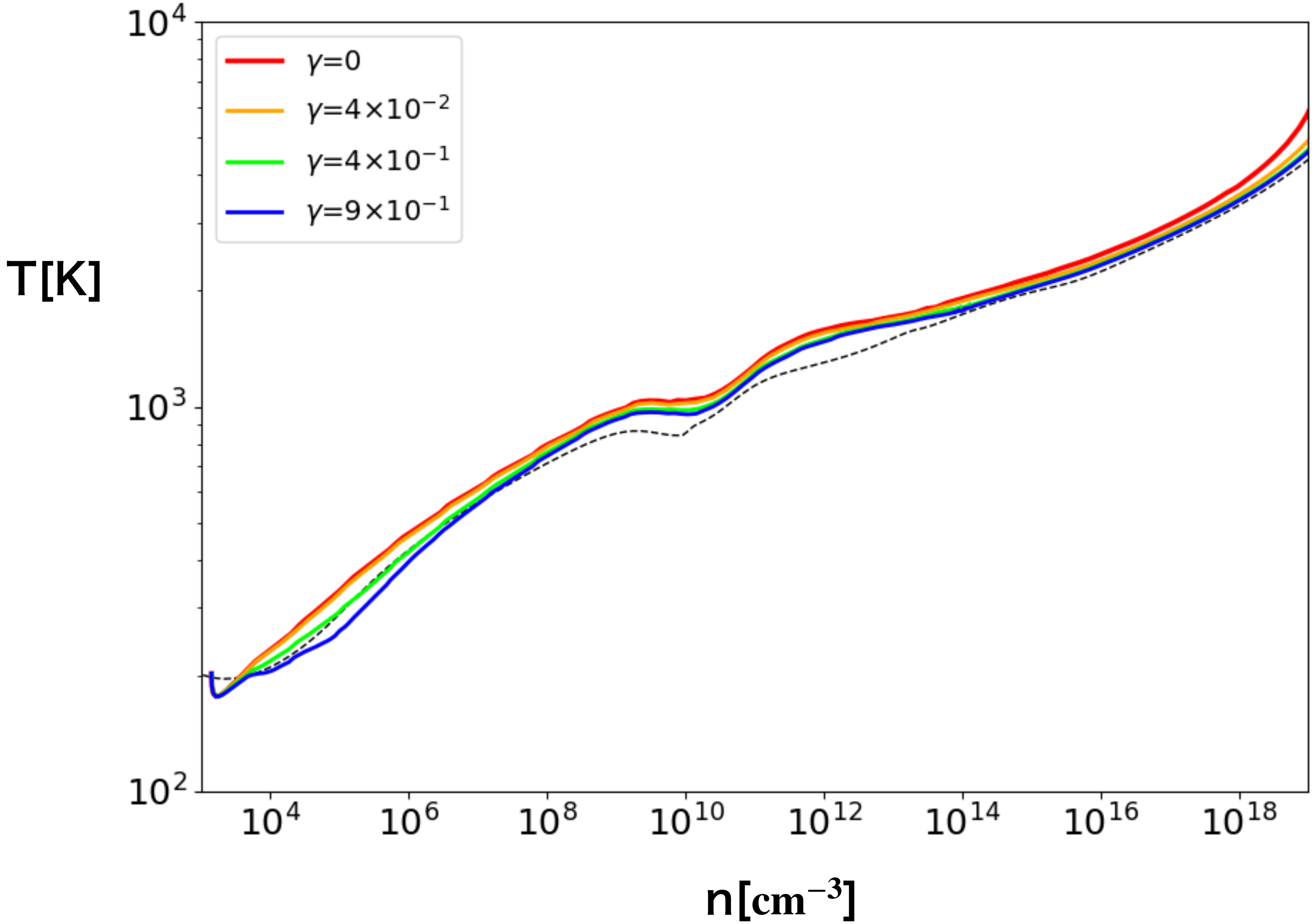
Effect of magnetic fields : case of $\gamma = 4 \times 10^{-2}$



Effect of magnetic fields : case of $\gamma = 4 \times 10^{-2}$

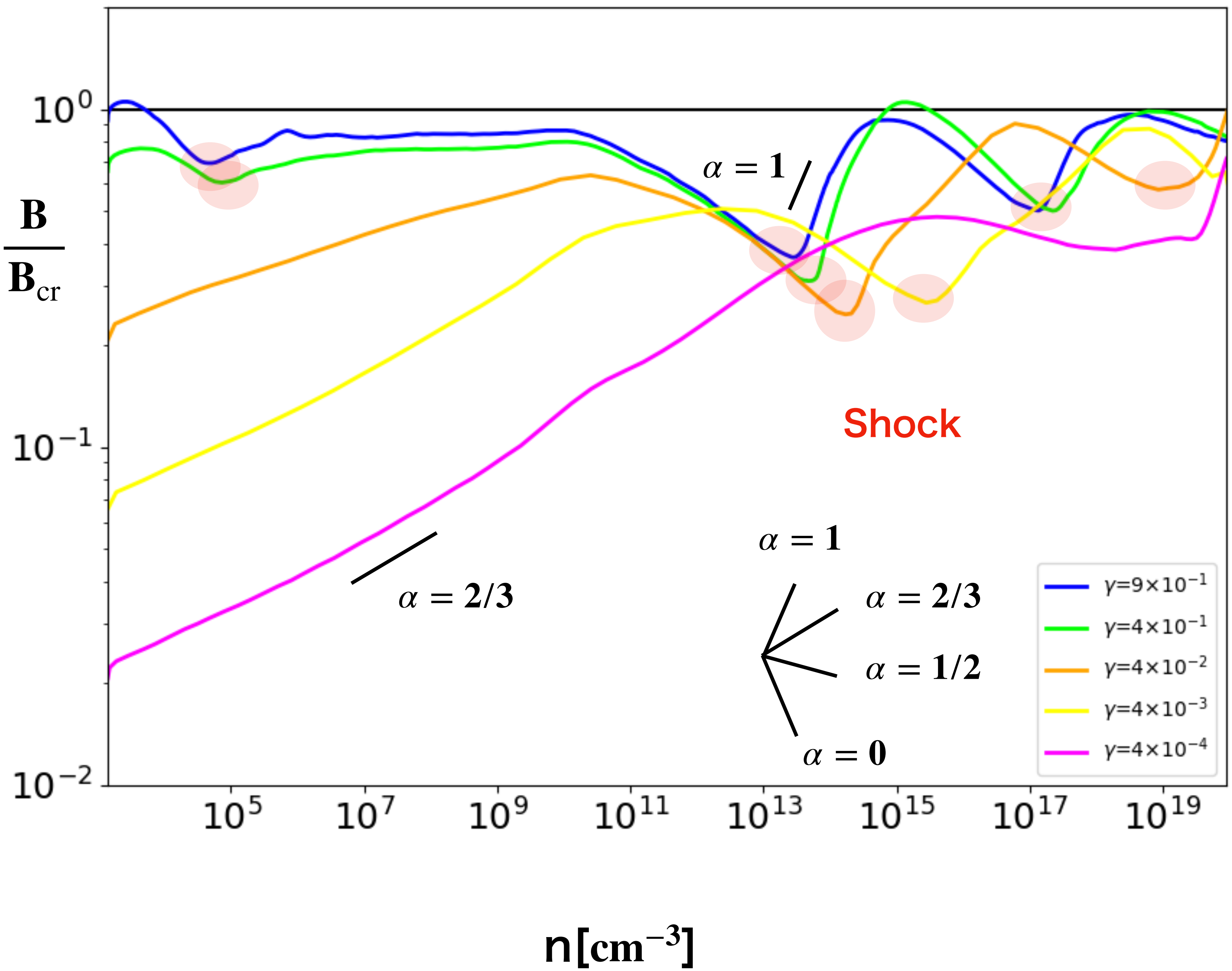


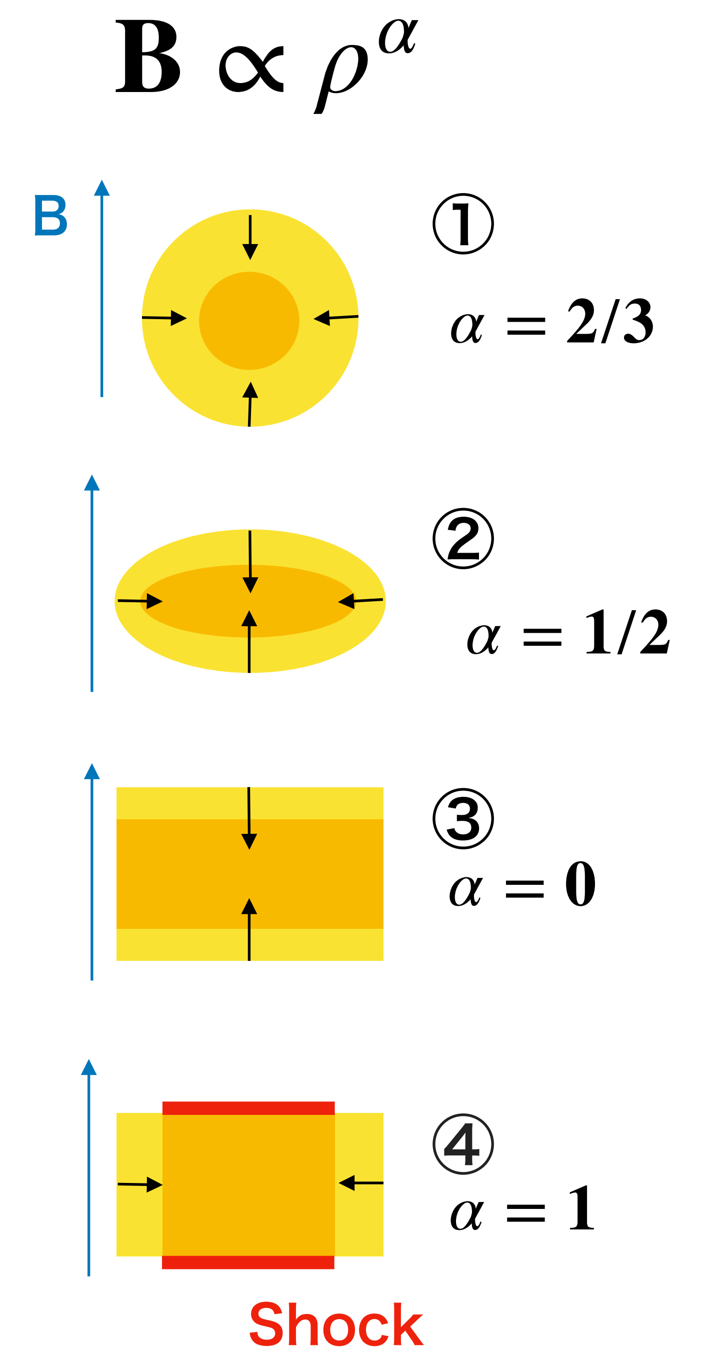
Thermal evolution at center



T-evolution changes only slightly even in strong B-field

Magnetic evolution at center





Gas collapse progresses due to the inflow along B-field

Summary & Future work

I investigated the effect of the B-field on the thermal evolution of primordial gas using 3D MHD simulation which solves energy eq & chemistry

Gas collapse progresses due to the inflow along the B-field and thermal evolution did not change much from one-zone model

This MHD simulation was able to reproduce shock heating formed on the surface of the pseudo disk

[future work]
Starting from a rotating magnetized cloud and examine the effect of angular momentum transport and jet/outflow

Study on effect of Magnetic dissipation heating by non-ideal MHD simulation .