YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

1次元モデルによる初代星周りの円盤進化

Evolution of the Disk around Pop III Star by One-Dimensional Model

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1. Introduction

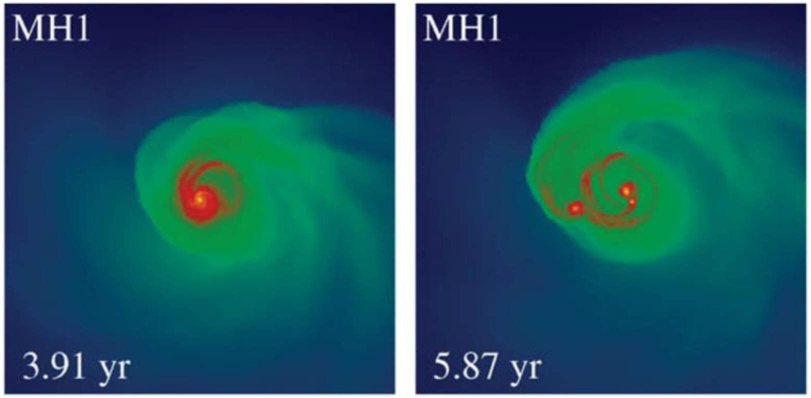
Fragmentation of Circumstellar Disk

- observed in many simulations of pop III star formation
- affect accretion rate and evolution of central star
- formation channel of binary or multiple stars

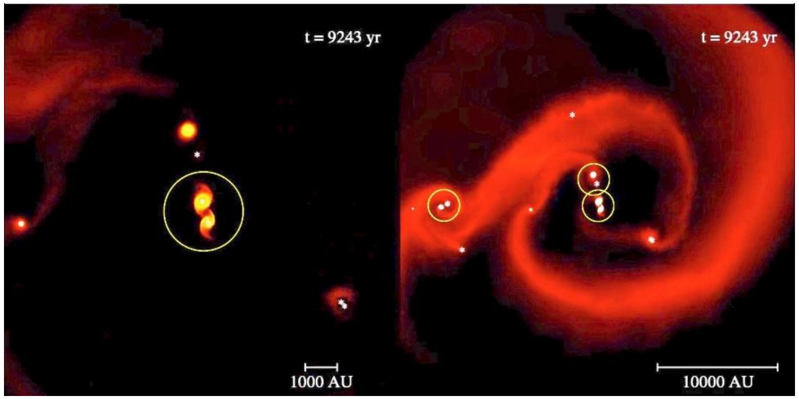
→ Gravitational Wave ?

- change IMF from the cases of single star

Grief et al. (2012)



Chon, Hosokawa & Yoshida (2018)



Previous Study and Motivation

Matsukoba et al (2019) ： **Primordial Case**

- one-dimensional and steady disk model
- discuss the condition for disk fragmentation
- not compared with simulation

Takahashi et al (2013) ： **Solar Metallicity Case**

- one-dimensional and <u>**non-steady**</u> disk model
- One-dimensional model is <u>**in good agreement with 3D simulation**</u>

We incorporated the physical processes in pop III star formation into Takahashi's model
(and want to compare with 3D simulation)

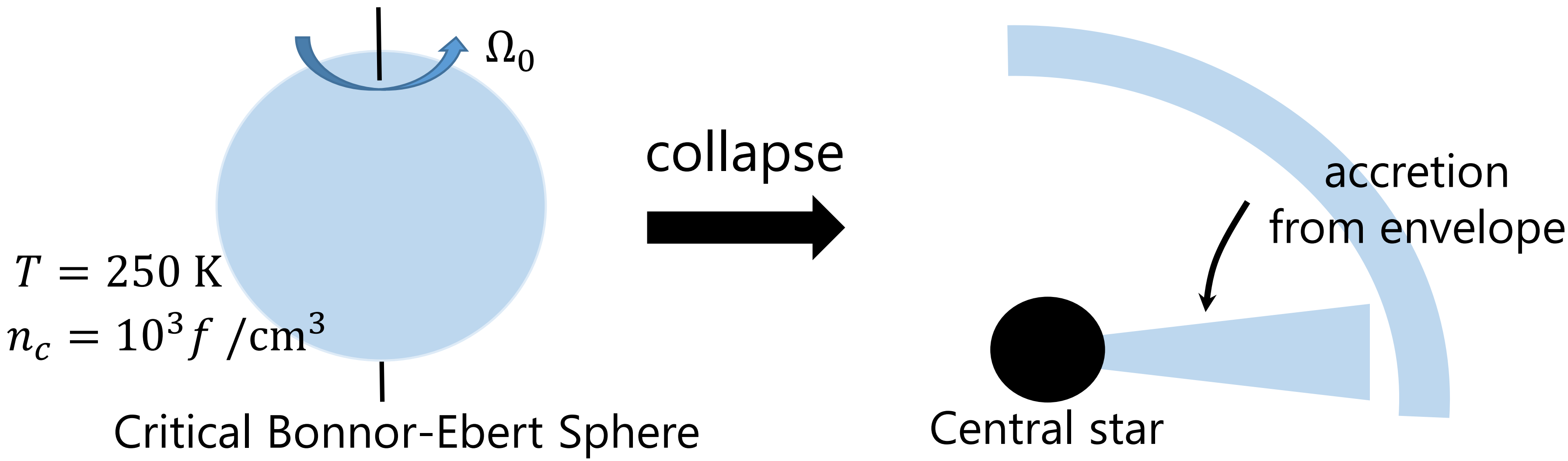
The advantages of one-dimensional model are

- long time evolution with high resolution
  (but in limited situation)
- parameter search

2. Model

Model

- **model accretion from envelope to the disk <u>analytically</u>**



- **One-dimensional equation of the Disk**
  - Mass Conservation
  - Angular Momentum Conservation (EOM)
  - **Energy Conservation**

$$\frac{\partial}{\partial t}(2\pi r \Sigma) + \frac{\partial}{\partial r}(2\pi r \Sigma v_r) = \dot{M}_{infall}$$

Thermal Evolution : visocosity , radiation , advection , chemistry

Chemical Evolution (Saha) : H , $\mathrm{H_2}$, $\mathrm{H^+}$, $\mathrm{H^-}$, e

Model

- **Viscosity : $\boldsymbol{\alpha}$ model**

Gravitational Torque

$$\nu = \alpha c_s H$$

$$\alpha = \begin{cases} \exp(-Q^4) \\ 0.01 + \exp(-Q^4) \ \ (\text{if } \alpha_{max} > 0.1) \end{cases}$$

If $\alpha > 0.1$ somewhere in the disk, clumpy structures transfer angular momentum globally

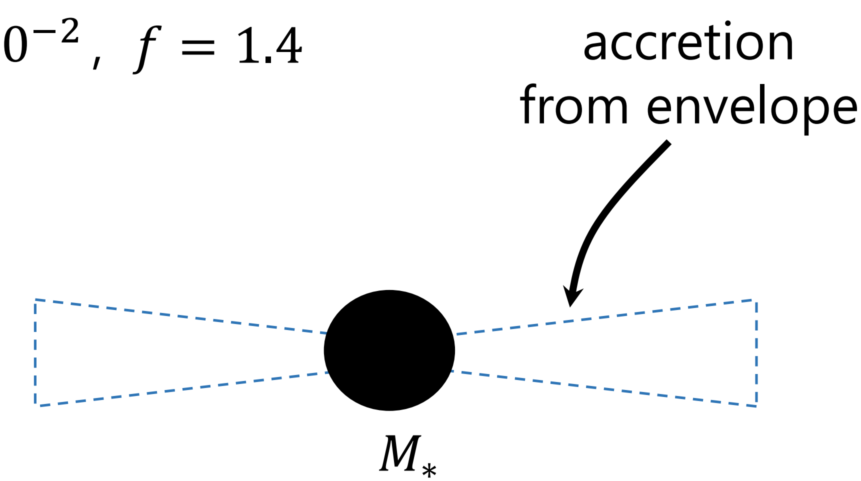
- **Parameter**

$$\beta_0 = \frac{E_{\mathrm{rot}}}{E_{\mathrm{grav}}} = \frac{\Omega_0^2 R_0^3}{3GM_{BE}} = 10^{-3} \sim 10^{-2}, \ \ f = 1.4$$

- **Initial Condition of the Disk**

Central Star $M_* = 10^{-2}\ \mathrm{M}_\odot$

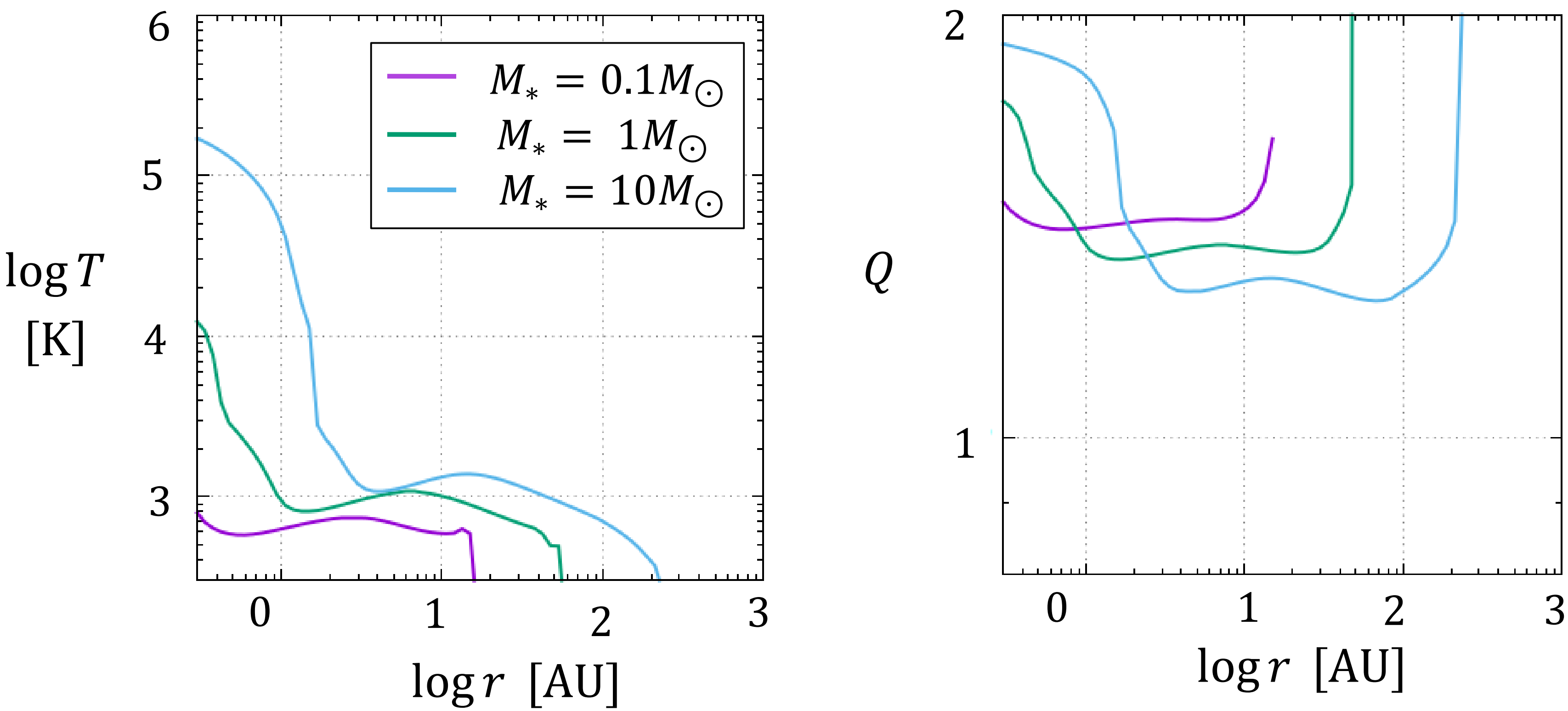
No Disk



3. Result

Outer region is maginally stable

- $\beta_0 = 10^{-2}$, $f = 1.4$ snapshot at $M_* = 0.1, 1, 10\ M_\odot$

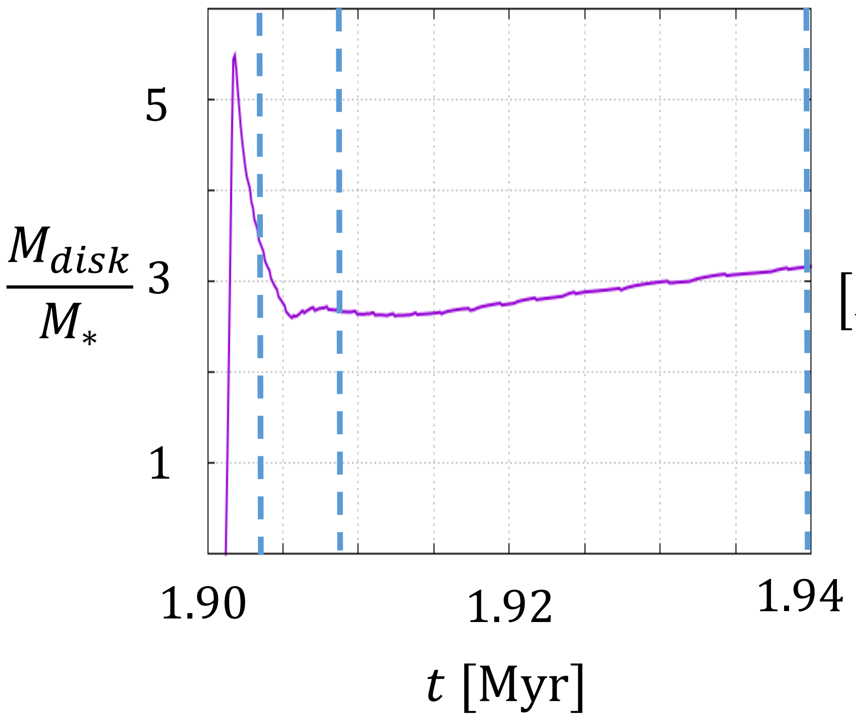


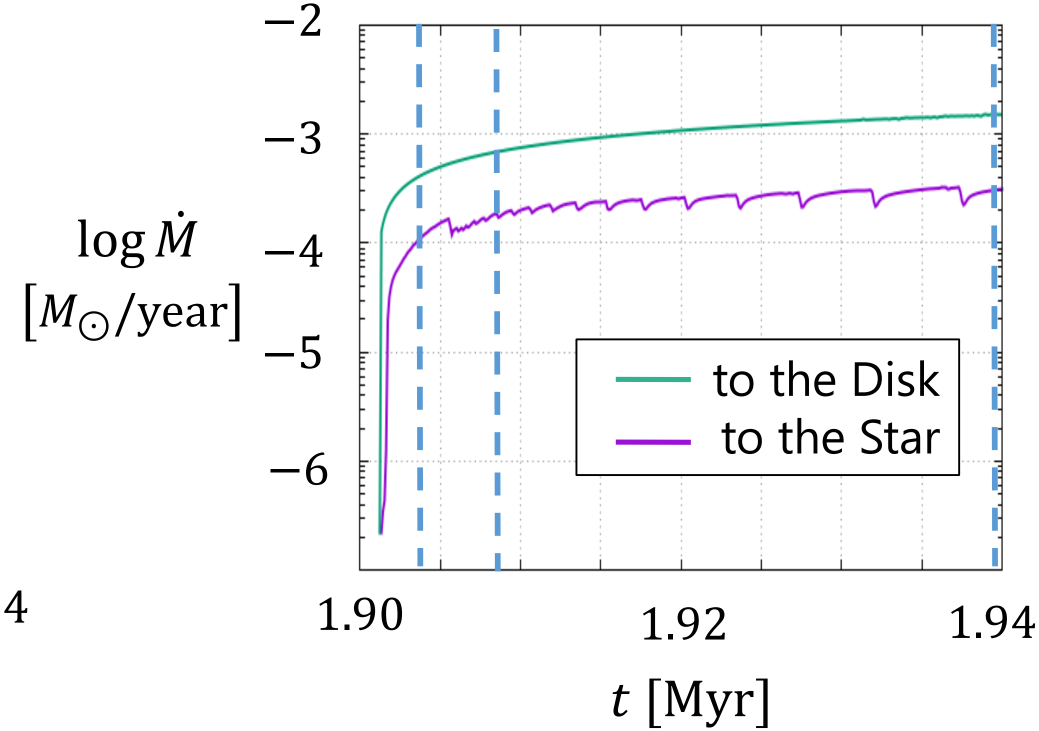
outer region (optically thin) : viscous heating = H_2 cooling

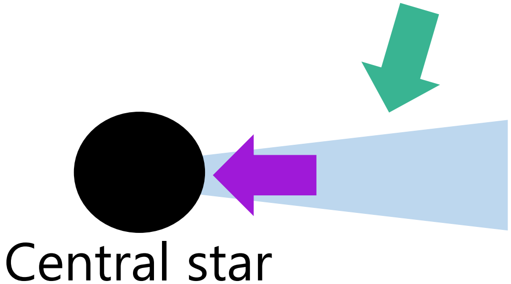
inner region (optically thick) : viscous heating dominant
Temperature gradually increase

Circumstellar disk is massive

- $\beta_0 = 10^{-2}$, $f = 1.4$,

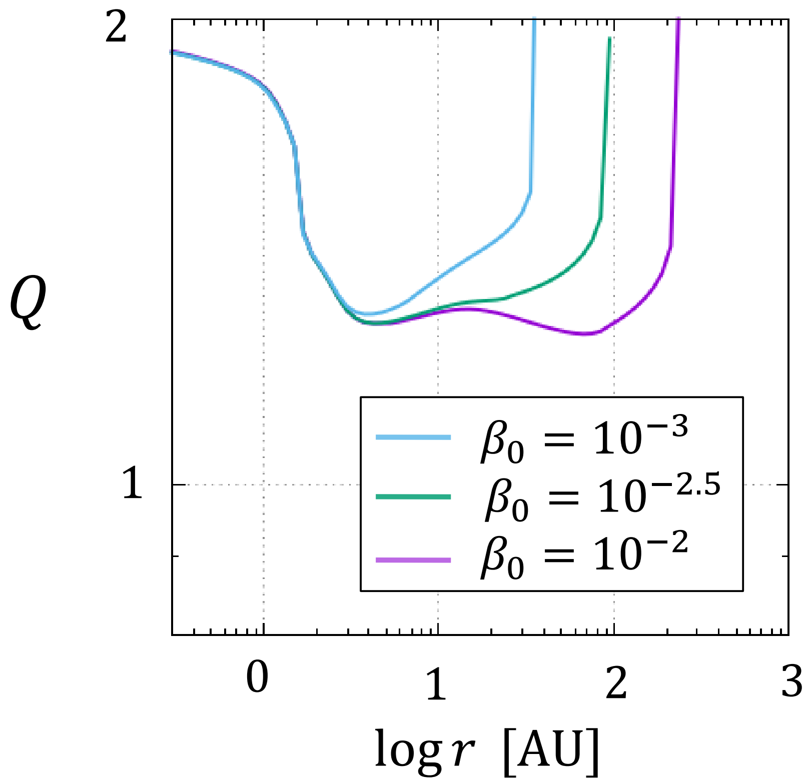


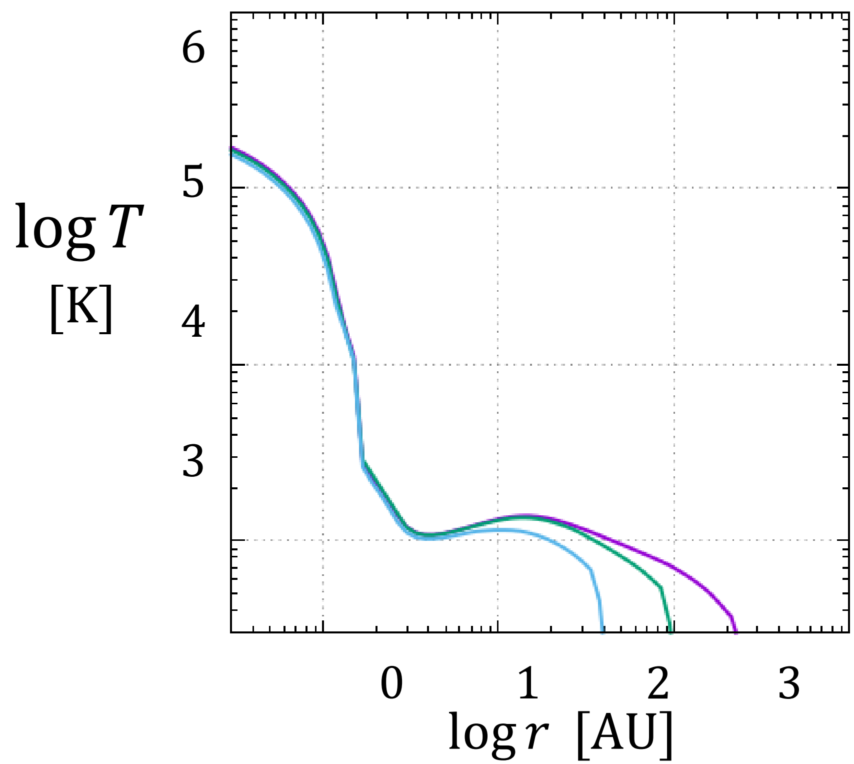




The radius where Q takes least value

- $\beta = 10^{-3}, 10^{-2.5}, 10^{-2}$ $f = 1.4$ snapshot at $M_* = 10M_\odot$

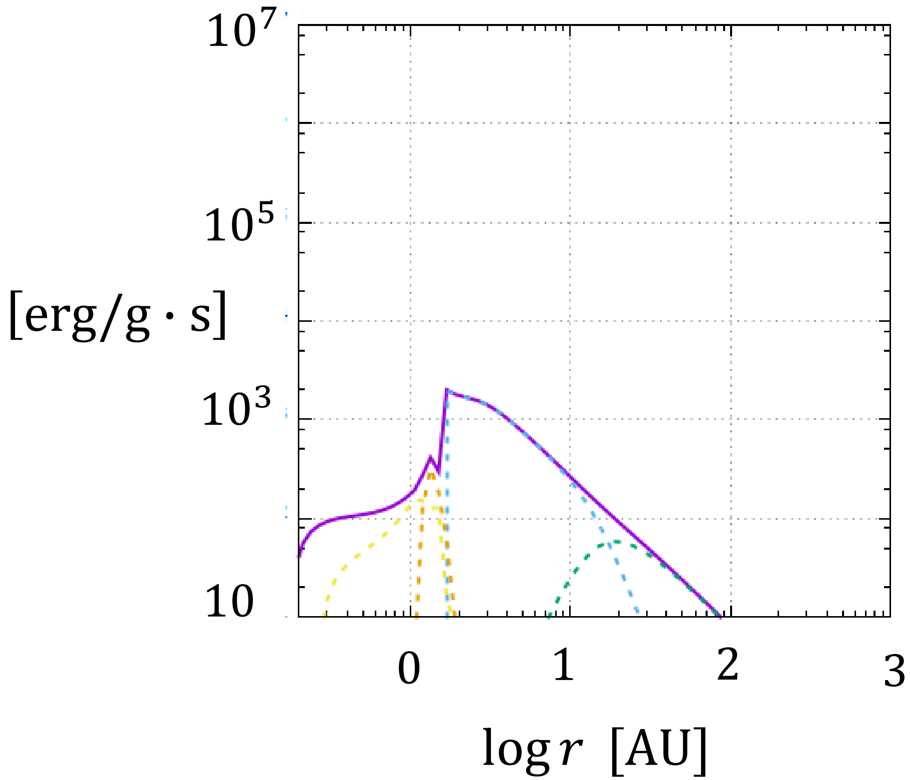


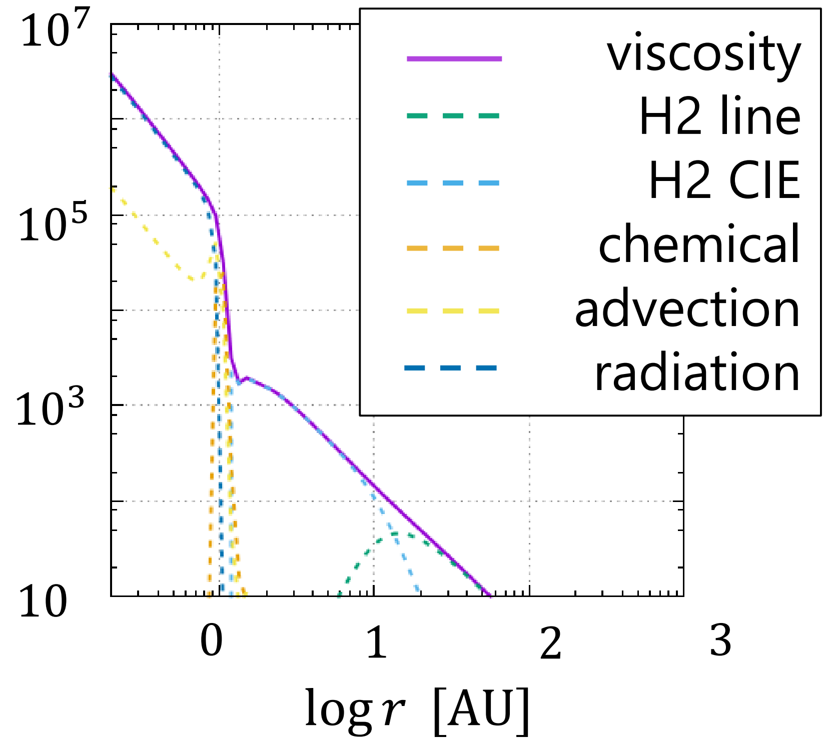


- $\beta_0 \leq 10^{-2.5}$ $n_c \sim 10^{16}$ where disk becomes optically thick
- $\beta_0 = 10^{-3}$ more outer region

Comparison with Different Viscosity Model

- heating and cooling processes , snapshot at $M_* = 10M_\odot$





only gravitational torque

$$\alpha = \begin{cases} \exp(-Q^4) \\ 0.01 + \exp(-Q^4) \ \ (\text{if } \alpha_{max} > 0.1) \end{cases}$$

MRI + gravitational torque

$$\alpha = 0.01 + \exp(-Q^4)$$

Summary

- We investigated time evolution of the disk around pop III star by one-dimensional model

Result

- In outer region, viscous heating = H2 cooling
- In inner region, viscous heating is dominant
- The radius where Q takes least value depends on β_0
- If MRI viscosity is added ,
  viscous heating = radiative cooling in inner region

Future Work

- Calculation in other parameter ranges
- Comparison with 3D simulation