超大質量星形成過程における星周円盤の進化

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1. Introduction

Supermassive Black Holes (SMBHs)

High-z QSOs observation

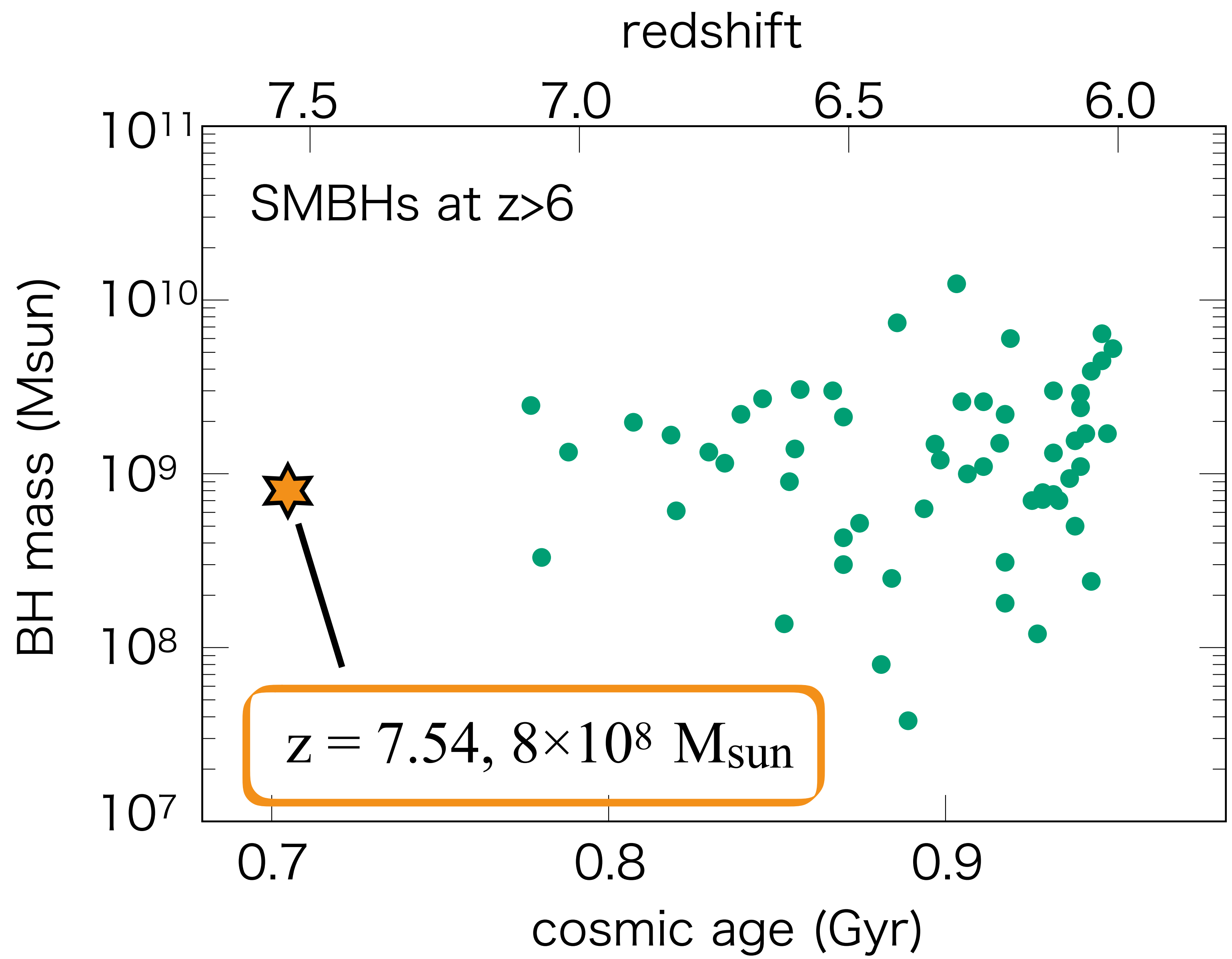
z > 6 (cosmic age $\lesssim$ 1 Gyr)

- More than 100 QSOs are observed.
- BH mass : 10^7-10^{10} M_{sun}

Most distant one

z=7.54 (cosmic age~0.7 Gyr)

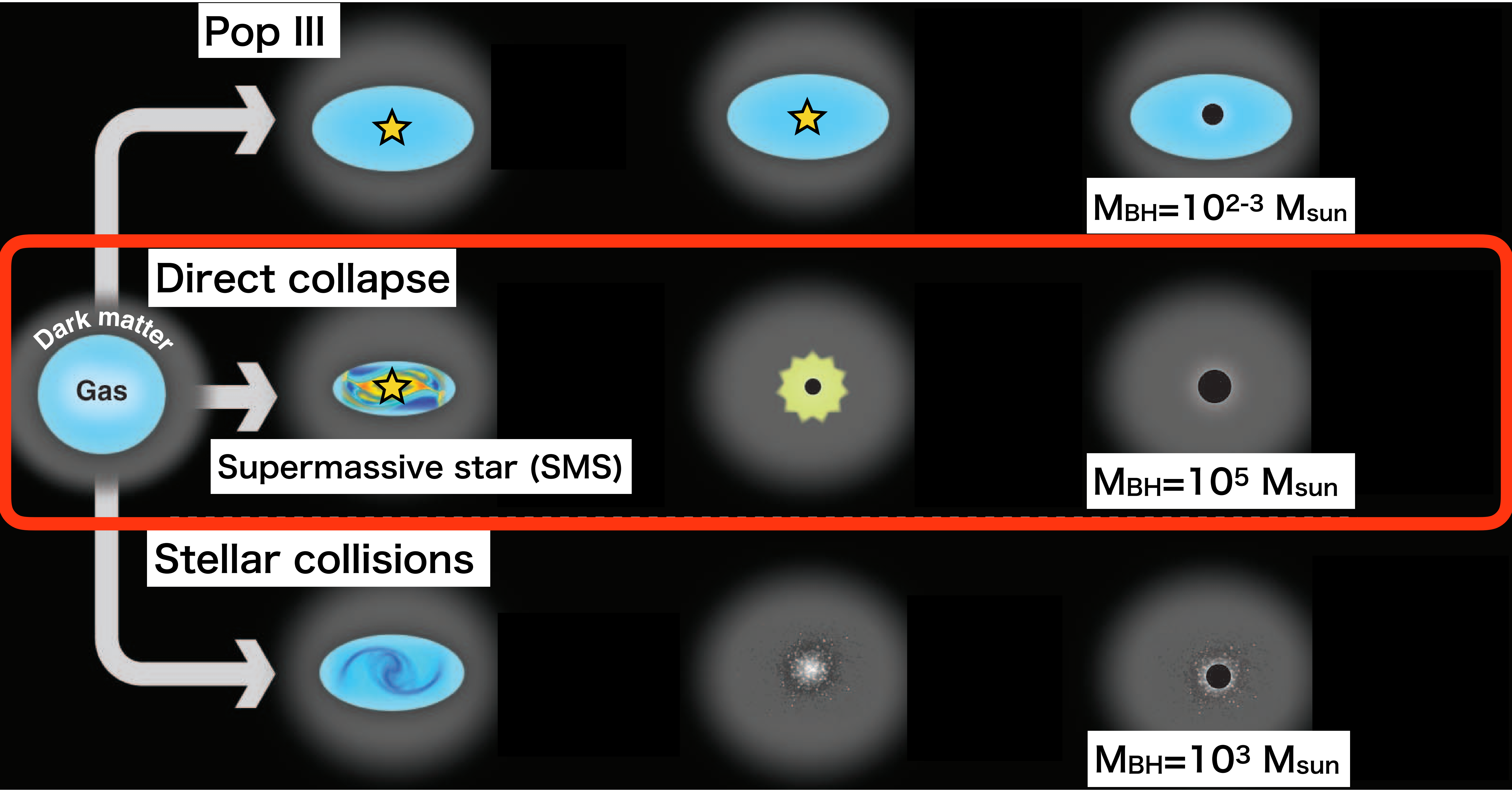
Bãnados+18



The origin of those BHs is still a mystery.

What is the formation scenario of high-z massive BHs?

Formation scenarios of seed BHs



Volonteri 12

Thermal evolution of SMS formation

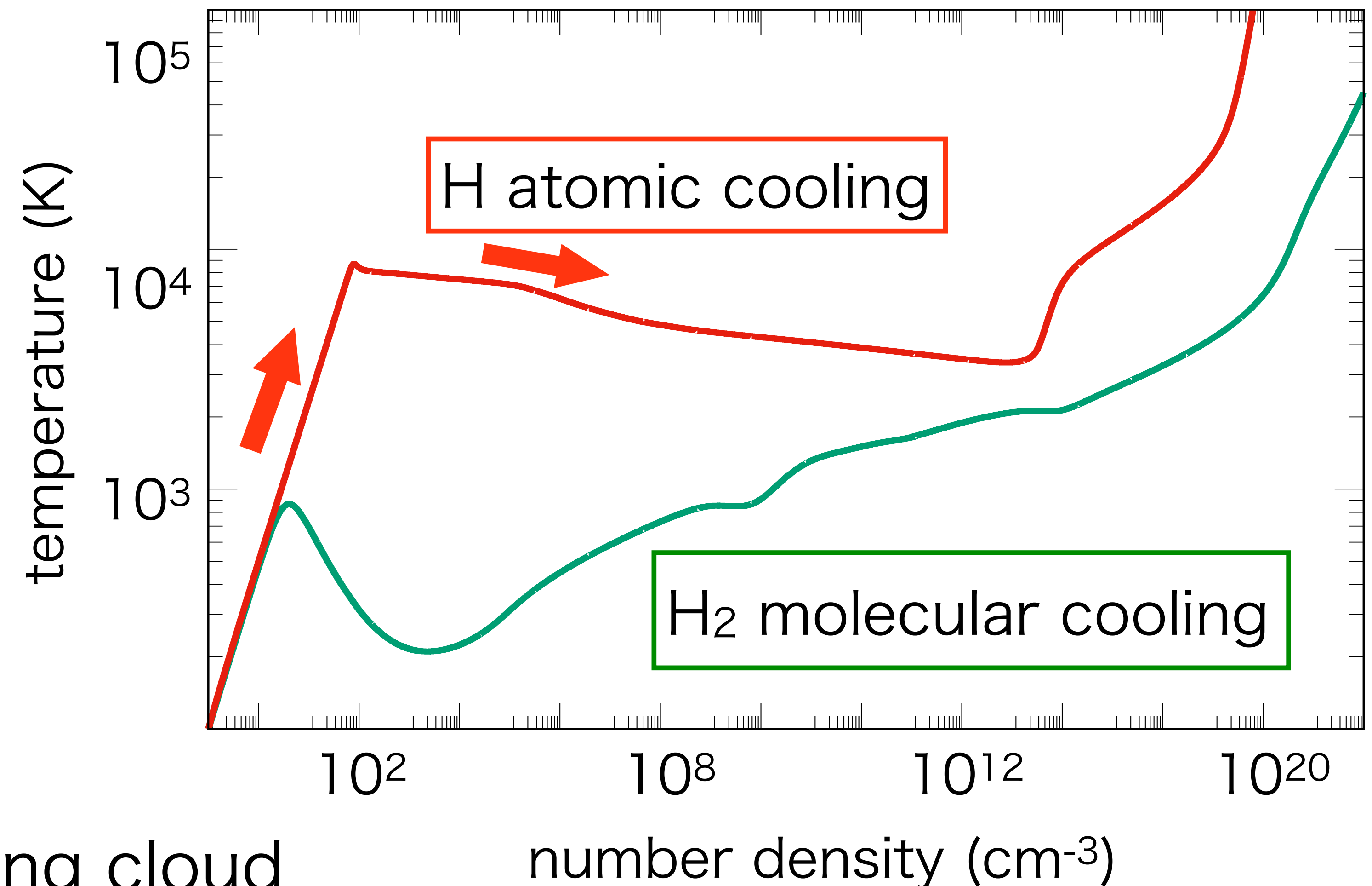
H_2 formation is suppressed by FUV radiation.

- Photodissociation

$$H_2 + \gamma \rightarrow {H_2}^* \rightarrow 2H$$

- Photodetachment

$$H^- + \gamma \rightarrow H + e$$



Omukai 01

Accretion rate of H atomic cooling cloud

$$\dot{M} \sim \frac{M_J}{t_{ff}} \sim 0.1\ M_\odot\ \mathrm{yr}^{-1} \left(\frac{T}{10^4\ \mathrm{K}}\right)^{3/2}$$

High accretion rate

→ ✔ Stellar mass can reach 10^5 M_{sun} within its lifetime.

✔ Protostar becomes "supergiant". Hosokawa+12, 13

Stability of the steady accretion disk

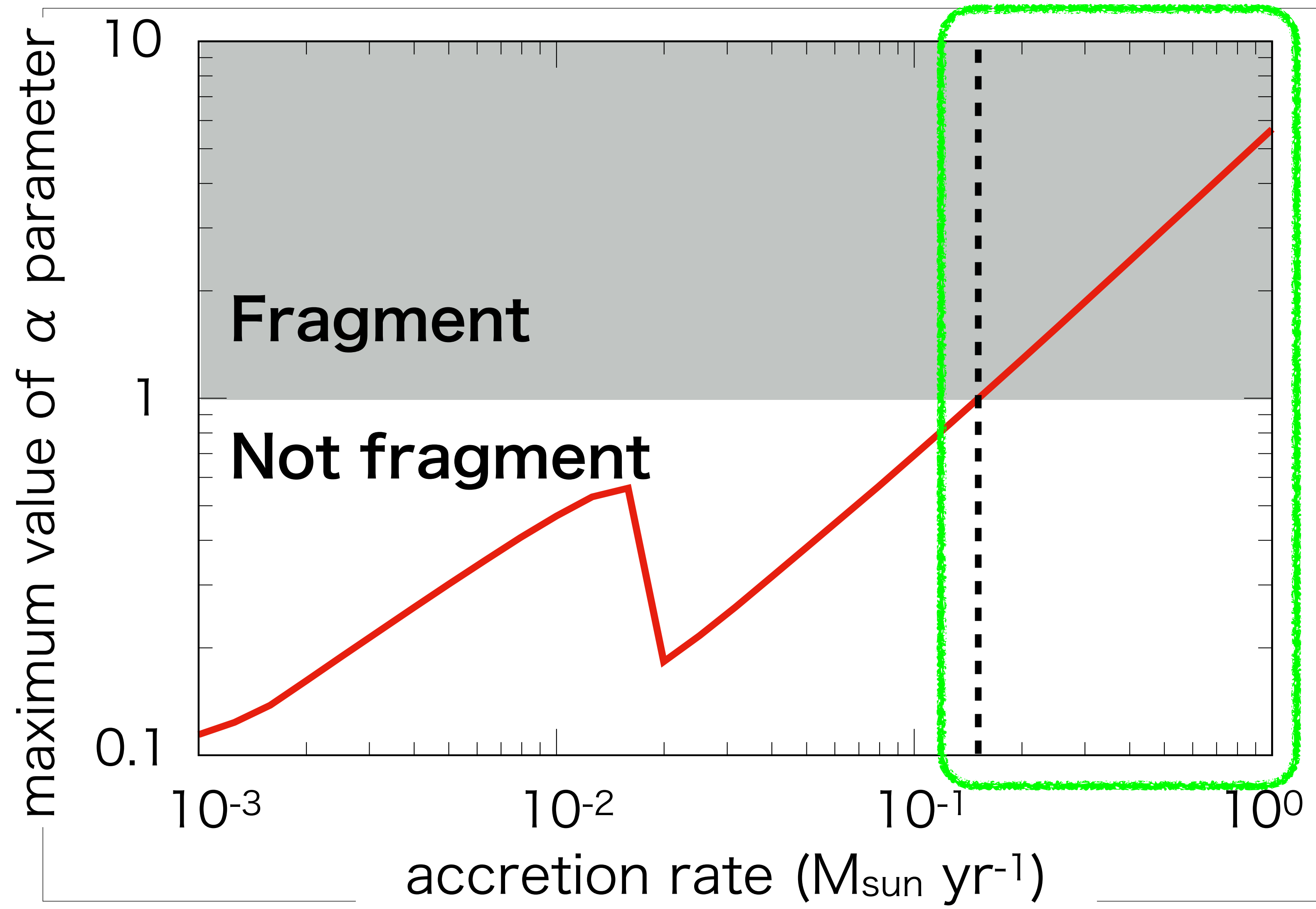
✔ Disk structure

$$Q = \frac{c_s \Omega}{\pi G \Sigma} = 1$$

$$\Rightarrow \quad \Sigma = \frac{c_s \Omega}{\pi G}$$

✔ Fragmentation condition

$$\alpha = \frac{\nu \Sigma}{c_s^2} > 1$$



RM+19

When the accretion rate > 0.1 Msun yr-1, the disk becomes gravitationally unstable and fragments.

➡ **The accretion flow has time variation.**

Motivation

If the accretion rate has time variation,

stellar radius decreases and the effective temperature rises.

→ Ionization feedback becomes efficient.

The length of time that accretion rate falls below $4\times10^{-2}\ M_{sun}\ yr^{-1}$ is important. Sakurai+15

→ **We should investigate the time evolution of the accretion rate.**

Previous work Sakurai et al. (2016)

They used barotropic relation as EOS,

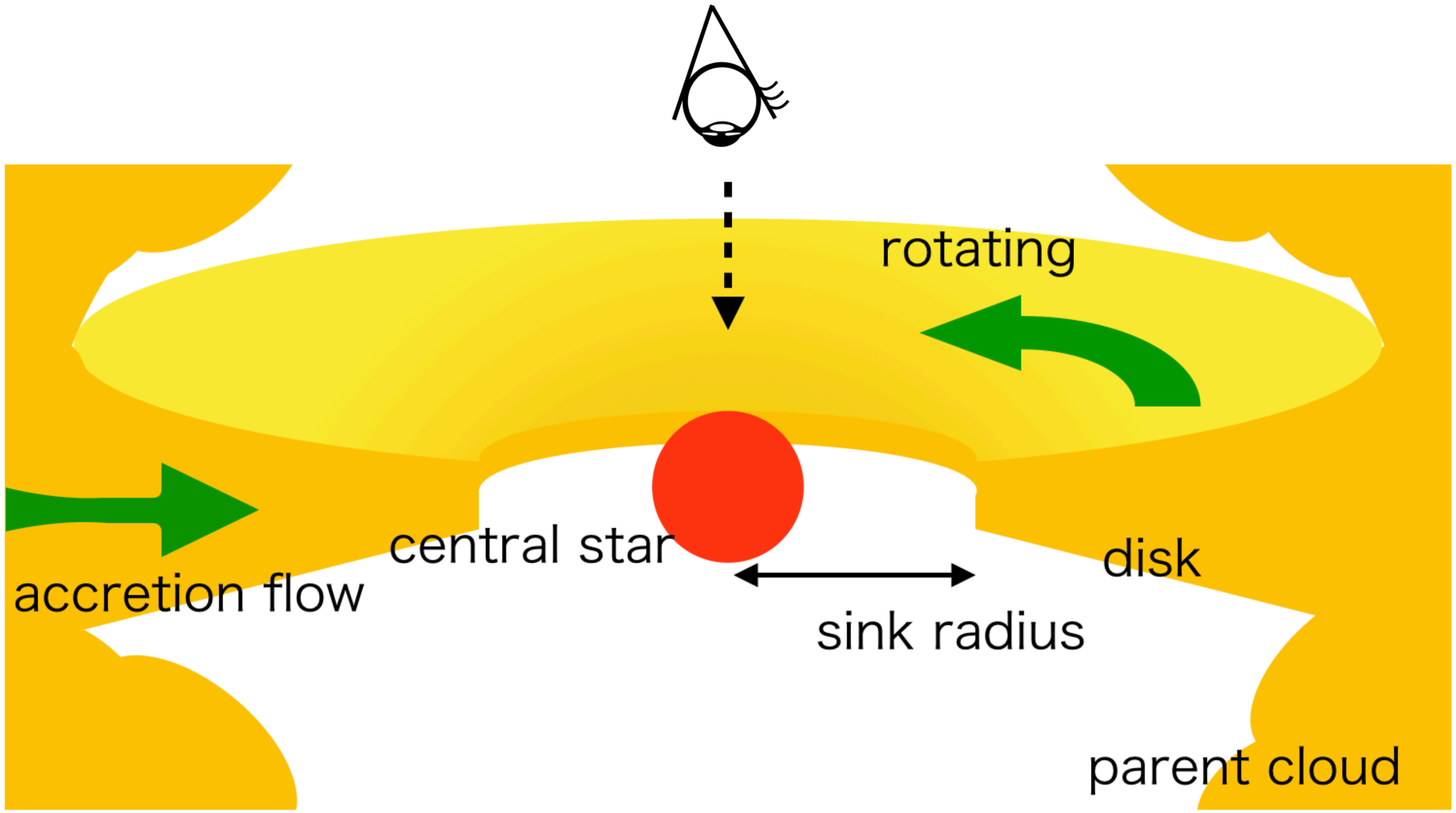
but gravitational instability depends on the temperature.

→ In this work, **we follow the disk formation process with detailed thermal and chemical treatments.**

2. Model

Calculation model

2D simulation, face-on



- Sink cell

  radius $r_{\mathrm{sink}} = 300\ \mathrm{au}$

- Chemistry

  H, H_2, H^+, e

- Thermal

  heating : viscous, compression, stellar radiation

  cooling : H_2 line, continuum, Ly α, chemical cooling

- Central stellar radiation

  $L_{star}=L_{Edd}$, $T_{eff}=5000$ K Hosokawa+12

Initial condition

Chon et al. (2016)

They identified two direct collapse cloud from the cosmological simulation.

Two dimensionalization

- Core mass

  Fil : $4.6 \times 10^4\ M_{sun}$

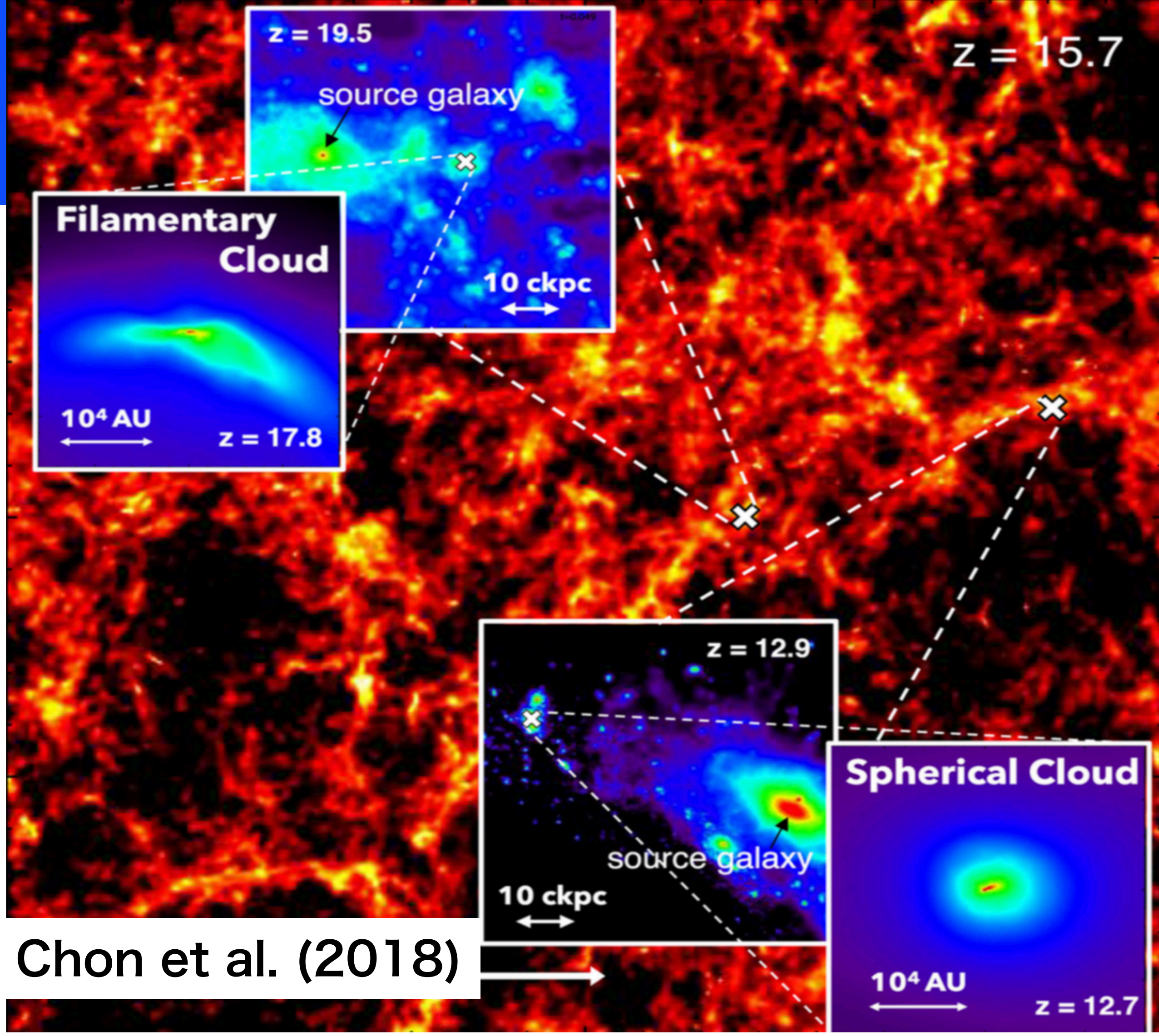
  Sph : $5.2 \times 10^4\ M_{sun}$

- (Thermal energy) / (grav. energy)

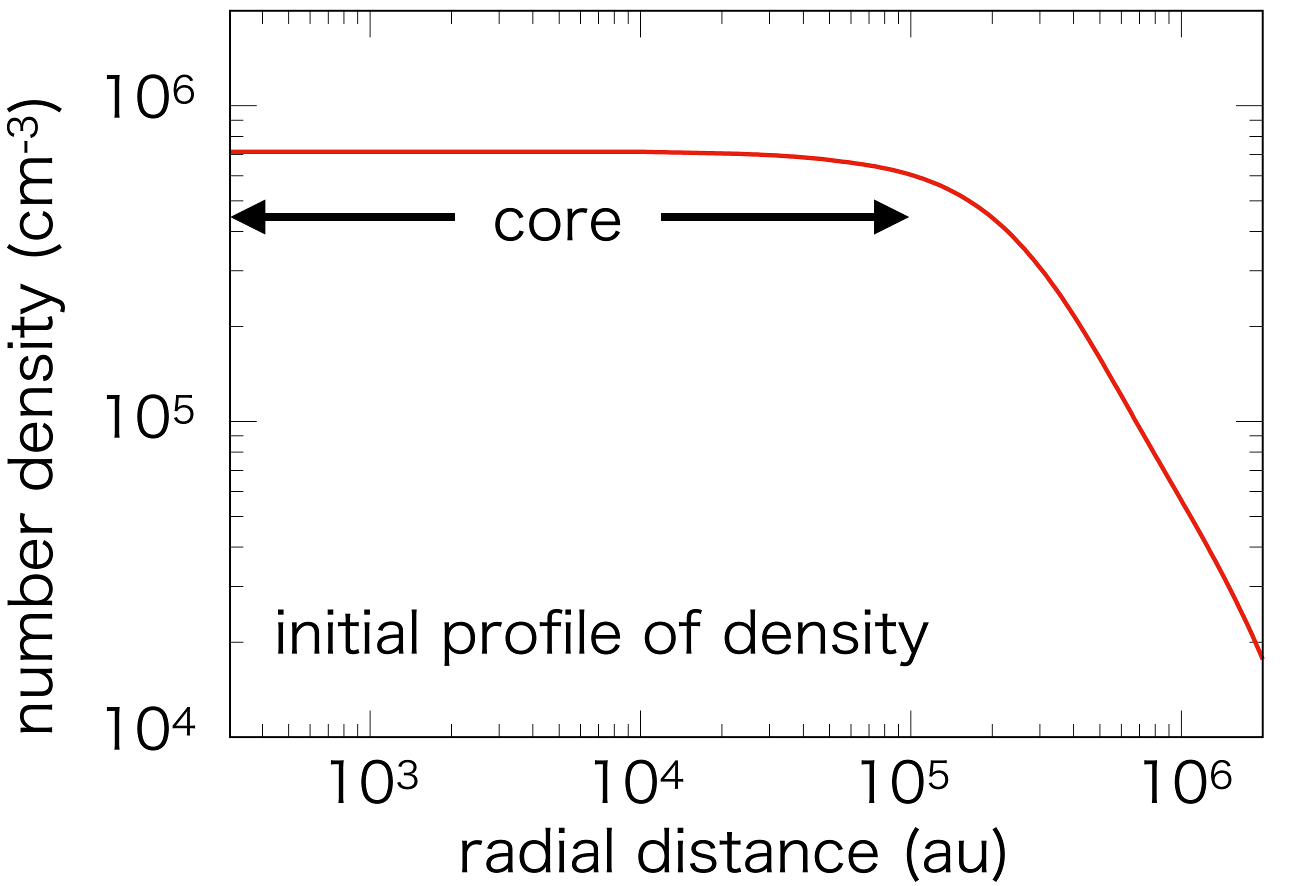
  α=0.24 (Fil), α=0.30 (Sph)

- (rotation energy) / (grav. energy)

  $\beta = 2.5 \times 10^{-2}$ (Fil), $\beta = 3.6 \times 10^{-2}$ (Sph)

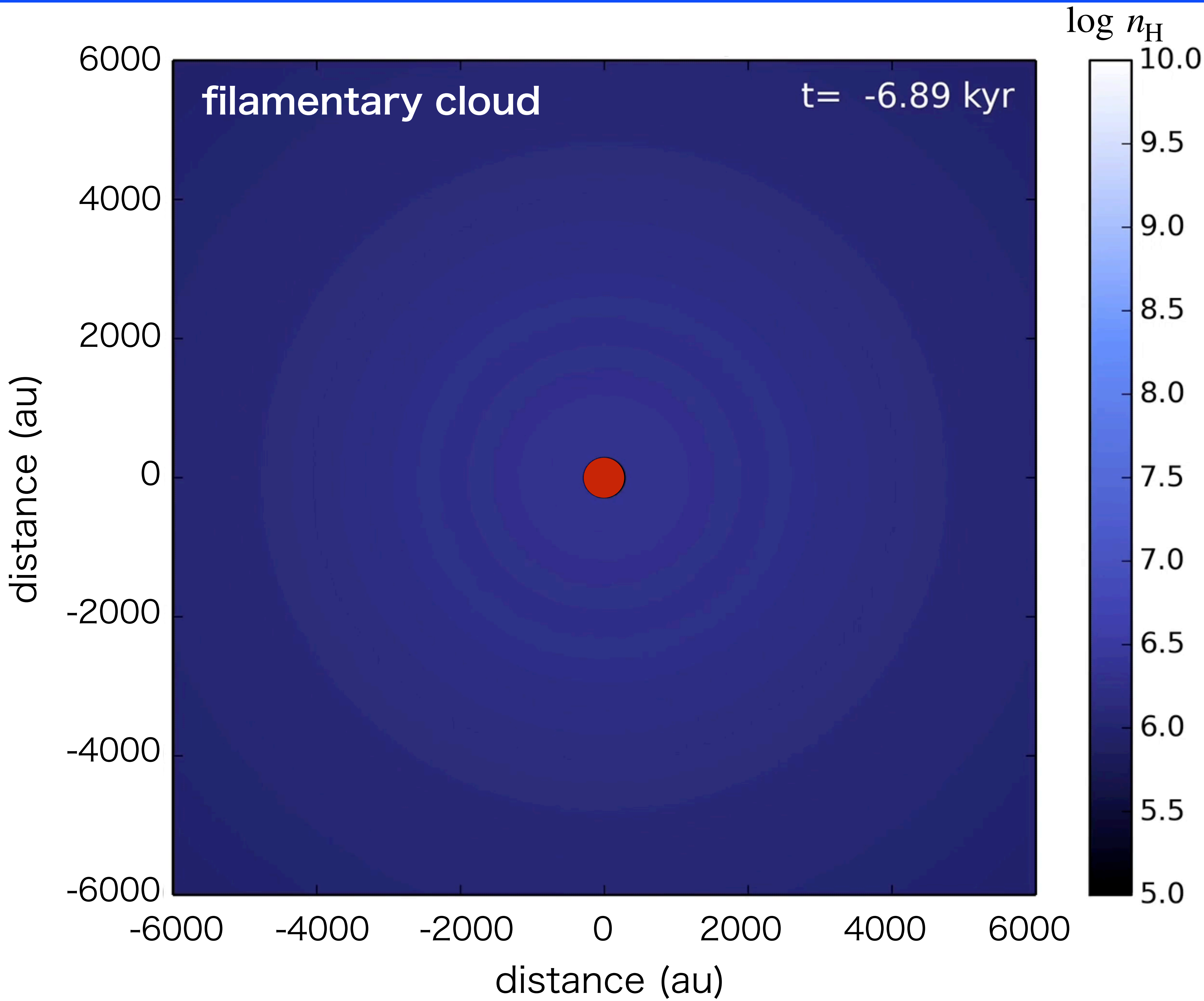


Chon et al. (2018)

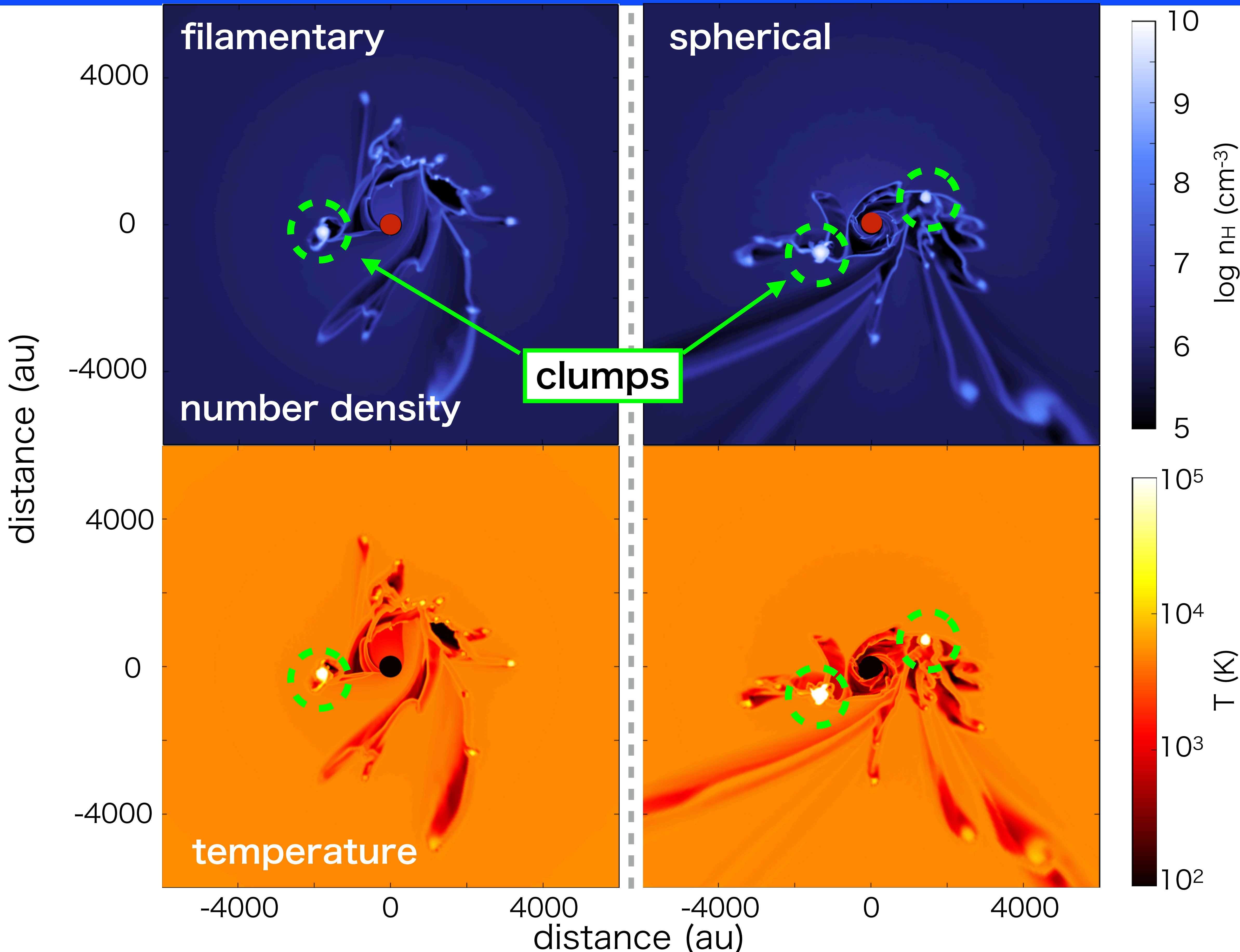


3. Result

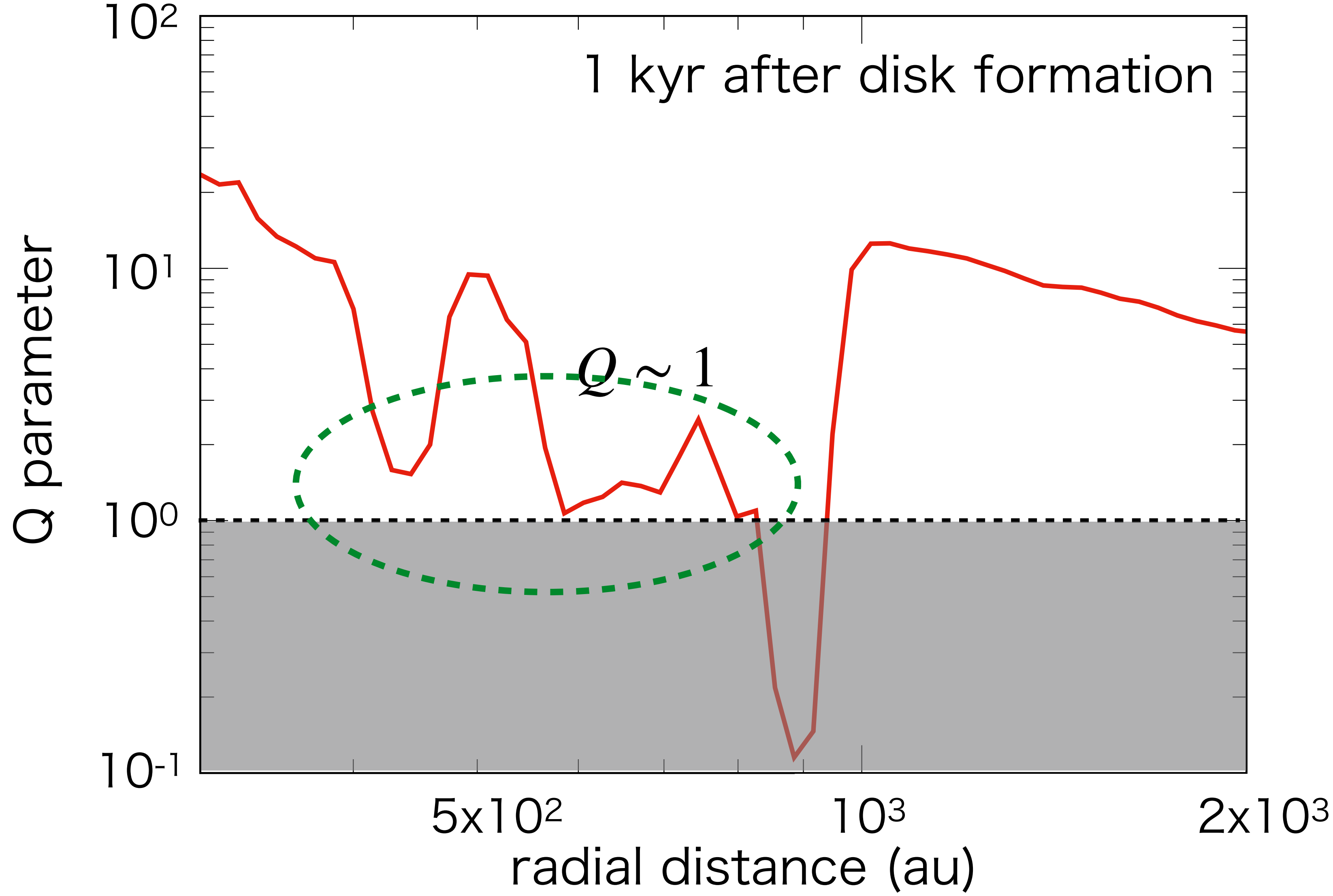
Time evolution of gas density



Spatial distributions



Gravitational instability of the disk



Toomre Q parameter

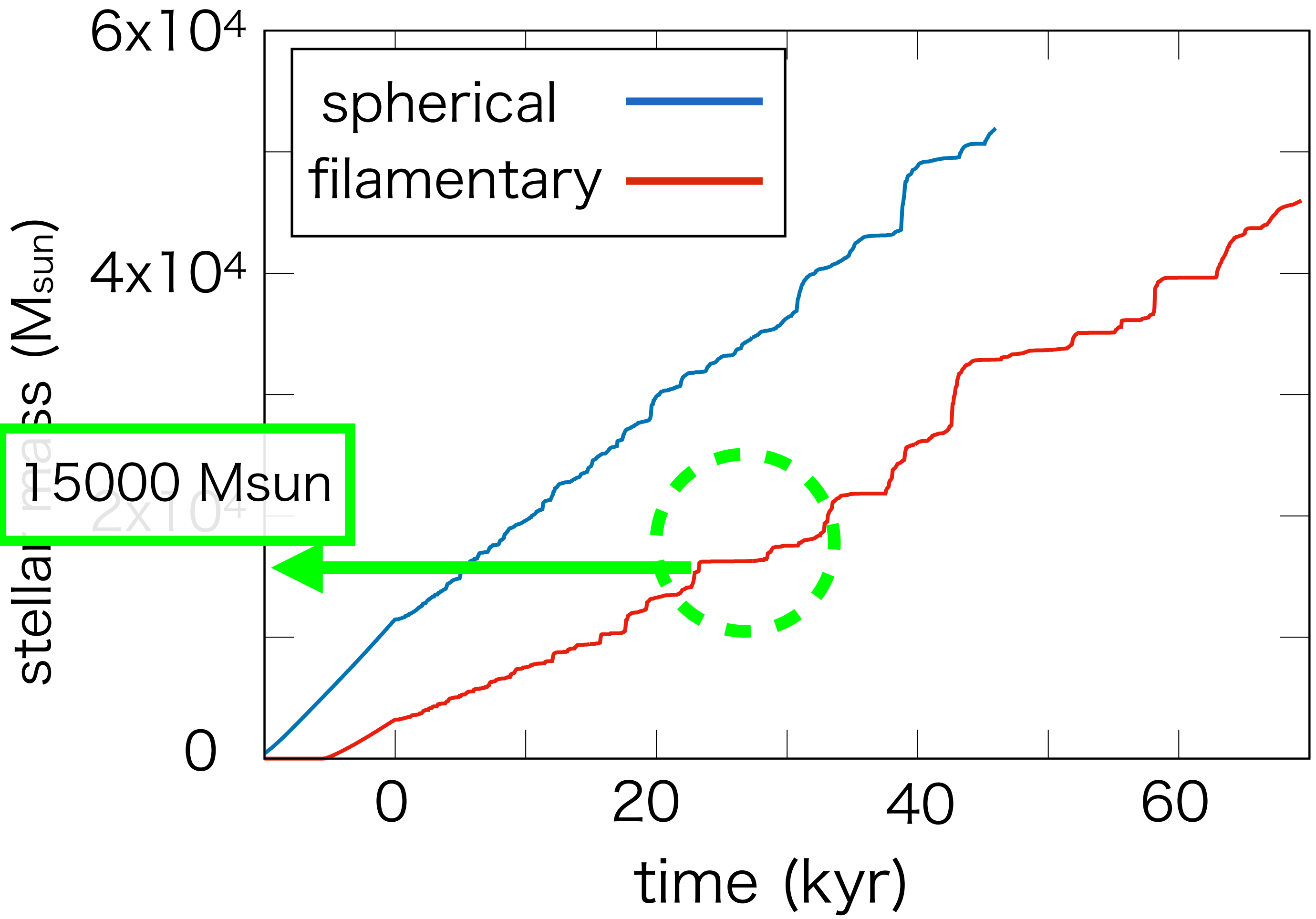
$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$ (> 1 stable, < 1 unstable)

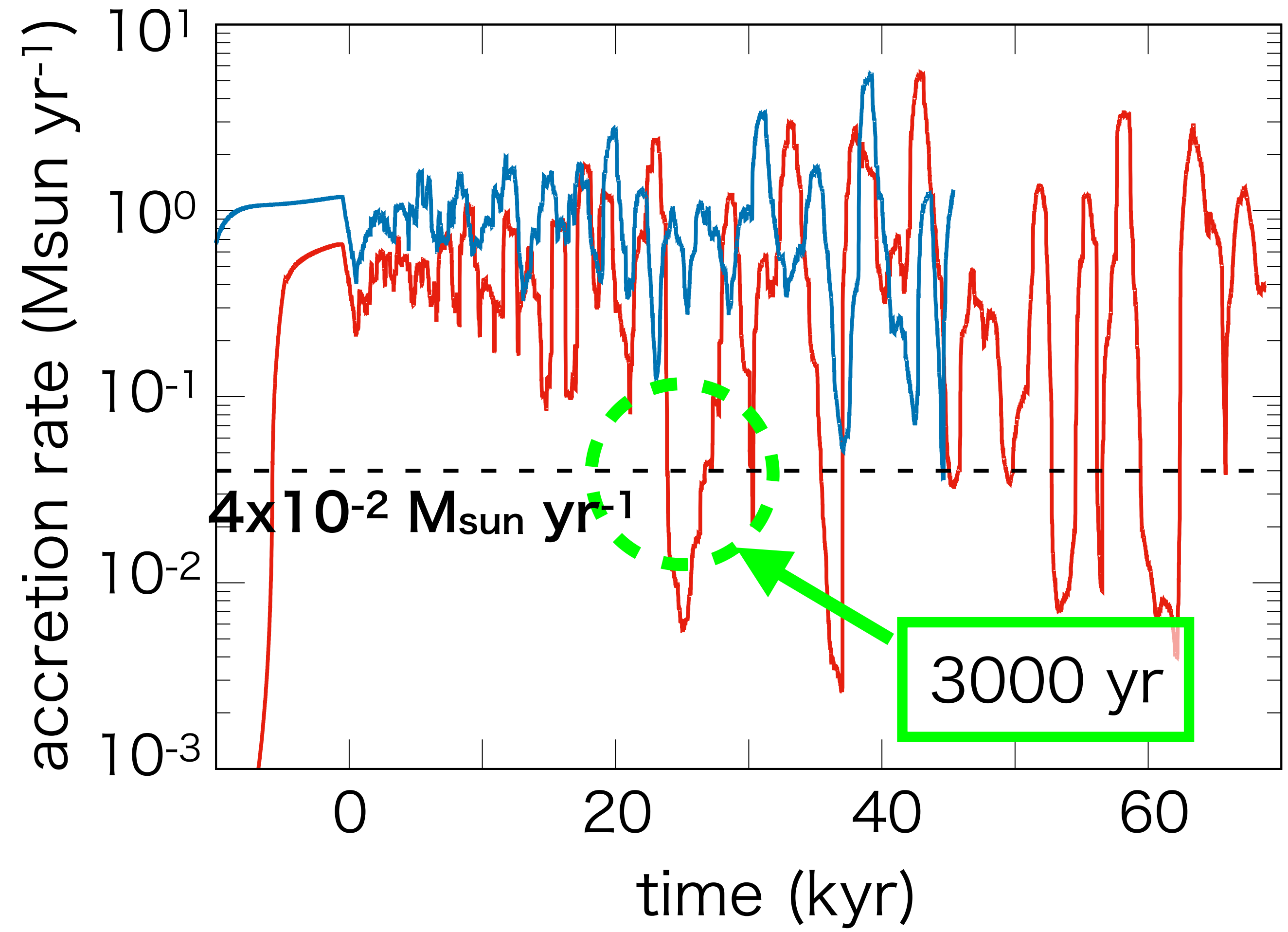
Q~1 at 400 au < r < 800au

➡ Spiral arms and fragments are formed by gravitational instability.

4. Summary and discussion

Time evolution of accretion rate





spherical : Accretion rate is always greater than the critical value M_{crit}.

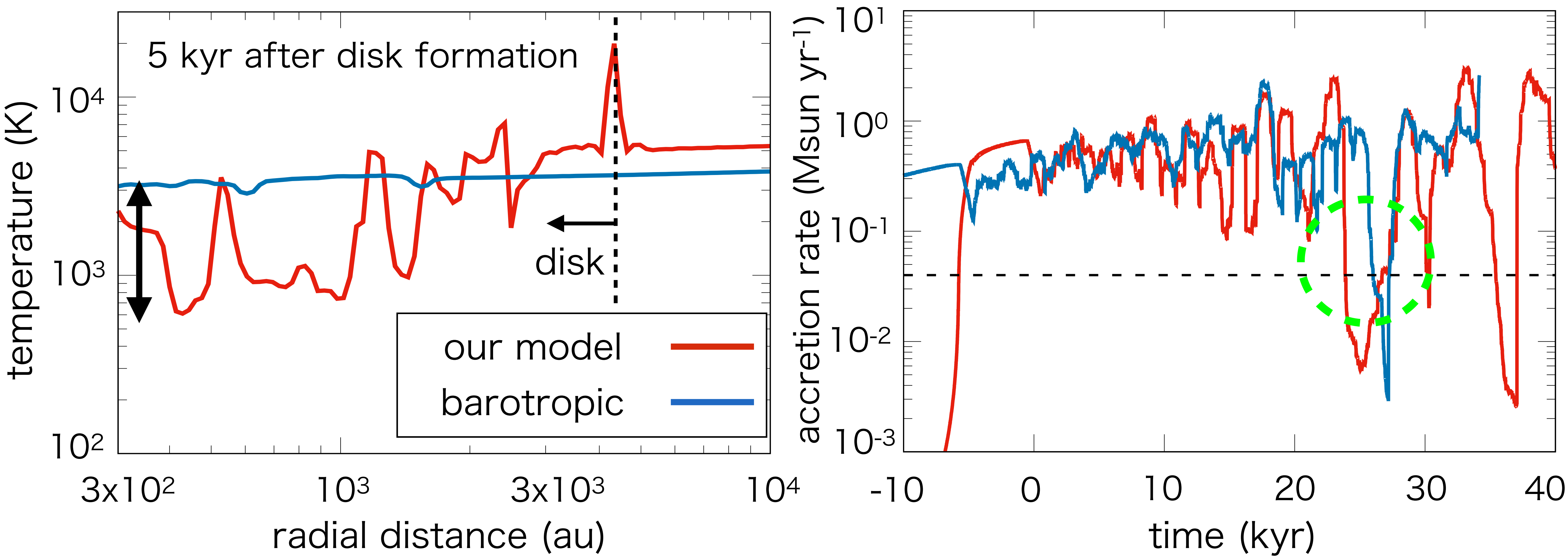
filamentary : **Accretion rate becomes less than M_{crit}.**

Surface KH time $t_{\rm KH,surf} \sim 10^3 \ {\rm yr} \left(\dfrac{M_*}{500 \ {\rm M}_\odot} \right)^{1/2}$ Sakurai+15

→ $t_{\rm KH,surf} = 6300 \ {\rm yr}$ when 15000 M_{sun}

Ionization feedback may affect stellar evolution.

Difference from the barotropic model



The temperature at the disk is lower than in the case of barotropic.

→ **More gravitationally unstable**

→ The time variation of accretion rate becomes strenuous due to the disk fragmentation.

↳ **More difficult to form SMS**

Summary

We followed the SMS formation process using hydrodynamical simulation with detailed thermal and chemical treatments.

✔ The formed disks are gravitationally unstable.

✔ Spherical : The accretion rate is always greater than the critical value.

Filamentary : The accretion rate becomes less than M_{crit} for 3000 yr.

➡ Ionization feedback may affect the stellar evolution.

How massive can formed seed black holes be?

Future work

✔ We should consider the stellar evolution and the effect of ionization.

✔ What about other initial conditions?