初代星・初代銀河研究会

星周円盤の自己重力不安定性

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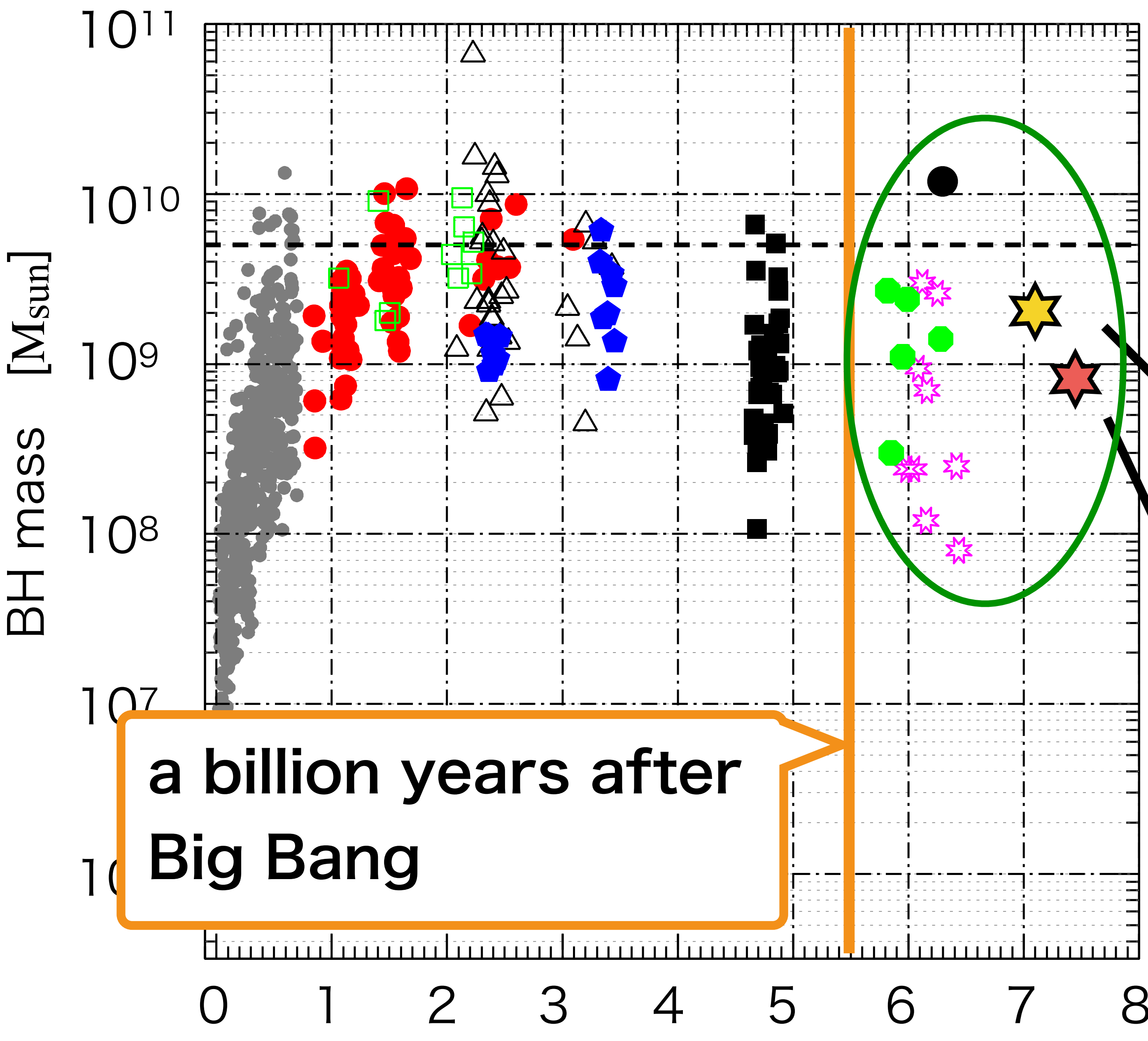
outline

1. Introduction
    - SMBH formation scenario
    - gravitational stability of the disk
2. Model
3. Result
4. Summary

1. Introduction

Supermassive Black Hole(SMBH)



a billion years after Big Bang

Marziani et al. (2012)

high-z SMBHs

dozens of quasars

with ~ $10^{8\text{-}9}$ M_{sun} at z > 6.5

$z = 7.09,\ 2\times10^{9}\ M_{sun}$

Mortlock et al. (2011)

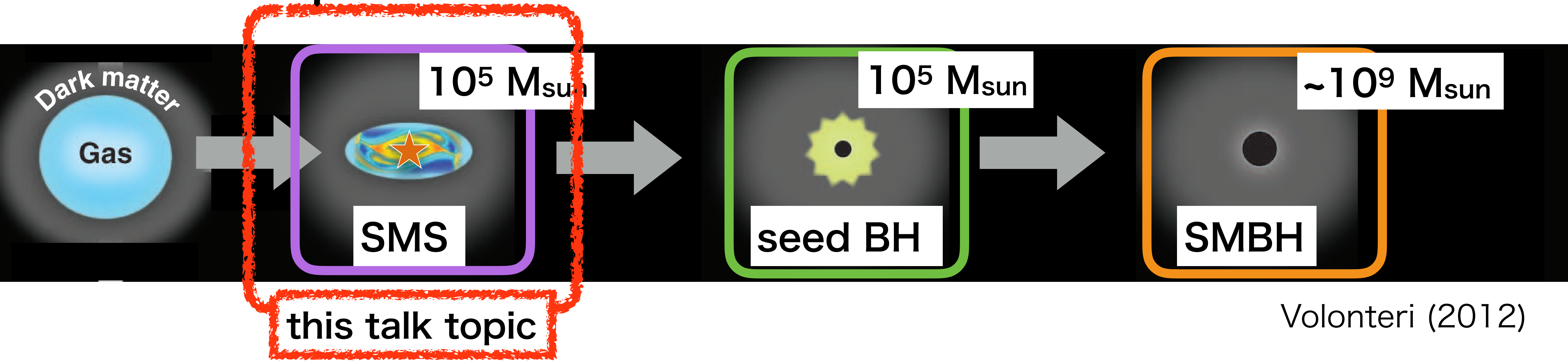
$z = 7.54,\ 8\times10^{8}\ M_{sun}$

Bañados et al. (2017)

⇨ How were SMBHs formed in such a short time?

SMBH formation scenario

Direct collapse scenario



Dark matter

Gas

10^5 M_{sun}

SMS

10^5 M_{sun}

seed BH

~10^9 M_{sun}

SMBH

this talk topic

Volonteri (2012)

- ✔ Supermassive star (SMS) with 10^5 M_{sun} is formed
- ✔ SMS collapse into a BH with a similar mass by GR effect
- ✔ A seed BH grows by accretion and/or merger

thermal evolution

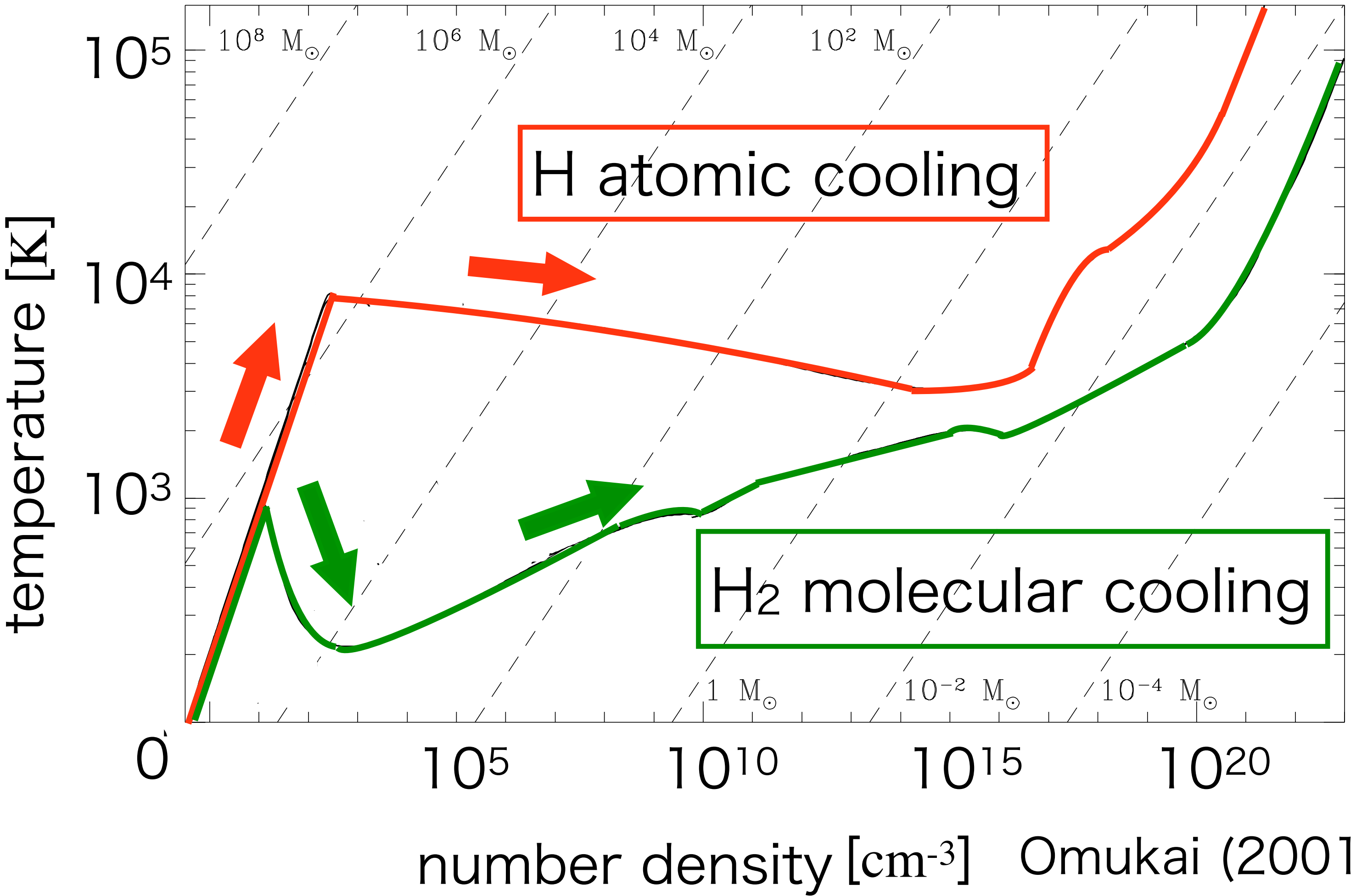
H_2 formation is suppressed by external far-UV radiation

- photodissociation

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

- photodetachment

$$\mathrm{H^-} + \gamma \rightarrow \mathrm{H} + \mathrm{e}$$



Omukai (2001)

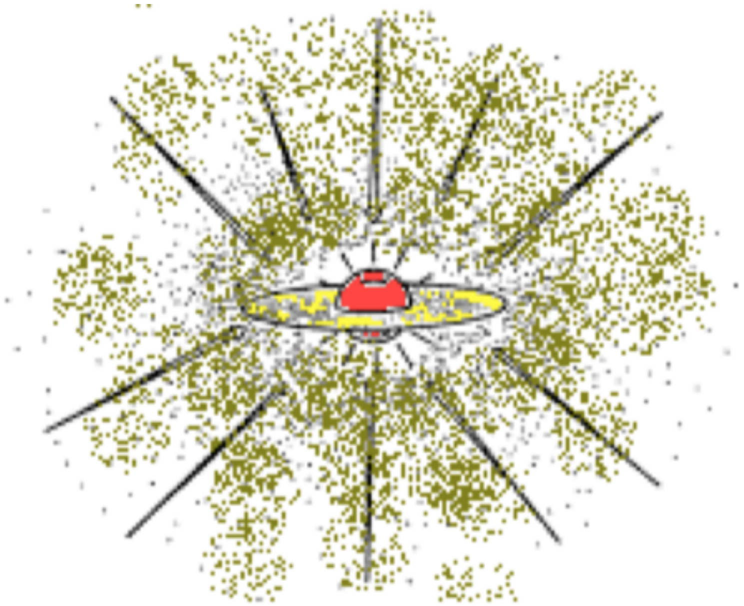
H atomic cooling gas (**red line**)

⇨ isothermal evolution ~ 10^4 K

without experiencing vigorous fragmentation

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

mass accretion onto the protostar



typical accretion rate ~ 0.1 M_{sun} yr^{-1} very high rate

⇨ The disk may fragment by gravitational instability

The accretion rate has time variation

⇨ The evolution and final mass of SMS are affected

Sakurai et al. (2015)

Does the disk fragmentation occur?

previous study

Latif & Schleicher (2015) ,   Inayoshi & Haiman (2014)

studied the gravitational stability of circum-stellar disks

without chemical evolution

Toomre's Q value

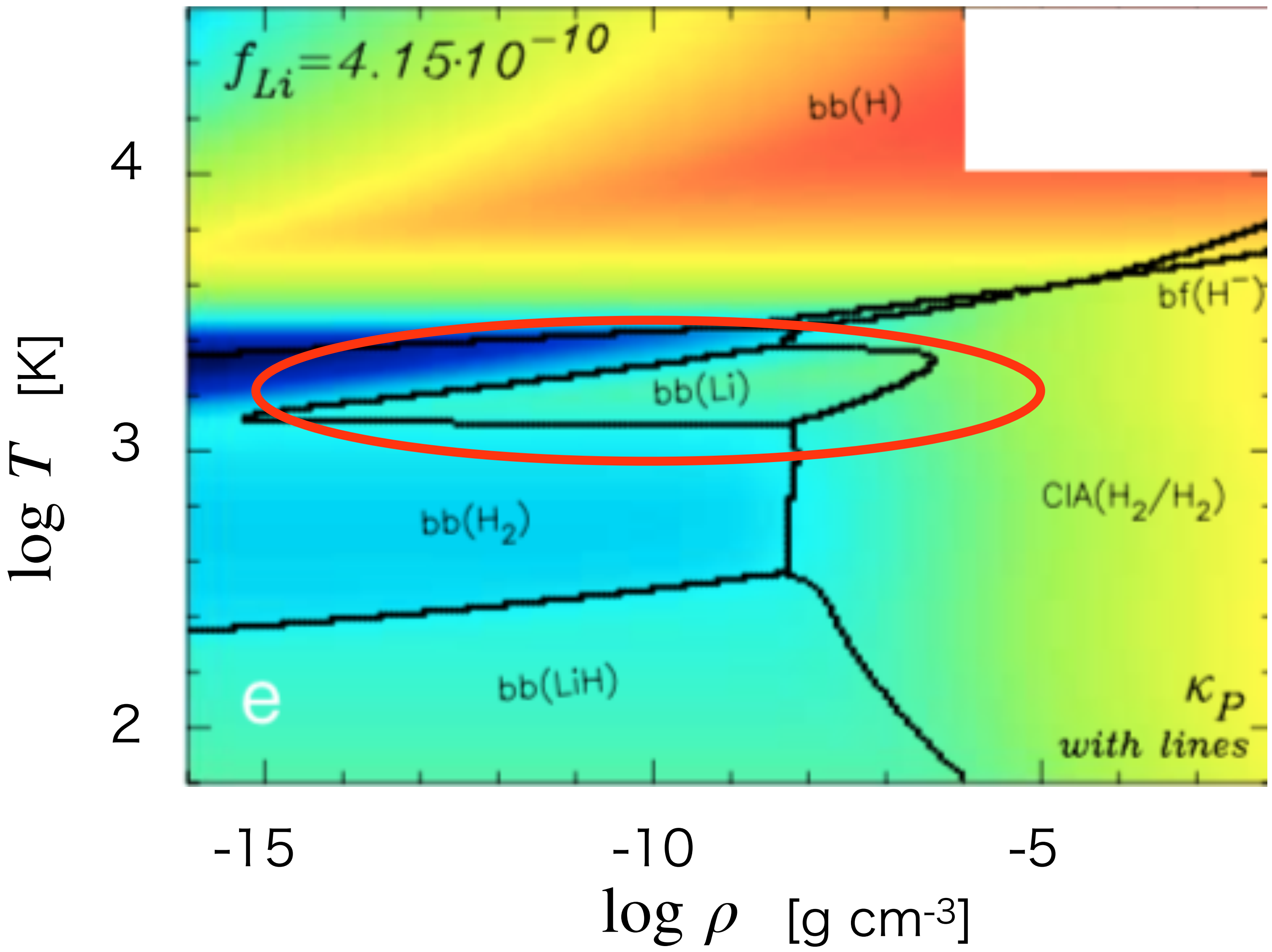
$$Q = \frac{\overset{\propto T^{1/2}}{\boxed{c_s}}\Omega}{\pi G \Sigma} \qquad \left(\begin{array}{ll} Q > 1 & : \text{ stable} \\ Q < 1 & : \text{ unstable} \end{array} \right.$$

Toomre (1964)

depends on the temperature

⇨ The thermal and chemical evolutions are important

Li bound-bound transition



Mayer & Dushl (2005)

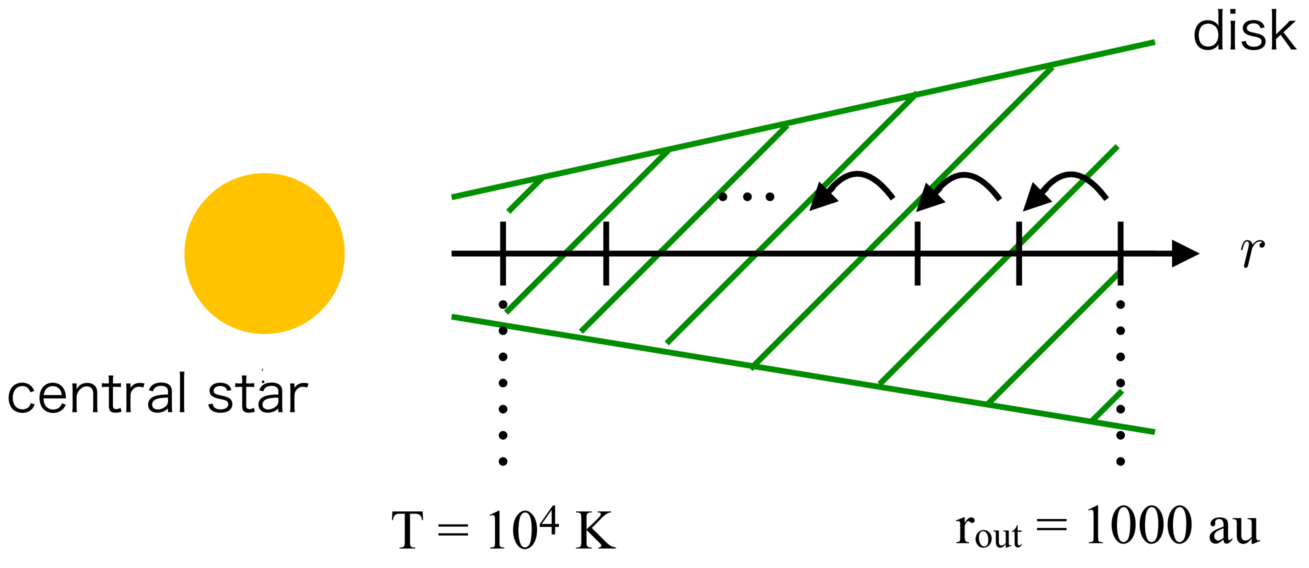
⇨ Li bound-bound transition becomes dominant opacity source

$$1000 < T\ [\mathrm{K}] < 3000\ ,\ 10^{-15} < \rho\ [\mathrm{g\ cm^{-3}}] < 10^{-7}$$

2. Model

model

one-dimensional axisymmetric and steady accretion disk



parameters

$M_\star$: stellar mass

$\dot{M}$: accretion rate

✔ Keplerian rotation

✔ We set $Q = \frac{c_s \Omega}{\pi G \Sigma} = 1$ ⇨ we obtain the density structure

✔ thermal evolution $\frac{\mathrm{d}e}{\mathrm{d}t} = \Gamma - \Lambda$

heating : viscous heating , compressional heating

cooling : H_2 line emission , Li line emission, H^- free-bound emission ,

H_2 CIE , chemical cooling

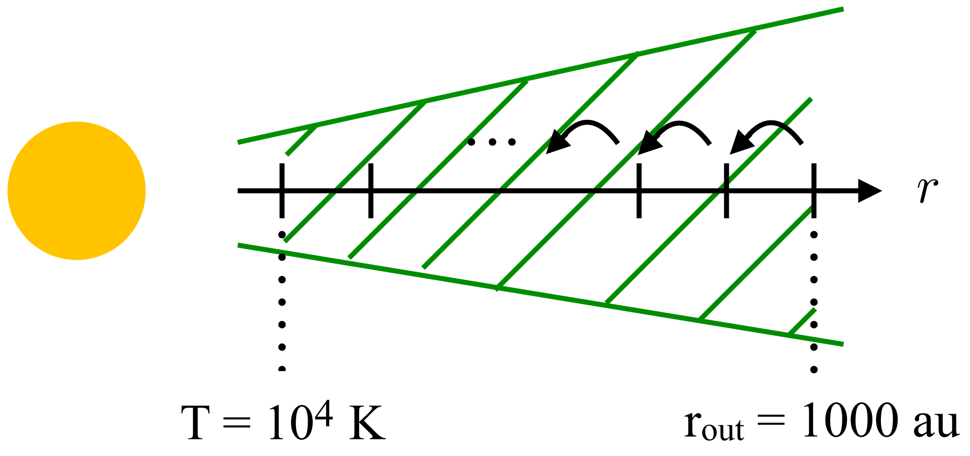
✔ chemical evolution H, H_2, H^+, H^-, e

fragmentation condition and model setup

✔ fragmentation condition

α viscosity Shakura & Sunyaev, (1973)

$$\alpha = \frac{\nu\Omega}{c_s^2} > 1$$ Zhu et al. (2012)



✔ parameter ranges

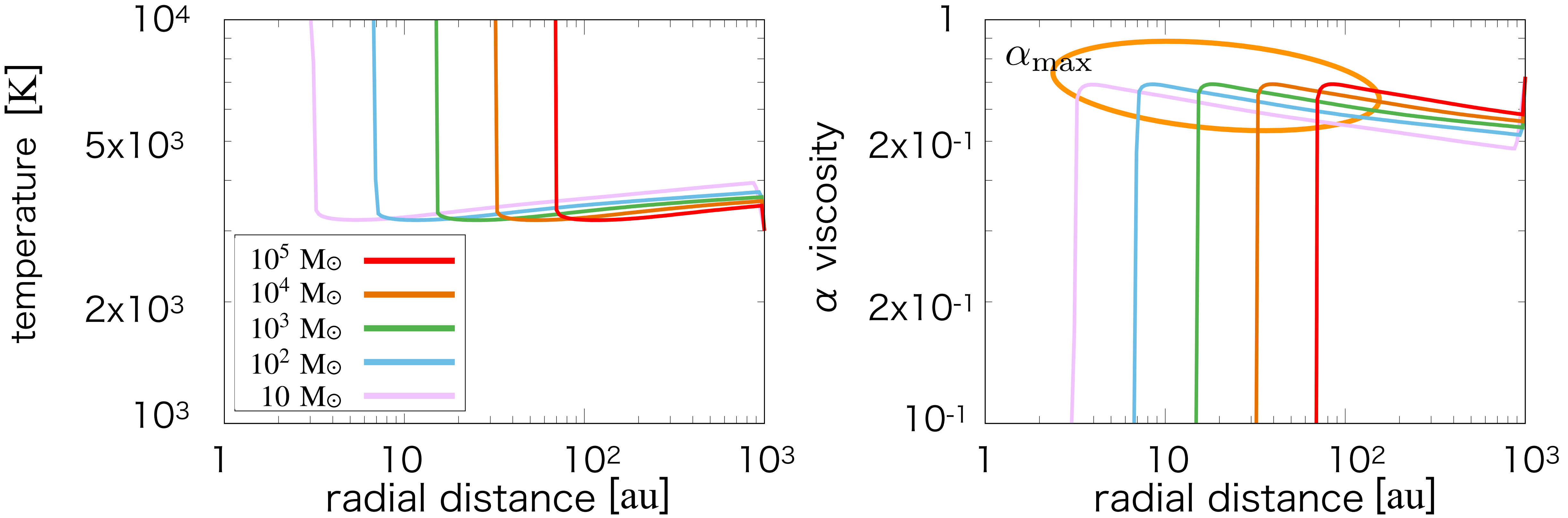
- stellar mass : 10 - 10^5 M_{sun}
- accretion rate : 10^{-3} - 1 M_{sun} yr^{-1}

✔ outer boundary temperature and chemical abundance $\left(y(\mathrm{i}) = \dfrac{n(\mathrm{i})}{n_H}\right)$

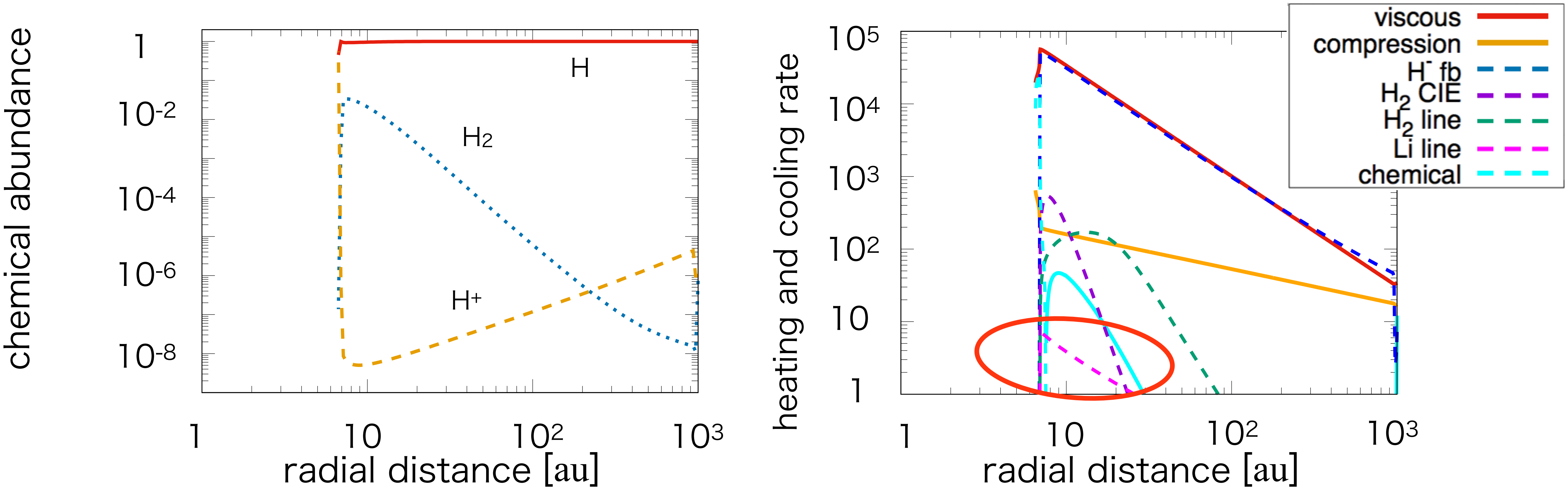
T [K]	H	H_2	H^+, e	H^-	He
3000 K	0.99	10^{-8}	10^{-6}	10^{-18}	8.33×10^{-2}

3. Result

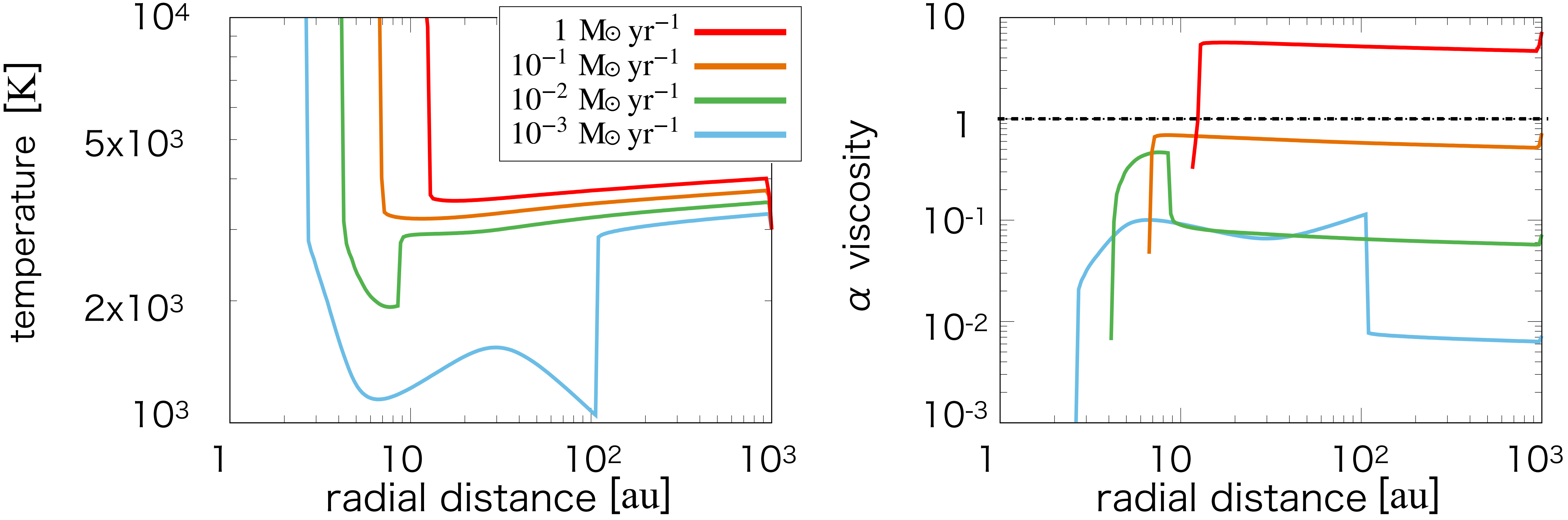
stellar mass dependency



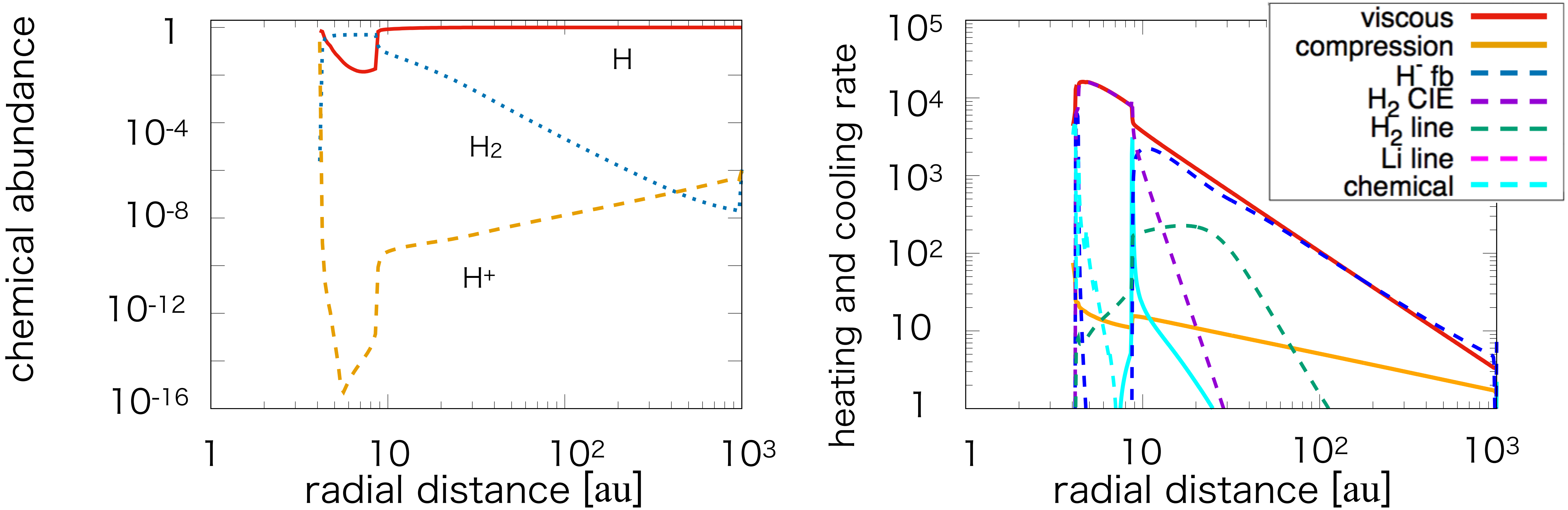
stellar mass : 10^2 $M_{\rm sun}$, accretion rate : 10^{-1} $M_{\rm sun}$ yr^{-1}



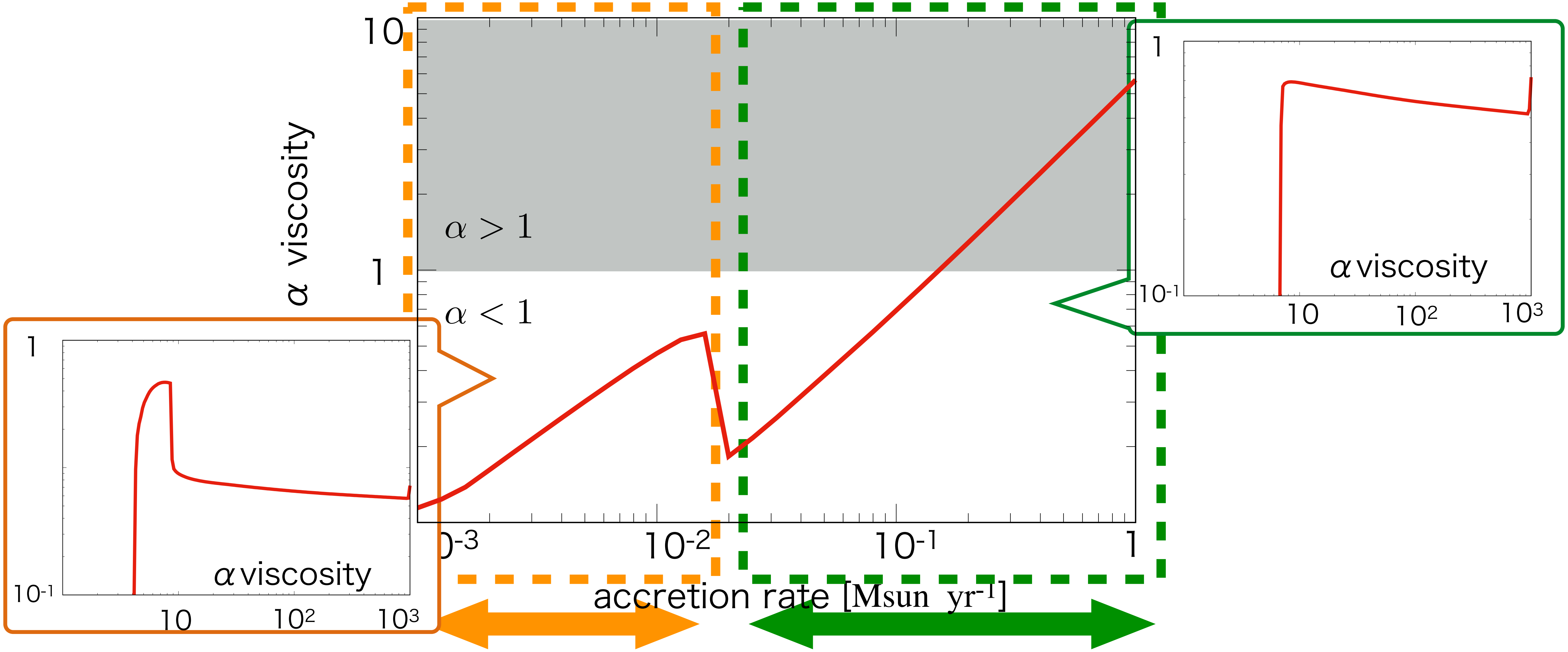
accretion rate dependency



stellar mass : 10^2 M_{sun} , accretion rate : 10^{-2} M_{sun} yr^{-1}

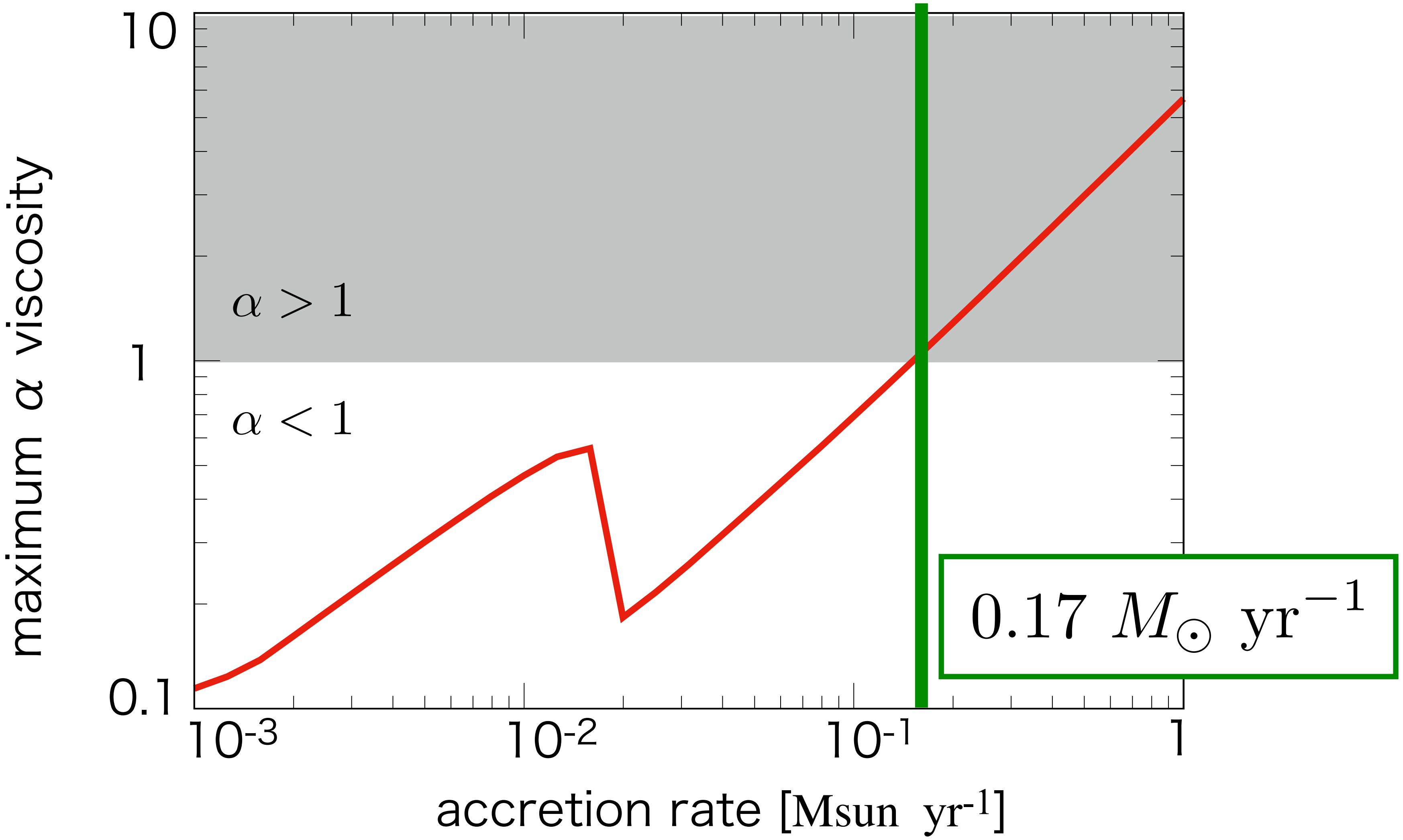


accretion rate dependency of the maximum α value



⇨ **If $\dot{M} > 0.1\ M_\odot\ \mathrm{yr}^{-1}$, the disk fragments by gravitational instability.**

critical accretion rate



$$\alpha = \frac{\nu\Omega}{c_s^2}\ , \nu = \frac{\dot{M}}{3\pi\Sigma}\ , Q = \frac{c_s\Omega}{\pi G\Sigma} = 1 \quad \Rightarrow \quad \dot{M} = \frac{3}{G}c_s^3\alpha$$

critical accretion rate at $\alpha = 1$

$$\dot{M}_{\mathrm{crit}} = 0.17\ M_\odot\ \mathrm{yr}^{-1}\left(\frac{T}{3500\ \mathrm{K}}\right)^{3/2}$$

Li bound-bound emission

Li bound-bound emission does not work as the dominant cooling source

Mayer & Dushl (2005) assumed LTE

critical density

$n_{crit}(e) > 10^{10}$ cm^{-3}

our results

⇨ outer region: n(e) is several order of magnitude

below the critical density

inner region: n(e) increases,

but the continuum optical depth exceeds unity.

Li line cooling rate is generally less than the LTE rate.

Summary

- We investigate the gravitational stability of the disk around the supermassive star with detailed treatment of chemical and thermal processes.

- result

The disk stability depends on only the accretion rate.

$\dot{M} < 0.1\ \mathrm{M_{SUN}\ yr^{-1}}$ ⇨ NOT fragment

$\dot{M} > 0.1\ \mathrm{M_{SUN}\ yr^{-1}}$ ⇨ fragment

If $\dot{M} < 10^{-2}\ \mathrm{M_{sun}\ yr^{-1}}$, H_2 molecular is formed in the inner region.

Li bound-bound emission cooling does not change

the thermal evolution of the disk.