超巨大BHの形成とその進化

東北大学　鄭 昇明

Image by NASA

outline

I. Introduction

II. Formation of Super Massive Stars (SMSs)
   - formation of protostars (collapse phase)
   - evolution of protostars (accretion phase)

III. Evolution of seed BHs to SMBHs

outline

I. Introduction

II. Formation of Super Massive Stars (SMSs)

So many studies!
Let me summarize them.

- formation of protostars (collapse phase)
- evolution of protostars (accretion phase)

I. Evolution of seed BHs to SMBHs

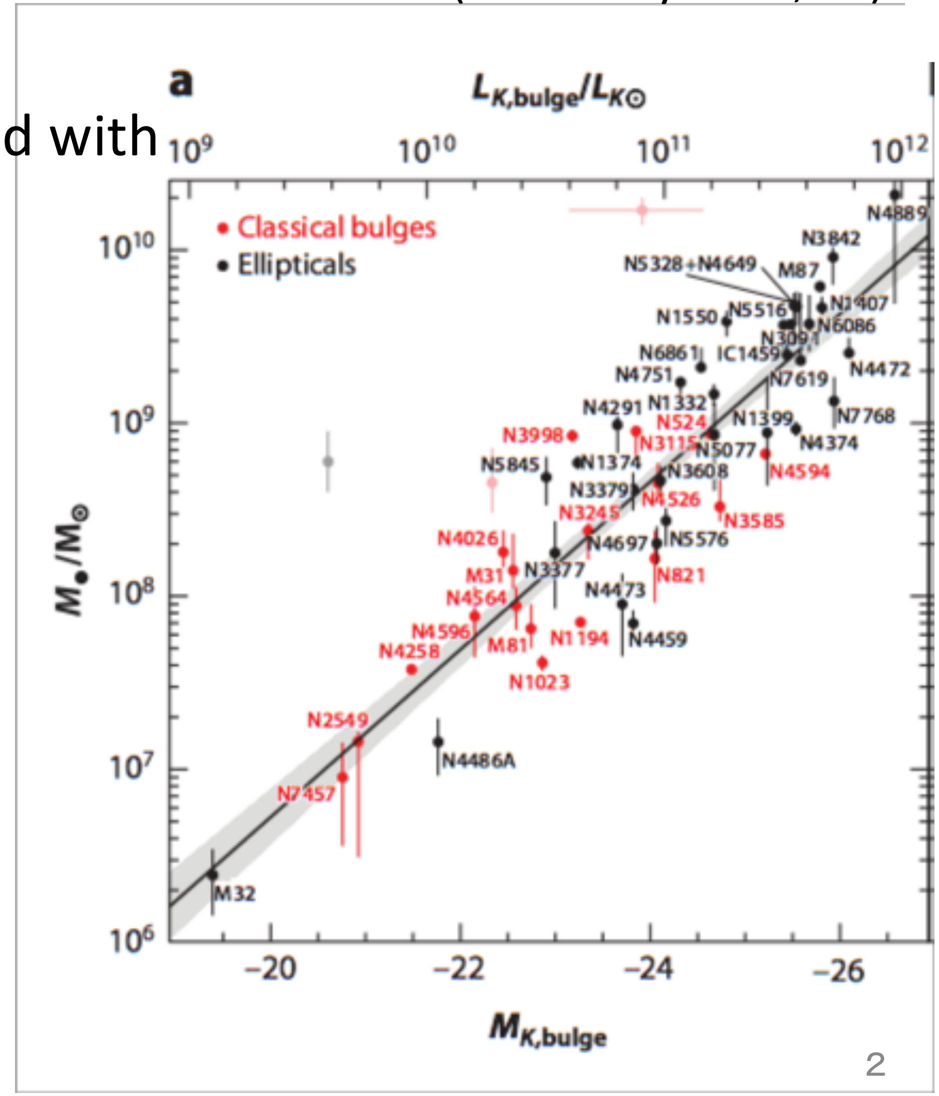
Super Massive Black Holes (SMBHs)

Super Massive Black Hole (SMBH)

- ✓ $10^6 - 10^{10}\ M_\odot$
- ✓ Reside at the galaxy center
- ✓ Their mass is strongly correlated with the host galaxy properties .
  (bulge mass, luminosity…)

Image by NASA

(Kormendy & Ho, 13)

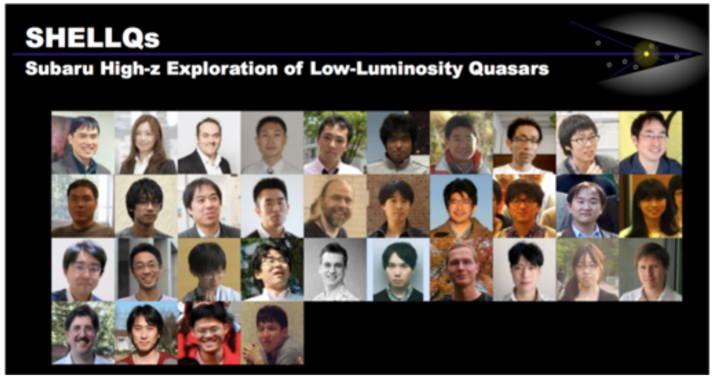


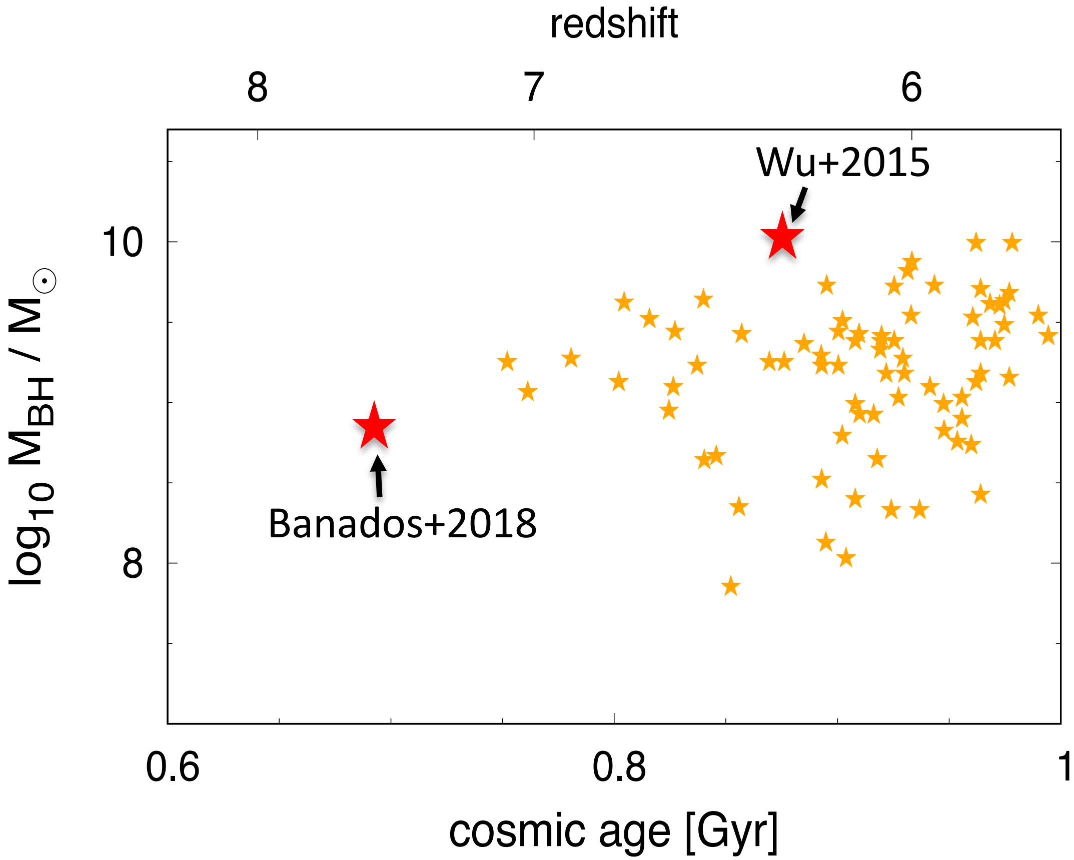
Super Massive Black Holes (SMBHs)

Many SMBHs reside at high-z universe (z > 6).

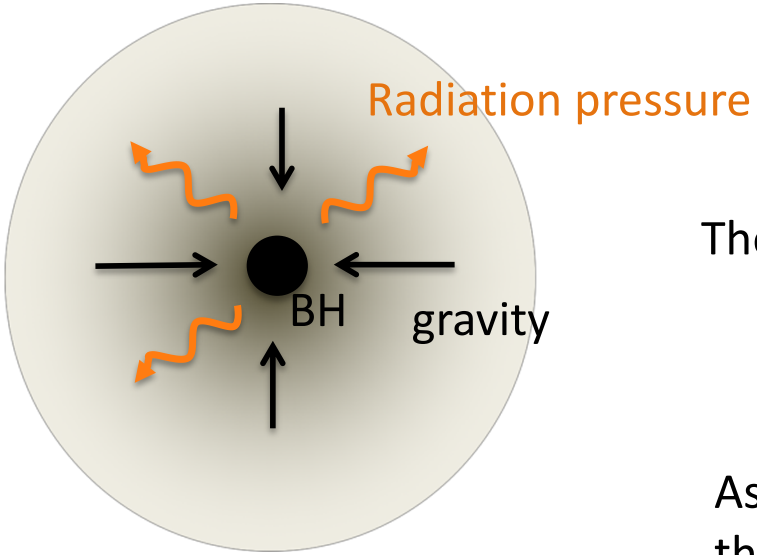
- ✓ observed as QSOs
- ✓ $10^9\, M_\odot$ at $z \sim 7.5$ (Banados+18)
- ✓ Number density ∼ a few/ Gpc^3
- ✓ More than 100 are found so far.

Other samples are found by SHELLQs





Eddington limit



When the radiation pressure balances with the gravity,

$$\sigma_{\rm Th} P_{\rm rad} = \frac{G M_{\rm BH} m_{\rm p}}{R^2}$$

Then, we can define the critical luminosity

$$L_{\rm Edd} = \frac{4\pi c G M_{\rm BH} m_{\rm p}}{\sigma_{\rm Th}}$$

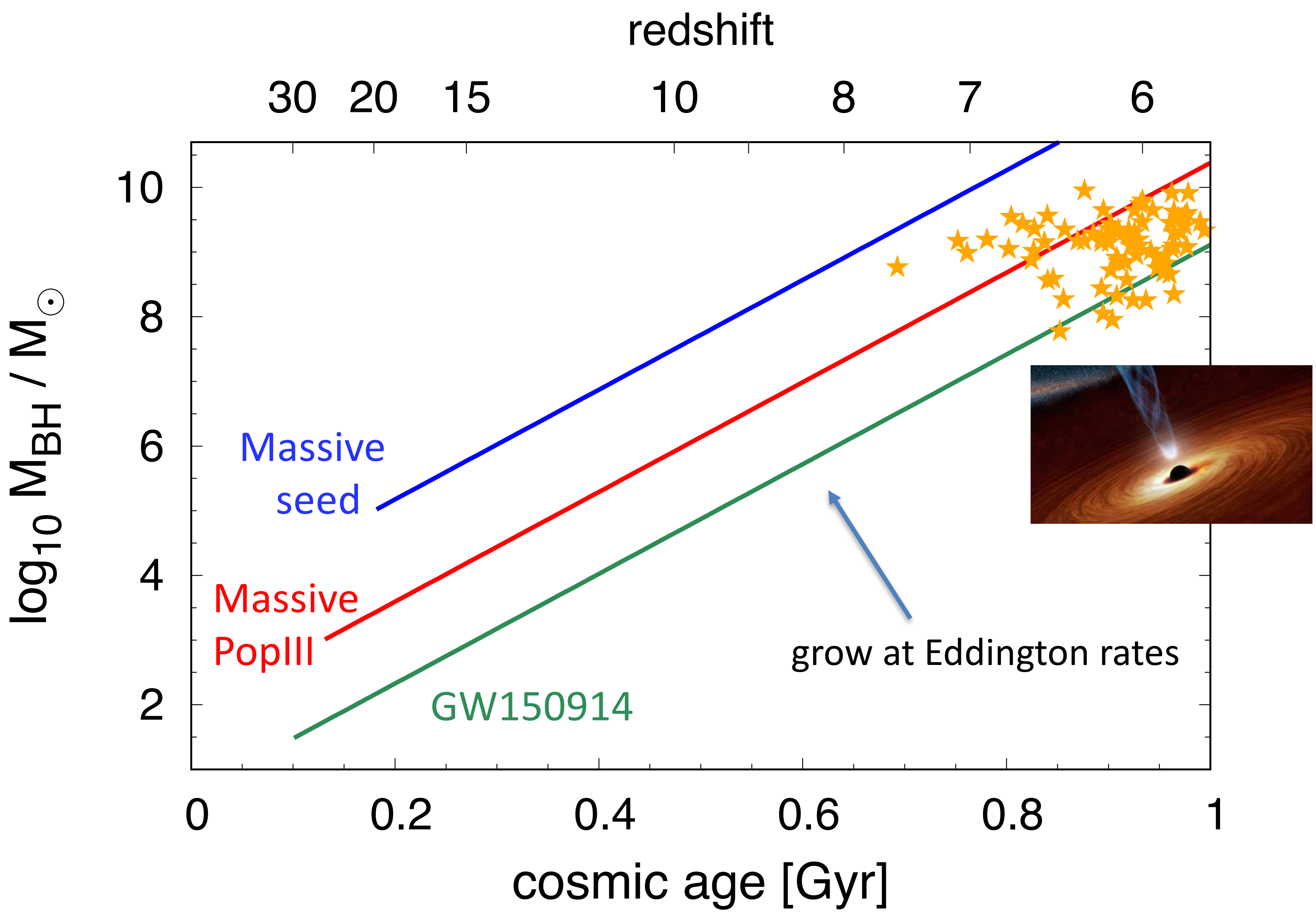
Assuming fraction ε of the energy of the accreting matter is liberated ($L = \varepsilon \dot{M} c^2$) 、

$$\dot{M}_{\rm Edd} = \frac{1-\epsilon}{\epsilon} \frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm Th} c} \propto M_{\rm BH}$$

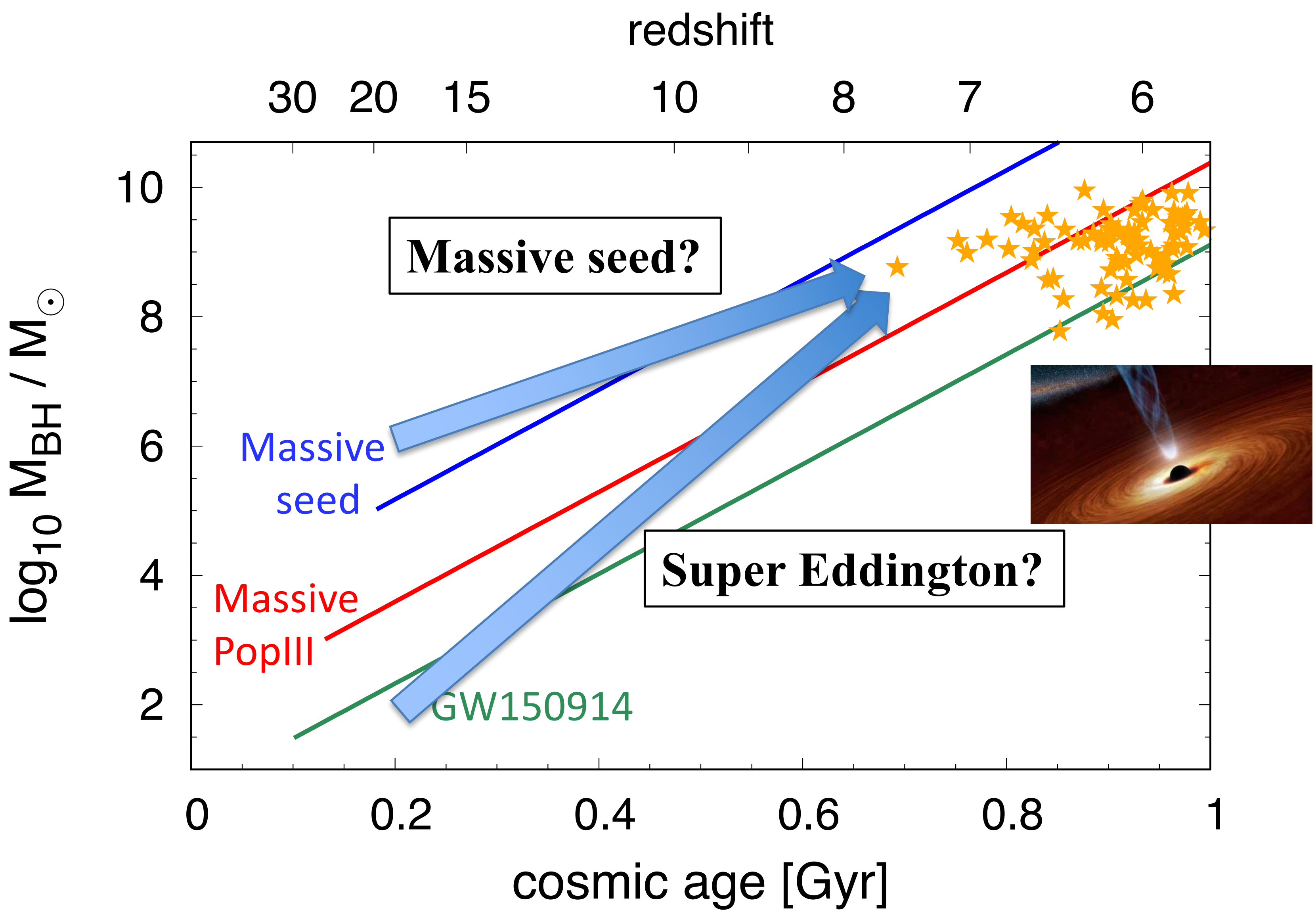
$$\frac{{\rm d}M_{\rm BH}}{{\rm d}t} = \dot{M}_{\rm Edd} \equiv \frac{M_{\rm BH}}{t_{\rm Sal}} \qquad \therefore M_{\rm BH} = M_{\rm ini} \exp(t/t_{\rm Sal})$$

$$t_{\rm Sal} = 52.5 \ {\rm Myr}$$

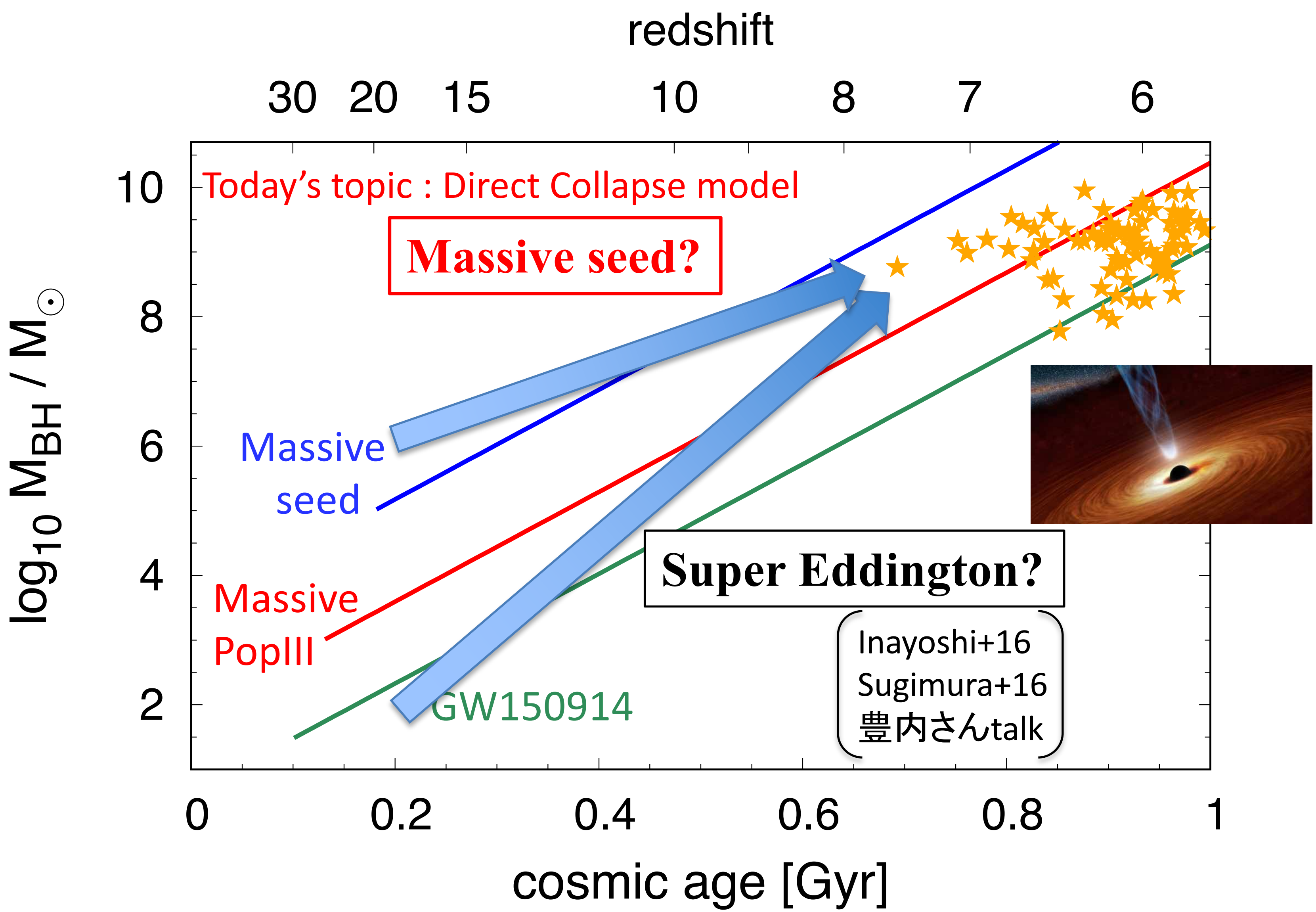
Super Massive Black Holes (SMBHs)



Super Massive Black Holes (SMBHs)

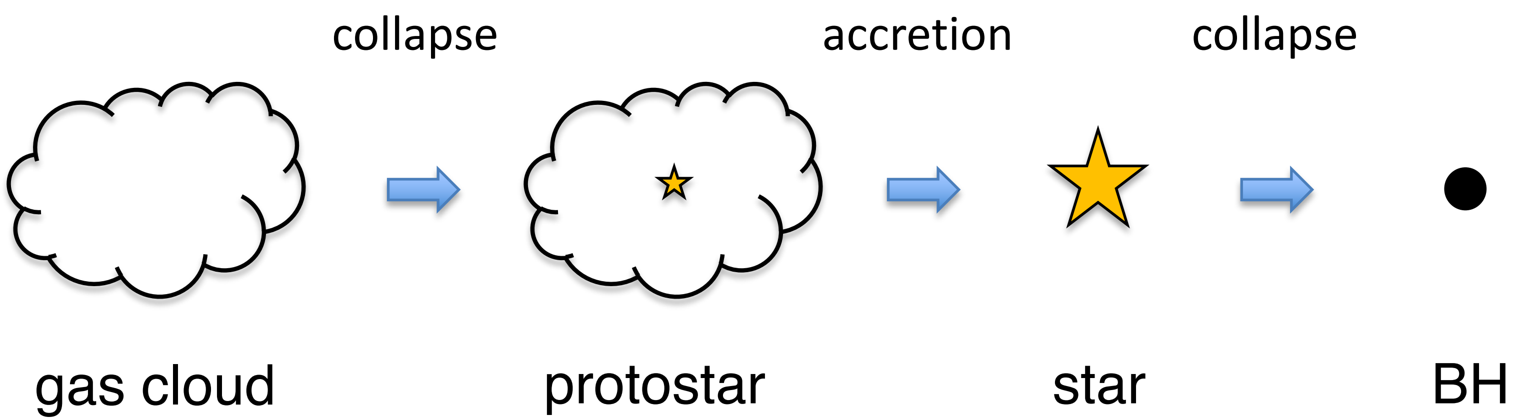


Super Massive Black Holes (SMBHs)



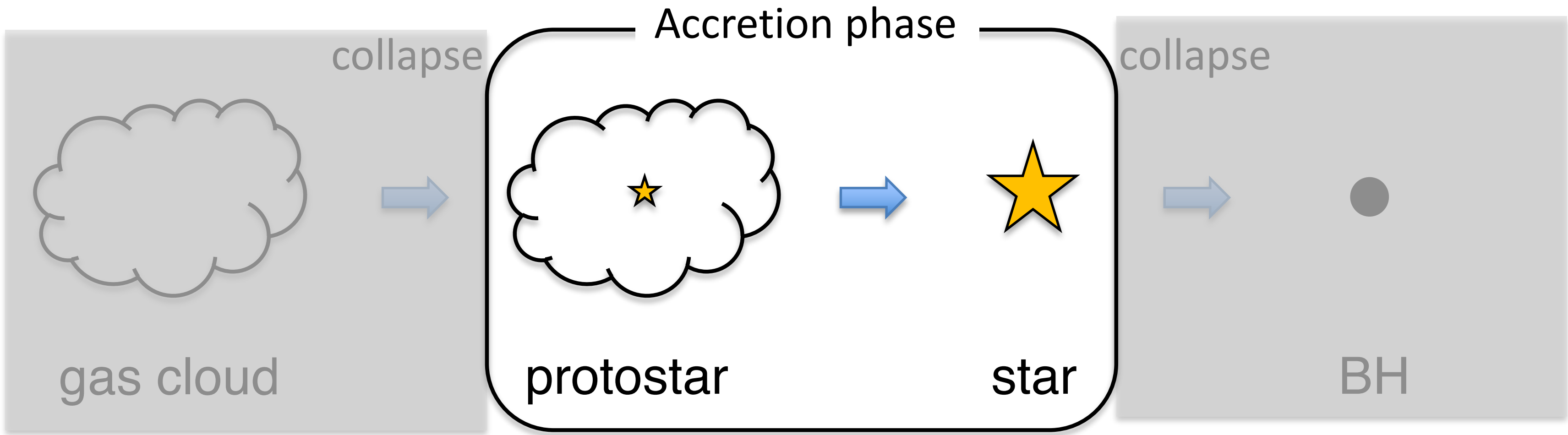
Massive Star Formation in the early universe

How massive the primordial stars can be?



Massive Star Formation in the early universe

How massive the primordial stars can be?



・Mass accretion rate onto the protostar

$$\dot{M} \sim M_{\rm J}/t_{\rm ff} \sim c_{\rm s}^3/G \propto T^{\frac{3}{2}}$$ (Larson 1969, Shu 1977 …)

➡ *The hotter the cloud is, the higher* $\dot{M}$ *and* M_*.

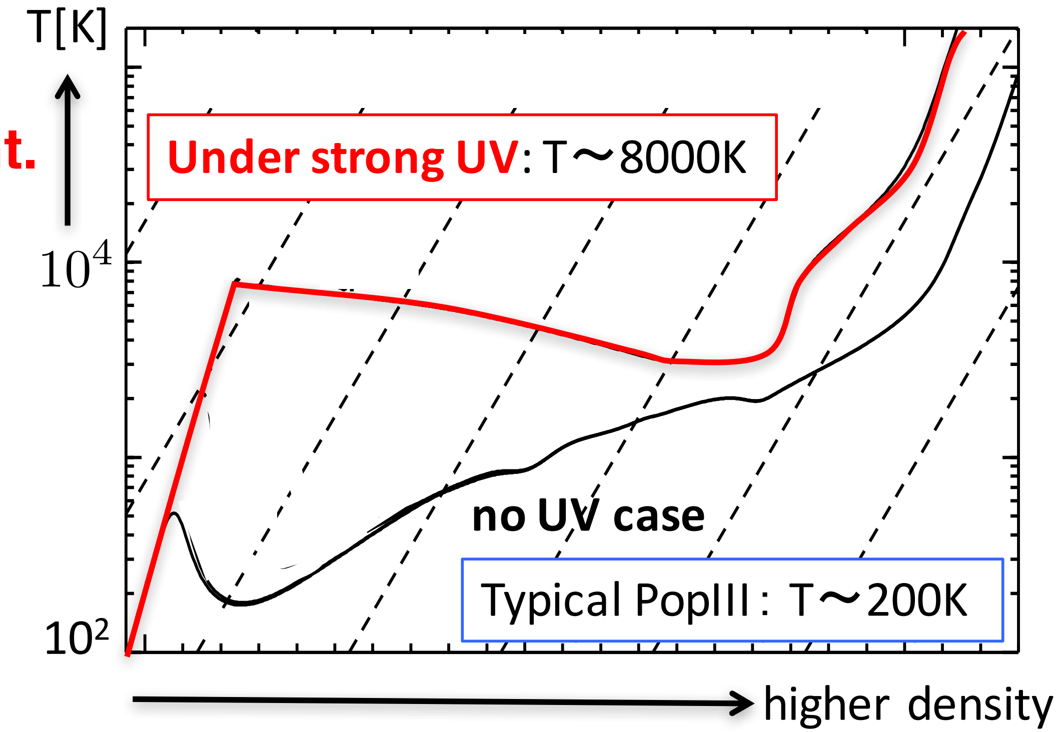
Super Massive Stars (SMSs)

- The temperature of the gas cloud
  ⇒ chemical composition、external radiation

- The cloud mainly cooled by **H_2 in the primordial environment.**

- **Strong radiation (Far-UV) dissociates H_2 and raises the gas temperature.**
  ⇒ $\dot{M} \sim 0.1 - 1\ M_\odot\ \mathrm{yr}^{-1}$
  ⇒ $M_* \sim 10^5\ M_\odot$

(Omukai 01)



Super Massive Stars (SMSs)

- The temperature of the gas cloud
  ⇒ chemical composition、external radiation

The region in which H_2 is dissociated by the collision with H

- The cloud mainly cooled by **H_2 in the primordial environment.**
- **Strong radiation (Far-UV) dissociates H_2 and raises the gas temperature.**

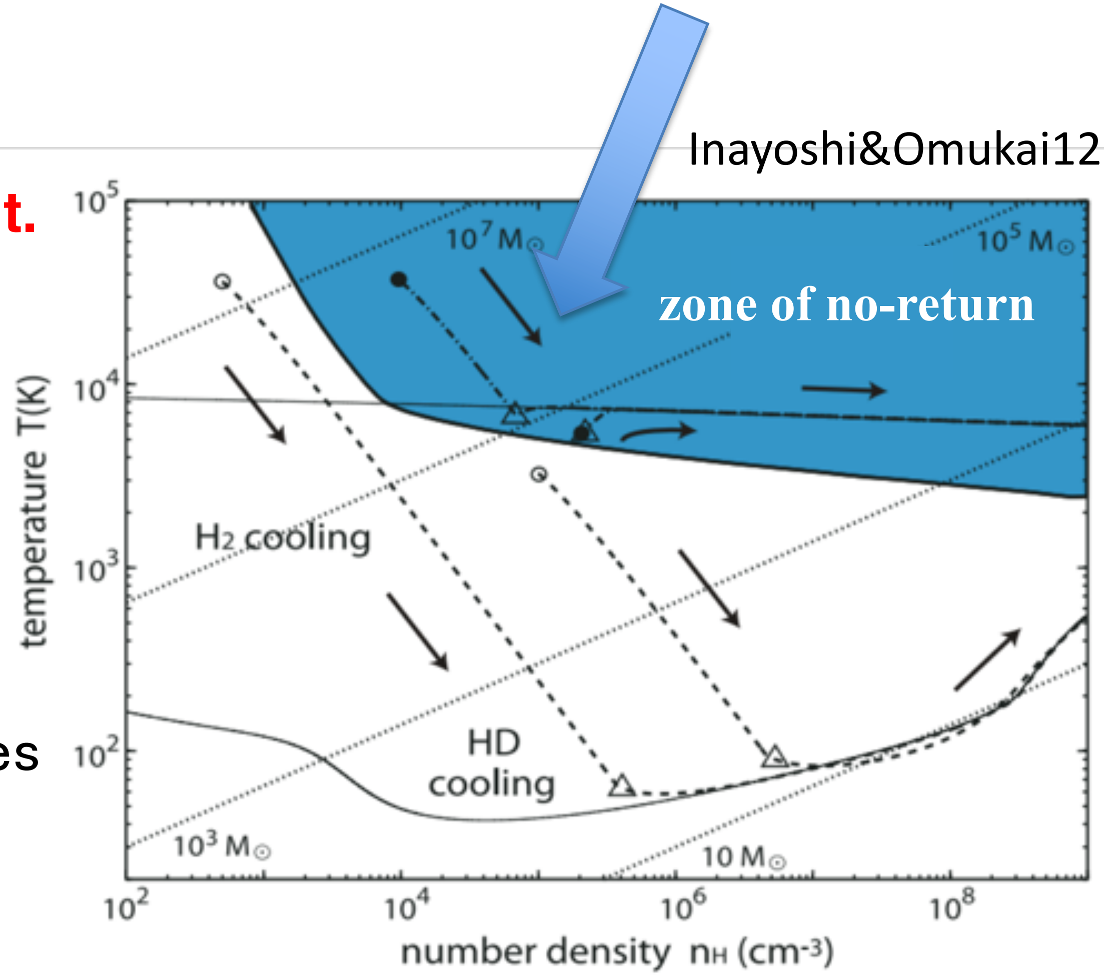
$$\Rightarrow \dot{M} \sim 0.1 - 1\ M_\odot\ \mathrm{yr}^{-1}$$

$$\Rightarrow M_* \sim 10^5\ M_\odot$$

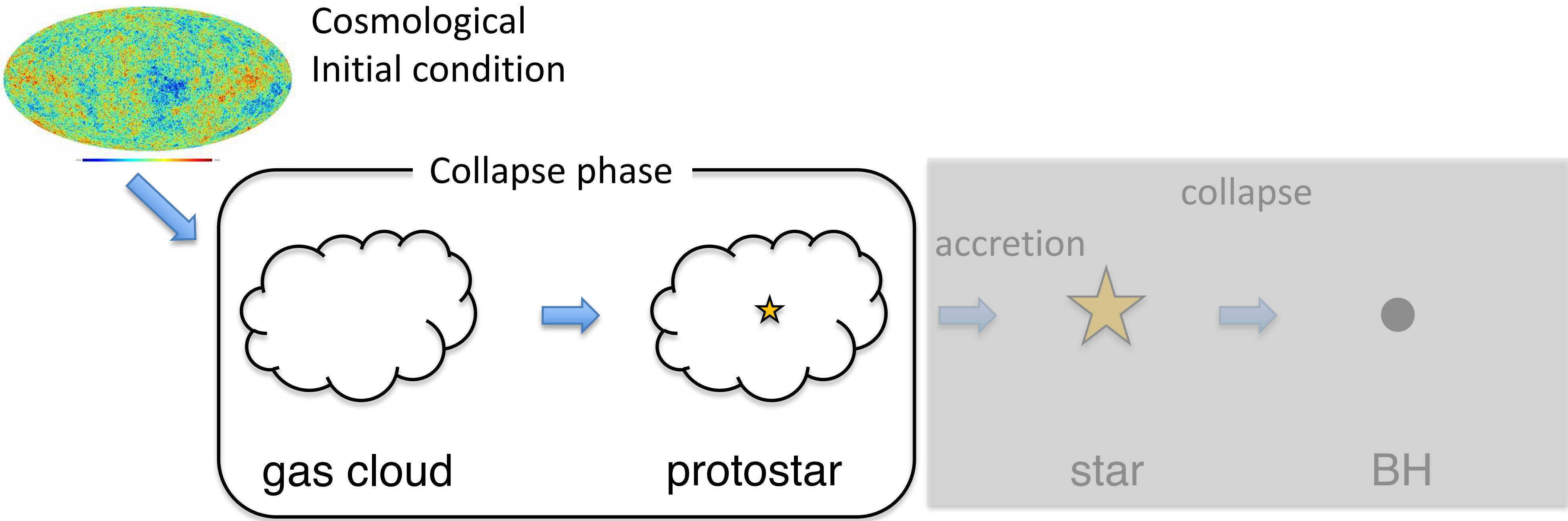
Other models、which dissociates H_2 by

- shock(Inayoshi&Omukai12)
- turbulence (Hirano+18)

Inayoshi&Omukai12



Formation of protostars



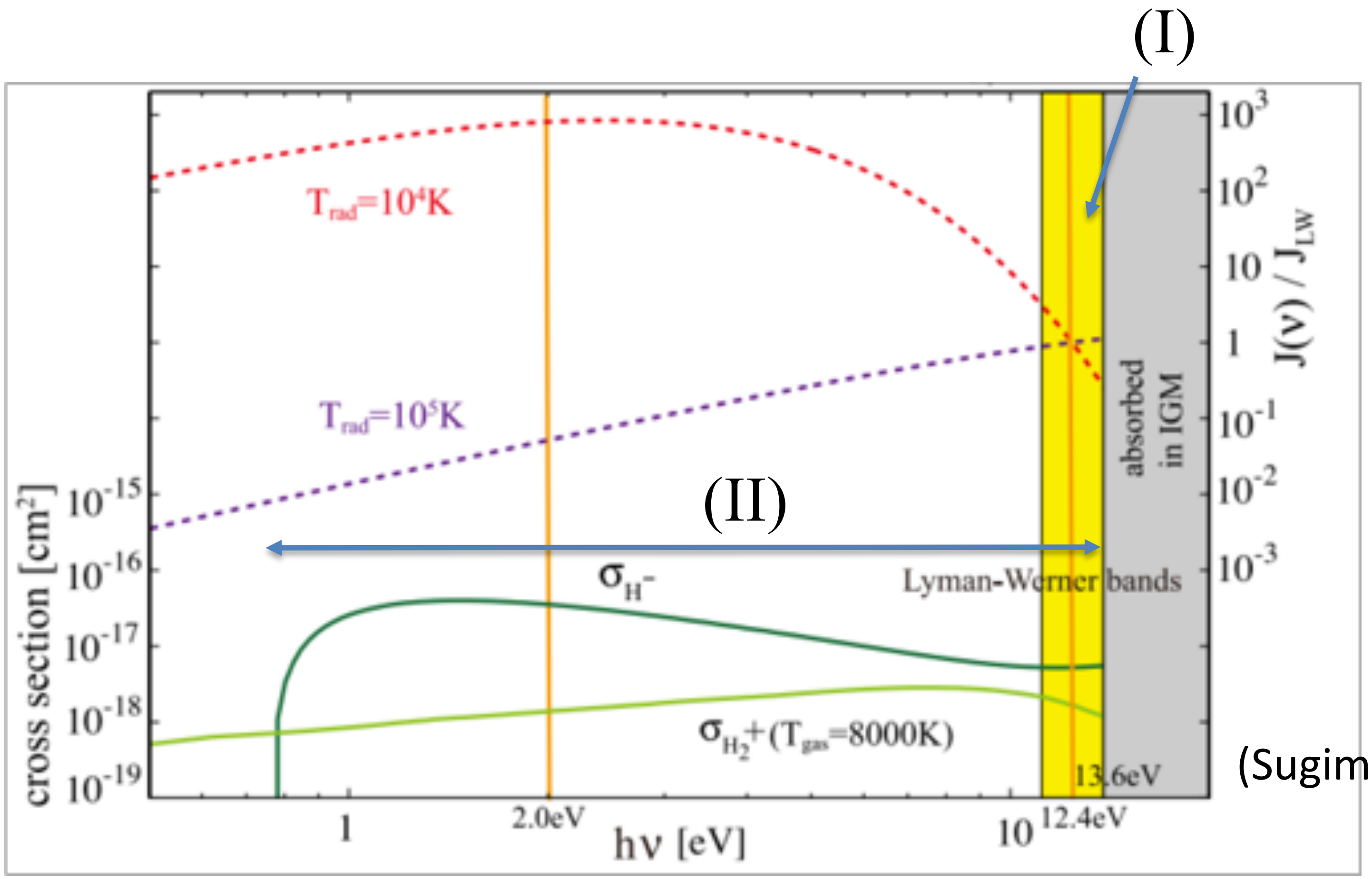
- ✓ What is the required condition for SMS formation?
- ✓ How the feasibility？
- ✓ How about the number density？

H_2 dissociation

(I) H_2 photo dissociation $H_2 + \gamma \longrightarrow 2H$

(II) Destruction of H-, which is the catalyzer for H_2 formation

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



(Sugimura+14)

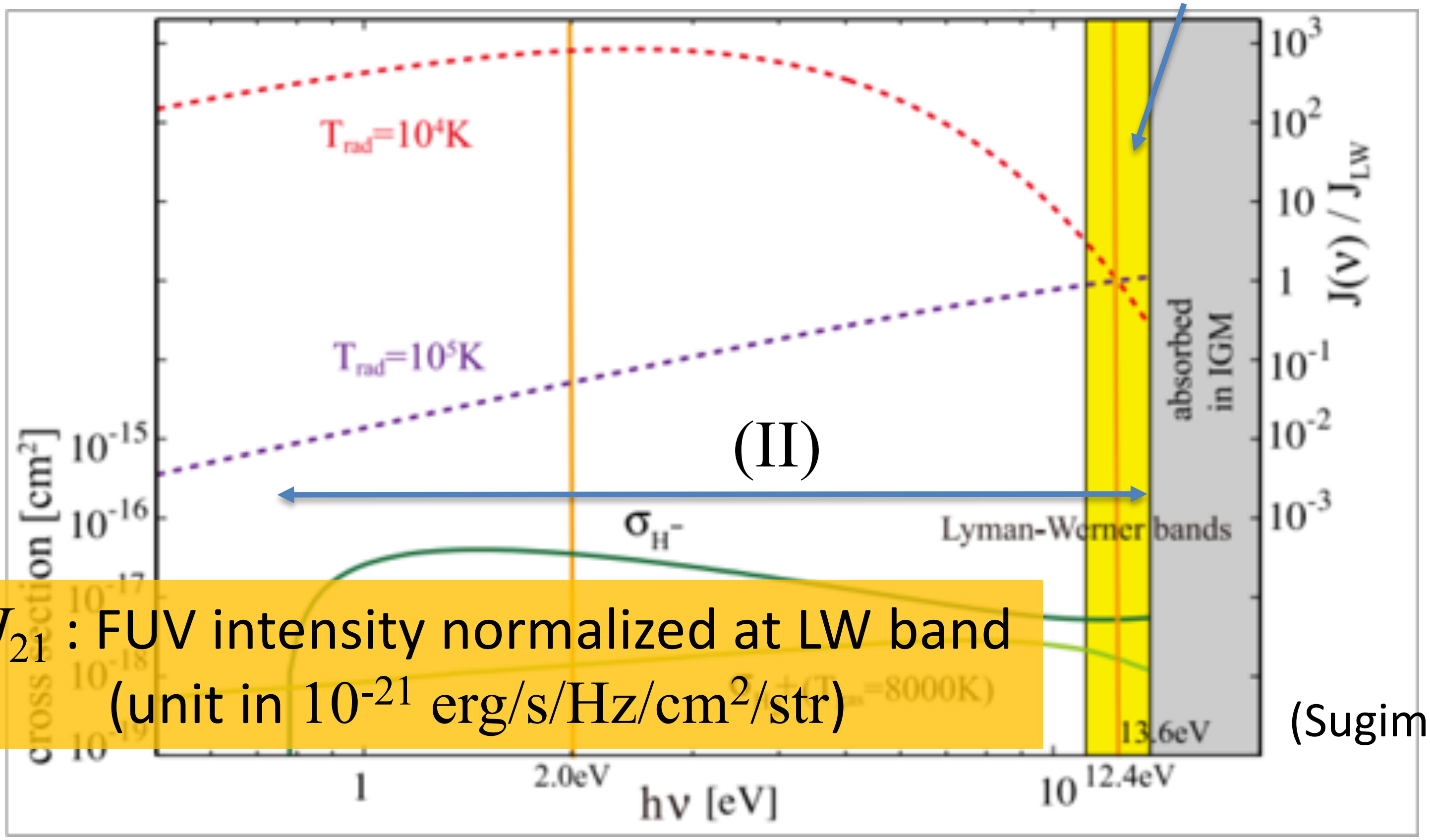
H_2 dissociation

(I) H_2 photo dissociation $H_2 + \gamma \longrightarrow 2H$

(II) Destruction of H-, which is the catalyzer for H_2 formation

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

(I)



J_{21} : FUV intensity normalized at LW band (unit in 10^{-21} erg/s/Hz/cm^2/str)

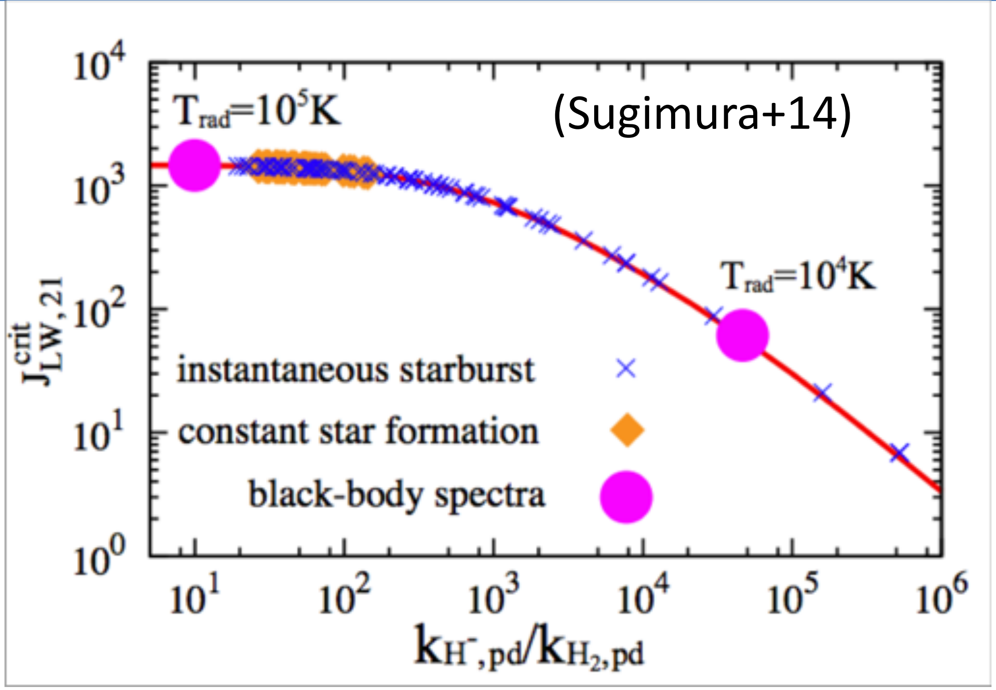
(Sugimura+14)

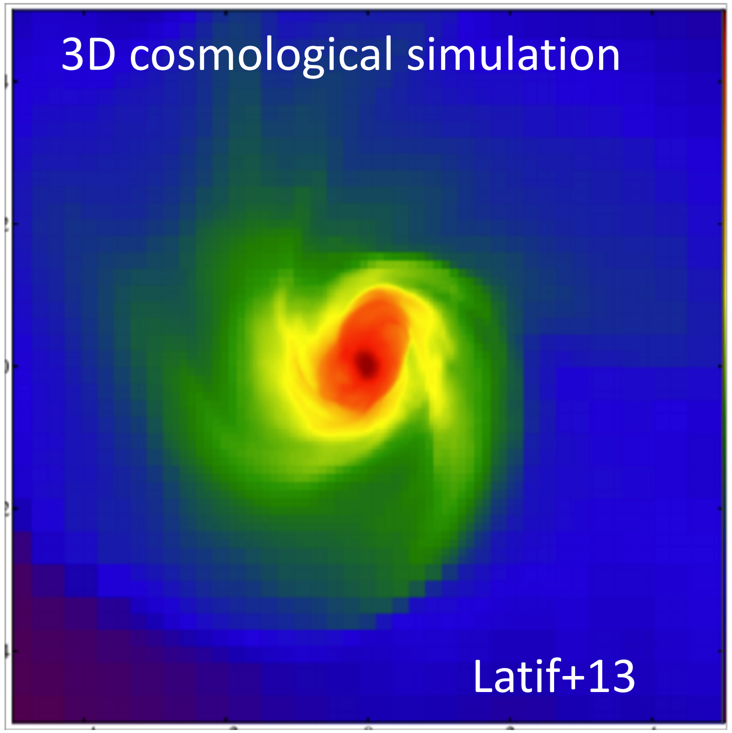
Critical intensity for Direct Collapse

- Critical intensity？

$$J_{\mathrm{crit},21} \begin{cases} = 100 \quad (T_{\mathrm{rad}} = 10^4\,\mathrm{K}) \\ \quad \text{old galaxy} > 100\ \mathrm{Myr} \\ = 2000 \quad (T_{\mathrm{rad}} = 10^5\,\mathrm{K}) \\ \quad \text{star forming galaxy} \end{cases}$$

by one-zone model





- 3D Cosmological simulation

⇒ 10 times larger FUV intensity is needed $J_{\mathrm{crit},21} = 1000$ - 10^4

⇒ due to **turbulence** inside the halo (Shang+10, Latif+14, 15)

Number density of massive seeds

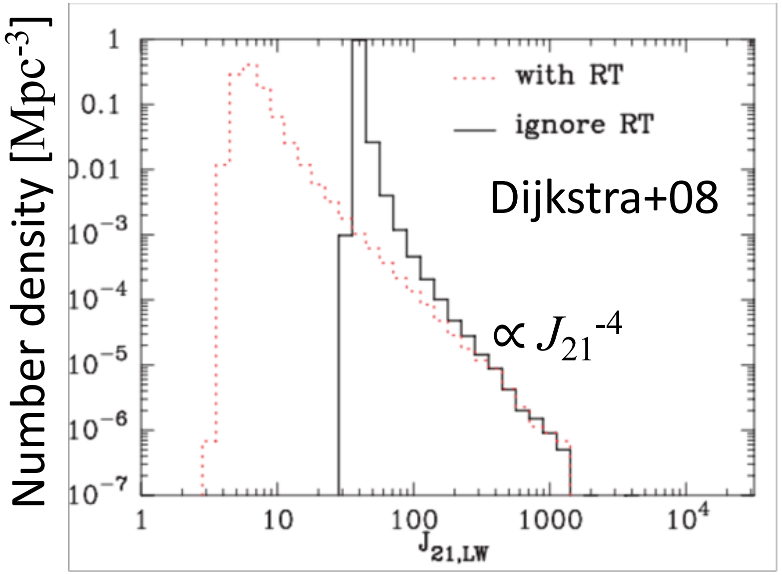
- Distribution of FUV intensity
  - ✓ Determined by the distribution of star forming galaxies

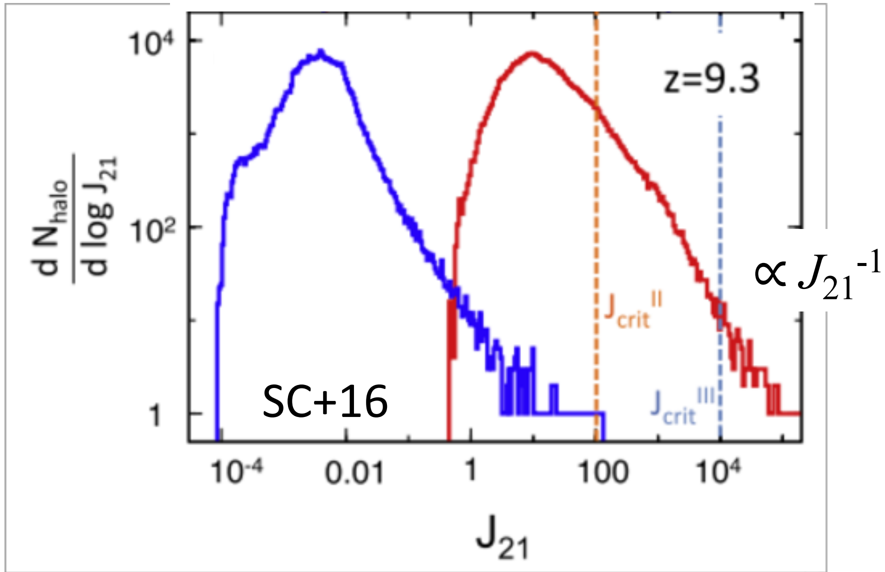
⇒ correlation function of galaxies (Dijkstra+08,14, Inayoshi+14)

⇒ construct galaxy distribution by N-body simulation (semi-analytic model) (Agarwal+12, Ahn+09, SC+16)

⇒ hydrodynamical simulation (Johnson+13)

✓ Much different behavior at larger J_{21} end.

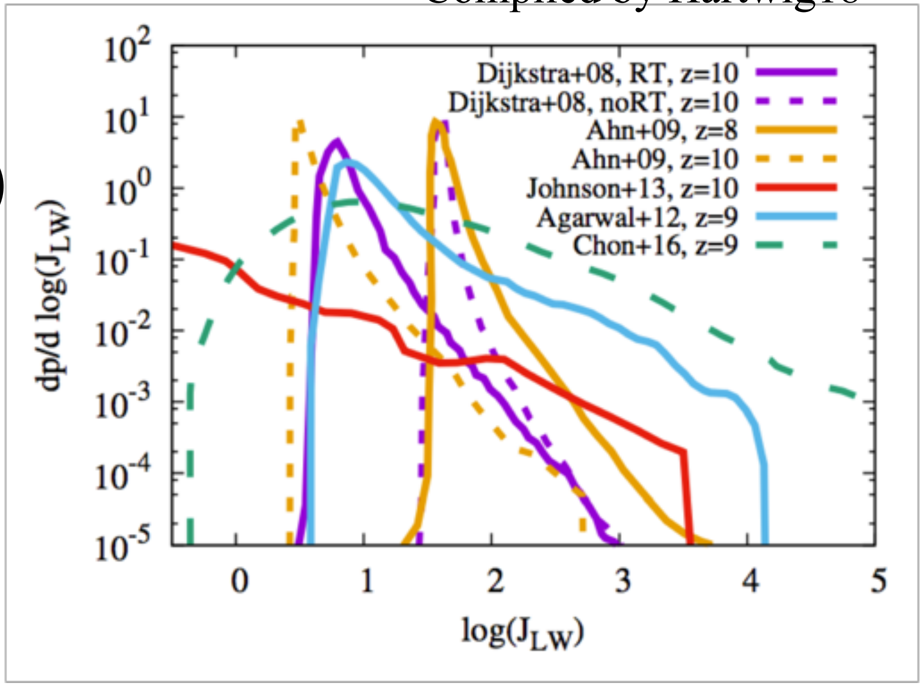




Number density of massive seeds

- Distribution of FUV intensity
  - ✓ Determined by the distribution of star forming galaxies
  - ⇒ correlation function of galaxies (Dijkstra+08,14, Inayoshi+14)
  - ⇒ construct galaxy distribution by N-body simulation (semi-analytic model) (Agarwal+12, Ahn+09, SC+16)
  - ⇒ hydrodynamical simulation (Johnson+13)
  - ✓ Much different behavior at larger J_{21} end.

Compiled by Hartwig18

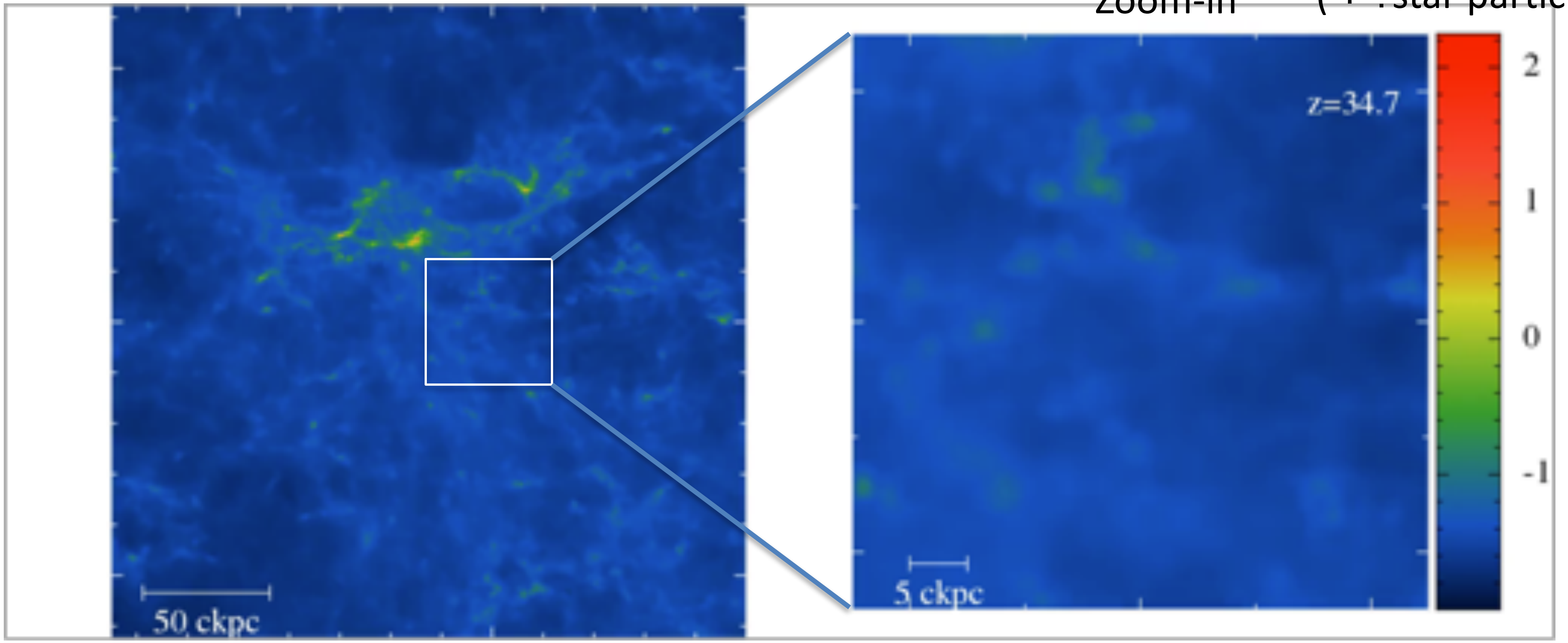


- It is important whether the halo substructure is resolved.

$$J_{21} \propto L / r^2 \propto M / r^2 \quad \Rightarrow$$ *The smaller r is, the larger J.*

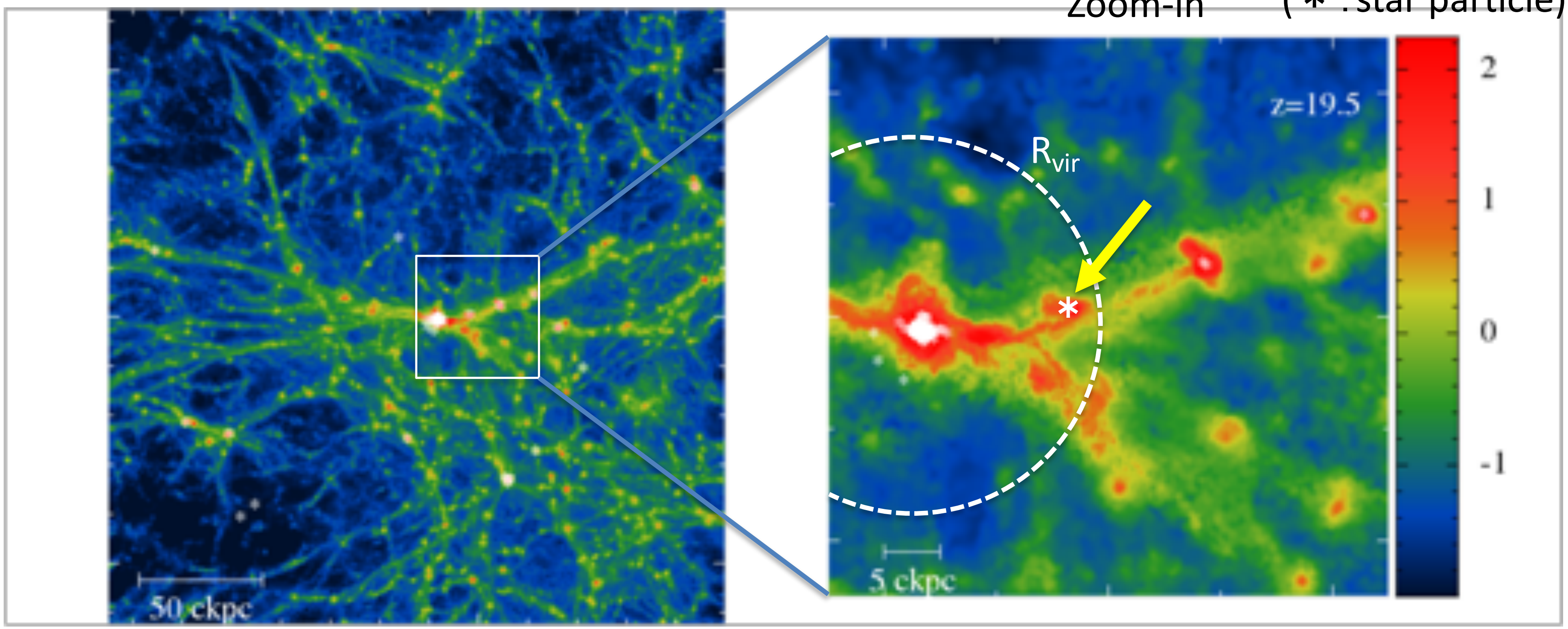
Cosmological SMS Formation

Zoom-in (∗ : star particle)



SC16+update

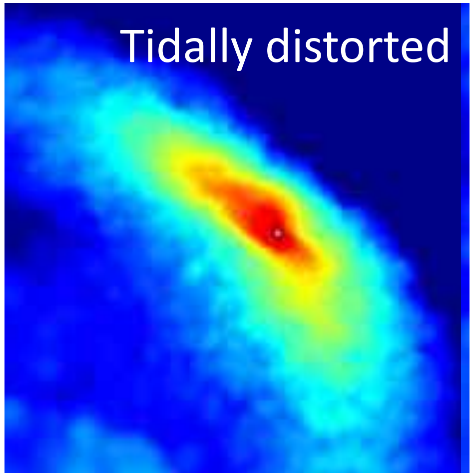
Cosmological SMS Formation

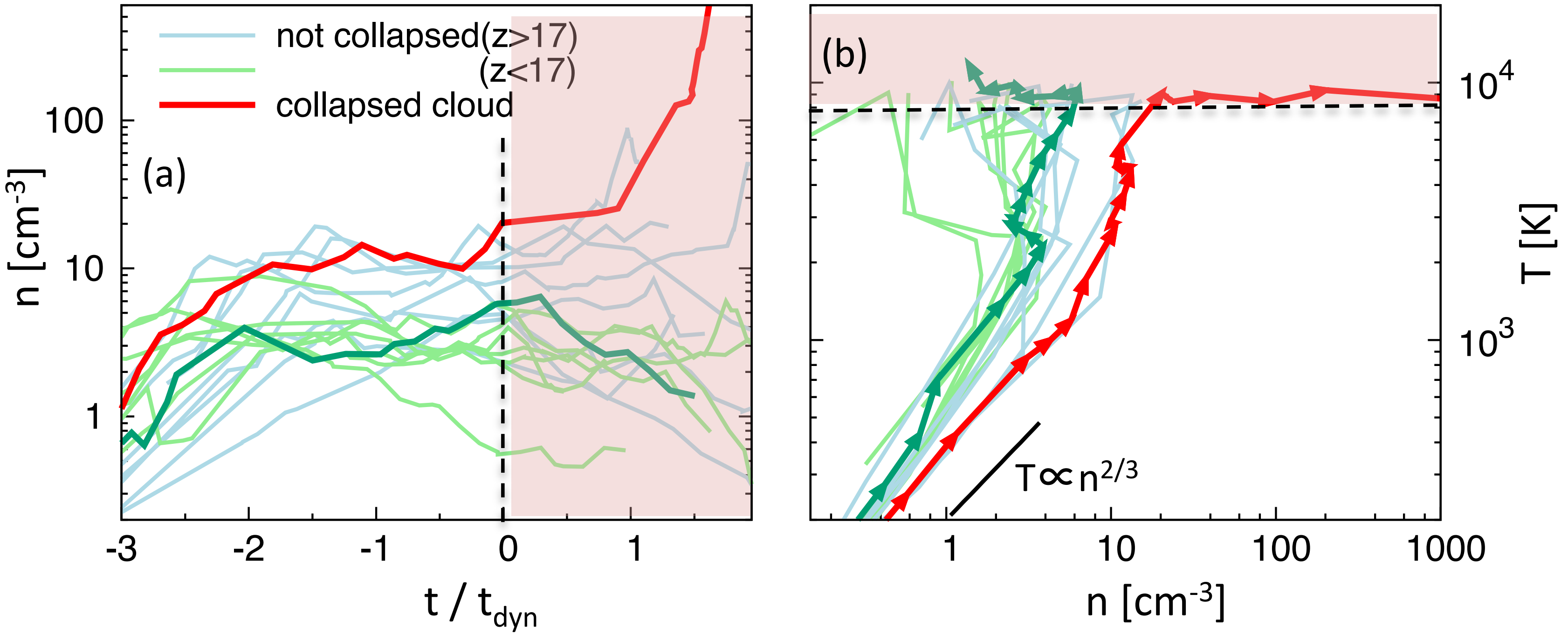


SC16+update

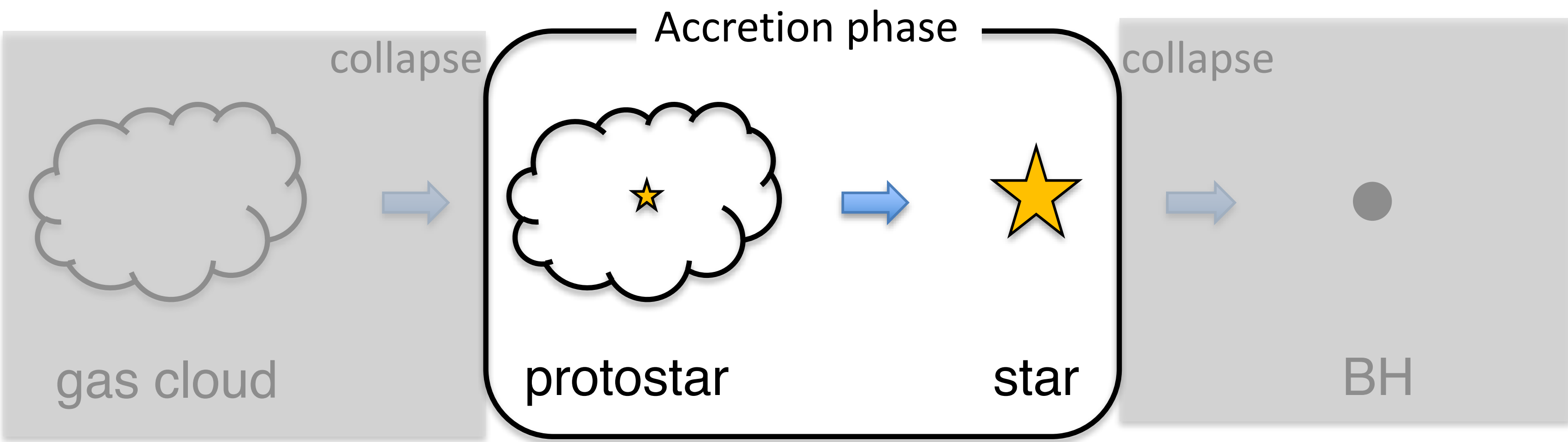
Environmental effects

Clouds under strong FUV radiation
⇒ Strong tidal force from the galaxy
⇒ delay the cloud collapse
⇒ **only 2 out of 42 halos collapse to form proto-star**

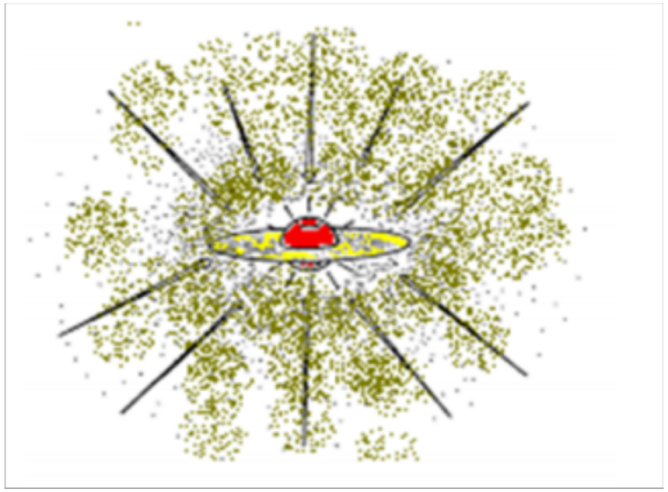




Accretion Phase

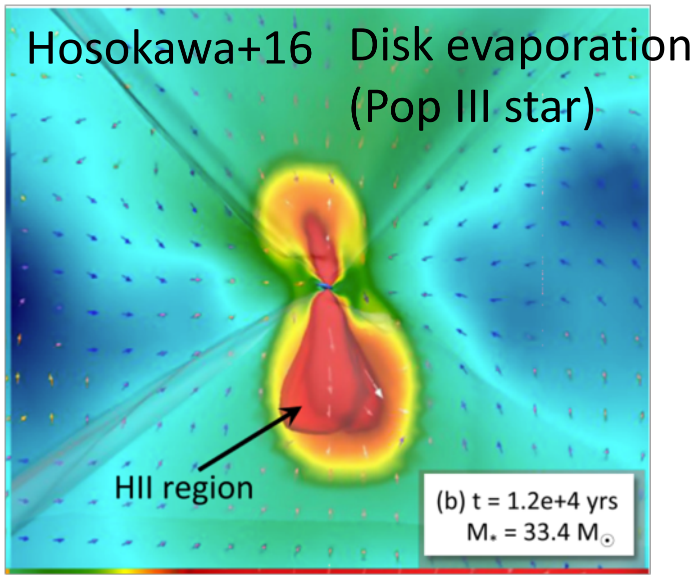


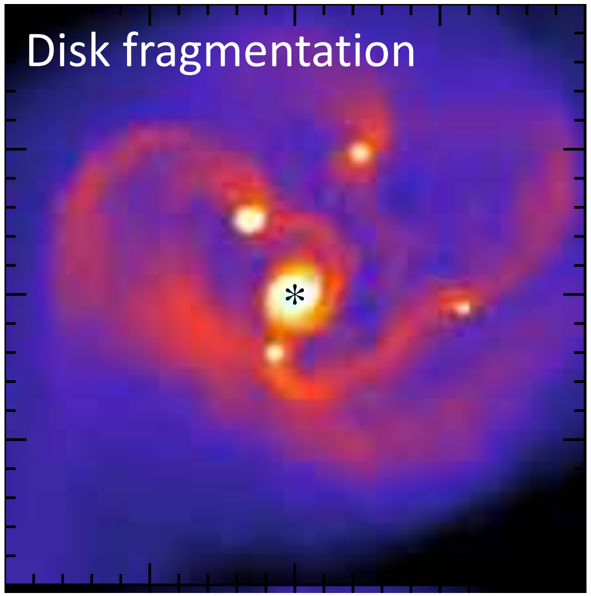
- ✓ Can the protostar grow into the SMS?



Accretion Phase

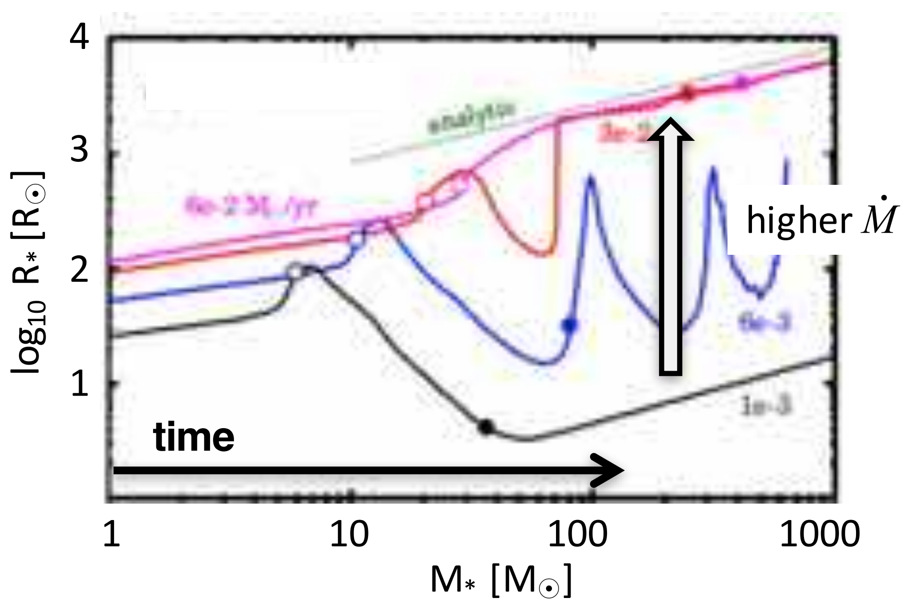
- Difficulties in the stellar mass growth
  - **The UV radiation from the protostar heats the surrounding gas and the cloud is evaporated.**
  - **The disk fragmentation** makes the mass of each star small.



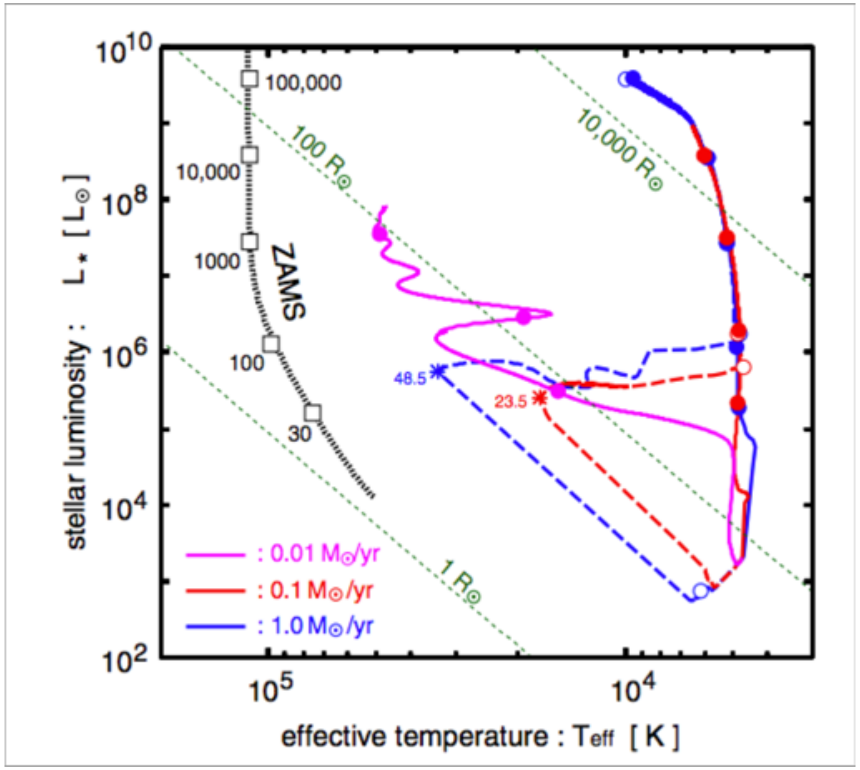


Accretion Phase

- Rapid mass accretion
  ⇒The emissivity of UV photons becomes so small
- The rapid mass accretion inject a large entropy into the stellar surface.
  ⇒ **expand the stellar envelope** (right panel)
  ⇒ The effective temperature of the star gets small.
  ⇒ The UV emissivity becomes negligible.

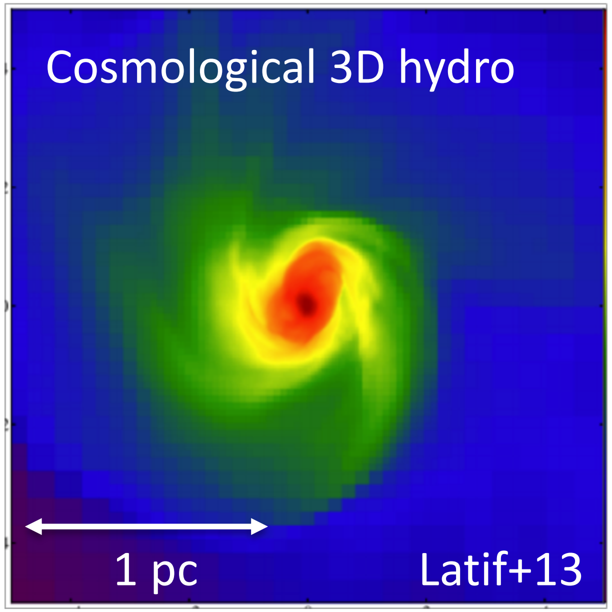


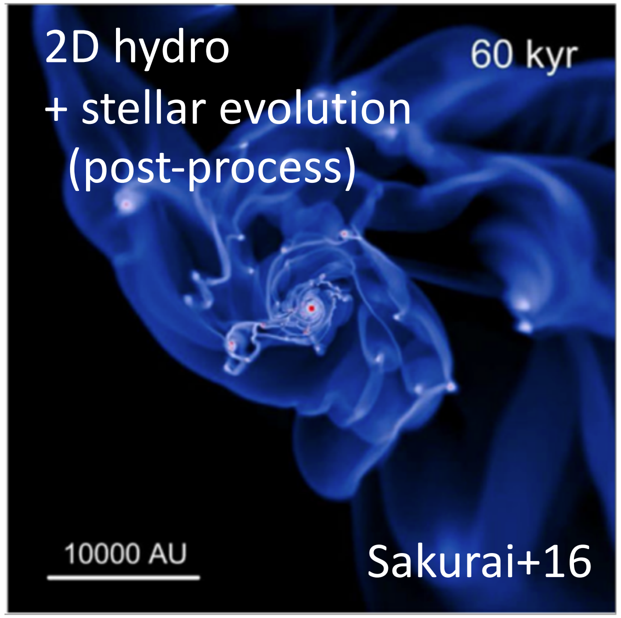
(Hosokawa+13)

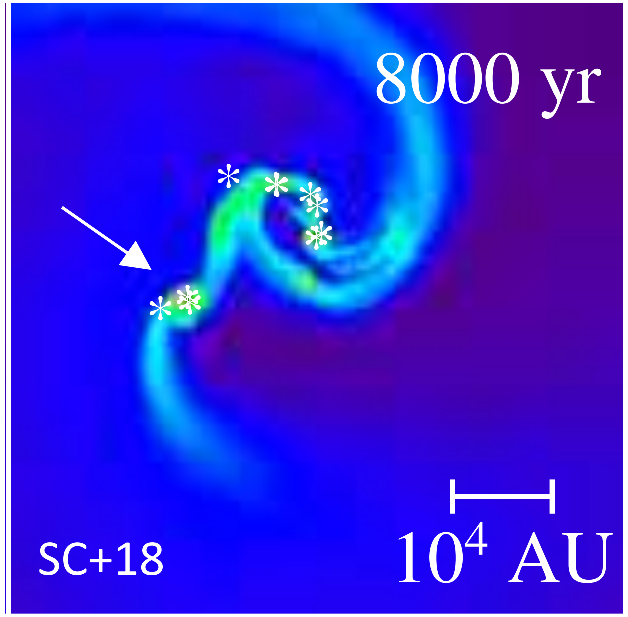


Accretion Phase

Several studies focus on the accretion phase of the SMS formation.





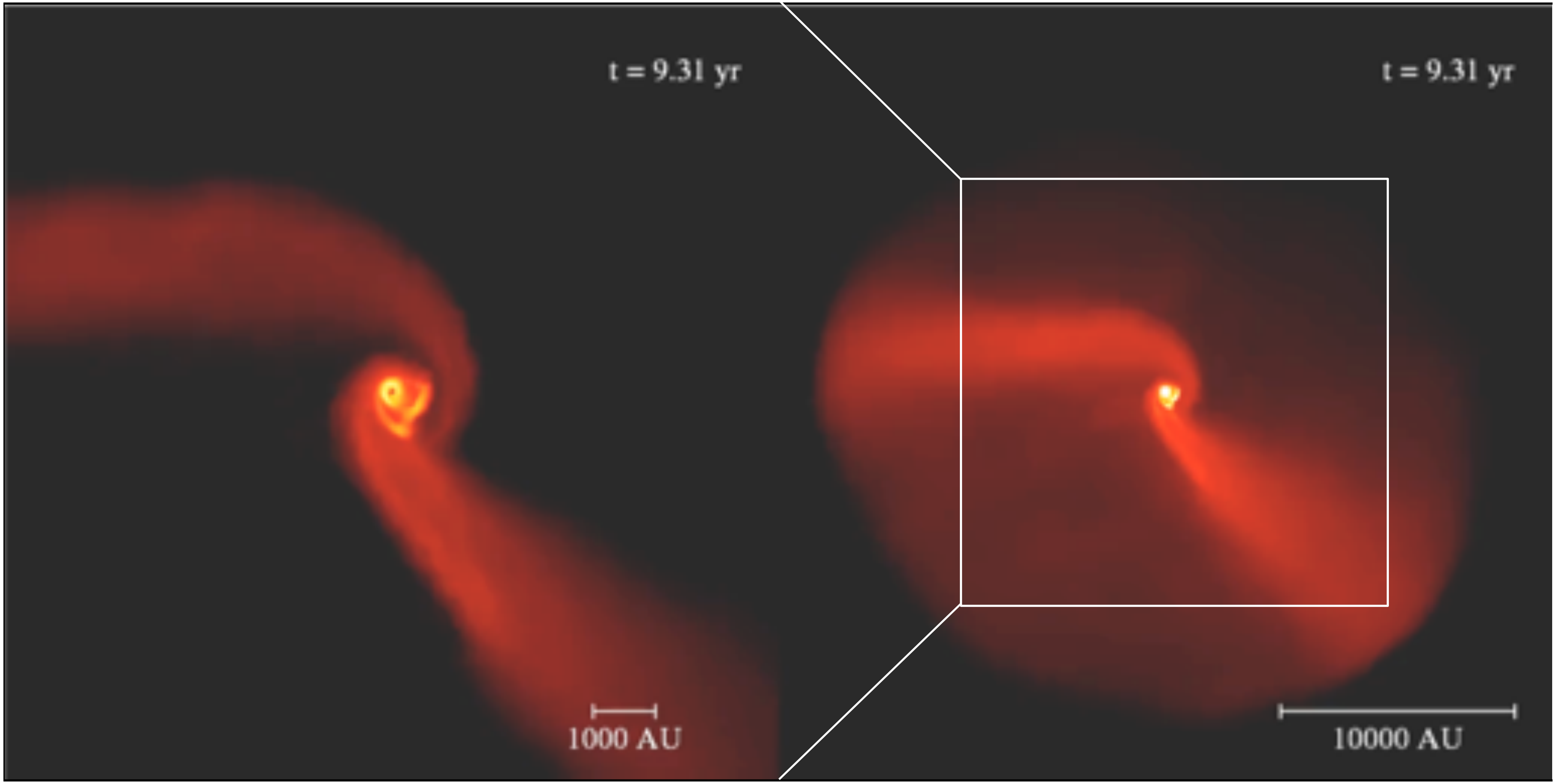


$\Rightarrow M_* \sim 10^5\ M_\odot$
(at t = 0.01 Myr)

$\Rightarrow M_{*,\ \mathrm{final}} \sim 10^4\ M_\odot$
(at t = 0.1 Myr)

$\Rightarrow M_{*,\ \mathrm{final}} \sim 10^3$ - $10^4\ M_\odot$
(at t = 0.1 Myr)

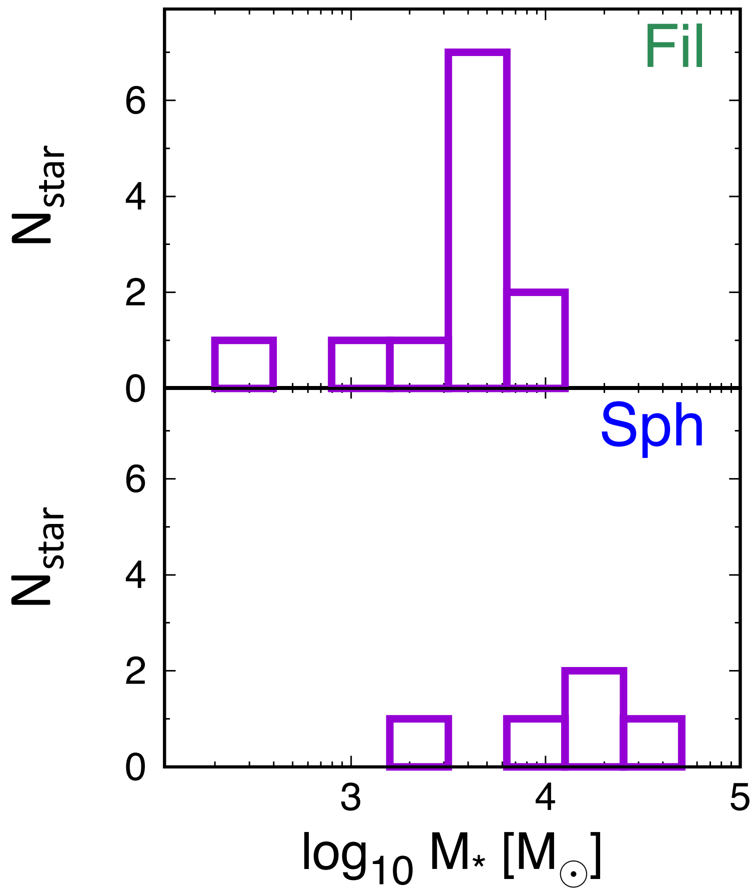
Accretion Phase (SC+18)

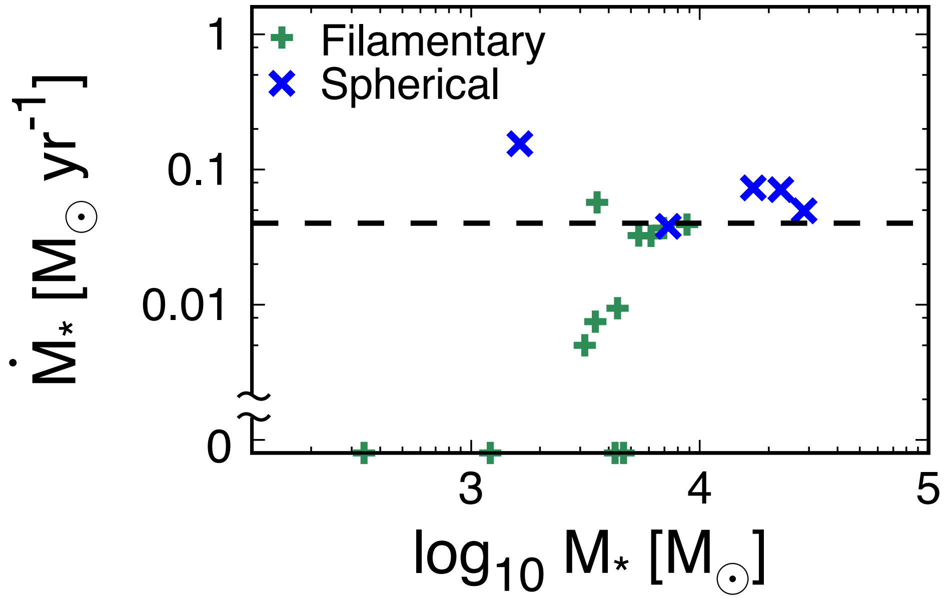


asterisk: star particle (sink particle)

Mass distribution (at 0.1 Myr)

0.1 Million yr





Spherical cloud

⇒ typical M_*: $\sim 10^4\ M_\odot$

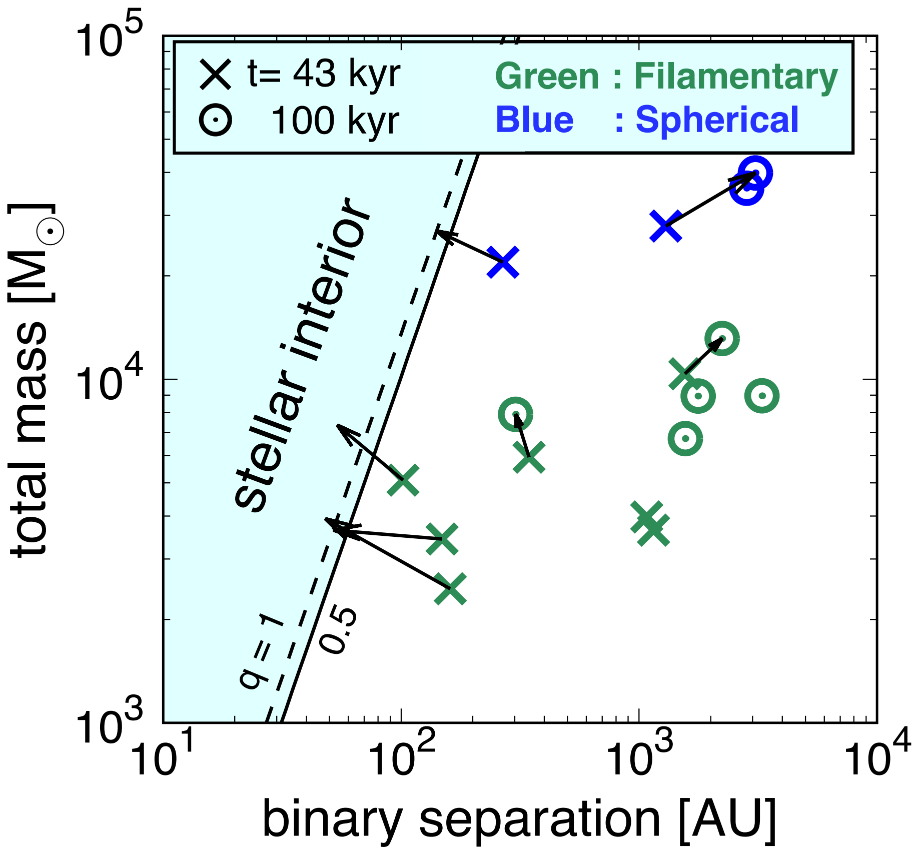
$\dot{M}$: $\sim 0.1\ M_\odot\ \mathrm{yr}^{-1}$

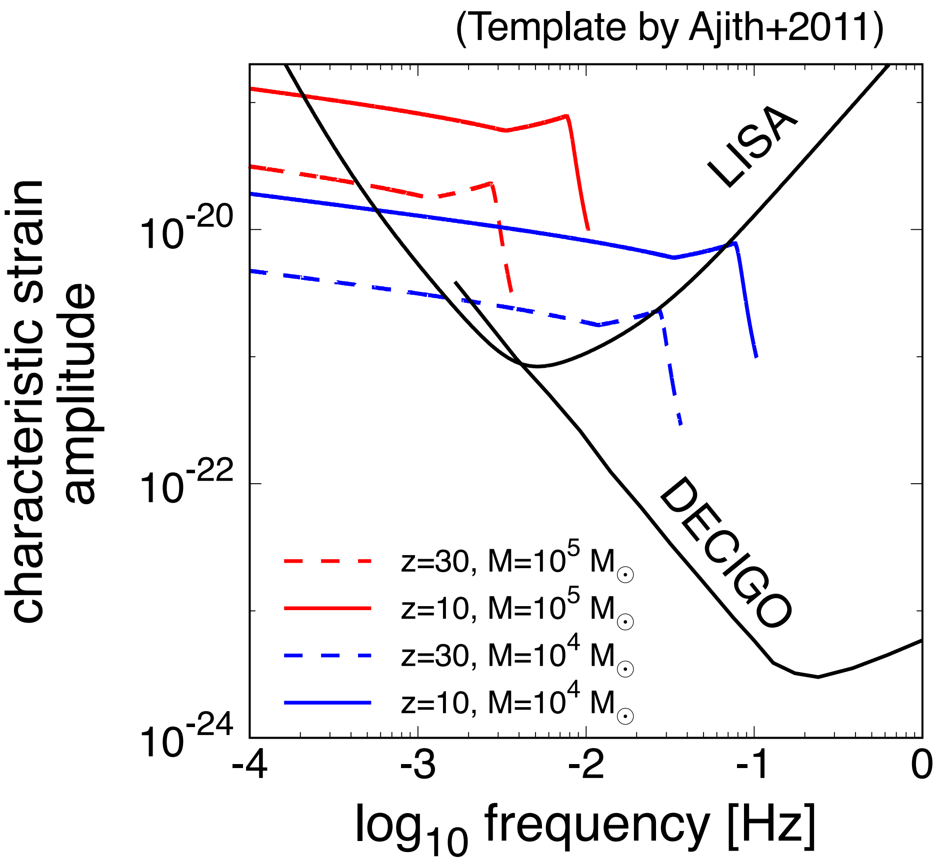
Filamentary cloud

⇒typical M_*: $\sim 10^3\ M_\odot$

$\dot{M}$: $\sim 0.01\ M_\odot\ \mathrm{yr}^{-1}$

Binaries and GW emission





We can observe GW emission from remnant binary BHs.

(DECIGO and LISA can target mergers at z **= 10-30)**

Detection rate of GWs

$$N_{\rm merge} = N_{\rm DC}\, f_{\rm binary}\, f_{\rm merge}$$

From SC+18

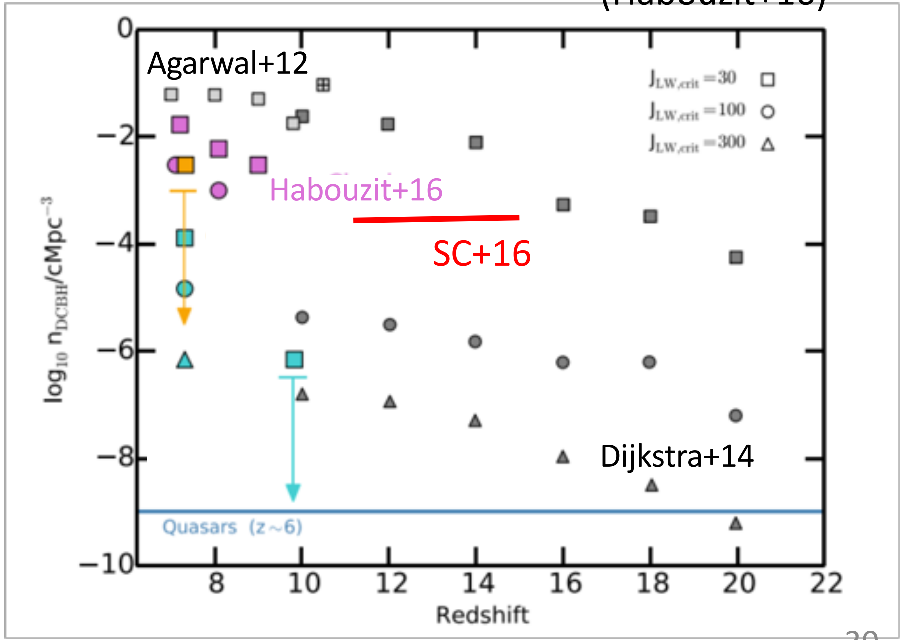
$$\sim 2\times10^{-3}\ {\rm Mpc^{-3}} \left(\frac{N_{\rm DC}}{5\times10^{-4}\ {\rm Mpc^{-3}}}\right)\left(\frac{f_{\rm binary} f_{\rm merge}}{4}\right)$$

$$\dot{N}_{\rm event} = 0.61\ {\rm yr^{-1}} \left[\frac{N_{\rm merge}}{2\times10^{-3}\ {\rm Mpc^{-3}}}\right]$$

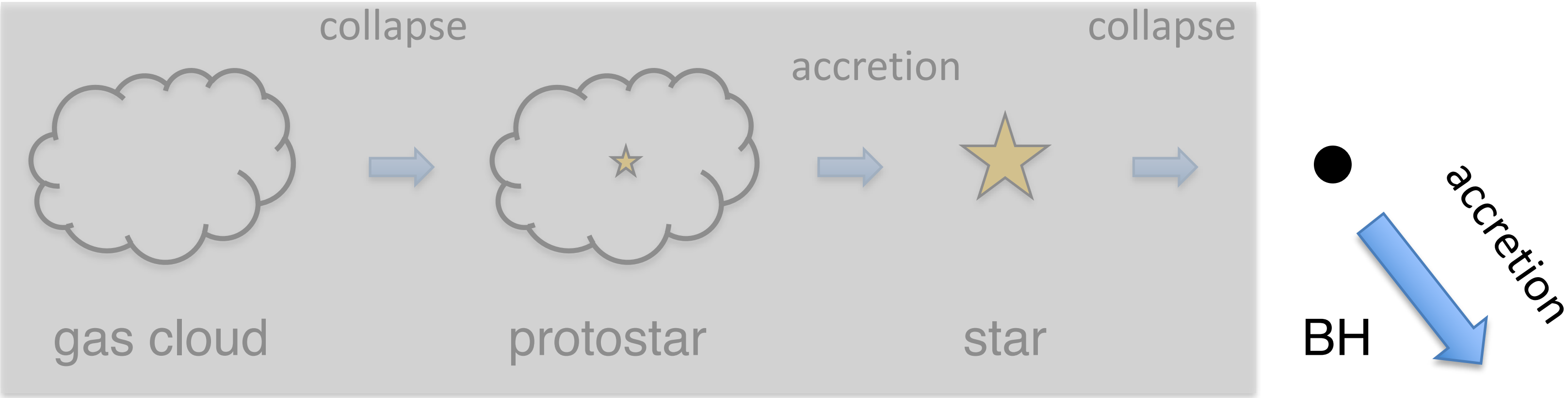
(Haehnelt, 1994)

Still there are so large scatter in the event rate of SMS formation.
Future observation of GW signals can give a constraint on their models. (Hartwig+18)

(Habouzit+16)



Further growth of seed BHs



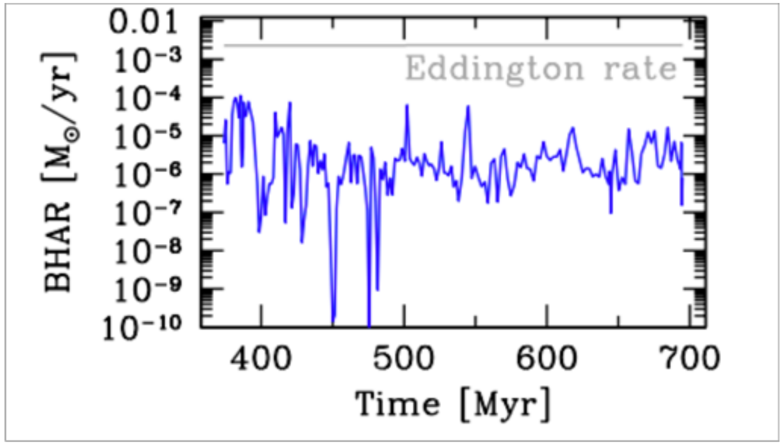
✓ The seed BHs($\sim 10^5\, M_\odot$) can grow into the observed SMBHs($\sim 10^9\, M_\odot$) ?

SMBH

Further growth of seed BHs

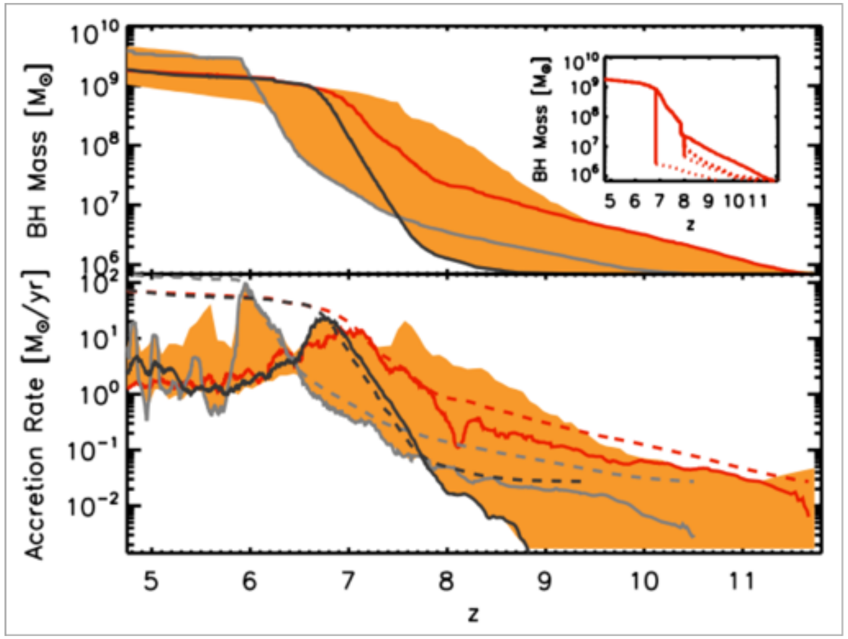
- The seed BHs can grow into the observed SMBHs？
  ⇒ still no consensus…

Latif+18



⇒ almost no mass growth

Di Matteo+12



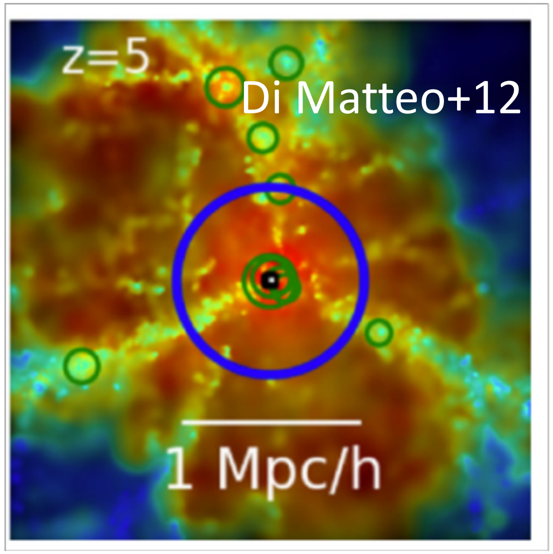
⇒seed BH grows into SMBH nearly at an Eddington rate!

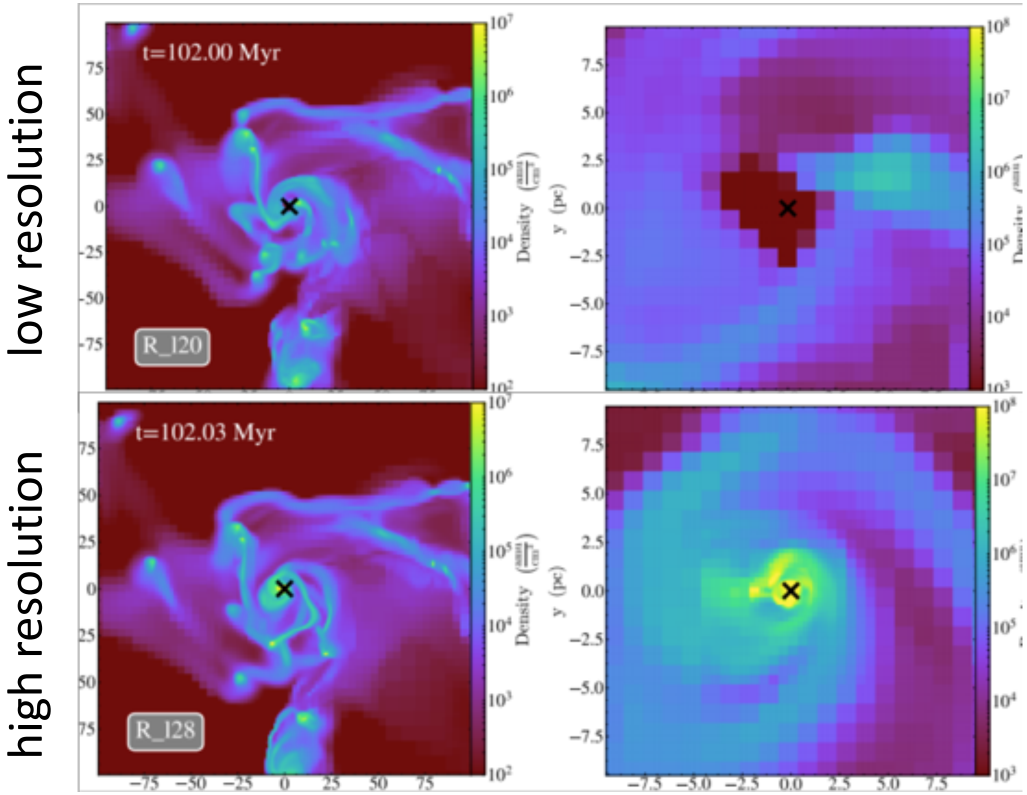
Further growth of seed BHs

- BHs grow efficiently at the simulations with lower resolution
  ⇒smoothed out the inner structure of the halo?
- The small scale structure (filamentary, clumpy) appears at higher resolution
  ⇒ underestimates the gas density around BHs
  ⇒ Bondi accretion rate becomes smaller

Beckmann+18

$$\dot{M}_{\mathrm{Bondi}} \propto n\, M_{\mathrm{BH}}^{2}\, T^{-3/2}$$





Further growth of DCBHs

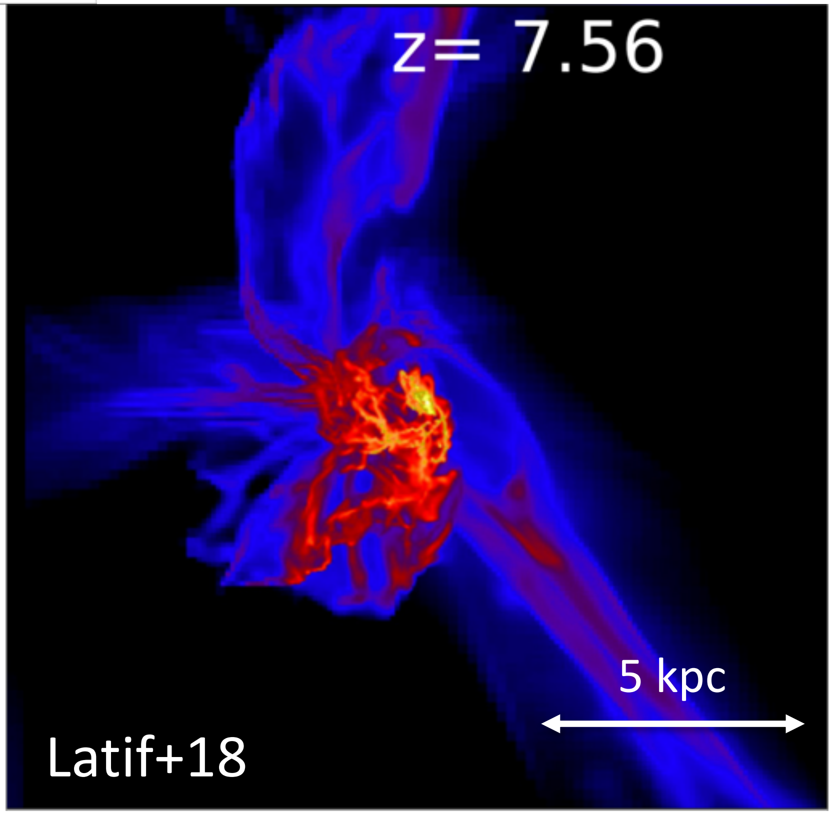
Characteristic accretion rates

$$\dot{M}_{\rm Bondi} = 1.3 \times 10^{-4}\ M_{\odot}{\rm yr}^{-1}\ \ M_5^2\ n_0\ T_4^{-3/2}$$
$$\dot{M}_{\rm Edd} = 2.2 \times 10^{-3}\ M_{\odot}{\rm yr}^{-1}\ \ M_5\ \eta_{0.1}^{-1}$$

The mean density inside a halo

$$n_{200} = 3.6 \times 10^{-2}\ {\rm cm}^{-3} \left(\frac{1+z}{10}\right)^3$$

⇒ To realize the Eddington accretion rate、the BH should located at region with higher density than the mean density inside the halo ($M_{\rm BH} = 10^5\ M_{\odot}$)。



Summary

- Direct Collapseモデル

 ⇒ 超巨大BHの起源(特にhigh-z)を説明するモデルの一つ

 ⇒ 初期宇宙における超大質量星形成を経て、SMBHの形成を説明する。

- 超大質量星形成

 ⇒ H原子の冷却により崩壊するガス雲で起こる

 ⇒ 原始星形成後は急激に質量成長 ($\sim 0.1\ M_{\odot}\ \mathrm{yr}^{-1}$)

 ⇒ 次世代重力波望遠鏡(LISA, DECIGO)により、
 event rateに制限がつけられる可能性

- 種BHからSMBHへ

 ⇒ Eddington rateを実現するためには比較的高密度領域に
 BHがいる必要がある。