2020/10/23
Kavli IPMU Postdoc Colloquium

Supermassive black hole seed formation in the early universe

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Outline

- Introduction
- Direct collapse (DC) model
- Supermassive star (SMS) formation in dynamical heated DM halos
- Summary

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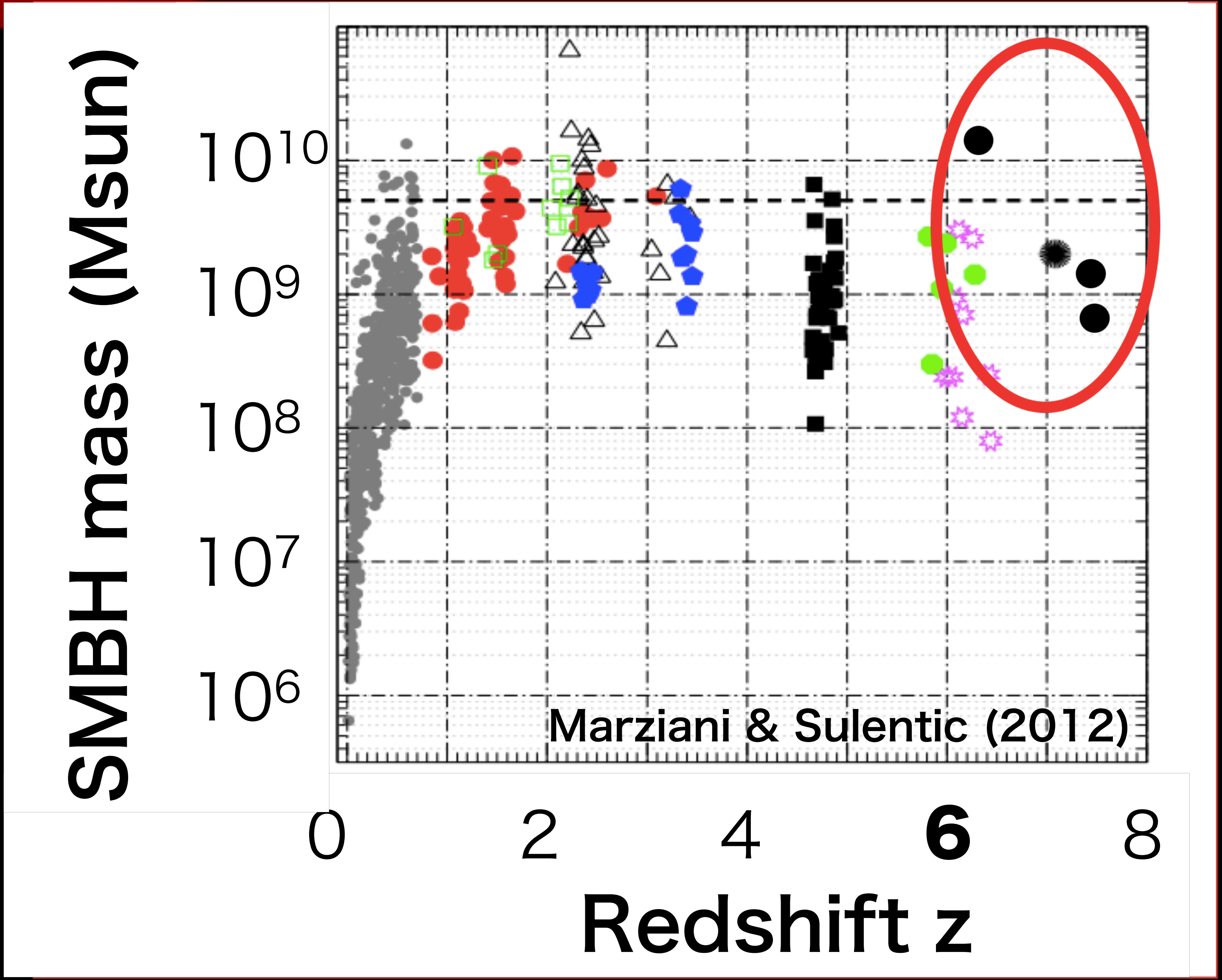
Observations of SMBHs in the early universe



Several z>6 supermassive black holes (SMBHs) are observed

Fan et al. (2001),
Mortlock et al. (2011),
Wu et al. (2015),
Matsuoka et al. (2016),
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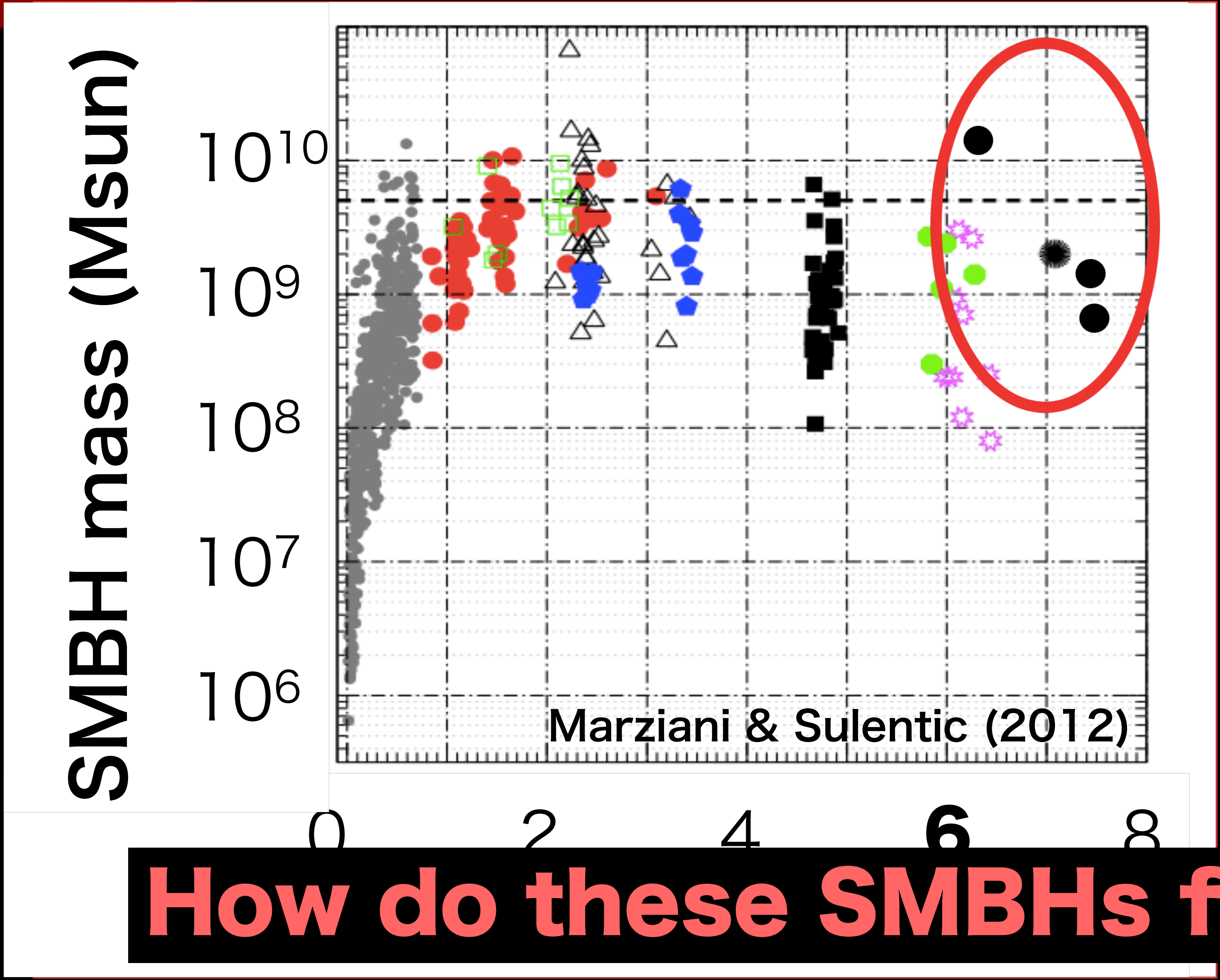

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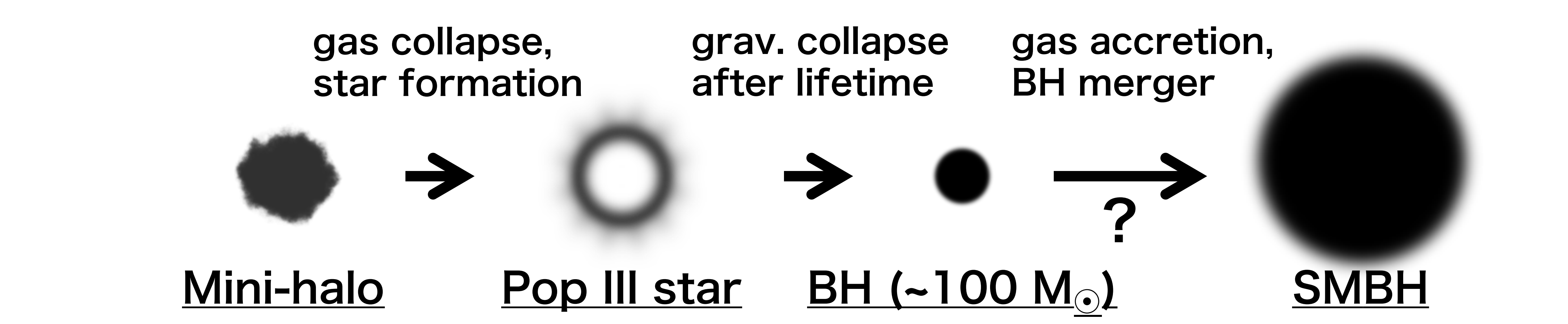
How do these SMBHs form so fast?

Formation model: Pop III BH origin



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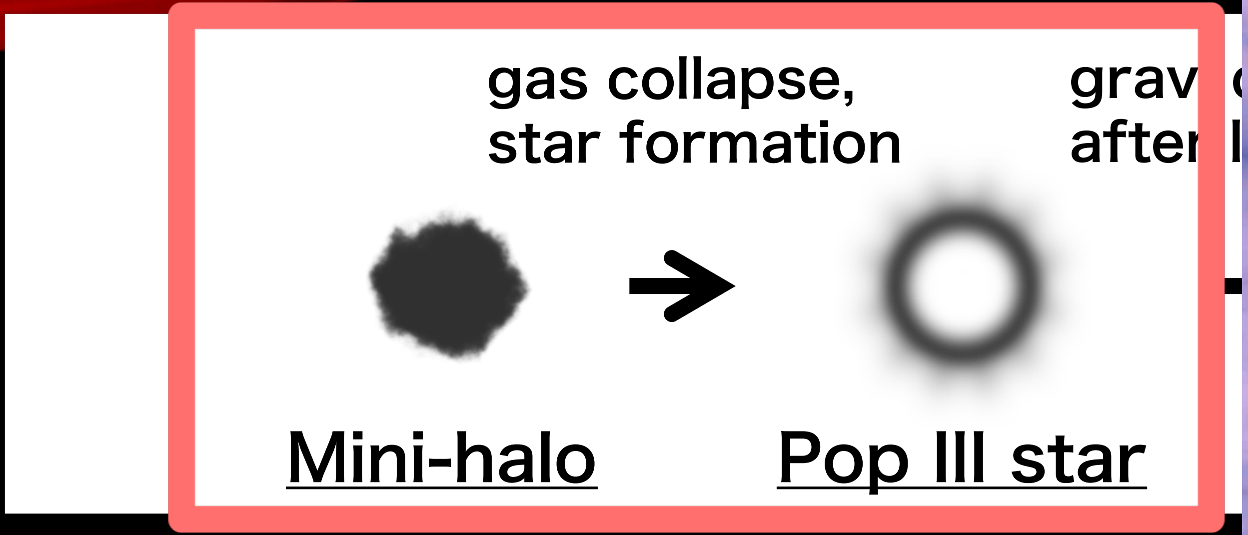
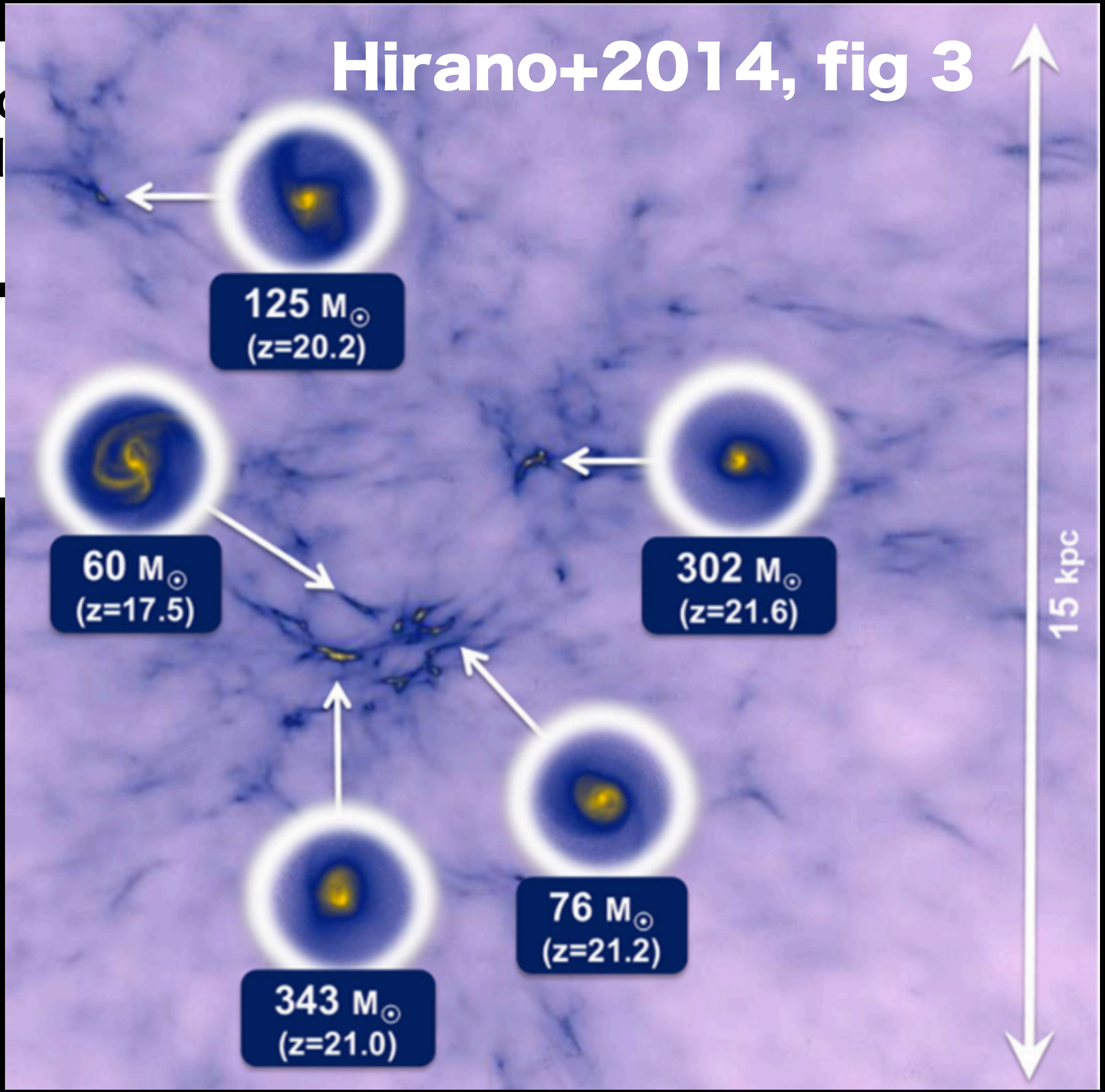
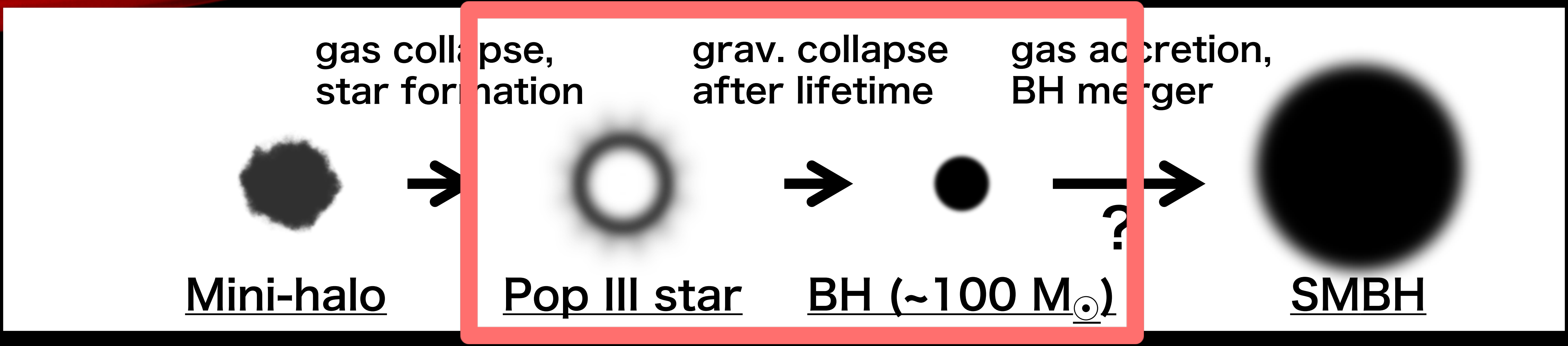




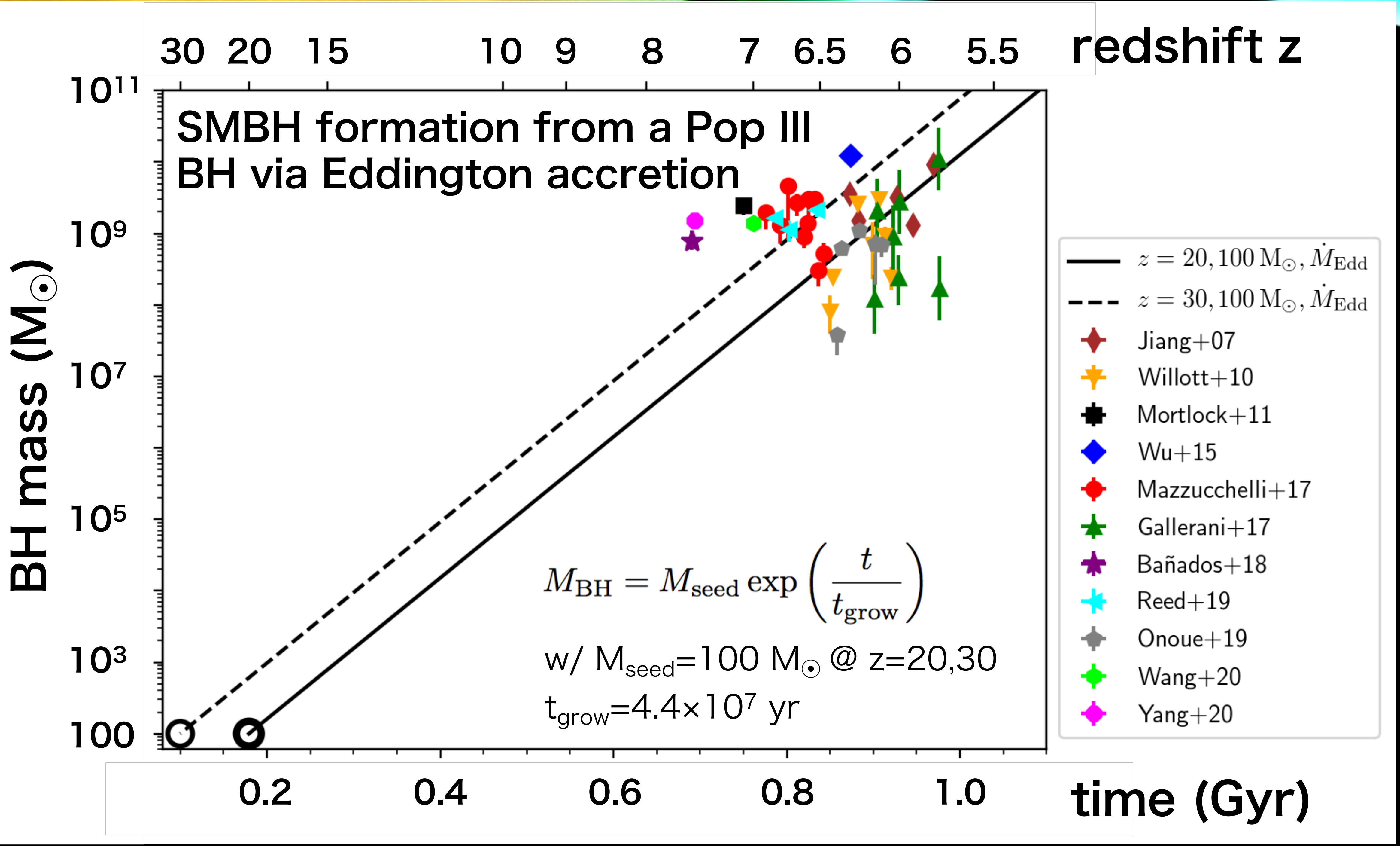
Pop III stars are though to be as massive as ~100 M$_\odot$

Massive ones have >~ 300 M$_\odot$

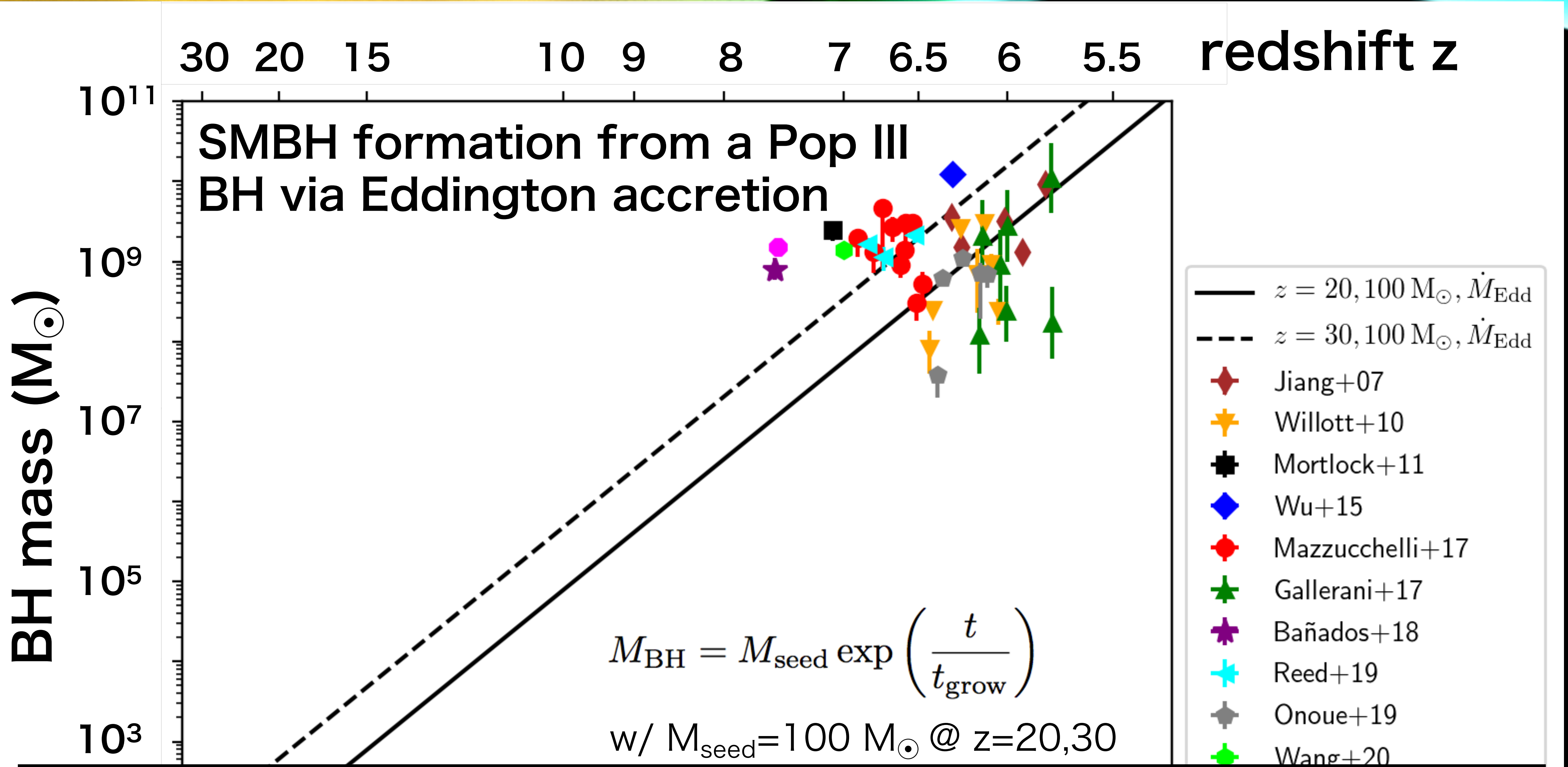
Formation model: Pop III BH origin



Massive Pop III stars collapse to BHs of >~ 100 $M_\odot$
(Heger & Woosley 2002)

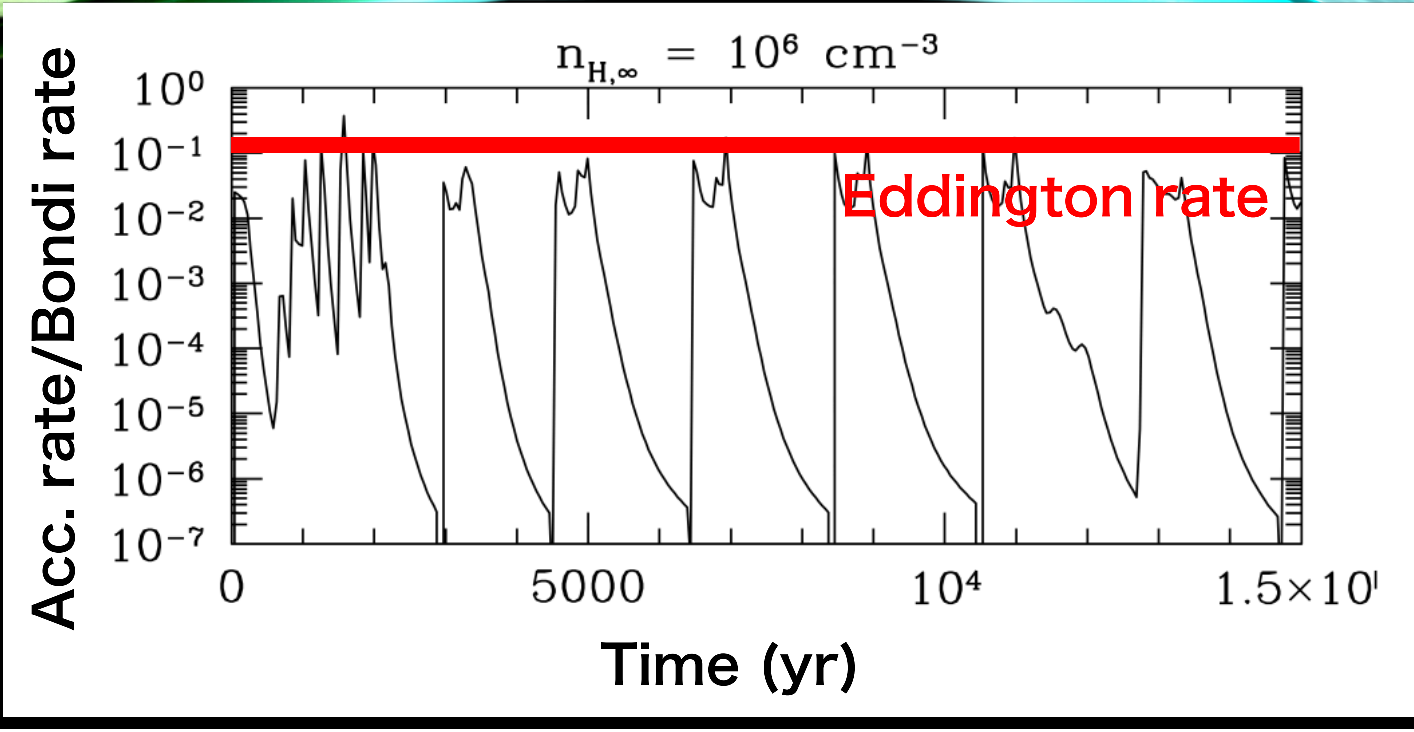


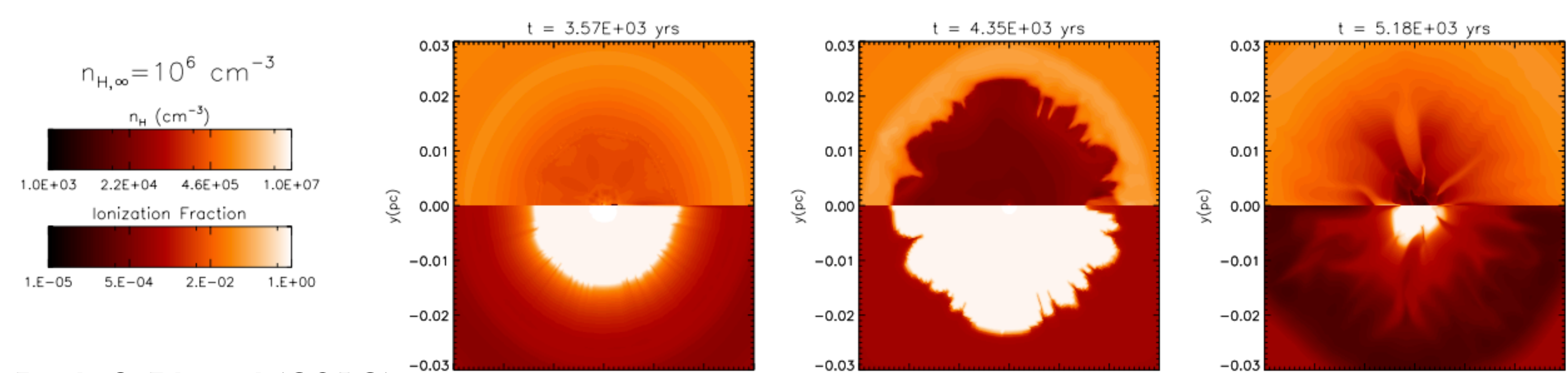
redshift z
30 20 15 10 9 8 7 6.5 6 5.5
SMBH formation from a Pop III
BH via Eddington accretion
BH mass ($M_\odot$)
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
100
0.2 0.4 0.6 0.8 1.0
time (Gyr)
$M_{\rm BH} = M_{\rm seed} \exp\left(\frac{t}{t_{\rm grow}}\right)$
w/ M_{seed}=100 $M_\odot$ @ z=20,30
$t_{grow}=4.4\times10^7$ yr
$z = 20, 100\,{\rm M}_\odot, \dot{M}_{\rm Edd}$
$z = 30, 100\,{\rm M}_\odot, \dot{M}_{\rm Edd}$
Jiang+07
Willott+10
Mortlock+11
Wu+15
Mazzucchelli+17
Gallerani+17
Bañados+18
Reed+19
Onoue+19
Wang+20
Yang+20



The Pop III BH seed model with Edd. accretion looks work, but...

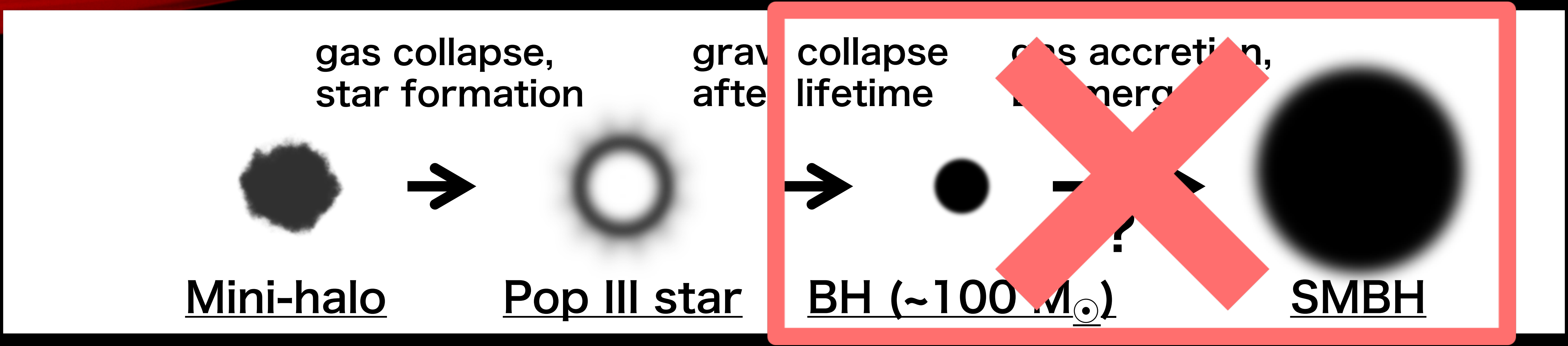
Radiation feedback suppresses accretion





Park & Ricotti (2012)

Formation model: Pop III BH origin



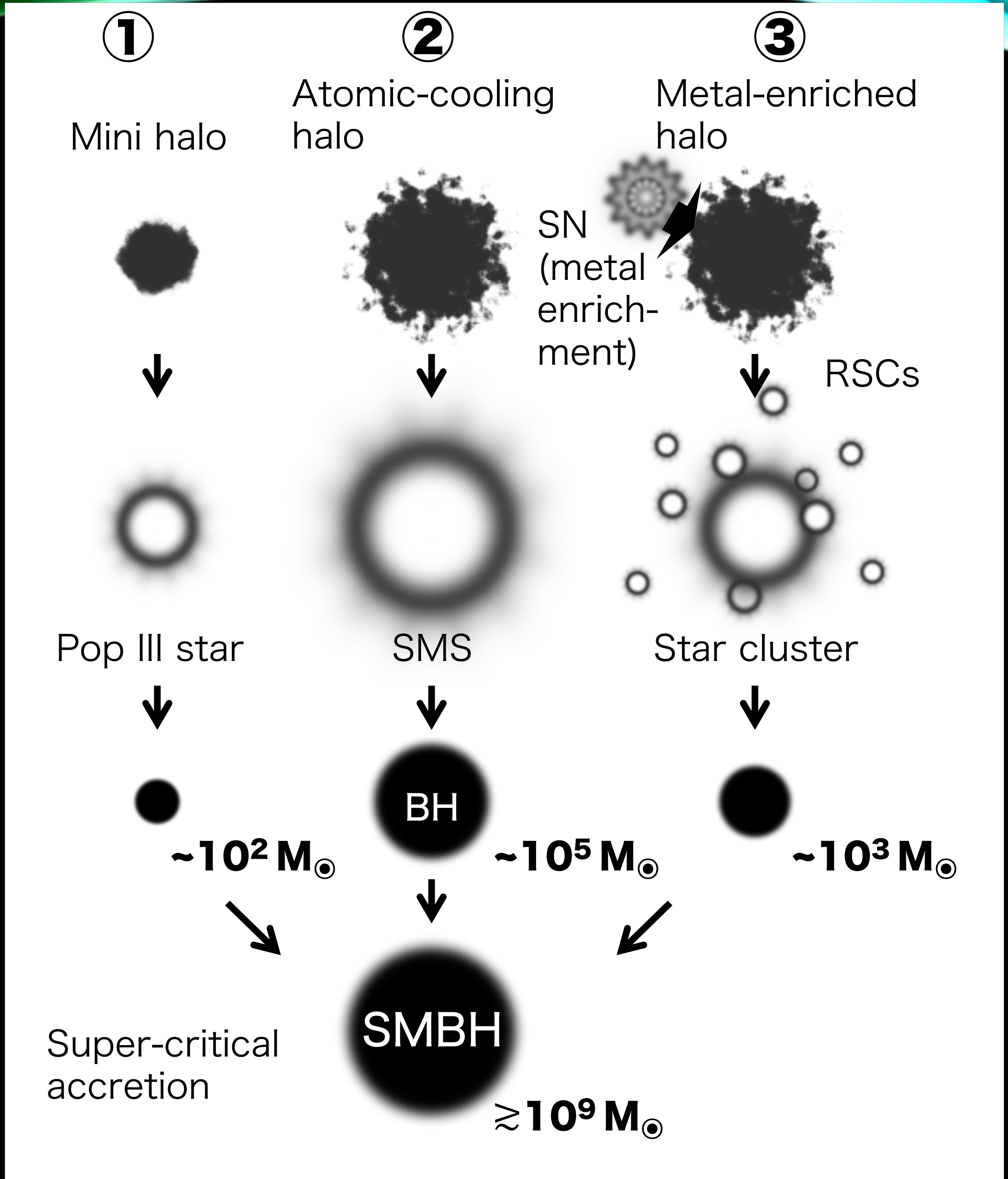
To alleviate the BH growth delay, alternative models are suggested

SMBH formation models

① Super-critical accretion

② SMS formation & DC

③ RSCs



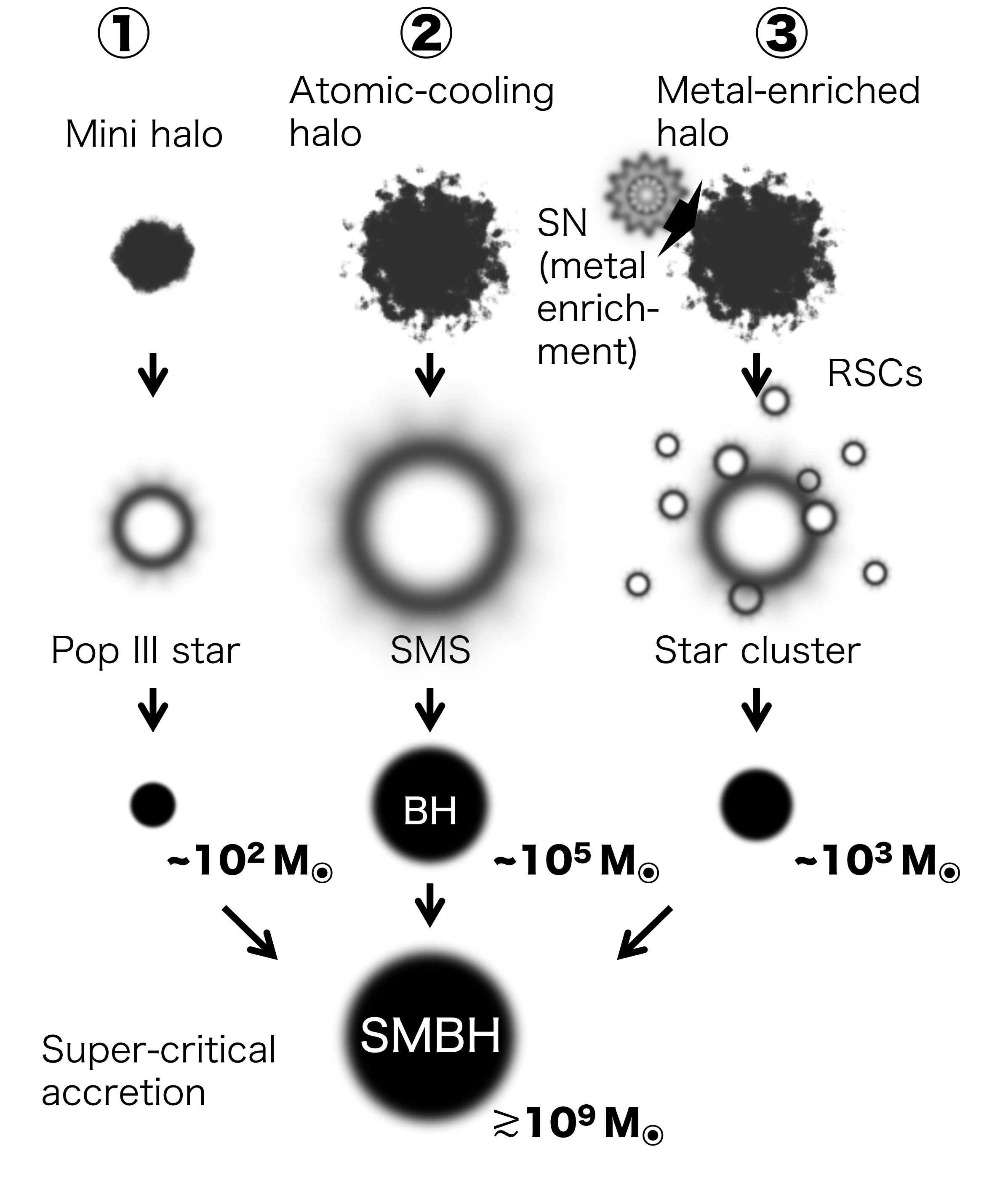
SMBH formation models

① Super-critical accretion

② SMS formation & DC

③ RSCs

Today's topic



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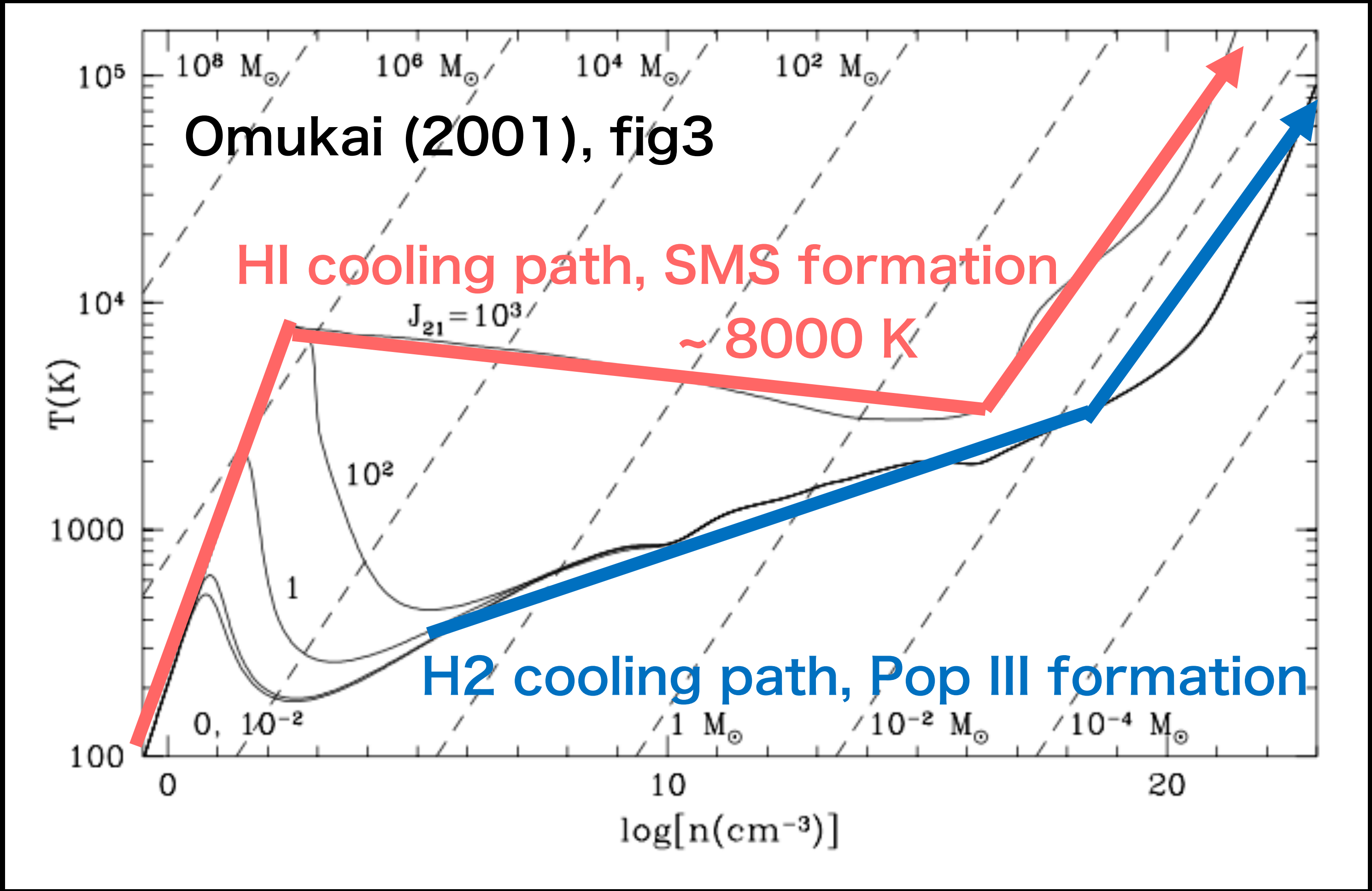
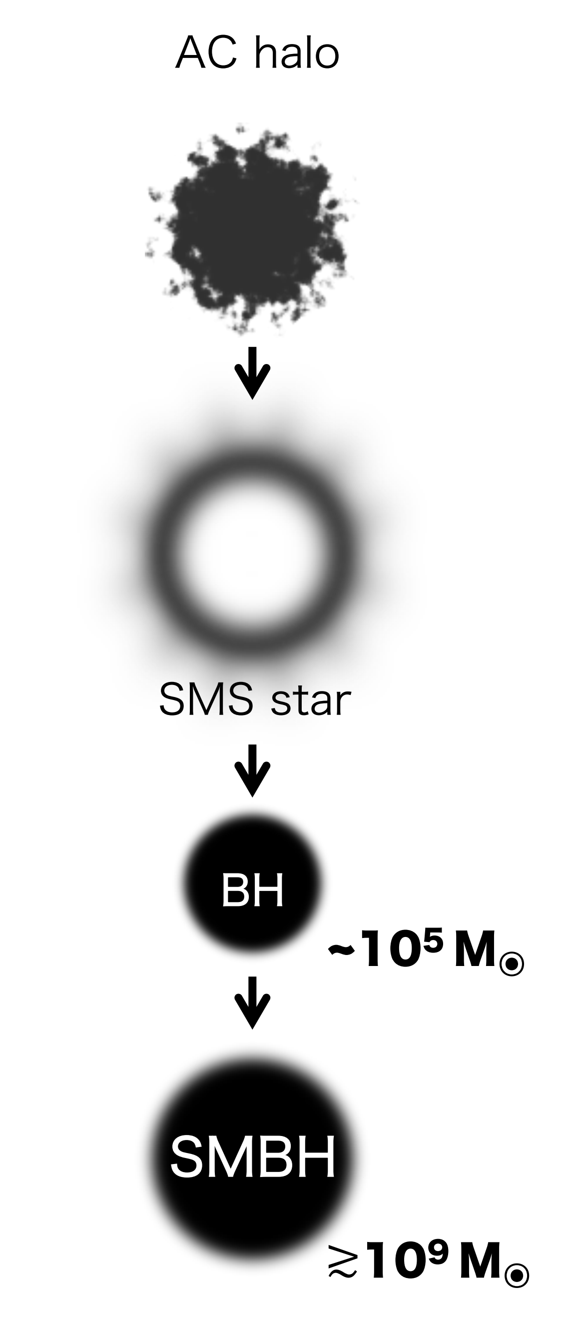
DC model

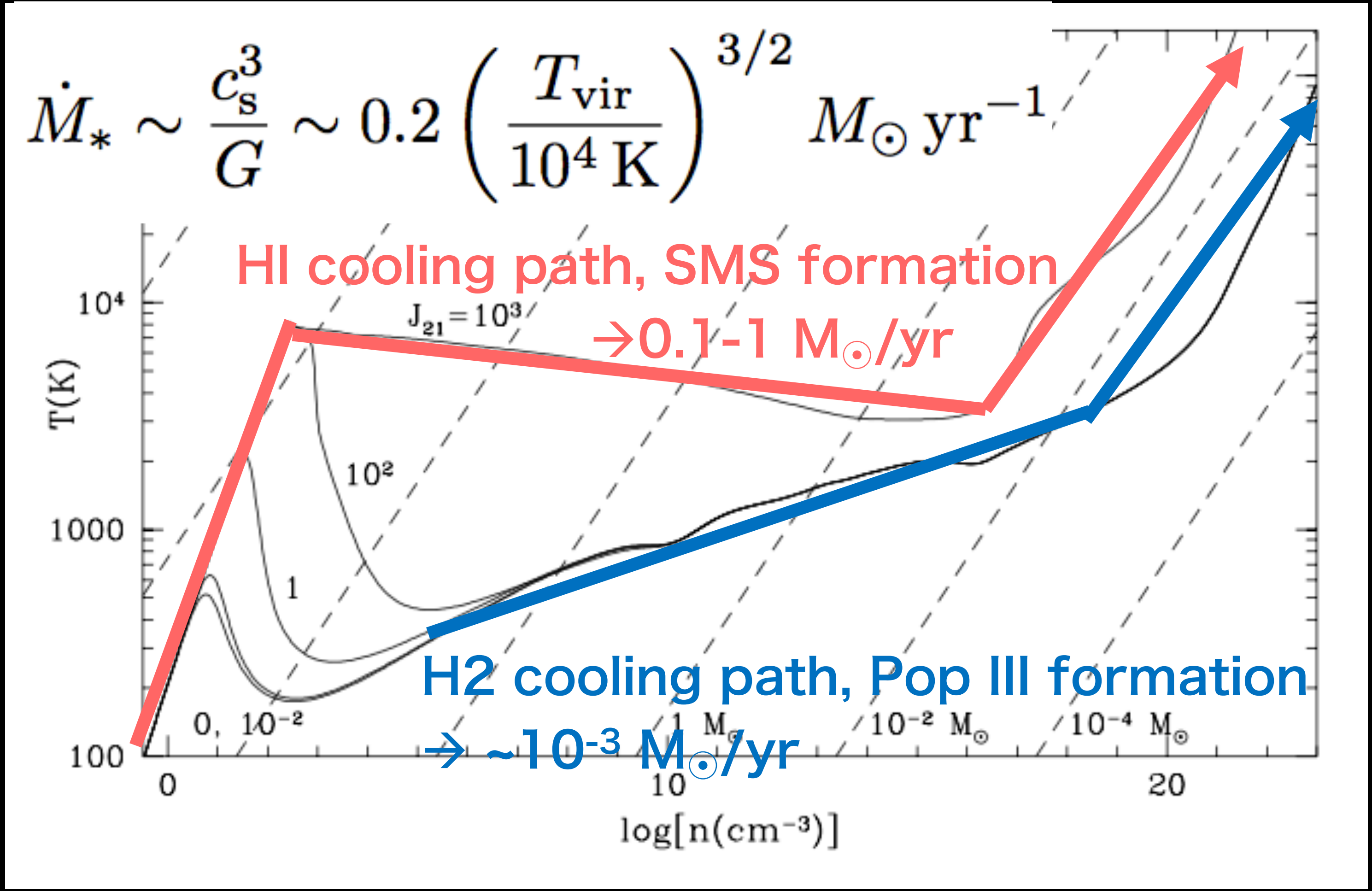
- SMS can form in an “atomic-cooling” (AC) halos which cool via mostly HI lines

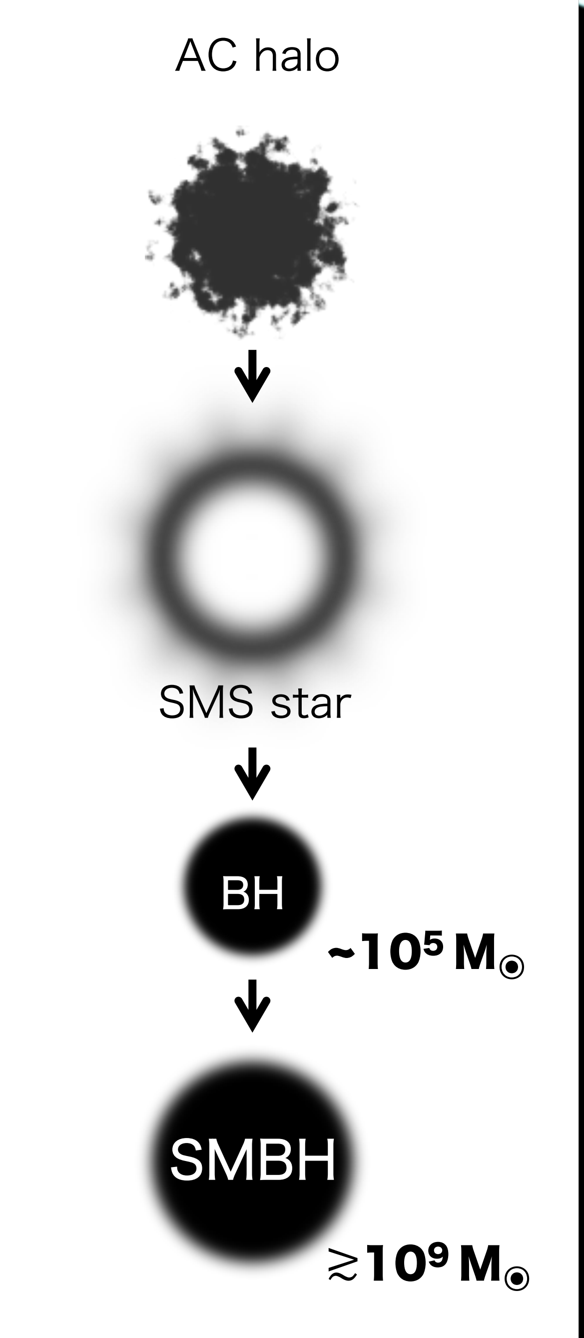




DC model

- High temperature leads to high accretion rates → more massive stars form





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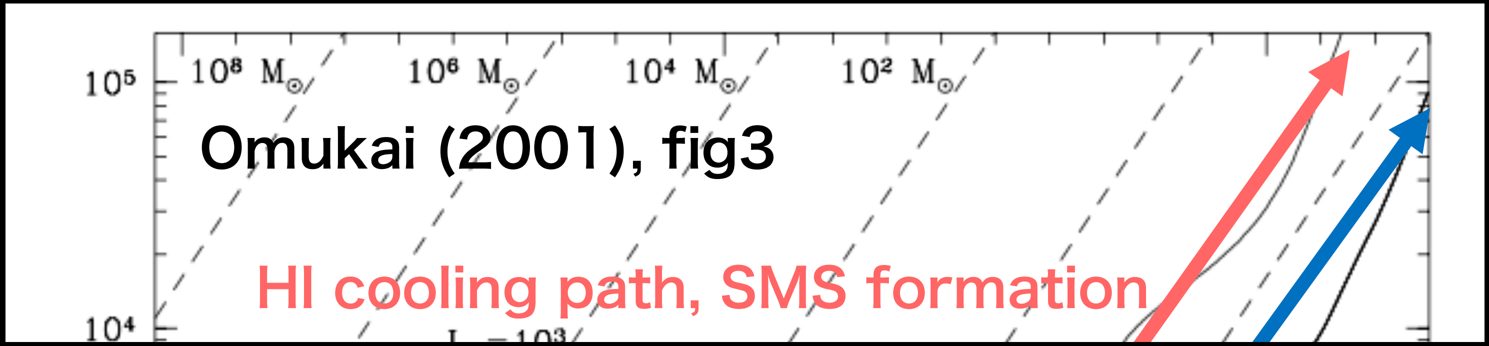
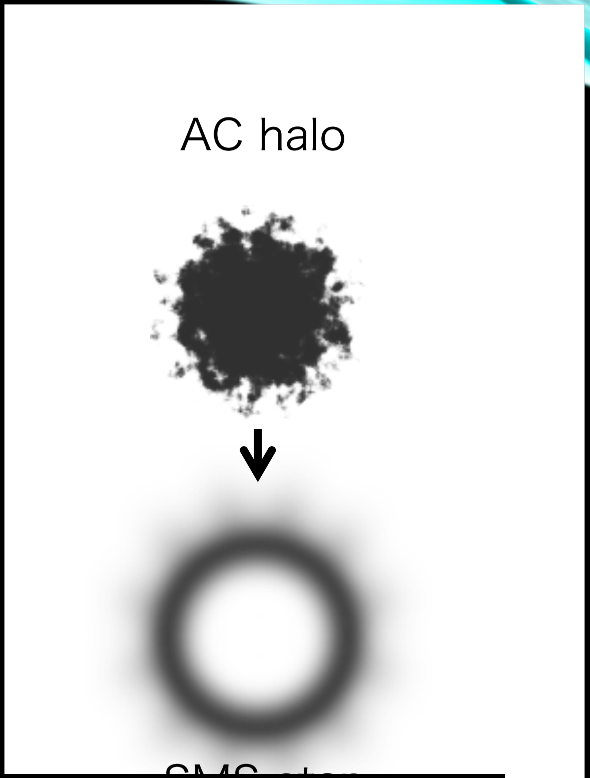




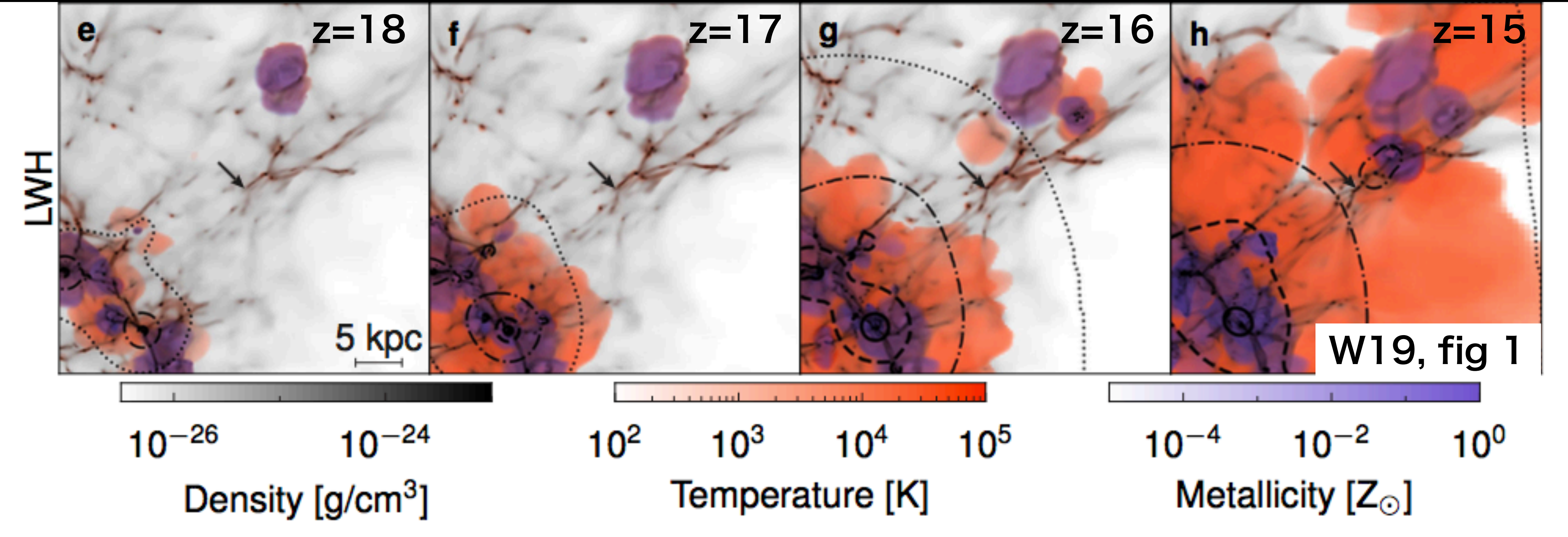
AC halo formation and SMS formation is usually thought to occur under the following conditions:

- **Extremely metal poor**
- **Irradiated by strong Lyman-Werner (LW) radiation**
- **Free from tidal force dispersion**

(e.g. Chon et al. 2016)

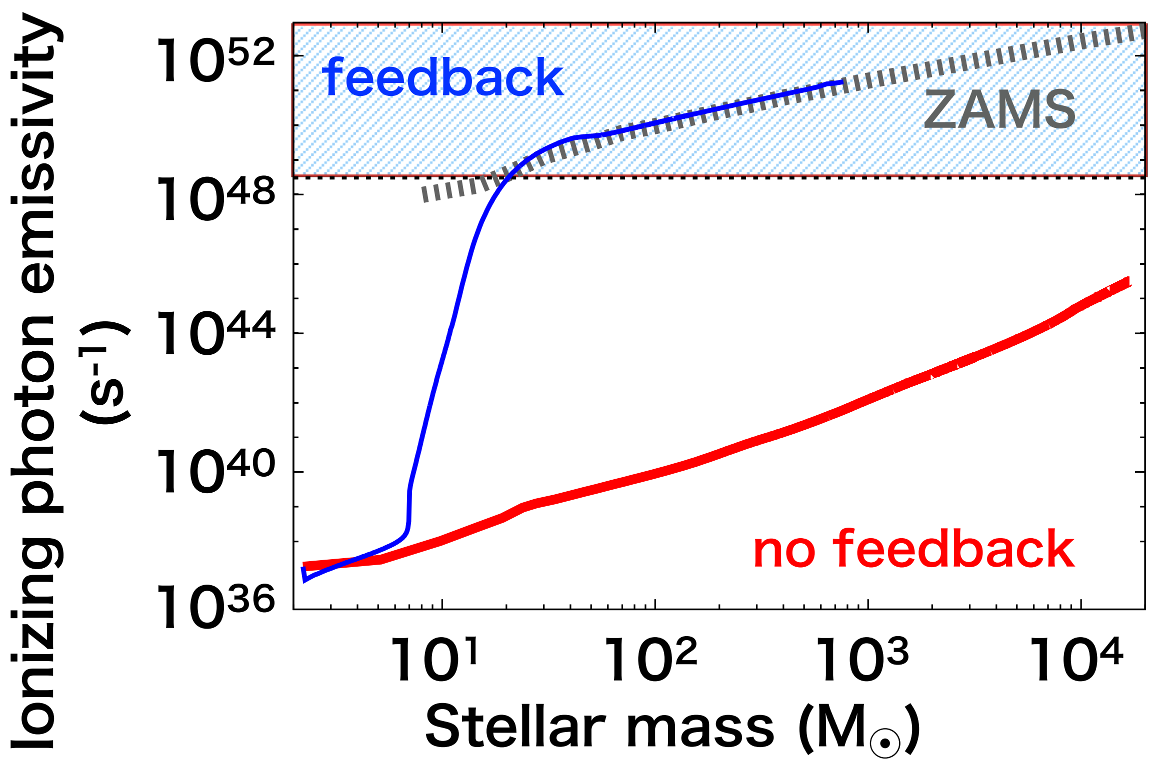
DC in dynamical heated DM halos

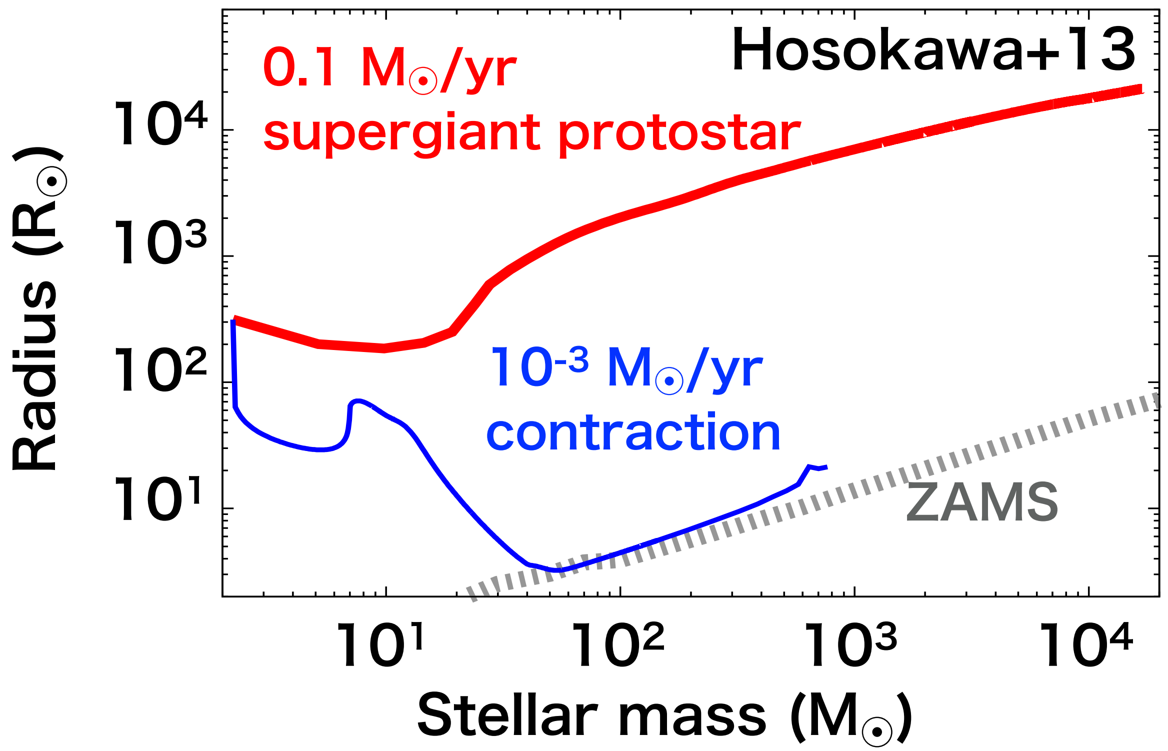
- Wise et al. (2019, hereafter W19) proposed another possibility for SMS formation:
  - ◆ Strong dynamical heating + moderate LW radiation can produce DC halos, even w/ H2



Do SMSs form in the halos of W19?

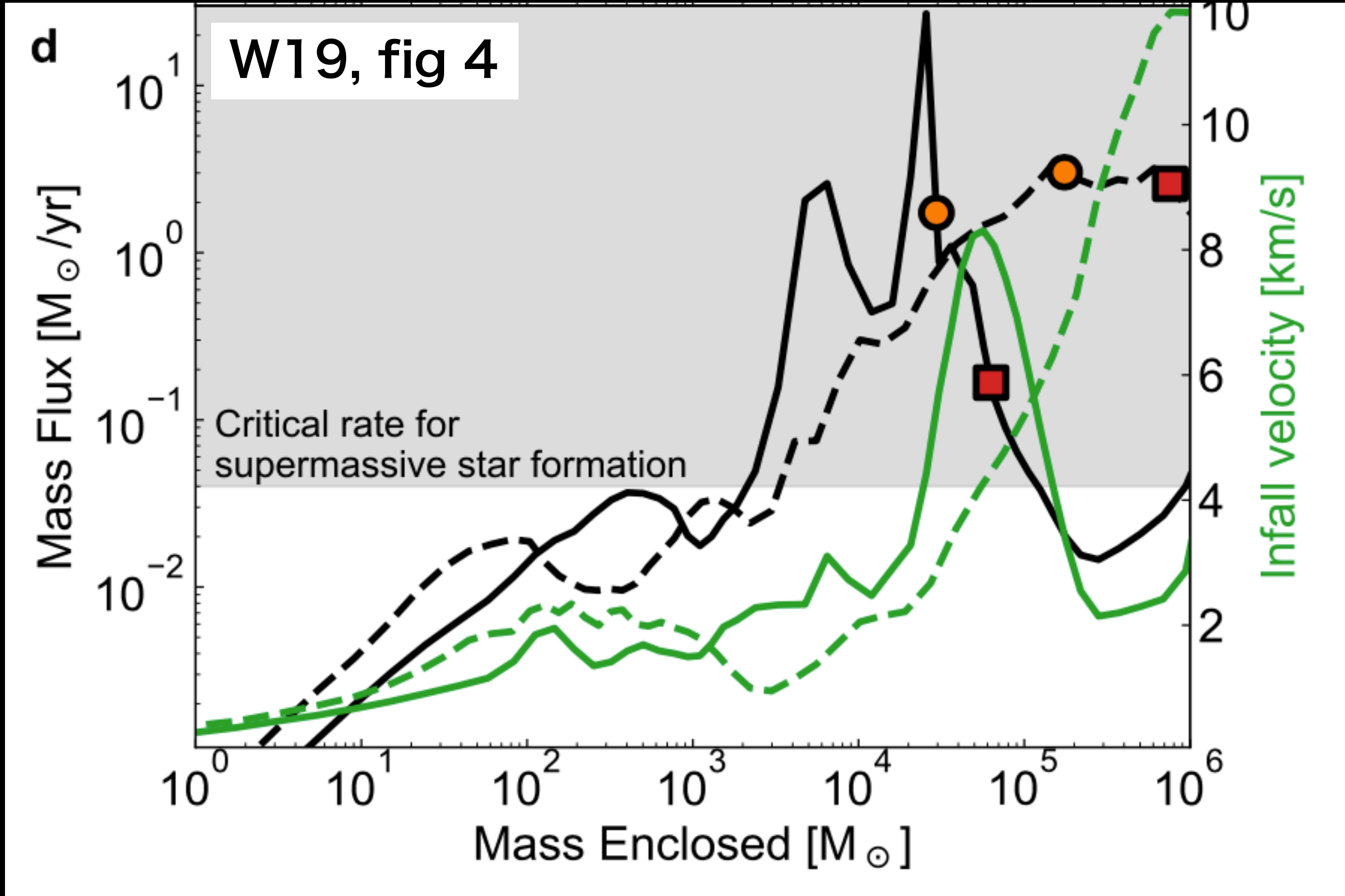
- W19 stopped simulations before star formation
- If stellar growth rate is <~ 0.04 $M_\odot$/yr, the growing protostar contracts and emits copious amounts of ionizing photons which can cause feedback





Do SMSs form in the halos of W19?

- W19 predicted small stellar growth rates <~ 0.04 $M_\odot$/yr for stellar masses <~ 10^3 $M_\odot$



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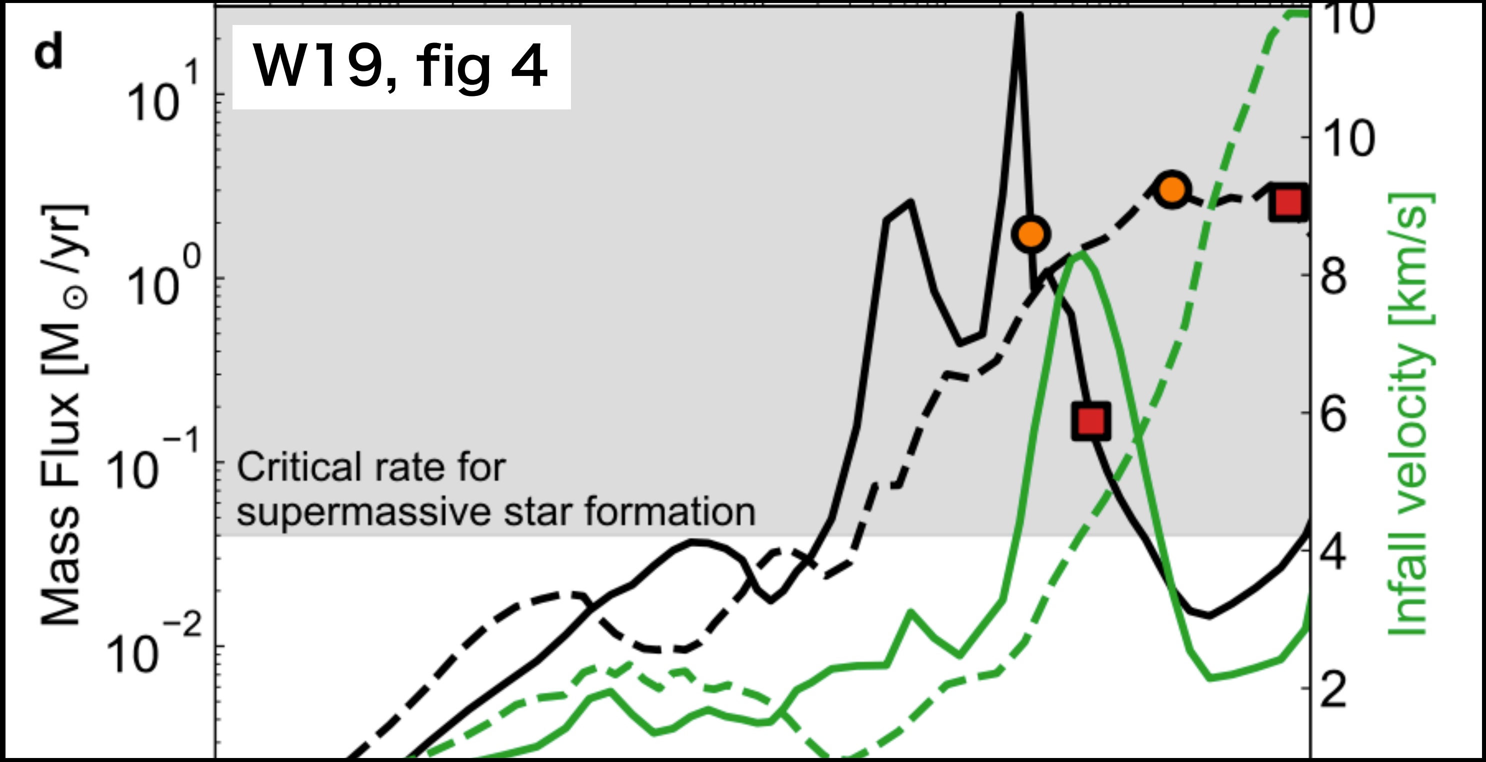

A growing protostar would contract, emit strong UV photons and may cause radiation feedback

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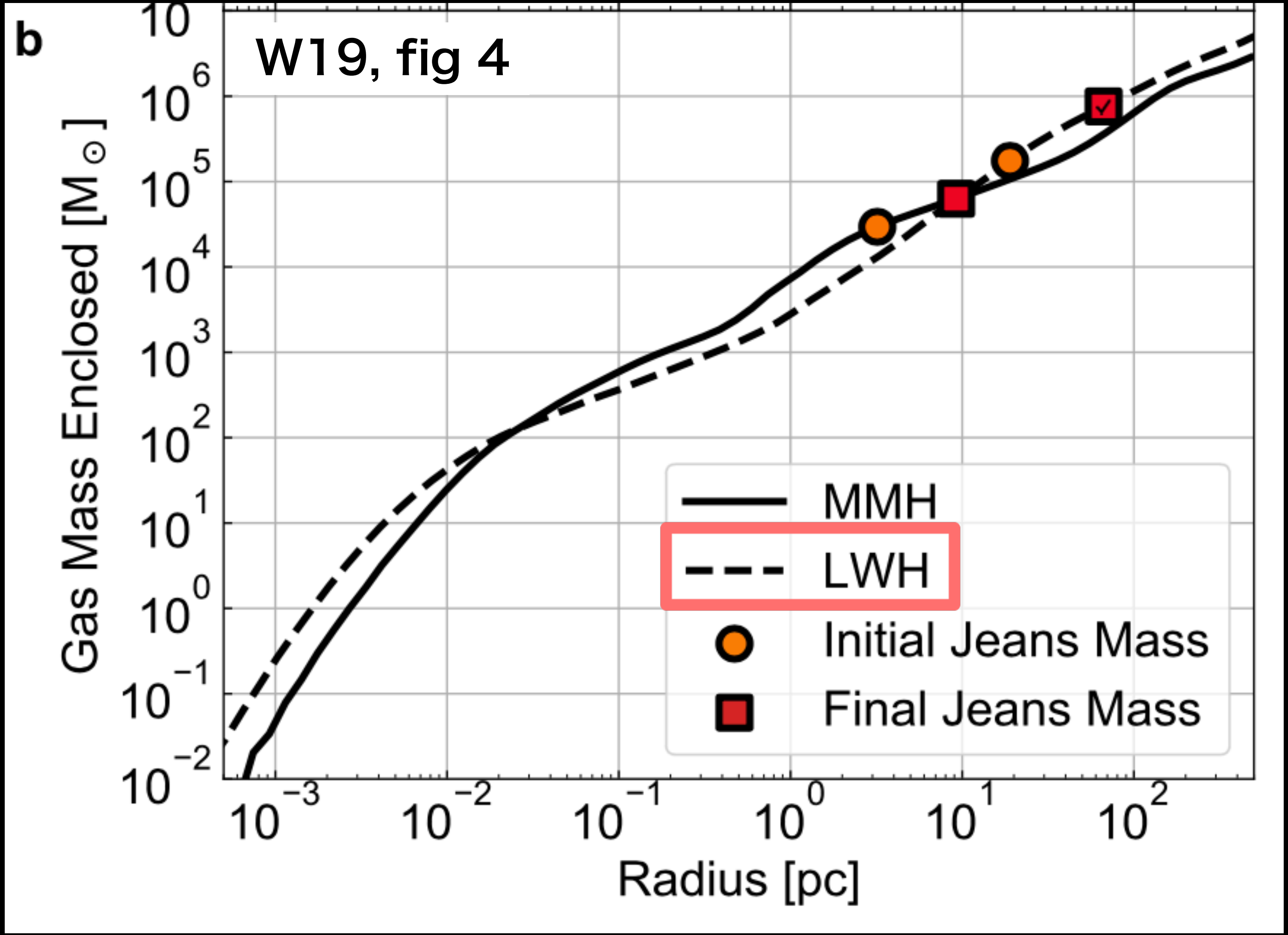
SMS formation in the halo of W19

- To judge whether the expectation is true, we performed 1D RHD simulations (Sakurai, Haiman & Inayoshi 2020)

- Initial conditions from the LWH halo in W19



Basic HD equations & chemistry

- 1D RHD simulations using the ZEUS code (Stone & Norman 1992)

continuity eq.

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0,$$

e.o.m

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r}\right) = -\frac{\partial p}{\partial r} - \rho\frac{\partial \Phi}{\partial r} + f_{\mathrm{rad}},$$

energy eq.

$$\rho\left(\frac{\partial e}{\partial t} + v\frac{\partial e}{\partial r}\right) = -p\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 v) - \Lambda + \Gamma,$$

chemical reactions & coolings
(9 species: H, H+, He, He+, He++, e-, H2, H2+, H-)

$$\frac{\partial n_i}{\partial t} = C_i - D_i n_i,$$

32 reactions

$$\Lambda = \Lambda_{\mathrm{H}} + \Lambda_{\mathrm{H_2}} + \Lambda_{\mathrm{H_2^+}} + \Lambda_{\mathrm{He}} + \Lambda_{\mathrm{H^+,rec}} + \Lambda_{\mathrm{He^+,rec}} + \Lambda_{\mathrm{ff}} + \Lambda_{\mathrm{H,col}} + \Lambda_{\mathrm{He,col}} + \Lambda_{\mathrm{H_2,dis}}.$$

Radiation transfer (RT)

- Steady state RT

$$F_{k,\nu} = \left(\frac{r_{k-1}}{r_k}\right)^2 F_{k-1,\nu} \exp\left[-(r_k - r_{k-1})\sum_i n_i \sigma_{i,\nu}\right]$$

Whalen & Norman (2006)

- # of frequency bins =50
- 0.04 eV < hν < 118 eV

- For LW radiation, we consider self-shieldings by H2 and HI (Wolcott-Green et al. 2011)

$$f_{\mathrm{sh},k+1}(N_{\mathrm{H_2}}, N_{\mathrm{HI}}, T, r) = \min(f_{\mathrm{sh,H_2},k+1} \times f_{\mathrm{sh,HI},k+1}, f_{\mathrm{sh},k}) \quad (9)$$

$$f_{\mathrm{sh,H_2}} = \frac{0.965}{(1+x/b_5)^{1.1}} + \frac{0.035}{(1+x)^{0.5}} \exp\left[-8.5\times10^{-4}(1+x)^{0.5}\right] \quad (10)$$

$$f_{\mathrm{sh,HI}} = (1 + x_{\mathrm{HI}})^{-1.6} \exp(-0.15 x_{\mathrm{HI}}) \quad (11)$$

where $f_{\mathrm{sh},0} = f_{\mathrm{sh,H_2},0} f_{\mathrm{sh,HI},0}$, $x \equiv N_{\mathrm{H_2}}/(5\times10^{14}\,\mathrm{cm^{-2}})$, $b_5 \equiv \sqrt{kT/m_{\mathrm{p}}}/(10^5\,\mathrm{cm\,s^{-1}})$ and $x_{\mathrm{HI}} \equiv N_{\mathrm{HI}}/(2.85\times10^{23}\,\mathrm{cm^{-2}})$

Photon processes

- H & He photo-ionizations, H- photo-dissociation and H2 photo-dissociations

Reactions								
H	$+$	γ	$\rightarrow$	H^+	$+$	e^-		
He	$+$	γ	$\rightarrow$	He^+	$+$	e^-		
He^+	$+$	γ	$\rightarrow$	He^{++}	$+$	e^-		
H_2	$+$	γ	$\rightarrow$	H_2^+	$+$	e^-		
H^-	$+$	γ	$\rightarrow$	H	$+$	e^-		
H_2^+	$+$	γ	$\rightarrow$	H	$+$	H^+		
H_2^+	$+$	γ	$\rightarrow$	$2H^+$	$+$	e^-		
H_2	$+$	γ	$\rightarrow$	$H_2^* \rightarrow$ H	$+$	H		

Reaction rates & heating rates

$$k_i = \int_{\nu_{\mathrm{th},i}} \frac{4\pi \hat{J}_\nu}{h\nu} \sigma_{i,\nu} \mathrm{d}\nu,$$

$$\Gamma_i = n_i \int_{\nu_{\mathrm{th},i}} \frac{4\pi \hat{J}_\nu}{h\nu} \sigma_{i,\nu} E_{\mathrm{heat},i} \mathrm{d}\nu,$$

Whalen & Norman (2006)

Radiation pressure force

$$f_{\mathrm{rad}} = \frac{n_e}{c} \int \sigma_{\mathrm{es}} F_\nu \mathrm{d}\nu + \frac{\Gamma}{c},$$

$$k_{\mathrm{LW}} = 1.1 \times 10^8 \frac{F_{k,\nu}}{\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}} \mathrm{s}^{-1}$$

$$\Gamma_{\mathrm{LW}} = 6.4 \times 10^{-13} n_{\mathrm{H_2}} k_{\mathrm{LW}} \,\mathrm{erg\,s^{-1}\,cm^{-3}}.$$

Abel et al. (1997)

Input radiation sources

- From center: Stellar BB + (putative) circum-stellar disk BB

$$F_{\mathrm{in},\nu} = F_{*,\nu} + F_{\mathrm{disc},\nu}$$

$$F_{*,\nu} = \pi \left(\frac{R_*}{r_{\mathrm{min}}} \right)^2 B_\nu(T_{\mathrm{eff}}),$$

$$F_{\mathrm{disc},\nu} = \frac{1}{6\pi r_{\mathrm{min}}^2 [(\nu_*/\nu_{\mathrm{min}})^{4/3} - 1]\nu_{\mathrm{min}}} \frac{GM_*\dot{M}}{R_*} \left(\frac{\nu}{\nu_{\mathrm{min}}} \right)^{1/3} \quad (\nu_{\mathrm{min}} \leqslant \nu \leqslant \nu_*), \quad (18)$$

where

$$\nu_* = 3.14 \times 10^{15}\ \mathrm{Hz} \times \left(\frac{M_*}{1\,\mathrm{M}_\odot} \right)^{1/4} \left(\frac{\dot{M}}{10^{-2}\,M_\odot\,\mathrm{yr}^{-1}} \right)^{1/4} \left(\frac{R_*}{1\,R_\odot} \right)^{-3/4}. \quad (19)$$

Note that the cutoff frequency $\nu_{\mathrm{cut}} \equiv \nu_*$, which corresponds to the frequency of the maximum flux of the optically thick disc, always remains below the maximum frequency $\nu_{\mathrm{max}} \simeq 2.85 \times 10^{16}$ Hz in our simulations. Since $h\nu_*$ is al-

- Background: LW background source (as in W19)

$$J_{\mathrm{LW}} = 3 \times 10^{-21} \mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$$

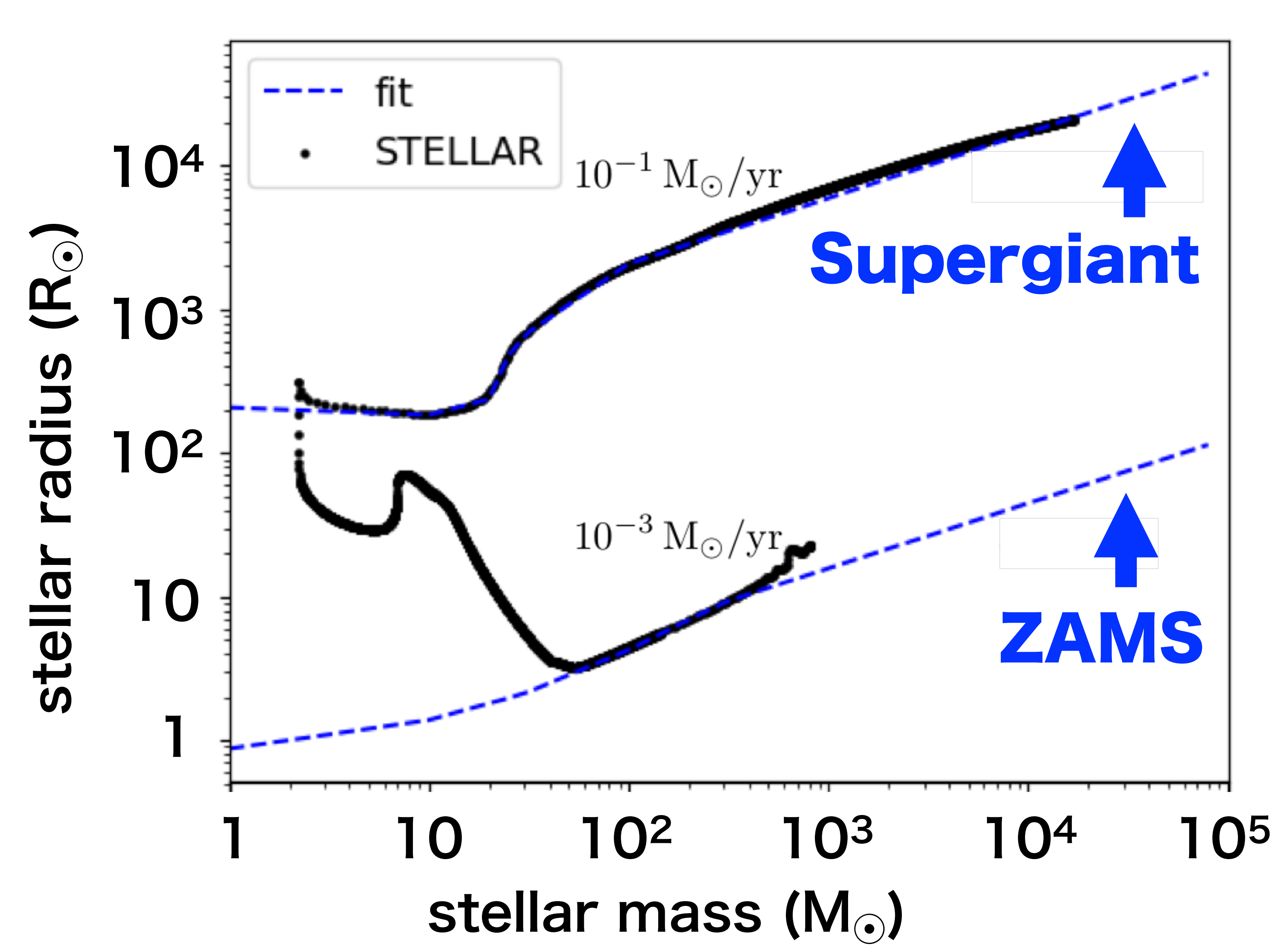
Grid parameters

- Grid points are logarithmically spaced
- r_{min} is chosen so that it is comparable to the star's initial gravitational radius

N	600
$r_{\rm min}$ (cm)	10^{16}
$r_{\rm max}$ (cm)	10^{20}
ϵ	1.008
$\nu_{\rm min}$ (Hz)	10^{13}
$\nu_{\rm max}$ (Hz)	2.85×10^{16}
N_ν	50

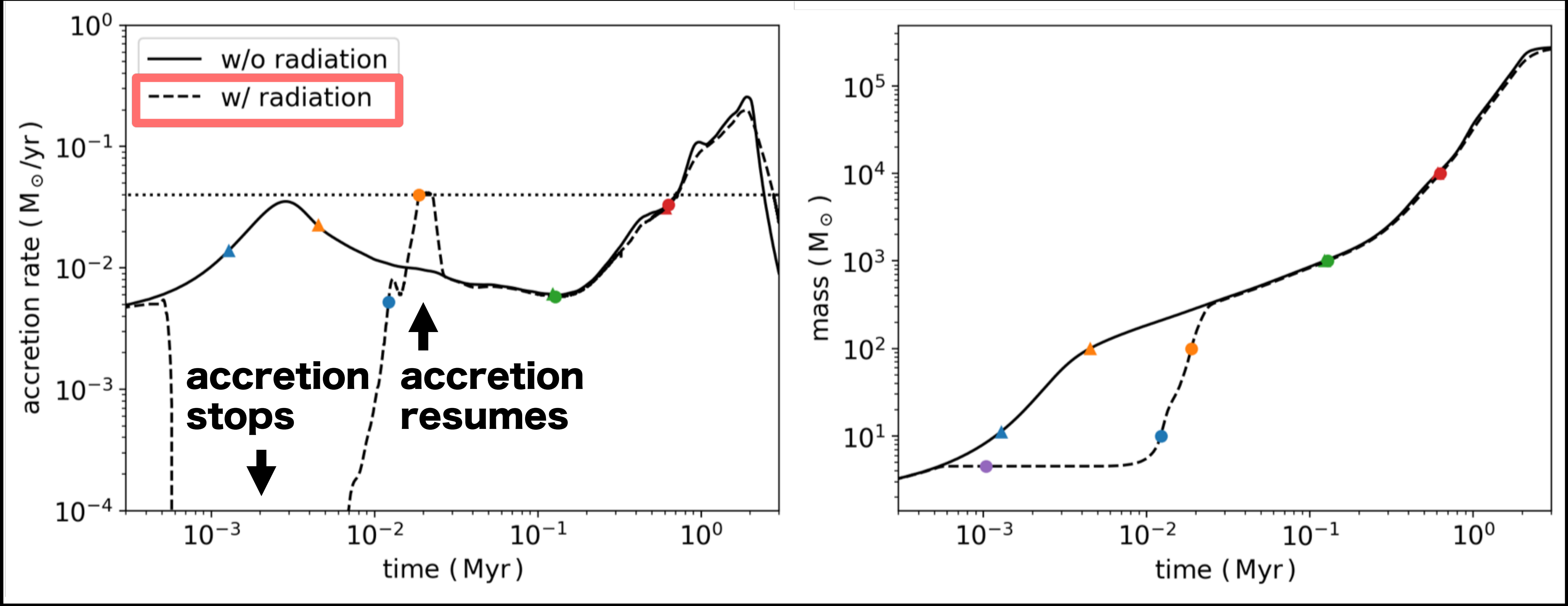
Fitting stellar models

- Fitting ZAMS models for <0.04 $M_\odot$/yr
- Fitting supergiant protostar models for >0.04 $M_\odot$/yr
- The latter models are fitted from calculations of the STELLAR code (Yorke & Bodenheimer 2008)
- $M_{star,ini}$= 2 $M_\odot$



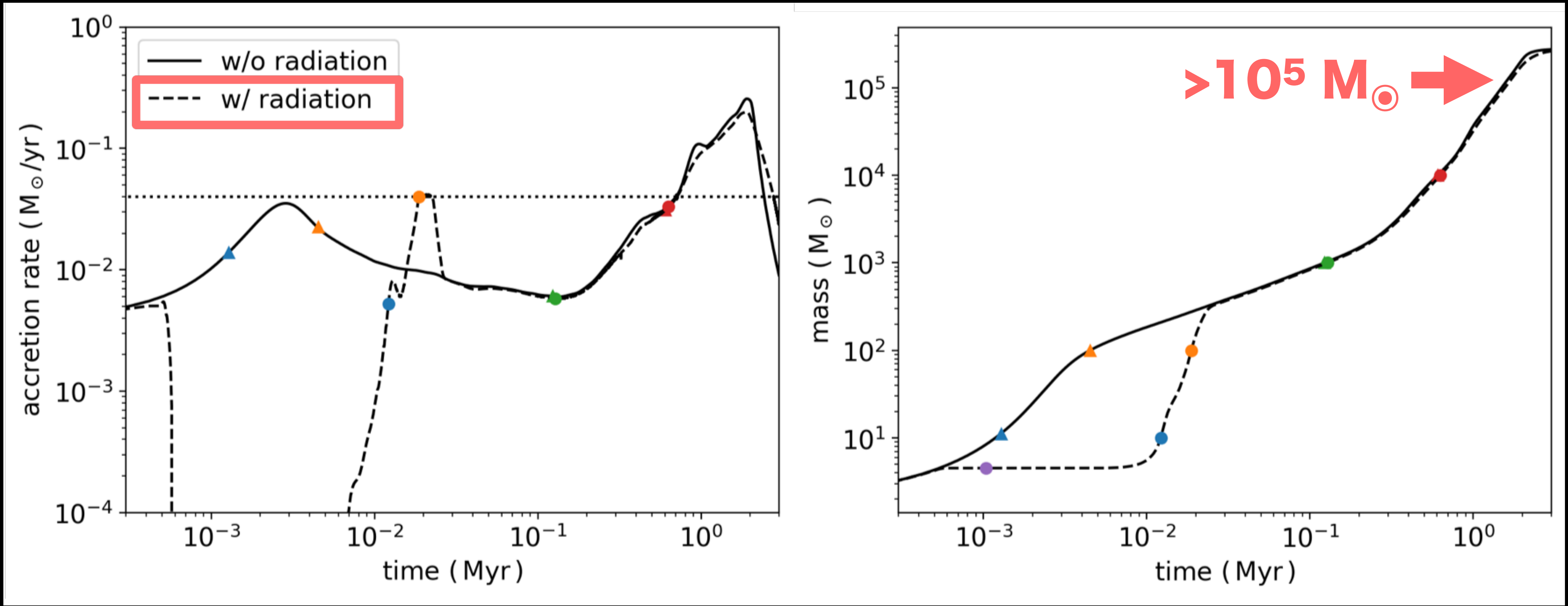
Accretion rates & stellar masses

- Radiation temporarily stops accretion @ 600-7000 yr
- The accretion rate recovers again @ >7000 yr



Accretion rates & stellar masses

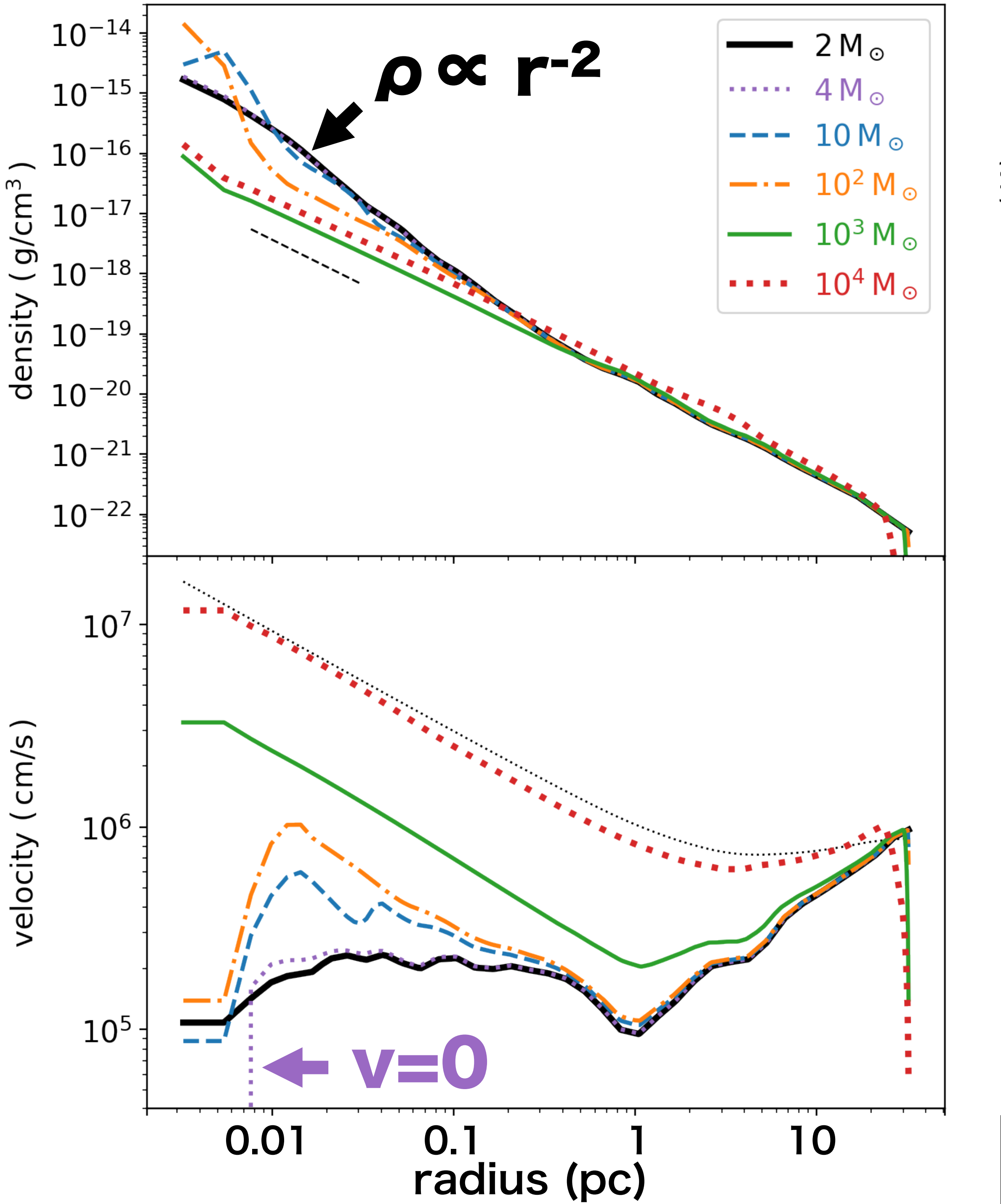
- Stellar masses grows to > 10^5 $M_\odot$
- **SMS forms** even with contracting protostars



Density & velocity (w/ radiation)

- Density is initially isothermal profile ∝ r^{-2} for r<1pc

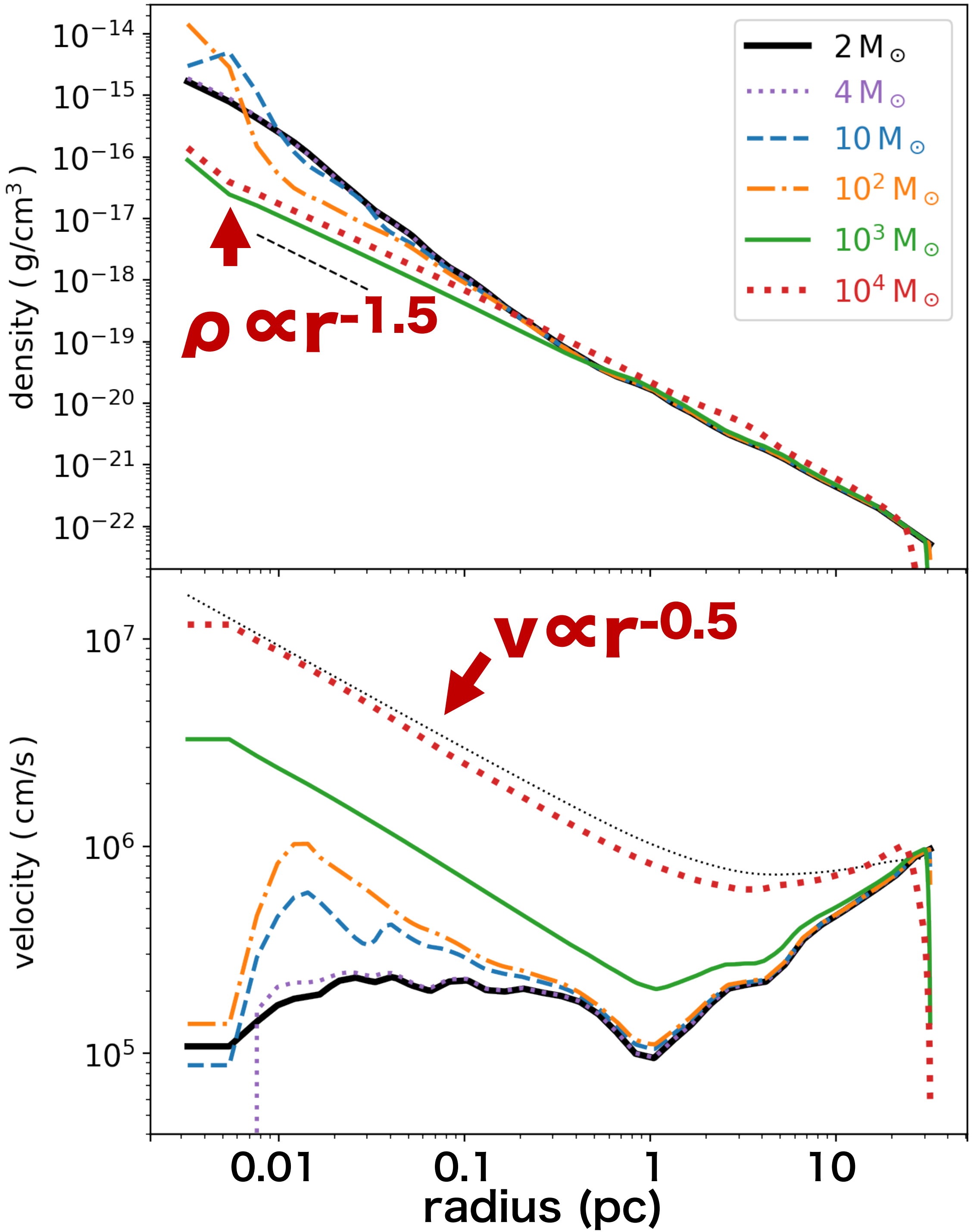
- While the accretion stops, inner density becomes high and inner velocity becomes 0 (r< 0.01 pc)



Density & velocity (w/ radiation)

- After the accretion rate recovers (M_{star}>100 $M_\odot$), the density profile follows a free-fall one ∝ $r^{-1.5}$

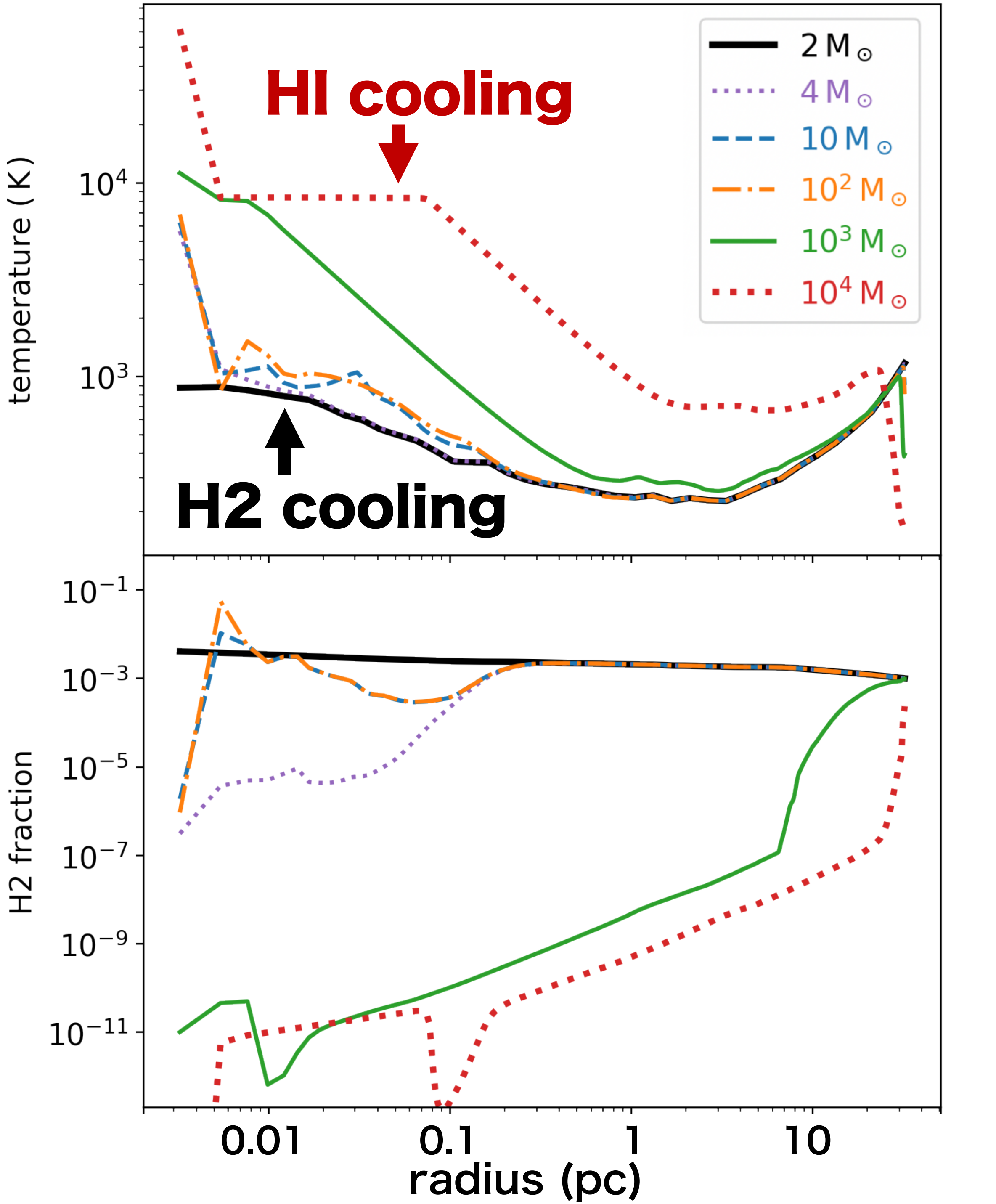
- The velocity becomes free-fall velocity for r <~1 pc



Temperature & H2 fraction

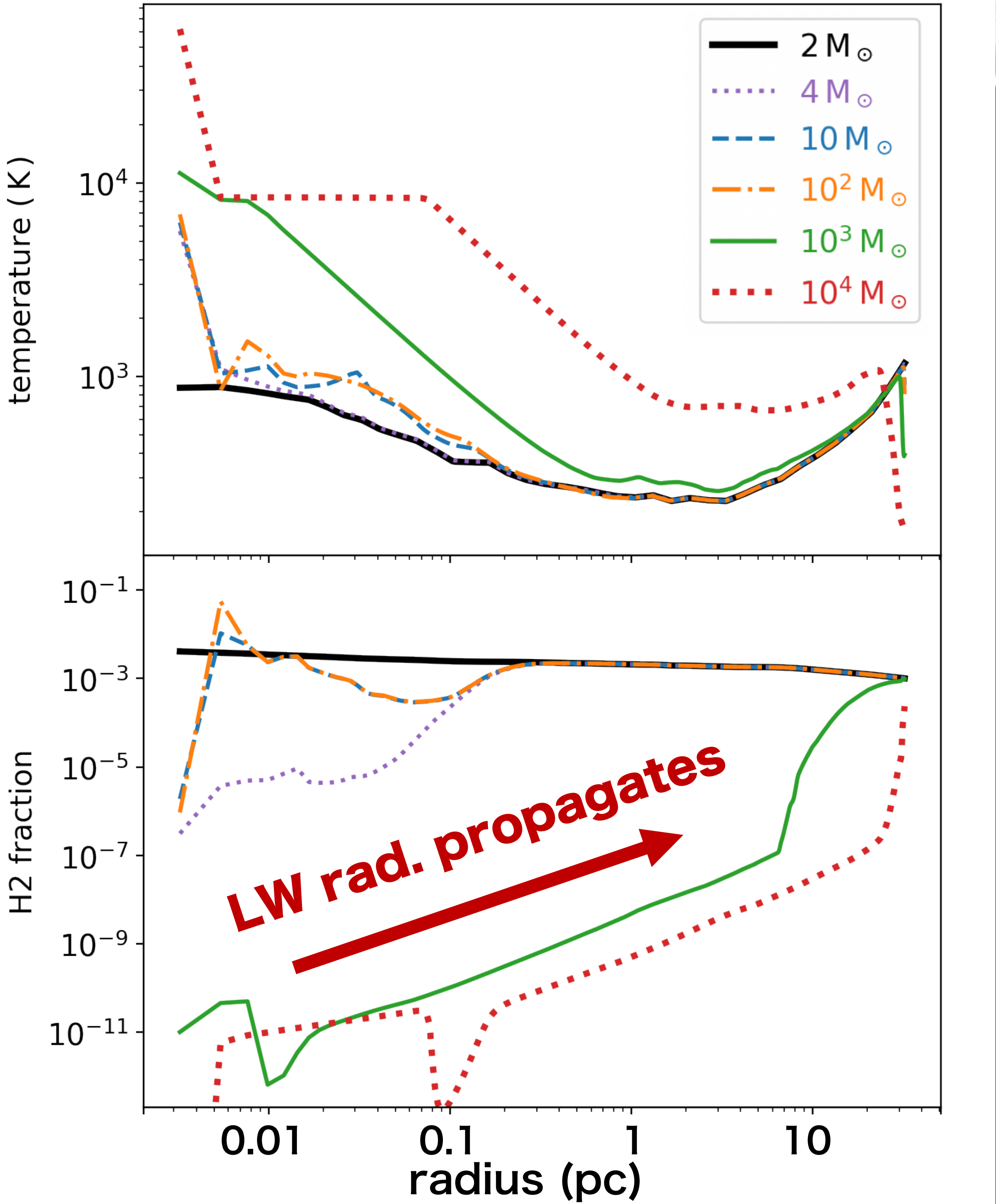
- Temperature is initially <~ 1000 K due to effective H2 cooling

- After the accretion rate recovers (M_{star}>100 $M_\odot$), the central temperature reaches ~ 8000 K where HI cooling is effective



Temperature & H2 fraction

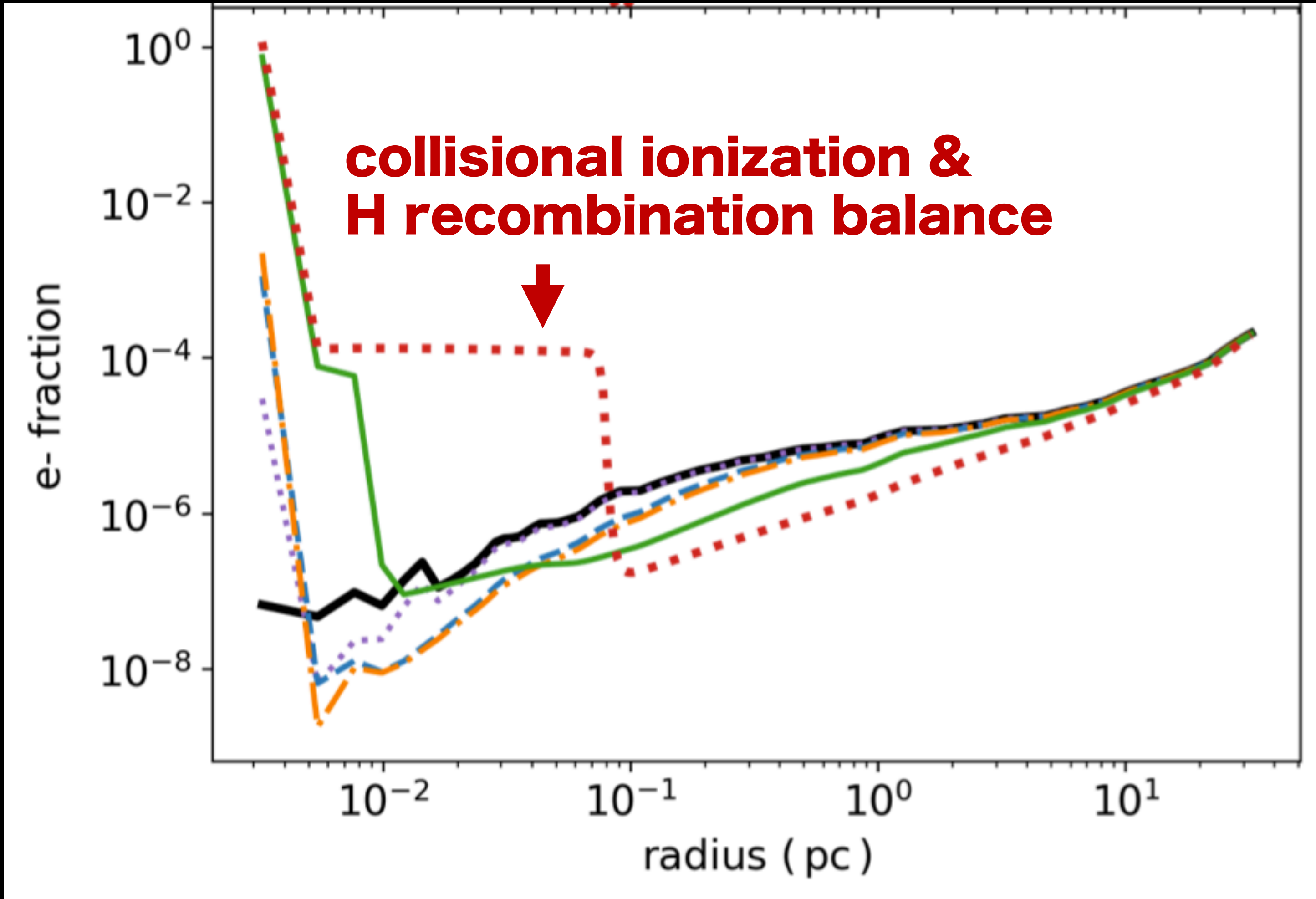
- For $M_{star} > 100\ M_\odot$, the central stellar LW radiation propagates out and dissociates H2 in the outer region (r <~10 pc)



Electron fraction

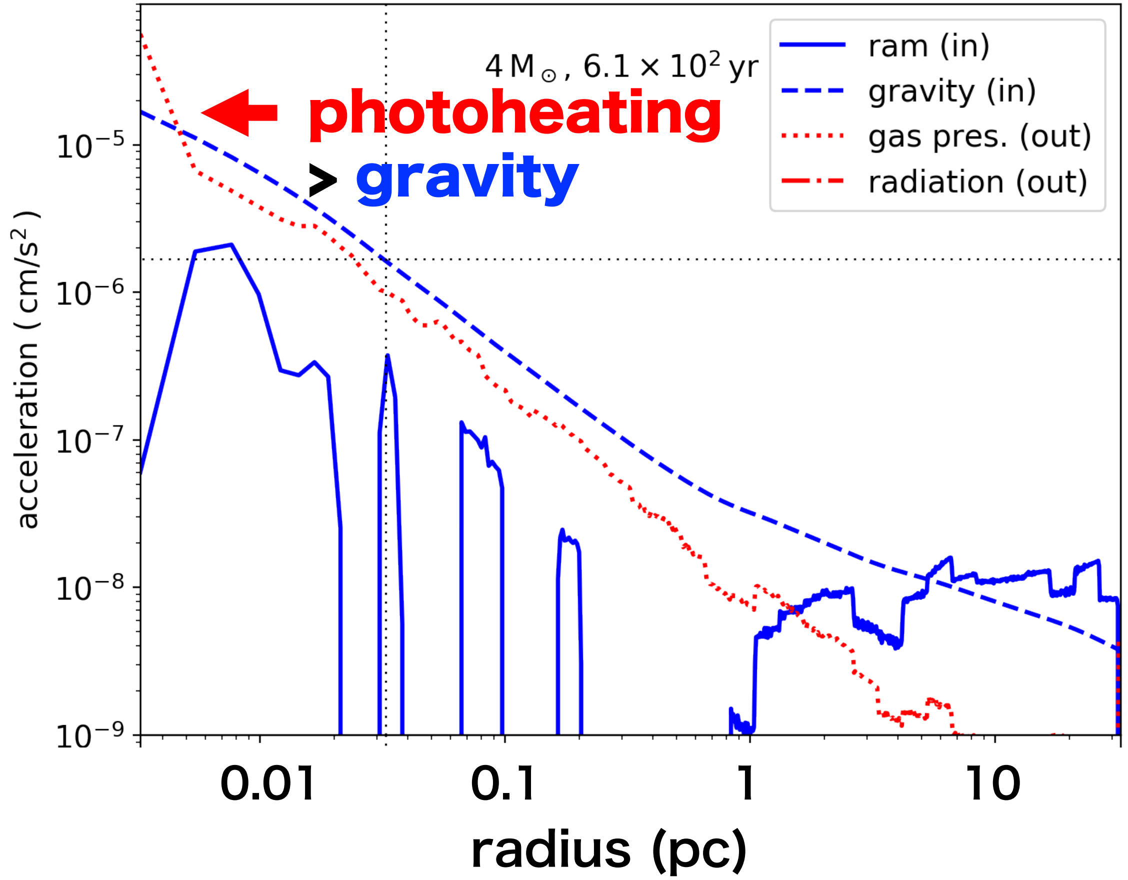
- At M_{star}~10^4 $M_\odot$, a fully ionized region (r<0.005 pc) and partially ionized region (0.005pc < r < 0.07 pc) form

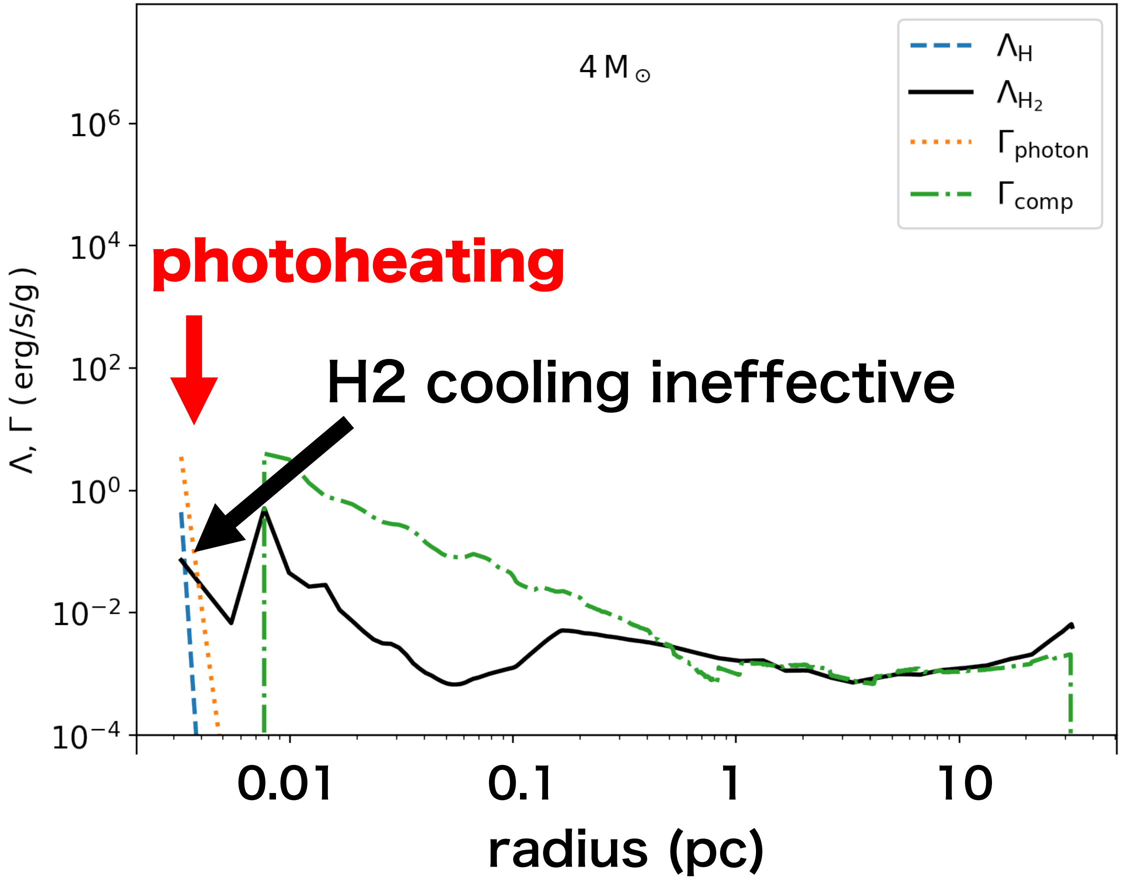
- Despite the strong stellar EUV radiation, the HII region does not expand due to high density and effective H recombination



Reason why the inflow is stopped

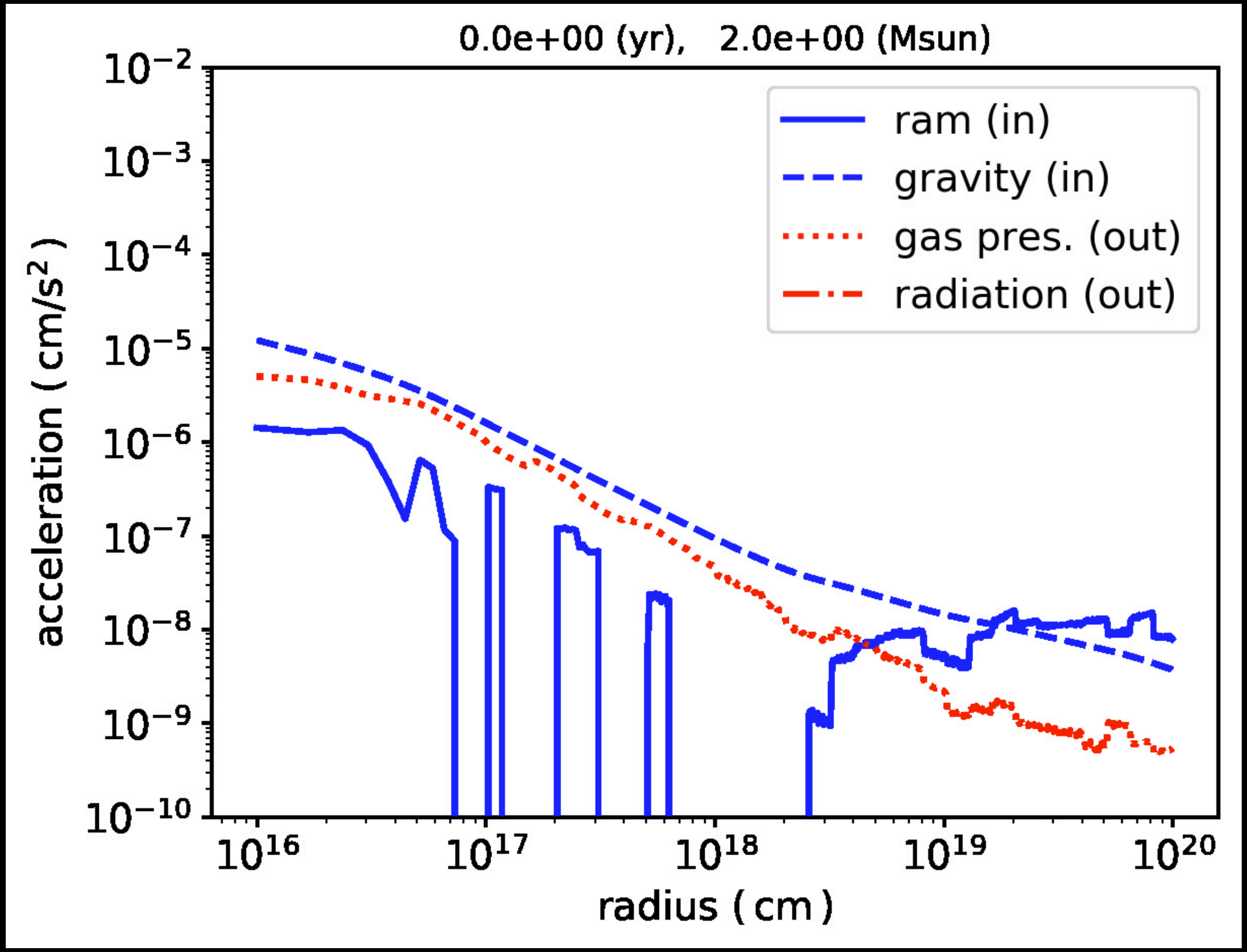
- Photoheating overcomes gravity while H2 is dissociated and H2 cooling becomes ineffective





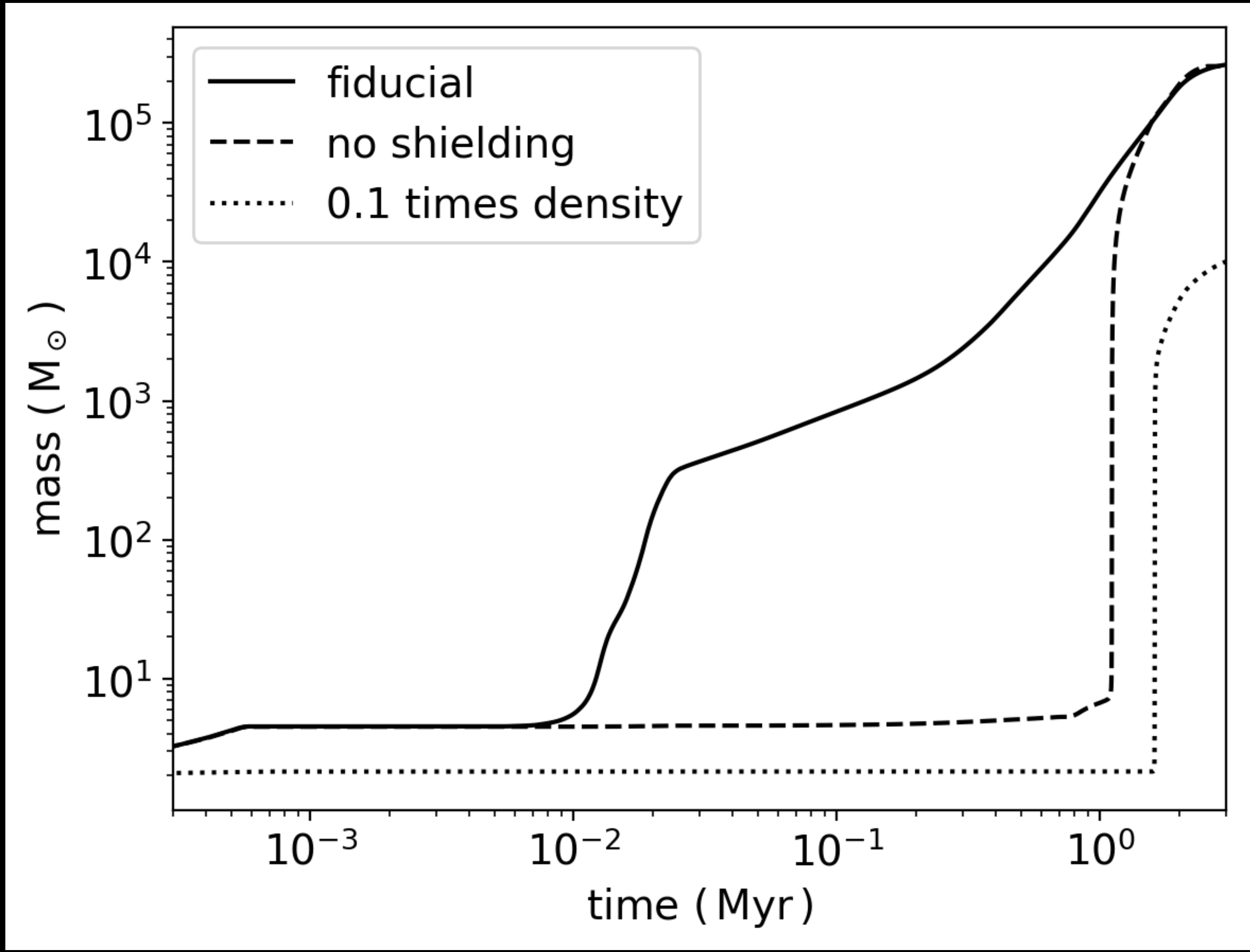
Reason why the inflow resumes

- The self-gravity of the gas builds up as the outer shells fall in and accumulate



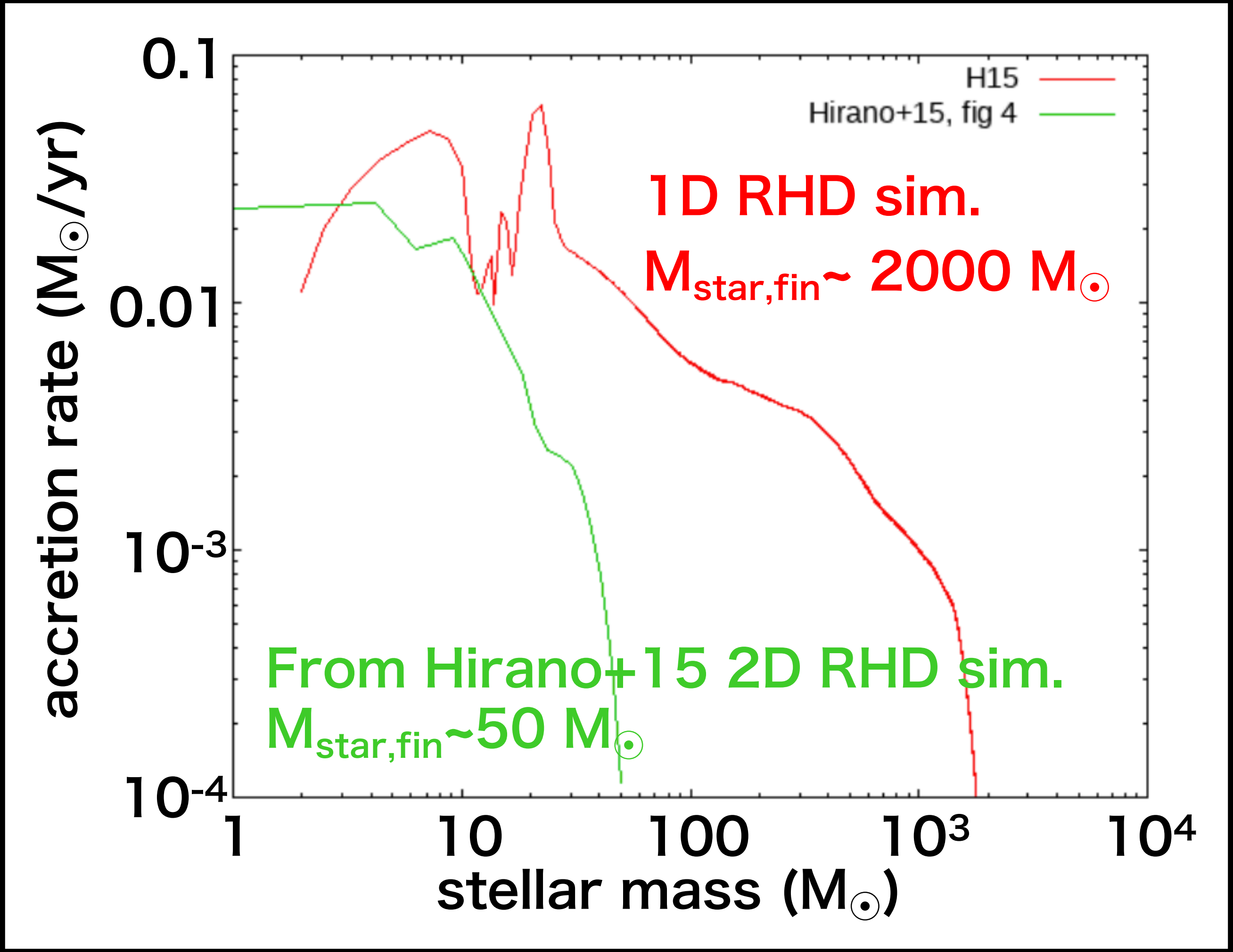
Impact of the parameters

- SMS >~ 10^4-10^5 $M_\odot$ forms even if there is no self-shielding, or even if the gas density is 0.1 times smaller



Comparison to other works

- We performed a simulation for a Pop III formation case with an initial condition from Hirano et al. (2015)



Caveats

- Spherical assumption
  - ◆ If an accretion disk forms, radiation can more easily escape from polar regions and can more suppress the accretion

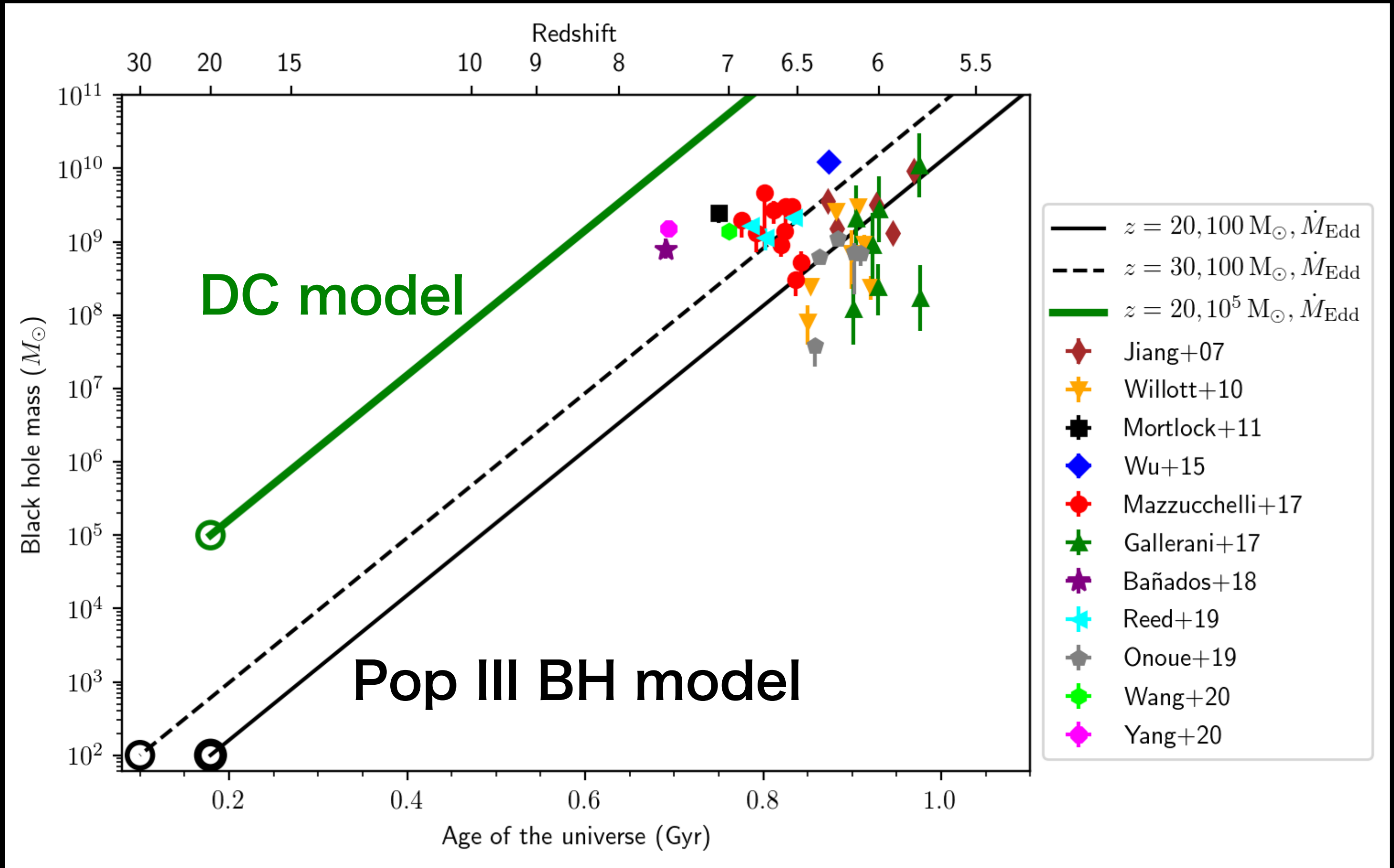
  - ◆ Turbulence and grav. interactions between stars can make the central star move to a lower density region (Regan et al. 2020)

  - ◆ Outflows and magnetic fields can also suppress the stellar growth (e.g. Rosen & Krumholz 2020)

Summary

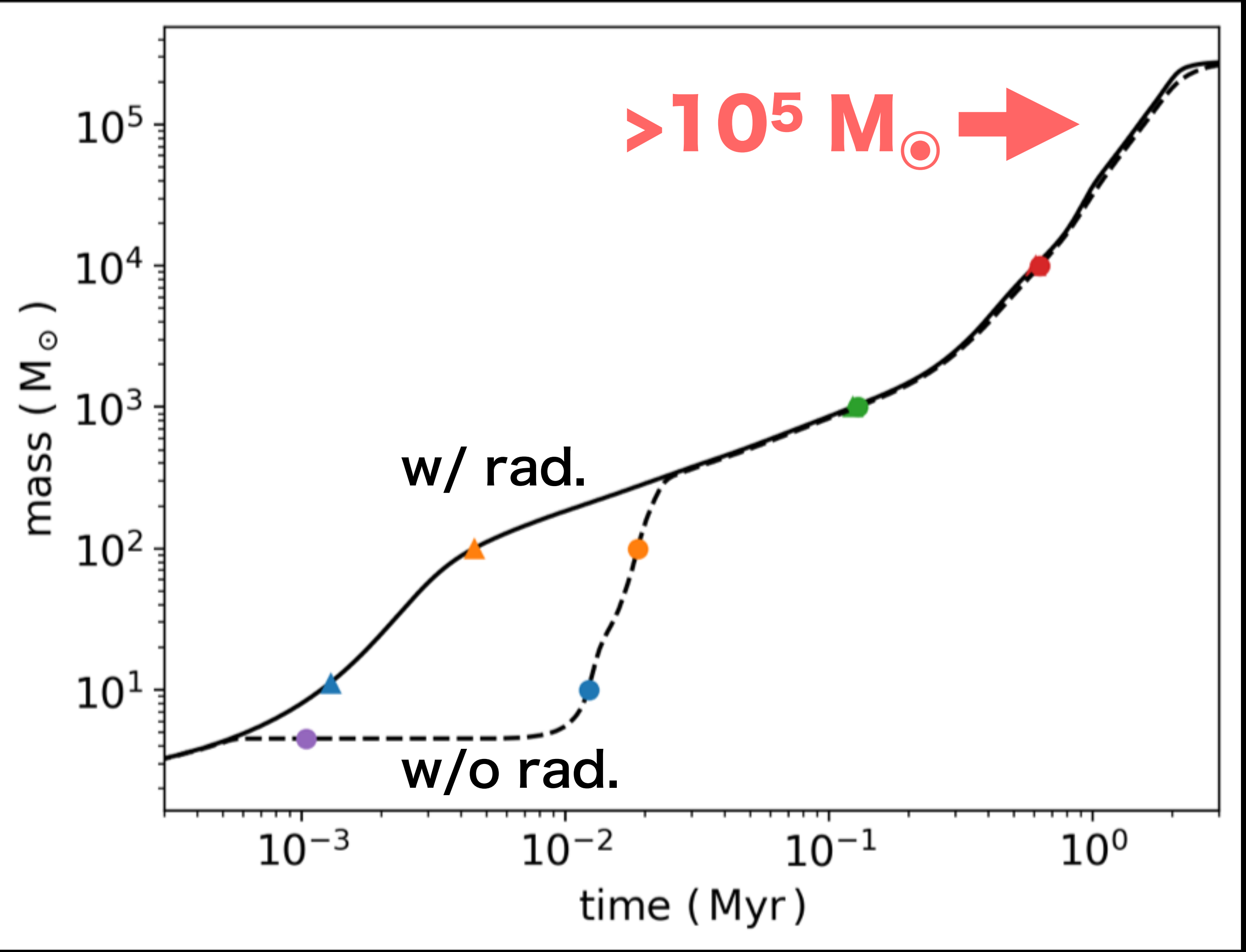
- Several SMBHs at high-z >~ 6 are observed but their origins are still uncertain

- The DC model is a promising model for explaining the origin



Summary

- We study whether SMS can form in a dynamically heated halo of W19 by 1D RHD simulations
- SMS > 10^5 $M_\odot$ forms even with strong stellar EUV radiation
- Multi dimensional studies with detailed physics are needed

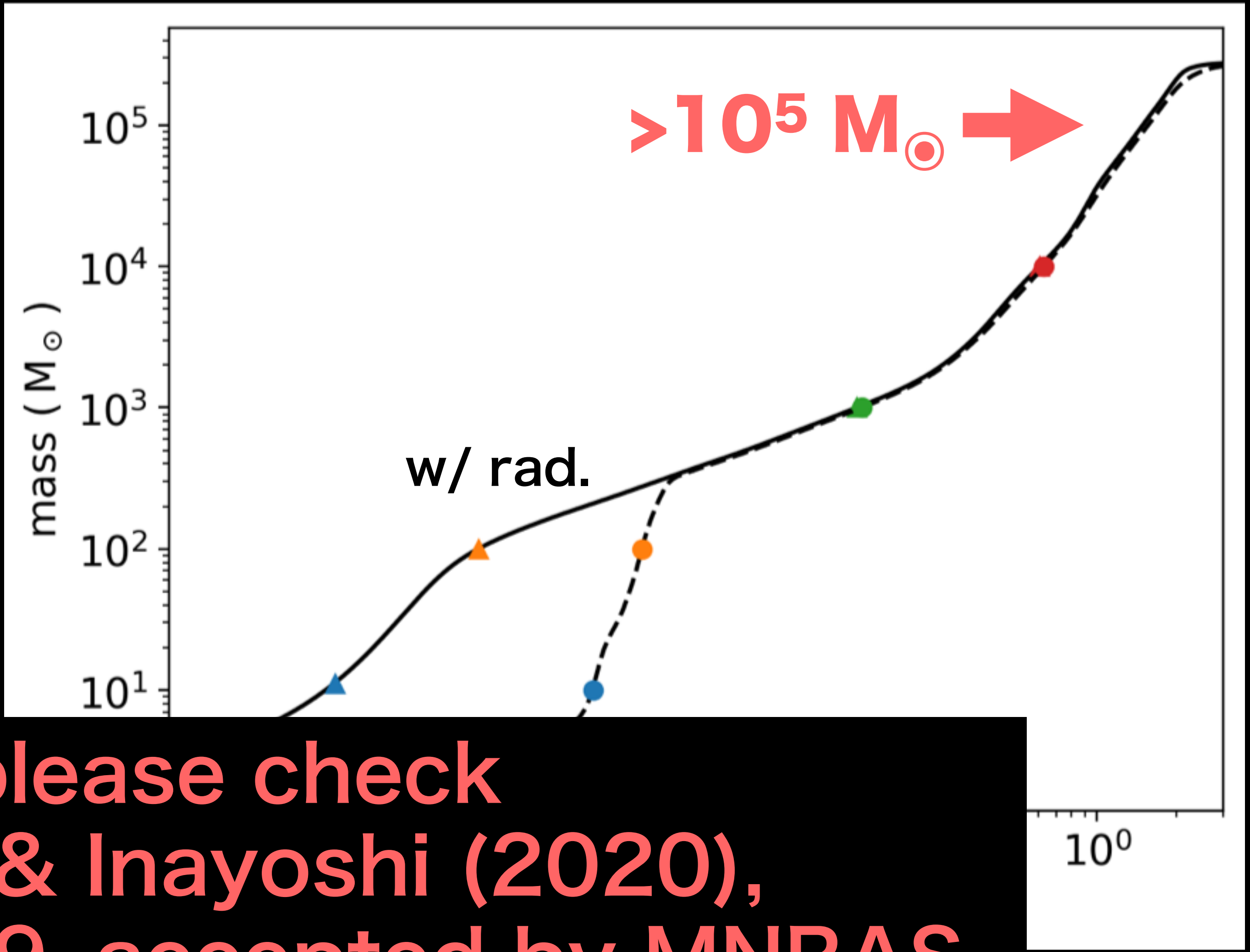


Summary

- We study whether SMS can form in a dynamically heated halo of W19 by 1D RHD simulations

- SMS > 10^5 $M_\odot$ forms even with strong stellar EUV radiation

- Mu stuc phy



For more detail please check Sakurai, Haiman & Inayoshi (2020), arXiv:2009.02629, accepted by MNRAS

Thank you for your attention