超大質量ブラックホール形成

Formation of Supermassive Black Holes

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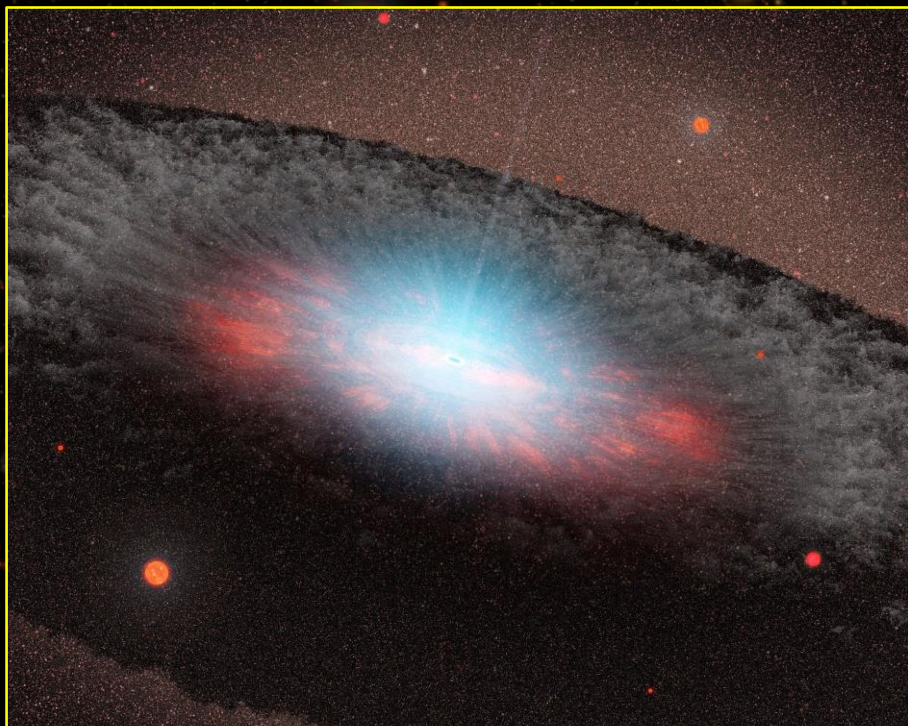
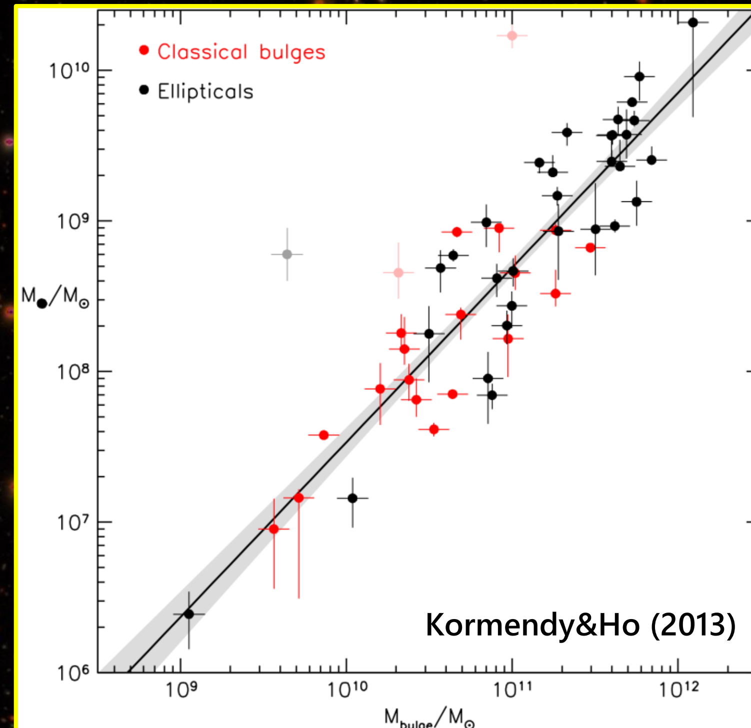
First Star & First Galaxy 2018 @ Kure, Hiroshima (Feb 10-12, 2018)

SuperMassive Black Hole (SMBH)

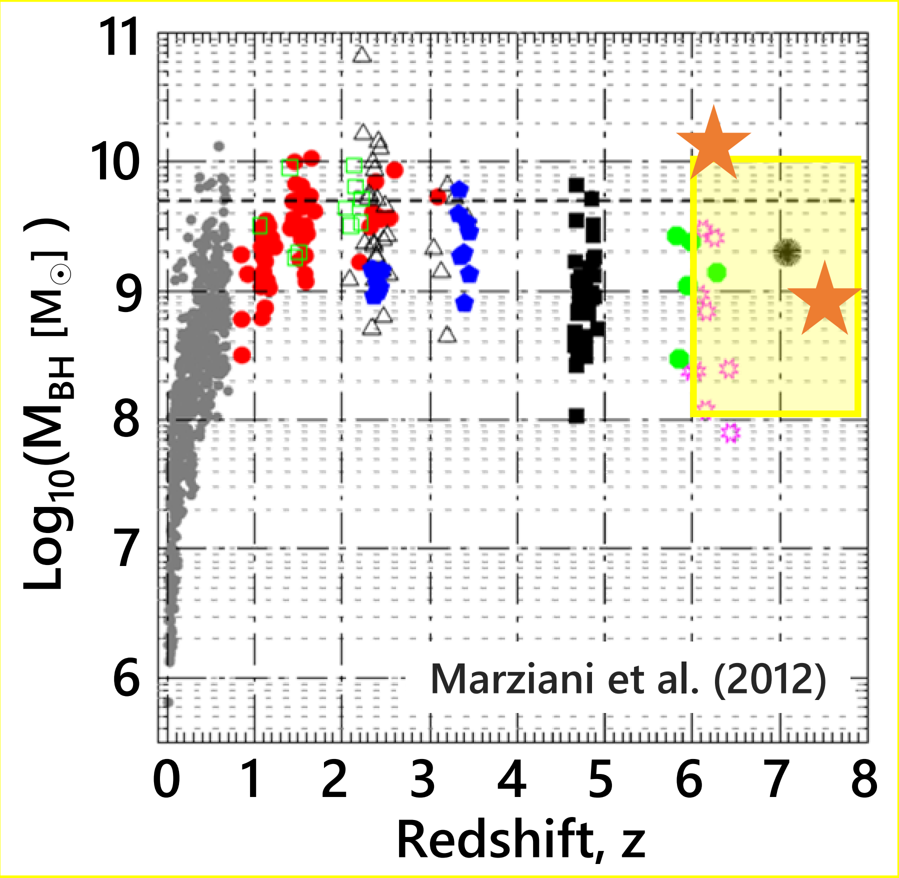




- with $10^6 - 10^{10}$ $M_\odot$ in the galaxy center (e.g. Milky Way)
- Co-evolution with the host galaxy

Credit: HSC Project

SMBHs in the early Universe (<1Gyr)



- with ~$10^8 – 10^{10}\ M_\odot$ at $z > 6$
  - ✓BH mass M_{BH} → $1.3\times10^{10}\ M_\odot$ (SDSS J0100+2802 ; Wu+'15)
  - ✓Redshift z → 7.54 (SDSS J1342+0928; Bañados+'17)
- Number density: n_{QSO} ~ a few (comoving Gpc)$^{-3}$

Growth Time of BH Mass

Accreting gas : gravitational energy → radiation pressure

$$L = \frac{GM_{\rm BH}\dot{M}_{\rm acc}}{R_{\rm in}} \simeq \frac{1}{6}\dot{M}_{\rm acc}c^2 \equiv \epsilon \dot{M}_{\rm acc}c^2$$

Eddington accretion rate : gravity = radiation pressure

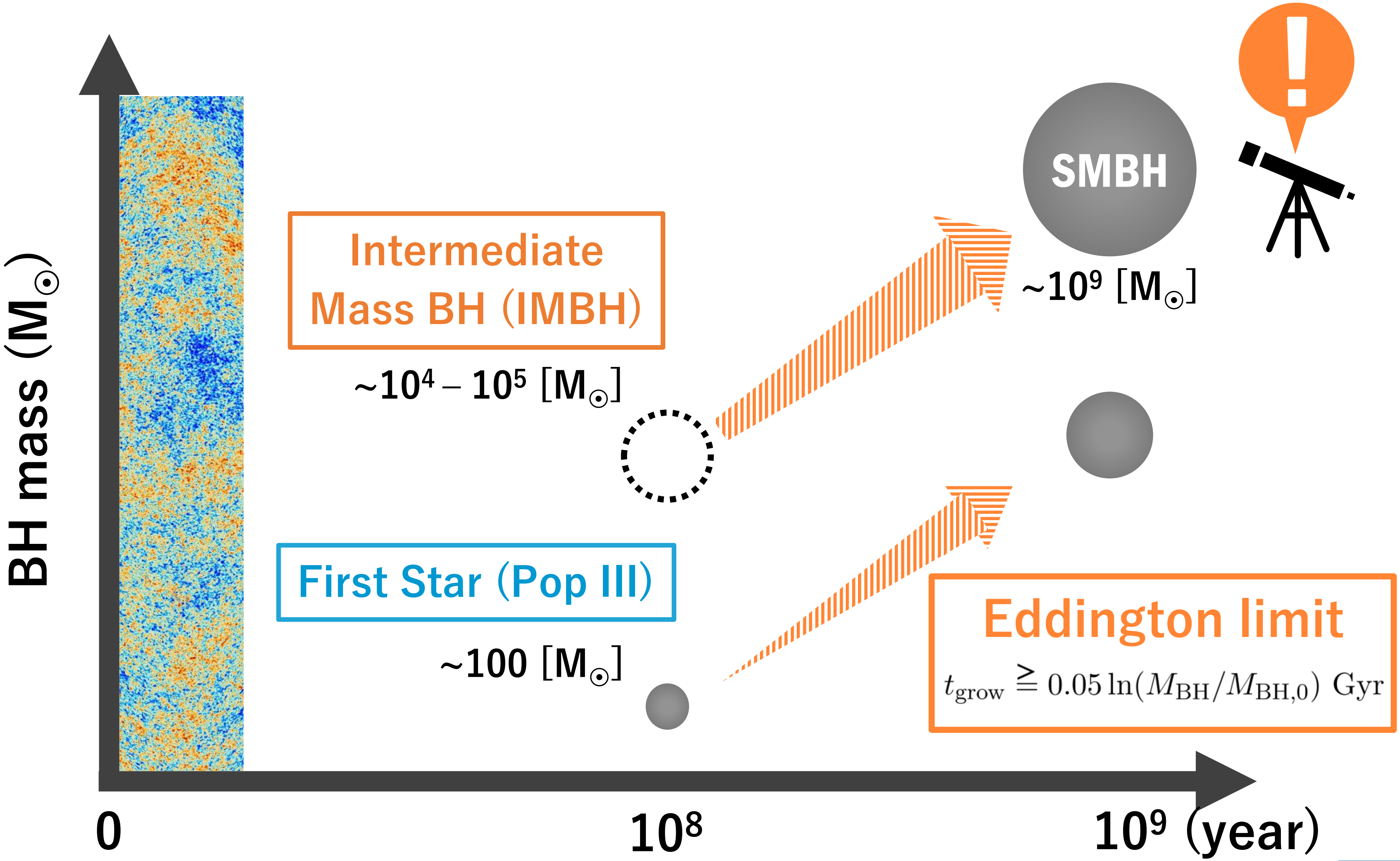
$$\dot{M}_{\rm BH} = \frac{1-\epsilon}{\epsilon}\frac{L}{c^2} < \frac{1-\epsilon}{\epsilon}\frac{L_{\rm Edd}}{c^2} = \frac{1-\epsilon}{\epsilon}\frac{M_{\rm BH}}{t_{\rm Edd}}$$

$$L_{\rm Edd} = \frac{4\pi c G M_{\rm BH}}{\kappa_{\rm T}} \qquad t_{\rm Edd} = 0.45\ \text{Gyr}$$

Mass growth timescale

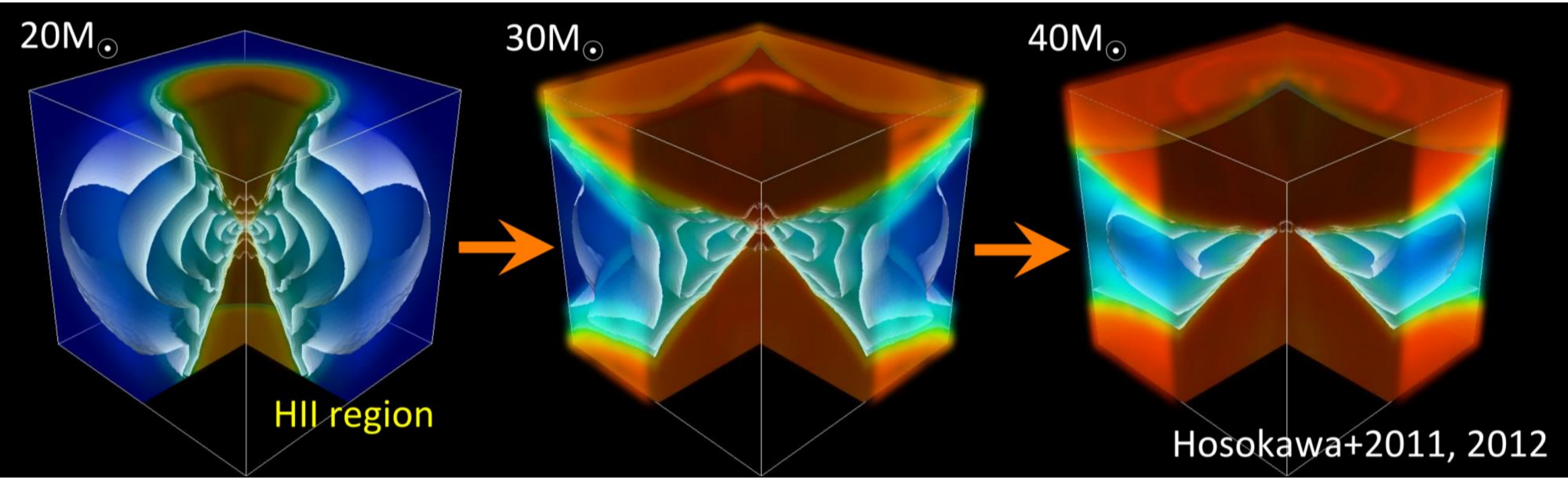
$$t_{\rm grow} \geqq 0.05 \ln(M_{\rm BH}/M_{\rm BH,0})\ \text{Gyr}$$

Time Limit : ~10^9 $M_\odot$ SMBHs by z~6



Mass Growth Limit of First Stars

In metal-free star-forming gas clouds, gas mass accretion onto protostar ceases due to **Ultra-Violet (UV) photo-evapolation** (McKee & Tan 2008)



Surrounding gas accrete through the accretion disk onto the central protostar.

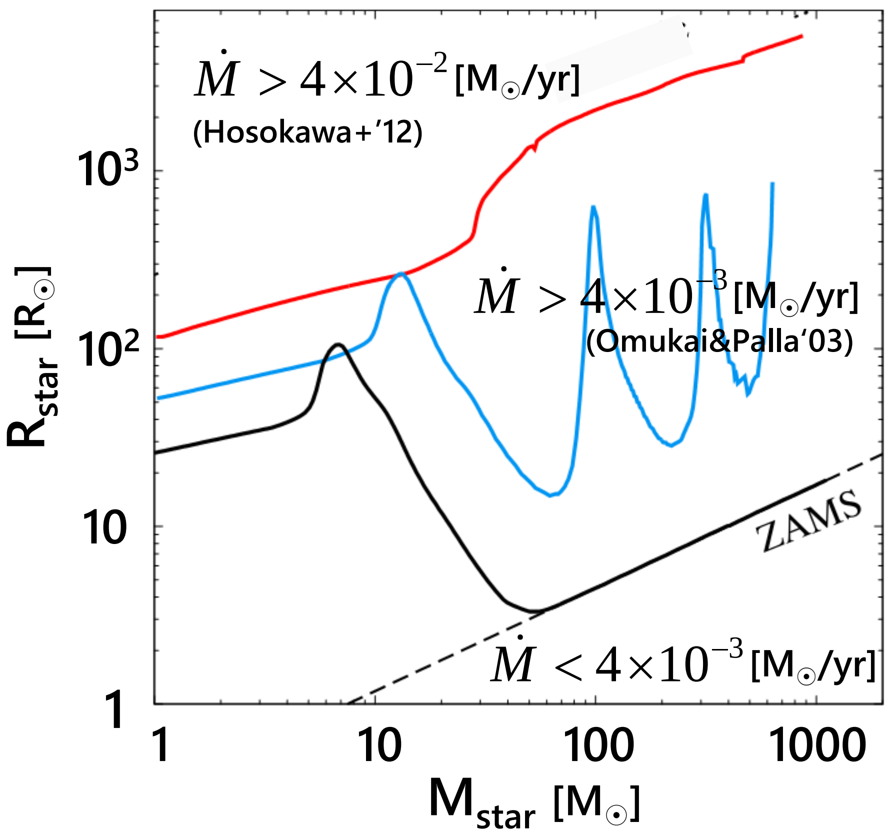
Expanding HII region evaporates the accretion disk.

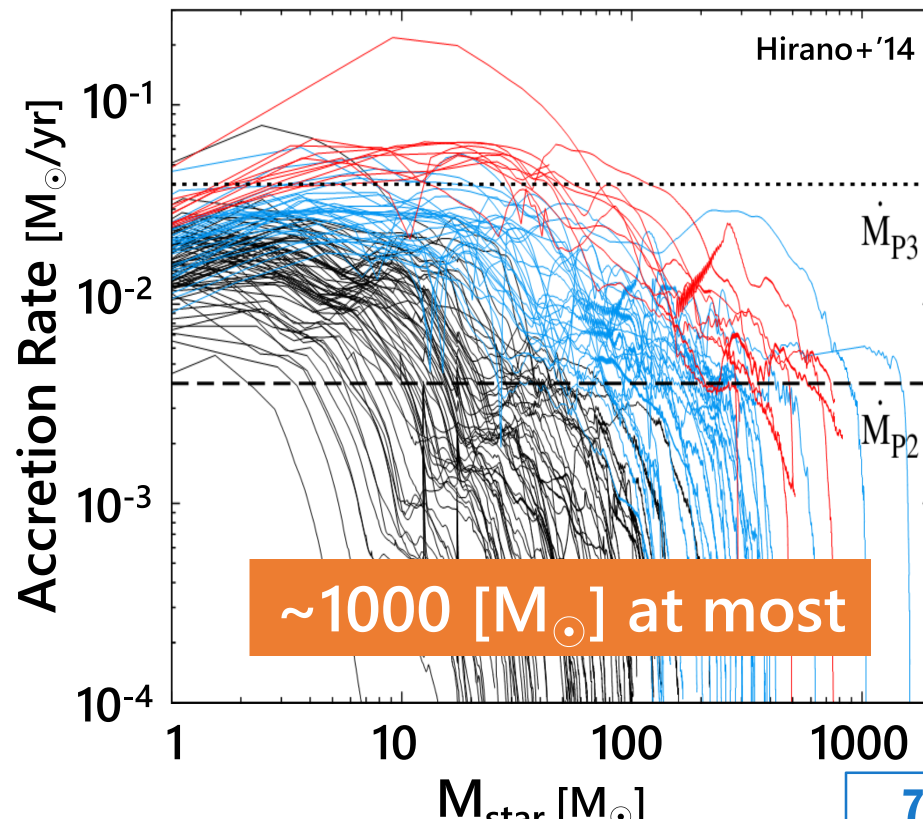
Stellar mass is determined when gas accretion ceases.

How Massive are First Stars?

"**Supergiant Protostar**" Phase (Hosokawa et al. 2012)

- with dM/dt > 0.04 [$M_\odot$/yr], T_{eff}~5000[K]
- Weak UV radiation ➔ Inefficient radiation feedback

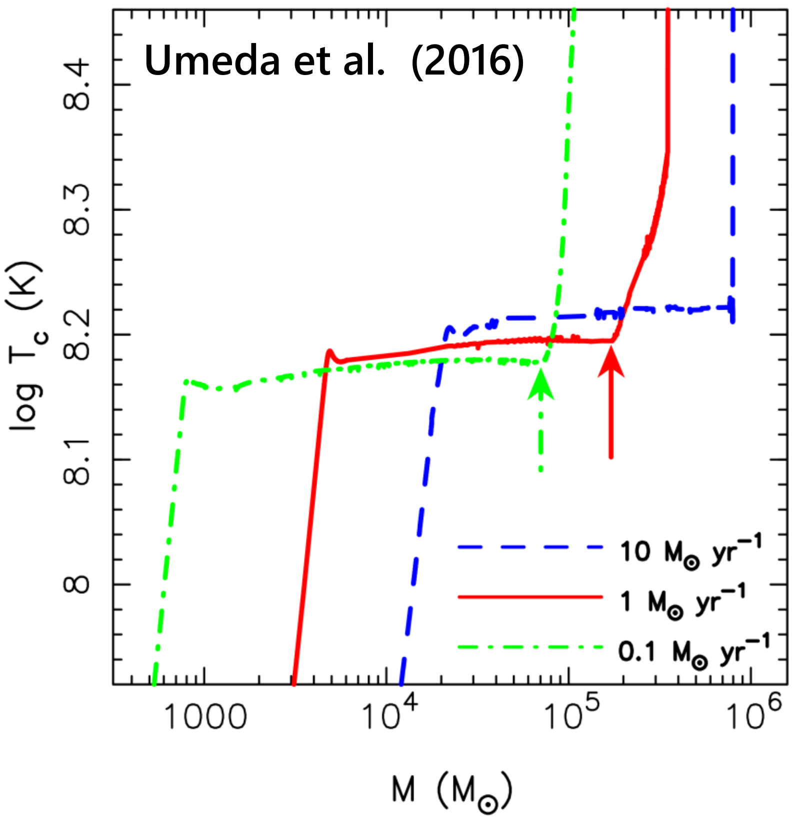


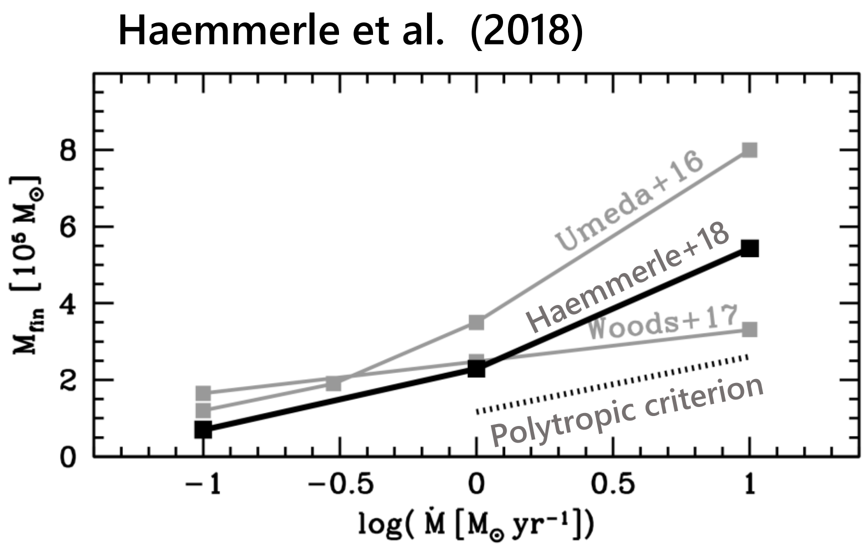


Final Masses of Rapidly Accreting Stars

Stellar evolution calculation with rapid accretion until star dies

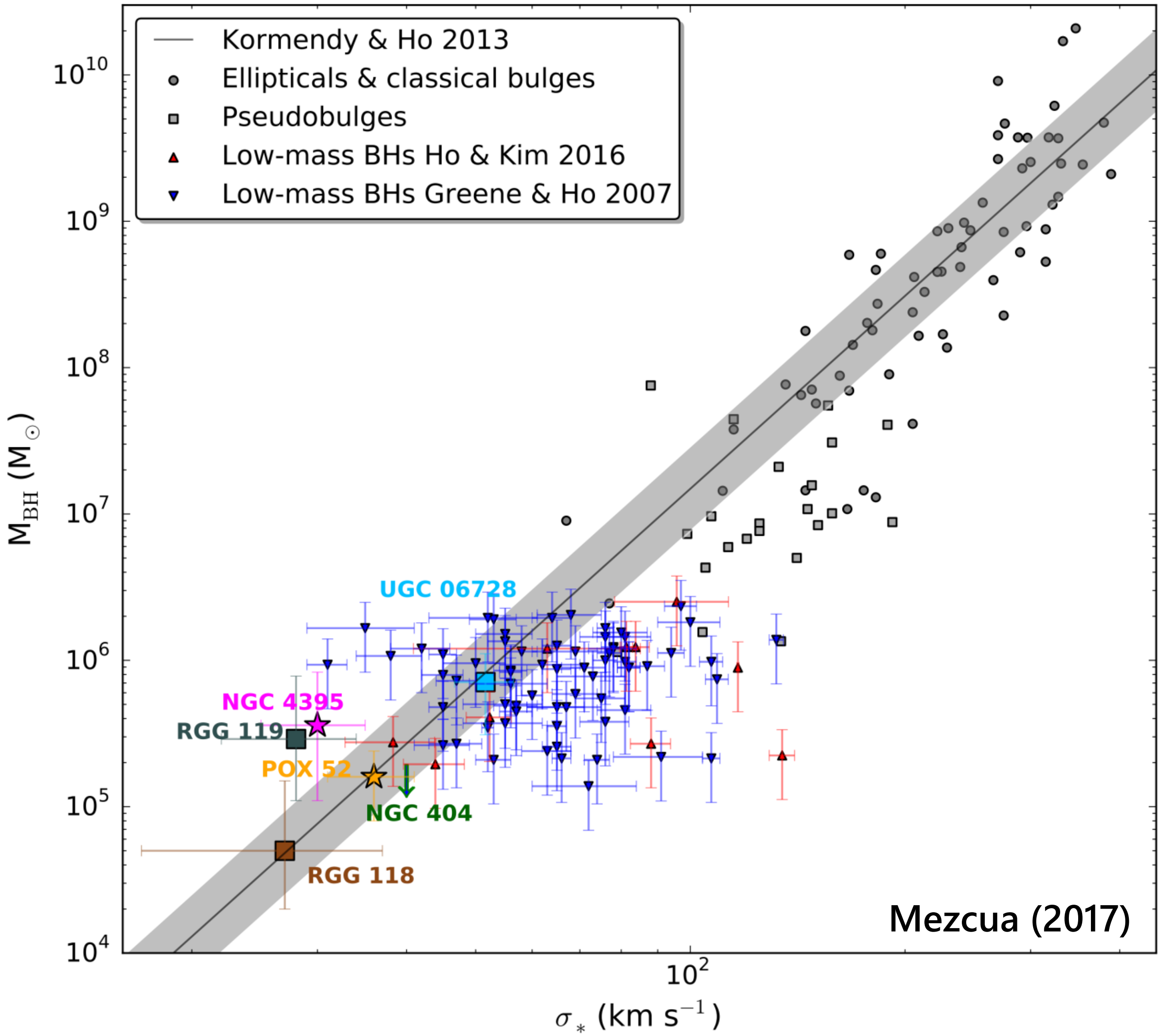
➔ IMBH can form!





CAVEATS: mass loss, angular-momentum transfer, …

Observed IMBHs



Origin of High Accretion : (A) Thermal

$$M_{\rm Jeans} \approx 1000 \left(\frac{T_{\rm Jeans}}{200\ {\rm K}}\right)^{3/2} \left(\frac{n_{\rm H}}{10^4\ {\rm cm}^{-3}}\right)^{-1/2} M_\odot$$

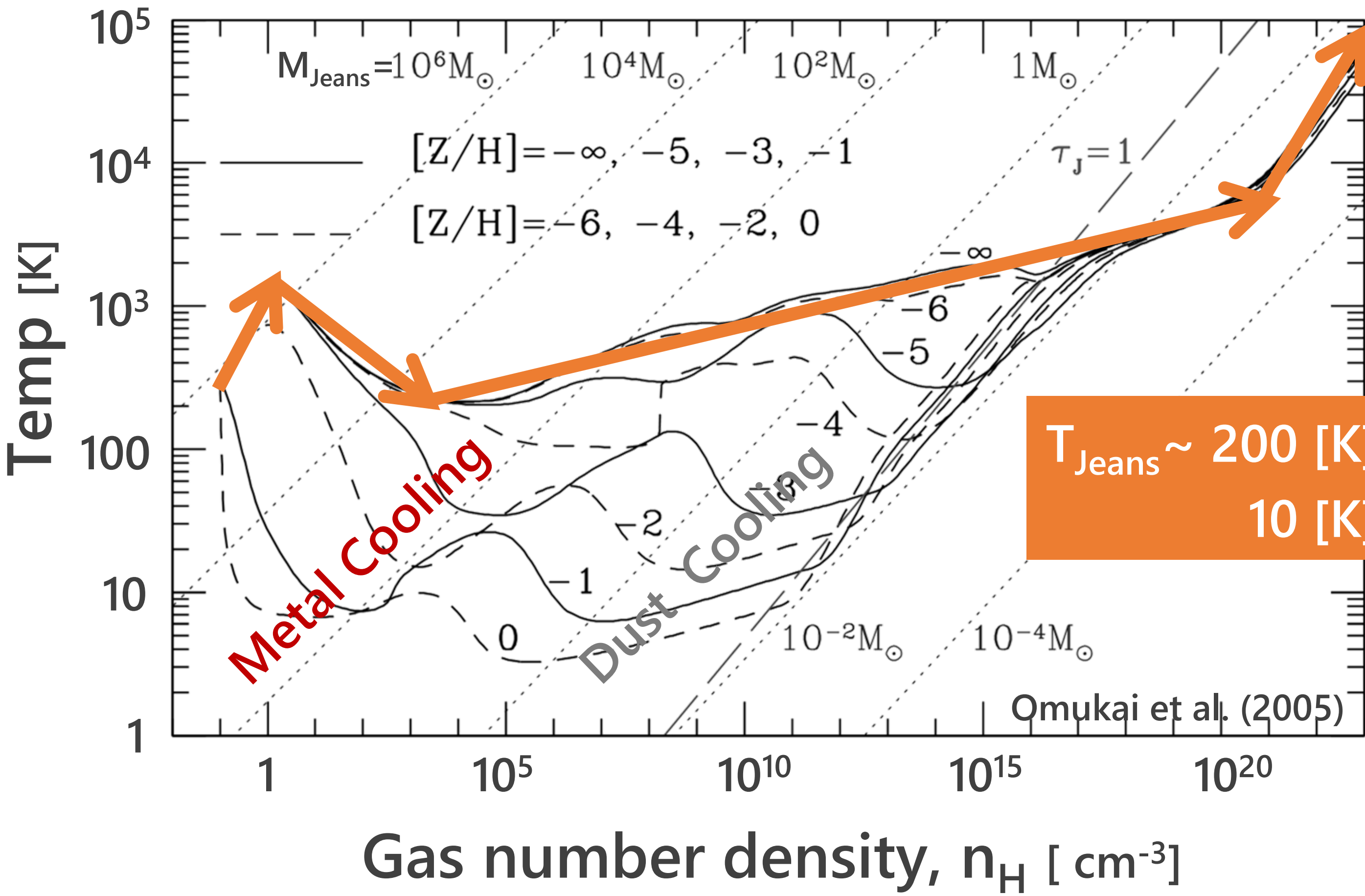
$$t_{\rm ff} = \sqrt{\frac{3\pi}{32\,G\rho}} = 5.2 \times 10^7\ {\rm yr} \left(\frac{n_{\rm H}}{{\rm cm}^{-3}}\right)^{-1/2}$$

$$\dot{M} \simeq M_{\rm Jeans}/t_{\rm ff} \propto T_{\rm Jeans}^{3/2}$$

Thermal Evolution of Gas Cloud

Jeans mass scale **Mass accretion rate**

$$M_{\rm Jeans} \approx 1000 \left(\frac{T_{\rm Jeans}}{200\ {\rm K}}\right)^{3/2} \left(\frac{n_{\rm H}}{10^4\ {\rm cm}^{-3}}\right)^{-1/2} M_\odot \rightarrow \dot{M} \simeq M_{\rm Jeans}/t_{\rm ff} \propto T_{\rm Jeans}^{3/2}$$

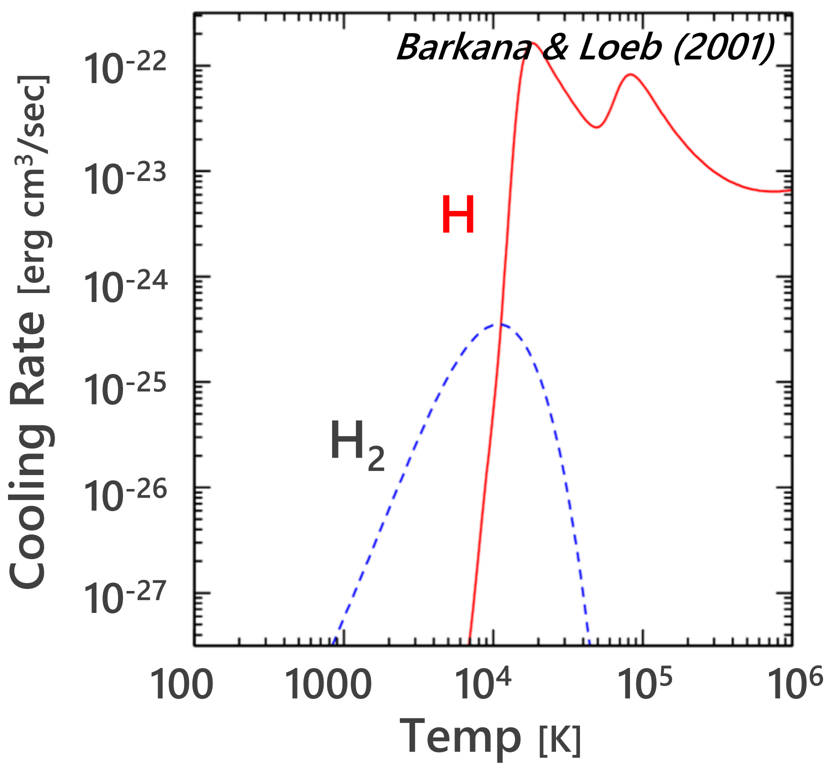


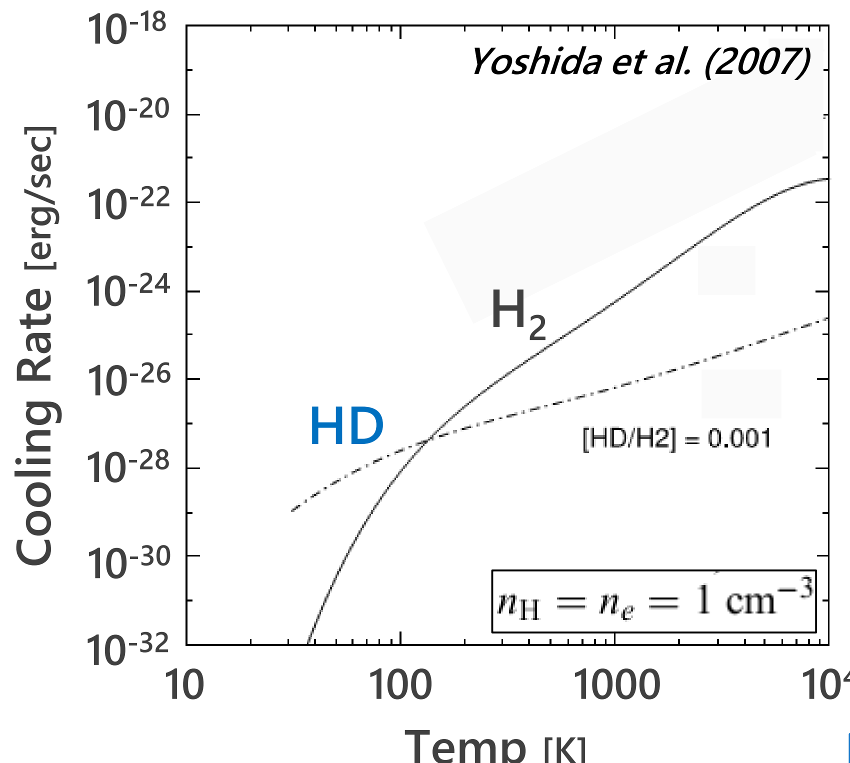
$T_{\rm Jeans}$ ~ 200 [K] @Pristine
10 [K] @Present-day

Coolants of Metal-free Gas

- H-cooling @>10^4 [K]
- H_2-cooling @~100-1000 [K]
- HD-cooling @<100 [K]

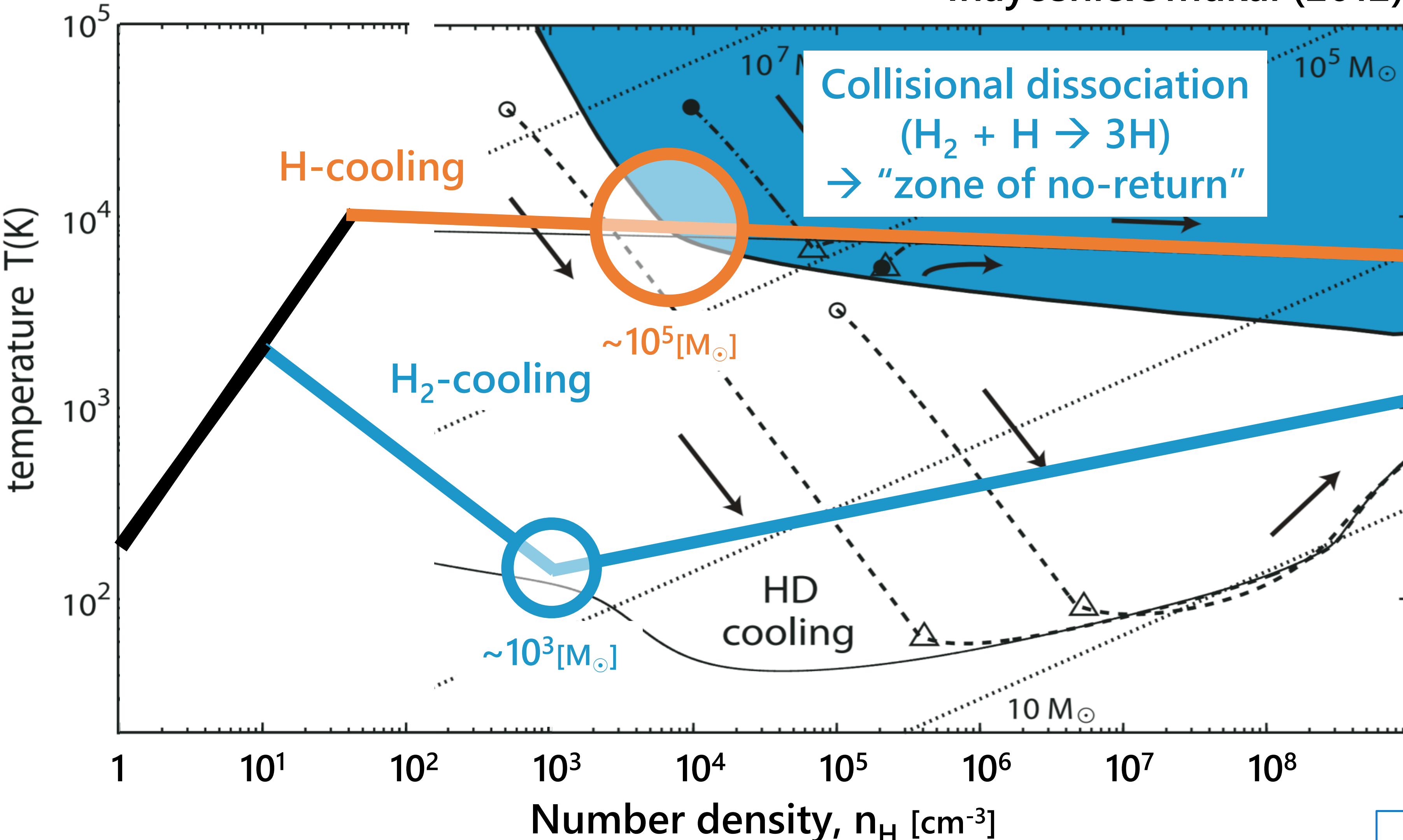
Processes for inefficient H_2-cooling
(a) Photo-dissociation
$H_2 + \gamma \rightarrow 2H$
(b) Collisional-dissociation
$H_2 + H \rightarrow 3H$





"Direct Collapse" Scenario

Inayoshi&Omukai (2012)



IMBH formation in atomically cooled halo

Dissociation of H_2 molecules

- Radiative process

  … external FUV radiation

- Collisional process

  … Collision of cold gas streams, galaxy merger

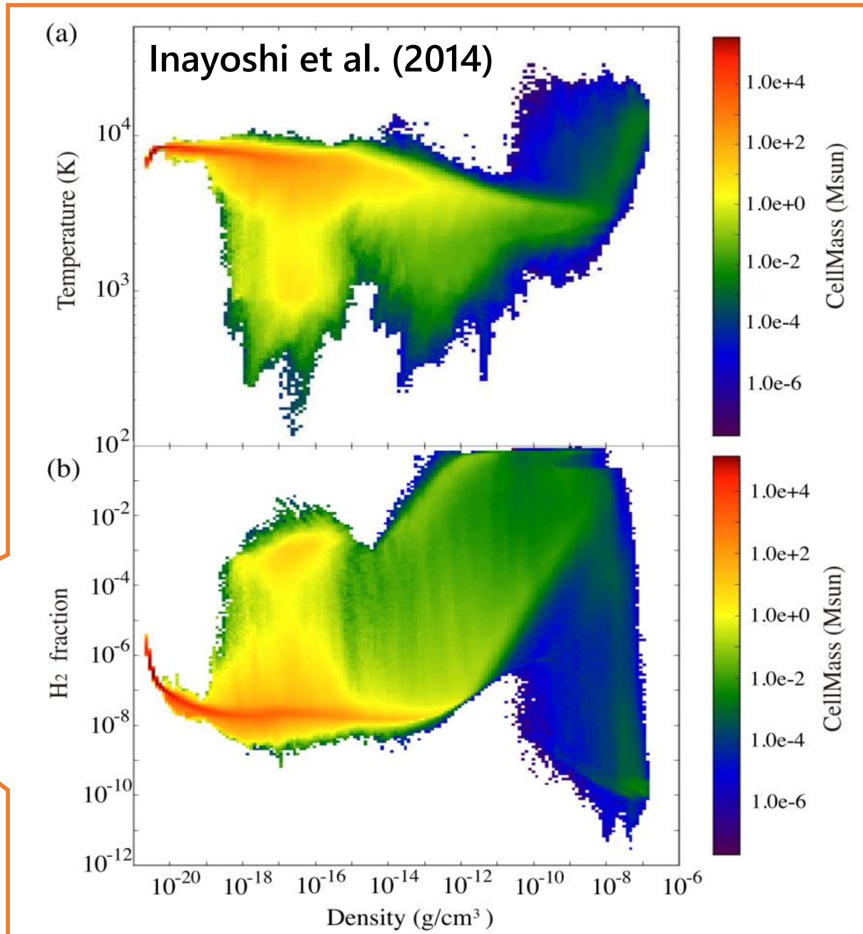
→H-cooling halo : massive & hot

→"zone of no-return"

→No UV radiation feedback with >0.04 [$M_\odot$/yr]

→Finally collapse at ~10^5 [$M_\odot$]

Thermal evolution of collapsing gas cloud in 'zone of no-return'



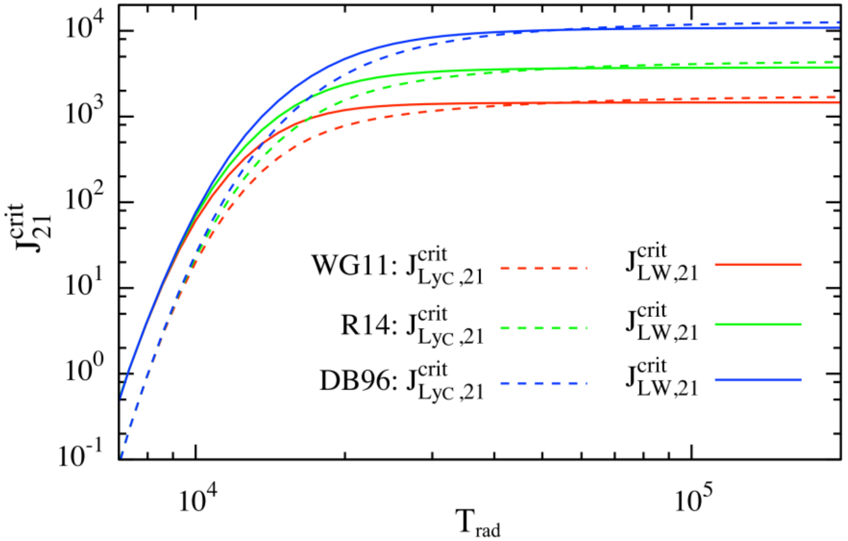
FUV Radiation

H_2 photo-dissociation

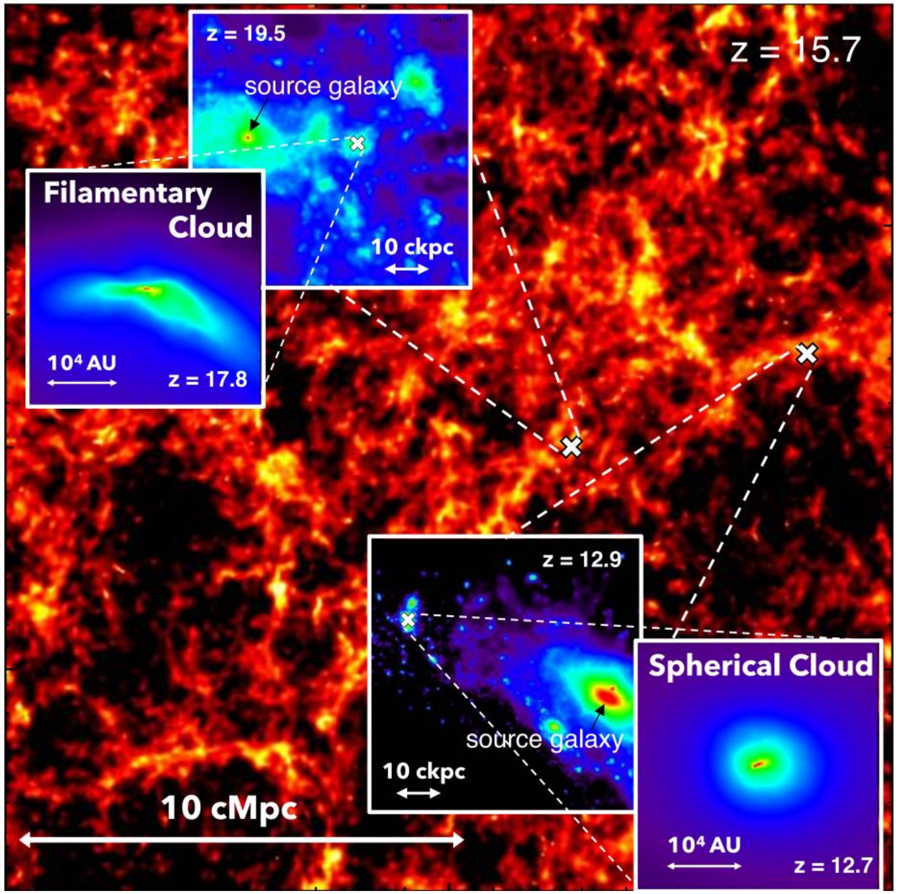
$H2 + \gamma \rightarrow 2H$

Nearby light source galaxy is required to photo-dissociate H_2 molecules in direct collapse halo.

Sugimura et al. (2014)



Chon et al. (2016;2018)



Origin of High Accretion : (B) Motion

$$\dot{M} \simeq M_{\rm Jeans}/t_{\rm ff}$$
$$\propto T_{\rm Jeans}^{3/2}$$

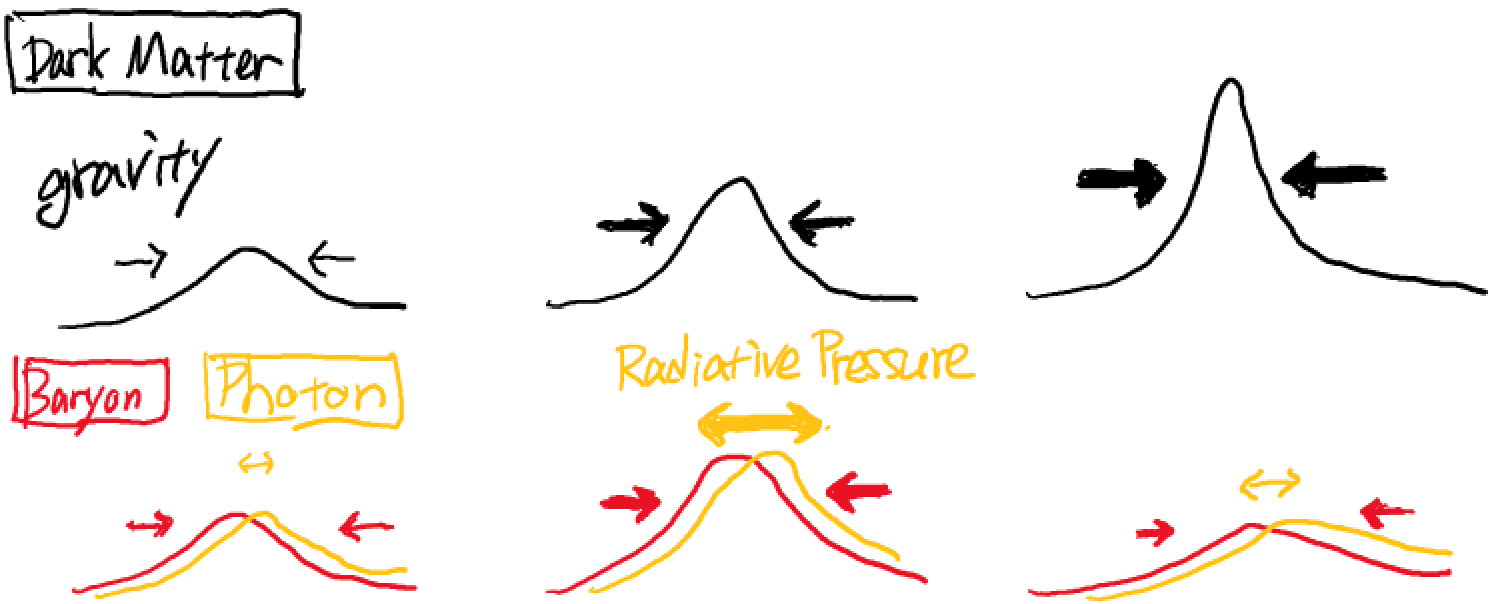
⬇ Additional Motion

$$\dot{M} \propto v_{\rm eff}^{3}$$
$$\sim (c_{\rm s}^2 + v_{\rm bc}^2)^{3/2}$$

Streaming Velocity

- Supersonic gas motions relative to DM fluid left over from the Big Bang
- Sound speed in the baryon fluid:

  $c_s \sim c/\sqrt{3}$ (coupled with photons via Thomson scattering)



→ $2 \times 10^{-5}c$ (after cosmic Recombination z~1000)

- Rapid motions prevent early gas cloud formation until rapid gas condensation is triggered in a protogalactic halo.

Suppression of Early Structure Formation

Supersonic coherent flows of the baryons relative to the dark matter at the epoch of recombination.

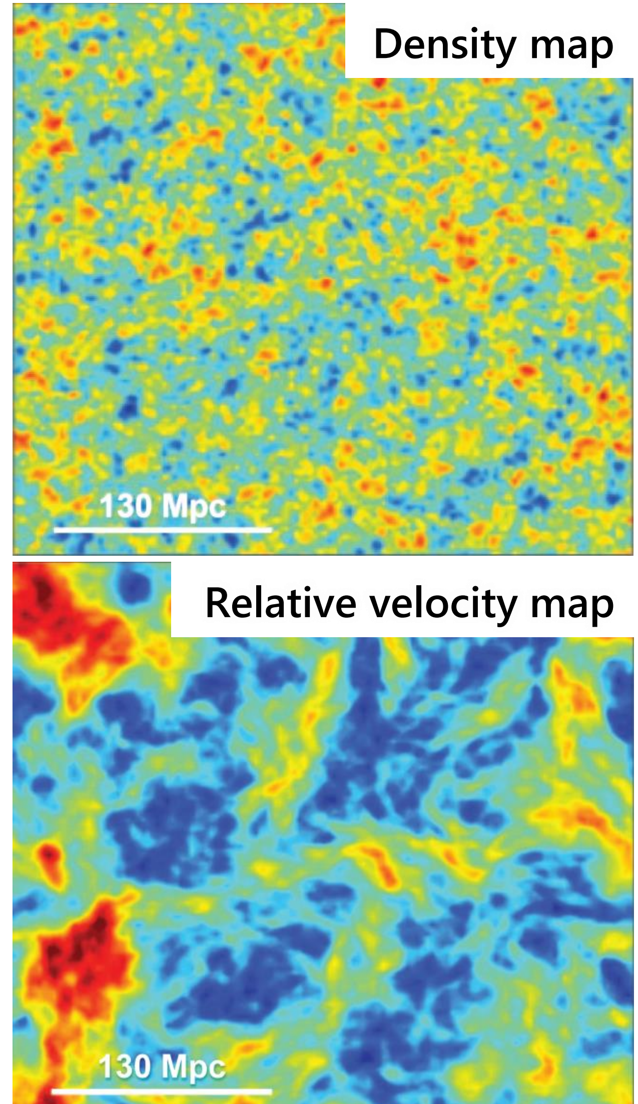
(Tseliakhovich & Hirata 2010)

The magnitude and direction randomly varies in space.

$$P_{MB}(v) = \left(\frac{3}{2\pi\sigma^2}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{3v^2}{2\sigma^2}\right)$$

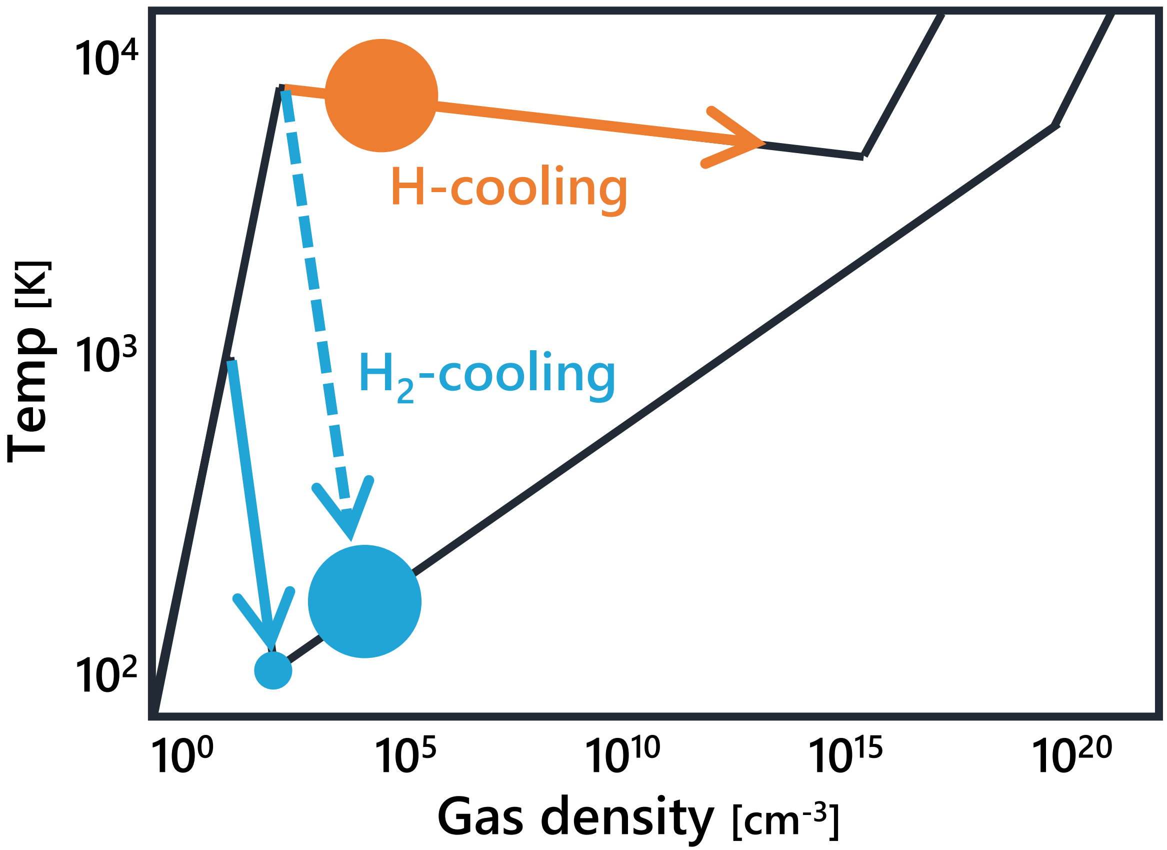
The velocity field is coherent on larger scales than the density fields become first object.

Visbal et al. (2012)



H_2-cooled but Massive Gas Cloud

- Gas cloud collapse is suppressed due to the coherent gas flow.
- When the gas cloud becomes gravitationally unstable, its mass can be similar with the pre-galactic halo under rapid streaming motion.

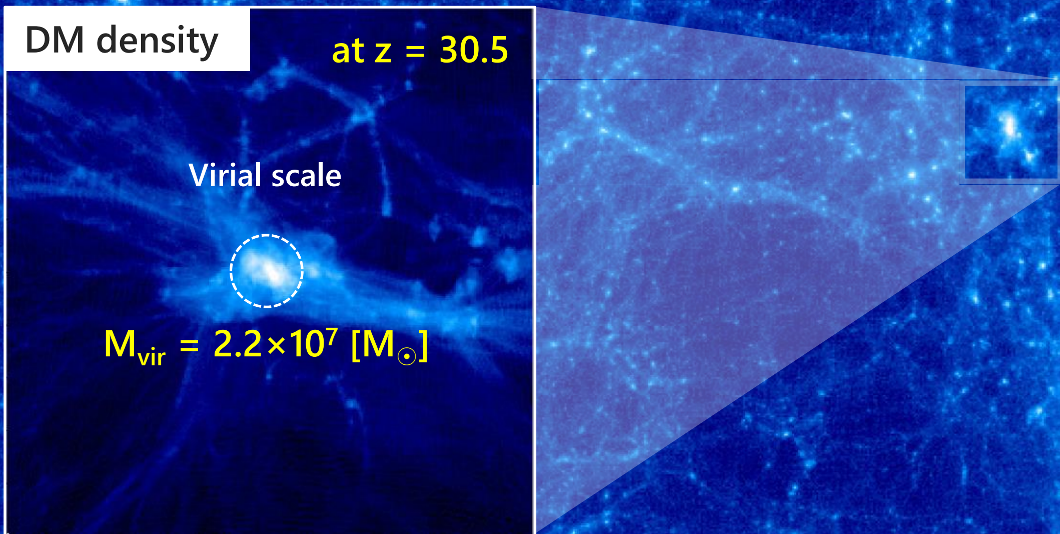


$$\dot{M} \simeq M_{\rm Jeans}/t_{\rm ff}$$
$$\propto T_{\rm Jeans}^{3/2}$$

Streaming Motion

$$\dot{M} \propto v_{\rm eff}^3$$
$$\sim (c_{\rm s}^2 + v_{\rm bc}^2)^{3/2}$$

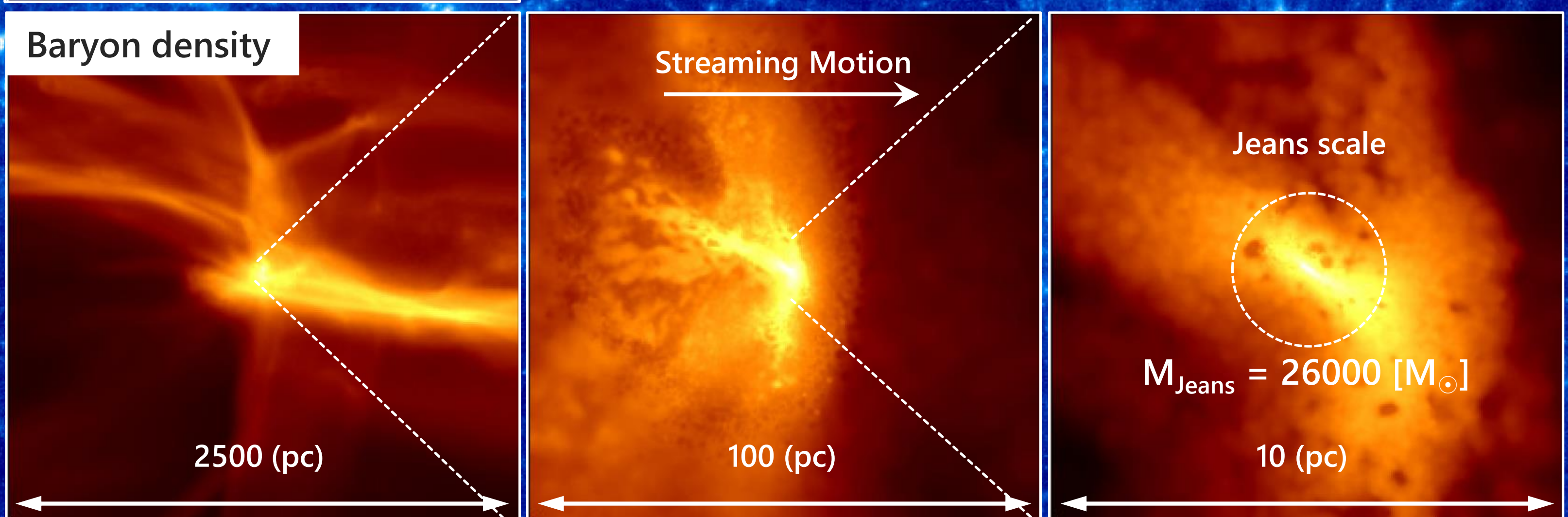
Cosmological Simulation with SV



Cosmological Simulation

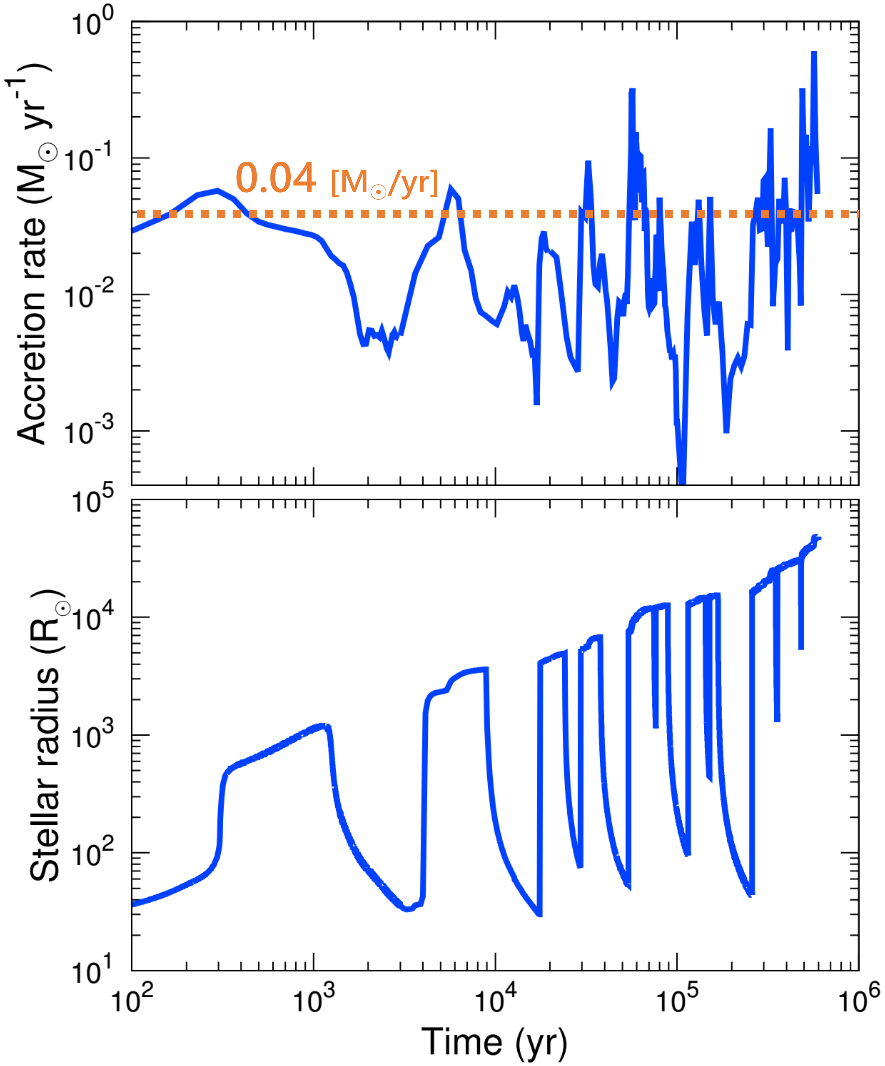
ICs ... MUSIC (Hahn&Abel 2011)
Code ... Gadget3 (Springel 2005)
modified version (Hirano et al. 2015)

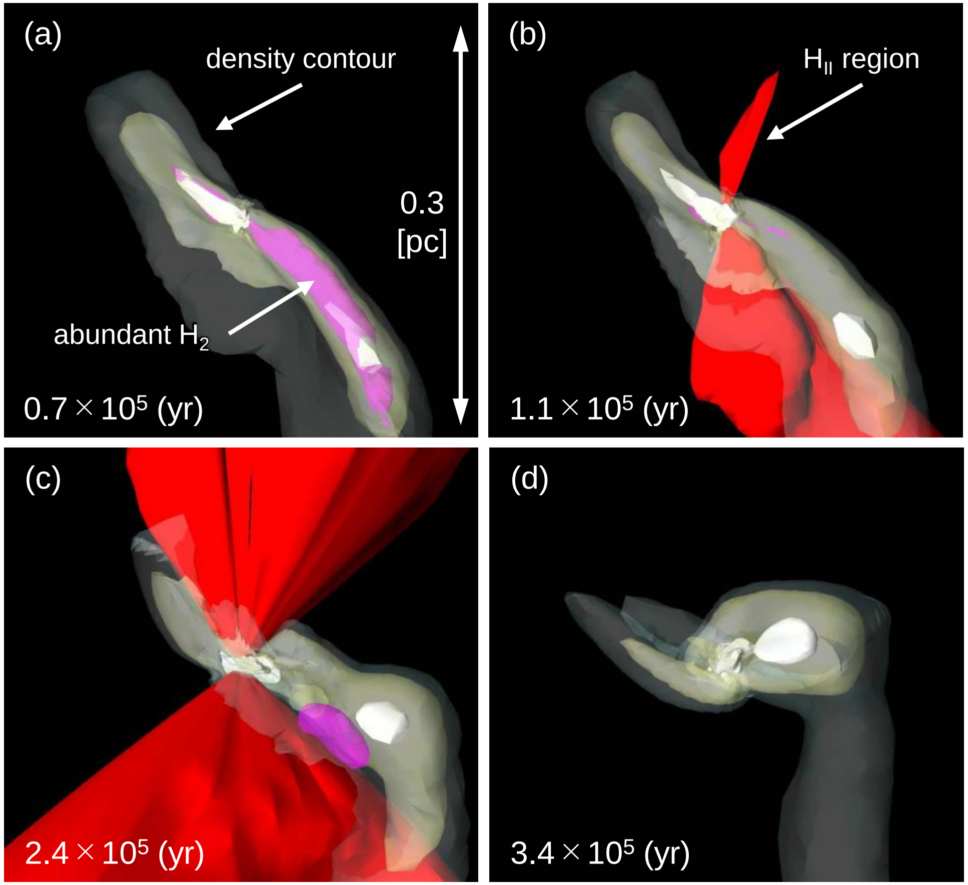
z_{ini} =499
L_{box} =10 comoving Mpc/h
l_{soft} =12.2 comoving pc/h
$m_{DM,zoom}$ =16.4 M_{sun}
$m_{Gas,zoom}$ =3.0 M_{sun}
$|v_{DM}-v_{Gas}|$ =3σ_{SV}
σ_8 =1.2
with Λ-CDM cosmology



10 (comoving Mpc/h)

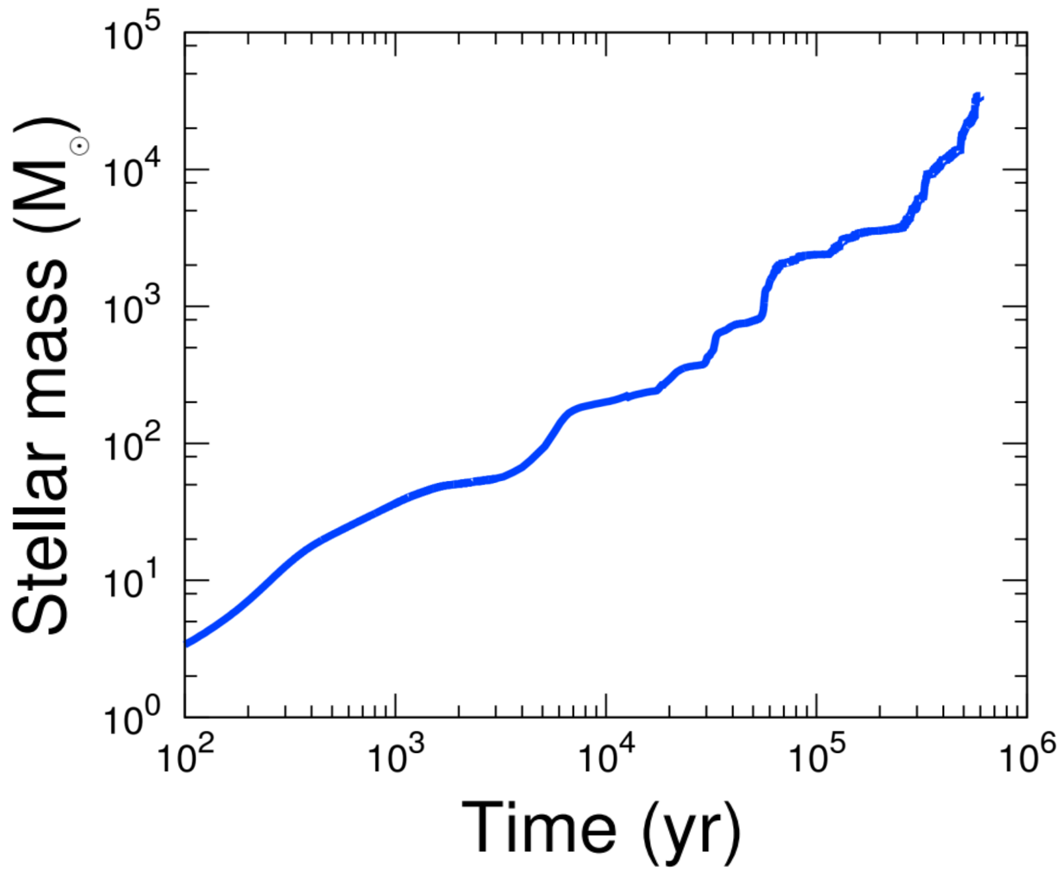
Rapid and Burst Accretion





Accretion bursts expand the stellar surface and weaken the protostellar radiation feedback.

Final Mass of Supermassive Star



34,000 $M_\odot$ BH at z = 30.5

⬇

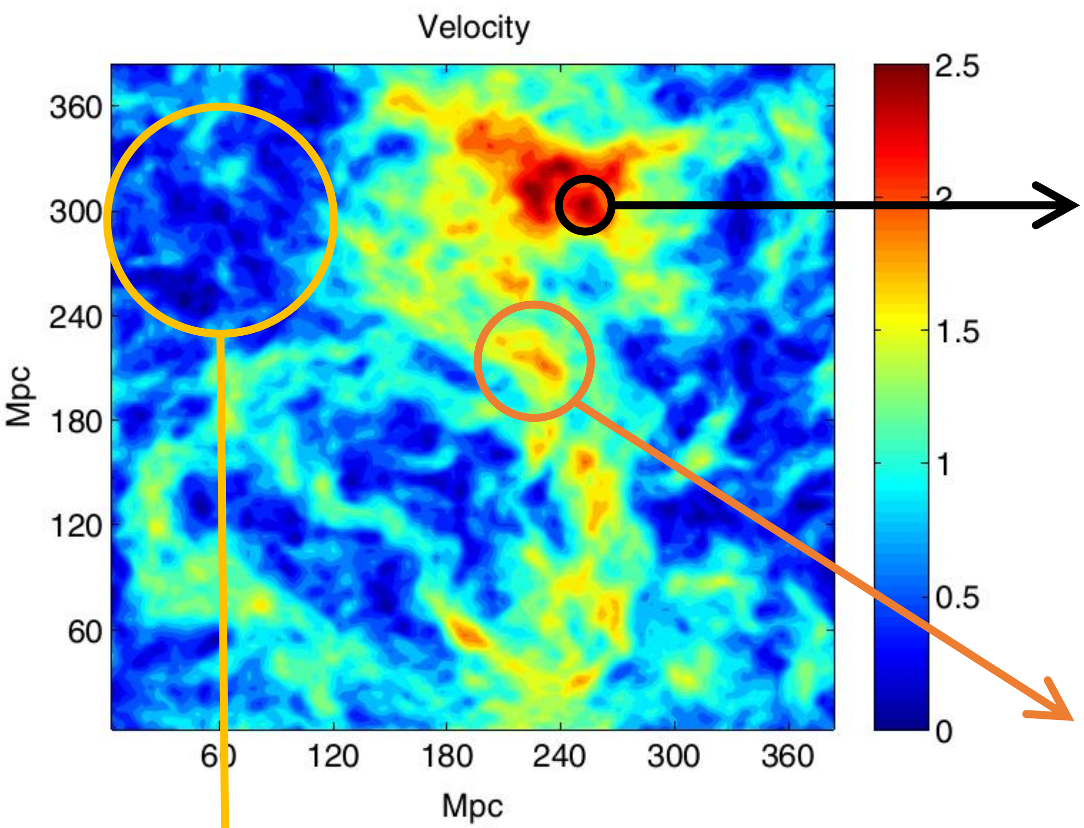
Growing at 55% of the canonical Eddington rate

⬇

2×10^9 $M_\odot$ BH at z = 7.1

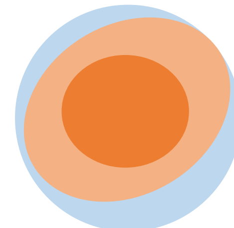
v_{bc} (σ_{bc})	σ_8	z	R_{virial} (pc)	M_{virial} ($M_\odot$)	V_{virial} (km s^{-1})	M_{Jeans} ($M_\odot$)	t_{acc} (10^6 yr)	M_{star} ($M_\odot$)
3	1.2	30.5	171	2.2×10^7	13.3	26,000	0.60	**34,000**

Various Formation of First Stars



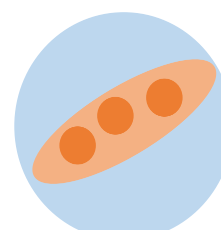
Single supermassive first star

~ 10^4-10^5 [$M_\odot$]



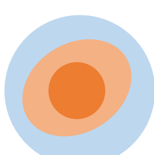
Multiple massive first stars

~ 100 [$M_\odot$] × ~10

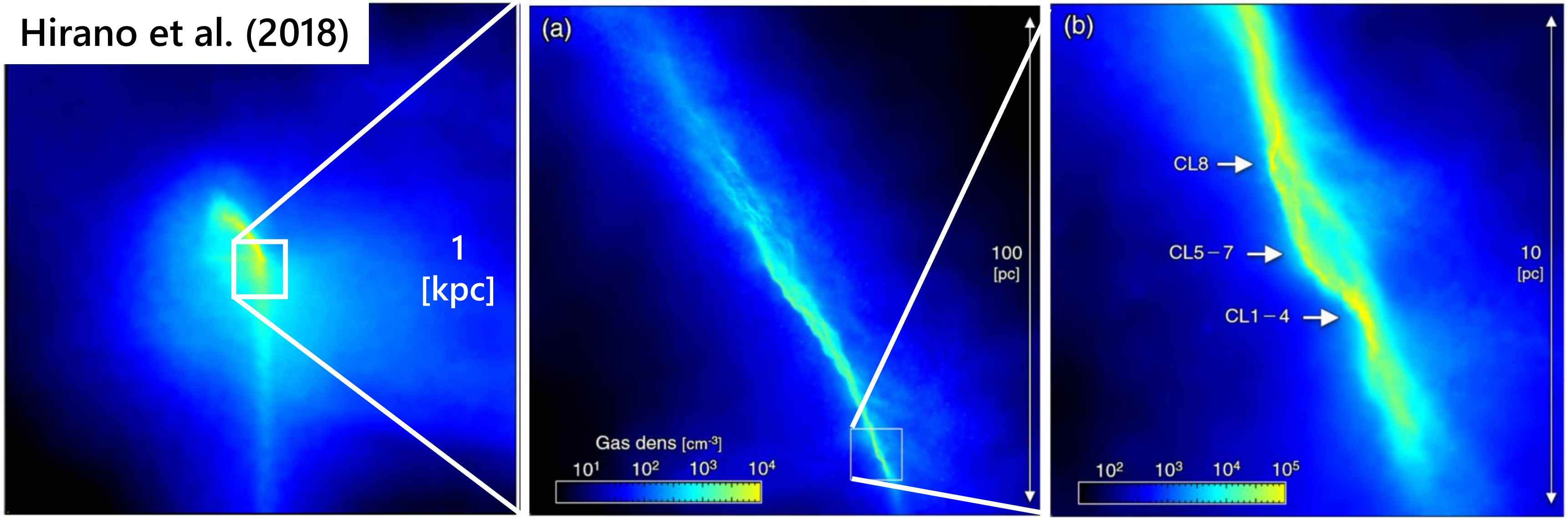


Single massive first star

~ 100 [$M_\odot$]



Fragmentation of Large-filemant



Example :

8 Jeans unstable clouds with 100-200 $M_\odot$ on a highly elongated filament

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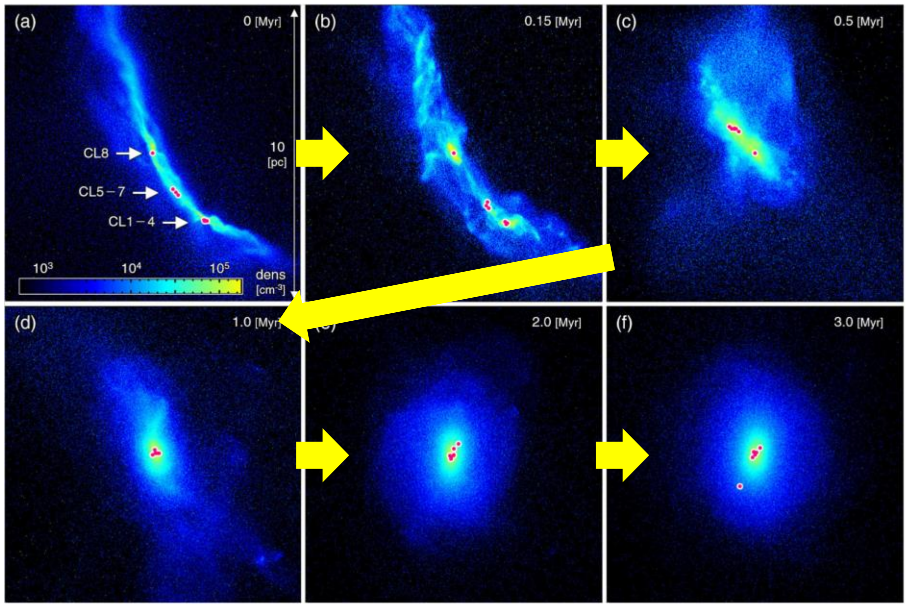
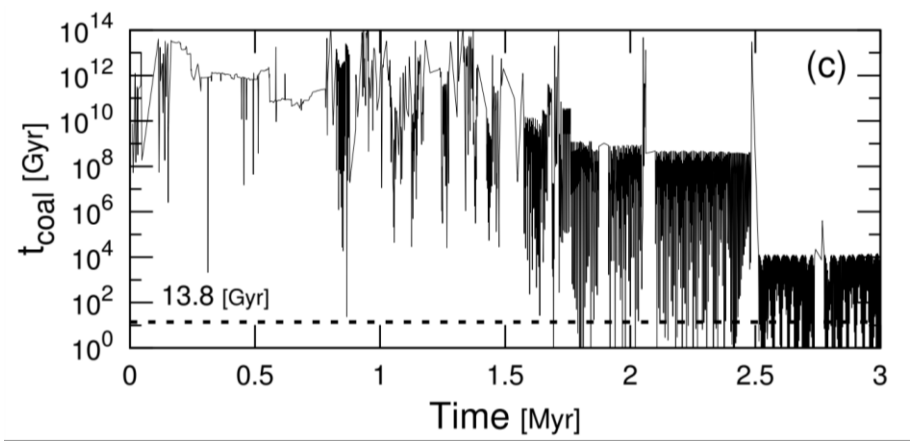
What is the final fate of this system: survive, merger, ejection?

Cluster of ~100 [$M_\odot$] First Stars

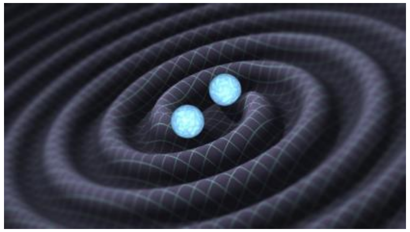


Merger of massive first stars
➔IMBH formation

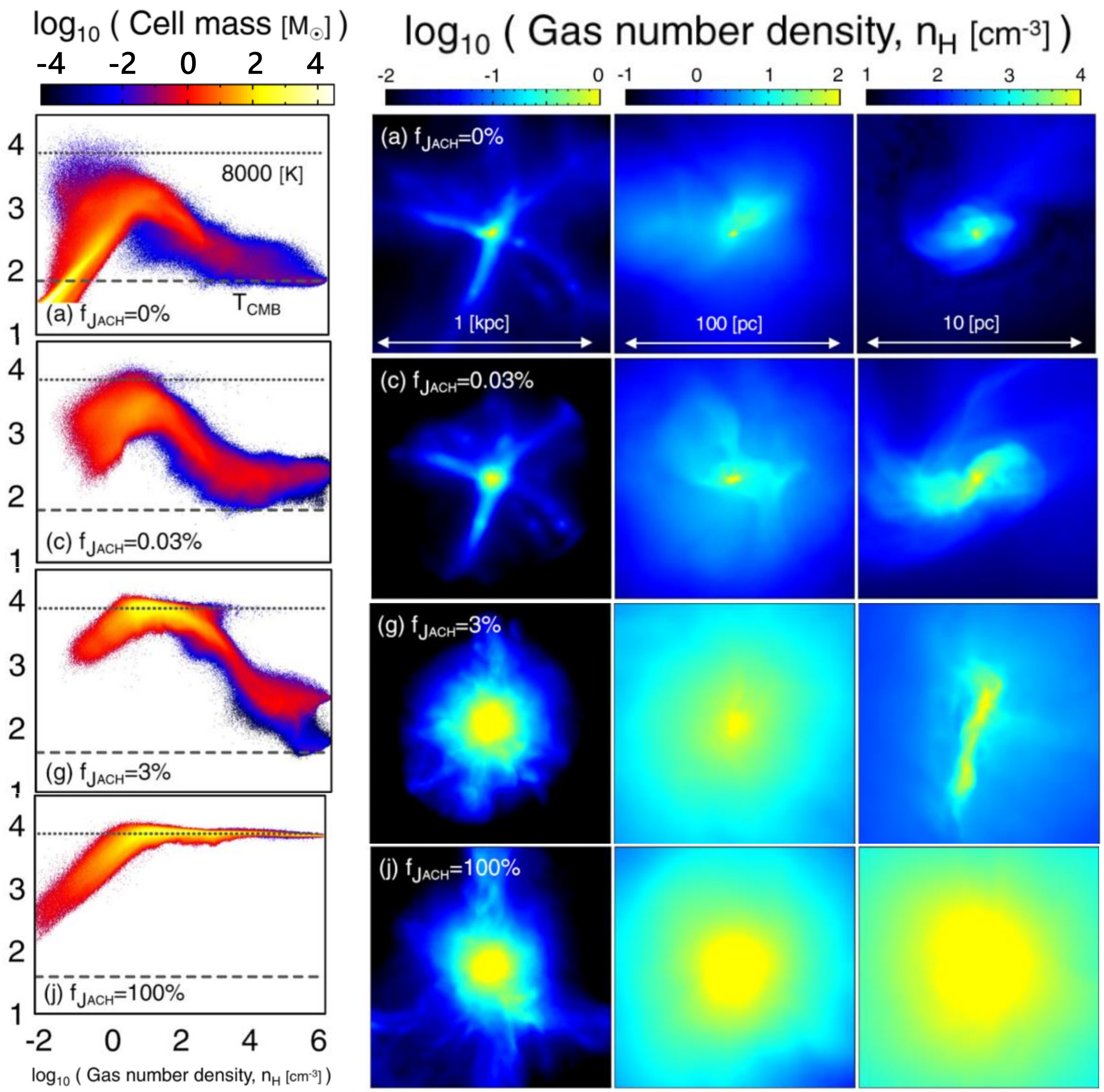
Close BH binary
➔Progenitor candidate of the gravitational-Wave signal



$$t_{\rm coal} \sim 10\ {\rm Gyr} \left(\frac{a_0}{0.2\ {\rm au}}\right)^4 (1-e_0)^{7/2} \left(\frac{M_1}{30\ M_\odot}\frac{M_2}{30\ M_\odot}\frac{M_1+M_2}{60\ M_\odot}\right)^{-1}$$



Unstable Filament with low-J_{21}

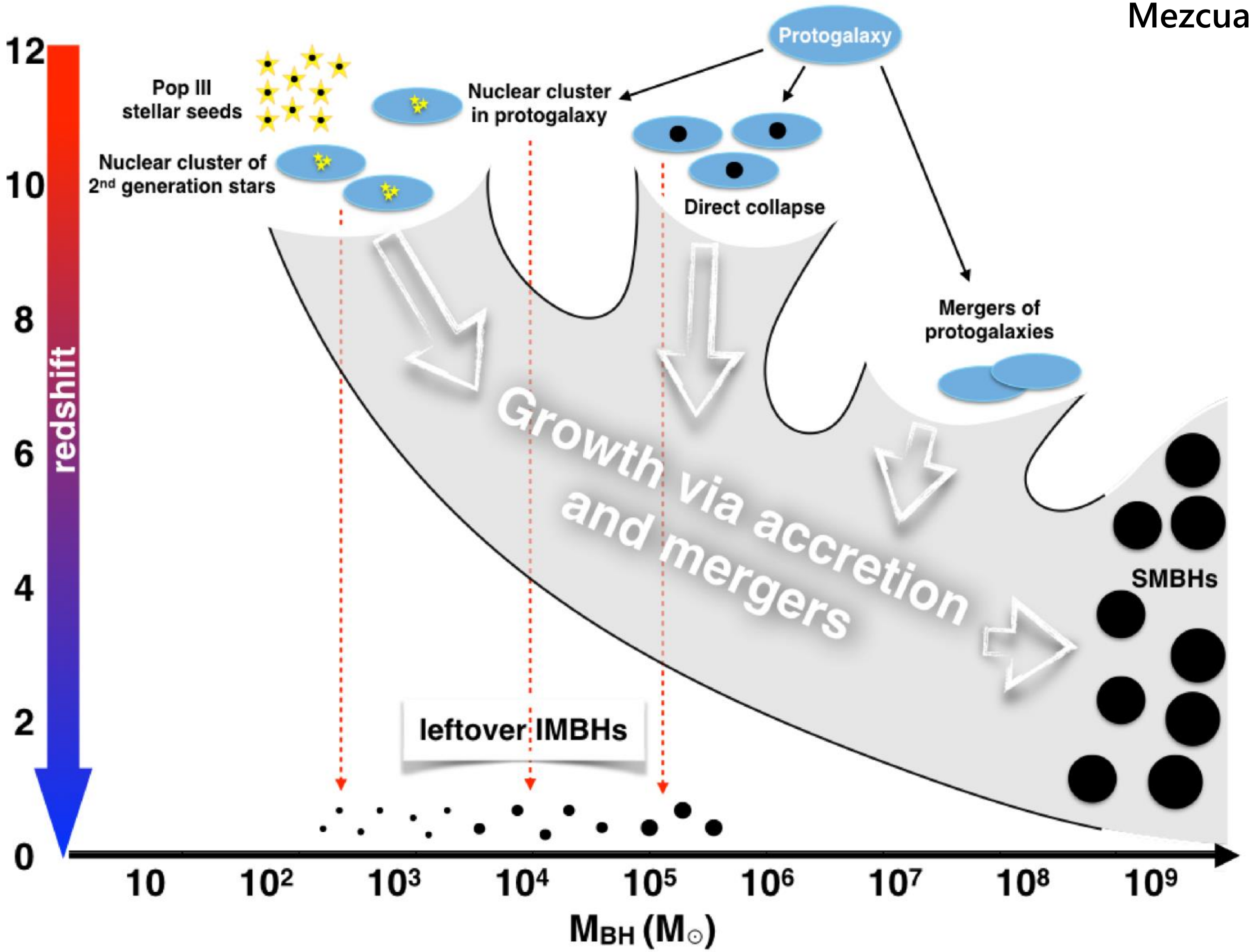


Hirano et al. (in prep)

- Same cosmological halo
- Uniform J_{21} background
- $f_{JACH} = J_{21}/J_{21,crit}$

Formation Scenarios of IMBH/SMBH

Mezcua (2017)



Summary

Supermassive stars formed from the direct collapse of massive gas cloud can be promising origin of high-z QSOs (SMBHs).

DCBH scenario : Rapid gas accretion history is necessary.

(1) Atomic-cooling halo (H_2 photo-/collisional-dissociation)

(2) Dynamical suppression of cloud collapse (streaming velocity)

Merger scenario : Final fate of first stars cluster

*** Questions ***

Number densities of seed BH (IMBH) and observed SMBHs

Growth from IMBH to SMBH : Cosmic gas flow