初代星＆初代銀河 2024
@ 信州大
12 Nov 2024

低金属度環境における超大質量星と高密度星団の形成

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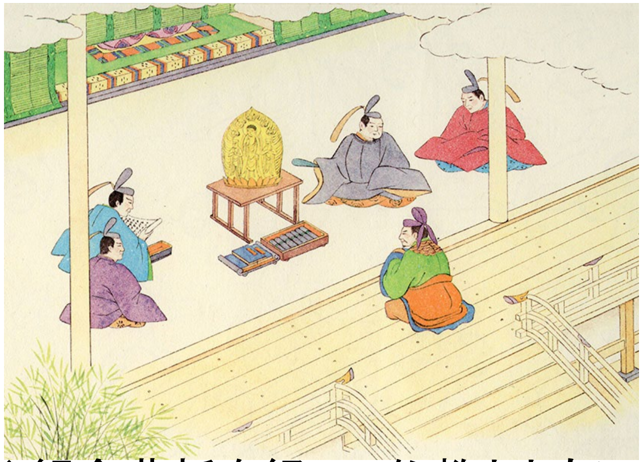
善光寺如来縁起

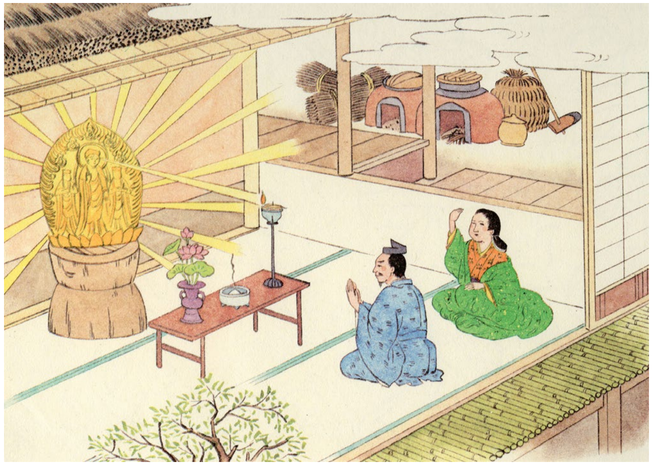
https://www.zenkoji.jp/about/engi/

1)お釈迦様の在世時の印度にて、
竜宮の金を使い、仏像が作られる



2）紆余曲折を経て、仏教とともに
日本に伝来（538年）

3）政争に巻き込まれ遺棄されたところ、
本田善光が拾って帰る

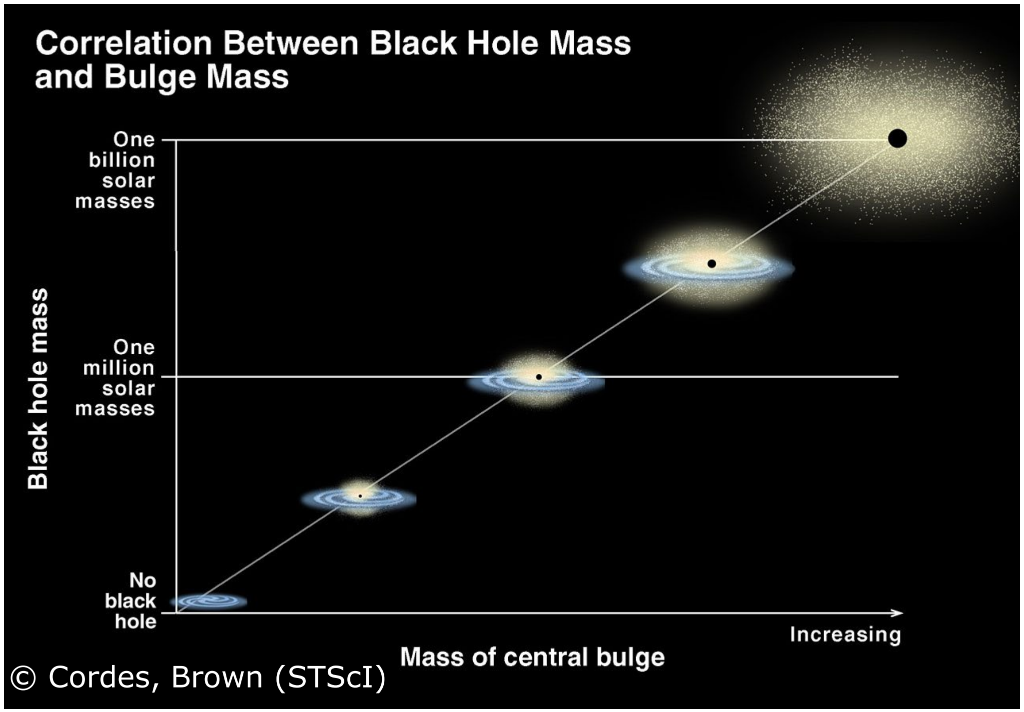


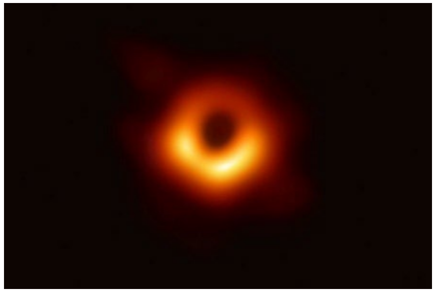
4）**ここ長野に落ち着く**

まさに日本の本尊といえる

Supermassive BHs

まさに銀河の本尊といえる





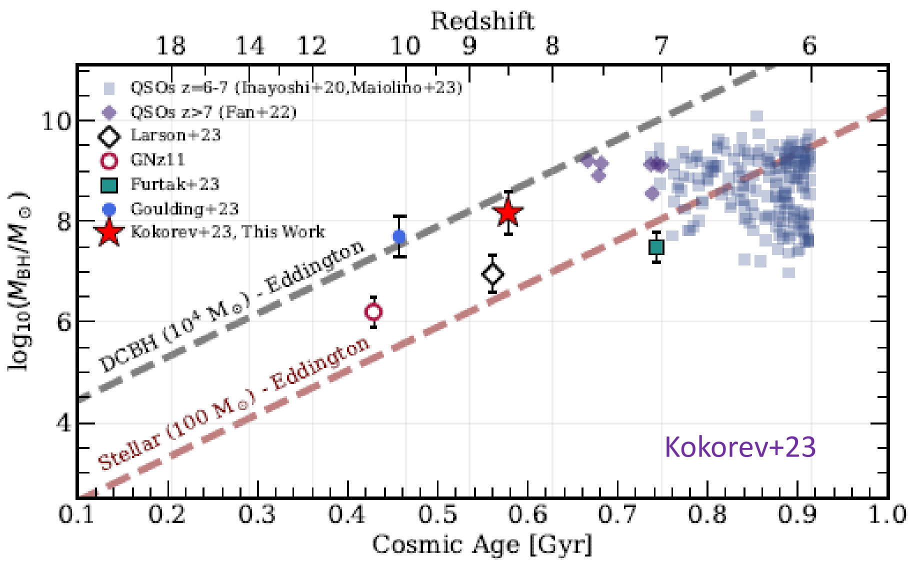
©EHT

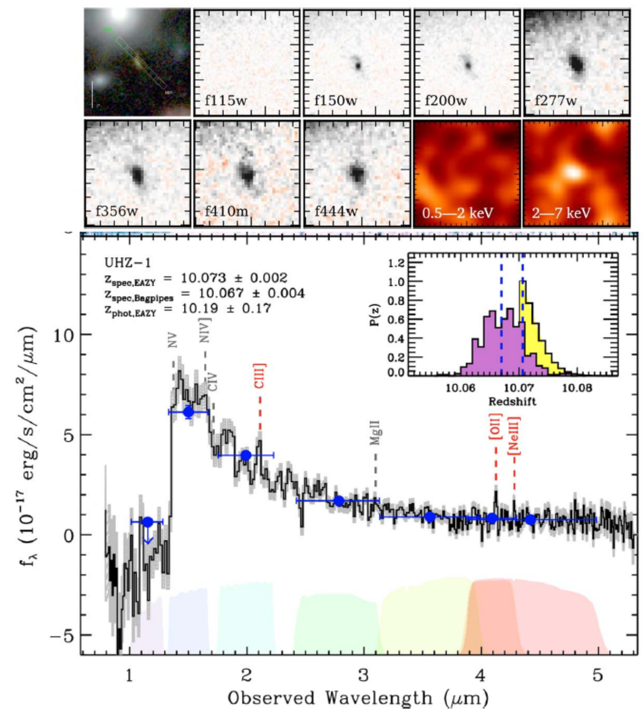
- ubiquitously reside at the center of galaxies
- BH mass correlates with the bulge mass

されどその縁起は明らかならず…

clues : Highest-z SMBHs

SMBHs are already in existence in infant universe





UHZ-1
@z=10

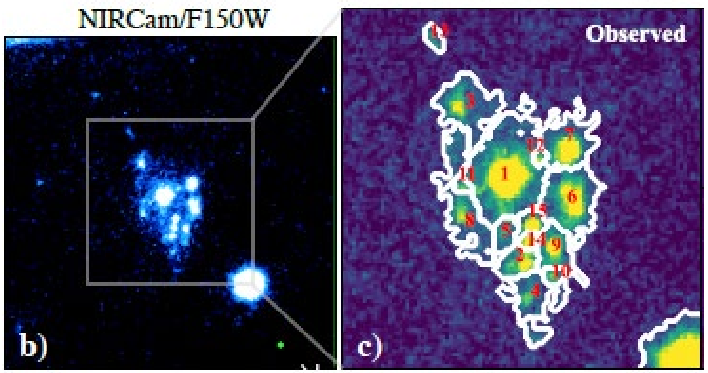
Goulding+23

- Dozens of quasars have been found at z>6.5 （Venemans +2014, Matsuoka+2017, 2018….）
- Ultra-massive BH of 1.2x10^{10}M$_{sun}$ at z=6.3 (Wu+2013)
- JWST is revolutionizing high-z QSO search (Onoue+ 2023, Maiolino+ 2023, etc.)

How did they grow to supermassive in such a short time?
What is their origin?

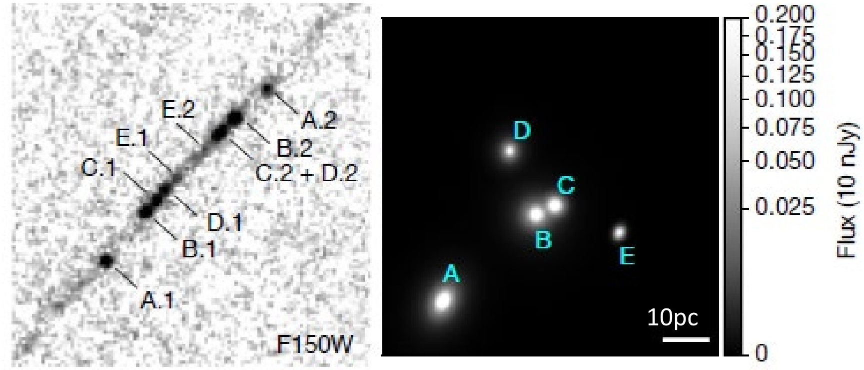
dense star clusters in high-z universe

Cosmic Grapes @z=6.07 (Fujimoto +2024)



Σ~$10^{3\text{-}5}M_{sun}/pc^2$

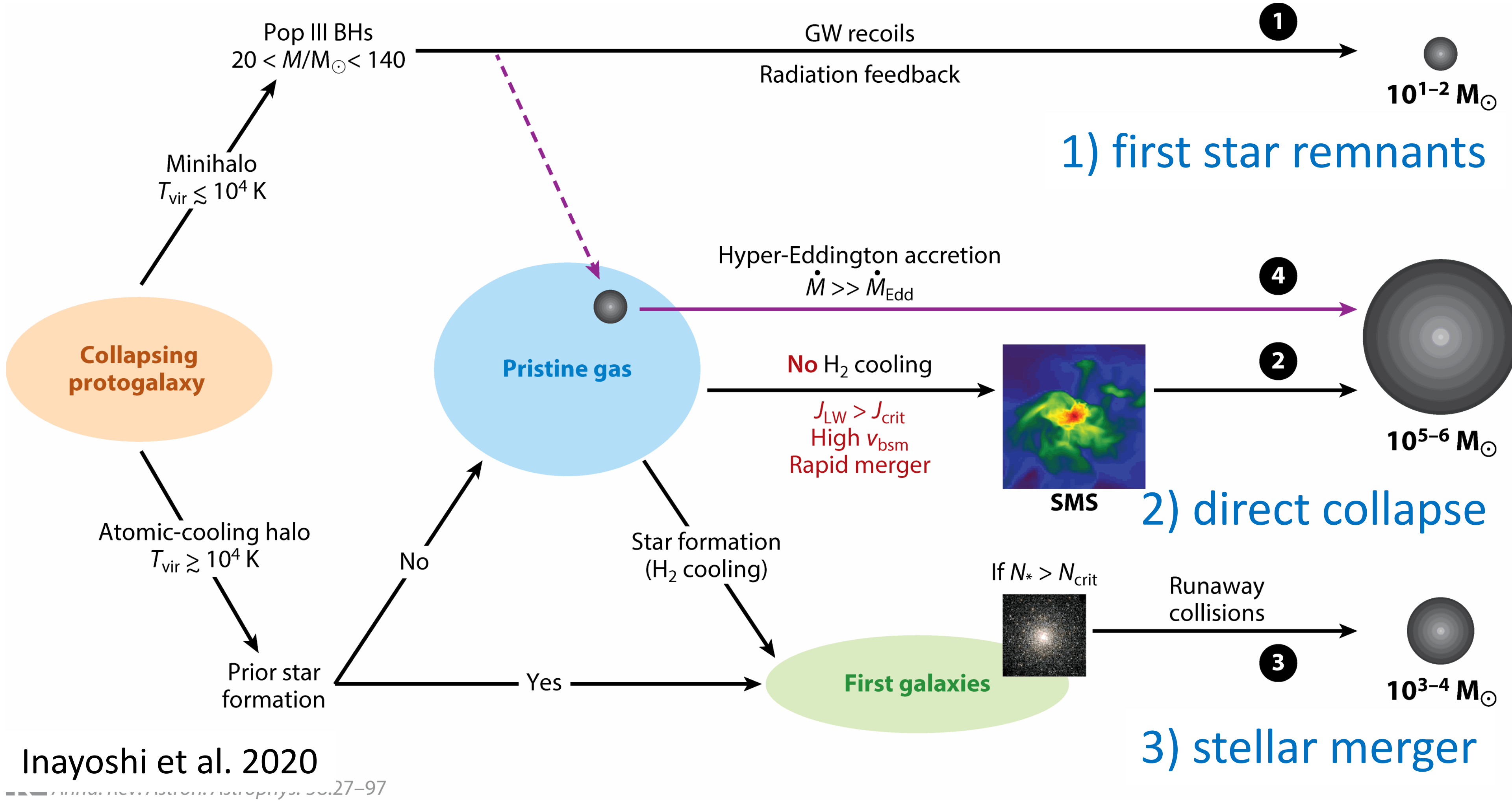
Cosmic Gems @z=10.2 (Adamo+ 2024)



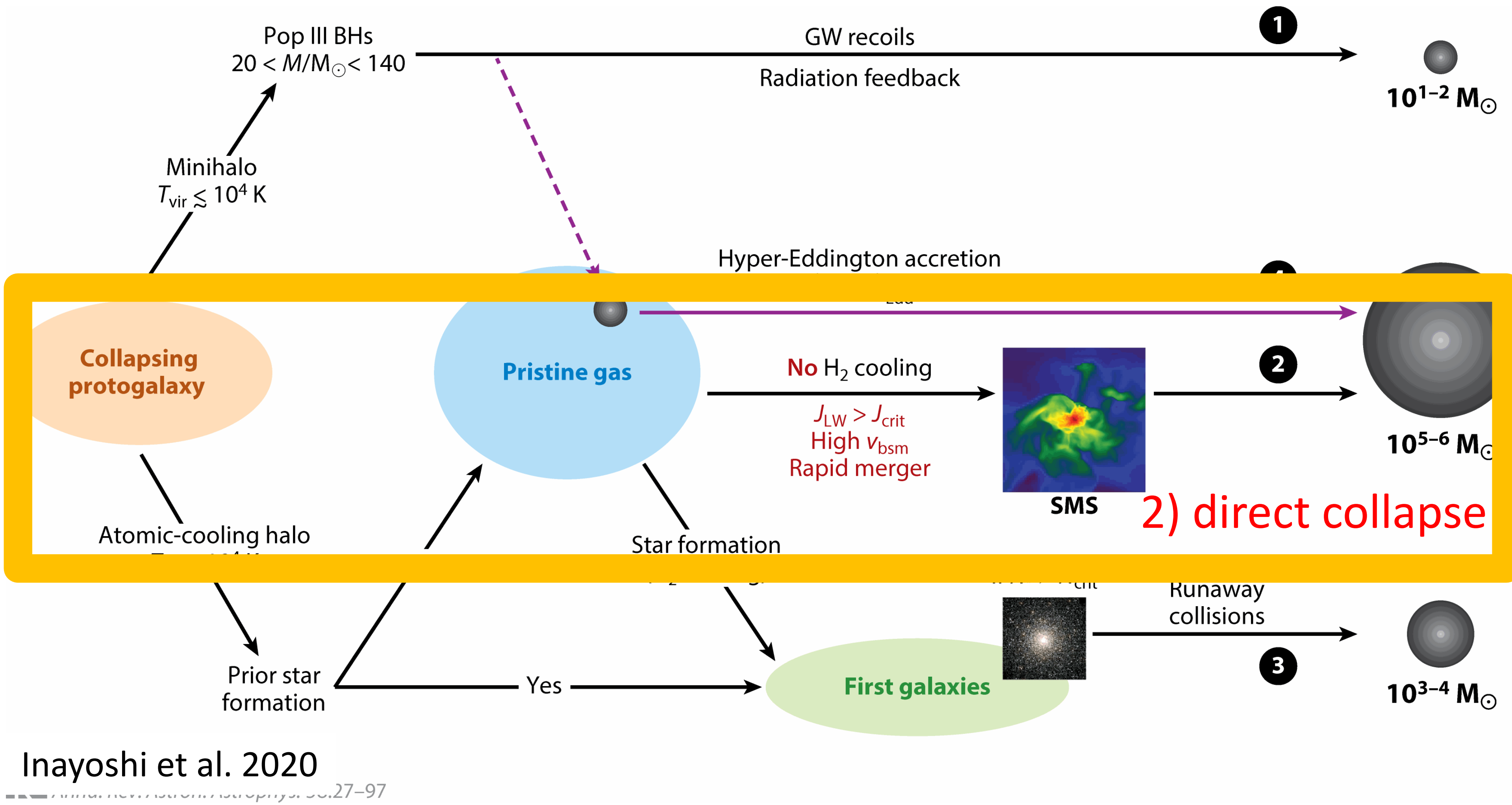
M~10^6Msun, Σ~$10^5M_{sun}/pc^2$

- Are we observing globular clusters in their formation phase?
- What environmental conditions enable the formation of such dense clusters?
- Is there something unique about the early universe facilitating this process?

seed BH formation scenarios



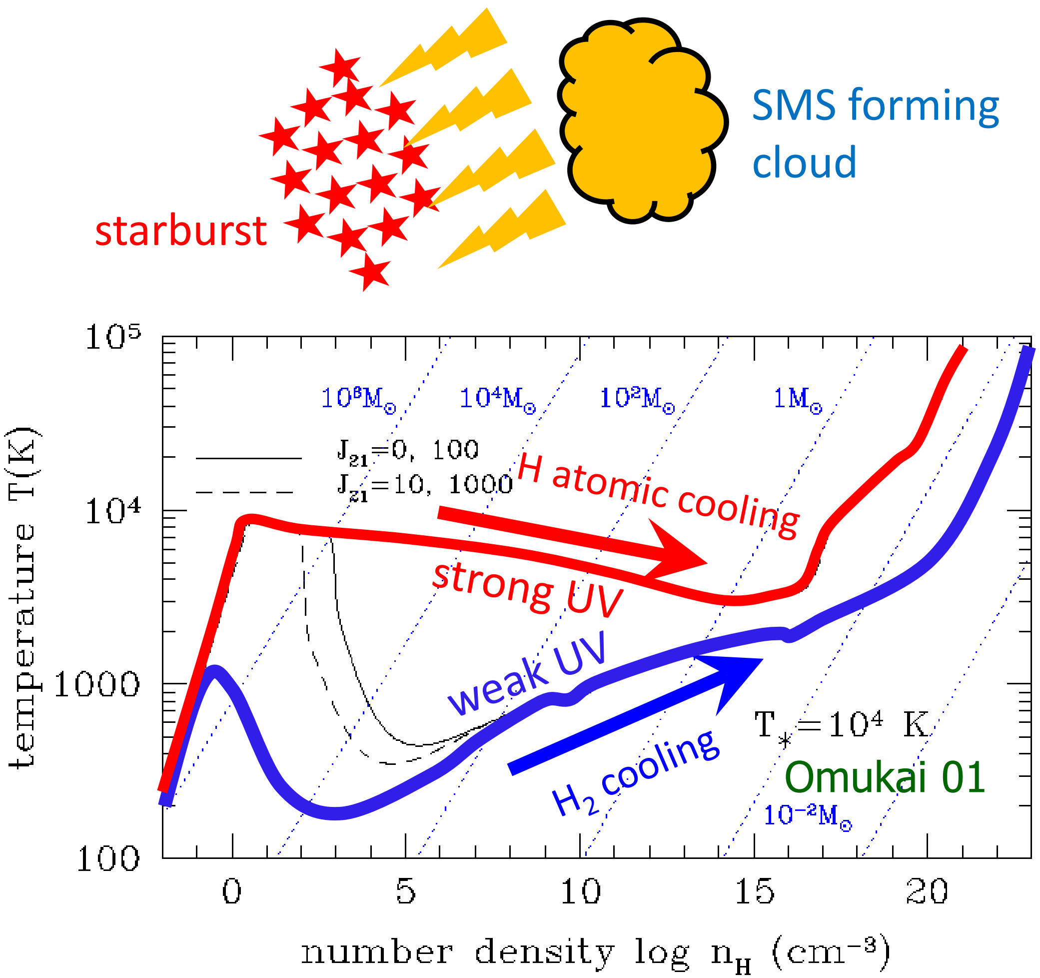
direct collapse BHs



Inayoshi et al. 2020

Direct collapse scenario for SMS formation

Collapse of a massive primordial cloud in strong FUV field



It cools solely by atomic cooling and collapses isothermally at ~8000K.

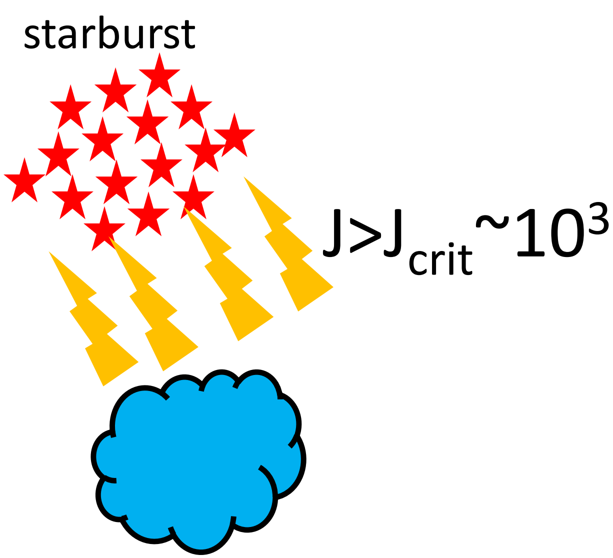
•No rapid cooling phase
→monolithic collapse without fragmentation

•high temperature during the collapse
→rapid accretion in protostellar phase

$dM_*/dt \sim c_s^3/G$
$\sim 0.1 M_{sun}/yr \, (T/10^4 K)^{3/2}$

SMSs ($>10^5 M_{sun}$) are likely to form

Are they abundant enough ?



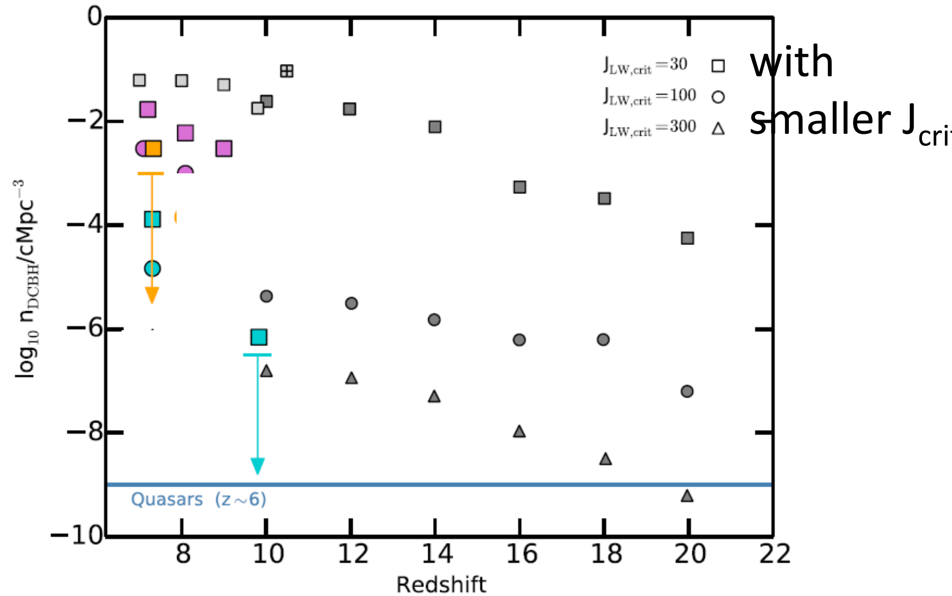
massive pristine halo:
potential site
of direct collapse

estimated number density

$\sim 10^{-4}$ Mpc^{-3} or even smaller

$\ll$ all the SMBHs (~ 0.1 Mpc^{-3})

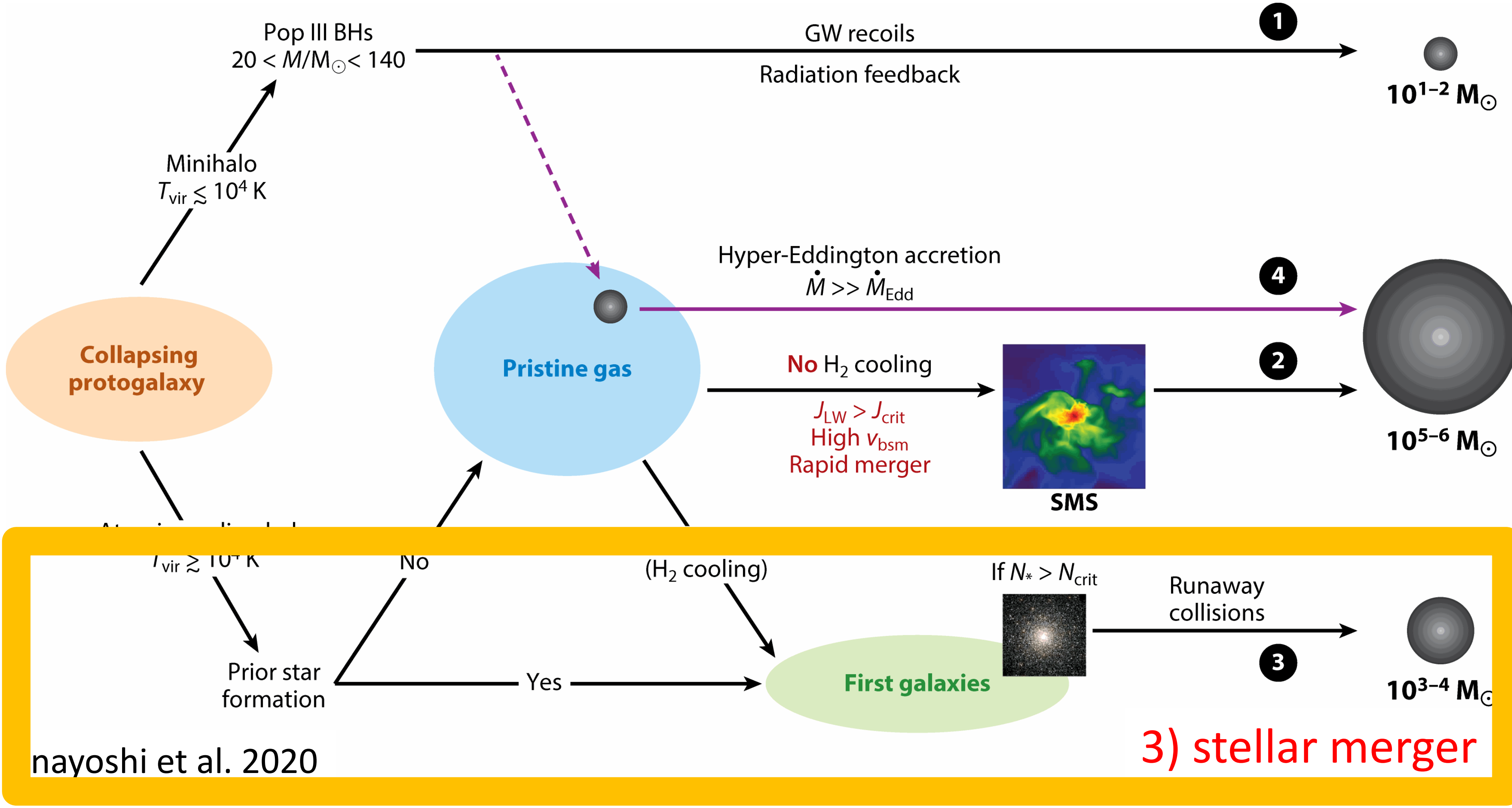
Habouzit et al (2016)



- very strong FUV irradiation is required.
- massive halos are likely to be metal enriched

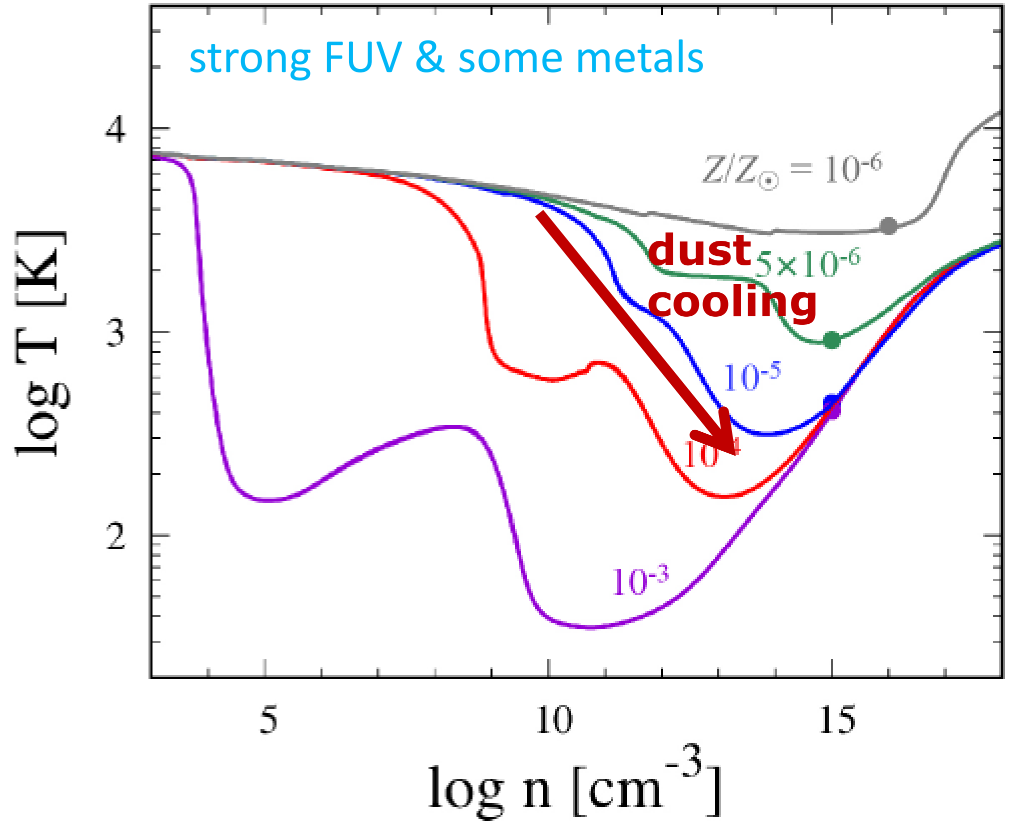
→ DCBHs by this path may be abundant enough for highest-z QSOs, but not for all the SMBHs

stellar merger in dense clusters



What if there are some metals ?

Is it really impossible to form SMSs in metal-enriched case?

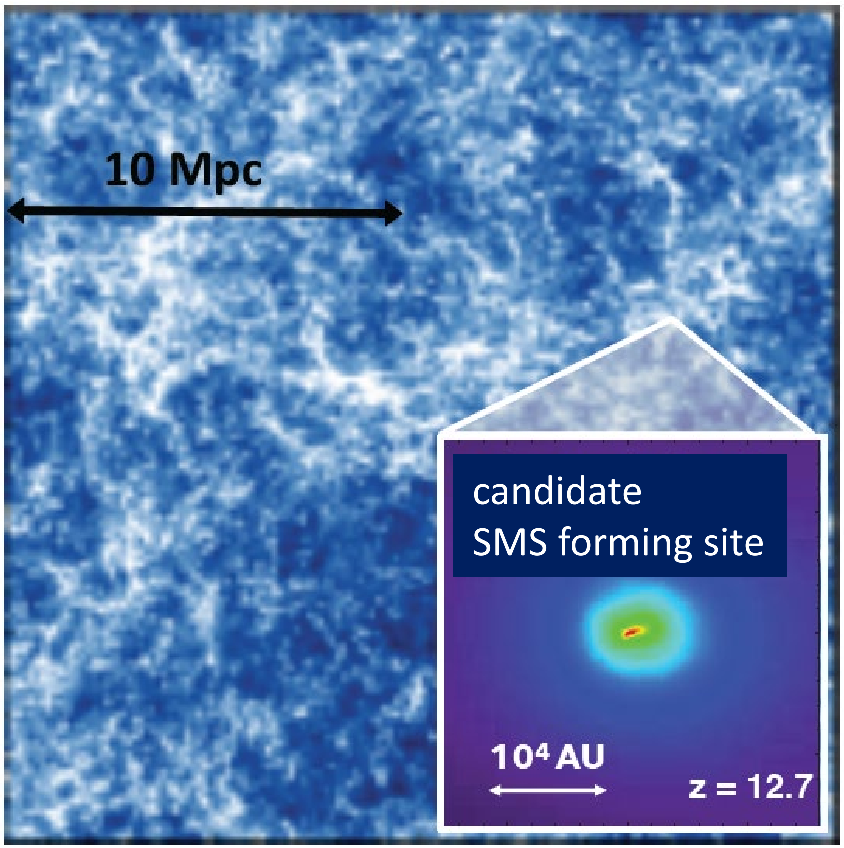


KO, Schneider, Haiman 2008

For Z/Z_{sun} > ~10^{-5},
dust cooling causes rapid temperture drop

cloud fragments and forms a star cluster ?

Numerical Setup



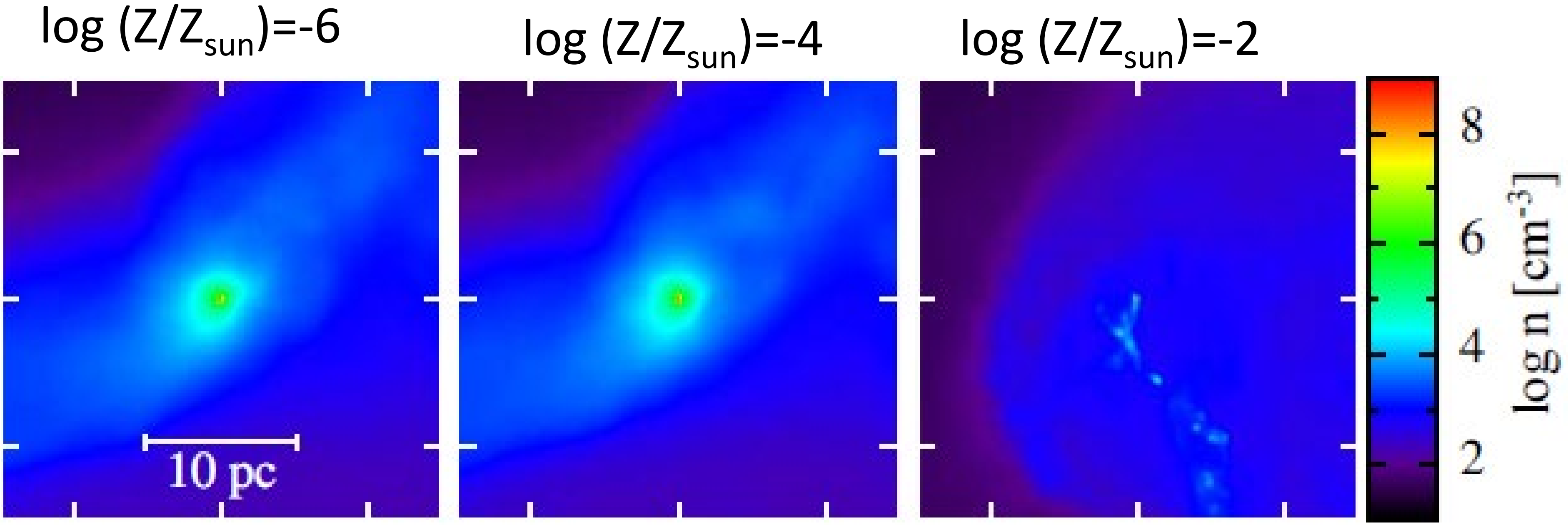
S.Chon & KO
2020

Initial condition:

a halo that is strongly irradiated in cosmological simulation of Chon et al. (2016, 18)

method

•SPH + N-body simulation (Gadget 3)
•primordial gas chemistry + simplified metal treatment
•radiative feedback (LW, ionization)
•sink formation at $2\text{x}10^{16}$-$2\text{x}10^{17}\text{cm}^{-3}$



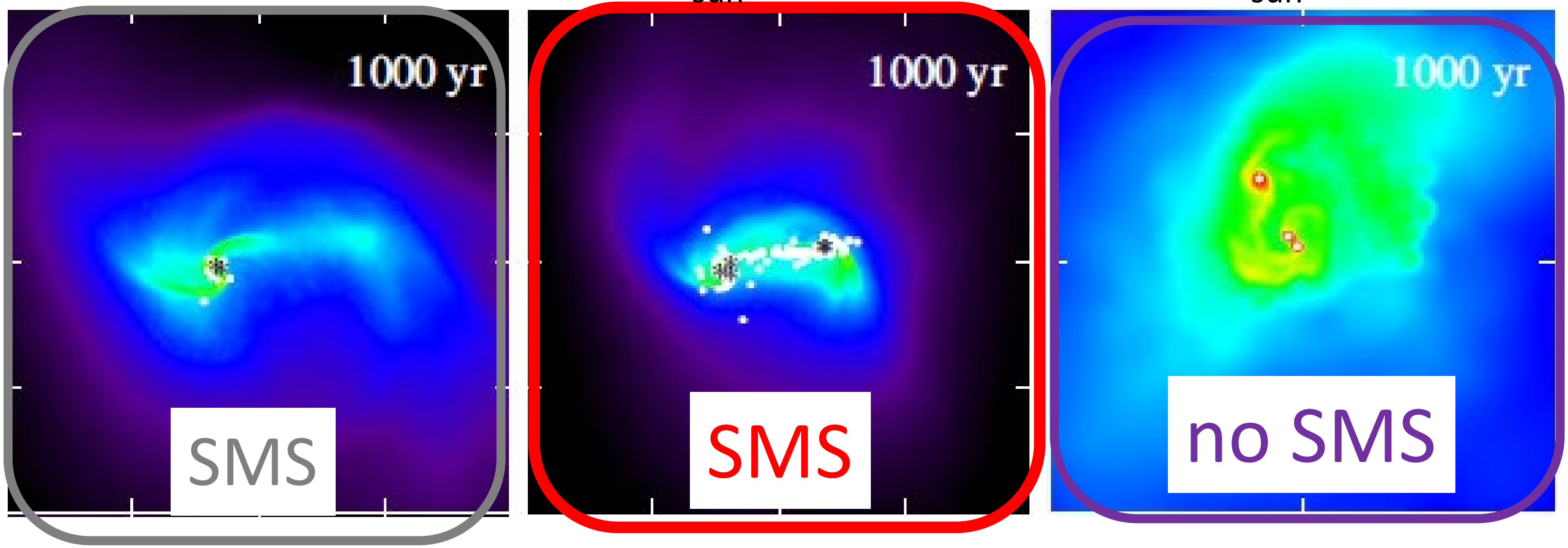
log (Z/Zsun)=-6
log (Z/Zsun)=-4
log (Z/Zsun)=-2
10 pc
8
6
4
2
log n [cm-3]

asterisks >$10M_{sun}$
white dots <$10M_{sun}$

Conventional direct collapse

star cluster formation

log (Z/Z_{sun})=-6   log (Z/Z_{sun})=-4   log (Z/Z_{sun})=-2



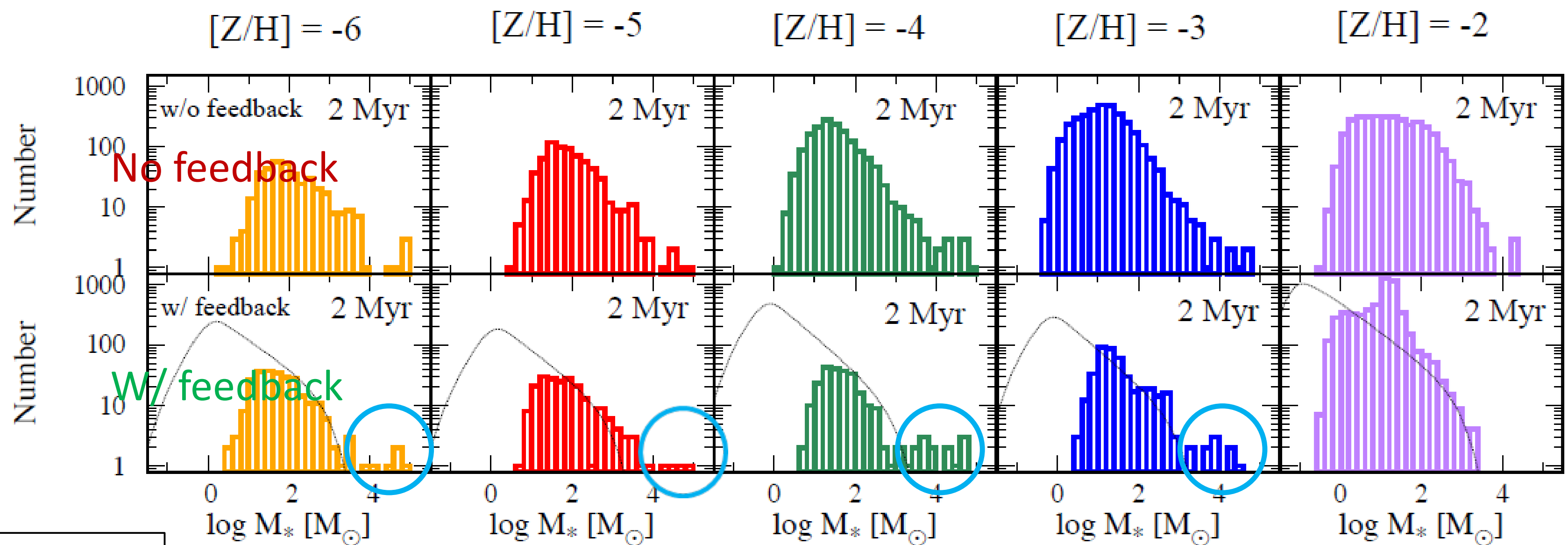
Super Competitive Accretion

only little fragm
→ SMS formatio
at the center

numerous fragments
but the central star grows supermassive

oling
al flow
pattern
star cluster formation by fragmentation

Stellar masses after ~Myr



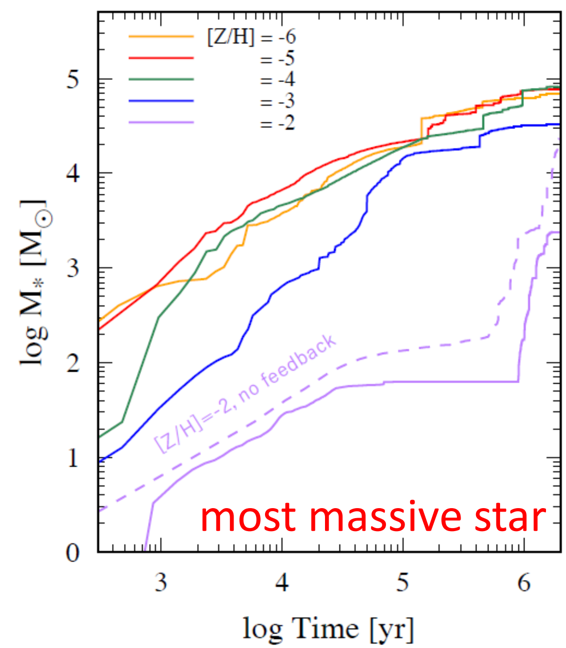
[Z/H] <= -3

Bimodal IMF: Salpeter-like (peaking at ~10 M☉) + SMSs

-low mass stars (<~10 M☉) reduced by dust heating by stellar irradiation

-massive stars (~100-1000 M☉) also reduced by ionizing radiation

Formation of SMSs >~ 10^5M☉ is not prevented by radiative feedback



[Z/H] = -2

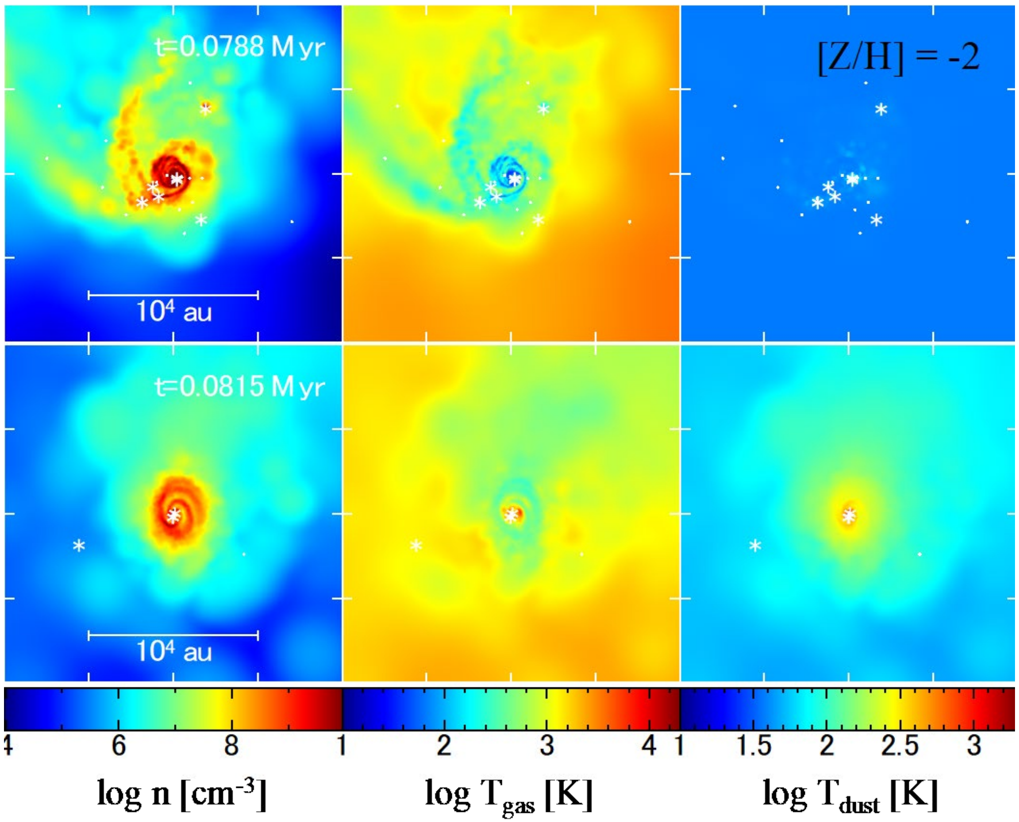
single Chabrier-like IMF (the slope shallower above ~100 M☉)

−The most massive stars ~1000 M☉.

−Ionization feedback reduces stars above 10 M☉.

Effects of stellar feedback

Radiation feedback from forming stars is now included



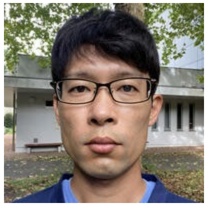
S. Chon & KO in prep.

-Due to stellar irradiation of dust, T~200-300 K.

-disk stabilized and fragmentation suppressed

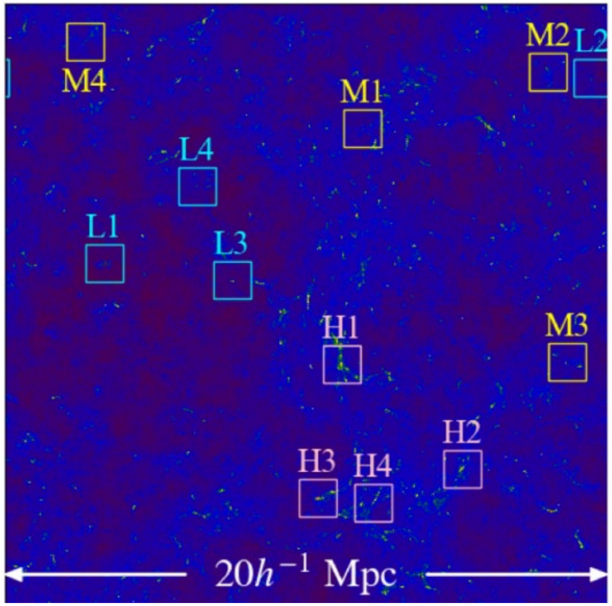
how many seeds in the universe?

G. Chiaki + (KO) 2023

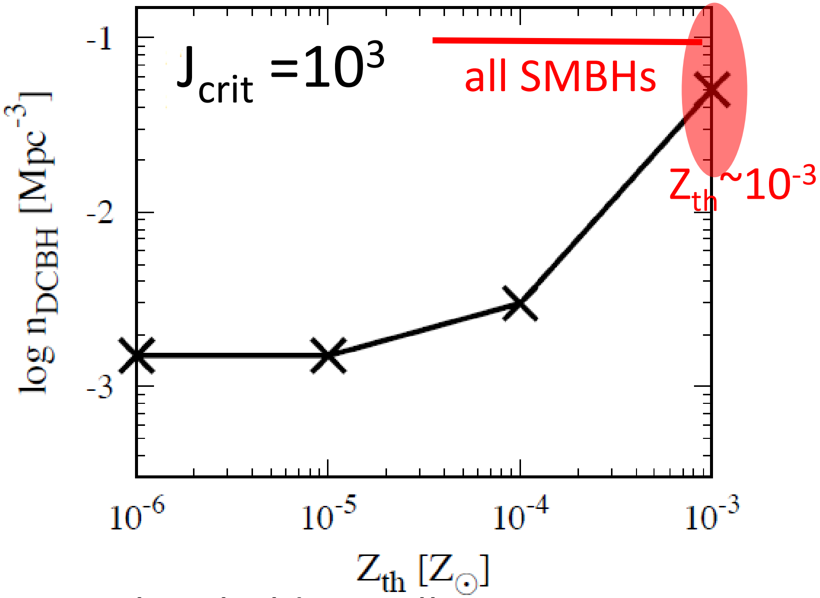


cosmological N-body simulation
+ semi-analytic galaxy formation model

count candidate halos
with $J > J_{crit}$ & $Z < Z_{th}$



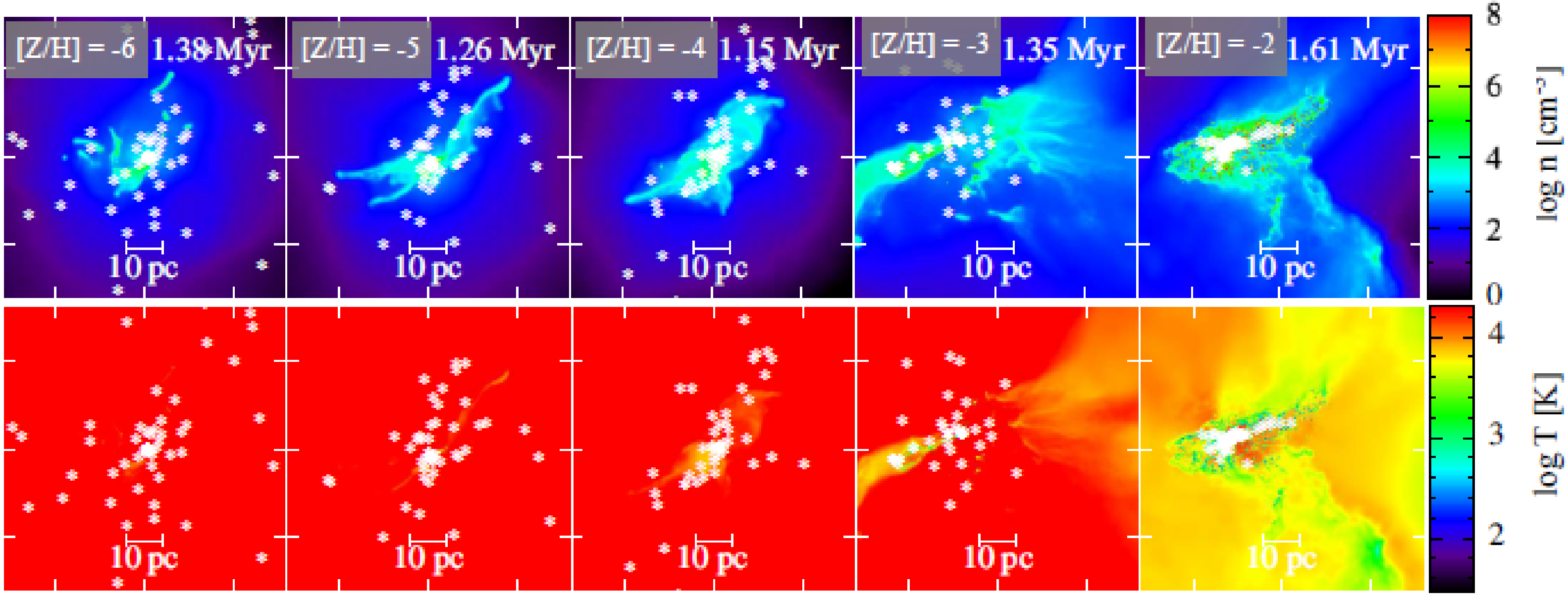
seed density = progenitor halo number x success fraction (~1/20, e.g., Chon+16)



threshold metallicity
below which SMSs can form

Seed BH formation in metal-enriched regions can account for the number of SMBHs in the local universe.

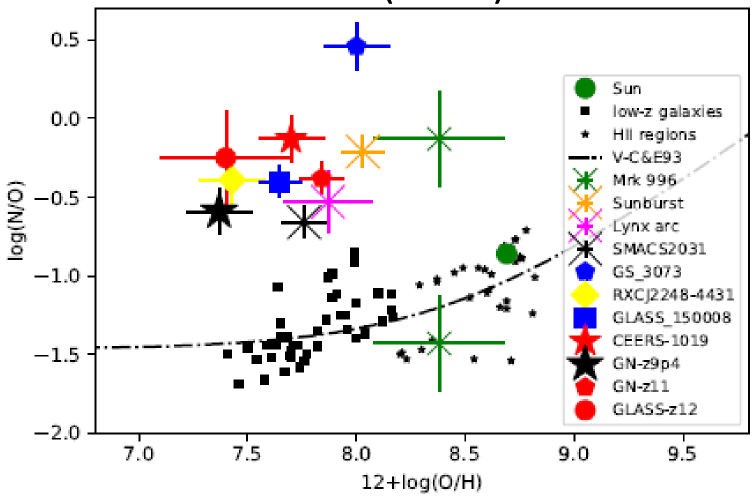
properties of forming star clusters



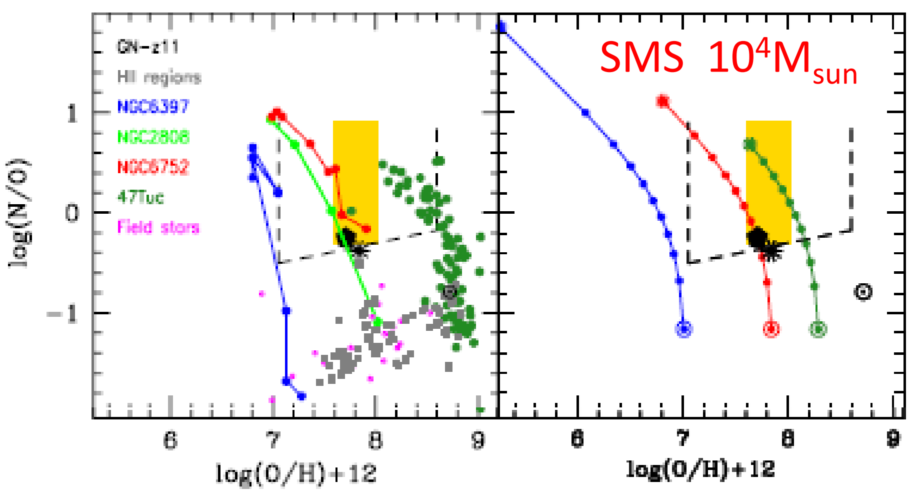
- [Z/H]<= -3: stars are ejected by dynamical interactions with SMSs (~$10^5 M_{sun}$)
  -> formation of sparse clusters
- [Z/H]=-2 : very dense star cluster (~$10^4 M_{sun}/pc^2$)+ VMS (>$10^3 M_{sun}$)

high N/O by VMS pollution

Schaerer et al. (2024)



- high N abundances are observed in some high-z galaxies.
- These galaxies tend to be compact.
- globular clusters show similarly high N abundance



metal pollution by SMSs may be a possible origin of such high N/O abundance. (Charbonnel et al. 2024)

まとめ

We conducted simulations of star cluster formation in low-density environments, modeling each star individually and including radiation feedback.

For metallicity [Z/H] $\lesssim$ -3:

-a few stars undergo runaway growth through mergers and accretion, leading to the formation of supermassive stars (SMSs) $>10^5 M_{sun}$.

-These seed black holes potentially accounting for all SMBHs observed in the local universe.

-The resulting star clusters are less dense and become dispersed due to interactions with SMSs.

For metallicity [Z/H] ≈ -2:

-SMS formation fails, but very massive stars (VMSs) are still produced.

-This leads to the formation of dense star clusters, which could be linked to high-redshift dense clusters and globular clusters.

-This process may also be the origin of the observed N/O overabundance.