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First galaxy formation under stellar feedback

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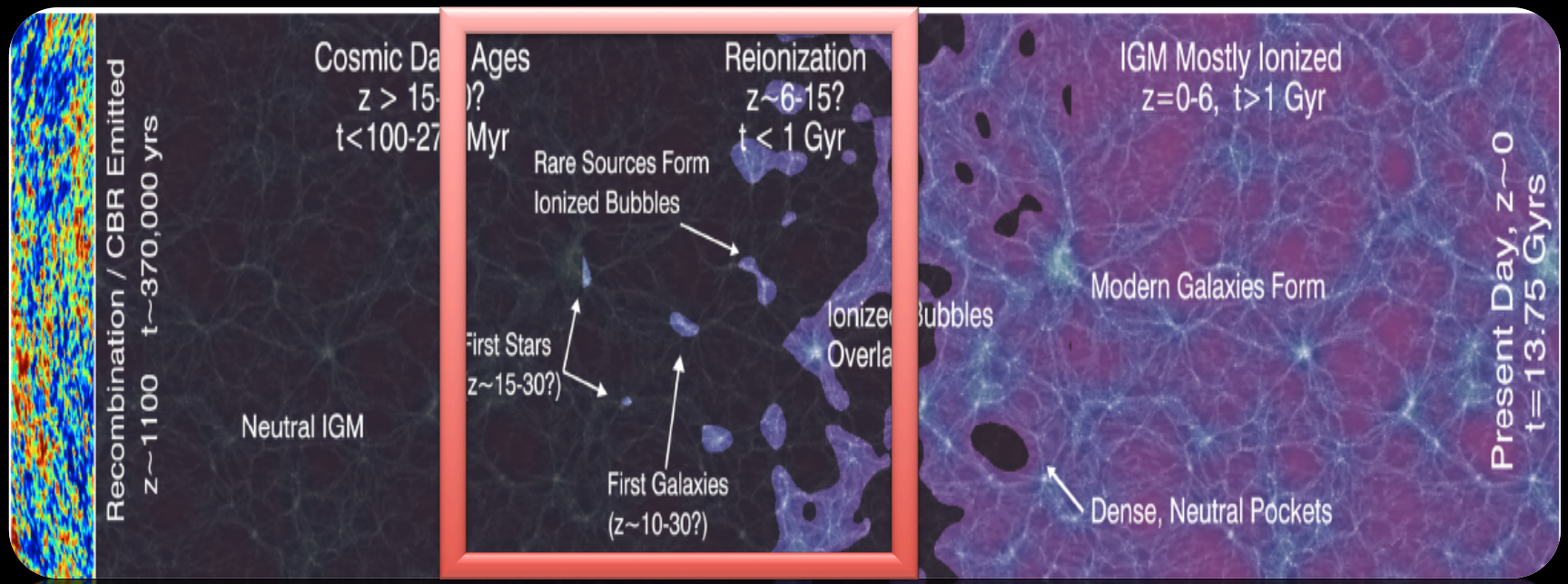
redshift 30 10 6

uniform → First Galaxies → Cosmic Web

Big Bang



today

neutral → Reionization → ionized

0 100 900 million years

Closing the gap (at z ~10)

ab initio simulations →

← current (HST)

← stellar light: JWST (2018)

← 21 cm of neutral hydrogen: LOFAR, MWA, SKA

$10^{5\text{-}6}$ $10^{7\text{-}8}$ 10^{10} M_{vir} [$M_\odot$]

10^3 10^4 T_{vir} [K]

minihalos (H_2 coolers) | atomic coolers | Lyman-alpha emitters

Courtesy: Volker Bromm, First Stars IV conference

Study goal

perform a realistic galaxy formation simulation from first principles and predict the properties of the first galaxies.

Ideal testbed for stellar feedback, one of the most important ingredients of galaxy formation.

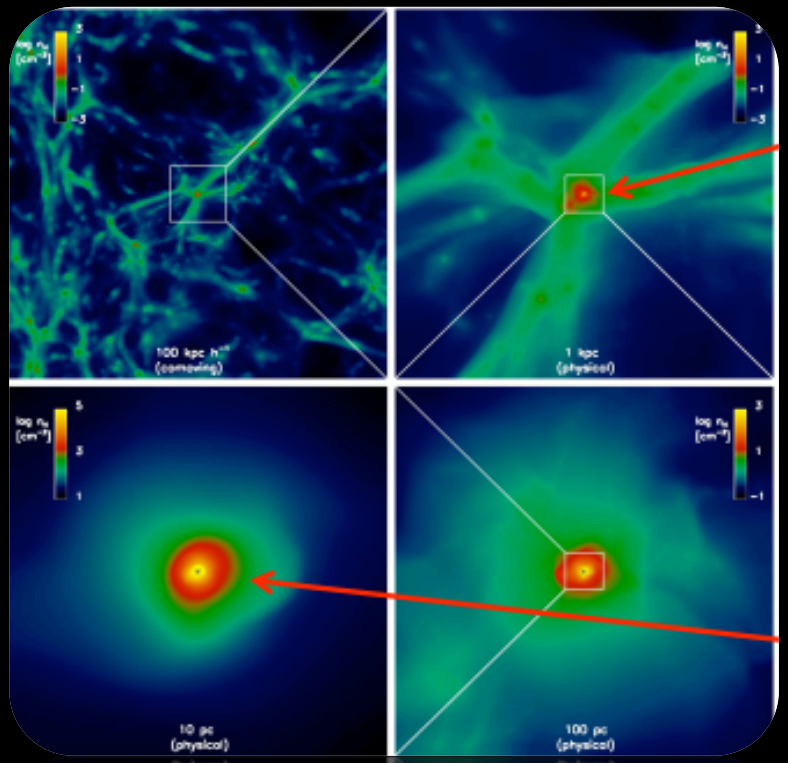
Outline

- Introduction
- Supernova feedback
- X-ray feedback
- First galaxy assembly
- Conclusion

First Stars (Pop III stars)

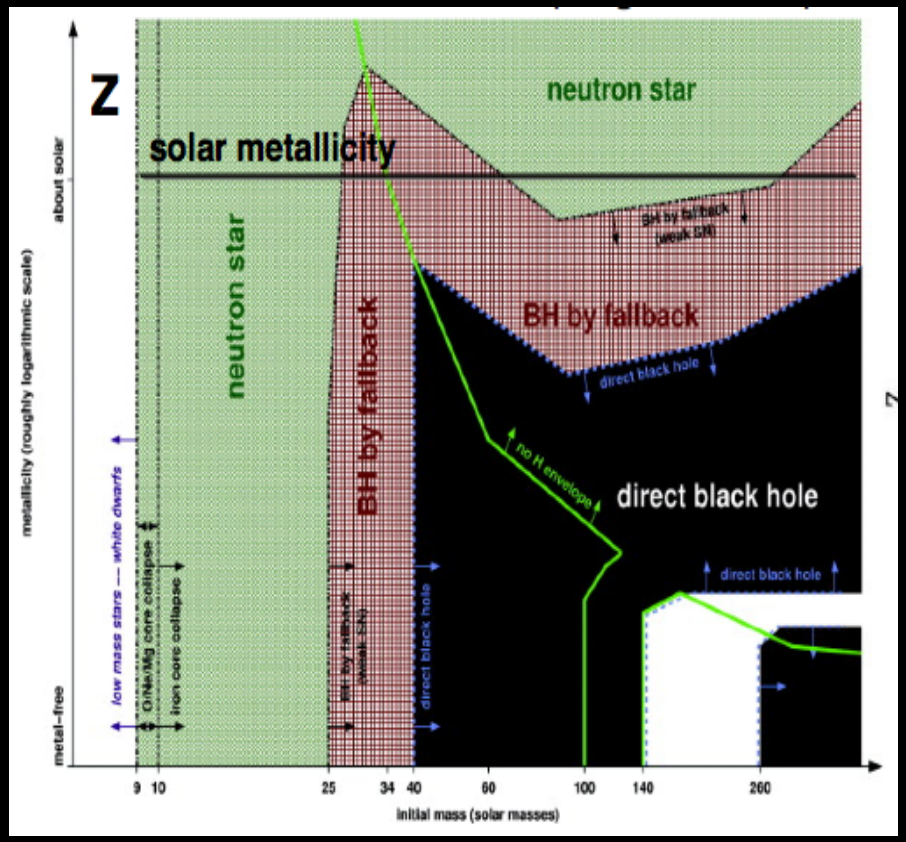
- z = 30-20
- Hosted by Minihaloes
- $M_{vir} = 10^{5\text{-}6}\ M_\odot$
- R_{vir} = 100 pc
- Coolant : H_2

- Mass : massive (>100 $M_\odot$)
  - Characteristic Mass: 10-60 $M_\odot$
  - Pop III can emerge as members of small multiple systems with a range of masses (Turk et al. 2009; Stacy et al. 2010, Dopcke et al. 2013).



Stacy et al. 2010

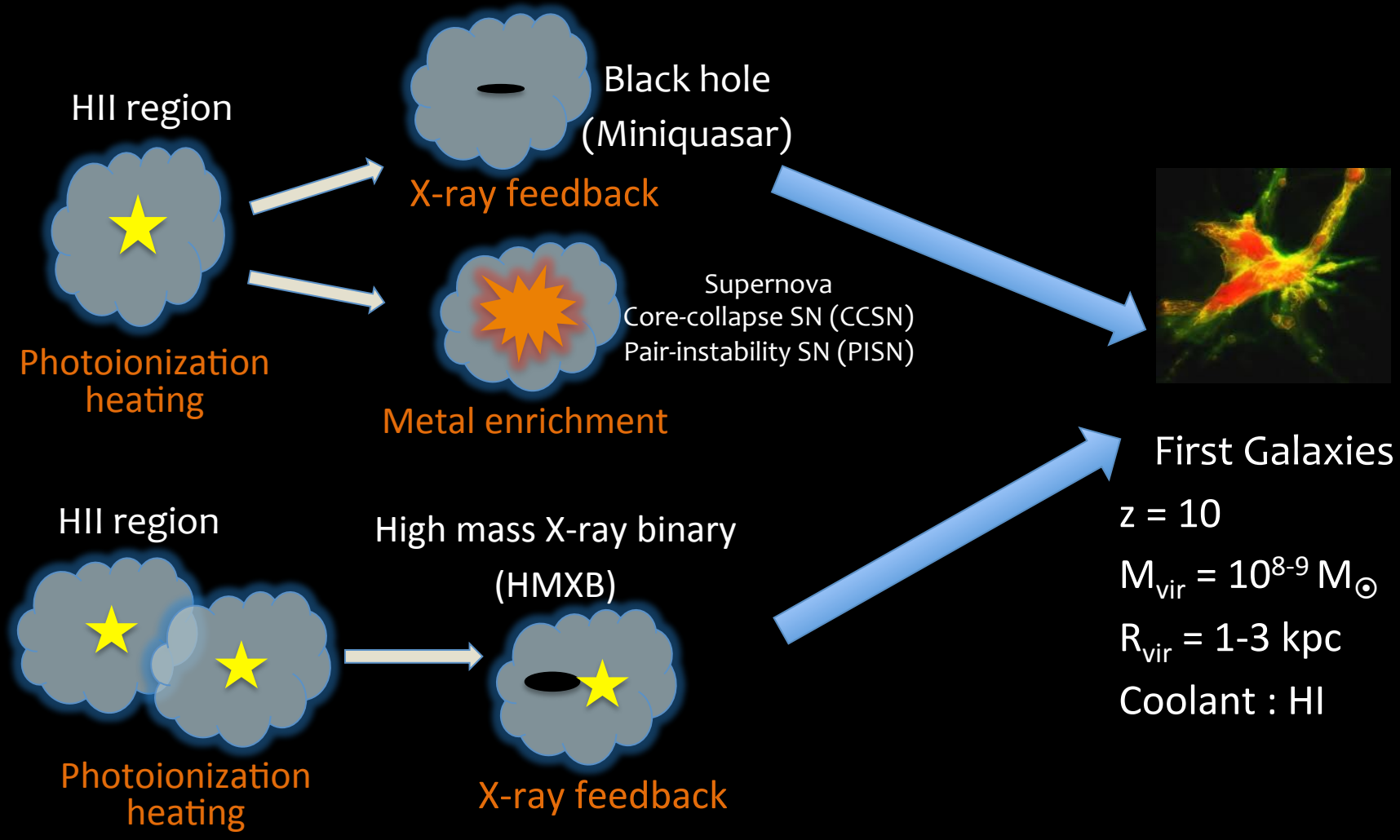
How did first stars die?



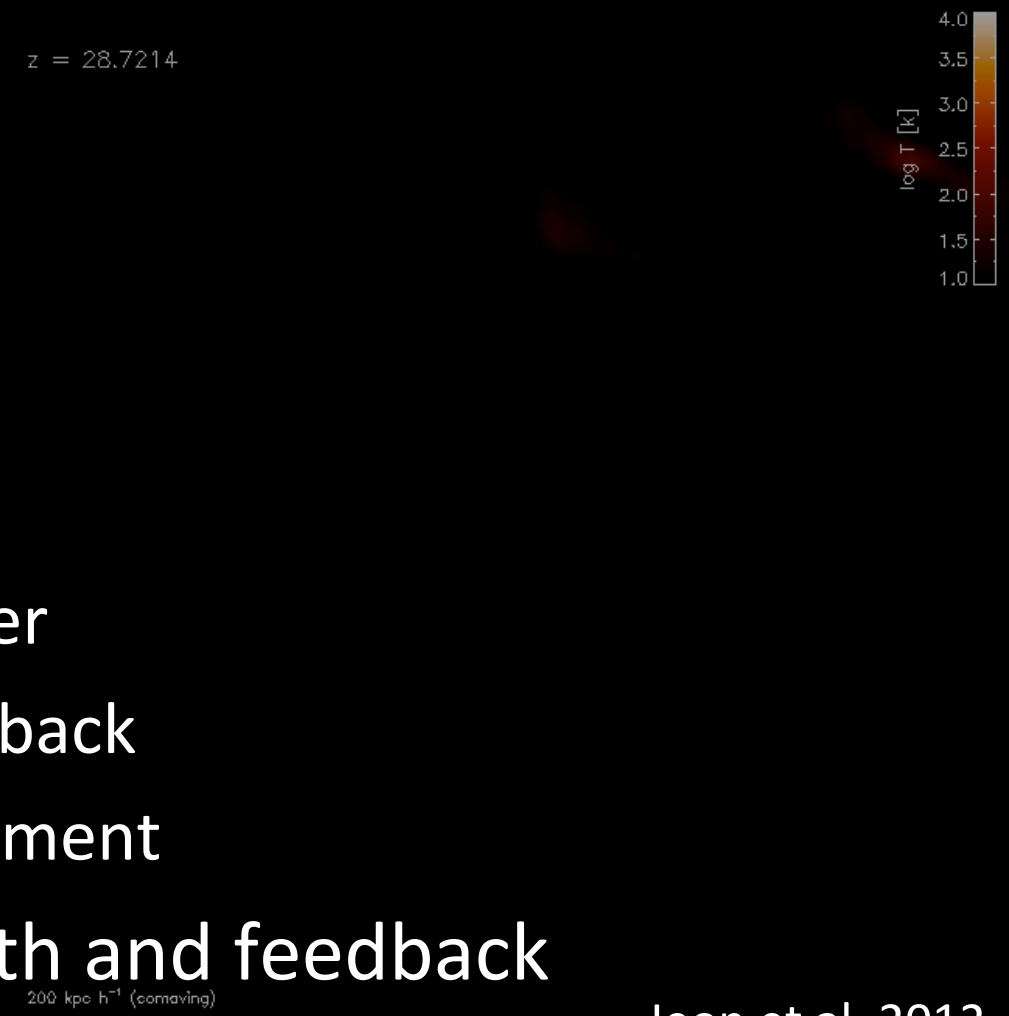
Heger & Woosley, 2003

- $10\ M_\odot < M < 40\ M_\odot$: core-collapse supernovae (CCSNe)
- $40\ M_\odot < M < 140\ M_\odot$: direct collapsed black hole
- $140\ M_\odot < M < 260\ M_\odot$: pair-instability supernovae (PISNe)
- $M > 260 M_\odot$: direct collapsed black hole

How did Pop III feedback shape initial conditions for first galaxies?



Cosmological simulations



- Dark matter
- Gas
- Star formation
- Stellar feedback
  - radiative transfer
  - supernova feedback
  - chemical enrichment
- Black hole growth and feedback

Jeon et al. 2012

Simulations

Cosmological zoom-in radiation hydrodynamic simulations (Gadget3)

Box : 1 Mpc (comoving)

Mass resolution : 5 $M_\odot$ (Gas) and 33 $M_\odot$ (DM)

Period : z~30 – 10 (~ 400 Myr)

Star formation : $n_H > 10^4$ cm^{-3}

Cooling : Non-equilibrium chemistry and cooling of the primordial gas + metal line cooling by C, O, and Si.

Ionizing radiative transfer (RT)

Code : TRAPHIC (Pawlik & Schaye 2008, 2010)

Trace X-ray with secondary ionization, Lyman-Werner (LW) radiation with self-shielding.

TRAPHIC
(TRAnsport of PHotons in Cones)

Pawlik & J. Schaye 2008, 2010

- Spatially adaptive (SPH/Gadget; vs. uni-grid)
- No scaling with # sources (vs. linear scaling)
- Radiation hydrodynamics (vs. post-process)

<u>The two key ideas:</u>

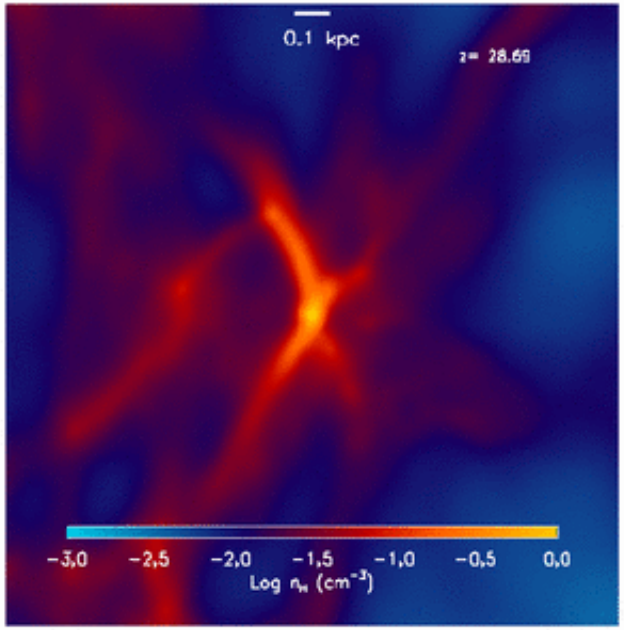
- Trace photons on particles in smoothed particle hydrodynamics simulations
- Merge photon packets (inside cones)

Supernova feedback

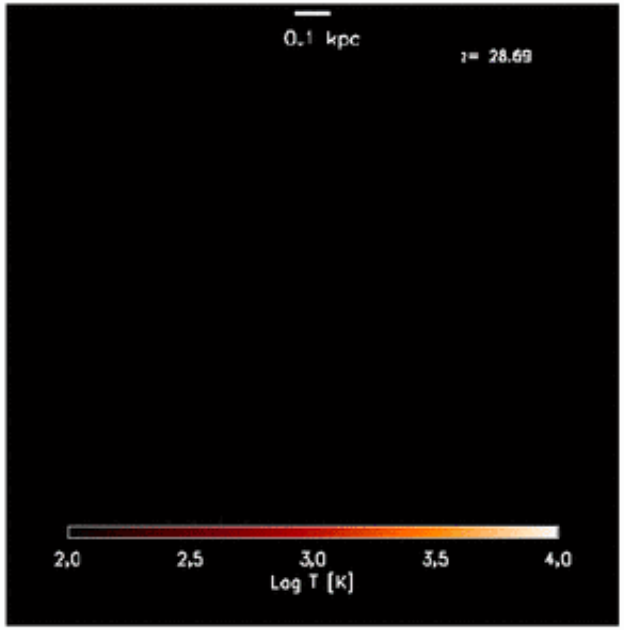
- How did first supernovae do on the gas inside of host haloes and on the IGM?
- To what levels can the first SNe enrich the surrounding medium prior to the onset of second generation star formation?
  (Transition from PopIII to PopulationII stars)

SN feedback: 40 $M_\odot$ progenitor

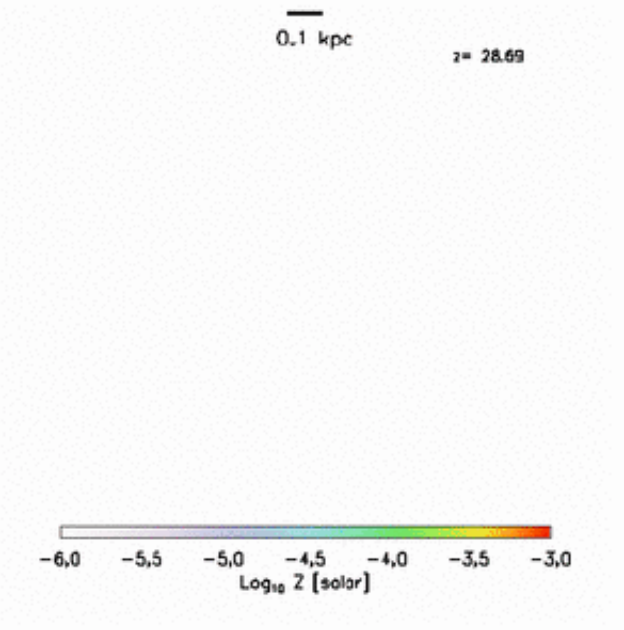
Density



Temperature



Metallicity

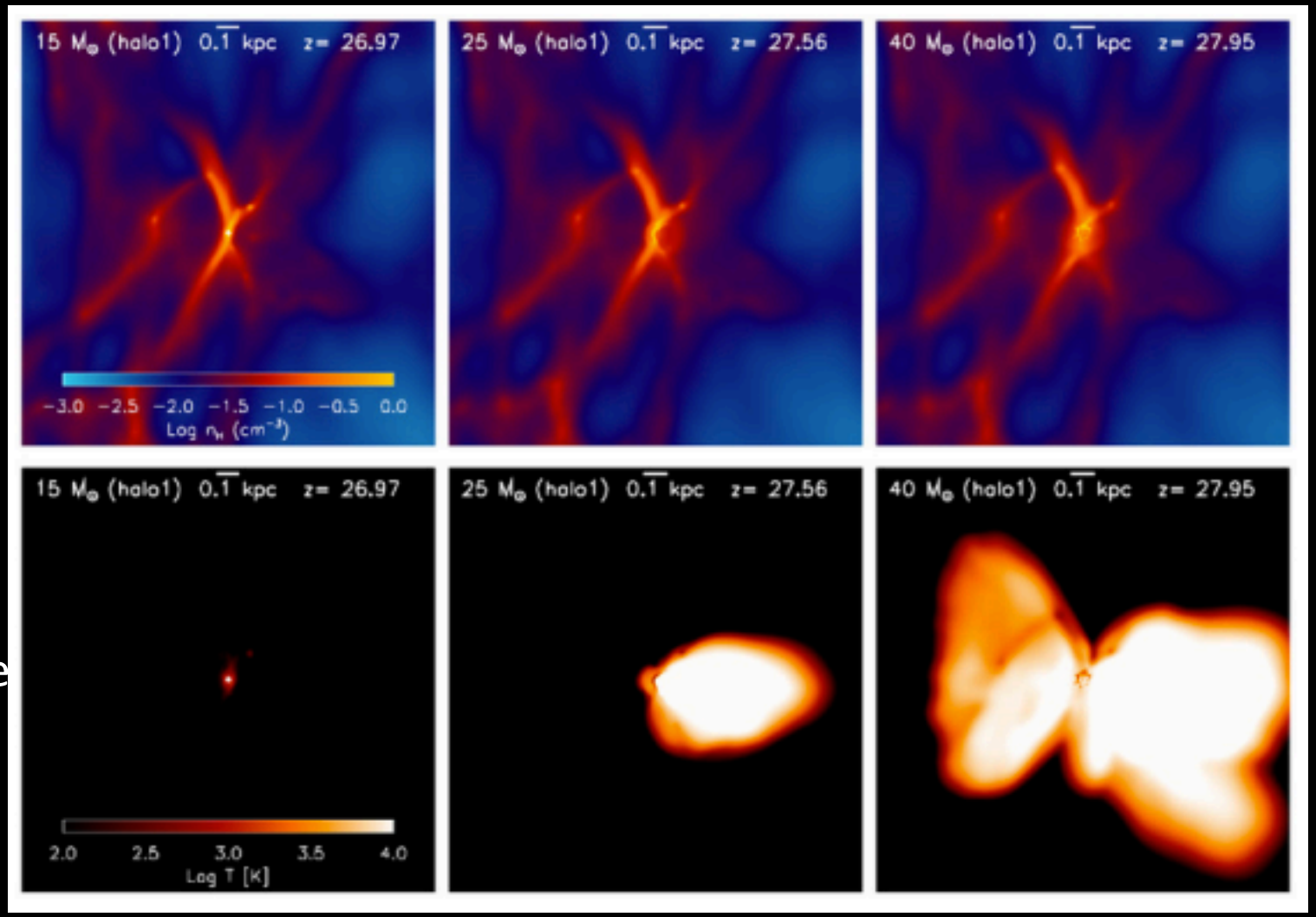


Gas conditions prior to SN

15 $M_\odot$ 25 $M_\odot$ 40 $M_\odot$

Density

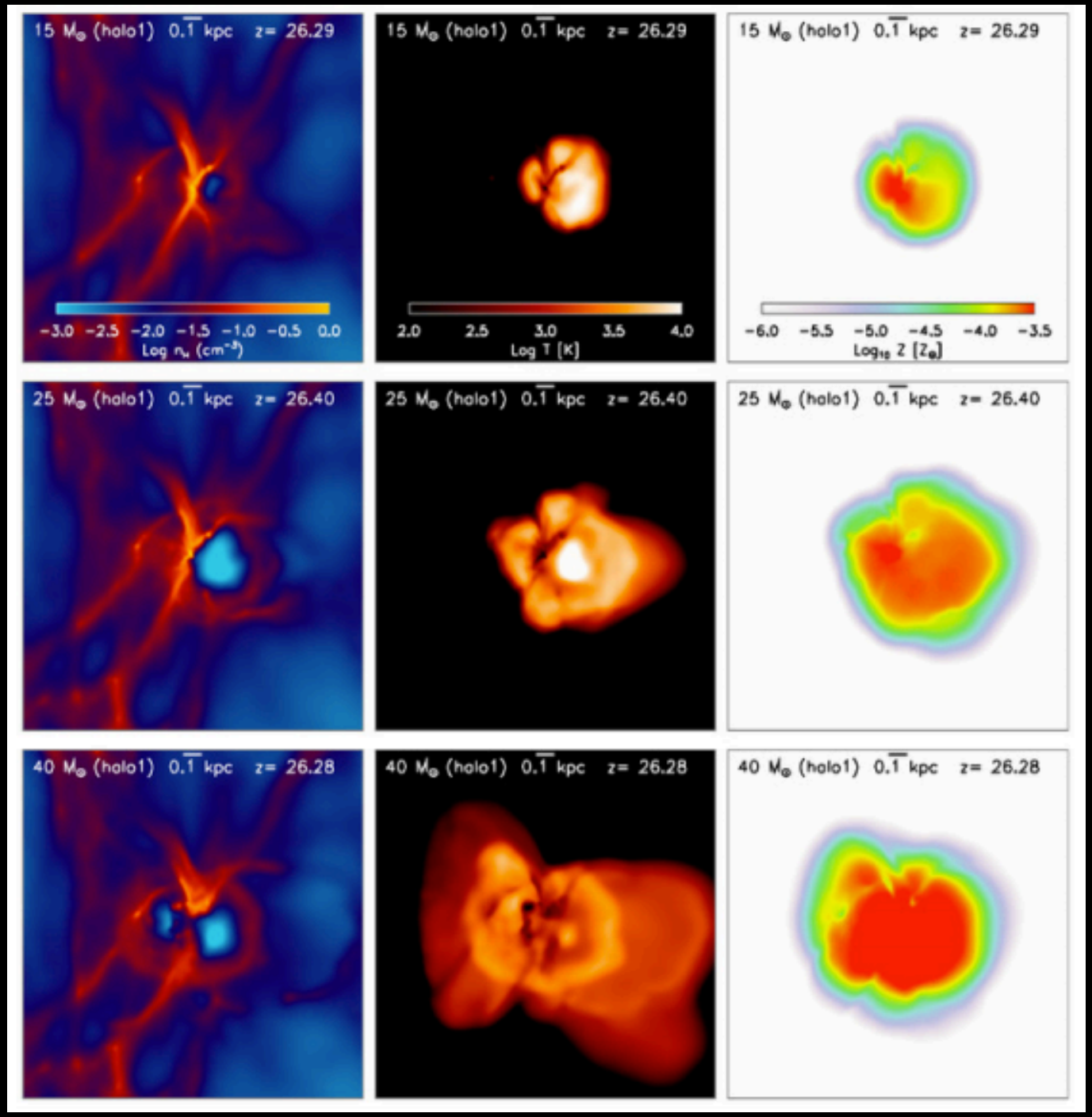
Temperature



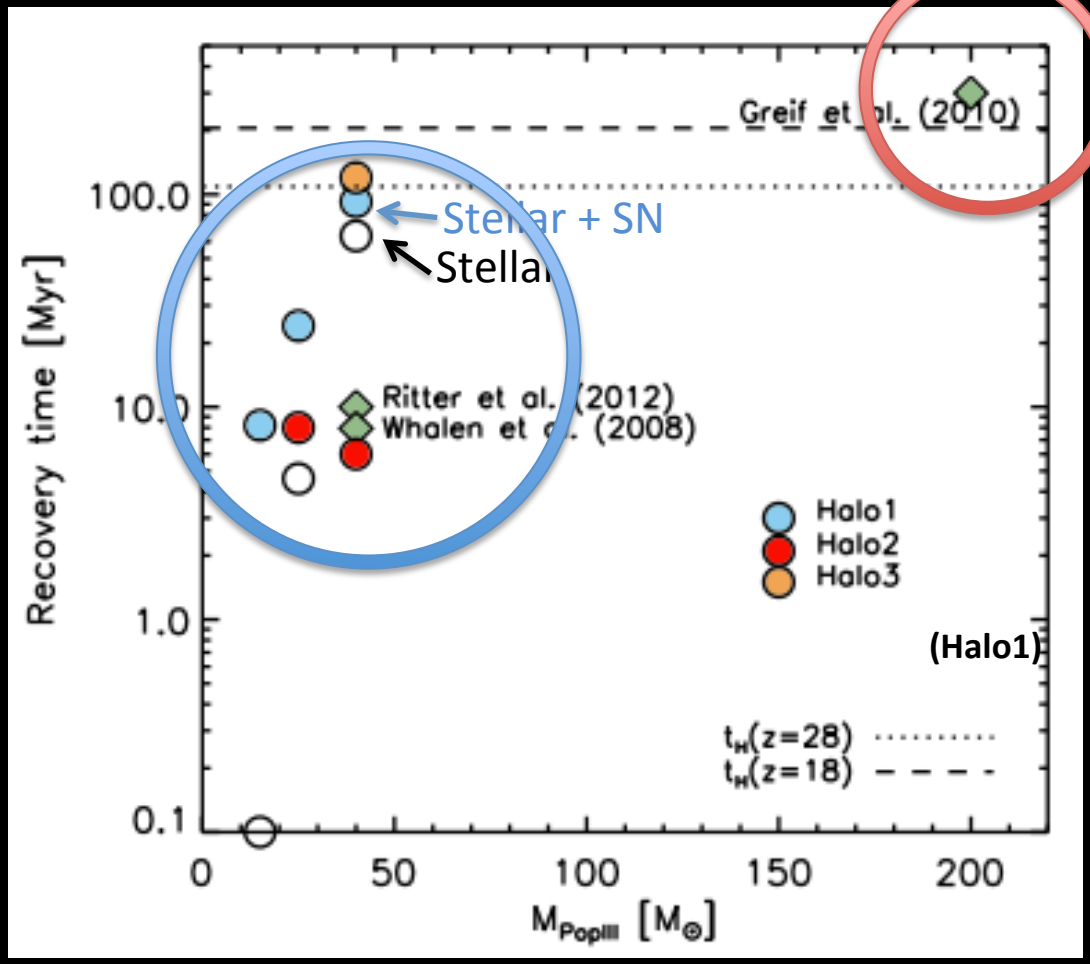
15 $M_\odot$

25 $M_\odot$

40 $M_\odot$



How long does it take for the recovery?

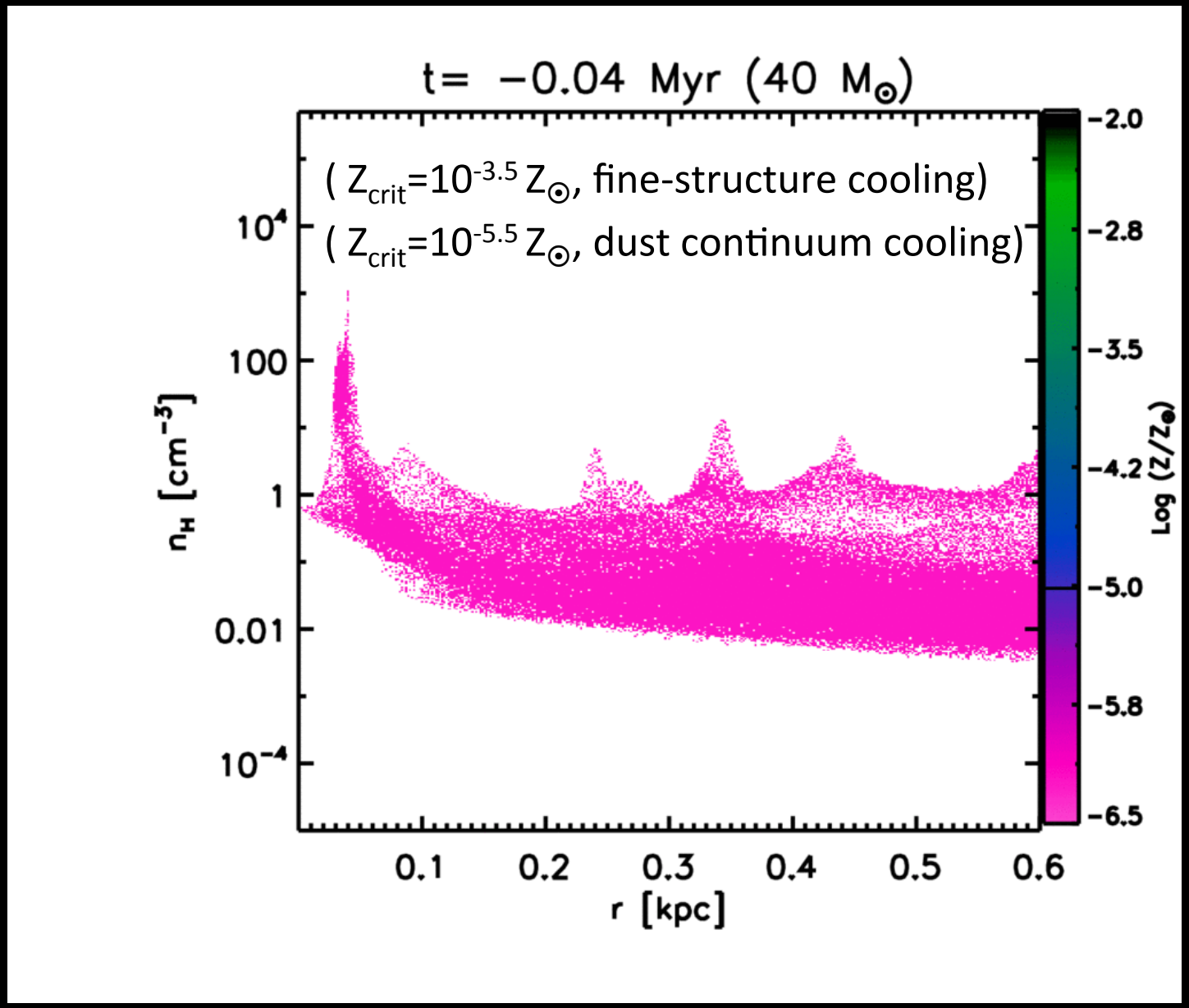


by PISN
Above Hubble Time

Jeon et al. 2014b

For PopIII progenitor masses $M \leq 40\ M_\odot$, recovery is prompt ~ 10 Myr.

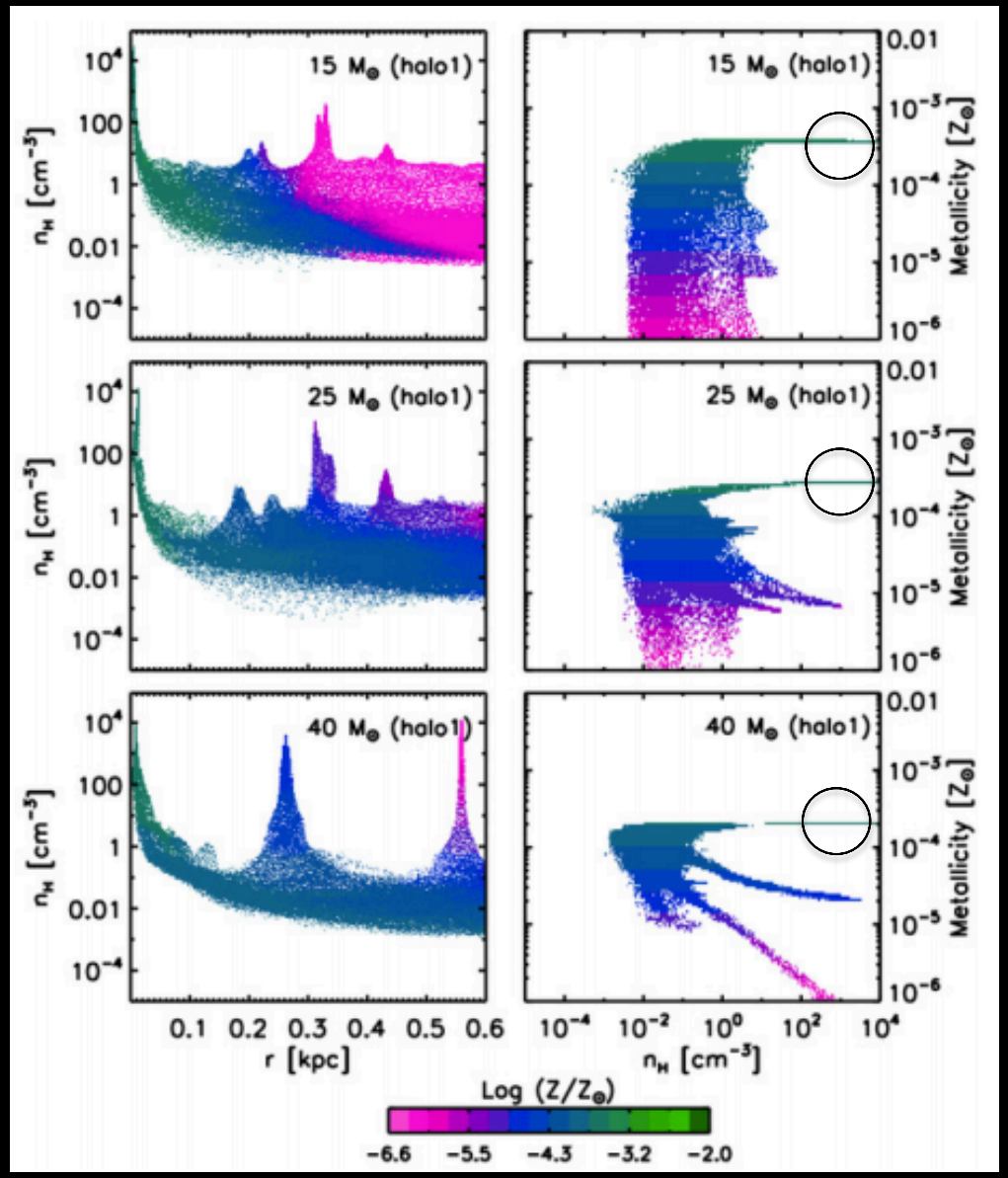
Metal diffusion : 40 $M_\odot$ progenitor



Single SN is enough for PopIII/PopII transition

The central cold and dense gas can be enriched above $Z=10^{-4}\ Z_{\odot}$ by a single core-collapse PopIII SN.

Second generation of stars belong to Population II.



X-ray feedback

Possible X-ray sources in high-z

- High-Mass X-ray Binaries (HMXBs)
- Miniquasars
- Supernova remnant shocks
- Halo accretion shocks
- Dark matter annihilations

- Did X-ray feedback promote or suppress star formation?
- What did X-ray feedback on a stellar-size black hole?

Did X-ray feedback promote or suppress star formation?

Positive feedback

Enhancement in molecular hydrogen (H_2)→ promote H_2 cooling → Star formation

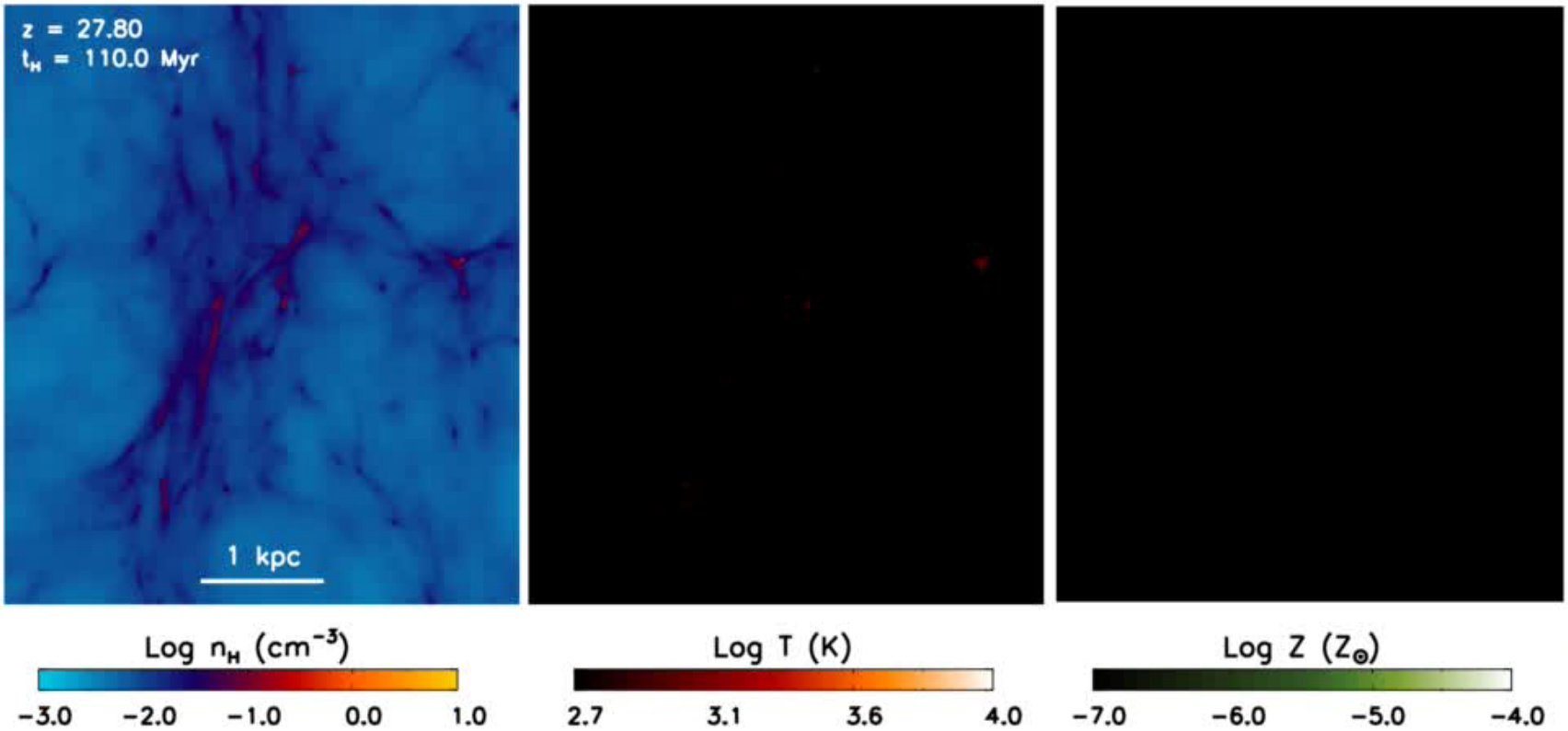
Negative feedback

Photoionization, Photoheating, and Photoevapolation

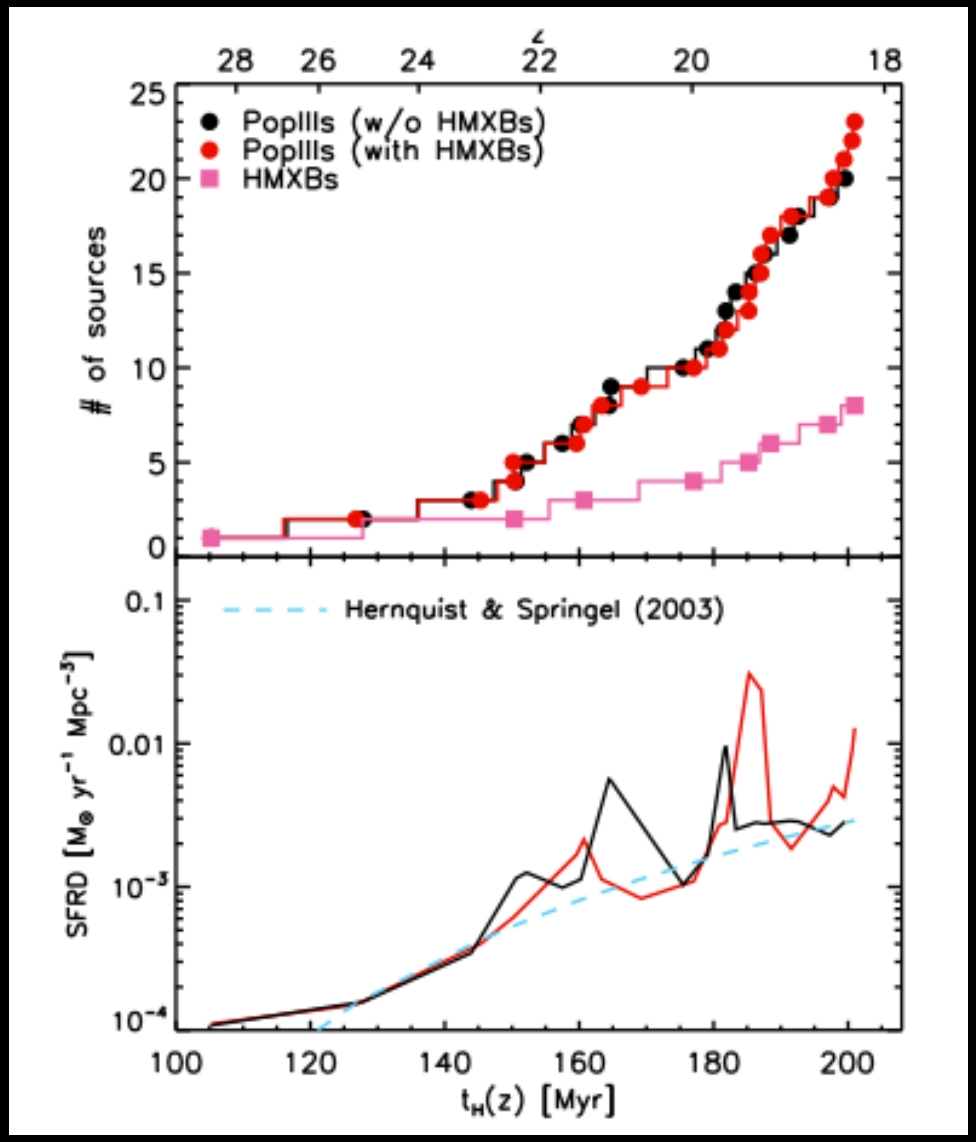
Heating the IGM → Increase Jeans mass → delay collapse of gas onto halos.

X-ray photons propagate further

Density Temperature



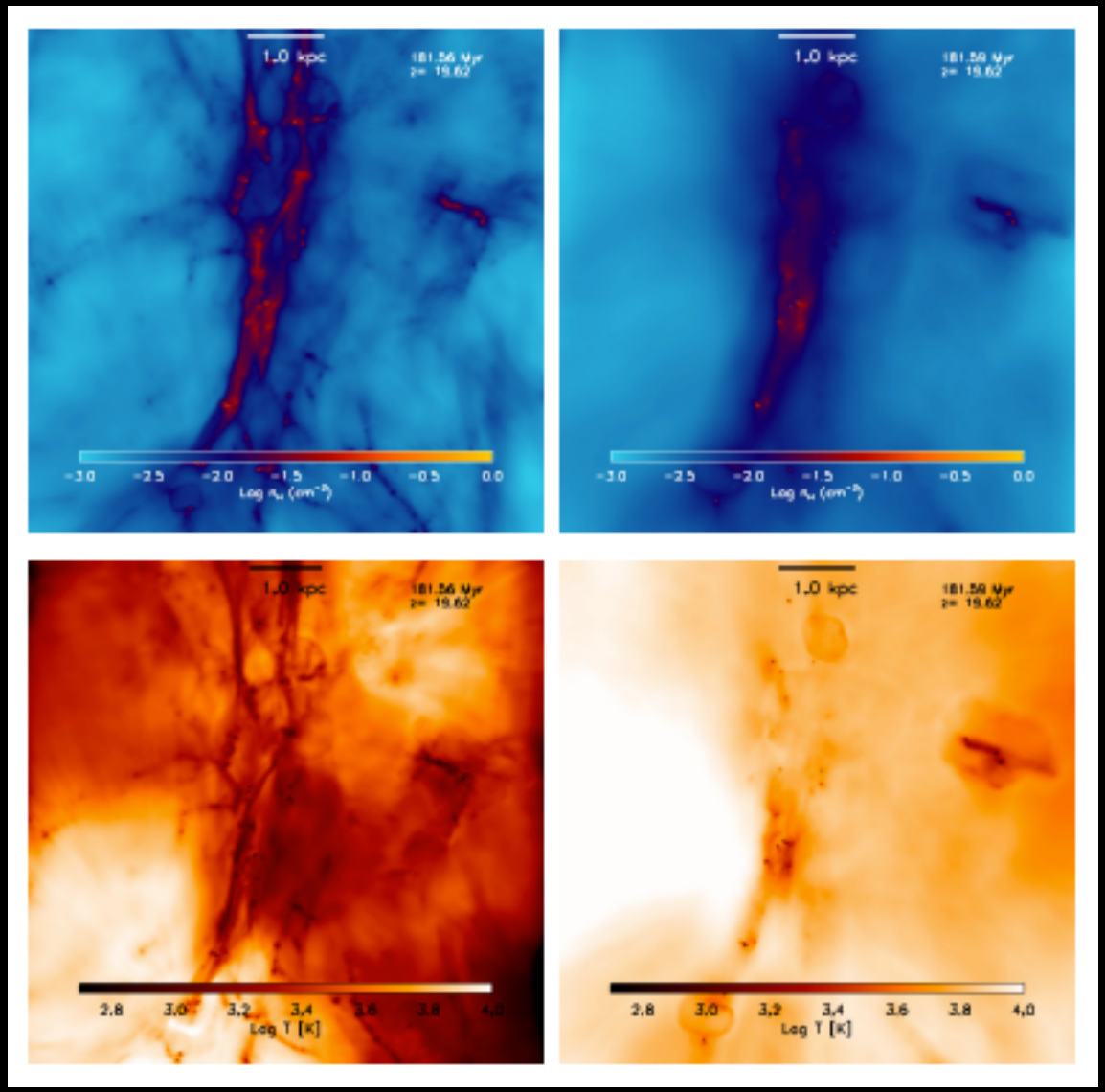
No effect on star formation



Found elevated H_2 fraction, but no positive effect of X-ray on star formation by Strong local feedback

X-ray feedback

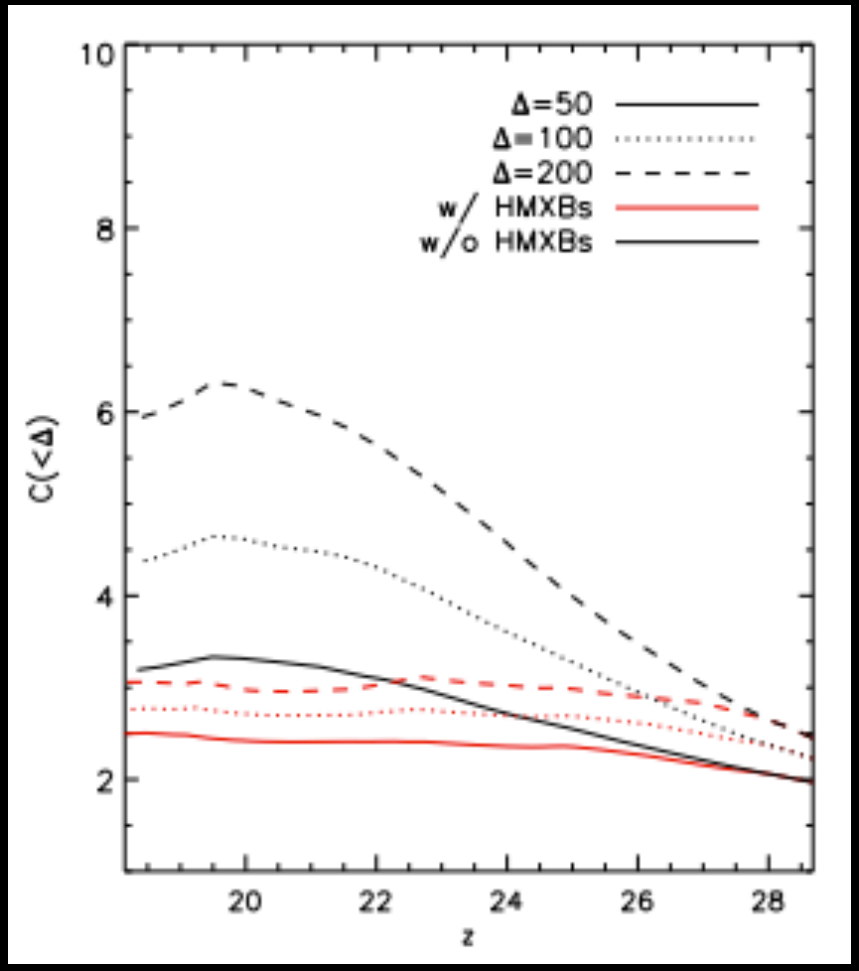
without with



- Smooth out cosmic filamentary structures.

Jeon et al. (2014a)

X-ray feedback reduces gas clumpiness



Clumping factor : $C = \langle n_H^2 \rangle / \langle n_H \rangle^2$

The gas clumpiness can be reduced by a factor of ~2 by X-ray.

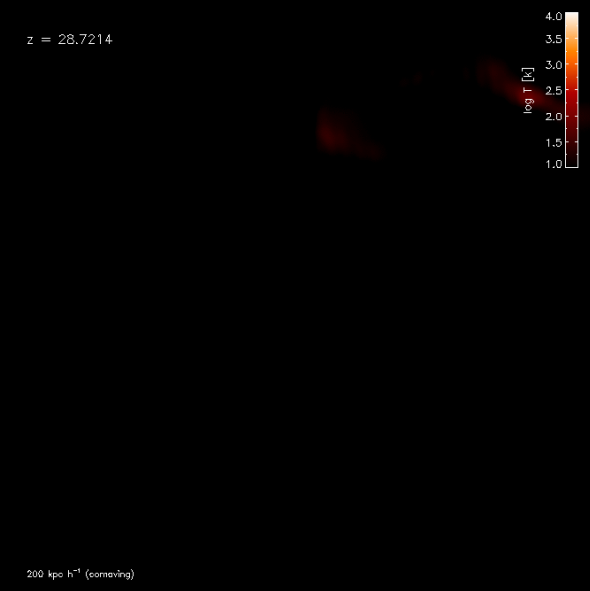
Possibly, provide a positive feedback on reionization.

How did Supermassive blackhole form?

- *STELLAR SEEDS*

uninterrupted near-Eddington accretion

- continuous gas supply
- avoid radiative feedback depressing accretion rate
- avoid overproducing 10^5-10^6 $M_\odot$ BHs



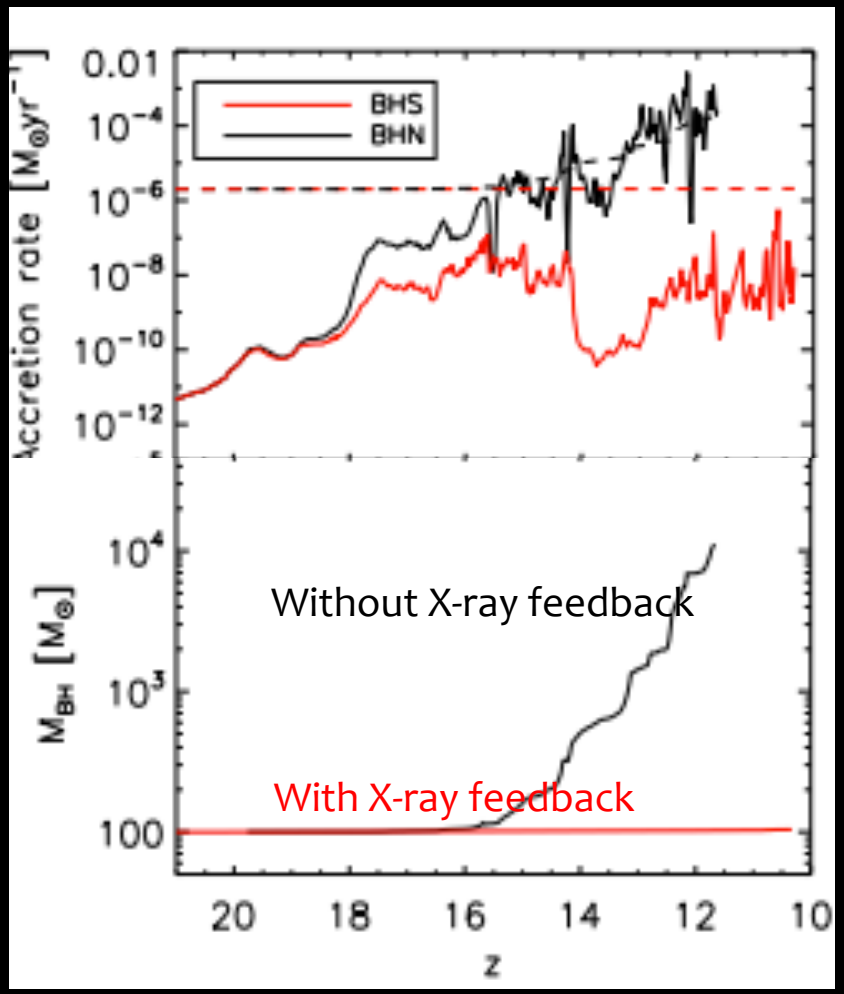
- *DIRECT COLLAPSE*

rapid formation of 10^5-10^6 M black holes

either bydirect collapse of gas

- gas must be driven in rapidly
- must avoid fragmentation

X-ray feedback prevents BH growth



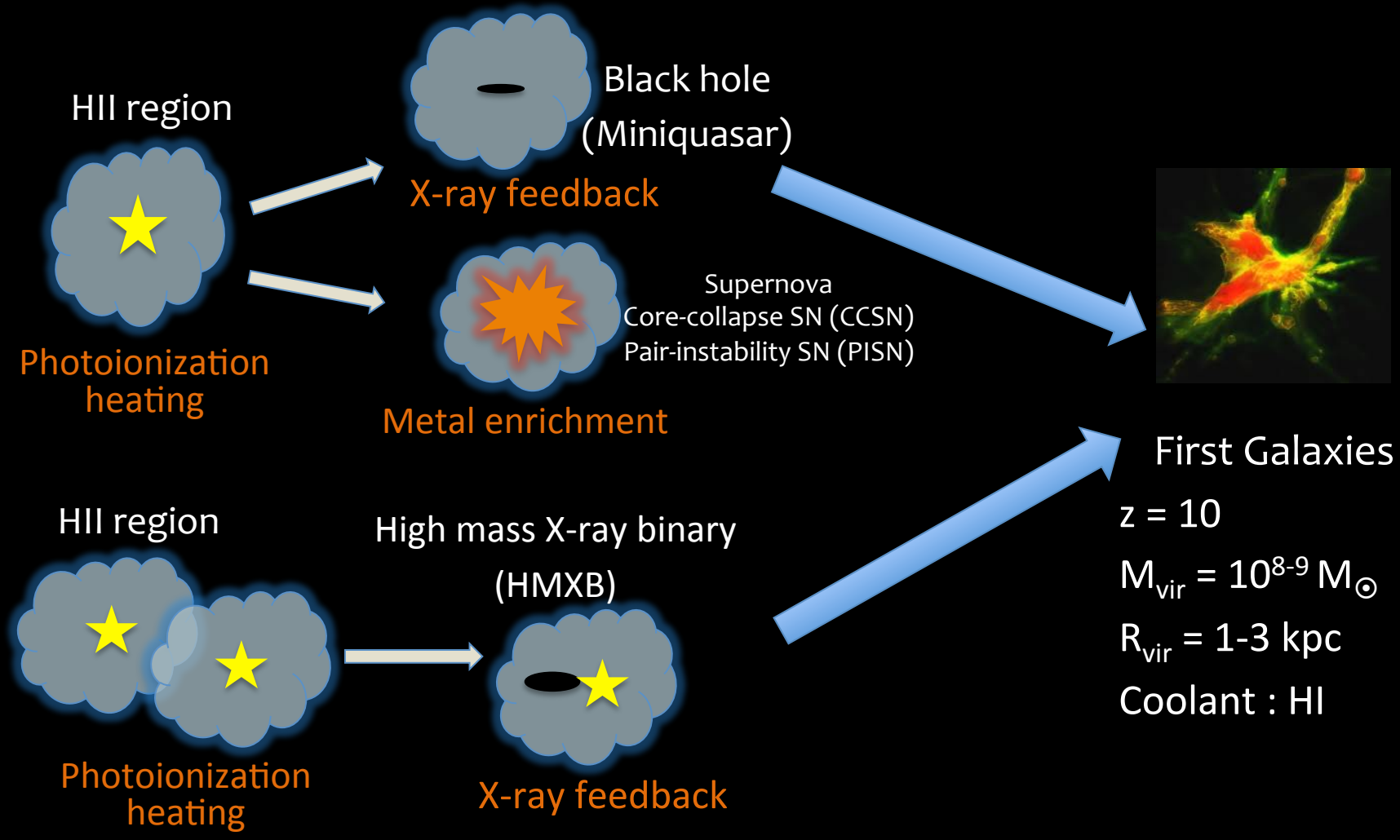
Accretion rate

Black hole growth

Jeon et al. (2012)

X-ray feedback from a single accreting BH is strong enough to prevent a stellar-mass BH from growing, thus constraining models for SMBH formation.

How did Pop III feedback shape initial conditions for first galaxies?



First galaxy formation

Up to z~10

Star Formation :

Pop III : $n_H > 10^4$ cm^{-3}

Pop II : $n_H > 10^4$ cm^{-3} and $z > 10^{-3.5}$ $Z_\odot$

Feedback :

Pop III : radiative feedback from individual stars (HII region)

- $10\ M_\odot < M < 40\ M_\odot$: core-collapse supernovae (CCSNe)
- $40\ M_\odot < M < 140\ M_\odot$: direct collapsed black hole
- $140\ M_\odot < M < 260\ M_\odot$: pair-instability supernovae (PISNe)
- $M > 260 M_\odot$: direct collapsed black hole

Pop II : radiative feedback from a cluster (HII region)

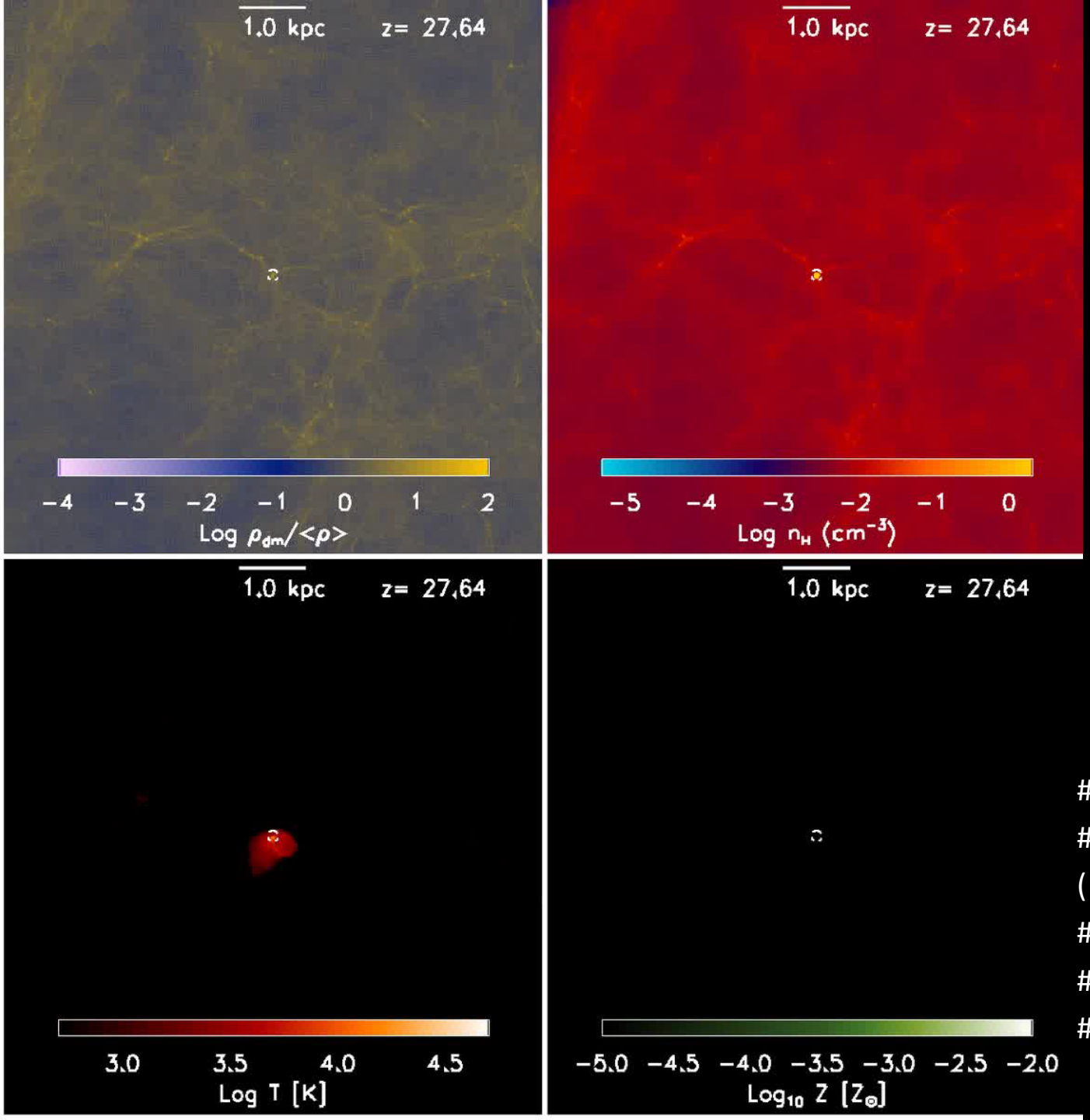
Core-collapse supernova (CCSN)

Dark Matter overdensity

Gas density

Temp.

Metallicity



#Pop II = 65
#Pop III = 183
(#CCSNe=128,
#PISNe=2,
#BHs=44,
#HMXB=11)

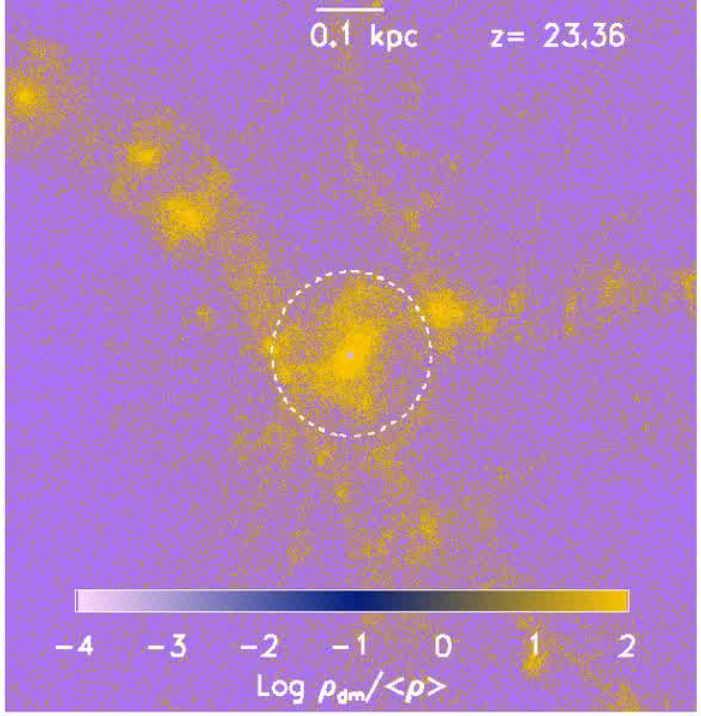
Dark Matter overdensity

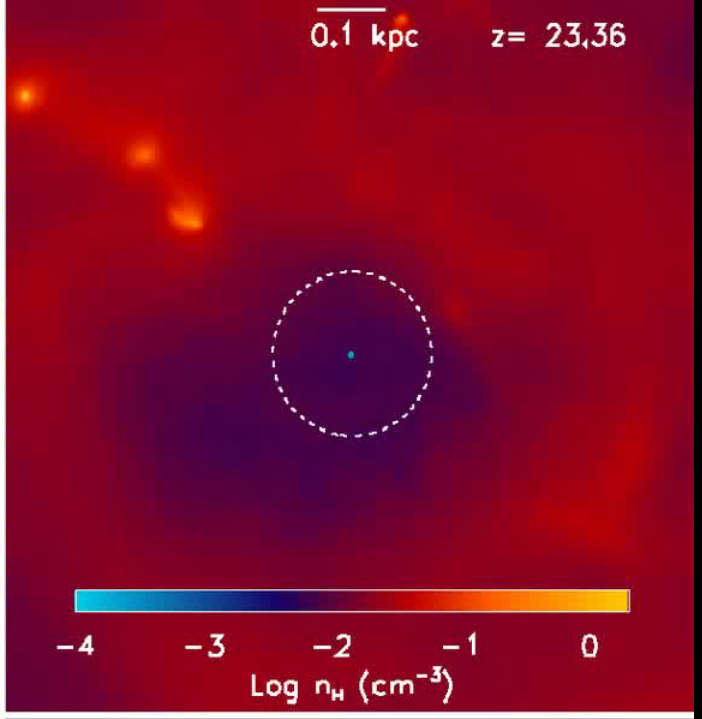
Virial mass :

$M_{vir} \sim 10^8 M_\odot$

Stellar mass :

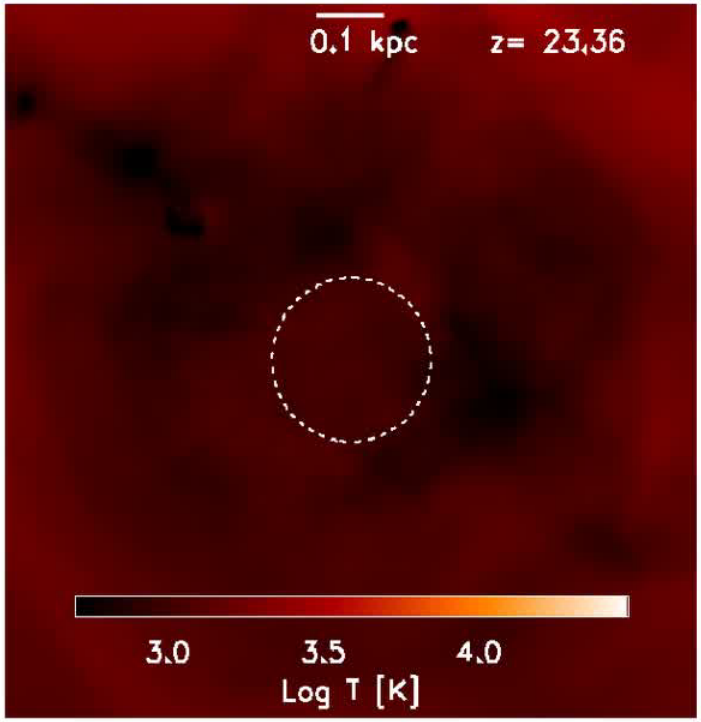
$6 \times 10^3 M_\odot$

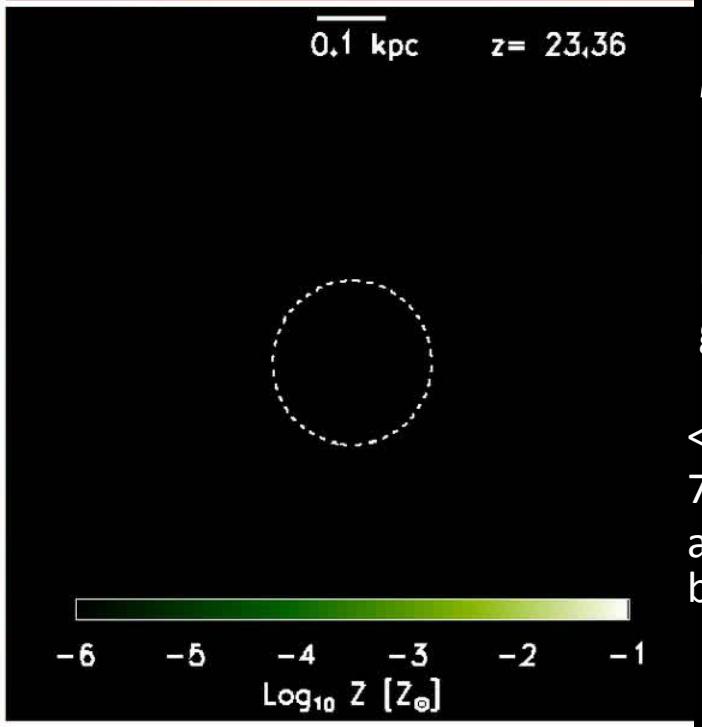




Gas density

Temp.





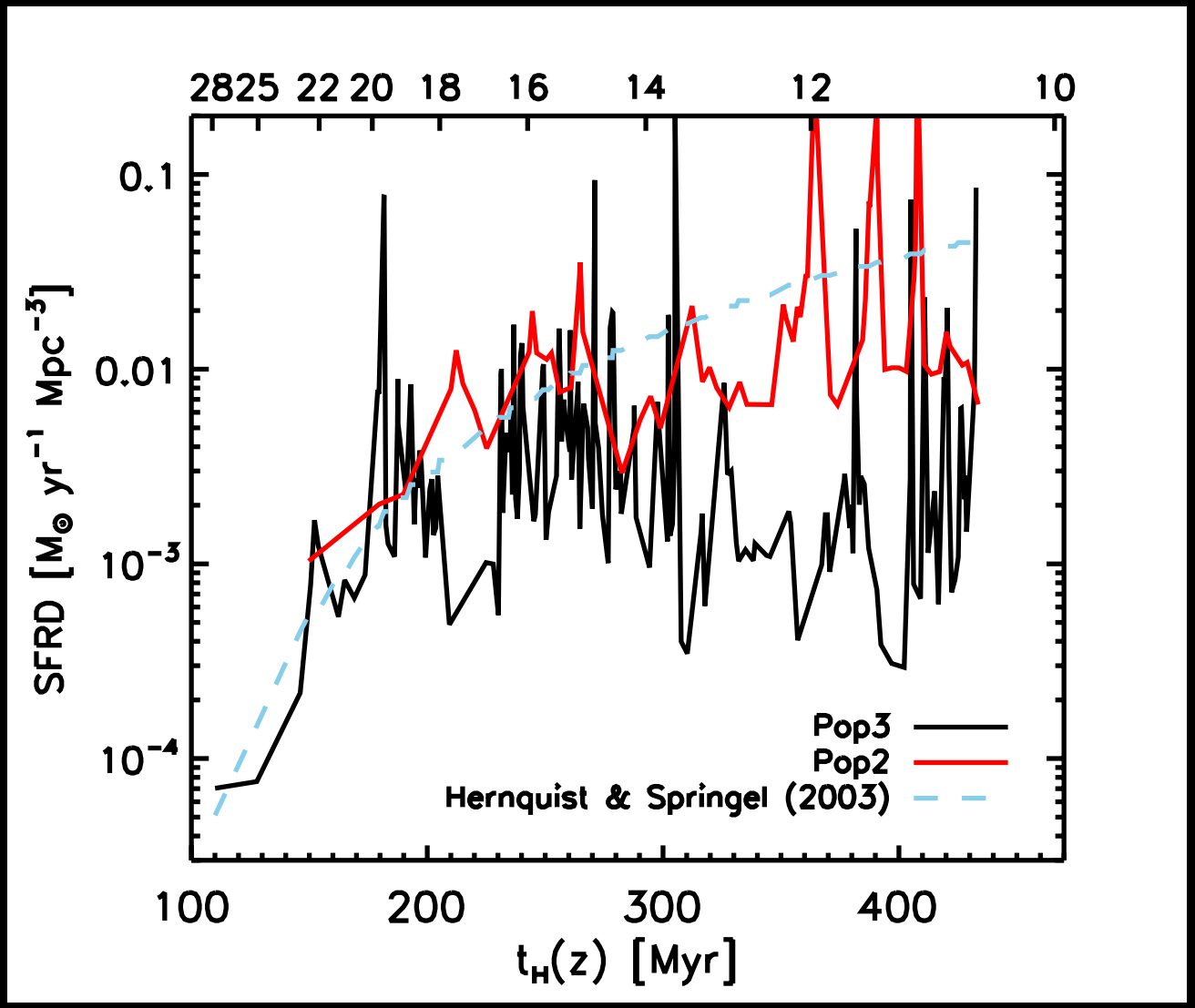
Metallicity

No primordial gas.

$\langle Z \rangle =$
$7 \times 10^{-4} Z_\odot$,
all produced by CCSNe.

Results:
Global Evolution
(Entire simulated region)

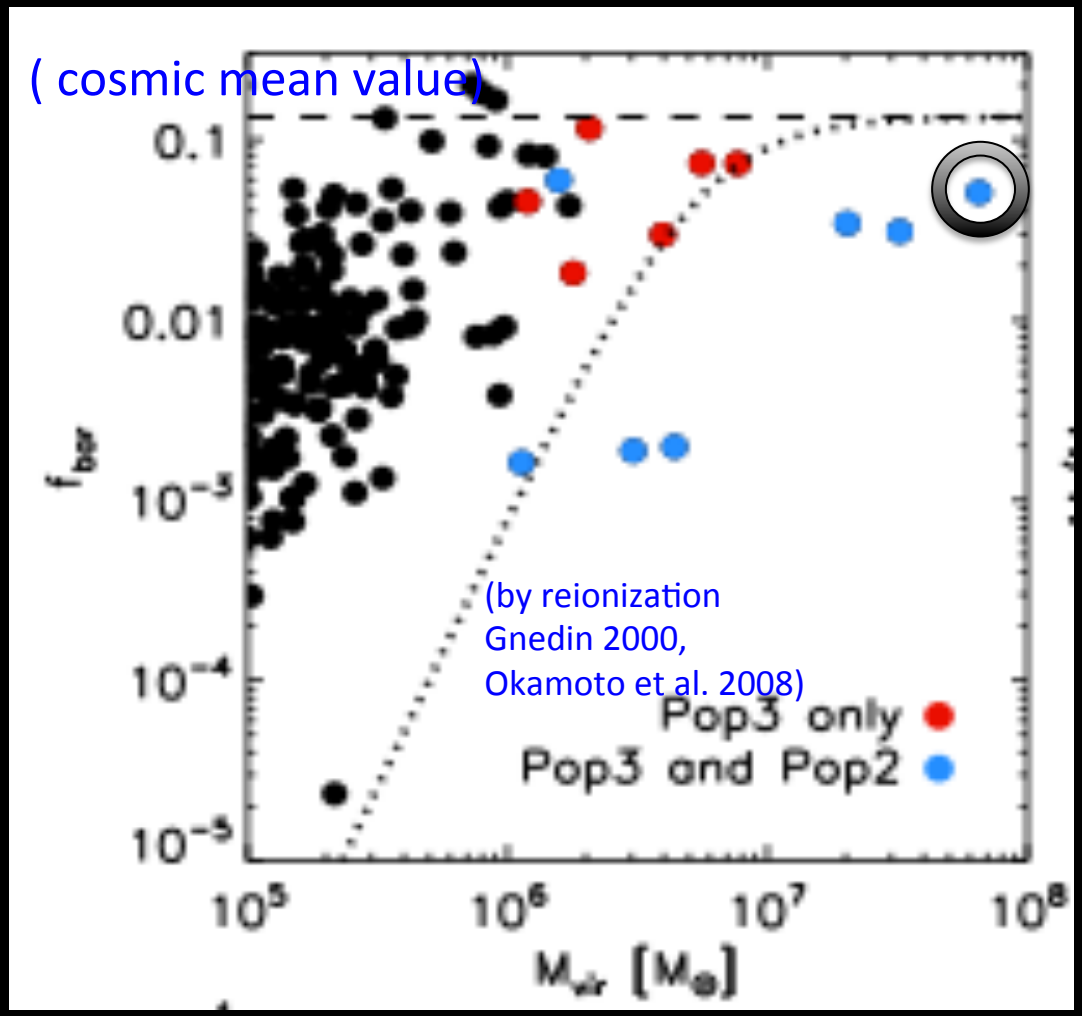
Transition from Pop III to Pop II



Jeon et al. 2015
(arXiv: 1501.01002)

Stellar feedback evacuates halo gas

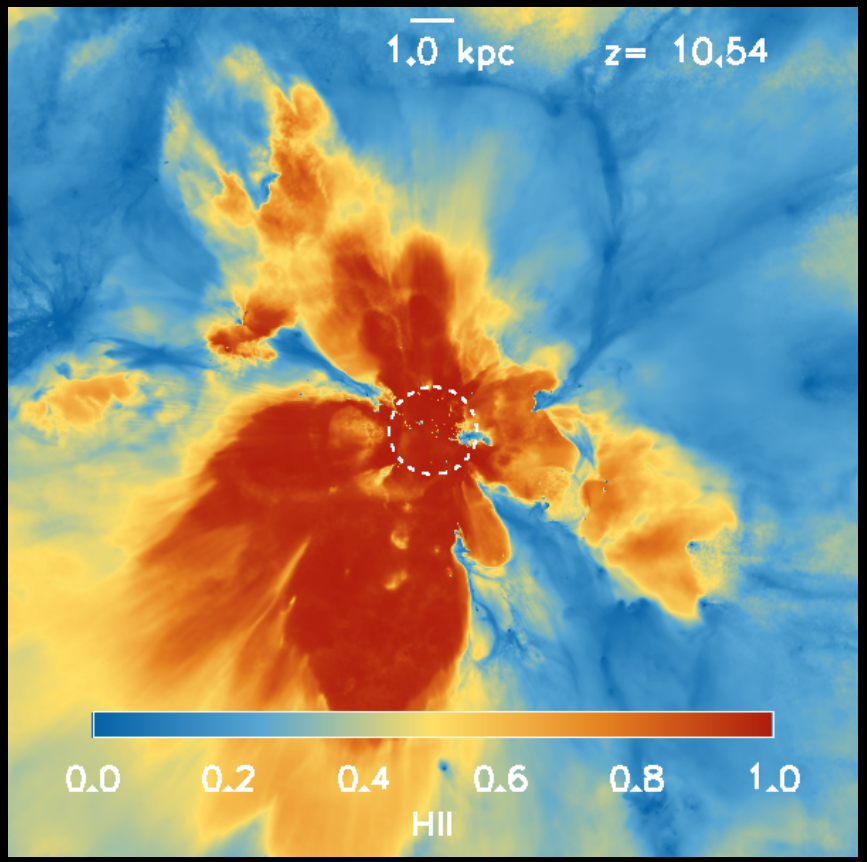
(Baryon fraction)

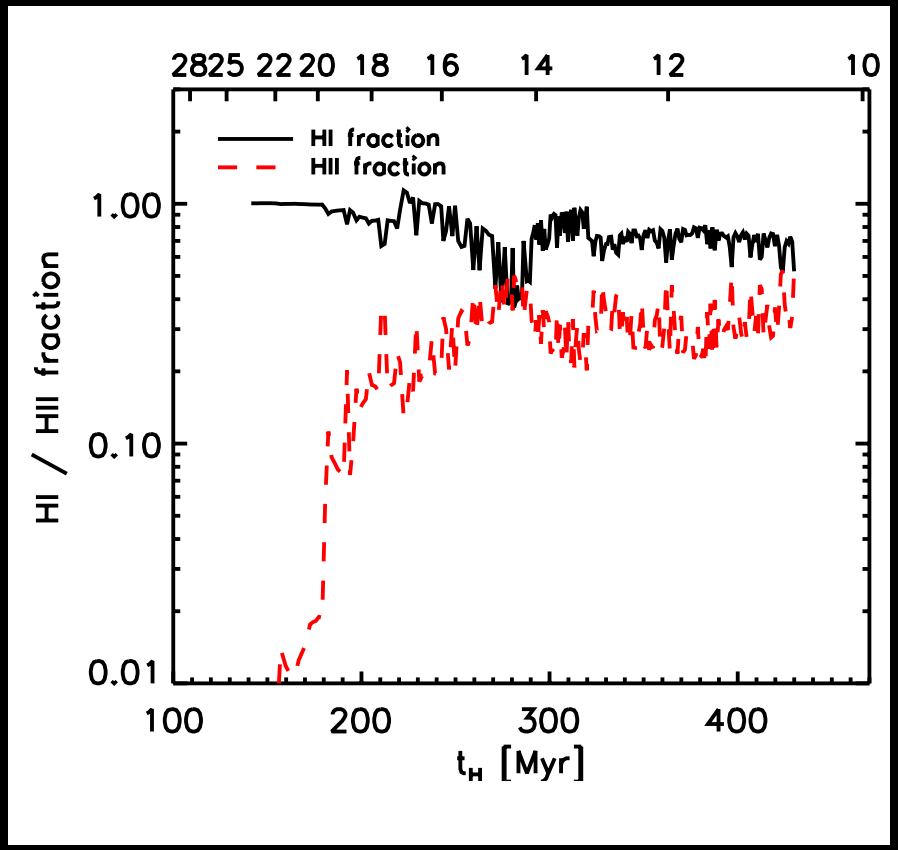


f_{bar} = 0.05
(Target halo)

Can radiation ionize medium?

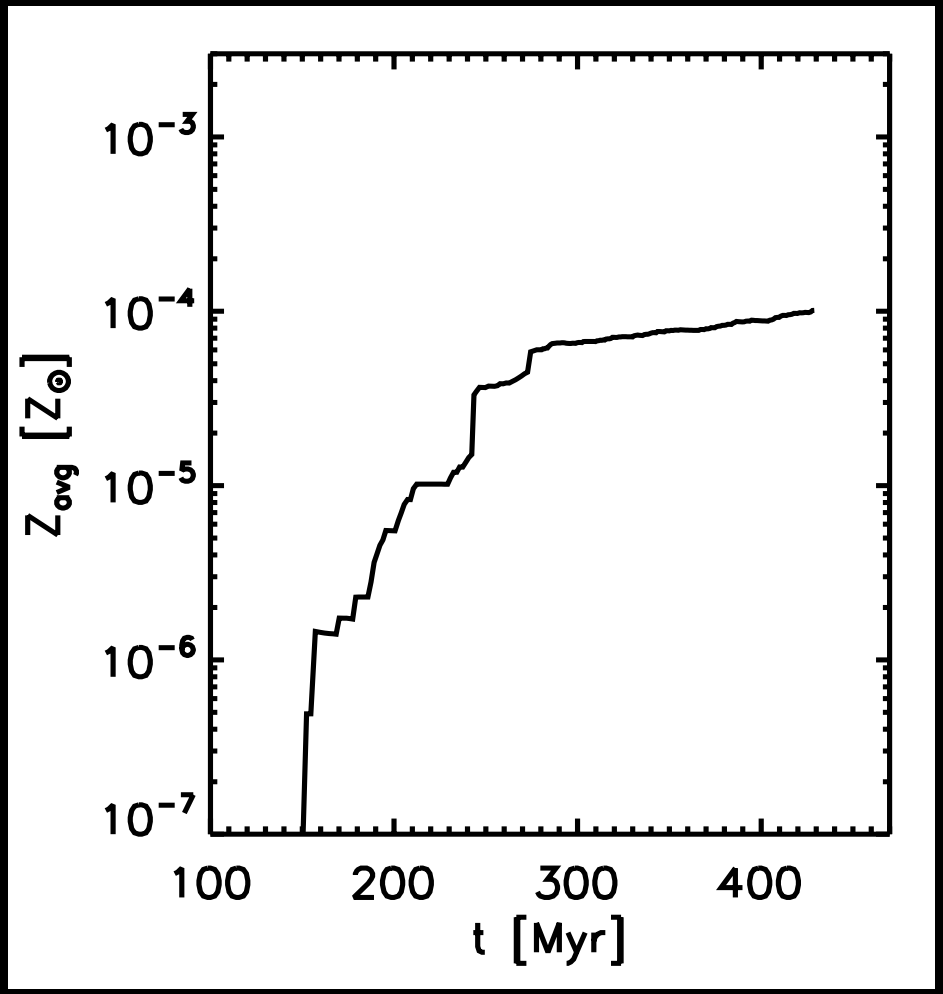
(HII fraction)





- 20%-30% of the simulated region is ionized at z~10.
- Pop III stars are mainly responsible for ionization.

Pop III PISNe are main metal contributors



- Metallicity floor, 10^{-4} $Z_\odot$

#Pop II CCSNe = 558 (> 8 $M_\odot$)

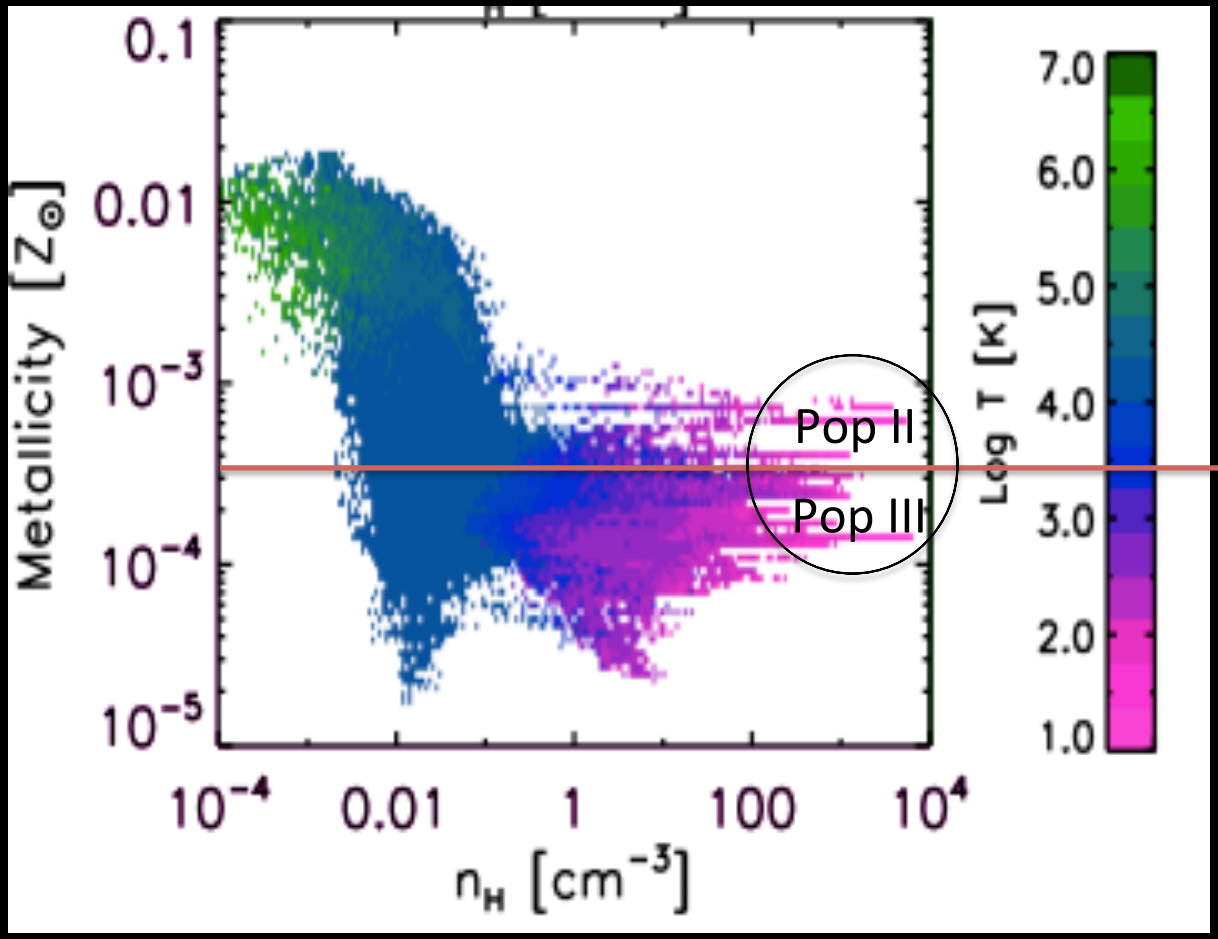
#Pop III CCSNe=128

#Pop III PISNe=2 (75% of total metals)

- Massive progenitors for PISNe (> 140 $M_\odot$) and large metal yield (y=0.5)

Results:
Target halo

Which population dominates the target galaxy?

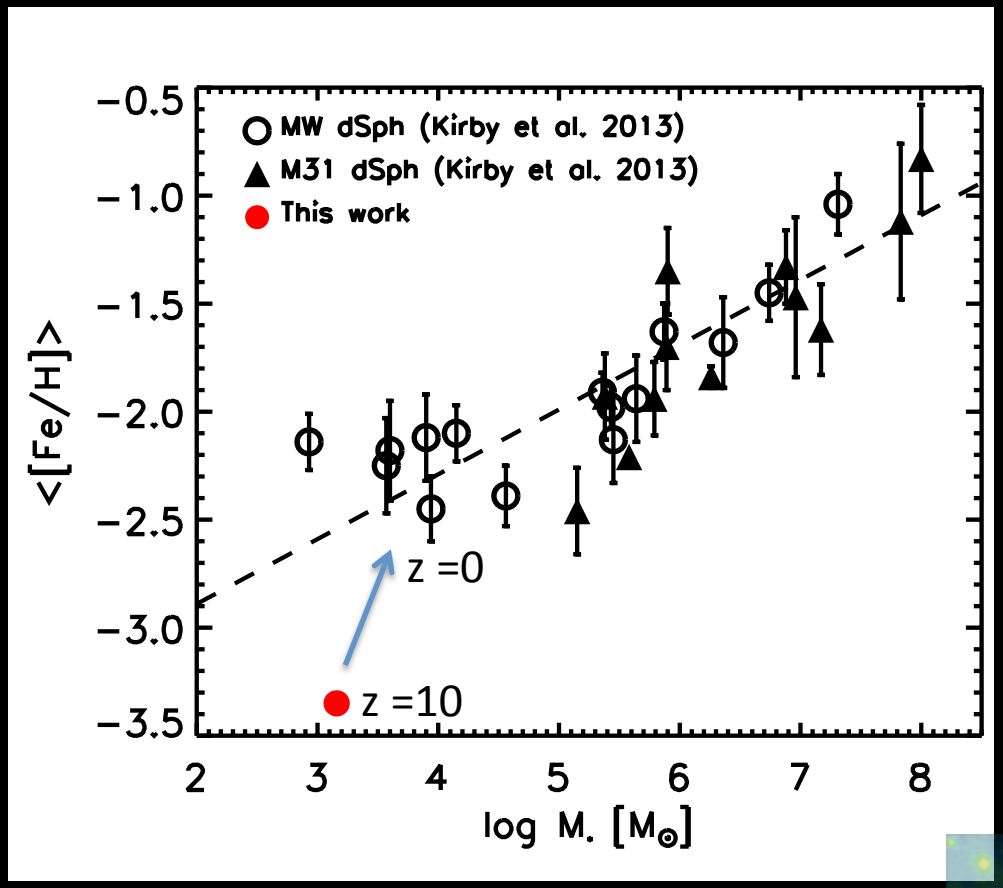


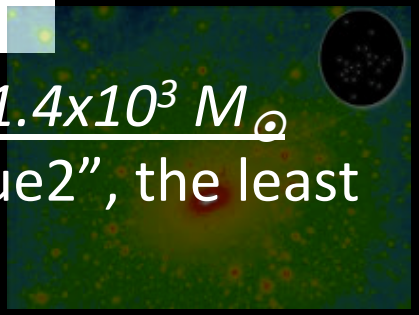
(no primordial gas exists)

($Z_{crit}=10^{-3.5}\,Z_{\odot}$ set by atomic line cooling)

Pop III and Pop II coexist, but a majority population is Pop II.

Is simulated galaxy similar to local dwarfs?

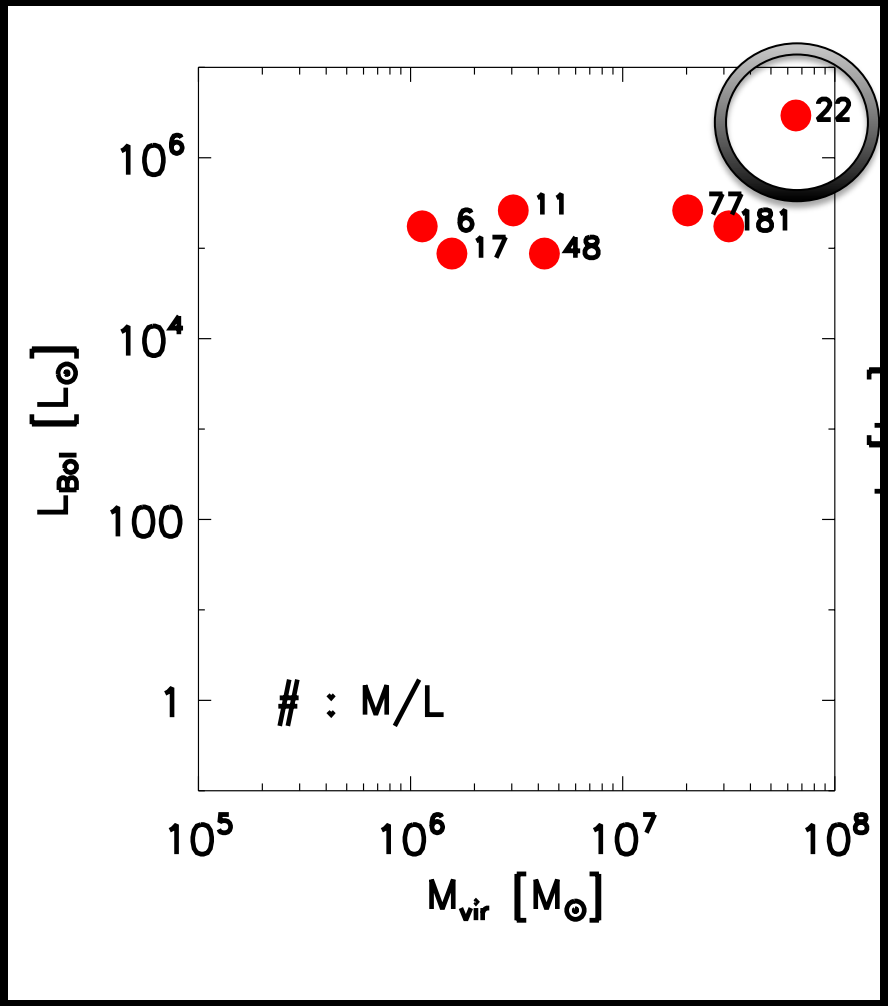




- The stellar mass of the simulated galaxy is *1.4x10^3 $M_\odot$* today, which is comparable to that of "Segue2", the least luminous dwarf known in the Local Group.

Can we detect the target galaxy?

(Bolometric luminosity)



Expected *intrinsic luminosity* and *flux* of the simulated galaxy are

$L_{bol} = 3 \times 10^6\ L_\odot$
$F_{1500} = 1.4 \times 10^{-3}$ nJy
(~ 1 nJy, JWST detection limit)

Future work

We will study the largest sample of early dwarf galaxies $M_{vir}=10^9\ M_\odot$ to z=7 to provide the physical properties of early dwarf galaxies with a *statistically meaningful sample*.

Alternative ways of studying first galaxies

- Explore more massive systems $M_{vir} > 10^9 M_\odot$.
- Study local dwarf galaxies as fossils of the first galaxies.
- Gravitationally lensed system ($\mu > 100$)
- Observe superluminous supernovae.
- 21 cm emission heated by X-ray sources.

Conclusions

- *Stellar feedback plays a crucial role in shaping the initial conditions for the first galaxies.*
  - evacuates gas from minihalo and reduces baryon fraction.
  - single SN is enough for PopIII/PopII transition.
  - X-ray prevents a stellar-size BH from growing.
  - X-ray does not neither promote or suppress star formation.
- *The properties of the simulated first galaxy are*
  - CCSNe main metal contributor in the target galaxy.
  - Pop III and Pop II coexist, but a majority population is Pop II.
  - Target galaxy with $M_{vir}=10^8\ M_\odot$ below JWST detection limit.
- *More works are need to close the gap z~10.*

Thank you!