# Cosmological simulations of galaxy formation in protocluster regions

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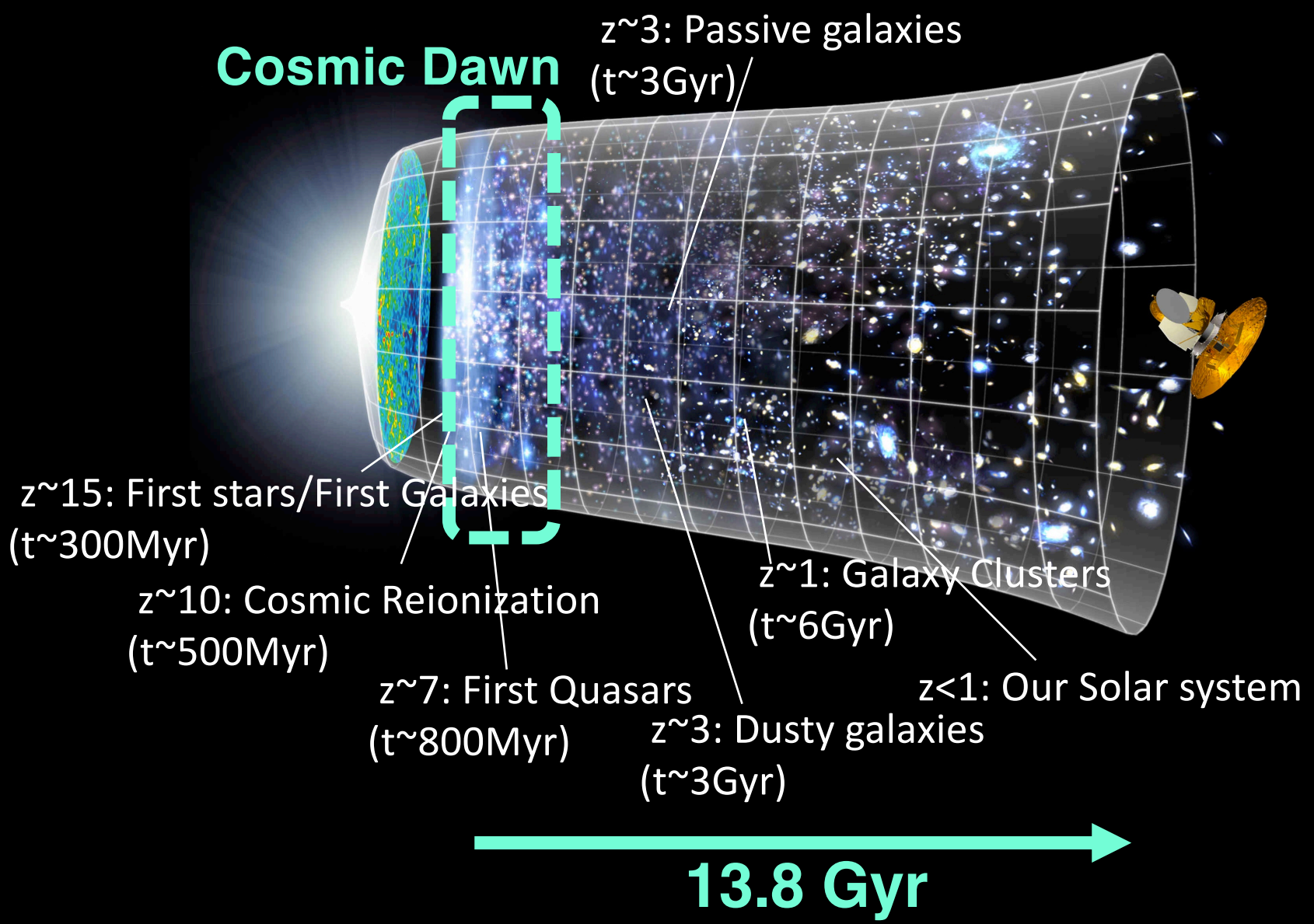
HY et al. 2017, ApJ, 846, 30
Arata, HY, et al., submitted to MNRAS, arXiv:1810.07621
Abe, HY et al. in prep.

# Outline

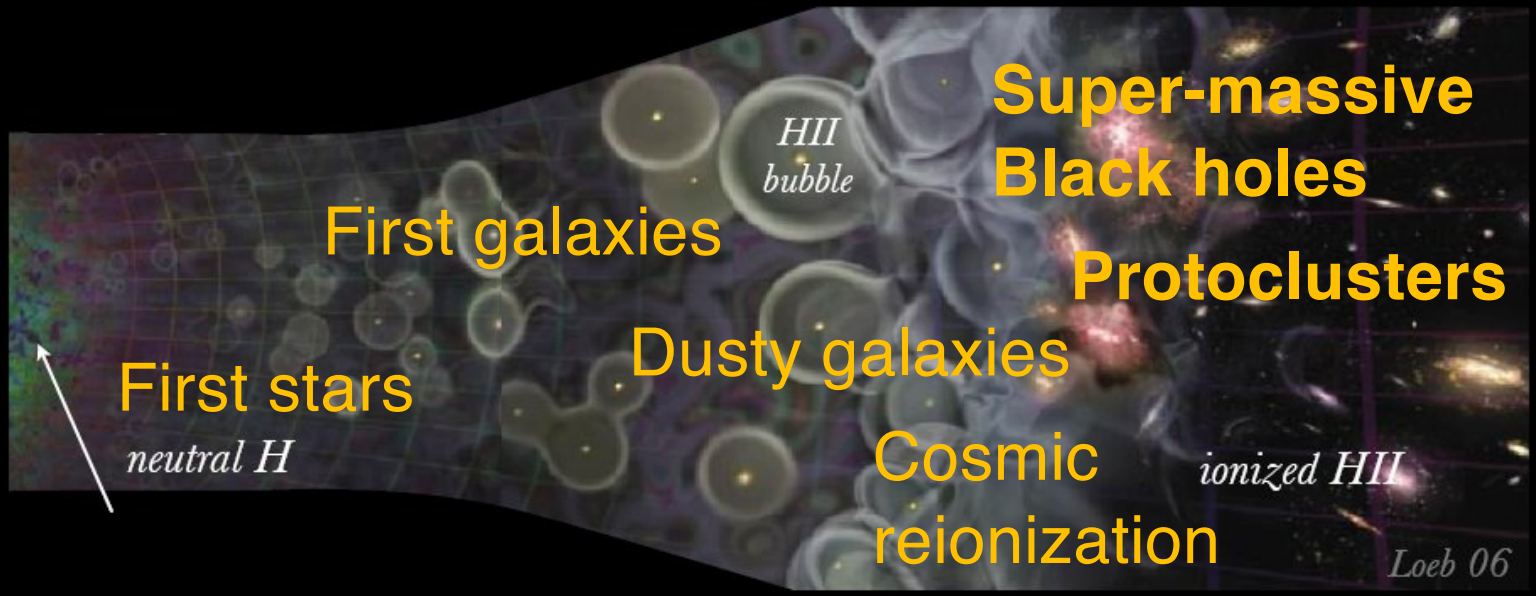
- Introduction
- Methodology
- Results:
- 1: Formation of first galaxies
- 2: Evolution of first galaxies to Massive ones
- 3: Formation of protoclusters
- Summary

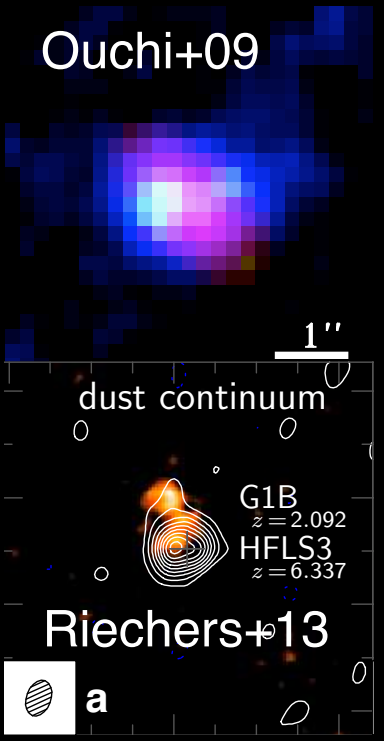
# History of our Universe




NASA/WMAP team

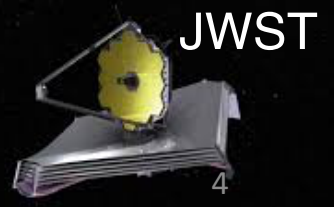
# First billion years




How first galaxies form and evolve?
What star formation history?
How radiation properties change with the galaxy evolution?
How massive BH form?






~2020s-2030s

# First billion years

~300 Myr

z~15

~500 Myr

z~10

~1 Gyr

z~6

?

First stars
->First galaxy

*neutral H*

*HII bubble*

Cosmic reionization

*ionized HII*

*Loeb 06*

① **Formation of first galaxy**

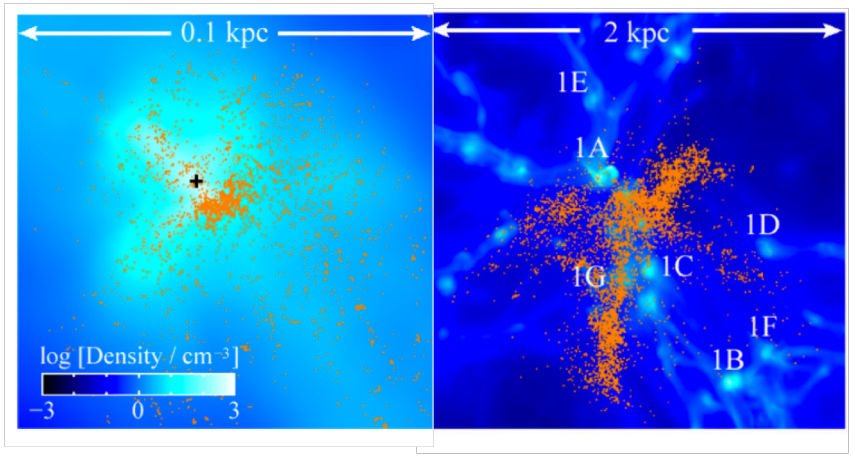
② **Evolution of first galaxy**

③ **Massive galaxies quasars**

# Previous works

**Small scale** gap **Large scale**

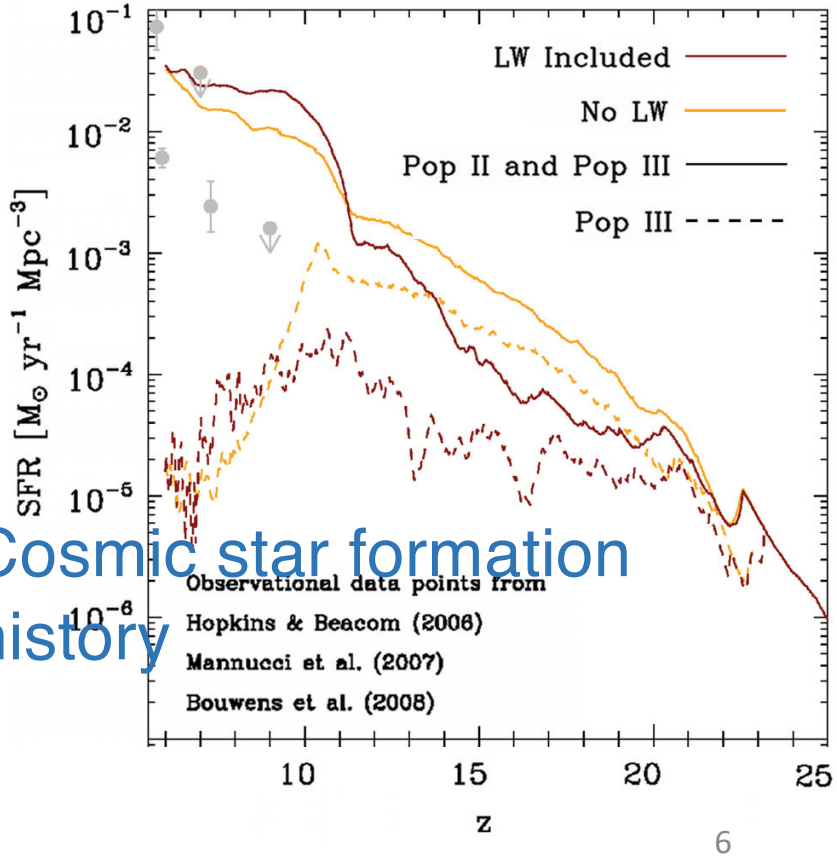
Chiaki+2018




Metal enrichment of mini-haloes by nearby PopIII SNe

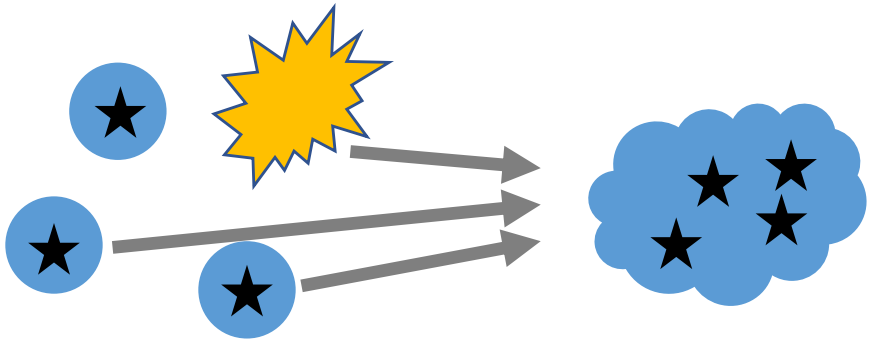
(see also, Greif+10; Jeon+14; Safranek-Shrader+16; Smith+16)

Johnson+2013

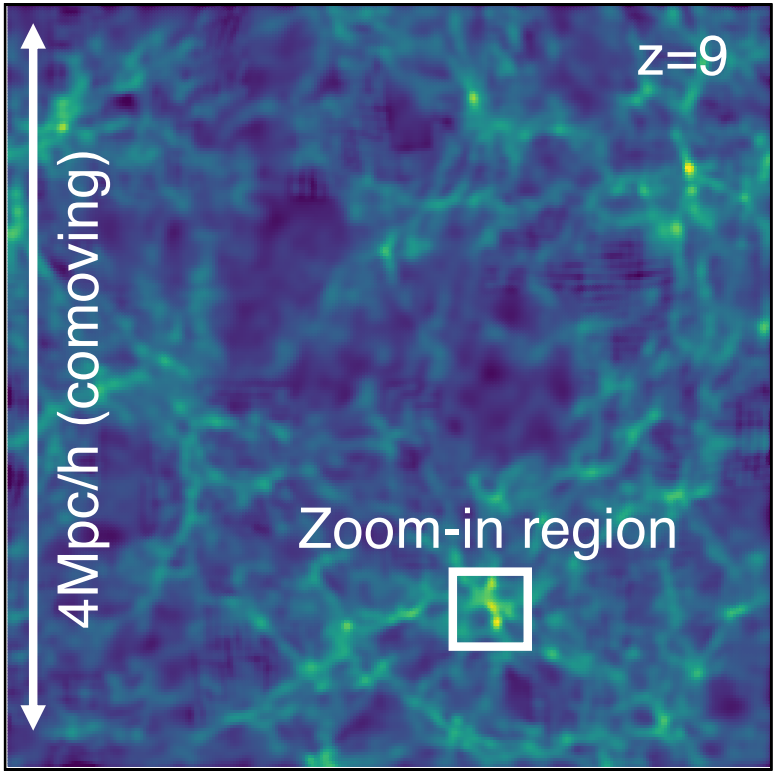



Cosmic star formation history

# Model/Method



Gadget-3 (Springel 2005)
+ sub-grid models of OWLS/FiBY projects (Johnson+2013)
+ new models
(photo-ionization, radiation pressure, star formation)



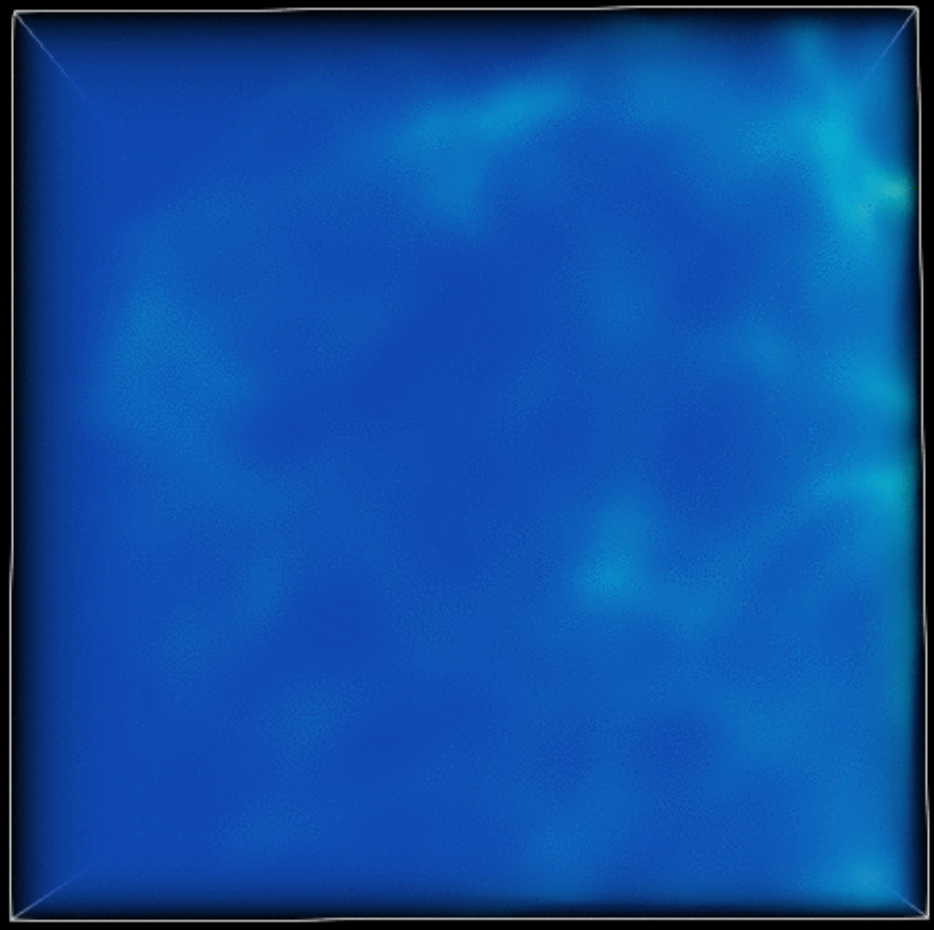

M8run
10^8 Msun halo forms at z=9
(IMF: Salpeter-like, M=10-500 Msun)

M8run_th
Top-heavy initial mass function
(IMF: Flat, alpha=0, M=10-500 Msun)

M9run
10^9 Msun halo forms at z=9

$m_{gas}$~10 $M_{sun}$/h, $m_{DM}$~60 $M_{sun}$/h
Softening: 90 pc (comoving)

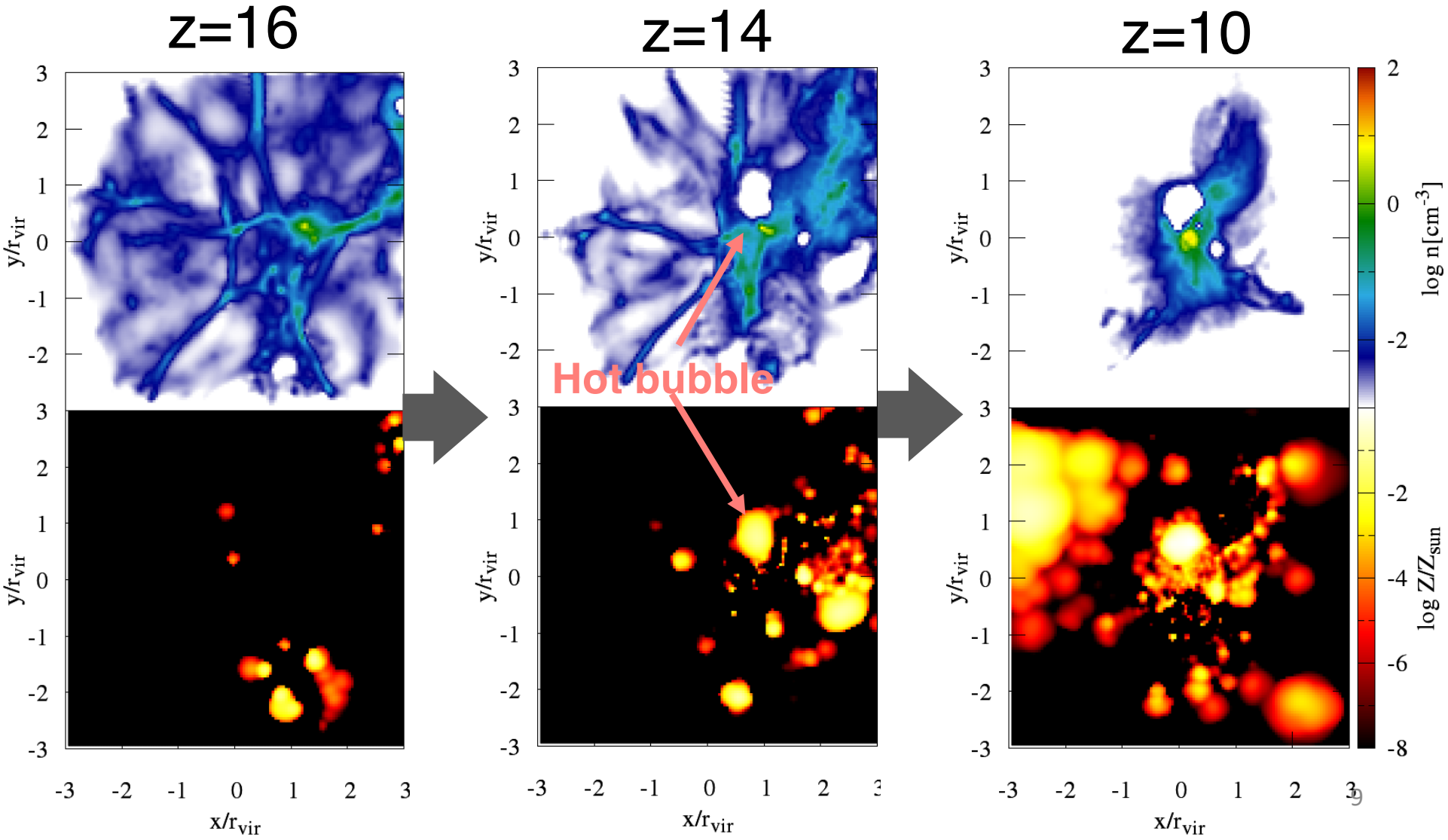
# Large-scale gas structure



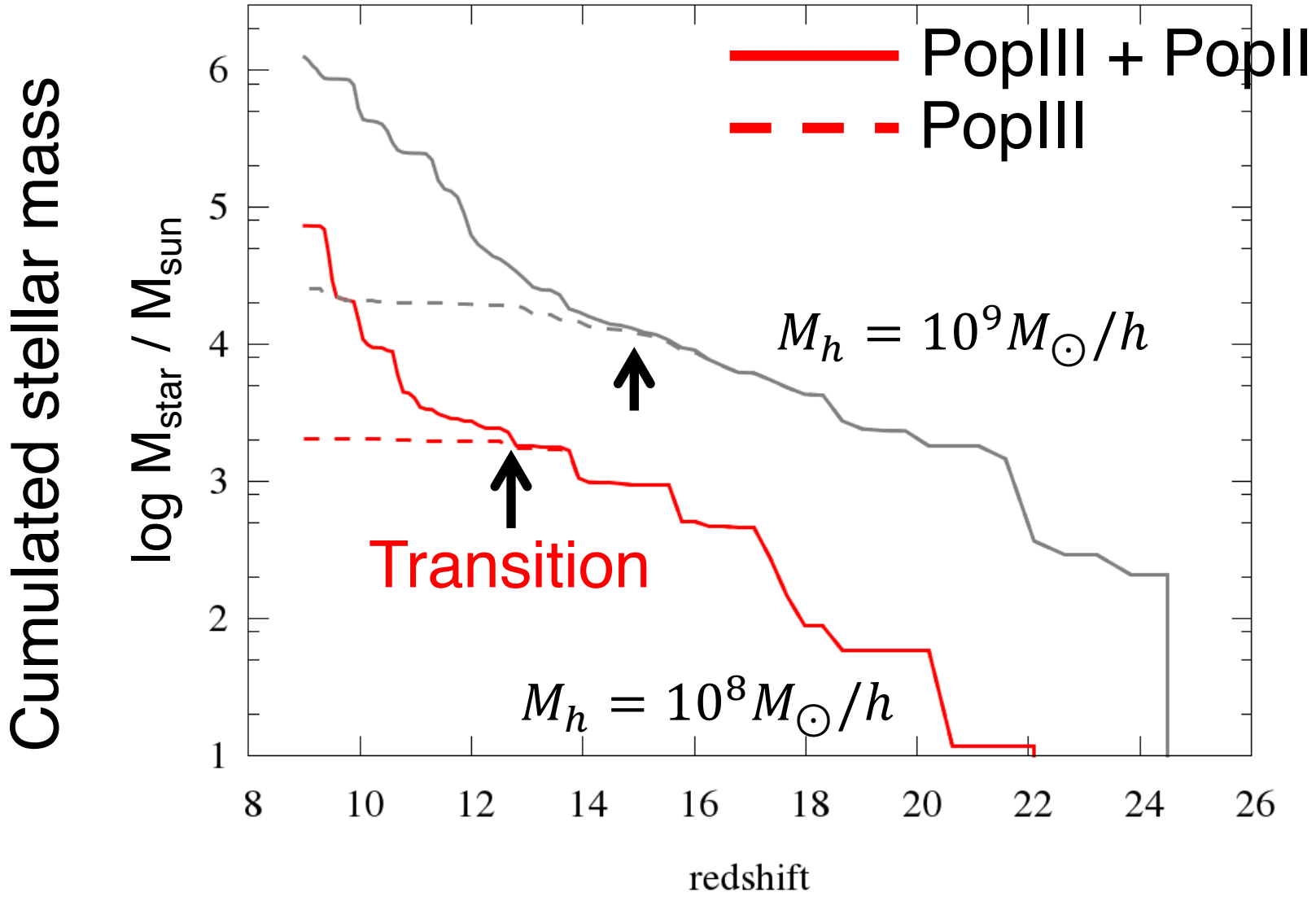
~60 ckpc

# Metal enrichment

Abe, HY, in prep.

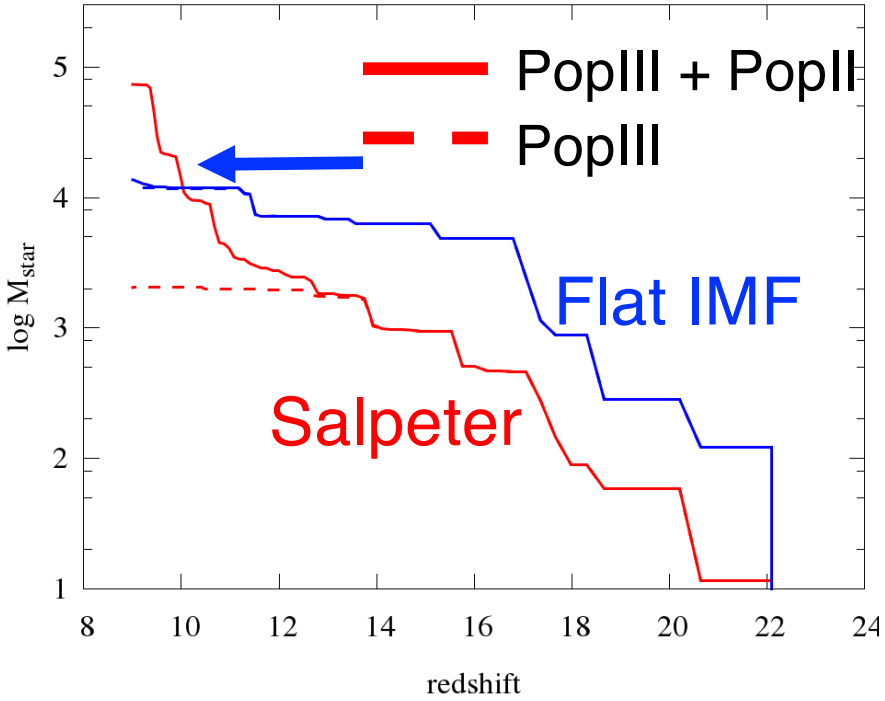


# Pop III - Pop II transition

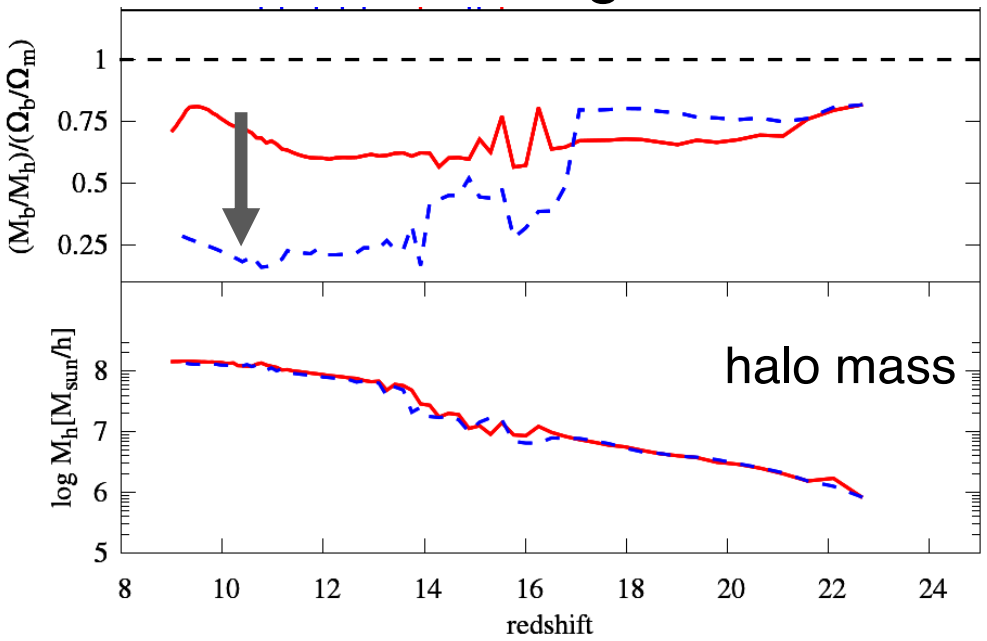


# Impacts of the IMF Pop III stars

Cumulative stellar mass



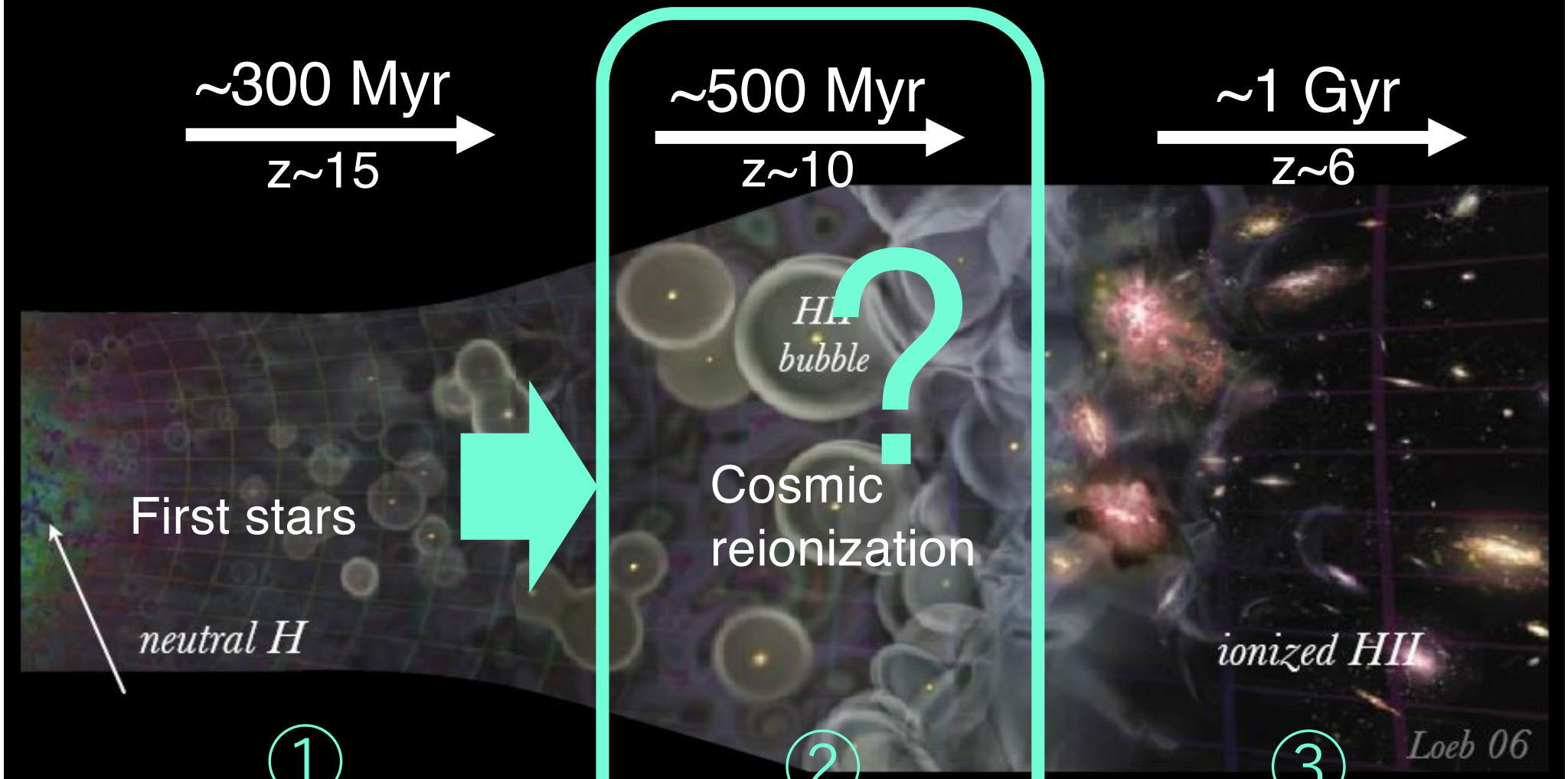

Gas fraction in galaxies




In the flat IMF run, PISNe induce the low gas fraction of first galaxies and suppress PopII star formation

Future: we increase galaxy samples and make luminosity functions reflecting the IMF of Pop III stars

# First billion years



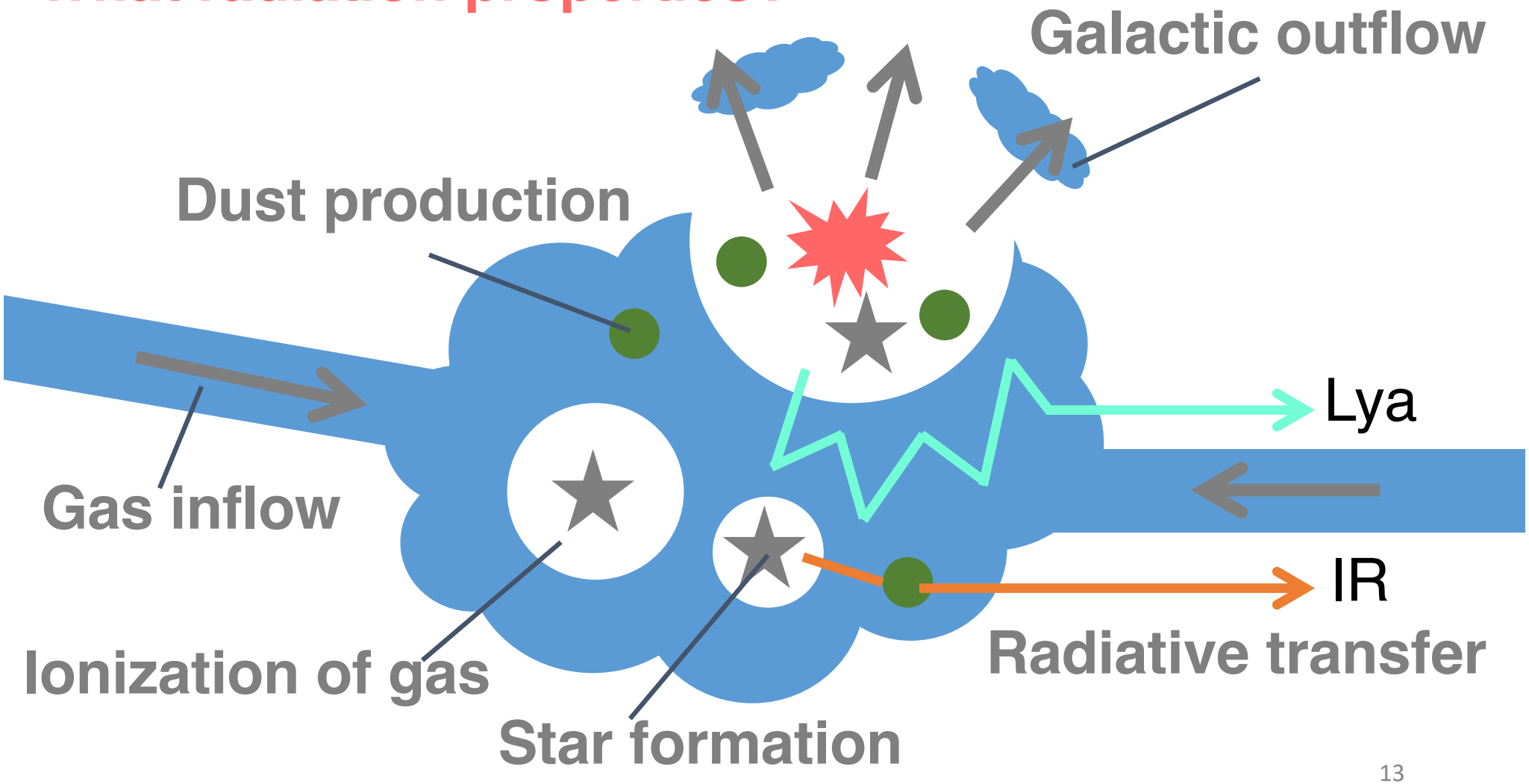

① **Formation of first galaxy**

② **Evolution of first galaxy**

③ **Massive galaxies quasars**

# Galaxy evolution and radiation properties

**How first galaxies evolve under stellar feedback?**
**What radiation properties?**

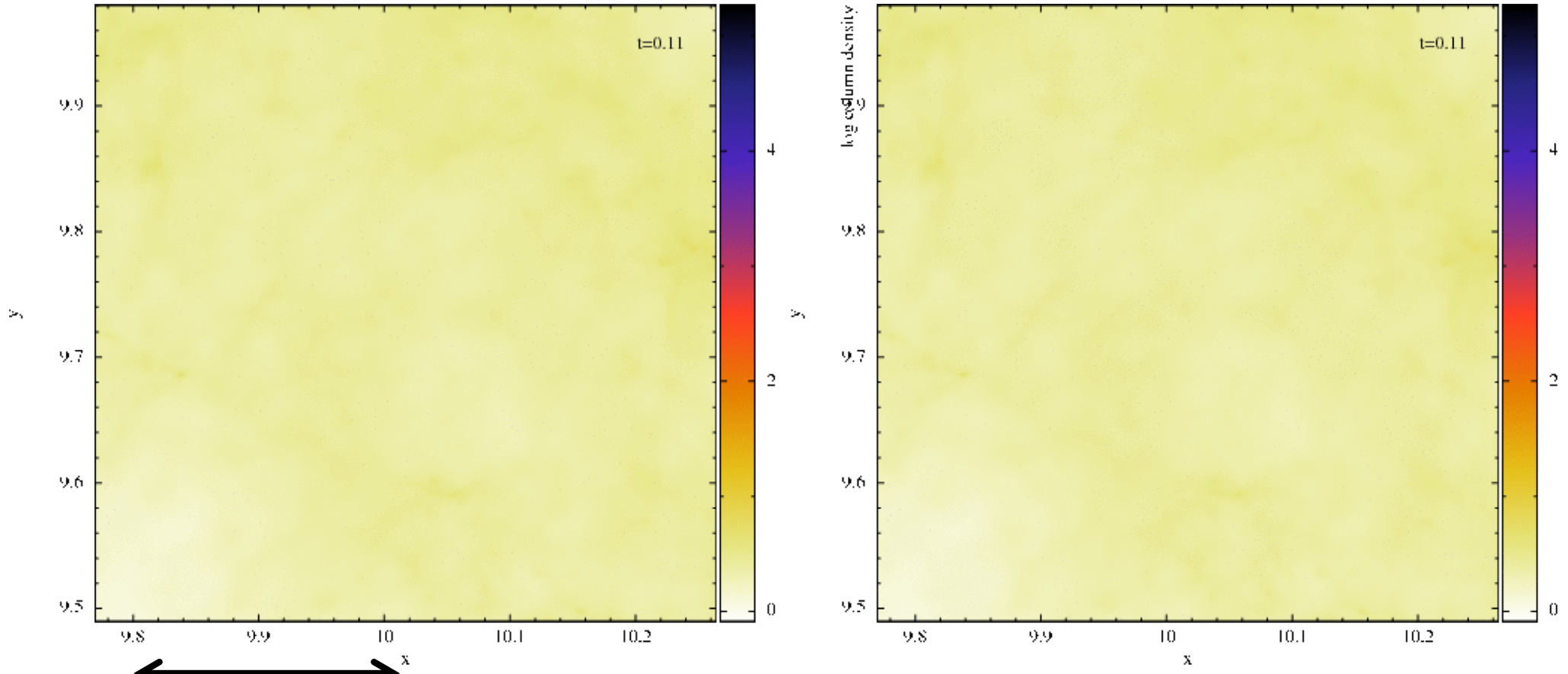


# Evolution of gas structure in galaxies (z=20 –> 6)

$M_{halo}=10^{11}M_{sun}@z=6$

With Feedback

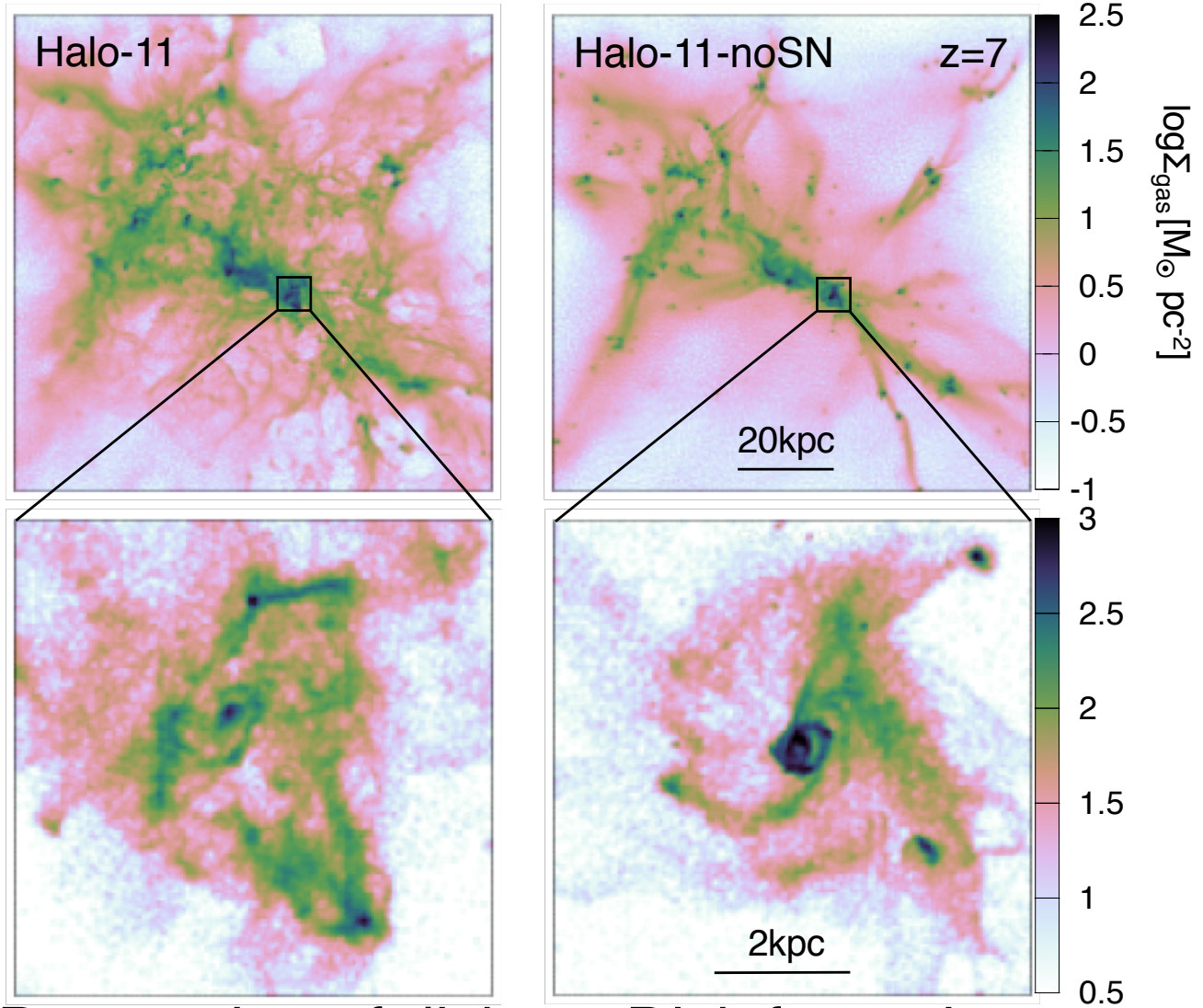
Without Feedback




200kpc(comoving)

Gas column density

# Formation of first galactic disks



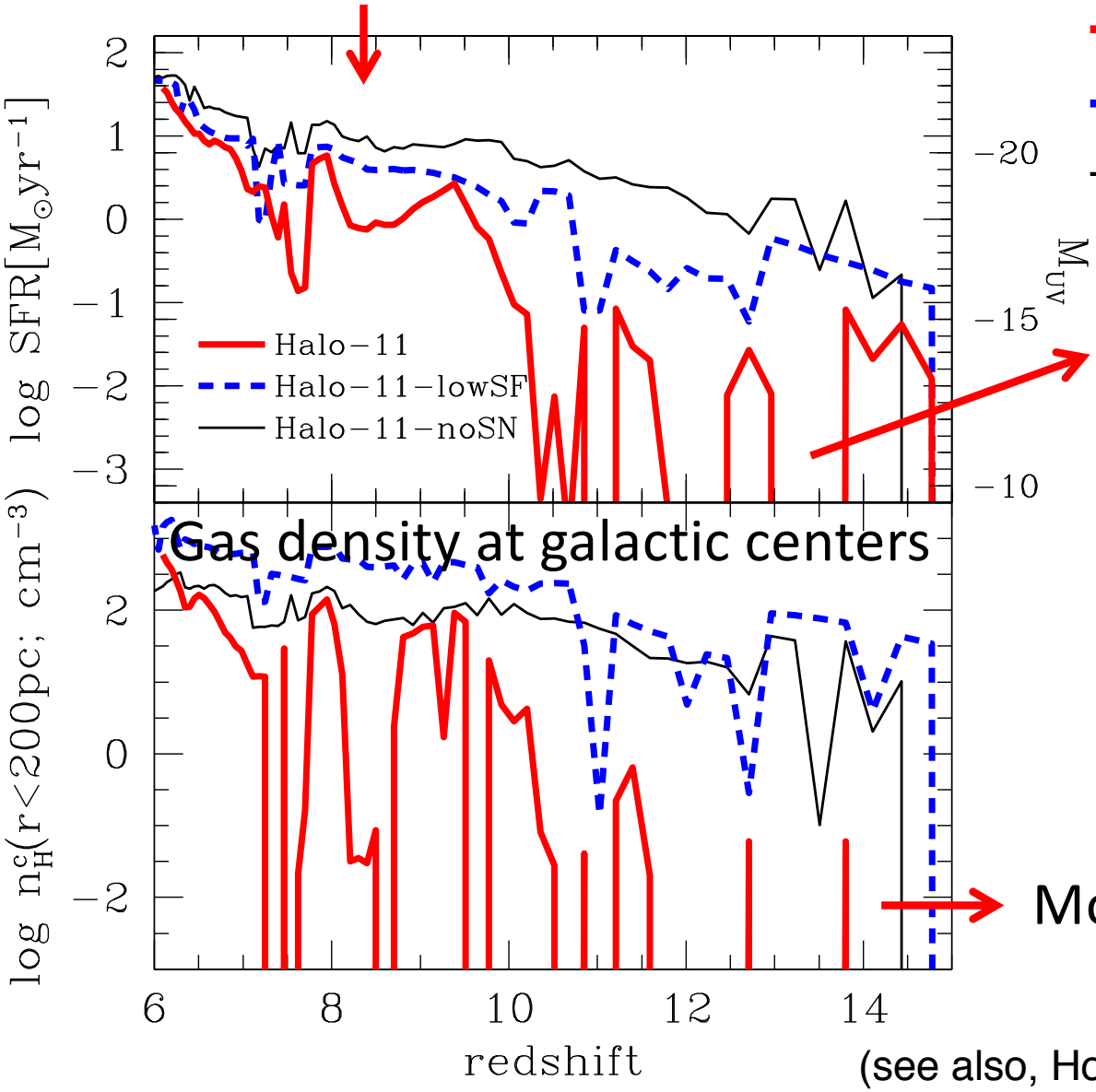

Destruction of disk

Disk formation

# Star formation history

(**HY** et al. 2017, ApJ, 846, 30)

Stable star formation mode




Halo-11

Low SF efficiency

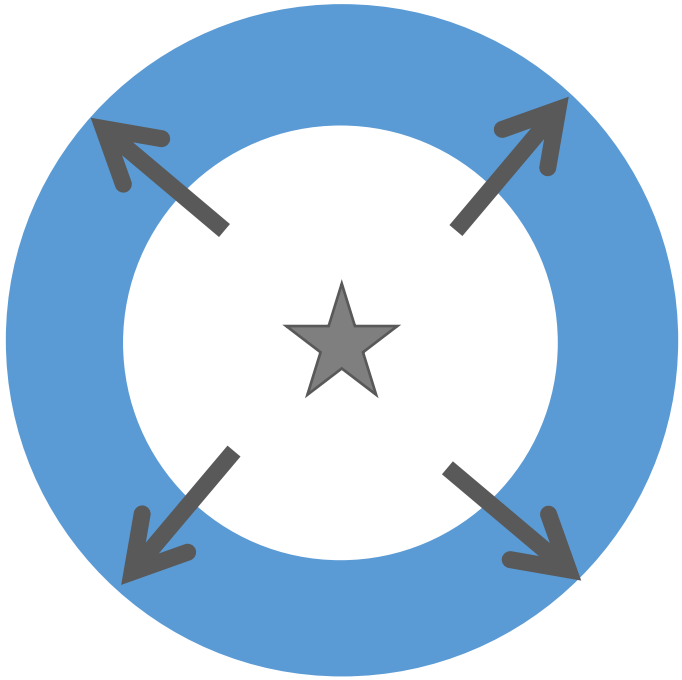
No feedback

Star formation in first galaxies proceeds intermittently due to the supernova feedback

Most gas are evacuated

(see also, Hopkins+15; Kimm+15; Ceverino+18)

# Critical halo mass based on a spherical shell model



**$V_{outflow} > V_{esc}$ ?**

$$M_{\rm gas} V_{\rm outflow} = \sqrt{2\eta_{\rm SN}^{0} E_{\rm SN} M_{\rm cool}}$$

$$\eta_{\rm SN} = \eta_{\rm SN}^{0} \frac{M_{\rm cool}}{M_{\rm gas}}$$

Gas mass in cooling radius

Total gas mass

$$V_{\rm esc} = \sqrt{\frac{2GM_{\rm h}}{R_{\rm vir}}}$$

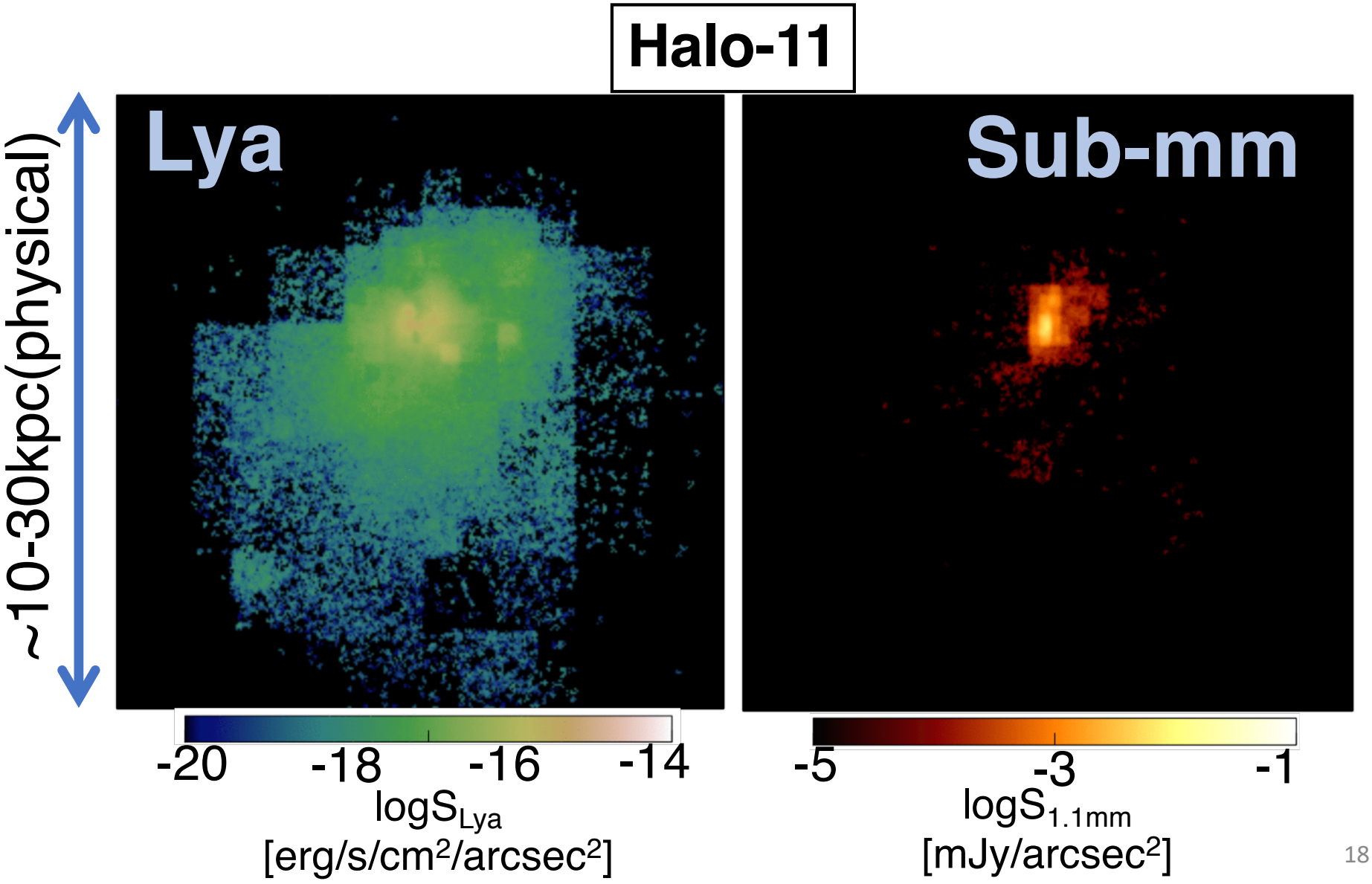
$$M_{\rm h,crit} = 0.8 \times 10^{10}\ M_{\odot} \left(\frac{\epsilon_{\rm SF}}{0.1}\right)^{3/2} \left(\frac{\eta_{\rm SN}}{0.5}\right)^{3/2} \left(\frac{1+z}{7}\right)^{-3/2}$$

Star formation efficiency

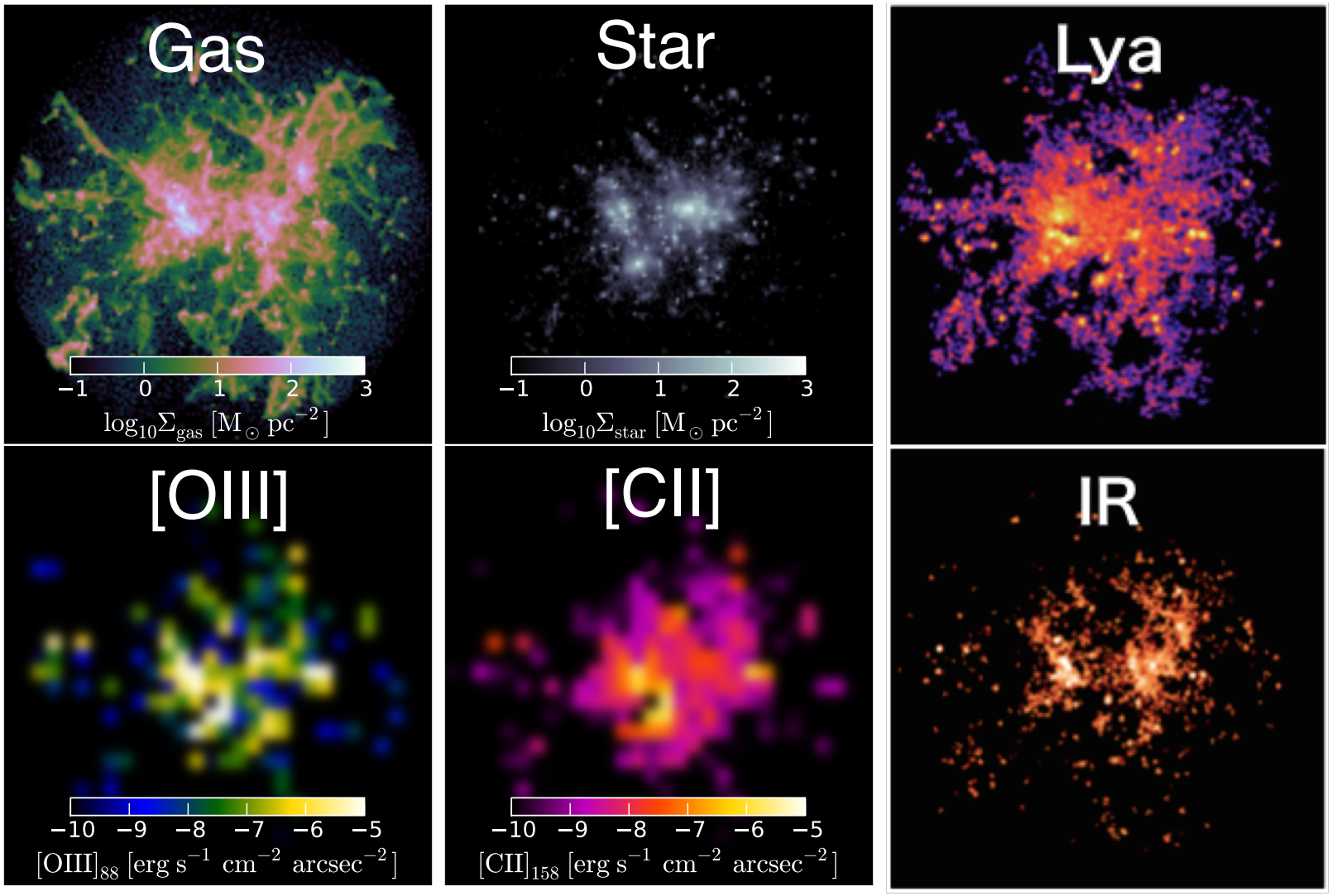
Energy conversion rate

# Radiative transfer calculations

## Surface brightness (z=10➔6)

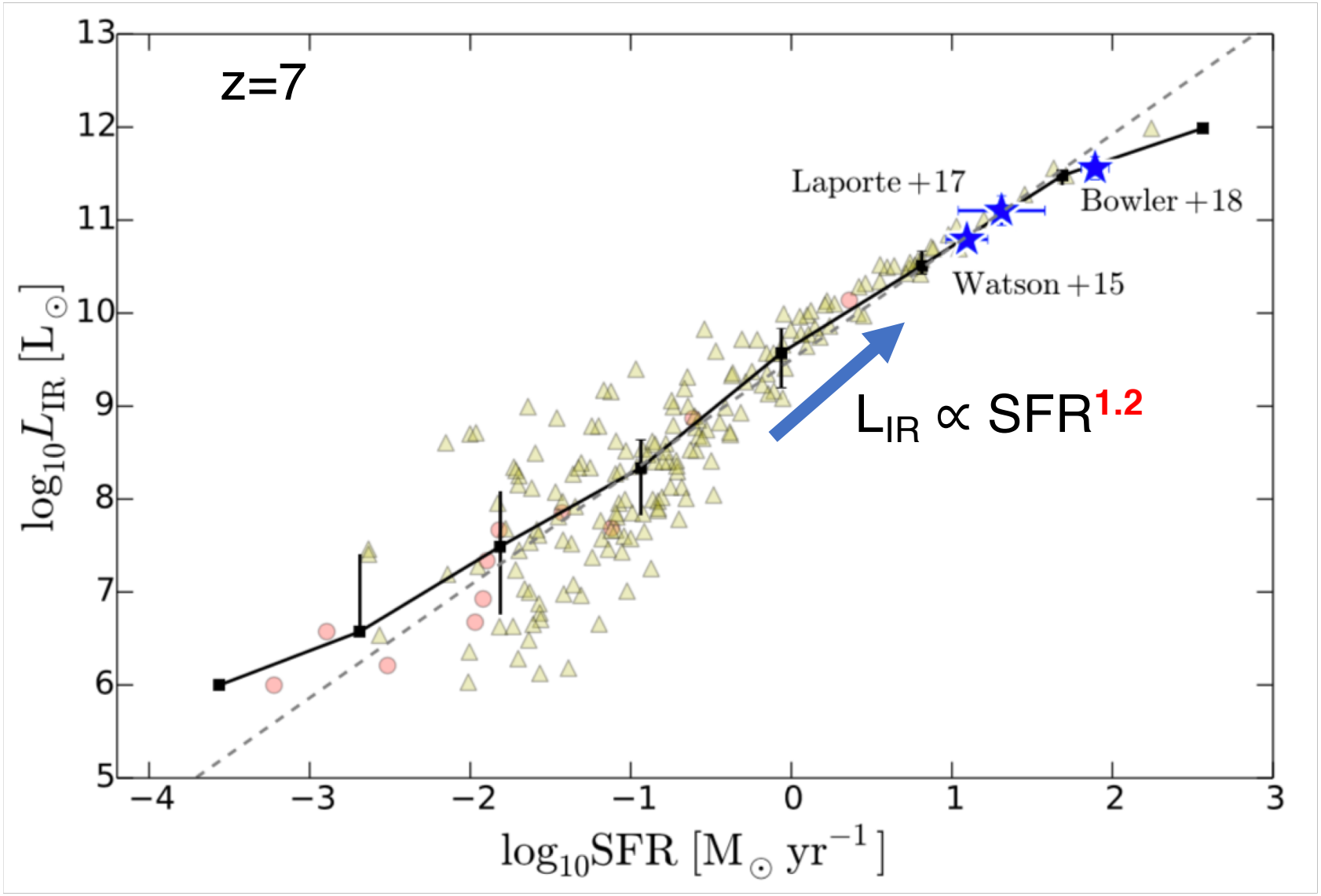


# Surface brightness (Halo-11 at z=6)



# Infrared luminosity

Arata, HY et al. arXiv:1810.07621

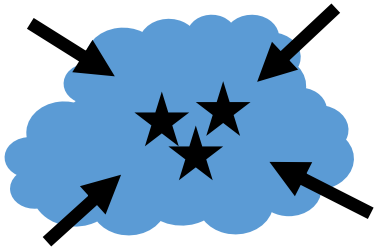


# Redshift evolution of flux

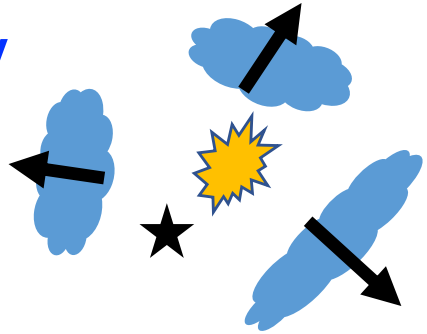
Time scale of the fluctuation

$$t \simeq \frac{\lambda R_{\rm vir}}{V_{\rm c}} \lesssim 10\ {\rm Myr}$$

IR



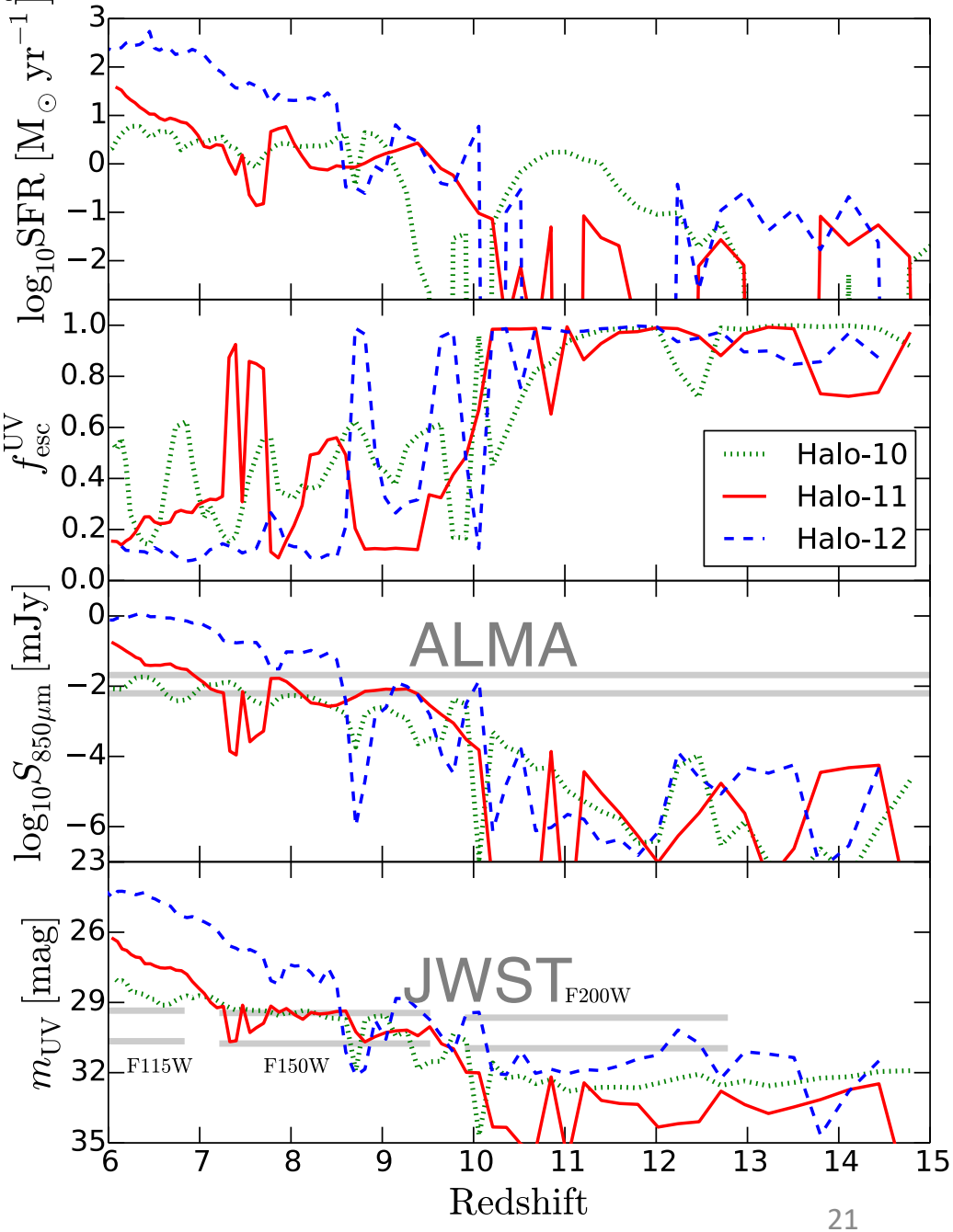
UV



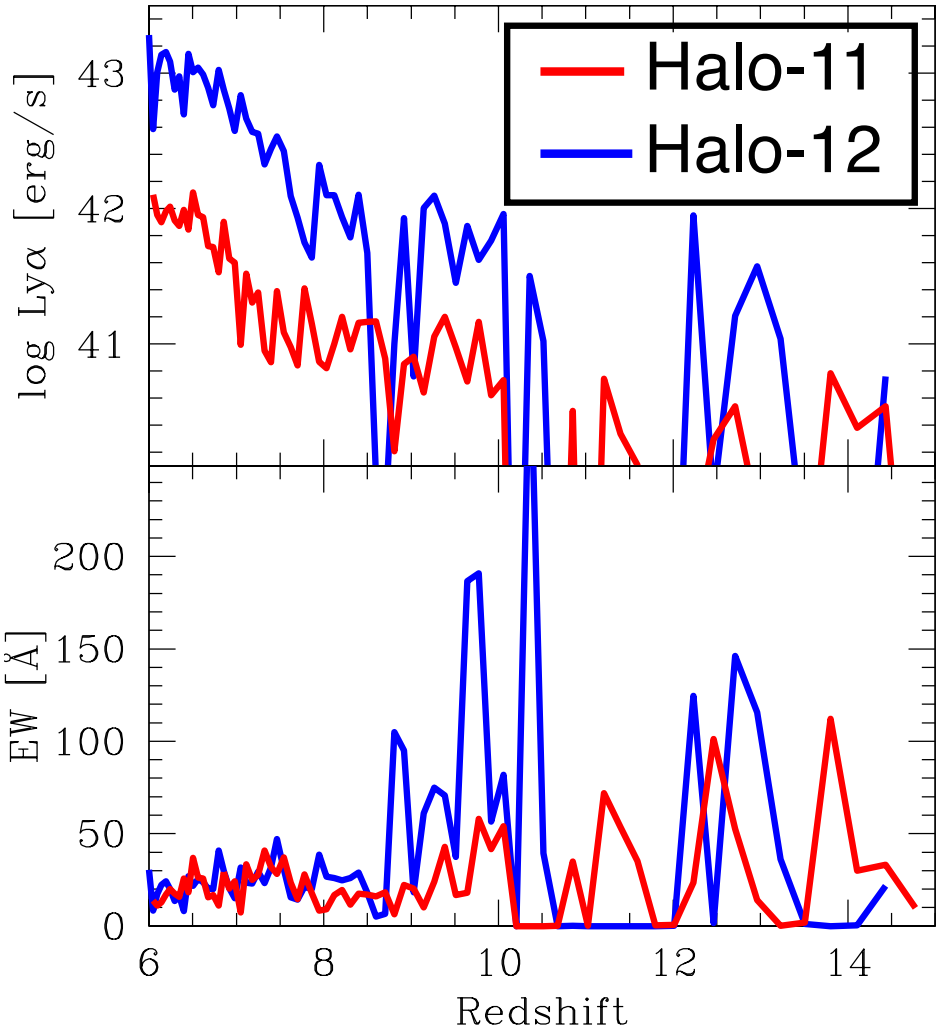
SFR

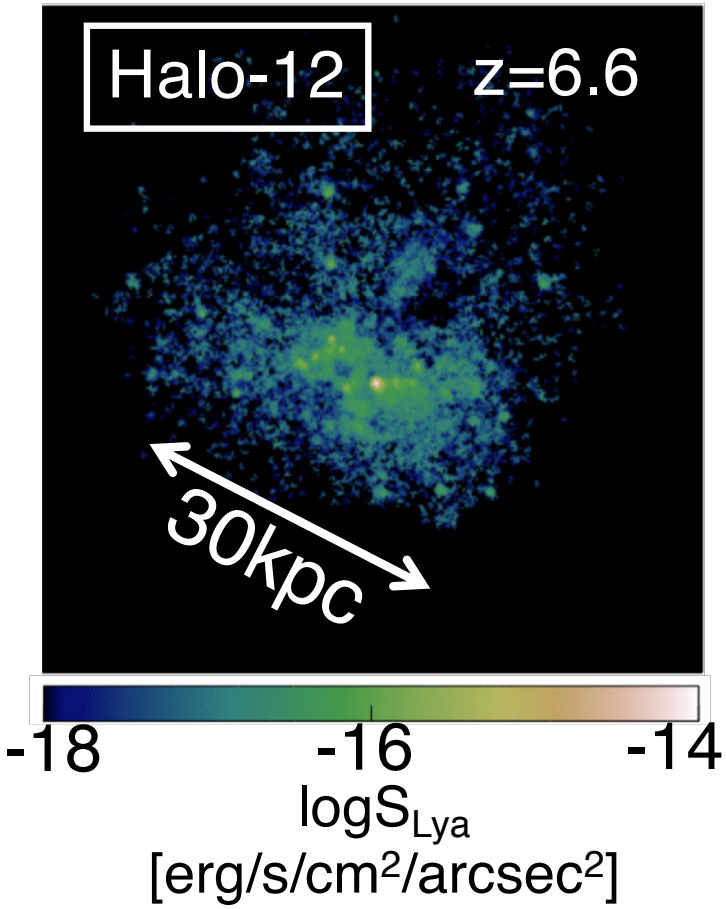
Escape fraction

UV cont. Sub-mm



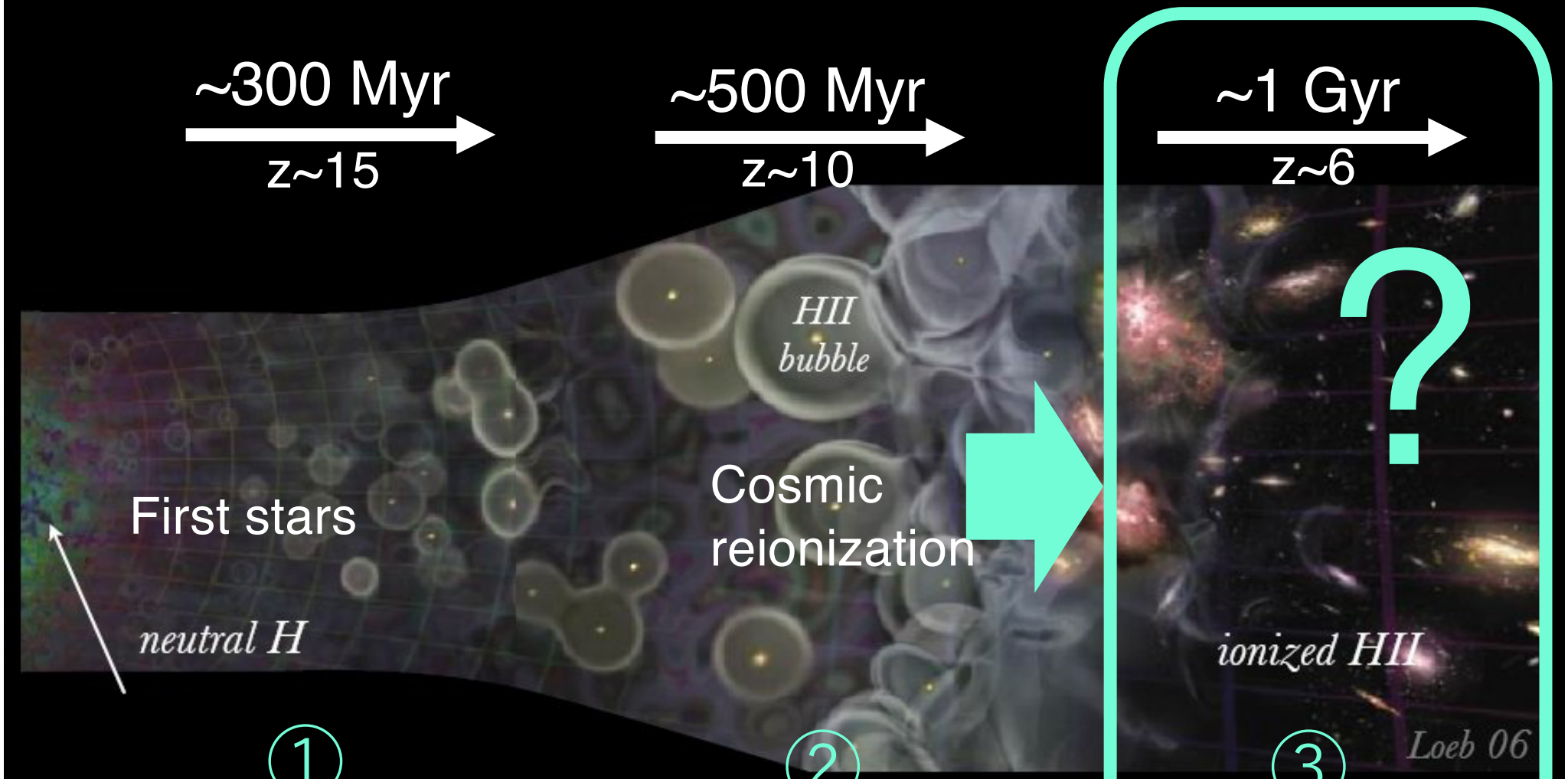
# Lyman-alpha luminosity




Radiative properties of first galaxies change drastically due to the galactic outflow

# First billion years




① **Formation of first galaxy**

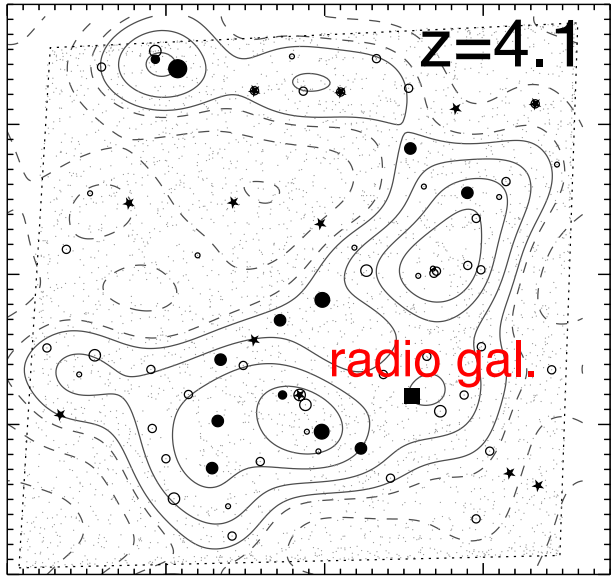
② **Evolution of first galaxy**

③ **Massive galaxies quasars**

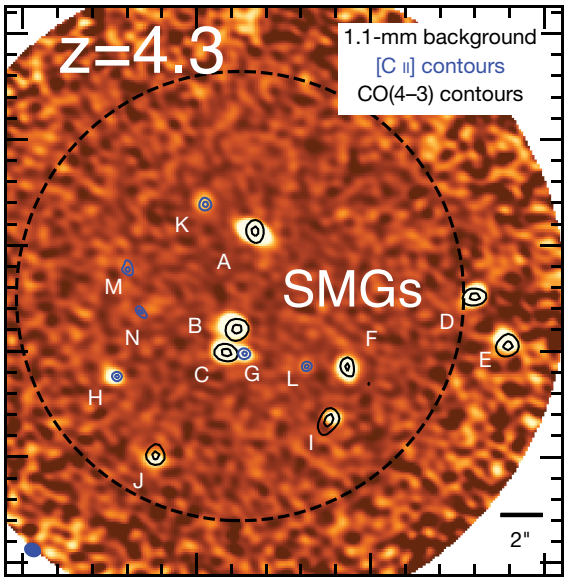
# Protoclusters in the early Universe

How galaxies evolve in protocluster regions?
What their radiative properties?
Super-massive BHs form?

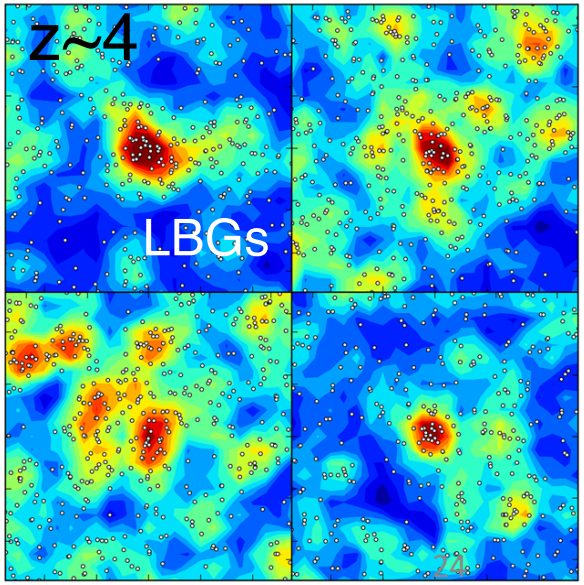
Overzier+08



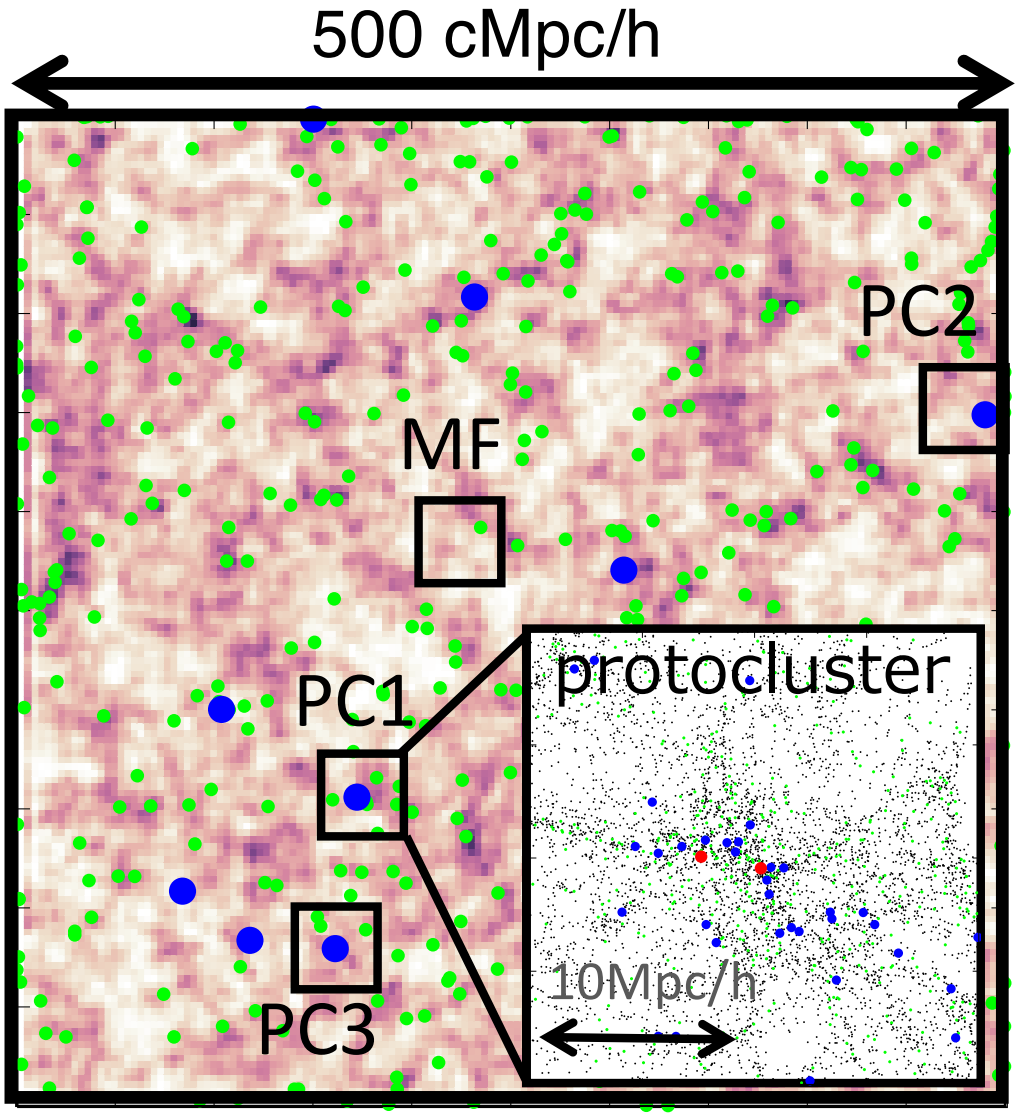

Miller+18, Nature

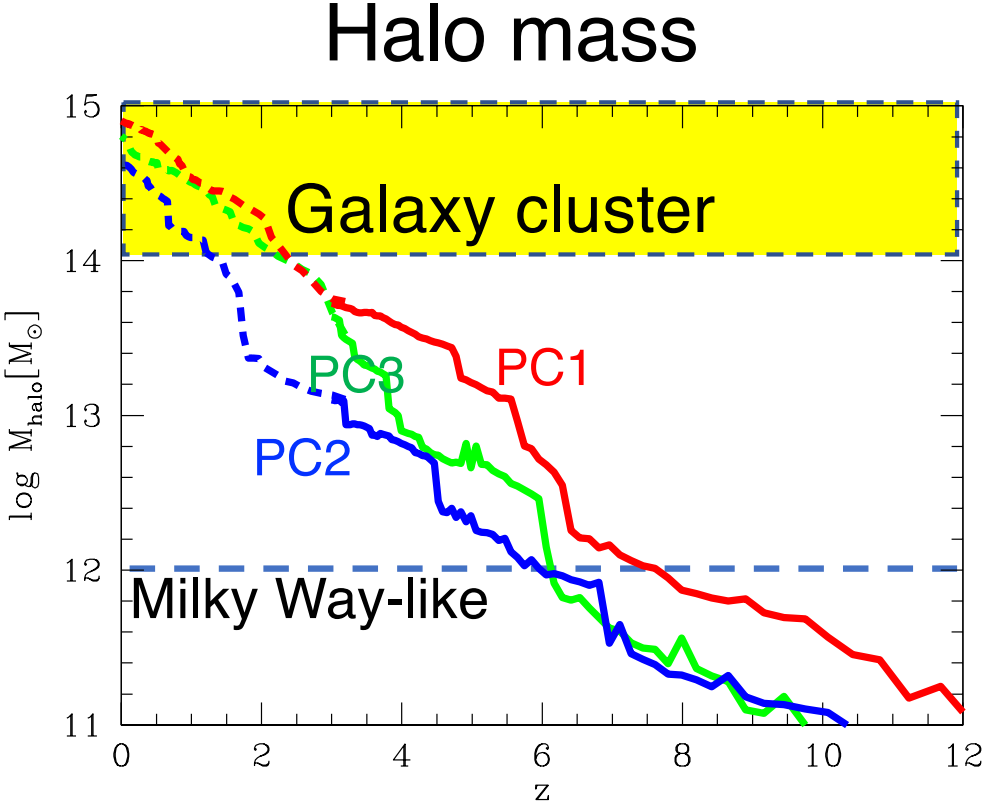



Toshikawa+18



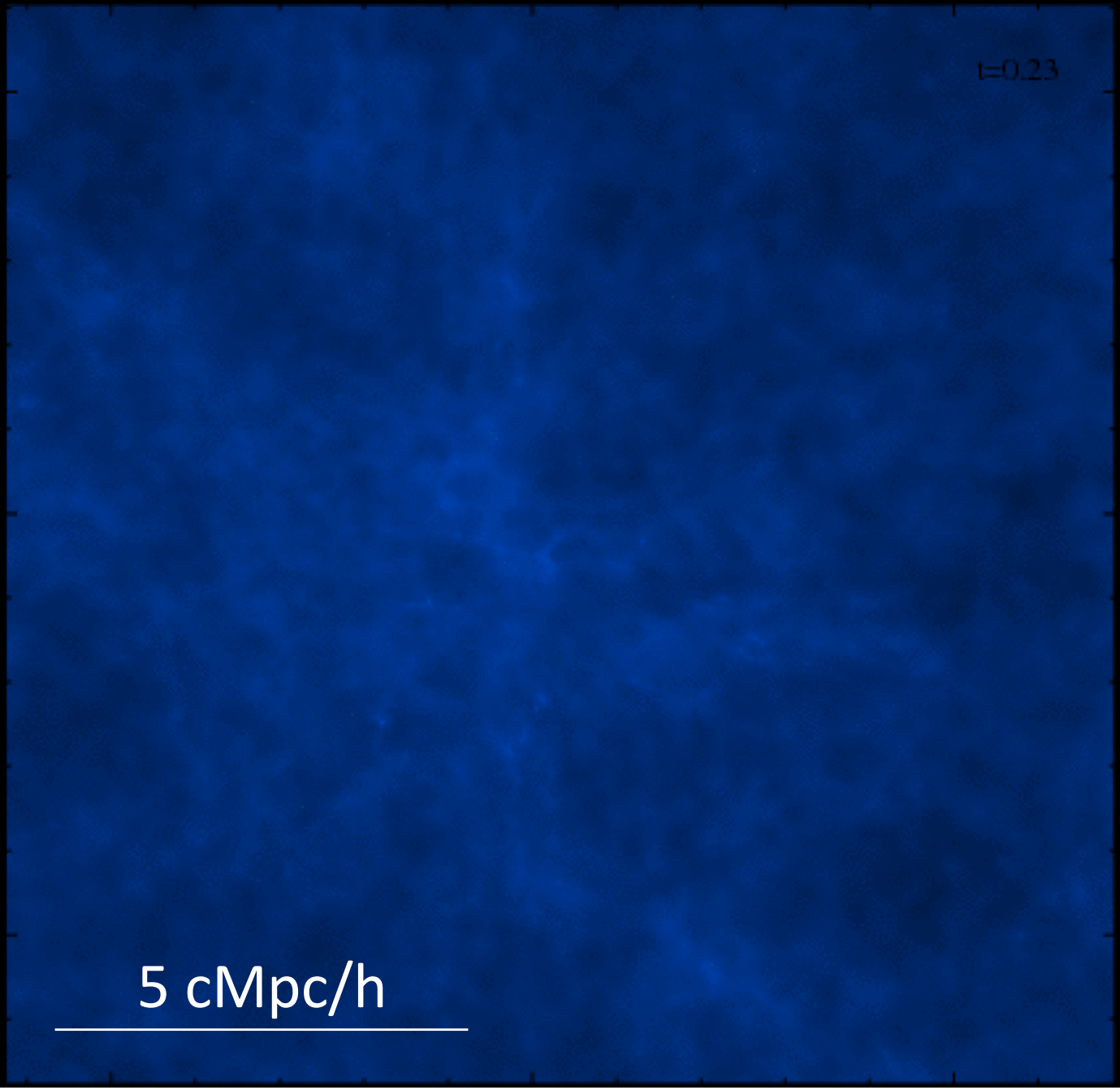
# Protoclusters in large-scale structure



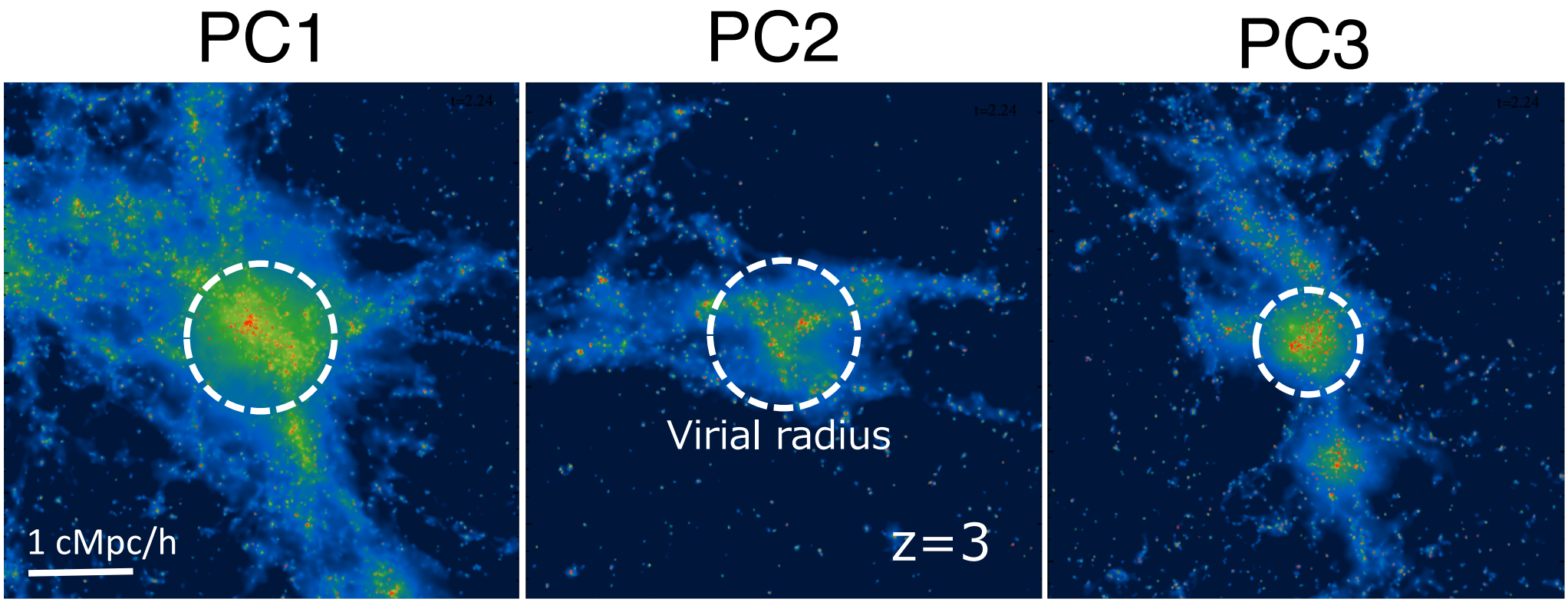




(HY et al. in prep.)

# Gas structure

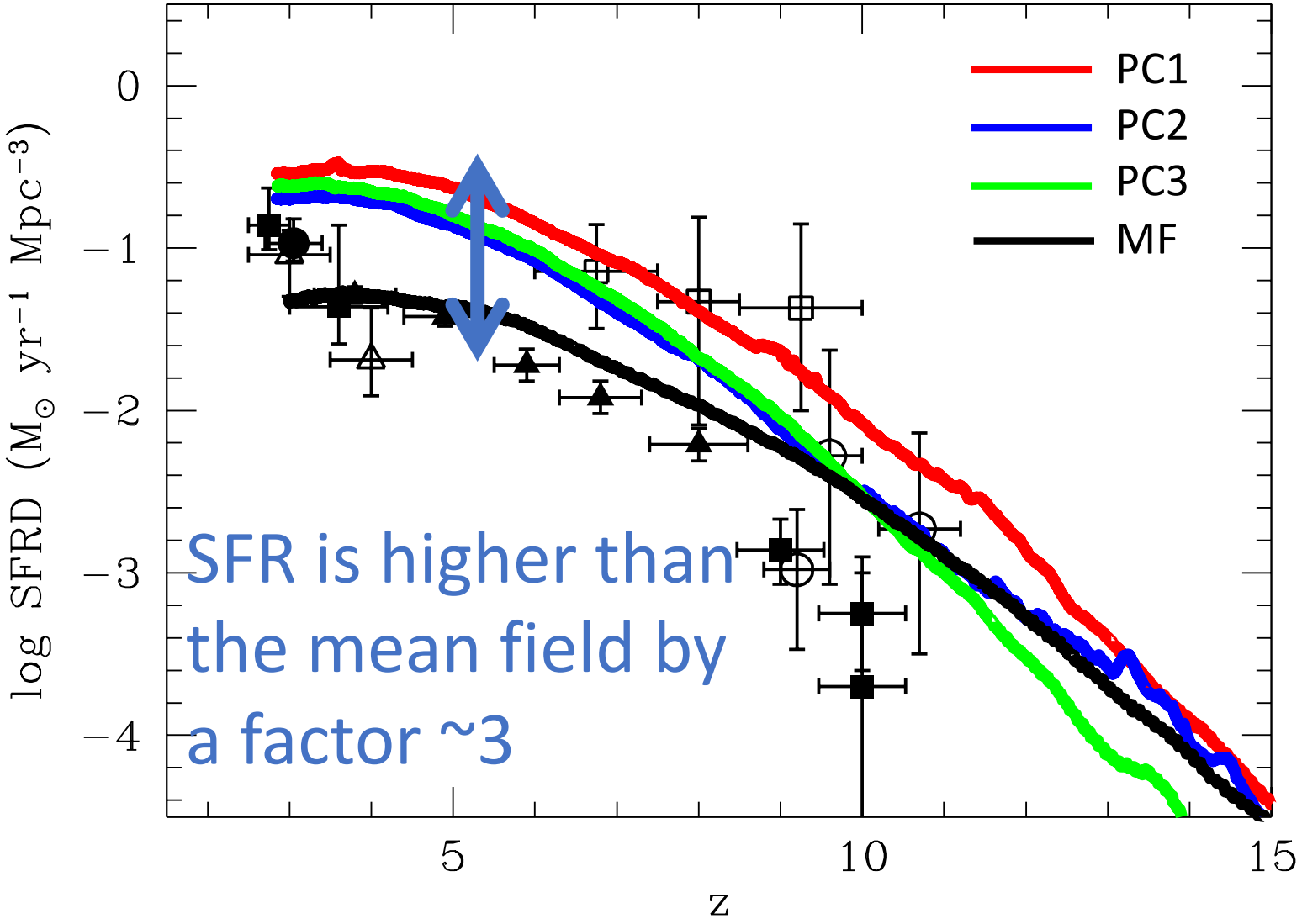


# Protocluster regions

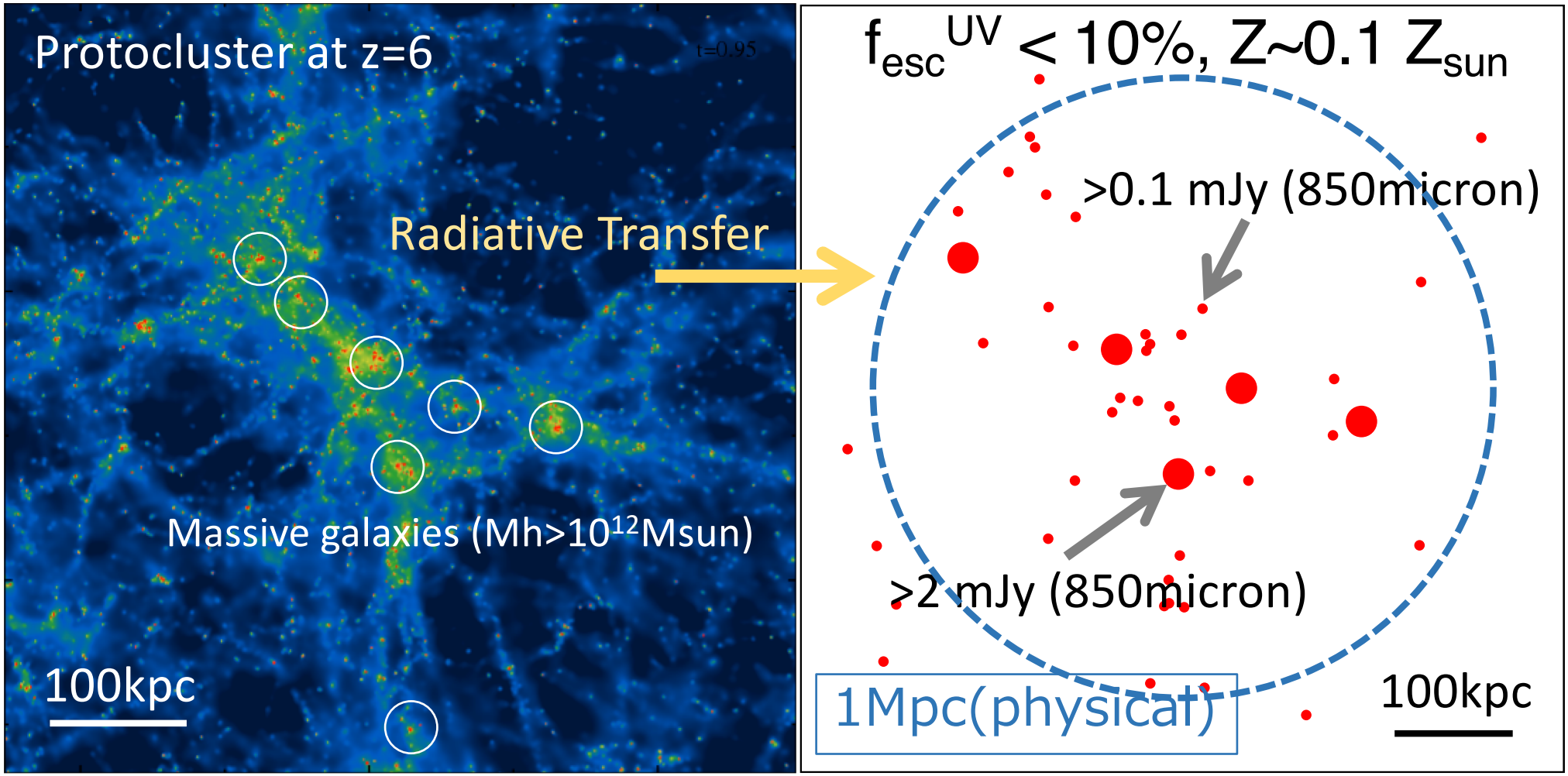



Various shapes of protoclusters

# Star formation history

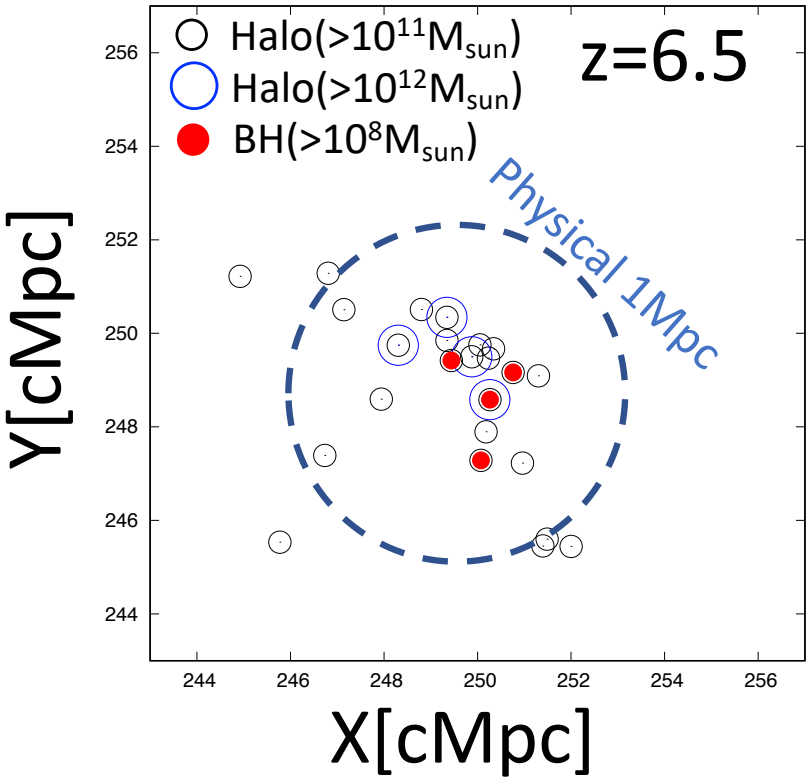


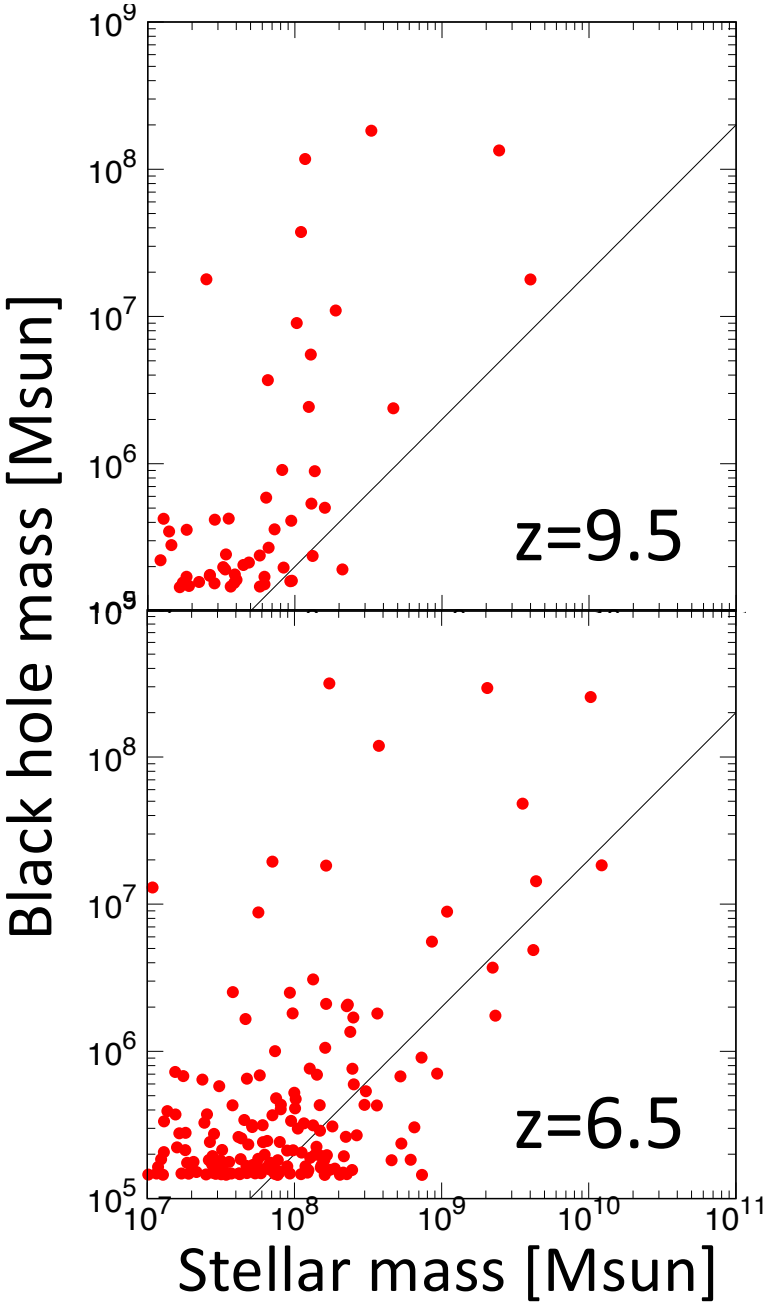
# Distribution of SMGs




Clustering of SMGs along the filamentary structure!

# Formation of massive black holes




BHs grow rapidly at z > 8

Massive BHs form in protoclusters

# Summary

We study high-redshift galaxies by combining cosmological hydrodynamics simulations and radiative transfer calculations

- Star formation and gas fraction of first galaxies sensitively depend on the initial mass function of Population III stars
- star formation in first galaxies proceeds intermittently due to supernova feedback
- UV and sub-mm fluxes fluctuate with the intermittent star formation history
- As the halo mass increases, galaxies become bright at sub-millimeter wavelengths (~1mJy at 850μm)
- Five bright SMGs can form in protoclusters even at z~6