Giant HII bubbles in protocluster regions

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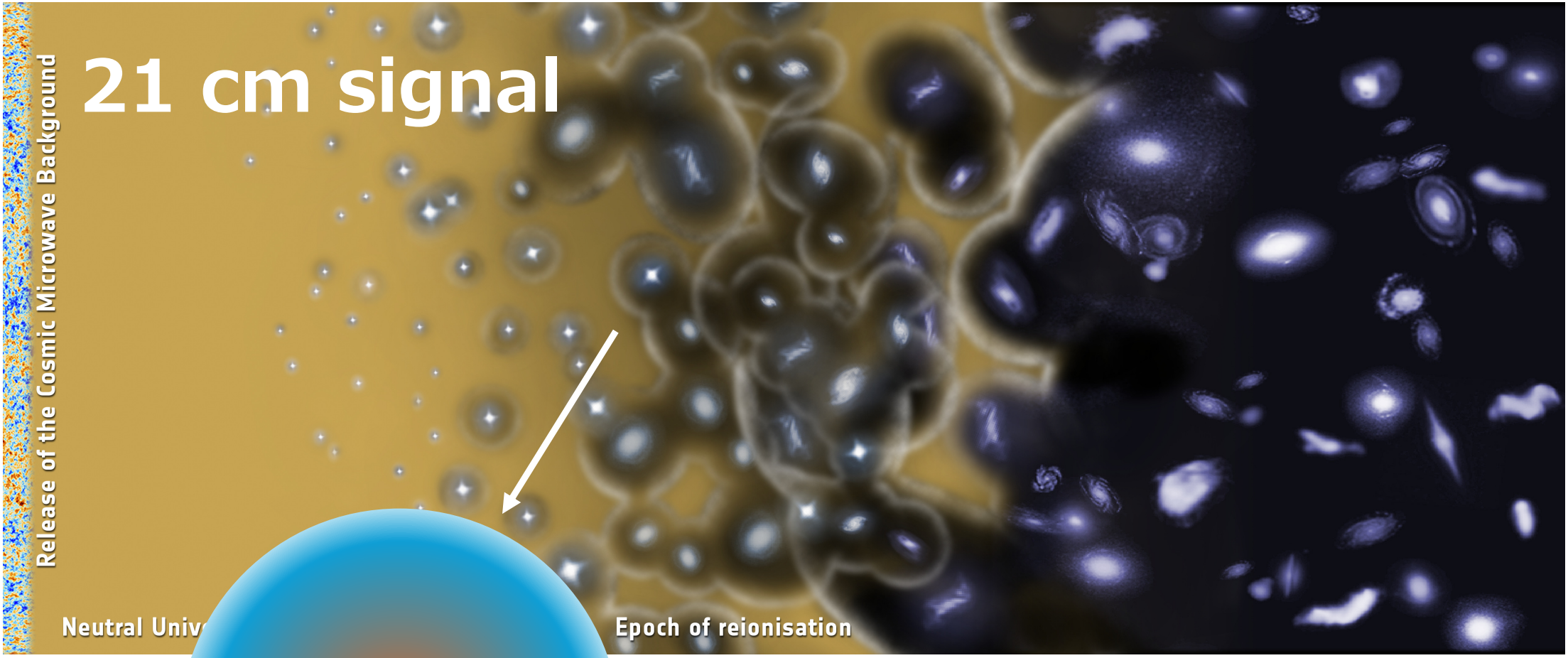
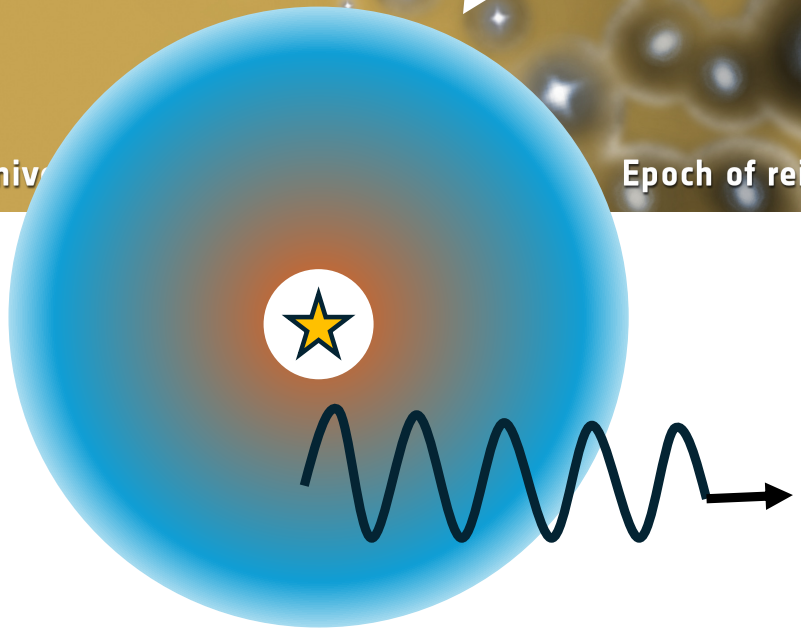
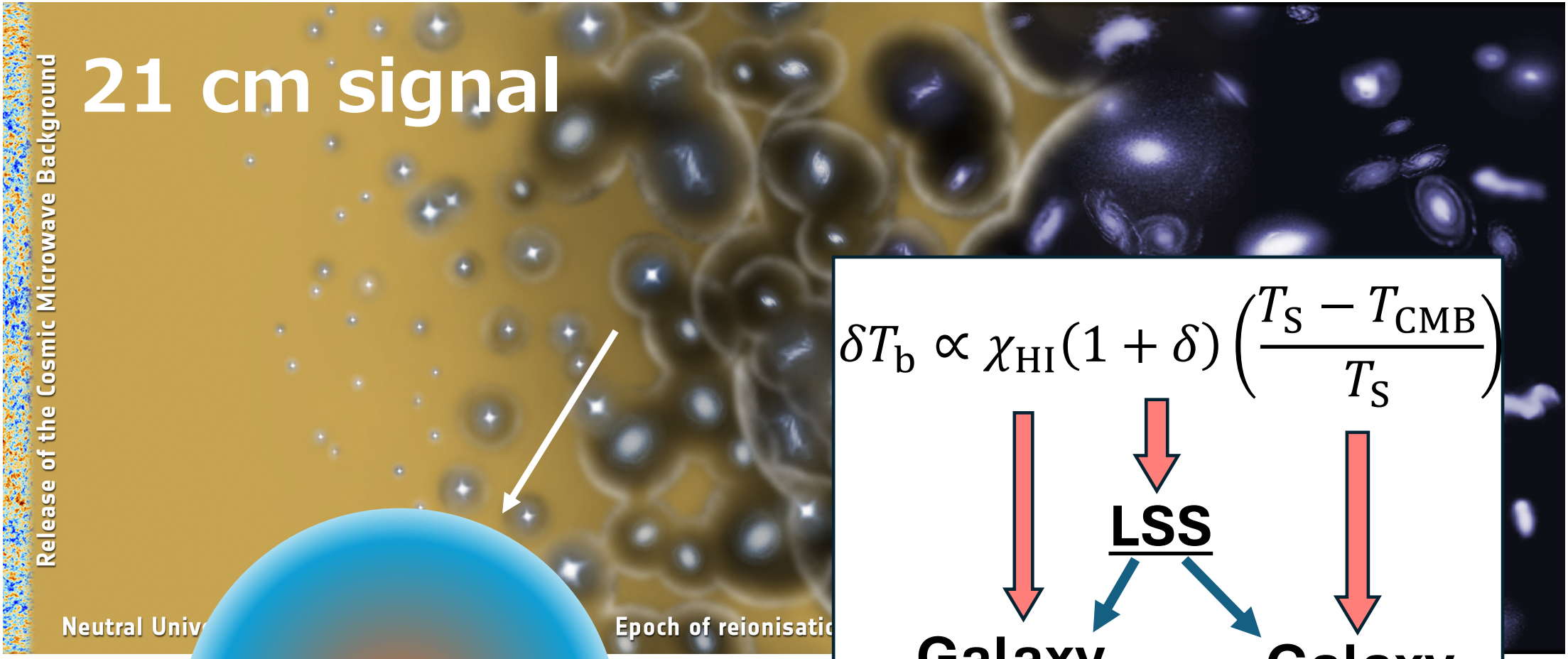
Hongo 21cm workshop @ Tokyo U., 2024/10/3-4

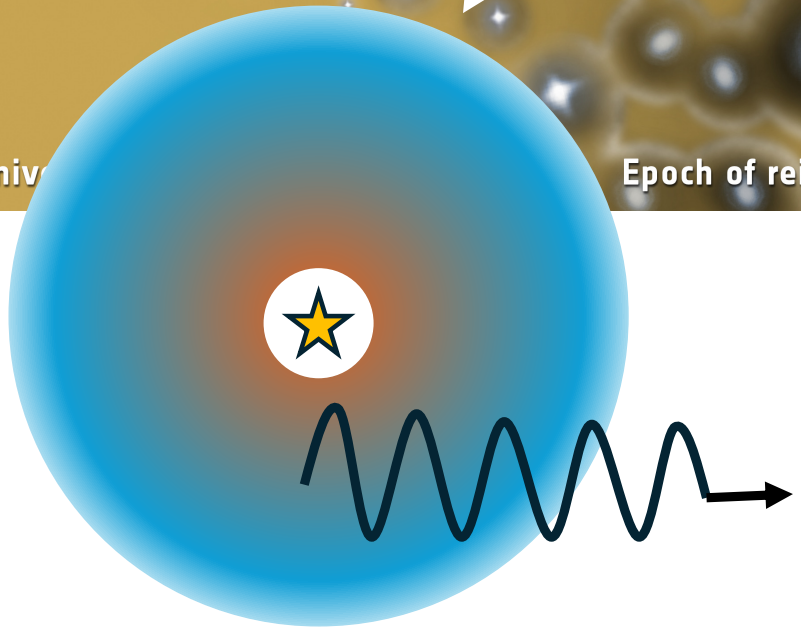
21 cm signal


Release of the Cosmic Microwave Background
Neutral Univ
Epoch of reionisation



21 cm signal





$$\delta T_{\mathrm{b}} \propto \chi_{\mathrm{HI}}(1+\delta)\left(\frac{T_{\mathrm{S}}-T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right)$$

LSS

Galaxy

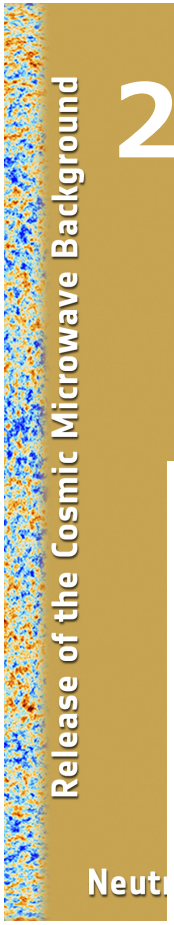
$\dot{N}_{\mathrm{Ion}}$

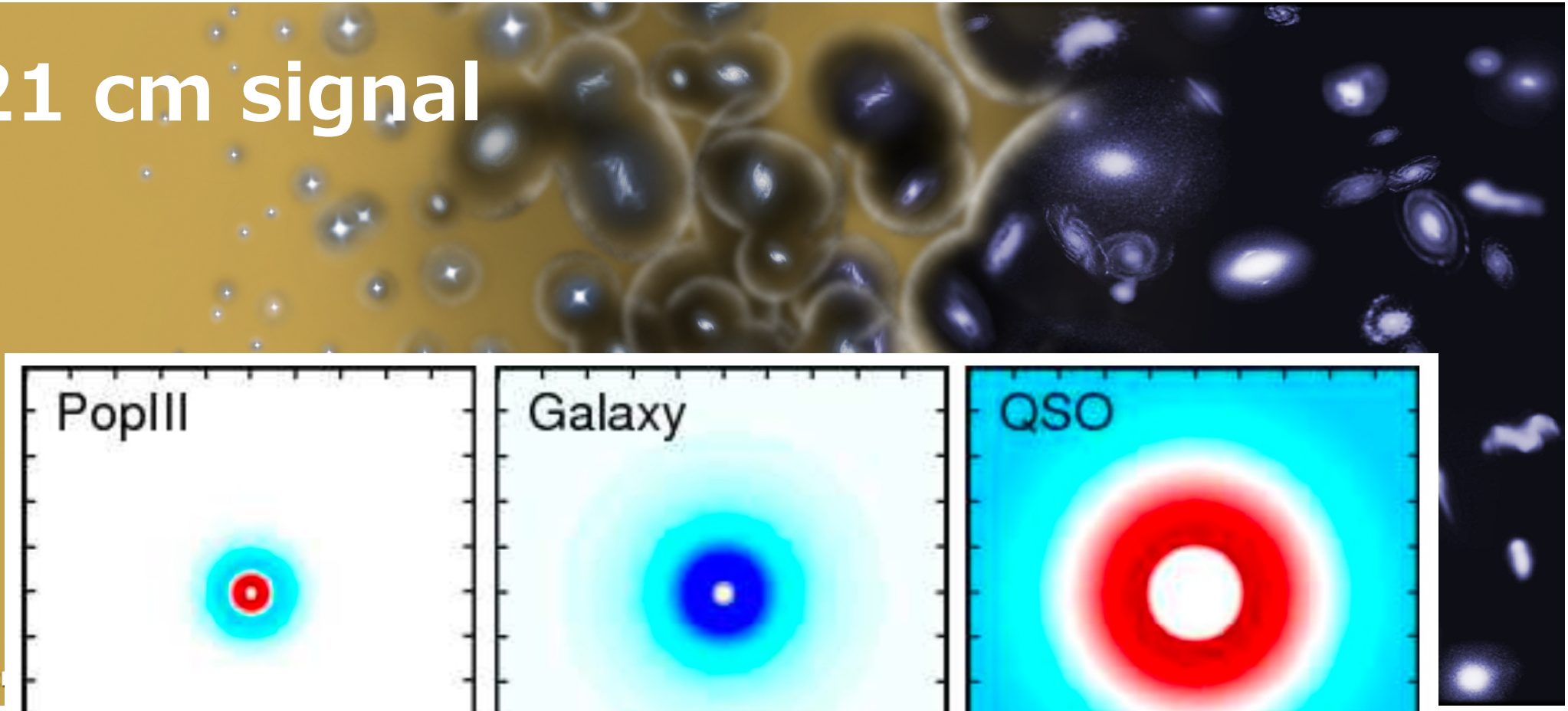
Galaxy

L_{UV}

SED

21 cm signal

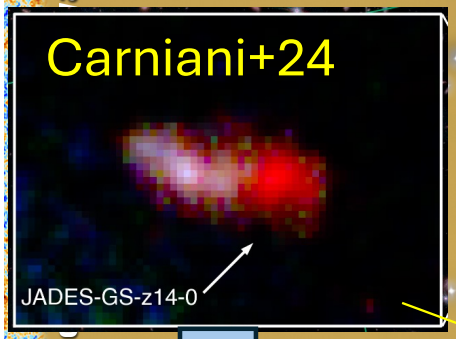




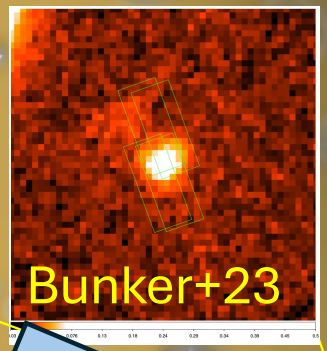
Yajima & Li (2014)

Super-distant galaxies in JWST era

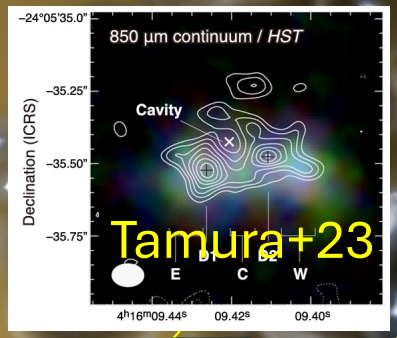
z=14.3



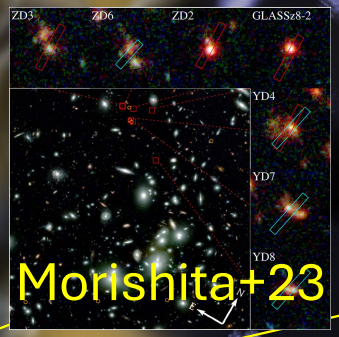
z=10.6



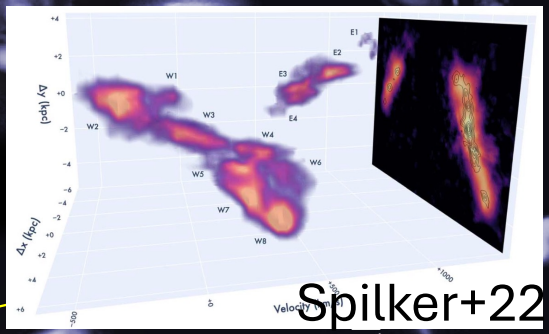
z=8.3



z=7.9



z=6.9



Release of Cosmic Microwave Background

Neutral universe

First stars

Epoch of reionisation

NASA/WMA

Active star formation

Dusty/clumpy

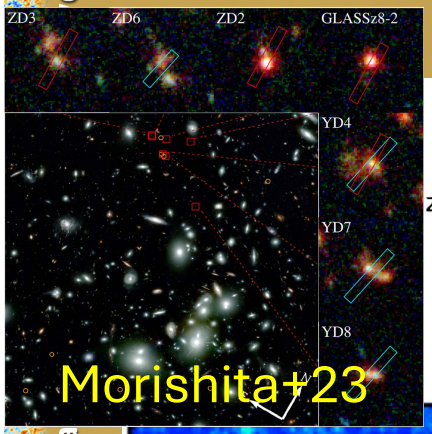
Dusty starburst

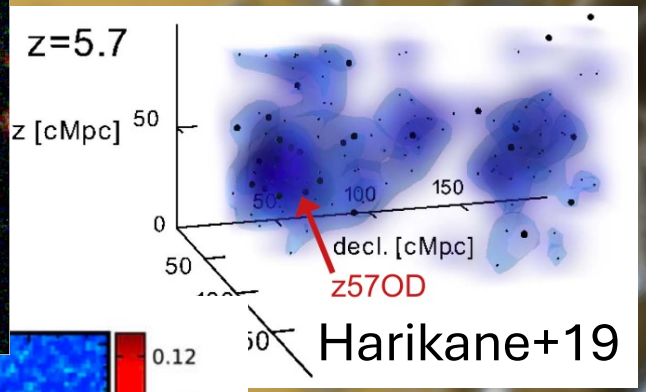
Abnormal N/O ratio
Rapid rotational disk?

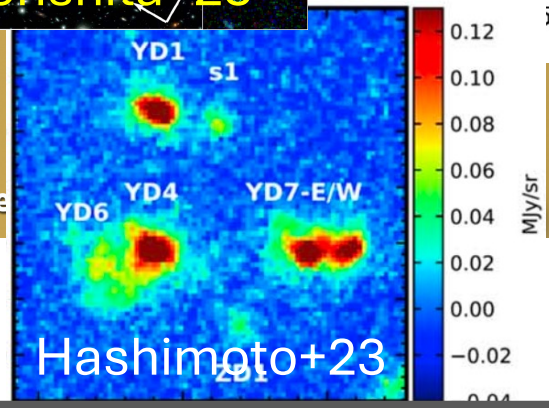
Galaxy clutering
Protocluster?

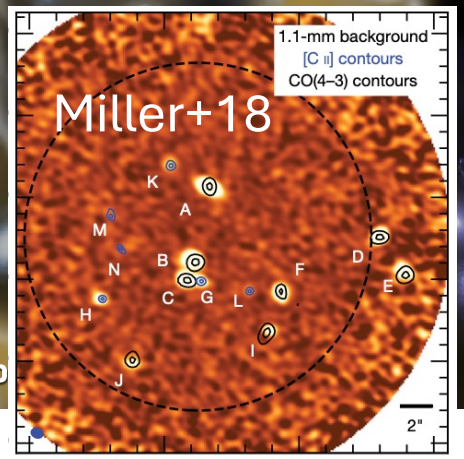
What induces the various properties?

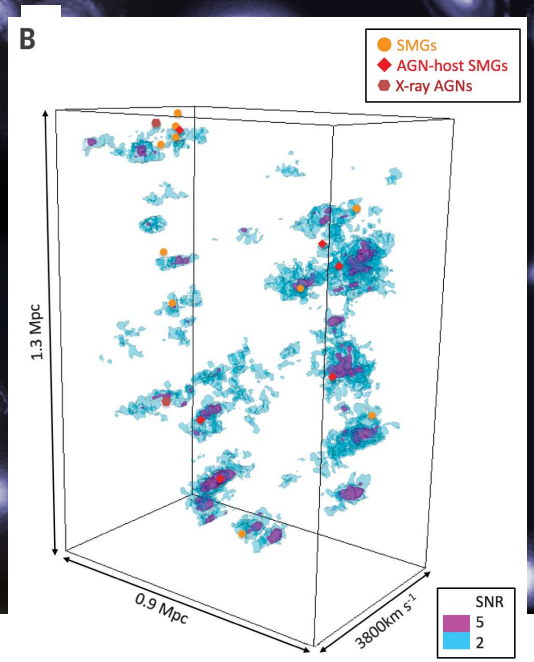
Protoclusters











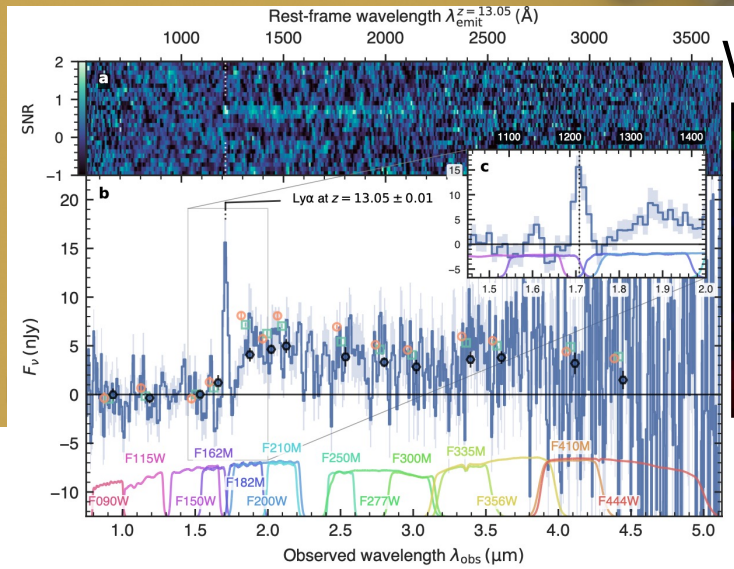
z~8 **z~6** **z~4** **z~3**

How galaxies form in overdense regions?

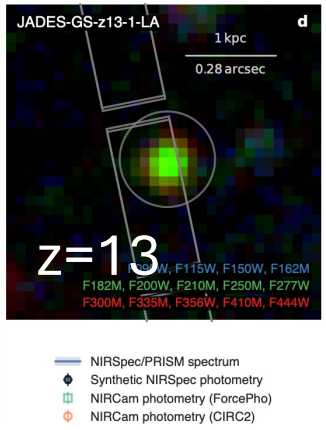
Cosmic reionization

Release of the Cosmic Microwave Background

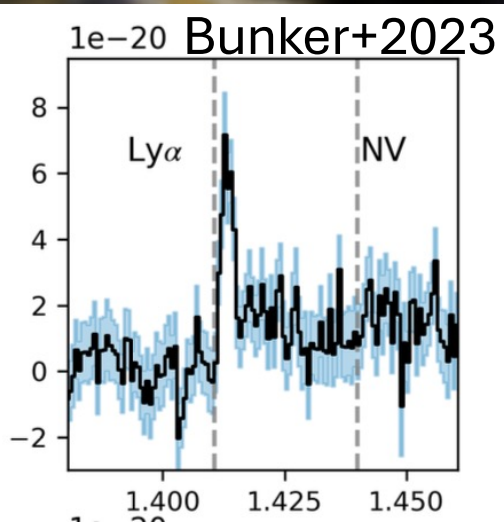
JWST observations

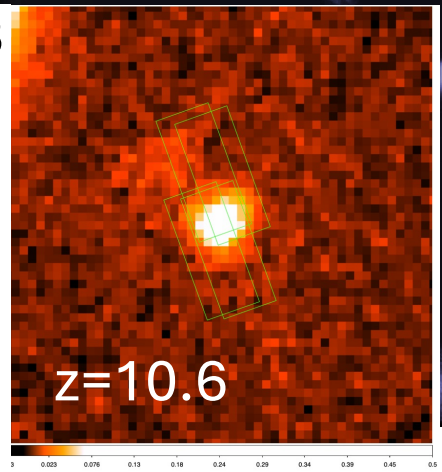


Witsitok+2024



Bunker+2023

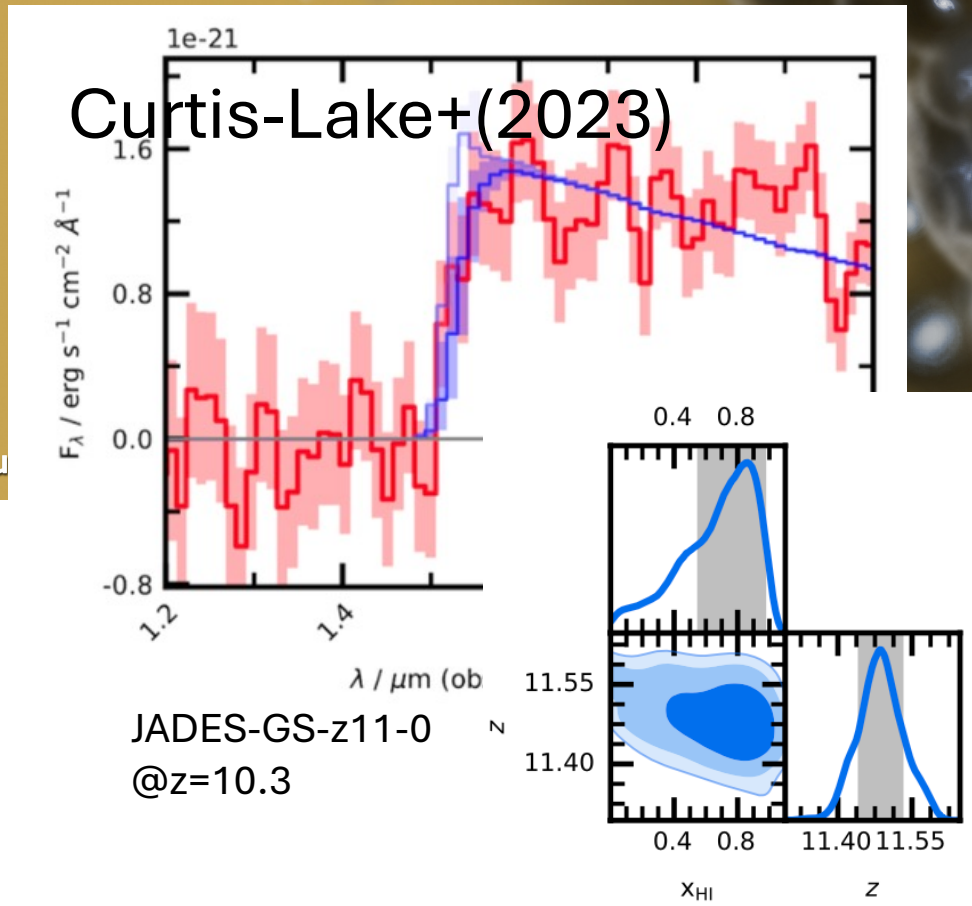


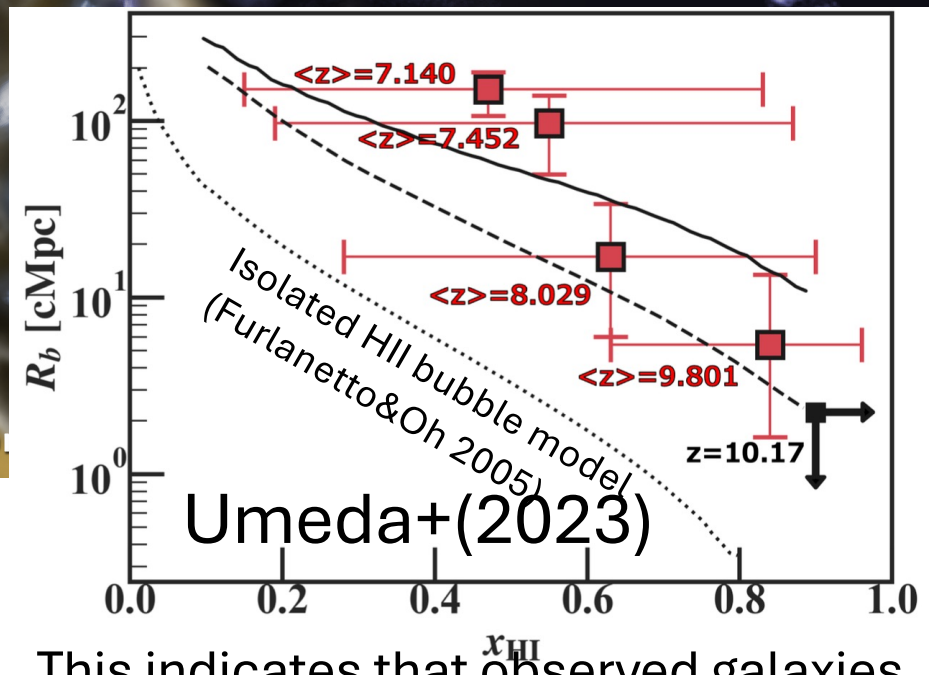


Detection of Lyman-alpha lines from galaxies at z > 10.

Were giant HII bubbles formed?

Constraints on the reionization using IGM absorption profiles

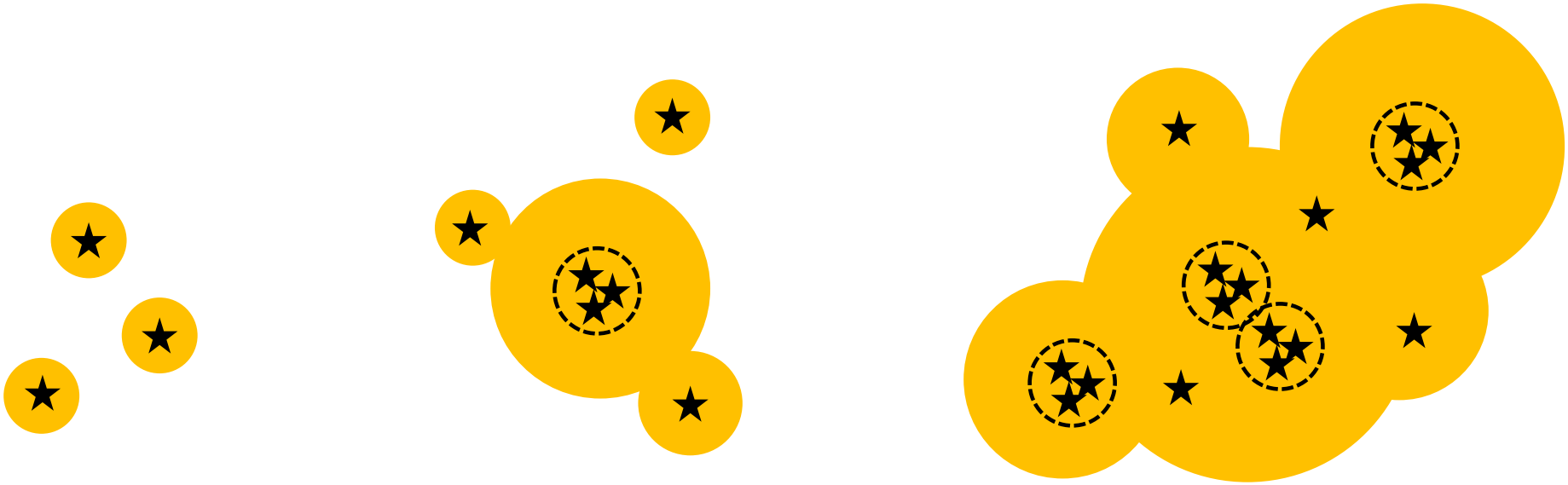




This indicates that observed galaxies distributes within giant HII bubbles with the overlap effect

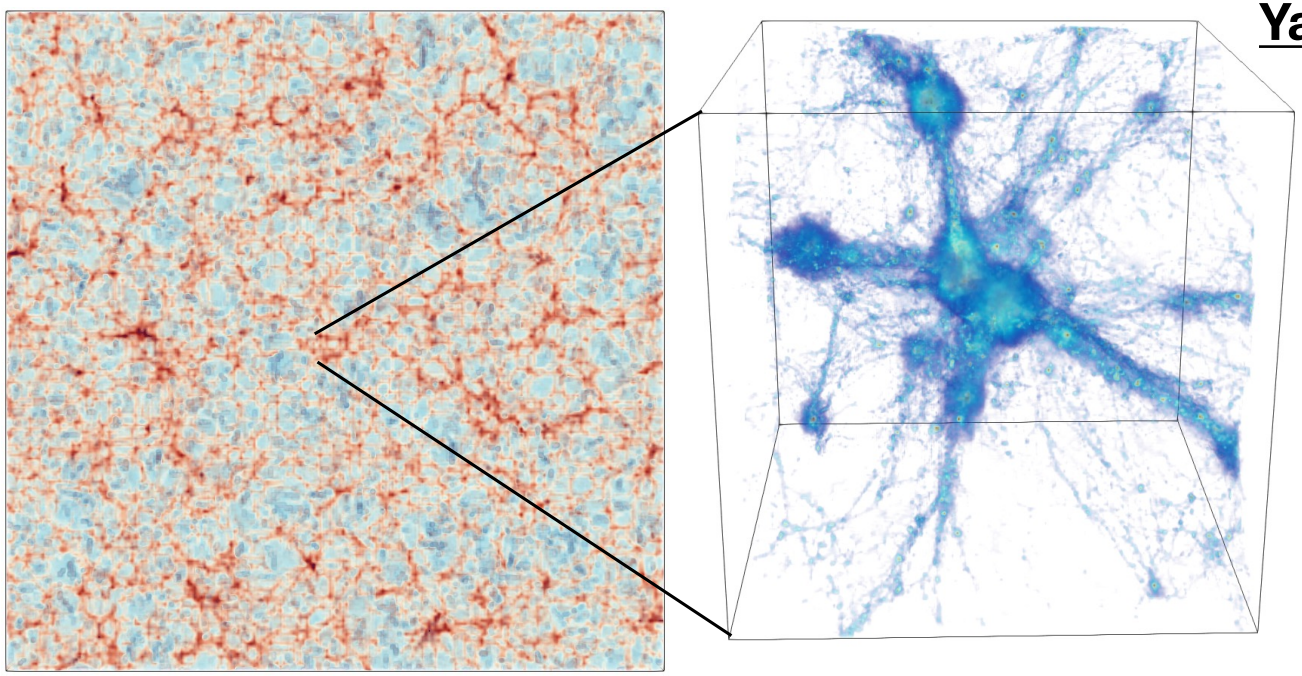
1) How did first galaxies form in overdense regions?

2) How was IGM ionized in overdense regions?



FOREVER22 (FORmation and EVolution of galaxies in Extremely overdense Regions motivated by SSA22)

Yajima et al. (2022, MNRAS, 509, 4037)



Whole volume: (714 cMpc)^3

Top 10 protoclusters at z=2 are selected
Zoom-in cosmological simulations

Gadget-3 (Springel+05)

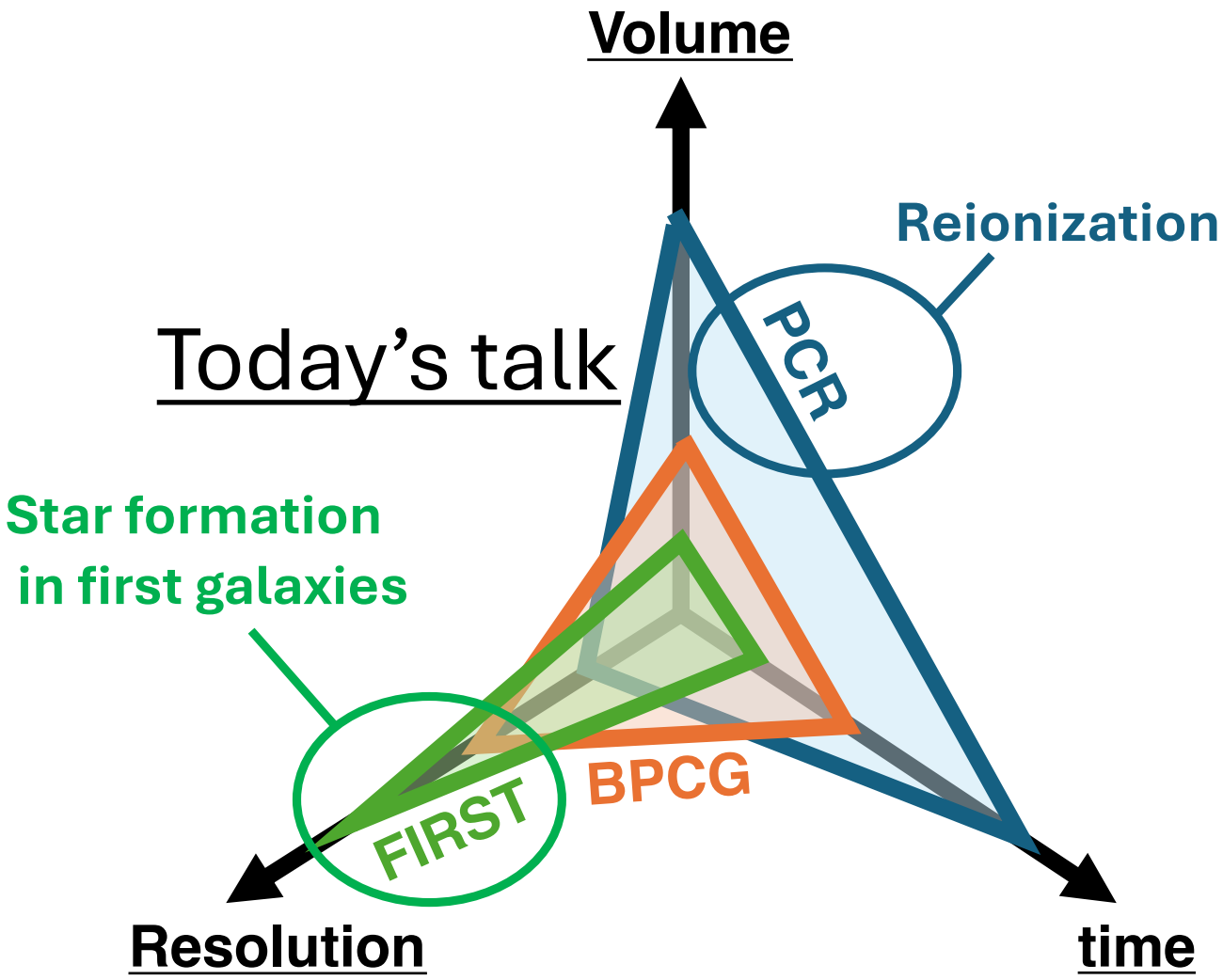
OWLS/EAGLE model
(Schaye+10, 15)

FiBY model
(Johnson+13)

FOREVER22 model

- ✓ Pop III stars and Pop II stars
- ✓ Supernova feedback (stochastic thermal)
- ✓ Non-eq. primordial chemistry
- ✓ Photoionization heating
- ✓ Radiation pressure on dust
- ✓ BH feedback (thermal and jet)
- ✓ Dust growth and destruction

3 levels of zoom-in simulations



PCR run (10 regions)

L = 28.6 cMpc

$m_{gas} = 4 \times 10^6\ M_{sun}$

$M_{halo} \sim 10^{14}\ M_{sun}$

$z_{end} = 2$

BPCG run (10 regions)

L ~ 10 cMpc

$m_{gas} = 5 \times 10^5\ M_{sun}$

$M_{halo} \sim 10^{13}\ M_{sun}$

$z_{end} = 4$

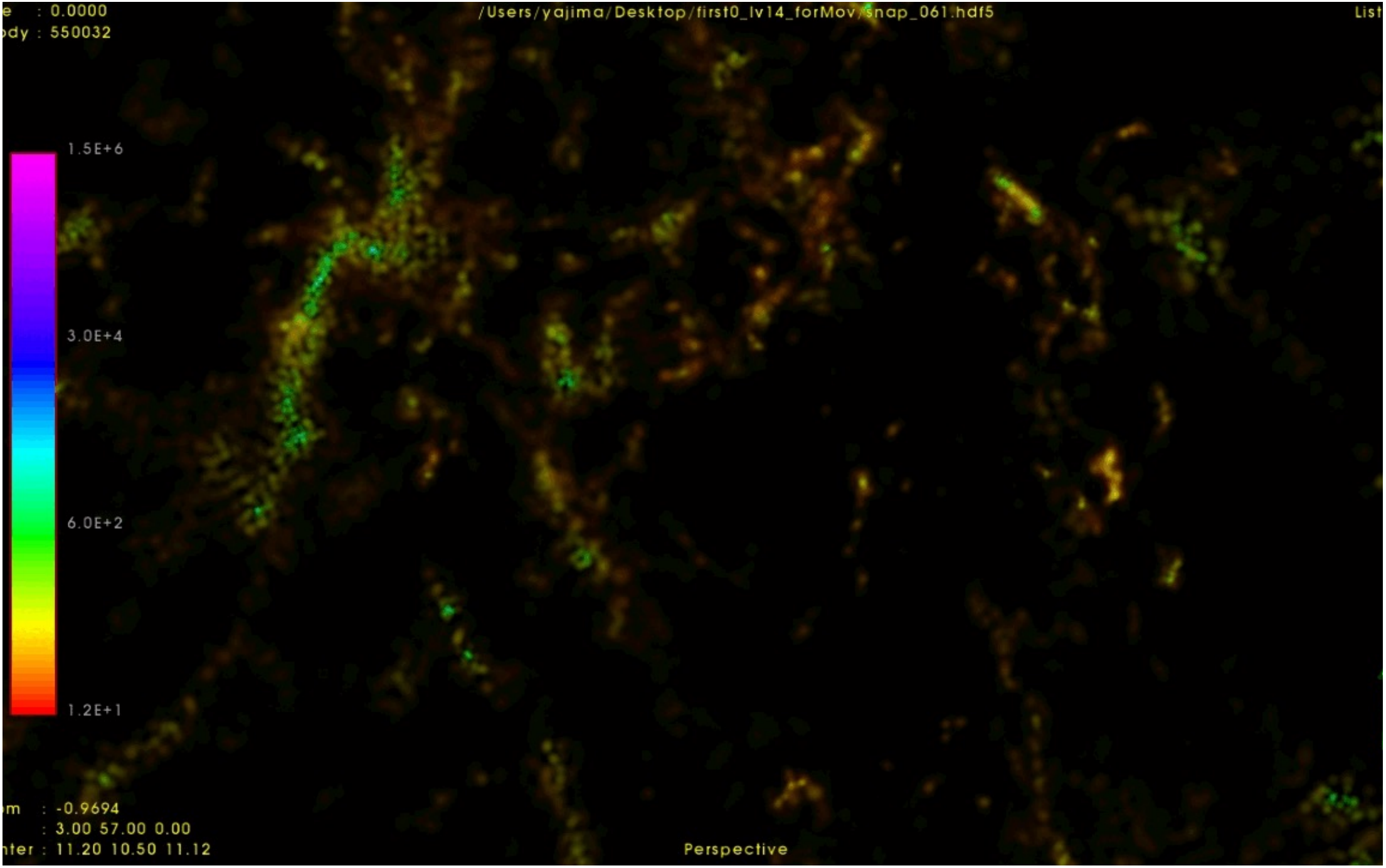
FIRST run (2 regions)

L ~ 3 cMpc

$m_{gas} = 8000\ M_{sun}$

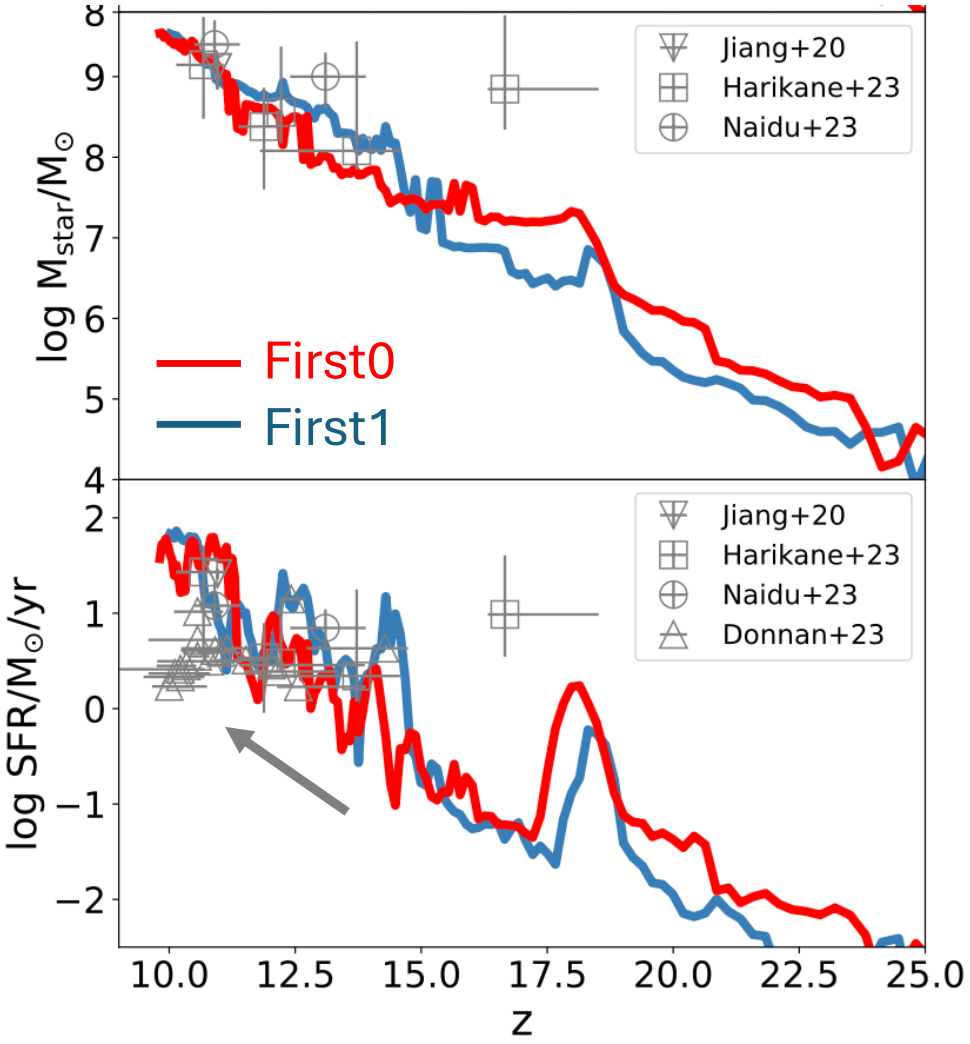
$M_{halo} \sim 10^{11}\ M_{sun}$

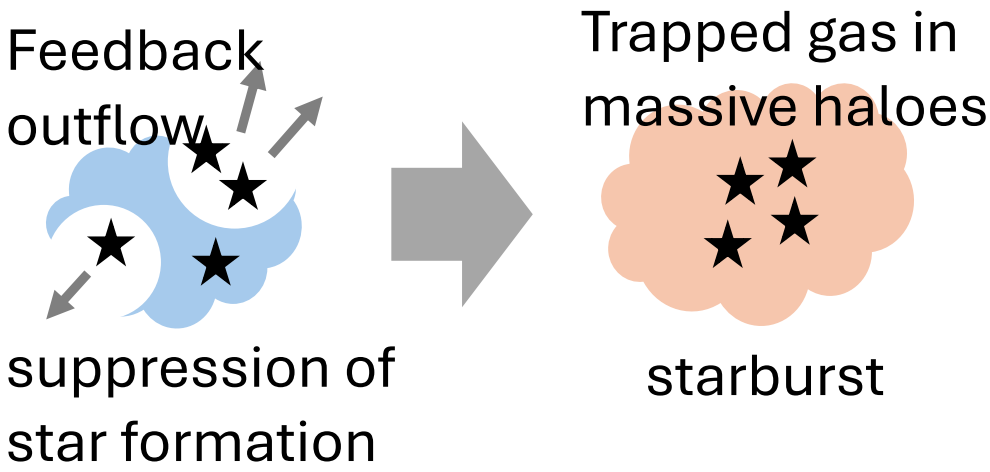
$z_{end} = 9$


e : 0.0000
dy : 550032
/Users/yajima/Desktop/first0_lv14_forMov/snap_061.hdf5
List
1.5E+6
3.0E+4
6.0E+2
1.2E+1
m : -0.9694
: 3.00 57.00 0.00
nter : 11.20 10.50 11.12
Perspective

Star formation history of the first galaxies

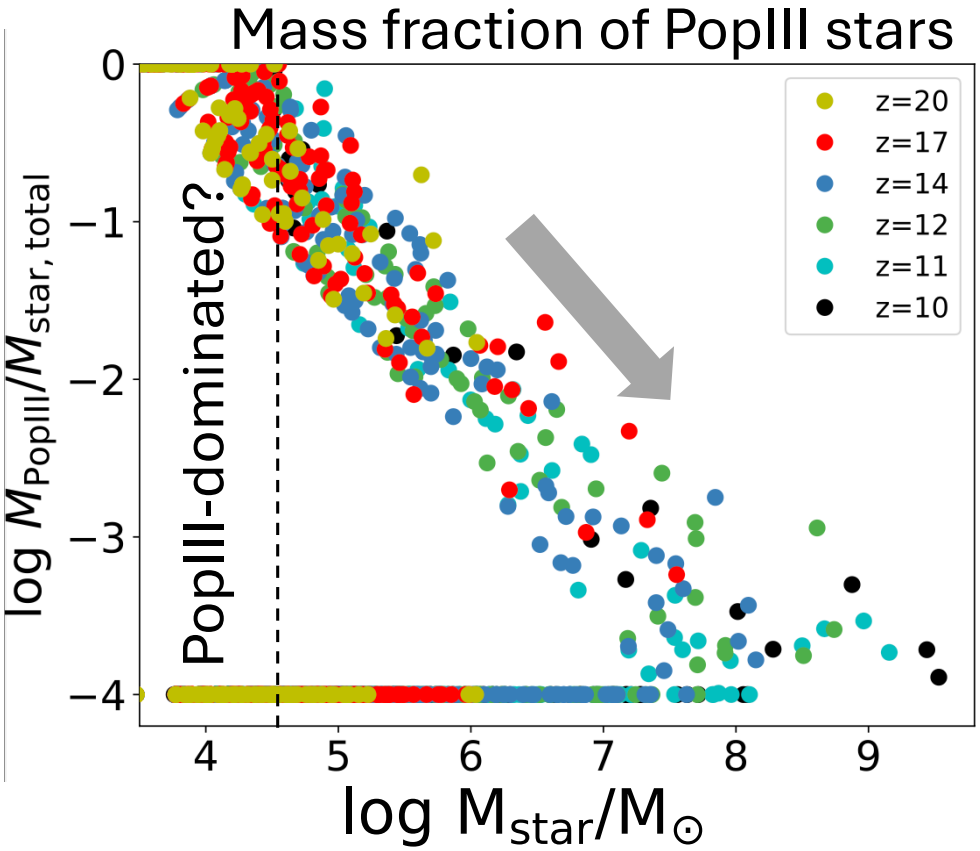
(**Yajima** et al., 2023)

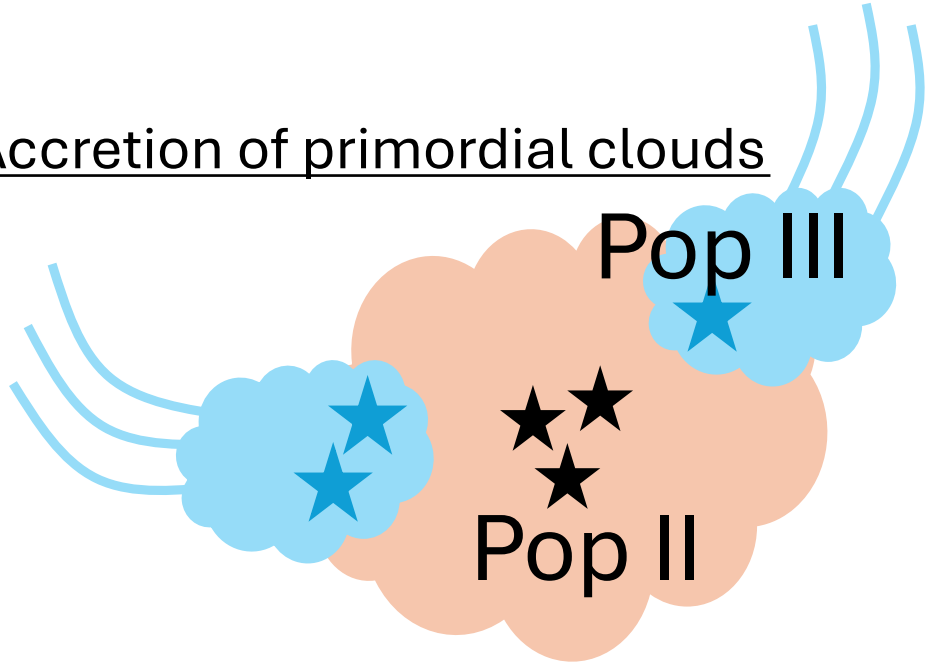




Modelled galaxies at the overdensity regions can reproduce the observed SFRs at z~10-14, while the SFRs at z=16 are much lower than the observations.

First galaxies with Pop III stars?





Mass fraction of Pop III stars decreases with total stellar mass

it is <~ 1% for galaxies with $M_{star}>10^6 M_{sun}$

Distribution of POPIII stars

- Pop II
- Pop III

z=10

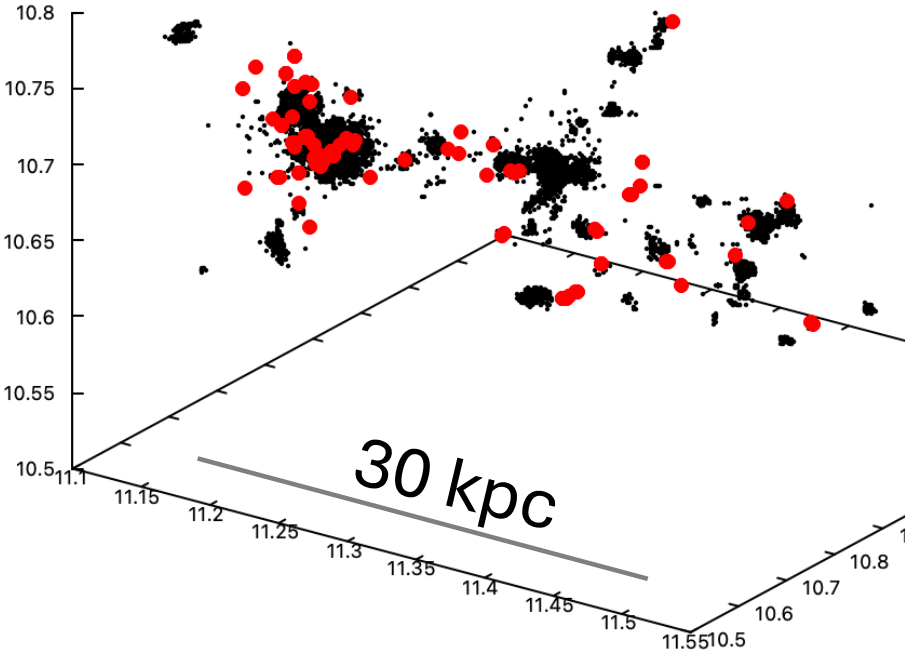
f_{popIII}=0.017%

SFR=41.5 M_{sun}/yr

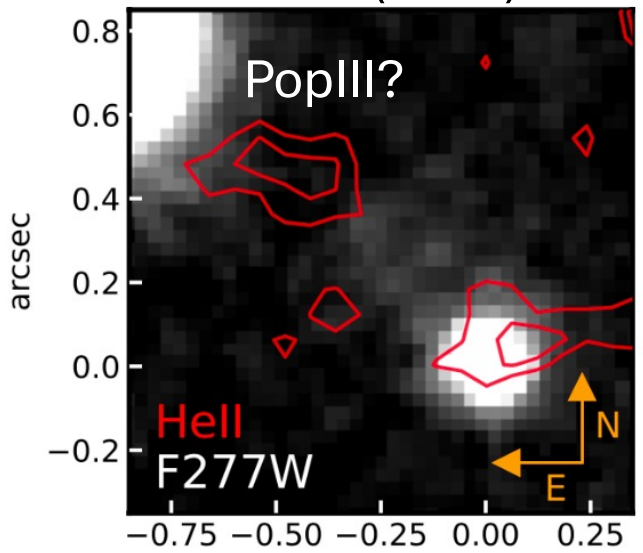
M_{star} =2.8x10^9 M_{sun}

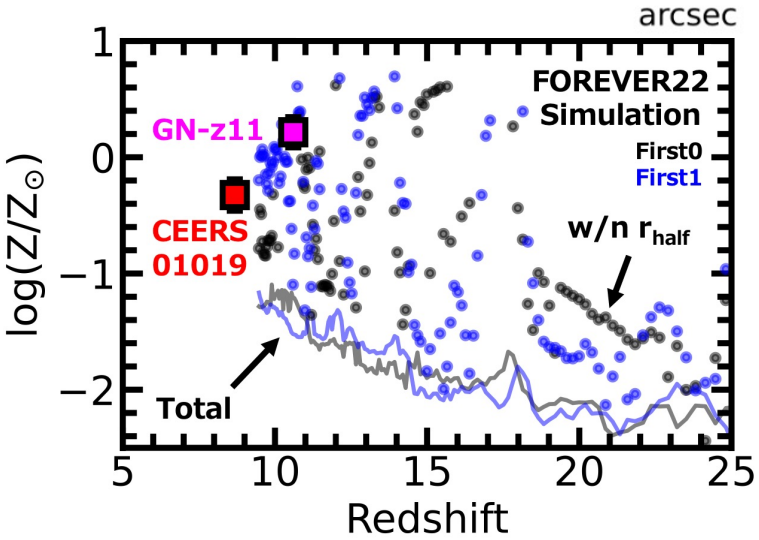
M_{POPIII} = **4.8x10^5** M_{sun}

Z=6.6x10^{-2} Z_{sun}



Maiolino+(2023)

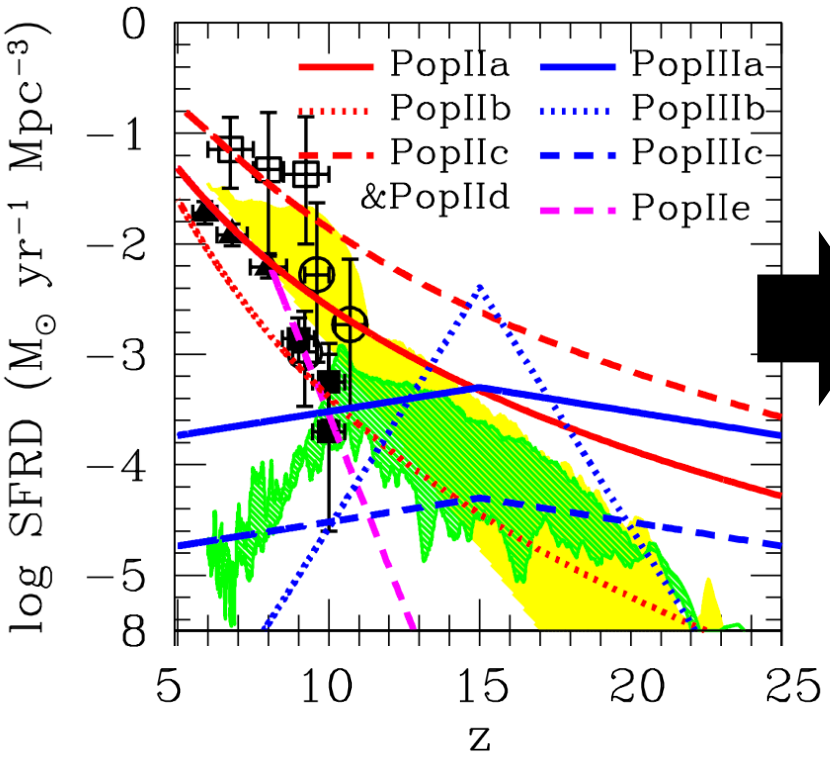




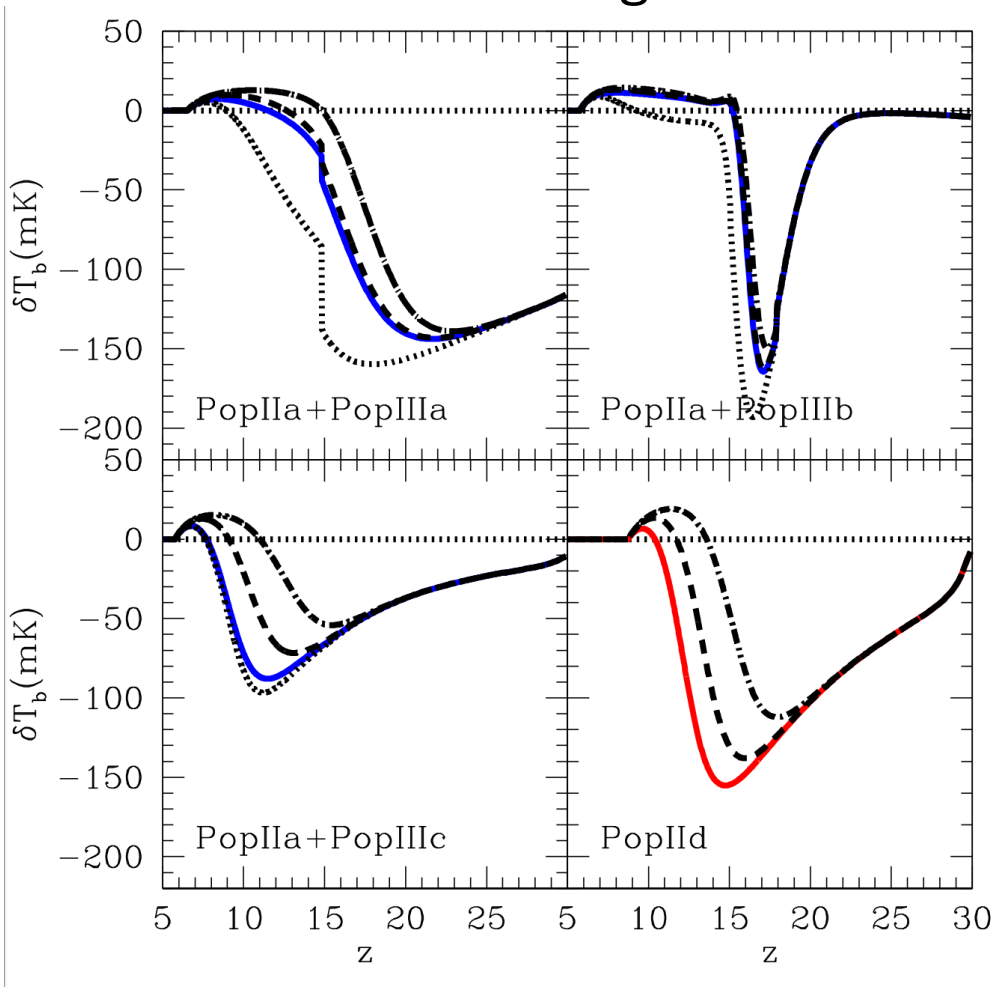
Isobe+(2023)

Impacts of Pop III stars on the 21-cm global signal

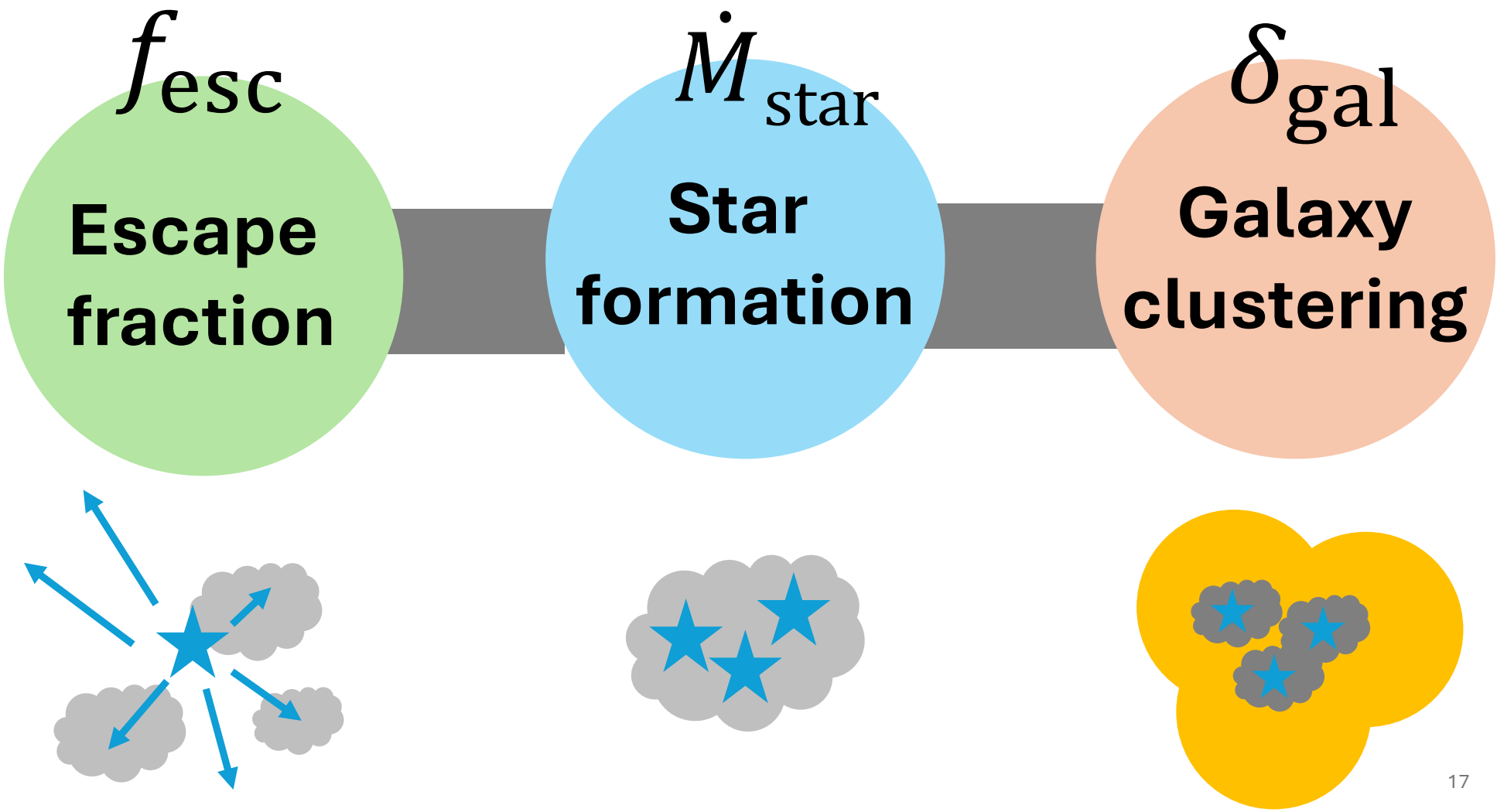
(**Yajima**, et al., 2015)



21 cm signal



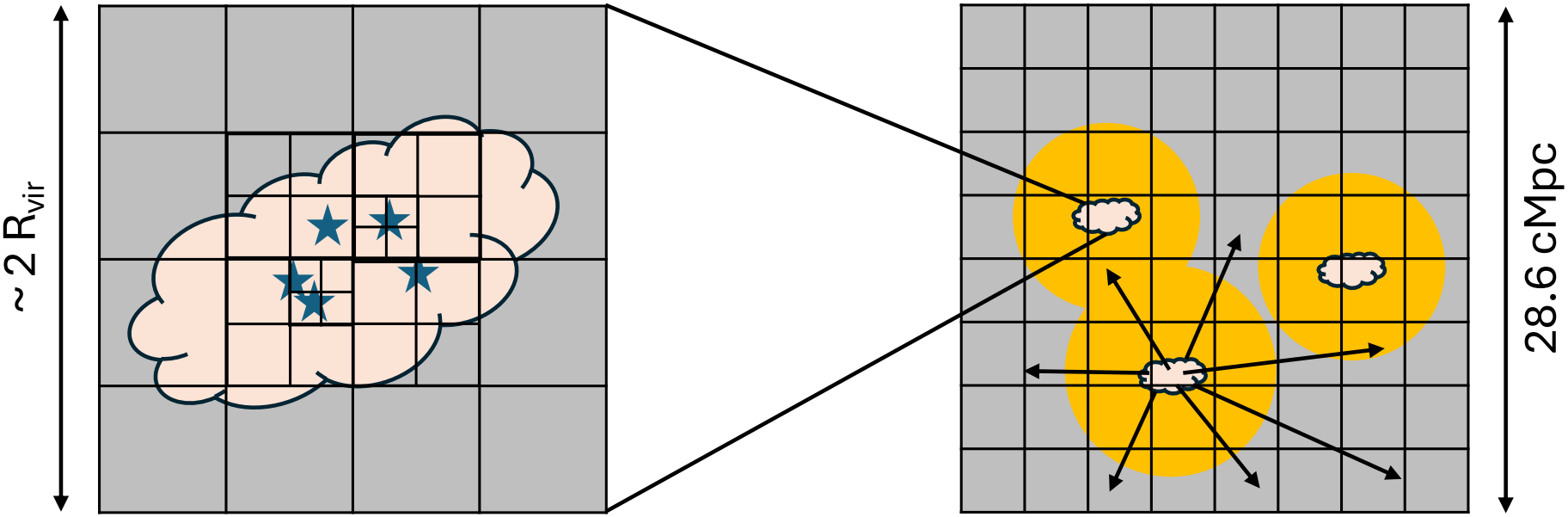
Reionization simulations



Radiative transfer calculations

1) Escape of ionizing photons from galaxies

2) Ionization of IGM HII bubbles in protocluters



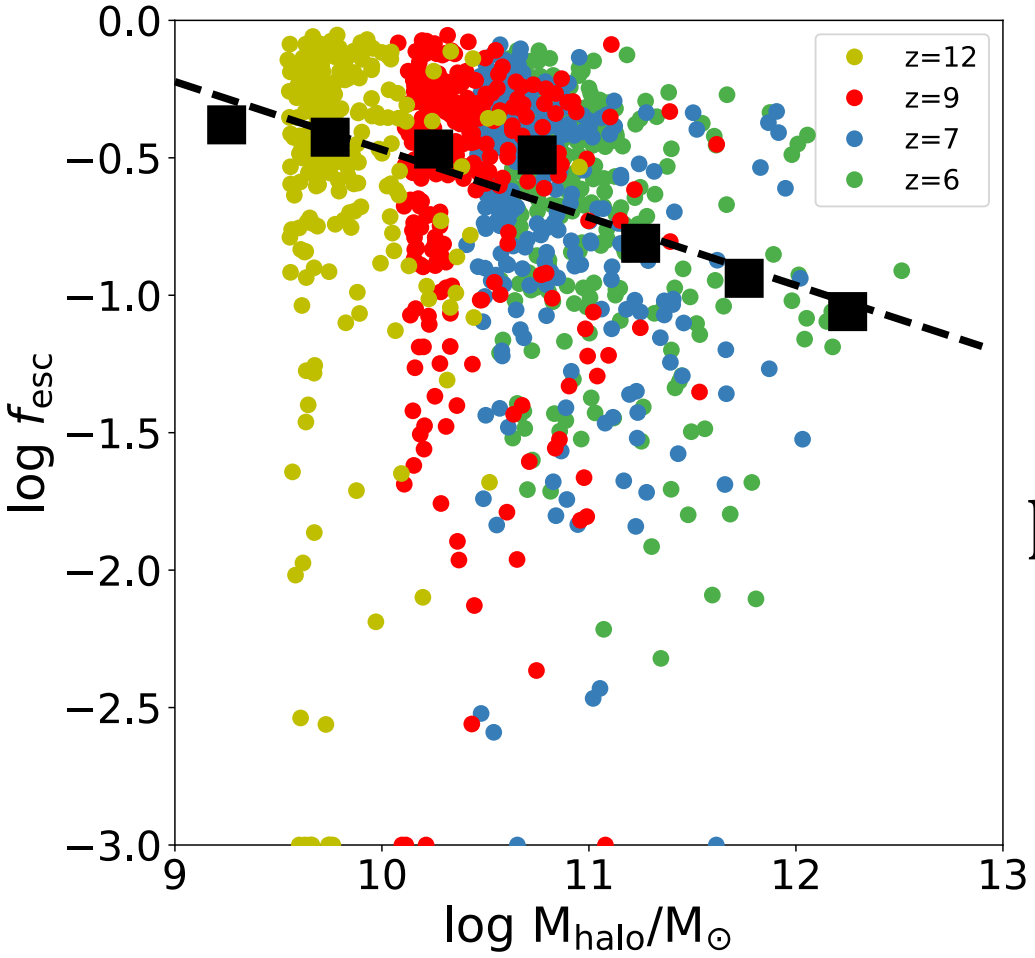
Monte Carlo in AMR
ART^2 code (**HY**+12; Li+21)

10^6 photon packets for each galaxy

Ray-tracing in uniform cells
ART code (**HY**+09)

10^5 radiation rays for each galaxy

Escape fraction of ionizing photons



Median values show 10-30%

f_{esc} decreases slightly as the halo mass increases

There are large dispersions

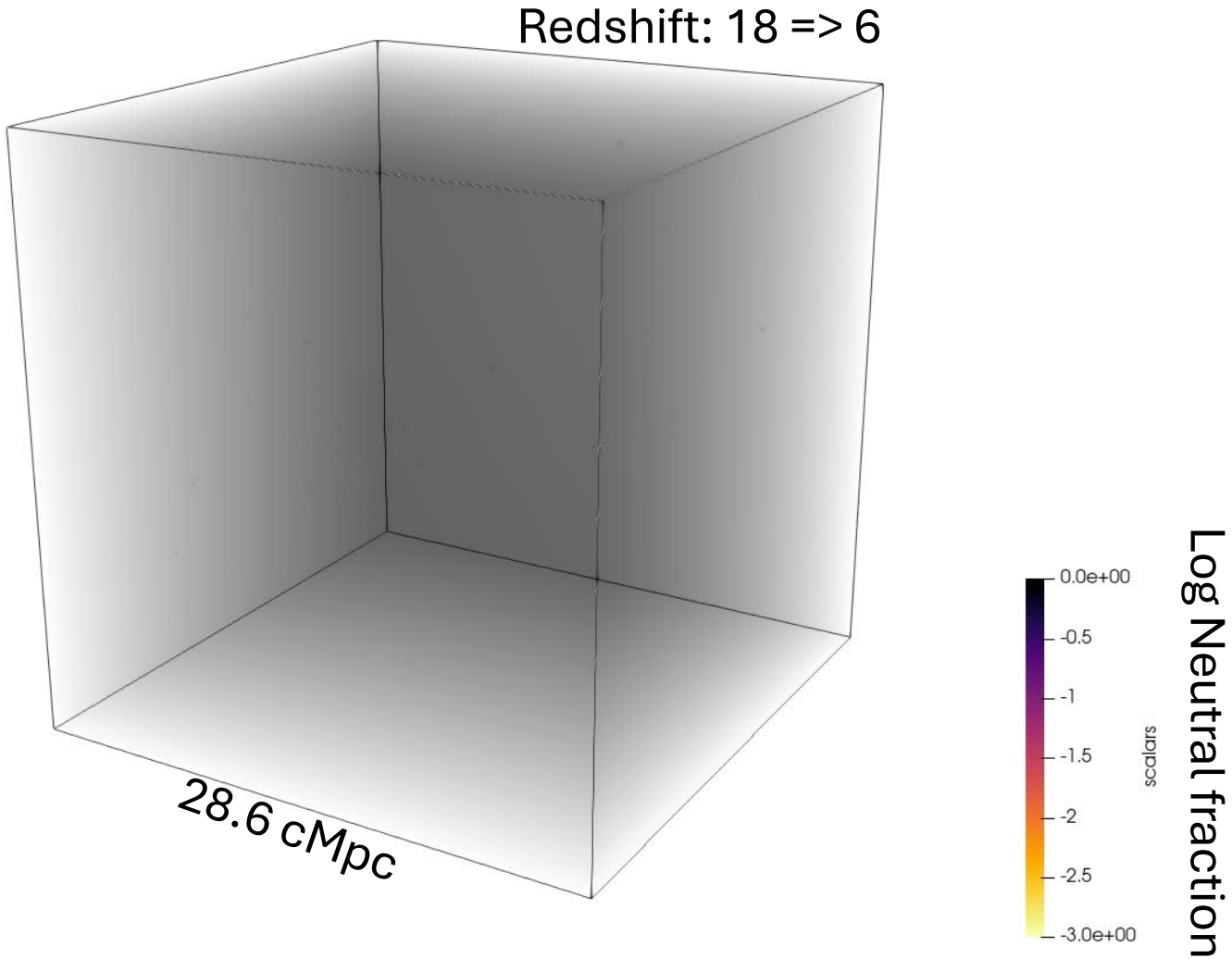
$$\log f_{esc} = \alpha \log M_{halo} + \beta$$

$$\alpha = -0.25$$

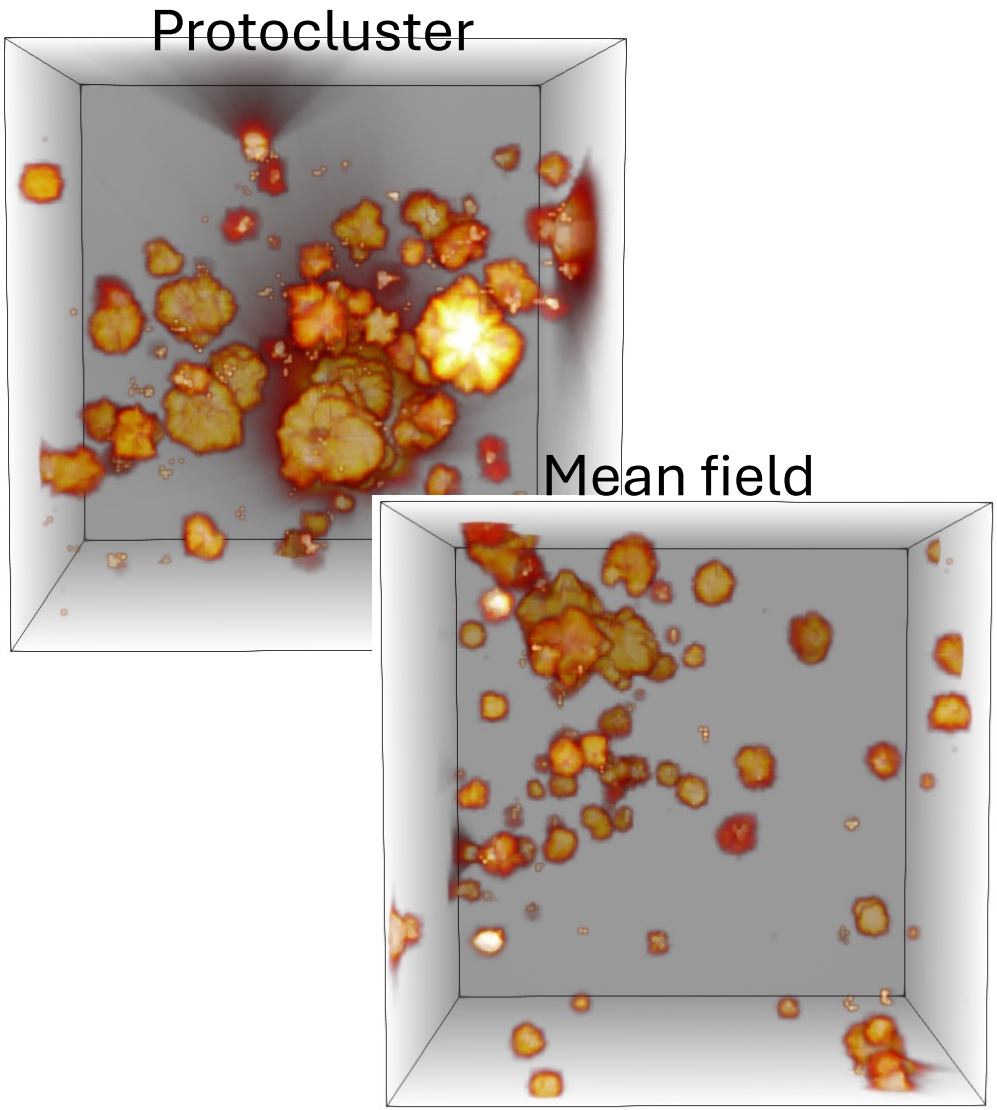
$$\beta = 2.0$$

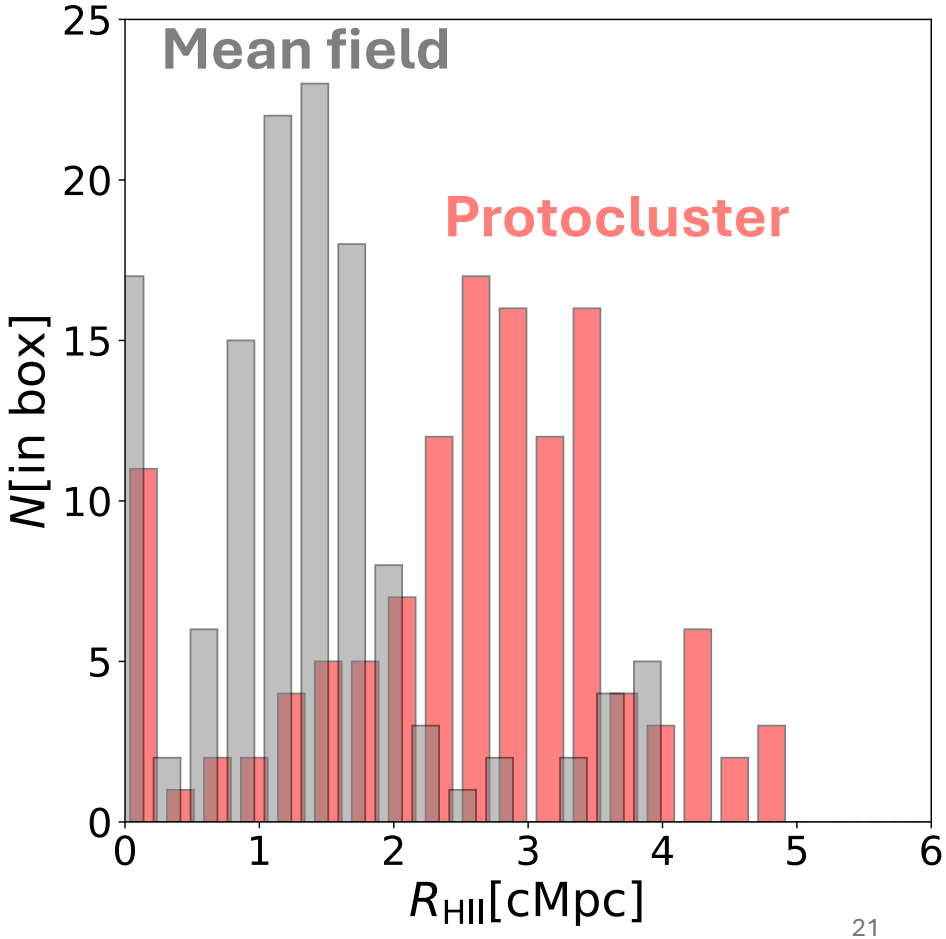
Ionization structure (Protocluster)

(**Yajima** et al. in prep.)

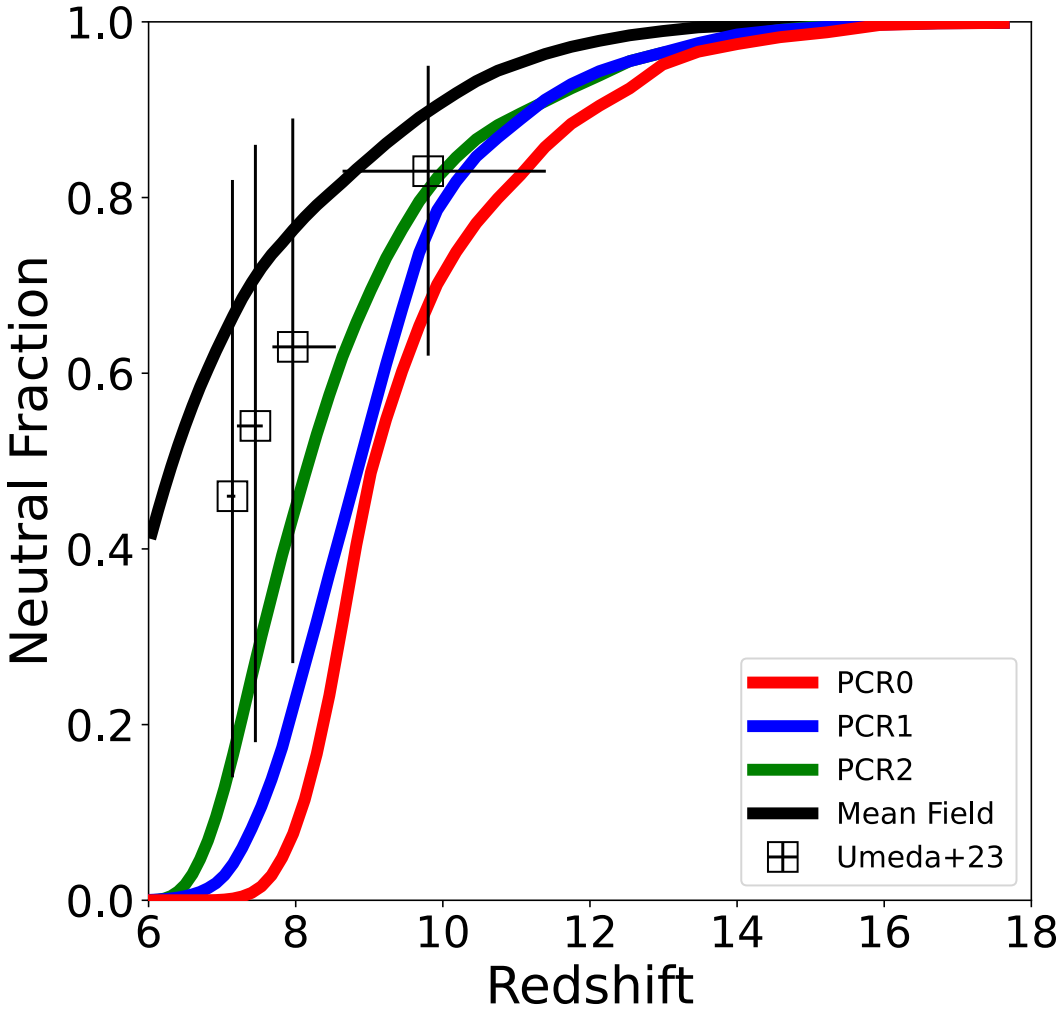


Bubble distributions (z=10)



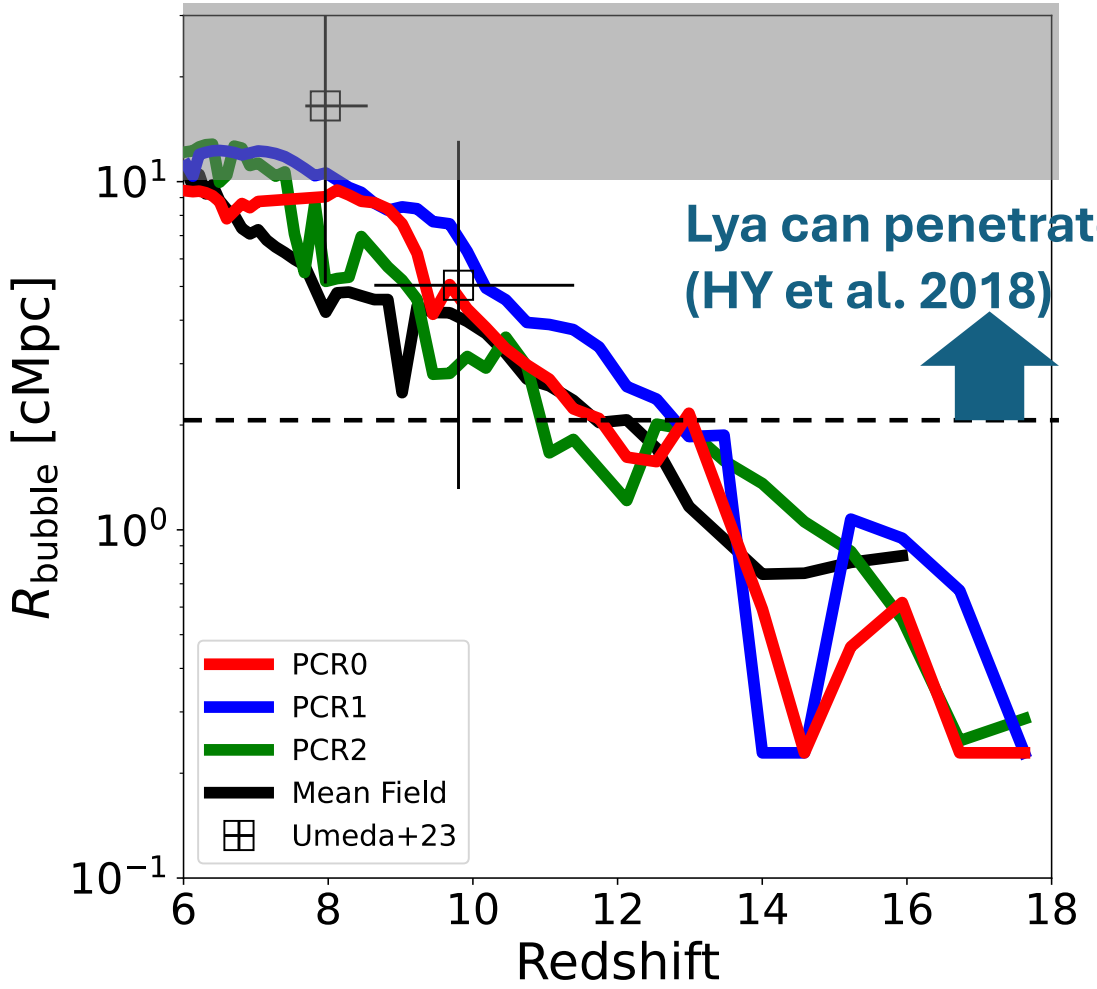


Ionization history



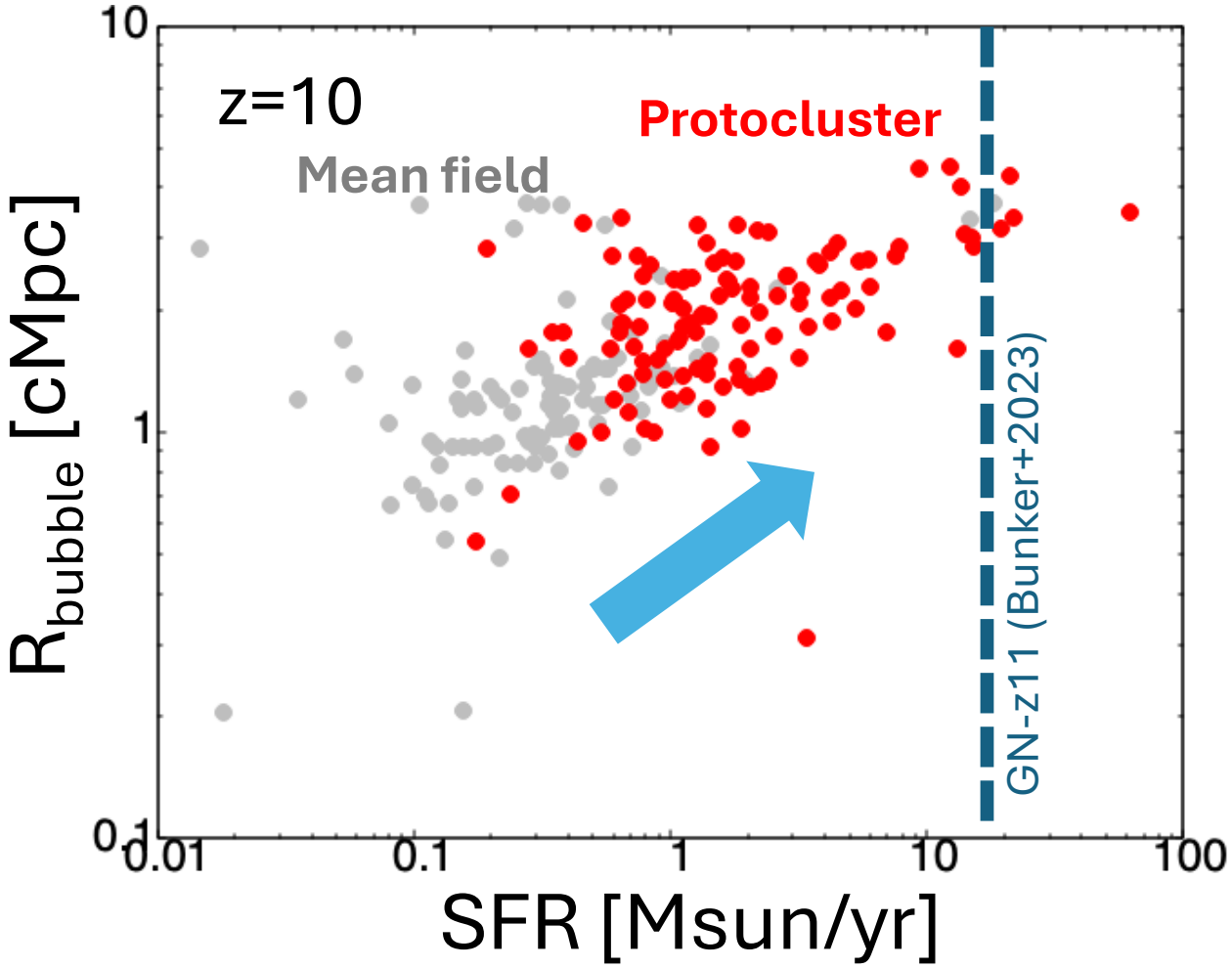
Protocluter regions are ionized earlier
It completes at z~7-8

Time evolution of HII bubbles around most massive haloes

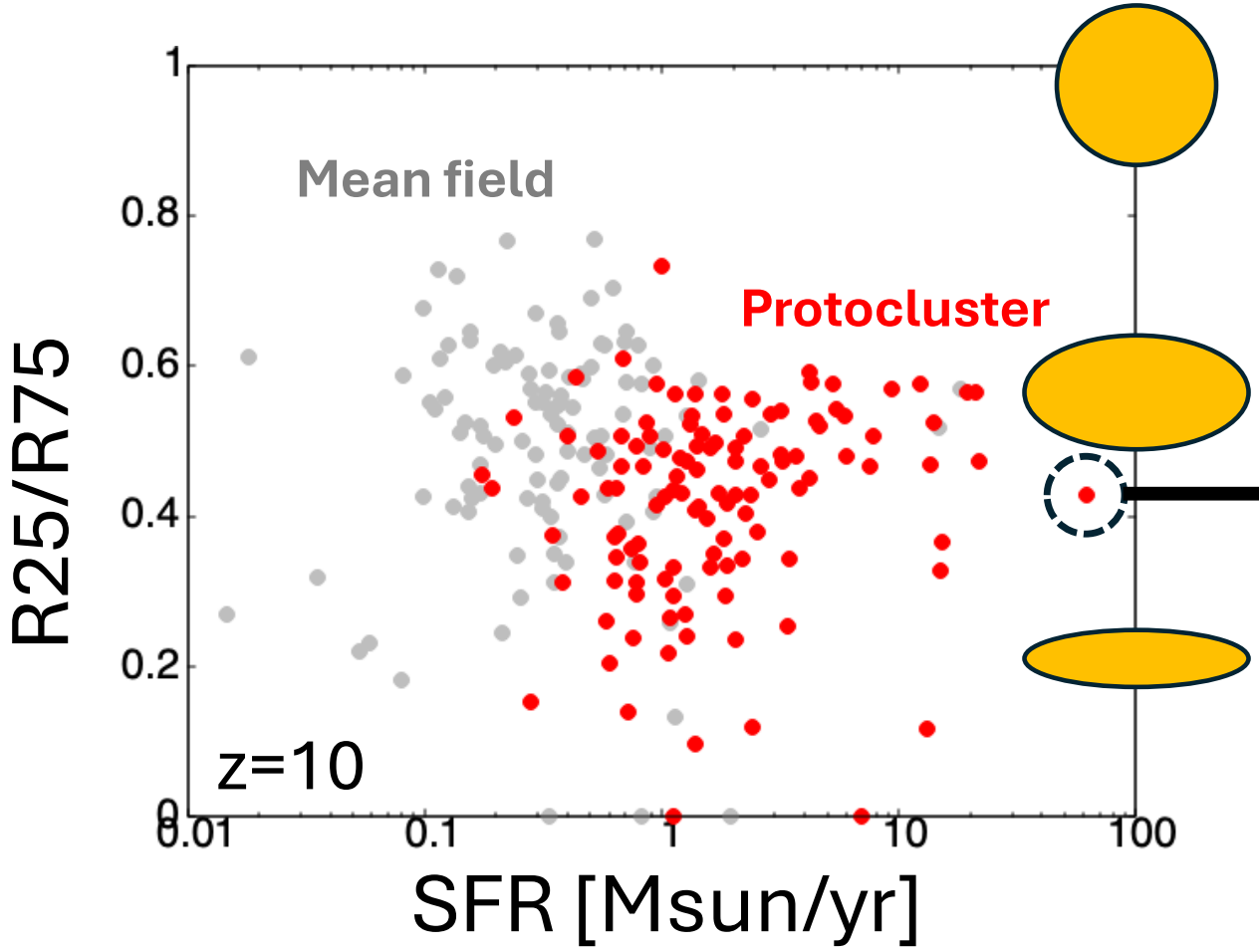


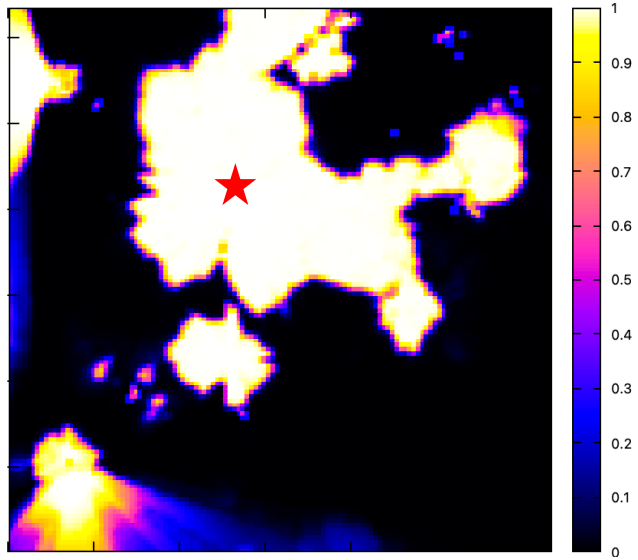
The radii of HII bubbles reach 2~8 cMpc at z~10
Lya lines can be observed even from galaxies at z~13

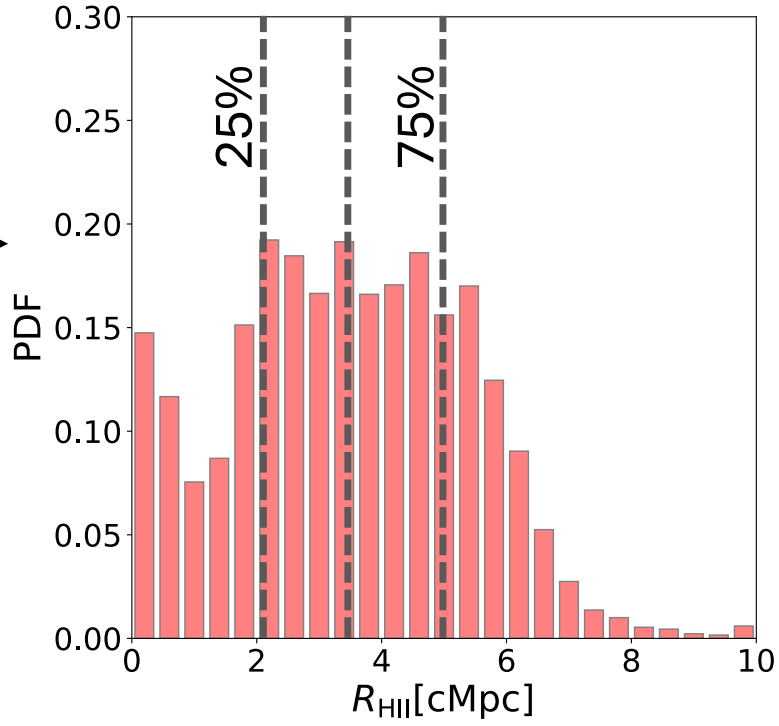
Bubble size v.s. Star formation rate



Skewness of HII bubbles







Summary

We perform cosmological simulations focusing on protocluter regions. Our findings are as follows.

- First galaxies show bursty star formation and quecing phases.
- Mass fraction of Pop III stars decreases gradually as halo/stellar mass increases, and it is ~1% for galaxies with Mstar~10^6 Msun
- Massive galaxies form giant HII bubbles with R~2-8 cMpc even at z~10.
- The cosmic volumes with L=28.6 cMpc including protocluters are almost completely ionized at z~7-8.