Galaxy-IGM workshop 2018 in Tsukuba

Radiative properties of the first galaxies: rapid transition from blue to red

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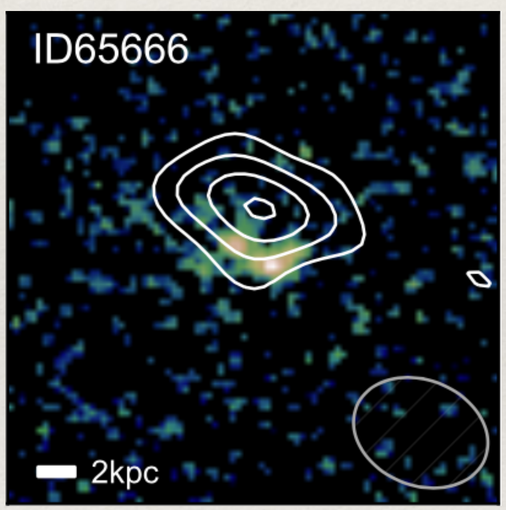
Observational properties

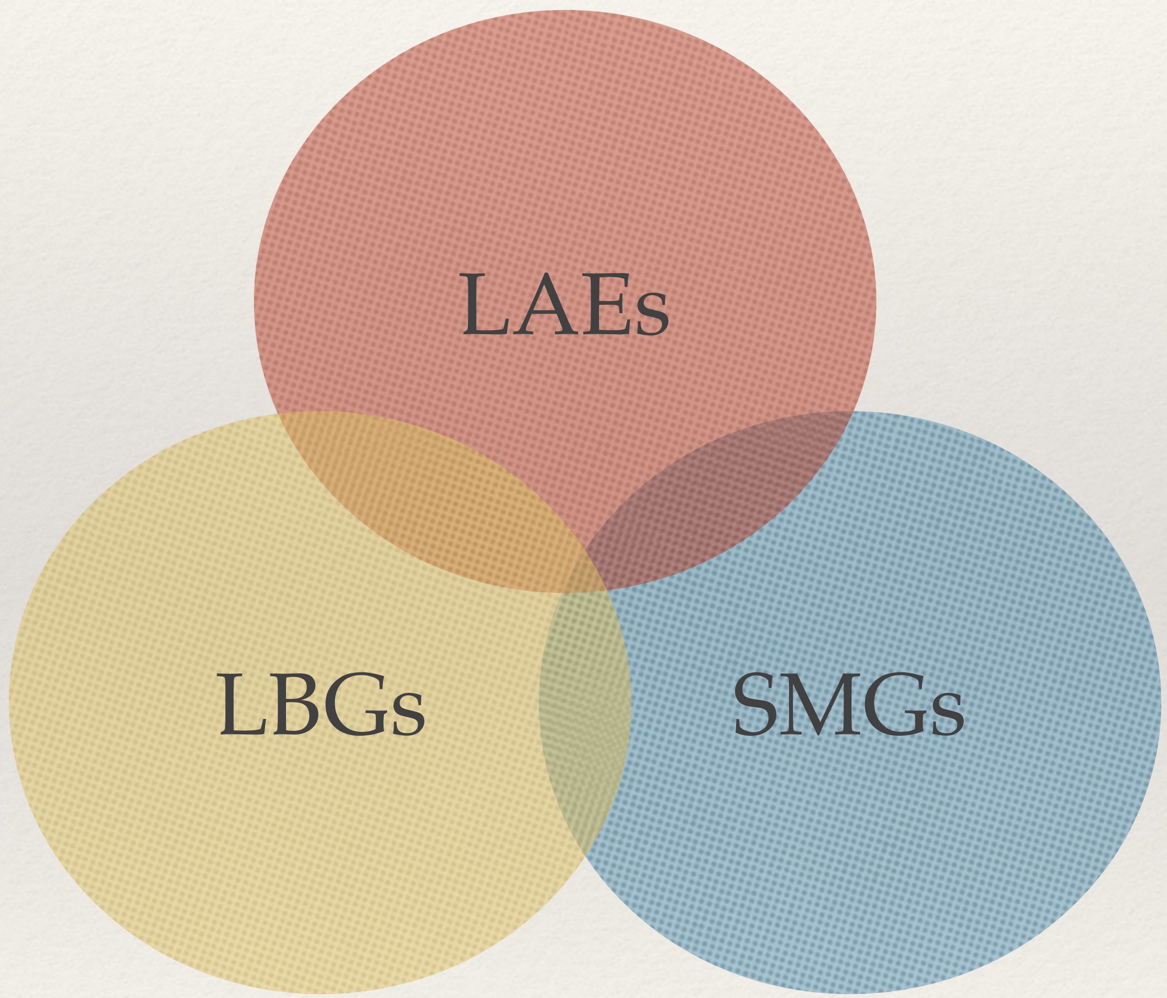
In the early Universe ($z > 6$)…

$z = 7.17$

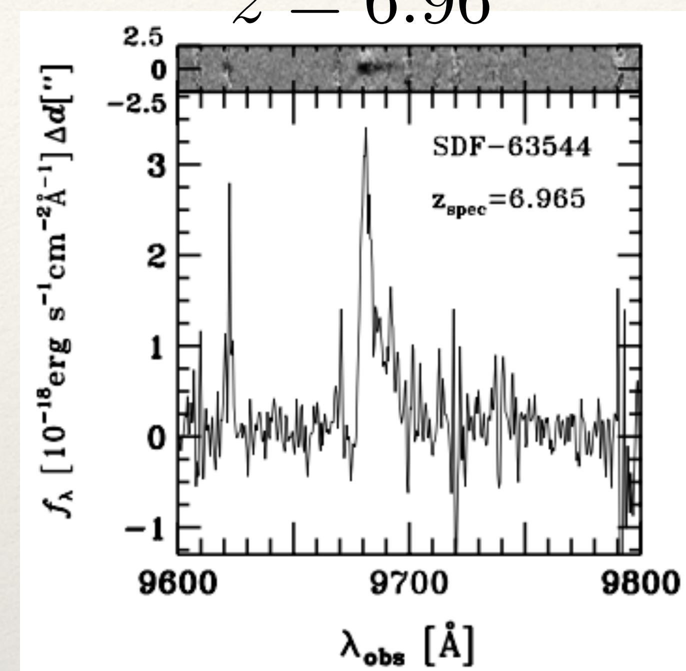


Bowler+17

$\mathrm{SFR} \sim 70\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$



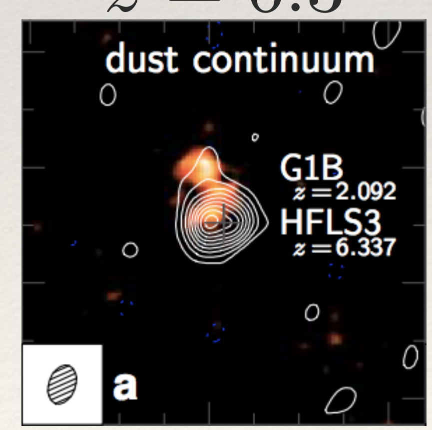
$z = 6.96$



Ono+12

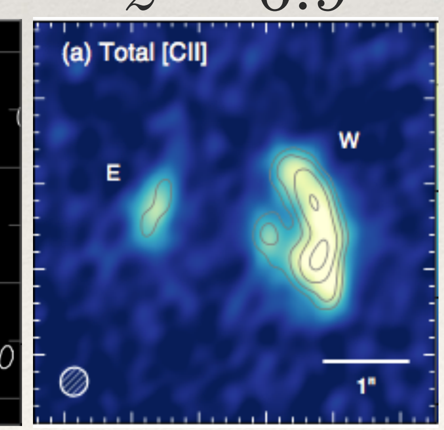
$\mathrm{SFR} \sim 10^2\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

$z = 6.3$



Riechers+13

$z = 6.9$



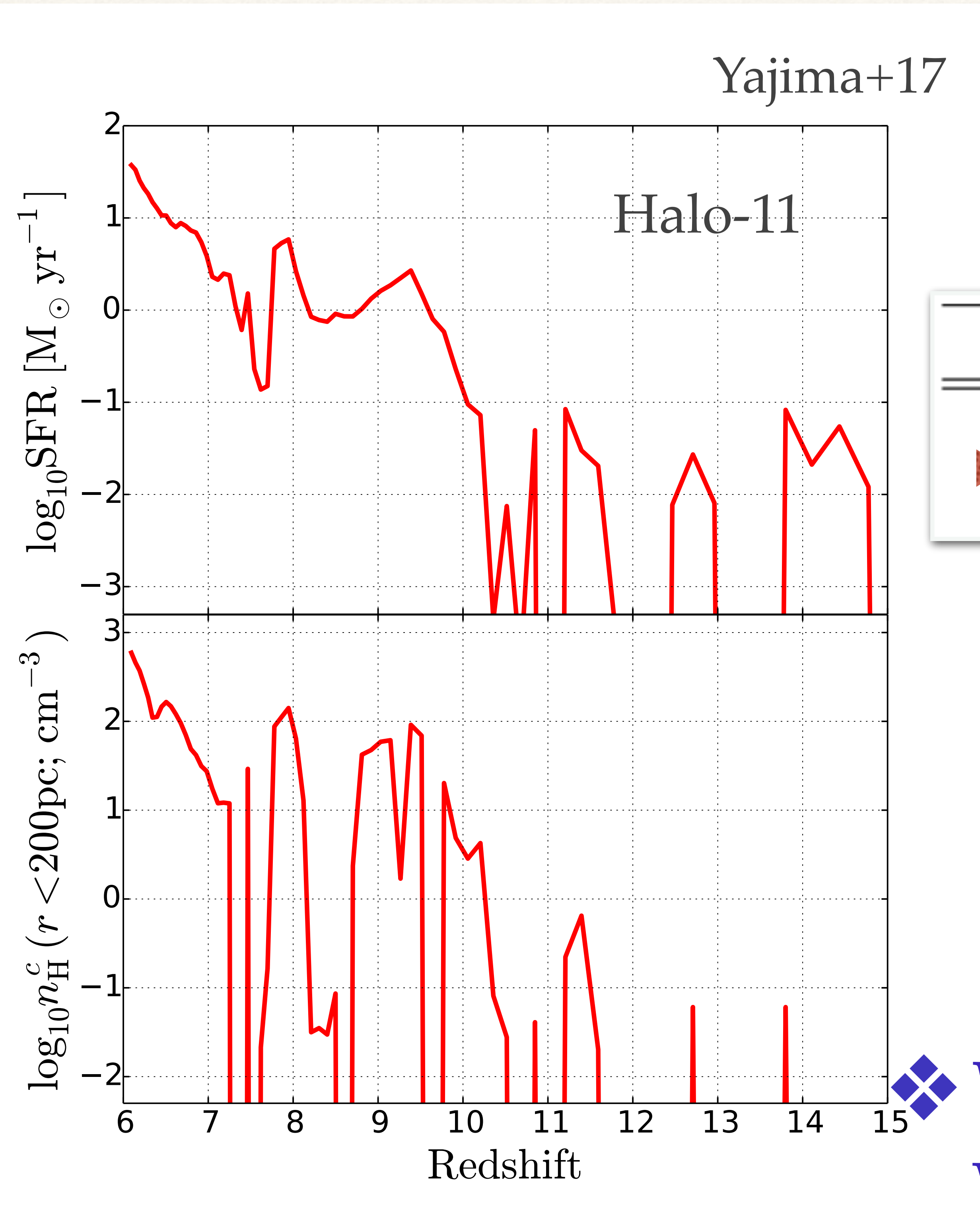
Marrone+18

$\mathrm{SFR} \sim 10^3\ \mathrm{M}_\odot\ \mathrm{yr}^{-1},\ M_\mathrm{d} \sim 10^9\ \mathrm{M}_\odot$

How does this variety emerge?

How does it relate to galaxy evolution?

Star formation in the first galaxies (simulation)



Code: Gadget3-FiBY
(Johnson+13, Khochfar in prep.)

— zoom-in simulation —

Halo ID	$M_{\mathrm{h}}\ [h^{-1}\ \mathrm{M_\odot}]$	$m_{\mathrm{DM}}\ [h^{-1}\ \mathrm{M_\odot}]$	$m_{\mathrm{gas}}\ [h^{-1}\ \mathrm{M_\odot}]$
Halo-10	2.4×10^{10}	6.6×10^{4}	1.2×10^{4}
▶ Halo-11	1.6×10^{11}	6.6×10^{4}	1.2×10^{4}
Halo-12	7.5×10^{11}	1.1×10^{6}	1.8×10^{5}

Gas accretion

stars form intermittently

SNe feedback

❖ **We examined radiative properties with intermittent star formation**

Multi-wavelength radiative transfer

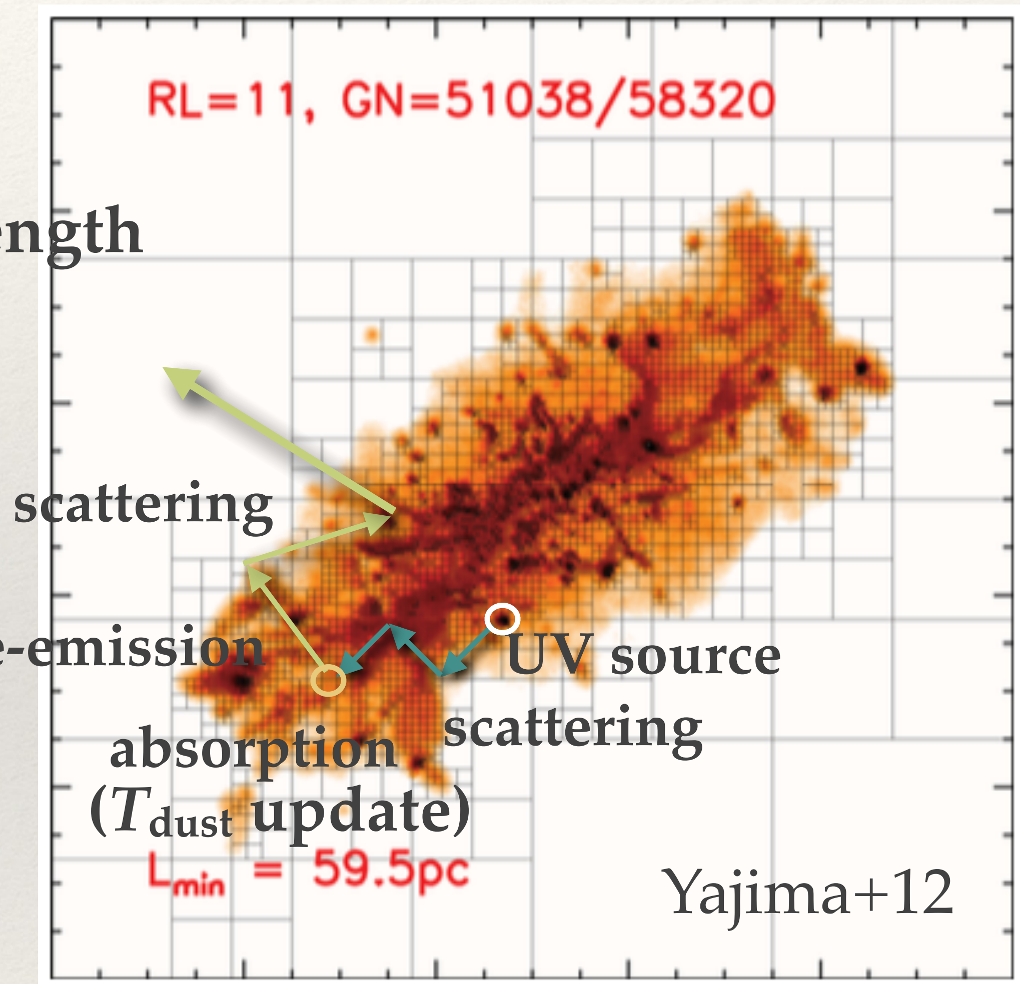
ART² code: *All-wavelength Radiative Transfer with Adaptive Refinement Tree*

(Li+08, Yajima+12, Li+ in prep.)

- **Montecarlo radiative transfer of multi-wavelength**
  - **Ionizing photons**
  - **UV continuum**
  - **Dust absorption and re-emission**

    size distribution:
    Type-II SNe origin (Todini & Ferrara 01)
  - **Lyα photons**
- **Adaptive mesh refinement (AMR)**

  AMR grid tracing gas structure of SPH simulation



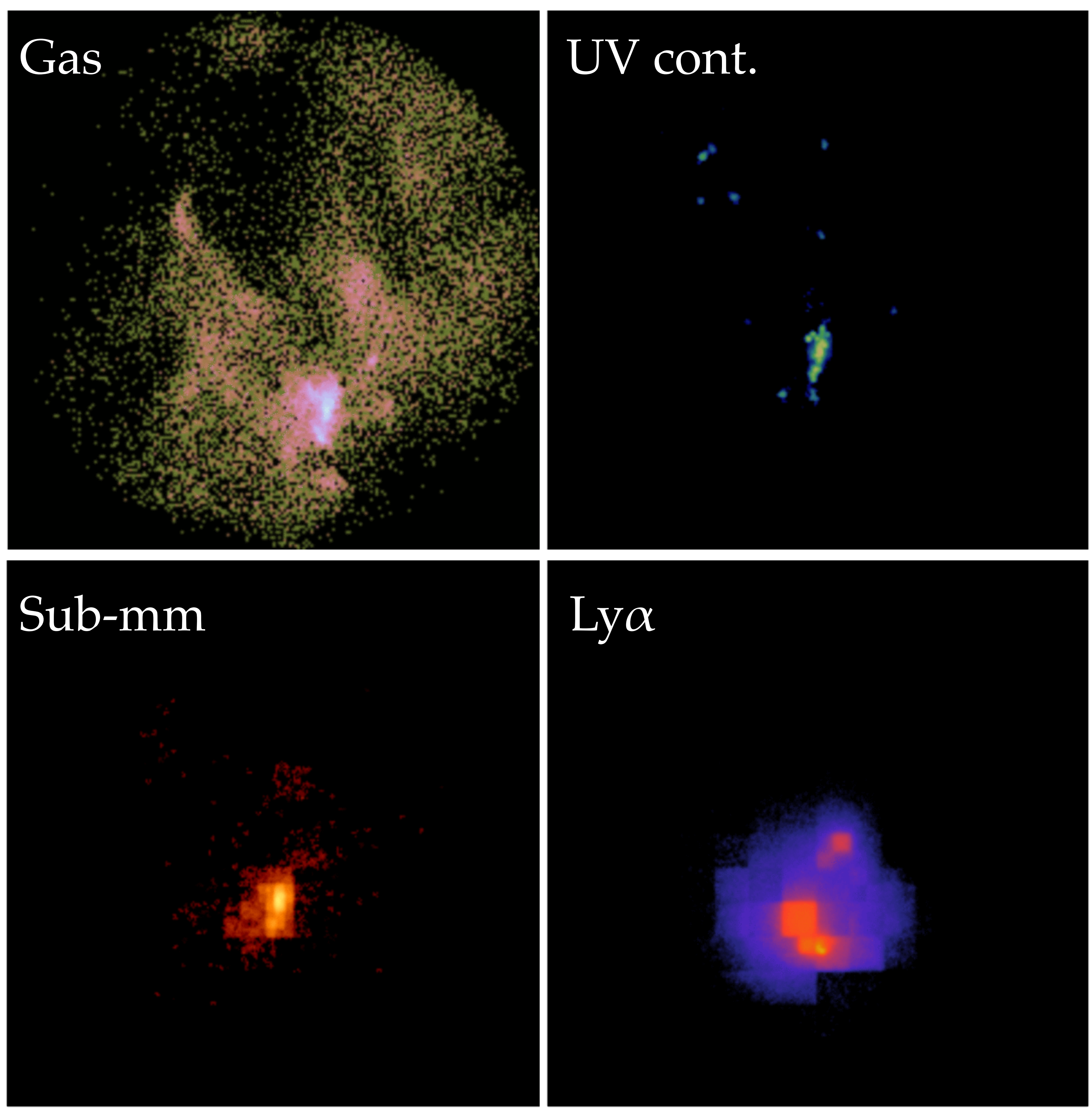
dust mass in a cell:

from SPH sim.

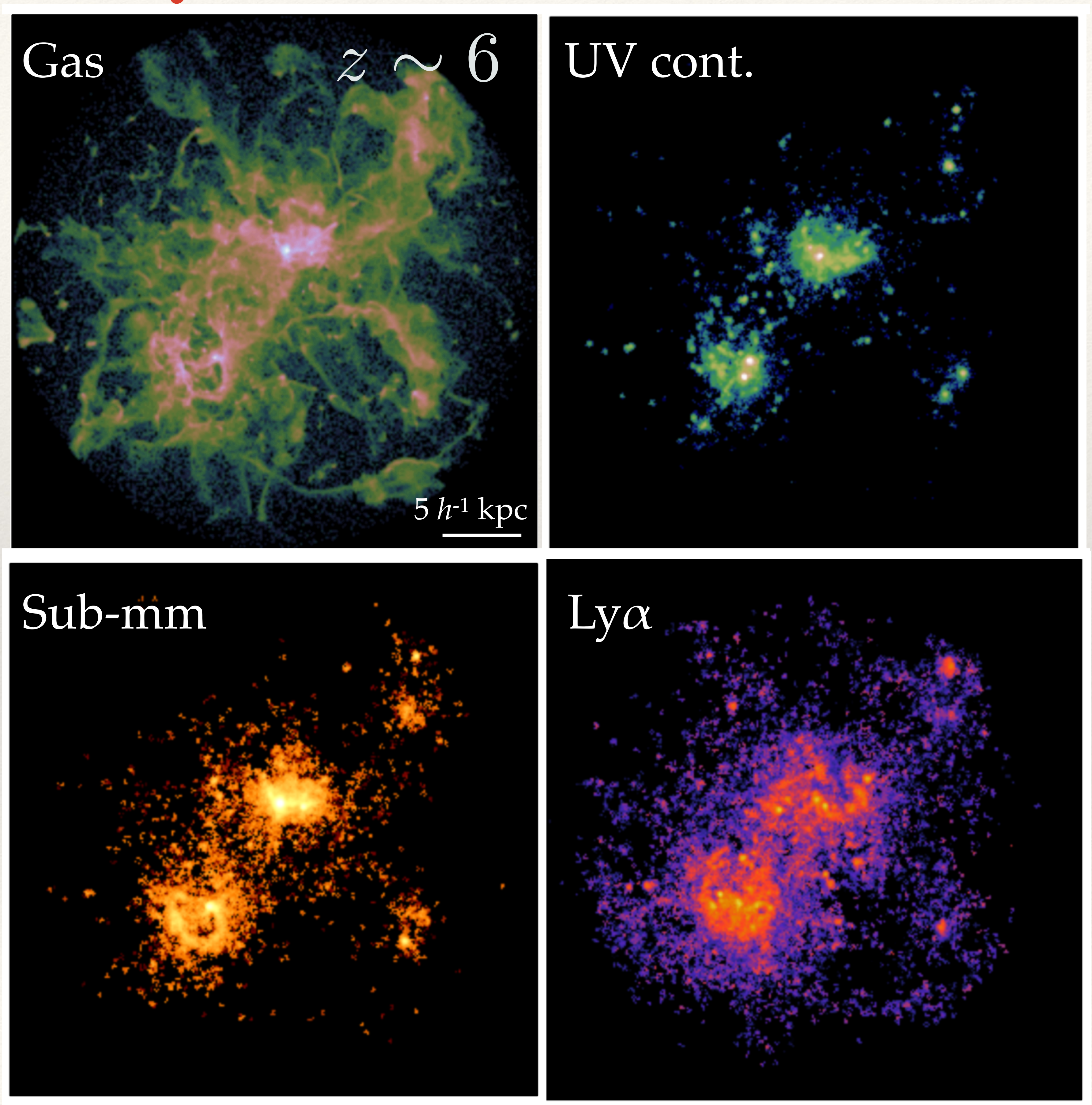
$$m_{\rm d} \approx x_{\rm c}\rho_{\rm c} V \mathcal{D}_{0.01}\left(\frac{Z}{Z_\odot}\right)$$

$x_{\rm c}$: volume filling factor of cold phase

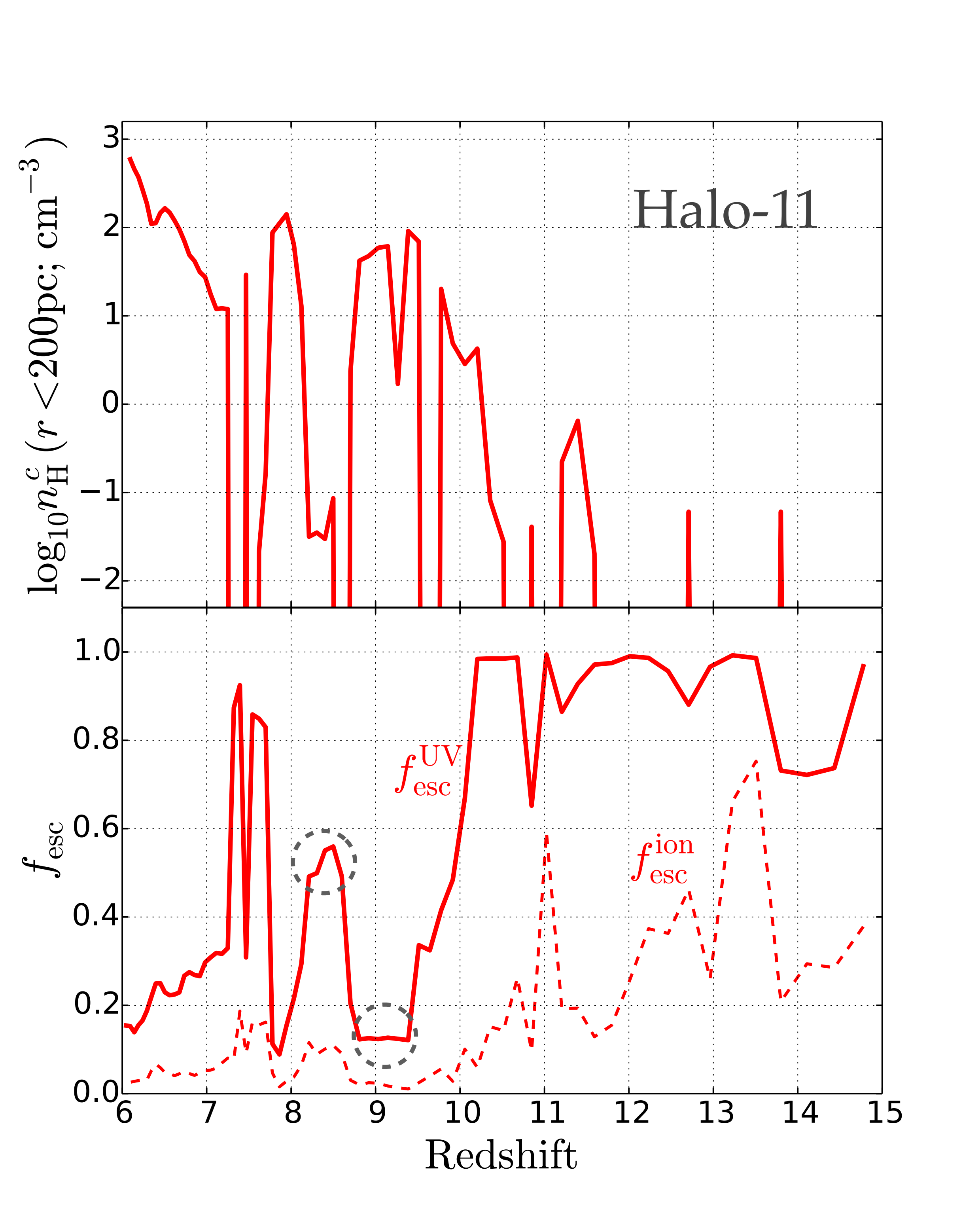
Galaxy evolution at z = 6 - 15



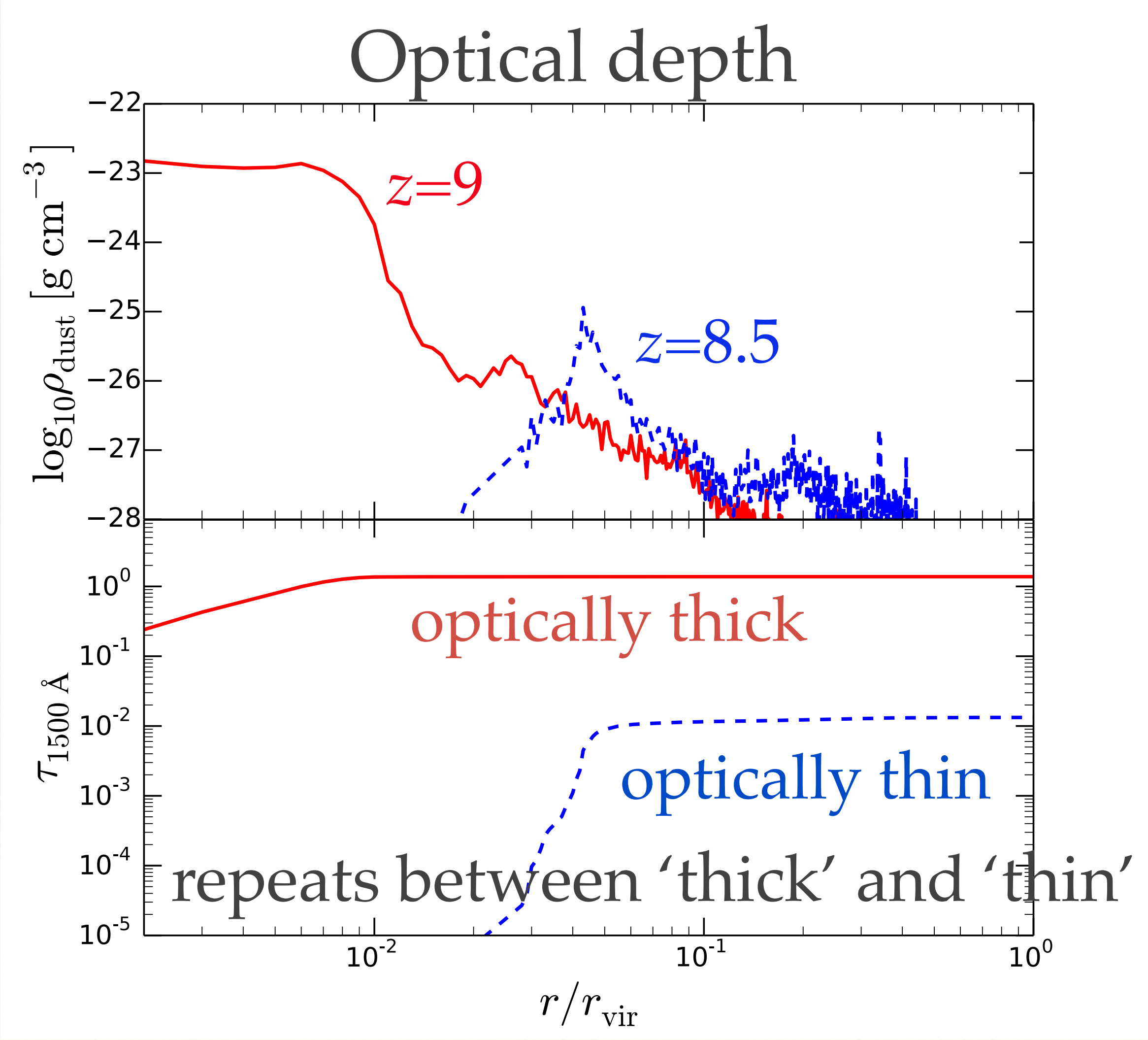
Galaxy evolution at $z = 6 - 15$



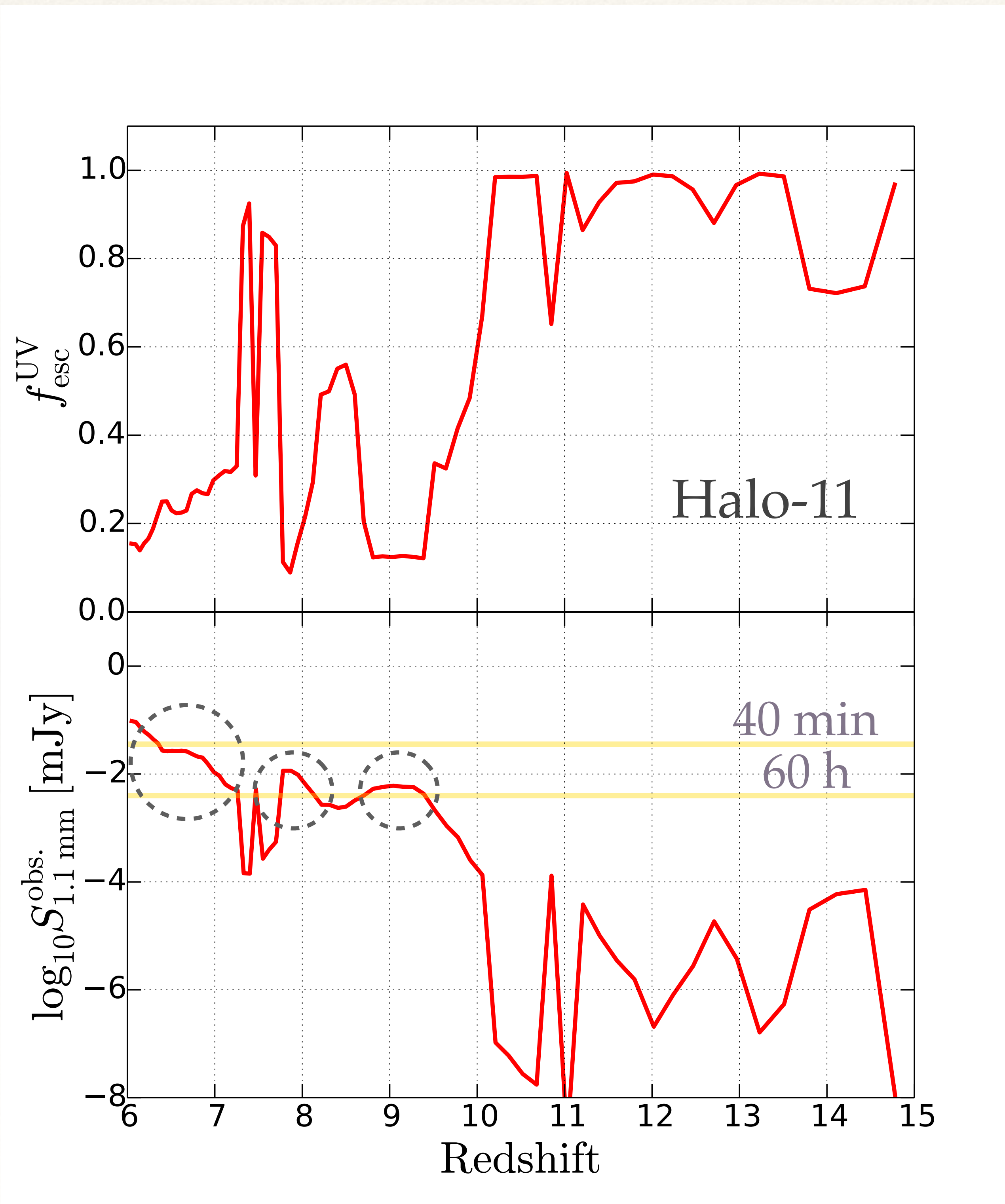
Escape fraction of UV photons

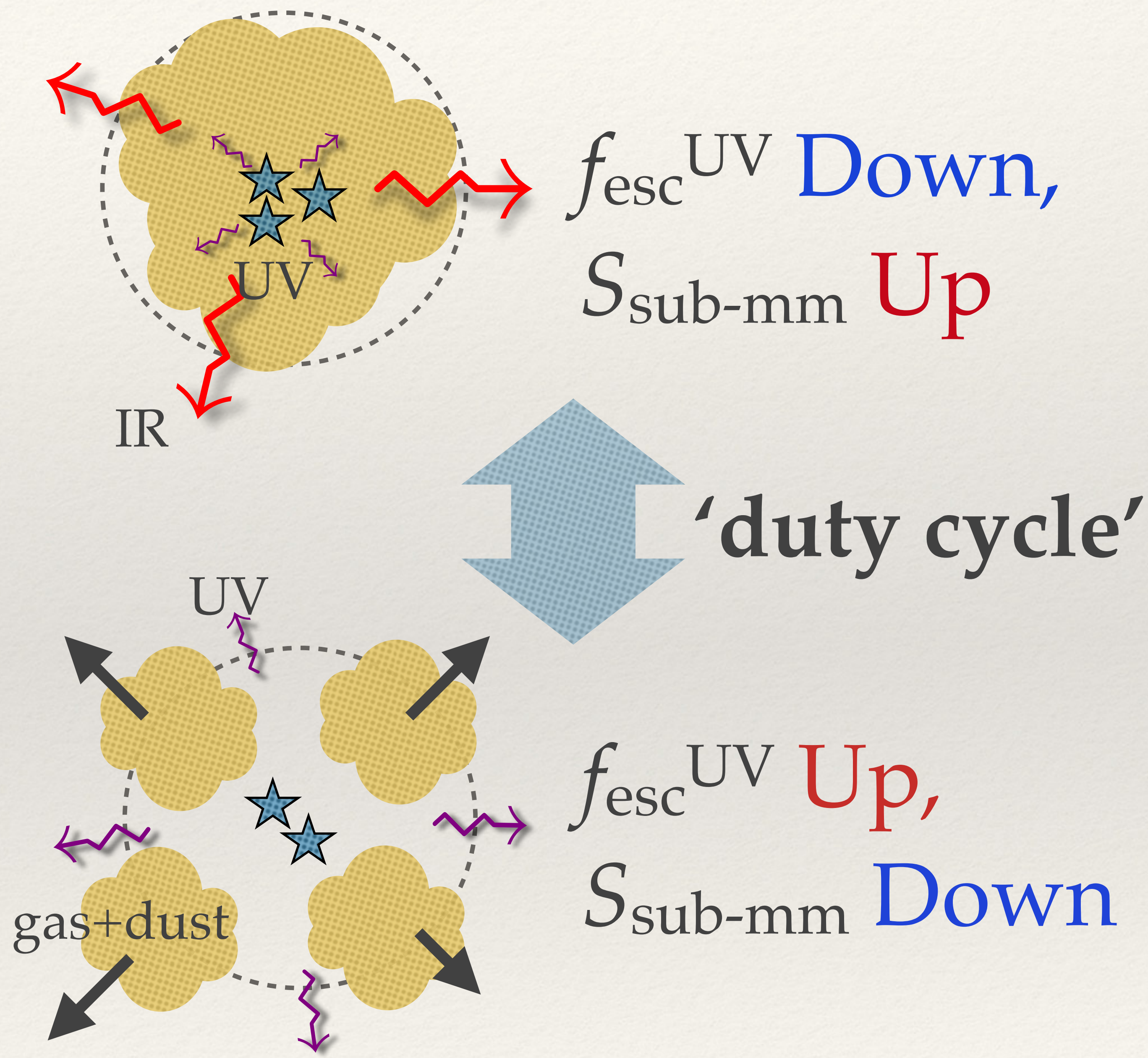


$f_{\rm esc}^{\rm UV}$ fluctuates between ~20-80 % due to gas accretion and SNe feedback



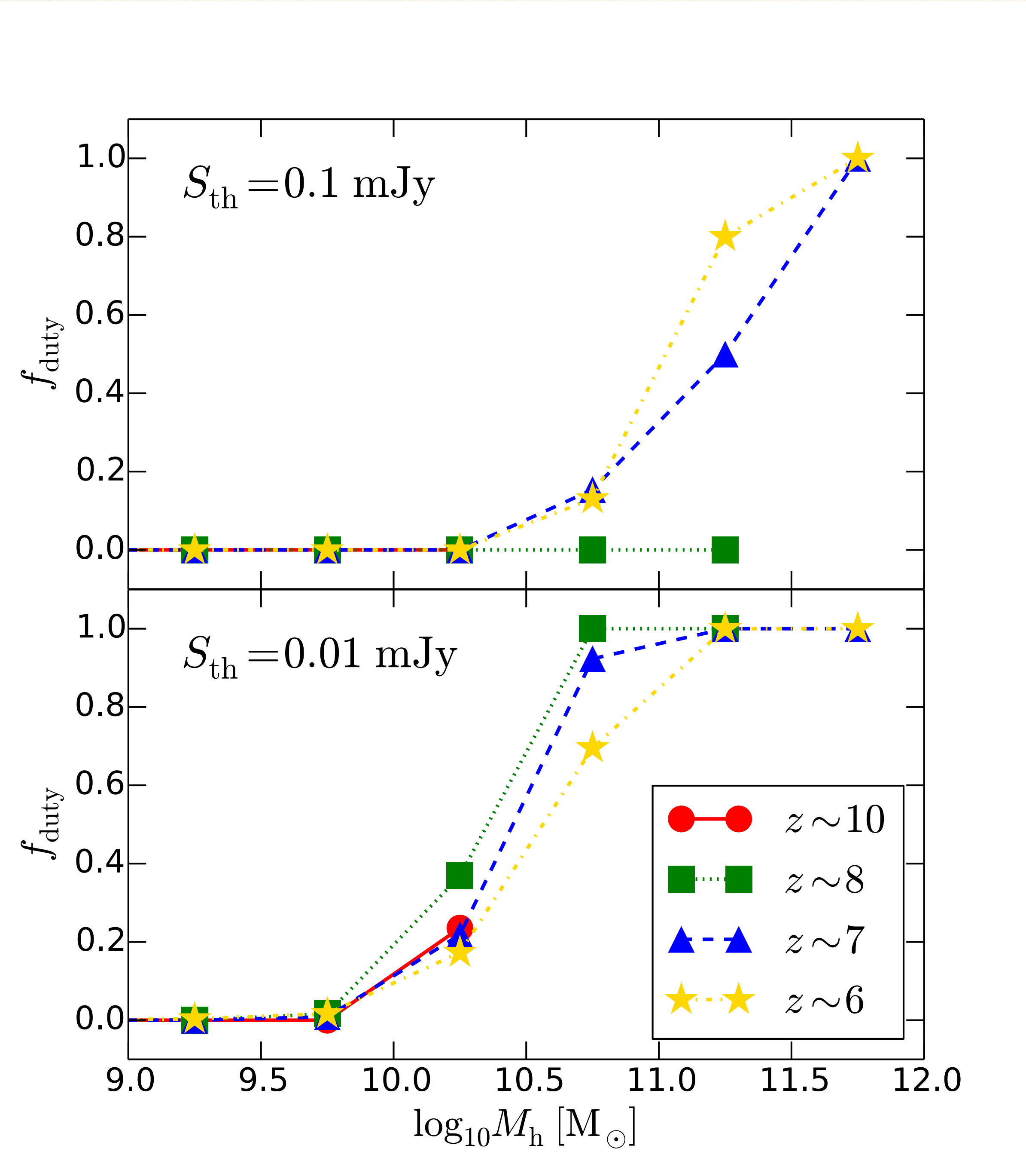
Fluctuation of infrared flux



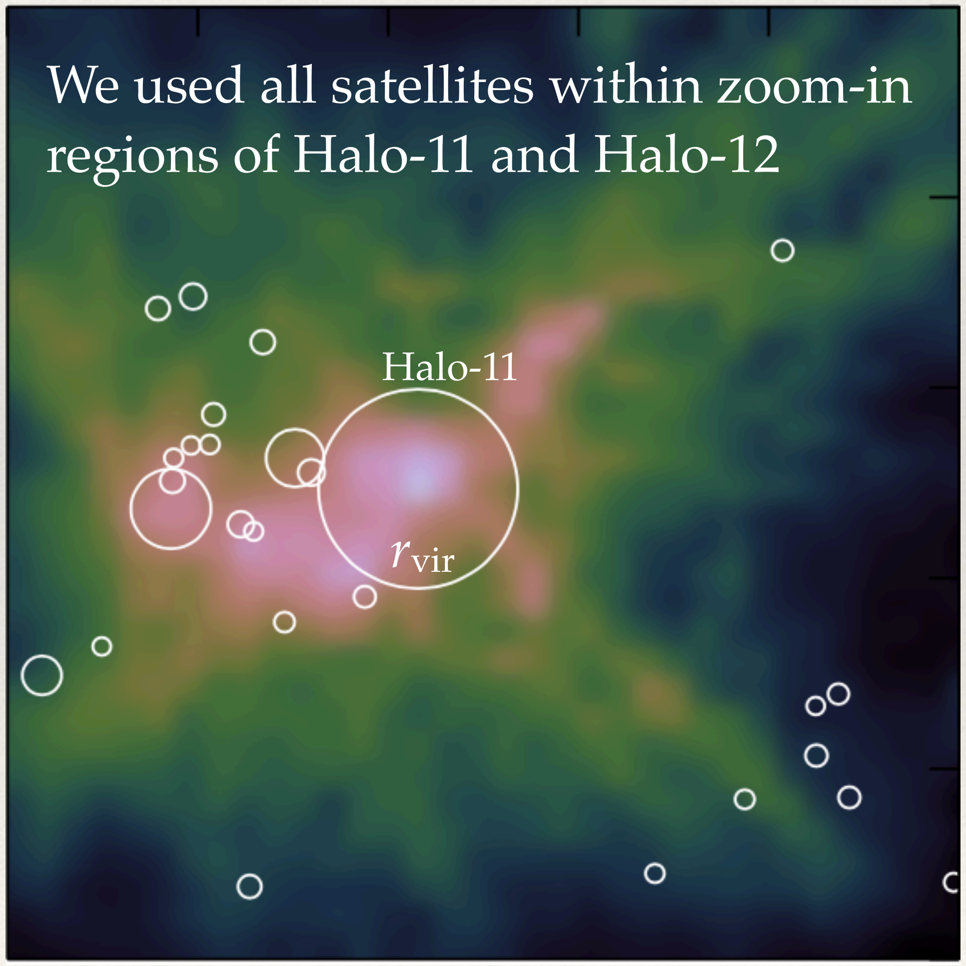


Temporally bright at sub-mm band

Detectability of ALMA telescope

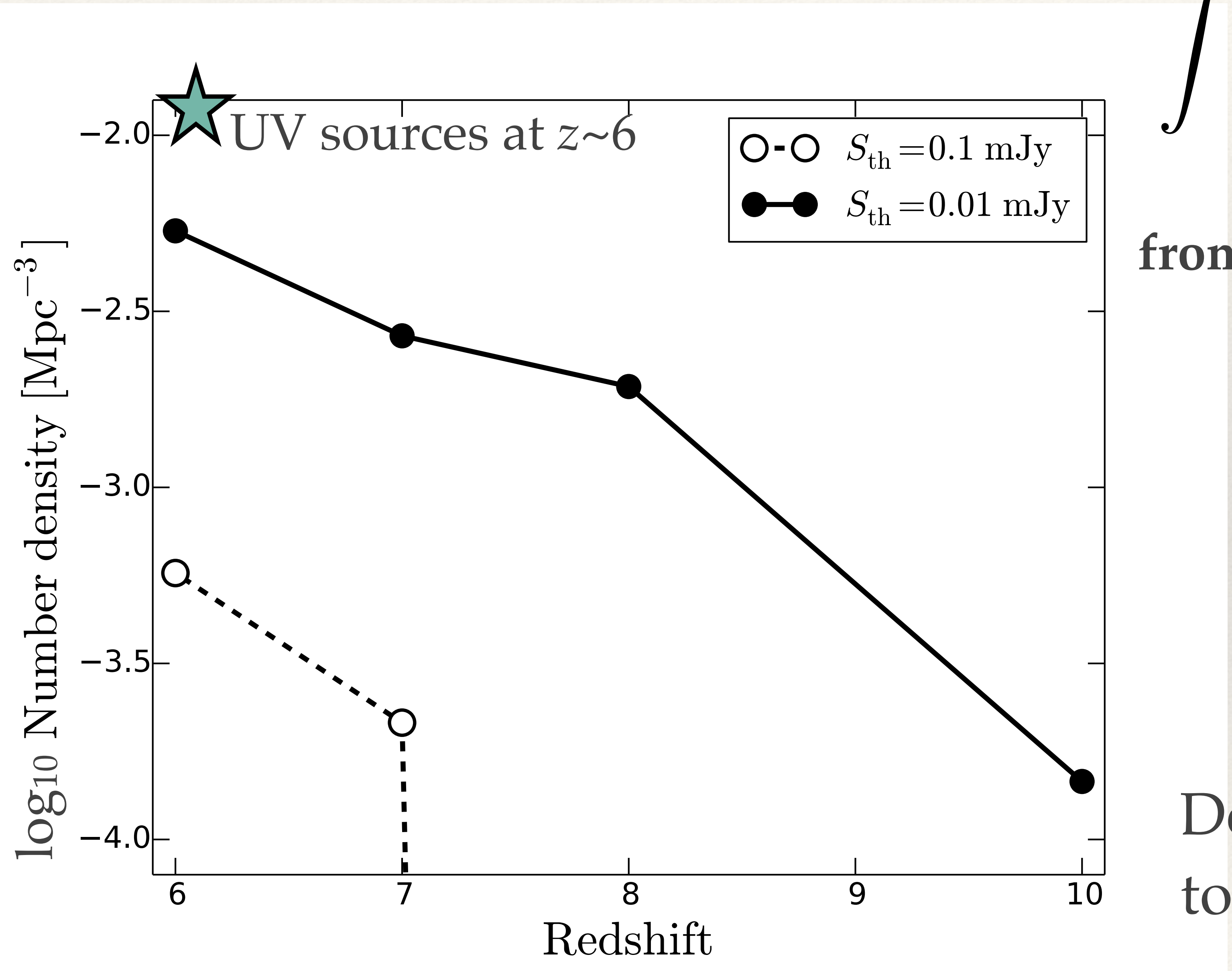


$$f_{\rm duty} \equiv \frac{N(S > S_{\rm th})}{N_{\rm tot}}$$



In $S_{\rm th}$<0.1mJy obs., $f_{\rm duty}$ becomes > 50% for $M_{\rm h}$>10^{11}M$_\odot$ and z<7

Number density of sub-mm sources



$$\int \underbrace{f_{\rm duty}}_{\text{from simulation}} \underbrace{\left(\frac{dN}{d\ln M_{\rm h}}\right)}_{\text{halo mass function}} d\ln M_{\rm h}$$

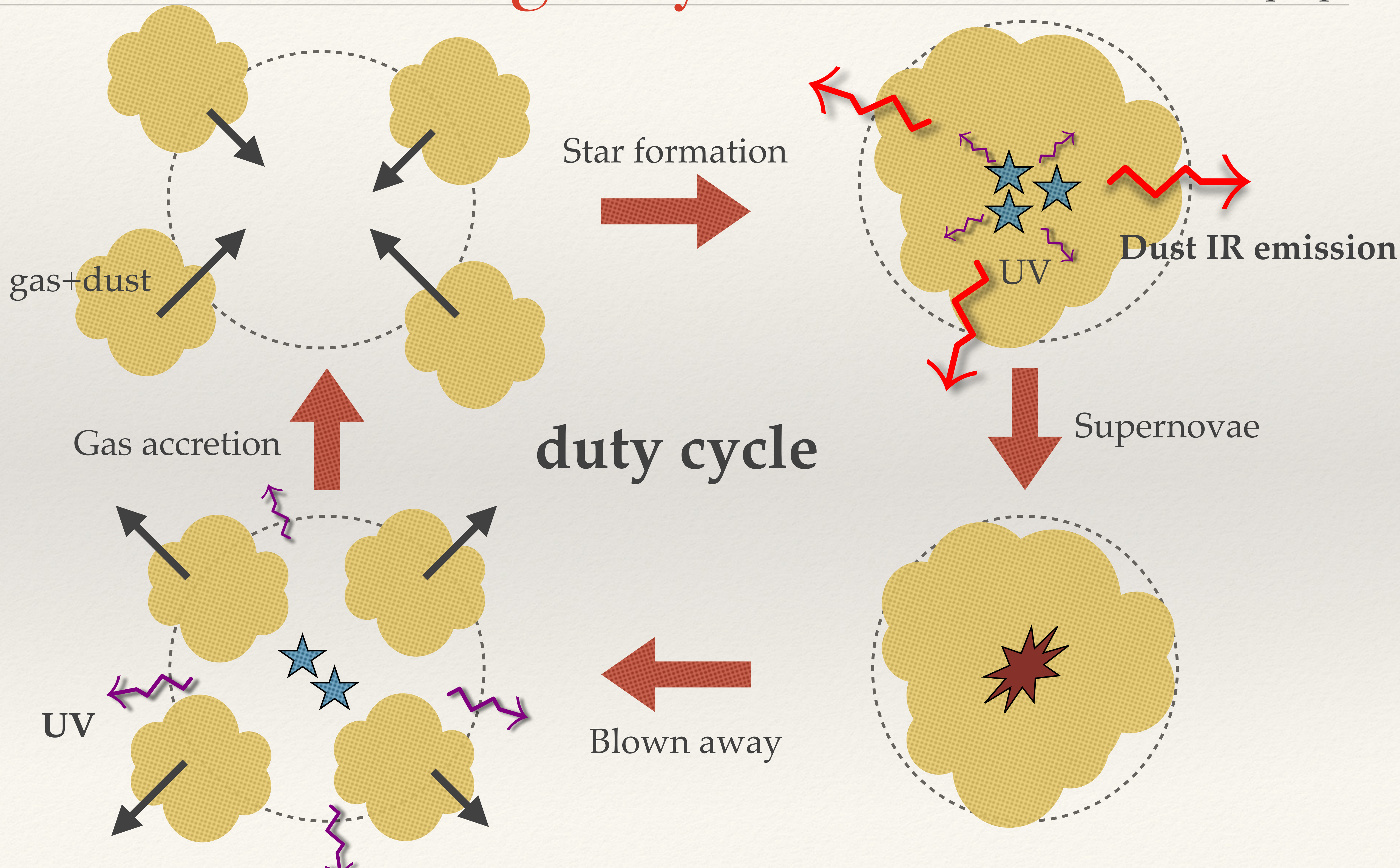
from simulation

halo mass function (Sheth & Tormen 2002)

Deep observations allow us
to detect ‘overlapping’ galaxies
(detectable at UV and sub-mm)

Changing radiative properties with galaxy evolution

Arata+ in prep.



Changing radiative properties with galaxy evolution

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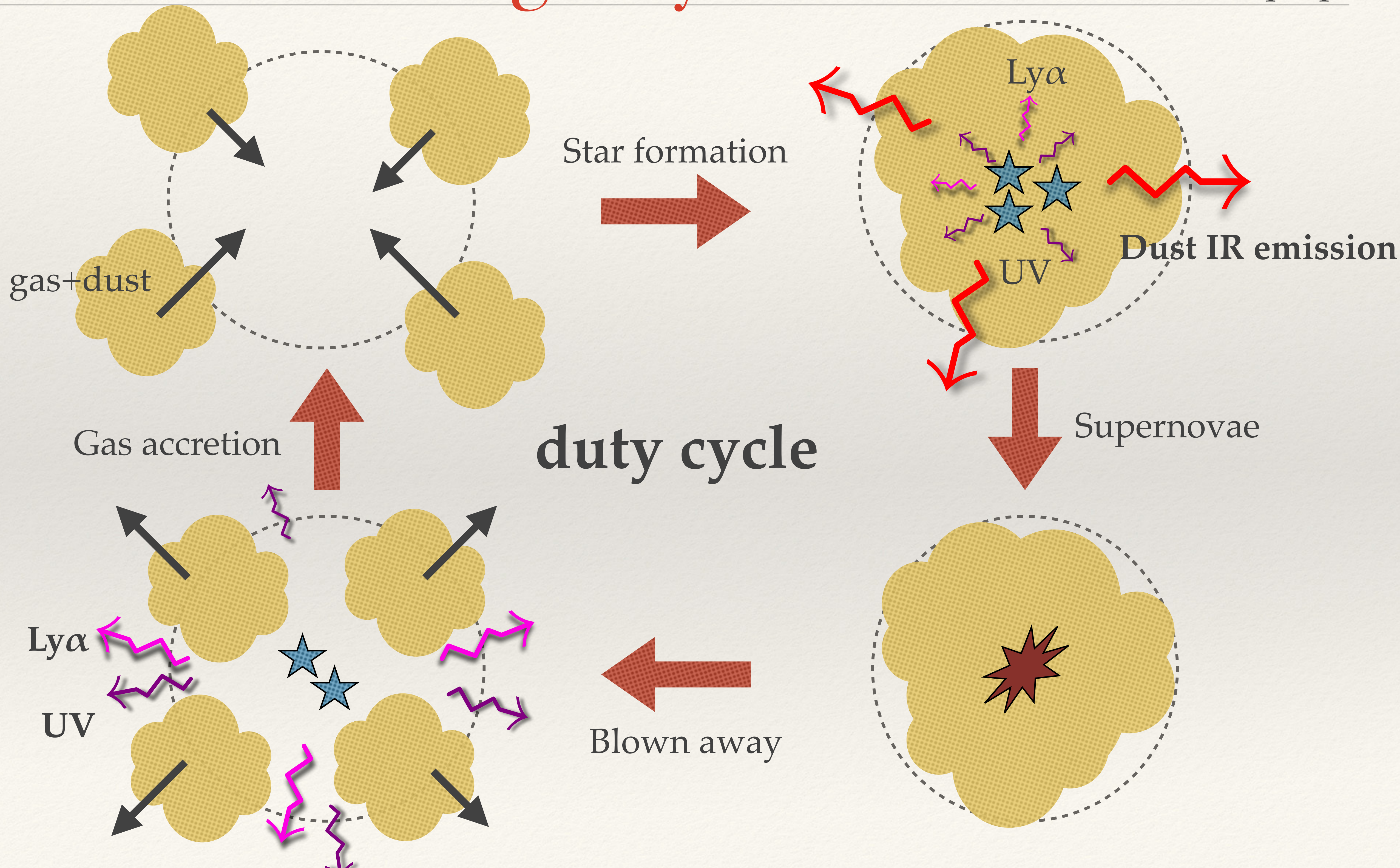
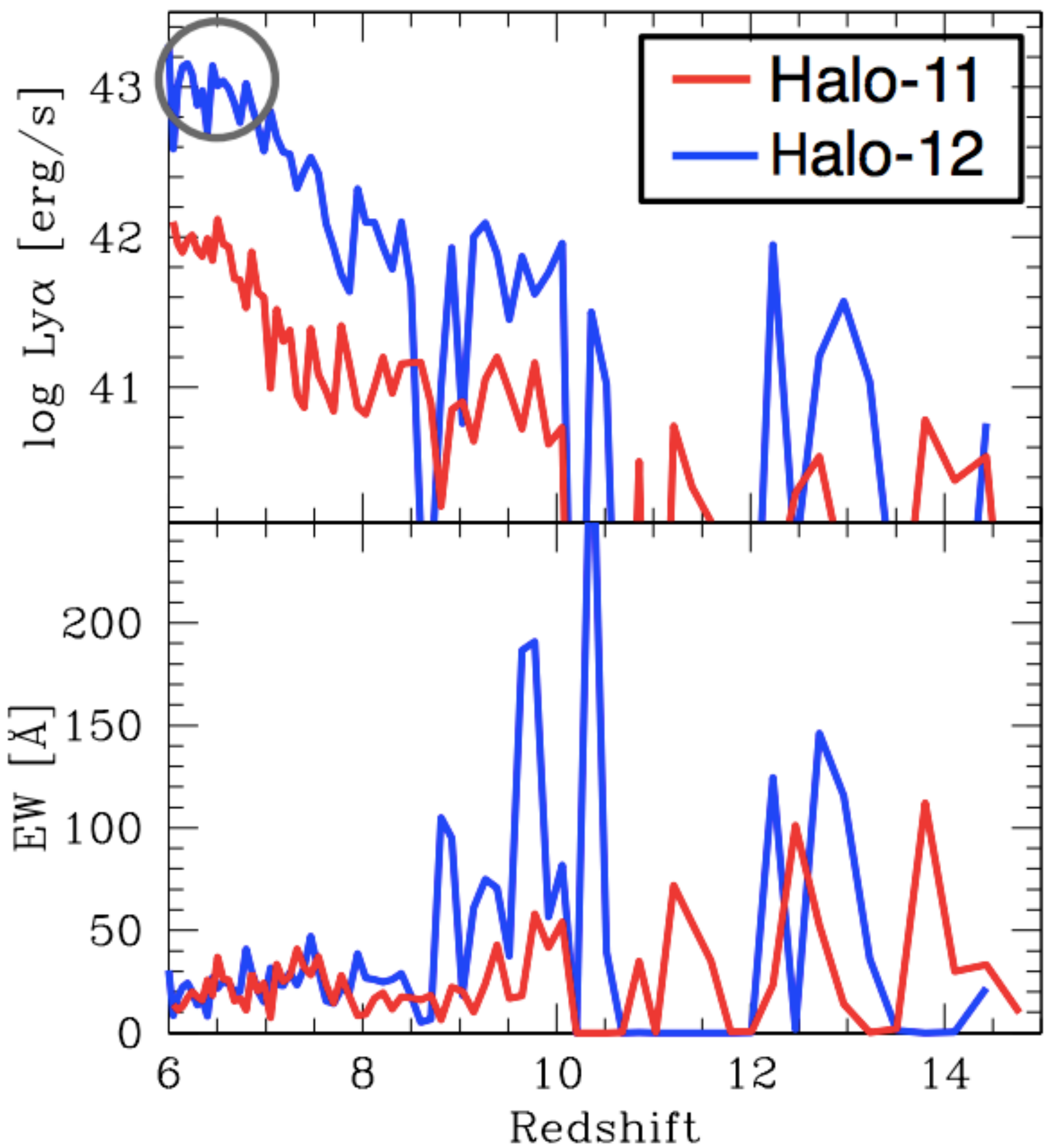
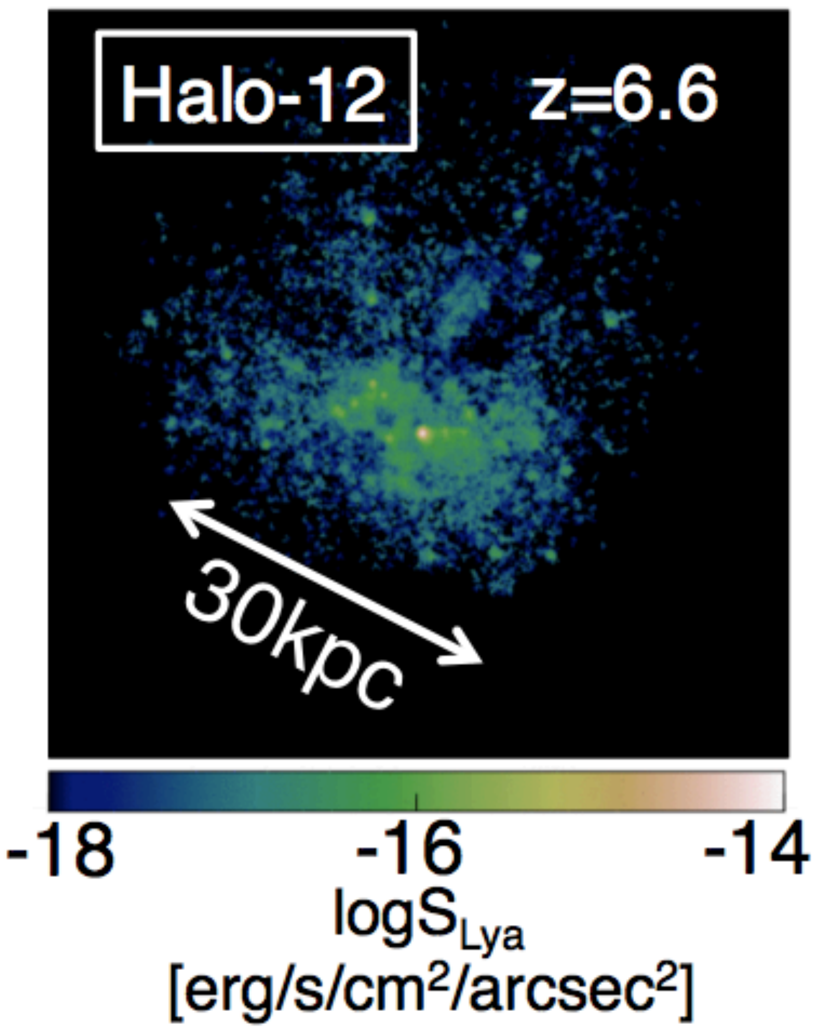


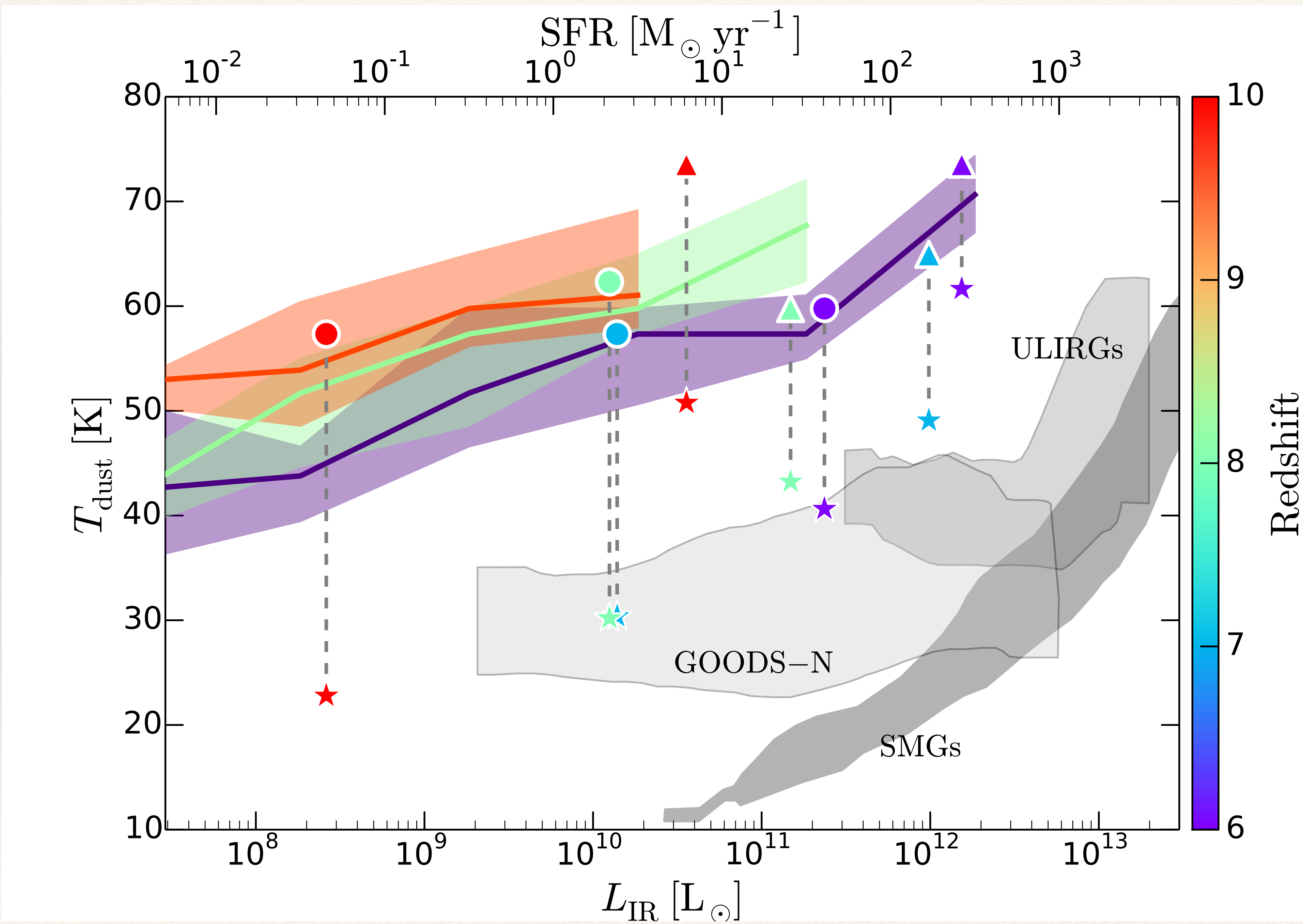
Lyman-Alpha

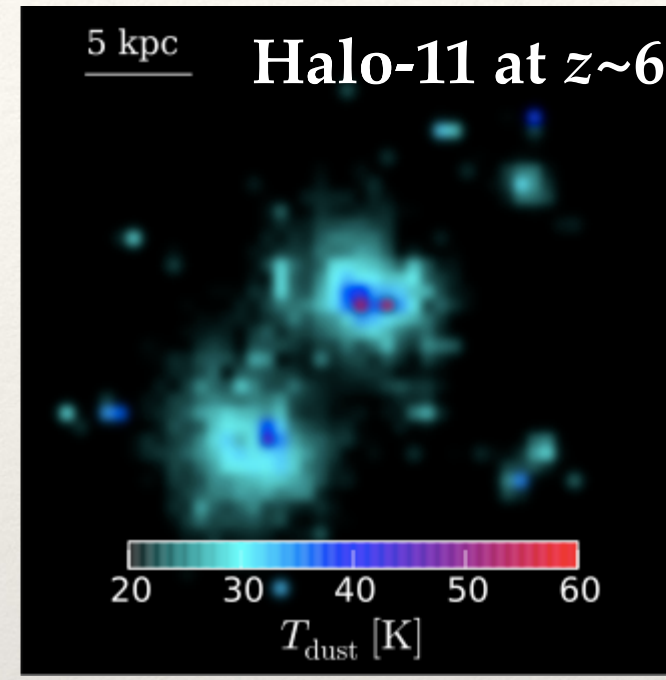
Yajima, SA+ in prep.





Dust temperature





○…from modified SED

☆…mass-weighted mean

Typical temperature is 50~70 K

Summary

- Studied radiative properties of the first galaxies
- Simulated galaxy evolution at z~6-15 and radiative transfer

Intermittent star formation due to SNe relates to the wide varieties

- Escape fraction of UV photons fluctuates between 20-80$\%$
- Duty cycle makes galaxies be ALMA sources temporally

  $z \lesssim 7,\ M_{\rm h} > 10^{10.5}\ {\rm M_{\odot}}$ galaxies are detectable if the sensitivity is <0.1 mJy

- Dust temperature is ~50-70 K
- Galaxies are detected as Lyman-Alpha Emitters in dust-less regime
- Size evolution is consistent with observation