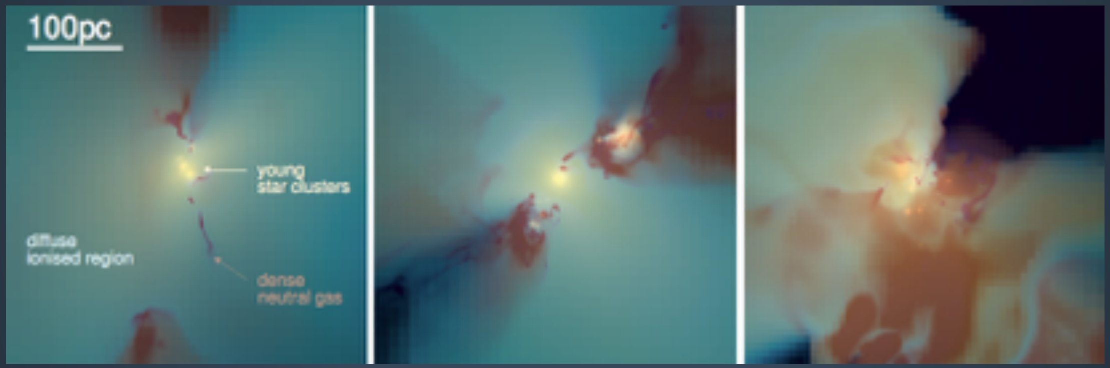
Radiation-Hydrodynamic Simulation of mini-haloes



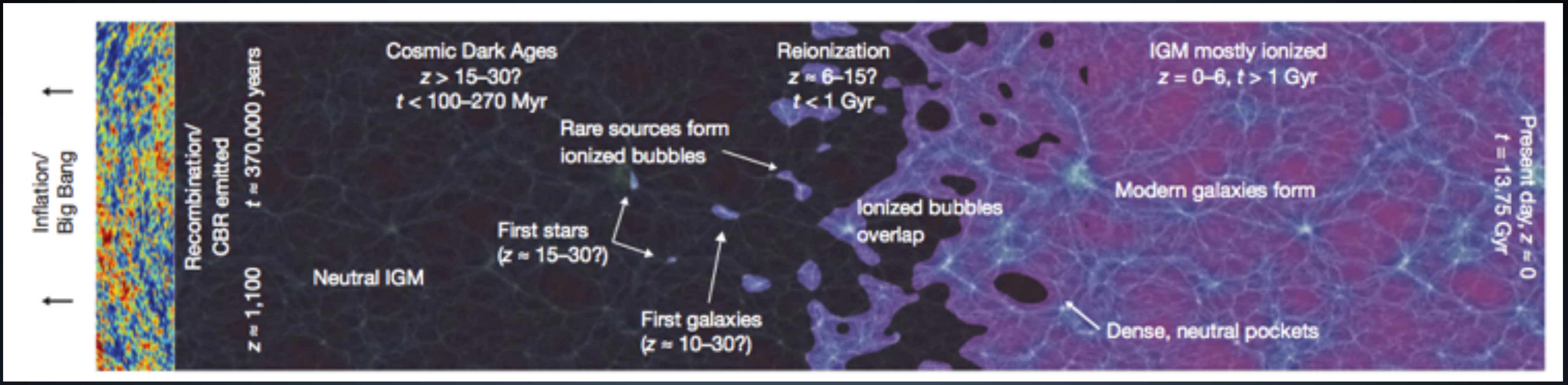
Taysun Kimm *(Cambridge)*

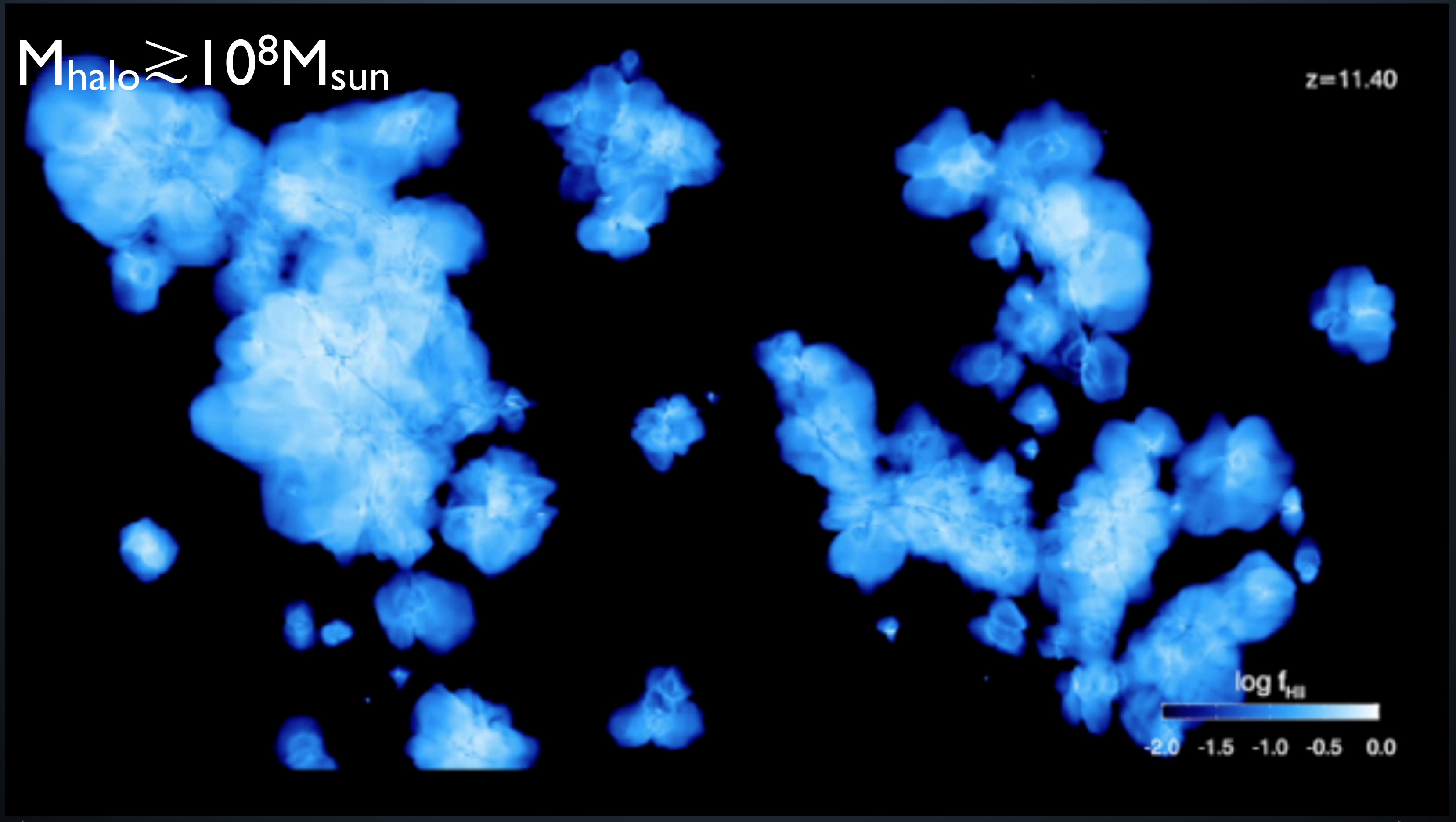
Harley Katz, Martin Haehnelt *(Cambridge)*
Joakim Rosdahl *(Leiden->CRAL)*
Julien Devriendt, Adrianne Slyz *(Oxford)*

DiRAC

Reionisation of the Universe

Robertson et al. (2010)





HII fraction

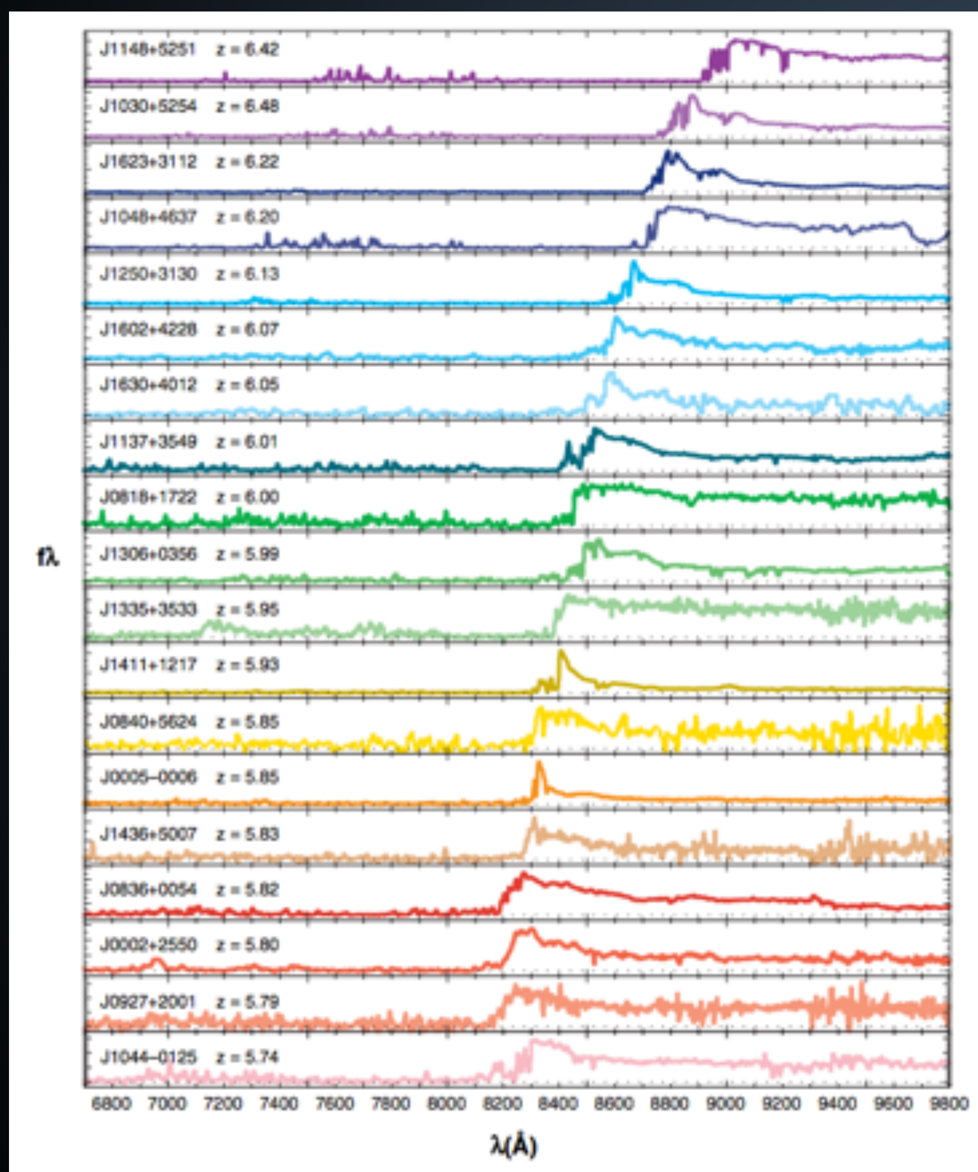
~10 cMpc

Kimm & Cen (2014)

Observational constraints

HI Gunn-Peterson Absorption Trough

z~6.5

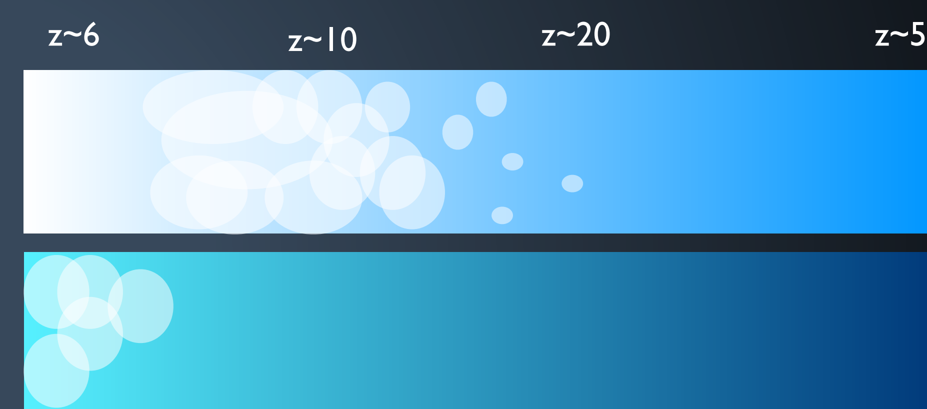


z~5.7

Fan et al. (2006)

Thompson optical depth

$$\tau_e(z) = \int_0^z c\,\langle n_{\rm H}\rangle\,\sigma_T\,f_e\,Q_{\rm HII}(z')\,\frac{(1+z')^2 dz'}{H(z')}$$



$\tau_e \sim 0.1$

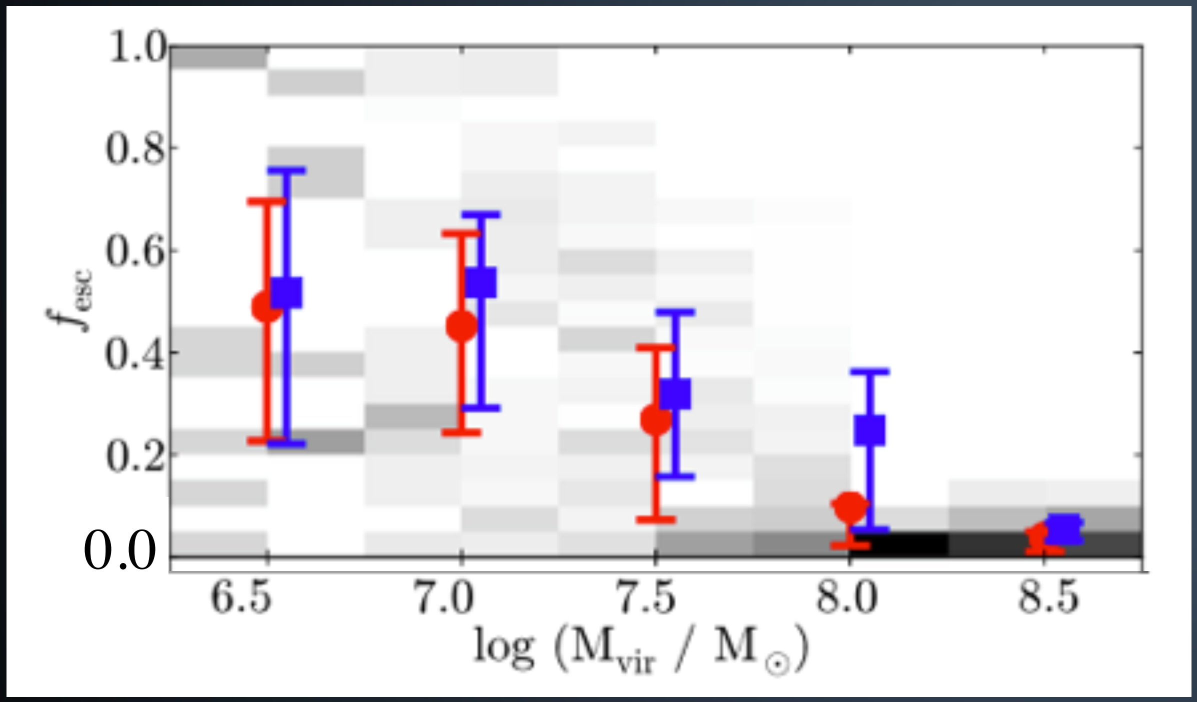
$\tau_e \sim 0.04$

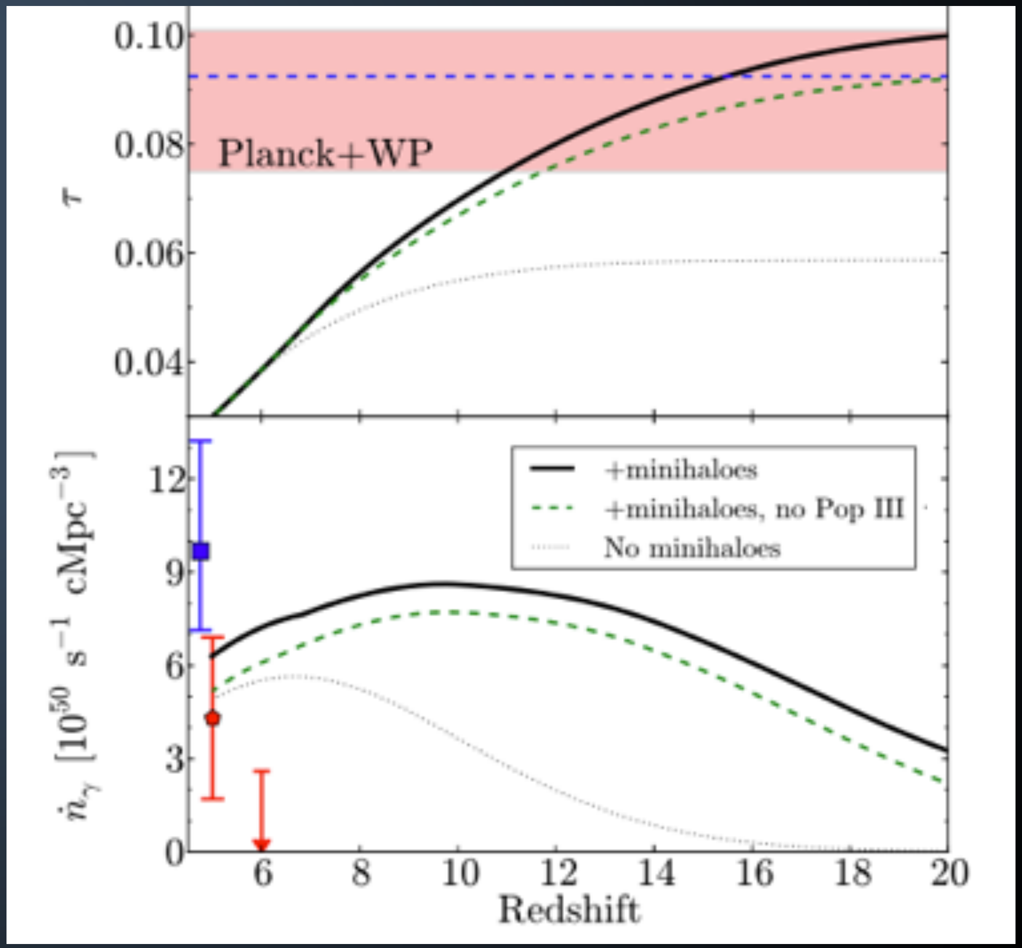
WMAP9: $\tau_e = 0.089 \pm 0.014$

Deficit of LyC photons?

Bright galaxies in UV (MUV<~-19) alone do not seem to explain the optical depth measured from the WMAP experiments
(e.g., Bunker+10; Finkelstein+10; Bouwens+12; Robertson+13)

A possible solution: mini-haloes (Wise+14; Ahn+12)





Planck15: τ_e = 0.066 ± 0.016
Planck16: τ_e = 0.055 ± 0.009

Question

Are mini-haloes mainly
responsible for reionisation?

Expansion of HII bubbles

Q_{HII}=HII filling factor

Madau+(1999)

$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}(C_{\rm HII})}$$

$$C \equiv \frac{\langle n_{\rm HII}^2\rangle}{\langle n_{\rm HII}\rangle^2}$$

(outside a DMH)

escaping rate of LyC photons

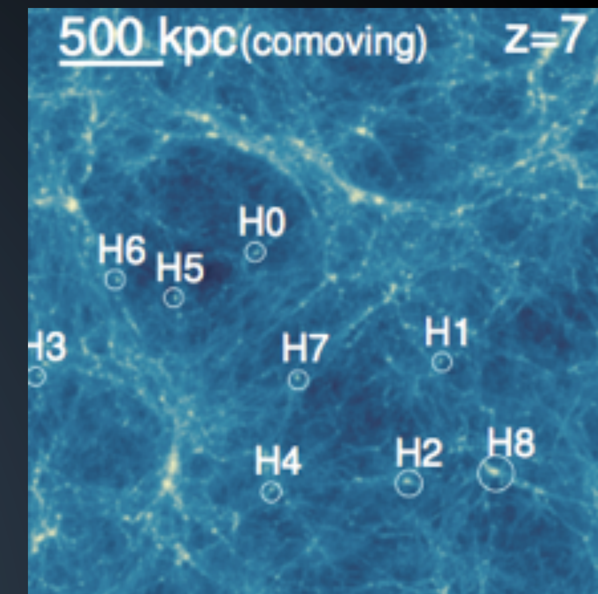
$$\dot{n}_{\rm ion} \propto \dot{M}_{\rm star} f_{\rm esc}$$

Baryon-to-star conversion efficiency

Escape fraction

Radiation-Hydrodynamic Simulations

- RAMSES-RT (Teyssier 2002; Rosdahl et al. 2013, 2015)
- 9 Cosmological zoom-in simulations of ~$10^8 M_{sun}$ haloes
- M_{dm}~ 90 M_{sun}, $M_{star,popII}$~90 M_{sun}, 10 < M_{popIII} < $10^3 M_{sun}$
- dx_{min} ~ 0.7 pc (physical)
- Jeans length resolved by 32 cells
- Non-equilibrium chemistry and cooling with 8 photon groups (Katz, TK,+16, to be submitted soon)
- H_2 formation and destruction by LW radiation
- Star formation based on local thermo-turbulent conditions (gravitational binding + turbulence) (Devriendt, TK,+16, in prep)
- Mechanical SN feedback (Kimm & Cen 2014, Kimm et al. 2015)
- Photoionisation heating, Radiation pressure from UV and IR photons (Rosdahl & Teyssier 15)

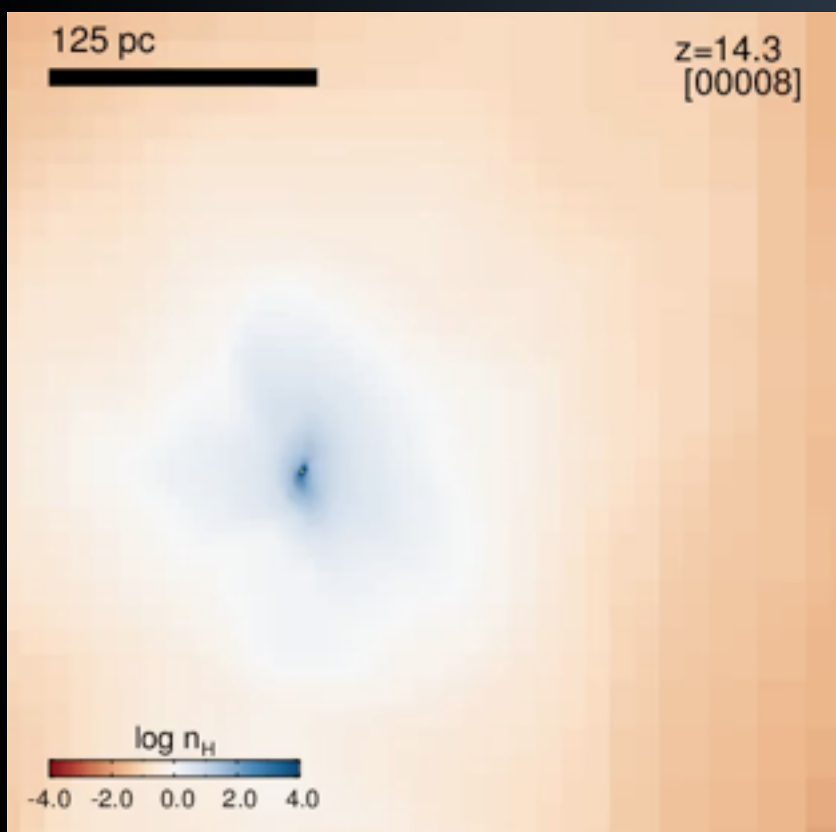


Photon group	ϵ_0 [eV]	ϵ_1 [eV]	κ [cm^2/g]	Main function
IR	0.1	1.0	5	Radiation pressure (RP)
Optical	1.0	5.6	10^3	Direct RP
FUV	5.6	11.2	10^3	Photoelectric heating
LW	11.2	13.6	10^3	H_2 dissociation
$EUV_{HI,1}$	13.6	15.2	10^3	HI ionisation
$EUV_{HI,2}$	15.2	24.59	10^3	HI and H_2 ionisation
EUV_{HeI}	24.59	54.42	10^3	HeI ionisation
EUV_{HeII}	54.42	∞	10^3	HeII ionisation

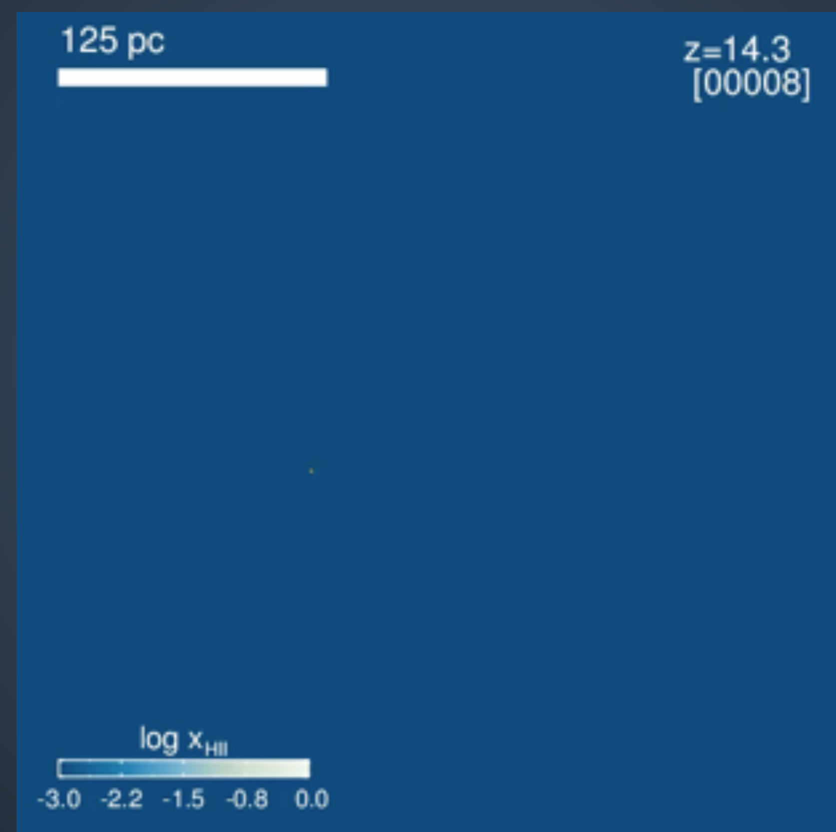
galaxies fainter than Muv~ -13

Radiation-Hydrodynamic Simulations

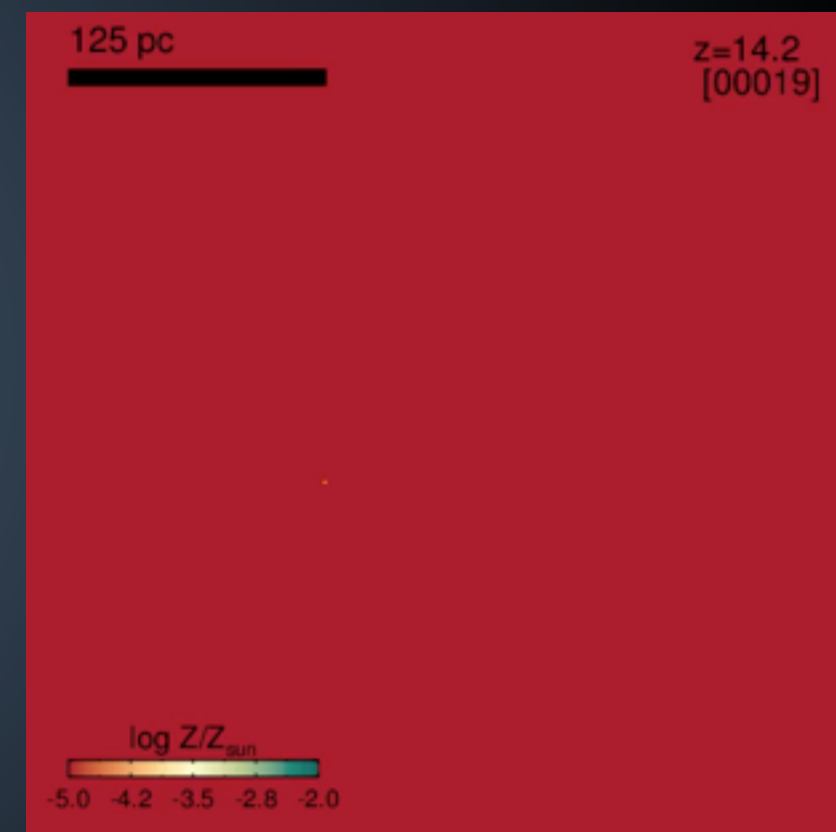
Density



HII fraction



Gas Metallicity

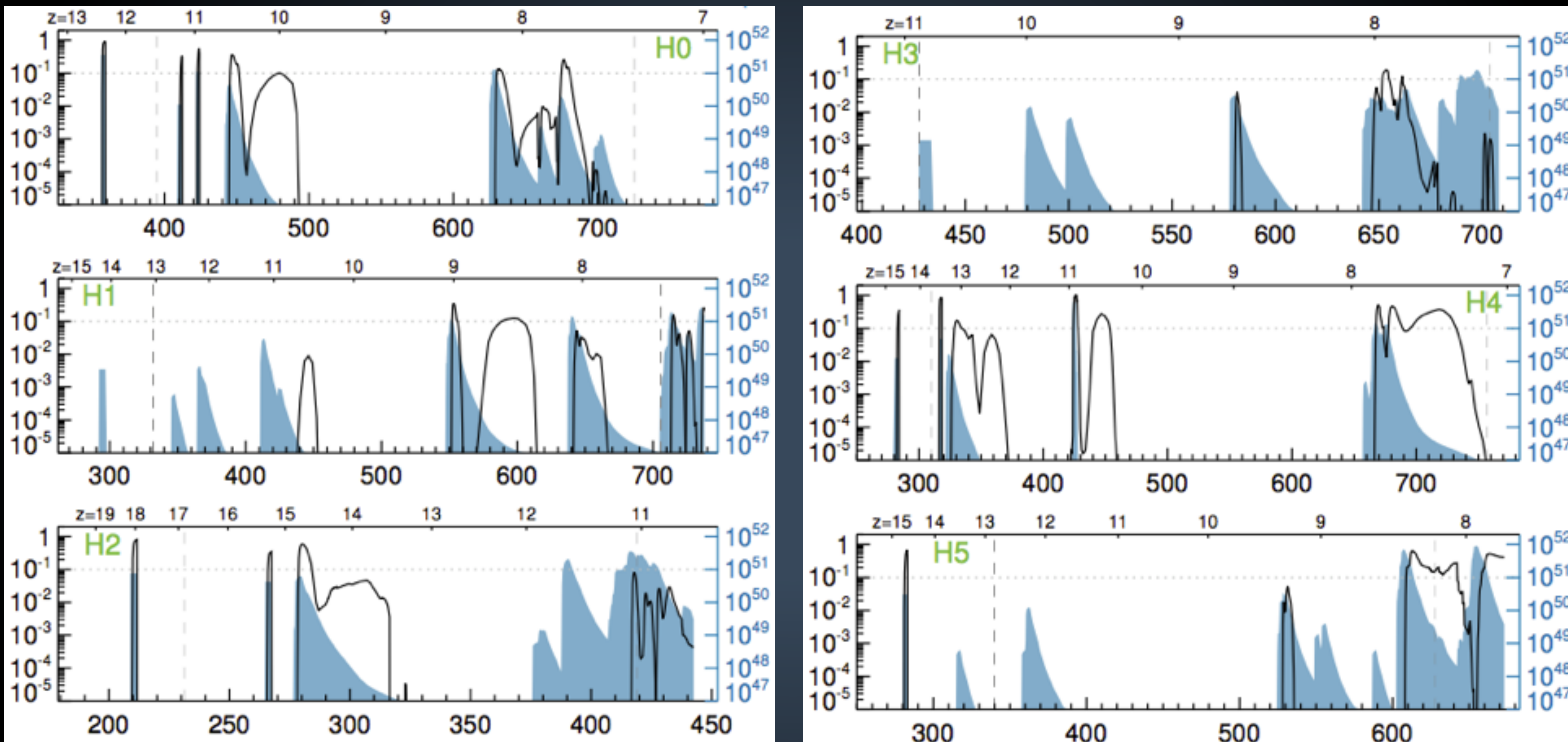


orange dots: young stars ($\lesssim$ 40 Myr)

black dots: old stars (after SNe)

Evolution of Escape Fraction in individual halos

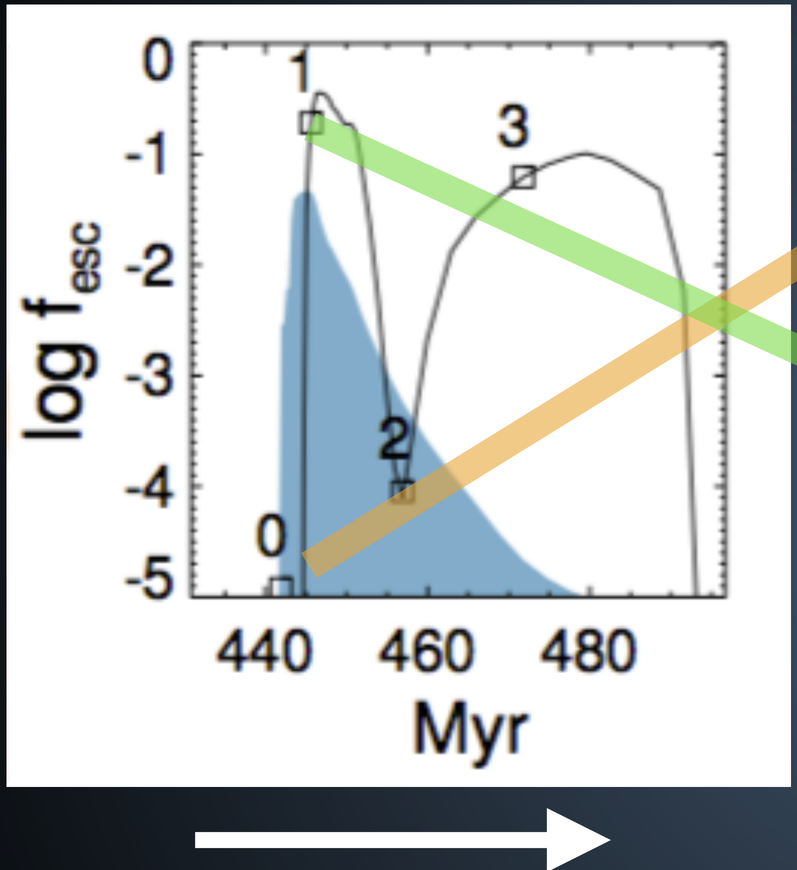
black: fesc   cyan: Nph [#/s]

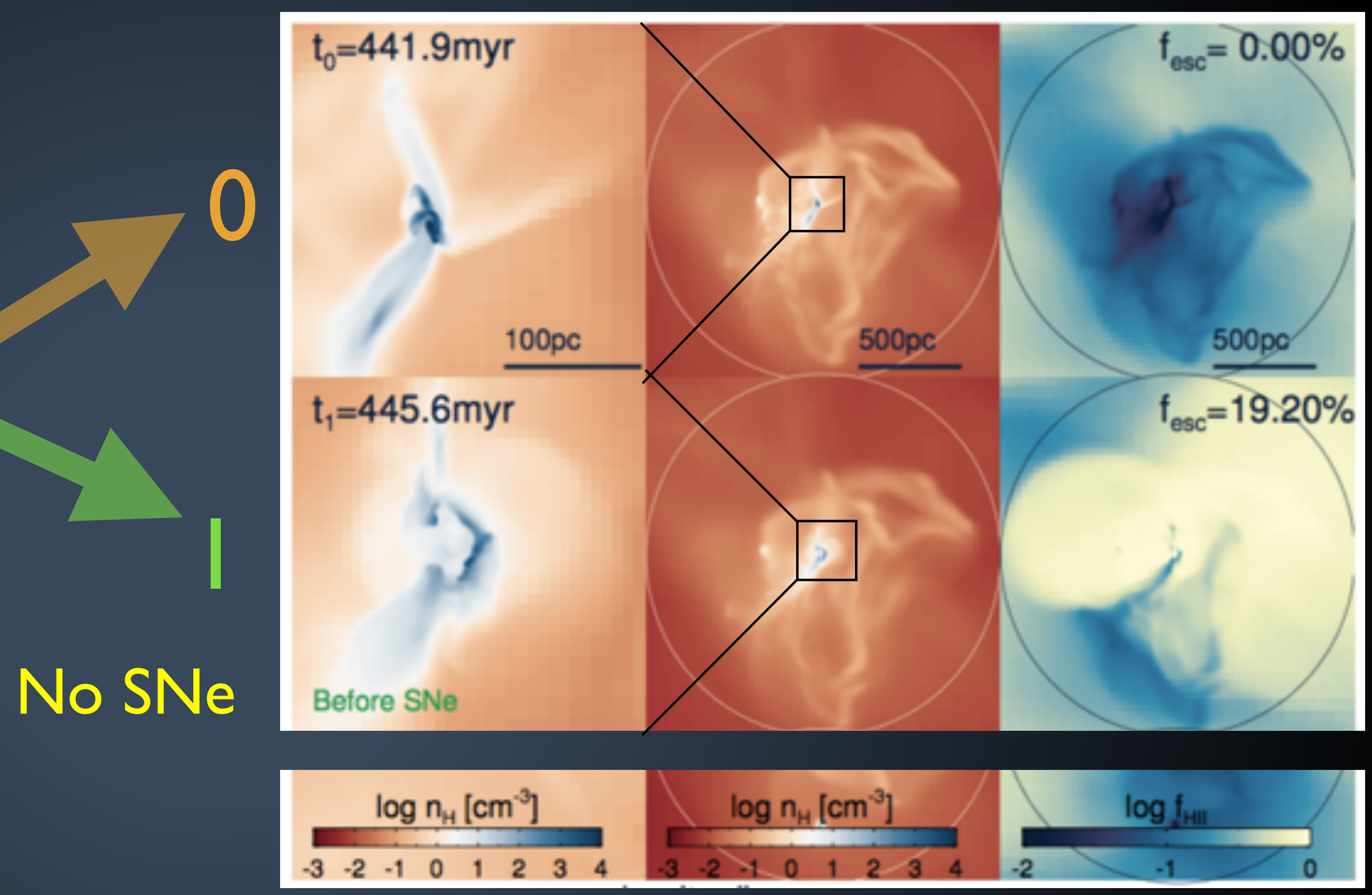


t_{univ}[Myr] t_{univ}[Myr]

- if fesc is high, the time delay is very short (≲5Myr)

Escape of LyC – radiation feedback

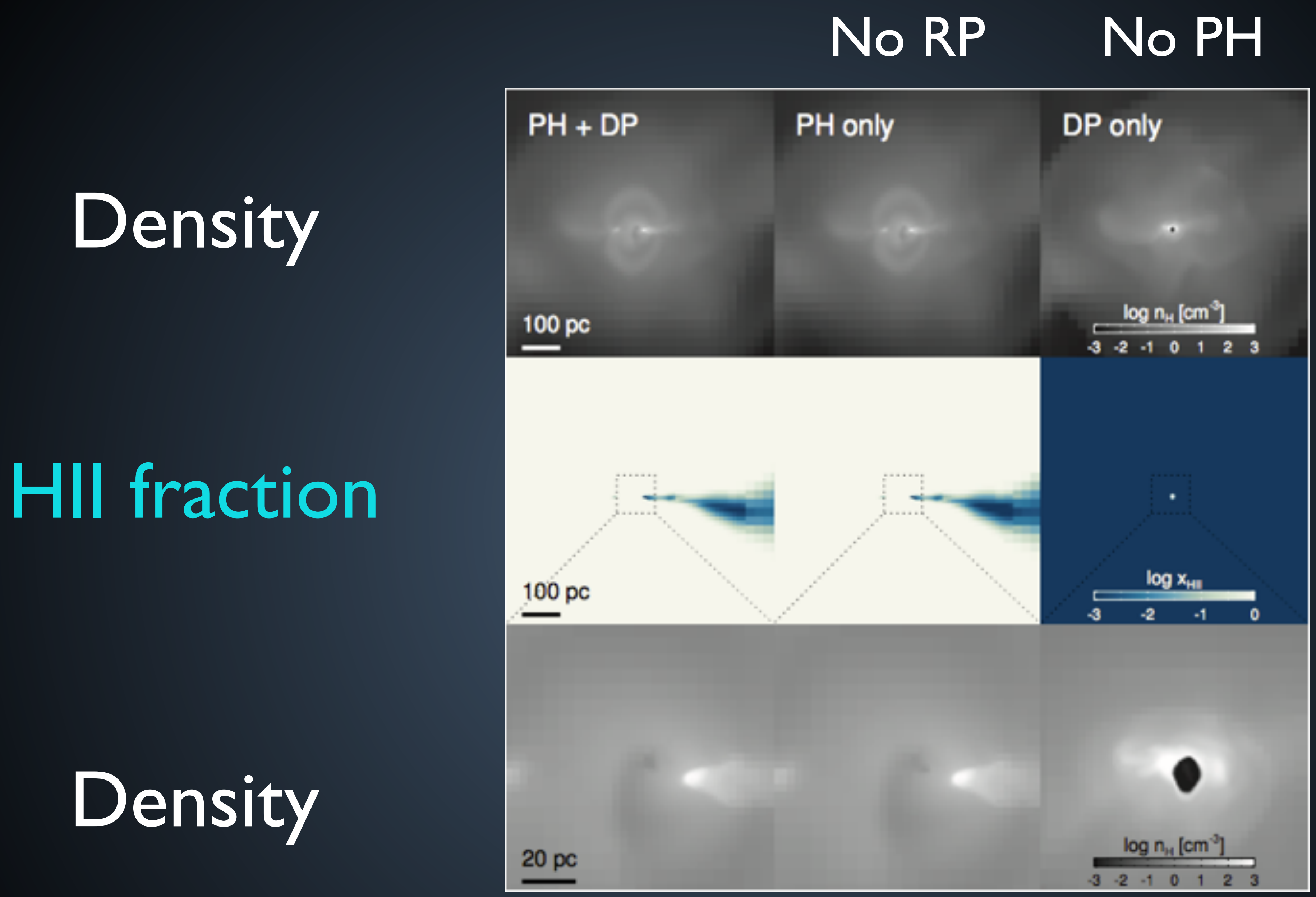




The escape fraction increases to 20% before SNe explode

- Radiation (Photo-heating) is responsible for the high escape fraction in mini-halos

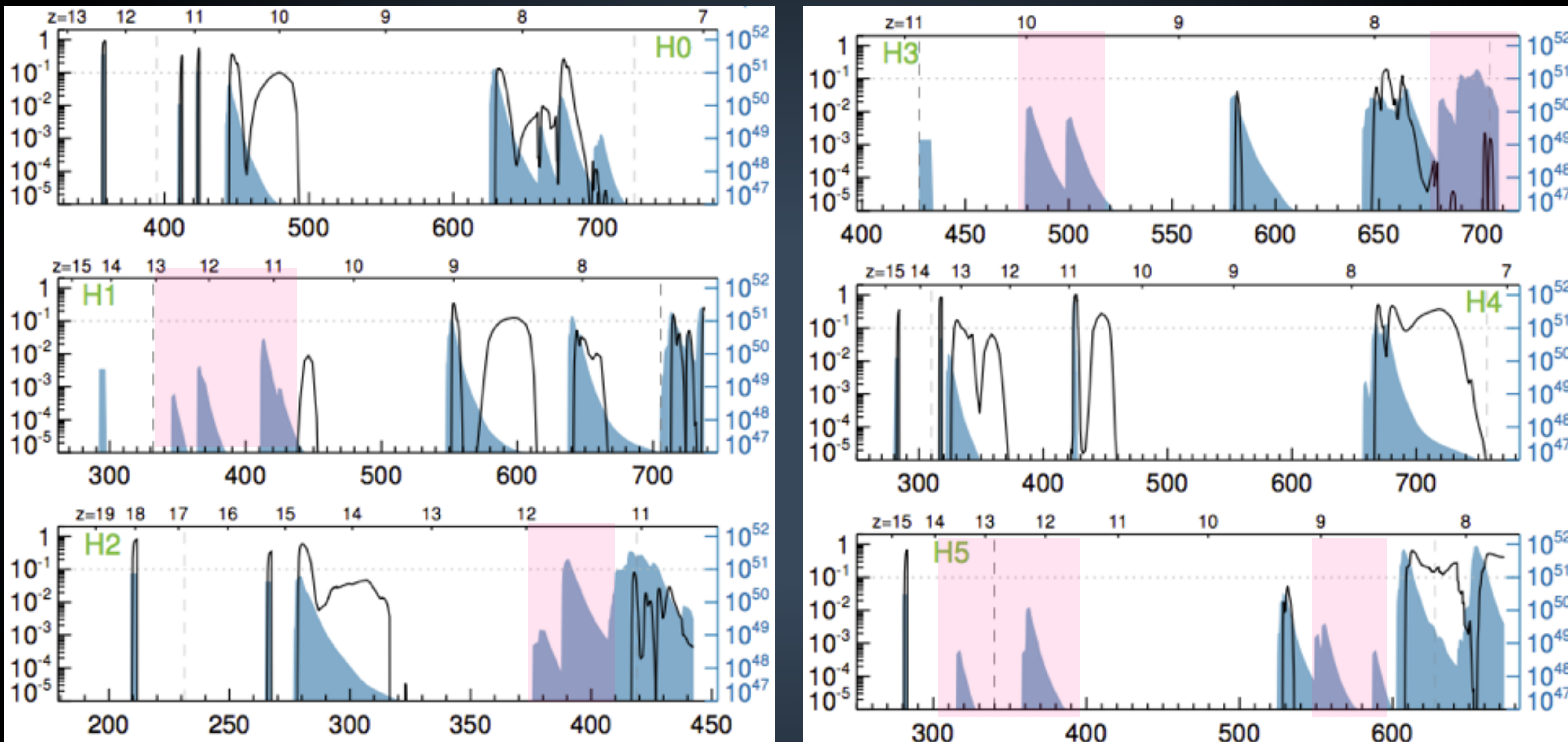
Photo-heating vs Direct Radiation Pressure



Rosdahl & Teyssier (15): photo-heating dominates in most galactic environenments

Evolution of Escape Fraction in individual halos

black: fesc   cyan: Nph [#/s]

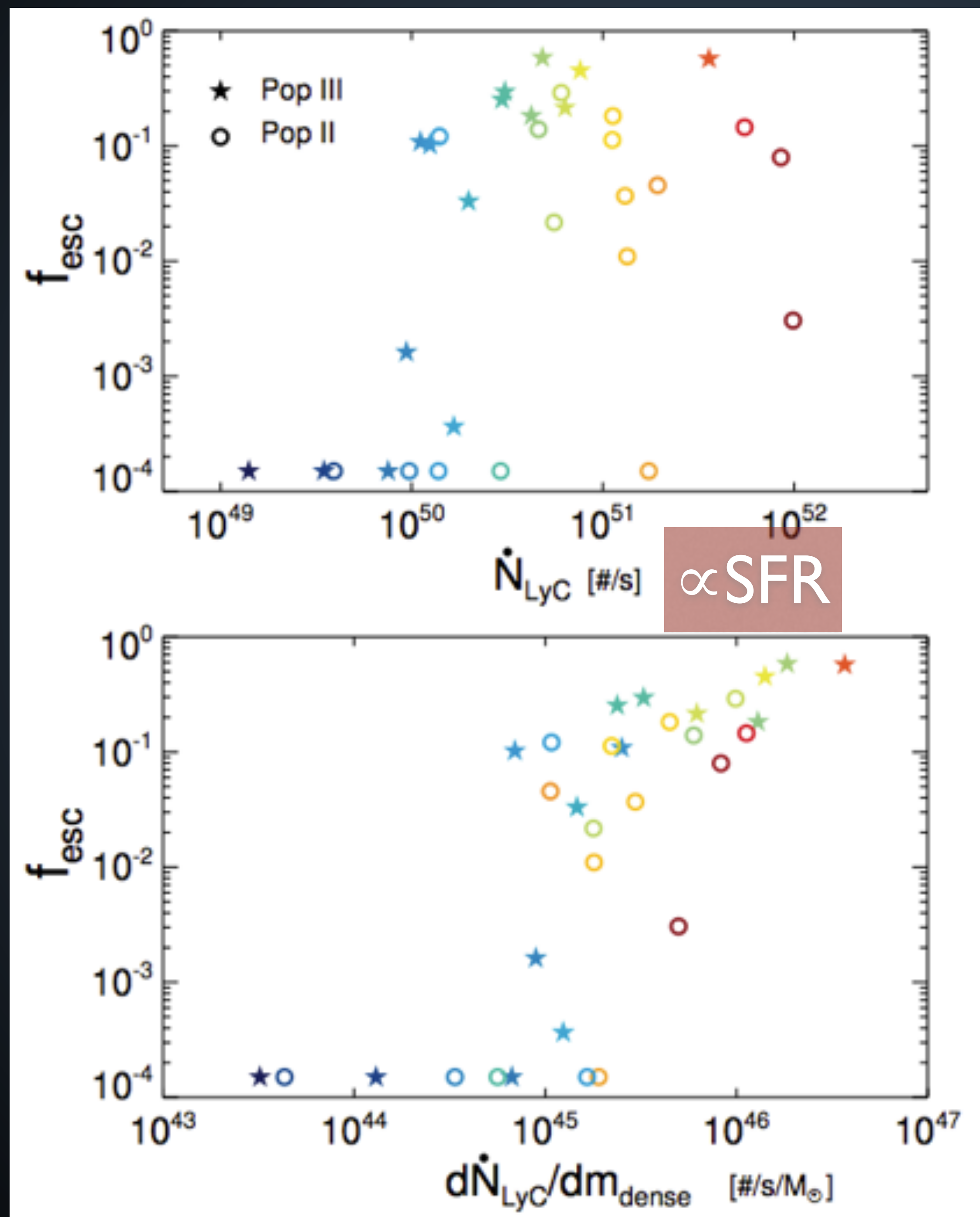


t_{univ}[Myr] t_{univ}[Myr]

- not every SF episode leads to high f_{esc}

Radiation-Hydrodynamic Simulations

Photon number-weighted

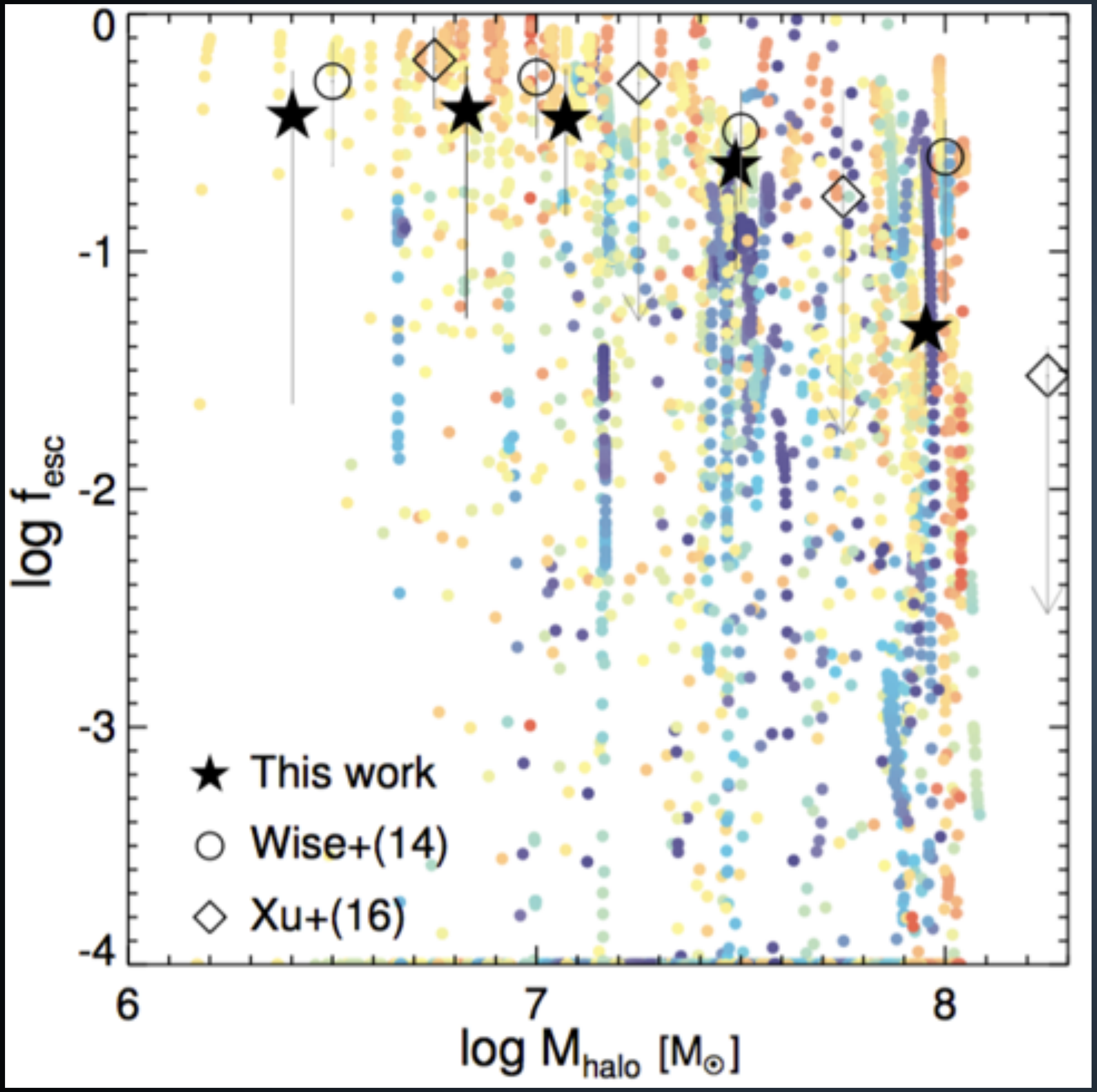


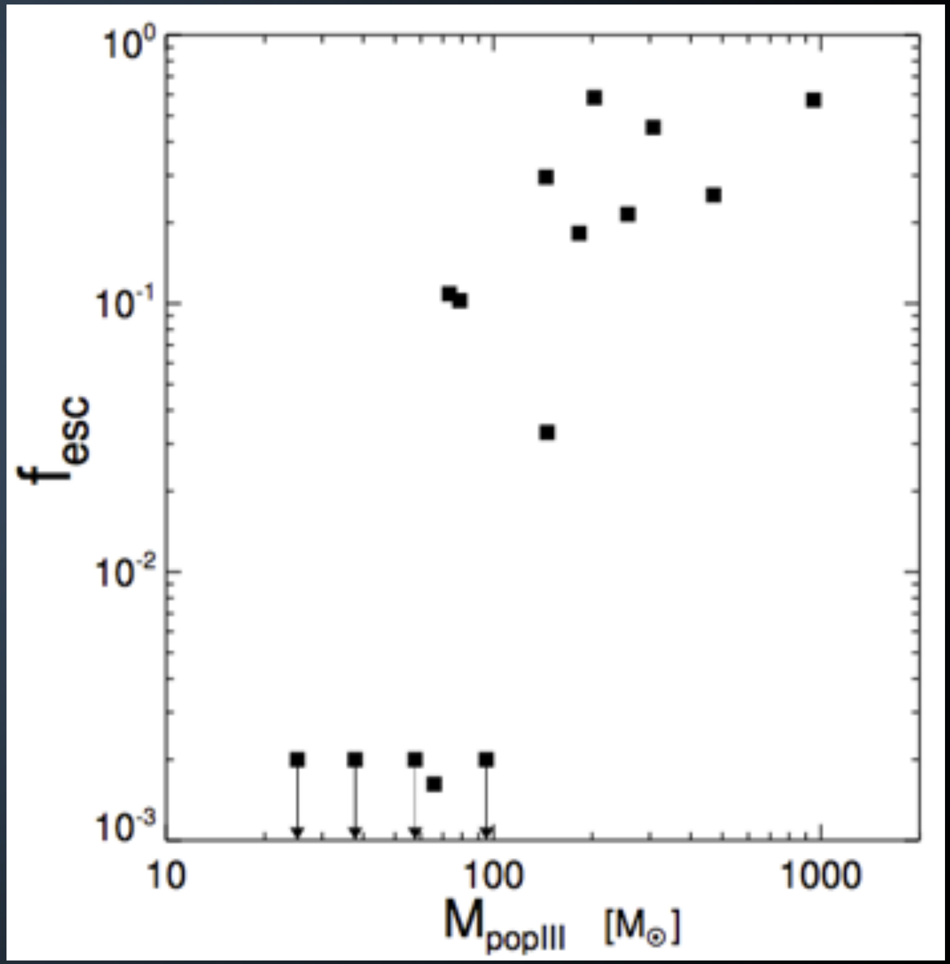
$f_{esc} \gtrsim 0.1$

$f_{esc} \ll 0.1$

Photon number-weighted Escape fraction

redder colours - larger photon production rates

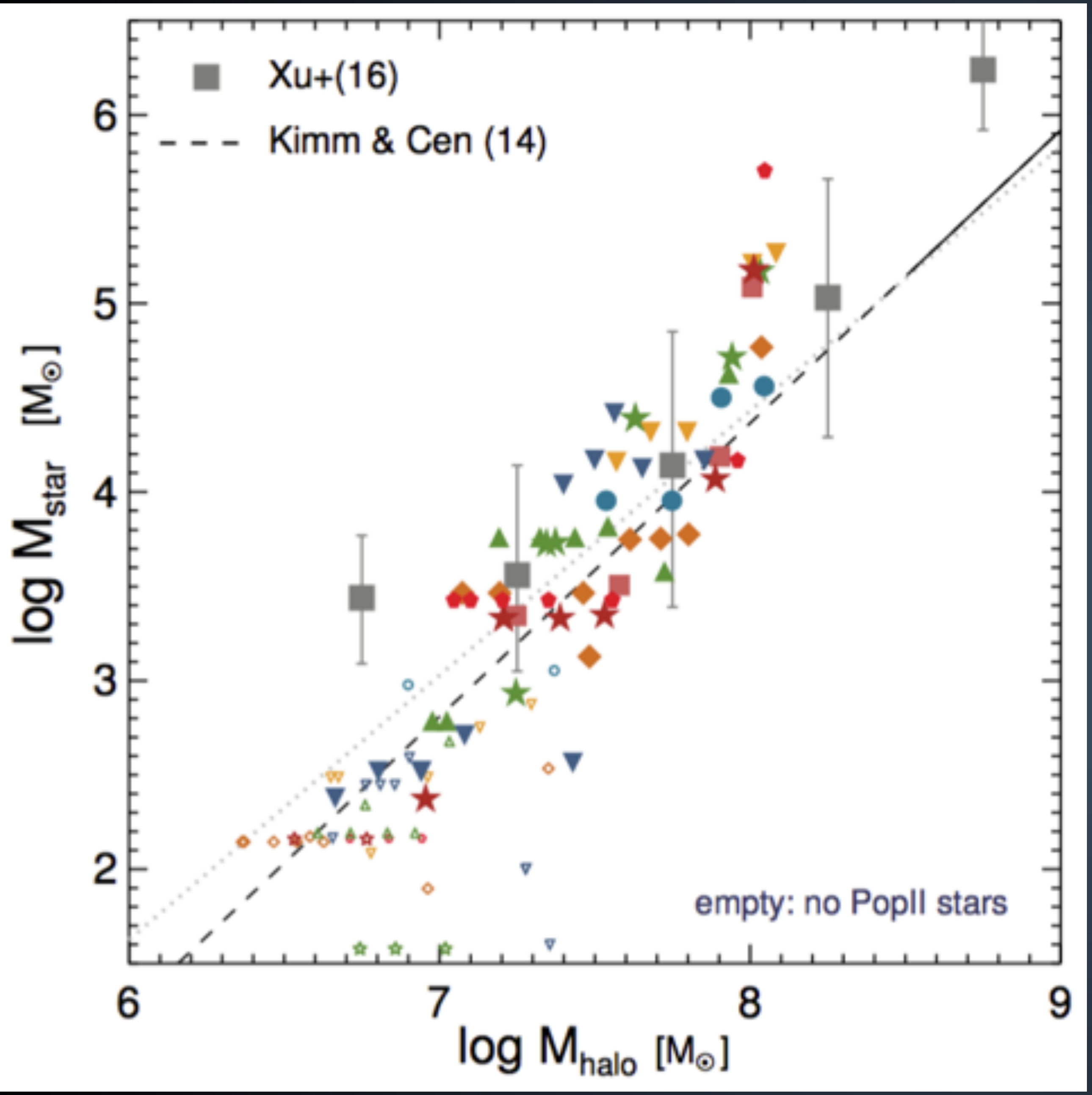




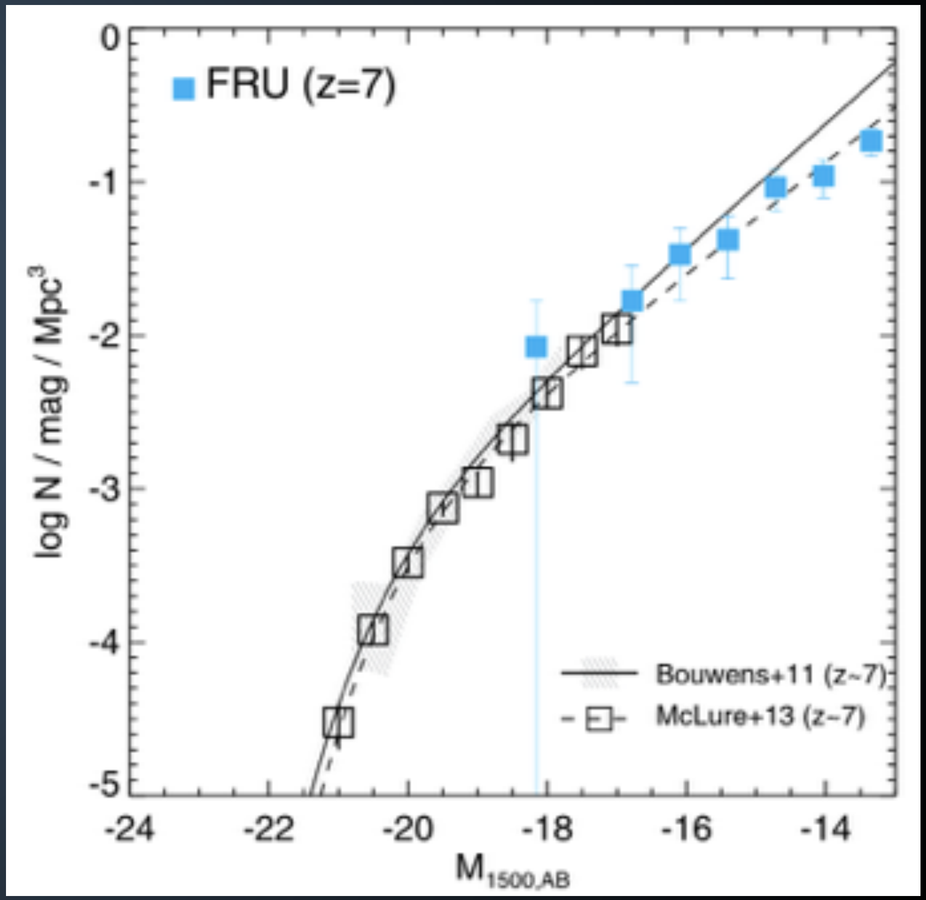
(e.g., Whalen+04)

Large escape fraction of 20-40 %,
consistent with other AMR simulations (Wise+14, Xu+14)

Star formation in mini halos



Kimm & Cen (2014)



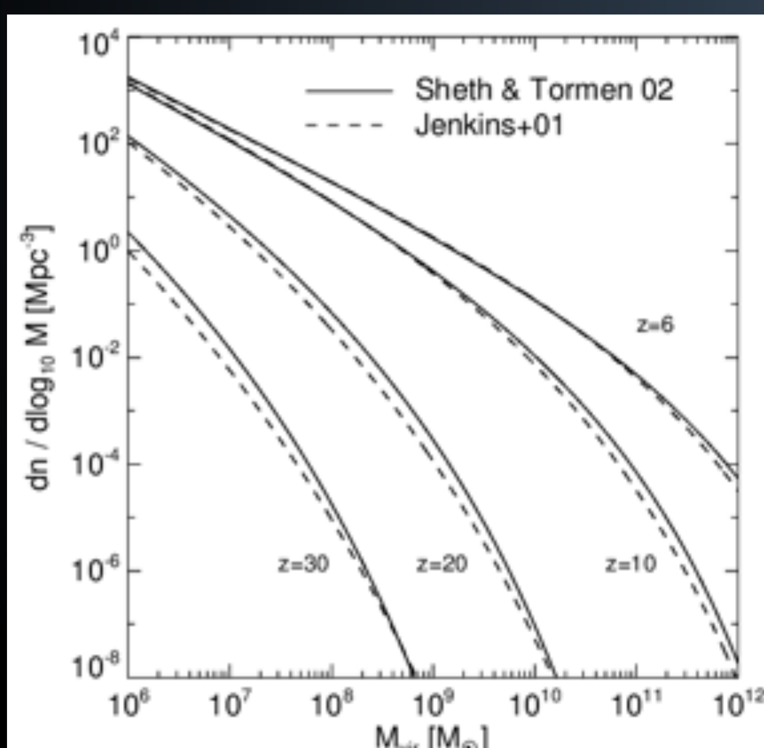
Simple analytic model for reionisation

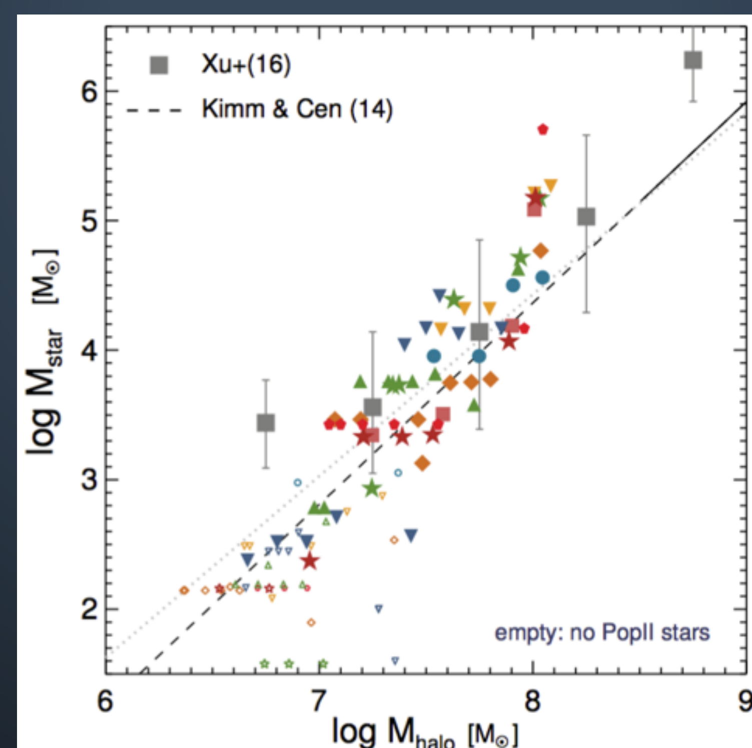
$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}(C_{\rm HII})}$$

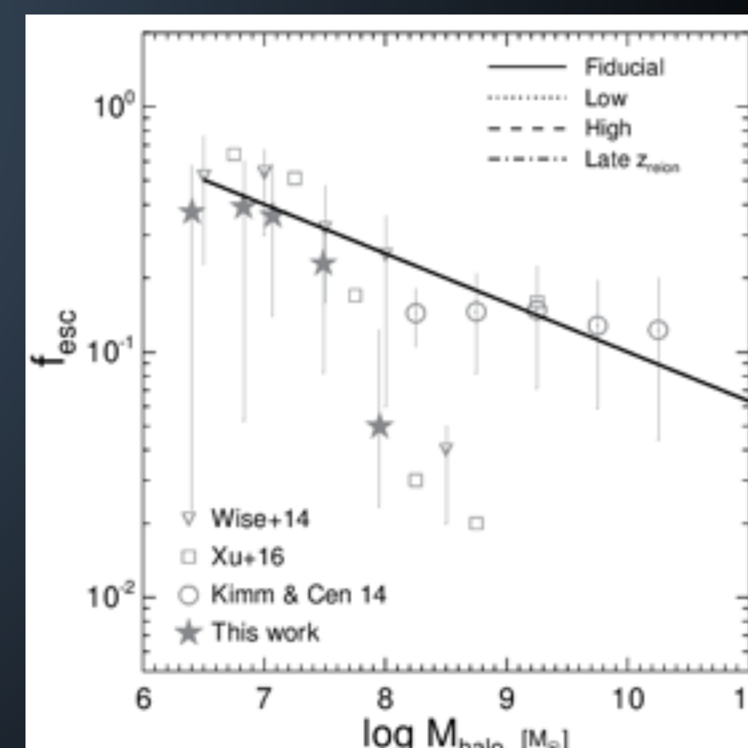
$$\frac{dN_{DMH}(z)}{d\log M}$$

$M_{star}=f(M_{halo})$

$f_{esc}=f(M_{halo})$

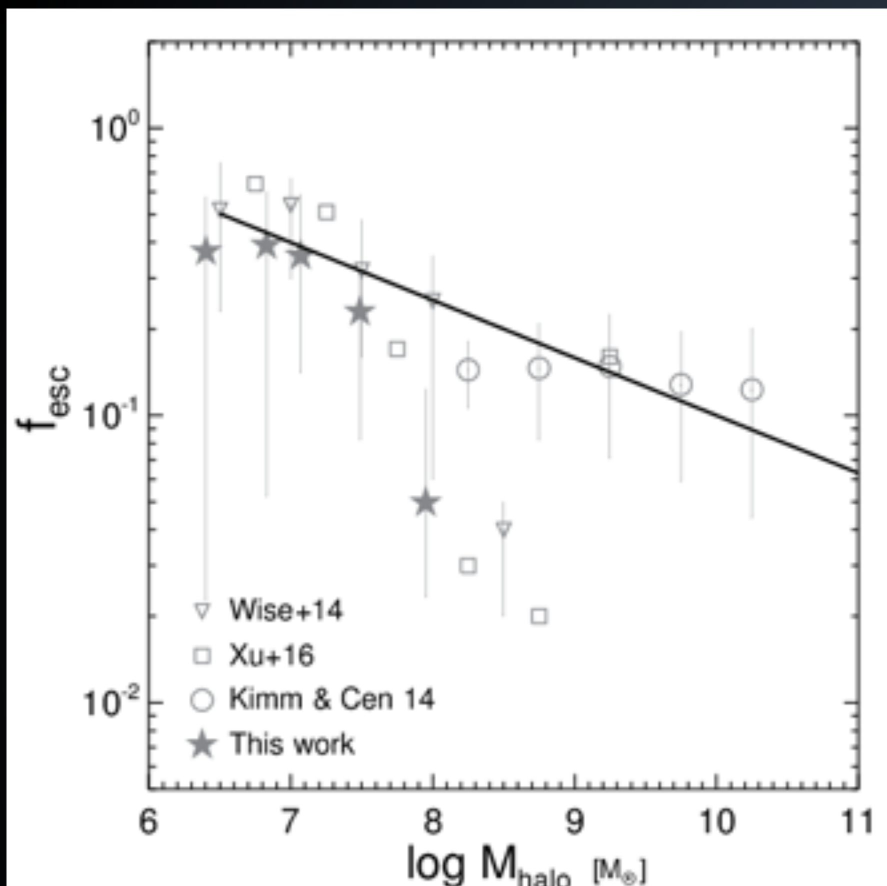


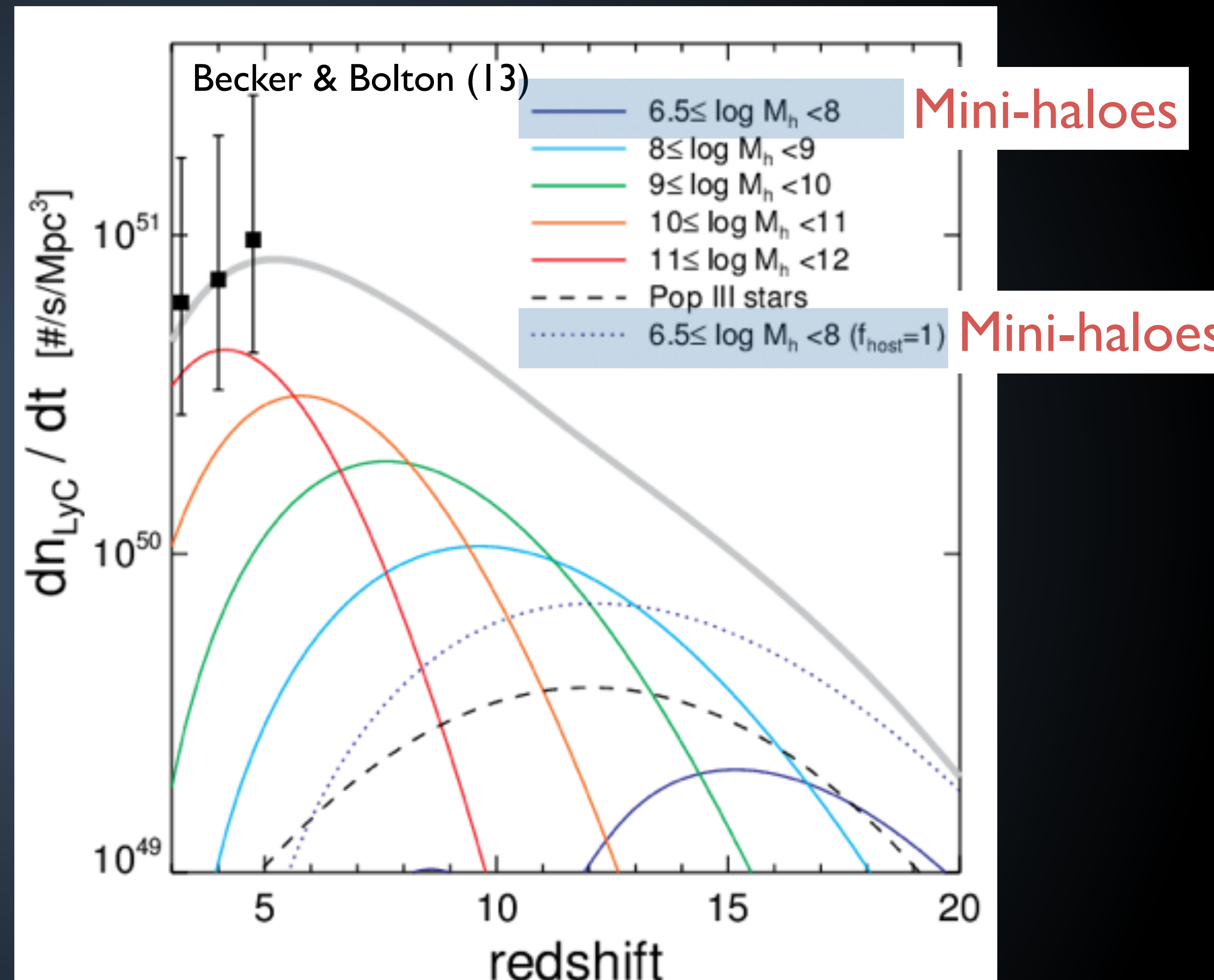




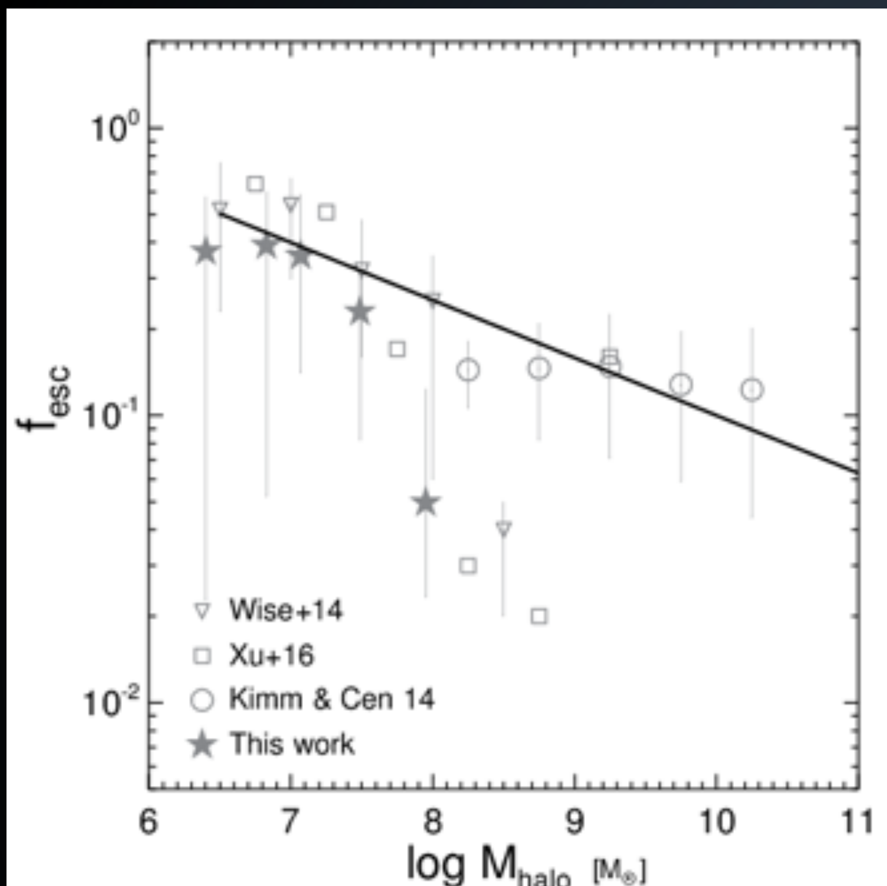
$$\log Q_{\rm LyC} = 60.31 - 0.237 \log Z$$

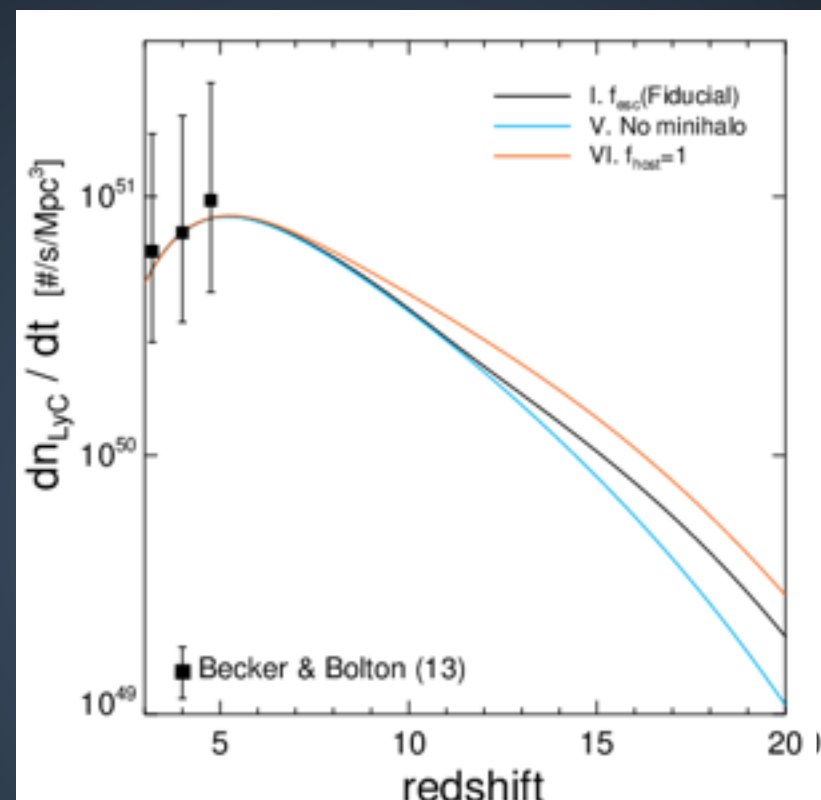
Photon Budget in halos of different masses

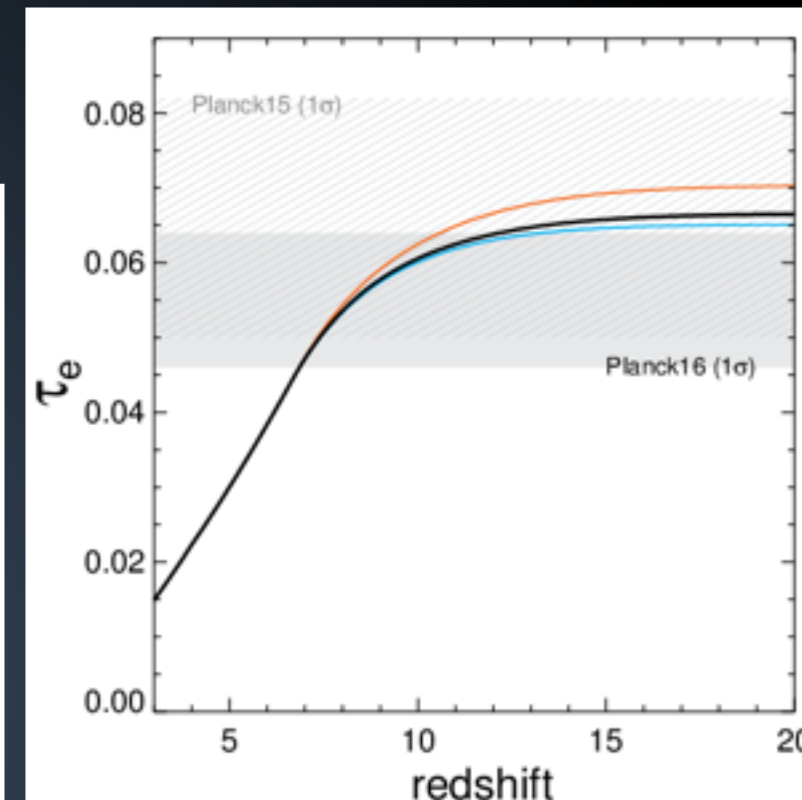


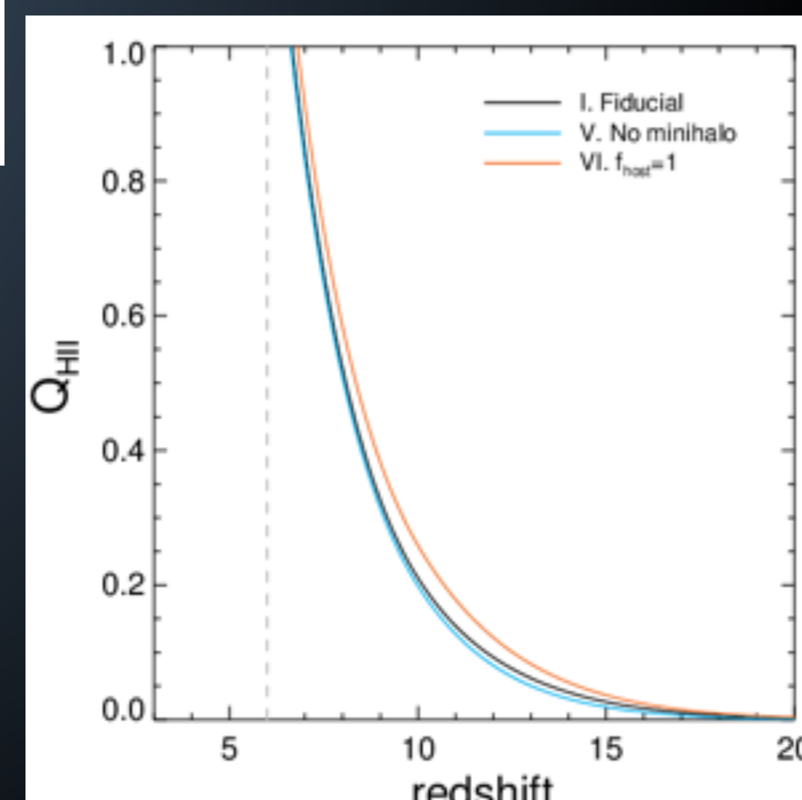


Minihalos?





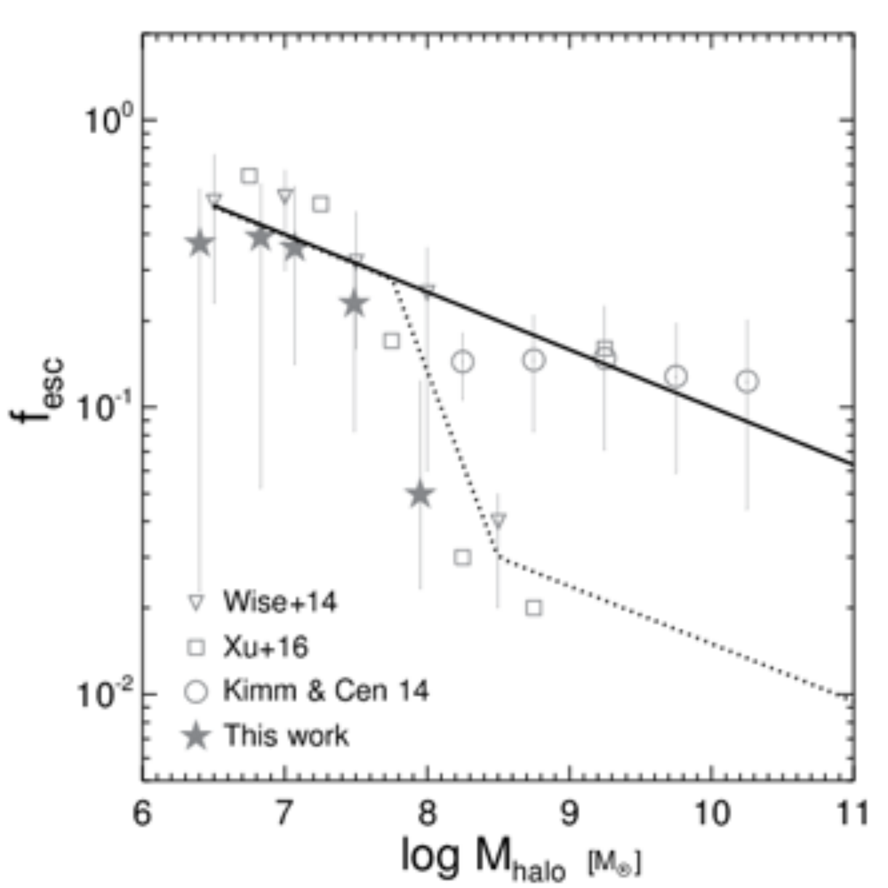


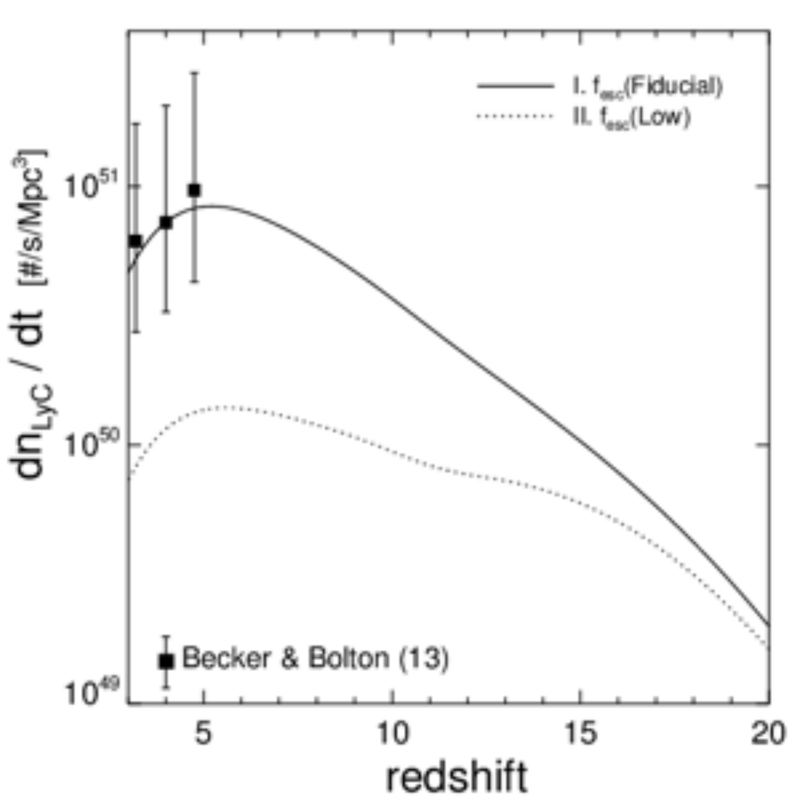


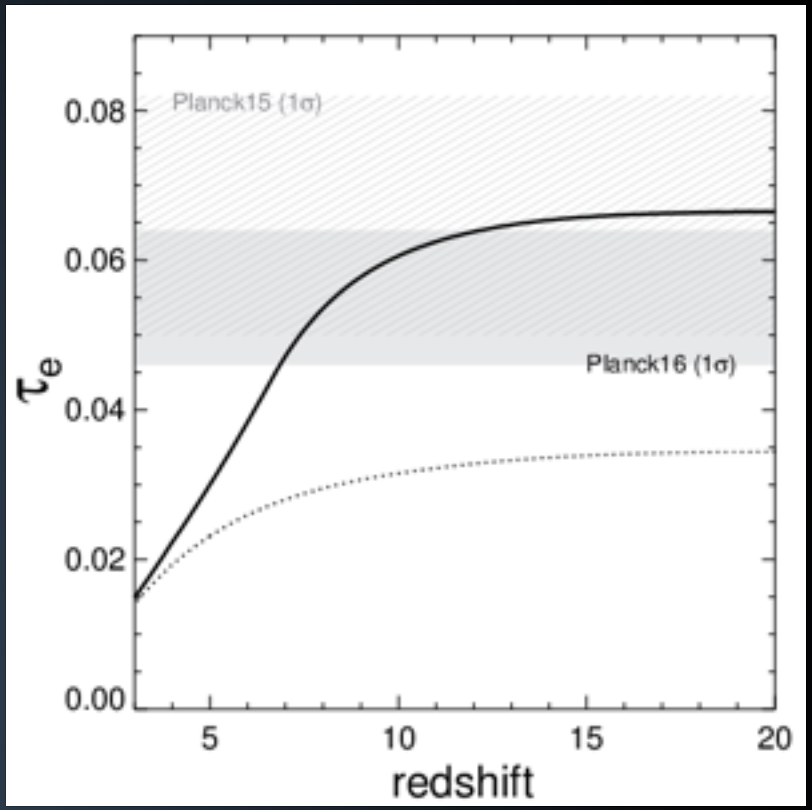
Mini-haloes are of minor importance for reionisation of the Universe!

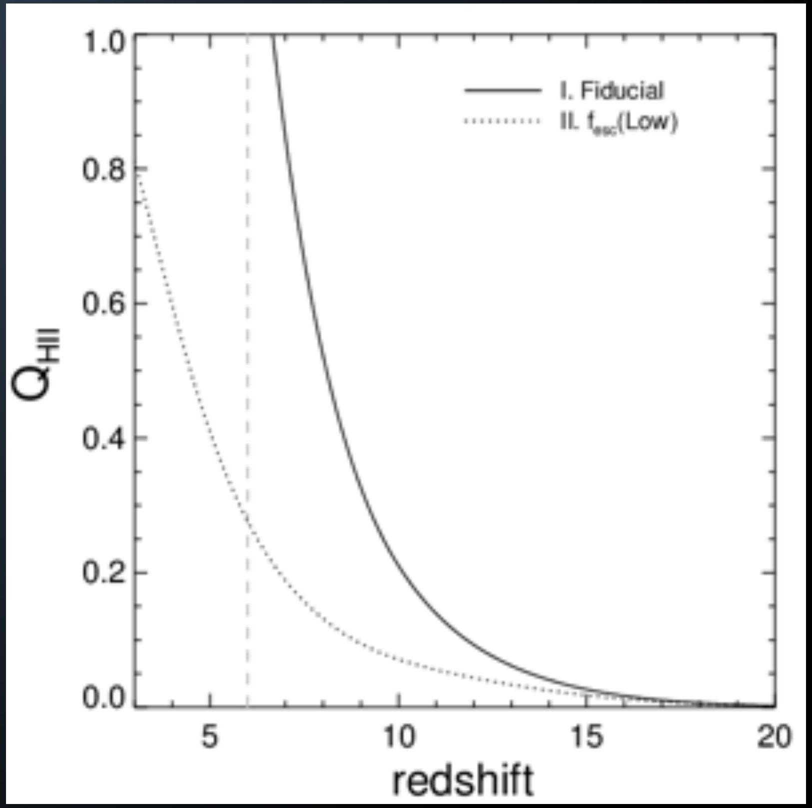
- due to inefficient SF

ACHs need to have high escape fractions



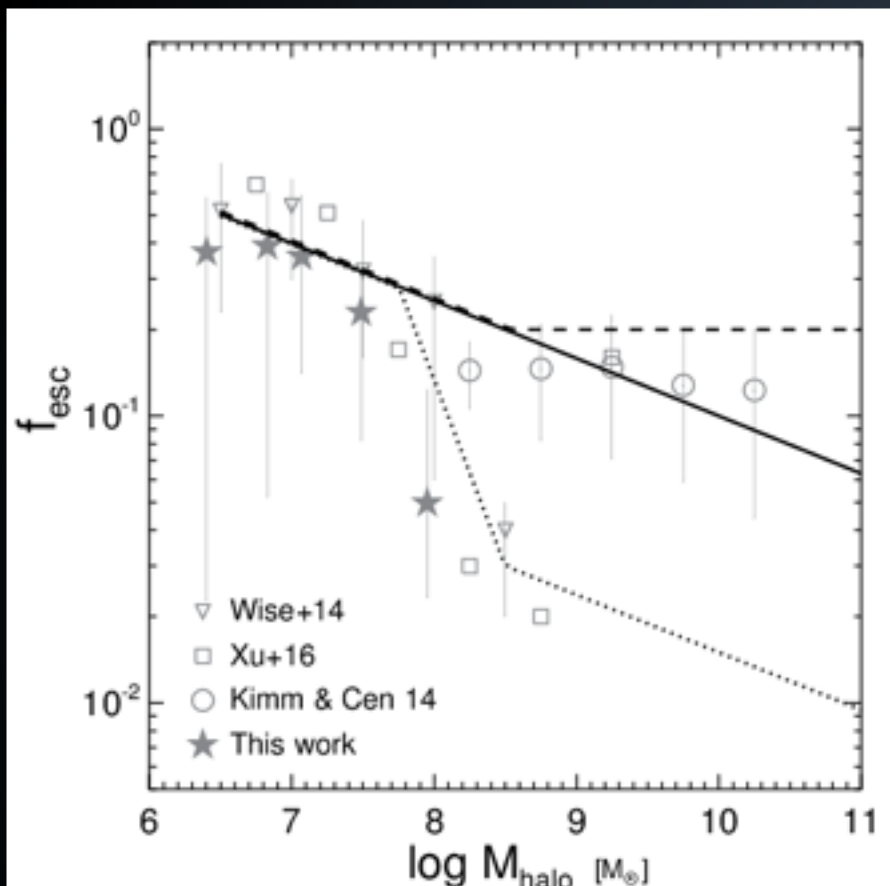


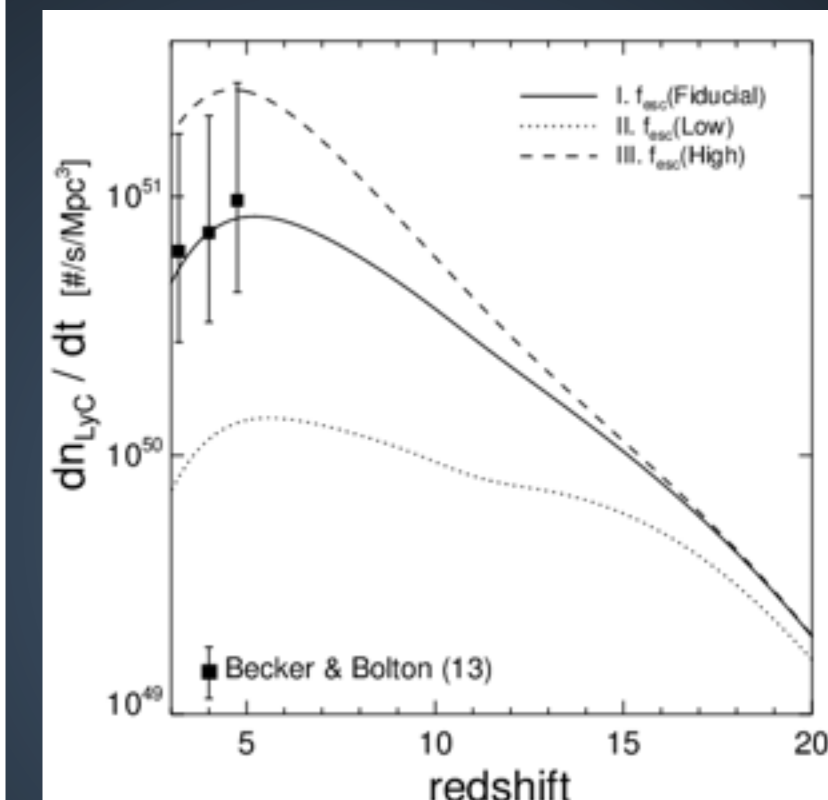


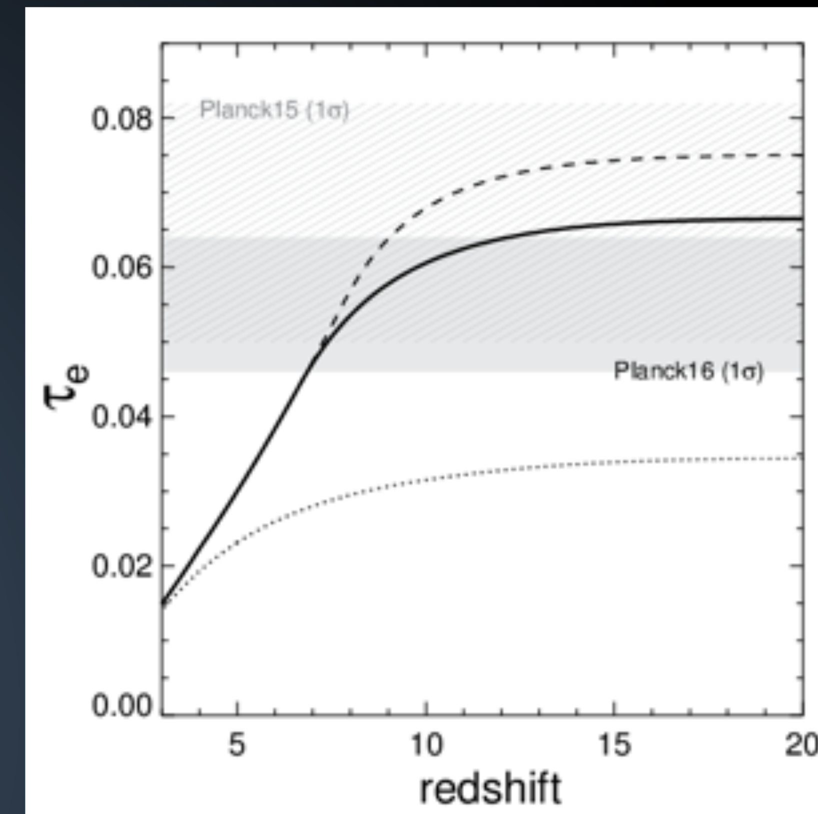


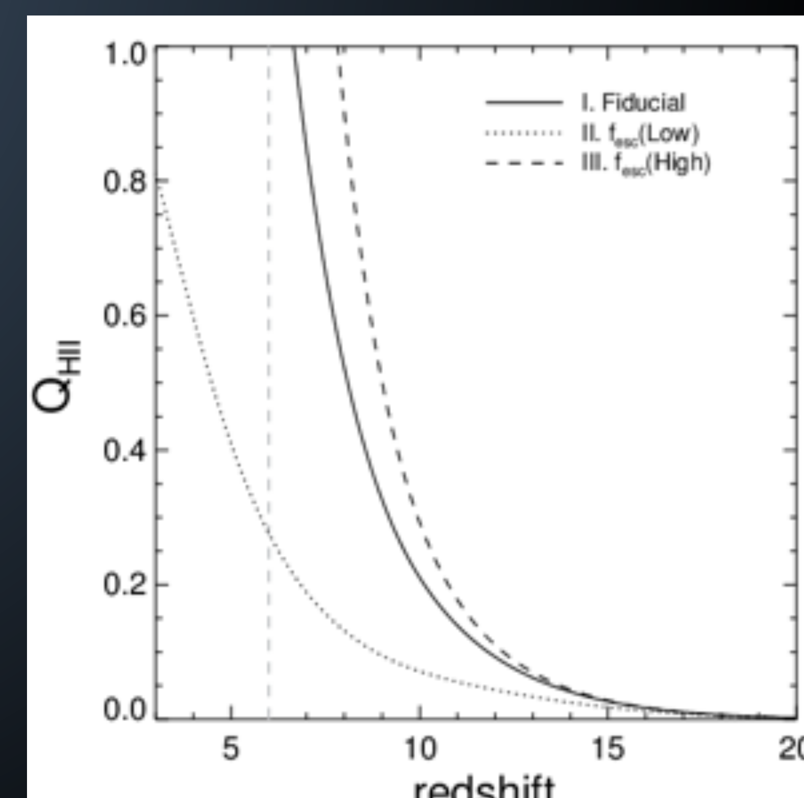
The low fesc case would require significant contributions from other sources

Optimistic escape fraction – too early reionisation









Binary stars etc (Ma et al. 16)

Future work:
RHD simulations of ACHs with physically motivated SF models and binary stellar evolution

Summary

- The escape fraction in mini-haloes is large (20 - 40 %)
- Heating from photoionisation governs the escape of LyC photons in mini-haloes
- Star formation is very inefficient in mini-haloes
(intriguingly similar to z~0 Mstar-Mhalo)
- Mini-haloes are of minor importance for reionisation of the Universe
- Atomic-cooling haloes with $10^8 M_{sun}$- $10^{11} M_{sun}$ are still the leading candidate

Thank you!