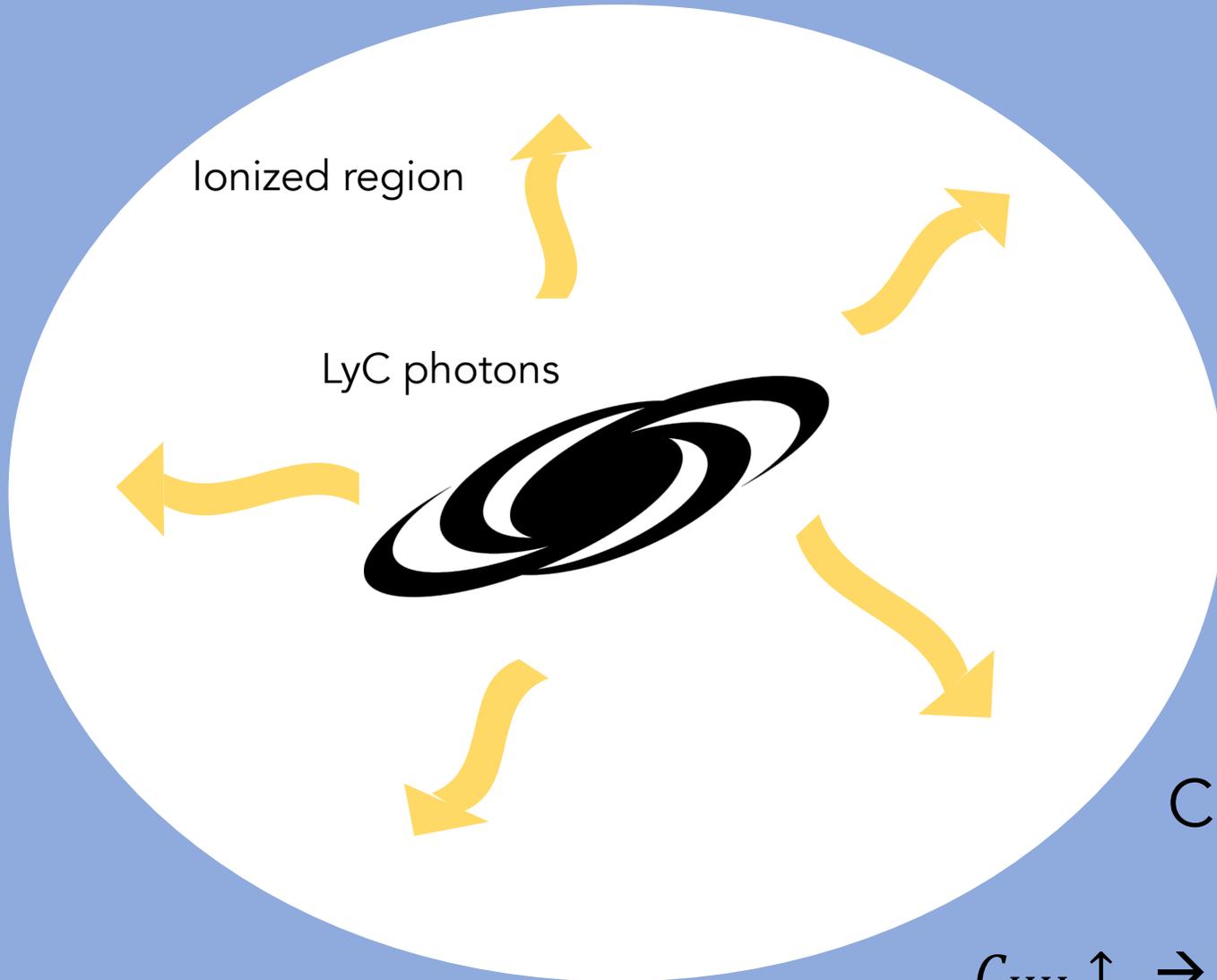


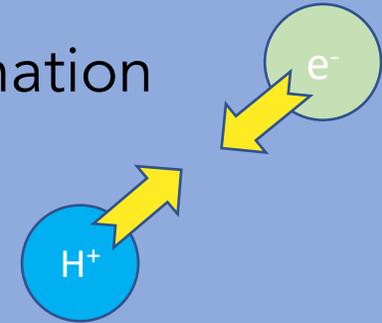
The clumping factor of the IGM at the epoch of reionization in the SPHINX simulations

Taehwa Yoo, Taysun Kimm (Yonsei University)
and SPHINX collaboration

Photo-ionization and recombination of hydrogen



Recombination



Recombination timescale

$$t_{rec} \equiv [\langle n_H \rangle (1 + 2\chi) \alpha_B C]^{-1}$$

Clumping factor $C_{HII} = \frac{\langle n_{HII}^2 \rangle}{\langle n_{HII} \rangle^2}$

$$C_{HII} \uparrow \Rightarrow t_{rec} \downarrow \Rightarrow \text{net ionization rate} \downarrow$$

Clumping factor

$$\text{Clumping factor } C_{HII} = \frac{\langle n_{HII}^2 \rangle}{\langle n_{HII} \rangle^2}$$

$$\frac{dn_{HII}}{dt} = -\alpha_B n_e n_{HII} \propto n_{HII}^2$$



Photo-ionization of the IGM = air dry of laundry



= gas with high clumping factor



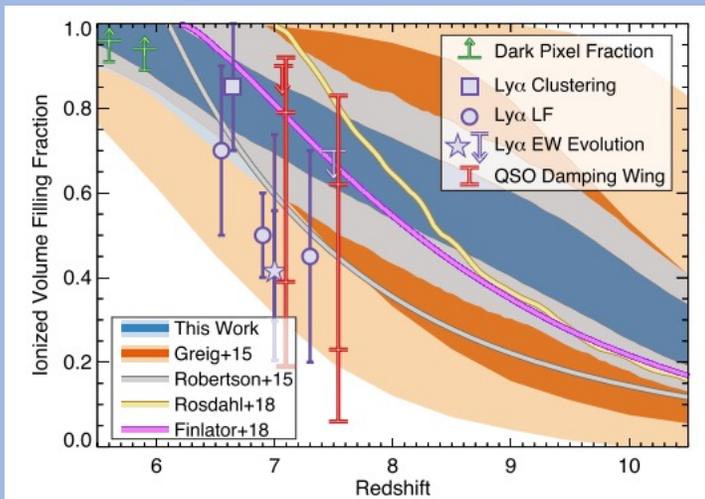
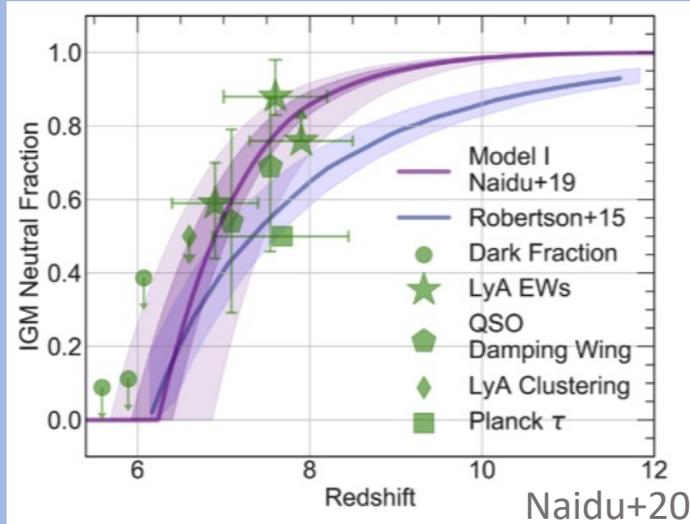
= slow dry



= slow photo-ionization

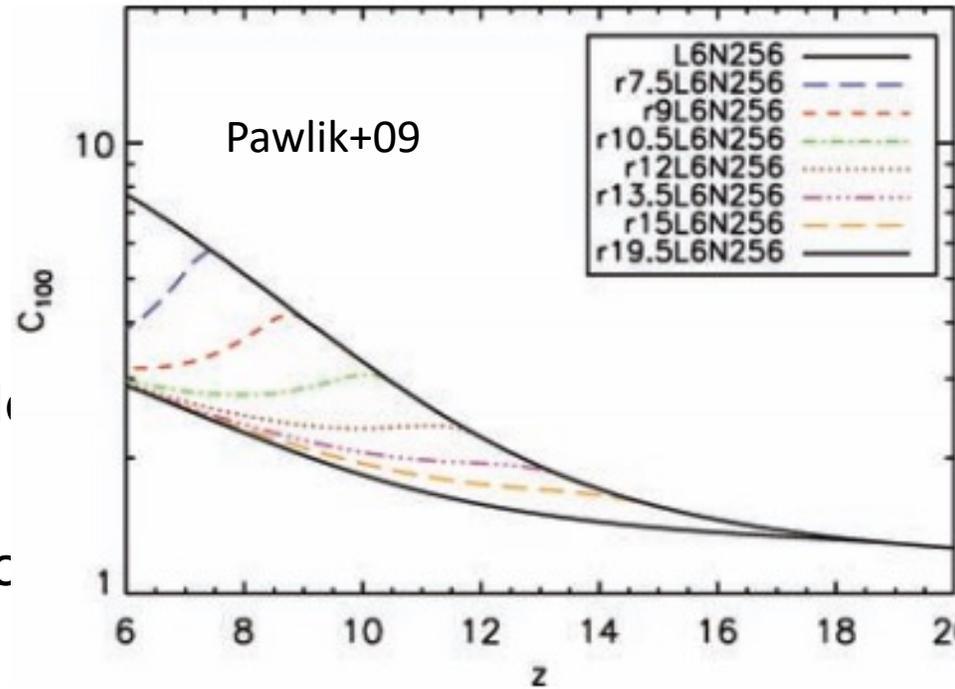
Analytic approaches based on clumping factors

Reionization models



Ionized volume filling fraction

$$\frac{dQ_{HII}}{dt} = \dot{n}_{ion} - \frac{Q_{HII}}{\langle t_{rec} \rangle}$$



1) No

2) cc

3) evolving clumping factor from numerical simulations (e.g Sharma+16; Finkelstein+19; Aaron+21)

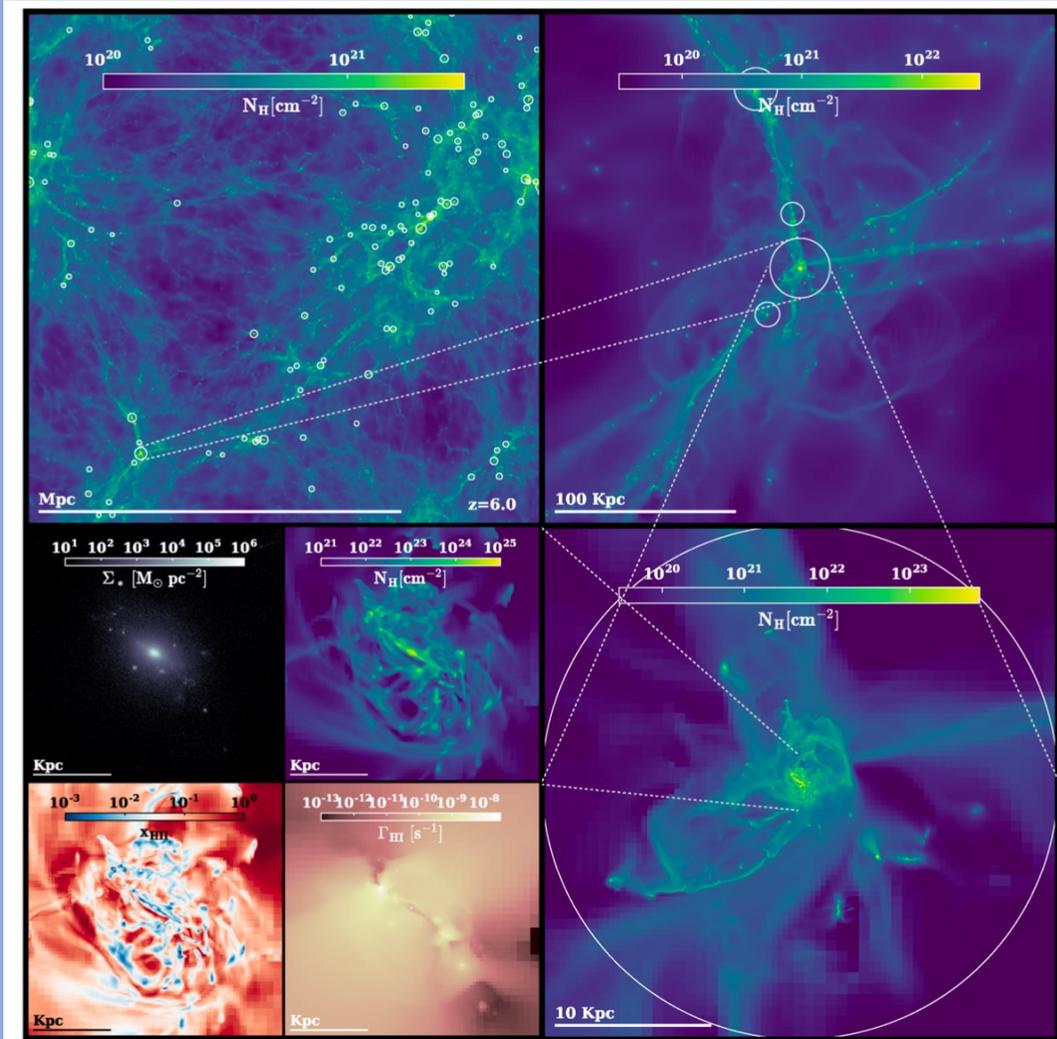
$$2\chi) \alpha_B C_{HII}]^{-1}$$

da-Escude 04)

aidu+20)

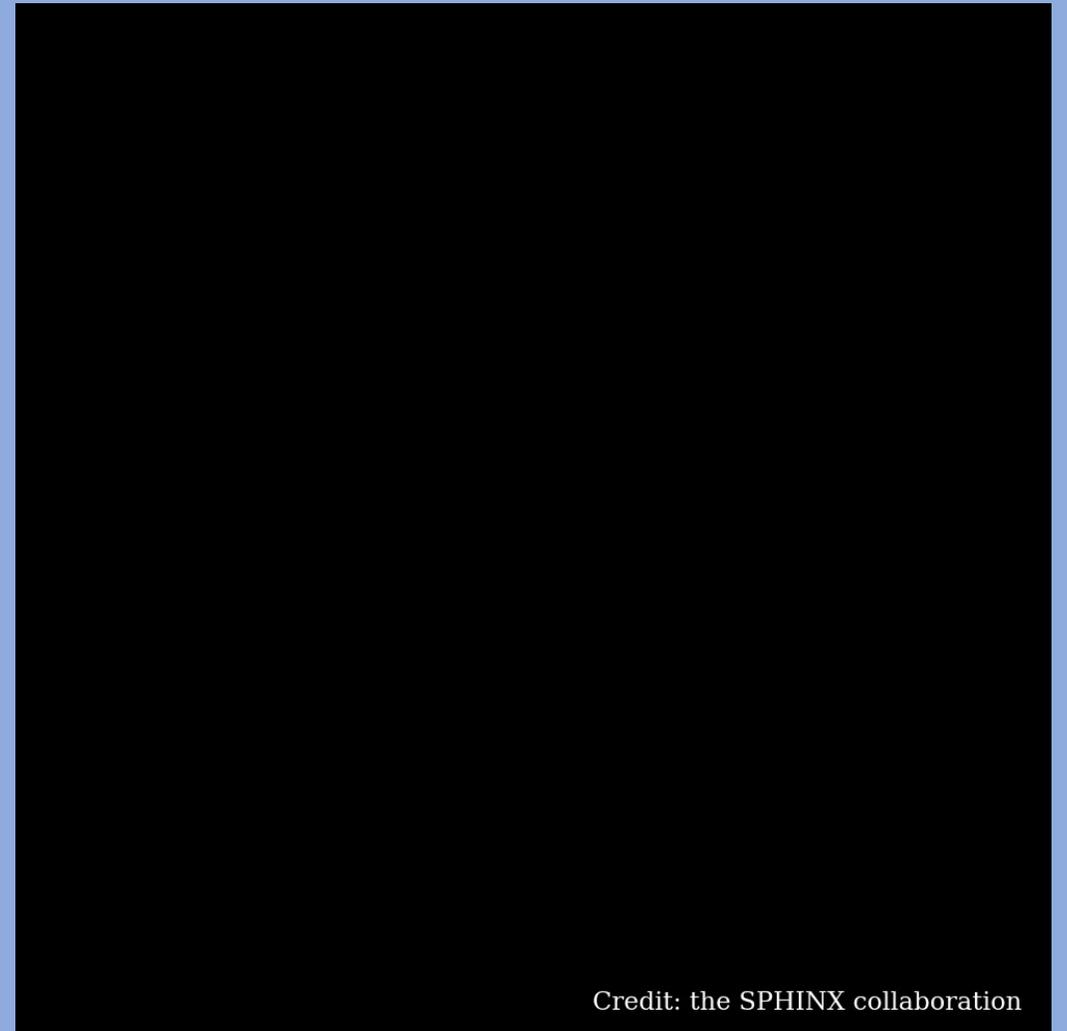
SPHINX simulation

High spatial resolution (~ 10 pc)



Rosdahl+18

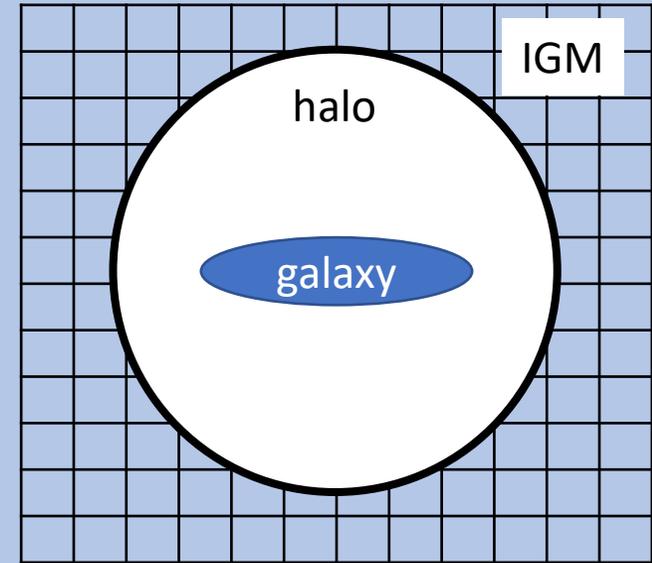
Fully radiative transfer



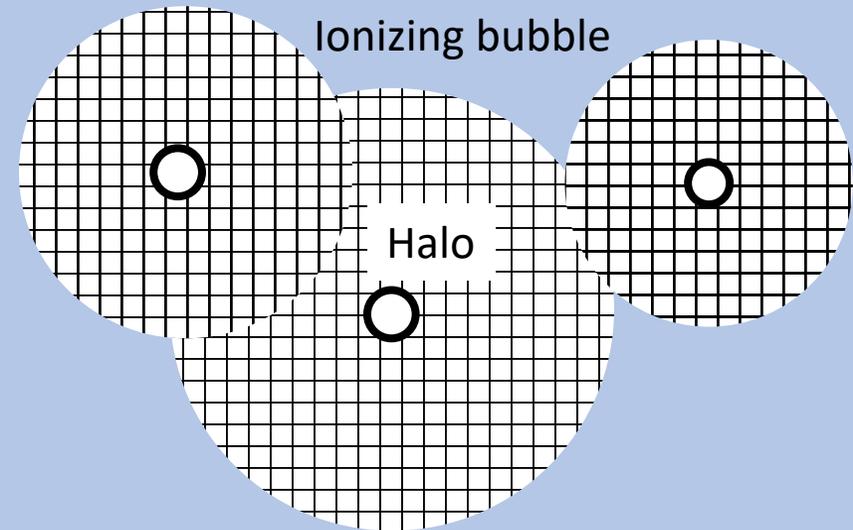
Criteria for the cell calculation

$$C_{HII} = \frac{\langle n_{HII}^2 \rangle}{\langle n_{HII} \rangle^2} = \frac{\frac{\sum_i n_{HII,i}^2 dV_i}{\sum_i dV_i}}{\left(\frac{\sum_i n_{HII,i} dV_i}{\sum_i dV_i} \right)^2}$$

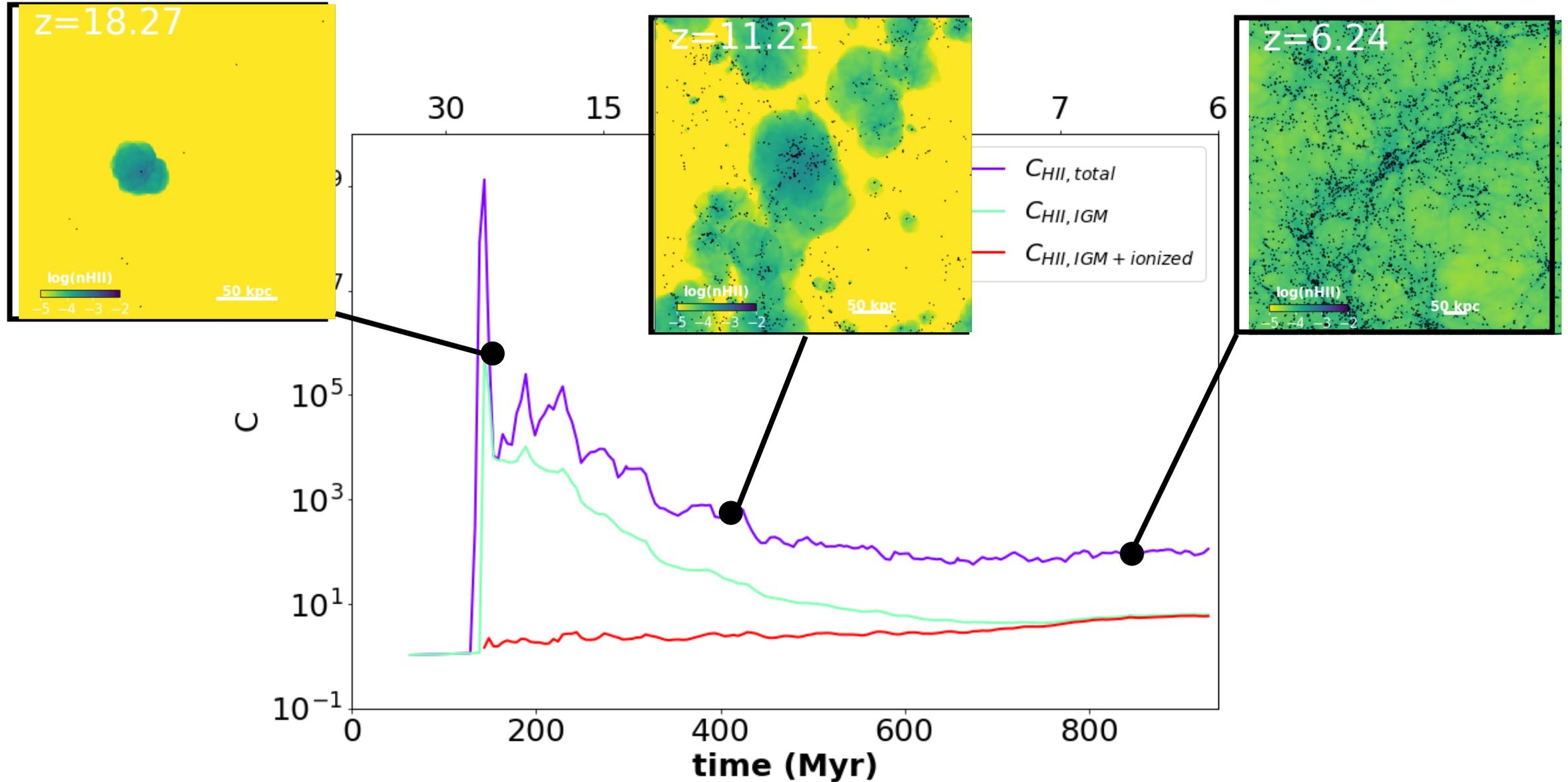
IGM



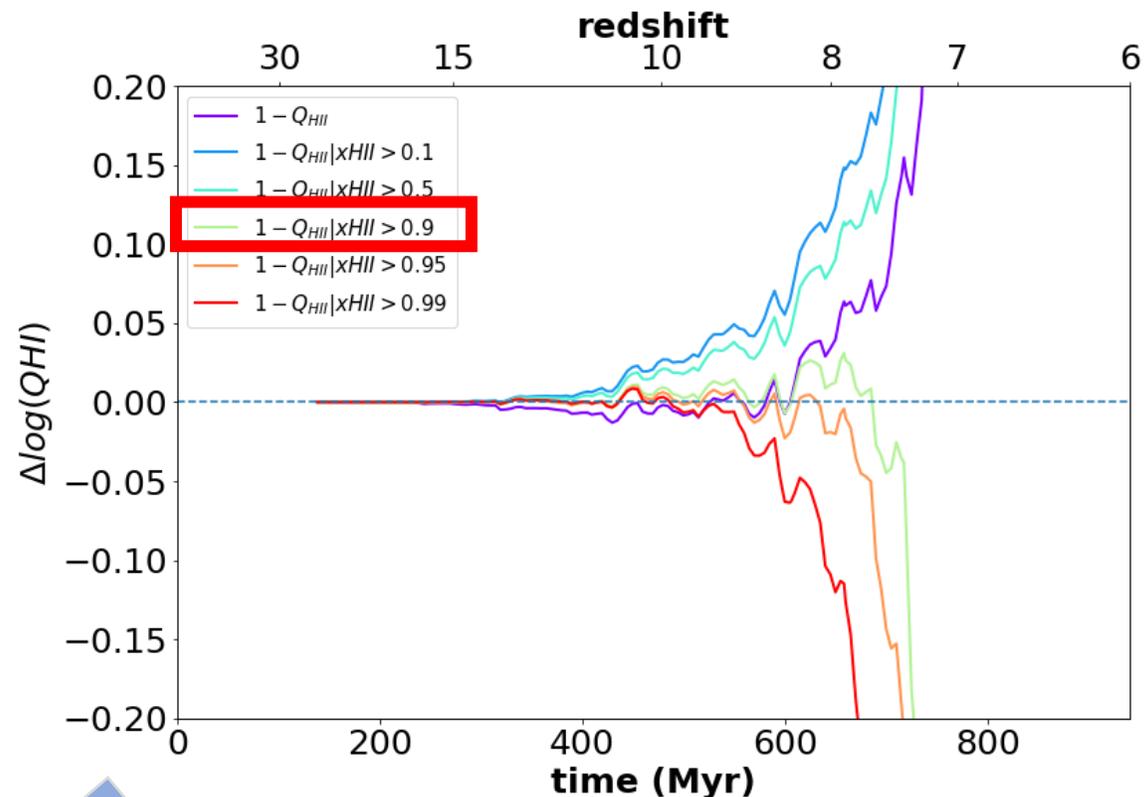
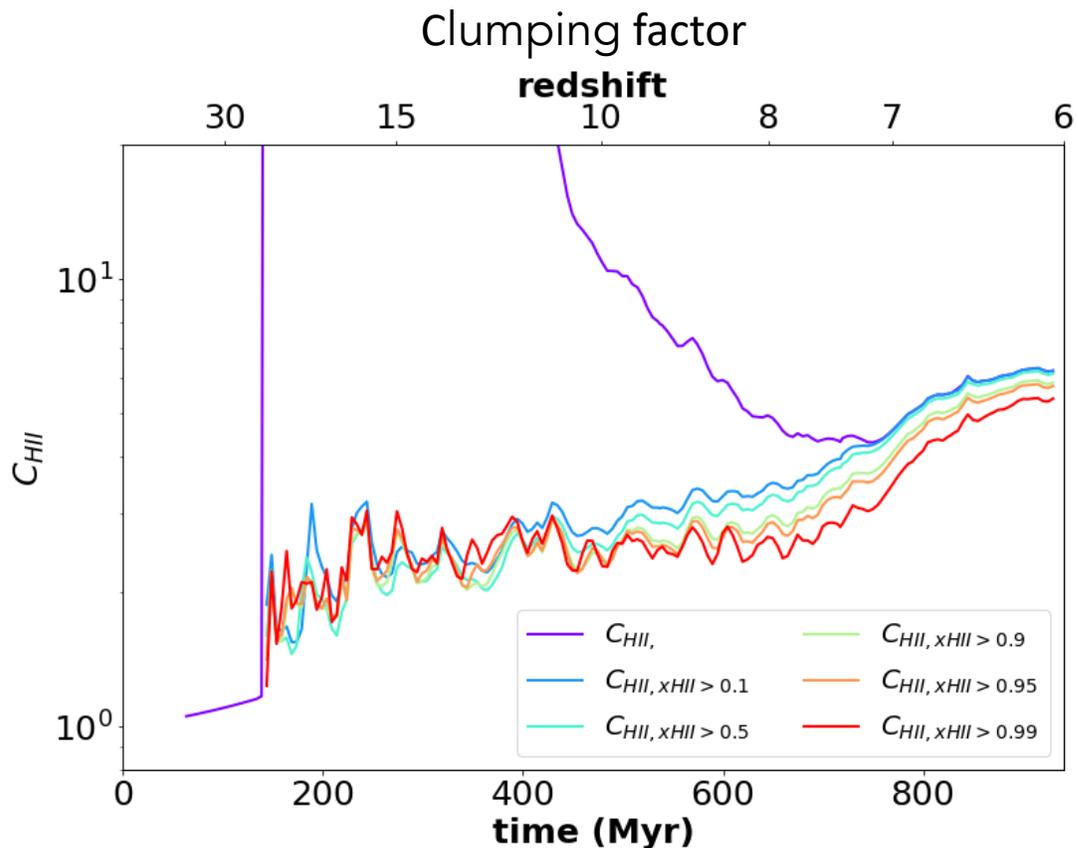
ionized regions



Example of clumping factors with different criteria



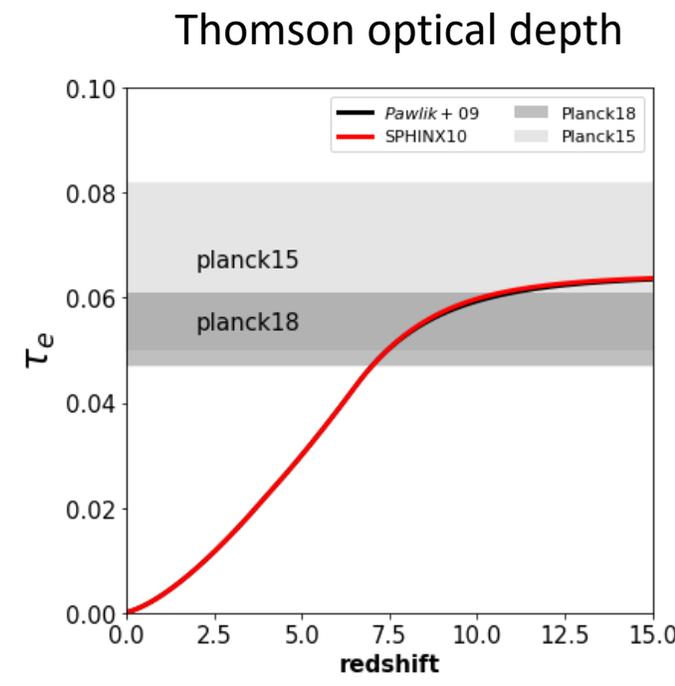
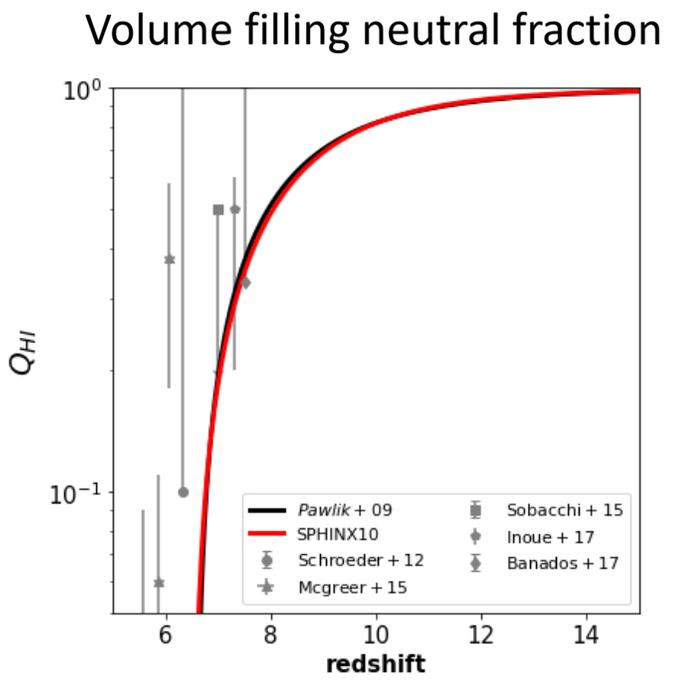
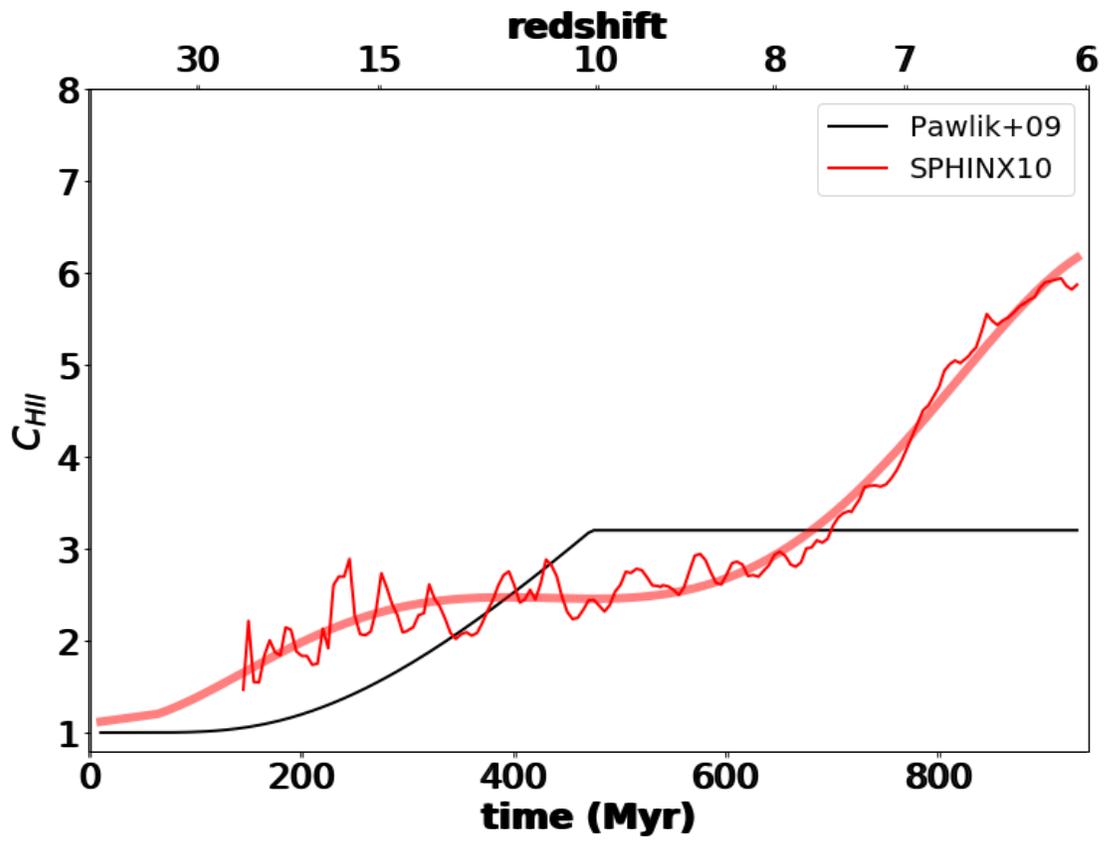
$x_{\text{HII}} > 0.9$ for the ionized regions



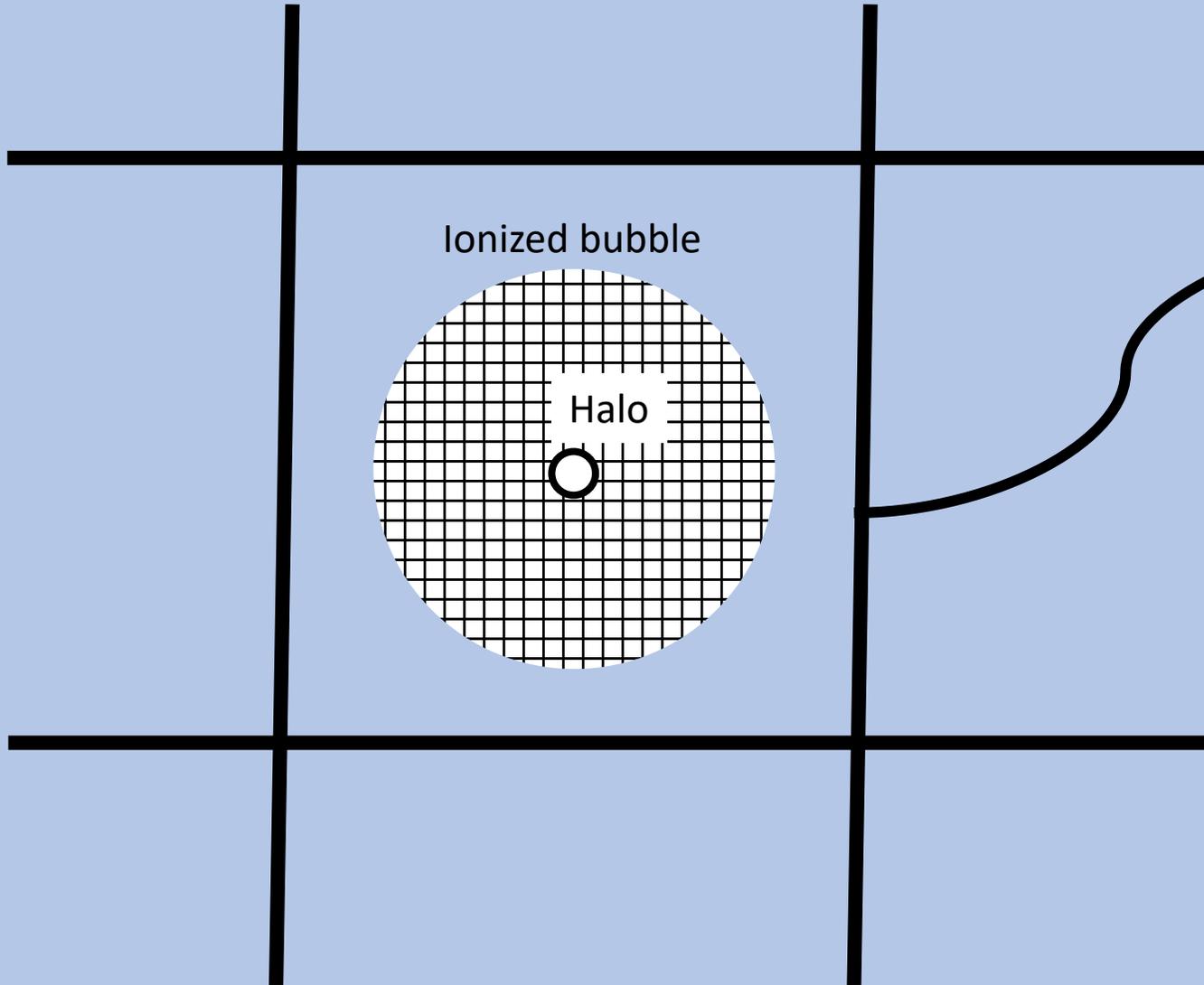
$$t_{\text{rec}} \equiv [\langle n_{\text{H}} \rangle (1 + 2\chi) \alpha_{\text{B}}(T) C]^{-1}$$

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

Clumping factor with $x_{\text{HII}} > 0.9$



Local clumping factors



Local ionization history

$$\frac{dx_e(x, z')}{dt} = \frac{dt}{dz'} (\Lambda_{ion} - \alpha_A C x_e n_b f_H)$$

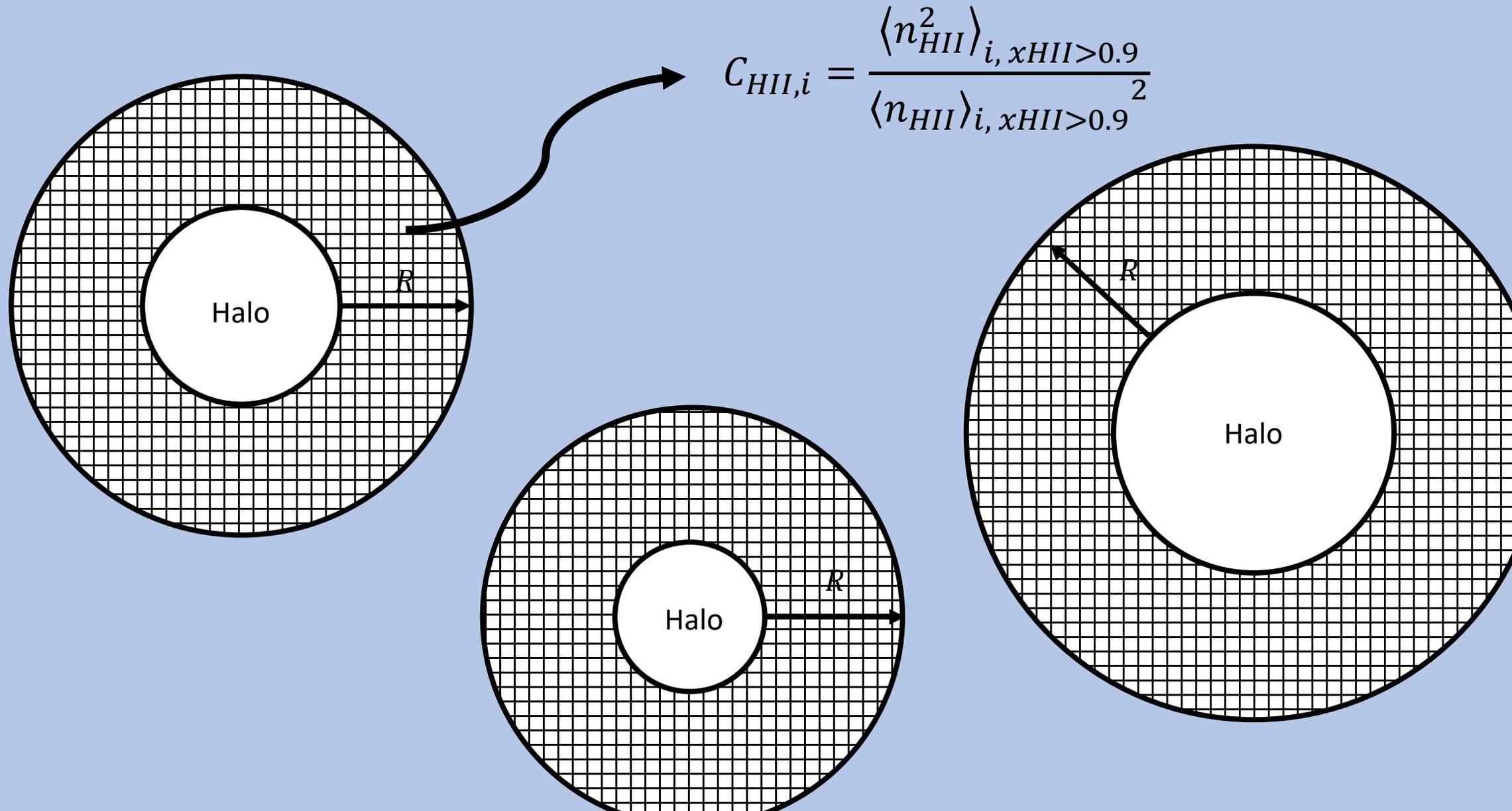
Mesinger+11

\neq

C from whole IGM

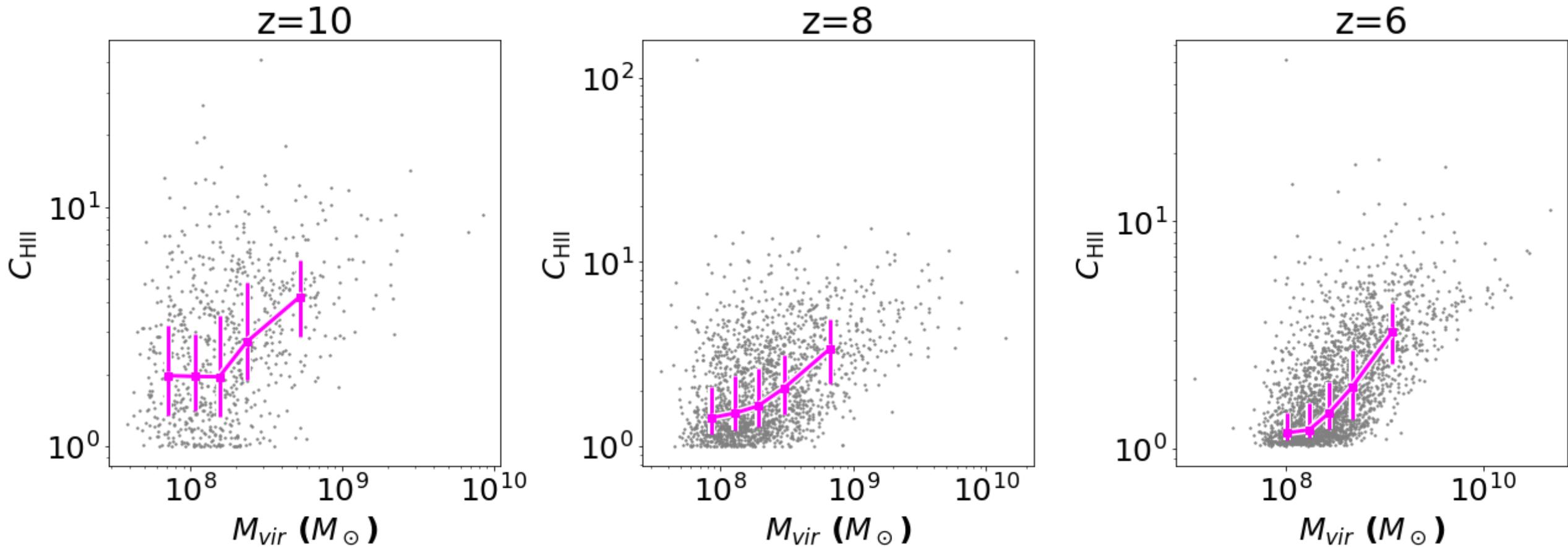
It is worth to explore the local clumping factors!

Local clumping factors



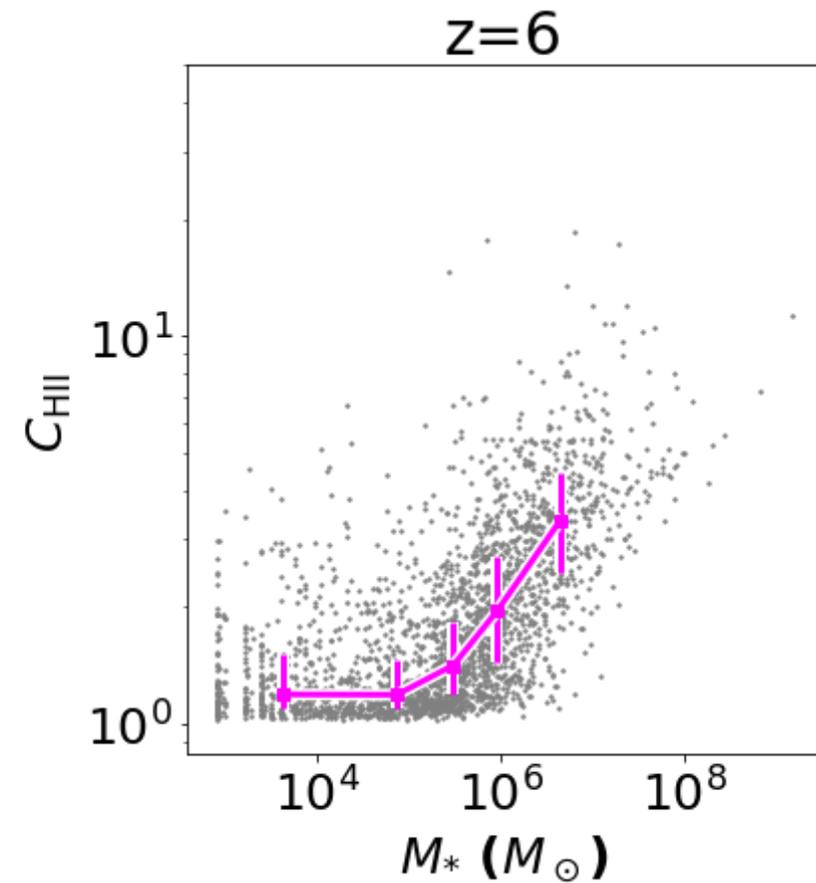
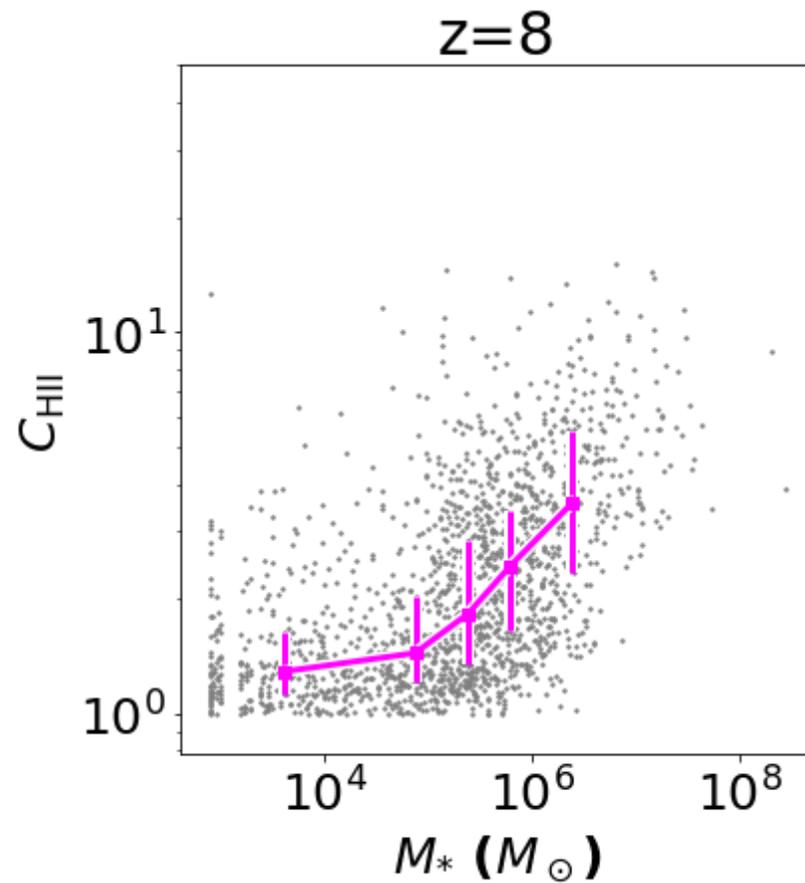
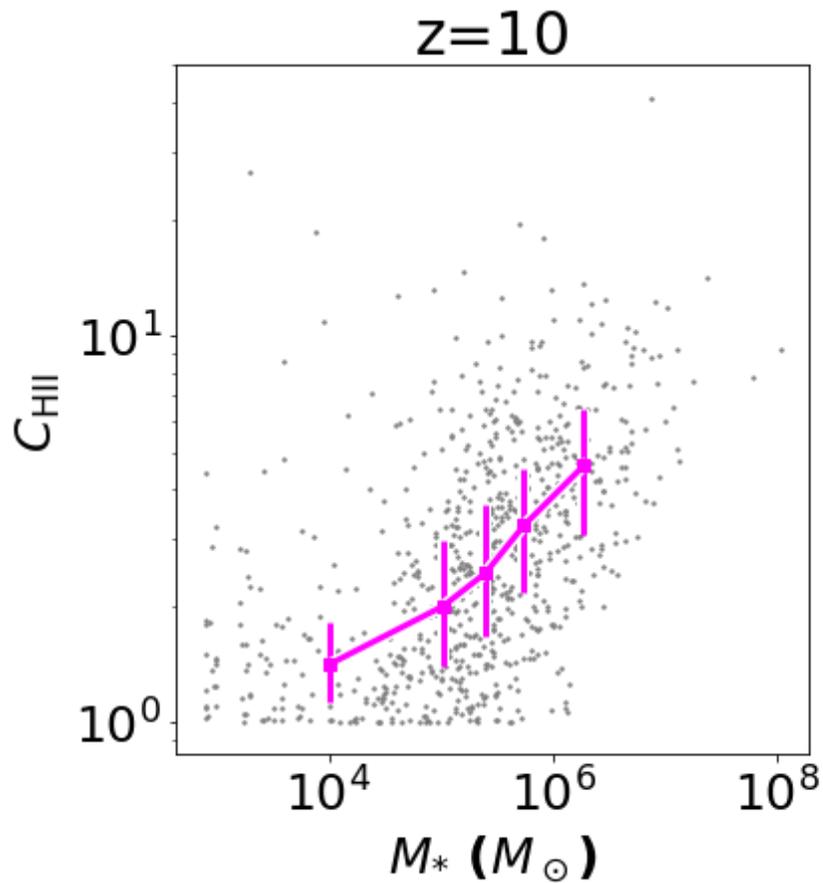
Halo mass vs Local clumping factors

$R = 1$ kpc



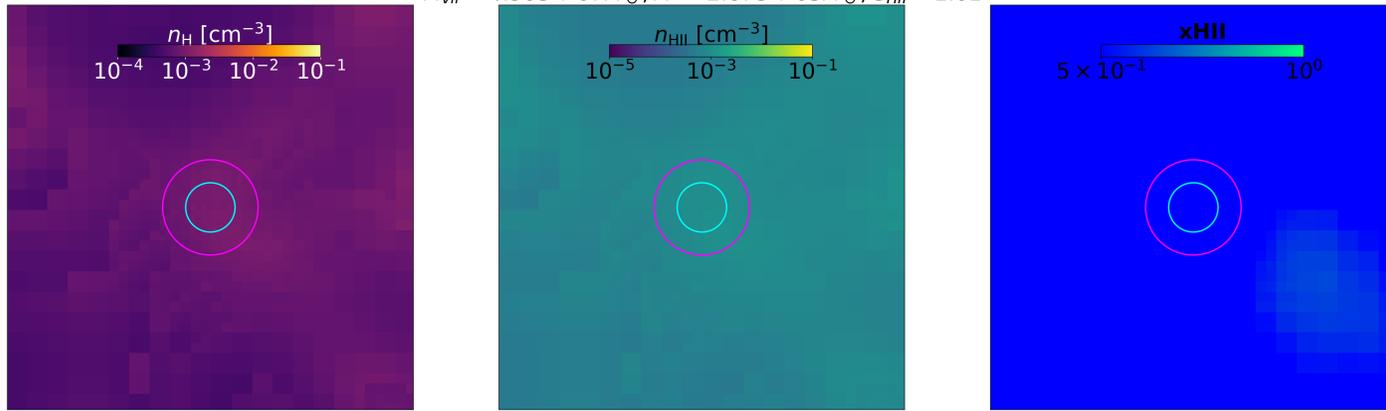
Stellar mass vs Local clumping factors

$R = 1$ kpc



Stellar mass vs Local clumping factors

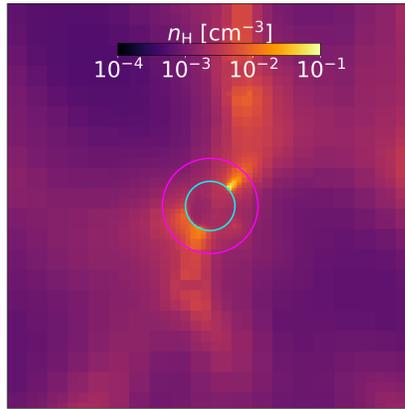
$M_{vir} = 4.90e + 07 M_{\odot}, M_{*} = 2.67e + 03 M_{\odot}, C_{HII} = 1.01$



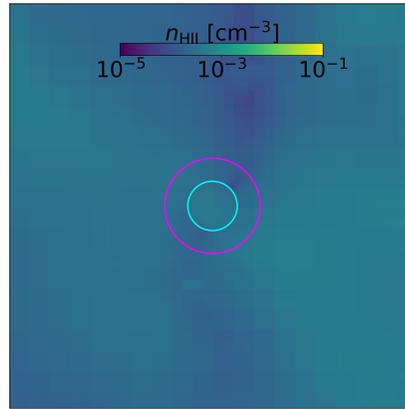
n_H ($x_{HII} > 0.9$)

n_{HII} ($x_{HII} > 0.9$)

x_{HII}

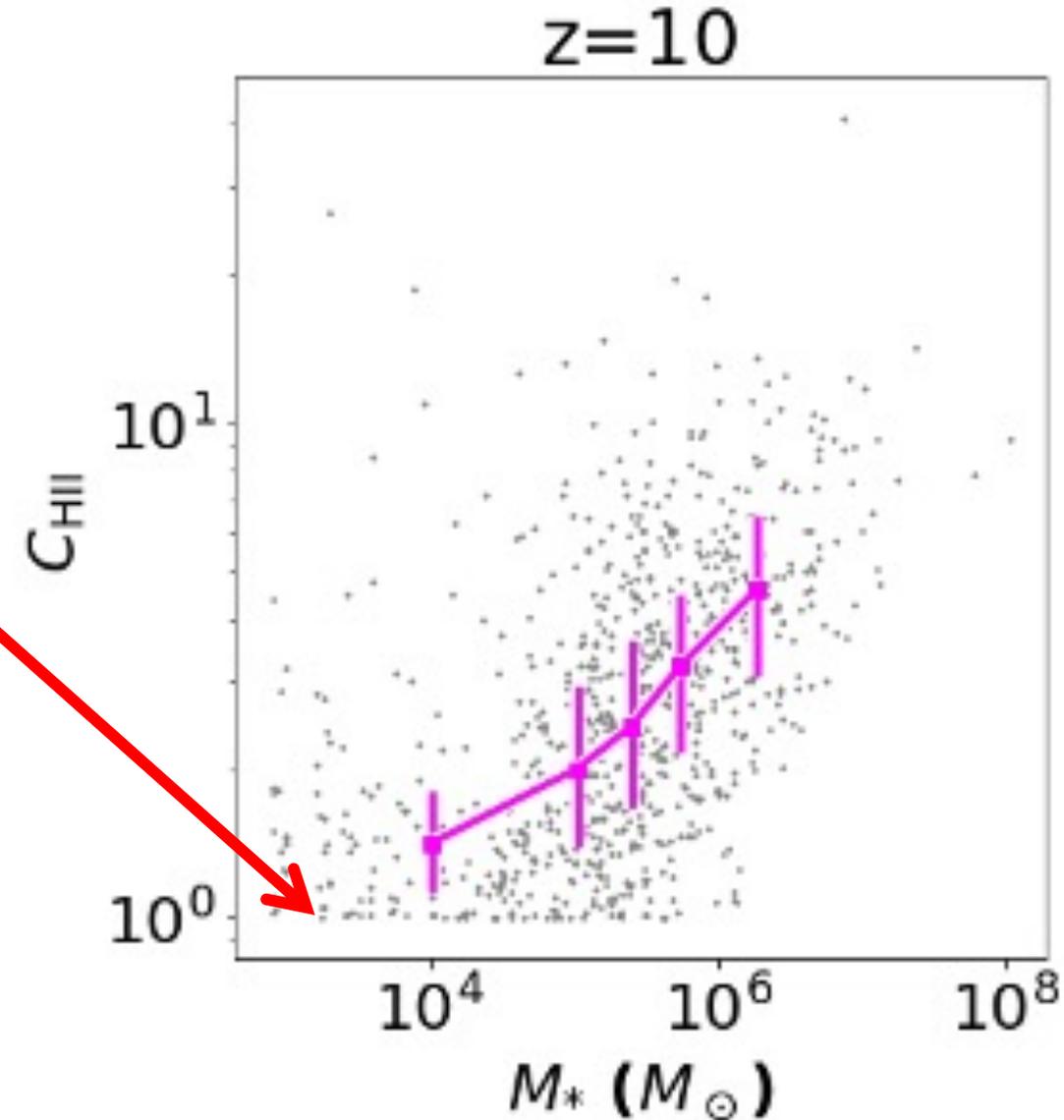


Total n_H



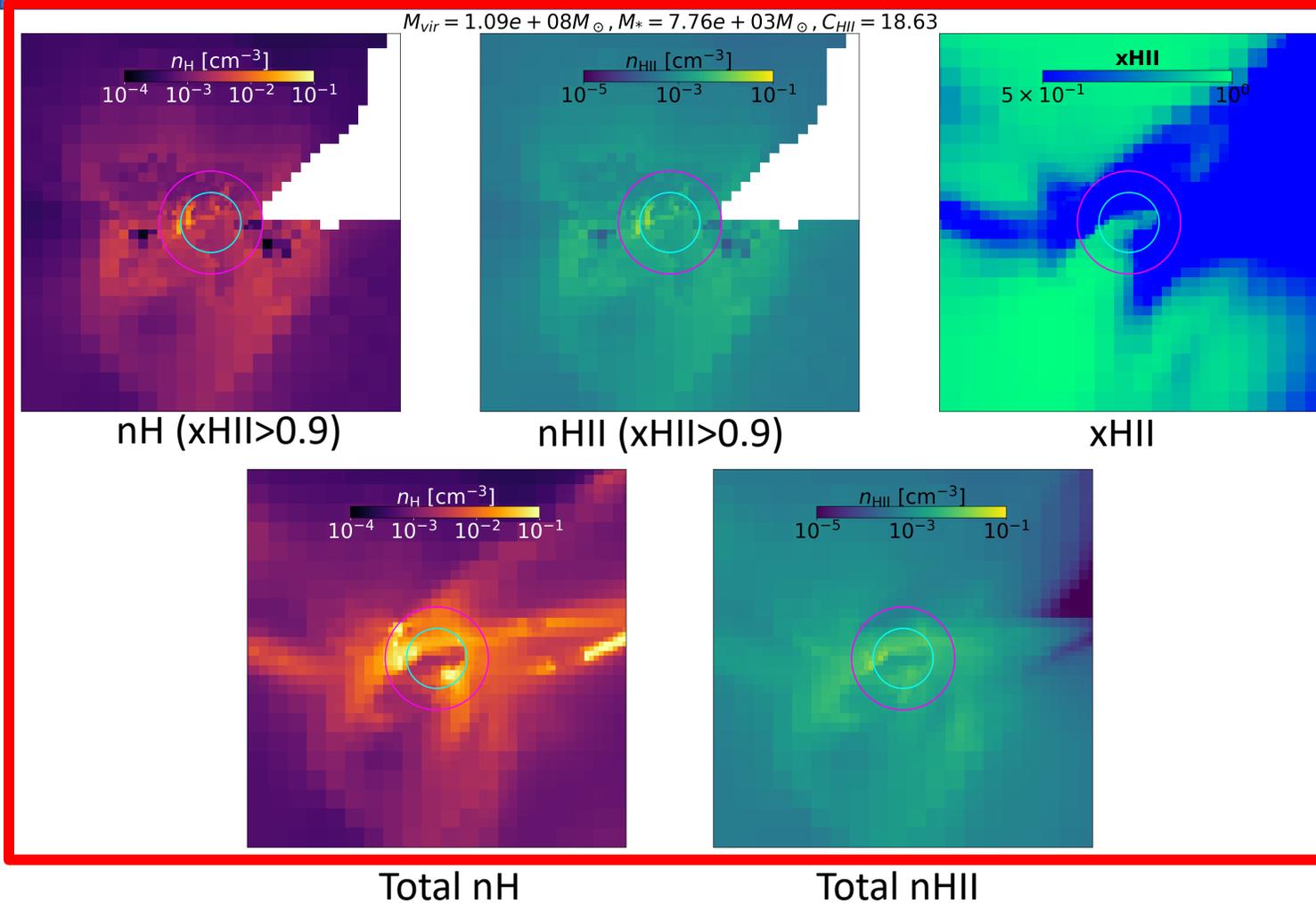
Total n_{HII}

Ionizing bubble is not formed yet

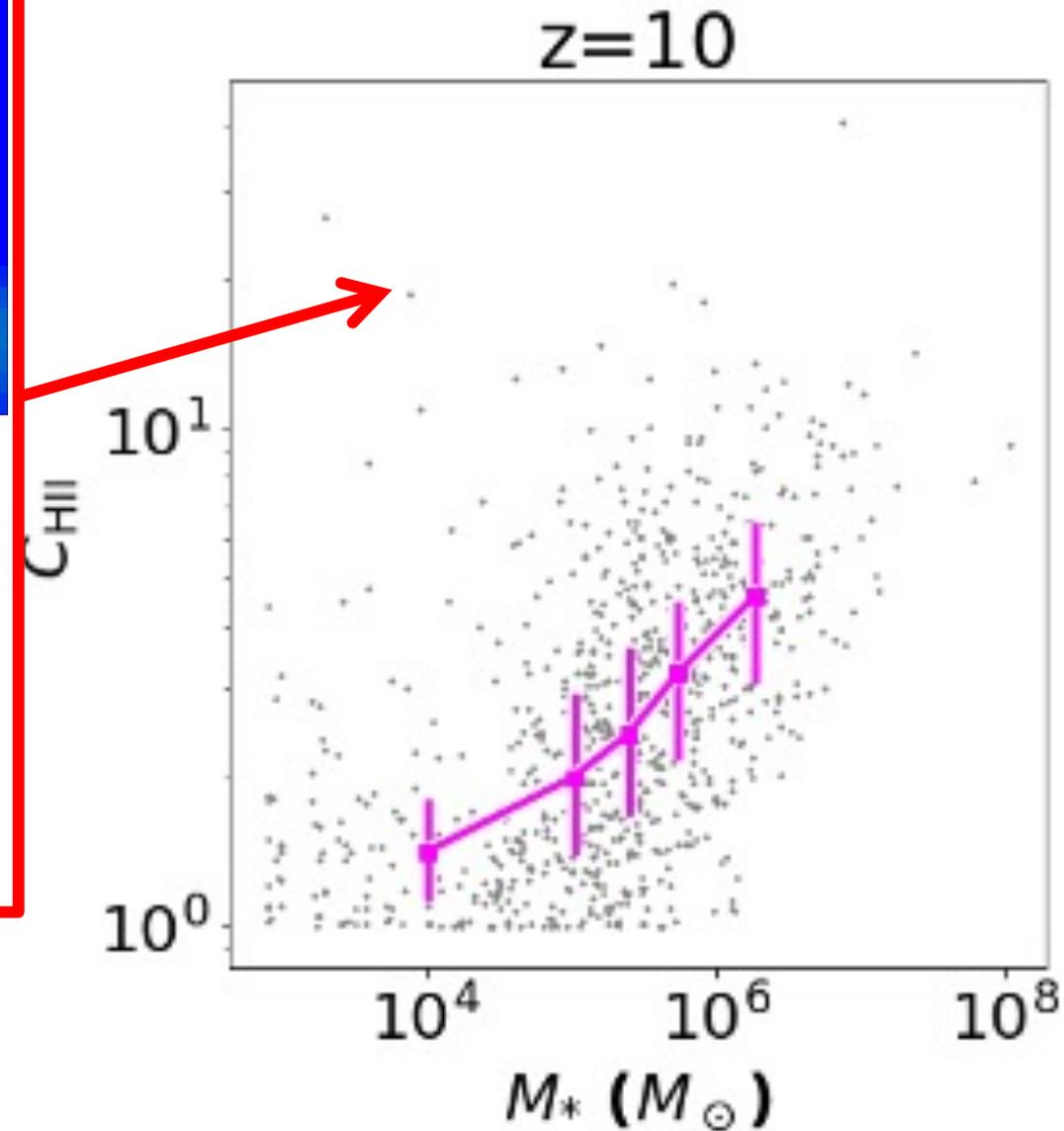


Stellar mass vs Local clumping factors

$M_{vir} = 1.09e + 08 M_{\odot}$, $M_{*} = 7.76e + 03 M_{\odot}$, $C_{HII} = 18.63$

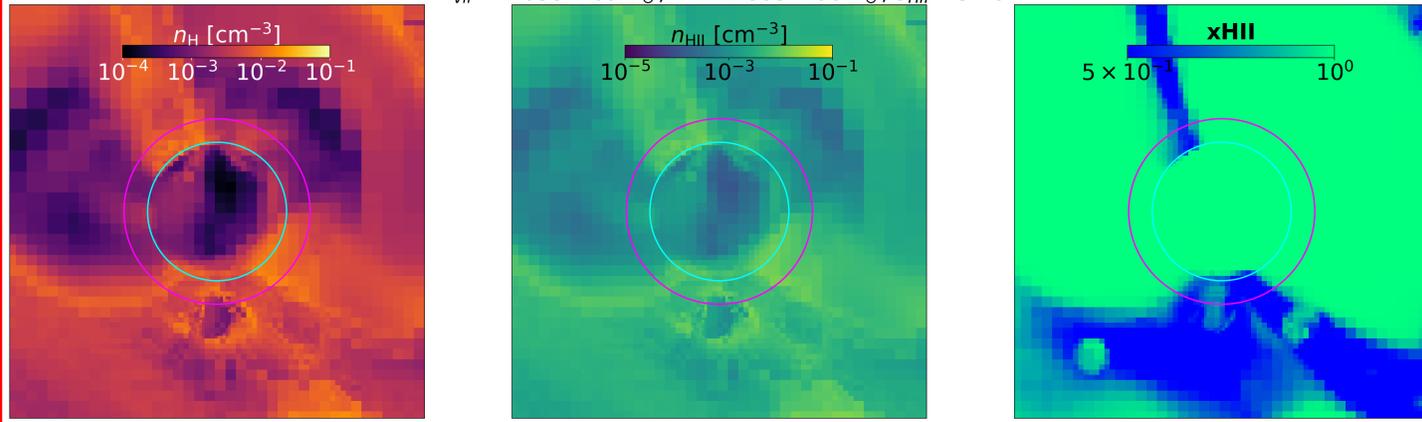


Some neighboring gas cells are ionized



Stellar mass vs Local clumping factors

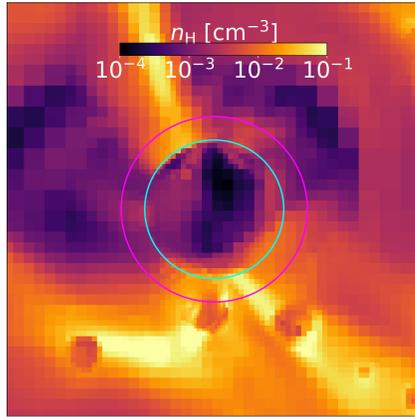
$M_{vir} = 1.03e + 09 M_{\odot}$, $M_{*} = 7.88e + 06 M_{\odot}$, $C_{HII} = 3.70$



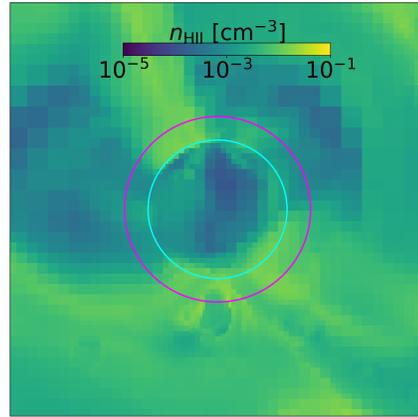
n_H ($x_{HII} > 0.9$)

n_{HII} ($x_{HII} > 0.9$)

x_{HII}

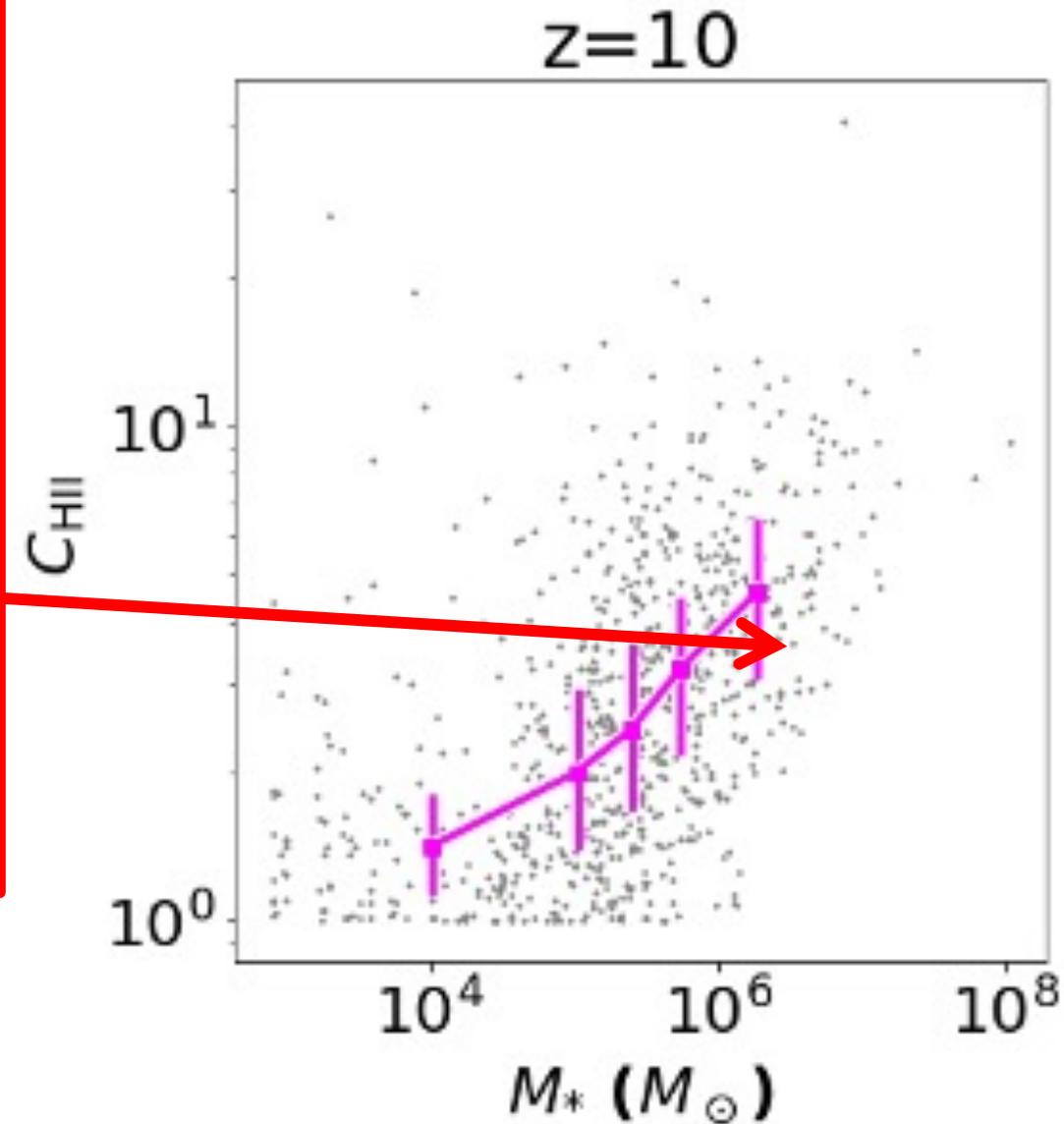


Total n_H



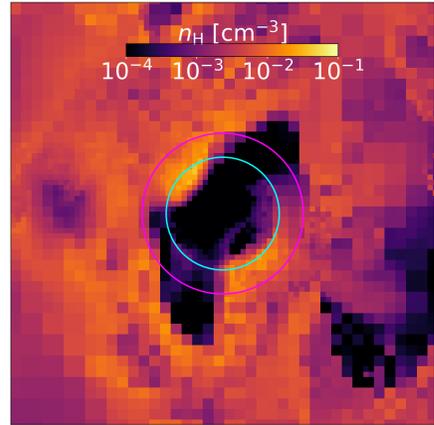
Total n_{HII}

Developed ionized bubble

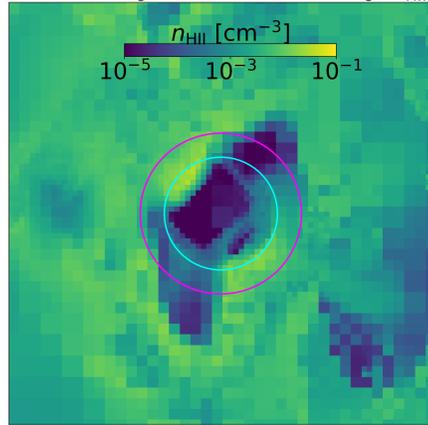


Stellar mass vs Local clumping factors

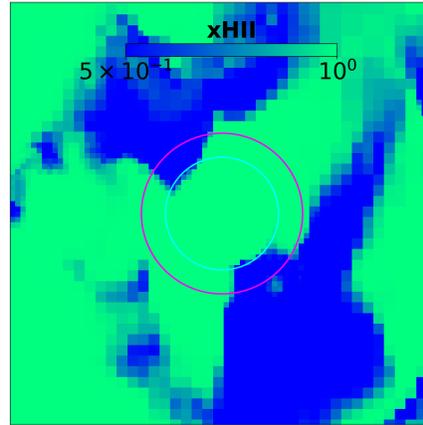
$M_{vir} = 5.14e + 08 M_{\odot}$, $M_{*} = 8.12e + 06 M_{\odot}$, $C_{HII} = 12.23$



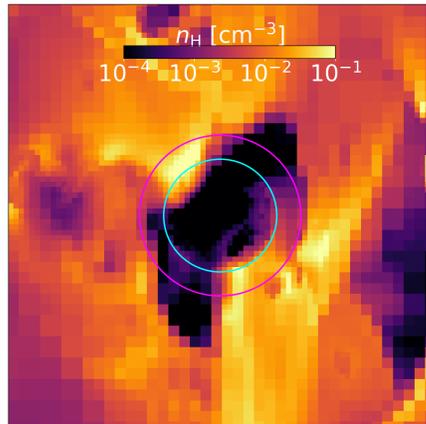
nH ($x_{HII} > 0.9$)



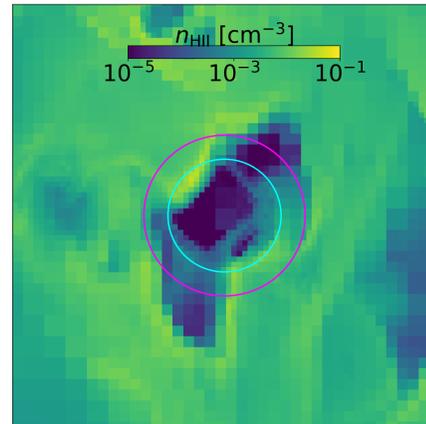
nHII ($x_{HII} > 0.9$)



xHII

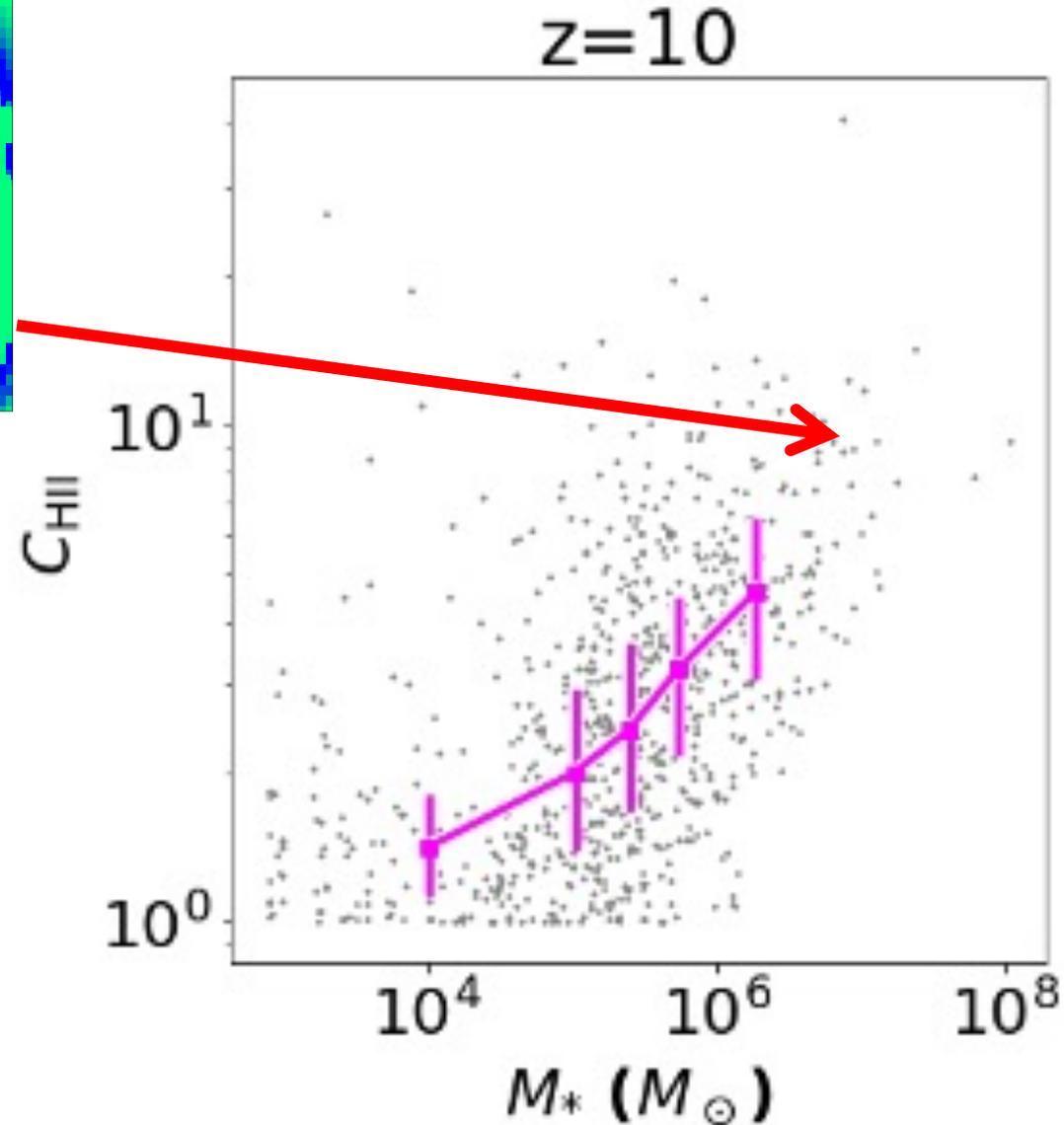


Total nH



Total nHII

Complex density distribution + cavity



Conclusions

- When we only consider for the ionized region ($x_{\text{HII}} > 0.9$), we found that the clumping factor of the IGM slightly increases from $C = 2$ at $z = 15$ to $C = 6$ at $z = 6$, reproducing similar results with previous estimation (Pawlik+09).
- We found the positive correlation between local clumping factors and halo / stellar masses, which is useful information for subgrid calculation of local ionization history.

Backup slides

Clumping factors : which definition?

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\langle n_H \rangle} - \frac{Q_{HII}}{\bar{t}_{rec}} \quad (\text{Madau+99})$$

Local recombination timescale

$$\frac{dn_{HII}}{dt} = -n_{HII}n_e\alpha_B(T),$$
$$\frac{dn_{HII}}{dt} \equiv -\frac{n_{HII}}{t_{rec}}$$

$$\rightarrow t_{rec} = [n_e\alpha_B(T)]^{-1}$$

Global recombination timescale

Average for inhomogeneous densities,

$$\bar{t}_{rec} = [\langle n_e \rangle \alpha_B(T) C_{RR}]^{-1}$$

$$C_{RR} \equiv \frac{\langle n_{HII} n_e \alpha_B(T) \rangle}{\langle n_{HII} \rangle \langle n_e \rangle \langle \alpha_B(T) \rangle}$$

(Shull+12, So+14)

T=20000K, fully ionized helium

$$\bar{t}_{rec} = [\langle n_{HII} \rangle (1 + 2\chi) \alpha_B C_{HII}]^{-1}$$



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

(Gnedin&Ostriker97,
Finlator+12, So+14)

Fully ionized hydrogen

$$\bar{t}_{rec} = [\langle n_H \rangle \alpha_B C_b]^{-1}$$

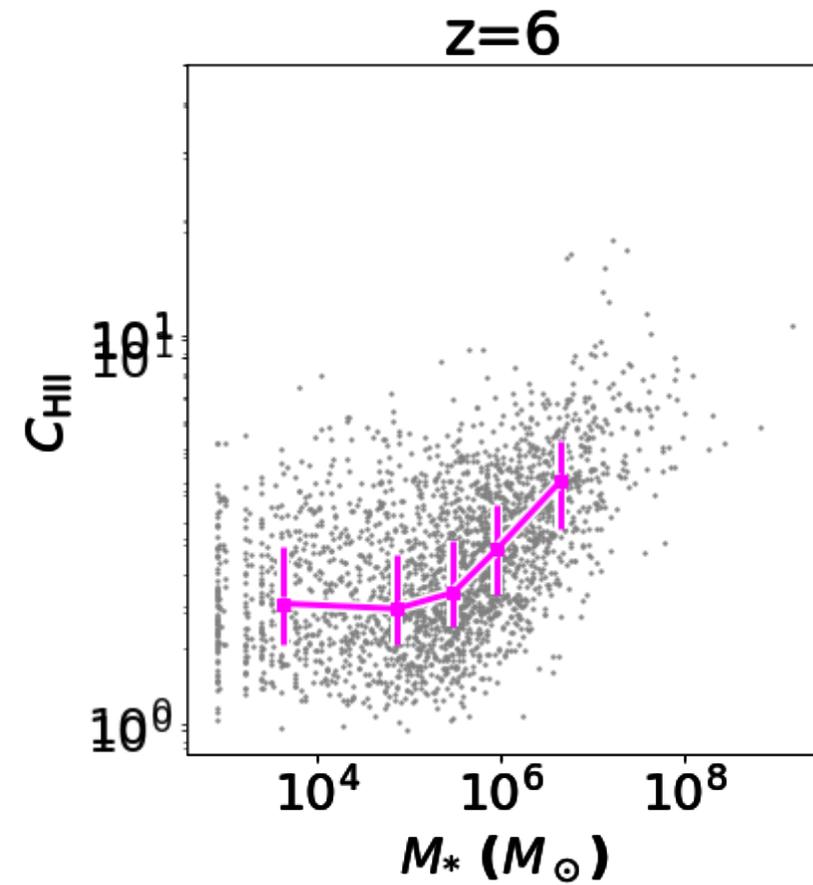
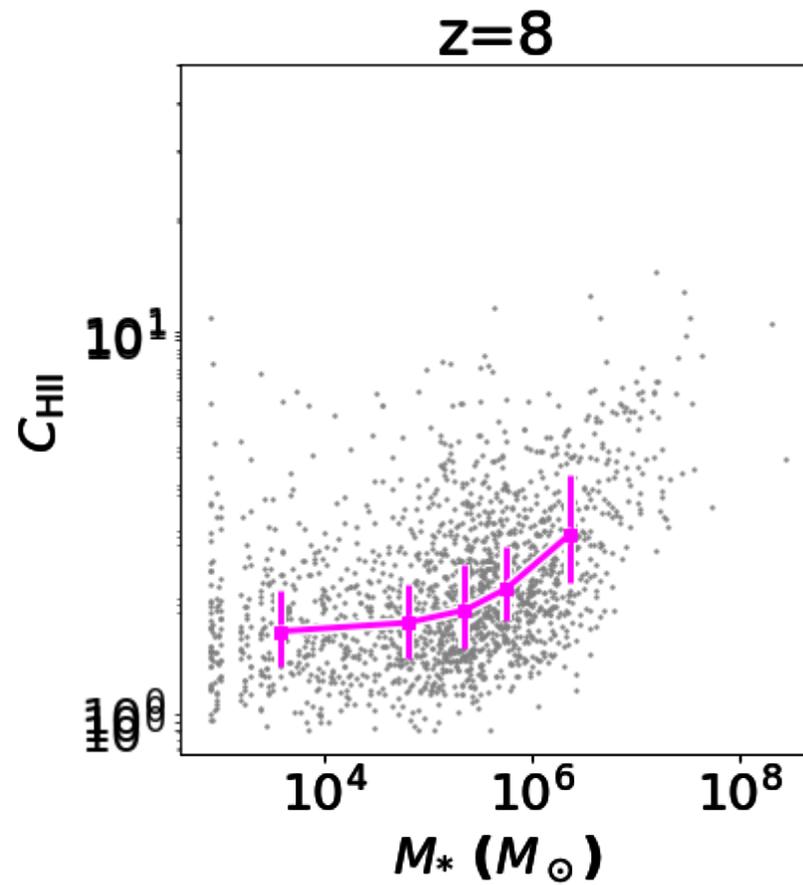
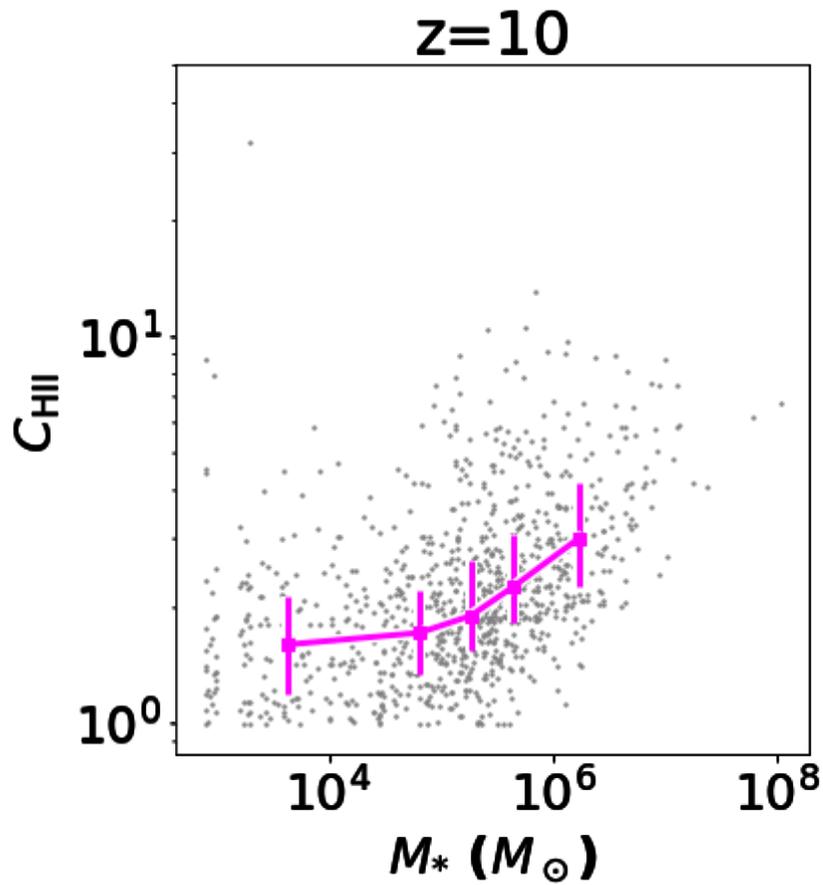


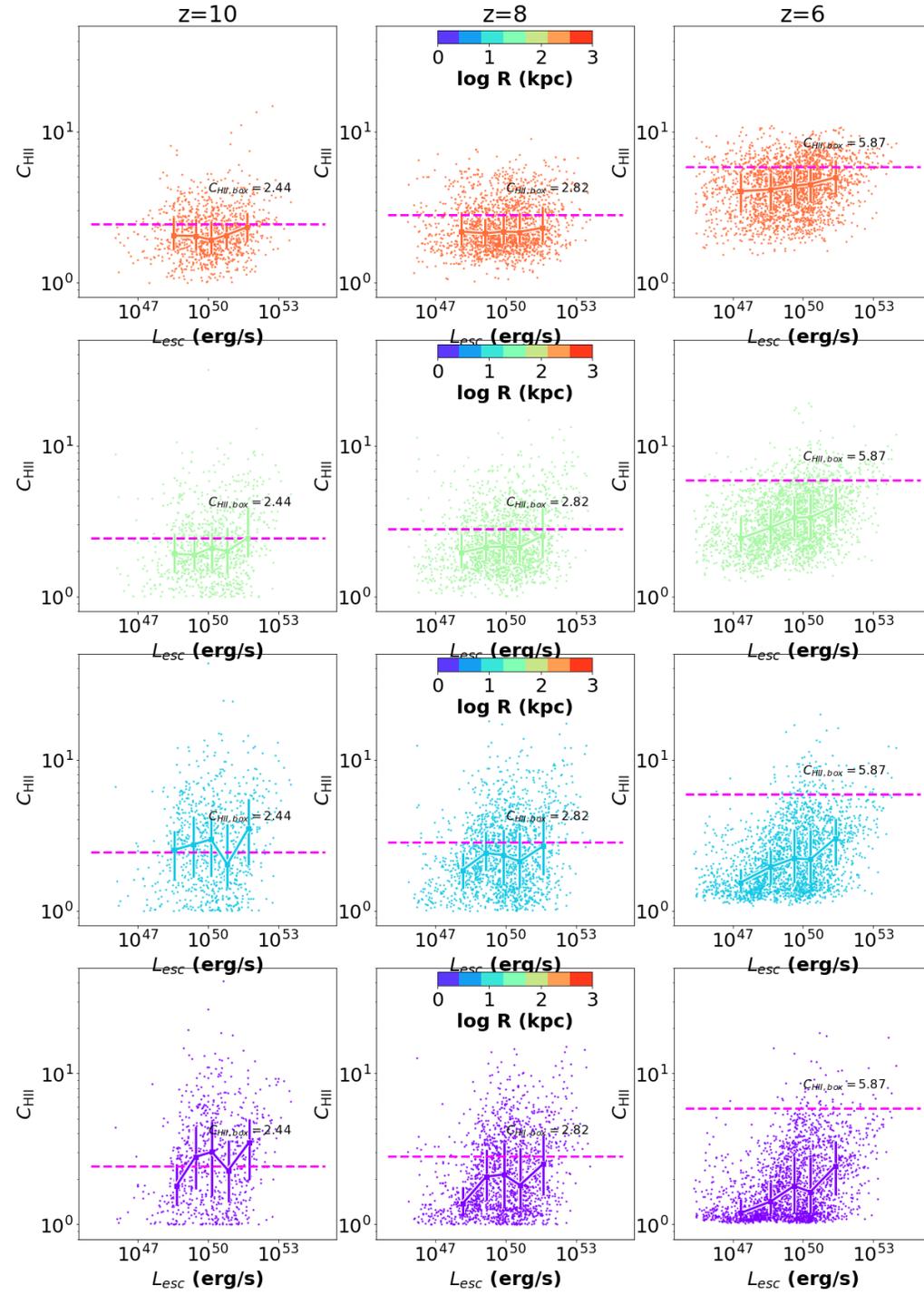
$$C_b \equiv \frac{\langle n_H^2 \rangle}{\langle n_H \rangle^2}$$

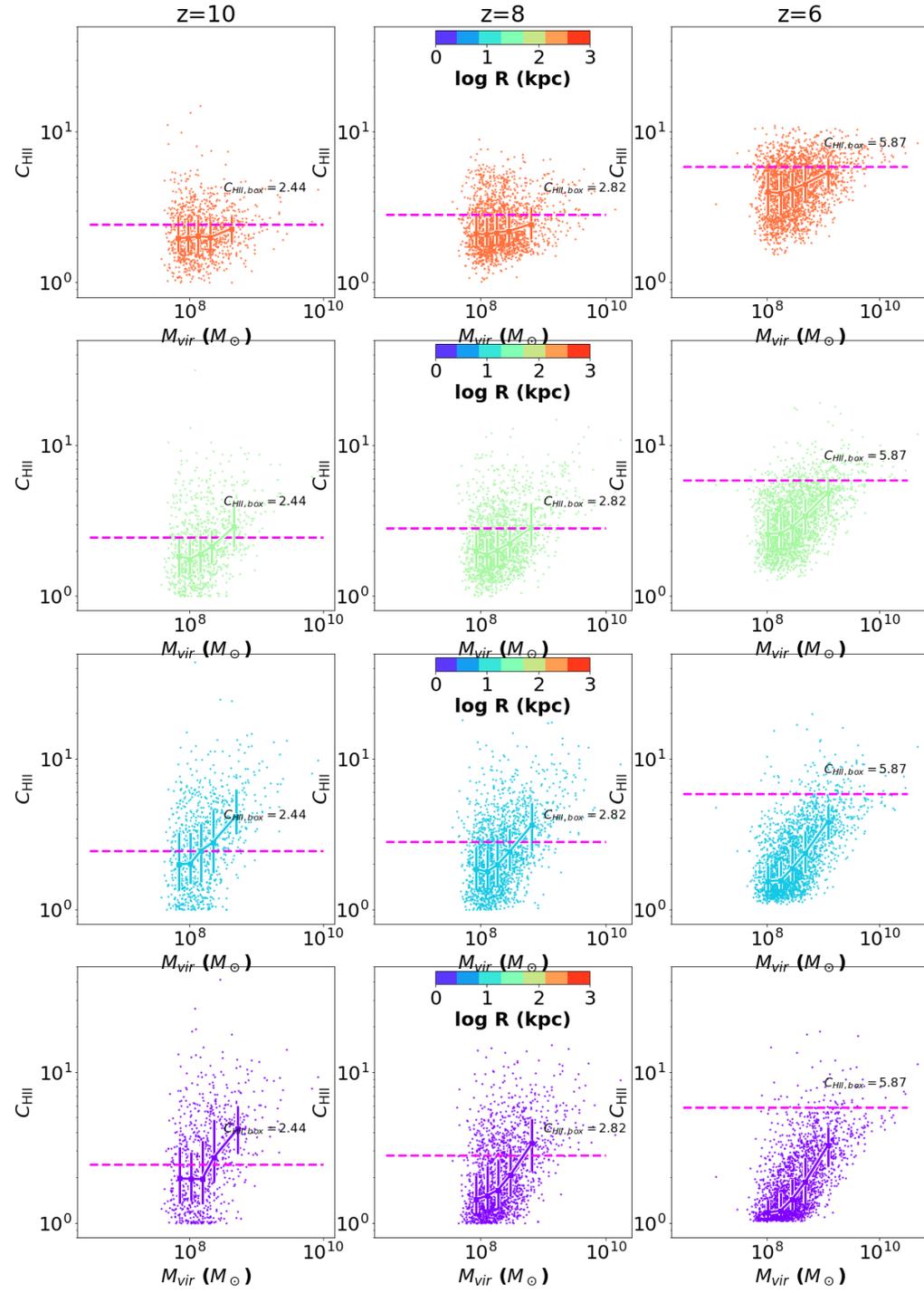
(Pawlik+09,+15)

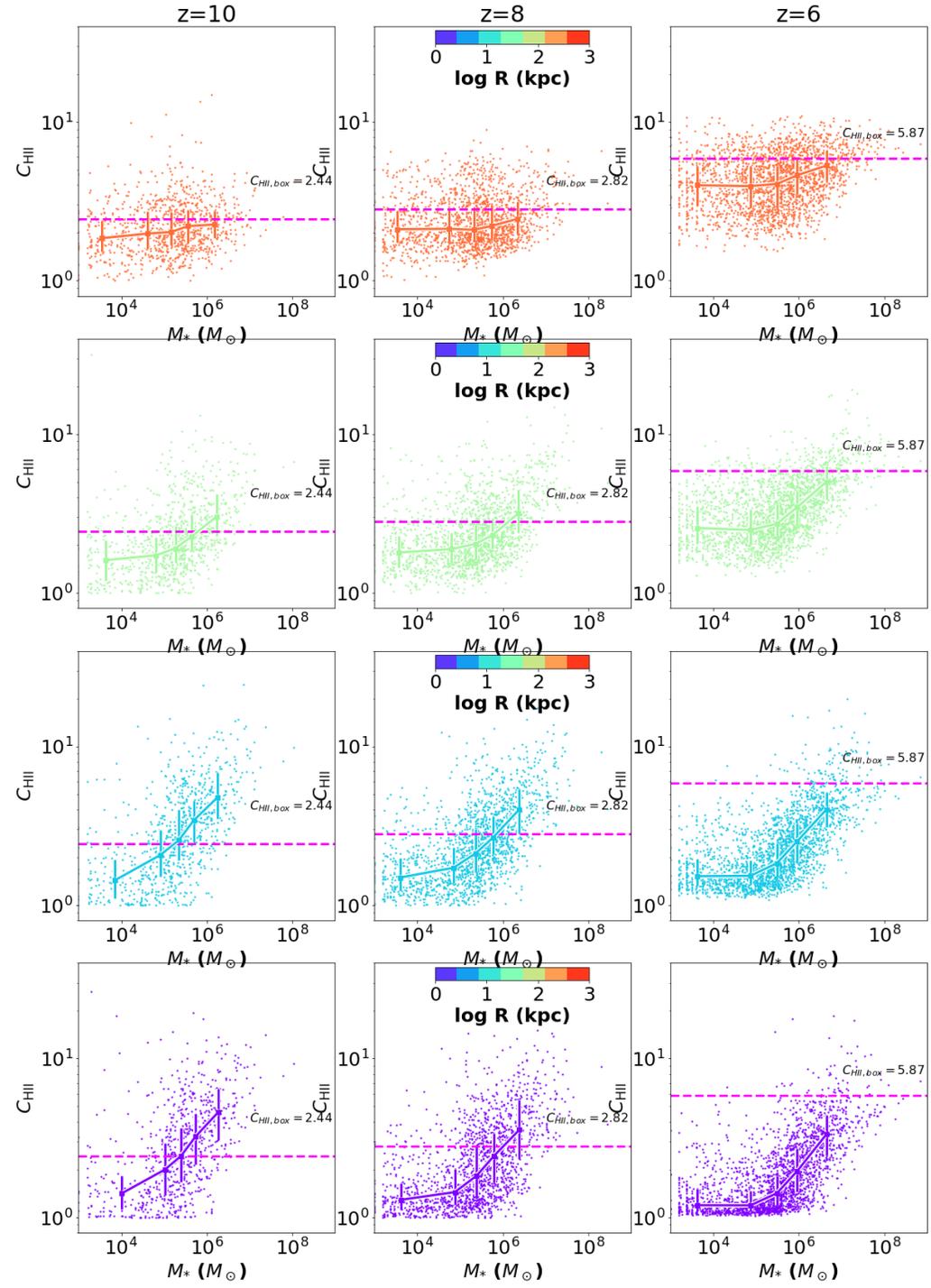
Stellar mass vs Local clumping factors

$R = 100$ kpc

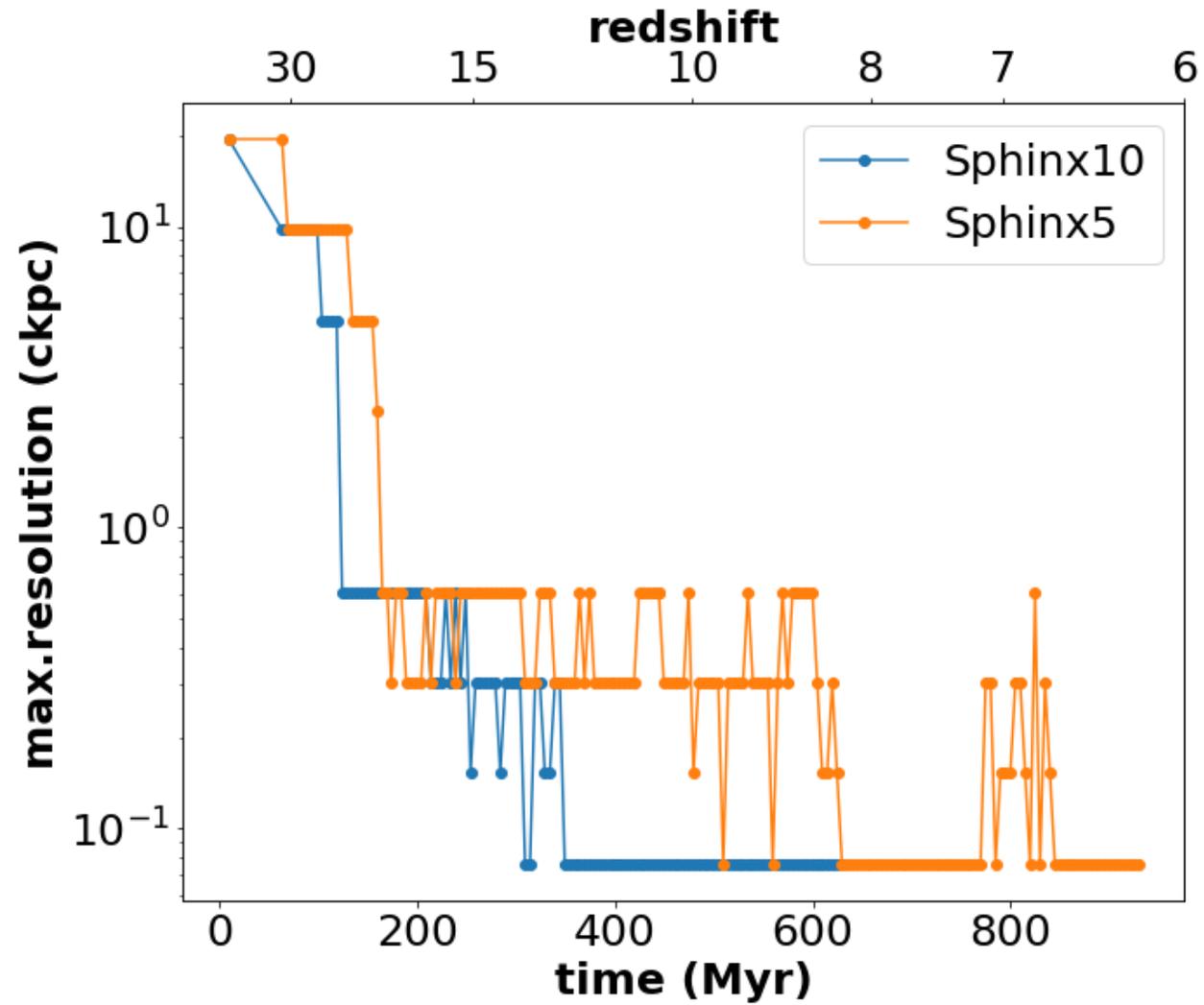






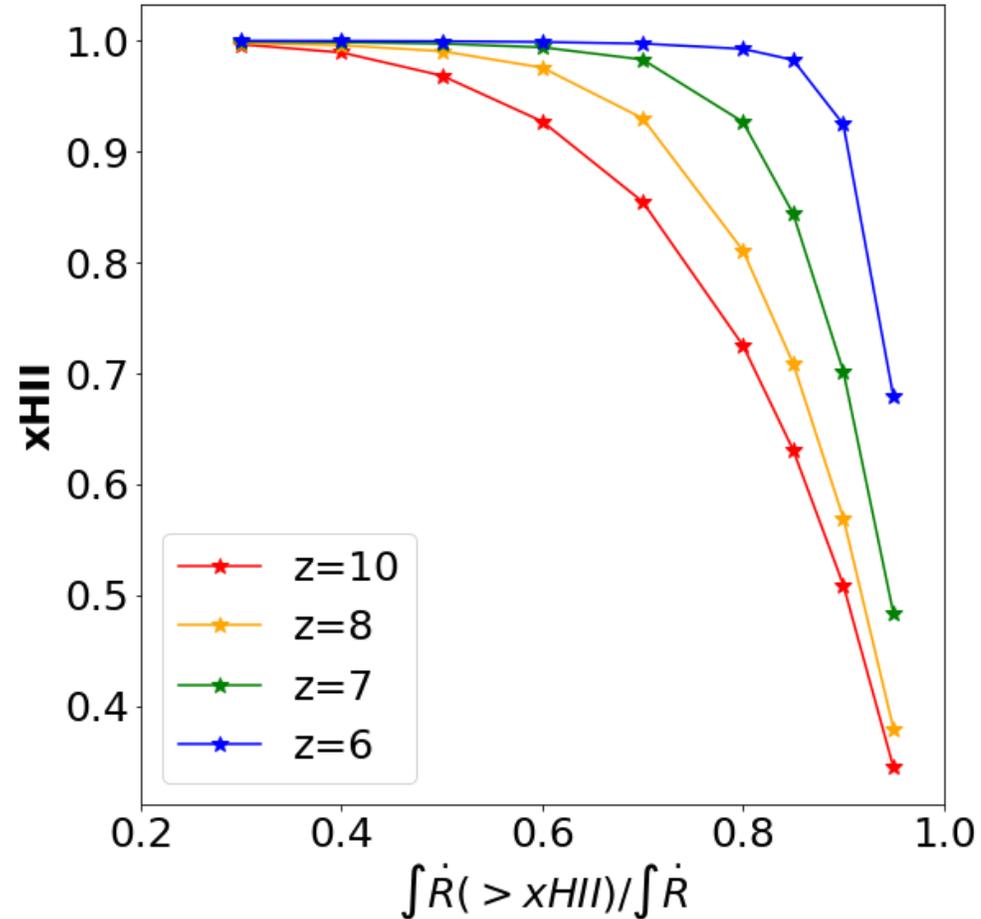


Max. resolution in the IGM



evolving ionized fraction threshold

Ionized fraction threshold



Cumulative function for the contribution to total recombination rate