CAASTRO
ALL-SKY ASTROPHYSICS

THE UNIVERSITY OF MELBOURNE

Clumping factors of HII, HeII and HeIII

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Big simulation box and high spatial resoution

- Sources – PopIII stars, galaxies, quasars – high σ peaks (100s Mpc box) [e.g. Barkana & Loeb 2004] at high mass resolution [e.g. Bolton & Haehnelt 2007].
- Resolving IGM (~10 kpcs) [e.g. Schaye 2001; McQuinn et al. 2007] and ionized bubbles (~ Mpc) [e.g. Wyithe & Loeb 2004].

100 cMpc box with

10s kpc spatial resolution

Clumping factors

For example, in the case of a H only simulation, the ionization balance is given by –

$$\frac{d}{dt}n_{\mathrm{HI}} = -3Hn_{\mathrm{HI}} - n_{\mathrm{HI}}\Gamma + R(T)n_e n_{\mathrm{HII}}, \quad (5)$$

This can be re-written as –

$$\frac{d}{dt}\tilde{n}_{\mathrm{HI}} = -3H\tilde{n}_{\mathrm{HI}} - C_I\tilde{n}_{\mathrm{HI}}\tilde{\Gamma} + C_R\tilde{R}\tilde{n}_e\tilde{n}_{\mathrm{HII}}, \quad (7)$$

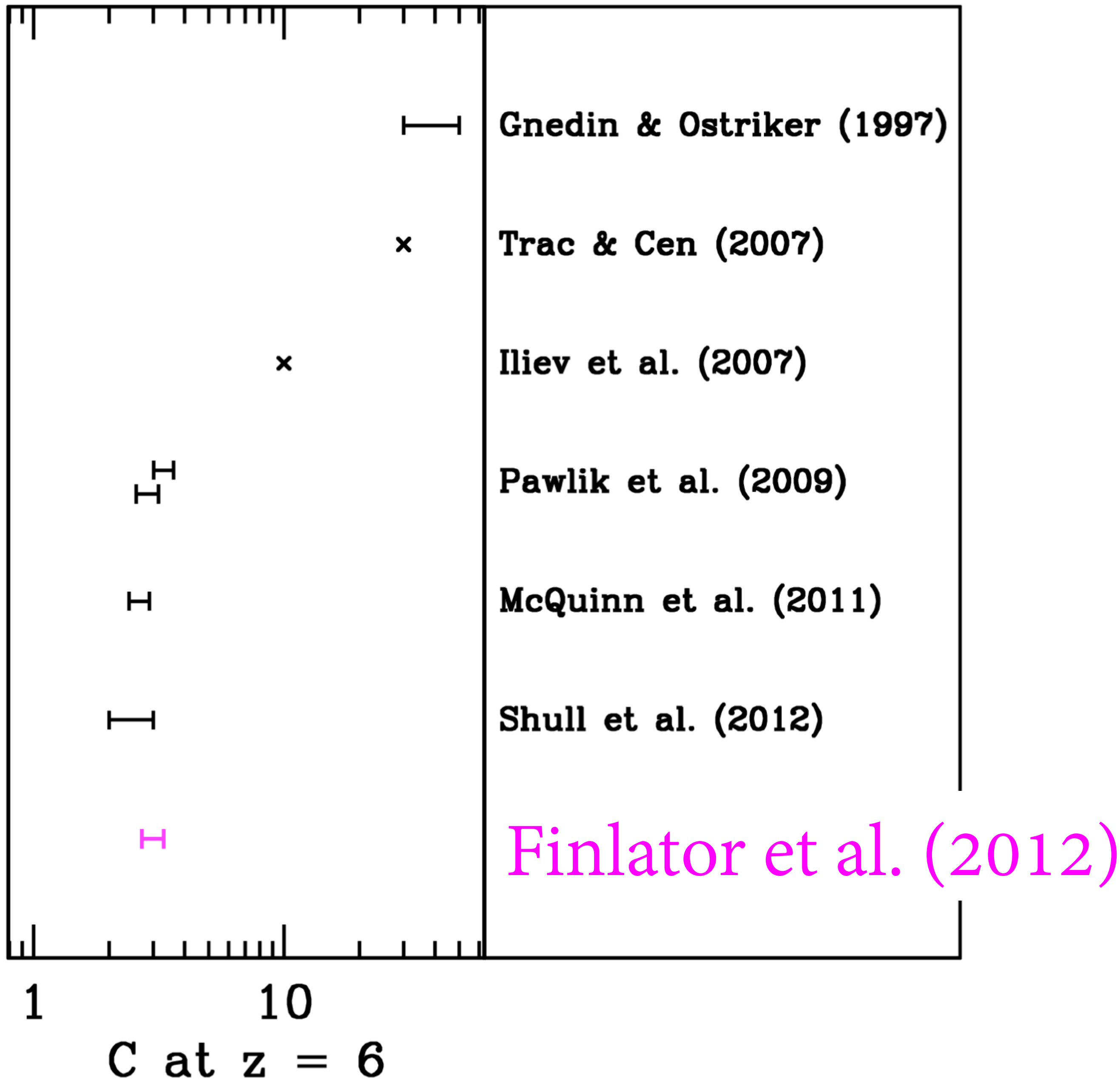
where

$$C_I = \frac{\langle n_{\mathrm{HI}}\Gamma\rangle}{\langle n_{\mathrm{HI}}\rangle\langle\Gamma\rangle},$$

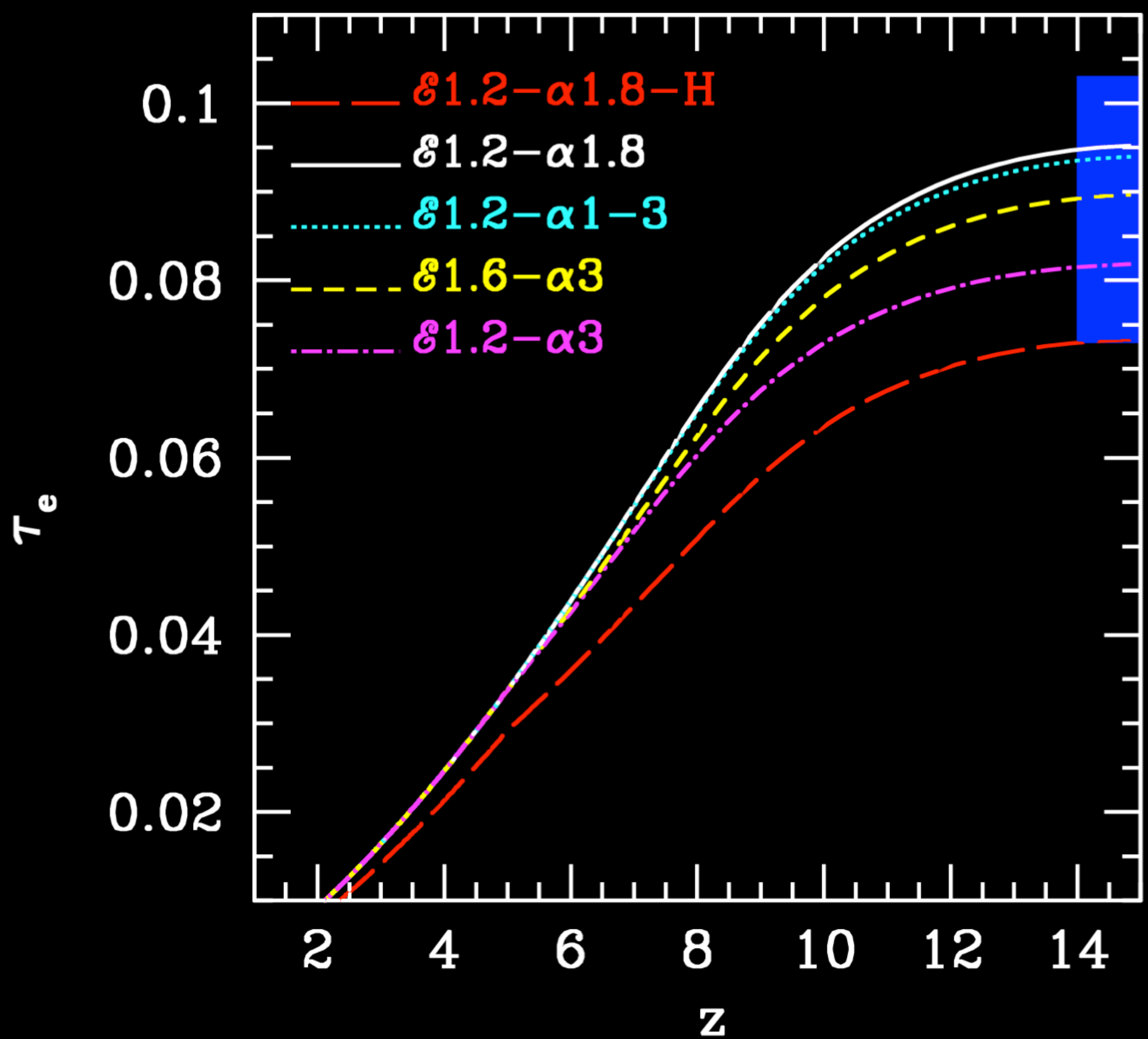
$$C_R = \frac{\langle R(T)n_e n_{\mathrm{HII}}\rangle}{\langle R(T)\rangle\langle n_e\rangle\langle n_{\mathrm{HII}}\rangle}.$$

Kohler et al. 2007

IGM clumping factors



Helium is important to get the electron density and temperatures correct



Ciardi , Bolton, Maselli & Graziani 2011

Therefore, we need estimates of HeII and HeIII clumping factors along with HII.

Our Simulations

Gadget-3 simulations + CRASH

Box sizes - 2.20, 4.40, 8.80 cMpc/h

Gadget particle number - $2*256^3$

CRASH grid size – 32^3, 64^3, 128^3 RT cells.

Best RT resolution – 17 ckpc/h

EUV spectral index - alpha = 1.8

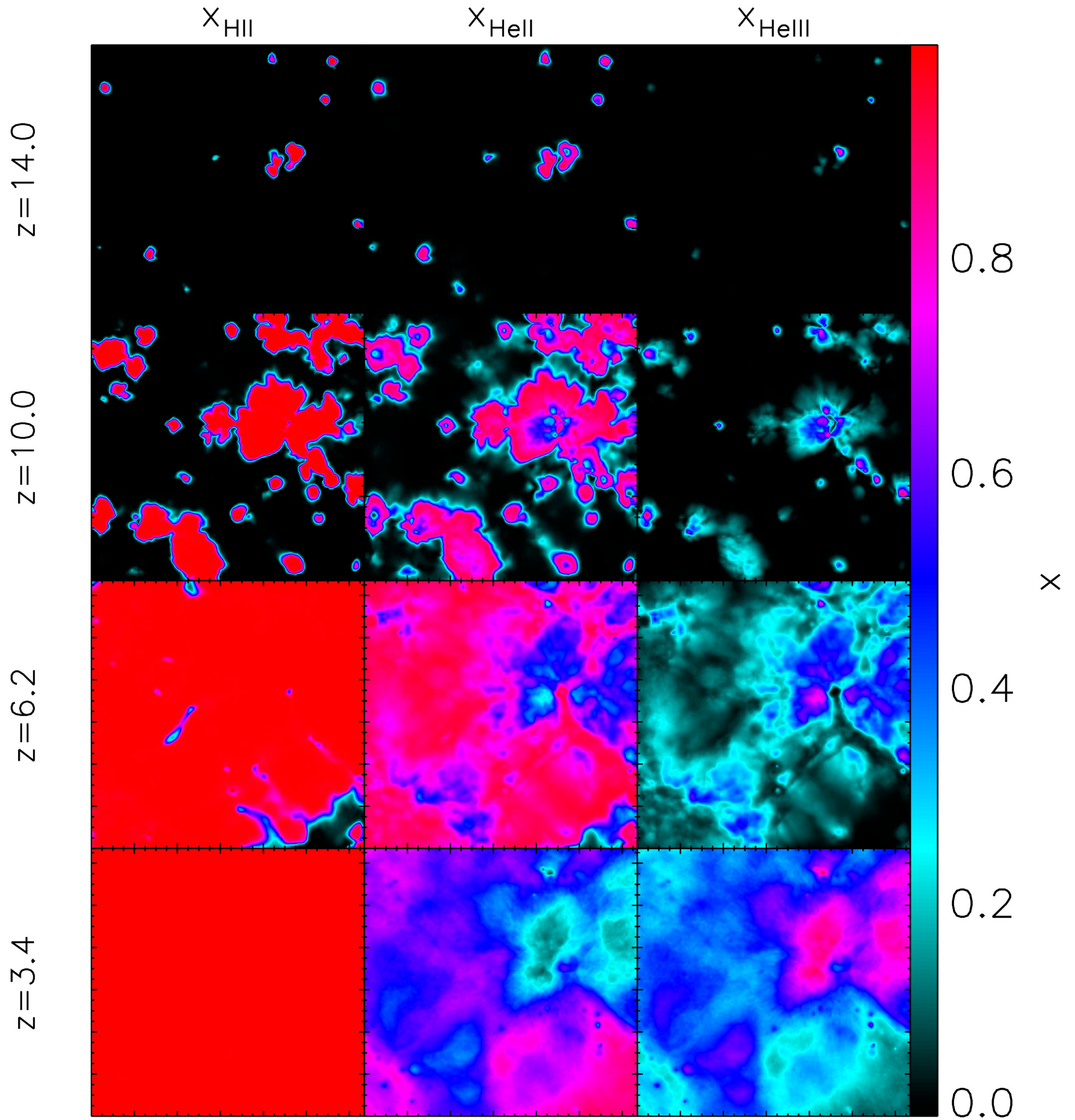
No escape fractions assumed – Emissivity calibrated to ' τ ' from WMAP7 (**Komatsu et. al 2011**) and photo ionization rates computed from observations of Ly α forest at z~6 (**Bolton et. al 2007**).

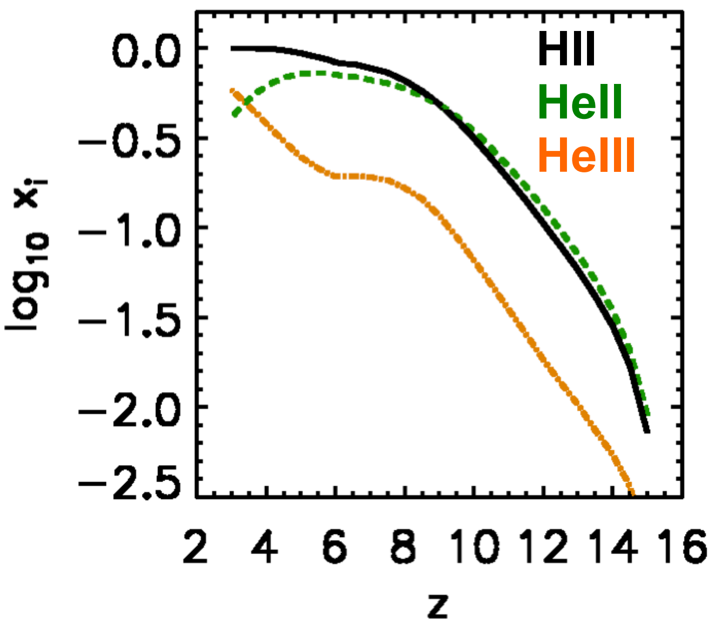
Ciardi, Bolton, Maselli & Graziani 2011

EoR simulation

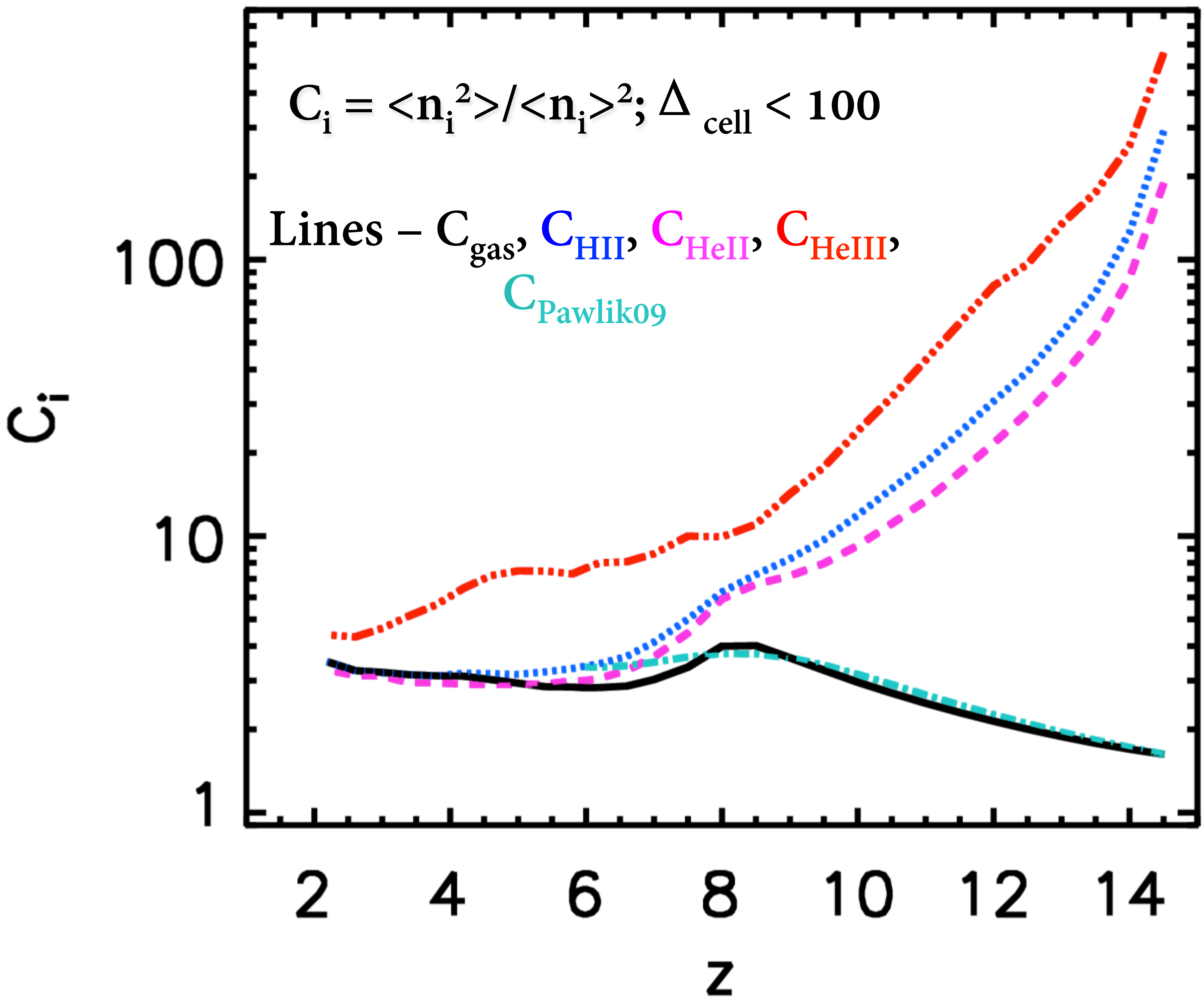
2.2 cMpc/h

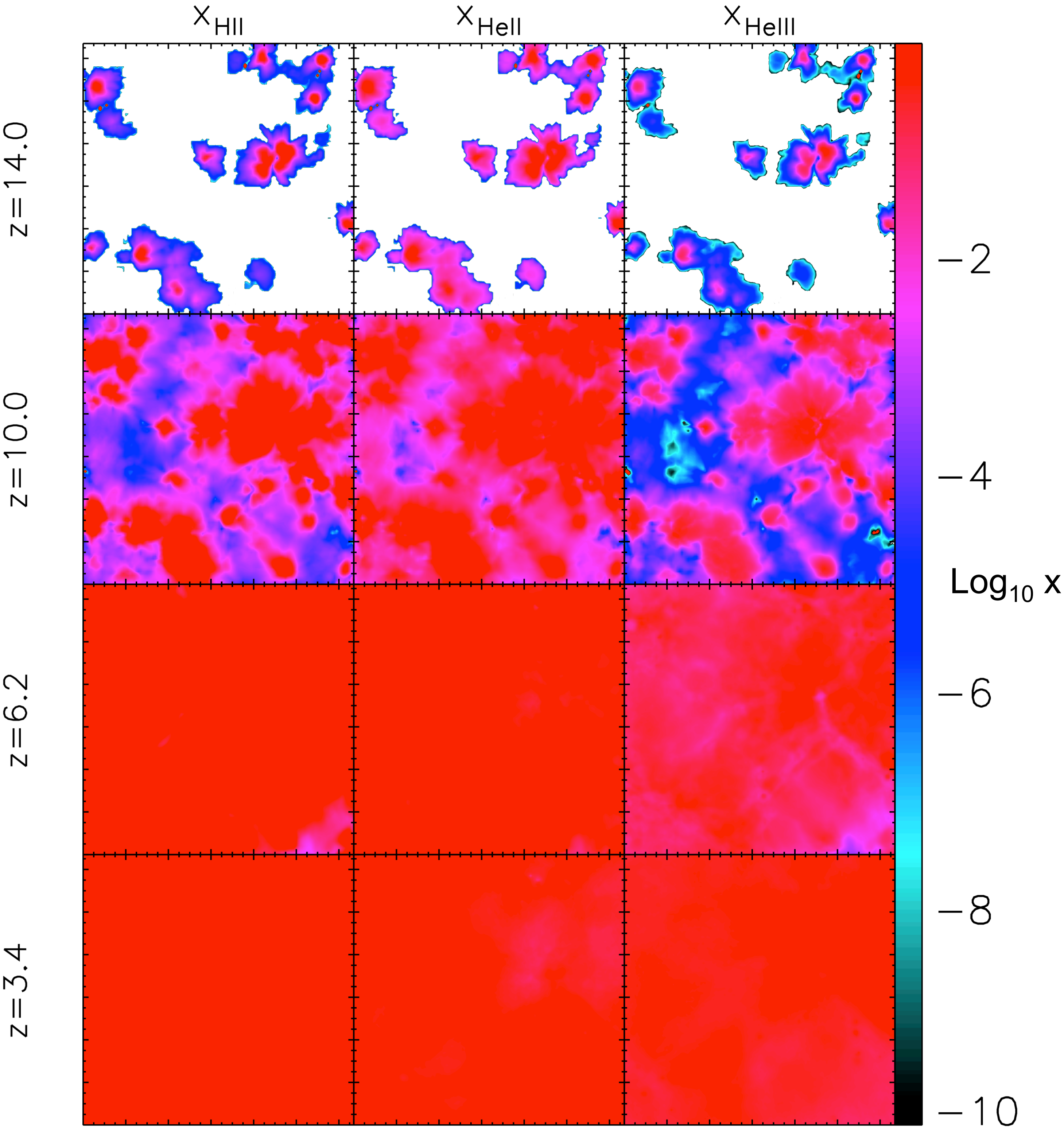
128^3 RT





Clumping factor

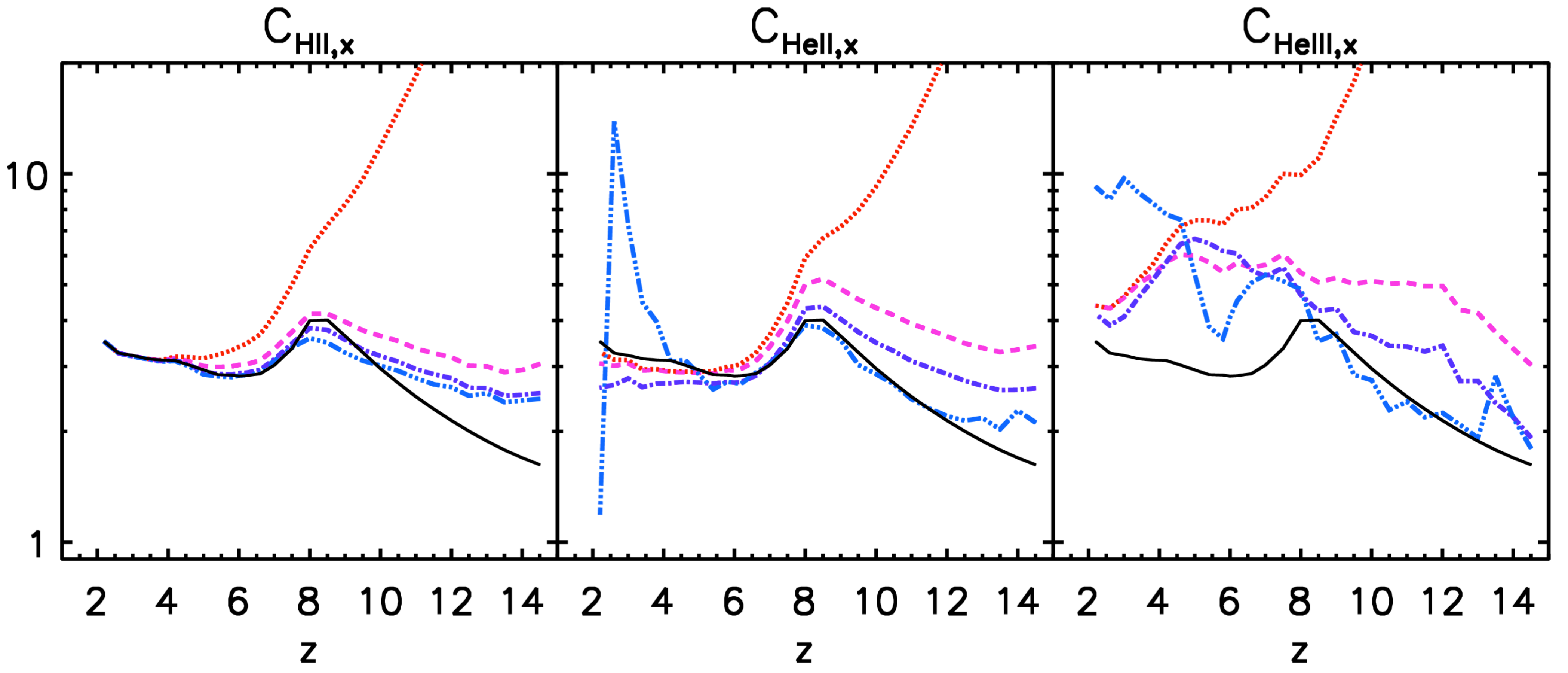


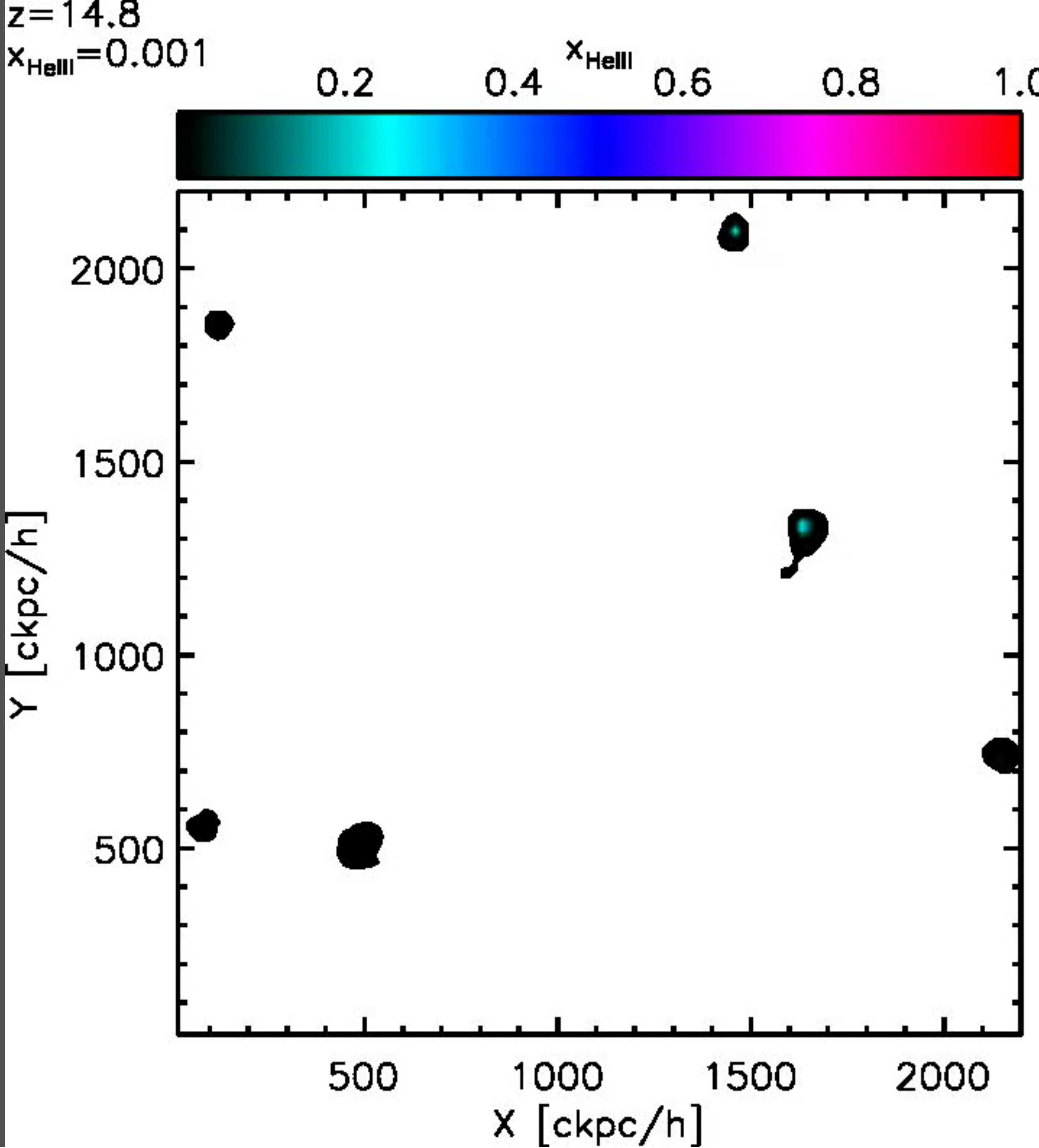

x_{HII}
x_{HeII}
x_{HeIII}
z=14.0
z=10.0
z=6.2
z=3.4
−2
−4
−6
−8
−10
Log_{10} x

For different ionization thresholds

$$C_{i,x} = \langle n_i^2 \rangle_{(x>xth)} / \langle n_i \rangle_{(x>xth)}^2$$

$\Delta_{cell} < 100$; Lines – C_{gas}, $x > 0$, $x > 0.1$, $x > 0.5$, $x > 0.9$



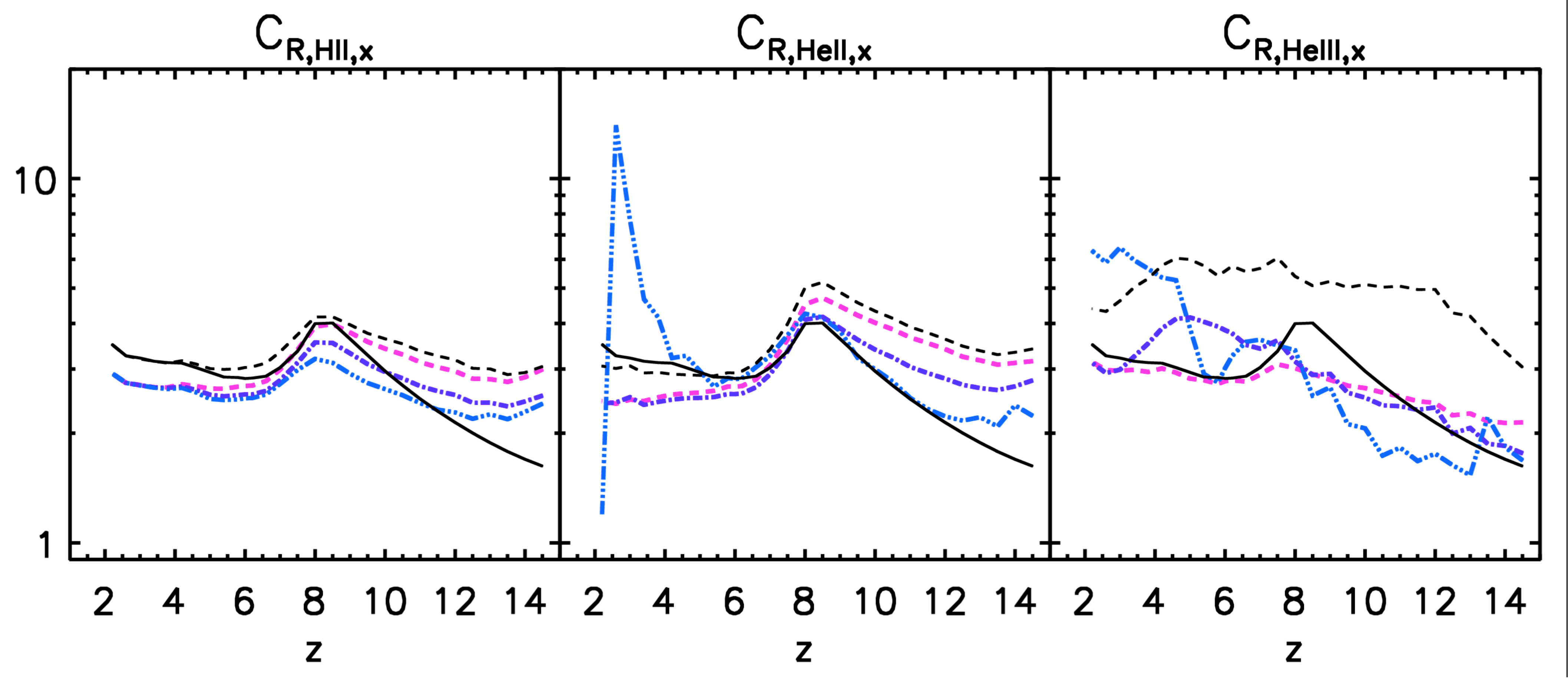


z=14.8
x_{HeIII}=0.001
x_{HeIII}
0.2
0.4
0.6
0.8
1.0
2000
1500
1000
500
Y [ckpc/h]
500
1000
1500
2000
X [ckpc/h]

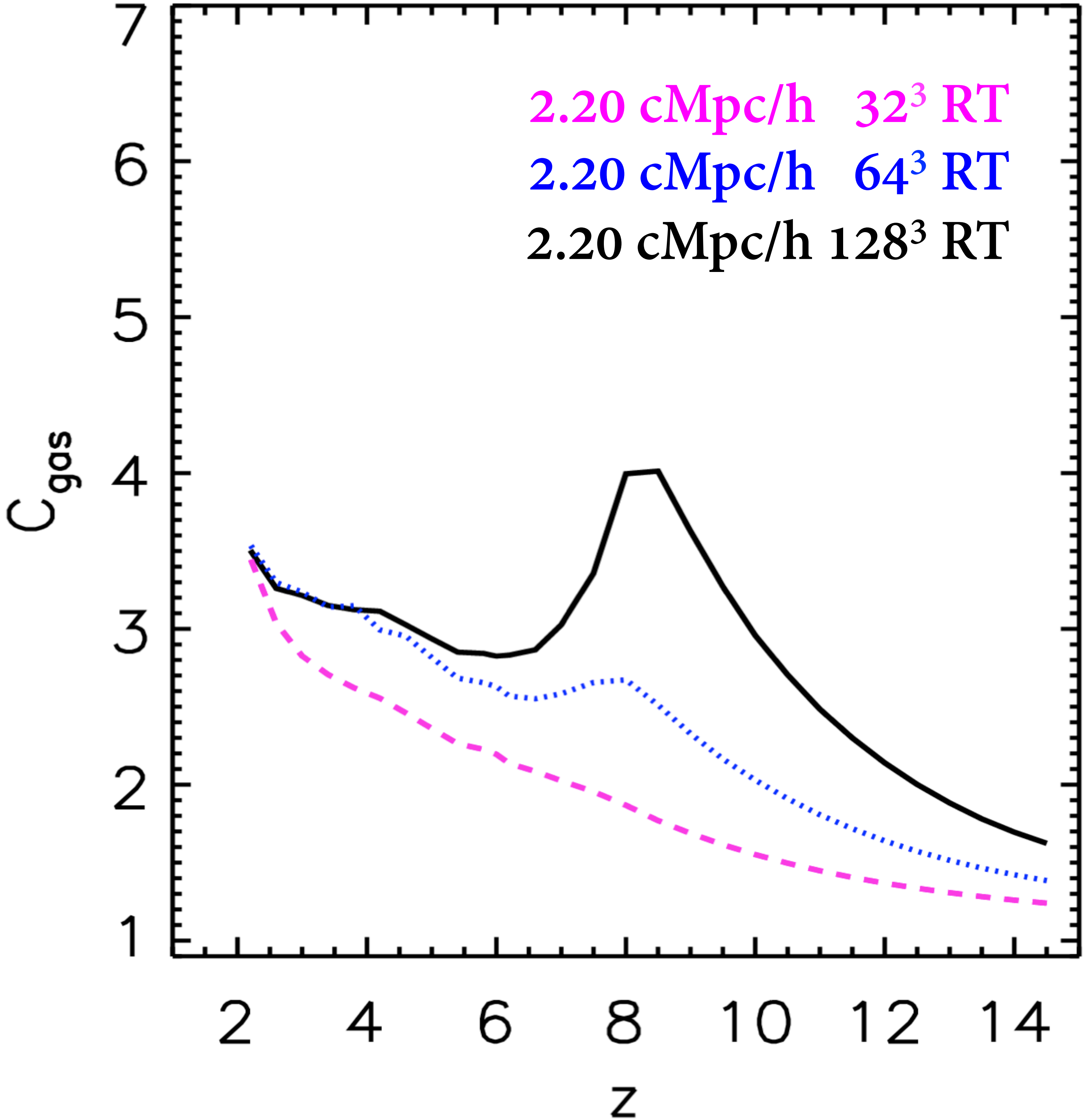
Effect of temperature dependent recombination rates

$$C_{R,i,x} = \langle n_i * n_e * \alpha_i(T) \rangle_{(x>xth)} / (\langle n_i \rangle_{(x>xth)} * \langle n_e \rangle_{(x>xth)} * \langle \alpha_i(T) \rangle_{(x>xth)})$$

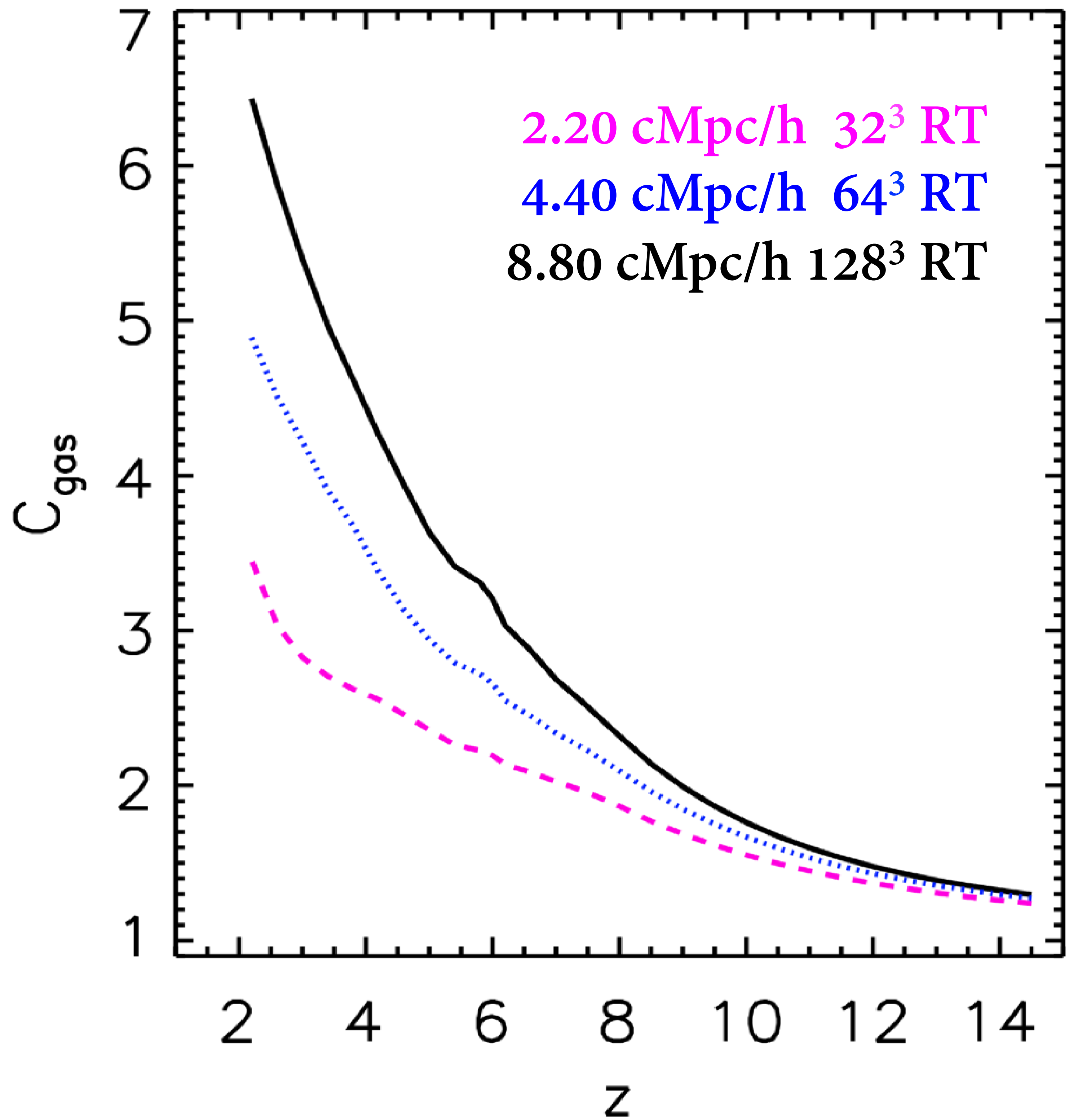
$\Delta_{cell} < 100$; Lines – C_{gas}, $x > 0$, $x > 0.1$, $x > 0.5$, $x > 0.9$



Grid size test



Box size test



Overdensity of the region

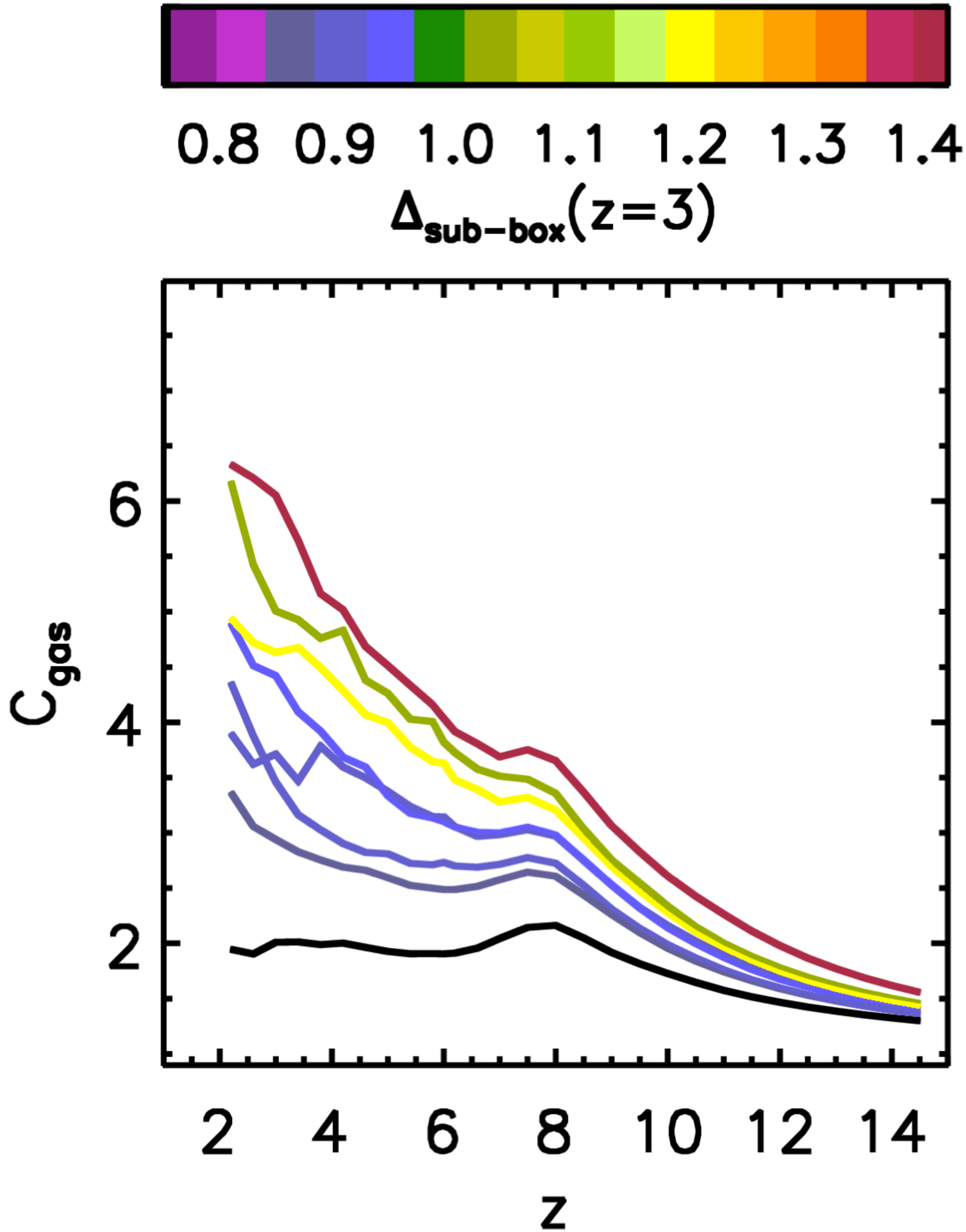
4.40 cMpc/h 128^3 RT
divided to
8 equal sub-boxes
equivalent to
2.20 cMpc/h 64^3 RT

$\Delta_{\text{sub-box}} = \langle n_{gas} \rangle_{\text{sub-box}} / \langle n_{gas} \rangle_{\text{box}}$

$C_{gas} = \langle n_{gas}^2 \rangle / \langle n_{gas} \rangle^2$

$\Delta_{\text{cell}} < 100$

Also seen by Kohler et al 2007, Reicevic & Theuns 2011



Conclusions

- C_{gas} is consistent with previous values calculated for z>6.
- $C_{R,i,0.1}$ for i=HII, HeII and HeIII are close to C_{gas} .

But clumping factors do depend on box size and mean overdensity of the region. Therefore, the range needs to be explored.