The environmental effect on LAEs galaxies at the end of reionization $z \sim 6$

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1 Constants:

In this section we define the constants used in this work.

Constant name	Symbol	Value	Units
Boltzmann	k_B	1.3806488×10^-23	$[J/K]$
Gravitational	G	6.67384×10^{-11}	$[\frac{m^3}{Kgs^2}]$
Mean molecular weight	μ_n	0.59	–
Proton mass	m_p	$1.672621777 \times 10^{-27}$	[kg]
Slope parameter	β	0.4	–
Matter density	Ω_m	0.3089	–
Barions density	Ω_B	0.0455102	–
Dark energy density	Ω_Λ	0.6911	–
Spatial curvature density	Ω_k	-0.0023	–
Hubble parameter	H_0	$7.11449538303 \times 10^{-41}$	$[1/s]$
Solar mass	$M_\odot$	1.9891×10^{30}	[kg]

2 Gas density profile:

Makino et al (1997) found an analytical expresion (Eq.8 in that paper) for the gas profile assuming that the gas is isothermal and it is inside a DM halo with a NFW profile. They argue that this equation it's well approximated by the following profile:

$$\rho_g(r) = \frac{\rho_{g,0} A}{\left[1 + \left(\frac{r}{r_{c,eff}}\right)^2\right]^{3\beta_{eff}/2}} \tag{1}$$

Where $A(b) = -0.178b + 0.982$ and $\beta_{eff} = 0.9b$

In order to compute $\rho_{g,0}$ we used Eq.14 in that paper:

$$\rho_{g0} = \frac{f_{gas}\Omega_b\rho_{c0}\delta_c}{\Omega_0} e^{27b/2}\left[Ln(1+c) - \frac{c}{1+c}\right]\left[\int_0^c x^2(1+x)^{27b/2x}dx\right] \tag{2}$$

As an example for a DM halo of $M = 1E12M_\odot$ at $z = 2$ and a concetrarion parameter of $c = 3.75$ the gas profile is shown in Fig. 2

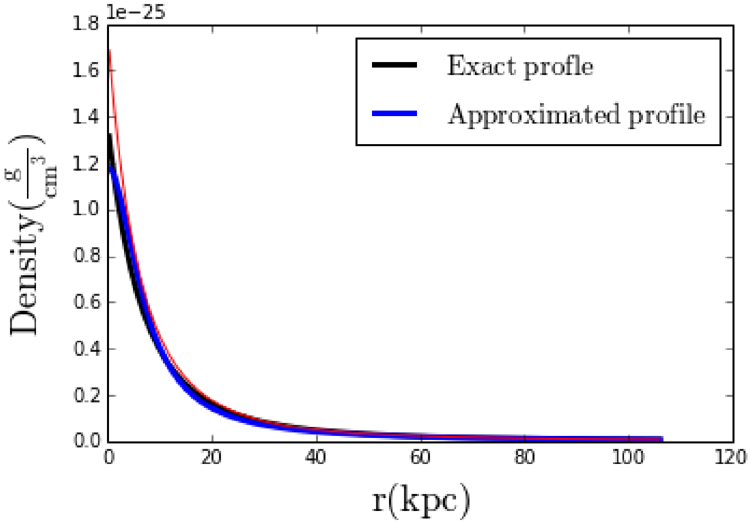


Figure 1: Gas density profile for a DM halo of $M = 1E12M_{\odot}$ at $z = 2$ and a concetrarion parameter of $c = 3.75$

3 Neutral Hydrogen fraction η:

Following Rahmati et al 2013, we compute de neutral hydrogen fraction $\eta = n_{HI}/n_H$. We follow the procedure implemented in the Appendix A in that paper.

$$\eta = \frac{B - \sqrt{B^2 - 4AC}}{2A} \tag{3}$$

Where A , B and C are defined as:

$$\begin{aligned} A &= \alpha_A + \Lambda_T \\ B &= 2\alpha_A + \frac{\Gamma_{Phot}}{n_H} + \Lambda_T \\ C &= \alpha_A \end{aligned} \tag{4}$$

where Λ_T, α_A and Γ_{Phot} are defined as:

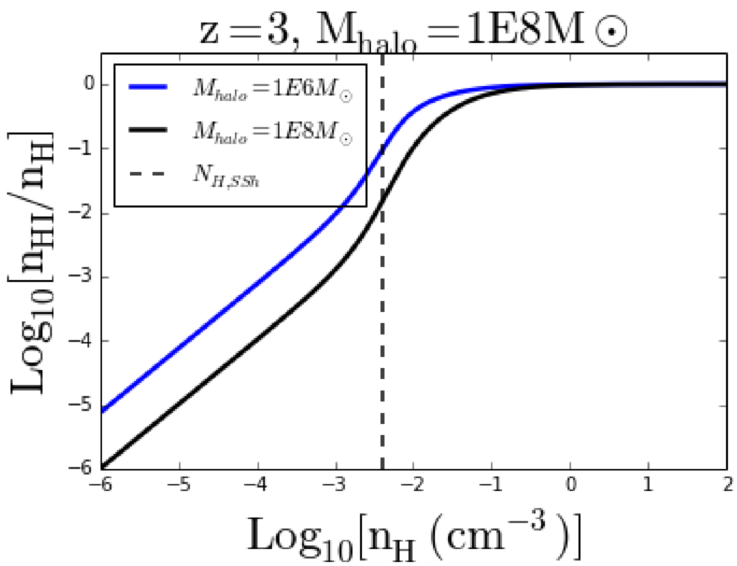
$$\Lambda_T = 1.1.7 \times 10^{-10} \frac{T^{1/2} exp(-157809/T)}{1 + \sqrt{(}T/10^5)} cm^3 s^{-1} \tag{5}$$

$$\alpha_A = 1.269 \times 10^{-13} \frac{\lambda^{1.503}}{(1 + (\lambda/0.522)^{0.47})^{1.923}} cm^3 s^{-1} \tag{6}$$

where $\lambda = 315614/T$.

$$\Gamma_{Phot} = \Gamma_{UVB} \left(0.98 \left[1 + \left(\frac{n_H}{n_{H,SSh}} \right)^{1.64} \right]^{-2.28} + 0.02 \left[1 + \frac{n_H}{n_{H,SSh}} \right]^{-0.84} \right) \tag{7}$$

The up of Fig.3 shows how neutral Hydrogen fraction changes for diferent hydrogen densities, for different Halo Mass. While the bottom figure shows the bahaviour of η as a function of the temperature T. The blue line is for a Hydrogen density $n_H = 0.01cm^{-3}$ which is above the selfshielding density limit, while the black line is for $n_H = 0.001cm^{-3}$.



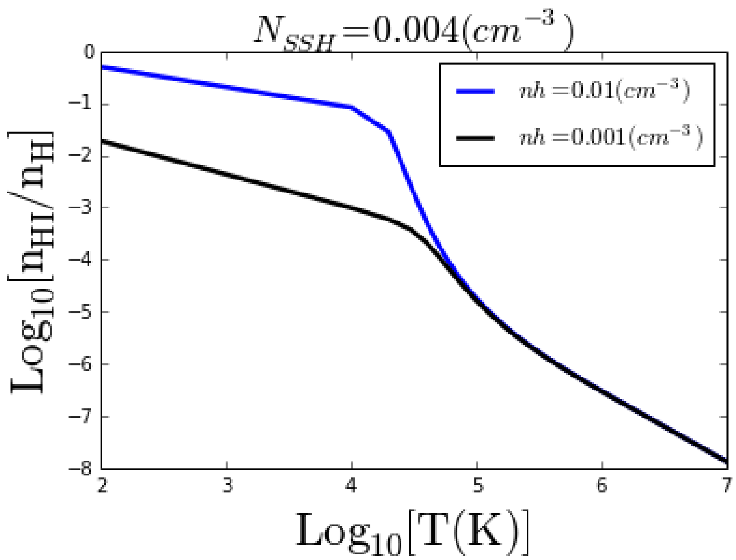
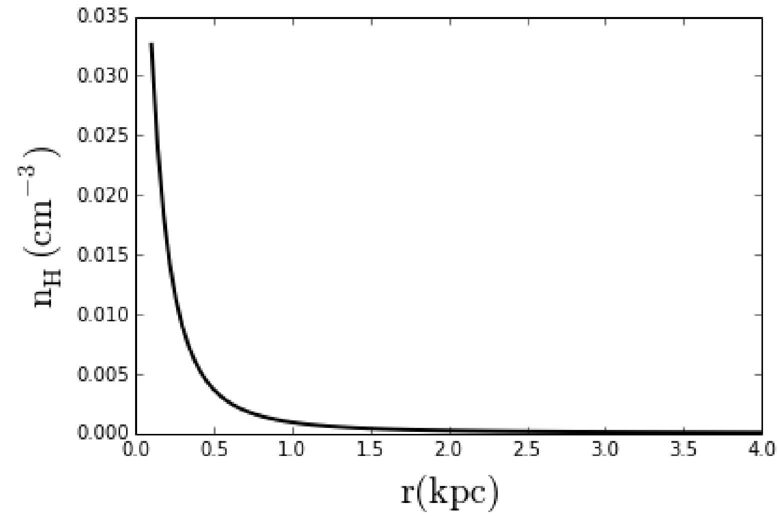


Figure 2: (Up)

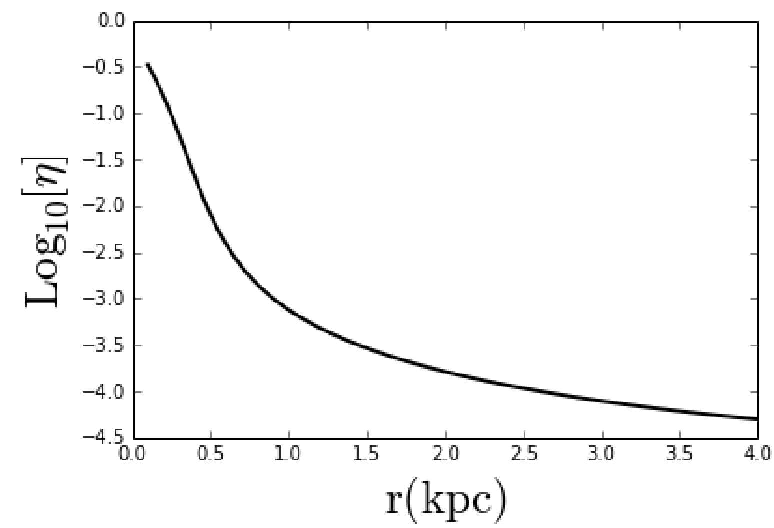
4 Neutral Hydrogen density profile

In ordert to study the effect of the environment in LAEs we are interested in the neutral Hydrogen. To this aim we want to derive the neutral Hydrogen gas profile using Makino's profile alongside the neutral hydrogen fraction derived in the previous section.

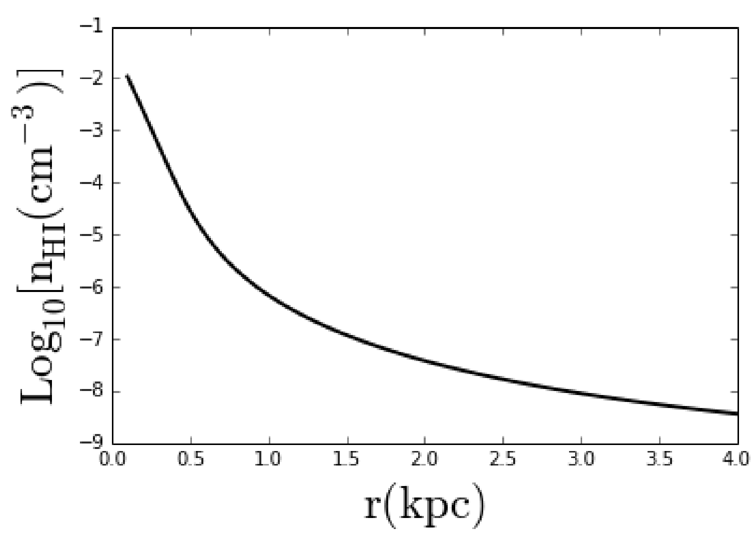
The first step here is to find the Hydrogen density n_H from the ρ this is related by $n_H = \rho/m_p$, this profile is shown in Fig.4.



With this density n_H we compute the neutral Hydrogen fraction η as function of r, Fig.4 show the fraction of neutral Hydrogen inside a DM halo of mass $M = 10^8 M_\odot$ at $z = 6$ with $r_{vir} = 1.67Kpc$.



With this information we can compute the Neutral Hydrogen profile corresponding to this DM halo by multplying $n_{HI}(r) = \eta(r) n_H(r)$, this is shown in Fig.4.



5 Column density derivation:

In order to compute the column density of the gas profiles, we first make an integral over the z axys of the gas profile to get N_Hi.e:

$$N_H = \int_{-\infty}^{\infty} \rho_g(r) dz \tag{8}$$

Where $r^2 = z^2 + b'^2$ and b' is the impact parameter. Changing variables from z to r we get:

$$N_H = \rho_{g0} A \int_{-\infty}^{\infty} \frac{dz}{\left[1 + \left(\frac{r}{r_{c,eff}}\right)^2\right]^{3\beta_{eff}/2}} = \rho_{g0} A \int_{b}^{\infty} \frac{r}{\sqrt{r^2 - b'^2}} \frac{dr}{\left[1 + \left(\frac{r}{r_{c,eff}}\right)^2\right]^{3\beta_{eff}/2}} \tag{9}$$

The result of the integral is:

$$N_H = \rho_{g0} A \frac{\sqrt{\pi}(\frac{1}{r_c(M_h)^2})^{-3\beta_{eff}(M_h)/2}(b'^2 + r_c(M_h)^2)^{1/2 - 3\beta_{eff}(M_h)/2}\Gamma(-1/2 + 3\beta_{eff}/2)}{2\Gamma(\frac{3\beta_{eff}(M_h)}{2})} \tag{10}$$

The N_H for all the halo masses and for all the impact parameters would be defined as:

$$< N_H >= 4 \int_0^{0.5} dx \int_0^{0.5} dy \int_{M_{Hmin}}^{M_{Hmax}} N_H(b, M_H)\xi(M_H) dM_H \tag{11}$$

Where the impact paremeter $b'^2 = x^2 + y^2$ and $M_{Hmin} = 1 \times 10^4 M_\odot$ and $M_{Hmax} = 1 \times 10^{12} M_\odot$. And $\xi(M_H) = \frac{dn}{dM_H}$. The dependence with the redshift is in the computation of r_{vir} and in the mass function.

In order to evaluate Eq. 11 we first make the integral over the mass using the trapezoid method as follows:

$$\int_{M_{HMin}}^{M_{HMax}} N_H(b, M_H)\xi(M_H) dM_H = \sum_0^{1000} \Delta_M \left[\frac{N_H(b, M_H + \Delta_M)\xi(M_{H+\Delta_M}) + N_H(b, M_{HM}\xi(M_H))}{2}\right] \tag{12}$$

Which can be expressed as:

$$\int_{M_{HMin}}^{M_{HMax}} N_H(b, M_H)\xi(M_H) dM_H = \sum_0^{1000} \Delta_M M_\odot \frac{\rho_{g0} A(b)\sqrt{\pi}\Gamma(-\frac{1}{2} + \frac{3\beta}{2})}{4\Gamma\frac{3\beta}{2}}$$
$$\left[\left(\frac{1}{r_c(M_{HMin})^2}\right)^{-3\beta/2} (b^2 + r_c(M_{Hmin})^2)^{1/2 - 3\beta/2}\xi(M_{Hmax}) + \right.$$
$$\left(\frac{1}{r_c(M_{HMax})^2}\right)^{-3\beta/2} (b^2 + r_c(M_{Hmax})^2)^{1/2 - 3\beta/2}\xi(M_{Hmin}) \tag{13}$$

The average column density of a ray traced in a volume of $1Mpc^3$ at redshift $z = 6$ is then given by:

$$< N_H >= 4\rho_{g,0}A \int_0^{0.5} dx \int_0^{0.5} dy N_H(b) db = 1.68 \times 10^{-42} \frac{g}{cm^3} \tag{14}$$