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

September 23, 2015

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 $M = 1E12 M_\odot$ at $z = 2$ and a concetrarion parameter of $c = 3.75$ the gas profile is shown in Fig. 2

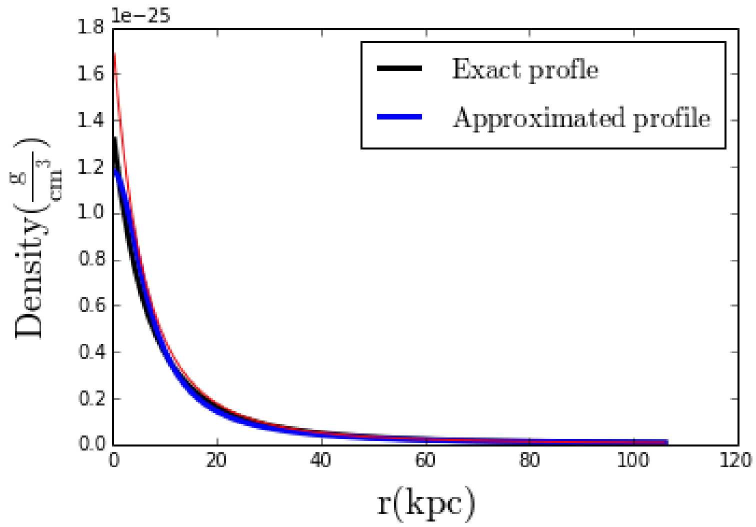


Figure 1: Gas density profile for a DM halo of $M = 1E12M_{\odot}$ at $z = 2$ and a concetrarion parameter of $c = 3.75$

3 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:

$$N_H = \int_{-\infty}^{\infty} \rho_g(r)dz \tag{3}$$

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

$$N_H = \rho_{g0}A \int_{-\infty}^{\infty} \frac{dz}{\left[1+\left(\frac{r}{r_{c,eff}}\right)^2\right]^{3\beta_{eff}/2}} = \rho_{g0}A \int_{b}^{\infty} \frac{r}{\sqrt{r^2-b'^2}} \frac{dr}{\left[1+\left(\frac{r}{r_{c,eff}}\right)^2\right]^{3\beta_{eff}/2}} \tag{4}$$

The result of the integral is:

$$N_H = \rho_{g0}A \frac{\sqrt{\pi}(\frac{1}{r_c(M_h)^2})^{-3\beta_{eff}(M_h)/2}(b'^2 + r_c(M_h)^2)^{1/2-3\beta_{eff}(M_h)/2}\Gamma(-1/2 + 3\beta_{eff}/2)}{2\Gamma(\frac{3\beta_{eff}(M_h)}{2})} \tag{5}$$

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

$$< N_H >= 4 \int_0^{0.5} dx \int_0^{0.5} dy \int_{M_{Hmin}}^{M_{Hmax}} N_H(b, M_H)\xi(M_H)dM_H \tag{6}$$

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. 6 we first make the integral over the mass using the trapezoid method as follows:

$$\int_{M_{HMin}}^{M_{HMax}} N_H(b, M_H)\xi(M_H)dM_H = \sum_0^{1000} \Delta_M \left[\frac{N_H(b, M_H + \Delta_M)\xi(M_{H+\Delta_M}) + N_H(b, M_{HM}\xi(M_H))}{2} \right] \tag{7}$$

Which can be expressed as:

$$\int_{M_{HMin}}^{M_{HMax}} N_H(b, M_H)\xi(M_H)dM_H = \sum_0^{1000} \Delta_M M_\odot \frac{\rho_{g0} A(b) \sqrt{\pi} \Gamma(-\frac{1}{2} + \frac{3\beta}{2})}{4\Gamma \frac{3\beta}{2}}$$
$$\left[\left(\frac{1}{r_c(M_{HMin})^2} \right)^{-3\beta/2} (b^2 + r_c(M_{Hmin})^2)^{1/2-3\beta/2} \xi(M_{Hmax}) + \right. \tag{8}$$
$$\left(\frac{1}{r_c(M_{HMax})^2} \right)^{-3\beta/2} (b^2 + r_c(M_{Hmax})^2)^{1/2-3\beta/2} \xi(M_{Hmin})$$

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

$$< N_H >= 4\rho_{g,0} A \int_0^{0.5} dx \int_0^{0.5} dy N_H(b) db = 1.68 \times 10^{-42} \frac{g}{cm^3} \tag{9}$$

4 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.

$$\eta = \frac{B - \sqrt{B^2 - 4AC}}{2A} \tag{10}$$

Where A , B and C are defined as:

$$\begin{aligned} A &= \alpha_A + \Lambda_T \\ B &= 2\alpha_A + \frac{\Gamma_{Phot}}{n_H} + \Lambda_T \\ C &= \alpha_A \end{aligned} \tag{11}$$

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

$$\Lambda_T = 1.1.7 \times 10^{-10} \frac{T^{1/2} exp(-157809/T)}{1 + \sqrt{(T/10^5)}} cm^3 s^{-1} \tag{12}$$

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

where $\lambda = 315614/T$.

$$\Gamma_{Phot} = \Gamma_{UVB} \left(0.98 \left[1 + \left(\frac{n_H}{n_{H,SSh}} \right)^{1.64} \right]^{-2.28} + 0.02 \left[1 + \frac{n_H}{n_{H,SSh}} \right]^{-0.84} \right) \tag{14}$$

The up of Fig.4 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 $n_H = 0.001cm^{-3}$.

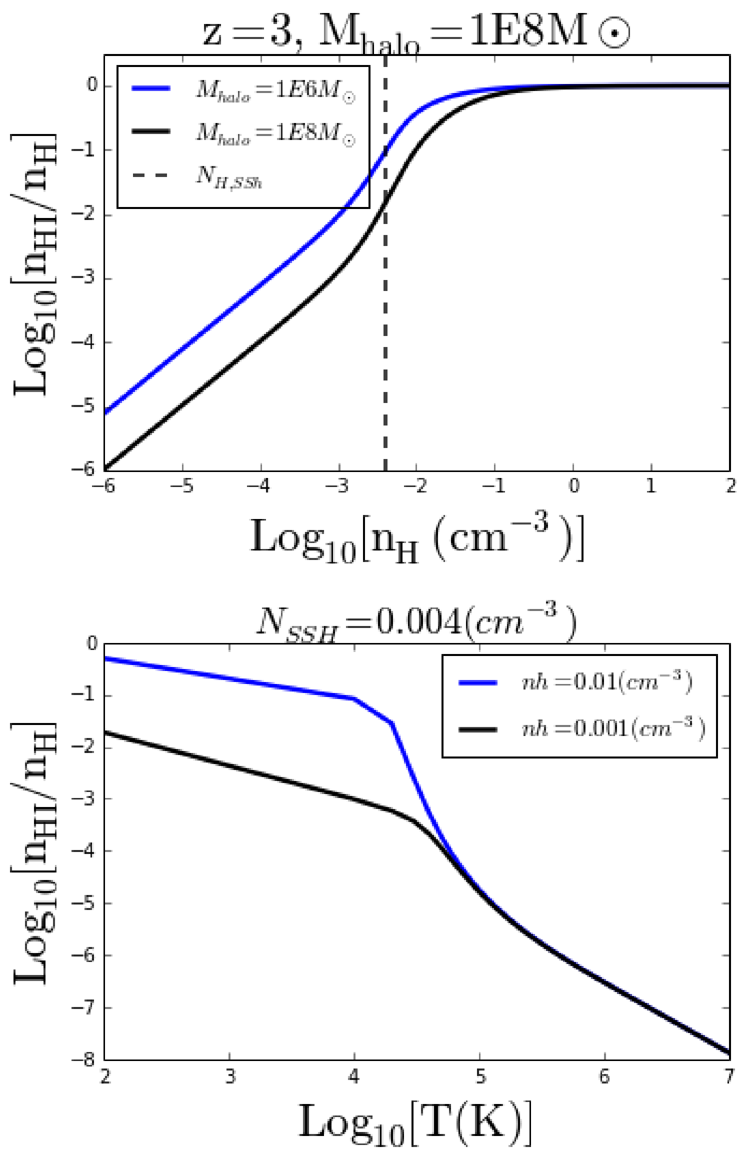
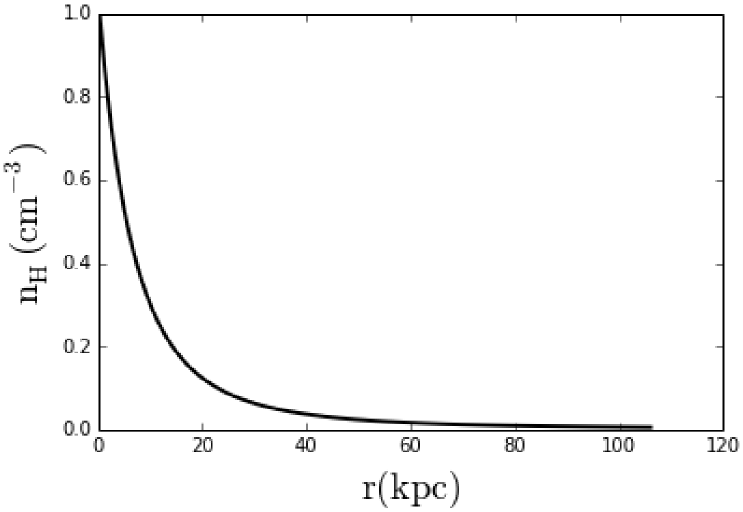


Figure 2: (Up)

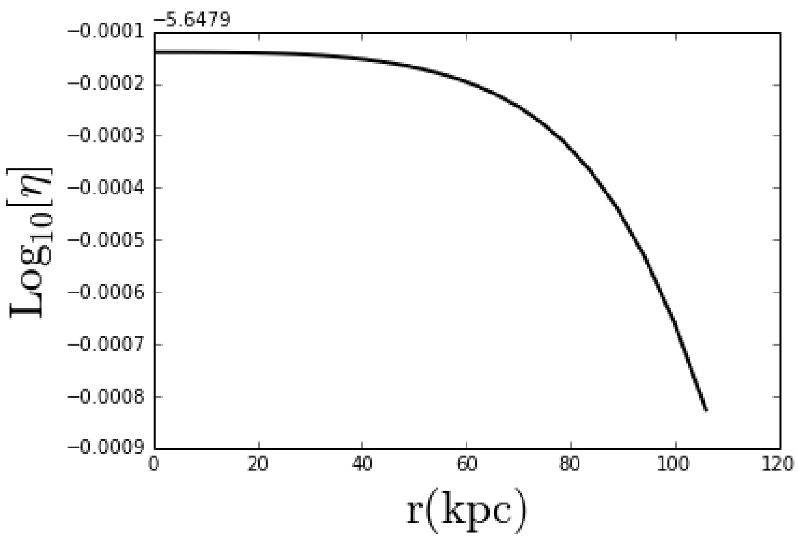
5 Neutral Hydrogen density profile

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.

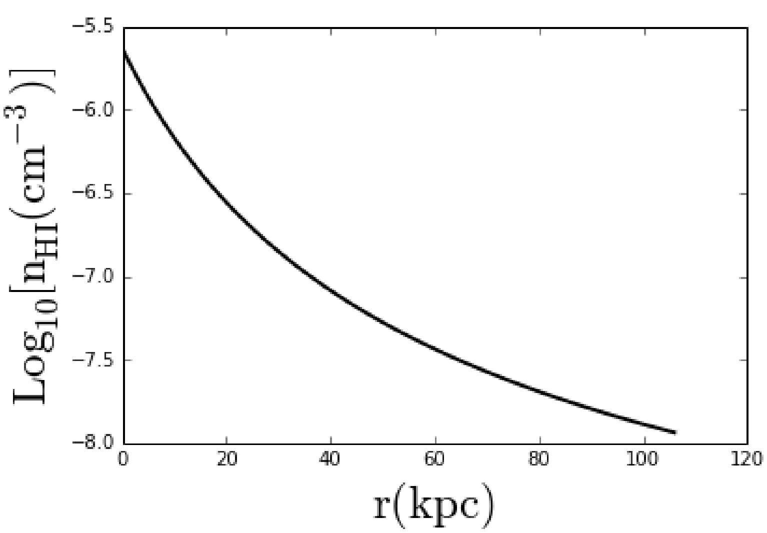
The first step here is to find the Hydrogen density n_H from the ρ this is related by $n_H = \rho/m_p$, this profile is shown in Fig.5.



With this density n_H we compute the neutral Hydrogen fraction η as function of r, Fig.5 show the fraction of neutral Hydrogen inside a DM halo of mass $M = 10^8 M_\odot$ at $z = 6$ with $r_{vir} = 1.67 Kpc$.



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.5.



6 Numerical Approch

We use the results of a DM only simulation Illustris1 with the aim of studing how the environment affects the absorption of Lyα radiation at $z \sim 6$. We chose emitters halos to be those in a range of mass $7 \times 10^{10} - 2 \times 10^{11}$, this halos have different environments (**Make a plot of this**). We then trace rays of Lyα photons in random dierections, and we derive the gas properties of those halos that interact with the ray implementing the equations described in §2, §3,§4.§5. Then we sum the column density of every Lyα ray. In the following subsections we describe these steps in detail.

6.1 Dark Matter halo catalogue

We use the public available data from the Illustris simulation, in particular we use the Illustis1-dark catalogue. This is a simulation of 1820^3 dark matter particles with a mass of $m_{DM} = 6.3 \times 10^6 M_\odot$ in a box of $L = 106.5Mpc$. We use the data of halos at $z = 6.01$.

6.2 Ray tracing

We select emitter galaxies in the range of $7 \times 10^{10} - 2 \times 10^{11}$. There are N halos in this mass range in the simulation. All these halos are in different environmets.

After selecting randomly an emitter we follow the trayectory of a Lyα photon in a random direction and for ray length of $10Mpc$. In $10Mpc$ a Lyα would have a Δ_z of:

We then compute the impact parameter b between the ray and all the halos that could possibly absorbe the photons, we select those halos in which the condition $b < R_{vir}$ is ensured, those halos would be the absorbers.

How many absorbers have each ray, try to visualize this

6.3 Colulmn density properties and Environment

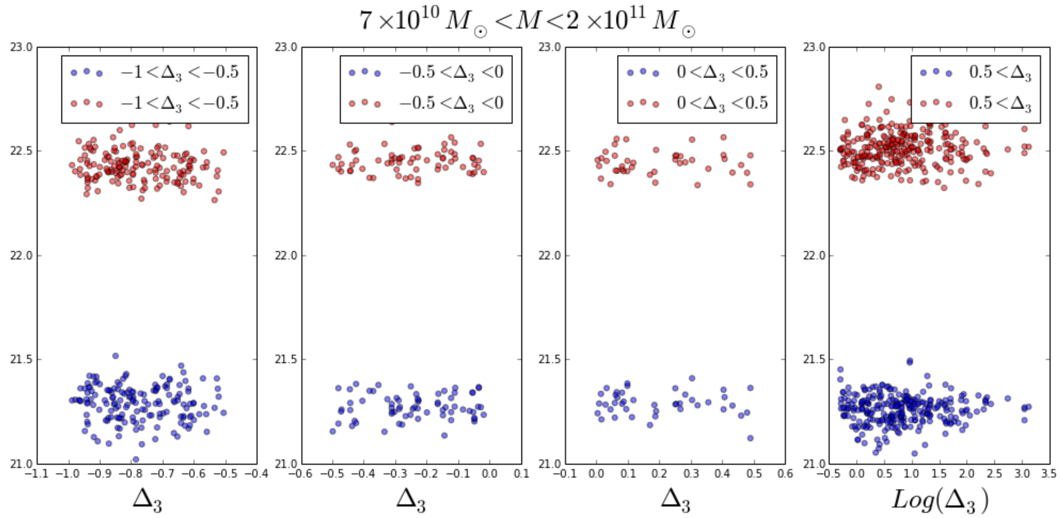
We compute the density profiles of using Eq.1, the we compute the column density using Eq.5. Then we compute the fraction of neutral column density n_{HI} using Eq.10

We define the environment of a emitter halo as:

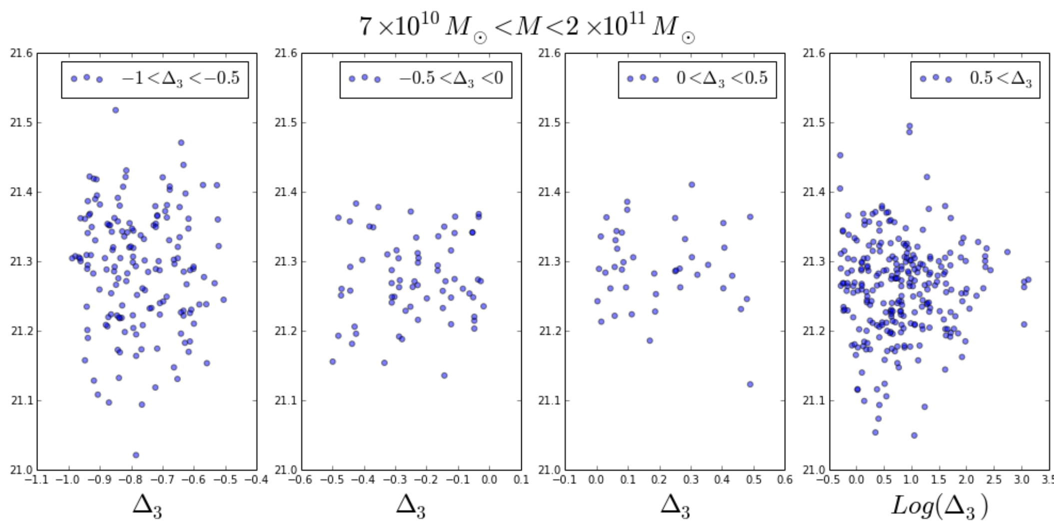
$$\Delta_3 = \bar{r}^3 \left(\frac{1}{r^3} - \frac{1}{\bar{r}^3} \right) \tag{15}$$

Where if $\Delta_3 < 0$ we say that the halo is in an overdense enviroment while if $\Delta_3 > 0$ the halo is in an underdense environment.

7 Results



$7 \times 10^{10}\, M_\odot < M < 2 \times 10^{11}\, M_\odot$
$-1 < \Delta_3 < -0.5$
$-0.5 < \Delta_3 < 0$
$0 < \Delta_3 < 0.5$
$0.5 < \Delta_3$
Δ_3
$Log(\Delta_3)$



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