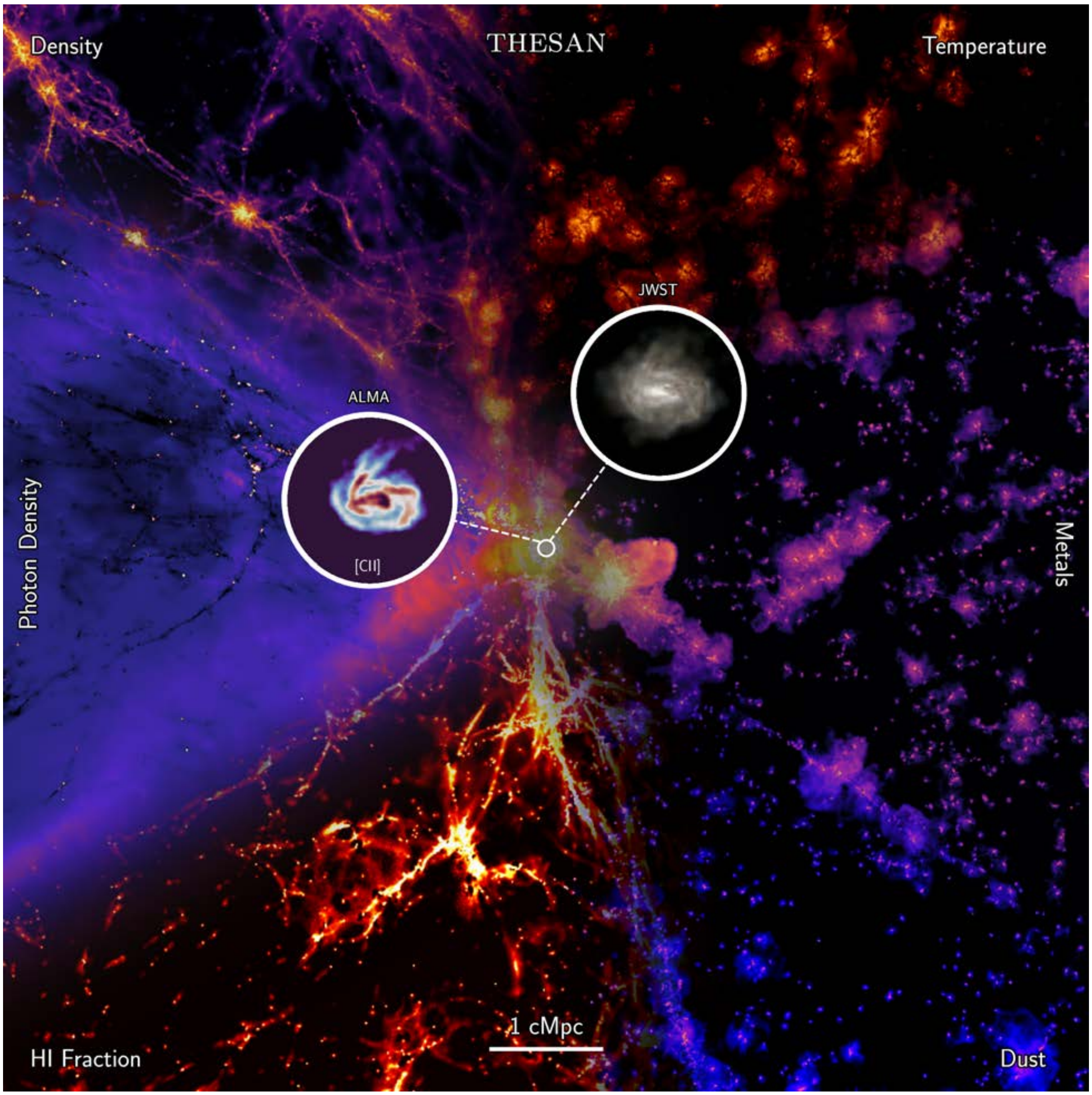
Part IV

Selected Topics



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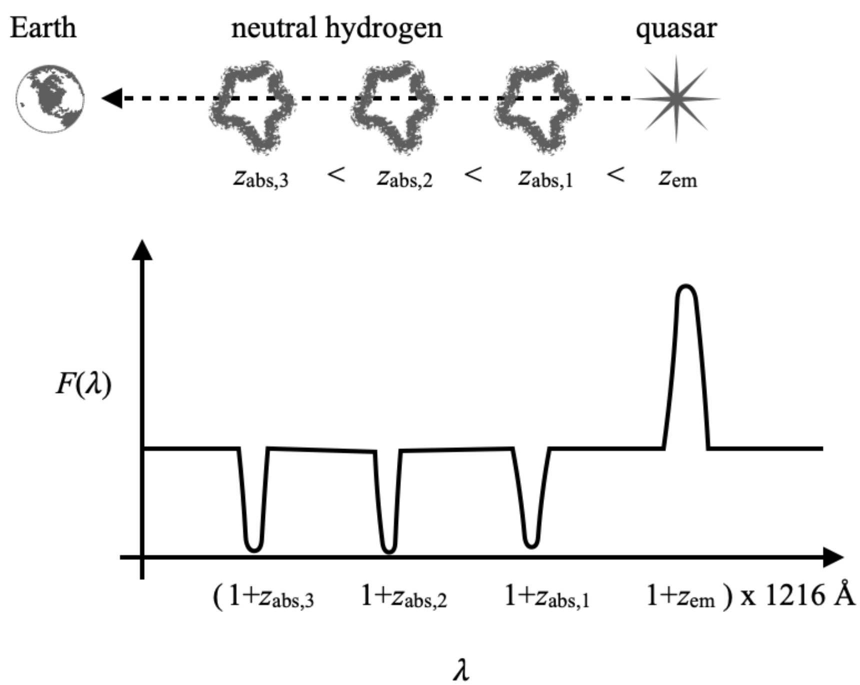
So far, we have gone through the basic concepts of the early universe, galaxies, and structure formation. We have built the basis to discuss some more advanced topics.

1 The Lyman-α forest

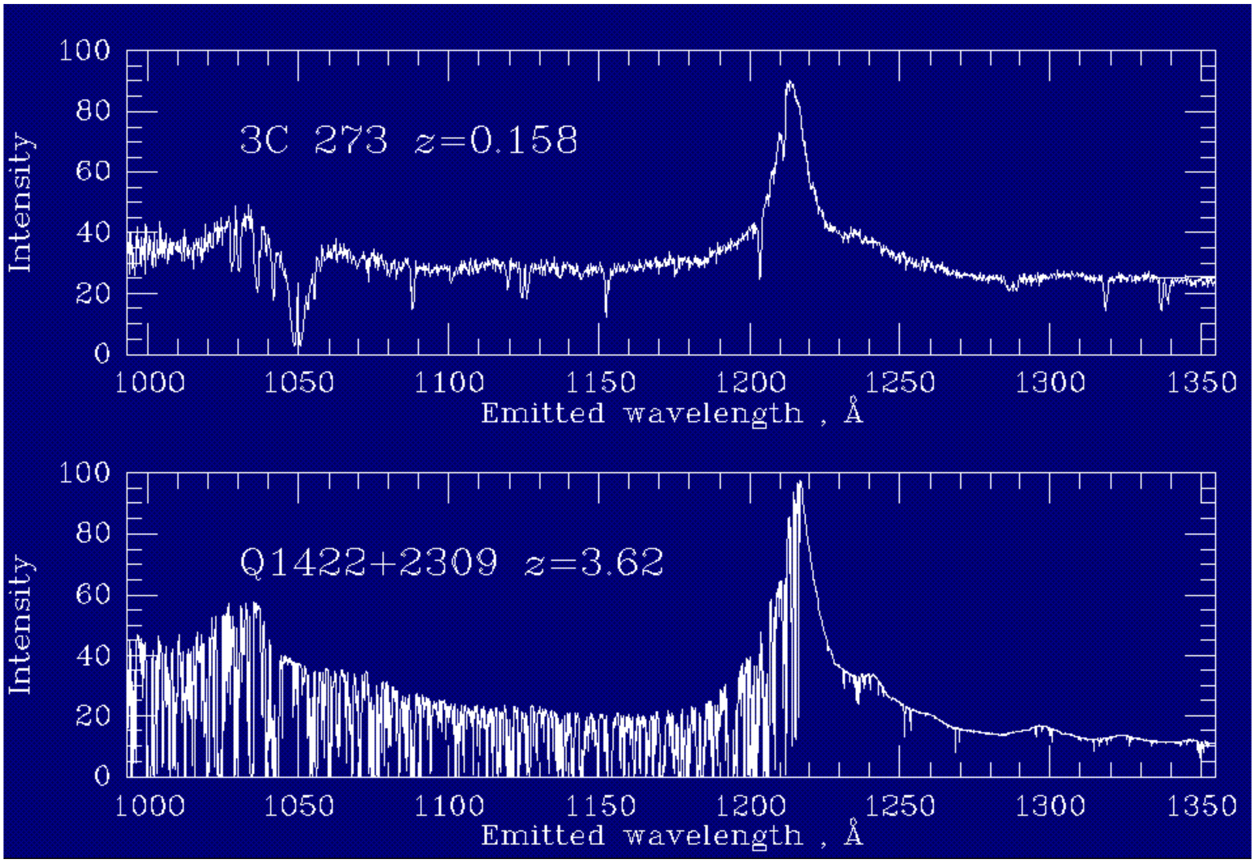
1.A Basics

The Lyman-α forest is the absorption spectrum of quasars. Quasars are very bright from accretion onto supermassive black holes so can be observed out to very high redshifts. They can therefore probe gas between the quasar and us along the line of sight through their absorption lines.



The quasar emits at 1216 Å from the hydrogen $n = 2$ to $n = 1$ transition. This emission line is redshifted as it travels through space. The light also passes through neutral hydrogen clouds, which absorb at 1216 Å, and these absorption lines are also redshifted as the light continues to travel through space. By the time the light reaches Earth, there is a series of absorption lines redshifted from 1216 Å, so the absorption lines are observed at different wavelengths.

By observing quasar spectra passing through the intergalactic medium (IGM), we can use the Lyman-α forest to probe the density, ionization, temperature, chemistry, and structure of the IGM. Below are a few examples of quasar spectra. At higher redshift, there are more opportunities for the light to pass through neutral hydrogen clouds.

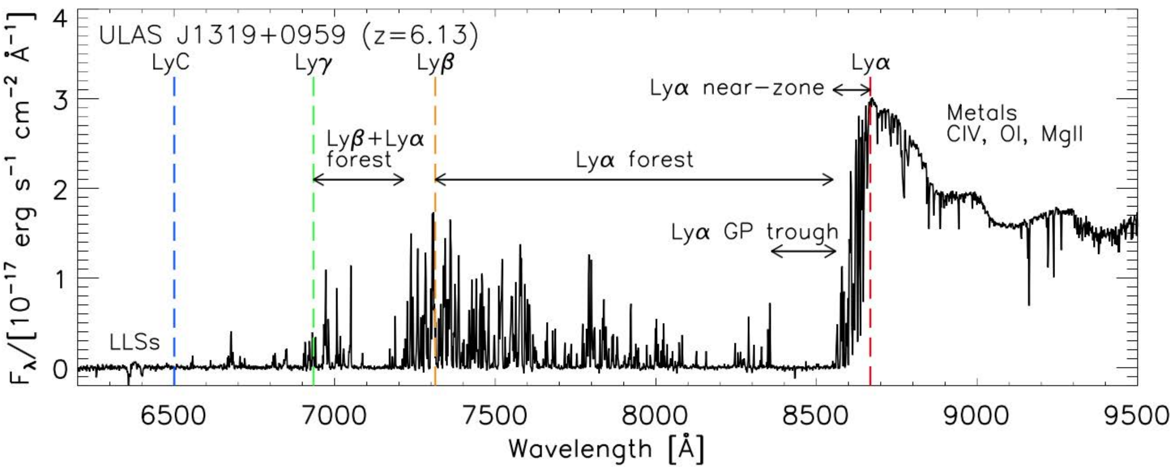


Notes:

- Identify lines in general through doublets: μ_{0II} ($\lambda = 2795$Å, 2802Å...)
- Lyman-α forest is only visible if it extends to shorter wavelengths than the observed Lyα emission line at $(1 + z_{\rm em})1216$ Å. Photons emitted with $1216\text{Å}(1 + z_{\rm em} < \lambda) < 1216\text{Å}$ will have at some point along the line of sight the right rest frame wavelength (1216Å) to be absorbed.
- There are three cases for HI along the line of sight
  - column density $N_{\rm H} \lesssim 10^{17}$ cm^{-2} gives narrow lines, i.e. the forest
  - column density $N_{\rm H} \gtrsim 10^{17}$ cm^{-2} are Lyman-limit systems, i.e. photons with $\lambda \lesssim 912\text{Å} = 13.6$eV in the rest frame are completely absorbed as the light moves through the cloud
  - column density $N_{\rm H} \gtrsim 10^{32}$ cm^{-2} are damped Ly-α systems, i.e. absorption lines become very broad.

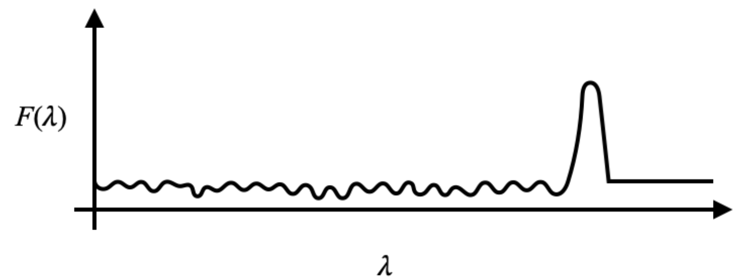
The Gunn-Peterson Test:
We can use quasar absorption spectra as a hint about reionization and determining how baryons are distributed in the universe and in which state. The key idea is that neutral hydrogen along the line of sight leads to absorption, so if there is a significant amount of

neutral hydrogen then a quasar spectrum should be totally absorbed. When the redshift is high enough so that the hydrogen is almost all neutral, the high-wavelength region of the spectrum will be almost totally absorbed. This is called the *Gunn-Peterson trough*.

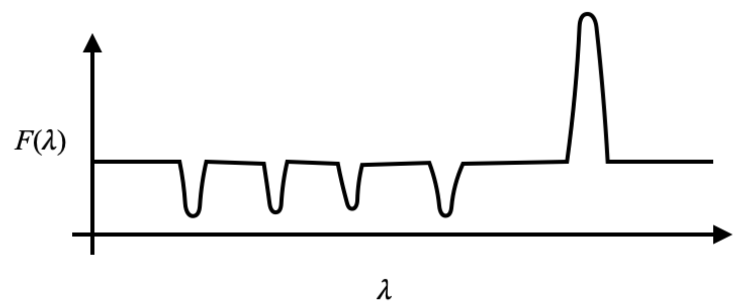


What is observed?

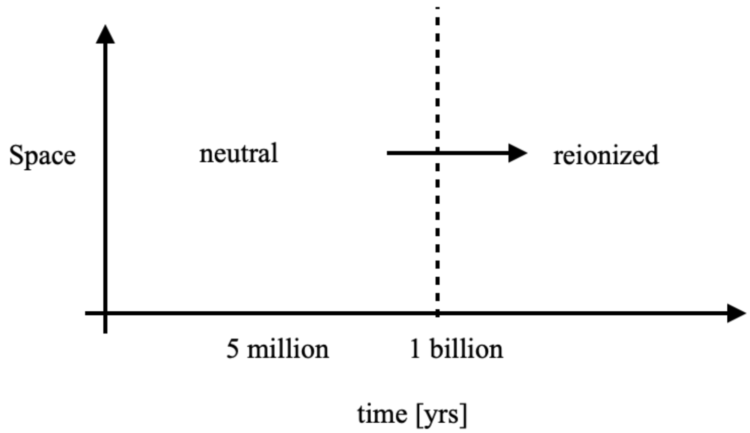
For $z \gtrsim 6$ we see suppression due to lots of neutral hydrogen along the line of sight.



For $z \lesssim 6$, we see little suppression due to little neutral hydrogen along the line of sight.



This implies that hydrogen above $z \approx 6$ is mostly neutral and mostly ionized below $z \approx 6$.

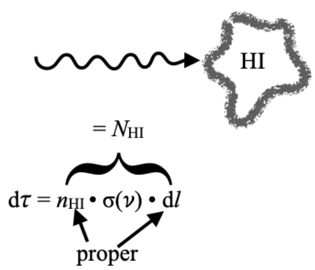


1.B A quantitative approach to Lyman-α

We now look in more detail at the absorption process:

$$F(\lambda_{\mathrm{obs}}) = F(\lambda_{\mathrm{em}}(1+z))e^{-\tau} \tag{494}$$

where τ is the optical depth, which we need to calculate.



Photons en route through a neutral HI cloud hit atoms in the ground state which then transition to an excited state ($n=1\to 2,\ n=1\to 2, ...n=1\to$ ionized). Each transition has a frequency dependent cross-section. The atoms then settle back to the ground state and a photon is emitted in some other direction within the solid angle 4π.

From atomic physics, we know that

$$\sigma(\nu) = \frac{\pi e^2}{m_{\mathrm{e}} c} f\phi(\nu-\nu_0) \tag{495}$$

where f is the oscillator strength (i.e. the probability for absorption) and ϕ is the Voigt profile with $\int \phi \mathrm{d}\nu = 1$. For the Lyman-$\alpha$ transition, $\sigma(\nu) = 10^{-2}\ \mathrm{cm}^2\phi(\nu-\nu_0)$ with units $\mathrm{cm}^2\mathrm{Hz}^{-1}$.

The proper length dl can be related to redshift (taking only the magnitude and ignoring signs):

$$\mathrm{d}l = c\mathrm{d}t = c\frac{\mathrm{d}a}{\dot{a}} = \frac{c}{a}\frac{\mathrm{d}a}{\dot{a}/a} = \frac{c}{a}\frac{\mathrm{d}a}{H} = (1+z)c\frac{\mathrm{d}a}{H} \tag{496}$$

and since $a = 1/(1+z)$ then $\frac{\mathrm{d}a}{\mathrm{d}z} = 1/(1+z)^2$ so

$$\mathrm{d}l = \frac{1}{1+z}c\frac{\mathrm{d}z}{H(z)} = \frac{c\mathrm{d}z}{(1+z)H(z)} \tag{497}$$

giving

$$\mathrm{d}l = \frac{c\mathrm{d}z}{(1+z)H(z)} = c\left(H_0(1+z)\sqrt{\Omega_{M,0}(1+z)^3+\Omega_\Lambda}\right)^{-1}\mathrm{d}z\ . \tag{498}$$

For the matter dominated regime ($z \gtrsim 1$), we get

$$\mathrm{d}l = \frac{c\mathrm{d}z}{H_0\sqrt{\Omega_{M,0}}(1+z)^{\frac{5}{2}}} \ . \tag{499}$$

Then the optical depth is

$$\tau_\nu = \sigma_0 \frac{c}{H_0\Omega_{M,0}^{\frac{1}{2}}} \int_0^z \mathrm{d}z' \frac{n_{\mathrm{HI}}(z')}{(1+z')^{\frac{5}{2}}} \phi(\nu(1+z') - \nu_0) \tag{500}$$

and we can assume that ϕ, which has a Gaussian shape, is very narrow so is approximately a delta function

$$\begin{aligned} &\approx \sigma_0 \frac{c}{H_0\Omega_{M,0}^{\frac{1}{2}}} \int_0^z \mathrm{d}z' \frac{n_{\mathrm{HI}}(z')}{(1+z')^{\frac{5}{2}}} \delta(\nu(1+z') - \nu_0) \\ &= \sigma_0 \frac{n_{\mathrm{HI}}(z)}{H_0\Omega_{M,0}^{\frac{1}{2}}} \frac{c}{\nu_0} \frac{1}{(1+z)^{\frac{3}{2}}} \end{aligned} \tag{501}$$

and using $\lambda_0 = \frac{c}{\nu_0}$, we get

$$\tau_\nu(z) = \sigma_0 \frac{n_{\mathrm{HI}}(z)\lambda_0}{H_0\Omega_{M,0}^{\frac{1}{2}}(1+z)^{\frac{3}{2}}} \tag{502}$$

where $\sigma_0 = 10^{-2}\,\mathrm{cm}^2$ and z is the redshift when $\lambda(1+z) = \lambda_0$, i.e. when absorption happens. This gives the optical depth for one frequency, so is necessary to evaluate at many frequencies to get the optical depth for different parts of a spectrum.
As an example, we can evaluate $\tau_\nu(z=3)$ assuming hydrogen is uniformly distributed and neutral. Using

$$\begin{aligned} H_0 &= 70\,\mathrm{km/s/Mpc} = 2.3 \times 10^{-18}\,\mathrm{s}^{-1} \\ n_{\mathrm{HI}} &= \frac{\rho_{\mathrm{crit}}\Omega_{b,0}}{m_{\mathrm{H}}}(1+z)^3 \sim 10^{-5}\,\mathrm{cm}^{-3}\left(\frac{1+z}{4}\right)^3 \approx 10^{-5}\,\mathrm{cm}^{-3} \qquad \text{at } z=3 \\ \lambda_0 &= 1216\,\text{Å} \\ \sigma_0 &= 10^{-2}\,\mathrm{cm}^2 \end{aligned} \tag{503}$$

we get $\tau_{\mathrm{Ly}\alpha} \sim 10^5$, but we observe that $\tau \sim 1$.

There are a couple possible solutions to this discrepancy. It could be that gas isn't in intergalactic space. However, we know that this is not the case since we have observed it. The other option is that the gas isn't neutral. To bring $\tau_{\mathrm{Ly}\alpha}(z=3)$ down to ~ 1, we need to have the neutral hydrogen fraction $X_{\mathrm{HI}} \equiv \frac{n_{\mathrm{HI}}}{n_{\mathrm{H}}} \sim 10^{-5}$.

Ionization:
How does the hydrogen get ionized?

Ionization can occur in hot temperatures. We can estimate the temperature from absorption line widths:

$$\begin{aligned}
&\Delta v \sim 20\,\mathrm{km/s} \\
&\frac{1}{2}mv^2 \sim kT \\
\Rightarrow &20\,\mathrm{km/s} \ \sim \sqrt{\frac{2kT}{m}} \\
\Rightarrow &T \sim 30,000\,\mathrm{K} \sim 3eV
\end{aligned} \tag{504}$$

which is not enough to ionize hydrogen.

Another option is photoionization. Integrated light from galaxies and quasars emits $\Gamma \sim 10^{-12}$ ionizing photons per second. The ionization rate is then Γn_{HI}, and the ionization timescale is

$$\frac{n_{\mathrm{HI}}}{n_{\mathrm{HI}}\Gamma} \sim 10^{12}\,\mathrm{s} \sim 30,000\,\mathrm{yr} \tag{505}$$

We can compare this with the recombination rate $Rn_{\mathrm{HII}}n_{\mathrm{e}}$ where $R = 4.3 \times 10^{-13} \left(\frac{T}{10^4\,\mathrm{K}}\right)^{-0.7}$ which gives the recombination timescale

$$\frac{n_{\mathrm{HII}}}{Rn_{\mathrm{e}}n_{\mathrm{HII}}} \sim 2 \times 10^{17}\,\mathrm{s} \sim 3 \times 10^6\,\mathrm{yr} \tag{506}$$

so recombination is much slower than ionization and photoionization is plausible.

To establish the predicted ionization fraction, we find equilibrium by setting the ionization and recombination timescales equal:

$$Rn_{\mathrm{HII}}n_{\mathrm{e}} = \Gamma n_{\mathrm{HI}} \tag{507}$$

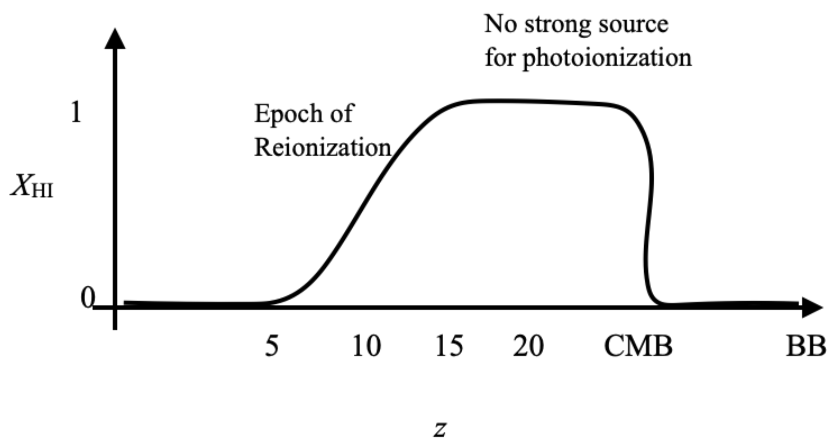
and assume that $n_{\mathrm{HII}} \sim n_{\mathrm{e}} \sim n_{\mathrm{H}}$ and $n_{\mathrm{HI}} \ll n_{\mathrm{HII}}$ so

$$Rn_{\mathrm{H}}^2 = X_{\mathrm{HI}}n_{\mathrm{H}}\Gamma \tag{508}$$

which gives a neutral fraction of

$$X_{\mathrm{HI}} \approx \frac{Rn_{\mathrm{H}}}{\Gamma} \sim 5 \times 10^{-6}\ . \tag{509}$$

So at the present day, the ionization fraction is very small. However, it took a while between recombination and the present day for ionizing sources to form and begin emitting radiation to ionize the neutral gas. Once they formed, the gas was ionized over a period of time. Before recombination, the gas was mostly ionized in the hot universe. Exactly how and when reionization occurred is an active area of research that is being probed by both telescopes like HERA and simulations like THESAN.


No strong source
for photoionization
1
Epoch of
Reionization
$X_{\rm HI}$
0
5
10
15
20
CMB
BB
z