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The High Redshift Universe

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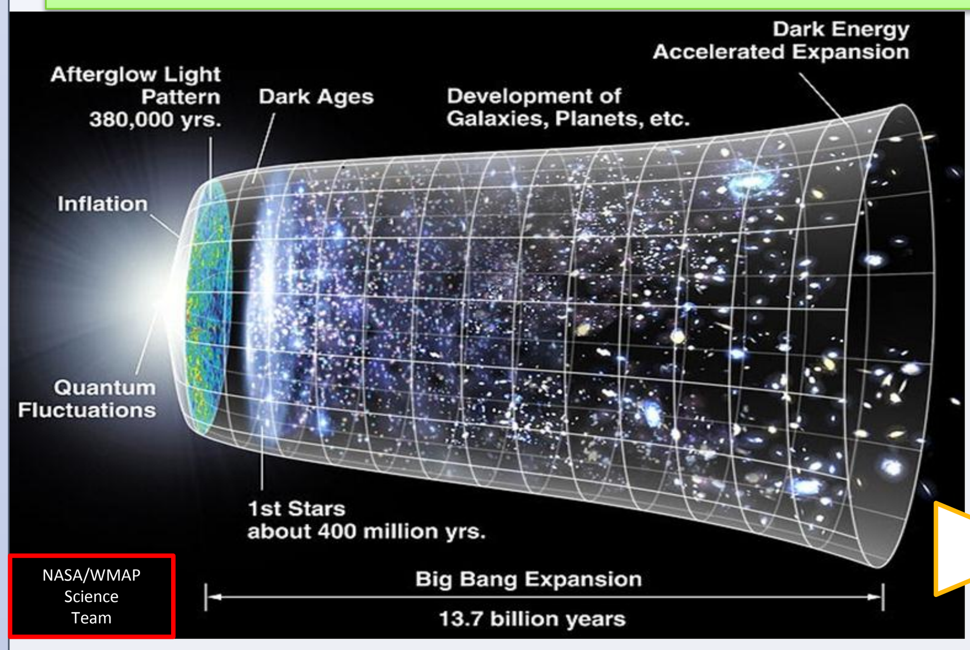
The Early Universe



Space and time began with the Big Bang which is estimated to have occurred 13.7 billion years ago.

The universe at this time was in an extremely hot ionized plasma state, comprising mainly of elementary particles and the nuclei of the lightest elements.

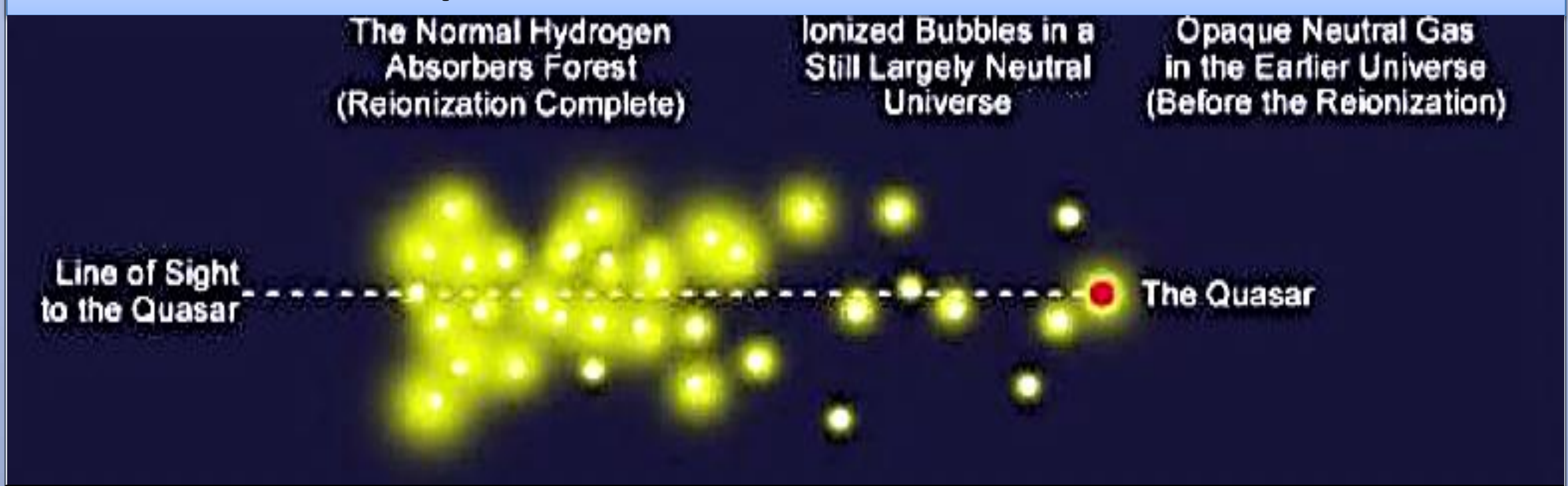
Photons were continually scattered by matter. Hence no radiation could reach us.

About 380,000 years after the big bang, the universe gradually expanded and cooled and became neutral.

Then there was a 'Dark Age' when the universe had no light sources.

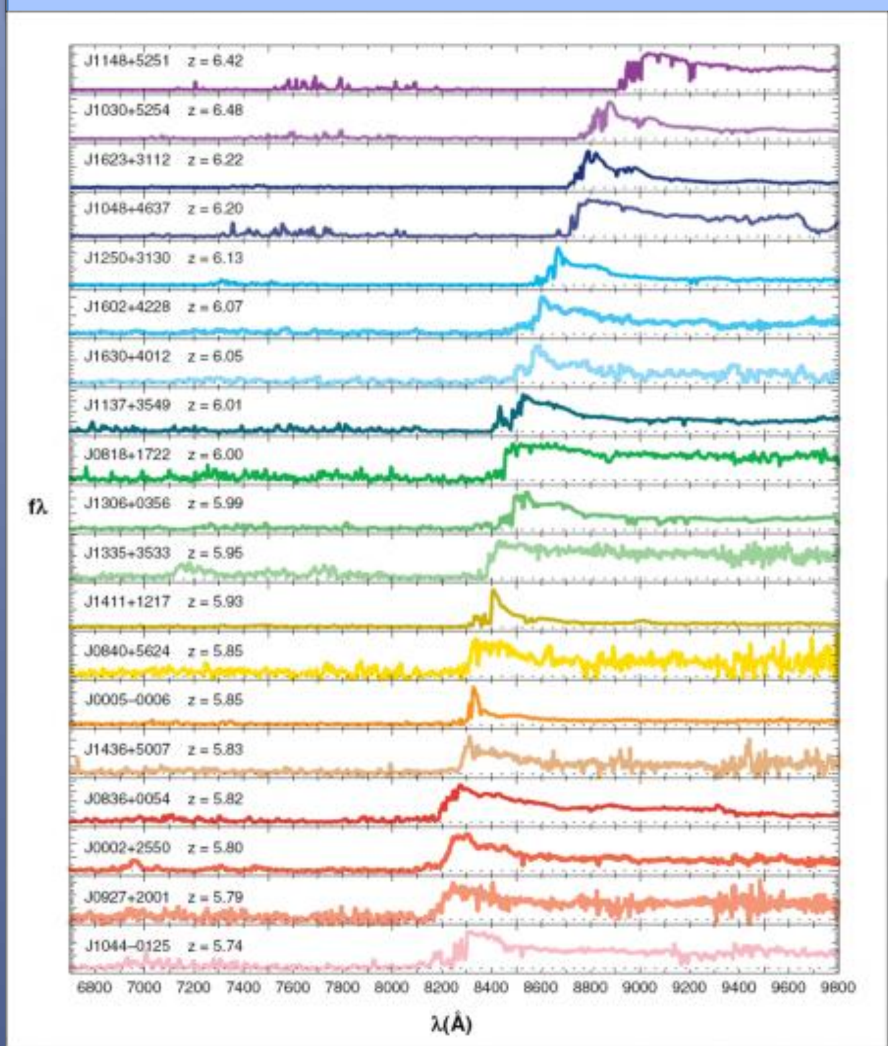
- The first stars and galaxies were formed ~ 400 million years after the big bang.
- The emergence of these first sources of light and the subsequent re-ionization of the universe led to end of the dark ages.

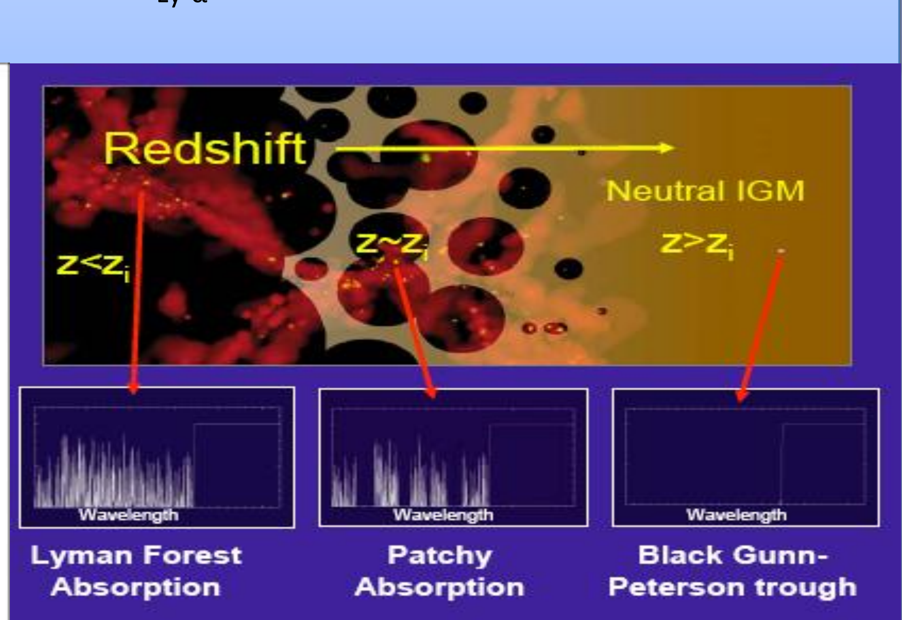
Epoch of Re-ionization



The Gunn-Peterson Effect

- The clear evidence for the epoch of re-ionization is the Gunn-Peterson effect.
- The electron of a neutral hydrogen atom can undergo a Lyman alpha transition by absorption of a photon of wavelength $\lambda_{Ly\text{-}\alpha}$=1216Å.
- The neutral hydrogen clouds along the line of sight to the background source will absorb Lyman-α photon resonantly at their rest frame wavelength that corresponds to a range of observed wavelengths in the spectrum of the background source.
- However, for photons at wavelengths > $\lambda_{Ly\text{-}\alpha}$ such absorption is not possible. The flat absorption trough that we observe on the blue side of $\lambda_{Ly\text{-}\alpha}$ line is known as the Gunn-Peterson effect.





- At higher redshifts, rich L-α absorbing systems and therefore a strong Gunn-Peterson effect.
- At lower redshifts, presence of ionized medium, weakens the Gunn-Peterson trough.

Sources of Re-ionization

The high energy required for re-ionization may have been obtained from:

- the formation of the first stars,
- the formation of the first galaxies,
- the active galactic nuclei.

So the study of the first stars and galaxies should provide important clues on Re-ionization.

Formation of stars

- For the formation of stars to occur, gas must fall into the dark matter halos.
- The Jean's mass criteria gives the minimum mass required for the gravitational binding energy to overcome the thermal energy of the gas.
- After the infall into the dark matter halos, the gas must also cool and condense into clouds in which stars can be formed.
- Since Hydrogen and Helium are the only dominant elements present at this time, cooling is mostly dominated by them.
- Since cooling by atomic Hydrogen is efficient only above 10^4 K, the cooling in these stars- which are at around 3000K- can only be explained by molecular Hydrogen.
- The high energy photons released from these massive and hot stars can cause the re-ionization of the universe.

The Lyman Break Galaxies

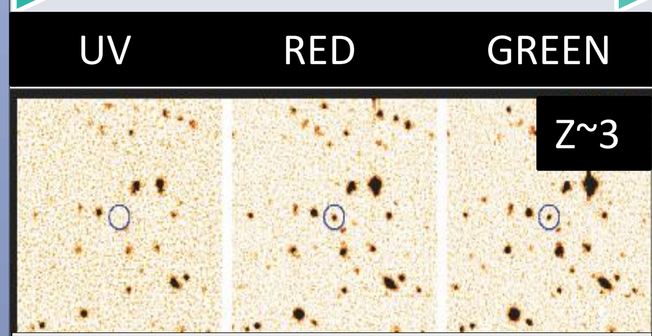
The first galaxies were formed at nearly the same time as the first stars. These are also much easier to observe. Typically therefore it is these galaxies at high redshifts that are studied to gain insights into re-ionization.

The Lyman Break technique is used to identify these galaxies at high redshifts. And it works as follows:

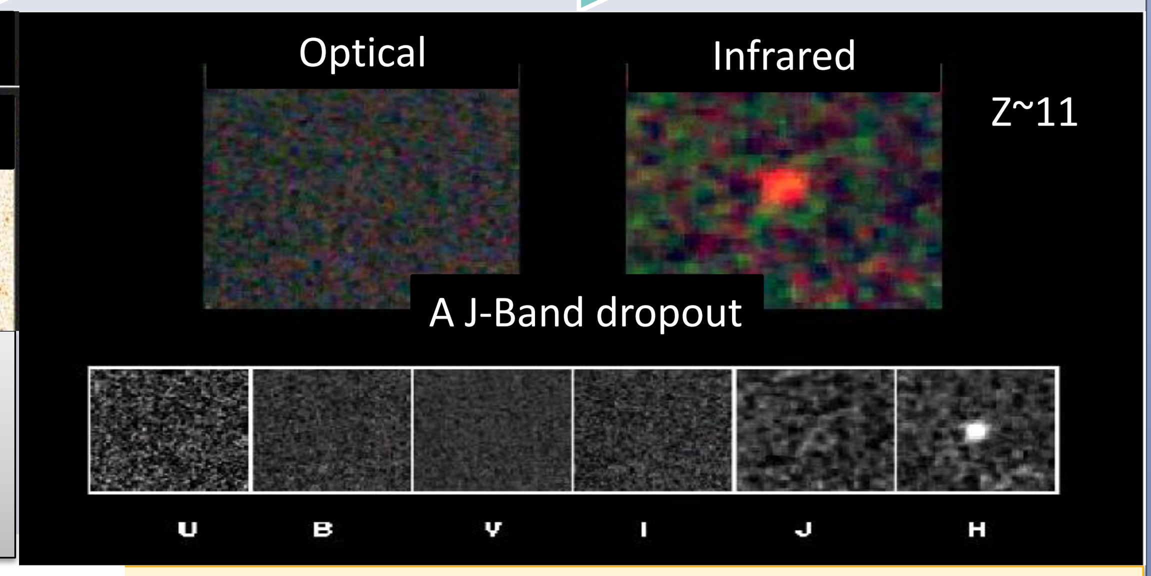
- The ionization potential of Hydrogen is 13.6 eV, which corresponds to a rest frame wavelength of 912 Å .
- Star forming galaxies at high redshifts have a spectrum that is rich in high energy UV photons.

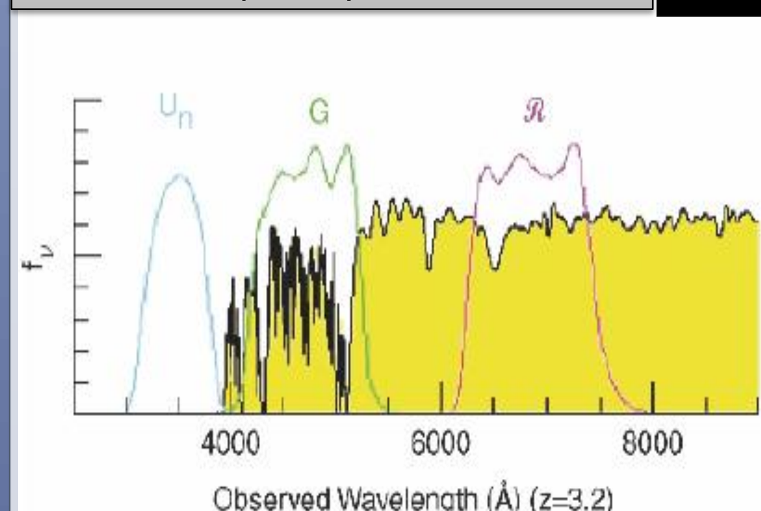
Photons at wavelengths shorter than 912 Å must be strongly suppressed due to absorptions by the ISM of the galaxy.

A Lyman Break Galaxy (LBG) at a redshift z, must therefore be virtually invisible at filters corresponding to wavelengths < (1+z)912 Å whereas it will be visible at filters corresponding to wavelengths larger than this (a.k.a dropout technique).

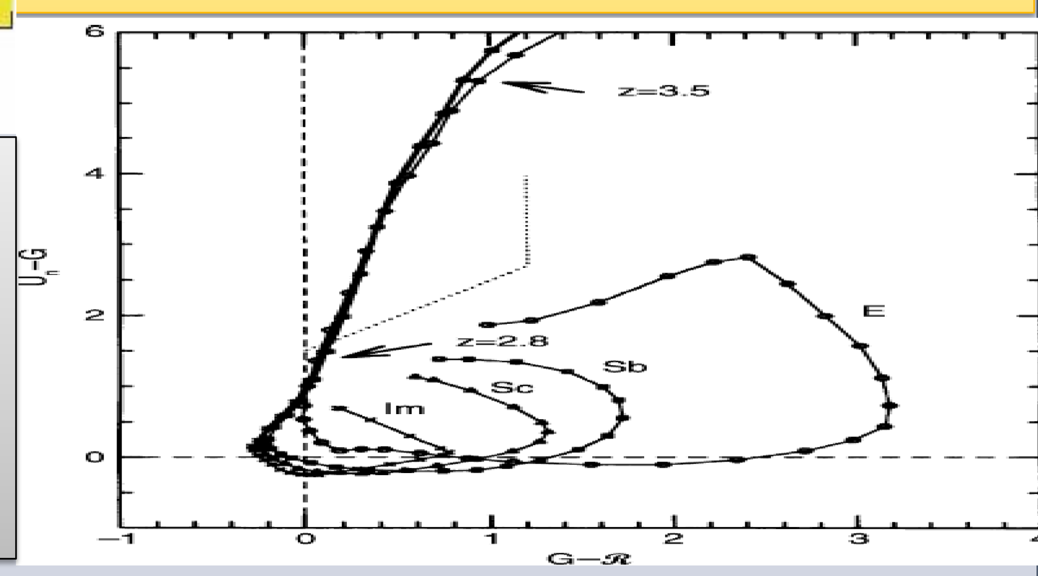


A U-band drop-out galaxy. It is clearly detected in the two redder filters, but vanishes almost completely in the U-filter.





When different broad-band filters are applied to the spectrum of the galaxy and the ratios of adjoining filter fluxes are measured and compared, then the location corresponding to the Lyman Break can be easily identified, and the redshift can be calculated.



The color-color diagram(right) can be used to identify galaxies at high redshifts. At z ≥ 3 almost all the galaxies lie between the dotted & dashed lines in the diagram, due to ISM absorptions – a highly effective method of collectively identifying high redshift galaxies.

References:

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