Reionization - I

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Cosmology - The Next Decade
ICTS-TIFR, Bangalore
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Topics to be covered

Concentrate on the physics of underlying structure of the IGM

- Observational constraints on reionization
- Theoretical models of reionization
- Future probes of reionization

References:

- Textbook: *Galaxy Formation and Evolution* by Houjun Mo, Frank van den Bosch & Simon White
- Review: *In the beginning: the first sources of light and the reionization of the universe* by Rennan Barkanaa & Abraham Loeb, Phys. Rept., 349, 125 (2001)
- Review: *Analytical Models of the Intergalactic Medium and Reionization* by T. Roy Choudhury, Current Science, 97, 841 (2009)

Epoch of reionization

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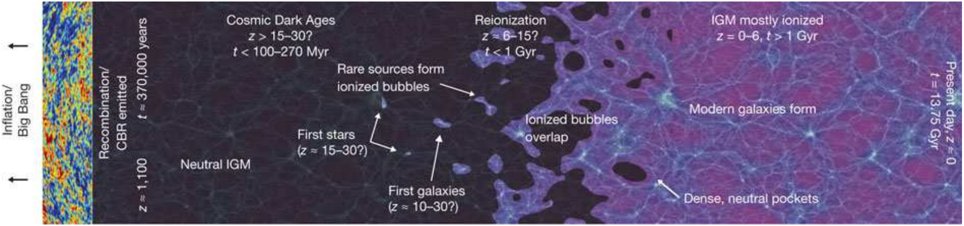
Big Bang | Universe expanding and cooling → | Present day



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Epoch of reionization

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Universe expanding and cooling

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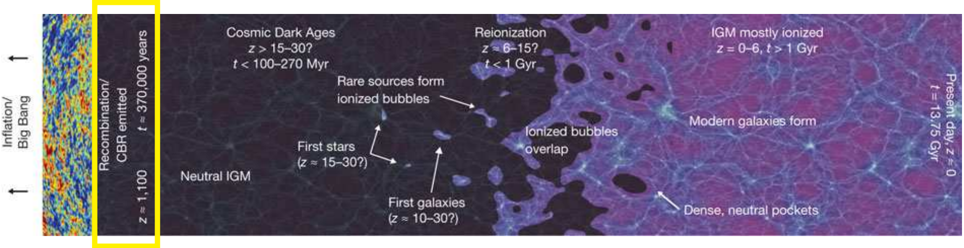

Last scattering epoch
First hydrogen atoms form

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

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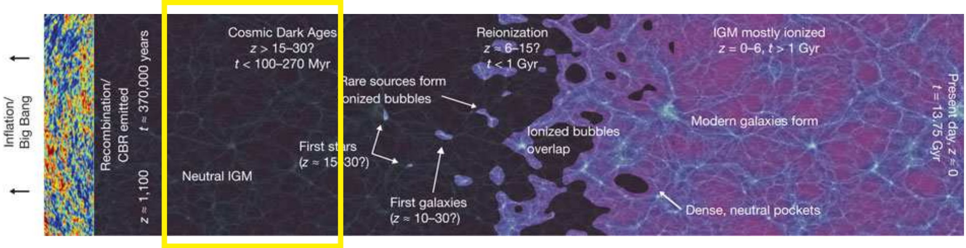
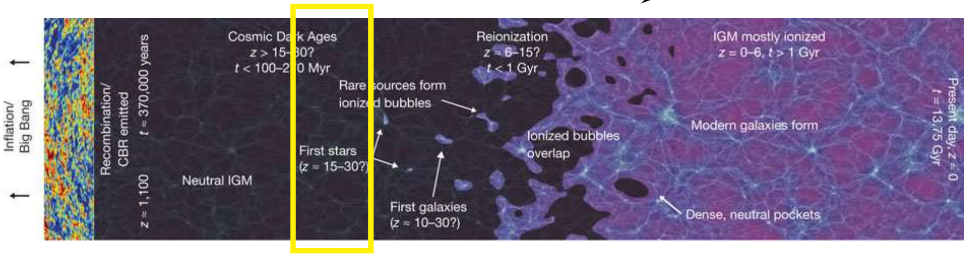


Dark ages

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

Big Bang　Universe expanding and cooling　Present day



First stars form

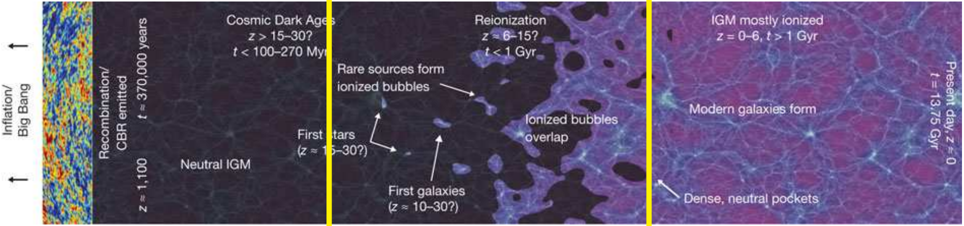
Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



Reionization

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Epoch of reionization

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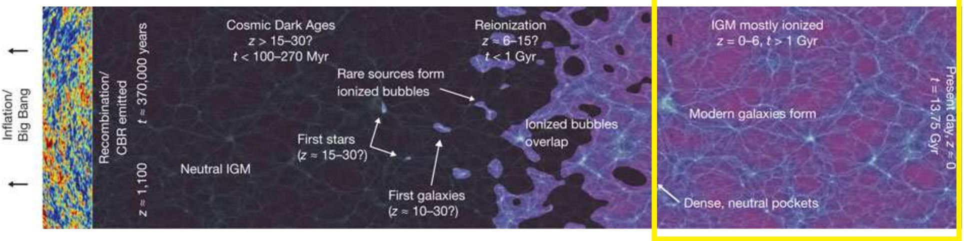

Post-reionization

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

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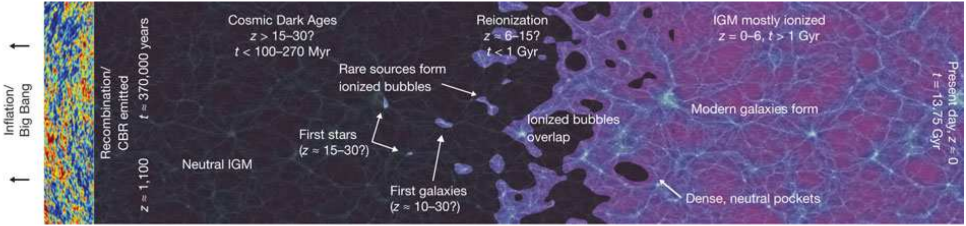

Dark ages

Strong probe of cosmology

Reionization

1. First stars
2. Cosmology

Post-reionization

1. Galaxy formation
2. Cosmology

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

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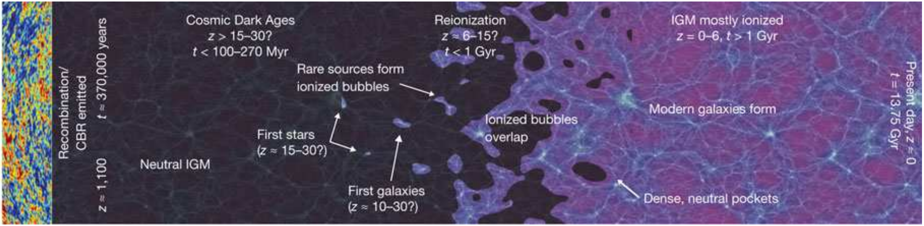

Dark ages

Strong probe of cosmology ✖

Reionization

1. First stars
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Post-reionization

1. Galaxy formation
2. Cosmology

Phase transition

“Final frontier” of observational cosmology

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Issues

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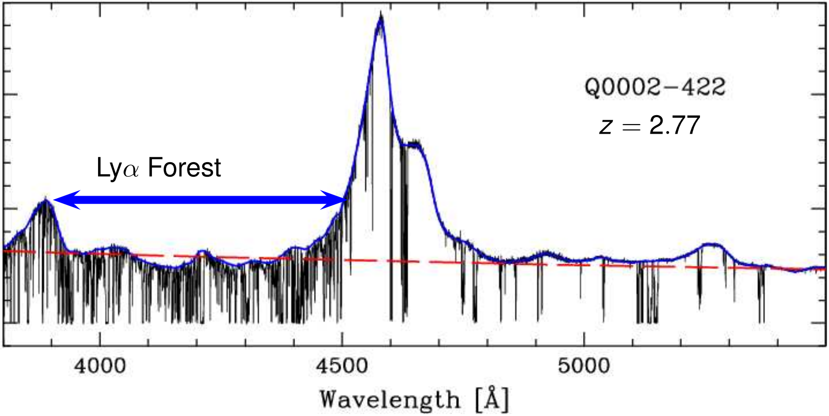
- Epoch of reionization? When did the sources produce enough photons to ionize the Universe? $z = 20$ or $z = 6$?
- Nature of reionization? Sudden or Gradual? Homogeneous or Inhomogeneous?
- What are the sources responsible? Stars, quasars, Exotic Particles?

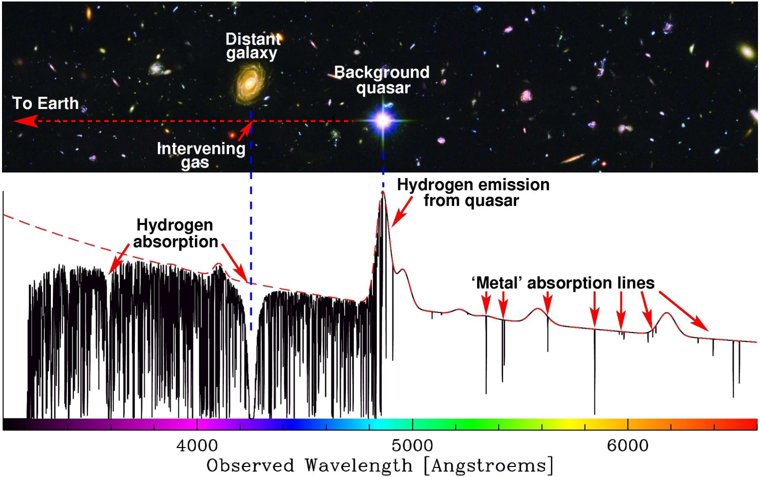
Evidence for reionization: Lyman-α forest



The absorption lines blueward of the emission line arise from Lyα transition ($n = 1$ to $n = 2$) of neutral hydrogen (HI) present between the quasar and us.

Absorption lines

The IGM is detected through the absorption features it produces in the spectrum of a background bright source of light (typically a QSO).



http://www.eso.org/~jliske/qsoal/

Ground states to higher ones

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- In absence of any interaction, hydrogen atoms in the IGM are likely to be in the ground state.

Ground states to higher ones

- In absence of any interaction, hydrogen atoms in the IGM are likely to be in the ground state.
- Lyman series: $i = 1$ to $f = n > 1$, absorb one photon of frequency ν_{fi}.

Absorption lines

- Consider radiation (photons) emitted at the QSO (at $z = z_Q$) rest frame frequency $\nu_Q > \nu_{fi}$. As the universe expands, the frequency will decrease and will reach ν_{fi} at a redshift z given by

$$\frac{\nu_Q}{1 + z_Q} = \frac{\nu_{fi}}{1 + z} \implies \lambda_Q(1 + z_Q) = \lambda_{fi}(1 + z)$$

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- Example: Consider a QSO at $z_Q = 3$. Consider a photon emitted at wavelength $\lambda_Q = 1187$ Å, then it would reach the Lyα wavelength 1216 Å at $z \approx 1187 \times 4/1216 - 1 \approx 2.9$. If there is neutral hydrogen at that position, it will produce an absorption signature.

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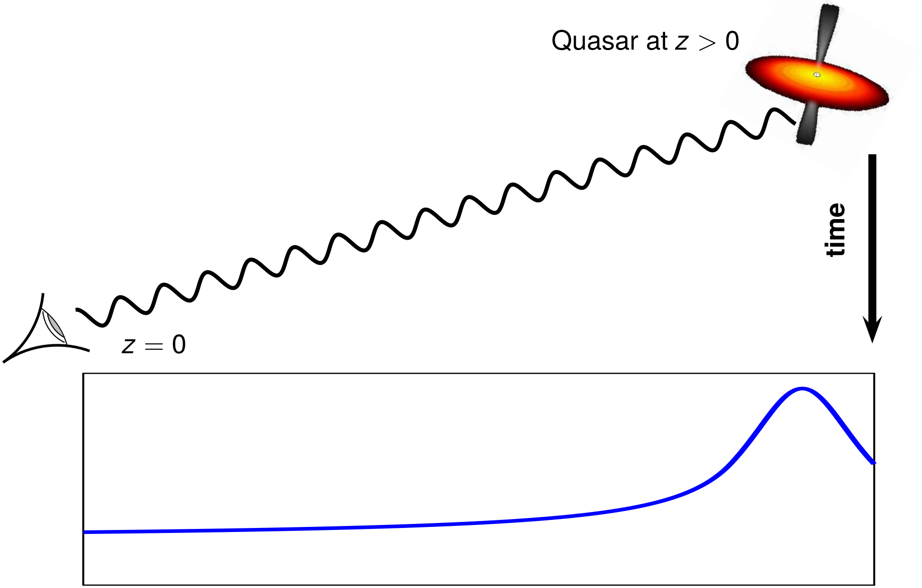
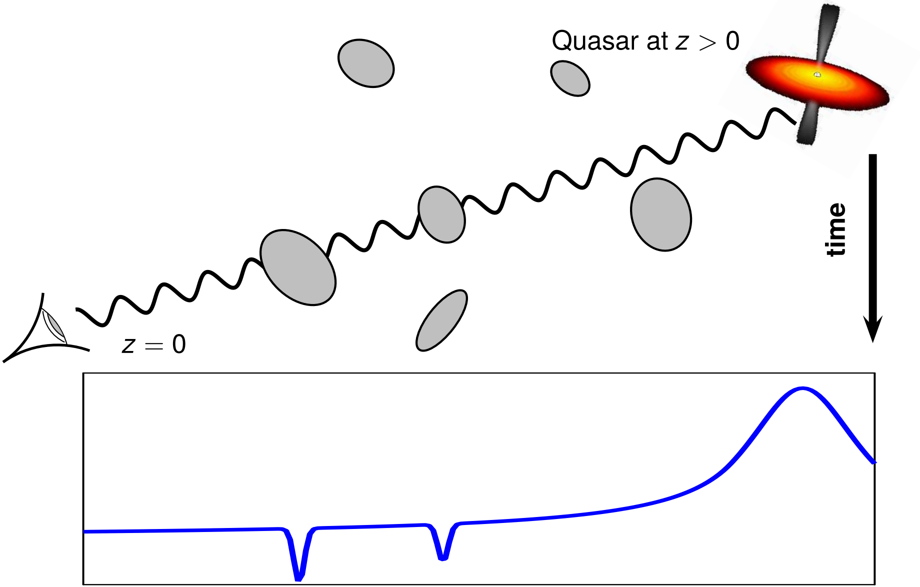
- We will observe the feature at $\lambda = \lambda_Q(1 + z_Q) \approx 4742$ Å. Thus any absorption arising at a redshift z will show up at $\lambda = \lambda_{fi}(1 + z)$.

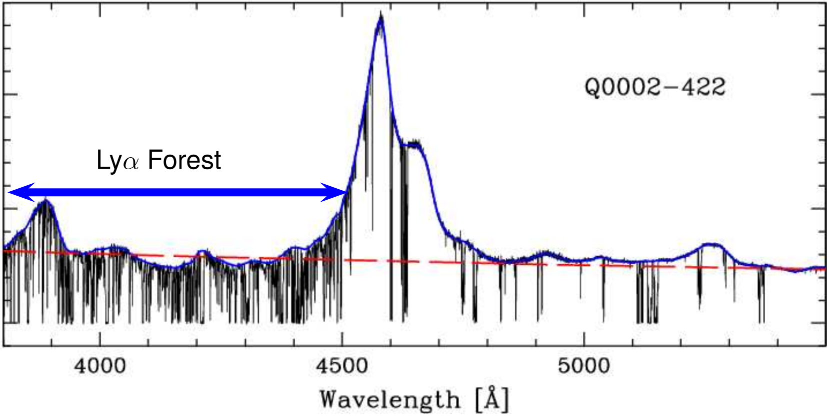
Absorption signatures



Absorption signatures



Absorption spectra



- The absorption lines blueward of the emission line arise from Lyα transition of neutral hydrogen (HI) present between the QSO and us.
- The unabsorbed regions correspond to either ionized regions or no matter at all.

Radiative transfer

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- The radiative transfer equation, in presence of only absorption, is

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \hat{\mathbf{n}}\cdot\nabla I_\nu = \frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -n_{\mathrm{abs}}\sigma_\nu I_\nu$$

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- The formal solution:

$$I_\nu(s, t) = I_\nu(0, t_{\mathrm{ret}}) \exp\left[-\int_0^s \mathrm{d}s' \; n_{\mathrm{abs}}(s') \; \sigma_\nu\right]$$

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- Define the optical depth

$$\tau_\nu = \int_0^s \mathrm{d}s'\; n_{\rm abs}(s')\;\sigma_\nu$$

so that the effect of absorption can be written as

$$I_\nu(s,t) = I_\nu(0,t_{\rm ret})\;\mathrm{e}^{-\tau_\nu}$$

In absence of any absorption $\tau_\nu = 0$.

Cosmological radiative transfer

- The radiative transfer equation, in presence of only absorption, is

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{1}{c}\frac{\dot{a}}{a}\left(3I_\nu - \nu\frac{\partial I_\nu}{\partial \nu}\right) + \hat{\mathbf{n}}\cdot\nabla I_\nu = -n_{\rm abs}\sigma_\nu I_\nu$$

- The formal solution:

$$I_\nu(s,t) = I_{\nu_i}(0,t_i)\left(\frac{a_i}{a}\right)^3 \exp\left[-\int_0^s \mathrm{d}s'\; n_{\rm abs}(s',t')\;\sigma_{\nu'}\right],$$

 where $\nu_i = \nu a/a_i$ and $\nu' = \nu a/a(t')$.
- Define the optical depth

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 In absence of any absorption $\tau_\nu = 0$.

...in terms of redshifts

- Observer at $z = 0$ (i.e., $a = 1$), QSO at $z = z_Q$:

$$I_\nu = I_{\nu_Q}(t_Q) \left(\frac{1}{1 + z_Q} \right)^3 \mathrm{e}^{-\tau_\nu},$$

$$\tau_\nu = \int_0^s \mathrm{d}s' \; n_{\mathrm{abs}}(s', t') \; \sigma_{\nu'}$$

where $\nu_Q = \nu(1 + z_Q)$ and $\nu' = \nu(1 + z')$.

Lyα optical depth

- The observed flux

$$I_\nu = I_{\nu_Q}(t_Q)\left(\frac{1}{1+z_Q}\right)^3 \mathrm{e}^{-\tau_\nu} \equiv I_{\nu_Q}^{\mathrm{cont}} \mathrm{e}^{-\tau_\nu}$$

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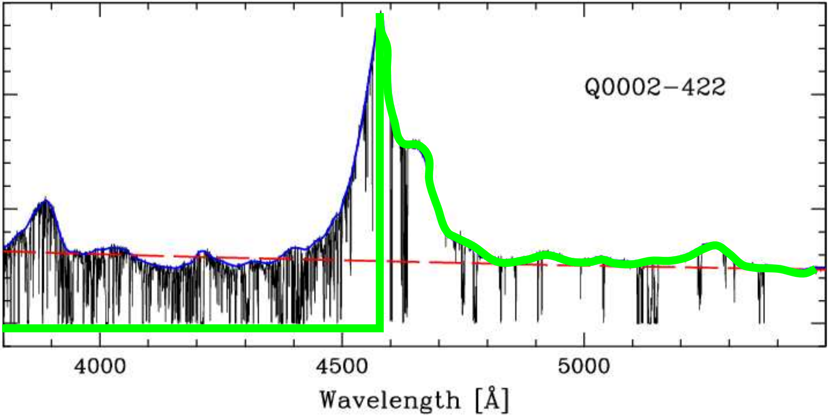
- Use $\mathrm{d}s' = c\mathrm{d}t' = -[c/H(z')]\,\mathrm{d}z'/(1+z')$, assume the profile to be very narrow (delta function), and calculate the optical depth for a uniform IGM. The result is (at $z \sim 3$)

$$\tau_\nu \approx 10^5 \left(\frac{n_{\mathrm{HI}}}{n_H}\right)$$

Gunn-Peterson effect



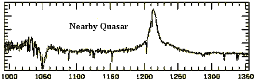
Observed flux $\sim$ Unabsorbed flux $\times$ $\exp\left(-10^5\, x_{\rm HI}\right)$, where $x_{\rm HI} = \rho_{\rm HI}/\rho_H$.

The fact that there is non-zero flux implies that $x_{\rm HI} \simeq 10^{-5}$

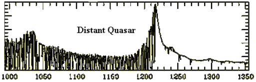
Non-zero flux observed till $z \sim 5.5$

QSO absorption lines at $z \sim 6$

$z \approx 0$



$z \approx 3$



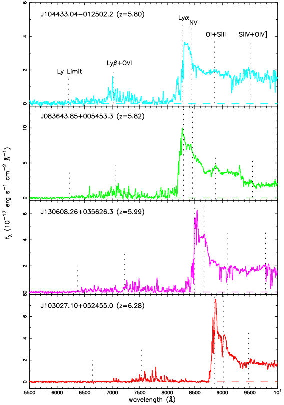
$x_{\rm HI} \lesssim 10^{-5}$

$z = 5.80$

$z = 5.82$

$z = 5.99$

$z = 6.28$



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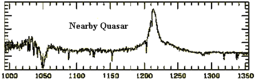

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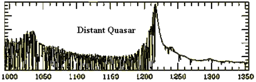

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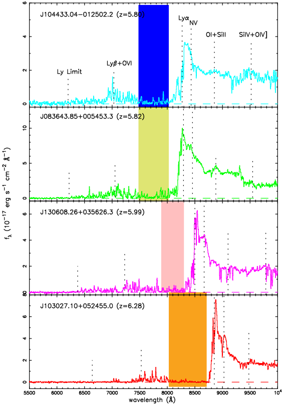

Does this absorption mean **high neutrality**?

QSO absorption lines at $z \sim 6$

- Gunn-Peterson optical depth:

$$\tau_{\rm GP} \approx \left(\frac{\bar{x}_{\rm HI}}{10^{-5}}\right)$$

- So, even a neutral fraction $x_{\rm HI} \approx 10^{-4}$ would produce **complete absorption**!
- Lyα transition “too strong”, saturates too easily....

Evolution equations

- Evolution equation for $n_H(\mathbf{x}, t) \equiv n_H(\mathbf{x}, z) = \bar{n}_H(z) \, [1 + \delta_B(\mathbf{x}, z)]$:

$$\frac{\mathrm{d}n_H}{\mathrm{d}t}$$

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Effect of expansion $n_{\mathrm{HI}} \propto a^{-3}$

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Density contrast

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Photoionization

- $\Gamma_{\rm HI}$: photoionization rate of neutral hydrogen, depends on ionizing sources

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Photoionization Recombination

- $\Gamma_{\rm HI}$: photoionization rate of neutral hydrogen, depends on ionizing sources
- $\alpha(T)$: recombination rate of ionized hydrogen with free electrons, known as a function of temperature T

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Photoionization Recombination

- $\Gamma_{\rm HI}$: photoionization rate of neutral hydrogen, depends on ionizing sources
- $\alpha(T)$: recombination rate of ionized hydrogen with free electrons, known as a function of temperature T
- Collisional ionization is negligible because of small densities

Photoionization rate

- Number of photoionizations per hydrogen atom per unit time:

$$\Gamma_{\rm HI} = 4\pi \int_{\nu_{\rm HI}}^{\infty} {\rm d}\nu \frac{J_\nu}{h\nu} \sigma_{\rm HI}(\nu)$$

(units s^{-1})
J_ν: flux of ionizing photons (units erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}), can be estimated from the emissivity of sources

$$J_\nu \sim \int c{\rm d}t \, \epsilon_{\nu'} \, {\rm e}^{-\tau_\nu}$$

Haardt & Madau (1996)

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Haardt & Madau (1996)

- The term $\mathrm{e}^{-\tau_\nu}$ is significant over a length scale λ_ν (the mean free path), then

$$J_\nu \sim \epsilon_\nu \, \lambda_\nu,$$

and

$$\Gamma_{\mathrm{HI}} \propto \int_{\nu_{\mathrm{HI}}}^{\infty} \mathrm{d}\nu \frac{\epsilon_\nu}{h\nu} \, \sigma_{\mathrm{HI}}(\nu) \, \lambda_\nu = \int_{\nu_{\mathrm{HI}}}^{\infty} \mathrm{d}\nu \, \dot{n}_\nu \, \sigma_{\mathrm{HI}}(\nu) \, \lambda_\nu$$

Calculation of $x_{\rm HI}$

- Define the neutral fraction

$$x_{\rm HI} \equiv \frac{n_{\rm HI}}{n_H}$$

so that

$$\frac{\mathrm{d}x_{\rm HI}}{\mathrm{d}t} = -\Gamma_{\rm HI}\, x_{\rm HI} + \alpha(T)\,(1 - x_{\rm HI})\, n_e$$

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- For a pure hydrogen gas (i.e., no helium), $n_e = n_{\mathrm{HII}}$, then

$$\frac{\mathrm{d}x_{\mathrm{HI}}}{\mathrm{d}t} = -\Gamma_{\mathrm{HI}}\, x_{\mathrm{HI}} + \alpha(T)\,(1 - x_{\mathrm{HI}})^2\, n_H$$

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- The equilibrium solution is:

$$x_{\mathrm{HI}}^{\mathrm{eq}} = \left(1 + \frac{q}{2}\right) - \sqrt{\left(1 + \frac{q}{2}\right)^2 - 1}, \quad q = \frac{\Gamma_{\mathrm{HI}}}{\alpha(T)\, n_H}$$

Calculation of $x_{\rm HI}$

- Define the neutral fraction

$$x_{\rm HI} \equiv \frac{n_{\rm HI}}{n_H}$$

so that

$$\frac{{\rm d}x_{\rm HI}}{{\rm d}t} = -\Gamma_{\rm HI}\, x_{\rm HI} + \alpha(T)\,(1 - x_{\rm HI})\, n_e$$

- For a pure hydrogen gas (i.e., no helium), $n_e = n_{\rm HII}$, then

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- Define the recombination time $t_{\rm rec} = [\alpha(T) n_H]^{-1}$, then $q = \Gamma_{\rm HI} t_{\rm rec}$ represents the *number of photoionizations per neutral atom over the recombination time-scale*.

Photoionization equilibrium

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- Assume q to be independent of time, also let $q \gg 1$ then the solution to the equation is

$$x_{\mathrm{HI}} \approx x_{\mathrm{HI}}^{\mathrm{eq}} + [x_{\mathrm{HI}}(0) - x_{\mathrm{HI}}^{\mathrm{eq}}(0)]\, \mathrm{e}^{-\Gamma_{\mathrm{HI}} t}, \quad x_{\mathrm{HI}}^{\mathrm{eq}} \approx \frac{1}{q} = \frac{\alpha(T)\, n_H}{\Gamma_{\mathrm{HI}}} \ll 1$$

  Hence x_{HI} approaches its equilibrium value in a time-scale $\Gamma_{\mathrm{HI}}^{-1}$.

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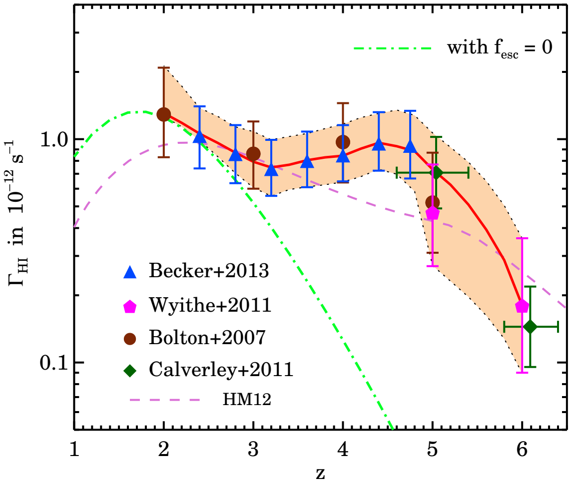
- Also $x_{\rm HI}^{\rm eq} \propto n_H$, thus high density regions tend to remain neutral.
- The Lyman-α forest observations can, in principle, provide constraints on $\Gamma_{\rm HI}$.

Observational constraints on $\Gamma_{\rm HI}$

Khaire, Srianand, **TRC** & Gaikwad (2016)



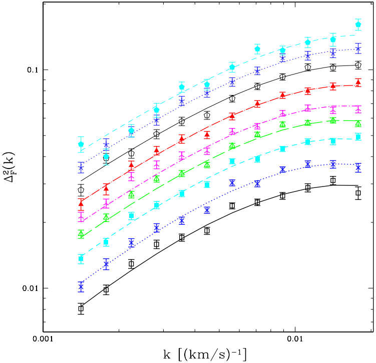
Flux power spectrum

- Transmitted flux $F(\nu) = \mathrm{e}^{-\tau_\nu}$.
- Convert the independent variable from ν to $\Delta v = c\Delta\nu/\nu$
- Define the contrast

$$\delta_F(\Delta v) = \frac{F(\Delta v)}{\langle F \rangle} - 1$$

- The power spectrum:$P_F(k) = \langle |\delta_F(k)|^2 \rangle$. The dimensionless power spectrum

$$\Delta_F^2(k) = \frac{kP_F(k)}{\pi}$$



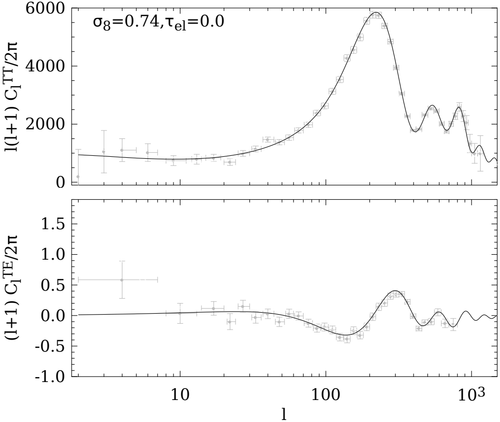
SDSS data
$z = 2.2, 2.4, \ldots, 4.2$ (bottom to top)
McDonald et al. (2006)

CMBR angular power spectrum

- CMBR photons scatter off free electrons.
- The measured quantity in CMBR observations is the optical depth due to Thomson scattering off **free electrons**:

$$\tau_{\rm el} = \sigma_T c \int_{t_{\rm LSS}}^{t_0} \mathrm{d}t\, n_e\, (1+z)^3$$

Provided by reionization



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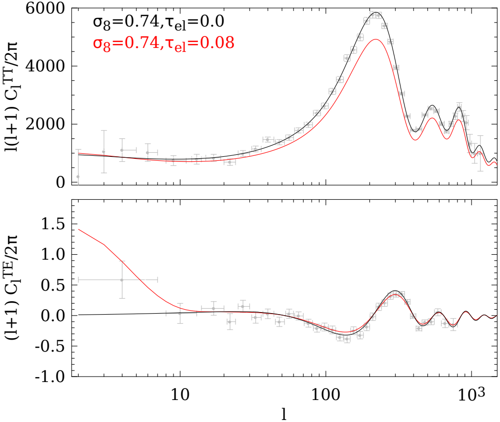

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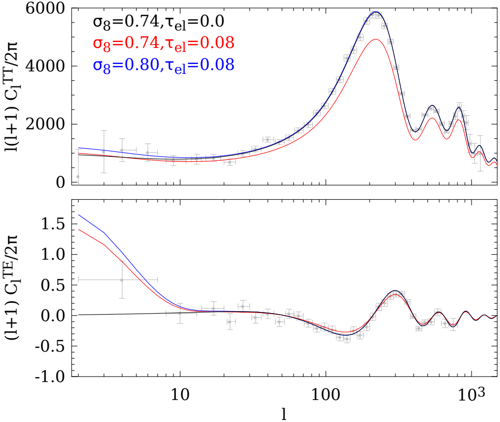

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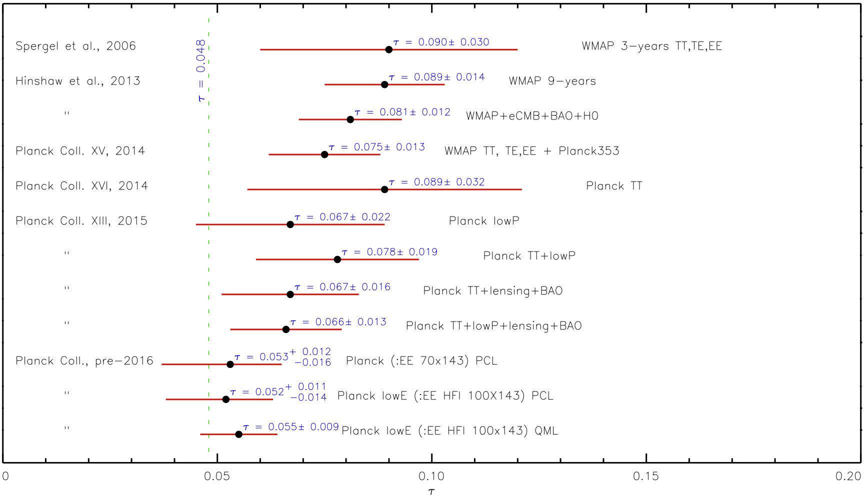
- Current constraints imply $z_{\rm re} \approx 7.5 - 8$

Thomson scattering $\tau_{\rm el}$ from CMBR

$$\tau_{\rm el} = \sigma_T c \int_0^{z[t]} {\rm d}t \; n_e \; (1+z)^3$$

Planck Collaboration (2016)



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  - the model should produce the right number of photons such that $x_{\rm HI} \gtrsim 10^{-4}$ at $z \sim 6$ (or, equivalently the correct value of $\Gamma_{\rm HI}$)