Cosmic Reionization

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From Re-ionization to large-scale structure: A multiwavelength approach
IUCAA, Pune
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Plan of the talk

- Introduction to reionization
- Observational constraints
- Modelling reionization
- Future scopes

What is reionization?

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- The IGM is highly ionized at $z \lesssim 6$. How did this happen?
- The sources are probably quasars and/or galaxies? Which one? Anything else?

Epoch of reionization

Big Bang | Universe expanding and cooling → | Present day

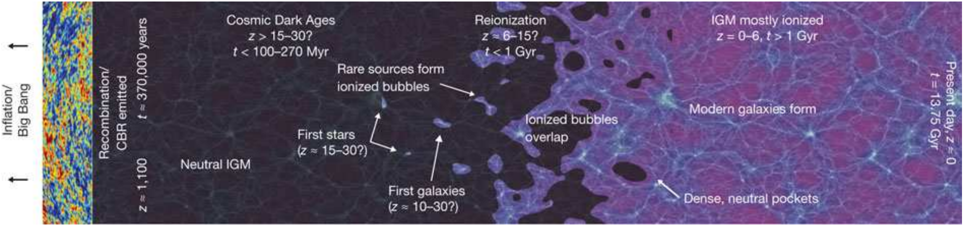

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

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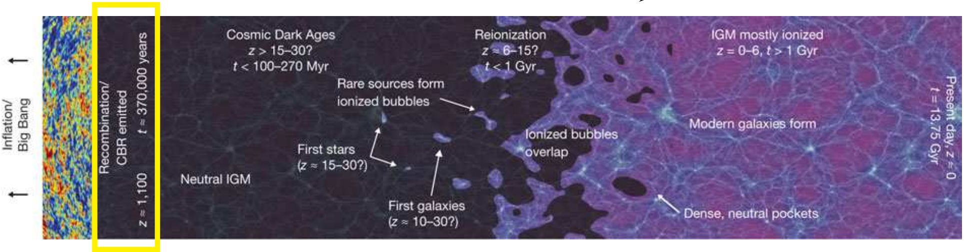

Last scattering epoch

First hydrogen atoms form

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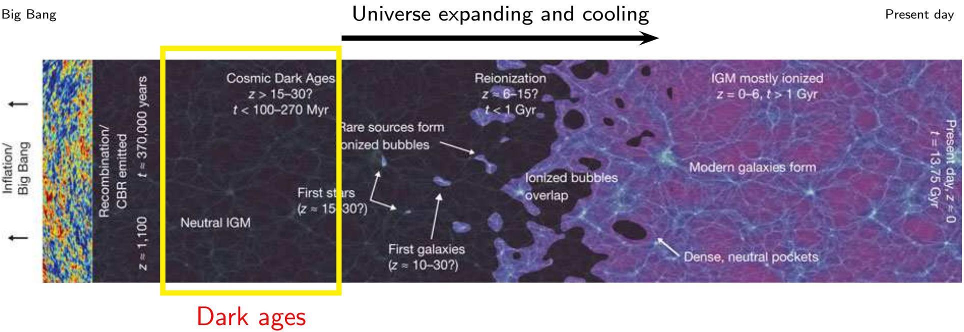

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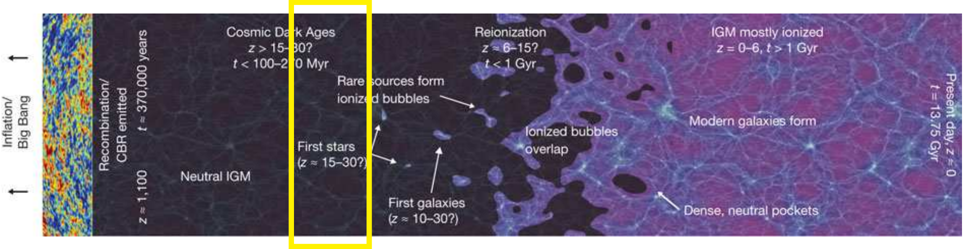

First stars form

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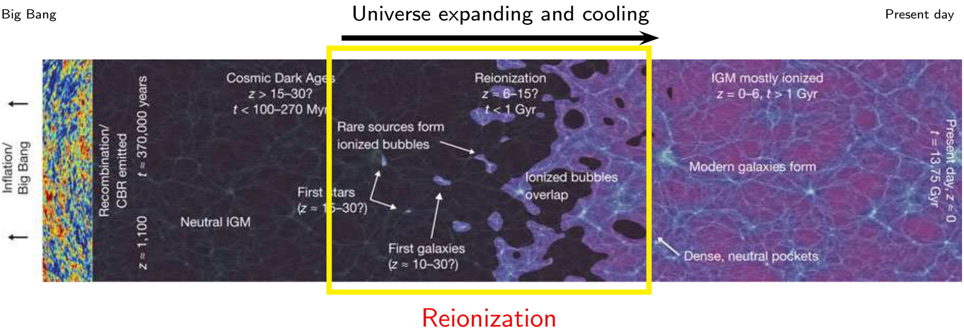

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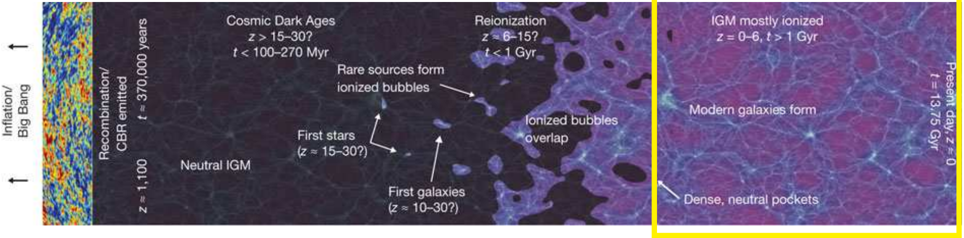

Post-reionization

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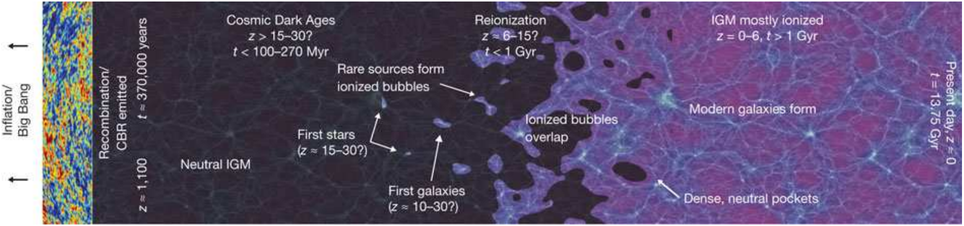

Dark ages

Strong probe of cosmology

✖

Reionization

1. First stars
2. Cosmology

Post-reionization

1. Galaxy formation
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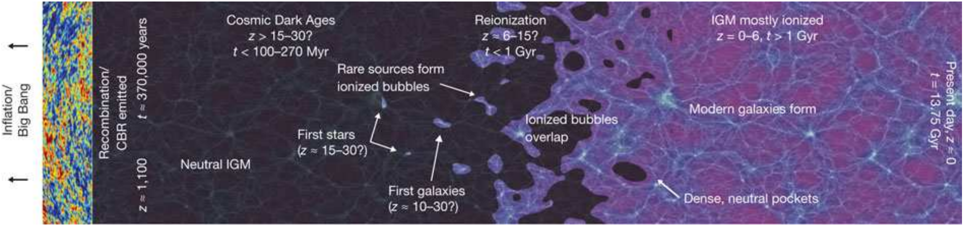

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Post-reionization

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Phase transition

"Final frontier" of observational cosmology

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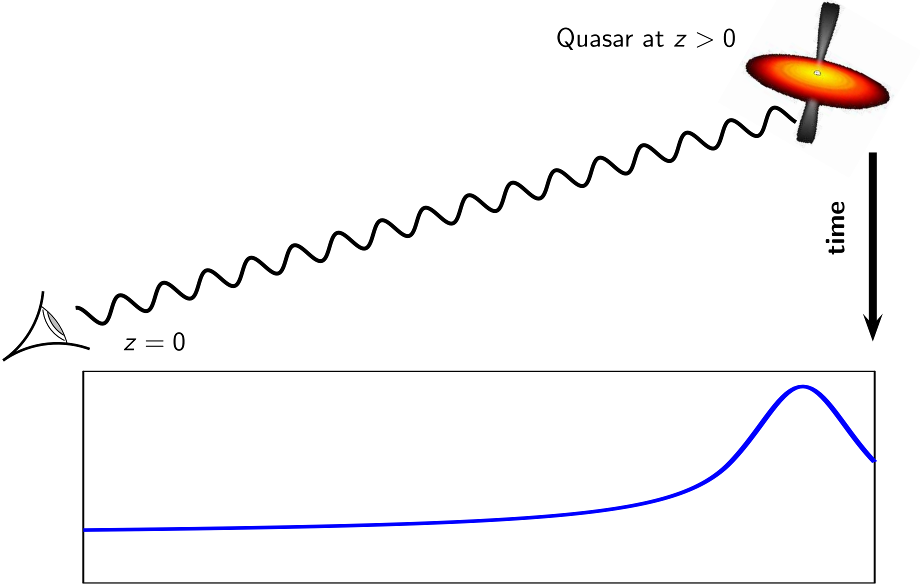
Absorption signatures



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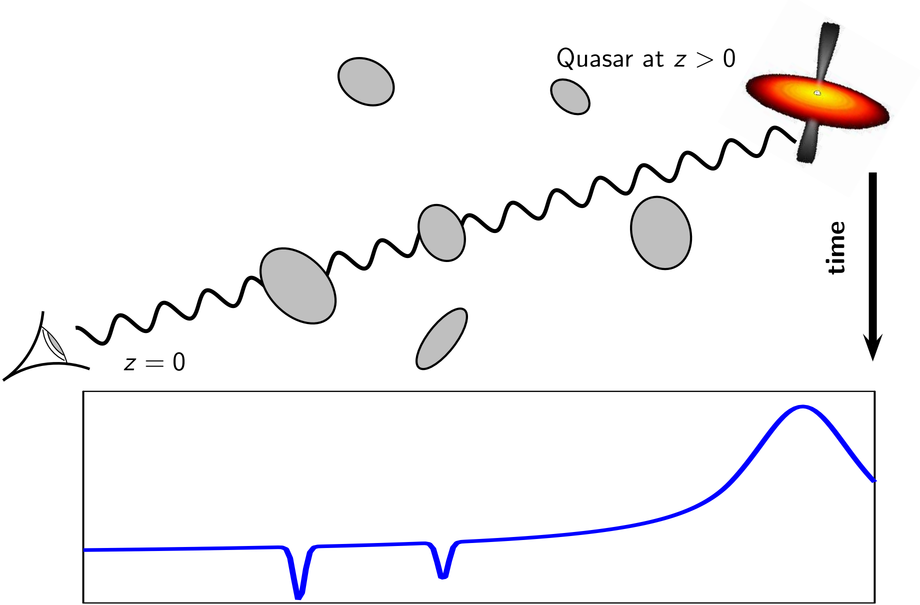
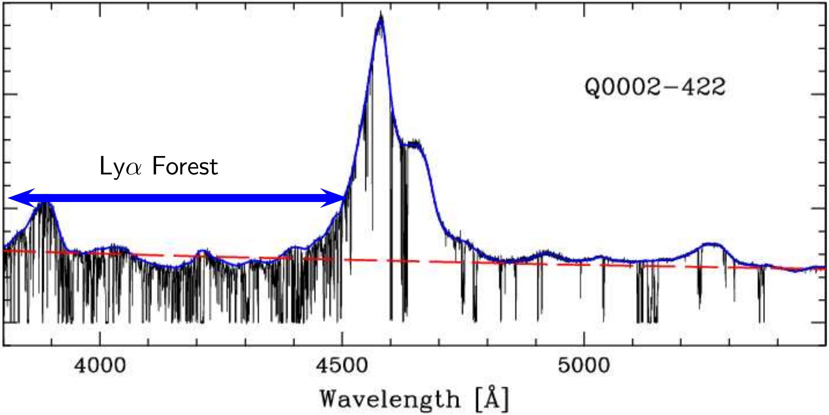
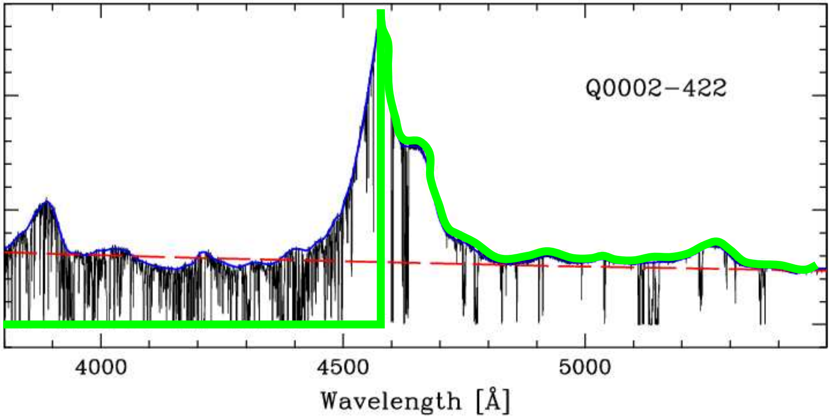


Lyman-α forest absorption lines



- 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.

Gunn-Peterson effect



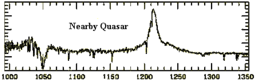
Observed flux $\sim$ Unabsorbed flux $\times$ $\exp\left(-10^5\, x_{\mathrm{HI}}\right)$, where $x_{\mathrm{HI}} = \rho_{\mathrm{HI}}/\rho_H$.

The fact that there is non-zero flux implies that

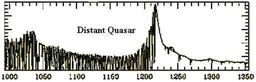
$$x_{\mathrm{HI}} \simeq 10^{-5}$$

QSO absorption lines at $z \sim 6$

$z \approx 0$



$z \approx 3$



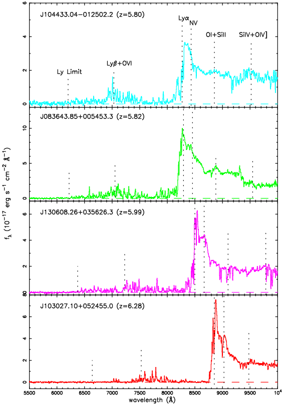
$x_{\rm HI} \lesssim 10^{-5}$

$z = 5.80$

$z = 5.82$

$z = 5.99$

$z = 6.28$



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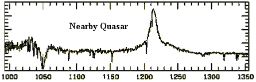

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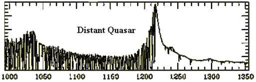

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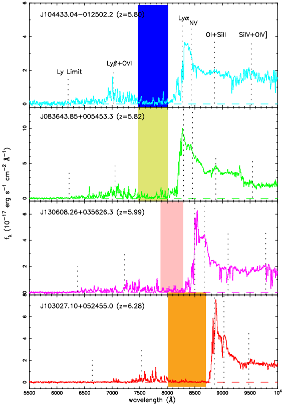
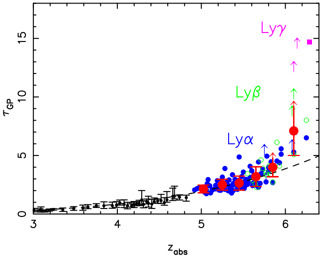


Does this absorption mean high neutrality?

QSO absorption lines at $z \sim 6$



Fan et al. (2005)

- Gunn-Peterson optical depth:

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

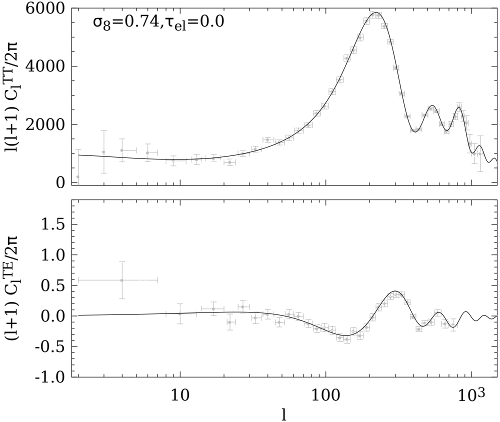
- So, even a neutral fraction $x_{\rm HI} \approx 10^{-4}$ would produce **complete absorption**!
- The IGM should not contain too much ionizing radiation at $z \approx 6$, otherwise one would end up with $x_{\rm HI} < 10^{-4}$.
- Lyα transition "too strong", saturates too easily...
  From here on, things get model-dependent and messy!!

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**:

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

Provided by reionization



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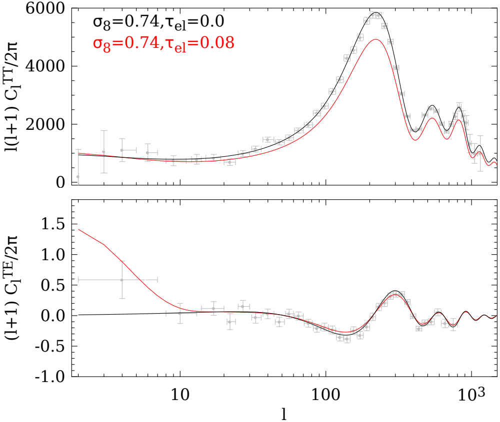

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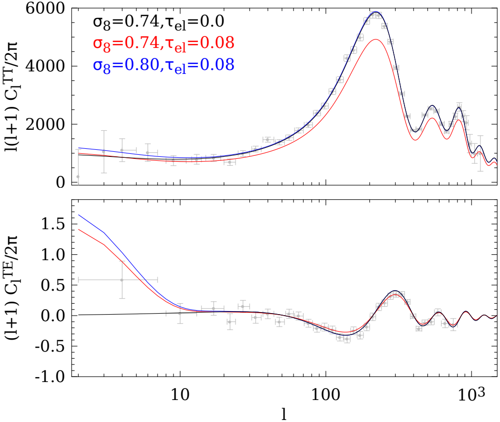

Probing reionization using CMBR

Current constraints on reionization come from

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  (effect is degenerate with amplitude of density power spectrum)
- Planck broke the degeneracy through lensing of the CMBR

Probing reionization using CMBR

Optical depth due to Thomson scattering off **free electrons**:

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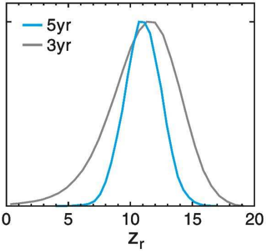
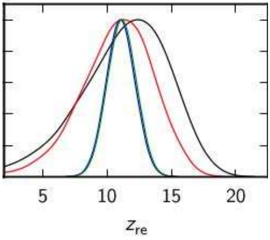
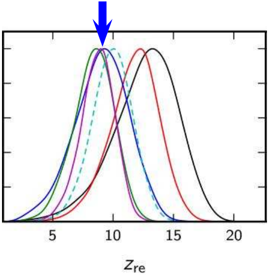
WMAP



Planck (2013)



Planck (2015)



Reionization redshift (assuming instantaneous process) according to Planck (2015)
$z \sim 9$

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  - reionization must end before $z \sim 6$
  - the model should produce the right number of photons such that $x_{\rm HI} \gtrsim 10^{-4}$ at $z \sim 6$

Reionization models: ingredients

Dark matter haloes M

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↓ cooling, fragmentation, feedback, ...

Galaxy + star formation $M_* = f_* M$

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Escape of photons from the galaxy f_{esc}

↓ propagation of ionization fronts

Radiative transfer through the intergalactic medium

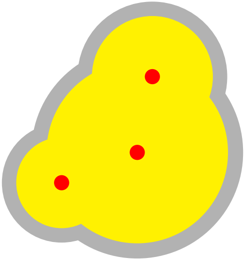
Growth of ionized regions

Number of photons produced per unit volume

$$\dot{n}_\gamma \; \Delta t = n_H \; \Delta Q_{\rm HII} \; + \; \Gamma_{\rm HI} \; (n_{\rm HI} \; Q_{\rm HII}) \; \Delta t$$

ionization of neutral regions

ionizing HI in already ionized regions



Photoionization equilibrium within ionized regions:

$$n_{\rm HI} \; \Gamma_{\rm HI} = \alpha_B \; \left(\mathcal{C} \; n_H^2\right) \; a^{-3}$$

clumping factor: $\mathcal{C} = \langle n_H^2 \rangle / \langle n_H \rangle^2$.

$$\frac{\mathrm{d}Q_{\rm HII}}{\mathrm{d}t} = \frac{\dot{n}_\gamma}{n_H} - Q_{\rm HII} \; \mathcal{C} \; \alpha_B \; n_H \; a^{-3}$$

Photon production

Photon production rate:

$$\frac{\dot{n}_\gamma}{n_H} = N_{\rm ion} \frac{{\rm d}f_{\rm coll}}{{\rm d}t}$$

Number of ionizing photons in the IGM per baryons

Collapse rate of dark matter haloes

$$N_{\rm ion} = \epsilon_* \ f_{\rm esc} \ \times \ \text{number of photons per baryons in stars} \times \left(\frac{\Omega_b}{\Omega_m}\right)$$

The relevant equations

The master equation:

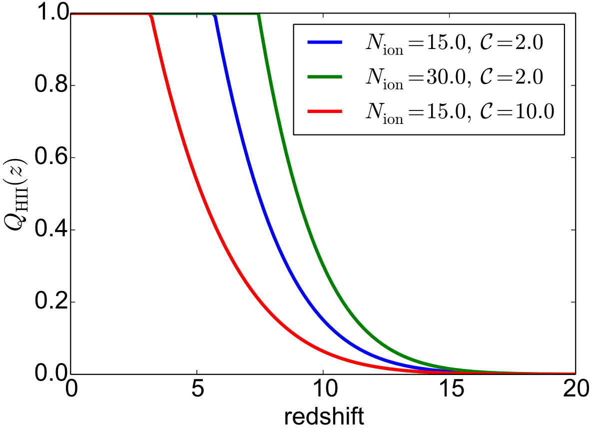
$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = N_{\mathrm{ion}} \; \frac{\mathrm{d}f_{\mathrm{coll}}}{\mathrm{d}t} - Q_{\mathrm{HII}} \; \mathcal{C} \; \alpha_B \; n_H \; a^{-3}$$

CMBR optical depth

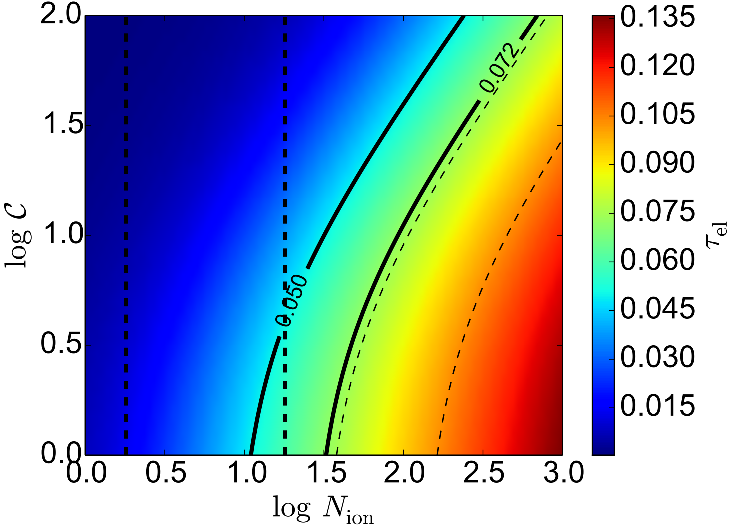
$$\tau_{\mathrm{el}} = c \; \sigma_T \; n_H \int_0^{z_{\mathrm{LSS}}} \mathrm{d}t \; Q_{\mathrm{HII}}(t) \; a^{-3}$$

Dependence on parameters

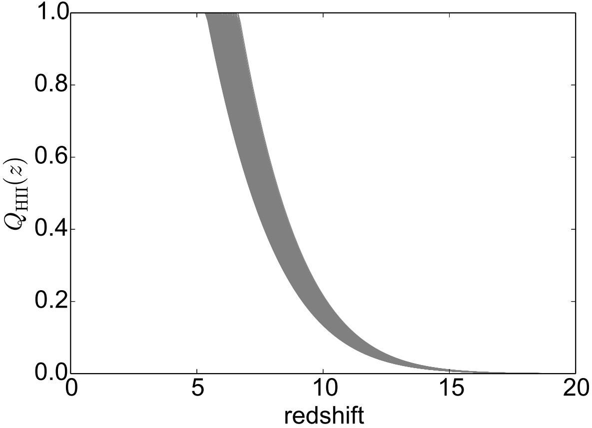
$$M_{\rm min} = 10^8 h^{-1} M_\odot$$



Constraints from $\tau_{\rm el}$ (and quasar spectra)



Allowed reionization histories



remember that $N_{\rm ion}$ and $\mathcal{C}$ are constants

Example of a detailed semi-analytical model

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- Standard FRW paradigm with ΛCDM model – **hierarchical structure formation** dominated by dark matter

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  1. Stars: modelled as $\dot{n}_\gamma = N_{\rm ion}(z)\, {\rm d}f_{\rm coll}/{\rm d}t$
  2. Quasars: significant at $z \lesssim 6$, model based on observed luminosity function
     (no free parameters)

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  1. Stars: modelled as $\dot{n}_\gamma = N_{\rm ion}(z)\, {\rm d}f_{\rm coll}/{\rm d}t$
  2. Quasars: significant at $z \lesssim 6$, model based on observed luminosity function
     (no free parameters)
- Only atomically cooled haloes, no molecular cooling

Example of a detailed semi-analytical model

Choudhury & Ferrara (2005,2006)

- Standard FRW paradigm with ΛCDM model – **hierarchical structure formation** dominated by dark matter
- Evolution of volume filling factor of ionized regions, supplemented by temperature and species evolution equations
- More sophisticated treatment: incorporate the fact that high density regions remain neutral for longer time (Lyman-limit systems)
  Miralda-Escude, Haehnelt & Rees (2000)
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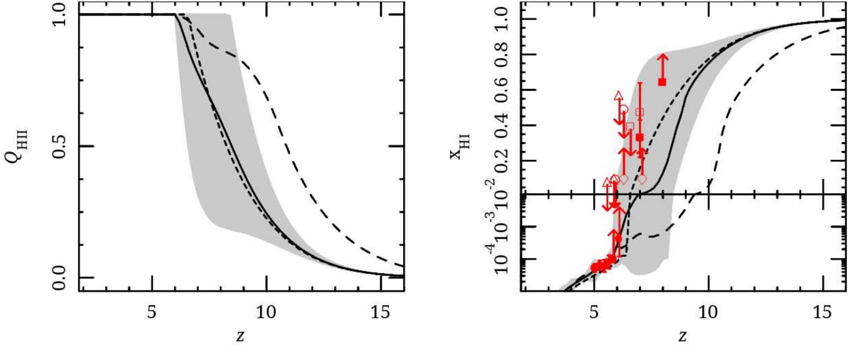
- Only atomically cooled haloes, no molecular cooling
- Radiative feedback suppressing star formation in low-mass haloes

Data constrained models

Mitra, **Choudhury** & Ferrara (2015)



Constraints based on Planck data + quasar absorption line measurements at $z \sim 6$
reionization starts at $z \sim 12$

Other probes of reionization

- Galaxy luminosity function: uncertain escape fraction
- Quasar absorption spectra (damping wings/near zones): only a few quasars known till date
- Lyman-α emitters (number density and clustering) systematics, model dependent constraints

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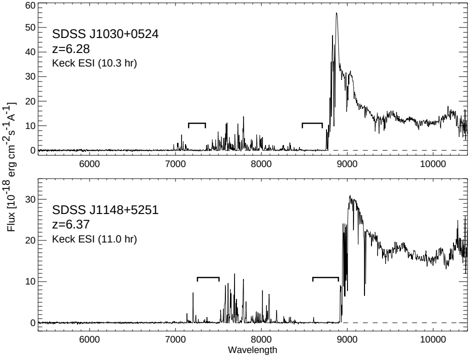

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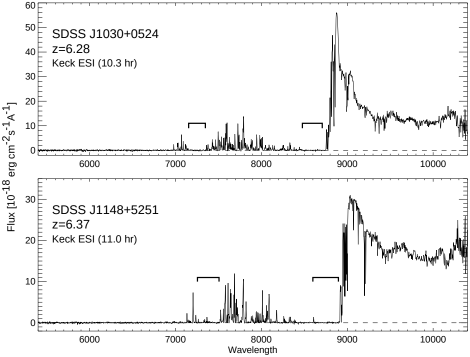
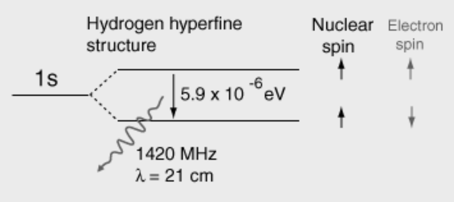


- Need a line transition which is “weak”

Redshifted 21 cm experiments

- 21 cm (1420 MHz) radiation: arises from the transition between the two hyperfine levels of the hydrogen 1s ground state, slightly split by the interaction between the electron spin and the nuclear spin.



  Line transition $\implies$ a transition originating at z will be observed at a frequency $\nu_{\rm obs} = 1420/(1+z)$ MHz.
- The higher energy level (with parallel spins) has a total spin 1, and hence $g_2 = 3$. Similarly, $g_1 = 1$.
- The $2 \rightarrow 1$ transition is a magnetic dipole transition, with transition probability $A_{21} = 2.85 \times 10^{-15}$ s^{-1} $\implies$ an atom in the upper level is expected to make a downward transition once in 10^7 yr. Impossible to observe in laboratory conditions.

  For Lyα transition, the corresponding coefficient is $A_{21} \approx 6 \times 10^8$ s^{-1}.

21 cm experiments: a new window to cosmology

- At $z \gtrsim 20$, HI traces the exact distribution of matter (dark ages). At $z > 8$, probes reionization and nature of first stars. At $z \lesssim 6$, probes high-density regions (just like galaxy surveys), potential probe of matter power spectrum.
- Possible to probe the distribution in 3-D (in contrast to CMBR which is 2-D).
- CMBR: multipoles probed $1 < \ell \lesssim 2000$; scales smaller than $k \sim 0.1$ Mpc^{-1} cannot be probed because of diffusion effects (Silk damping).
- 21 cm: power on all scales. Possible to probe scales as small as $k \sim 100$ Mpc^{-1}.
- Also possible to probe at different z "shells". $\Delta P(k) \sim 10^{-5} - 10^{-6}$ at ~ 0.05 Mpc.
- Challenge: ionosphere, terrestrial radio ($\nu \sim 70$ MHz), large galactic foregrounds, extragalactic point sources, ...
- Experiments: GMRT (India), MWA (Australia), LOFAR (Netherlands + Europe), SKA, . . .

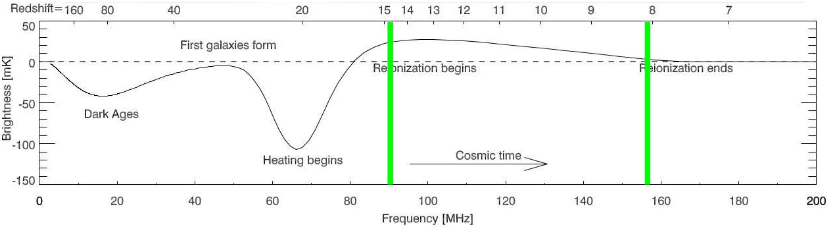
Global 21 cm signature

- 21cm radiation from HI observed against the backdrop of CMBR

$$\delta T_b \propto \frac{T_s - T_{\rm CMB}(z)}{T_s} n_{\rm HI}$$

The spin temperature

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



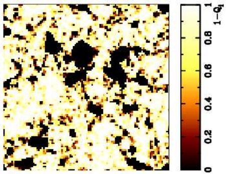
Pritchard & Loeb (2012)

- In most models, the neutral hydrogen will be **observed in emission** from $z \approx 15$ until reionization is completed. T_s couples to T_k via Lyα pumping, and $T_k \gg T_{\rm CMB}$ in the neutral regions mainly because of X-ray heating etc.

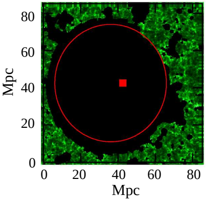
Modelling the 21cm signal

Two possible approaches:

- **Statistical**: Calculate quantities like power spectrum, correlation function etc
  Choudhury, Haehnelt & Regan (2009)

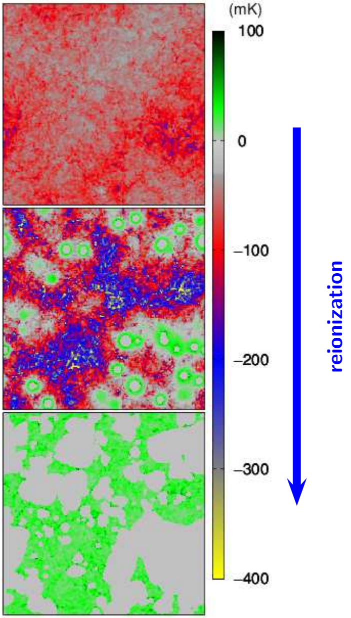


- **Individual sources**: Look towards ionized regions around sources
  Majumdar, Bharadwaj & **Choudhury** (2012)



21 cm intensity maps

Ghara, **Choudhury** & Datta (2014)



$z \sim 15$ ($\nu \sim 90$ MHz), $x_{\rm HII} \sim 10^{-3}$

$z \sim 12$ ($\nu \sim 110$ MHz), $x_{\rm HII} \sim 0.02$

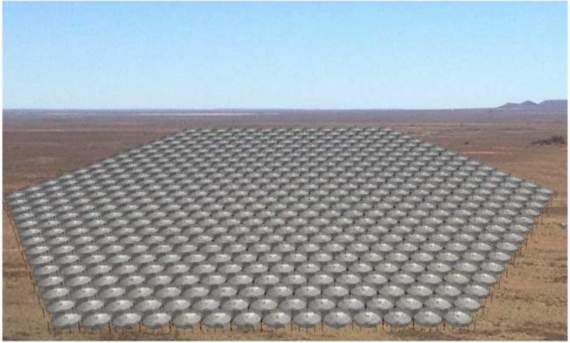
$z \sim 8$ ($\nu \sim 160$ MHz), $x_{\rm HII} \sim 0.56$

Low frequency instruments

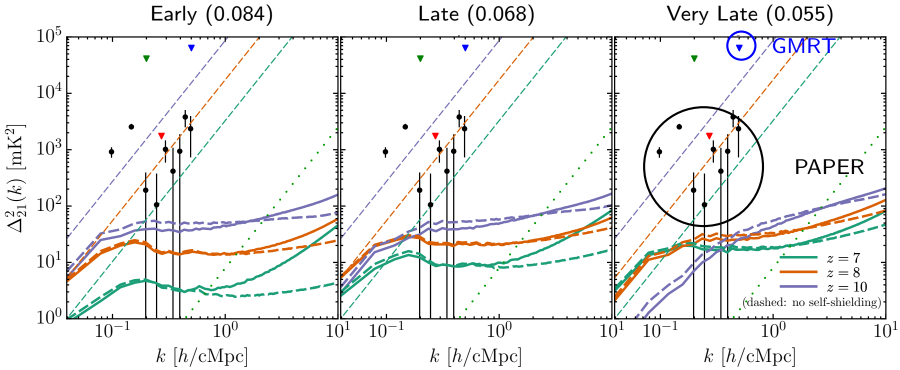
Future telescopes

SKA-LOW

HERA



21 cm power spectra



$z = 7$
$z = 8$
$z = 10$

Kulkarni, **Choudhury**, Puchwein & Haehnelt (2016)

Summary

- Reionization probes the first stars.
- Possible to develop models which are consistent with all available data.
- Hope to probe reionization history at $z > 6$ using the redshifted 21 cm signal.