Dark Ages and Cosmic Reionization

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NCRA • TIFR

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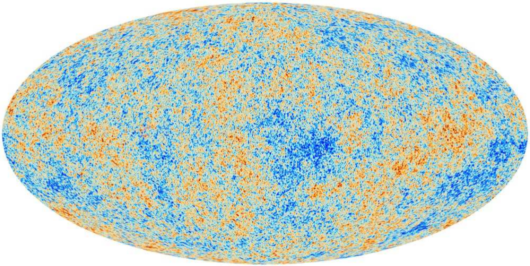
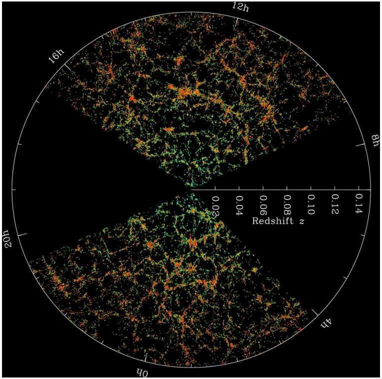
Flat ΛCDM model of cosmology

CMBR + SNe-Ia + Galaxy surveys + ... $\Longrightarrow$ ΛCDM cosmology with $\Omega_b + \Omega_{\rm DM} + \Omega_\Lambda = 1$.





Era of precision cosmology

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z = 0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z = 0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	$0.5952 \pm 0.0016\ ^\circ$	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

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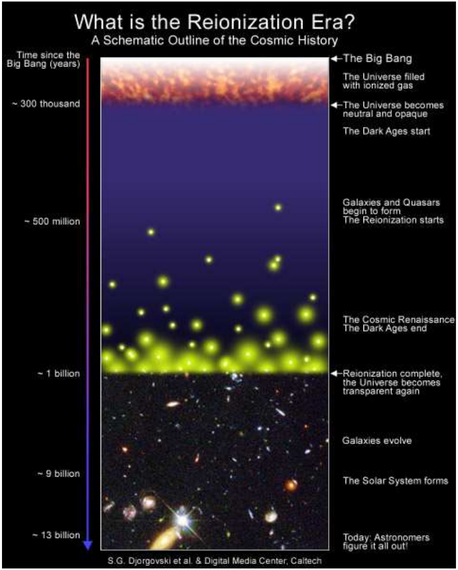
Optical depth due to reionization

Brief history of reionization

Start		**Big Bang**
$z \approx 1000$		**Last Scattering**
$z > 30$		**Dark Ages**
$z \approx 15 - 30$		**Cosmic Dawn**
$z \approx 6$		**Reionization**
$z \sim 3$		**Galaxies**
$z \sim 0$		**Now**

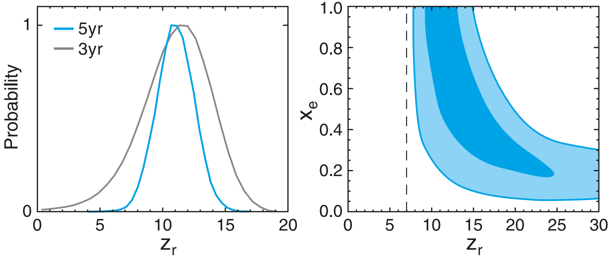


Electron scattering optical depth

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

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

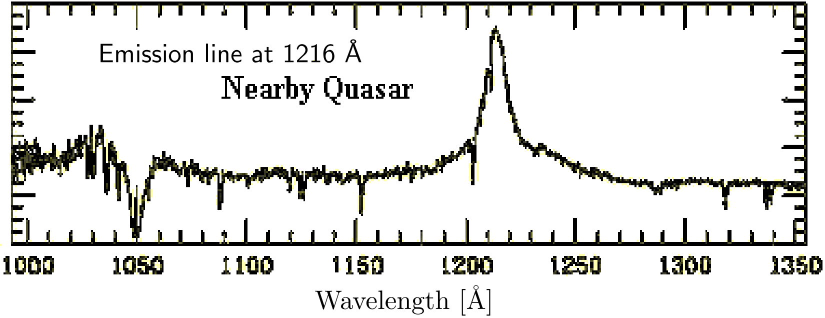
Provided by reionization → n_e



Dunkley et al. (2008)

Reionization starts around $z \sim 10$.

Evidence for reionization: quasars



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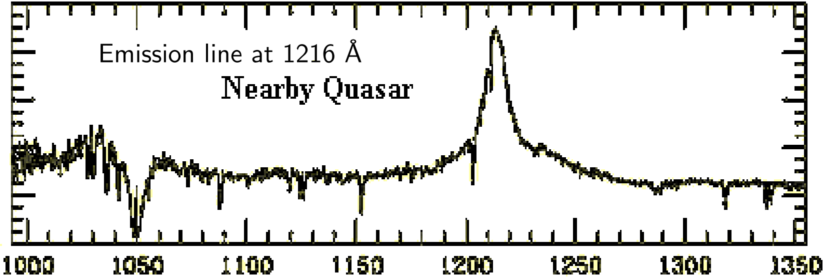

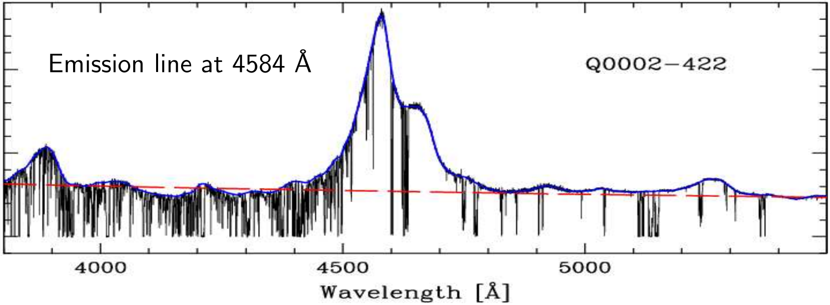

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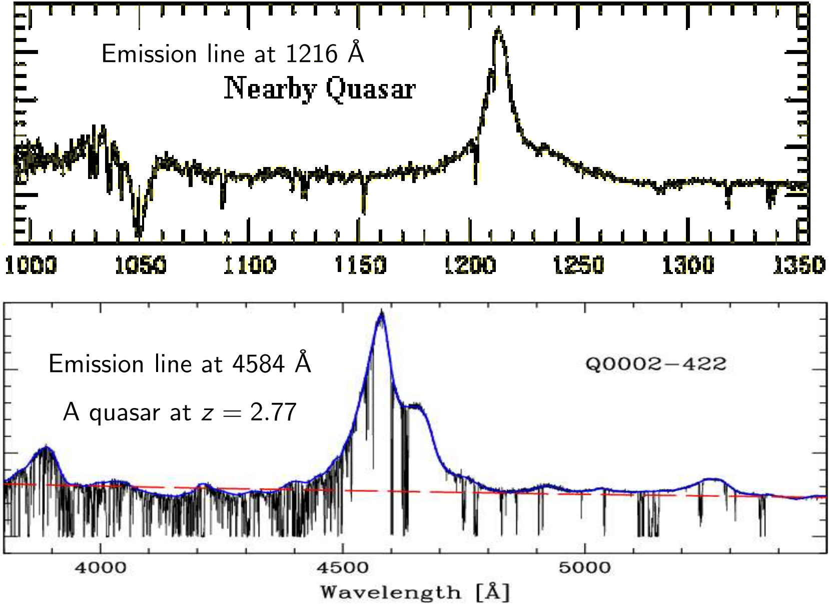

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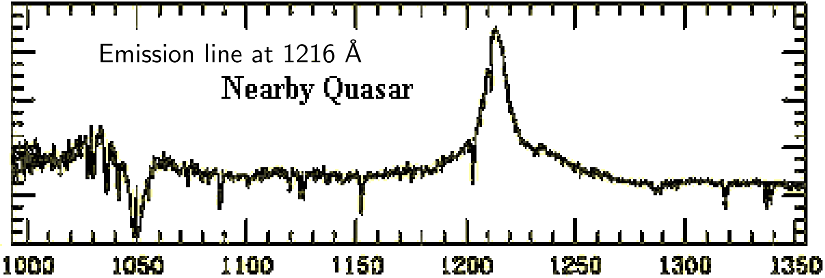
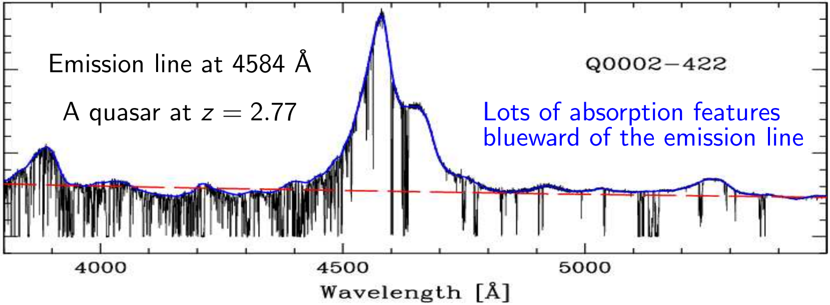
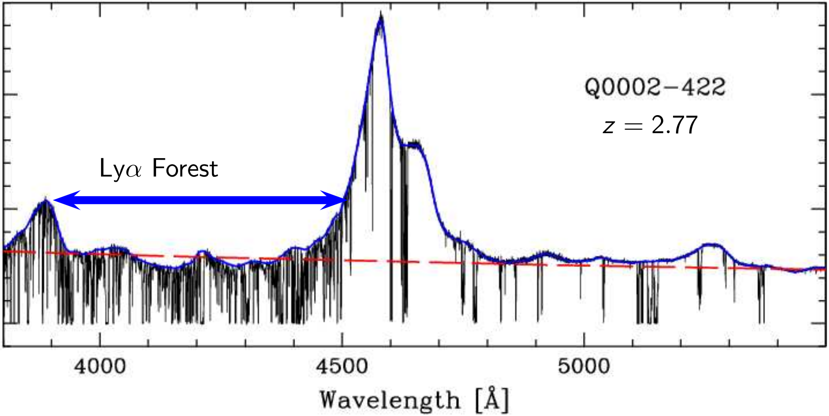


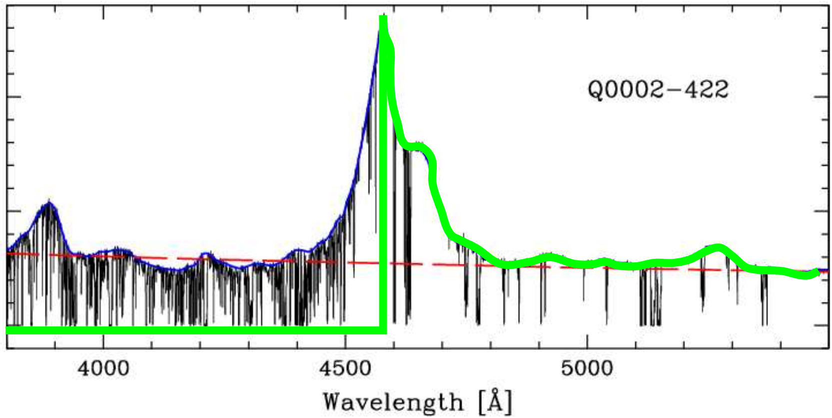


Lyman-α forest



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.

Gunn-Peterson effect

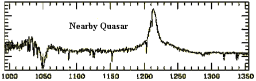


Observed flux $\sim$ Unabsorbed flux $\times$ $\exp\left(-10^5\, x_{\rm HI}\right)$, where $x_{\rm HI} = \rho_{\rm HI}/\rho_H$.

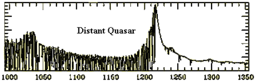
The fact that there is non-zero flux implies that $x_{\rm HI} \simeq 10^{-5}$

QSO absorption lines at $z \sim 6$

$z \approx 0$



$z \approx 3$



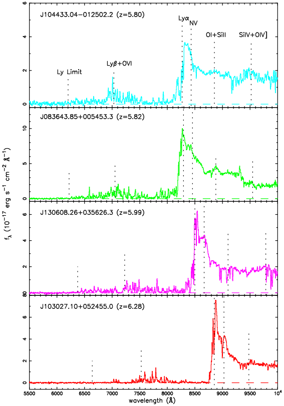
$x_{\rm HI} \lesssim 10^{-5}$

$z = 5.80$

$z = 5.82$

$z = 5.99$

$z = 6.28$



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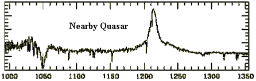

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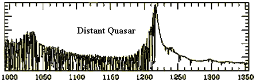

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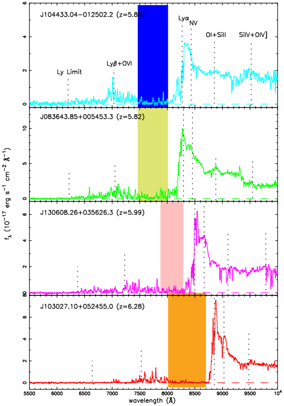


Does this absorption mean **high neutrality**?

QSO absorption lines at $z \sim 6$

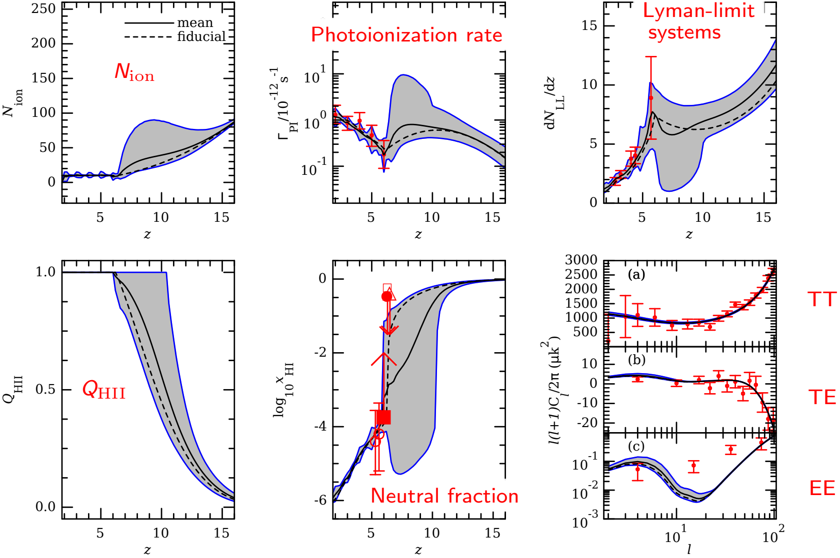
- Gunn-Peterson optical depth:

$$\tau_{\rm GP} \approx 3.6 \left(\frac{\Omega_b h^2}{0.022}\right) \sqrt{\frac{0.15}{\Omega_m h^2}} \left(\frac{1-Y}{0.76}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{\bar{x}_{\rm HI}}{10^{-5}}\right) \Delta^{\beta}$$

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

“Model-independent” constraints: QSO and WMAP7

Mitra, **Choudhury** & Ferrara (2011)



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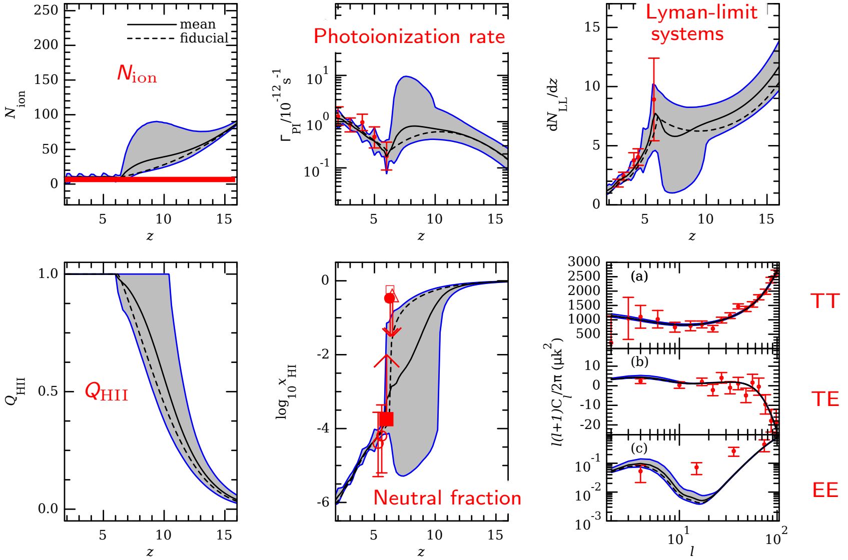

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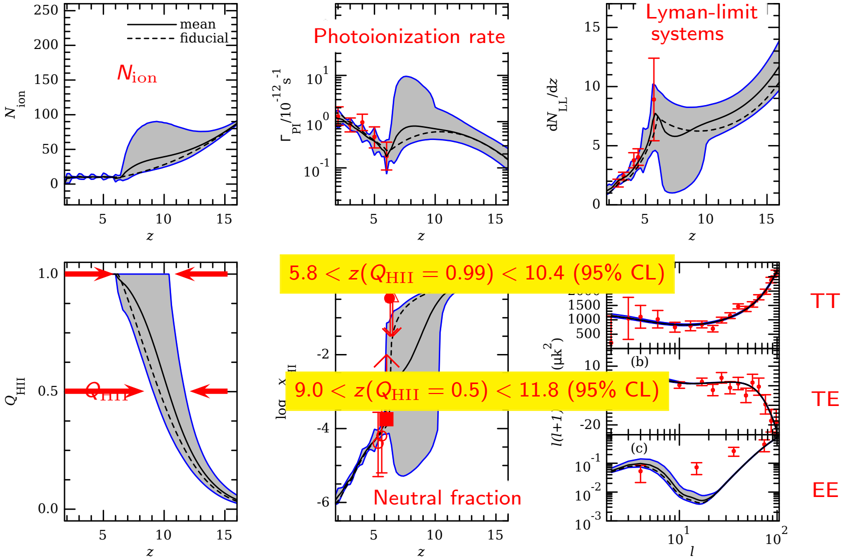


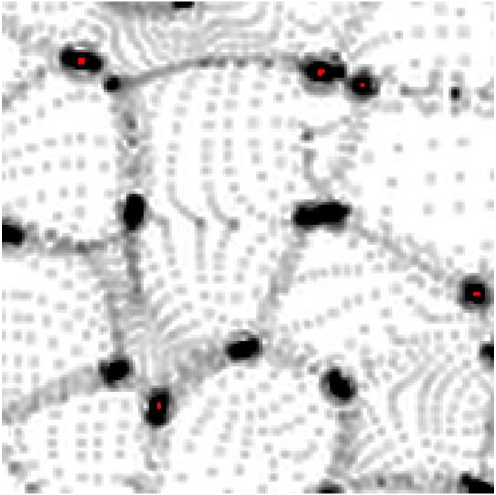
Effect of reionization on cosmological parameters

Pandolfi, Ferrara, **Choudhury**, Melchiorri & Mitra (2012)

Parameter	WMAP7	WMAP7 + ASTRO
Ω_m	0.266 ± 0.029	0.273 ± 0.027
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02183 ± 0.00054
h	0.710 ± 0.025	0.698 ± 0.023
n_s	0.963 ± 0.014	0.958 ± 0.013
σ_8	0.801 ± 0.030	0.794 ± 0.027
τ_{el}	0.088 ± 0.015	0.080 ± 0.012

when astrophysical data sets are included and physically motivated models used, parameters become more constrained

HI distribution: schematic diagram



JUST A SKETCH

Based on **Choudhury**, Haehnelt & Regan (2009)

- Density distribution: Collapsed Structures and the **Intergalactic Medium**

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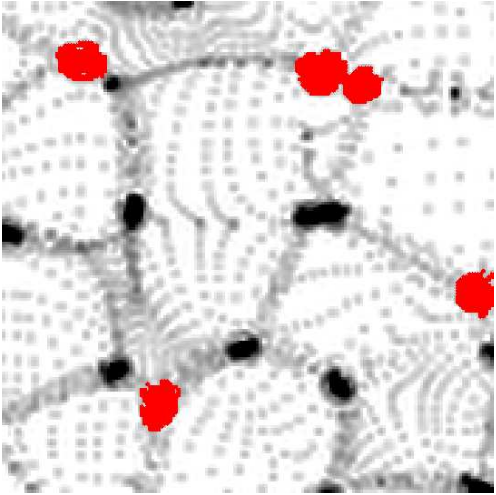

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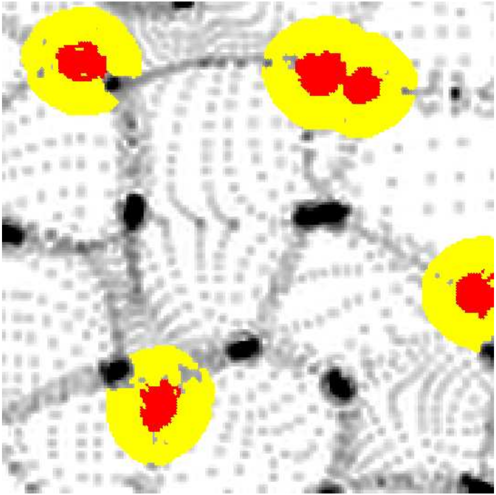

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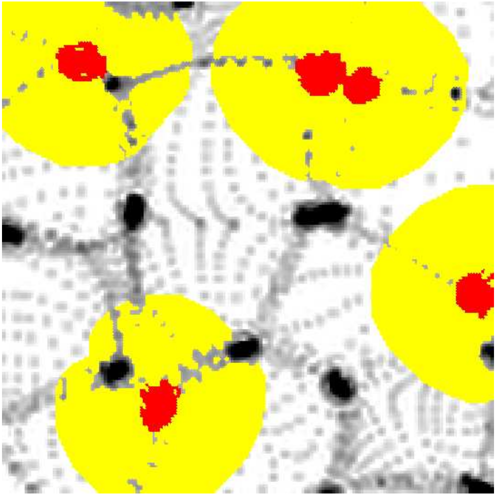

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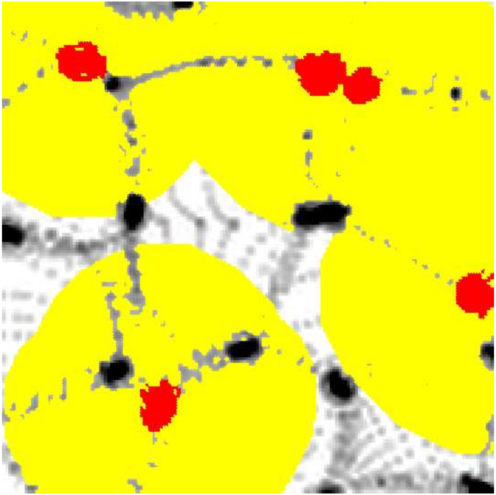

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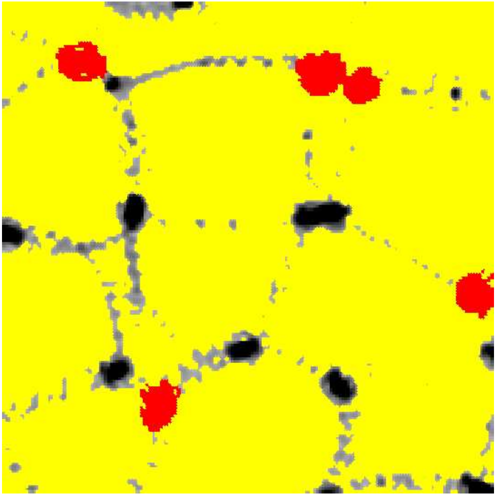

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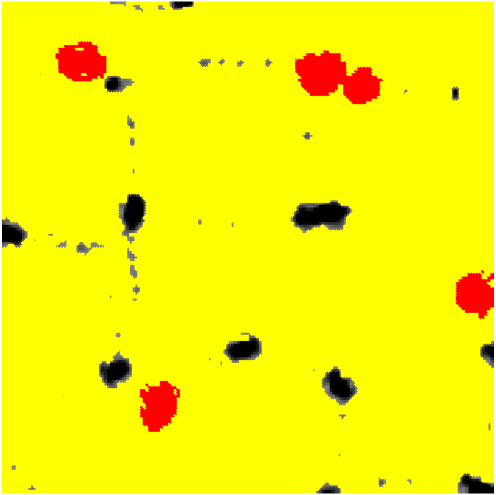

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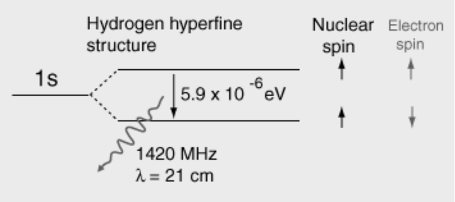
- **Reionization**
- **Post-reionization era**

Cosmological neutral hydrogen

- Post-reionization ($z \lesssim 6$): HI in galaxies/residual HI in the IGM $\Longrightarrow$ traces matter fluctuations; can be probe of cosmology
- Reionization ($6 \lesssim z \lesssim 20$): HI distribution patchy. Convolution of cosmology and galaxy formation. Probe of first stars (and cosmology).
- Pre-reionization ($z \gtrsim 20$): HI distribution $\equiv$ matter distribution. In principle, strong probe of cosmology.

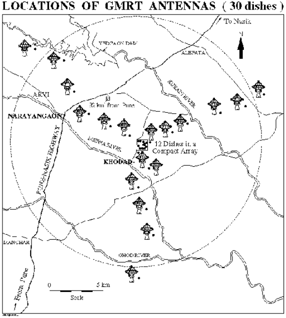
Probing HI through 21 cm line

- Lyα is a line transition, but too "strong" $\implies$ lines become saturated for $x_{\rm HI} \gtrsim 10^{-4}$
- Need a line transition which is "weak": 21 cm hyperfine transition
- 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.



- HI in high density regions (galaxies) would be observed in emission with respect to the background CMBR $\implies$ directly traces the matter distribution.
- Experiments: radio interferometers like GMRT (India), MWA (Australia), LOFAR (Netherlands + Europe)
- Main challenge: Foregrounds from Galactic synchrotron, Extragalactic point sources, RFI,...

Radio interferometric arrays: GMRT



30 antennas, 45 m diameter each.

Frequencies (MHz)	153	235	325	610	1420
z (HI detection)	8.3	5.0	3.4	1.3	0

Moving towards continuous frequency-coverage.

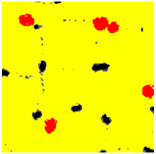
Other low-frequency instruments: LOFAR, MWA. **Upcoming: SKA**

Indian participation in the SKA

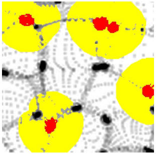
- SKA: most ambitious radio astronomy project ever attempted
- Phase I: target 2021. Main science goals: EoR, Cosmology, Pulsars
- India associated with SKA from the beginning, currently an associate member. GMRT often provides useful test-bed for SKA
- NCRA, working with partners from software research groups and industry, has already taken a lead role in some of the works (monitoring and control systems) in the Preparatory SKA phase
- NCRA associated with EoR and Cosmology science teams

Examples of science using radio experiments

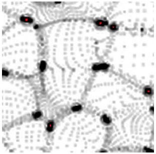
- Cosmology using HI in galaxies at $z \sim 1 - 3$.



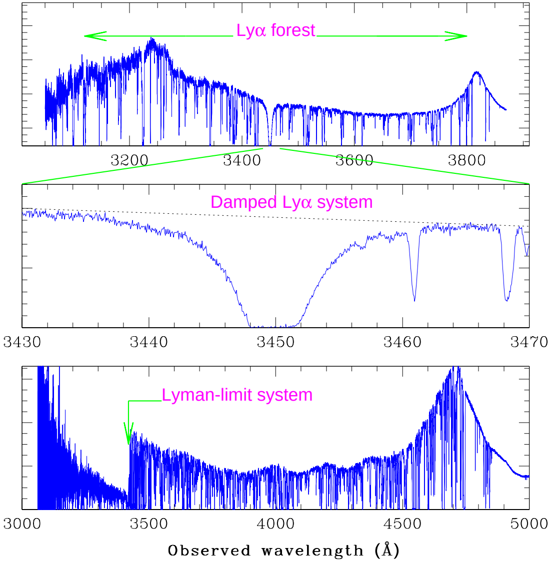
- Studying first stars via epoch of reionization at $6 < z < 15$.



- Power spectrum of dark matter fluctuations at $z \sim 30$.

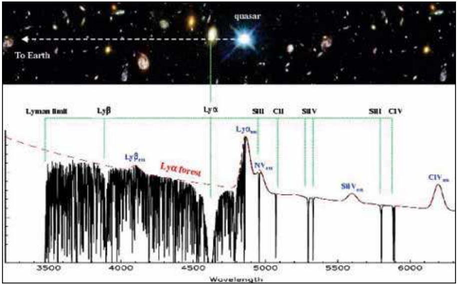


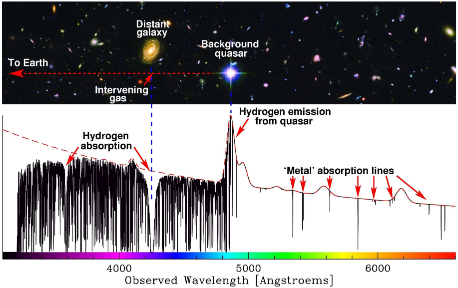
HI in galaxies: DLAs



$$\frac{\Omega_{\rm HI}({\rm DLA})}{\Omega_b} \sim 0.02$$

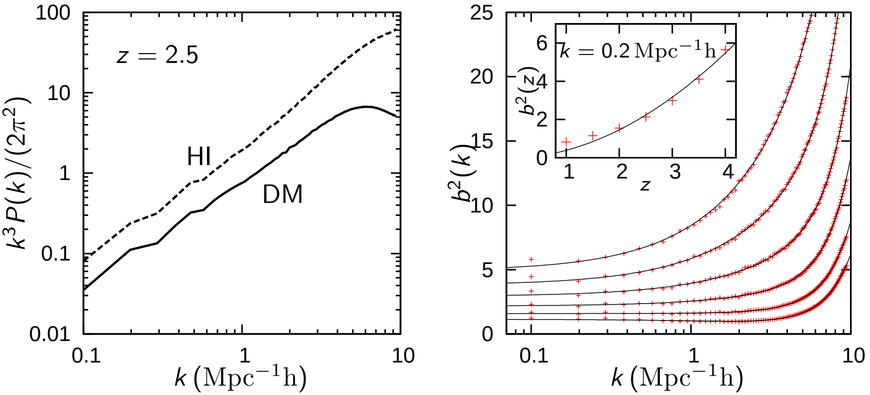
DLAs: intersecting galaxies?





Modelling the 21 cm signal at $z \sim 3$

Guha Sarkar, Mitra, Majumdar & **Choudhury** (2012)

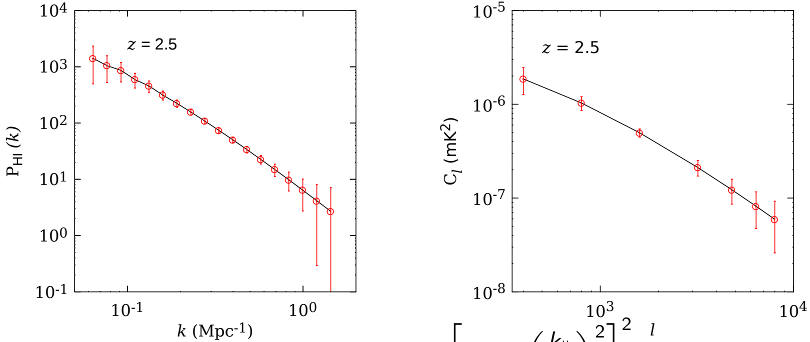


- Traces matter fluctuations, possible probe of cosmology.

Modelling the 21 cm signal at $z \sim 3$

Guha Sarkar, Mitra, Majumdar & **Choudhury** (2012)

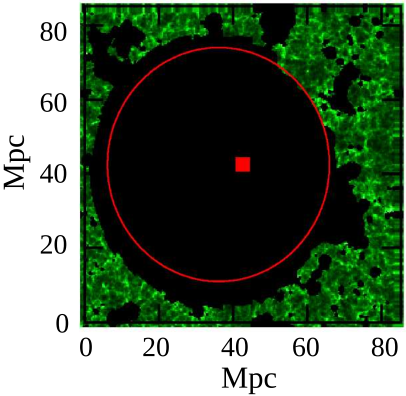
1000 hrs of (hypothetical) observation at GMRT



$$P_{\rm HI}(\mathbf{k}) = \bar{x}_{\rm HI}^2 b^2(k,z) D_+^2(z) \left[1 + \beta \left(\frac{k_\parallel}{k}\right)^2\right]^2 P(k)$$

$$C_\ell = \frac{\bar{T}^2}{\pi r^2} \int_0^\infty dk_\parallel \cos(k_\parallel \Delta r) P_{\rm HI}(\mathbf{k})$$

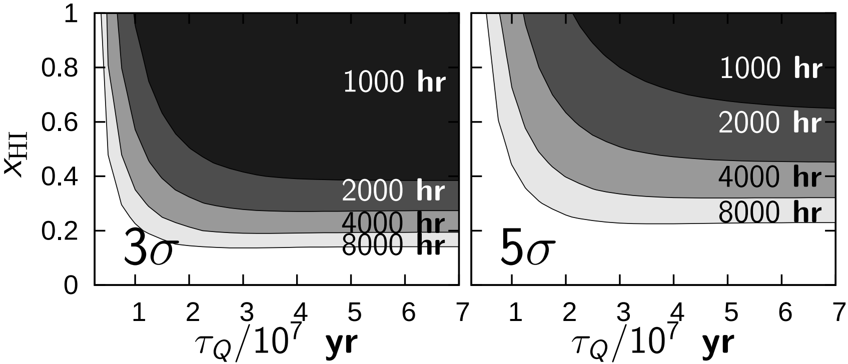
Bubble detection using 21 cm observations at $z \sim 7$



- Detection of bubble around a high-z QSO can be direct probe of HI
- Measuring the size easier. Possible to constrain $x_{\rm HI}$ and quasar properties.
- Signal very weak compared to foregrounds
- The HI fluctuations outside the bubble limit the constraints

HII region around the $z \approx 7$ quasar

Majumdar, Bharadwaj & **Choudhury** (2012)



For 1000 hrs of observation with GMRT, a 3σ detection is possible in a considerable region of parameter space where $x_{\rm HI} > 0.4$ and $\tau_Q > 1.5 \times 10^7$ yrs.

HII region around the $z \approx 7$ quasar

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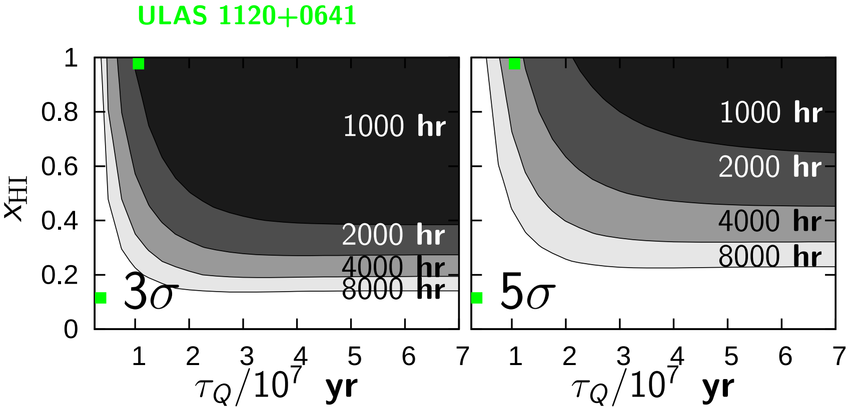
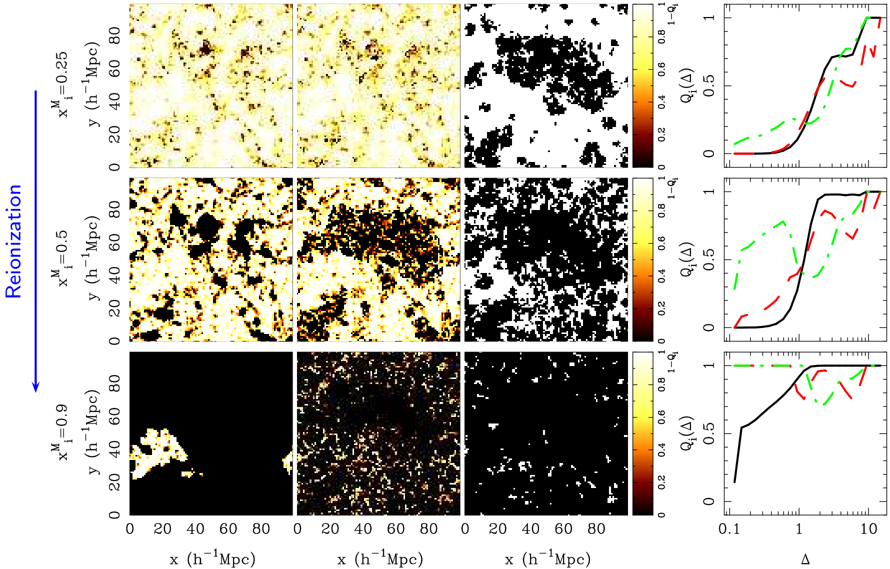


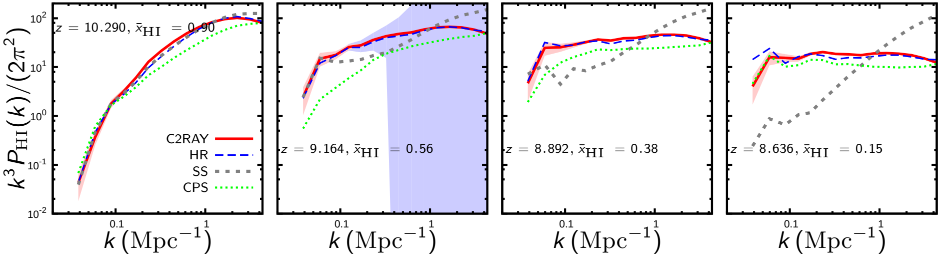
For 1000 hrs of observation with GMRT, a 3σ detection is possible in a considerable region of parameter space where $x_{\rm HI} > 0.4$ and $\tau_Q > 1.5 \times 10^7$ yrs.

21 cm emission observations **Choudhury**, Haehnelt & Regan (2009)

Homogeneous recombination | Self-shielding included | High mass



HI power spectrum Majumdar, Mellema, Jensen, **Choudhury**, et al. (2014)



Dark ages: probe of matter fluctuations

- At $z \gtrsim 20$, HI traces the exact distribution of matter (dark ages).
- 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.

Summary

- Epoch of reionization: “Final Frontier” of observational cosmology.
- HI distribution probes various cosmological and astrophysical processes at different epochs
- Future: Cosmology and Structure Formation using Radio Telescopes.