Cosmological Reionization

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From Black Holes to the Universe: Gravity at Work

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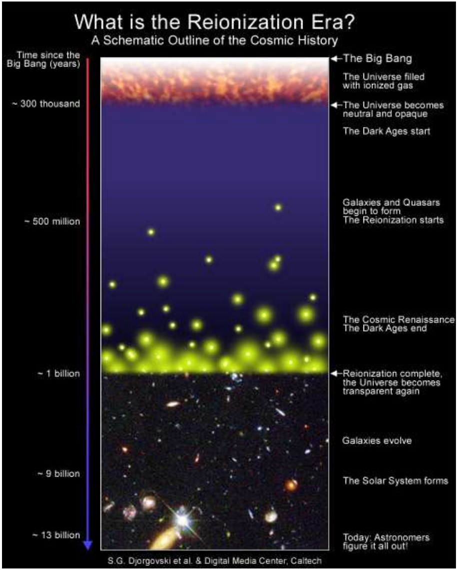
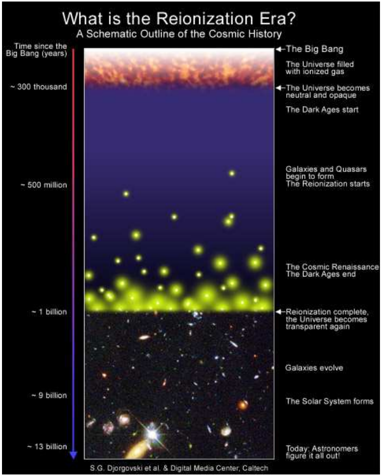
Reionization: The Basic Picture

Start		**Big Bang**
$z \approx 1000$		**Last Scattering** Initial conditions (WMAP)
$z > 30$		**Dark Ages**
$z \approx 15 - 30$		**First Sources**
$z \approx 6 - 15$		**Reionization**
$z \sim 3$		**Galaxies** Nonlinear Structures (HST)
$z \sim 0$		**Now**



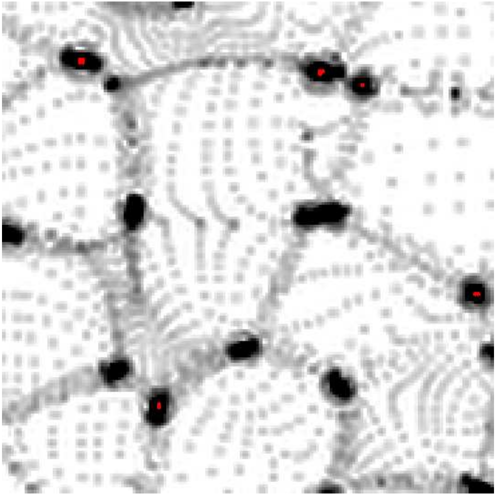
Why Study Reionization?



- Reionization: Second major change in the ionization state of hydrogen (and helium) in the Universe.
- Last phase of cosmic evolution to be tested
- Related to the quest for understanding first non-linear structures (stars, galaxies,...) in the Universe. **Gravity at work!**
- Reionization affects subsequent formation of galaxies **(feedback)**.

Qualitative description

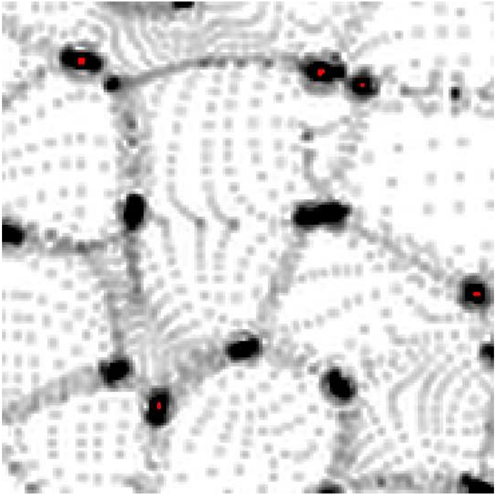
Reionization: Schematic Diagram



JUST A SKETCH

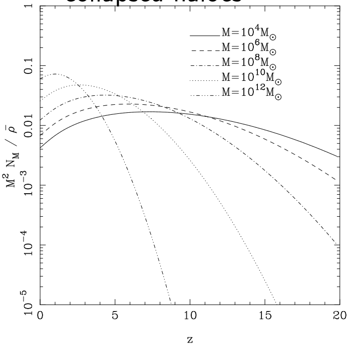
- Density distribution: Collapsed Structures and the **Intergalactic Medium**

Reionization: Schematic Diagram

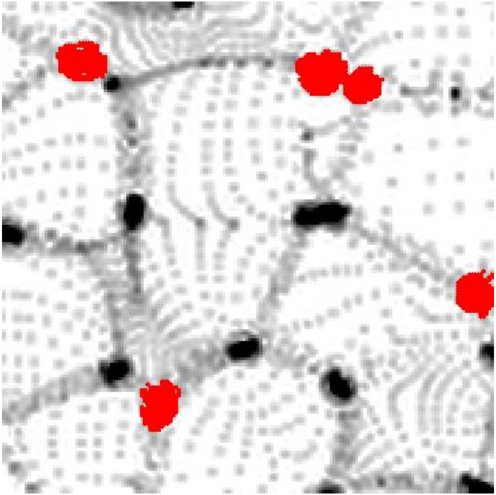


JUST A SKETCH

- Density distribution: Collapsed Structures and the **Intergalactic Medium**
- Fraction of mass in collapsed haloes



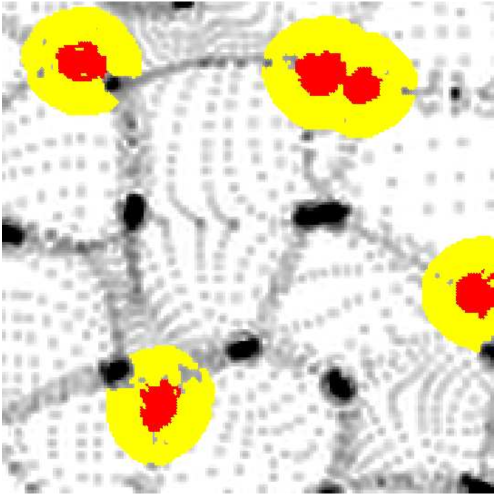
Reionization: Schematic Diagram



JUST A SKETCH

- Sources of ionizing photons

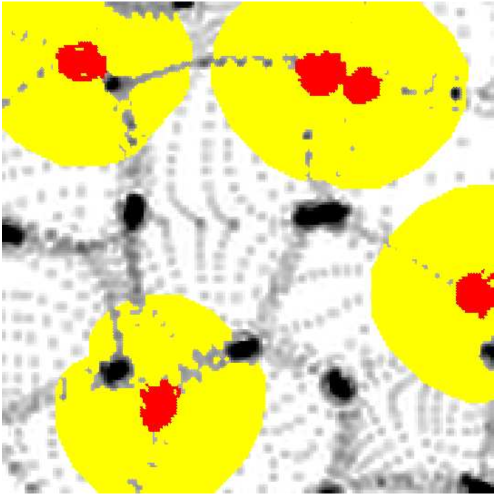
Reionization: Schematic Diagram



JUST A SKETCH

- Sources of ionizing photons
- Ionized regions

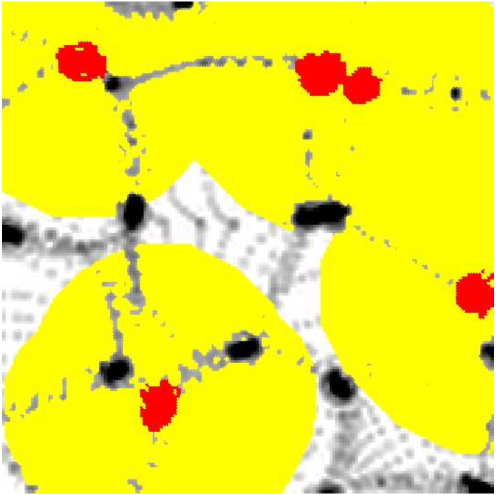
Reionization: Schematic Diagram



JUST A SKETCH

- Sources of ionizing photons
- Ionized regions
- **Pre-overlap era**

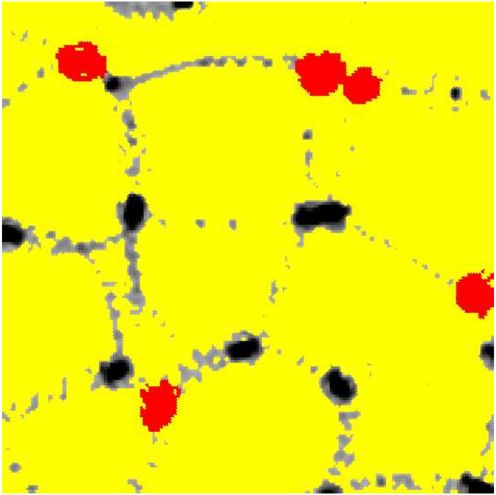
Reionization: Schematic Diagram



JUST A SKETCH

- Sources of ionizing photons
- Ionized regions
- **Pre-overlap era**
- Approaching reionization

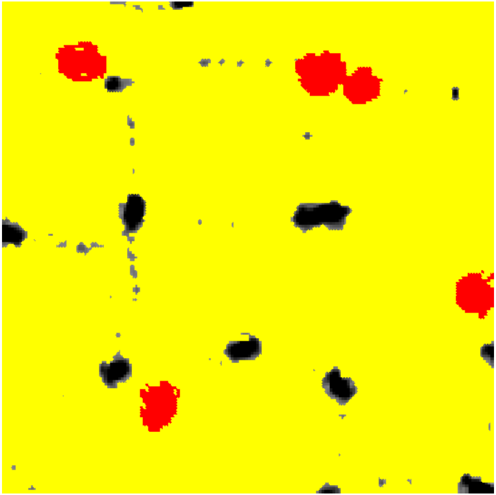
Reionization: Schematic Diagram



JUST A SKETCH

- Sources of ionizing photons
- Ionized regions
- **Pre-overlap era**
- Approaching reionization
- **Reionization**

Reionization: Schematic Diagram



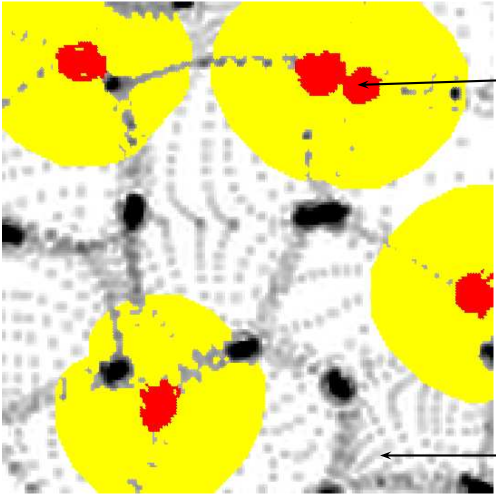
JUST A SKETCH

- Sources of ionizing photons
- Ionized regions
- **Pre-overlap era**
- Approaching reionization
- **Reionization**
- **Post-overlap era**

Issues

- 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, QSOs, Exotic Particles?

Looking for Answers

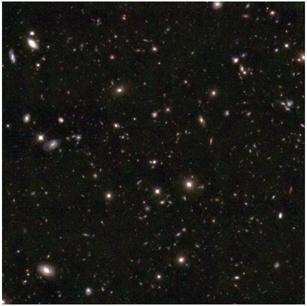


How many **sources?**

How **ionized** is the IGM?

High redshift sources

NICMOS Ultra-Deep Field (in the Hubble Space Telescope)



J-dropout: Quite a few possible $z \approx 10$ candidates
Various other surveys planned, some based on gravitational lensed sources.

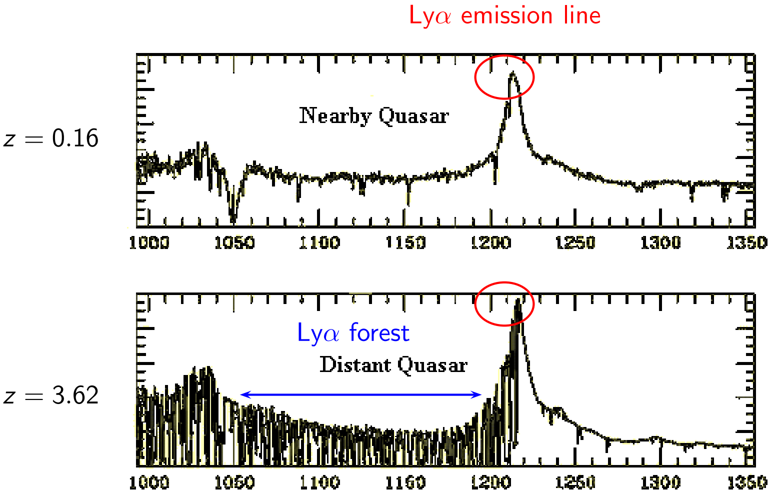
High redshift sources

James **W**ebb **S**pace **T**elescope

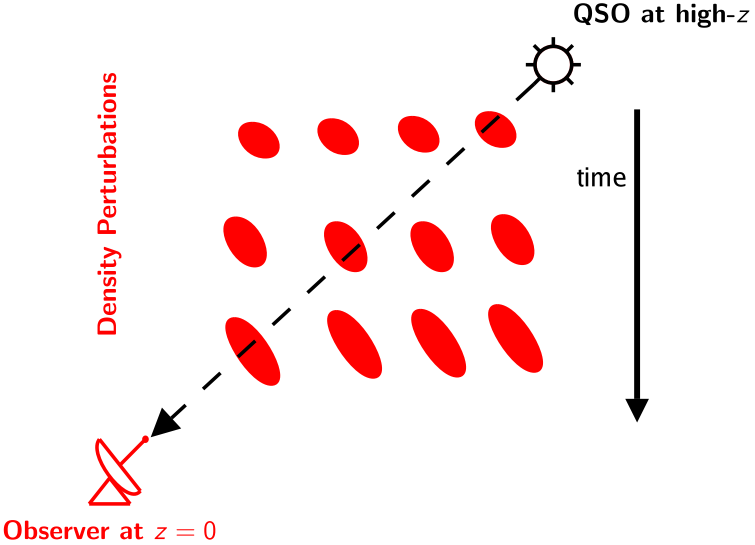
- Infrared-optimized **space telescope**, scheduled for launch in 2013.
- Funded by **NASA, ESA and CSA**.
- Expected to detect the first sources at $z > 15$.

Evidence for reionization

QSO absorption lines at $z < 6$



QSO absorption lines at $z < 6$



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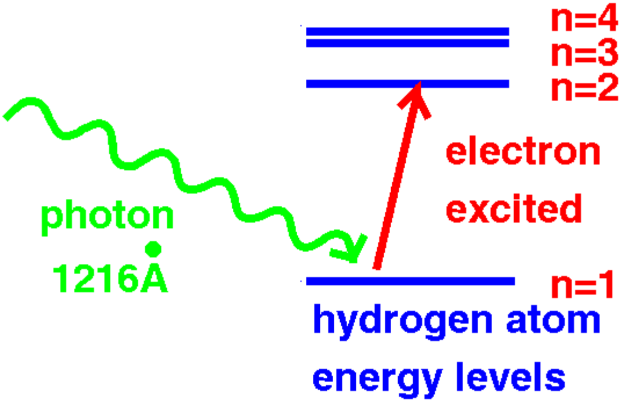
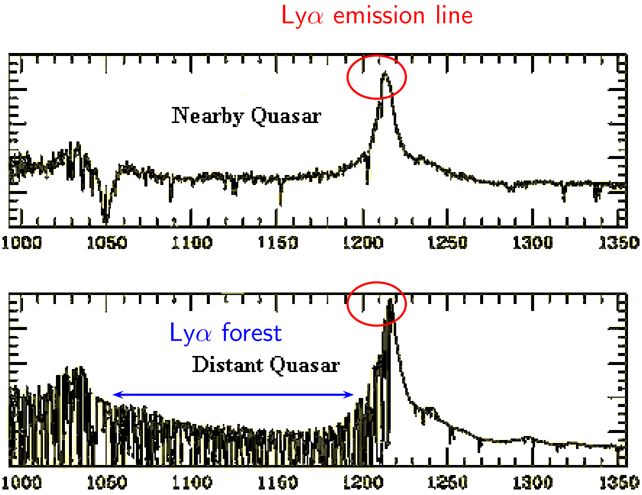


Lyα transition of neutral hydrogen

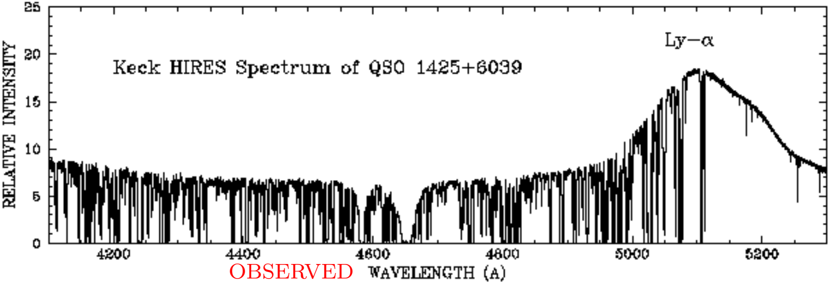
QSO absorption lines at $z < 6$



$z = 0.16$

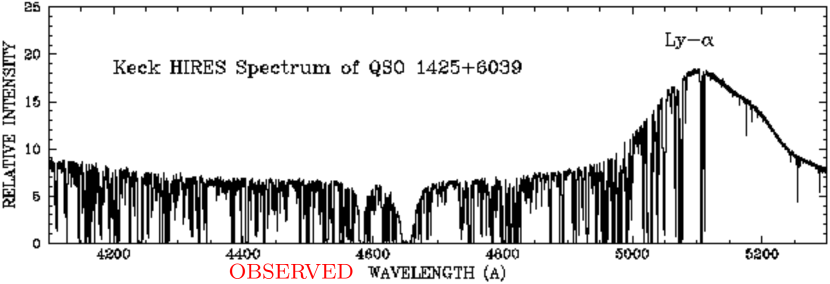
$z = 3.62$

QSO absorption lines at $z < 6$



- As an example: spectrum of a QSO at $z_{\rm em} = 3.18$
- **Ly**α **emission feature** at $\lambda_{\rm Ly\alpha} \approx 1216$ Å$(1 + z_{\rm em}) \approx 5080$ Å
- **Ly**α **forest** at $\lambda < \lambda_{\rm Ly\alpha}$

QSO absorption lines at $z < 6$

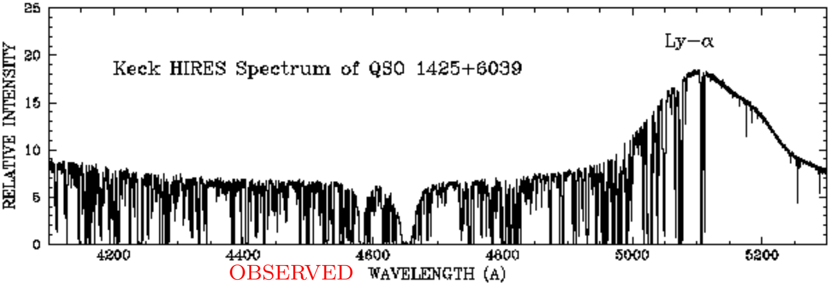


Observed Flux $=$ Unabsorbed Flux $\times \exp(-\tau_{\rm GP})$
Gunn-Peterson optical depth:

$$\tau_{\rm GP} \approx 1.5 \left(\frac{\Omega_b h^2}{0.022}\right) \sqrt{\frac{0.15}{\Omega_m h^2}} \left(\frac{1-Y}{0.76}\right) \left(\frac{1+z}{4}\right)^{3/2} \left(\frac{\bar{x}_{\rm HI}}{10^{-5}}\right) \Delta^{\beta}$$

Ionized Medium $\equiv$ Transparent

QSO absorption lines at $z < 6$

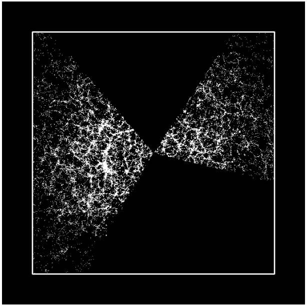


- **Gunn-Peterson Effect**: The **absence** of complete absorption of the QSO spectrum implies that hydrogen is highly ionized.
- This result is found to be true for $z \lesssim 6$.

Observational constraints

QSO absorption lines at $z > 6$

- **Sloan Digital Sky Survey (SDSS)**: largest astronomical survey project till date. Determined positions of millions of galaxies and $\sim 100,000$ QSOs.



- Observed ~ 10 QSOs at $z > 6$
- The spectra of these sources are markedly different from those at $z < 6$.

QSO absorption lines at $z > 6$

$z \approx 0$

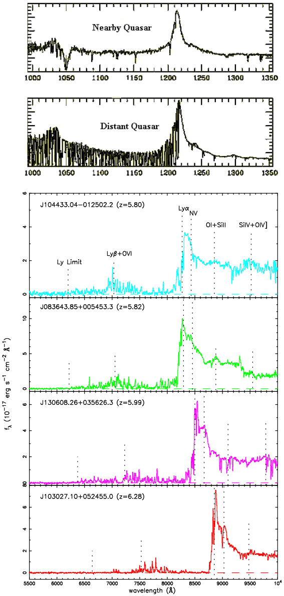
$z \approx 3$

$z = 5.80$

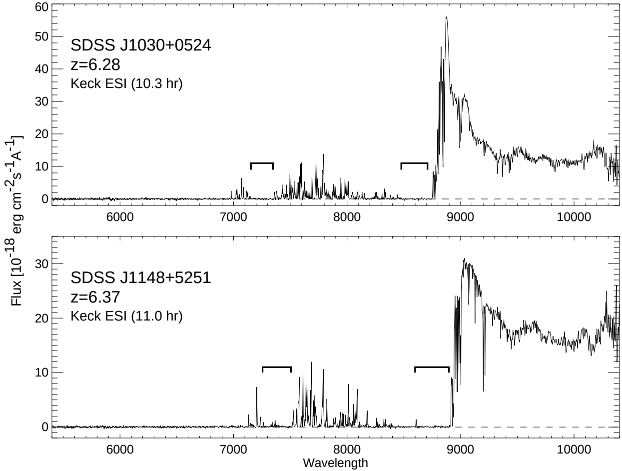
$z = 5.82$

$z = 5.99$

$z = 6.28$



QSO absorption lines at $z > 6$



Does this absorption mean high neutrality?

QSO absorption lines at $z > 6$

- Gunn-Peterson optical depth:

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

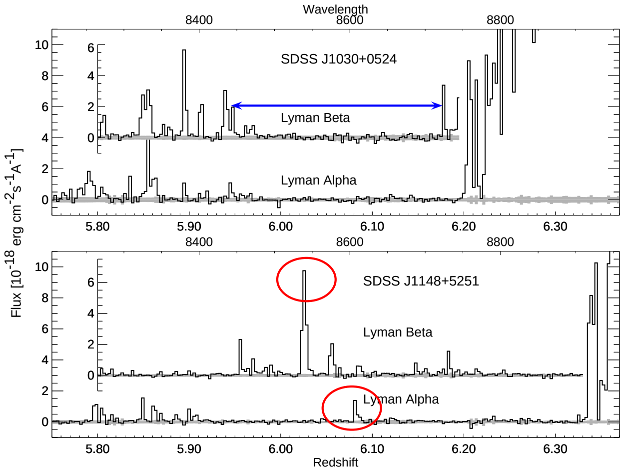
- So, even a neutral fraction $x_{\rm HI} \approx 10^{-4}$ would produce **complete absorption**!
- The only robust constraint from QSO absorption line is

$$x_{\rm HI} \gtrsim 10^{-4}.$$

- Reionization should not complete much earlier than $z \approx 6$, 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!!

QSO absorption lines at $z > 6$

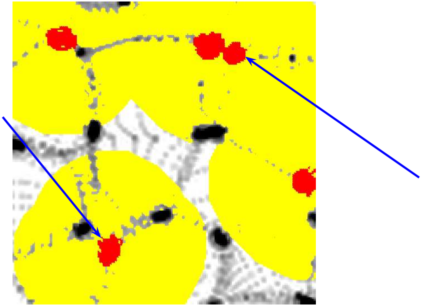
Closer look into individual QSO spectra

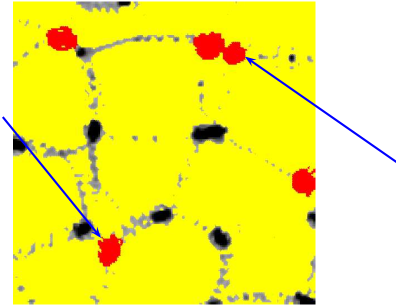


Some of the lines of sight towards QSOs at $z \approx 6$ are **definitely ionized**!!

QSO absorption lines at $z > 6$

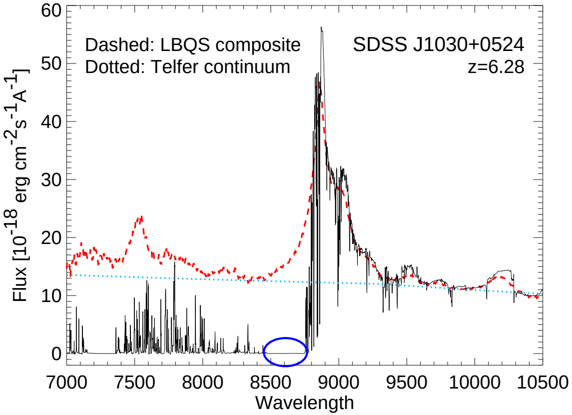
- Some of the lines of sight are definitely ionized!!
- Question is: what about the other lines of sight with **large regions of zero transmission**? Are they neutral, or can they be explained by cosmic variance of density fluctuations?





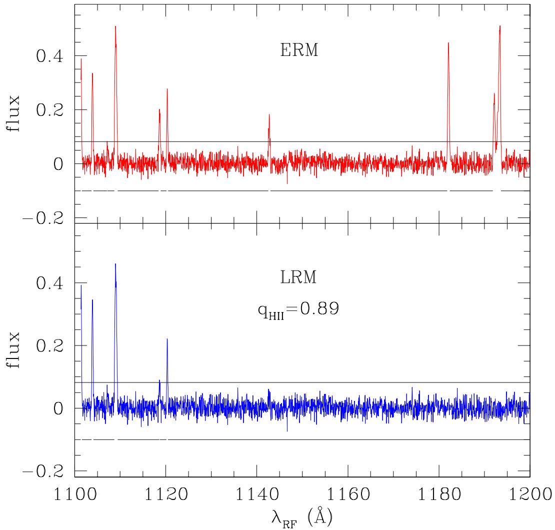
Closer look into $z \sim 6$ Gallerani, **Choudhury** & Ferrara (2005)

- What can be said from the **large absorption gaps** seen in the QSO absorption spectra?



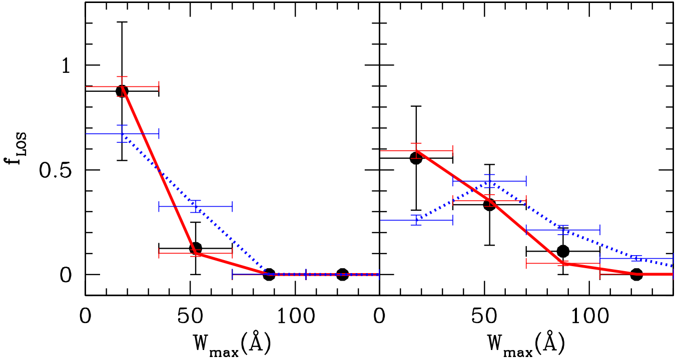
Closer look into $z \sim 6$ Gallerani, **Choudhury** & Ferrara (2005)

- Width of the gaps depend on the ionization state of the IGM



Closer look into $z \sim 6$ Gallerani, **Choudhury** & Ferrara (2005)

- Large absorption gaps seen in the QSO absorption spectra $\Longrightarrow x_{\rm HI} < 0.36$
  Gallerani, Ferrara, Fan & **Choudhury** (2007)



- Consistent with the constraints from sizes of HII regions around QSOs, though uncertainties remain
  Maselli, Gallerani, Ferrara & **Choudhury** (2007)

CMBR: Damping of Temperature anisotropies

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

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

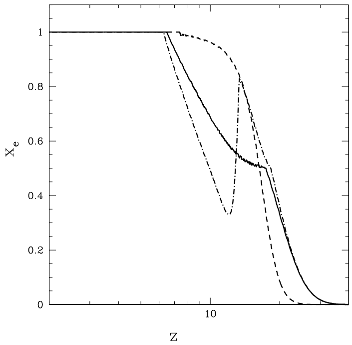
Provided by reionization

- Temperature anisotropies are damped at small scales by a factor ${\rm e}^{-\tau_{\rm el}}$.
- However, this damping can be compensated by hiking the power of density fluctuations $\Longrightarrow$ $\tau_{\rm el}$ is degenerate with n_s (slope) and σ_8 (normalization).

CMBR: Signal from Patchy reionization

- **Patchiness** in the electron distribution generates temperature anisotropies
- Signal peaks at very small scales $\ell \gtrsim 1000 \Longrightarrow$ possible to observe with future generation radio interferometers (ACT, SPT).

Ionization fraction



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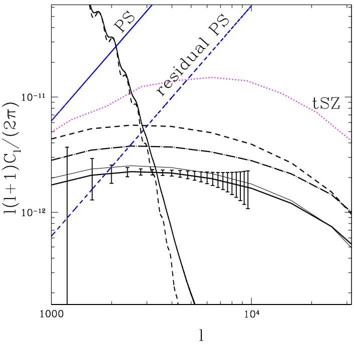
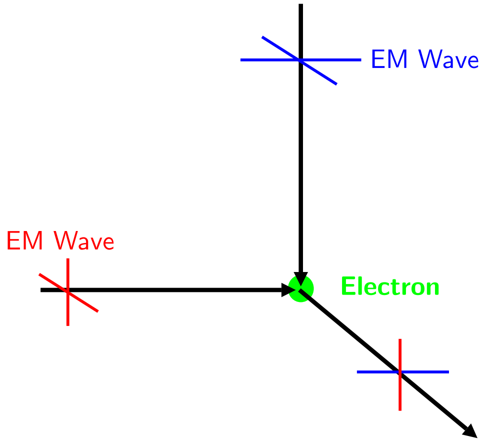


Holder et al. 2003

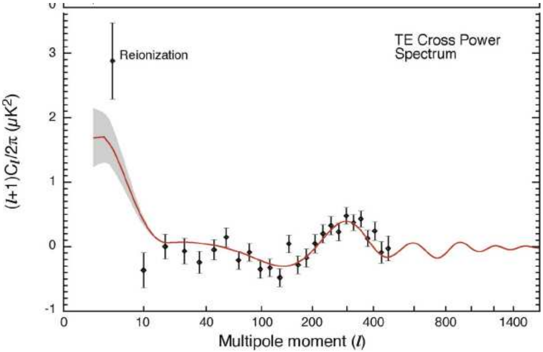
CMBR Polarization

Polarization: arises due to (i) quadrupole anisotropies in the radiation field and (ii) Thomson scattering off free electrons



CMBR Polarization

- Polarization signal typically dominant at the **angular size of the horizon** at scattering epoch.
- Scattering at last scattering surface can generate polarization signal at intermediate scales $\ell \gtrsim 100$
- Scattering off free electrons at post-recombination epochs generate polarization at large scales $\ell < 100$.



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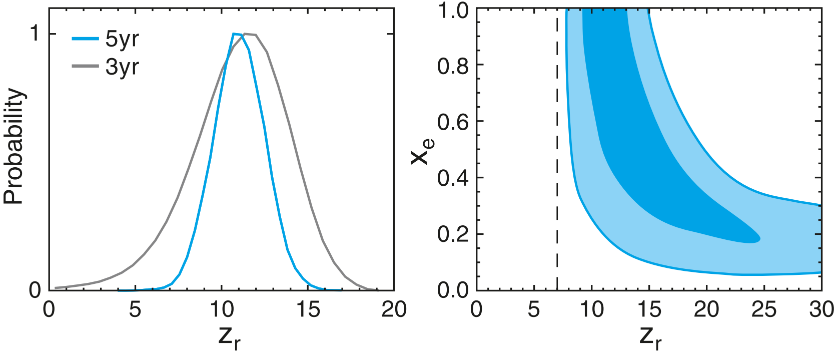


Dunkley et al. (2008)

Observations tell us...

- $10^{-4} \lesssim x_{\rm HI} \lesssim 0.4$ at $z \approx 6$. Should not complete reionization too early.
- Reionization should start early $z \gtrsim 10$.

REIONIZATION IS A SLOW AND EXTENDED PROCESS

Theoretical models

Reionization Models

Analytical Studies: Complex processes need to be incorporated:

- (Highly) Non-linear structure formation. Collapse of massive haloes and virialization. Press-Schechter formalism
- Galaxy formation physics: atomic and molecular cooling, fragmentation, star-formation, black hole accretion, feedback
- Escape of photons – depends on the distribution of stars and density structure of the halo.
- Evolution of ionization fronts. Strömgren spheres. Radiative Transfer: propagation depends on density structure of the IGM.
- Feedback: heating will suppress galaxy formation.

Not possible to track everything analytically

Reionization Models

Evolution of the volume filling factor of ionized regions:

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{n}_{\mathrm{ph}}}{n_H} - Q_{\mathrm{HII}}\mathcal{C}_{\mathrm{HII}}\frac{n_e}{a^3}\alpha_R(T)$$

Evolution of the temperature

$$\frac{\mathrm{d}T}{\mathrm{d}t} \approx -2H(z)T + \frac{2}{3k_{\mathrm{boltz}}n_B}\frac{\mathrm{d}E}{\mathrm{d}t}$$

Evolution of the ionization fraction

$$\frac{\mathrm{d}n_{\mathrm{HII}}}{\mathrm{d}t} = \mathrm{Photoionization} - \mathrm{Recombination}$$

Ionizing flux is determined by the mean free path

$$J_\nu \propto \lambda_\nu \ \dot{n}_{\mathrm{ph}}$$

Reionization Models

Numerical Simulations:

- Obtain distribution/location of haloes

  Identifying $10^9 M_\odot$ haloes within a $100 h^{-1}$ Mpc box requires $\sim 1000^3$ particles $\Longrightarrow$ high dynamic range

- Calculate $\dot{N}_\gamma$ for haloes

  Use simple prescription to calculate photon production efficiency

- Radiative transfer for generating ionization fronts

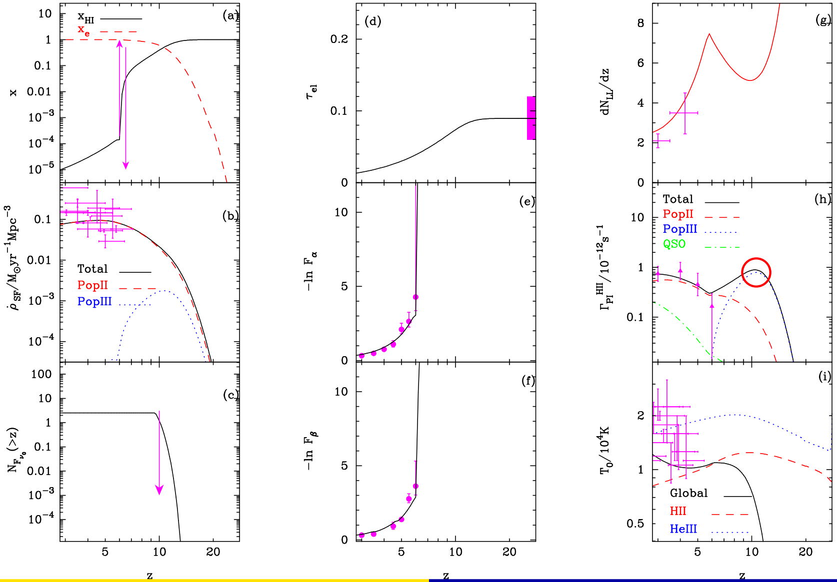
  Approximate semi-numeric methods

Example of a detailed semi-analytical model

Choudhury & Ferrara (2005,2006)

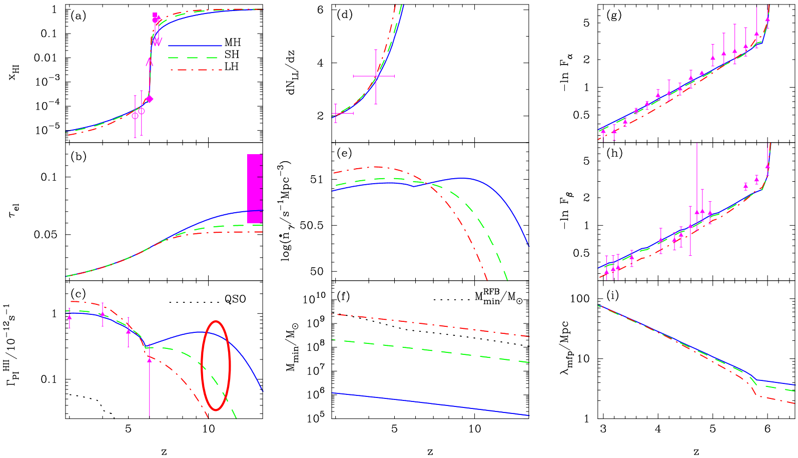
- Standard FRW paradigm with ΛCDM model – **hierarchical structure formation** dominated by dark matter
- Follow ionization and thermal histories of neutral, HII and HeIII regions simultaneously. Treat the IGM as a multi-phase medium.
- Take into account various stages of reionization
- Radiative feedback suppressing star formation in low-mass haloes
- Chemical feedback changing the nature of stars
- Three sources of ionizing radiation:
  1. PopIII stars: early redshifts, low metallicity
  2. PopII stars: normal stars, transition from PopIII via chemical feedback
  3. Quasars: significant at $z \lesssim 6$
- Constrain the free parameters from observations $\Longrightarrow$ determine which reionization histories are favoured by current data.

Observational constraints



Observational constraints

What if PopIII stars did **not** contribute significantly?



We need to introduce cooling via molecular hydrogen at high-z.

Observational constraints

- H-reionization starts at $z \approx 15$ [early reionization].
- Completes at $z \approx 6$
- Feedback regulated. Extended. "Slow".
- Require substantial sources of photons at $z \approx 10$. **What are the sources?**

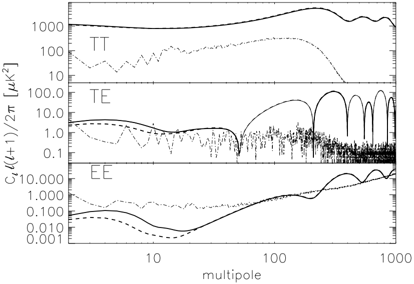
Overall picture emerging. But details remained to be filled:

- Properties of the first sources ($z \gtrsim 10$).
  1. **Stars?**: observations/models of **star-formation rate** at $z > 6$ do **not** predict enough photons to fully ionize the IGM at $z \gtrsim 6$. **Possible escape routes**: modify the stellar spectra, initial mass function, cooling etc.
  2. **QSOs?**: no significant population observed at $z > 6$. In fact, the number density declines from $z = 3$ to $z = 6$.
  3. **Intermediate-mass black holes, Miniquasars?**: strong limits from Soft X-ray Background – possible to ionize only partially
  4. **Exotic particles (decaying neutrinos)?**: Strong limits from X-ray and Gamma-ray backgrounds; distortions in the Planckian shape of CMBR – **not** enough!!
- Topology: Shapes of the ionized regions. Inside-out or Outside-in? Dense regions ionized first?
- Nature of feedback

Future

Better observations

- More QSO spectra at high redshifts. Also GRB spectra.
- Lyα emitters.
  - Galaxies with Lyα emission arising from hydrogen gas that is ionized by hot, young stars in these galaxies – extremely suitable for detecting sources at high redshifts.
  - Detection of these sources depends on **transparency of the medium**: a neutral IGM at high-z would imply less number of Lyα emitters observed.
  - Construct the luminosity function of Lyα emitters at different redshifts and check if they evolve. The evolution can put limits on the neutral hydrogen fraction.
- CMBR polarization: PLANCK data can constrain, e.g., the effects of feedback Burigana et al. (2008)

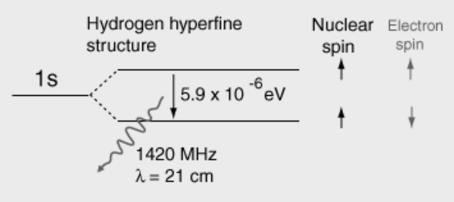


An "ideal" experiment

- CMBR probes the "integrated" reionization history. Require a line transition so that observations can be done in different redshifts.
- Lyα is a line transition, but too "strong" $\Longrightarrow$ lines become saturated for $x_{\rm HI} \gtrsim 10^{-4}$
- Need a line transition which is "weak"

Future: 21 cm emission observations

- 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 signal, forbidden (weak compared to, say, Lyα)
- Spin temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \mathrm{e}^{-0.068\ \mathrm{K}/T_s}; \qquad \frac{g_1}{g_0} = 3$$

Excitation rate = collisons + radiative scattering off CMBR

- Brightness temperature

$$\delta T_b \approx \frac{T_s - T_{\mathrm{CMB}}(z)}{1+z}\tau; \qquad \tau \propto \frac{n_{\mathrm{HI}}}{T_s}$$

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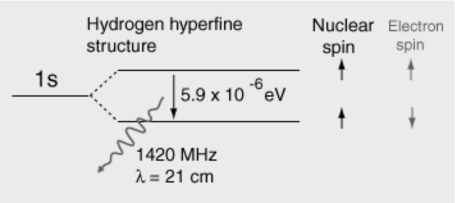
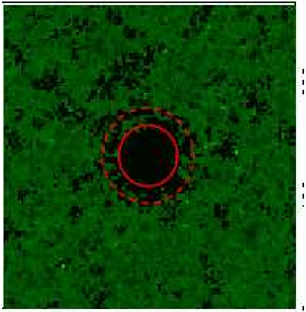


- In most models, the neutral hydrogen will be **observed in emission** from $z \approx 15$ until reionization is completed. T_s couples to T_k via Lyα pumping, and $T_k > T_{\rm CMBR}$ because of X-ray heating, shock etc.
- Possible to follow the evolution of ionized regions through maps at different redshifts (frequencies). $\nu_{\rm obs} = 1420 \text{ MHz}/(1+z)$
- Present Experiments: GMRT (India); Future Experiments: MWA (Australia), LOFAR (Netherlands + Europe), SKA (planning stage)
- Main challenge: Foregrounds from Galactic synchrotron, Extragalactic point sources, RFI,...

Future: 21 cm emission observations

Two possible approaches:

- **Individual sources**: Look towards ionized regions around sources



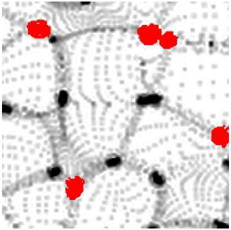
Datta, Majumdar, Bharadwaj & **Choudhury** (2008)

- **Statistical**: Calculate quantities like correlation function etc

Datta, **Choudhury** & Bharadwaj (2006)

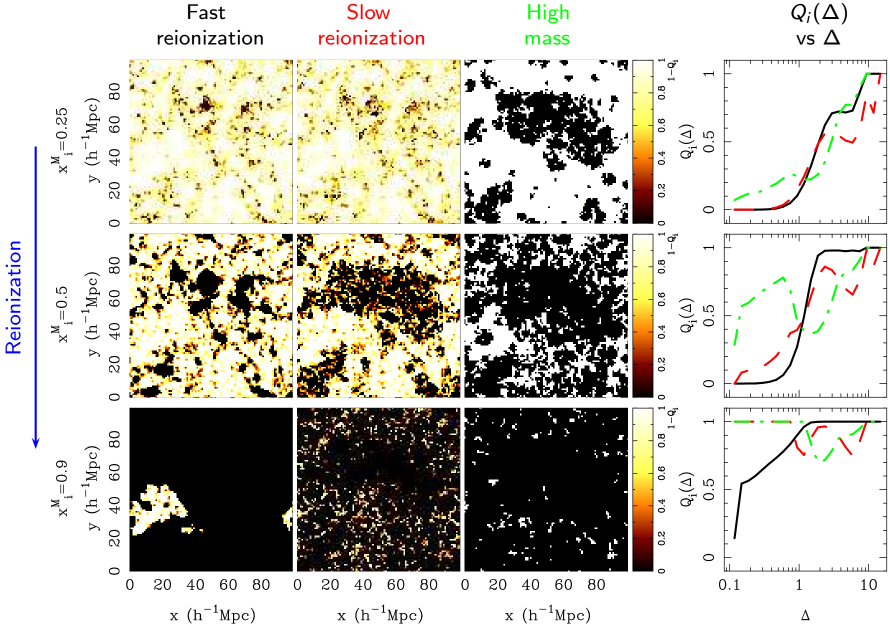
What can be probed with 21 cm experiments?

- Sources form in high density regions, so will the dense regions ionize first?
  Inside-out

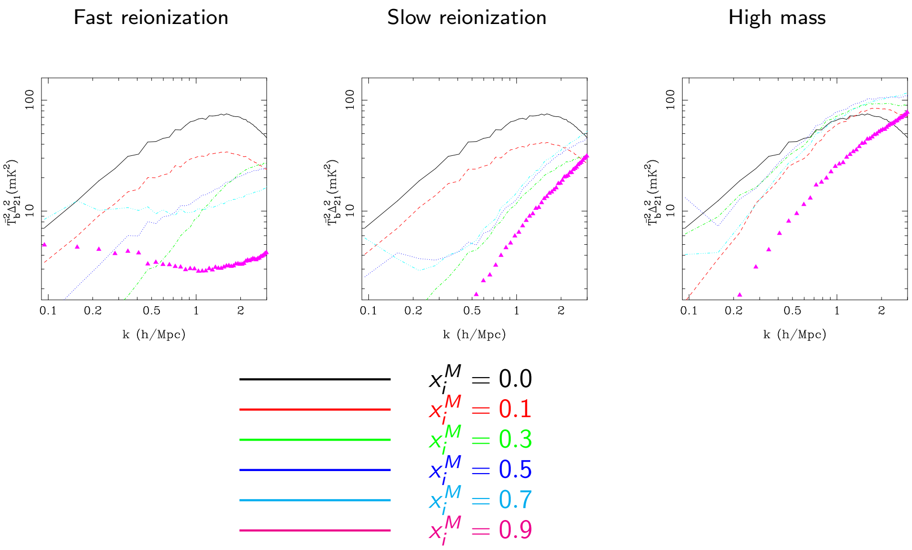


- But high density regions recombine very fast $\Longrightarrow$ self-shielding. So will they remain neutral till the end?
  Outside-in

Topology of reionization **Choudhury**, Haehnelt & Regan (2009)

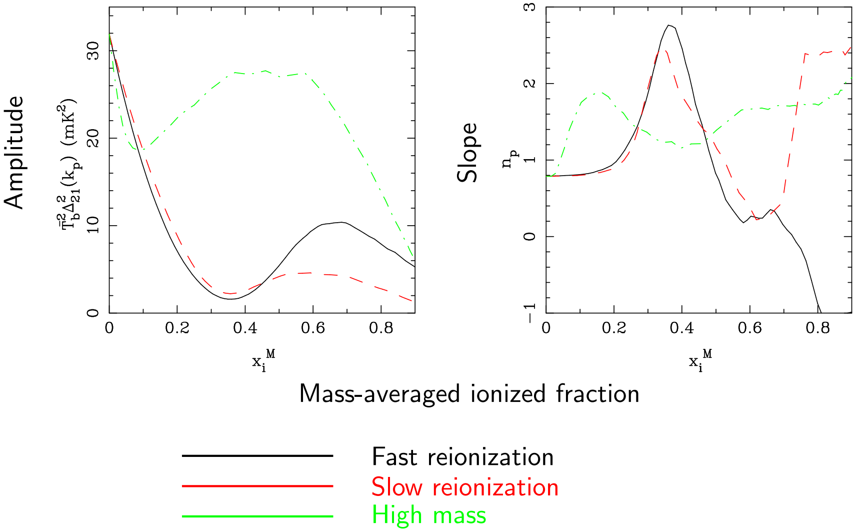


21 cm power spectrum **Choudhury**, Haehnelt & Regan (2009)



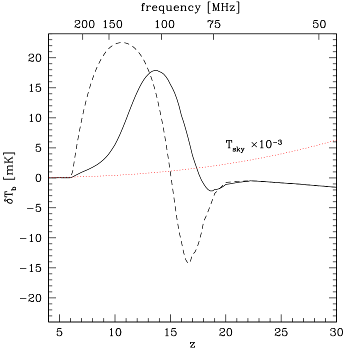
21 cm power spectrum **Choudhury**, Haehnelt & Regan (2009)

angular scale $\sim 10'$



21 cm: Wealth of information

- Feedback signatures



Schneider, Salvaterra, **Choudhury** et al. (2008)

- Cross correlate with other probes: high-z galaxies, CMBR kSZ, ...
- 21 cm signal from dark ages (3D probe as opposed to 2D CMBR sky; can probe $k \sim 10^3$ Mpc^{-1})

Summary

- Reionization is crucially linked to the first sources; also affects next generation of structure formation
- Good progress in theoretical modelling, possible to construct models consistent with all available data
- Field driven by observational data – observations related to
  - QSO absorption lines + GRBs
  - high-redshift galaxies,
  - CMBR Polarization + SZ signal,
  - Lyα emitters,
  - 21 cm emission

  will soon settle the long-standing question on when and how the Universe was reionized.
- Important to develop detailed analytical and numerical models to extract the maximum information about the physical processes relevant for reionization out of the expected **large and complex data sets**.