

Constraining Reionization and First Stars

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Confronting particle-cosmology with Planck and LHC
12 August 2011

Reionization: The Basic Picture

Start

$z \approx 1000$

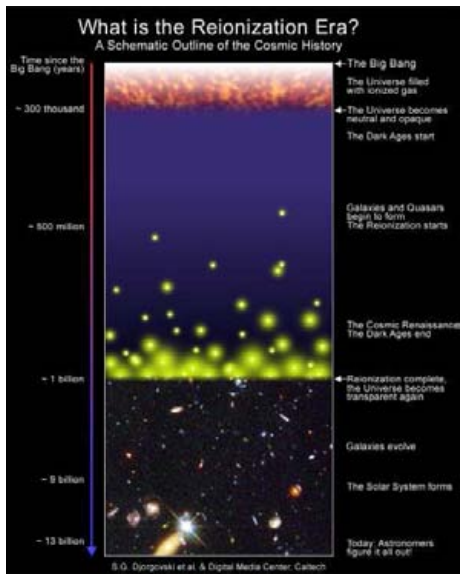
$z > 30$

$z \approx 15 - 30$

$z \approx 6$

$z \sim 3$

$z \sim 0$



Big Bang

Last Scattering
Initial conditions (WMAP)

Galaxies
Nonlinear Structures (HST)

Now

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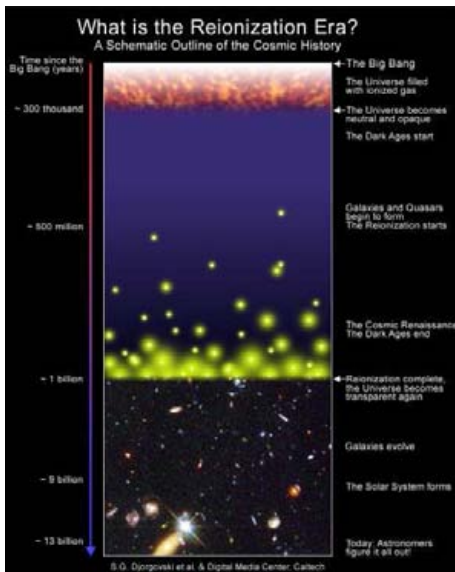
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Big Bang

Last Scattering
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Dark Ages

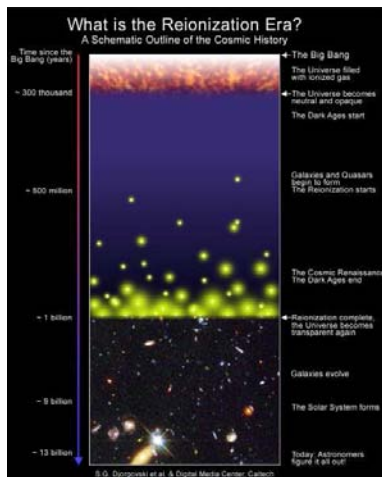
Cosmic Dawn

Reionization

Galaxies
Nonlinear Structures (HST)

Now

Why Study Reionization?



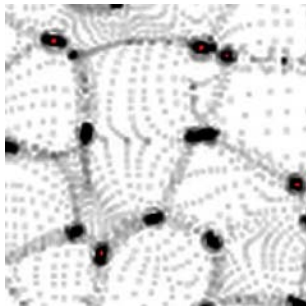
- Reionization: **Second major change in the ionization state of hydrogen (and helium)** in the Universe.
- Last phase of cosmic evolution **to be tested: Final Frontier of Observational Cosmology**
- Related to the quest for understanding **first luminous objects** (stars, galaxies,...) in the Universe.
- Reionization affects **subsequent formation of galaxies (feedback)**.
- Effect on **precision cosmology**?

Issues and Aims

- **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?

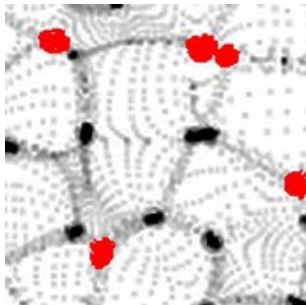
How to Model Reionization?

- ✓ Formation of (dark matter) haloes:
Press-Schechter formalism, collapsed fraction



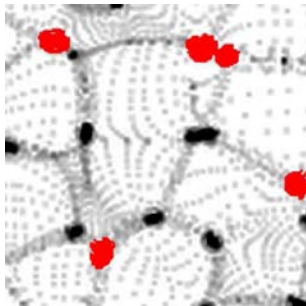
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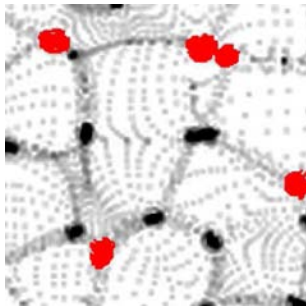
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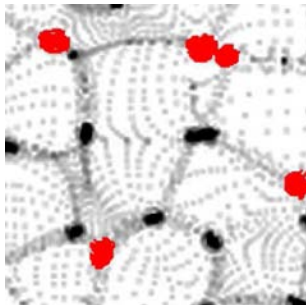
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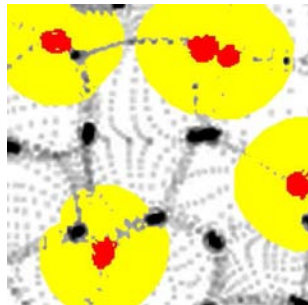
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 - ✗ Escape of photons: neutral hydrogen within the host galaxy
- ✗ Radiative transfer in the IGM: evolution of ionization fronts



Photon Production

Photon production rate:

$$\dot{n}_\gamma = N_{\text{ion}} \left(\frac{\Omega_b}{\Omega_m} \right) \frac{df_{\text{coll}}}{dt}$$

Number of ionizing photons in the IGM per baryons

Collapse rate of dark matter haloes

$$N_{\text{ion}} = \epsilon_* f_{\text{esc}} \times \text{number of photons per baryons in stars}$$

Radiative Transfer: Simulations

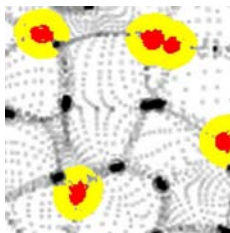
- Huge dynamical range required for simulating reionization
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$
⇒ either inaccurate or inefficient
- Alternatives: semi-analytical

Radiative Transfer: Analytic

- Averaging over globally representative volumes (and under certain approximations), the radiative transfer equation reduces to

$$\frac{dQ_{\text{HII}}}{dt} = \frac{\dot{n}_{\gamma}}{n_H} - Q_{\text{HII}} c_{\text{HII}} \frac{n_e}{a^3} \alpha_R(T)$$

Evolution of volume filling factor of ionized regions



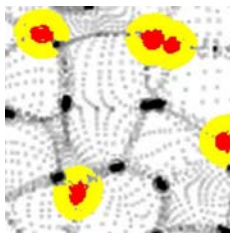
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Evolution of volume filling factor of ionized regions

- Supplemented by temperature and species evolution equations



Radiative Transfer: Analytic

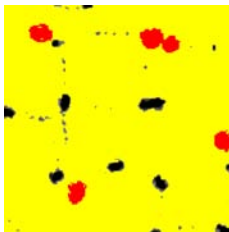
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Evolution of volume filling factor of ionized regions

- 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)

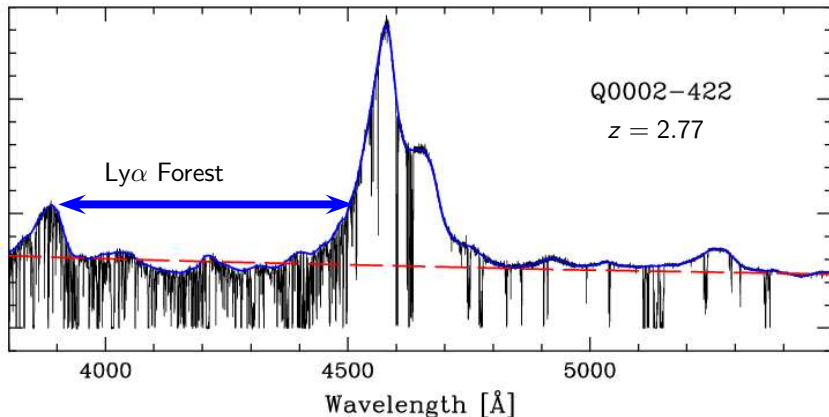


Example of a Detailed Semi-analytical Model

Choudhury & Ferrara (2005,2006)

- Standard FRW paradigm with Λ CDM model – **hierarchical structure formation** dominated by dark matter
- Follow ionization and thermal histories of neutral, HII and HeIII regions simultaneously.
- 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 $z \lesssim 6$
- **Radiative feedback** suppressing star formation in low-mass haloes
- **Chemical feedback** changing the nature of stars
- Constrain **the free parameters** from observations \implies determine which **reionization histories** are favoured by current data.

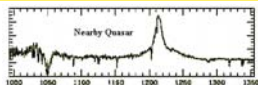
Observations: Lyman- α Forest



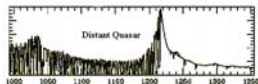
The absorption lines **blueward** of the emission line arise from Ly α transition of neutral hydrogen (HI) present between the quasar and us.

QSO Absorption Lines at $z \sim 6$

$z \approx 0$

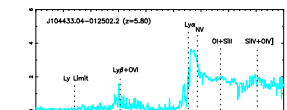


$z \approx 3$

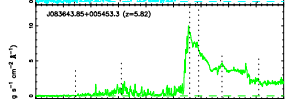


$$x_{\text{HI}} \lesssim 10^{-5}$$

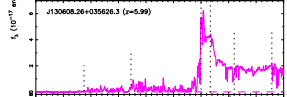
$z = 5.80$



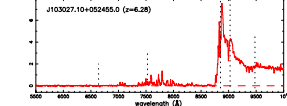
$z = 5.82$



$z = 5.99$

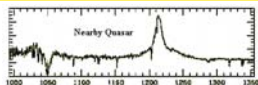


$z = 6.28$

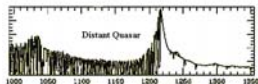


QSO Absorption Lines at $z \sim 6$

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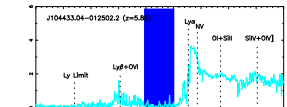


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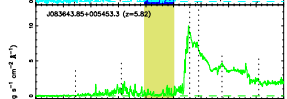


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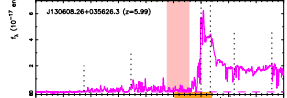
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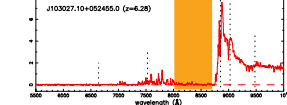
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Does this absorption mean
high neutrality?

Not necessarily!

$$x_{\text{HI}} \lesssim 10^{-4}$$

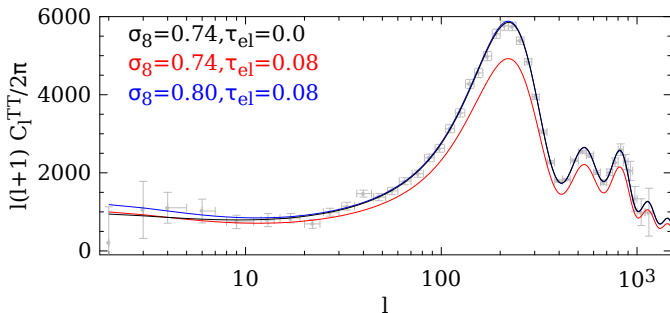
CMBR: Damping of Temperature Anisotropies

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

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

Provided by reionization

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



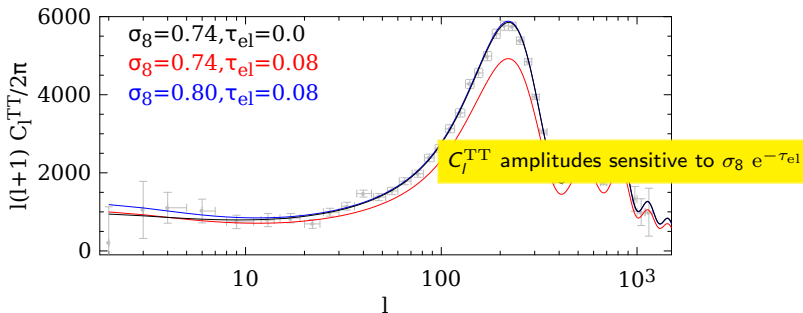
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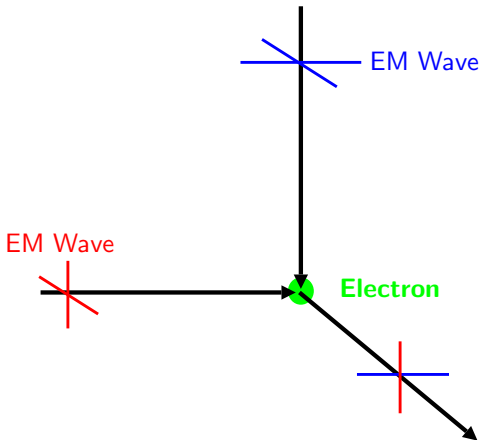
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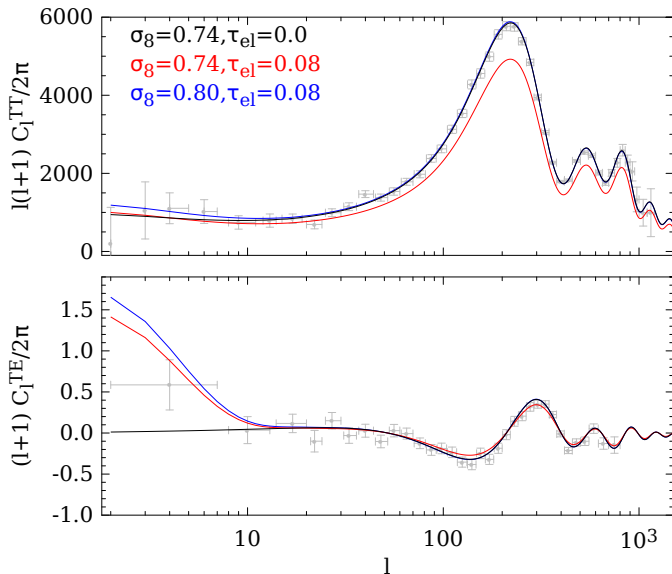
CMBR Polarization

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



Effect on C_l

Large angular scale polarization signal

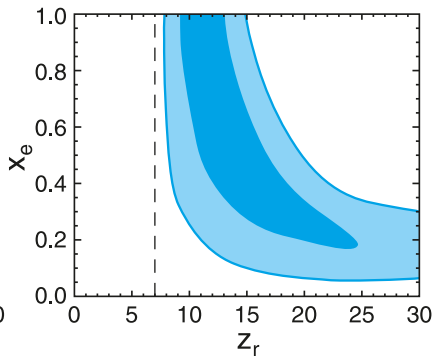
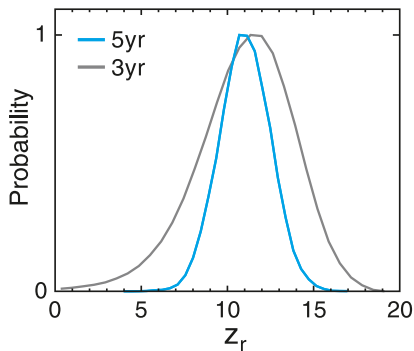


Constraints from WMAP

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

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

Provided by reionization



Dunkley et al. (2008)

Measures integrated n_e , not sensitive to details of reionization

Observations tell us...

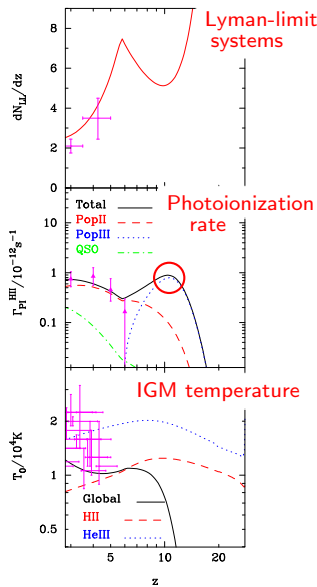
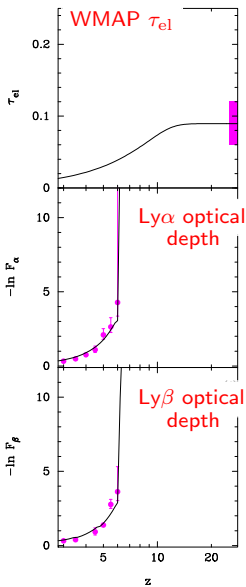
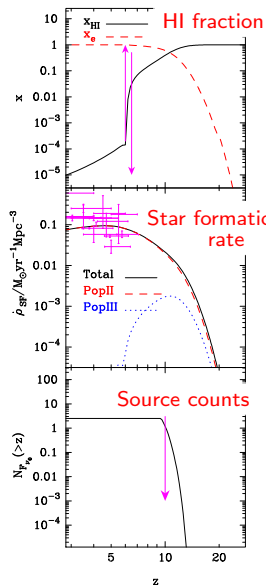
Robust conclusions:

- Ly α forest: IGM highly ionized at $z < 6$
- Ly α forest: $x_{\text{HI}} \gtrsim 10^{-4}$ at $z \approx 6$.
- CMBR polarization: Reionization should start early $z \gtrsim 10$.

Other constraints:

- Star formation rate (or galaxy luminosity function)
- Ly β forest
- IGM temperature
- Lyman-limit systems (mean free path of photons)
- ...

Observational Constraints Choudhury (2009)



Preferred Reionization History

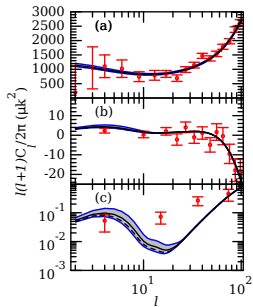
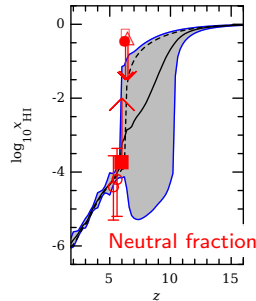
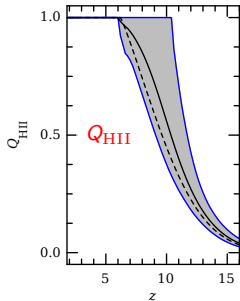
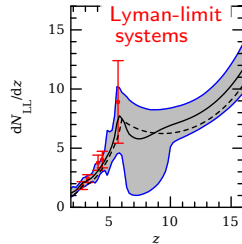
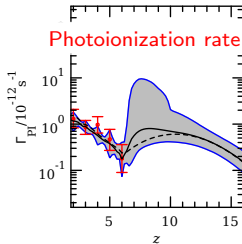
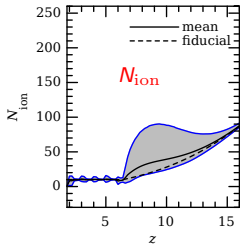
- H-reionization starts at $z \approx 15$ [early reionization].
- Completes at $z \approx 6$
- Feedback regulated. Extended. “Slow”.
- Require substantial sources of photons at $z \approx 10$.

Model-independent Constraints Mitra, Choudhury & Ferrara (2011)

- Our physically-motivated model is **based on various assumptions** (e.g., a particular prescription for chemical feedback). How general is it?
- It also assumes N_{ion} **to be constant** for each of the populations (PopII and PopIII) of stars. Most likely ϵ_* and/or f_{esc} varies with z .
- An alternate approach is to constrain reionization in a **model-independent** way \implies data-constrained scenario.
- Assume $N_{\text{ion}}(z)$ to be an arbitrary function of z and decompose into **principal components**. No assumption regarding the nature of stars.
- Obtain **most general constraints** on (galaxy-driven) reionization by comparing with QSO and CMB data.
- **Sourav Mitra's talk on the 1st day**

Model-independent Constraints: QSO and WMAP7

Mitra, Choudhury & Ferrara (2011)

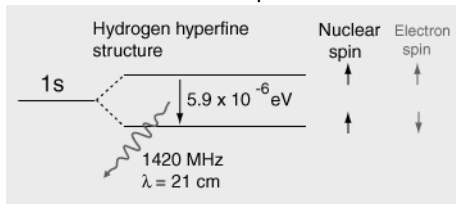


A “Better” Experiment

- CMBR probes the “integrated” reionization history. Require a **line transition** so that observations can be done in different redshifts.
- Ly α is a line transition, but too “strong” \implies lines become saturated for $x_{\text{HI}} \gtrsim 10^{-4}$
- Need a line transition which is “weak”: 21 cm hyperfine transition

Future: 21 cm Emission Observations

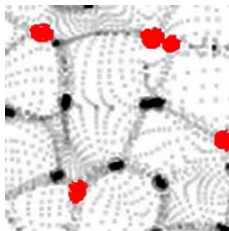
- 21 cm (1420 MHz) radiation: arises from the transition between the two **hyperfine levels** of the hydrogen 1s ground state, slightly split by the interaction between the electron spin and the nuclear spin.



- Possible to follow the **evolution of ionized regions** through maps at different redshifts (frequencies). $\nu_{\text{obs}} = 1420 \text{ MHz}/(1 + z)$
- Experiments: GMRT (India), MWA (Australia), LOFAR (Netherlands + Europe)
- Promising tool to probe the dark ages.
- Main challenge: Foregrounds from Galactic synchrotron, Extragalactic point sources, RFI,...

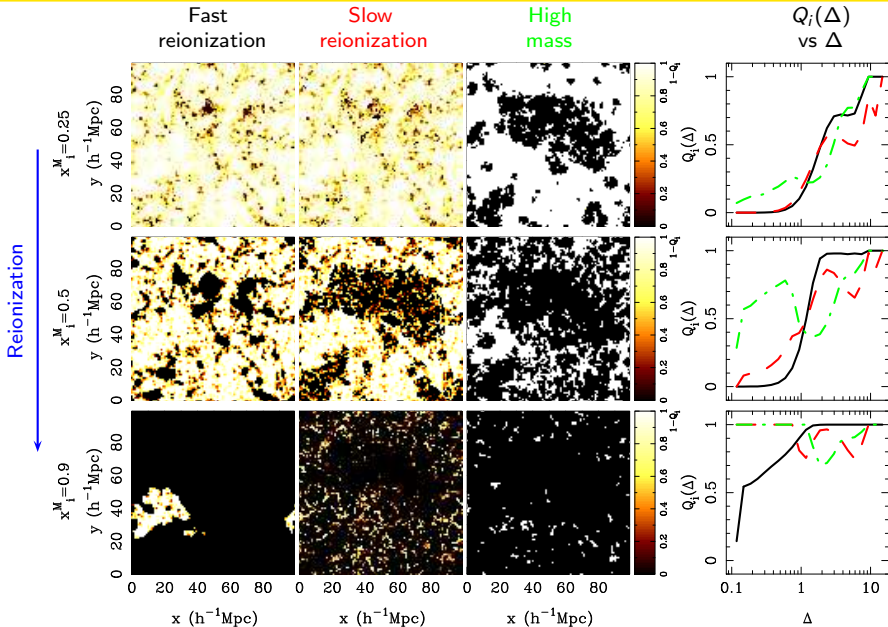
What can be probed with 21 cm experiments?

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



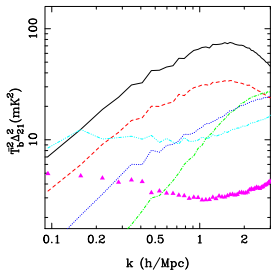
- But high density regions recombine very fast \implies self-shielding. So will they remain neutral till the end?
Outside-in

Topology of Reionization Choudhury, Haehnelt & Regan (2009)

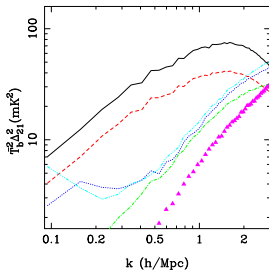


21 cm Power Spectrum Choudhury, Haehnelt & Regan (2009)

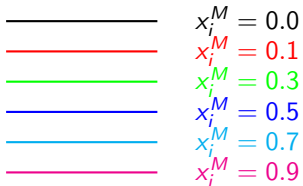
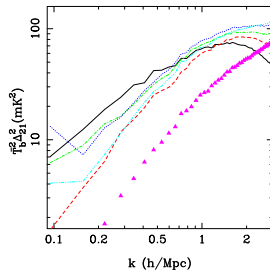
Fast reionization



Slow reionization

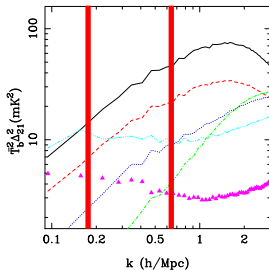


High mass

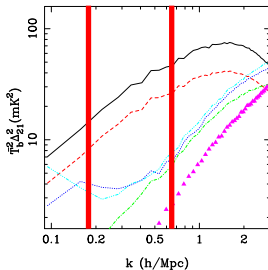


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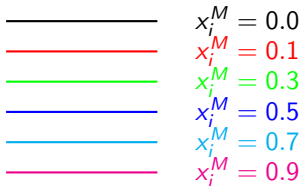
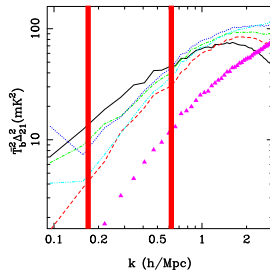
Fast reionization



Slow reionization



High mass



GMRT-EoR observations
at $z = 8.6$, signal < 500 mK²
Paciga et al. (2011)

Summary

- Reionization is crucially linked to the **first sources**; also affects next generation of structure formation. “**Final frontier**” of observational cosmology.
- Good progress in **theoretical modelling**, possible to construct **models consistent with all available data**.
- Clear indication of a **new population at $z > 6$** .
- Uncertainties remain around **$7 < z < 10$** . Not possible to constrain satisfactorily using Planck.
- Keep looking for **other observational constraints**.