Observational Constraints on Reionization History

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INDIAN CONFERENCE ON COSMOLOGY AND GALAXY FORMATION
31 October 2009

Plan of the talk

- Evidence for extended reionization from semi-analytical models
- Modelling ionization (21 cm) maps

Set of differential equations **Choudhury** & Ferrara (2006)

Evolution of the volume filling factor of ionized regions:

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

Source term

$\dot{n}_{\rm ph}$: Rate of ionizing photons per unit volume

Recombination term

$\mathcal{C}_{\rm HII} \equiv \langle n_{\rm HII}^2\rangle / \langle n_{\rm HII}\rangle^2$: Clumping factor

$\alpha_R(T)$: Recombination rate

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Evolution of the temperature

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

Adiabatic cooling

Net heating rate per baryon

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \text{Photoheating} - \text{Recombination cooling} - \text{Compton cooling}$$

Set of differential equations **Choudhury** & Ferrara (2006)

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Evolution of the ionization fraction

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

Set of differential equations Choudhury & Ferrara (2006)

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Evolution of the ionization fraction

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

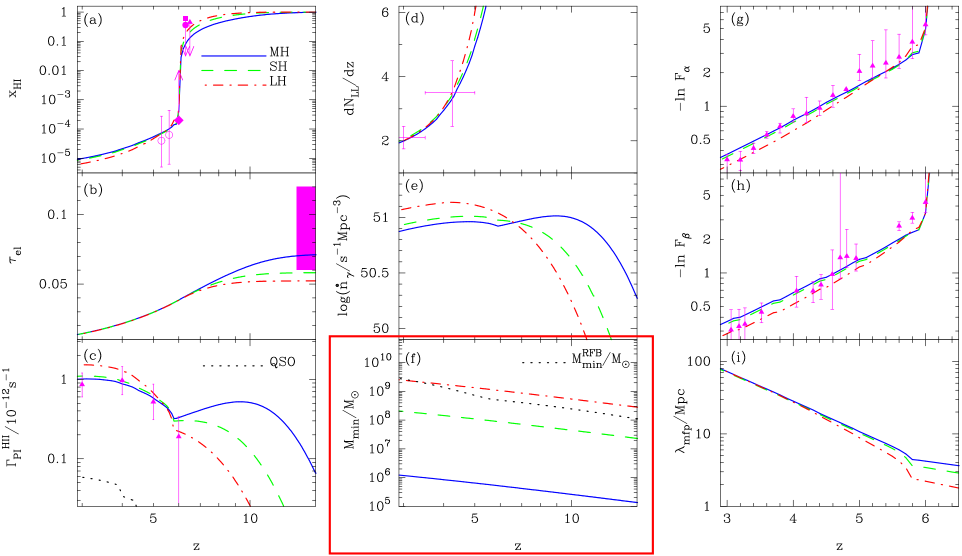
Ionizing flux is determined by the mean free path

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

Features of the semi-analytical model Choudhury & Ferrara (2005,2006)

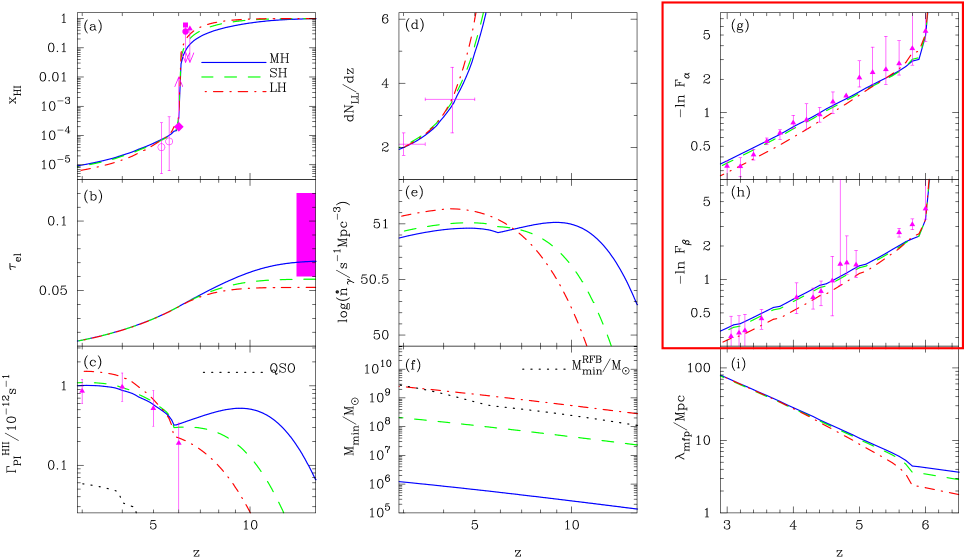
- Follow ionization and thermal histories of neutral, HII and HeIII regions simultaneously. Treat the IGM as a multi-phase medium.
- Take into account all the three stages of reionization
  - Pre-overlap: Ionized regions of individual sources propagate into the IGM
  - Overlap (Epoch of reionization): Individual ionized regions overlap, leaving islands of neutral regions (preferentially high density structures) identified as Lyman limit systems
  - Post-overlap: The ionization fronts penetrate into high density regions
- Sources of ionizing radiation:
  1. PopII stars: $\dot{n}_{\rm phot} = N_{\rm ion} \frac{{\rm d}f_{\rm coll}}{{\rm d}t}$
  2. Quasars: unimportant at $z \gtrsim 6$
- Radiative feedback suppressing star formation in low-mass haloes
- Uncertainties (free parameters):
  1. Number of photons per unit collapsed mass $N_{\rm ion}$
  2. Minimum mass of star-forming haloes $M_{\rm min}$

Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)



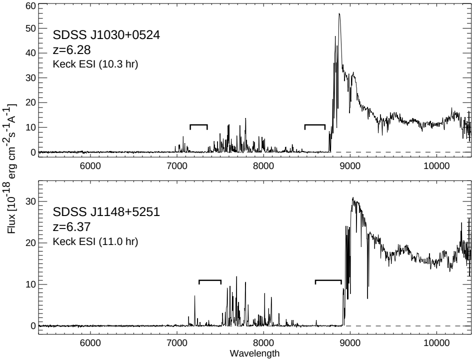
3 different choices for $M_{\min}$

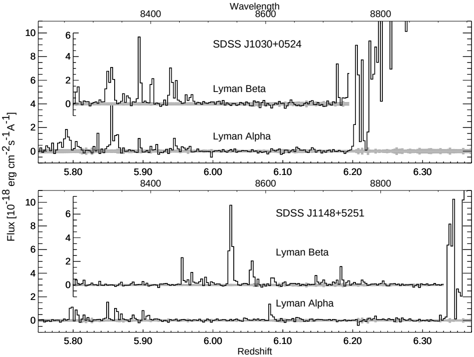
Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)



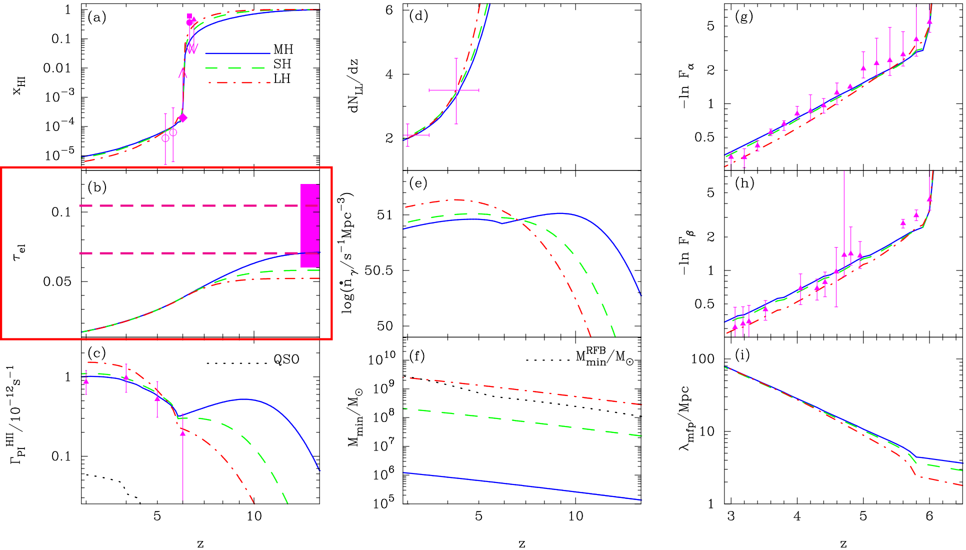
Estimate maximum allowed N_{ion} from GP τ at $z \approx 6$

Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)



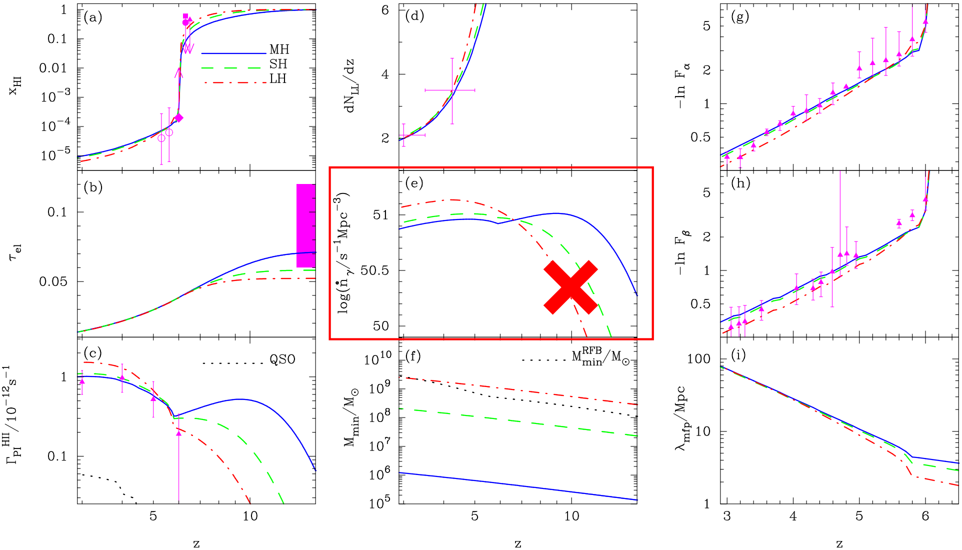


Semi-analytical models: Results Choudhury, Ferrara & Gallerani (2008)



Compare with τ_{el}

Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)



Low emissivity at $z = 6 \Longrightarrow$ extended reionization

What have we learnt?

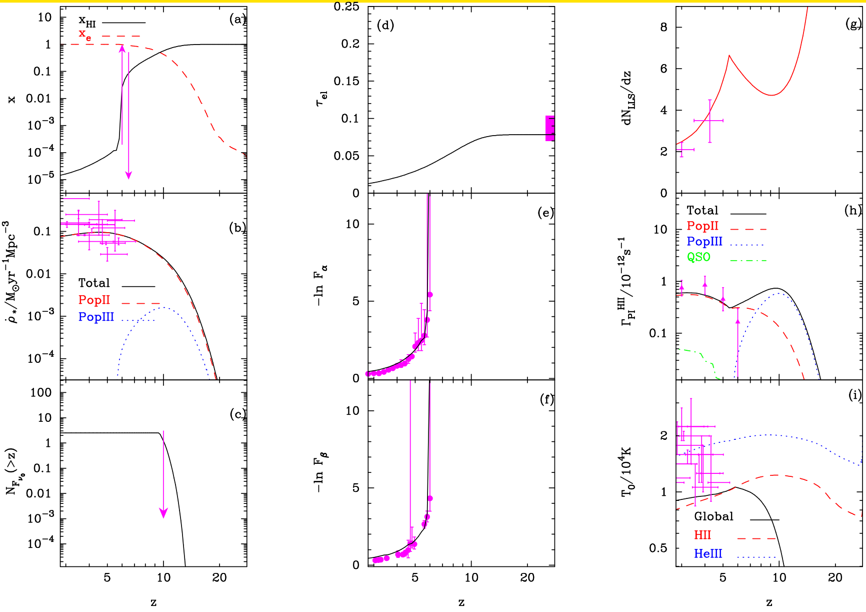
- Only (less than) $2-3$ photons per baryon at $z \approx 6$.
- If the galaxies never produce more that $2-3$ photons per baryon, then it is impossible to ionize the IGM by $z \approx 6$ (and impossible to match the WMAP constraints).
- Hence the galaxies emitted comparatively more efficiently at higher redshifts $\Longrightarrow$ a "bump" in the emissivity.

Possible scenarios

- Molecular cooling at high redshifts? √
- Redshift-dependent $N_{\rm ion}$: need high values at early times. Metal-free stars? Top-heavy IMF? √
- Mass-dependent $N_{\rm ion}$: need high values for low mass haloes. ×
- Lower values of mean free path. ×
- Feedback?

Model with metal-free stars matches all available observations.

Matching the observations **Choudhury** & Ferrara (2005,2006,2007)



Applications

- Which kind of sources are primarily responsible for reionization?
  Ans: Stars in very low mass haloes. They are too faint to be observed at current observational limits. **James Webb Space Telescope (2013)** should be able to see them.
  Choudhury & Ferrara (2007)
- Is there any way to constrain the feedback mechanisms?
  Ans: 21 cm observations (hyperfine transition of neutral hydrogen) and CMBR polarization measurements (possibly **PLANCK**).
  Schneider, Salvaterra, **Choudhury** et al. (2008), Burigana, et al. (2008)
- What about the intergalactic radiation field?
  Ans: Absorption of very high energy (GeV-TeV) photons from Blazars or GRBs through e^+e^- pair production.
  Inoue, Salvaterra, **Choudhury** et al. (2009)

Ionization maps: Motivation

- What do these models imply for 21cm observations?
- Important to consider models which are consistent with the extended and "low-emissivity" scenario.
- Extended reionization $\Longrightarrow$ recombinations (distribution of photon sinks).
- Develop a reionization picture consistent with post-reionization scenario (large ionized regions with self-shielded "islands" in-between).
- Generating 21 cm maps require large simulation boxes with realistic source and density distribution.

Ionization maps: Method

- Obtain distribution/location of haloes

  Identifying $10^9 M_\odot$ haloes within a $100h^{-1}$ 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

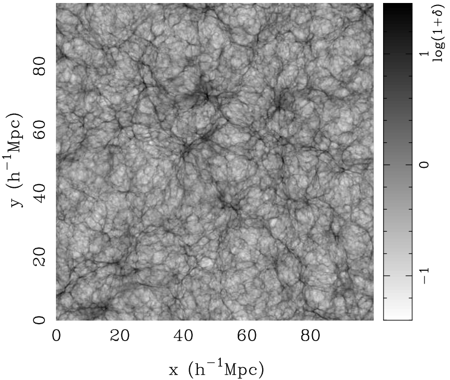
- Radiative transfer for generating ionization fronts

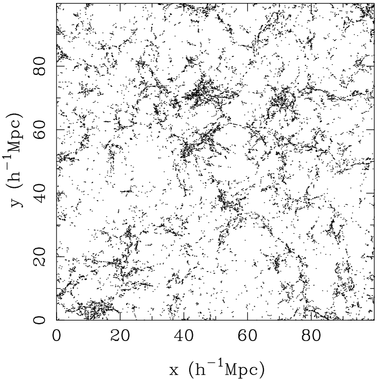
  Approximate semi-numeric methods

Simulations **Choudhury**, Haehnelt & Regan (2008)

Density field: Zel'dovich approximation

Haloes: Friends-of-friends





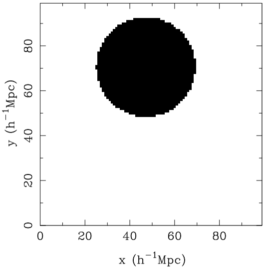
1000^3 particles, $100h^{-1}$ Mpc box

1. COSMOS supercomputer, Department of Applied Mathematics and Theoretical Physics, Cambridge.

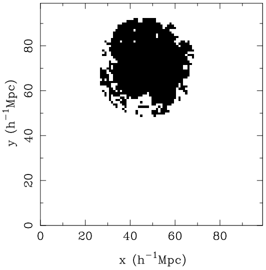
2. Cambridge High Performance Computing Cluster (Darwin).

Single source **Choudhury**, Haehnelt & Regan (2008)

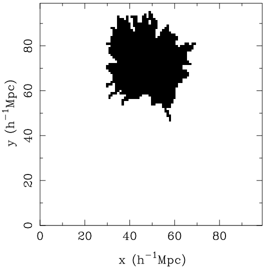
Homogeneous recombination



Inhomogeneous recombination



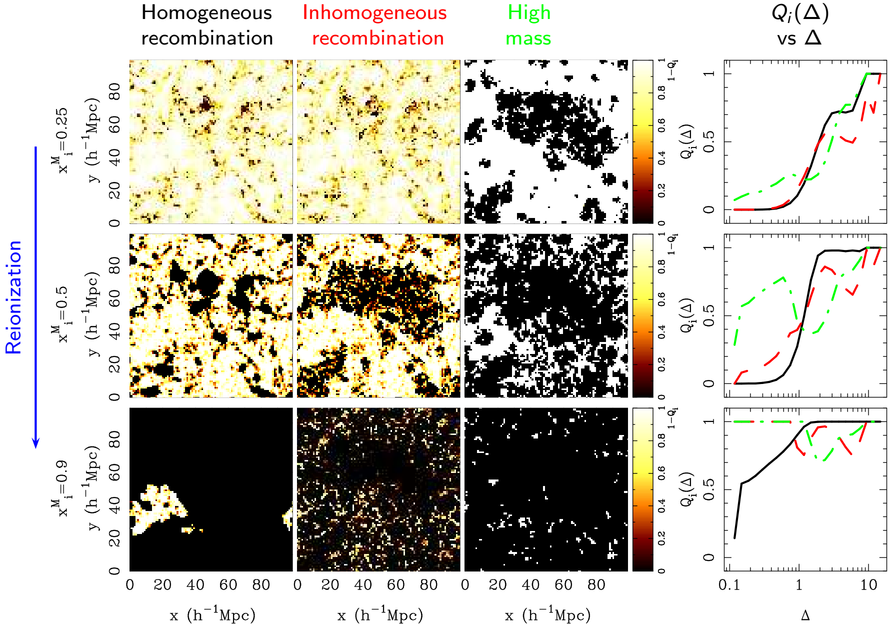
Ray-tracing



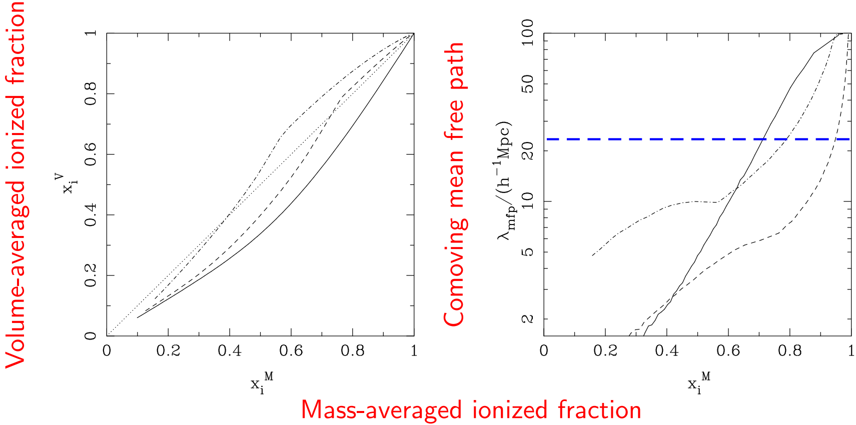
Main features of the method **Choudhury**, Haehnelt & Regan (2008)

- ✓ method is quite fast
- ✓ photons absorbed within high-density regions, propagate along low densities
- ✓ conceptually consistent with post-reionization self-shielding picture
- × shadowing
- × inaccurate ionization fronts
- × thermal/chemical history not possible

Global ionization maps **Choudhury**, Haehnelt & Regan (2008)



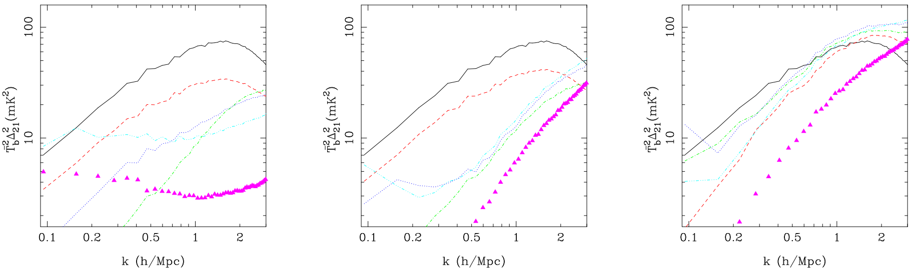
Mean free path **Choudhury**, Haehnelt & Regan (2008)



——— Homogeneous recombination
– – – – Inhomogeneous recombination
-·-·-·-·- High mass

21 cm power spectrum **Choudhury**, Haehnelt & Regan (2008)

Homogeneous recombination | Inhomogeneous recombination | High mass



$x_i^M = 0.0$

$x_i^M = 0.1$

$x_i^M = 0.3$

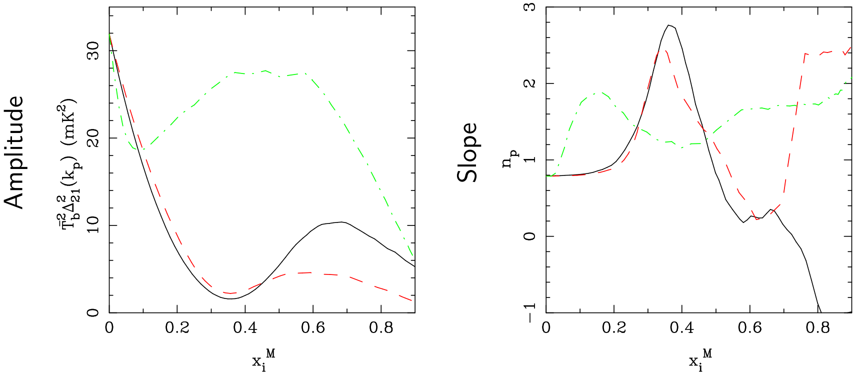
$x_i^M = 0.5$

$x_i^M = 0.7$

$x_i^M = 0.9$

21 cm power spectrum **Choudhury**, Haehnelt & Regan (2008)

angular scale $\sim 10'$



Mass-averaged ionized fraction

Homogeneous recombination

Inhomogeneous recombination

High mass

Conclusions

- Reionization extended; only 2-3 photons per hydrogen while completion ($z = 6$). Strong constraints on the parameter-space.
- Presence of efficient sources required at $z > 6$. Possible to detect in near future.
- Extended reionization $\Longrightarrow$ effect of local recombinations (sinks) important
- Reionization topology highly dependent on nature of recombinations and on the distribution of ionizing sources
- Possible to constrain the topology via near-future 21cm experiments