Probing the topology of reionization with 21 cm emission in the "photon-starved" scenario

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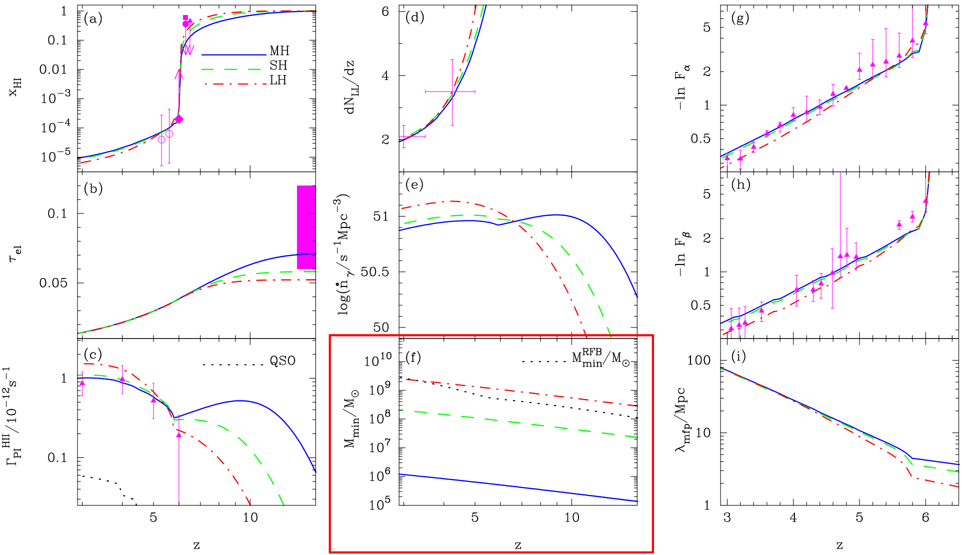
Plan of the talk

- Evidence for "photon-starved" reionization from semi-analytical models
- Modelling ionization (21 cm) maps
- Results

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

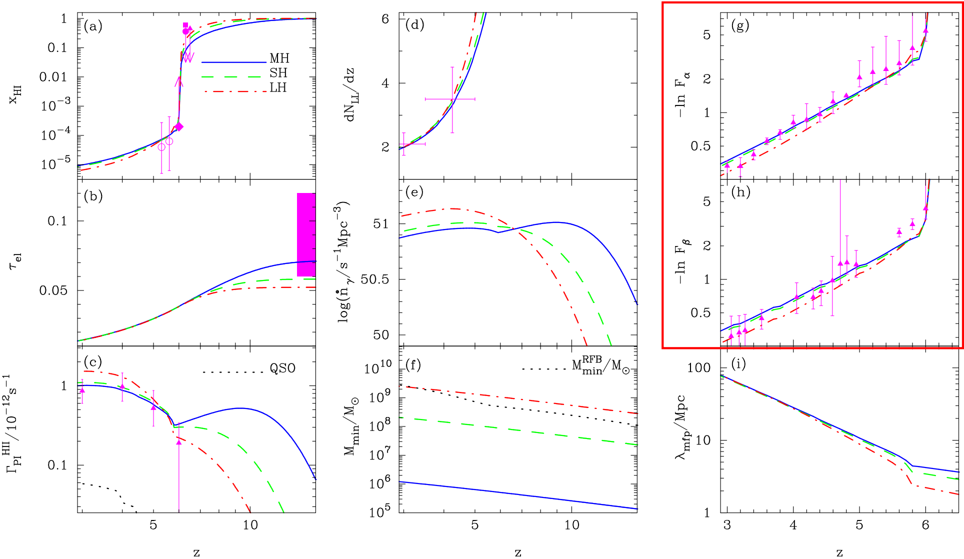
- Obtain the mass function of collapsed objects & assign the number of photons per collapsed mass
- Follow ionization and thermal histories of neutral, HII and HeIII regions simultaneously. Treat the IGM as a multi-phase medium.
- Sources of ionizing radiation:
  1. PopII stars: $\dot{n}_{\rm phot} = N_{\rm ion} \frac{{\rm d}f_{\rm coll}}{{\rm d}t}$
  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 **Choudhury**, Ferrara & Gallerani (2008)



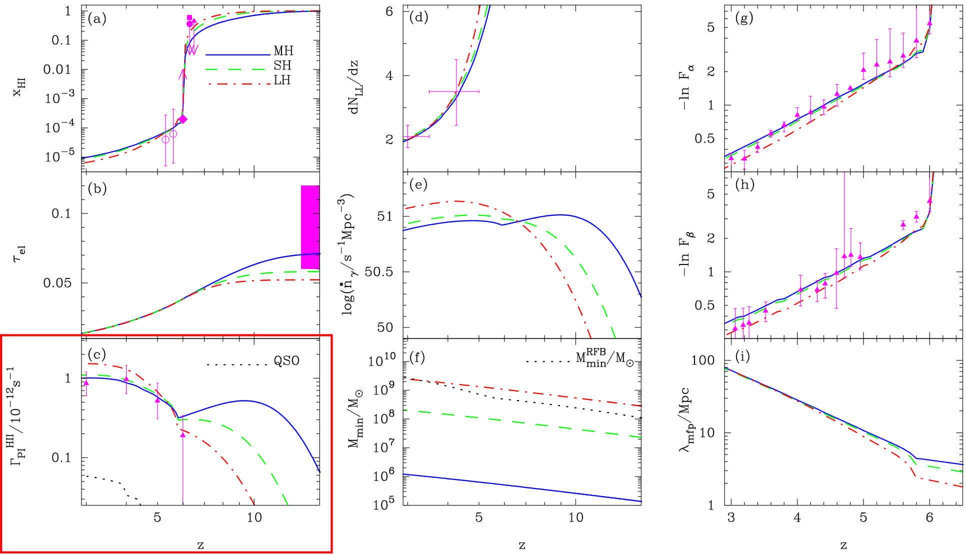
3 different choices for M_{min}

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



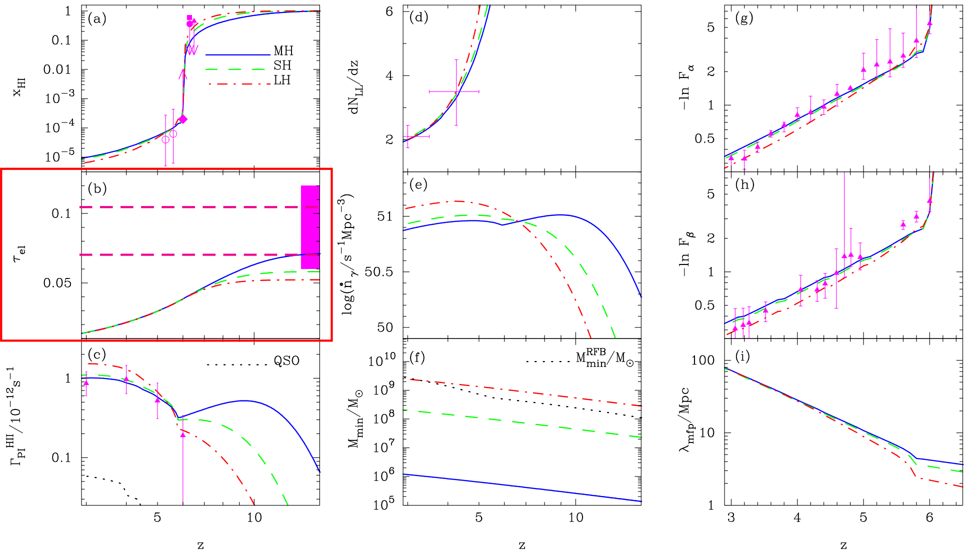
Estimate maximum allowed $N_{\rm ion}$ from GP τ at $z \approx 6$

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



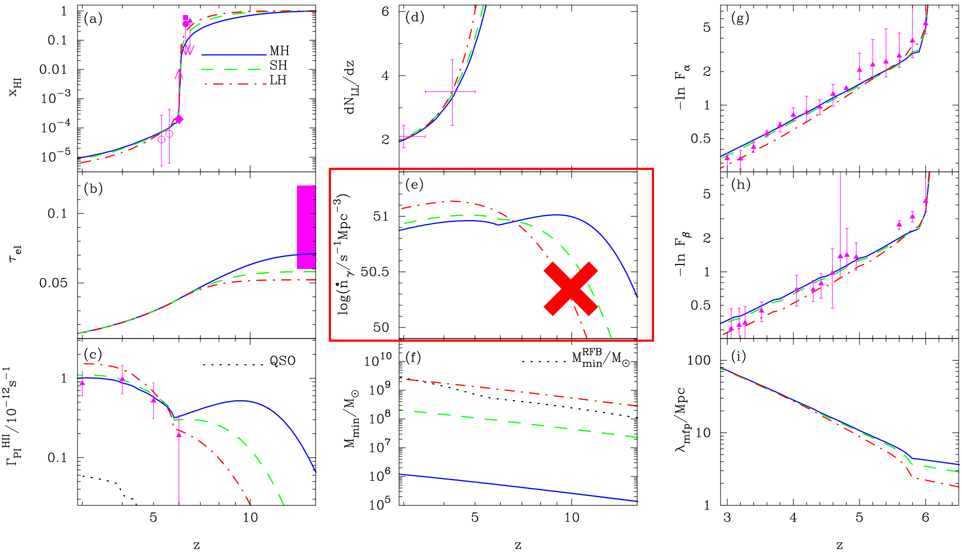
Photoionization rate

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



Compare with τ_{el}

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



Low emissivity at $z = 6 \Longrightarrow$ "Photon-starved" reionization Bolton & Haehnelt 2007

Ionization maps: Motivation

- Important to consider models which are consistent with the "photon-starved" 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)

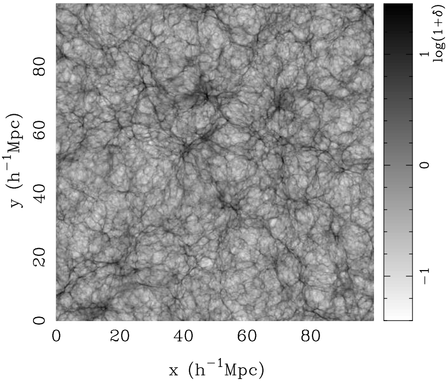
  Miralda-Escude, Haehnelt & Rees 2000
- Generating 21 cm maps require large simulation boxes with realistic source and density distribution

Ionization maps: Method

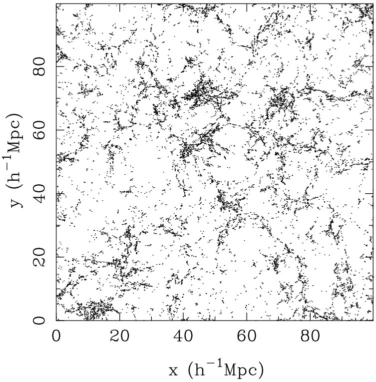
- Obtain distribution/location of haloes
  Identifying $10^9 M_\odot$ haloes within a $100 h^{-1}$ Mpc box requires $\sim 1000^3$ particles $\Longrightarrow$ high dynamic range
- Calculate $\dot{N}_\gamma$ for haloes
  Use simple prescription to calculate photon production efficiency
- Radiative transfer for generating ionization fronts
  Approximate semi-numeric methods

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

Density field: Zel'dovich approximation

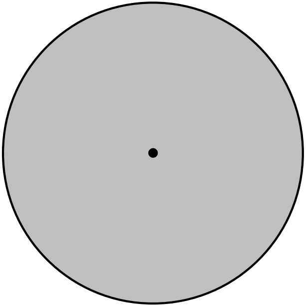


Haloes: Friends-of-friends



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

Identifying ionized regions



Self-ionization condition:

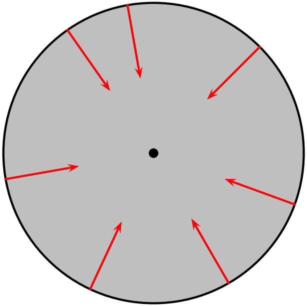
$n^R_{\rm phot} \geq n^R_H \Longrightarrow \zeta f^R_{\rm coll} \geq 1$

Uniform recombination:

$n^R_{\rm phot} \geq n^R_H (1 + \bar{N}_{\rm rec}) \Longrightarrow \zeta f^R_{\rm coll} \geq 1 + \bar{N}_{\rm rec}$

Mesinger & Furlanetto 2007, Geil & Wyithe 2008

Effects of recombination **Choudhury**, Haehnelt & Regan (2008)



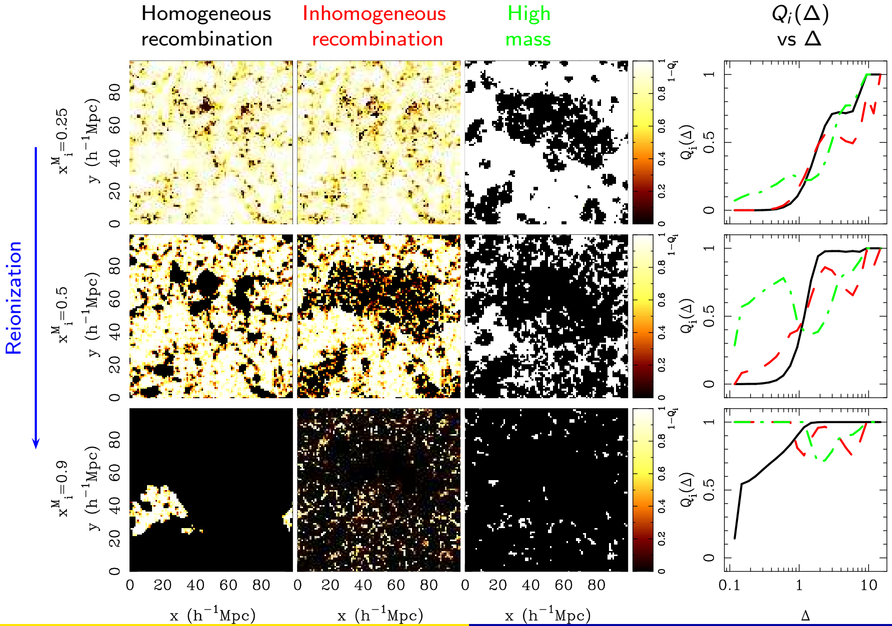
Self-shielding condition:

$N_{\rm HI}\ \sigma_{\rm H} \geq 1$

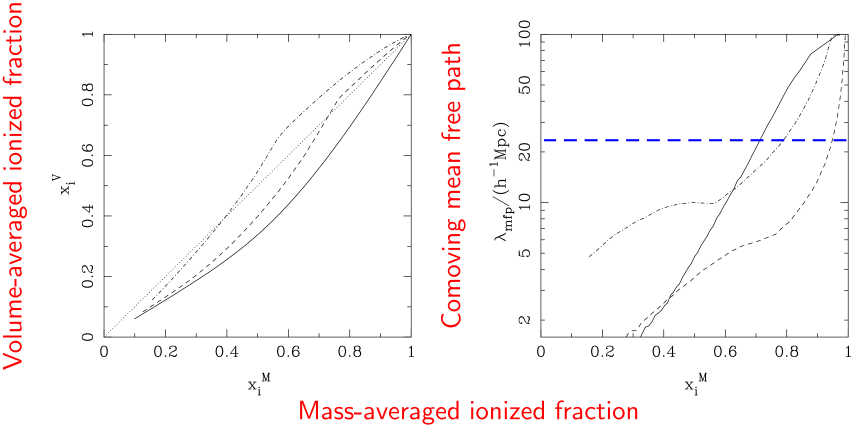
In terms of ionizing flux:

Flux $\leq (n_H L) \times (1 + N_{\rm rec})$

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



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



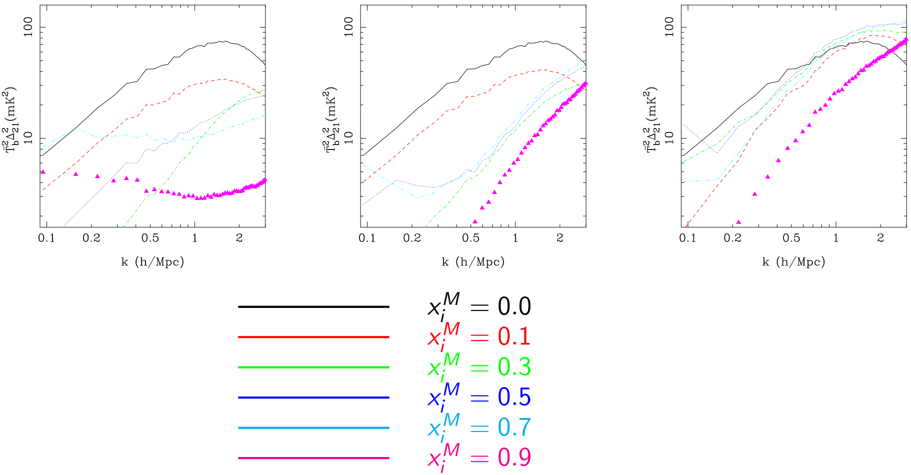
—— Homogeneous recombination

– – – – Inhomogeneous recombination

-·-·-·- High mass

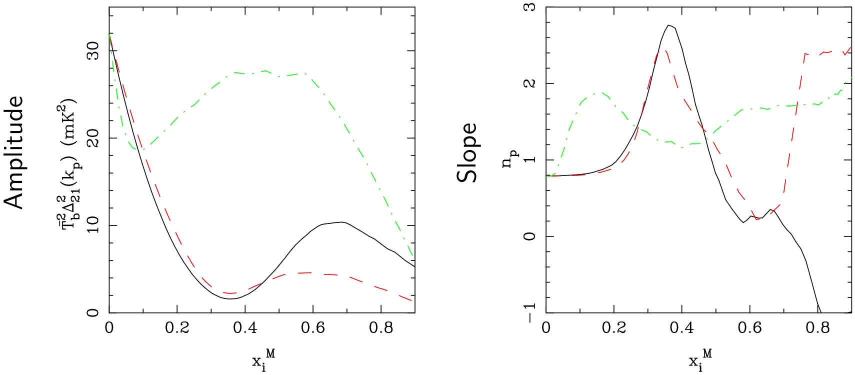
21 cm power spectrum **Choudhury**, Haehnelt & Regan (2008)

Homogeneous recombination | Inhomogeneous recombination | High mass



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

angular scale $\sim 10'$



Mass-averaged ionized fraction

Homogeneous recombination

Inhomogeneous recombination

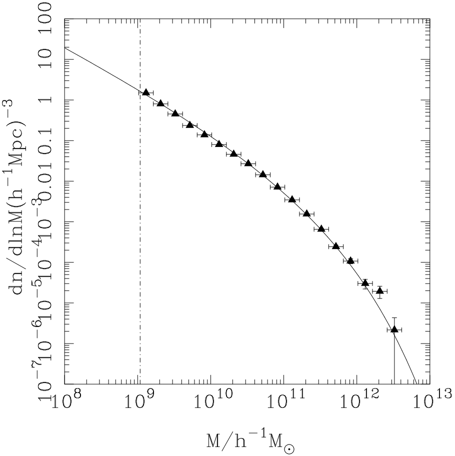
High mass

Conclusions

- Reionization "photon-starved": only 2-3 photons per hydrogen at $z = 6$. Strong constraints on the parameter-space.
- Low emissivity $\Longrightarrow$ 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

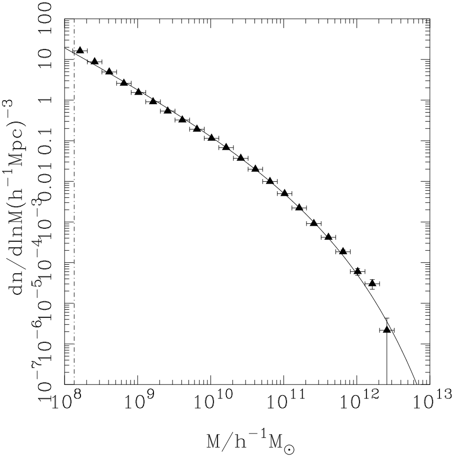
Supplementary Material

Halo mass function $z = 6$ **Choudhury**, Haehnelt & Regan (2008)



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

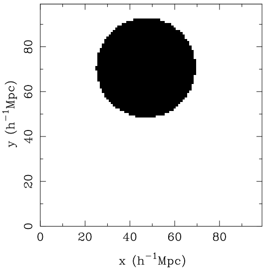
Halo mass function $z = 6$ **Choudhury**, Haehnelt & Regan (2008)

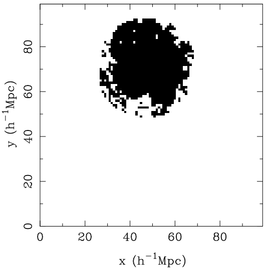


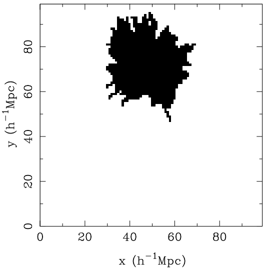
2000^3 particles, $100h^{-1}$ Mpc box

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 (MHR00) self-shielding picture (also with more recent studies like Furlanetto & Oh 2007)
- × shadowing
- × inaccurate ionization fronts
- × thermal/chemical history not possible