Observational Constraints on Reionization History

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Cosmological Reionization
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Plan of the talk

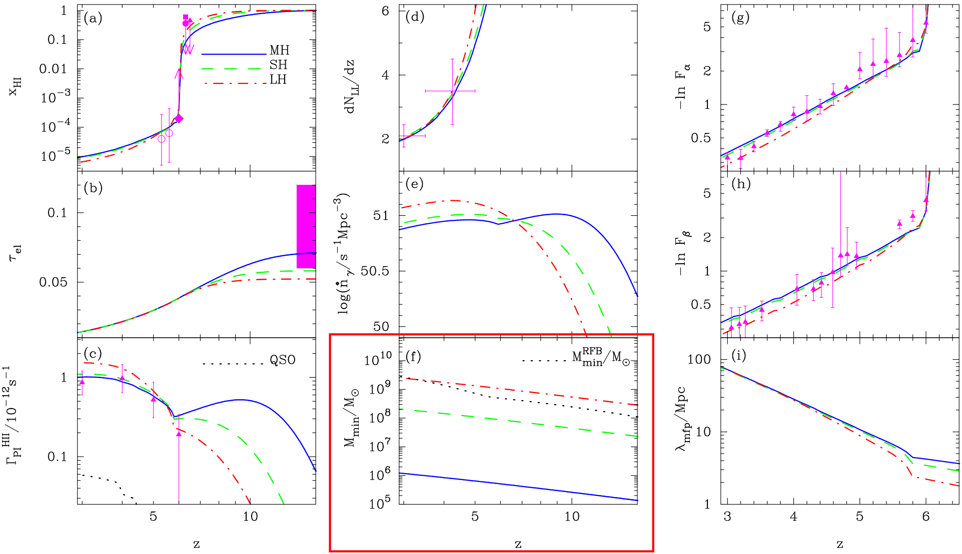
- Evidence for extended reionization from semi-analytical models
- Modelling ionization (21 cm) maps

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.
- Take into account the inhomogeneities in the IGM and also all the three stages of reionization

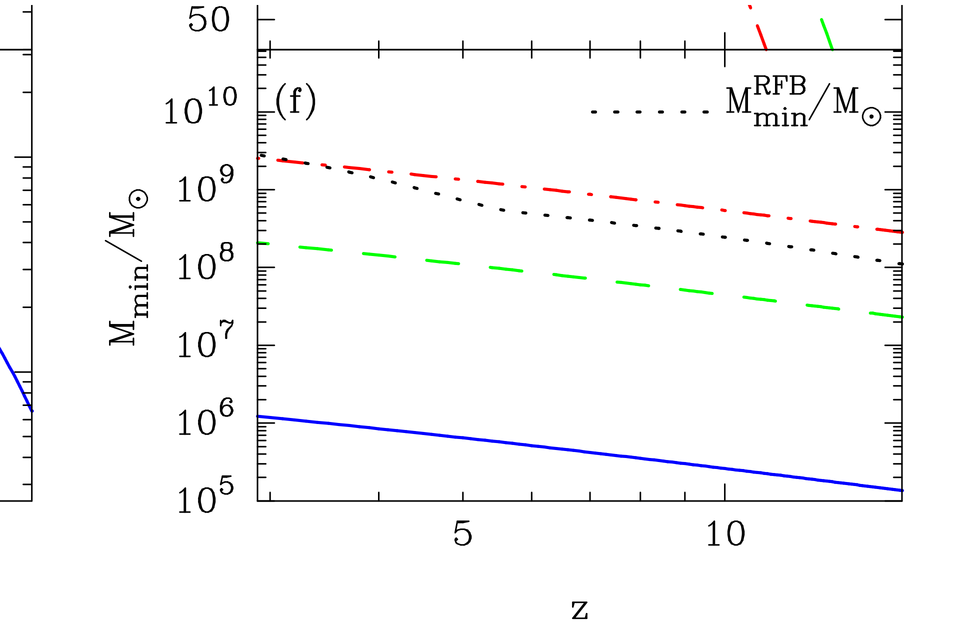
  Miralda-Escude, Haehnelt & Rees (1999)
- Sources of ionizing radiation:
  1. PopII stars: $\dot{n}_{\rm phot} = N_{\rm ion} \frac{{\rm d}f_{\rm coll}}{{\rm d}t}$
  2. Quasars: unimportant at $z \gtrsim 6$
- Radiative feedback suppressing star formation in low-mass haloes using a Jeans mass prescription.
- 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)

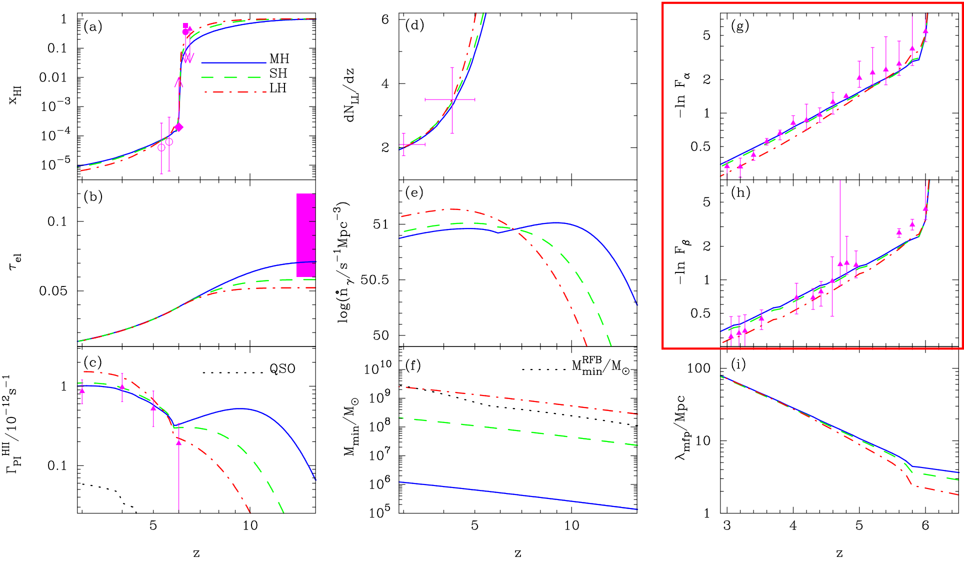


3 different choices for $M_{\rm min}$

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

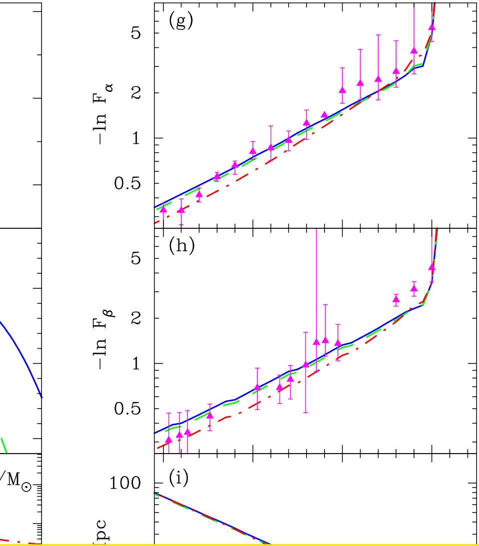


Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)

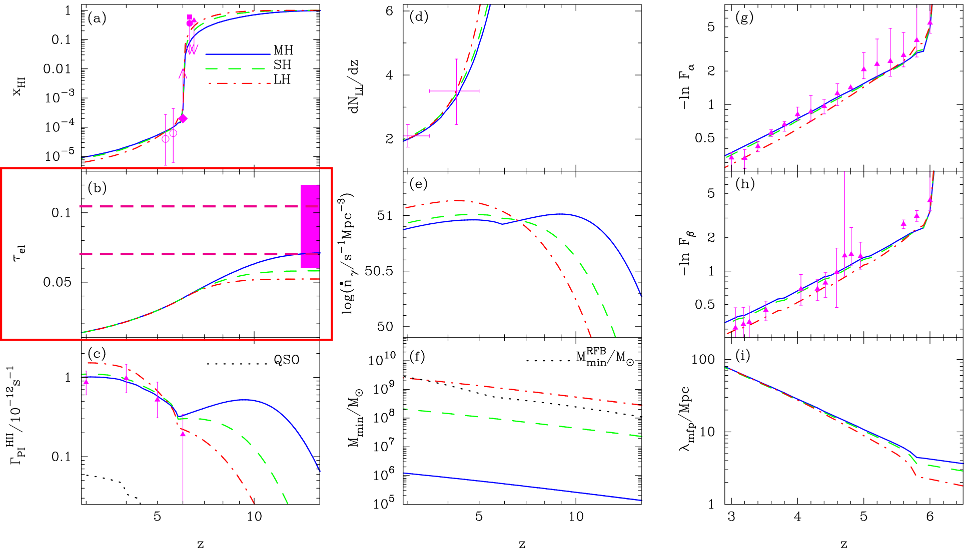


Estimate maximum allowed $N_{\rm ion}$ from GP τ at $z \approx 6$

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

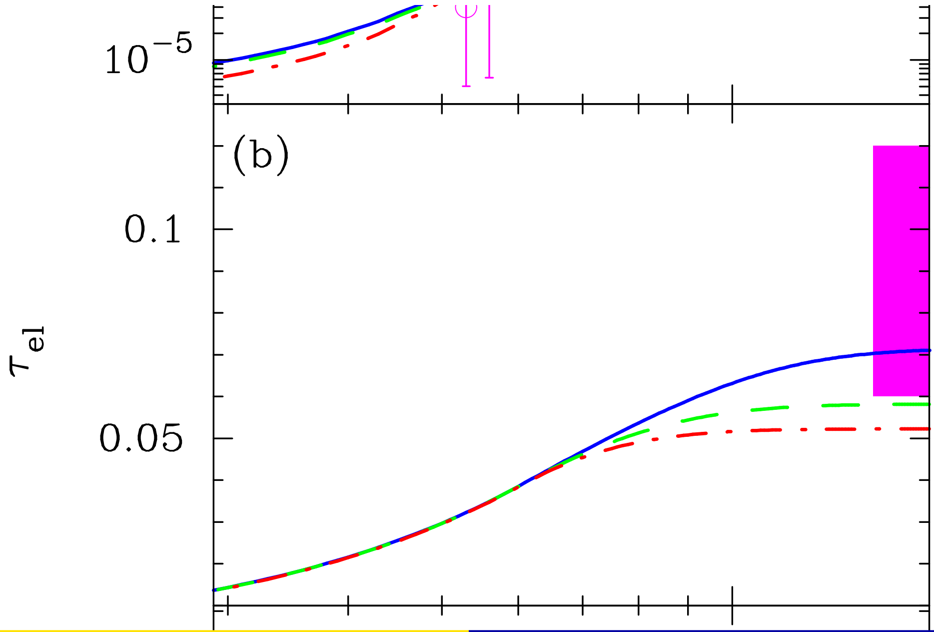


Semi-analytical models: Results **Choudhury**, Ferrara & Gallerani (2008)

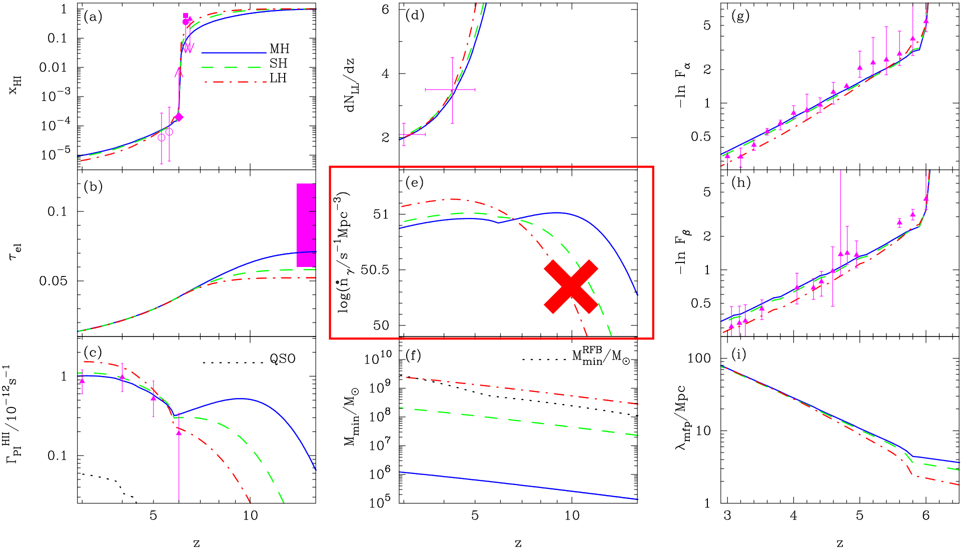


Compare with τ_{el}

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



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

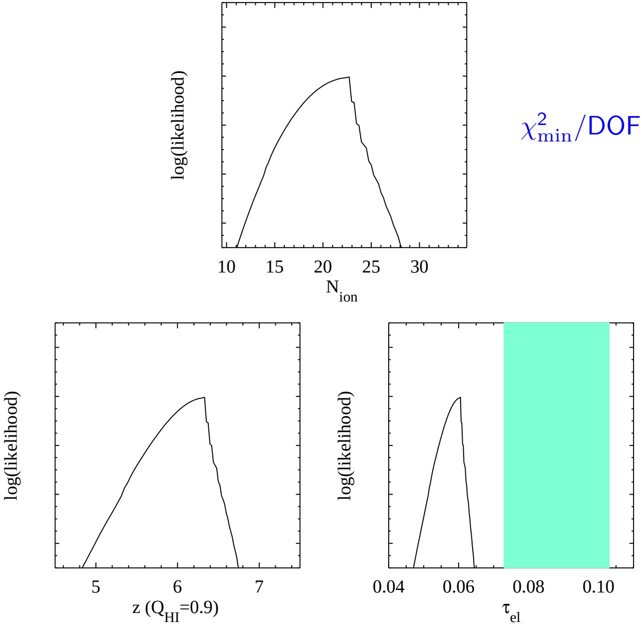


Low emissivity at $z = 6 \Longrightarrow$ extended reionization

Statistical analysis with Sourav Mitra and Andrea Ferrara, work in progress

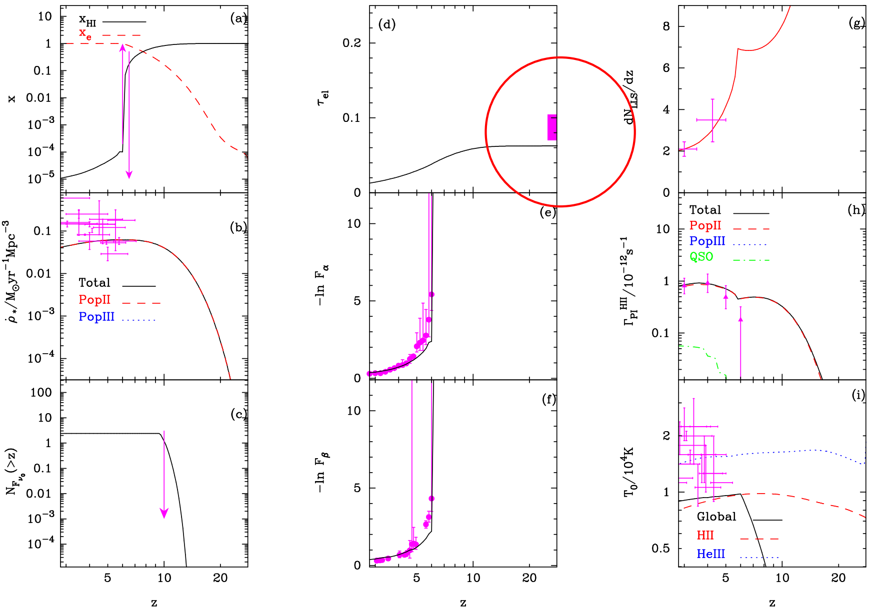
- Good constraints using only Lyα forest and WMAP data.
- Do a likelihood analysis using Lyα forest and WMAP7. Then compare with other observations and see if the model is consistent.
- Understand the physics of reionization and make further predictions.

Statistical analysis: Atomic cooling

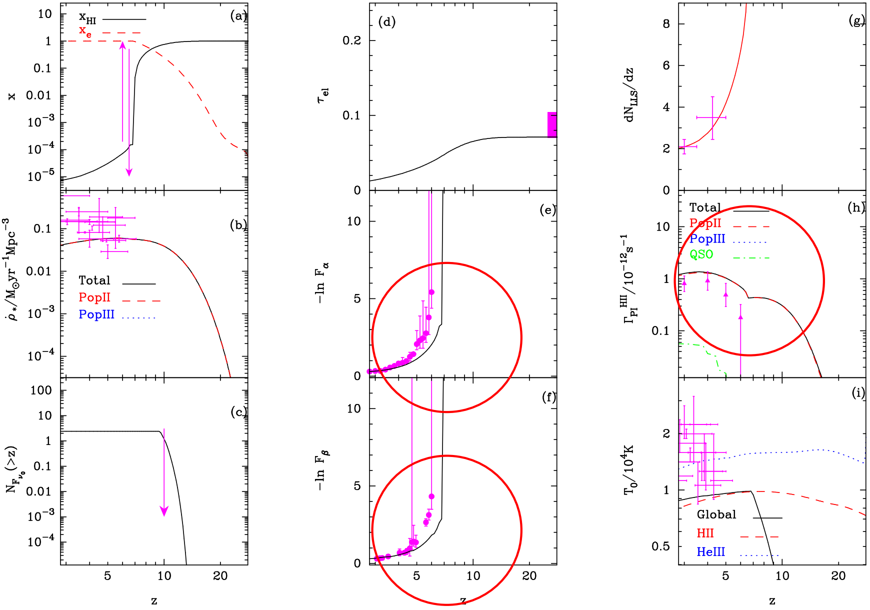


$\chi^2_{\rm min}/\text{DOF} \approx 1.5$

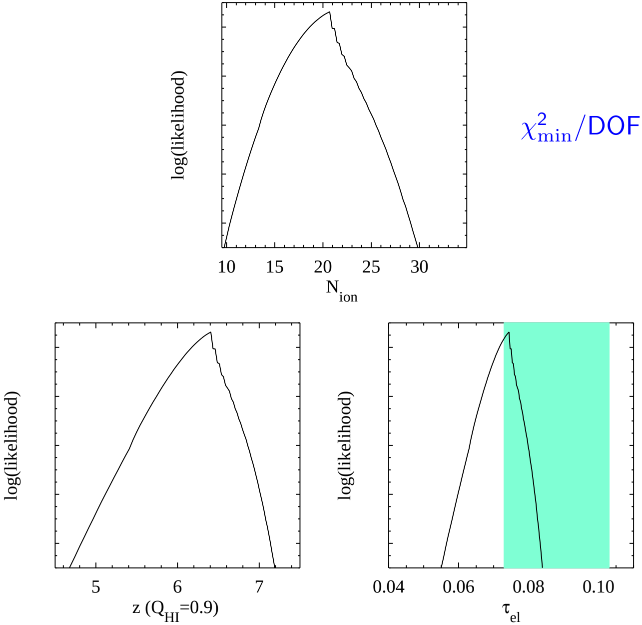
Atomic cooling: best-fit model



Molecular cooling: fit WMAP7 data

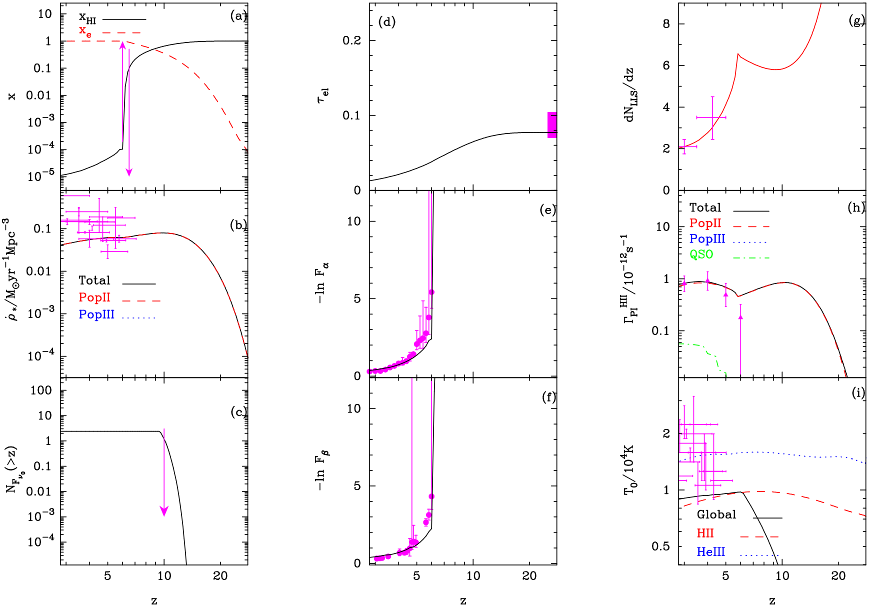


Statistical analysis: Molecular cooling



$\chi^2_{\rm min}$/DOF ≈ 1

Molecular cooling: best-fit model



Possible scenarios

- Simple "single-component models" (considering only atomic cooling and constant $N_{\rm ion}$) are "in tension" with the data (ruled out by 1–σ confidence). Galaxies must emit comparatively more efficiently at higher redshifts $\Longrightarrow$ a "bump" in the emissivity.
- Caveats:
  - Need lower values of mean free path. Simulations with Lyman-limit systems?
  - Feedback? Need more "severe" feedback to match the data. Clustering of sources?
  - Mass-dependent $N_{\rm ion}$: need high values for low mass haloes. Minihaloes?
  - Redshift-dependent $N_{\rm ion}$: need high values at early times. Metal-free stars? Top-heavy IMF?
- Other unknown sources/physics?

Consider a model with two types of stellar sources: PopII and PopIII (no molecular cooling).

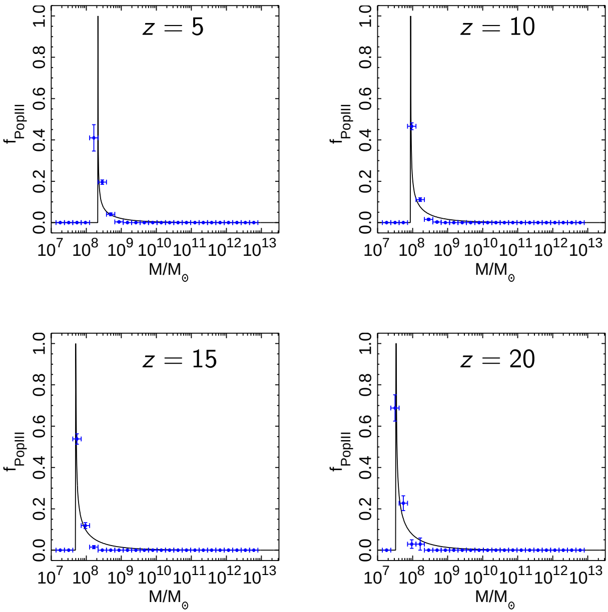
Transition from PopIII to PopII phase

- Use a merger-tree based "genetic" approach. If a given star-forming halo has a progenitor which formed PopIII stars, then the halo under consideration is "enriched" and cannot form PopIII stars.
- Possible to construct a analytic formula: the probability that a halo of mass M at z never had a progenitor in the mass-range $[M_{\rm min}(z), M + M_{\rm res}]$:

$$f_{\rm PopIII}(M, z) = \frac{2}{\pi} \tan^{-1} \left[\frac{\sigma(M + M_{\rm res}) - \sigma(M)}{\sigma(M_{\rm min}(z)) - \sigma(M + M_{\rm res})} \right]$$

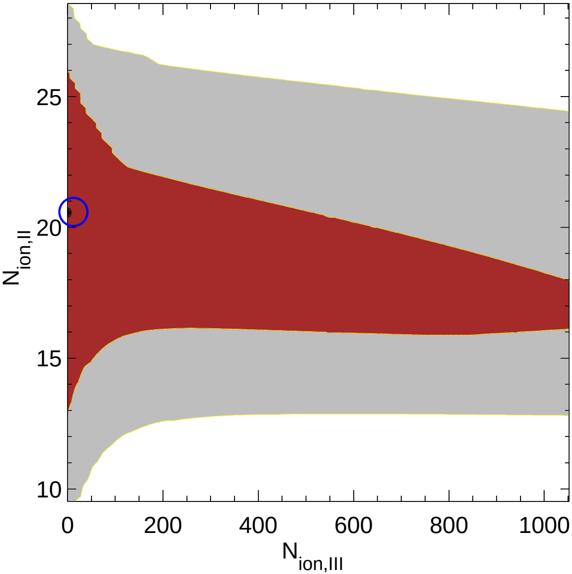
(based on conditional probability of Press-Schechter mass function).

PopIII → PopII transition: comparing with simulations

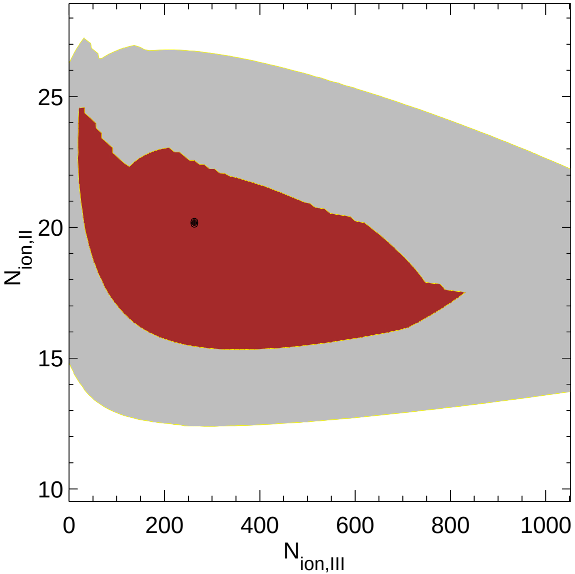


data points from
Schneider et al. (2006)
using PINOCCHIO

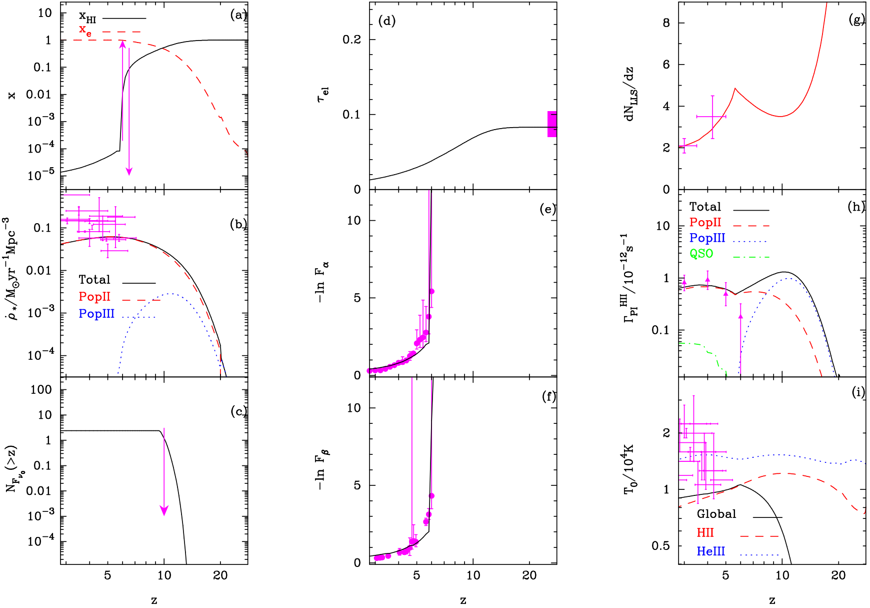
Likelihood analysis: Lyα forest data only



Likelihood analysis: Lyα forest + WMAP7



Likelihood analysis: Best-fit model



Likelihood analysis: derived parameters

Parameter	Best-fit value	95% (2-σ) limit
$z_{\rm re} = z(Q_{\rm HI} = 0.99)$	6.47	5.84 – 6.75
$z(Q_{\rm HI} = 0.90)$	7.06	6.20 – 8.14
$z(Q_{\rm HI} = 0.50)$	9.95	7.70 – 12.05
$\Delta z = z(Q_{\rm HI} = 0.01) - z(Q_{\rm HI} = 0.99)$	10.60	8.30 – 11.98
$x_{\rm HI}(z = 6)$	10^{-4}	8×10^{-5} – 0.05

Essential features of the 2-σ models

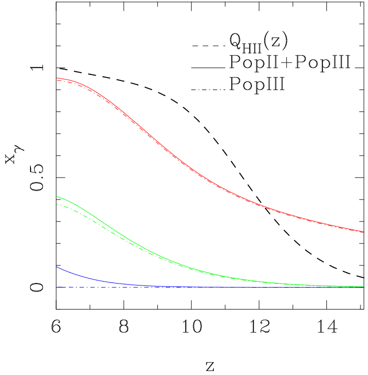
- Reionization extended with $\Delta z > 8$; 90% complete by $z \approx 7$; should not be much earlier than $z \approx 8$.
- Extended reionization arising from combined action of radiative and chemical feedback. Rapid suppression of PopIII star formation. "Self-regulated" reionization.
- IGM is highly ionized ($> 95\%$) at $z \approx 6$.
- Effect of radiative feedback can be independently tested with (possibly) PLANCK (and 21cm observations).

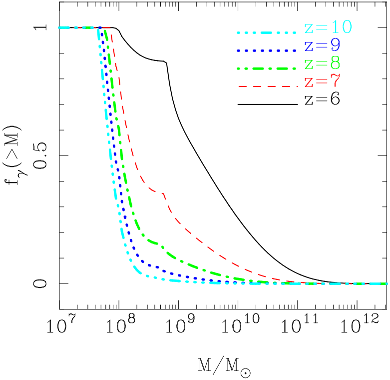
  Schneider, Salvaterra, **Choudhury** et al. (2008), Burigana et al. (2008)

Sources responsible for reionization

$$x_\gamma(z) \equiv \frac{n_\gamma(z)}{n_H} \frac{t_{\rm rec}(z)}{t_H(z)}$$

$$f_\gamma(> M, z) \equiv \frac{\dot{n}_\gamma(> M, z)}{\dot{n}_\gamma(z)}$$

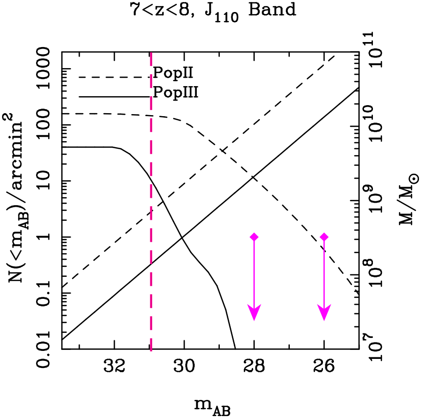


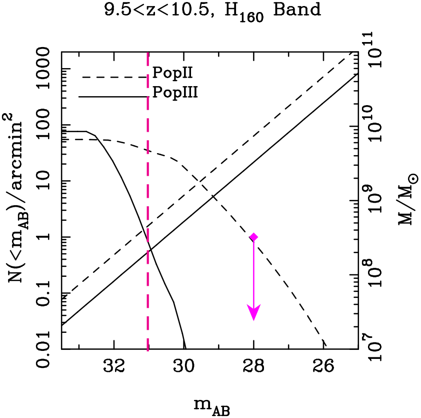


$M \lesssim 10^8 M_\odot$
$10^8 M_\odot < M < 10^9 M_\odot$
$M > 10^9 M_\odot$

bulk of the photons from $\sim 10^8 M_\odot$ haloes

Source counts at $z \approx 7 - 10$ **Choudhury** & Ferrara (2007)



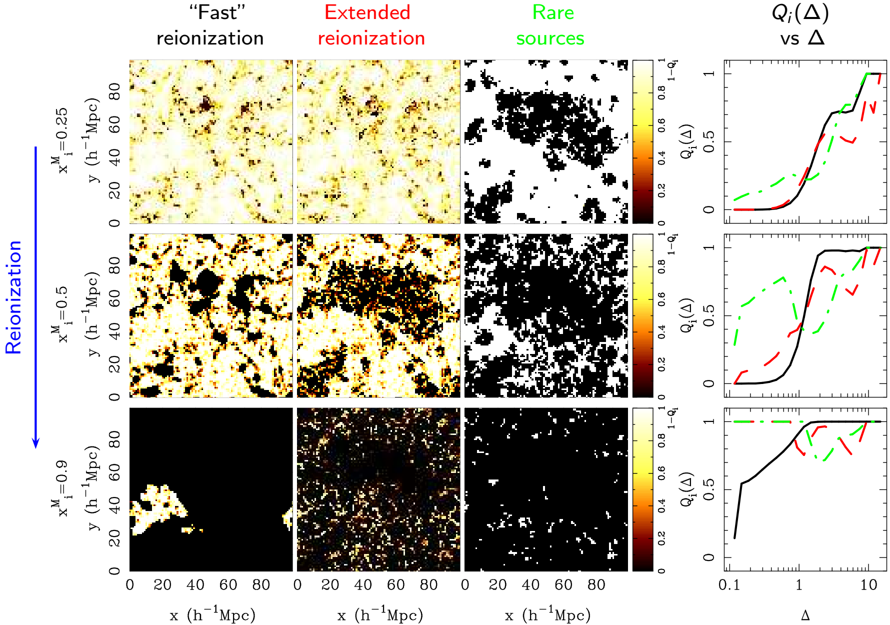


Ionization maps: Motivation

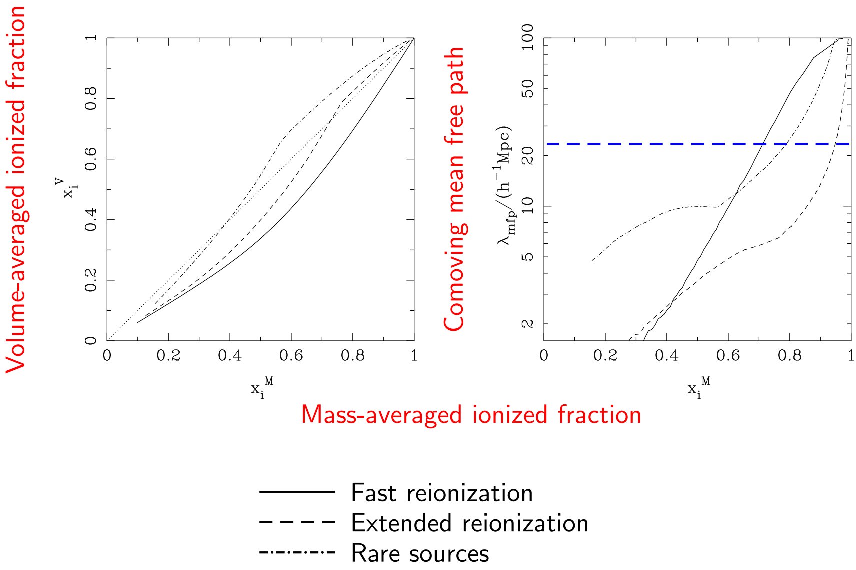
- What do these models imply for 21cm observations?
- Important to consider models which are consistent with the extended and "low-emissivity" scenario.
- Extended reionization $\Longrightarrow$ recombinations (distribution of photon sinks).
- Develop a reionization picture consistent with post-reionization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

  Mesinger & Furlanetto(2007), Geil & Wyithe (2008)

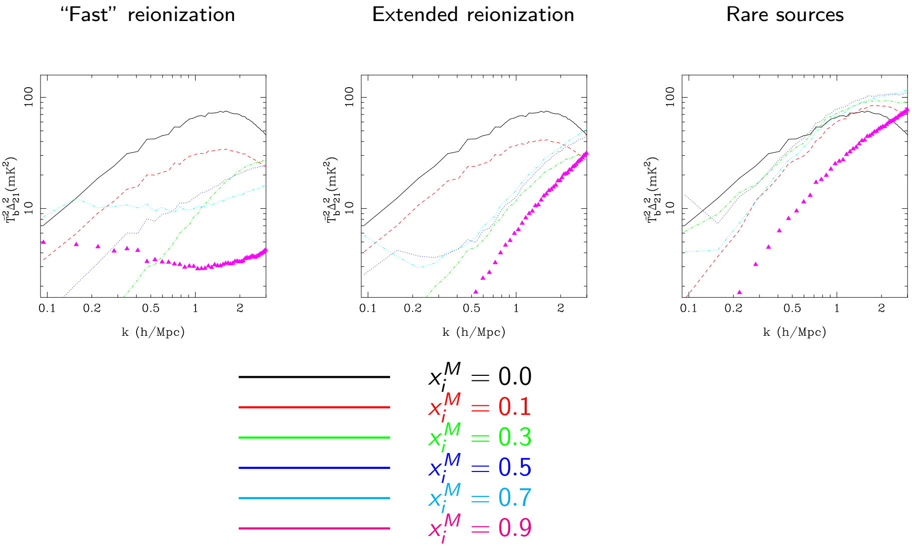
Global ionization maps **Choudhury**, Haehnelt & Regan (2008)



Mean free path Choudhury, Haehnelt & Regan (2008)

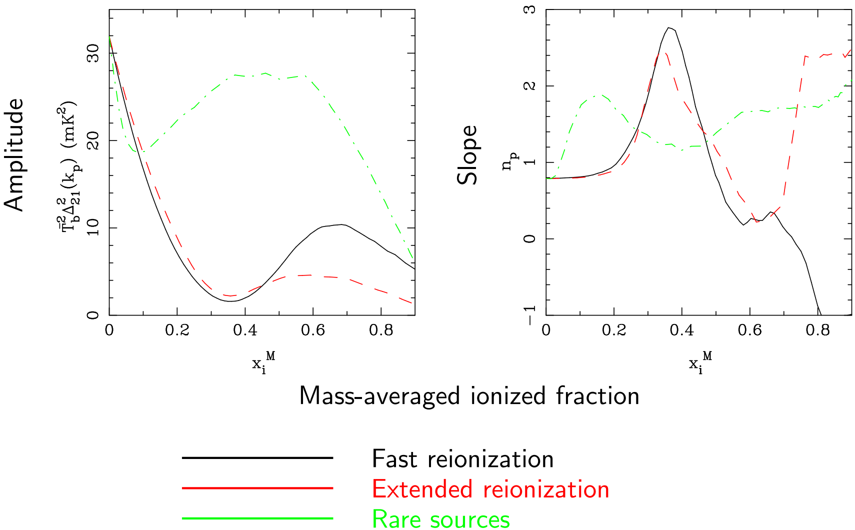


21 cm power spectrum **Choudhury**, Haehnelt & Regan (2008)



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

angular scale $\sim 10'$



Conclusions

- Strong constraints on the parameter-space. Reionization extended; 90% complete by $z = 7$. IGM highly ionized at $z \approx 6$.
- Effect of feedback important.
- Reionization driven by small-mass sources, currently too faint to be observed. Galaxies observed at $z \approx 7$ contribute only $\sim 1\%$ to the photon budget.
- Extended reionization $\Longrightarrow$ effect of local recombinations (sinks) important
- Reionization topology highly dependent on nature of recombinations and on the distribution of ionizing sources