Self-consistent Reionization Models: Observational Constraints

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Plan of the talk

- Background
- Formalism
  - Simple reionization models
  - Reionization of the inhomogeneous IGM
  - Self-consistent models
- Results
- Future work

Background

- Apparent discrepancy between Gunn-Peterson optical depths at $z \gtrsim 6$ and the first year WMAP results? White et al. (2003); Kogut et al. (2003)
- Explanation of the excess in the cosmic Near Infra Red Background observations requires Population III stars at $z > 9$ – what effect do they (and other sources) have on the reionization history? Salvaterra & Ferrara (2003)
- Require reionization models to deal with wide variety of spatial scales:
  - IGM inhomogeneities – sub-kpc
  - formation of (first) haloes with luminous sources – kpc
  - transfer of the ionizing radiation – tens of kpc
  - background radiation – Mpc
  - effect of QSOs – tens of Mpc
- Goal is to develop semi-analytical models with most of the essential physics incorporated

Simple models of reionization

Evolution of the volume filling factor of ionized regions:

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

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

Recombination term
$\mathcal{C}_{\mathrm{HII}} \equiv \langle n_{\mathrm{HII}}^2 \rangle / \langle n_{\mathrm{HII}} \rangle^2$: Clumping factor
$\alpha_R(T)$: Recombination rate

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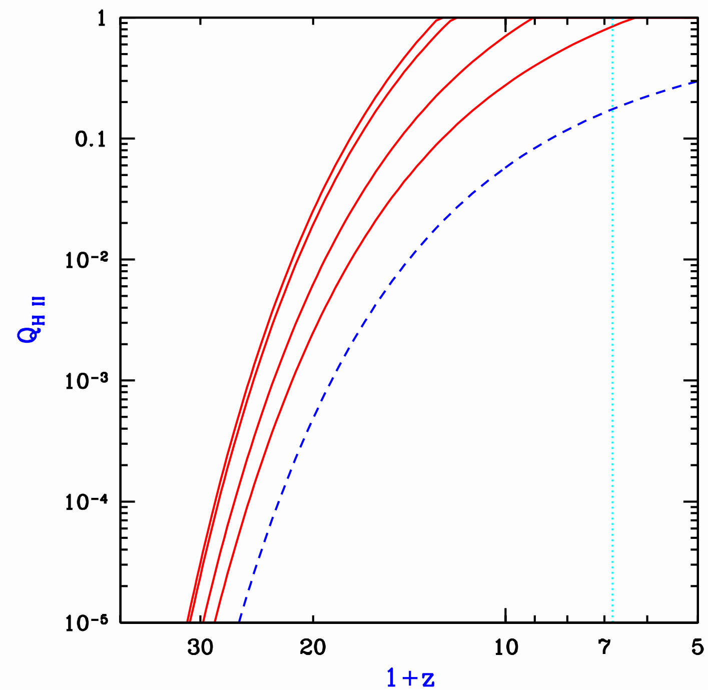
$$\dot{n}_{\mathrm{ph}} = n_B N_{\mathrm{ion}}\frac{\mathrm{d}F_{\mathrm{col}}}{\mathrm{d}t}$$



Barkana & Loeb (2000)

Simple models of reionization

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Evolution of the temperature

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

Adiabatic cooling

Net heating rate per baryon

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

Simple models of reionization

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Evolution of the ionization fraction

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

Simple models of reionization

Evolution of the volume filling factor of ionized regions:

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

Evolution of the temperature

$$\frac{dT}{dt} \approx -2H(z)T + \frac{2}{3k_{\rm boltz}n_B}\frac{dE}{dt}$$

Evolution of the ionization fraction

$$\frac{dn_{\rm HII}}{dt} = \text{Photoionization} - \text{Recombination}$$

Simple models of reionization

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Evolution of the ionization fraction

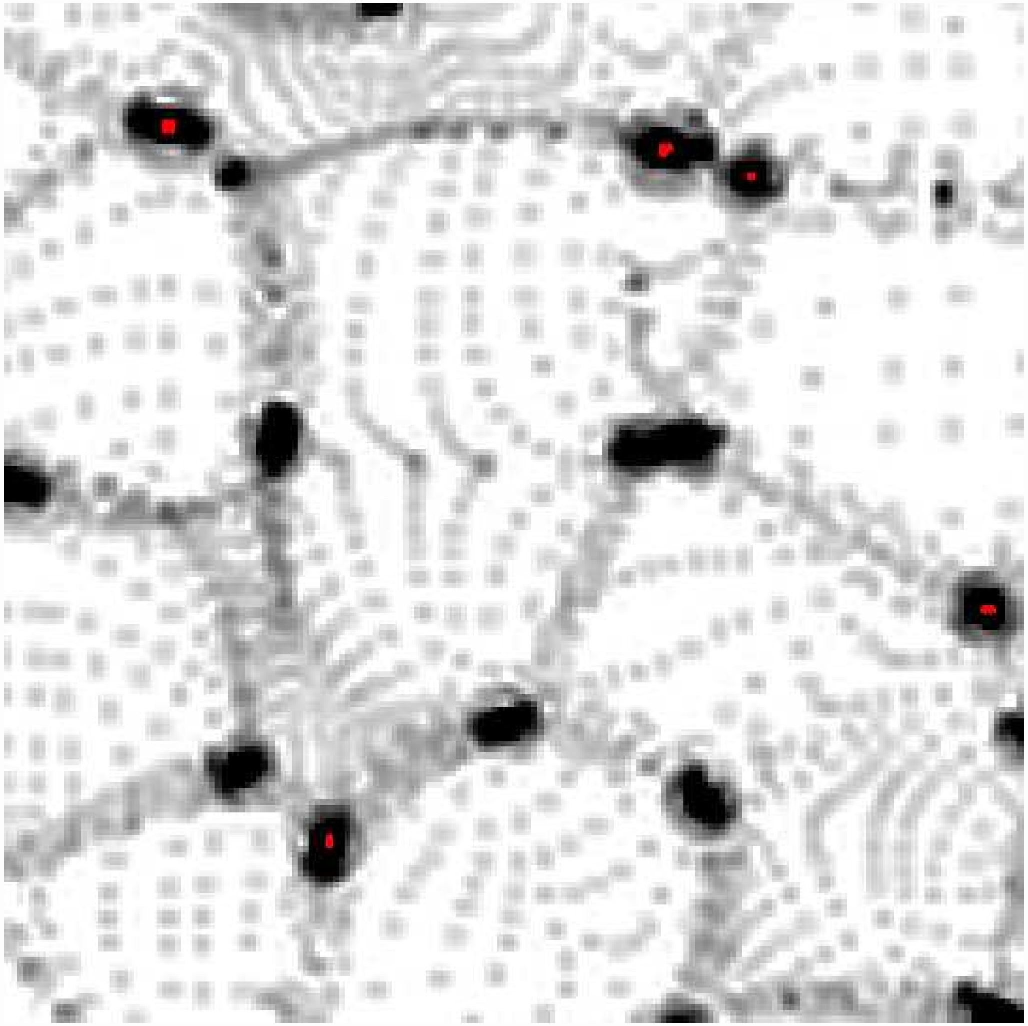
$$\frac{\mathrm{d}n_{\mathrm{HII}}}{\mathrm{d}t} = \text{Photoionization} - \text{Recombination}$$

Ionizing flux is determined by the mean free path

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

Madau, Haardt & Rees (1999)

Reionization: Schematic Diagram



Just a sketch

- Random density distribution

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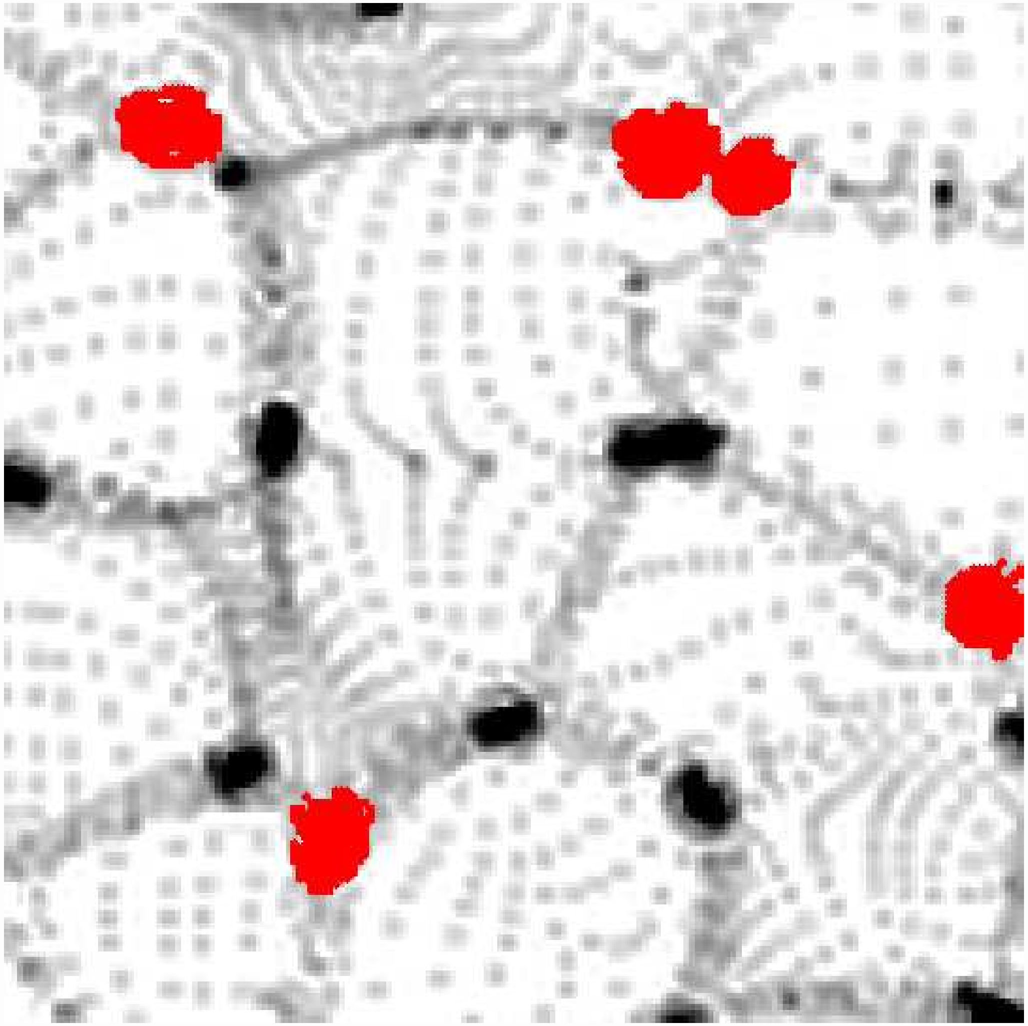

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- Random density distribution
- Sources of ionizing photons

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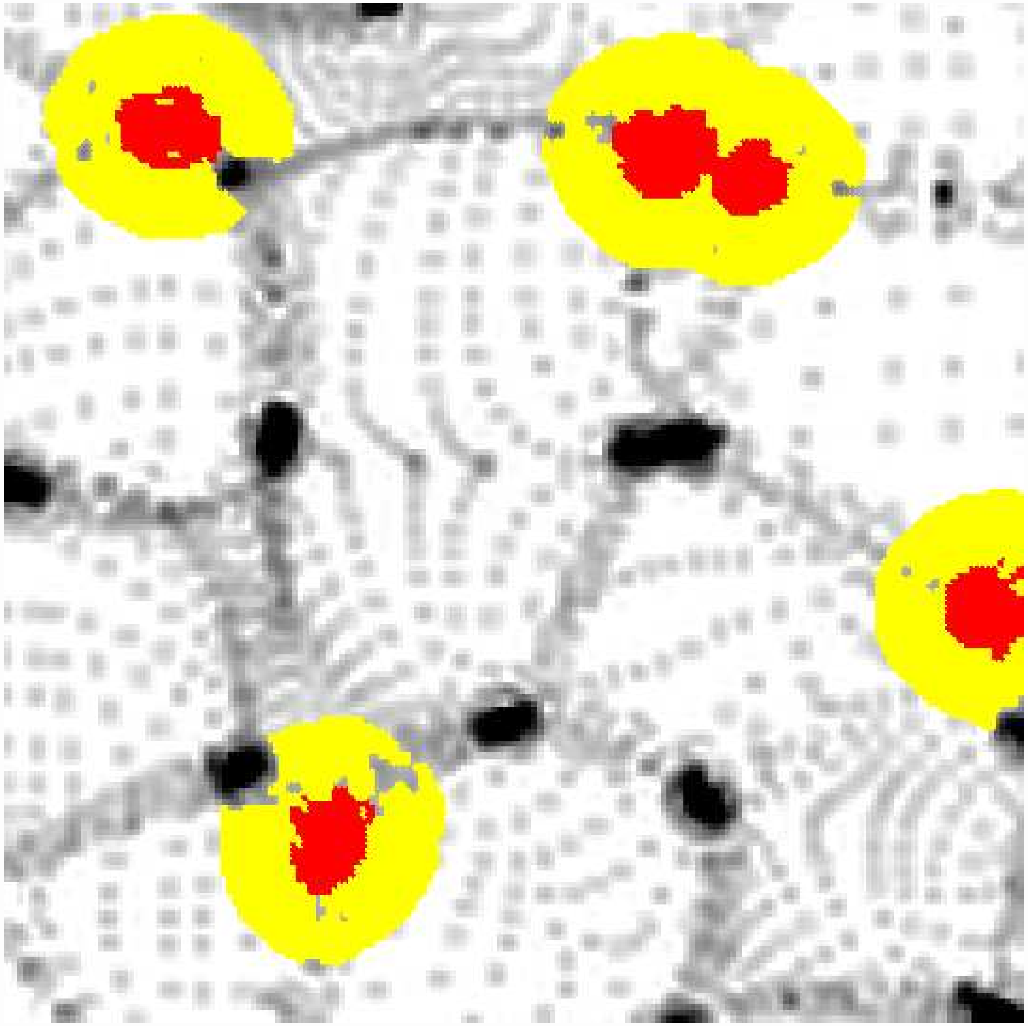

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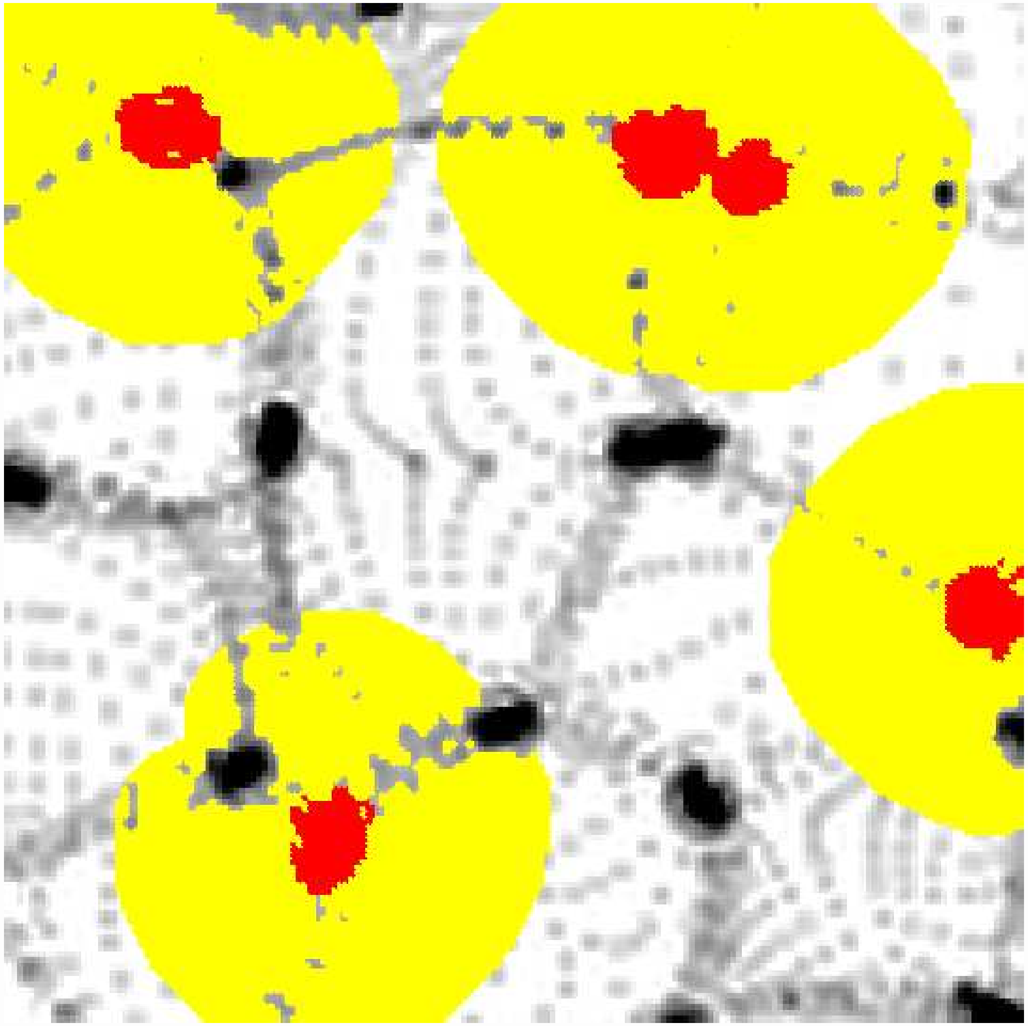

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- Random density distribution
- Sources of ionizing photons
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- Pre-overlap era

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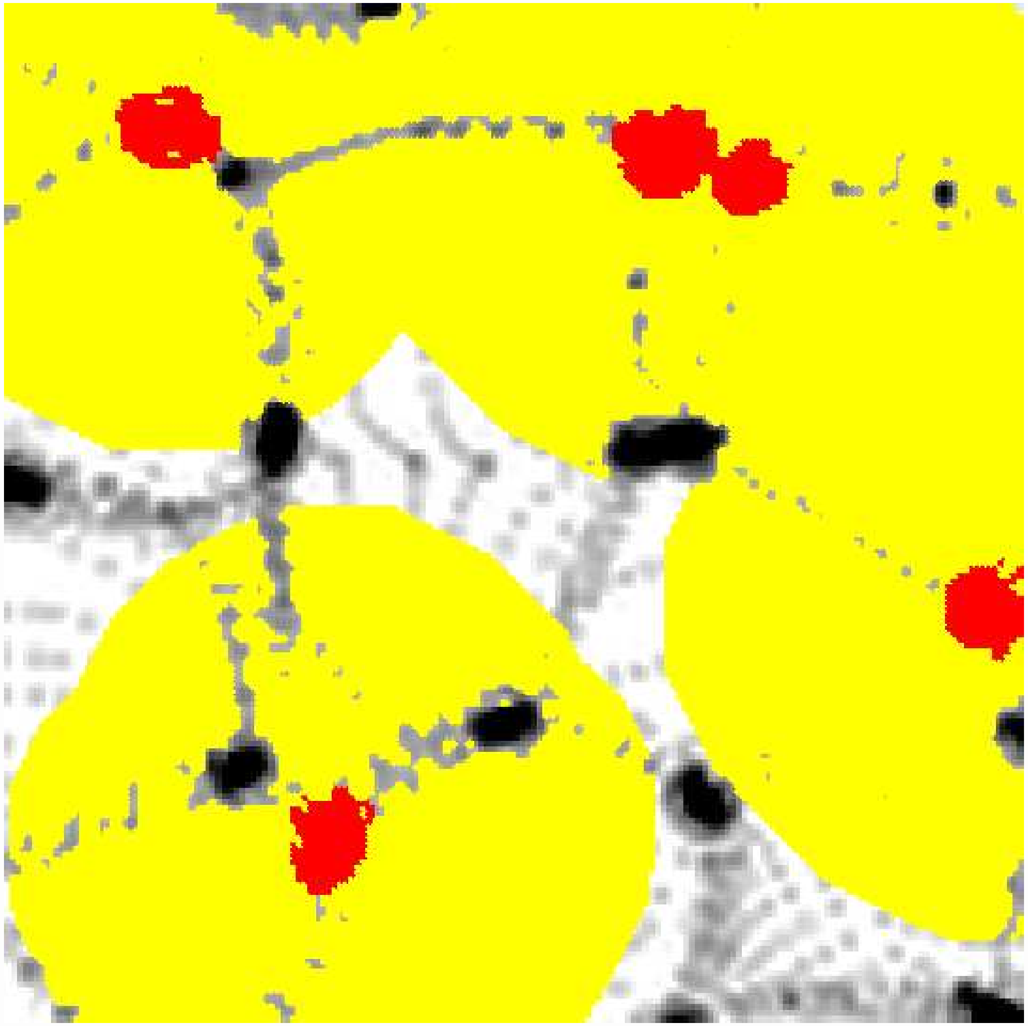

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- Approaching reionization

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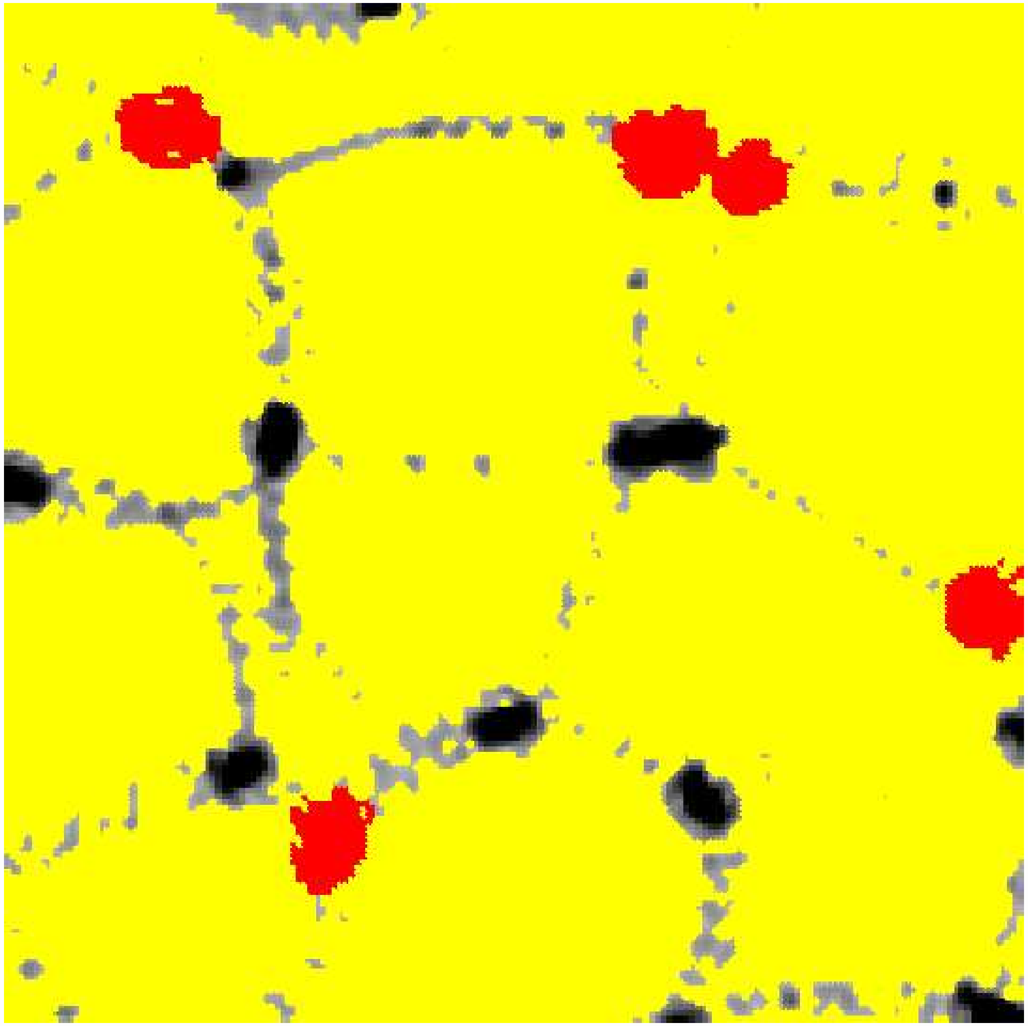

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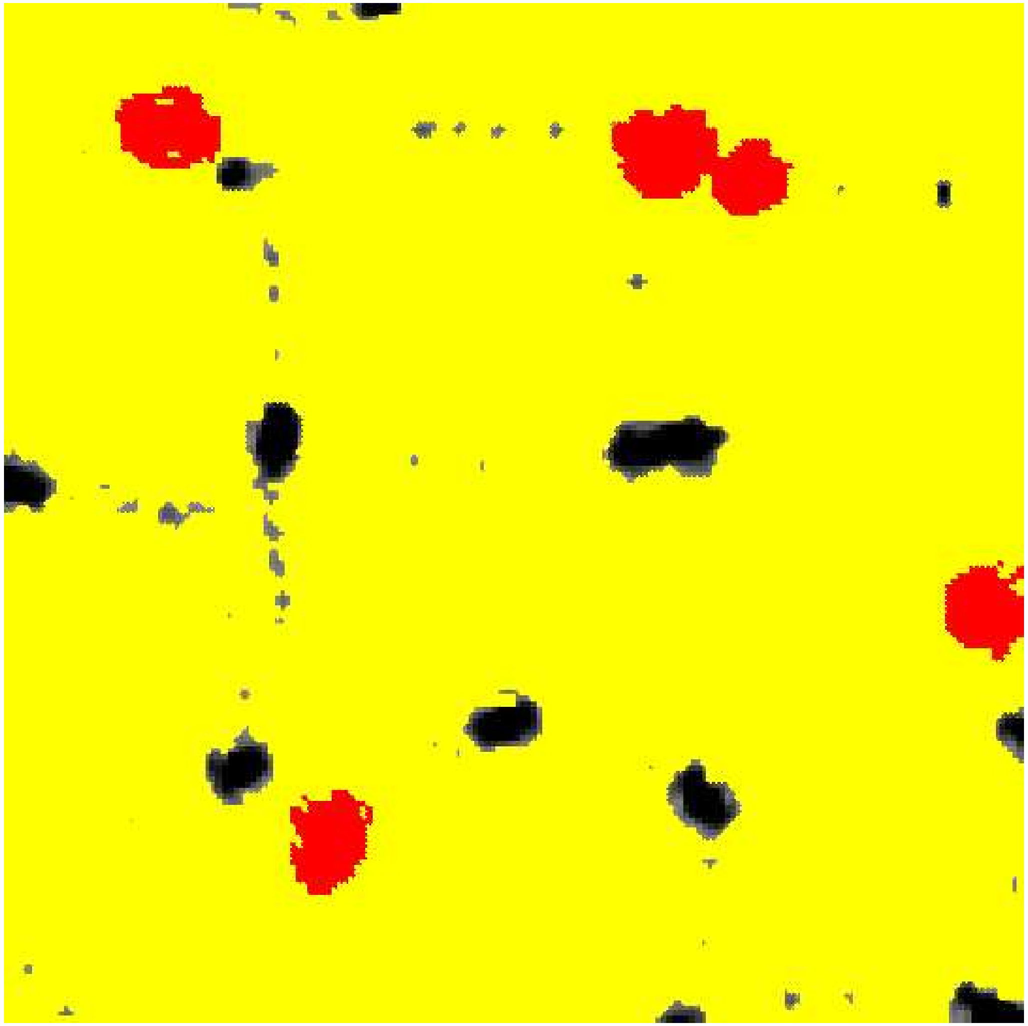

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- Random density distribution
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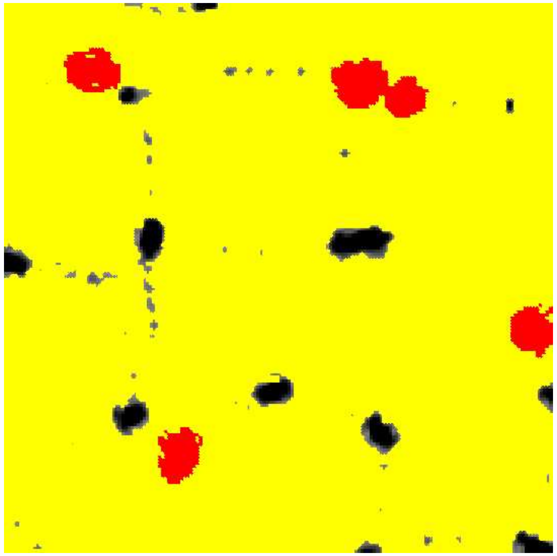
- Pre-overlap era
- Approaching reionization
- Reionization
- Post-overlap era

Reionization of the inhomogeneous IGM

- Post-overlap era

$$\frac{\mathrm{d}[F_M(\Delta_{\rm HII})]}{\mathrm{d}t} = \frac{\dot{n}_{\rm ph}(z)}{n_H} - R(\Delta_{\rm HII})\frac{n_e}{a^3}\alpha_R(T)$$

Clumping Factor: $R(\Delta_{\rm HII}) = \int_0^{\Delta_{\rm HII}} \mathrm{d}\Delta\ \Delta^2\ P(\Delta)$



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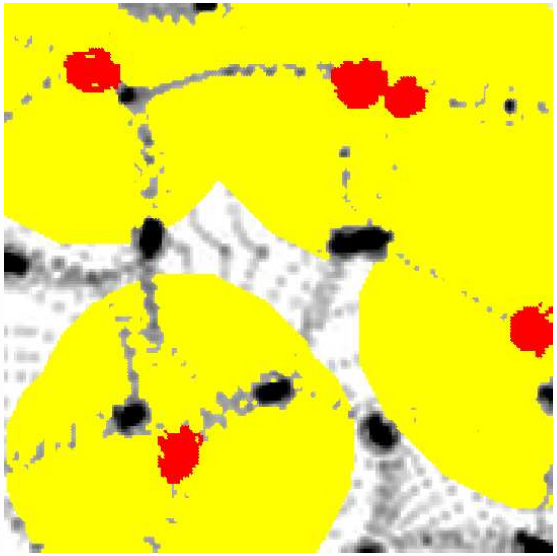

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Mean free path determined by the fraction of ionized volume

Miralda-Escude, Haehnelt & Rees (2000)

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- Inhomogeneous IGM density distribution: lognormal model

  Found to be a reasonable approximation for the low-density IGM at $2 < z < 6$

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  1. PopIII stars: early redshifts, high mass, low metallicity
     Required to match the excess in NIRB

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  2. PopII stars: normal stars, transition from PopIII at $z \gtrsim 9$

     Press-Schechter and Sasaki formalism to calculate the formation rate and survival time of dark matter haloes.

     Model for SFR: peaking around the dynamical time of the halo, decreasing exponentially thereafter.

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  3. Quasars: significant at $z \lesssim 6$

     Model based on the empirical $v_c - M_{\rm BH}$ relation; Wyithe & Loeb (2002); Mahmood et al. (2003)

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- Radiative feedback suppressing star formation in low-mass haloes

  Lower limit of the mass function
  - set by molecular cooling in neutral regions
  - set by photoionization temperature in the ionized regions

Free parameters

- Star forming efficiencies (ϵ_*) and escape fractions ($f_{\rm esc}$) for PopII and PopIII stars
- Transition redshift ($z_{\rm trans}$) for PopIII $\longrightarrow$ PopII

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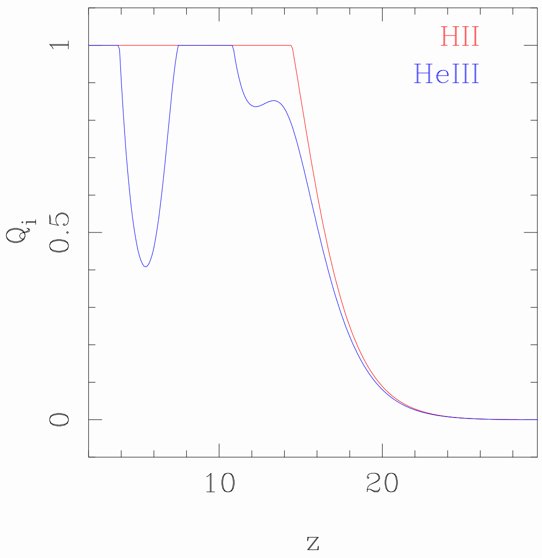
Use a model with "fiducial" values of parameters.

- $\epsilon_{*,\rm III} \sim$ 0.5% (NIRB studies)
- $f_{\rm esc,III} \sim 1$ (Whalen et al. (2004))
- $\epsilon_{*,\rm II} \sim$ 10% (Low-z SFR)
- $f_{\rm esc,II} \sim$ 2% (uncertain)
- $z_{\rm trans} \approx 10$ (NIRB studies)

Check the effects of varying the parameters, and try to constrain by matching with observations.

Results: Reionization History

Volume filling factor



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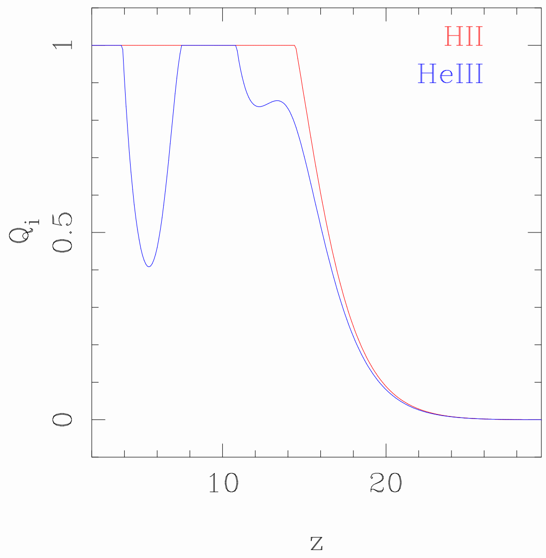
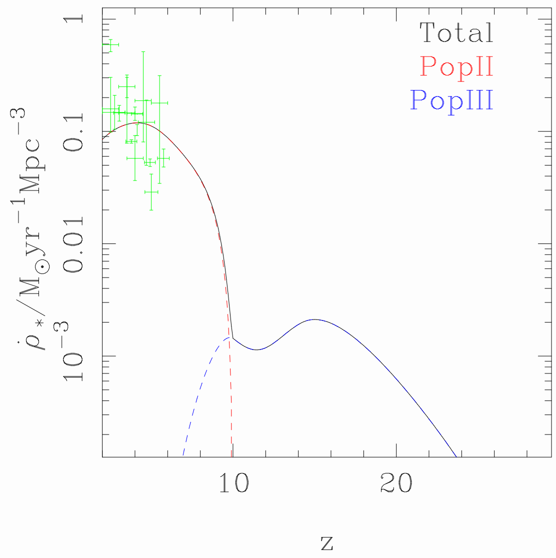


SFR



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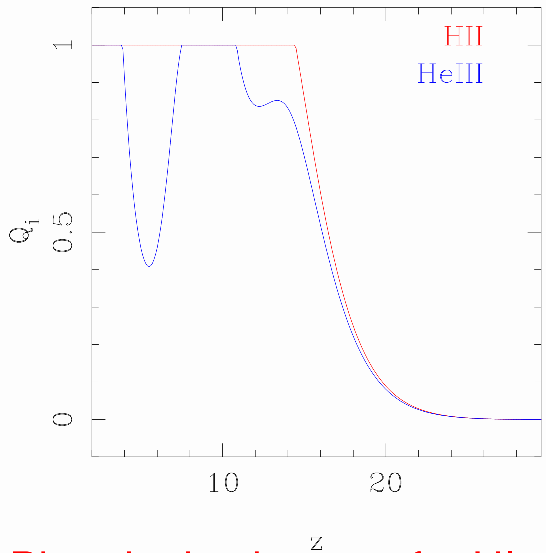
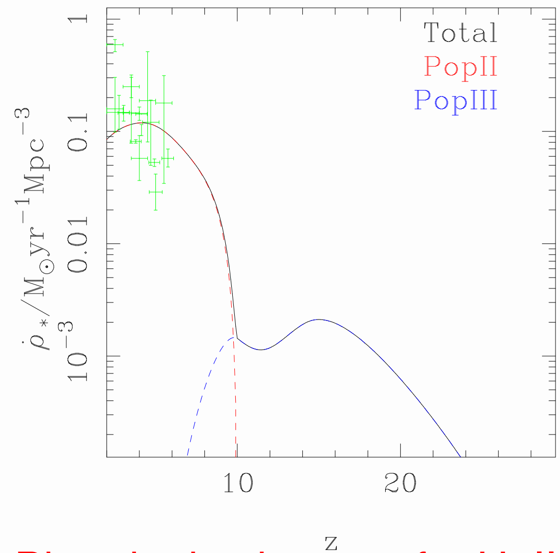
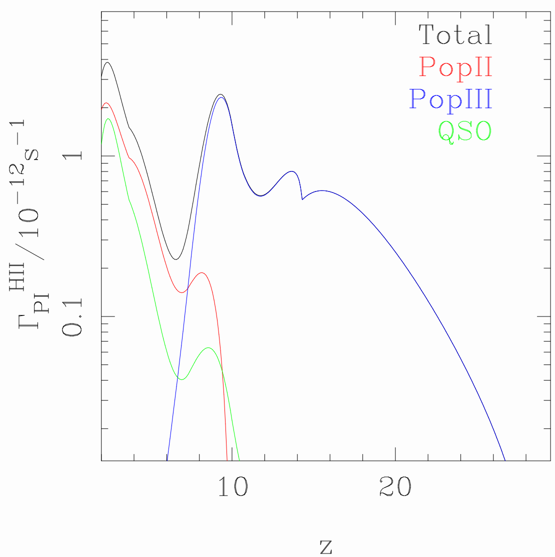


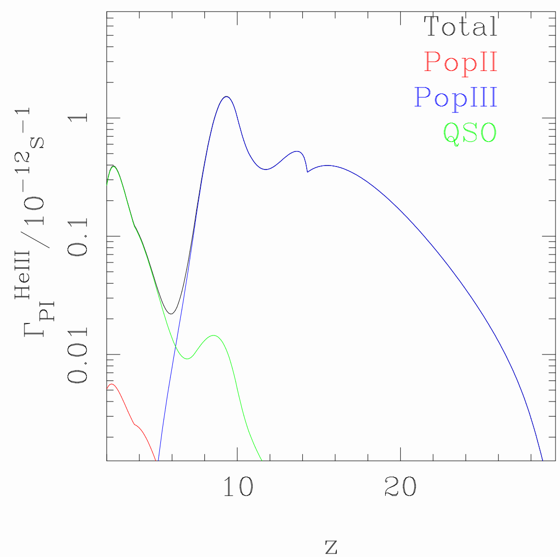
SFR



Photoionization rate for HI



Photoionization rate for HeII



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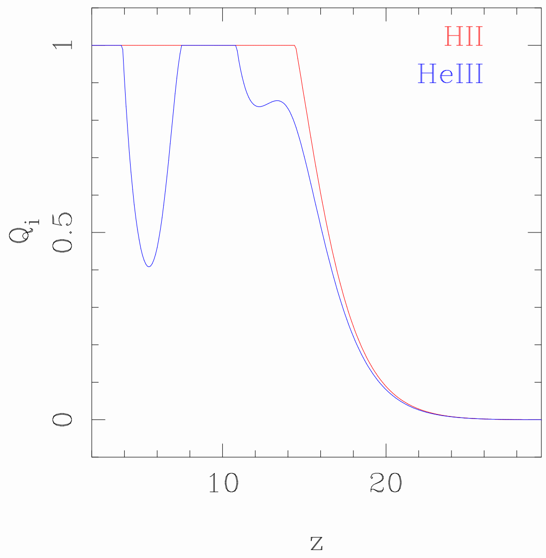
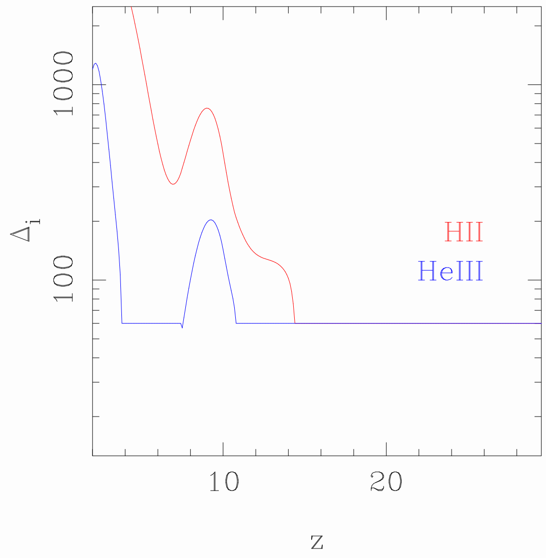


Δ_i



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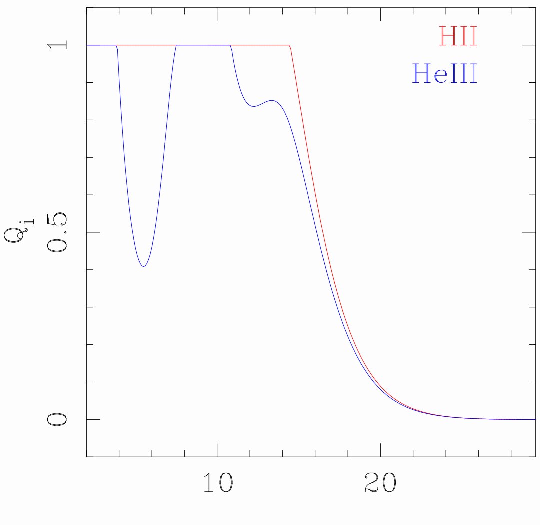

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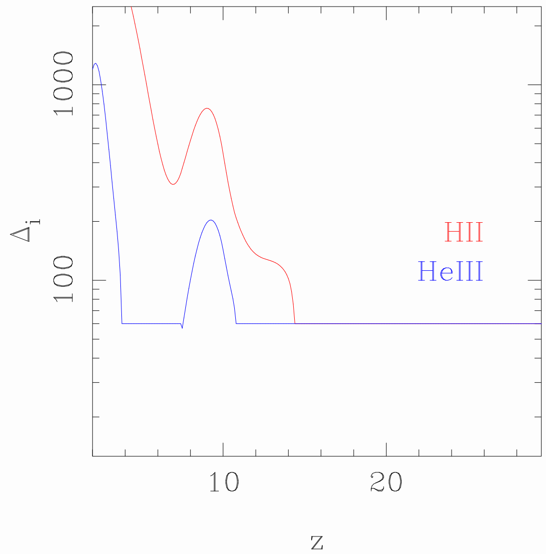
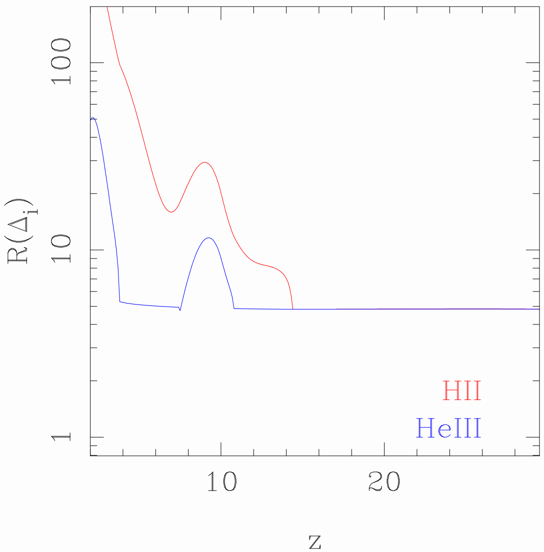


Clumping factor



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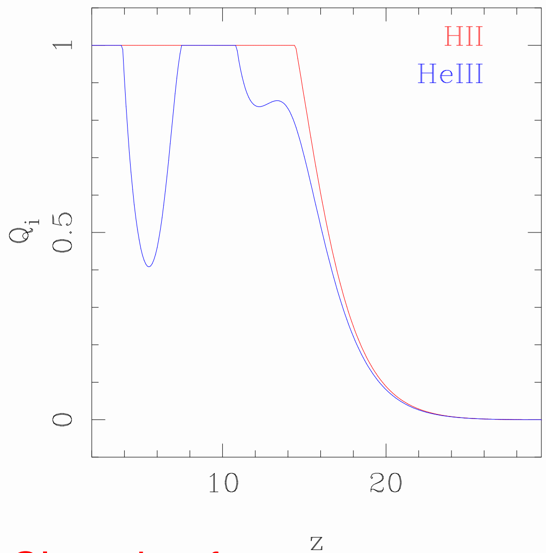

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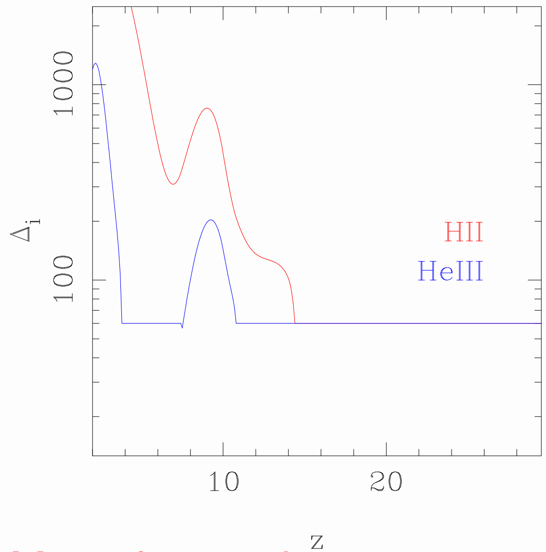

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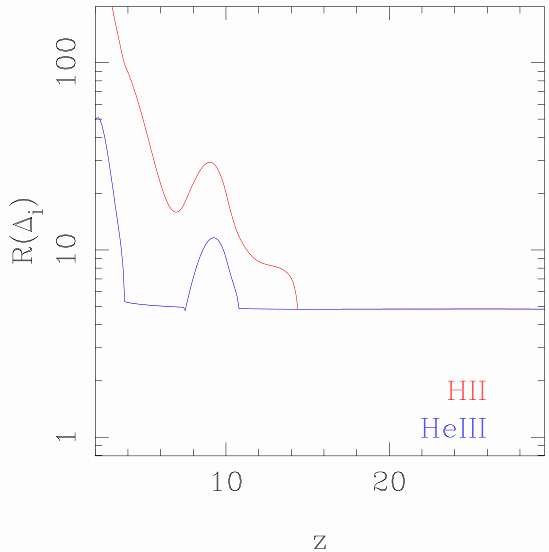
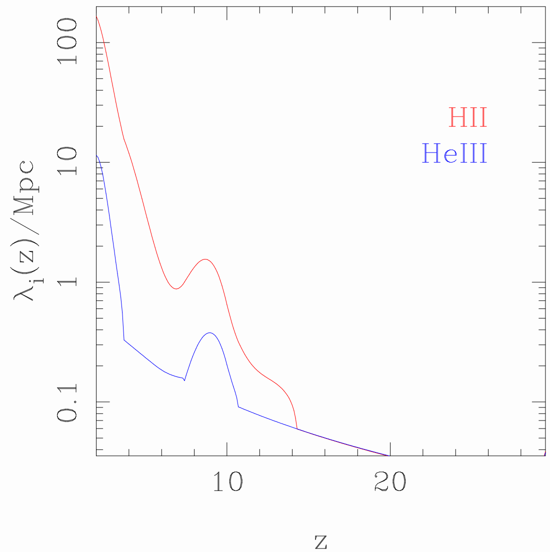


Mean free path



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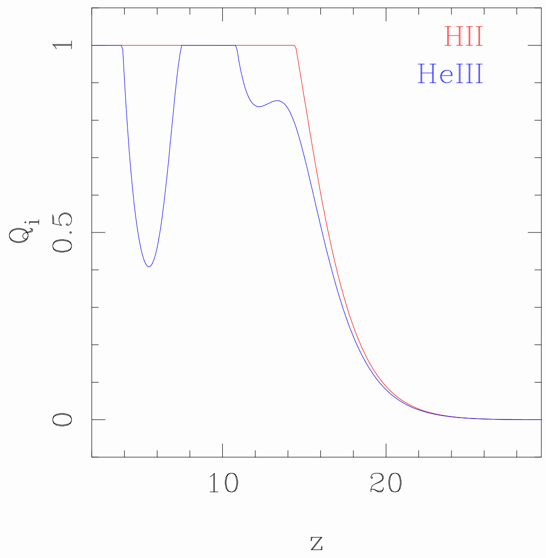
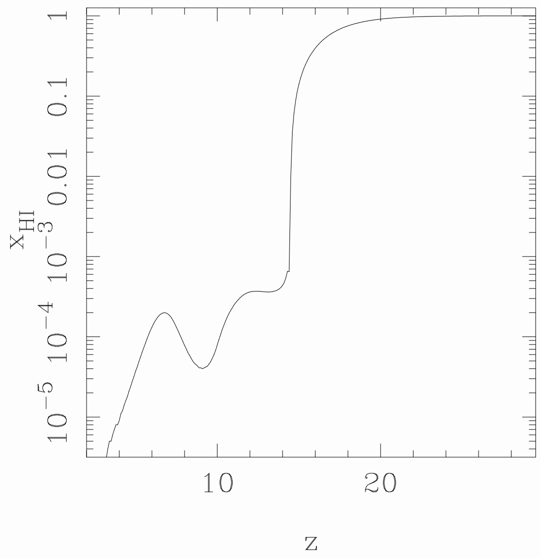
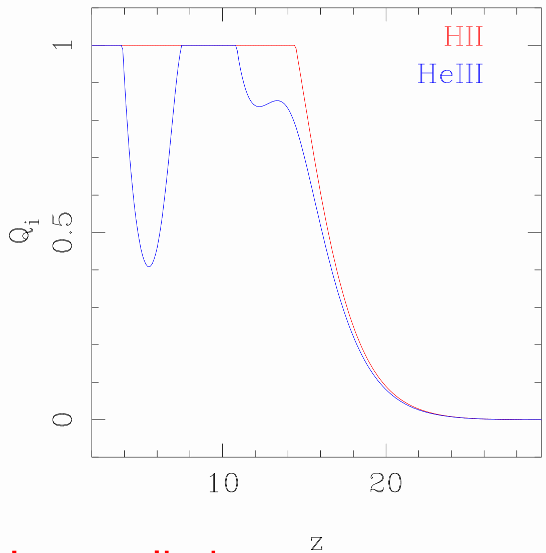


Neutral fraction



Results: Comparison with Observations

Volume filling factor



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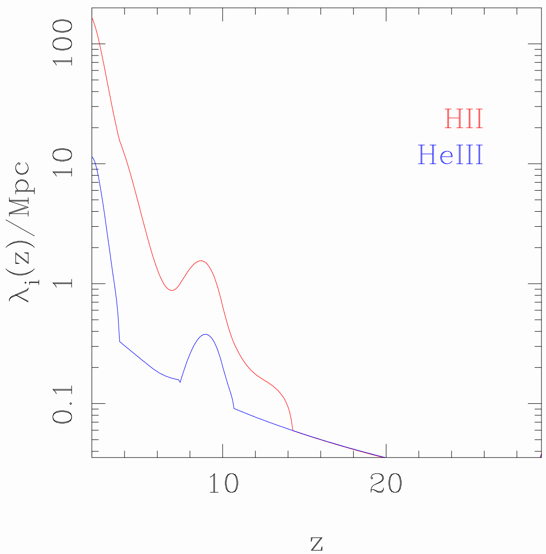
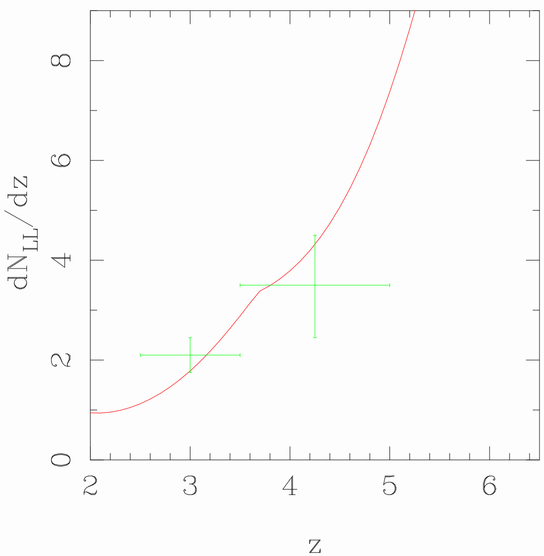


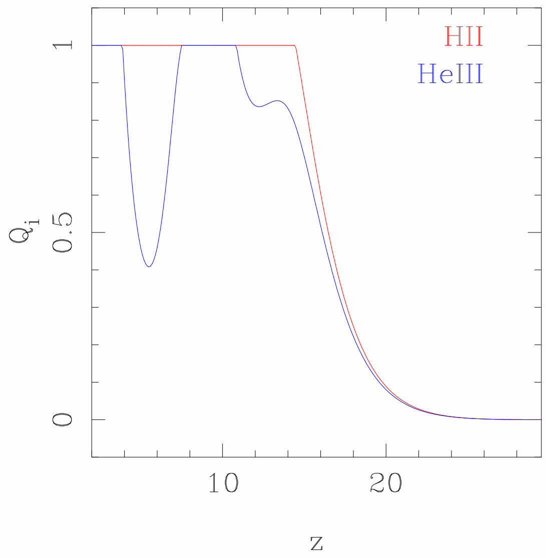
Lyman limit systems



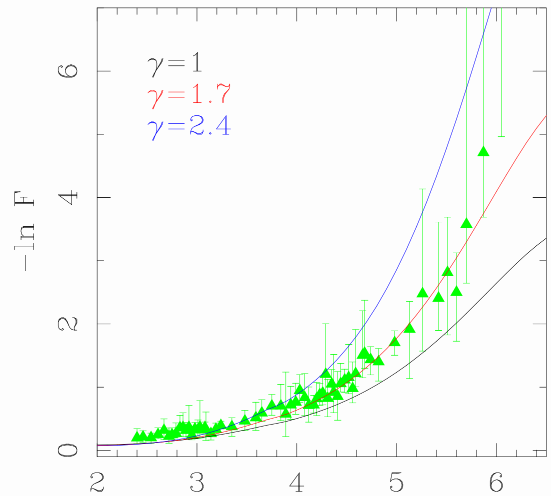
Lyman limit system data points from Storrie-Lombardi et al. (1994)

Results: Comparison with Observations

Volume filling factor



GP optical depth



GP optical depth data from Songaila (2004)

Results: Comparison with Observations

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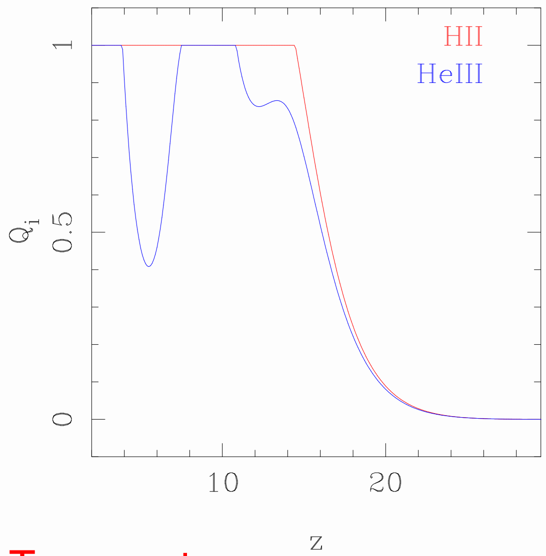

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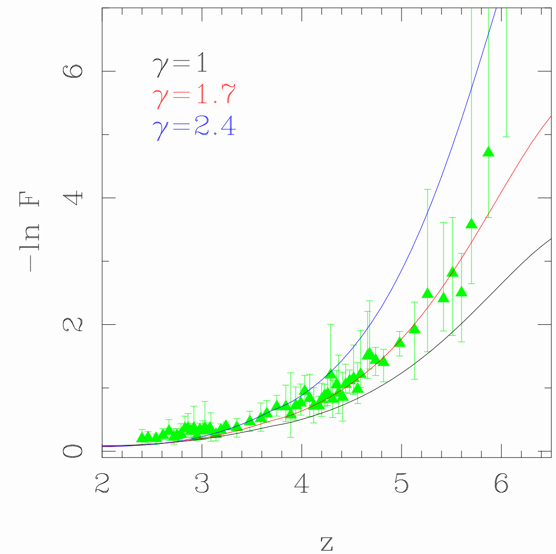
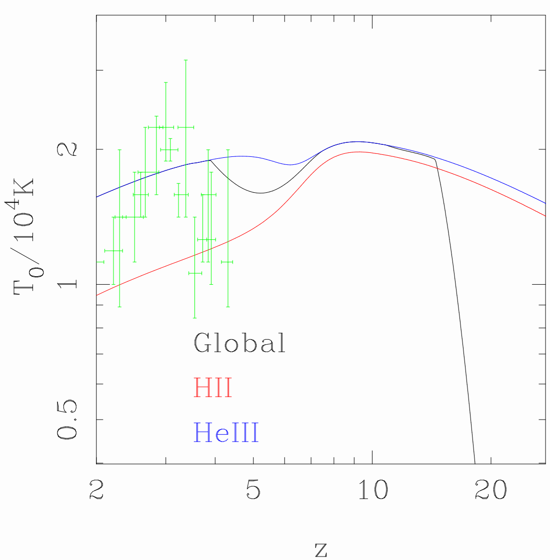


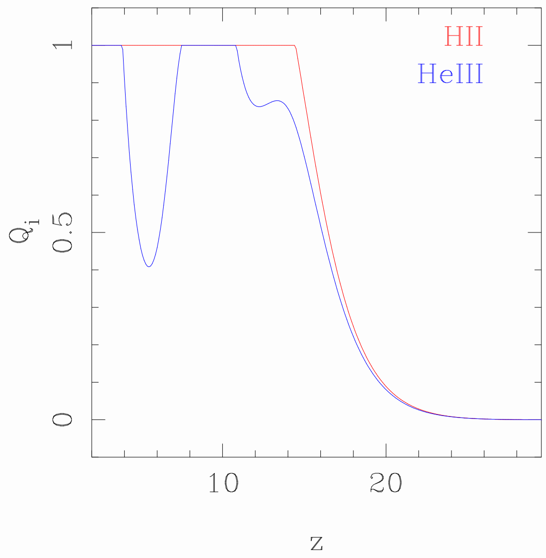
Temperature



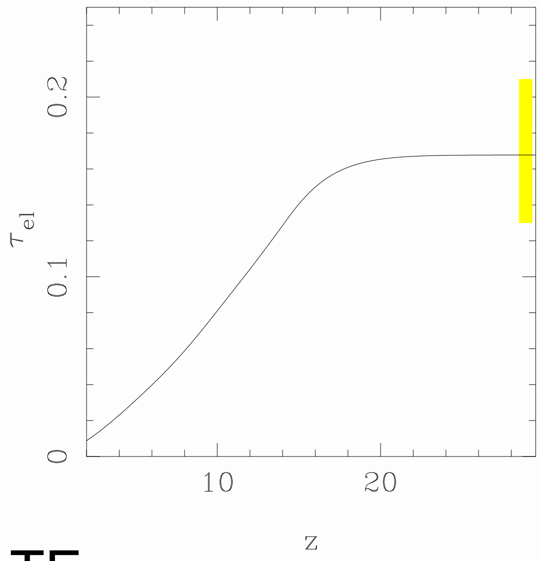
T_0 data from Schaye et al. (1999)

Results: Comparison with Observations

Volume filling factor



Electron scattering optical depth



TE cross power spectrum (WMAP) data from Kogut et al. (2003)

Results: Possible variations

- 0.15% $< \epsilon_{*,\mathrm{III}} <$ 2% from WMAP data.
- $f_{\mathrm{esc,II}} <$ 10% from GP optical depth at $2 \lesssim z \lesssim 6$.
- Different feedback models: Higher feedback at high redshifts can suppress the growth of HeIII regions and can delay or prohibit the (first) HeII reionization.
- Reduced power on small scales by suppressing cooling in minihaloes ($T_{\mathrm{vir}} < 10^4$ K):
  - require higher $\epsilon_{*,\mathrm{III}}$ to match WMAP data
  - the effect of feedback is less severe

Results: Summary

- H-reionization at $z \approx 14$.
- Double HeII-reionization at $z \approx 12$ (PopIII-induced) and at $z \approx 3.5$ (QSO-induced). Recombination at $z \lesssim z_{\rm trans}$.
- Observations of T_0: consistent with HII regions at $z \gtrsim 3.5$ and with HeIII regions at $z \lesssim 3.5$.
- About 0.2% of total stars need to be PopIII in order to explain the WMAP data and to achieve the H-reionization at high redshifts.

Future Studies

- Detailed look into the Gunn-Peterson optical depths around $z \approx 6$ using line-of-sight realizations.
- Implications on future CMB polarization and 21cm observations.
- Incorporate evolution of the IGM metallicity?