The IGM and reionization

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Contents:

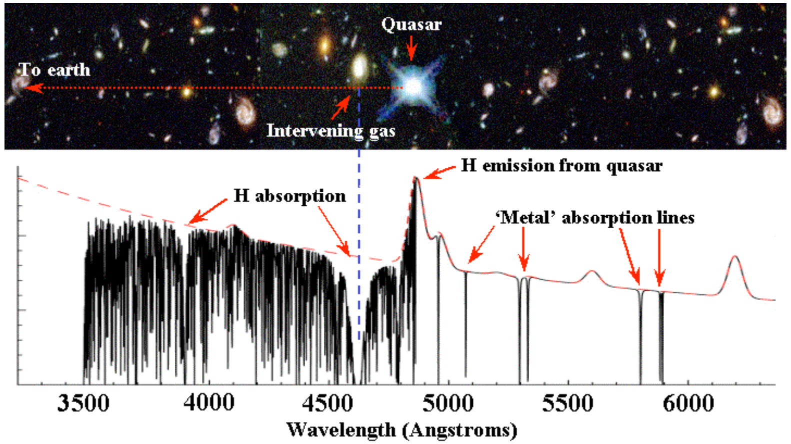
- Constraints on HI/H at high z
- Topology of reionization
- Impact of reionization on galaxies

Recent reviews:

- Observational Constraints on Cosmic Reionization (Fan, Carilli & Keating 2006 ARAA)
- The Reionization of the Universe by the First Stars and Quasars (Loeb & Barkana, 2001 ARAA)
- The First Cosmic Structures and Their Effects (Ciardi & Ferrara, 2005 SSR)

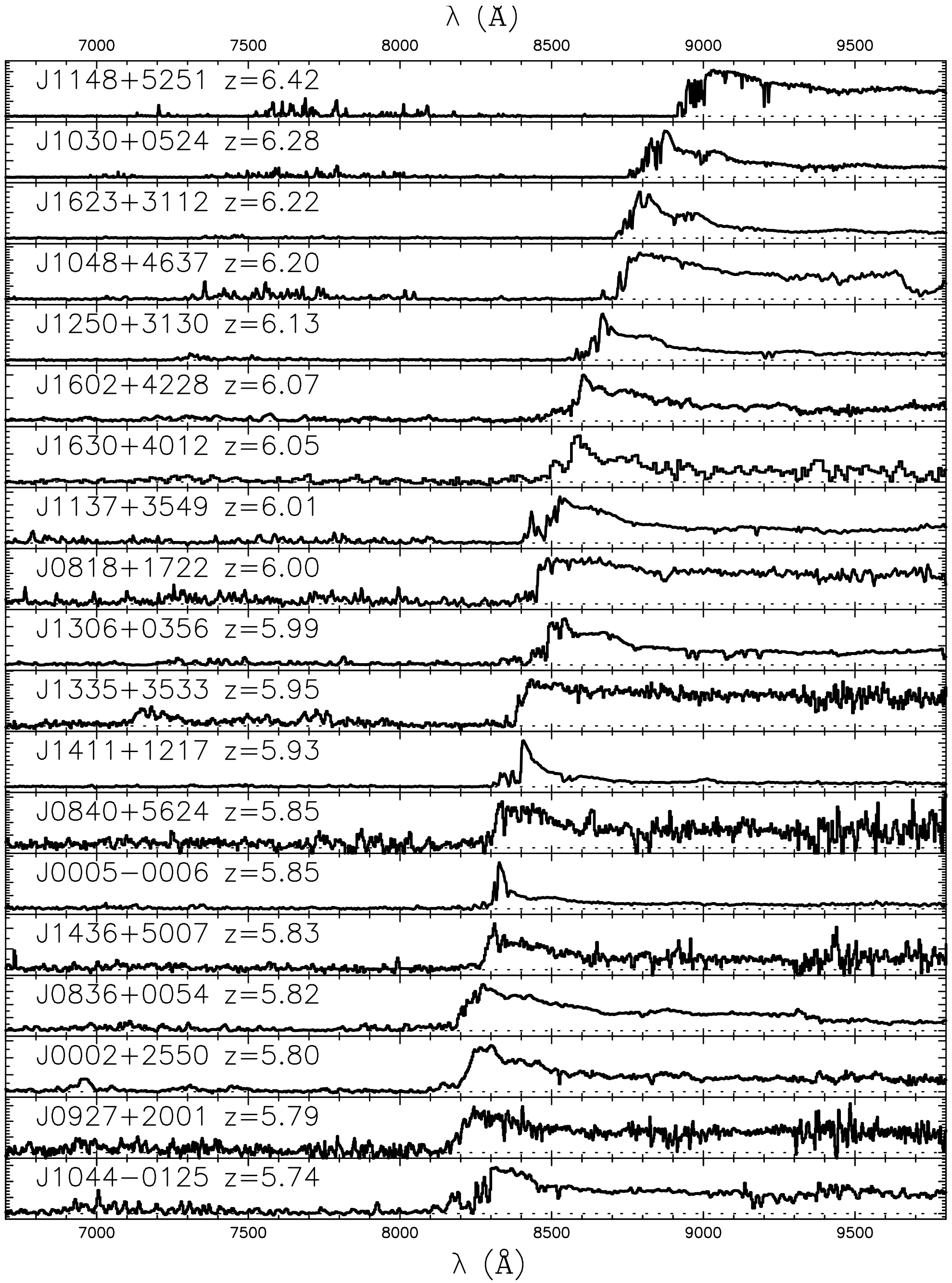
Basics: neutral hydrogen along the sightline to a distant source (QSO, GRB) scatters light due to Lyman-alpha transition, decreasing the amount of observed flux

$$\frac{F_{\rm observed}}{F_{\rm emitted}} = \exp(-\tau)$$

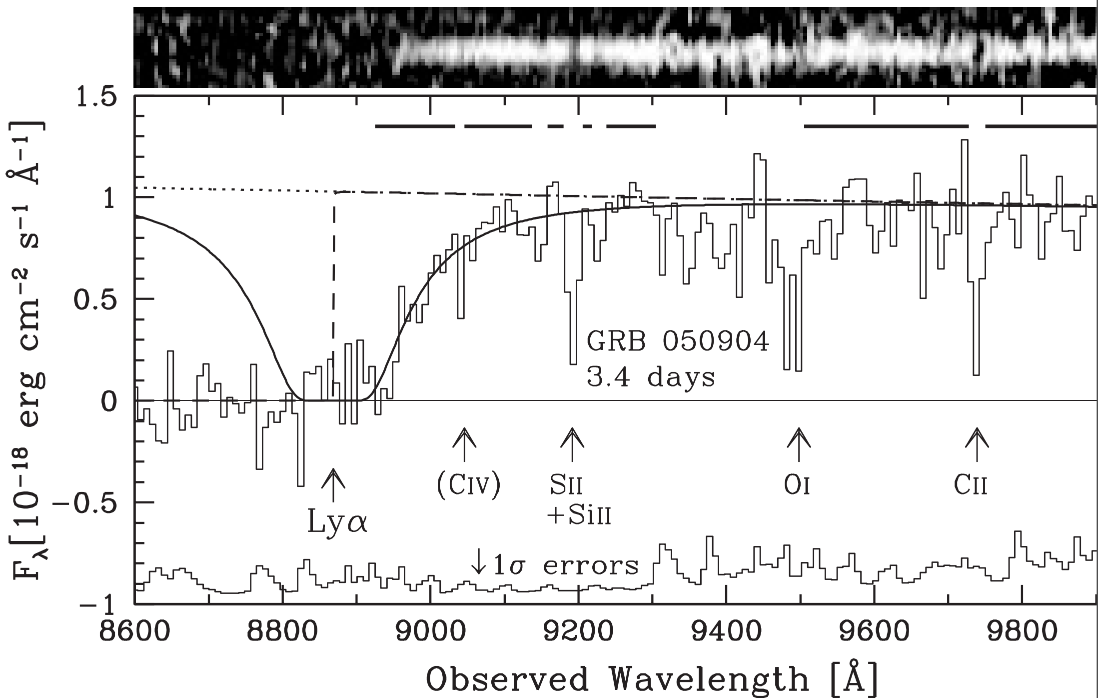


$$\tau = 2.5\left(\frac{\Omega_m}{0.3}\right)^{-1/2}\left(\frac{h}{0.72}\right)^{-1}\left(\frac{T}{10^4{\rm K}}\right)^{-0.7} \times \left(\frac{\Gamma}{10^{-12}\,{\rm s}^{-1}}\right)^{-1}\left(\frac{\Omega_b\,h^2}{0.02}\right)^{2}\left(\frac{1+z}{6}\right)^{4.5}$$

Optical depth of uniform IGM; Gunn & Peterson 1965



Fan et al: QSO spectra

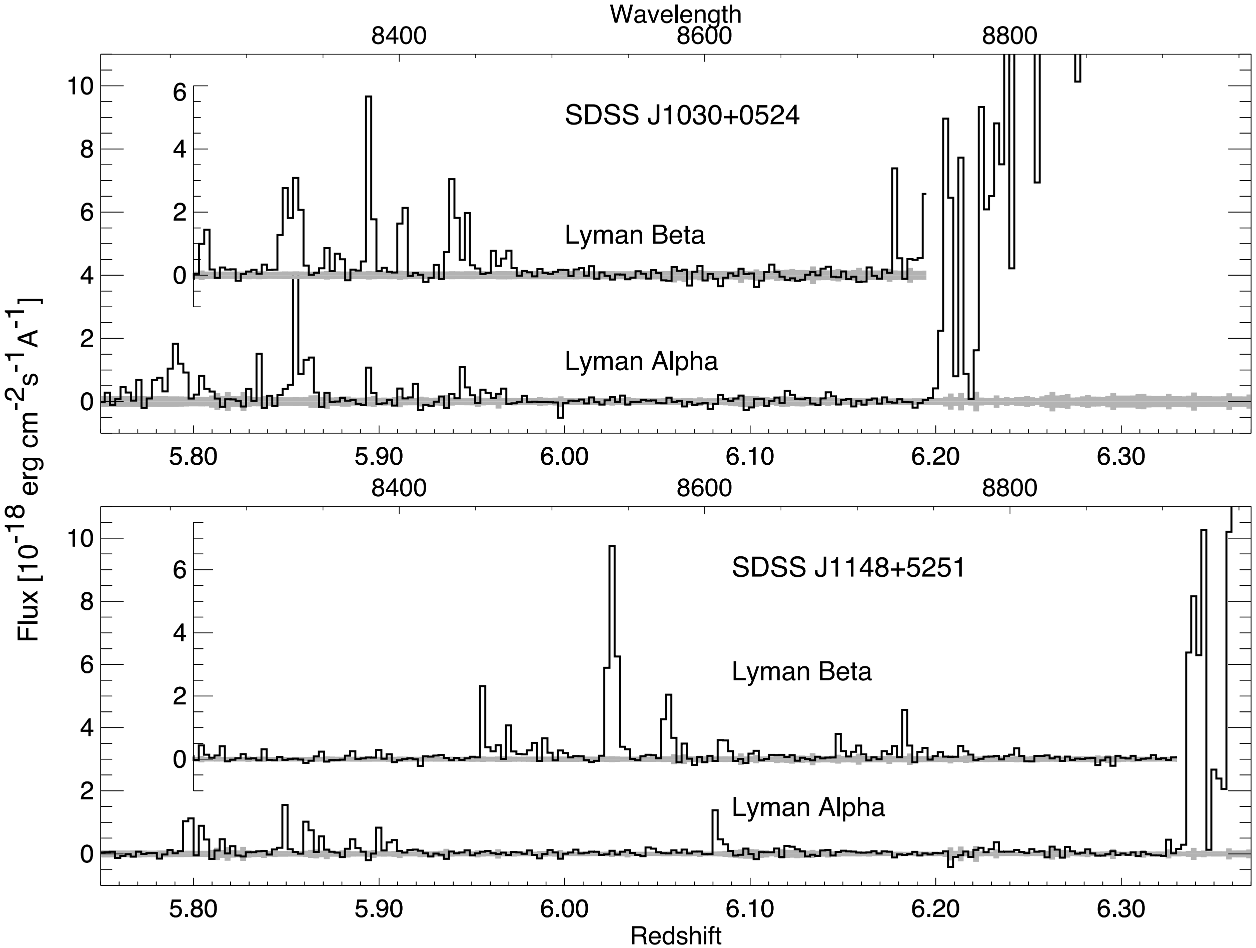


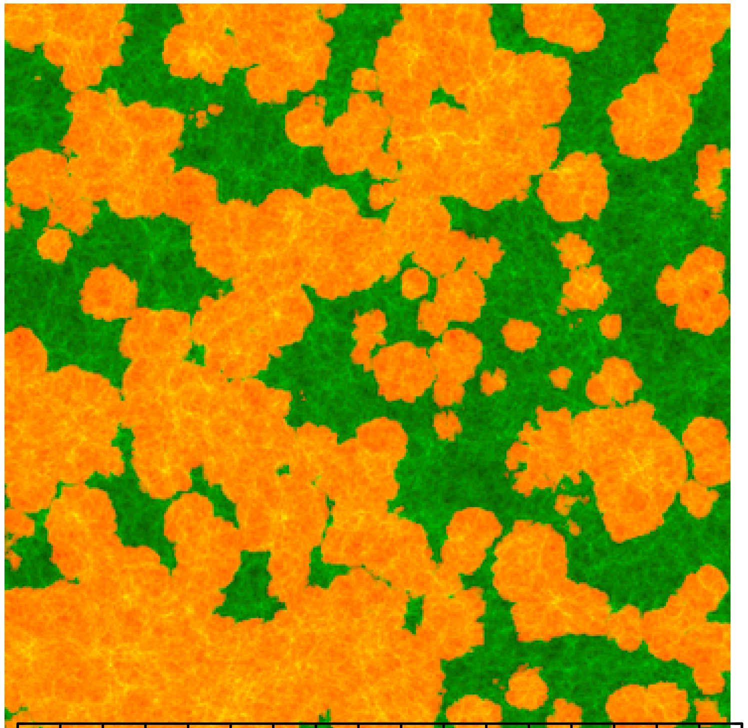
Totani et al: GRB spectrum

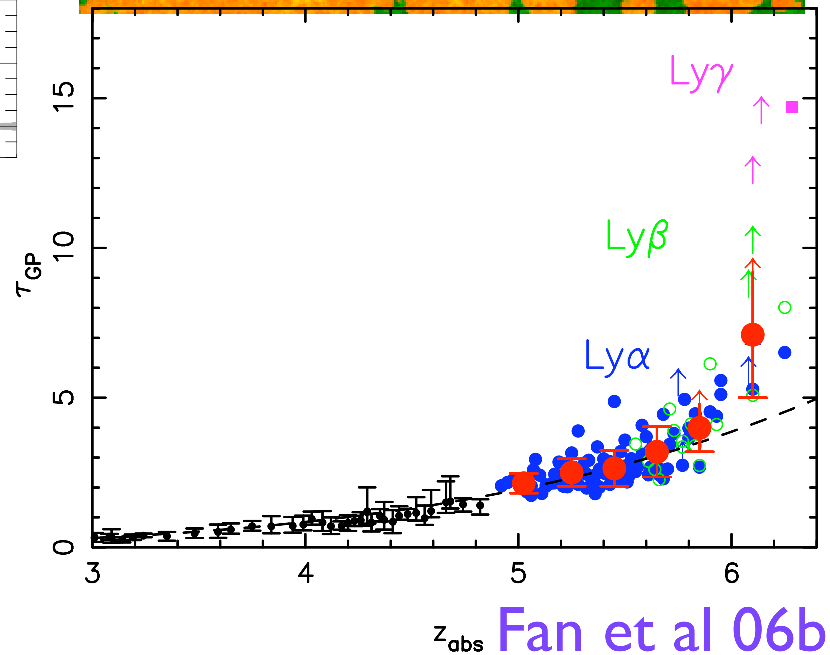
$$\tau = 2.5\left(\frac{\Omega_m}{0.3}\right)^{-1/2}\left(\frac{h}{0.72}\right)^{-1}\left(\frac{T}{10^4\mathrm{K}}\right)^{-0.7} \times \left(\frac{\Gamma}{10^{-12}\,\mathrm{s}^{-1}}\right)^{-1}\left(\frac{\Omega_b\,h^2}{0.02}\right)^{2}\left(\frac{1+z}{6}\right)^{4.5}$$

How neutral is the gas?

Iliev et al







White et al 2003

Fan et al 06, also

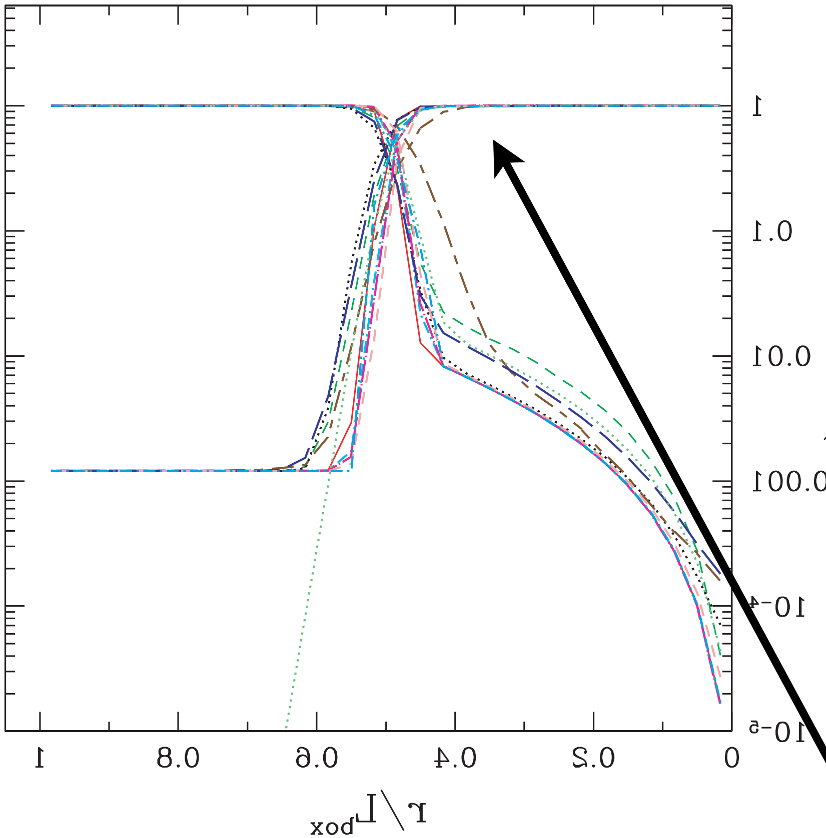
Djorgovski et al 01

Becker et al 01

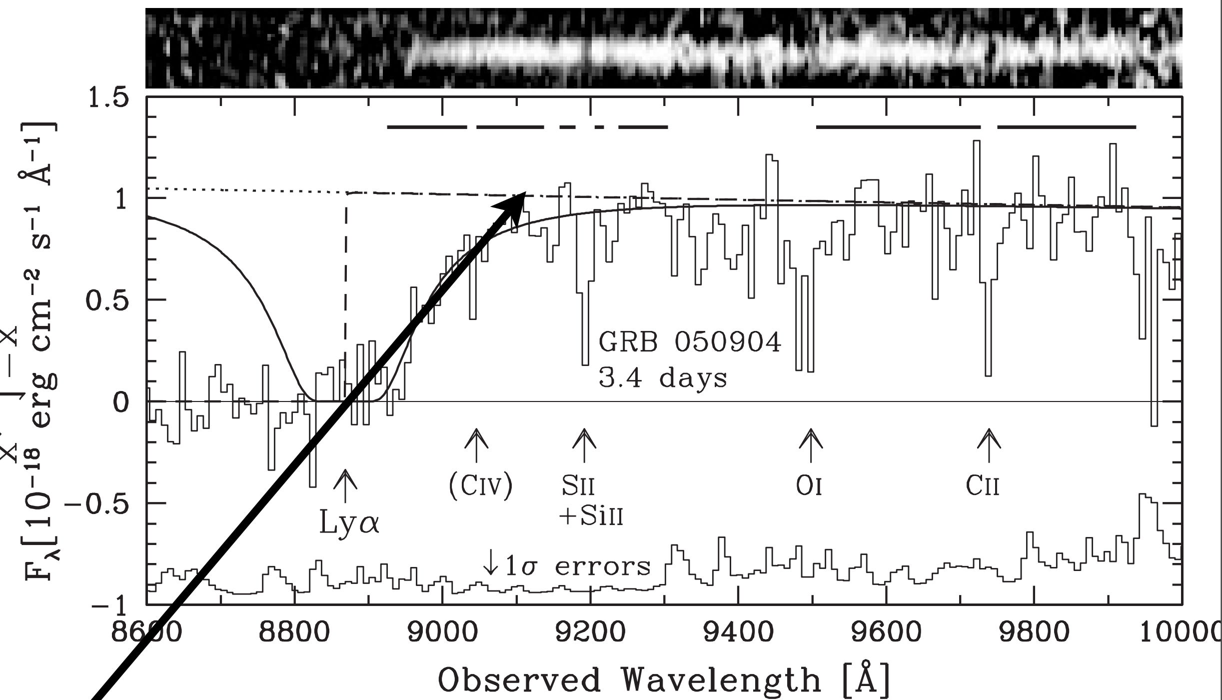
Oh & Furlanetto 05

Fan et al 06b

Neutral gas and the Lyman-alpha damping wing



Ionised fraction of HII region

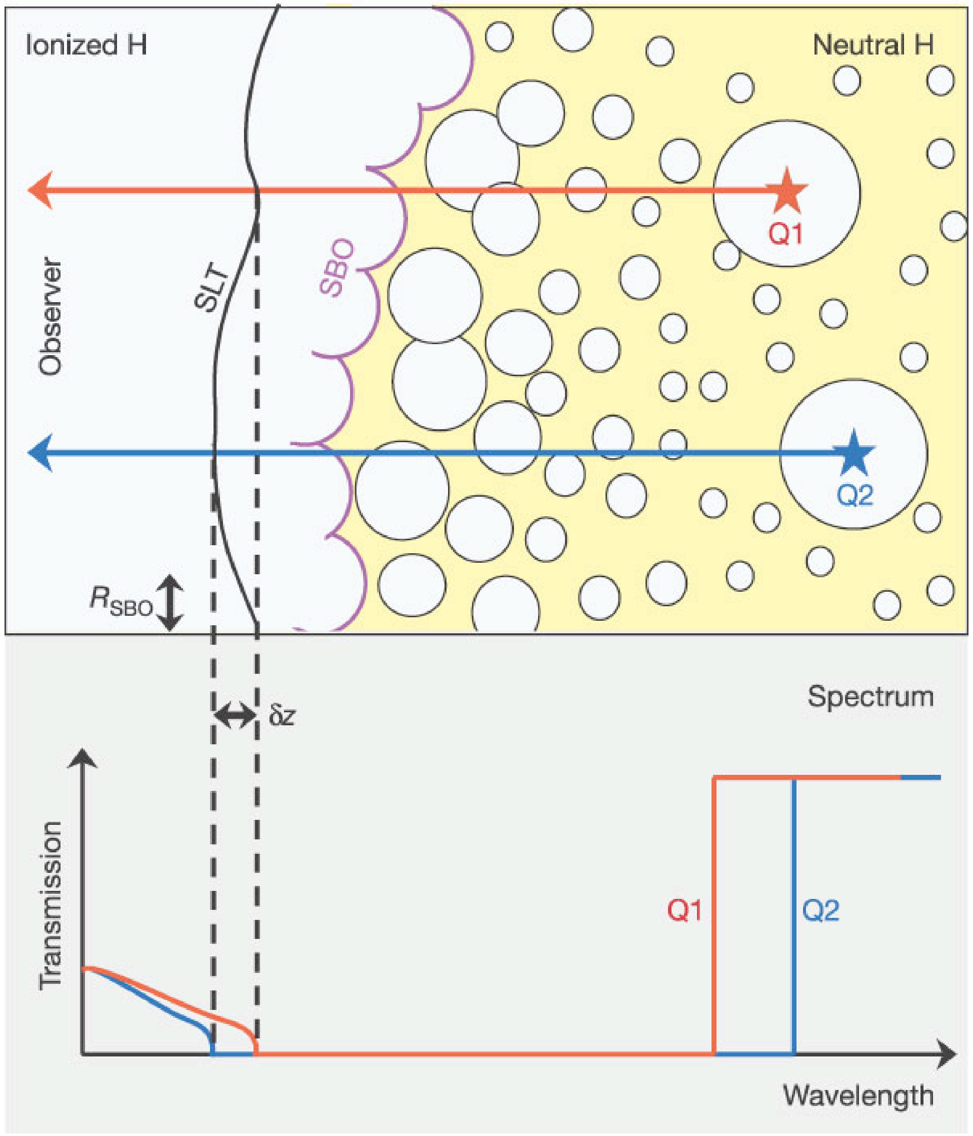


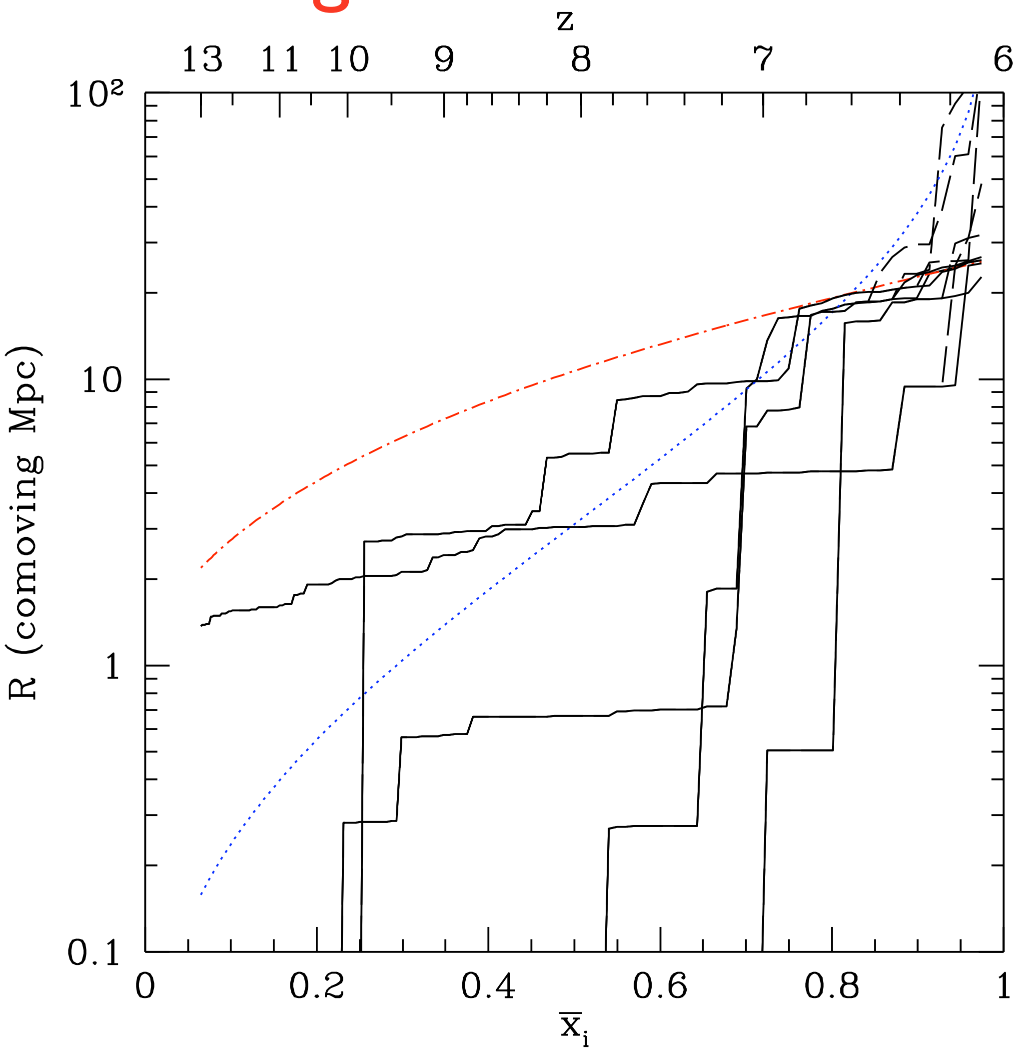
Neutral region may produce damping wing, as seen in GRB spectrum, not in QSO spectra

but see Mesinger & Haiman

Totani et al: damping wing is due to DLA, not neutral IGM. Why not the case for QSOs?

Statistics of ionized regions

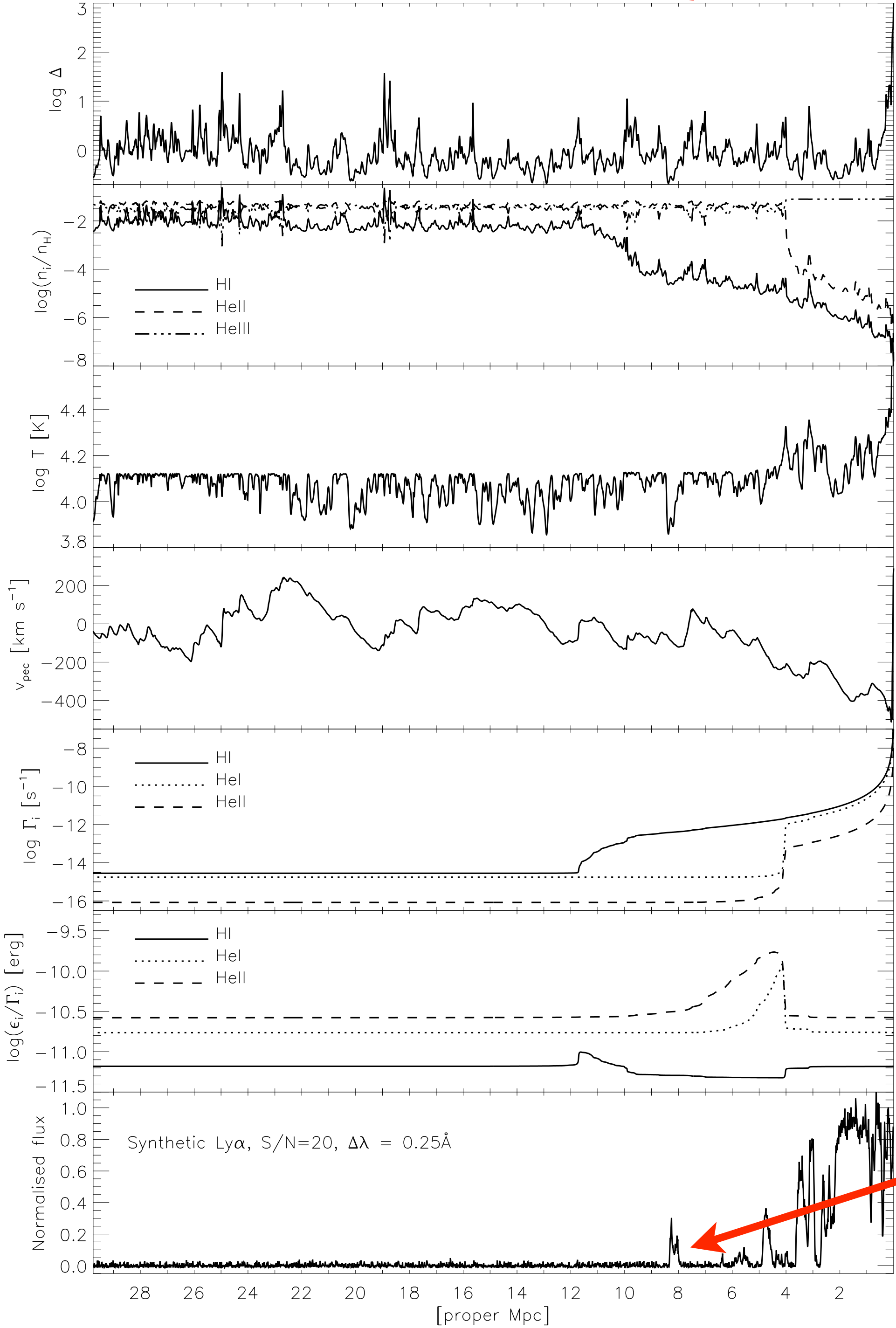


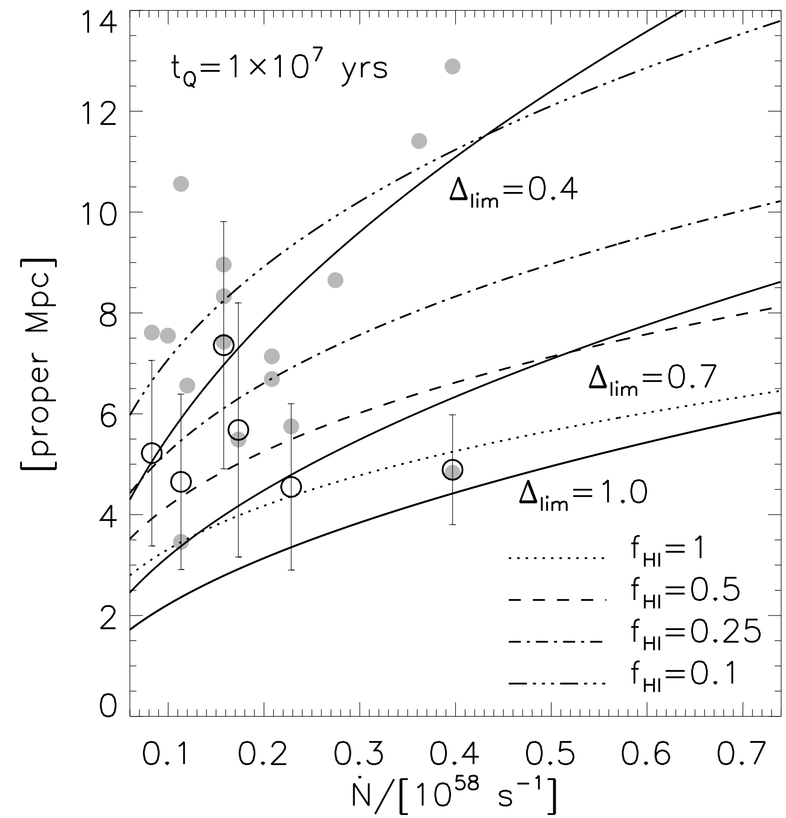


Furlanetto & Oh 08

Wyithe & Loeb 04

QSO near zones





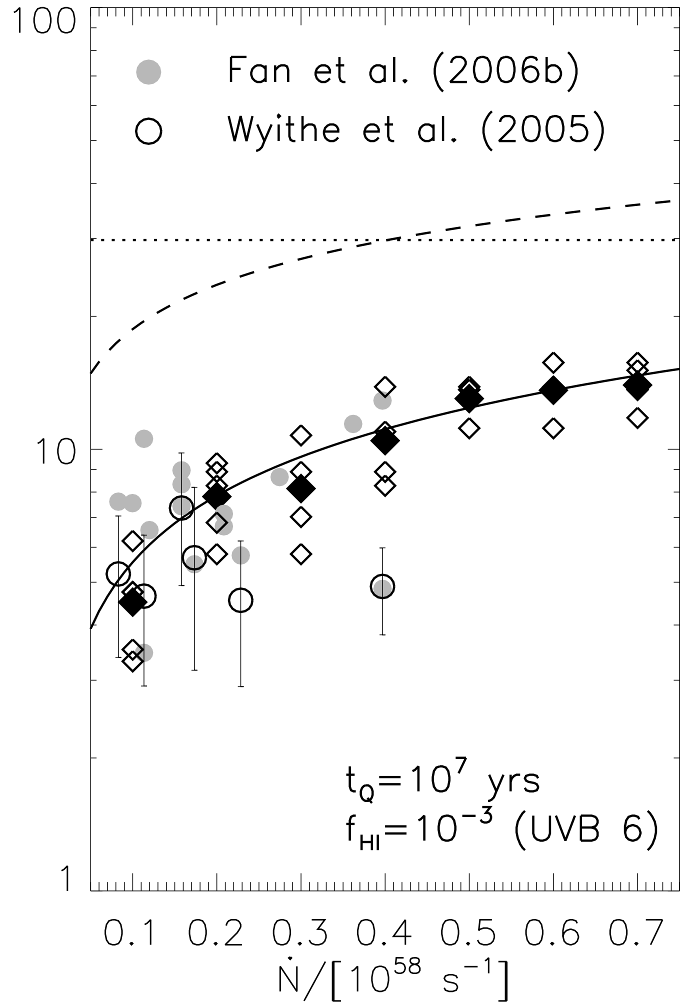
Size of region affected by QSO depends on:

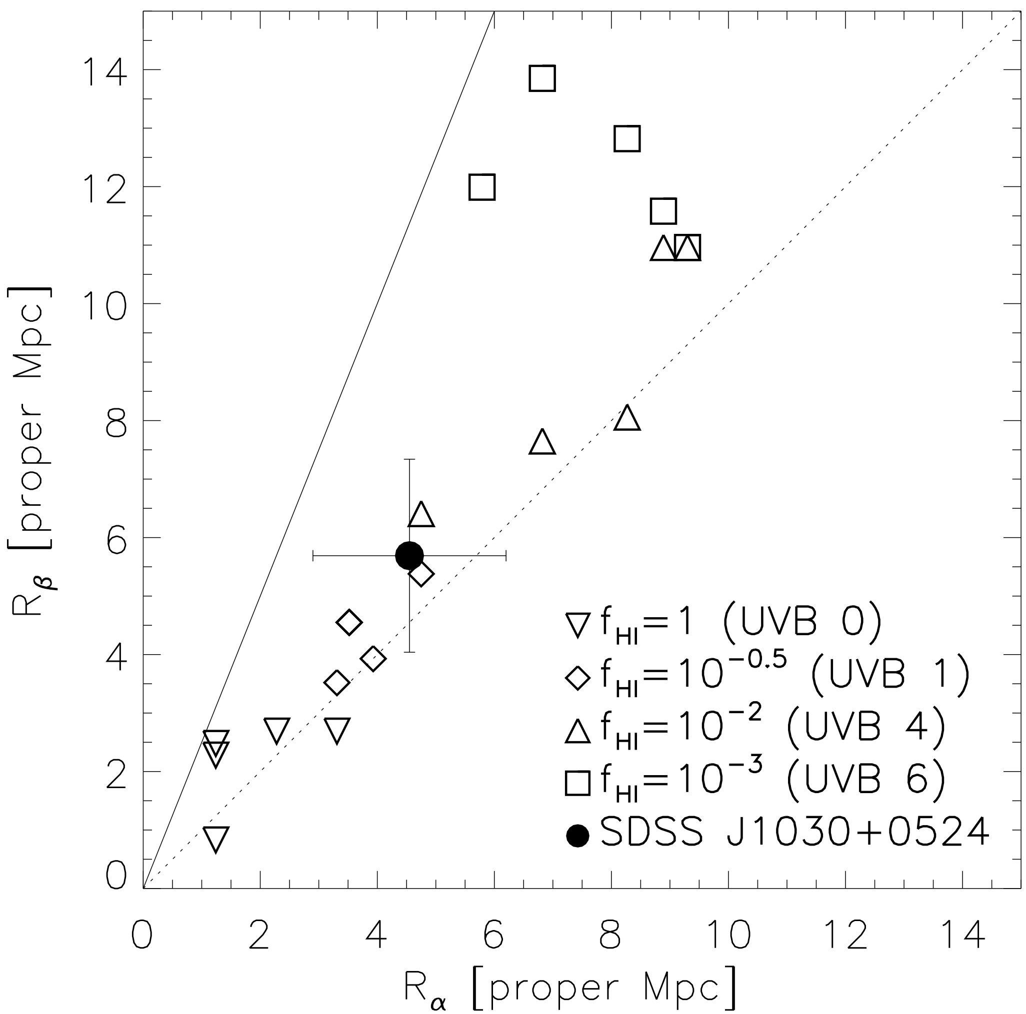
- Luminosity, age
- IGM density distribution
- Ionizing background

Bolton & Haehnelt 08
Maselli et al 08
Lidz et al 07

QSO near zones

Bolton & Haehnelt 08

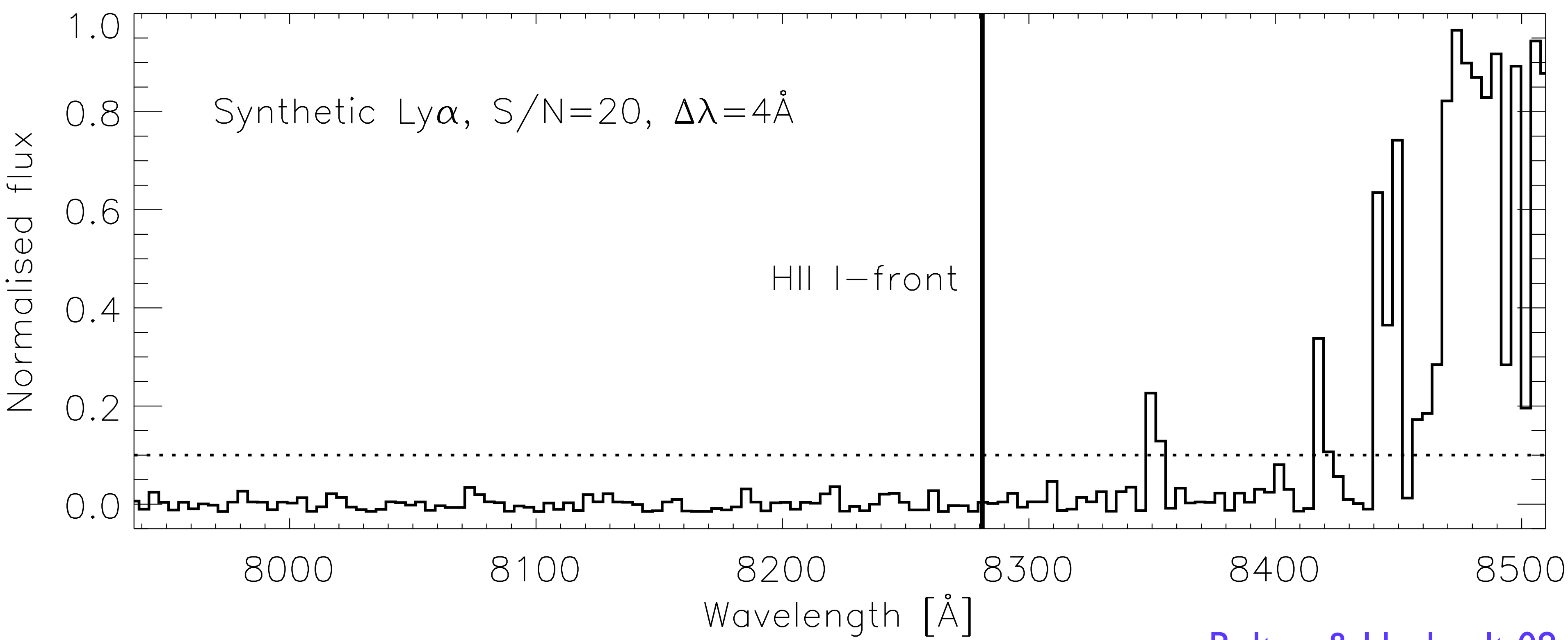




Size of near zones as function of QSO luminosity

Size of Ly-beta vs Ly-alpha near zones

QSO near zones



Bolton & Haehnelt 08
Lidz et al 07
Maselli 07

Topology and source properties

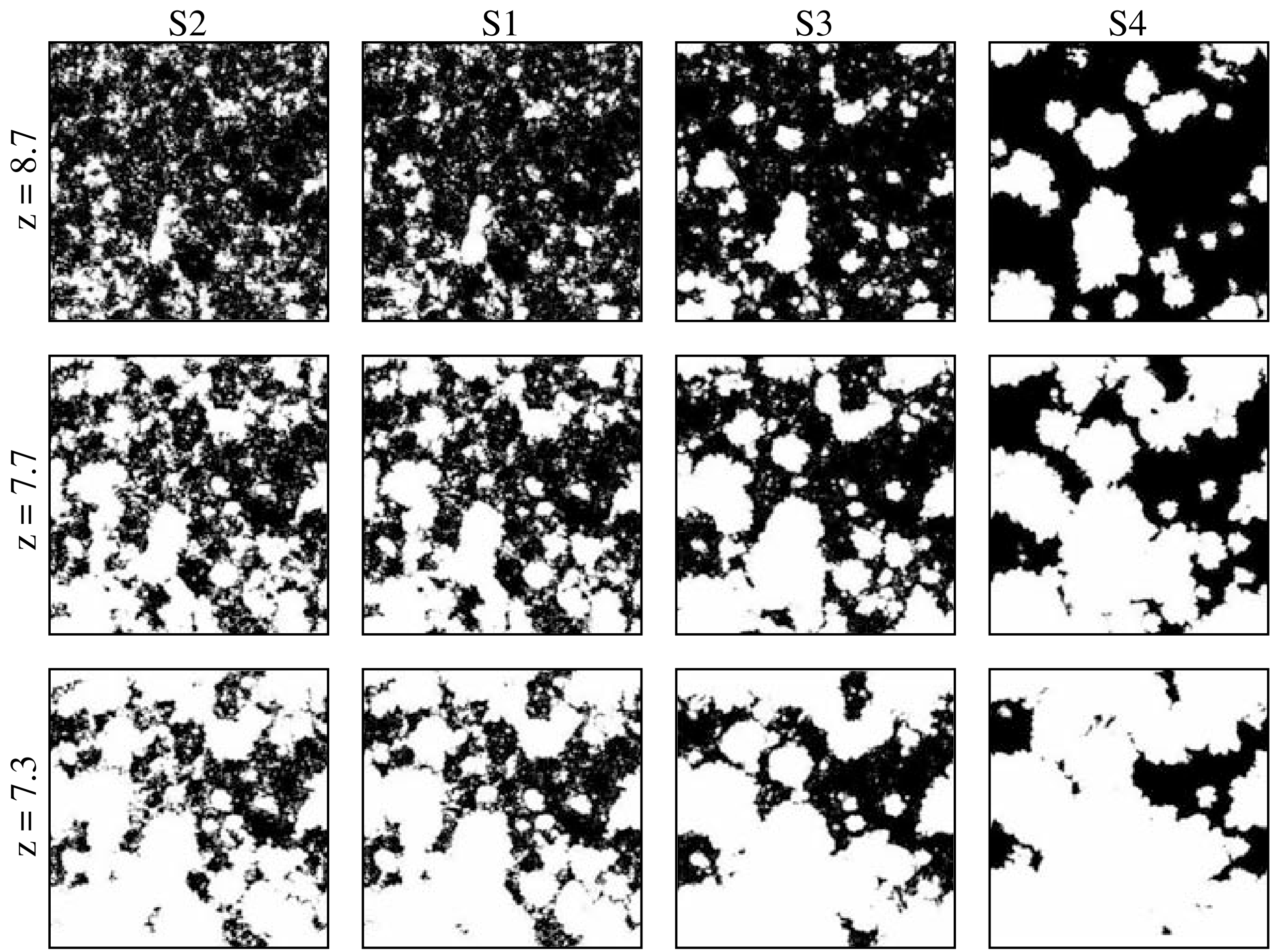
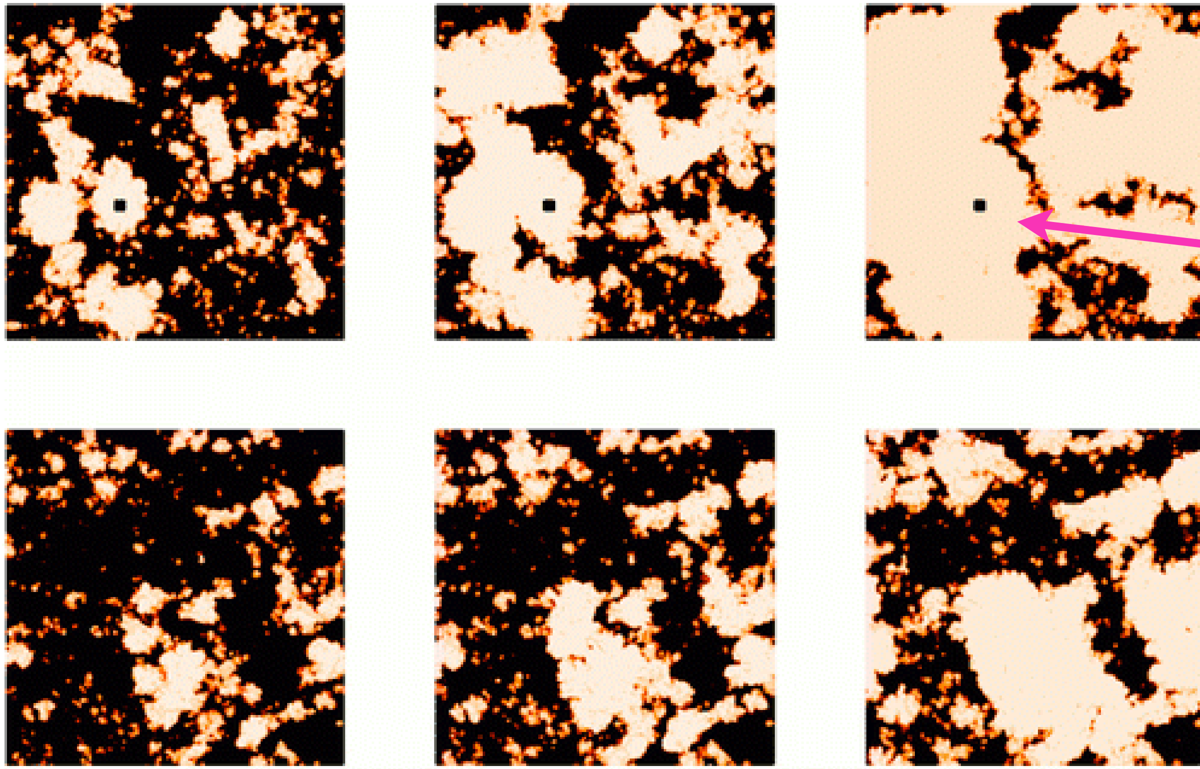


Figure 3. Comparison of four radiative transfer simulations post-processed on the same density field, but using different source prescriptions parametrized by $\dot{N}(m) = \alpha(m)\,m$. The white regions are ionized and the black are neutral. The left-hand panel, left centre panel, right centre panel and right-hand panels are, respectively, cuts through Simulations S2 ($\alpha \propto m^{-2/3}$), S1 ($\alpha \propto m^0$), S3 ($\alpha \propto m^{2/3}$) and S4 ($\alpha \propto m^0$, but only haloes with $m > 4 \times 10^{10}\,\mathrm{M}_\odot$ host sources). For the top panels, the volume-ionized fraction is $\bar{x}_{i,V} \approx 0.2$ (the mass-ionized fraction is $\bar{x}_{i,M} \approx 0.3$) and $z = 8.7$. For the middle panels, $\bar{x}_{i,V} \approx 0.5(x_{i,M} \approx 0.6)$ and $z = 7.7$, and for the bottom panels, $\bar{x}_{i,V} \approx 0.7(\bar{x}_{i,M} \approx 0.8)$ and $z = 7.3$. Note that the S4 simulation outputs have the same $\bar{x}_{i,M}$, but $\bar{x}_{i,V}$ that are typically 0.1 smaller than that of other runs. In S4, the source fluctuations are nearly Poissonian, resulting in the bubbles being uncorrelated with the density field ($\bar{x}_{i,V} \approx \bar{x}_{i,M}$). Each panel is 94 Mpc wide and would subtend 0.6 degrees on the sky.

Quinn et al 08

QSO sites are likely biased

Ionized fractions:



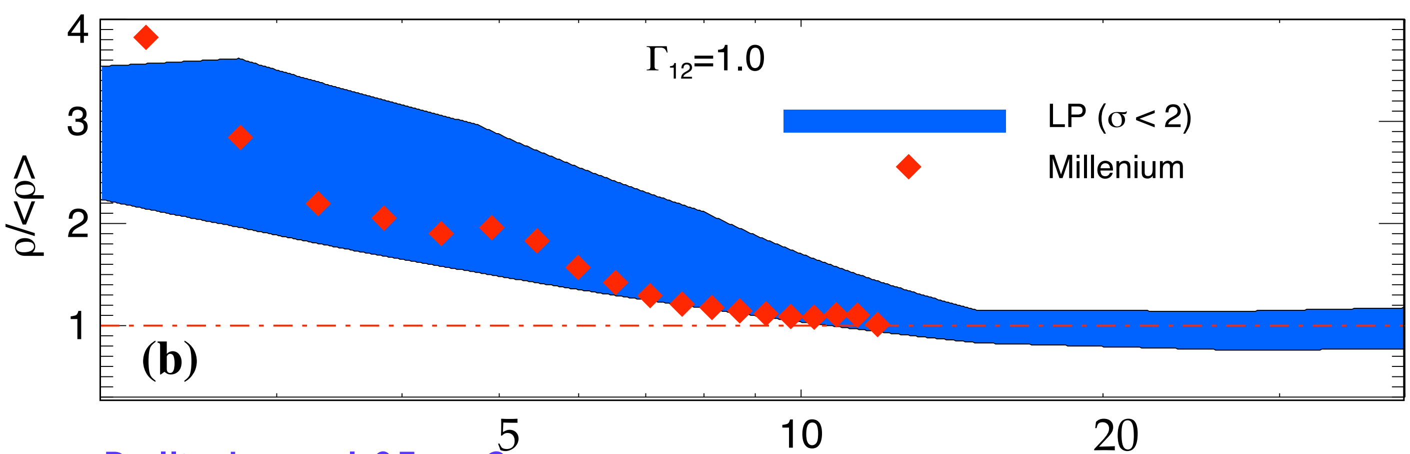
(z=6)

Likely QSO site

Random site

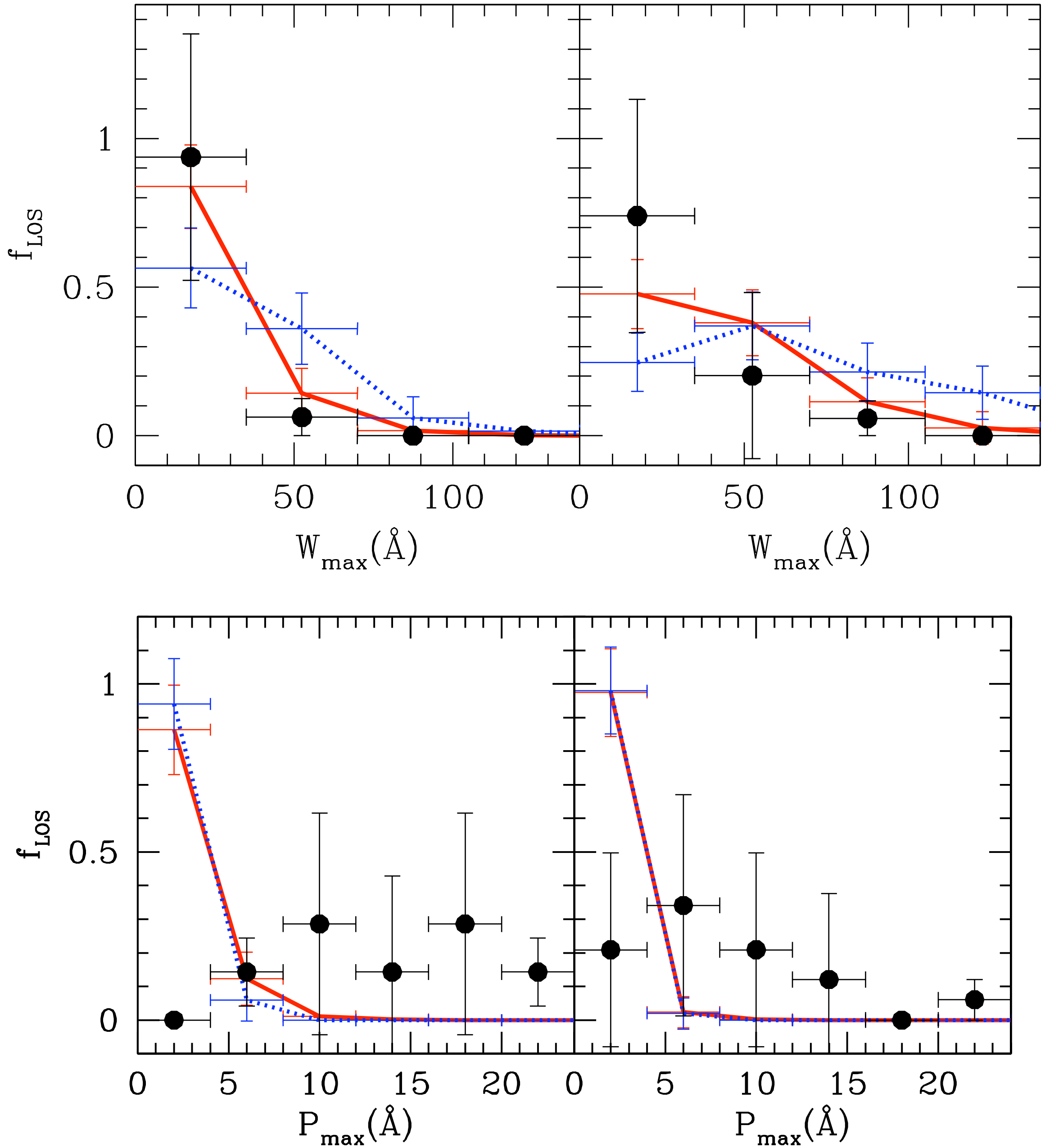
Lidz et al, 07
Wyithe et al 08

Density structure:
(z=2)



Rollinde et al 05, z=2

Gap statistics



Dark regions

data

early reionization

late reionization

Bright regions

Gallerani et al 08

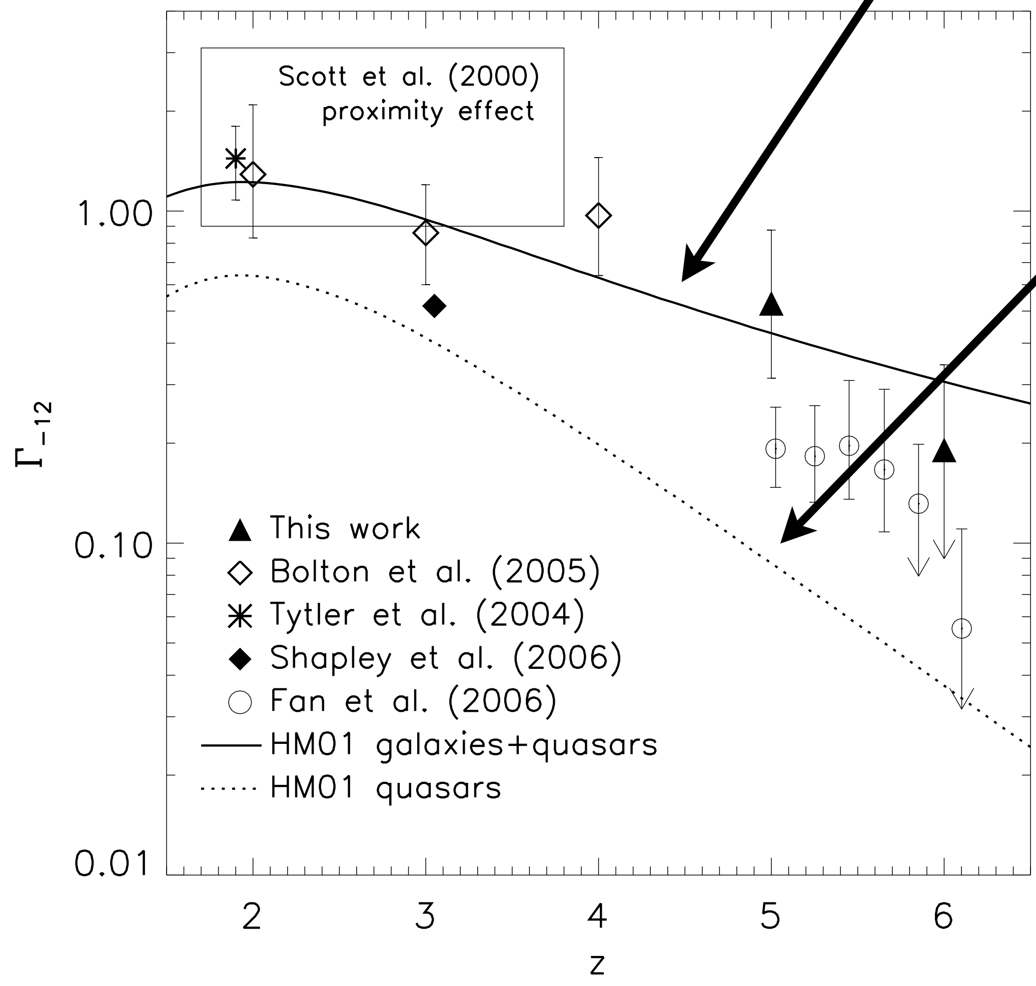
Change in IGM properties

Haardt & Madau

QSO + galaxies

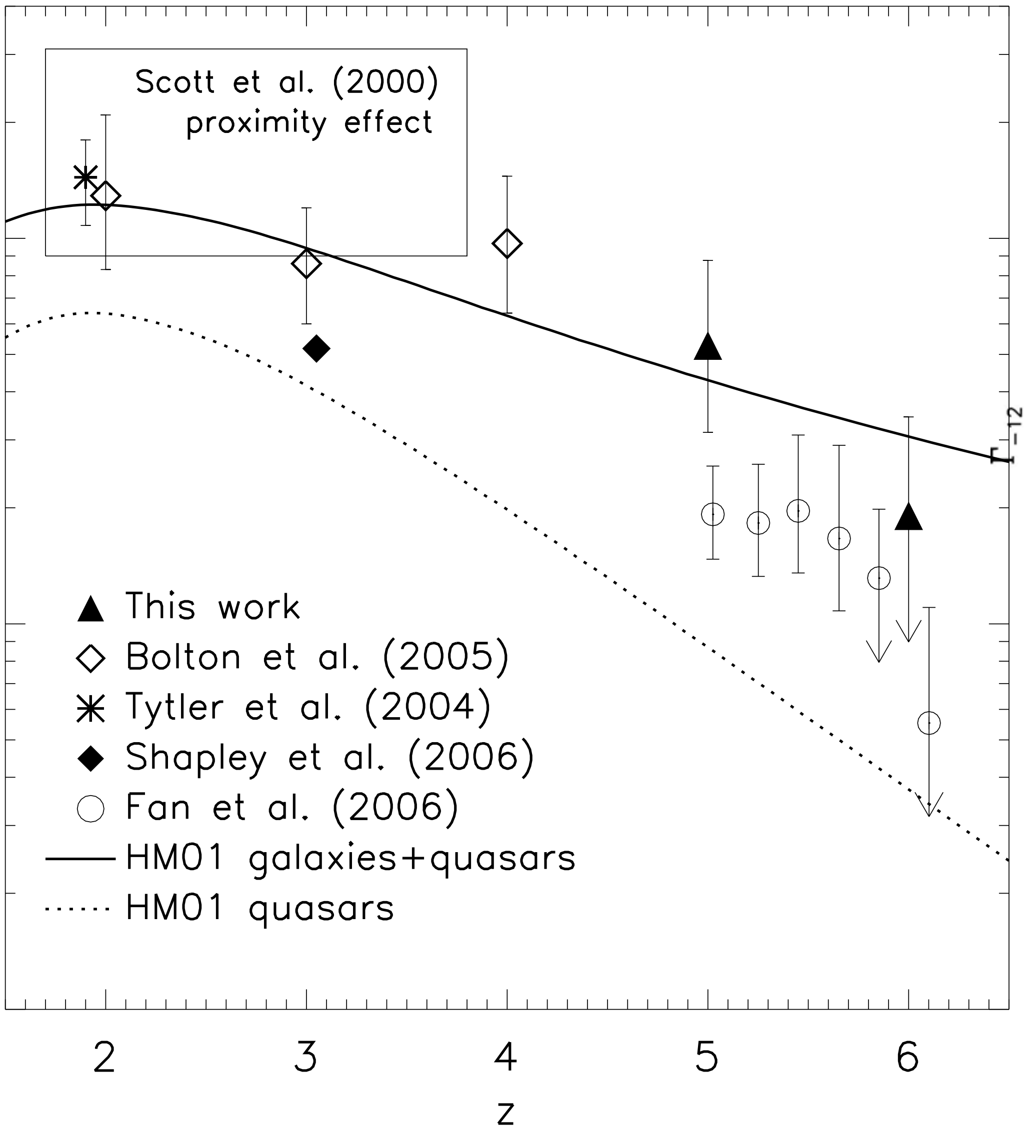
QSO alone

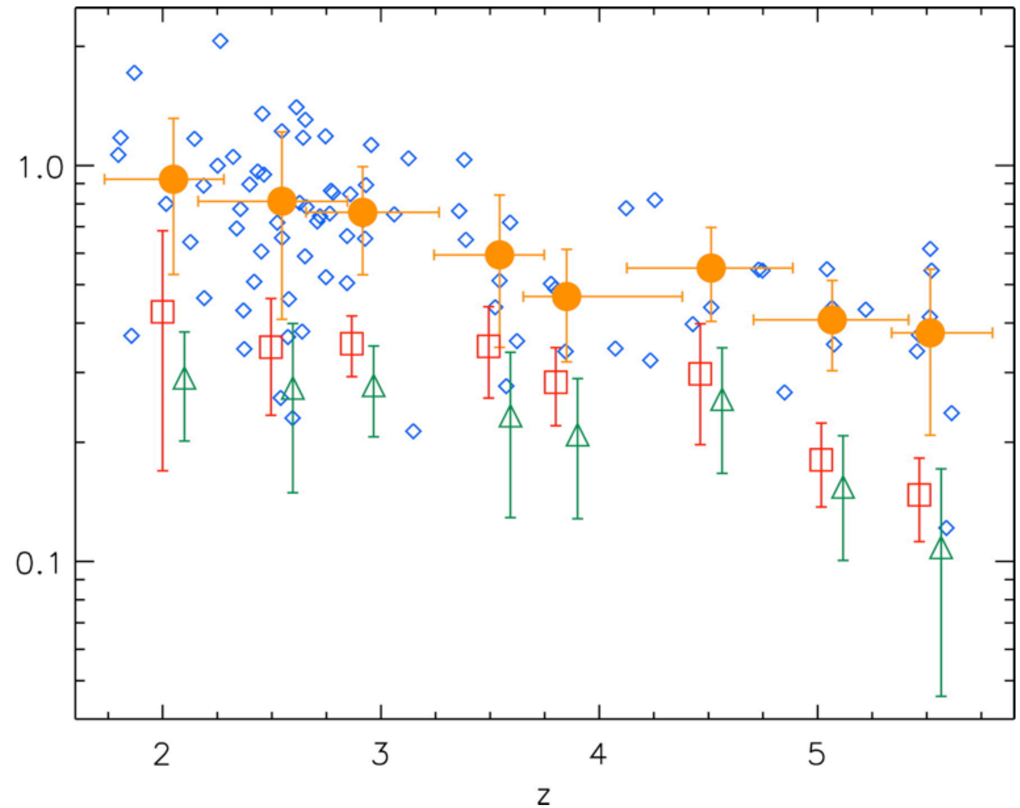
Amplitude of ionizing background



Bolton & Haehnelt 06

Change in IGM properties





Becker et al 07

Bolton & Haehnelt 06

OI forest

$$\mathrm{O} + \mathrm{H}^+ \rightarrow \mathrm{O}^+ + \mathrm{H}^0$$
$$\mathrm{O}^+ + \mathrm{H}^0 \rightarrow \mathrm{O} + \mathrm{H}^+$$

The equilibration time-scale is

$$\sim \frac{1}{k_{\mathrm{ce}} n_{\mathrm{HI}}} \sim 1.7 \times 10^5 x_{\mathrm{HI}} \Delta \left(\frac{1+z}{7}\right)^3 \mathrm{yr}$$

Oh 2002

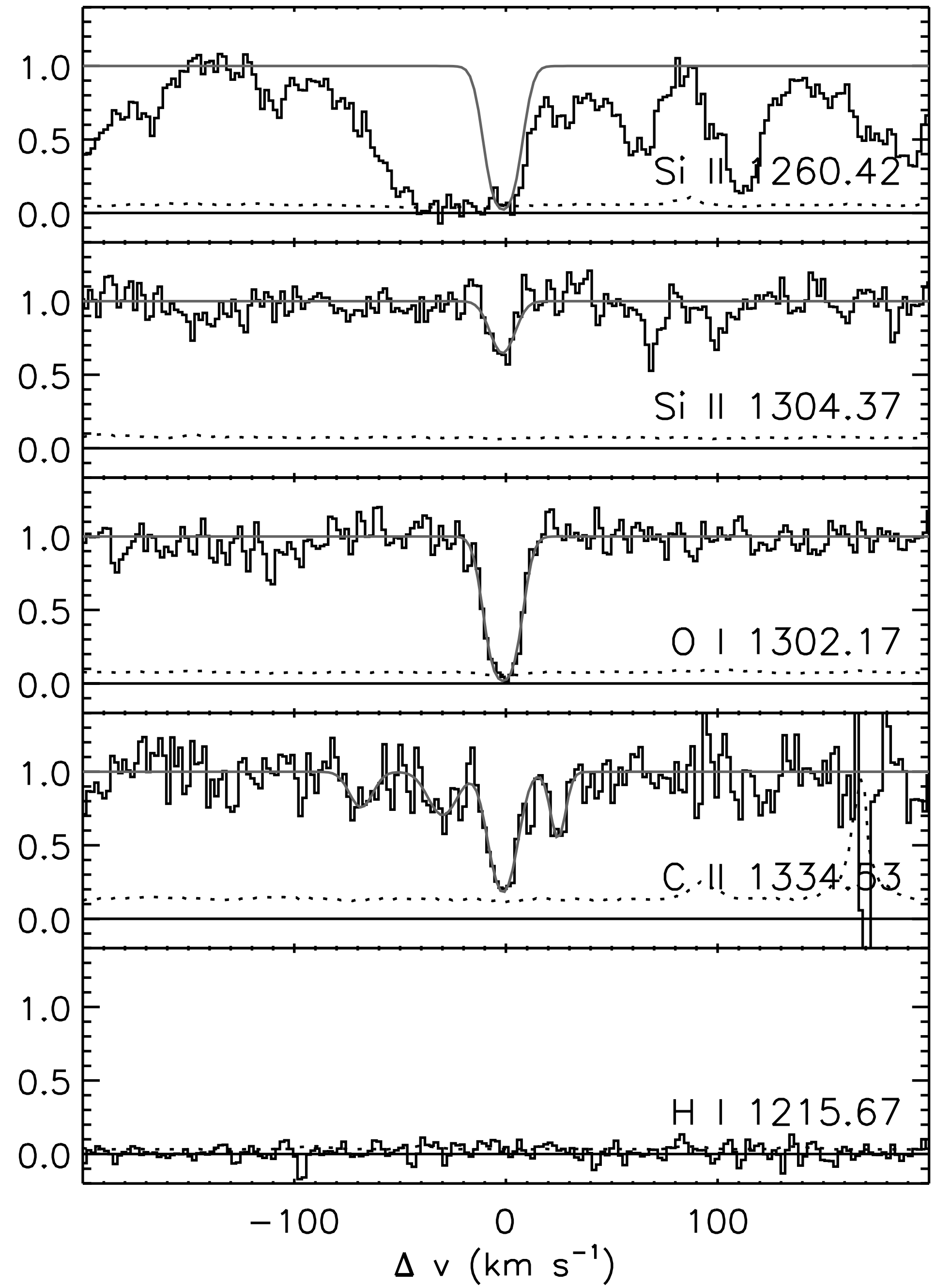
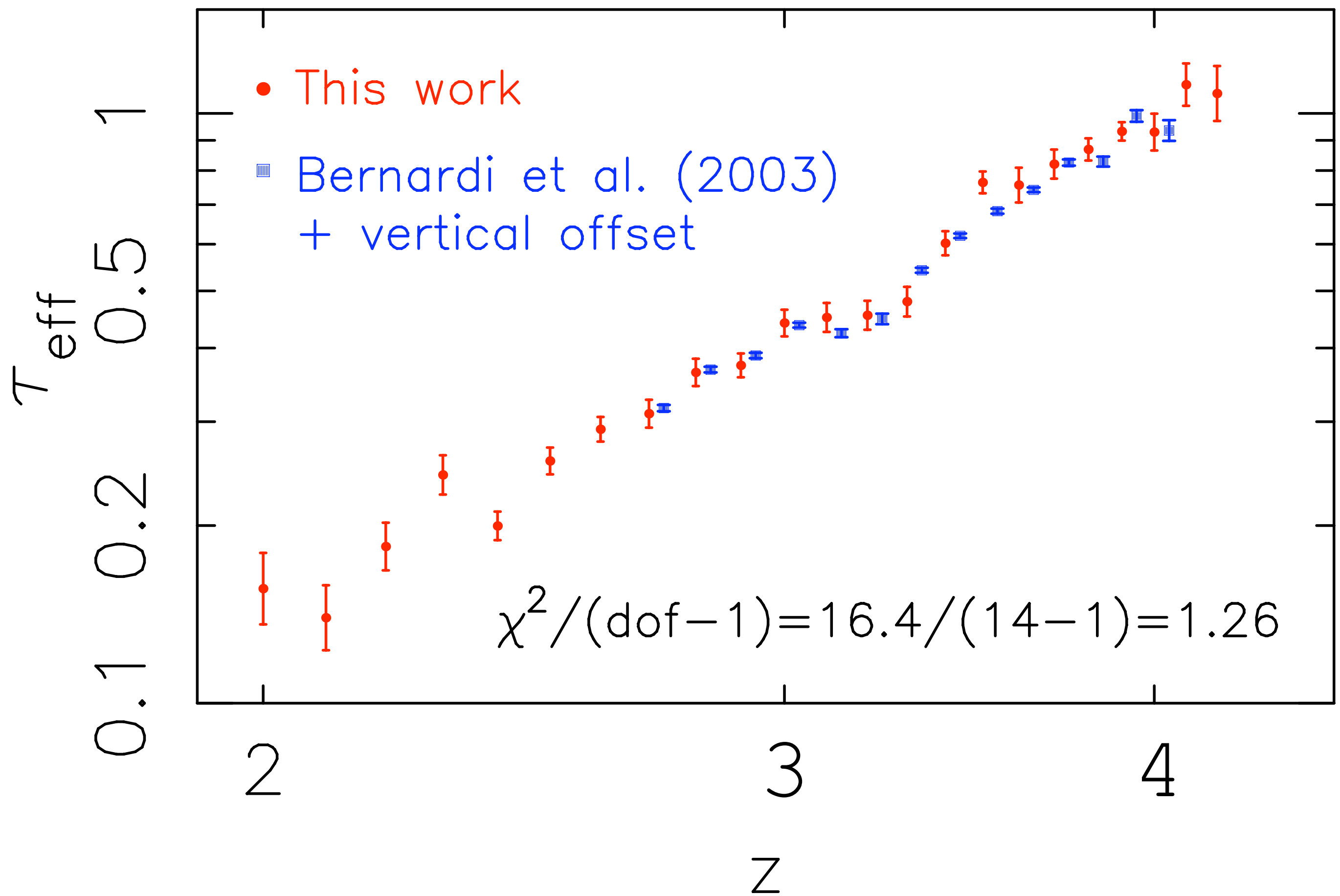


FIG. 4.—Absorption lines for the $z_{\mathrm{sys}} = 6.1293$ O I system toward SDSS 1148+5251. See Fig. 1 for details. The features around Si II λ1260 are Lyα absorption in the quasar proximity region. The C II components at $\Delta v = -67$, -29, and 26 km s^{-1} are unconfirmed.

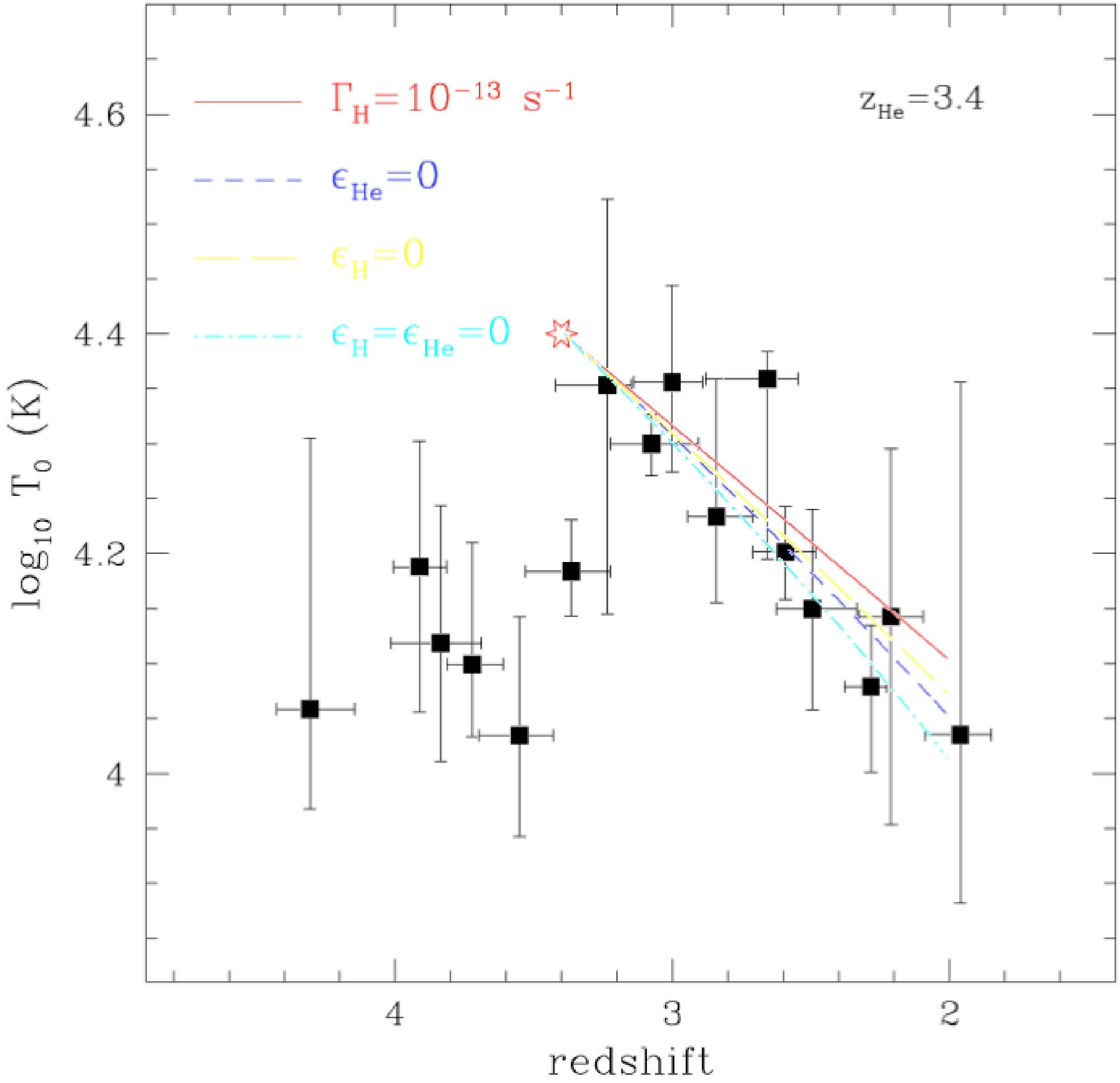
Becker et al 06

Thermal evolution



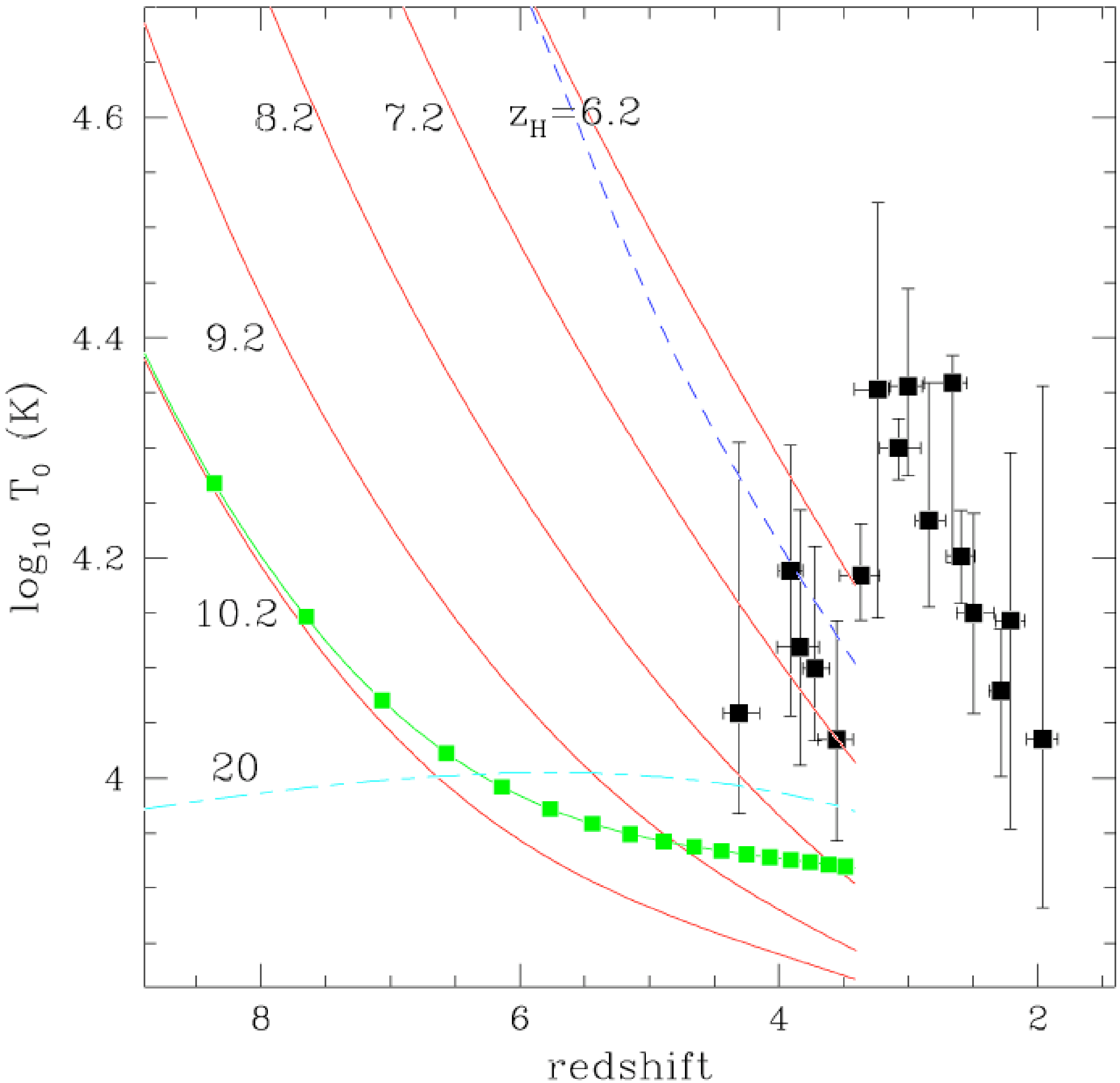
Faucher-Gigere et al 07, Bernardi et al 03

Thermal evolution



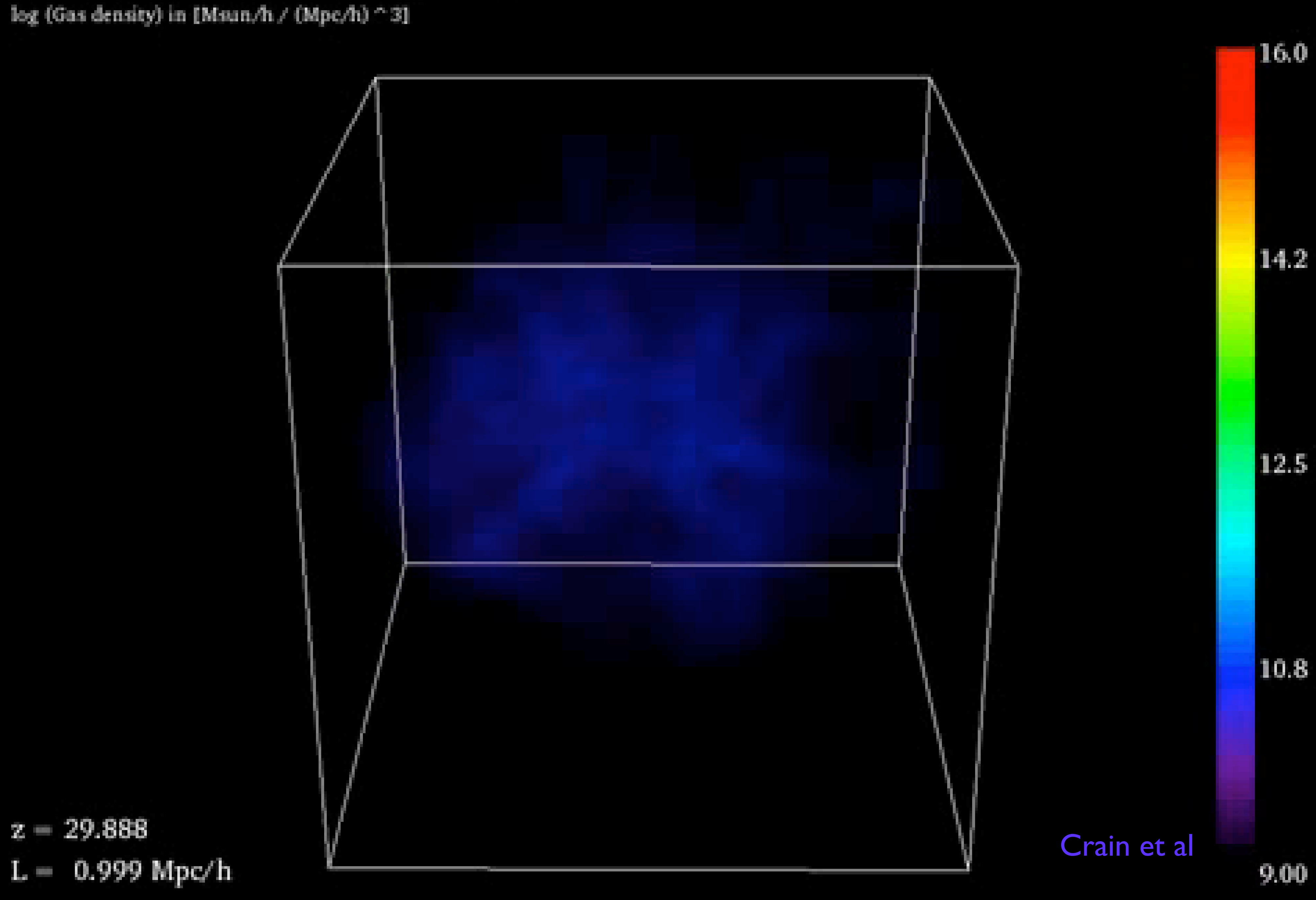
Theuns et al 02
Schaye et al 00

Thermal evolution



Theuns et al 02

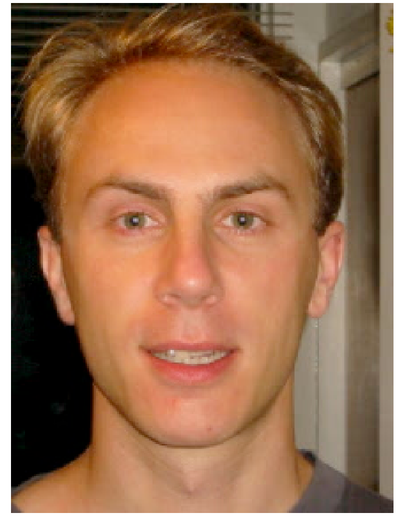
Dwarf galaxy with GIMIC/OWLS code



Crain et al

•Simulating the forest

Leiden:
Claudio Dalla Vecchia
Joop Schaye



Trieste:
Luca Tornatore

Aims:
- simulate IGM and galaxies together
- investigate numerical/physical uncertainties

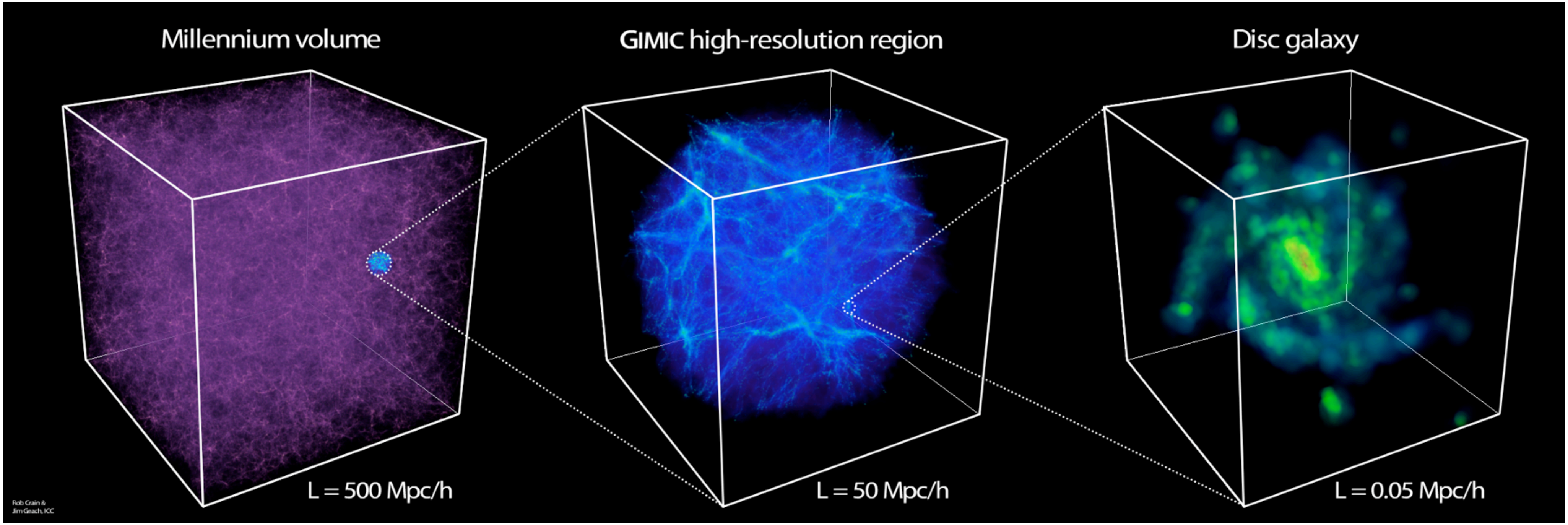
MPA:
Volker Springel

- Gadget 3
- Star formation guarantees Schmidt law
- Stellar evolution
- Winds
- Metal-dependent cooling

Durham University

Suite of simulations: GIMIC/OWLS

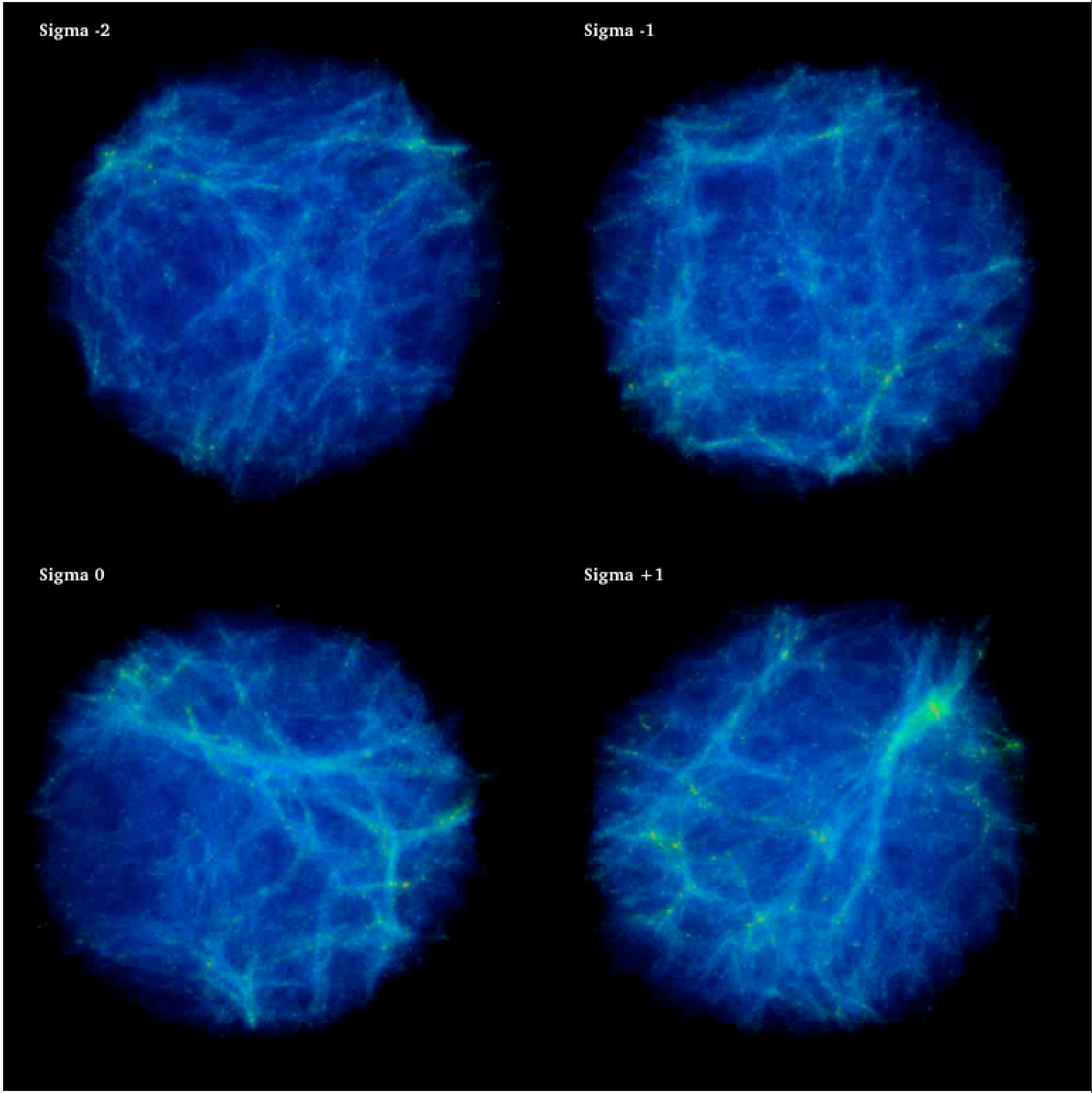
Galaxy-Intergalactic Medium Interaction Calculation



Zoomed simulations of 5 spheres picked from the Millennium Simulation

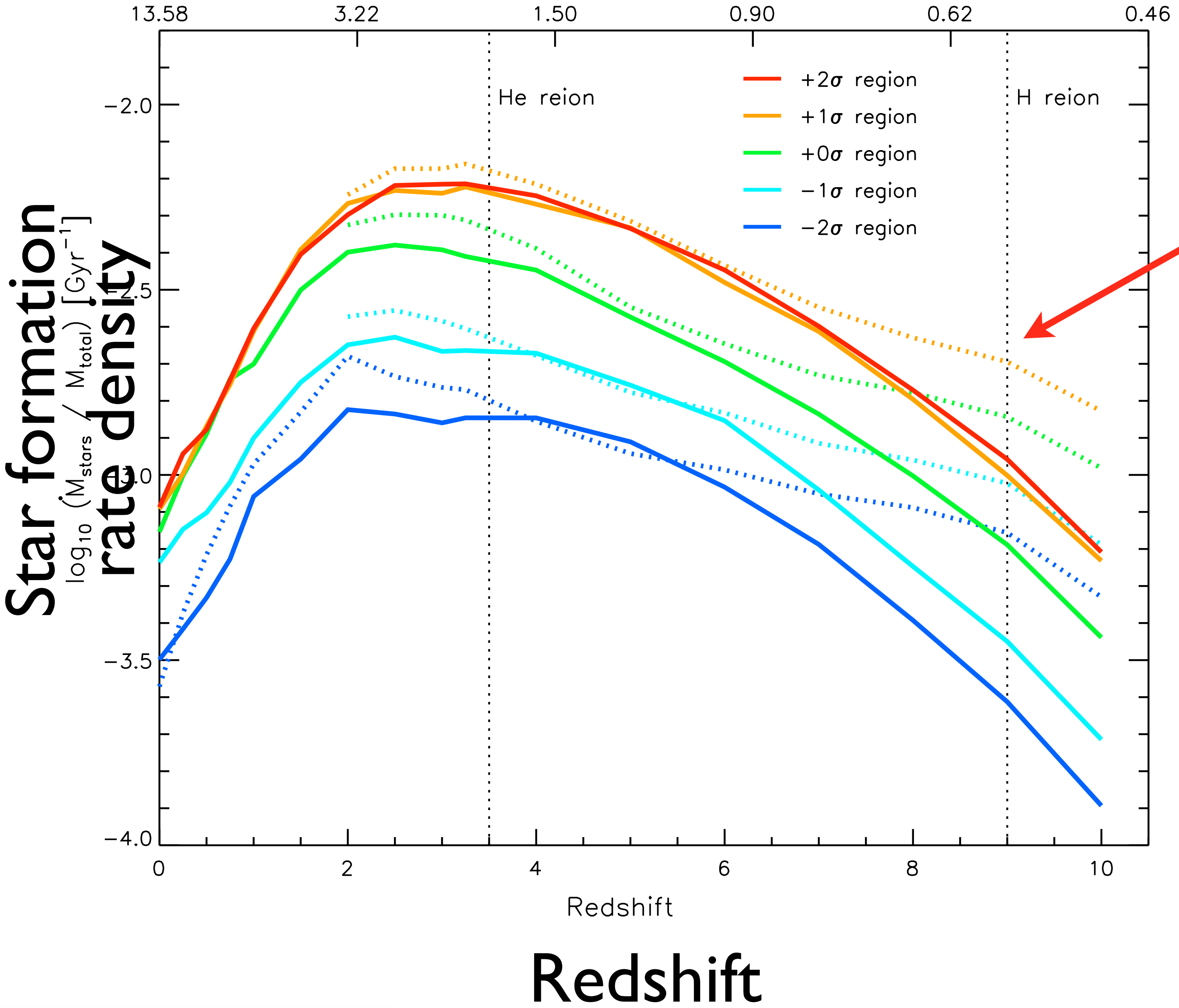
Combine LSS with high numerical resolution

Durham University



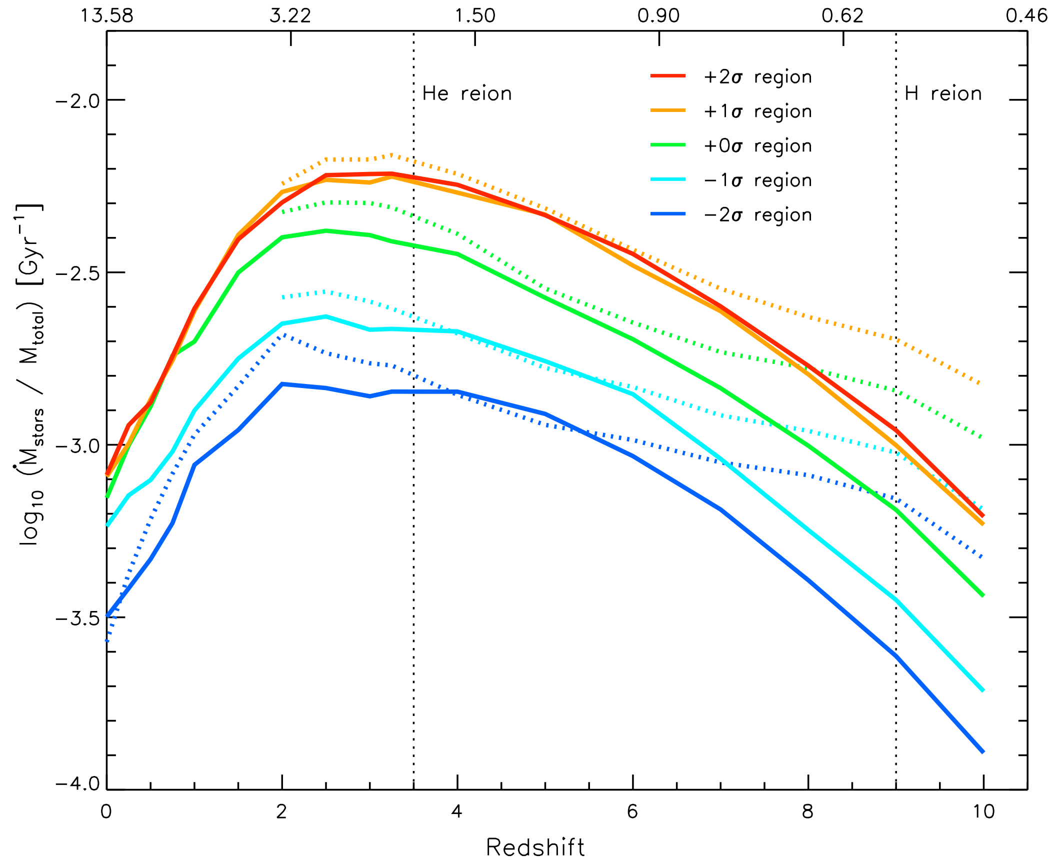
Tom Theuns

reionization and galaxies



HI reionization suppresses global star formation

Virgo



If reionization due to low-mass galaxies, radiative feedback might lead to extended EoR.

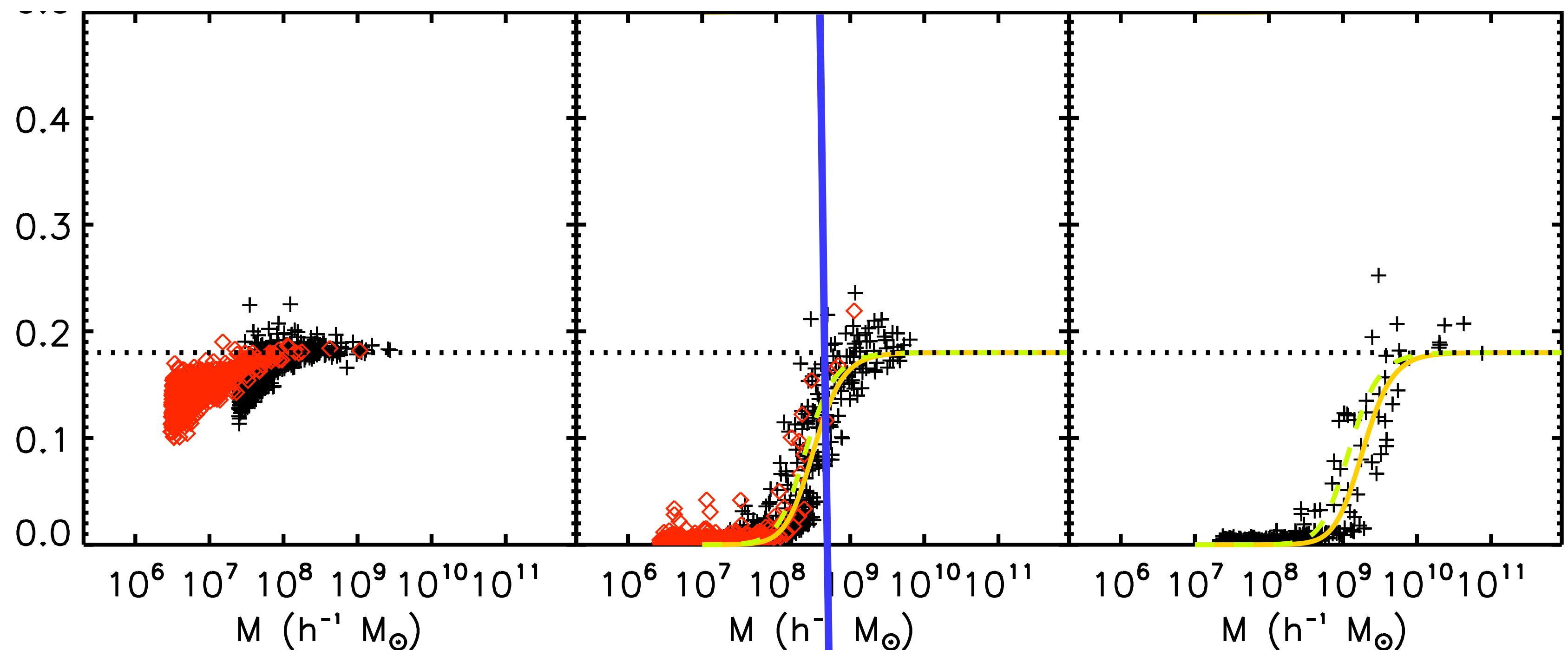
reionization and galaxies

$z_{reion}=9$

Baryon-loss of galaxies during reionization

z=9.3 z=5 z=2

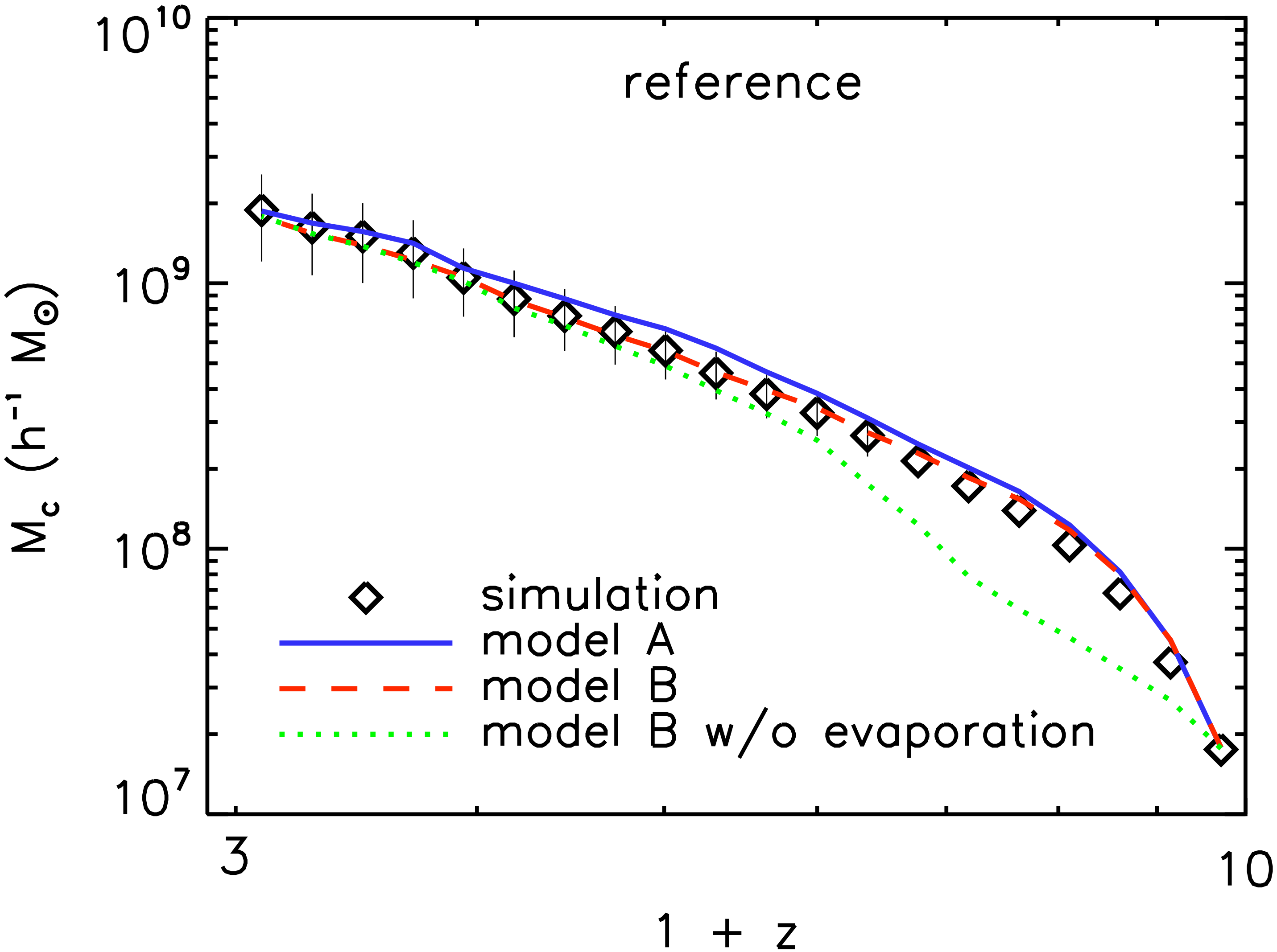
Baryon fraction



Characteristic mass

Okamoto et al 08

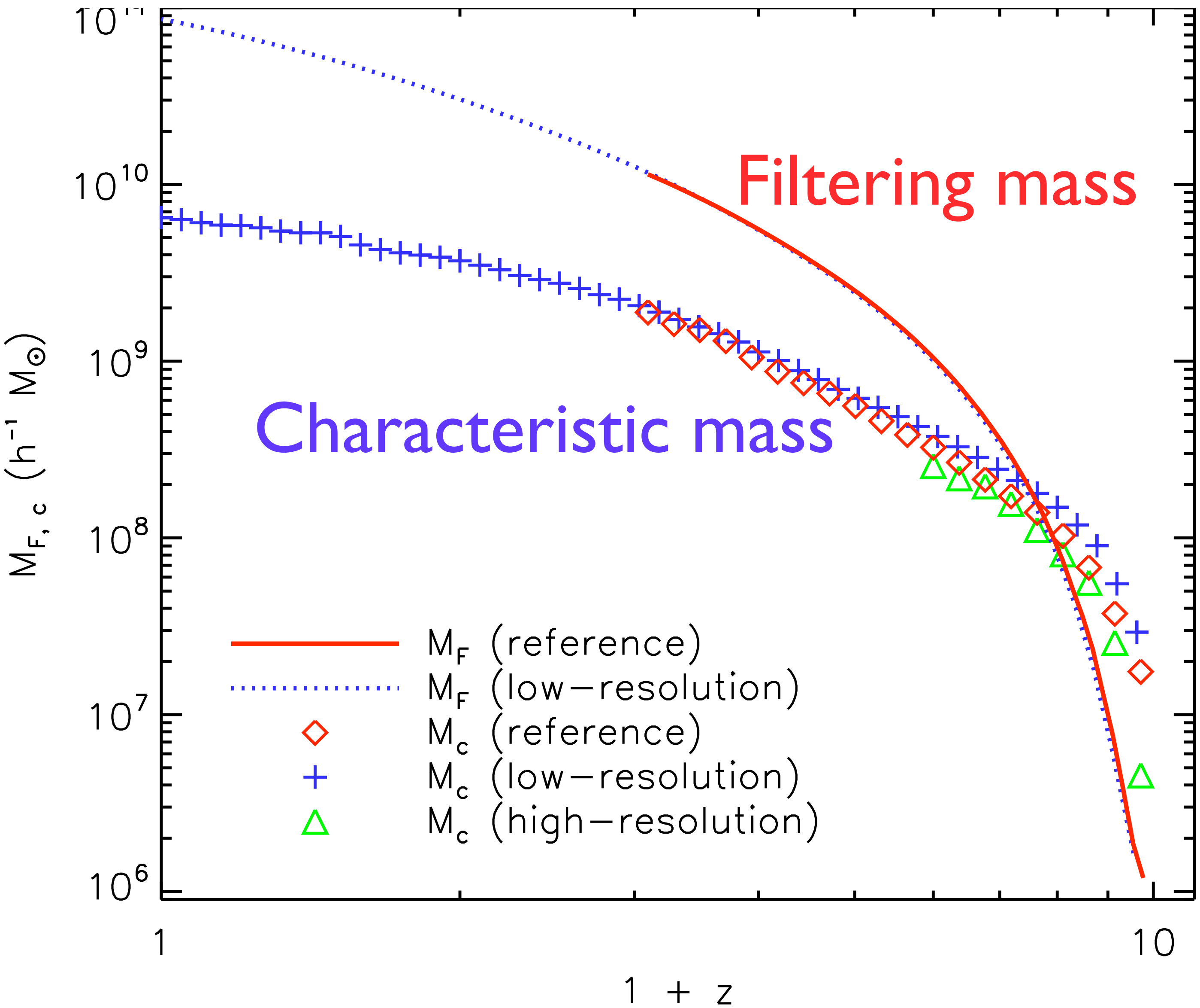
reionization and galaxies



Model limits accretion of hot gas onto small haloes, and photo-evaporation

Okamoto et al 08

reionization and galaxies

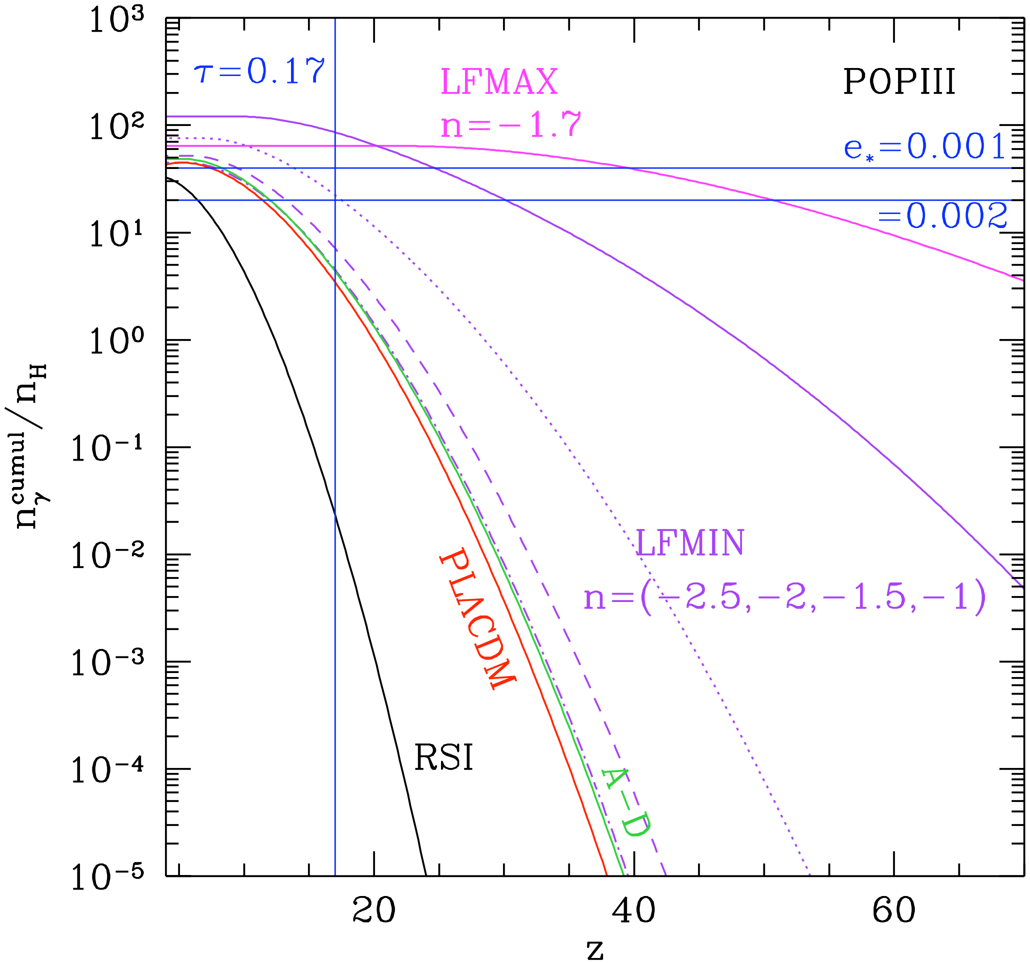


Characteristic mass is much smaller than filtering mass

Okamoto et al 08

reionization and sources

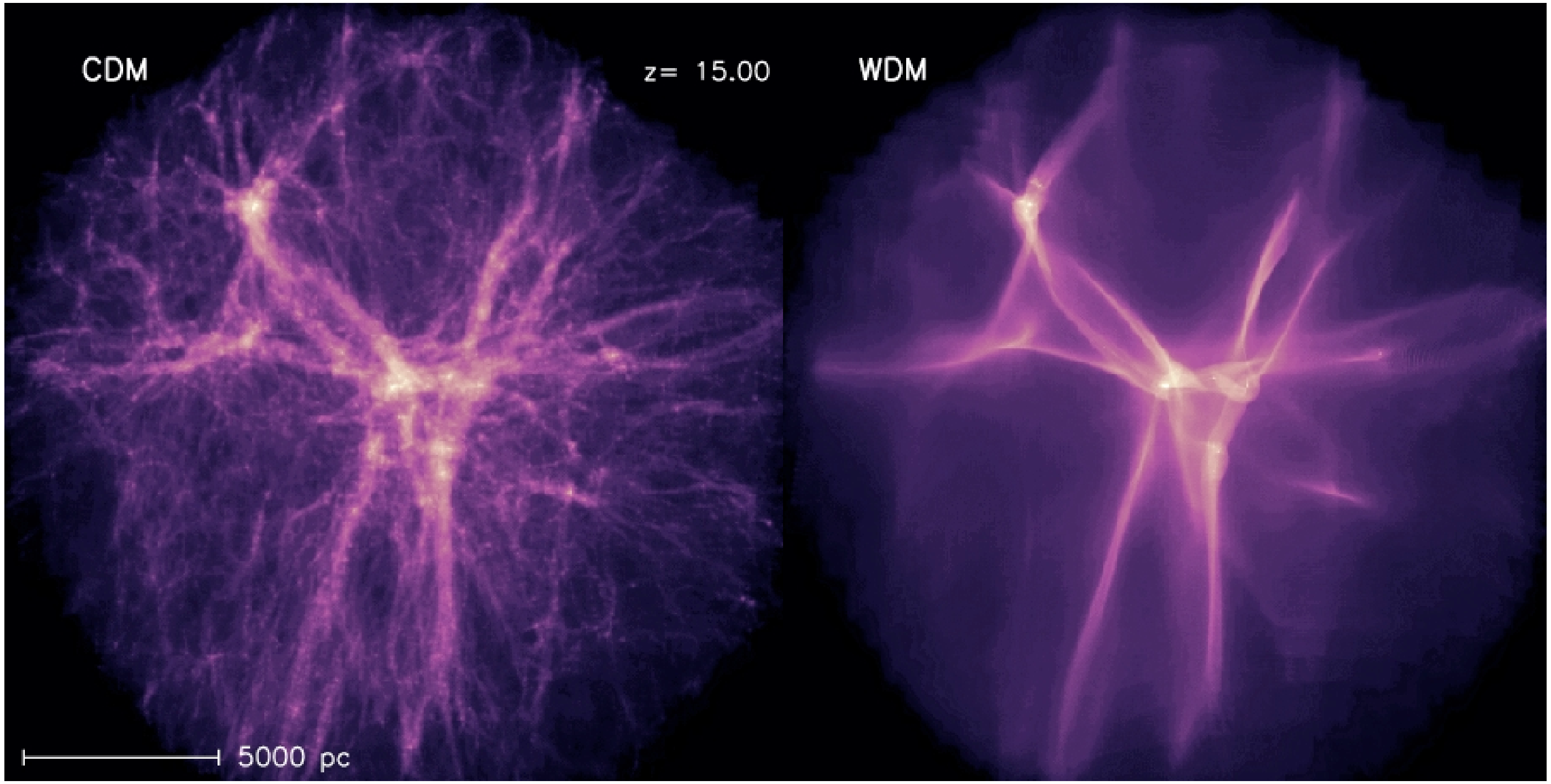
Cumulative number of ionizing photons



Does early reionization constrain small-scale powerspectrum?

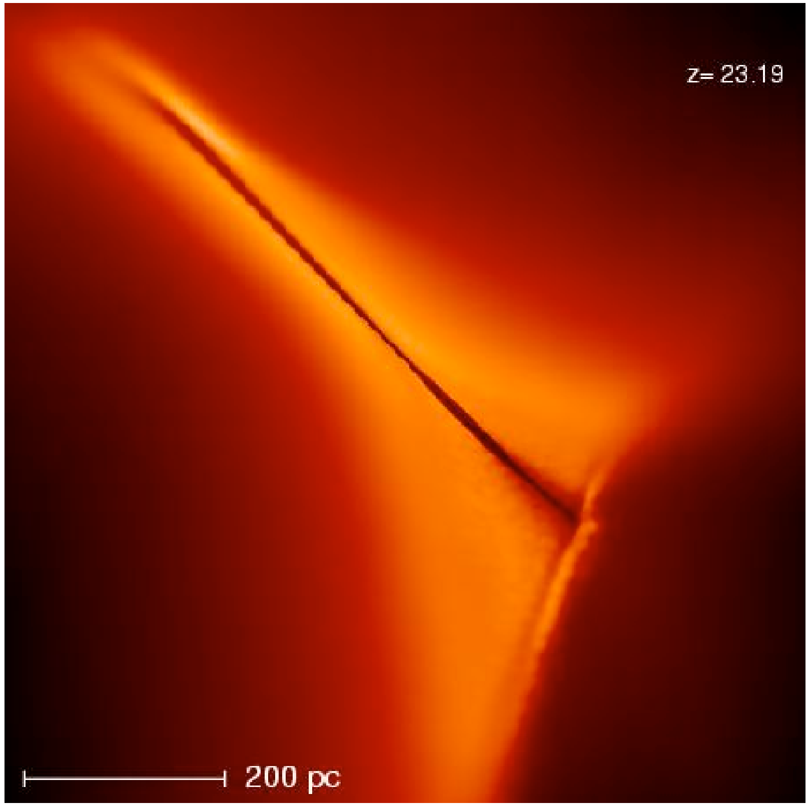
Sugiyama et al 05

Structure formation is suppressed below warm dark matter free streaming scale. How does that affect first stars?

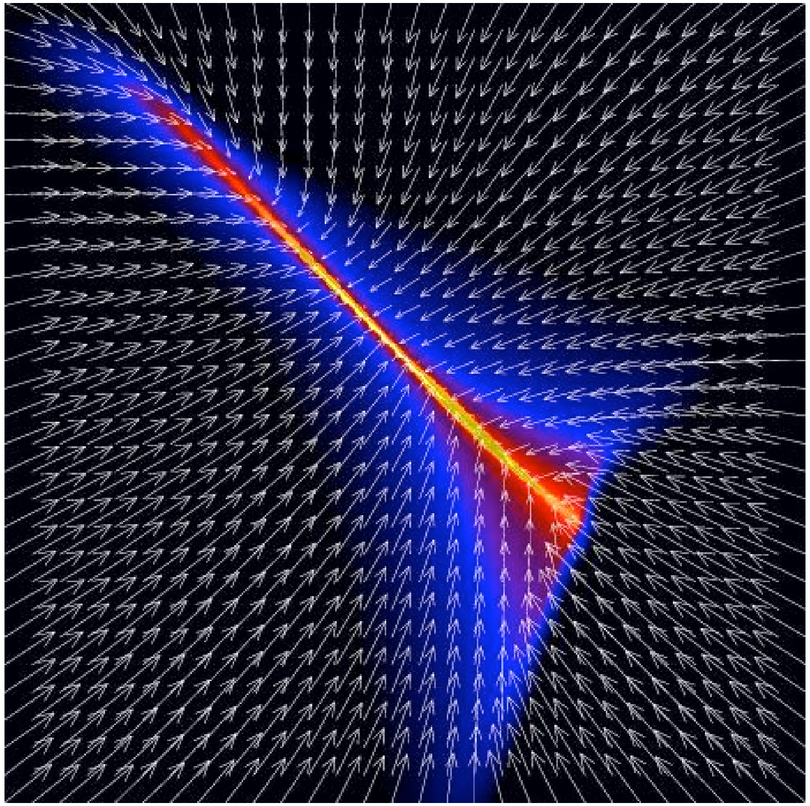


M_{dm} = 3 keV, M_{fs} ~ 3 x 10^8 solar masses

First stars in WDM form in filaments

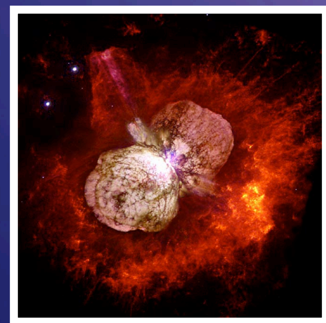


Temperature

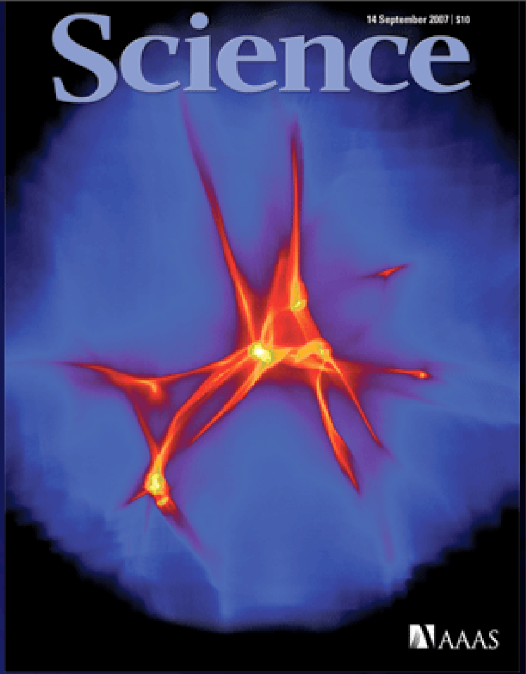


Density

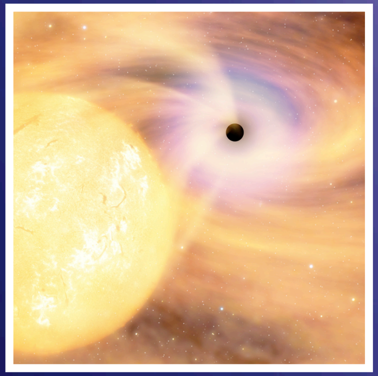
M_{dm} = 3 keV, M_{fs} ~ 3 x 10^8 solar masses



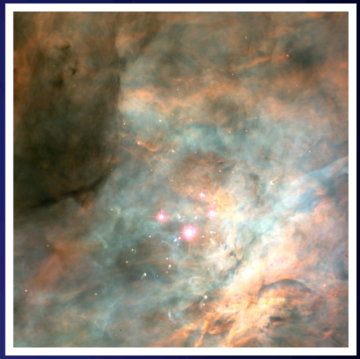
Massive stars



Gao & Theuns
Science 2007



Seed for super-massive BH



Low-mass stars

Conclusions

z_{reion} > 6, but fluctuation in ionised fraction large

are we observing end-of-pre-overlap at z=6?

gap statistics, and QSO near-sizes confusing

was to be expected?

why do we not see the OI forest?

enrichment and metals go together?

what can topology tell us about sources?

need more modelling