Hell Reionization

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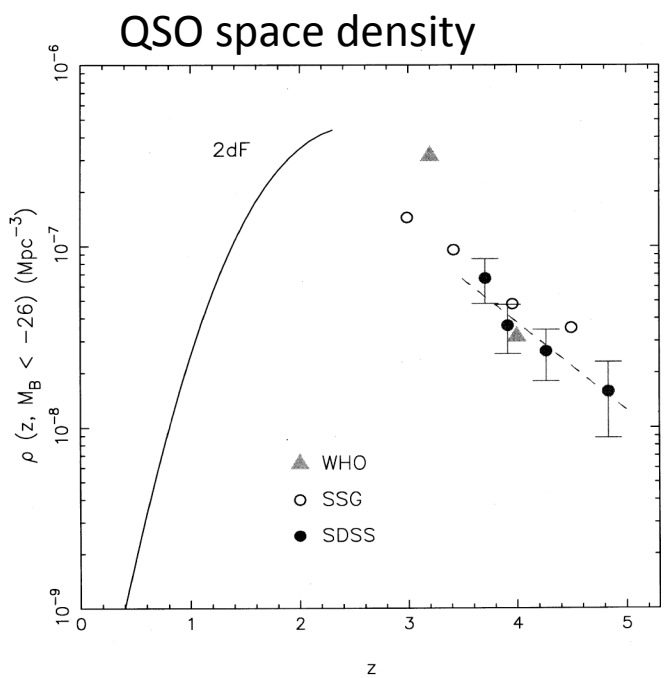
astro-ph/0807.2799

Reionization History

- Best Guess for reionization history of IGM
  - stars ionized HI (13.6 eV) and HeI (24.6 eV) at z > 6
  - quasars ionized HeII (54.4 eV) at z ~ 3.



Fan et al. (2001)

Evidence for HeII reionization occurring at z ~ 3:

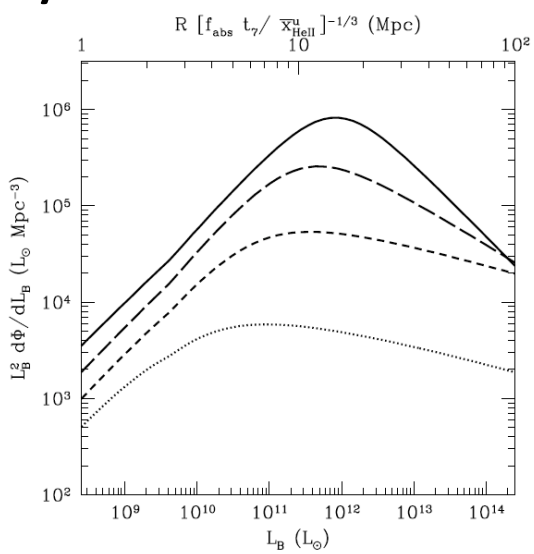
- Measurements from Lyα forest find high IGM temperature and temperature increase at z~3
- Gunn-Peterson troughs in HeII Lyα forest at z > 2.8
- IGM Metal absorption lines suggest ionizing background is hardening around 55eV between 3.5 > z > 2.5 (Songaila '98, Boksenberg et al. '03, etc.)

Why study HeII reionization?

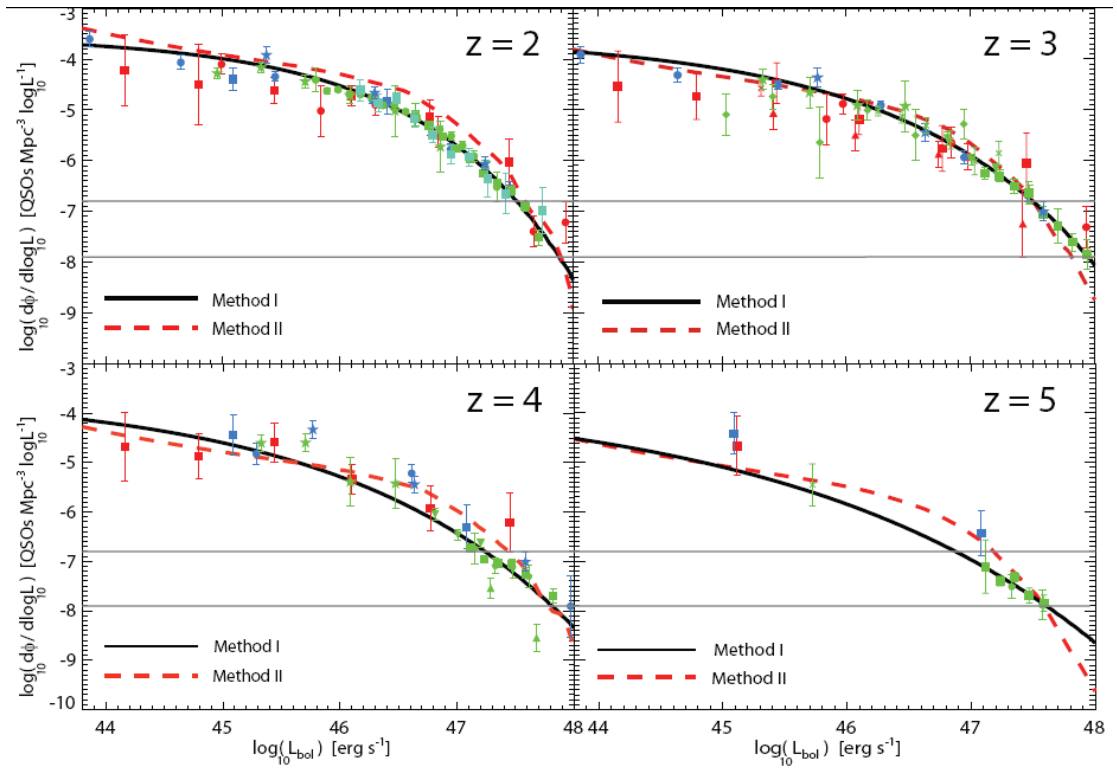
- Determines IGM temperature
- Less modeling uncertainty compared to HI reionization: many observations of quasars and of the z~3 IGM properties
- May be detectable in current data sets
- Affects cosmological parameter measurements as well as measurements of other quantities from the Lyman-α forest.

The sources: Quasars

- Beamed?
- Spectral index (α)?
- Lifetime/duty cycle?

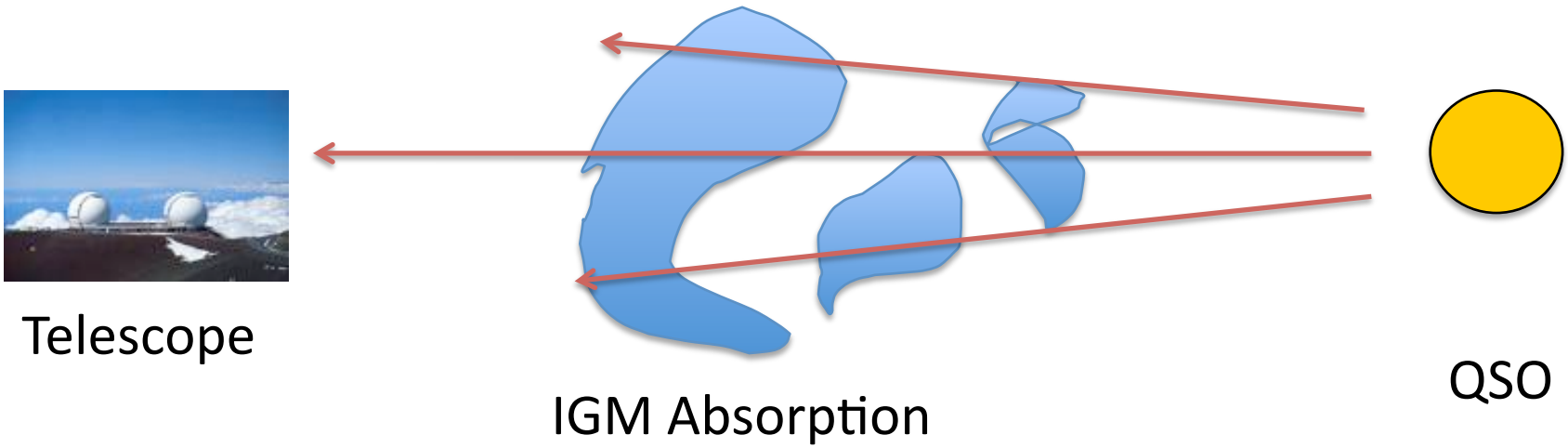


Furlanetto & Oh (2008)



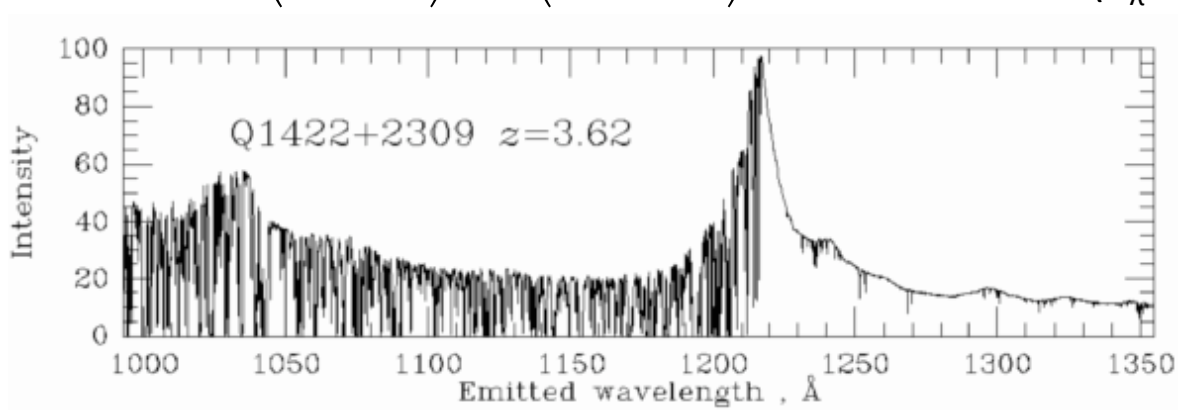
Hopkins et al. (2007)
Plot from McQuinn et al. (2008)

The Lyα forest and the IGM



$$\tau \sim 1 \left(\frac{1+z}{4}\right)^{9/2} (1+\delta_b)^2 \left(\frac{T}{10^4\ \mathrm{K}}\right)^{-0.7} \left(\frac{\Gamma}{10^{-12}\mathrm{s}^{-1}}\right)^{-1}$$

Dense clouds are Jeans smoothed ($L_J \sim T^{.5}$), and lines are thermally broadened ($\sigma_\lambda \sim T^{.5}$)



Keck HiRes observation, Rauch

Cosmological simulations provide excellent agreement (e.g. Cen et al. 94):

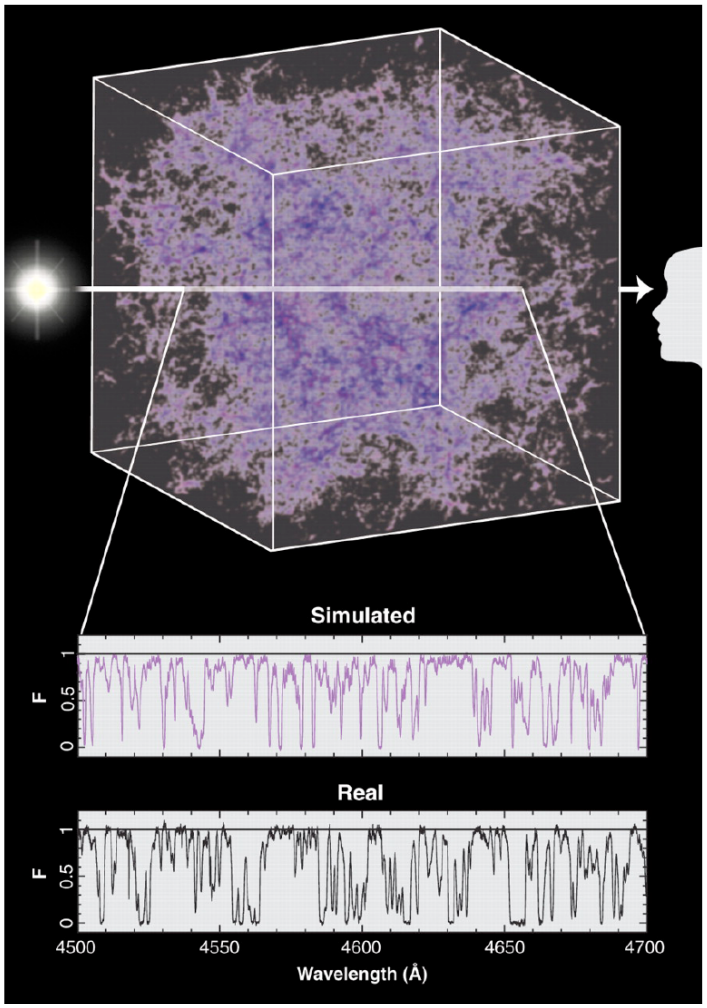
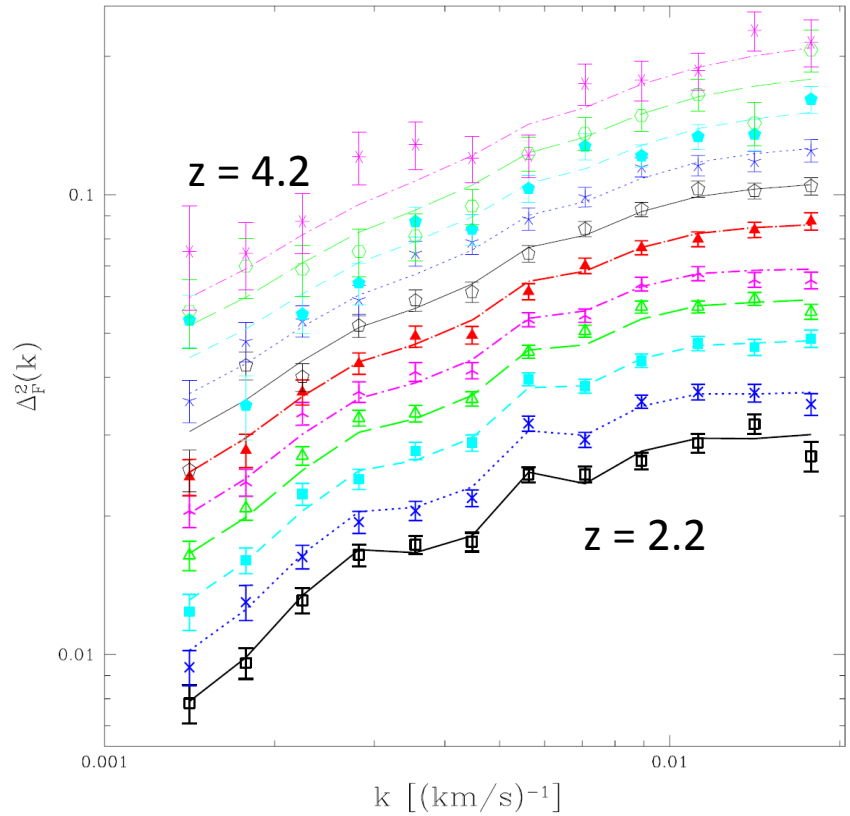


Illustration from
Faucher-Giguere, Lidz, and Hernquist (2008)

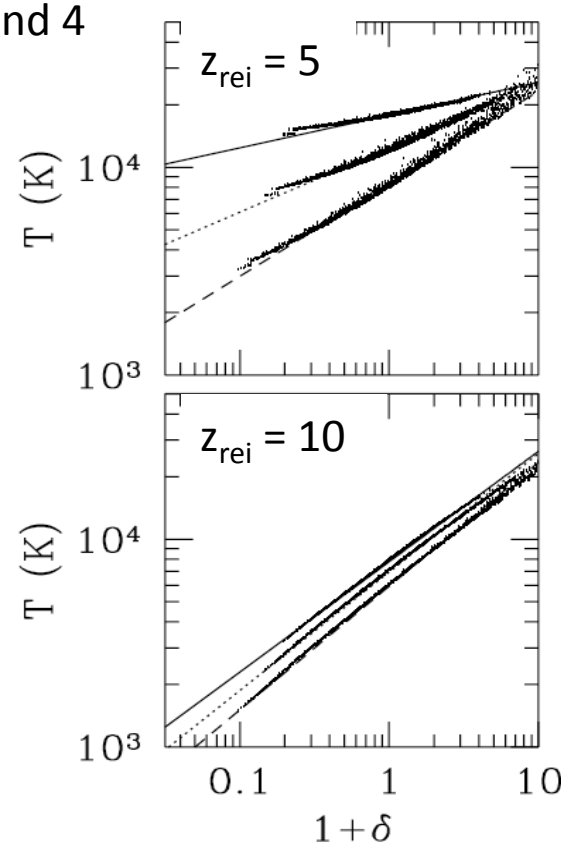
Cosmology from forest :



McDonald et al. (2005)
using SDSS QSO sample

Temperature-Density Relation in HI Lyman-α forest

Scatter plot of simulated gas parcels in the IGM at z = 2, 3, and 4



Hui and Gnedin (1997)

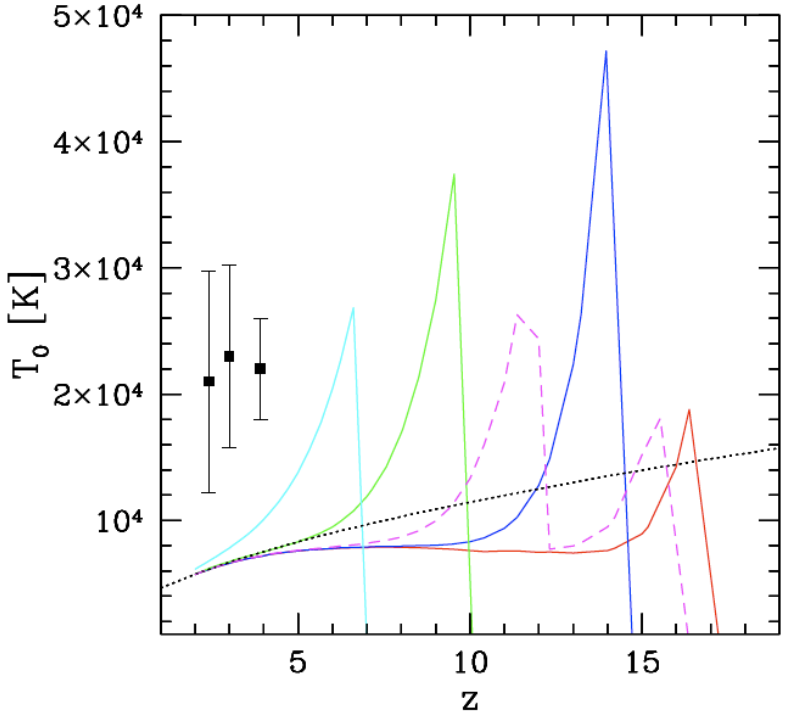
- A power-law relationship between T and ρ is assumed in all estimates from Lyα forest (such as estimates of cosmological parameters)

Is this justified if HeII reionization occurs at z ~ 3?

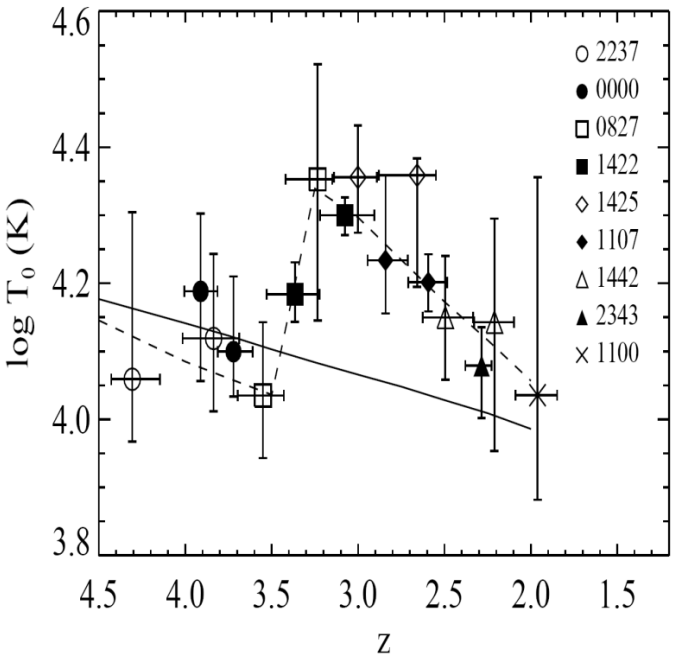
Lyα Forest Temperature

T_0 = temperature at mean density

Hui & Haiman (2003)

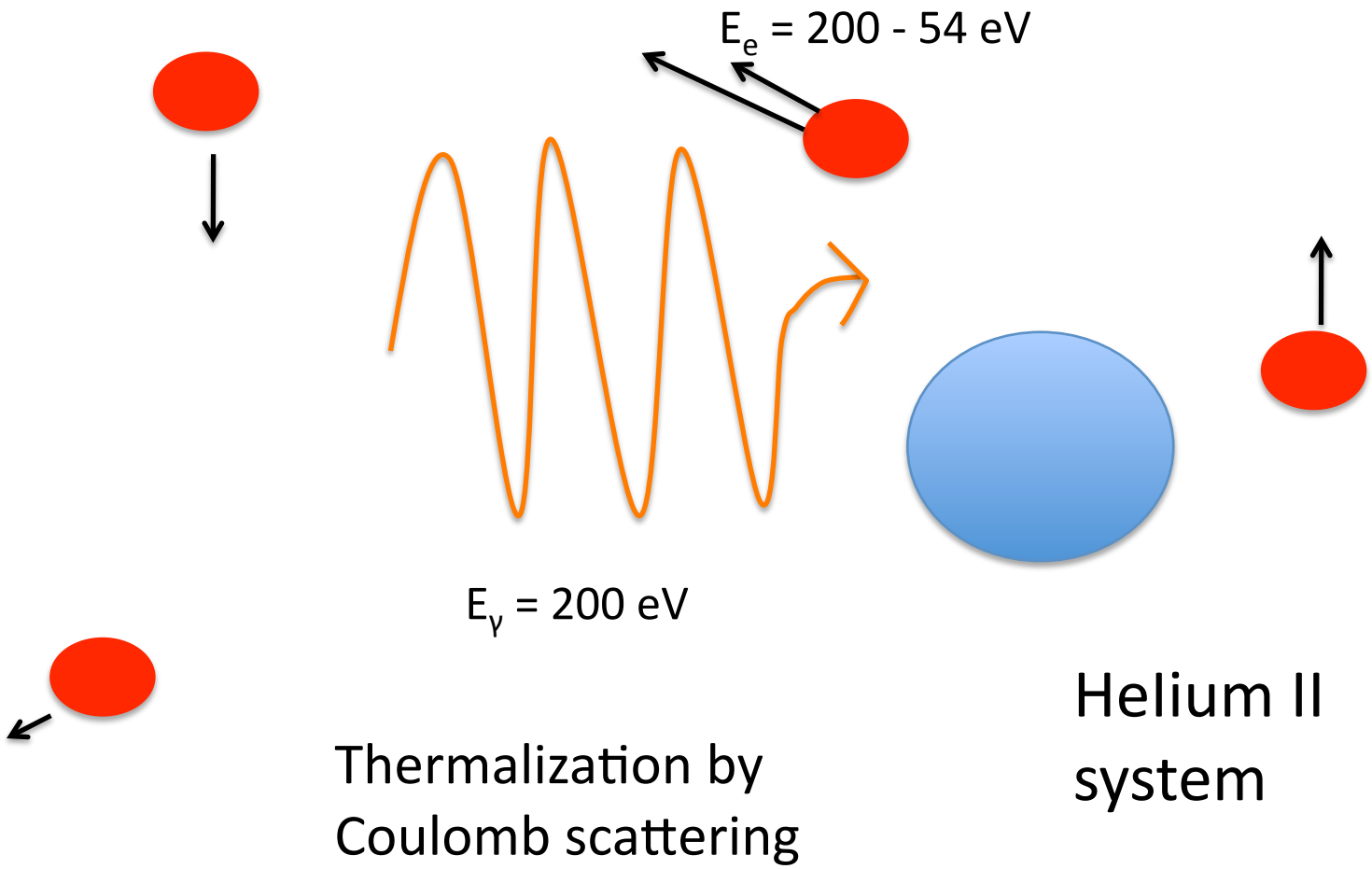


Schaye et al. (2000)



Temperature increase confirmed by Ricotti et al. 2000 and Theuns et al. 2000.
McDonald '01 and Zaldarriaga '01 did not find a temperature increase.

Photo-ionization heating



Important Numbers

- Heating Input
  - Optically thick limit

$$\Delta T_{HeII} = 30{,}000 \left(\frac{0.5}{\alpha - 1}\right) \mathrm{K}$$

  - Optically thin limit

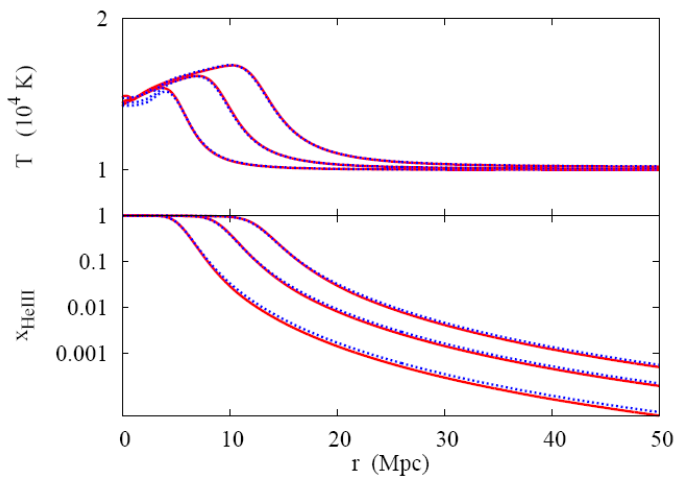
$$\Delta T_{HeII} = 5{,}000 \left(\frac{3.5}{\alpha + 2}\right) \mathrm{K}$$

  - Mean Free Path

$$\lambda = 5\, x_{\mathrm{HeII}}^{-1} \left(\frac{E_\gamma}{100\,\mathrm{eV}}\right)^3 \left(\frac{1+z}{4}\right)^{-2} \text{comoving Mpc}$$

  - For α = 1.5, ½ energy in photons with E > 150 eV, 1/2 of photons below 90 eV

Propagation of QSO HeIII front in Homogenous Universe at z = 3

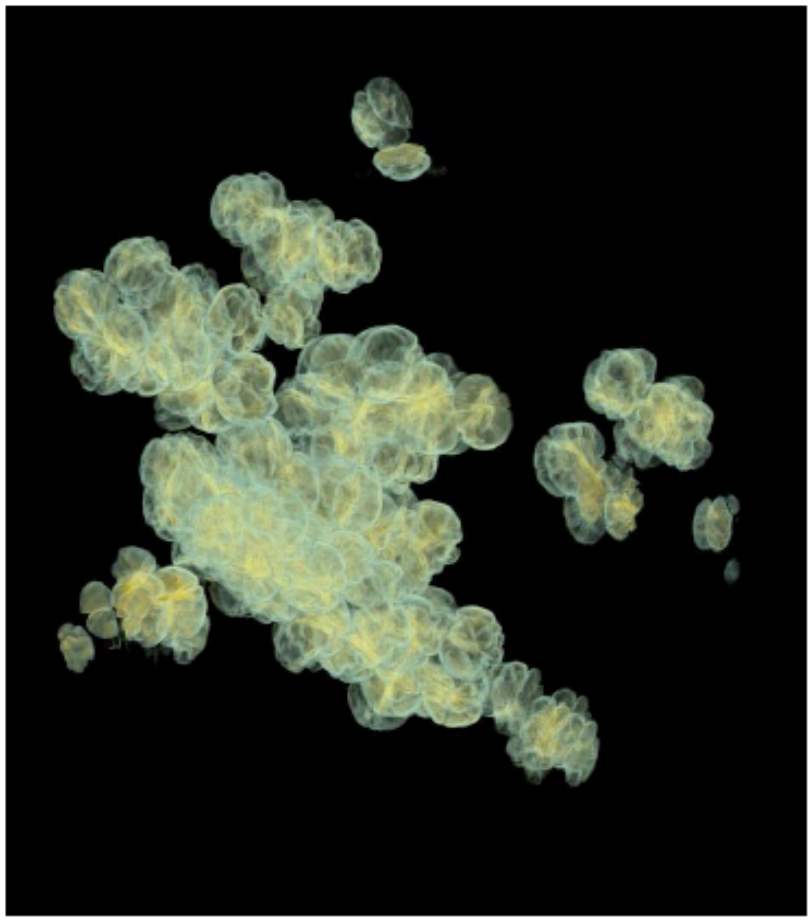


An L_* quasar has R_b = 20 cMpc

SIMULATING HEII REIONIZATION

Previous Work on HeII Reionization

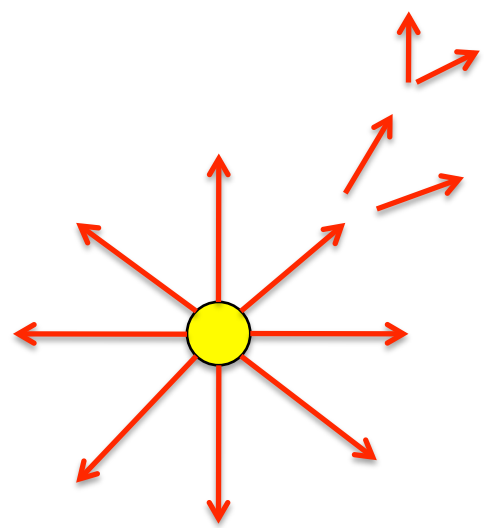
- Assumed all the heating is within HeIII front/sharp fronts
- Used simulation boxes that are too small (<= 100 Mpc)
- Did not study heating and spatial structure of temperature fluctuations



HeII reionization in 100 Mpc box (Paschos et al. 2007)

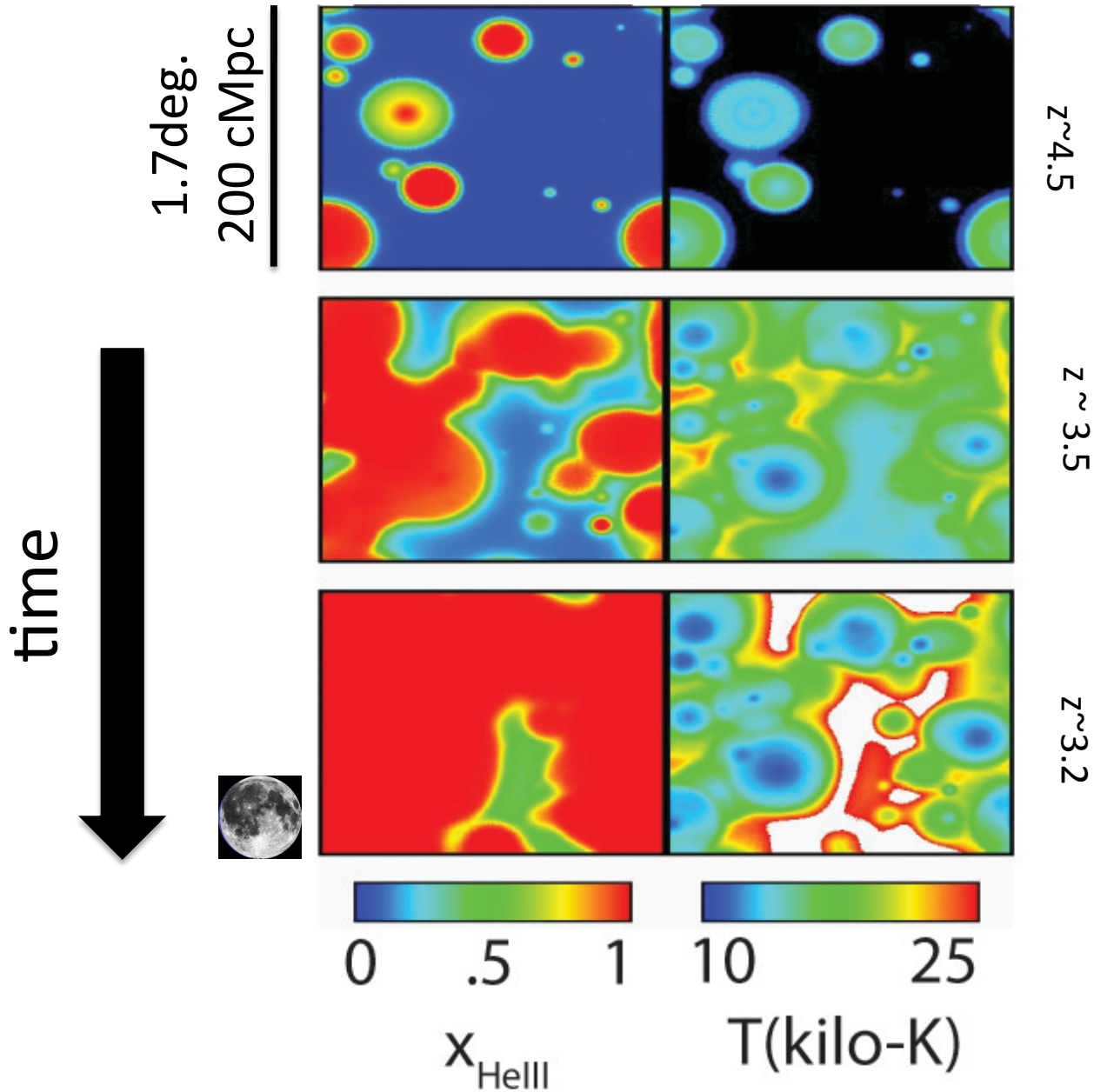
Radiative Transfer Simulations

- Follow rays from each source. Case B recombination. Rays travel c Δt in a timestep.
- $256^3/512^3$ grid RT in 190 Mpc and 430 Mpc box
- 1024^3 N-body simulations. Assume smoothed dark matter field approximates gas.
- Radiative transfer done in post processing.
- $M_{cell} = 10^9 - 10^{10}\ M_{sun}$. We have run a series of tests that show results are robust to resolution. (McQuinn '08)
- Initial conditions:
  - T = 10,000 K @ z = 6
  - $x_{HeII} = 1$, $x_{HI} \sim 0$



Fiducial QSO model assumes t_{qso} ~50 Myr, α = 1.6, isotropic emission, & L_* QSOs in ~$10^{12}\ M_{sun}$ halos

No density Fluctuations



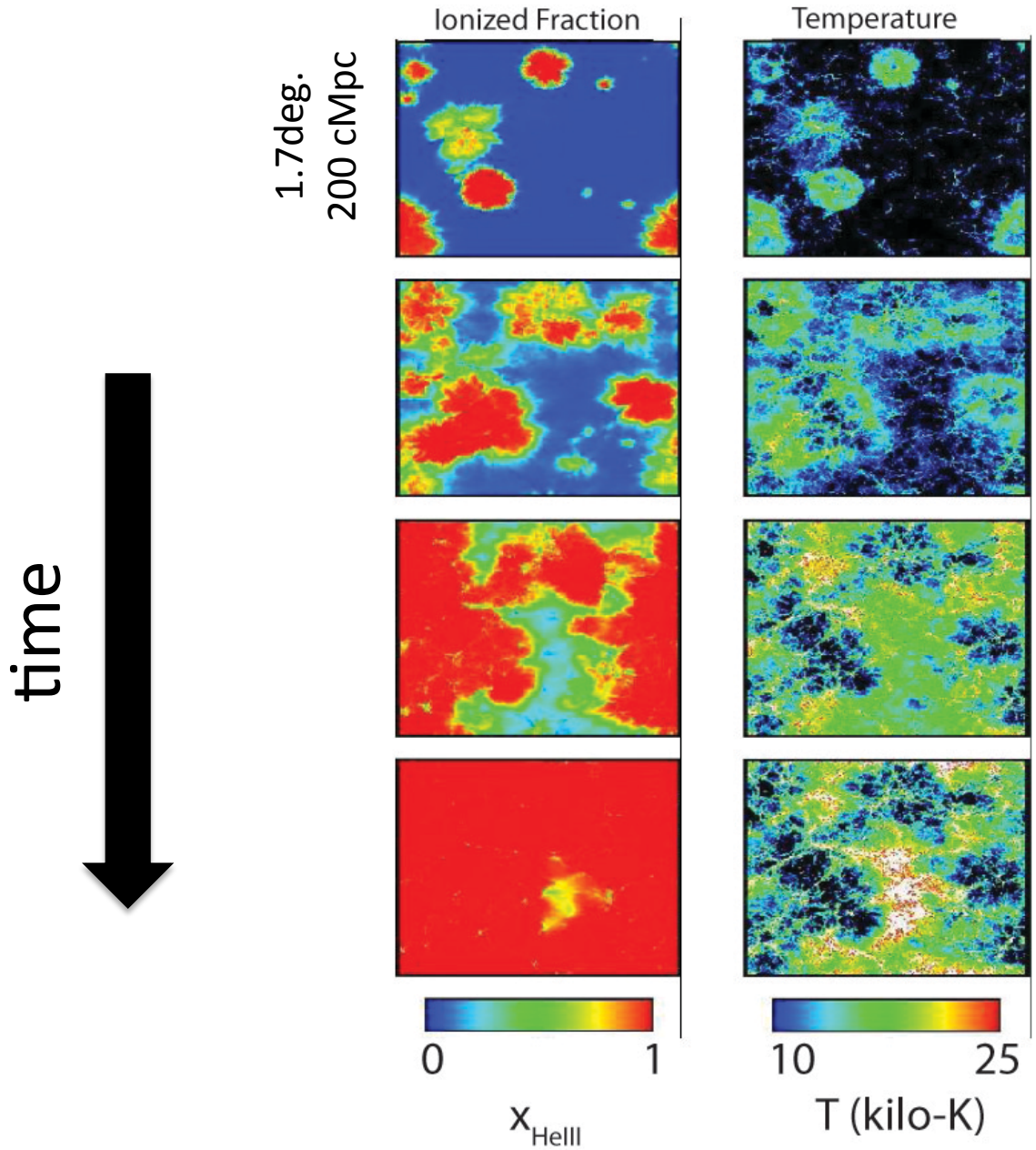
White > 25,000 K
Black < 10,000 K

Initial conditions (@ z = 6):
$x_{HeIII} = 0$
$T = 10^4$ K

QSO model assumes t_{qso} ~50 Myr, $\alpha = 1.6$, isotropic emission, & L_* QSOs in 10^{12} M_{sun} halos

McQuinn et al. (2008)

Using LCDM Density Field

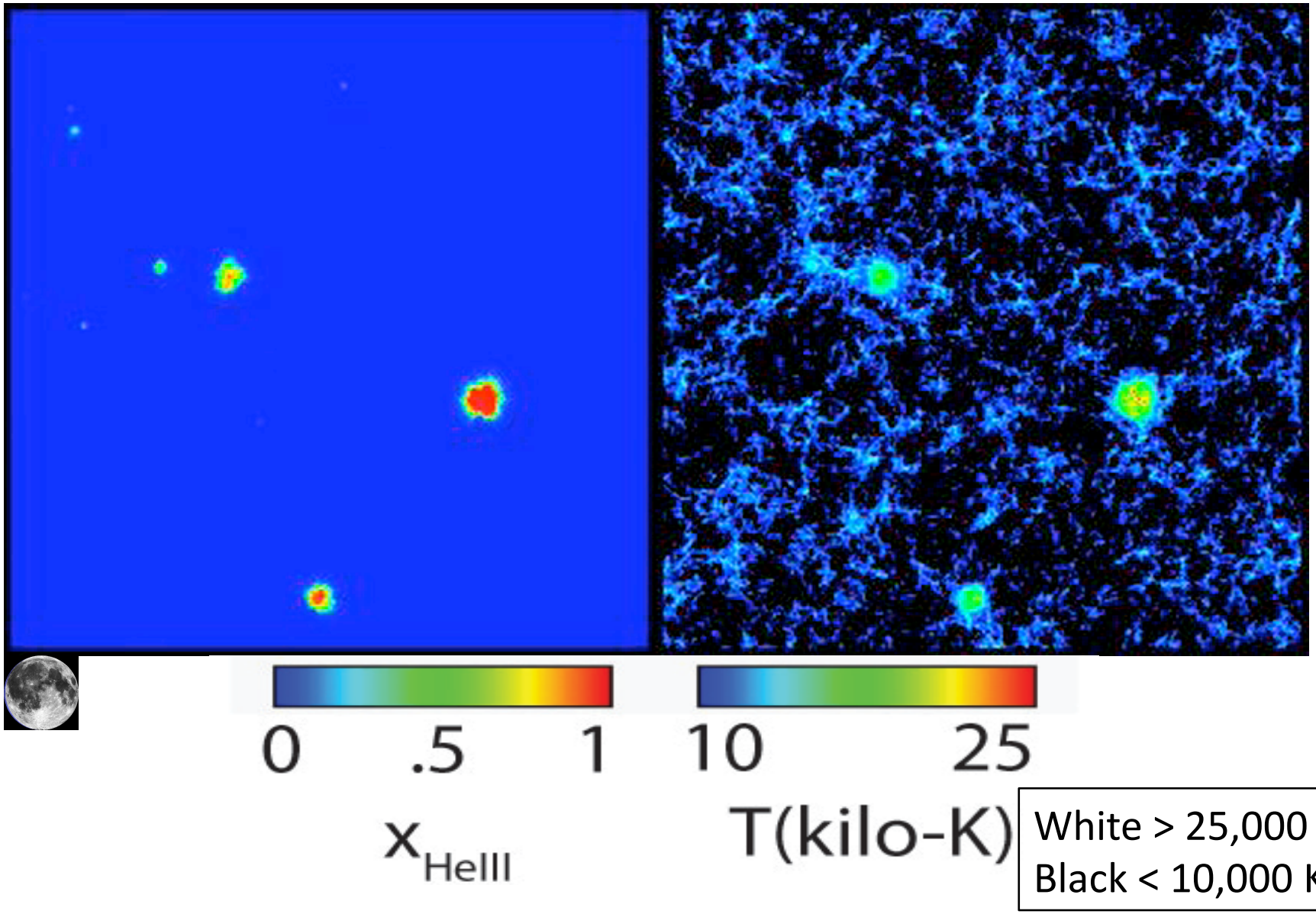


QSO model assumes t_{qso} ~50 Myr, α = 1.6, isotropic emission, & L_* QSOs in 10^{12} M_{sun} halos

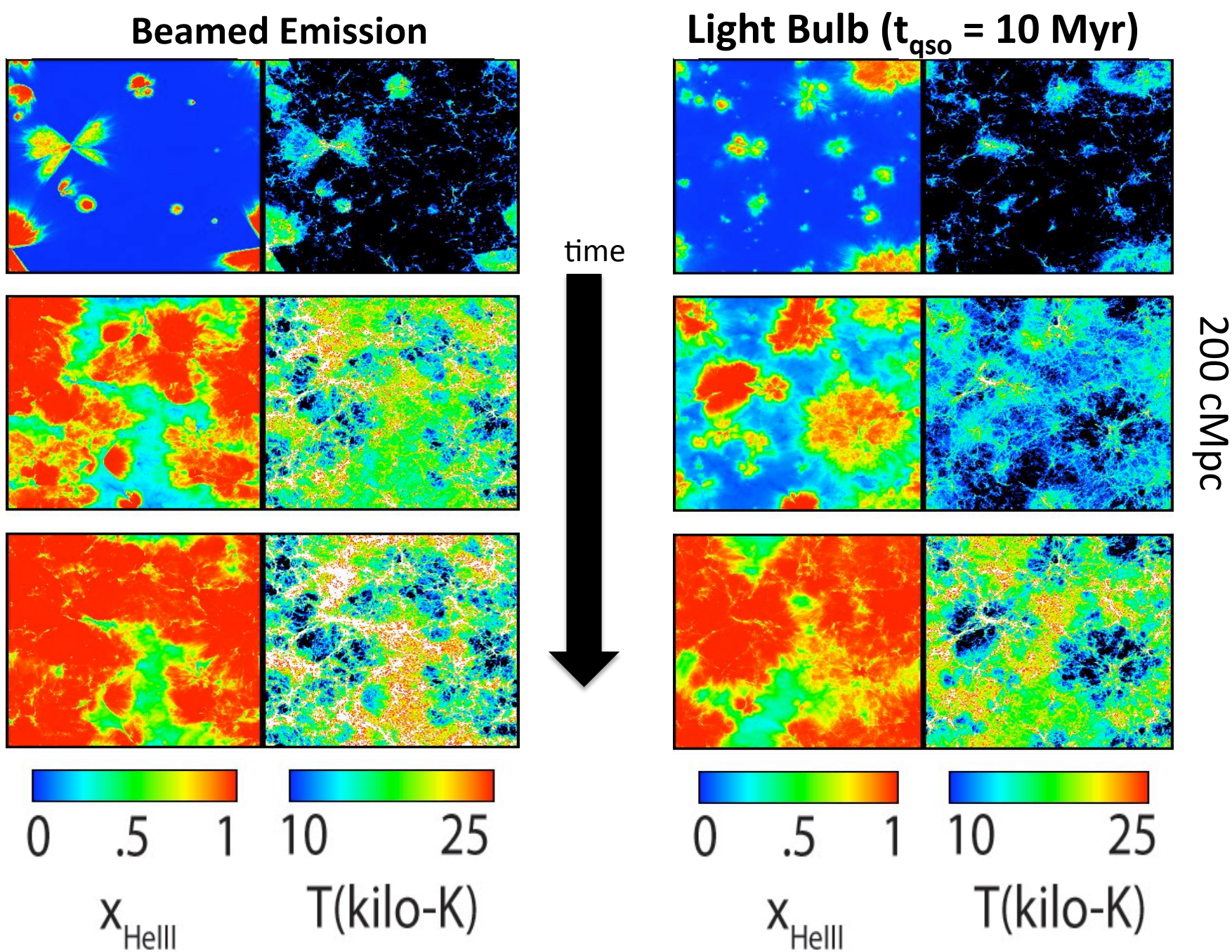
White > 25,000 K
Black < 10,000 K

McQuinn et al. (2008)

HeII Reionization in 430 Mpc (4°) Box



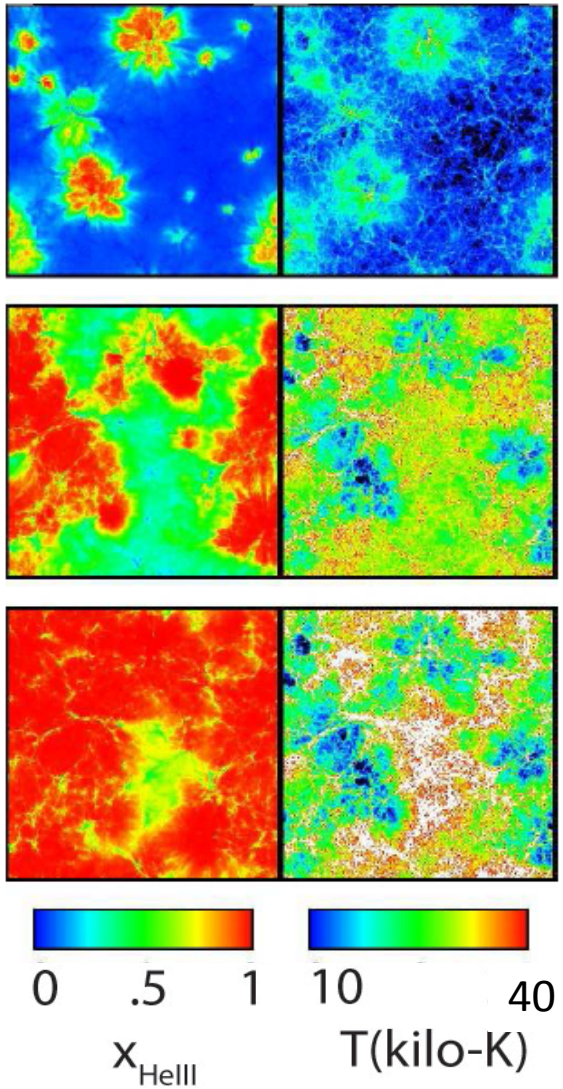
White > 25,000 K
Black < 10,000 K


Beamed Emission
Light Bulb (t_{qso} = 10 Myr)
time
200 cMpc
0
.5
1
10
25
x_{HeIII}
T(kilo-K)
0
.5
1
10
25
x_{HeIII}
T(kilo-K)

Harder Spectrum

- UV spectral index uncertain
  - 1.6 results if extrapolate between optical and X-ray of individual QSOs
  - Telfer et al ('02) finds 1.6 between 1 Ry and 4 Ry from composite spectrum
  - Scott et al ('04) finds 0.6 between 1 Ry and 4 Ry
  - HeII absorption in host system will harden spectrum

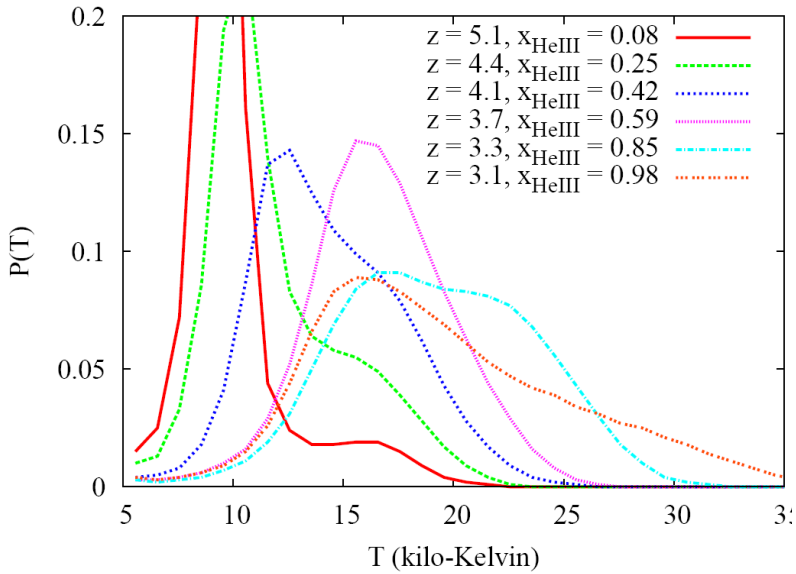
simulation w/ α=0.6 rather than 1.6



McQuinn et al. (2008)

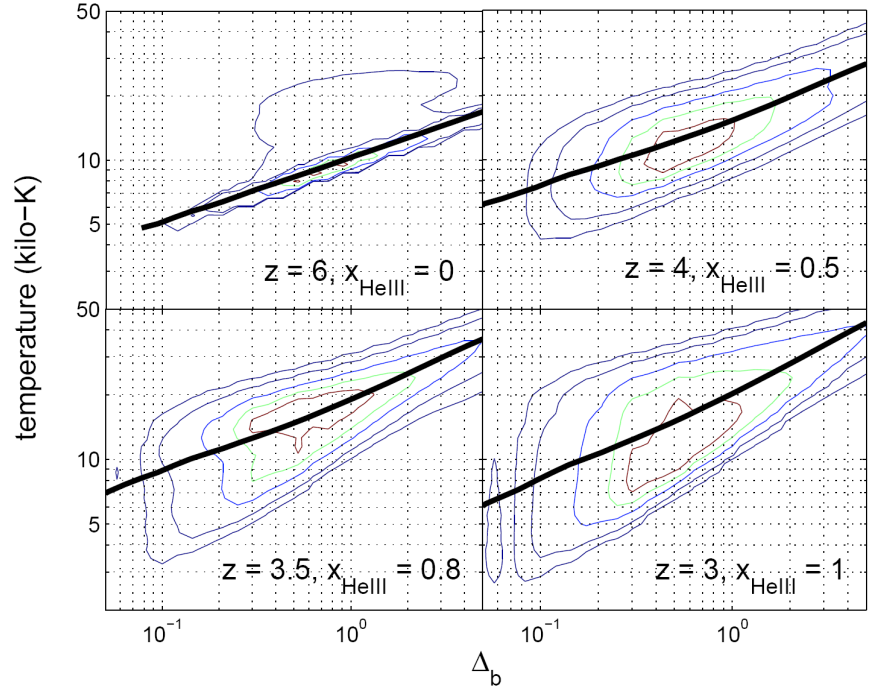
Temperature Structure

Temperature at mean density



T-Δ Relation

Contours enclose 33, 66, 90, 99, 99.9% of cells

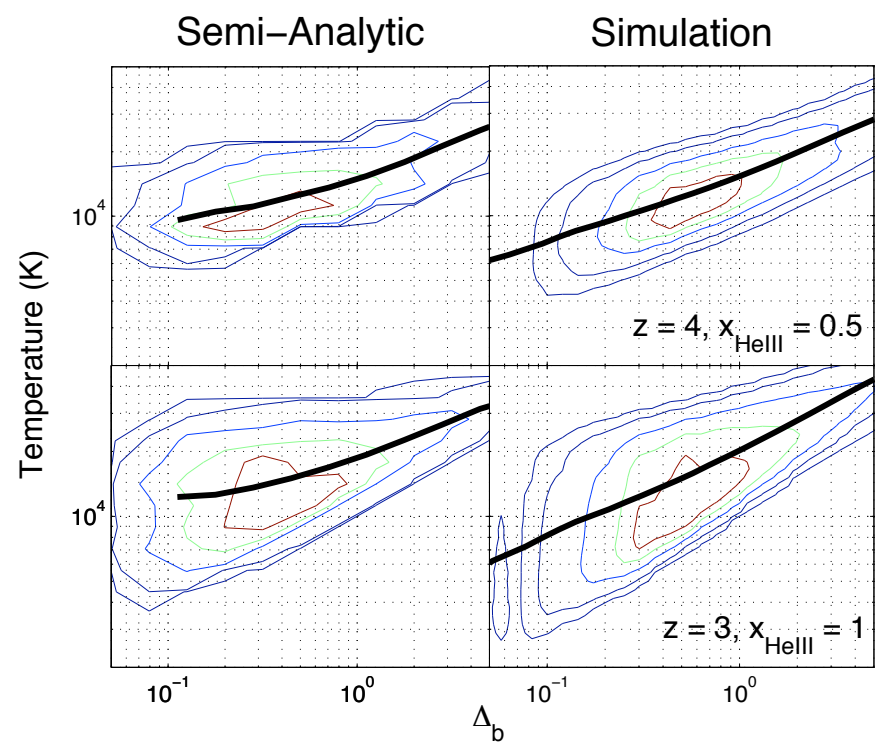


Gas Density in units of mean density

McQuinn et al. (2008)

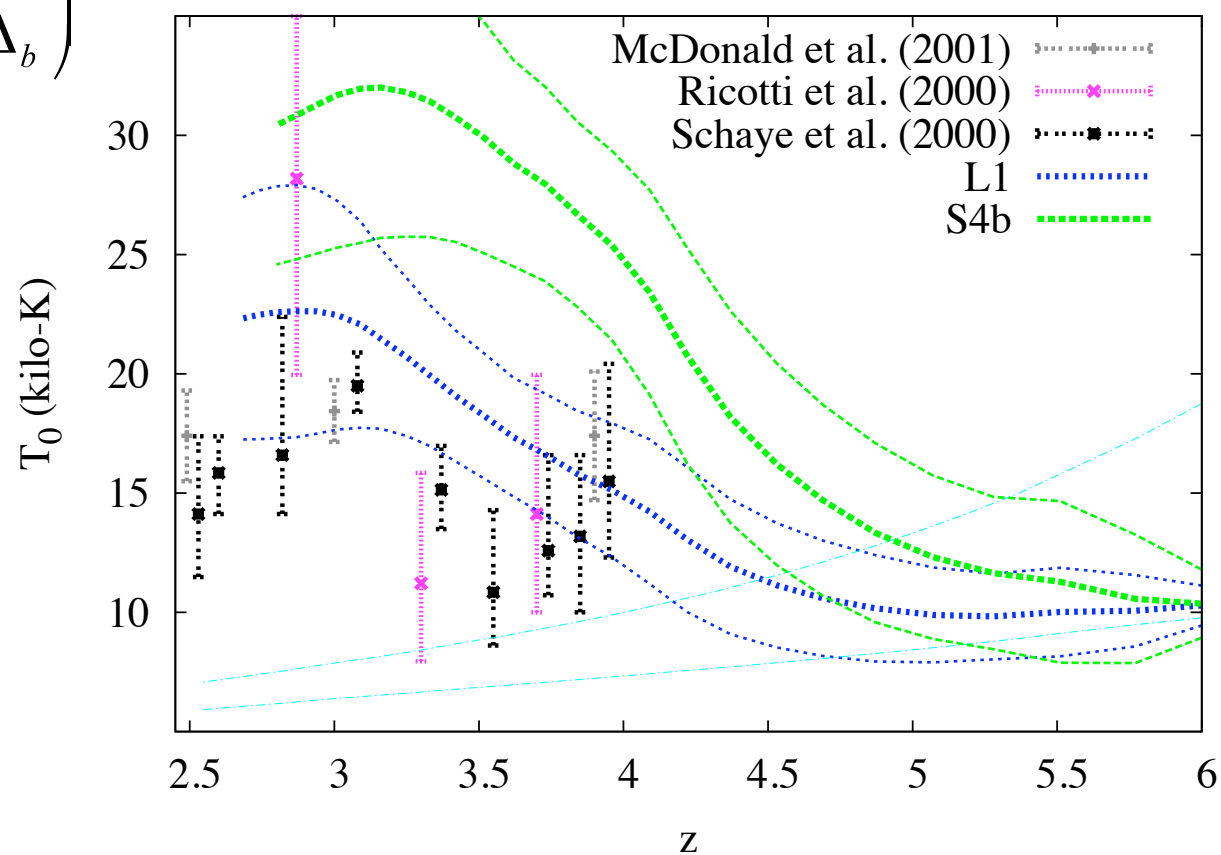
Toy Model

- Photons with MFP > bubble size go into uniform background
- A region is heated by background until an ionizing front crosses
- Hopkins et al '07 QSO luminosity function
- HeIII regions are uncorrelated with density
- Density evolved with Zel'dovich approximation



Comparison with Observations

$$T = T_0 \left(\frac{\Delta}{\Delta_b} \right)^{\gamma - 1}$$



McQuinn et al. (2008)

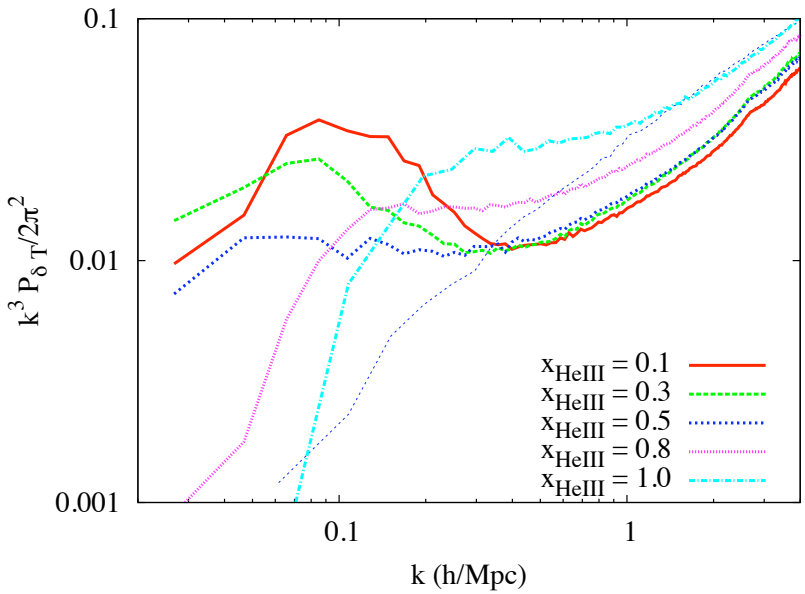
SEARCHING FOR HEIII BUBBLES IN HI AND HEII LYMAN-A FOREST

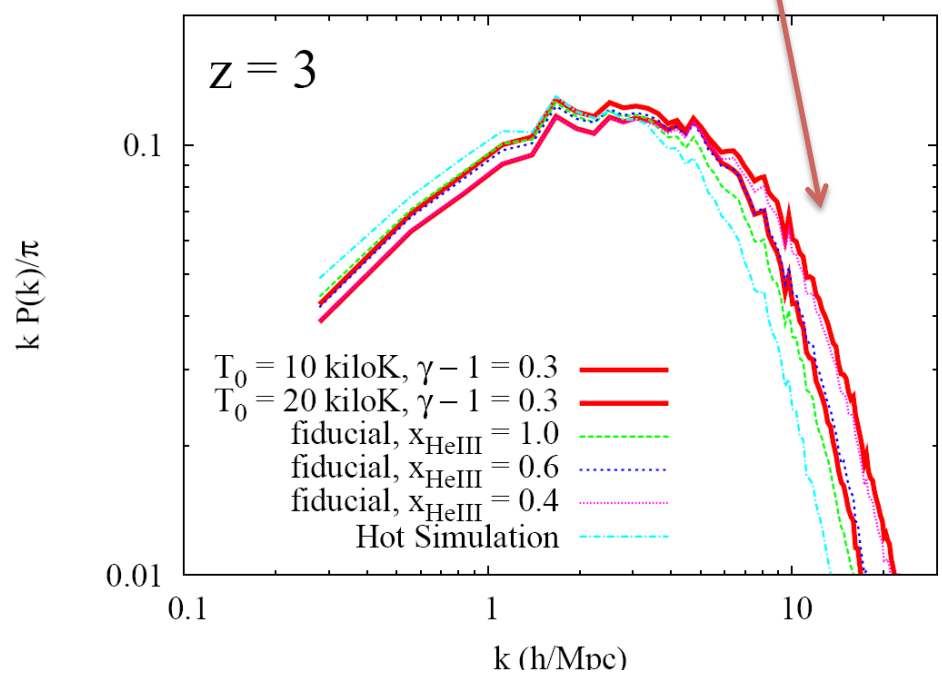
Lyα forest 1D Power Spectrum

Large Scales: used for Cosmology with SDSS

Small-scales: sensitive to temperature

Temperature Power Spectrum during HeII Reionization



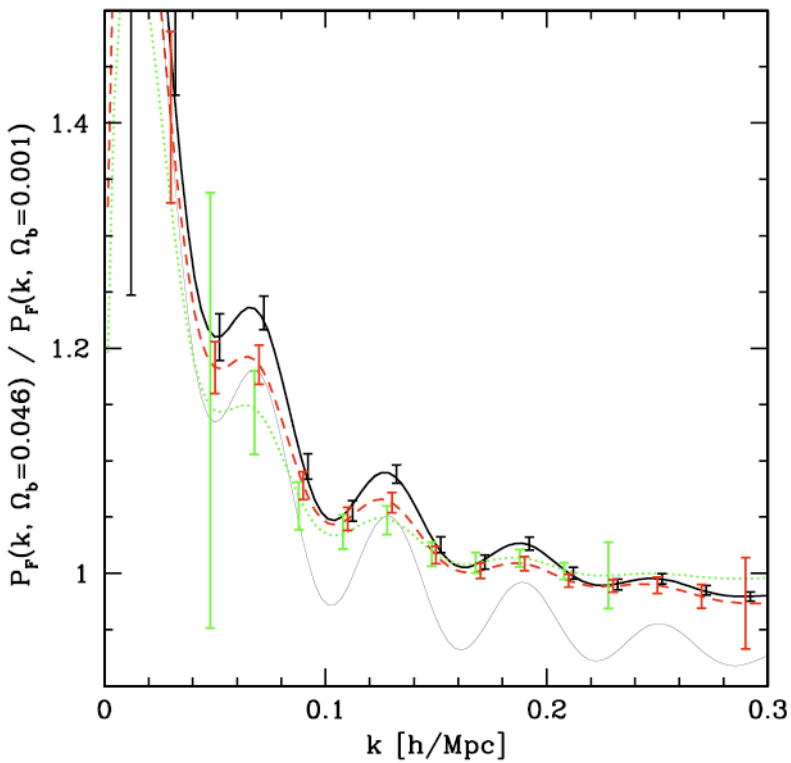


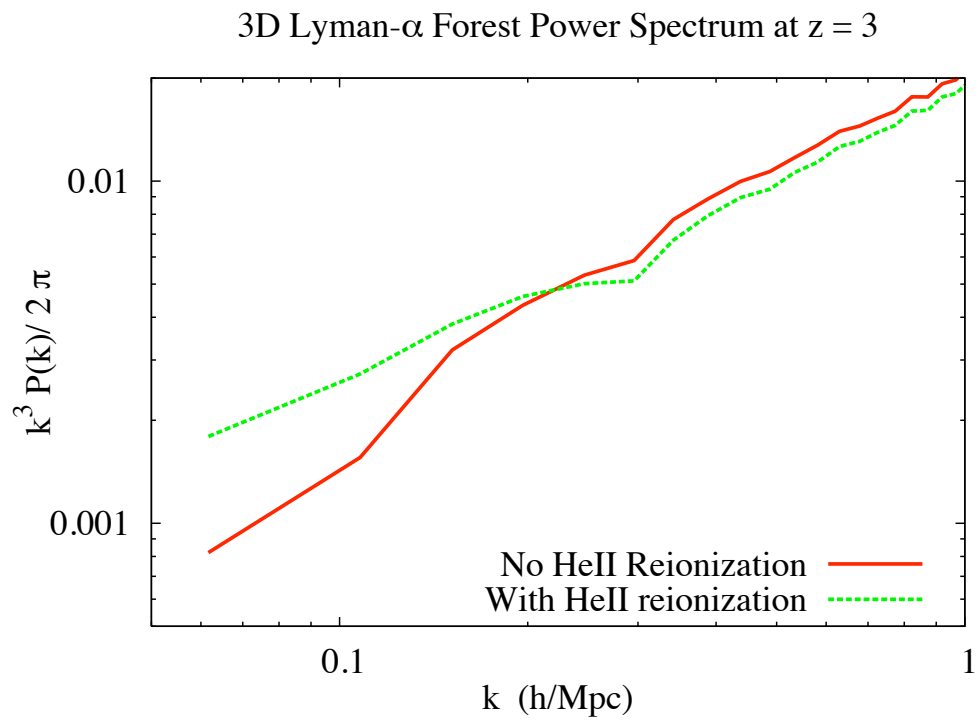
$$P_{1d}(k_\parallel) = \int_{k_\parallel}^{\infty} \frac{dk}{2\pi} k P_{3d}(k).$$

Lai et al. (2005) also showed with toy models that HeII reionization has small effect on large-scale 1D forest power spectrum.

3D Lyman-α Forest Power Spectrum

McDonald and Eisenstein (2007)
Errors are forecasts for SDSS III



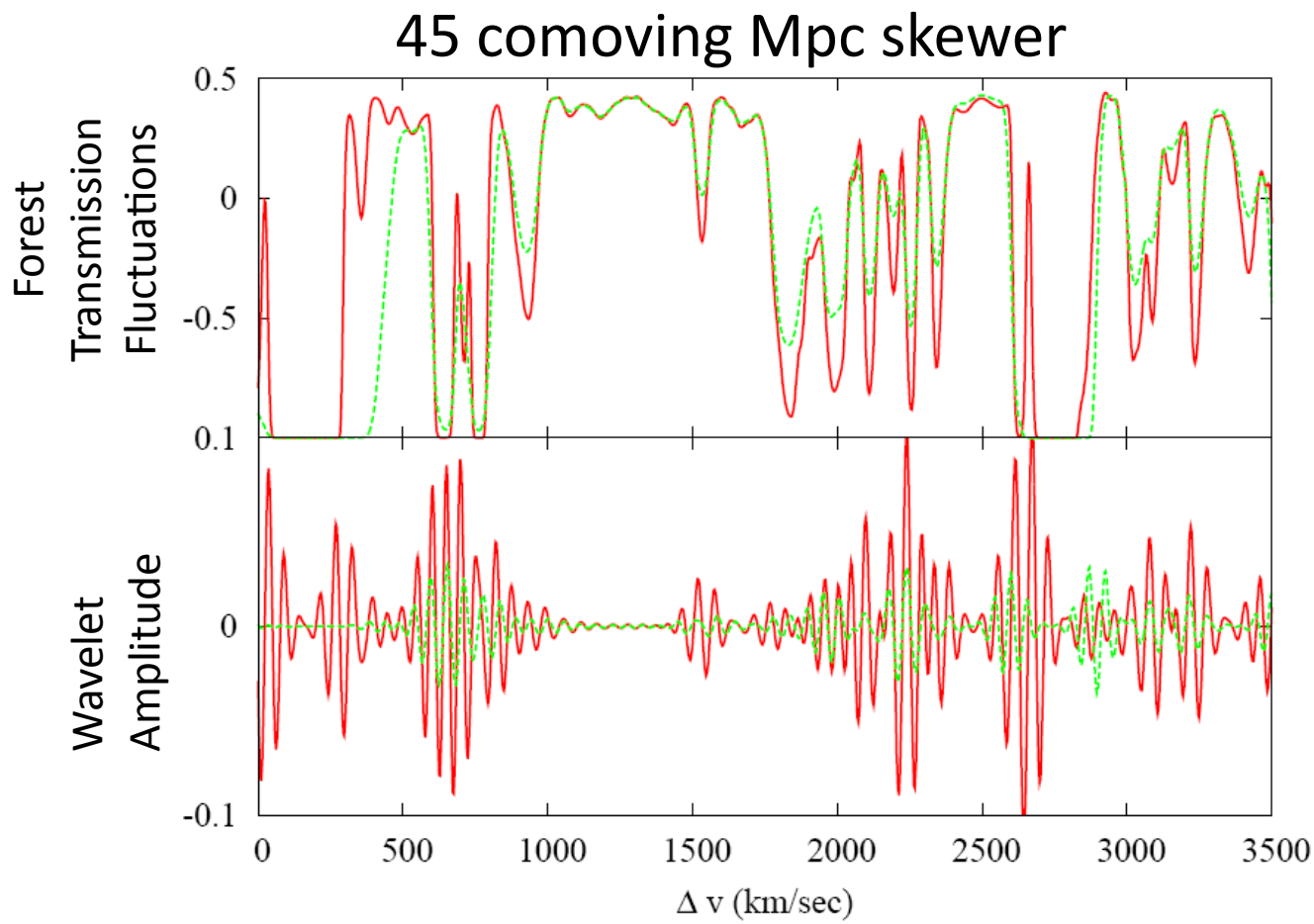


SDSS III: 120,000 QSO spectra

Transfer function used to initialize simulation does not have baryon wiggles.

Wavelets

This wavelet is a Gaussian times a sine wave with σ = 35 km/s, k = 6/σ



Green: HeII reionization simulation

Red: T_0~10^4 K

Similar method discussed in Theuns and Zarubi '00, Zaldarriaga '02, Theuns et al '02.

Detecting Temperature Fluctuations with Wavelets

This wavelet is a Gaussian times a sine wave with σ = 35 km/s, k = 12π/σ

|Wavelet amplitude|^2 averaged over 1000 km/s

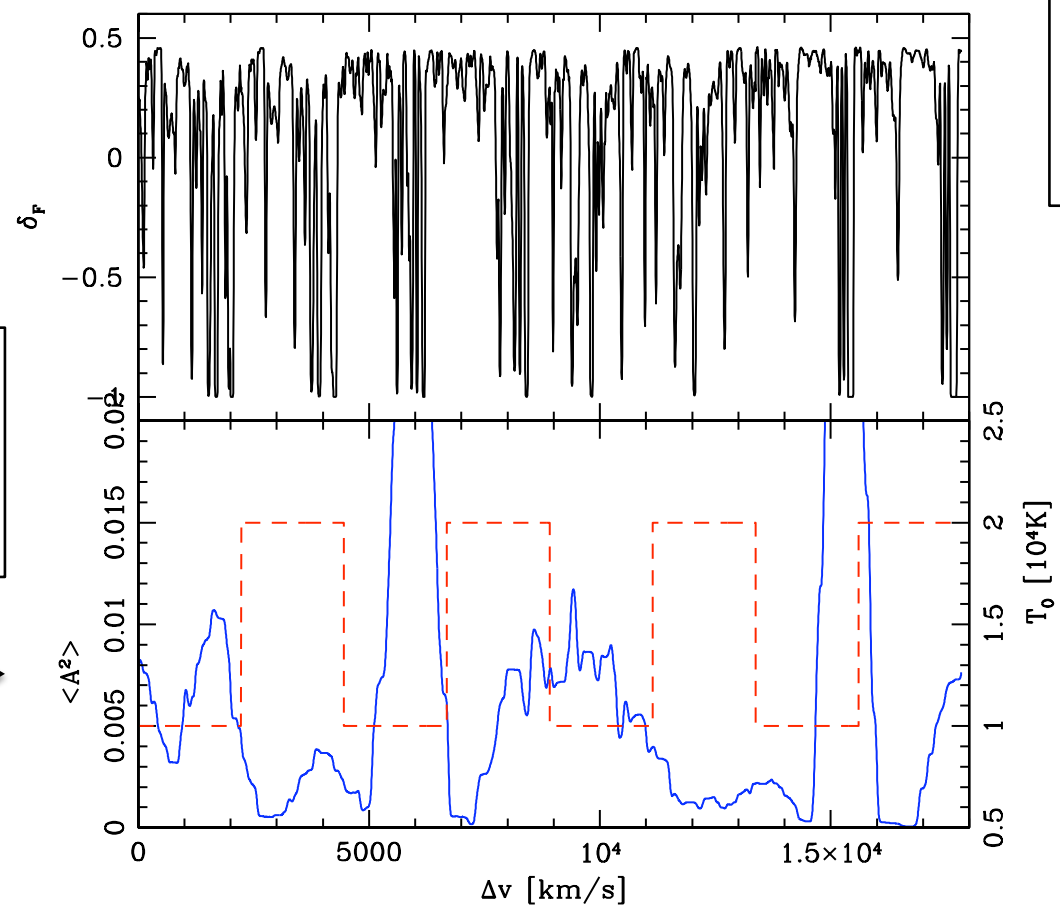
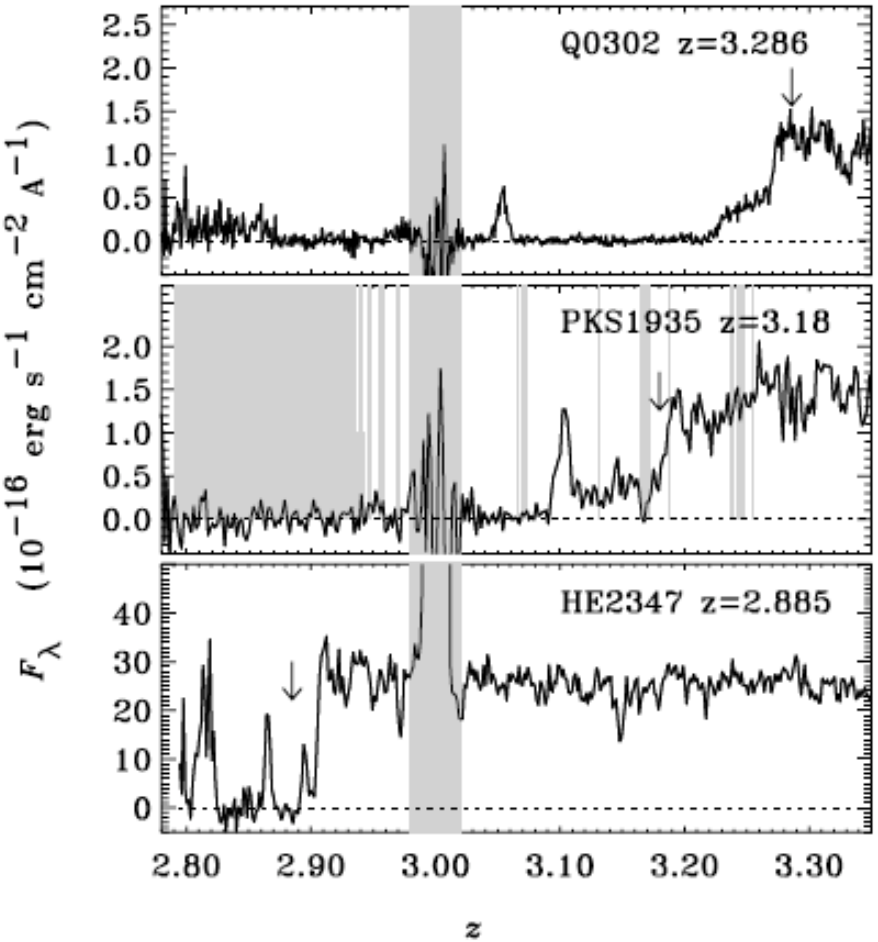


Illustration from Lidz,…, McQuinn et al. (in prep)

Future Directions: HeII Lyman-α Forest



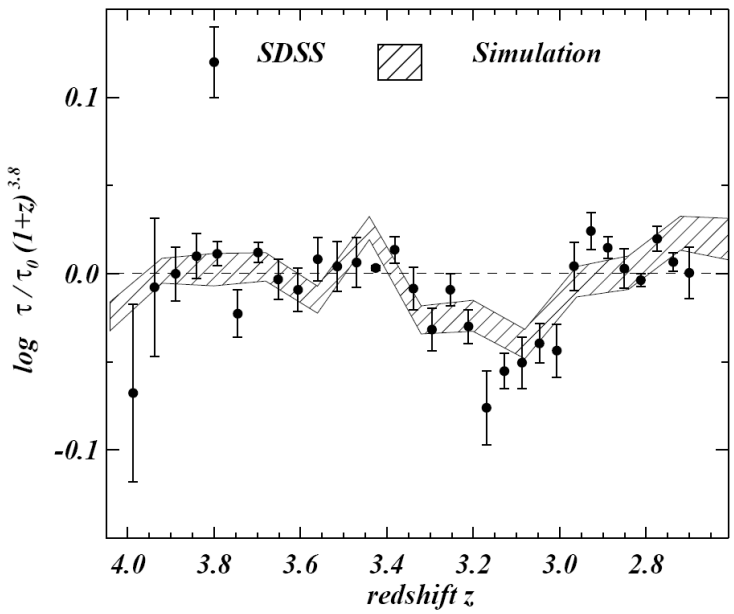
Heap et al. ('98)

- Our simulations (for which $z_{\text{HeII reion}} \sim 3$) in agreement with observations of HeII forest mean opacity (McQuinn et al. '08)
- COS on Hubble will increase number of sightlines <u>soon</u>

Mysterious Dip in HI Effective Optical Depth

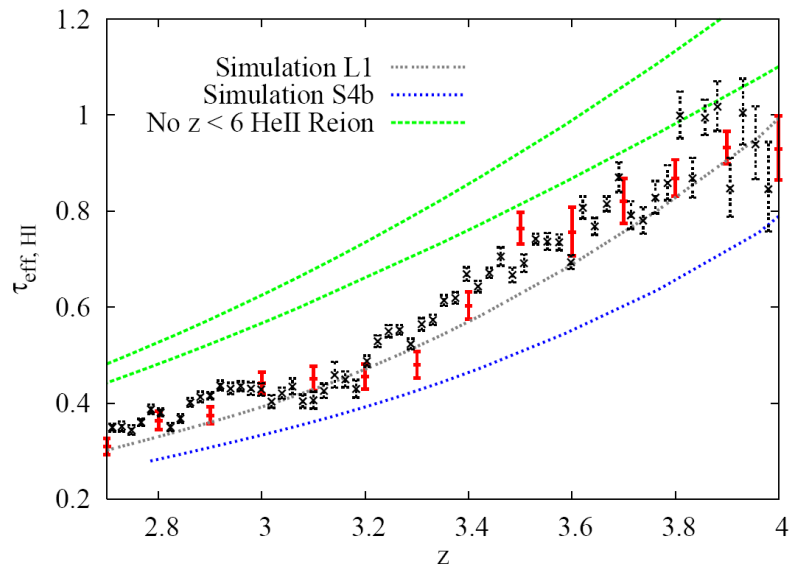
$$\tau_{eff} = -\log(< Transmission >)$$

Instantaneous HeII reionization:



Theuns et al. (2002)

Extended HeII reionization:



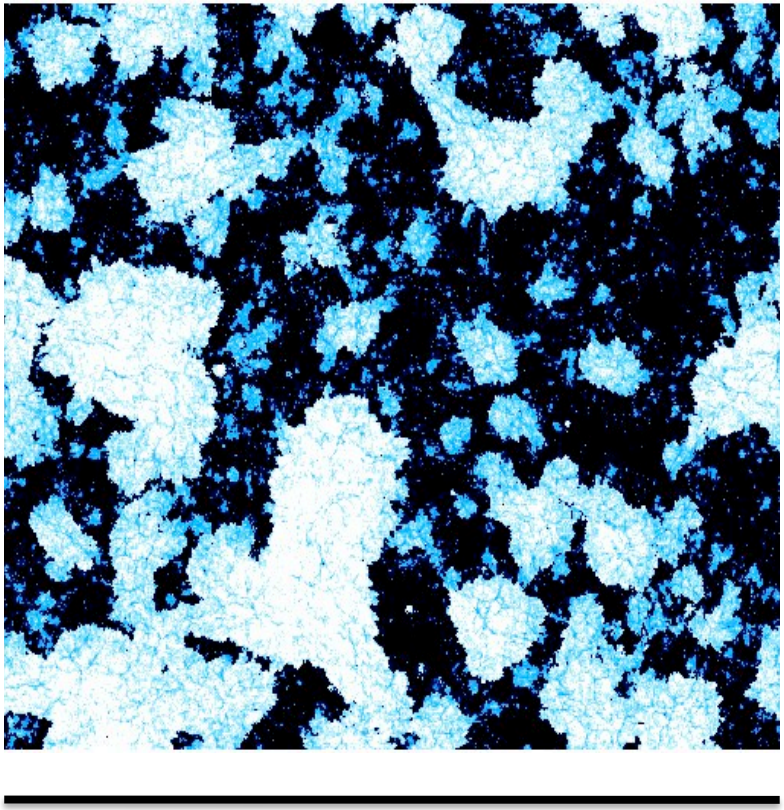
McQuinn et al. (2008)

Feature seen in measurements of Bernardi et al. (2002), Faucher-Giguere et al. (2008)

Can HeII reionization teach us about hydrogen reionization?

Hydrogen Reionization ($\log[x_{HI}]$)

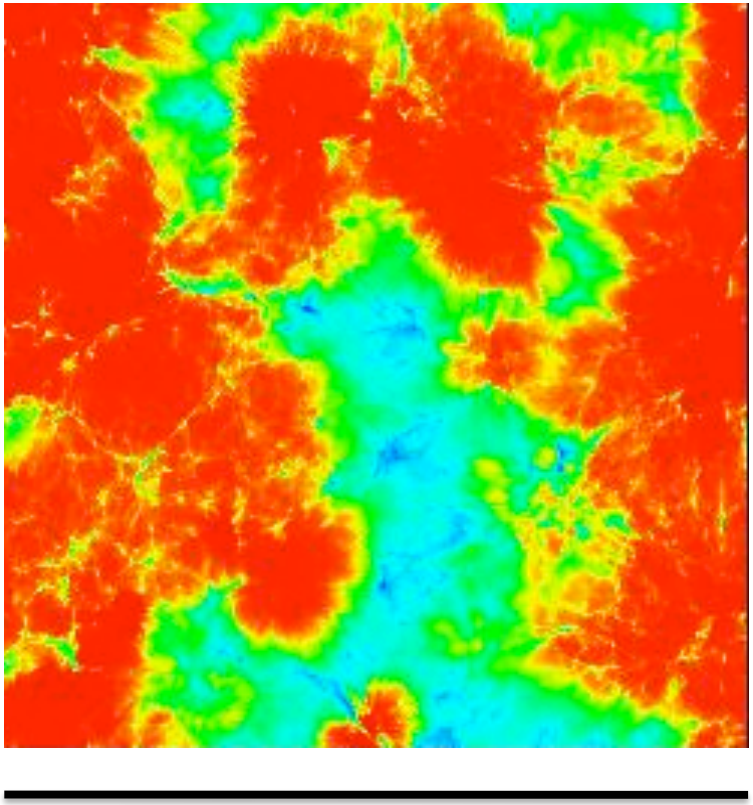
McQuinn et al (2006)



100 Mpc

HeII Reionization (x_{HeIII})

McQuinn et al (2008)

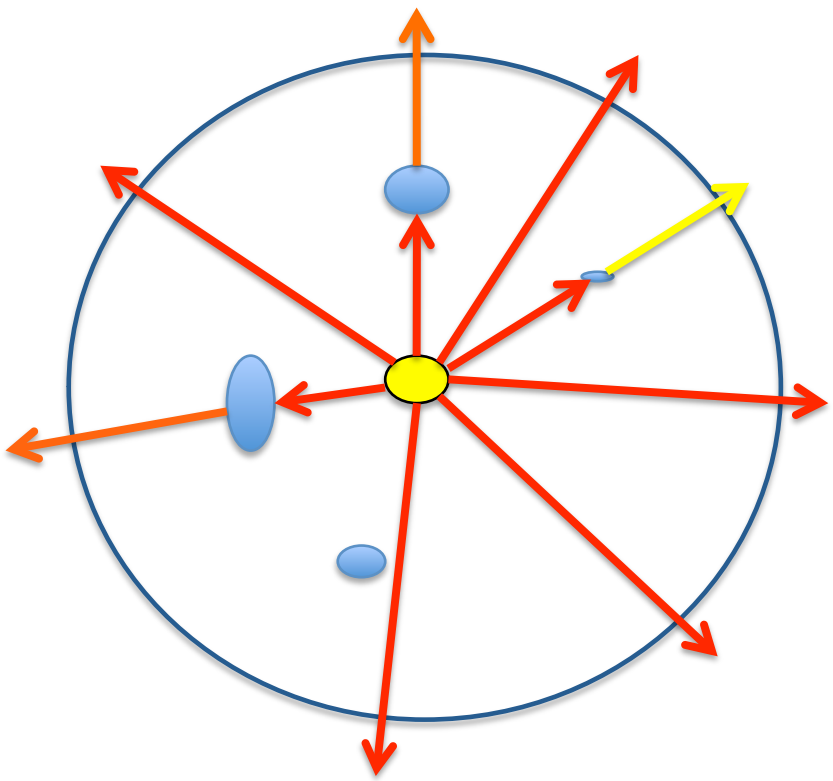


200 Mpc

Conclusions

- Hard photons heat regions far from quasars, leading to the regions that are ionized last being the hottest and 10^4 K temperature fluctuations on 50 cMpc scales.
- HeII reionization results in $\Delta T \sim 10^4$ K. Can reconcile observed z~3 IGM temperatures.
- Results in complicated T-Δ relation.
- Difficult, but possible, to isolate effect of HeII reionization in HI Lyman-α forest

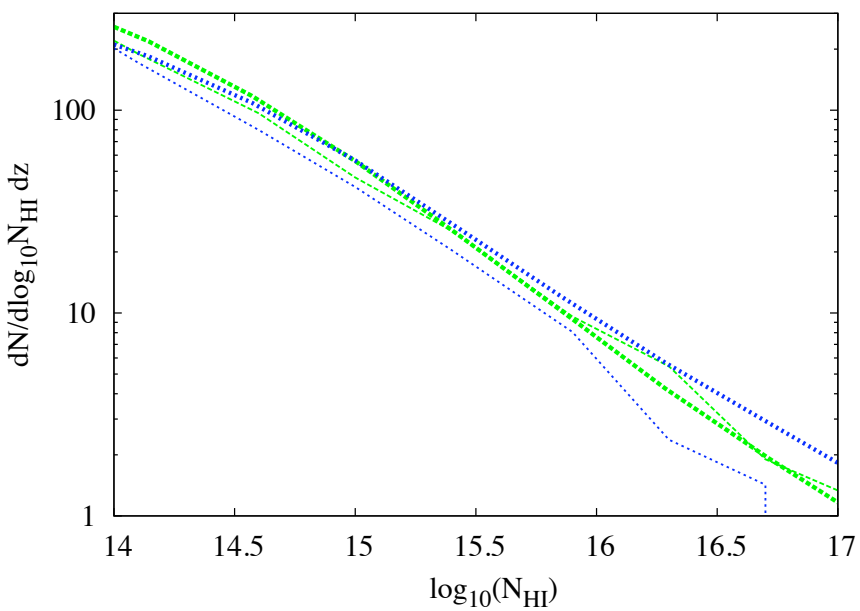
Filtering by Dense Systems



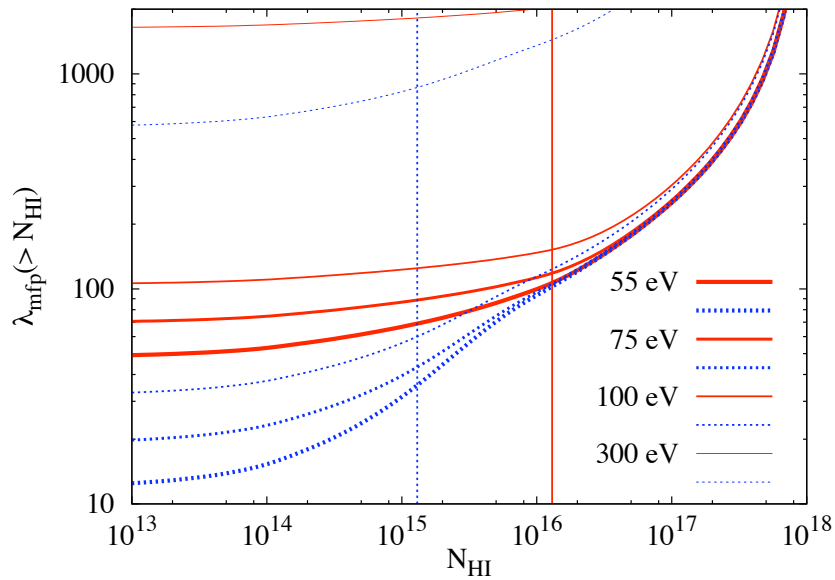
- Harder photons reach ionization front
- Harder photons outside of front preferentially absorbed by dense gas (e.g. Bolton, Oh, & Furlanetto 2008) -- τ_{eff} has weaker dependance than E^{-3} for dense systems

Filtering by Dense Systems (continued)

Our Sim's Resolution

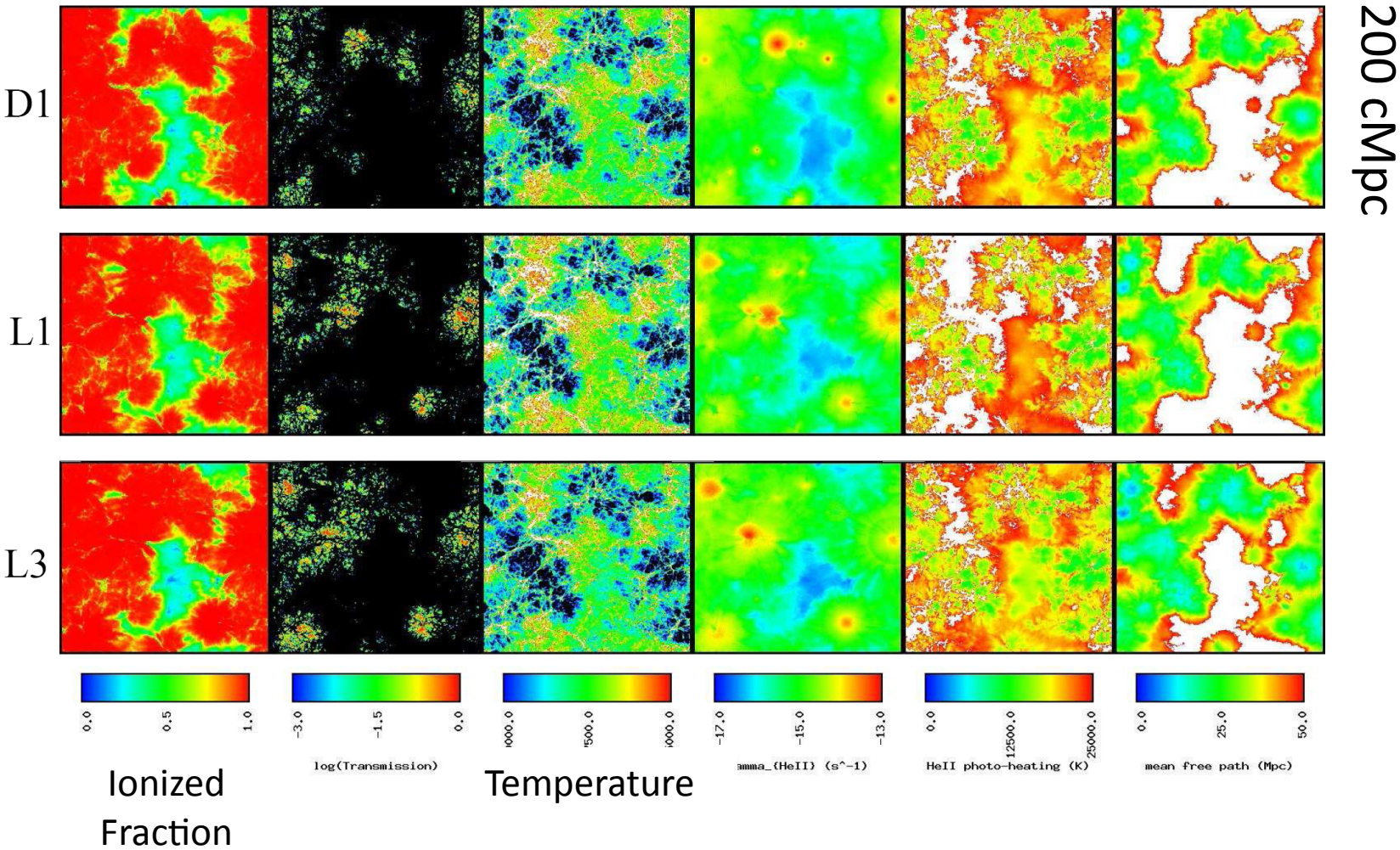


Mean Free Path in ionized medium
(blue: $\Gamma_{HeII} = 10^{-15}\ s^{-1}$
Red: $\Gamma_{HeII} = 10^{-14}\ s^{-1}$)

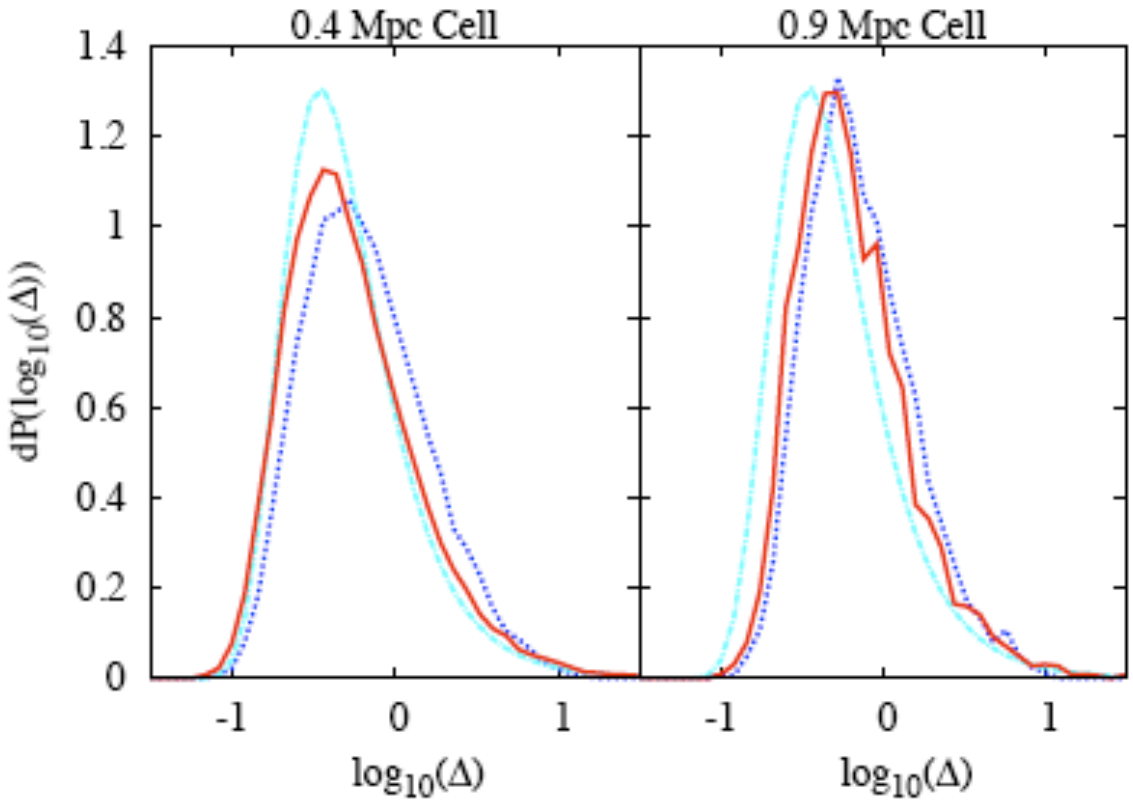


McQuinn et al. (2008) using method of Haardt and Madau (1996)

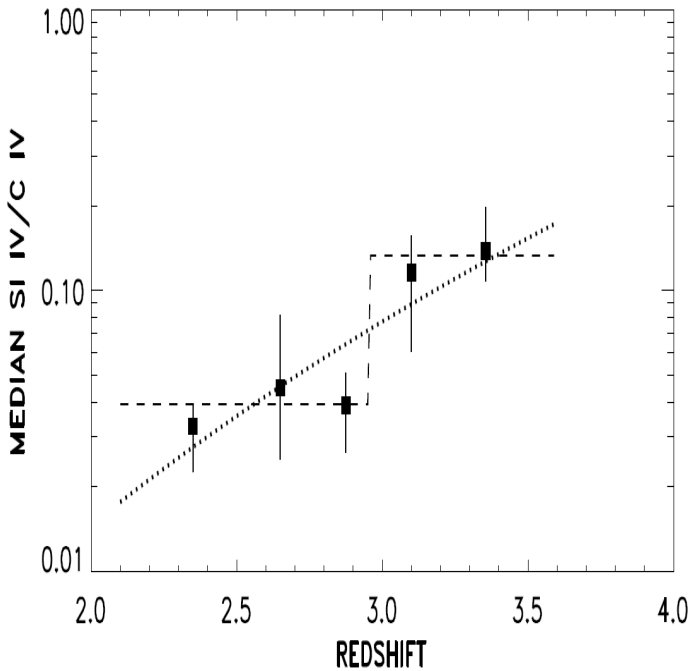
Filtering By Dense Systems: Results



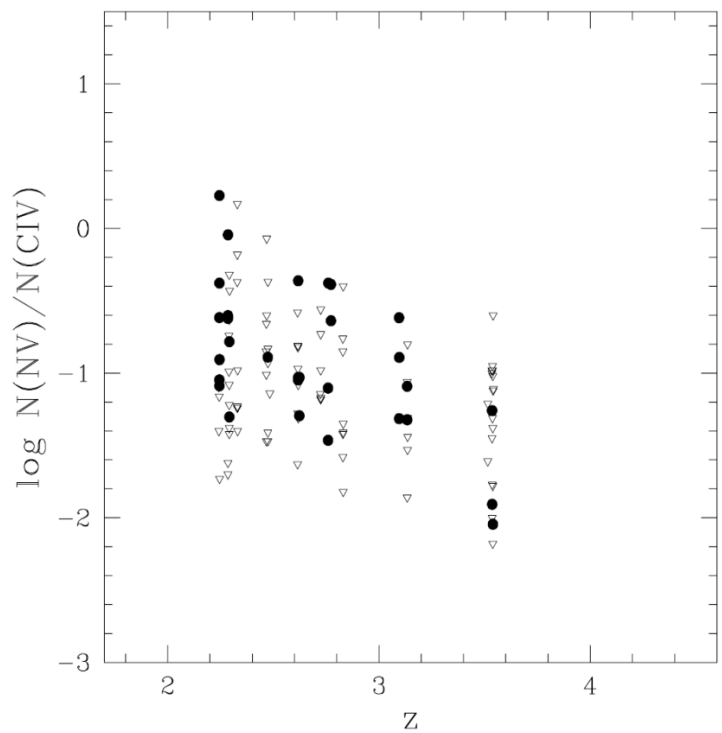
How dark matter traces the gas.



Metal Lines

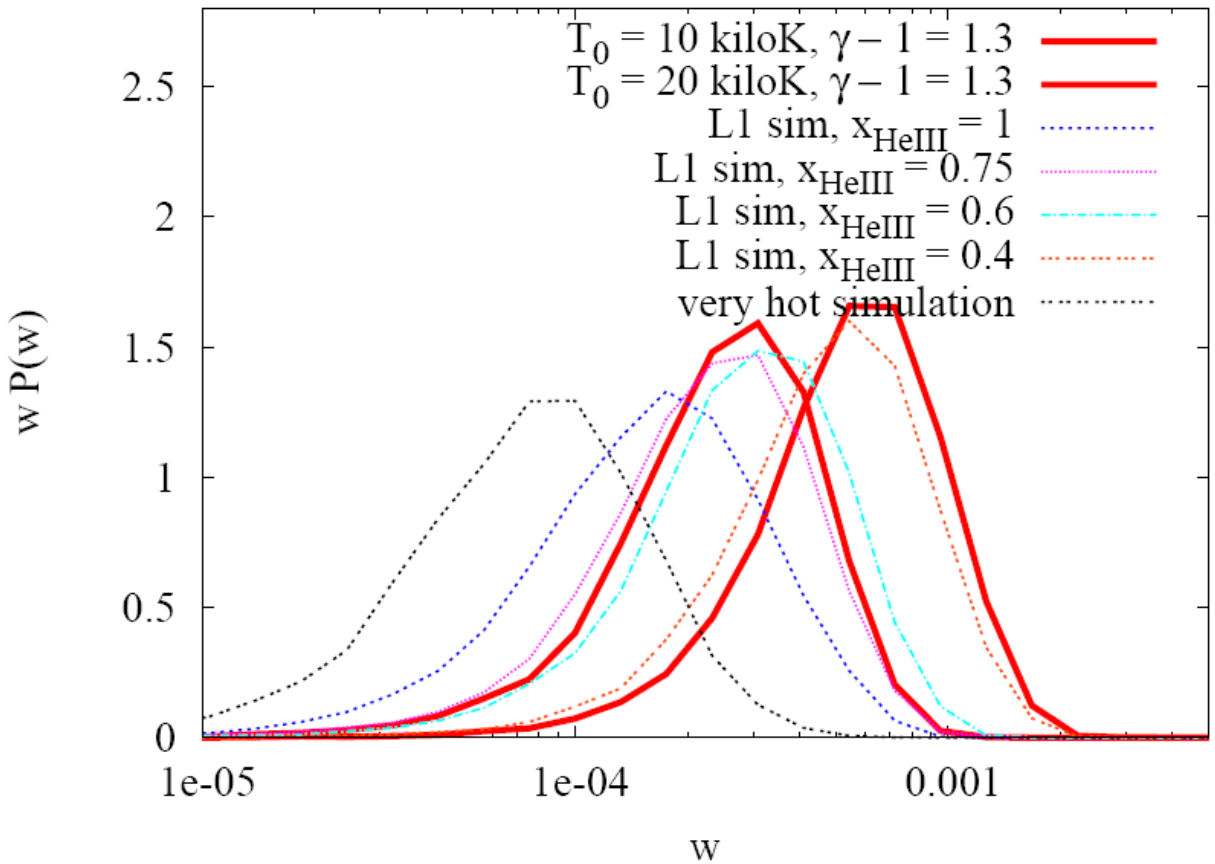


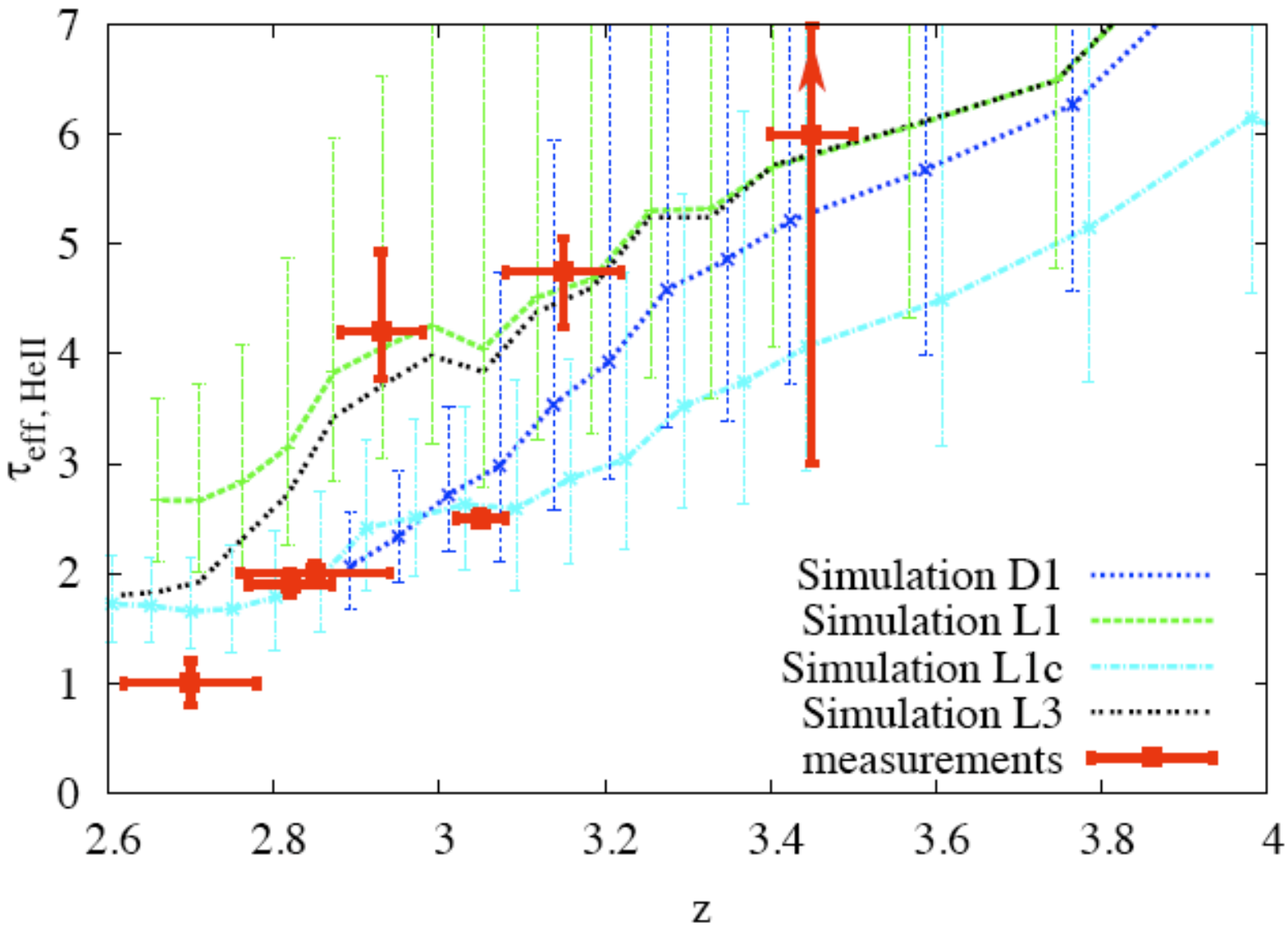
Songaila (1998)



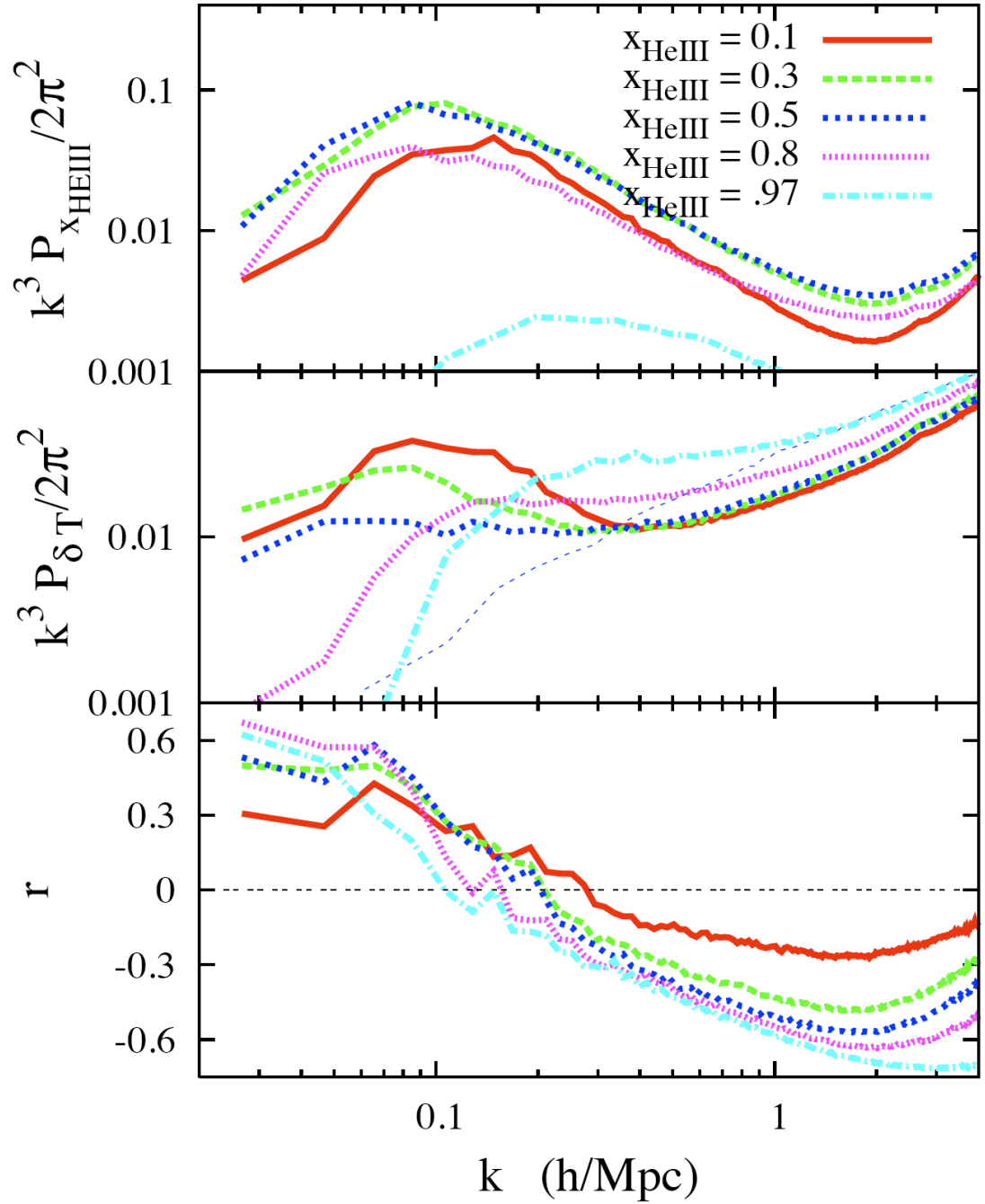
Boksenberg et al. (2003)

Wavelet PDF (averaged over skewer)




7
6
5
4
3
2
1
0
2.6
2.8
3
3.2
3.4
3.6
3.8
4
z
$\tau_{eff,HeII}$
Simulation D1
Simulation L1
Simulation L1c
Simulation L3
measurements

Power Spectrum



Ionized Regions in the Universe

- <u>Around a star</u>
  - $n_H \sim 10^3$ cm^{-3}
  - R ~ 10^{16}-10^{20} cm
  - $\lambda_{mfp} \sim 10^{14}$ cm
  - Stromgren radius
  - often subsonic
- <u>HII region during hydrogen reionization</u>
  - $n_H \sim 10^{-4}\,(1+z/10)^3$ cm^{-3}
  - R ~ 10 cMpc (many galaxies within)
  - $\lambda_{mfp} \sim 10$ kpc
  - supersonic
- <u>HeII Reionization</u>
  - $n_{He} \sim 10^{-6}\,(1+z/4)^3$ cm^{-3}
  - R ~ 20 cMpc (1 QSO)

$$\lambda_{mfp} = 5\, x_{HeII}^{-1} \left(\frac{E_\gamma}{100\ \mathrm{eV}}\right)^3 \left(\frac{1+z}{4}\right)^{-2} \mathrm{cMpc}$$

  - Supersonic
  - Never reaches Stromgren radius