Helium Reionization

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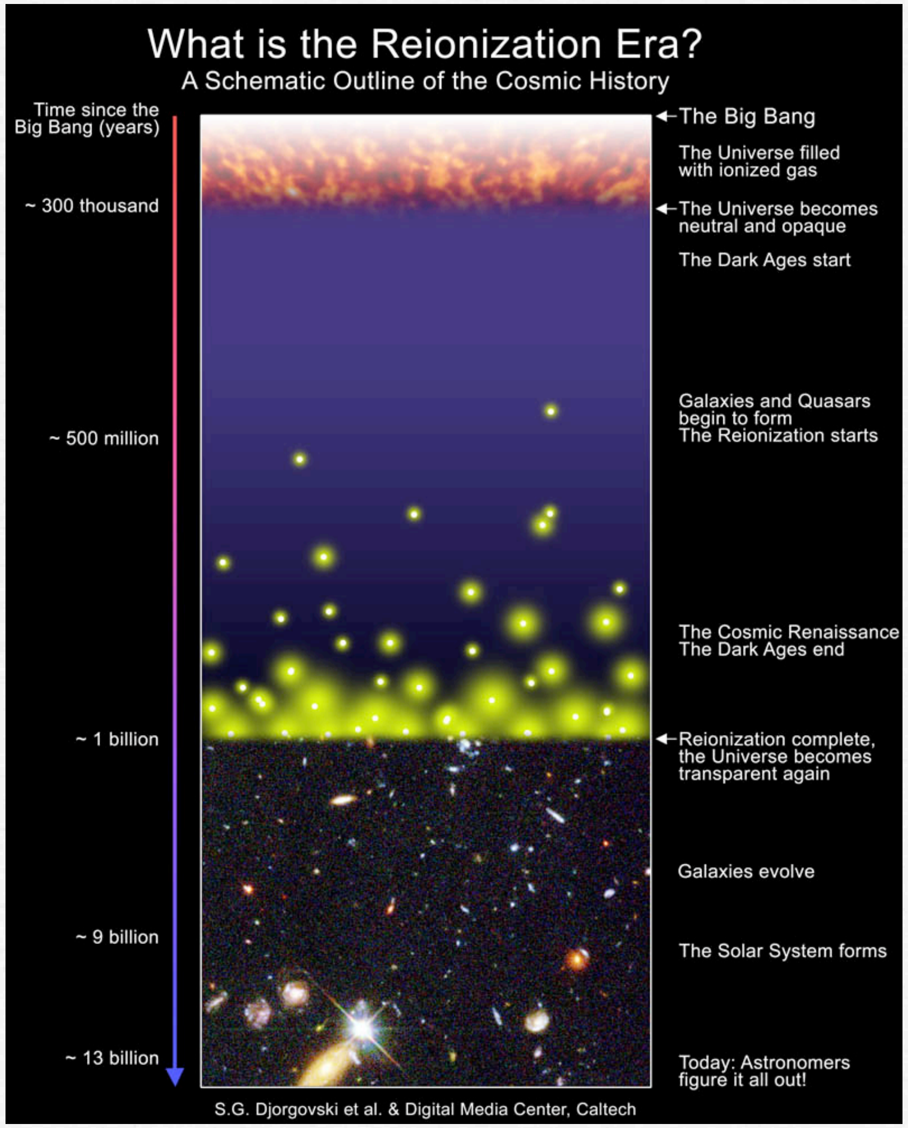
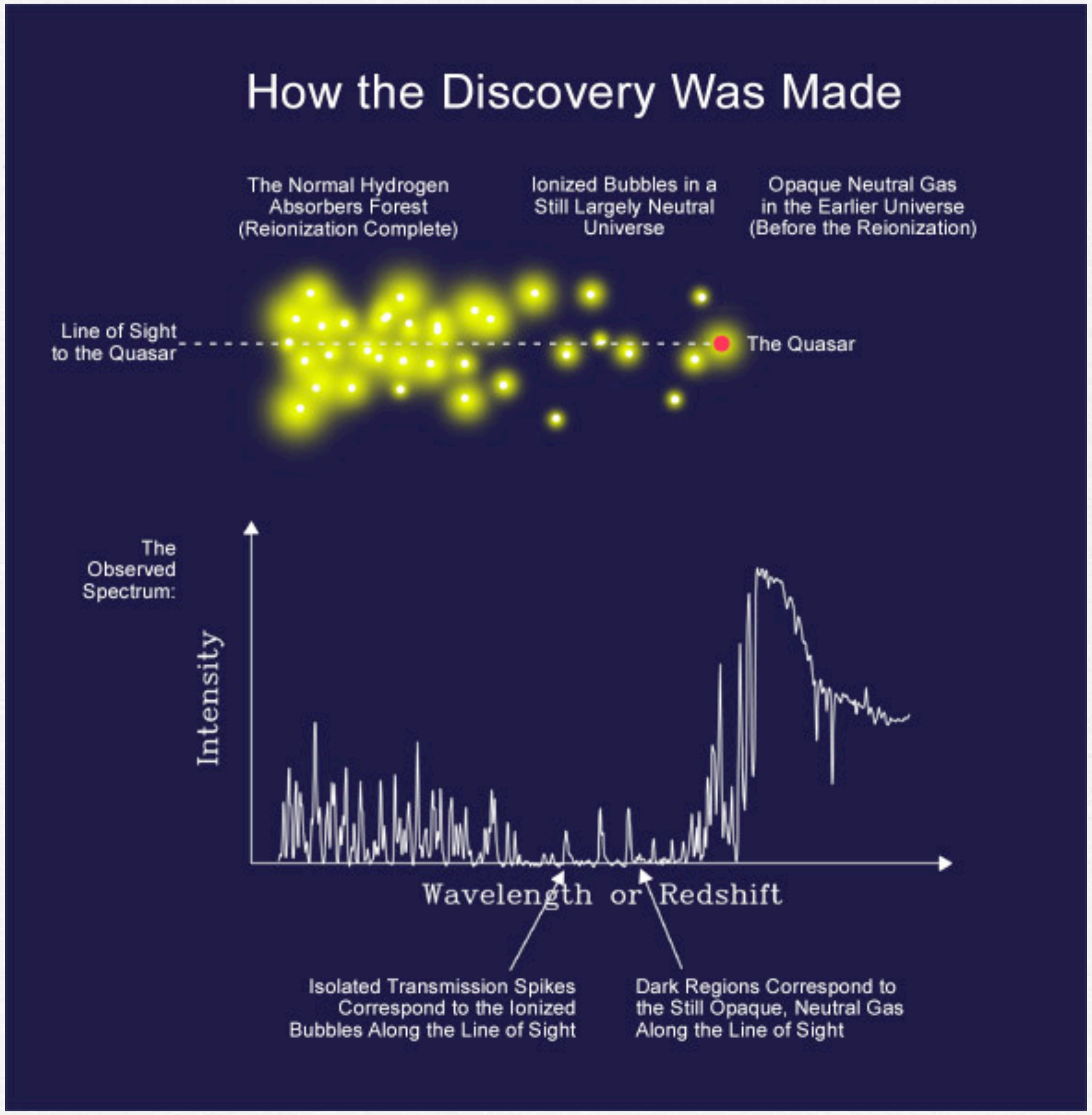
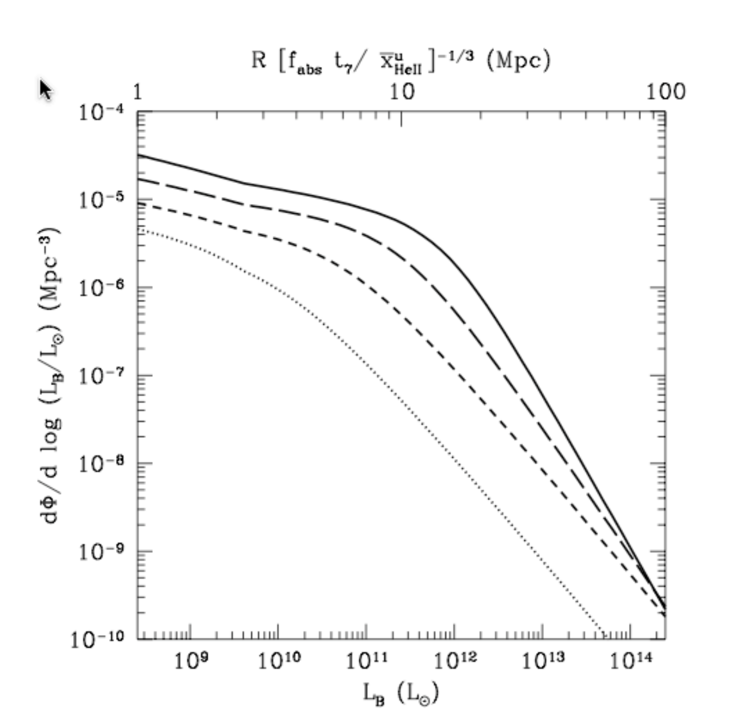
You've heard a lot of hype about hydrogen reionization...

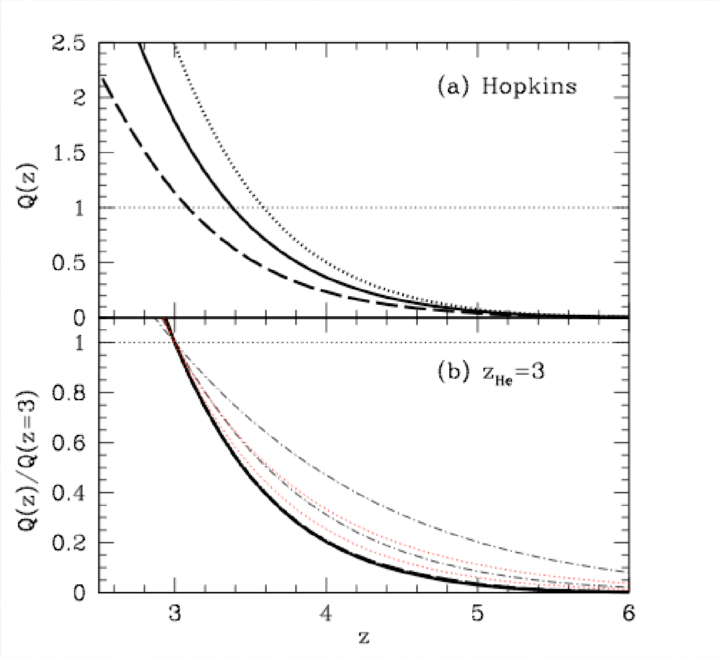




We know MUCH more about Helium reionization...

- What the sources are (quasars)
- Their number density and clustering properties
- Properties of IGM at these redshifts





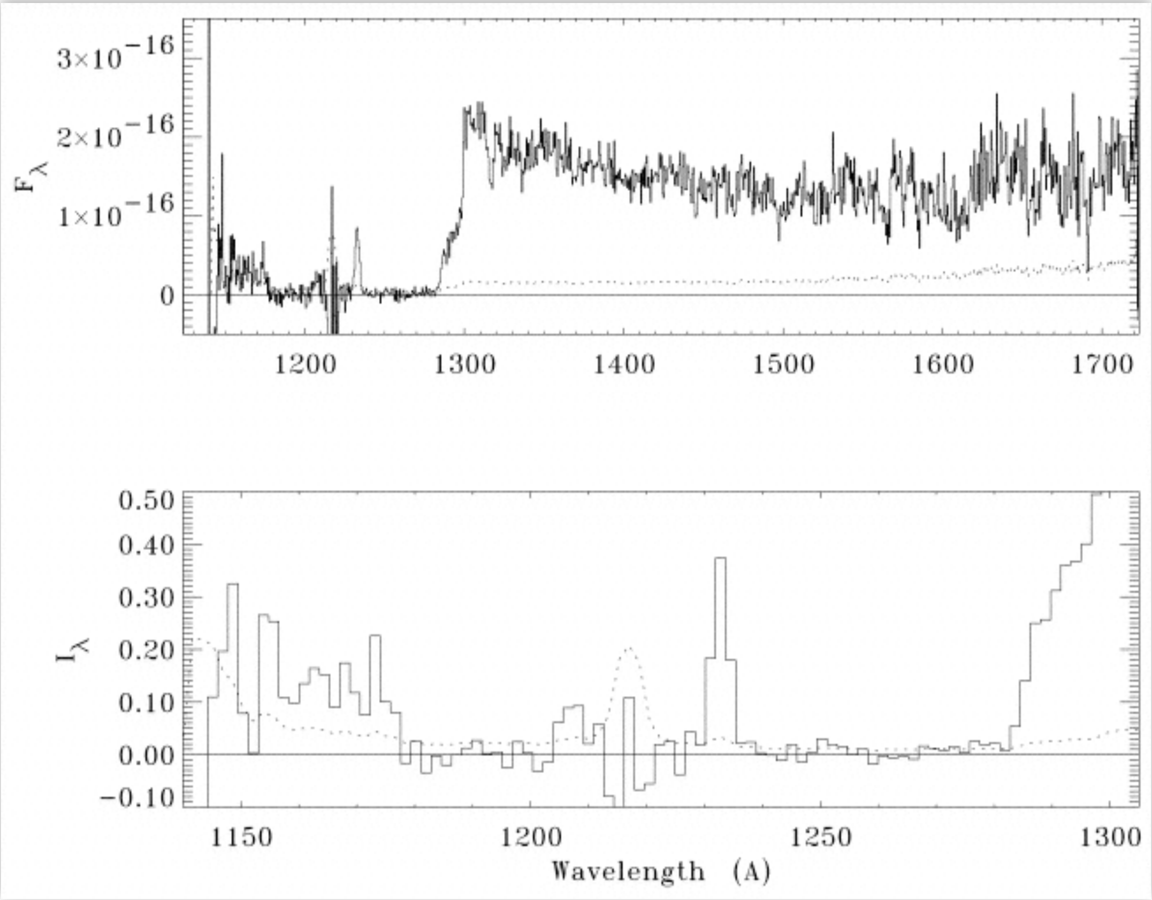
...but we still don't understand it!

- ☐ Increase in He optical depths (but few lines of sight; saturation)
- ☐ Sudden increase in Doppler widths (But no change in small-scale power spectrum)
- ☐ Hardening of spectrum detectable in Si IV/C IV ratio (3 for; 2 against, in spectra of comparable quality)

Little theoretical attention

COS is coming on HST!

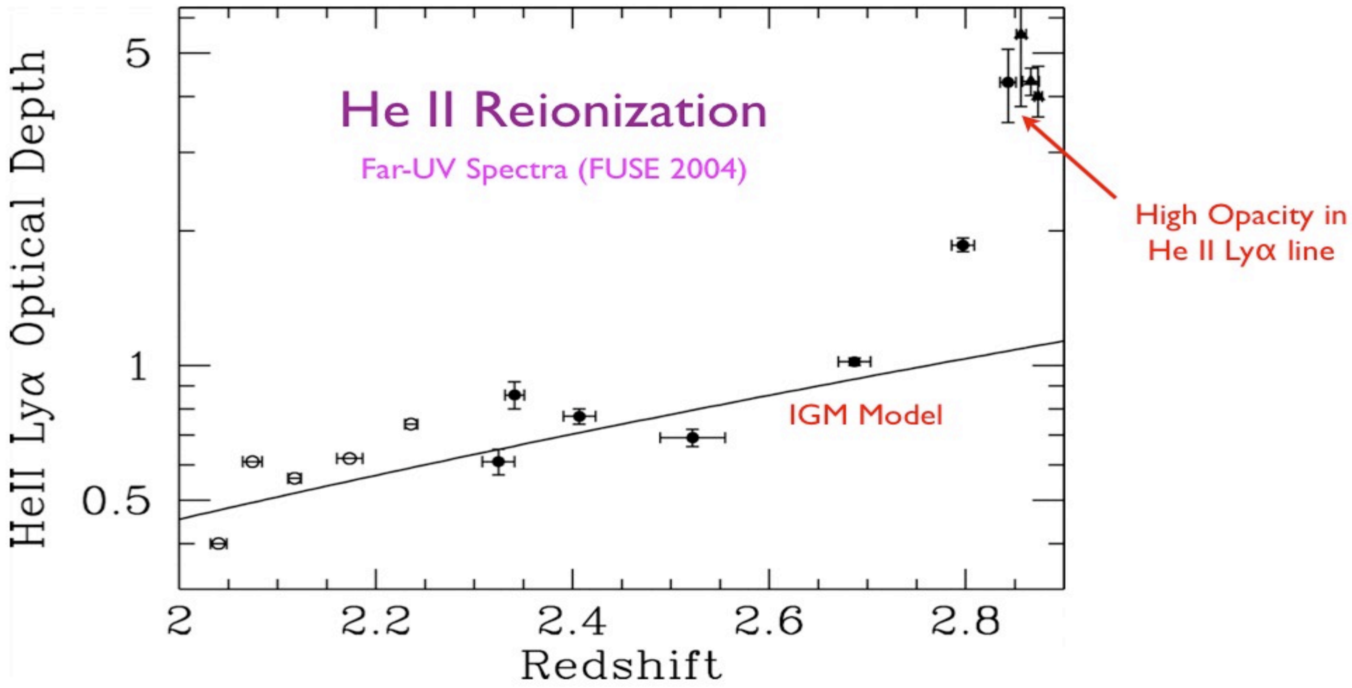
We have direct evidence from quasar spectra



Heap et al (2000)

Very similar to hydrogen reionization case....

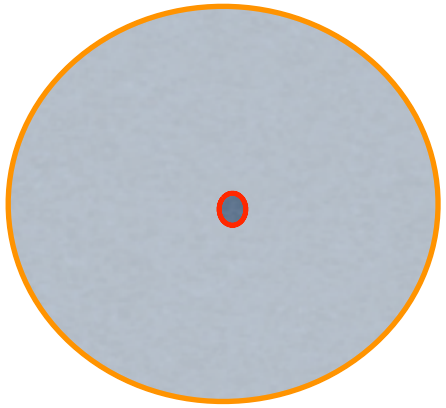
We should test out our machinery on this!



Shull et al 2004

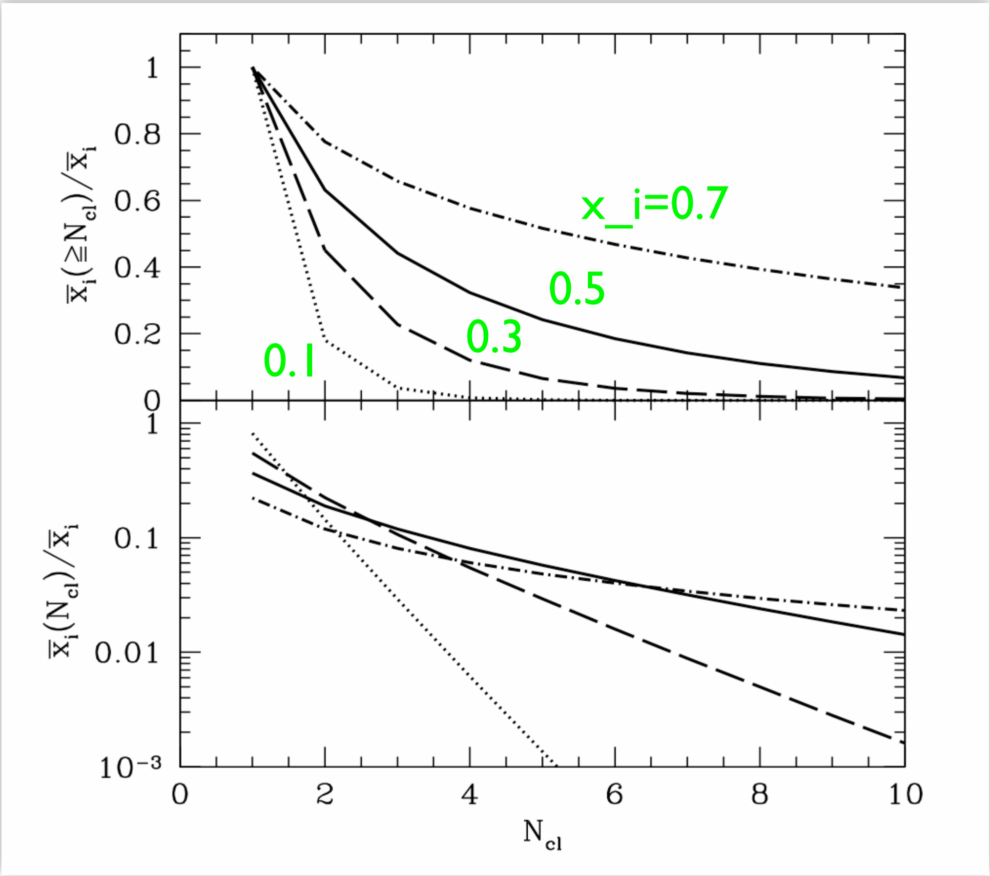
Three key differences

1) Helium reionization: Driven by rare, bright sources (quasars)

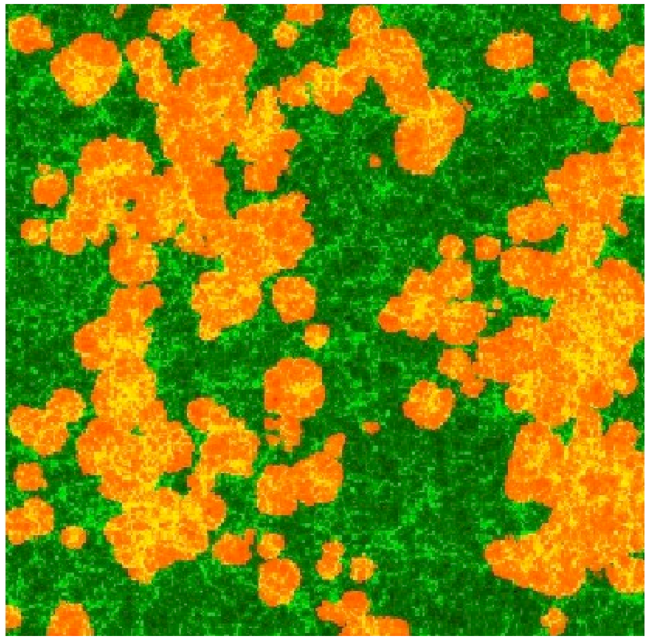


Poisson fluctuations dominate

No density dependence



Furlanetto & Oh 2008a



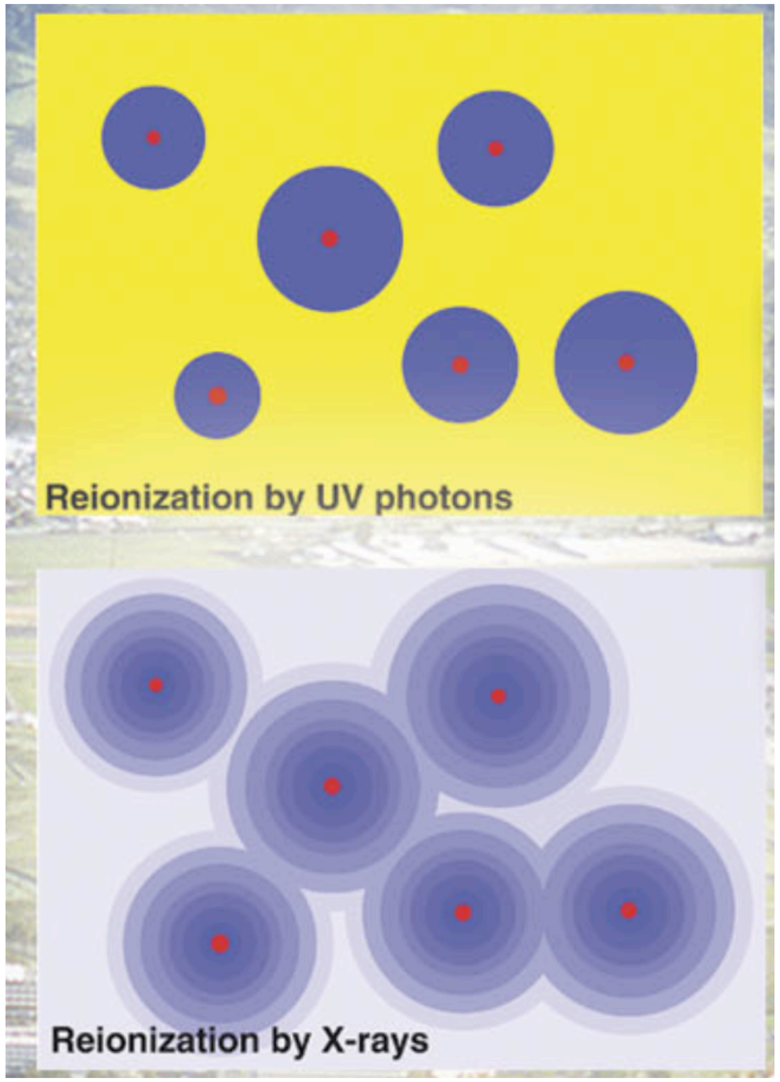
Hydrogen reionization: many sources contribute

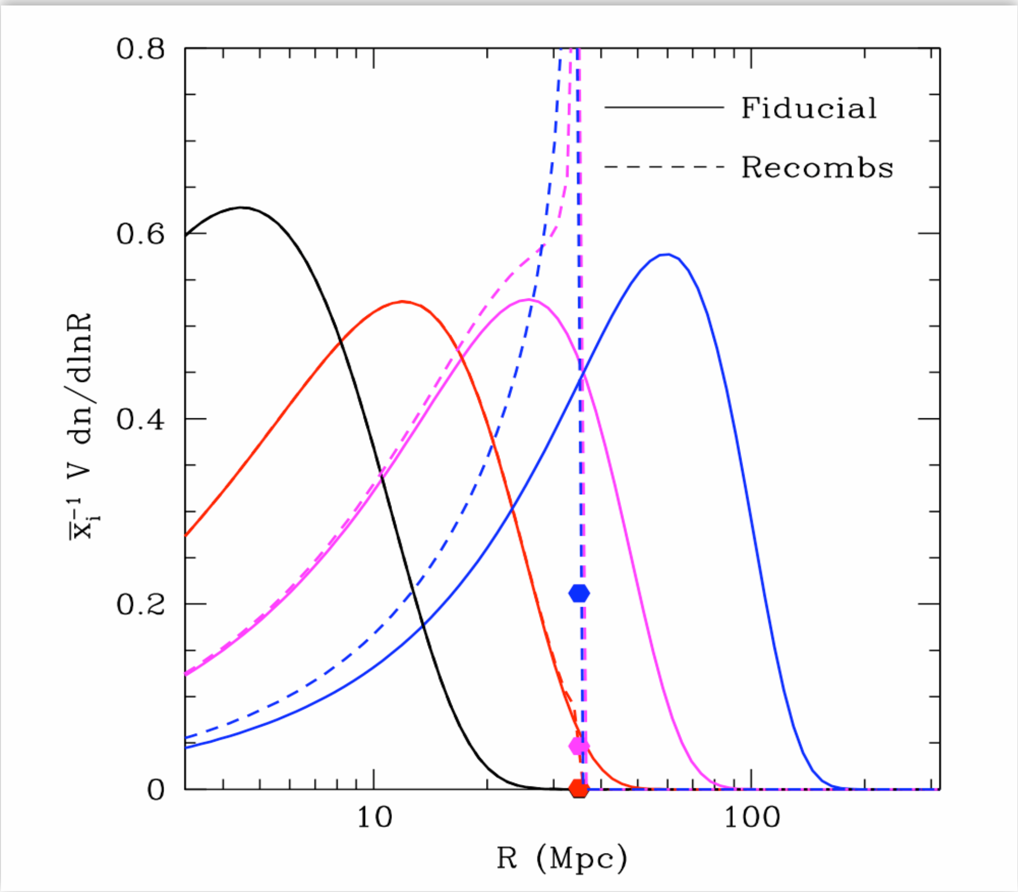
Clustering dominates

'inside-out' topology

2) Hard photons more important (influence topology + heating)

(for α=1.5, half of photons have E > 150 eV)

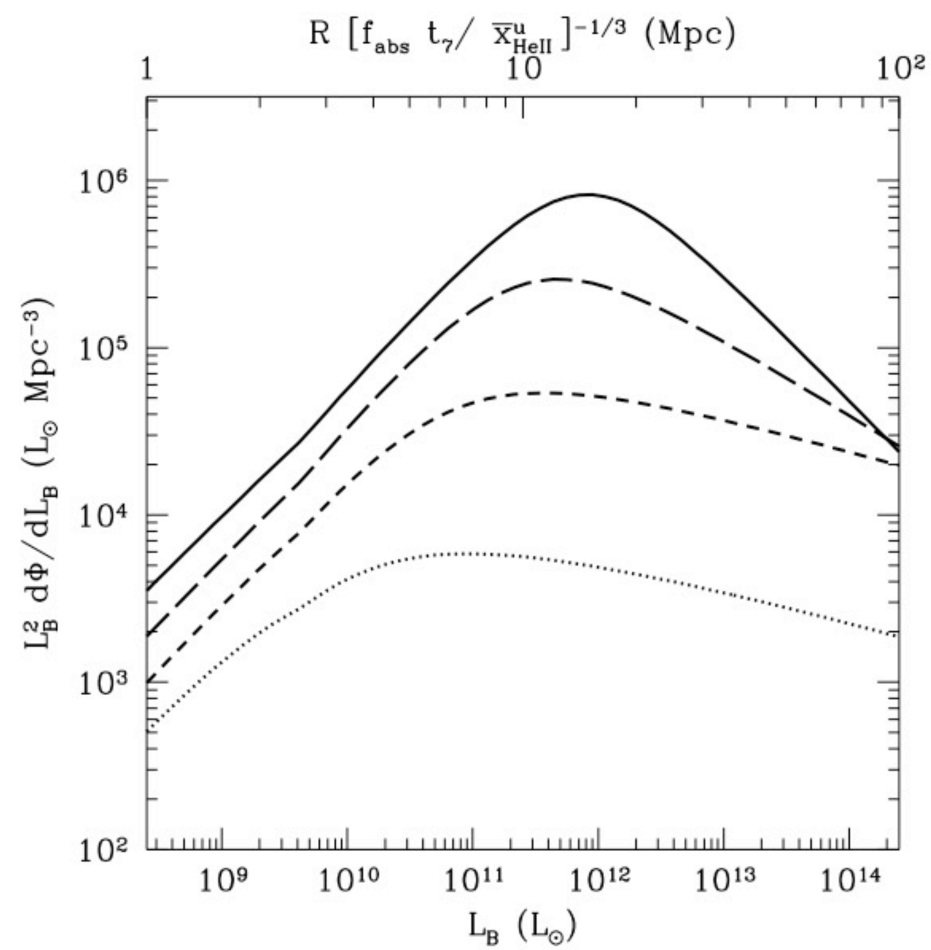




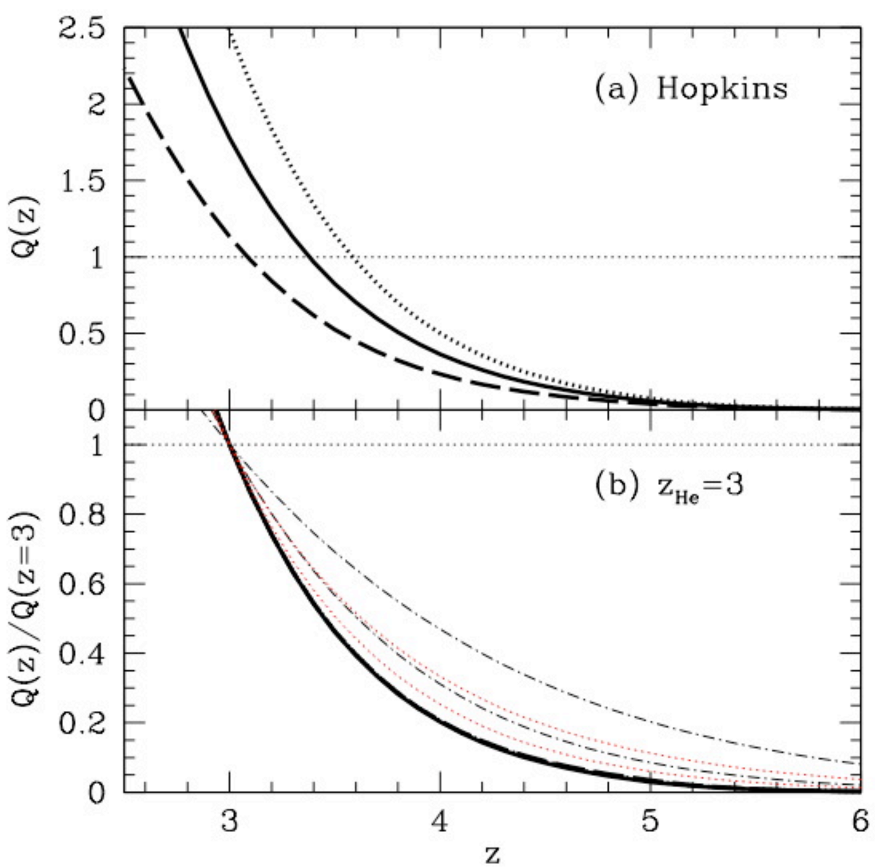
Furlanetto & Oh (2008)

3)Recombinations more important: He recombines 5.5x faster IGM more clumpy

Who done it? (Quasars)

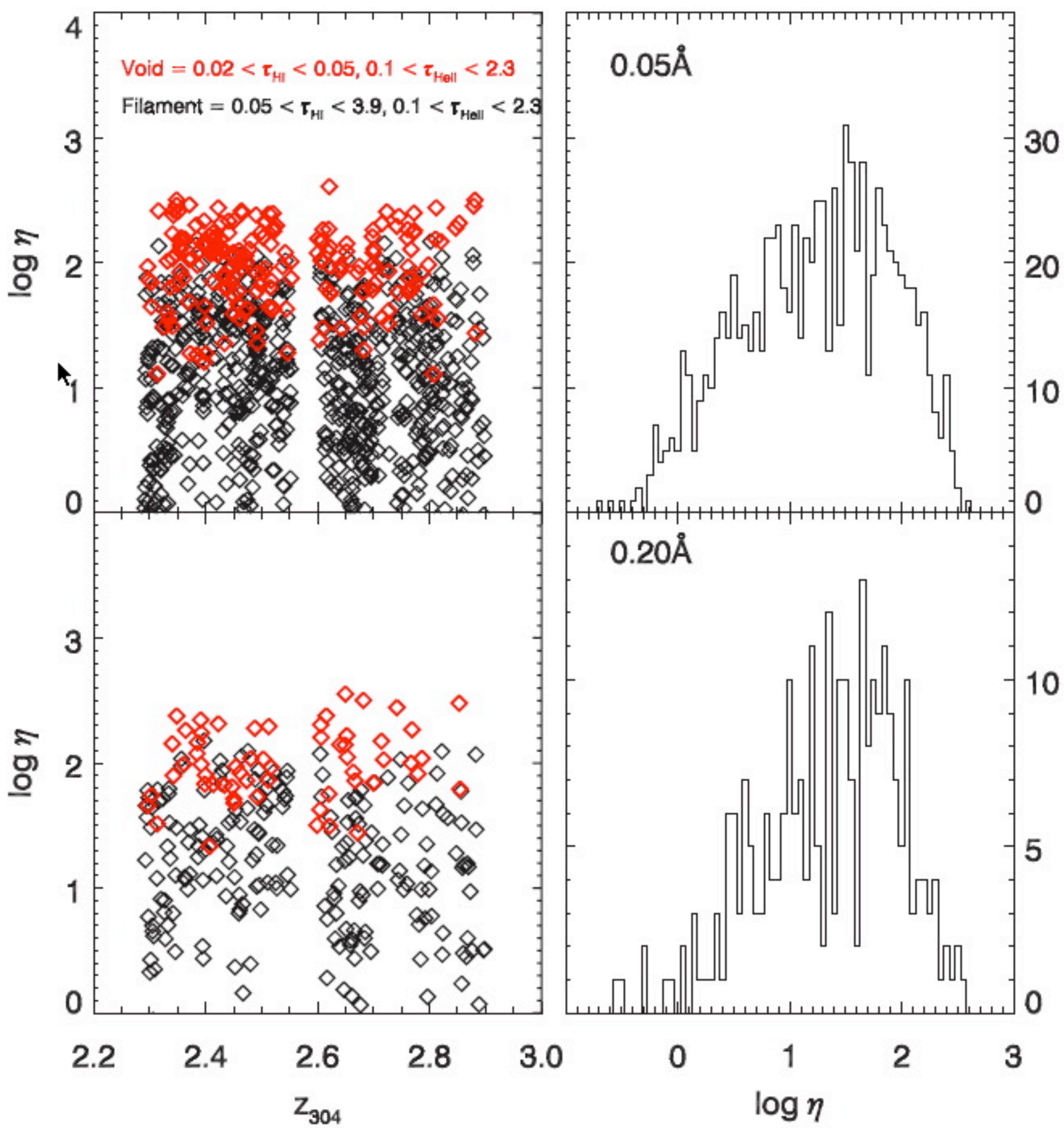


Contribution dominated by quasars near ‘knee’



Observed quasars provide enough photons to reionize He

Furlanetto & Oh 2008a



Shull et al 2004

But...

Large small-scale fluctuations in hardness

$$\eta \equiv \frac{\tau_{\rm HeII}}{\tau_{\rm HI}}$$

on ~ Mpc scales

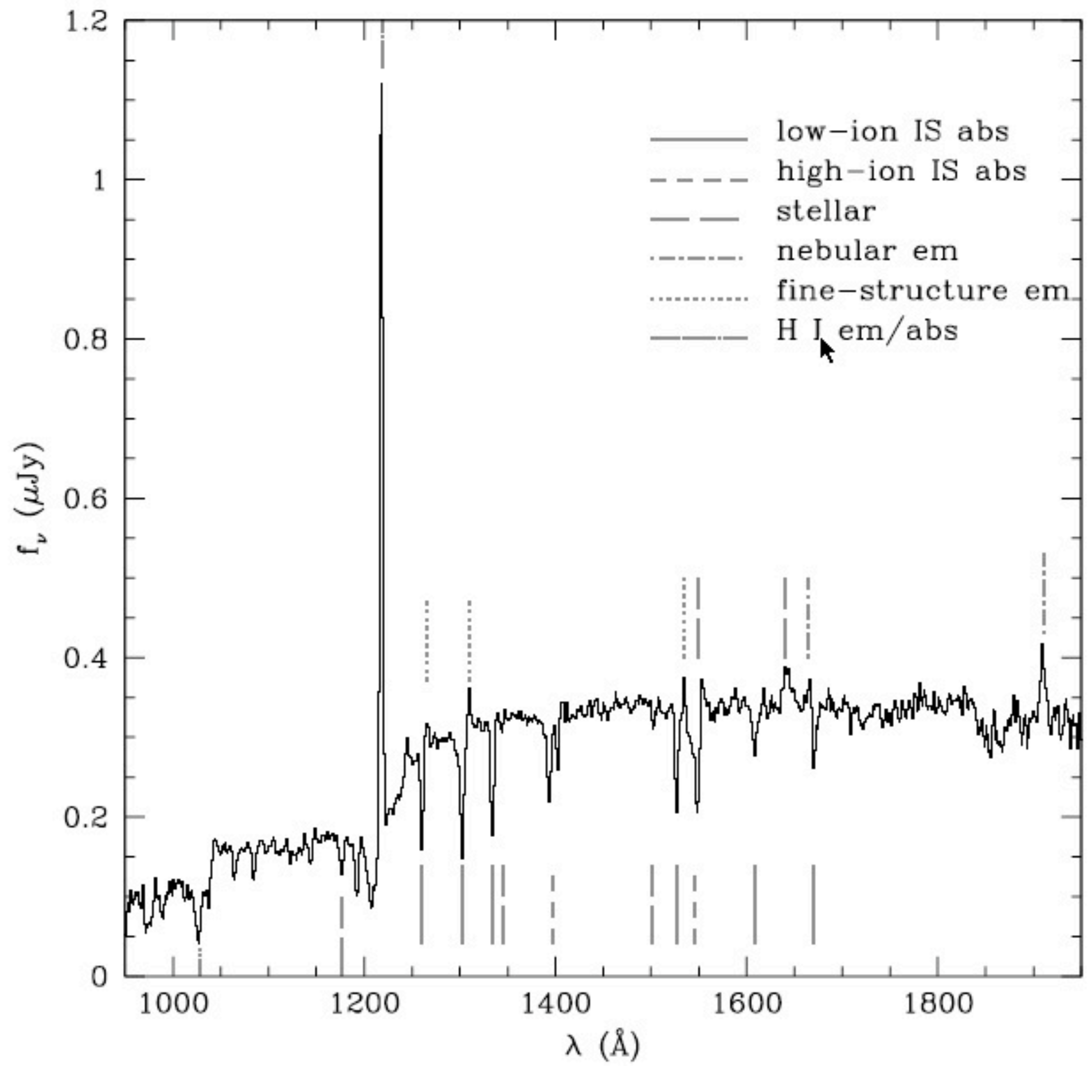
Could be variations in spectra of sources, density fluctuations, or radiative transfer effects

Could galaxies have done it?

Composite spectrum of 811 LBGs shows strong HeII 1640 line emission

Implies large source of He ionizing photons

New calculations suggest it is a Wolf-Rayet line (Brinchmann et al 2008)



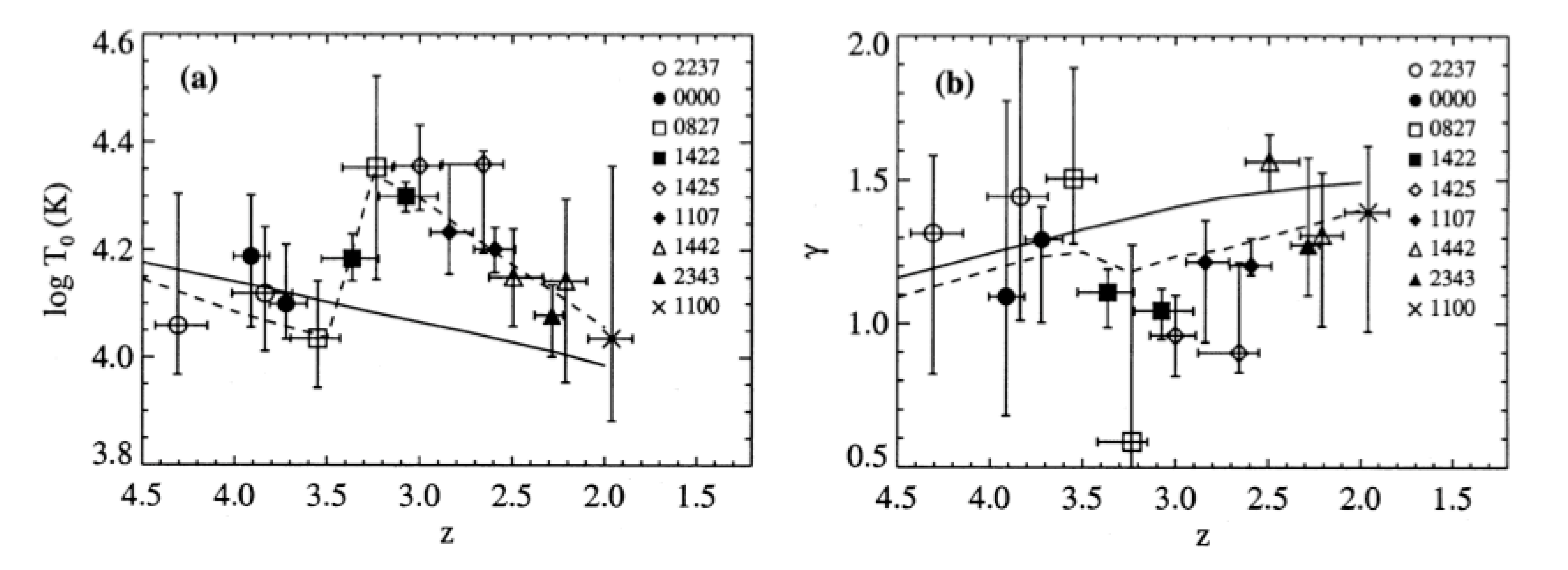
Shapley et al 2003

$$Q_\star(z) = \zeta^\star_{\rm He} f_{\rm coll} = \eta f_{\rm esc} f_\star f_{\rm coll} \sim 2 \frac{f_{\rm esc}}{1 - f_{\rm esc}} \left(\frac{f_{\rm coll} f_\star}{0.03} \right), \quad (13)$$

Furlanetto & Oh 2008a

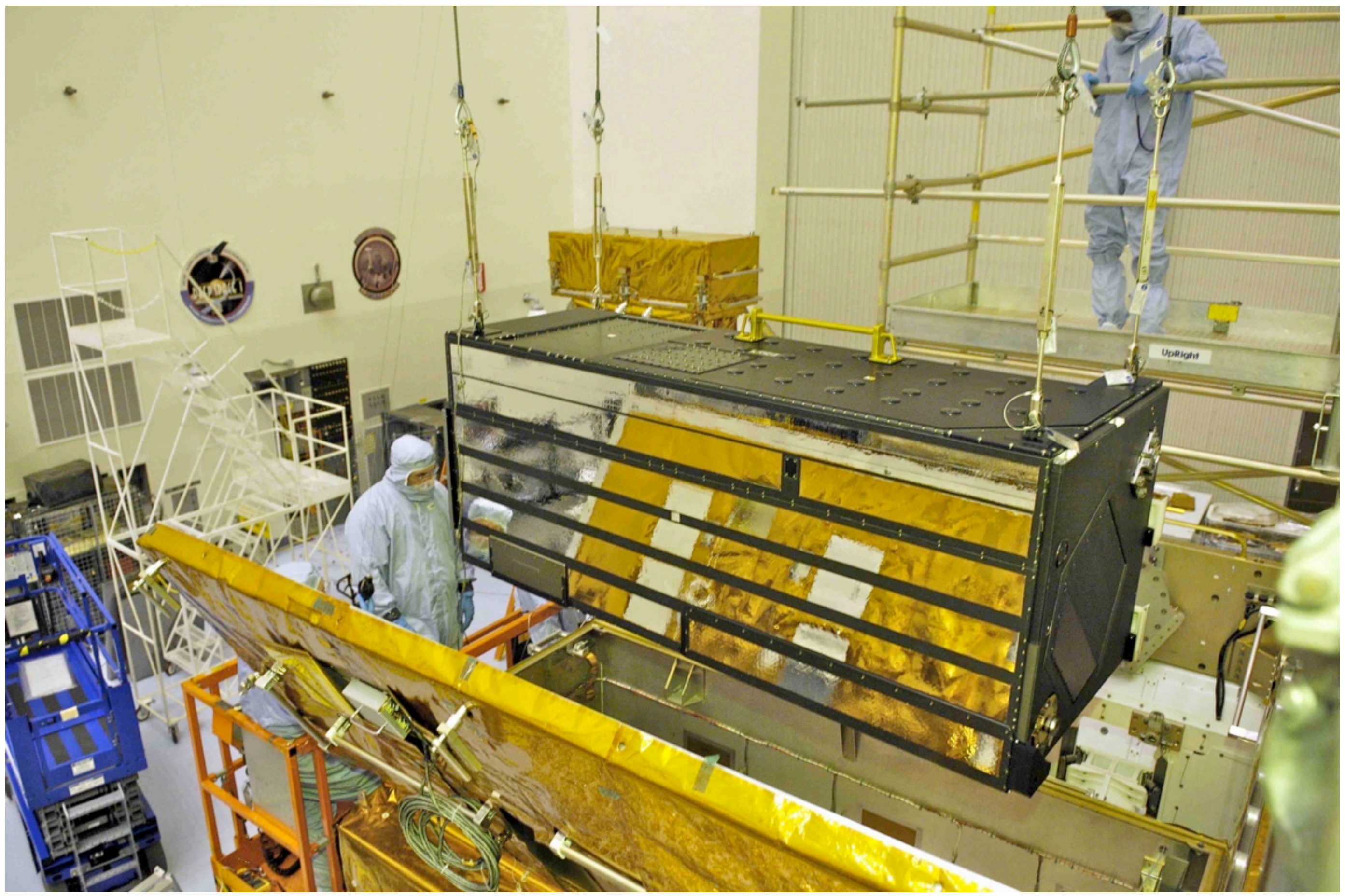
What's at stake?

- Thermal history of IGM
- Equation of state---> feeds into power spectrum measurements



Schaye et al 2000

Another motivation...

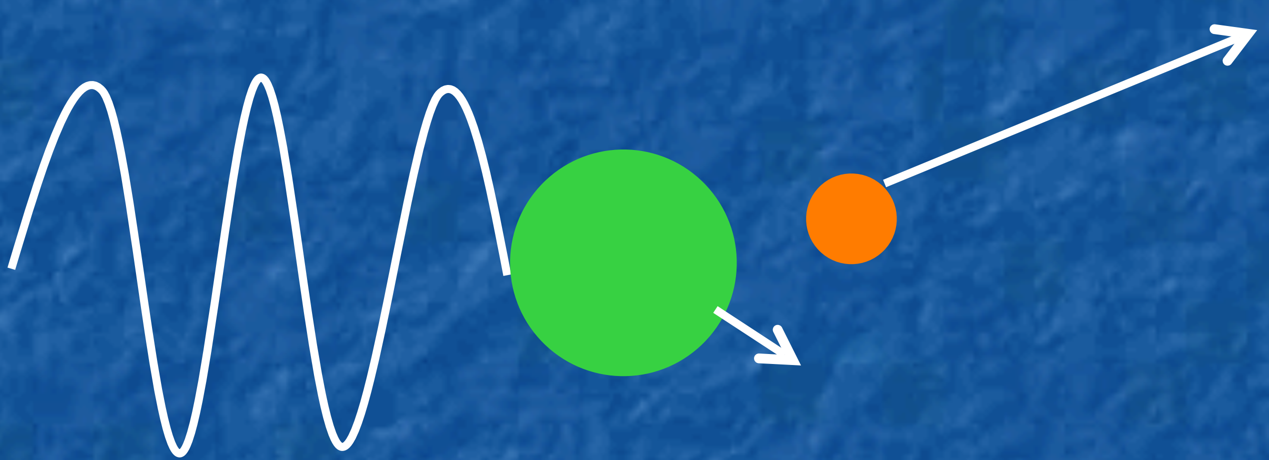


COS will be installed on SM4
(mid-May 2009)

Heating during He reionization

Photoionization Heating

- Photon typically has >54 eV
  - Excess energy becomes kinetic energy of electron
- Electron scatters through IGM and heats it
- Independent of density



$$He^{+} + \gamma \rightarrow He^{++} + e^{-}$$

Optically thin or thick heating?

What is the mean energy per He ionization?

Optically thin: weight by photoionization cross-section

$$\langle E_{\rm ph}^{\rm thin} \rangle = \frac{\int_{\nu_{\rm th}}^{\infty} \left[J(\nu)/h\nu\right] \sigma(\nu)(h\nu - h\nu_{\rm th})d\nu}{\int_{\nu_{\rm th}}^{\infty} \left[J(\nu)/h\nu\right] \sigma(\nu)d\nu},$$

$$\langle E \rangle = \frac{h\nu_{\rm th}}{\alpha + 2} \Rightarrow \Delta T = 4200\,{\rm K}$$

Optically thick: all photons are absorbed

$$\langle E_{\rm ph}^{\rm thin} \rangle = \frac{\int_{\nu_{\rm th}}^{\infty} \left[J(\nu)/h\nu\right] \cancel{\sigma(\nu)}(h\nu - h\nu_{\rm th})d\nu}{\int_{\nu_{\rm th}}^{\infty} \left[J(\nu)/h\nu\right] \cancel{\sigma(\nu)}d\nu},$$

Abel & Haehnelt 1999

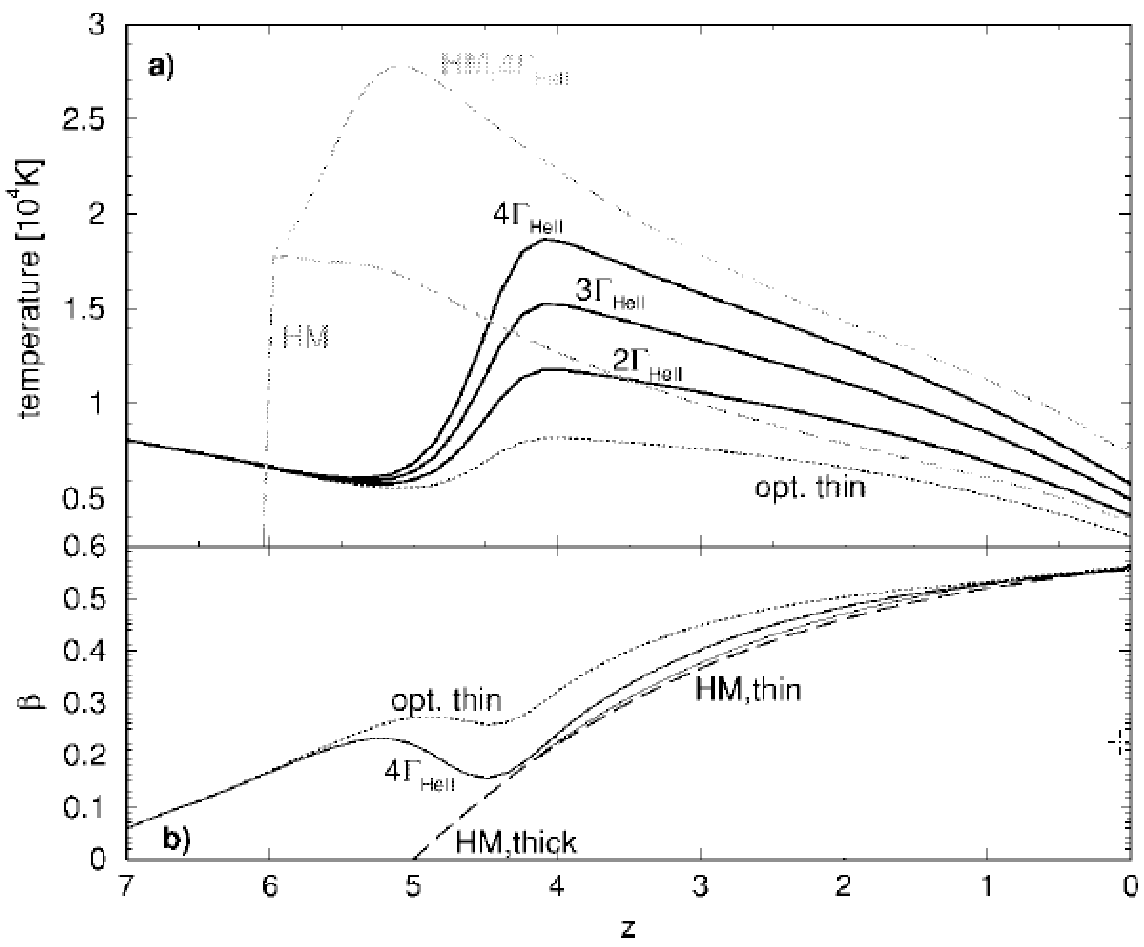
$$\langle E \rangle = \frac{h\nu_{\rm th}}{\alpha - 1} \Rightarrow \Delta T = 30,000\,{\rm K}$$

A larger temperature boost...

Mfp of He ionizing photons :

$$\lambda_{\rm He} = 0.66 \left(\frac{4}{1+z}\right)^2 \left(\frac{\nu}{\nu_{\rm HeII}}\right)^3 \ {\rm Mpc},$$

Optically thick heating rates apply



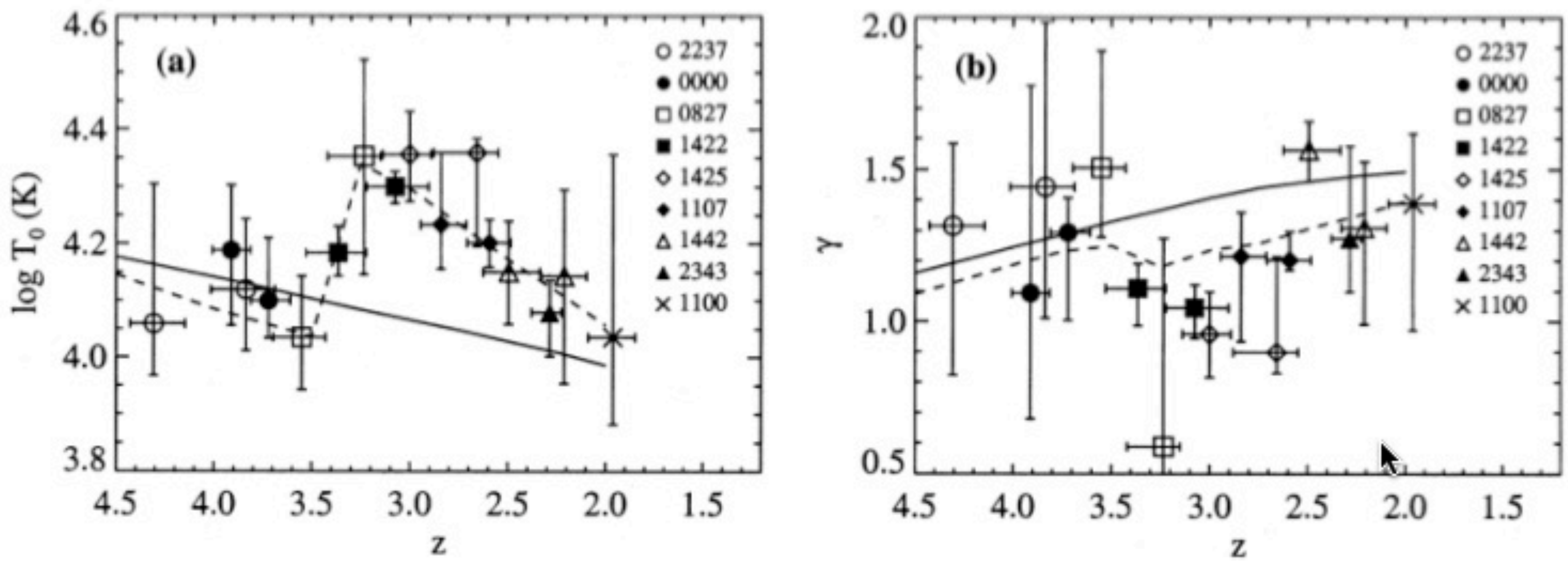
Abel & Haehnelt 1999

Radiation field hardens as propagates outwards from quasar

$$n_{\rm LLS}^{-1/3} \approx 30 Mpc < n_{\rm QSO}^{-1/3} \approx 100 Mpc$$

IGM reionized by filtered, hardened radiation field

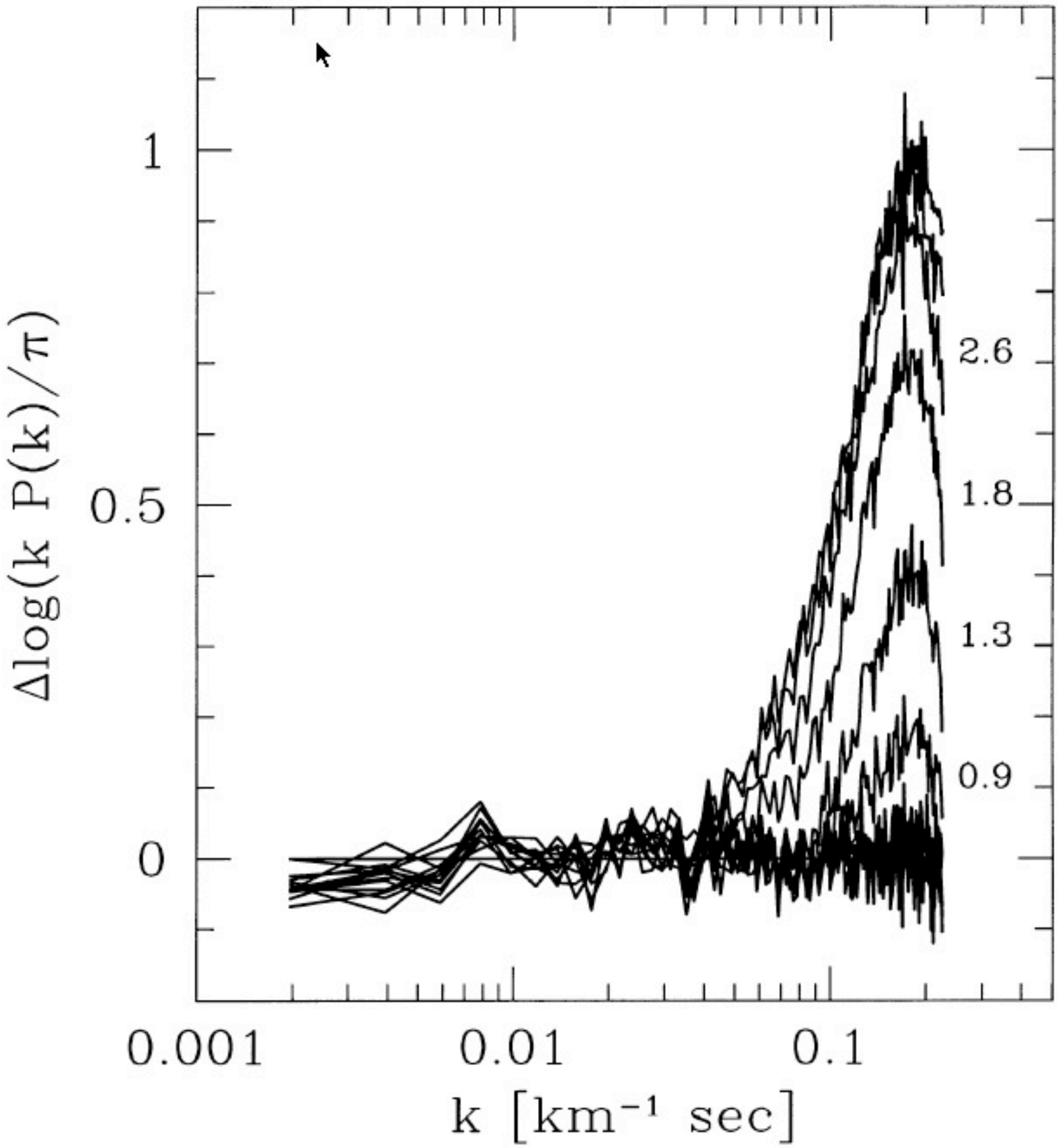
Look for He reionization in the H Ly-alpha forest!



Schaye et al 2000

Expected boost in Doppler widths--YES

but it's a tricky business...



Zaldarriaga et al 2001

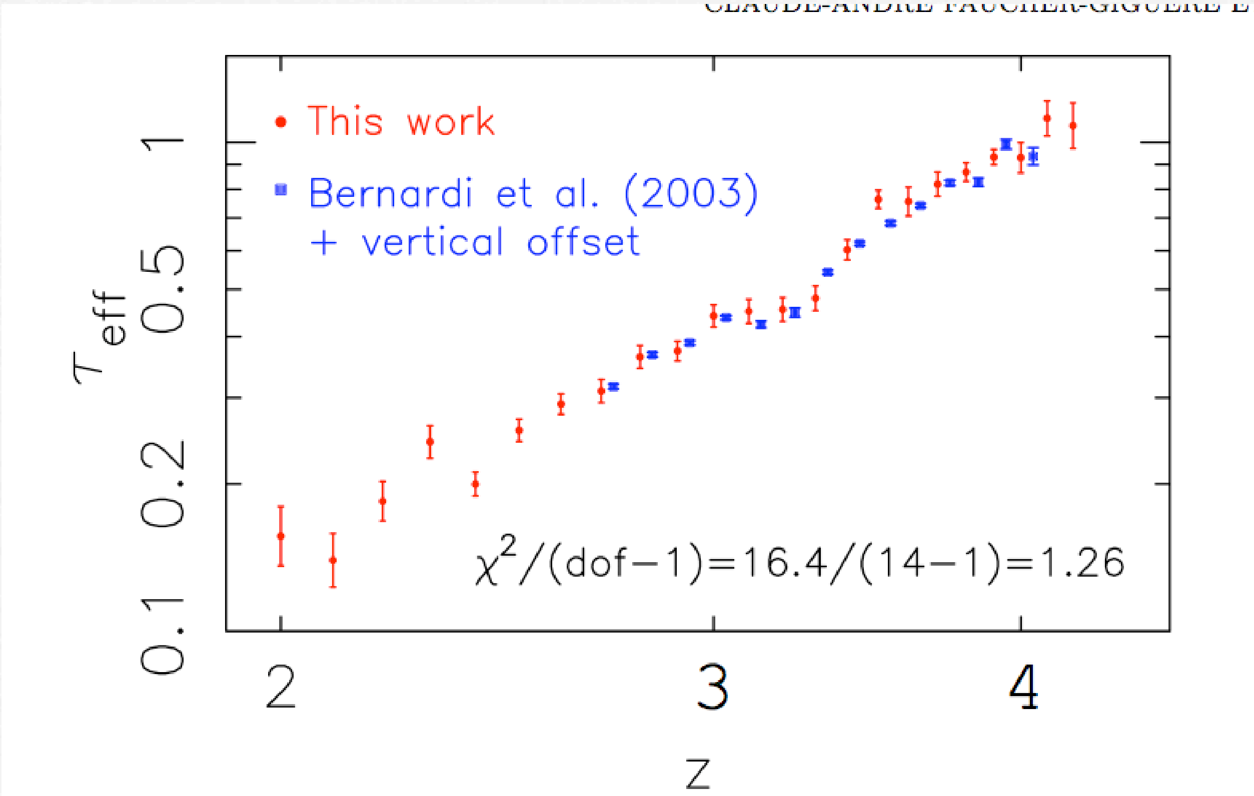
Jeans smoothing should suppress power at small scales

None seen

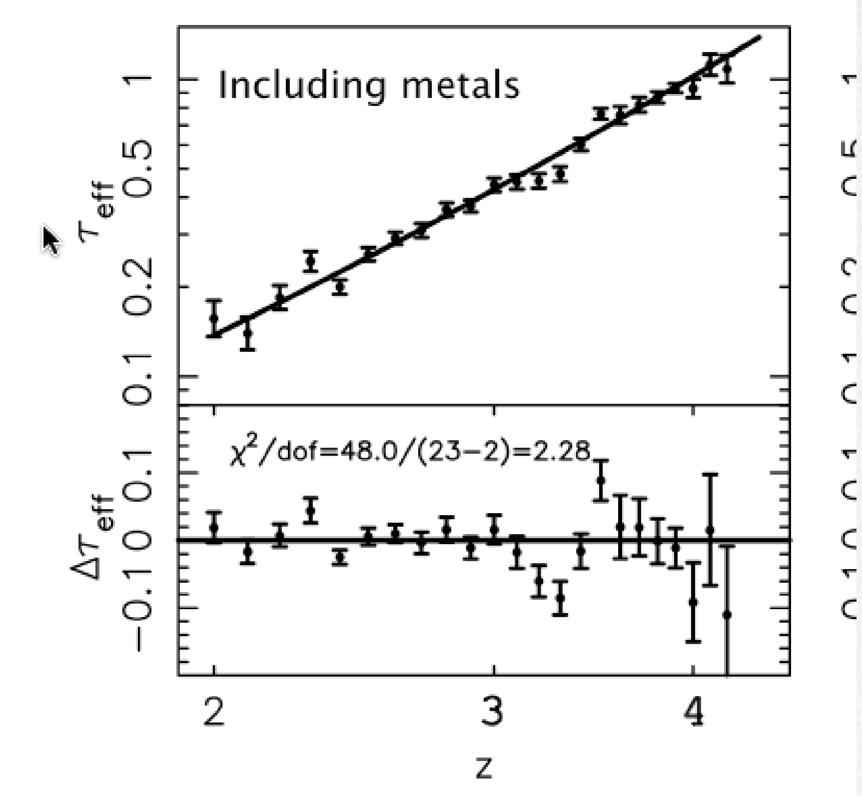
(Zaldarriaga et al 2001, Viel et al 2004, McDonald et al 2006)

Change in small scale power spectrum -- NO

Culprit: "The Bump"



Faucher-Giguere et al 2007



Change in hydrogen opacity due to temperature dependence of recombination

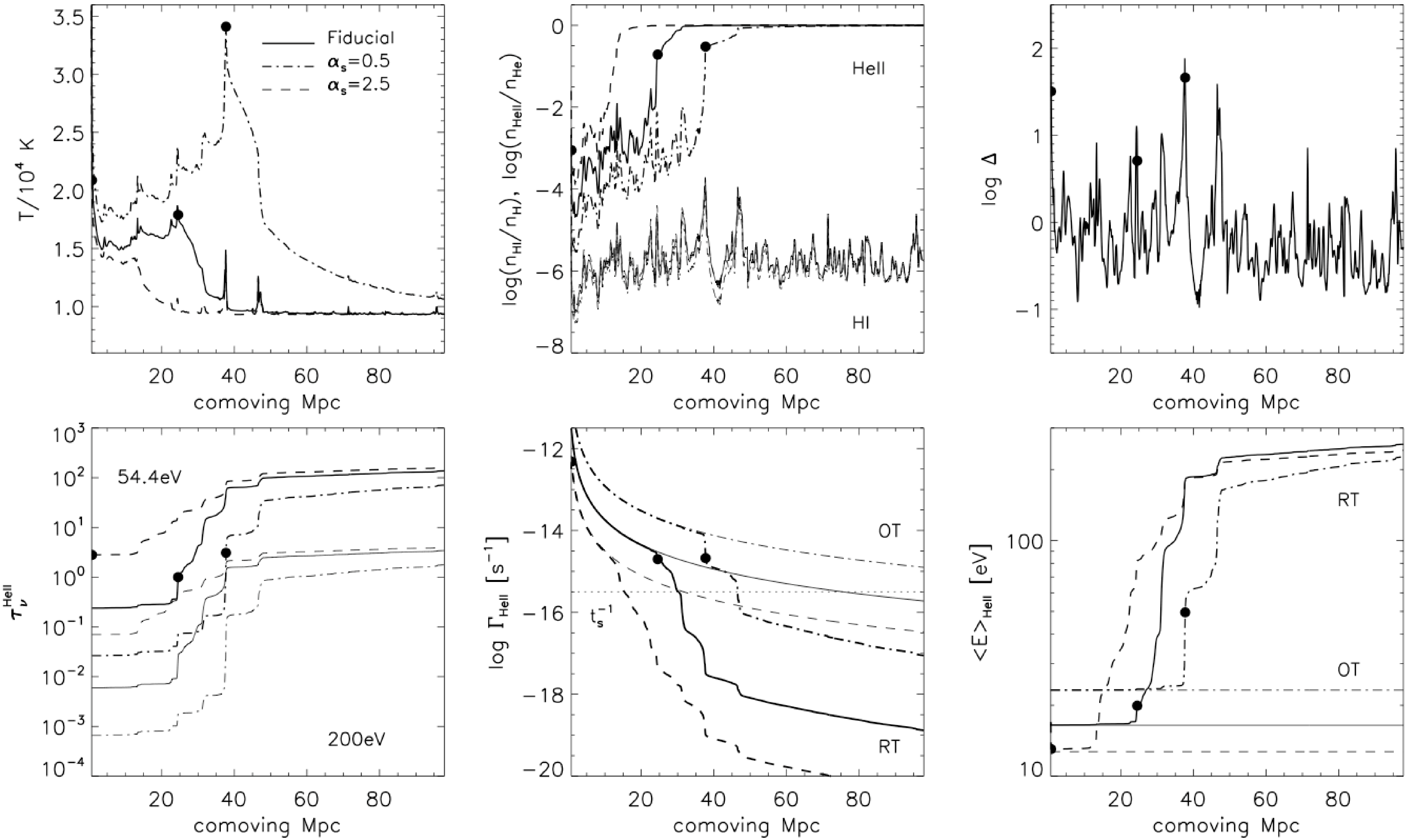
The latest outrage...very sudden heating and cooling

Why is it difficult to have sudden heating?

$$\frac{dT}{dt} \simeq \frac{2\mu m_{\rm H}}{3k_{\rm B}\rho_{\rm b}} \left| \frac{dn_{\rm HeII}}{dt} \right| \langle E \rangle_{\rm HeII},$$

Filtered radiation is has a much weaker ionization rate

Overall heating rate is still lower than optically thick rate



...as seen in the radiative transfer/hydo simulations (30 cMpc, GADGET2, 2 x 400^3 particles)

So where do all the hard photons go?

- IGM is optically thick--we have to apply to apply optically thick heating rate, right?

No, clumpiness alters the optically thick heating rate--it becomes intermediate between the thick and thin rates

- LLSs more abundant than quasars

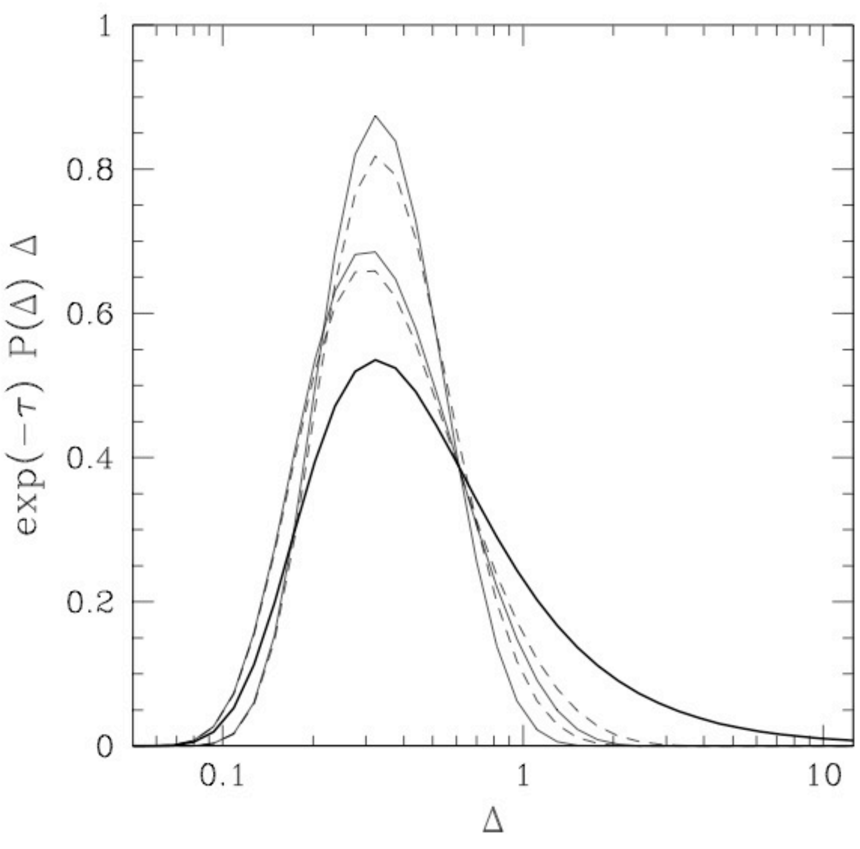
No, most quasars ionize a small local patch before encountering a LLS. Most IGM is ionized by extinct QSOs

Most important: hard photons are preferentially absorbed by LLSs

Density dependence

We can only probe low-density regions with the H Ly-alpha forest.

We only care if the low density regions are heated!



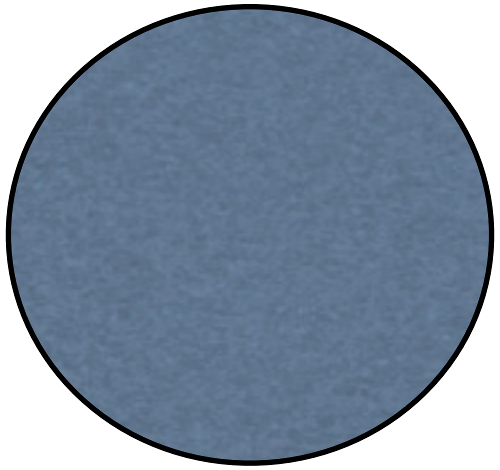
$$N_{\rm HI} = 2.7 \times 10^{13}\,{\rm cm}^{-2} \Delta^{3/2} T_4^{-0.26} \Gamma_{-12}^{-1} \left(\frac{1+z}{4}\right)^{4.5}$$

Filtering in a clumping medium

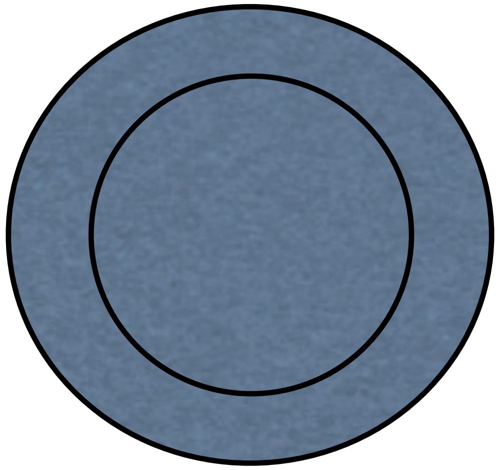
In a clumpy medium, $\lambda \propto \nu^{-\beta}, \beta \approx 1.5 - 2.5$

instead of $\lambda \propto \nu^{-3}$ in uniform medium

Reason: optically thick systems have reduced contribution to opacity



hard photon sees this



soft photon sees this

Net result (for β=1.5)

$$\langle E \rangle_{\rm HeII} = \frac{\epsilon_{\rm HeII}}{\Gamma_{\rm HeII}} = \frac{\int_{\nu_{\rm HeII}}^{\infty} d\nu\ h_{\rm p}(\nu - \nu_{\rm HeII})\epsilon_\nu \lambda_\nu \sigma_\nu}{\int_{\nu_{\rm HeII}}^{\infty} d\nu\ \epsilon_\nu \lambda_\nu \sigma_\nu}$$

$$\simeq \frac{h_{\rm p}\nu_{\rm HeII}}{(\alpha_{\rm s} + 0.5)},$$

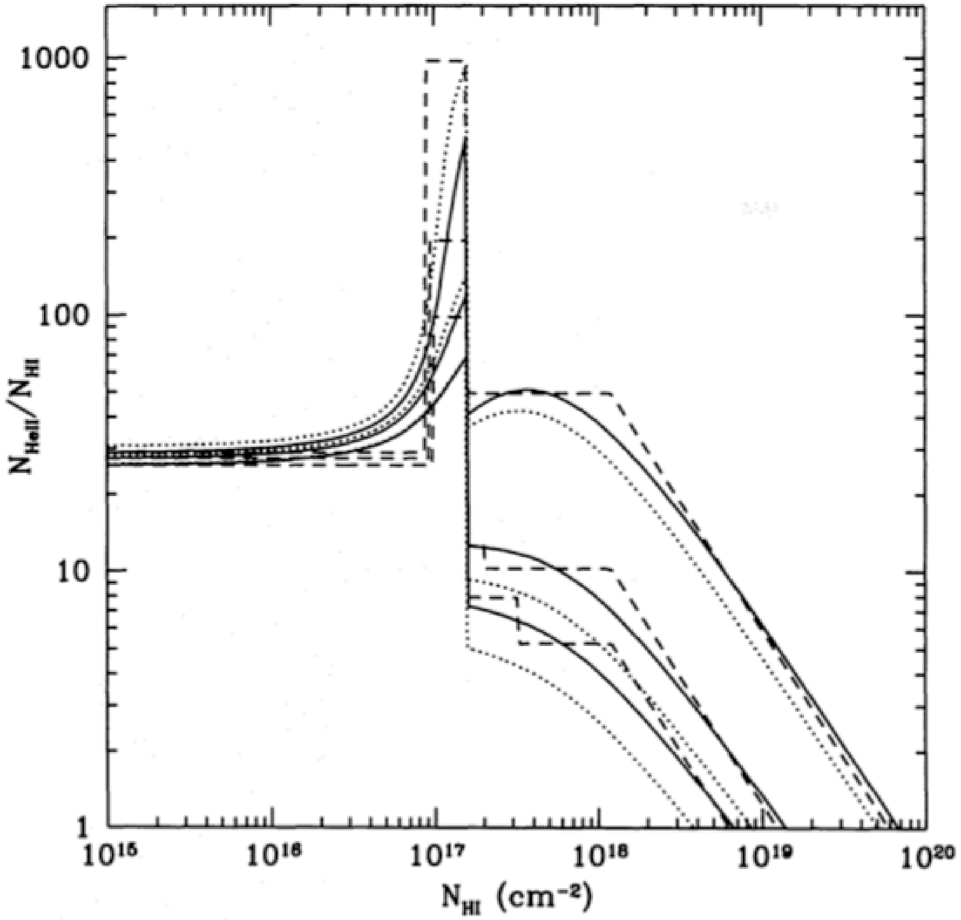
$$\Delta T \approx 7000\, K$$

Intermediate between optically thick and thin case!

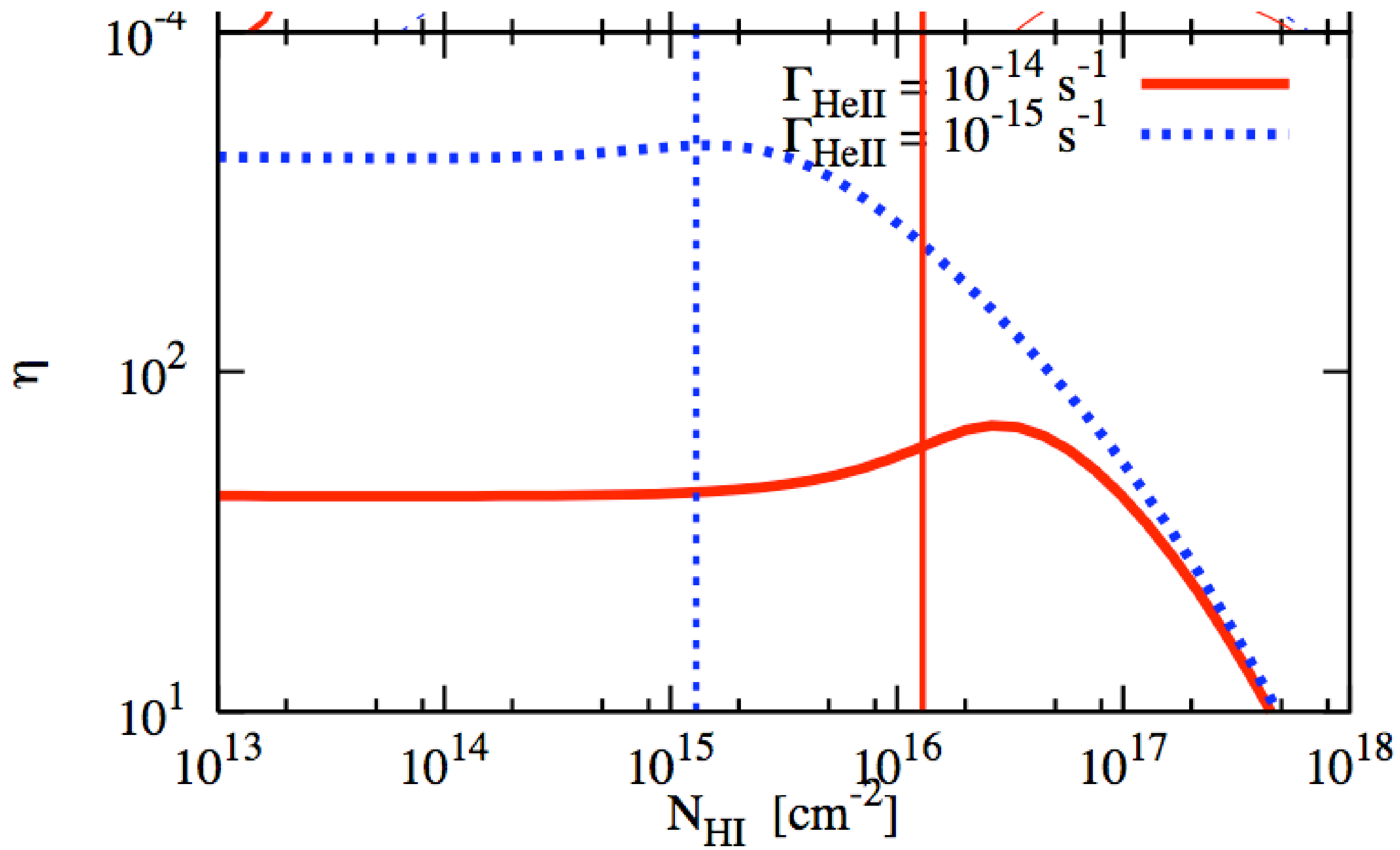
Whether this occurs depends critically on the number of high column density systems...

Uncertainty in HeII absorber abundance...

Haardt & Madau 1996



McQuinn et al 2008



Measure abundance of HI system, dN/dN_HI

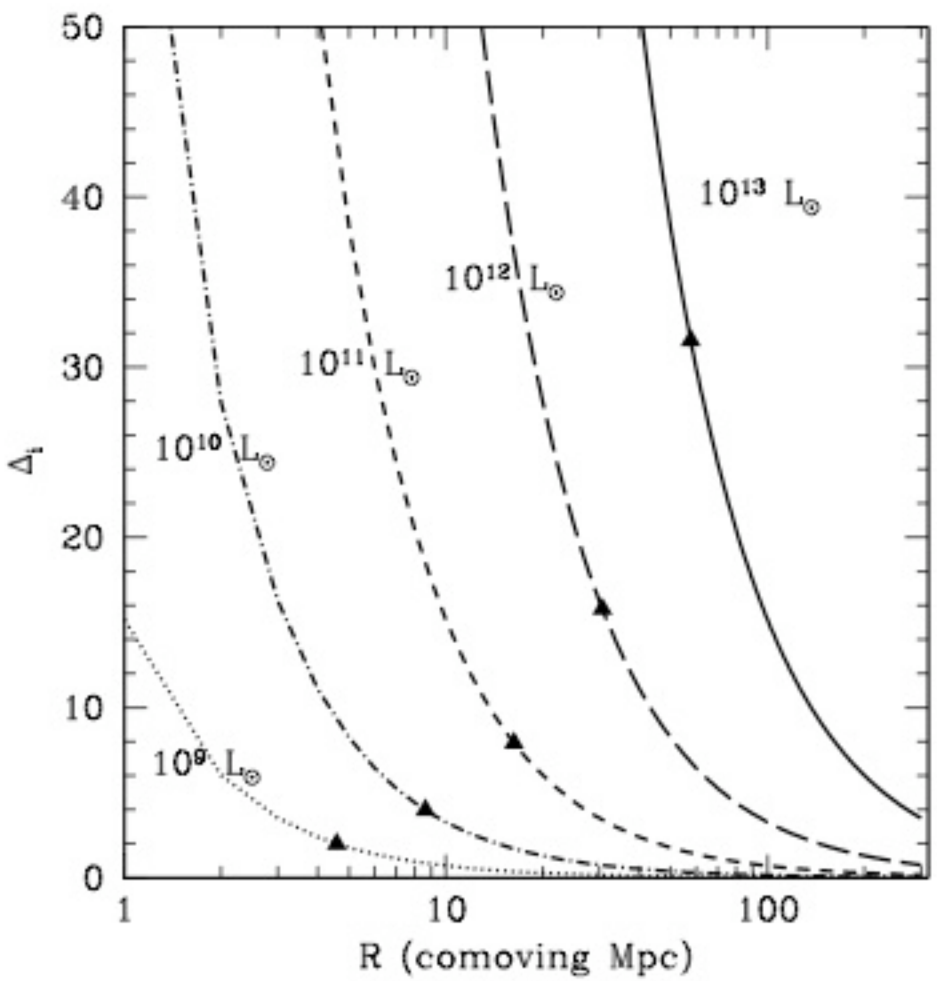
Use theoretical model for $\eta \equiv N_{\rm HeII}/N_{\rm HI}$

Depends on uncertain link between N_HI and density

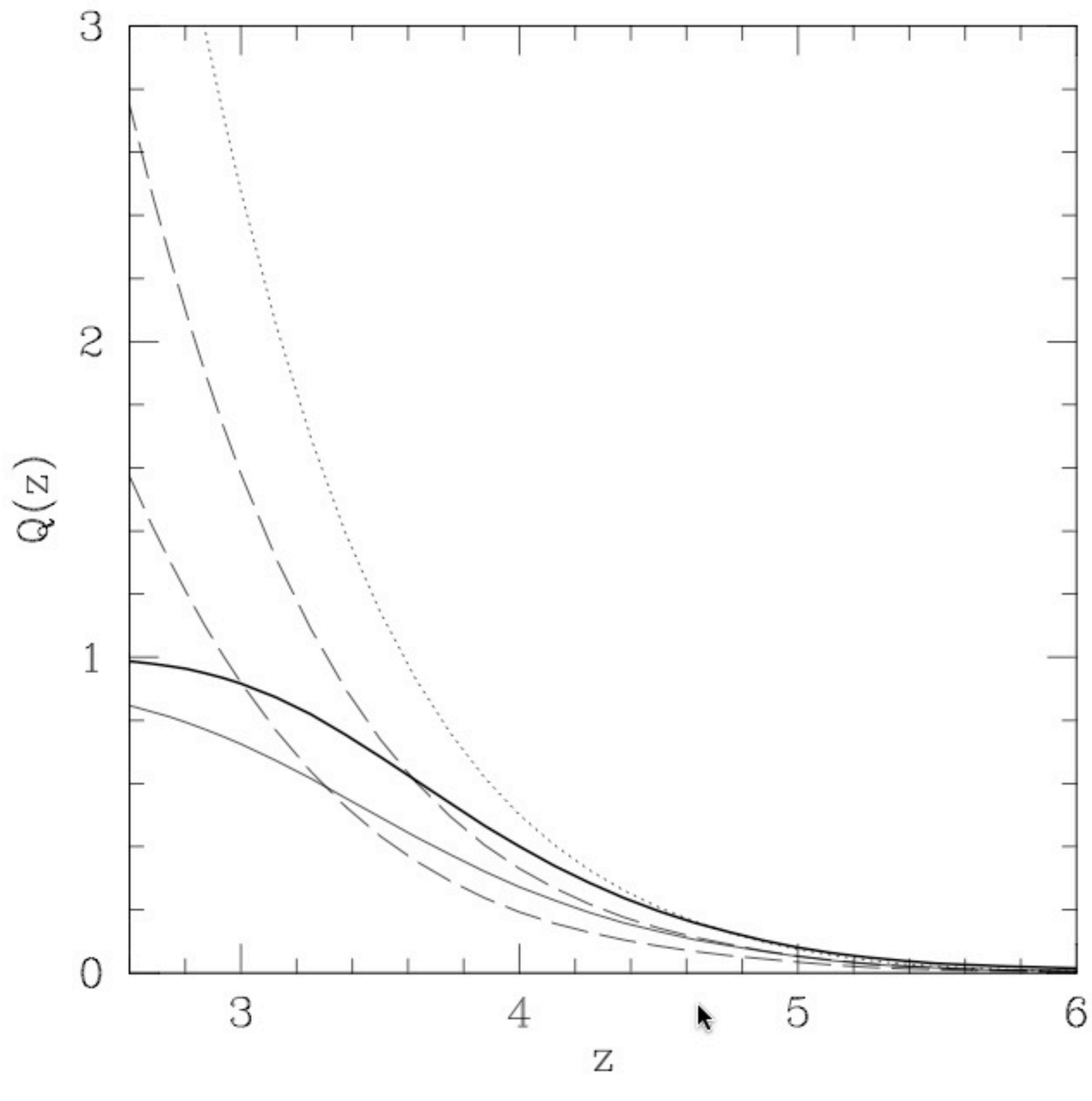
...translates into uncertain heating rates

- HM model: $\lambda \propto \nu^{1.5}, \Delta T \approx 7000K$
- McQuinn 08 model: $\lambda \propto \nu^{2-2.8}, \Delta T \approx 15,000K$
- This also translates into considerable uncertainty in UV background above 4 Ry, metal-line ratios....

Most He is ionized by previous generations



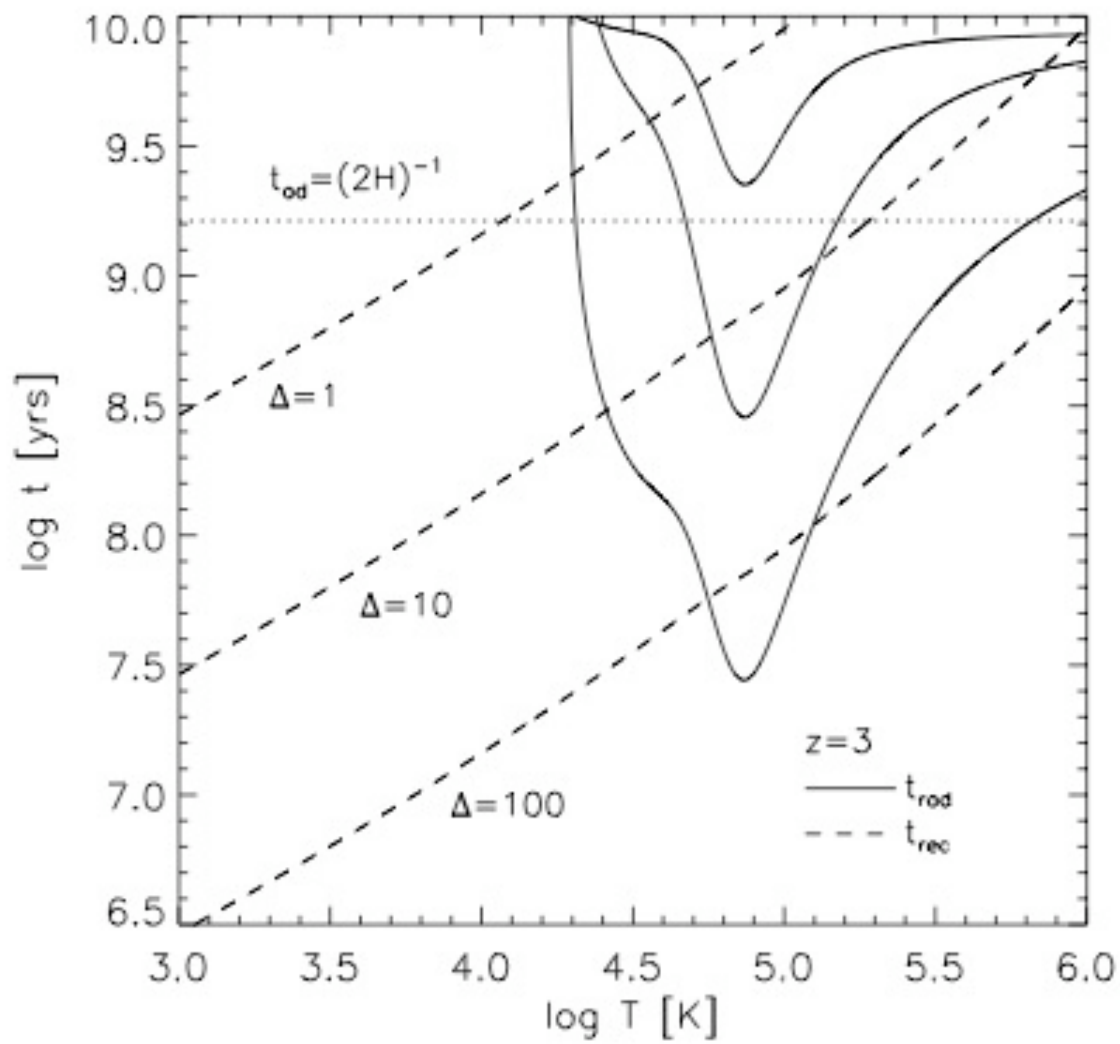
BOF08



Heating of Fossils?

Recombination time long in low density regions

Multiple heating episodes only possible in high density regions



BOF08

Some other recent work..

McQuinn et al 2008

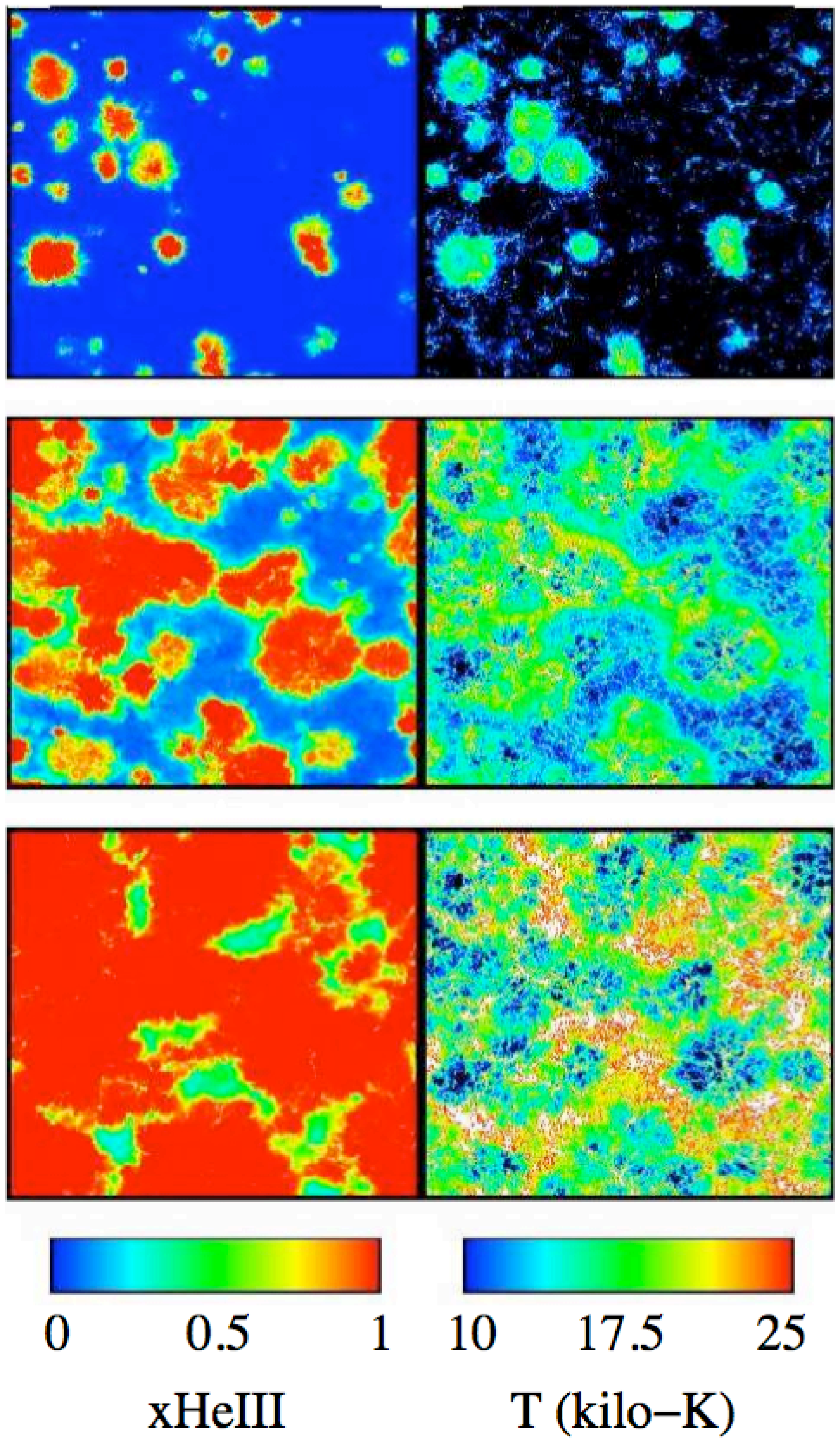
N-body only (no hydro; superimpose jean-smoothed gas)

Large box (190, 430 cMpc); fully 3D radiative transfer

Broadly consistent results

Mean temperature boost ~12, 000 K

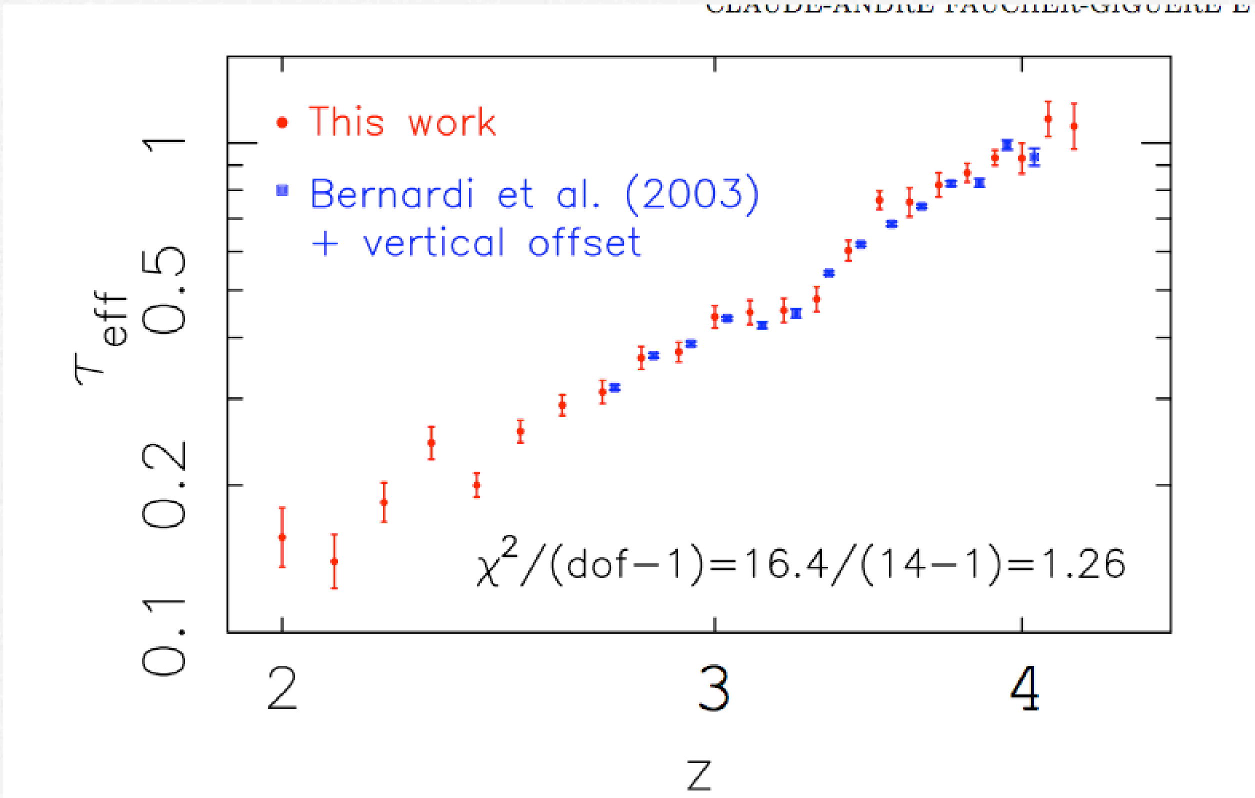
Max temperature boost ~30,000 K



McQuinn et al 2008

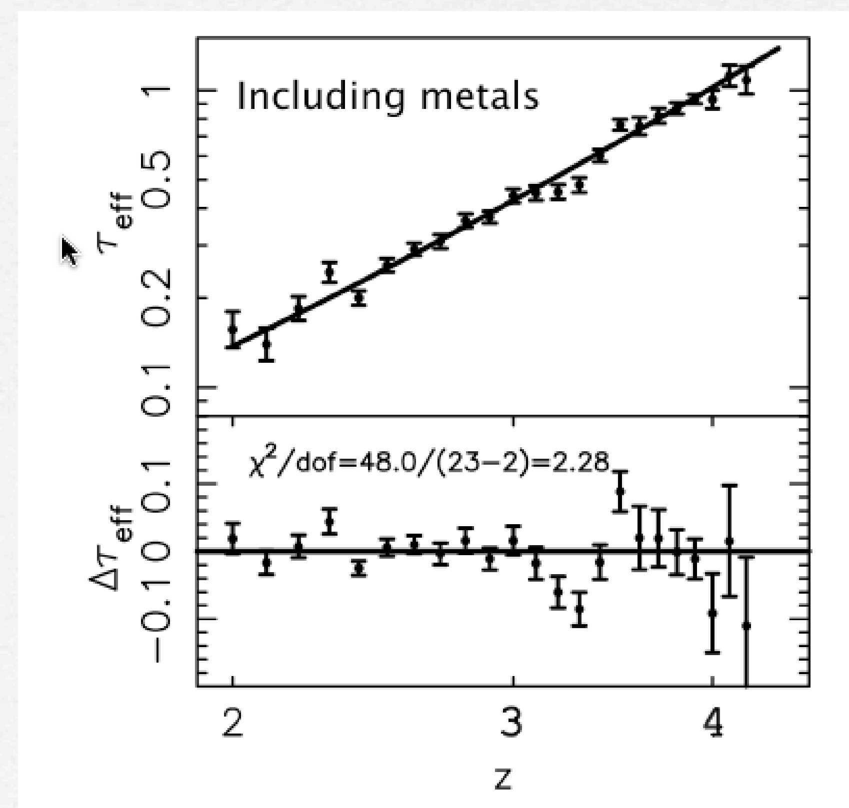
Have we seen He reionization in the HI forest?

Culprit: “The Bump”



Faucher-Giguere et al 2007

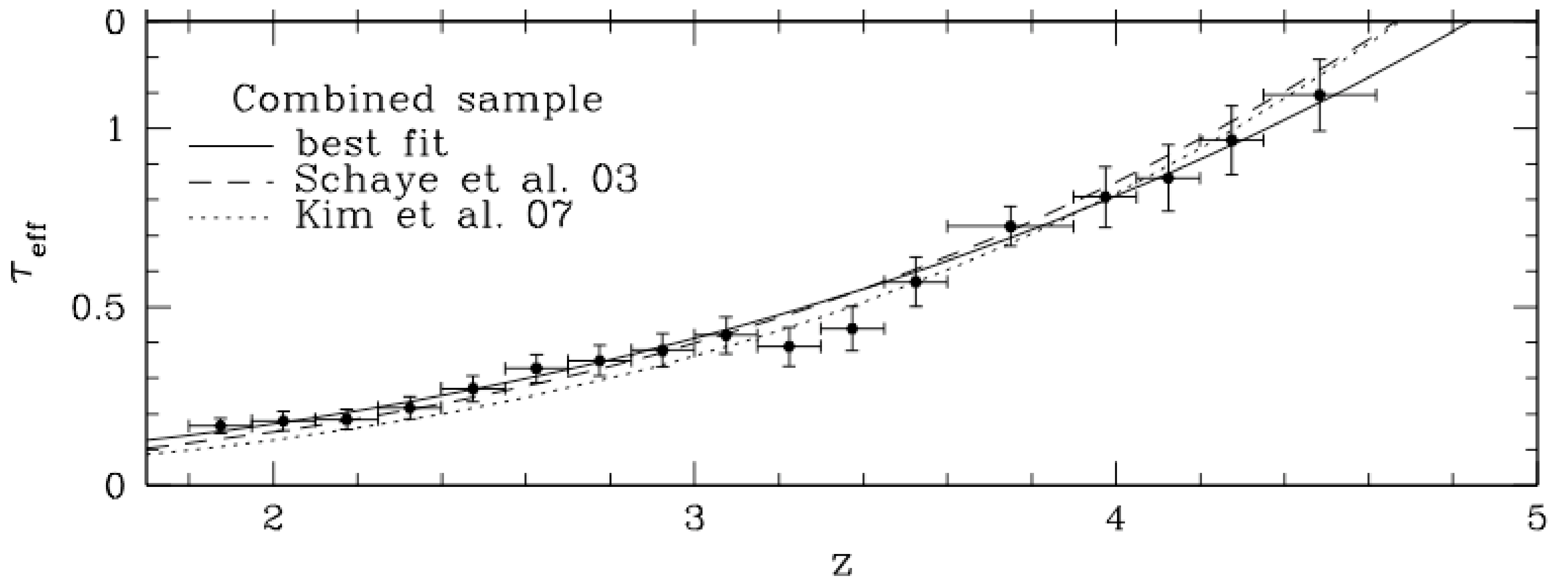
Change in hydrogen opacity due to temperature dependence of recombination



The latest outrage...very sudden heating and cooling

Should we believe it?

- Seen in 3 independent data-sets, but not in all (e.g., McDonald et al (2006))
- Issues of color selection, continuum placement...
- can we even make sense of it theoretically? ("π in the sky...")

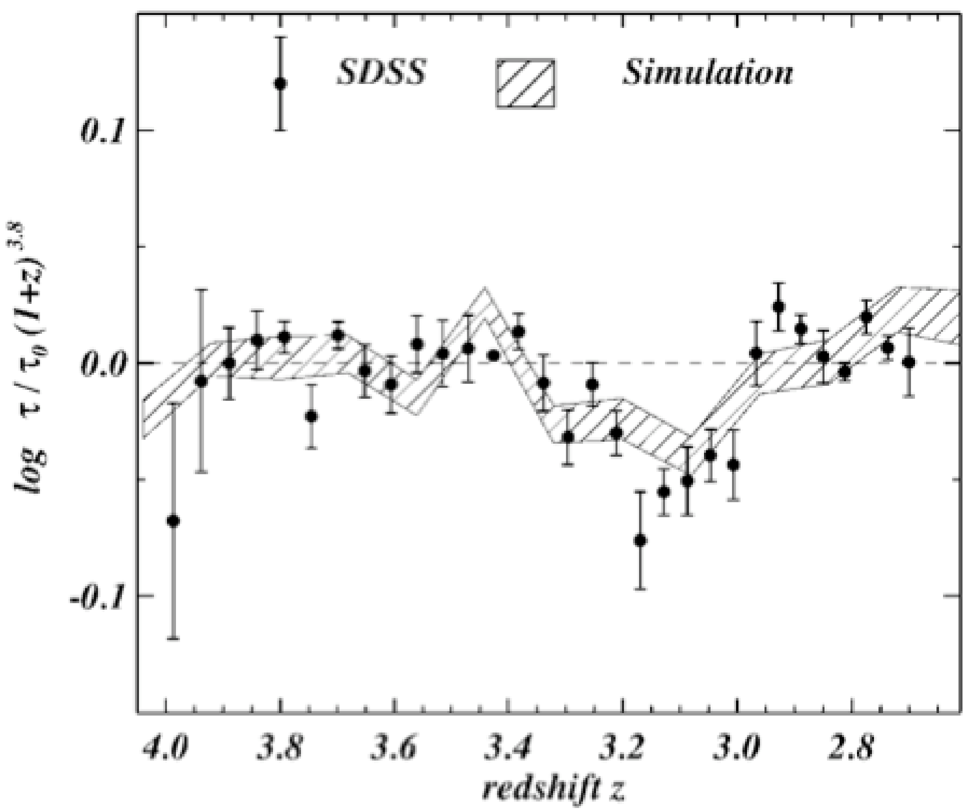


Dall'Anglio et al 2007

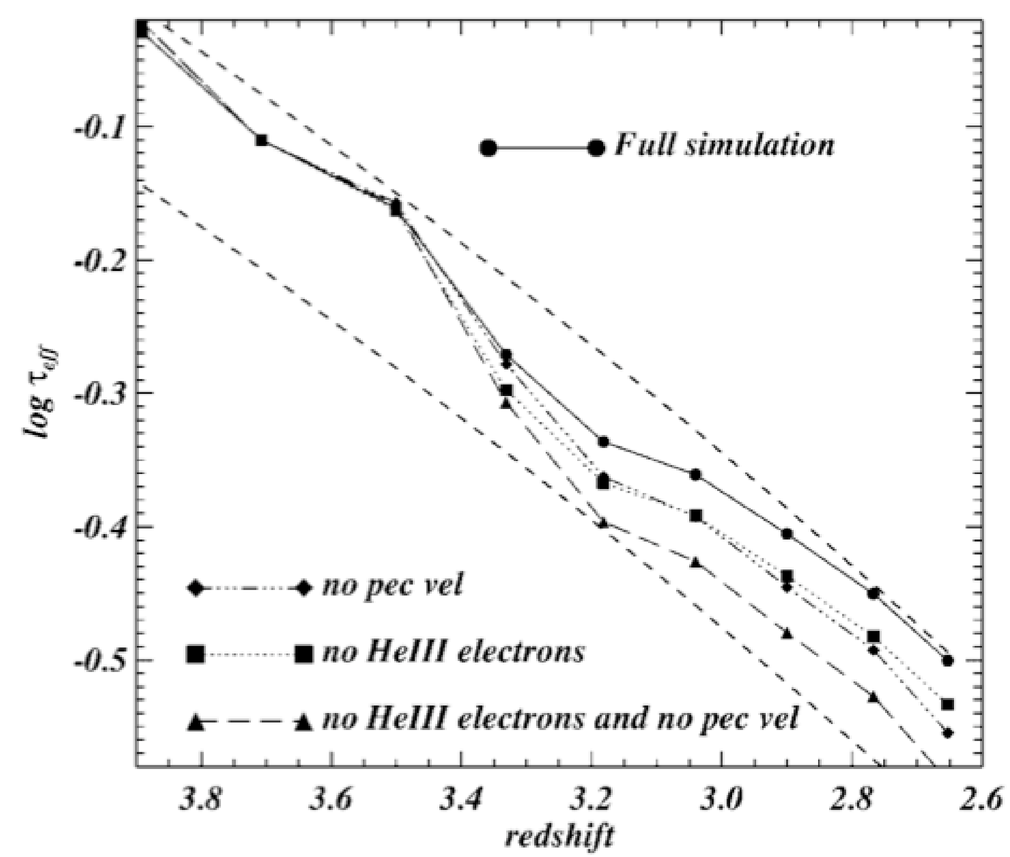
It's very difficult to explain this...

Thermal heating (+hydrodynamic effects) has been standard explanation

We find this untenable



Theuns et al (2002)

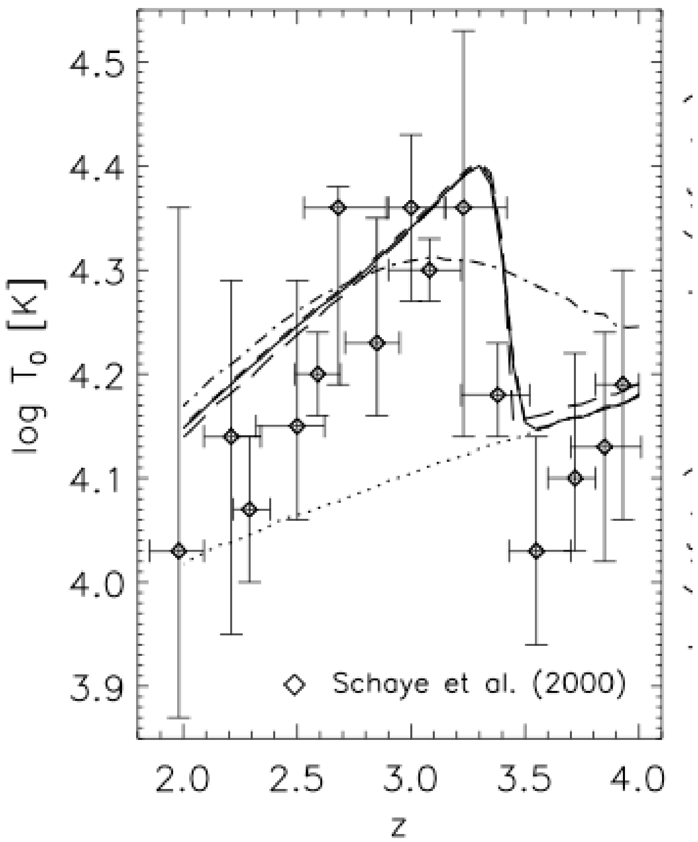


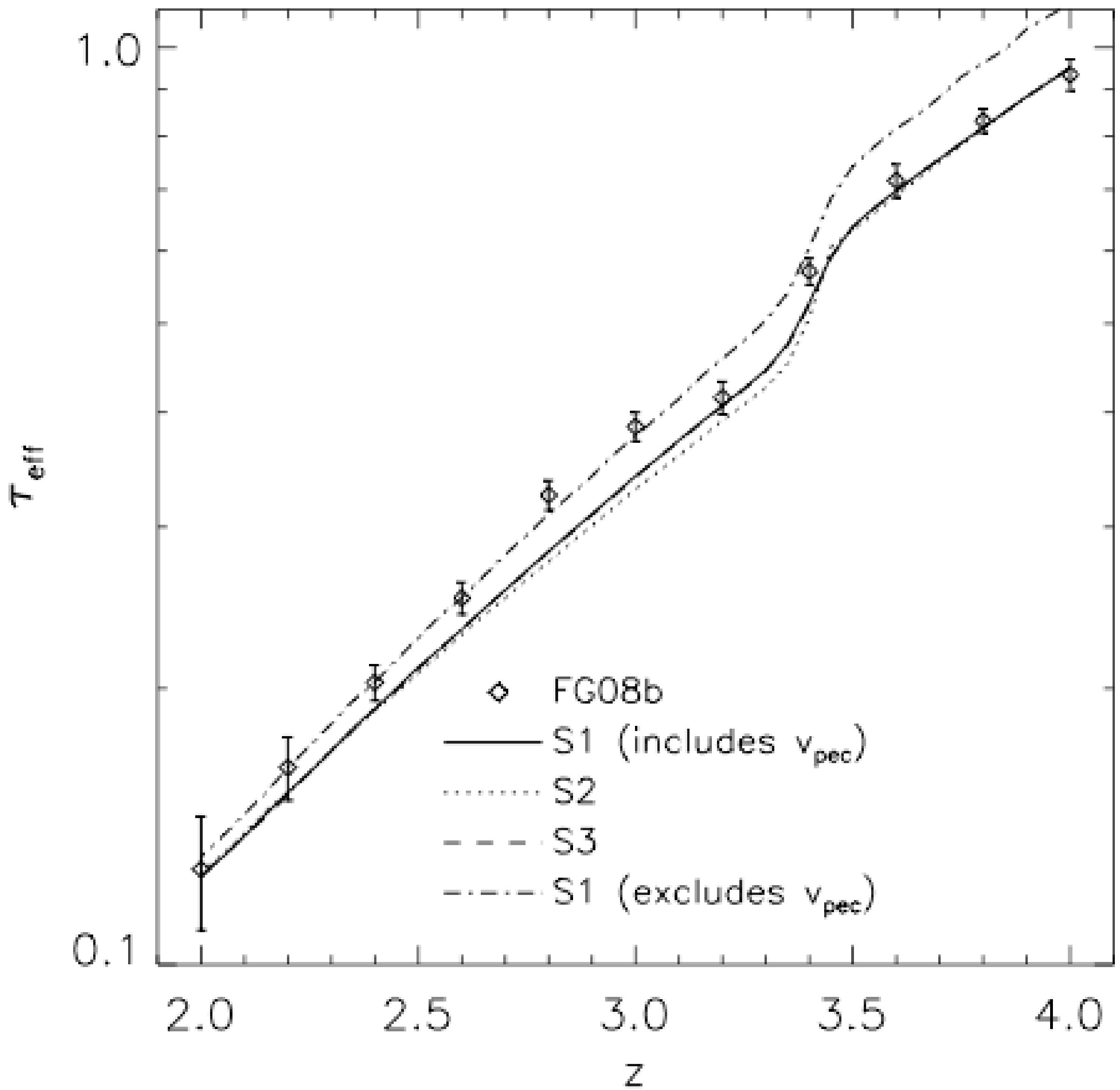
Simulate this!

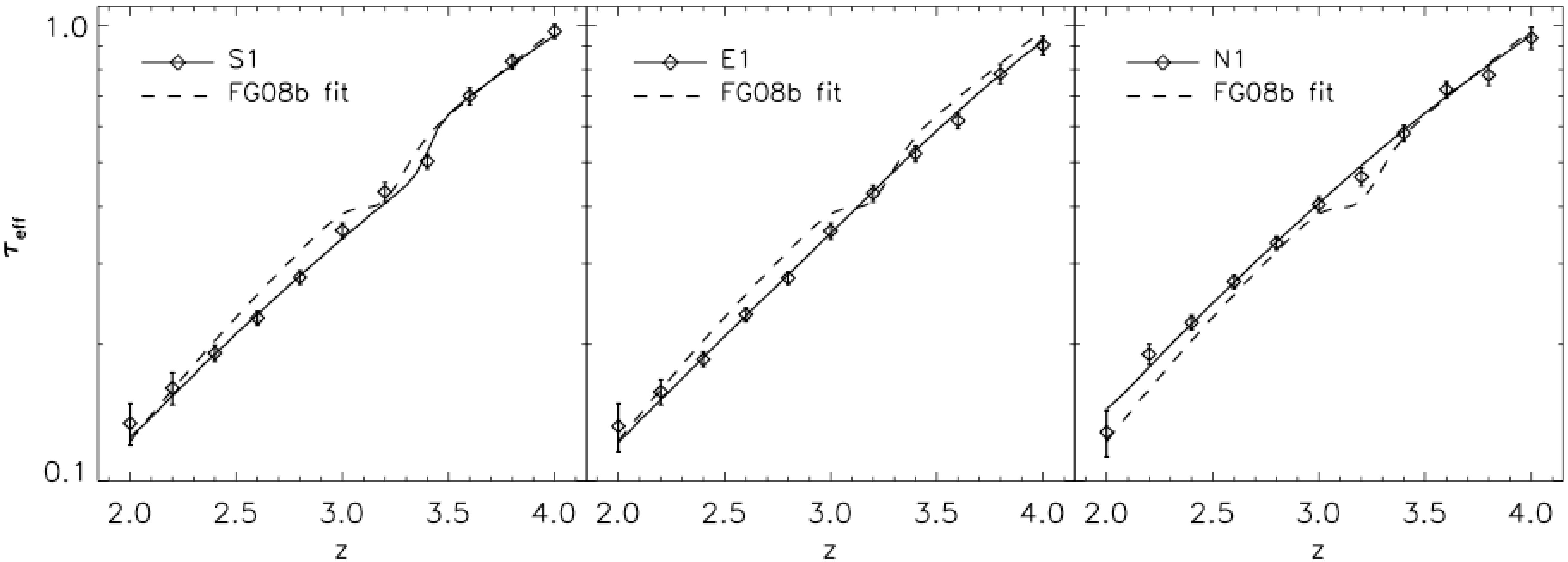
Bolton, Oh & Furlanetto (2009)

Upgraded Gadget2, 15 cMpc, 2 x 400^3 particles
Follow non-equilibrium chemistry

Model	Thermal history description
S1	Sharp temperature boost
E1	Extended temperature boost
N1	No temperature boost; control model
S2	Similar to S1, but with a rapid change in n_e
S3	Identical to S1, but with a stricter timestep limit

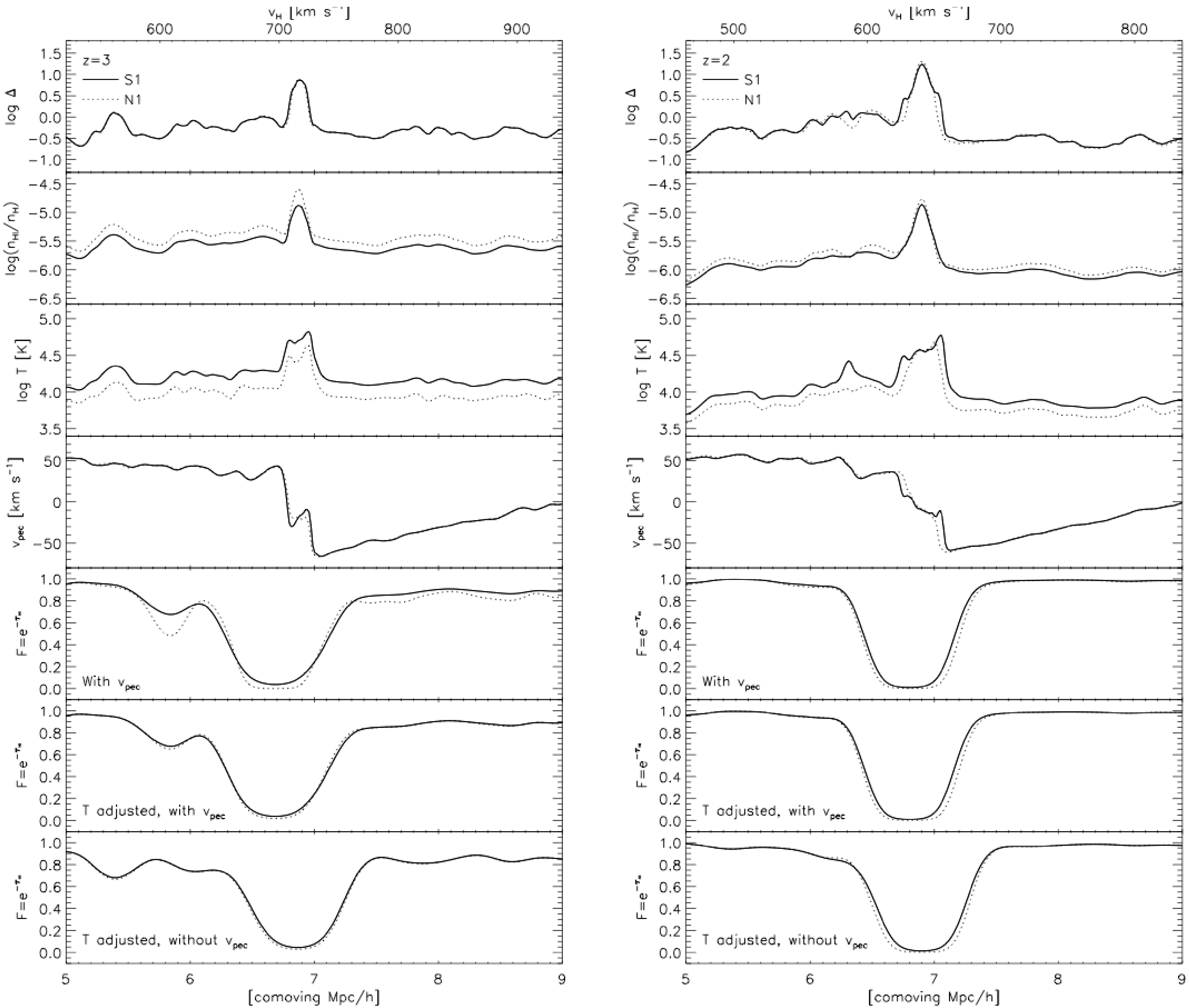






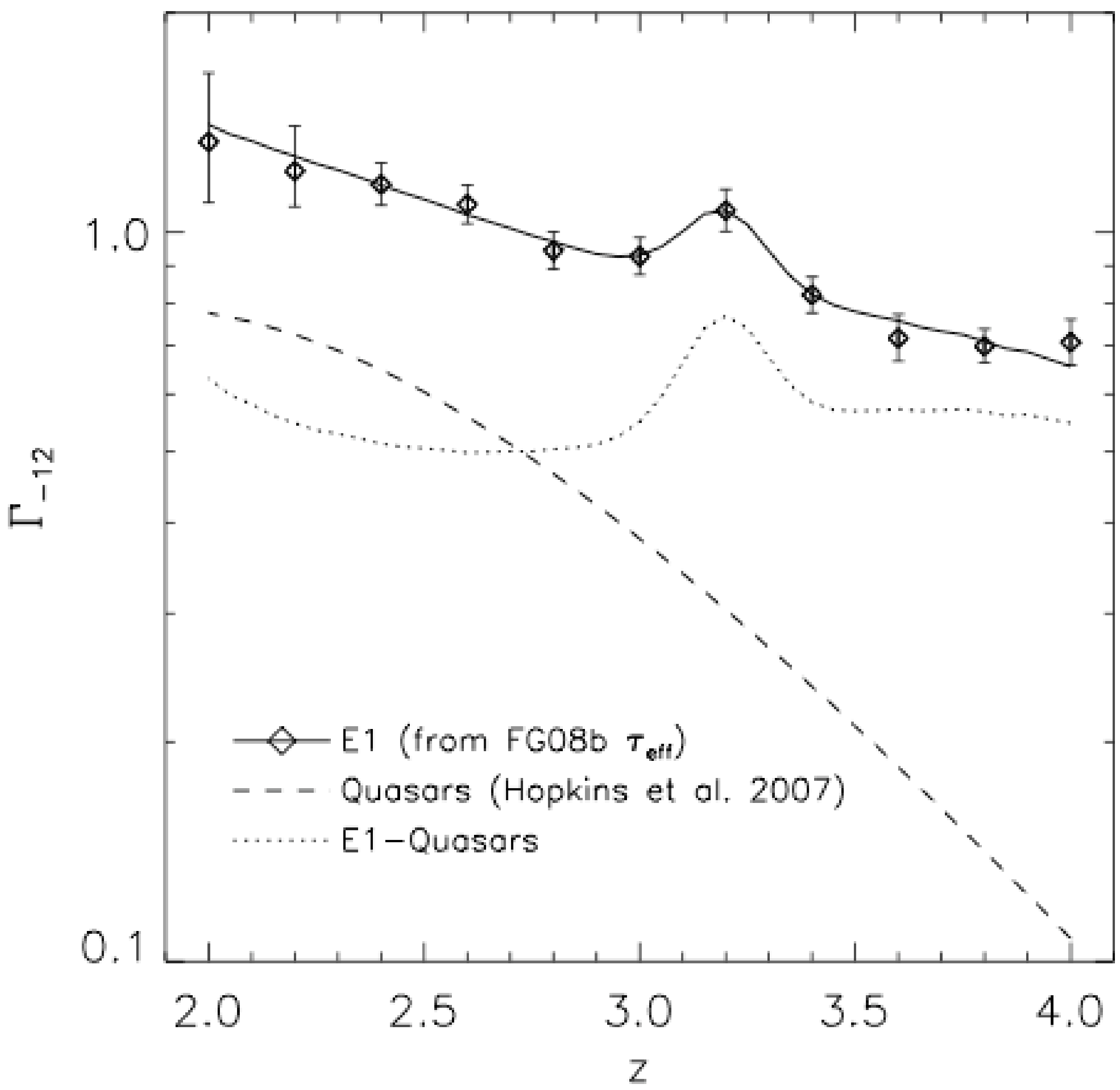
data point: after processing to reproduce observations of spectra

Evolution is smooth!



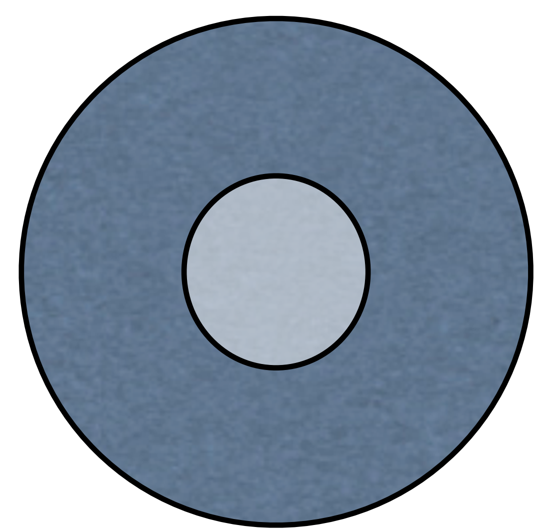
Peculiar velocity gradients from heating are small

Radiative Transfer Effects? !



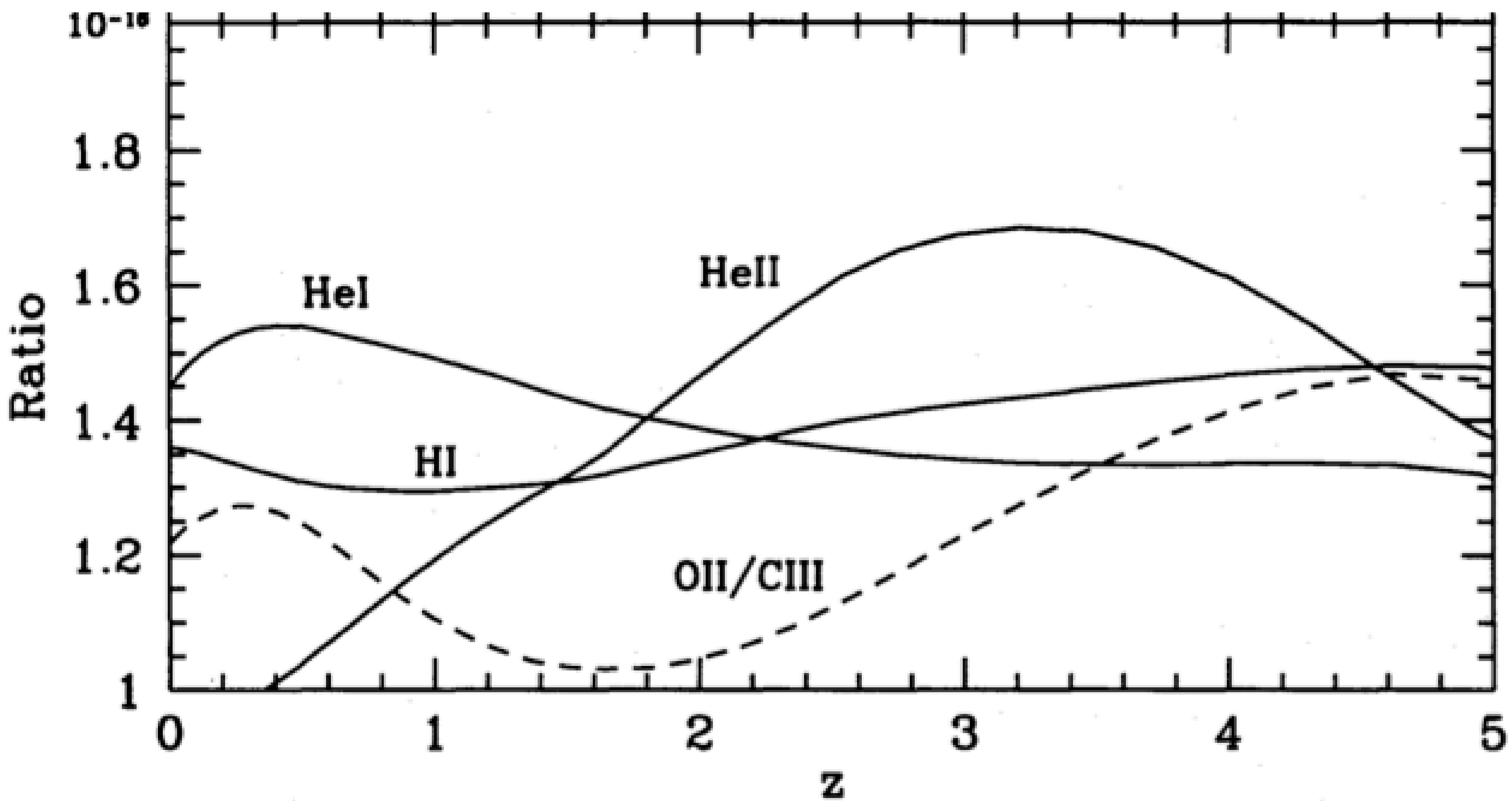
FOB09

1) Change size or temperature of hydrogen lyman limit systems



2) Change emissivity of reprocessed photons?!

He Ly-alpha, Ly-beta, Balmer, two photon...

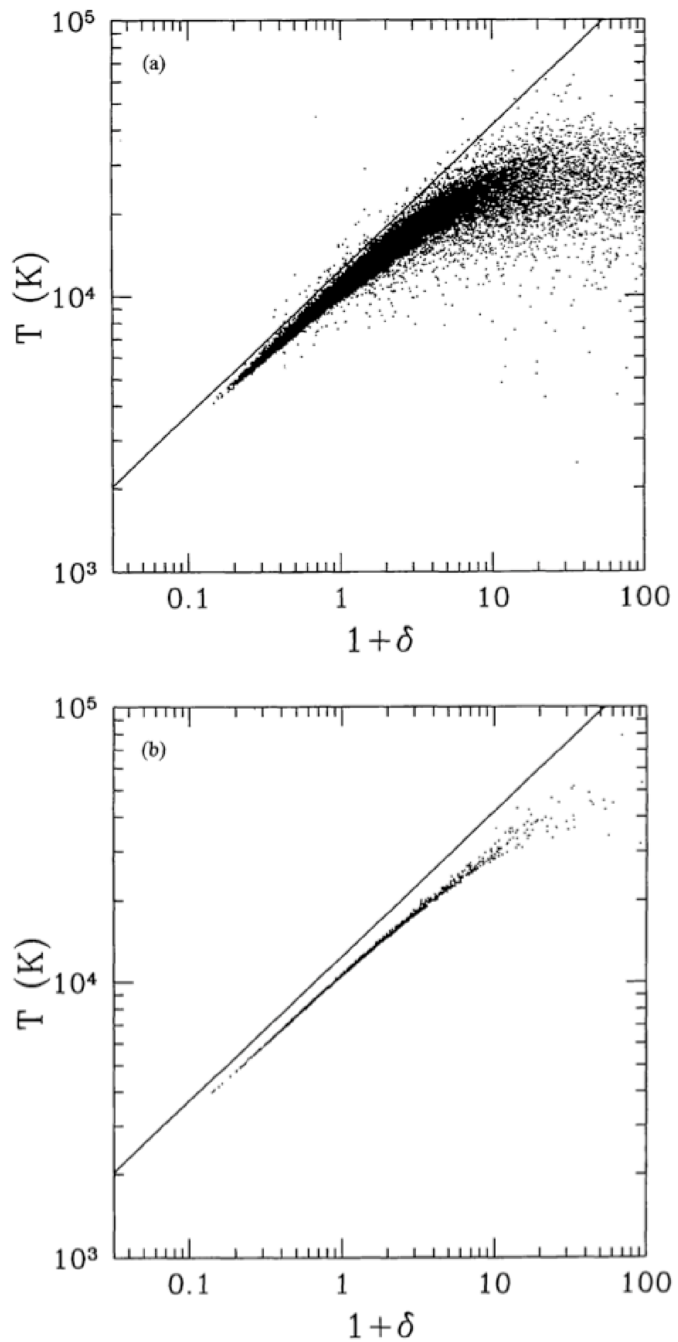


Haardt & Madau (1996)

But recent calculations (Faucher-Giguere et al 2009) disagree...

Equation of State

Power-law equation of state



Hui & Gnedin (1997)

A power-law arises from competition between photo-heating + adiabatic cooling

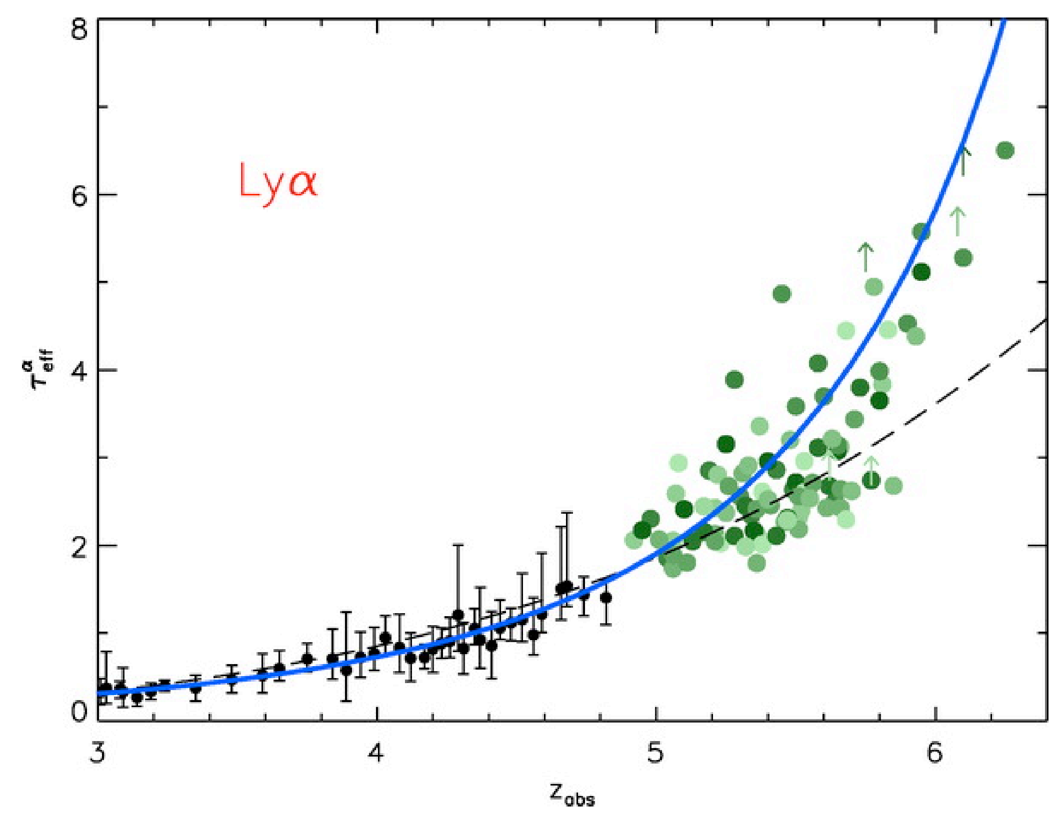
Used in almost all numerical simulations of Ly-alpha forest

Will be altered by Helium reionization! :

Inhomogeneous heating (RT effects)

Finite duration of reionization

What's at stake?

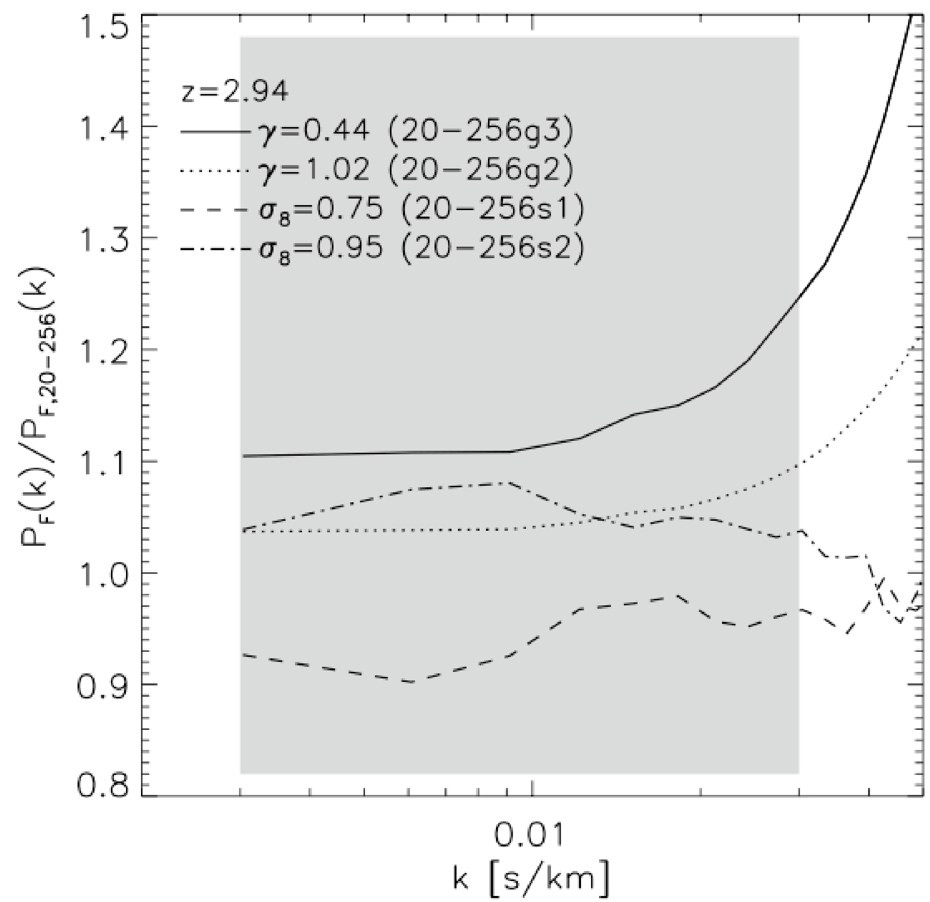


Becker et al (2007)

Affects predictions for effective optical depth

derived ionizing background evolution

fidicial model has



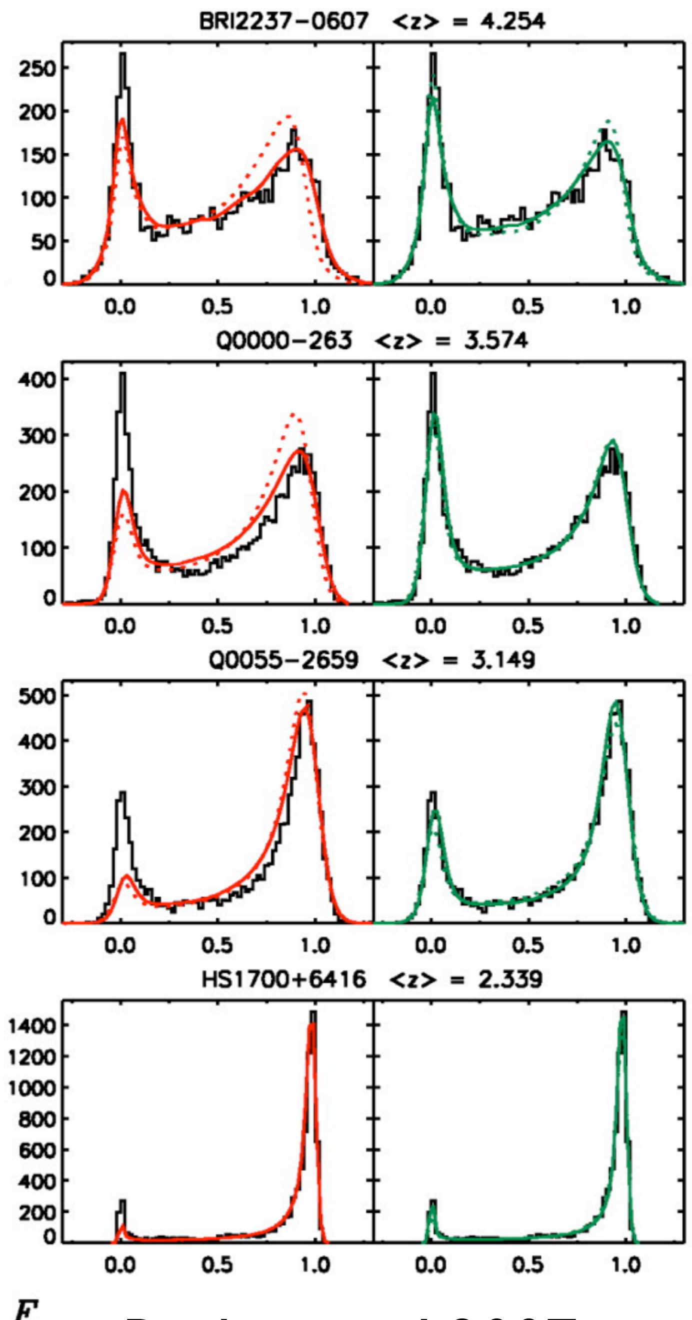
Bolton et al 2008

Also affects power spectrum estimates

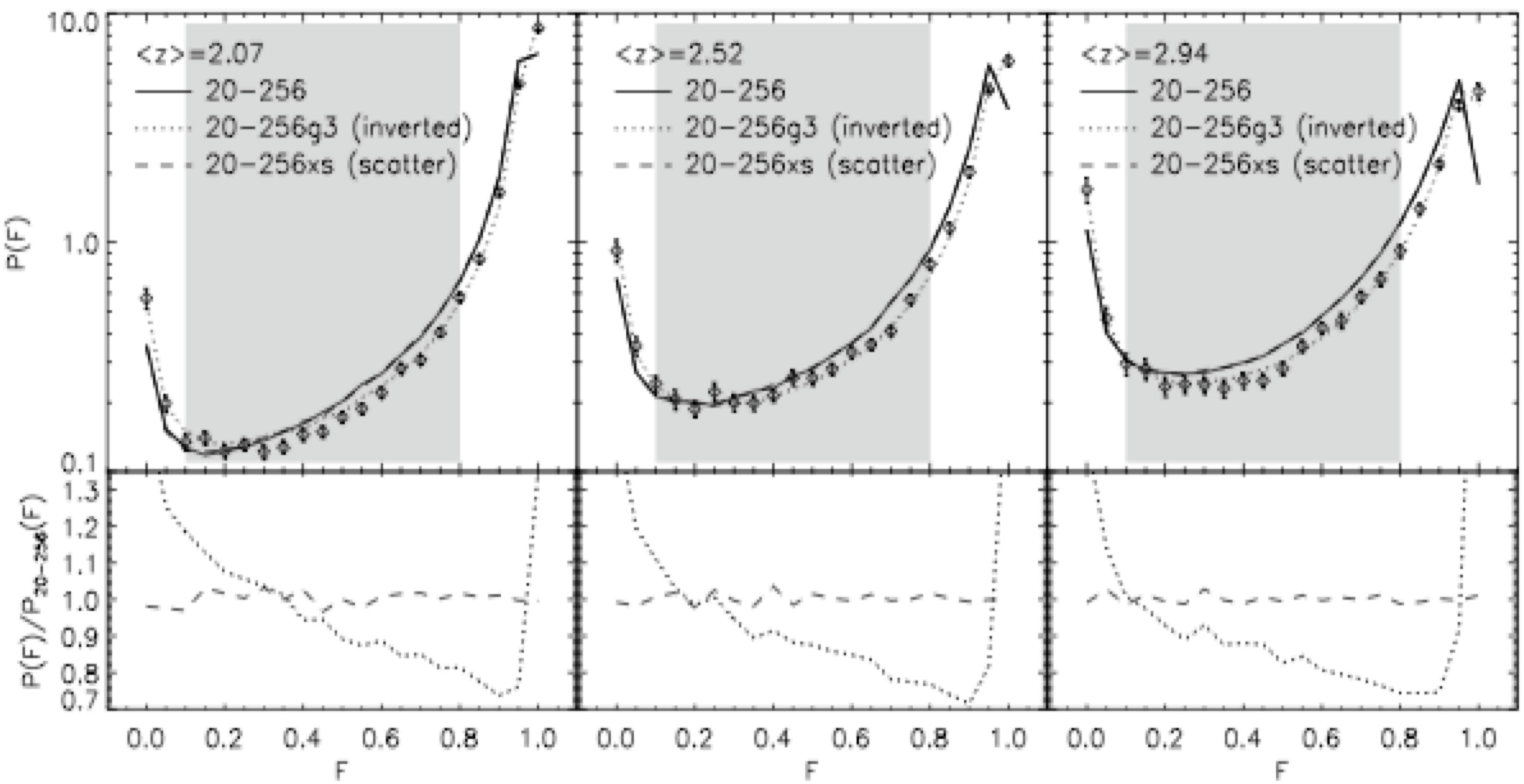
σ_8 estimates

Standard power-law EOSs do not fit observations

isothermal inverted



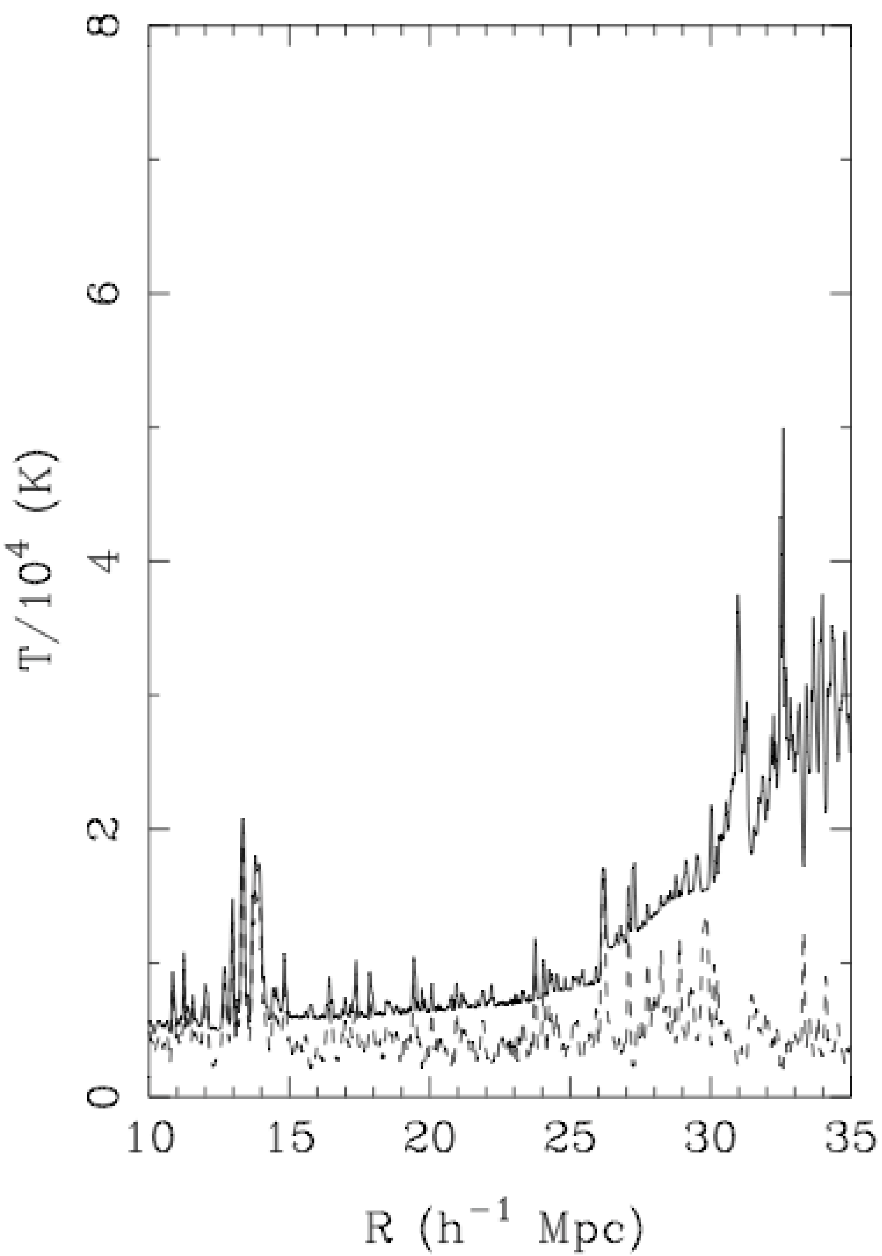
Becker et al 2007



Bolton et al 2008

Flux PDFs show that EOS is inverted

An inverted equation of State?



Bolton, Meiskin & White (2004)

Voids potentially hotter than expected. Could be because:

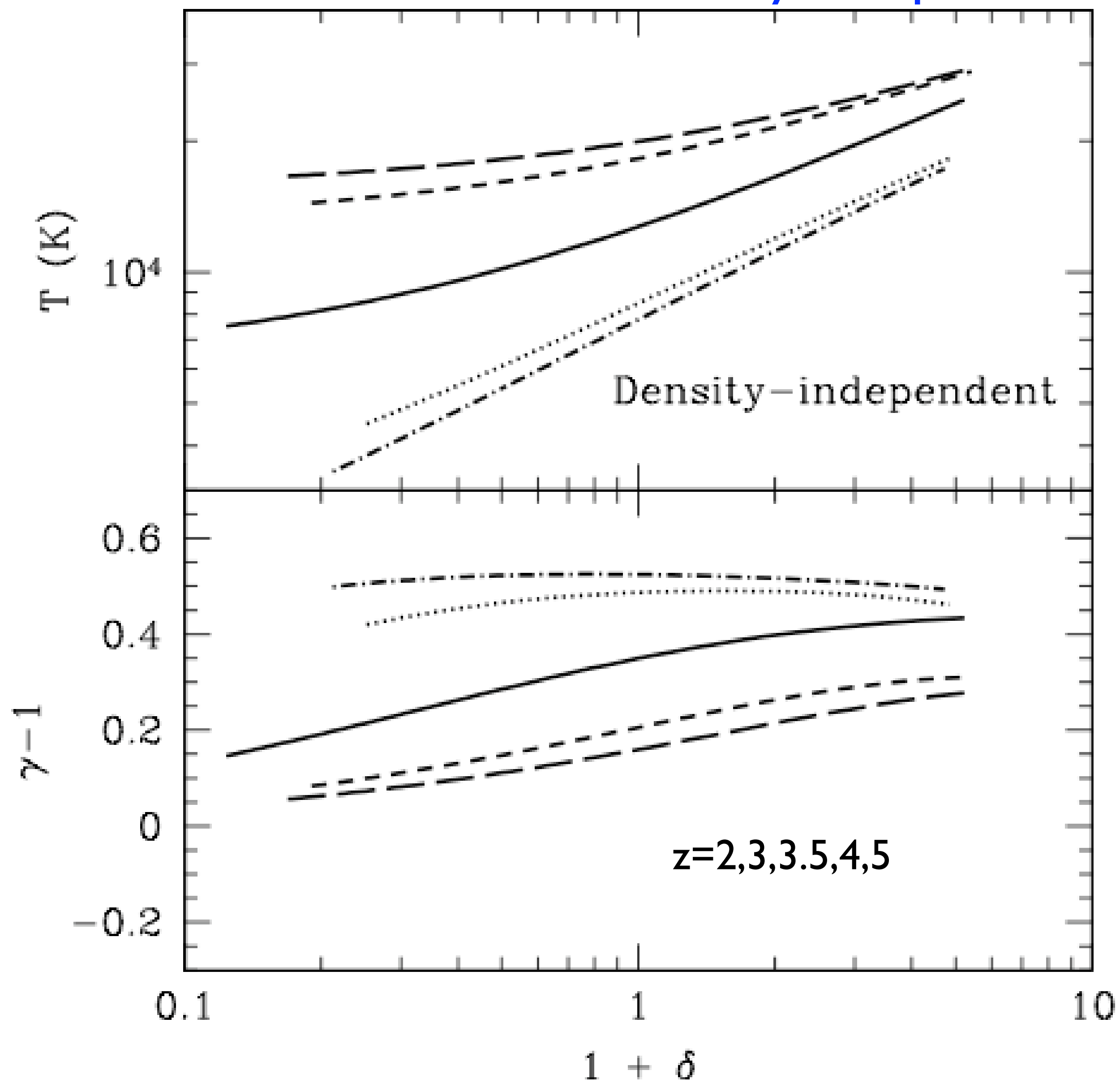
--radiative transfer effects (Bolton et al 2004)

---voids are reionized later (Furlanetto & Oh 2008b)

Problem with both: anti-correlation between voids & biased quasars is weak

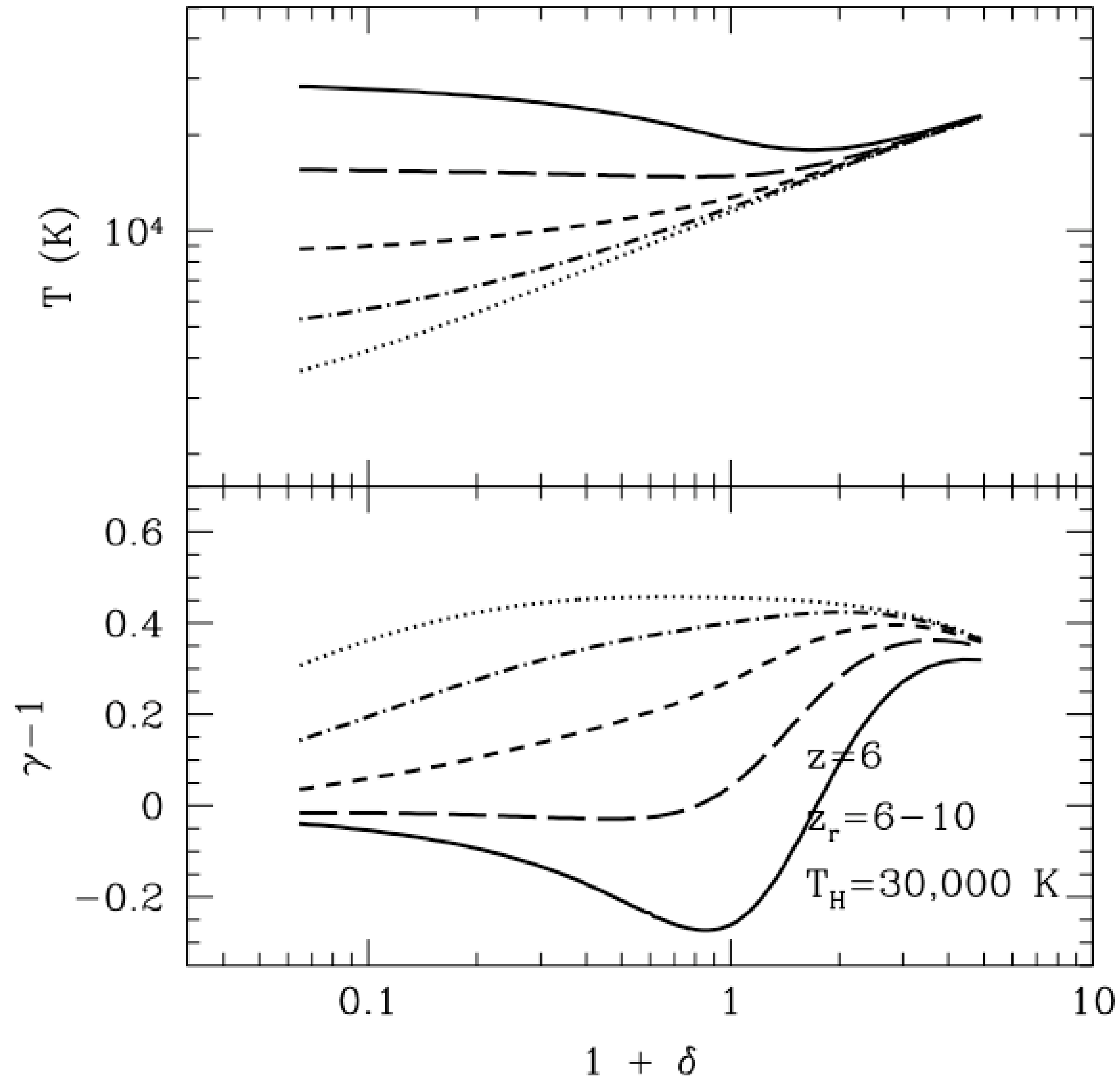
Reionization imprint on EOS: Helium vs. Hydrogen

Helium Reionization: Density Independent



Furlanetto & Oh (2008)

Hydrogen Reionization: Density Driven



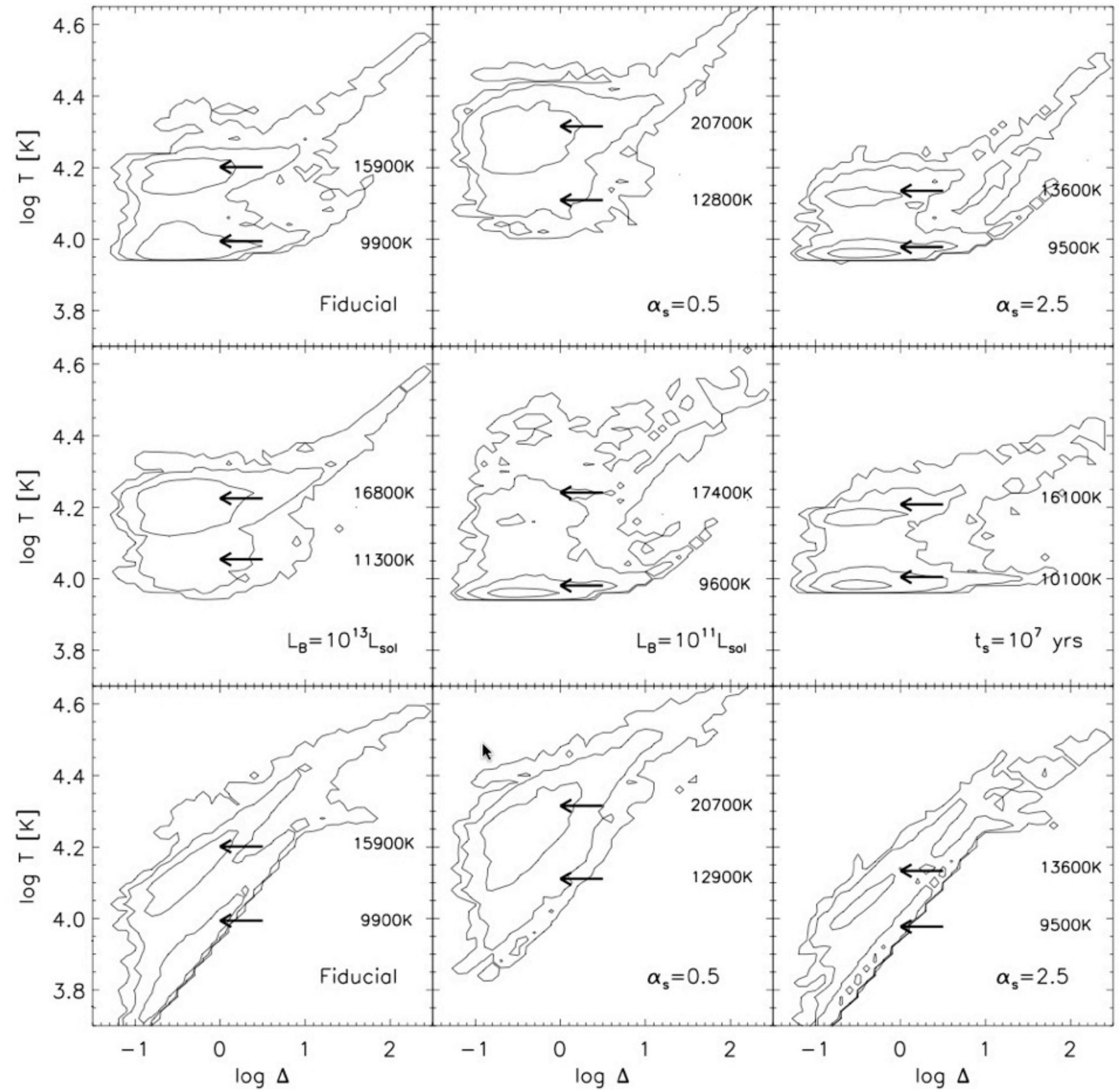
Furlanetto & Oh (2009)

Simulated equation of state after He reionization...

...is multi-valued and complex...with two phase structure

Inverted EOS not seen

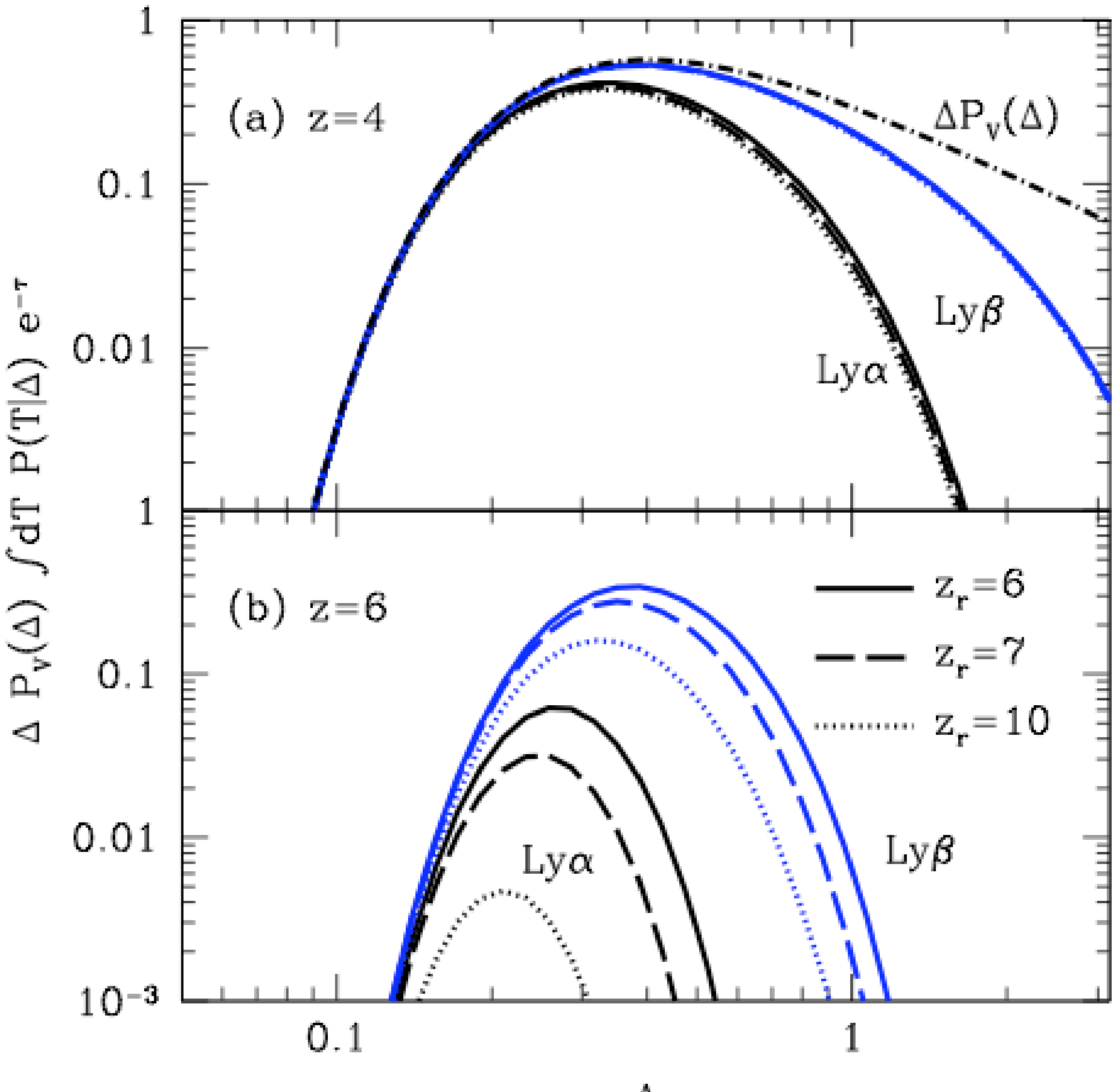
Could scatter be responsible for observed flux PDF?

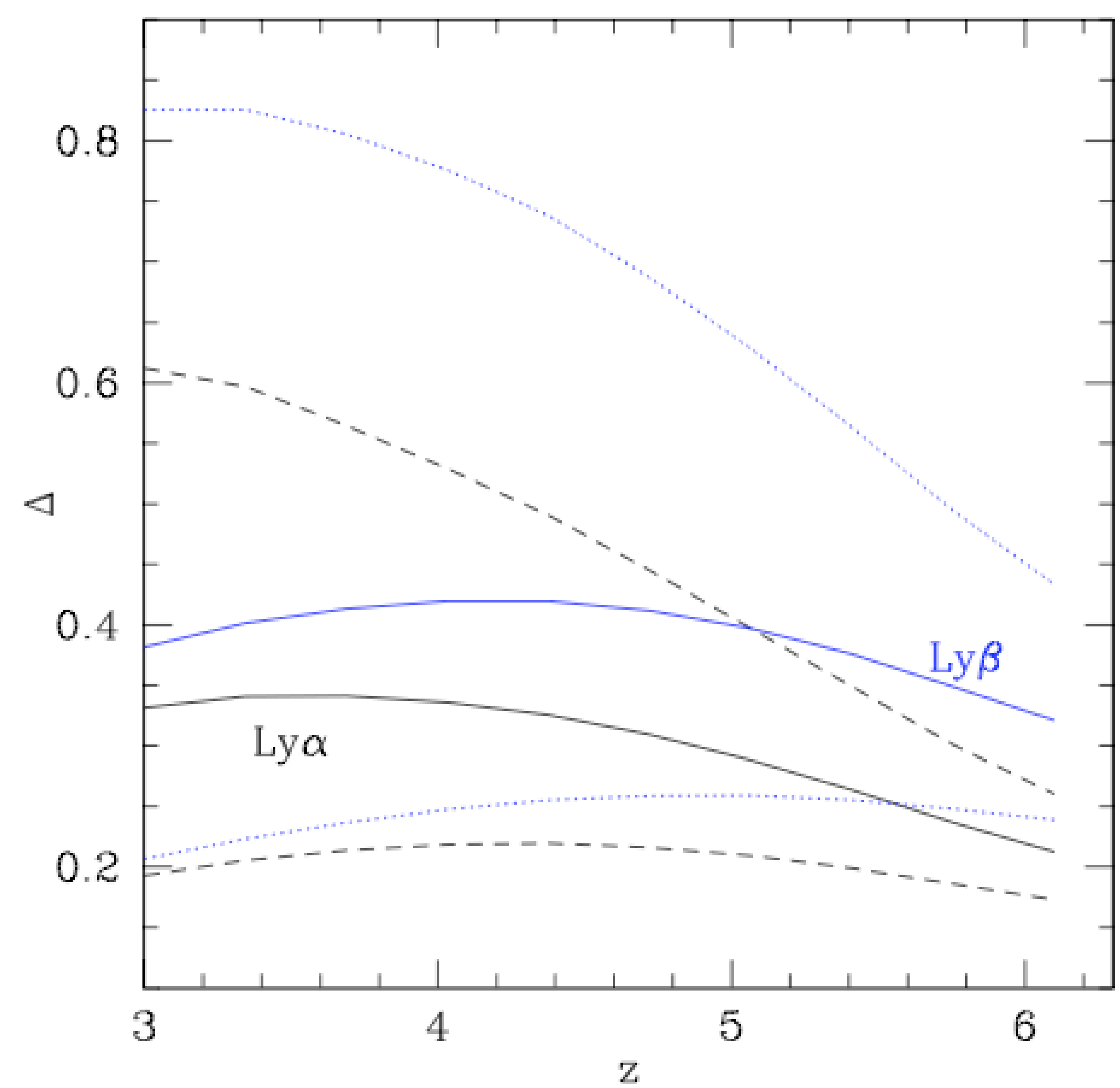


Bolton, Oh & Furlanetto 08

A New Way to Measure the EOS

Furlanetto & Oh 2009

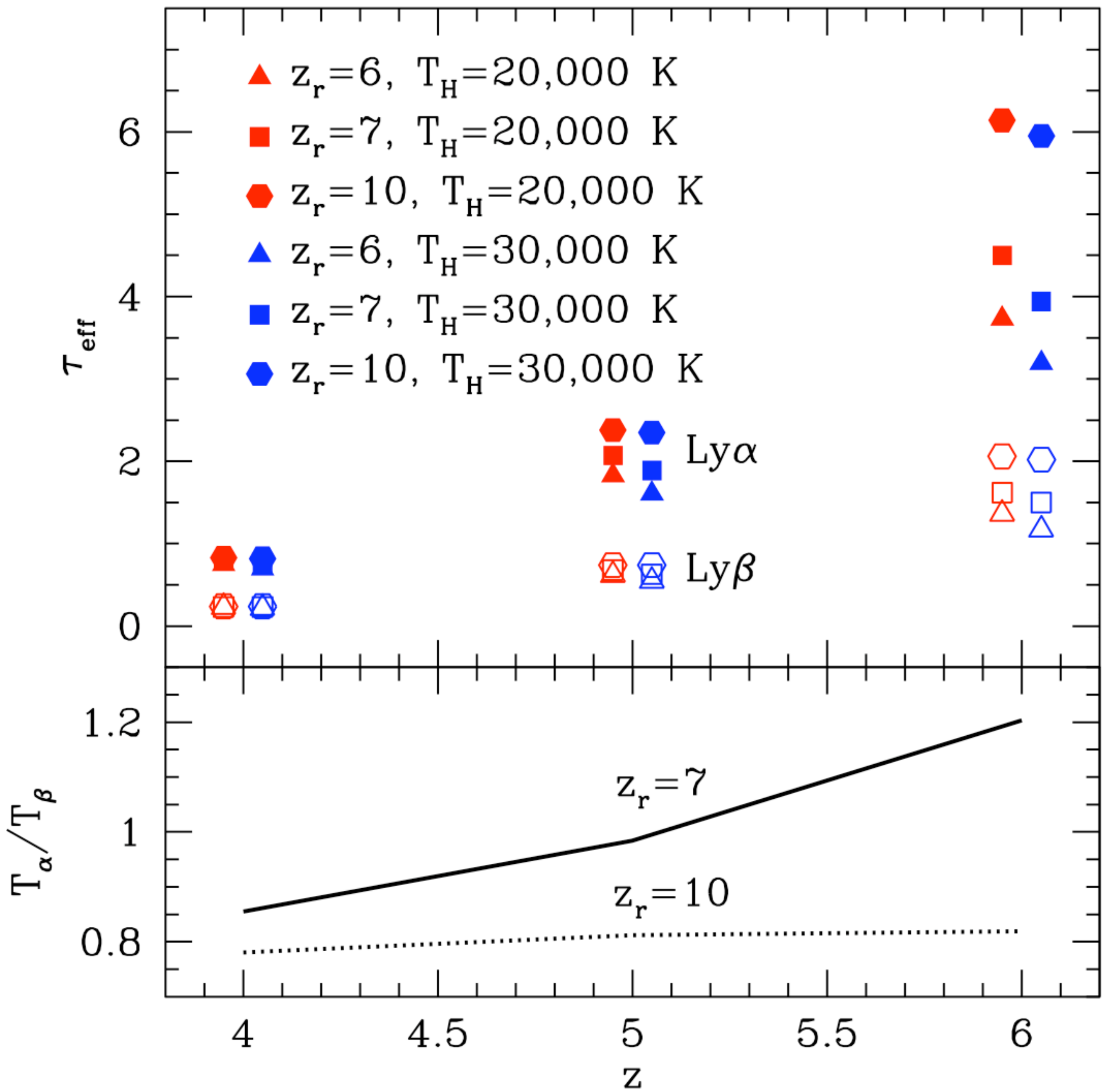




Ly α / Ly β flux ratios --each measure $\Gamma T^{0.7}$ over different density regime

Previously inaccessible redshift range!

...could it tell us when reionization happened?



Furlanetto & Oh 2009

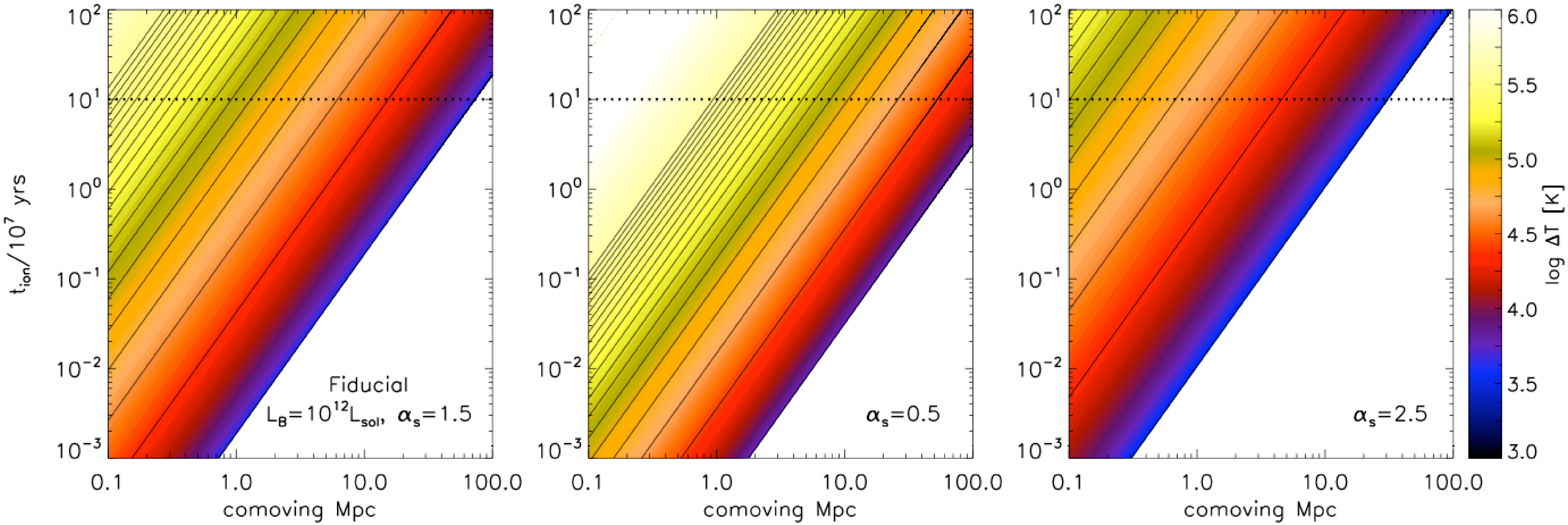
Ly α / Ly β flux ratio depends on how long ago reionization happened

Relaxes from inverted/ isothermal to usual power-law

Data appears to show an inverted EOS at high z

Conclusion

- Helium reionization: an interesting and yet unsolved problem
- Heating rates and spectral shape above 54.4 eV more model-dependent than previously thought
- Difficult to get sudden heating/cooling; hydro effects negligible. Interesting RT effects?
- A new way to measure the equation of state at high redshift



Ionization rate (and associated heating) drop significantly if filter all radiation below some cut-off frequency