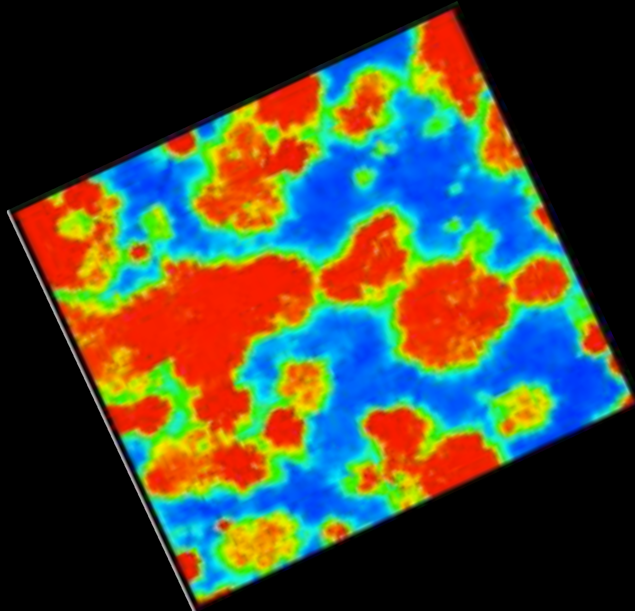
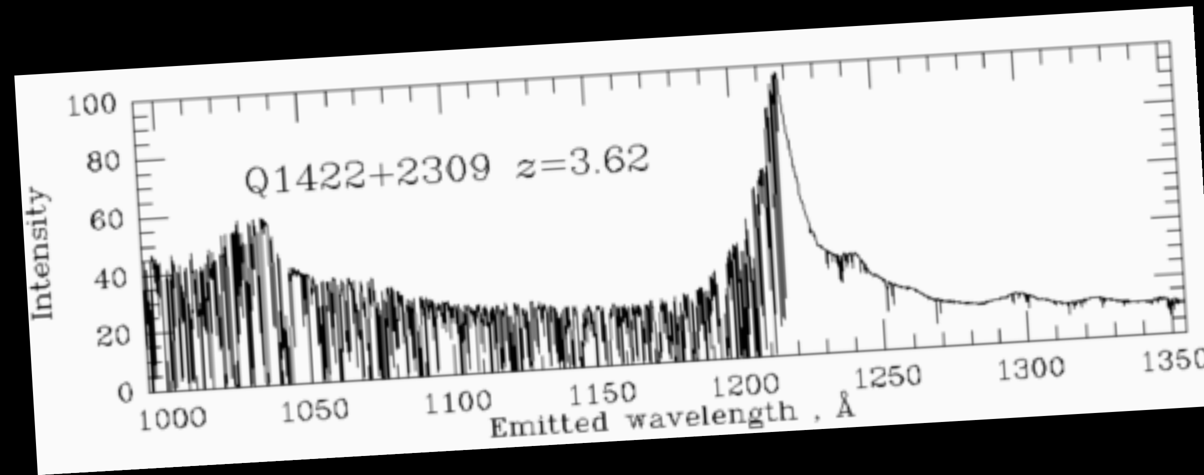
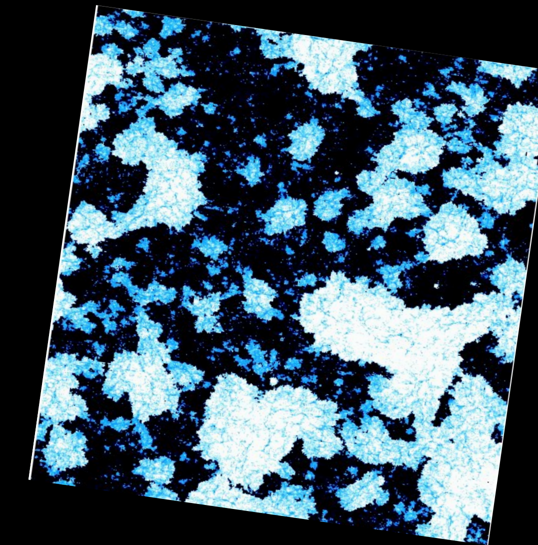


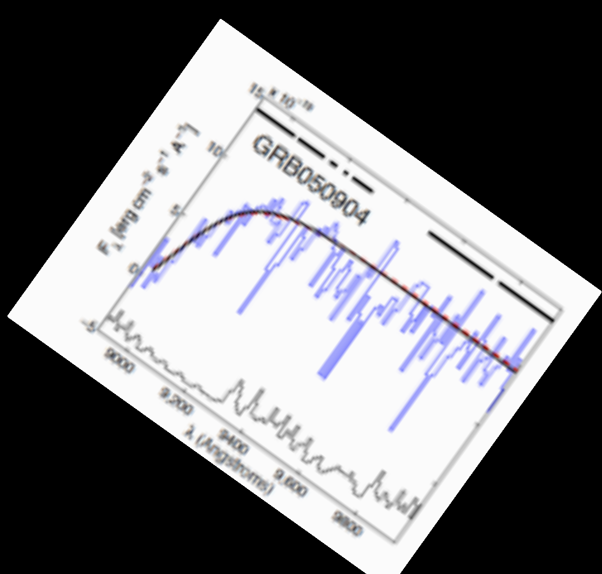


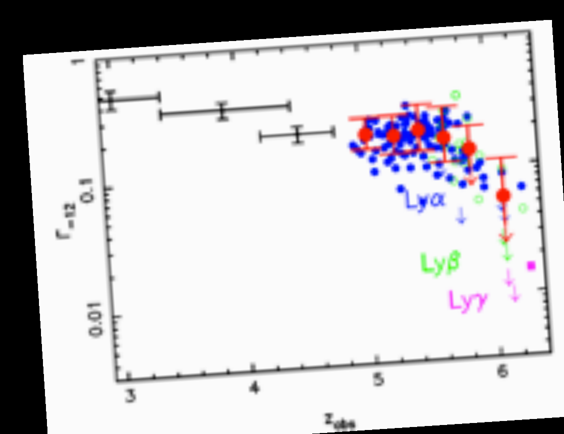


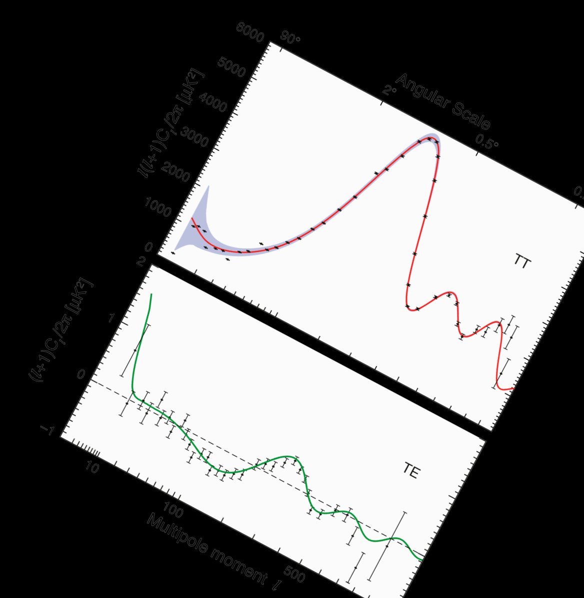
What do we know about the IGM?

And what do we want to know?

Matthew McQuinn (UC Berkeley)

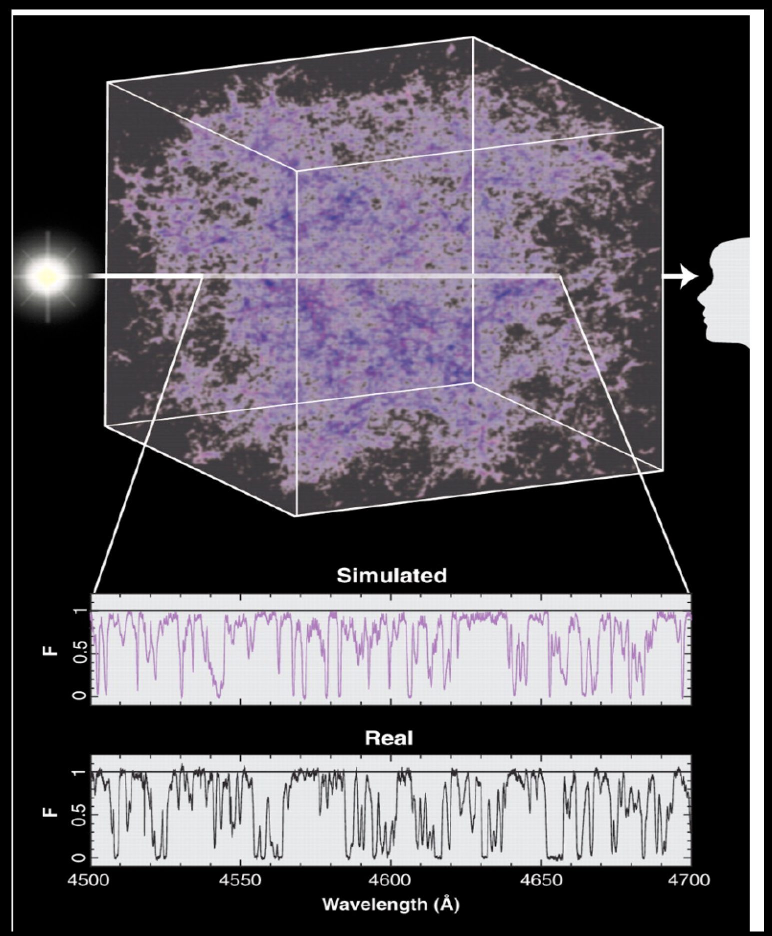






Outline

- Part 1: the z< 6 IGM



Plot from Faucher-Giguere, Lidz, & Hernquist (2008)

- Part 2: z>6 (reionization)

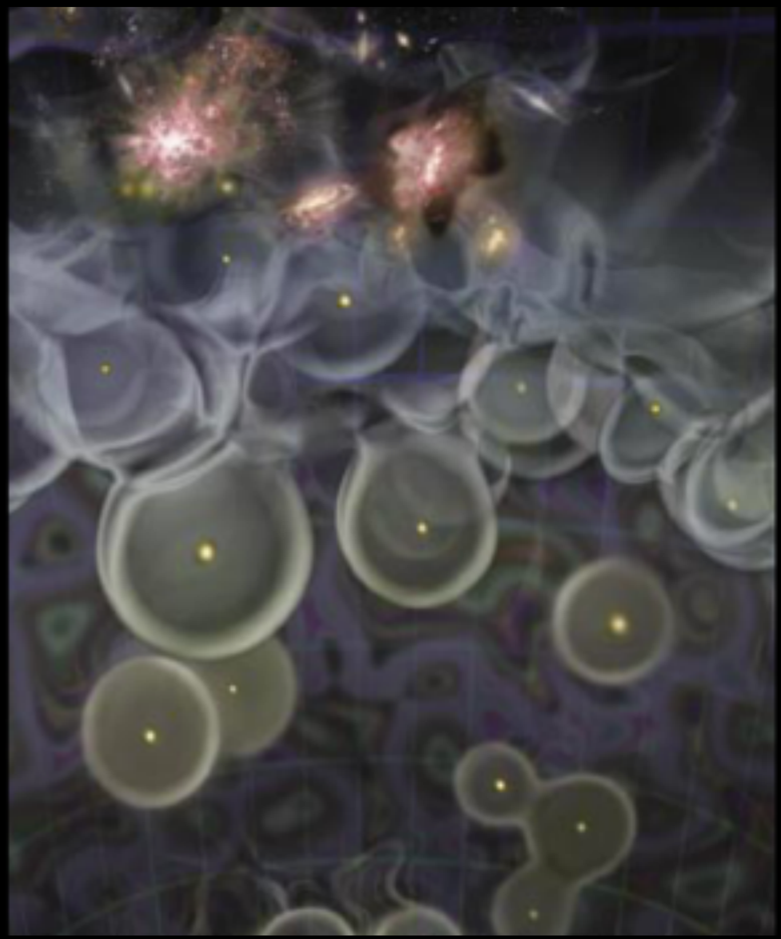
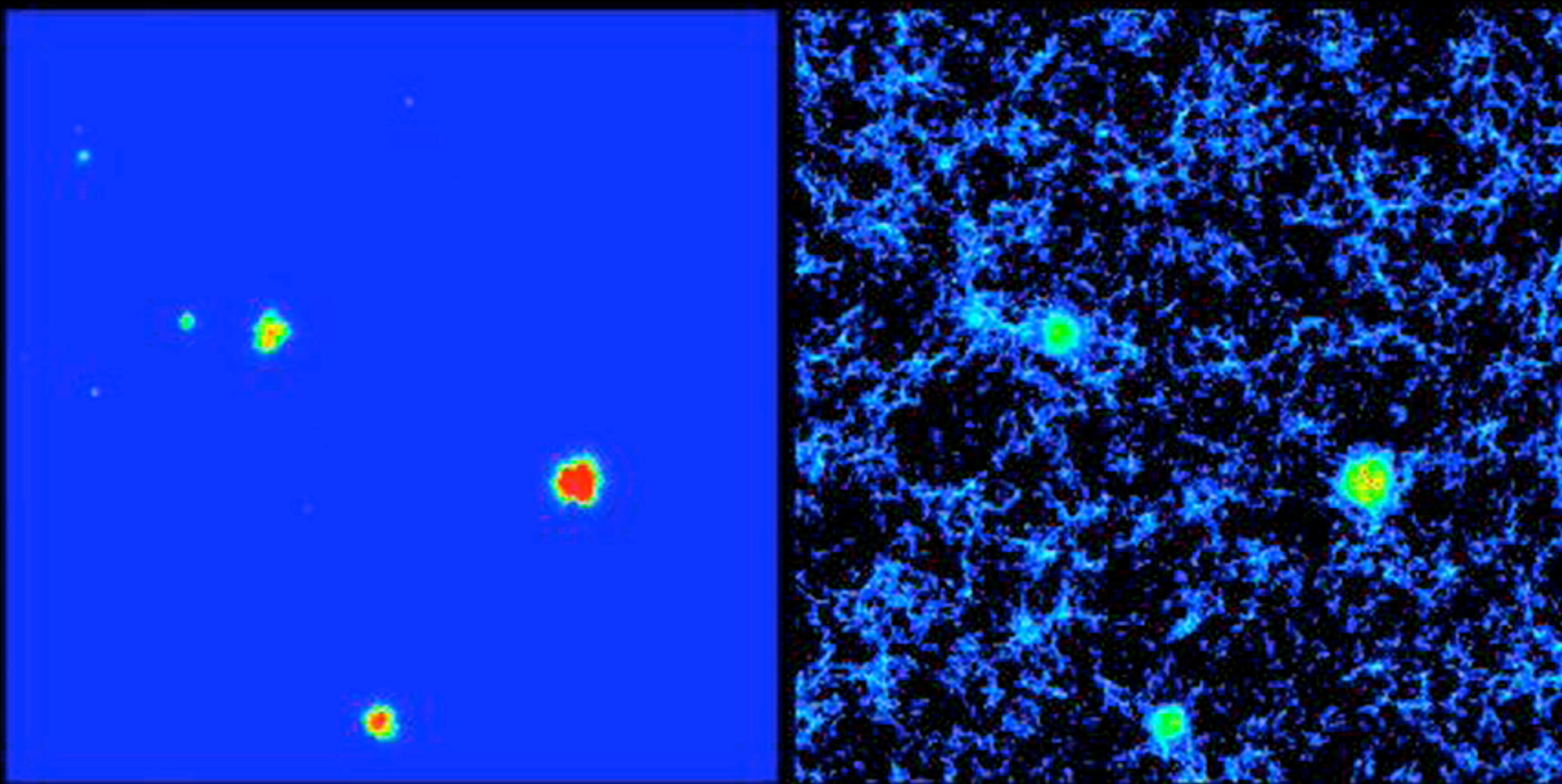


illustration from Scientific American article by Avi Loeb

Movie of HeII reionization



Part 1: the z<6 IGM

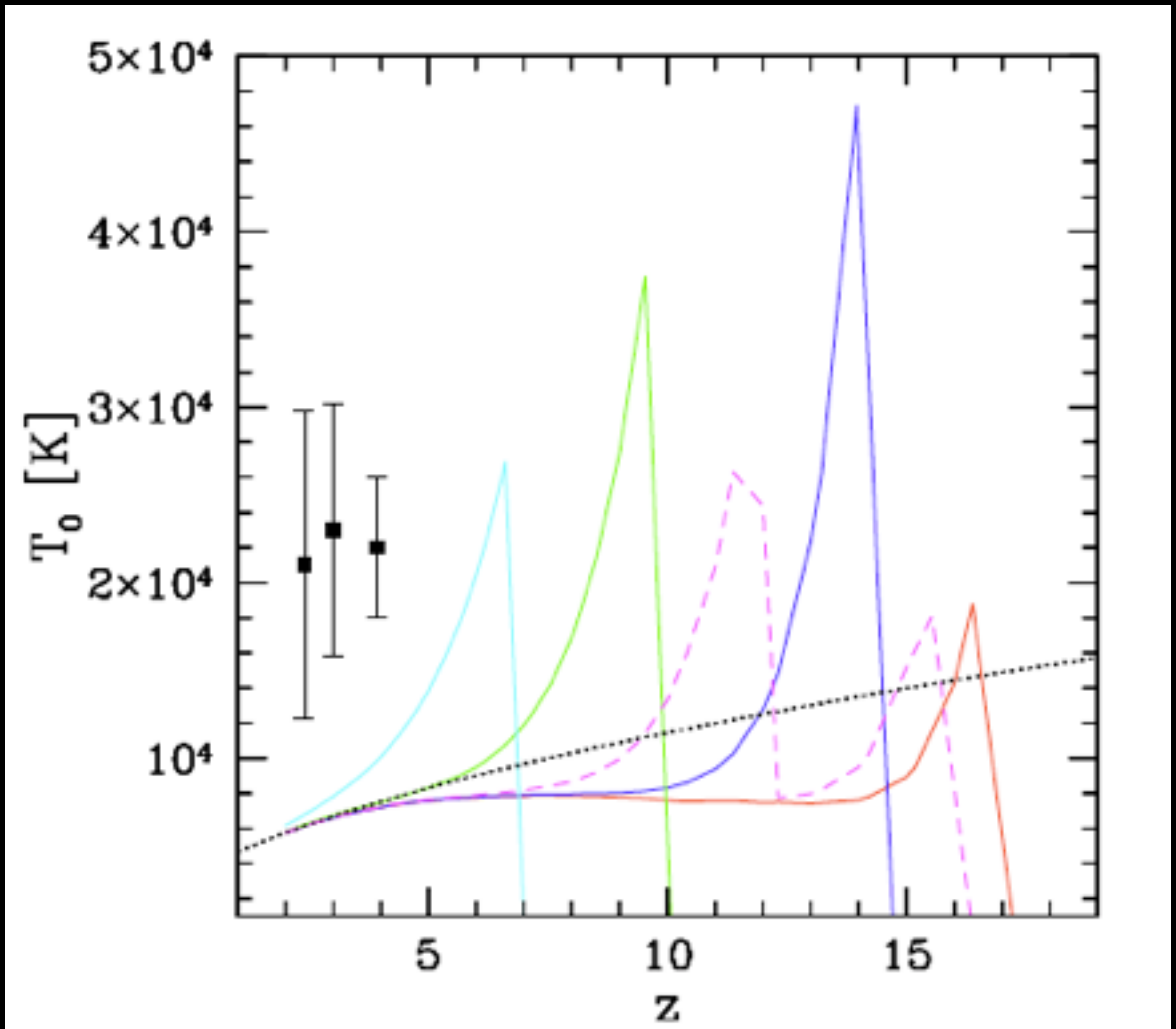
(my focus will be on z>2)

Exciting directions in recent IGM research

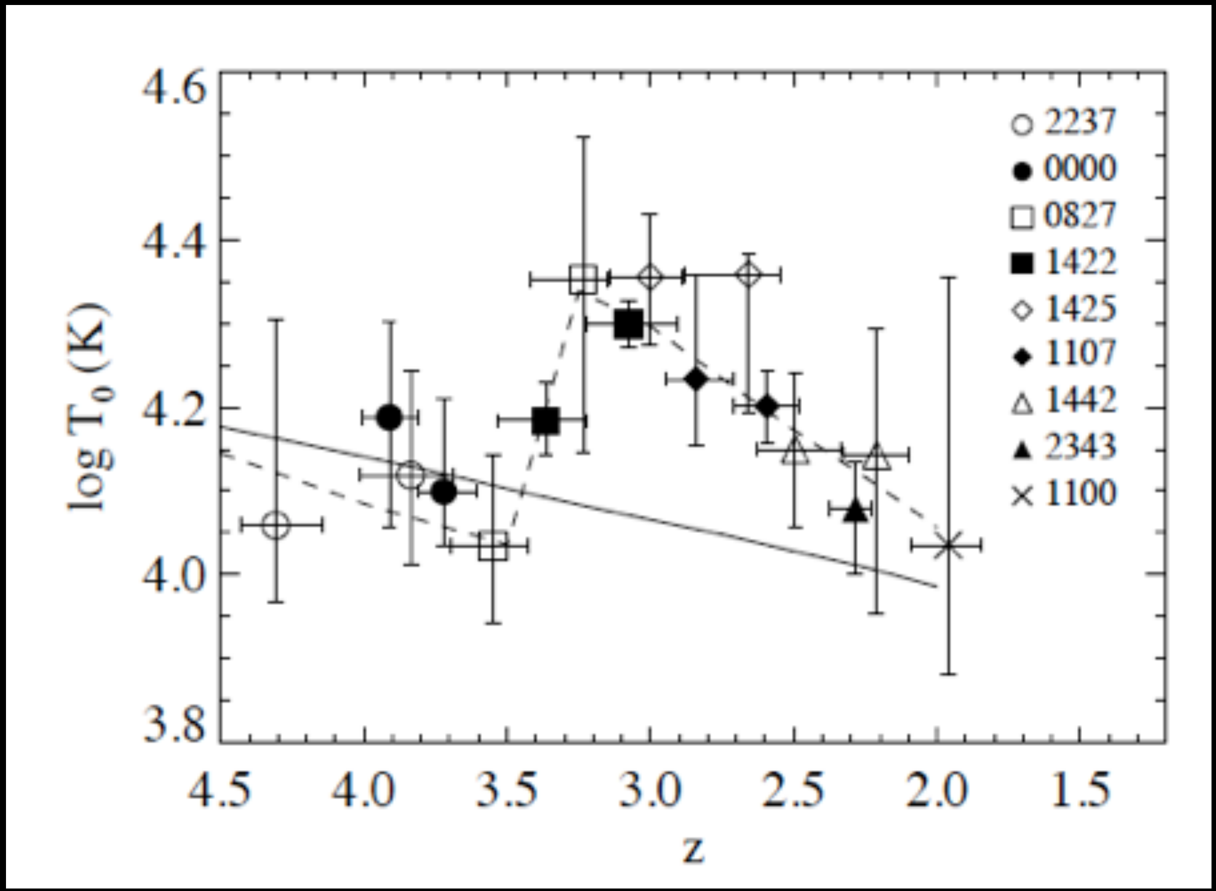
- Circum-galactic medium with large ground-based telescopes/COS (@z~6; see Ryan-Webber's talk)
- better determinations of the IGM thermal history
- HeII Lyα forest with COS (Graziani, Shull, Worseck)
- 3D Lyα forest using ~10^5 quasars (BAO, bias of quasars and DLAs) with BOSS and extensions
- higher column-density HI absorbers

There has been a recent resurgence in IGM research.

Topic 1: intergalactic thermal history



Haiman & Hui ’03



Schaye++ 00

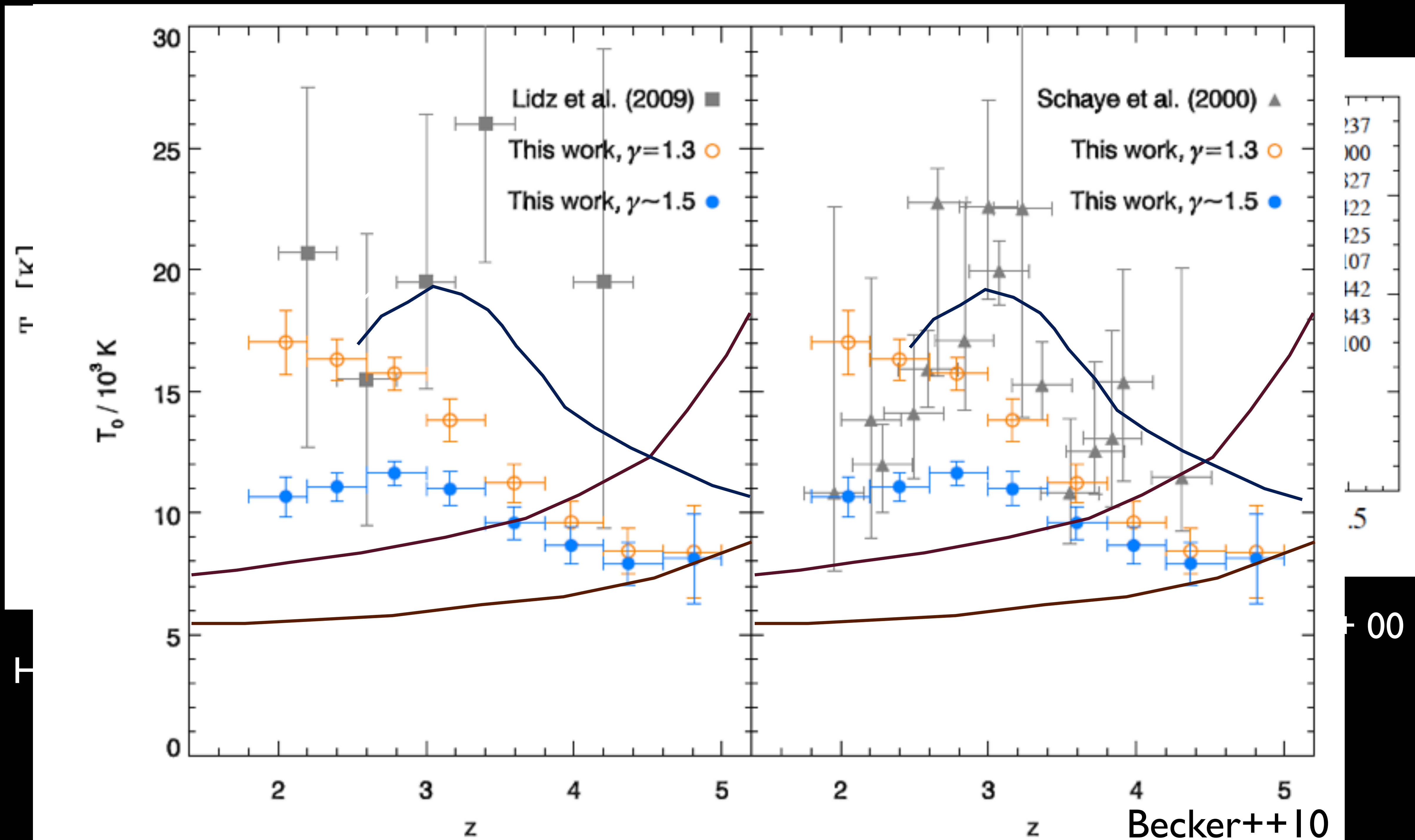
Open Questions:

Is the thermal evidence for HeII reionization definitive?

Are there any other heating sources beyond photoionization?

Can we measure T-δ relation? Temperature fluctuations?

Topic 1: intergalactic thermal history



Is the thermal evidence for HeII reionization definitive?

Are there any other heating sources beyond photoionization?

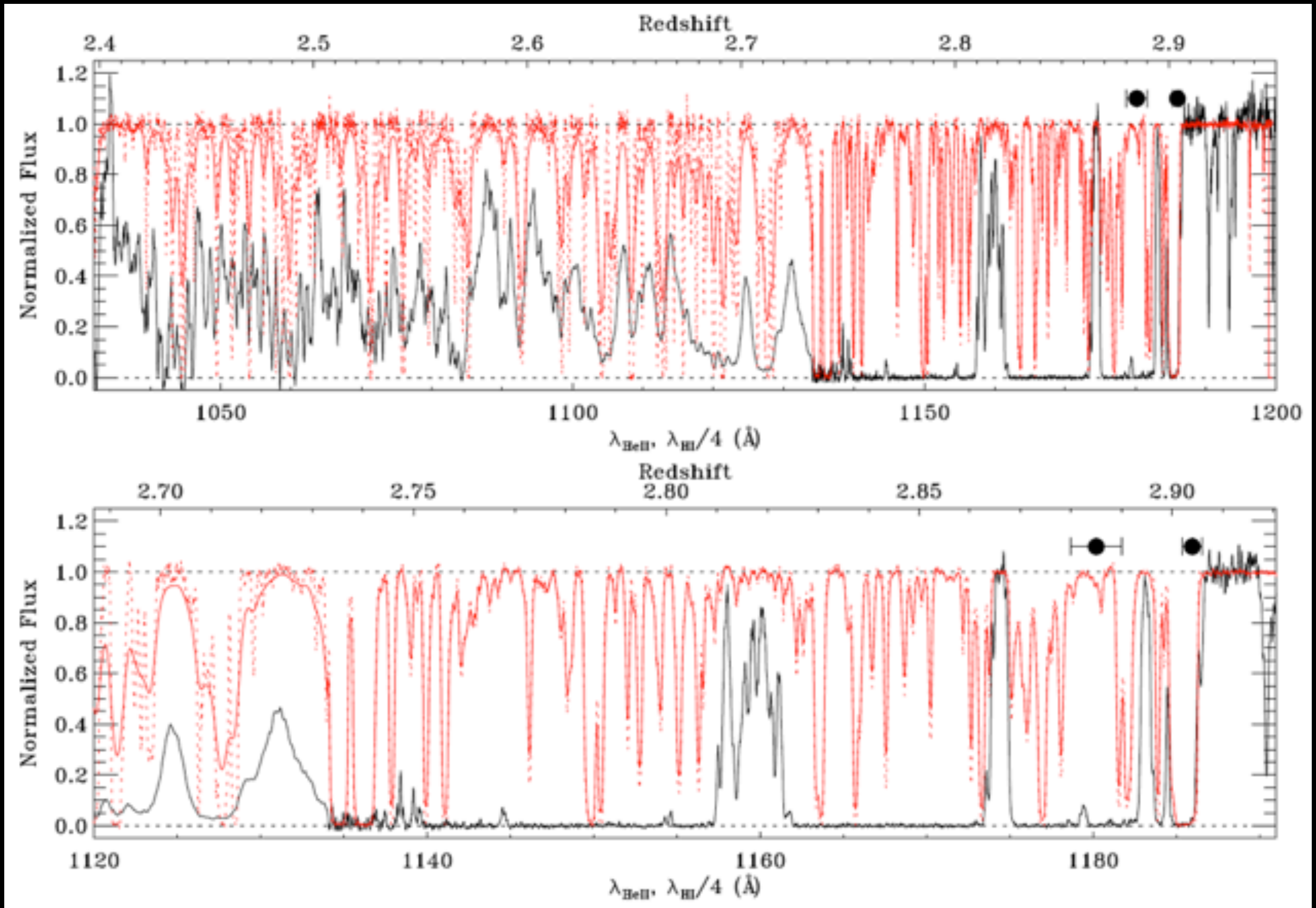
Can we measure T-δ relation? Temperature fluctuations?

Topic 2: HeII Lyα forest:

Gunn-Peterson troughs in HeII Lyα forest indicate the end of HeII reionization

$$x_{\rm HeII} = 0.01 \left(\frac{\tau_{\rm HeII}}{3.4}\right)\left(\frac{1+\delta}{0.1}\right)^{-1}\left(\frac{1+z}{4}\right)^{-3}$$

Figure from Shull et al (2010)



Either GP region is HeII region or HeII is photoionized. But the latter implies $x_{\rm HeII}$ >0.1 at mean density (see MM 2009)

Topic 3: Lyman-limit systems ($N_{HI}>10^{17} cm^{-2}$)

Simulations agree well with Ly α forest observations (probing δ ~< 3). How well do they fare at δ ~ 100 ?

Motivations for studying Lyman-limits in simulations:

(1) It had been a while since people looked at this in simulations, and the observations have gotten much better (e.g., new novel mfp estimate from stacking quasars; Prochaska++)

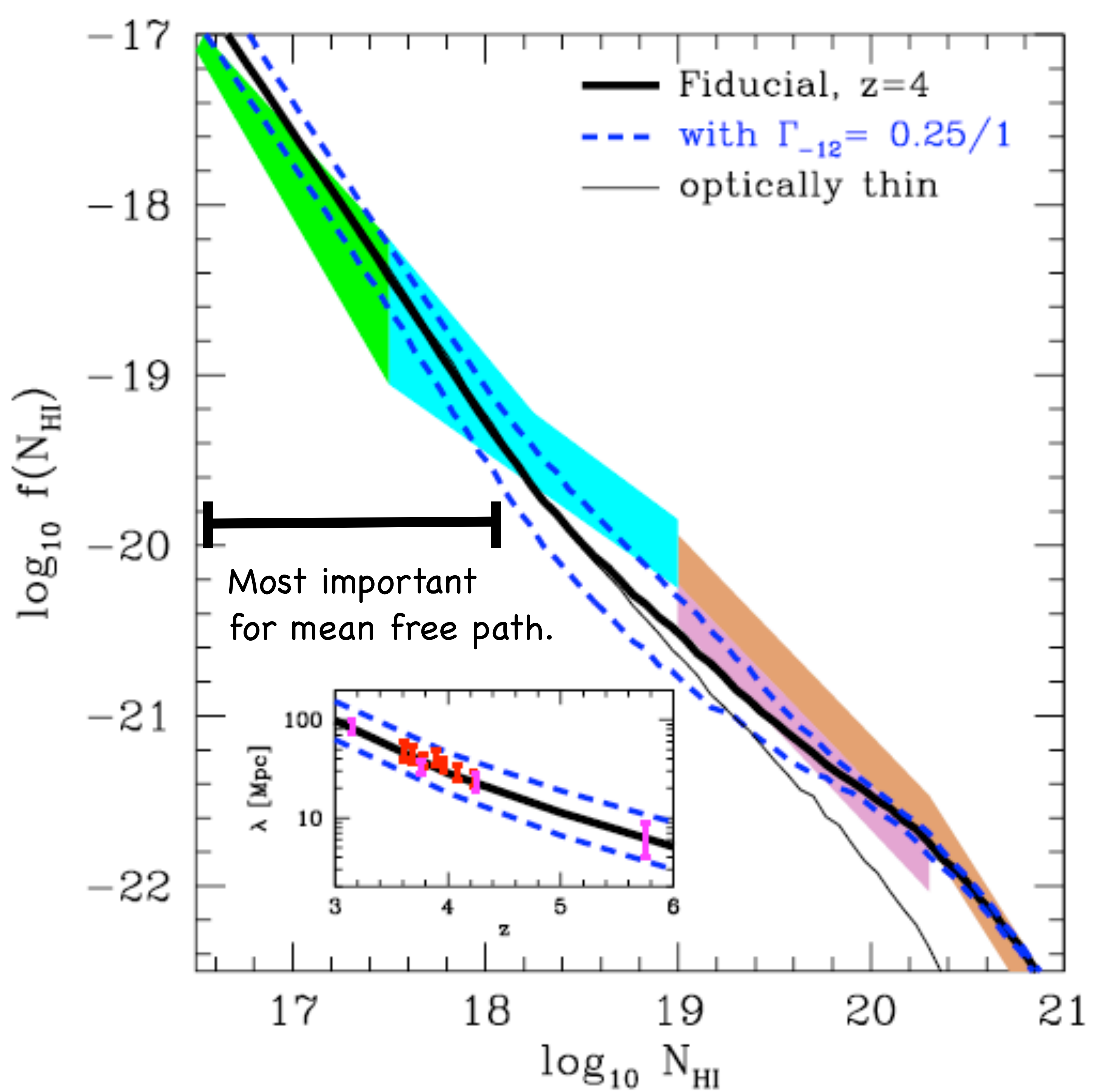
(2) Overdensities of Lyman-limits at z>4 are <100

(3) Hot phase is irrelevant at $z \gtrsim 4$

(4) Lyman limits are crucial ingredient in IGM RT

High densities: Comparison w/ Observations at z=4 Observations

HI Column density distribution



Highlighted regions are observational constraints derived/ compiled in Prochaska, Omeara, Worseck (2010)

MM, Oh, Faucher-giguere, '11 (also see Altay++ '11 and Rahmati++ '13)

Questions: How well do the simulations and data really agree?
Is it a miracle that they work so well at high columns?

High densities: Comparison w/ Observations at z=4 Observations

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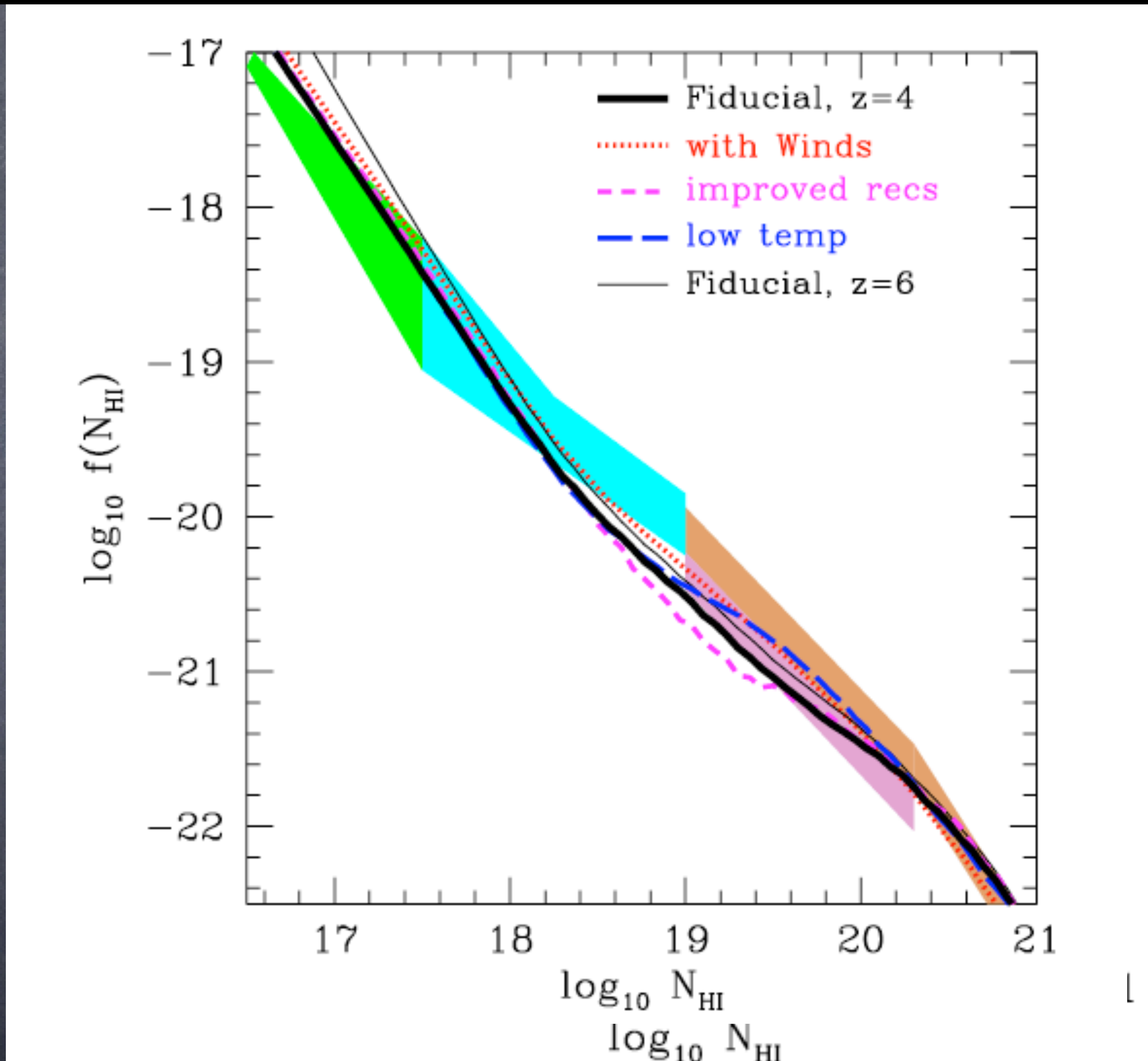

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Questions: How well do the simulations and data really agree? Is it a miracle that they work so well at high columns?

Some open questions regarding the z~3 IGM

- How does mechanical feedback impact the IGM as a function of δ?
- What are the sources of ionizing photons?
- Is there any physics we are missing? Is the IGM consistent with the CDM model?

List of oft referenced IGM anomalies

- high z~2-3 temperatures; sims cannot match b values vs. N_{HI}
- large fluctuations in $\eta = N_{HeII}/N_{HI}$ after HeII reionization
- weird features in $\langle F_{HI} \rangle$
- inverted T-δ relation (hot voids; Bolton++ '07)
- ubiquitous metal absorption
- simulations can't match obs. # of high N_{HI} absorbers

- Temperature values came down and simulations can reproduce them (Becker++ 09, McQuinn++09, Rudie++)
- fluctuations are small and consistent w/ models (McQuinn & Worseck '13)
- went away (Becker et al '12)
- inverted relation in FPDF in tension with other measures Blazar heating ruled out (Miniati & Elyiv '12)
- filling factor can be 10% and consistent w/ outflows flowing ~100 kpc from dwarf gals (Schaye++, Simcoe++)
- they match well (maybe not perfectly)

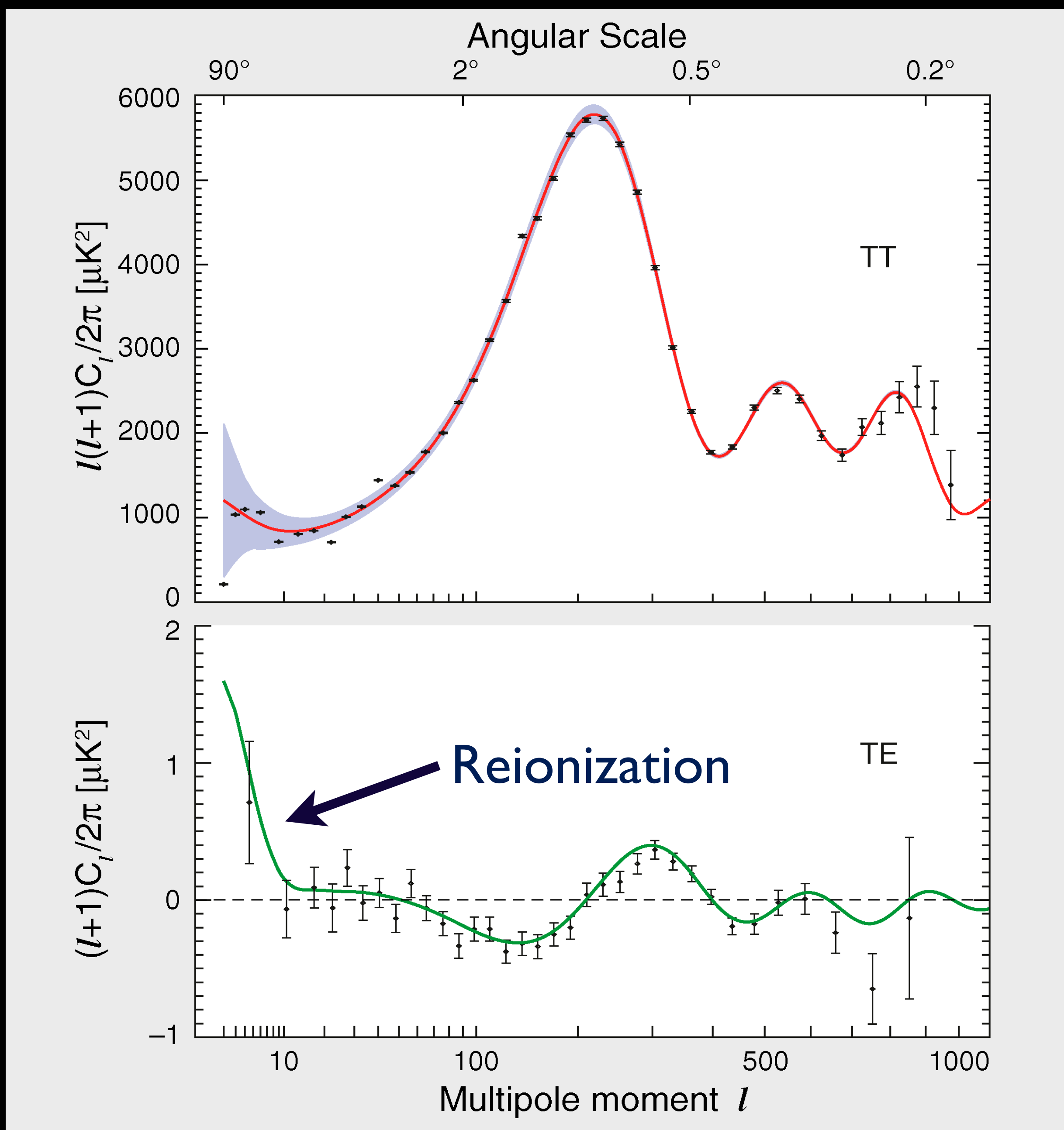
Part 2:
Reionization

The five things we already know about hydrogen reionization

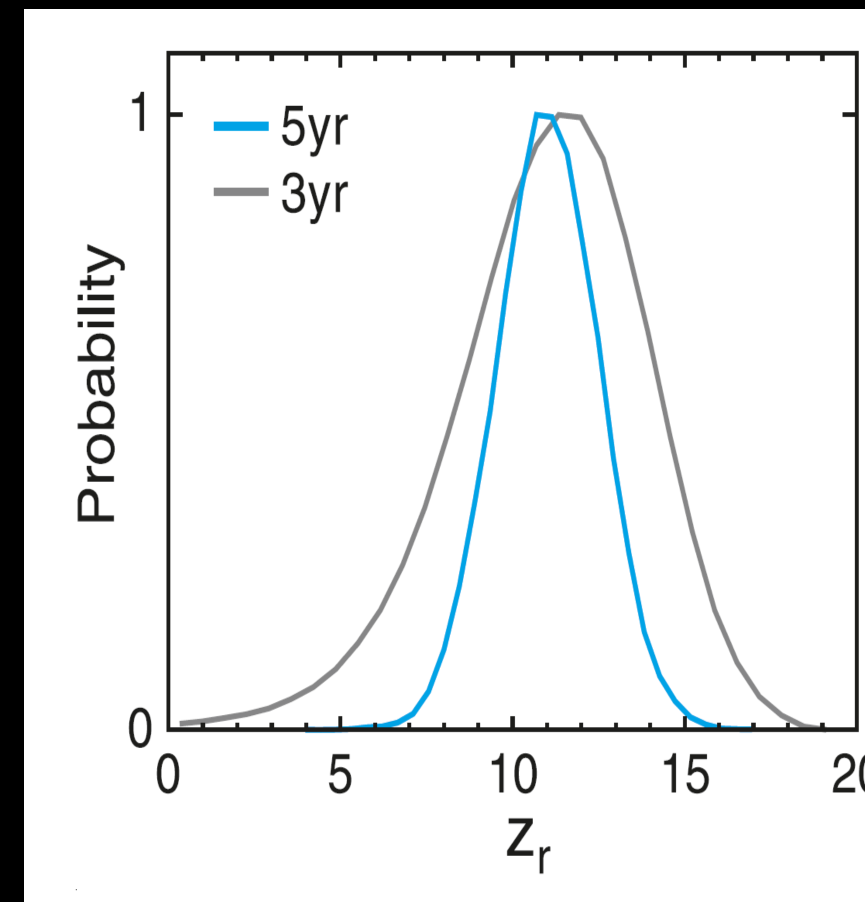
(a few will be boring to you)

(I) The mean redshift

(CMB constrains Thomson optical depth to recombination, which can be roughly translated to mean redshift)



Komatsu et al ’07

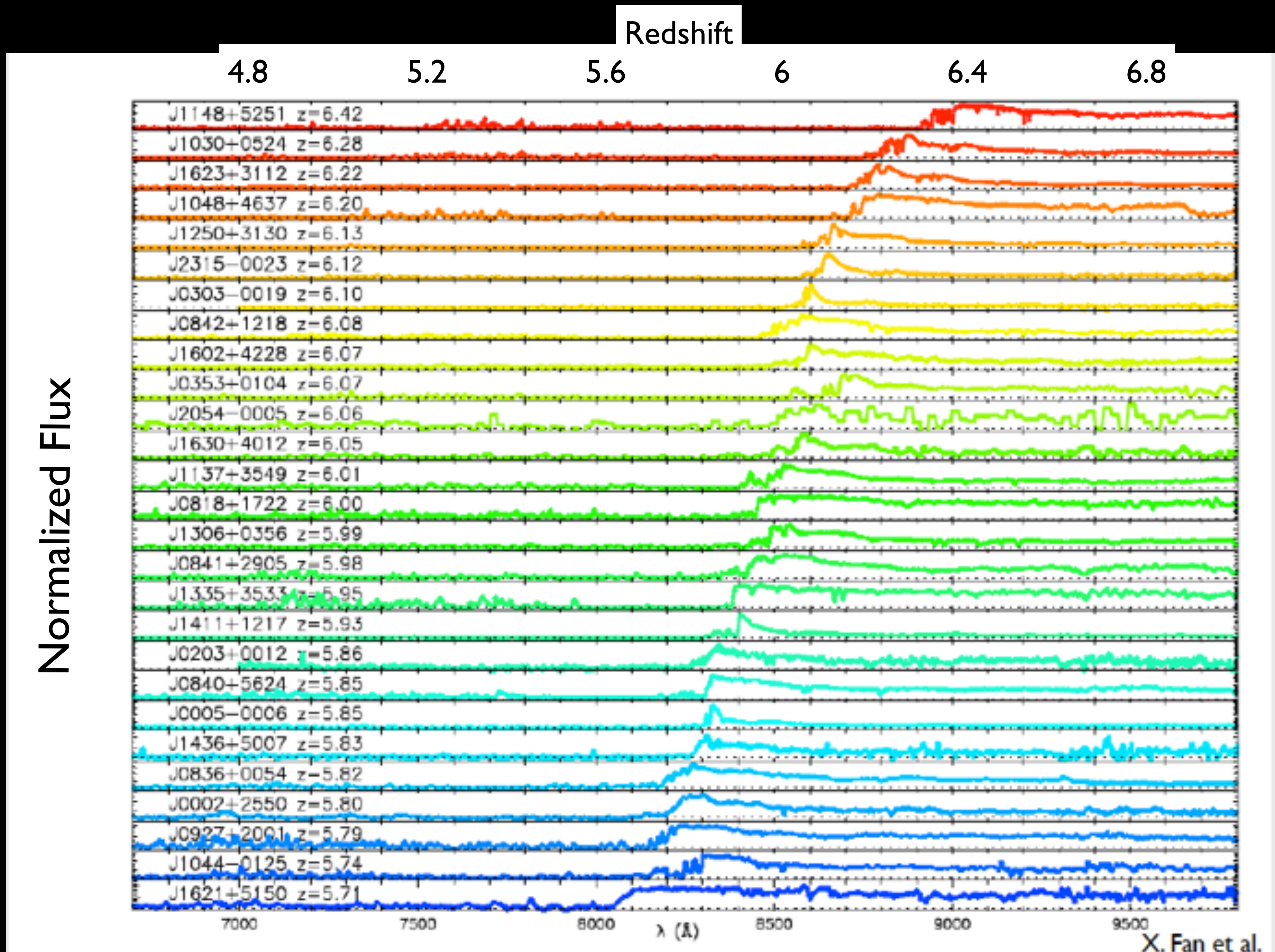


Dunkley ’09

error on z_r will improve by factor of 3 w/ Planck polarization; see talk by Ahn

CMB polarization will soon be close to cosmic variance limited w/ Planck

(2) A lower bound on the redshift: z_{rei}>~6

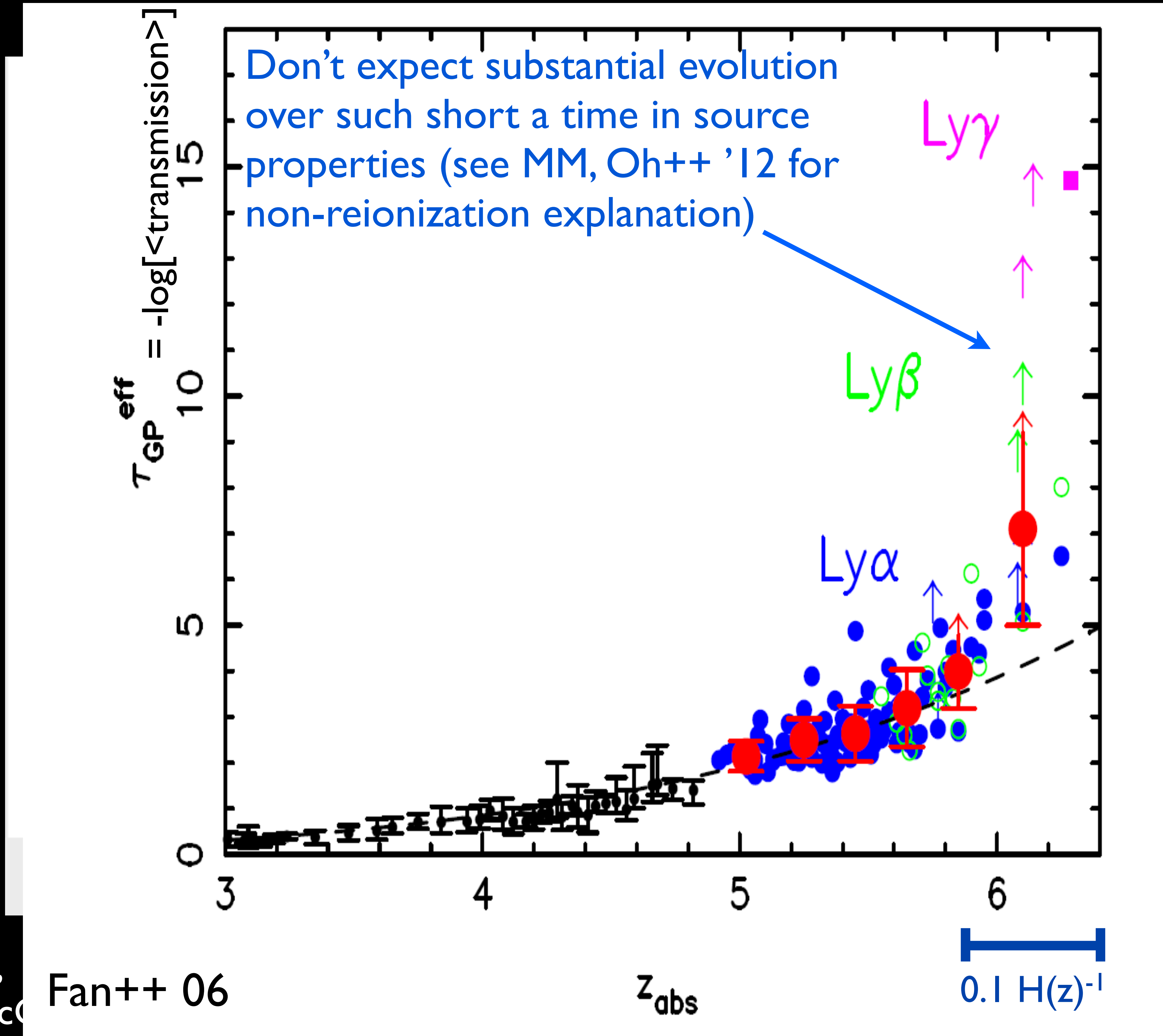


Currently ≥47 z > 5.7 QSOs known (many faint)

Fan et al (2006),
see Mesinger, McGreer, & Fan ’11 for gap statistic

$$\tau_{\rm GP} = 3 \times 10^5 \, x_{\rm HI} \, (1+\delta) \left(\frac{1+z}{7} \right)^{3/2}$$

(2) A lower bound on the redshift: z_{rei}>~6

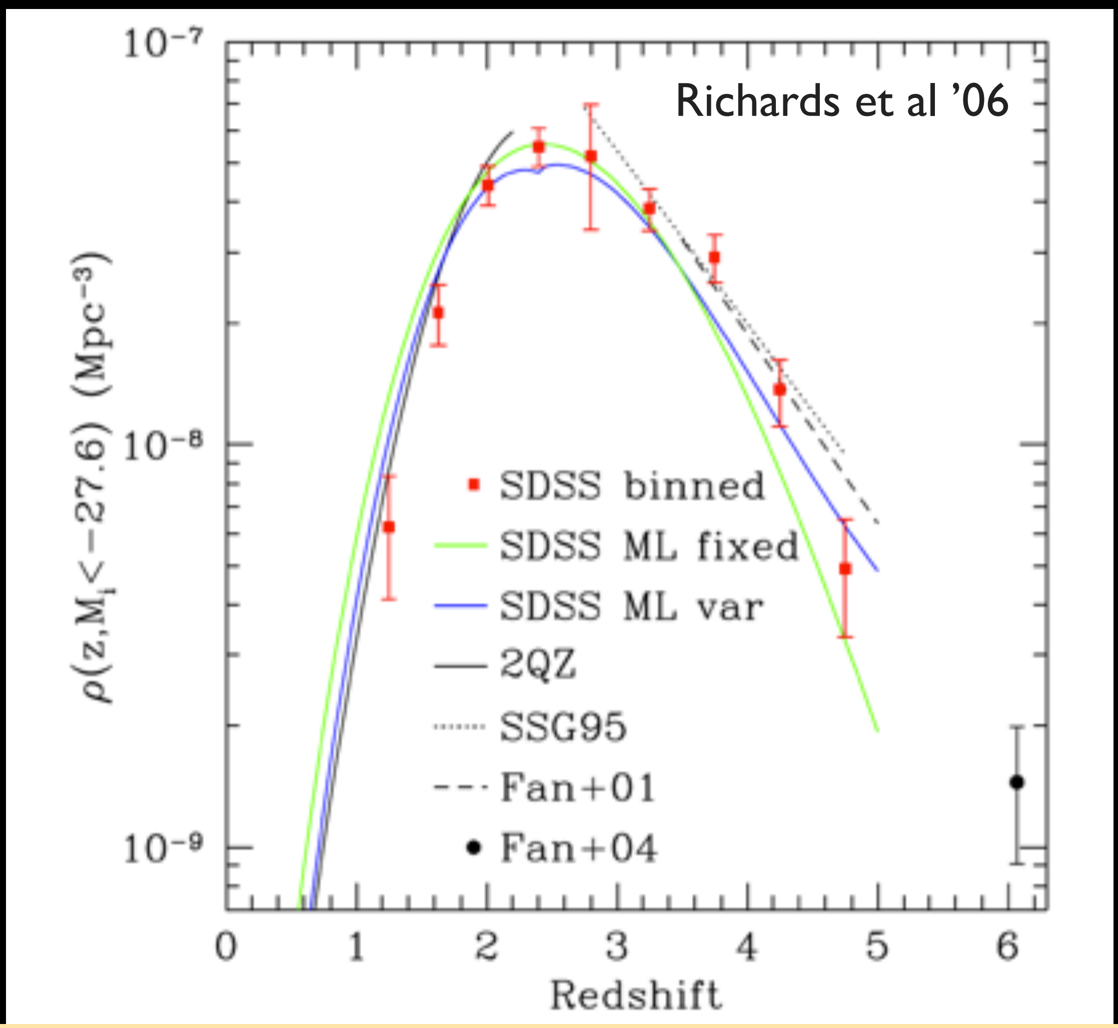


Fan et al (2006),
see Mesinger, Mc

$\left(\frac{1+z}{7}\right)^{3/2}$

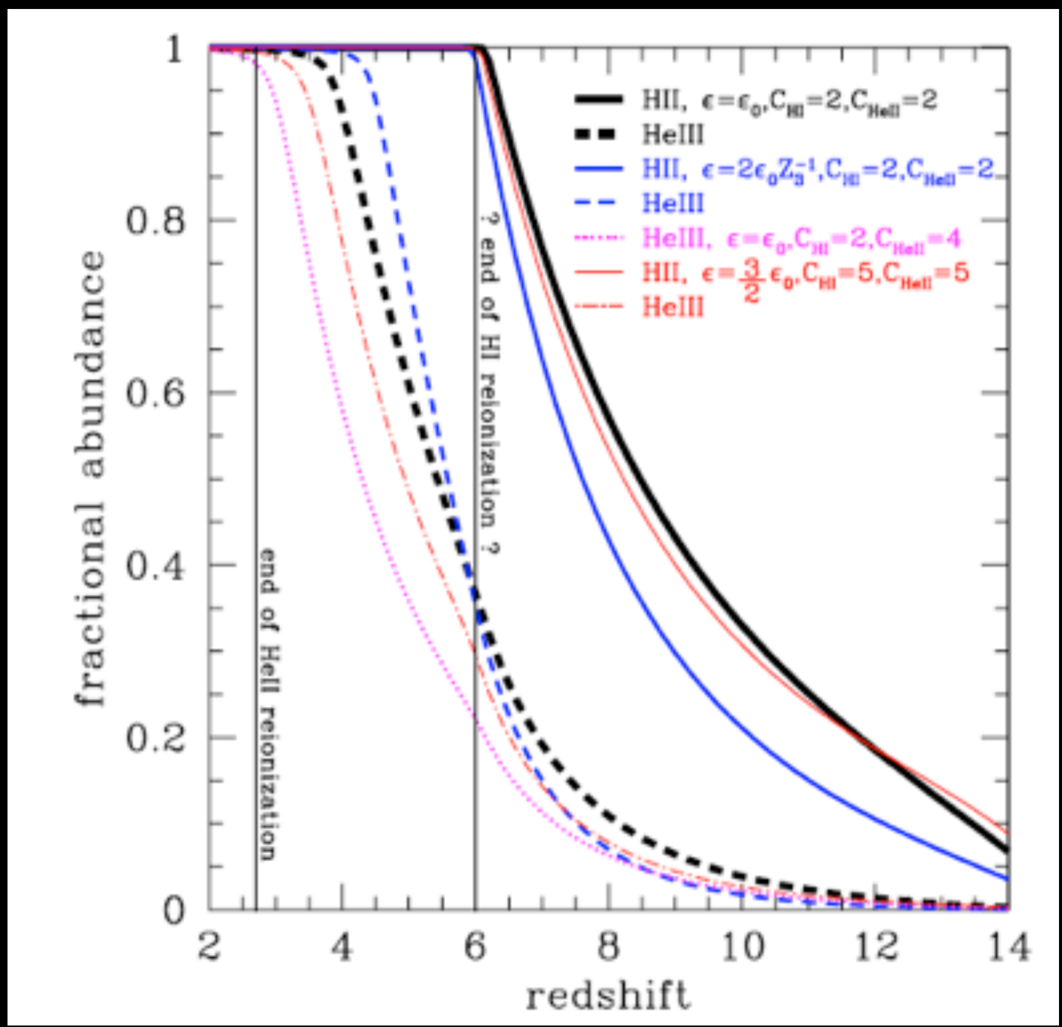
(3) The sources are probably not quasars

Quasar abundance falling rapidly:



Richards et al '06

HeII reionized late requires spectral softening with ↑ z:



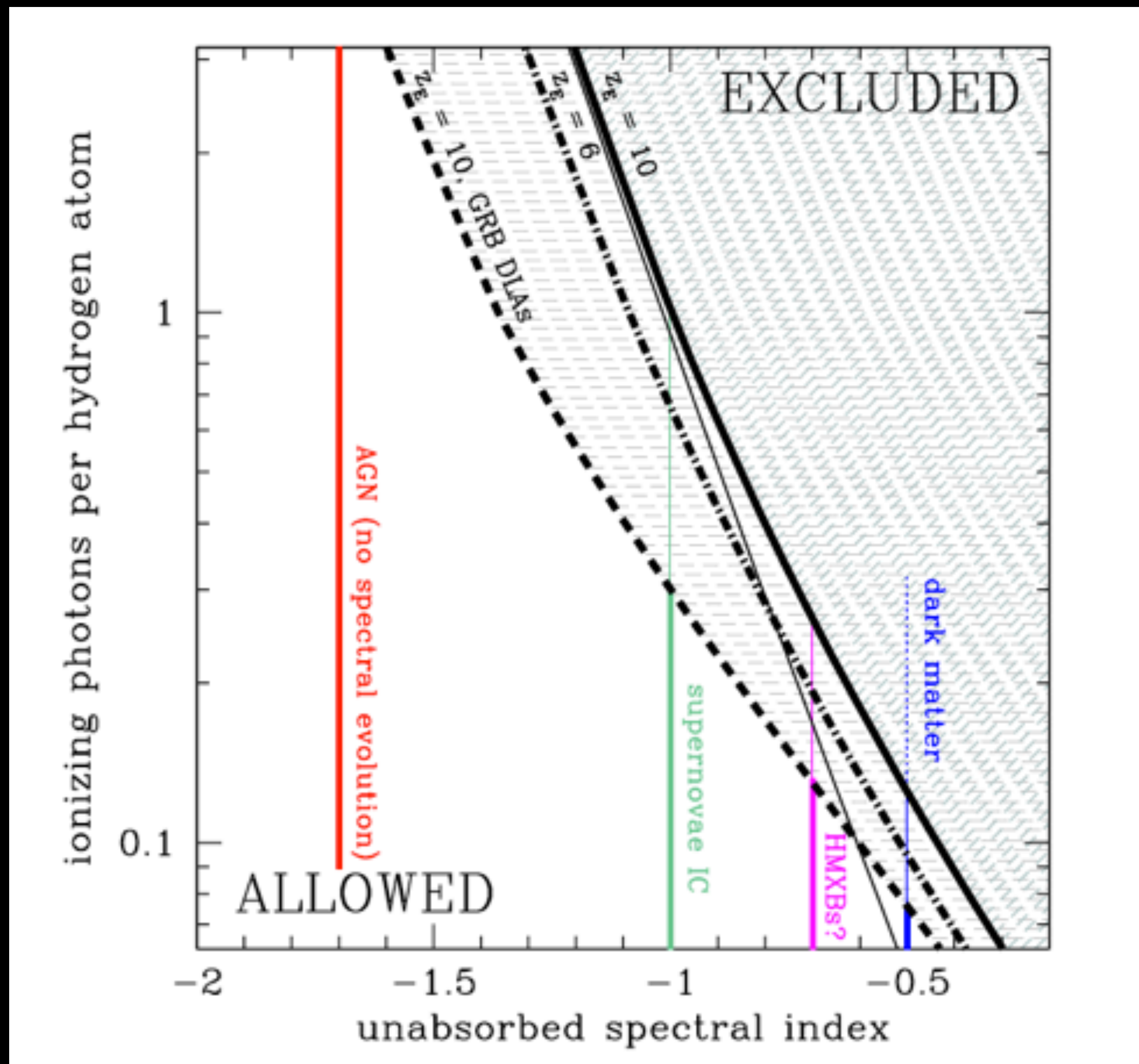
Caveat: this plots shows > L* quasars
Must combine w/ evidence that faint end slope is softening out to z=3 (Hunt++ 2004) and z=4 (Glickman++ 2011).

Recent constraints w/ CFHT may rule out steep faint end at z=6 (Willott++ '10).

MM (2012)

(3 b) The sources are not X-rays from galaxies, supernovae, dark matter (spectra must be soft)

Unresolved Soft X-ray Background Limits



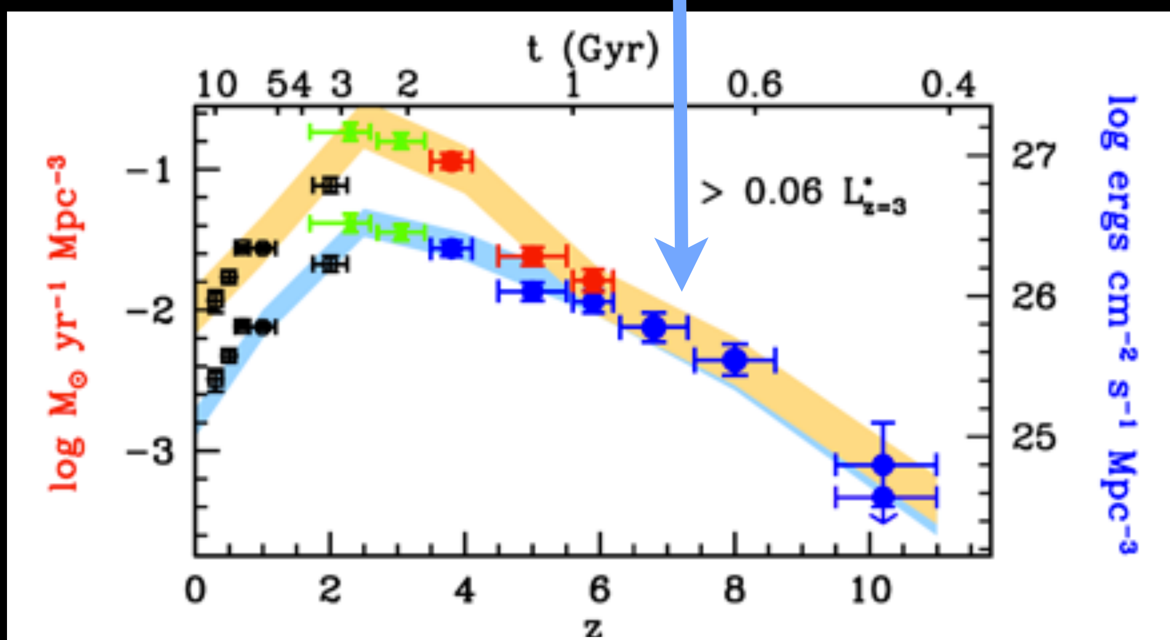
From MM '12; originally discussed in Dijkstra, Haiman, Loeb (2004).

(4) Galaxies most likely drove reionization, but their emissivity is not evolving as one might anticipate

emissivity = (Intensity of Ionizing Background) /(mean free path)

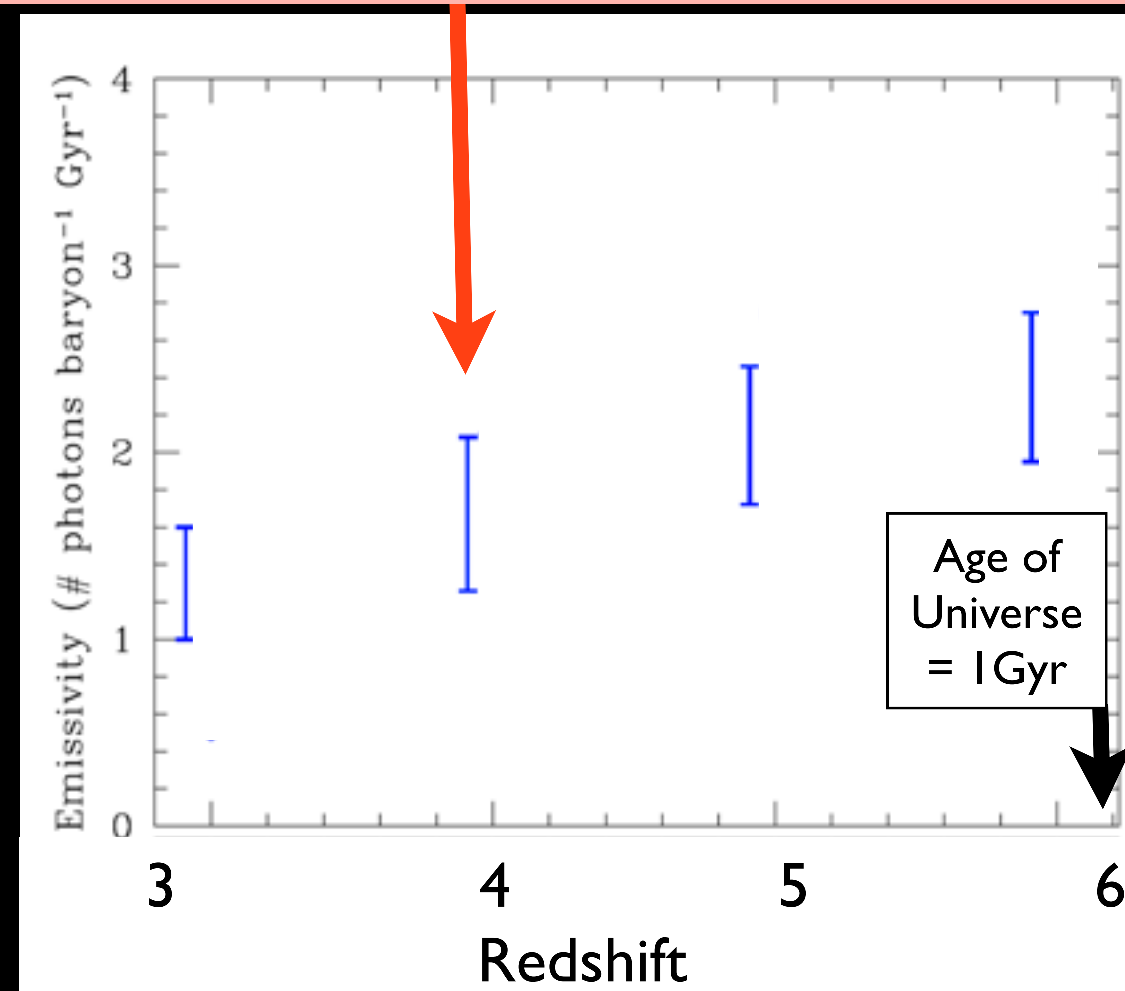
Measurements imply
emissivity < 2.5 photons per H-atom per Gyr at z=4
(Miralda-escude, 2004)

Need f_{esc} ~ 0.2 to reionize universe



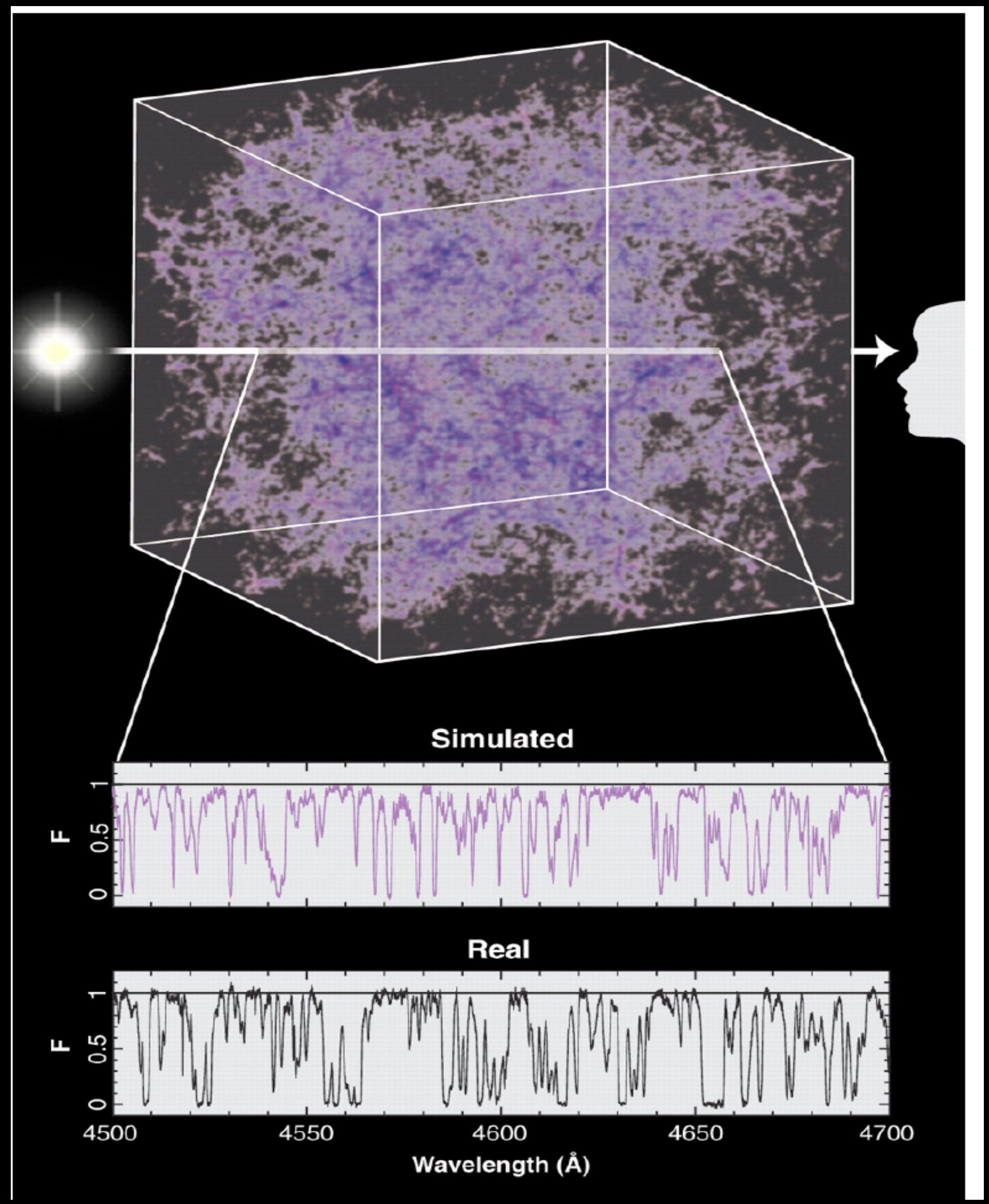
Bouwens, Illingworth et al (2010)

yellow band = after dust correction



MM, Oh, and Faucher-Giguere (2011)
also see Bolton & Haehnelt (2007), Miralda-Escude (2003)

(5) We have a well-tested model for the the clustering of sources and distribution of gas in the IGM



- Lyman-α forest

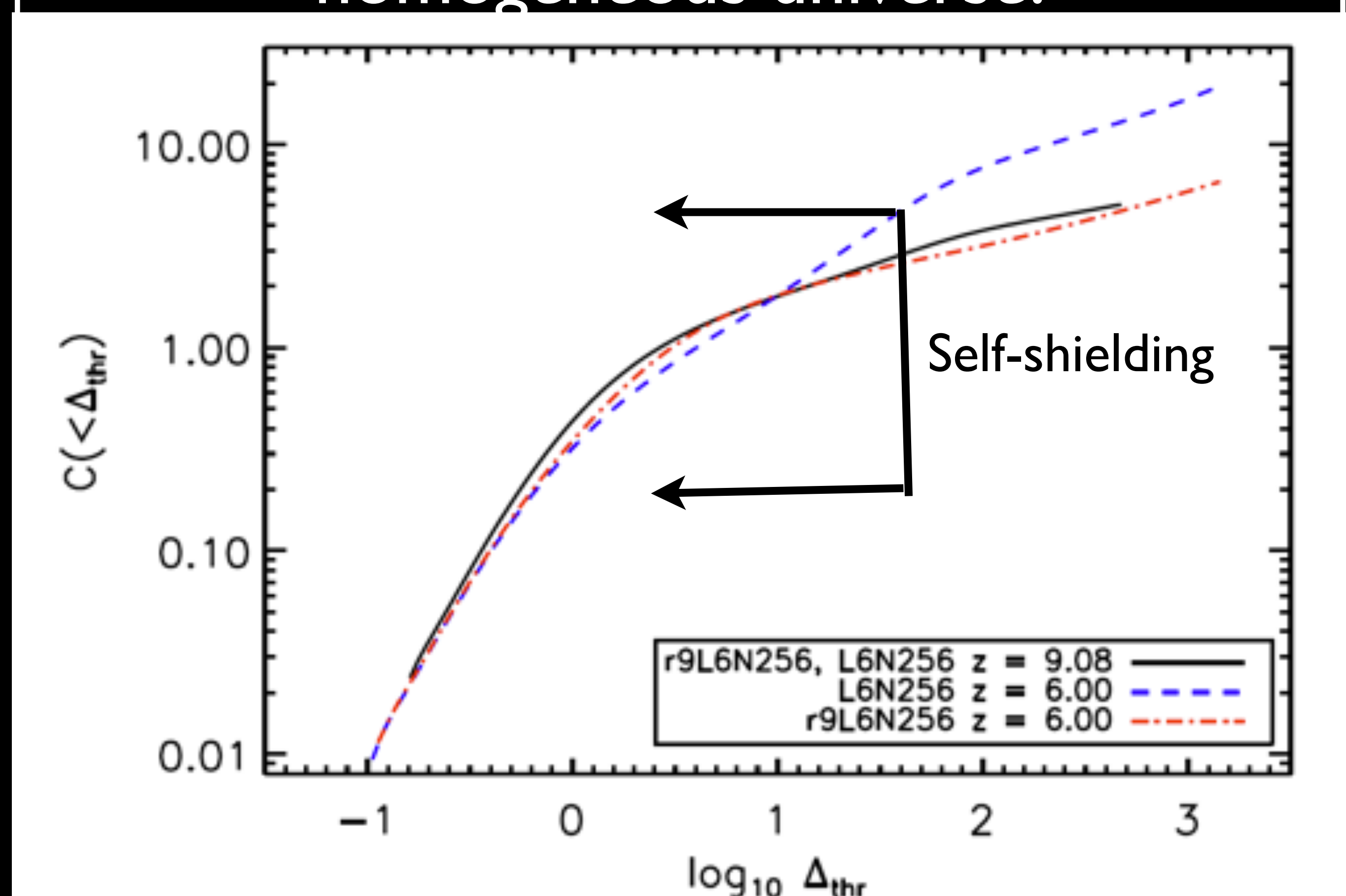
  absorption explained by simple physics: structure formation, ≈10^4 K gas, uniform background

- Cen et al '94, Miralda-Escude et al '96, Hernquist et al '96

Plot from Faucher-Giguere, Lidz, & Hernquist (2008)

(5 cont) The density structure of the simulations tells us that the number of recombinations per baryon during reionization had to be <~2

Enhancement in recombination rate over homogeneous universe.



Pawlik++ (2008); with RT see MM++ (2012); See talk by Jeeson-Daniel.

Our Best Ideas for Directly Studying Reionization

- the kSZ; SPT finds < 3-6 μK^2 (Reichardt, Mesinger)
- Ly-α damping wing in GRBs (only one at $z>6$ with adequate spectrum, but intrinsic N_{HI} too high) and $z>6$ quasars (Morlock, Mesinger)
- Ly-α emitters (Ellis, Dijkstra)
- 21cm; MWA, LOFAR, and PAPER are all doing science runs (Dillon, Prober, Koopmans, Mellema). Also, global signal effort (Bowman, Ekers, Liu).

What do we want to know about HI reionization?

- when?
  - Current incomplete answer: <z>=10, z_{end}~6 (maybe)
- by what?
  - Best answer is galaxies...maybe the ones we see at z=6, but probably not
- what does this tell us about galaxy / black hole formation?
  - Current answer is that early galaxies were likely more efficient at sourcing intergalactic ionizing photons

Conclusions

- $z < 6$ IGM
  - temperature consist. w/ expectations
  - HeII reionization ended at z=2.7
  - simulations reproduce abundance of high-column density HI absorbers
  - we are running out of IGM anomalies!!
- $z > 6$ IGM
  - quite a lot we don't yet know, but we have made progress in last decade (since WMAP and SDSS quasars)

Aside: What is the reason for quick evolution in τ_{eff}

Intensity = (mean free path) x (source emissivity)

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↑

Determines absorption in Ly-alpha forest

Aside: What is the reason for quick evolution in τ_{eff}

Distance between
dense self-shielding
systems

↓

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Distance between dense self-shielding systems ↓

# of Recombinations (clumpiness of dense systems) ↓

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$\approx$ emissivity$^{1/(2-\beta)}$

(assumes power-law profile for systems)

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$\approx$ emissivity$^{1/(2-\beta)}$ (assumes power-law profile for systems)

↑ Determines absorption in Ly-alpha forest

- At z=4, simulations predict a 10% change in emissivity can result in 30% change in intensity.
- At z=6, simulations predict a 20% change in emissivity can result in factor of 2 change in intensity. May explain rapid $\tau_{eff,Ly\alpha}$ evolution seen in Fan et al (2006).
- Strong scaling related to result that IGM clumping factor is small independent of SS density threshold (e.g. Pawlik & Schaye '08)