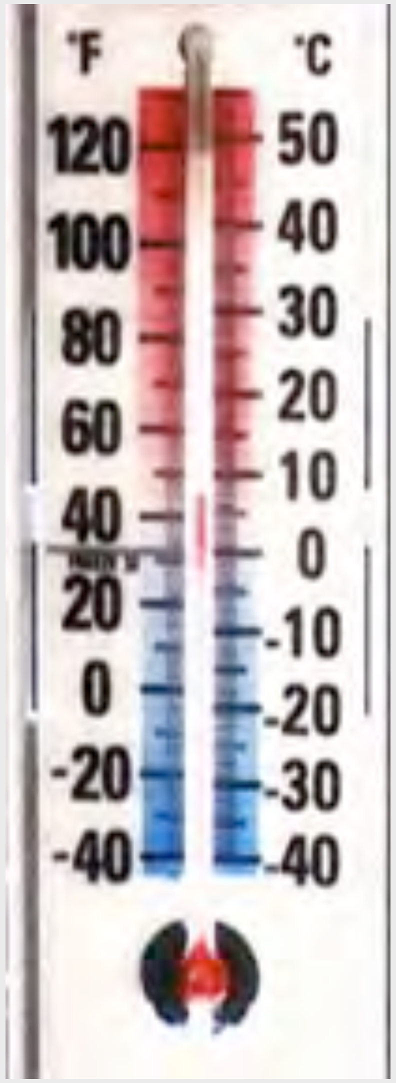


New Insights into Hydrogen & Helium Reionization from the Thermal History of the IGM

George Becker

Cambridge IoA & KICC

3.8.2010

Overview

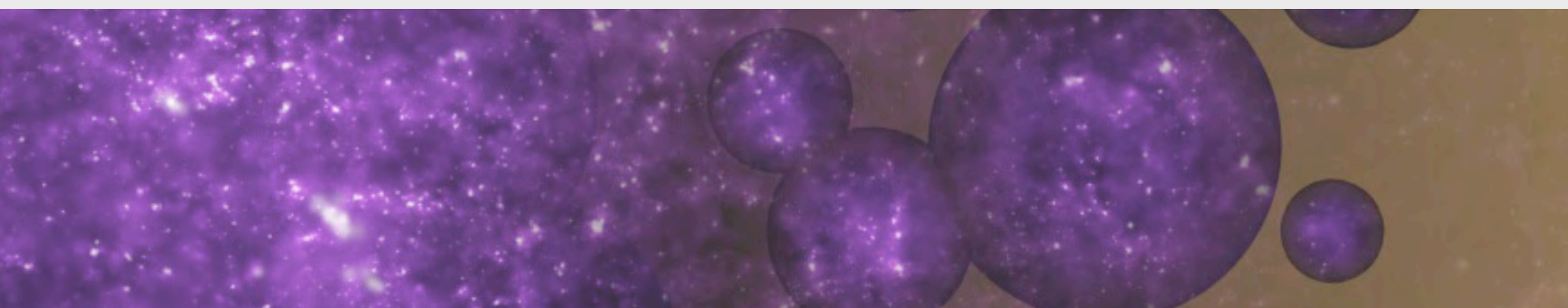
- Review of reionization probes
- IGM temperatures probing He II reionization
  - Curvature of the Lyα forest
- IGM temperatures probing H I reionization
  - QSO near zones

Jamie Bolton (Melbourne)
Martin Haehnelt (IoA)

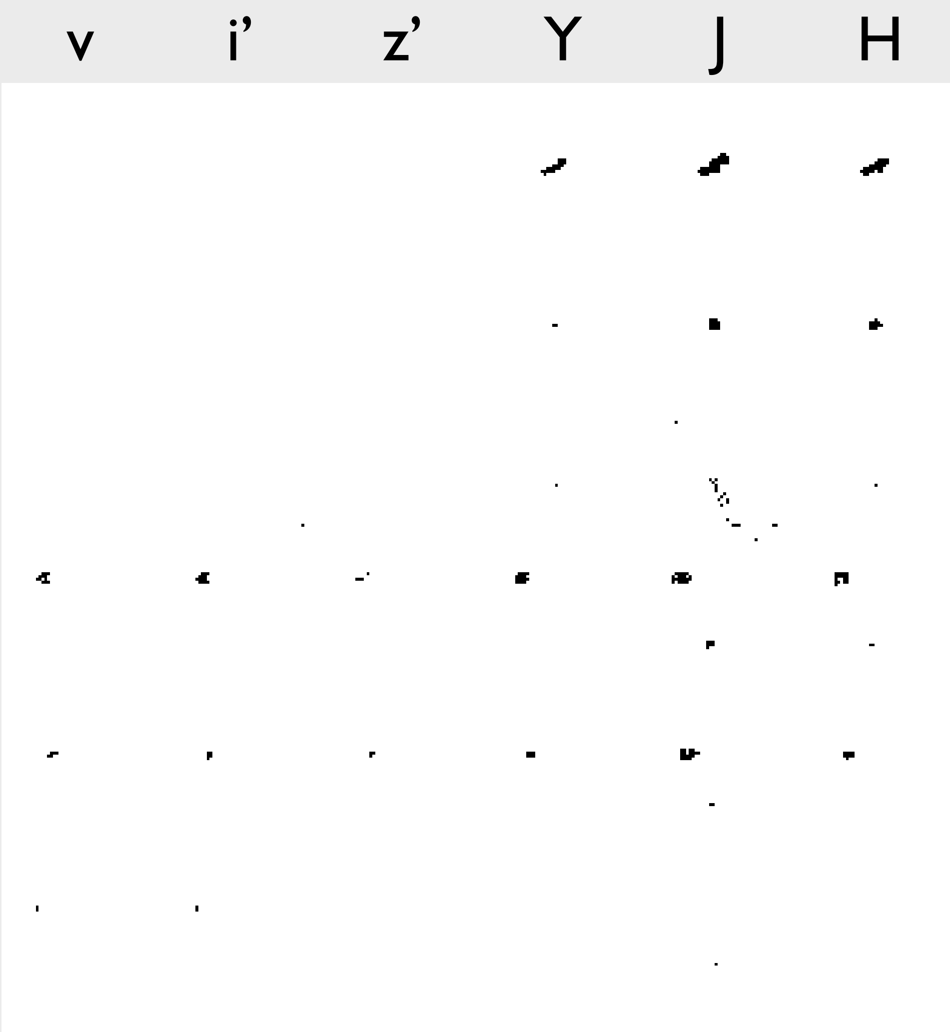
Marcelo Alvarez

Reionization -- Quick facts

	Hydrogen	Helium
Species	H I and He I	He II
ΔE	13.6 eV (24.6 eV for He I)	54.4 eV
Source	Galaxies?	QSOs?
z_{reion}	z > 6	z > 3



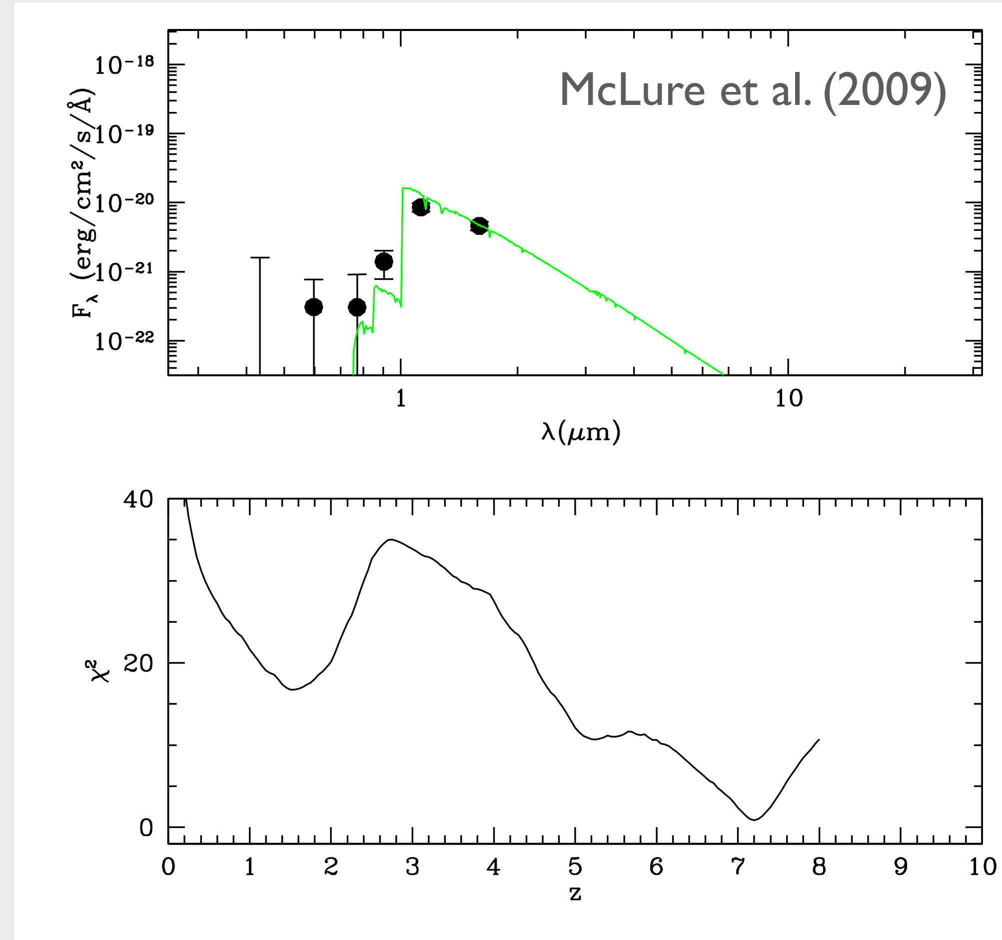
Hydrogen reionization: galaxies

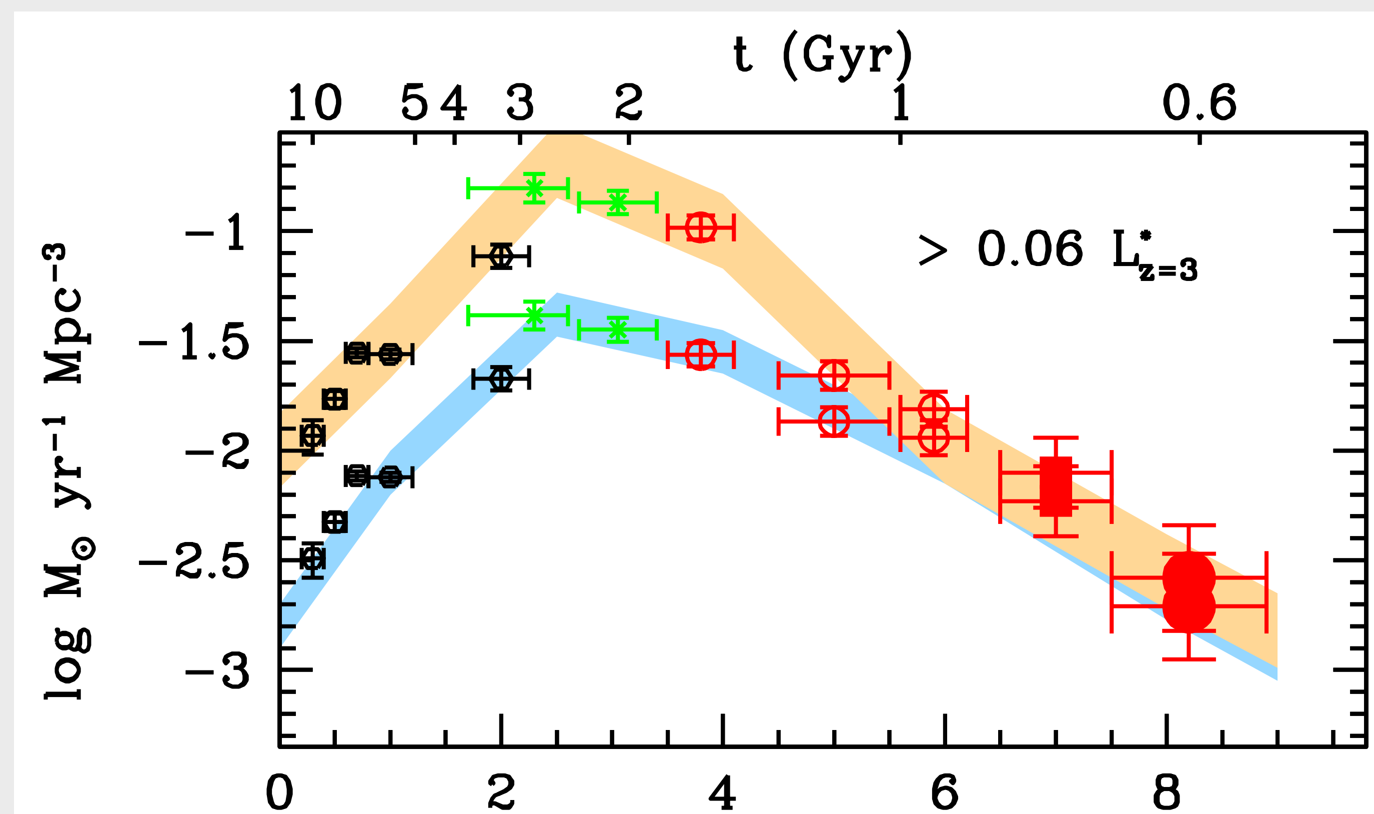


Bunker et al. (2009)

McLure+ 09
Oesch+ 09
Bouwens+ 09,10
Bunker+ 09

Ouchi+09
Labbe+ 09
Yan+ 09
etc.

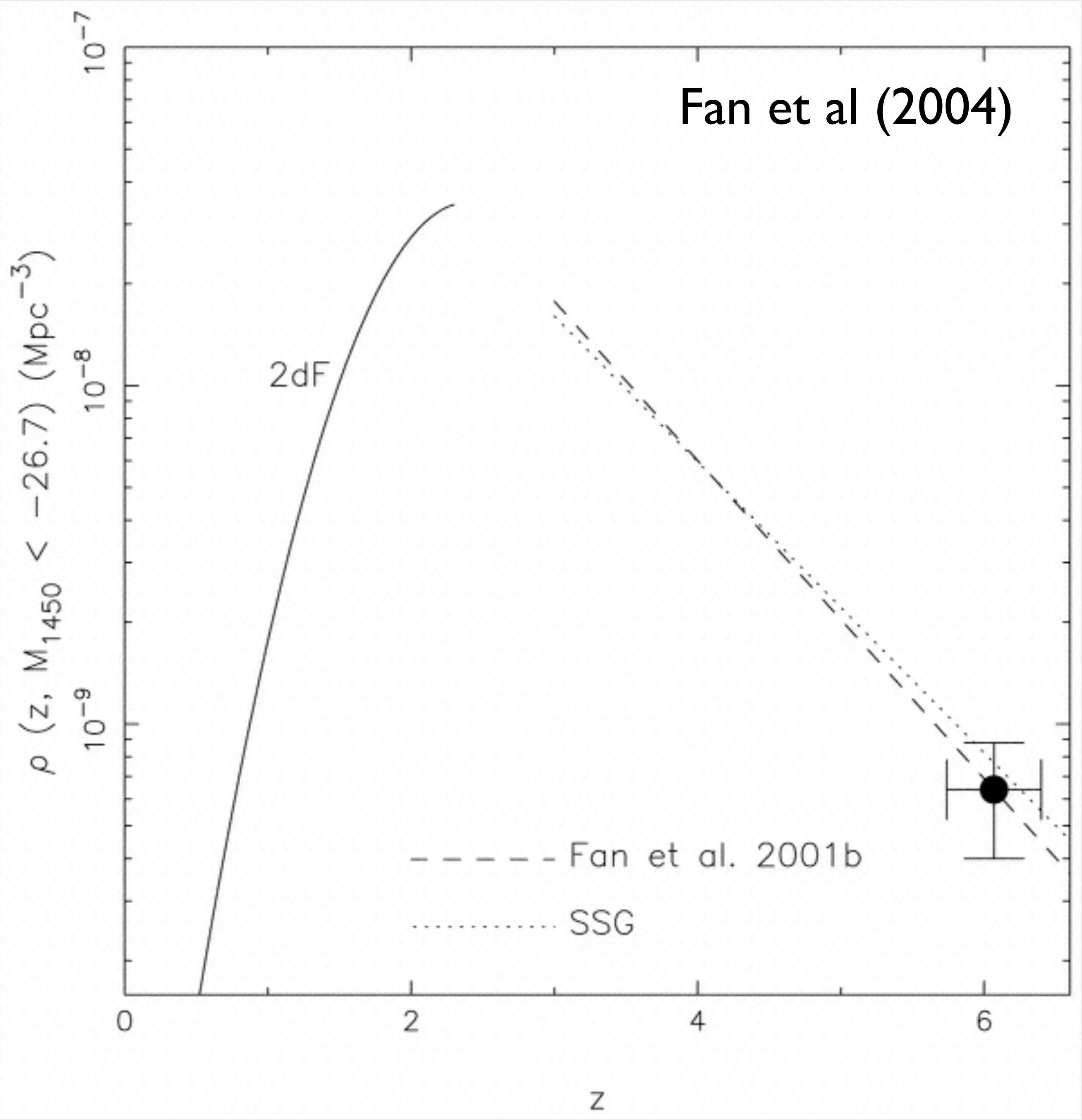




Bouwens et al. (2009)

Helium reionization: QSOs

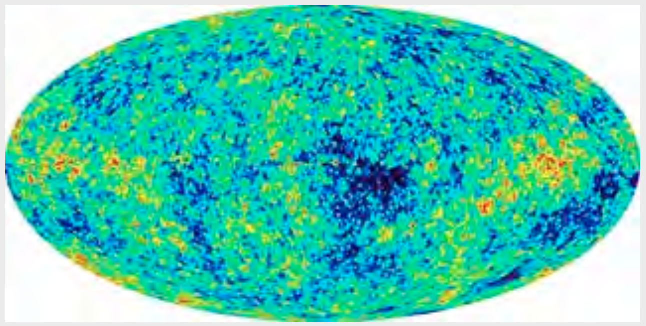
He II, ΔE = 4 Ryd



2dF: Croom et al. (2004)

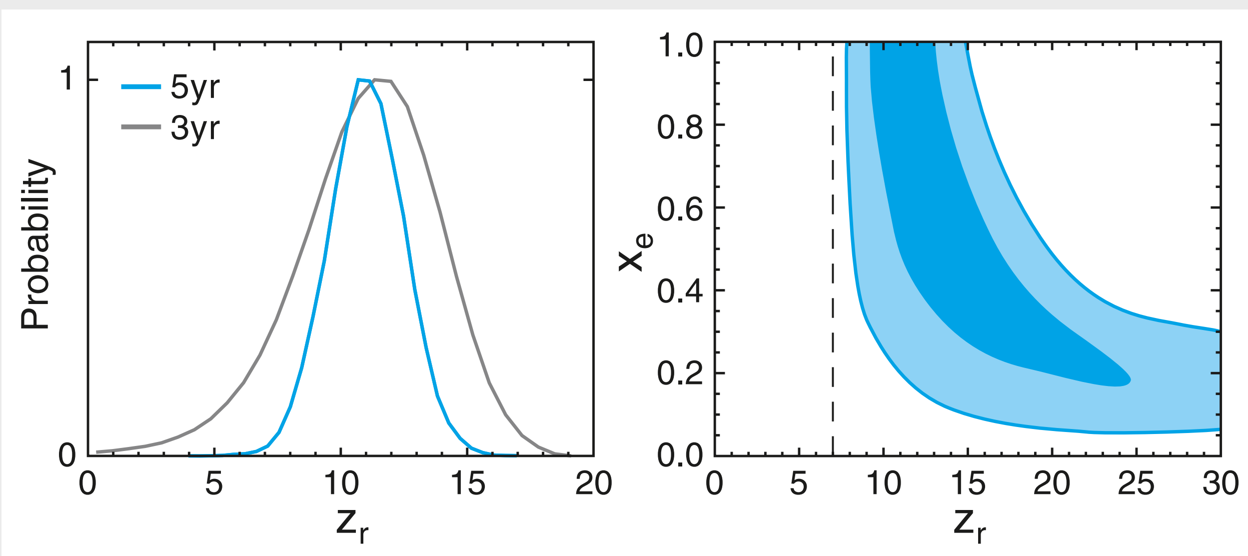
see also Jiang et al. (2008, 2009), Willott et al. (2009)

Hydrogen Reionization - Two limits



Early
CMB

τ_e to Thomson scattering

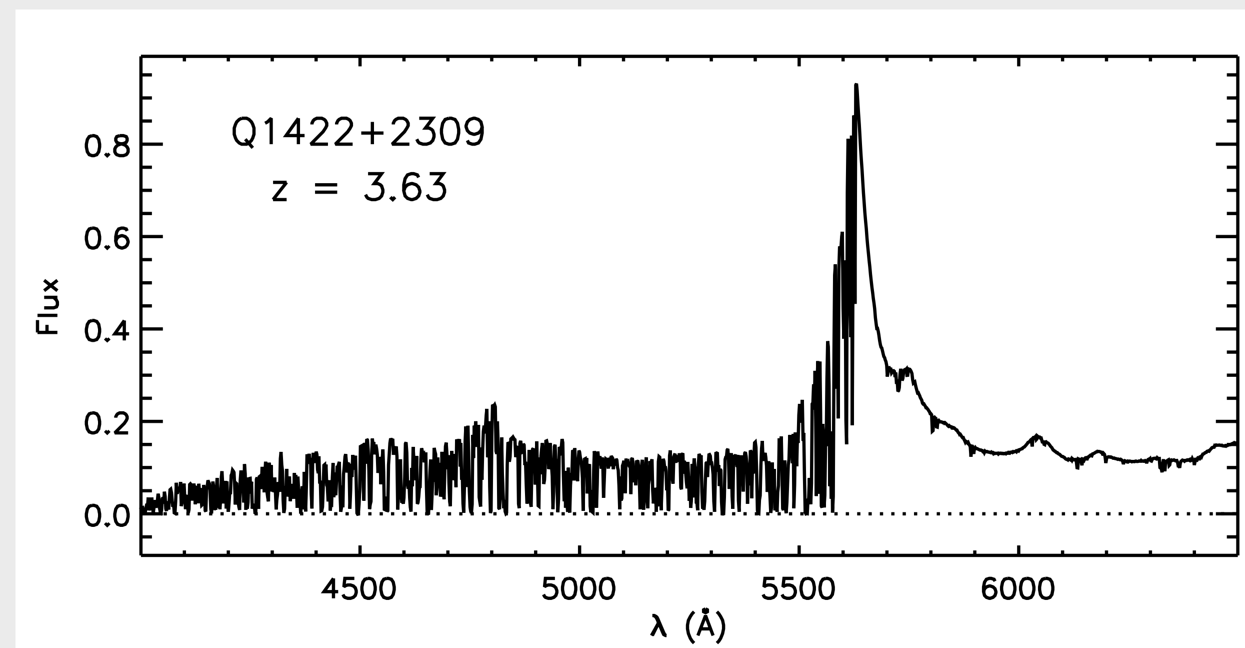


WMAP7: $z_{\rm reion} = 10.4 \pm 1.2$ ("instant")

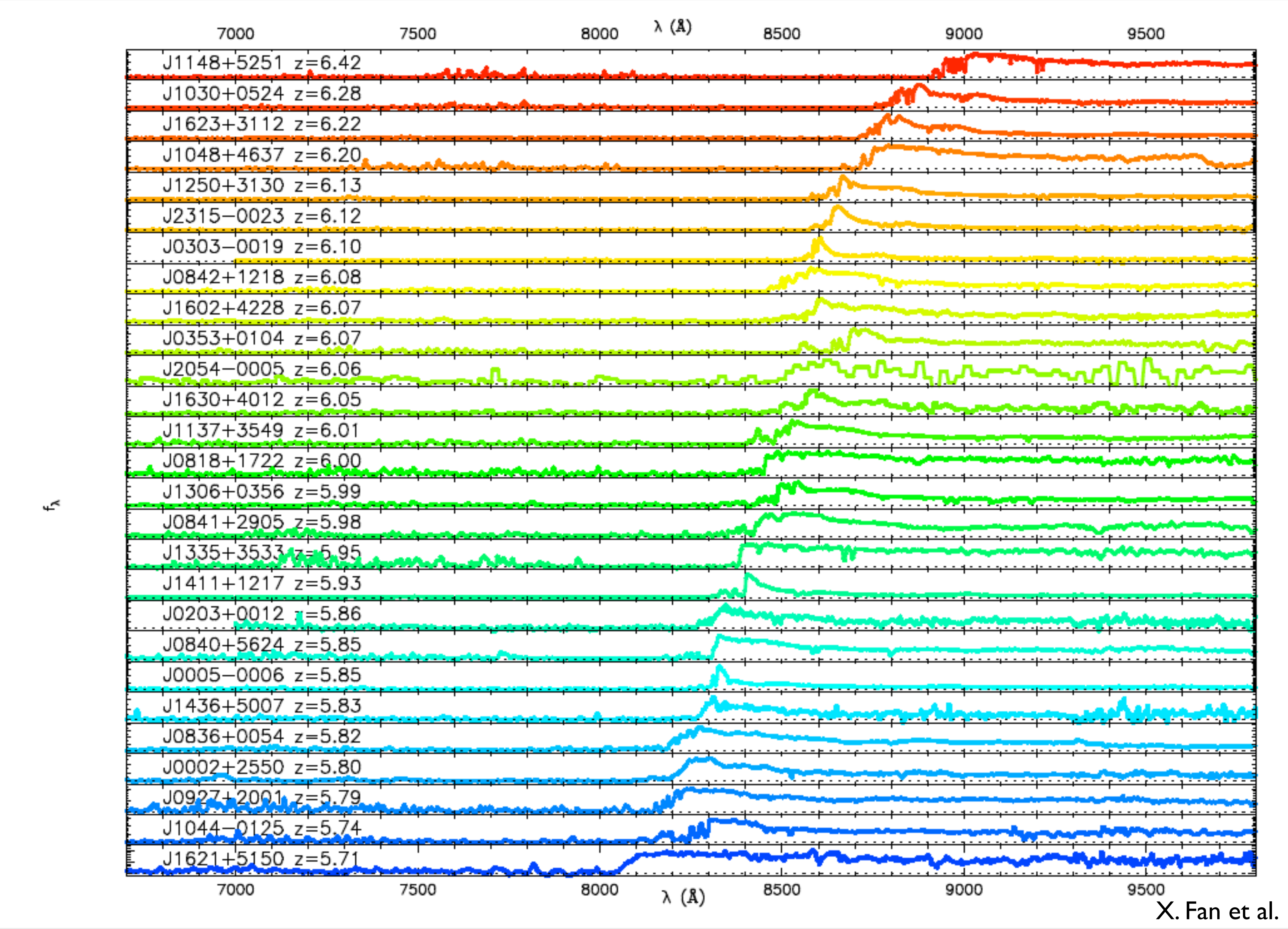
but consitent with a range of reionization histories

Dunkley et al. (2008), Jarosik et al. (2010)

Late
Transmission in the Lyα forest

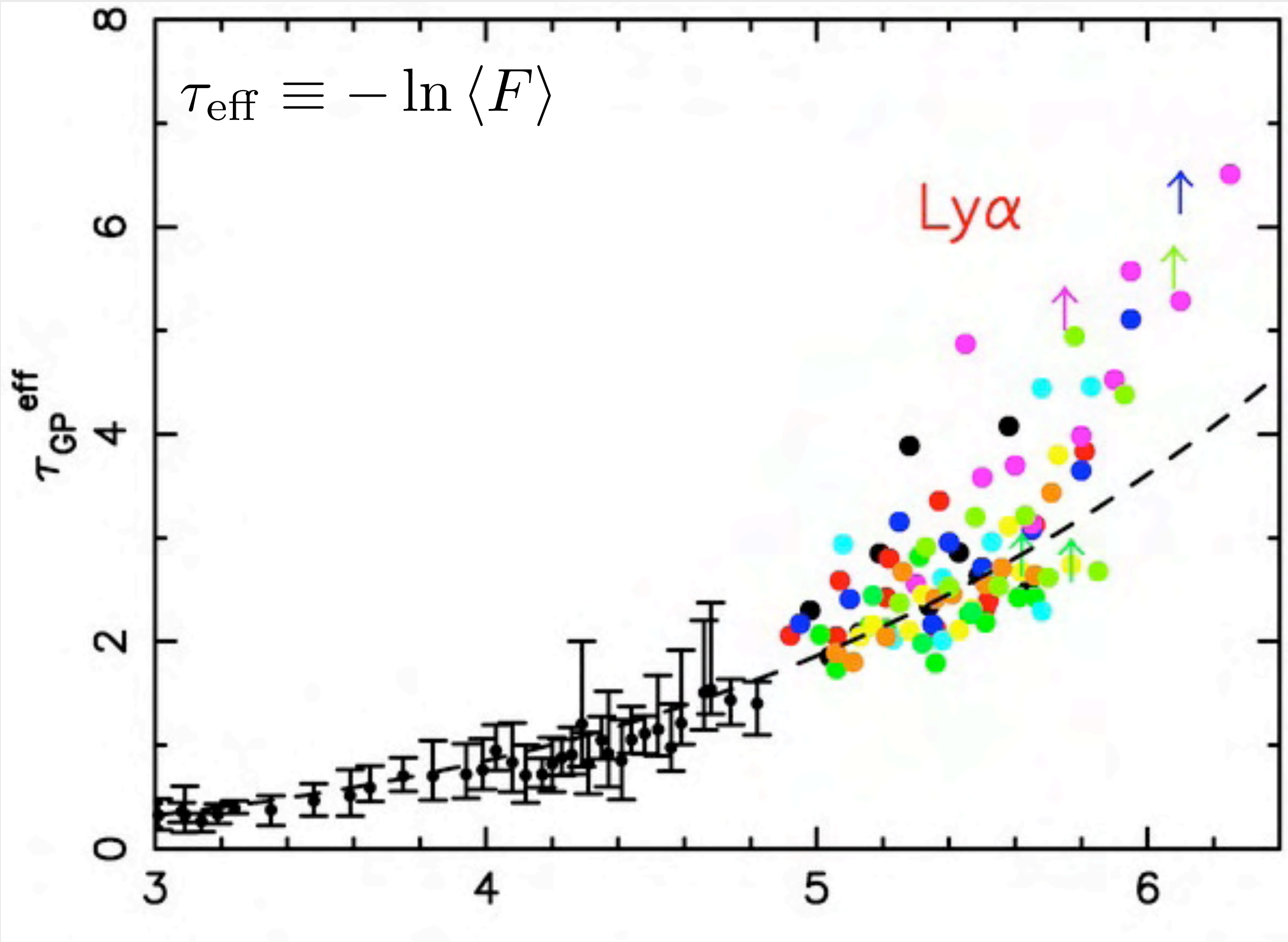


IGM must be highly ionized at z < 6

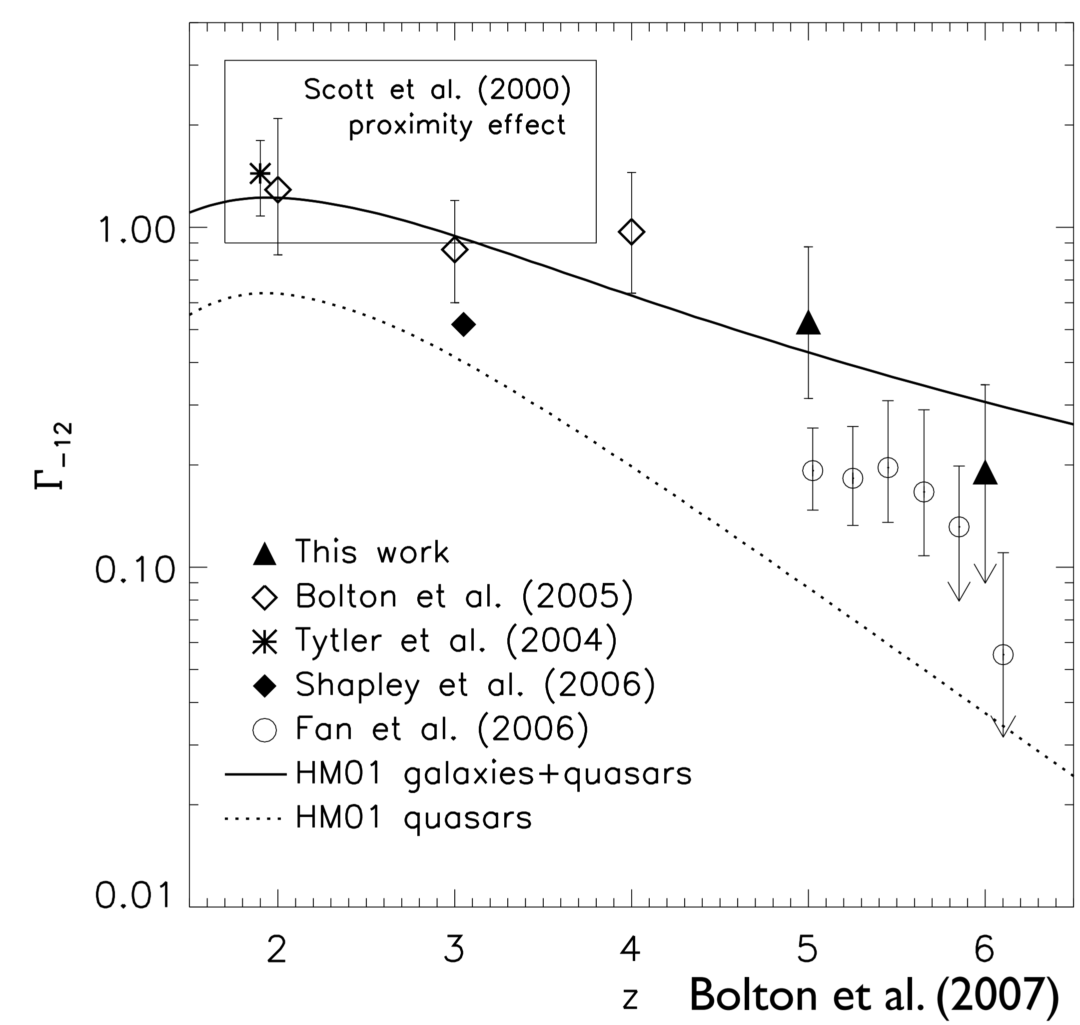


Currently ≥47 z > 5.7 QSOs known (many faint)

Mean transmitted flux



Fan et al. (2006)

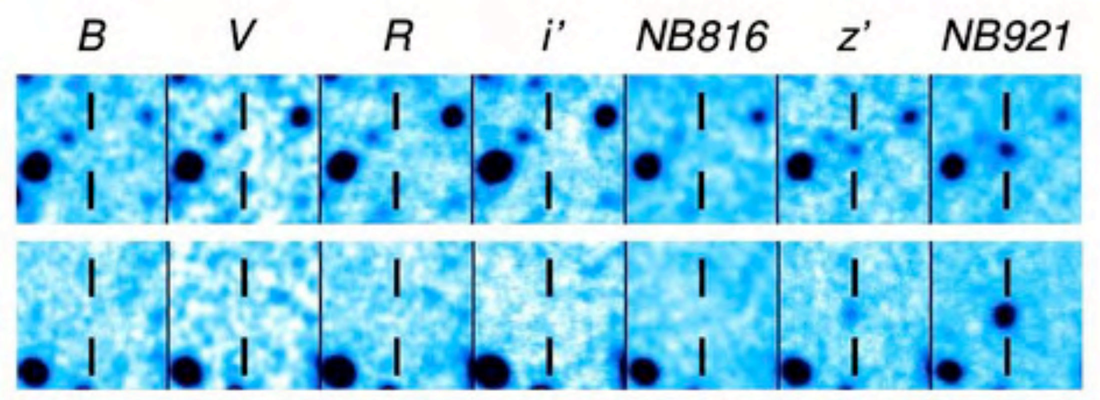


Bolton et al. (2007)

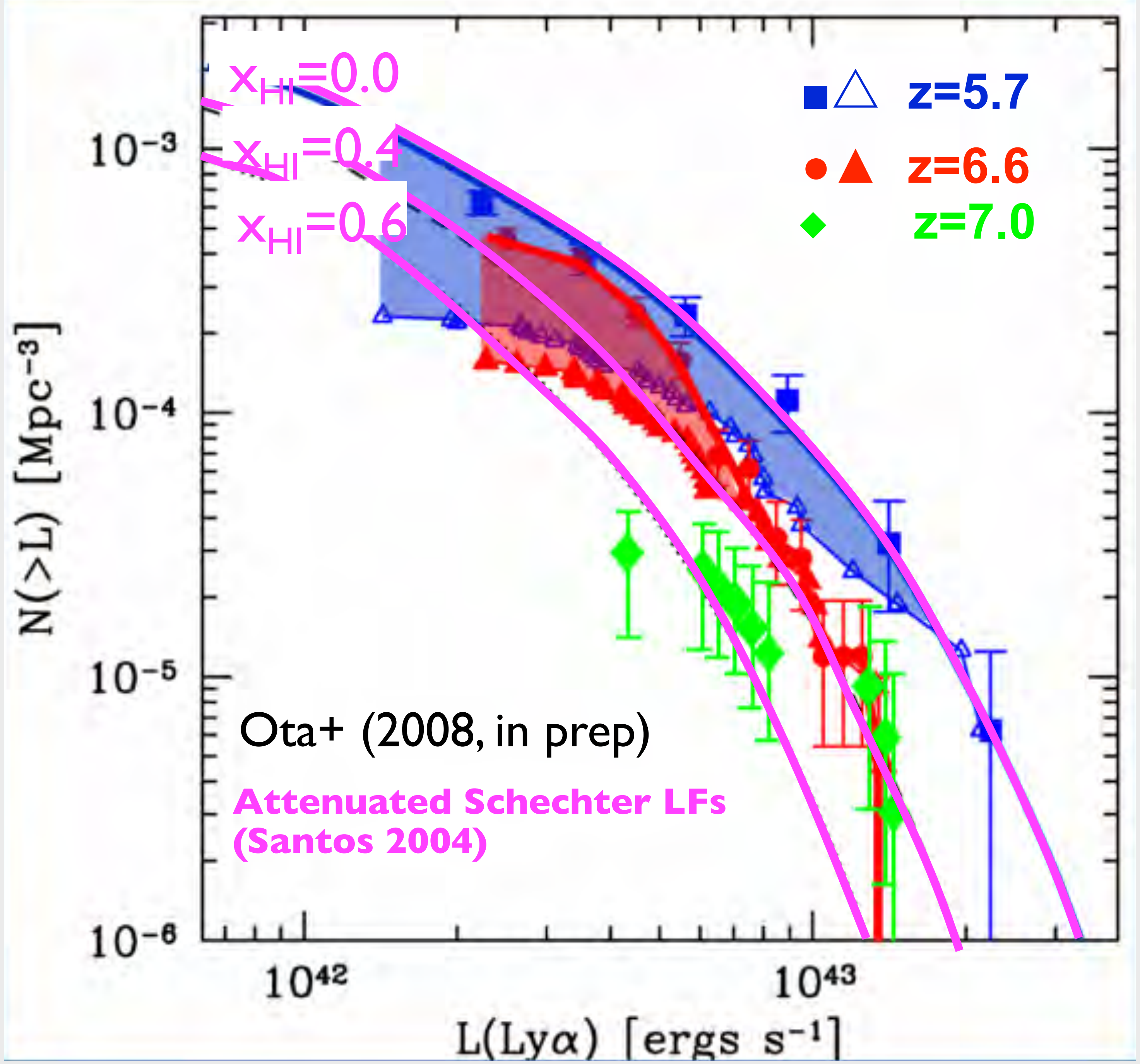
$$\tau_{\rm Ly\alpha} \sim 10^5 f_{\rm H\,I}$$

Possible downturn in UV background at z > 6, but not a clear signature of the end of H reionization

Lyα Emitters



Kashikawa+ 2006



Decreasing apparent LAE number density suggests an increasing neutral fraction?

*** Interpretation of Lyα LFs is debated (e.g., Dijkstra+ 2007) ***

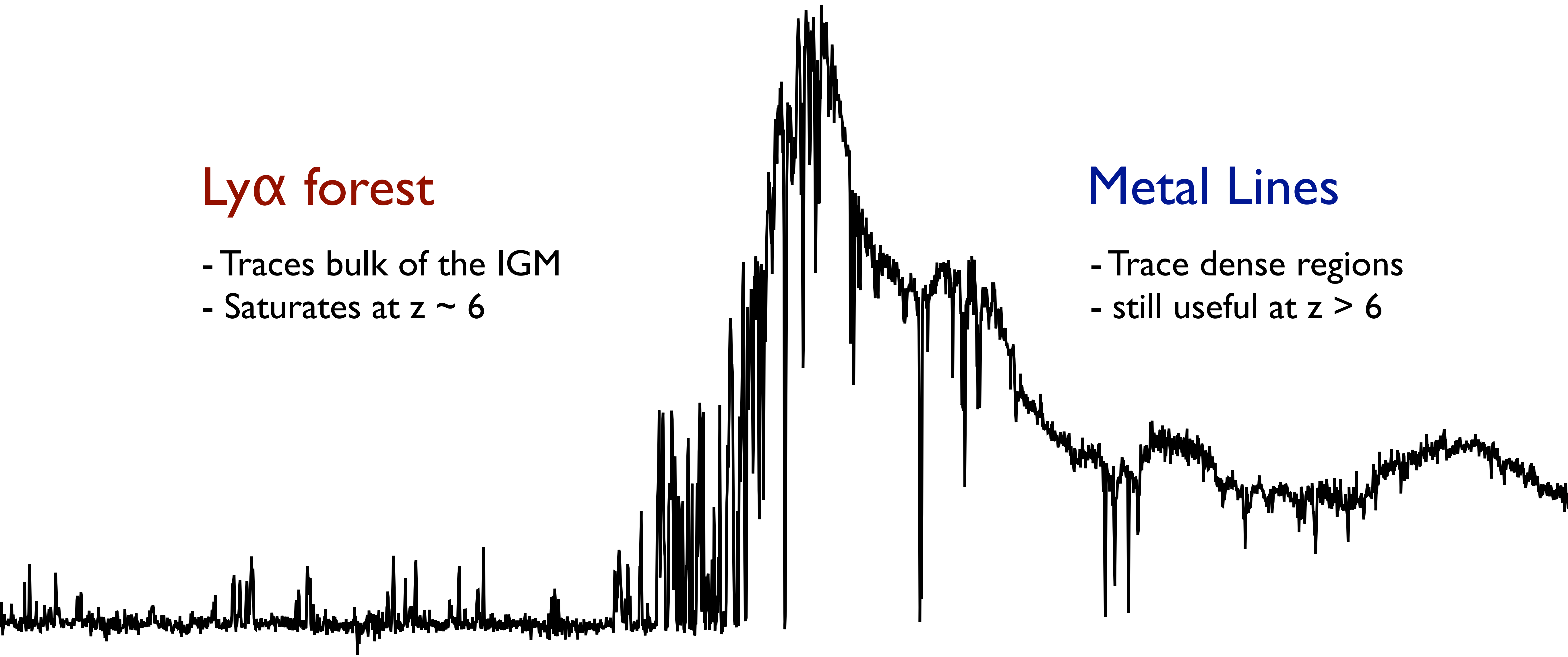
Metal Lines as IGM Probes

Lyα forest

- Traces bulk of the IGM
- Saturates at $z \sim 6$

Metal Lines

- Trace dense regions
- still useful at $z > 6$

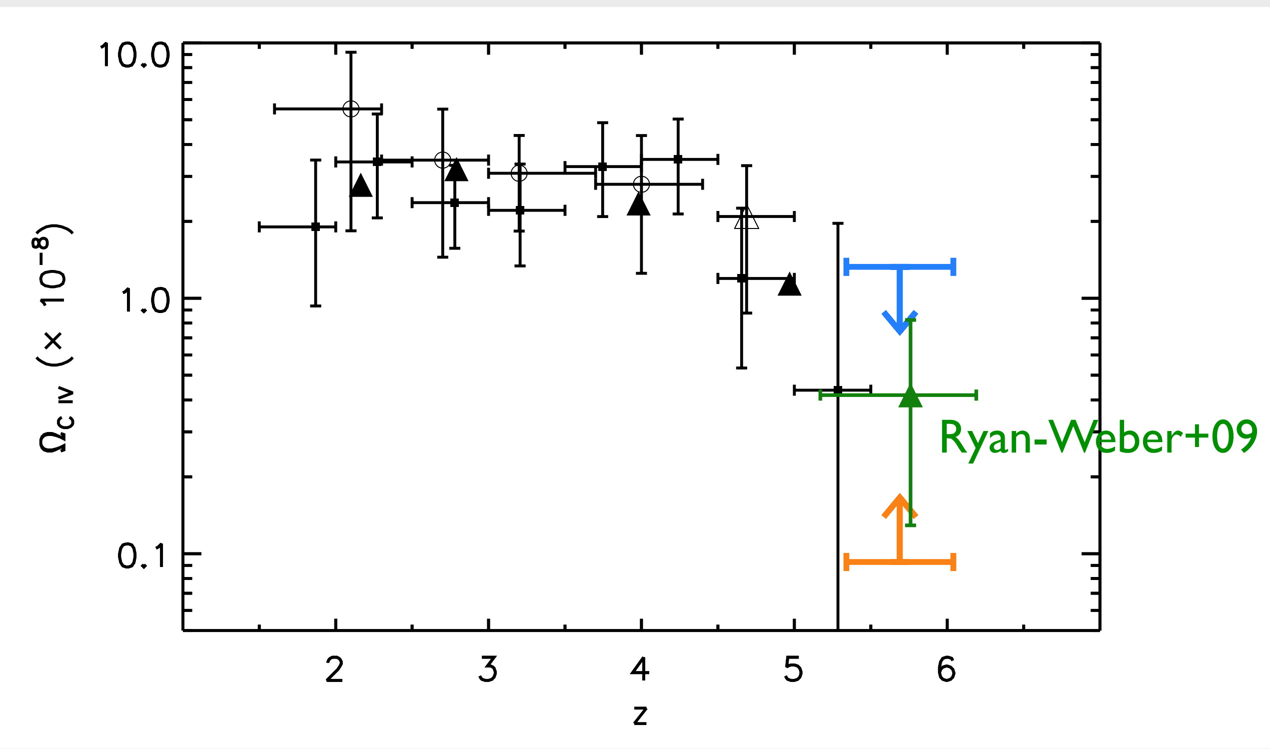


Metal lines at z > 5

2-part survey

C IV

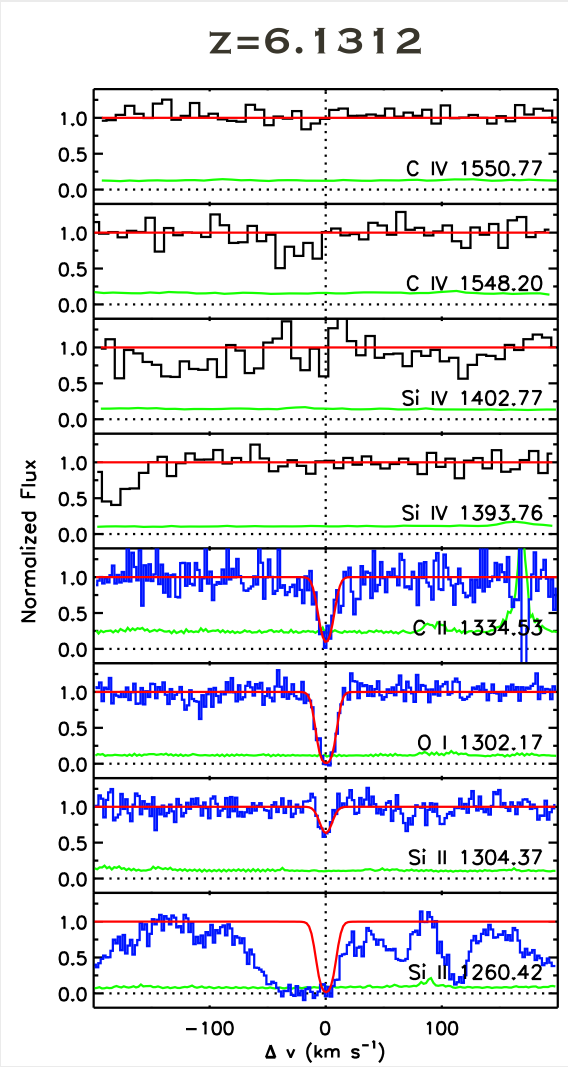
Typical tracer of IGM metals over z~2-5



declines rapidly at z > 5

O I

More rare - traces galaxy ISM over z~2-5 (DLAs)

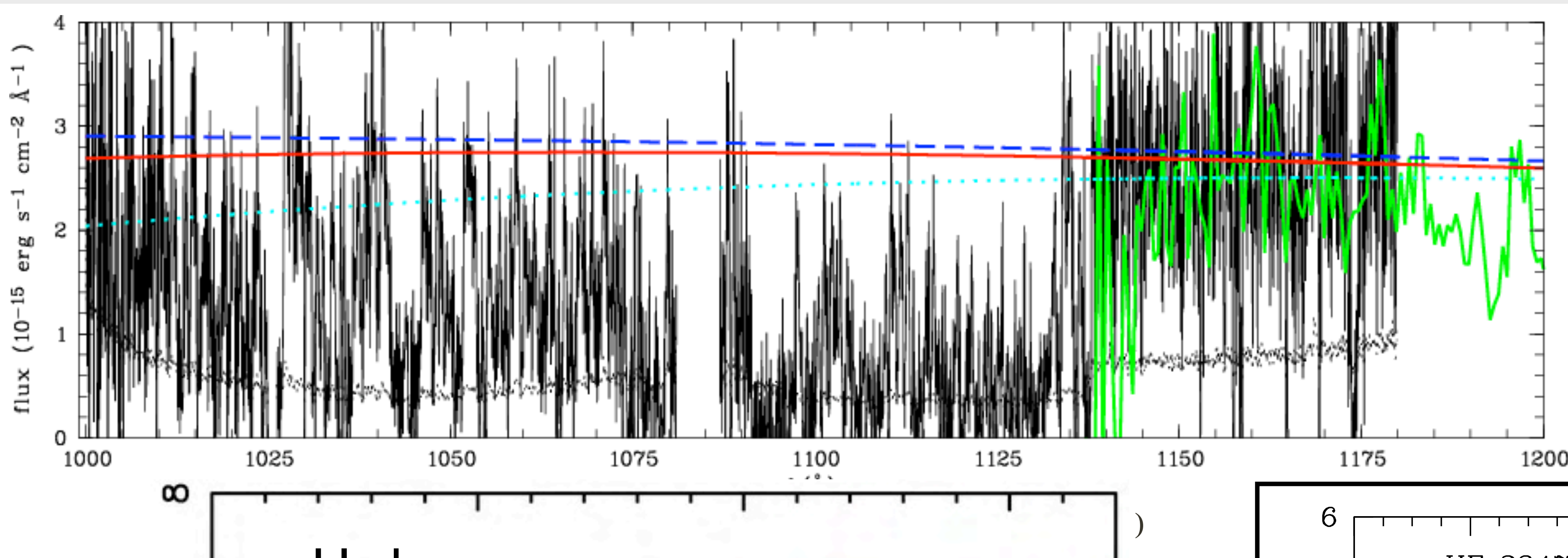


much more numerous at z ~6 (?)

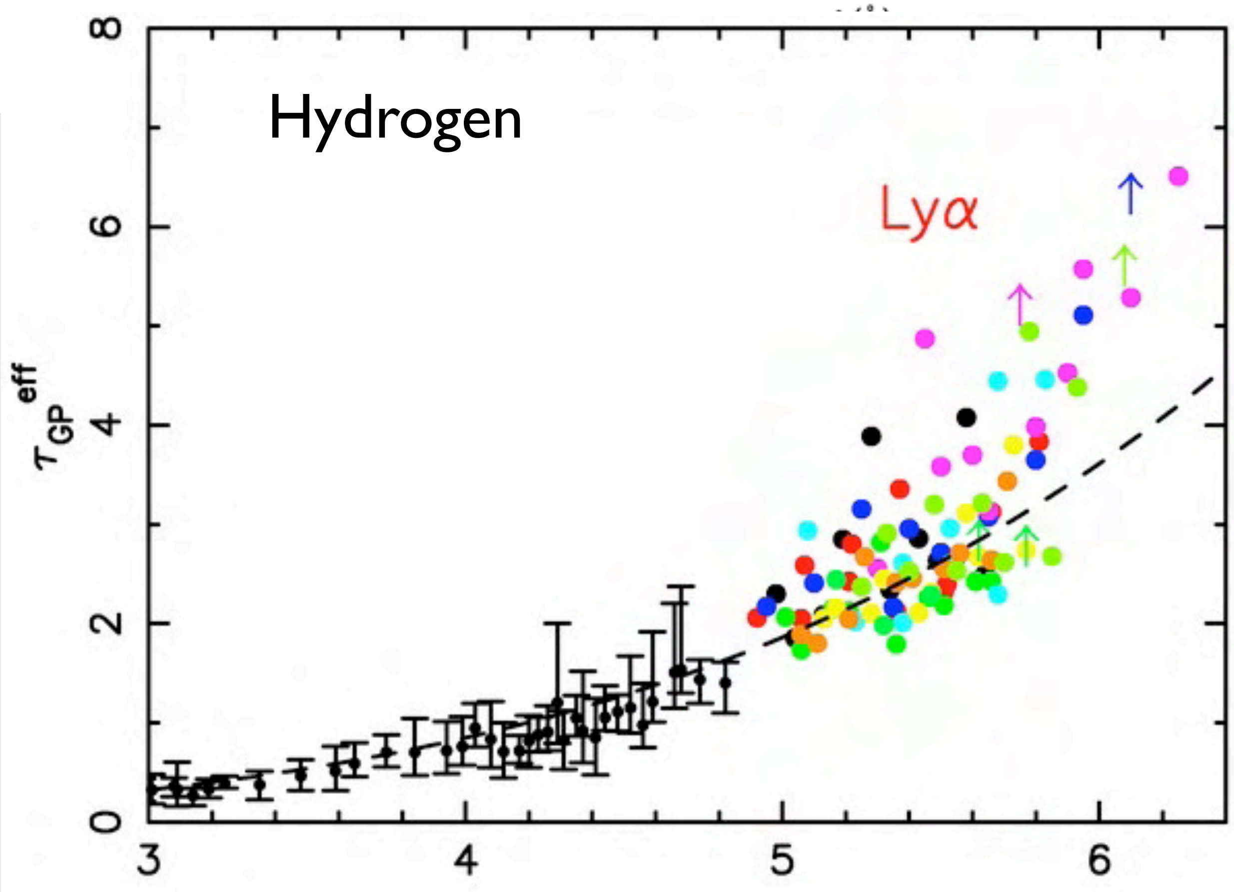
Seeing end of hydrogen reionization?

GDB+ 2006, 2009, & in prep

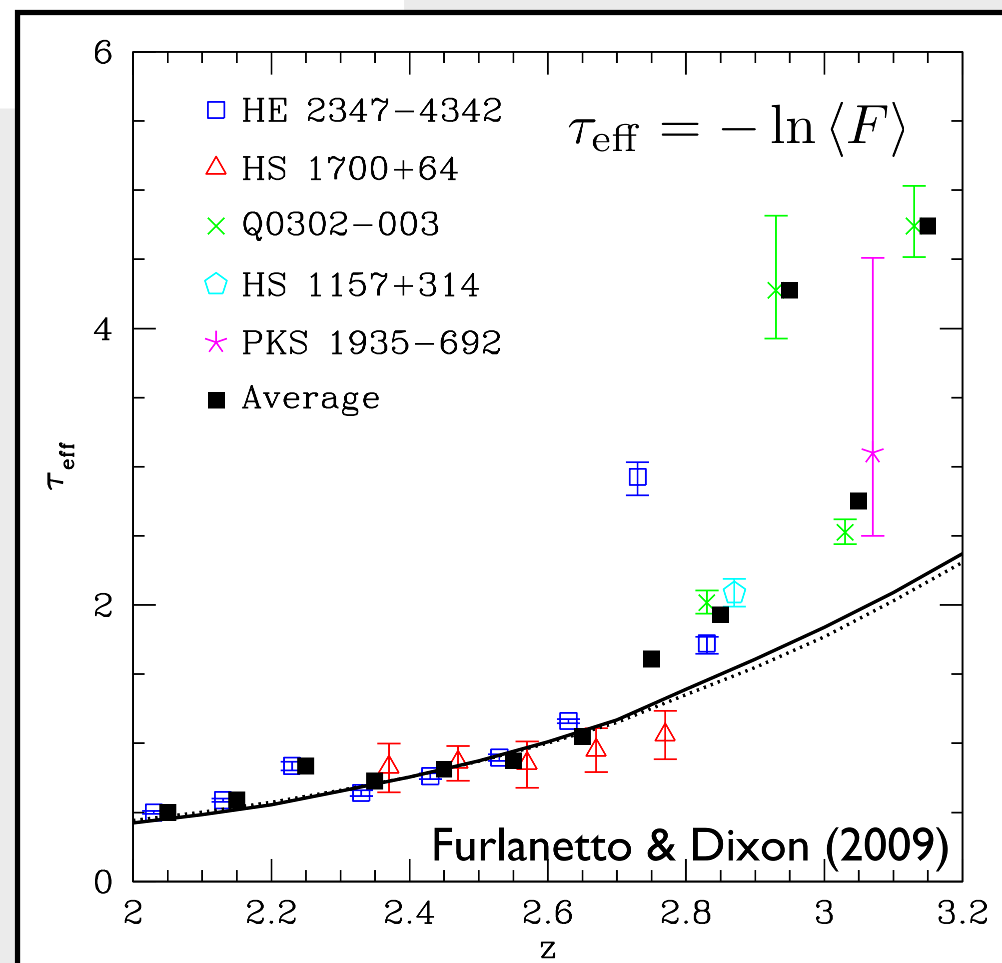
He II opacity evolution



He II Lya
λ_{rest} = 304 Å



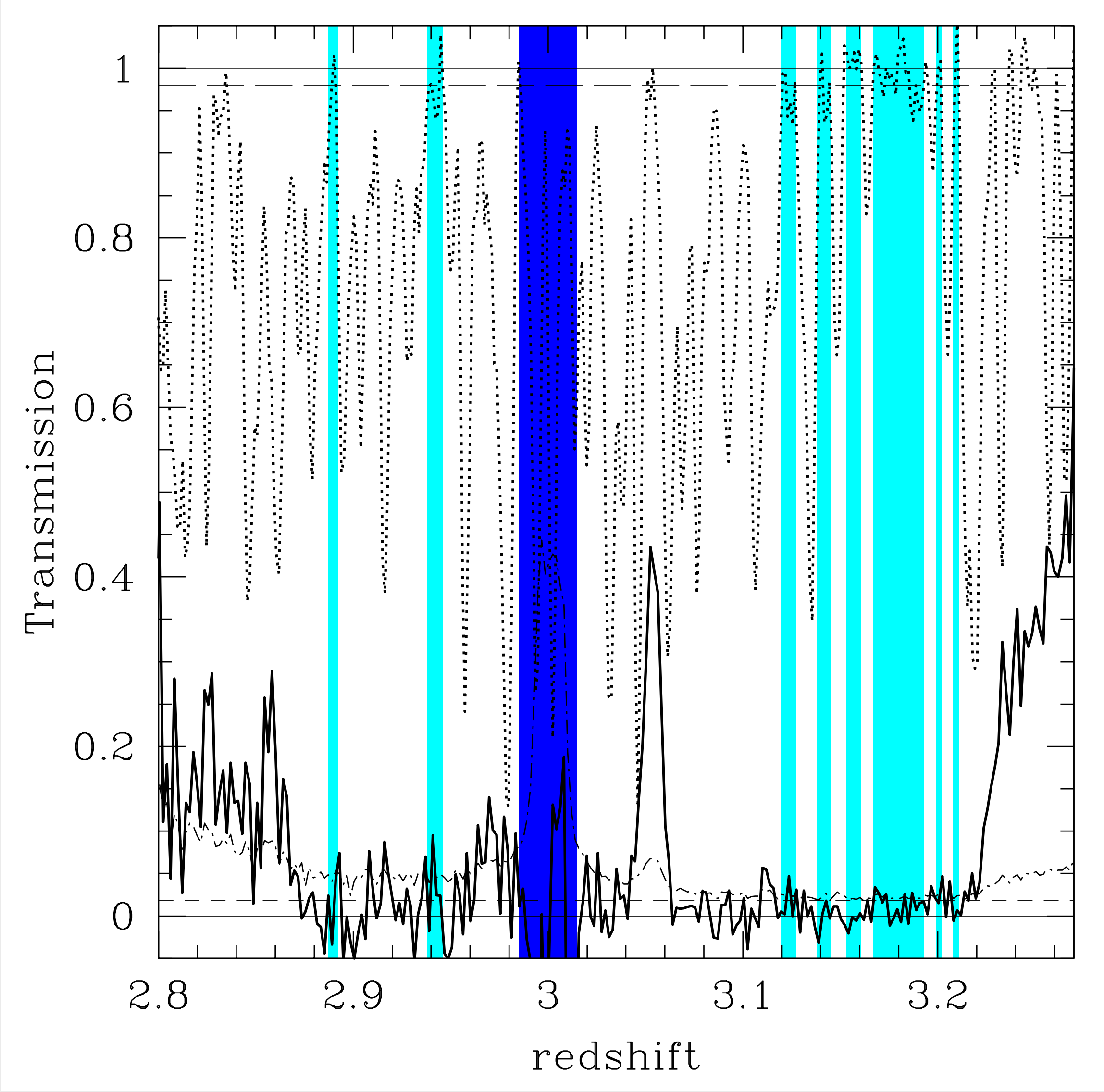
Fan et al. (2006)



Furlanetto & Dixon (2009)

He II opacity evolution

- High opacity in He II Lyα is a stronger indication of large He II fraction than high opacity in H I Lyα is of a large H I fraction
  - x14 lower abundance
  - x4 lower optical depth for a given column density
  - Voids are emptier at z~3 than at z~6
  - Can use H I Lyα to identify voids
- $x_{\mathrm{He\,II,V}} > 0.03$ in 10 Mpc patches at z~3
  - 100x stronger constraint than on H I at z~6



McQuinn (2009)

Summary of Reionization Probes

Hydrogen

- H I Lyα forest -- mean opacity
  - Saturates for tiny neutral fractions (see end of reionization only?)
- Lyα emitters
  - Transmission of Ly photons depends on both local factors and IGM
  - DM halos, galaxies evolve
- Metals
  - Sensitive to large neutral fractions
  - Only probe enriched regions
- 21 cm -- potentially powerful (future)
- Others -- Gap statistics, QSO near zone sizes

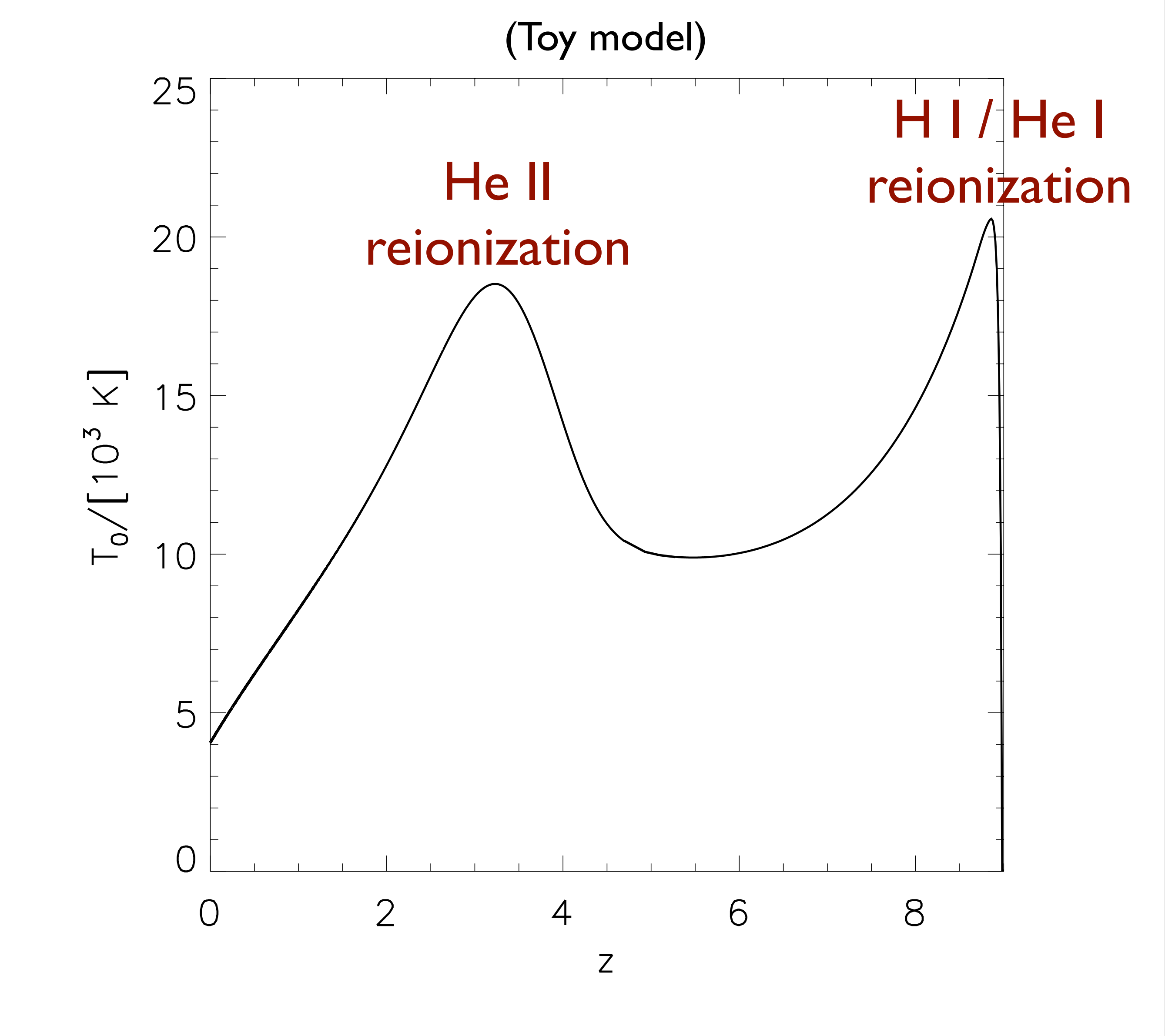
Helium

- He II Lyα forest -- mean opacity
  - Saturates for small neutral fractions (see end of reionization only)
- Metals
  - C IV / Si IV may trace hardening UVBG, but observations unclear
  - Lack of C IV at $z > 5.2$ due to He II?
  - Only probe enriched regions
- ^{3}He+ 8.7 GHz ? (Mcquinn 2009)

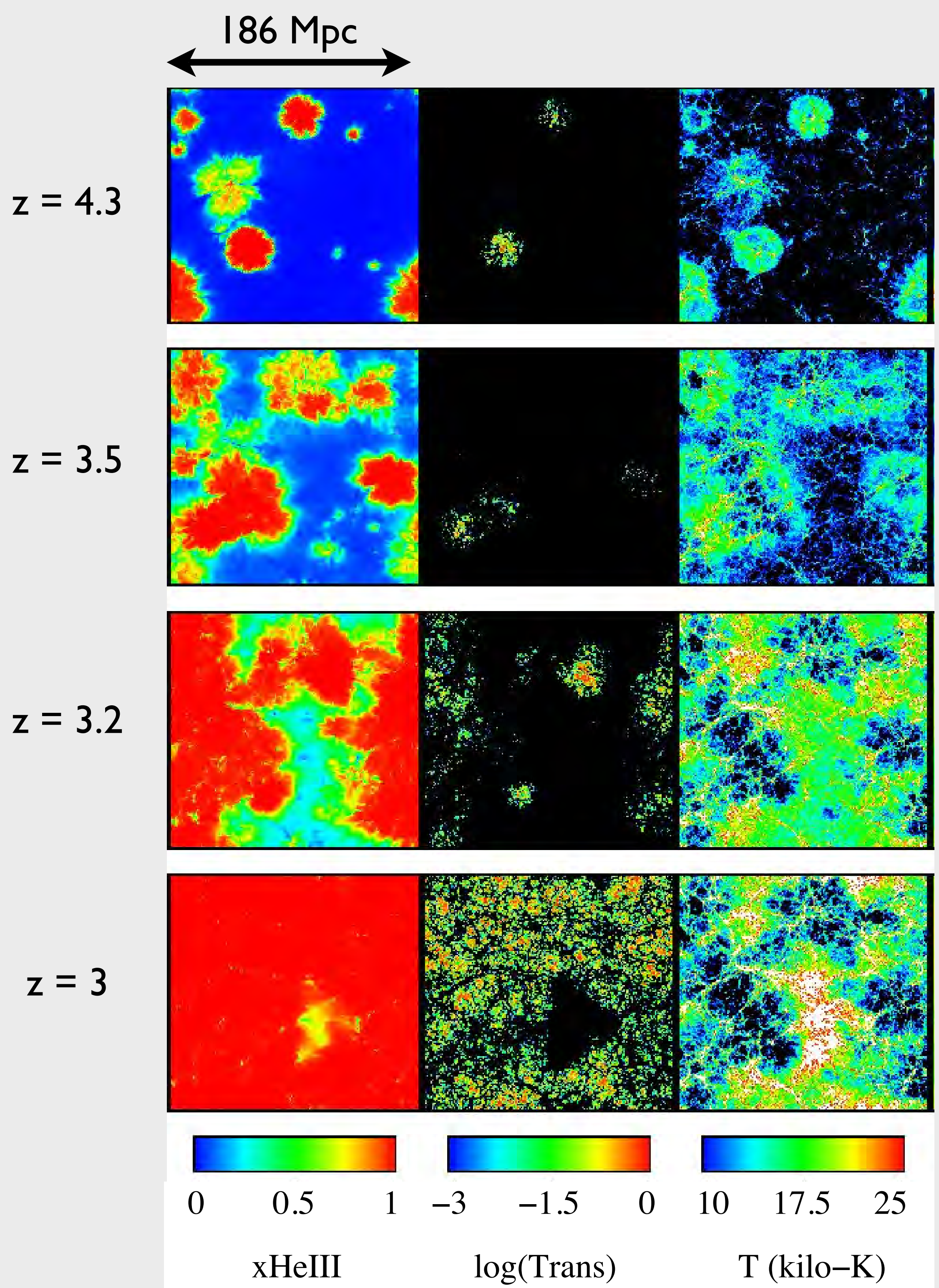
Need a probe that will allow us to study reionization *as it is happening...*

The Thermal Signature of Reionization

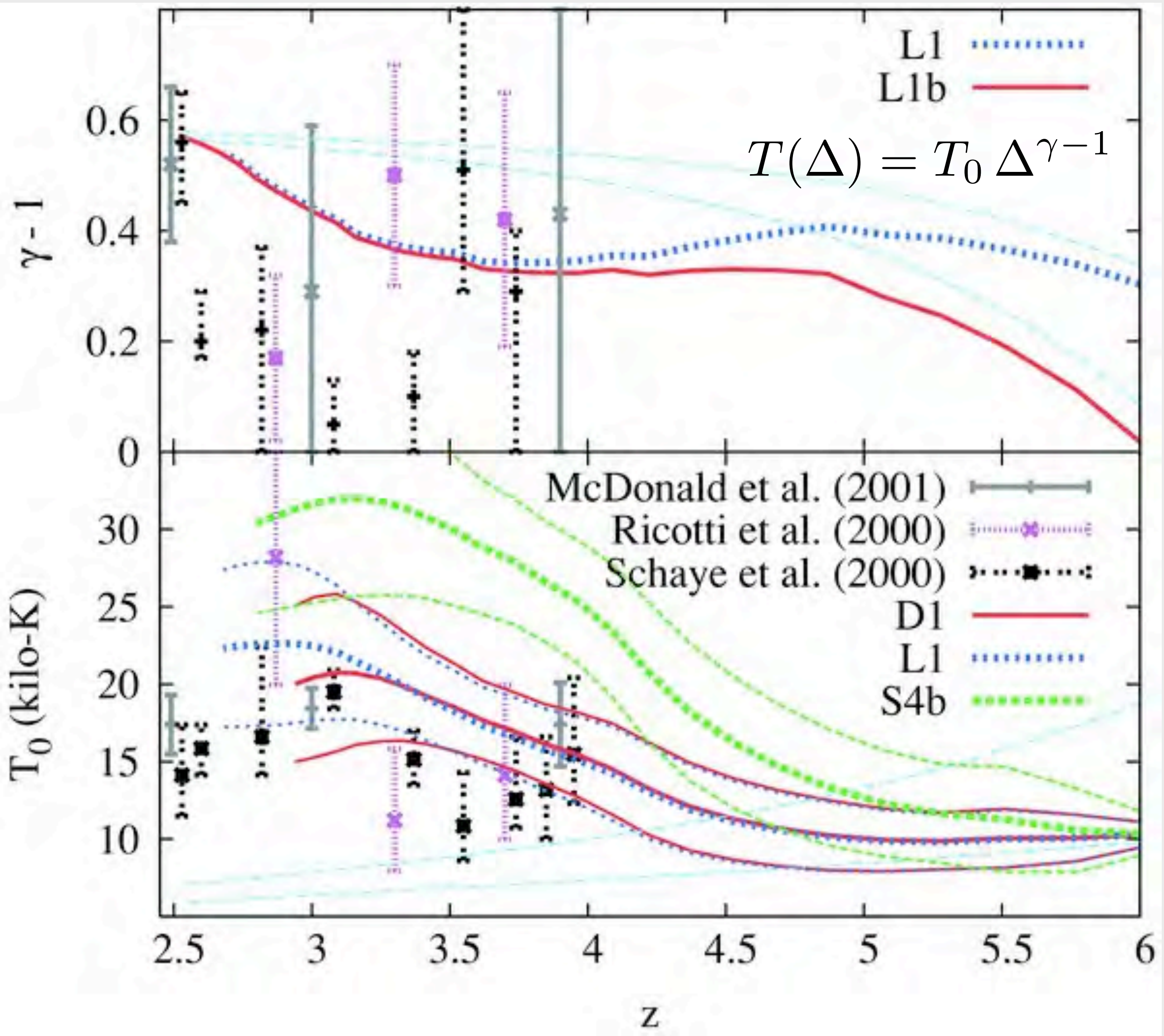
- Reionization photo-heats the gas
- Expect boosts in temperature from both H I and He II reionization, followed by rapid cool-downs due to adiabatic expansion
- T(z) sensitive to:
    - patchiness of reionization
    - spectrum of ionizing sources
    - radiative transfer effects
- One of the only ways to observing reionization *in progress*



Temperature Evolution: He II reionization



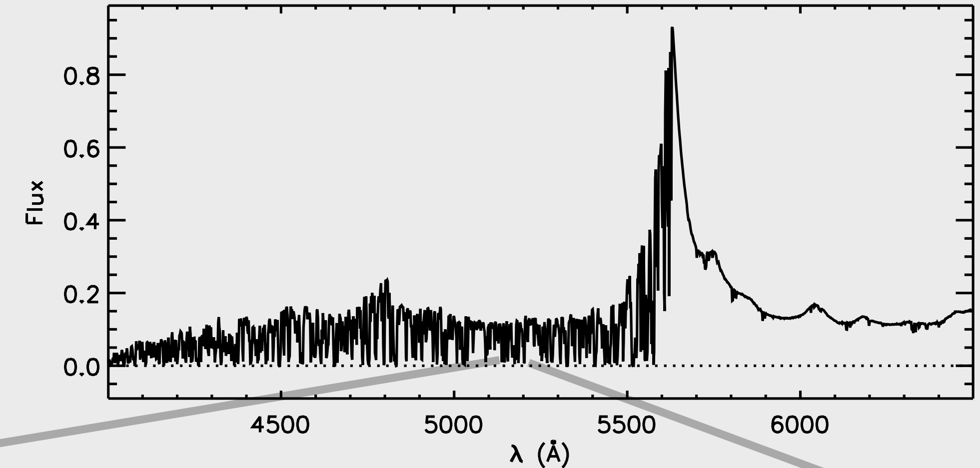
McQuinn+ (2009)



Photoionization heating ⇒ Temperature increase during He II reionization

$$\Delta T \approx 5000 - 30000\ \mathrm{K}$$

Temperatures from the Lyα forest



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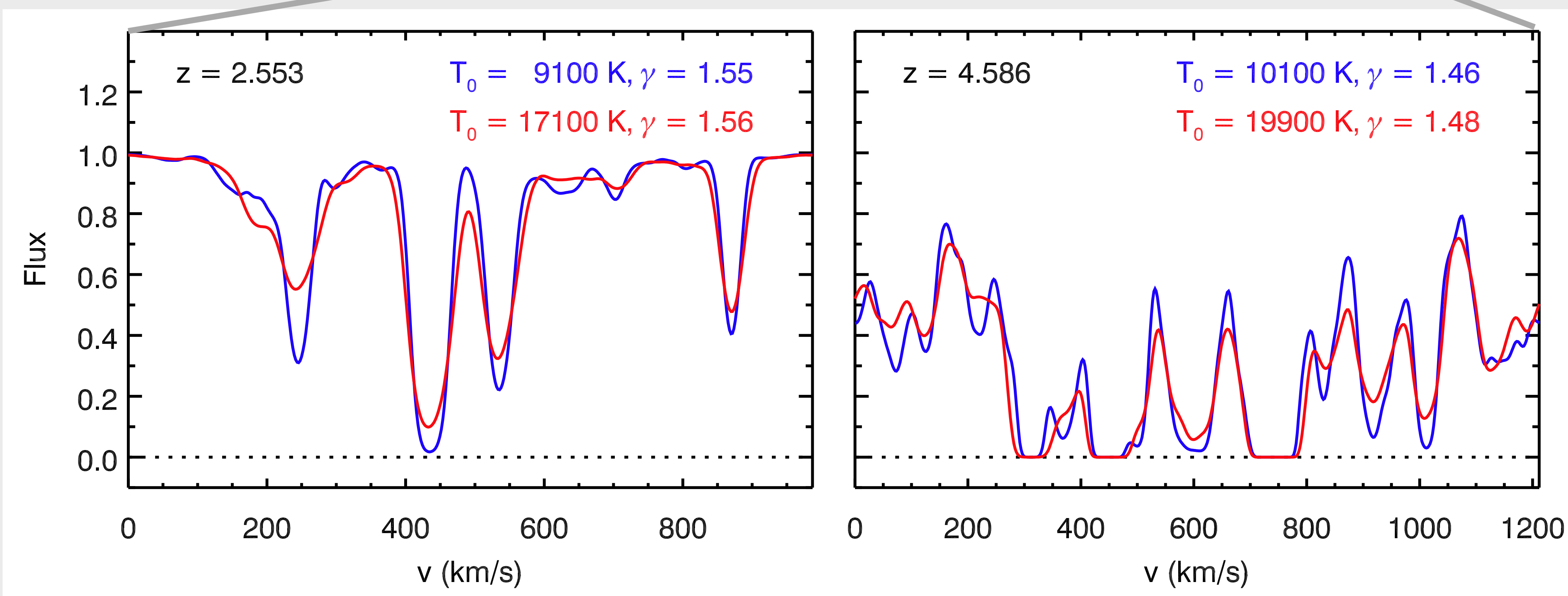
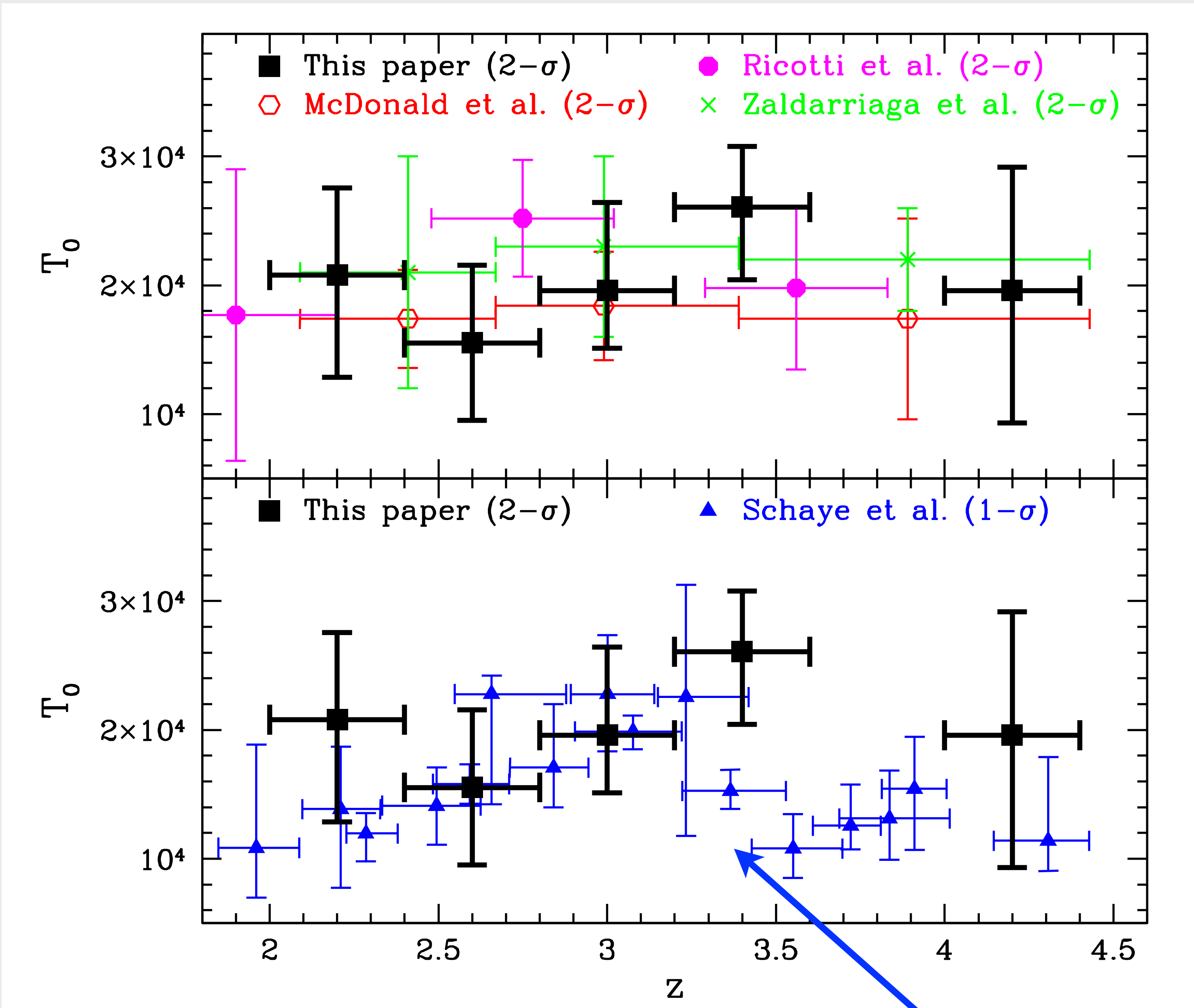
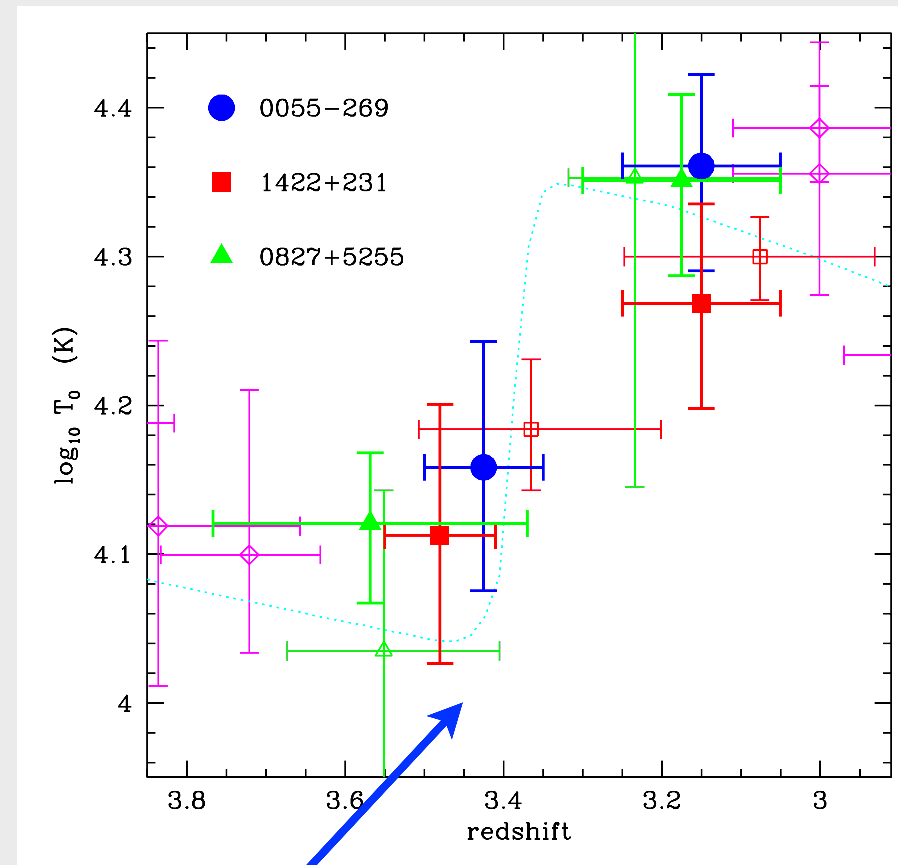


- Small-scale structure
  - Thermal Broadening
  - Jeans Smoothing
- "Classic" Analysis Methods
  - Power spectrum / Wavelets
  - Line widths

Existing Measurements



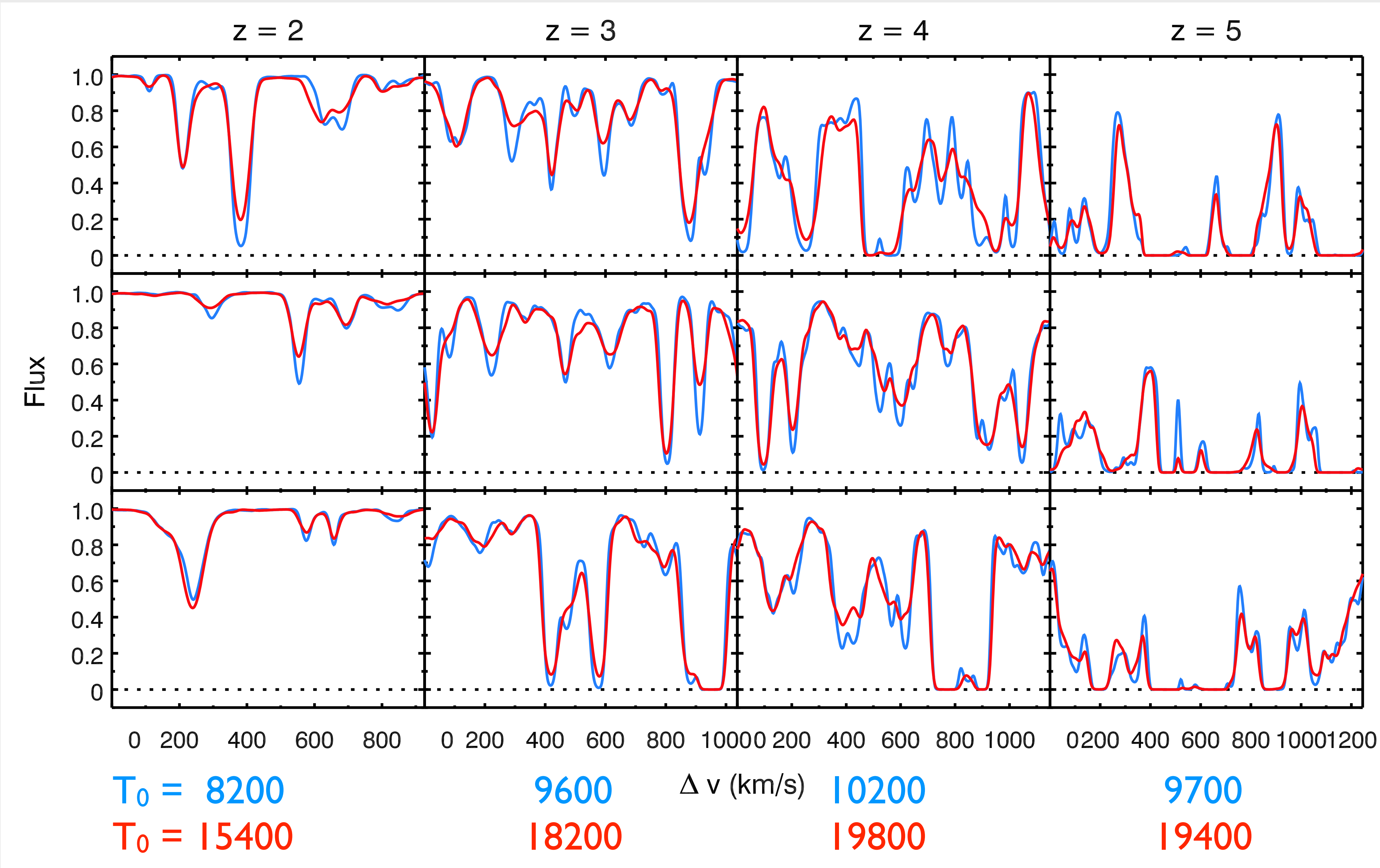
Lidz et al (2009)

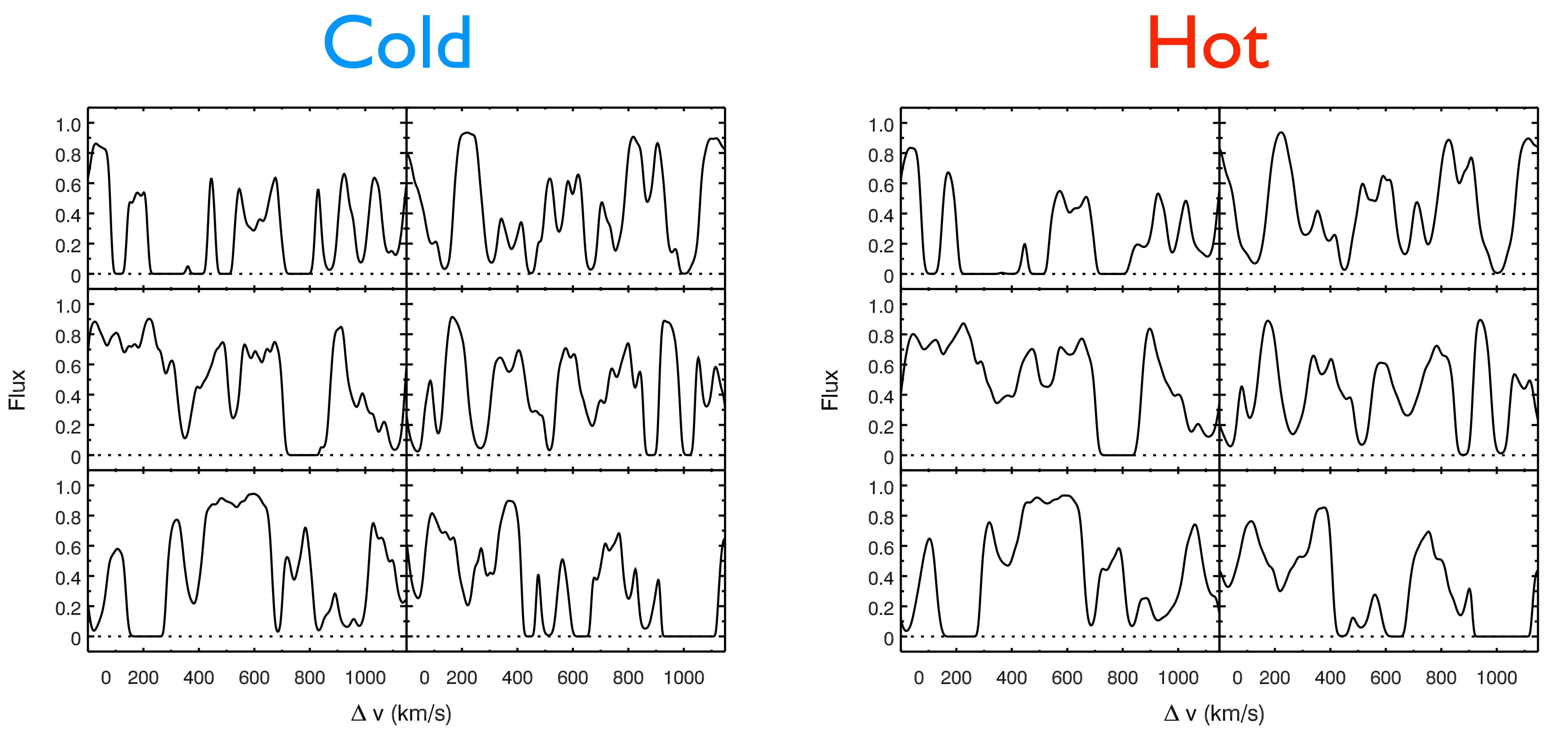


Theuns et al. (2002)

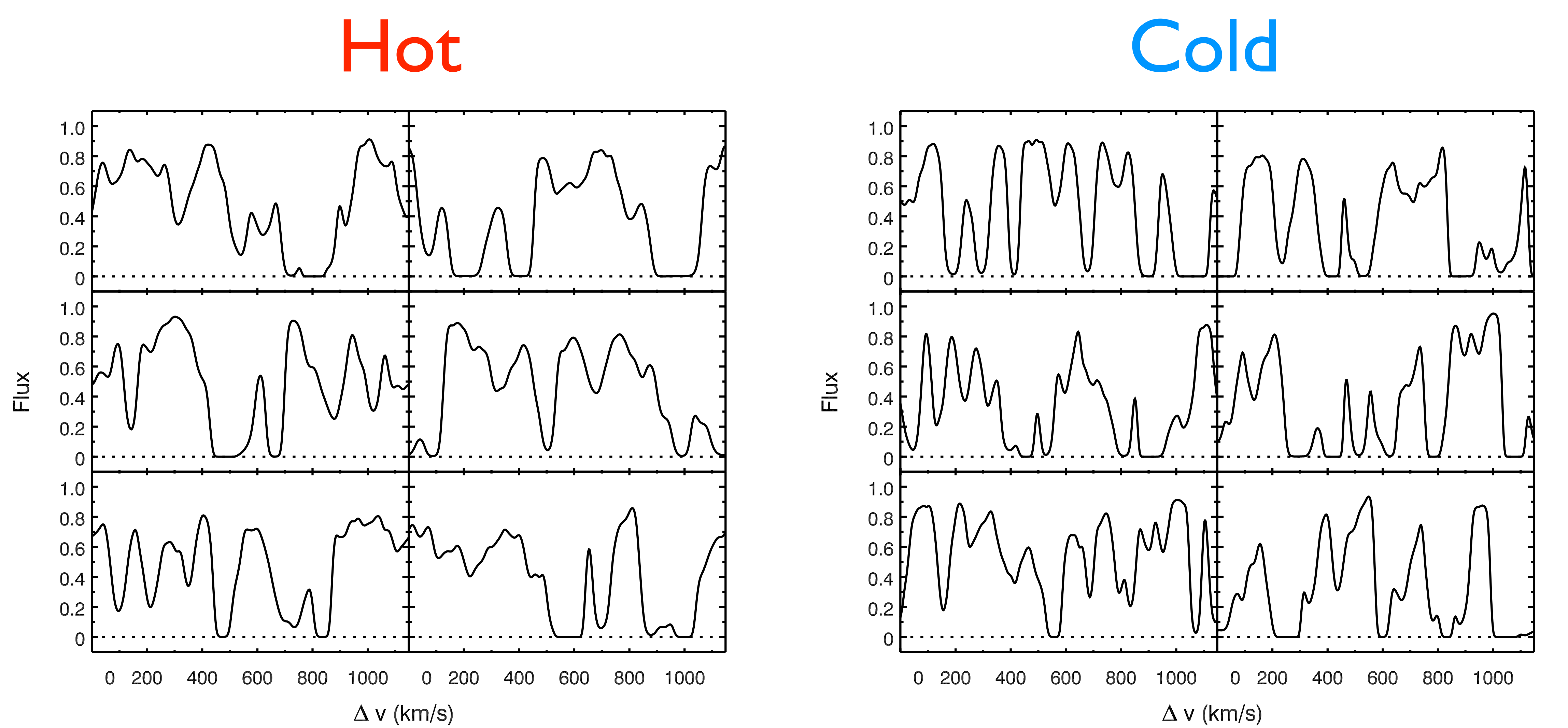
Possible bump?

Temperatures by eye

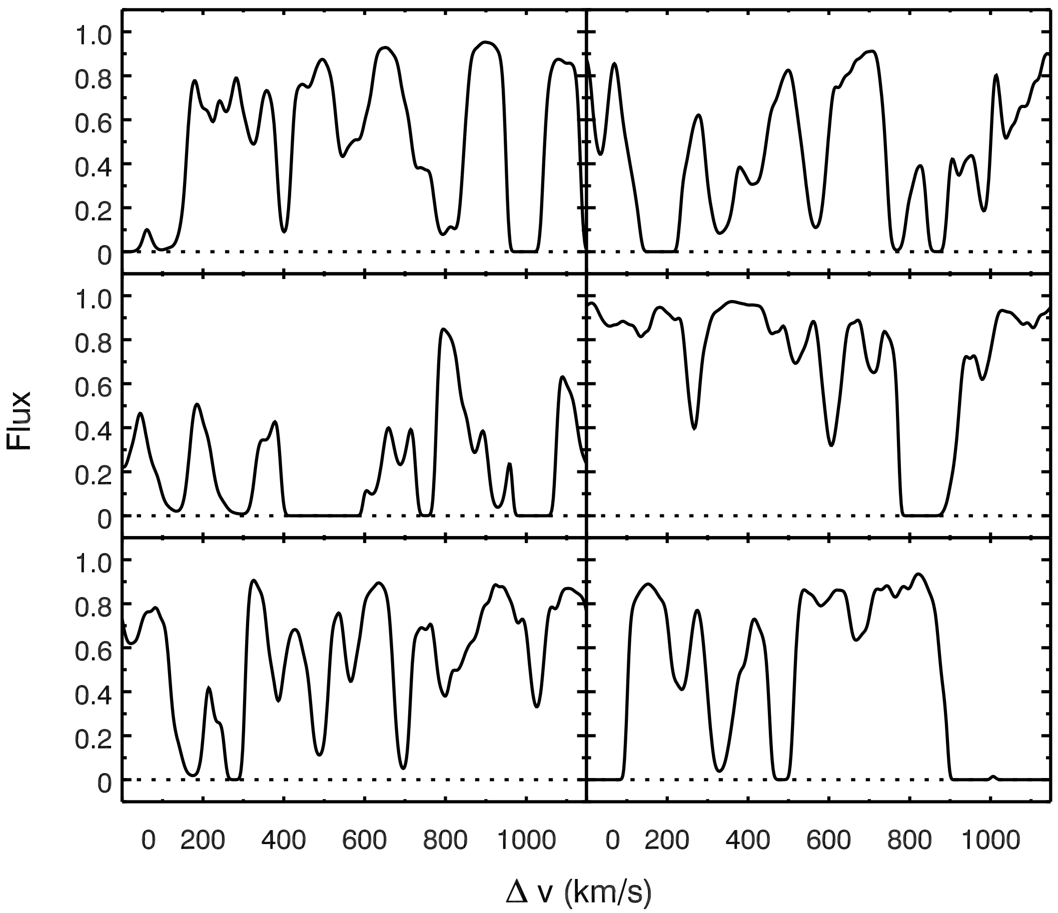




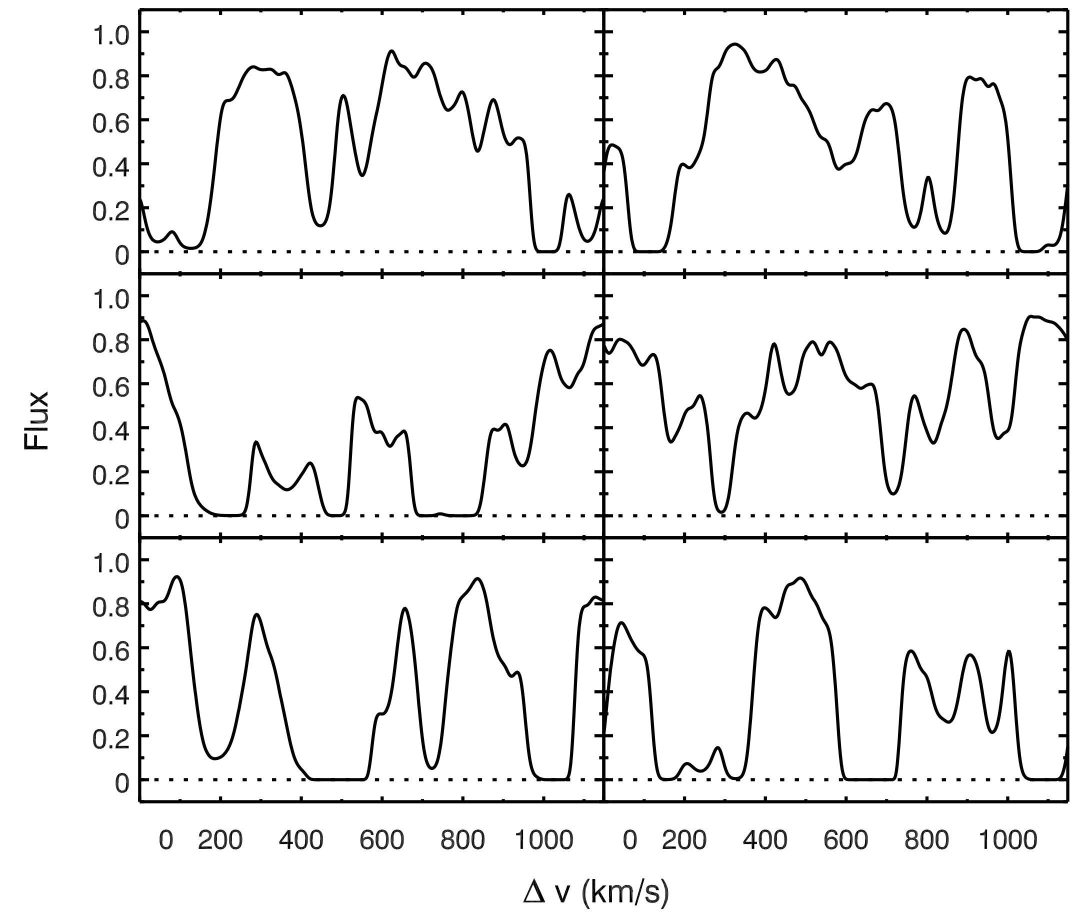
Cold
Hot
Flux
1.0
0.8
0.6
0.4
0.2
0
0 200 400 600 800 1000
Δ v (km/s)


Hot
Cold
Flux
1.0
0.8
0.6
0.4
0.2
0
0 200 400 600 800 1000
Δ v (km/s)

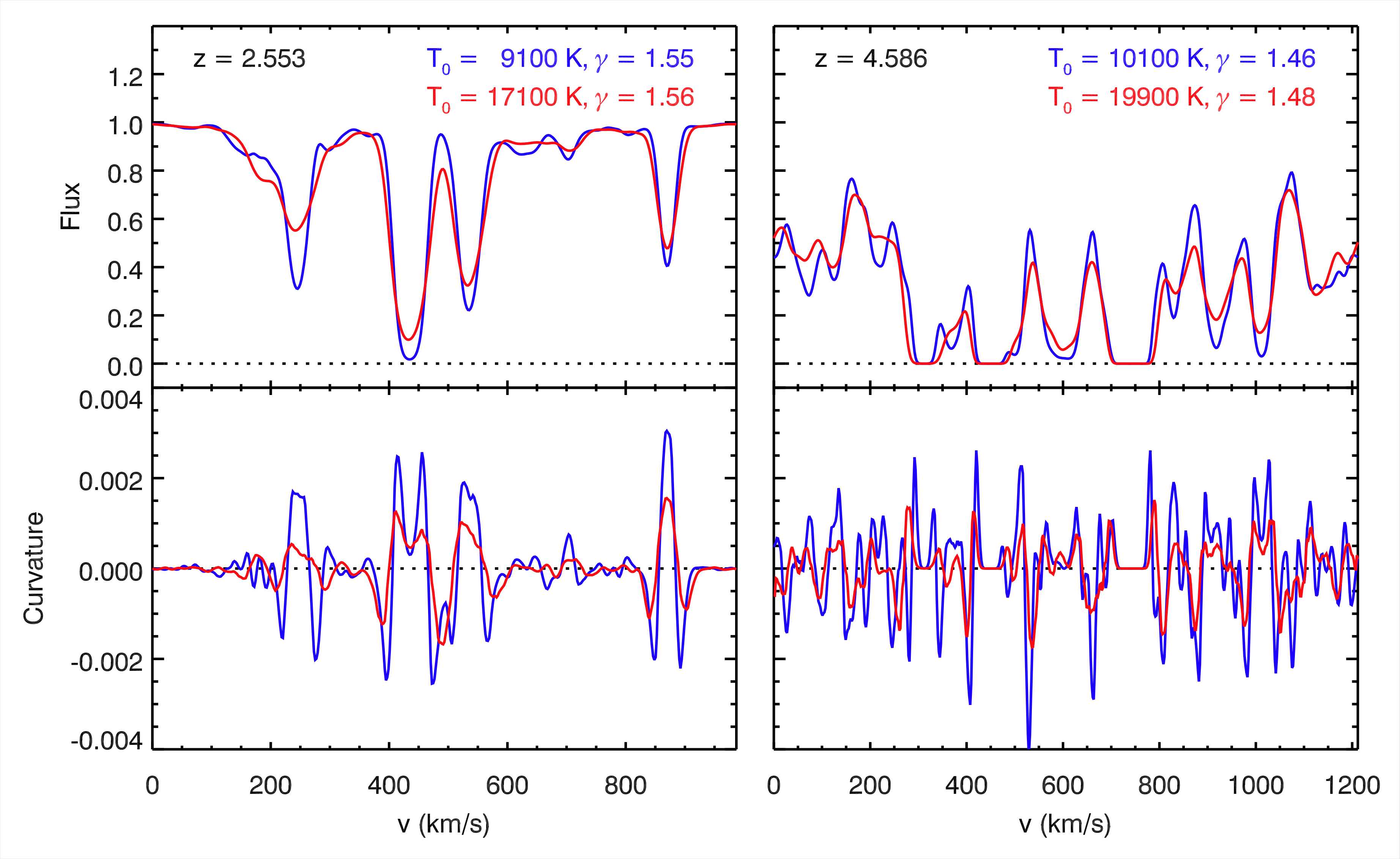
Cold


Flux
1.0
0.8
0.6
0.4
0.2
0
0 200 400 600 800 1000
Δ v (km/s)

Hot


Flux
1.0
0.8
0.6
0.4
0.2
0
0 200 400 600 800 1000
Δ v (km/s)

Curvature

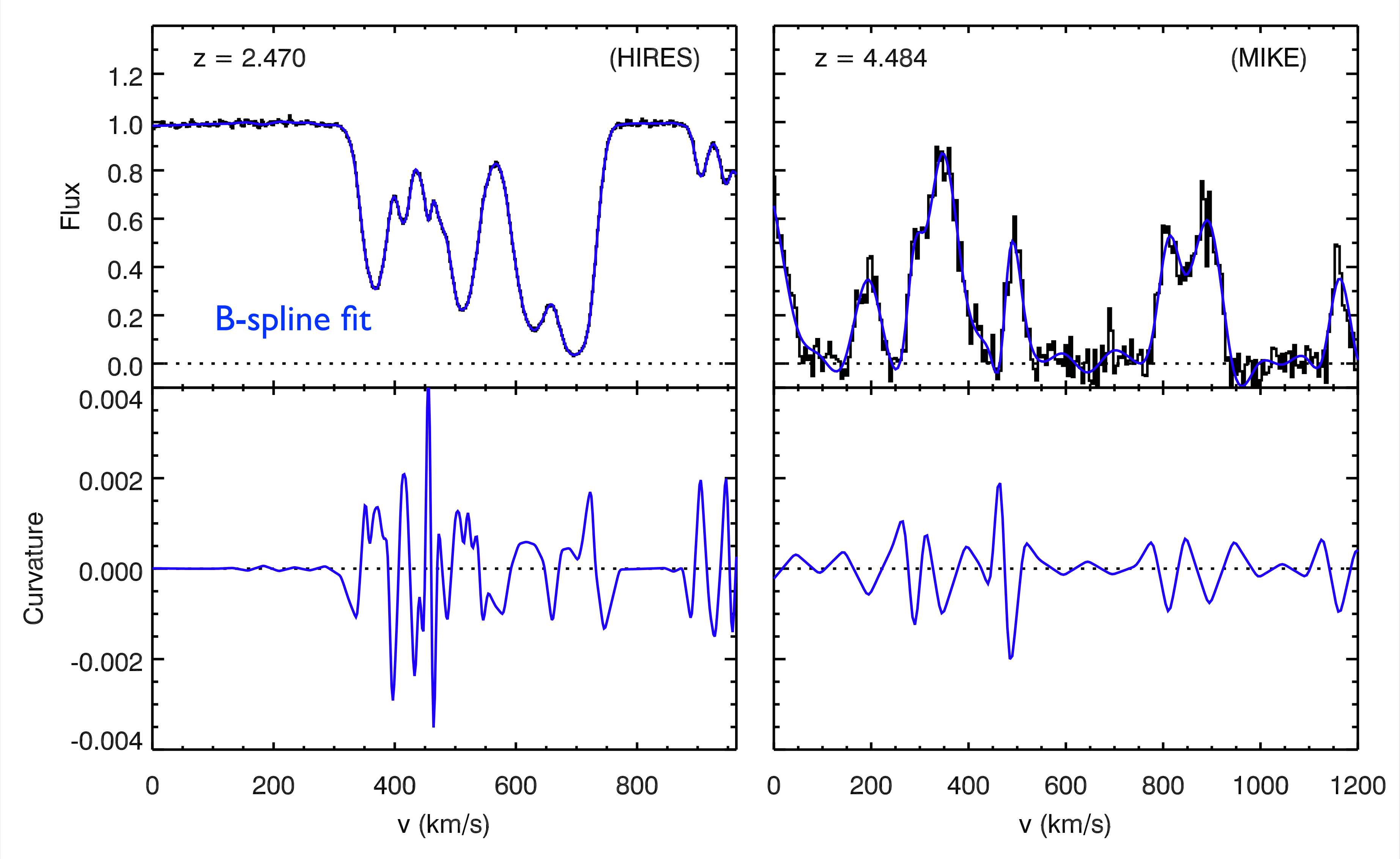


$$\text{Curvature} = \frac{F''}{[1 + (F')^2]^{3/2}}$$

Higher curvature = Colder

Measuring Curvature in the data

b-spline fits

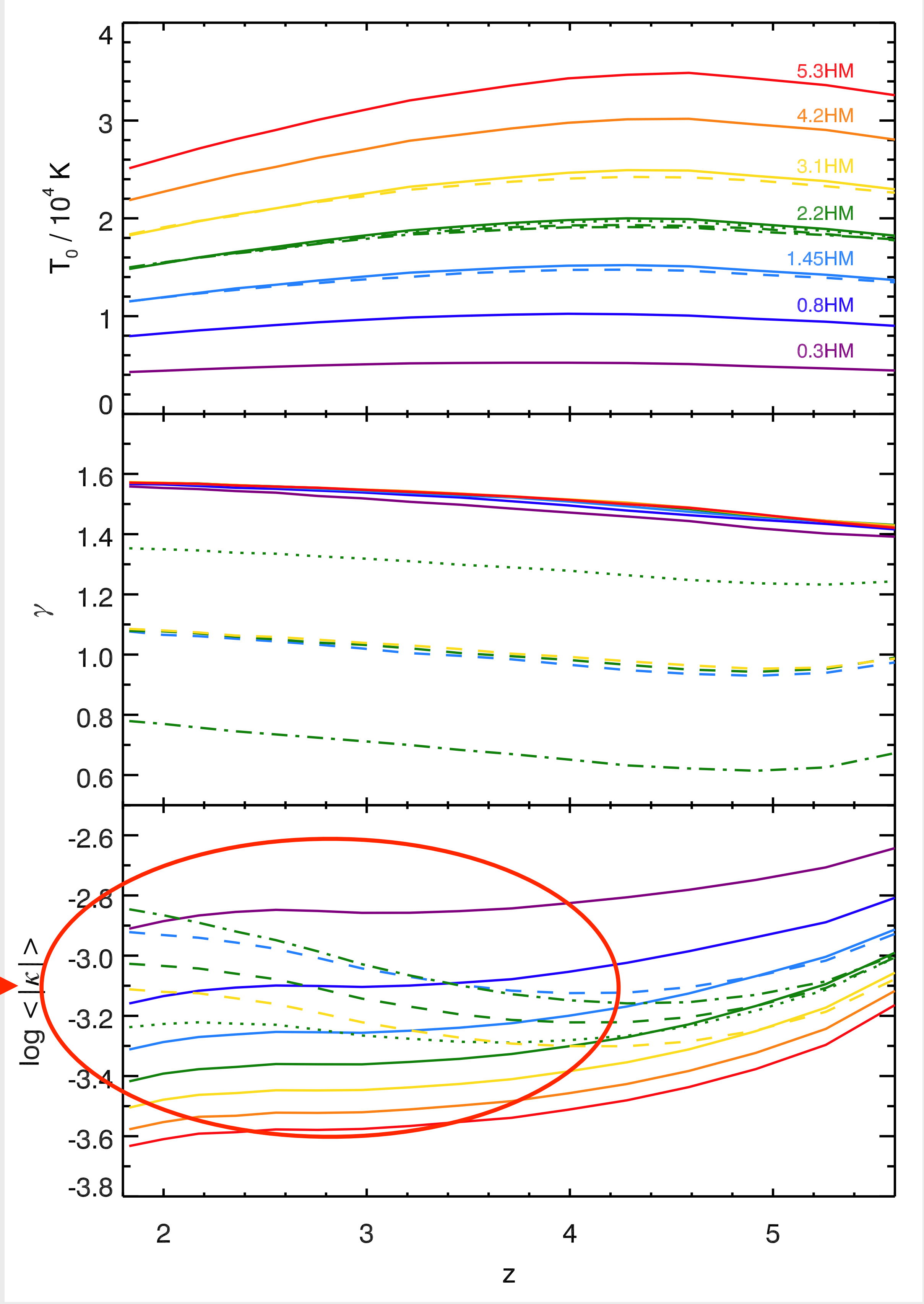


- 64 high-resolution (R=22000-40000) QSO spectra
  - Keck/HIRES & Magellan/MIKE
  - $2 < z_{QSO} < 6.4$

The simulations

- Large grid of thermal histories
- Grid in T_0 and γ
    - $T(\Delta) = T_0\,\Delta^{\gamma-1}$
- Very high resolution
    - 10 Mpc box, $m_{gas} = 10^5\ M_{sol}$
    - Needed for z > 4 Lyα forest

Curvature depends on T_0 and γ



Temperature-density relation

Adiabatic heating/cooling creates a powerlaw T-Δ relation in the IGM:

$$T(\Delta) = T_0\,\Delta^{\gamma-1}$$

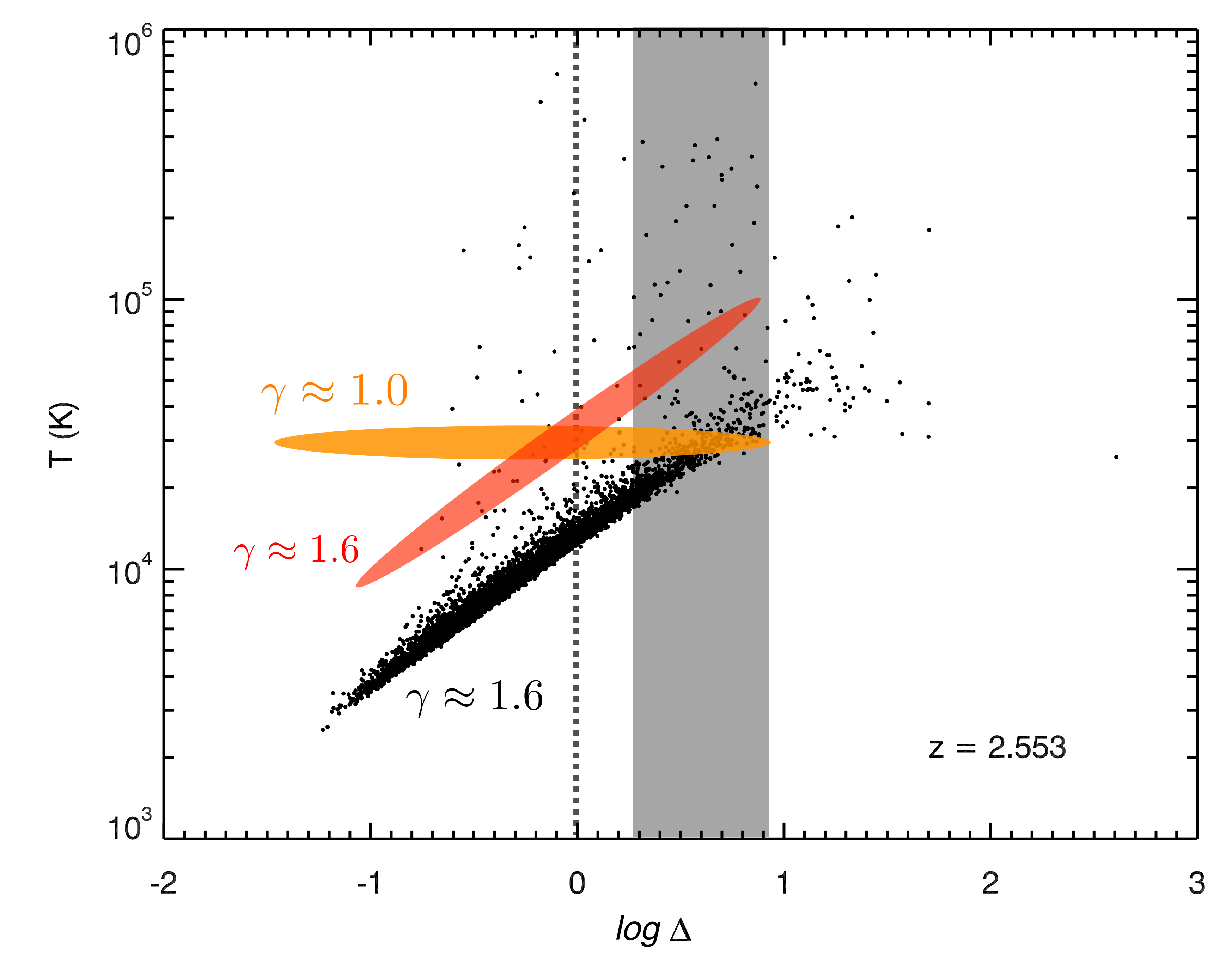
Overdensity:

$$\Delta \equiv \frac{\rho}{\langle\rho\rangle}$$

Temperature at the mean density:

$$T_0 \equiv T(\Delta = 1)$$

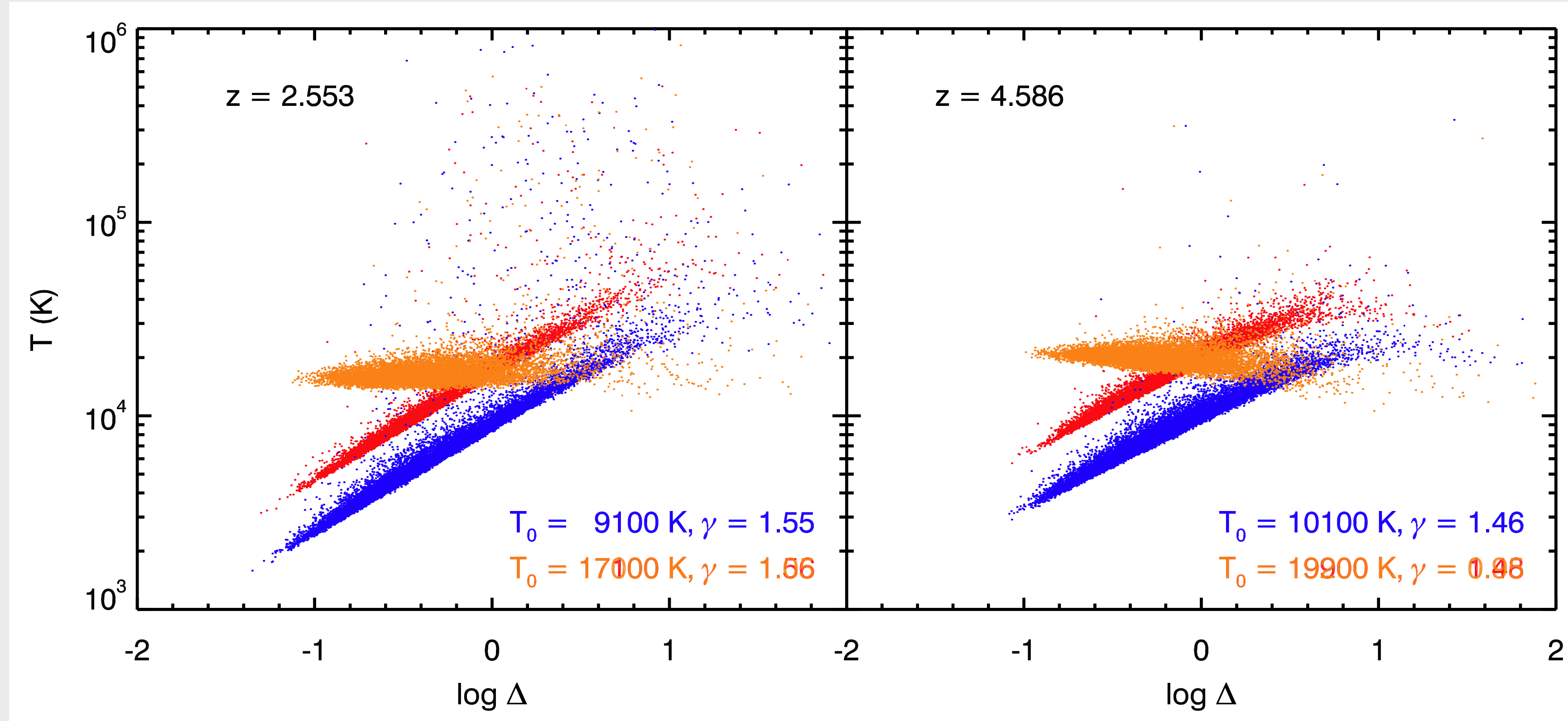
(Hui & Gnedin 1997)

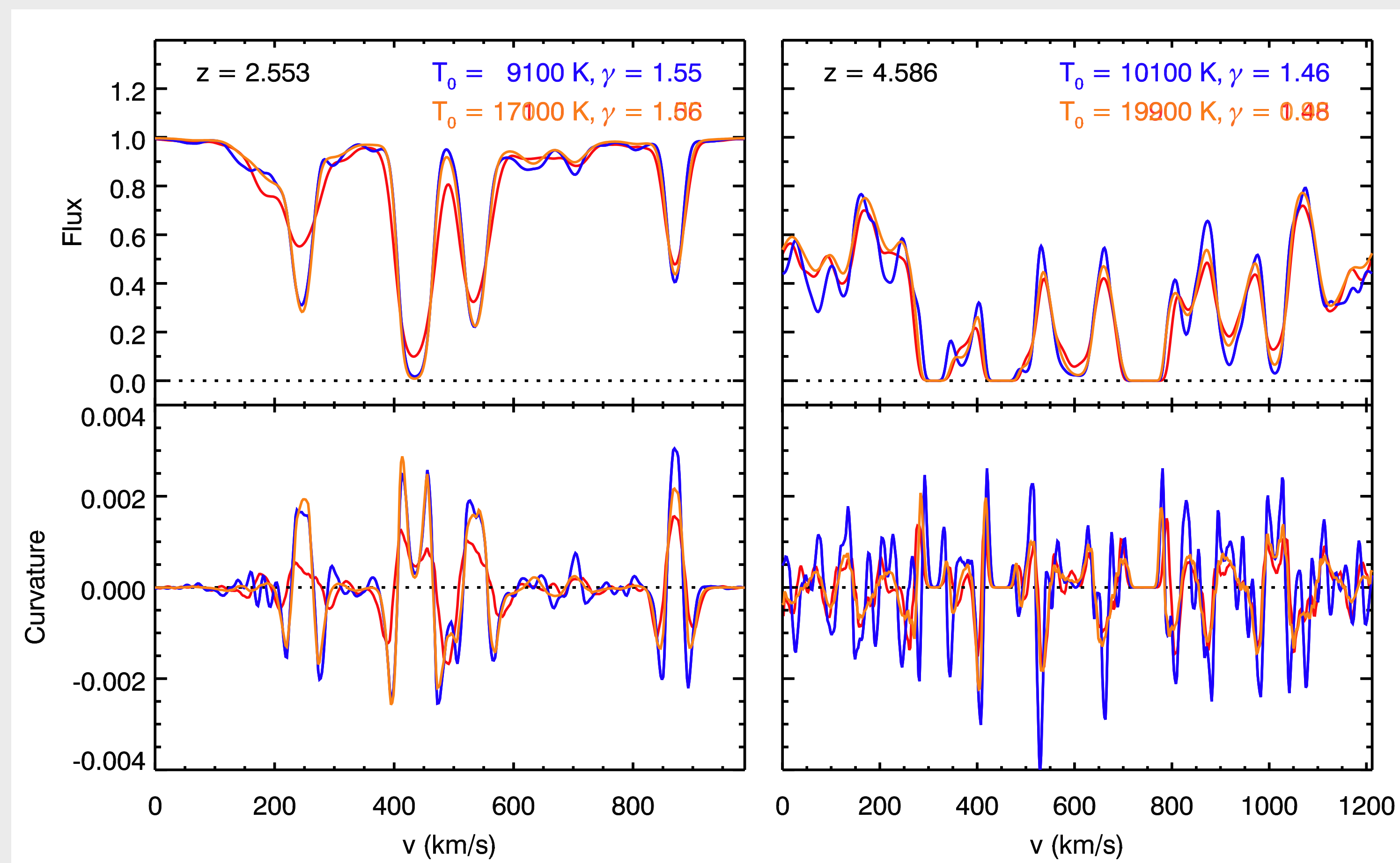


best to normalize T(Δ) near the Δ that dominates your signal

Lyα forest “sees” a limited density range

$$T(\Delta) = T_0\,\Delta^{\gamma-1}$$





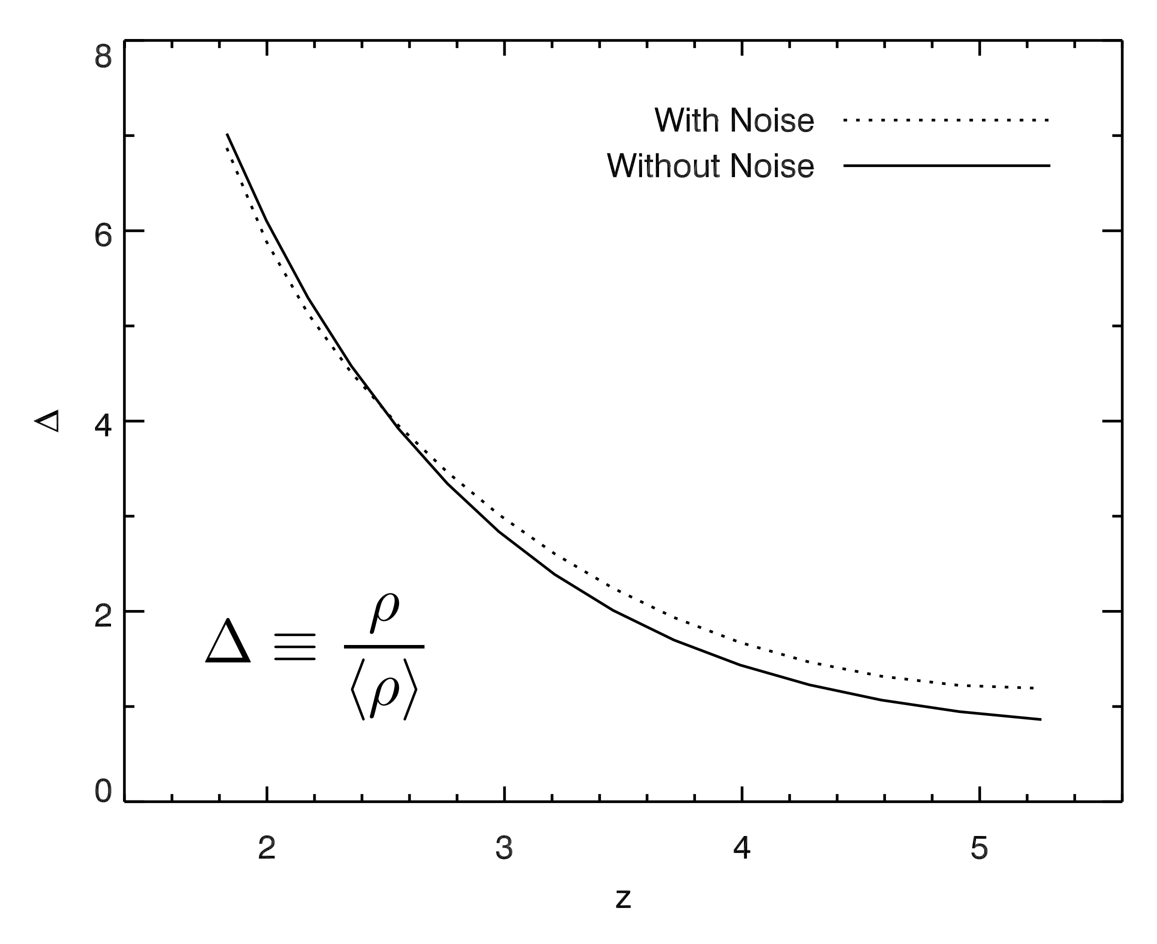
Densities probed by the Lyα forest

- Forest is most sensitive to overdensities (Δ) that produce $\tau \sim 1$
- Strong redshift evolution

$$\tau_{\mathrm{Ly}\alpha}(\Delta) \propto H^{-1}(z)\, n_{\mathrm{H\,I}}$$
$$\propto (1+z)^{4.5}\,\Gamma^{-1}\,T_0^{0.7}\,\Delta^{2-0.7(\gamma-1)}$$

$$\longrightarrow \quad \Delta \propto (1+z)^{-2.8}\Gamma^{0.6}\,T_0^{0.4}$$

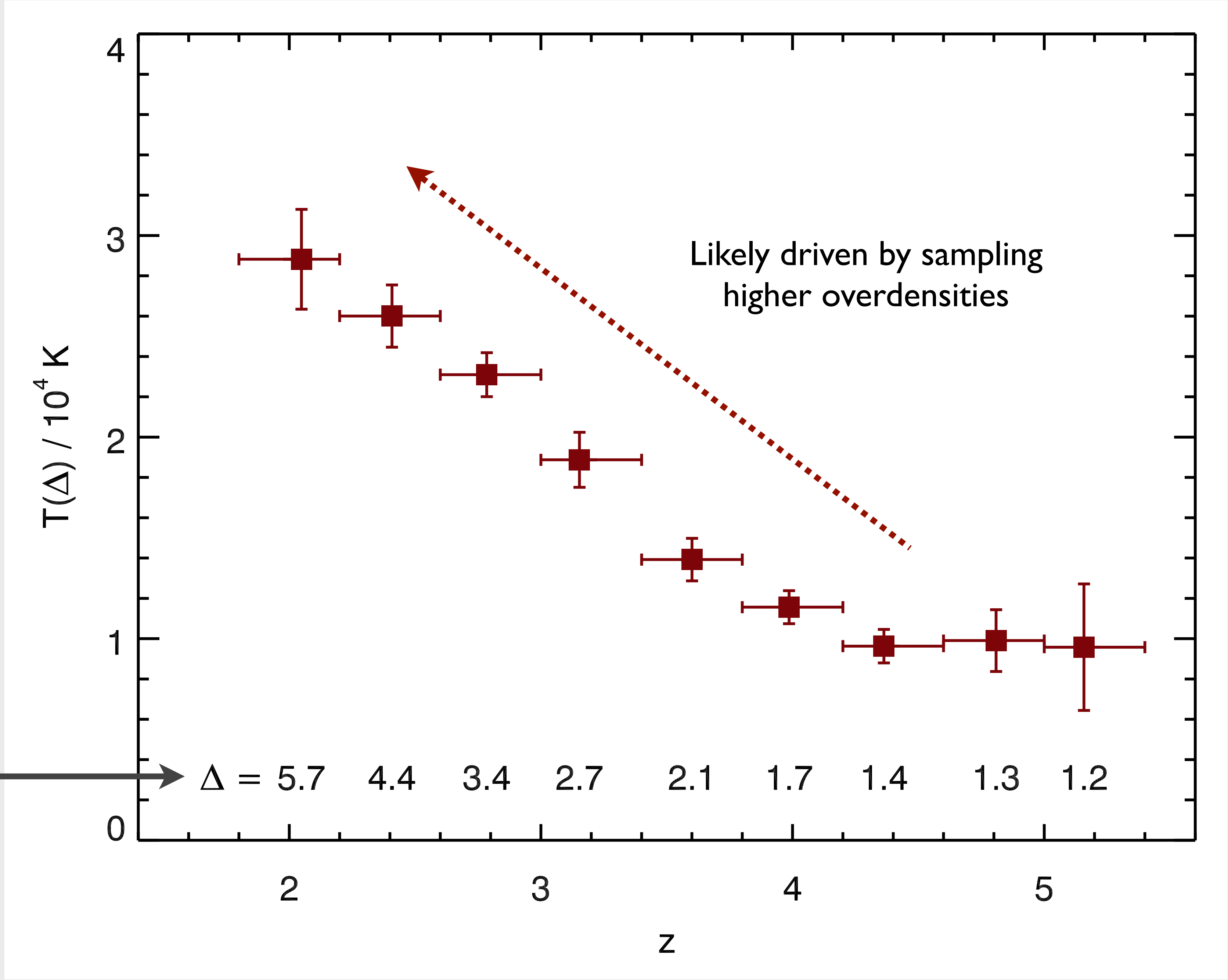
- Probe higher Δ at lower redshift



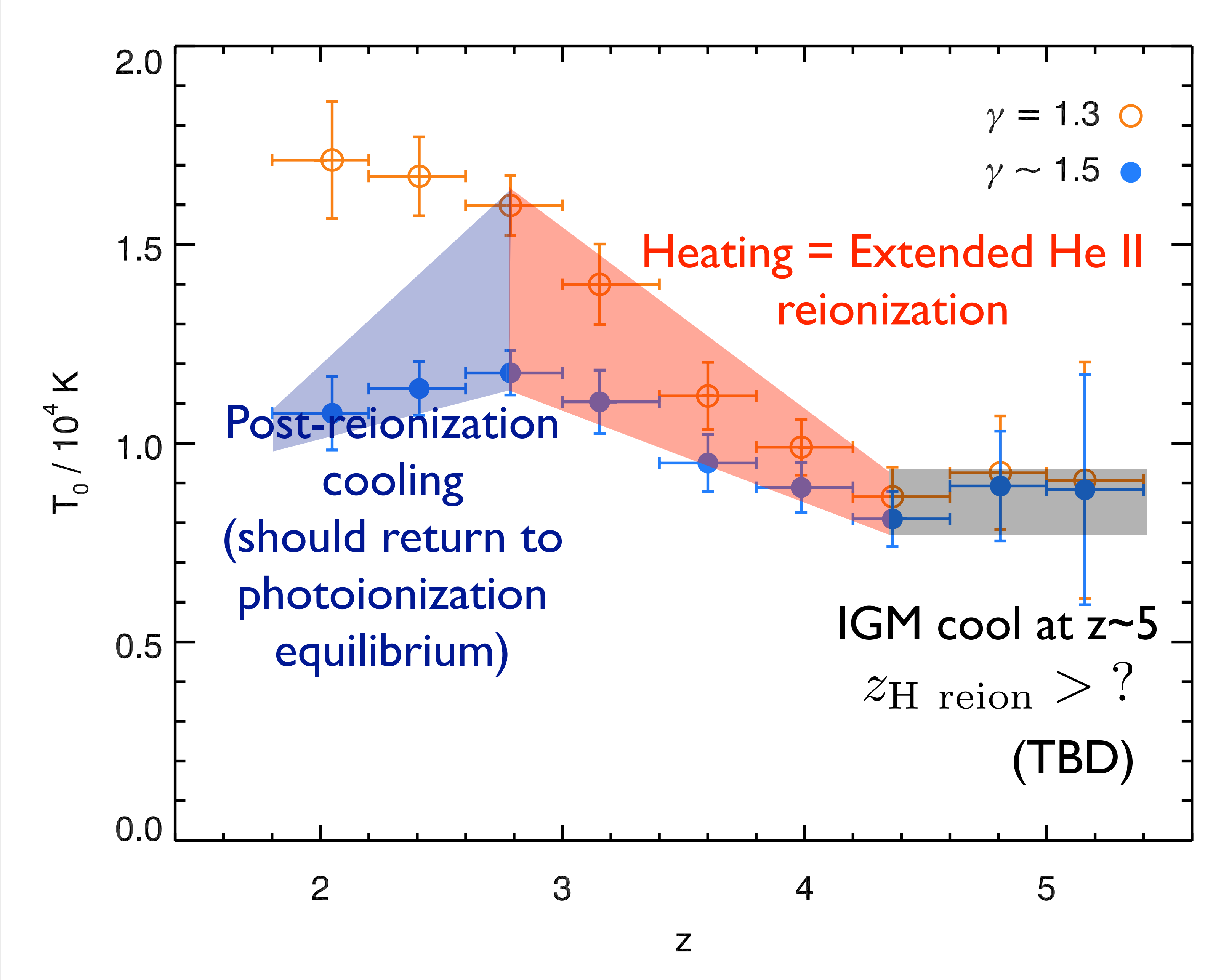
Temperature results - T(Δ)

64 QSOs
$2 < z_Q < 6.4$

optimal overdensity

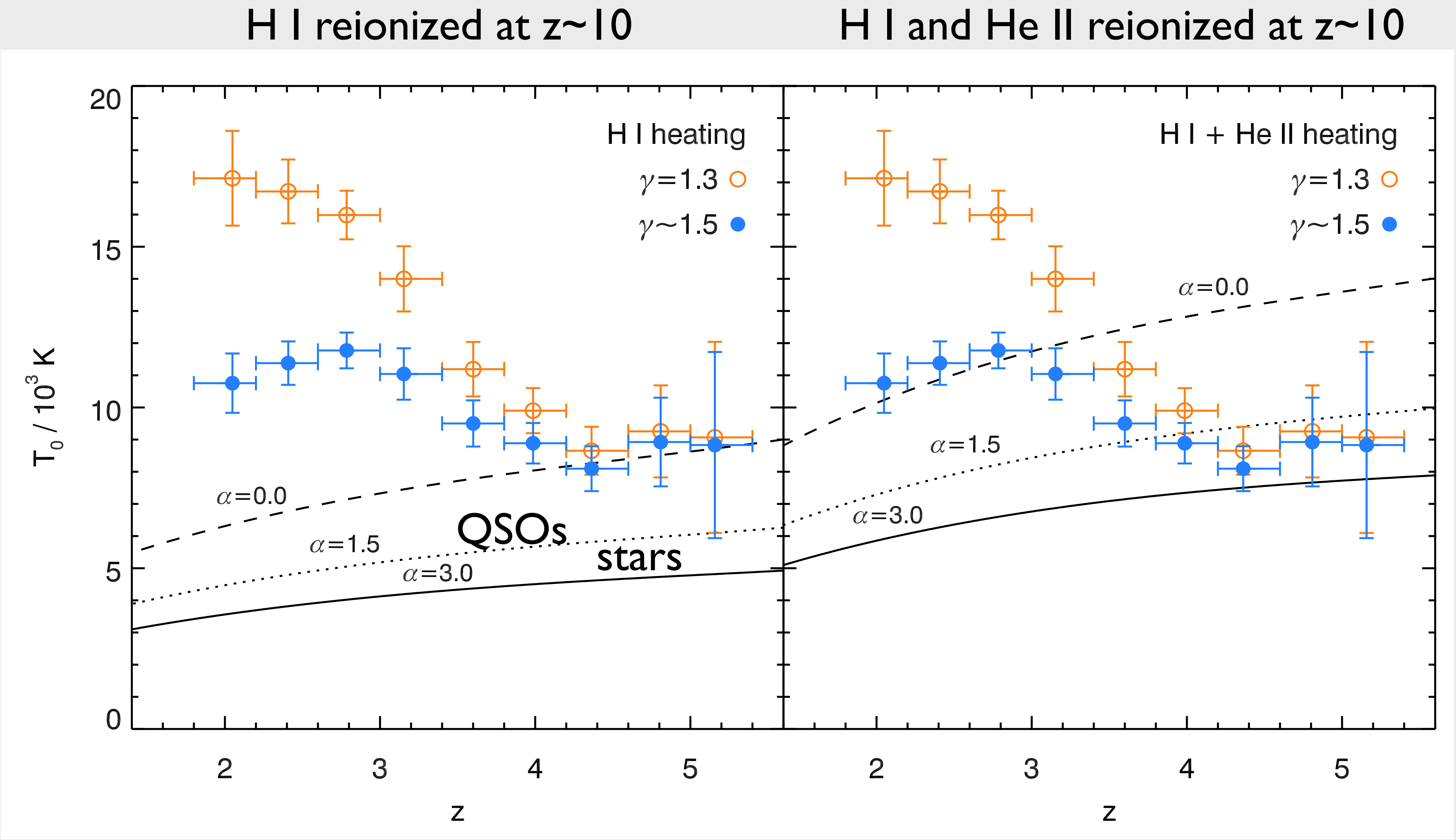


Temperature results - T_0



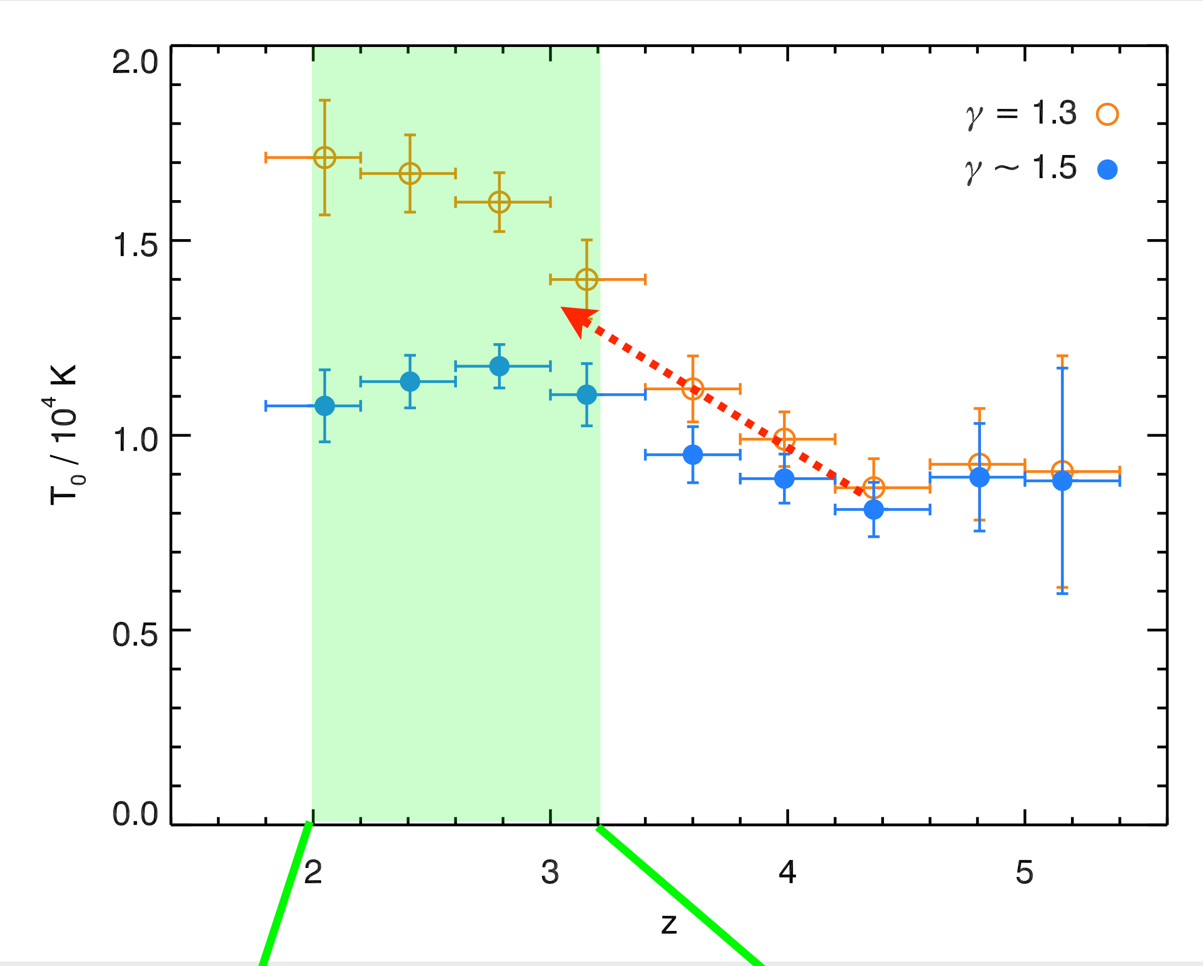
$\gamma \sim 1.5$	Maximum in photoionization equilibrium
$\gamma = 1.3$	Minimum suggested by simulations of He II reionization (McQuinn et al. 09)

He II reionization required

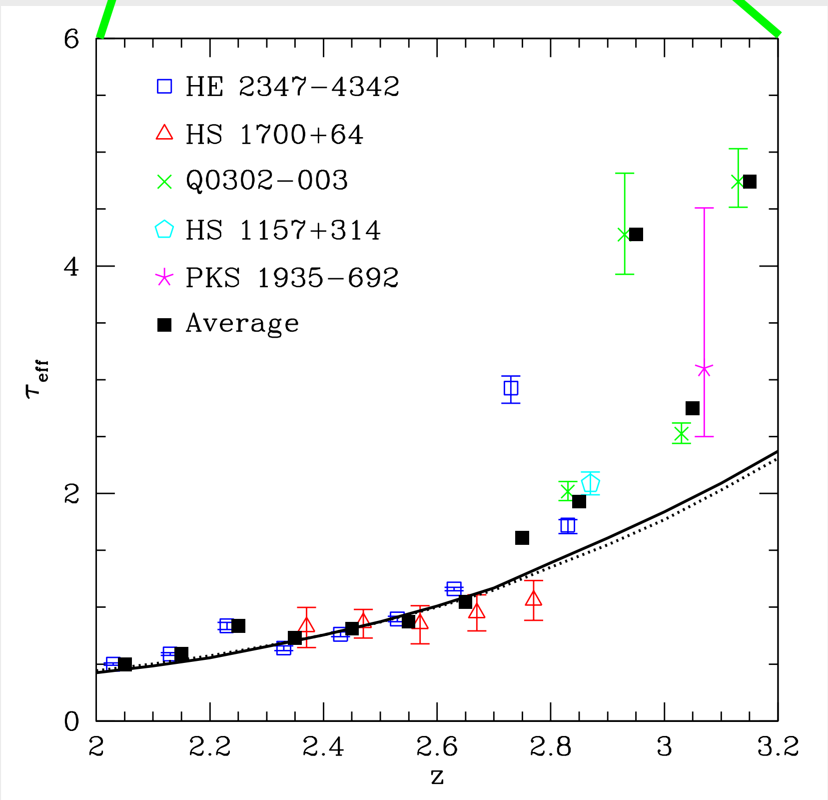


Post-reionization: T0 will depend on the spectral shape of the ionizing background, $J_\nu \propto \nu^{-\alpha}$

Putting together τ_{eff} and T_0

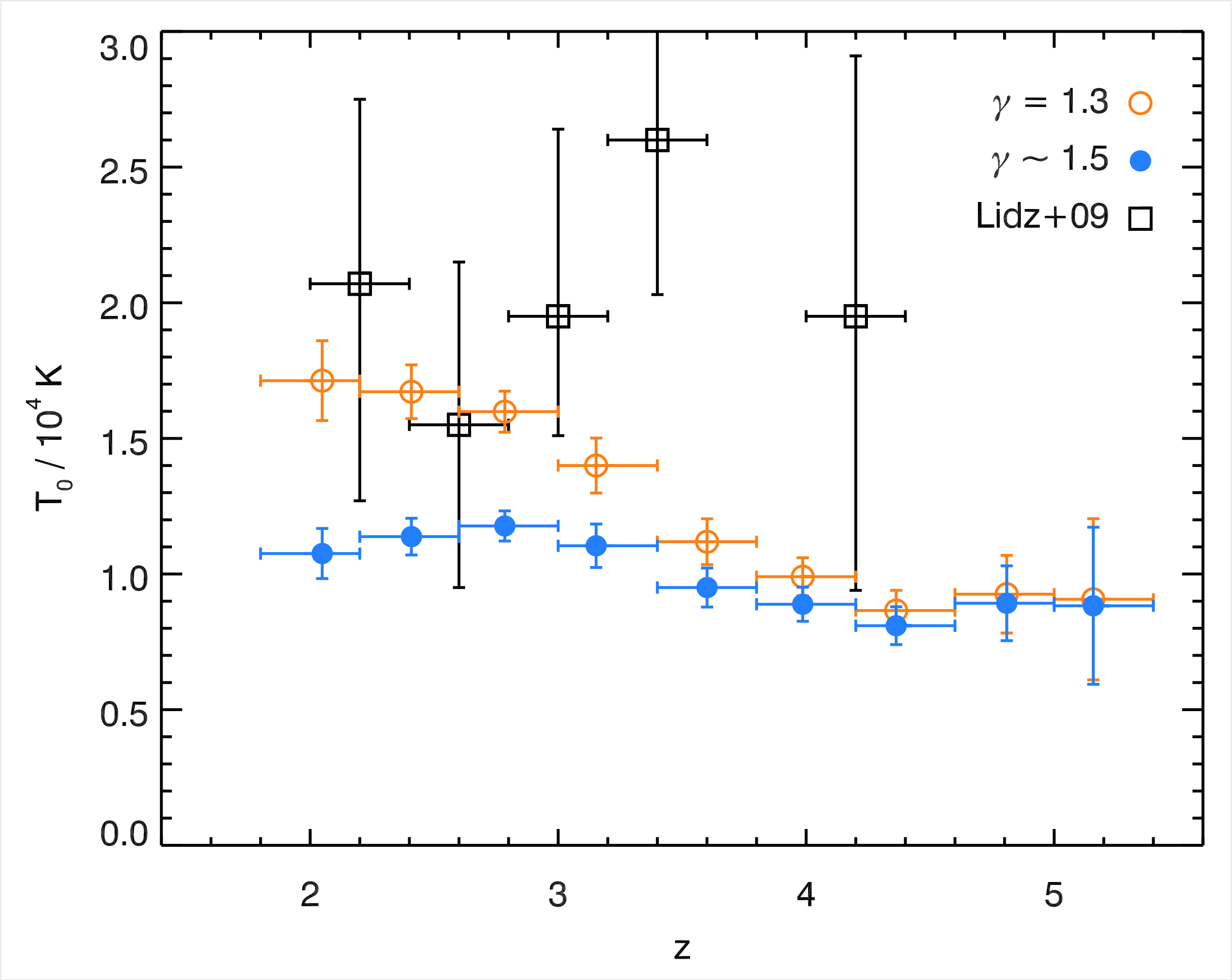


T_0 increases during reionization

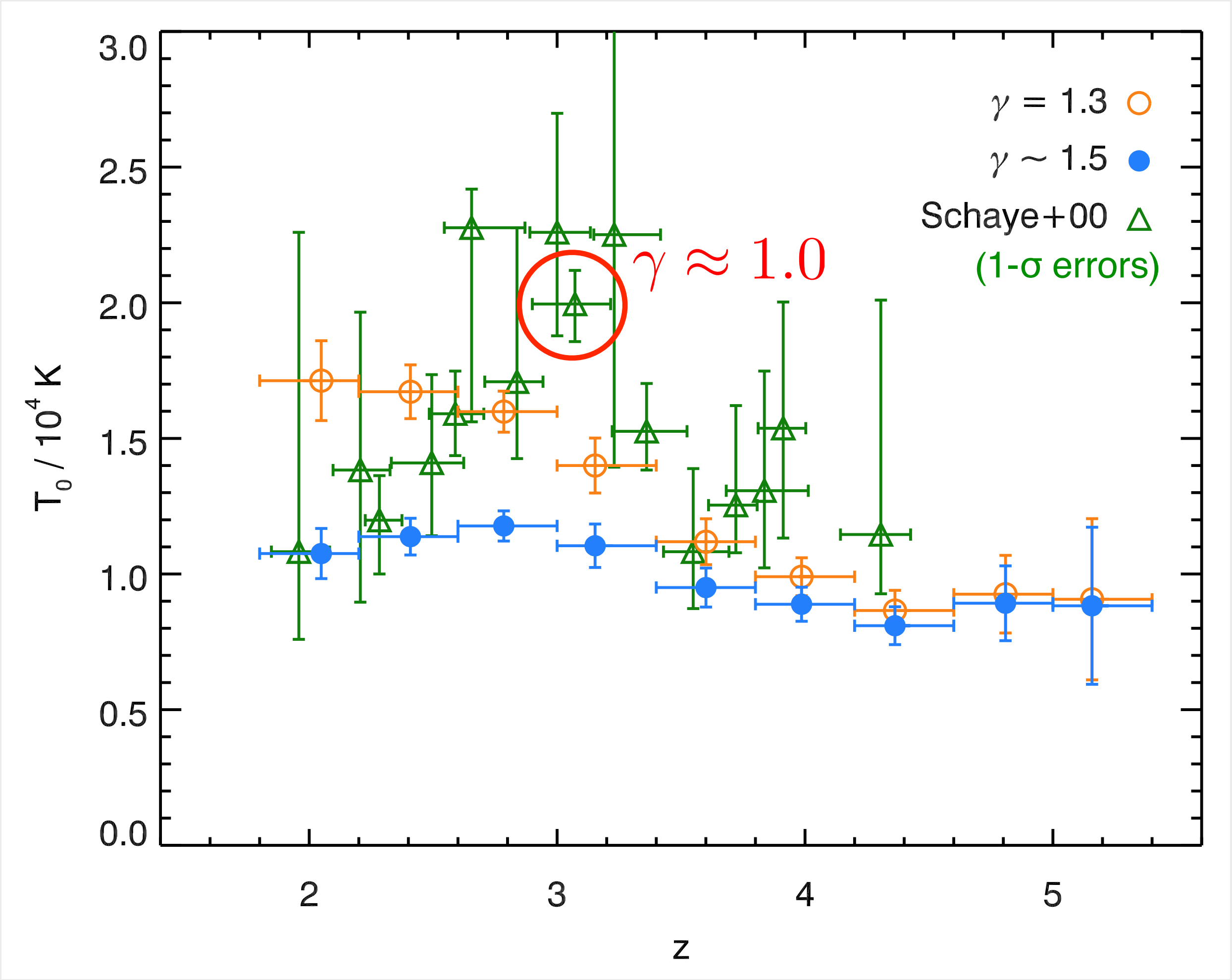


Following reionization, the He II Lyα forest becomes transparent

Curvature vs. Other Methods



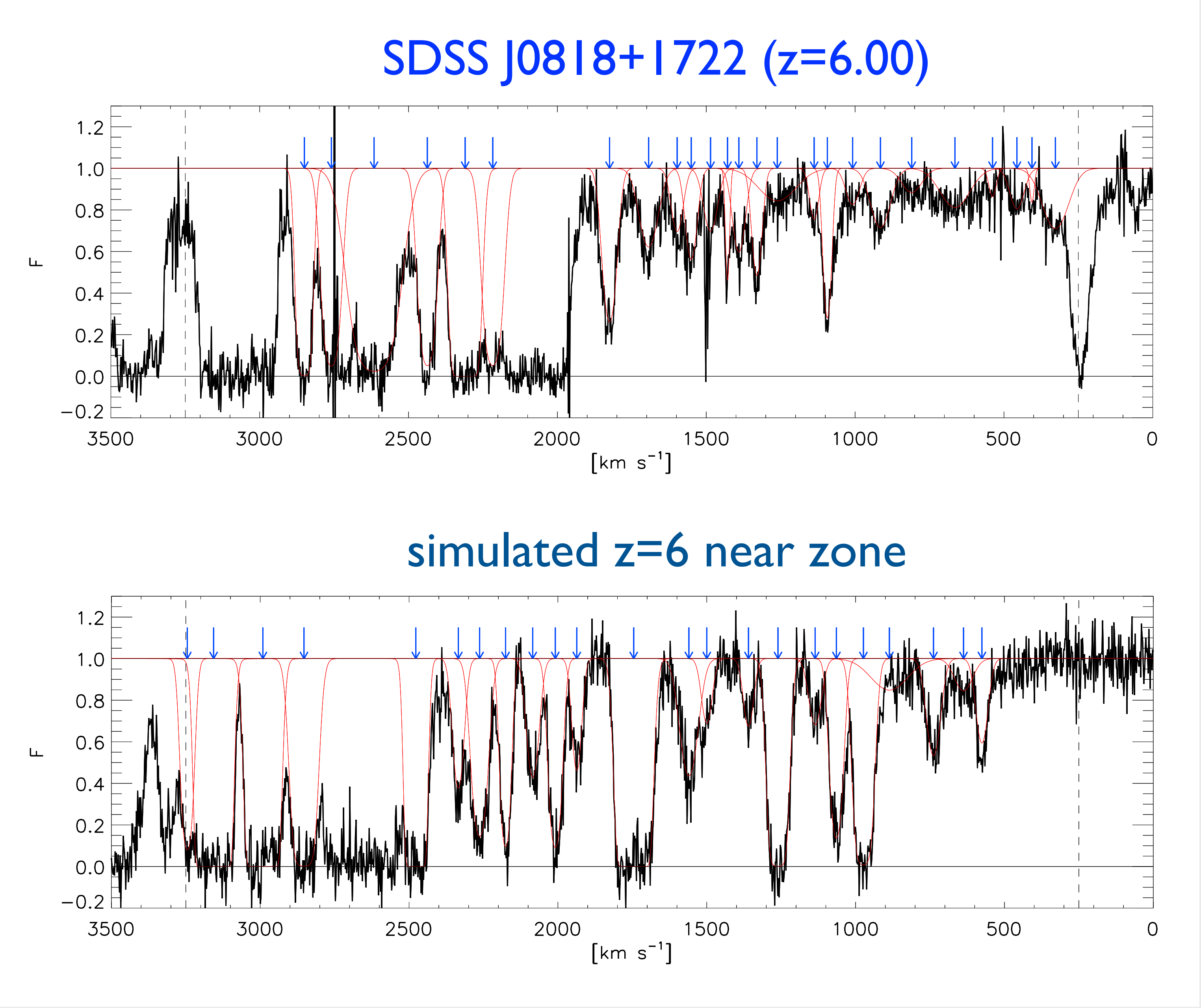
vs. wavelets



vs. line widths

Temperature constraints on Hydrogen reionization

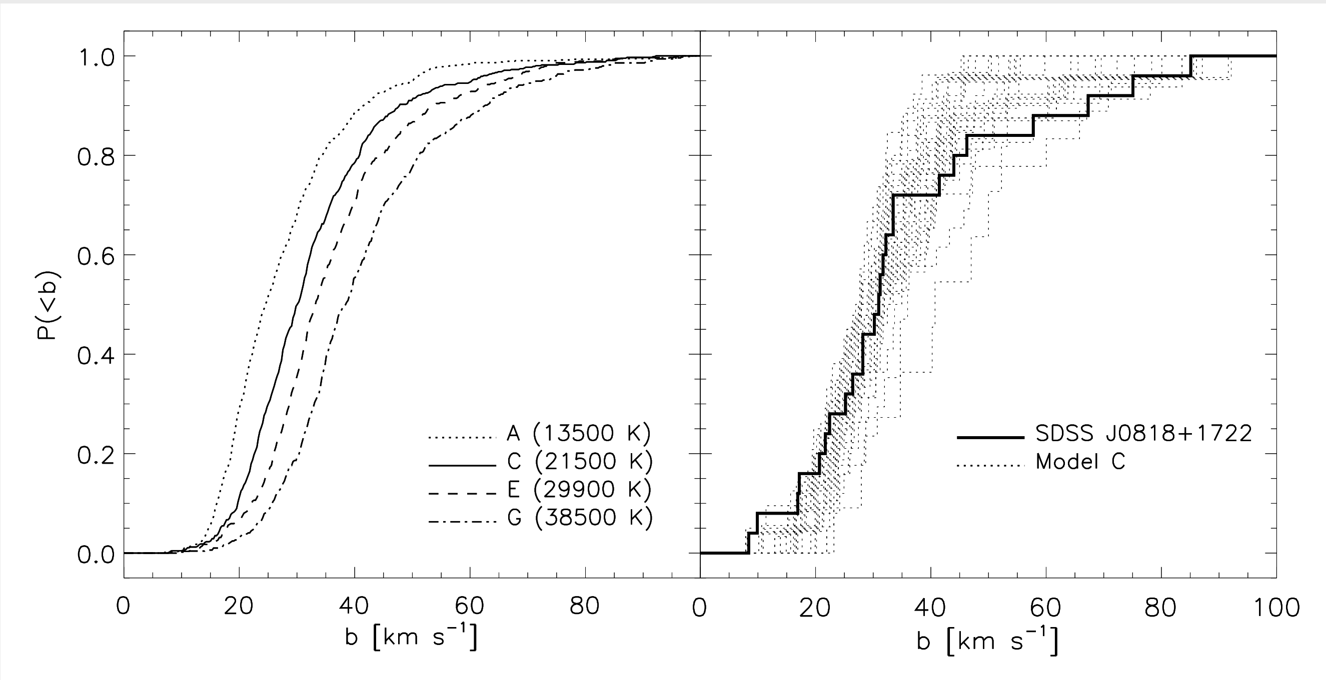
- Lyα forest is opaque at $z > 6$
- Still get temperature information from QSO near zones
  - Line width distribution
- Cautions:
  - Biased regions
  - QSO will also ionize He II



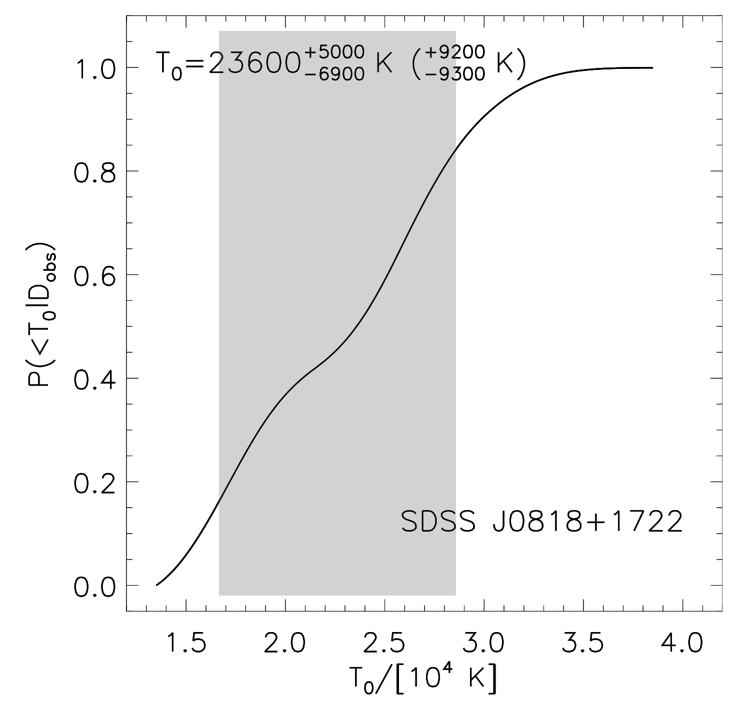
Bolton, GB+ 2010

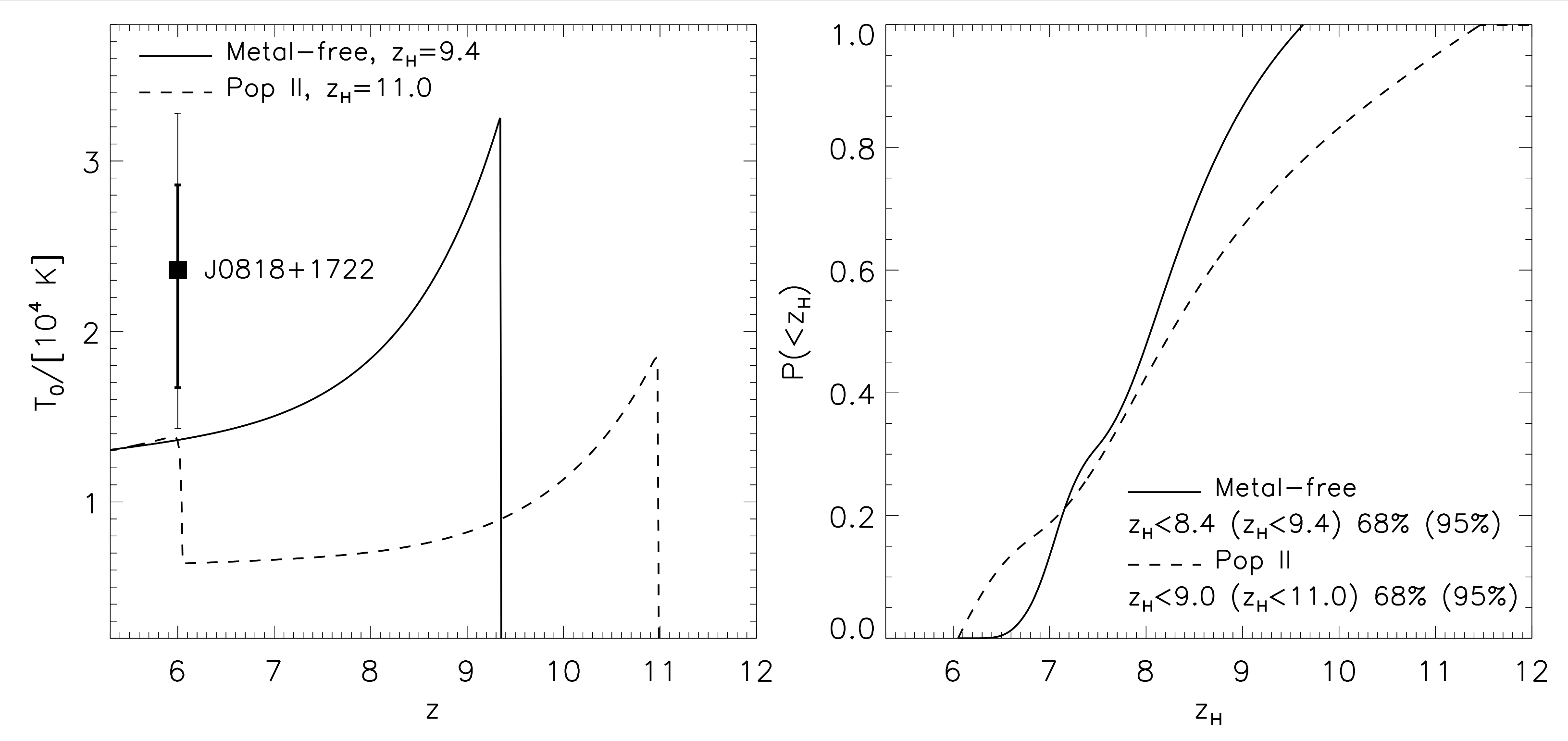
Near zone line widths

Hotter IGM produces wider absorption lines



T_0 constraints





Set limits on the *local* redshift of H I reionization

Bolton, GB+ 2010

Conclusions

- The thermal history of the IGM can be used to trace both hydrogen and helium reionization.
- Improved measurements of the IGM temperature over $1.8 < z < 5.4$ by using the curvature, and by measuring the temperature at the density actually probed by the Lyα forest
  - T_0 increase from $z > 4$ to $z{\sim}3$ is a clear signature of an extended He II reionization. May also be seeing the subsequent "cool down" from $z{\sim}3$ to 2
- At $z > 6$, temperatures can still be measured in the near zones of QSOs
  - For the first case measured, $z_{H\ reion} < 11$ *locally*
- Future:
  - Fit the entire temperature-density relation
  - Separate Jeans smoothing from temperature changes using QSO pairs
  - Look for temperature fluctuations indicative of patchy reionization
  - Thermal proximity effect