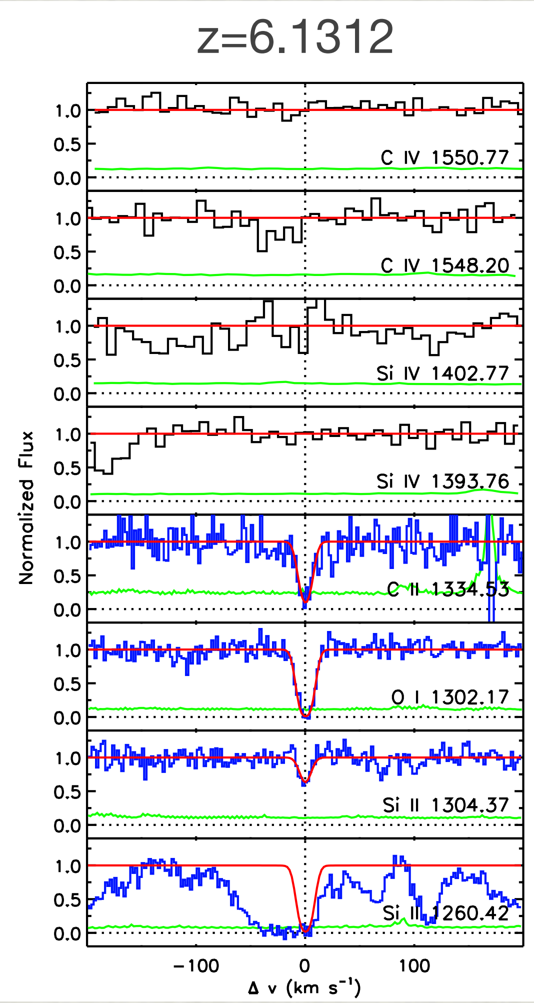
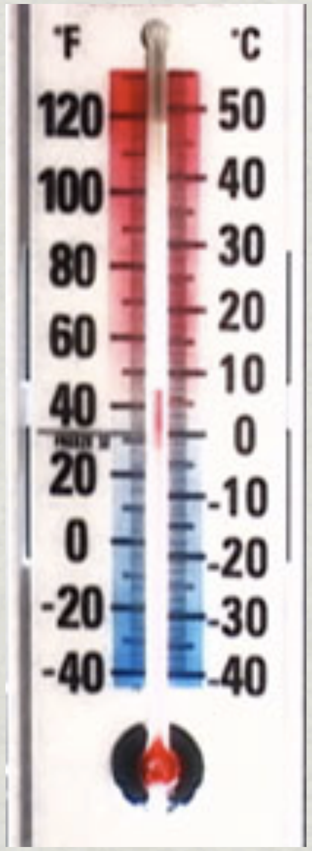


What We're Learning about Reionization from Metal Absorption Lines

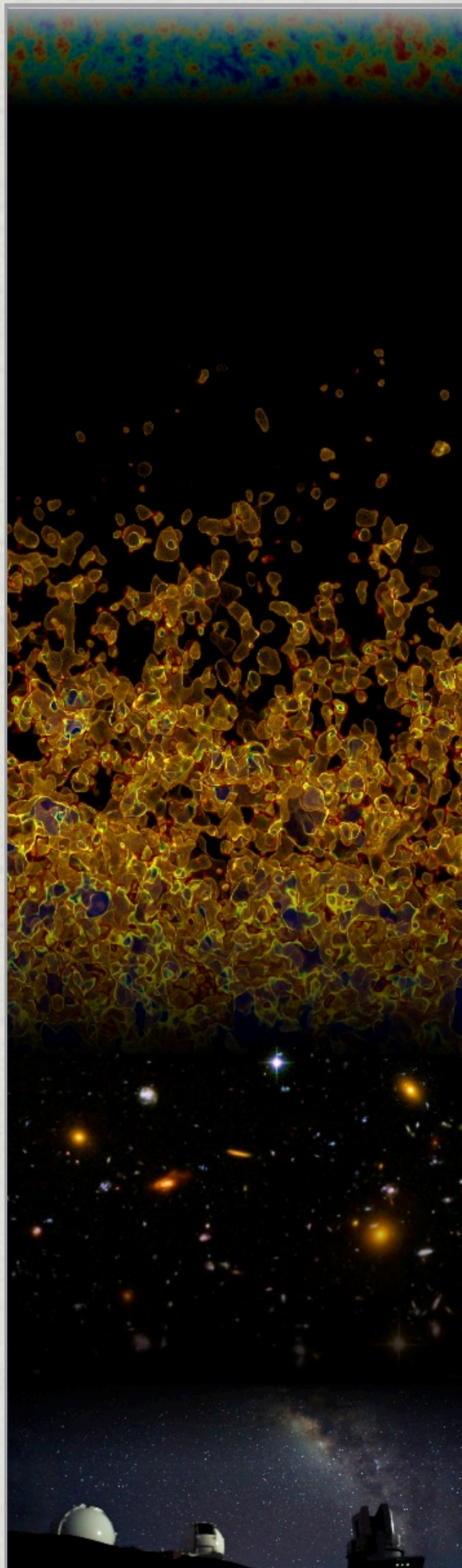
AND

IGM Temperatures



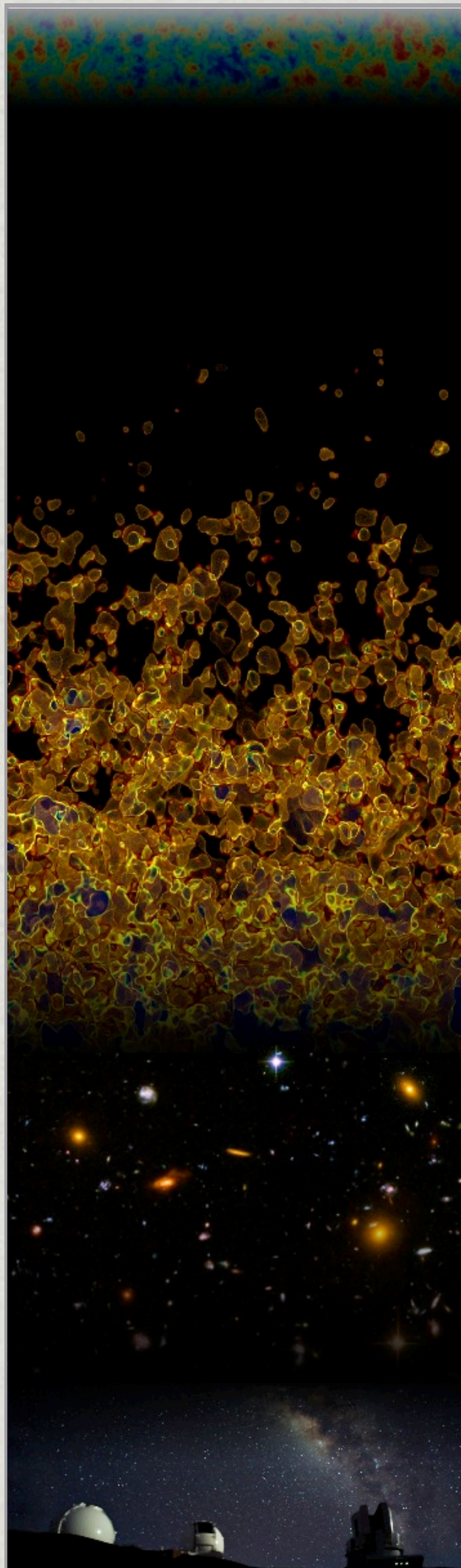
George Becker (KICC)

Feb 16, 2010
Allahabad



Overview

- Introduction to Reionization
- Metal Lines
    - Recent surveys for metal lines (C IV and O I)
    - Implications for star-formation at $z > 6$
- IGM Temperatures
    - New Measurements over $2 < z < 5$
    - Implications for He II reionization



“Reionization”

A) A riddle inside a mystery, wrapped in an enigma.

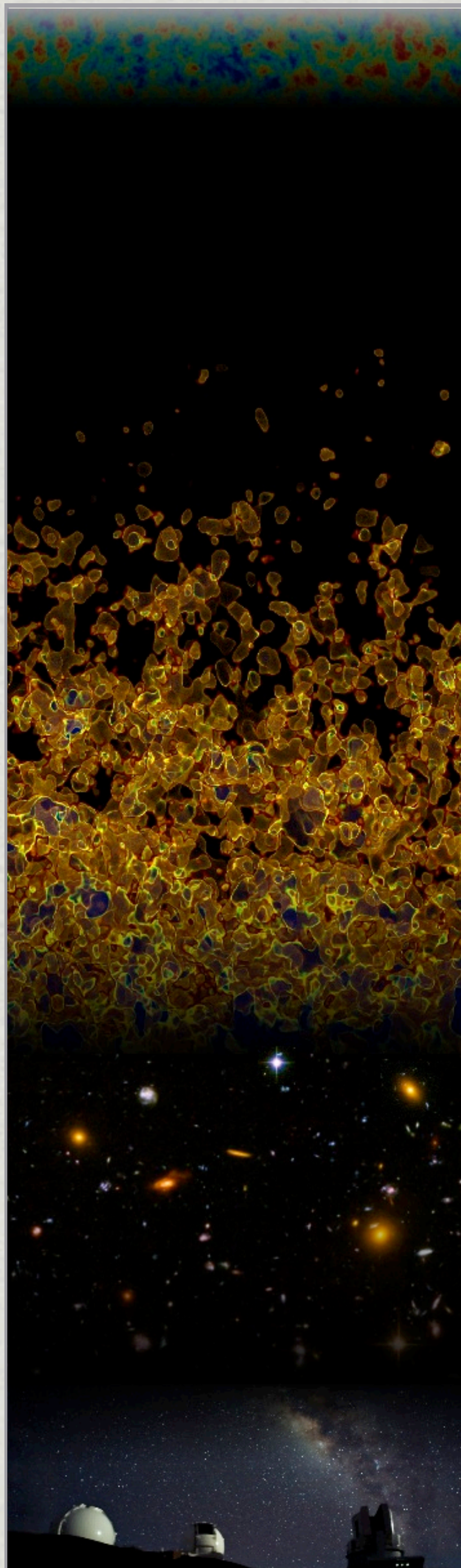
B) A process whose properties can be predicted from first principles in numerical simulations, without need for observations.

C) An event for which interpretation of the existing data requires already knowing the "correct" answer.

D) A somewhat over-rated "landmark" event in the history of the universe whose importance is surprisingly difficult to justify to friends and family.

- Steve Furlanetto

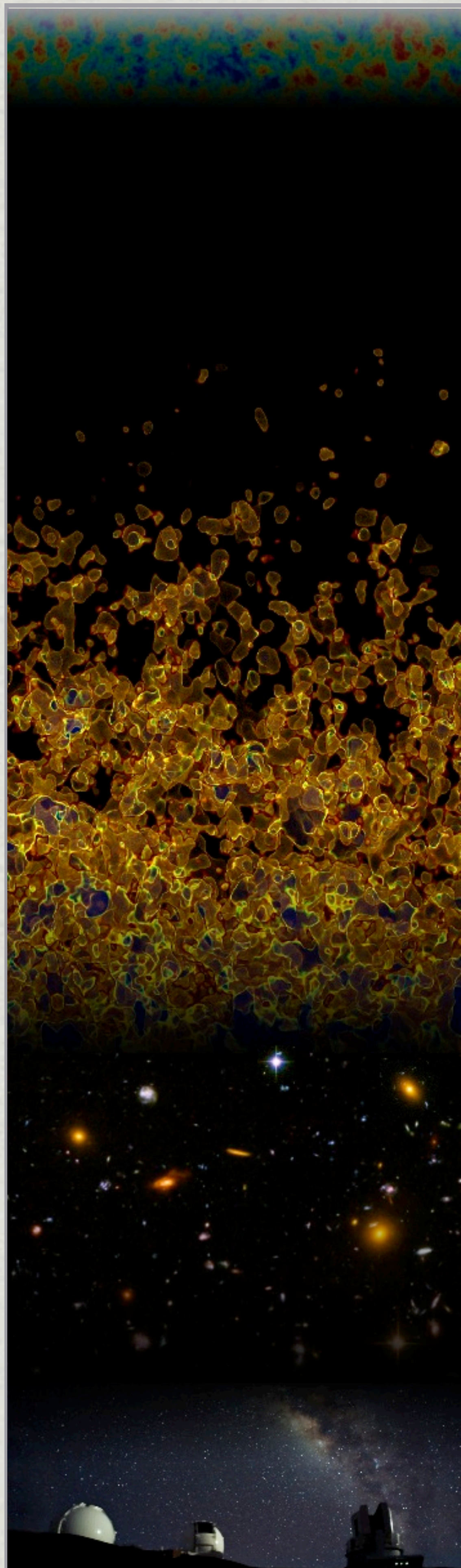
Marcelo Alvarez



Key Questions

Understanding hydrogen and helium reionization will help us to answer:

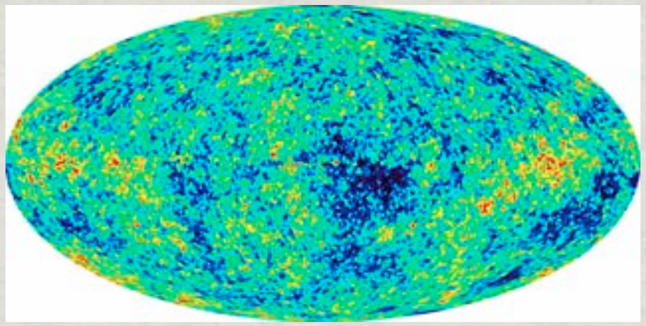
- When and how did the first stars and galaxies (and AGN) form during the first 1 Gyr after the Big Bang?
- How did reionization affect affect subsequent galaxy and AGN formation?
- What it the detailed structure of the galaxy-IGM network?
- How do ionizing photons escape from galaxies and propagate through a neutral / ionized medium?
- How do metals get mixed into the IGM and recycled into galaxies?
- How do BHs grow? What determines QSO activity?



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

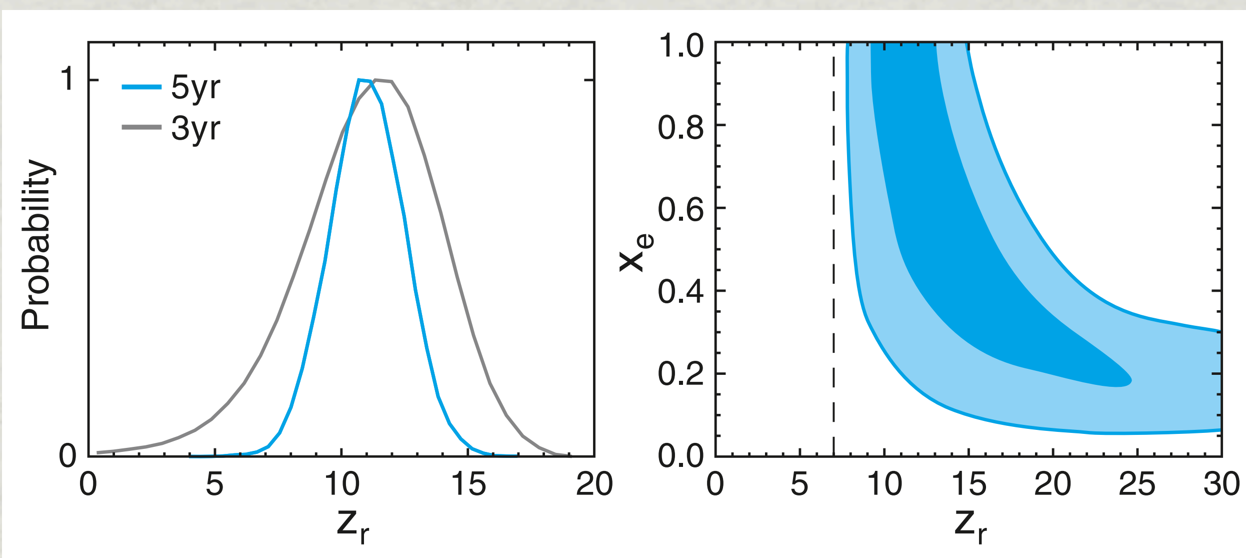
Hydrogen Reionization - Two limits



Early

CMB

τ_e to Thomson scattering



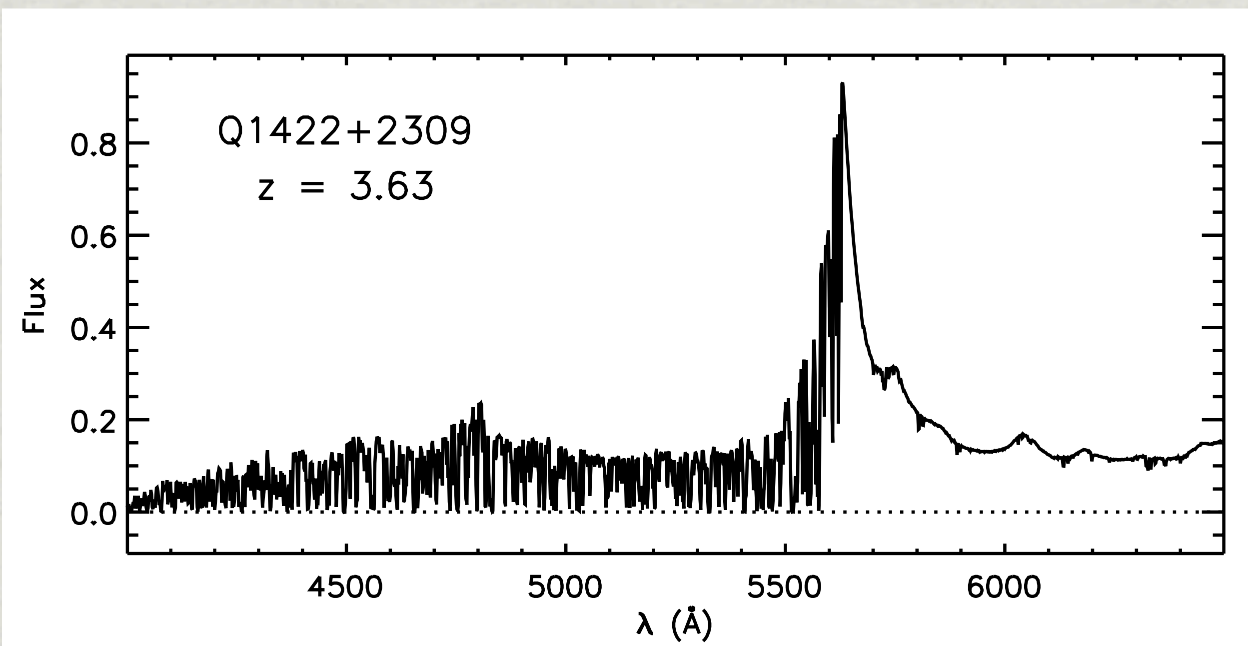
WMAP7: $z_{\rm reion} = 10.4 \pm 1.2$ ("instant")

but consistent with a range of reionization histories

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

Late

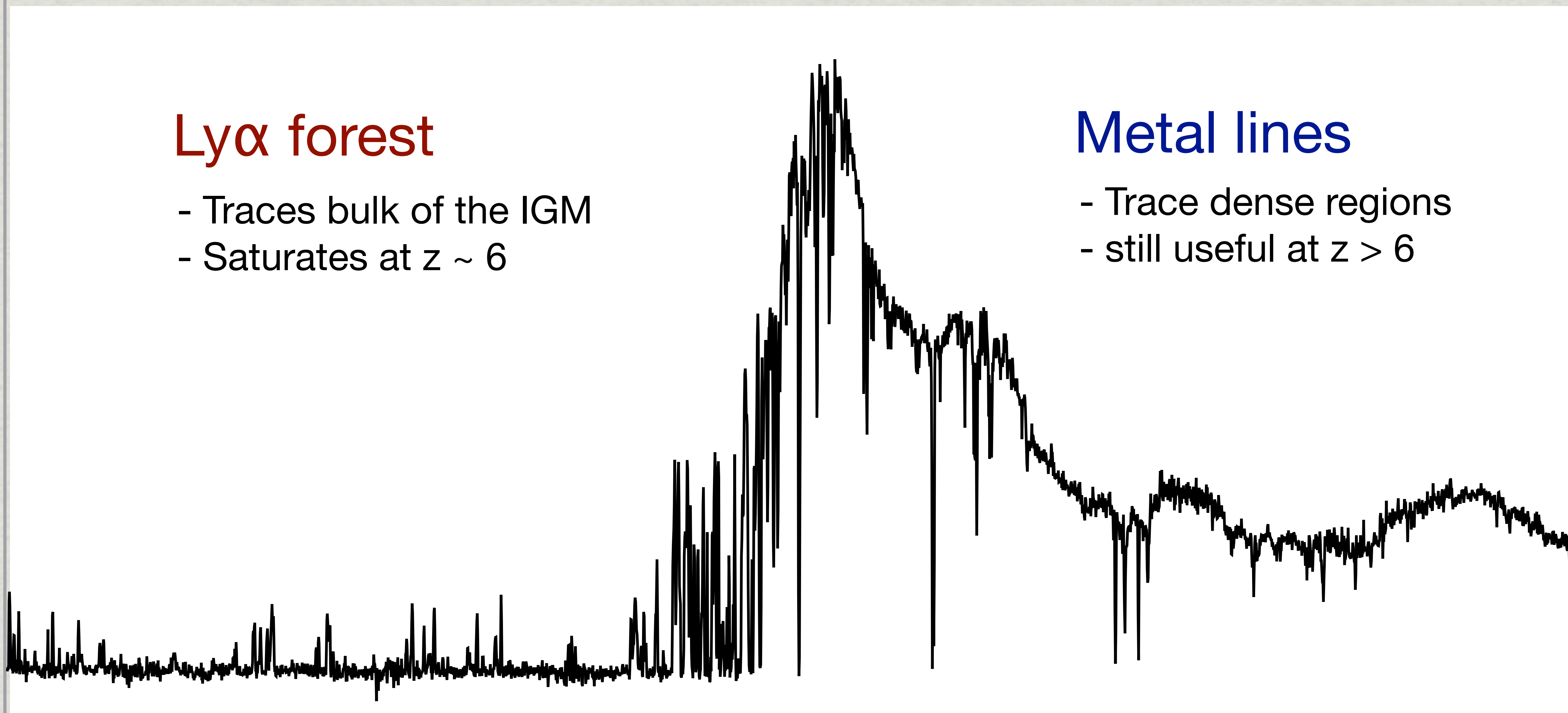
Transmission in the Lyα forest



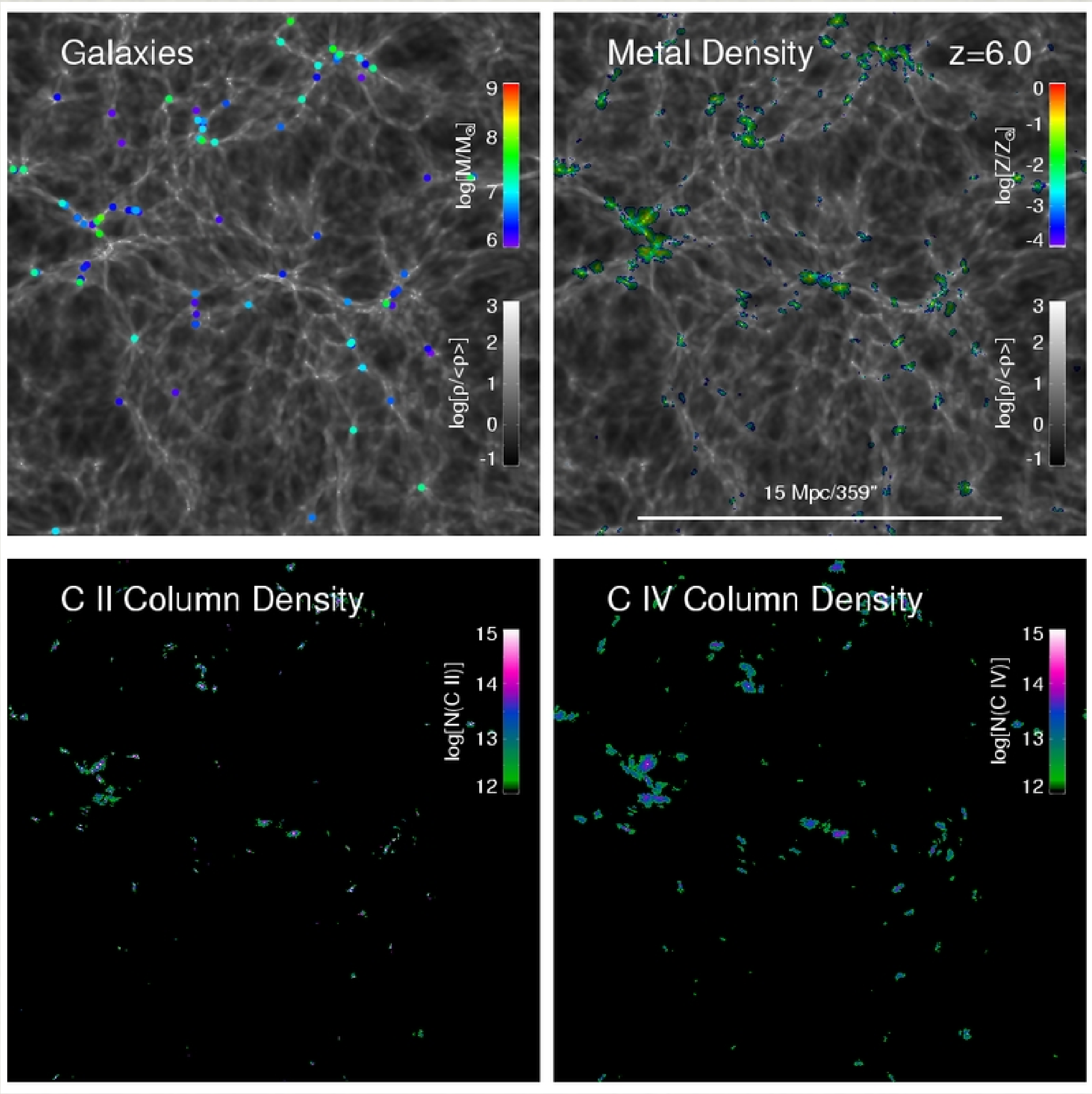
$$\tau_{{\rm Ly}\alpha} \sim 10^5 \, f_{\rm H\,I}$$

IGM must be highly ionized at z < 6

Metal lines at high redshift



Metals



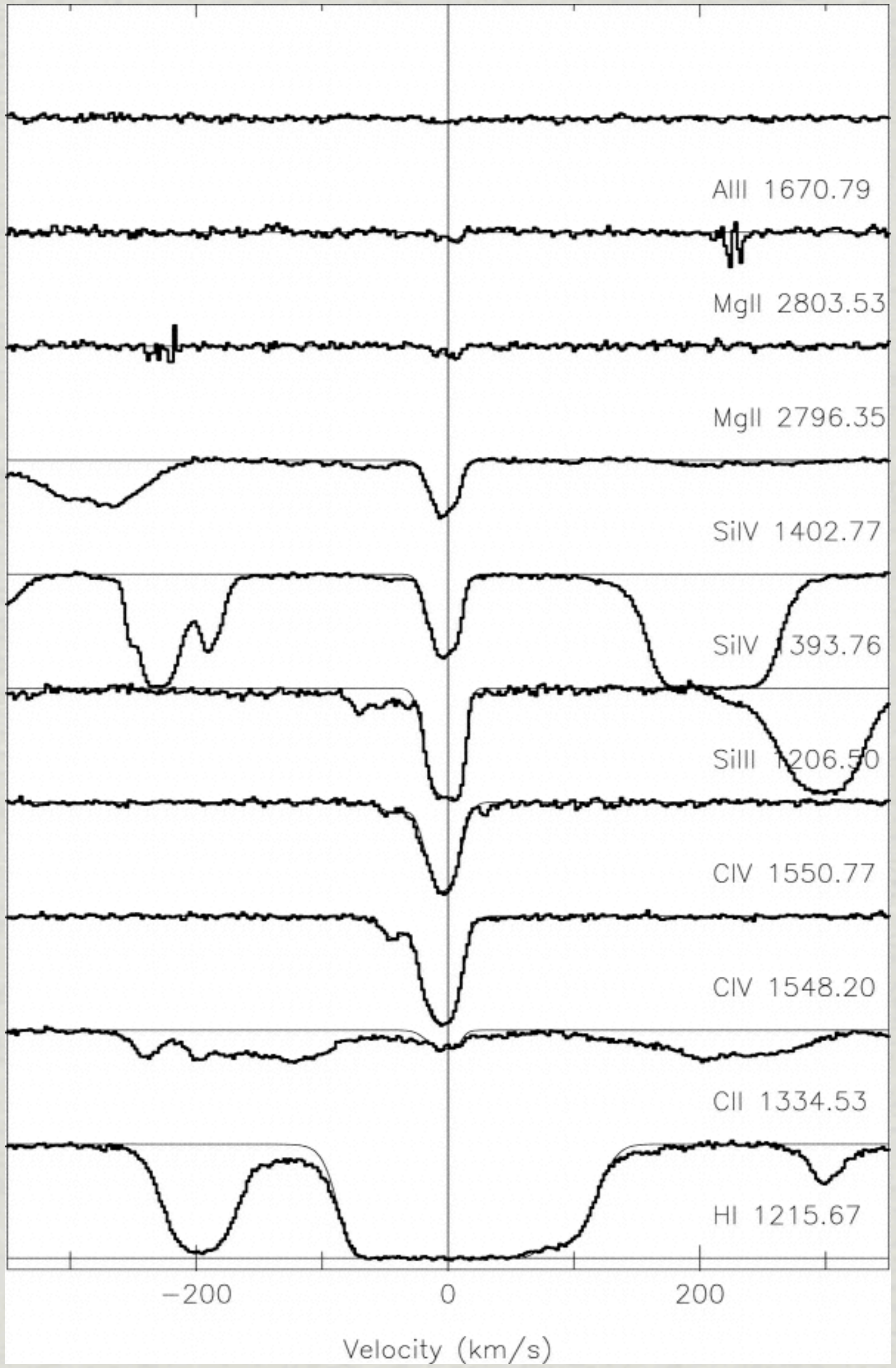
Oppenheimer+ 09

- Encode information about high-z galaxies and galaxy/IGM interactions
  - star formation, winds, stellar populations...
- Absorption lines can be markers for galaxies too faint to image
- Reionization probe (Oh 2002)
  - O I, C II, Si II
  - O ↔ H charge exchange:

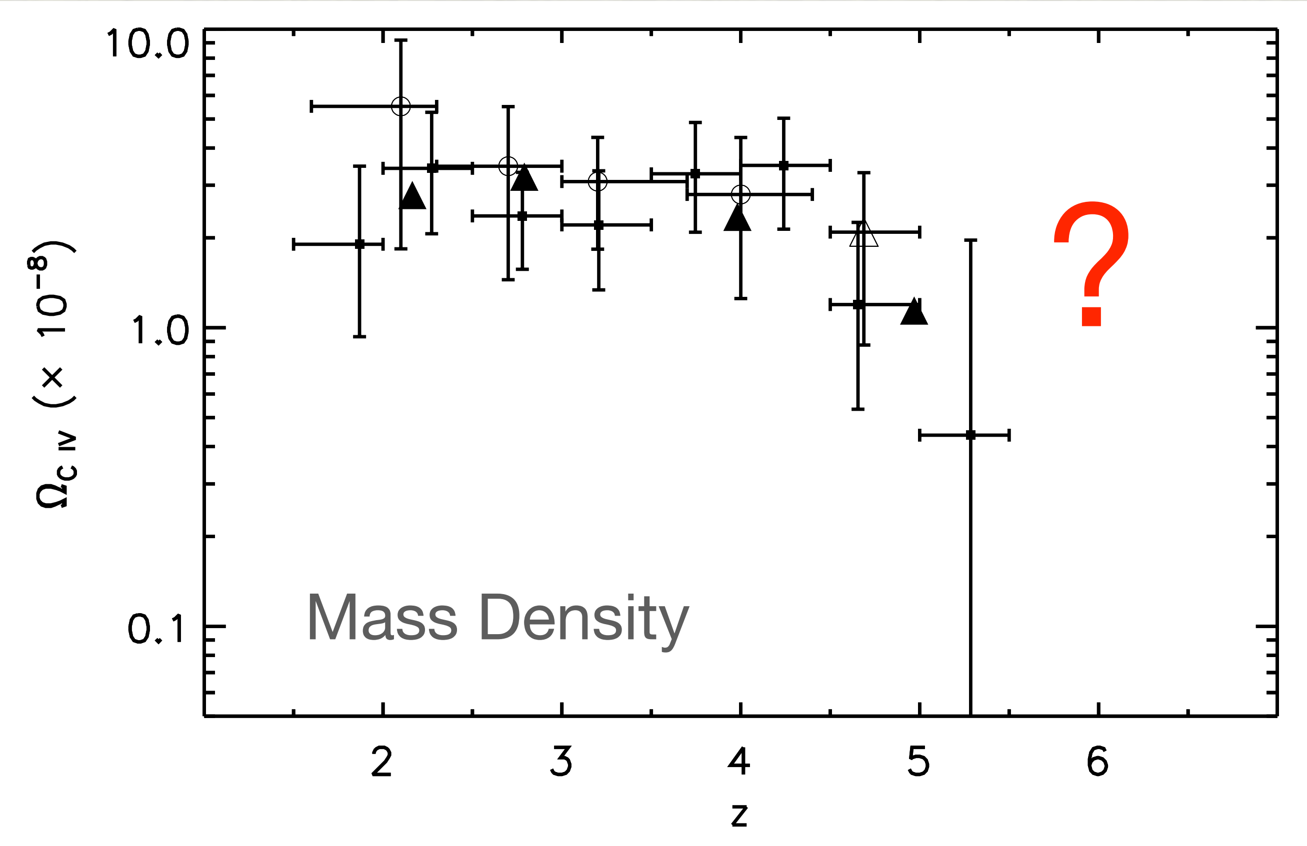
$$\Delta E(\mathrm{O\,I}) \approx \Delta E(\mathrm{H\,I}) \longrightarrow f_{\mathrm{O\,I}} \approx f_{\mathrm{H\,I}}$$

  - Joint constraint on enrichment & ionization
  - MUST MEASURE HIGH AND LOW-IONIZATION SPECIES

C IV at z~2-4



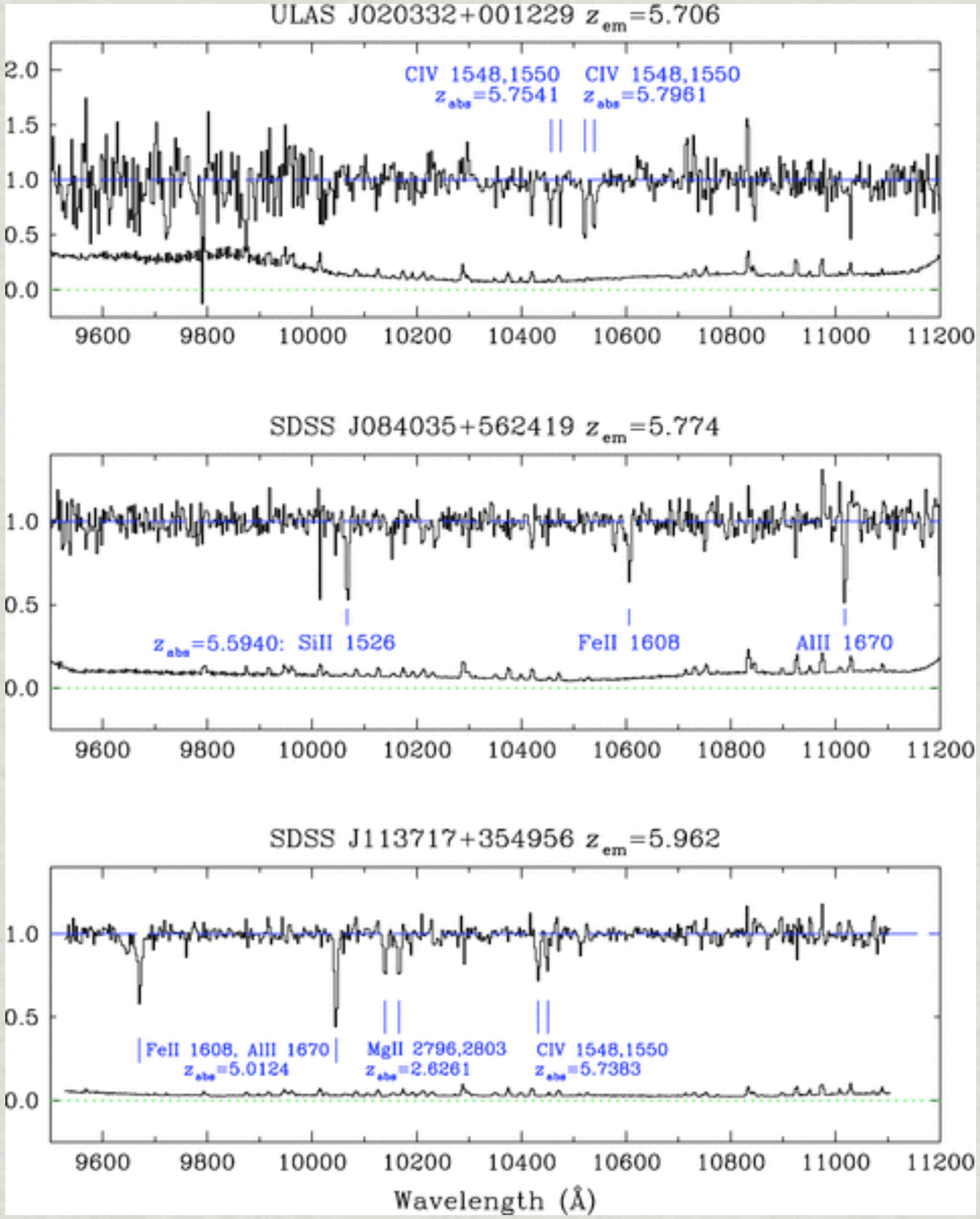
Simcoe+ 2004

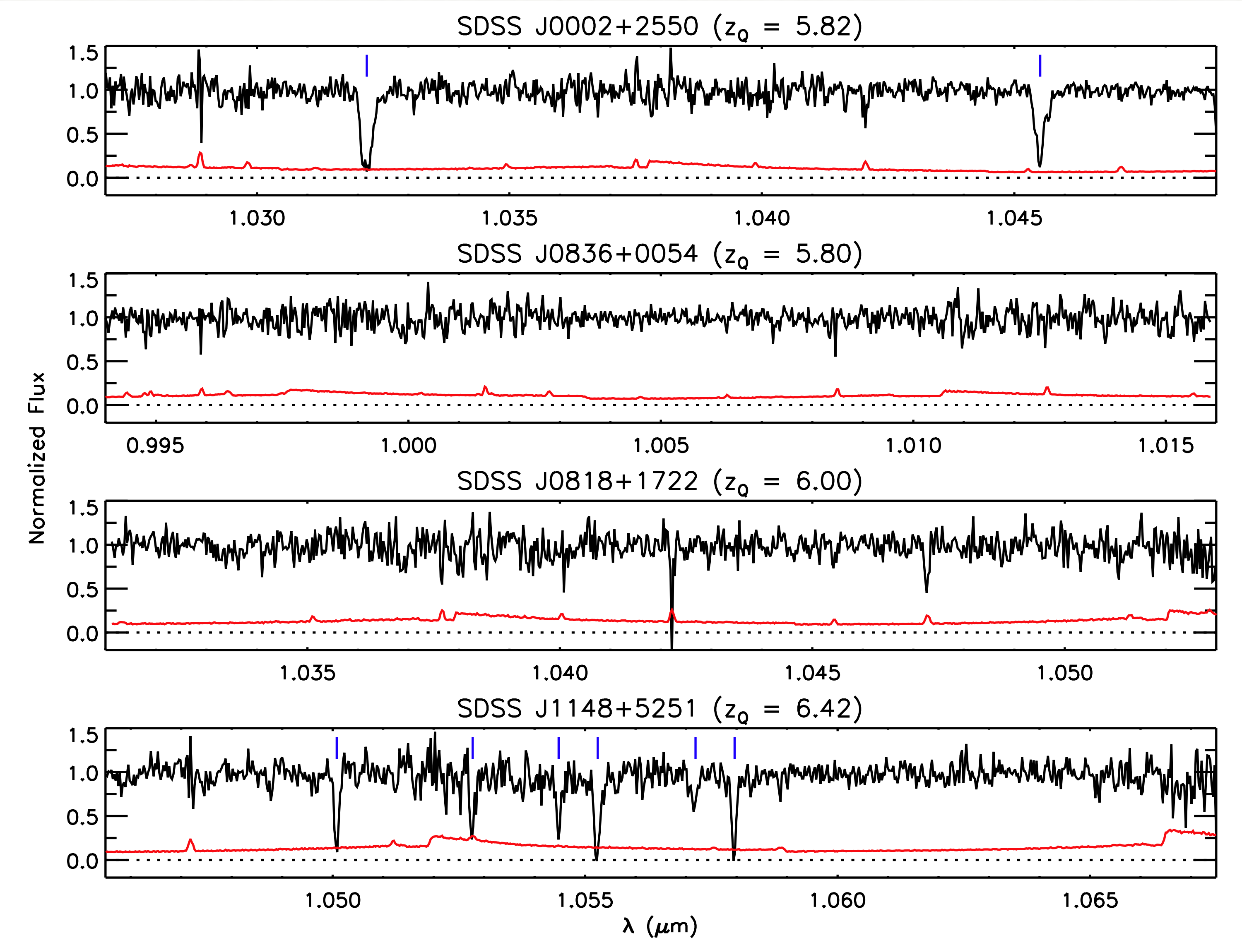


C IV in the IGM stays relatively constant over z~2-4.5

- Number density
- Mass density

Recent z~6 C IV observations



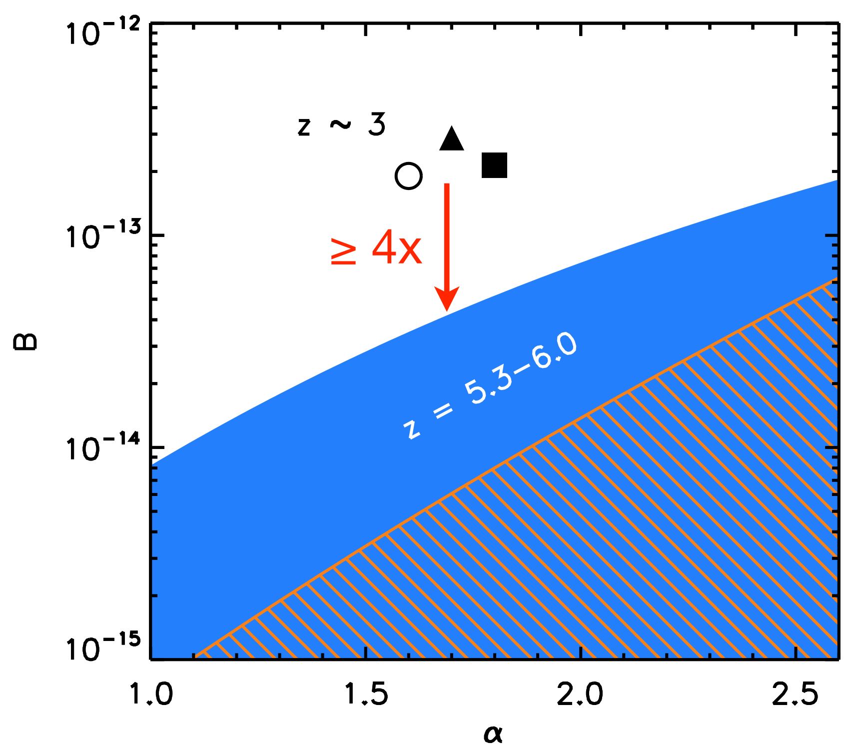


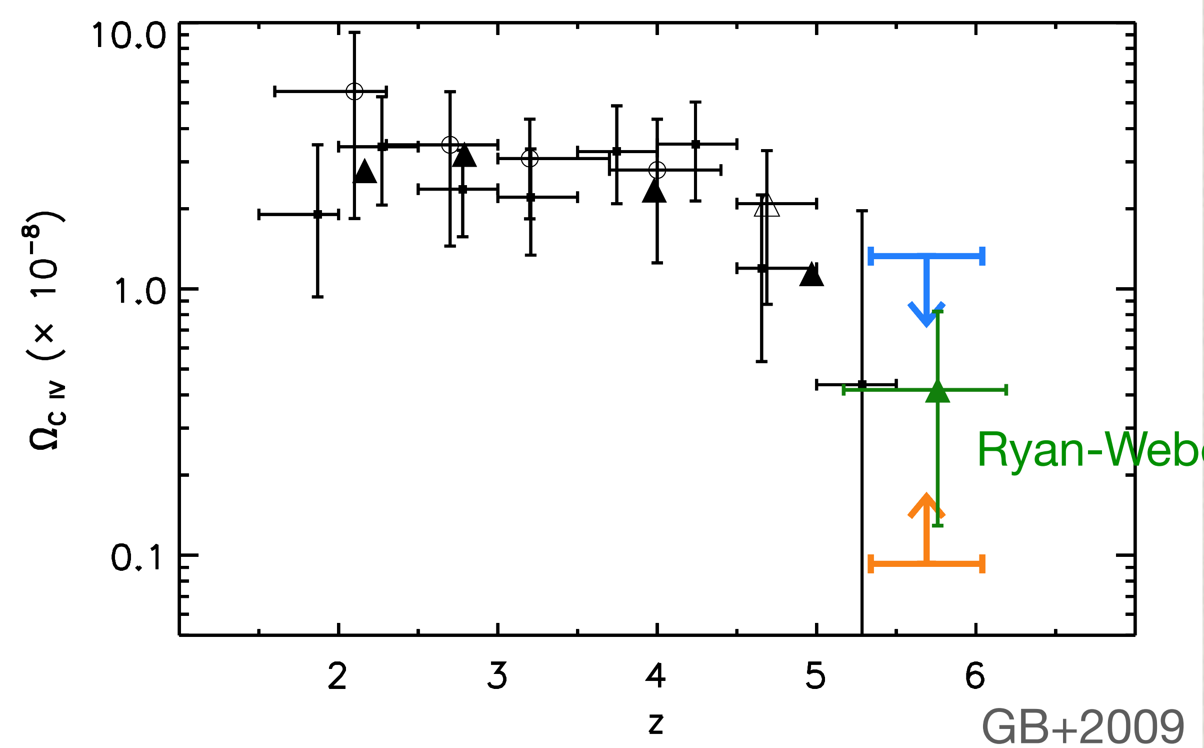
Ryan-Weber + (2009)
9 z > 5.7 QSOs
low resolution

Becker + (2009)
4 z > 5.7 QSOs
high resolution

Recent z~6 C IV results

Number density and mass density of C IV both decline sharply at z > 5.4





Number density

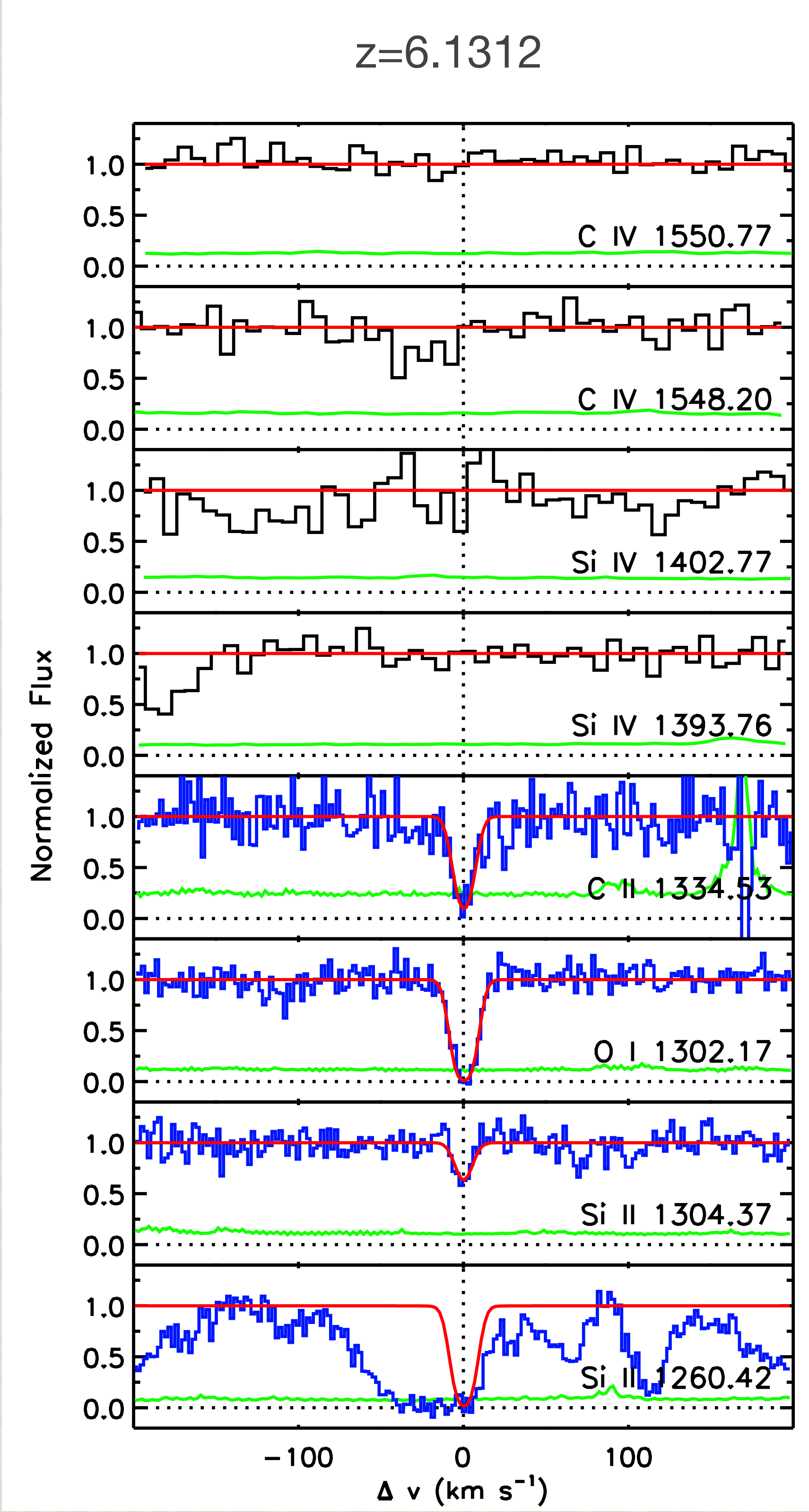
$$f(N) = B\left(\frac{N}{N_0}\right)^{-\alpha}$$

Comoving mass density

(dominated by rare, strong systems)

O I Survey

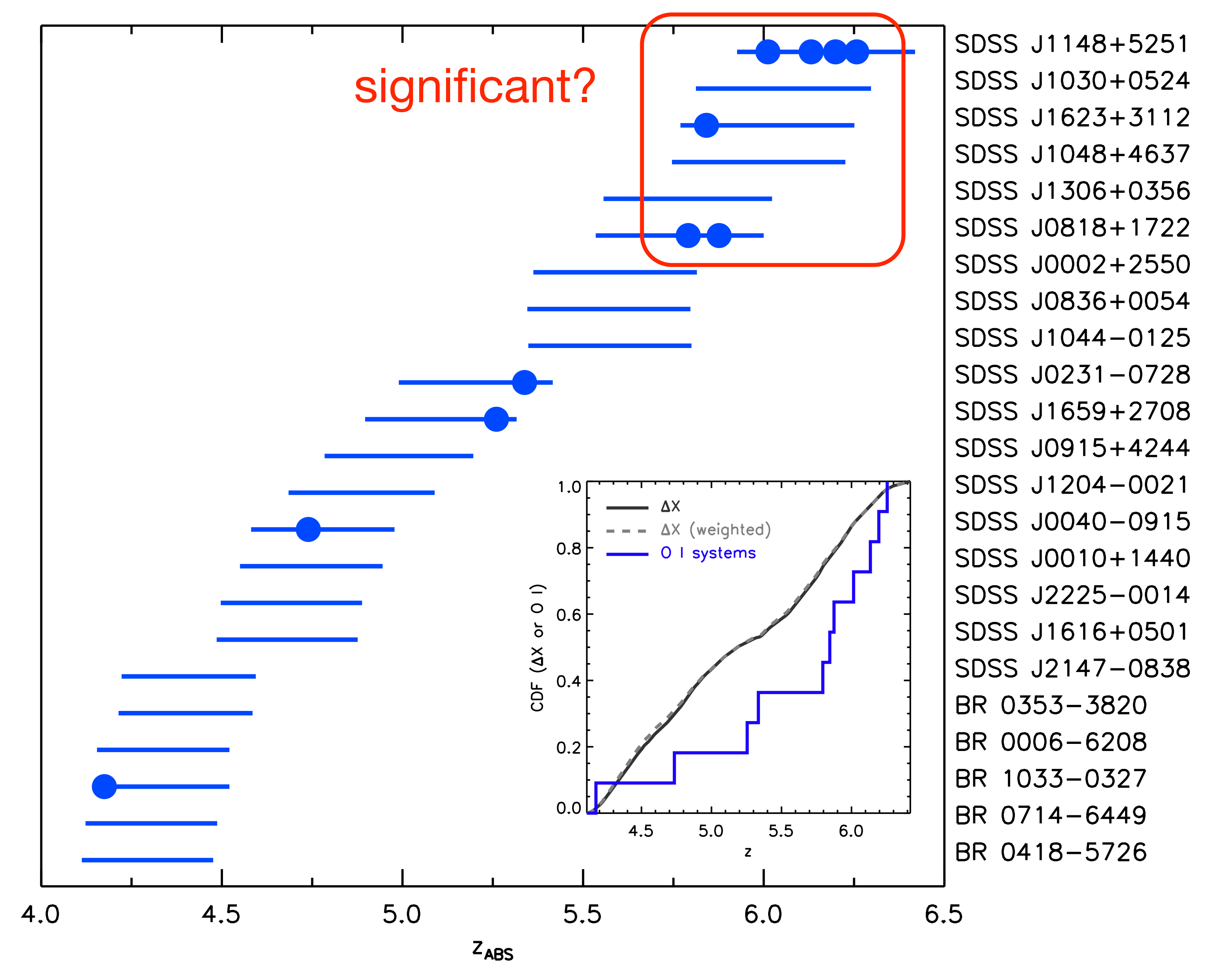
- Search for enriched gas in low-ionization states
- High-resolution spectra of 23 QSOs at z = 4.5-6.4
- Keck/HIRES + Magellan/MIKE
- Look for coincidences of O I, Si II, C II



GB+ 2006

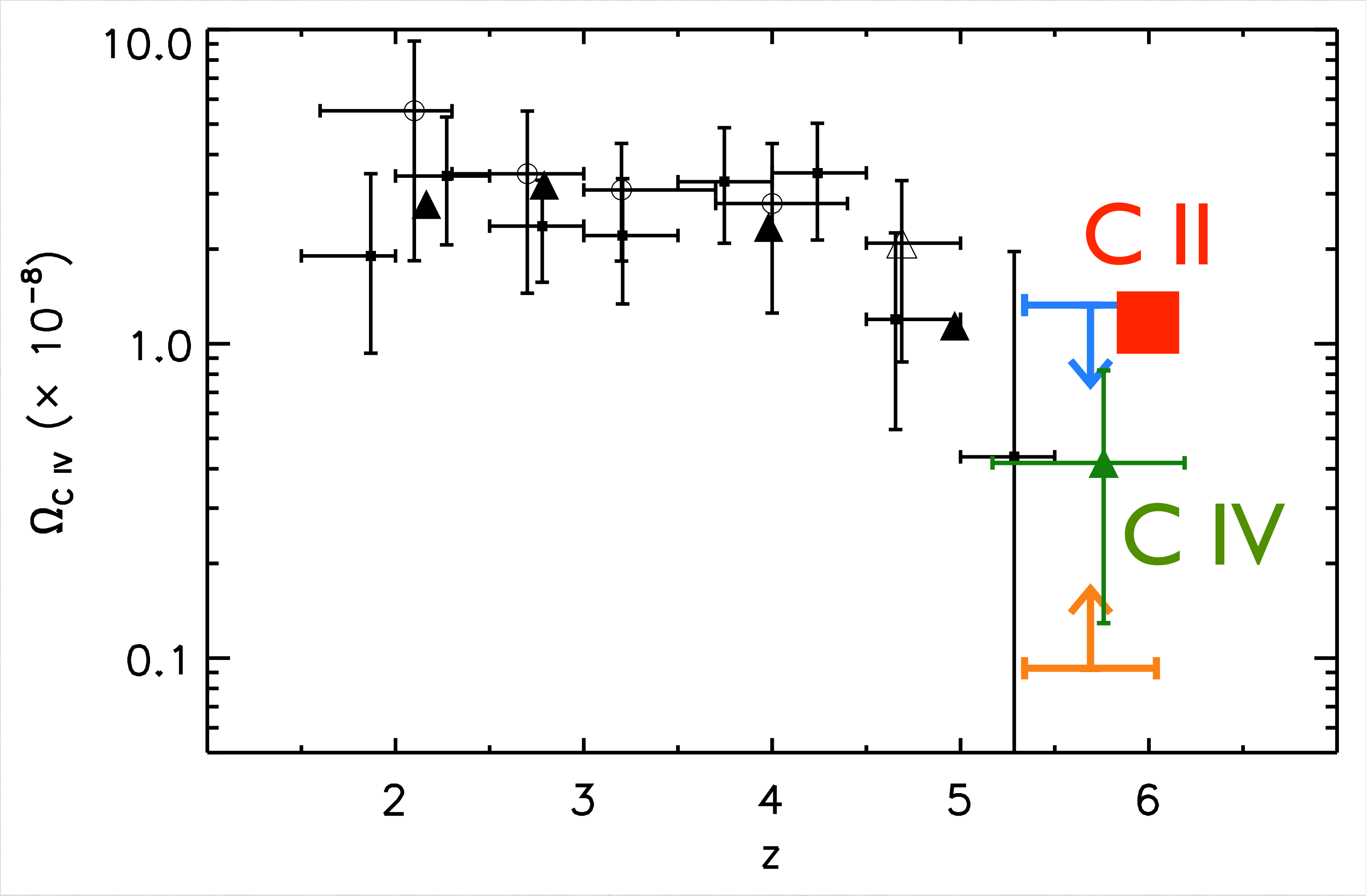
O I Survey results

- 11 O I systems
  - 7 at z > 5.8
- 99% probability of a real increase in number density at z > 5.8



GB+ in prep

O I vs. C IV



Low-ionization (O I) systems are more numerous and contain more carbon than high-ionization (C IV) systems

-- the opposite scenario from z~2-4

Metal production

Can the metals we observe at z~6 be produced by the galaxies we observe at z > 6?

- Stellar mass density at z~6

$$\rho_* \sim 1 \times 10^7 \ \mathrm{M_\odot \ Mpc^{-3}}$$

- Mass-weighted mean carbon yield
(Chieffi & Limongi 04 yields, Kroupa IMF)

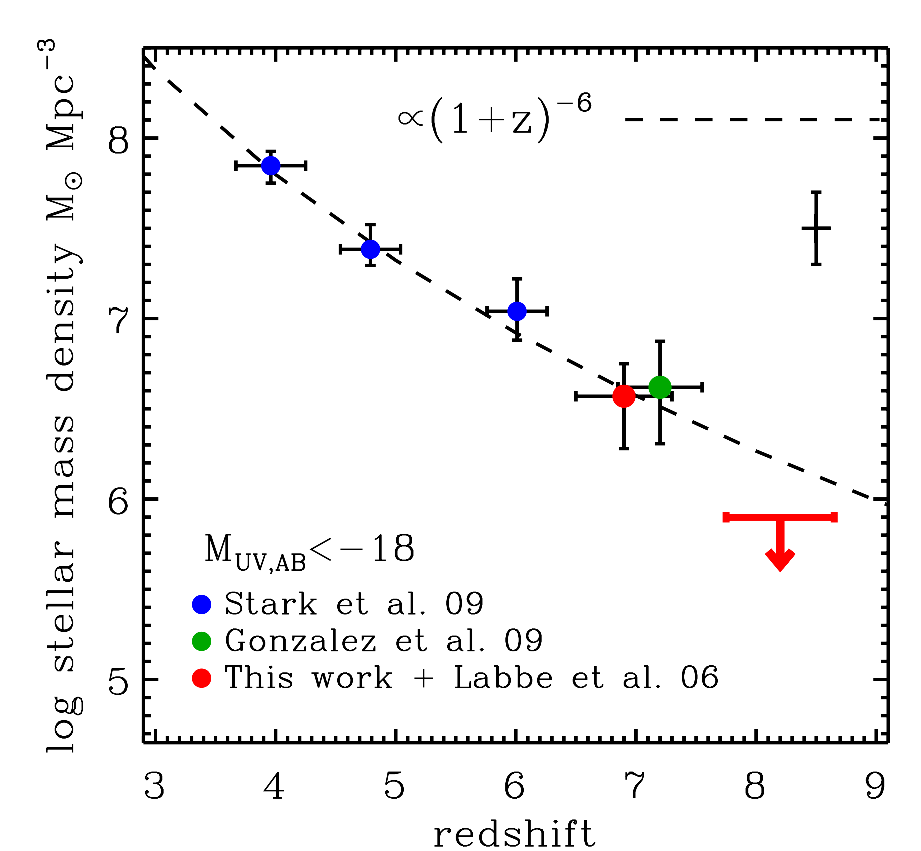
$$\langle y_\mathrm{C} \rangle \approx 0.004$$

- Expected carbon production

$$\rho_\mathrm{C} \sim 4 \times 10^4 \ \mathrm{M_\odot \ Mpc^{-3}}$$

- Seen in absorption

$$\rho_\mathrm{C,abs} \sim 2 \times 10^3 \ \mathrm{M_\odot \ Mpc^{-3}}$$

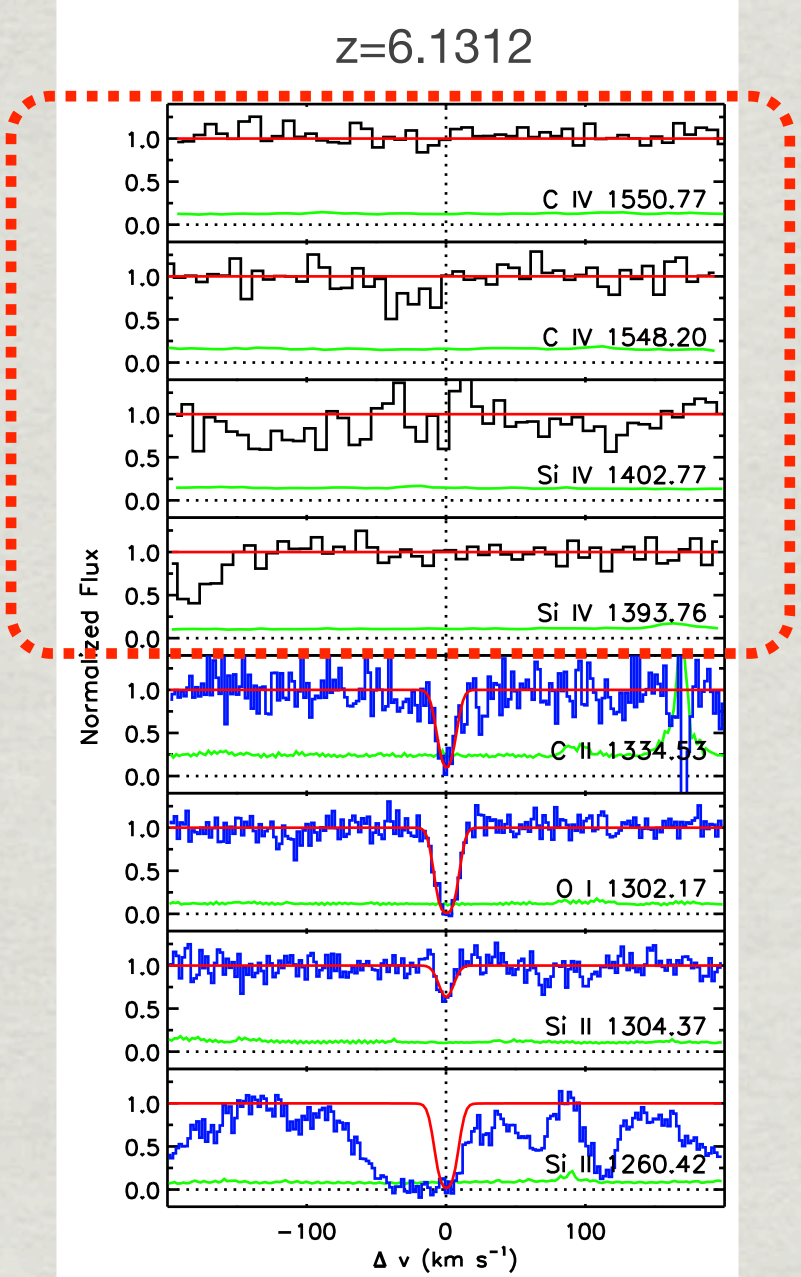


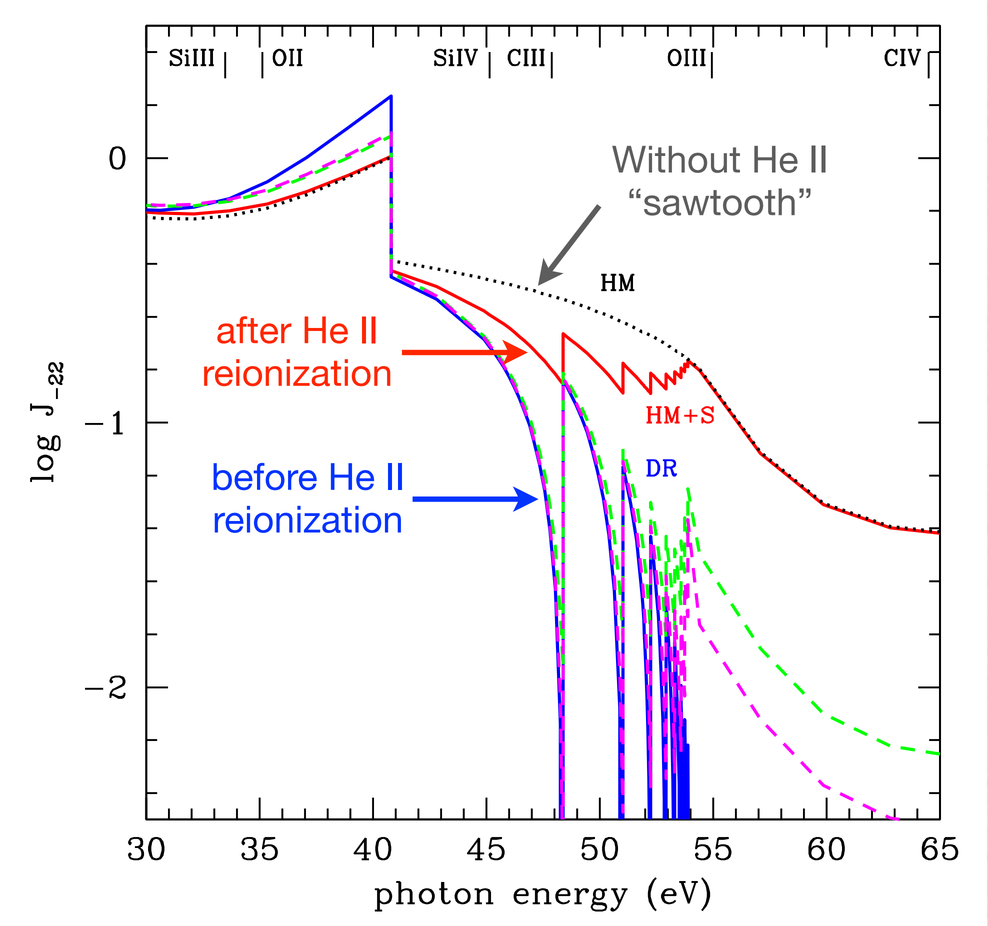
Labbe+ 2010

Observed metals do not directly imply more SF at z > 6 than what is observed.

Metals hiding?

- z~6 O I systems do not show C IV or Si IV, unlike lower-redshift DLAs
- He II in the IGM may significantly soften the UVBG near 3.5 Ryd
- Expect most C to be in C III ? Would be lost in the forest (C II 977, Si III 1207)



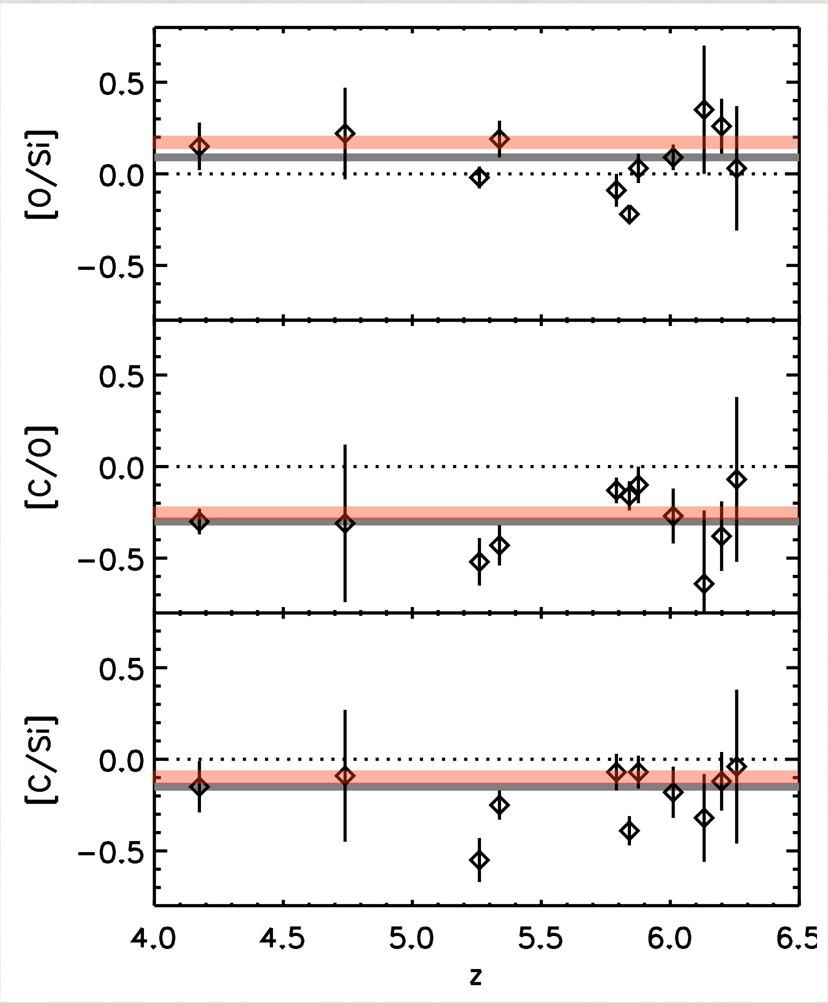


Madau & Haardt (2009)

Abundances

What do the metals tell us about the stars that ended the dark ages?

Low-Metallicity Type II SNe

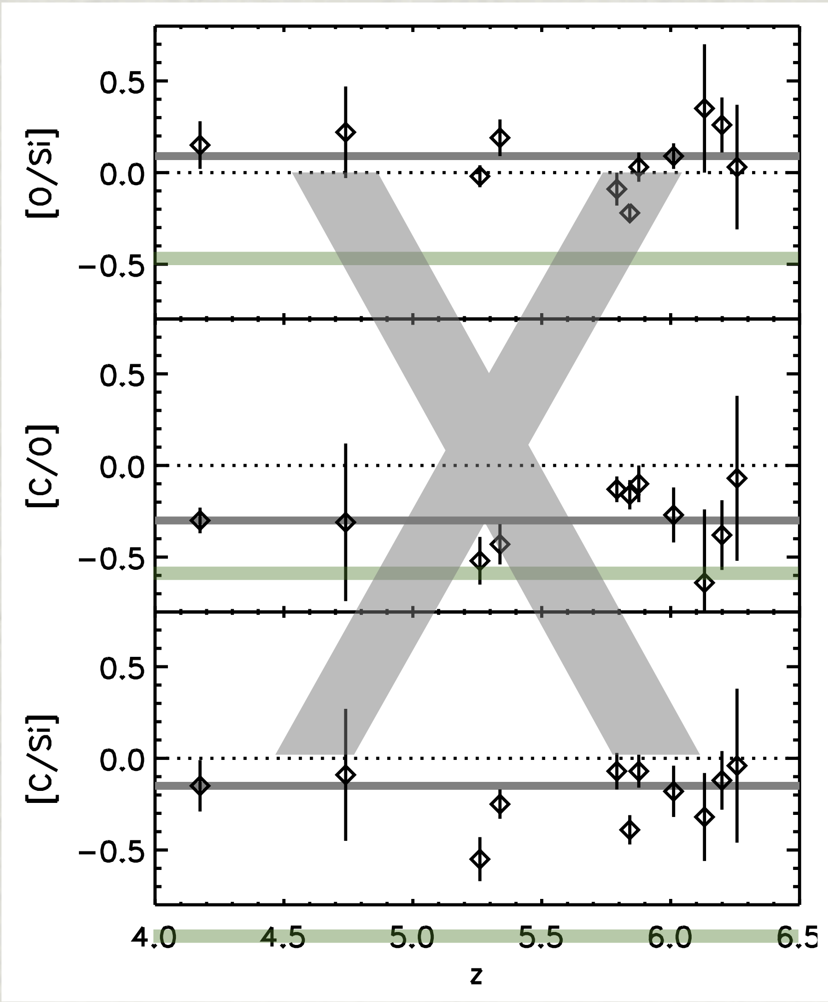


Chieffi & Limongi 04 yields

$Z = 10^{-3} Z_\odot$

$13 - 35\ M_\odot$

Very Massive Stars



Heger & Woosley 02 yields

$Z = 0$

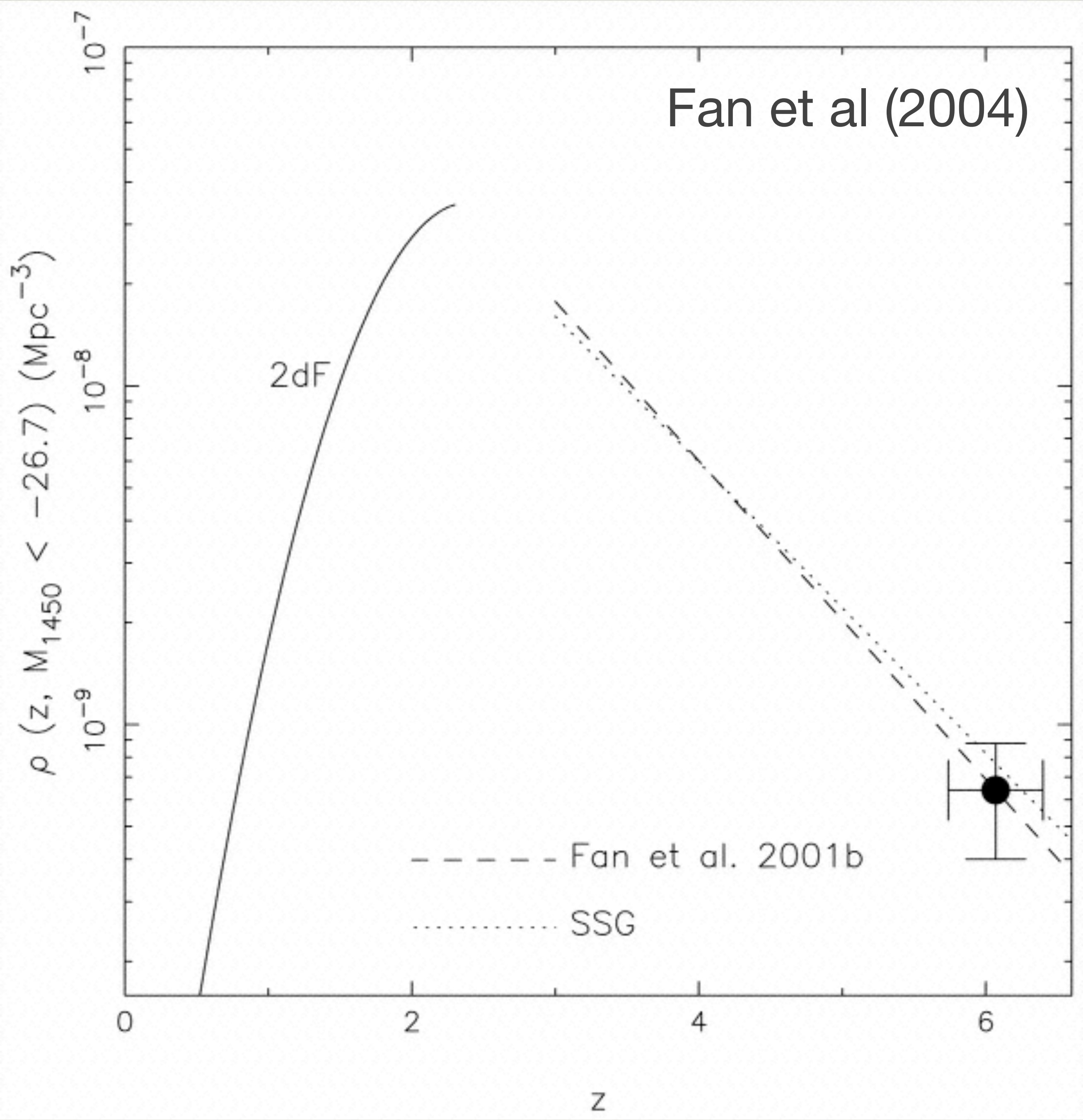
$140 - 260\ M_\odot$

Conclusions -- Metals

- Metals allow us to probe enriched regions of the IGM -- even before the end of reionization
- Much less C IV at z~6 than at z~3, but more low-ionization (O I) systems
    - Ionization change at the tail end of reionization?
    - O I systems represent the last stage of hydrogen reionization?
- The observed star-formation at z > 6 more than accounts for the metals seen in absorption at z~6
- Additional metals may be hiding in intermediate ionization states (C III), especially if He II has not been reionized by z~6 (which is likely)
- Abundances are consistent with yields from “normal” Pop II stars, and NOT with Pop III stars

Helium reionization: QSOs

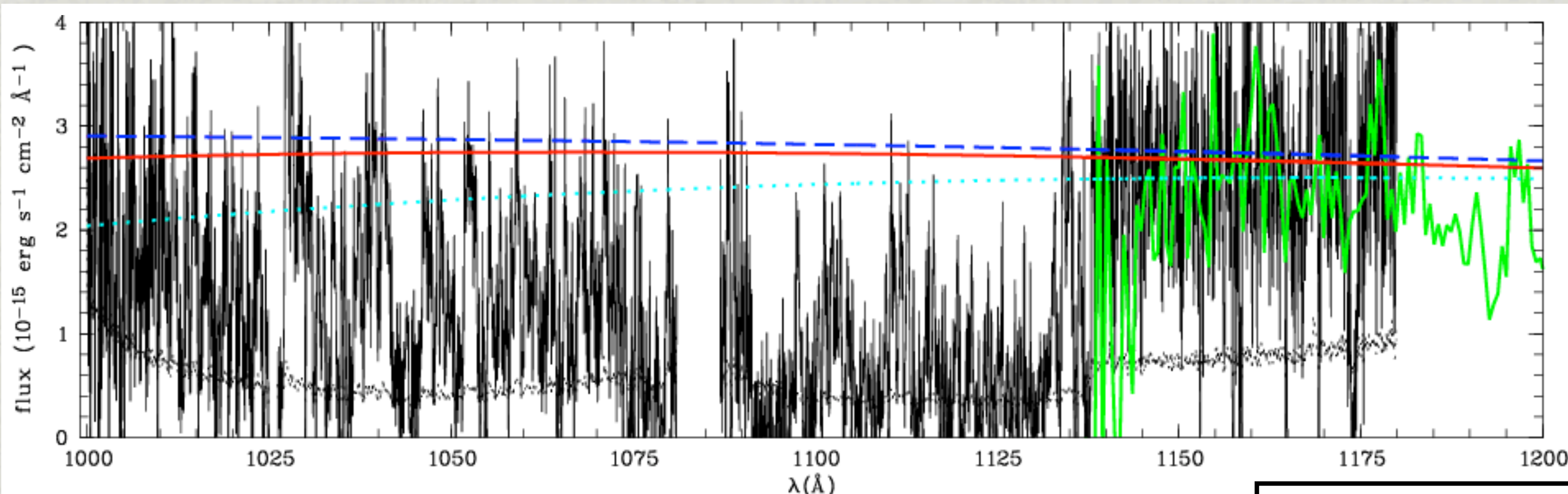
He II, ΔE = 4 Ryd



2dF: Croom et al. (2004)

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

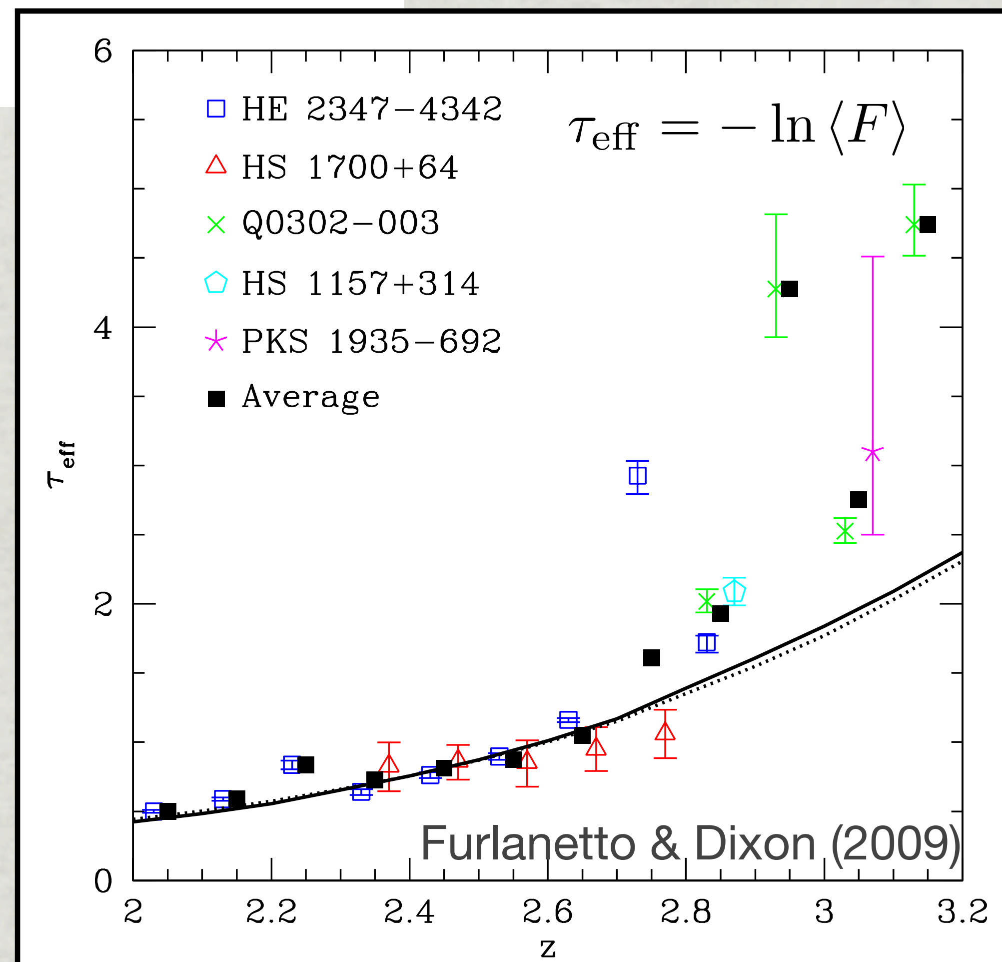
He II opacity evolution



HS 1700+6416, z=2.72 (FUSE)   Fechner+ (2006)

He II Lya
λ_{rest} = 304 Å

$$\tau^{\rm GP}_{\rm He\,II} = 3.4 \left(\frac{x_{\rm HeII}}{0.01}\right)\left(\frac{1+z}{4}\right)^{3/2}\left(\frac{\Delta_b}{0.1}\right)$$



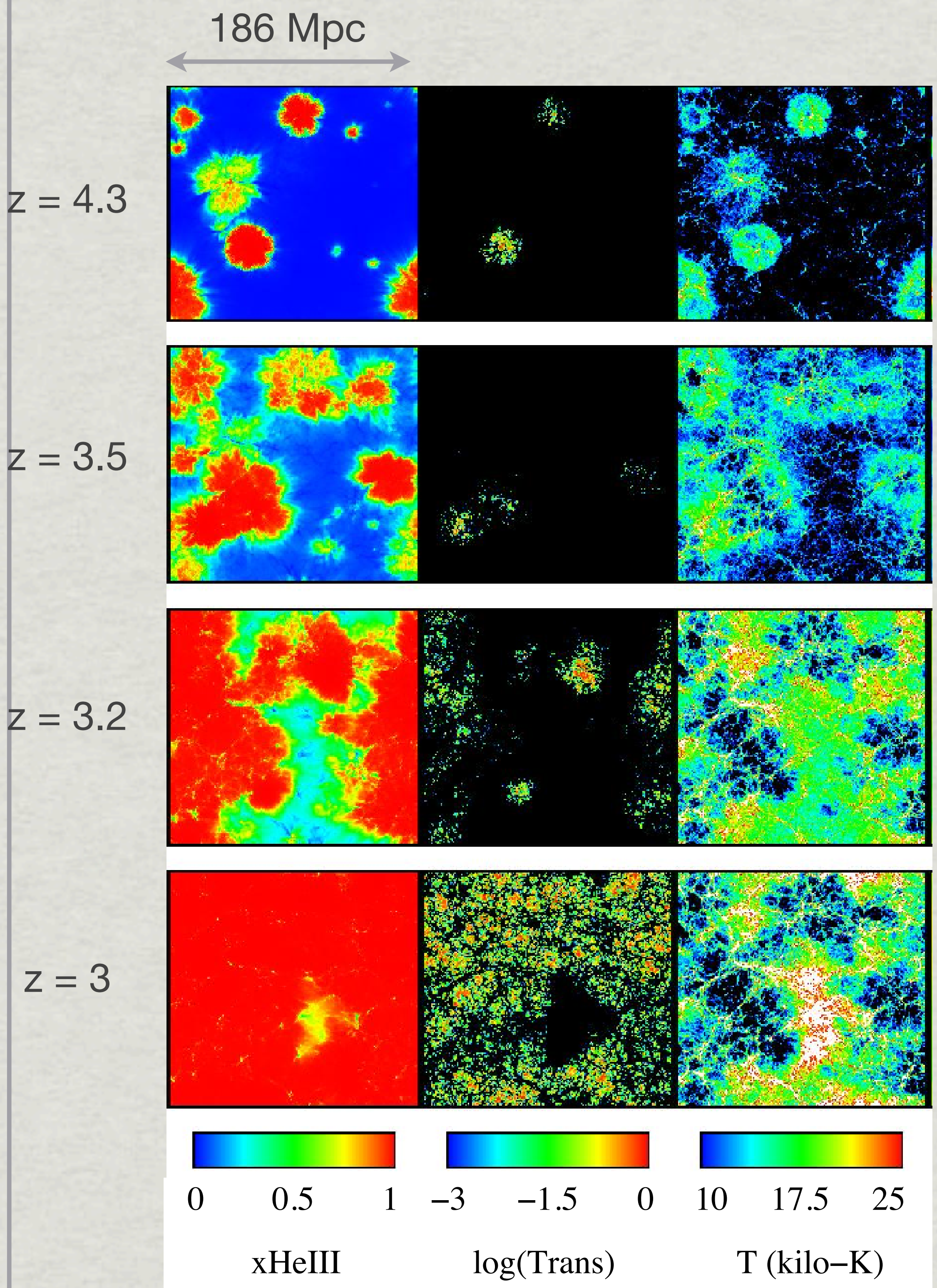
Furlanetto & Dixon (2009)

Seeing a drop in opacity at the end of He II reionization?

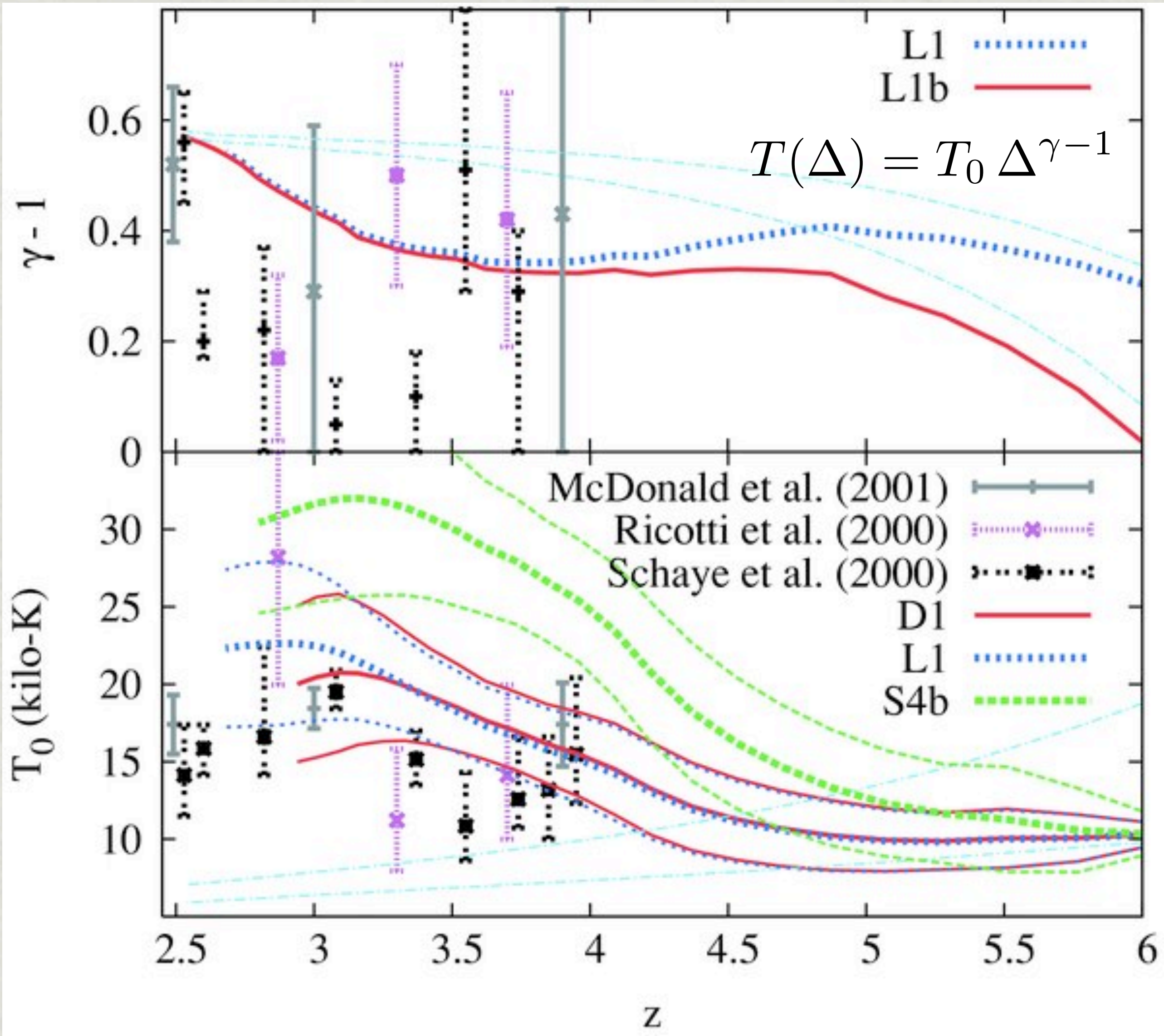
$x_{\rm He\,II,\,V}$ > 0.03 at z~3 (McQuinn 09)

Coming soon: COS data!

Temperature Evolution for He II reionization



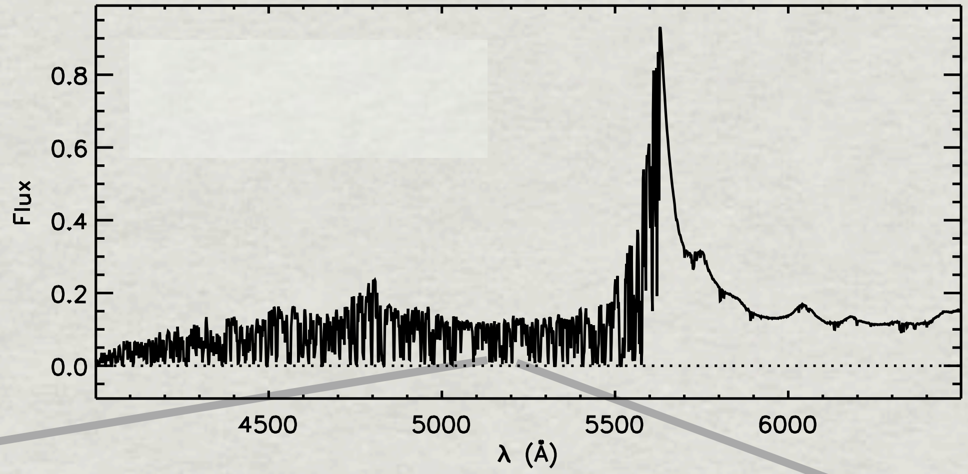
McQuinn+ (2009)



Photoionization heating ⇒ Temperature increase during He II reionization

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

Temperatures from the Lyα forest



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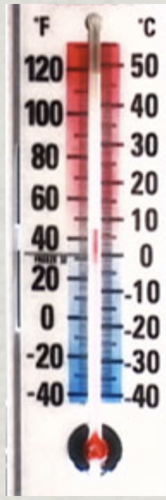
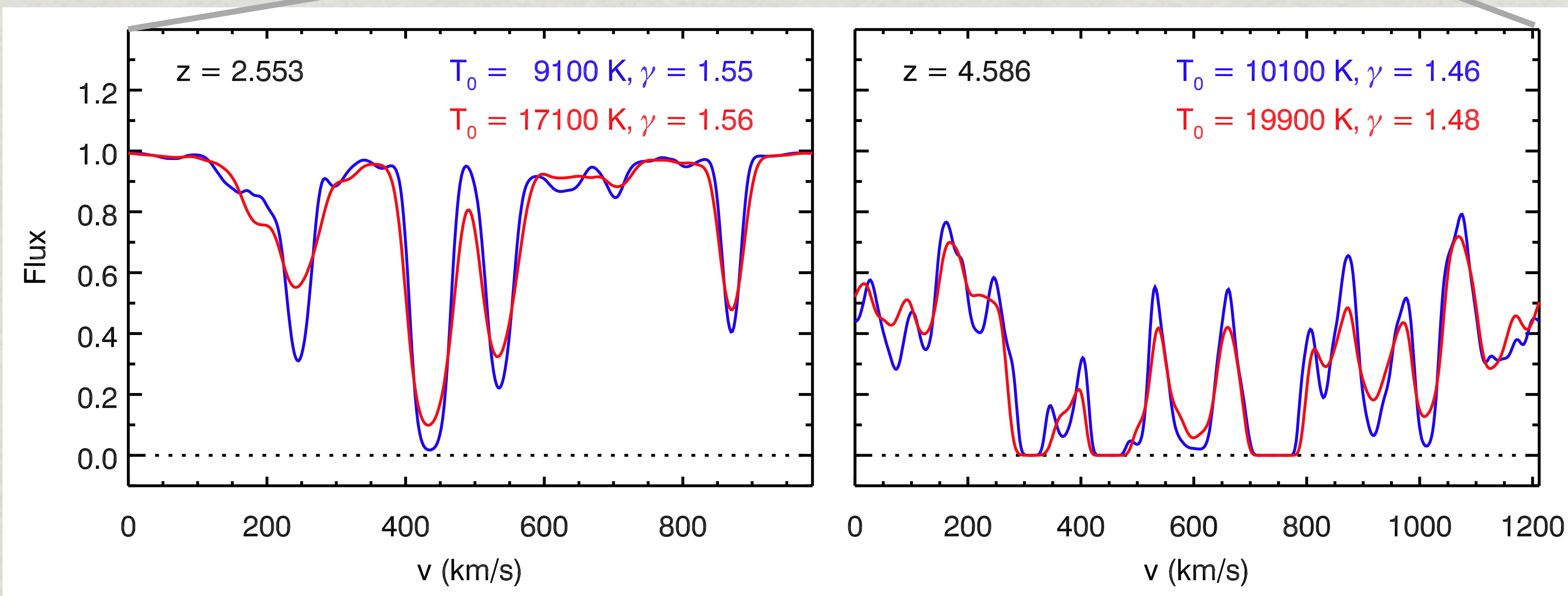
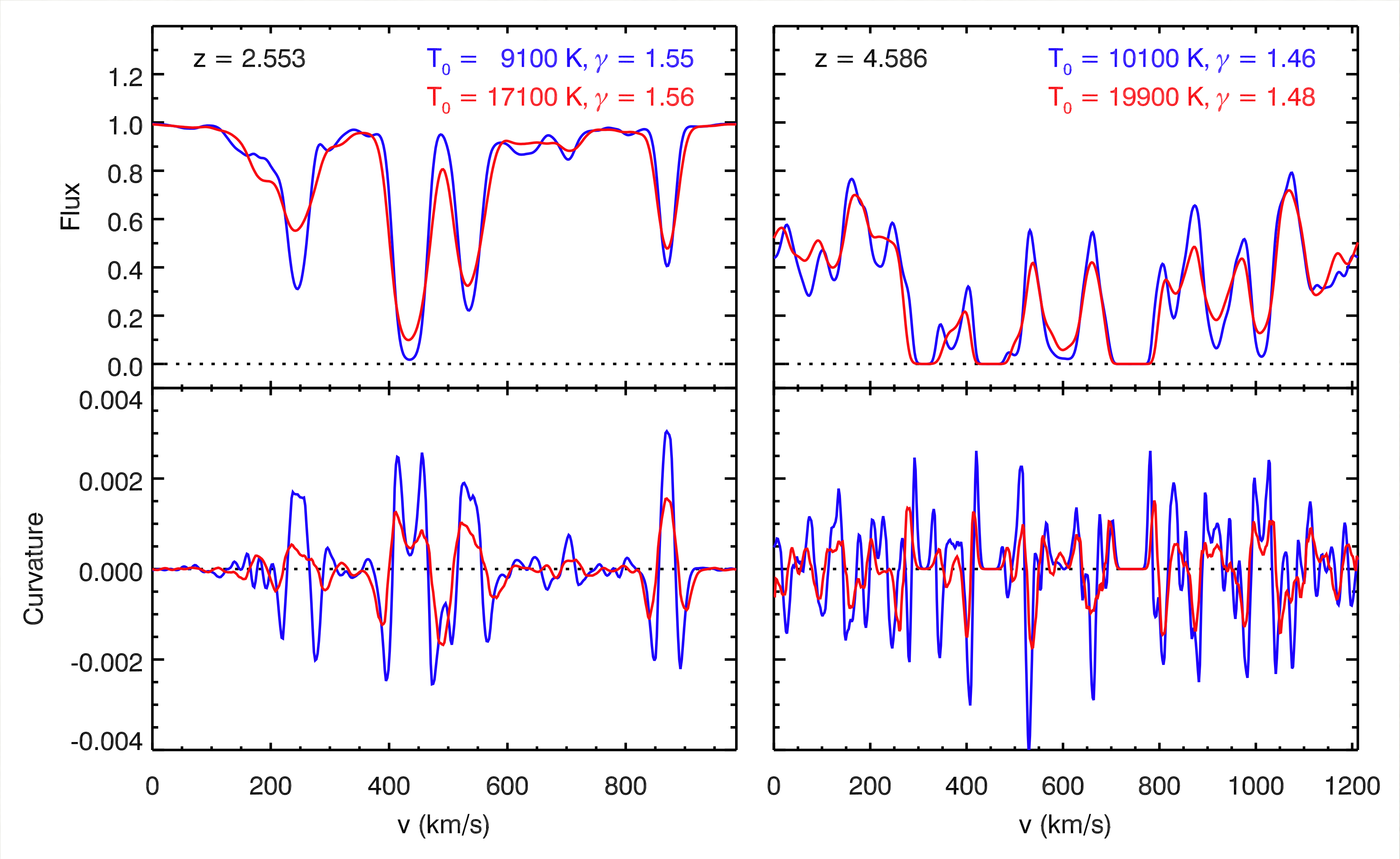




- Small-scale structure
  - Thermal Broadening
  - Jeans Smoothing
- "Classic" Analysis Methods
  - Power spectrum / Wavelets
  - Line widths

Curvature

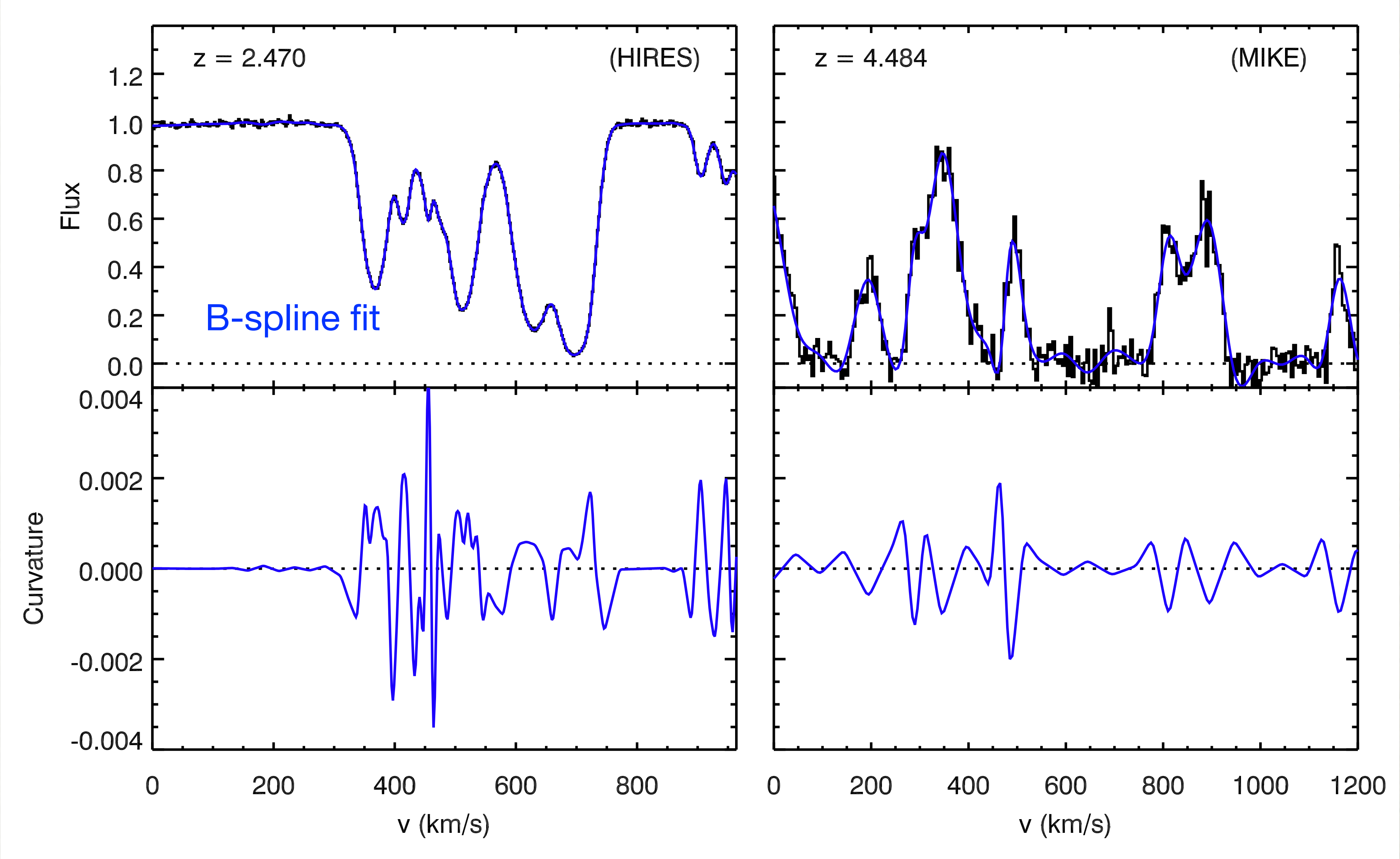


$$\text{Curvature} = \frac{F''}{[1 + (F')^2]^{3/2}}$$

Higher curvature = Colder

Curvature in the data

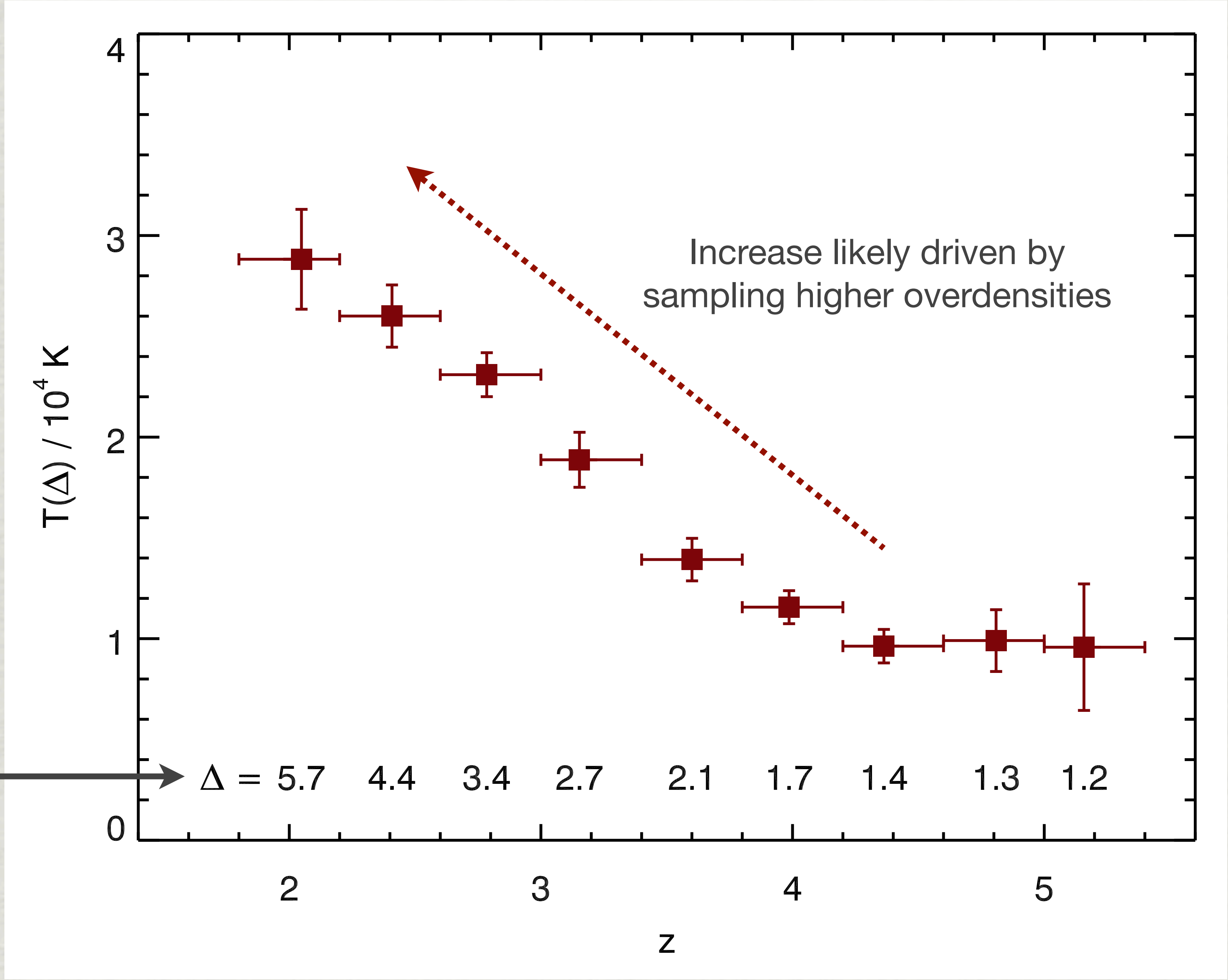
b-spline fits



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

Temperature results - T(Δ)

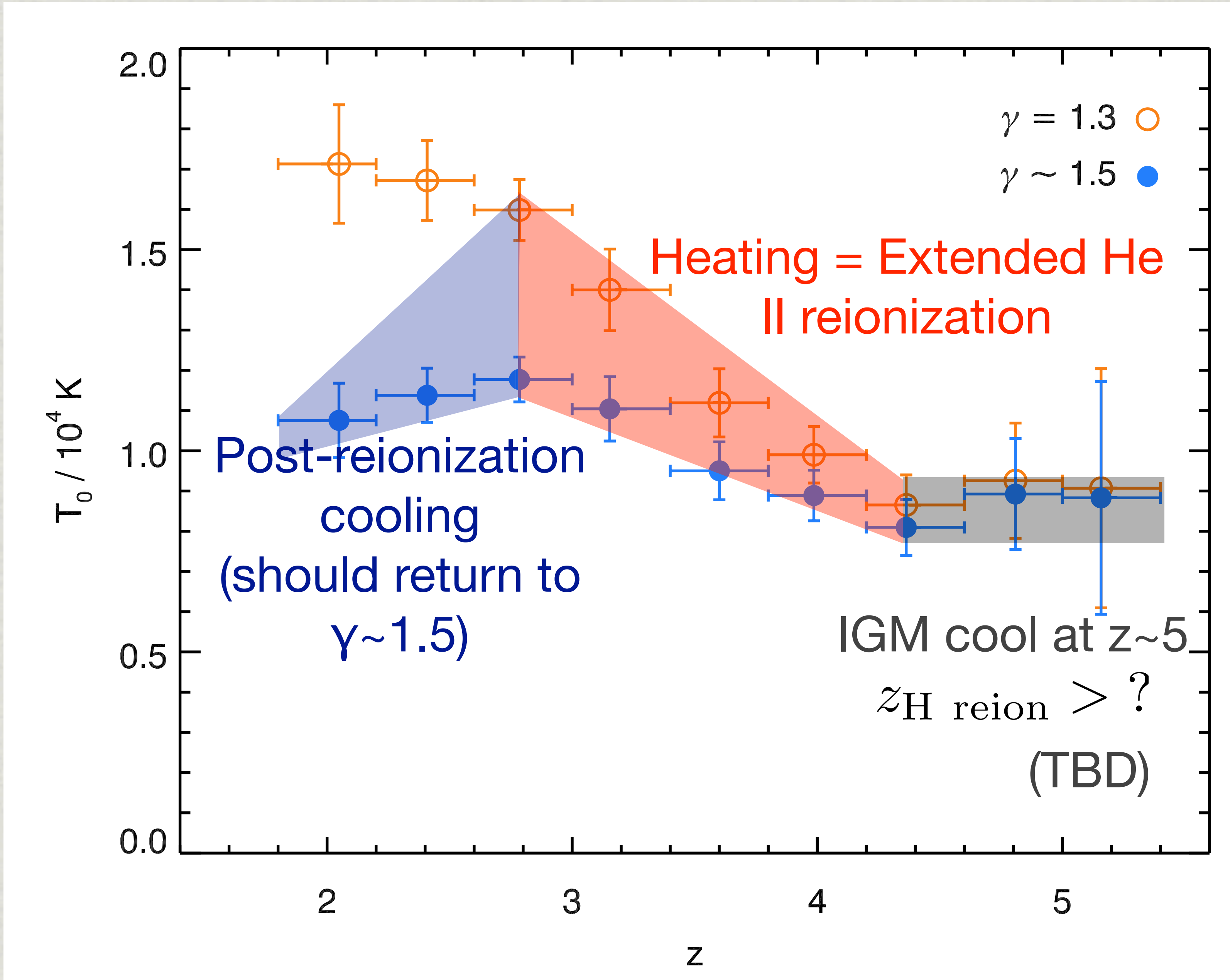
64 QSOs
$2 < z_Q < 6.4$



optimal overdensity

Temperature results - T_0

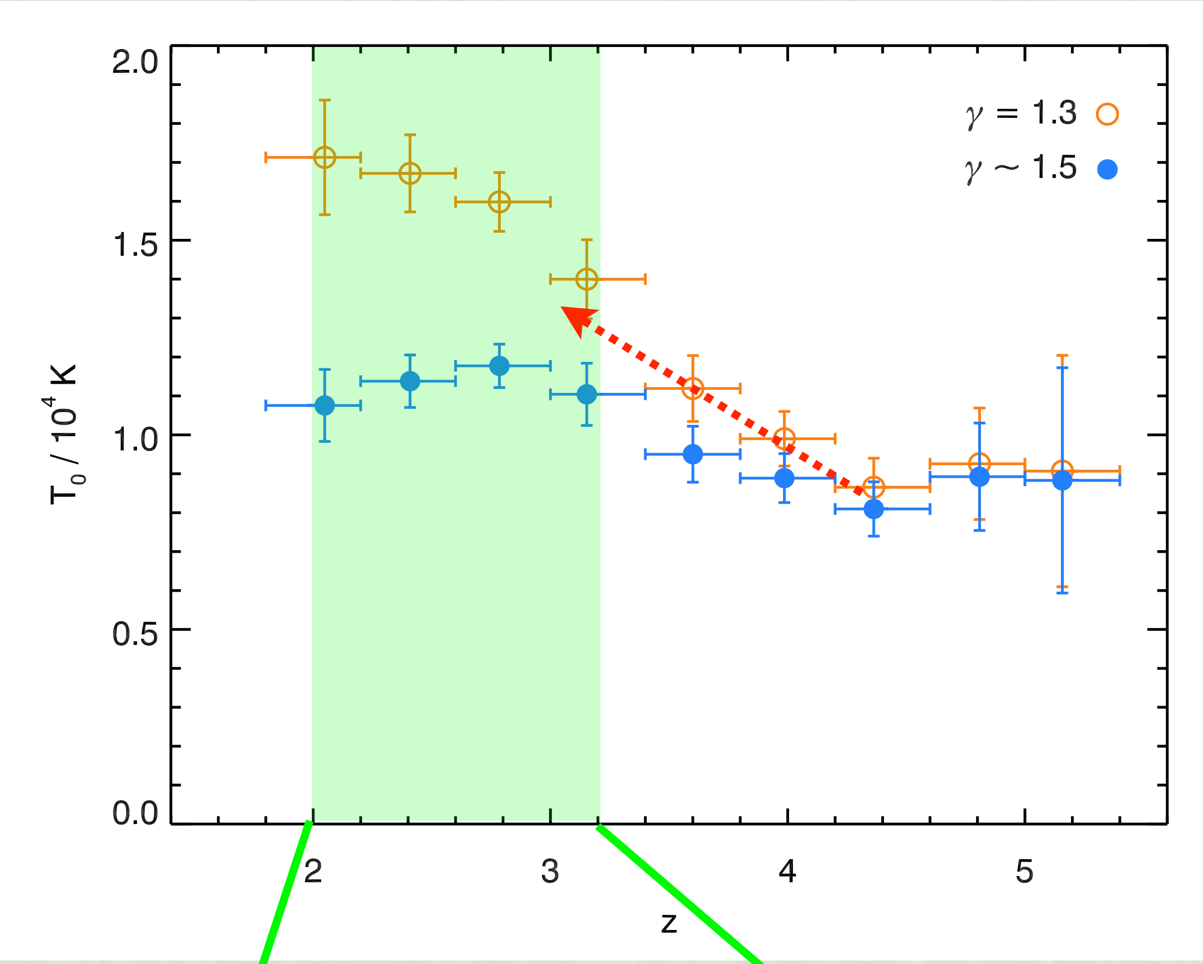
$$T(\Delta) = T_0\,\Delta^{\gamma-1}$$



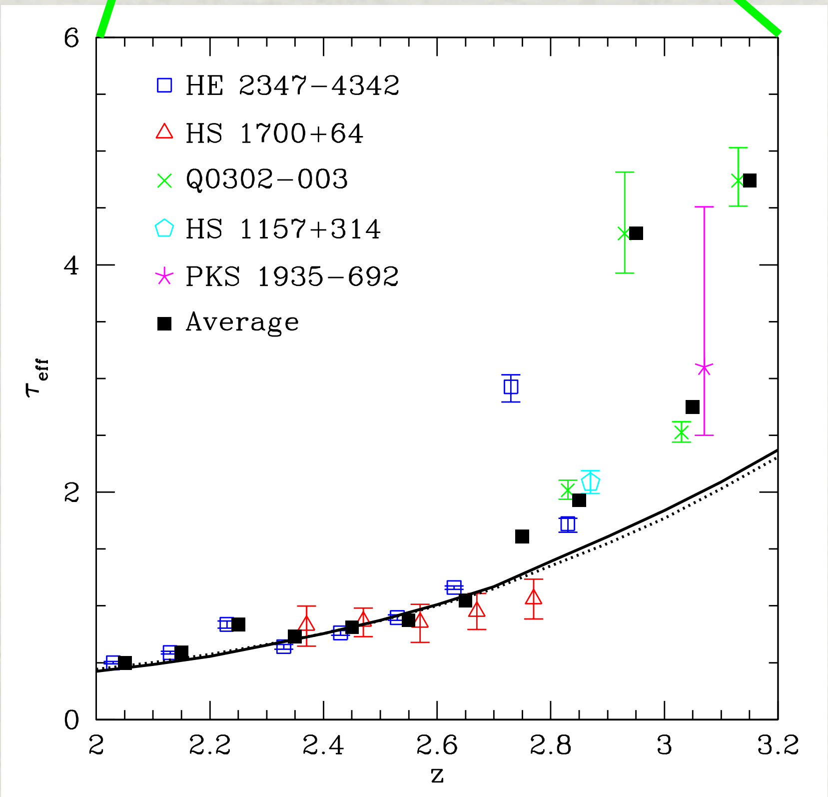
$\gamma \sim 1.5$ Maximum in photoionization equilibrium

$\gamma = 1.3$ Minimum suggested by simulations of He II reionization (McQuinn et al. 09)

Putting together τ_{eff} and T_0



T_0 increases during reionization



Following reionization, the He II Lyα forest becomes transparent

Conclusions -- Temperatures

- New IGM temperature measurements from the curvature of the Lyα forest over z~2-5
- Measure temperature at the densities probed by the forest
- Clear increase in T_0 from $z > 4$ to $z \sim 3$, consistent with an extended He II reionization process
- Results are consistent with a cool-down at $z < 3$, as expected from He II opacity measurements
- 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

Temperature-density relation

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

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

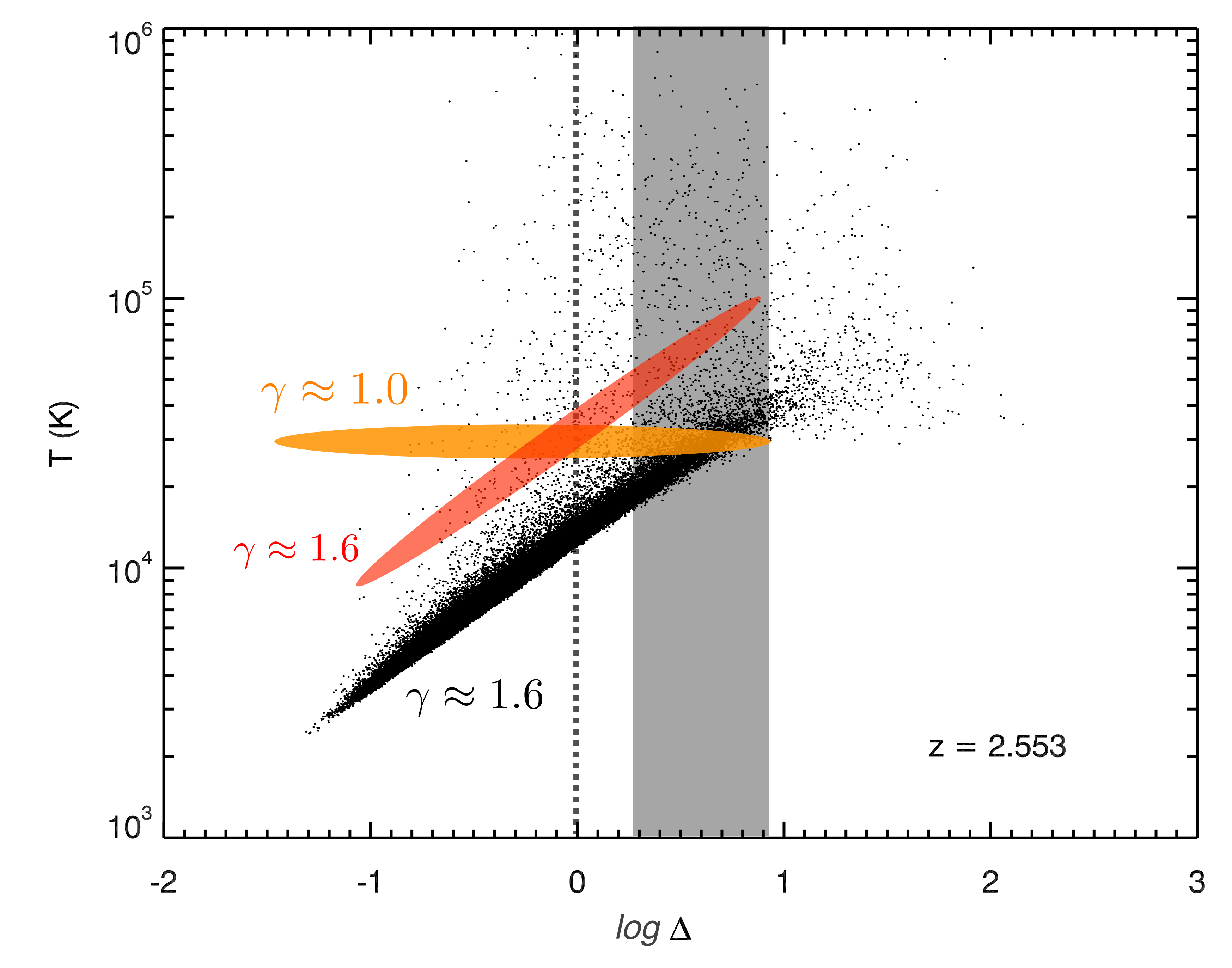
Overdensity:

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

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