Heavy Element Abundances at High Redshifts

Wallace Sargent

Palomar Observatory, California Institute of Technology

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Outline

- QSO absorption lines: introduction
- Abundances in DLA systems
- Very low metallicity DLA systems
- C and O abundances in the IGM at z ~ 2.5
- Abundances at z ~ 6:
    - C, O and Si and Very Massive Stars
    - Fe/O and the origin of Fe at early times

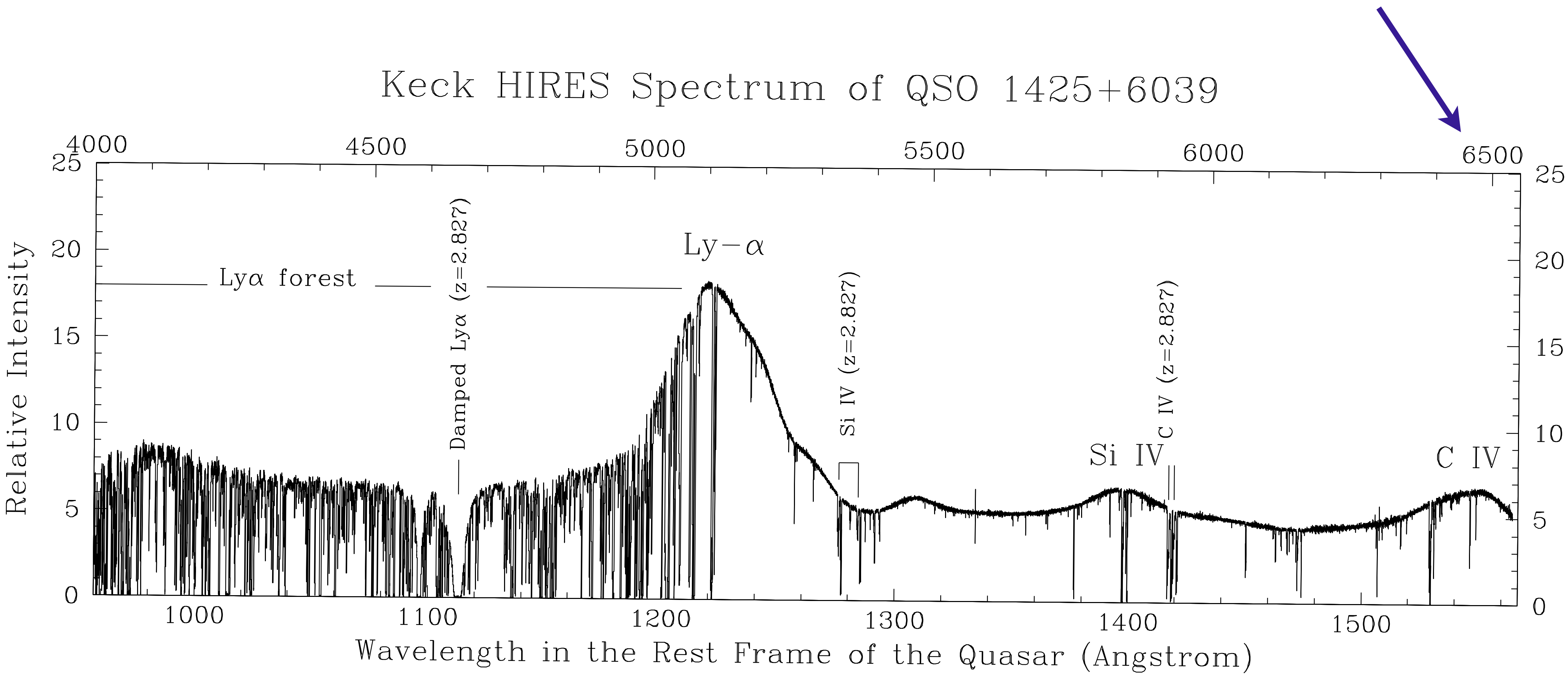
Galaxies at Low Redshifts

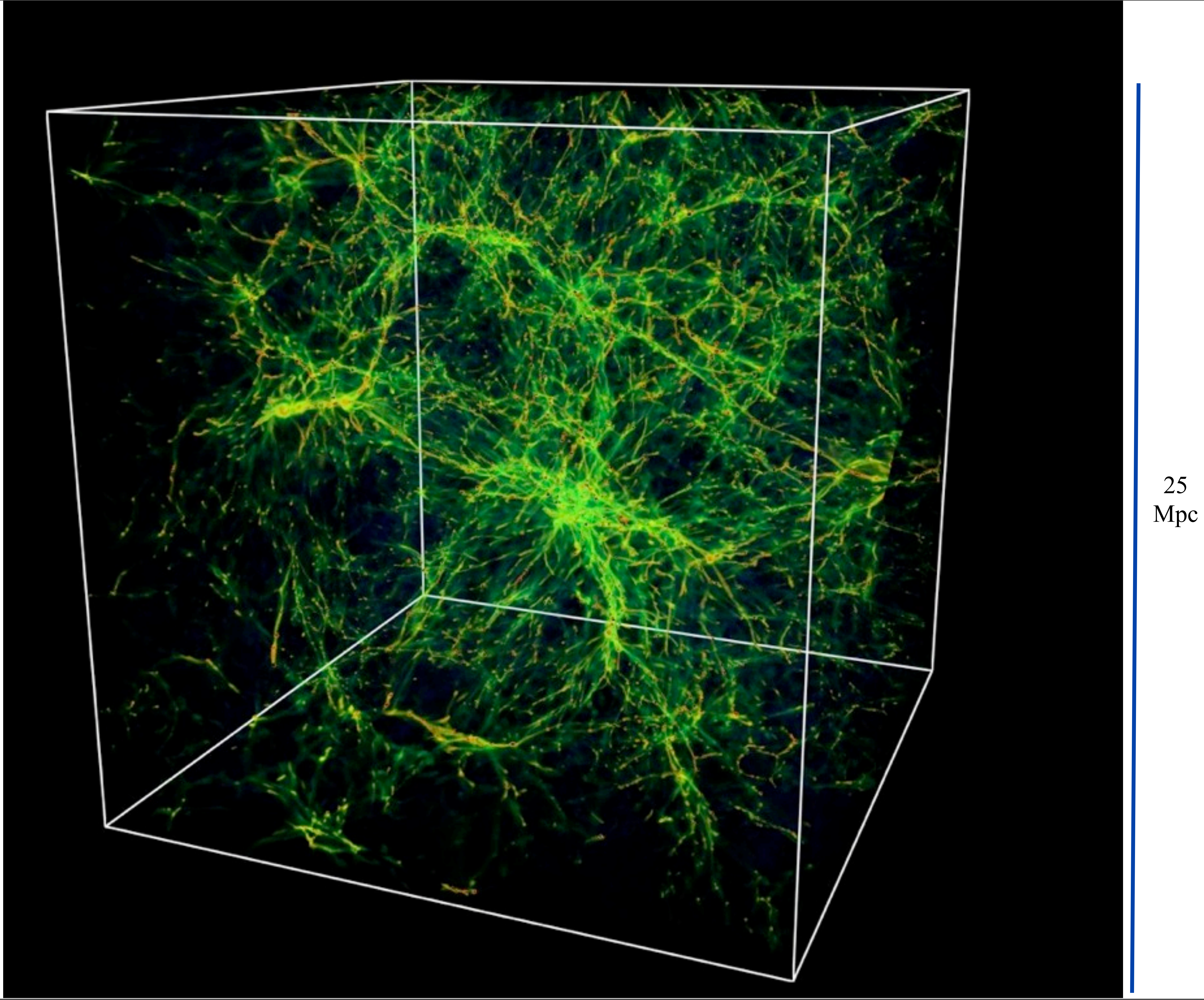
- Only *Dwarf* galaxies are metal-poor overall
- Dwarf spheroidals have [Fe/H] ~ -2
- Dwarf irregulars (BCGs) have O/H ~ 1/50 solar (and no lower)
- None of these systems appear to be very young
- We have not found local gas clouds devoid of stars or heavy elements (?)

The Lyman Break Galaxies

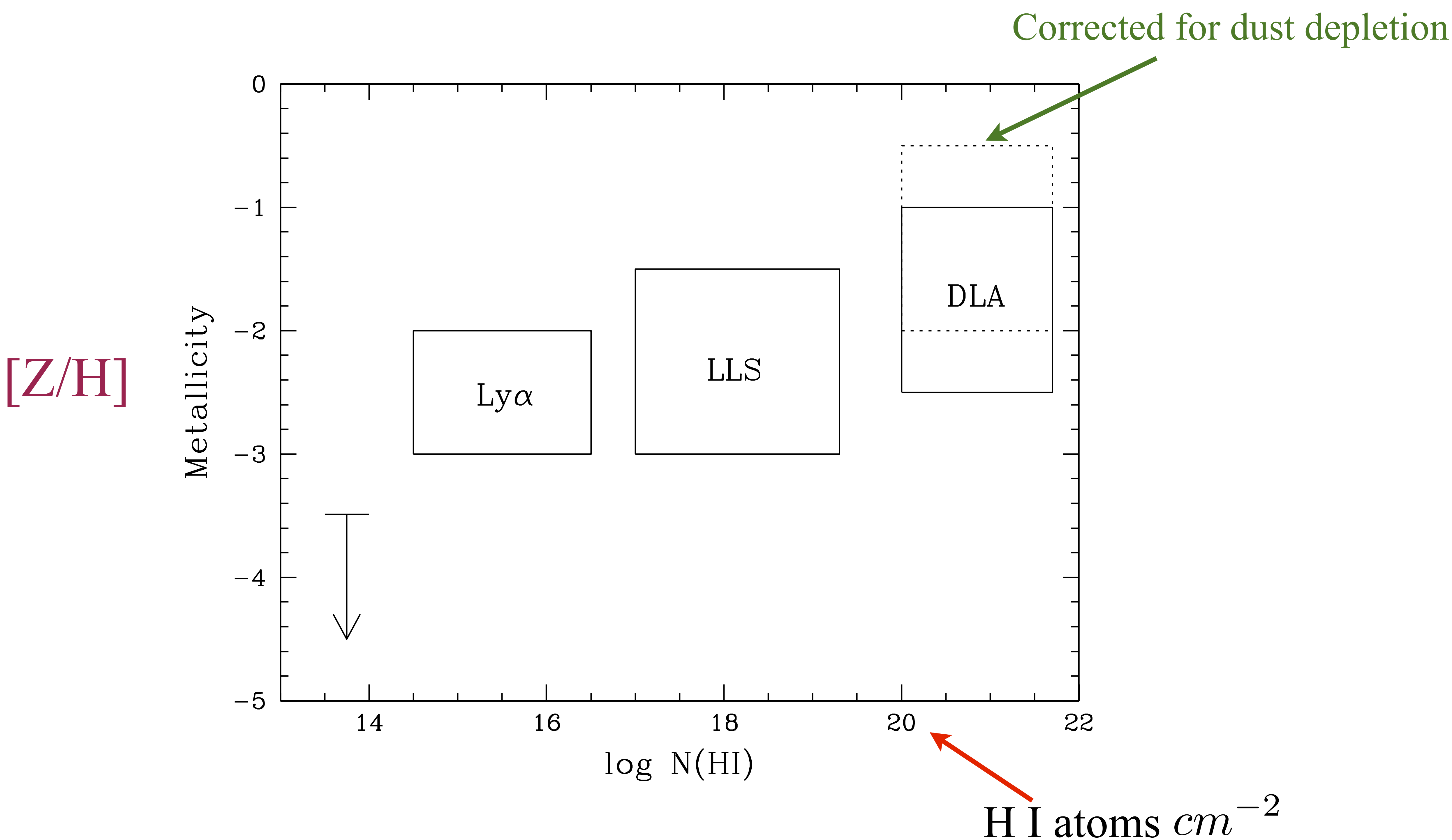
- LBGs: regions of star formation a few kpc in size at $z \sim 3$.
- Evidence for galactic winds– blue-shifted broad absorpion lines.
- Early star-forming galaxies eject metal-enriched gas into IGM.
- Emission and absorption lines from stars, ISM (seen against the background stars) all point to $[\mathrm{Z/H}] \sim 0.5$ solar value *in* star-forming regions at $z \sim 3$
- This, together with evidence from QSO emission lines at $z \sim 6$, indicate *very rapid build-up of heavy elements in early protogalaxies.*

Observed frame



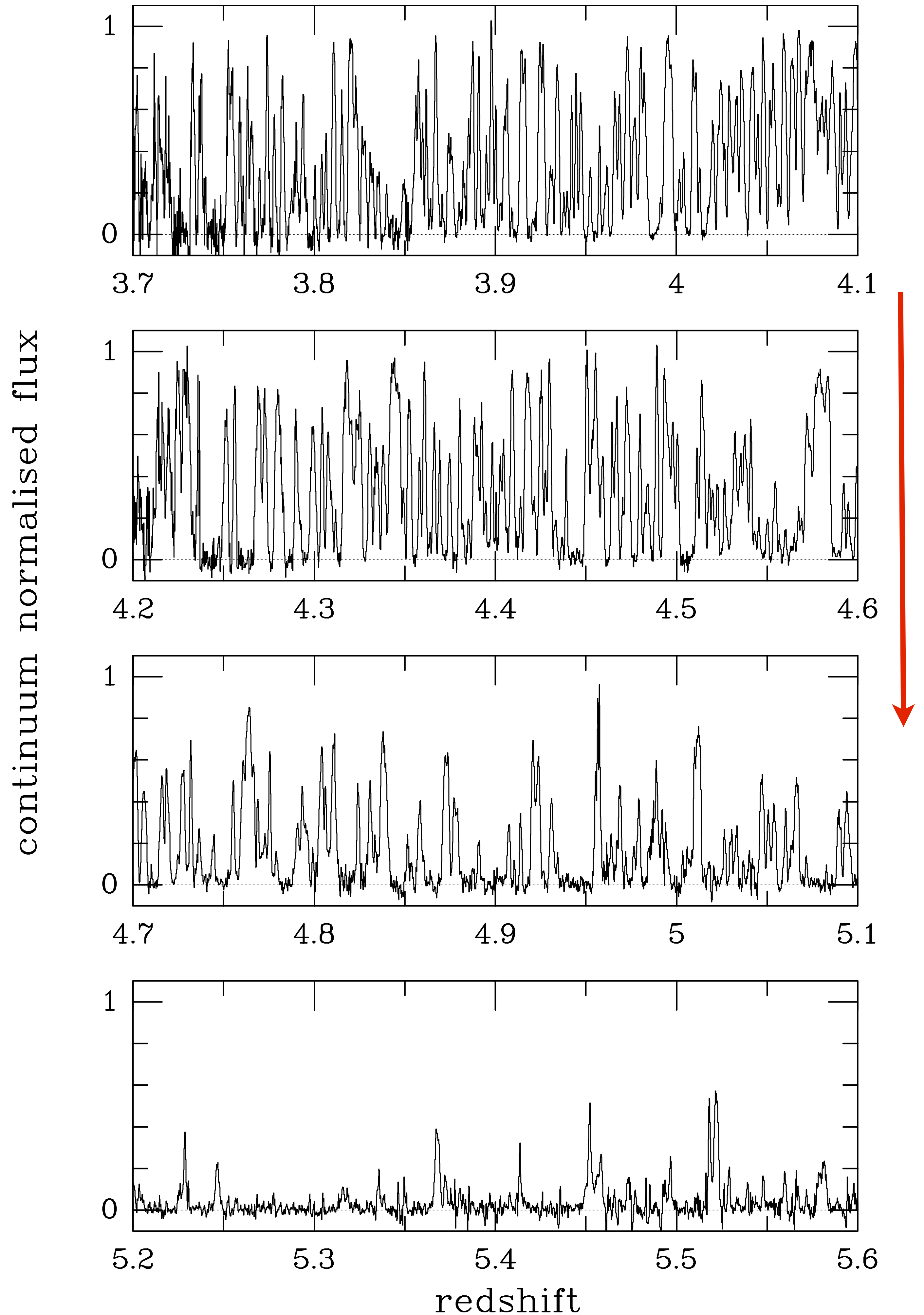

25
Mpc

Abundances as a function of H I column density



Abundances at high redshifts - questions:

- When were the first heavy elements produced ?
- Initial mass function of the ‘First Stars’?
- How has the mass in elements heavier than H evolved in time?
- Distribution of [Z/H] in the IGM?
- Are there regions (e.g. in the voids) devoid of heavy elements?



Lyman-alpha forest gets thicker with increasing redshift

Universe gets denser with increasing z and density of ionizing sources decreases above z ~2.5

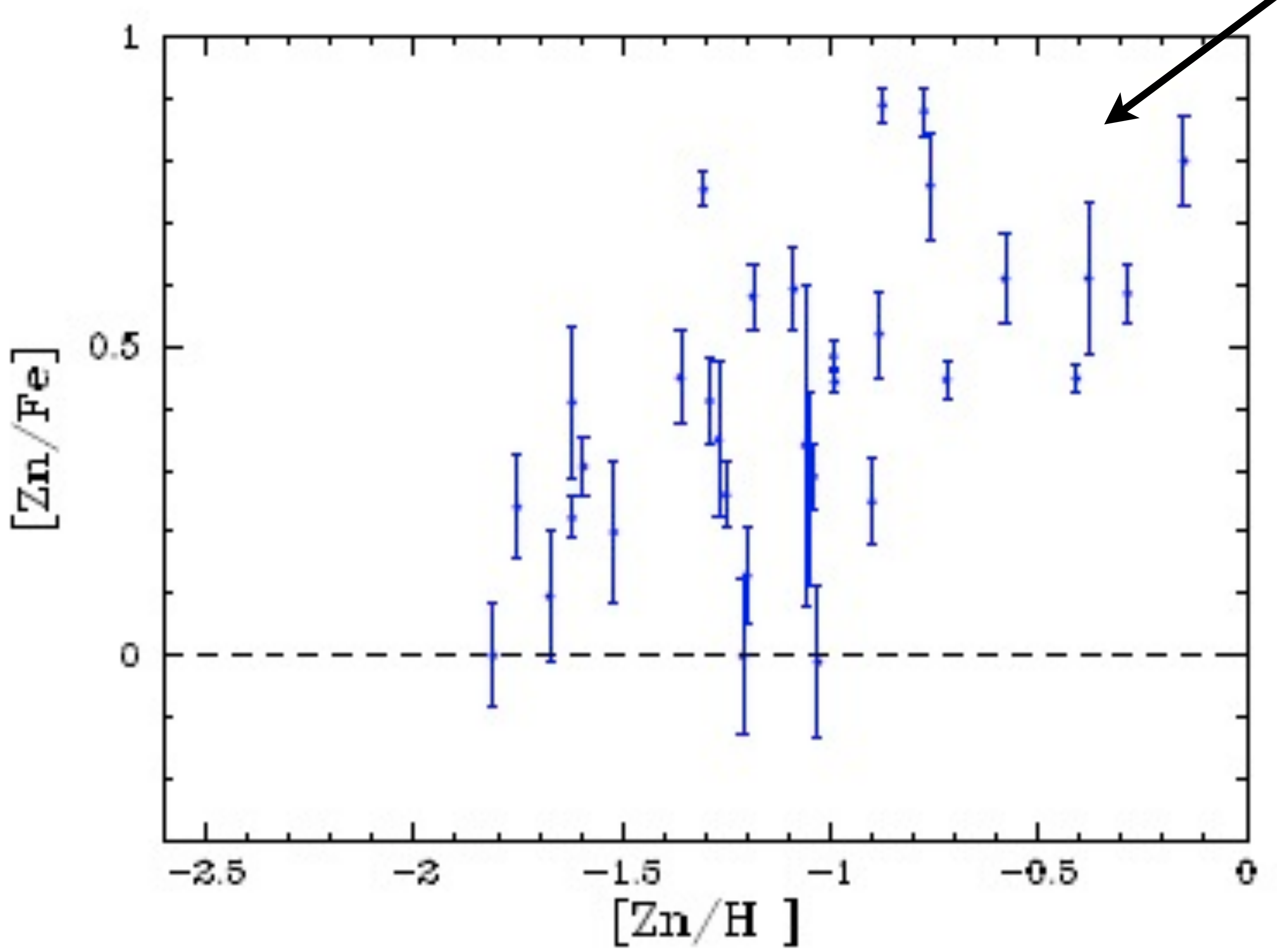
$$n_{HI} \propto n_H^2 / n_\gamma$$

$$n_H \propto (1+z)^3$$

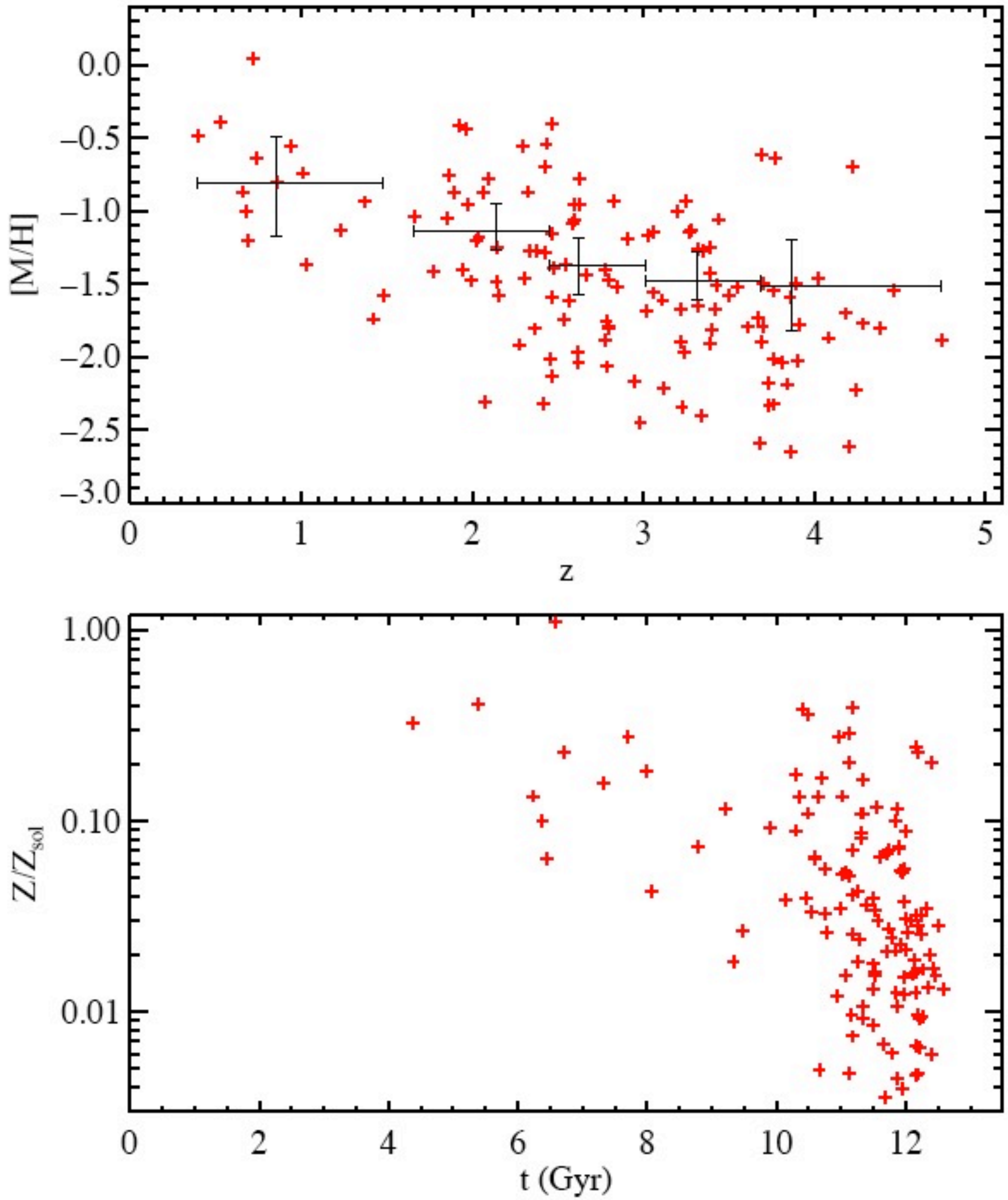
The Damped Lyman-alpha absorbers

- DLA absorbers *defined by their H I column density*
- H I regions: no ionization corrections.
- Can observe more elements at high z than by any other method.
- Problem of differential depletion onto *dust grains*

Zn/Fe high in gas phase because Fe depleted into dust grains



Evidence for dust in DLA absorption systems. Zn is not depleted in the Galactic ISM -- low condensation temperature.



0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
[M/H]
0
1
2
3
4
5
z
1.00
0.10
0.01
Z/Z$_{sol}$
0
2
4
6
8
10
12
t (Gyr)

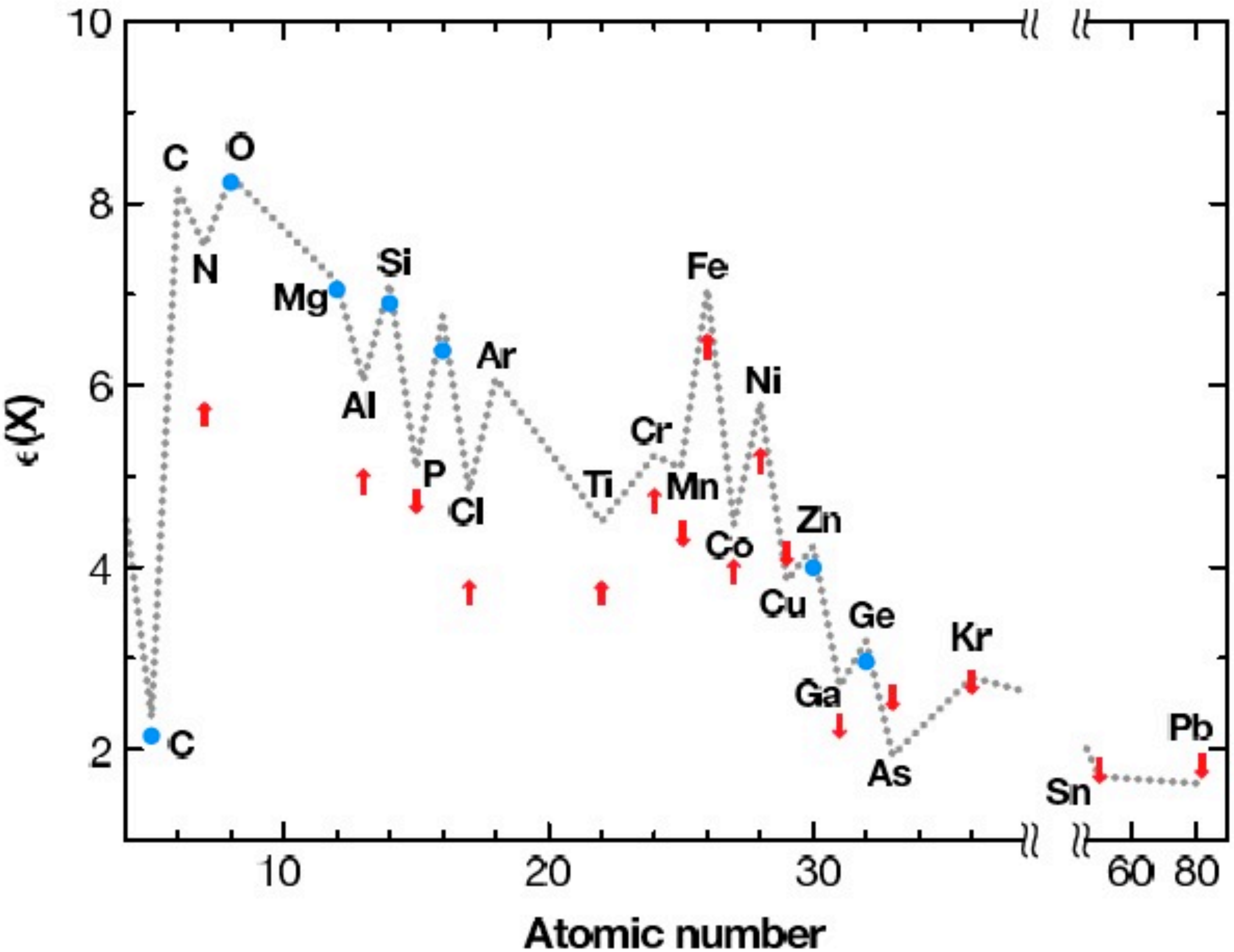
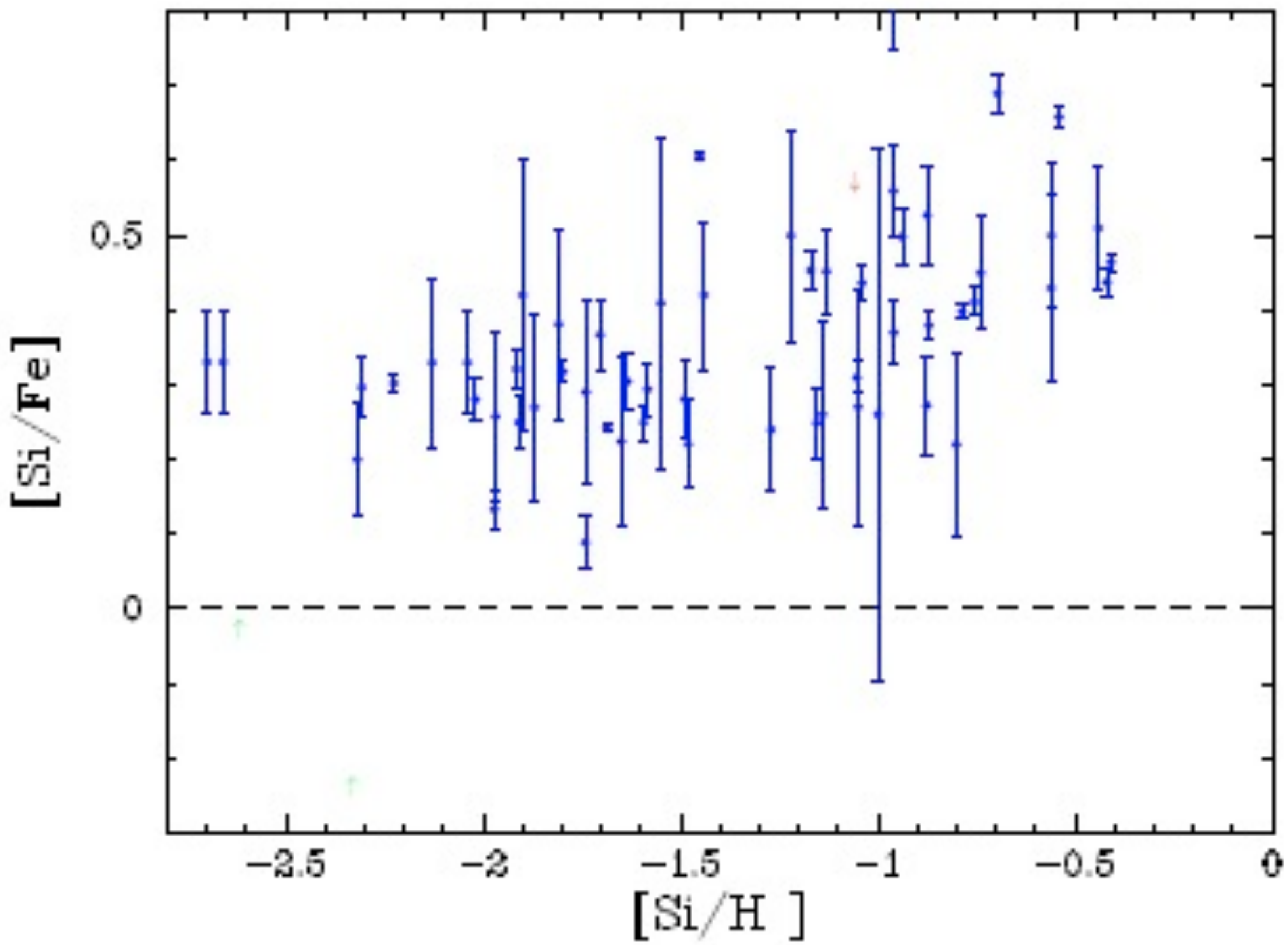
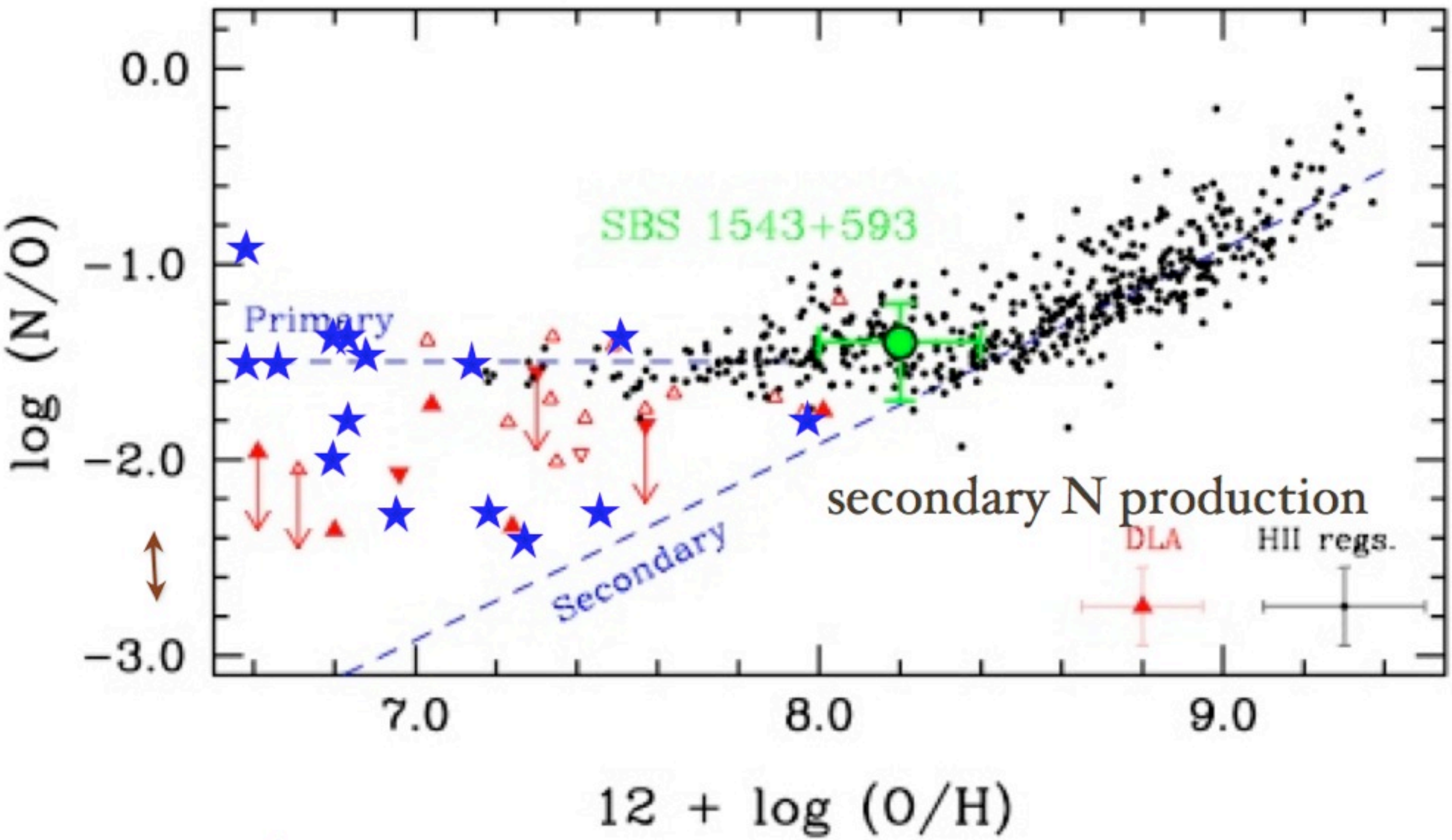


Figure 9: Abundance pattern for the metal-strong damped Lyα system at z = 2.626 toward Q0812+32. Because of the high metal abundance, [O/H] = −0.44, a dust correction is necessary, and in this case a conservative 'warm halo' correction (Savage & Sembach 1996) was applied. The dotted line traces the Solar abundance pattern scaled to match the oxygen abundance of the damped Lyα system.



Si/Fe ratios in DLA systems. Fe is dust depleted at high Si/H.
At low Si/H values the Si/Fe ratio is typical of Type II SNe.

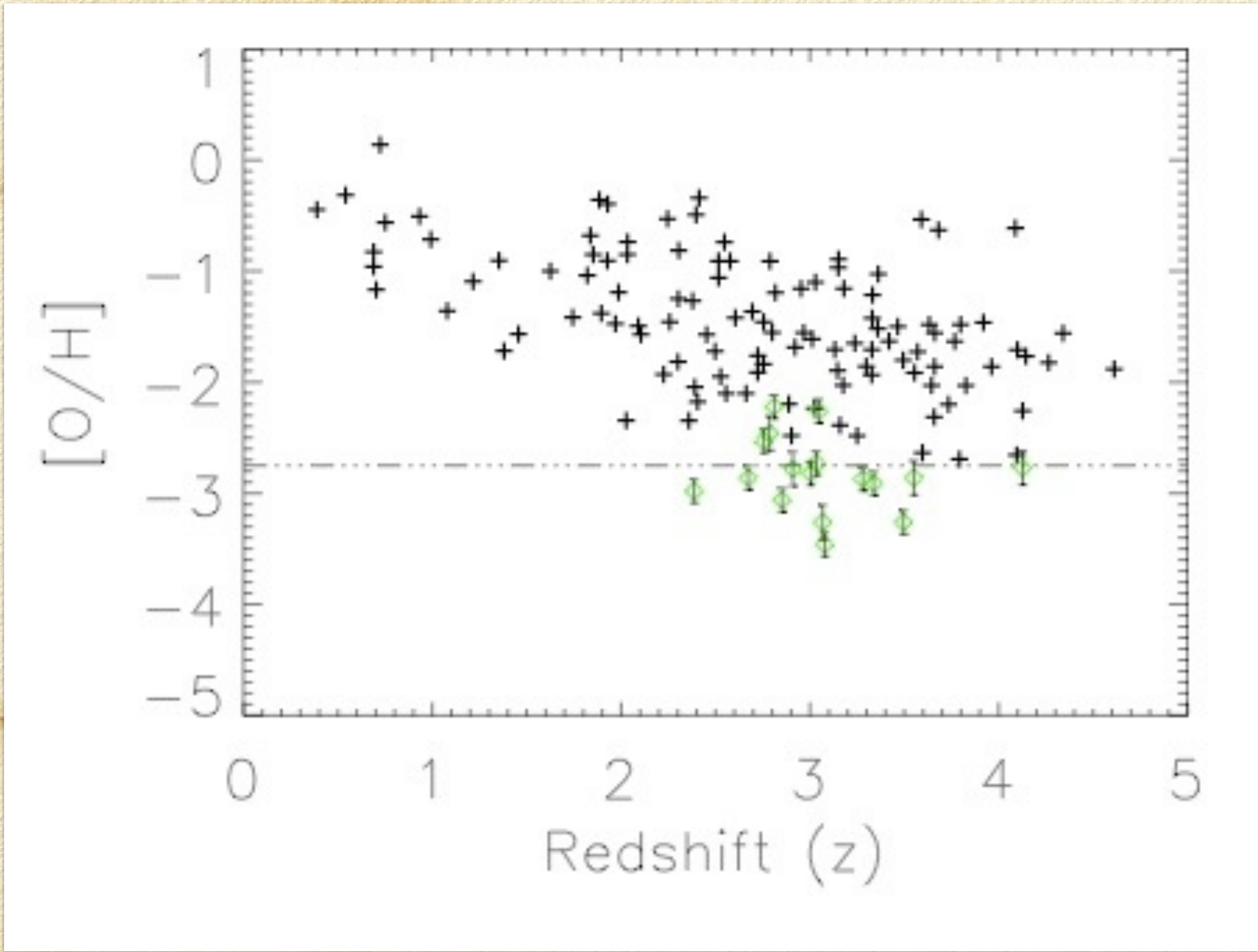


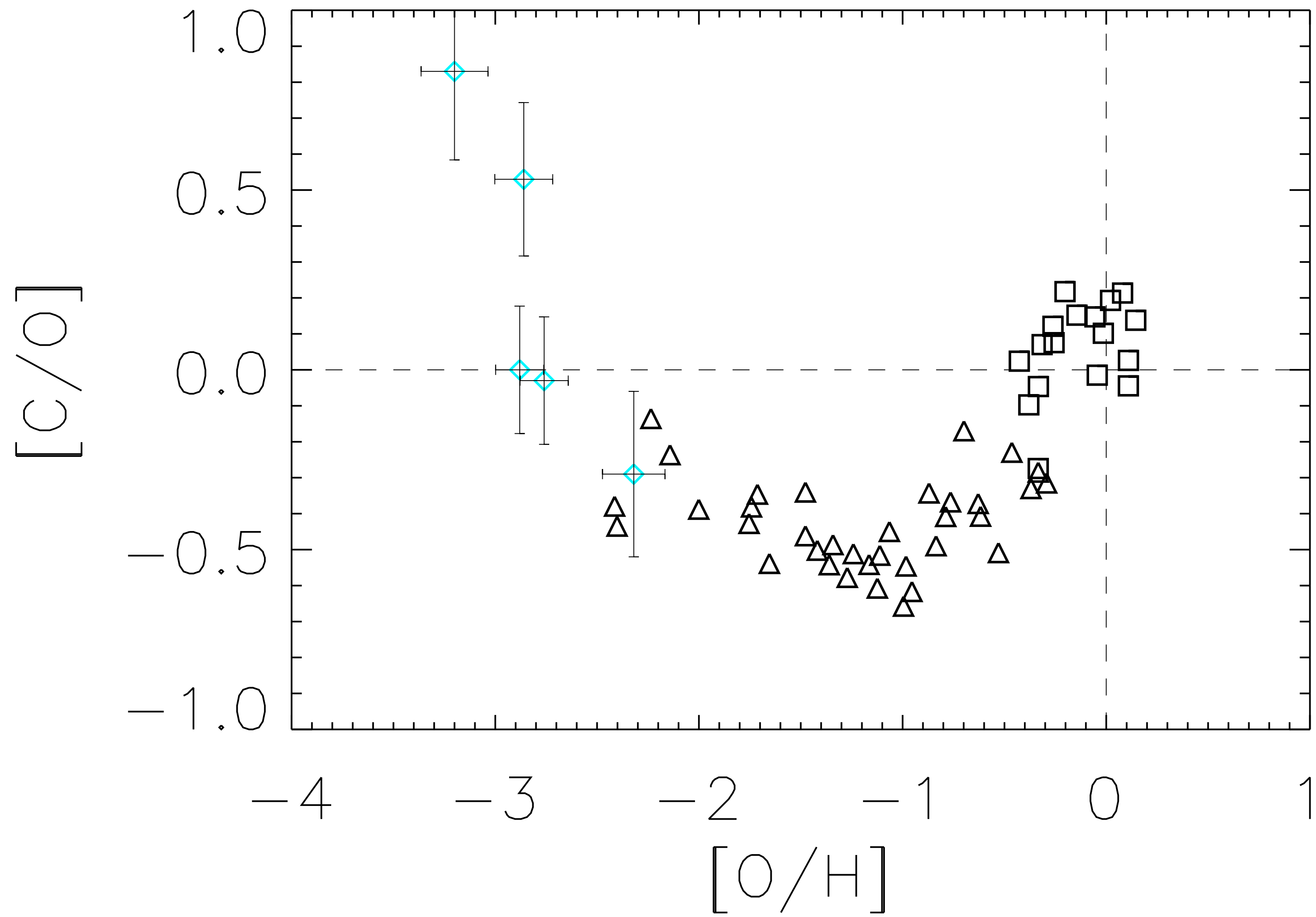
(our DLA HIRES sample)

Damped Lyman-alpha Galaxies

- Large dispersion in [Fe/H] at all redshifts.
- Little change in the mean [Fe/H] with redshift.
- No value of [Fe/H] *below* -2.7 (1/500 solar value).
- High Si/Fe indicates Type II supernovae (massive stars)

New results showing O/H for sample





1.0
0.5
0.0
−0.5
−1.0
[C/O]
−4
−3
−2
−1
0
1
[O/H]

Search for very metal poor DLA absorbers in Prochaska SDSS sample: conclusions:-

- No absorbers with M/H convincingly below 0.001 solar - there is a ‘floor’
- Usually one velocity component - most metal poor DLAs are dwarf systems as in local universe
- C/O rises probably to super-solar value for [O/H] ~ -3 continuing a trend observed in DLAs and halo stars at lower [O/H]

Abundances in the IGM at High Redshifts

- Almost all of the baryons are in the IGM.
- The IGM is highly ionized-- log(N(H I)/N(H)) ~ -5.
- General IGM ionized mostly by observed QSOs at z ~ 2- 5.
- Abundant ions: C IV, Si IV, N V, O VI, C II, Si II.
- Relative strengths depend on IGM density (big contrasts between the voids and the walls and filaments).
- Few elements can be observed.

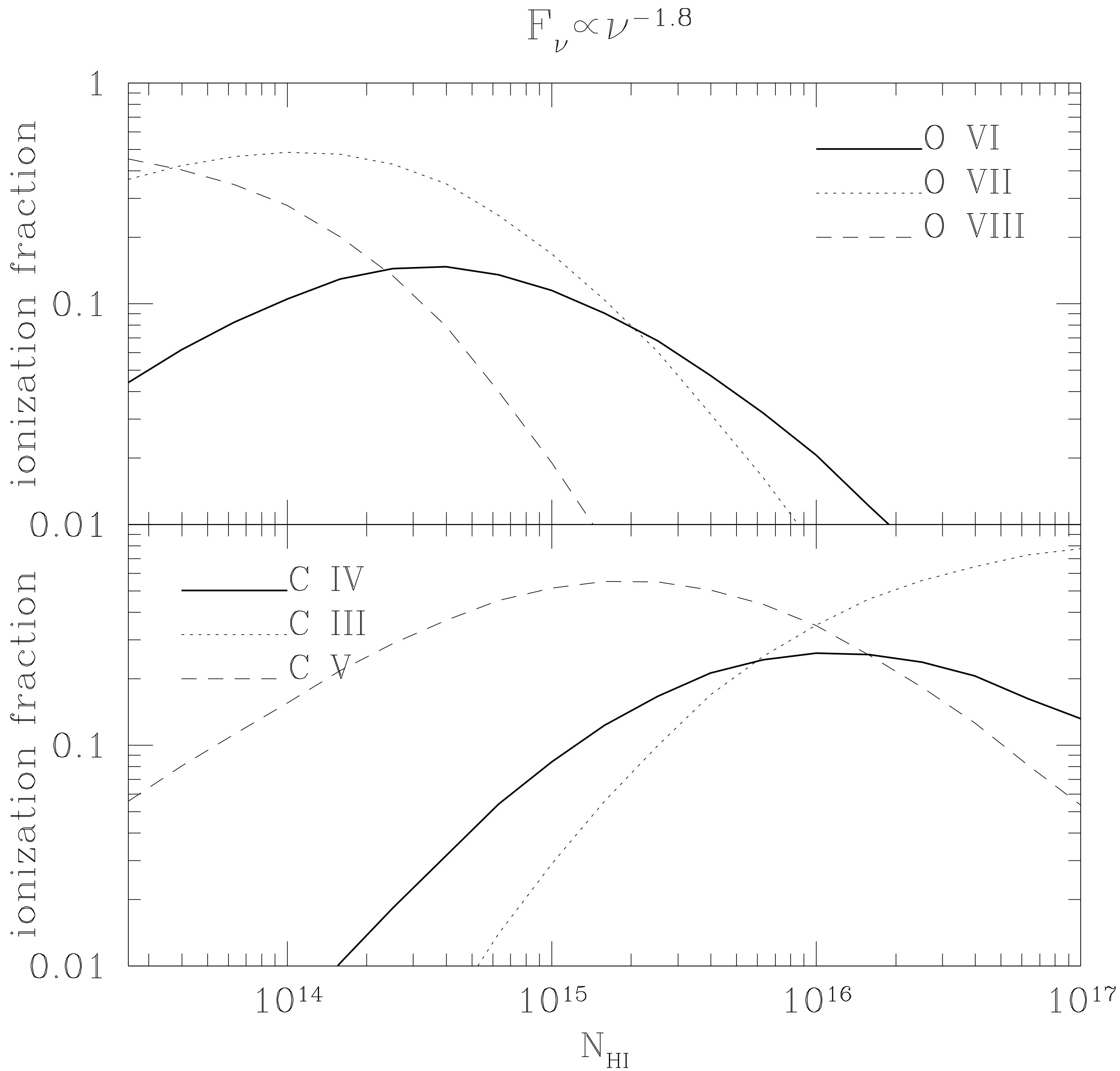
Element Abundance Distributions in the IGM

- *Best ions are C IV 1548, 1550A and O VI 1032, 1036A doublets*
- *C IV and O VI constitute roughly 20 percent of the C and O in the tenuous IGM*
- *O VI is always in the Lyman-alpha forest*
- *At z ~ 2.5 have thin forest and bright QSOs to use as background sources for spectroscopy*

IGM metal abundances from O VI and C IV

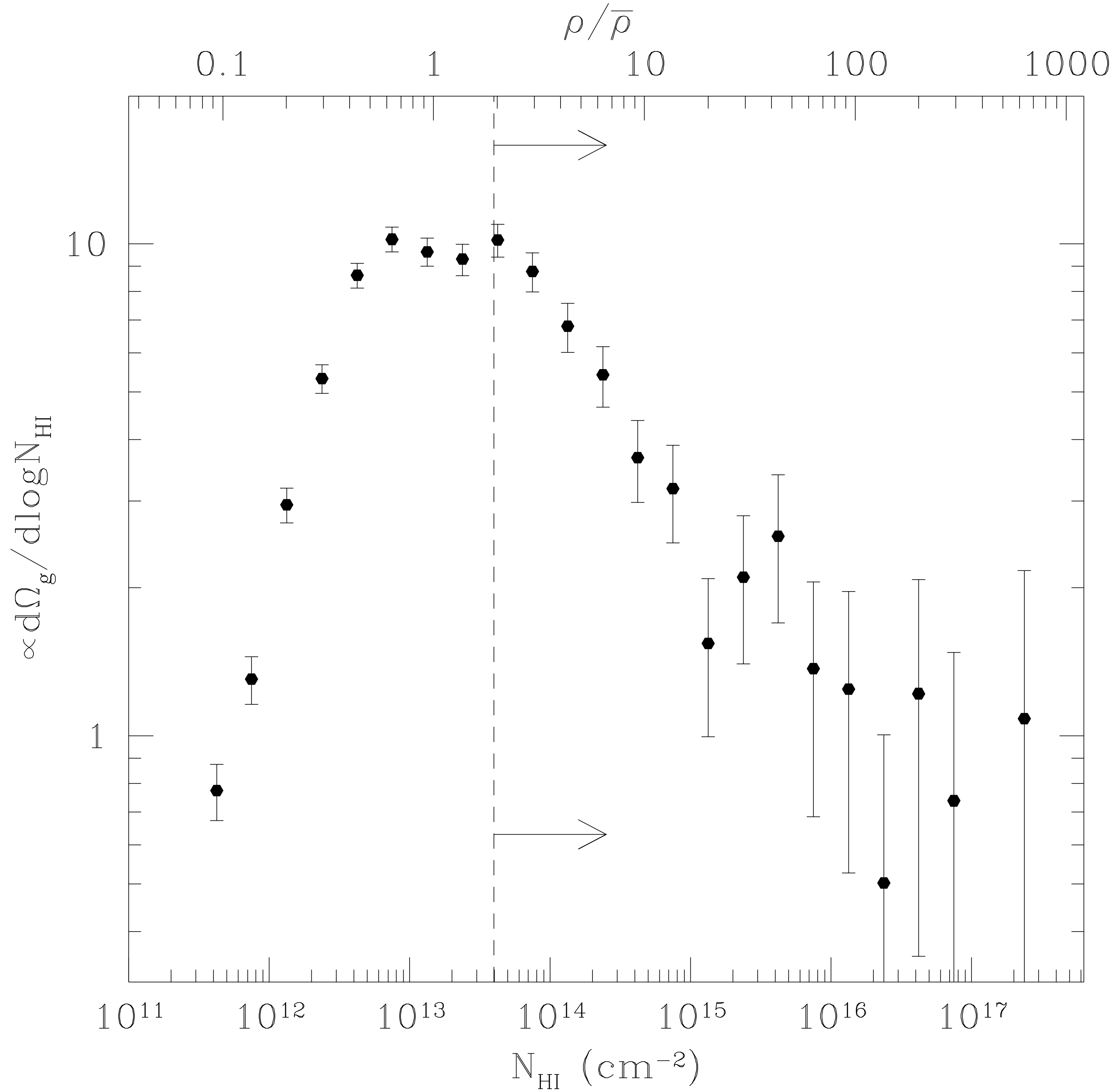
- O VI is most sensitive measure of metallicity in the tenuous IGM.
- O VIλ1032-1037 always in Lyα forest.
- Optimal redshift from ground $z \sim 2.5$ to get thinnest forest.
- UV radiation from QSOs dominates metagalactic ionization.

Simcoe, Sargent and Rauch, ApJ 2004



Predicted ionization fractions for O and C in the IGM as a function of H I column density. O VI predominates over C IV for log N(H I) < 15.

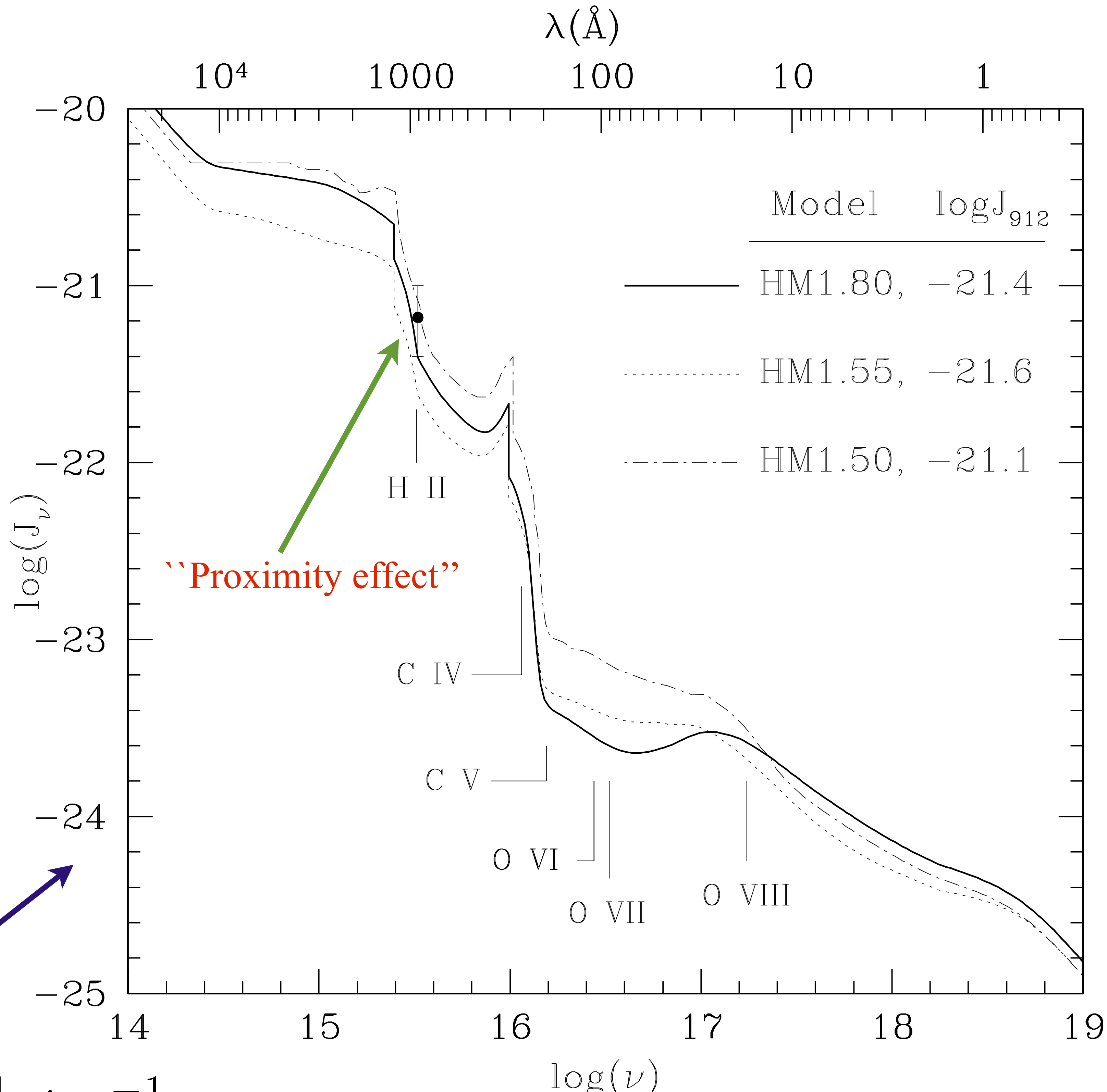
Simcoe, Sargent and Rauch (2004)



Contribution of different H I column densities to Ω_{baryon} and their mean dependance on overdensity. The maximum contribution is from lines with $10^{13} \leq N(HI) \leq 10^{14}$. Our O VI survey is complete for overdensities $\rho/\bar{\rho} \geq 2$ and for column densities $N(HI) \geq 3 \times 10^{13}$.

Simcoe, Sargent and Rauch (2004)

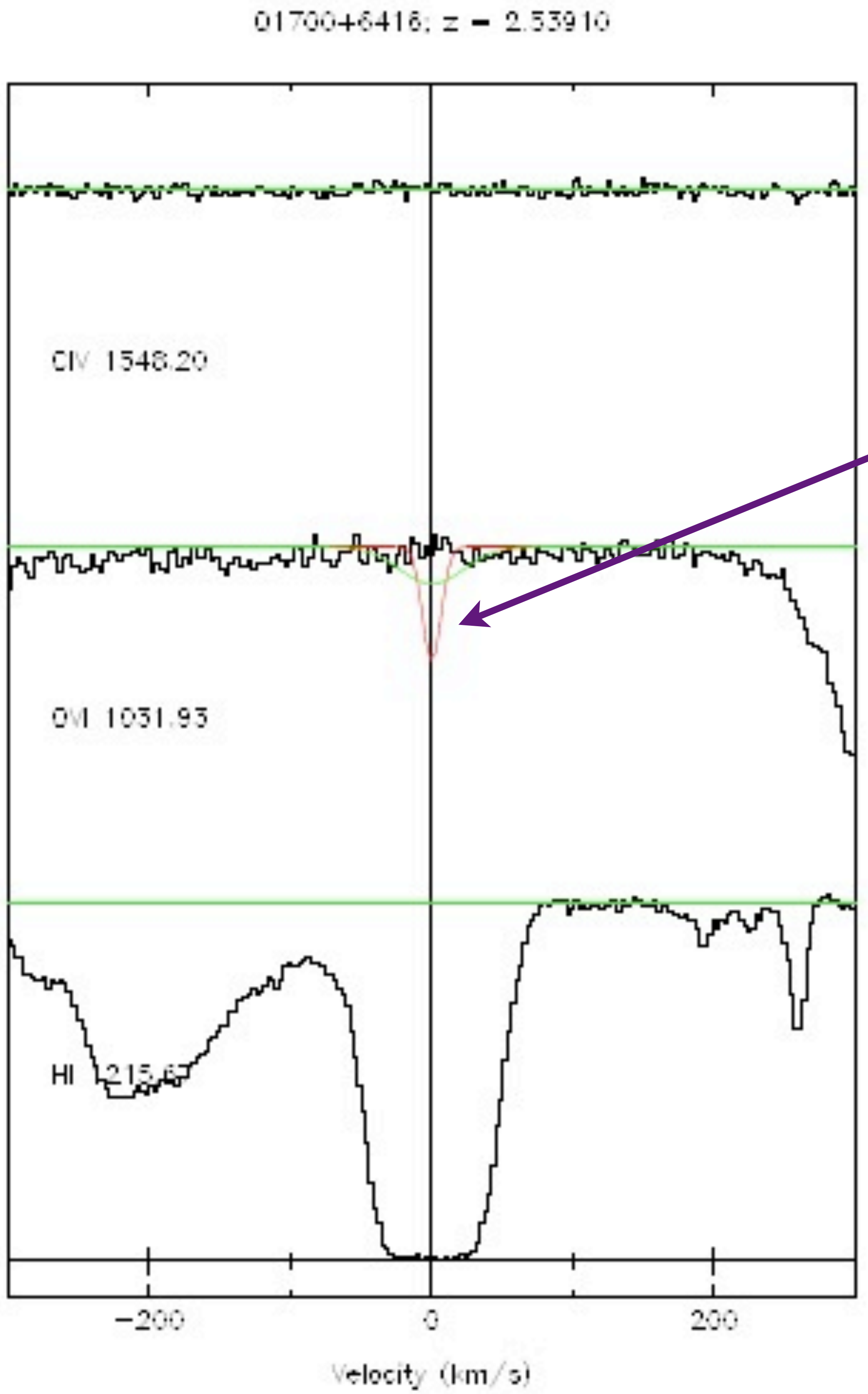
Haardt-Madau metagalactic ionizing spectrum



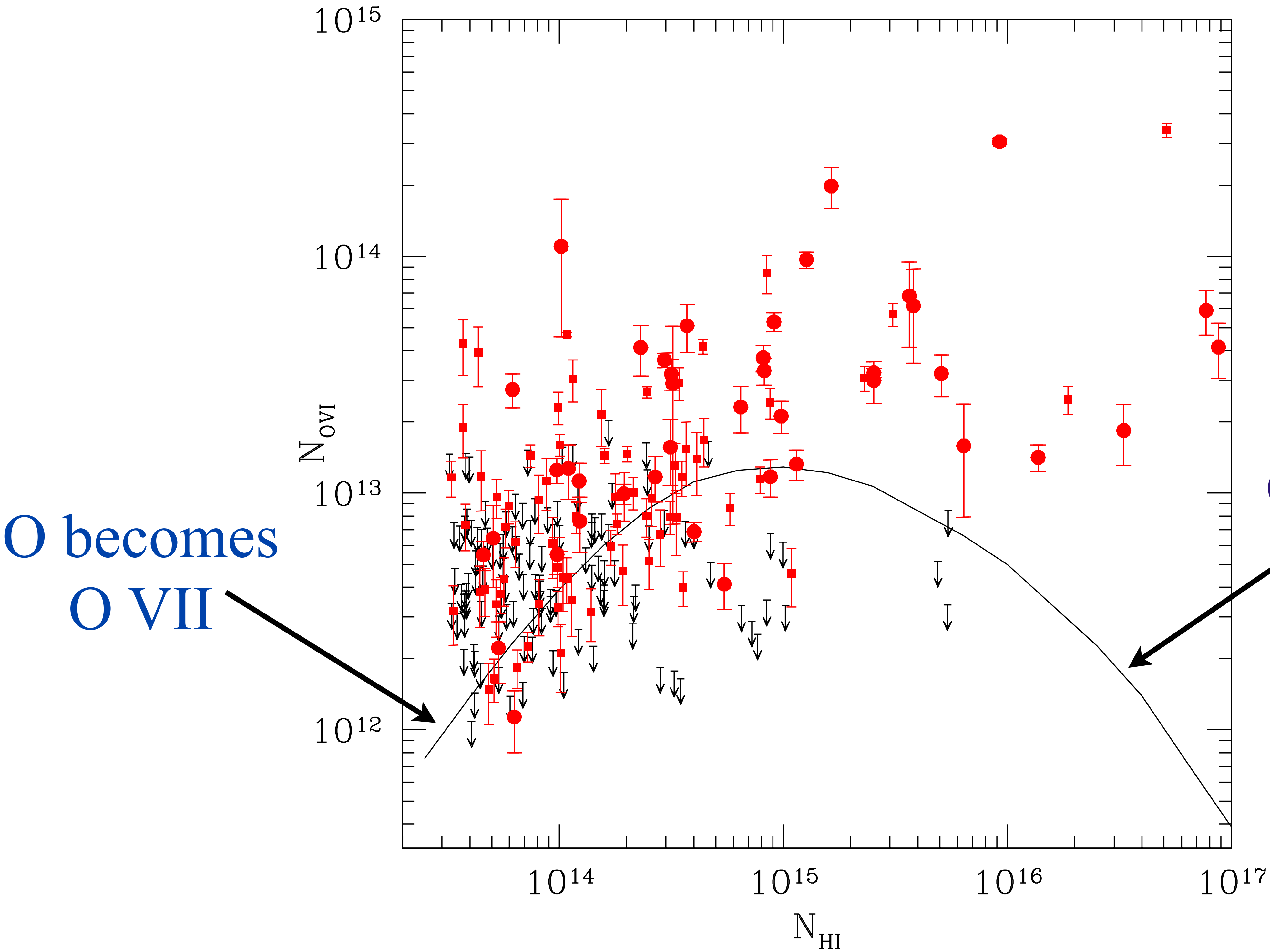
$ergs\ cm^{-2} s^{-1} Hz^{-1} ster^{-1}$

O VI and C IV Observations

- Seven very bright QSOs observed with Keck HIRES; $2.5 \leq z_{em} \leq 2.8$
- Fit Lyα forest to remove Lyβ,γ, etc
- Look for O VI and C IV associated with each Lyα
- Estimate completeness of O VI using simulations.
- Plot points and upper limits in log N(H I) - log N(O VI, C IV) planes.



Expected strength of O VI 1032 for [O/H] = -2.5

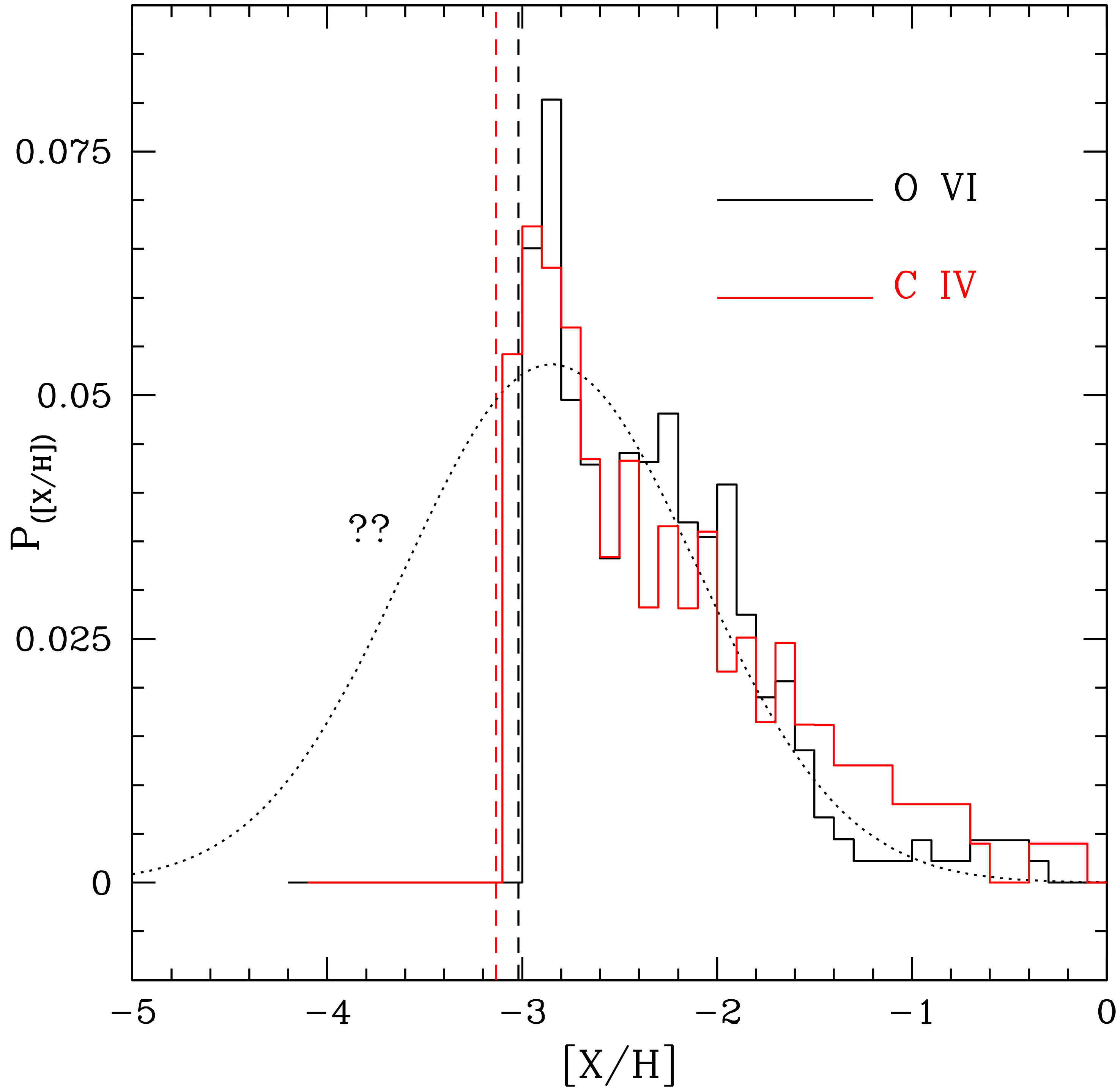


Plot of N(O VI) versus N(H I). The black points are upper limits. The curve shows the expected relation for [O/H] = -2.5

Simcoe, Sargent and Rauch (2004)

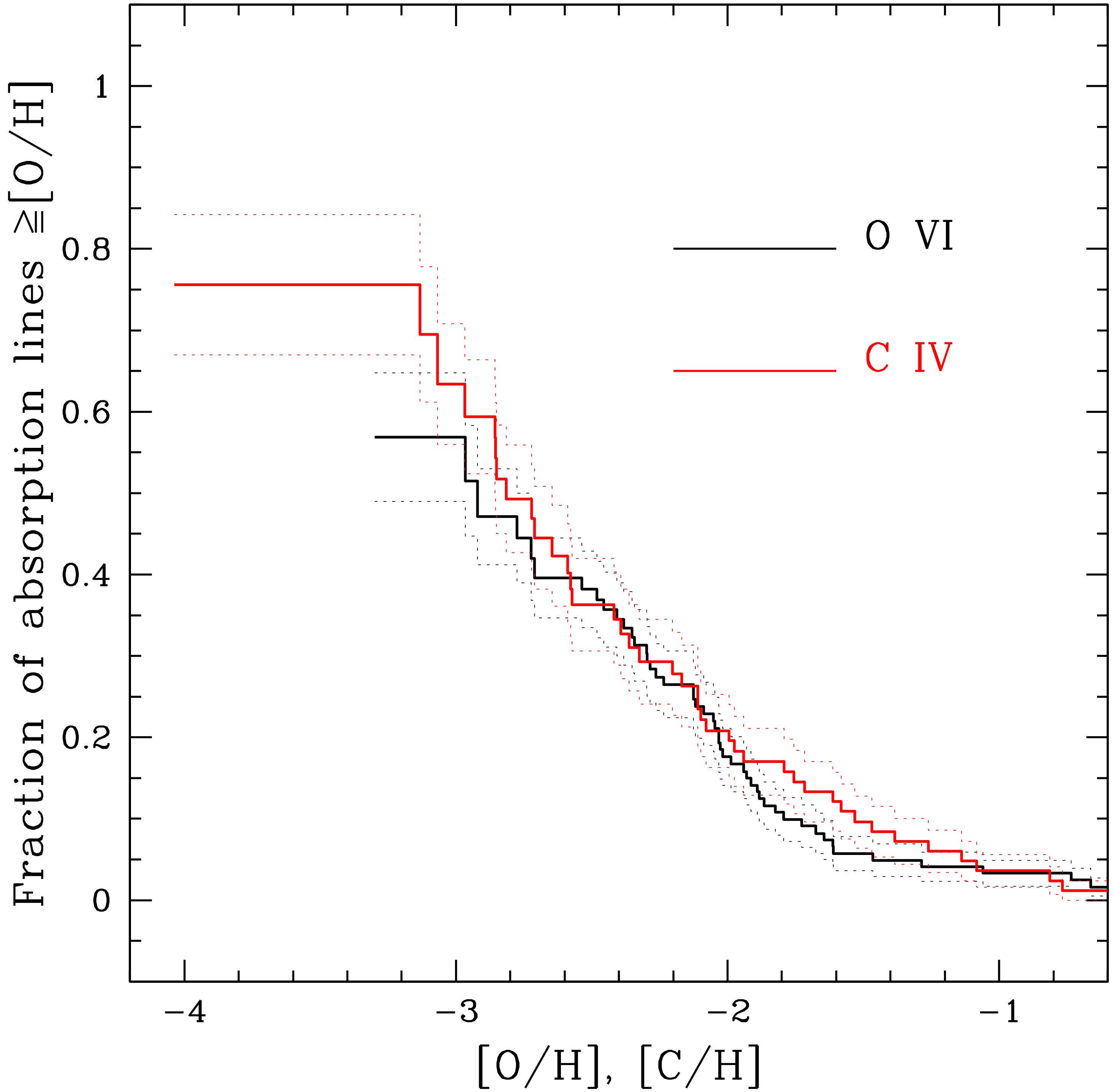
Distribution of O/H and C/H in the IGM at $z \sim 2.5$

- Ionization correction derived from Hardt-Madau metagalactic QSO spectrum modified by intervening IGM absorption.
- Used correlation between Ly-α *column density* and H *density* to estimate the latter.
- Used survival statistics incorporating the *upper limits* to get cumulative O/H distribution. Kaplan-Meier estimator.



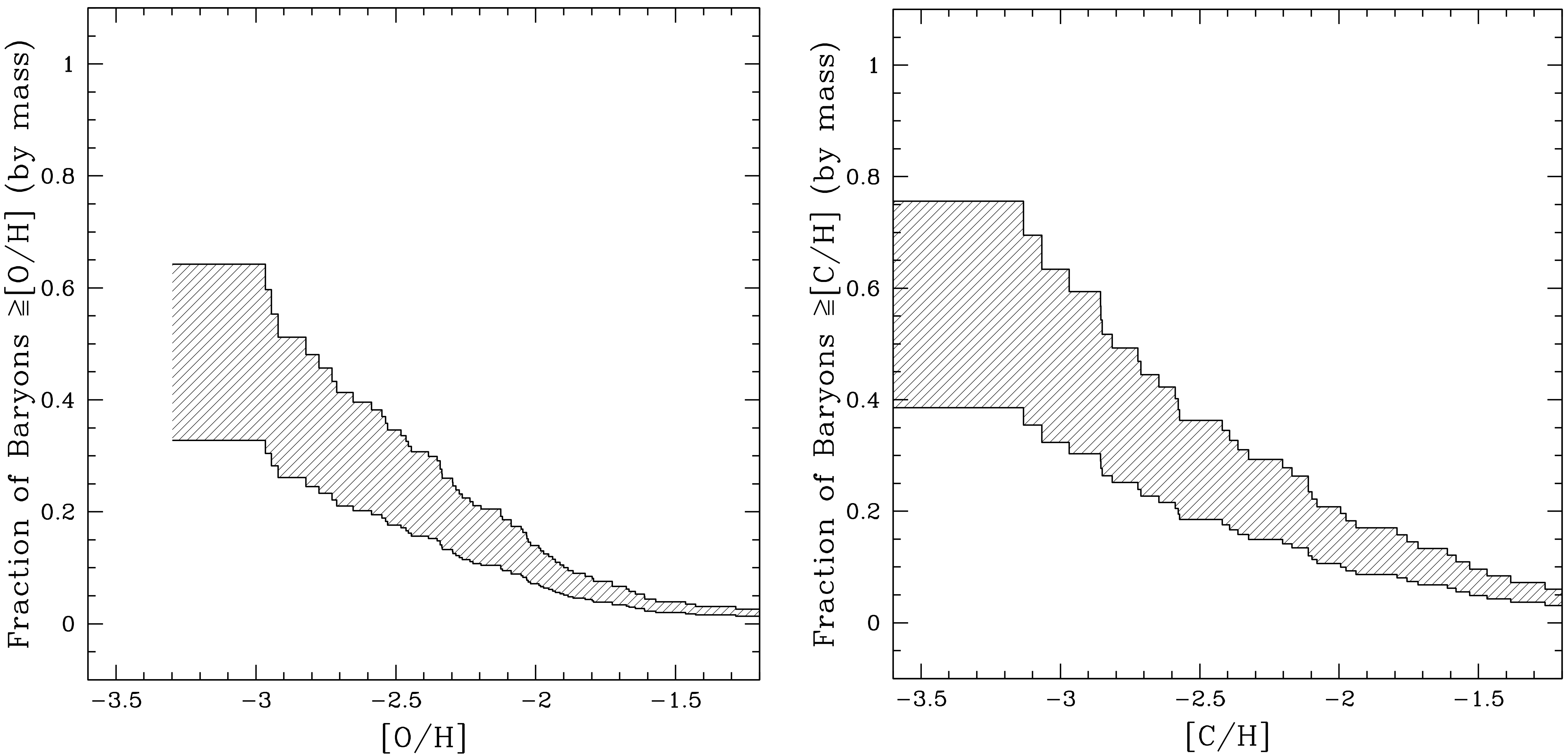
The distribution of [O/H] and [C/H] for absorption systems at z ~ 2.5.

Simcoe, Sargent and Rauch (2004)



Cumulative fraction of H I lines (with log N(H I) > 13.3) as a function of [O/H] and [C/H]

Simcoe, Sargent and Rauch (2004)

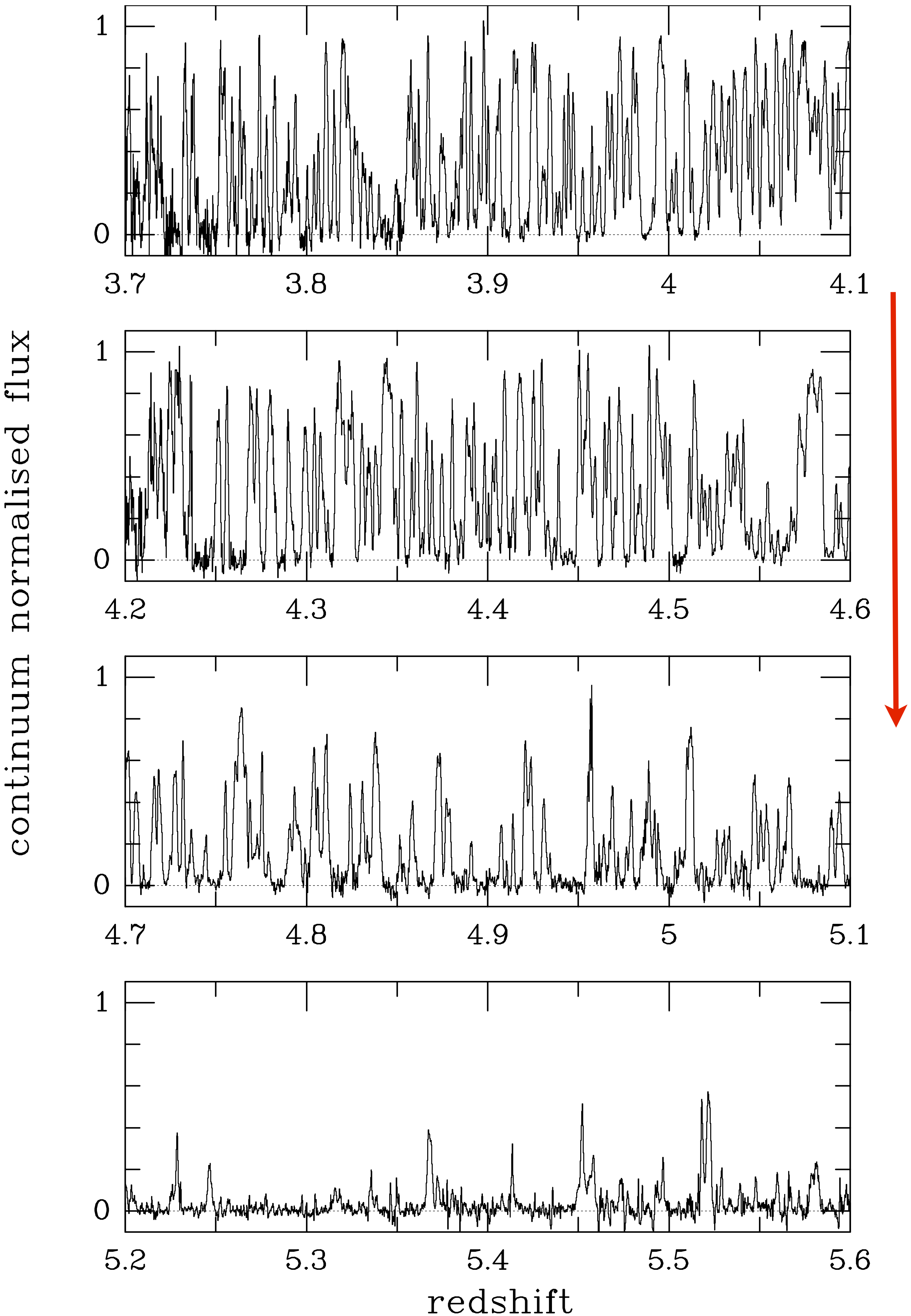


Cumulative fraction of baryons by mass as a function of [O/H] and [C/H]. About 30 percent of the mass in the IGM has [Z/H] < -3.

Simcoe, Sargent and Rauch (2004)

C IV, O I and the end of reionization?

- Below z ~ 5 IGM is highly ionized
- O VI and C VI predominate
- What happens at z ~ 6?
- C IV 1548, 1550 redshifted to 10,848, out of the HIRES regime and into NIRSPEC echelle (R ~ 15,000) territory
- O I 1302, C II 1335, Si II 1304 move to ~9240, still observable with HIRES



Lyman-alpha forest gets thicker with increasing redshift

Universe gets denser with increasing z and density of ionizing sources decreases above z ~2.5

$$n_{HI} \propto n_H^2 / n_\gamma$$

$$n_H \propto (1+z)^3$$

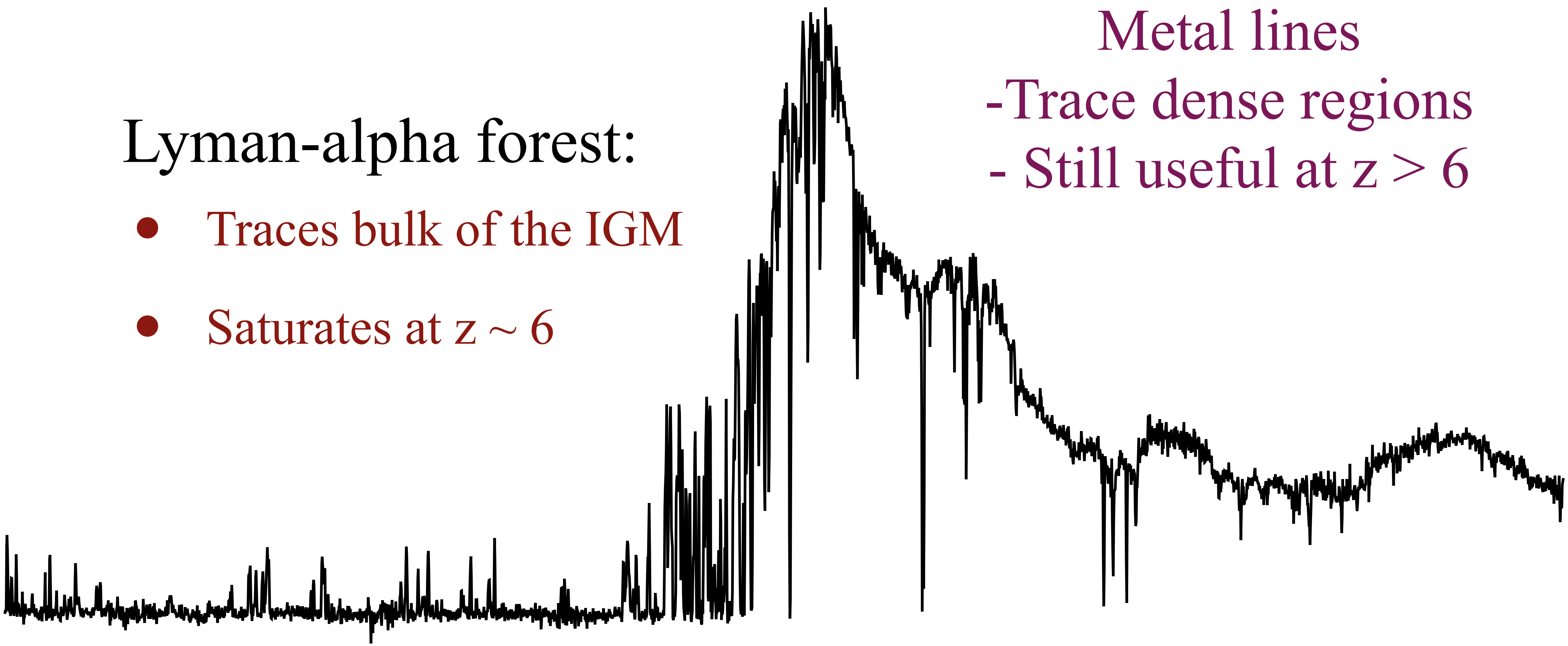
Significance of z ~ 6

Spectrum (without axes) of SDSS J0002+2550 (z = 5.93)

Lyman-alpha forest:

- Traces bulk of the IGM
- Saturates at z ~ 6

Metal lines
-Trace dense regions
- Still useful at z > 6

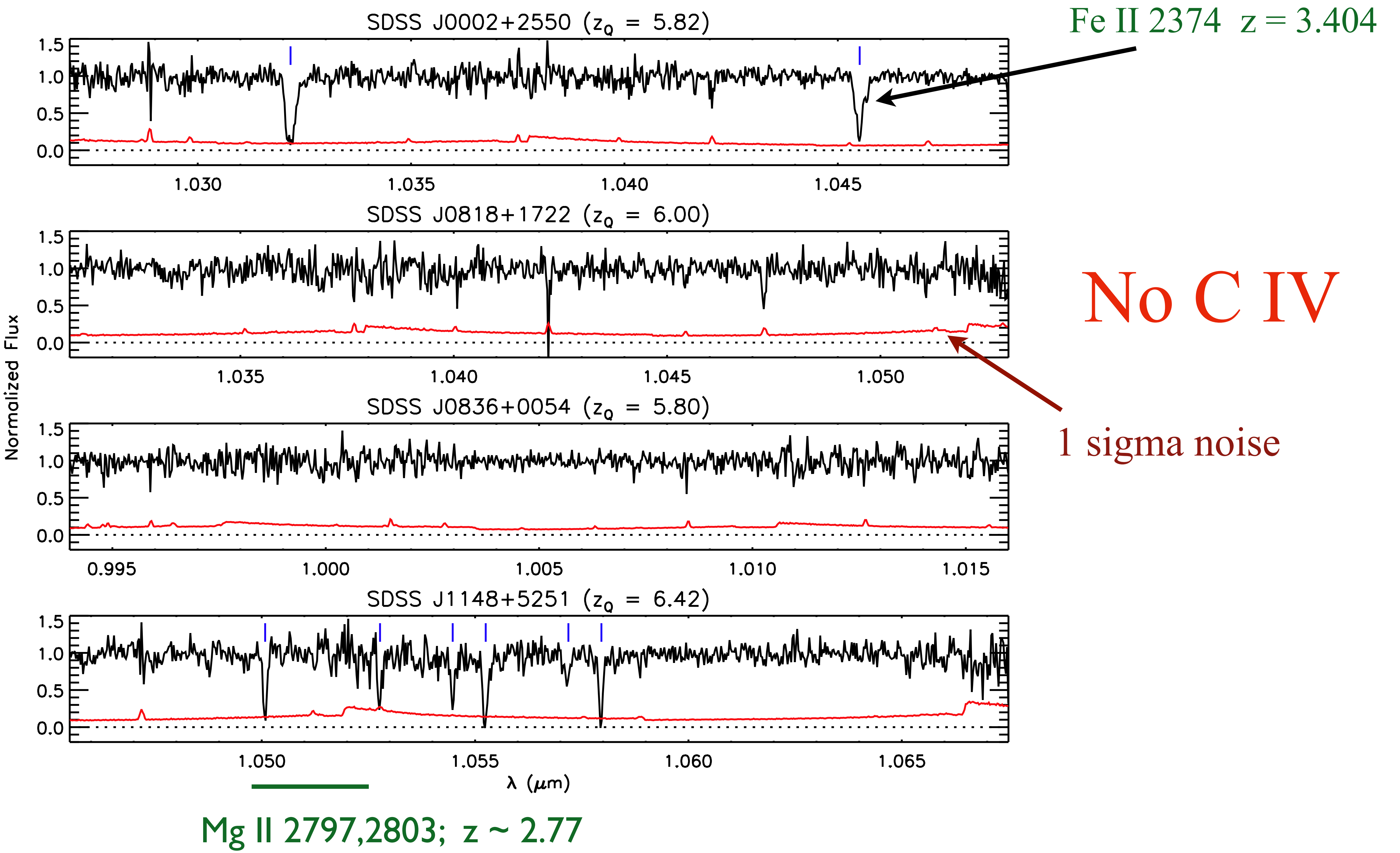


Observed wavelengths at z ~ 6

	Rest (A)	Observed (A)	
Ly alpha	1216	8512	HIRES (R = 45000)
O I	1302	9114	
C II	1334	9338	
Si II	1526	10682	NIRSPEC (R = 25000)
C IV	1548,50	10843	
Fe II	2344	16408	

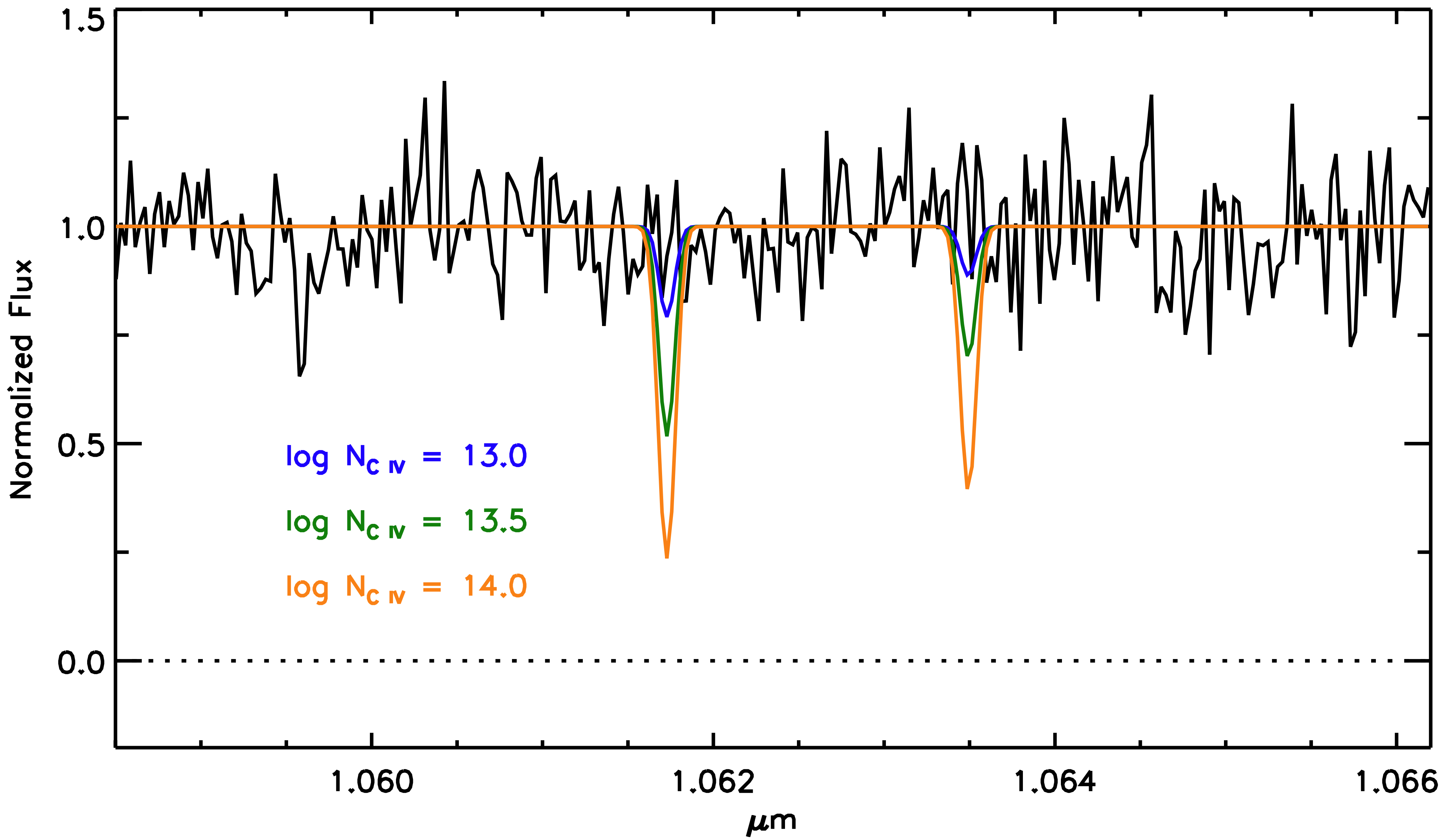
Examples of NIRSPEC echelle data on z ~ 6 QSOs

(Typical exposure times 10-12 hours: R = 13,000)



Detectability of C IV in Keck NIRSPEC data

(Typical exposure times 10-12 hours)



Calculation of Ω_{ion}

Can calculate contribution of a particular ion to density parameter from:

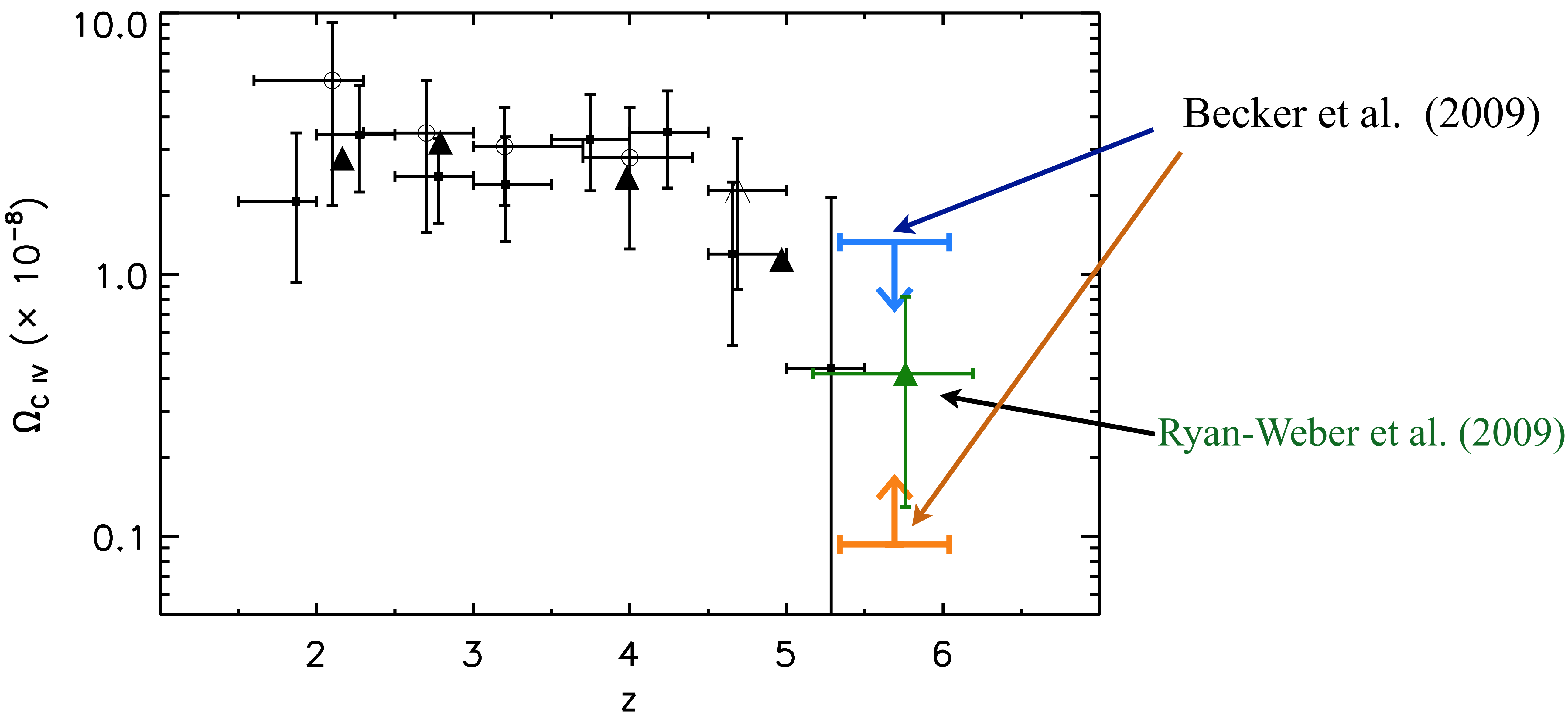
$$\Omega_{ion} = \frac{1}{\rho_c} m_{ion} \frac{\Sigma_n N_n}{c/H_0 \Sigma \Delta X_i}$$

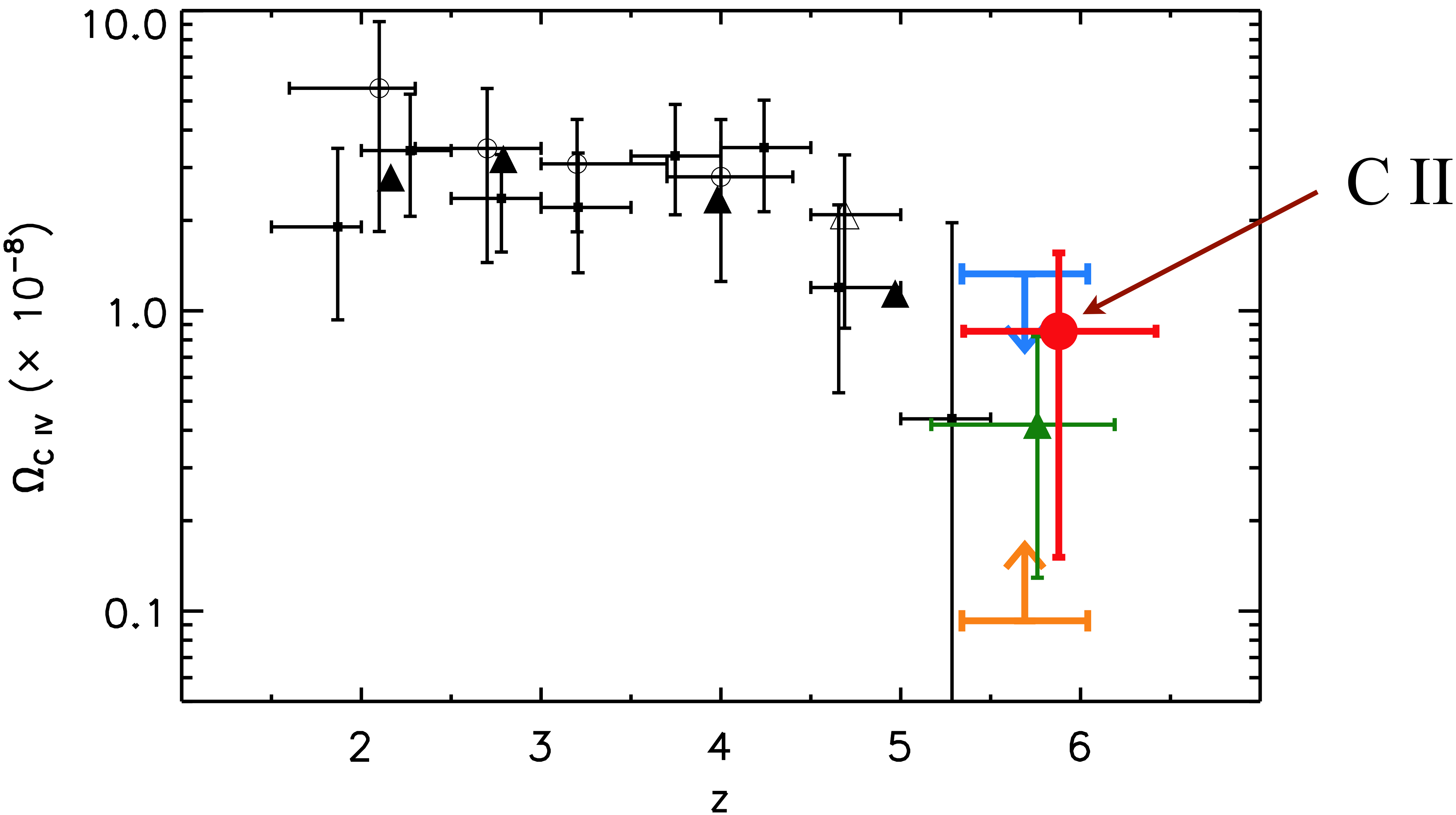
where ρ_c is the critical density, m_{ion} is the mass of the ion, n is the number of absorbers along the line of sight N_n is the column density of each absorber and $c/H_0 \times \Delta X$ is the cosmologically calculated distance over which absorption lines could have been found.

Usually need ionization correction from theory to get $\Omega_{element}$

Ω_{baryon} is known so dermination of Ω_H is not necessary.

Contribution of C IV to Omega as a function of z

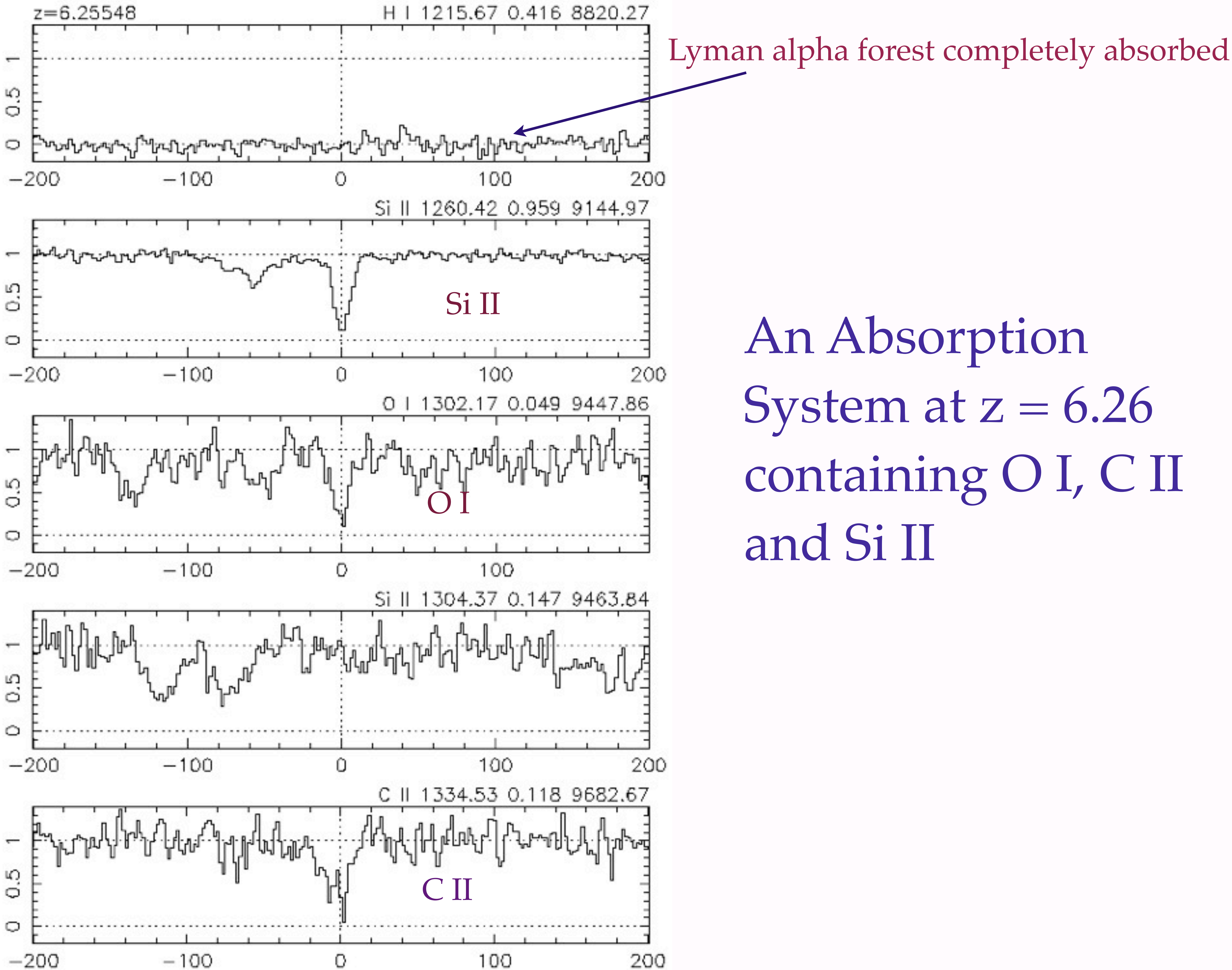



C II
10.0
1.0
0.1
$\Omega_{C\ IV}$ ($\times\ 10^{-8}$)
2
3
4
5
6
z

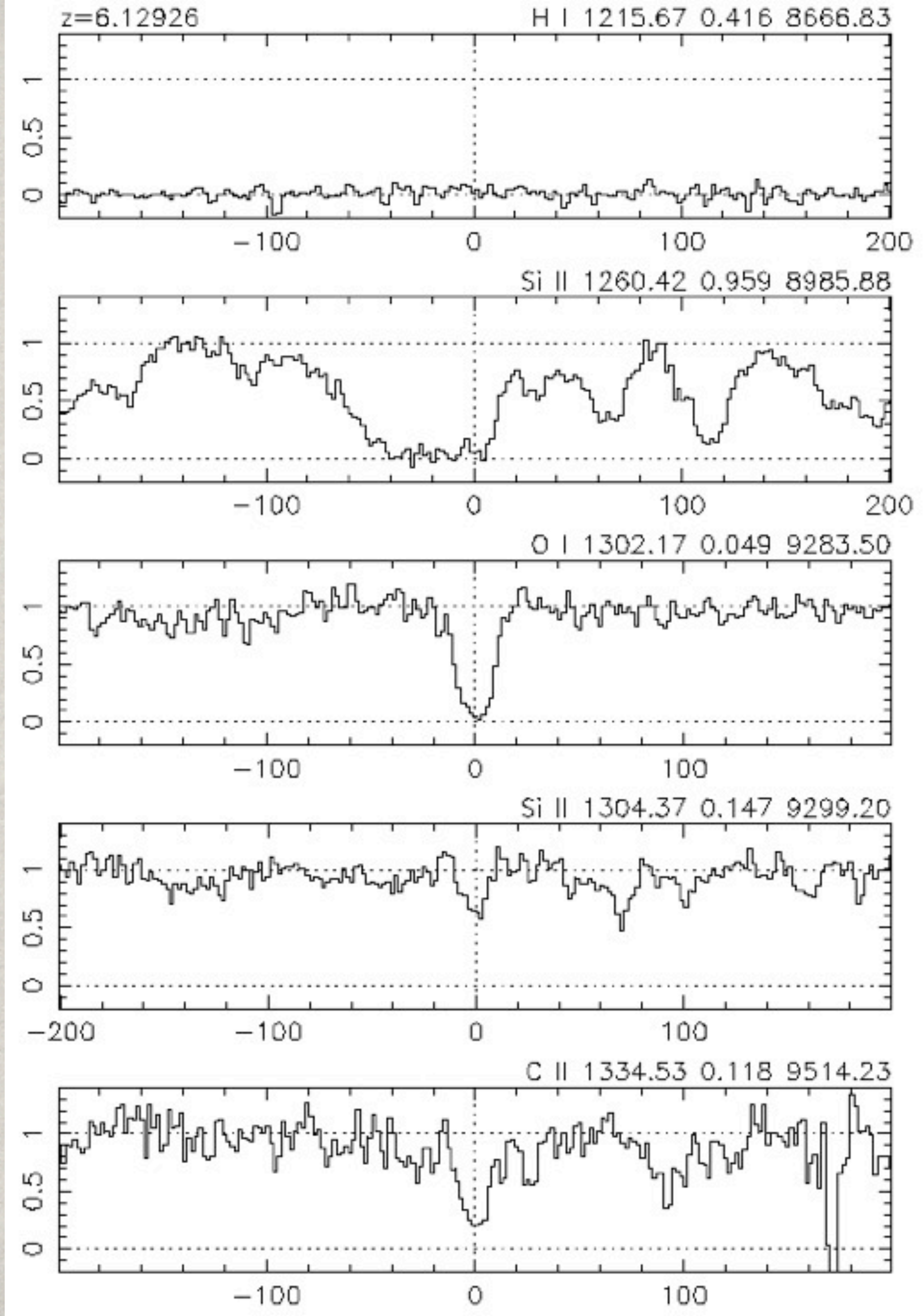
The HIRES z > 5 sample

- 12 Keck nights
  - Upgraded detector
- 9 QSOs at z > 4.8
- 3 at z > 6
- Sensitive to O I 1302 over a narrow redshift range:
  - Max z = z_{QSO}
  - Min z = z where O I enters the Lyα forest (1216 A)
  - Loose some coverage due to the atmosphere and/or poor S/N
- Can study C IV 1548,1550 up to z ~ 5.5

Name	z_{QSO}	Max $\Delta z_{O\ I}$
SDSS 2225-0014	4.87	0.39
SDSS J1204-0021	5.09	0.40
SDSS J0915+4244	5.20	0.41
SDSS J0231-0728	5.42	0.43
SDSS J0836+0054	5.80	0.45
SDSS J0002+2550	5.82	0.45
SDSS J1623+3112	6.25	0.48
SDSS J1030+0524	6.30	0.49
SDSS J1148+5251	6.42	0.49

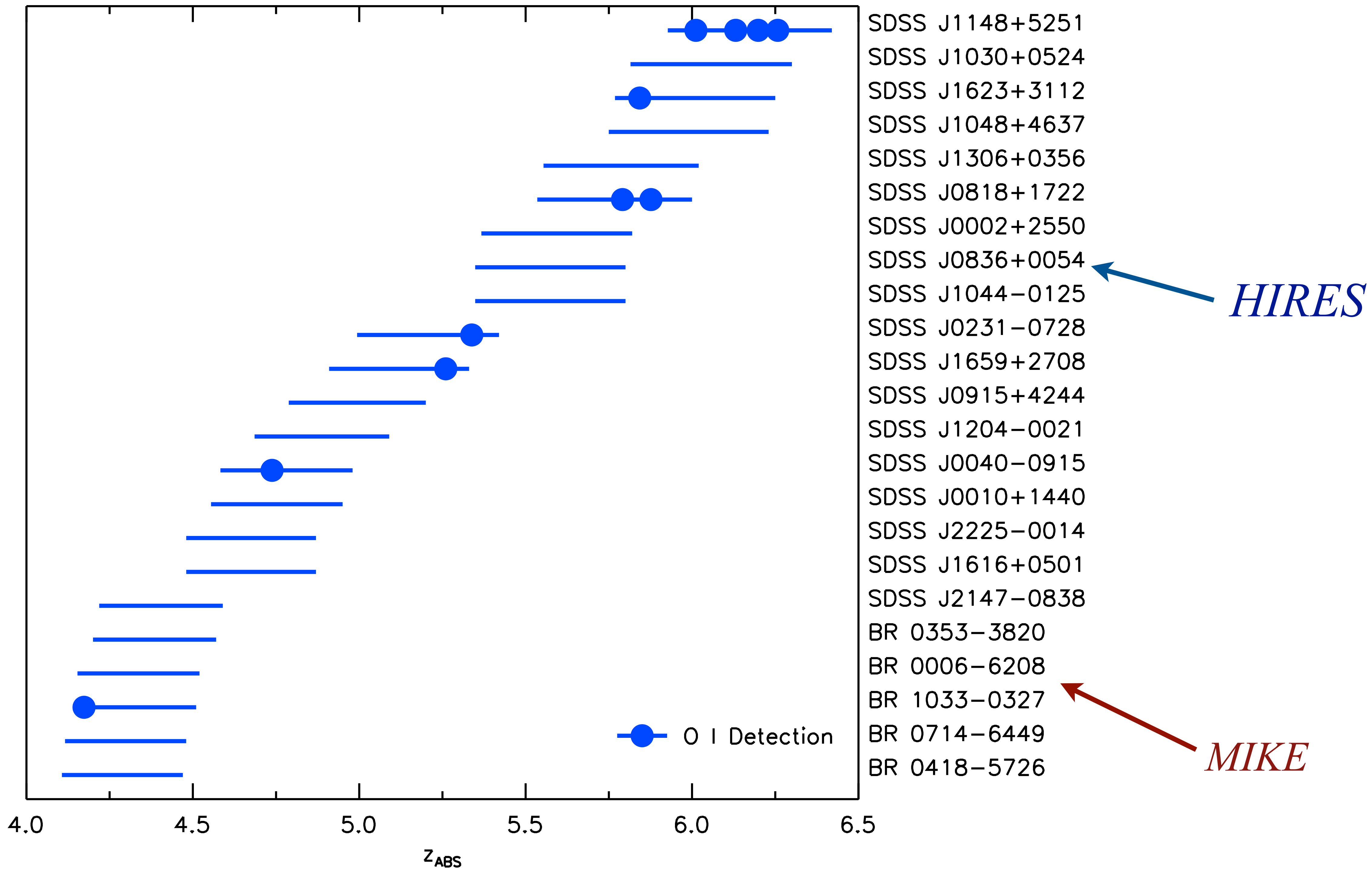


An Absorption System at z = 6.26 containing O I, C II and Si II



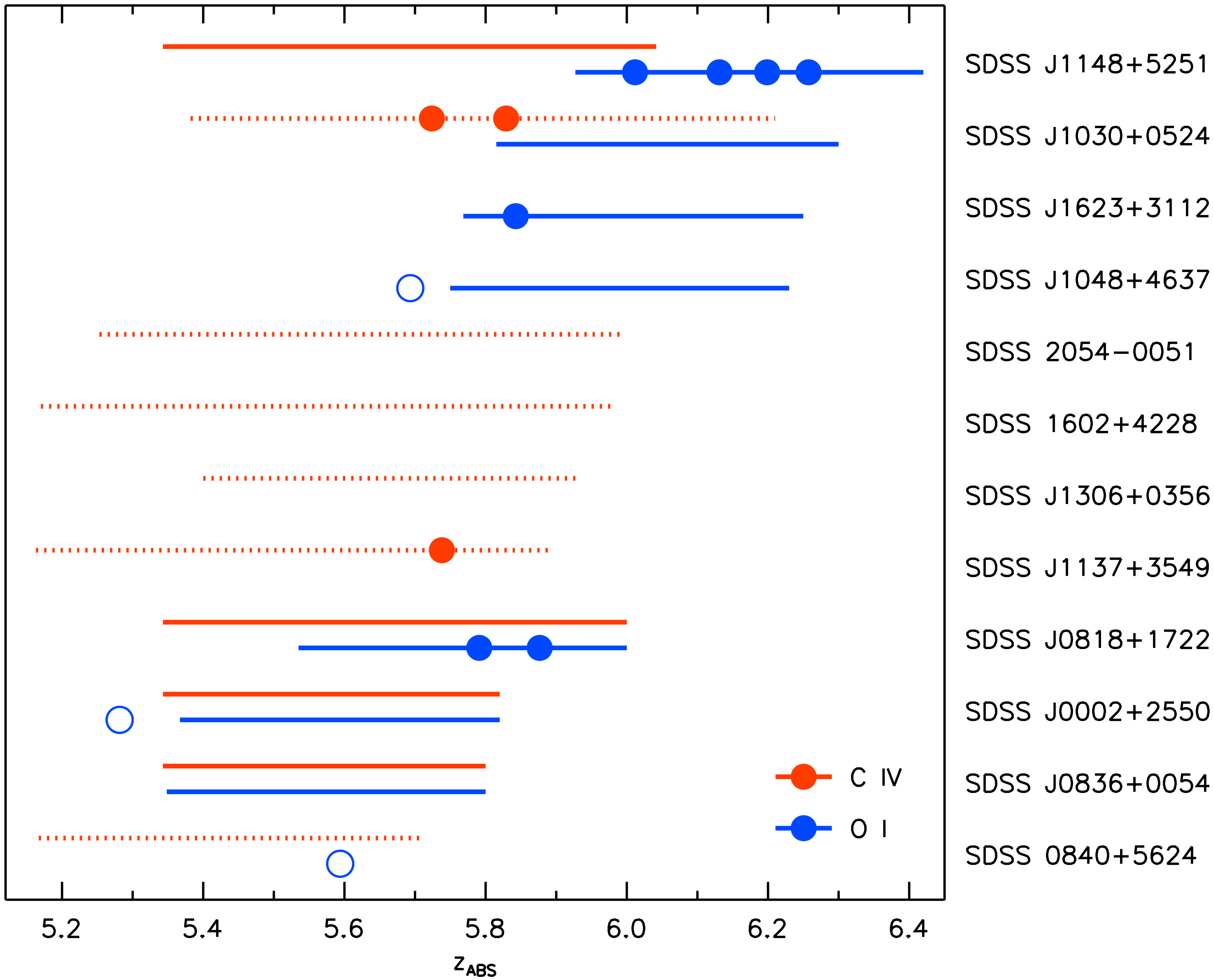
An Absorption System at z = 6.13 containing O I, C II and Si II

O I 1302A sightlines

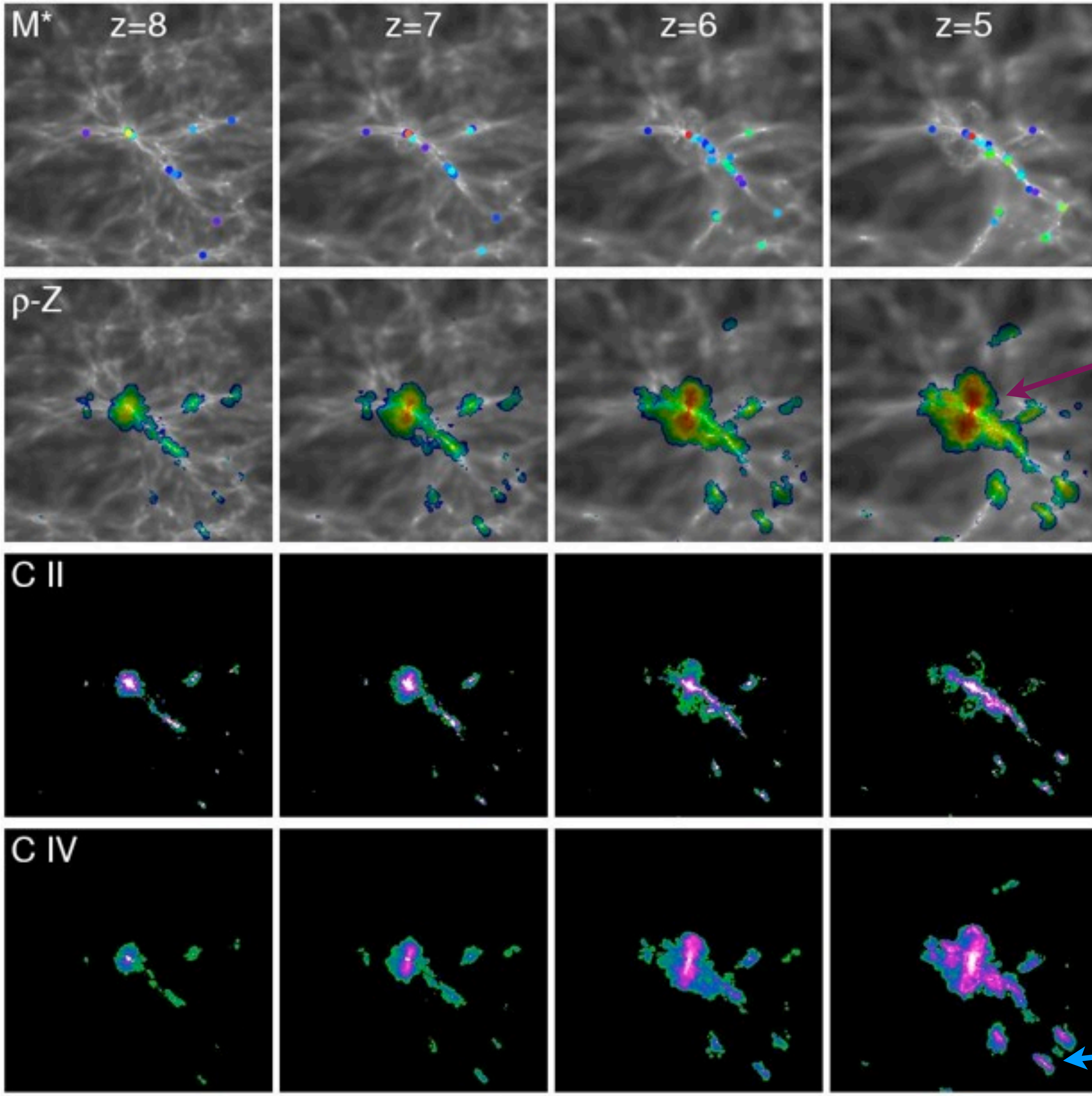


Schematic plot of 23 $4.5 < z < 6.4$ QSO sightlines surveyed for O I, and the detections. The data are HIRES and MIKE. The O I detections appear to pile up at the high-redshift end, and there is a 95% probability that dn/dX increases at $z > 5.6$. This ignores corrections for completeness, which is naturally much higher at lower redshifts.

Sightlines observed for C IV and O I



Solid lines: sightlines observed by Becker et al.
Dotted lines: sightlines observed by Ryan-Weber at al. to a shallower depth



Zoom in on a galaxy

2.4×10^8 to $1.8\times10^9 M_\odot$

Bipolar outflow

Heavy element density

C II traces higher overdensities near galaxies

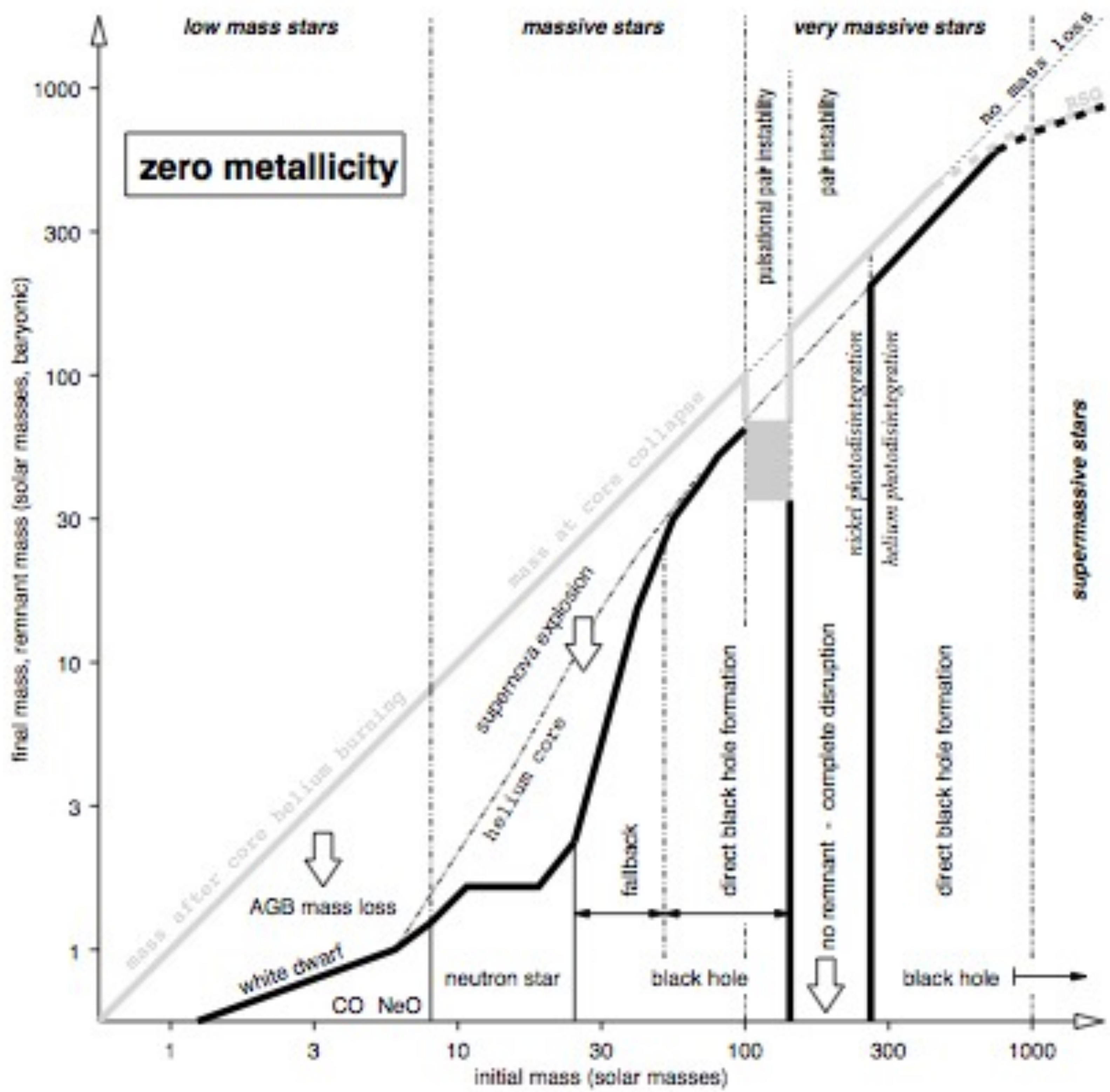
C IV evolves to trace the more diffuse IGM by z ~ 5

$10^{7-8} M_\odot$ ***galaxies produce most HEs***

$4 \times 4h^{-1}$ Mpc by 25 km s^{-1} simulation

Oppenheimer et al. 2008

The fates of zero metallicity stars (Heger et al.)



Note: the assumption of no mass loss by stellar winds may not be valid

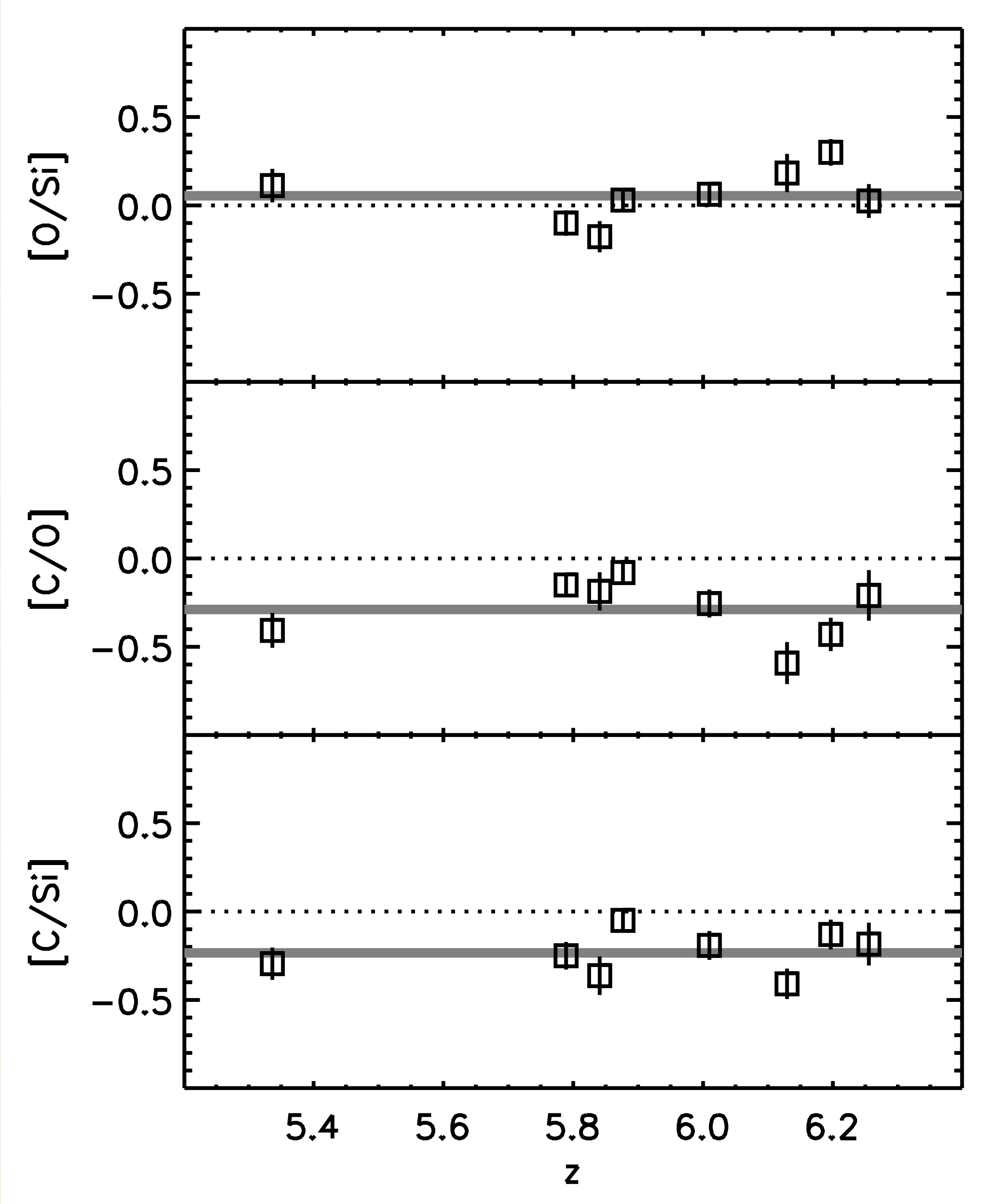
Relative Abundances at z ~ 6

- Chemical signatures of the first stars
- Lines mostly unsaturated
- [O/Si]= 0.05
  - Near solar value implies ordinary Type II supernovae

$$\Delta E_{OI} < \Delta E_{SiII}$$

- O I implies neutral gas:

$$N_{\mathrm{Si}} \approx N_{\mathrm{Si\ II}}$$
$$N_{\mathrm{O}} \approx N_{\mathrm{O\ I}}$$
$$N_{\mathrm{C}} \approx N_{\mathrm{C\ II}}$$



Mean values

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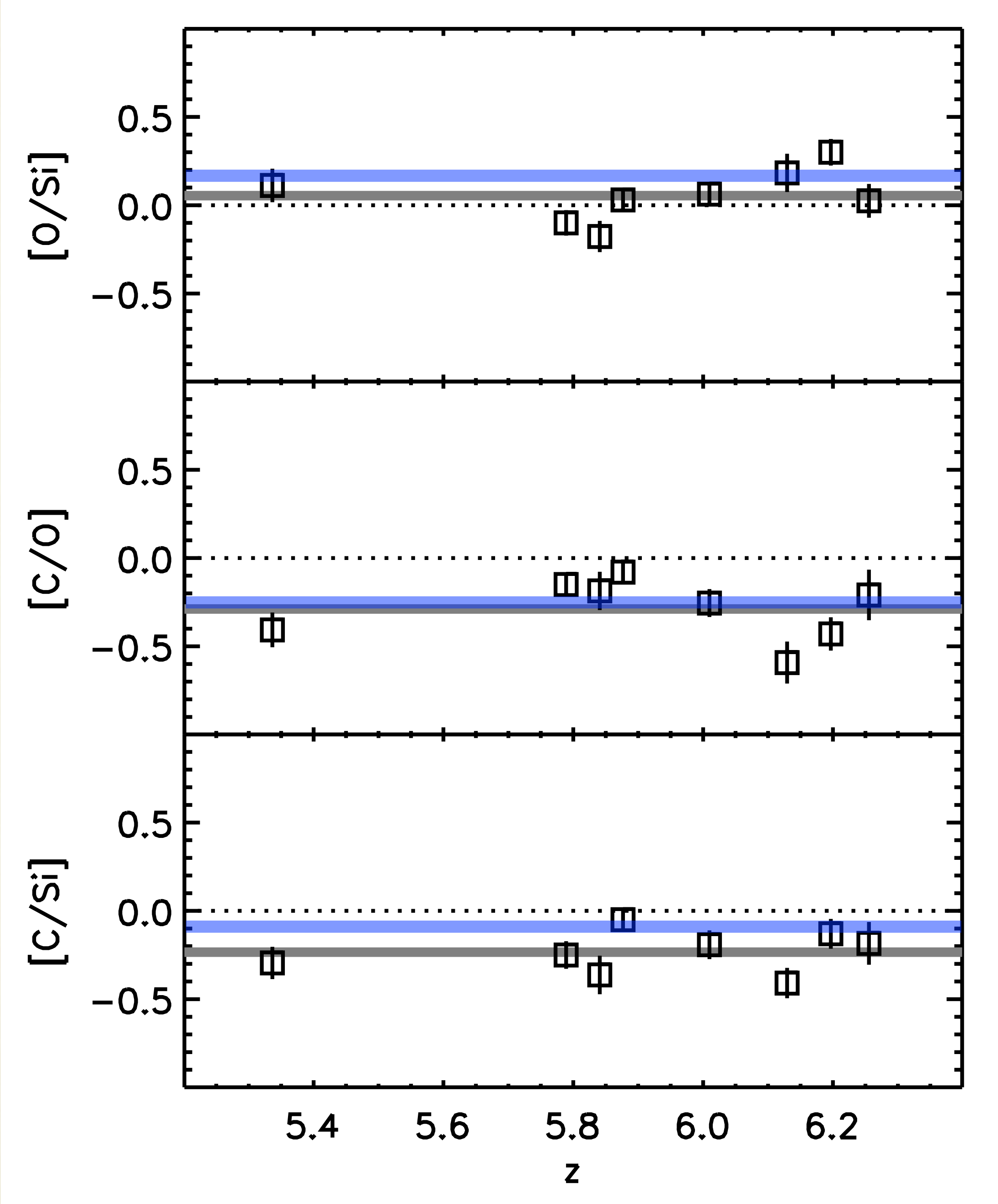
  $N_{\mathrm{O}} \approx N_{\mathrm{O\ I}}$

  $N_{\mathrm{C}} \approx N_{\mathrm{C\ II}}$



Mean values

Type II SNe

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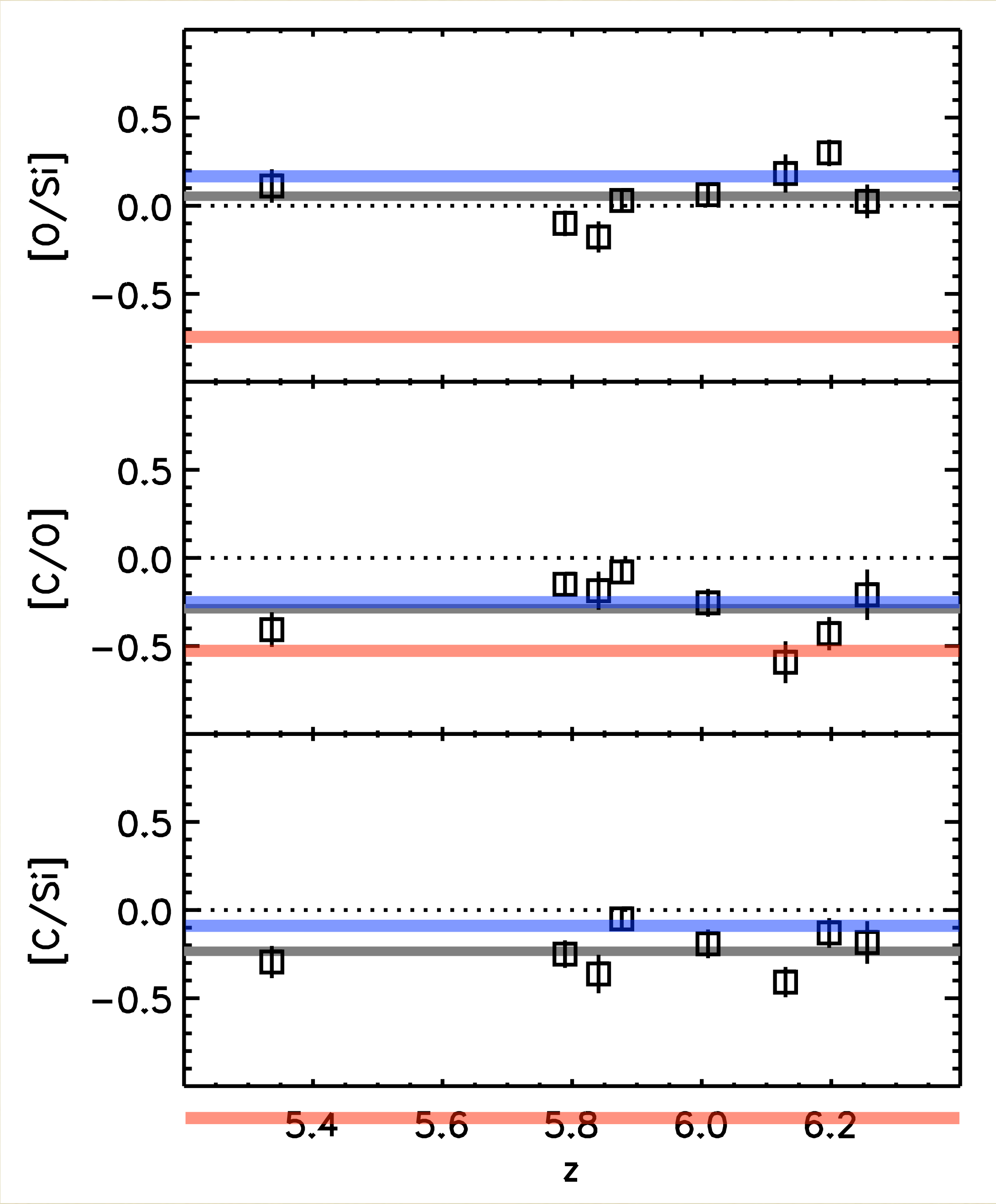
  $N_{\mathrm{O}} \approx N_{\mathrm{O\ I}}$

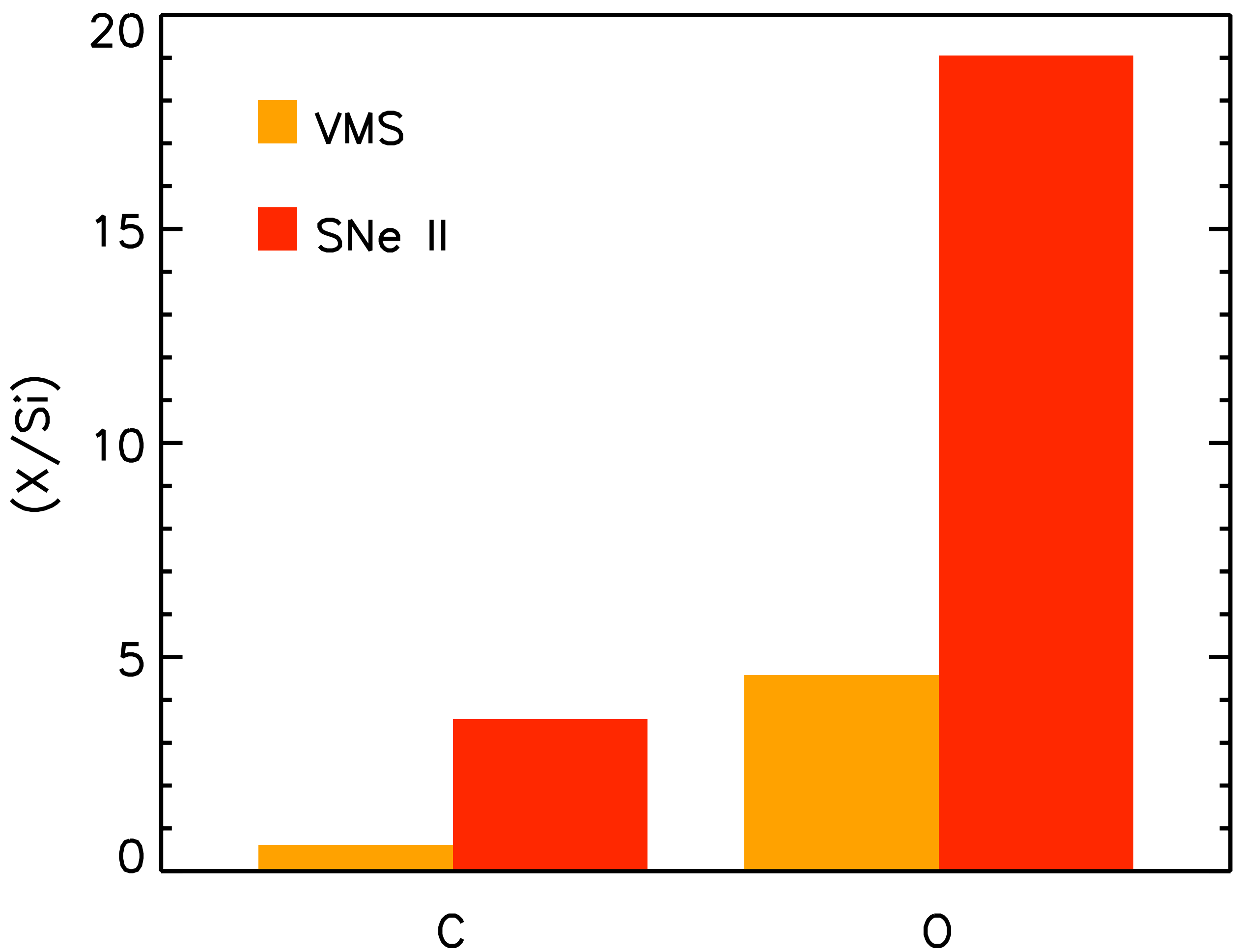
  $N_{\mathrm{C}} \approx N_{\mathrm{C\ II}}$

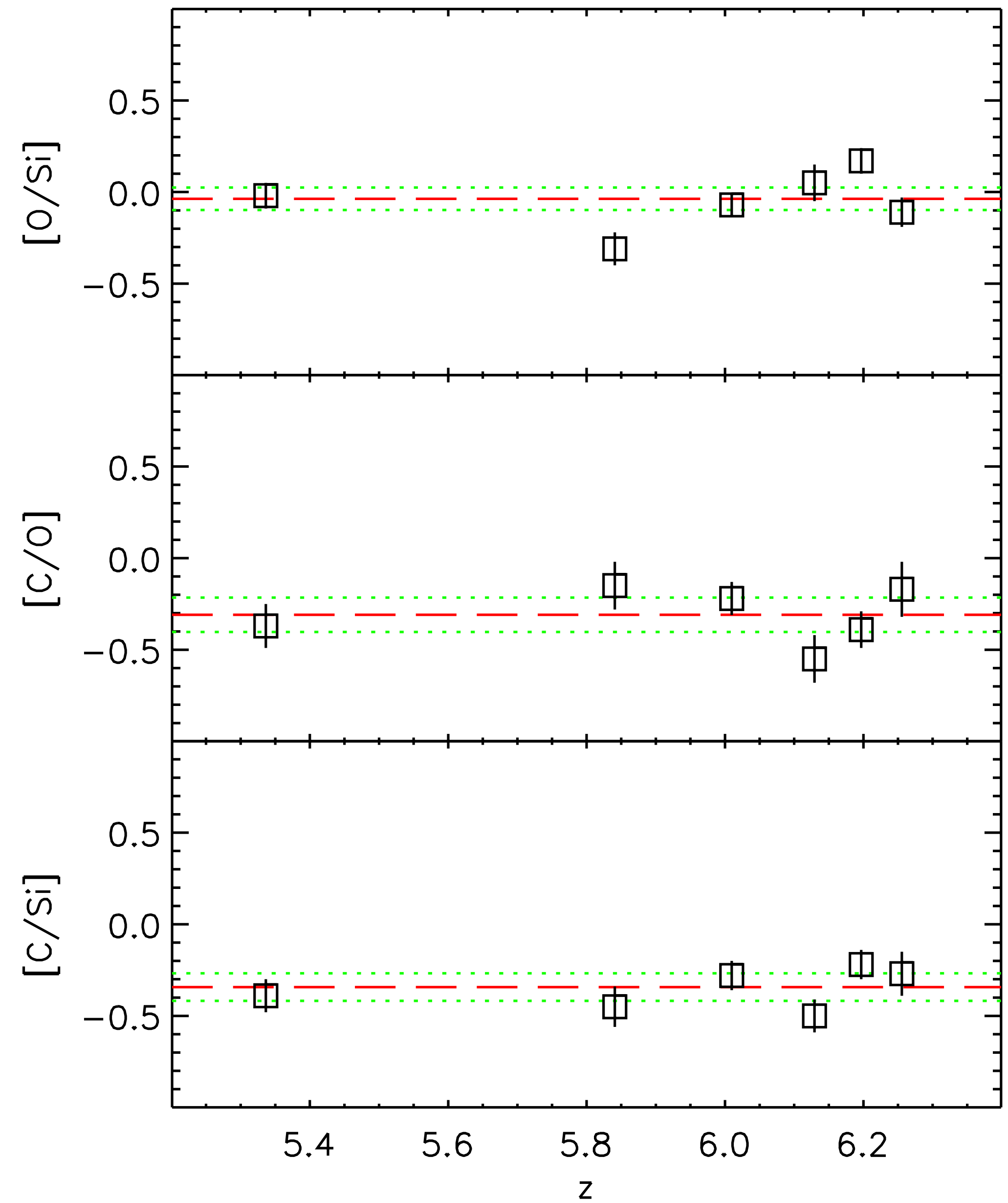


Mean values

Type II SNe

Very Massive Stars





Left panel: Expected C/Si and O/Si ratios from normal Type II SN and from Very Massive Stars (Woosley and Hager)

Right panel: Observed ratios O:C:Si in QSO absorption systems at $z > 5$. The values are consistent with ordinary Type II SN.

Prompt production of Fe and the alpha/Fe ratio

- Traditional view: Type II SN produce C, O, Si, etc and Type Ia SN produce Fe; expect high alpha/Fe at early times, approaching solar value after 2 - 4 Gyrs.
- Various lines of evidence for ‘prompt’ Fe production:
  - Emission spectra of z ~ 6 QSOs show no evolution in Mg II/Fe ratios 900 Myr after the Big Bang
  - High Fe content of intracluster gas
  - Observed redshift evolution of Type 1a SN
  - Much higher rate of SN 1a in late type galaxies
  - alpha/Fe trends with metallicity in Galactic halo stars
- All point to multiple modes of Fe production

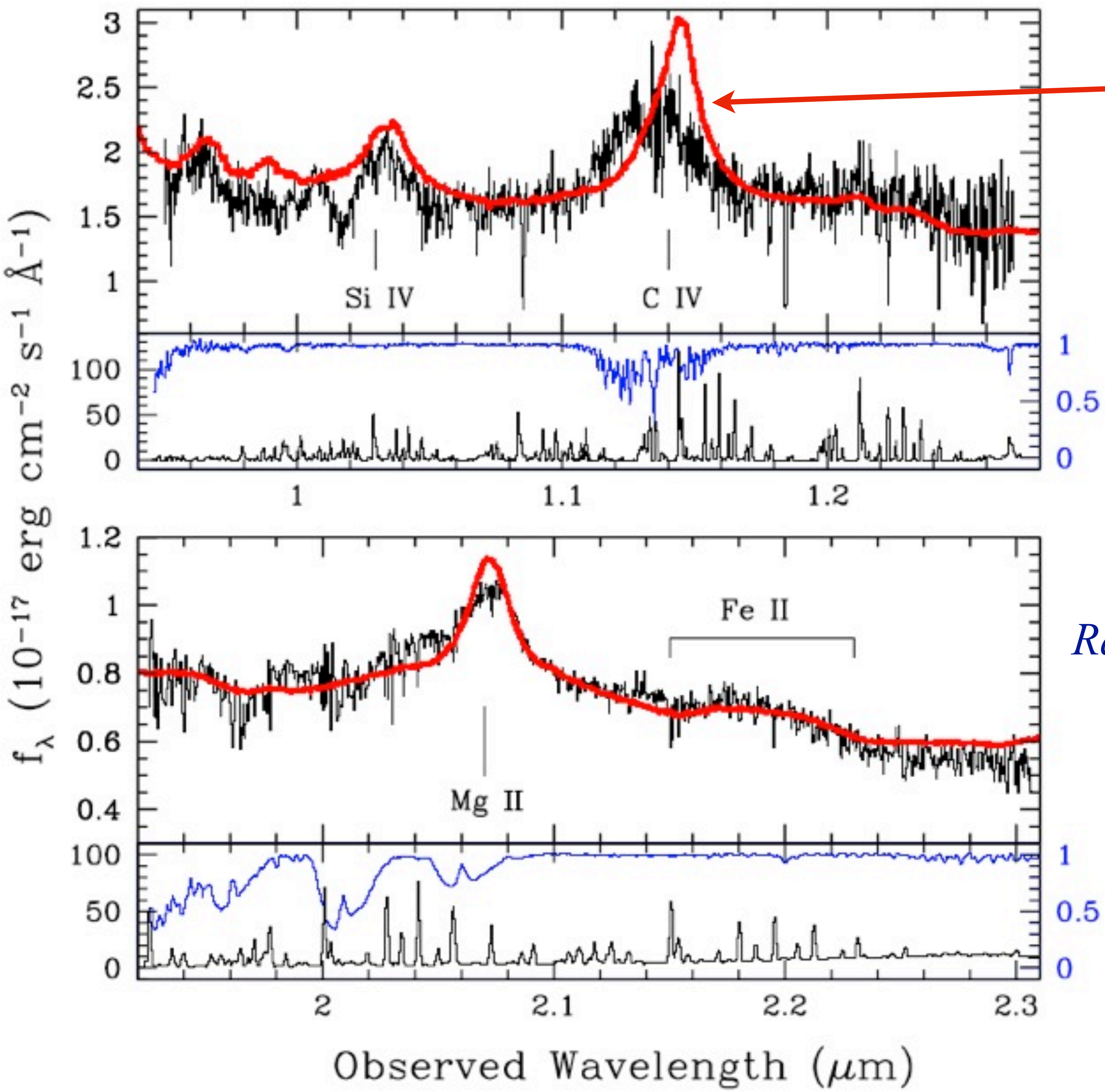
Scannapieco & Bildsten 2005, Mannucci et al. 2006

Prompt Fe production (2)

- Theoretical studies - very low metallicity ($Z < 0.001$ solar) intermediate mass stars may produce SN Ia - like events
  - Weak radiation driven stellar winds; little mass loss during AGB phase
  - Degenerate C, O cores grow to Chandrasekhar limit by the burning shells reaching into the H envelope
  - Runaway nuclear reaction resulting in explosions like Type Ia SN
- These 'Type IIa' SN yield large quantities of Fe and possibly explain ~solar alpha/Fe ratios at early times

Arnett 1969, Iben & Renzini 1983, Zijlstra 2004, Lau et al. 2008

Fe II emission in the spectrum of SDSS 1148+5251 (z = 6.42)



Standard quasar spectrum redshifted

Ratio Fe II/Mg II same as at lower redshifts

Keck NIRSPEC: Barth et al. 2003

Summary

- Work on abundances and ionization at z ~ 6 using QSO absorption lines requires *high dispersion* in the J, H, K bands
- The Lyman-alpha forest is optically thick; information comes principally from *metal lines*
- Observations of C IV and O I indicate that absorbers are becoming less ionized at z ~ 6
- Relative C, O, Si abundances indicative of normal Type II supernovae; no evidence for Very Massive Stars
- Fe/O ratio is low as expected from Type I supernovae being a major source of Fe at later times

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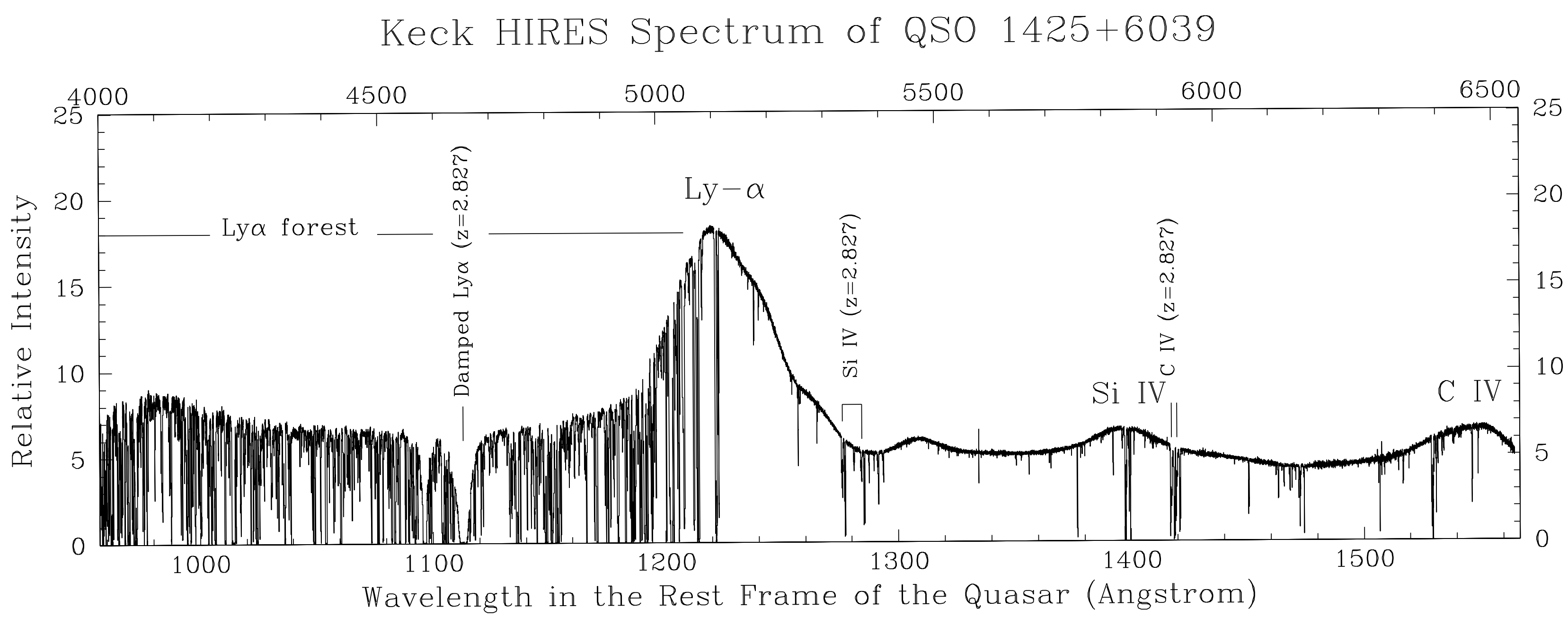
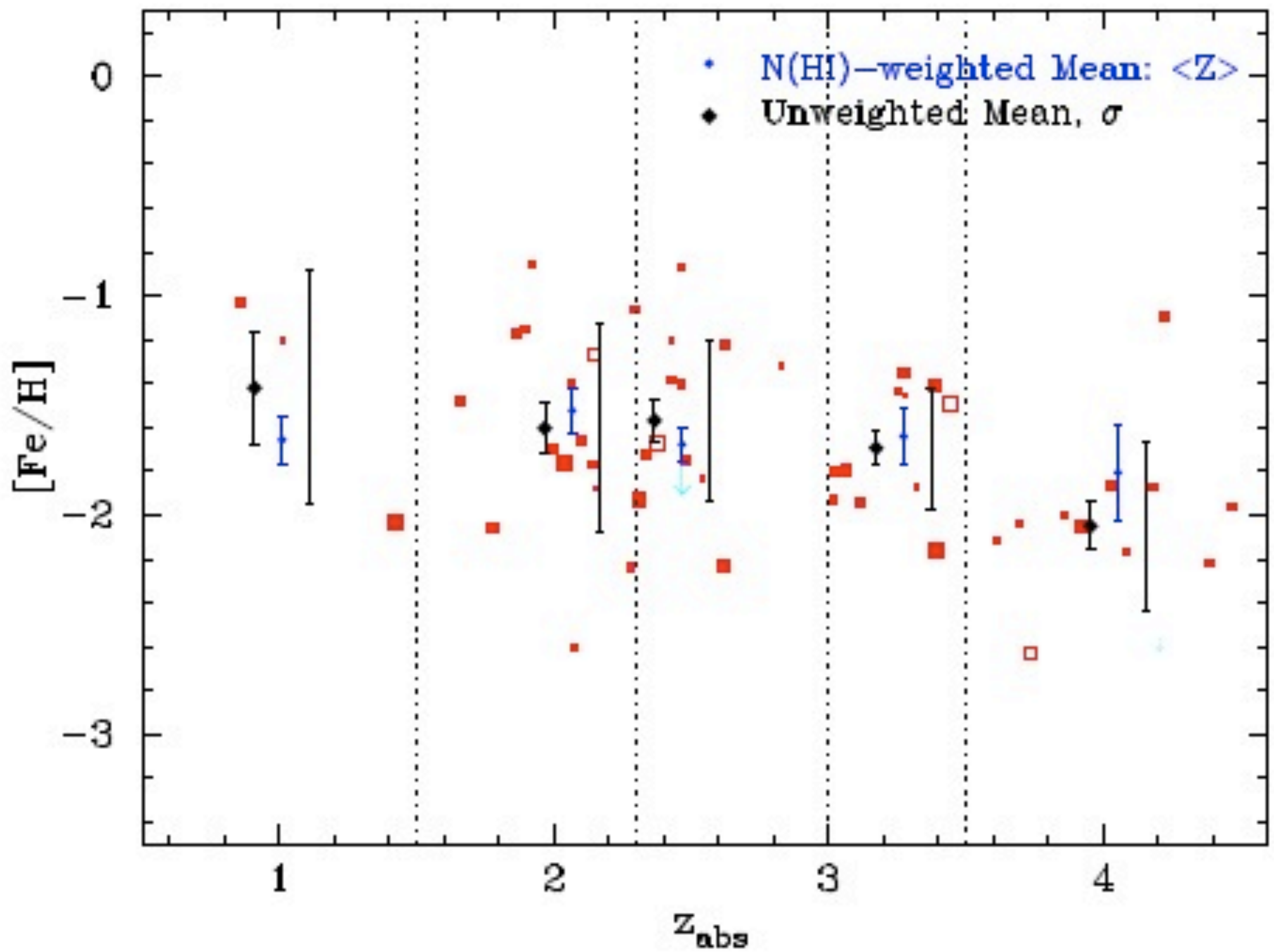
Galaxies at low redshift

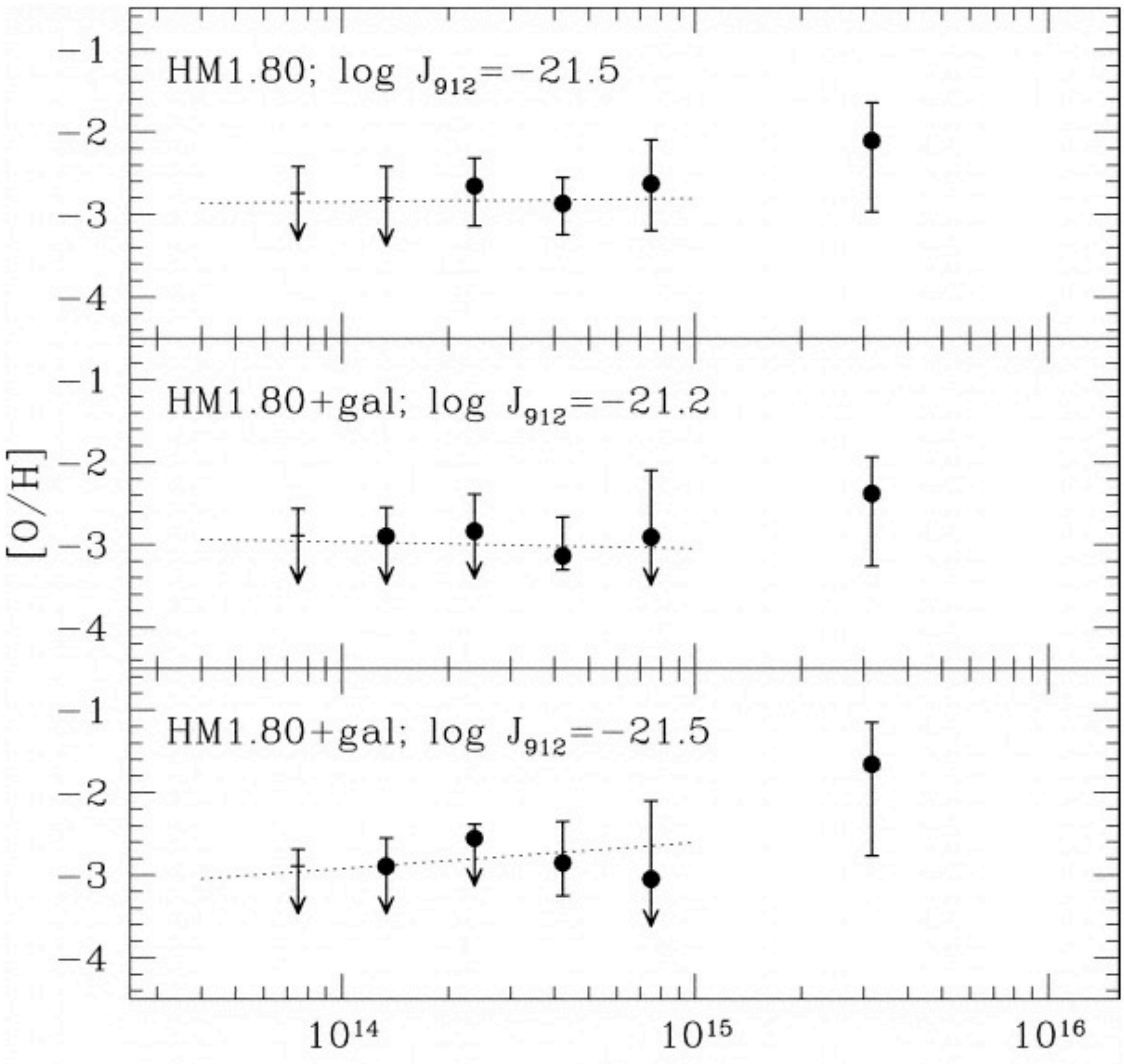
- Only *dwarf* galaxies are metal-poor overall
- Dwarf spheroidals have [Fe/H] $\sim$-2
- Dwarf Irregulars (BCG's) have O/H $\sim 1/50$ solar and no lower.
- None of these systems appear to be very young.
- We have not found local gas clouds devoid of stars or heavy elements.



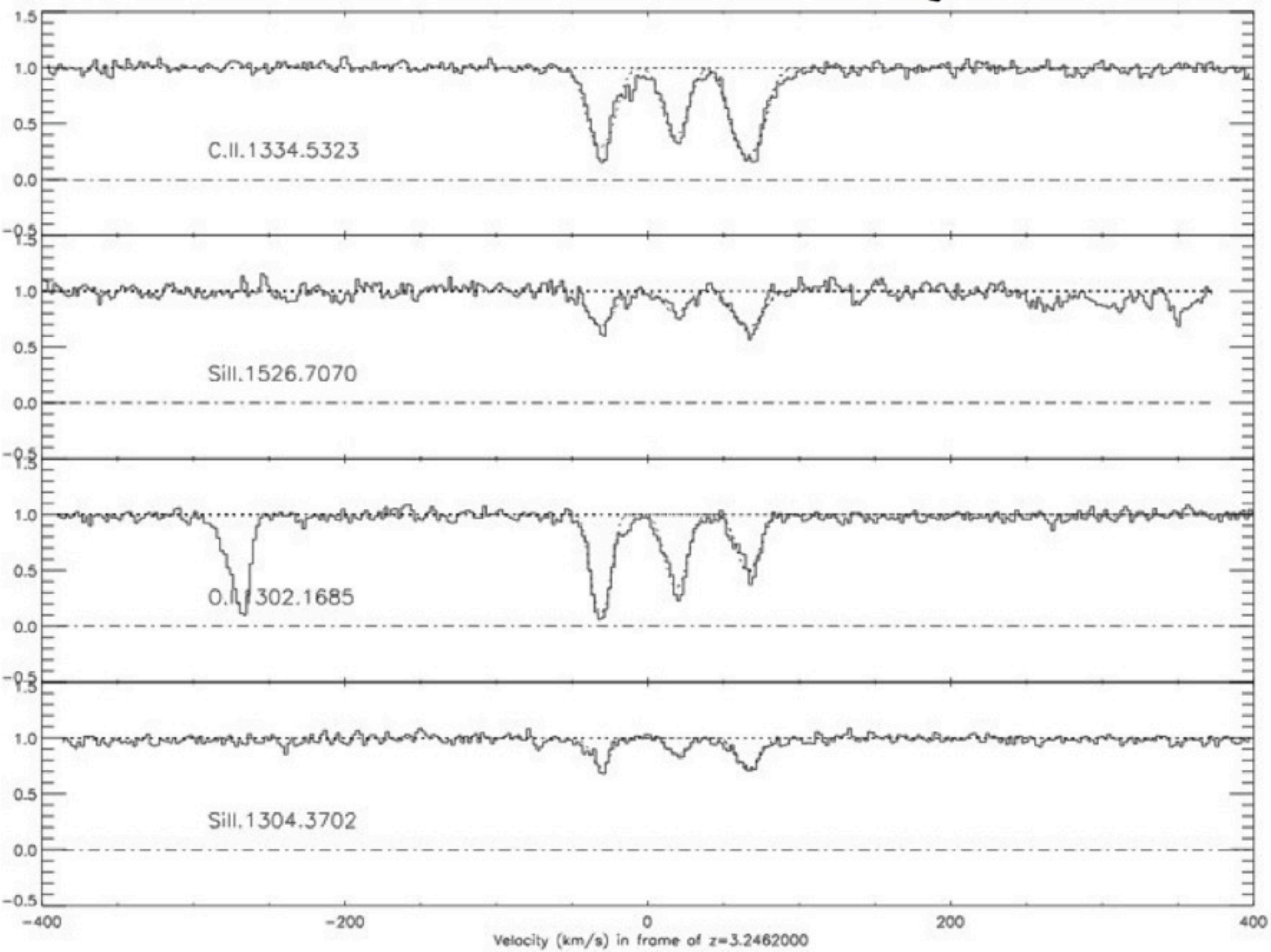
Keck HIRES Spectrum of QSO 1425+6039
4000
4500
5000
5500
6000
6500
Relative Intensity
Lyα forest
Damped Lyα (z=2.827)
Ly−α
Si IV (z=2.827)
C IV (z=2.827)
Si IV
C IV
1000
1100
1200
1300
1400
1500
Wavelength in the Rest Frame of the Quasar (Angstrom)



N(HI)−weighted Mean: <Z>
Unweighted Mean, σ
0
−1
−2
−3
[Fe/H]
1
2
3
4
z_{abs}


HM1.80; log J_{912}=−21.5
HM1.80+gal; log J_{912}=−21.2
HM1.80+gal; log J_{912}=−21.5
[O/H]
−1
−2
−3
−4
10^{14}
10^{15}
10^{16}

Q930+2858


C.II.1334.5323
SiII.1526.7070
O.I 1302.1685
SiII.1304.3702
Velocity (km/s) in frame of z=3.2462000

Calculation of Ω_{ion}

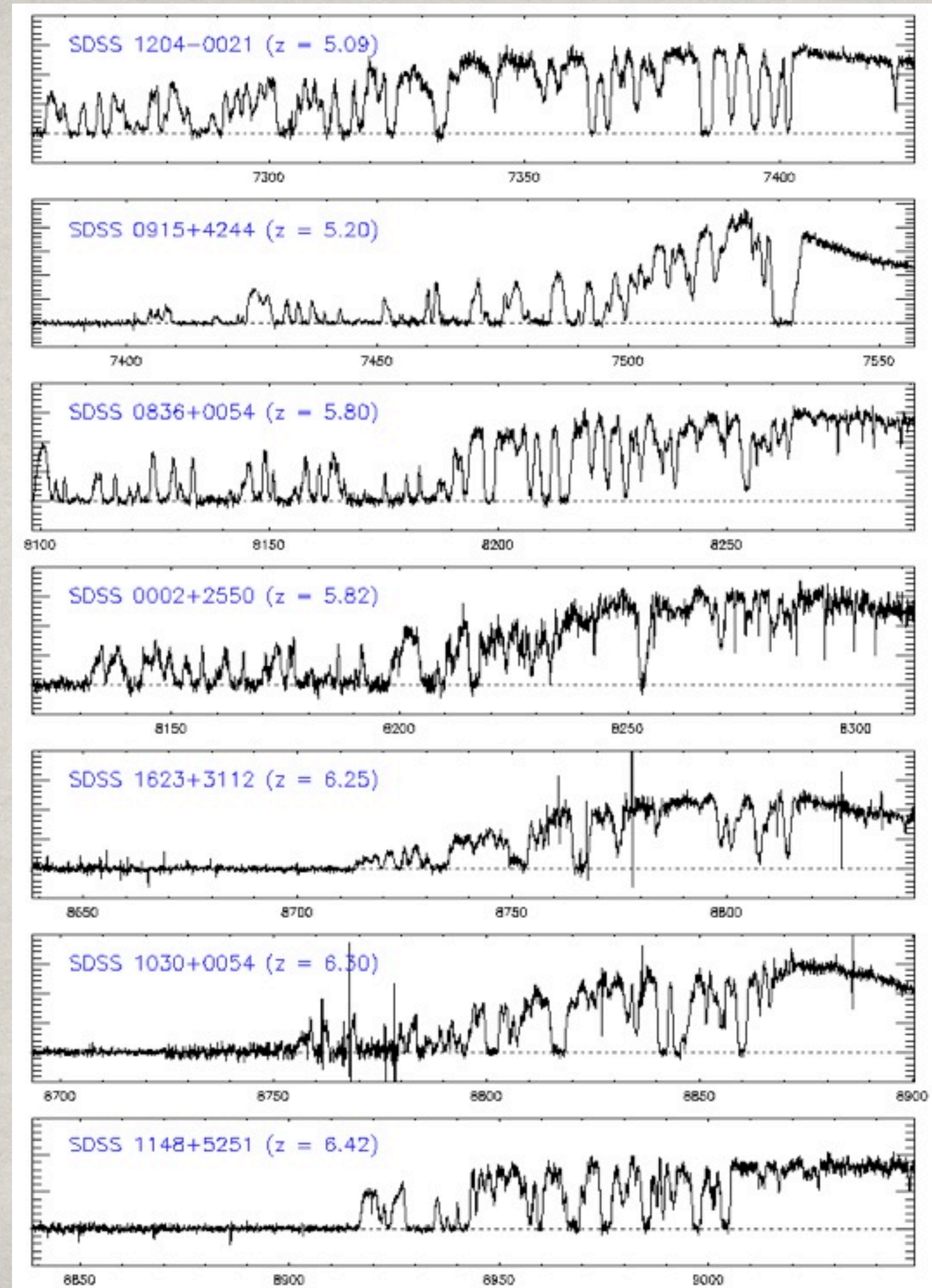
Can calculate contribution of a particular ion to density parameter from:

$$\Omega_{ion} = \frac{1}{\rho_c} m_{ion} \frac{\Sigma_n N_n}{c/H_0 \Sigma \Delta X_i}$$

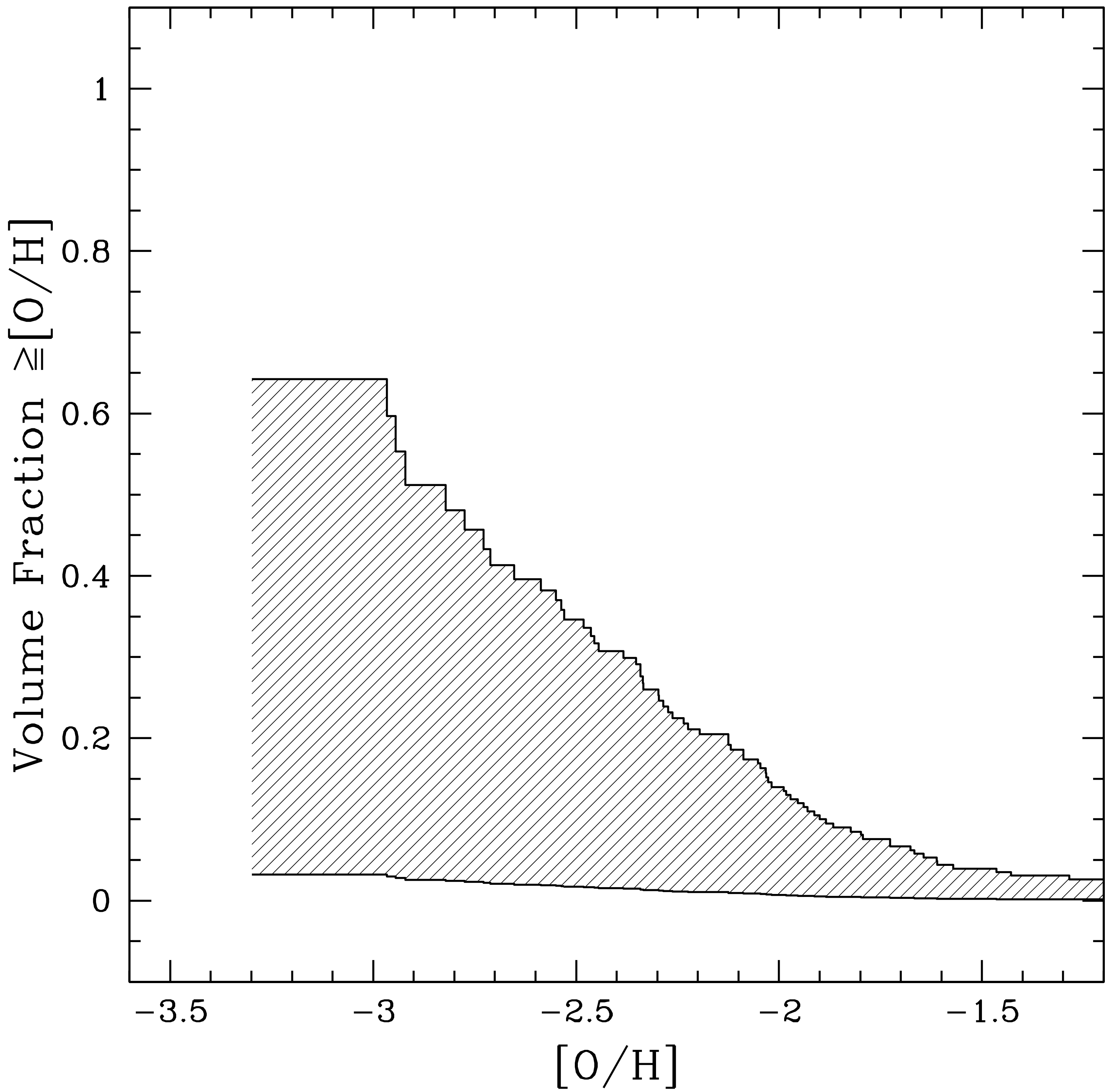
where ρ_c is the critical density, m_{ion} is the mass of the ion, n is the number of absorbers along the line of sight N_n is the column density of each absorber and $c/H_0 \times \Delta X$ is the cosmologically calculated distance over which absorption lines could have been found.

Usually need ionization correction from theory to get $\Omega_{element}$

Ω_{baryon} is known so dermination of Ω_H is not necessary.

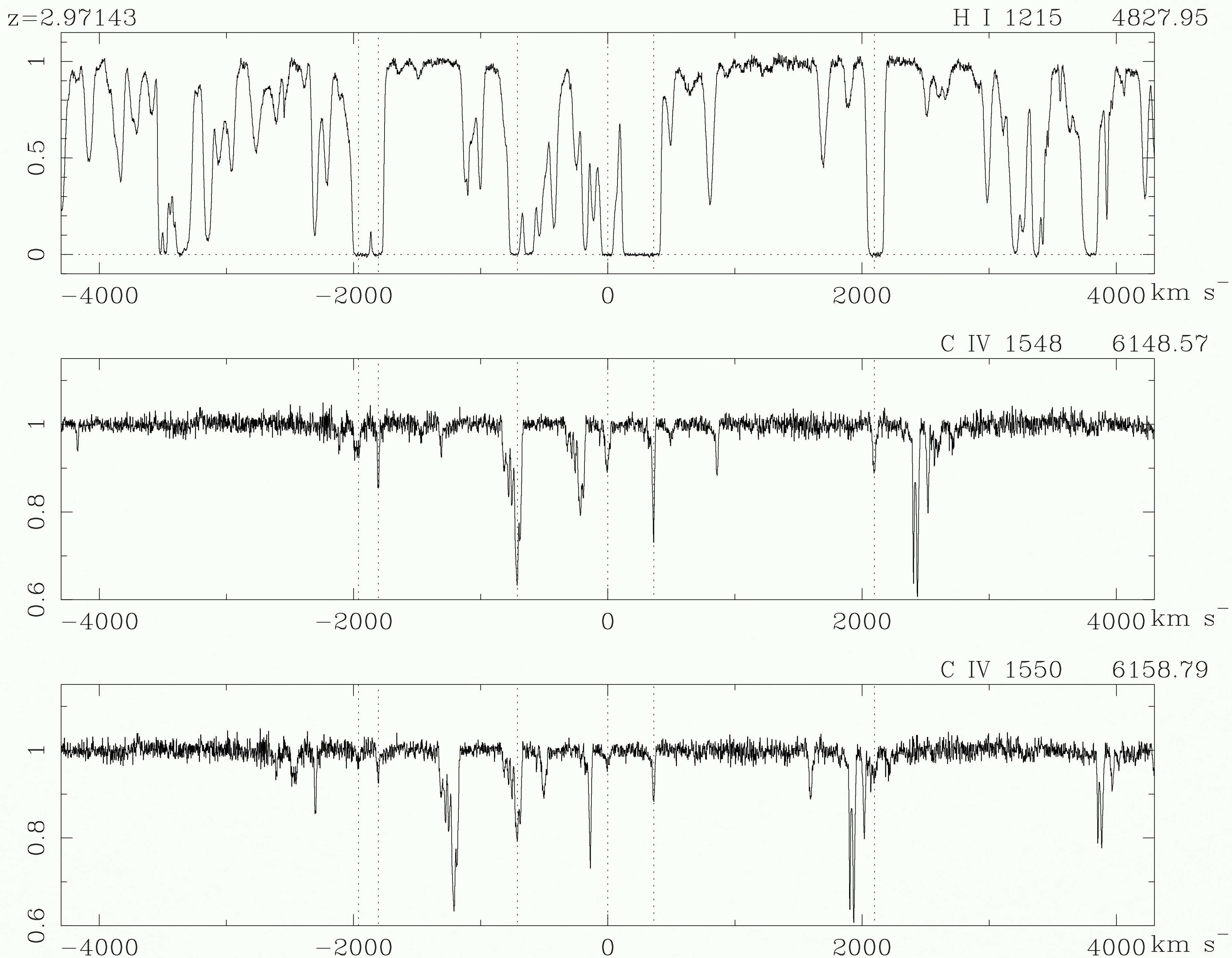


The "proximity region" in the Lyman-alpha Forest shortward of the Lyman-alpha emission line for QSOs with z = 5.09 to 6.42

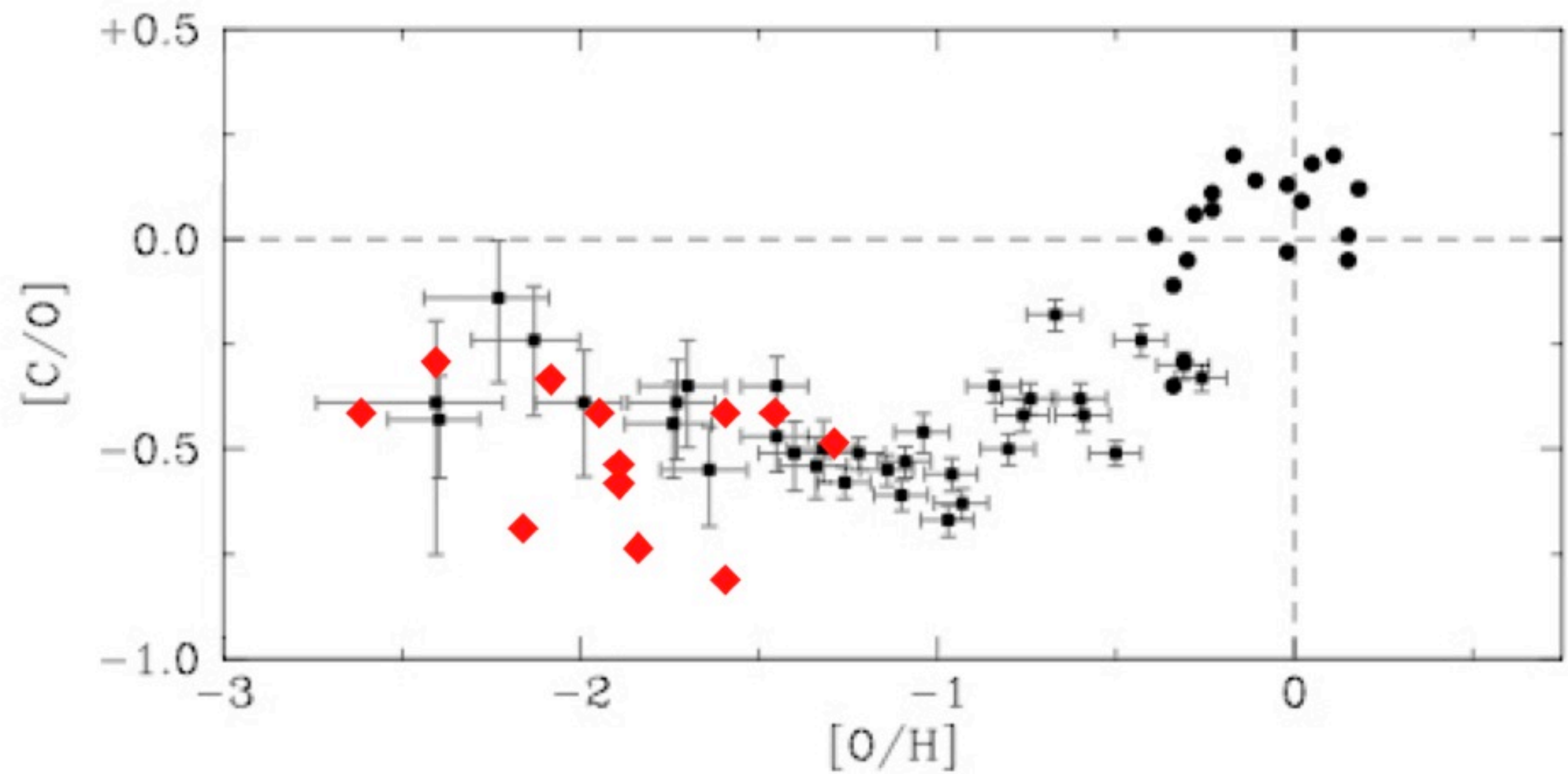


Most of the *volume* of the universe is in the voids which produce H I lines of too low a column density to be observed currently. So the distribution of [O/H by volume is largely unconstrained.

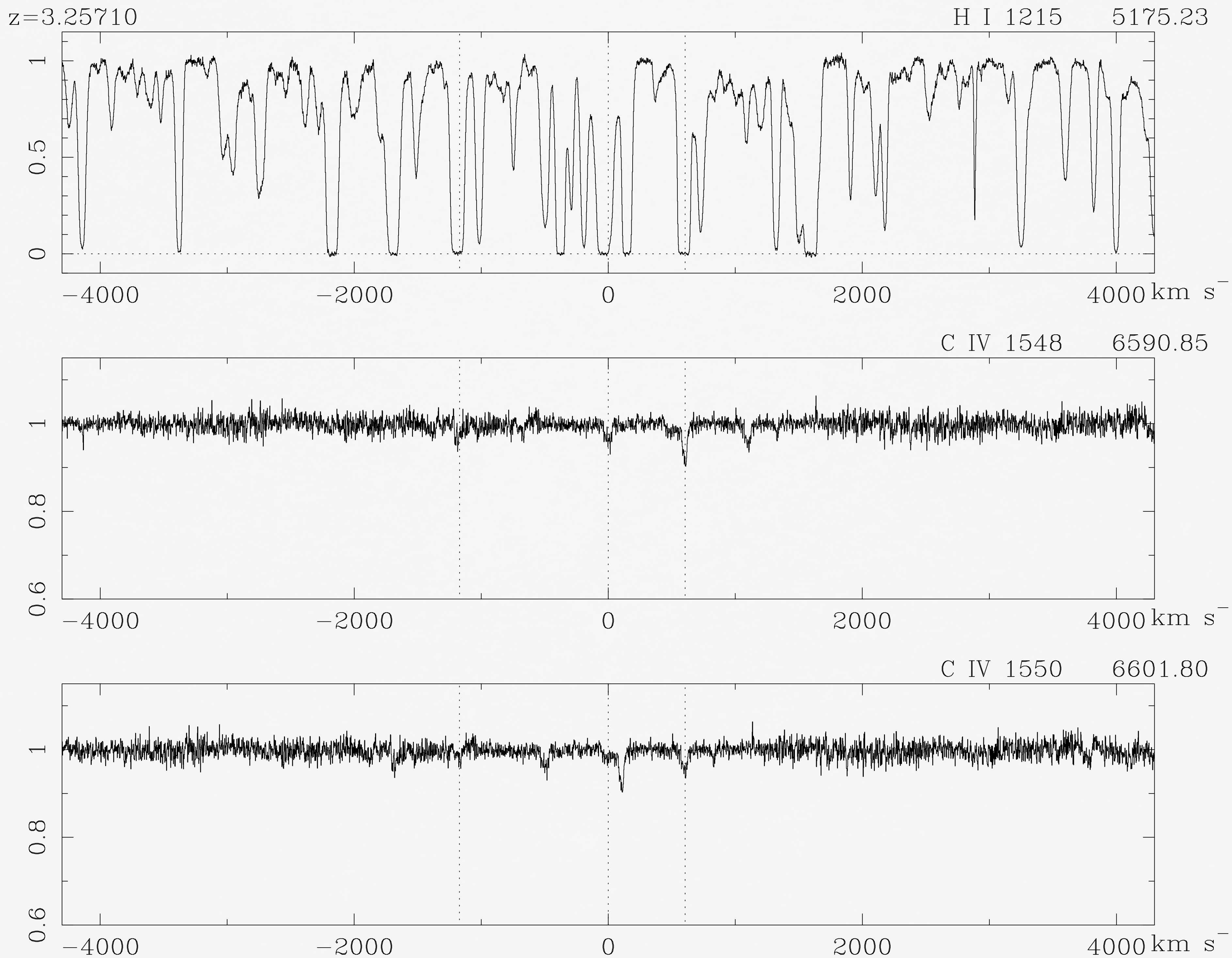
Simcoe, Sargent and Rauch (2004)



Part of the Ly-alpha and C IV forests around z_abs = 2.97 in Q1423+2309 (z = 3.66)

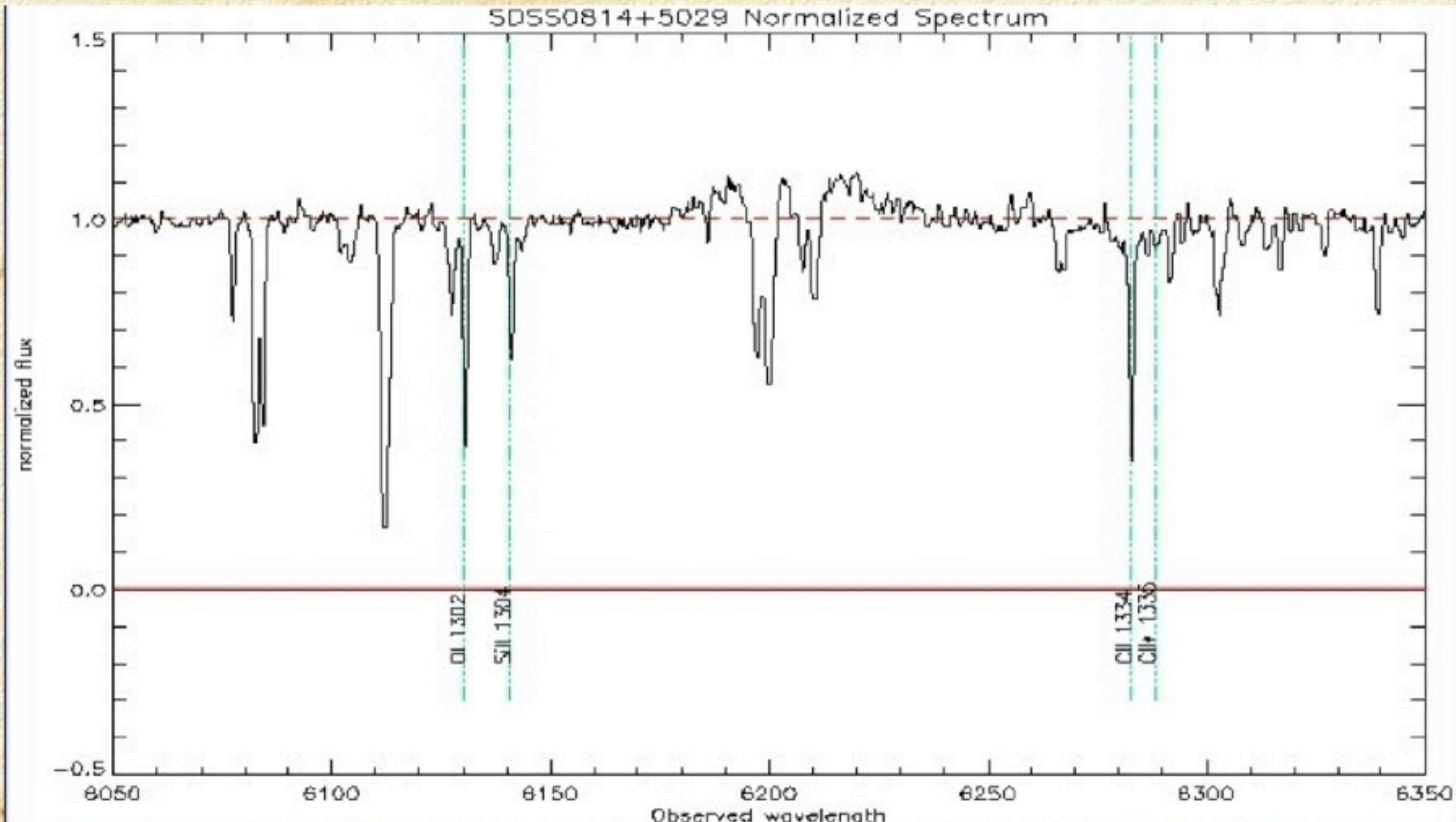


DLA C/O abundance ratios (red diamonds) compared with metal poor stars (Akerman, Pettini et al. 2003)



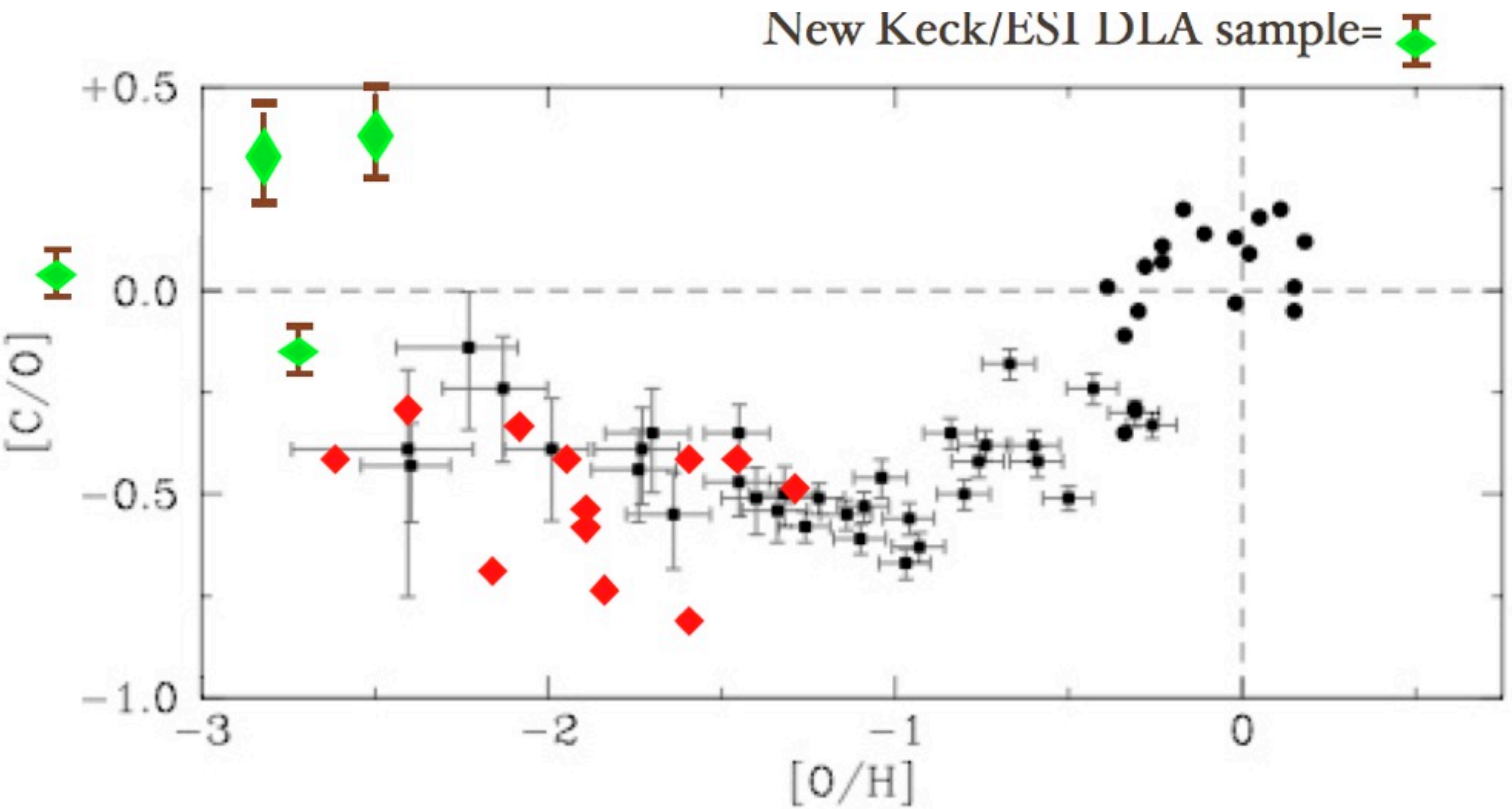
Lyman-alpha and C IV Forests around z _abs = 3.26 in Q1422+2309 (z = 3.66)

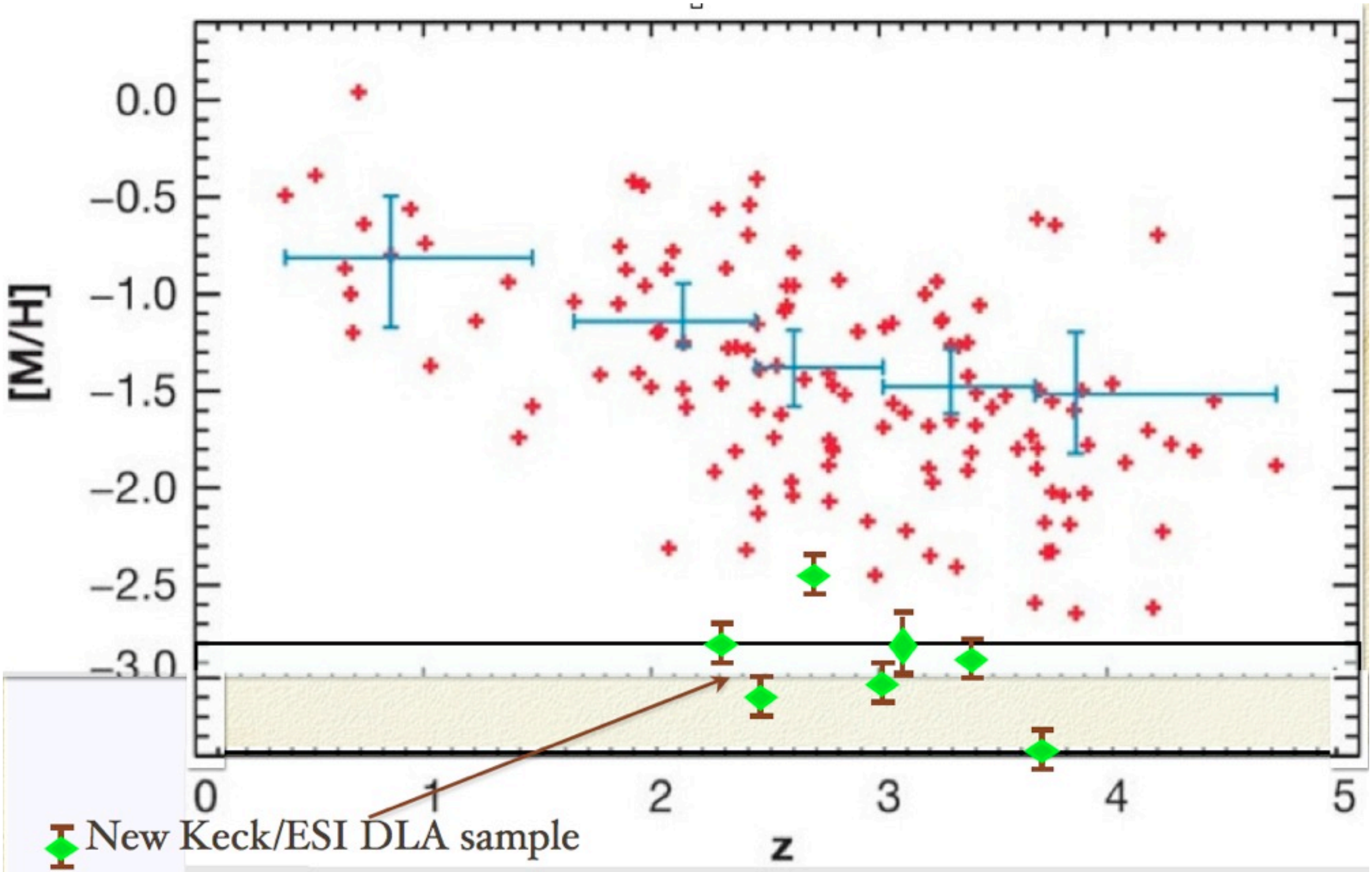
Example of ESI low-Z spectrum with [C/H] = -3.5



The nature of Damped Lyman-alpha galaxies

- Strong H I lines in Lyman-alpha forest with log N(H I) > 20.3 per
- Can measure abundances of many elements--- C, O, Si, Ca, Mg, Al, Zn, Fe, Cr, Ti, Mn, Cu, Ge
- Problem of differential dust depletion: Zn, O, C, not much depleted: Si, Fe depleted
- Elements with high condensation temperatures are depleted


New Keck/ESI DLA sample=
+0.5
0.0
−0.5
−1.0
[C/O]
−3
−2
−1
0
[O/H]


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
[M/H]
0
1
2
3
4
5
z
New Keck/ESI DLA sample

Two strategies using QSO absorption lines:

- Go to the highest possible redshift (currently z $\sim$ 6) and find, e.g., Damped Lyman-alpha absorbers with no associated heavy elements.

- Go to the most underdense regions of the IGM, *possibly* unpolluted by ejecta from proto-galaxies. From the ground this is best done at $z \sim 2.5$.

Outline

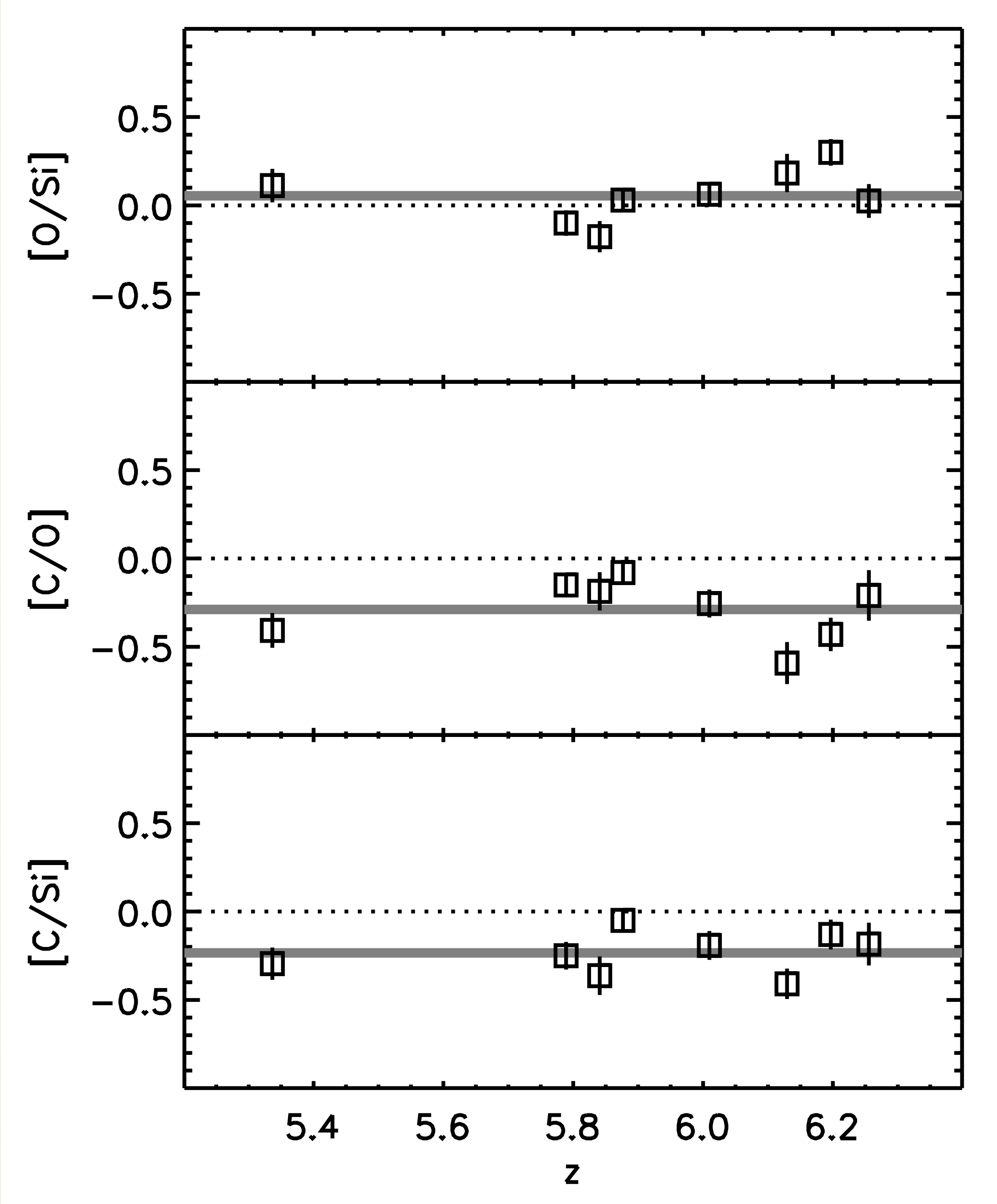
- QSO absorption lines: introduction
- Abundances in DLA systems
- Very low metallicity DLA systems
- C and O abundances in the IGM at $z \sim 2.5$
- Abundances at $z \sim 6$:
  - C, O and Si and Very Massive Stars
  - Fe/O and the origin of Fe at early times

Relative Abundances at z ~ 6

- Chemical signatures of the first stars
- Lines mostly unsaturated
- O I implies neutral gas

$$N_{\rm Si} \approx N_{\rm Si\ II}$$
$$N_{\rm O} \approx N_{\rm O\ I}$$
$$N_{\rm C} \approx N_{\rm C\ II}$$

- Future: compare to metal-poor stars



Mean values

Relative Abundances at z ~ 6

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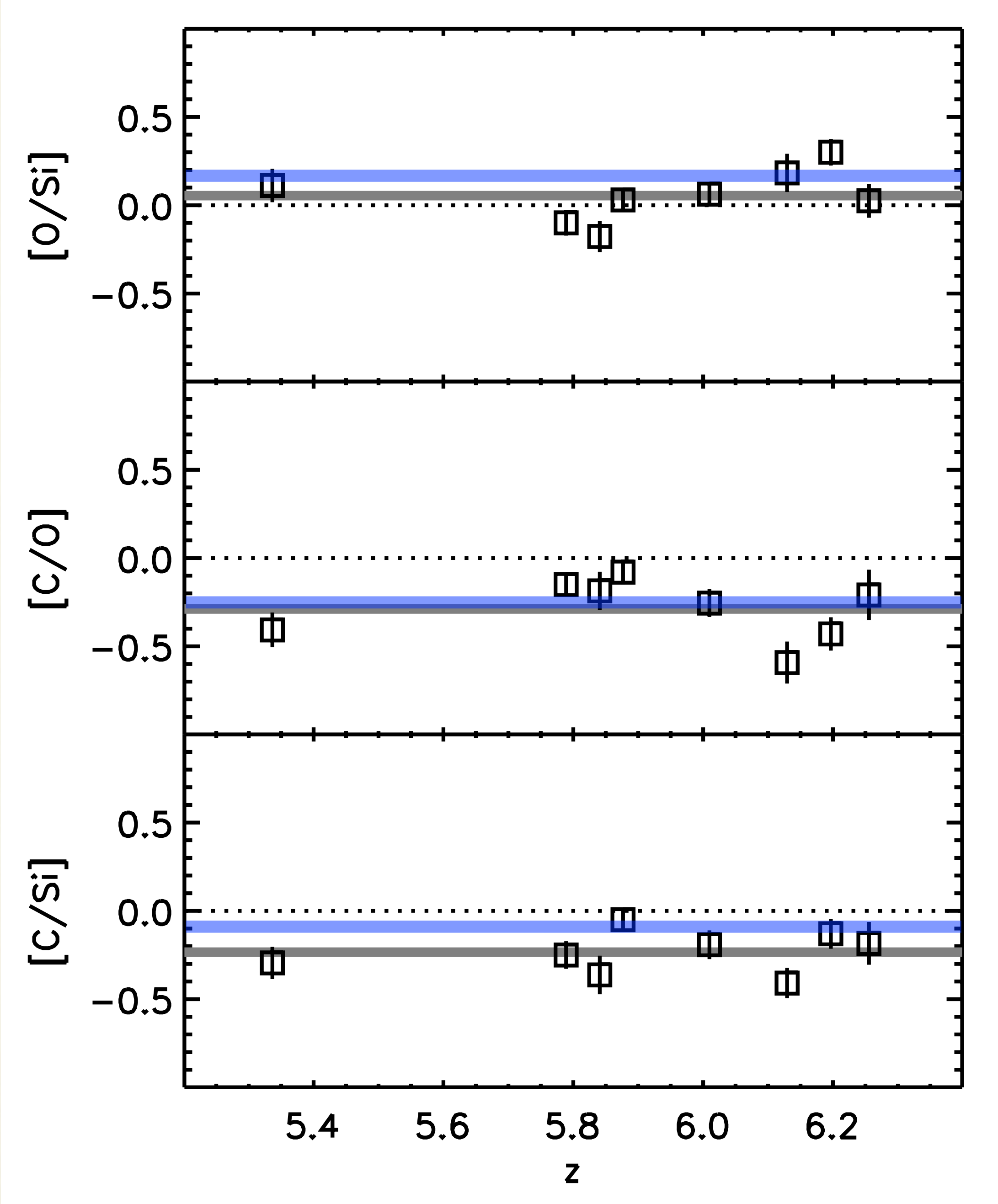

Mean values

Type II SNe

Relative Abundances at z ~ 6

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  $N_{\rm Si} \approx N_{\rm Si\ II}$

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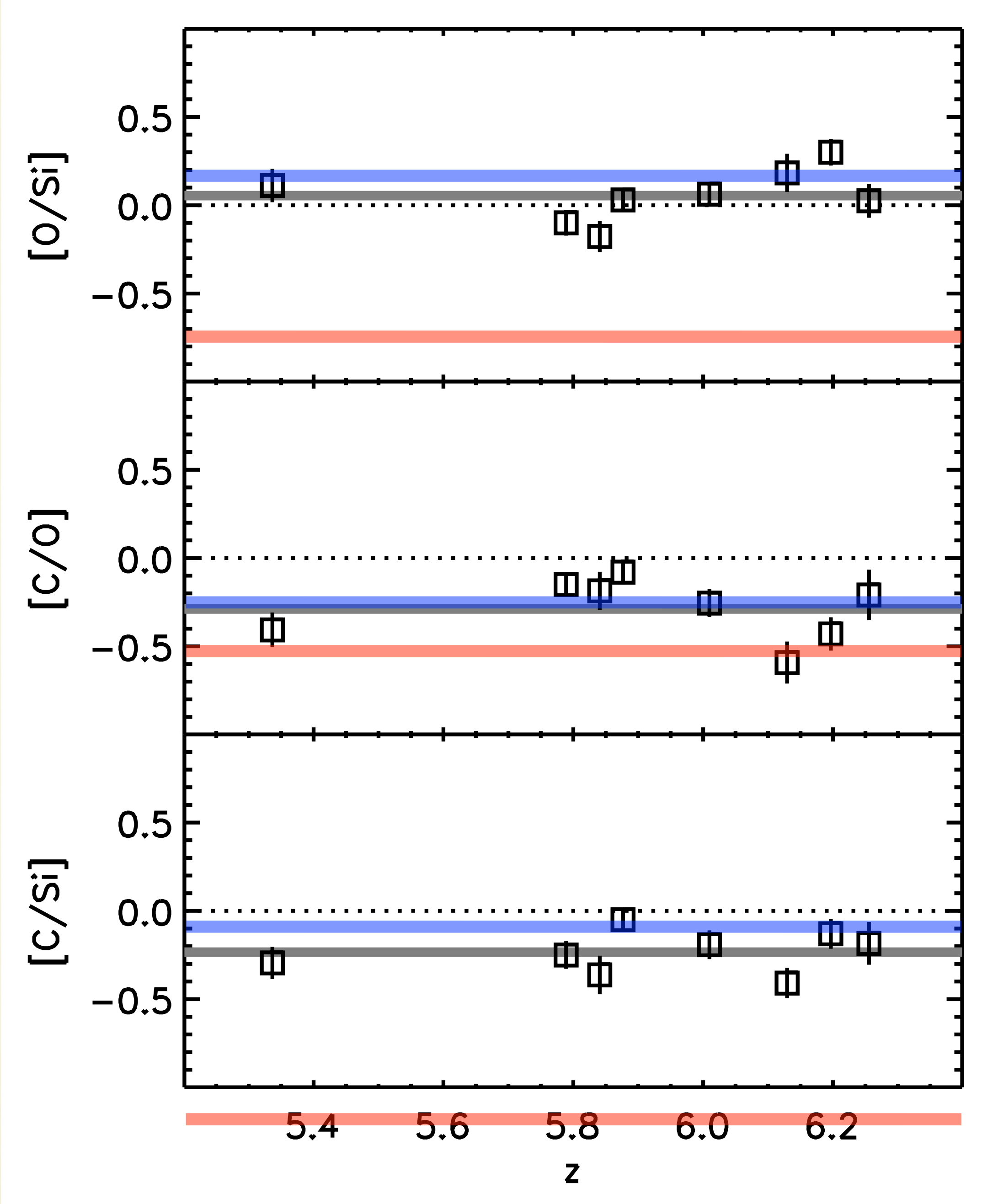
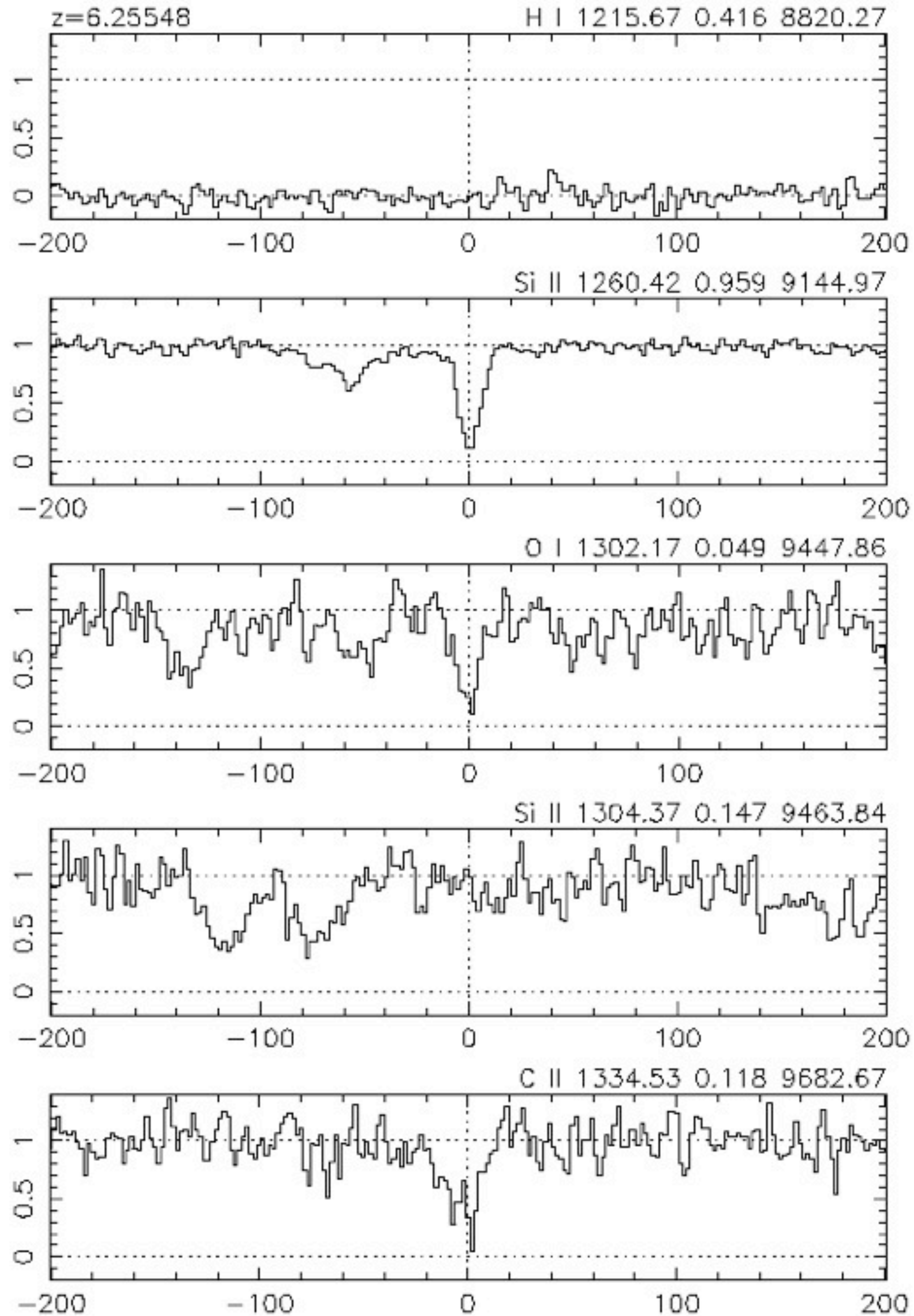


Mean values

Type II SNe

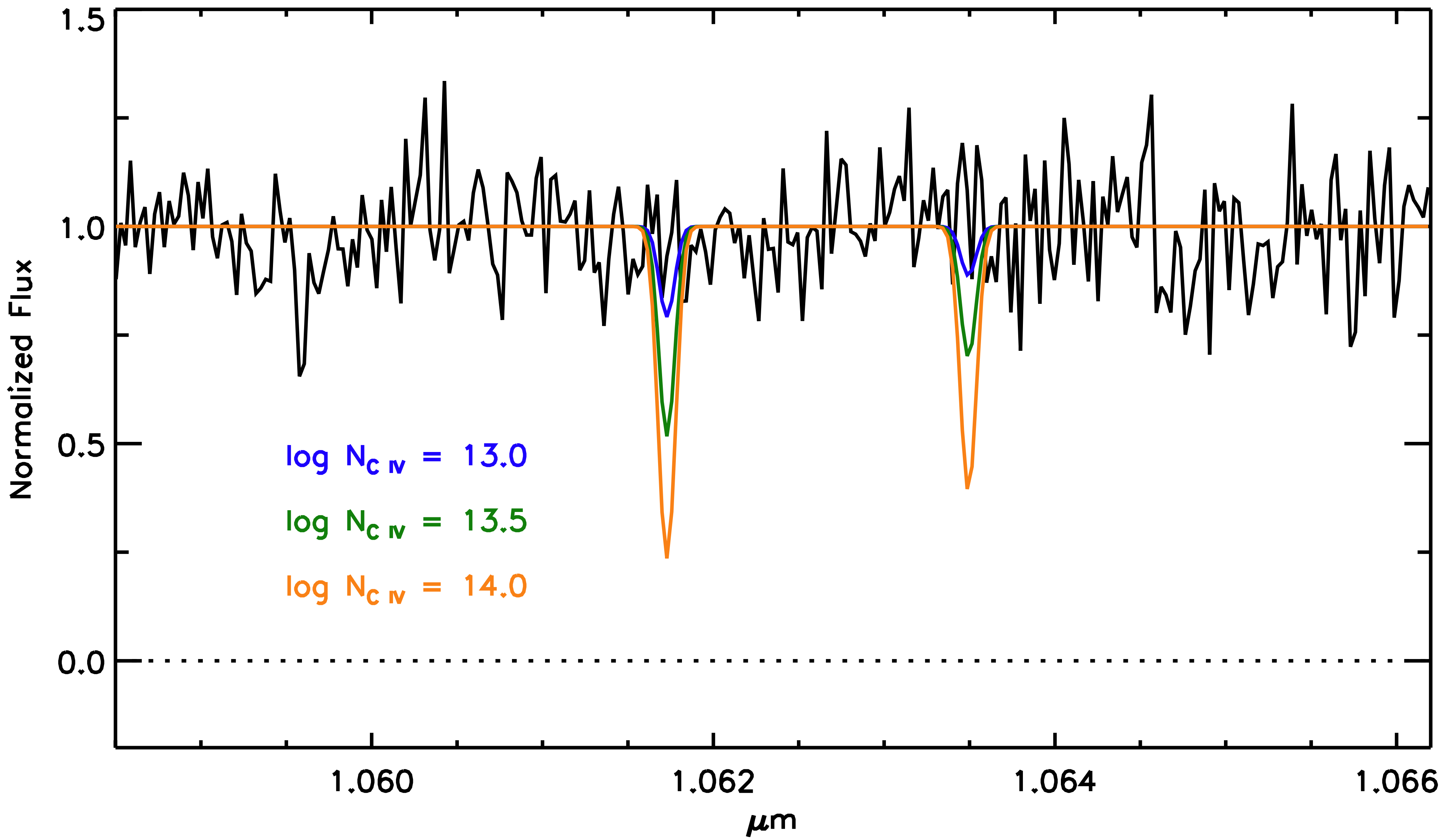
Very Massive Stars



An Absorption System at z = 6.26 containing O I, C II and Si II

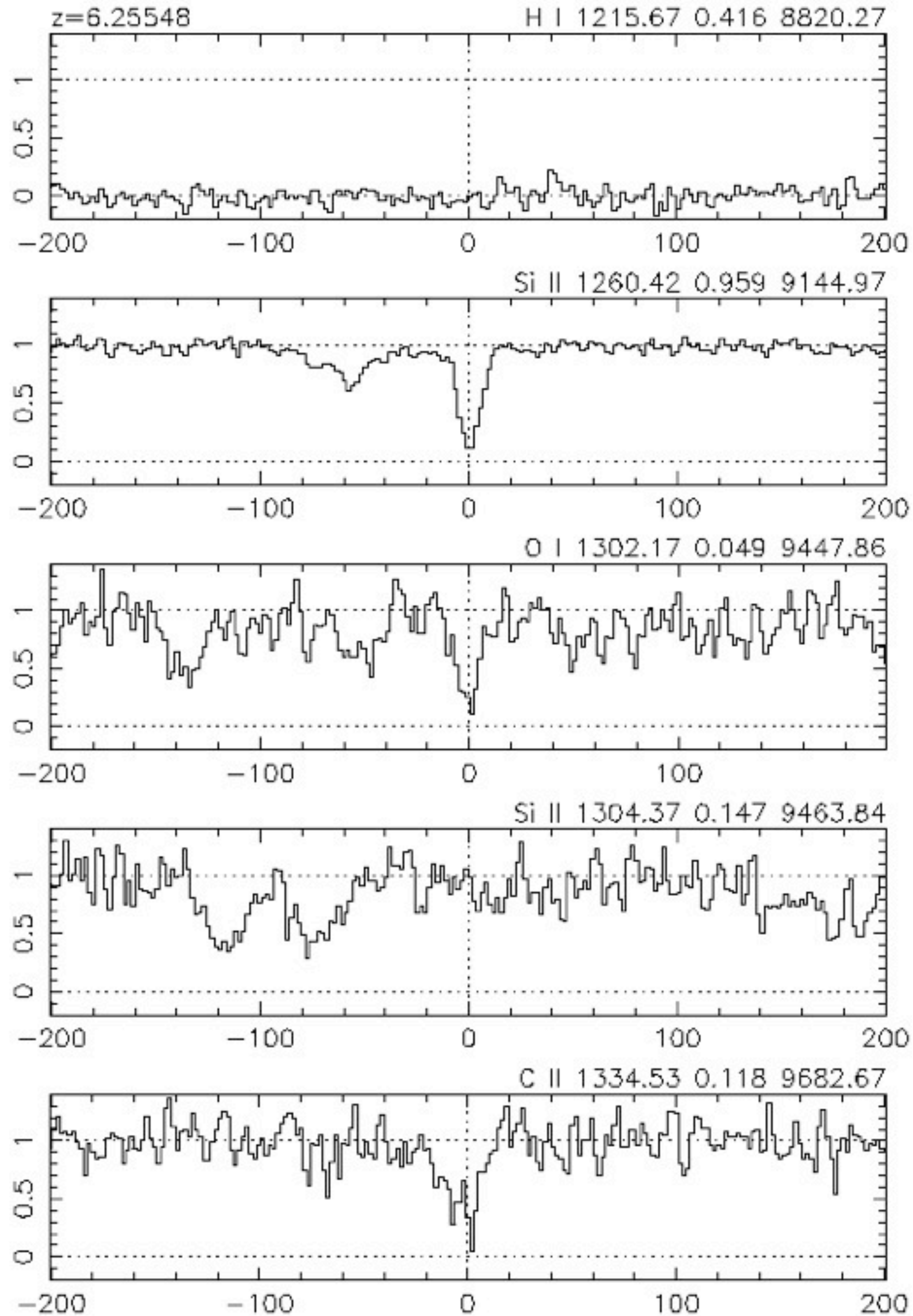
Detectability of C IV in Keck NIRSPEC data

(Typical exposure times 10-12 hours)



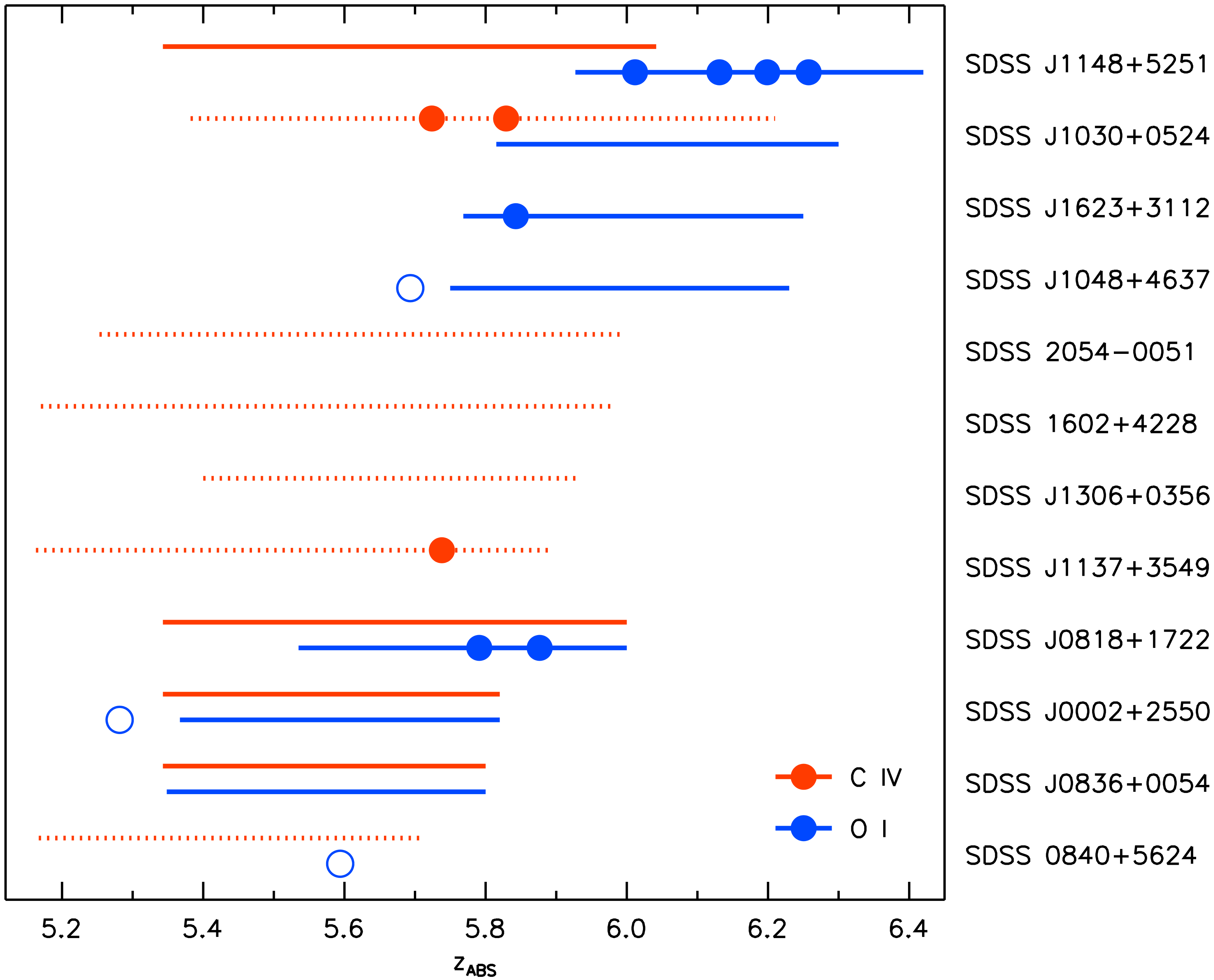
Relative Abundances at $z \sim 6$

- Have observed 9 QSOs at $z \sim 6$ with Keck HIRES.
- Very long exposures:- $\sim$ 10 hours per QSO.
- Measured absorption lines of C II, O I and Si II to get relative abundances of C, N and O at redshifts up to z = 6.25



An Absorption System at z = 6.26 containing O I, C II and Si II

Sightlines observed for C IV and O I



Solid lines: sightlines observed by Becker et al.
Dotted lines: sightlines observed by Ryan-Weber at al. to a shallower depth