(Metals in) the Very High Redshift IGM

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Where do metals in the IGM come from ?

And do they occur only in the overdense regions ?

- Population III early VMSs
- Early galaxy formation
- Later enrichment by winds

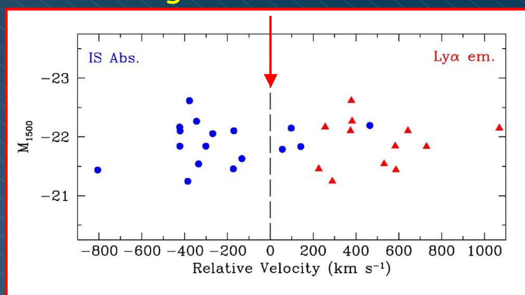
LBGs & IGM metal enrichment …

Kinematics of Lyman break galaxies:

19 galaxies, evidence of **superwinds** ?

Pettini et al. 2001, ApJ, 554, 981

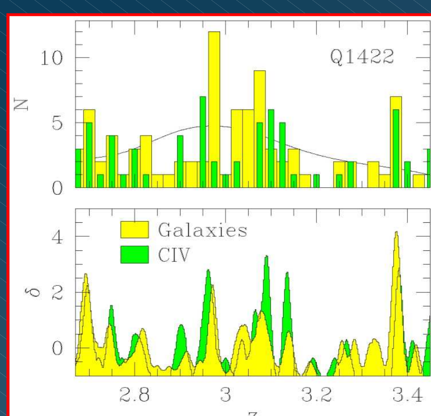
HII region emission lines



e.g., MS 1512–cB58, v(IS,abs) = –390 km s^{-1}

mass ouflow ~ 60 M/yr

Correlations between LBGs and IGM CIV …

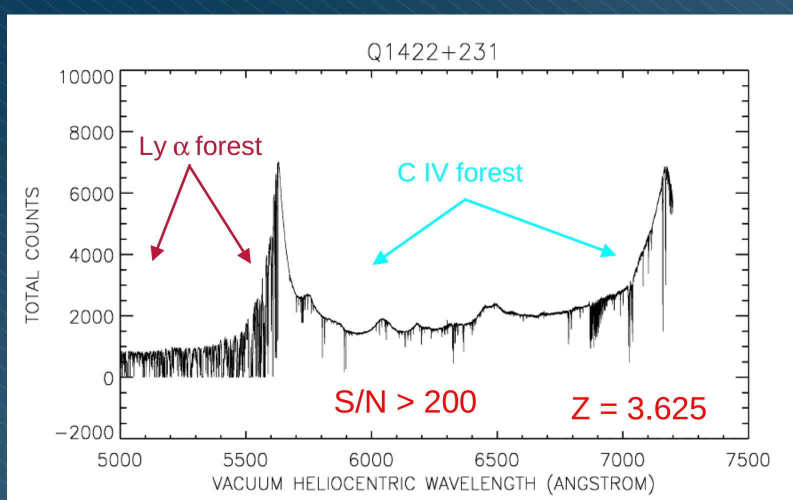


Adelberger et al. 2003, ApJ 584,45

Two key issues --

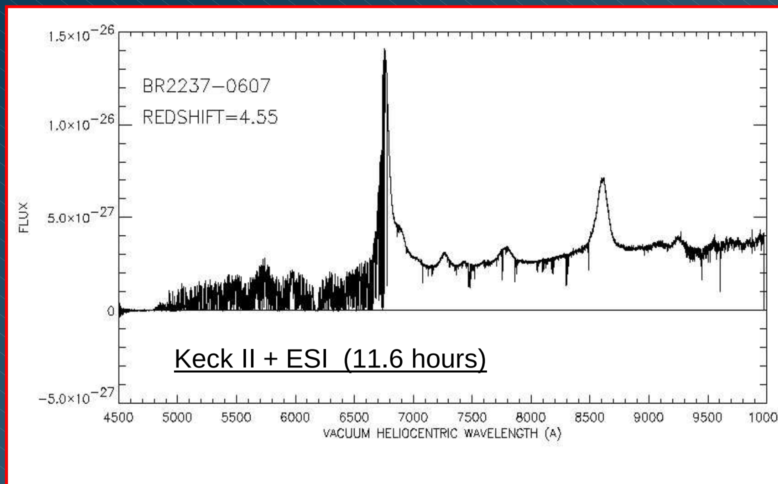
- How do metals evolve with redshift ?
- To what overdensity in the IGM do we still see metals ? i.e., are the voids enriched ?

Possible to obtain very high S/N spectra at z ~ 3 ..



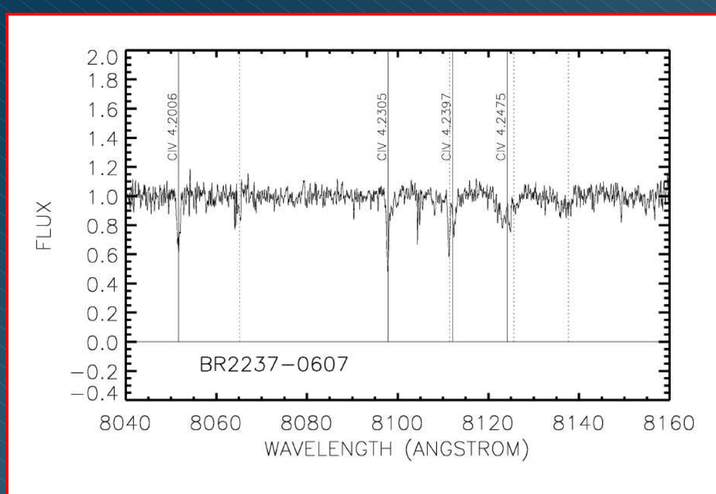
C IV forest to log N(CIV) = 11.7

… and at high redshift, with ESI (R ~ 5000)…



e.g., BR 2237-0607 z = 4.55 R = 18.3 11.6 hour exposure

… but the HIRES upgrade gives R = 67,000 spectra at high redshift …



e.g., BR 2237-0607 z = 4.55 R = 18.3 160 min exposure

The need for high S/N --

Extremely high S/N is required for these problems.

Voigt profile fitting limits for S/N = 200 in a 20 km/s window :

... 5 - 6 σ reasonable for C IV : need to see other doublet member.

.. based on stronger member of doublet.

		log N
C IV	6 σ	11.9
Si IV	3 σ	11.2
C II	3 σ	11.9
Si II	3 σ	11.9

.. comparable to Ellison et al. (2000)

But <ION>/C IV is low in the forest --- need high sensitivity.

With automatic methods -- hope to get to 2-3 σ in CIV, statistically.

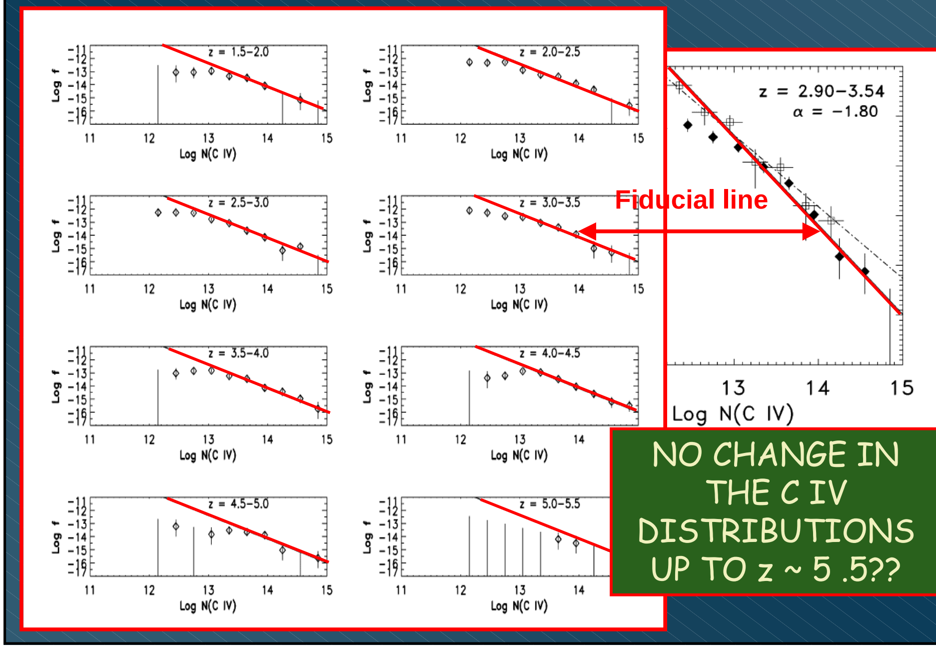
The high S/N sample

27 QSOs z_{em} = 2.08 - 6.39 S/N ~ 100 - 200

	z_{em}	S/N 1250	S/N 1400
SDSS1148+52	6.39000	80	--
SDSS1048+46	6.23000	75	--
SDSS1306+03	5.98500	95	--
SDSS0836+00	5.76500	130	55
SDSS1044-01	5.75500	70	25
SDSS1204-00	5.05500	105	80
SDSS0338+00	4.99000	115	45
SDSS1737+58	4.84000	100	115
SDSS2200+00	4.76300	125	65
BR1202-0725	4.60000	135	95
BR0334-1612	4.36000	130	85
BR0353-3820	4.55500	100	60
BR2237-0607	4.55000	230	220

	z_{em}	S/N 1250	S/N 1400
PSS0747+443	4.43200	95	60
BRI0952-011	4.40800	100	90
PSS0926+305	4.19000	135	120
BR2237-0607	4.55000	55	35
Q1422+2309	3.62000	340	285
HS0741+4741	3.22000	210	185
Q0636+680	3.18000	220	165
HS1946+7658	3.03000	210	200
HE2347-4342	2.88000	115	105
HS0119+1432	2.87000	115	95
HS1700+6416	2.72000	205	175
HE1122-1648	2.40000	60	75
HS1626+6433	2.31000	55	80
Q1331	2.08000	30	110

METAL EVOLUTION Z = 1.5 - 5.3 (ca. 2002)



NO CHANGE IN THE C IV DISTRIBUTIONS UP TO z ~ 5 .5??

METAL DENSITY AT z ~ 3 (Songaila 1997, ApJ 490, L1)

$$\Omega_{ion} = \frac{H_o}{\rho_{crit}\, c} \frac{dz}{dX} \sum \frac{N_{ion}}{\Delta z} m_{ion}$$, where

$$\frac{dX}{dz} = \frac{(1+z)^2}{[(1+z)^2 (1+\Omega_m z) - z(z+2)\,\Omega_\Lambda]^{0.5}}$$

Ω_{CIV} = (2.0 +/- 0.5) x 10^{-8}

Ω_{SiIV} = (7.0 +/- 2.6) x 10^{-9}

<z> = 3.18

H_0 = 65 km/s/Mpc

q_0 = 0.02

Assume $\Omega(C) \cong 2\,\Omega_{CIV}$ and $\Omega(Si) \cong 2\,\Omega_{SiIV}$

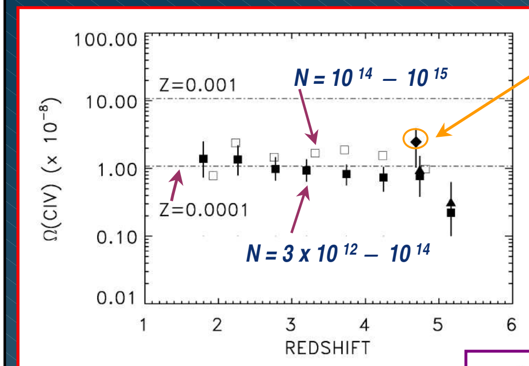
Scale α with Silicon & Fe with carbon

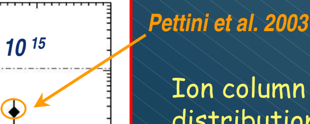
Ω_{metals} = (3.3 +/- 0.8) x 10^{-7}

WITH $0.005 < \Omega_b h^2 < 0.016$

MINIMUM METALLICITY RELATIVE TO SOLAR = –3.3 ~ –2.8

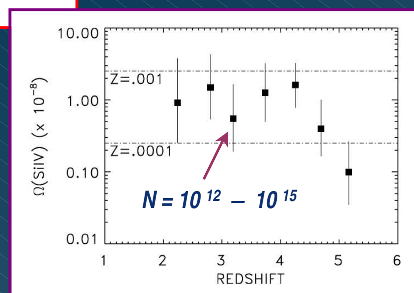
Minimum Ω (C IV) …





Ion column density distributions from Voigt profile fitting give the minimum metallicity history …

… and Ω (Si IV)



Turn down at z ~ 5 ??

Metallicity drop ?? or

Change in ionization ??

(June, 2004)

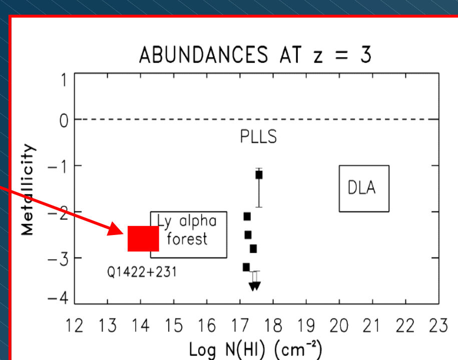
Metals in the low density IGM

Is the very low density forest enriched with metals ?

The pixel optical depth method – "POD" – gives a LIMITED answer …

Ellison et al. (2000)

Consistent with Schaye et al. (2003)



Statistical methods ---

We would like to make a more objective analysis than the Voigt profile fitting provides & also achieve the maximum sensitivity the data can provide

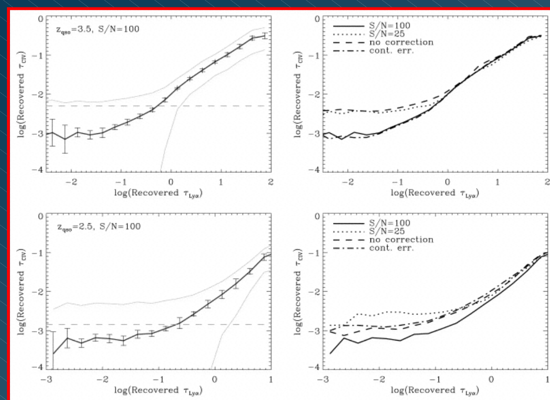
Best way to do this is by correlating features in the spectra --- the so-called pixel optical depth techniques, or "POD"s

Original POD

In 1998 we introduced a technique in which the HI optical depth traced using the Lyman series was cross-correlated with the CIV absorption line optical depths (Cowie & Songaila 1998).

This method has been used in great detail by Schaye, Aguirre and collaborators (Schaye et al 2003 …) ---

Original POD ---



Aguirre, Schaye & Theuns 2002, ApJ 576, 1

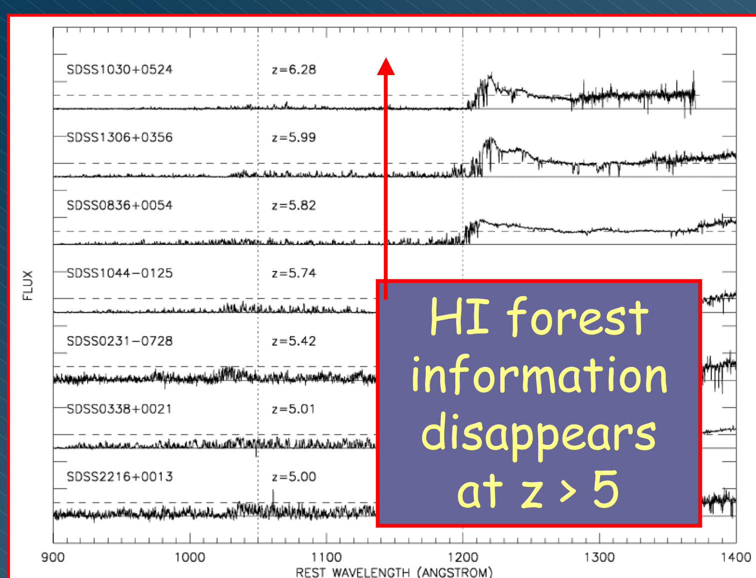
Limitation of POD method ---

z = 6.28

z = 5.82

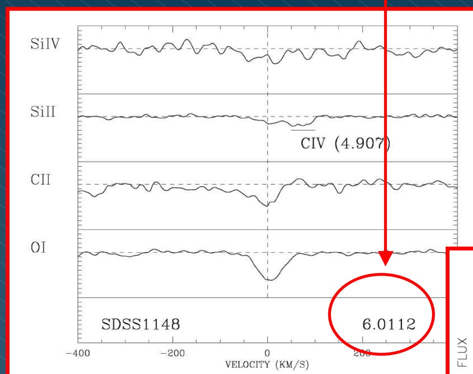
z = 5.42

z = 5.0

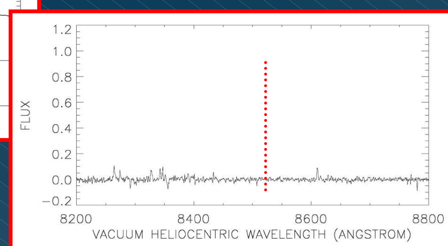


Limitation of POD method ---

Absorption systems exist at z ~ 6 …



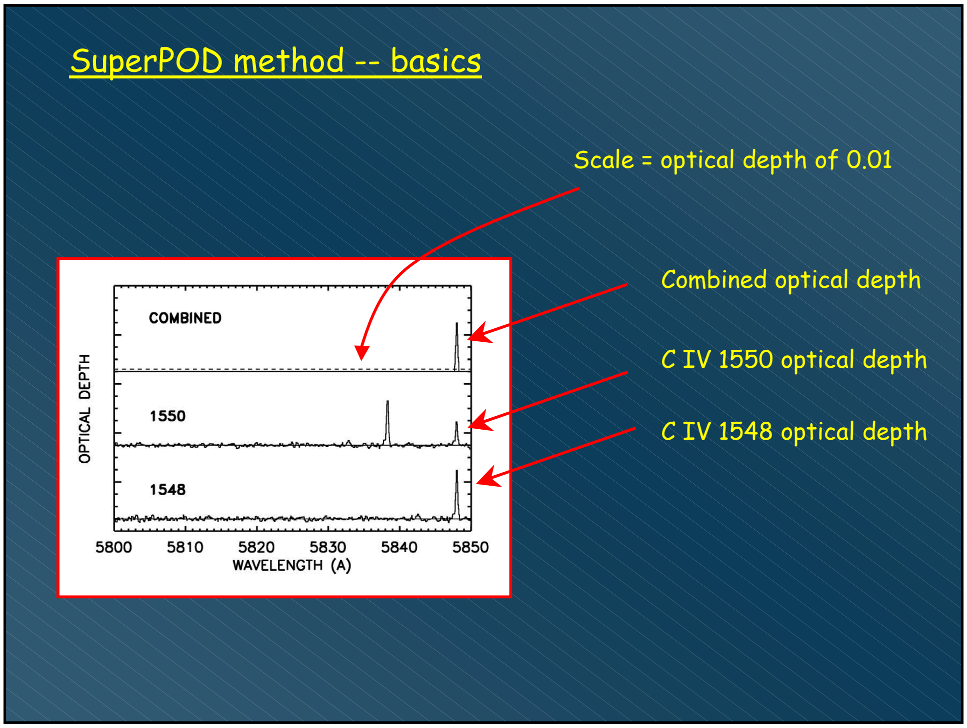
… but there is no corresponding HI

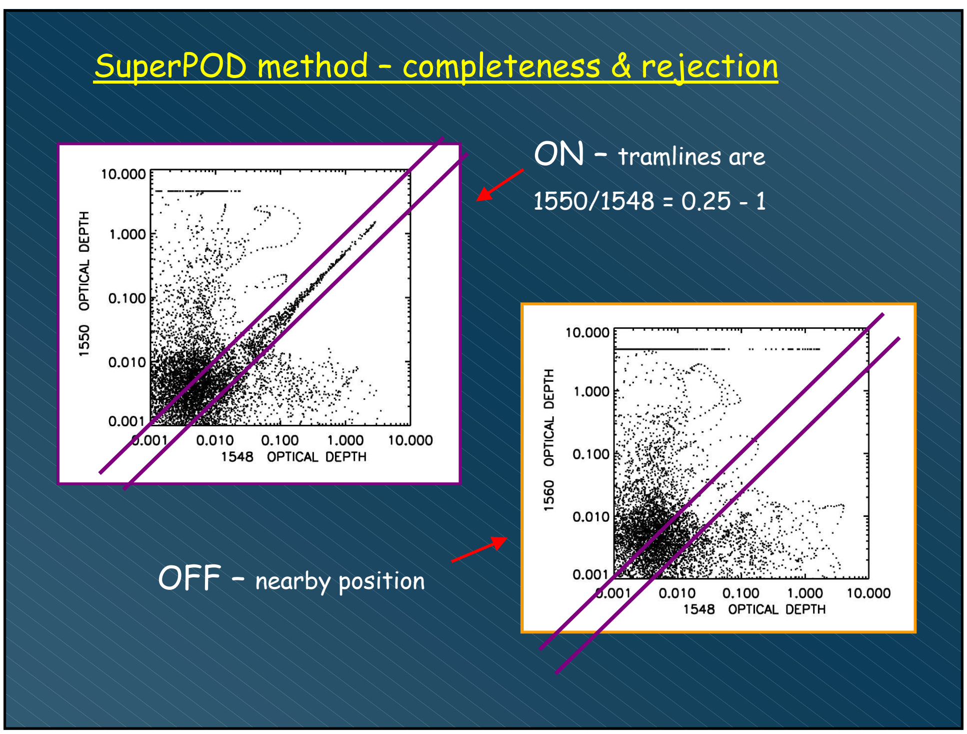


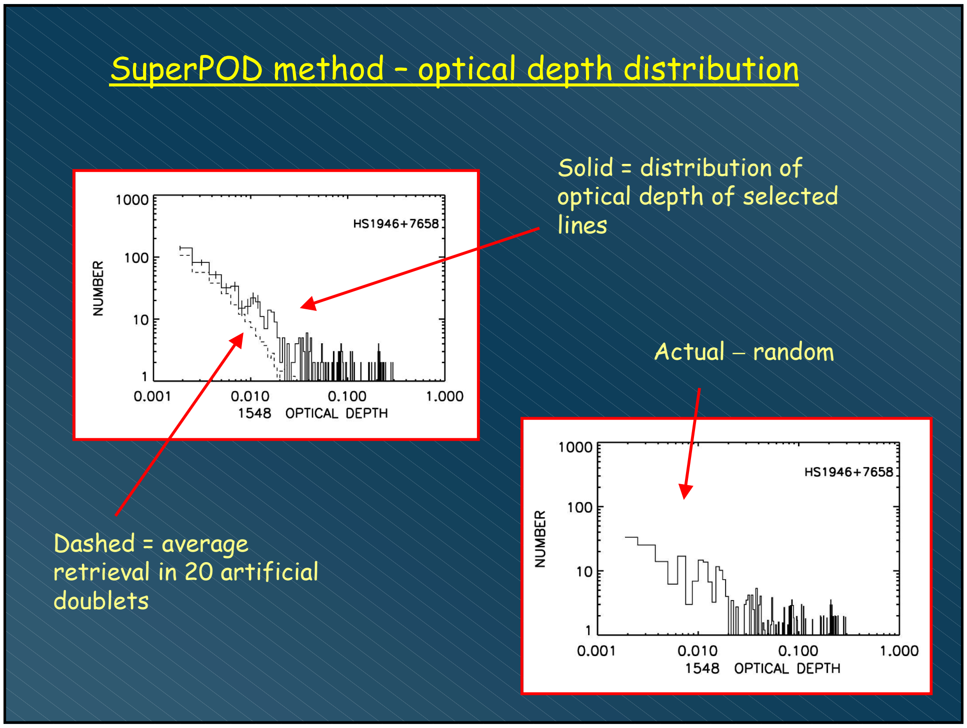
Superposed optical depths – "SuperPOD"

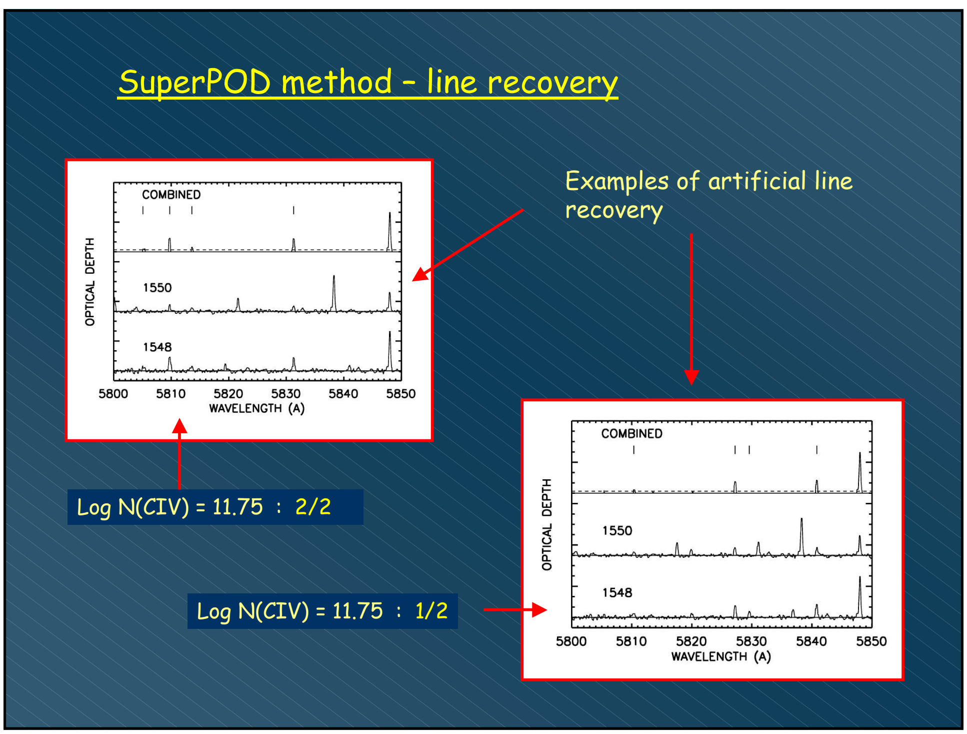
Use only the doublet information

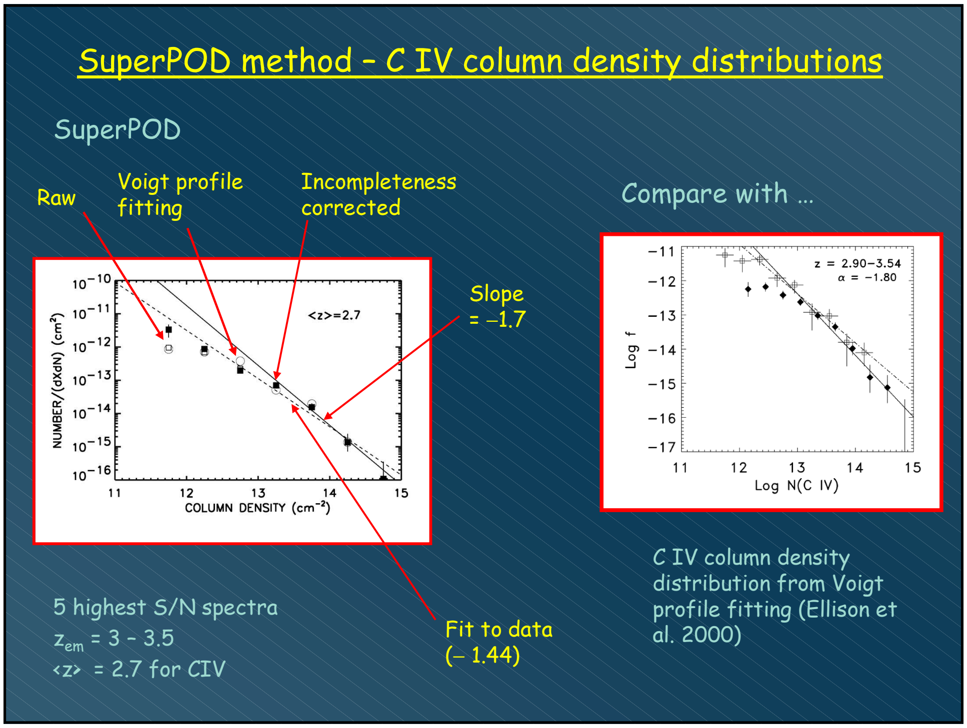
Find all positions in the optical depth vs wavelength plot where the ratio of the optical depths in the two members of the doublet approximately satisfies the 2:1 condition

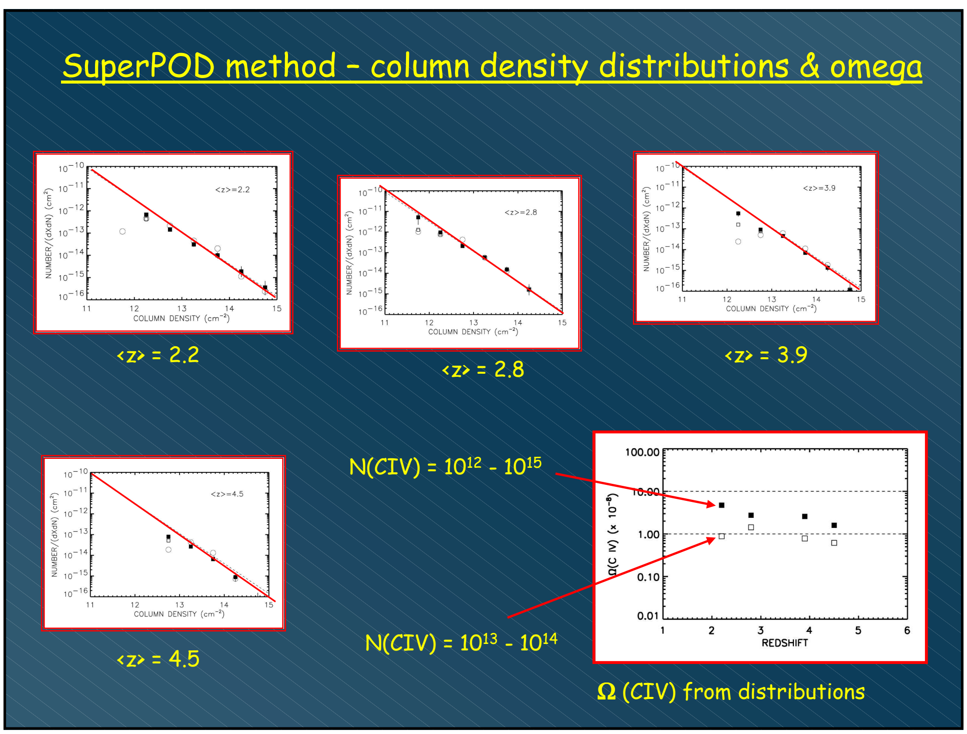

SuperPOD method -- basics
Scale = optical depth of 0.01
Combined optical depth
C IV 1550 optical depth
C IV 1548 optical depth
COMBINED
1550
1548
OPTICAL DEPTH
5800
5810
5820
5830
5840
5850
WAVELENGTH (A)


SuperPOD method – completeness & rejection
ON – tramlines are
1550/1548 = 0.25 - 1
OFF – nearby position
1550 OPTICAL DEPTH
1548 OPTICAL DEPTH
1560 OPTICAL DEPTH
10.000
1.000
0.100
0.010
0.001


SuperPOD method – optical depth distribution
Solid = distribution of optical depth of selected lines
Actual – random
Dashed = average retrieval in 20 artificial doublets
HS1946+7658
NUMBER
1000
100
10
1
0.001
0.010
0.100
1.000
1548 OPTICAL DEPTH


SuperPOD method – line recovery
Examples of artificial line recovery
Log N(CIV) = 11.75 : 2/2
Log N(CIV) = 11.75 : 1/2
COMBINED
1550
1548
OPTICAL DEPTH
5800
5810
5820
5830
5840
5850
WAVELENGTH (A)


SuperPOD method – C IV column density distributions
SuperPOD
Raw
Voigt profile fitting
Incompleteness corrected
Compare with …
Slope = –1.7
<z>=2.7
NUMBER/(dXdN) (cm²)
COLUMN DENSITY (cm⁻²)
z = 2.90–3.54
α = –1.80
Log f
Log N(C IV)
5 highest S/N spectra
z_em = 3 - 3.5
<z> = 2.7 for CIV
Fit to data (– 1.44)
C IV column density distribution from Voigt profile fitting (Ellison et al. 2000)

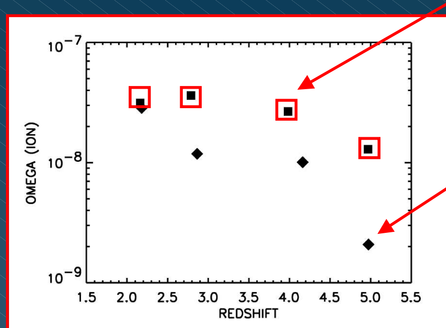

SuperPOD method – column density distributions & omega
<z> = 2.2
<z> = 2.8
<z> = 3.9
<z> = 4.5
N(CIV) = 10^12 - 10^15
N(CIV) = 10^13 - 10^14
REDSHIFT
Ω (CIV) from distributions

SuperPOD – no need for clouds --

However, SuperPOD doesn't require us to artificially break down the spectrum into clouds.

The distribution of C IV optical depths directly measures Ω(CIV).

Omega (ION) from optical depths



Average Ω (C IV)

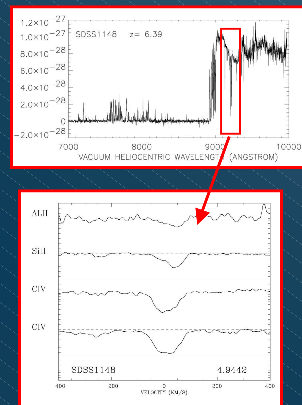
Average Ω (Si IV)

No Voigt profile fitting

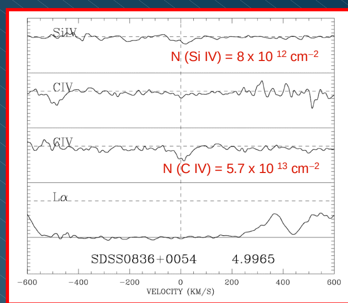
Ω (C IV) and Ω (Si IV) --

Are Ω (CIV) and Ω (SiIV) turning down at high redshift ?

We can still see metal systems at these redshifts :



z= 4.9442



z= 4.9965

The high S/N sample

27 QSOs z_{em} = 2.08 - 6.39 S/N ~ 100 - 200

	z_{em}	S/N 1250	S/N 1400
SDSS1148+52	6.39000	80	--
SDSS1048+46	6.23000	75	--
SDSS1306+03	5.98500	95	--
SDSS0836+00	5.76500	130	55
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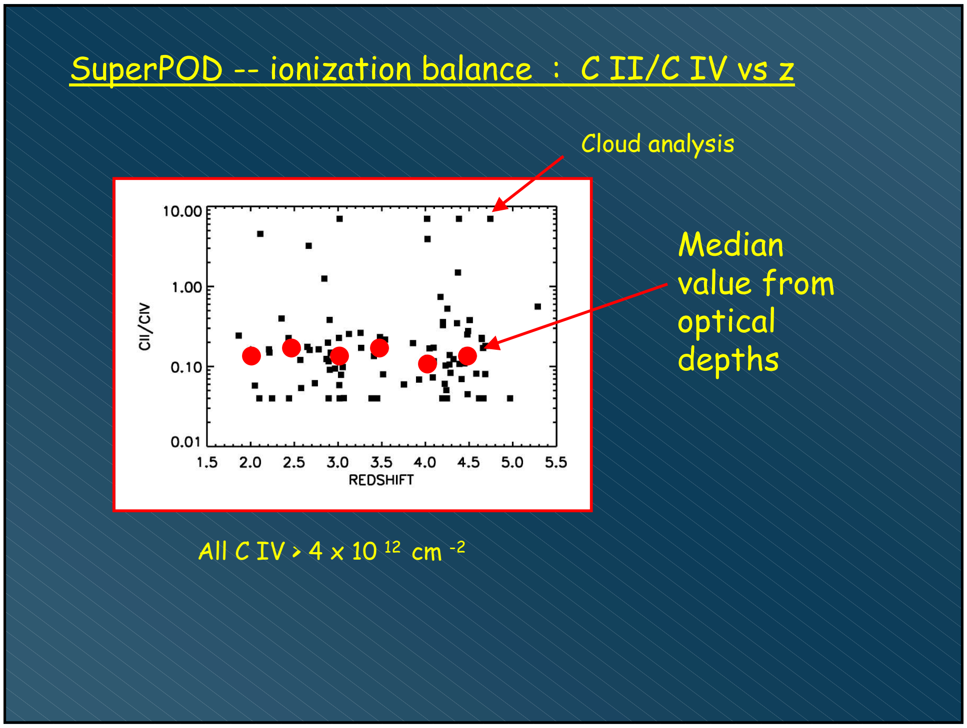
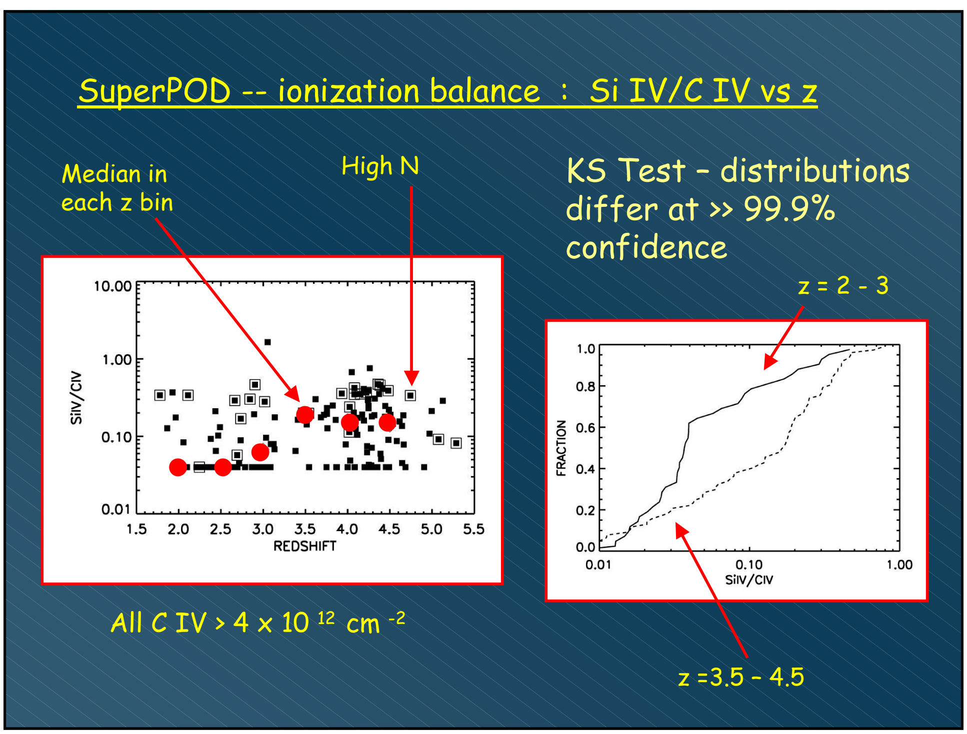
Q1331	2.08000	30	110


SuperPOD -- ionization balance : C II/C IV vs z
Cloud analysis
Median value from optical depths
CII/CIV
10.00
1.00
0.10
0.01
1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5
REDSHIFT
All C IV > 4 x 10 12 cm -2

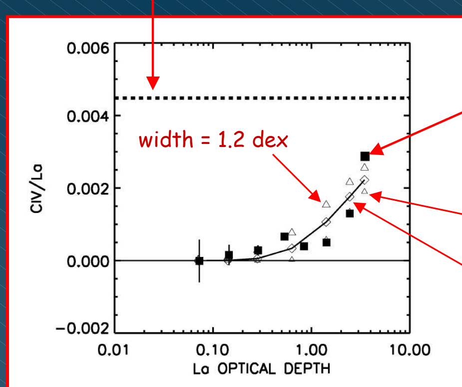

SuperPOD -- ionization balance : Si IV/C IV vs z
Median in each z bin
High N
KS Test – distributions differ at >> 99.9% confidence
z = 2 - 3
SiIV/CIV
10.00
1.00
0.10
0.01
1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5
REDSHIFT
FRACTION
1.0
0.8
0.6
0.4
0.2
0.0
0.01 0.10 1.00
SiIV/CIV
All C IV > 4 x 10 12 cm -2
z =3.5 – 4.5

SuperPOD – C IV vs H I

SuperPOD doesn't use the HI information --- but we can use the CIV information to find the HI properties of the CIV systems

SuperPOD method – C IV/Lyα ratio

<CIV/HI> = 4.5×10^{-3}

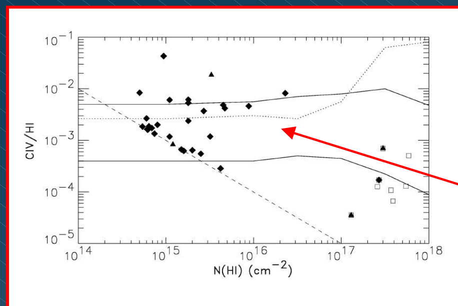


CIV/Lyα measured by SuperPOD – 1 σ error bars

width = 0.4 dex

width = 0.8 dex

SuperPOD – CIV/HI spread



-- spread of ~1 dex in CIV/HI

Songaila et al. 1996

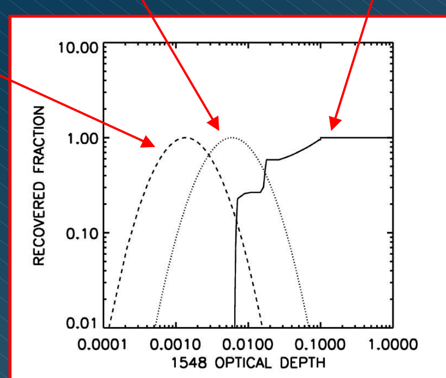
SuperPOD method – C IV/Lyα ratio

High S/N is CRUCIAL !

Fraction of inserted CIV systems recovered by SuperPOD

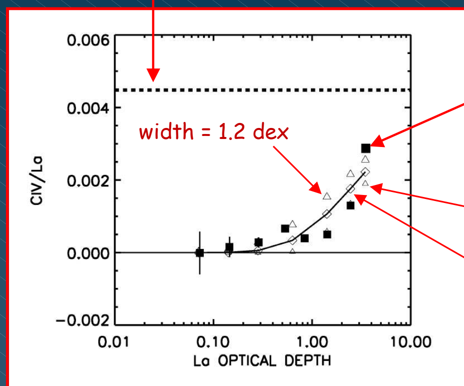
τ(Lyα) = 3.5

τ(Lyα) = 0.8



SuperPOD method – C IV/Lyα ratio

<CIV/HI> = 4.5 x 10 $^{-3}$



CIV/Lyα measured by SuperPOD – 1 σ error bars

width = 0.4 dex

width = 0.8 dex

Metals in the high redshift IGM --- Summary

Objectively analyzed a sample of high S/N spectra from z = 2 to 5

Ω(CIV) and **Ω**(SiIV) relatively constant for z = 2 – 5, with some turndown at the highest redshifts

CII/CIV nearly constant from z = 2 – 5

SiIV/CIV increases with increasing redshift. Break between z < 3 and z > 3.5 significant at > 99.9% level

There are metals present at z ~ 3 down to log δ ~ -0.75