Putting Metals into the IGM

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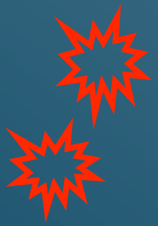
Minneapolis October 2005

Where do metals in the IGM come from ?

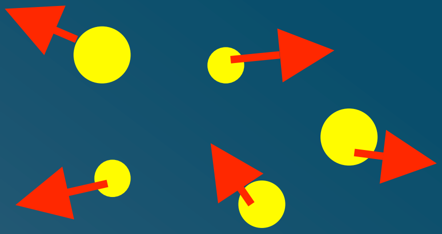
- Population III early VMSs
- Early galaxy formation
- Later enrichment by winds

How do metals get into the IGM ?



Early very
massive stars ?

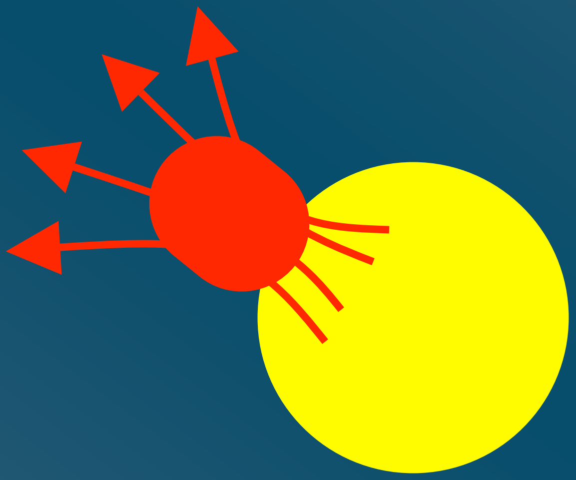
OR



Small galaxies
at z = 6 - 12 ?

OR

Superwinds
at z > 2-3 ?



Putting metals into the IGM --- Questions

- Can we see metals at high redshift?
- How does the early Universe evolve into the z=2 universe?

Are most of the metals clumped around galaxies?

Are metals still present in low density regions?

Are there other ways of distinguishing?

KEY QUESTION : Is CIV absorption seen in the IGM predominantly a consequence of early star formation or is it mostly contemporary injection via superwinds? (OR BOTH ??)

- How does the overall star formation history relate to the history of IGM metal enhancement?

Putting metals into the IGM --- Questions

- Is there a way to directly constrain the amount of contemporary injection via superwinds?

  Spatial correlation ? Velocities ?

- Are there metals in the lowest density regions of the IGM?

  Hard to do with superwinds ?

- Can we measure the redshift evolution of IGM metals?

  Most direct – high-z metals come from high-z sources.

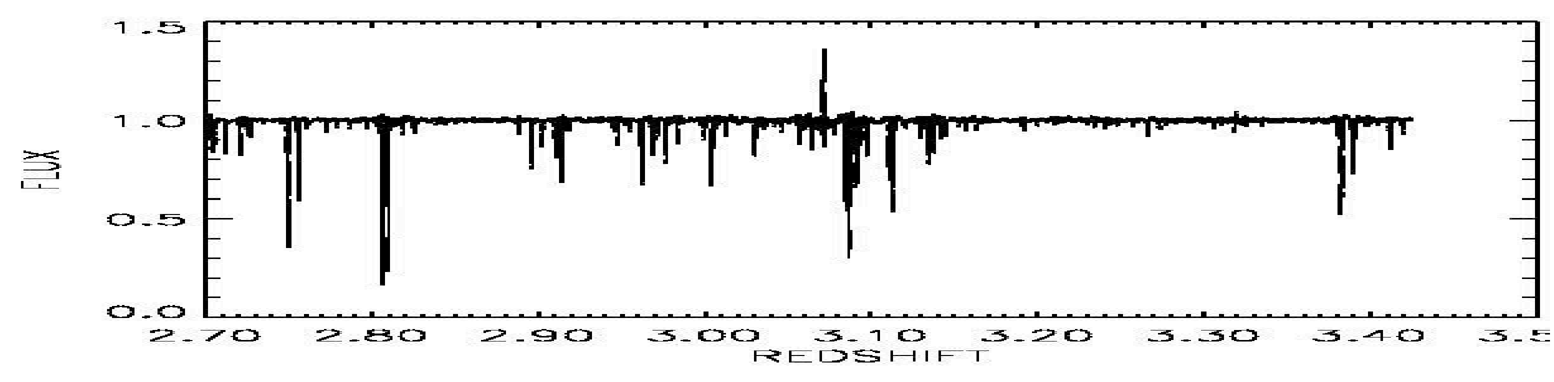
Early injection vs. superwinds -- correlation

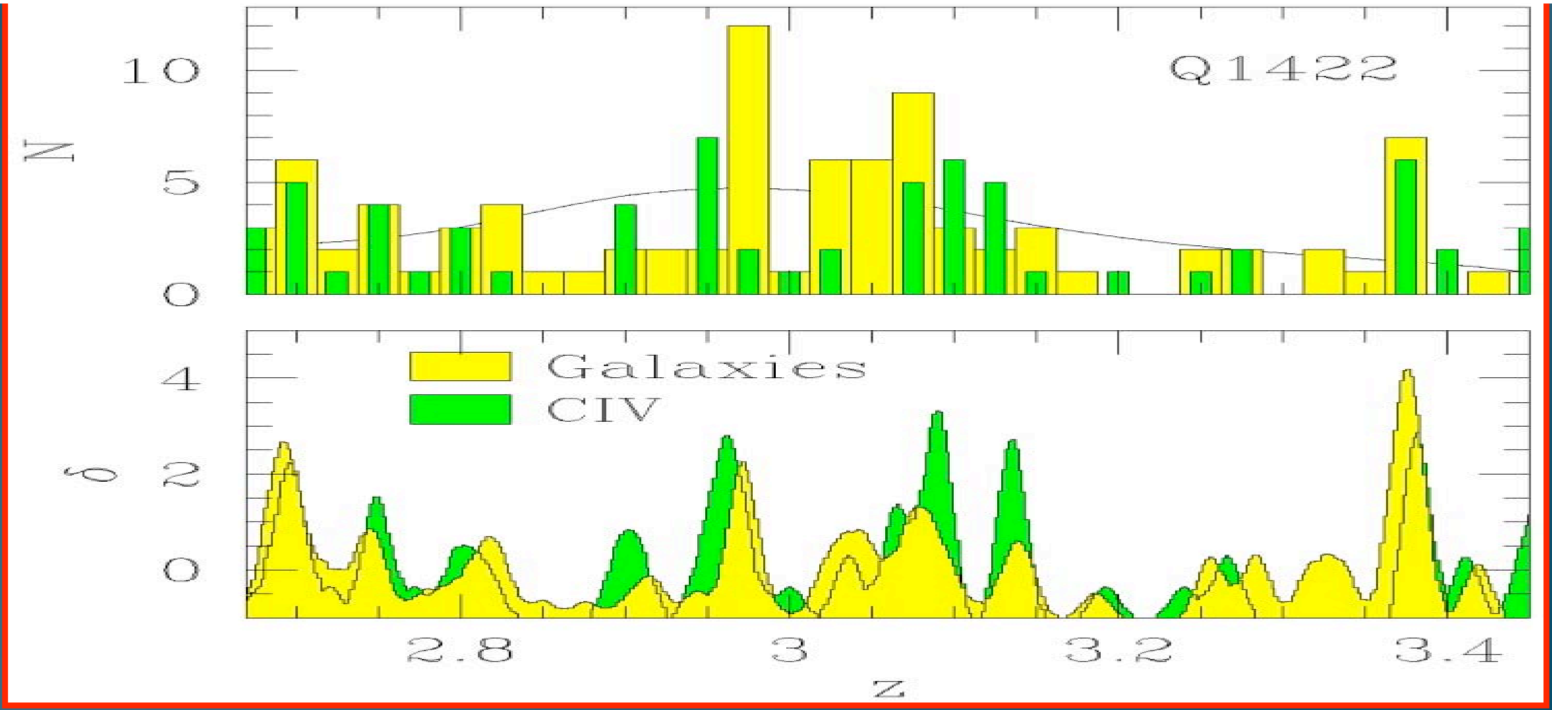
Late injection could result in a closer correlation between the absorbers and the galaxies (Adelberger et al. 2005).

There is a strong correlation between CIV absorption and galaxies at $z = 2$ even down to fairly low CIV column densities ($N(\mathrm{CIV}) \sim 10^{13}$ cm^{-2}).

About one third of systems with $N(\mathrm{CIV}) > 10^{14}$ cm^{-2} can be directly associated with LBGs within an impact parameter of 80 kpc.

Correlations between LBGs and IGM CIV …

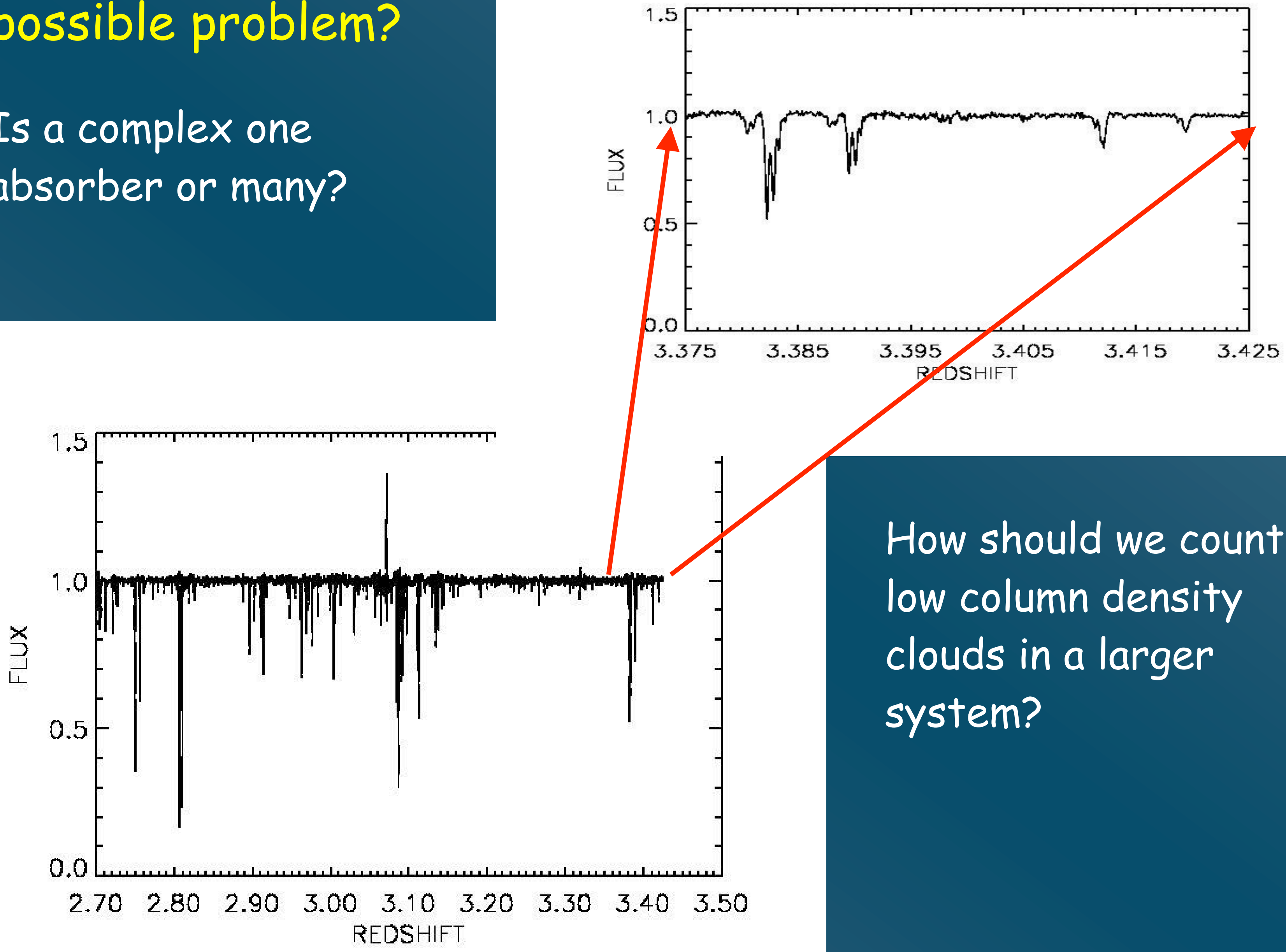




Adelberger et al. 2003, ApJ 584,45

A possible problem?

Is a complex one absorber or many?



How should we count low column density clouds in a larger system?

Early injection vs. superwinds -- correlation

In practice it is hard to decide between scenarios in which the material is injected from early galaxies and from late superwinds, based on the correlation function.

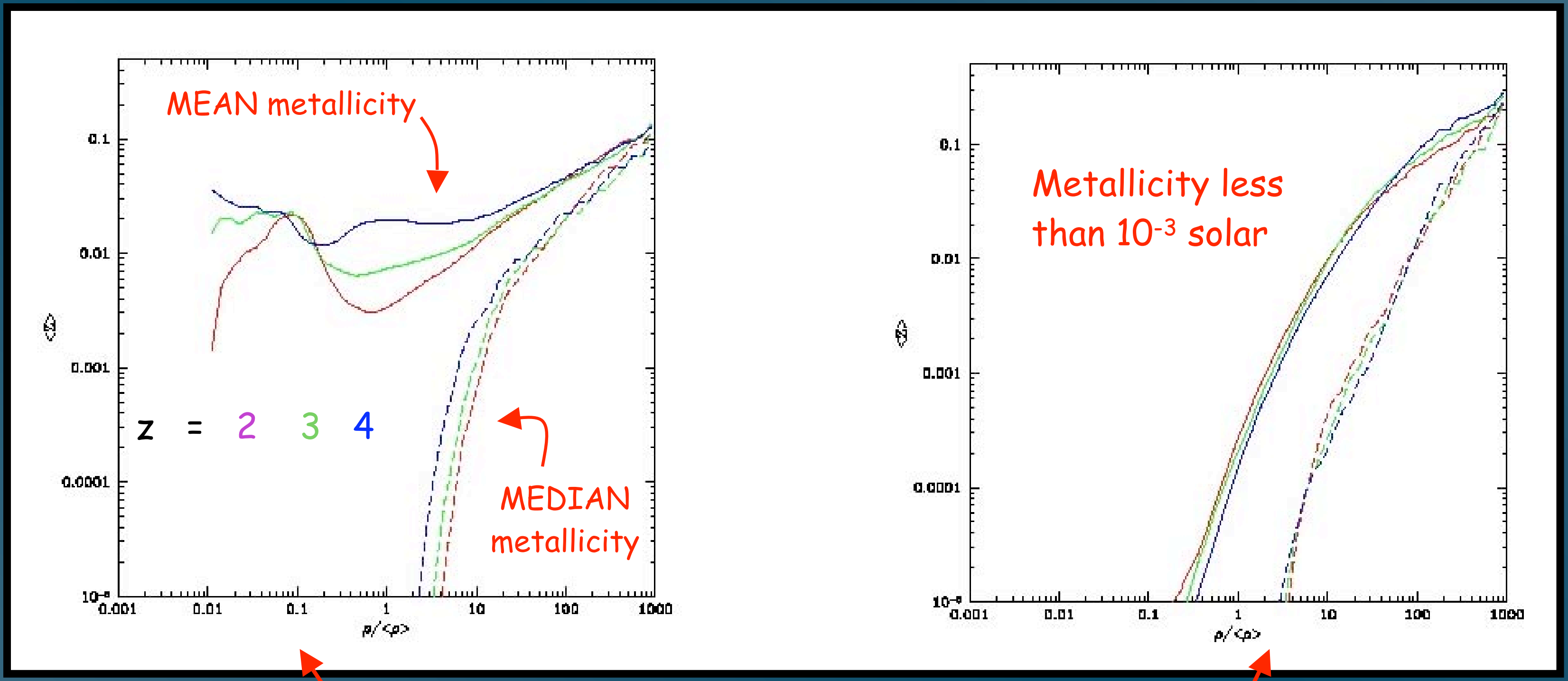
Porciani & Madau 2005:
Even early galaxy injection still results in a strong correlation between galaxies and CIV absorbers at $z=2$.

Early injection vs. superwinds -- density

The different scenarios will also produce different patterns of enrichment as a function of overdensity in the IGM …

… but this is still at the edge of our observational ability.

Enrichment as a function of overdensity


MEAN metallicity

z = 2 3 4

MEDIAN metallicity

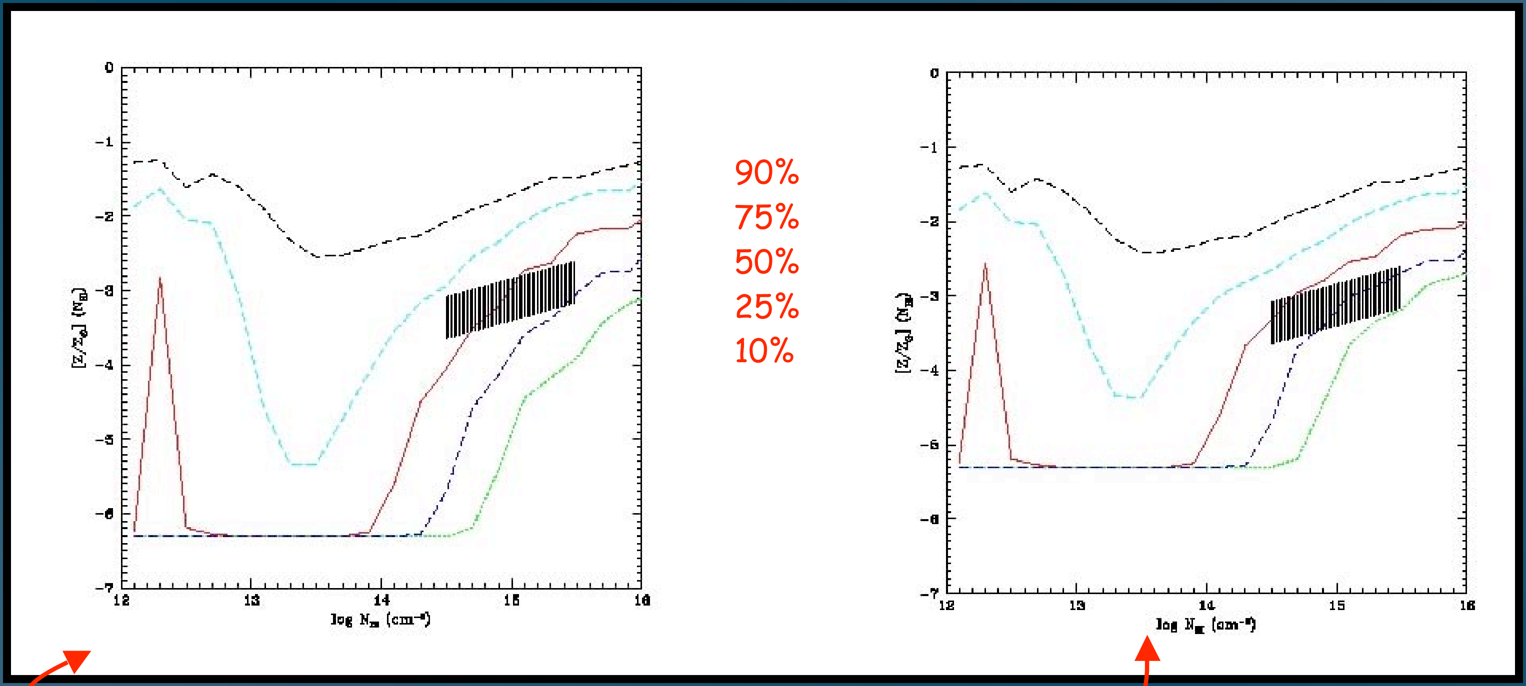
Metallicity less than 10^{-3} solar

Models with late superwinds

Cen et al. 2005

Models without

Viewed as a function of HI column density and compared with Shaye et al. 2003 (shaded).



With superwinds

With superwinds

Need to get to N(HI) < 10^{14} cm^{-2}

Cen et al. 2005

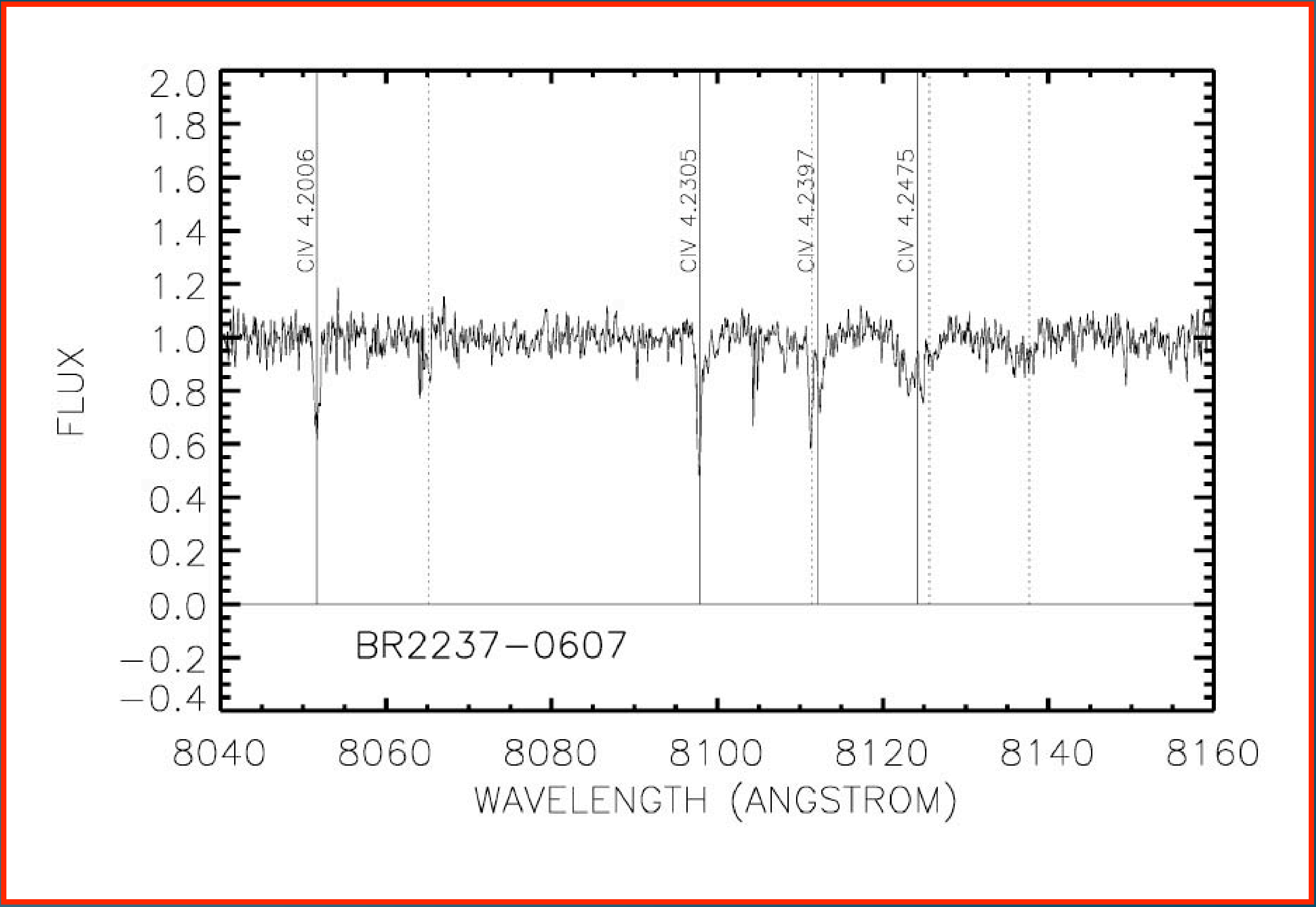
What information do we have ?

Apart from the neutral hydrogen of the Lyman forest, we have only a very limited number of absorption lines that we can detect in the low density intergalactic gas :

Most of the information comes from CIV with limited ionization information from the SiIV and CII lines outside the forest and other lines that lie in the forest (e.g. SiIII) and some information on the hotter gas from OVI … but OVI lies in the Lyman forest.

Essentially the current situation is that, within the variation in the CIV/HI ratio, we see CIV in the IGM to the limits that we can detect it to and to the redshifts we can measure to.

We can make CIV measurements out to just beyond z = 5



e.g., BR 2237-0607 R=67000 z = 4.55 R = 18.3 160 min exposure

How sensitive do observations need to be?

It is at optical depths near unity in the neutral hydrogen --- close to the point at which we are no longer overdense --- that we should start to see differences in the enrichment, depending on the enhancement mechanism.

This means we need to measure CIV column densities of a few times 10^{11} cm^{-2} --- at least in some sort of statistical way --- if we are to test the enrichment mechanisms.

This is hard with direct profile fitting and even the very best quality spectra available at present don't get us there.

How deep can we go with direct detection ?

With state of the art spectra with S/N = 200 in an R = 40,000 resolution element:

Voigt profile fitting limits in a 20 km/s line width :

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

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

.. based on stronger member of doublet.

.. comparable to Ellison et al. (2000)

This gets us roughly to overdensities of a few in the neutral hydrogen: just above the place where things get more interesting.

Statistical methods --- POD technique

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 : HI optical depth traced using the Lyman series was cross-correlated with the CIV absorption line optical depths (Cowie & Songaila 1998).

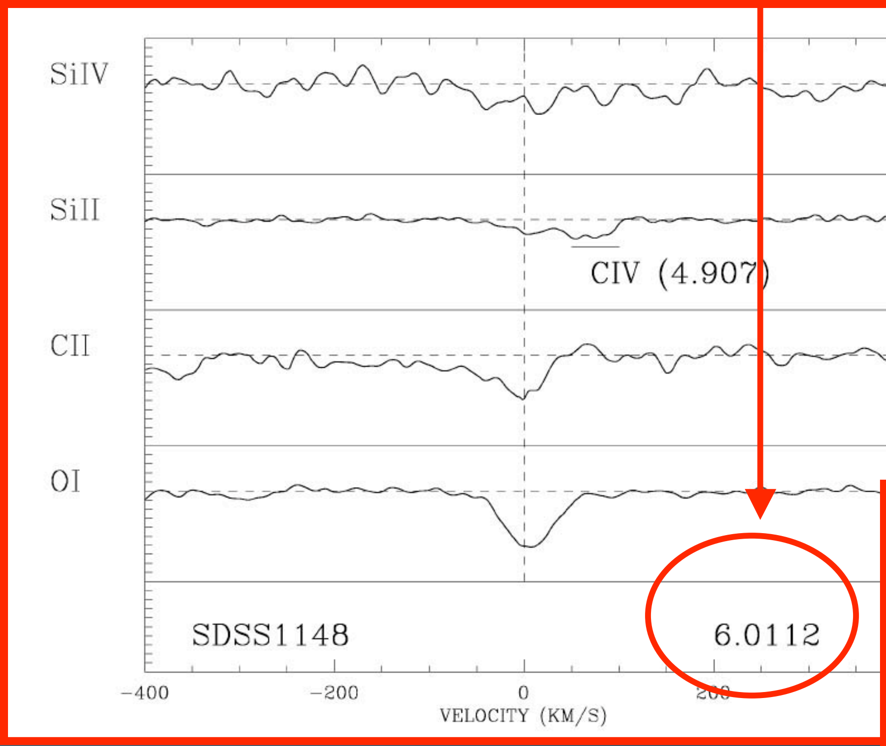
This method has been refined and used with great success by Schaye, Aguirre and collaborators (Schaye et al 2003 …). BUT …

it is not well suited to high redshift…

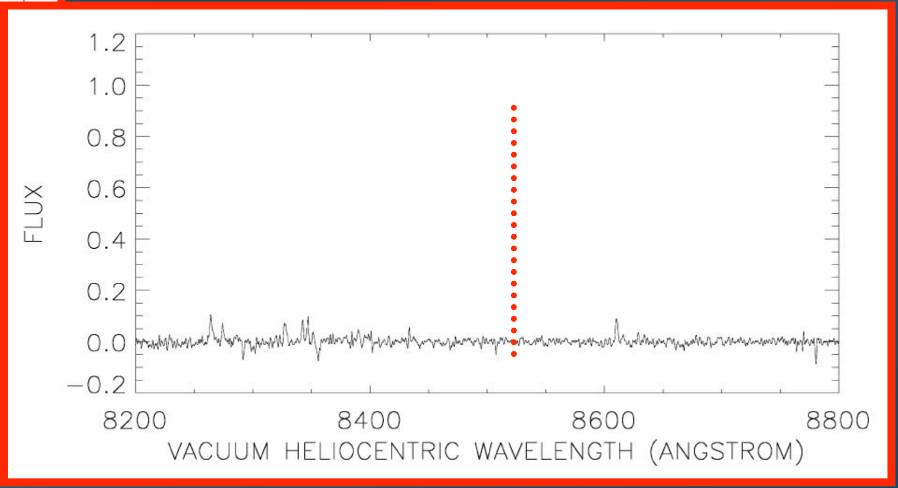
it may not be best way to find metals at low density

Limitation of POD method ---

Absorption systems exist at z ~ 6 …



… but there is no corresponding HI



SuperPOD ("Superposed Pixel Optical Depths")

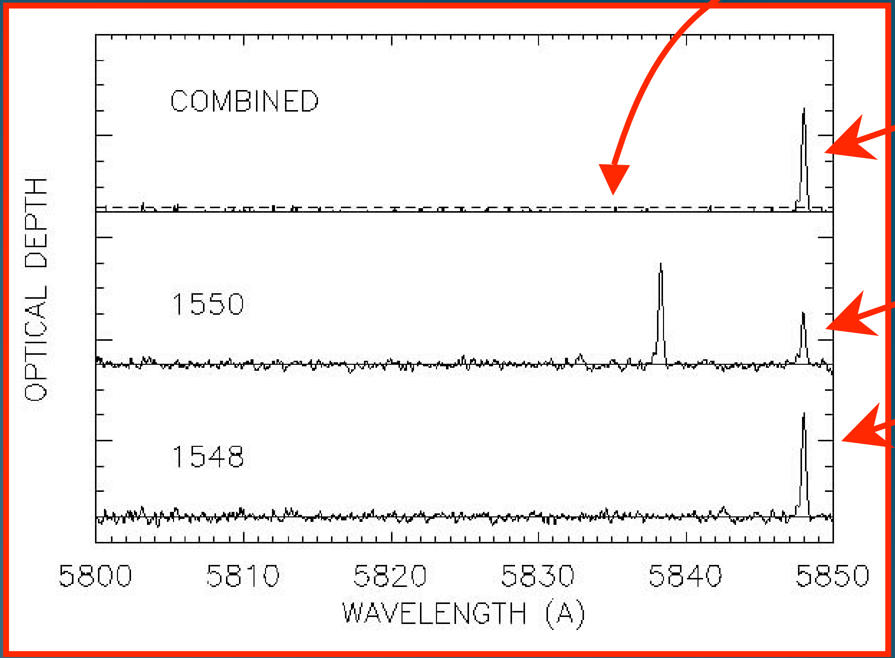
An alternative approach to this problem is to use the doublet structure of the CIV and SiIV absorption lines. Analysis of the absorption in this way lets us take maximum advantage of the spectra and, since it avoids the subjectivity of Voigt profile fitting, can be subject to analysis of incompleteness and bias.

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

Songaila 2005, AJ, in press (astro-ph/0507649)

SuperPOD method -- basics



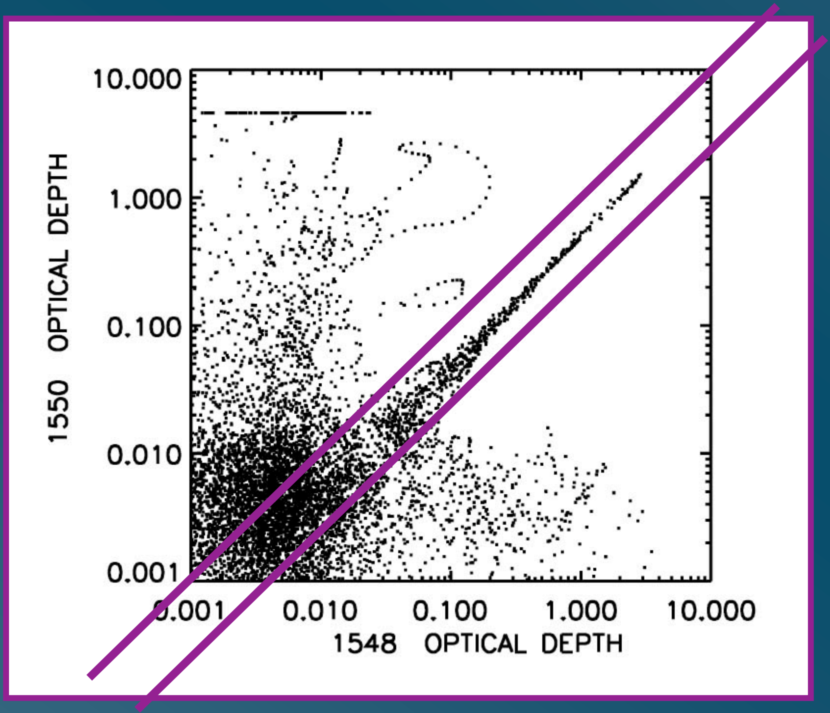
Scale = optical depth of 0.01

Combined optical depth

C IV 1550 optical depth

C IV 1548 optical depth

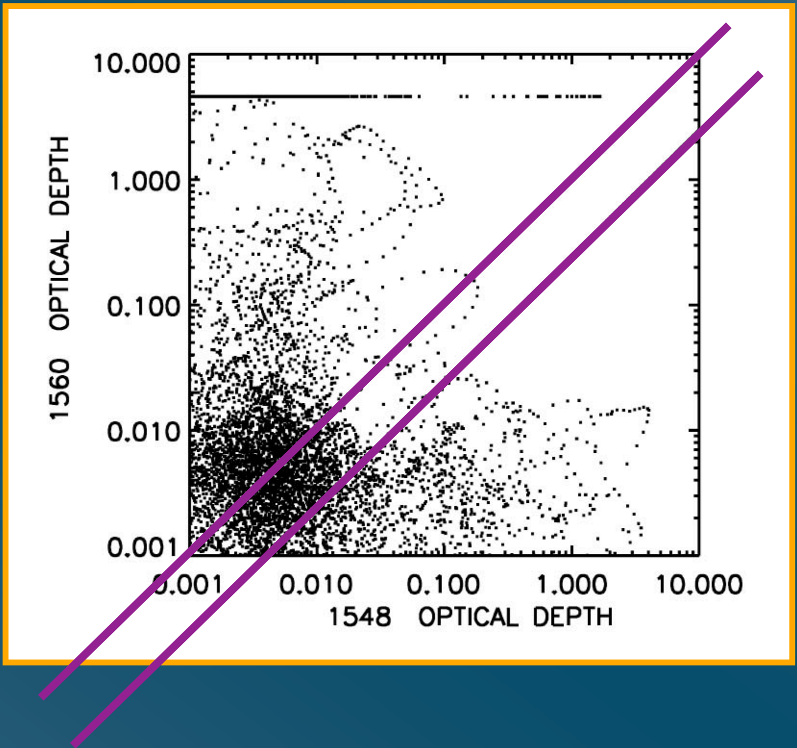
SuperPOD method – completeness & rejection



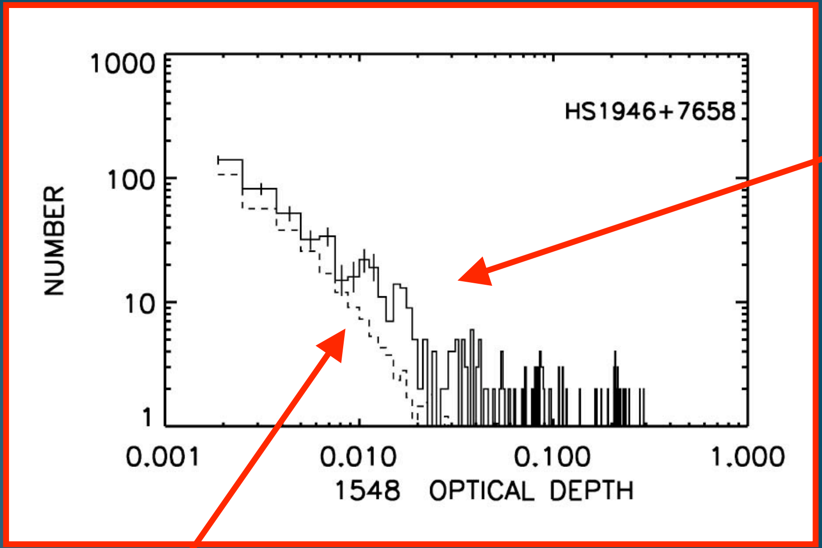
ON – tramlines are

1550/1548 = 0.25 - 1

OFF – nearby position

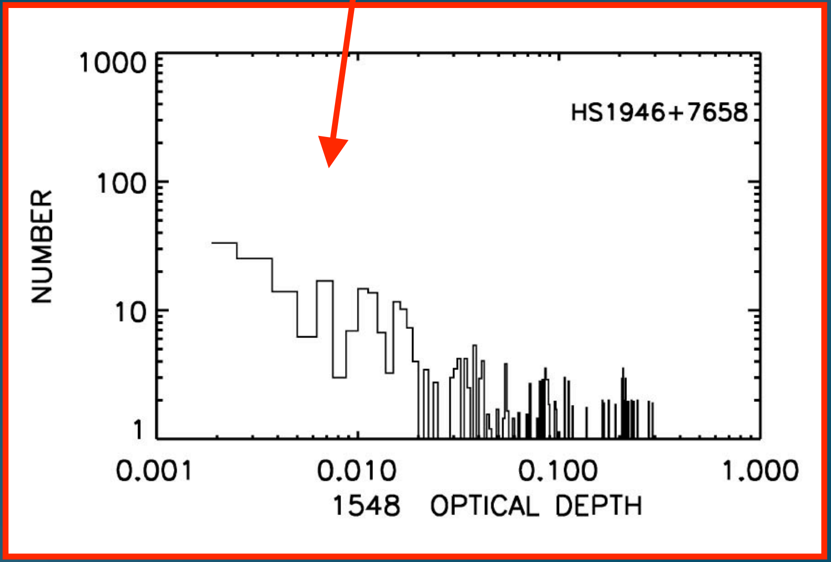


SuperPOD method – optical depth distribution



Solid = distribution of optical depth of selected lines

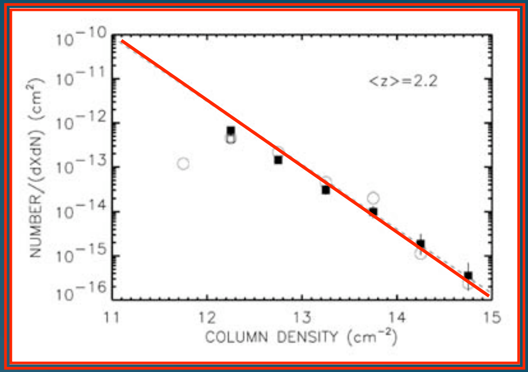
Actual – random



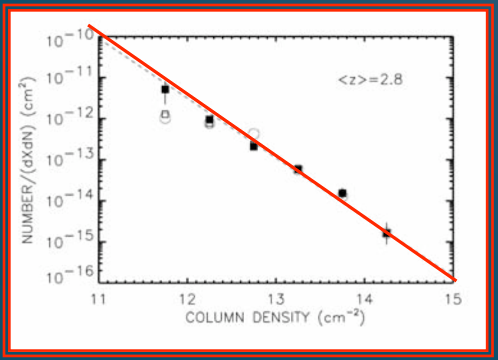
Dashed = average retrieval in 20 artificial doublets

Model incompleteness by adding artificial lines

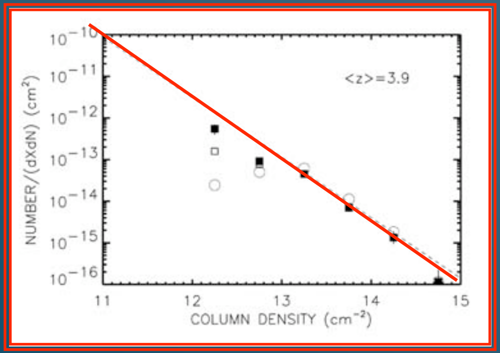
SuperPOD method – column density distributions & omega



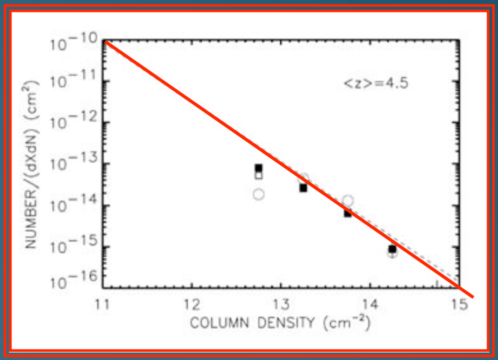
<z> = 2.2



<z> = 2.8



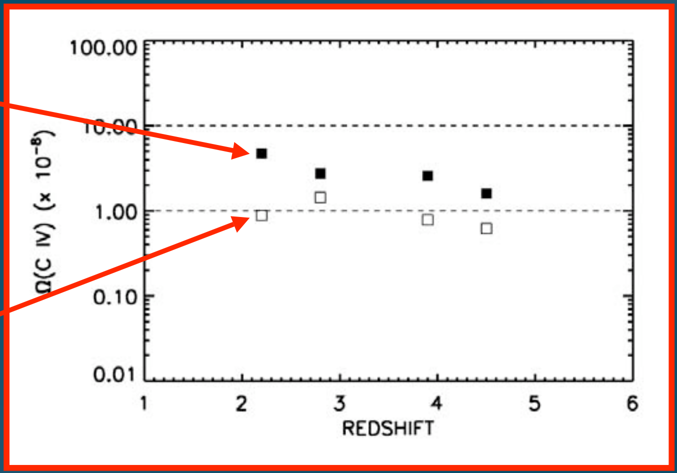
<z> = 3.9



<z> = 4.5

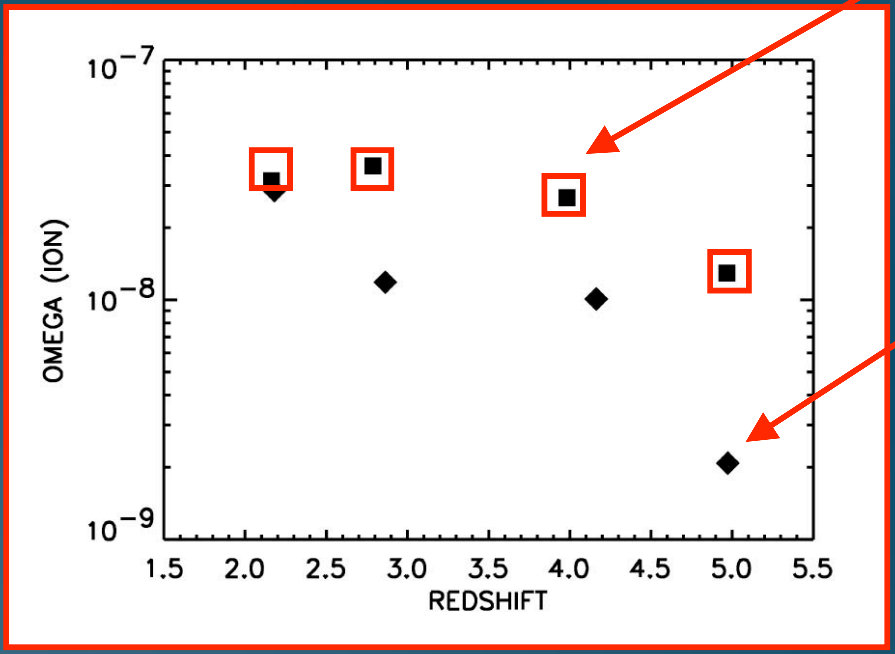
N(CIV) = 10^{12} - 10^{15}

N(CIV) = 10^{13} - 10^{14}



Ω (CIV) from distributions

Omega (ION) from optical depths



Average Ω (C IV)

Average Ω (Si IV)

No Voigt profile fitting

Still a lot of CIV at z = 5

Gives 0.5 dex increase in sensitivity:

Turns a 10m telescope into a 20-30 m telescope!!

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

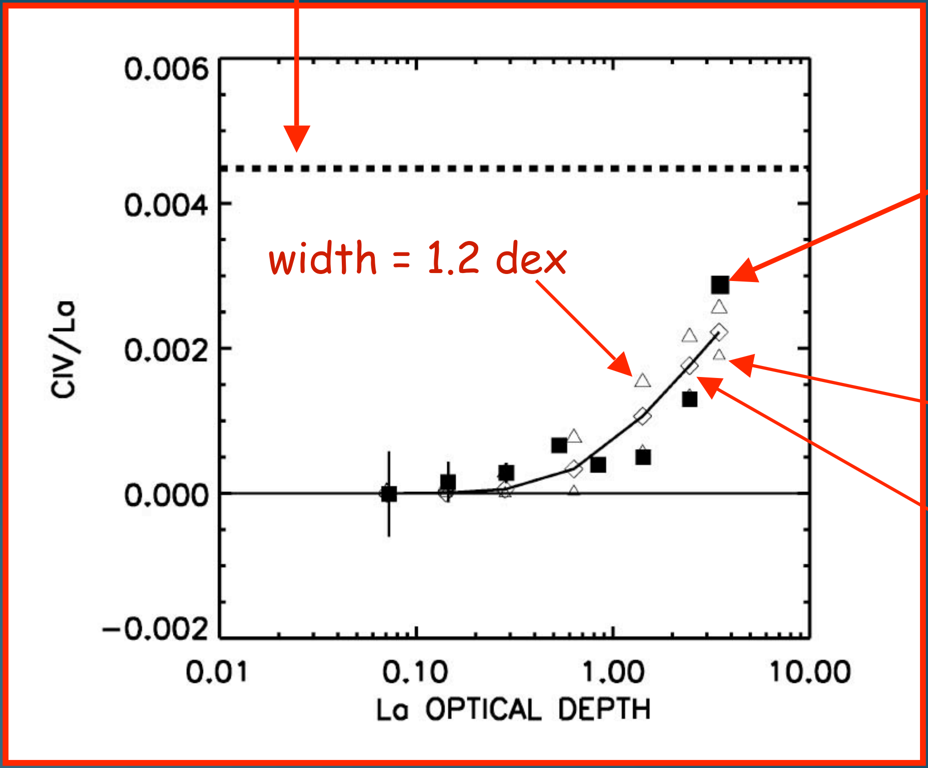
Can find the strong CIV/weak HI systems that the Cen simulations suggest

Original POD -- measures mean CIV at a given N(HI)

SuperPOD -- some CIV systems reside in low-HI regions?

SuperPOD method – C IV/Lyα ratio

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



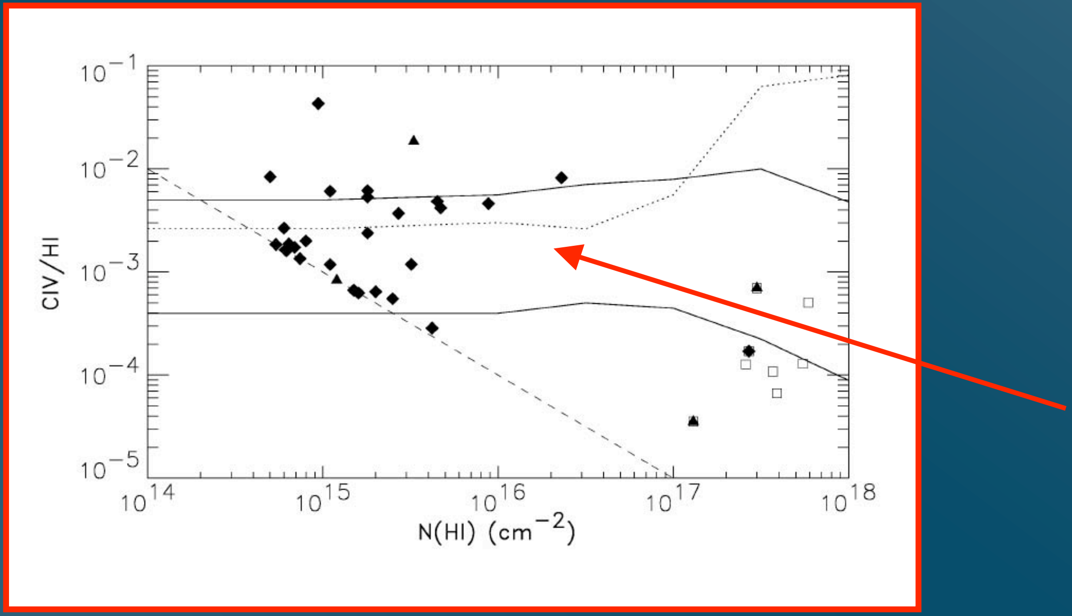
width = 1.2 dex

CIV/Lyα measured by SuperPOD – 1 σ error bars

width = 0.4 dex

width = 0.8 dex

SuperPOD – CIV/HI spread



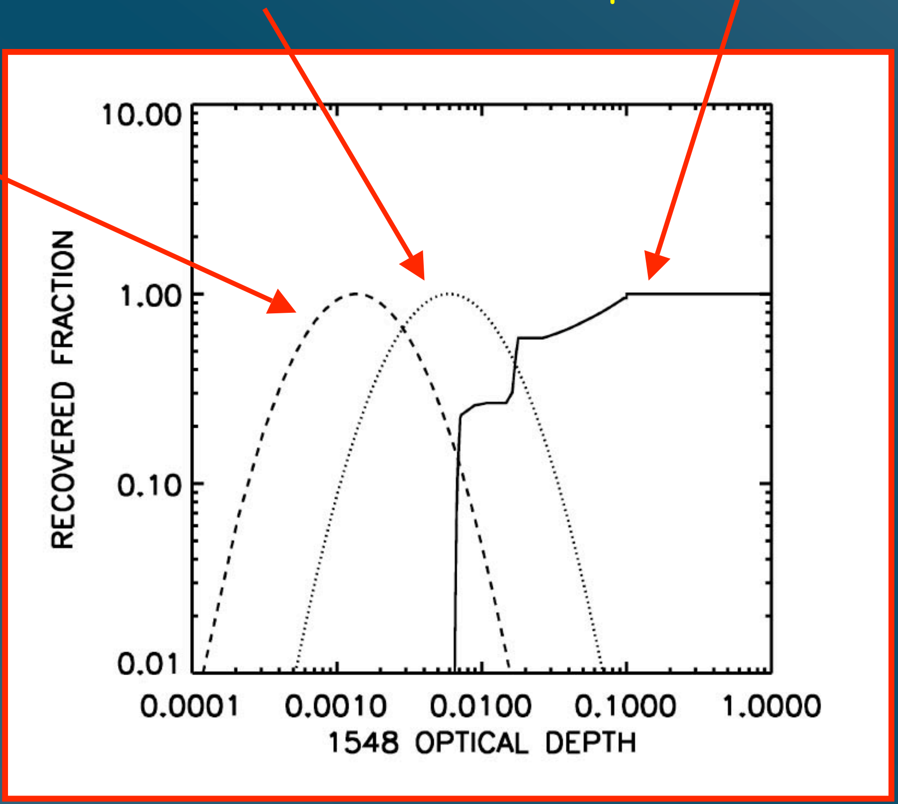
-- spread of ~1 dex in CIV/HI

Songaila et al. 1996

Schaye et al. (2003) : $\sigma([C/H]) = 0.76 + 0.02(z-3) - 0.23(\log \delta - 0.5)$

SuperPOD method – C IV/Lyα ratio

High S/N is CRUCIAL !

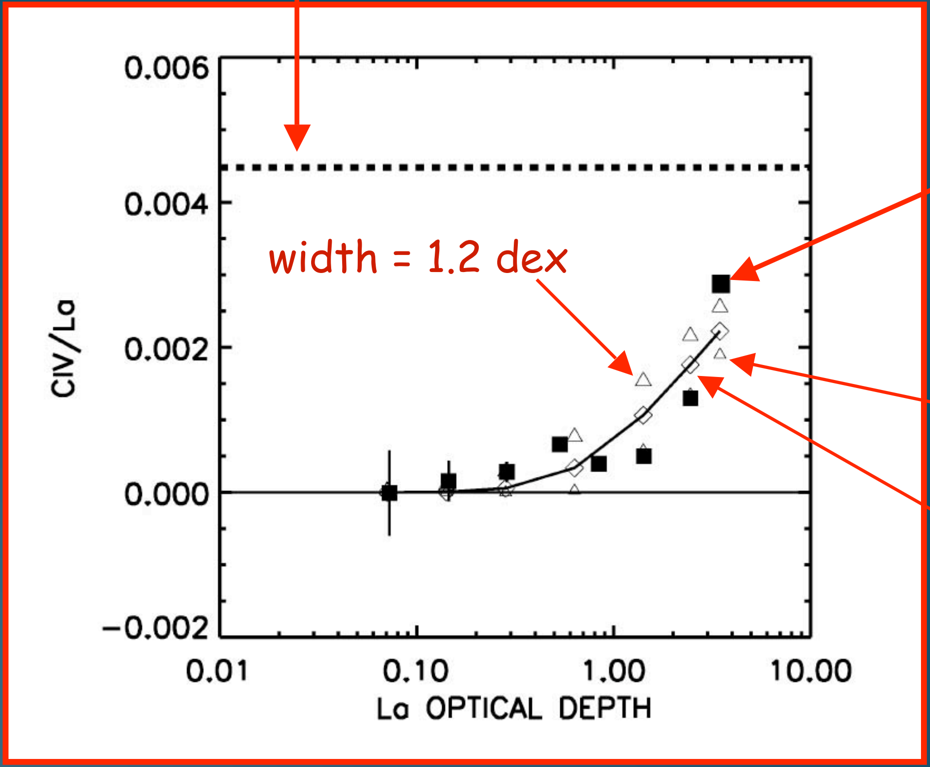


Distribution may not be gaussian;; more likely high metallicity tail

Would see stronger signal at given Ly a tau.

SuperPOD method – C IV/Lyα ratio

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



width = 1.2 dex

CIV/Lyα measured by SuperPOD – 1 σ error bars

width = 0.4 dex

width = 0.8 dex

But ………

This is all still very marginal and we need an alternate approach to the problem…

The velocity structure of the absorption lines may give us this new approach.

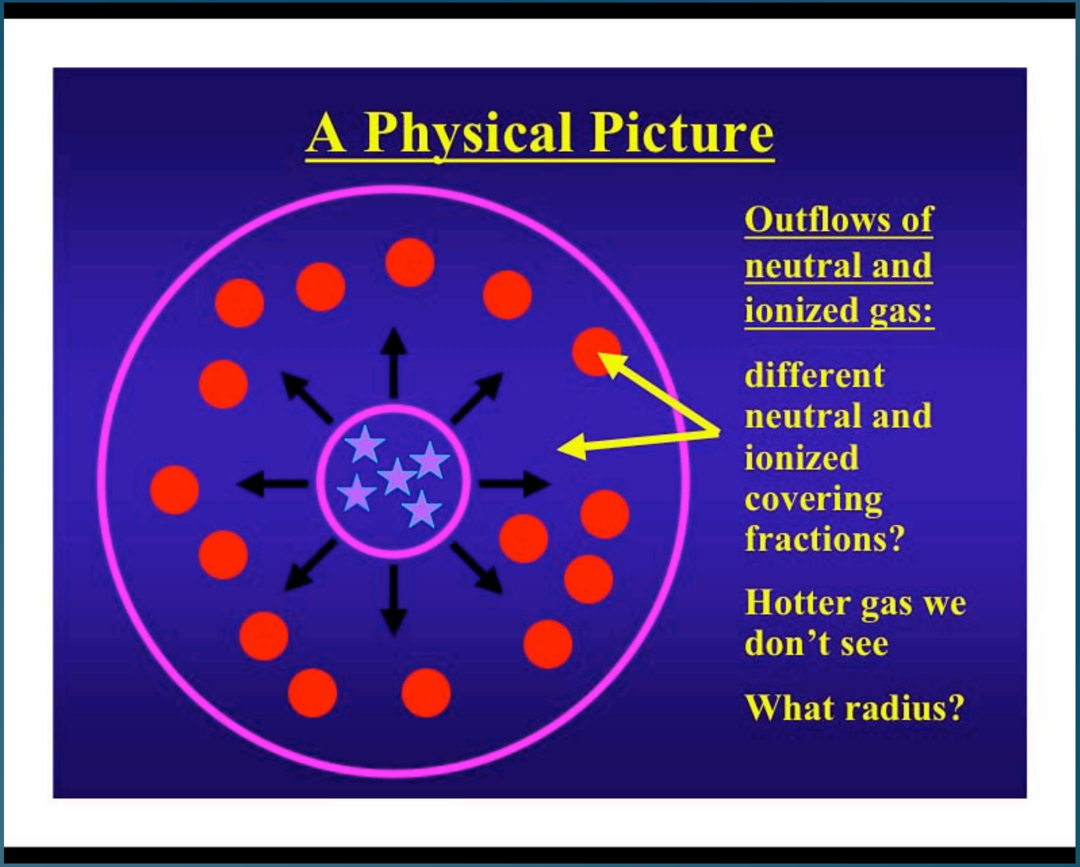
Early injection vs. superwinds -- velocities

An alternative way to distinguish is to look at the velocity structure of the absorbers. We can distribute material through the IGM with lower velocities in the early enrichment mechanisms but late superwind injection involves very high velocities.

This type of analysis seems very powerful and may already be able to constrain the enrichment mechanisms.

Songaila 2005, AJ, in press (astro-ph/0509821)

Superwinds have to leave the galaxy at high velocity (many hundreds of km/s) and have high covering factors in the ionized gas and large radii (hundreds of kpc) if they are to produce the absorbers.



A Physical Picture

Outflows of neutral and ionized gas:

different neutral and ionized covering fractions?

Hotter gas we don’t see

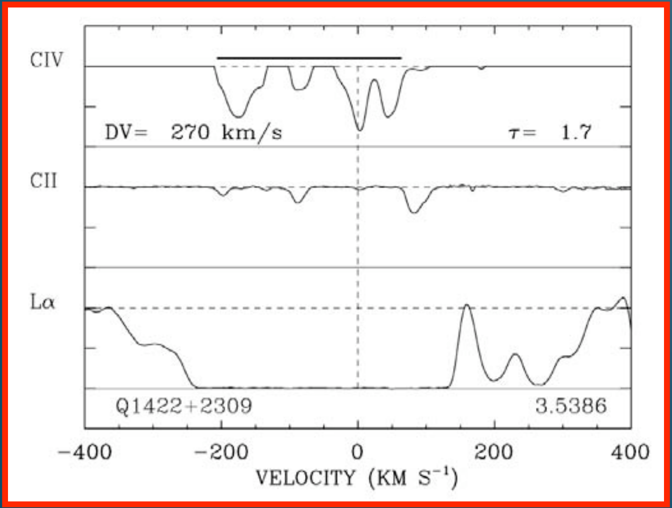
What radius?

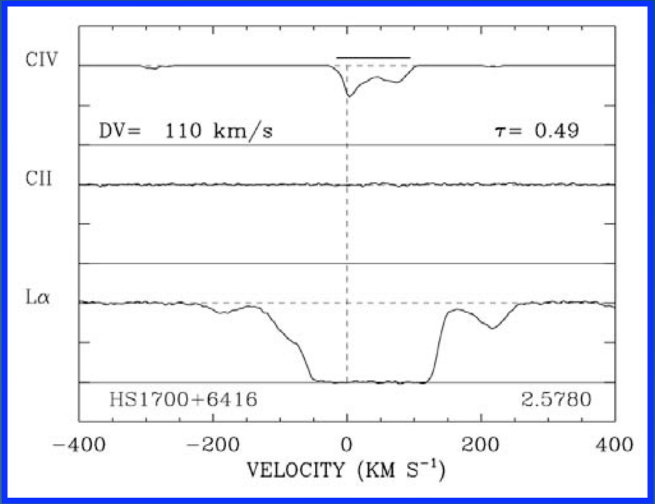
Shapley (Arizona-Heidelberg meeting, 2004)

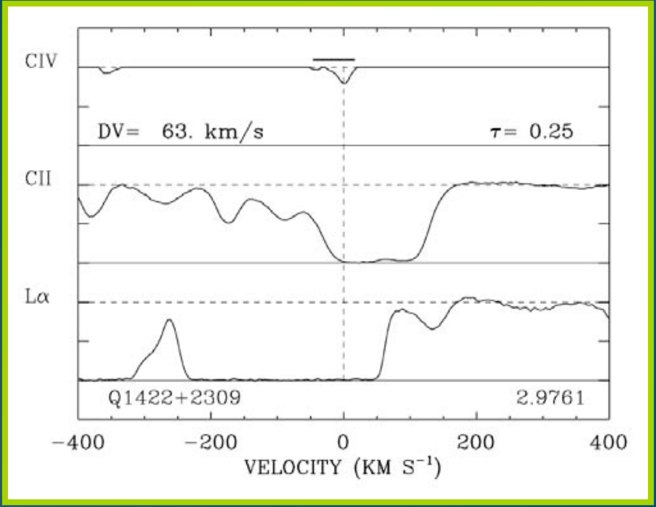
Can’t afford to turn kinetic velocities of the low ionization entrained material into thermal velocities: thermal widths too high (Schaye 2005).

Widths of CIV systems

Range of widths …



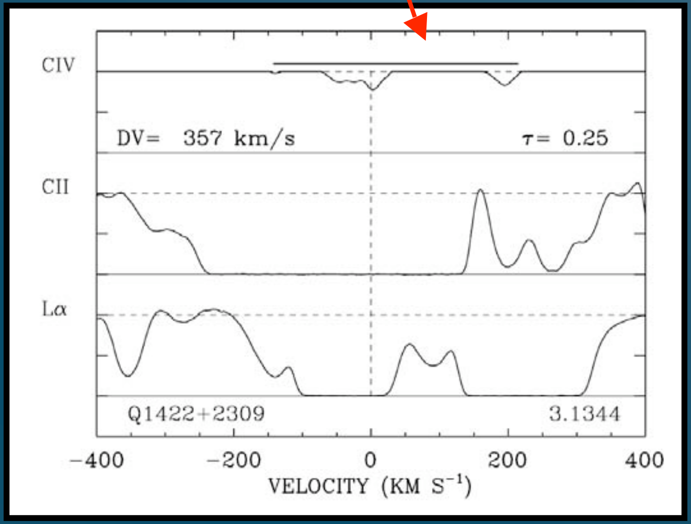




SuperPOD method – widths of CIV systems

… and sometimes two systems are connected (within 350 km/s)

… correct statistically



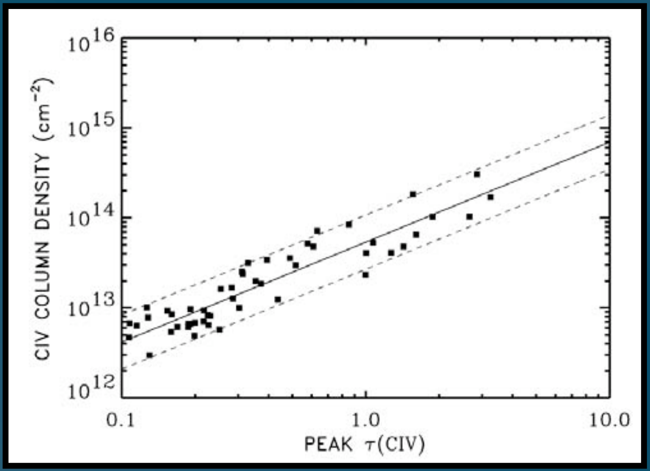
Column density is correlated with width.

Need two independent quantities to characterize absorption :

Strength ↔ peak τ

Velocity width ↔ full width at tenth max (FWTM)

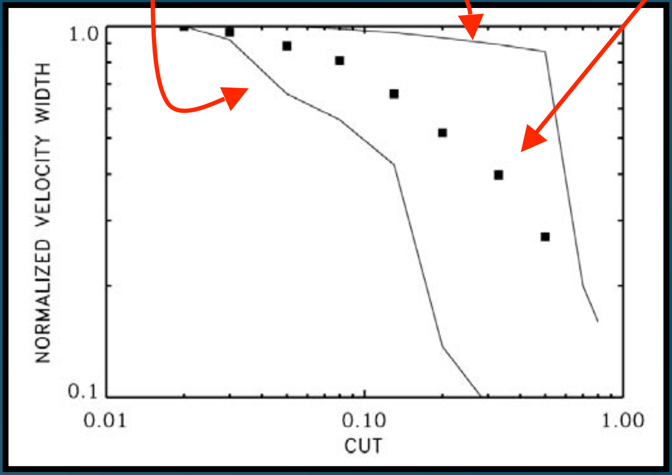
SuperPOD method – widths of CIV systems



Peak τ correlated with CIV column density

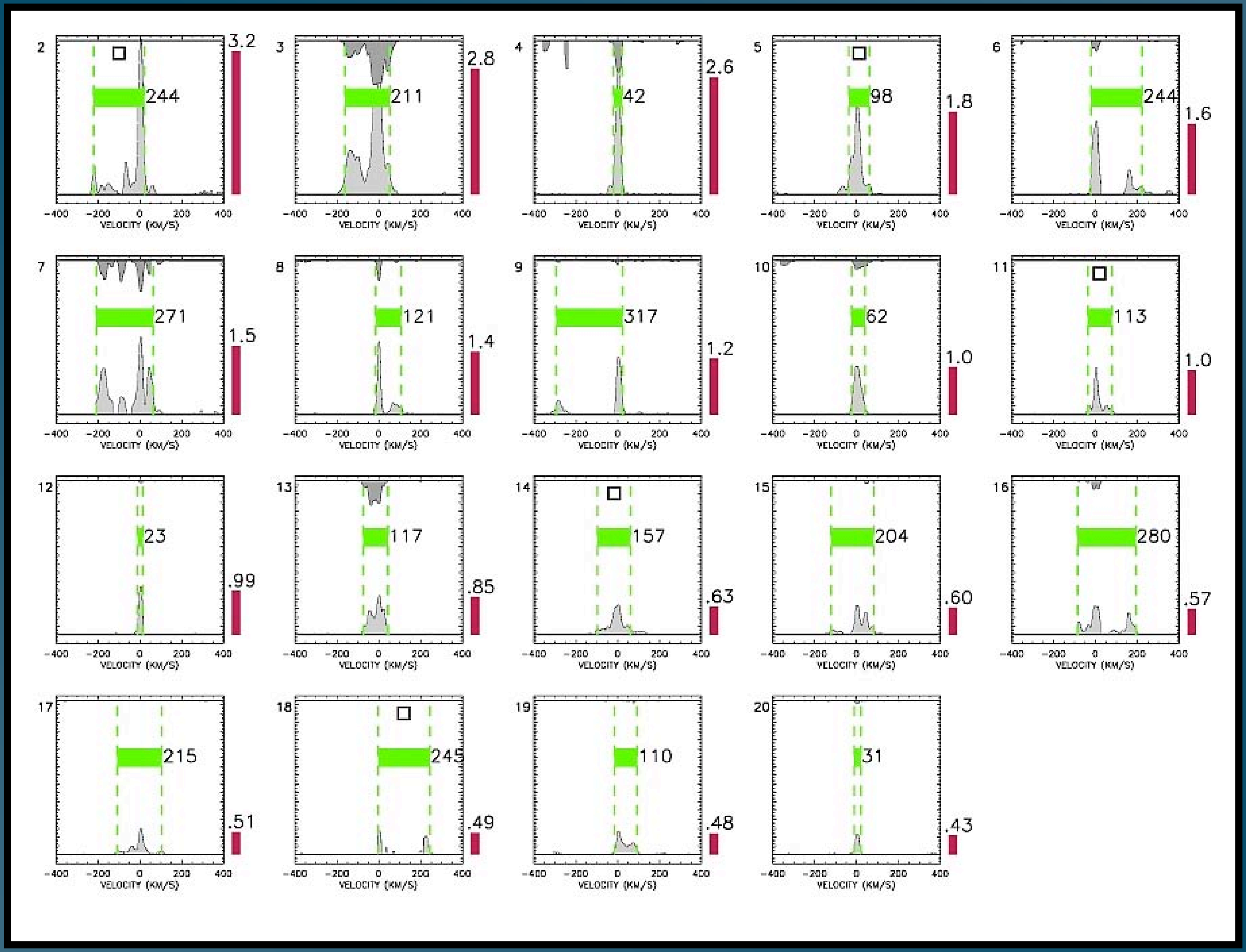
Max & min values

Mean values

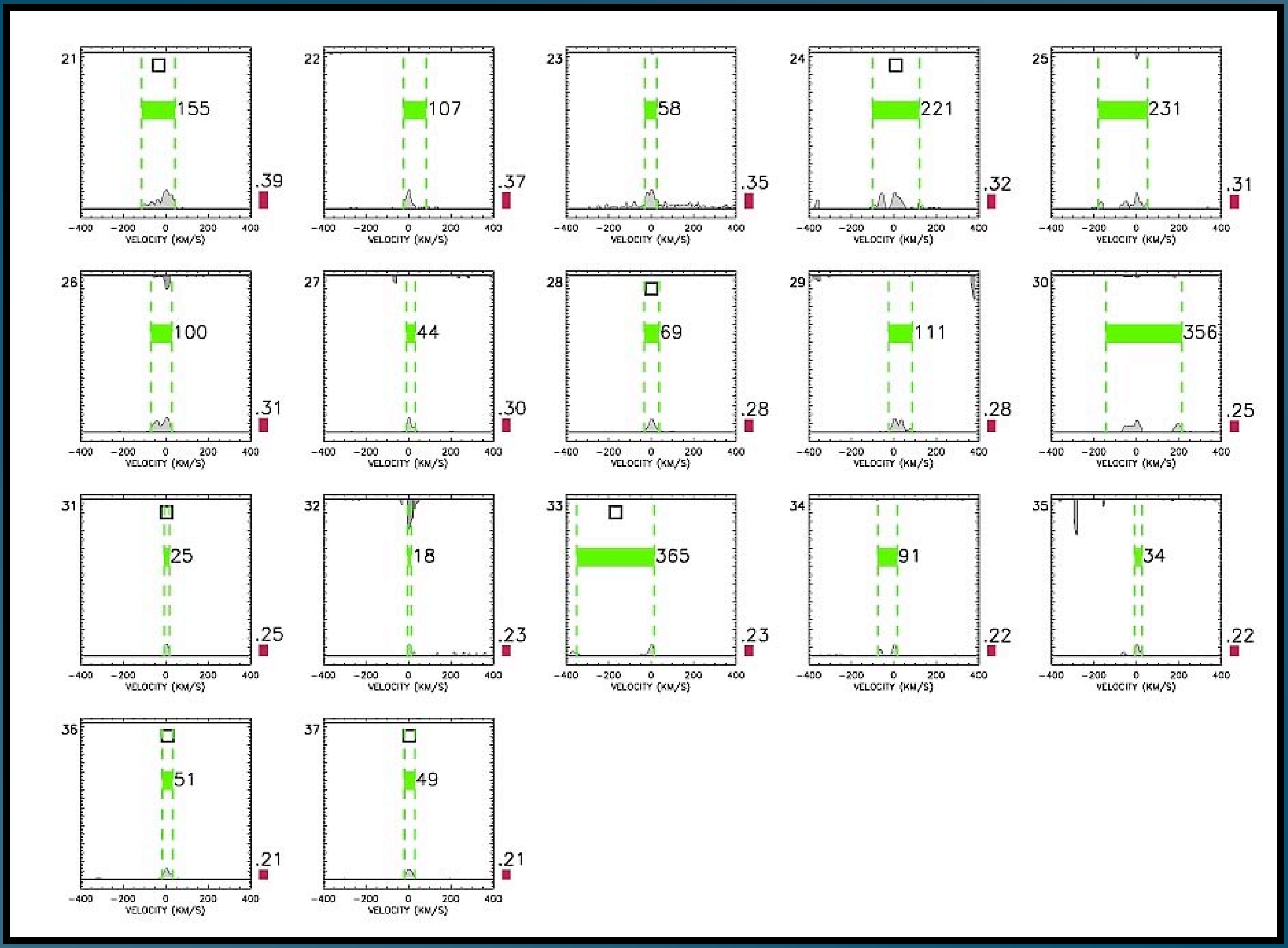


FWTM a good measure of velocity width of system

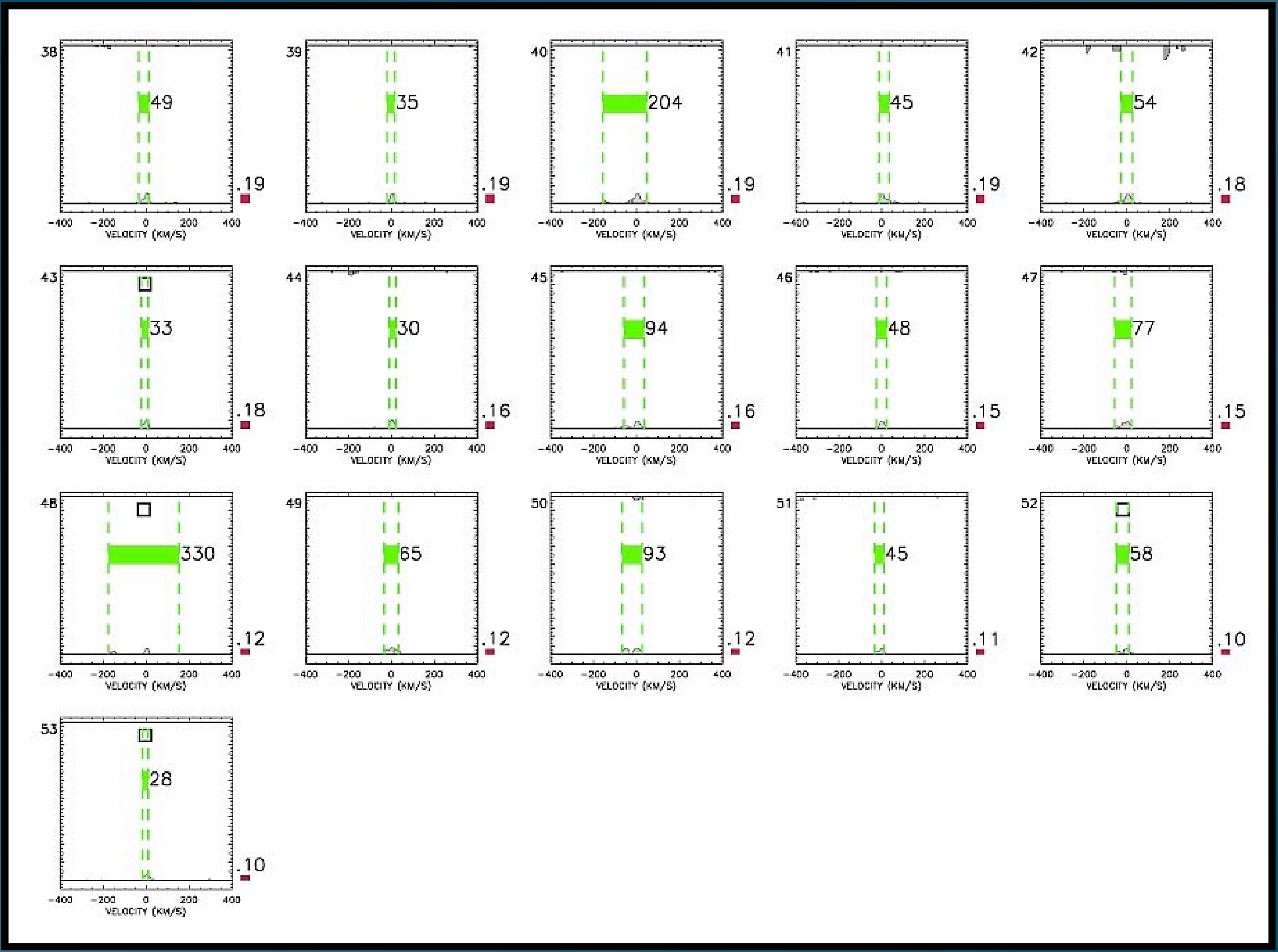
CIV absorption systems in high S/N sample



CIV absorption systems in high S/N sample



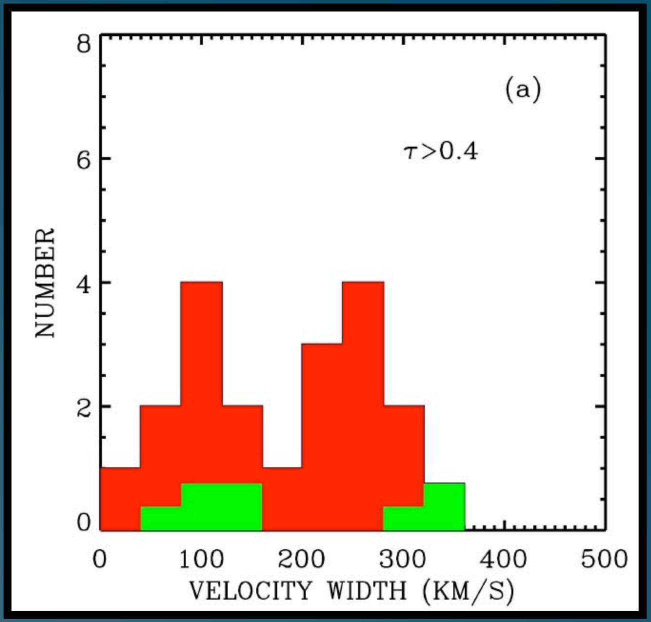
CIV absorption systems in high S/N sample

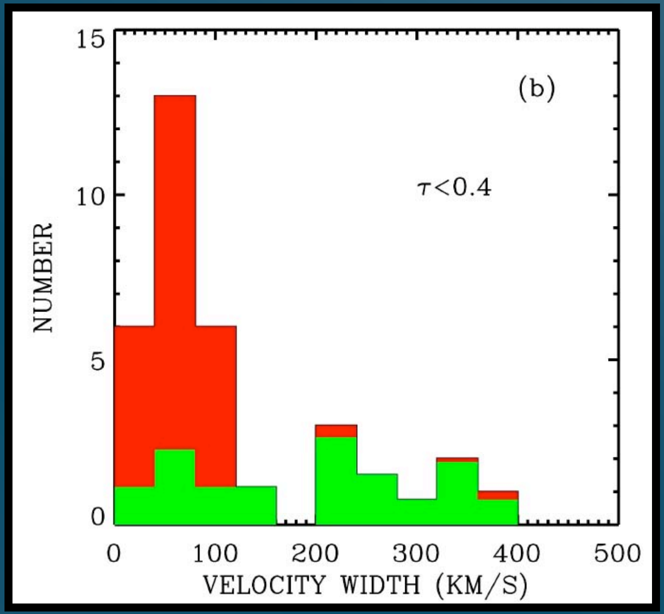


Widths of IGM metal systems

Red → real systems

Green → false systems





τ (CIV) > 0.4

N(CIV) > 2×10^{13} cm^{-2}

τ (CIV) < 0.4

N(CIV) < 2×10^{13} cm^{-2}

Widths of IGM metal systems

Peak optical depth > 0.4:

~ half systems are wide (> 100 km/s) and half narrow

Very few false systems

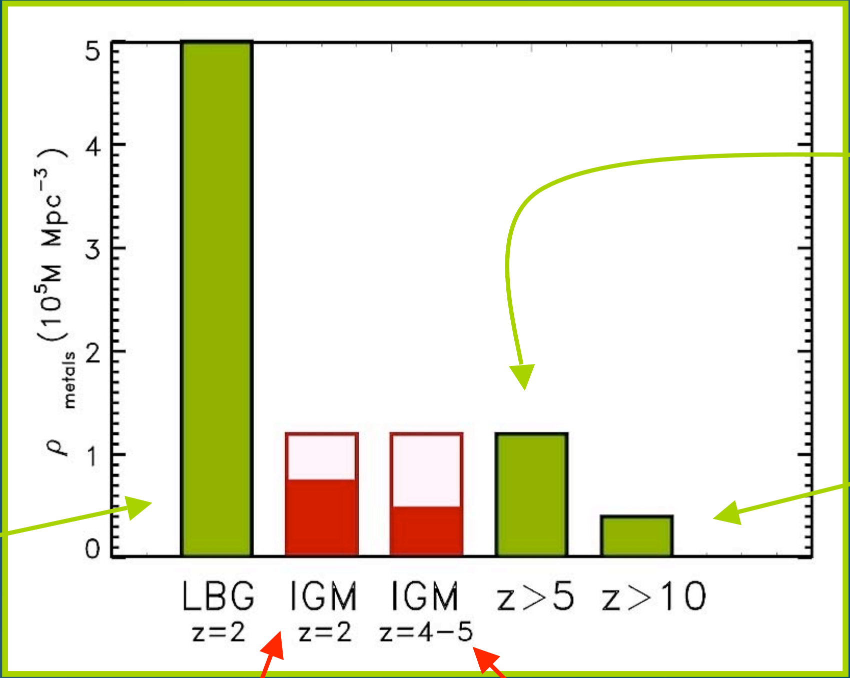
Peak optical depth < 0.4 :

Nearly all systems are narrow

Broad systems are all consistent with being false

None of the low column density systems can easily be identified as superwind outflows and only some fraction of the high column density systems can be.

Star formation history & metal enhancement



Metal production from SFR in LBGs at z = 2

Adelberger 2005

Metal production at z > 5

Metal production at z > 10

IGM metallicity at z = 2

Schaye et al

IGM metallicity at z = 4-5

Observations of metals in the IGM --- Summary

1. Need very high S/N observations to distinguish among enrichment scenarios and POD techniques provide free enhancement by factor of a few
2. CIV-galaxy correlation suggests late enhancement by superwinds, but is ambiguous
3. Distinguishing via enrichment patterns is hard to do in practice
4. Velocity structure of absorbers is a promising method: suggests most low column density CIV systems do not arise in outflows
5. Relating the star formation and metal production histories at z = 4-5 suggests we are undercounting the z > 5 SFR or there are high-z populations we haven't observed yet