

Observations of metals in the IGM

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Garching August 2005

Observations of metals in the IGM --- Outline

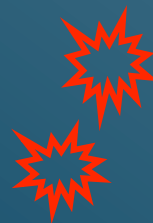
- o How high a redshift have we seen metals to?
- o When were they first ejected into the IGM?
- o How does this evolve into the $z = 2-3$ universe?
- o How uniformly are they distributed?
- o **KEY QUESTION : Is CIV absorption seen in the IGM a consequence of early star formation or is it contemporary injection via superwinds? (OR BOTH ??)**
- o How does the star formation history relate to metal enhancement?

Where do metals in the IGM come from ?

And do they occur only in the overdense regions ?

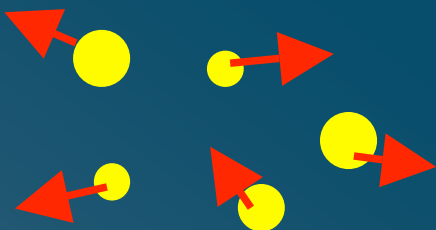
- Population III early VMSs
- Early galaxy formation
- Later enrichment by winds

How do metals get into the IGM ?



Early very massive stars ?

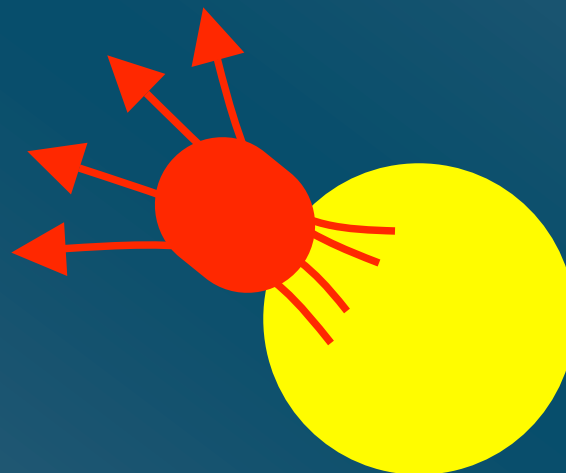
OR



Small galaxies at $z = 6 - 12$?

OR

Superwinds at $z > 2-3$?



How can we distinguish ??

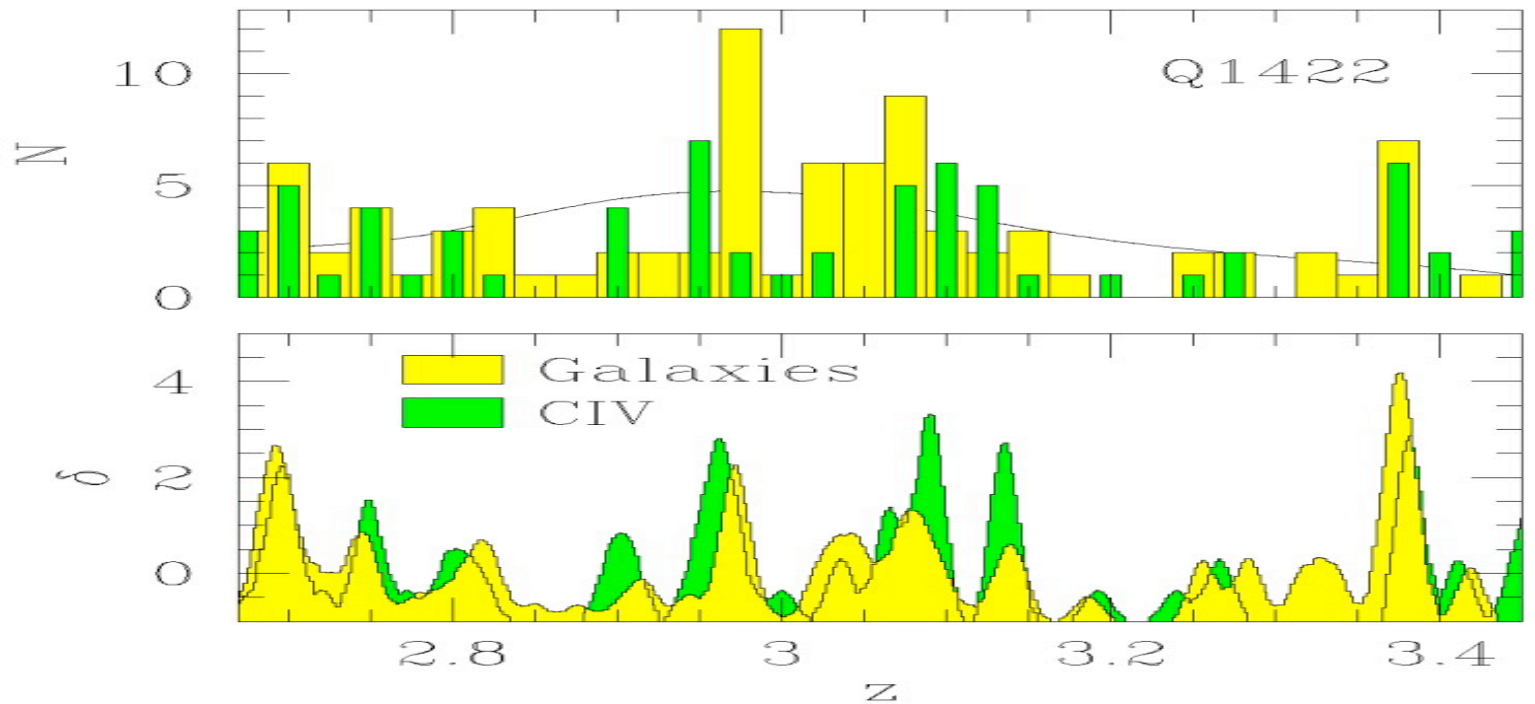
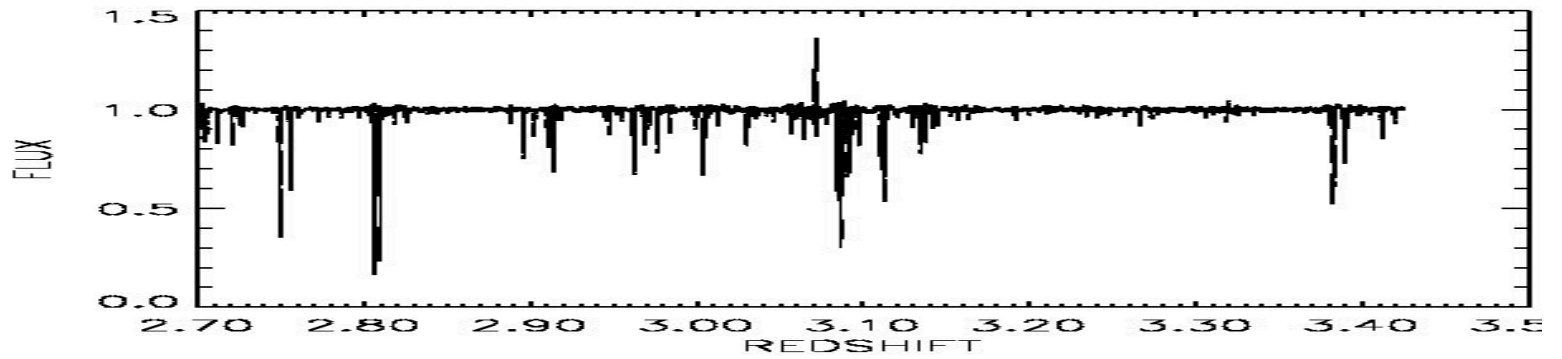
There are various ways in which these mechanisms can be differentiated in principle :

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 ($N(\text{CIV}) < 10^{13} \text{ cm}^{-2}$).

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

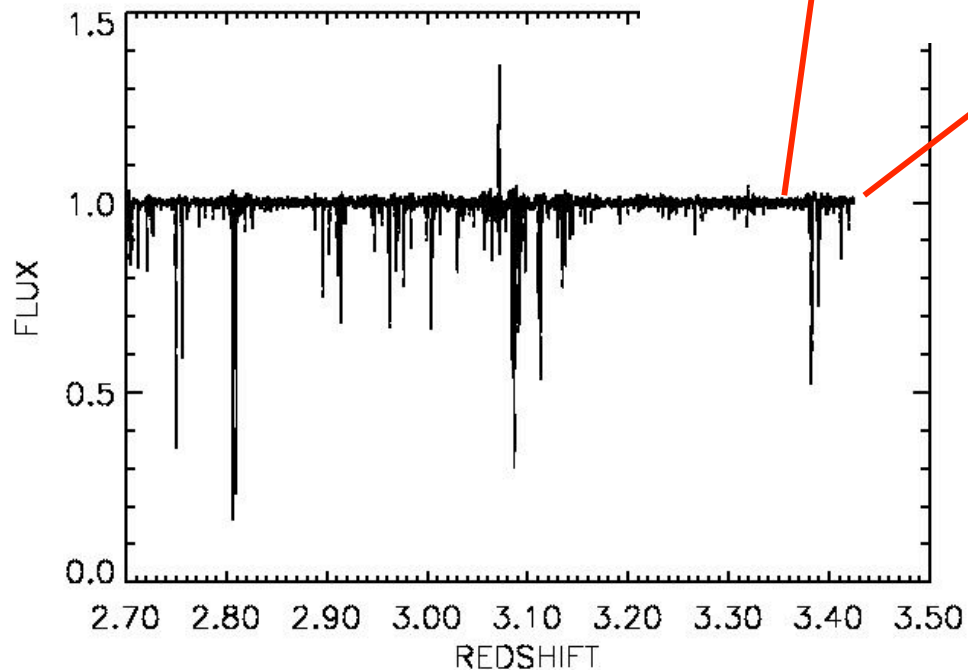
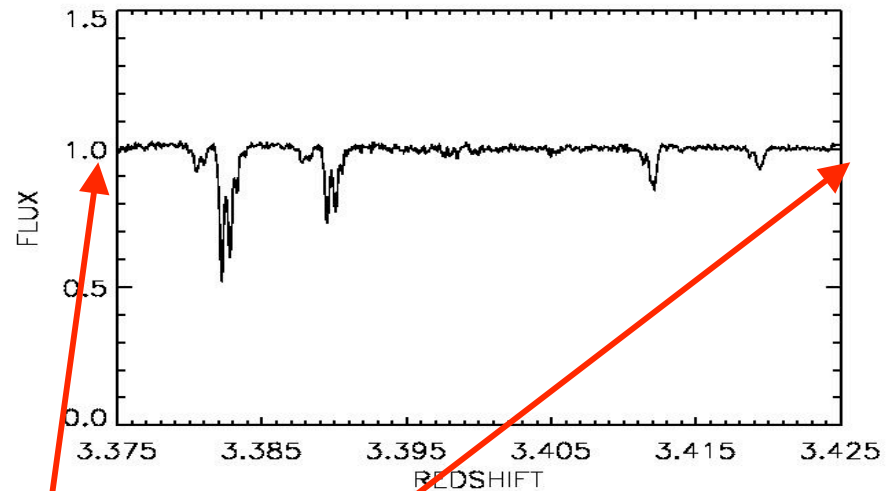
Correlations between LBGs and IGM CIV ...



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?

(Pieri et al. 2005 show
using POD methods
that much CIV arises
far from complexes.)

Early injection vs. superwinds: How can we distinguish ?

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:

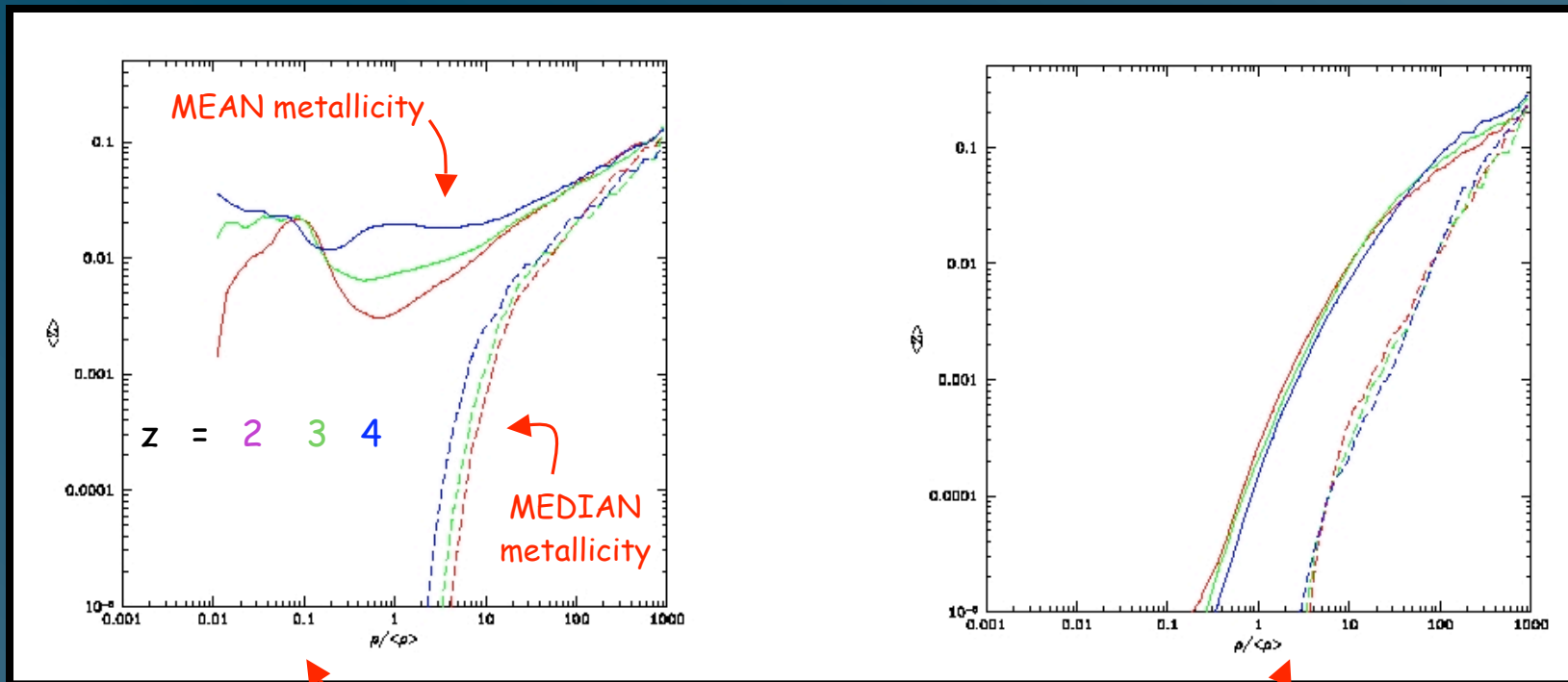
Even early galaxy injection still results in a strong correlation between galaxies and CIV absorbers at $z=2$.

Early injection vs. superwinds: How can we distinguish ?

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

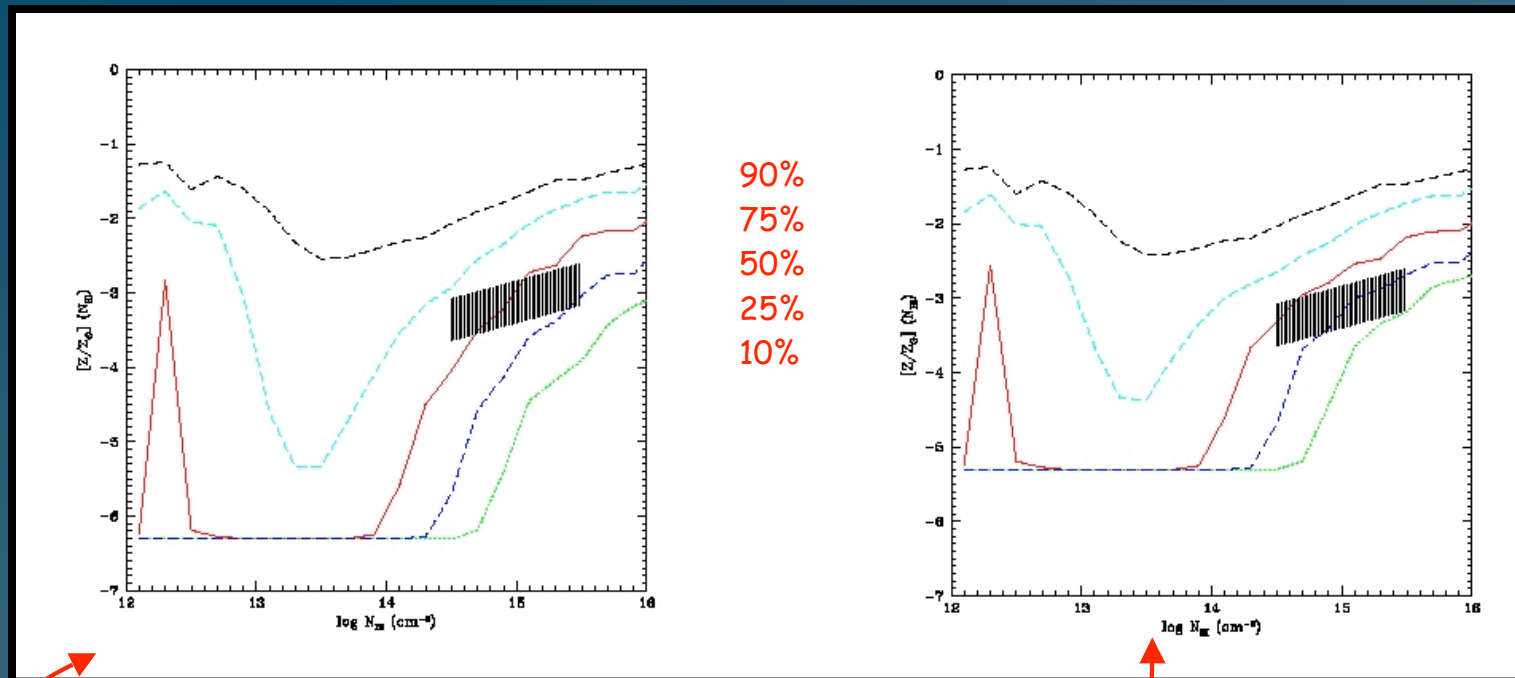


Models with
late superwinds

Cen et al. 2005

Models
without

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



With superwinds

Constant metal yield

With superwinds

Variable metal yield

Cen et al. 2005

Transition to higher yield at $Z = 10^{-3}$ solar

Early injection vs. superwinds: How can we distinguish ?

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. I will spend time on this later.

Finally, I will try briefly to relate the enrichment and star formation histories.

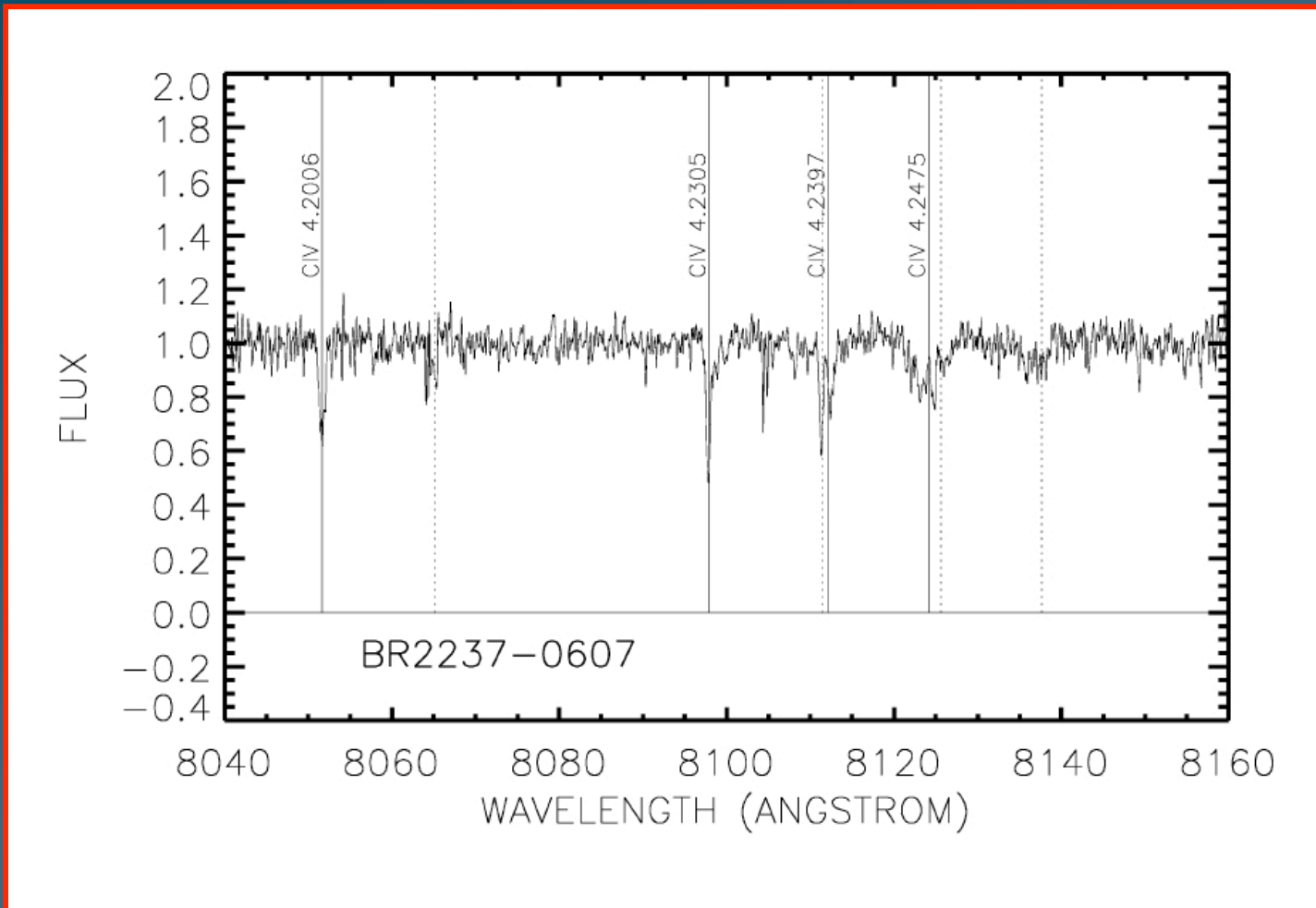
What information do we have ?

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.

		<u>log N</u>
C IV	6 σ	11.9
Si IV	3 σ	11.2
C II	3 σ	11.9
Si II	3 σ	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 ---

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

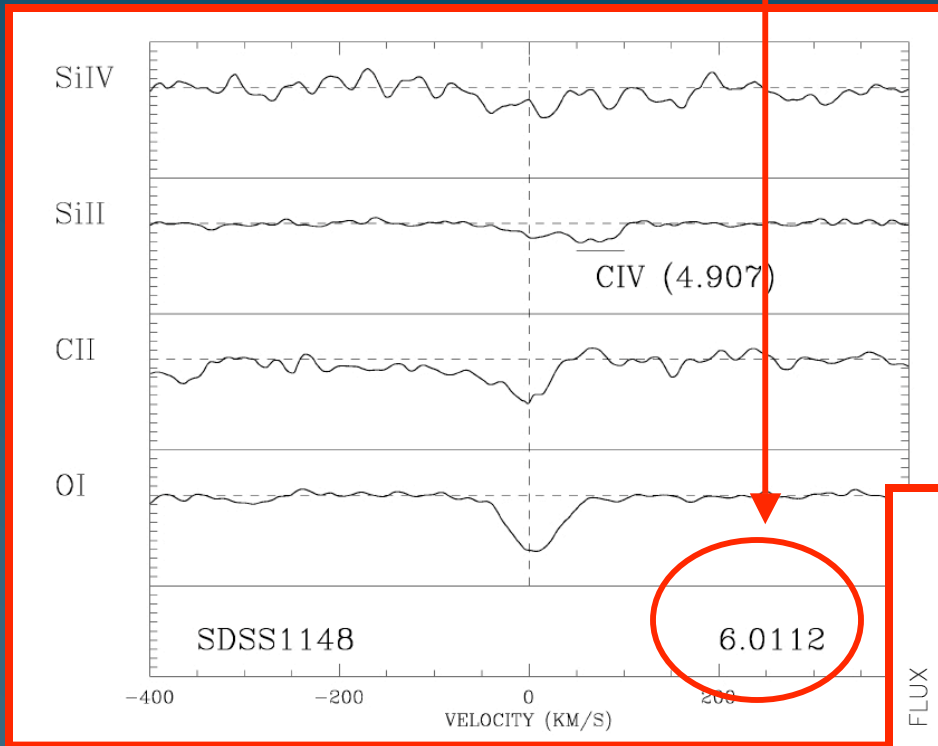
In 1998 we introduced a technique in which the HI optical depth traced using the Lyman series was cross-correlated with the CIV absorption line optical depths (Cowie & Songaila 1998).

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

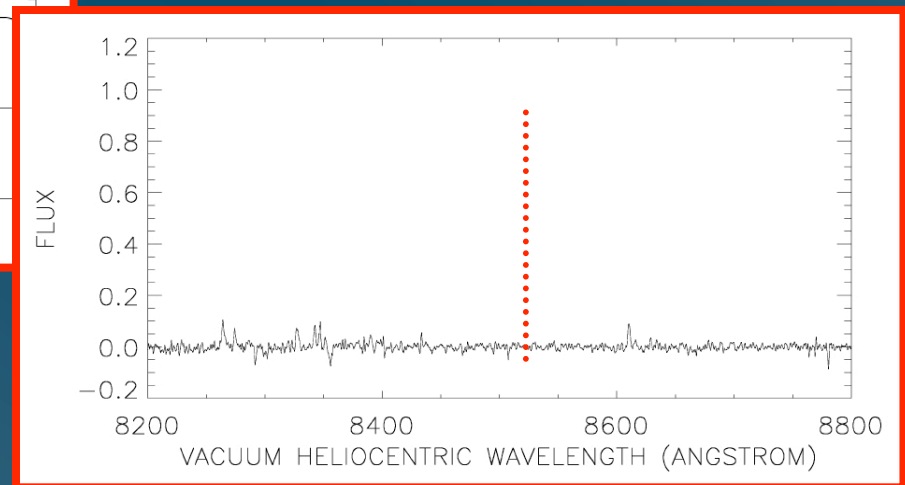
... but it is not well suited to high redshift...

Limitation of POD method ---

Absorption systems exist at $z \sim 6$...



... 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**.

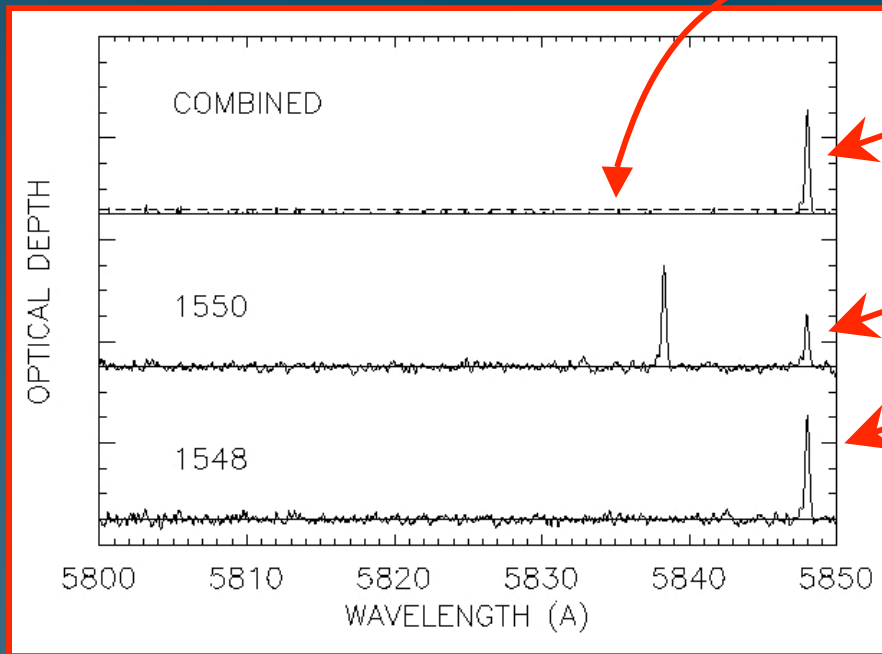
Superposed optical depths - "SuperPOD"

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

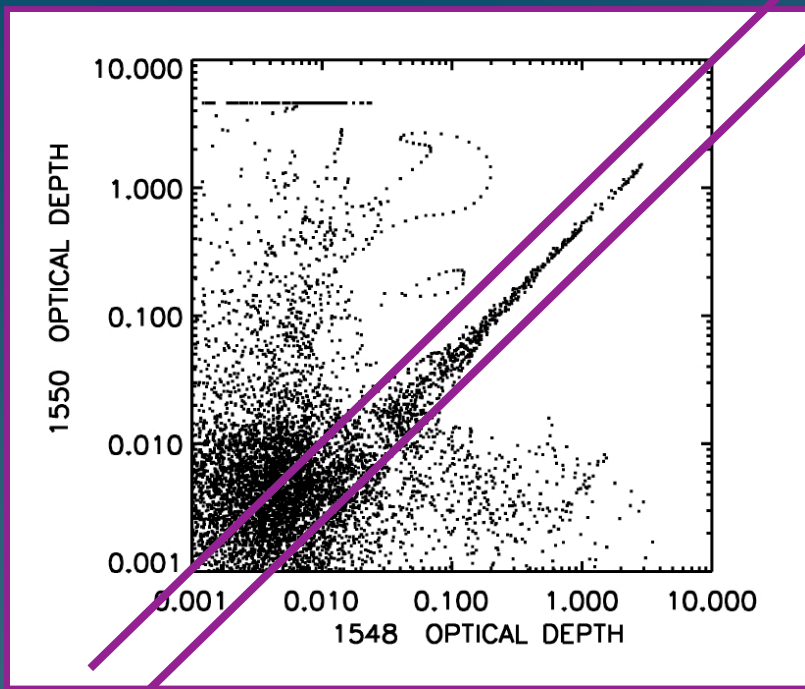


Combined optical depth

C IV 1550 optical depth

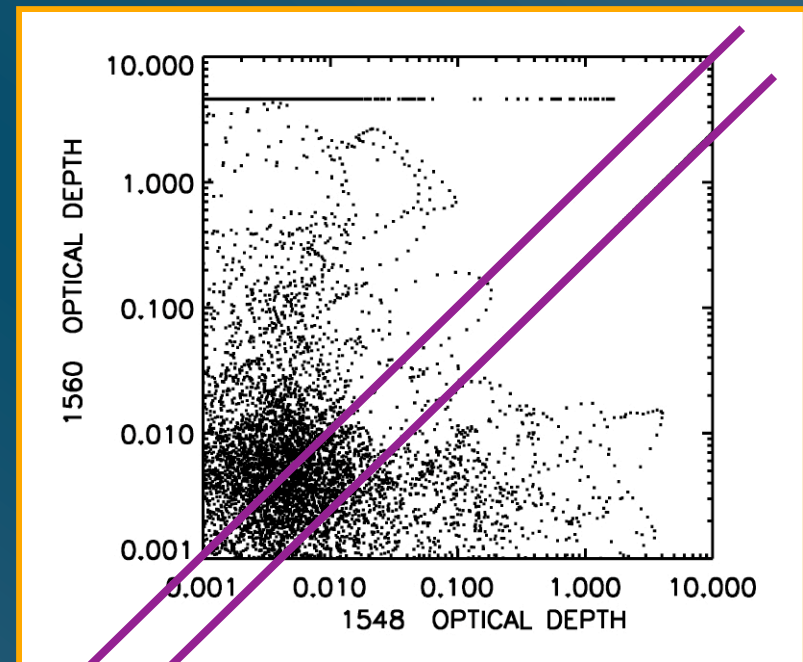
C IV 1548 optical depth

SuperPOD method - completeness & rejection

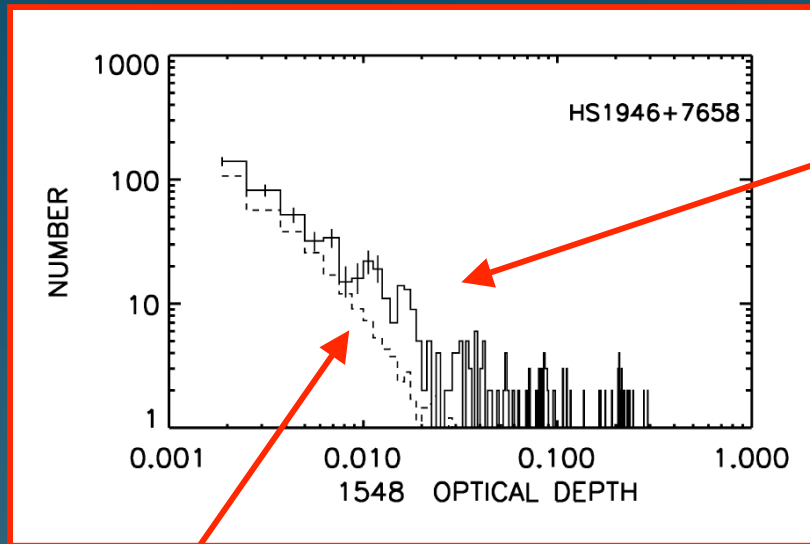


ON - tramlines are
 $1550/1548 = 0.25 - 1$

OFF - nearby position

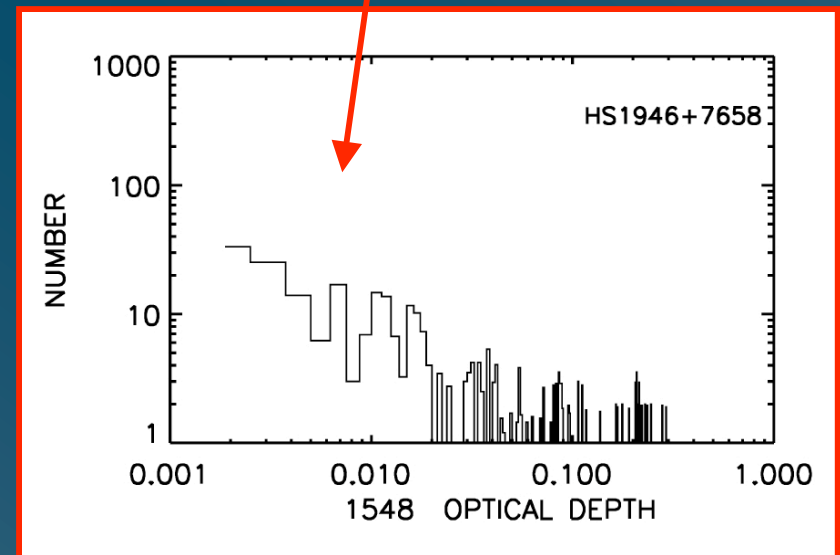


SuperPOD method - optical depth distribution



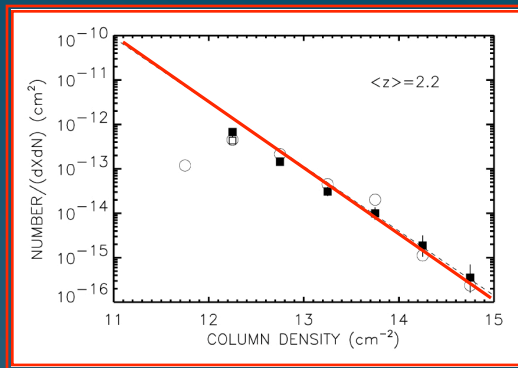
Solid = distribution of optical depth of selected lines

Actual - random

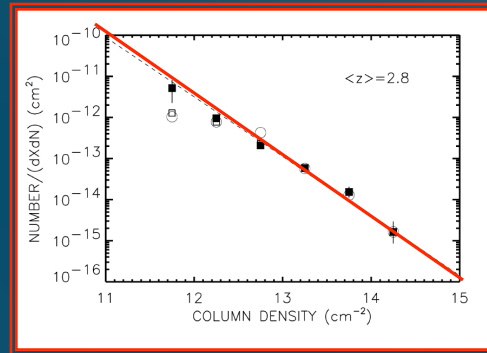


Dashed = average retrieval in 20 artificial doublets
Model incompleteness by adding artificial lines

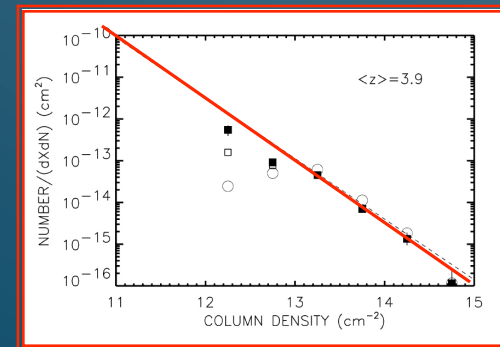
SuperPOD method - column density distributions & omega



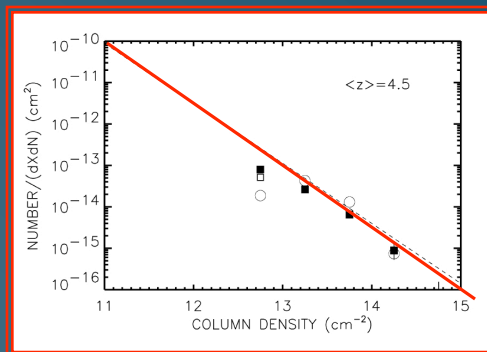
$\langle z \rangle = 2.2$



$\langle z \rangle = 2.8$



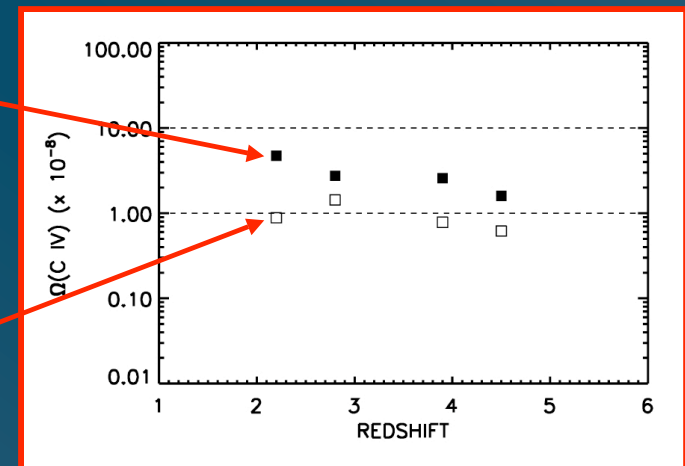
$\langle z \rangle = 3.9$



$\langle z \rangle = 4.5$

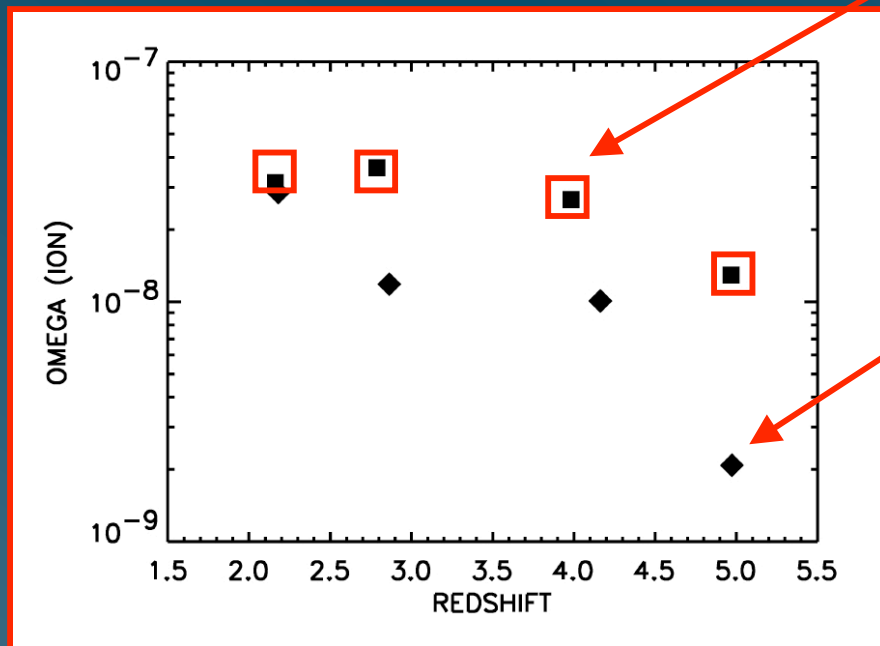
$N(\text{CIV}) = 10^{12} - 10^{15}$

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



$\Omega(\text{CIV})$ from distributions

Omega (ION) from optical depths



Average Ω (C IV)

Average Ω (Si IV)

Gives 0.5 dex increase in sensitivity:

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

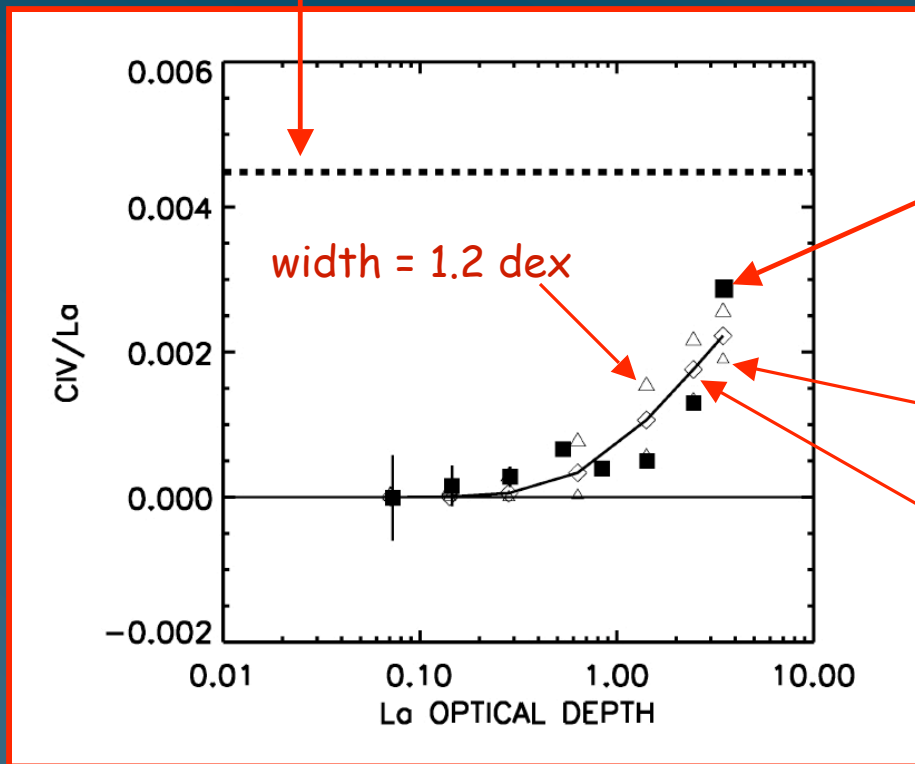
No Voigt profile fitting

SuperPOD - CIV vs HI

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/Ly α ratio

$$\langle \text{CIV/HI} \rangle = 4.5 \times 10^{-3}$$

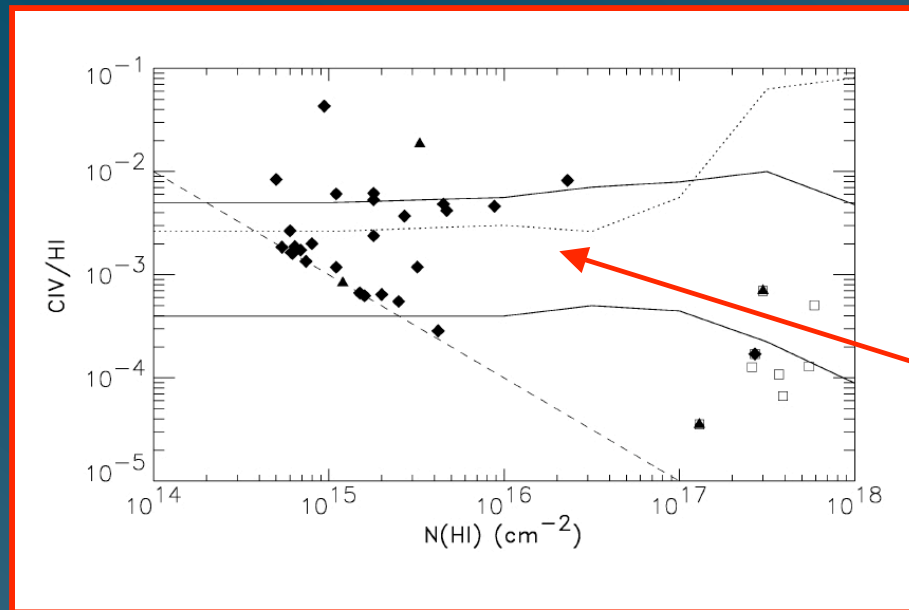


CIV/Ly α
measured by
SuperPOD -
1 σ error
bars

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) : $\sigma ([\text{C}/\text{H}]) = 0.76 + 0.02(z-3) - 0.23(\log \delta - 0.5)$

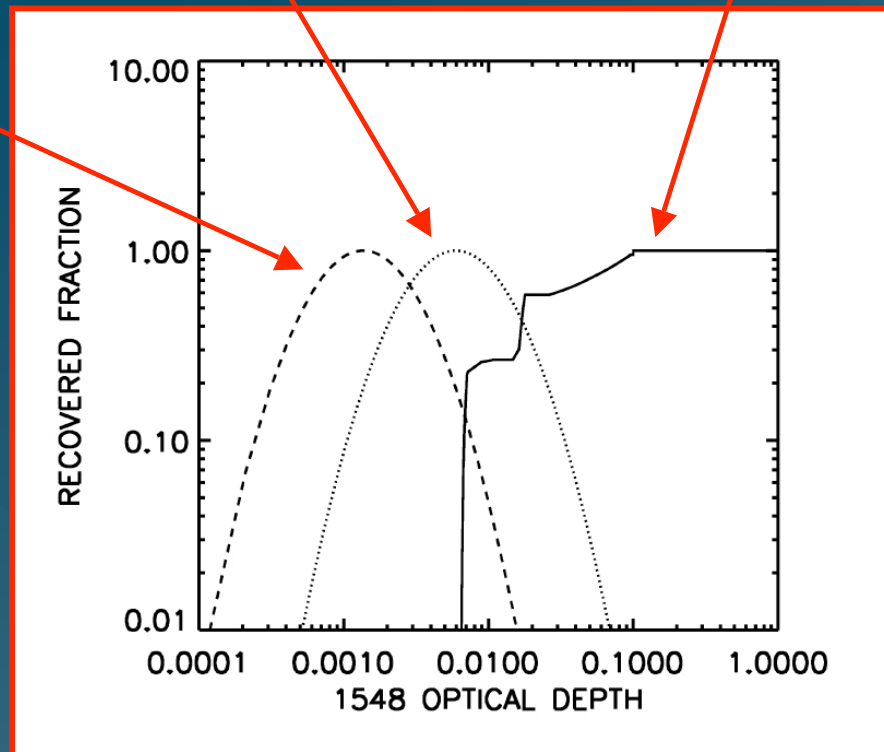
SuperPOD method - C IV/Ly α ratio

High S/N is CRUCIAL!

$\tau(\text{Ly}\alpha) = 0.8$

$\tau(\text{Ly}\alpha) = 3.5$

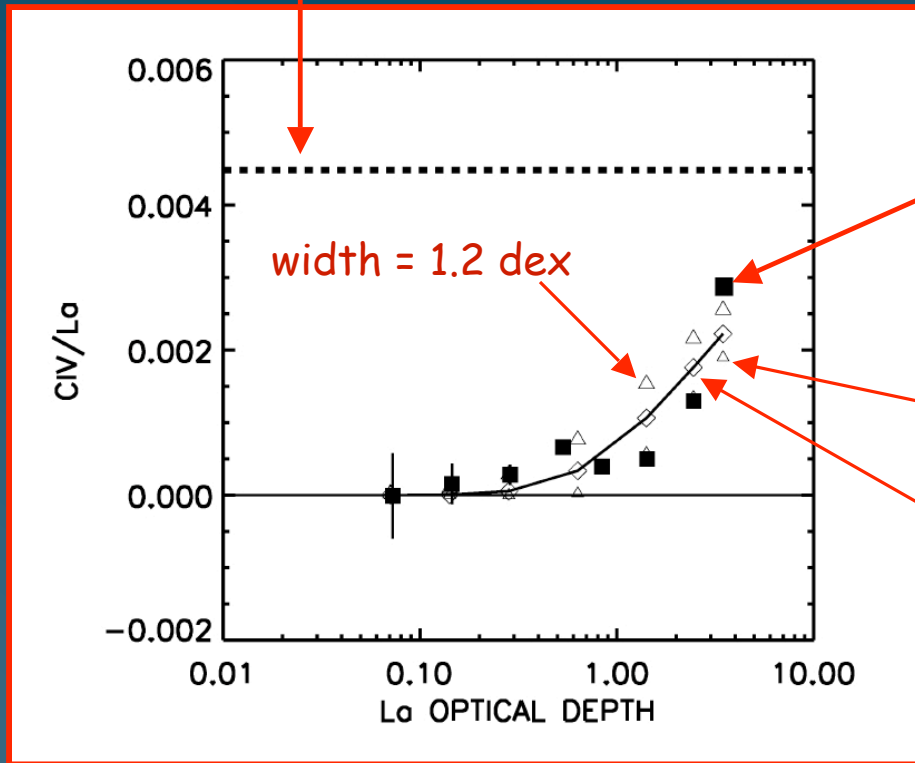
Fraction of inserted CIV systems recovered by SuperPOD



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

SuperPOD method - C IV/Ly α ratio

$$\langle \text{CIV/HI} \rangle = 4.5 \times 10^{-3}$$



CIV/Ly α
measured by
SuperPOD -
1 σ error
bars

width = 0.4 dex

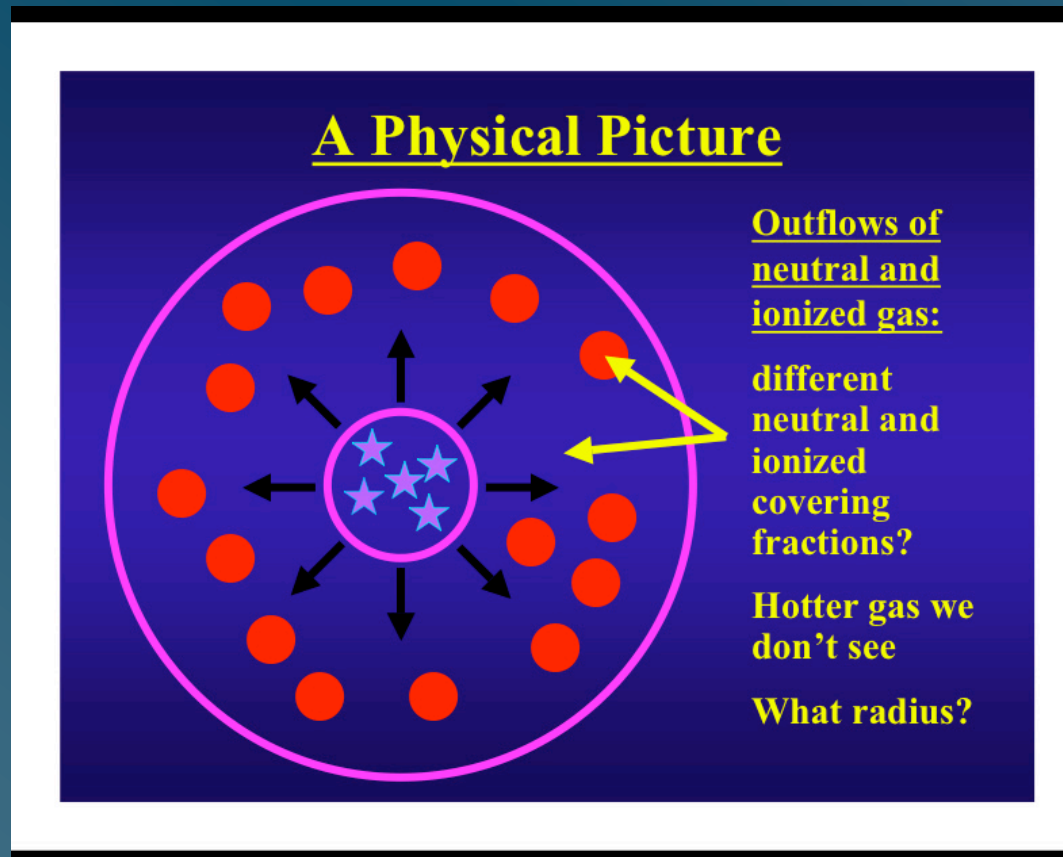
width = 0.8 dex

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.

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.

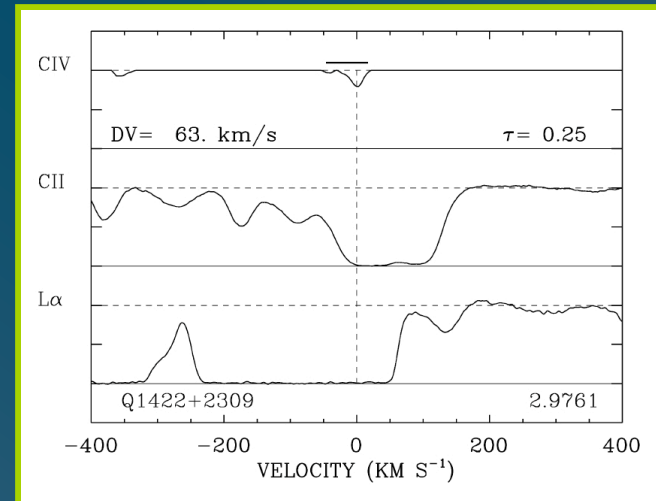
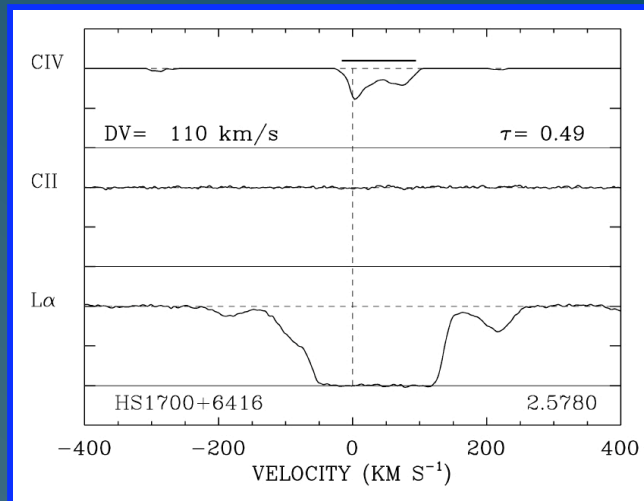
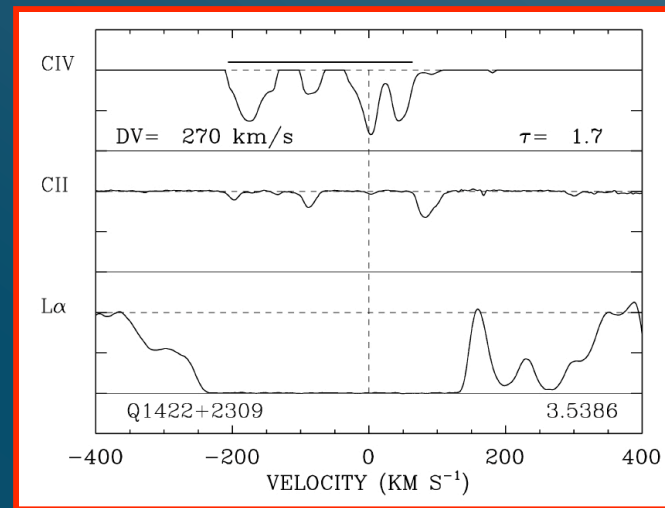


Can't afford to turn kinetic velocities of the low ionization entrained material into thermal velocities:
thermal widths too high (Schaye 2005).

Shapley (Arizona-Heidelberg meeting, 2004)

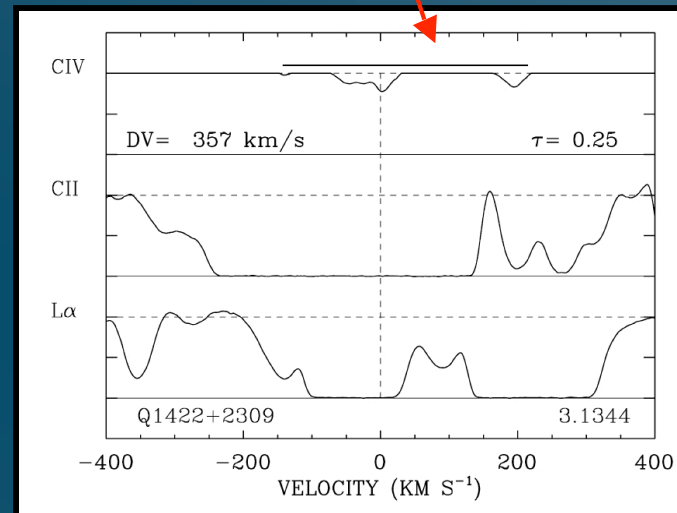
Widths of CIV systems

Range of widths ...



SuperPOD method - widths of CIV systems

... and sometimes two systems are connected



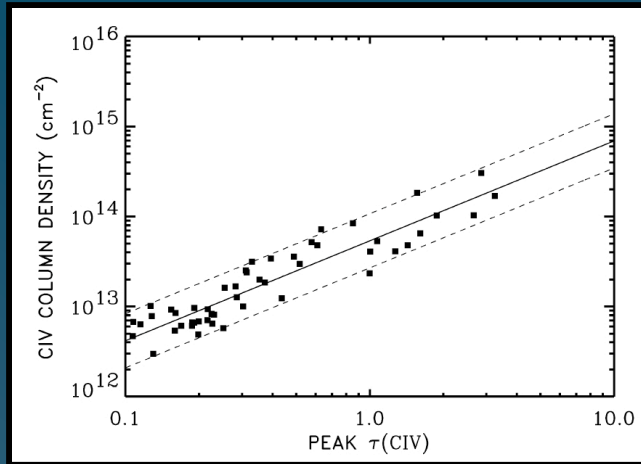
Column density is correlated with width.

Need two independent quantities to characterize absorption :

Strength \longleftrightarrow peak τ

Velocity width \longleftrightarrow full width at tenth max (FWTM)

SuperPOD method - widths of CIV systems

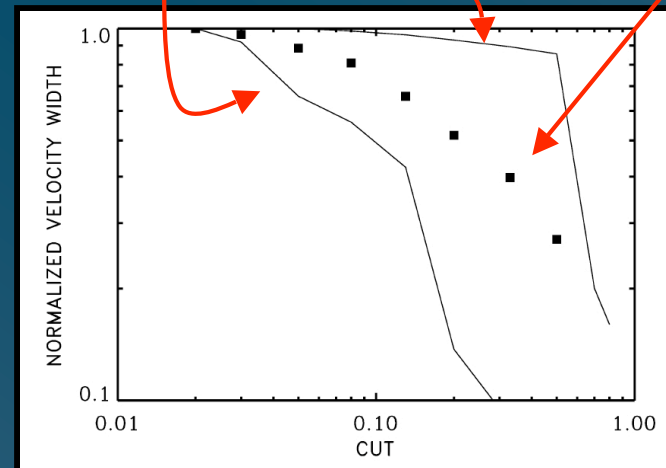


Peak τ correlated with CIV column density

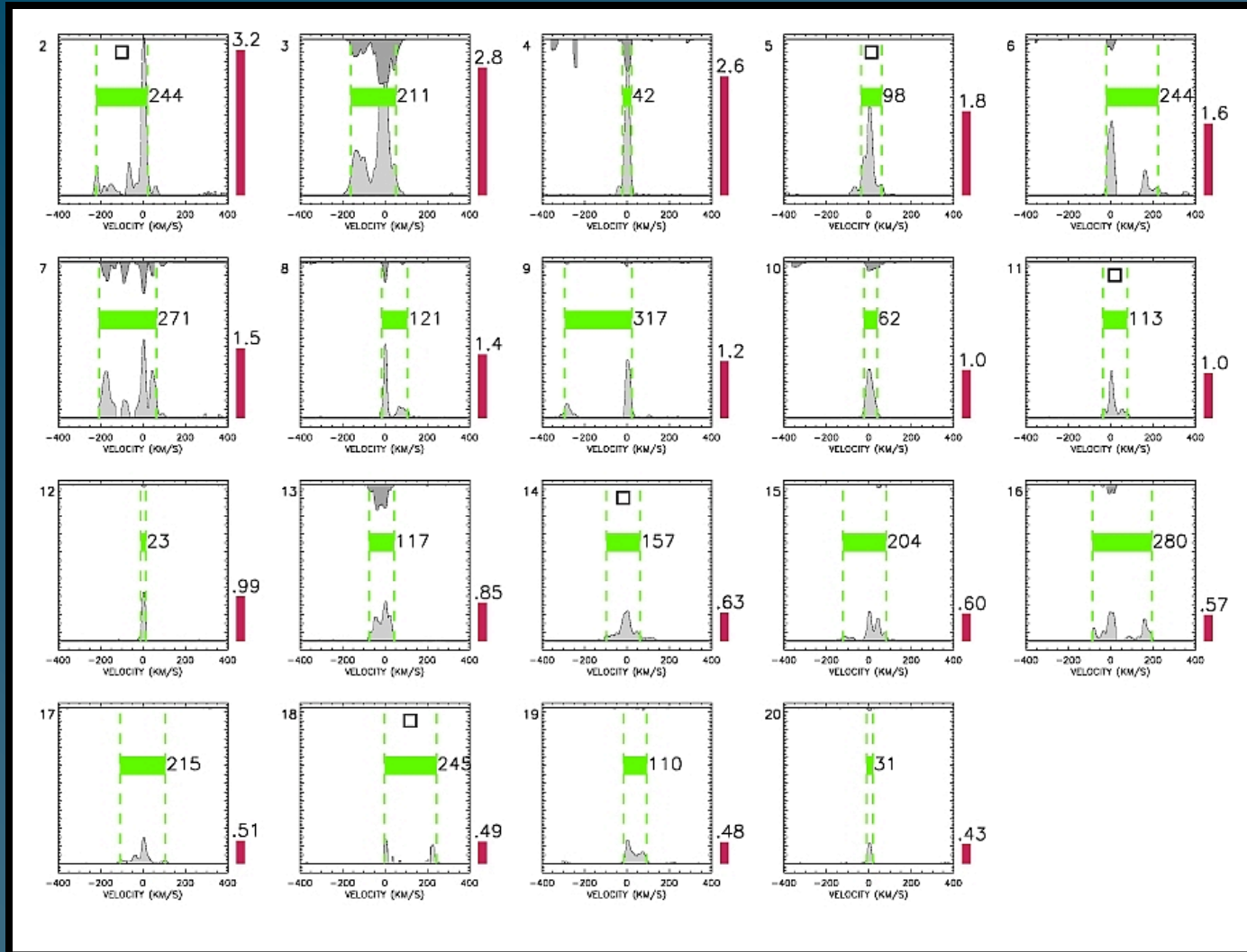
FWTM a good measure of velocity width of system

Max & min values

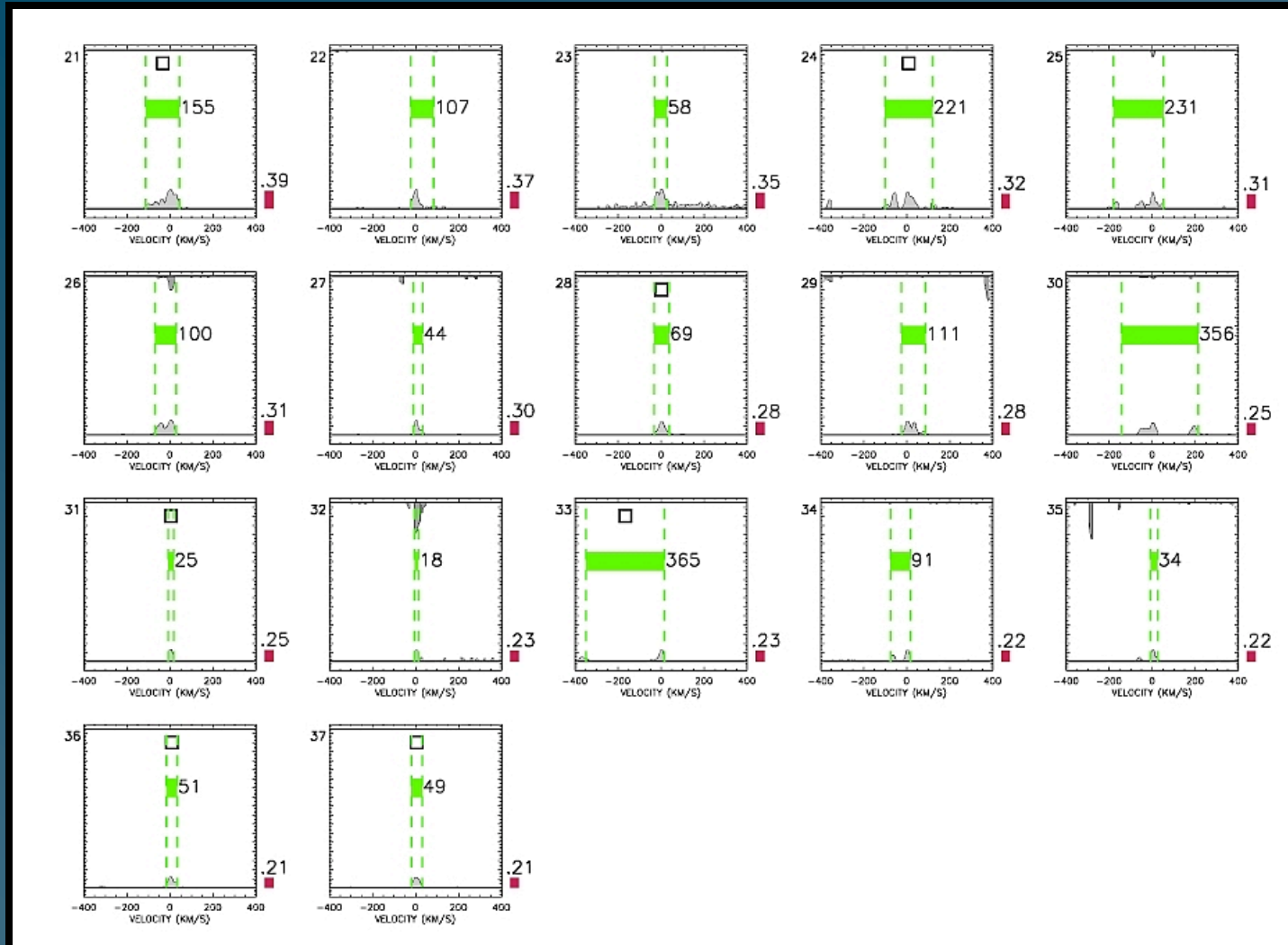
Mean values



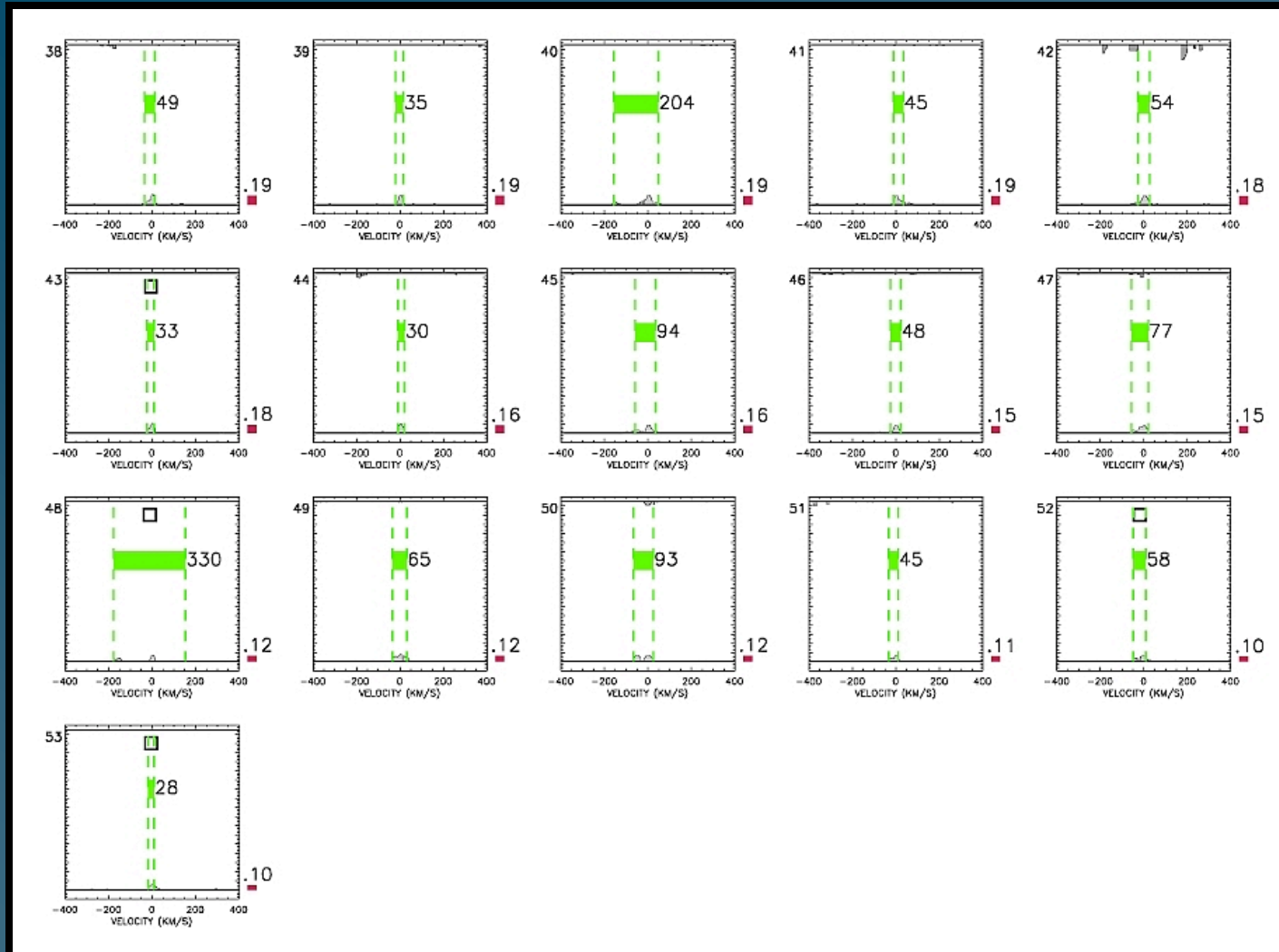
CIV absorption systems in high S/N sample



CIV absorption systems in high S/N sample

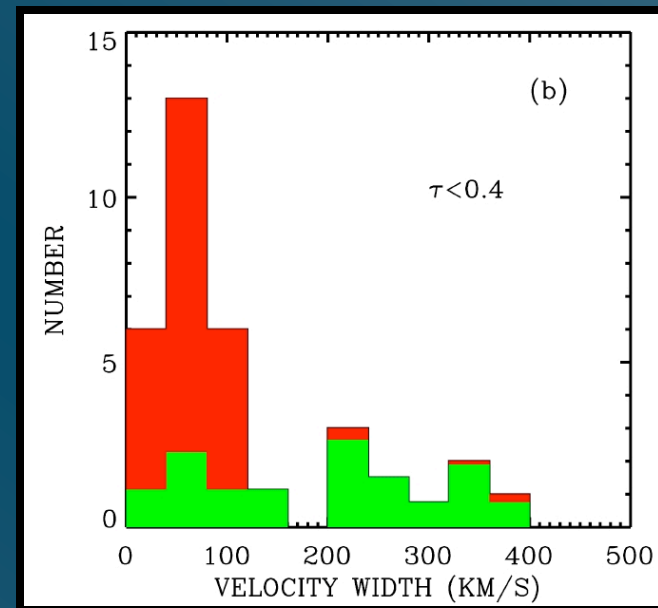
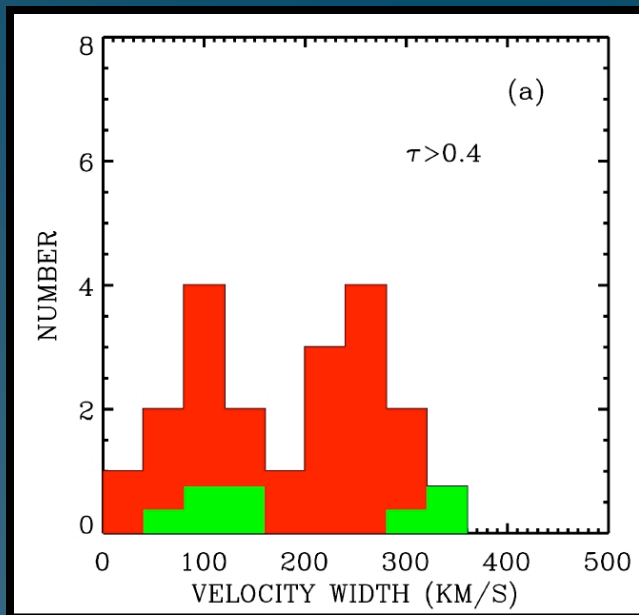


CIV absorption systems in high S/N sample



Widths of IGM metal systems

Red → real systems
Green → false systems



$$\tau(\text{CIV}) > 0.4$$

$$N(\text{CIV}) > 2 \times 10^{13} \text{ cm}^{-2}$$

$$\tau(\text{CIV}) < 0.4$$

$$N(\text{CIV}) < 2 \times 10^{13} \text{ cm}^{-2}$$

Widths of IGM metal systems

Peak optical depth > 0.4 :

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

Very few false systems

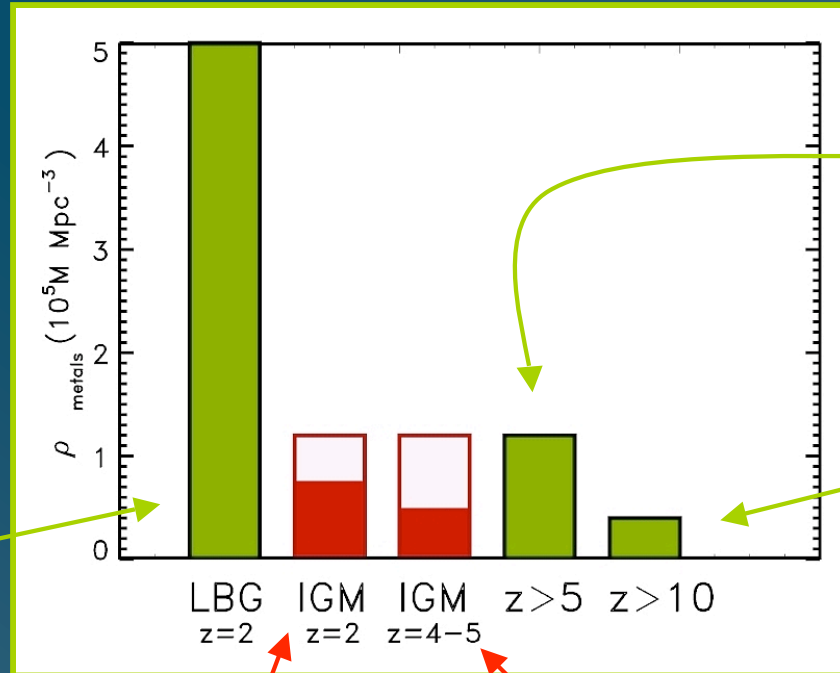
Peak optical depth < 0.4 :

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