Lyman Limit Systems Throughout Cosmic History

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1935-2012

PHOTOELECTRIC SPECTROPHOTOMETRY OF 4C 05.34

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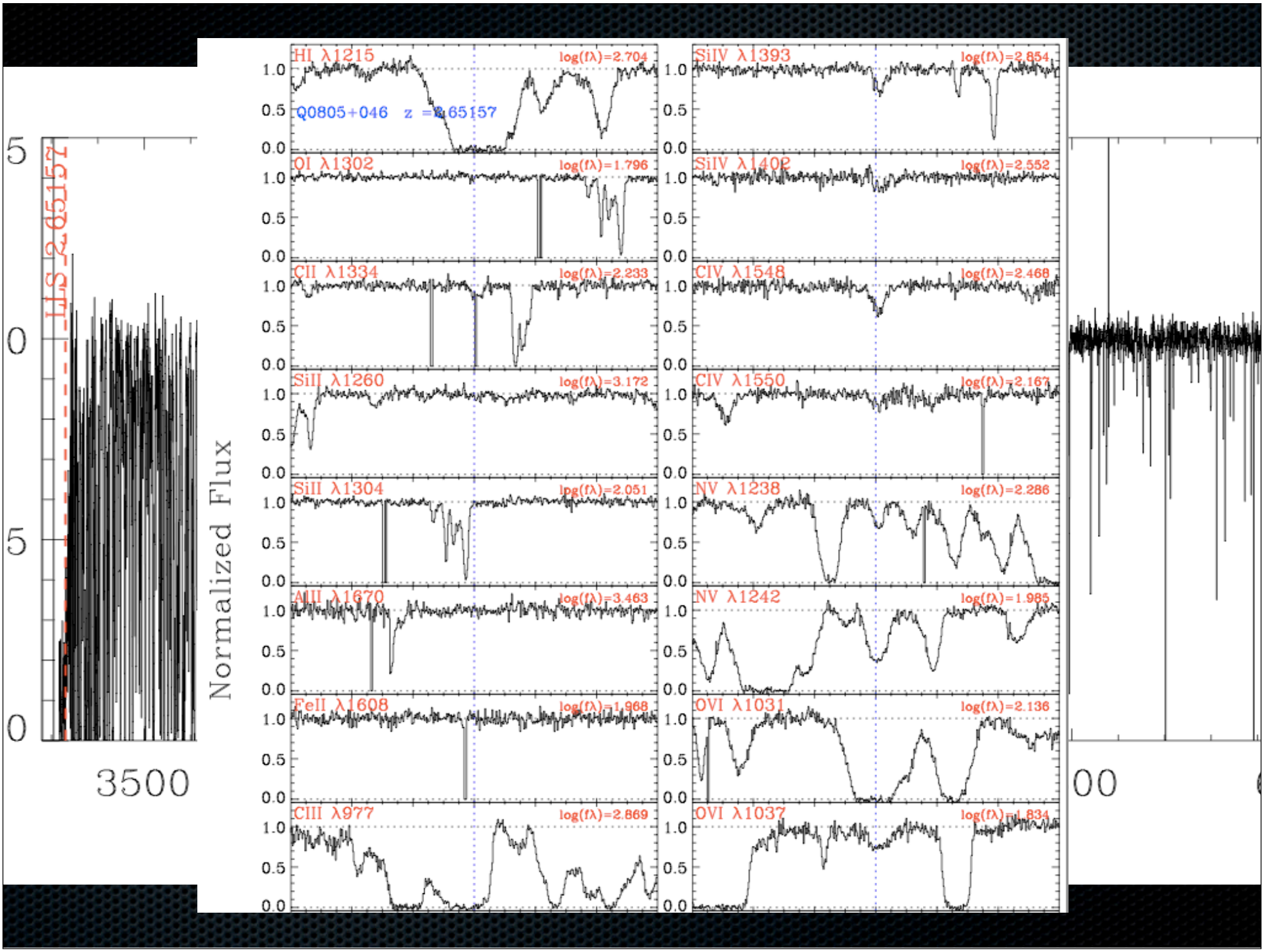
ABSTRACT

The multichannel photoelectric spectrometer has been used to obtain the absolute spectral-energy distribution in the quasi-stellar radio source 4C 05.34 from λ3220 to λ9000. The strengths of the emission lines, in terms of both equivalent width and absolute intensity, the spectral index, and the absolute flux are typical of quasi-stellar sources. Lyman β is observed, and there is a drop of intensity by a factor of 2 at the Lyman limit. From the data it is inferred that the optical depth is of the order of unity in the Lyman continuum and is approximately 3 at the center of Lβ.

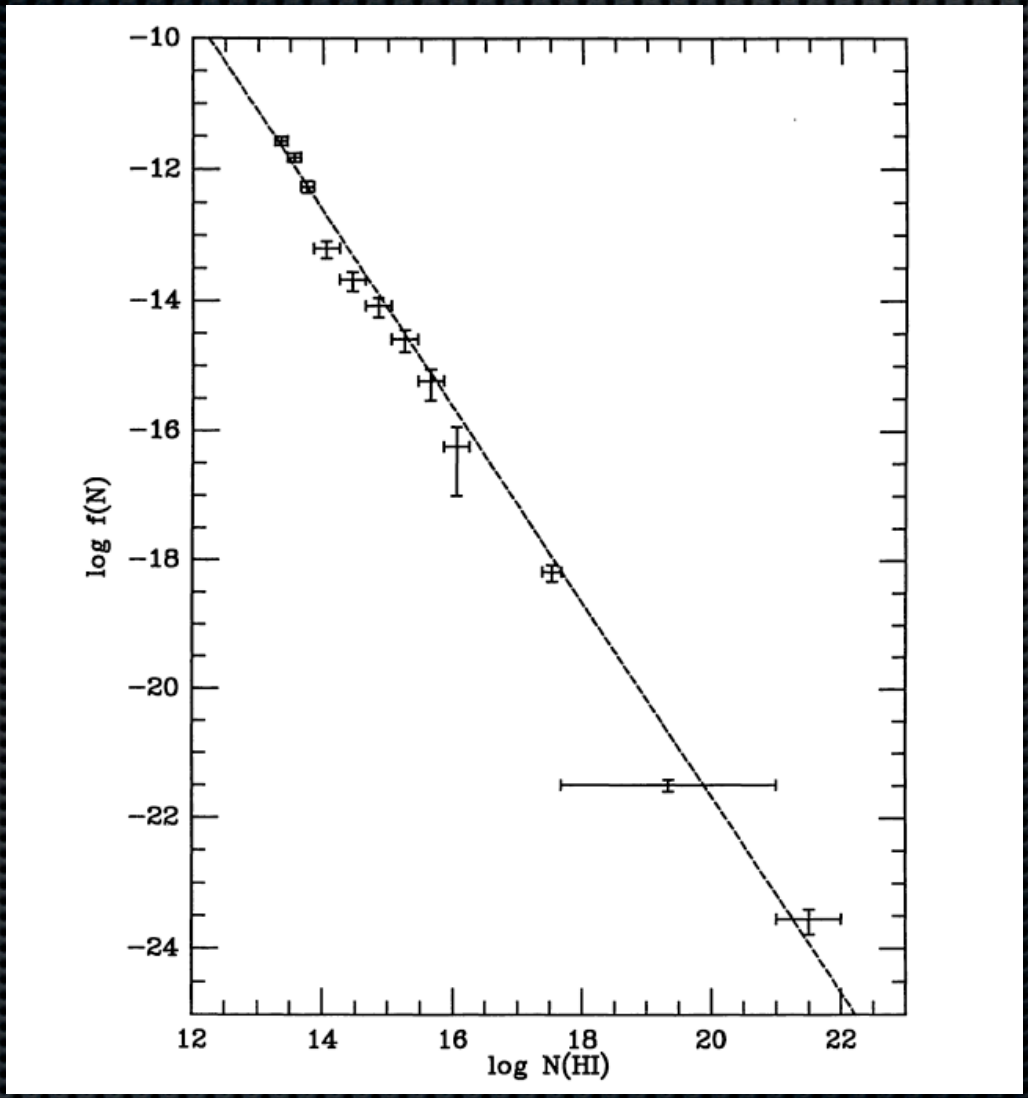

HI λ1215
log(fλ)=2.704
Q0805+046 z =2.65157
SiIV λ1393
log(fλ)=2.854
OI λ1302
log(fλ)=1.796
SiIV λ1402
log(fλ)=2.552
CII λ1334
log(fλ)=2.233
CIV λ1548
log(fλ)=2.468
SiII λ1260
log(fλ)=3.172
CIV λ1550
log(fλ)=2.167
SiII λ1304
log(fλ)=2.051
NV λ1238
log(fλ)=2.286
AlII λ1670
log(fλ)=3.463
NV λ1242
log(fλ)=1.985
FeII λ1608
log(fλ)=1.968
OVI λ1031
log(fλ)=2.136
CIII λ977
log(fλ)=2.869
OVI λ1037
log(fλ)=1.834
Normalized Flux
3500

LLS as the laboratory of choice

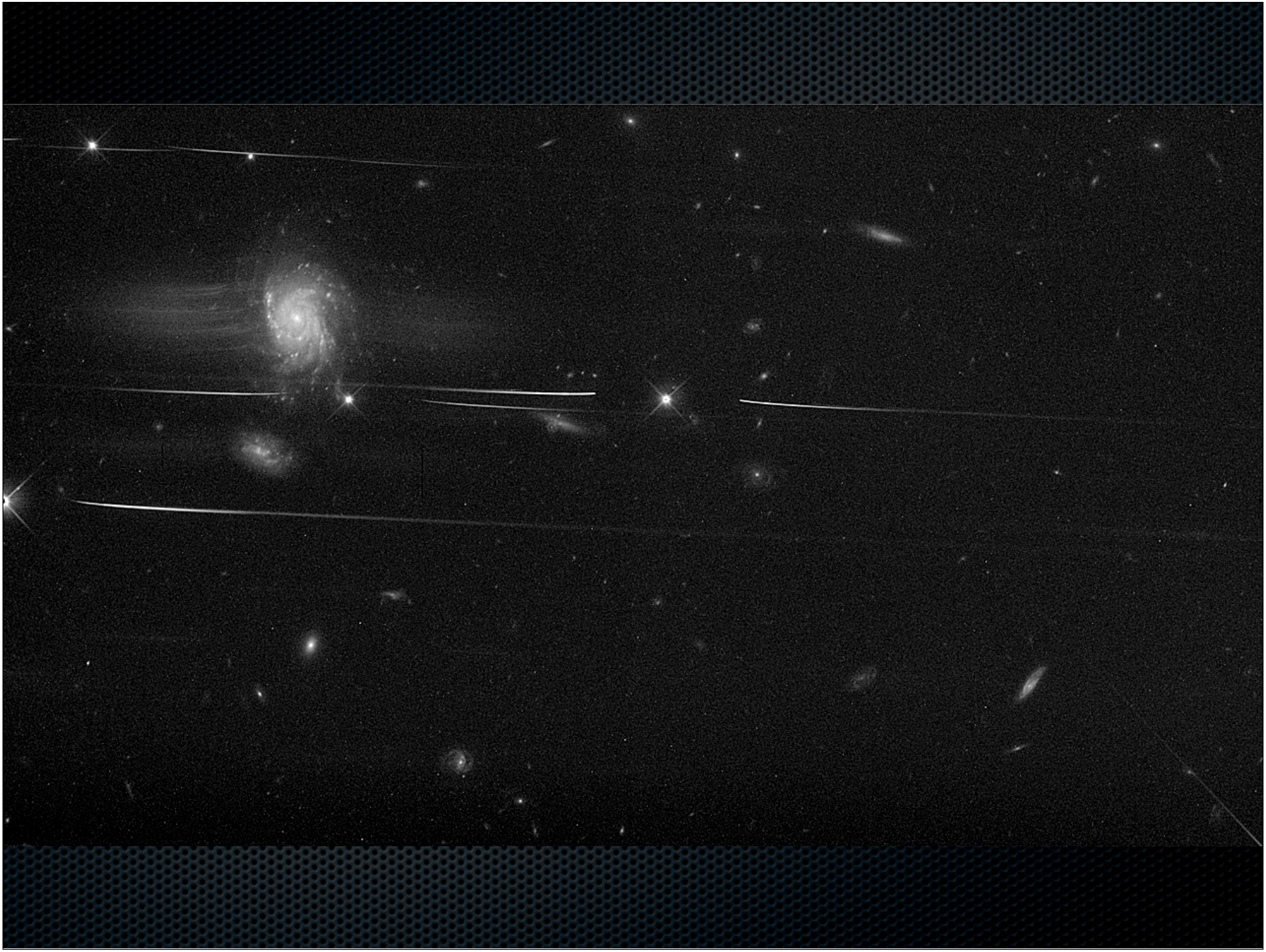
Questions

- What is the LLS incidence frequency and column density distribution?

The Column Density Distribution Function f(N,X)



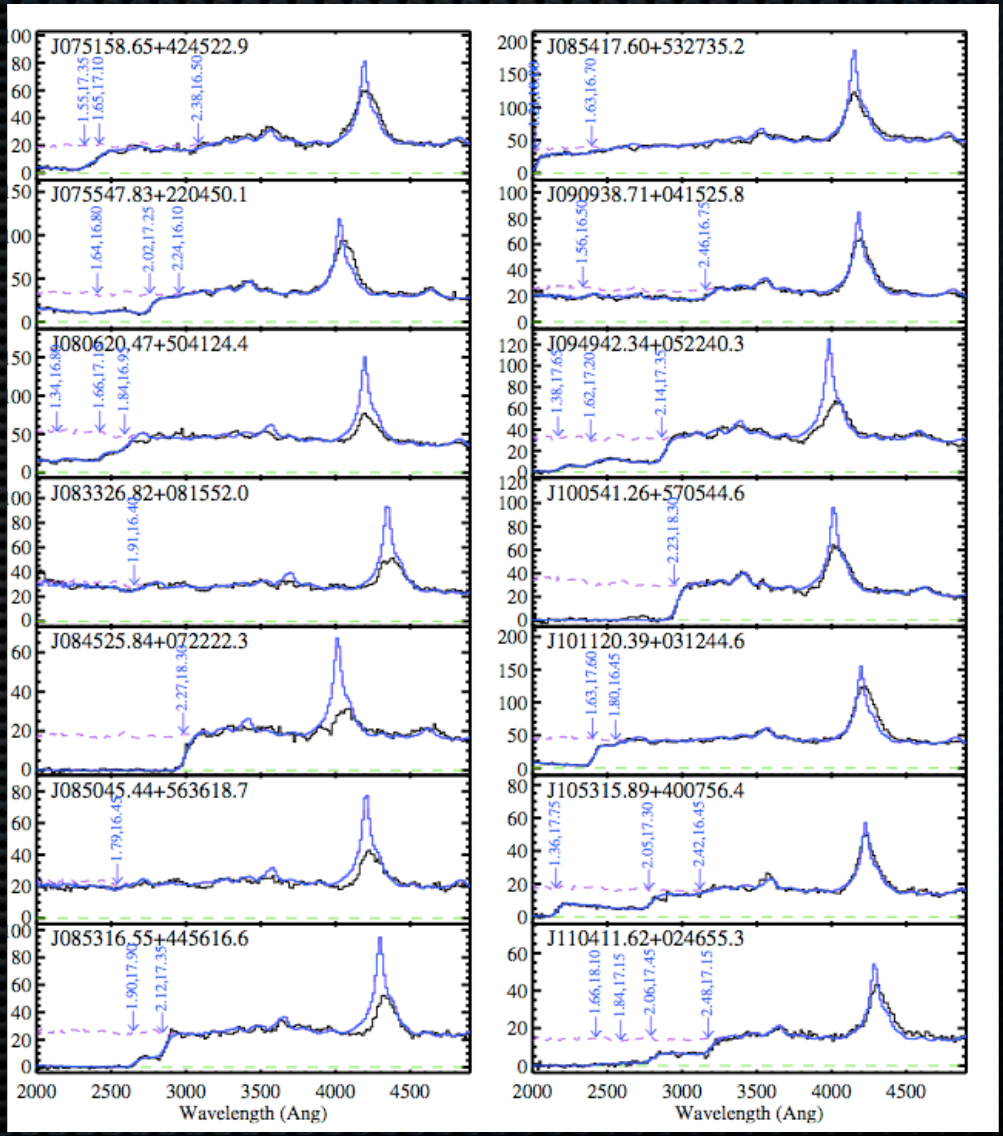
SSB 1989



The low z road

O'Meara+ 2013

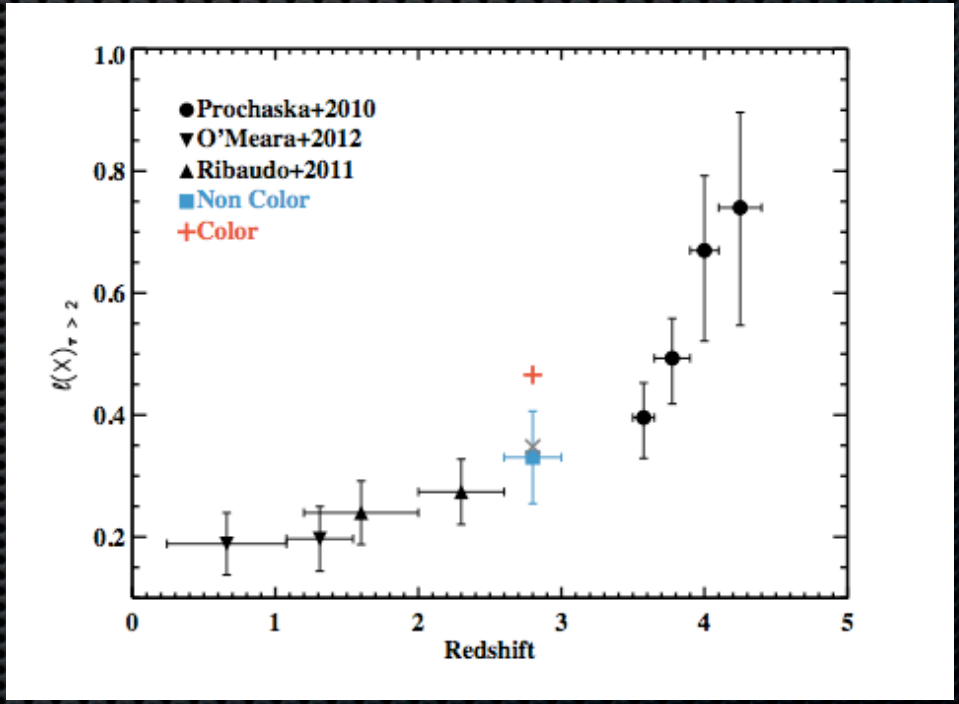
HST ACS/WFC3 program at z~2.5



The middle *z* road

Fumagalli, O'Meara, & Prochaska 2013 ApJ submitted

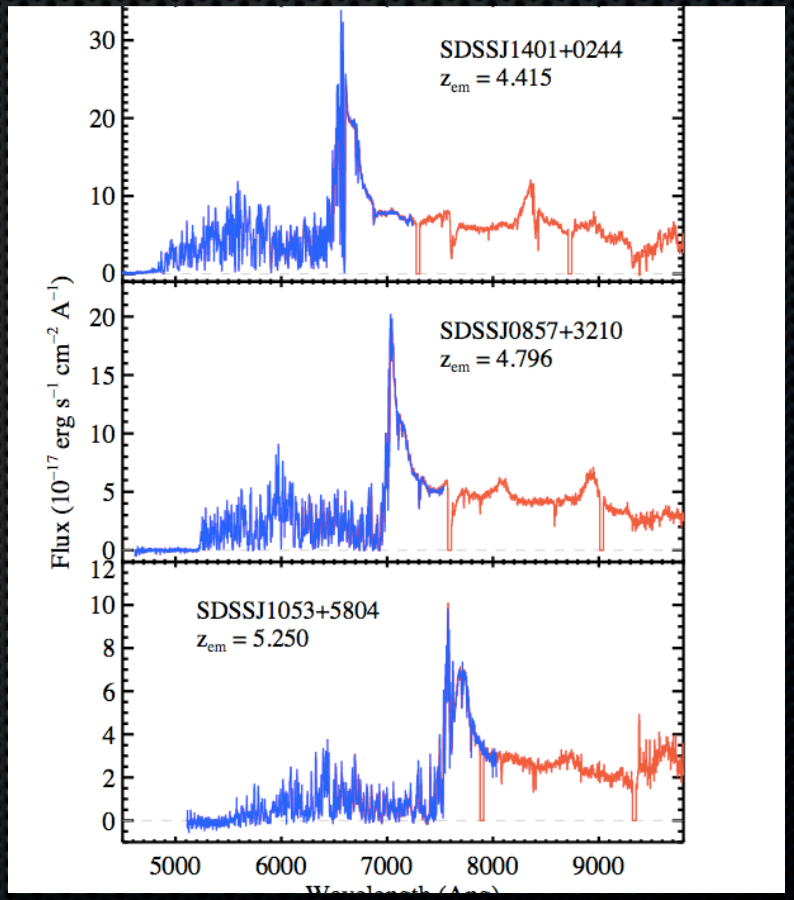
MagE *z*~3



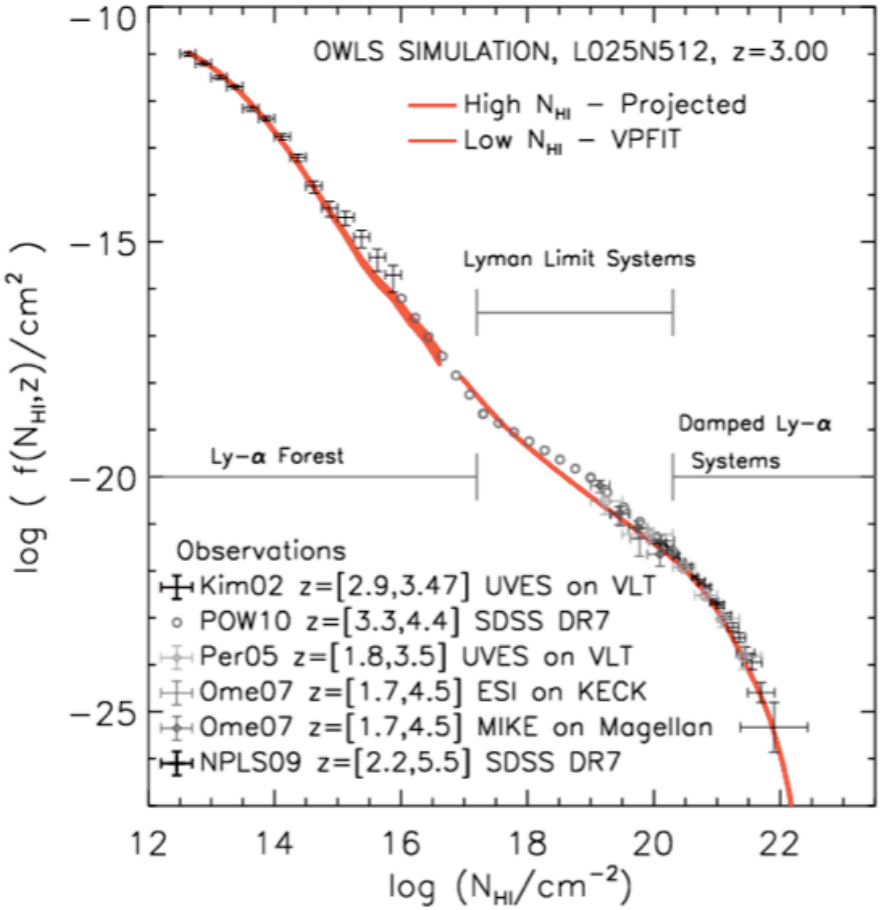
The high z road

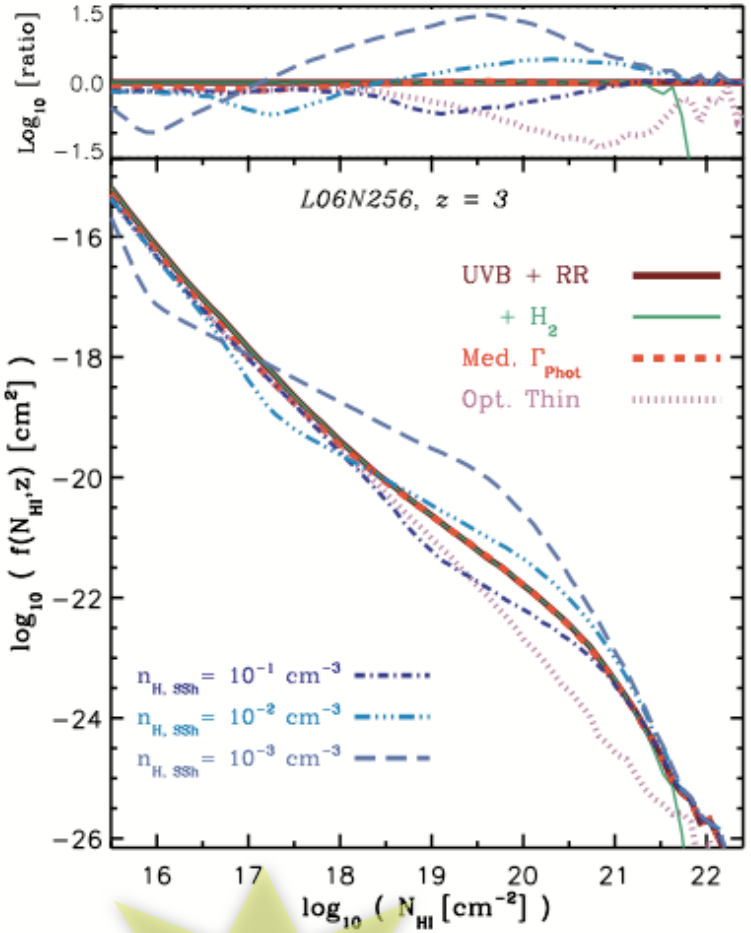
Gemini GMOS Worseck+ 2013 in prep

SDSS, Prochaska+ 2010



f(N,X) at z=2.4
O'Meara+ 2013





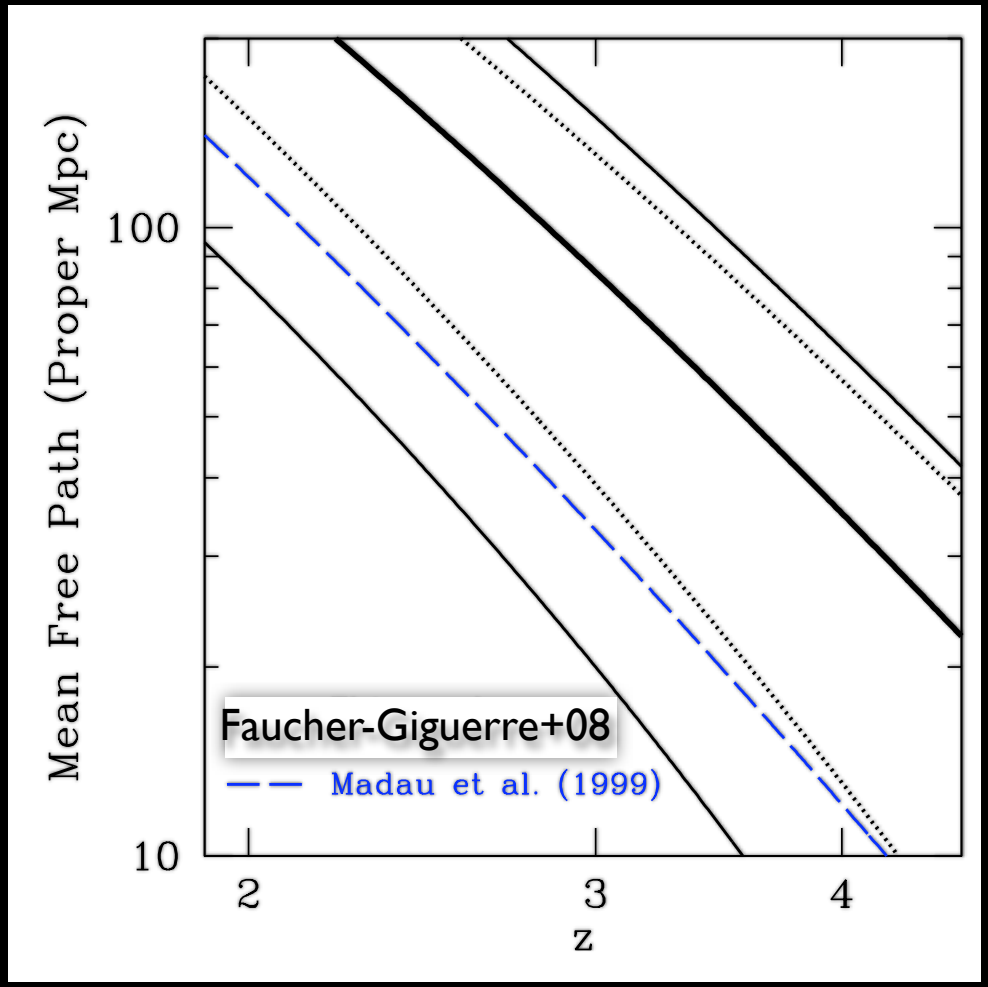
Altay+ 2011

Rahmati+ 2013

Questions

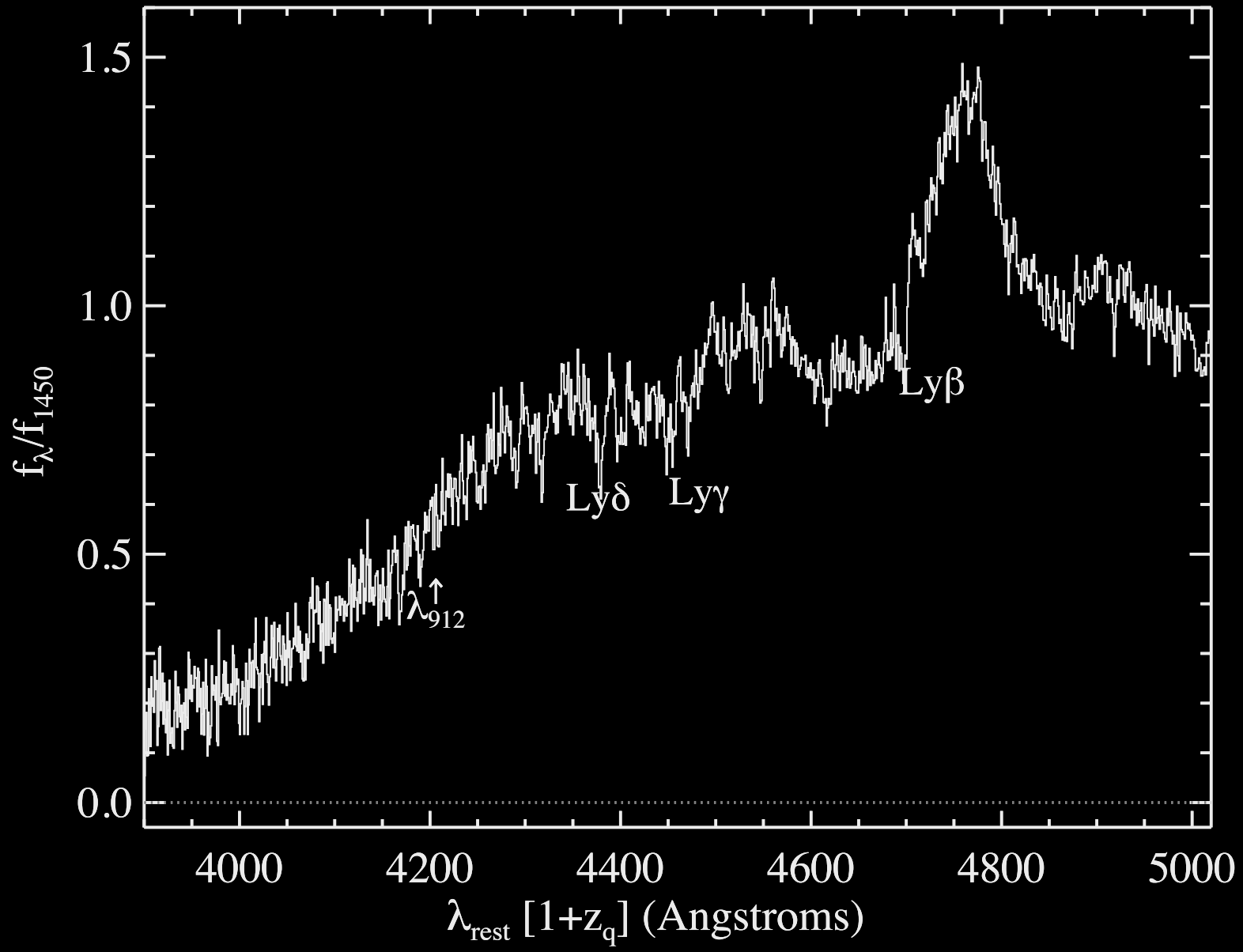
- What is the LLS incidence frequency and column density distribution?
- What is the effect of the LLS on ionizing photons?

LLS & The Mean Free Path

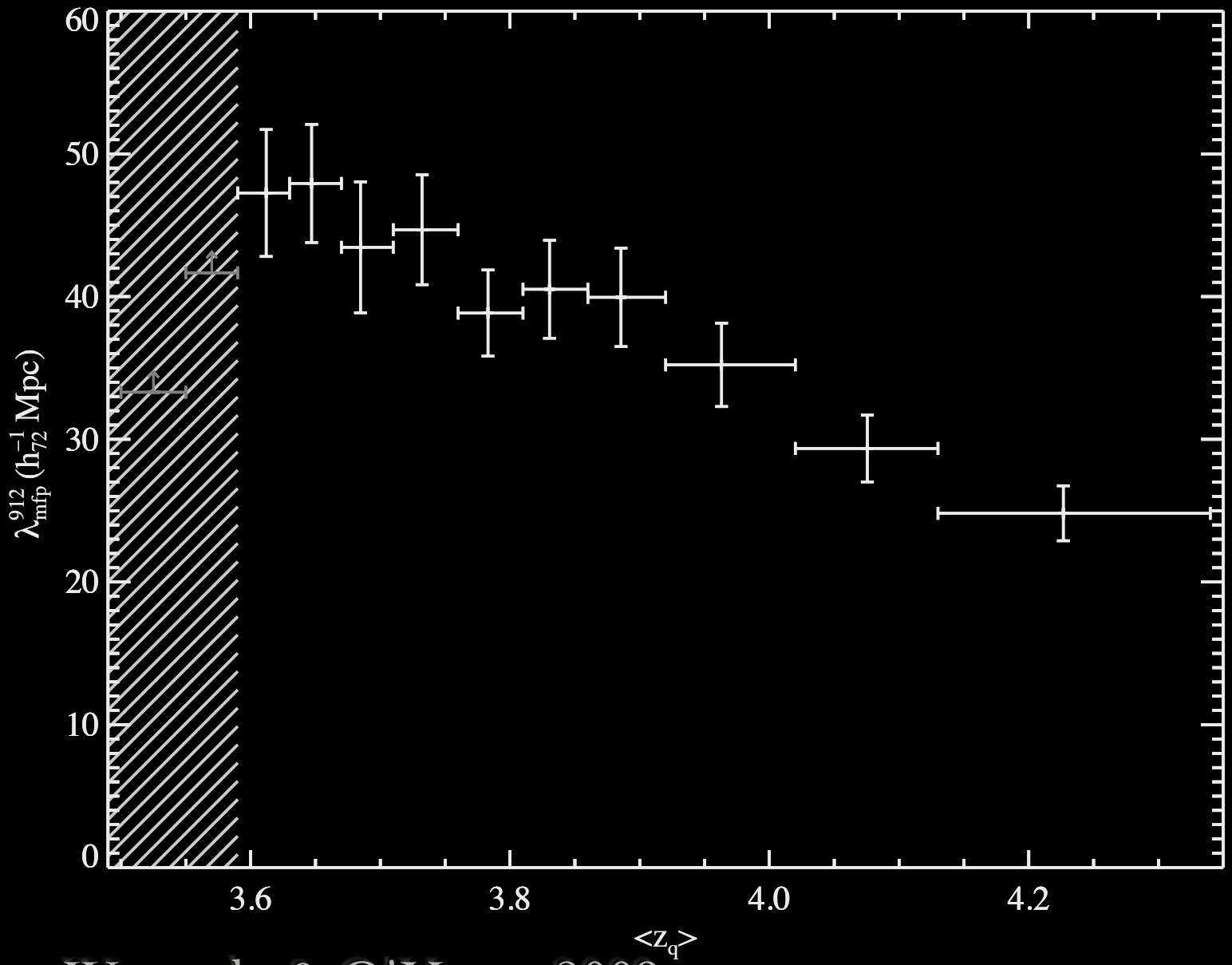


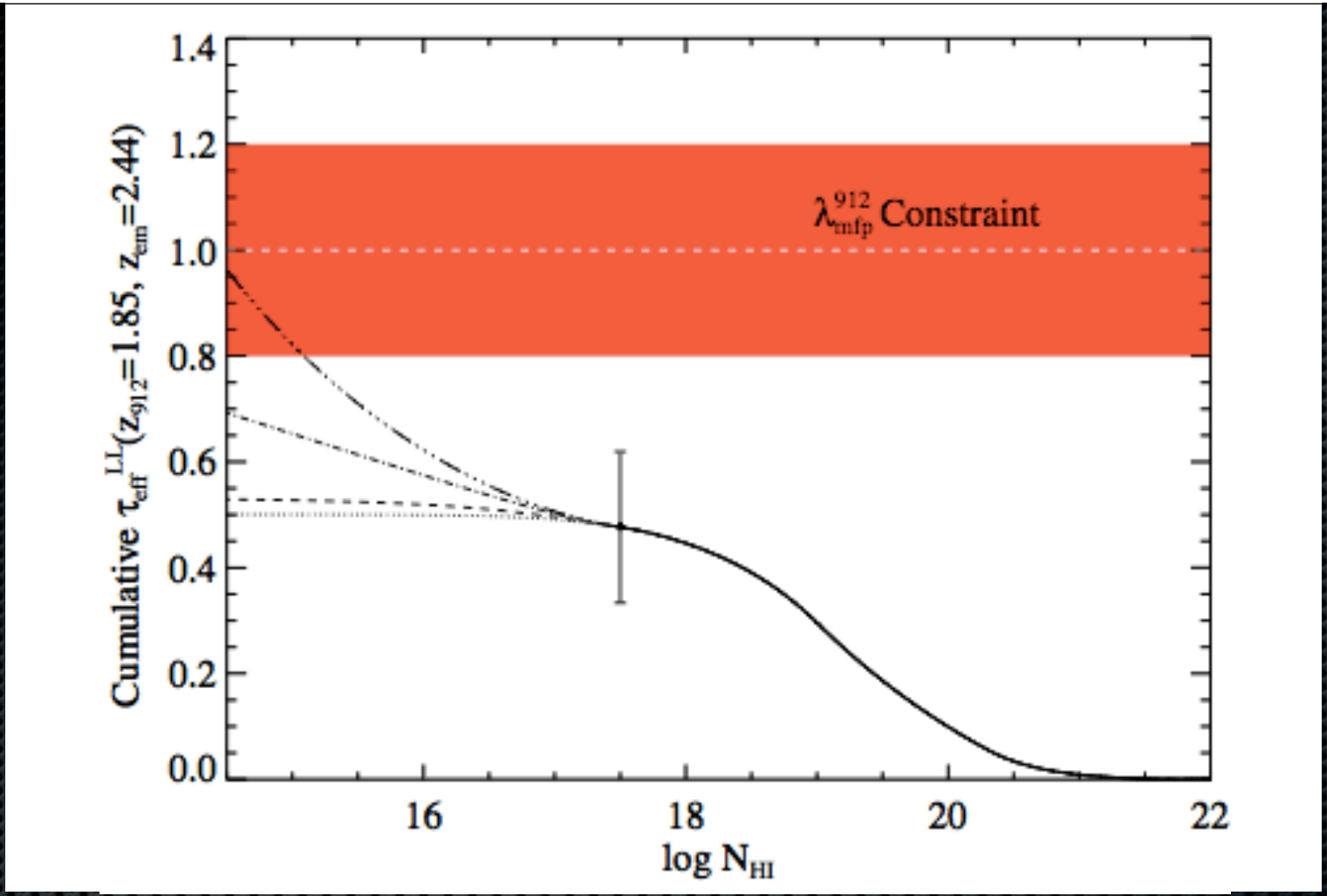
$$\tau_{\rm eff,LL}(z_{912}, z_q) = \int_{z_{912}}^{z_q} \int_{0}^{\infty} f(N_{\rm HI}, z')\{1 - \exp\,[\,-N_{\rm HI}\sigma_{\rm ph}(z')\,]\}dN_{\rm HI}dz'$$

SDSS Stacked Quasar Spectra



λ_{mfp}: SDSS Measurements (z>3.6)





$(1+z)^{\alpha}$ $\alpha = -5.45 \pm 0.39$

Hot off the (hopefully) presses

Fumagalli, O'Meara, & Prochaksa, 2013

Worseck+ 2013

Questions

- What is the LLS incidence frequency and column density distribution?
- What is the effect of the LLS on ionizing photons?
- How many metals are locked up in the LLS?

The Large, Oxygen-Rich Halos of Star-Forming Galaxies Are a Major Reservoir of Galactic Metals

J. Tumlinson,[1]* C. Thom,[1] J. K. Werk,[2] J. X. Prochaska,[2] T. M. Tripp,[3] D. H. Weinberg,[4] M. S. Peeples,[5] J. M. O'Meara,[6] B. D. Oppenheimer,[7] J. D. Meiring,[3] N. S. Katz,[3] R. Davé,[8] A. B. Ford,[8] K. R. Sembach[1]

The circumgalactic medium (CGM) is fed by galaxy outflows and accretion of intergalactic gas, but its mass, heavy element enrichment, and relation to galaxy properties are poorly constrained by observations. In a survey of the outskirts of 42 galaxies with the Cosmic Origins Spectrograph onboard the Hubble Space Telescope, we detected ubiquitous, large (150-kiloparsec) halos of ionized oxygen surrounding star-forming galaxies; we found much less ionized oxygen around galaxies with little or no star formation. This ionized CGM contains a substantial mass of heavy elements and gas, perhaps far exceeding the reservoirs of gas in the galaxies themselves. Our data indicate that it is a basic component of nearly all star-forming galaxies that is removed or transformed during the quenching of star formation and the transition to passive evolution.

Galaxies grow by accreting gas from the intergalactic medium (IGM) and converting it to stars. Stellar winds and explosions release gas enriched with heavy elements [or metals (*1*)], some of which is ejected in galactic-scale outflows (*2*). The circumgalactic medium (CGM)—loosely defined as gas surrounding galaxies within their own halos of dark matter (out to 100 to 300 kpc)—lies at the nexus of accretion and outflow, but the structure of the CGM and its relation to galaxy properties are still uncertain. Galactic outflows are observed at both low (*2*–*4*) and high (*5*–*7*) redshift, but it is unclear how far they propagate, what level of heavy-element enrichment they possess, and whether the gas escapes the halo or eventually returns to fuel later star formation. Models of

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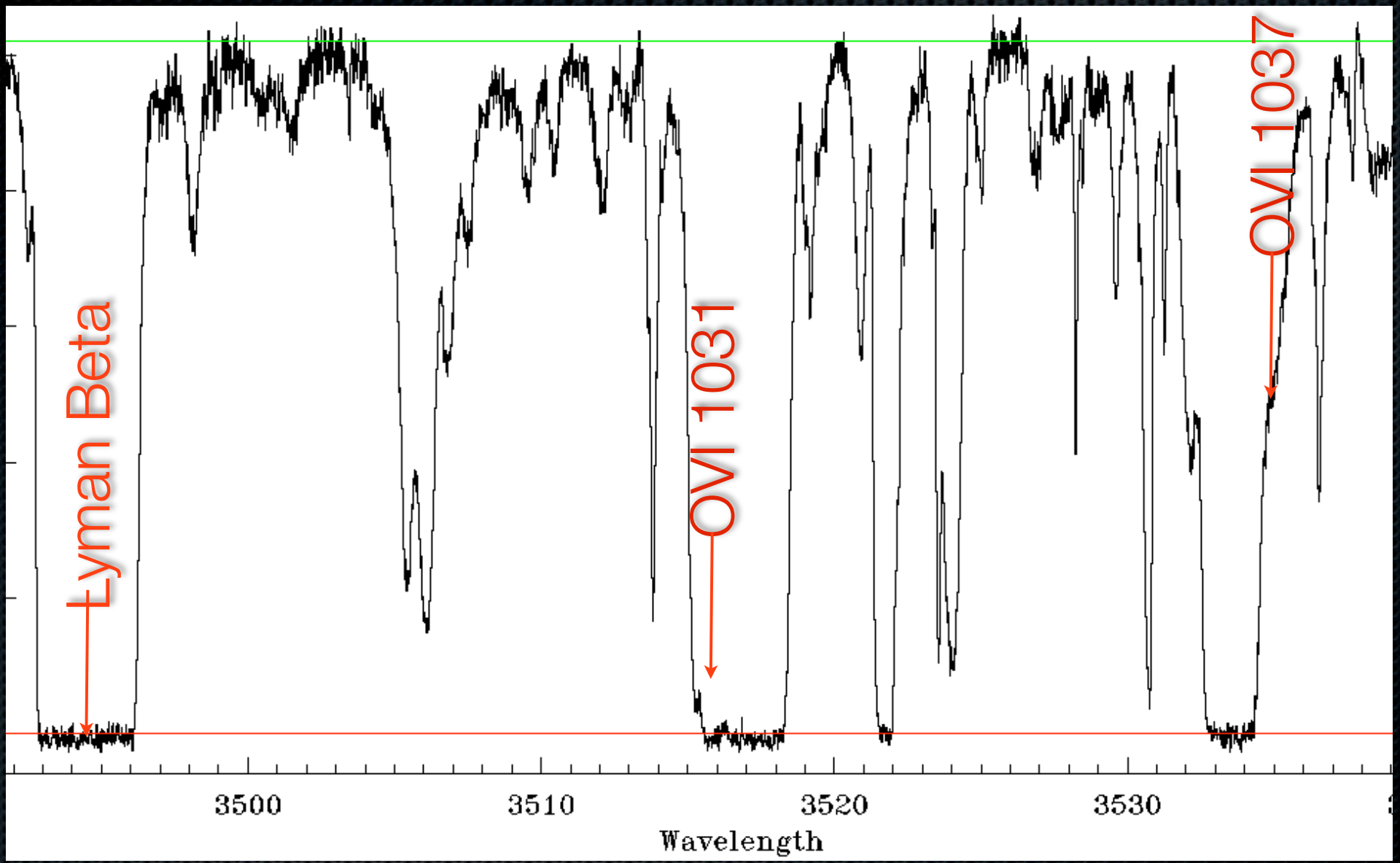


OVI is hard at z > 2

to measure gas in the universe you must avoid gas in the universe

Keck Observatory Database (of) Ionized Absorbers (toward) Quasars

The KODIAQ Survey

KOA

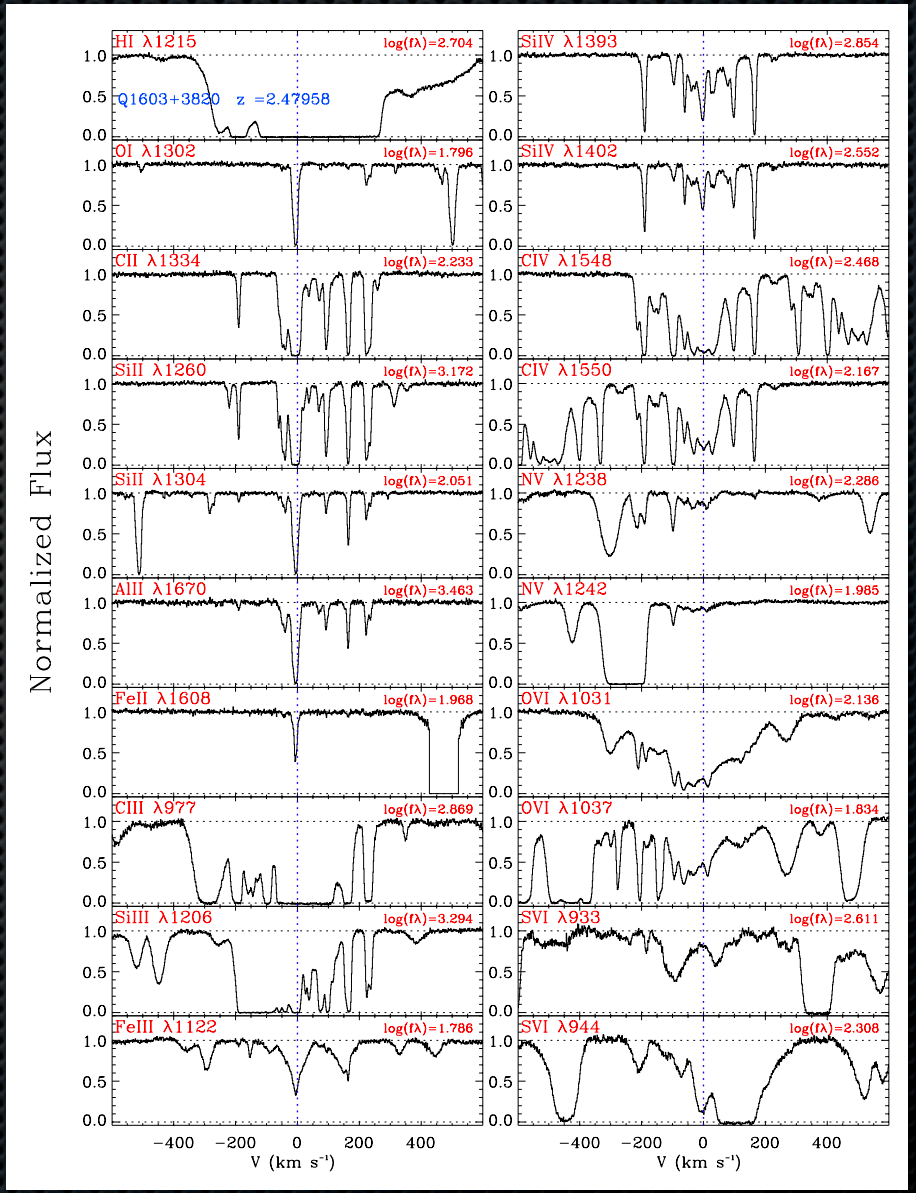
- HIRES data since 1994
- Mosaic chip data since 2004

KODIAQ DATABASE

- >25,000 individual frames
- >500 unique objects
- Final data products will be made public

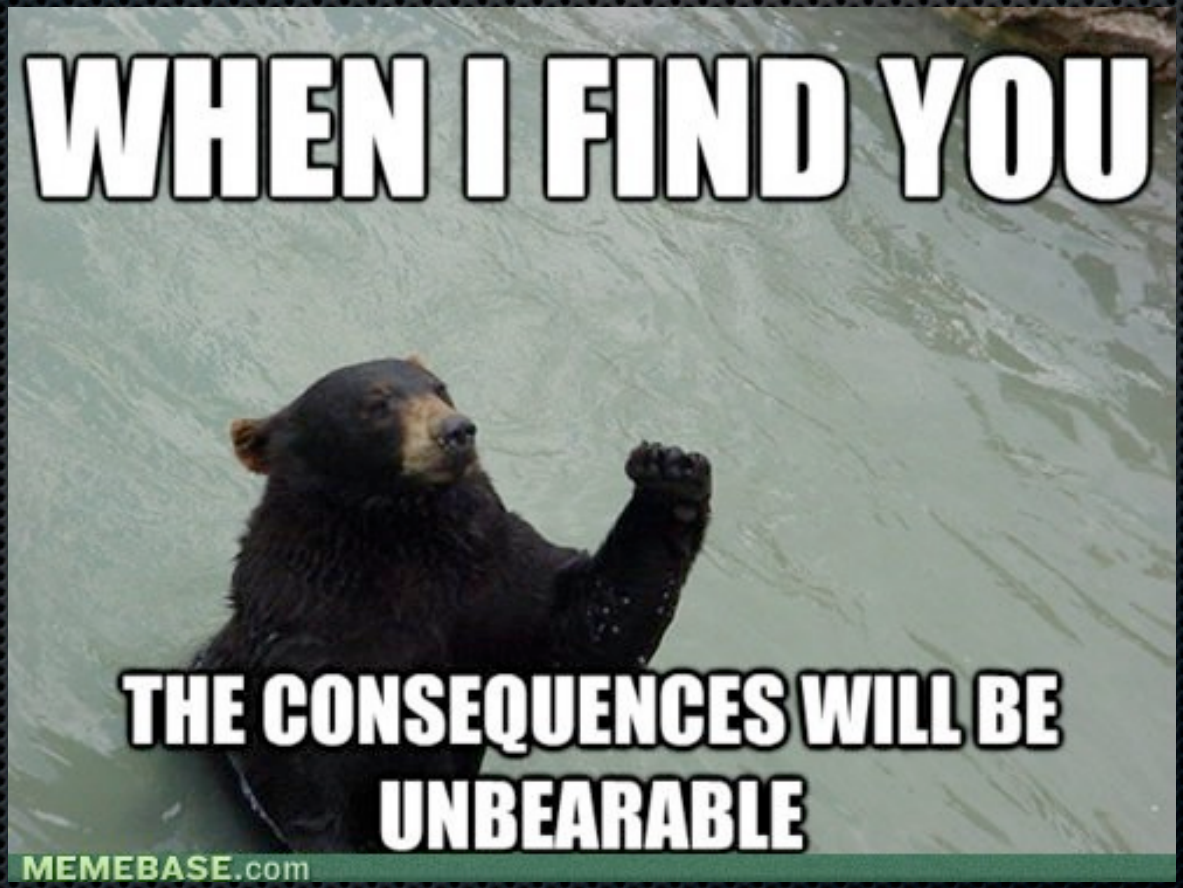
THE SURVEY SO FAR

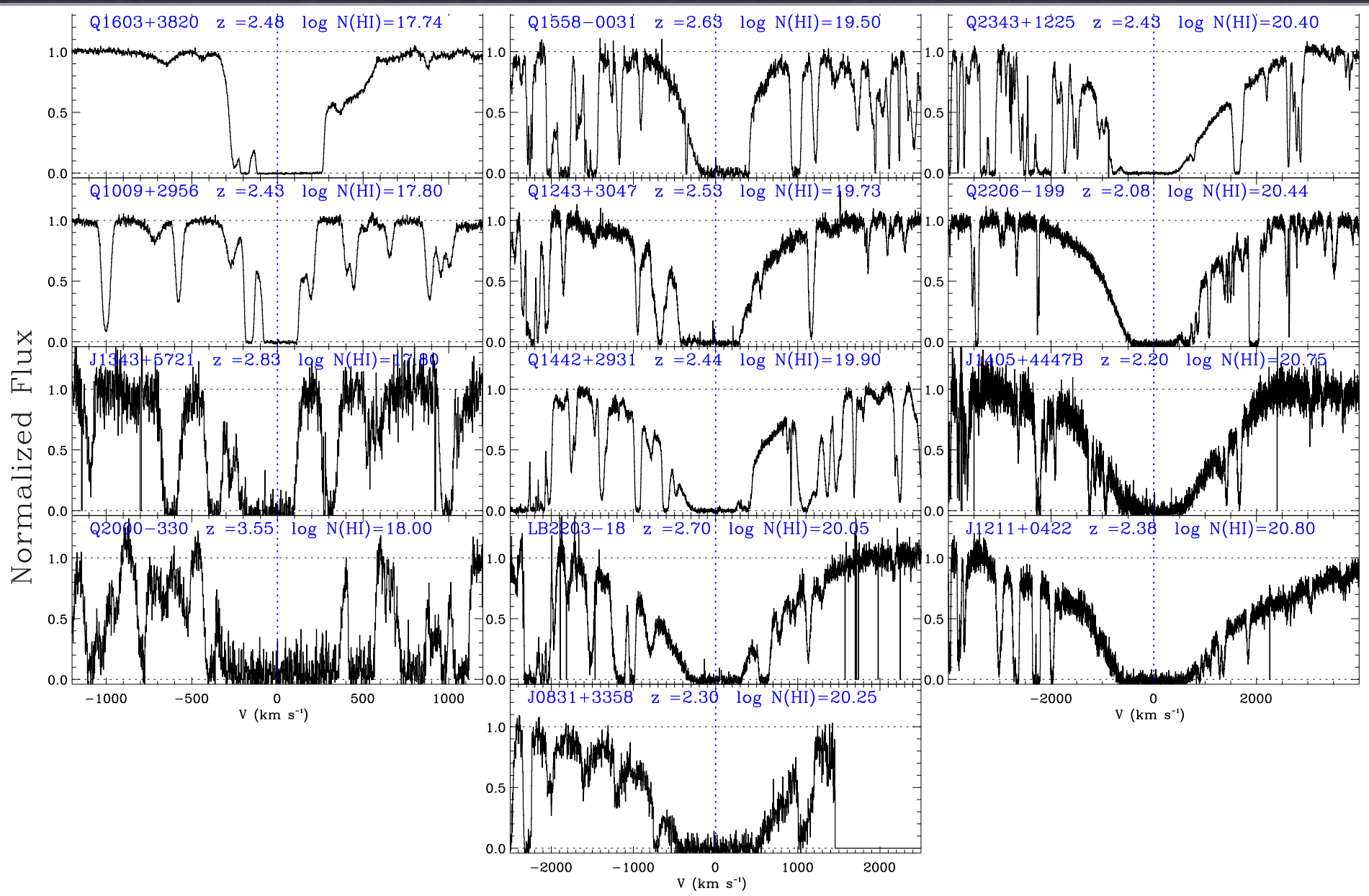
- >100 quasars surveyed for LLS + OVI + others
- Require both OVI transitions to make a measurement



First Results

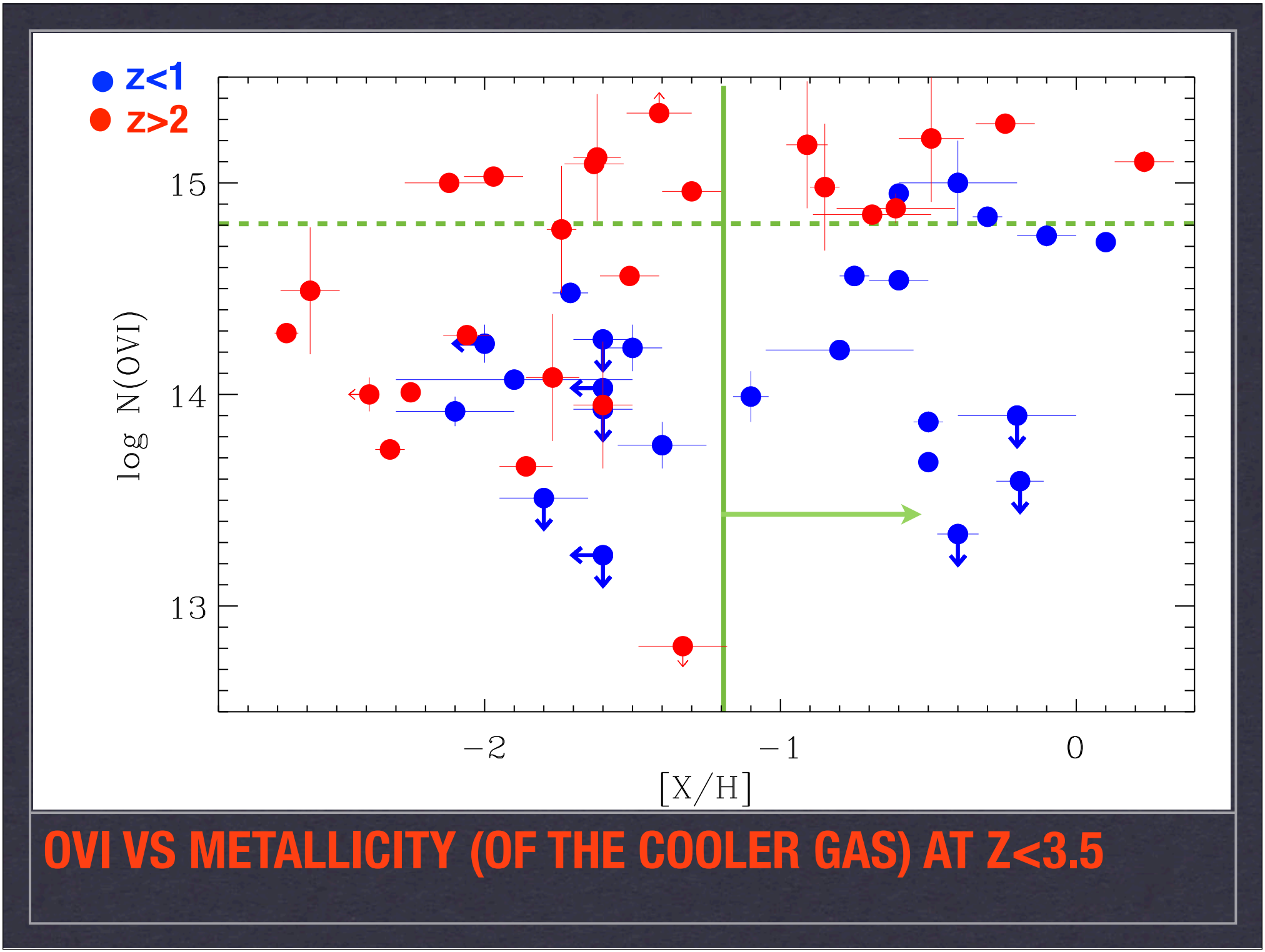
Lehner+ 2013 in prep



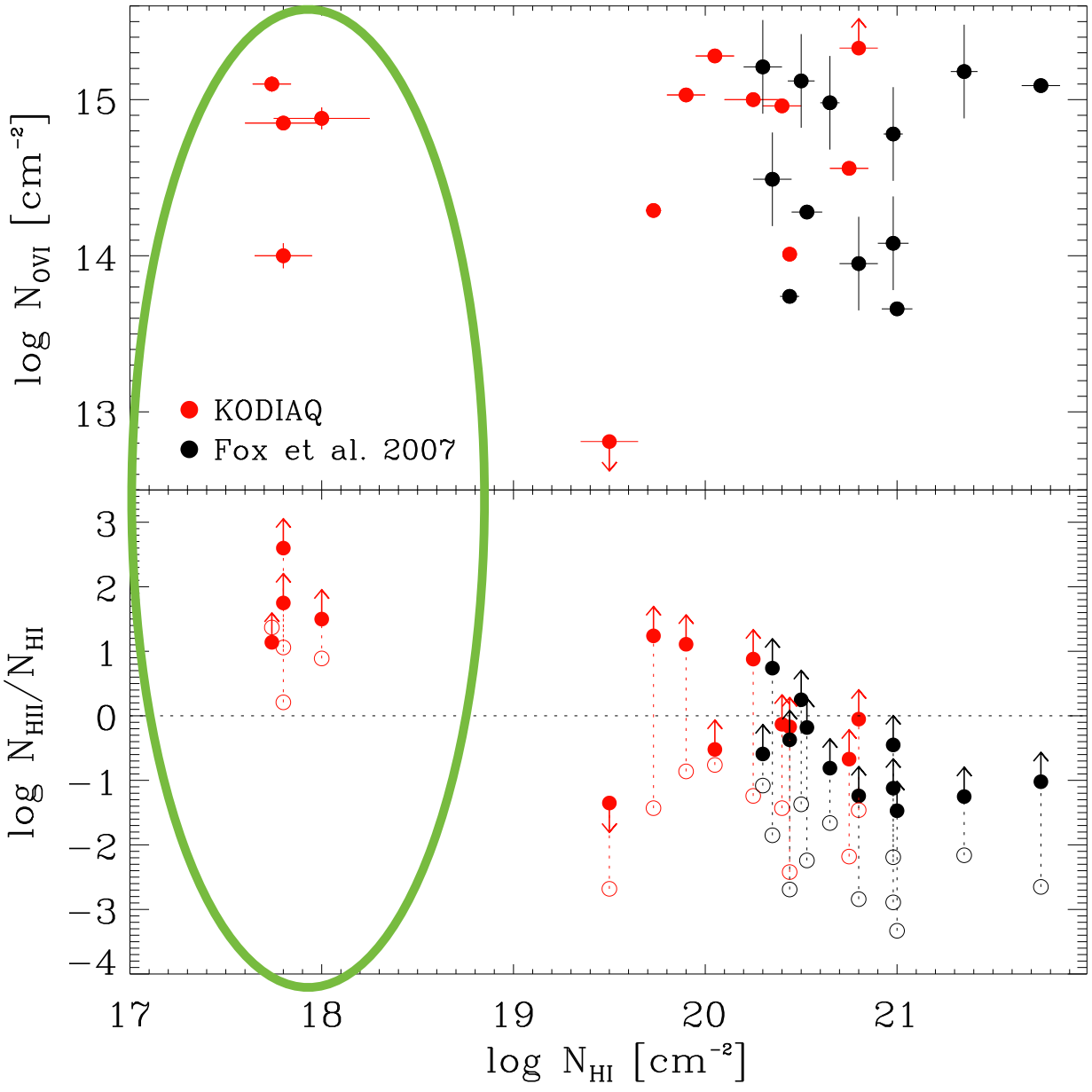


LYMAN ALPHA PROFILES

4 LLS, 5 SLLS, 4 DLA



OVI VS METALLICITY (OF THE COOLER GAS) AT Z<3.5



TOTAL GAS FROM OVI

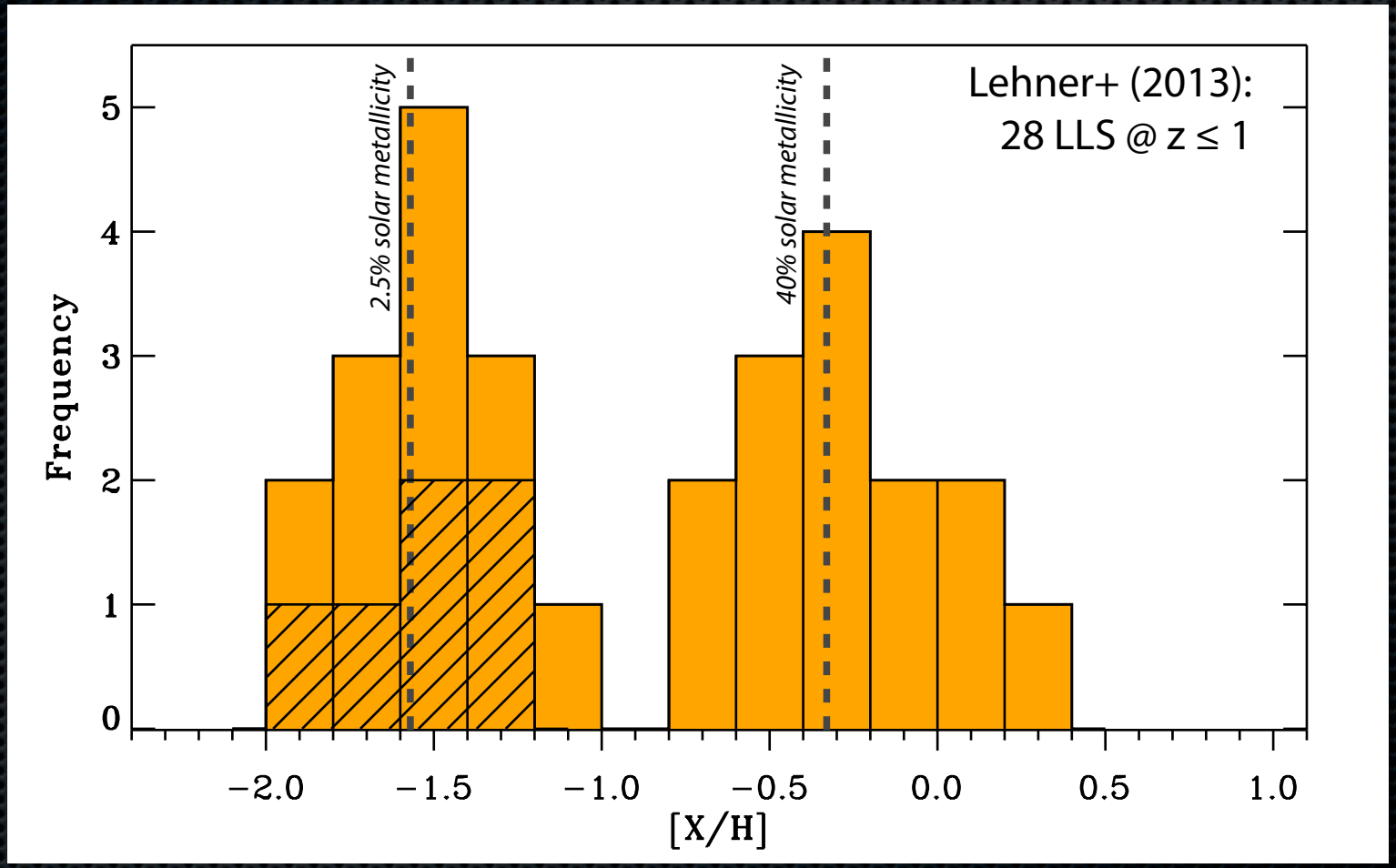
$$N_{HII}^{OVI} = N_{OVI}/(f_{OVI}[O/H])$$

$$f_{OVI} < 0.2$$

Questions

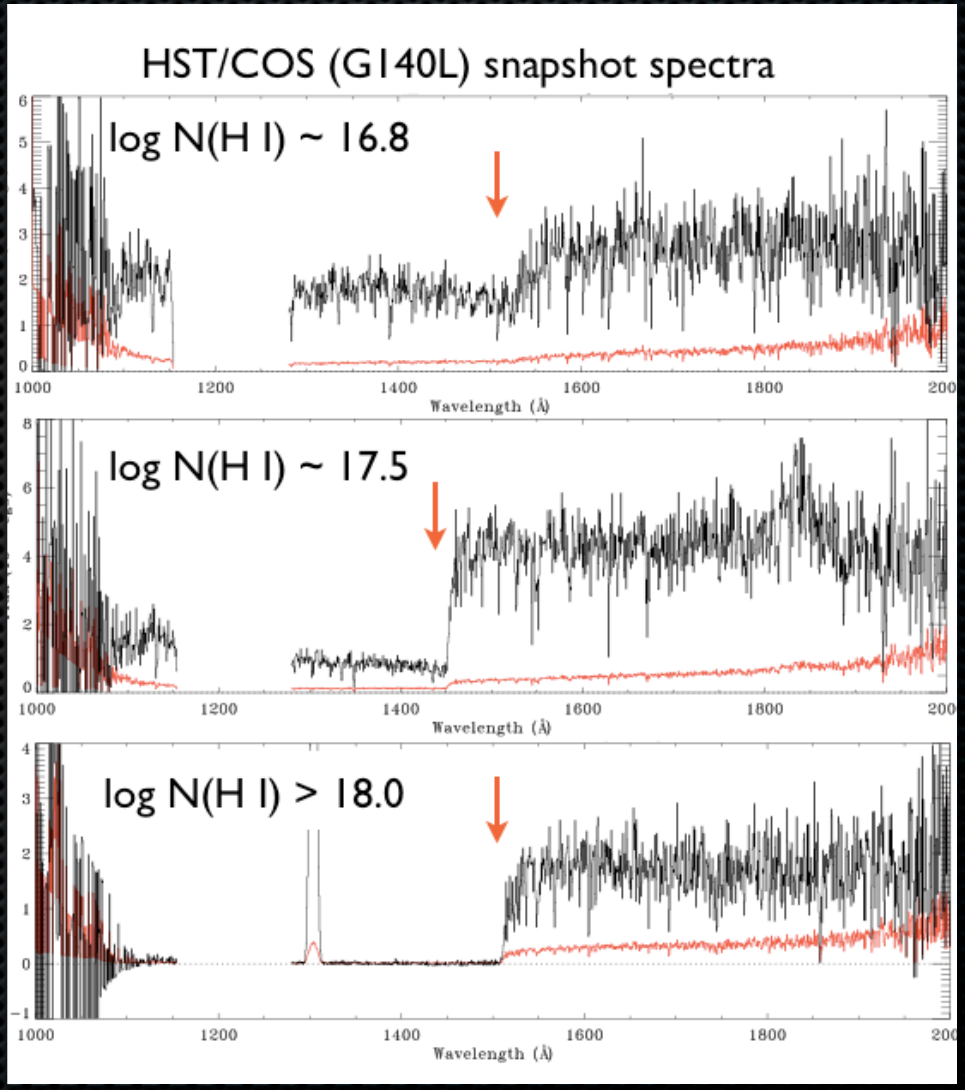
- What is the LLS incidence frequency and column density distribution?
- What is the effect of the LLS on ionizing photons?
- How many metals are locked up in the LLS?
- What is the link between LLS and outflows? Infall?

Metallicity distribution of z ≤ 1.0 Lyman limit systems [16.1 ≤ log N(H I) ≤ 18.5]



LLS at lower z

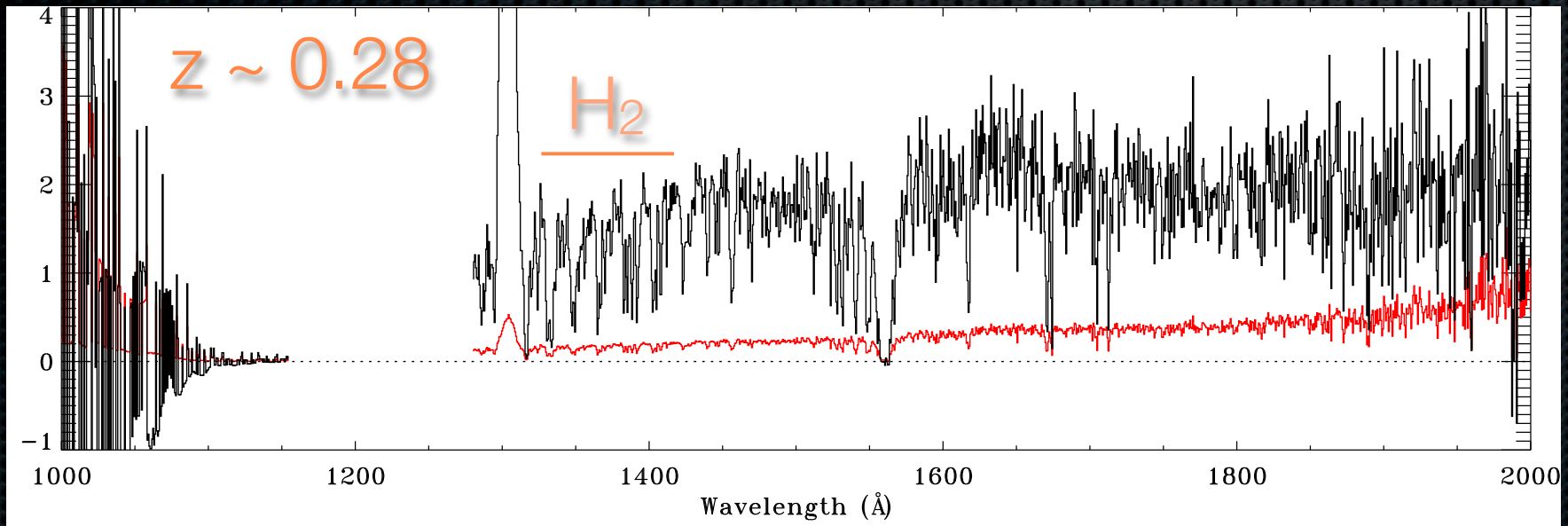
- Go to lower z and sample galaxies lower down the luminosity function
- Easier to interpret metallicities
- These are *HI selected*

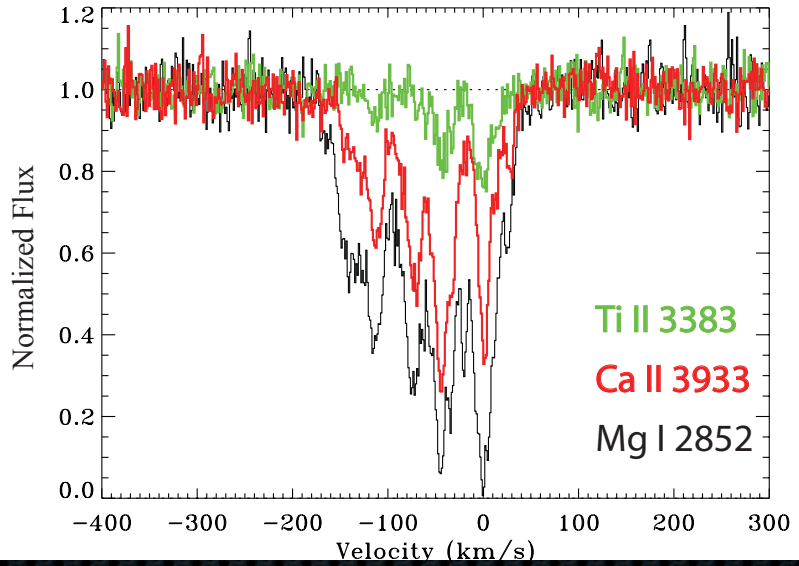


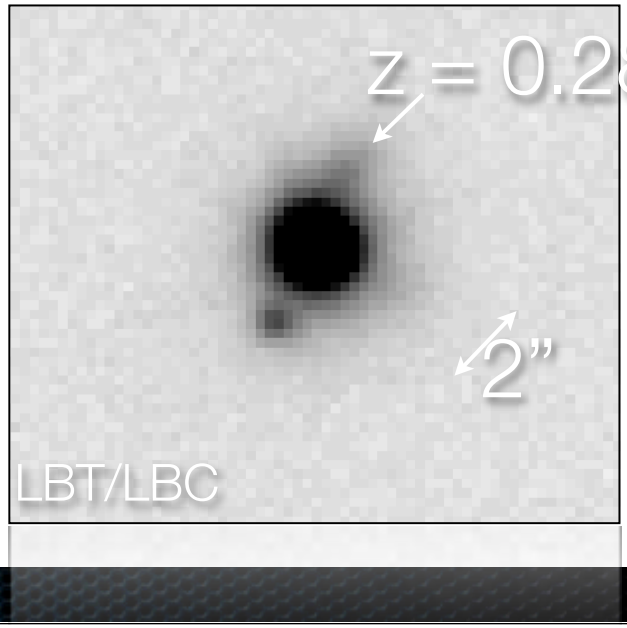
Howk+ 2013, in prep

Lyman limit systems at low redshift

"The Macho Man"



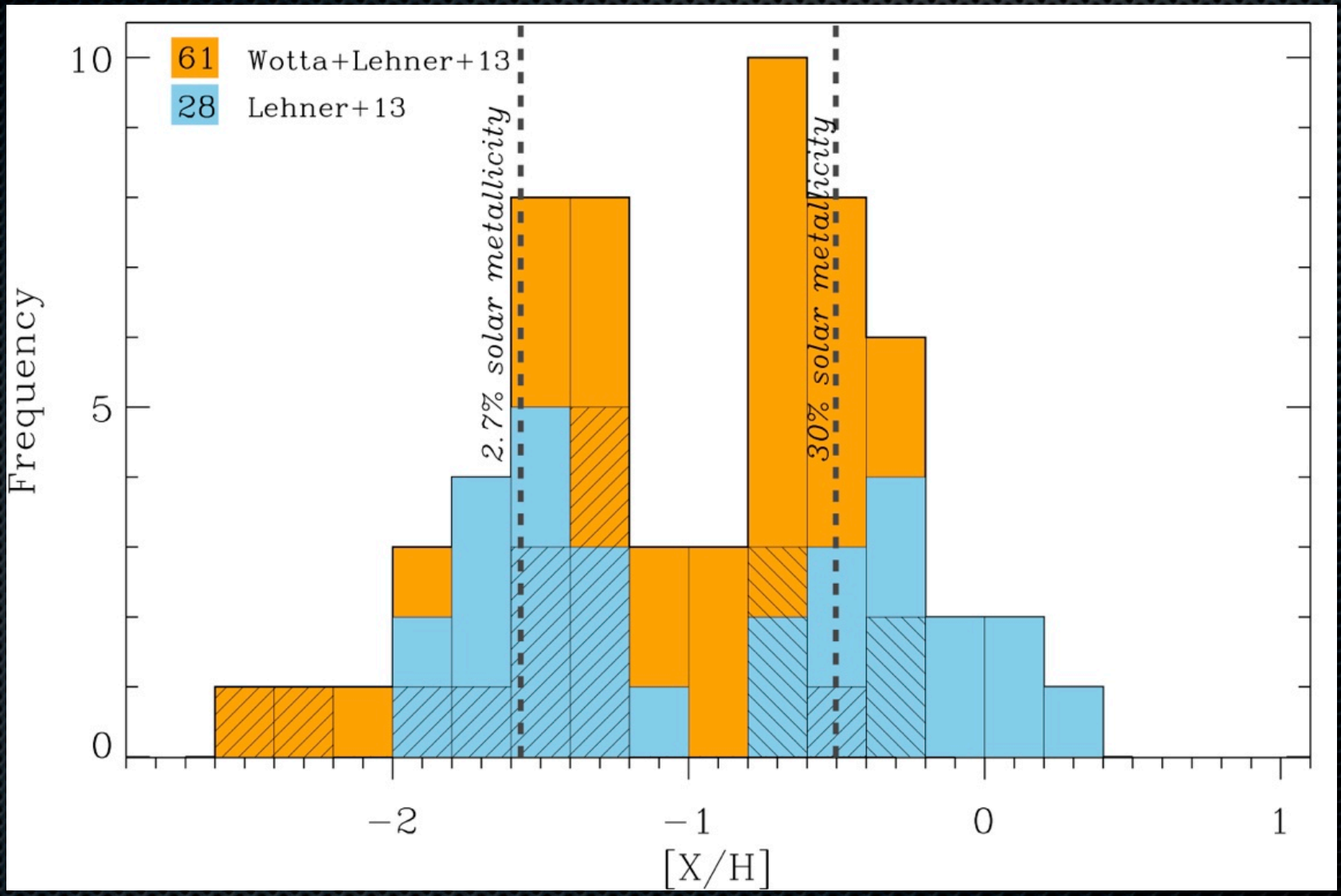




O'Meara+ (in prep.)

Adding to the mix

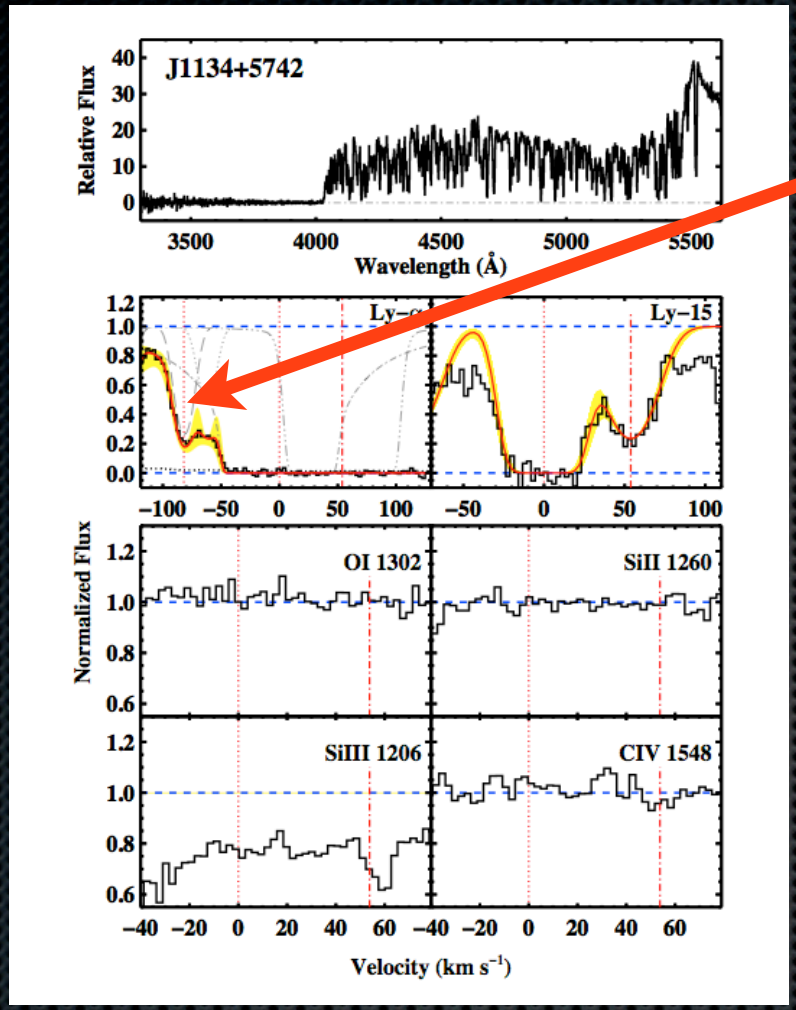
Tripp

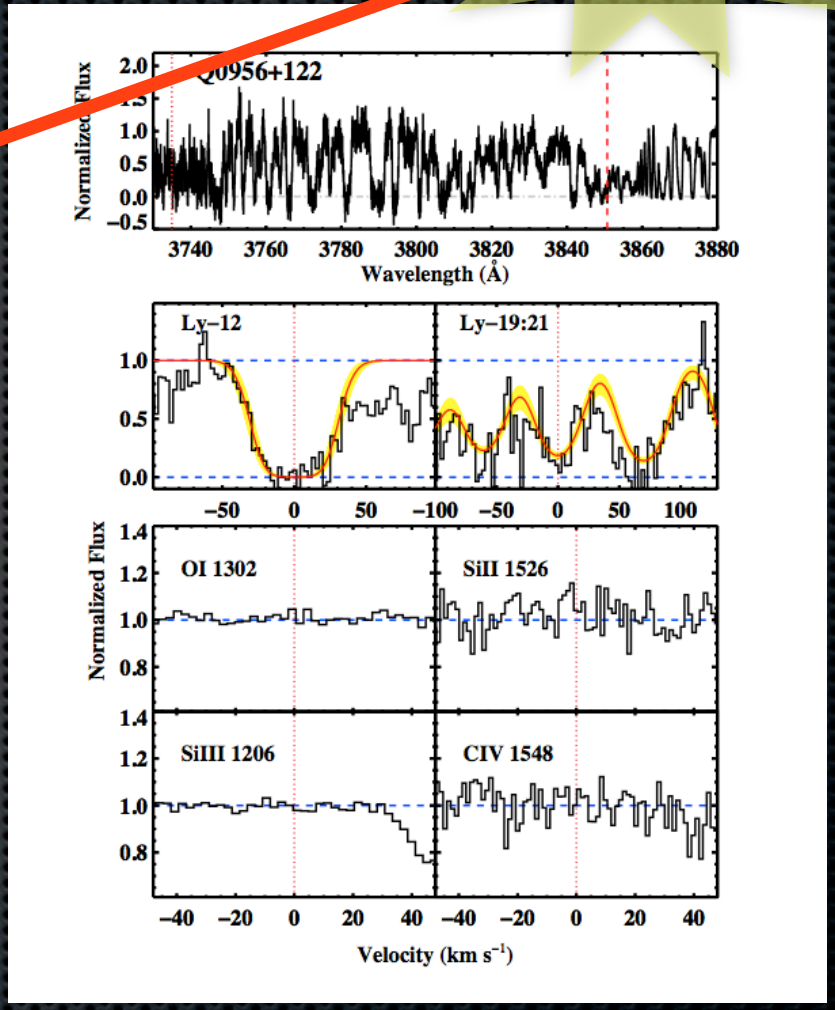


Can We play this game at higher z?

Inflows?

Cooke





[X/H] < -4.2

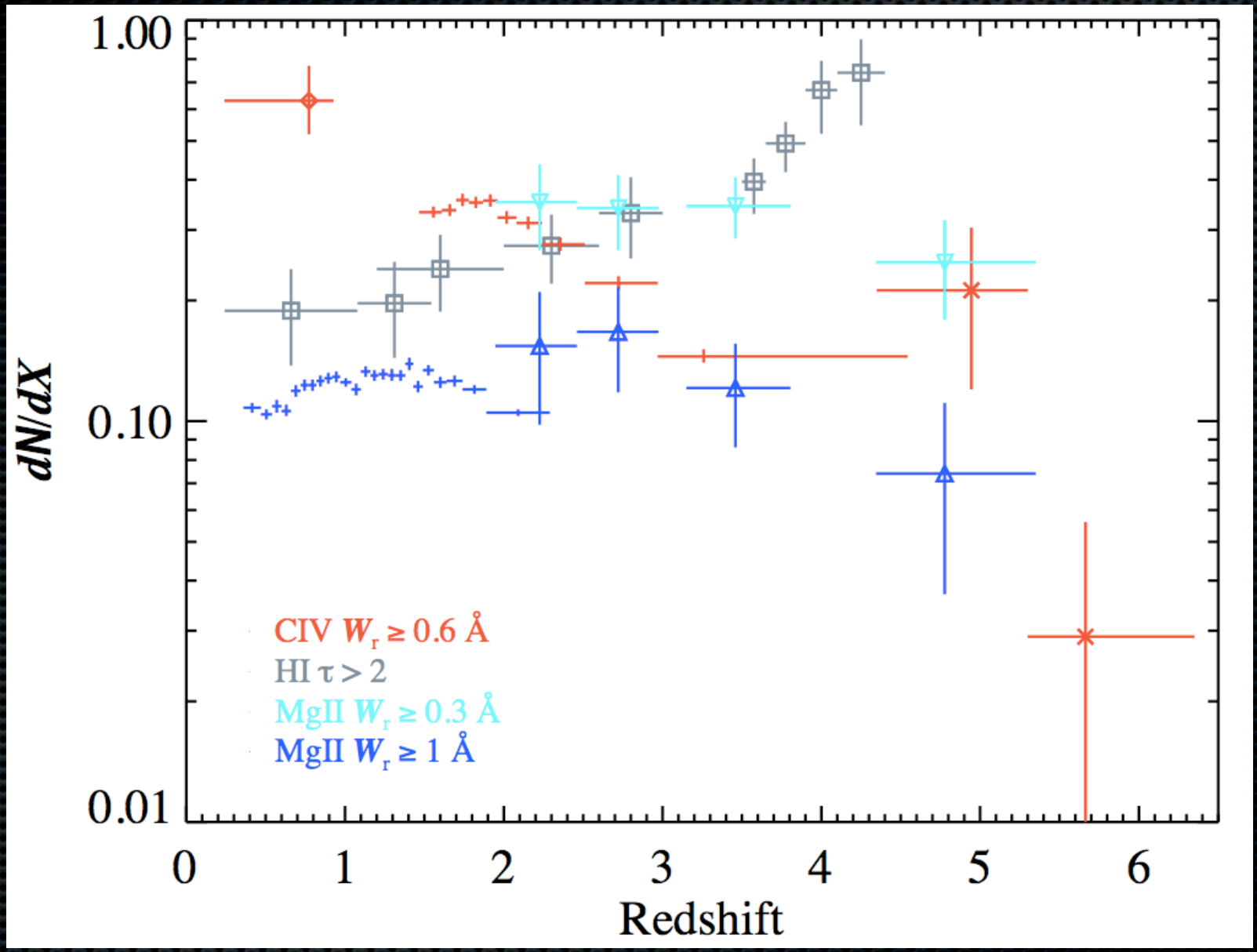
[X/H] < -3.8

The Hunt is On!

Fumagalli, O'Meara, & Prochaska 2011

Outflows/Mixing?

hmmm


1.00
0.10
0.01
dN/dX
0
1
2
3
4
5
6
Redshift
CIV $W_r \geq 0.6$ Å
HI $\tau > 2$
MgII $W_r \geq 0.3$ Å
MgII $W_r \geq 1$ Å

Summary

- What is the LLS incidence frequency and column density distribution?
  - *Getting better here, but high z?*
- What is the effect of the LLS on ionizing photons?
  - *Have determined the MFP over nearly the full range we can. LLS only ~50%!*
- How many metals are locked up in the LLS?
  - *A lot!*
- What is the link between LLS and outflows? Infall?
  - *Sit tight, it'll be a good meeting!*