Global properties of circumgalactic medium at high-redshift: spectroscopic study of strong Lyman-α forest absorbers

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Forging Connections
Michigan State University
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• Stars <> ISM: Continuous cycles of star formation and stellar demise enrich the ISM with metals

• Galaxy evolution governed by: star formation, gas flow interactions of galaxies with their surroundings, mergers.

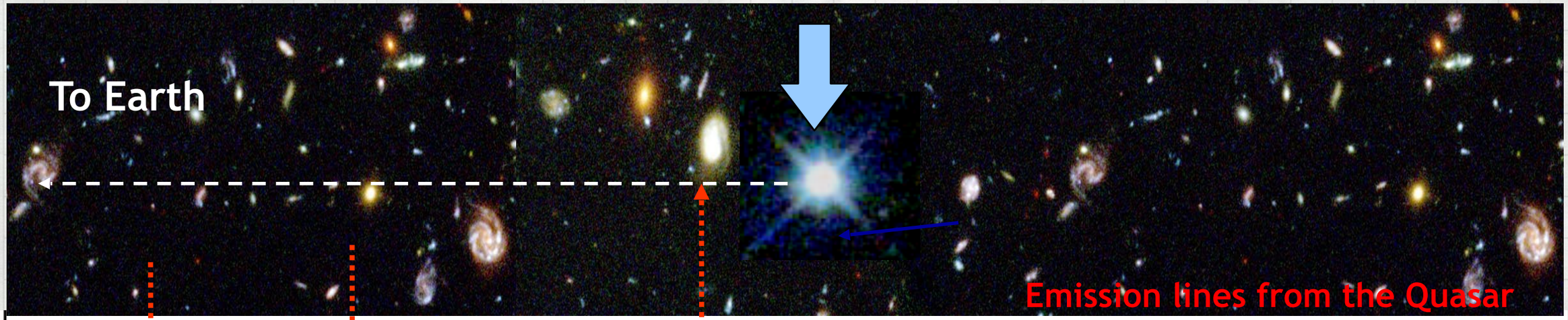
The Circum Galactic Medium (CGM): Inflow and Outflow Caught in the Act

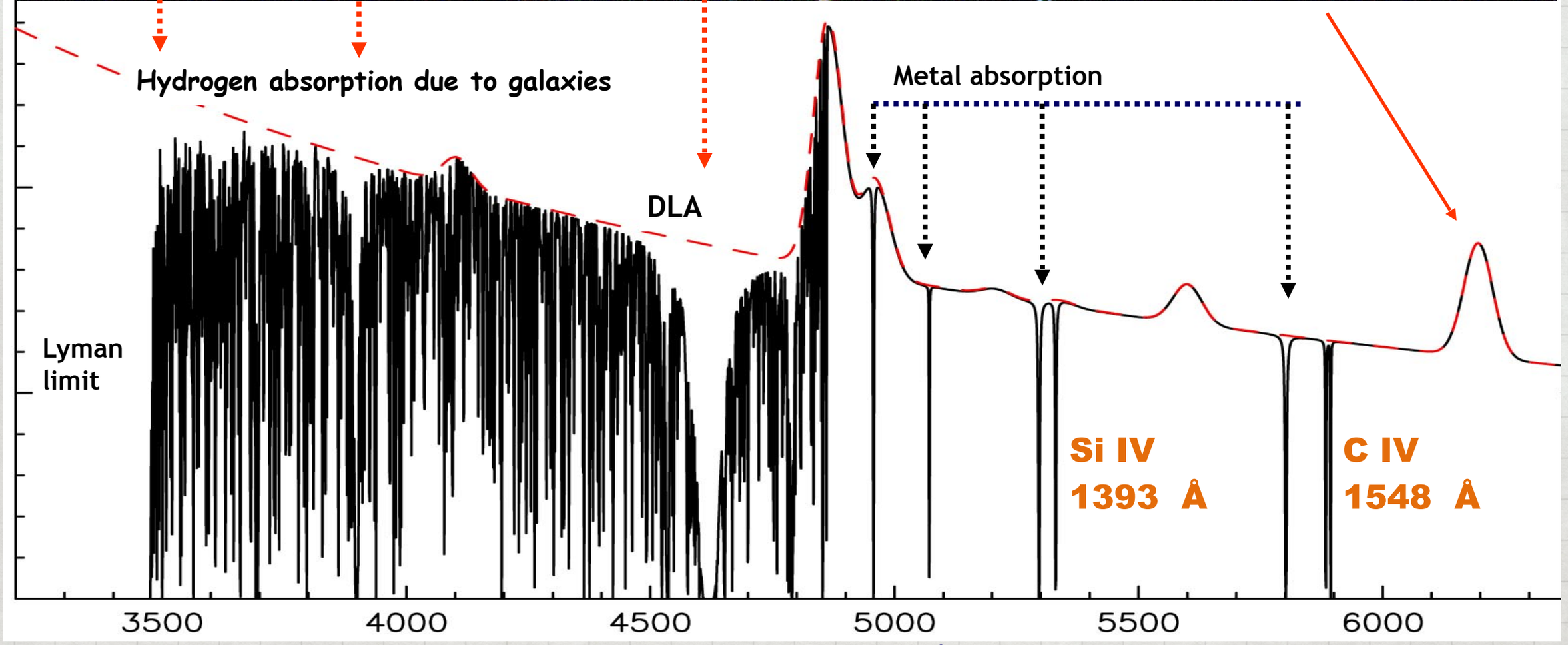
The challenge:

Numbers! Numbers! Numbers!

large samples of CGM data hard to acquire in detail at all epochs

Quasar



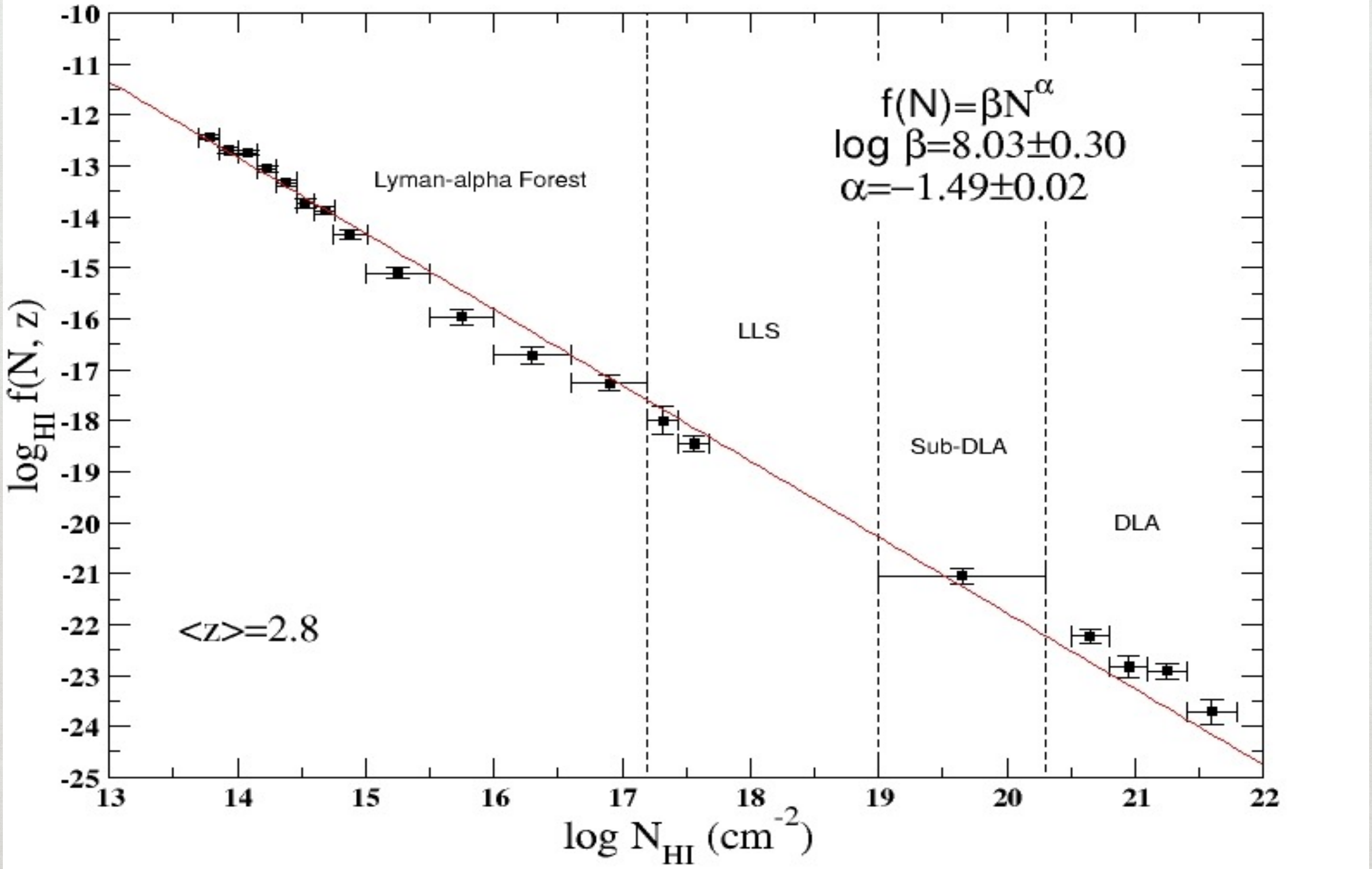


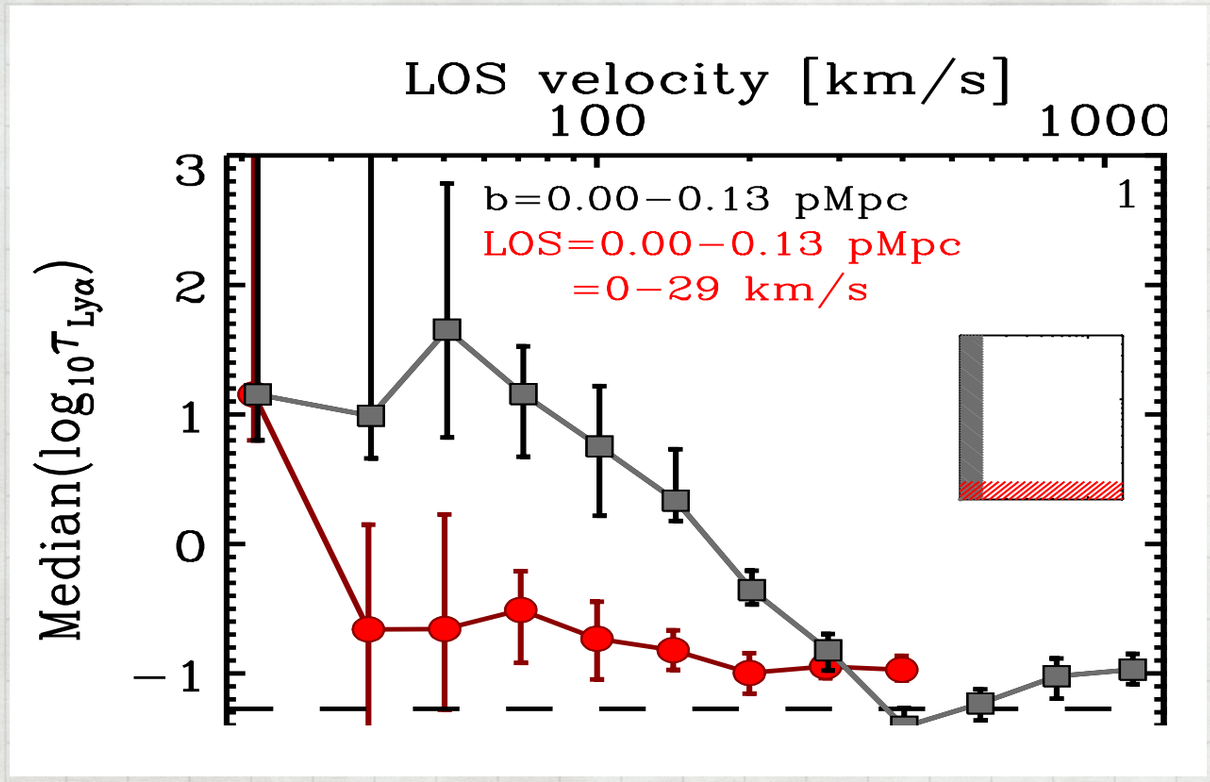
Lyman alpha forest

- Pettini (2004)

Different QSO absorbers:

- Lyman-α forest: $N(HI) < 10^{17.2}$ cm^{-2}.
- Lyman Limit systems: $10^{17.2}$ cm^{-2} < $N(HI) < 10^{19}$ cm^{-2} .
- Sub-damped Ly-α systems (sub-DLAs):
  10^{19} cm^{-2} < $N(HI) < 10^{20.3}$ cm^{-2} .
- Damped Ly-α systems (DLAs): $N(HI) > 10^{20.3}$ cm^{-2} .

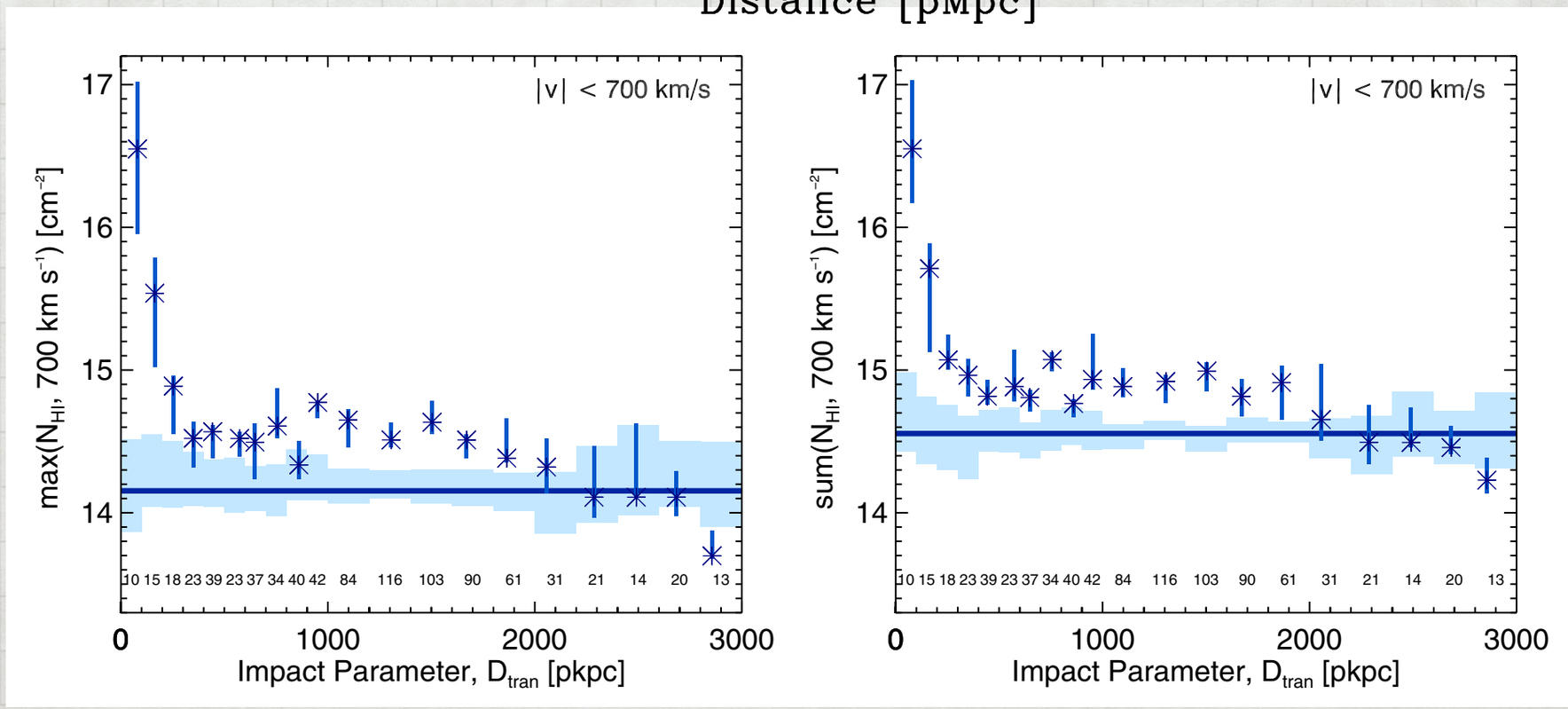

f(N)=βN^α
log β=8.03±0.30
α=−1.49±0.02
Lyman-alpha Forest
LLS
Sub-DLA
DLA
<z>=2.8
log f(N, z)
log N_HI (cm^-2)
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
13
14
15
16
17
18
19
20
21
22



BLENDED HI AS A PROXY FOR CGM

Lyman α absorbers around galaxies are blended on SDSS resolution scales (Rakic et al. 2012, Turner et al 2014) ...

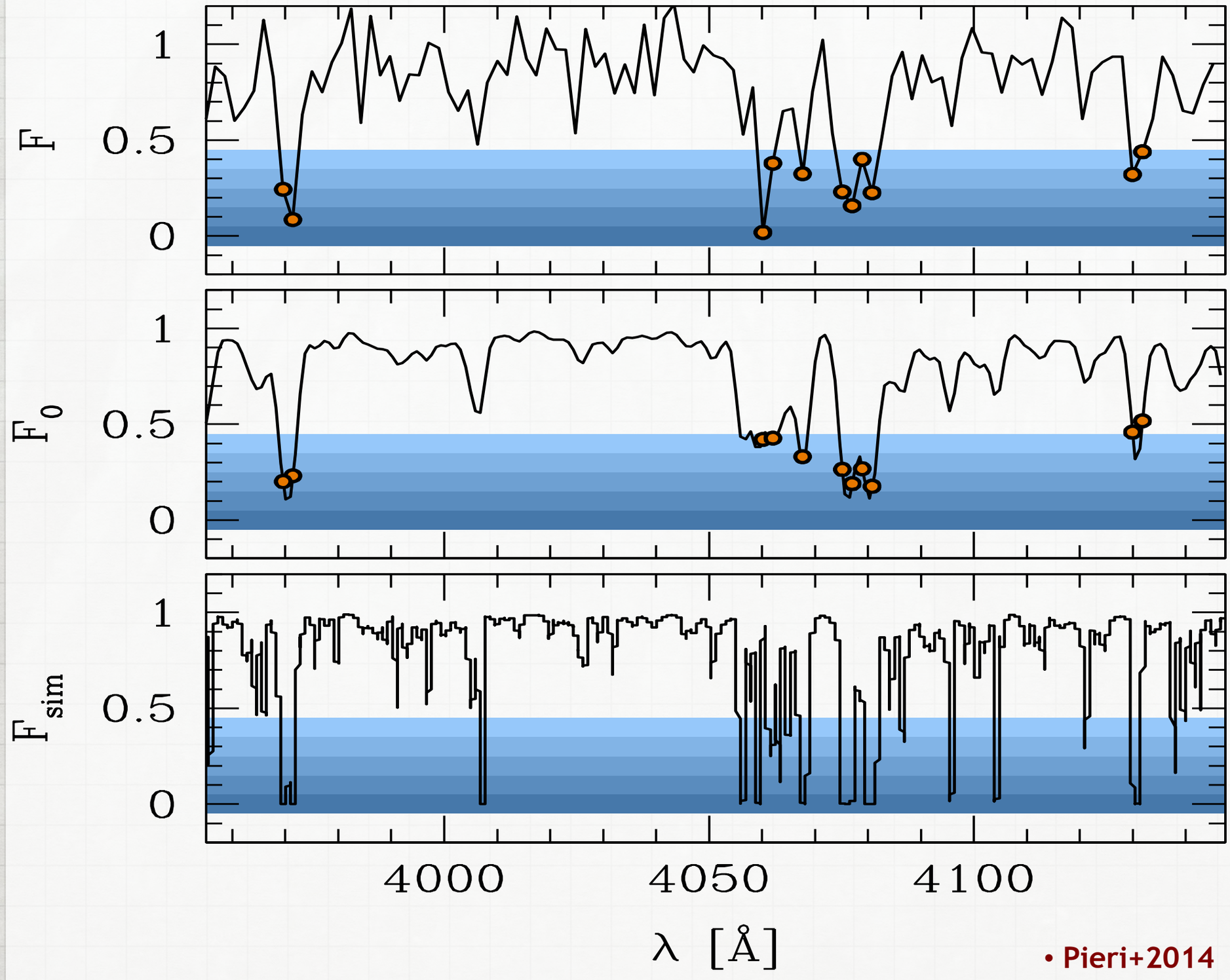
... have $10^{14.5}<N_{HI}<10^{16.5}$ 100-300 kpc scales (Rudie et al. 2012) ...



BOSS with noise

BOSS no noise

Perfect data



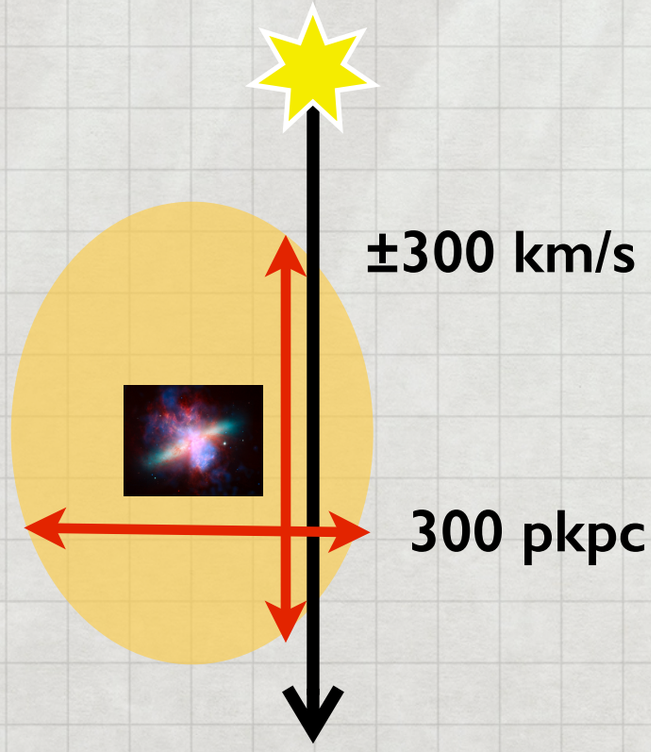
• Pieri+2014

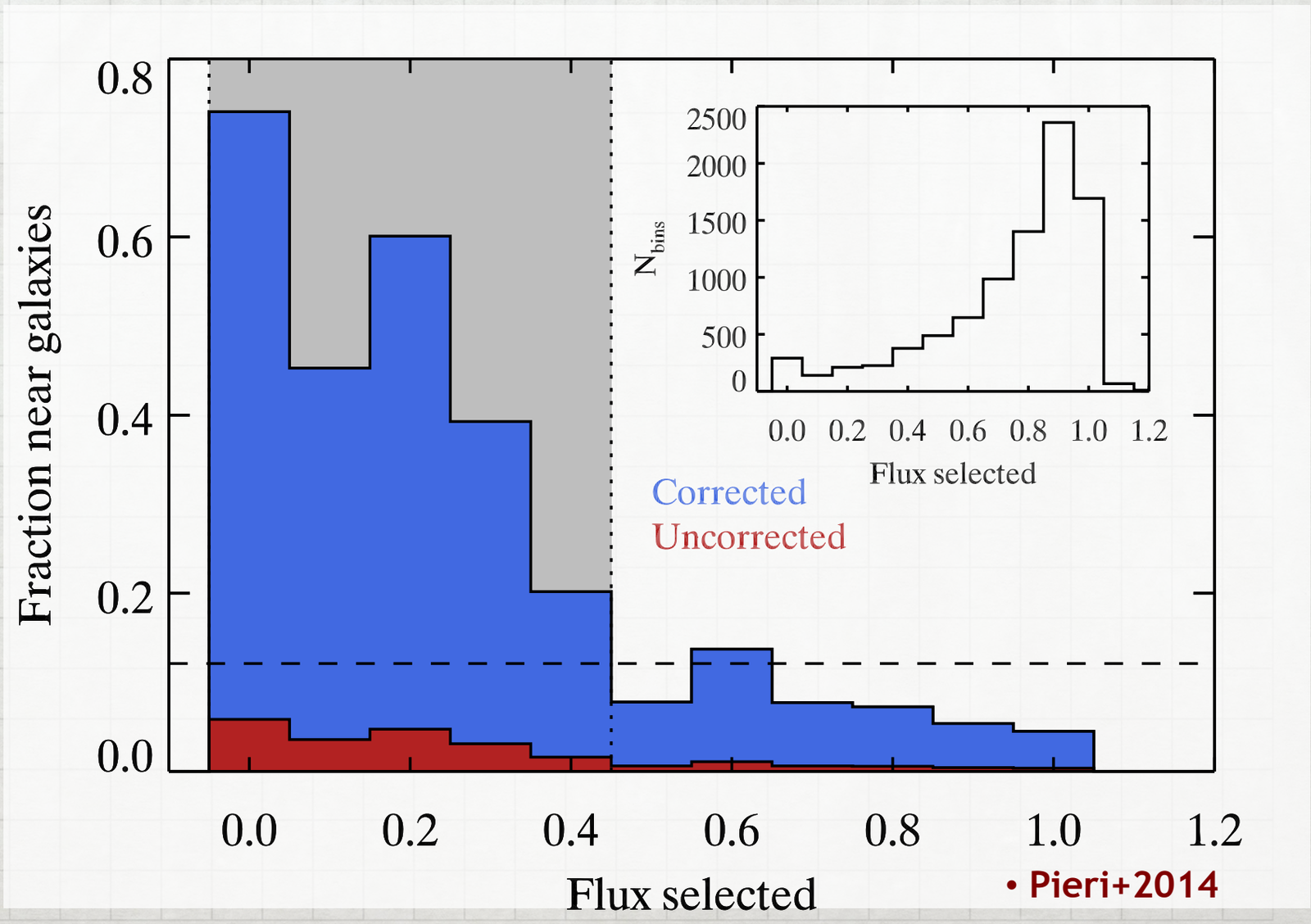
GALAXIES IDENTIFIED IN ABSORPTION

- Lyman break galaxies near bright quasar sightlines: VLT LBGs (Crighton et al 2011), subset of KBSS (Rudie et al 2012)
- Compare by matching BOSS resolution and binning

Rudie et al. (2012) working definition

"near galaxies" = CGM

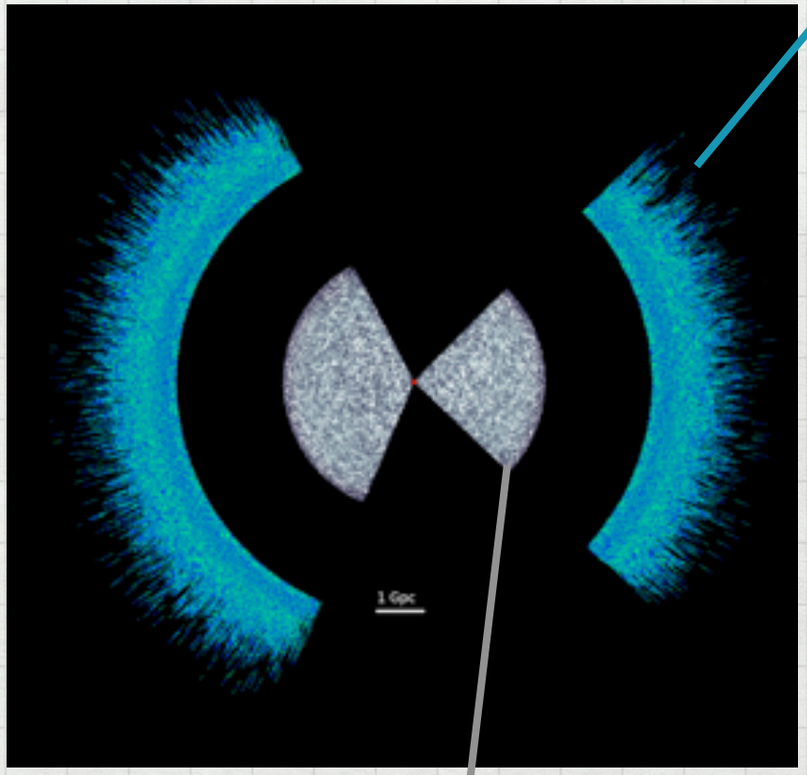


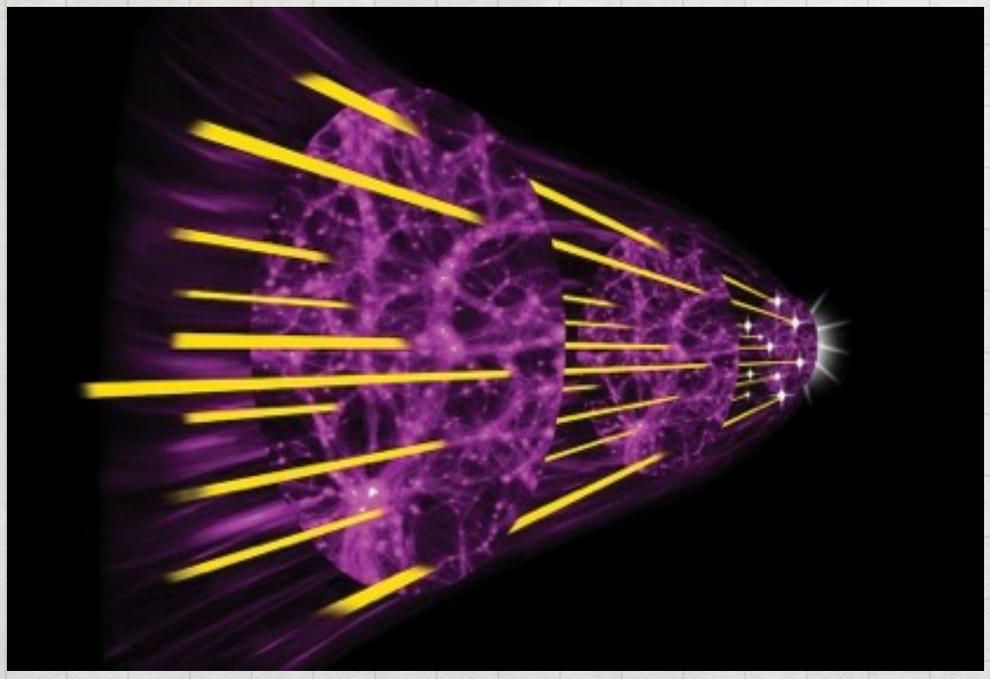


• Pieri+2014

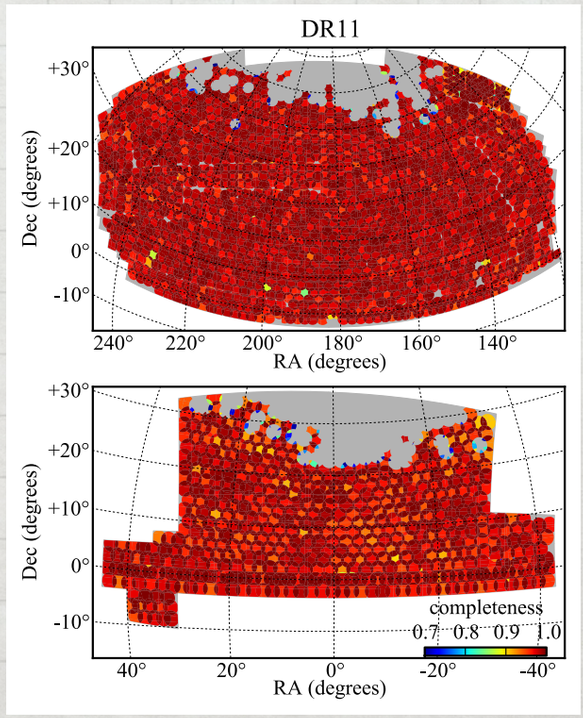
Baryon Oscillation Spectroscopic Survey

- 1 of 4 in SDSS-III 2009-2014
- 10k deg^2
- Goal:1.6M galaxies and >150k forest quasars
- Resolution R = 2000





DR12 with 158k QSOs



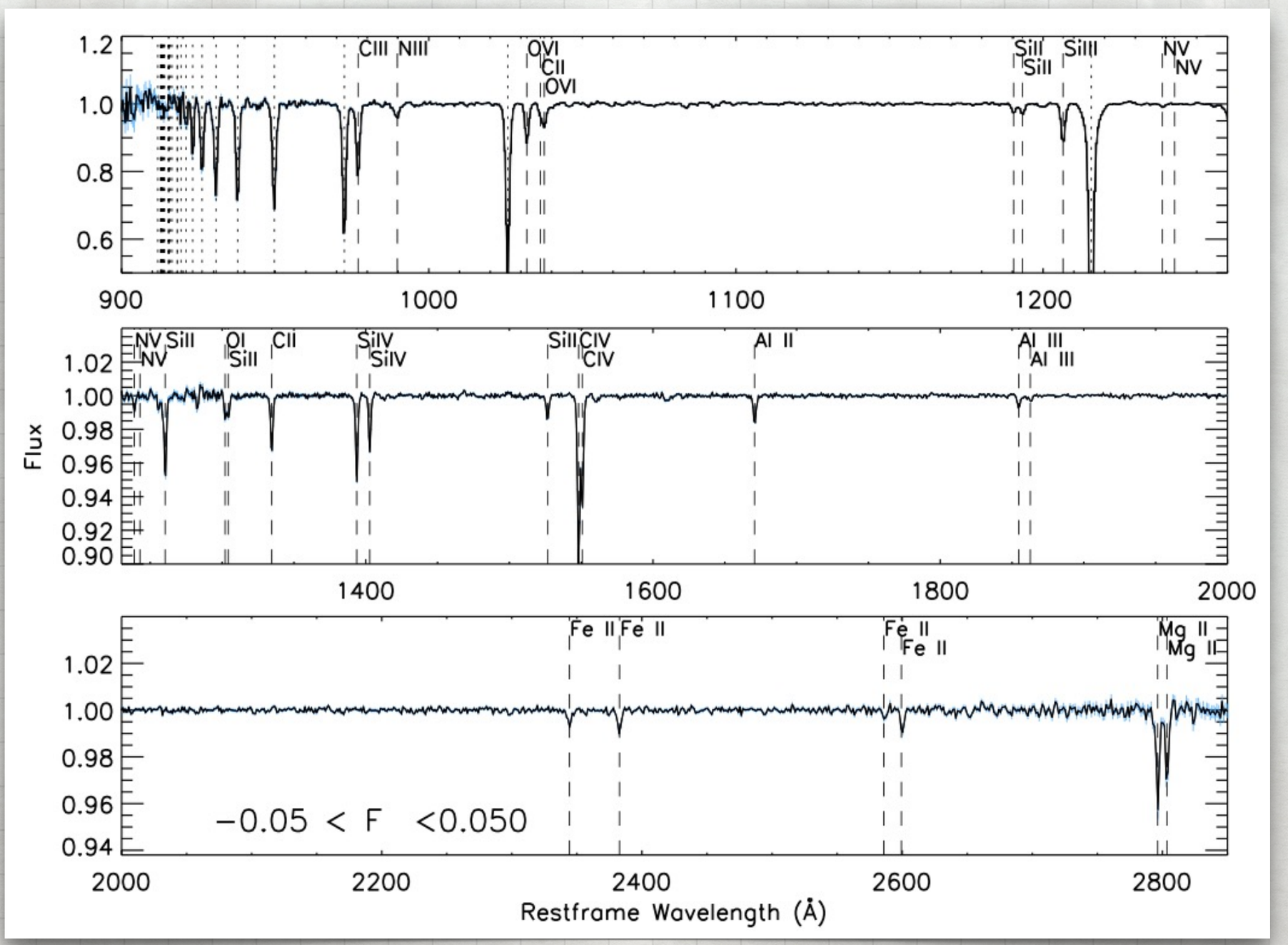
Composite Spectrum of Lyman α Forest Absorbers using BOSS Quasars

Lyα absorbers @ 2.4<z<3.1

Complete DR12 Sample

Multiple lines/ elements/ions - breaking degeneracies:

- **physical conditions of gas**
- **abundance patterns**
- **UV background shape, intensity**



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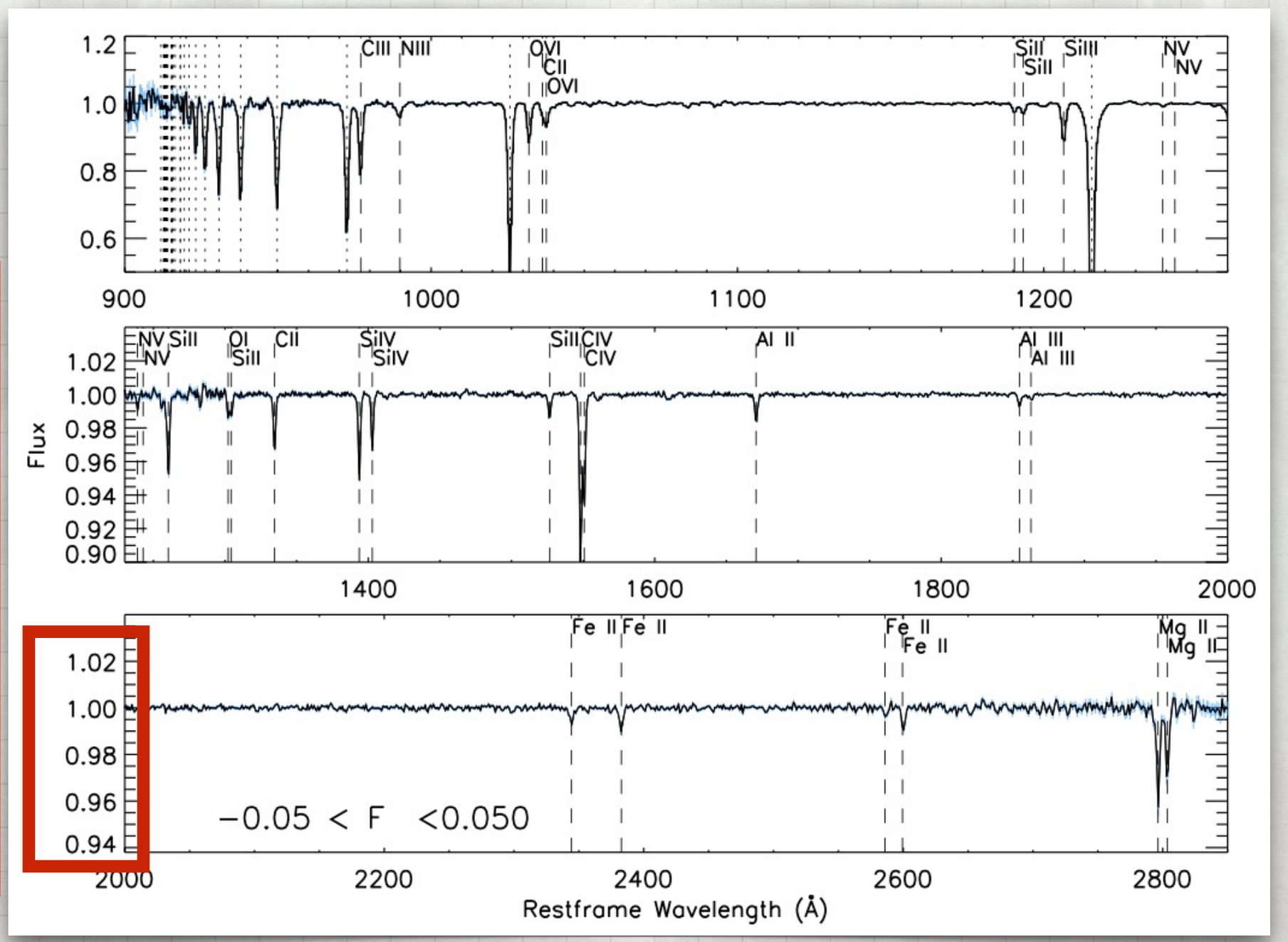
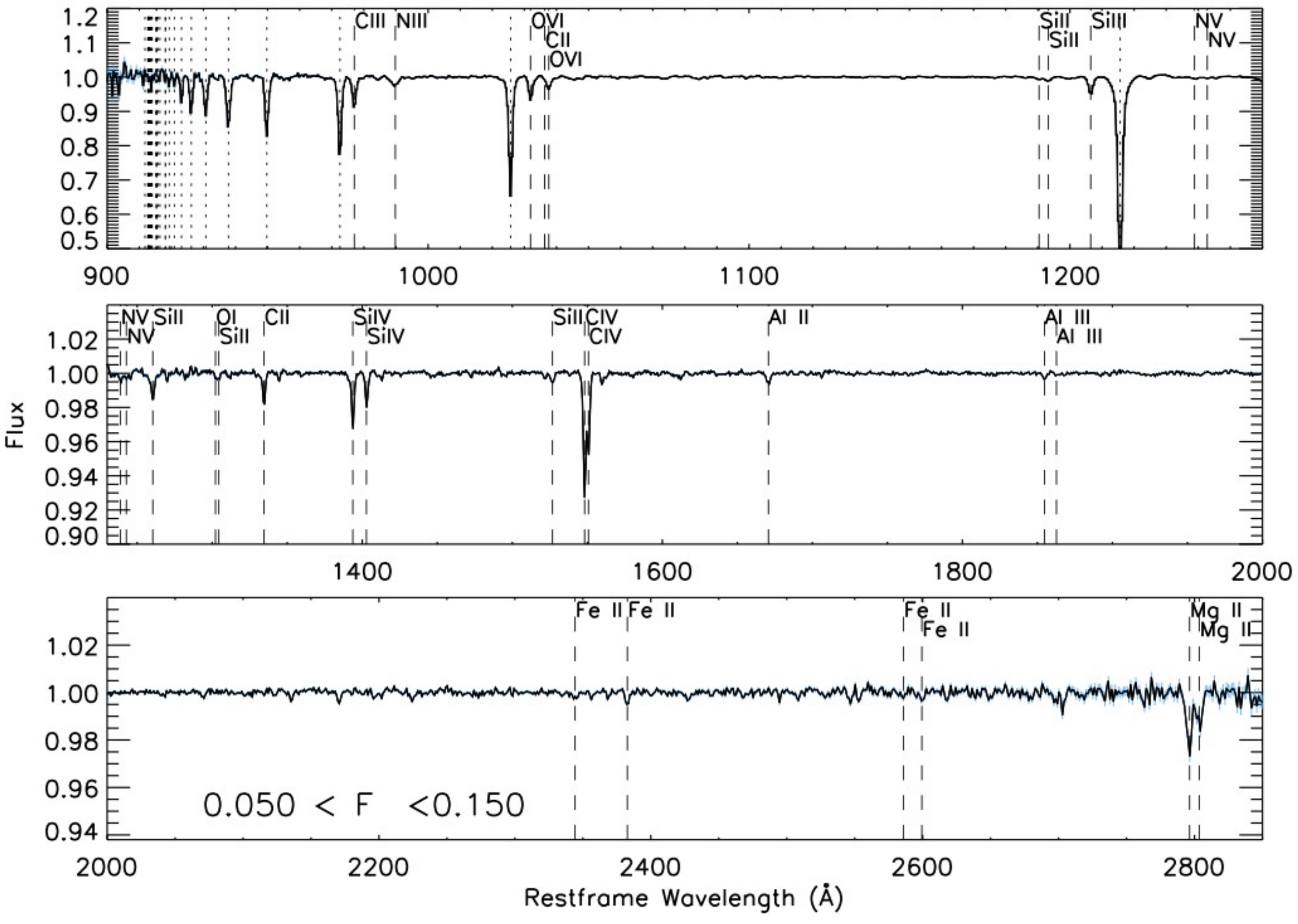
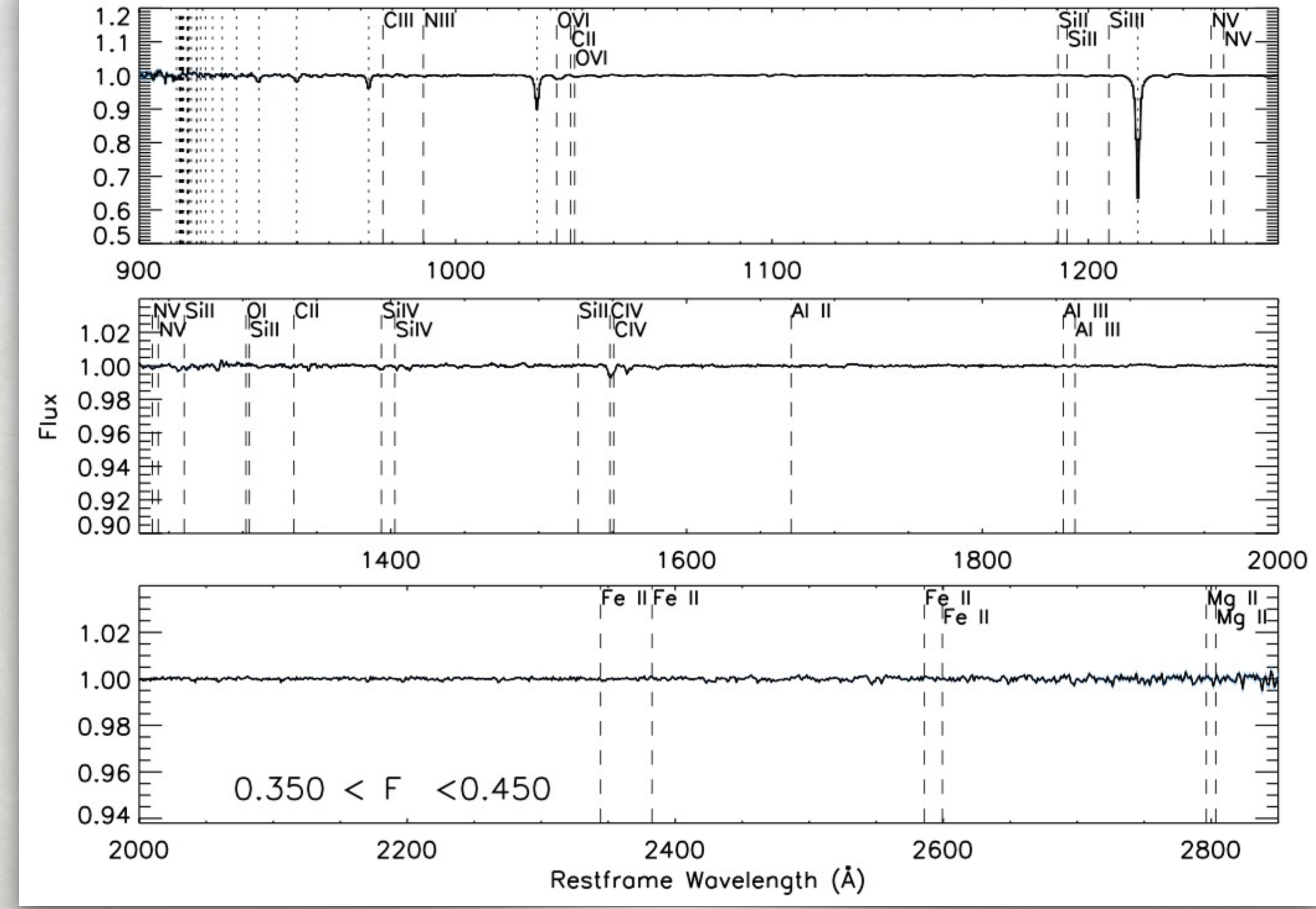
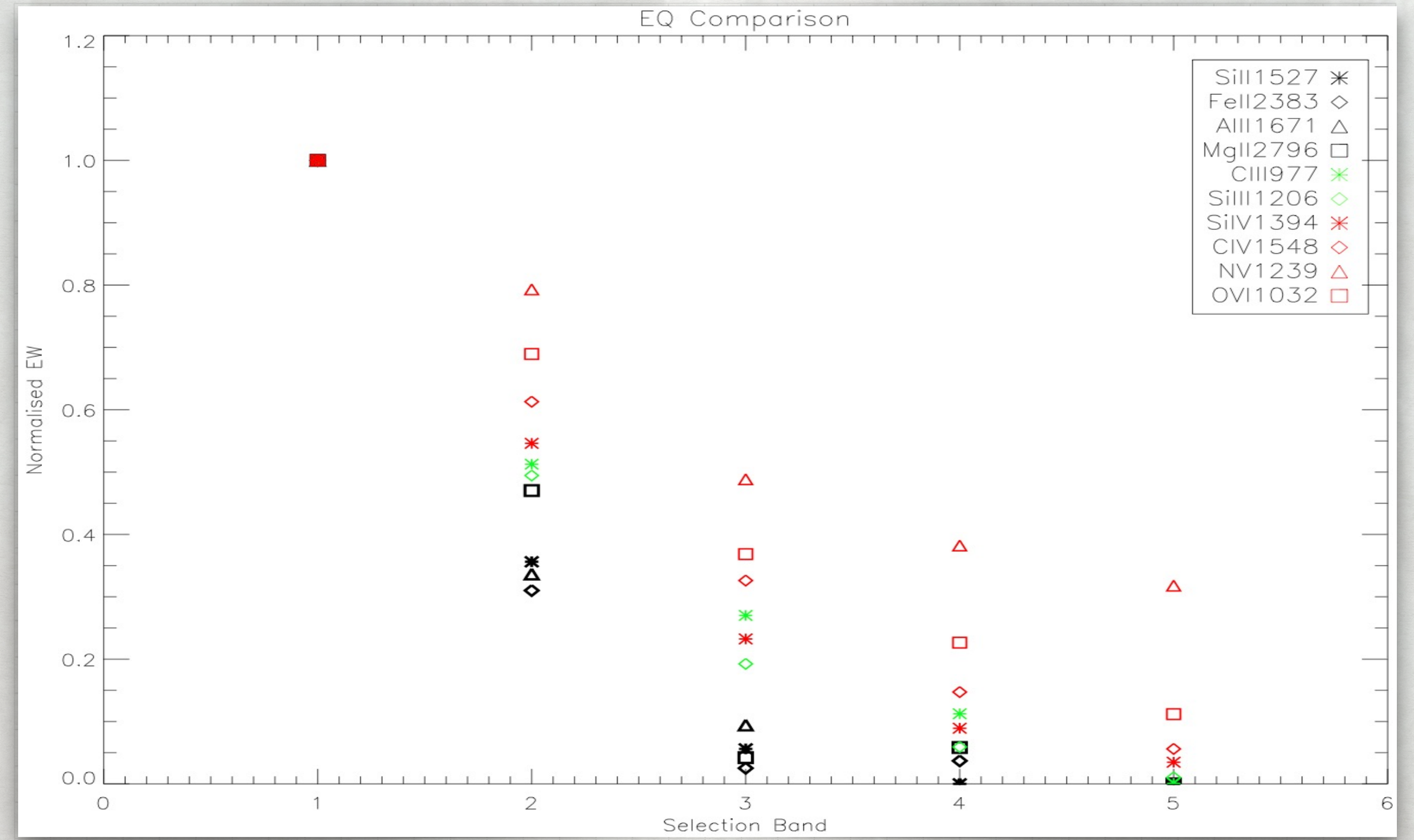


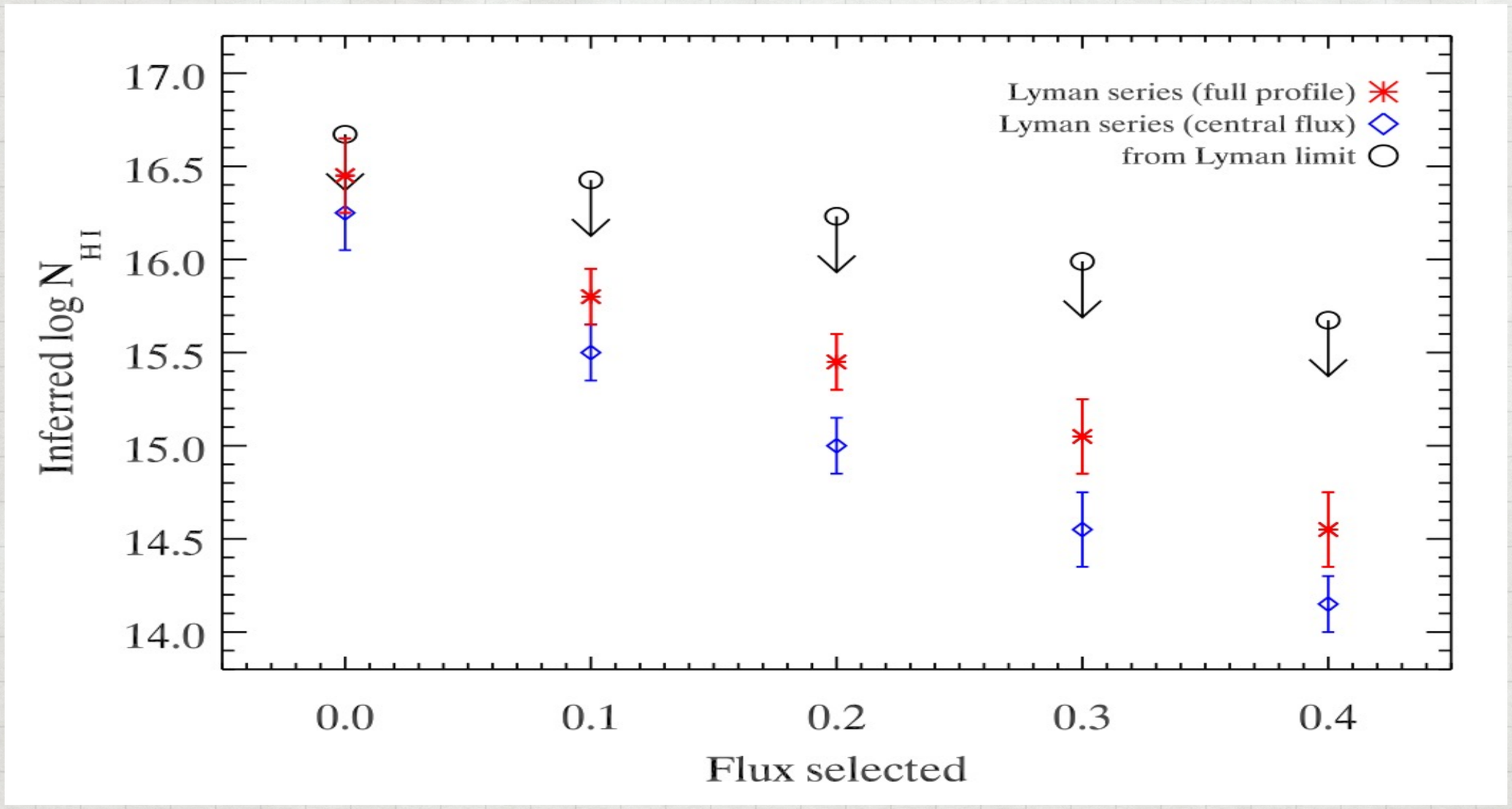

CIII
NIII
OVI
CII
OVI
SiII
SiII
SiIII
NV
NV
NV
SiII
OI
SiII
CII
SiIV
SiIV
SiII
CIV
CIV
Al II
Al III
Al III
Fe II
Fe II
Fe II
Fe II
Mg II
Mg II
0.050 < F <0.150
Flux
Restframe Wavelength (Å)


CIII NIII
OVI
CII
OVI
SiII
SiII
SiIII
NV
NV
NV SiII
OI
SiII
CII
SiIV
SiIV
SiII CIV
CIV
Al II
Al III
Al III
Fe II Fe II
Fe II
Fe II
Mg II
Mg II
0.350 < F <0.450
Flux
Restframe Wavelength (Å)


EQ Comparison
SiII1527
FeII2383
AlII1671
MgII2796
CIII977
SiIII1206
SiIV1394
CIV1548
NV1239
OVI1032
Normalised EW
Selection Band
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6

HI Column Density: Optically Thin Gas

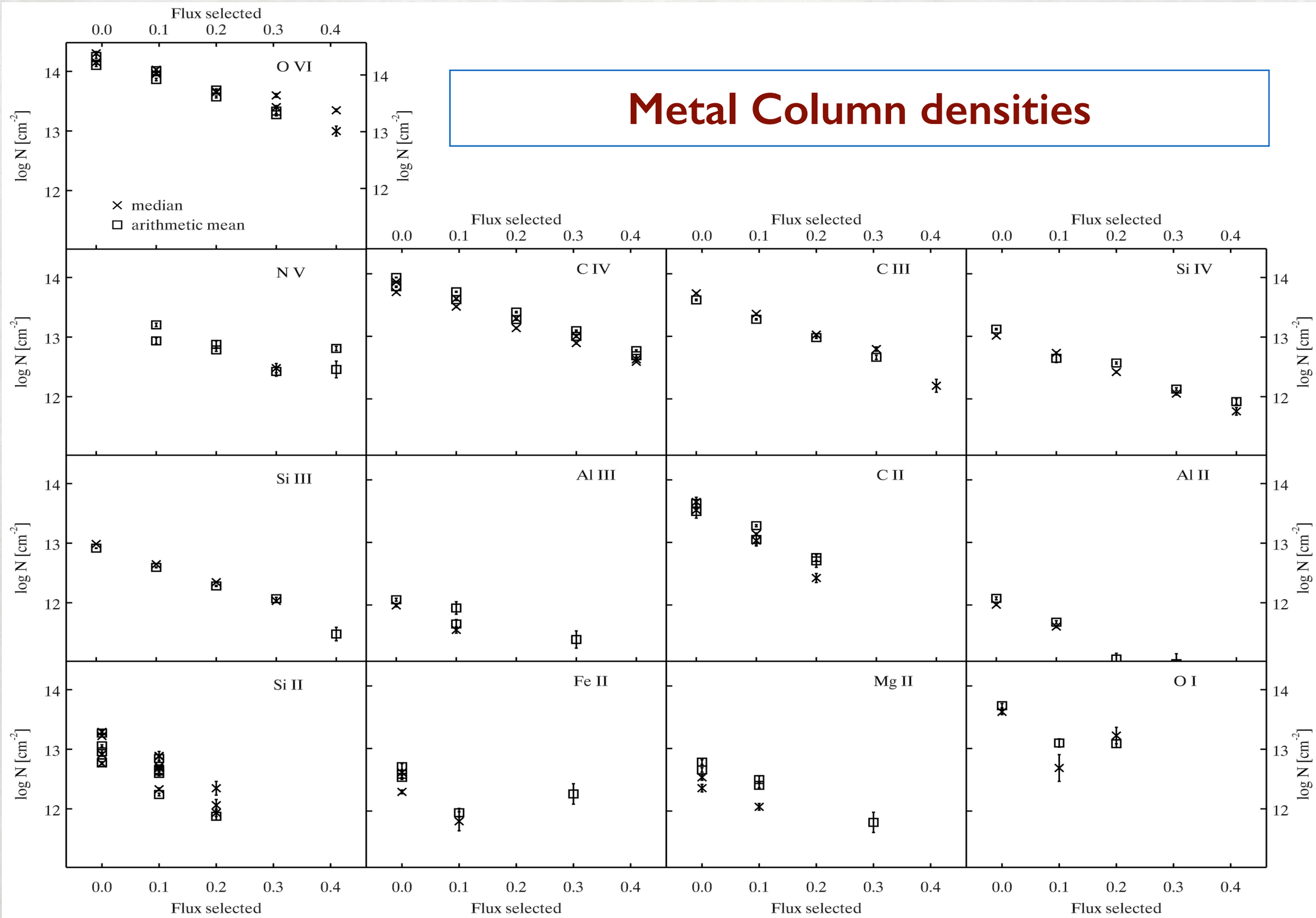
7 Lyman series lines and opacity to ionizing photons (Lyman limit)



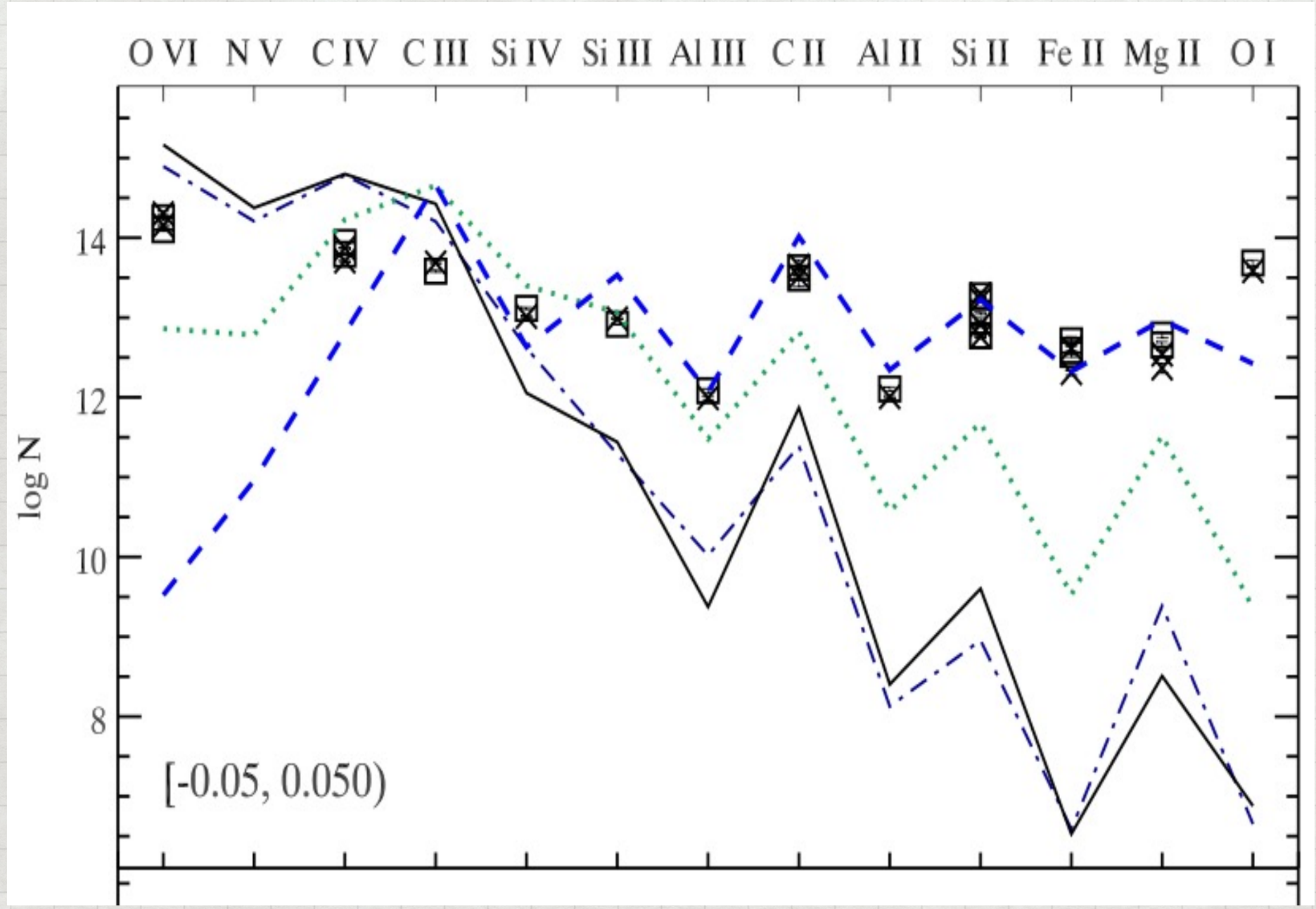
Impact of a subset of optically thick selected systems?

Even with 'perfect' selection of all LLS+DLA, they wouldn't dominate any metal line in the composite spectrum

Metal Column densities



Compared with Simple Models

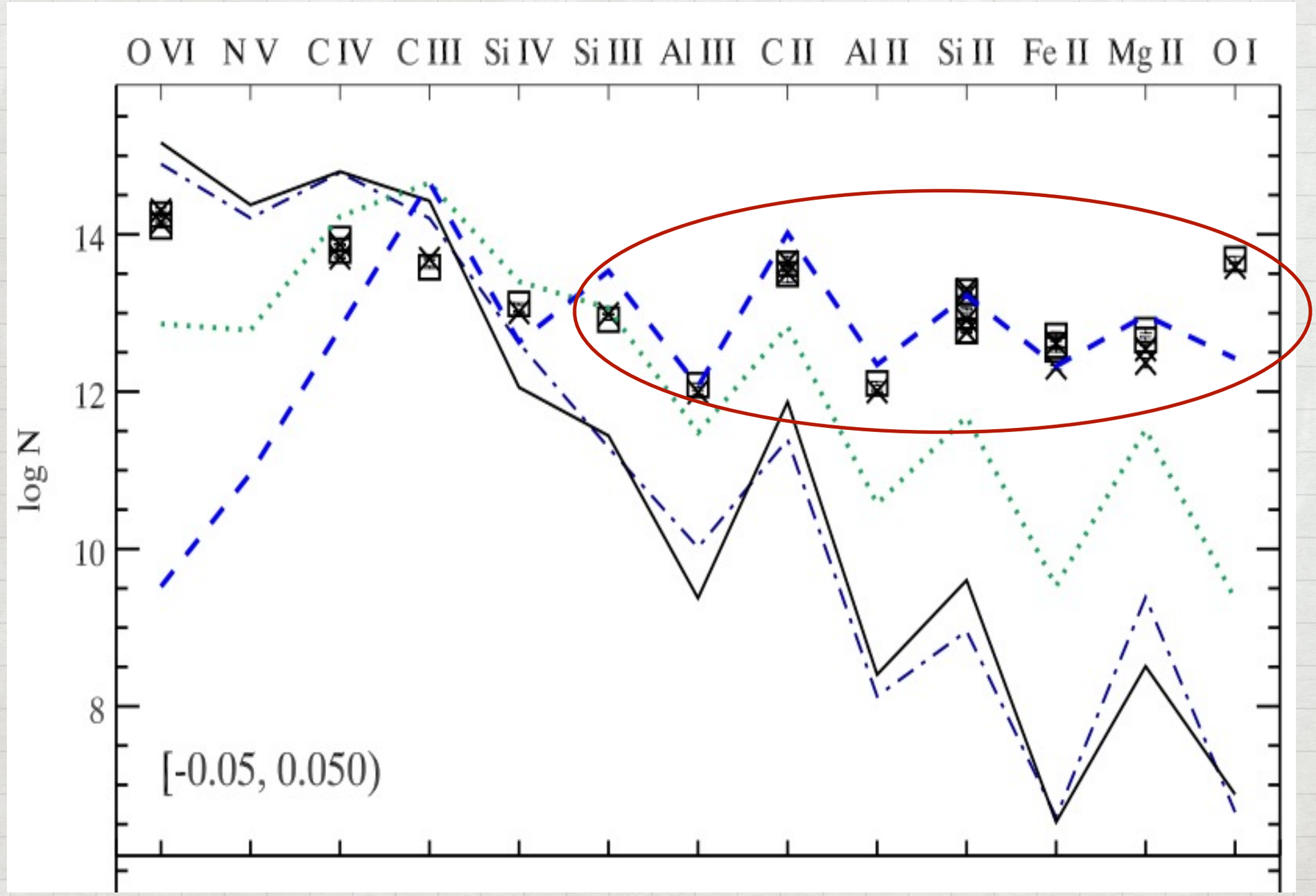


Column density ⟶

Lower ionization potential ⟶

Each model constrained by measured N(H I), solar abundance, UV background @ z ~ 2.7

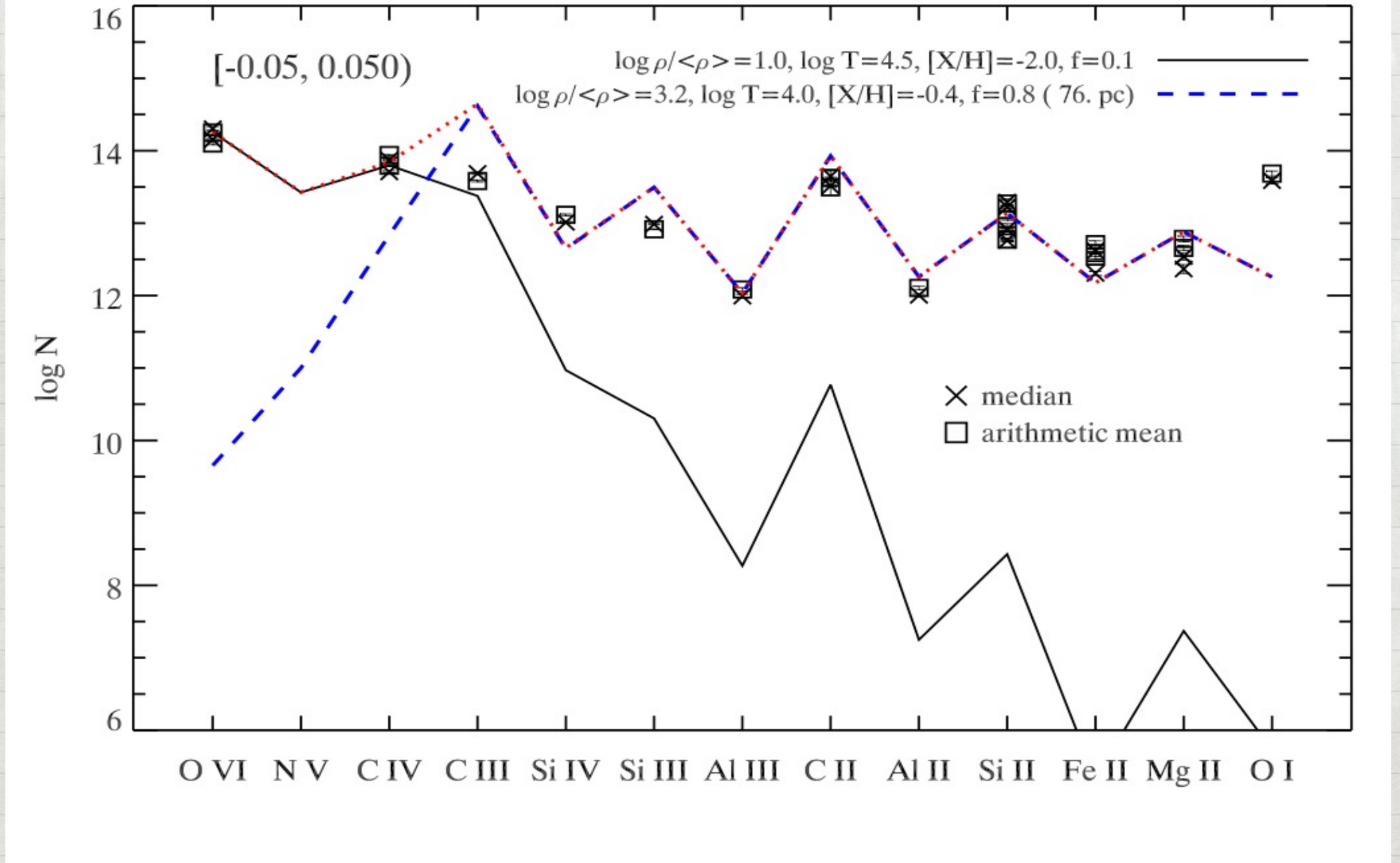
Compared with Simple Models



[X/H] ~ solar, ~90 pc scale clumping

Each model constrained by measured N(H I), solar abundance, UV background @ z ~ 2.7

Compared with a Simple Multi-phase Model



Column density ⟶

Lower ionization potential ⟶

Summary

- Strong Lyman α forest lines arising in CGM regions show clustering

- Clustered strong Lyman α forest lines are blended in BOSS spectra: appropriate selection of flux decrement in BOSS spectra picks out CGM tracers

- Stacking CGM tracers retrieve the metal signal associated with the CGM regions: power of large numbers

- The picture emerging is of a clumpy, multi-phase CGM: dense, metal-rich clumps ~100pc and more ionised, slightly overdense gas.

Stay tuned …

- Further exploration of the parameter space for multi-phase models, including:
  - The effect of abundance pattern: dust, α enhancement?
  - Exploring the effect of background ionising radiation: proximity to galaxies

- Exploring line strength scatter: variance between various elements/ ion species to get a better picture of the multi-phase nature of the gas

- Future large spectroscopic surveys such as DESI and WEAVE promise an order of magnitude increase in the spectra numbers and/or higher resolution and sir > Cosmic Web Mapping

Thanks!