Is the high-redshift inter-galactic medium metal enriched?

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Collaborators

DEEP SPECTRUM PROJECT

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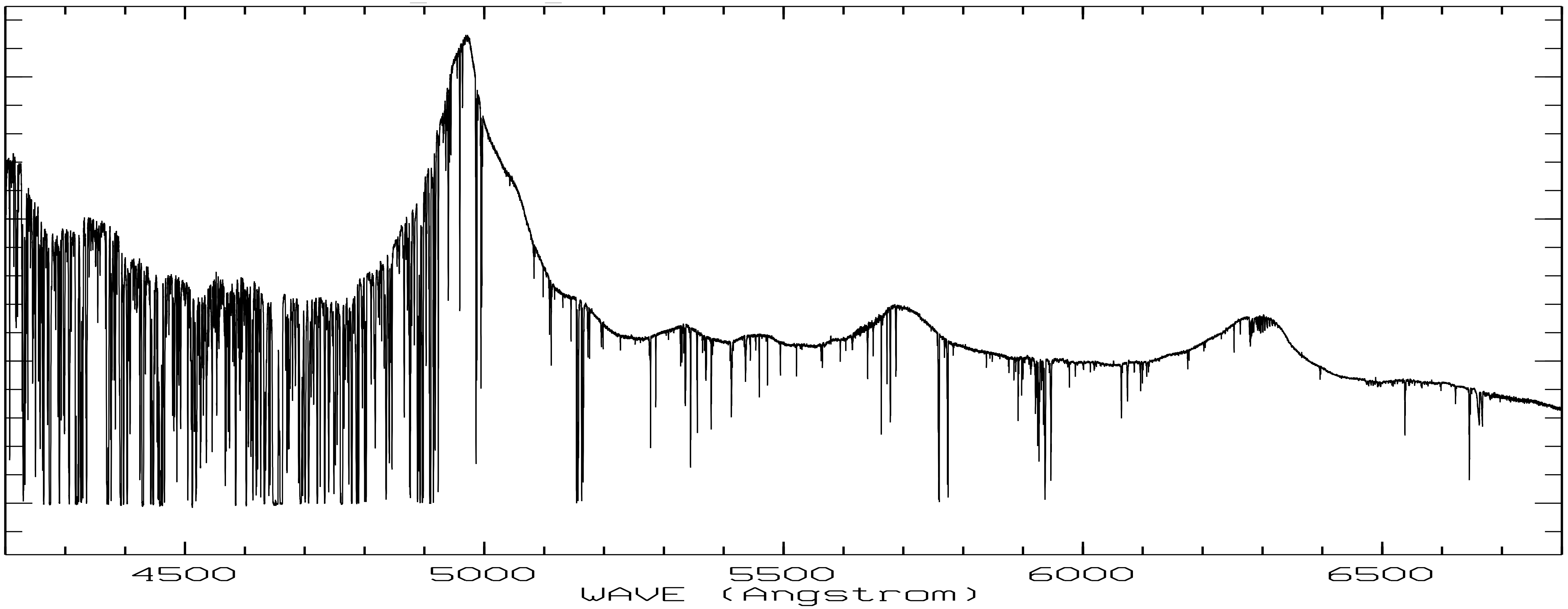
PhD students: Chiara Mongardi, Serena Perrotta, Emanuele Pomante



Why studying the IGM?

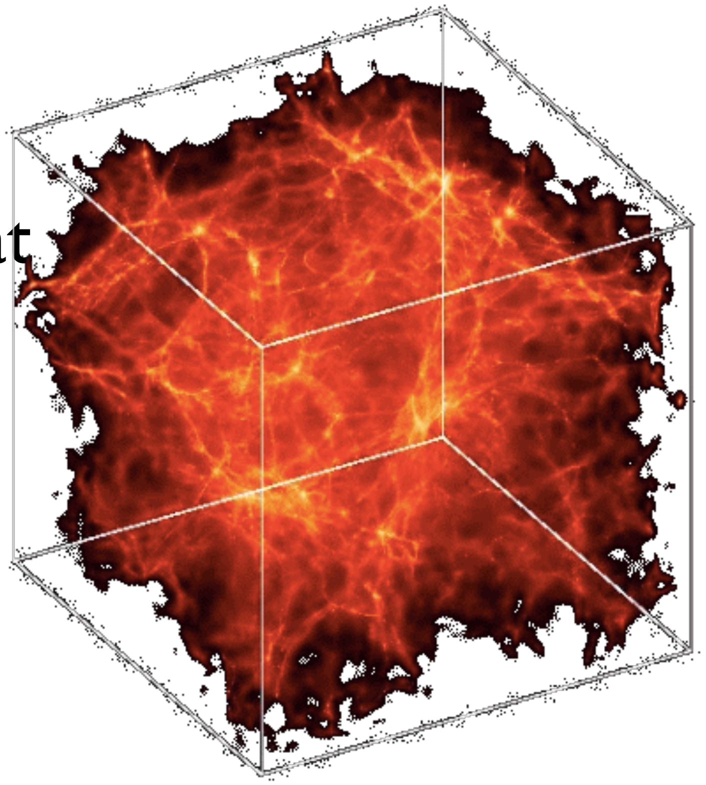
- ✧ At $z > 1.5$ about 90 % of the baryons are diffused in the IGM, the physical processes at work are simpler than for galaxies;
- ✧ The IGM acts as a reservoir of fresh gas for galaxy and stellar formation and as a sink for the products of galaxy/stellar evolution (radiation, chemical elements)

Big questions

❖When and how was the Universe reionized (HI and HeII) ?

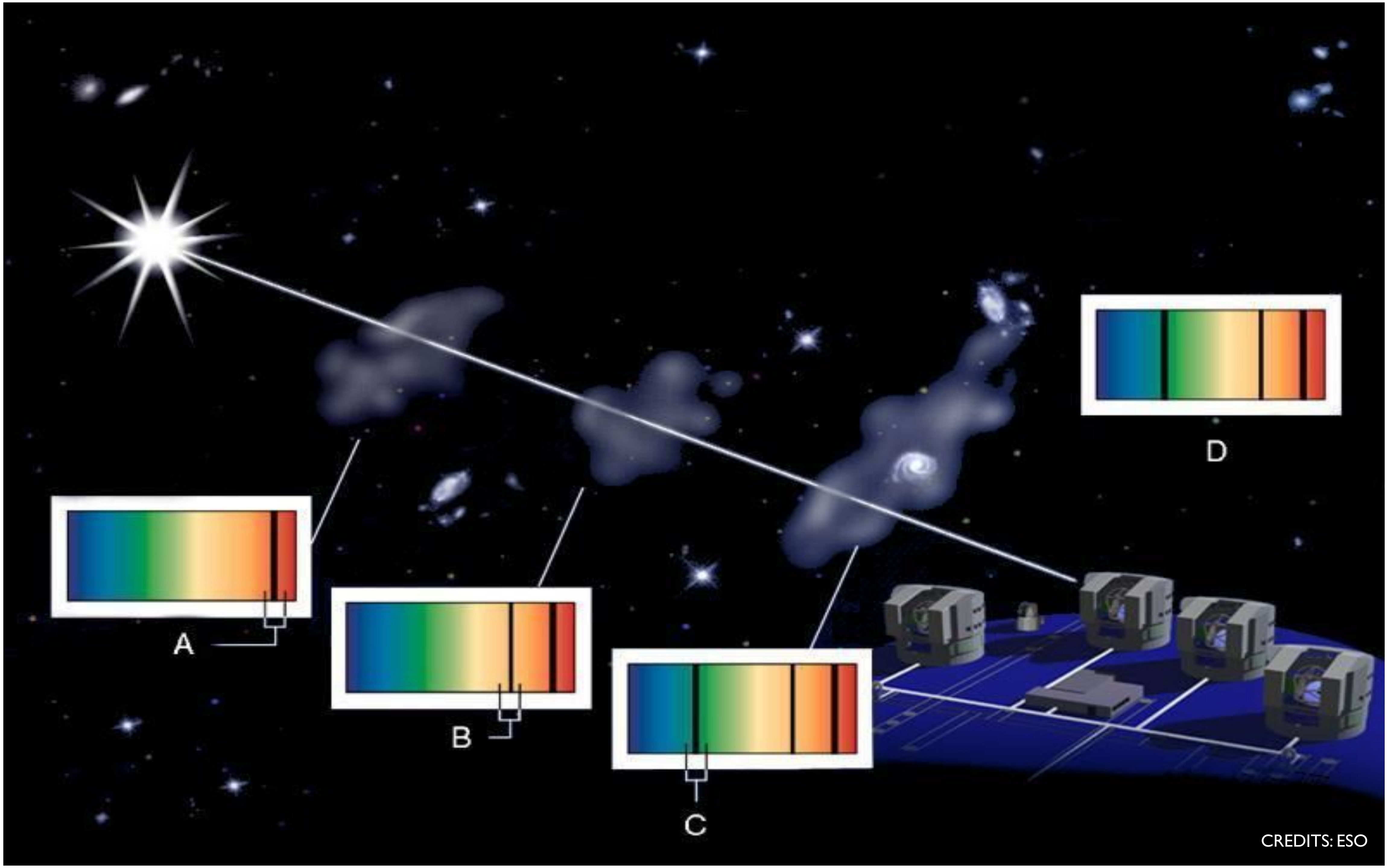
❖Which sources contribute to the UV ionizing background at the different redshifts?

❖What is the nature of feedback processes in galaxies and in AGNs?



Investigation technique

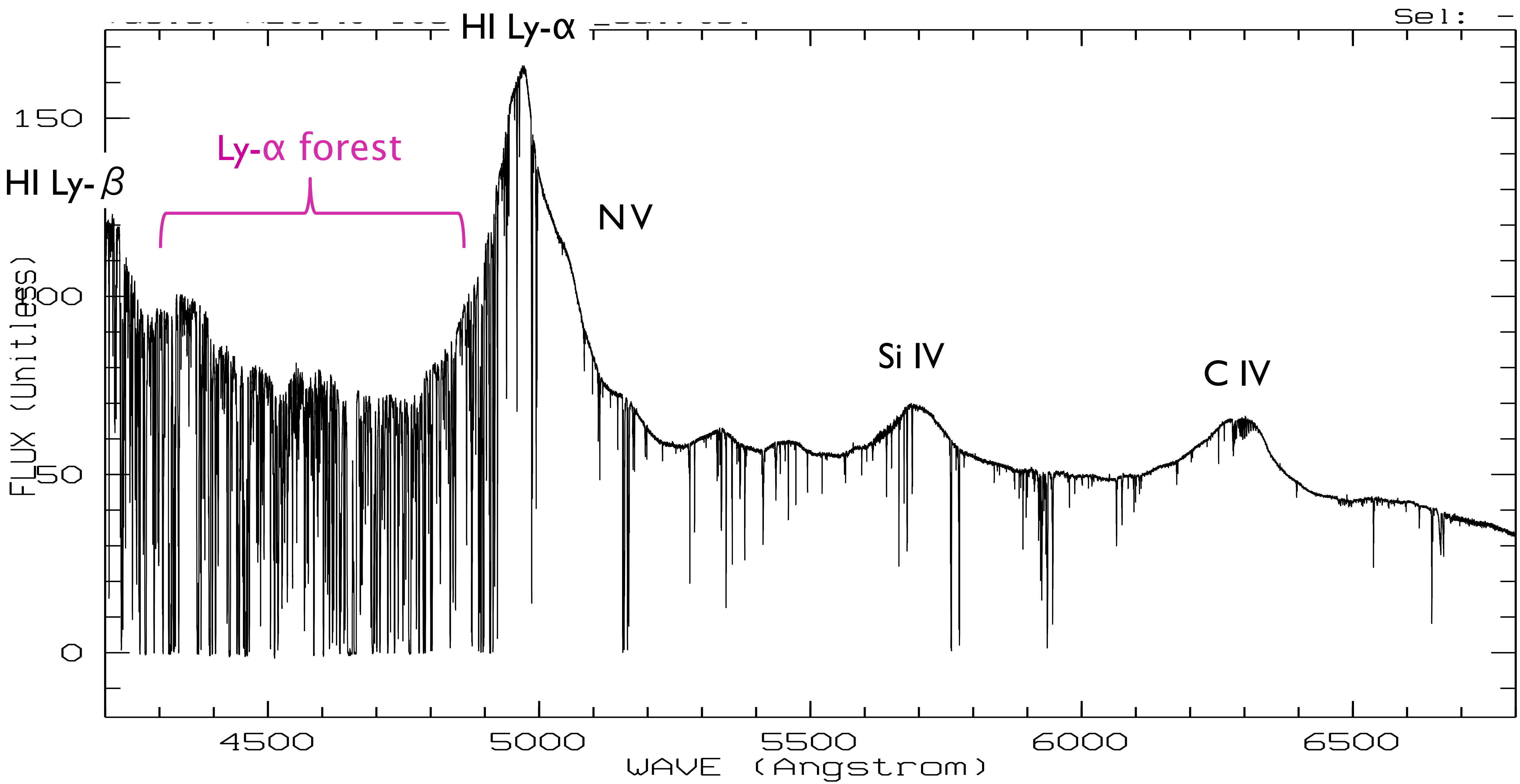
Features due to ionic transitions in chemical elements detected in absorption in the UV/optical/NIR spectra of high-redshift, relatively bright background sources



Investigation technique

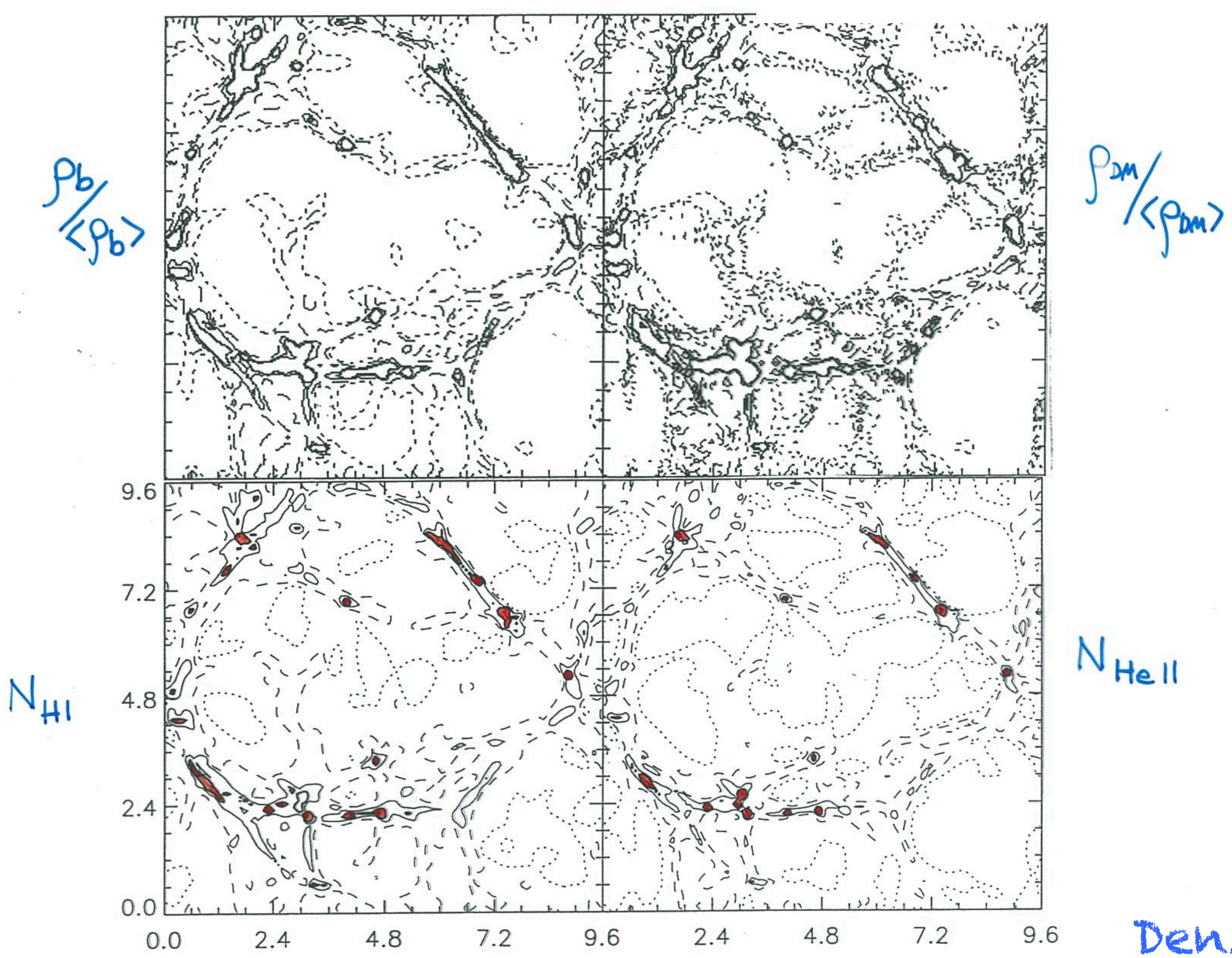
UVES "DEEP SPECTRUM"

QSO at z_{em}~3.0 with V=16.9 T_{exp}=64 h



Interpretation of the Lyman-α forest

Hydro-dynamical simulation in a standard CDM cosmology (Ω=1, H_0=50 km/s/Mpc, σ_8=0.7). Slices of 150 kpc at z=3 (from Zhang et al. 1998)



Zhang et al. 1998

Results

The Ly-α forest at z~2-5 is due to overdensities:

$(\delta+1) = \rho_b/<\rho_b> \leq 5\text{-}10$

➔ $\rho_b \cong \rho$

(smoothed at the IGM scale)

Density contrast

......	0.5
- - - -	1
—— (thin)	3
—— (thick)	5

Column density

......	$\log N_{HI}$ = 12
- - - -	13
—— (thin)	14
—— (thick)	15

Chase the metals outside galaxies

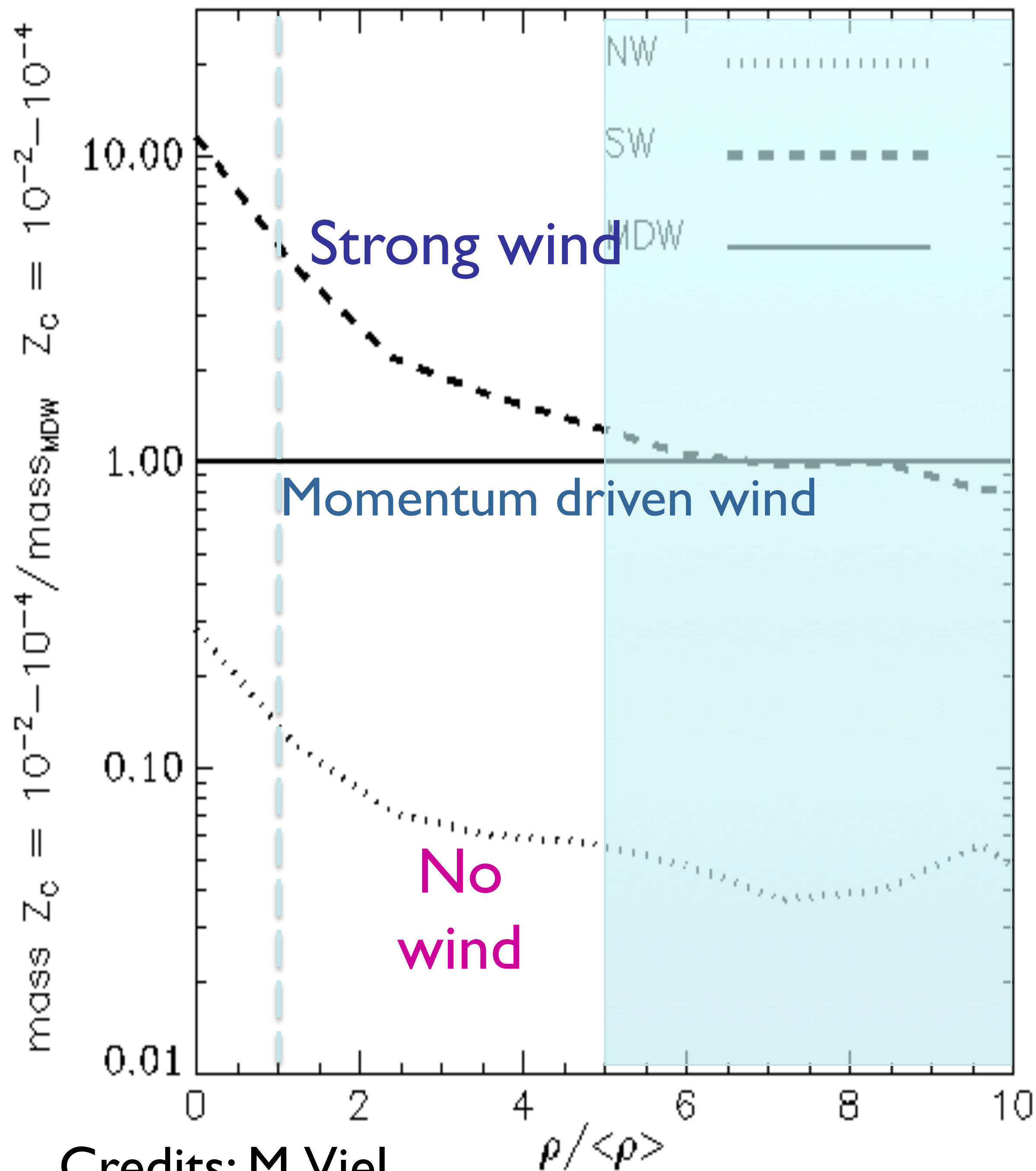
Probe the interaction between diffuse gas and galaxies
➔ feedback mechanisms

Enrichment scenarii

What is the origin of the metals that we observe at z~2-4?

❖ Old metals from previous generations of galaxies ➔ sprinkled in the IGM to low densities

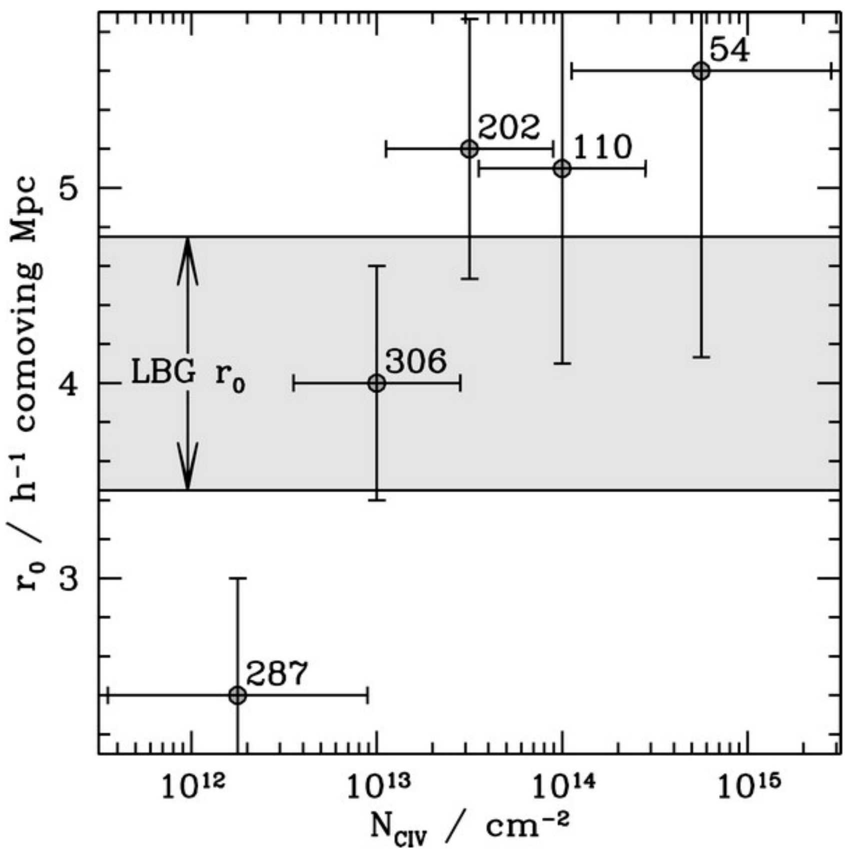
❖ Fresh metals expelled from coeval galaxies ➔ clustered in the CGM (see session on Thursday morning)



Credits: M.Viel

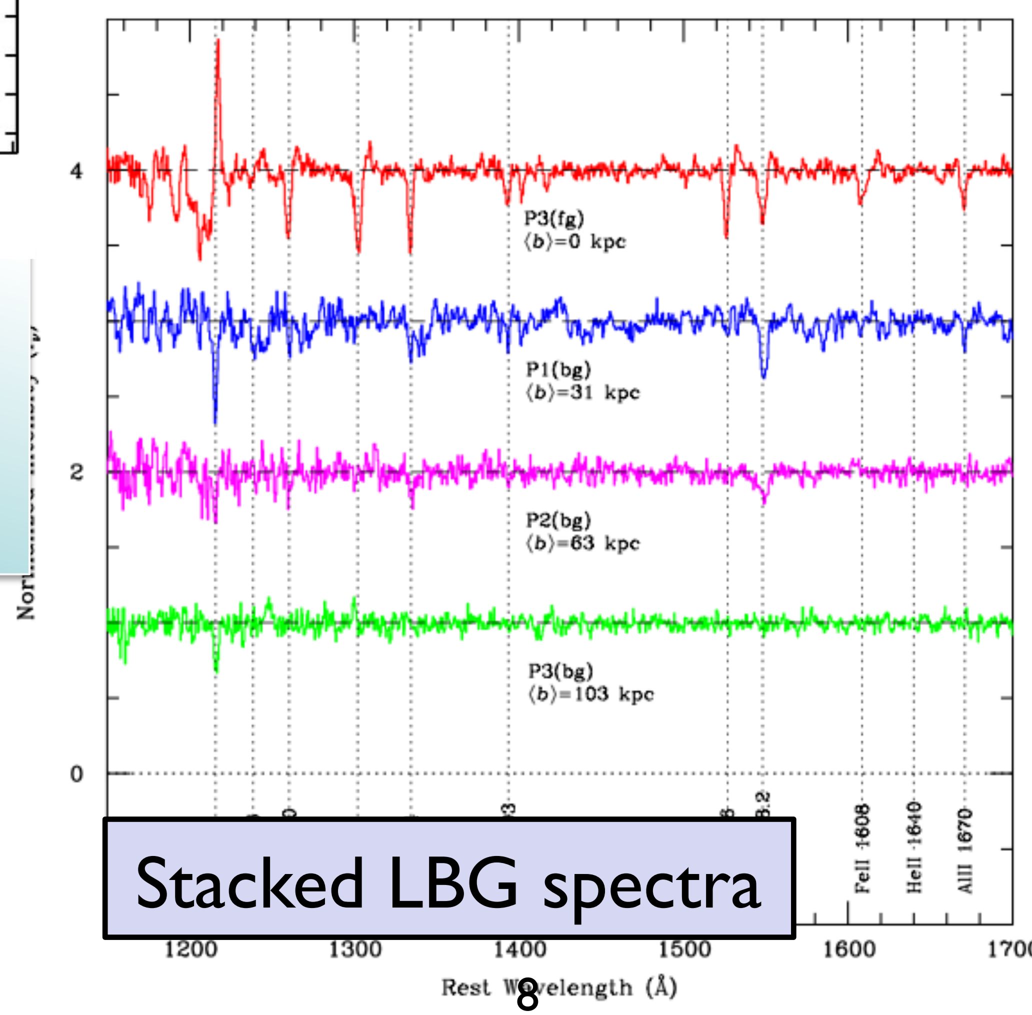
Investigate the enrichment pattern

Characterize the environment close to galaxies at z~2-3

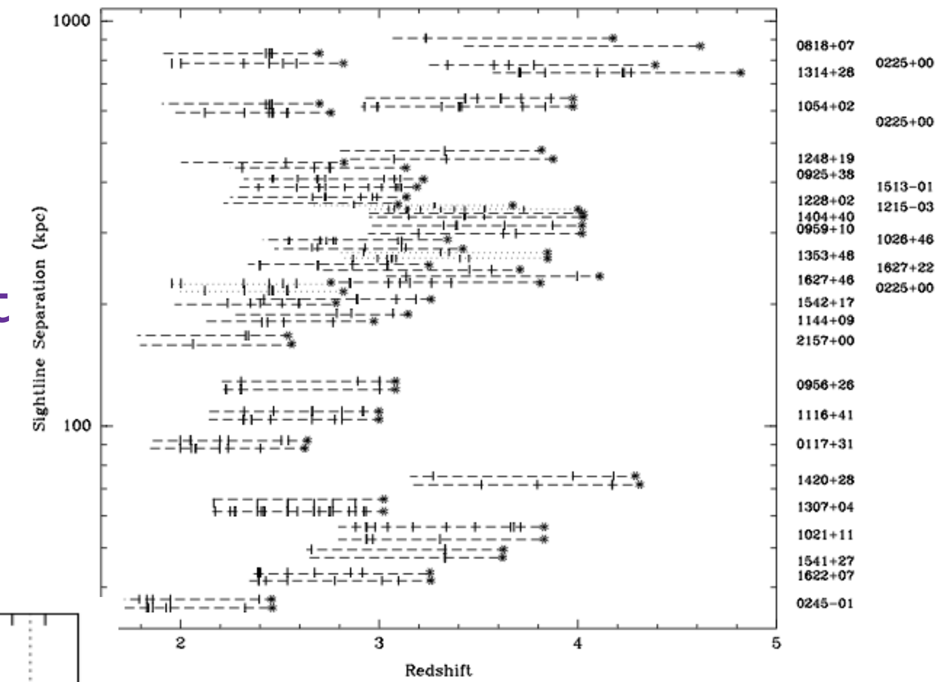


Adelberger et al. 2003, 2005: cross-correlation galaxy-CIV absorbers ➔ CGM is metal enriched out to ~300 kpc

Steidel et al. 2010: galaxy-galaxy pairs. Metal enriched gas at least out to ~125 kpc ➔outside the virial radius but consistent with winds



Stacked LBG spectra

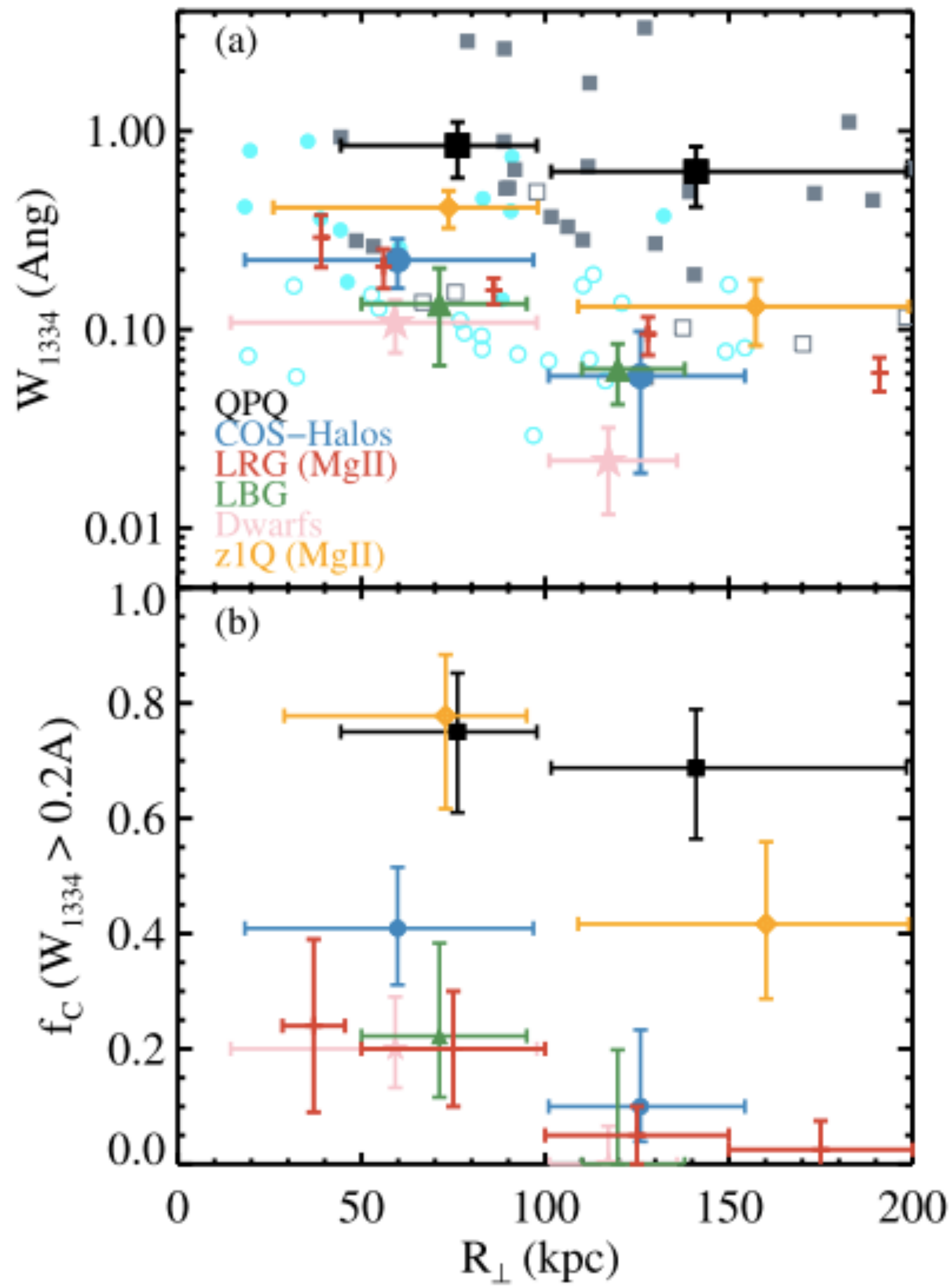


Martin et al. 2010: cross-correlation of CIV absorptions in QSO pairs. Size of enriched region ~420 h^{-1} kpc ➔ Metals deposited in the gas at z>4.3 by an earlier generation of gals

Investigate the enrichment pattern

Characterize the environment close to QSOs

Investigation ACROSS and ALONG the line of sight gives different results
➔ evidence of anisotropic emission



Results ACROSS the line of sight

The QPQ project (Prochaska, Hennawi et al.): the CGM around quasar at z~2-3 contains the largest masses of cool metals.

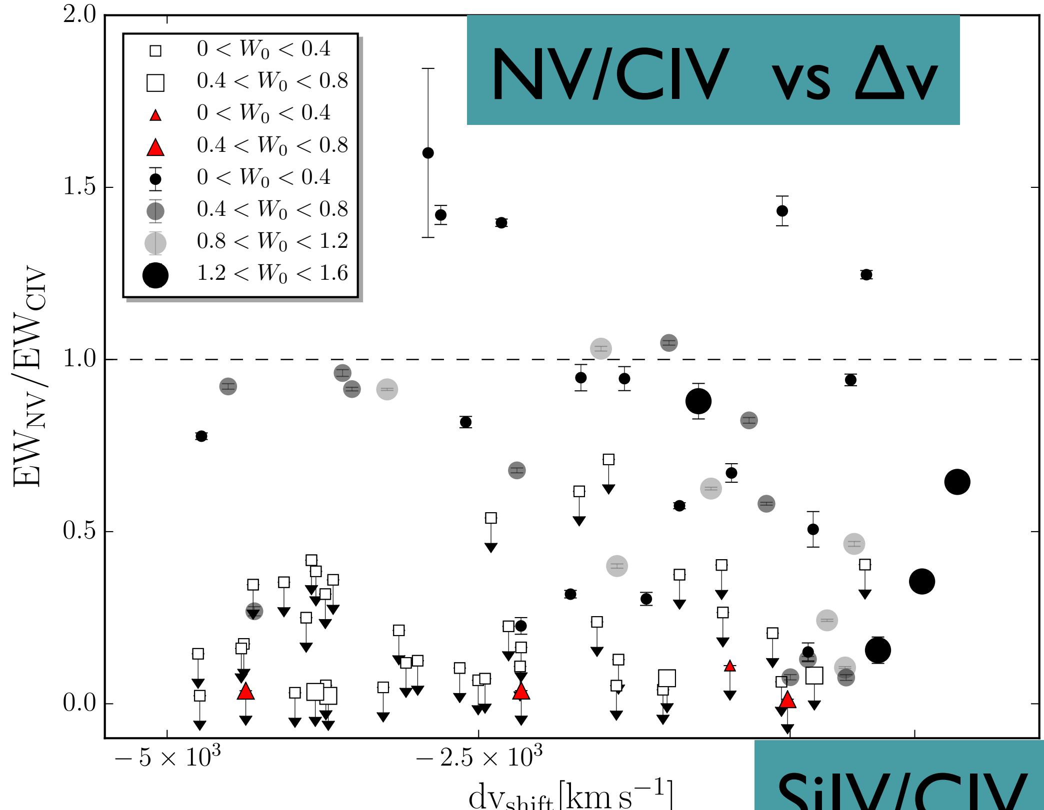
These metals likely represent the early enrichment of halo gas predicted by chemical evolution models that study the formation and enrichment of the IGrM and ICM.

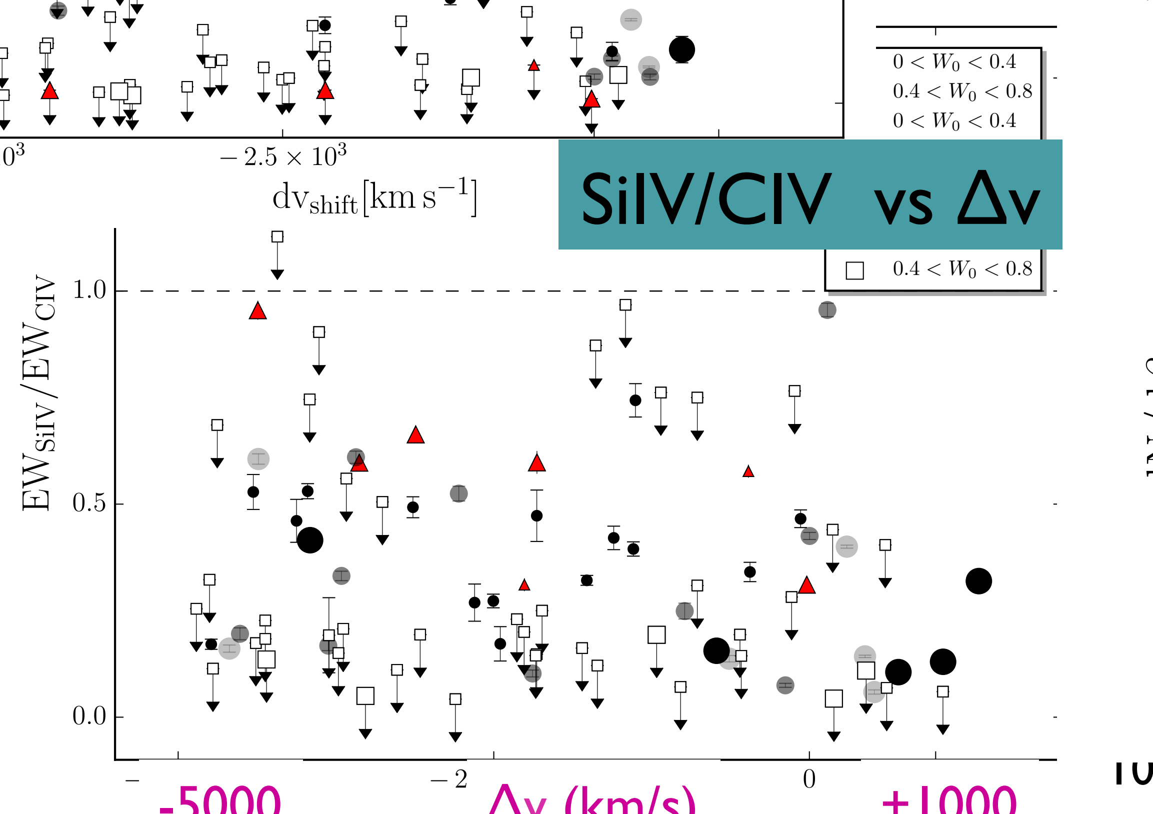
Investigate the enrichment pattern

Characterize the environment close to QSOs

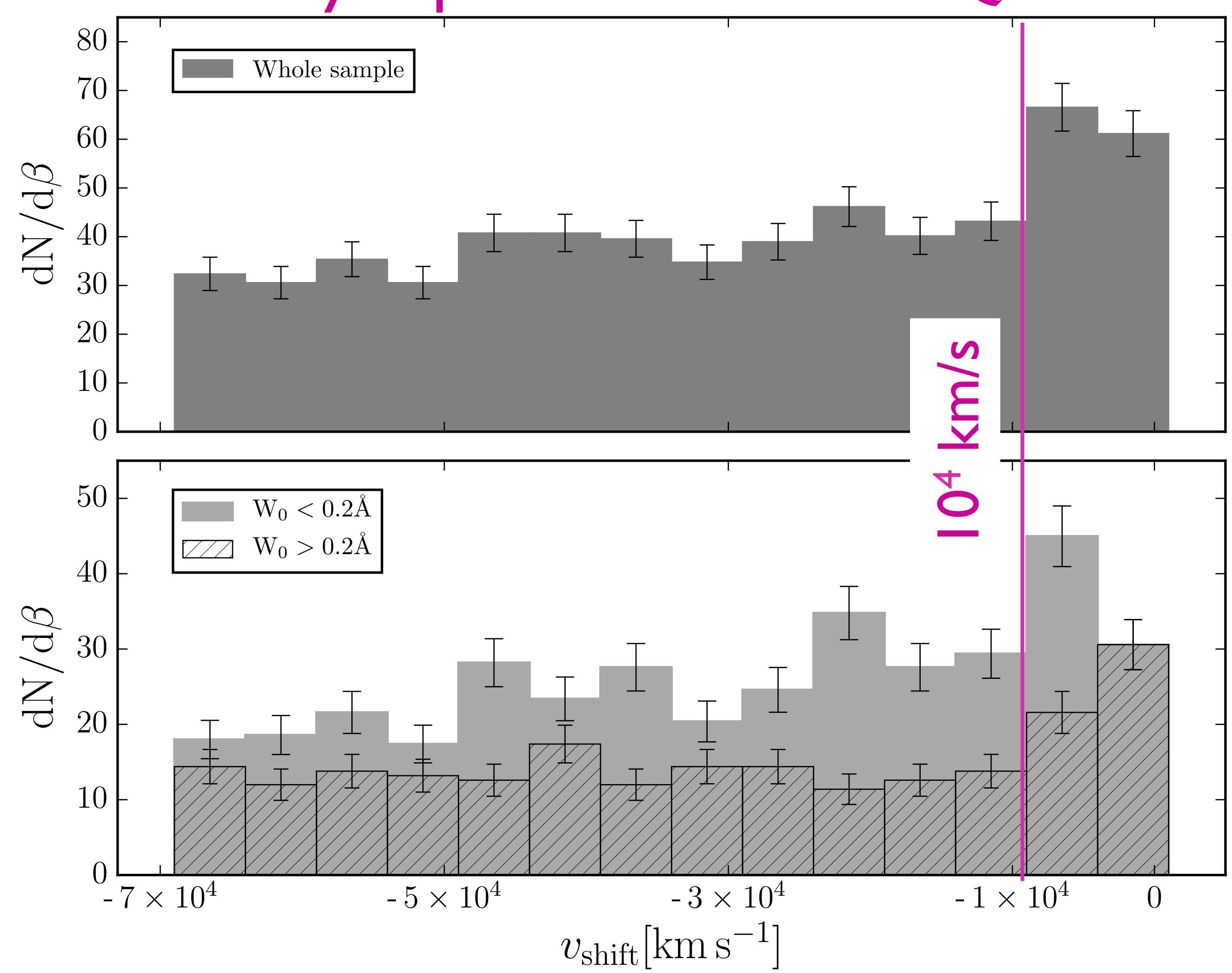
Results ALONG the line of sight ➔ see poster by S. Perrotta

Narrow Associated Absorption Systems in the XQ-100 survey: evidence of QSO ionization effects



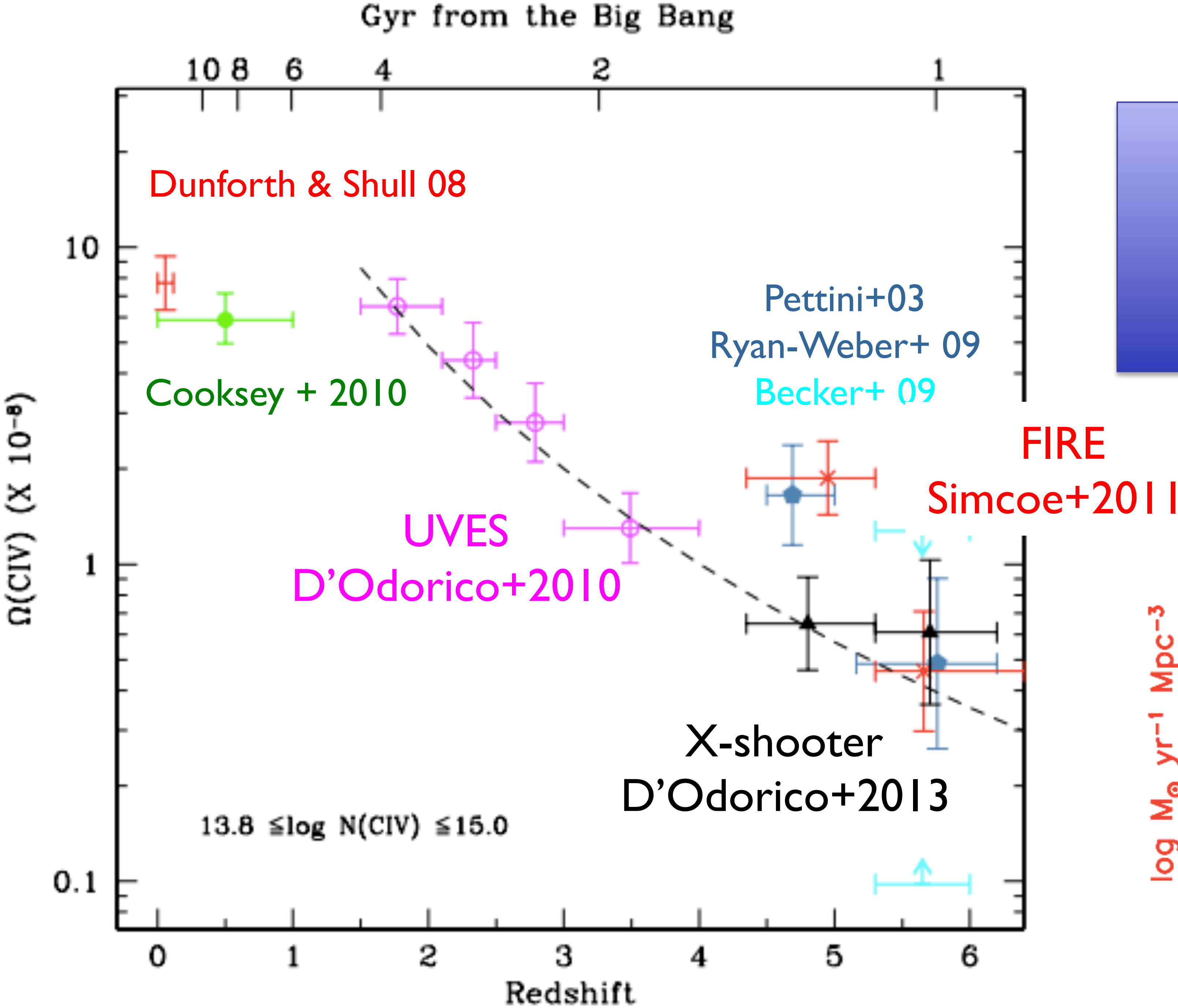


# of CIV systems as a function of the velocity separation from the QSO



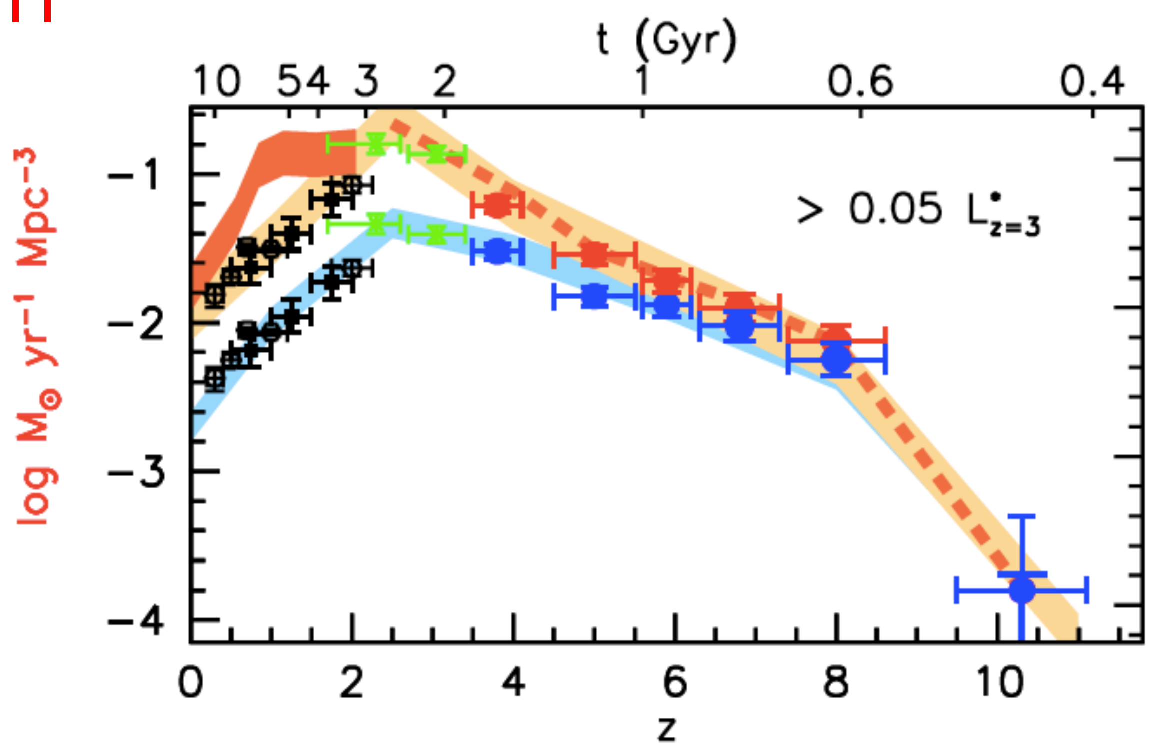
The C IV cosmic mass density

$$\Omega_{\mathrm{C\,IV}} = \frac{H_0\, m_{\mathrm{C\,IV}}}{c\,\rho_{\mathrm{crit}}} \frac{\sum_i N_i(\mathrm{C\,IV})}{\Delta X}$$



D'Odorico et al. 2013

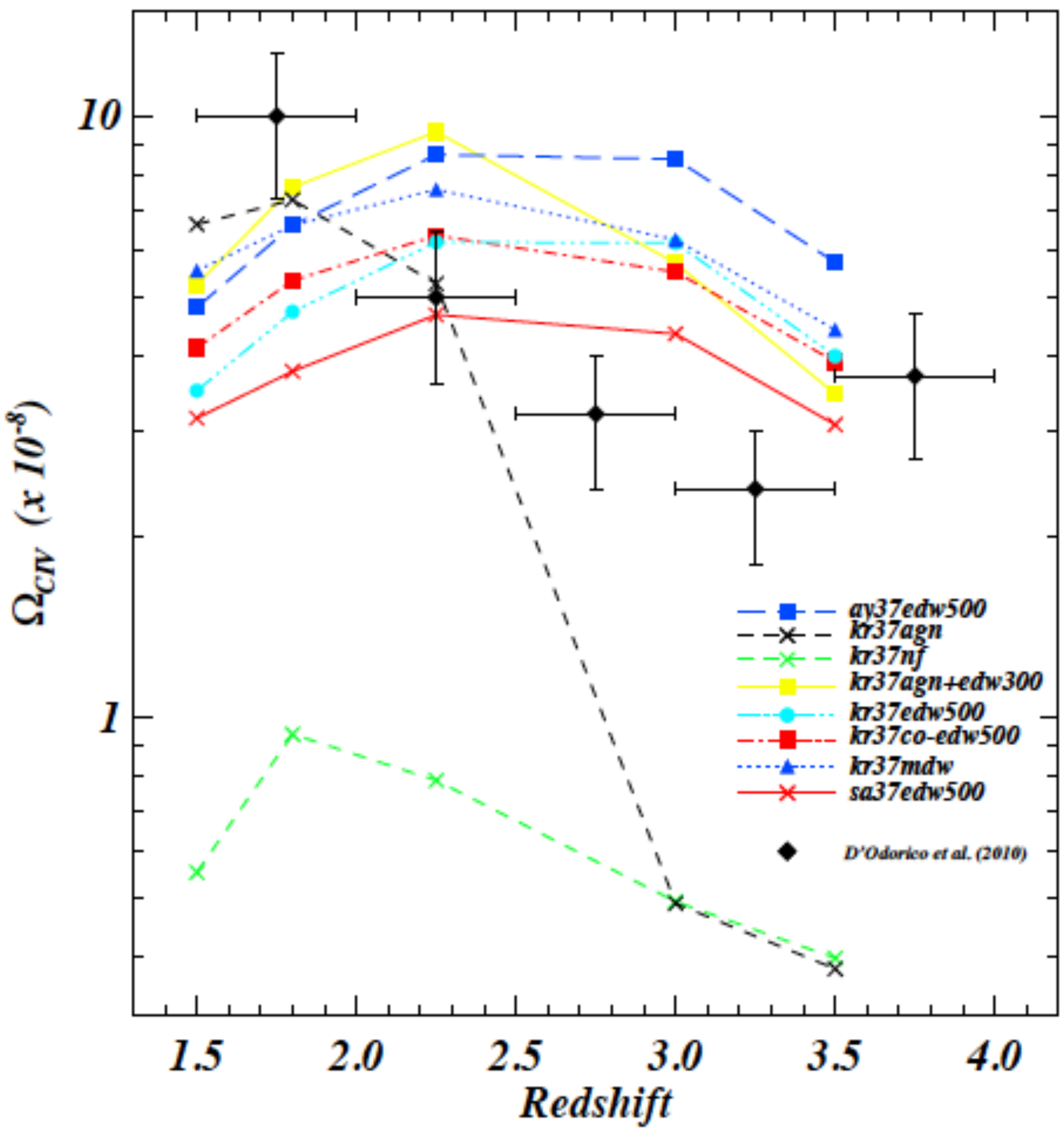
constrain the cumulative effect of the cosmic enrichment cycle



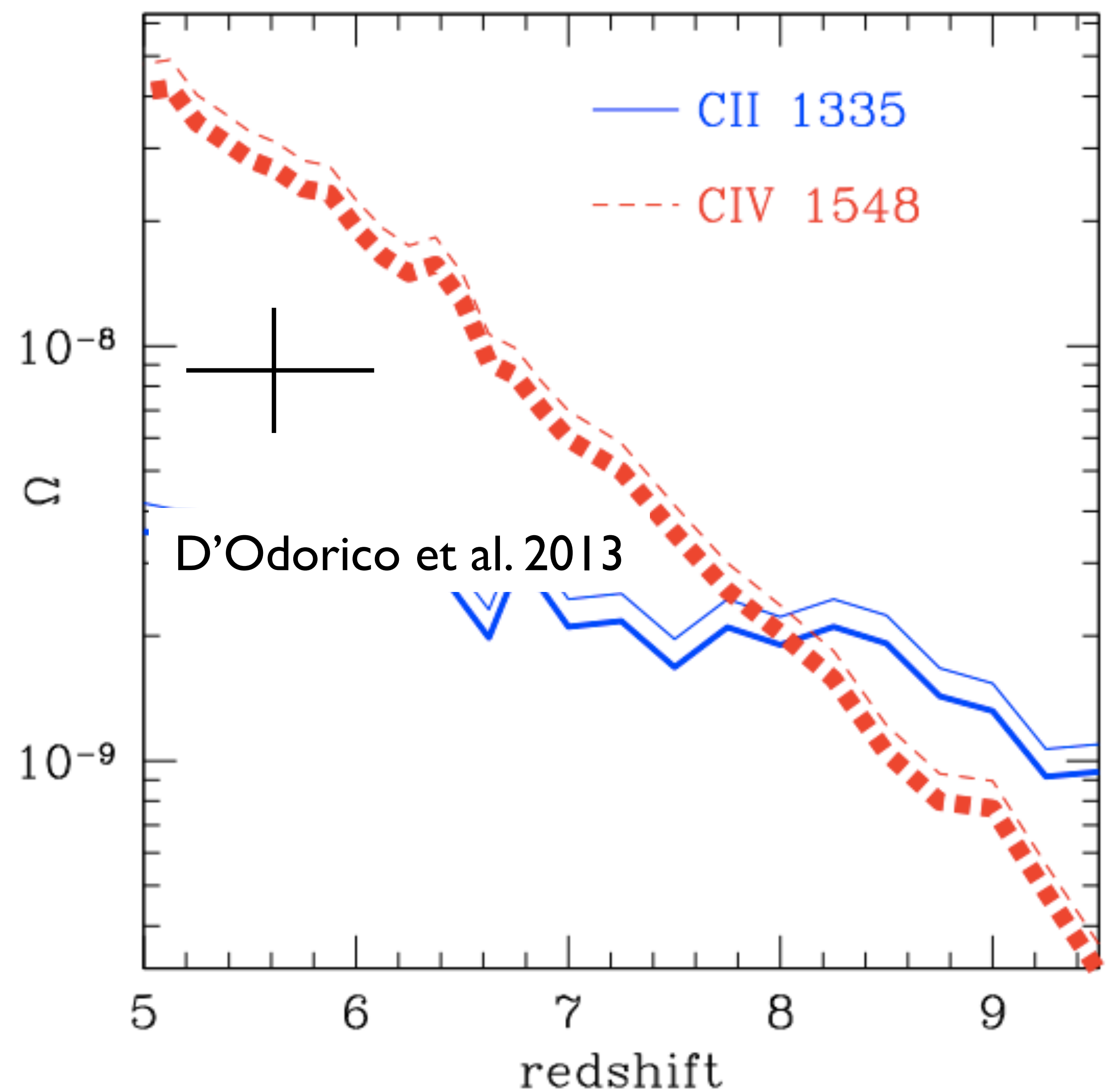
Bouwens et al. 2012

The C IV cosmic mass density

Predictions vs. observations: models fail!



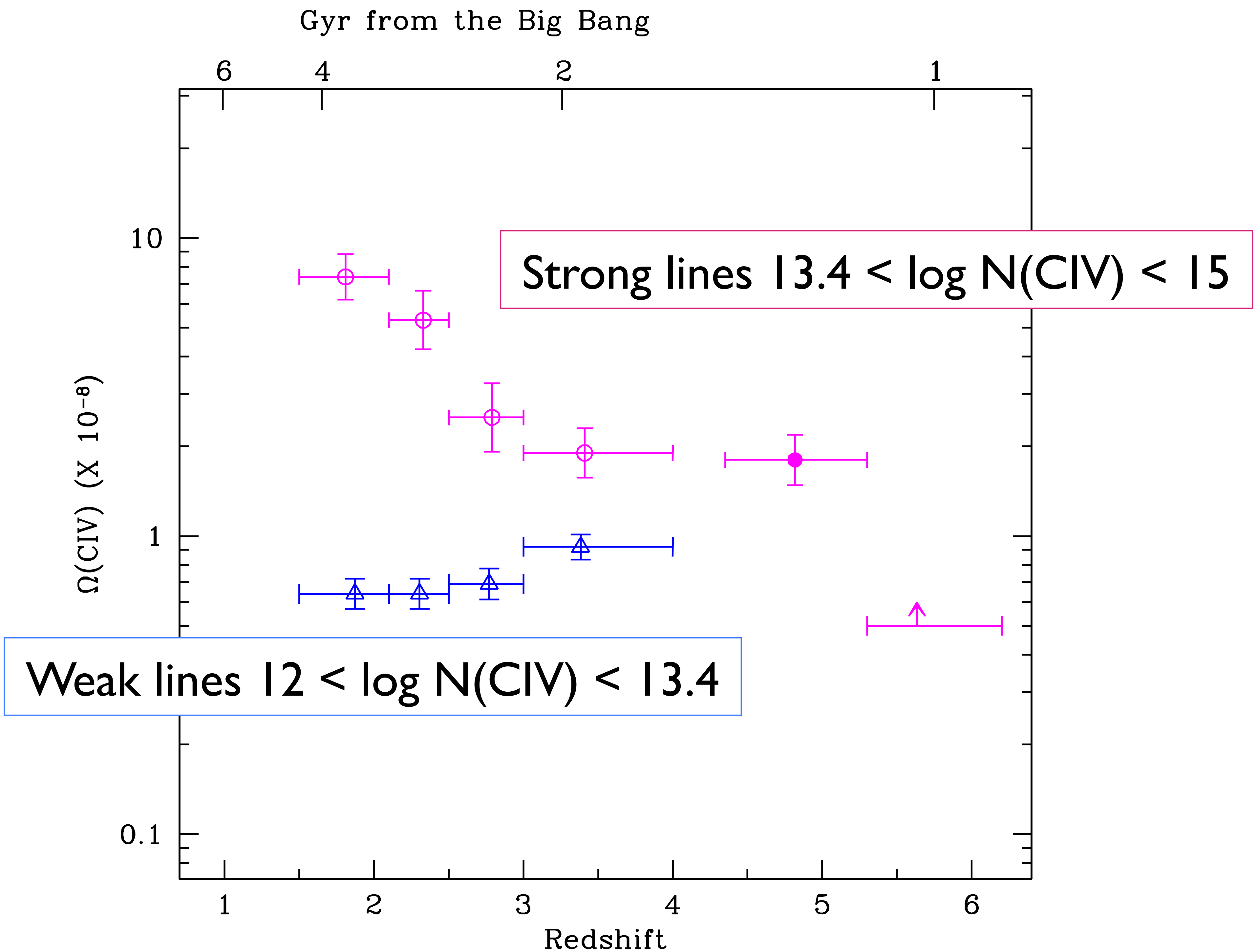
Tescari et al. 2011



Finlator et al. 2015

The C IV cosmic mass density

POSSIBLE EVIDENCE of DOUBLE ENRICHMENT!

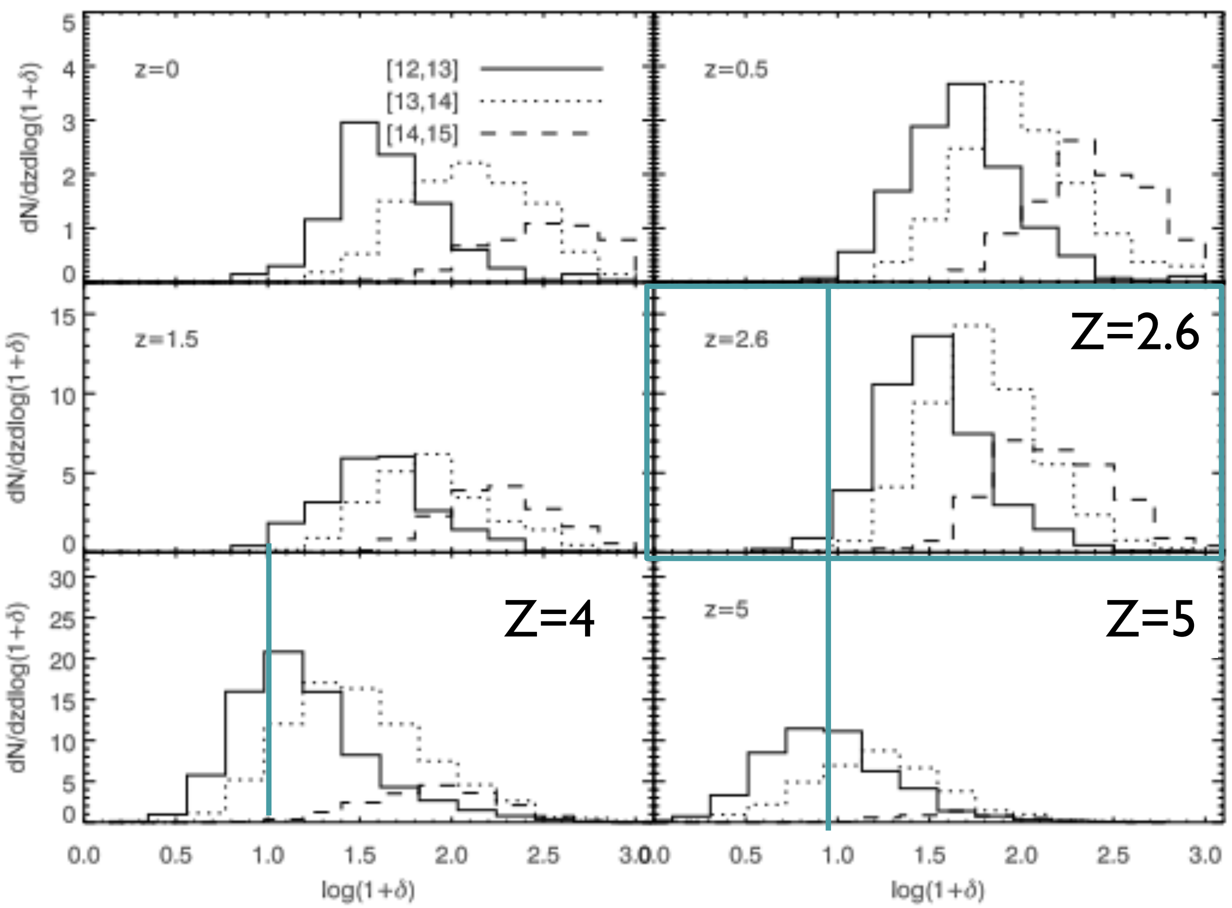


Investigate the enrichment pattern

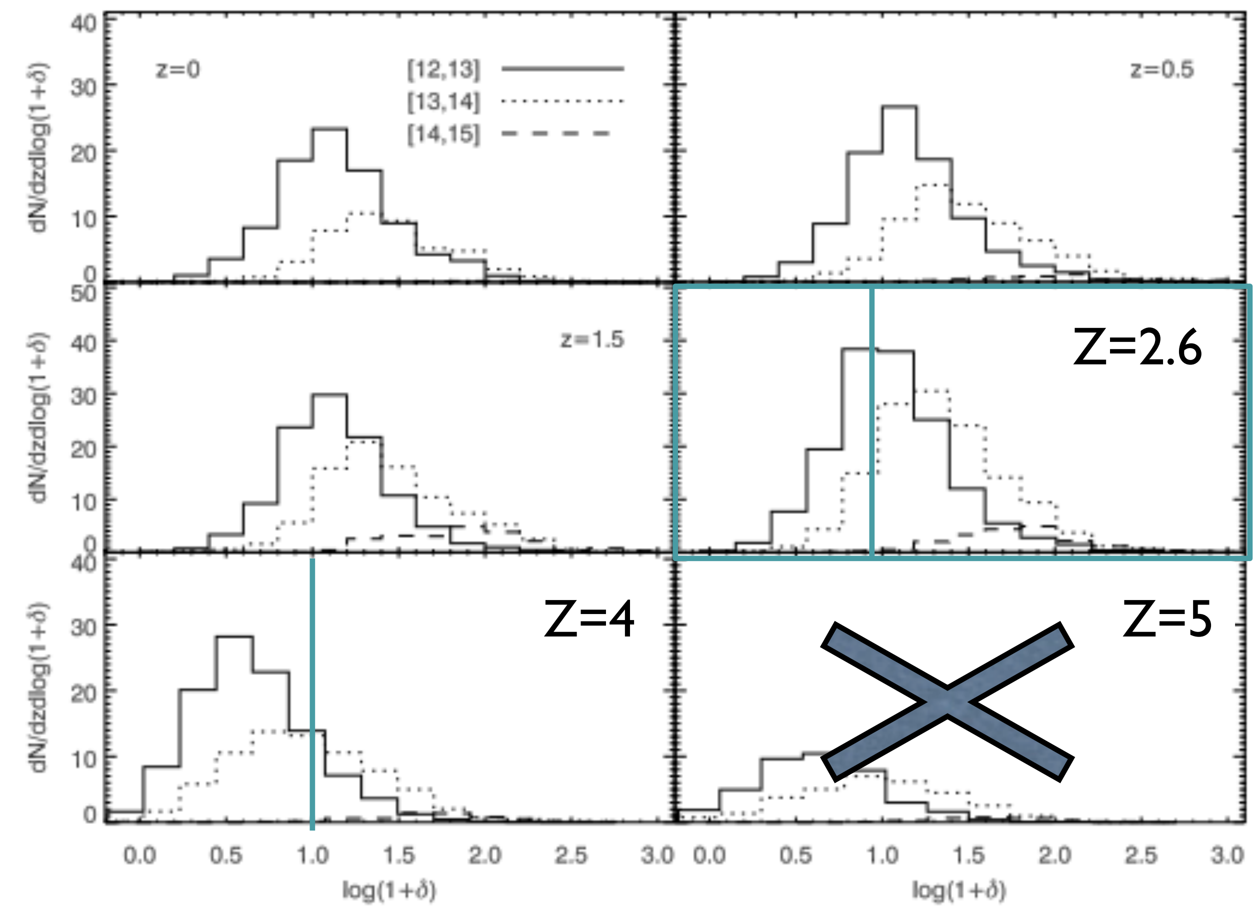
Probe the tenuous gas (close to the mean density)

Which probe?

CIV outside the Lyα forest



OVI in the Lyβ forest



Cen & Chisari 2011

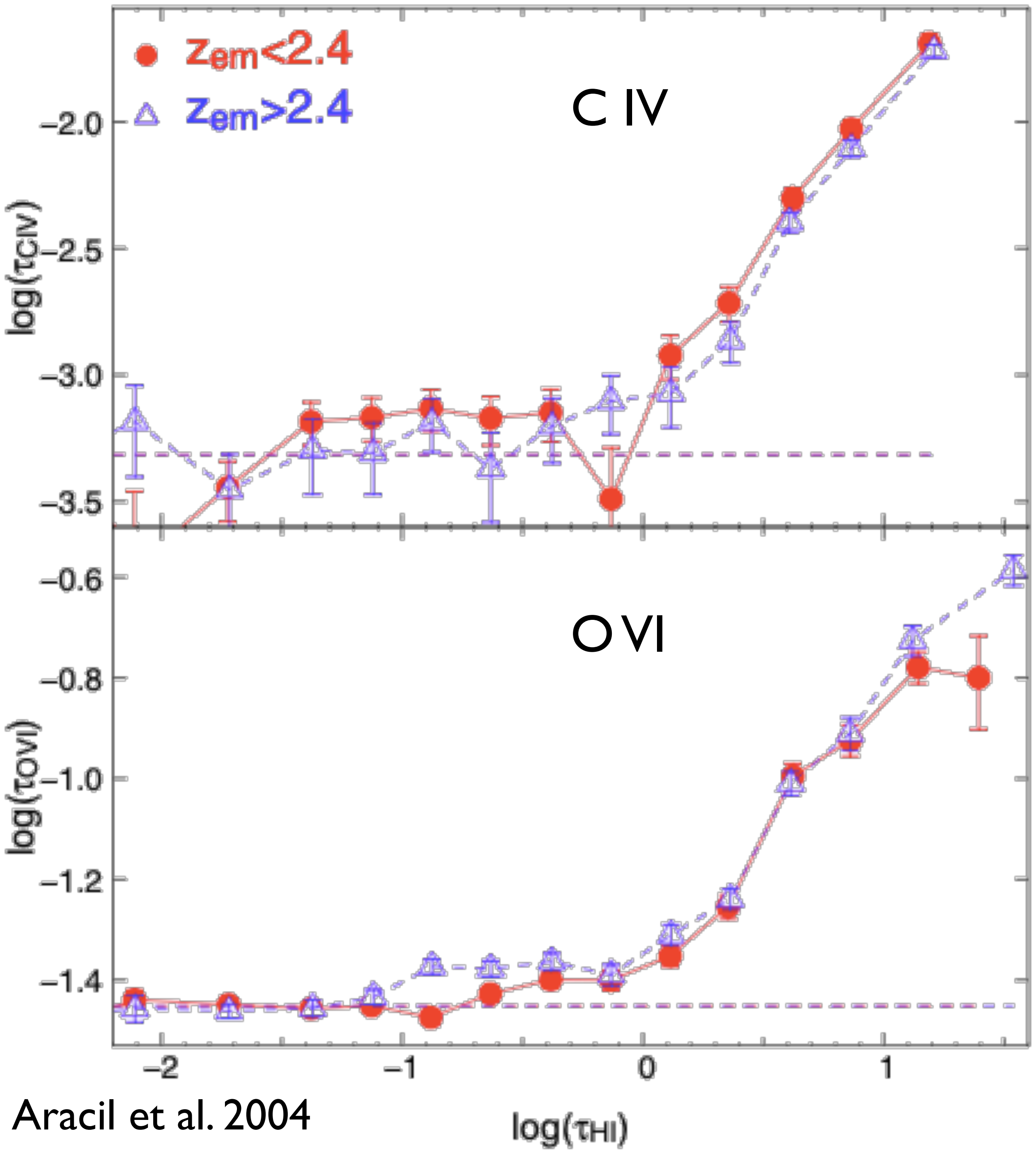
CIV at column density [12-13] is not tracing the mean density at z~3 need to go to log N(CIV) < 12

Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

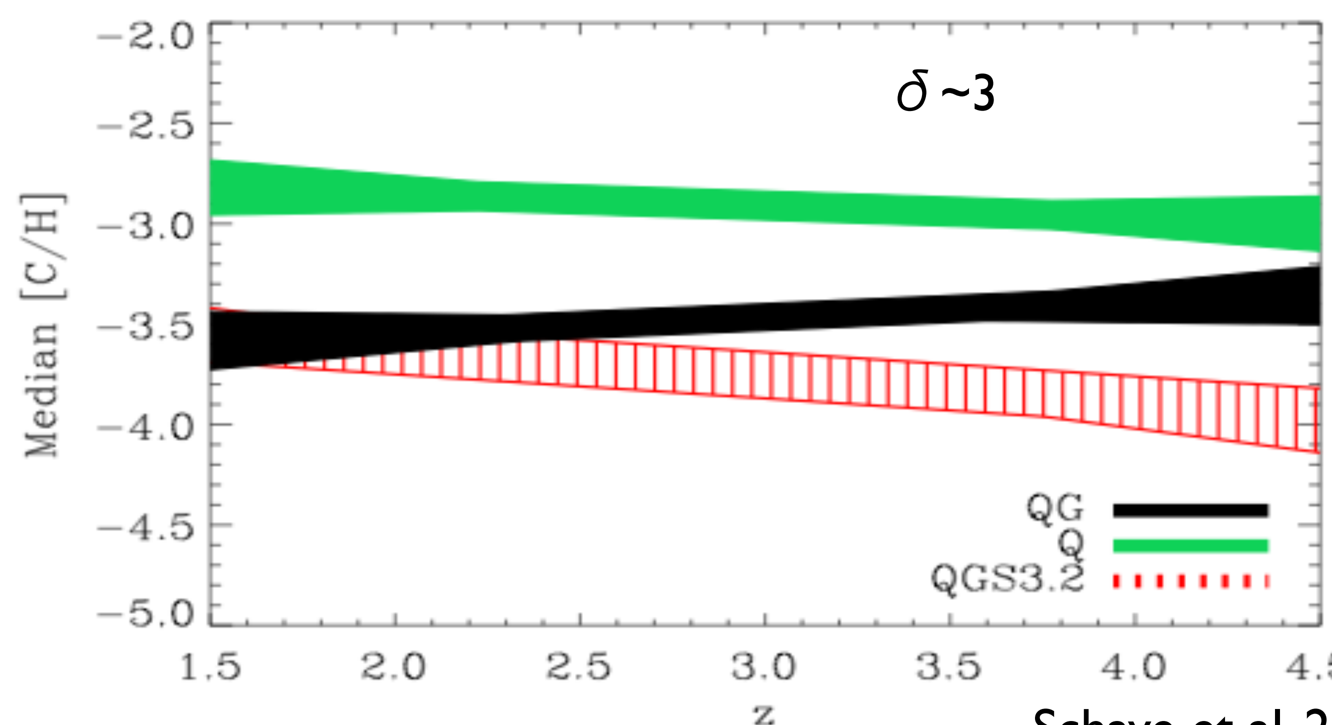
Statistical approach to detect metals at lower densities (Cowie & Songaila 1998; Ellison et al. 2000; Aguirre et al. 2002)

$F = \exp(-\tau)$: correlate the optical depth in HI with that of metals (CIV, OVI, SiIV)



Aracil et al. 2004

Mean density not reached
Probing less than 5% of the volume of the Universe (Pieri & Haehnelt 2004)



Schaye et al. 2003

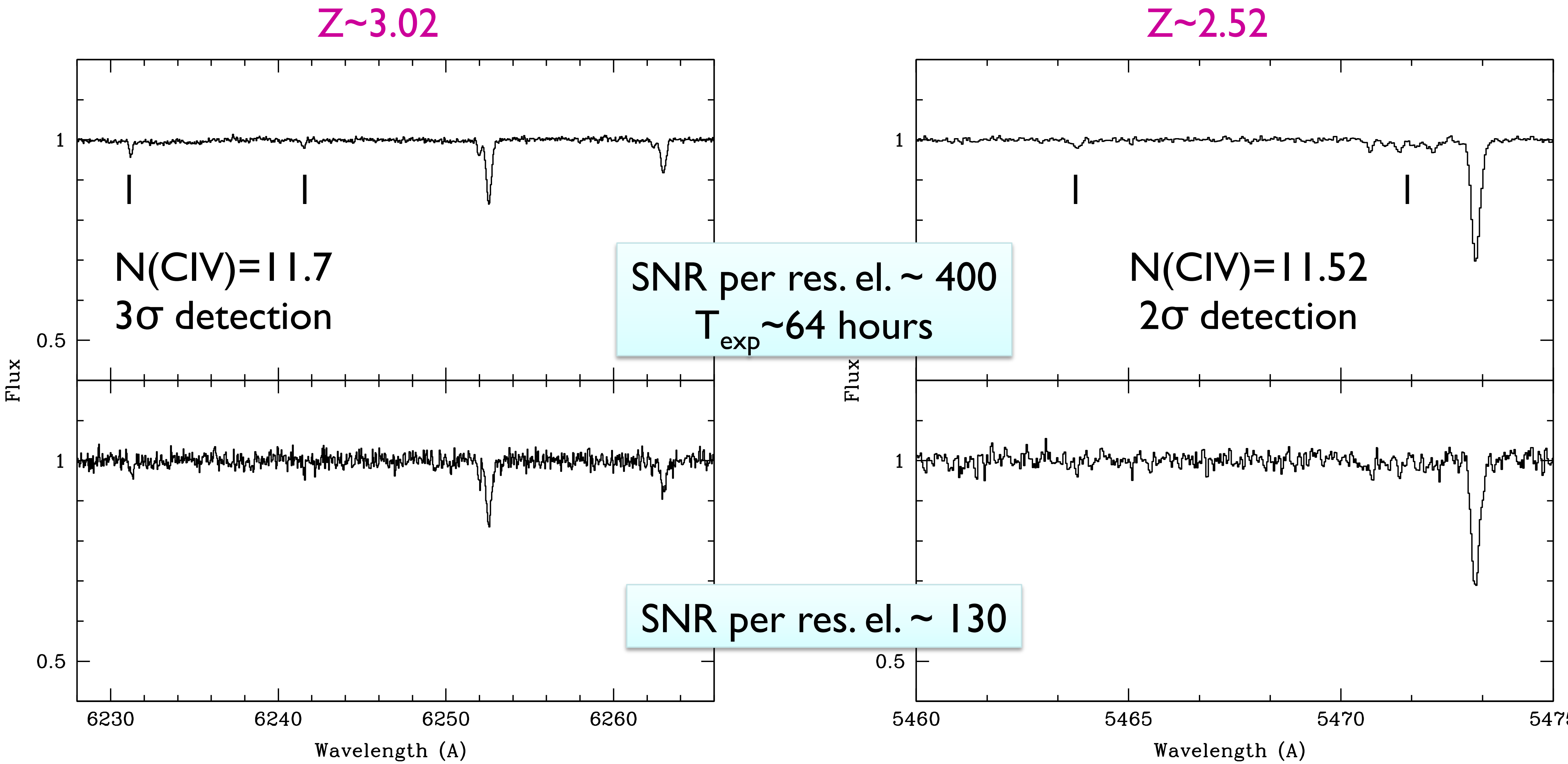
Limited by SNR, contamination, continuum errors

Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

UVES DEEP SPECTRUM QSO at z_{em}~3.0 with V=16.9 T_{exp}=64 h

D'Odorico et al., in prep.



Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

UVES DEEP SPECTRUM QSO at z_{em}~3.0 with V=16.9 T_{exp}=64 h

CIV DETECTION RATE at the low N(HI)s is LOW

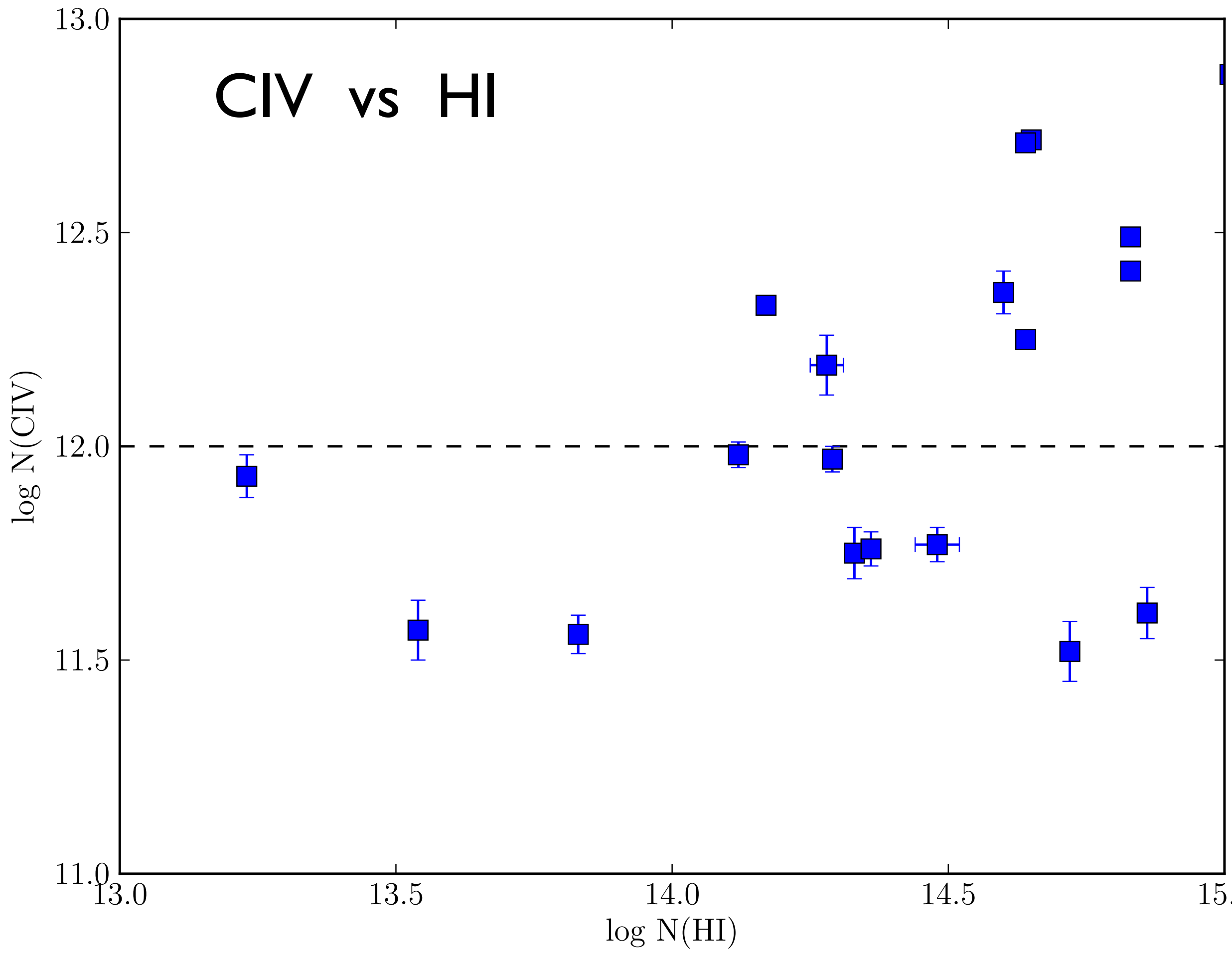
13 < logN(HI) < 13.5 ➔ ~1%

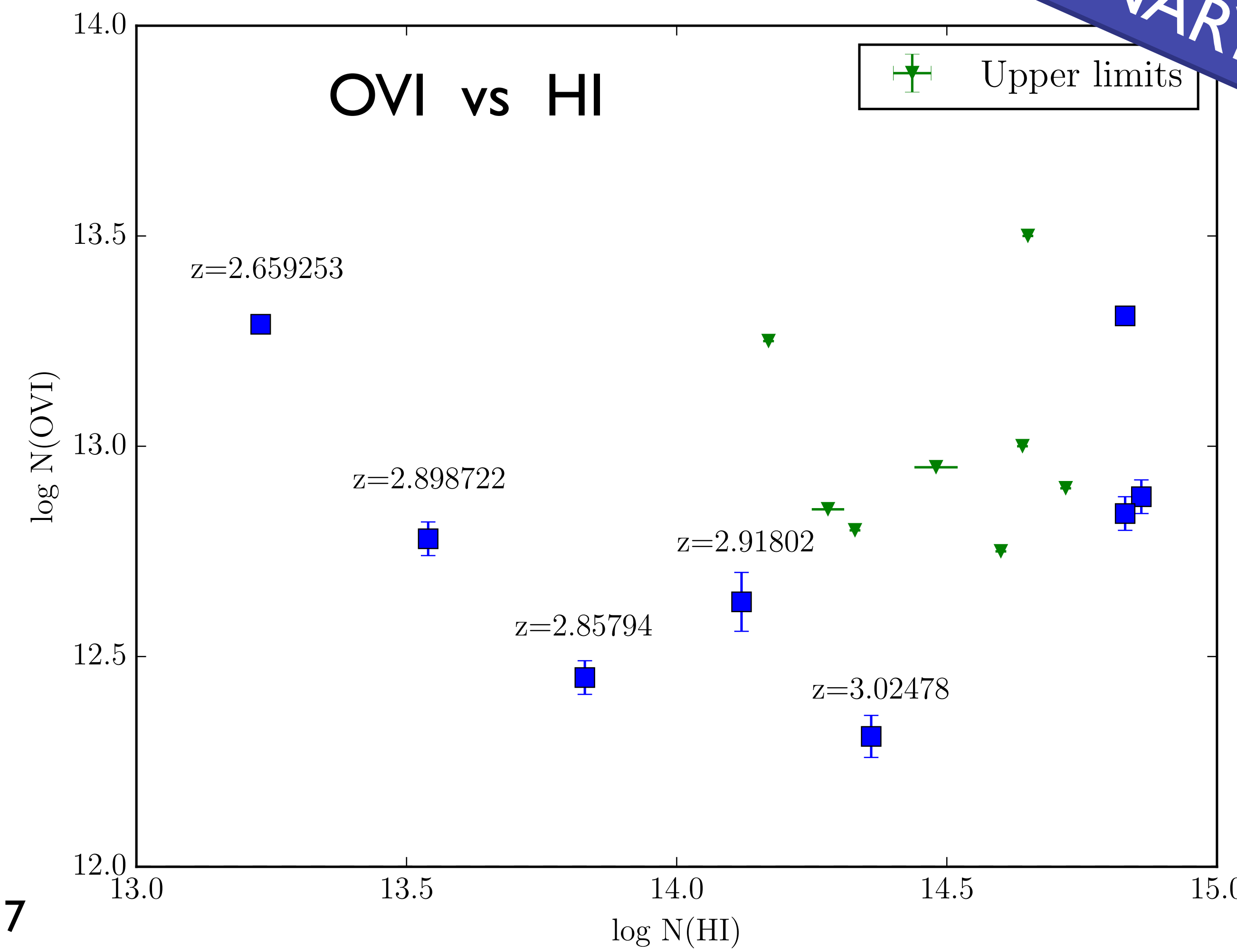
13.5 < logN(HI) < 14 ➔ ~4%

14 < logN(HI) < 14.5 ➔ ~20%

14.5 < logN(HI) < 15 ➔ ~60%

PRELIMINARY





Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

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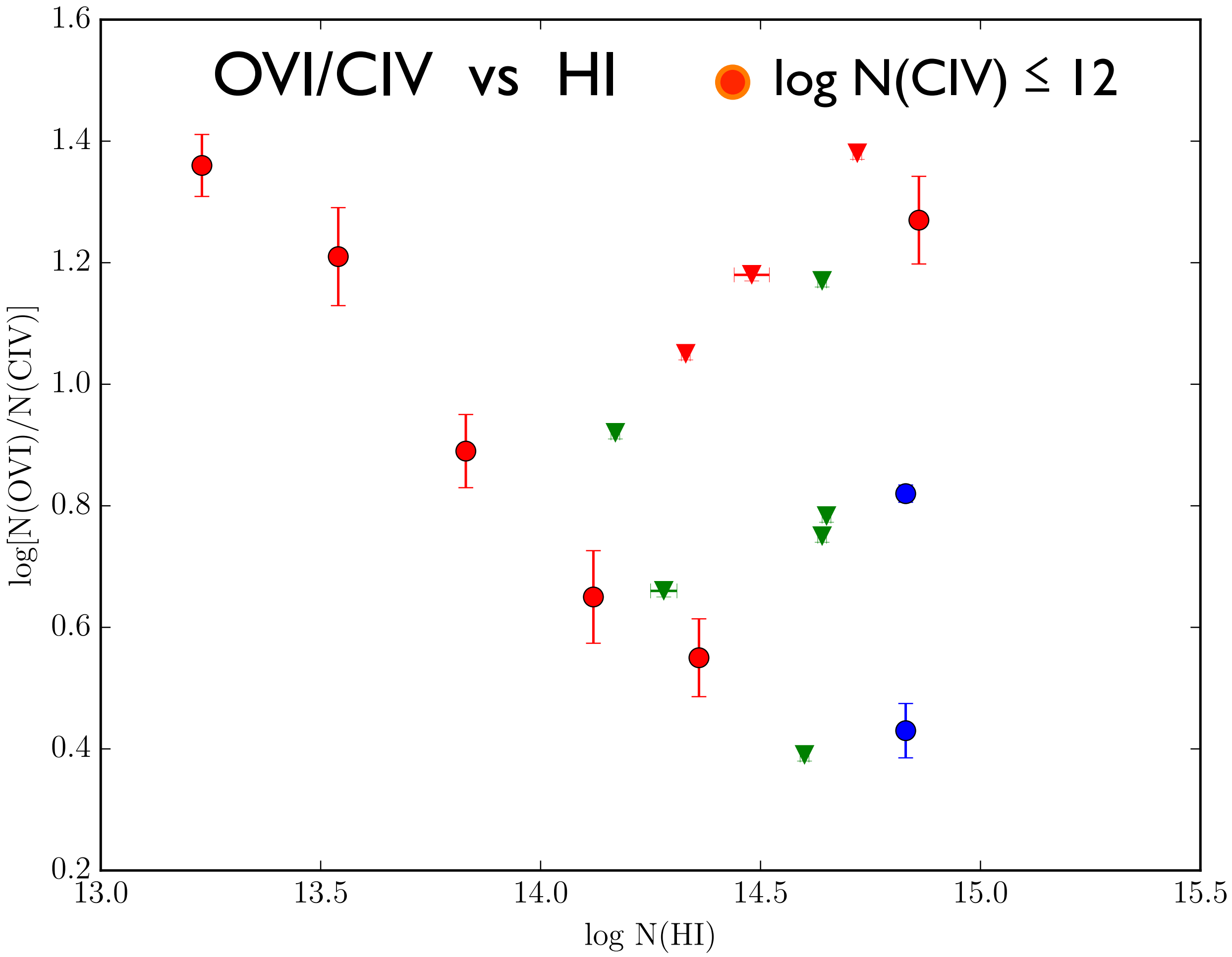
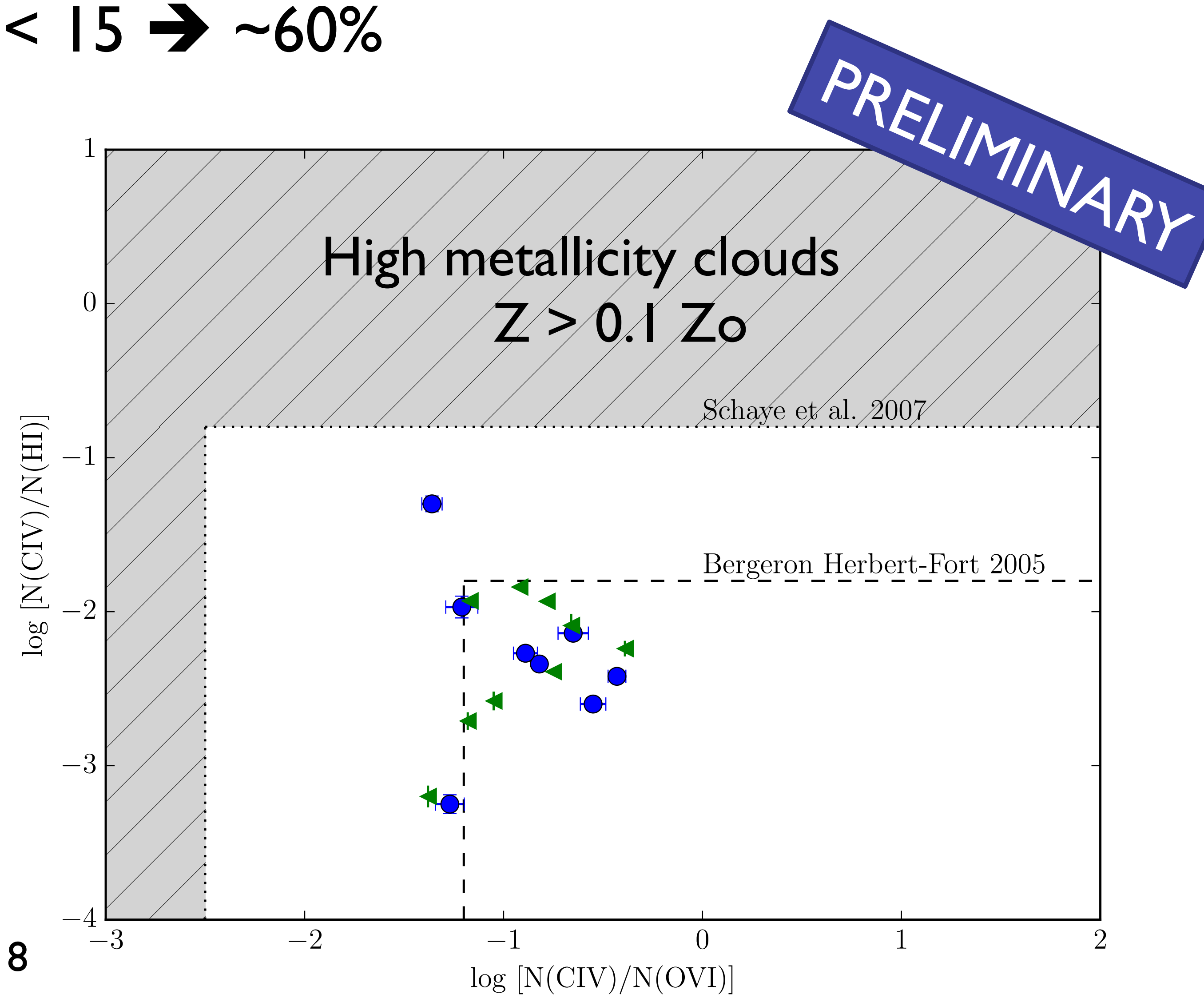
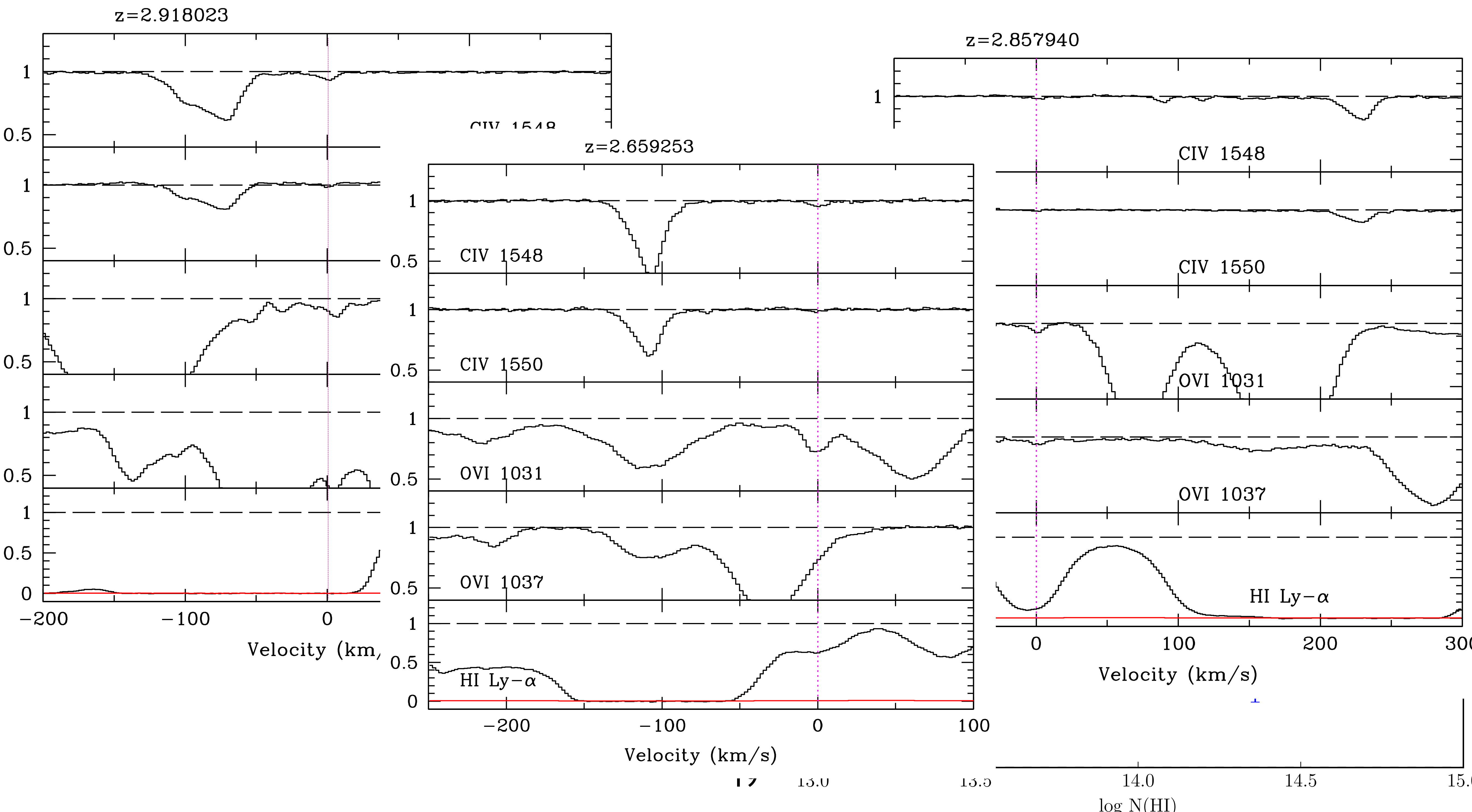




Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

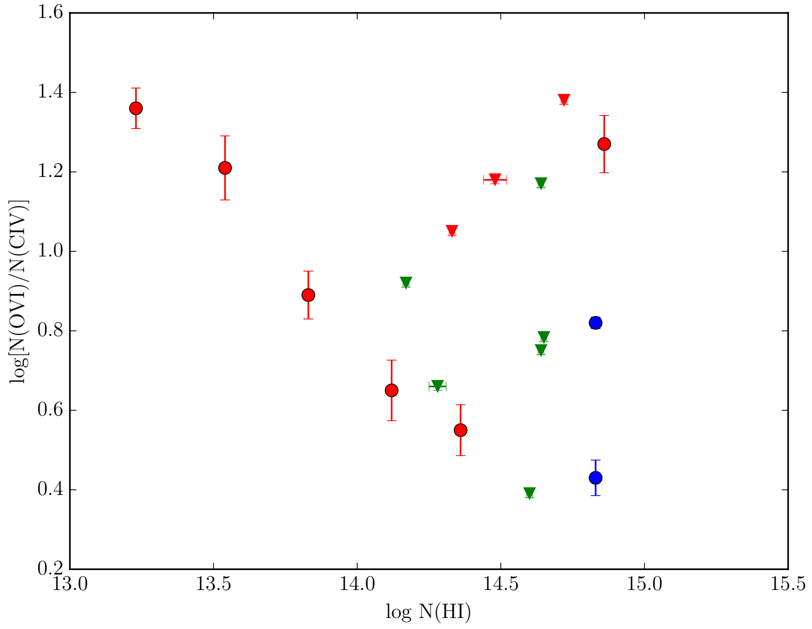
UVES DEEP SPECTRUM QSO at z_{em}=3.0932 with V=16.9 T_{exp}=64 h



Investigate the enrichment pattern

Results

- ✓ Metals (C traced by CIV) are always present around galaxies at distances even larger than the virial radius ➔ CGM
- ✓ Moving to δ < 10 (traced by HI with log N < 14.5-15 at z~2.5-3) detection rate becomes smaller and smaller ➔ metallicity step or ionization?
- ✓ OVI could be a better tracer but detectability is limited by blending with the forest
- ✓ All the metal systems with log N(HI) < 14.5 are at less than 200 km/s from a stronger system ➔ outflows? Filaments?



Conclusions (work in progress)

- ✓ Comparison with hydro-simulations is foreseen:
  - Constraints on wind models
  - Nature of weak absorbers
- ✓ POD computation is in progress
- ✓ Should we concentrate our effort on OVI to probe the IGM at $z<3$?
- ✓ High-resolution spectroscopy with 8-10m class telescopes has reached the "photon starving" regime for many of the IGM hot topics, which (observational) improvements are expected in the future?
- ✓ Is the IGM driving star formation? The abundance and distribution of metals in the IGM is a strong constraint on early star formation and feedback mechanisms

Future prospects: near

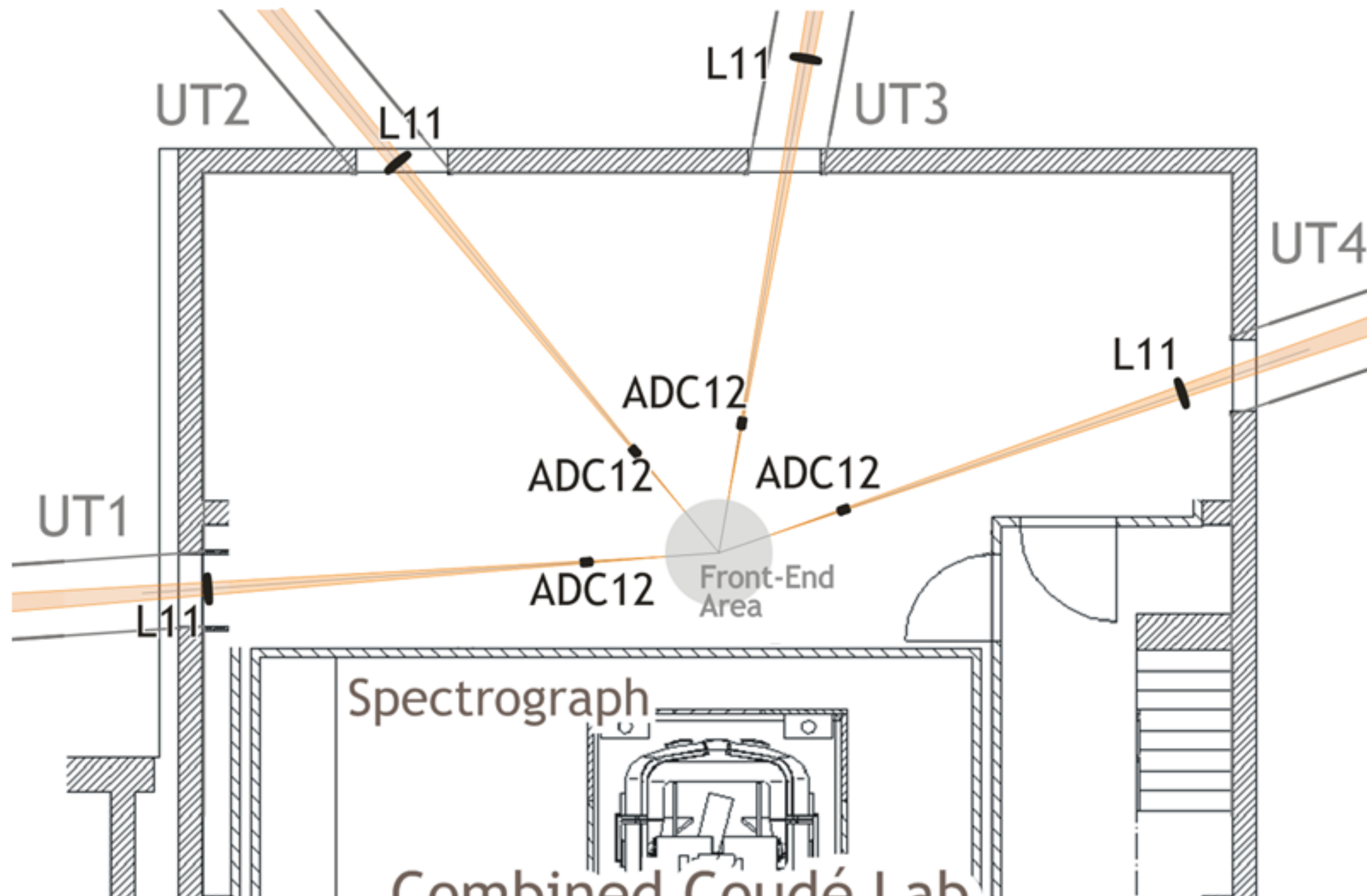
ESPRESSO@VLT

Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations

Consortium: Switzerland (Observatoire de Genève, Geneva and Bern Universities) F. Pepe P.I.; Italy (INAF-OATs, INAF-Brera); Spain (IAC); Portugal (Lisbon and Porto Universities).

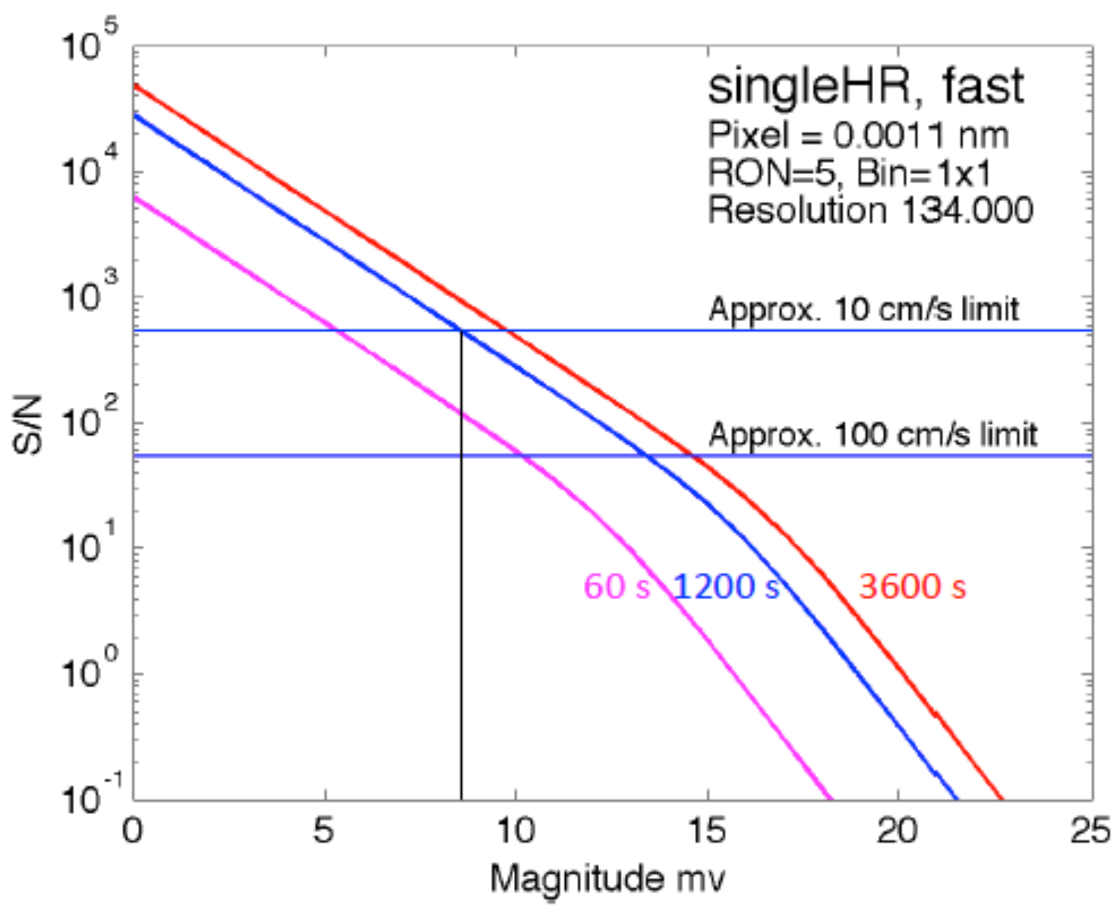
First light expected at the beginning of 2017

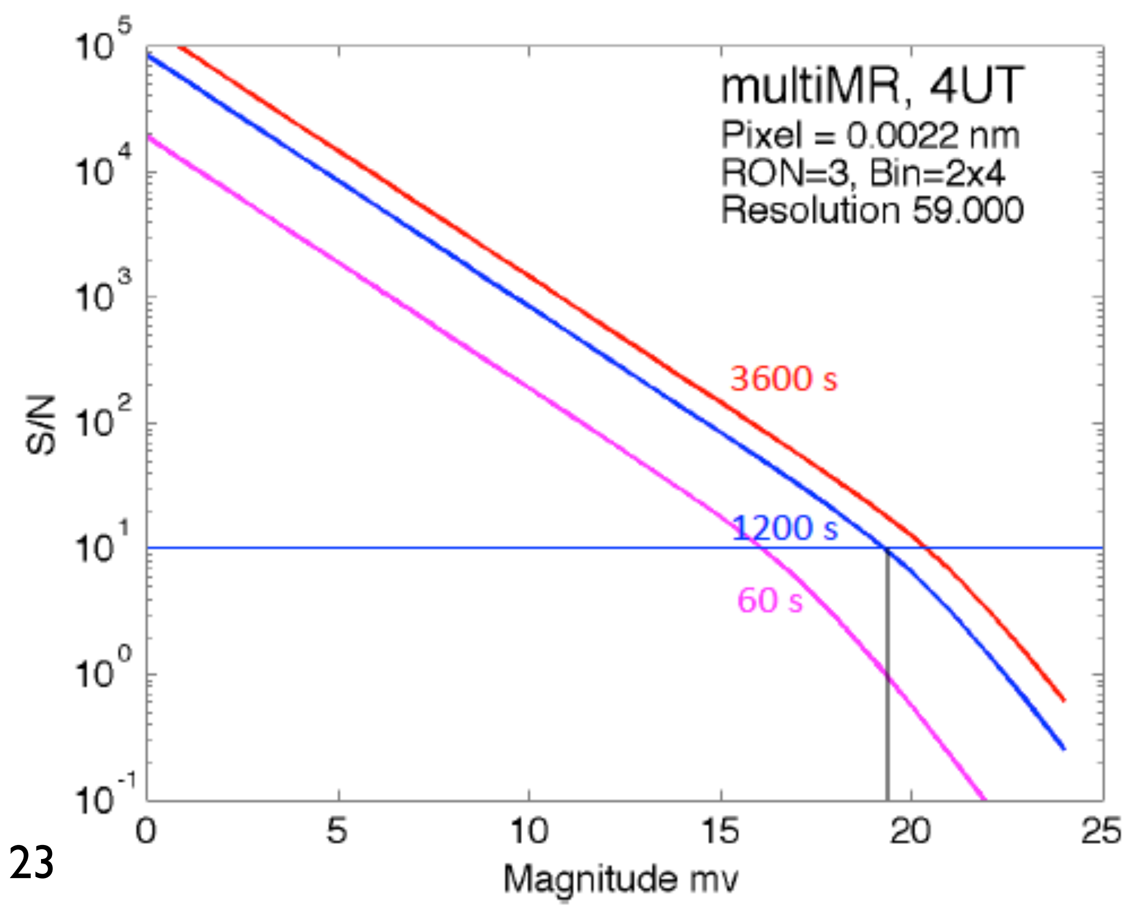
ESPRESSO is a fiber-fed, cross-dispersed, high-resolution, echelle spectrograph, which is located in the Combined-Coudé Laboratory (incoherent focus) where a front-end unit can combine the light from up to 4 Unit Telescopes (UT) of the VLT.



ESPRESSO for the IGM

Parameter/Mode	singleHR (1 UT)	multiMR (up to 4 UTs)	singleUHR (1 UT)
Wavelength range	380-780 nm	380-780 nm	380-780 nm
Resolving power	134’000	59’000	225’000
Aperture on sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Spectral ampling (average)	4.5 pixels	5.5 pixels (binned x2)	2.5 pixels
Spatial sampling per slice	9.0 (4.5) pixels	5.5 pixels (binned x4)	5.0 pixels
Simultaneous reference	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky subtraction	Yes (no sim. ref.)	Yes (no sim. ref.)	Yes (no sim. ref.)
Total efficiency	11%	11%	5%
Instrumental RV precision	< 10 cm s^{-1}	~ 1 m s^{-1}	< 10 cm s^{-1}





Future prospects: far

HiRes@E-ELT

- HiRes is a high resolution spectrograph capable of providing a spectrum
- at R~100,000 over 0.4-2.5 μm
- International Consortium led by Italy (PI A. Marconi)

E-ELT Timeline

➢ E-ELT Construction started in 2015

- Baseline plan, first light in 2024

  MICADO, HARMONI first light; METIS, HiRes, MOS to follow;
- If Brazil does not ratify by end of 2016, go to two-phase approach: first light in 2026 (or 2025)

  MICADO(+MAORY), HARMONI(+SCAO), METIS in phase 1

  HiRes, MOS, in phase 2

➢ Call for Competitive Phase A studies expected for July

Community White Paper: Maiolino et al. 2013, ArXiV:1310.3163