Metals outside galaxies: what do we learn from observations?

Valentina D'Odorico
INAF – Osservatorio Astronomico di Trieste

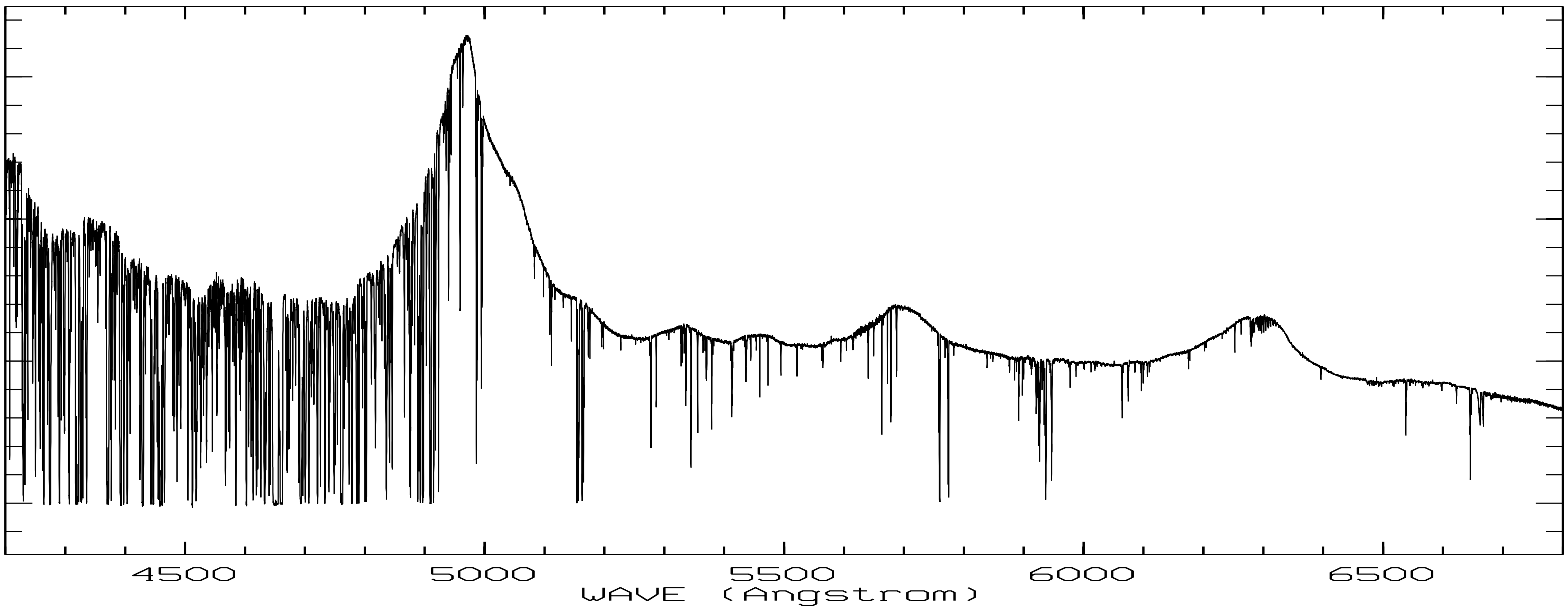
INAF – OARoma 16 febbraio 2016

Collaborators

DEEP SPECTRUM PROJECT

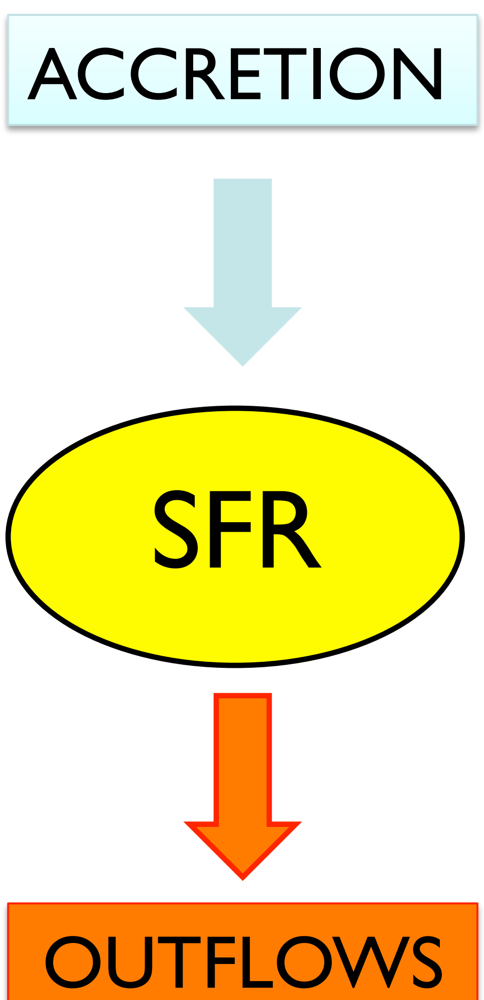
Paramita Barai, George Becker, Francesco Calura, Bob Carswell, Stefano Cristiani (Proposal P.I.), Guido Cupani, Fabio Fontanot, Martin Haehnelt, Tae-Sun Kim, Jordi Miralda Escude, Alberto Rorai, Eros Vanzella, Matteo Viel

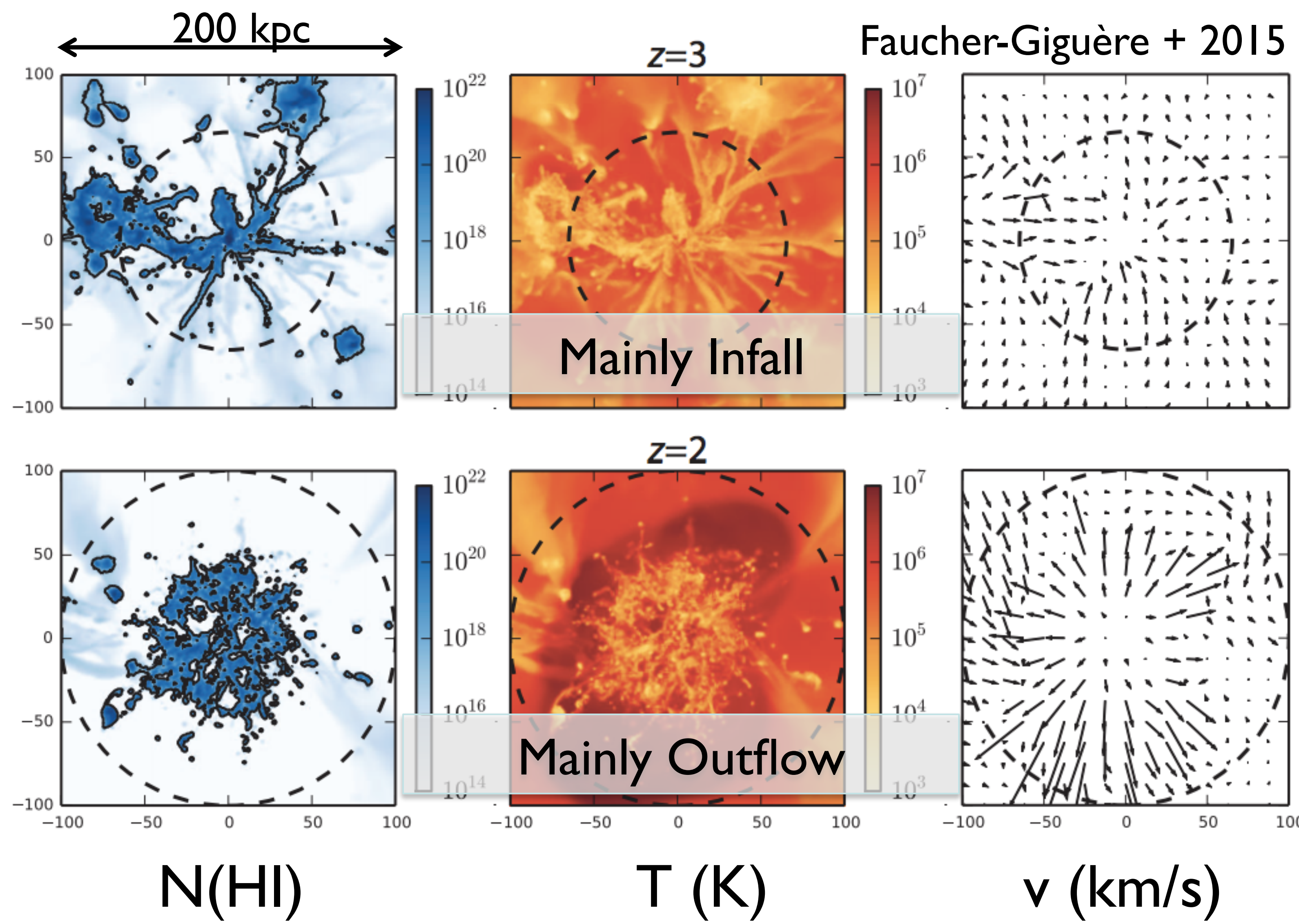
PhD students: Chiara Mongardi, Serena Perrotta, Emanuele Pomante



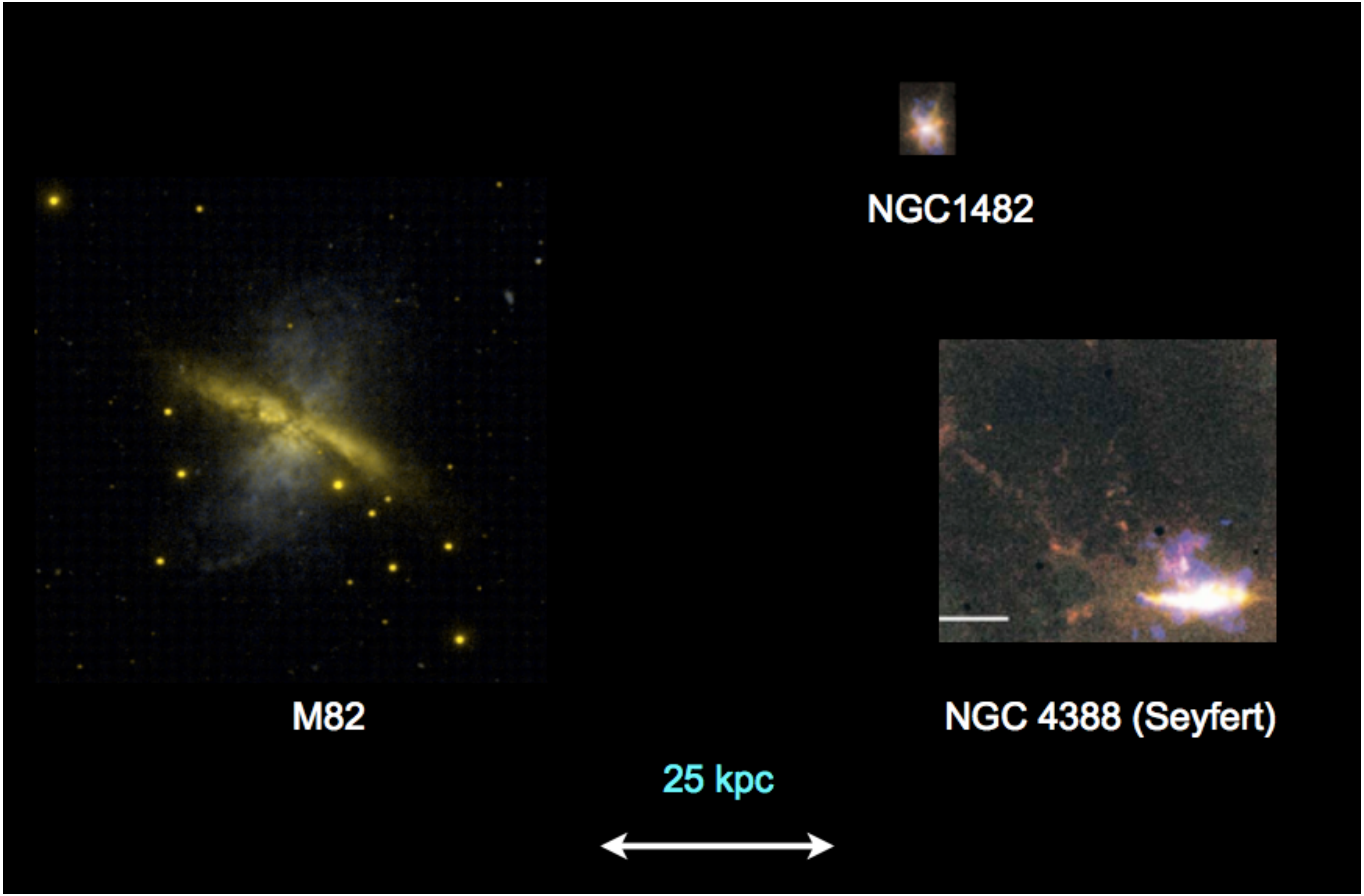
The cycle (and re-cycle) of baryons

- 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)



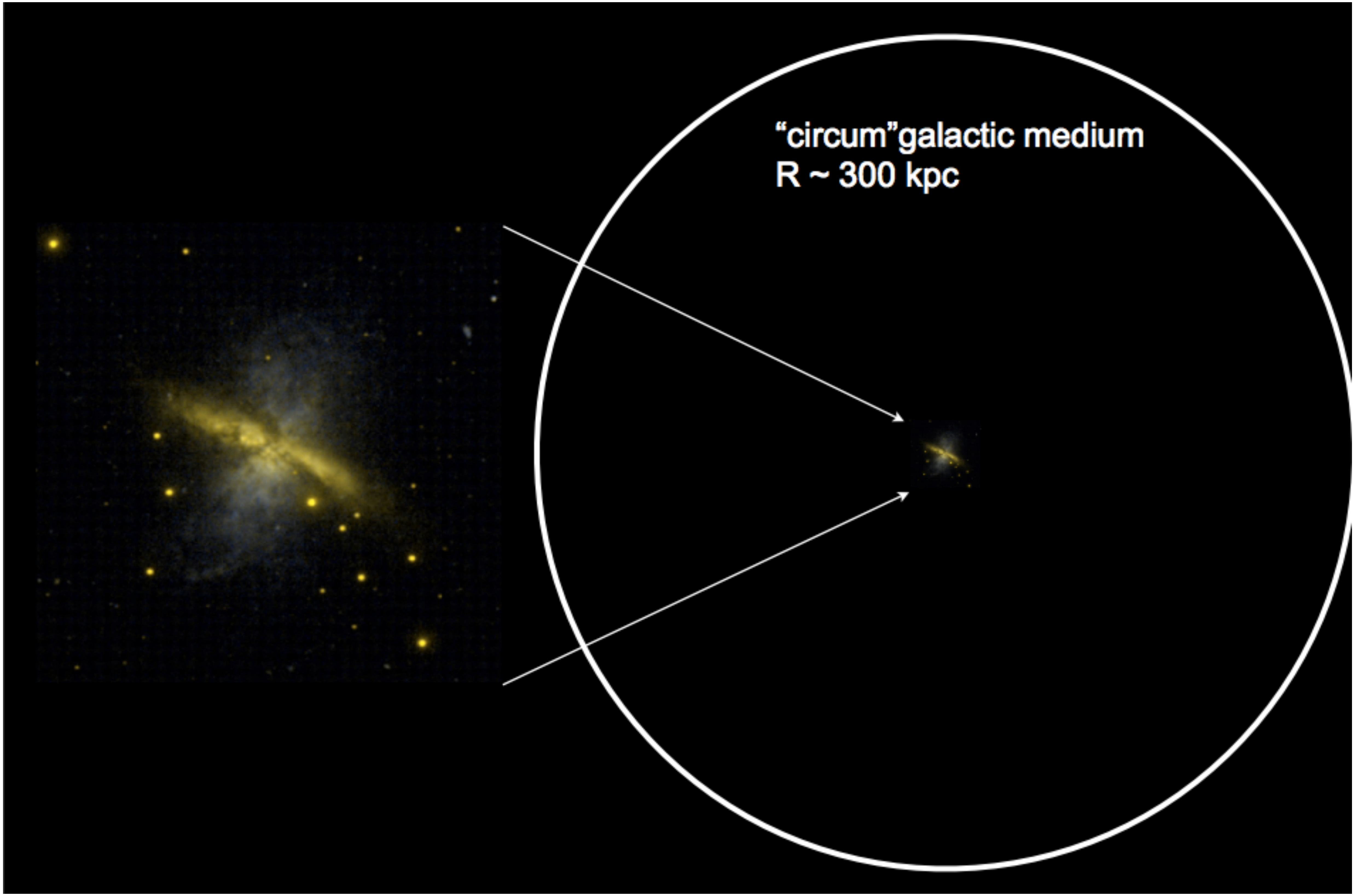


Local winds are observed



Credits: M. Rauch

Observed winds vs CGM

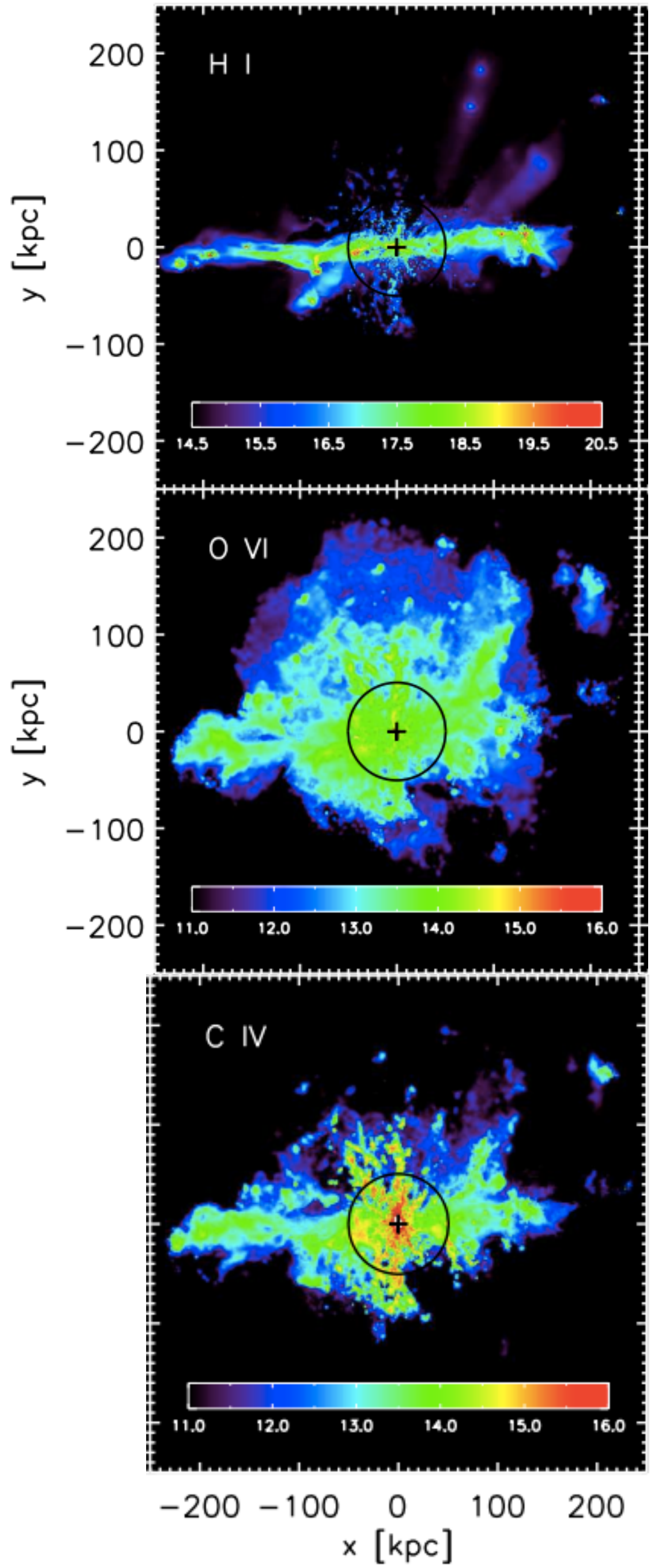


Credits: M. Rauch

The cycle (and re-cycle) of baryons

z=2.8

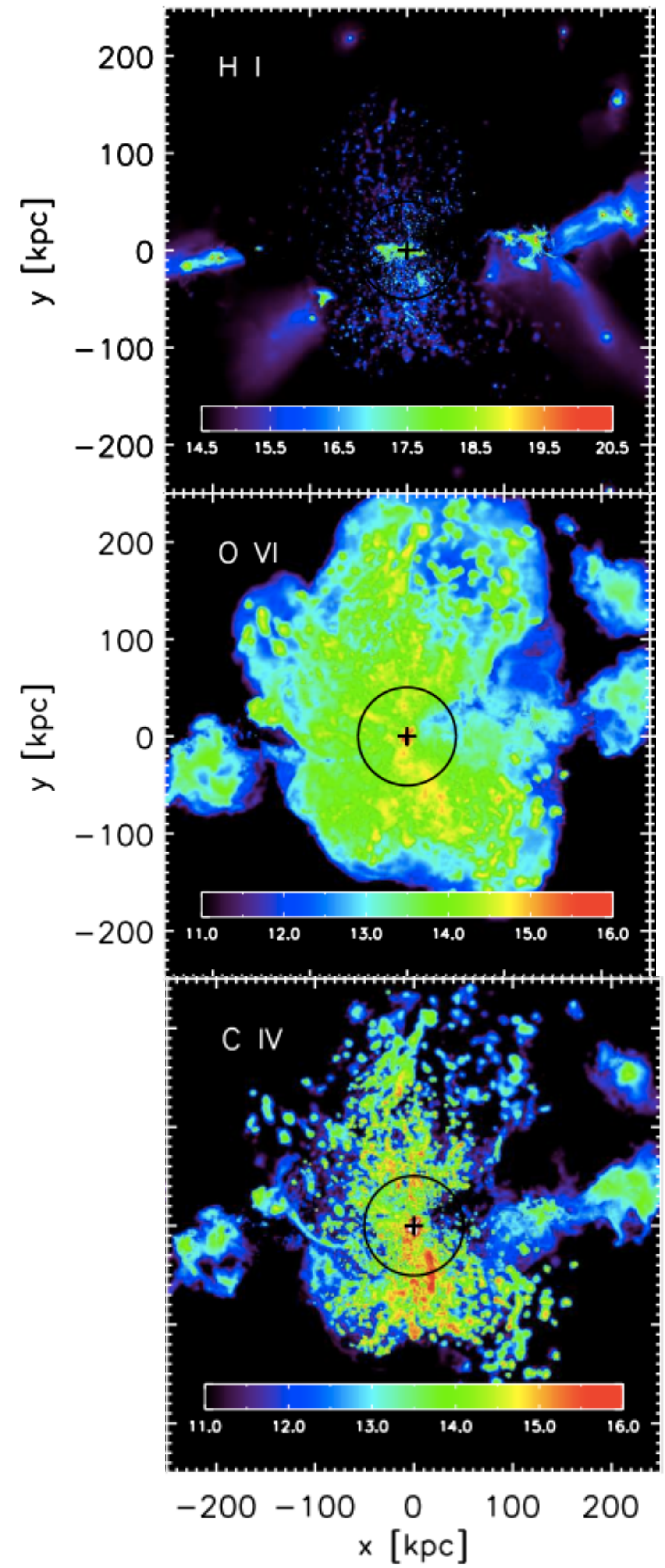
INFLOWING



HI

OVI

CIV

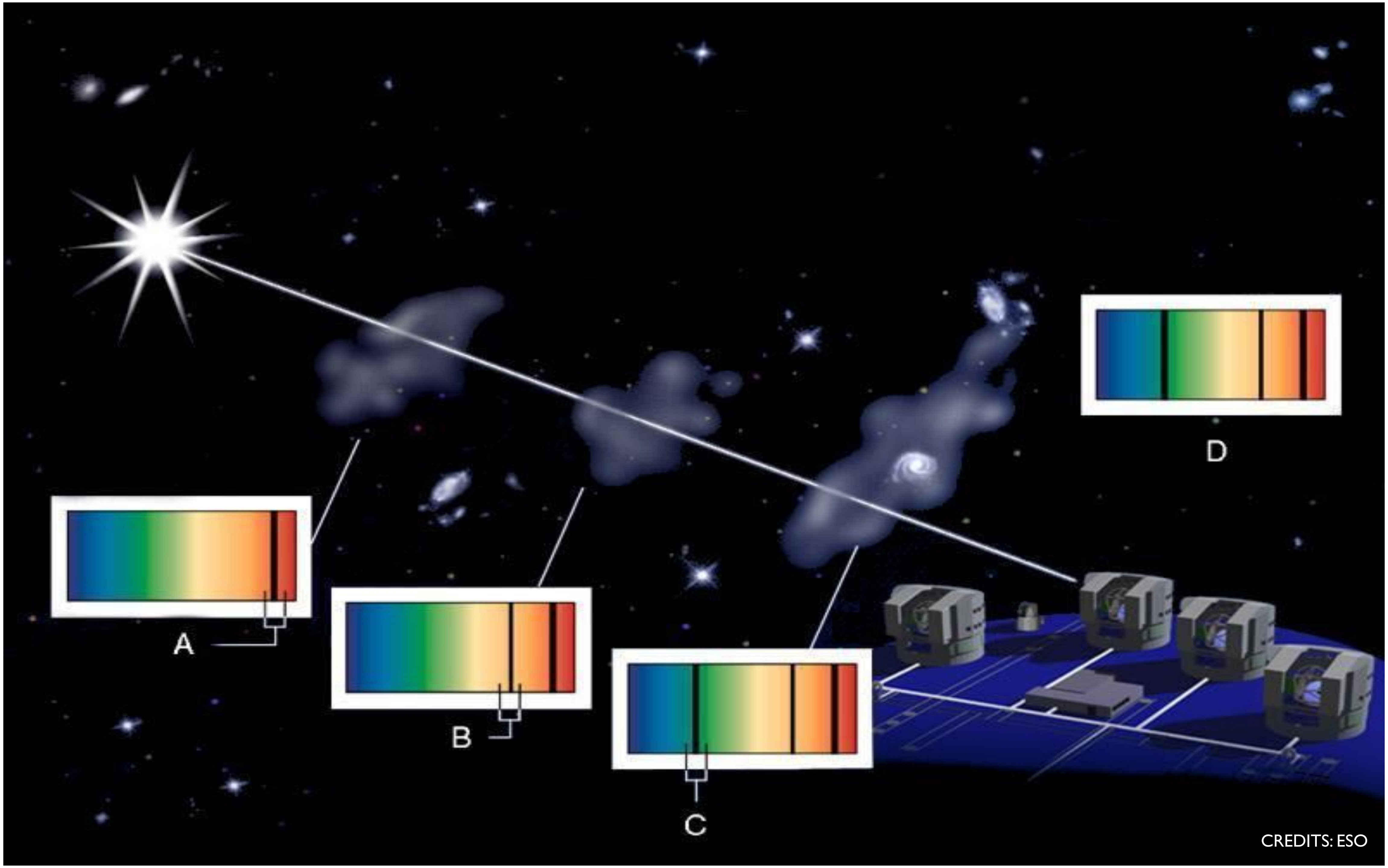


OUTFLOWING

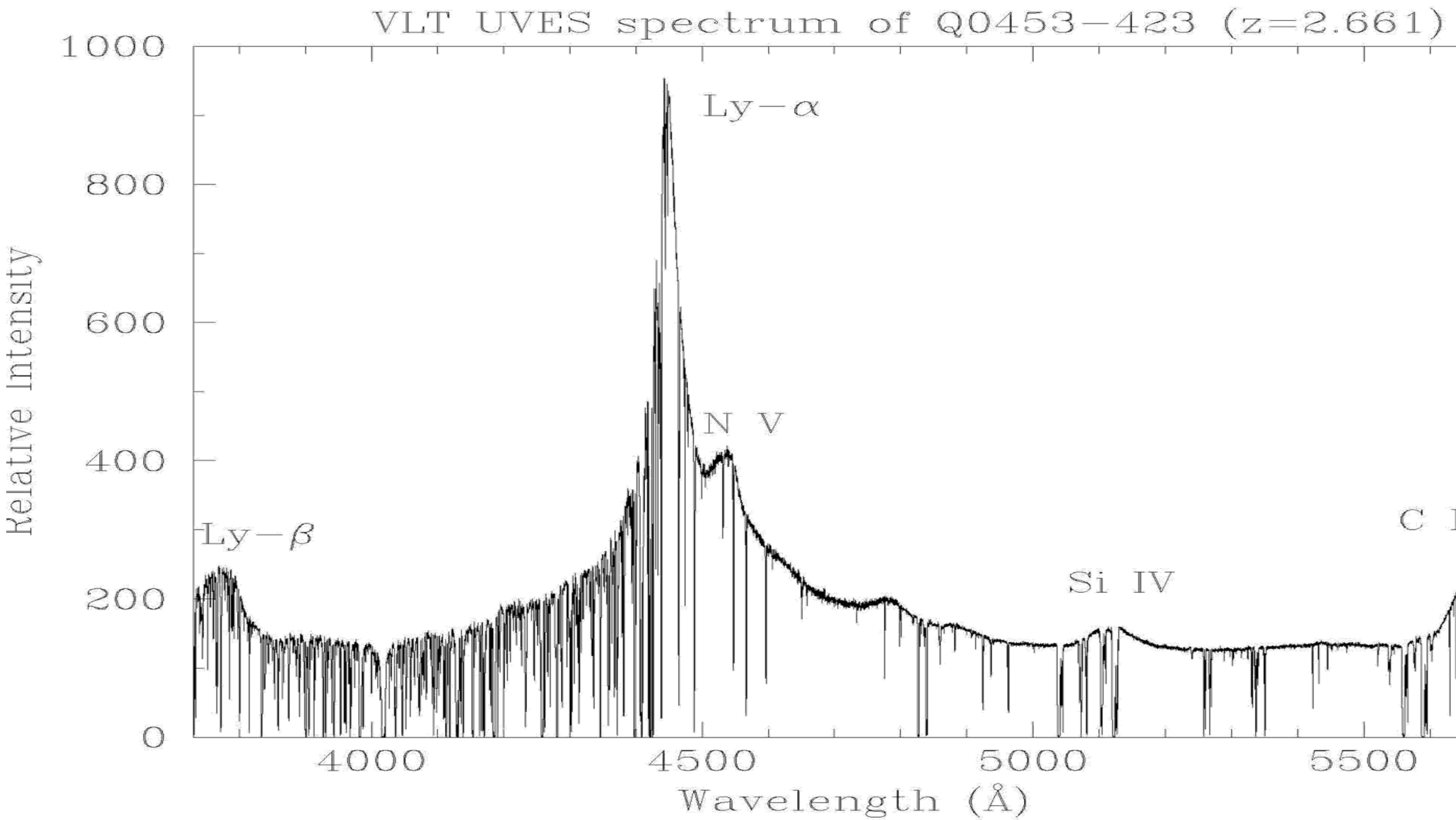
Shen et al 2013

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

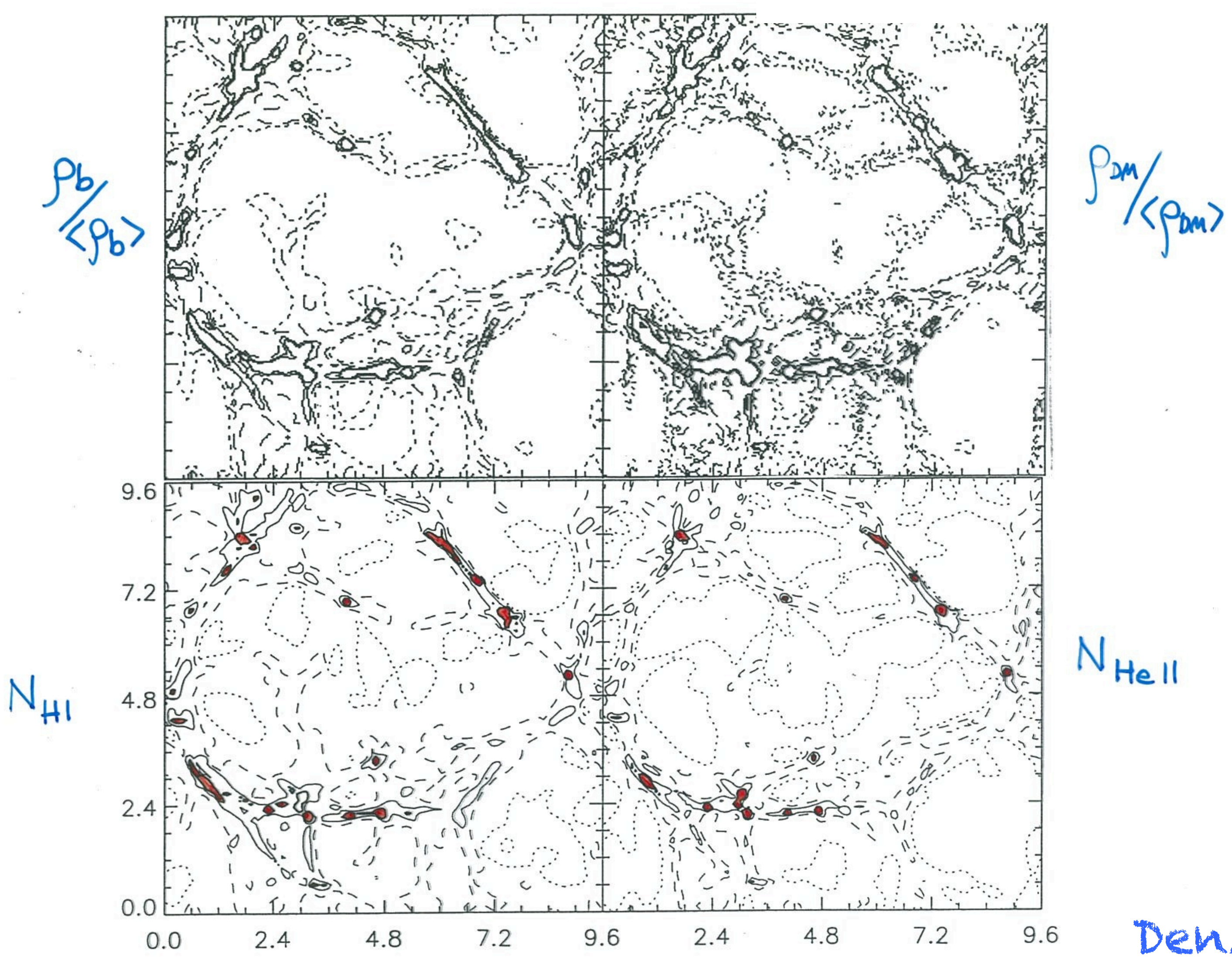


The cycle (and re-cycle) of baryons



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:

$(\delta+1) = \rho_b/\langle\rho_b\rangle \leq$ 5-10

➔ $\rho_b \cong \rho$

(smoothed at the IGM scale)

Density contrast

......	0.5
- - - -	1
——	3
——	5

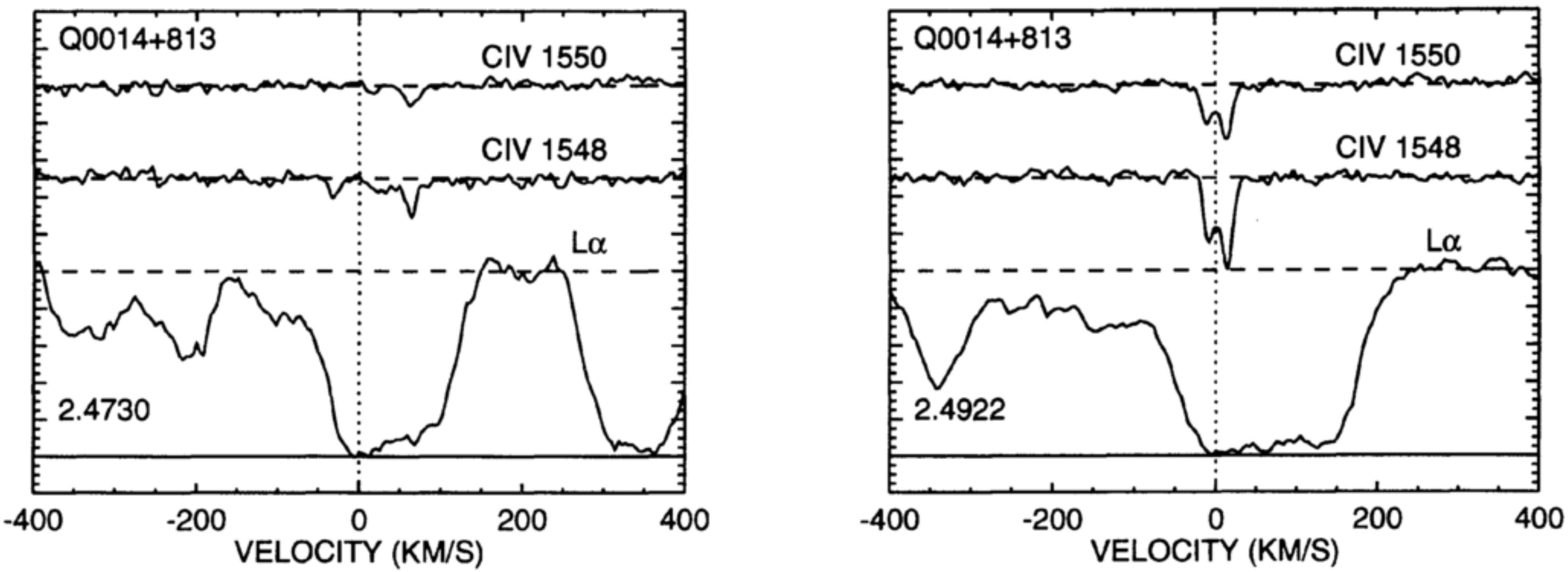
Column density

......	$\log N_{HI}$ = 12
- - - -	13
——	14
——	15

Metals in the IGM

2015 20th anniversary

Metals outside galaxies detected by their absorption lines in high-z QSO spectra, thanks to the advent of 8-10m class telescopes and high-resolution spectrographs (HIRES, UVES) Tytler et al. 1995 Cowie et al. 1995



All Lya systems with log N(HI) > 15 and 50-60 % of those with log N(HI) > 14.5 show associated CIV lines

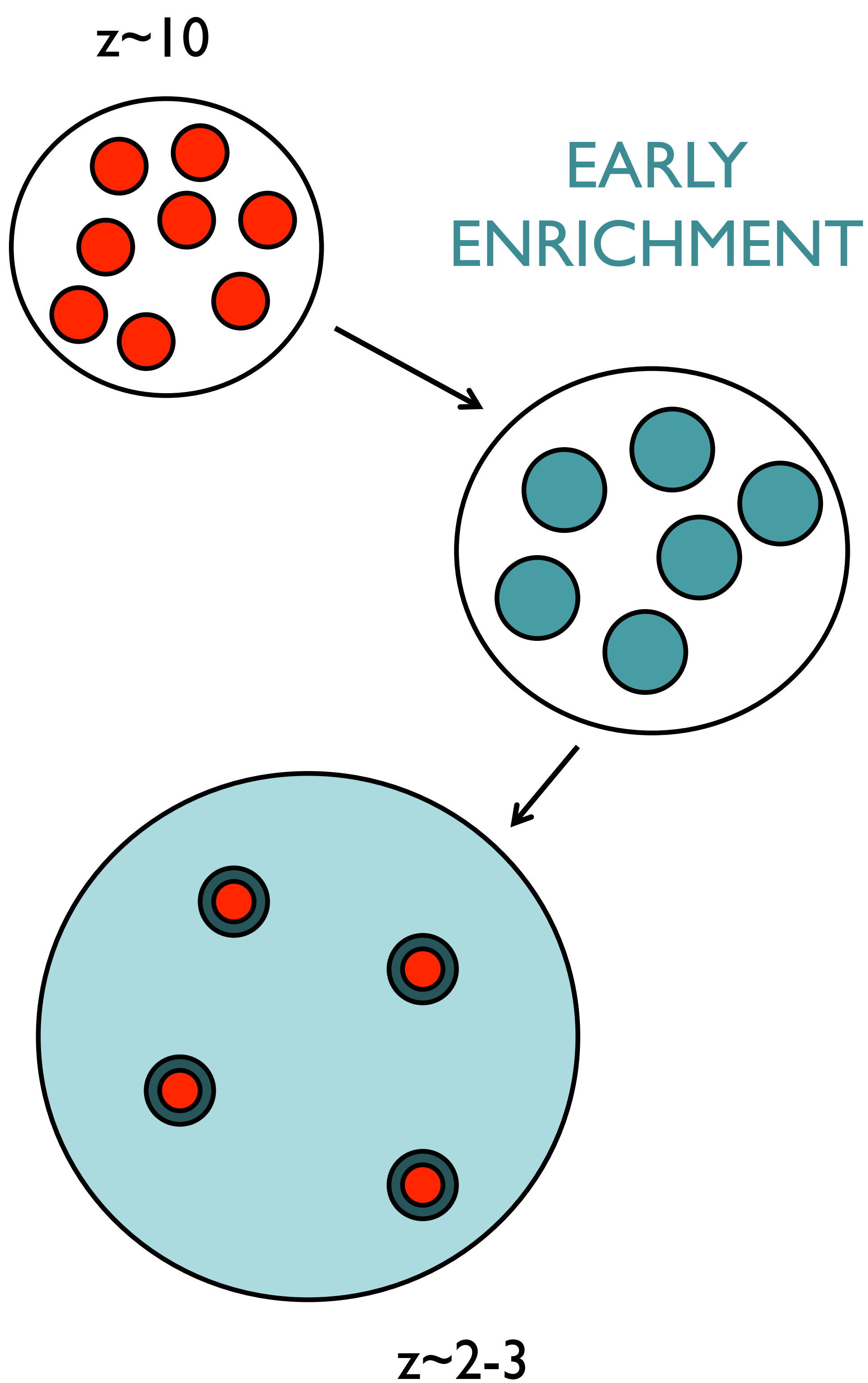
$10^{-3} < Z/Z_o < 10^{-2}$ at z~2-3

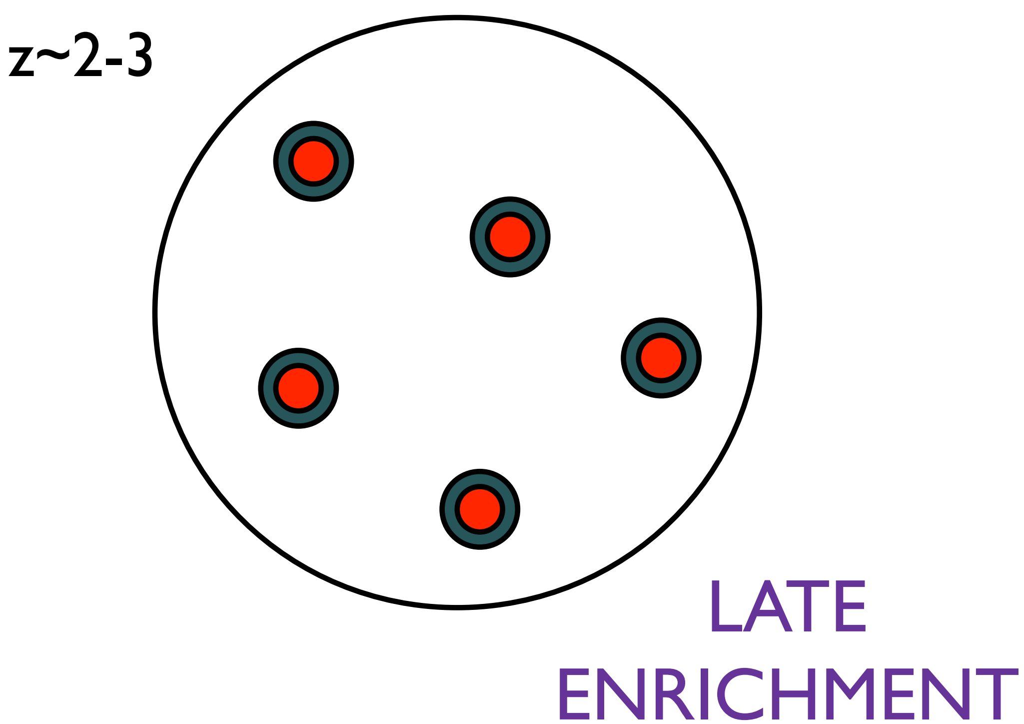
What is the origin of the observed metals?

Enrichment scenarii

- Old metals from previous generations of galaxies ➔ sprinkled in the IGM to low densities, metallicity floor at $Z\sim10^{-3}$ Zo

- Fresh metals expelled from coeval galaxies ➔ clustered in the CGM



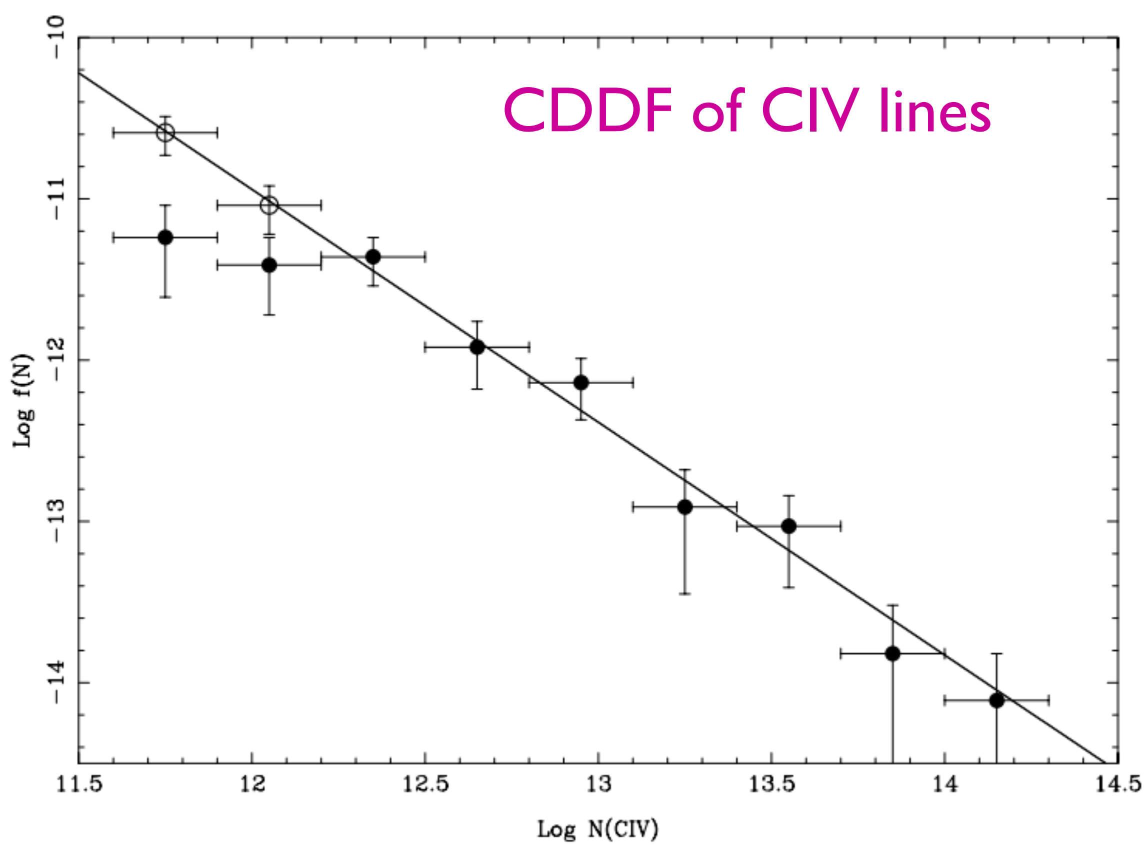


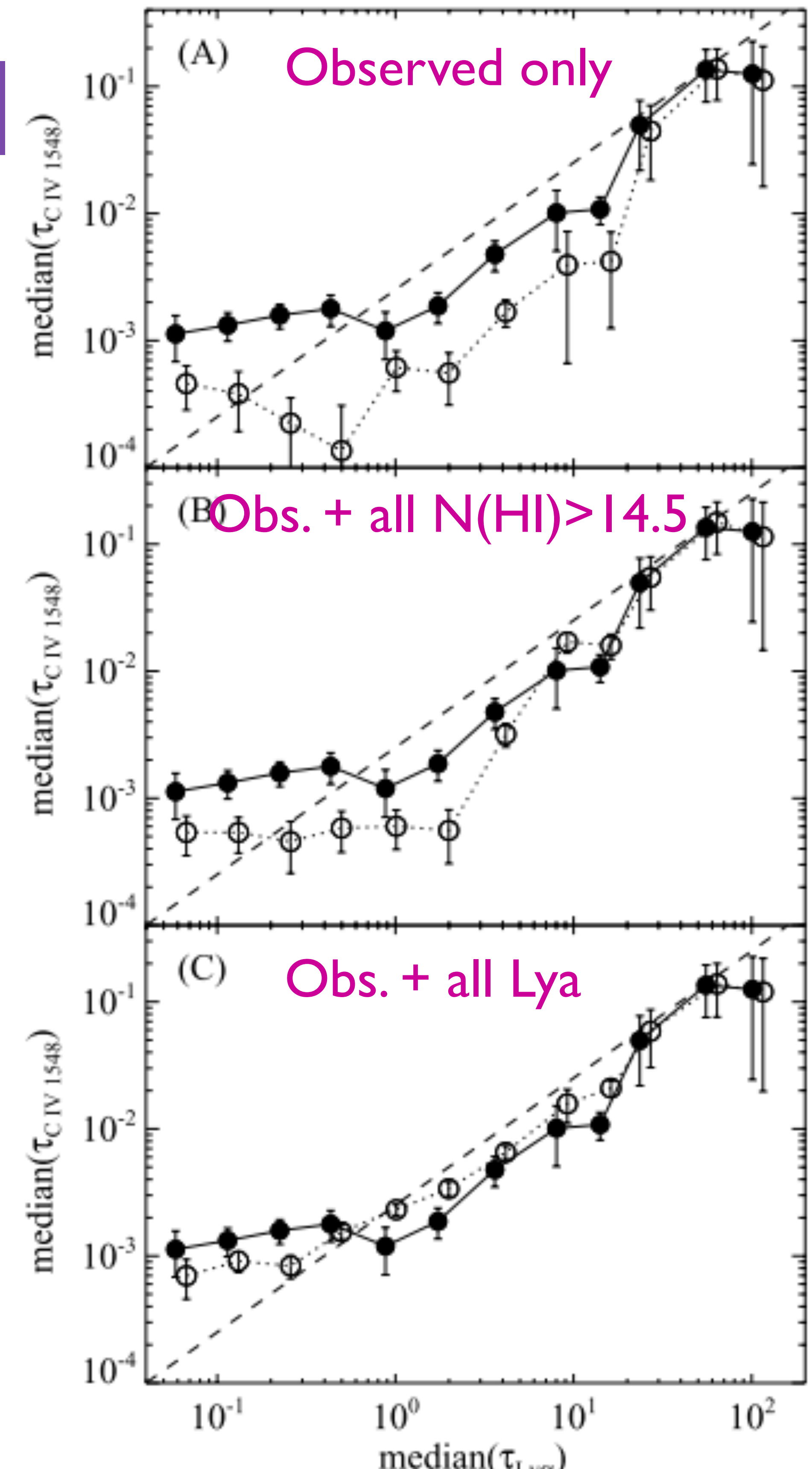
Investigate the enrichment pattern

Probe the tenuous gas

Very high signal-to-noise ratio (~200) of B1422+231

Ellison et al. 2000





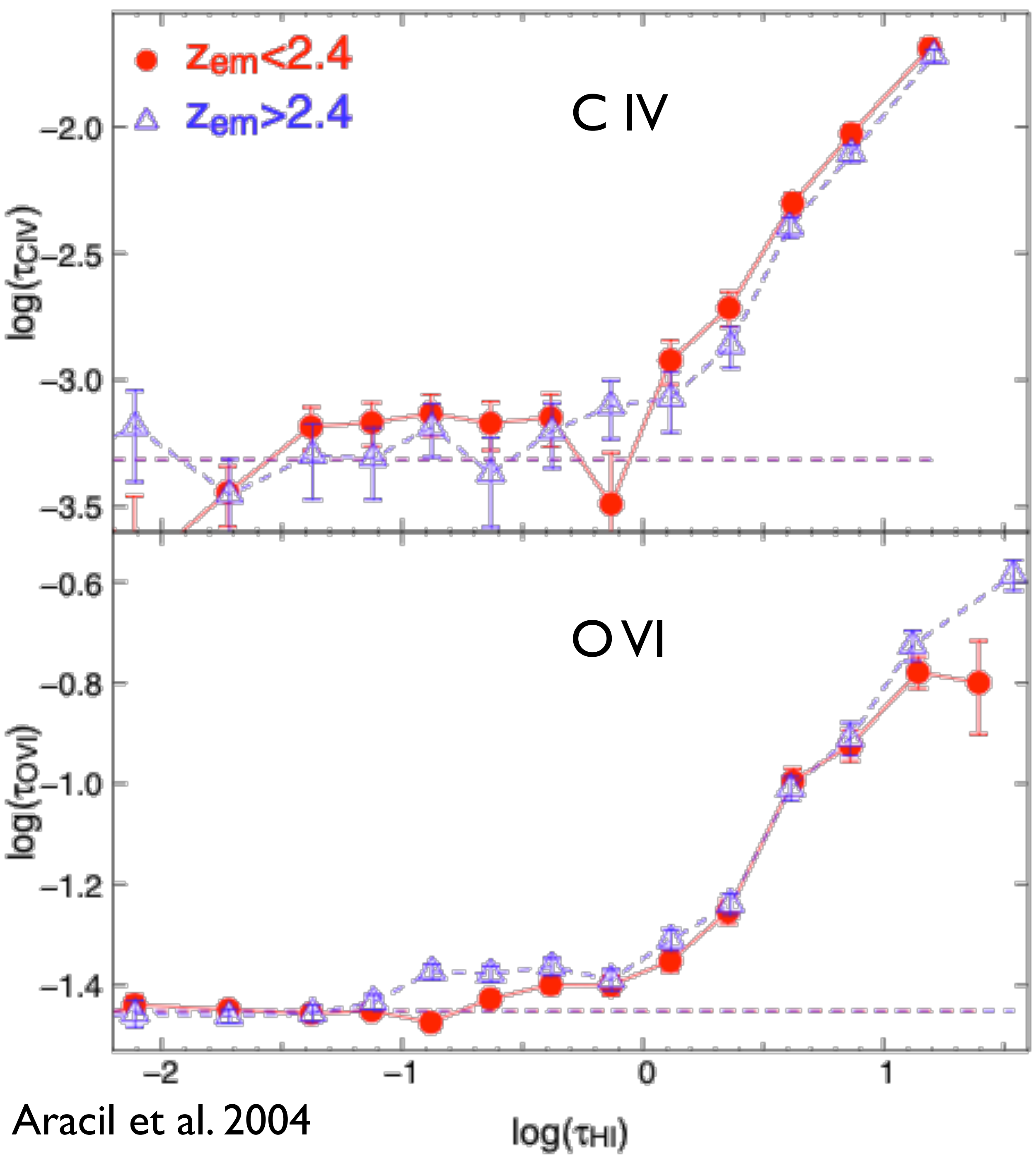
Evidence from the POD analysis that C IV associated with strong Lya lines [N(H I)> 14.5] but below the current detection limit, can reproduce the optical depths for τ(Lya)>3. For smaller values of τ(Lya), additional metals are required, associated with low column density H I lines [N(H I)<14.5].

Investigate the enrichment pattern

Probe the tenuous gas (close to the mean density)

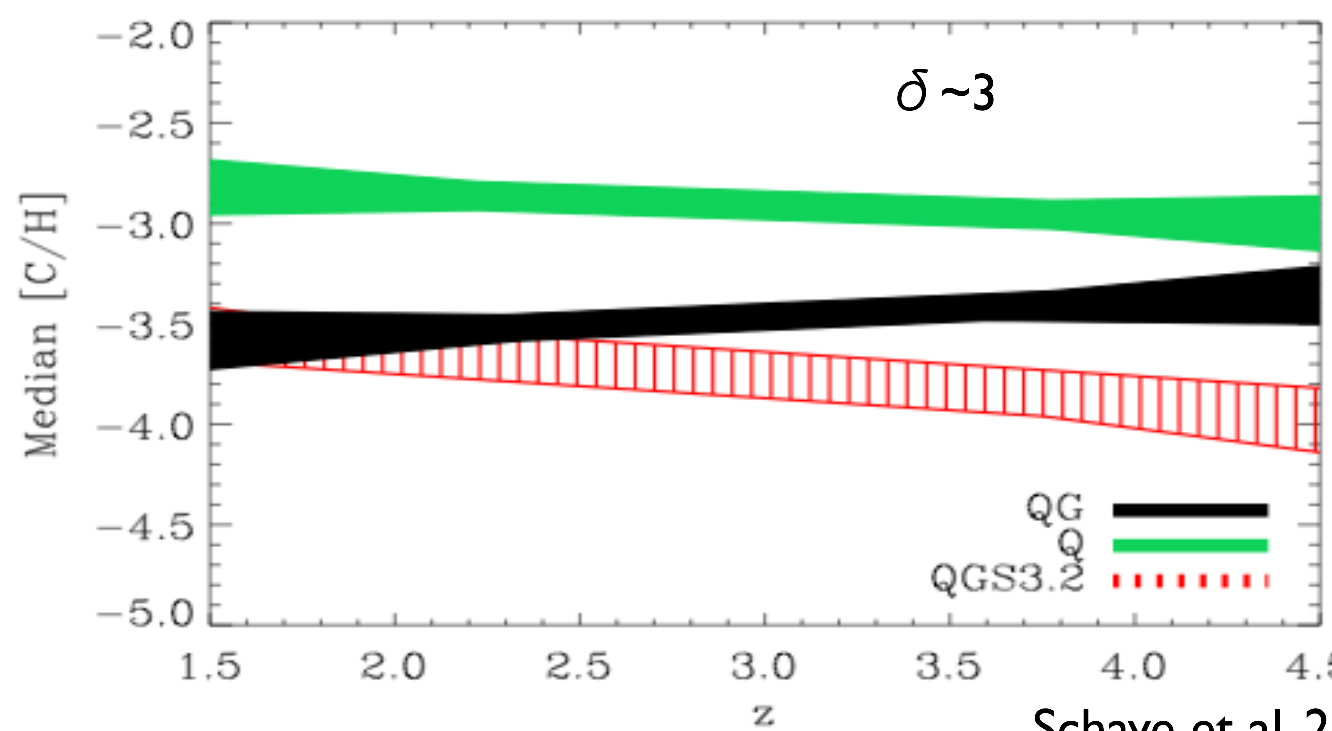
Statistical approach to detect metals at lower densities (Cowie & Songaila 1998; Ellison et al. 2000; Aguirre et al. 2002)

F = exp(-τ) : 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)

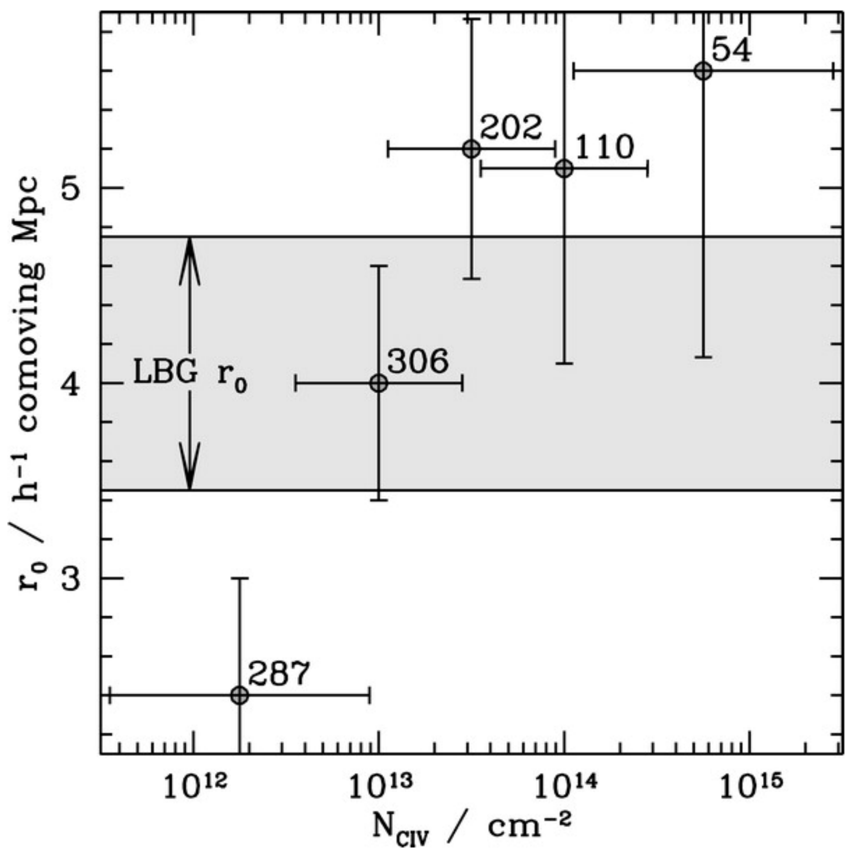


Schaye et al. 2003

Limited by SNR, contamination, continuum errors

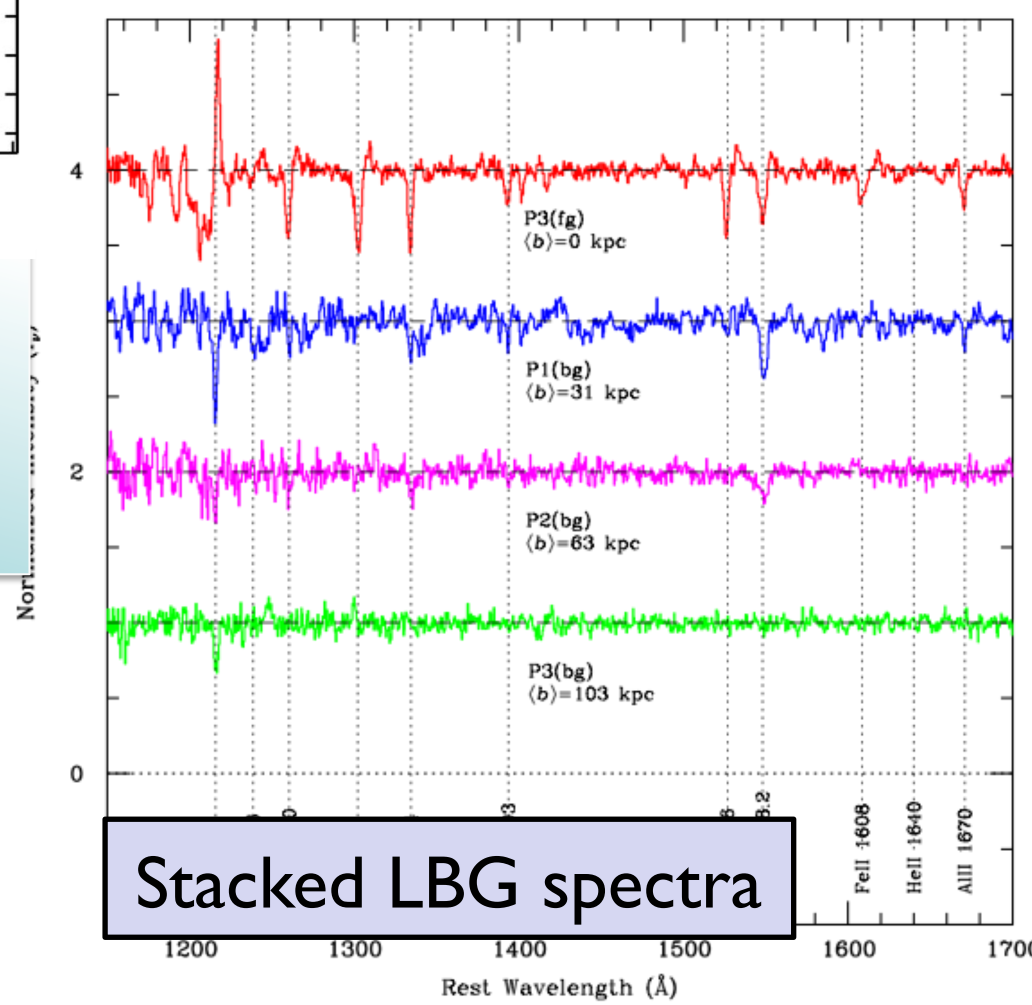
Investigate the enrichment pattern

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

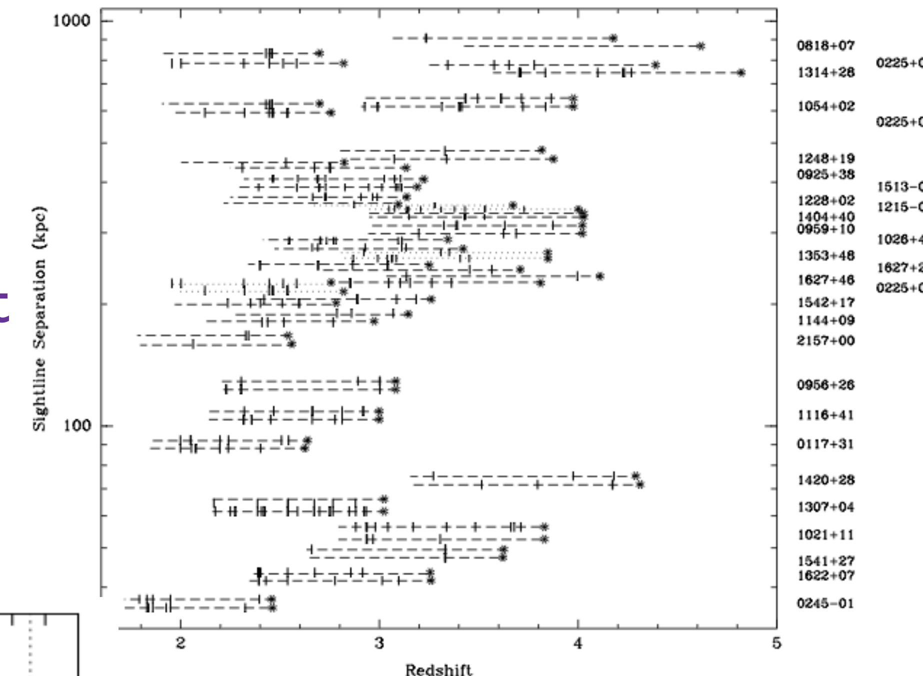


Adelberger et al. 2003, 2005: cross-correlation galaxy-CIV absorbers ➔ CGM is metal enriched out to ~300 kpc

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



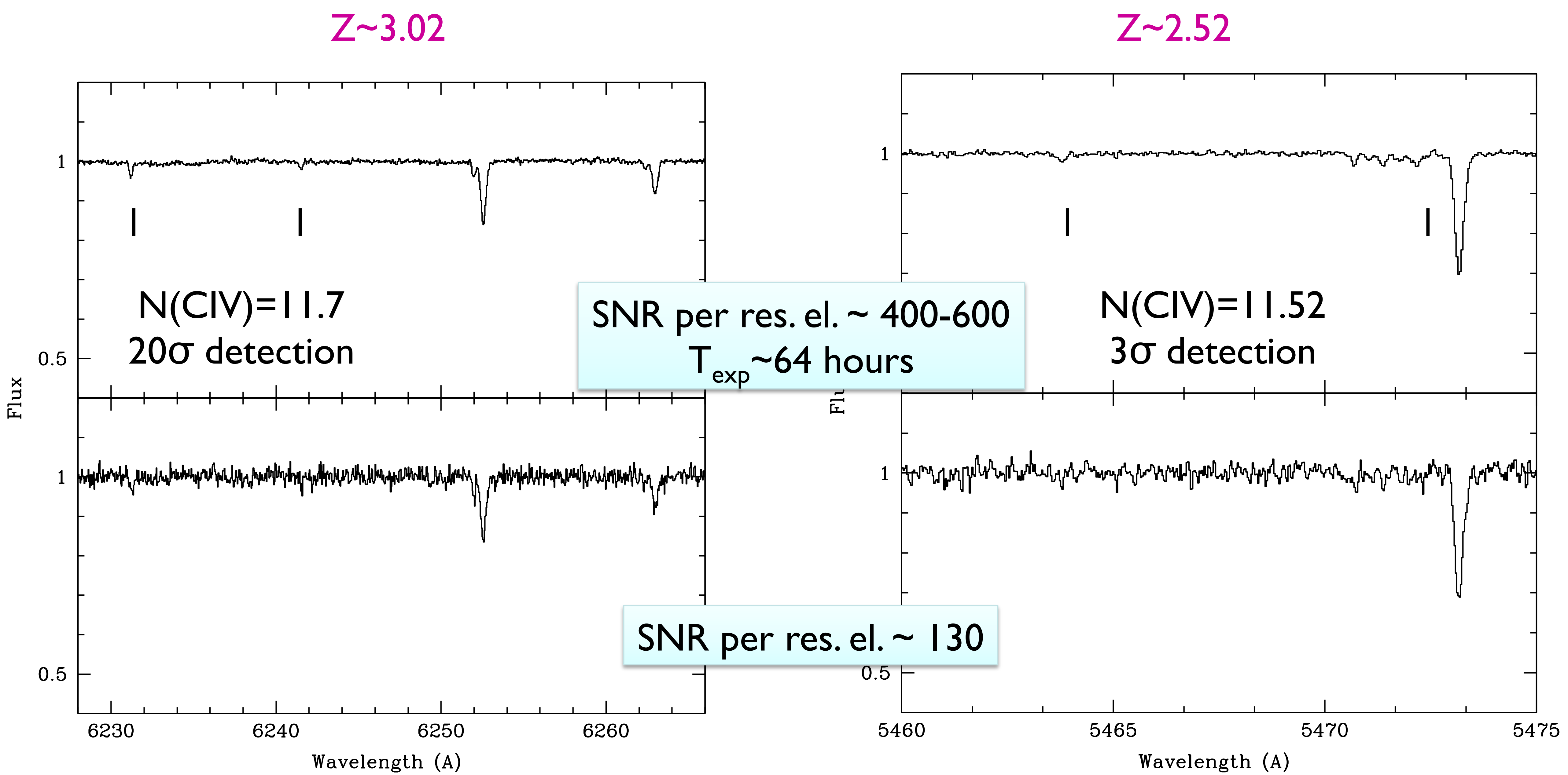
Martin et al. 2010: cross-correlation of CIV absorptions in QSO pairs. Size of enriched region ~420 h^{-1} kpc ➔ Metals deposited in the gas at z>4.3 by an earlier generation of gals

The UVES deep spectrum

D'Odorico et al. 2016

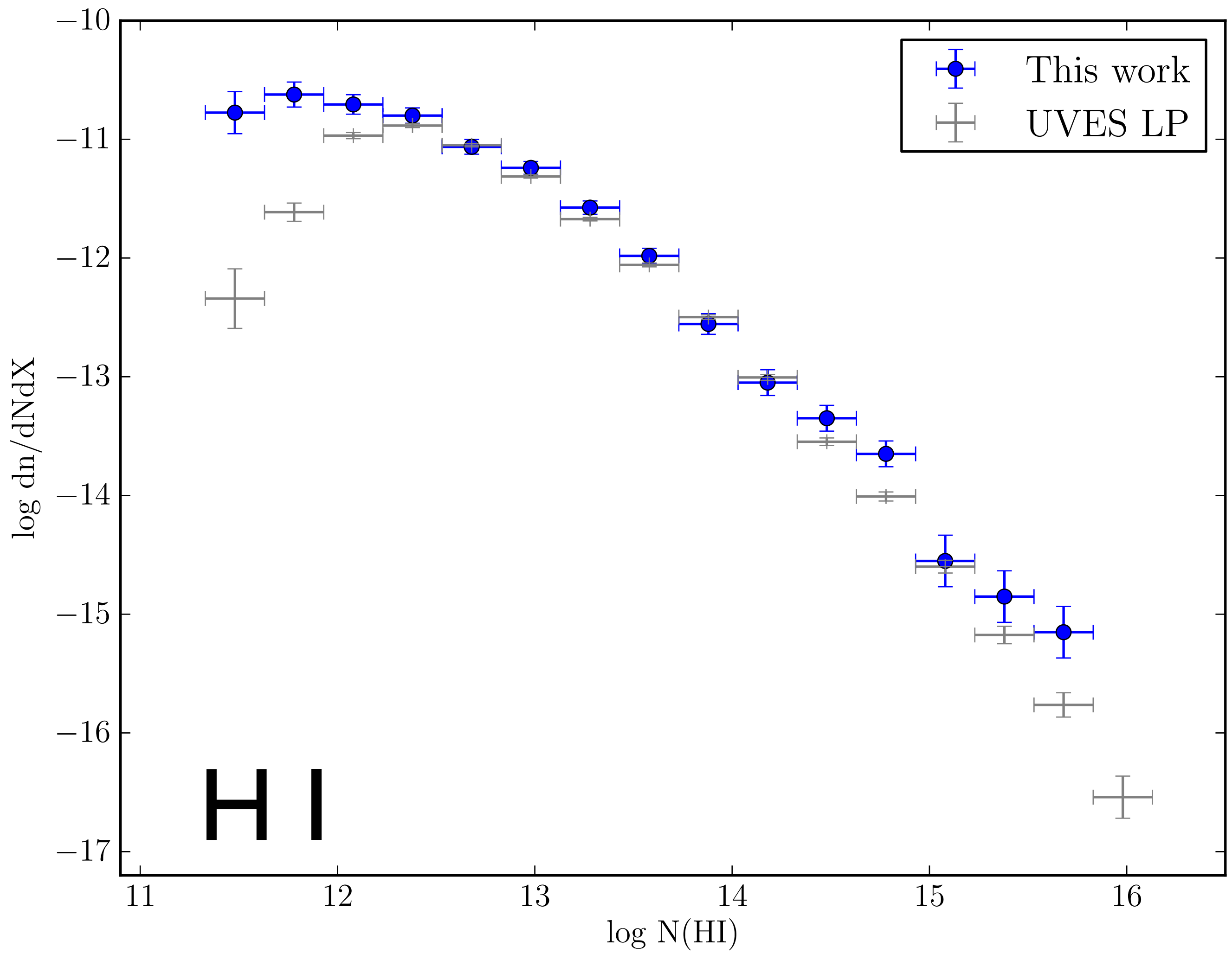
UVES DEEP SPECTRUM QSO at z_{em}~3.0 with V=16.9 T_{exp}=64 h

16 new weak isolated C IV doublets



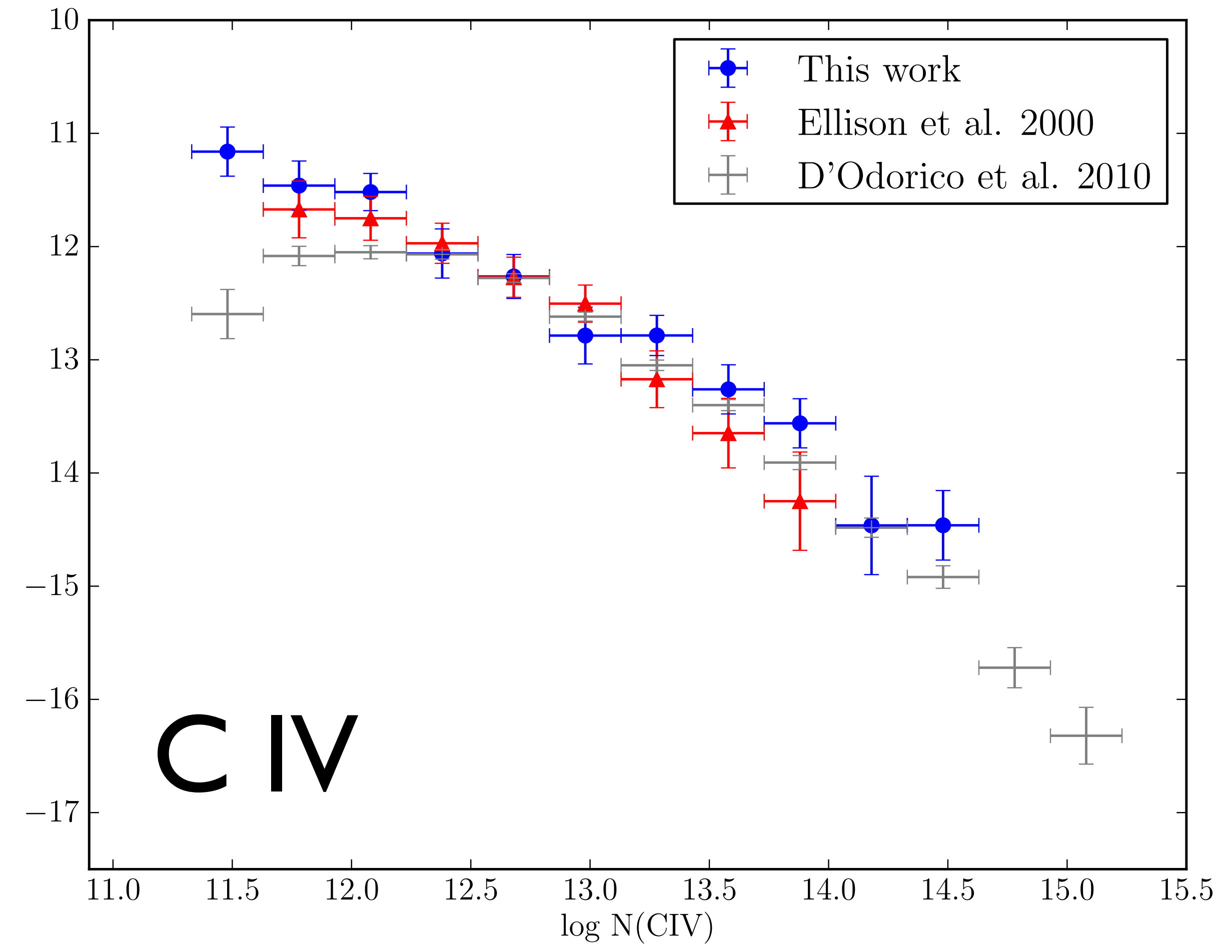
The UVES deep spectrum

Column density distribution functions



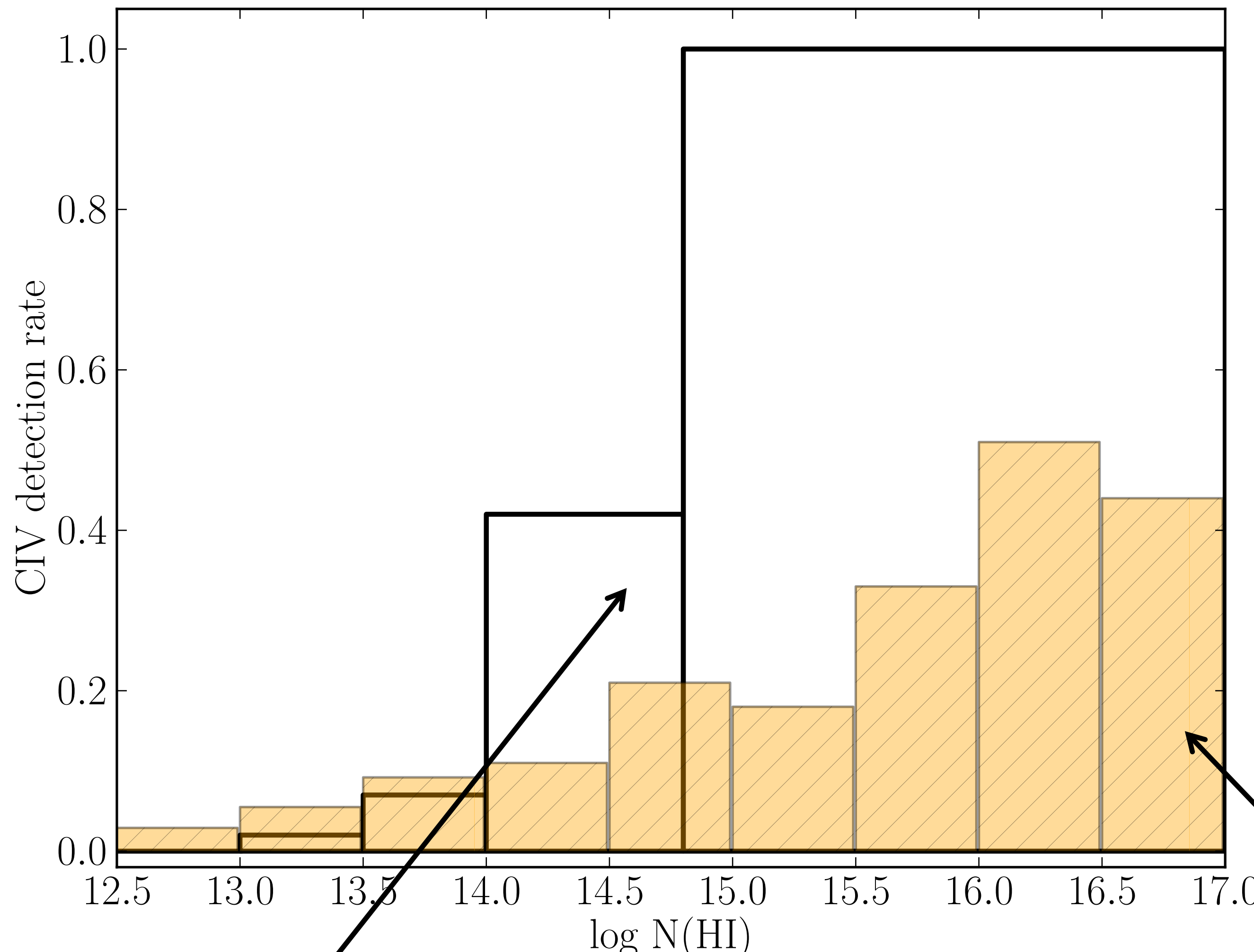
Number of lines per unit column density and per unit absorption path

$$dX \equiv (1+z)^2[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda]^{-1/2}\,dz.$$



The UVES deep spectrum

CIV detection rates and connection with galaxies

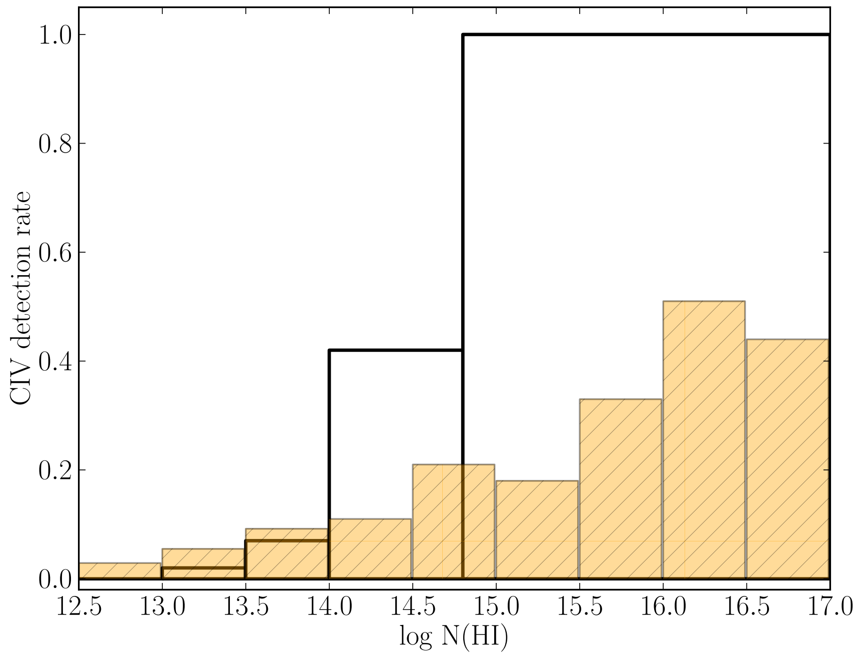


C IV detection rate = # of C IV-H I absorber pairs / # of H I absorbers

Fraction of Lyman-α lines in the CGM of LBGs at $2 \leq z \leq 2.7$, (KBSS, Rudie et al. 2012)

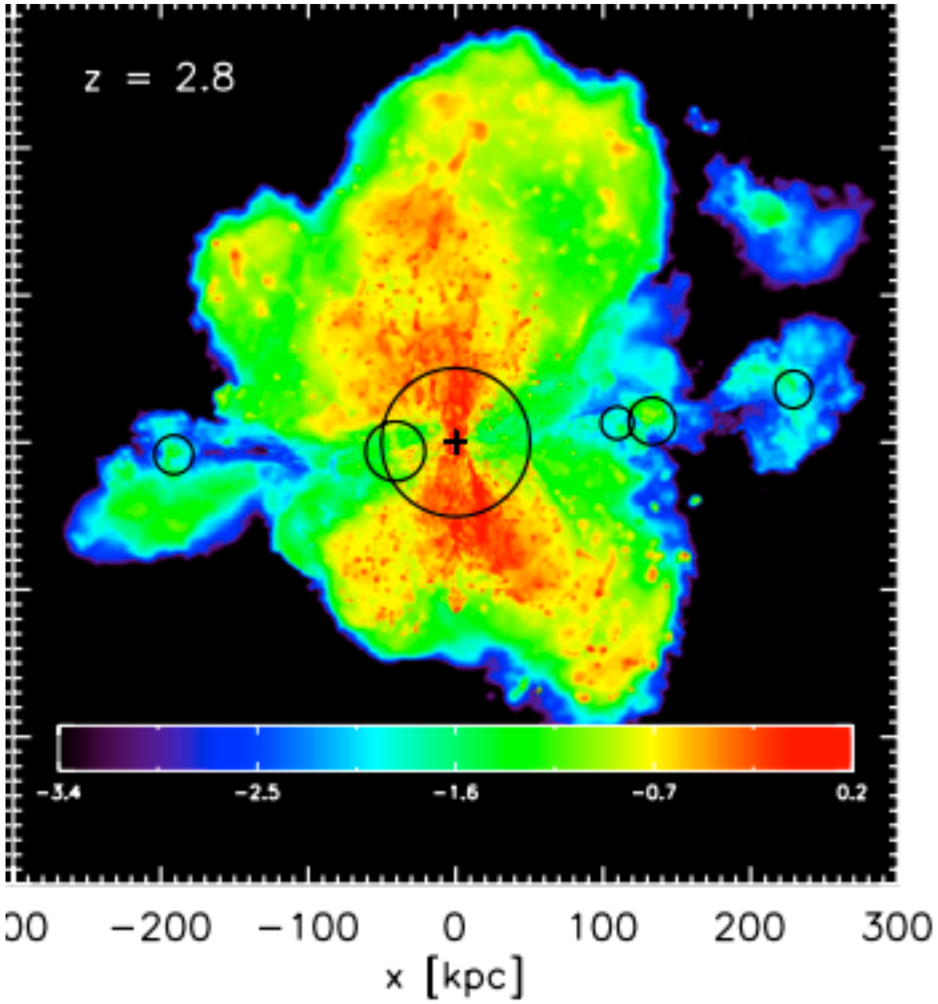
The UVES deep spectrum

CIV detection rates and connection with galaxies



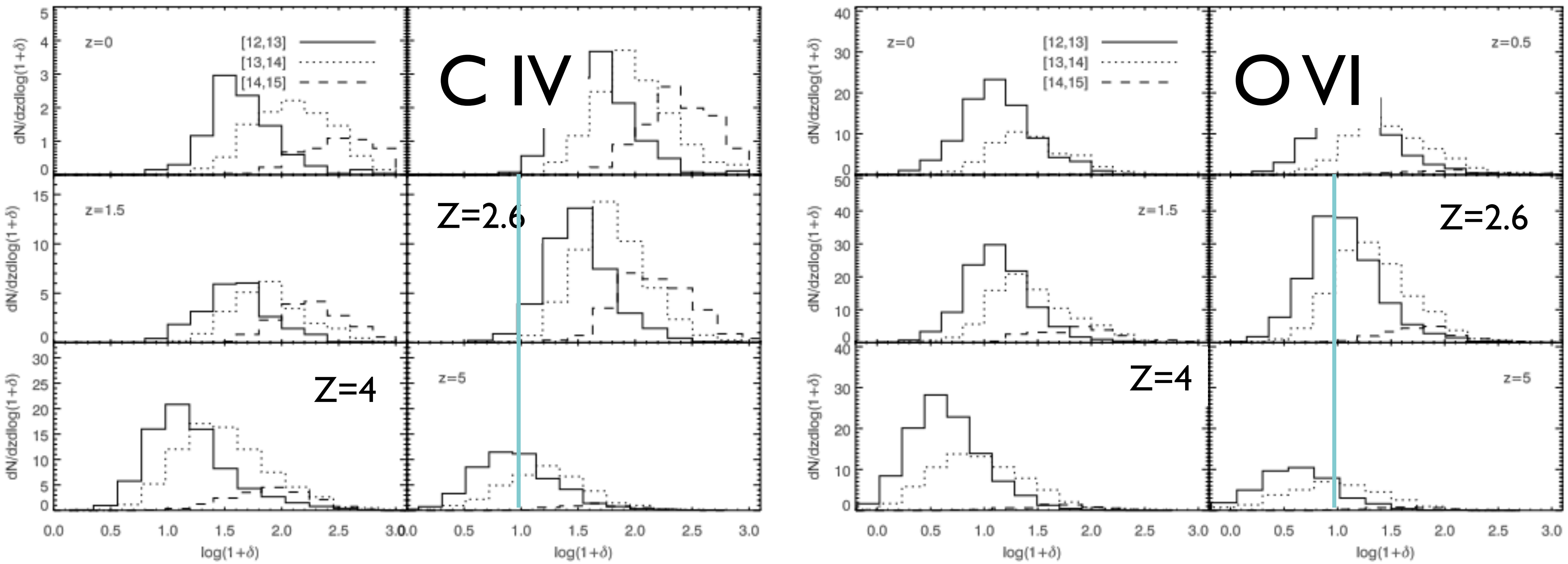
Metals are not found only in the CGM of bright star-forming galaxies at z~2-3 (LBGs).

They have to lie also around smaller galaxies.
Possibly, they have been produced at larger redshifts.



Metal enrichment at large distances from the main galaxy is due also to satellite dwarf galaxies (Shen et al. 2013)

The UVES deep spectrum



Cen & Chisari 2011

O VI better tracer of metallicity at low densities at z~2.6

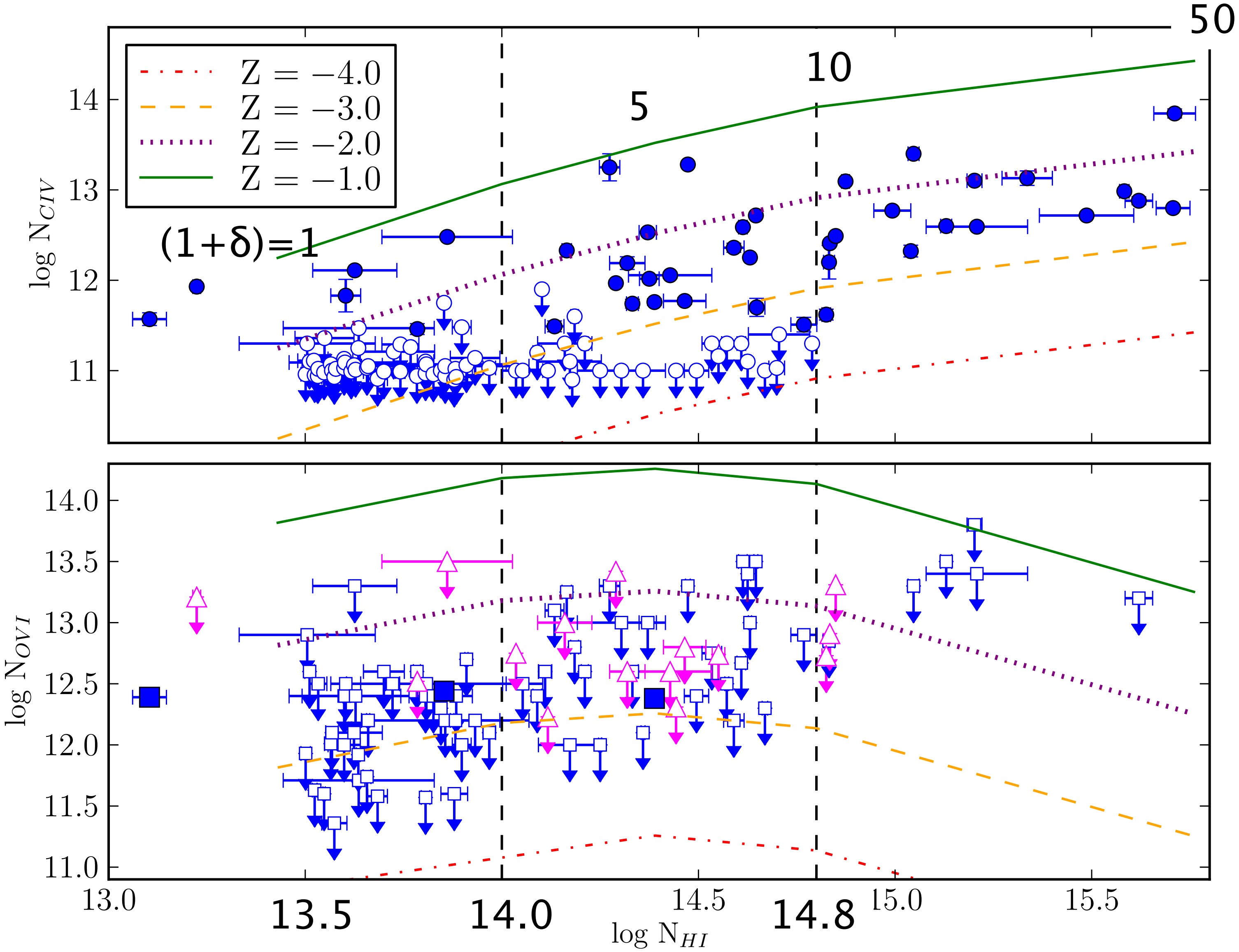
DRAWBACK: blended in the Lyb/Lya forests

The UVES deep spectrum

The metallicity of the IGM

N_{CIV} vs N_{HI}

N_{OVI} vs N_{HI}



Cloudy models
HM background
Solar relative abundances
Fixed $T=10^4$ K

Assumption: the Jeans scale is the characteristic scale of the IGM. Used to transform N_{HI} into $(1+\delta)$

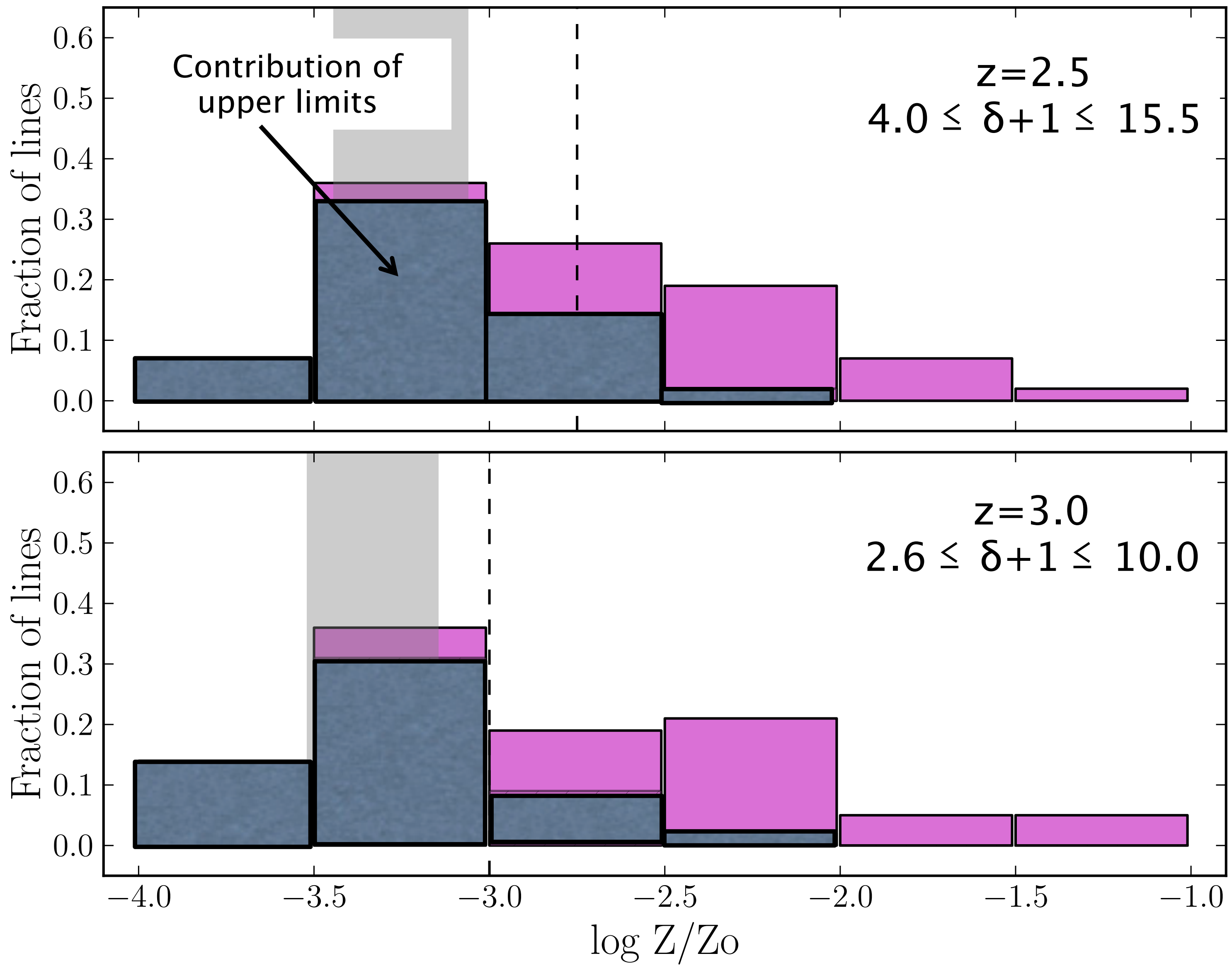
- ✧ All HI lines with log $N_{HI} \geq 14.8$ have an associated CIV line. They reside preferentially in complex systems and trace the CGM.
- ✧ 43 % of lines with $14 \leq \log N_{HI} < 14.8$ have an associated CIV line. They already trace the IGM.
- ✧ At log $N_{HI} < 14$ less than 10 % of HI lines have an associated CIV line.

The UVES deep spectrum

The metallicity of the IGM

$14 \leq \log N_{HI} < 14.8$

Fraction of CIV lines



Cloudy models

HM background

Solar relative abundances

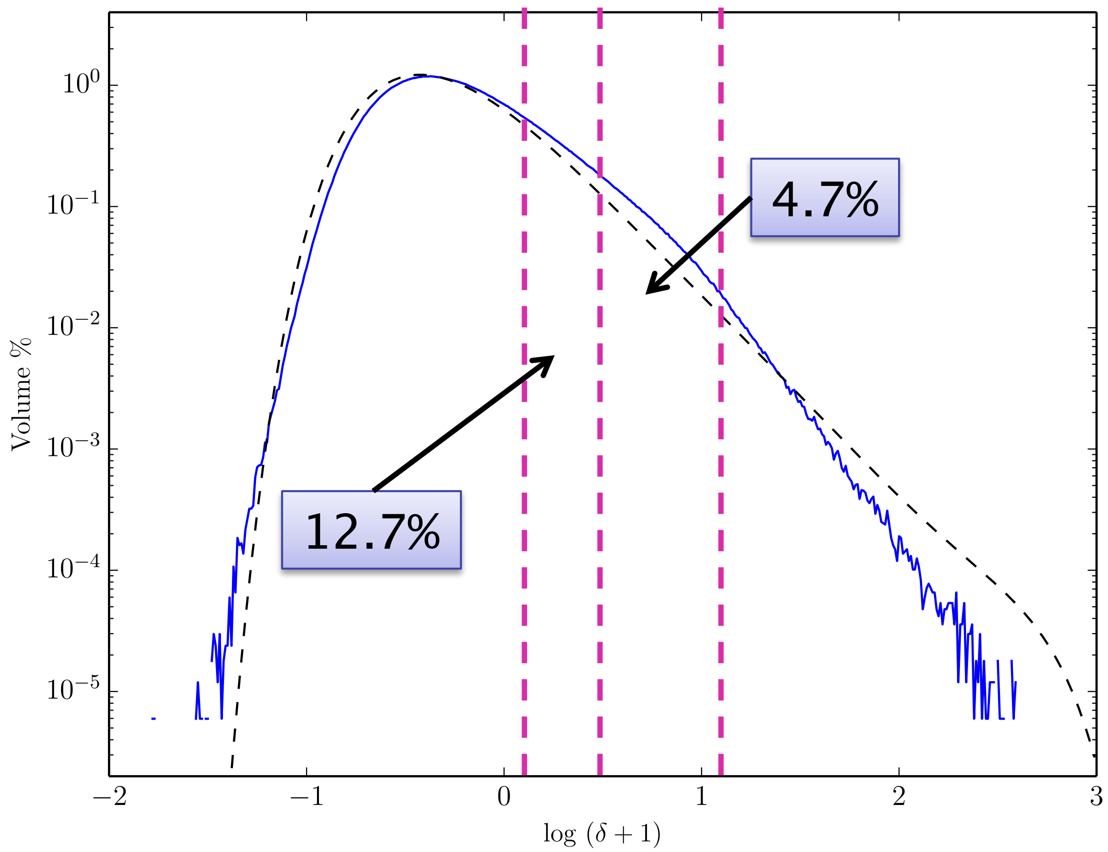
Fixed $T=10^4$ K

- ✧ 50-60 % of lines with metallicity $-3 \leq \log Z/Z_o < -1$
- ✧ 40-50 % of lines with $\log Z/Z_o < -3$

In the range of overdensities $(\delta+1) \sim 1.1-1.7$ to $2.6-4.0$ probed by OVI at least 27 % of lines has $\log Z/Z_o < -3$.

The UVES deep spectrum

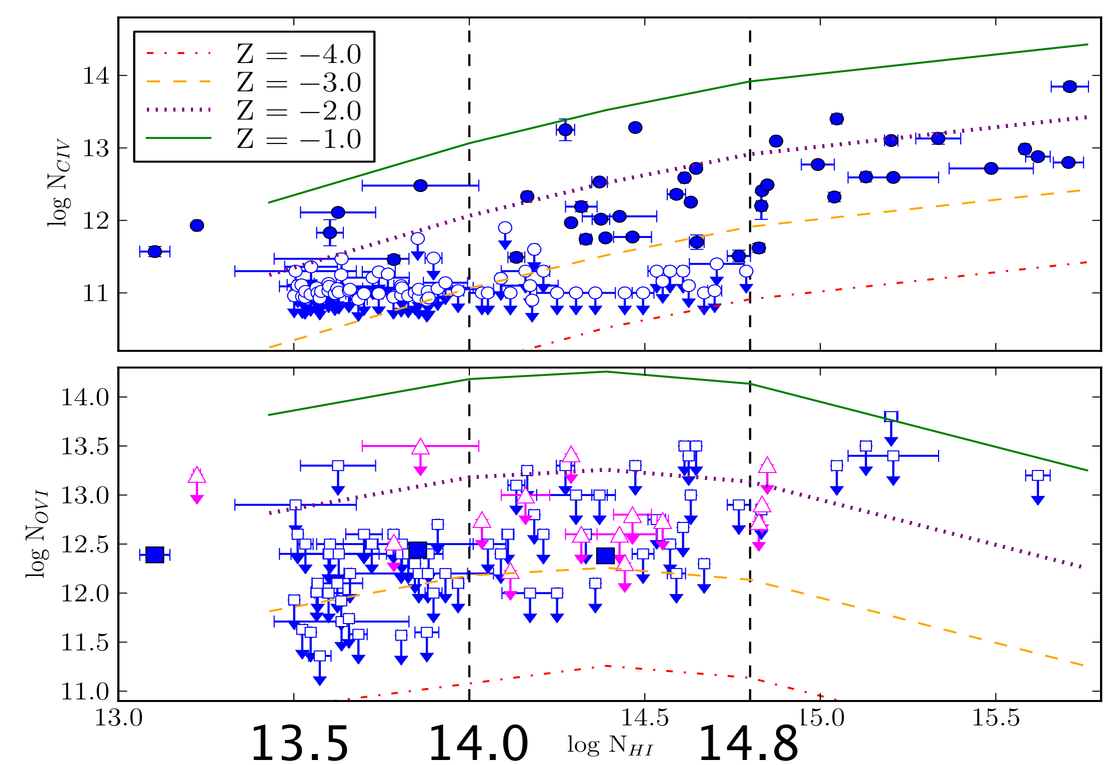
Enriched volume



Volume fractions occupied by a given overdensity derived from a cosmological hydrosimulation box of 60 h^{-1} comoving Mpc at z=2.8 (Viel et al. 2013)

Enriched volume to log Z/Zo ≥ -3:
14.0 ≤ log N_{HI} <14.8 ➔ 2.3-2.8 %
extending the same Z distribution to
13.5 ≤ log N_{HI} <14.0 ➔ TOT 8.6-10.4 %

Max volume from OVI ➔ MAX 12 %



Metals in the CGM and IGM

Conclusions

- ✓ Metals (C traced by CIV) are always present around galaxies at distances larger than the virial radius ➔ CGM

- ✓ Moving to $(\delta + 1) < 10$ (traced by HI with log N < 14.5-14.8 at z~2.5-3) metal detection rate becomes ~40% and then drops ➔ IGM

- ✓ The fraction of enriched systems with log N(HI) > 14 is at least a factor of 2 larger than the fraction of the same lines tracing the CGM of LBGs ➔ suggests enrichment by dwarf galaxies and/or pre-enrichment

- ✓ In the range of overdensities from $(\delta + 1) \sim 2.6 – 4$ to $(\delta + 1) \sim 10-15.5$ about 50-60 % of the absorbers are enriched to metallicity $-3 < \log Z/Z_\odot < -1$, while 40-50 % has $\log Z/Z_\odot < -3$

- ✓ The volume filling factor of IGM gas enriched to $\log Z/Z_\odot \geq -3$ should be at maximum 12 % ➔ agrees with predictions of theoretical studies with enrichment by dwarf galaxies and/or pre-enrichment

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?

Future prospects: near

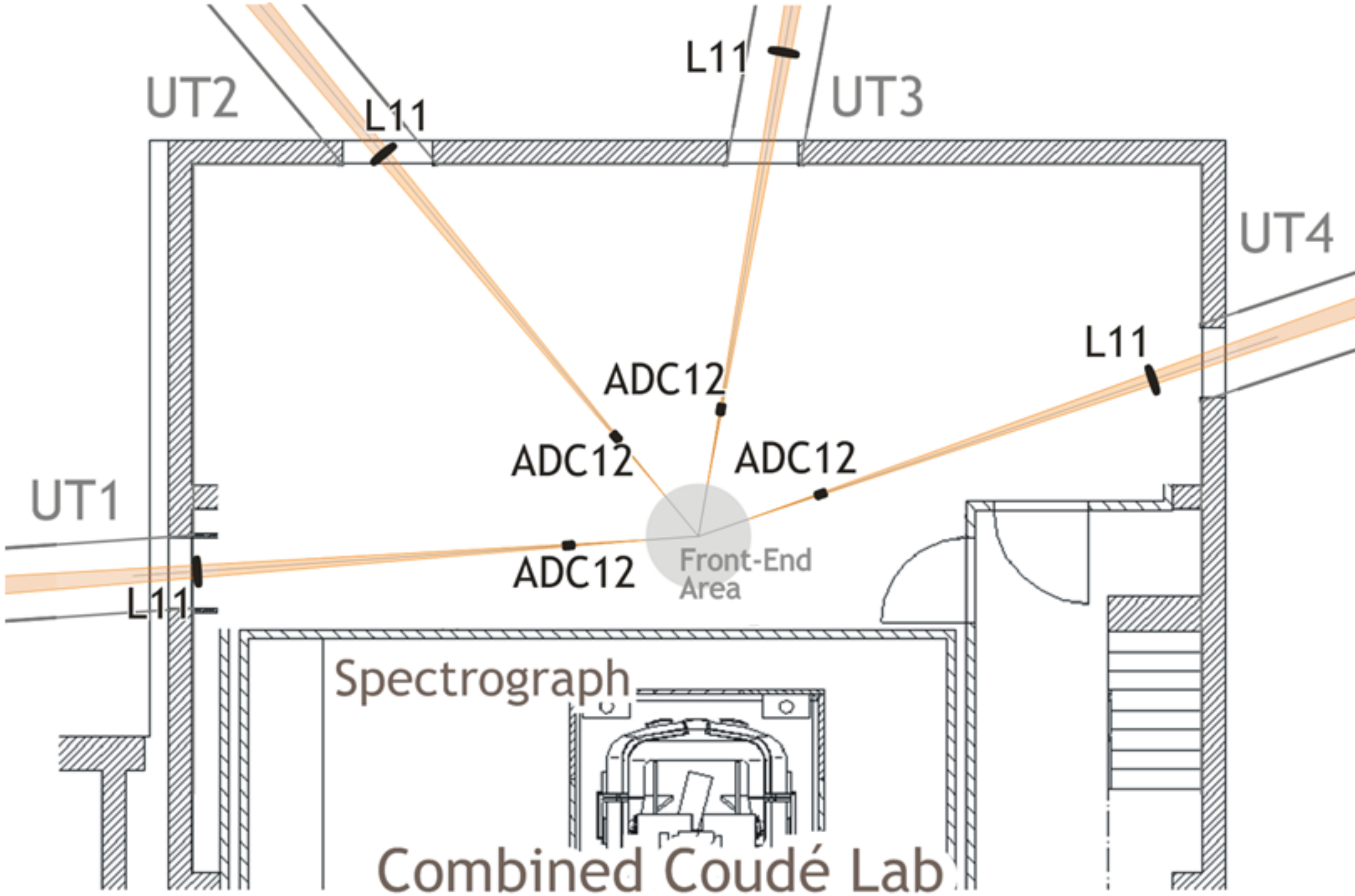
ESPRESSO@VLT

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).

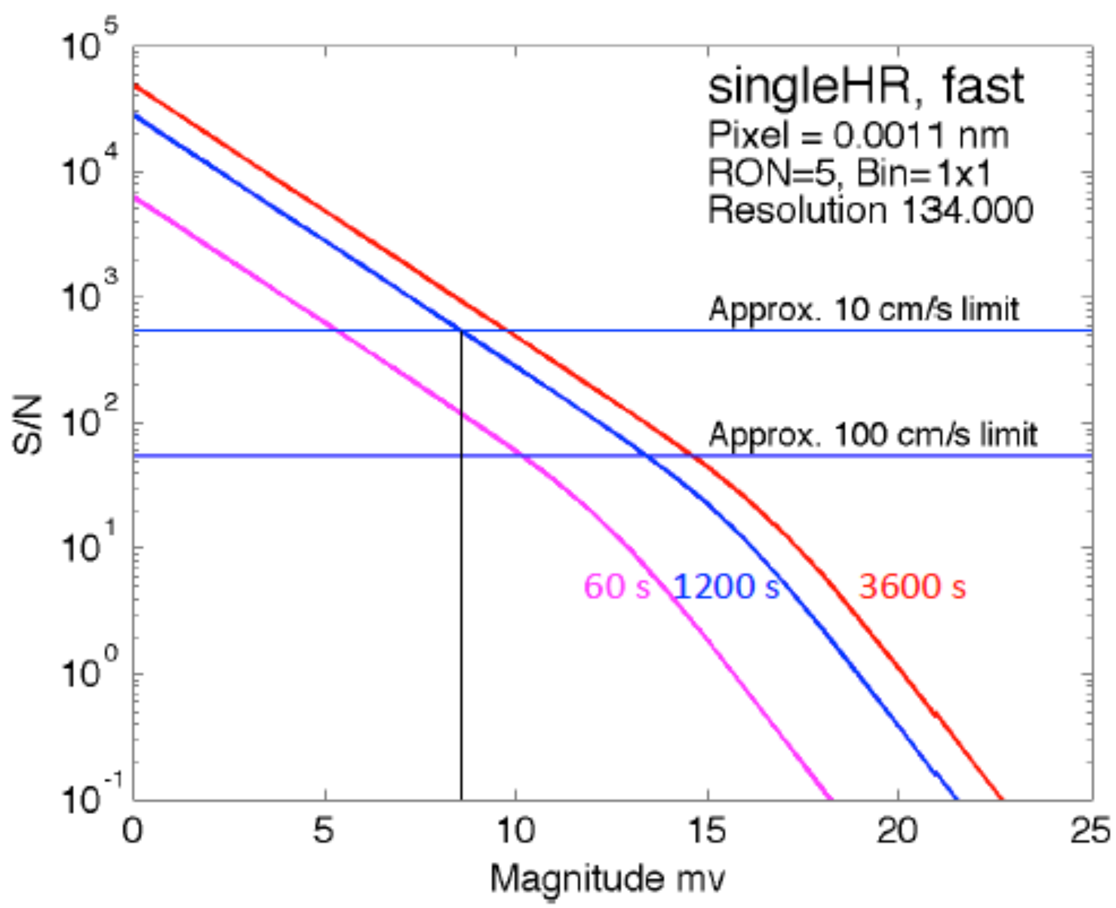
First light expected at the beginning of 2017

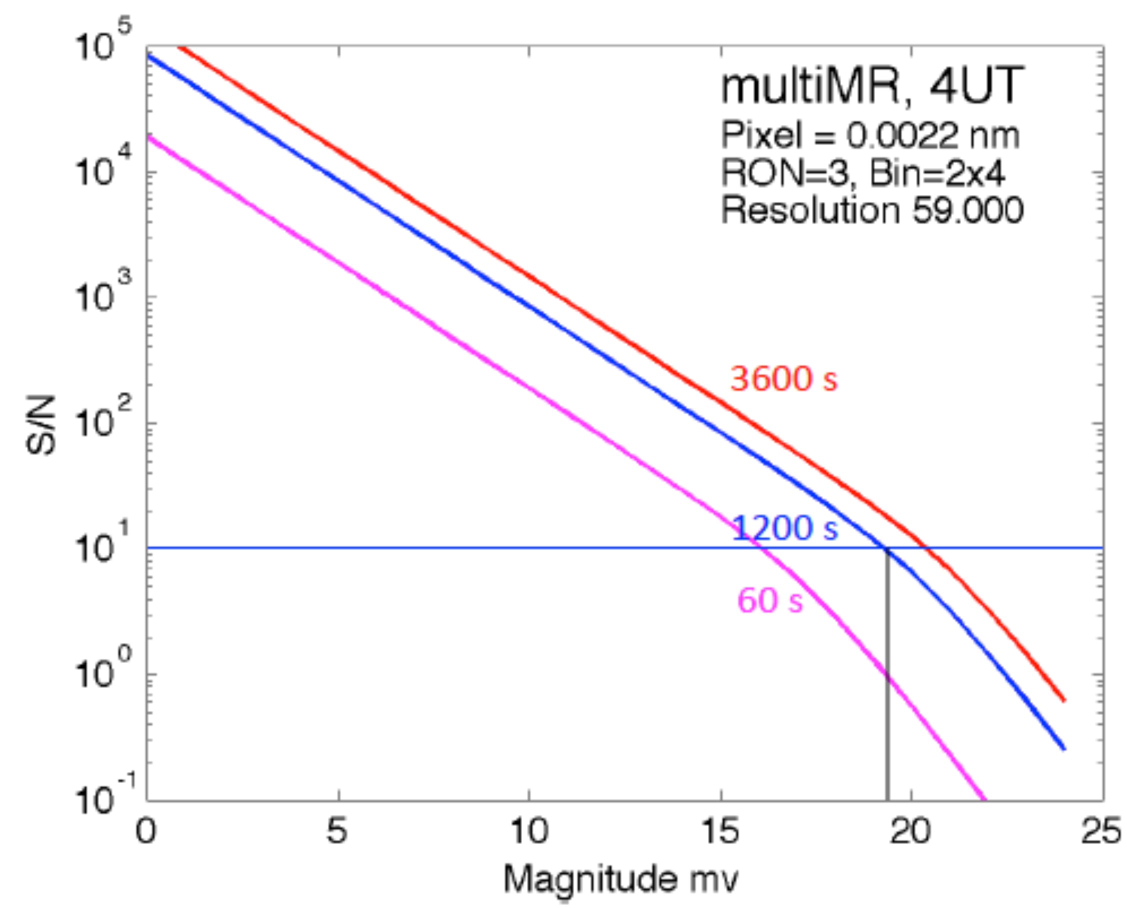
ESPRESSO is a fiber-fed, cross-dispersed, high-resolution, echelle spectrograph, which is located in the Combined-Coudé Laboratory (incoherent focus) where a front-end unit can combine the light from up to 4 Unit Telescopes (UT) of the VLT.



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}





ESPRESSO for the IGM

Scientific objectives

1. Improve the characterization of tenuous gas
   HOW Observe bright QSOs at z~3–3.5 to reach SNR > 500 per resolution element. Lines of sight possibly free from strong metal systems (DLAs, LLS). WHEN In the GTO (partly) using the same targets observed for fundamental constants. In normal time to increase the sample.

2. Constrain the nature of galactic winds
   HOW Do "tomography" of small fields with close QSO lines of sight (< 3 arcmin, z_{em}~2-3) and combine the information from observed absorbers with the galaxies (or galaxy proxies) present in the field.
   WHEN Pilot field in the GTO? Normal time.

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
  - Italy INAF lead institution, A. Marconi PI
  - Chile (Pontificia Universidad Catolica+), France (Laboratoire d'Astrophysique de Marseille+), Germany (Leibniz-Institute for Astrophysics Potsdam+), Portugal (Institute of Astrophysics and Space Sciences), Spain (Instituto de Astrofisica de Canarias+), Sweden (Uppsala University+), Switzerland (Observatoire de Genève+), United Kingdom (University of Cambridge+), Brazil (Theoretical and Experimental Physics of the Natal University), Denmark (Niels Bohr Institute Copenhagen +), Poland (Nicolaus Copernicus University Toruń +)

➢ Kickoff of Phase A study foreseen in March 2016.

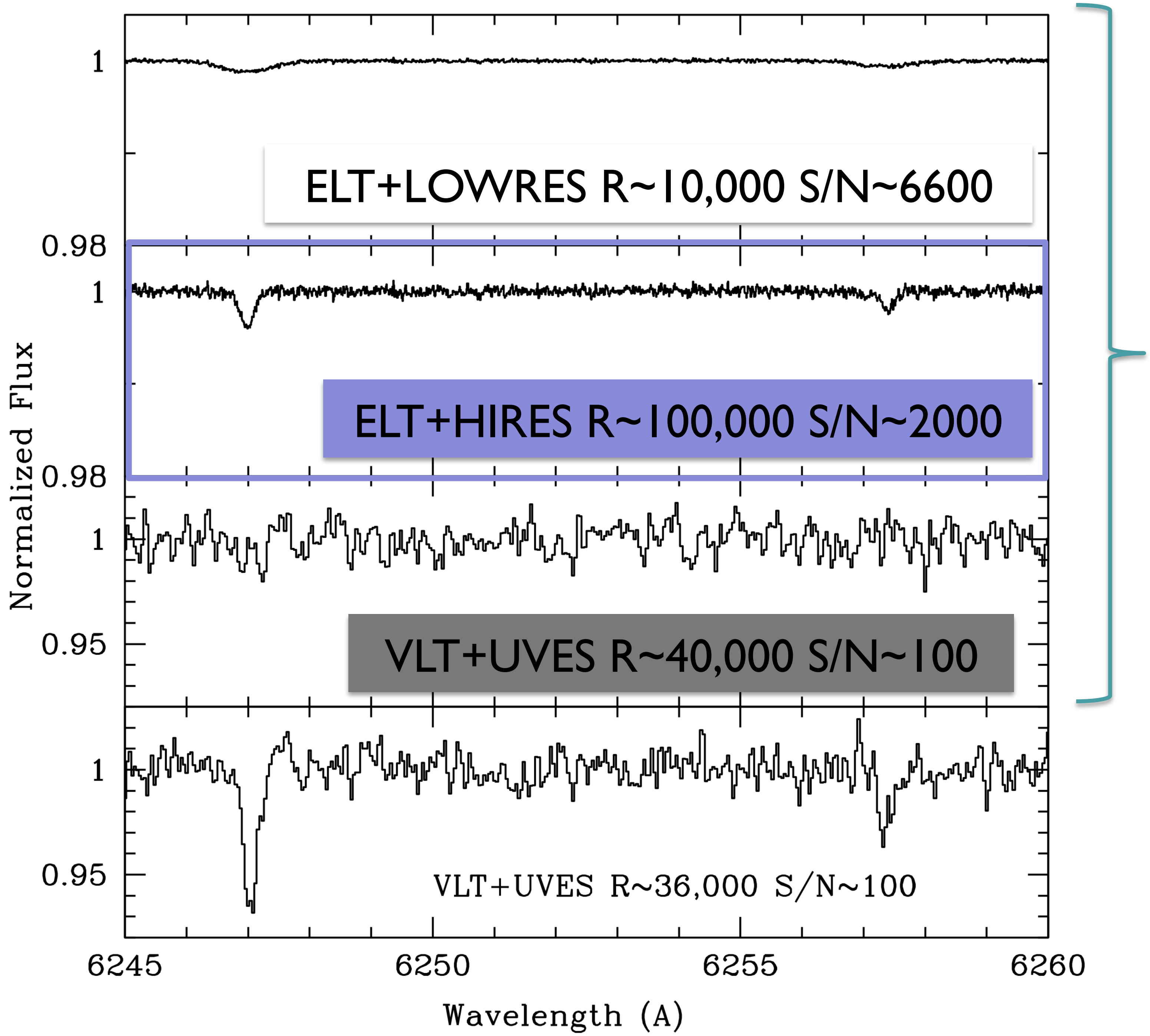
Science cases

- Exoplanets (characterisation of Exoplanets Atmospheres: detection of signatures of life)
- Stellar Astrophysics (abundances of solar type and cooler dwarfs in galactic disk bulge, halo and nearby dwarfs: tracing chemical enrichment of Pop III stars in nearby universe)
- Intergalactic Medium (Signatures of reionization and early enrichment of ISM and IGM observed in high-z quasar)
- Fundamental Physics (variation of fundamental constants α, m_p/m_e, Sandage test)
- Protoplanetary Disks (dynamics, chemistry and physical conditions of the inner regions)
- Stellar Populations (metal enrichment and dynamics of extragalactic star clusters and resolved stellar populations)
- Galaxy Evolution (massive early type galaxies during epochs of formation and assembly)
- Supermassive Black Holes (the low mass end)

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

HIRES@E-ELT for the IGM

Metal enrichment of the low density IGM at z~2-4 and signatures of the 1st generation of stars in very metal poor DLAs



T_{exp}~20 h
for an R~16 QSO at z~3

Scaled to the mean density:
log N(CIV) ~ 11

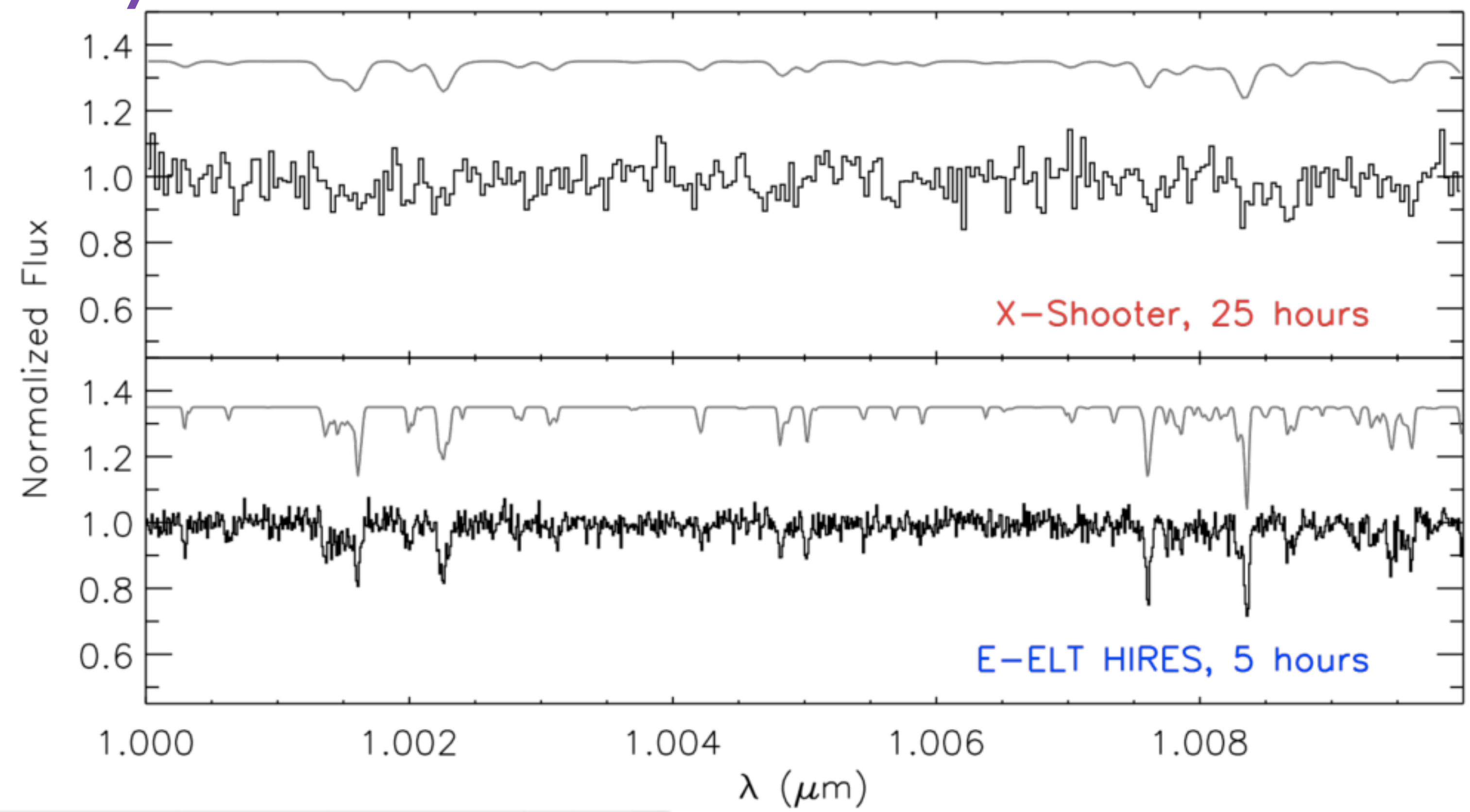
Limit of present observations:
log N(CIV) = 12 δ ~ 5-10

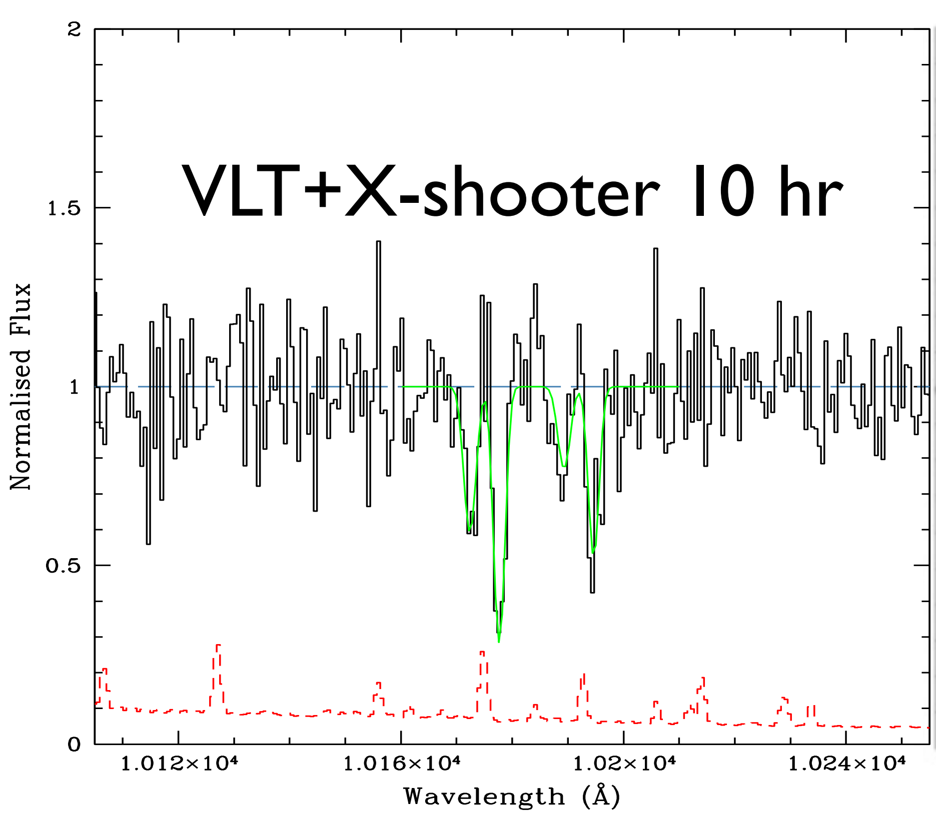
HIRES@E-ELT for the IGM

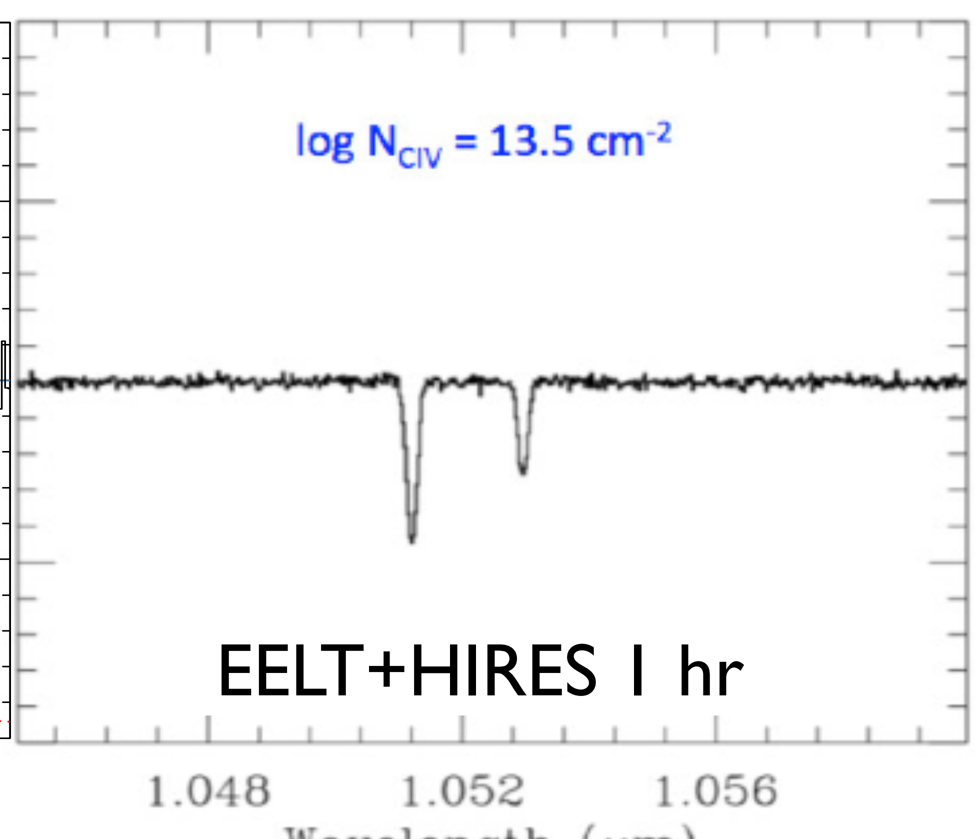
The reionization epoch with the Lyα forest and metal lines

NIR spectral range

Detect the O I forest at z~6-7 as a proxy of the H I distribution to constrain the reionization history







Detect lines due to several ionic transitions at z ≥ 6 to constrain the shape and intensity of the ionzing background and the enriching sources

THANK YOU!