Galaxies & Intergalactic Metals at the Conclusion of Reionization

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SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

PhD students: L. Angela Garcia, Alex Codoreanu
Papers: Diaz et al. (2014; 2015; in prep), Garcia et al. (2017a,b), Codoreanu et al. (submitted)

Why are we doing this?

The properties of the Intergalactic Medium (IGM) at redshifts ≥ 6 set the initial conditions from which modern galaxies form and evolve.

Properties:

- Scale of features – neutral & ionized bubbles
- Metal content
- Fraction of neutral hydrogen
- Spectral shape of the ionizing background

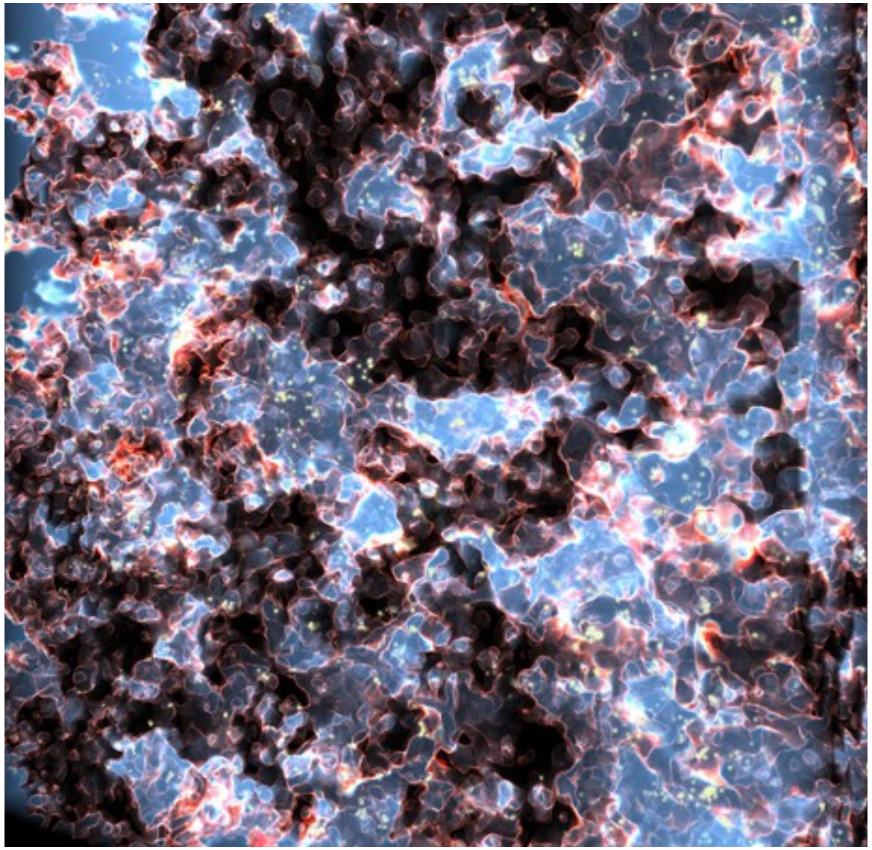
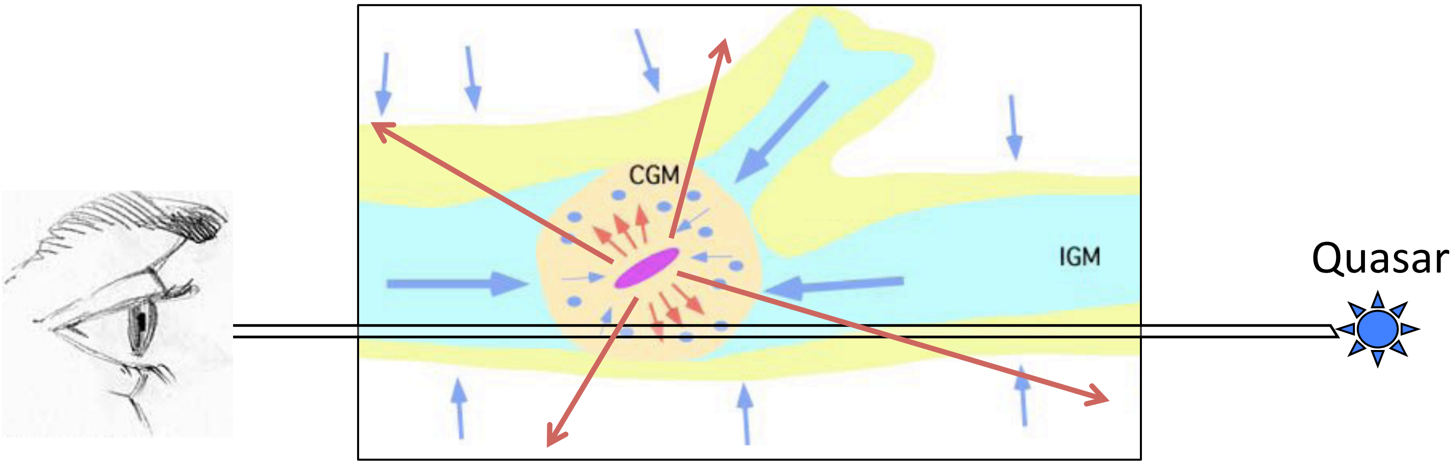


Image Credit: Alvarez, Abel & Kaehler

Definitions

Galaxy – makes the metals
IGM – Intergalactic medium, highly ionized at z<6, including metals, e.g. CIV
CGM – Circumgalactic Medium, higher density region around a galaxy,
leads to "self shielded" clouds, e.g. CII, MgII
Quasar Absorber – metals detected via absorption towards higher redshift quasar



Base Image credit: Martin+09

Galaxy – Metal Absorber Relationship

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1. Global relationships

2. Individual galaxy-absorber pairs

Questions to be addressed:

Does the highly ionized IGM change sharply at z~6 (as seen for Hydrogen)?

Are metal absorbers due to star formation associated with the highest density peaks at early times?
OR
Are metal absorbers due to recent stars in low luminosity galaxies very close to the quasar line of sight?

Cosmic timeline

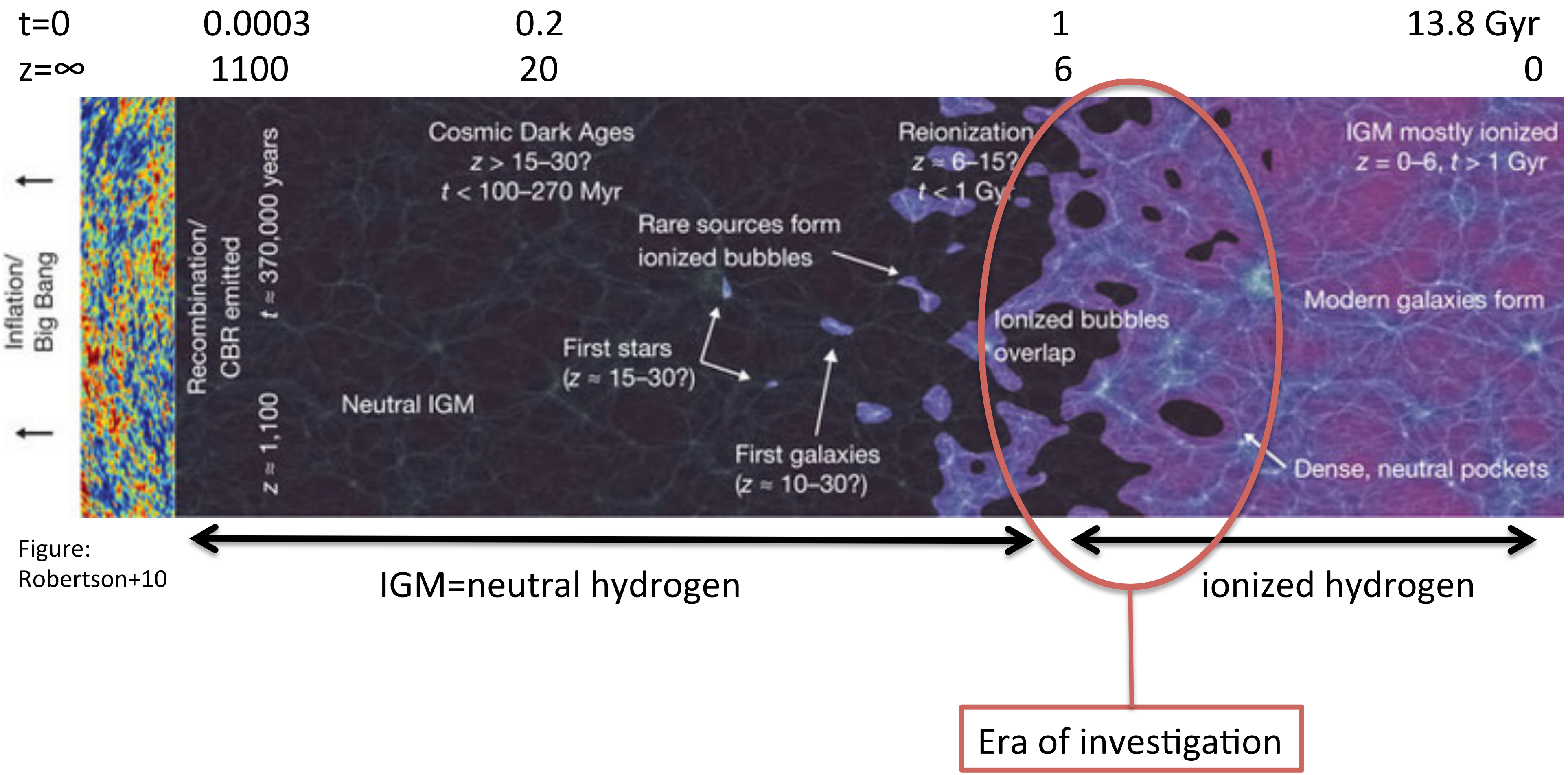

Figure: Robertson+10

Cosmic timeline

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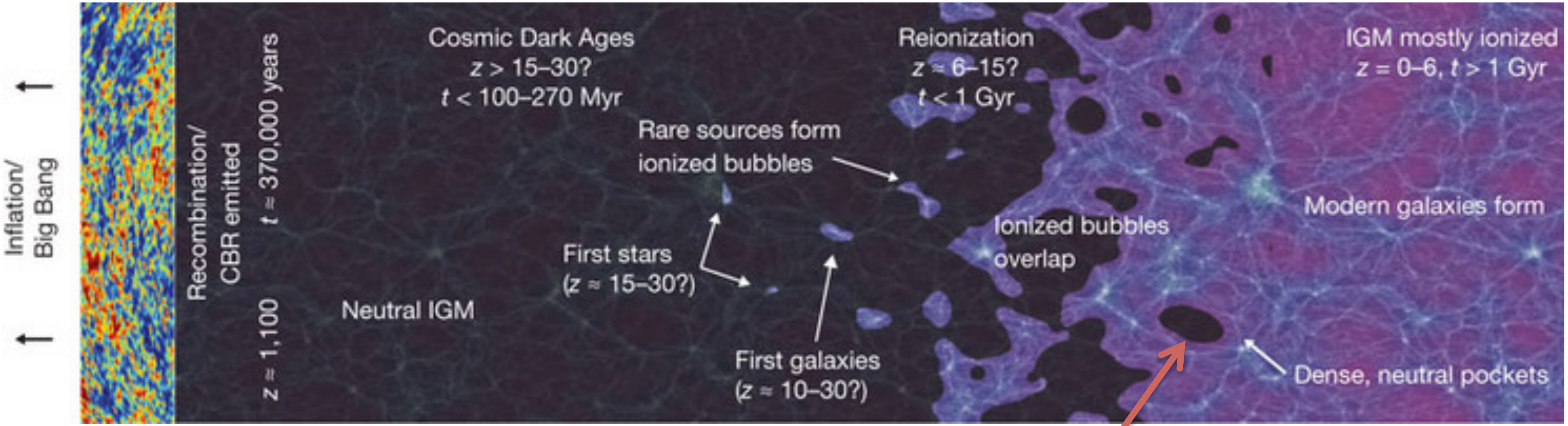
t=0 0.0003 0.2 1 13.8 Gyr

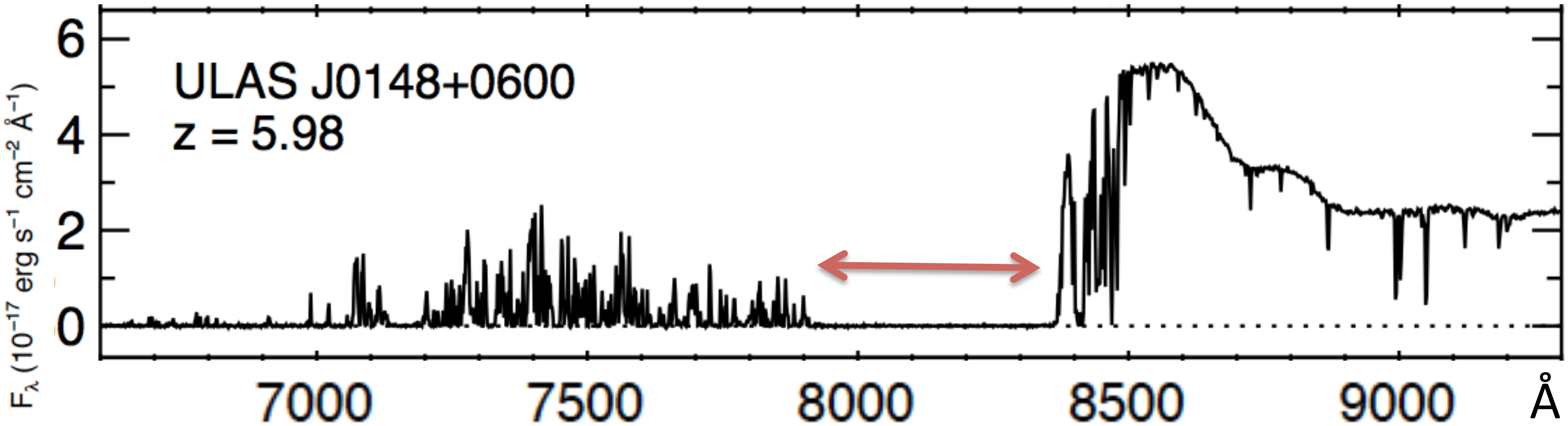
z=∞ 1100 20 6 0



We found one of these at 5.5<z<5.9
(Becker et al. 2015)

Evidence that Hydrogen Reionization is still on-going at z<6

A Gunn-Peterson trough 110 Mpc in length at 5.5<z<5.9



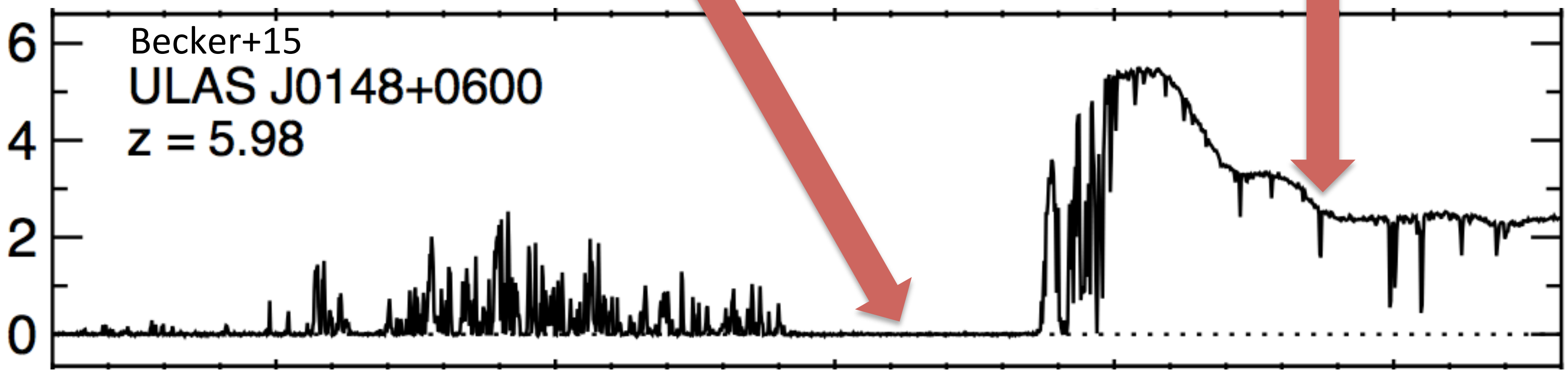
Becker+15

Statistically this dark trough is unlikely to be due to random fluctuation in the UV background.

Intergalactic Metals: Our approach in a nutshell

It's challenging, but not impossible to extract information from Lyman-α absorption at z~6

Complementary information can be obtained from metal absorption line systems in the IGM & CGM



Significant challenges:
OH skylines, atmospheric absorption

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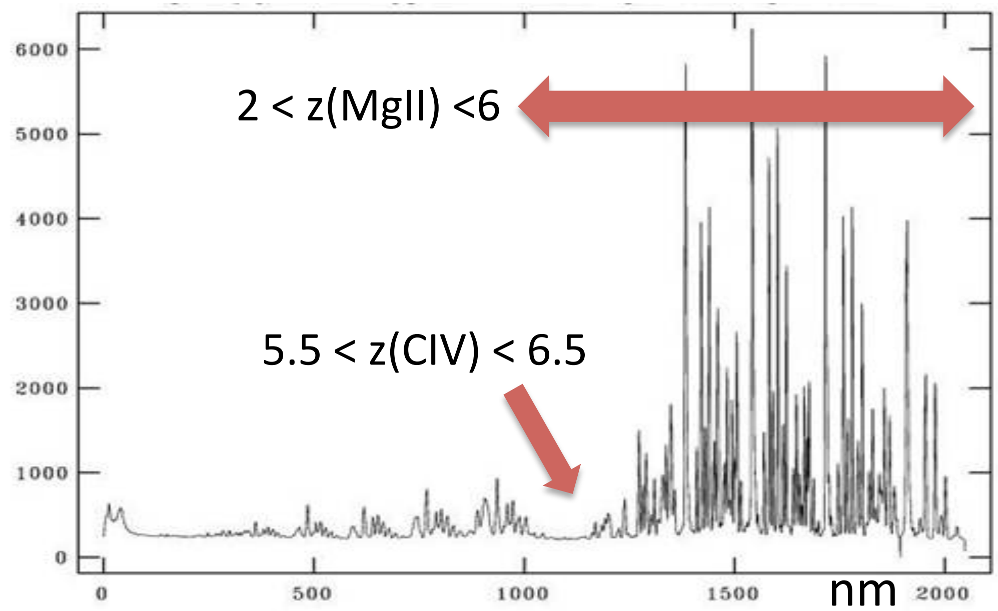

Demonstrated that medium resolution quasar absorption line spectroscopic is viable in the near-IR (ERW+06; Simcoe '06)

Further CIV studies: Becker+09; ERW+09; Simcoe+11 & D'Odorico+13.
MgII studies: Matejek +12,+13, Chen+17 (dN/dz incidence rate)

Search for CIV at 5<z<6.3 & MgII 2<z<5.5

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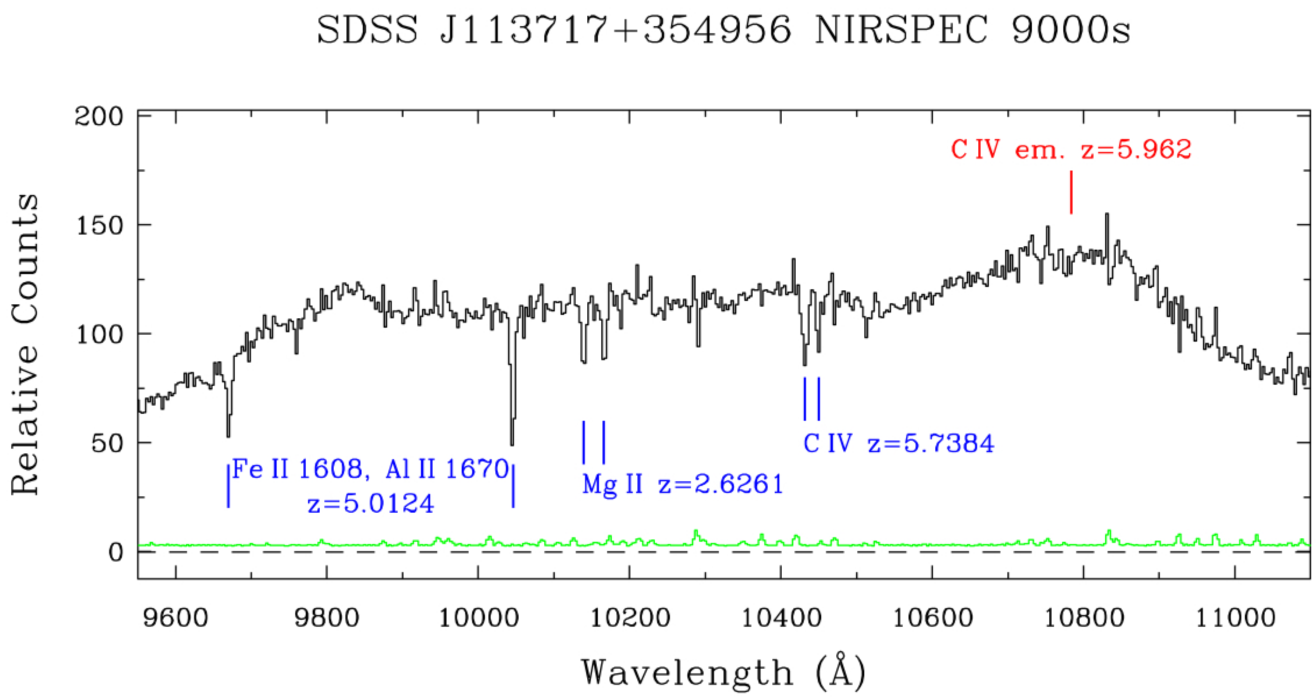


Ion	λ (Å)	ΔE (eV)
O I	1302.2	< 13.62
C II	1334.5	11.26 – 24.38
C IV	1548.2	47.89 – 64.49
Mg II	2796.4	7.64 – 15.03

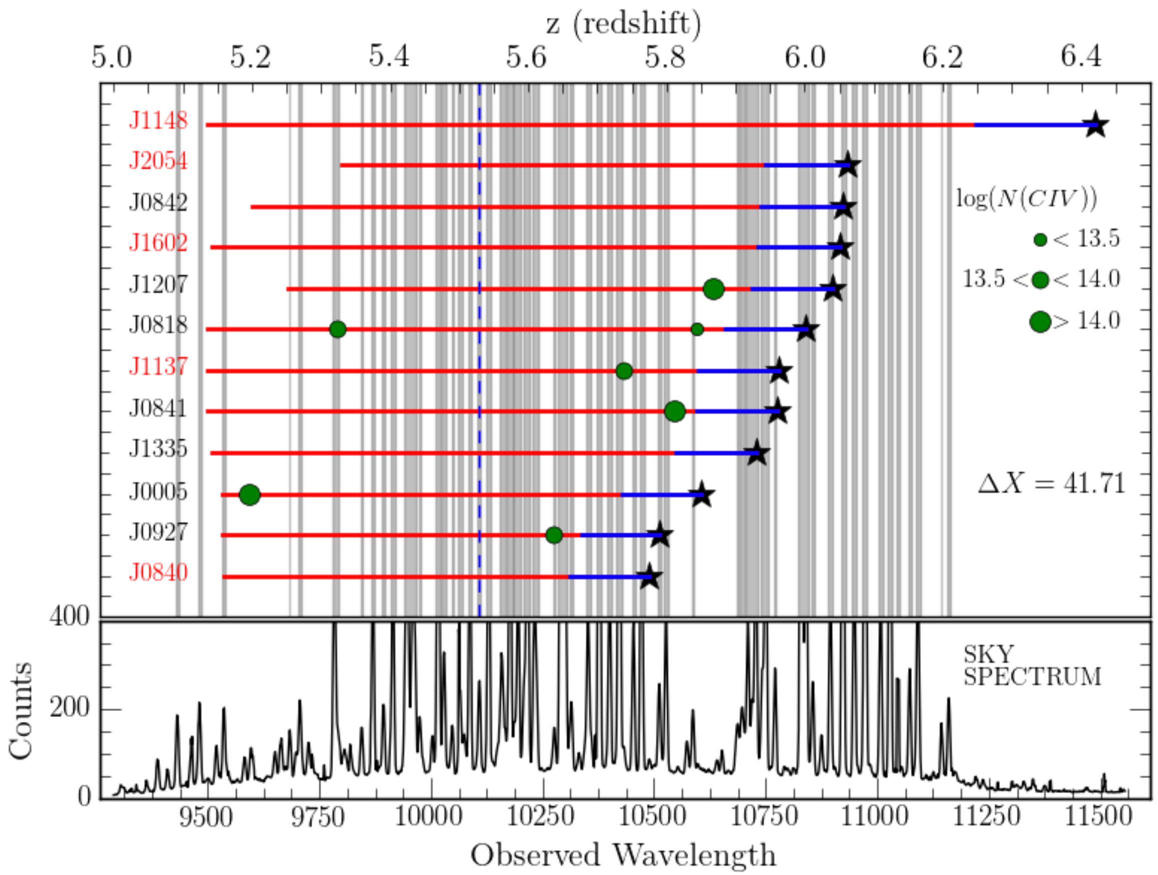
Courtesy Keating+16

Currently ~ 70/179 quasars with z_{em}>5.7 bright enough (J<20) for follow-up spectroscopy with 6-10m telescopes (discovered in SDSS, UKIDSS, CFHQS, VIKING, PANSTARRS).

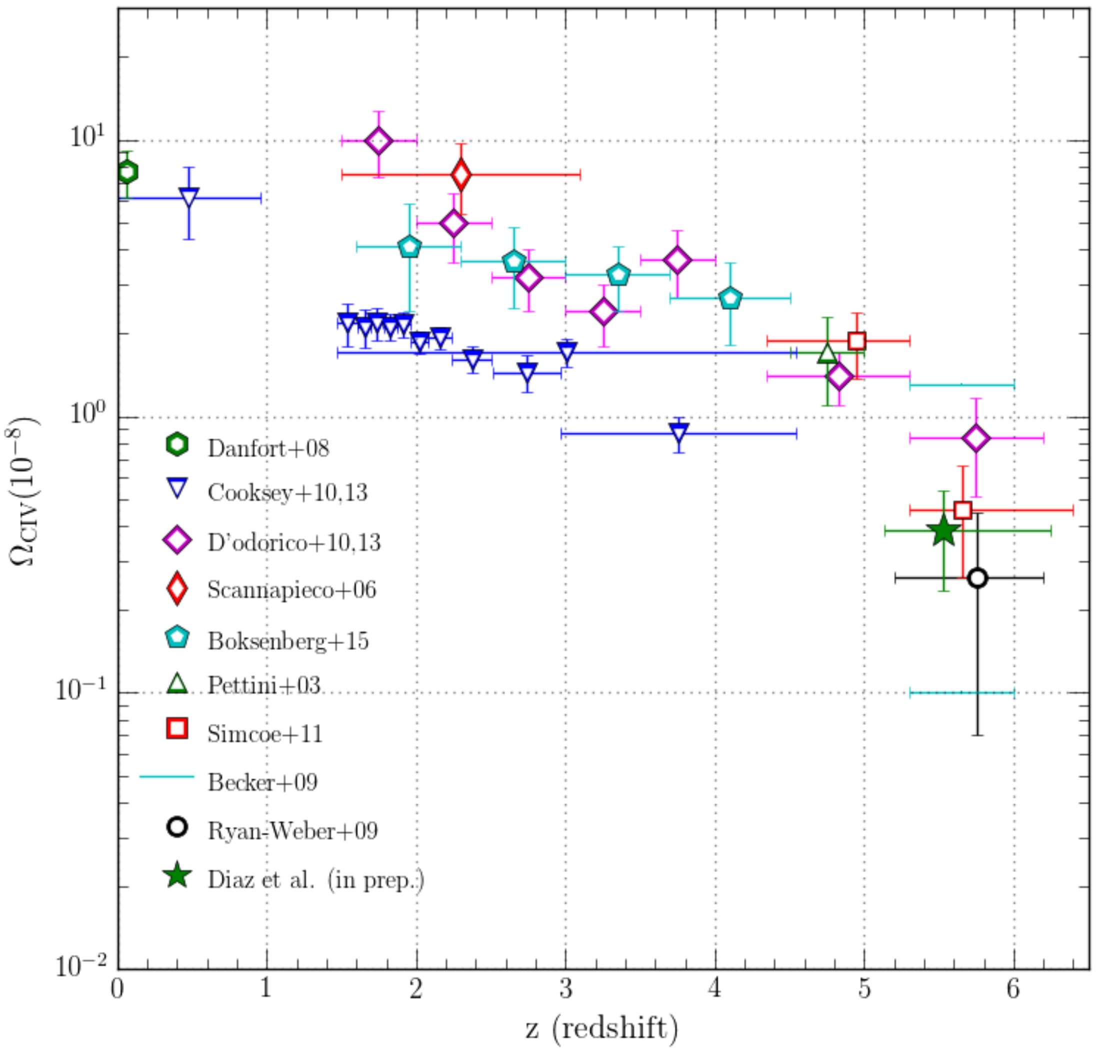
Keck/NIRSPEC survey for CIV

12 QSO lines of sight
(Diaz+ in prep)

Includes reanalysis of 5 NIRSPEC lines of sight from ERW+09 with consistent completeness correction.

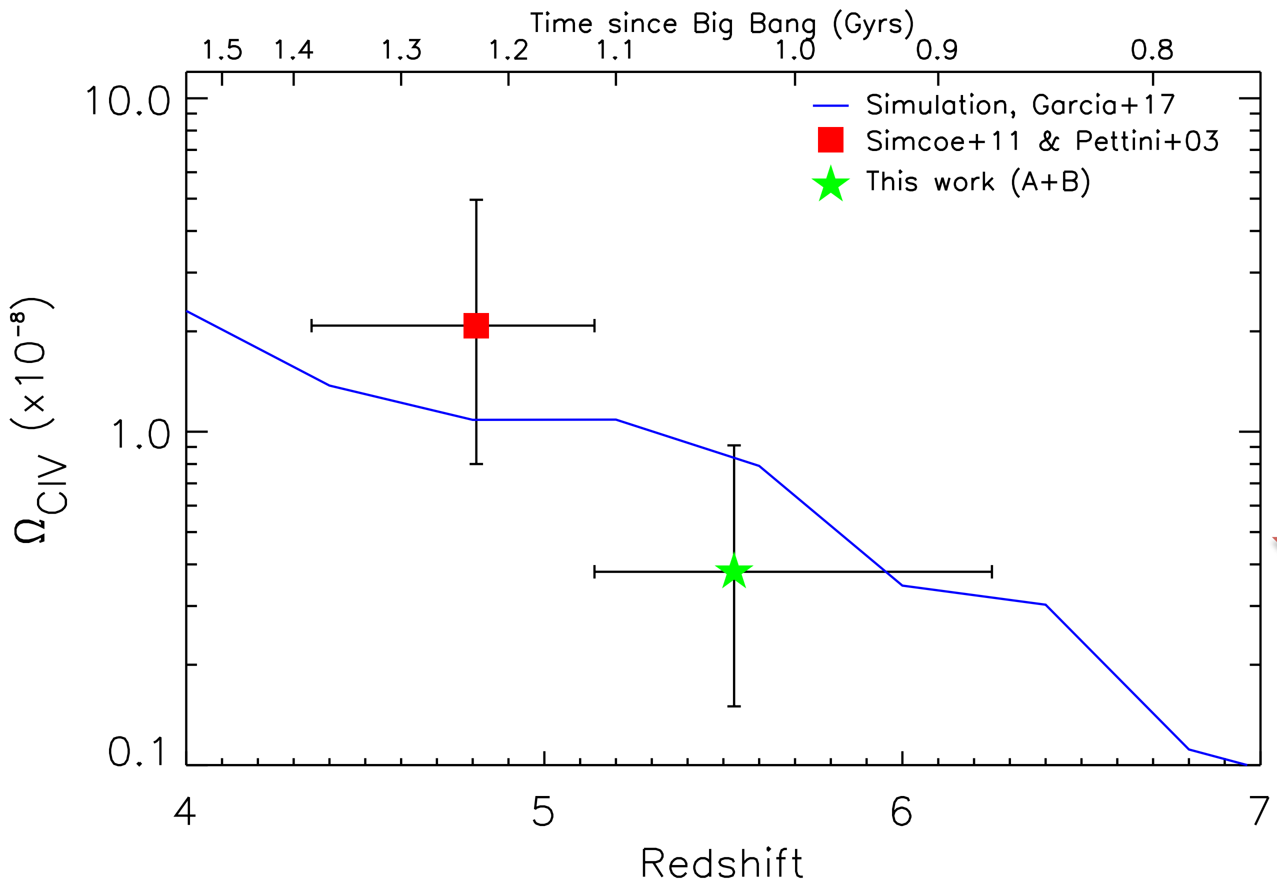


Cosmological Mass Density of CIV



$$\Omega_{CIV} = \frac{H_0 m_{CIV}}{c\rho_{crit}} \frac{\sum N_{CIV}}{\Delta X}$$

Cosmological Mass Density of CIV

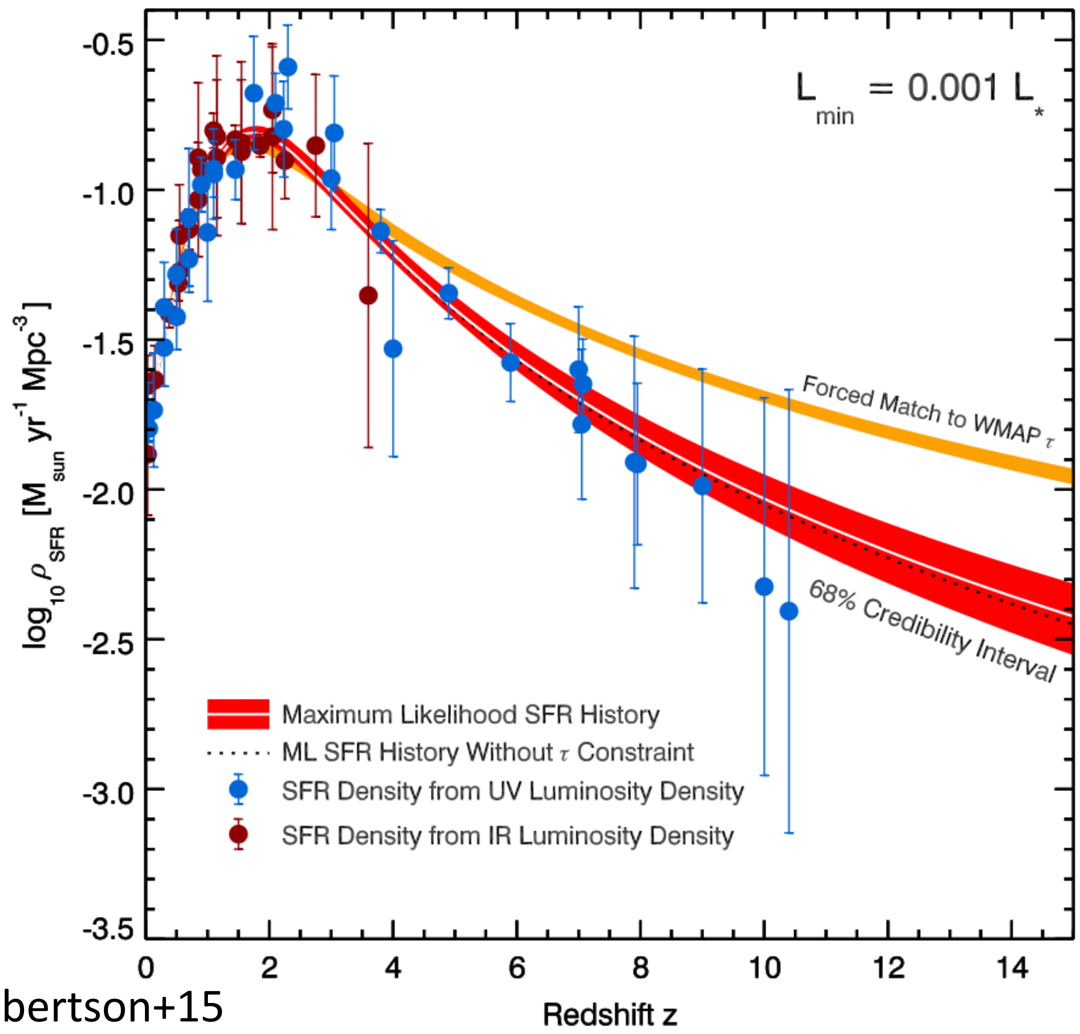


Ω(CIV) drops by a factor of ~5.5x in 200 Myrs

from z=4.8 to 5.5

Diaz, ERW et al (in prep)

Star formation rate density



Robertson+15

Maximum likelihood SFRD from joint constraint of τ(Planck 2015)=0.066 and compilation of UV & IR SFRDs from Madau & Dickinson (2014).

Integrate SFRD with return fraction, R and yield, y to obtain the mean metallicity of the Universe.

Mean Metallicity of the Universe

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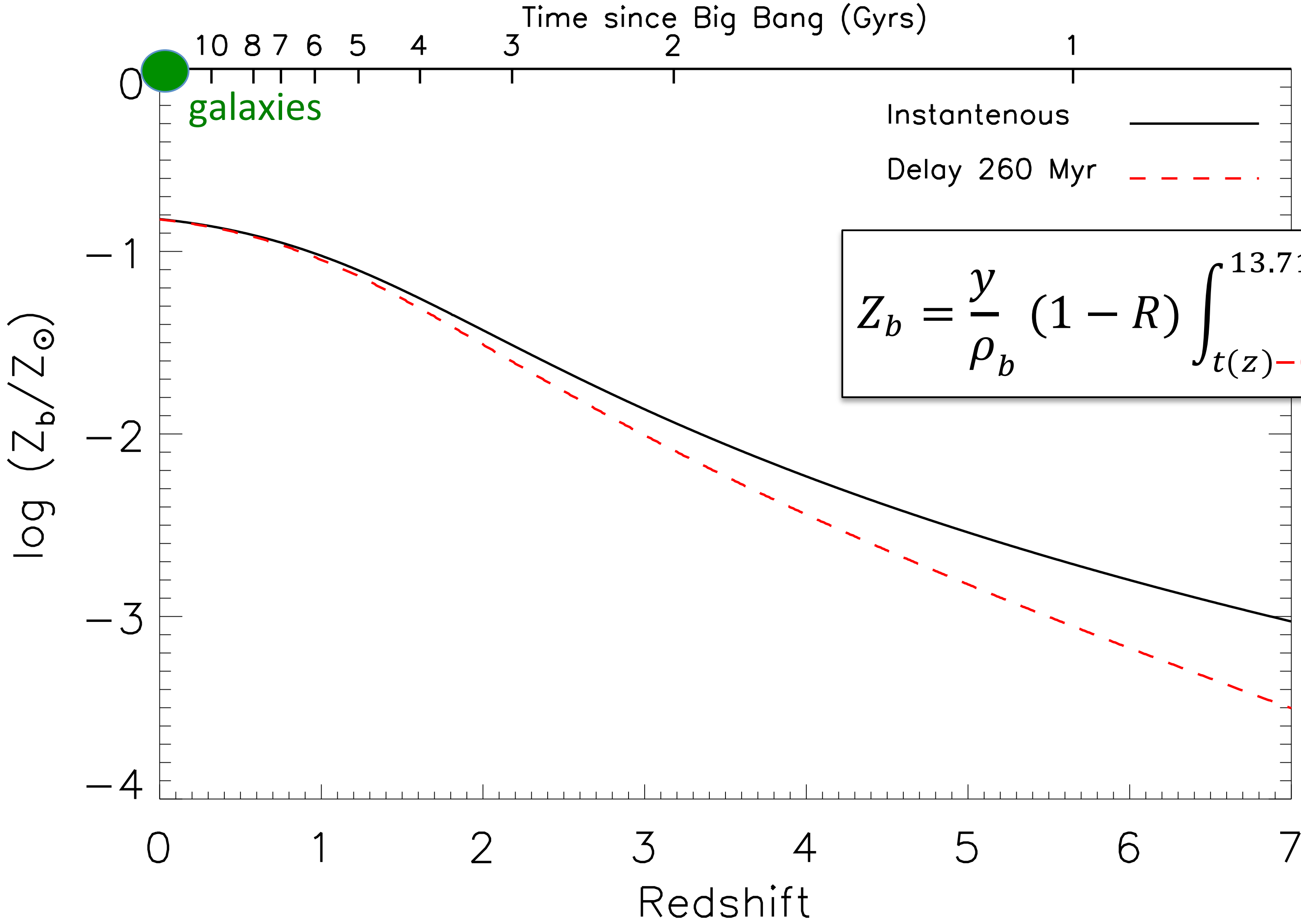

$$Z_b = \frac{y}{\rho_b}\,(1-R)\int_{t(z)-0.26\,Gyrs}^{13.71\,Gyrs} \rho_{SFR}\,dt$$

Mean Metallicity of the Universe

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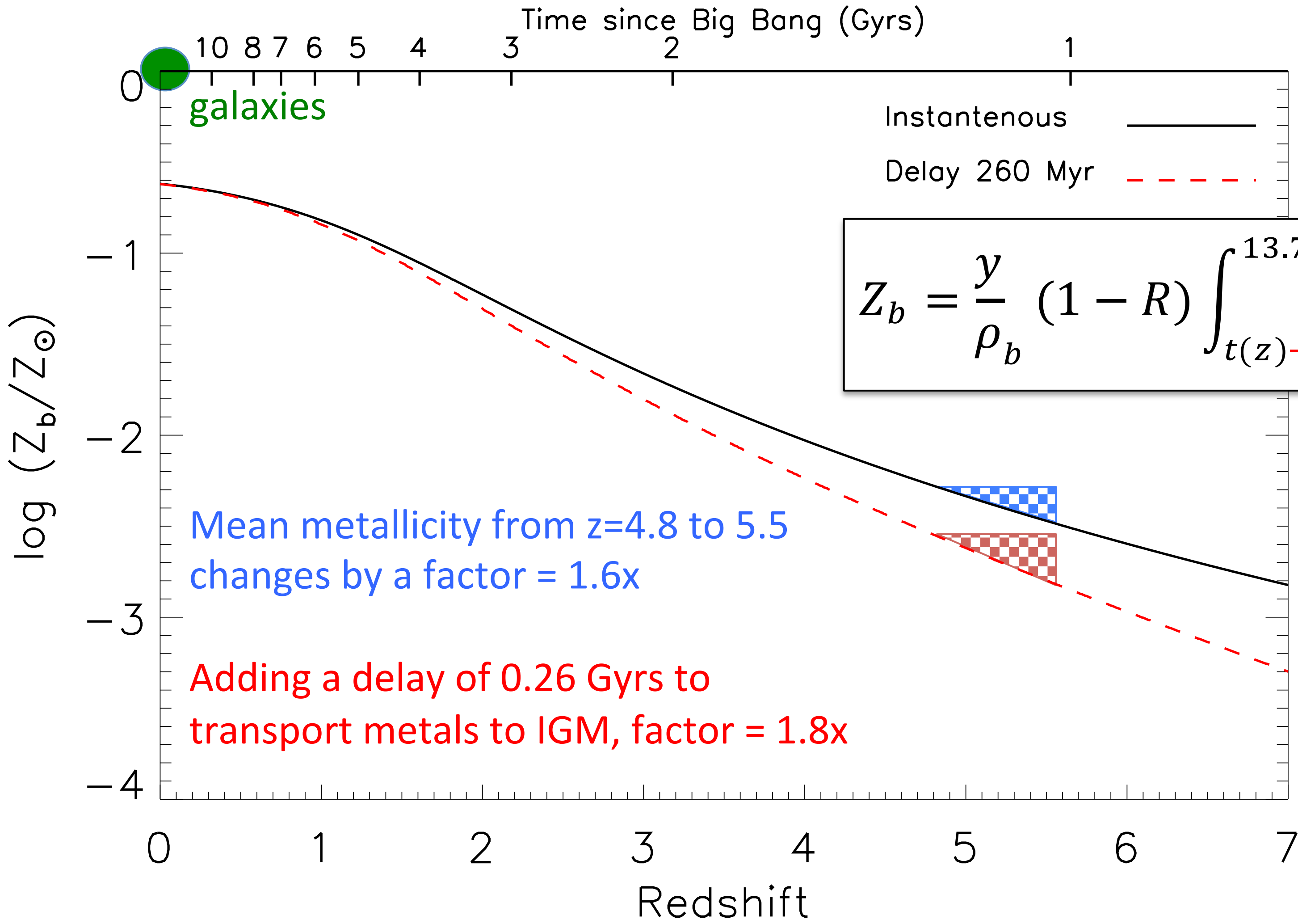
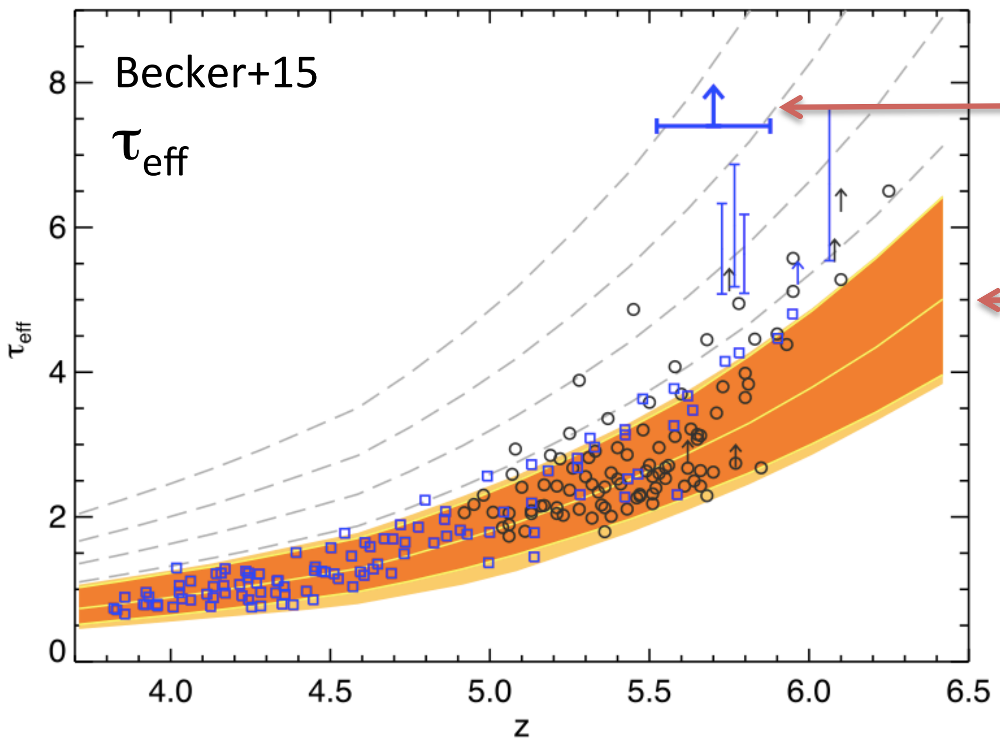


$$Z_b = \frac{y}{\rho_b}\,(1 - R)\int_{t(z)-0.26\,Gyrs}^{13.71\,Gyrs} \rho_{SFR}\,dt$$

Increasing effective optical depth

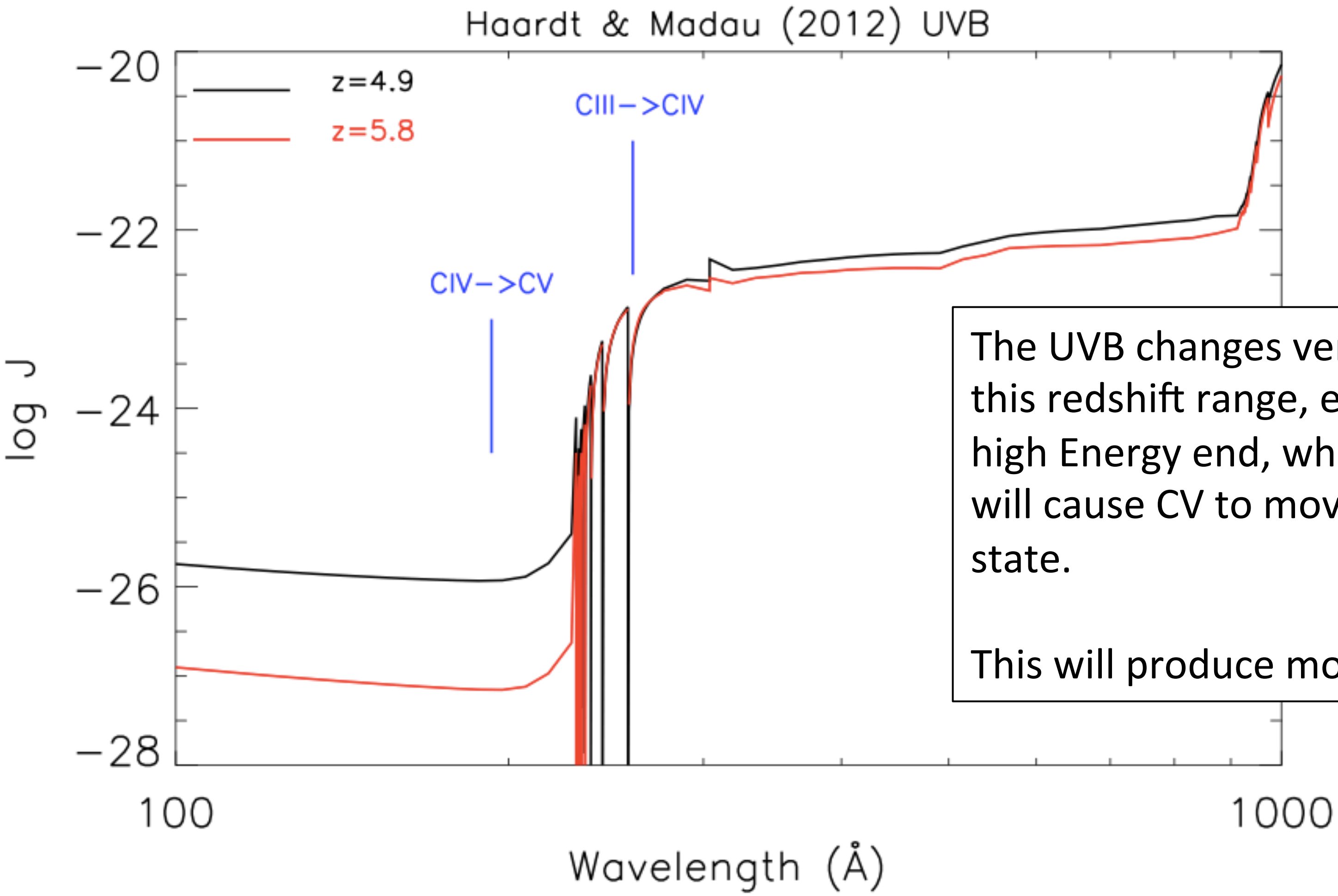


Increased neutrality due to the patchy tail end of reionization.

Increasing mean cosmic density is also causes an underlying increase in the neutral fraction of hydrogen.

A number of effects in the IGM at these redshifts, see also:
Chardin+15 – rare bright sources
D'Aloisio+15 – relic temperature
Davies & Furlanetto+16 – mean free path

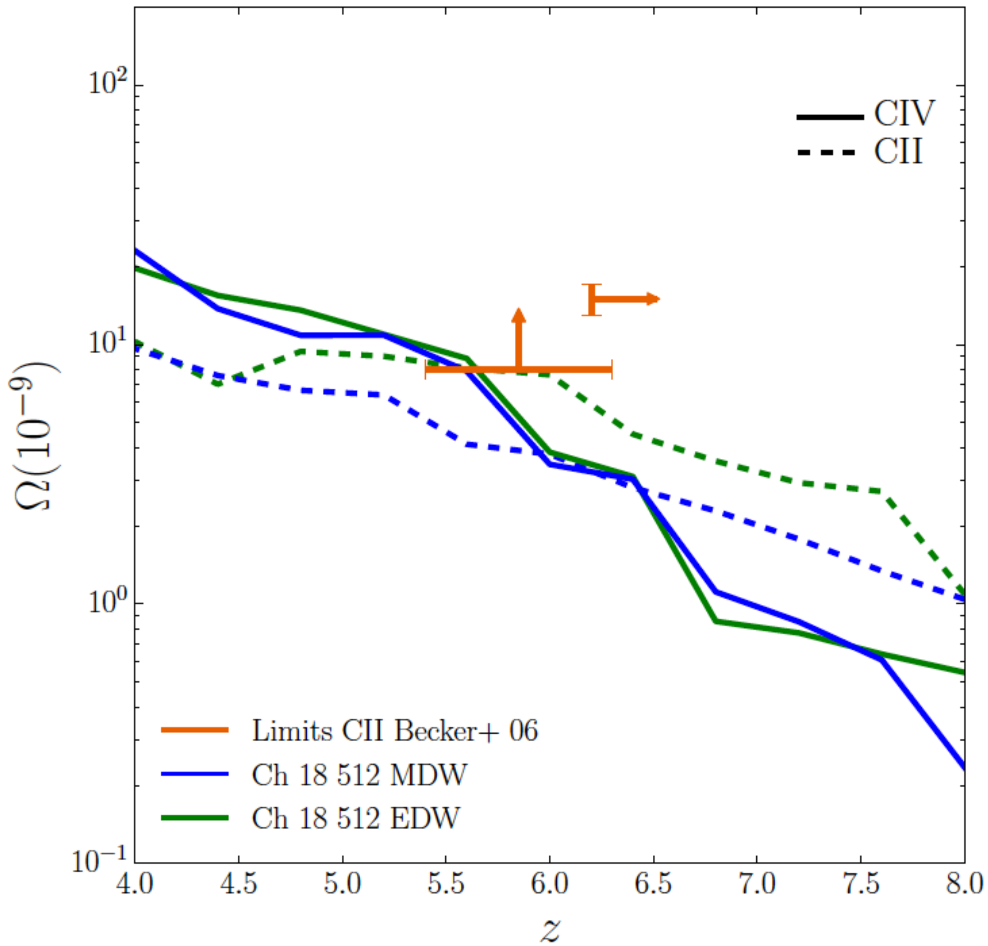
The UVB as seen by CIV



The UVB changes very little over this redshift range, except at the high Energy end, where a drop in J will cause CV to move to the CIV state.

This will produce more CIV not less!

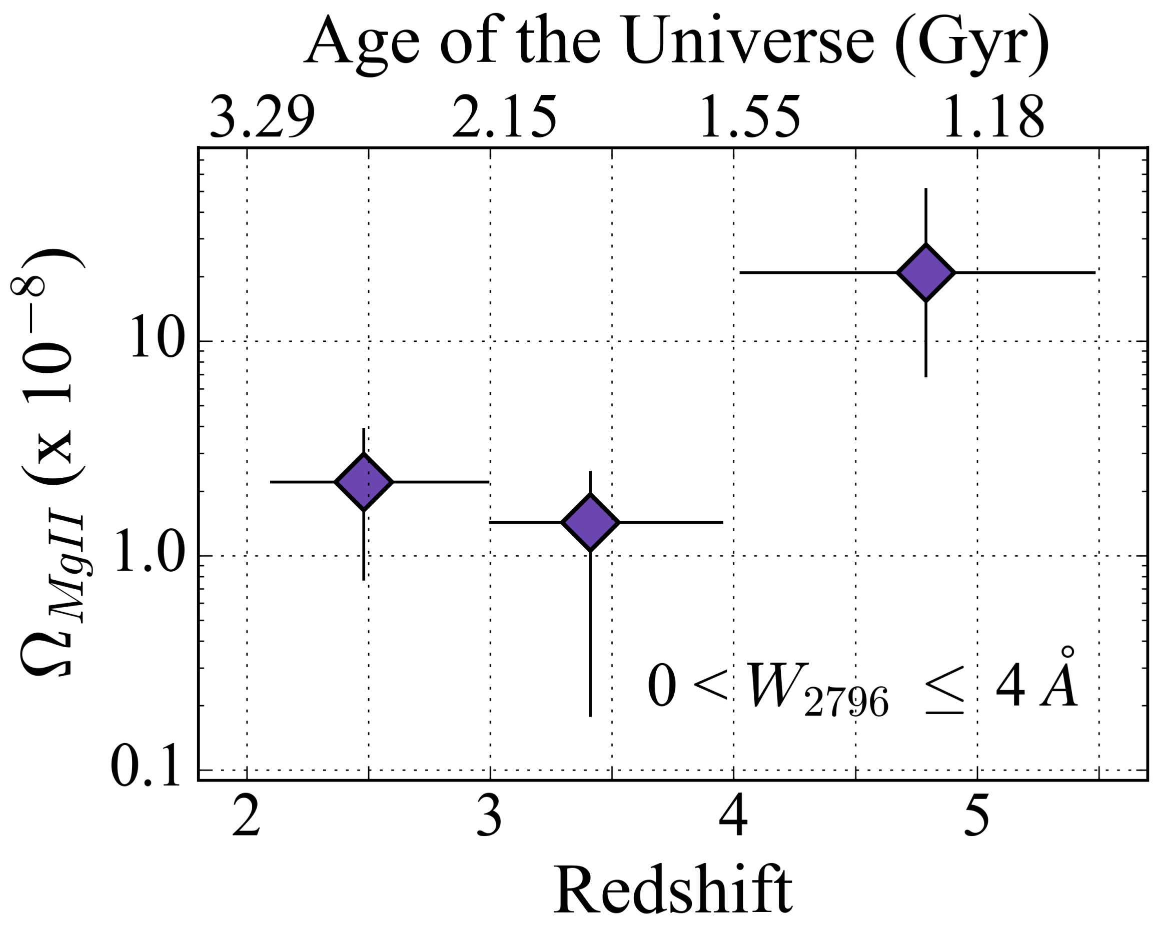
What about low ionization metal ions?



Simulations from Garcia, Tescari, ERW & Wyithe (2017, submitted)

Observations of CII are more difficult than CIV.

Cosmological Mass density of MgII also increases



Codoreanu et al. (2017, Submitted) based on 28 MgII absorbers along 4 quasar lines of sight (X-shooter/VLT)

24.4 eV 64.5 eV 138.1eV

Oppenheimer, Davé, & Finlator (2009)

What is the environment of CIV absorbers at z~5.7?

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Observational Approach:

0. Find CIV absorbers in foreground spectra of z~6 quasars
   Near-IR spectroscopy: ISAAC/X-shooter/VLT and NIRSPEC/Keck ✔

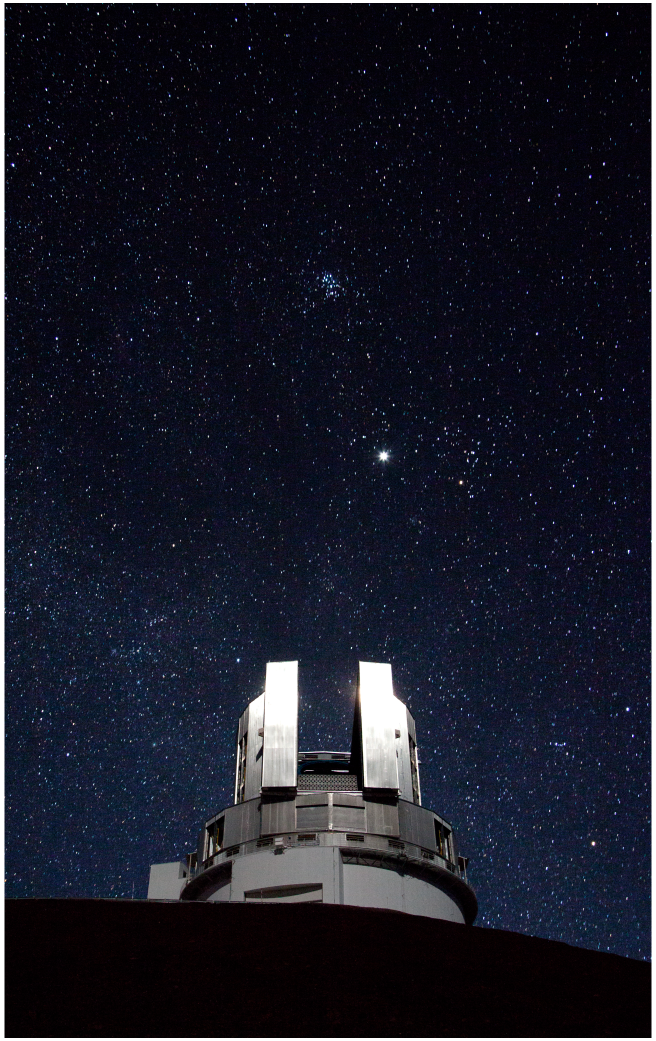
LBG: UV bright star-forming galaxy identified by the “drop-out” technique (Lyman break technique, Steidel et al. 1996)

LAE: UV faint, emission line galaxy (Lyman-α)

1. Image fields in broadband (LBGs)
   and narrowband (LAEs)
   Two fields: J1030 & J1137
   Suprime-Cam/Subaru (Diaz+2014)

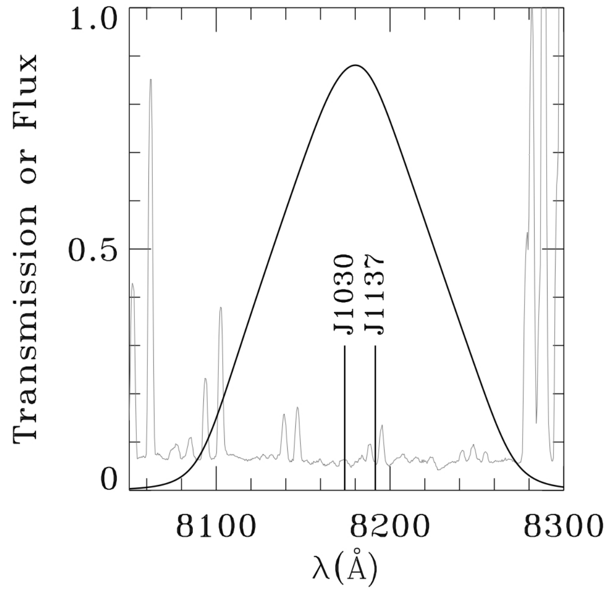
2. Follow-up spectroscopy to detect Lyman-α emission line of LAEs
   DEIMOS/Keck (Diaz+2015)

Image field in broadband & narrowband



Observations with Suprime-Cam/Subaru.

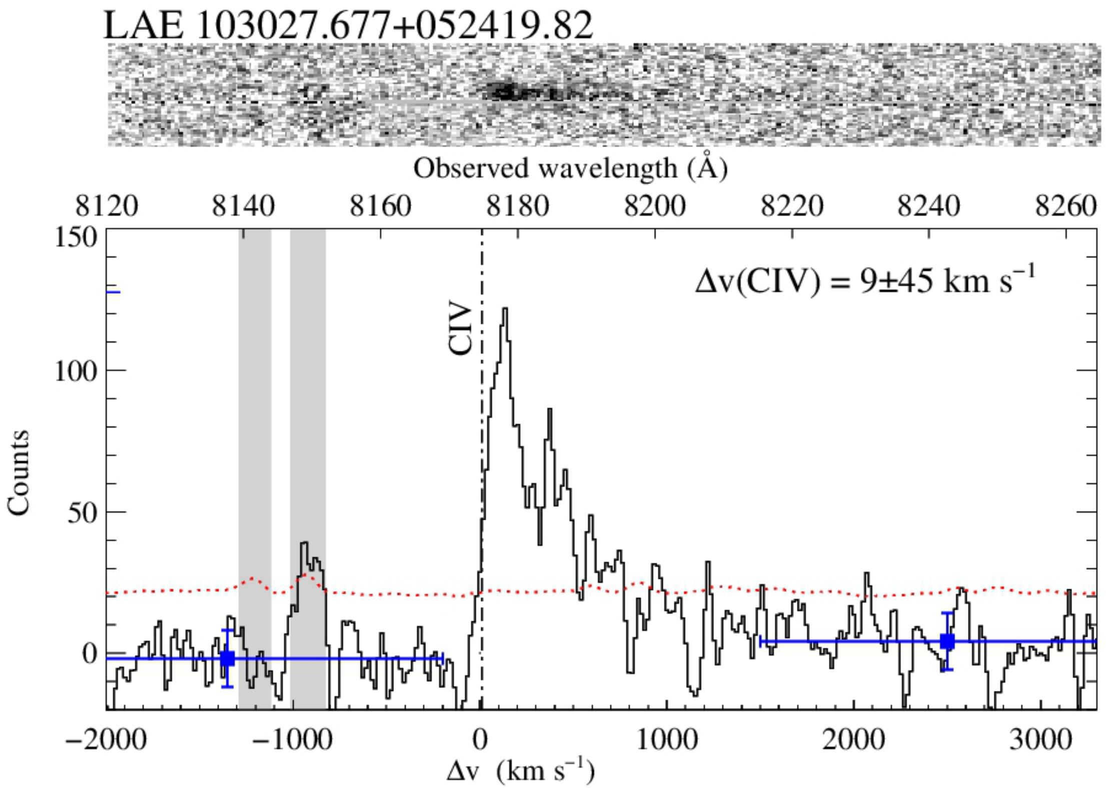
Customized narrow band filter to target Lyman-α emission in galaxies surrounding the z~5.7 CIV absorbers (identify LAEs).



PLUS
R_c, i’, z’
broadband
imaging to
identify LBGs.

Spectroscopic confirmation of Lyman-α emission lines

DEIMOS/Keck
Optical multi-object spectroscopy
(followed-up 33 LAEs in 2 fields)



Spectroscopic confirmation of Lyman-α emission lines

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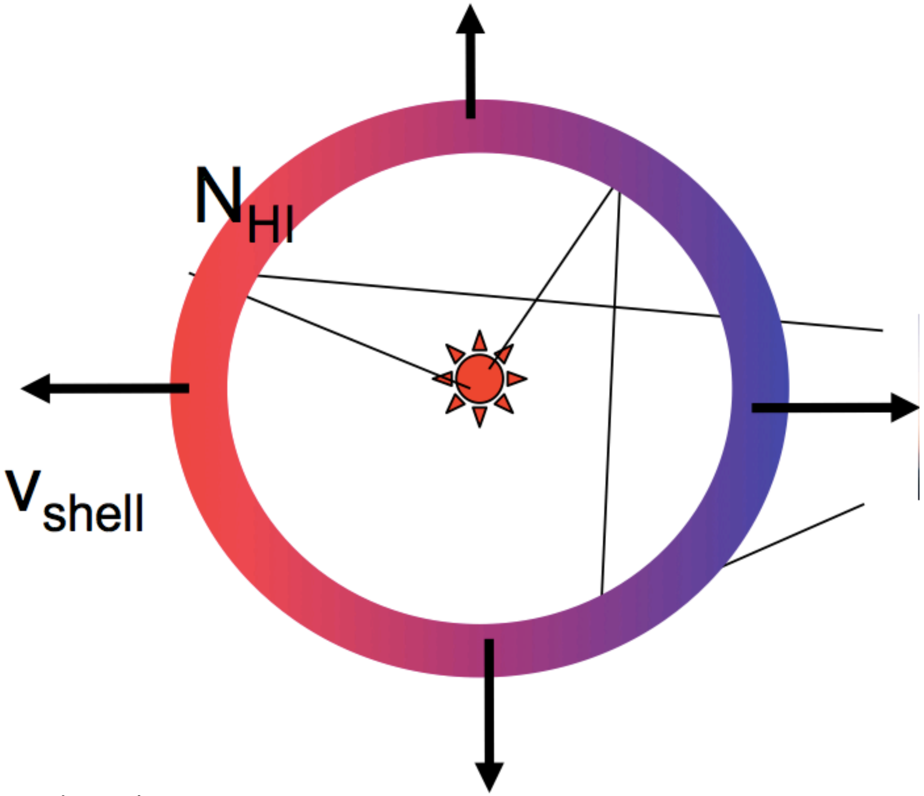
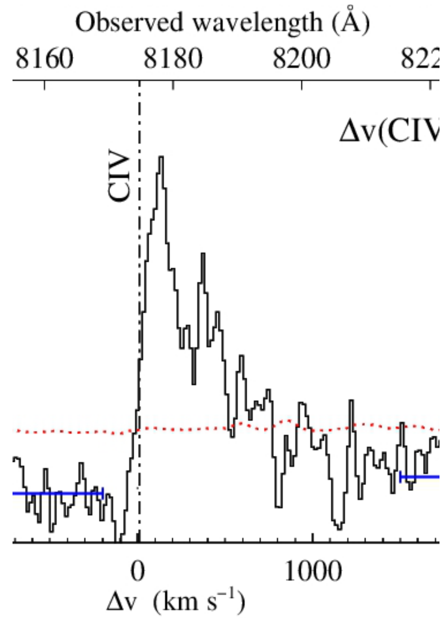
Lyman-α emission is well modelled by resonance scattering off a an expanding shell of HI. An asymmetric profile is expected.





Credit: Dijkstra+06

Large-scale environment

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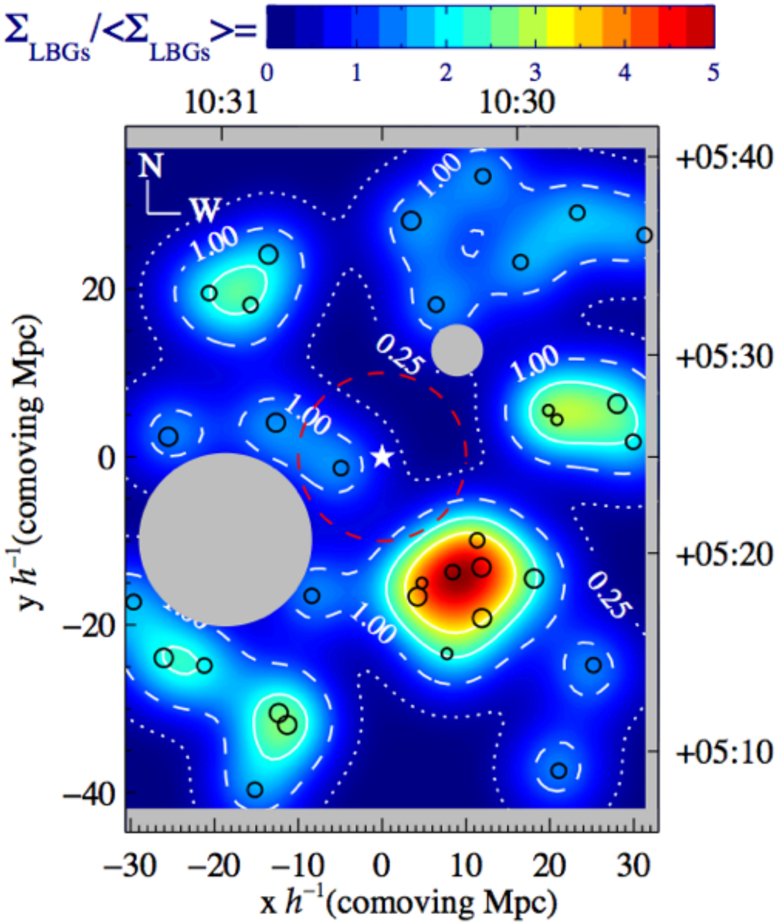
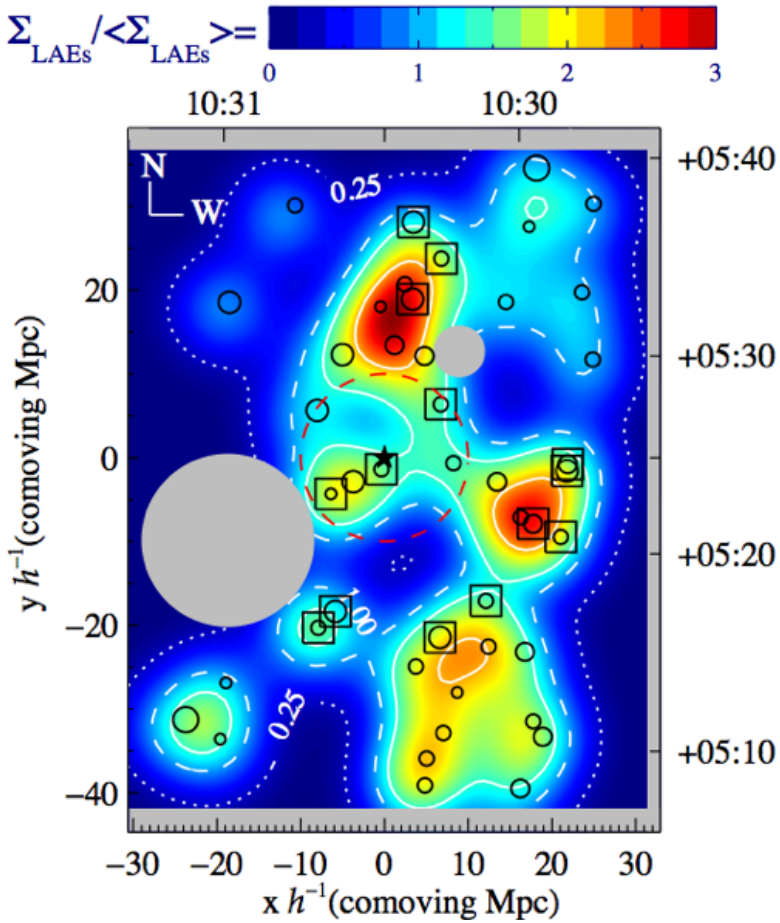
O z~5.7 LBG



O z~5.7 LAE



☐ spectroscopically confirmed

Conclusions from large-scale environment analysis

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Results from 2 independent fields:
Deficit of bright LBGs within ~5-10 cMpc/h from the CIV absorber.
No LBGs within 5 cMpc/h.

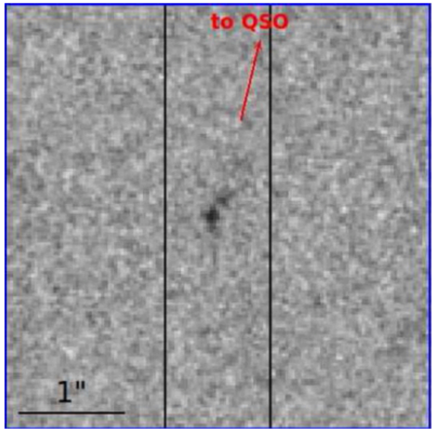
Excess of LAEs within 10 cMpc/h of the detected metals.

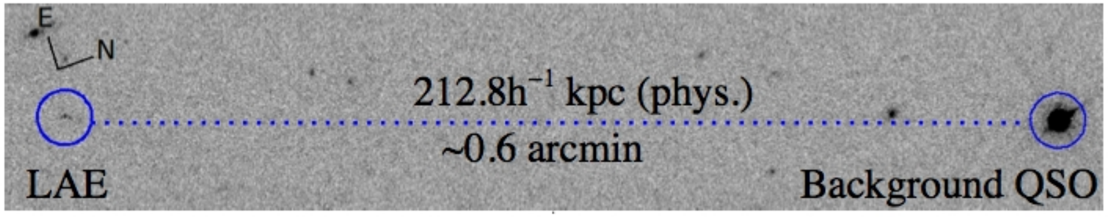
CIV absorbers prefer the LAE environment.

This is in stark contrast to CIV absorbers at z~3, which are found to arise in the circumgalactic medium of bright LBGs (the highest density peaks),
e.g. Steidel+10.

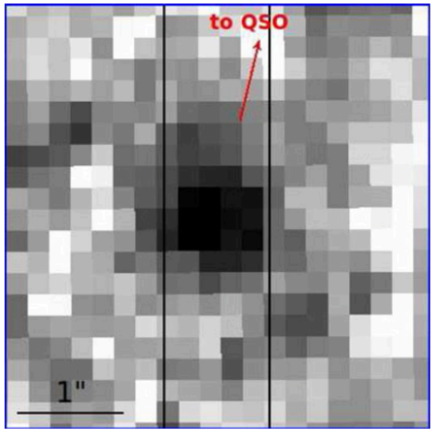
An LAE galaxy-CIV absorber pair at z=5.72

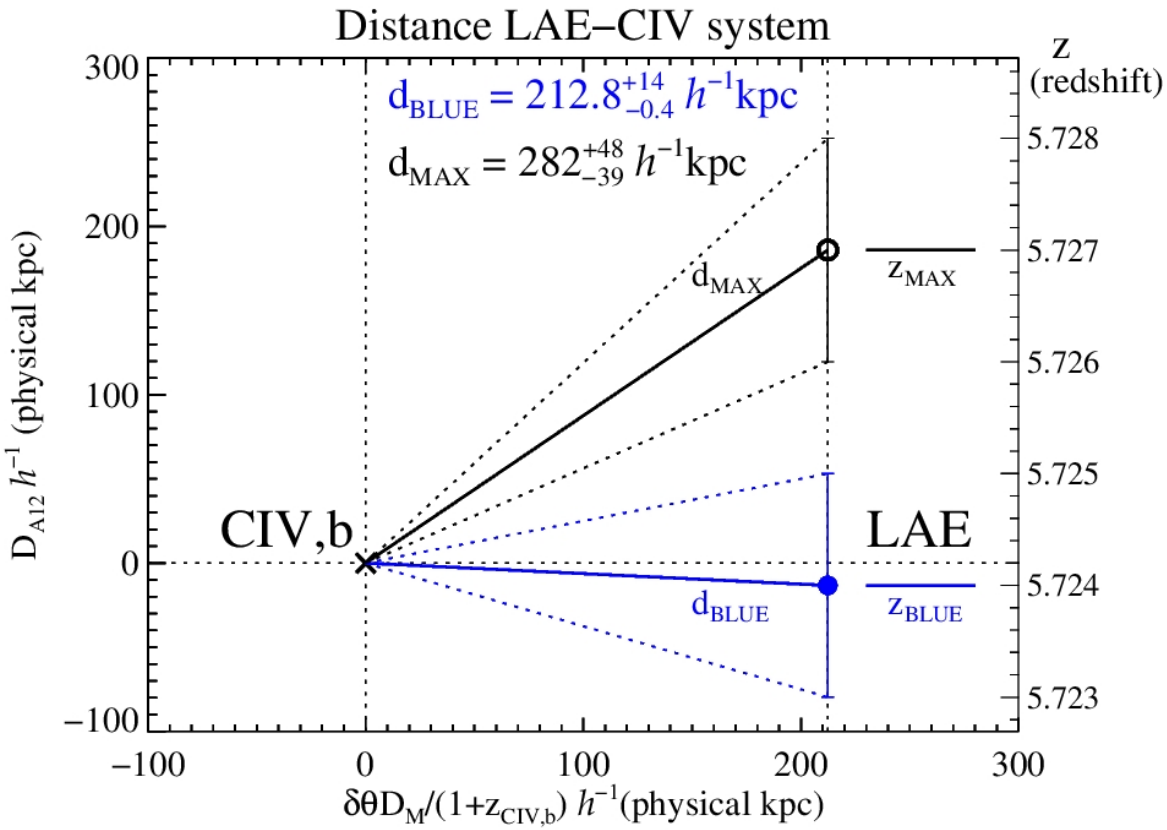
HST ASC, F850LP (z')



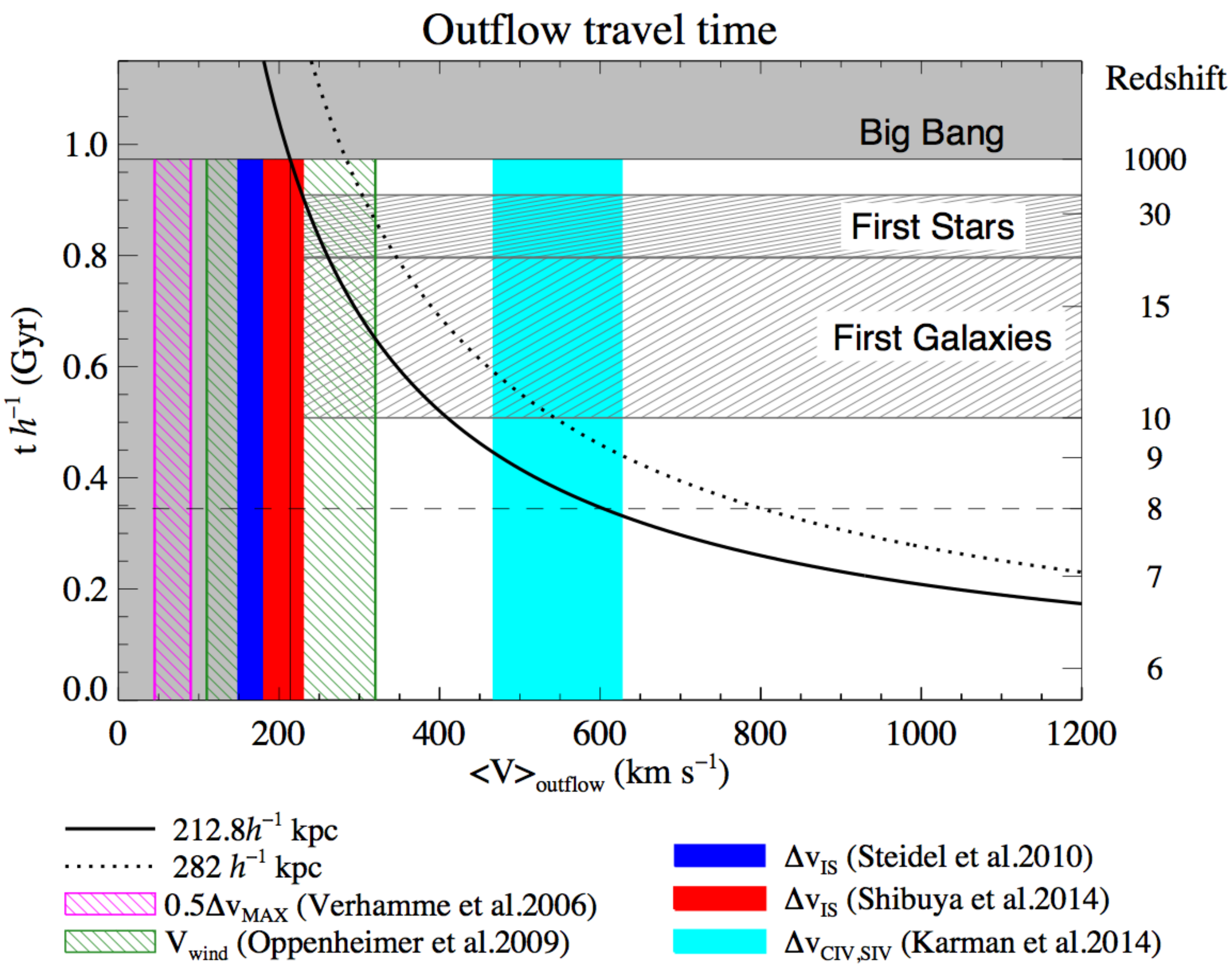


Subaru, NBCIV





Are the metals are a direct result of a wind from the LAE?



No, not if the winds have speeds less than 300 km/s, like those at z~2-3

Either the wind has v>500 km/s, or another closer, fainter galaxy has produced the metals.

Simulated example of an LAE-CIV pair at z~5.7

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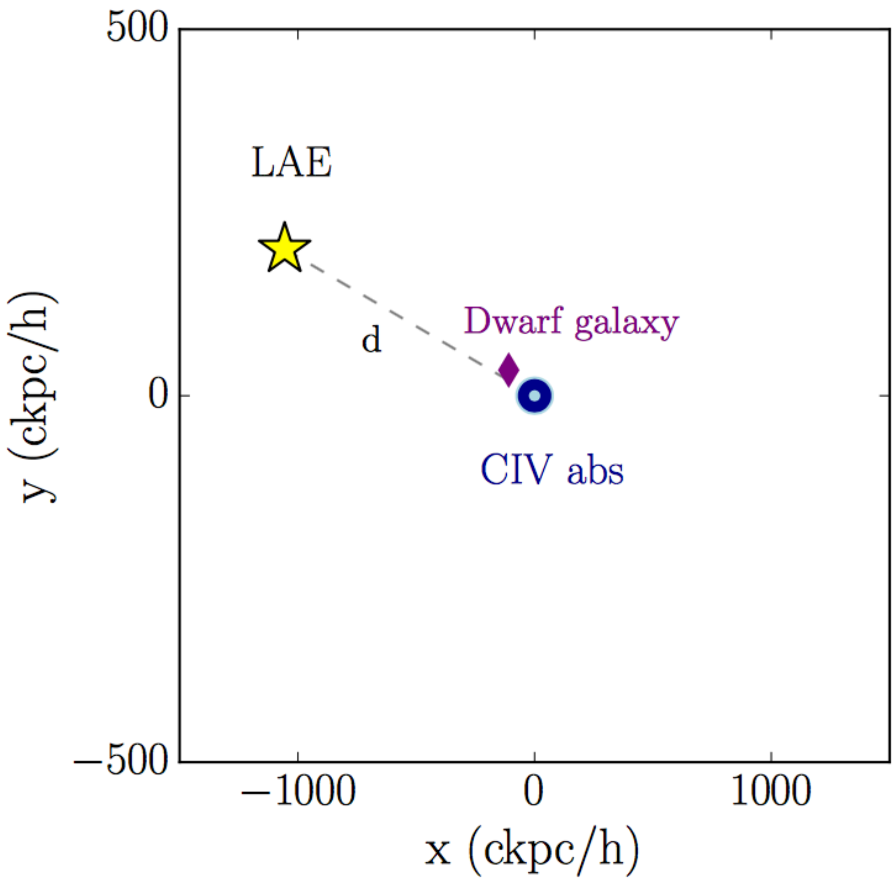


$$v_w = 2\sqrt{\frac{GM_h}{R_{200}}} = 2 \times v_{\rm circ}$$

Box size (cMpc/h)	M_h ($\times\ 10^{11} M_\odot$)	v_w (km/s)	t (Gyr)
18	4.9	446	0.73

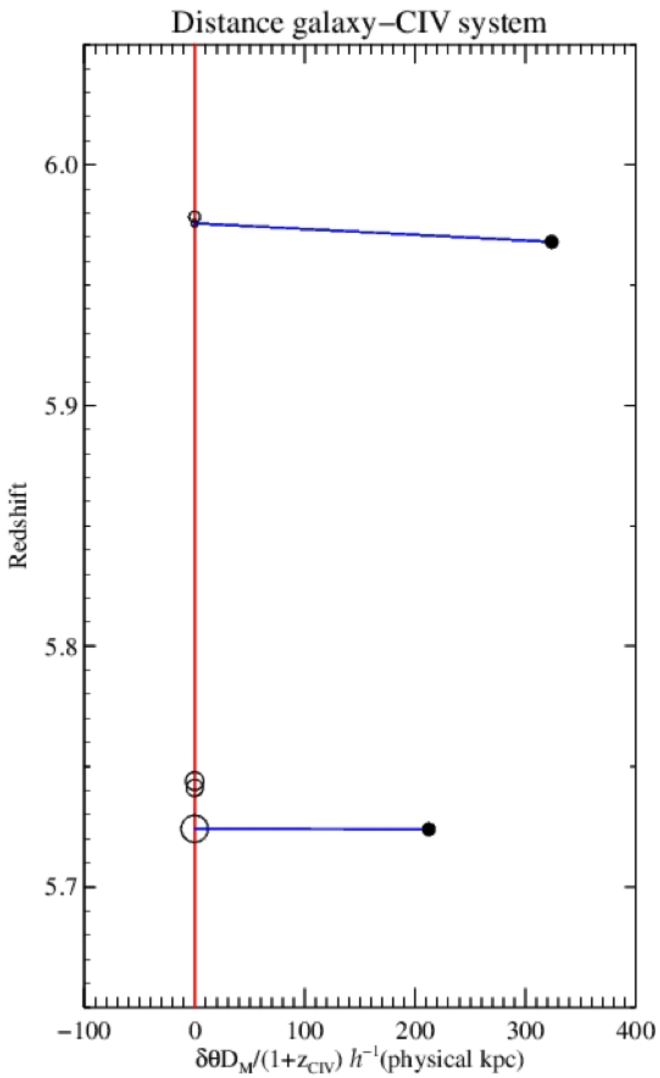
Simulated 1000 examples of LAE-CIV pairs – always find galaxies closer to the LOS, fainter than the detection limit of Diaz+15 (M_{uv}=-20.5)

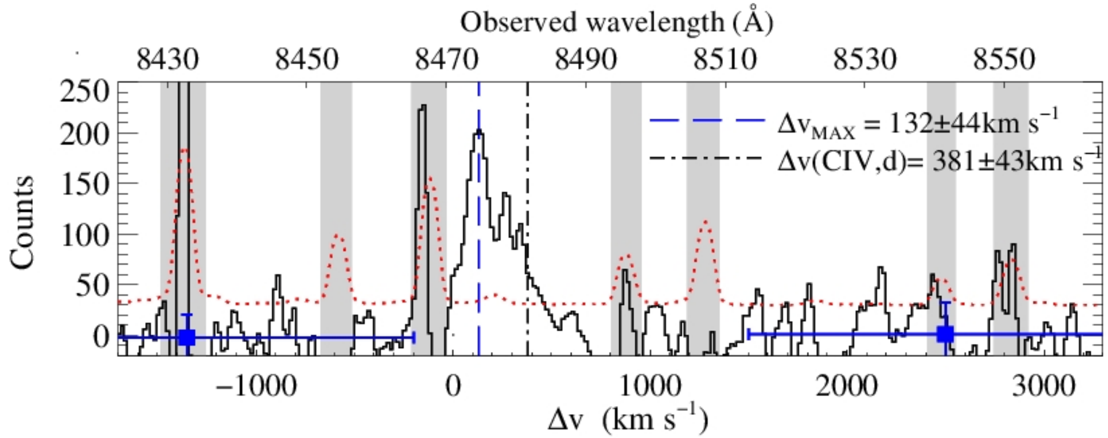
Scenario shown has a dwarf M_*=1.9x10^9 $M_\odot$, M_h=9.7x10^9 $M_\odot$, thus V_{wind}=100 km/s, launched 260 Myrs prior (z~7).

Garcia, Tescari, ERW, Wyithe (2017a)

119 comoving kpc = 18 physical kpc at this redshift.

Can't be the wind from this LAE, but here's another example…





VLT/MUSE observations

MUSE (Multi Unit Spectroscopic Explorer) is panoramic integral-field spectrograph operating in the visible wavelength range.

Wide Field mode uses 4 Sodium Laser Guide Stars 64" off axis to probe atmospheric turbulence and 1 visible Natural Guide Star to correct for the remaining atmospheric tip-tilt.

Our Observations:
6.4 hrs centred on QSO J1030+05
Wide Field Mode (1'x1')

Observational Parameters	
Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 arcmin^2
Spatial sampling	0.2x0.2 arcsec^2
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	3.9 10^{-19} erg.s^{-1}.cm^{-2}