The Chemical Enrichment of the Intergalactic Medium

Tae-Sun Kim

Astrophysikalisches Institut Potsdam

Outline

I. The Lyα forest

The low-density intergalactic medium

II. Metals in the Lyα forest

III. Metal enrichment mechanisms

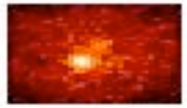
IV. Purpose of my visit to Trieste

The temperature evolution of the IGM

V. Summary

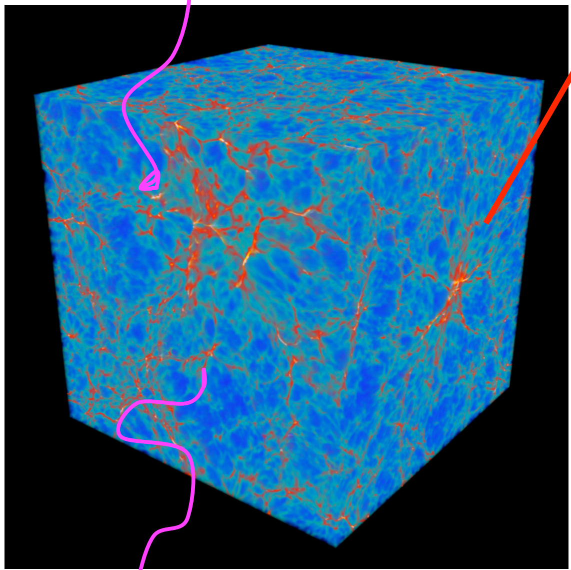
Photoionisation ⇔ Adiabatic cooling

QSOs

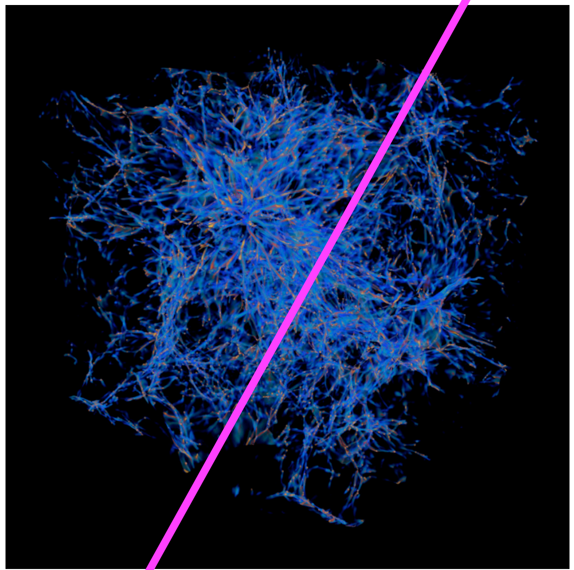


QSOs/Stars **UV photons**

Galaxy forming regions



$z = 7.5$



$z = 2.8$

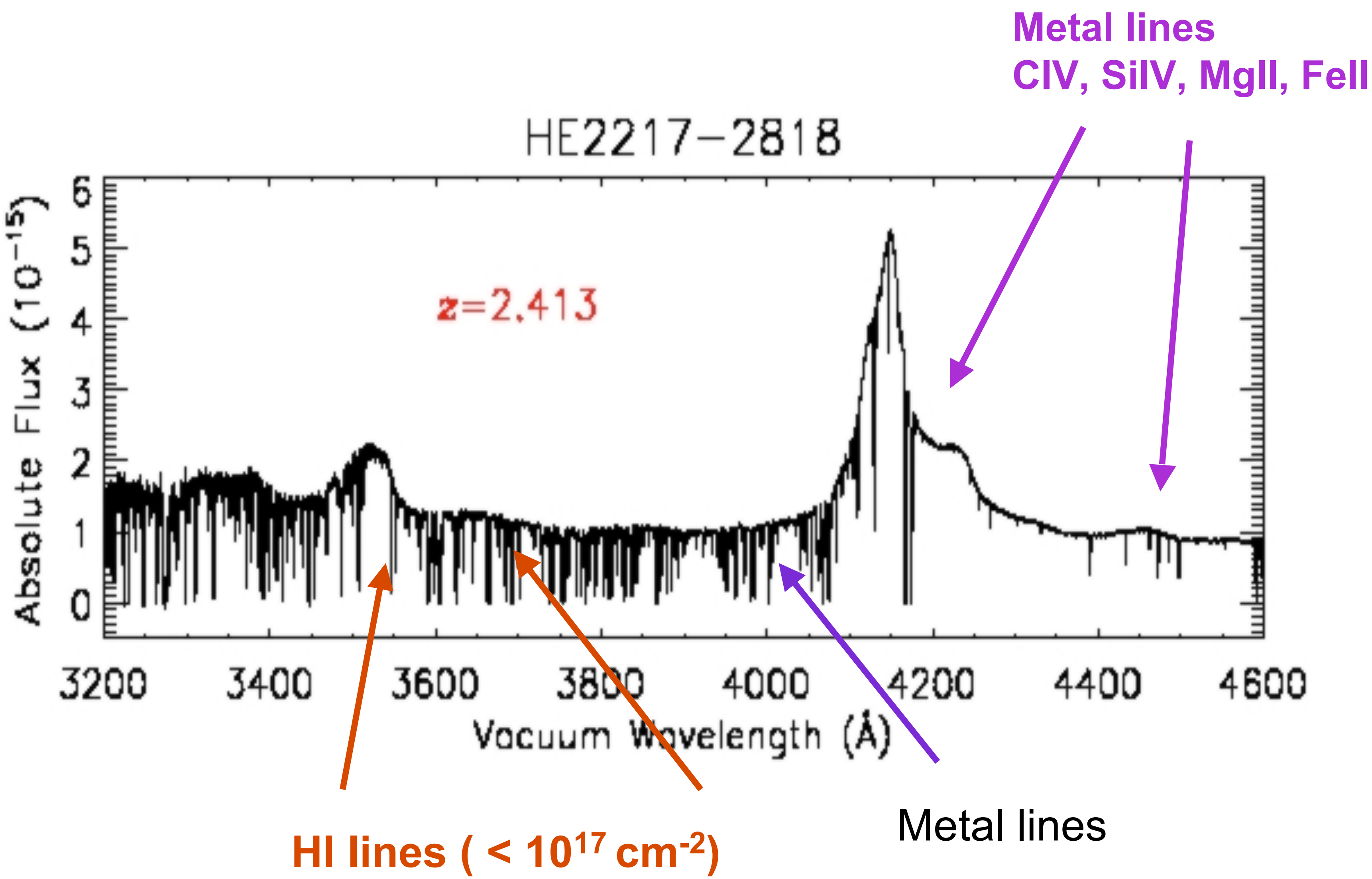
Cen (2005)

Highly ionised, n(HII)/n(HI) ~ 10^{5-6}
Temperature ~ 10^{4-5} K

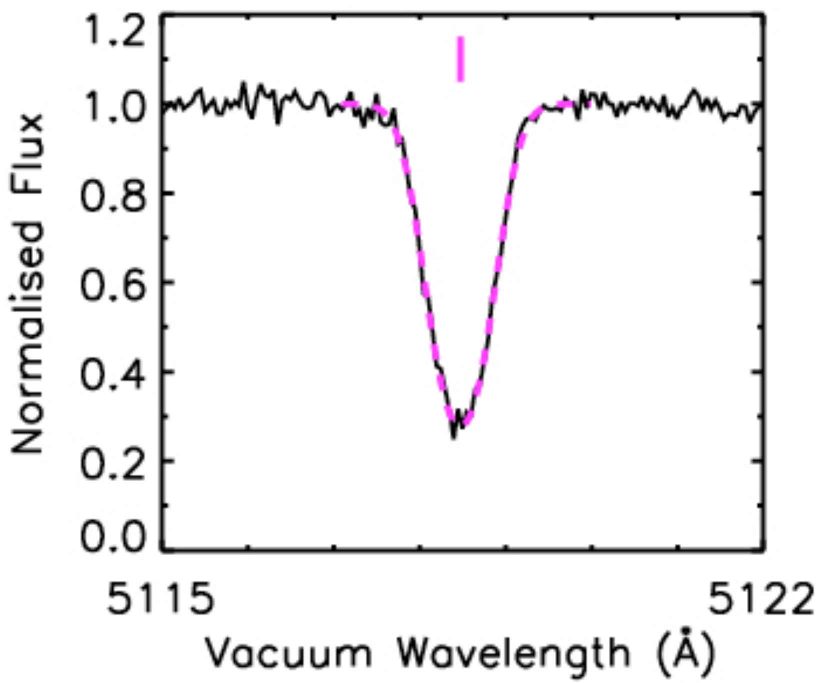
On large scale, traces Dark Matter

The Lyα forest (the intergalactic medium: H, He)

highly ionised, low density absorption lines



Observations: I. Voigt profile fitting



Profile fitting:

1. line identification
2. absorption redshift z
   $z=\lambda_{obs}/\lambda_{rest} - 1$
3. column density N (# cm^{-2})
4. line width b (km/sec)

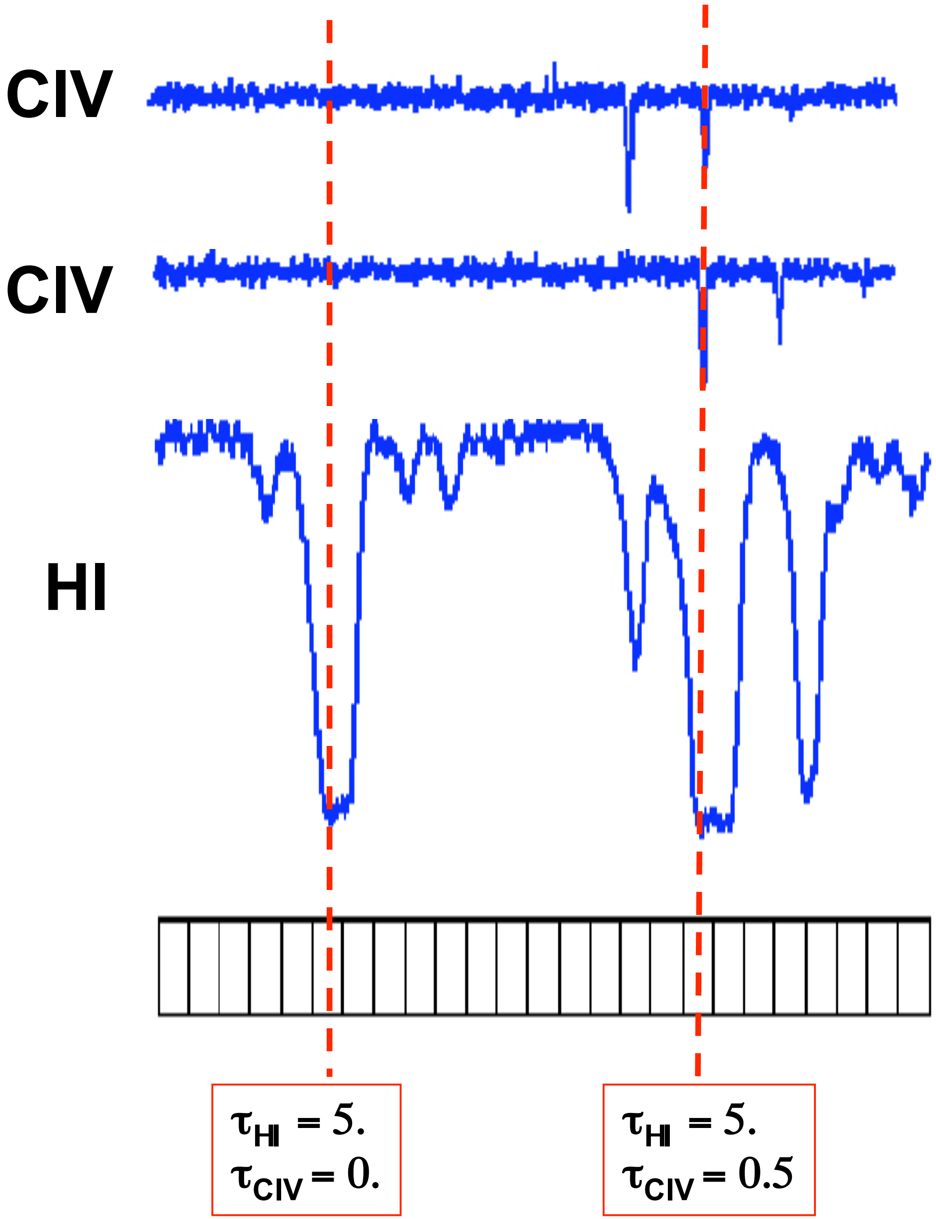
$$\underline{b^2} = \frac{2k\underline{T}}{m} + b_{\rm tur}^2$$

$$\rho \propto n(\mathrm{H\,I}) \propto N(\mathrm{H\,I})$$

(overdensity)

N (ions), #/dz, Temperature, Ω (ions)

II. Pixel optical depth method: CIV / HI



$N_{HI} \sim 10^{12.5-16}\ cm^{-2}$

$$f = f_o \exp^{-\tau}$$

Median distribution of

τ_{CIV} / τ_{HI}

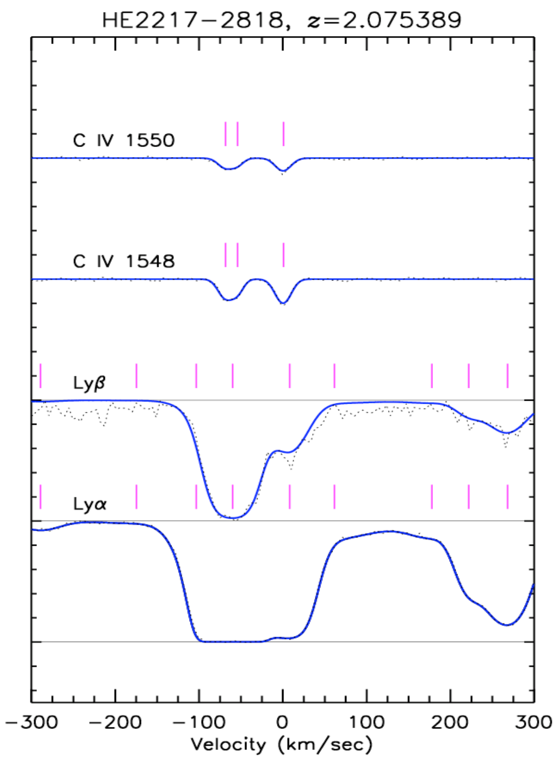
statistical measurement

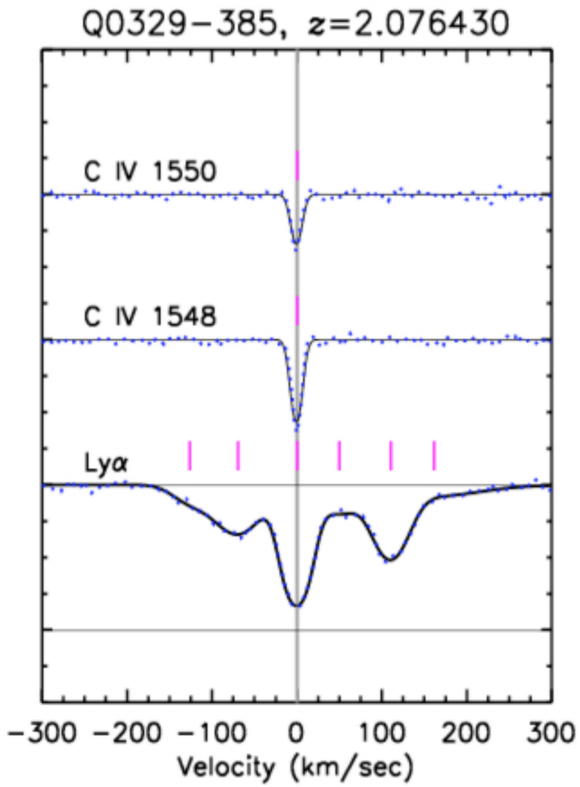
Cowie & Songaila (1998)
Ellision+ (2000)
Aguirre+ (2002)

CIV, SiIV, SiIII, CIII, OVI, NV: commonly observed

CIV (λλ1548, 1550) at 2 < z < 4

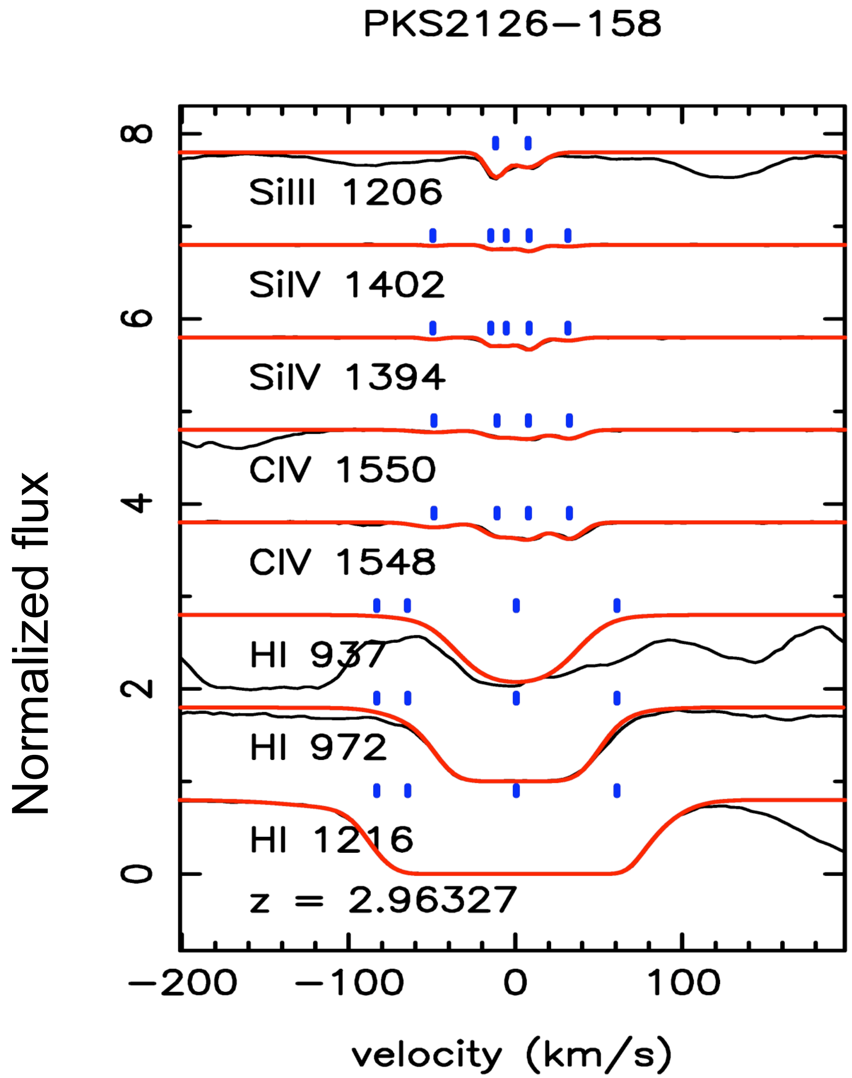
CVI (λ33.7) at z < 2





From UVES data

Highly ionised systems



N(HI) = $10^{15.81}$ cm^{-2}

For the metal systems: CIV, CII, SiIV, SiII, SiIII, OVI abundances, etc.

Photoionisation model

CI, CII, CIII, CIV, CV => C

[C/H] or [M/H]

II. Why do we study metals in the IGM?:

I. The forest contains a majority of baryons at $z \sim 3$

II. Does not have an in-situ star formation

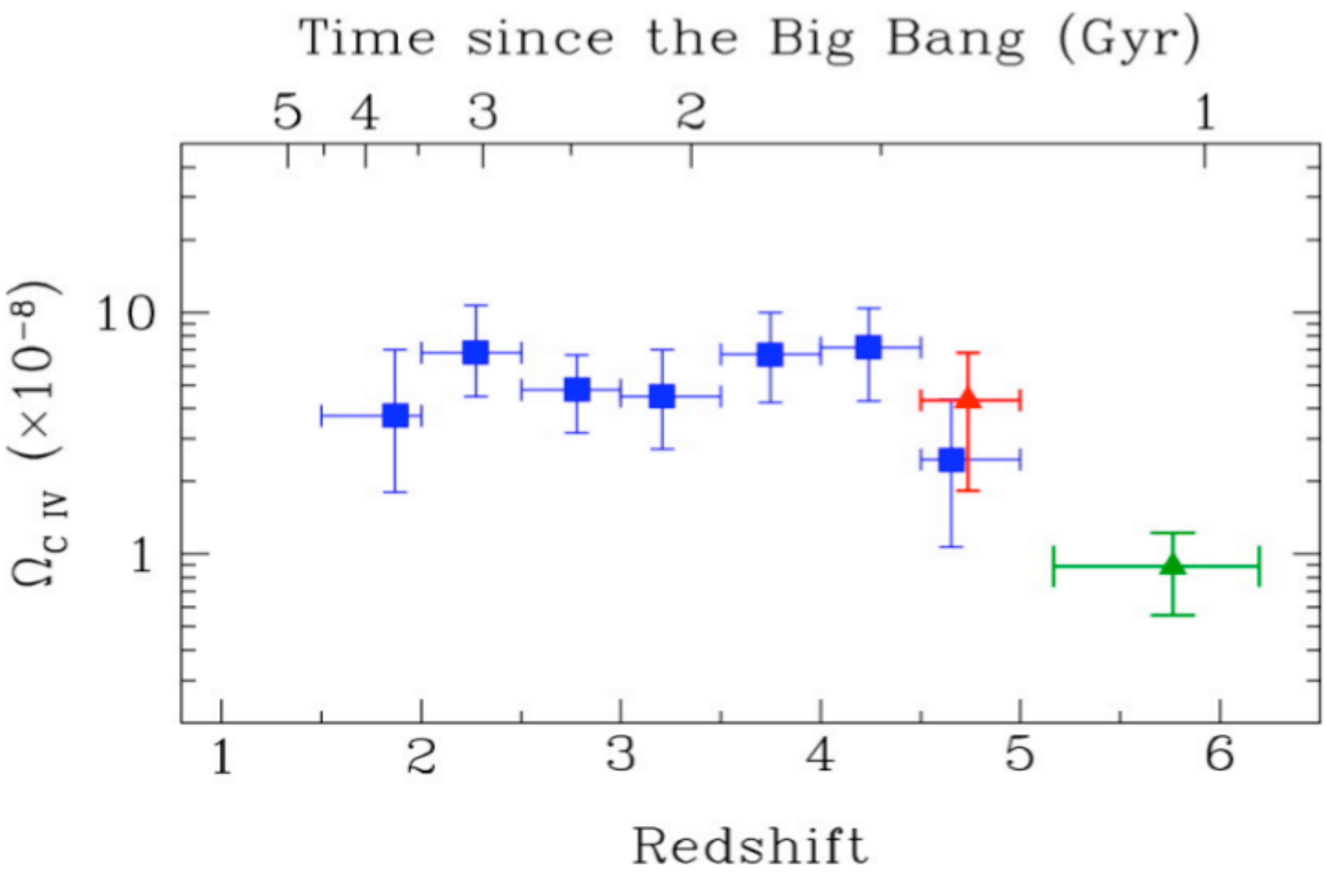
III. Feedback between galaxies and the IGM

IV. An archaeological record of past star formation

V. A window to the physics underlying the formation of galaxies

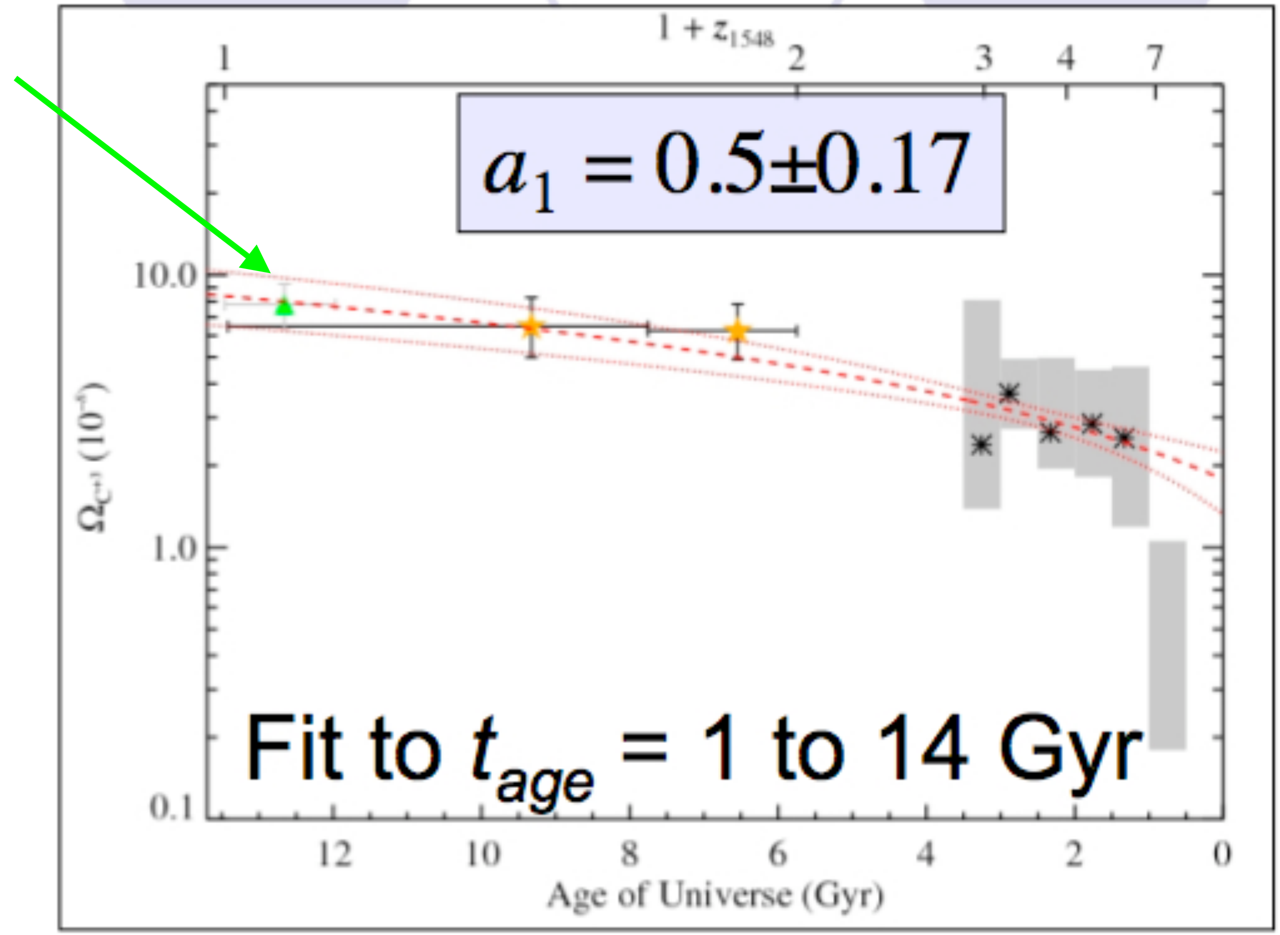
CIV: 1548/1550 A

UV(HST) Optical IR



Ryan-Weber+ (2009), 10 QSOs

Danforth & Shull (2008): 28 sightlines



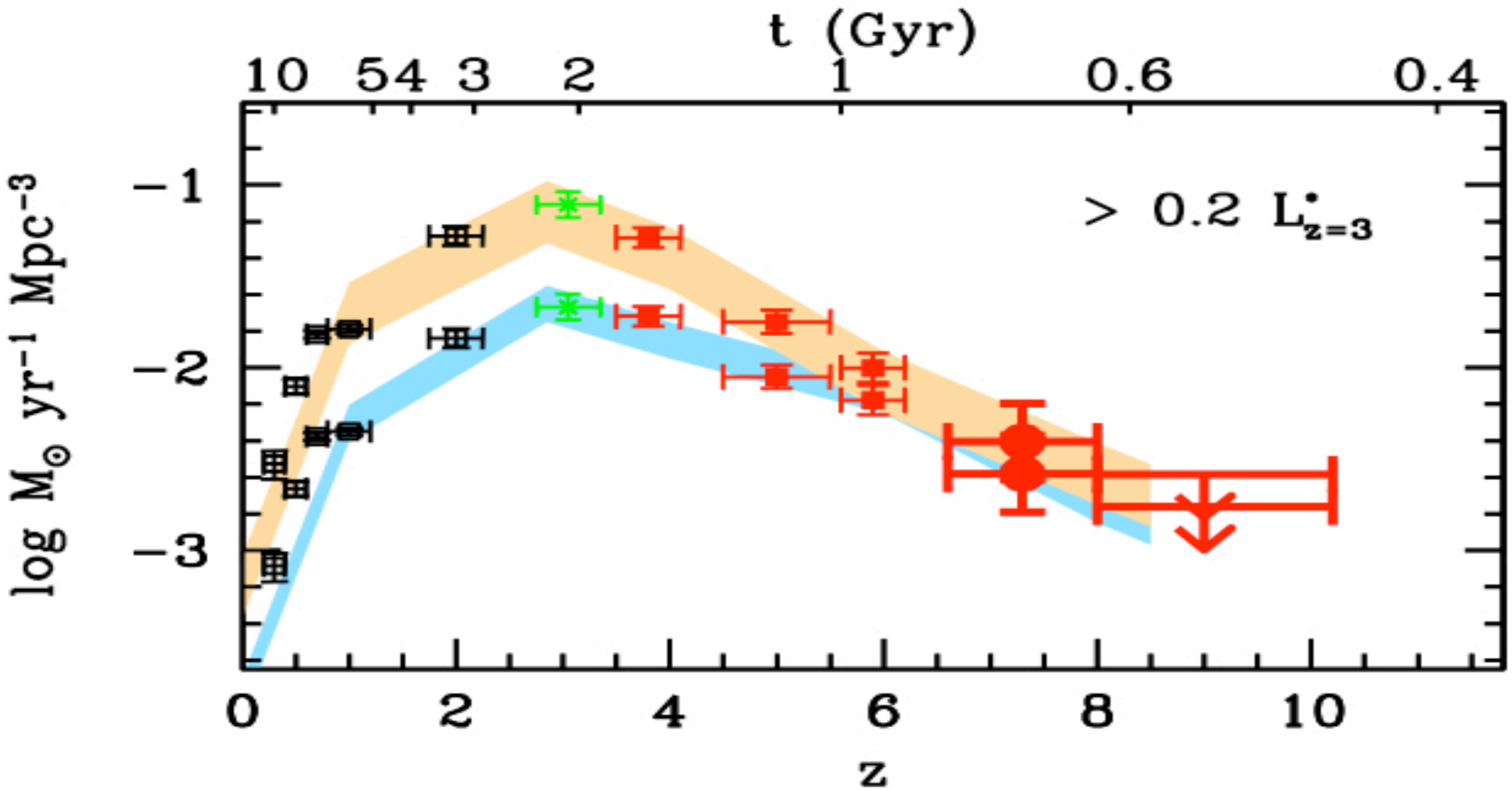
48 sightlines

$$\frac{\Omega_{C^{+3}}}{10^{-8}} = a_0 + a_1\left(\frac{t_{age}}{10^9\,\mathrm{yr}}\right)$$

From Cooksey's PPT (2009)

'Early' vs. 'Late' Enrichment

- The C IV we see at $z = 6$ was presumably synthesized at $z = 9 - 10$



Bouwens et al. 2008

From Pettini's talk

III. Metal enrichment mechanisms

PopIII stars: HI reionisation at $z \sim 10$

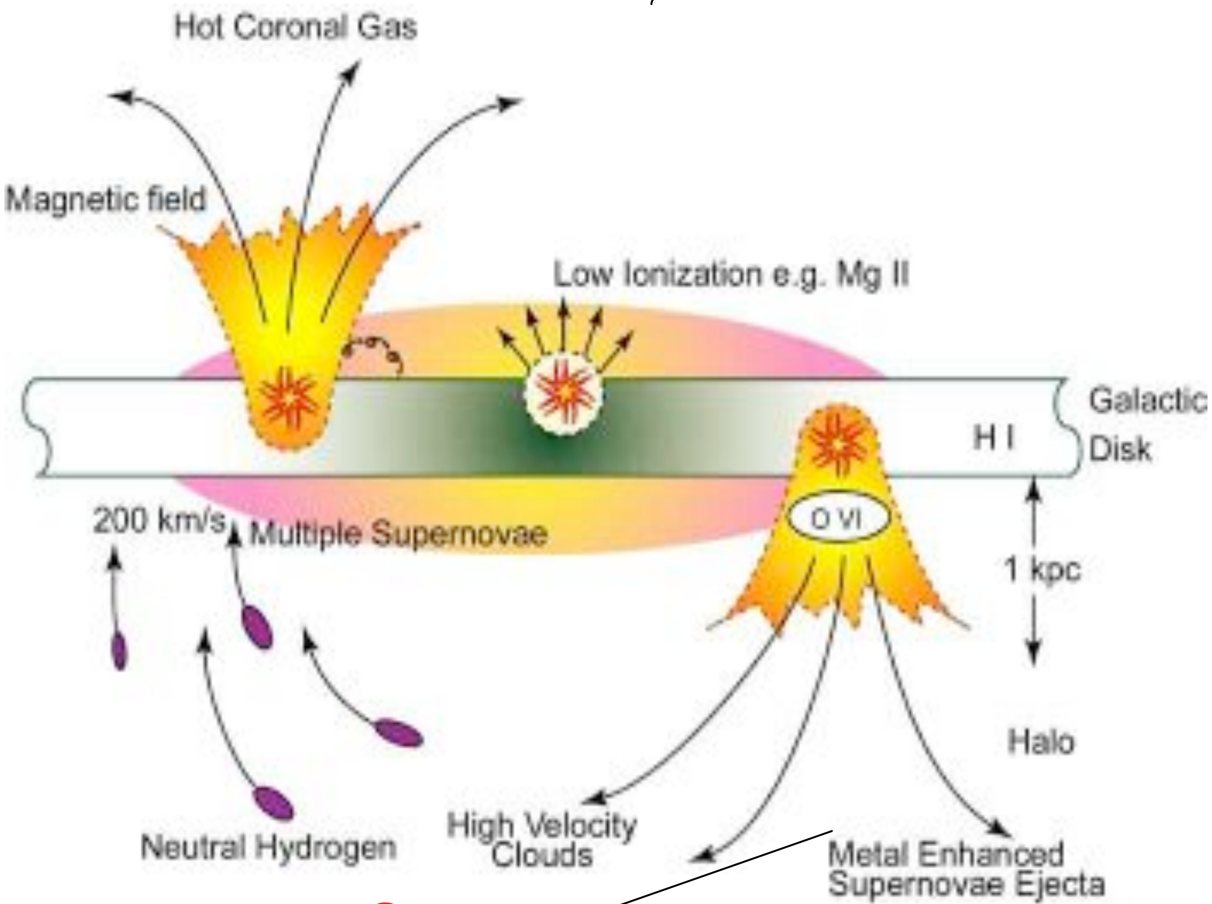
Pollutes the IGM at a lower, uniform level but what level?

Cannot be ruled out yet.

Dynamical mixing: too inefficient

Galactic-scale winds:

Wind mechanism?

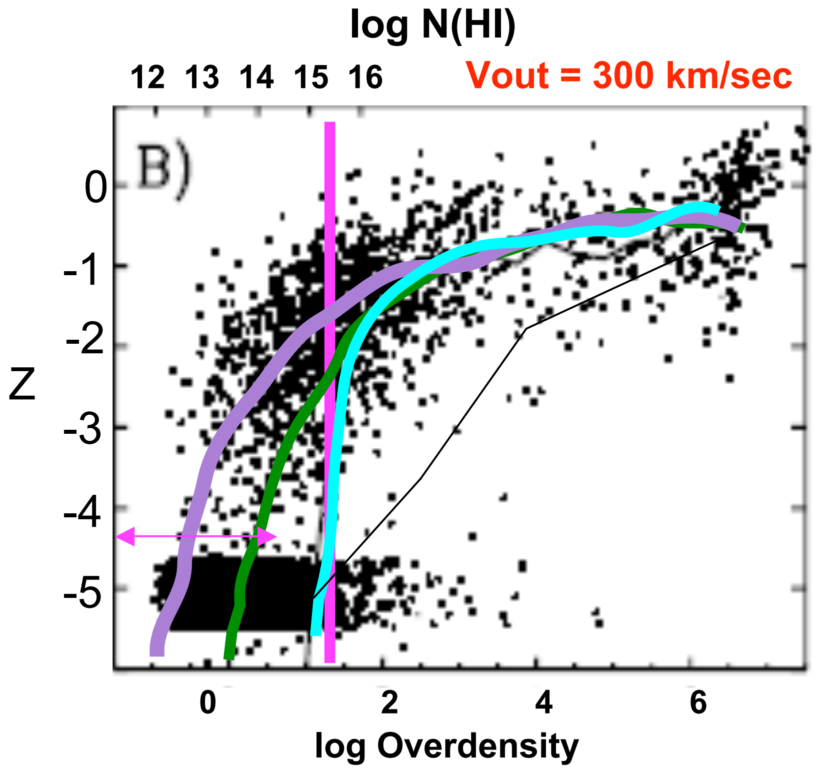


unknown NASA artist (from a web)

Cosmological simulations do not
Resolve this process.

Metals in Disk ==> Halo ==> IGM
? ?

Metal propagation in to the IGM: Overdensity-Metallicty relation

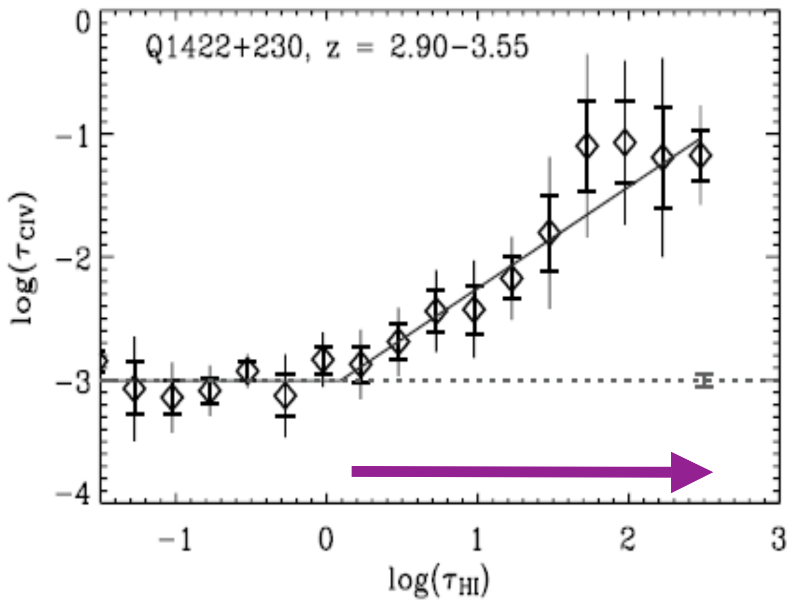


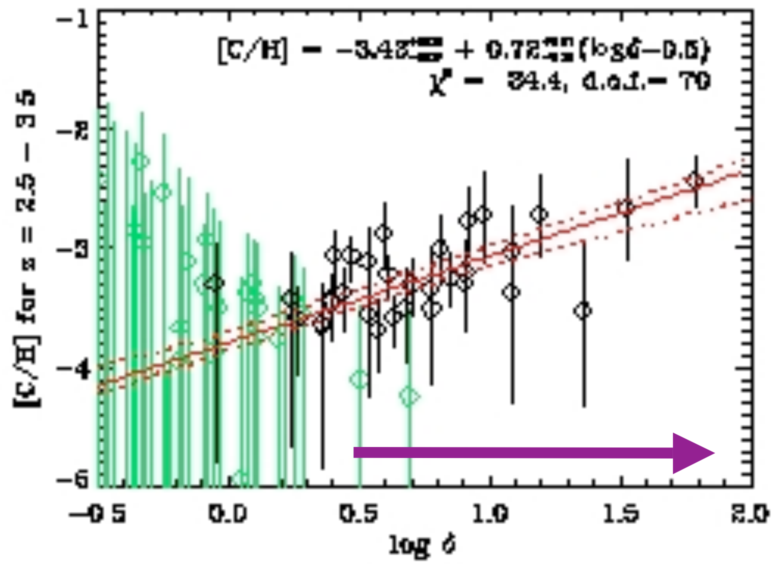
Volume-averaged metallicities

As *z* decreases
Overdensity-Metallicty relation shifts towards the left.
Dependent on
Outflow velocity

Aguirre et al. (2001)

From the 19 UVES/HIRES spectra at 1.8 < *z* < 4.1



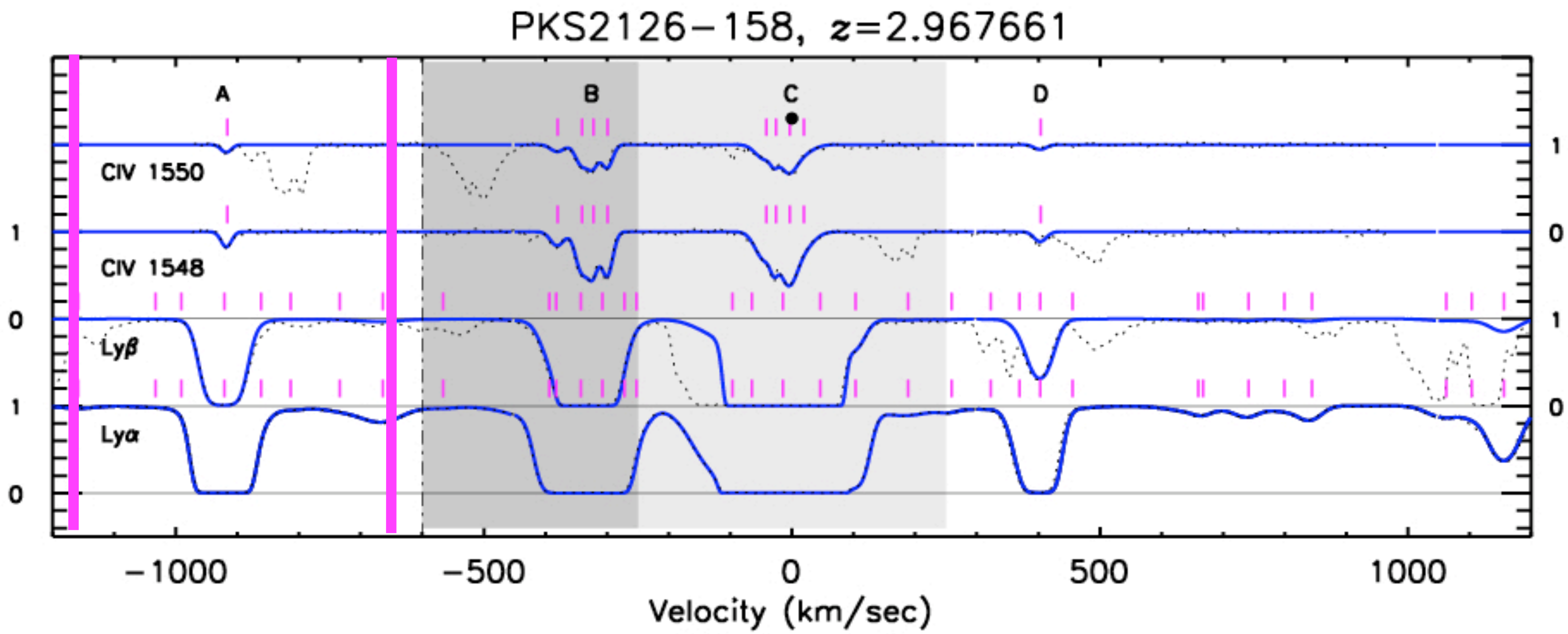


Schaye+ (2003)

[C/H]: power-law as a function of overdensity
[C/H]: no (very weak) redshift evolution

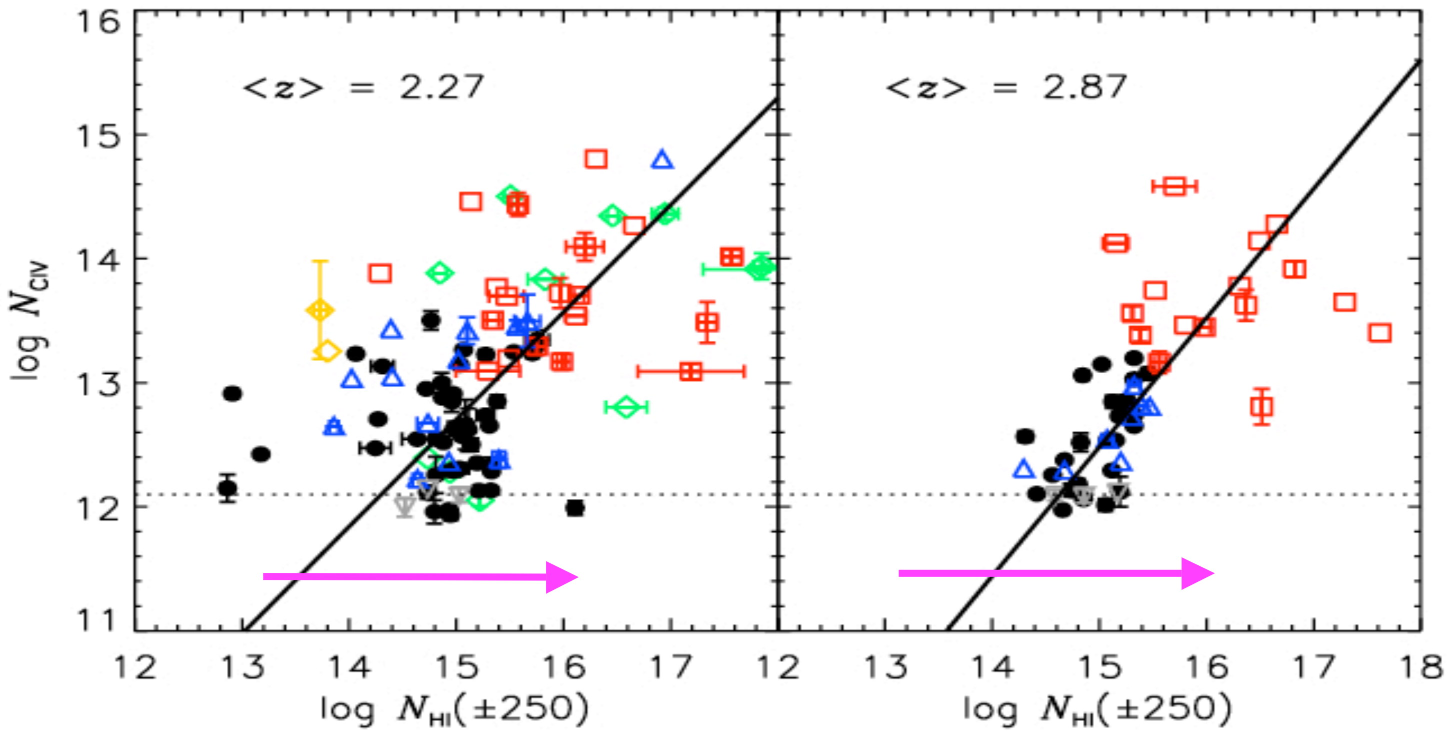
Definnition of a CIV system: Volume-averaged

- ±250 km/sec ==> -600 km/sec or +600 km/sec



- From the 17 UVES QSO spectra,
- <z> = 2.27, $2 < z < 2.6$, 78 systems, dX = 19.6
- <z> = 2.87, $2.6 < z < 3.5$, 49 systems, dX = 8.1

N(HI)-N(CIV) relation

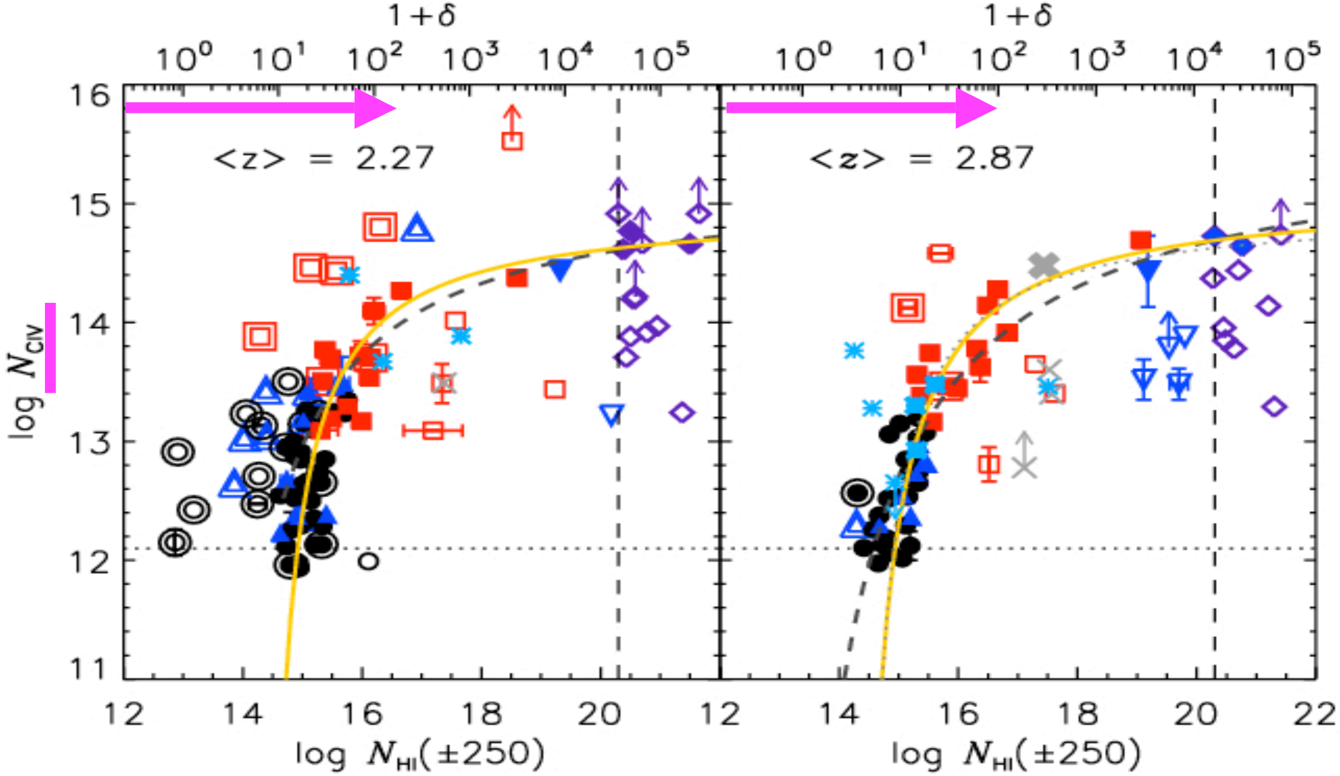


CIV+SiIV systems

CIV-SiIV systems

CIV+bl systems

<z> = 2.87; power law
<z> = 2.27; power law ??



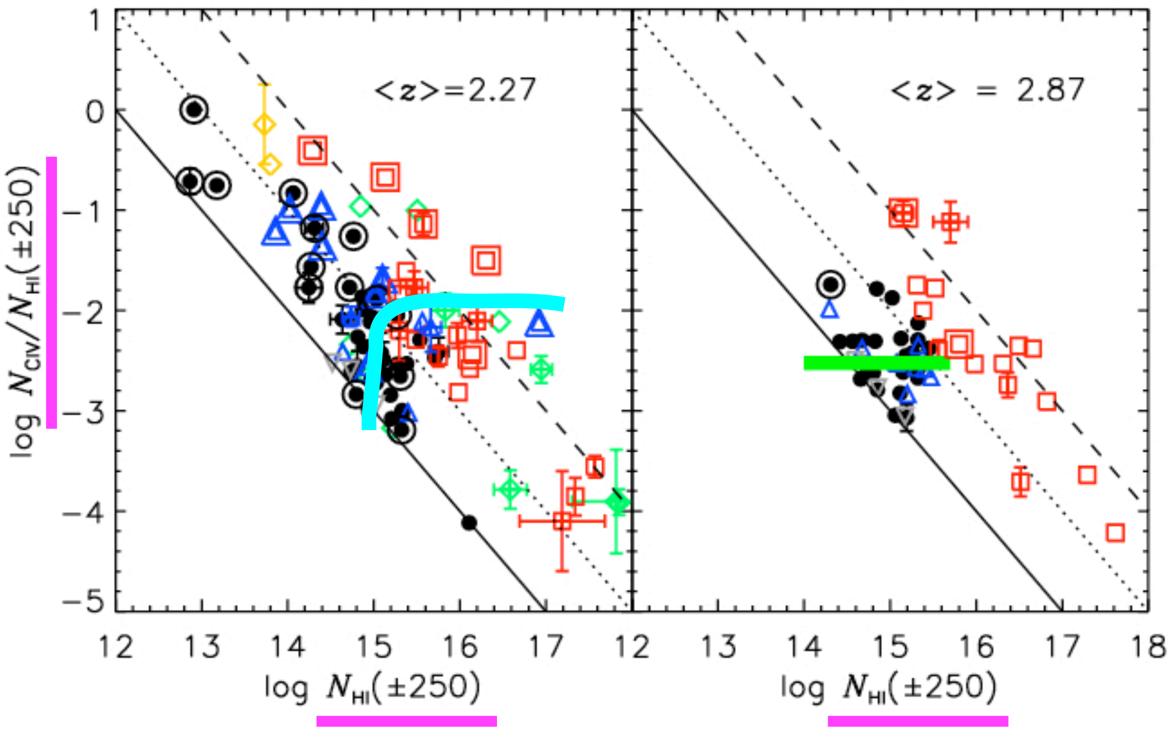
CIV+SiIV systems

CIV-SiIV systems

CIV+bl systems

Double symbols: highly ionised systems

N(HI)-N(CIV)/N(HI) relation



<N(CIV)/N(HI)>
= 0.003 at z = 3
Cowie et al. (1995)

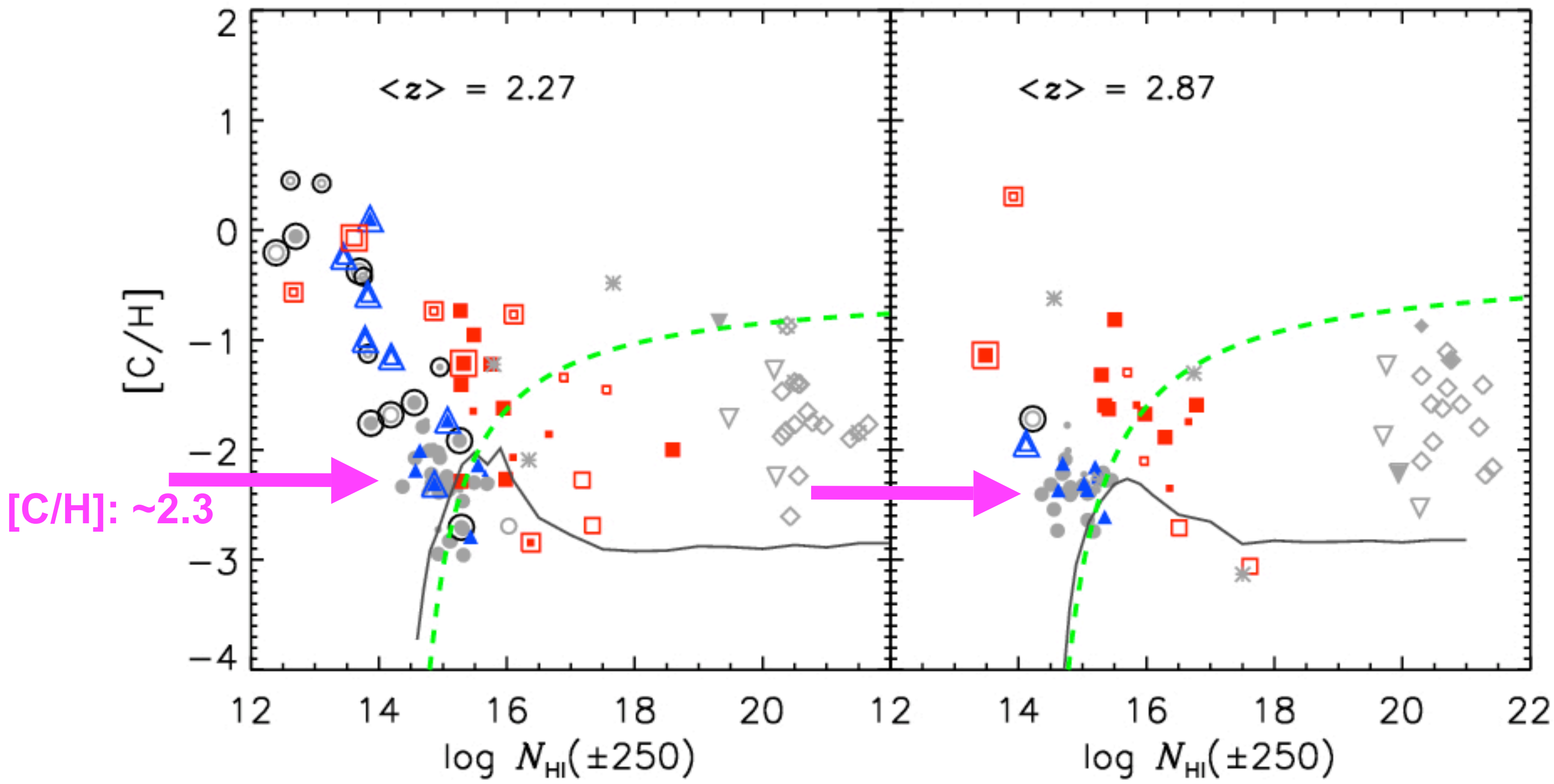
N(CIV)/N(HI) ➔ N(C)/N(H) ➔ [C/H]

The b values: 90% less than 20 km/sec (T < 2.8 10^5 K)

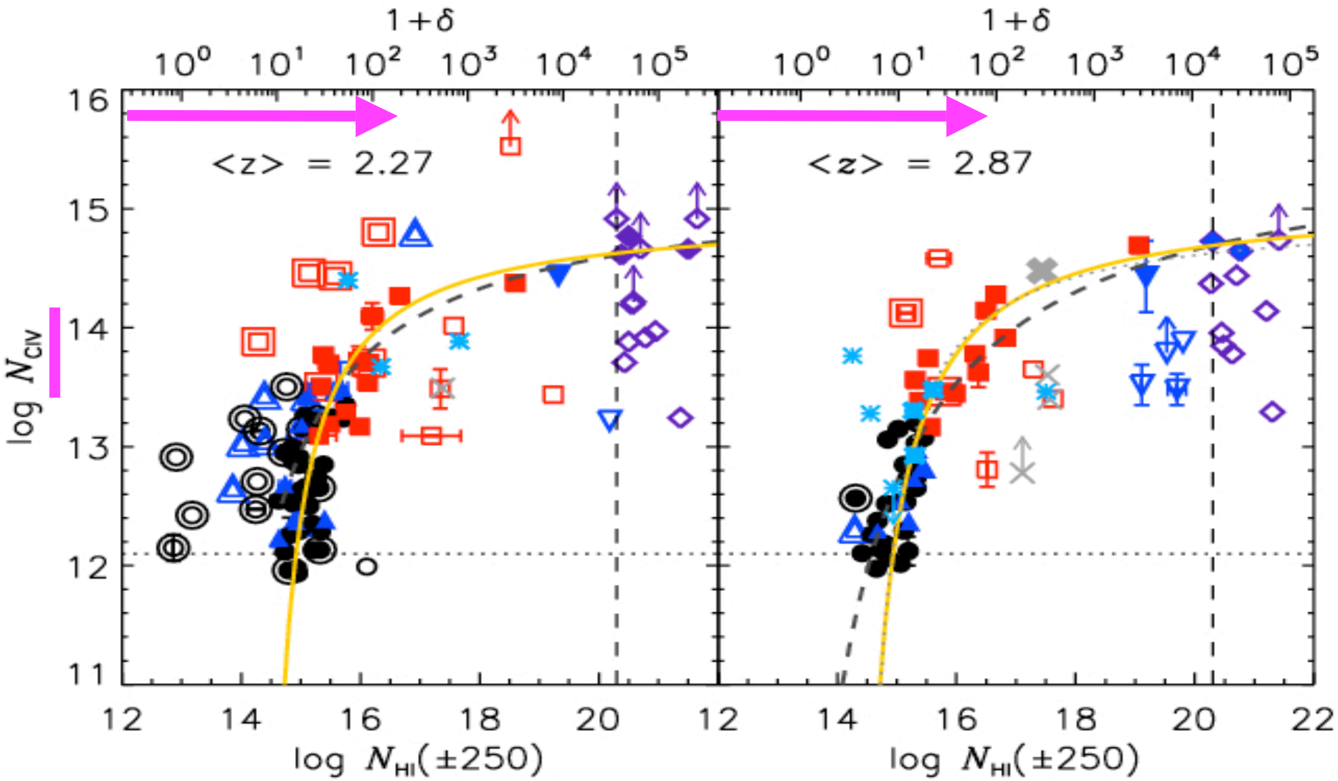
Photoionisation: CLOUDY

Haardt-Madau QSO+Galaxies UV background
Solar abundance pattern

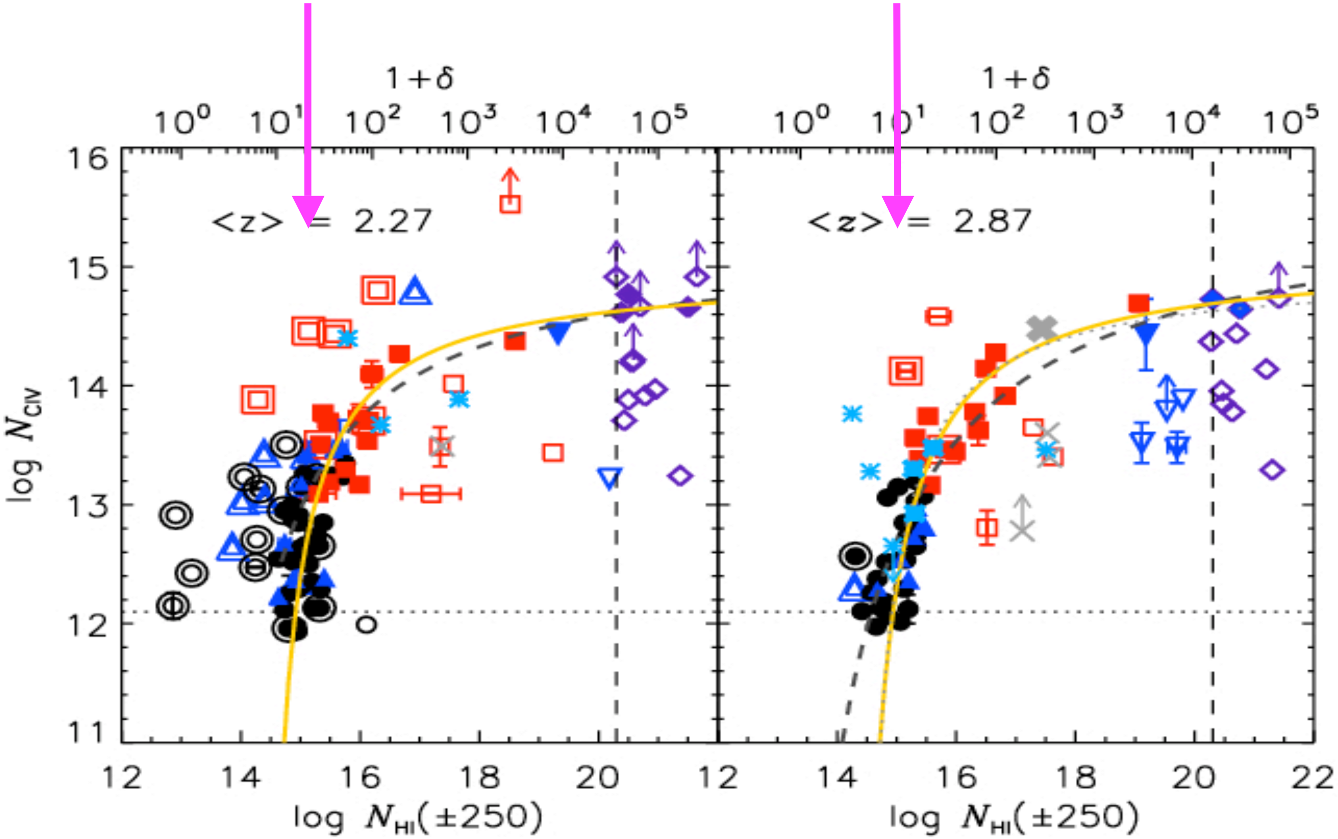
N(HI)-Metallicity relation: Photoionisation model (CLOUDY)



Big Caution: Large uncertainty of [C/H]
due to incomplete ion abundance

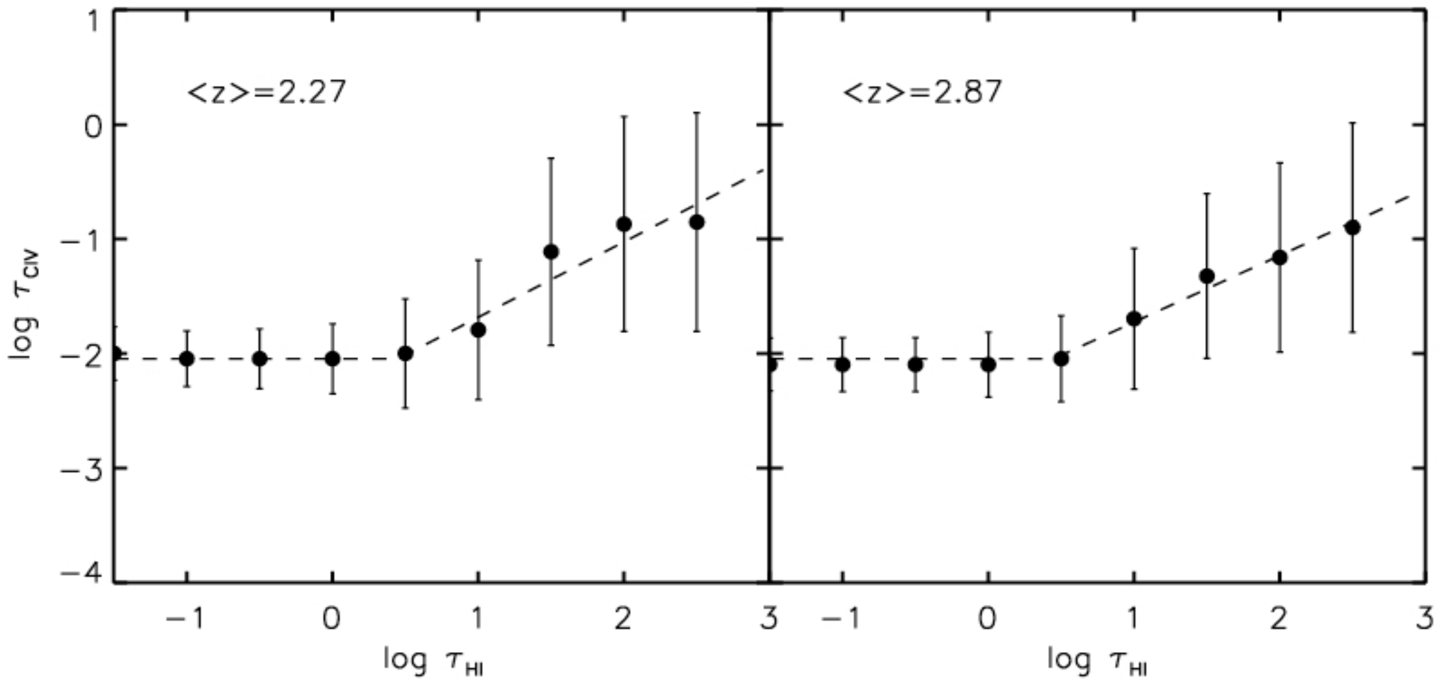


- log N(CIV) = [-4.43 / (log N(HI) – 13.04)] + 15.22 at <z> = 2.27
- Drop-off N(HI) ~ $10^{15.2}$ cm^{-2} at <z> = 2.87
- Outflow velocity ~300-400 km/sec based on Aguirre+ (2001)



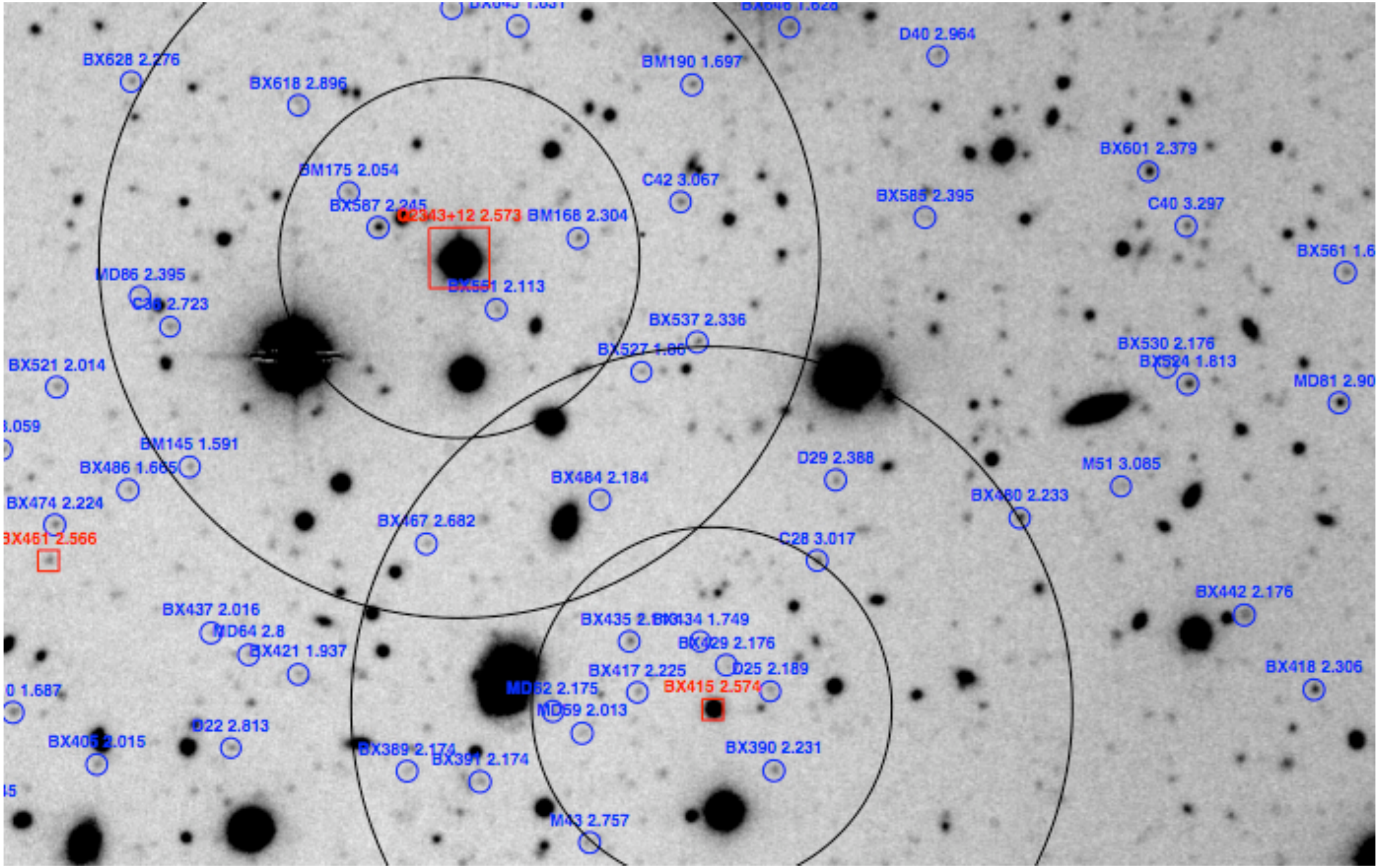
- No significant difference between the two redshifts
- time: 0.65 Gyr, ~0.26 Mpc with 400 km/sec
- Highly ionised systems peaks towards *z* ~ 2, SFR is highest
- probably small, metal-contained gas in to the IGM

Optical depth analysis:

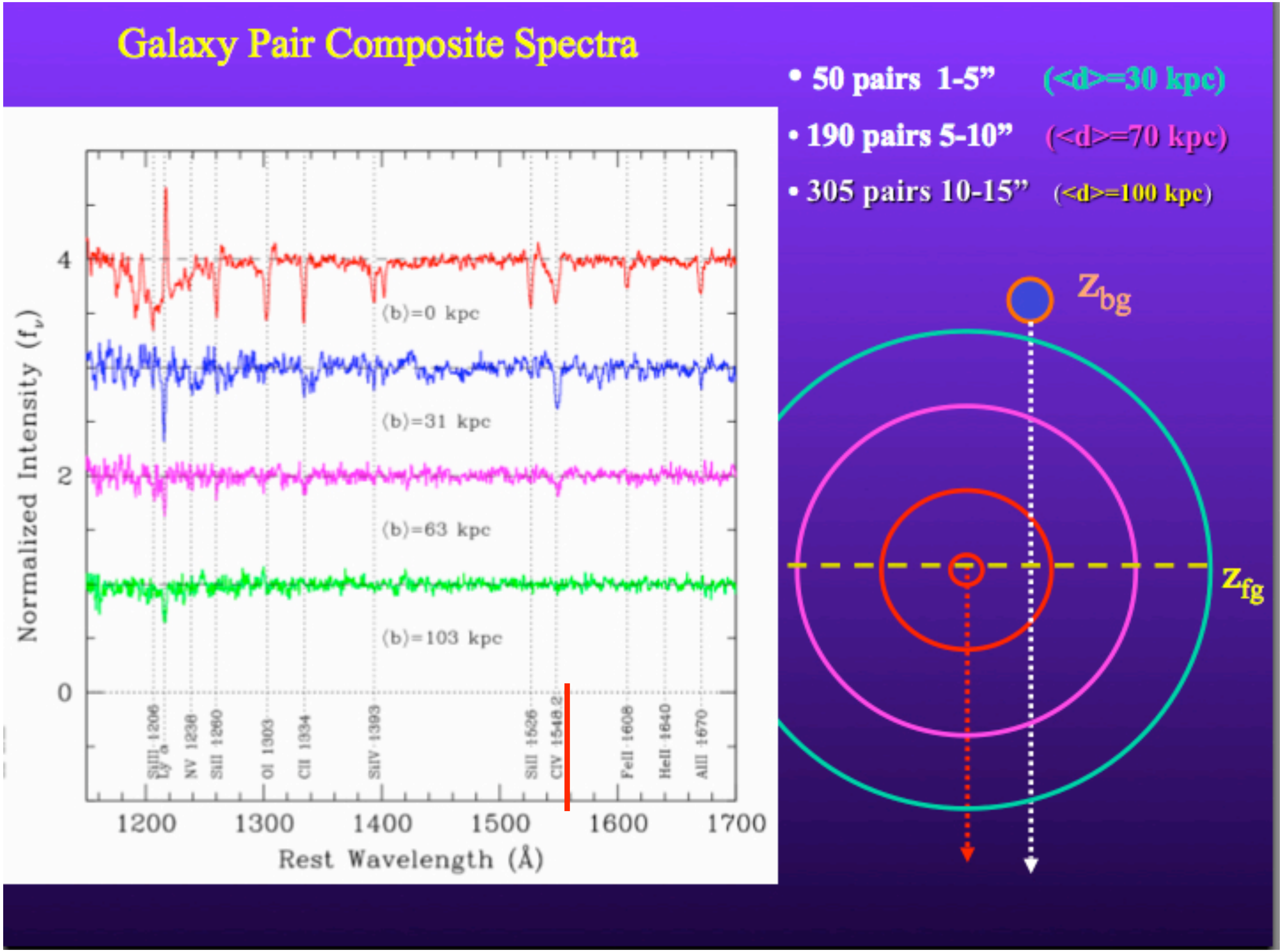


At <z> = 2.27,
less than 5% of clouds with N(HI) = $10^{12.5\text{-}14.5}$ cm^{-2} contains CIV

Needs three-dimensional studies:



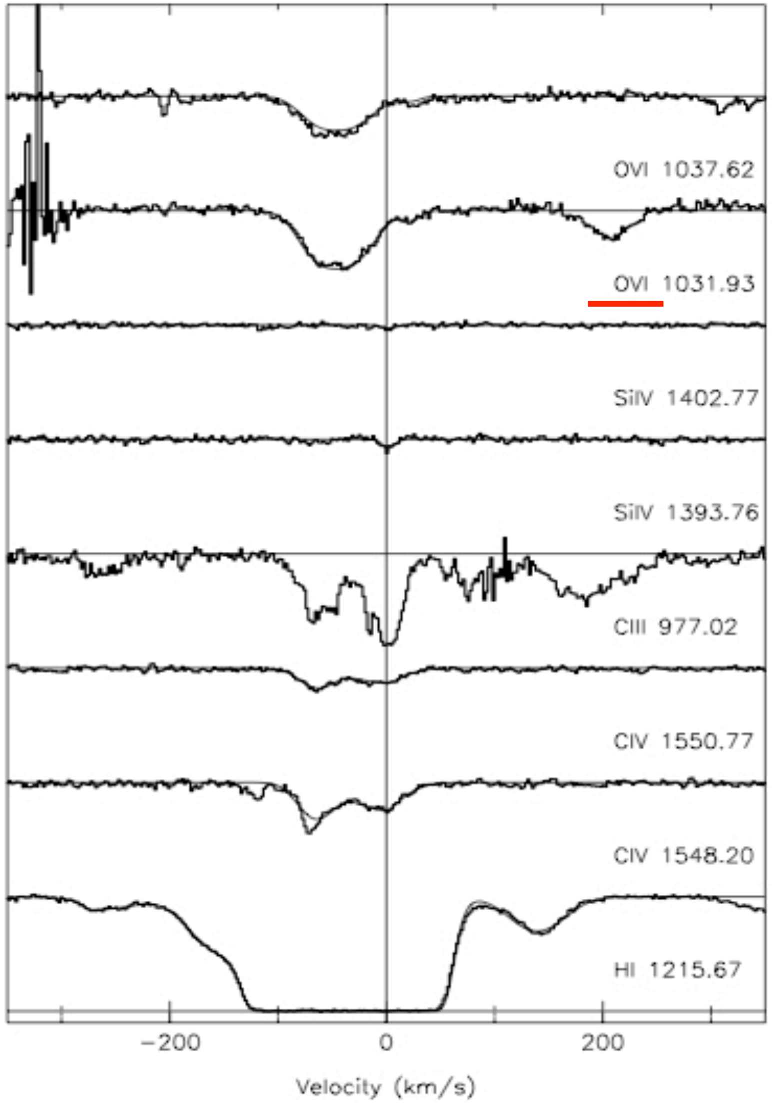
From Pettini's talk



~200 h^{-1} kpc size of CIV halo

From Ravic’s talk

OVI??: embedded in the forest, hard to detect

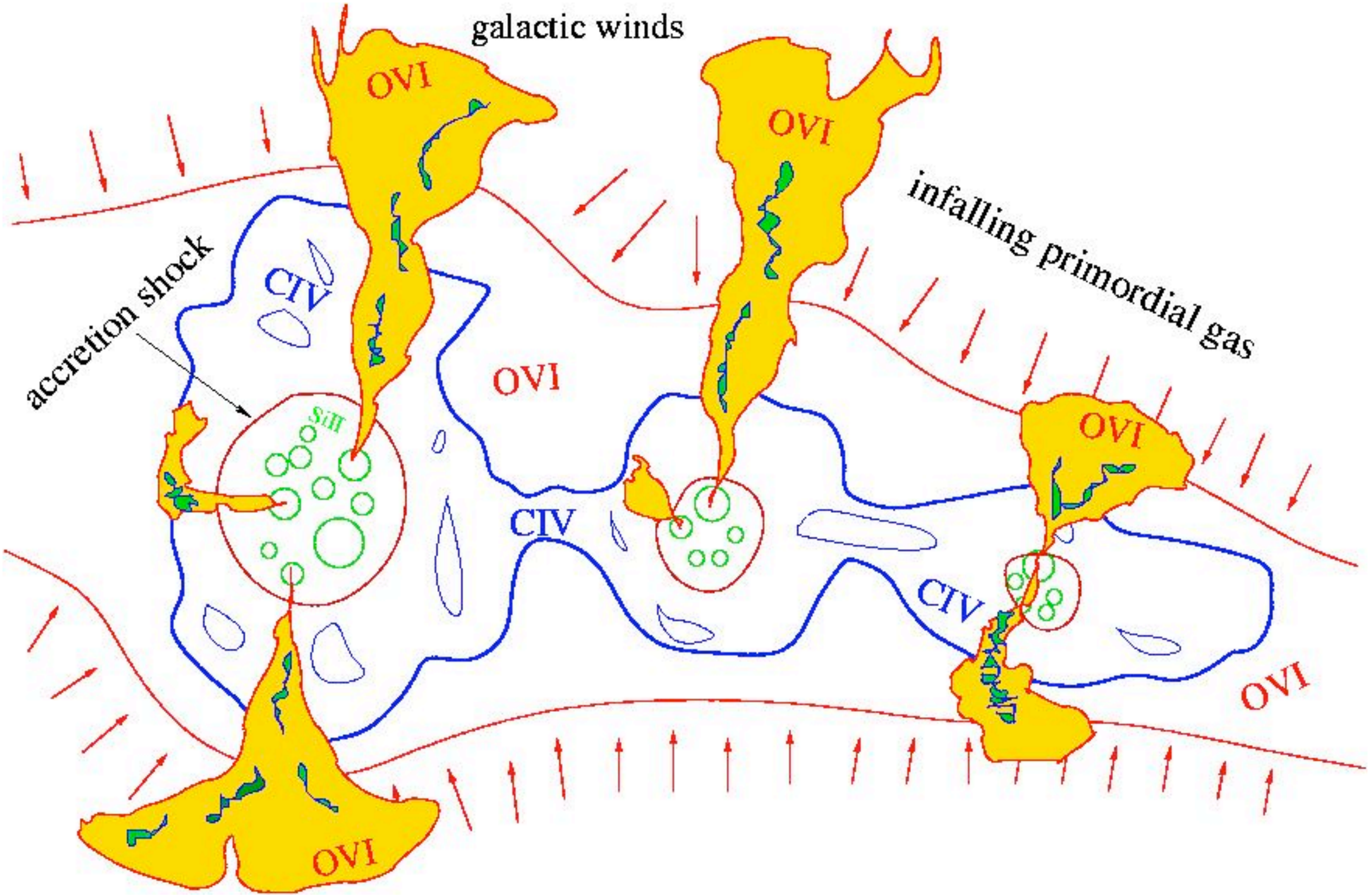


1 QSO sightline

Photoionisation models:
Sheets, bubbles:
100-200 h^{-1} kpc

~400 km/sec => 250 kpc

Simcoe+ (2006)



Kindly provided by M. Rauch

CIV: Circumgalactic medium

IV. My visit to Trieste:

Thermal history of the IGM at $3 < z < 3.6$

w. D'Odorico, Calura, Cristiani, Viel

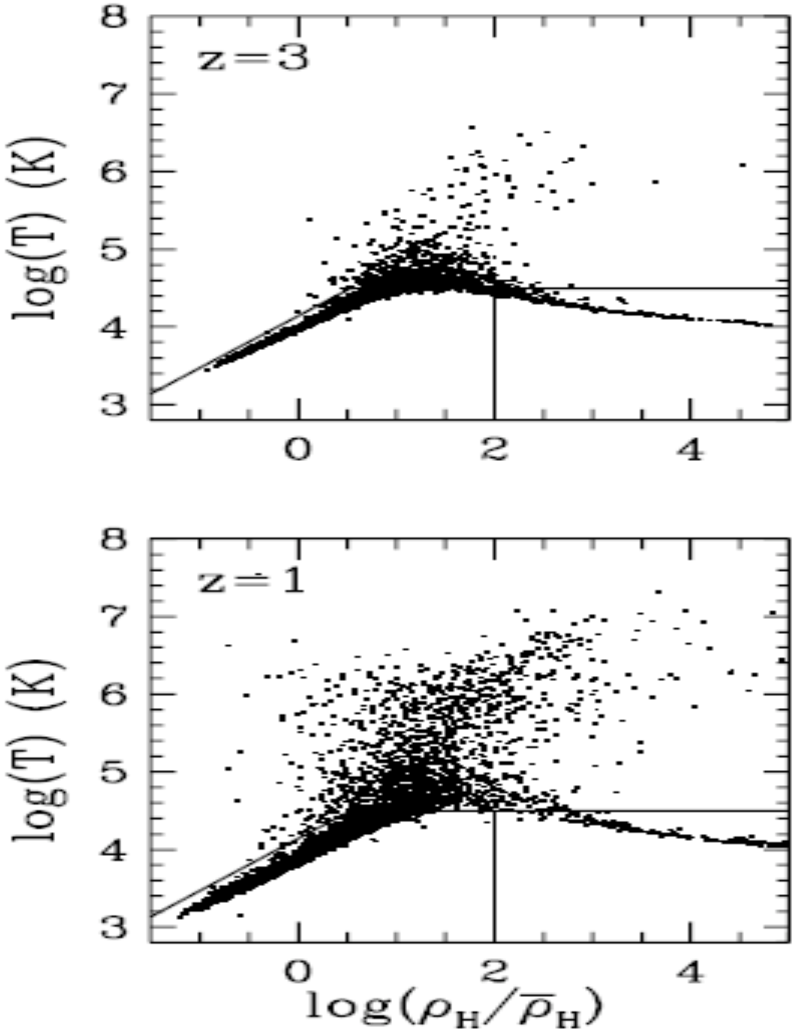
Effective Equation of State:

adiabatically expanding photoionised gas
higher densities: less expansion, more photoheating

$$T = T_0\,(1+\delta)^{\gamma-1}$$

δ : overdensity, $\rho/\bar{\rho}$
T: temperature
T_0: temperature at δ=1

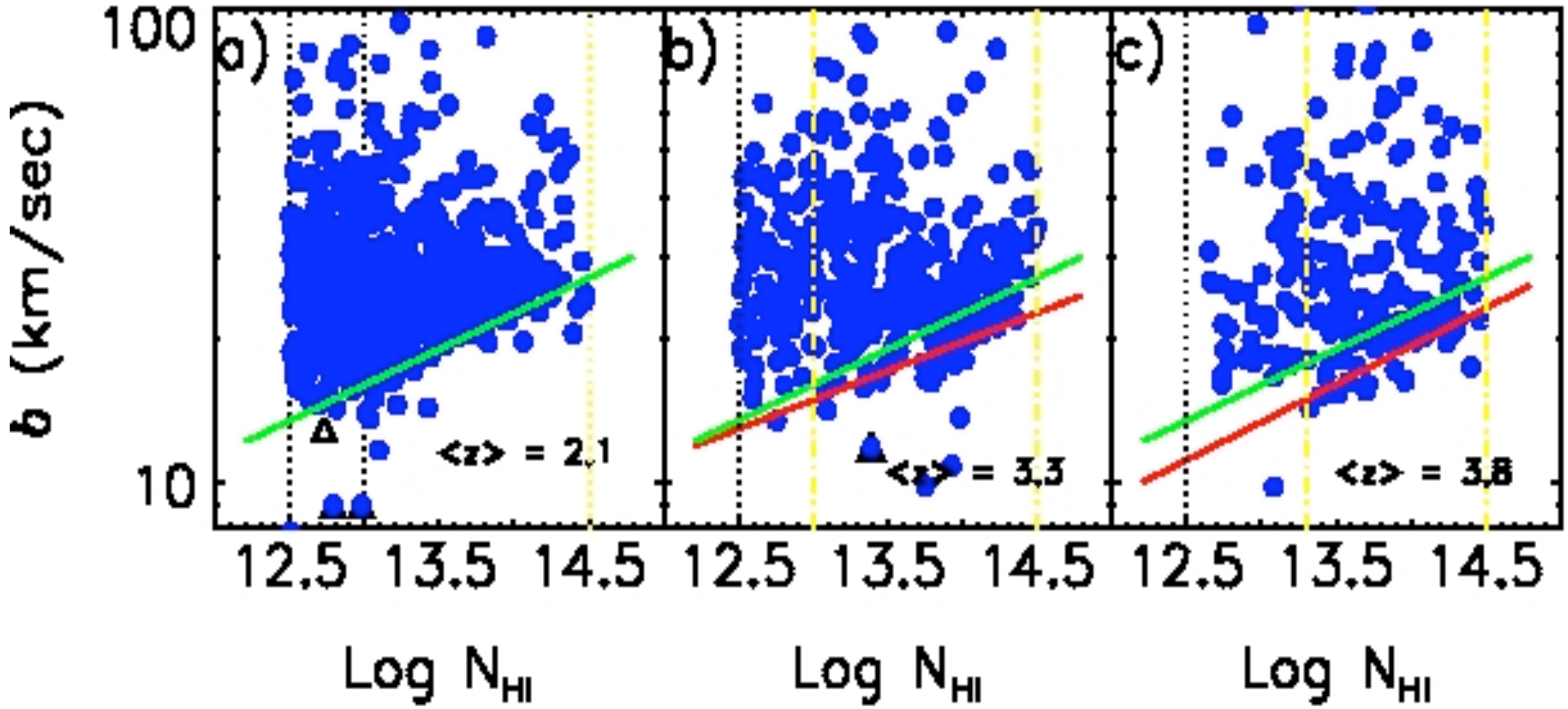
Hui & Gnedin (1997)



Dave+ (1999)

In simulations, the Temperature Normalisation Is needed.

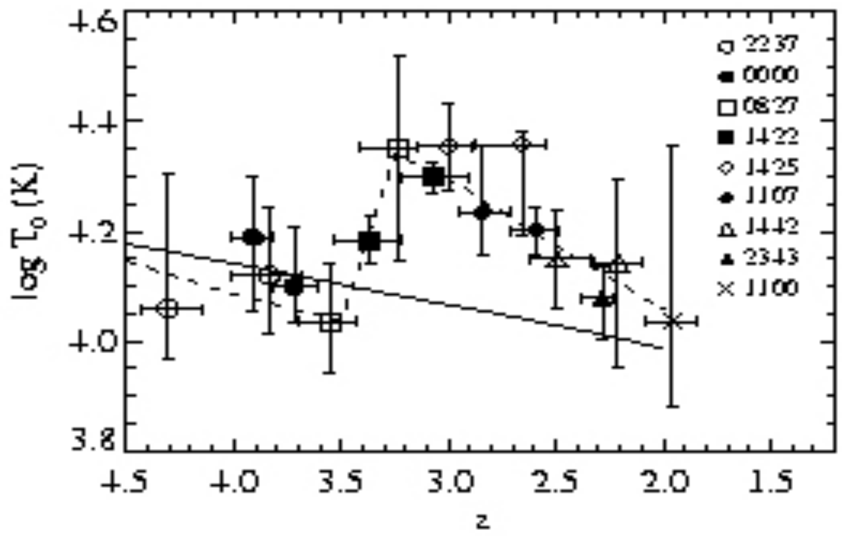
UVES/VLT



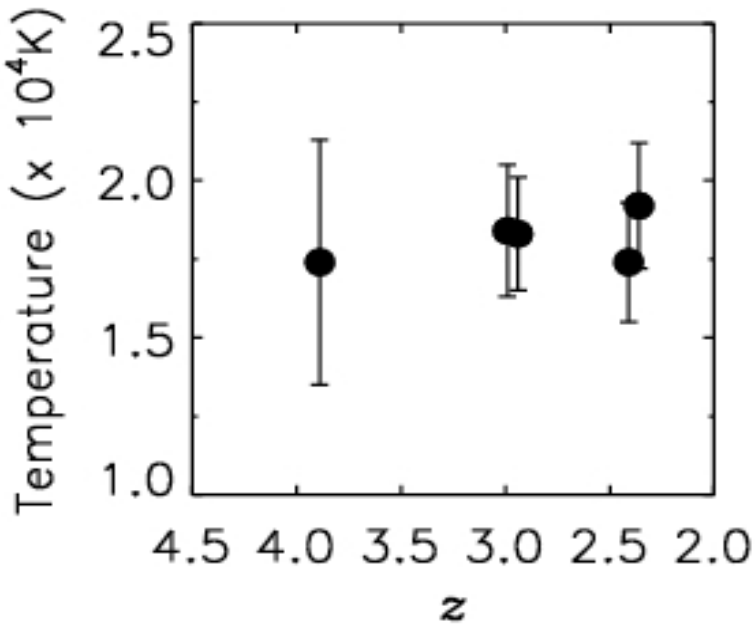
Kim+ (2001)

***b* evolution of the IGM**

Using the same QSO spectra



Schaye+ (2000)



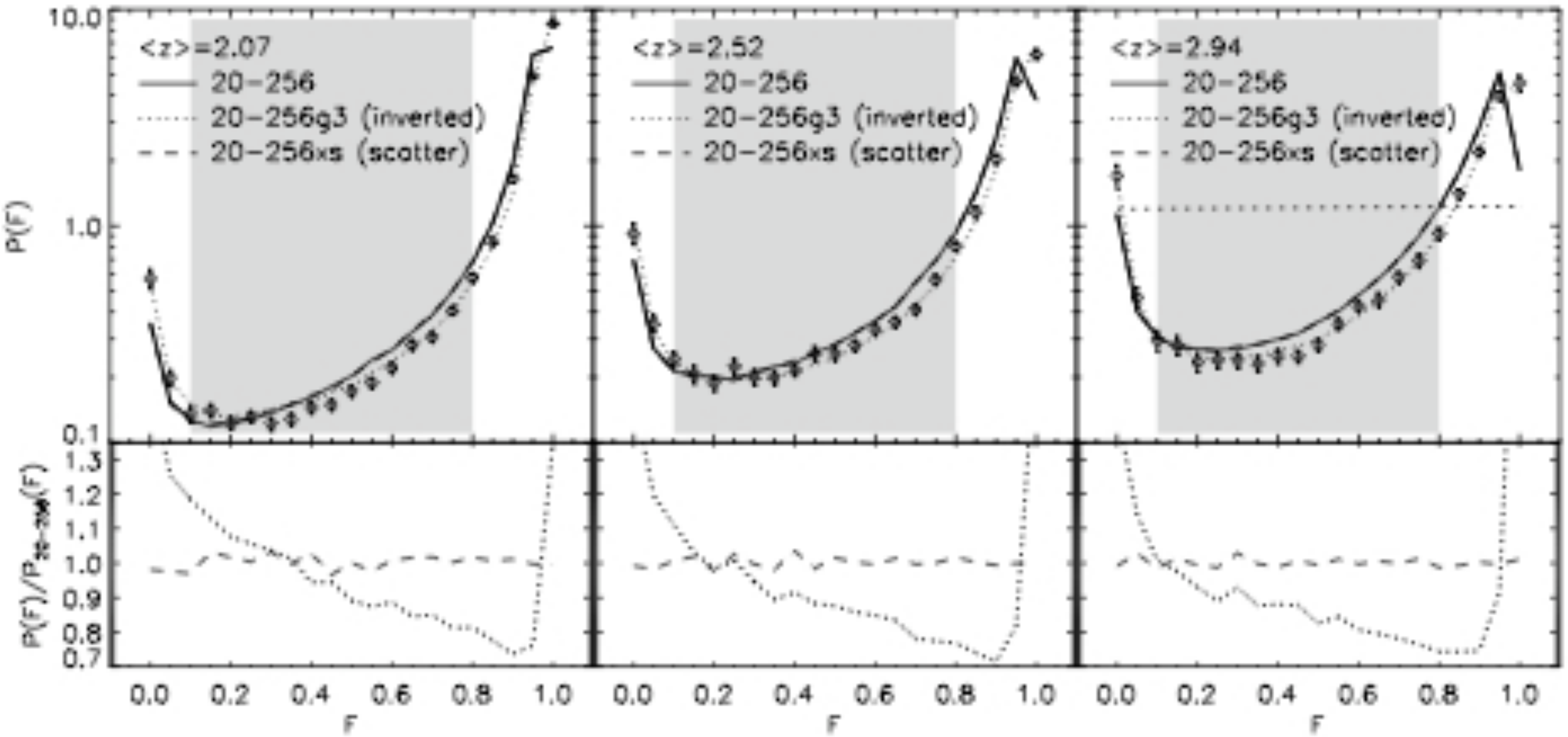
McDonald+ (2000)

HeII reionisation at z ~3.2??

Only 2 QSOs at this redshift range

PDF: Probability density distribution function

$$T = T_0\,(1+\delta)^{\gamma-1}$$



Bolton+ (2008)

Inverted equation of state works better.

Our previous work: 17 QSOs, $2 < z < 3$

In the new work: 7 QSOs, $3 < z < 3.6$

covering the hypothetical HeII reionisation at $z \sim 3.2$

I. PDF consistent with the inverted equation of state?

II. From the full profile fitting: constraining the equation of state

III. The HeII reionisation?

V. Summary

Metals are present in the IGM up to the redshift range we can observe, e. g. $z < 6$.

High-redshift galaxies have a CIV halo with a size of ~200 kpc proper.

Metals in the IGM are very closer to the parent galaxies, e. g. circumgalactic medium.

Galactic outflows seem to be the most plausible mechanism of the metal transport.

The IGM has the N(HI)-N(CIV) relation.