Cosmology with Damped Lyman-α absorption systems

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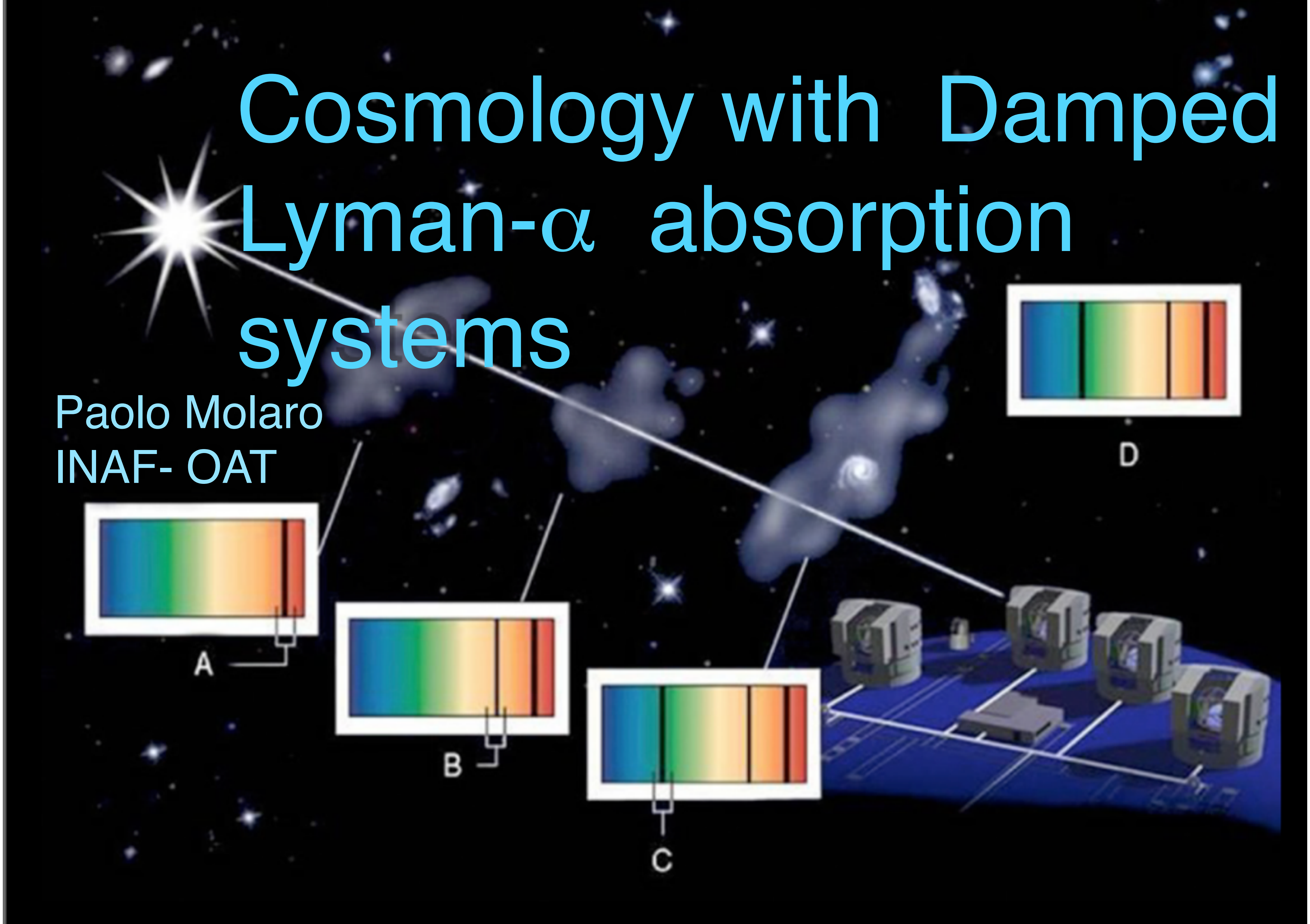
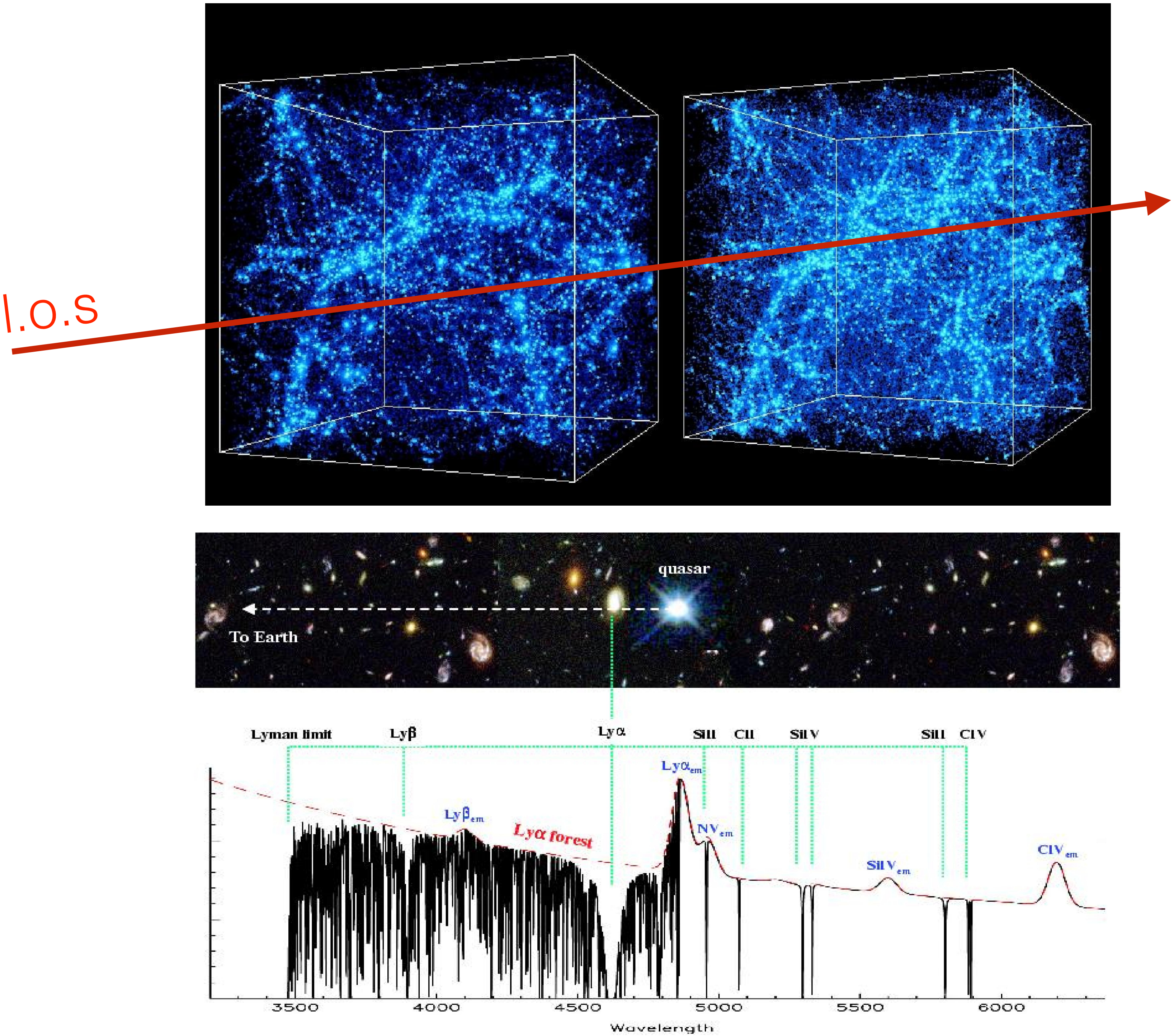
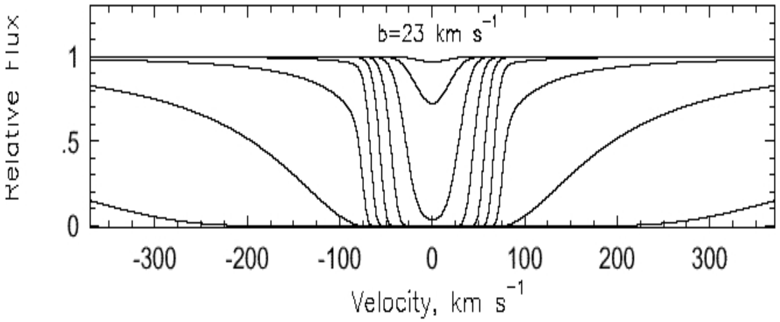




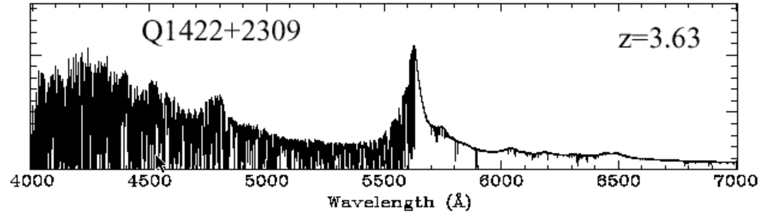
l.o.s
quasar
To Earth
Lyman limit
Lyβ
Lyα
SiII
CII
SiIV
SiII
CIV
Lyα_em
Lyβ_em
Lyα forest
NV_em
SiIV_em
CIV_em
3500
4000
4500
5000
5500
6000
Wavelength

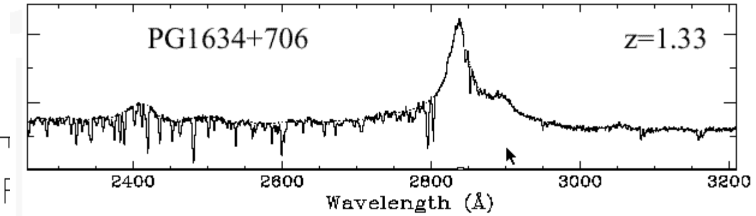
QSO absorbers

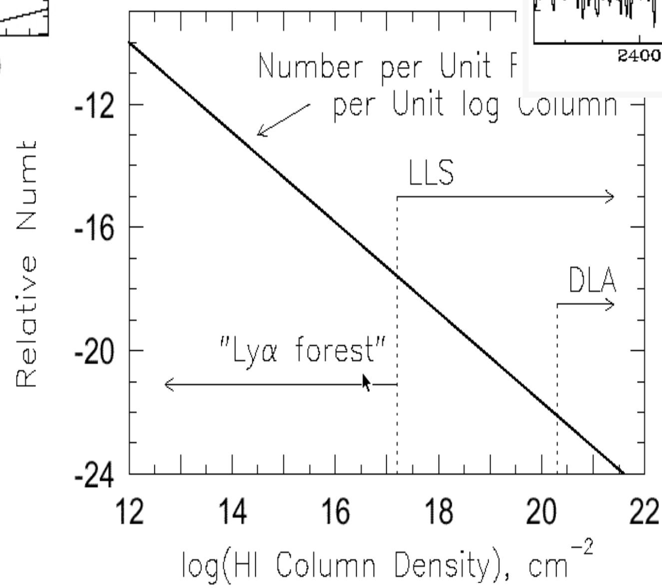
classified according to HI (or metals).



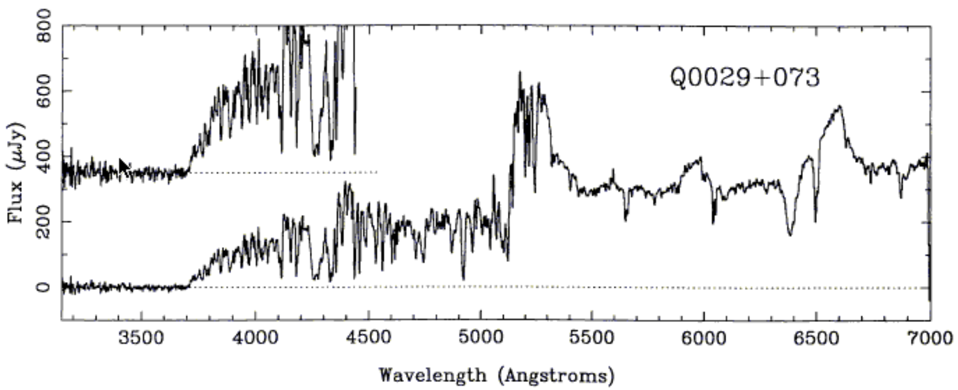
Lyman forest





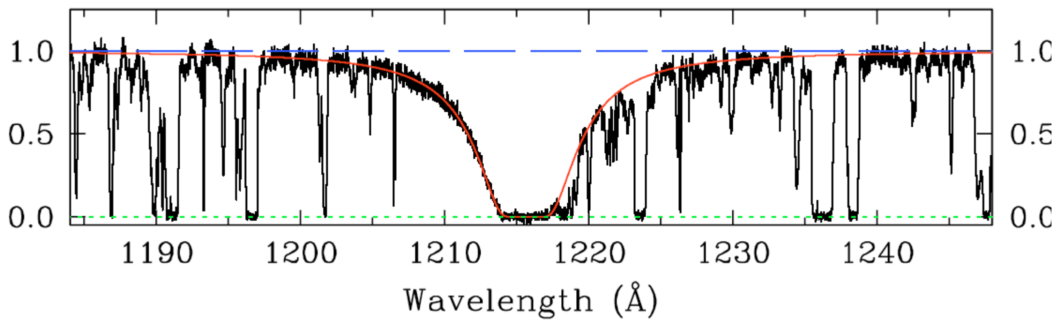


Lyman Limit System



Lyman 912 Å discontinuity

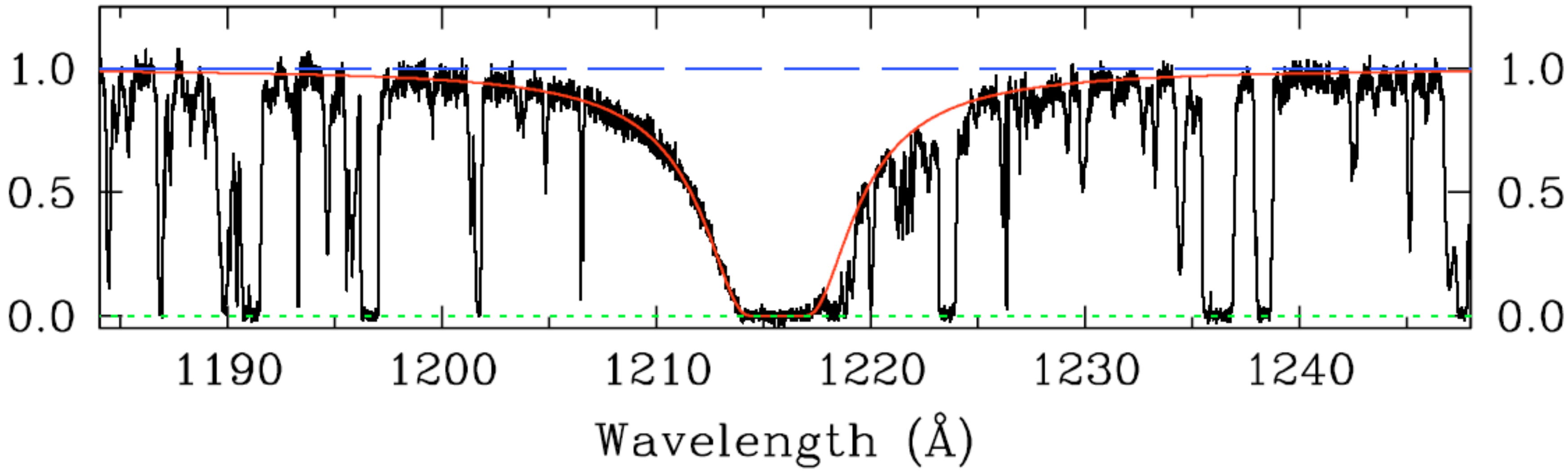
DLA



Damped Ly α systems (DLAs)

Definition: DLA N(HI) > $10^{20.3}$ atoms cm^{-2} (Wolfe 1986)
Sub-DLAs N(HI) > 10^{19} atoms cm^{-2} (Peroux et al. 2001)

Ly α absorption profile with damping wings



Optically thick to ionizing radiation
$\tau_{LL} >> 10^3$
hν > 400 eV

Pro: unique way of detecting low star formation objects at cosmological distances

Con: very narrow sightline , no info on global properties of the absorber

outline

I

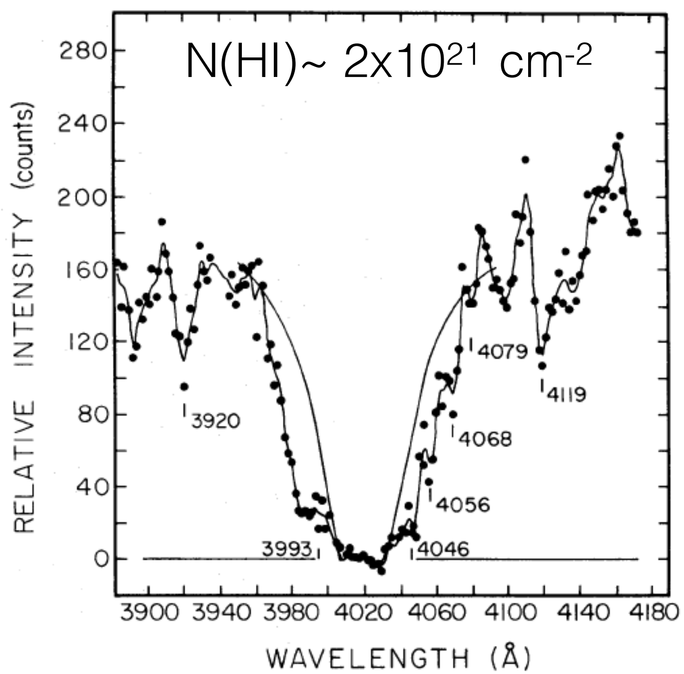
- What are the DLAs?
- The neutral gas content of the Universe
- Chemical abundances, dust, chemical patterns.
- DLA and First stars

II

- Primordial Deuterium
- Molecules gas in DLAs: H_2, HD, CO
- T_{CMB} (z)

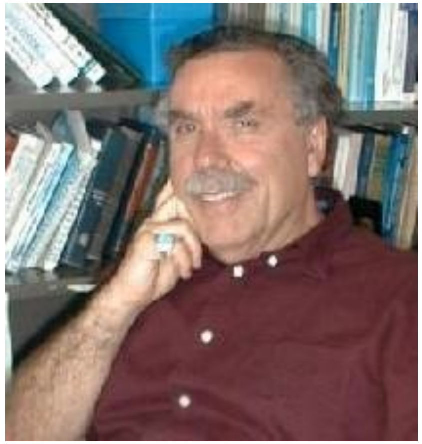
Discovery Beaver et al (1972)

PHL957

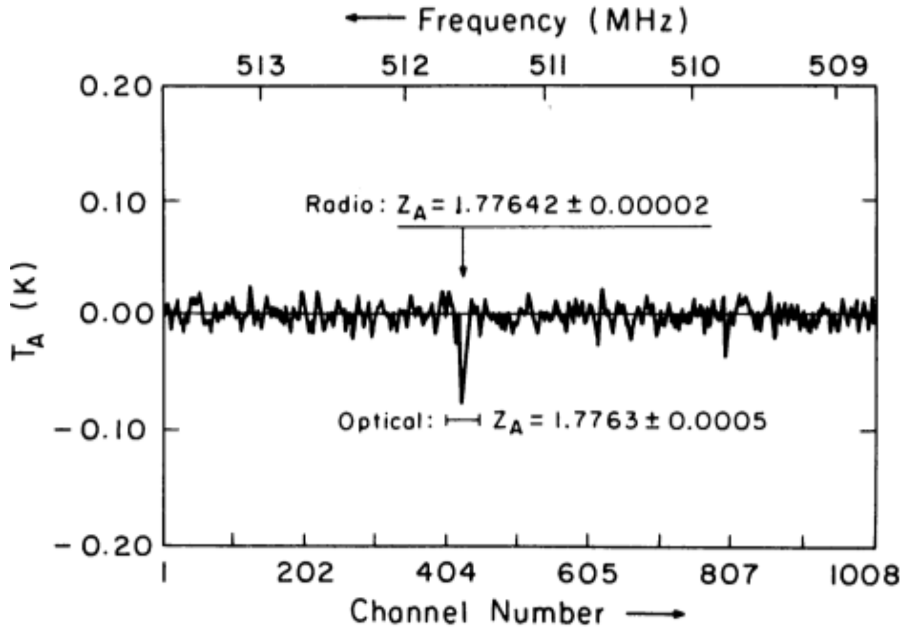


Wolfe et al. (1986) started a survey for neutral gas in disk of galaxies at high redshift (Ly-α several orders more sensitive to neutral gas than 21cm)

Wolfe & Davis (1979) measured in QSO 1331+170 the first 21 cm associated to an absorption system revealing cool gas (T<1000 K)



1939-2014



How many?

Optical surveys ($z > 1.7$)

Lick survey: low res spectra search for W > 5 A + follow up HR Wolfe et al. 1986, ApJS, 61, 249)

Large Bright QSO (Wolfe et al. 1995, ApJ 454, 698)

High redshift survey ($z > 4$) (Storrie-Lombardi et al. 1996, MNRAS, 282, 1330; Storrie-Lombardi & Wolfe, 2000, ApJ 543, 552) Peroux et al. 2001, AJ, 121, 1799)

CORALS: DLAs towards radio selected QSOs (Ellison et al. 2001, A&A)

SIOAN SDSS

DR2 &DR3 525 DLA candidates, (Prochaska & Herbert-Fort &Wolfe 2005; Prochaska Wolfe 2009)

DR7 ~2000 Noterdaeme e t al 2009, Abazajian et al 2009

SLOAN-III/BOSS

DR9 **120081** candidates with LogN(HI) > 20 and 6839 LogN(H) > 20.3 Noterdaeme et al 2012

DR11 ~100 candidates of LogN(HI) >21.7 (ESDLA) Noterdaeme et al (2014)

DR 12 under analysis (cfr Paris et al 2017)

UV surveys ($z < 1.7$)

IUE survey (Lanzetta et al. 1995, ApJ, 440, 435)

HST QSO absorption line project (Jannuzzi et al. 1998, ApJS, 118, 1)

HST + MgII sample (Rao & Turnshek 2000, ApJS, 130, 1)

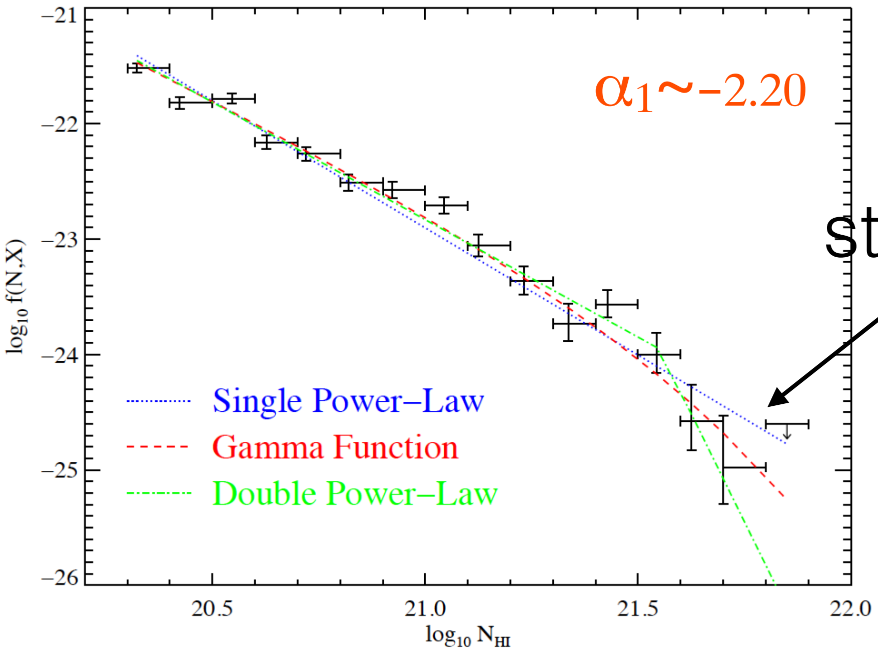
~ 41 DLAs

The column density distribution

f(N,X): a power law but one or two?

Prochaska et al 2005

600 DLAs



$$f(N,X) = k_1 N^{\alpha_1};$$

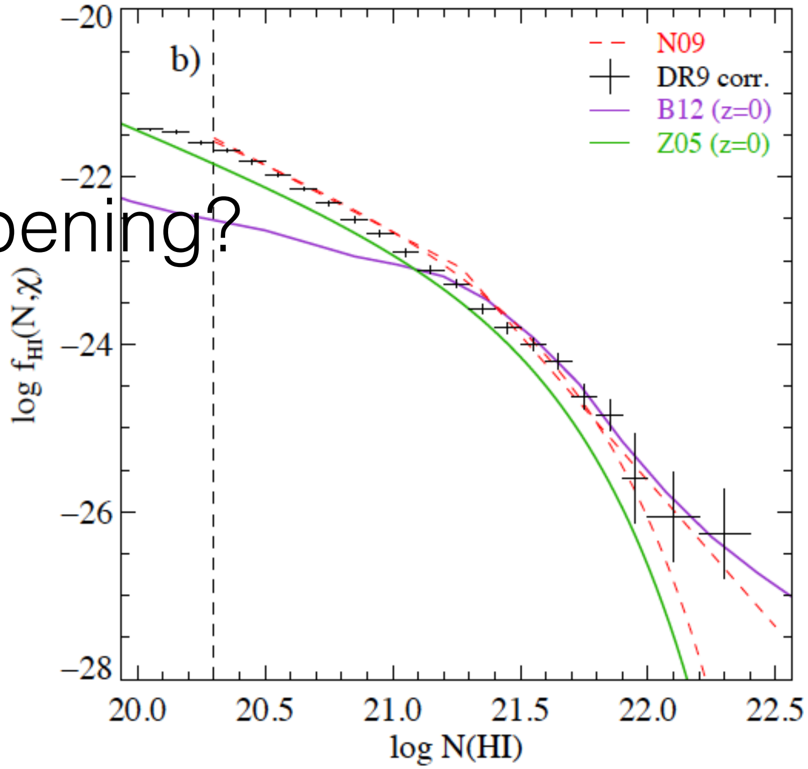
$$f(N,X) = k_3 (N/N_\gamma)^{\beta}$$

$$f(N,X) = k_2 (N/N_\gamma)^{\alpha_2} \exp(-N/N_\gamma)$$

steepening?

Noterdaeme et al 2012

5428 DLAs



The neutral gas content of the Universe

with the column density distribution f(N,X) we can measure of the mass per comoving volume of the neutral gas at redshift z

total HI in a redshift bin

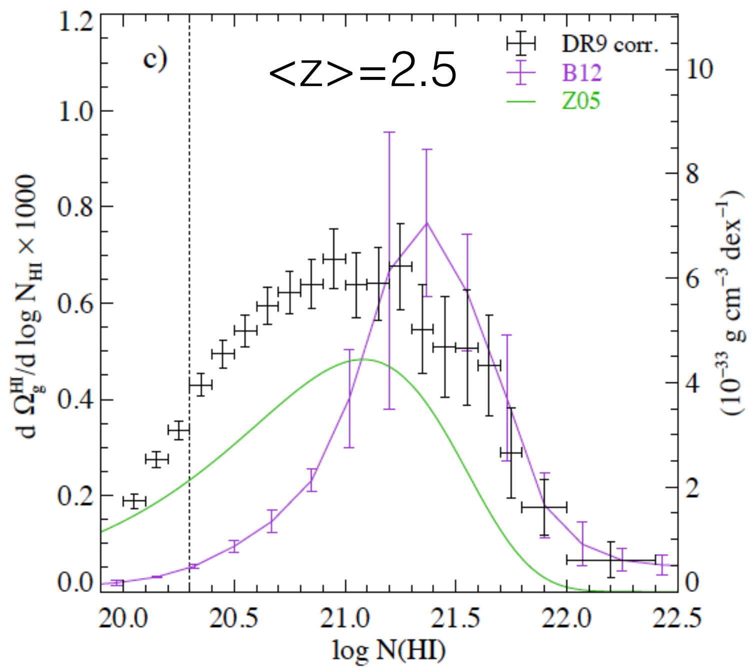
$$\Omega_g = \frac{H_0}{c}\frac{\mu m_H}{\rho_{crit}}\int_{N_{min}}^{N_{max}} dN\, N\, f(N,X)$$

in the discrete limit

$$\Omega_g(X) = \frac{H_0}{c}\frac{\mu m_H}{\rho_{crit}}\frac{\sum_{i=1}^{n} N_i}{\Delta X}$$

n: number of DLA within X,X+dX

$$X(z) = \int_0^z (1+z)^2 \left[(1+z)^2(1+z\Omega_M) - z(2+z)\Omega_\Lambda\right]^{-1/2} dz$$



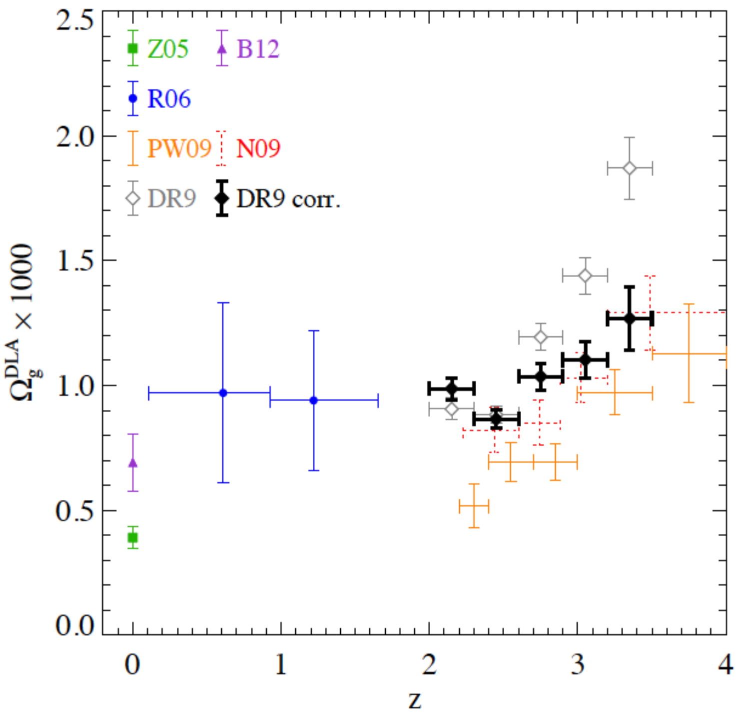
DLA with logN(HI)~ 21 systems contribute most, the few new DLA >21.7 contribute ~ 10%.

we expect neutral gas evolution to be linked with the cosmic star formation history

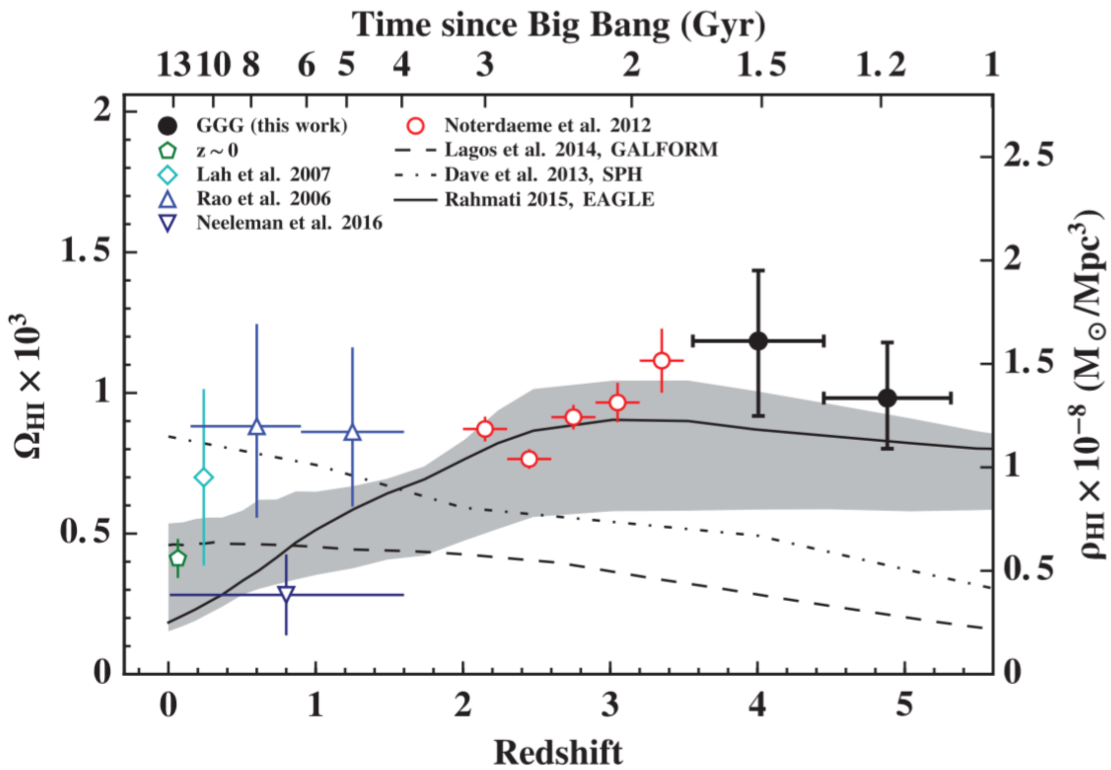
DLAs & Ω_b

163 QSO, increase by 8x for z>4.5.
(High z data also from Peroux et al 2003, Guimaraes et al 2009, Songaila & Cowie 2010)

correction for false positives ↓
for incompleteness ↑



Crighton et al 2017



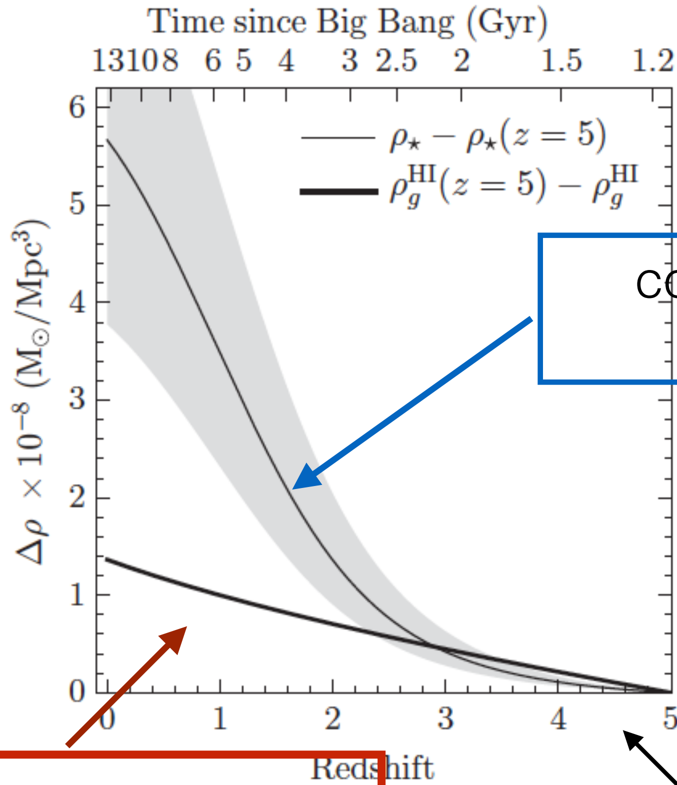
large errors due to incompleteness

Decrease with cosmic time ?

Behaviour suggestive of gas consumption due to star formation in the course of cosmic evolution

Apparent lack of evolution, no clear evidence that neutral gas of the Universe was larger at high redshift

comparison with the comoving stellar mass density



Crighton et al 2017

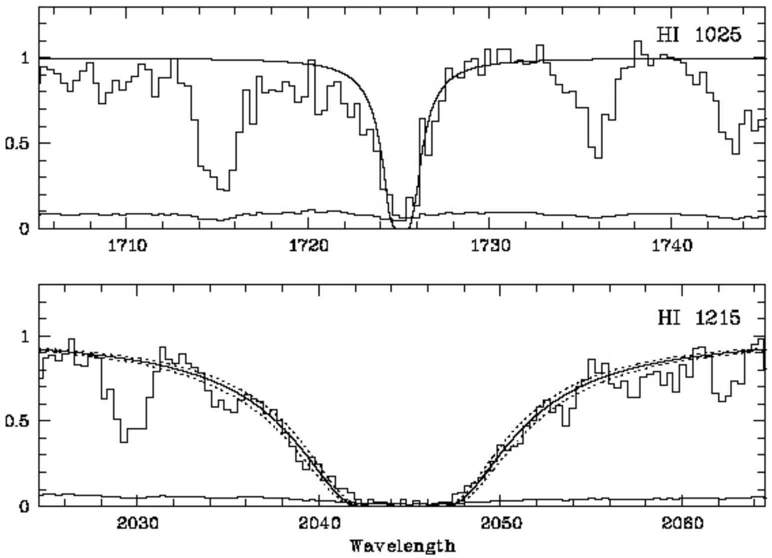
comoving stellar mass density (Madau Dickinson,2014)

- comoving neutral gas mass density

z>3 ~ ok
z<3 not enough gas

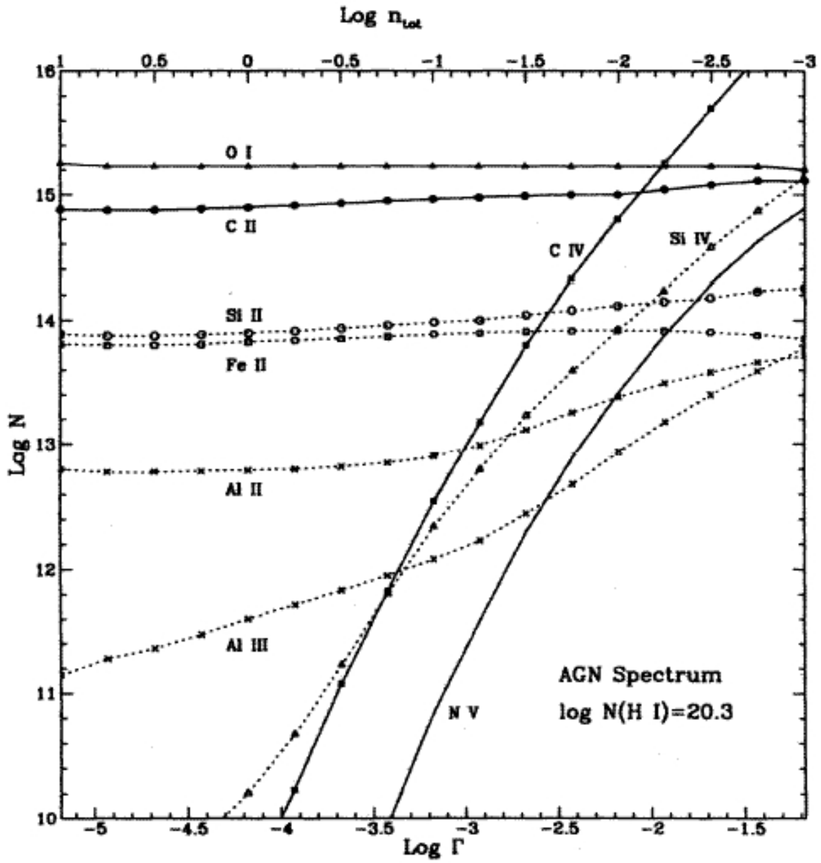
- HI refilled from IGM (Dekel et al 2009, Oppenheimer et al 2010, Fumagalli et al 2011)
- do DLA galaxies represent only a part of the gas that has been transformed into present-day luminous matter ?

DLA chemical abundances



Accurate measurement of N(HI) (0.1 dex):
Damping profile of Ly α lines (+ other lines of the Ly series)

Accurate measurement of metals N(X) (0.05 dex) with unsaturated lines outside the Ly α forest

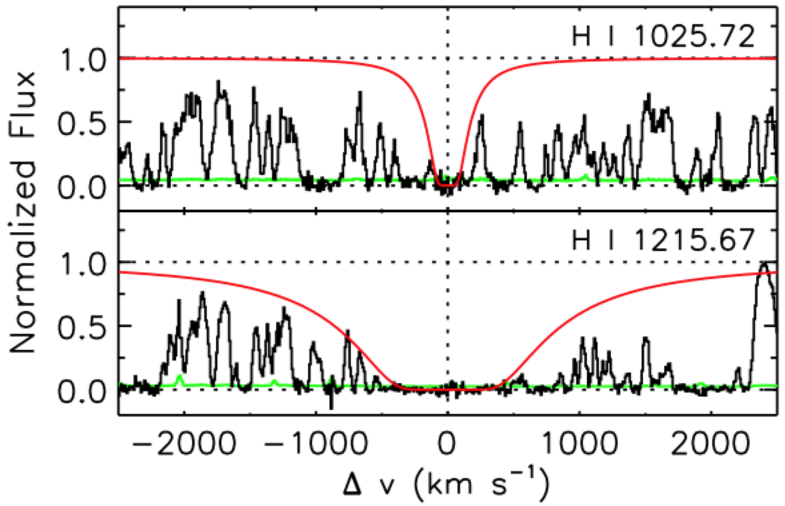


- low ionization species are dominant ionization states in the HI gas
- ionization corrections derived via photoionization equilibrium computations show that ionization corrections are small and **not** required in DLAs.

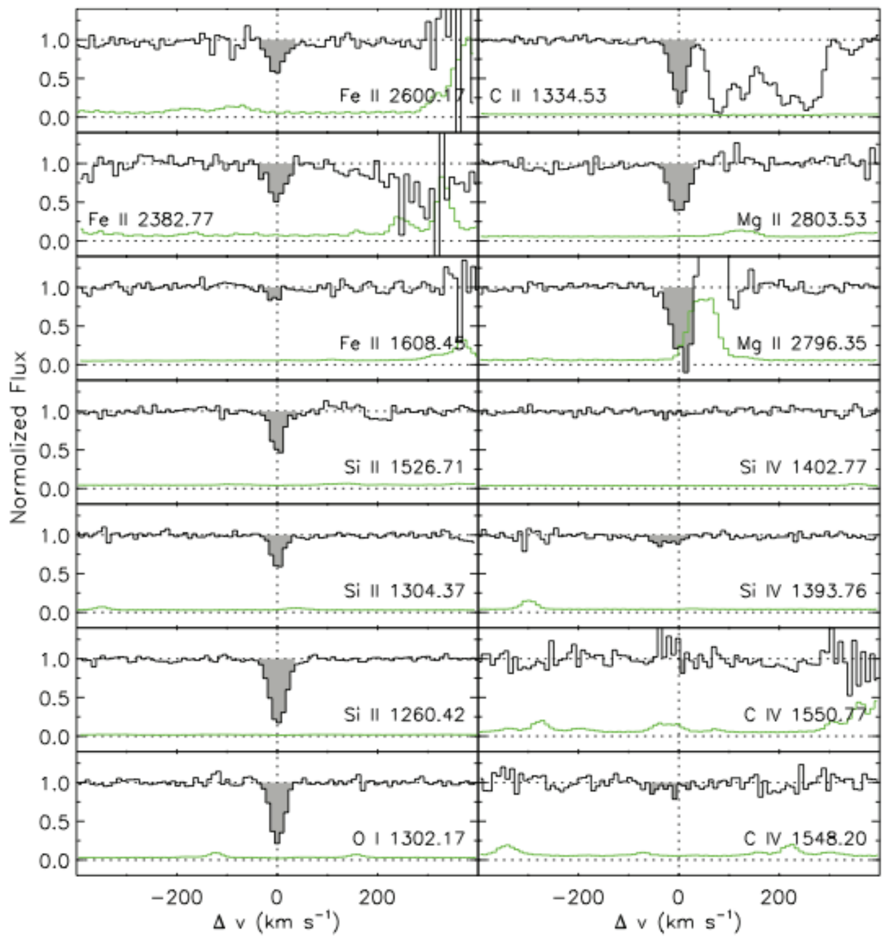
Becker et al (2012)

X-Shooter

LogN(HI)=20.3



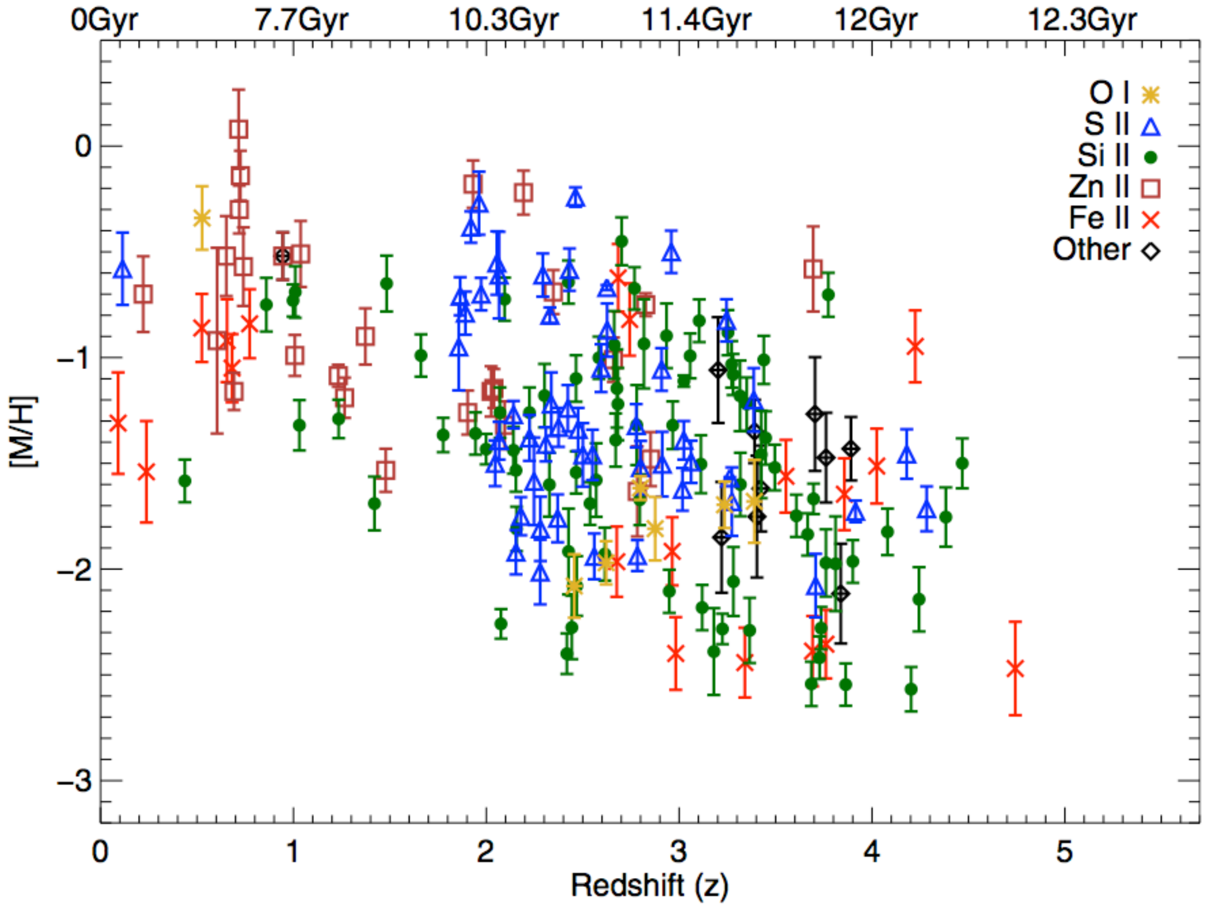
SDSS J1208+0010 z_{abs}=5.0817



- DLA allow determination of precise chemical element abundances throughout z~ 5 (12.3 Gyrs, 90% of the universe), unbiased with respect to Luminosity or Mass

~ 242 DLAs

Rafelski et al 2012



- dispersion: two dex -2.5 < [Fe/H] <-0.5, plateau at [Fe/H]~-3 ?
- ~ no evolution 0<z<2.5; mild evolution z > 2.5.
- [M/H]~ -1 also at z~ 0

and at z ~5?

evolution with mean HI weighted metallicity:

Morrison et al 2016

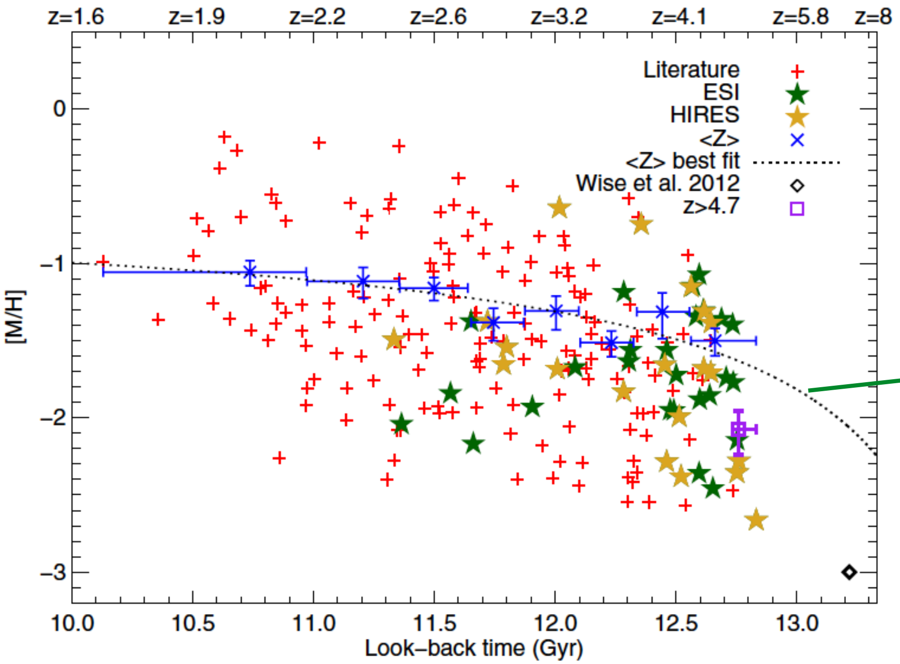
$<Z> = \Omega_{metals} / \Omega_{gas}$

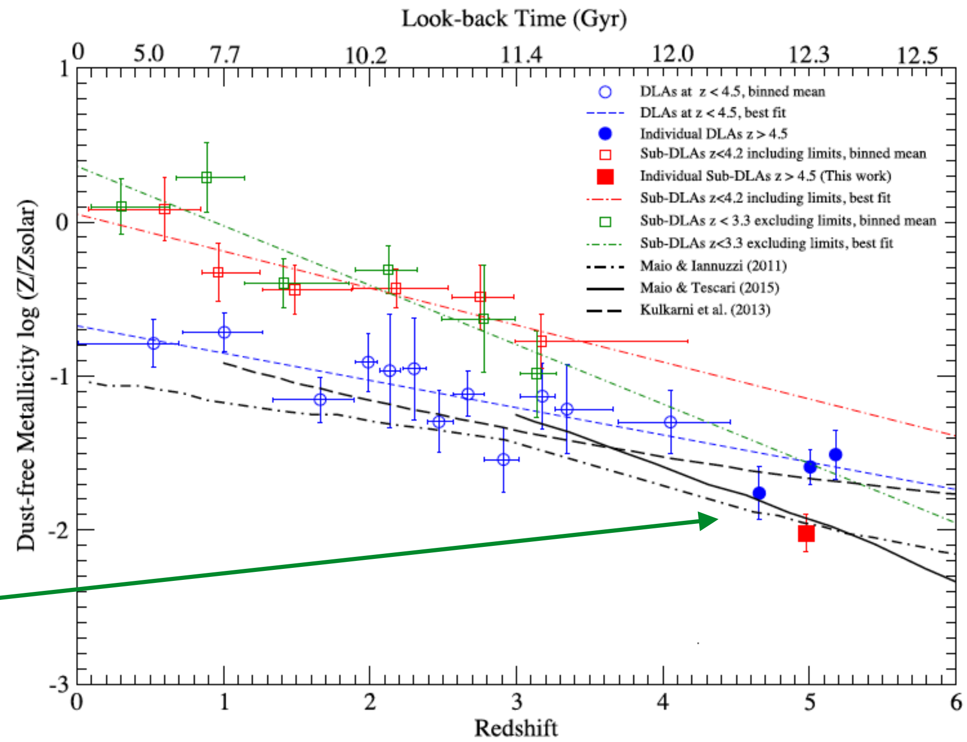
$$< Z > = \log_{10}\left[\frac{\sum_{i=1}^{n} 10^{[M/H]_i} N_i}{\sum_{i=1}^{n} N_i}\right] - \log_{10}(M/H)_{\odot}$$

sub-DLA at z~ 5

Rafelski et al (2014)

17 measurements (8 new) with z> 4.5





only dust free DLA: 3 DLA at z>4.7!

- no strong evolution z< 4
- possible drop off at z>4.7 (but not seen in neutral gas)

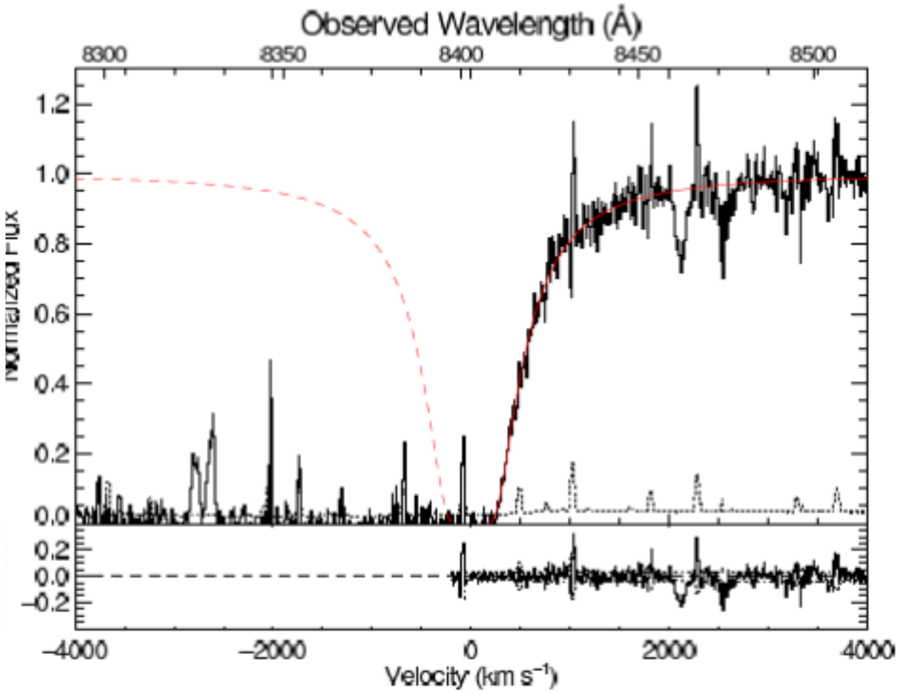
- no decline for DLA
- possibly in the sub-DLA, but only one object

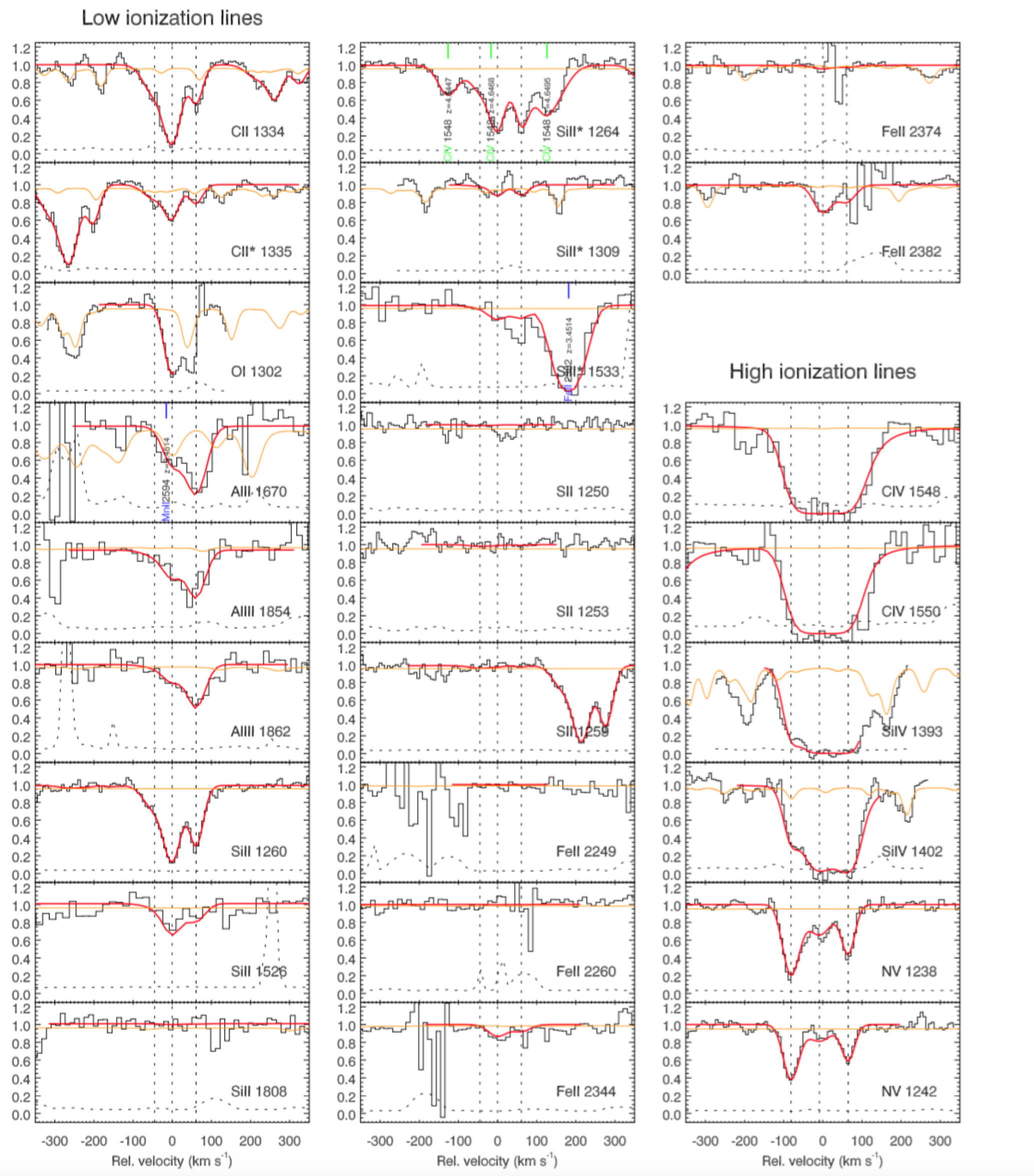
at z~6

Hartoog et al 2015

GRB 130606A

Sub-DLA: logN(HI) = 19.91





[Fe/H]> -1.8

- it challenges the drop off, but only one system is dangerous

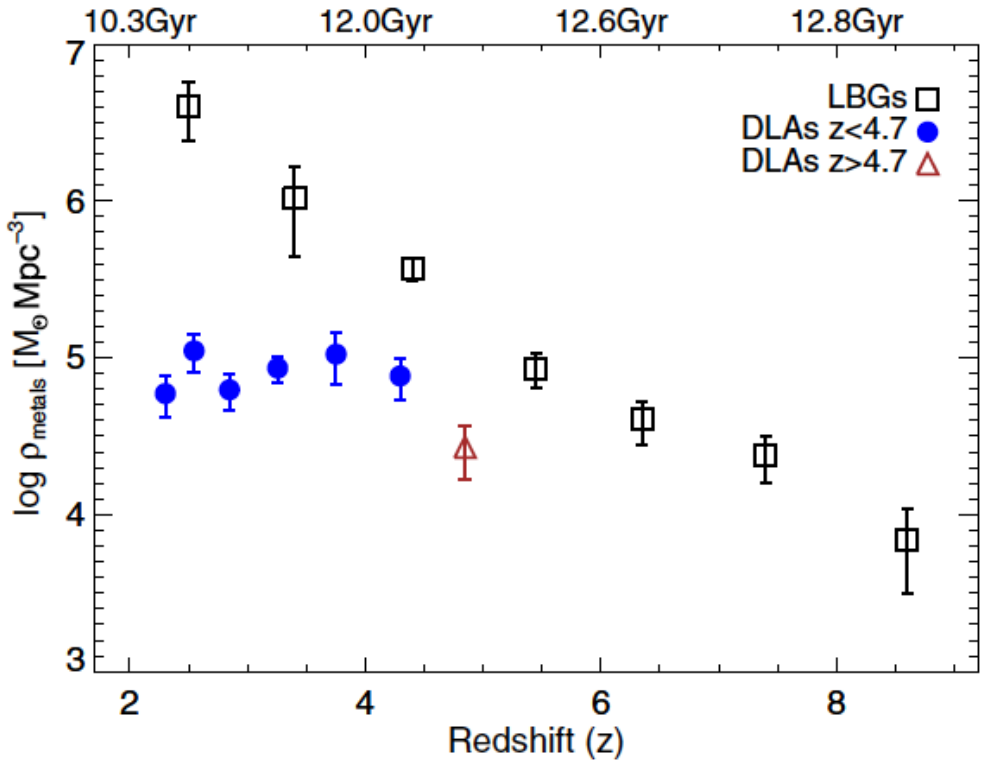
DLA & global metal budget

the comoving metal mass density in DLAs can be compared with the comoving global metals production (~ 50% by LBG)

Rafelsky et al 2014

$$\rho_{\rm metals}(z)_{\rm DLA} = 10^{\langle Z \rangle} \times \rho_{\rm H\,I} \times (Z/X)_{\odot}$$

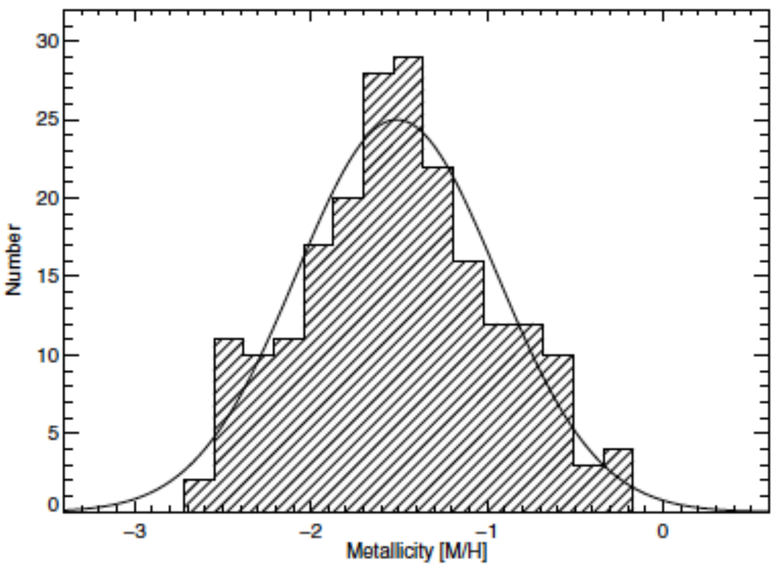
$$\rho_{\rm metals}(z)_{\rm LBG} = \frac{1}{64} \times \int_{z_1'}^{z_2'} \dot{\rho}_{*,\rm LBG}(z') \frac{dt}{dz'} dz'$$



at z ~ 1 DLA produce only ~1% of the metals of the LBG
at z~ 4 ~ 20% of the metals contributed by the LBG ,
at z~ 5 decrease of metals approaching the re-ionization?

DISPERSION

What is the origin of dispersion of metallicities in the DLA?



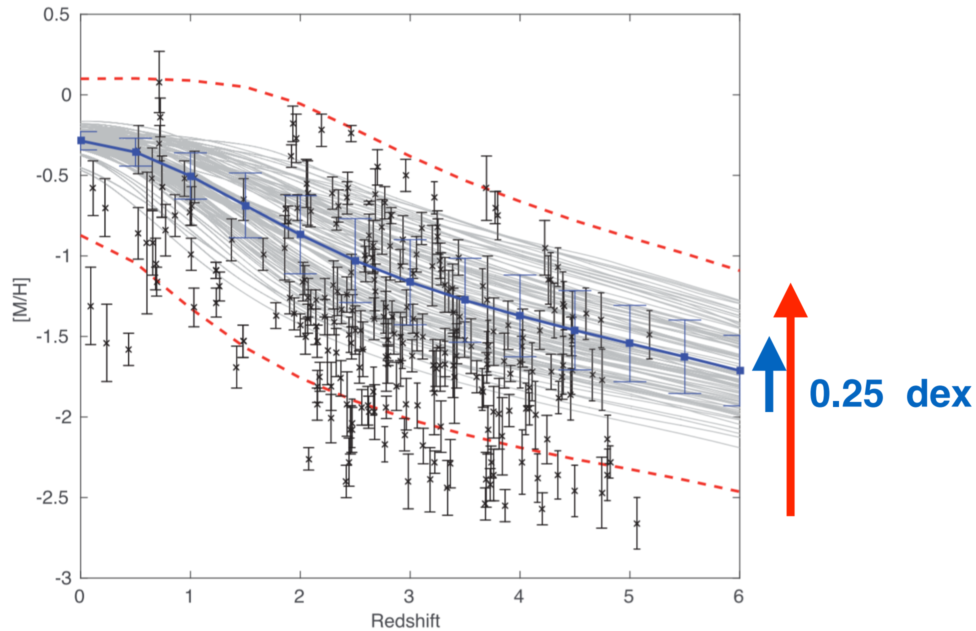
does not depend on z!

mean [M/H] = -1.5 sigma=0.57

Is dispersion the scatter of evolution of galaxies hosting the DLA?

Dvorkin et al 2016

cosmological simulation GALFORM
100 regions ,
each region of 10^3 Mpc^3 h^{-3}



different formation epochs of over and underdense regions can account for 0.25 dex

need to extend the range of masses

problem with very metal poor systems

DLA chemical patterns

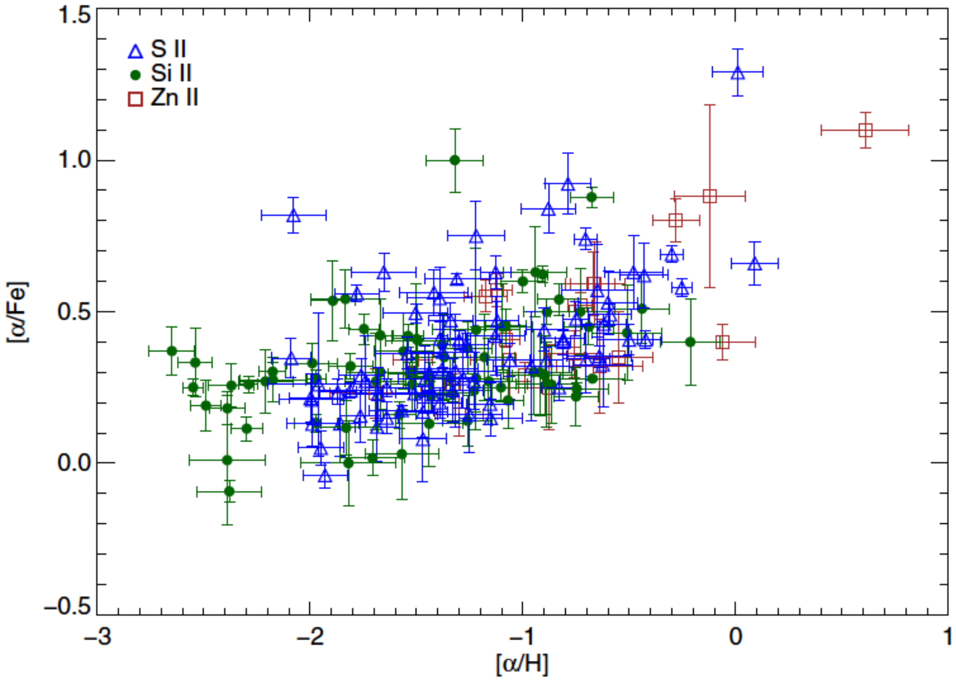
[α/Fe] ratio a diagnostic of chemical evolution.

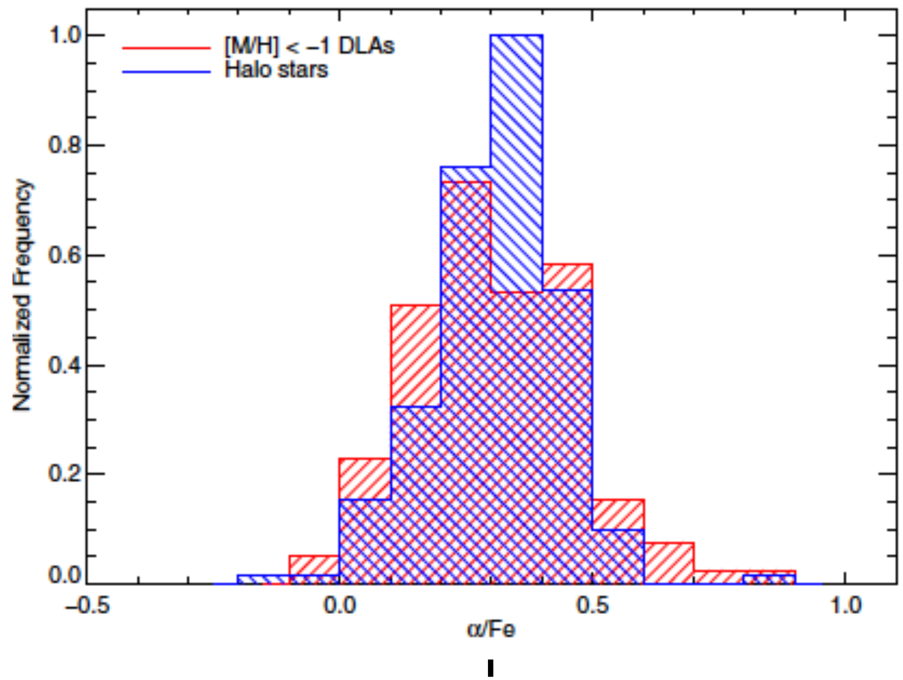
Different time scales for injection of products from Type II SNae (rich in α-capture elements) and Type Ia (rich in iron-group elements. In the MW 70% of iron is produced by Type Ia)

[α/Fe] ratios are [α/Fe] ~ +0.5 dex in Galactic Halo Typically at metallicity ~ -2 dex below solar

If DLAs are progenitors of present-day spiral galaxies we expect: a chemical evolution similar to that undergone by the Milky Way

[Fe/H]<-1.0





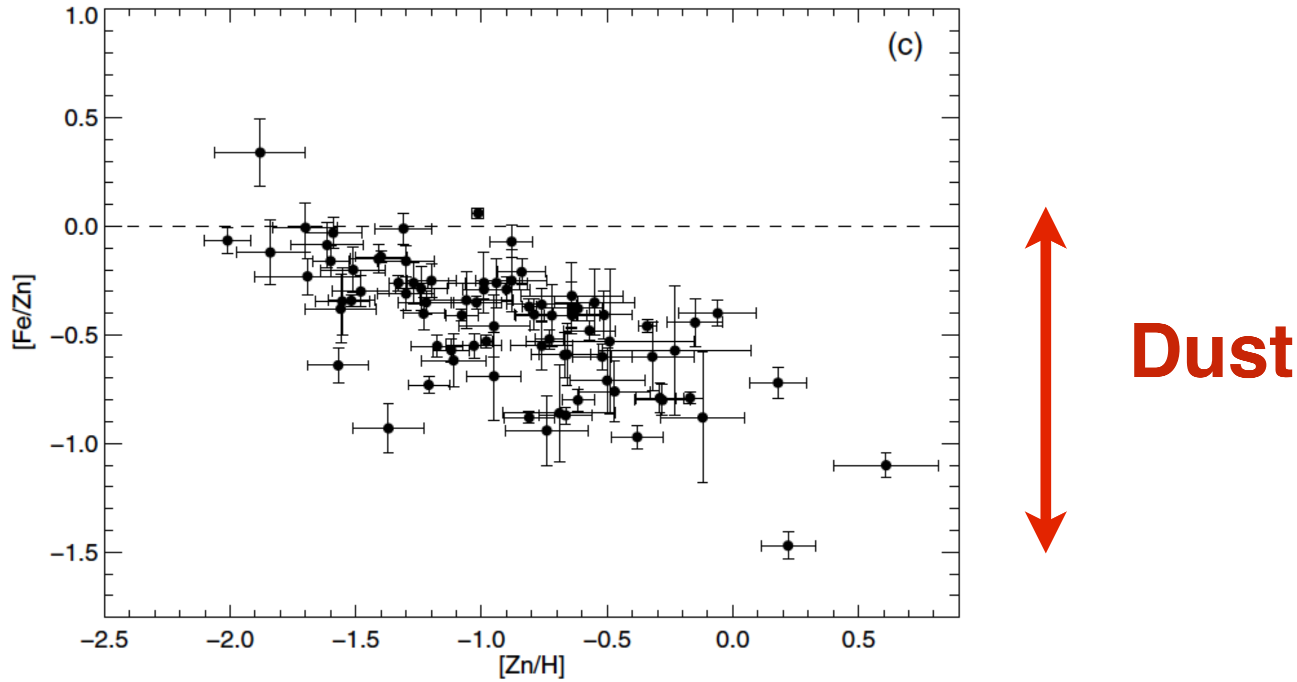
but [α/Fe] increase with the metallicity, just the opposite of the MW

DUST ?

Zn & Cr survey (Pettini et al. 1994, 1997

halo stars: Fe trace Zn
Zn is undepleted in the ISM, Fe strongly depleted

[Fe/Zn] < 0 evidence
for dust: missing Fe
incorporated into
dust grains



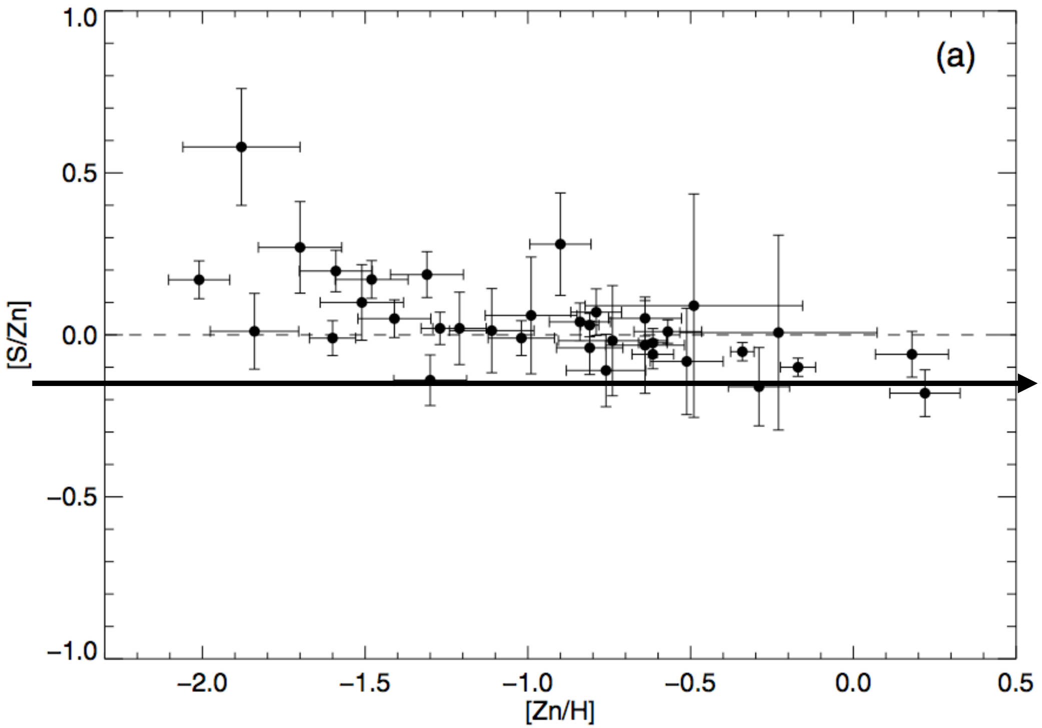
Other evidences for dust presence: Reddening of QSOs with DLA

Dust correction (Vladilo 1998, De Cia et al 2017)
DLA with no dust: [Fe/H]< -2
Volatile elements: Iron-peak elements: Zn; alpha-elements: O, S

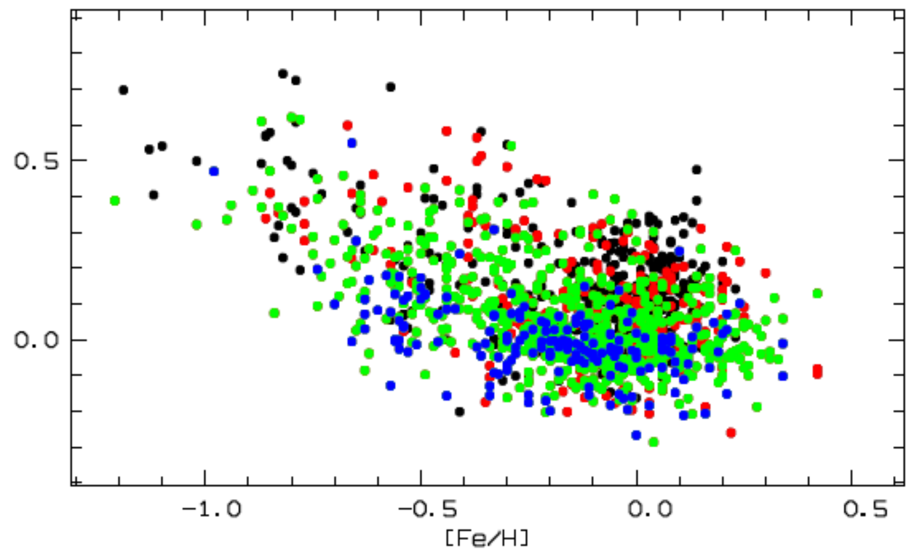
Sulphur

non-refractory, α-element
SII 1250.584, 1253.811, 1259.519 A

Rafelsky et al 2012 DLA



Galactic Stars Duffau et al 2017



But new oscillator strengths Kisielius et al (2014,2015) => [S/Zn] + 0.14 dex

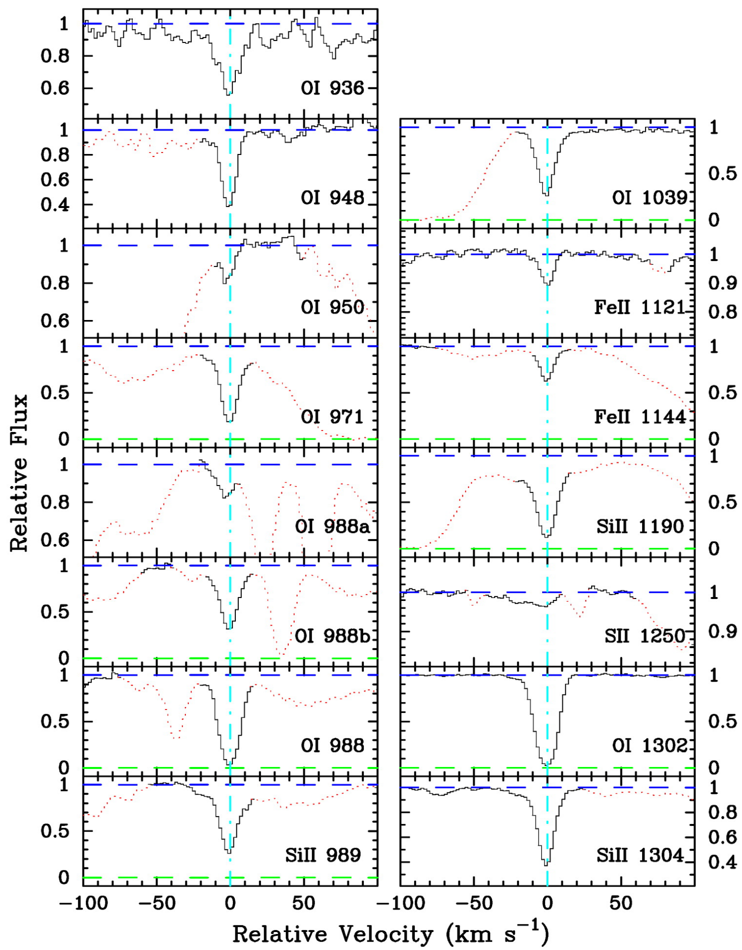
Rafelsky et al (2012) suggested Zn behaves as an α-element:

OXYGEN

Outside the Lyα forest: OI 1302 A: saturated (1355 A: too weak) => metal poor DLA (Cooke et al 2011)

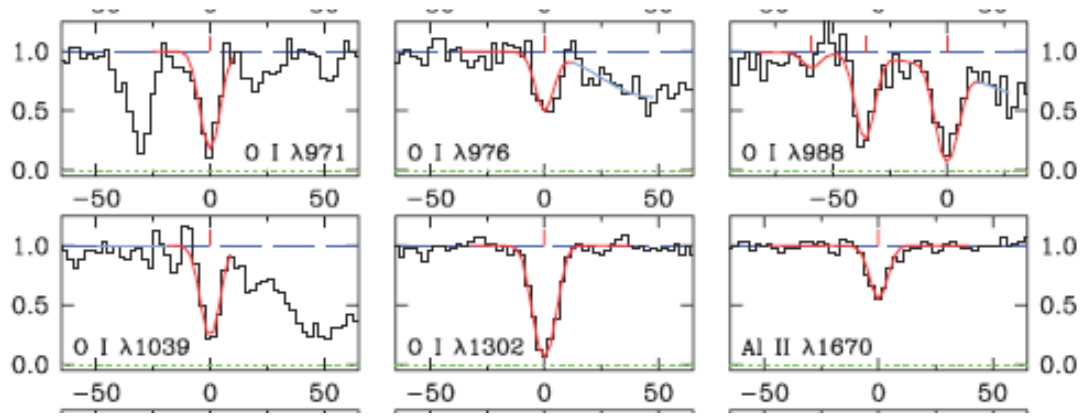
Inside the Lyα forest: OI 1039, 988, 976, 971, 948, 925 A (Molaro et al 2000)

Q1946+76



Prochawska et al 2001

[O/H]=-2.3

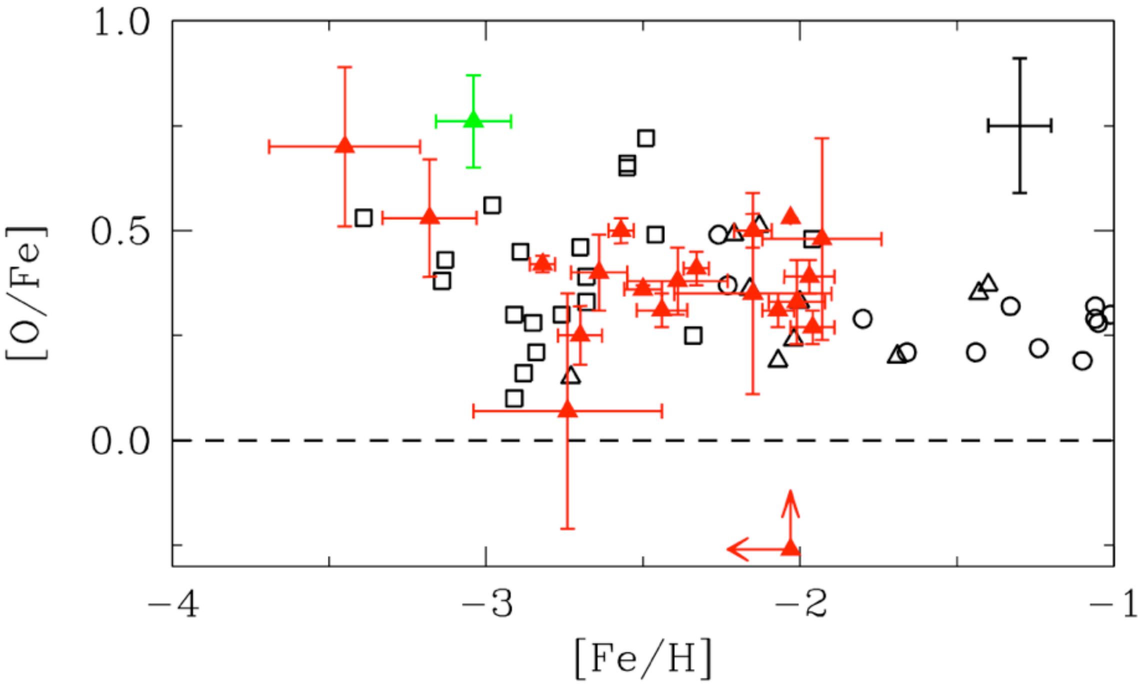


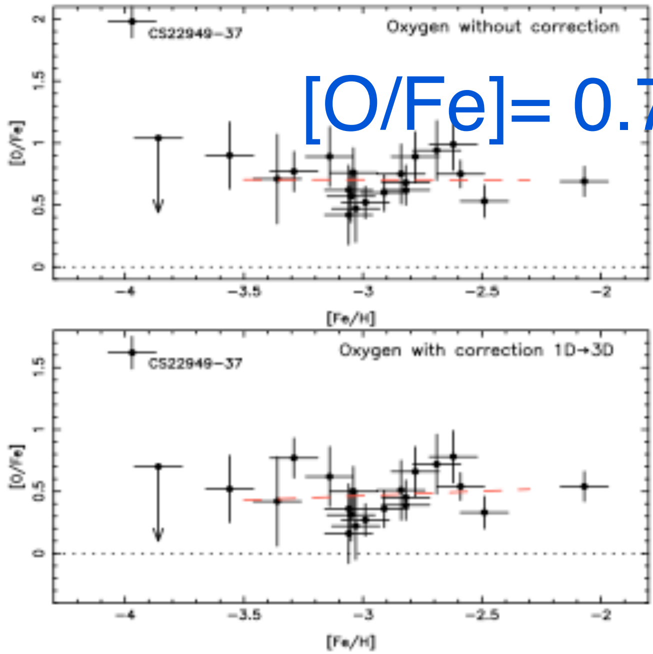
Cooke et al 2011, 2012

[O/Fe] in halo stars uncertain

OH UV 3D (+ non-LTE?)
OI 7770Å 3D + nonLTE
OH IR 3D (+ non-LTE?)
[OI]6300Å 3D?

Pettini et al





[O/Fe]= 0.75

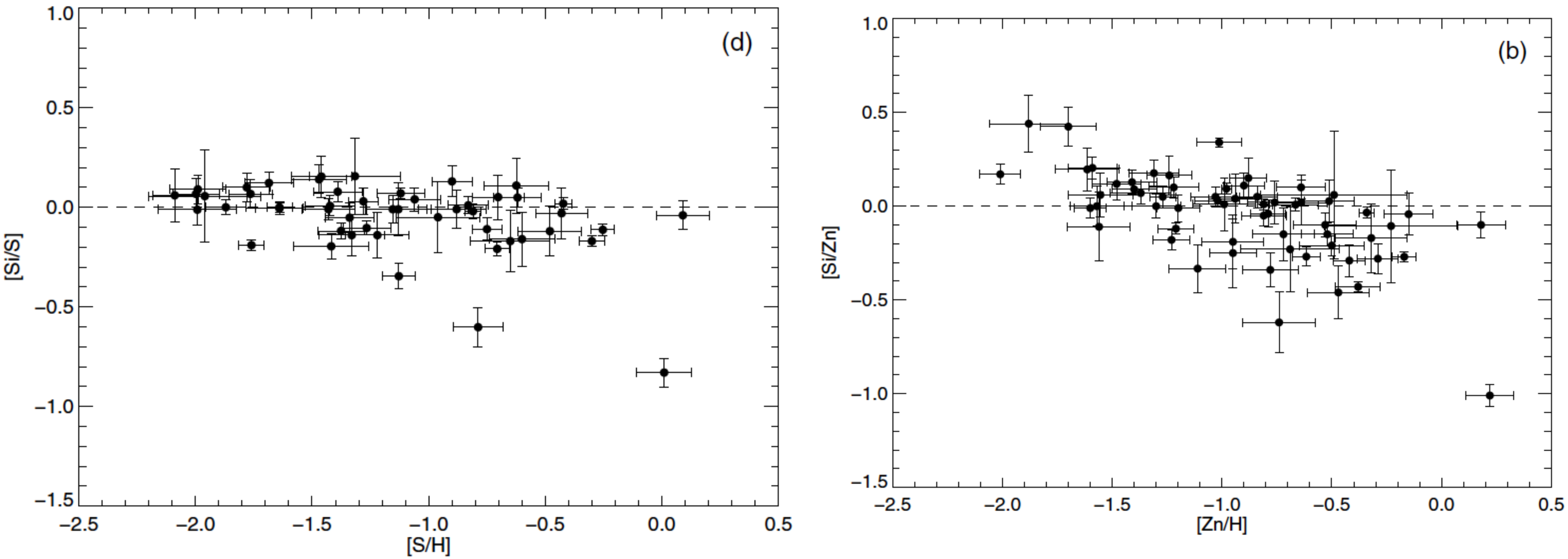
assuming no dust

☐ Cayrel et al. (2004) A&A, 416, 1117

[O/Fe]> 0.80 Bond et al 2013 from parallax of HD 140283

Silicon

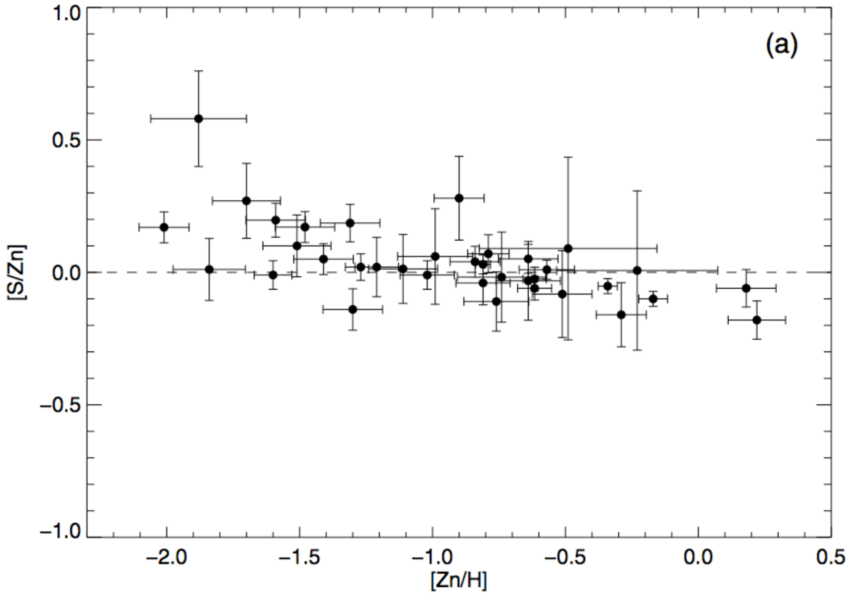
Si traces S (at least for [Fe/H]<-1.0)



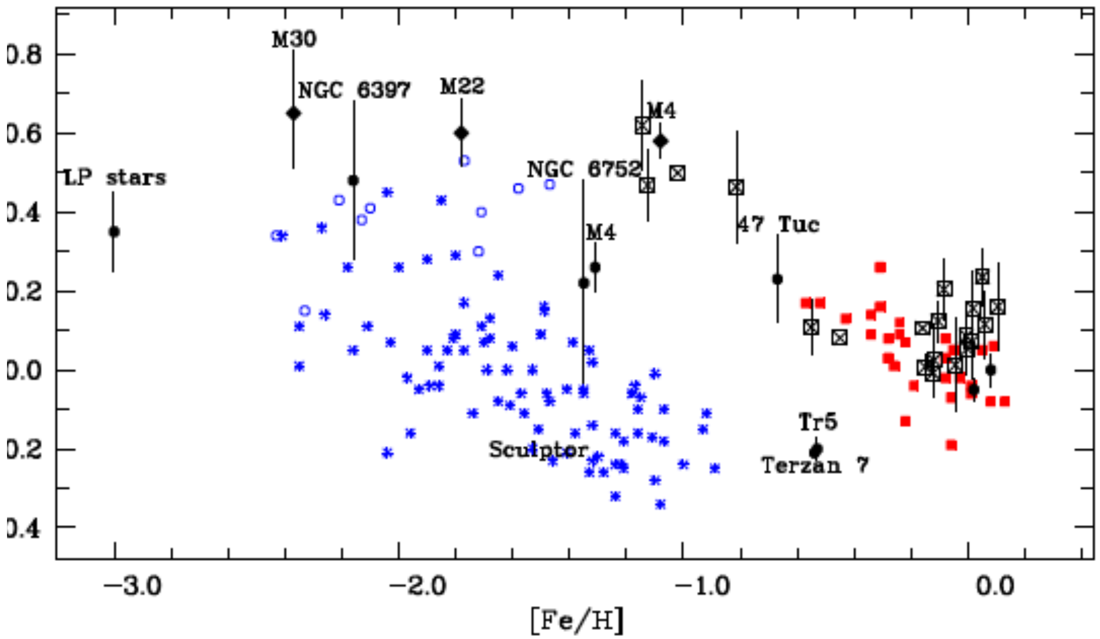
at low metallicity several [α/Zn] ~ 0, i.e. solar
few cases with α-enhancement of ~ 0.3, in particular for [Fe/H]<-2.0

Local Dwarf Galaxies

GC Stars



Duffau et al 2017



Similar ratios to Dwarf galaxies. characterized by low SFR

Local dwafs may be the local counterparts of DLA

Sculptor dfSph (Skuladottir et al 2015)

Models:

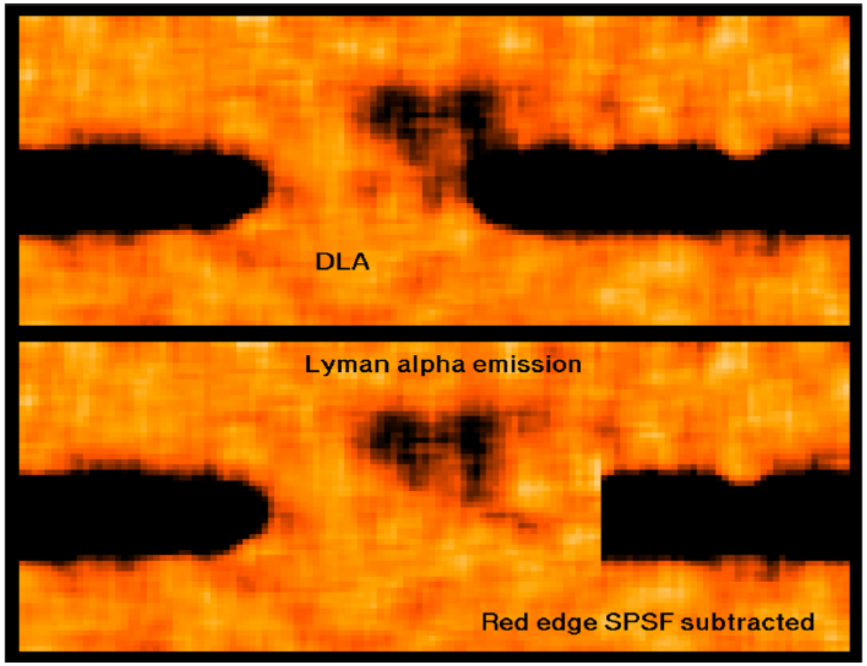
-Dwarf irregulars (Matteucci et al 1997 etc

-Discs of spirals at large galactocentric distances LSB (Jimenez et al 1998)

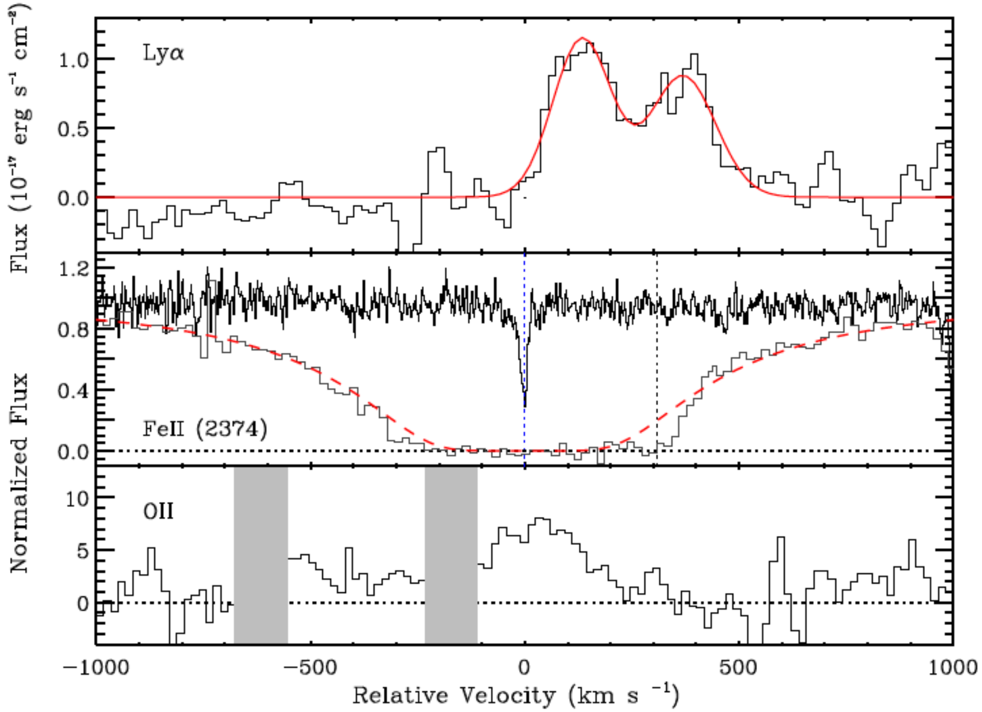
Link to Galaxies: emission Ly α of DLA

imaging difficult by the presence of the QSO

Q2239-2949 z_{abs}=1.825



Zafar et al 2017

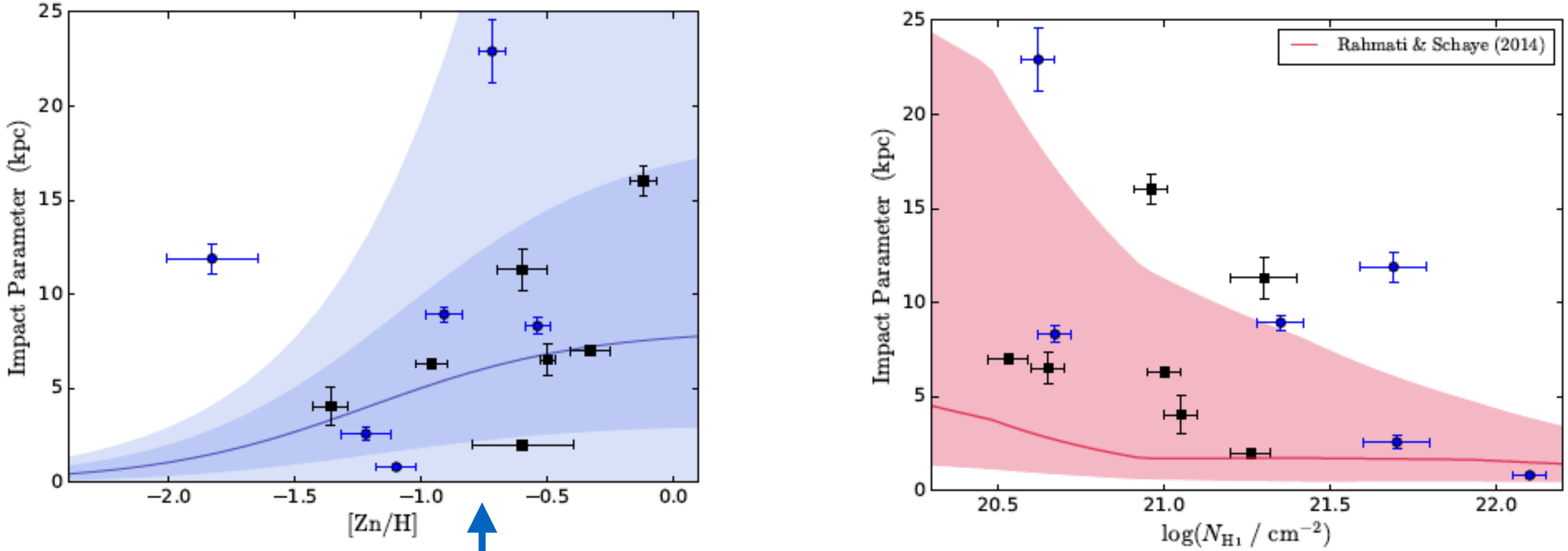


- 2".4 or 20.8 Kpc impact parameter
- from $F_{Ly\text{-}\alpha}$ => SFR ~ 0.13 $M_\odot$ yr^{-1}

from 1986 to 2010 only 3 detections at hgih redshift (Moller et al 2004)

13 DLA

Korgager et al 2017



Most detections are in metal rich DLAs

impact-luminosity $\sigma_{\rm DLA} \propto L^{0.8}$

luminosity -metallicity $\mathrm{M_{UV}} = -5 \times ([\mathrm{M/H}] + 0.3) - 20.8,$

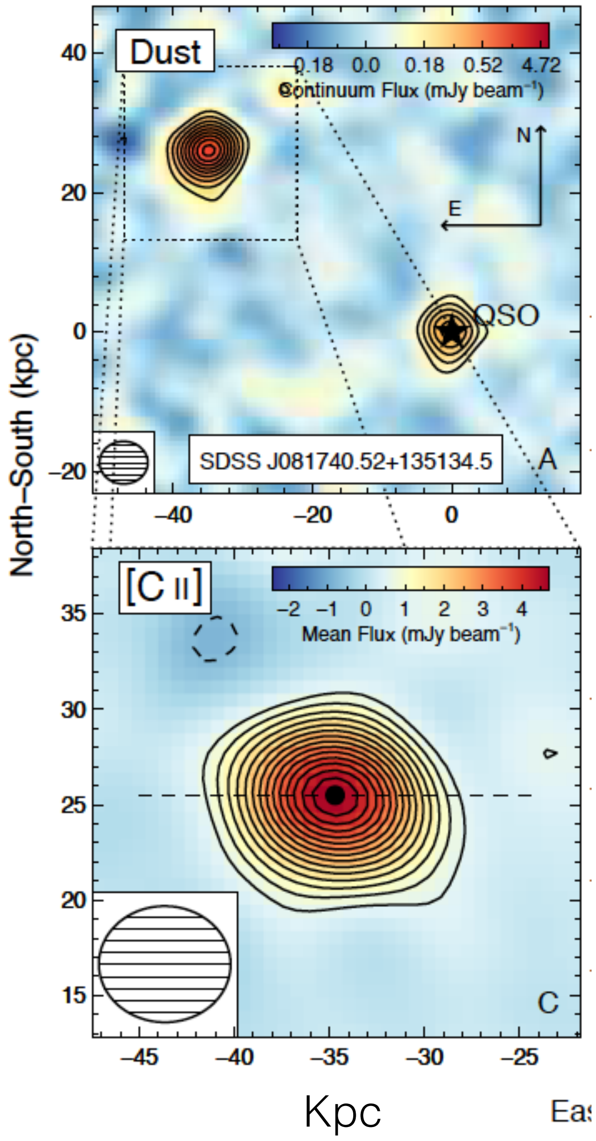
DLA the bright end overlap with the LBG but span 8 orders of fainter magnitudes

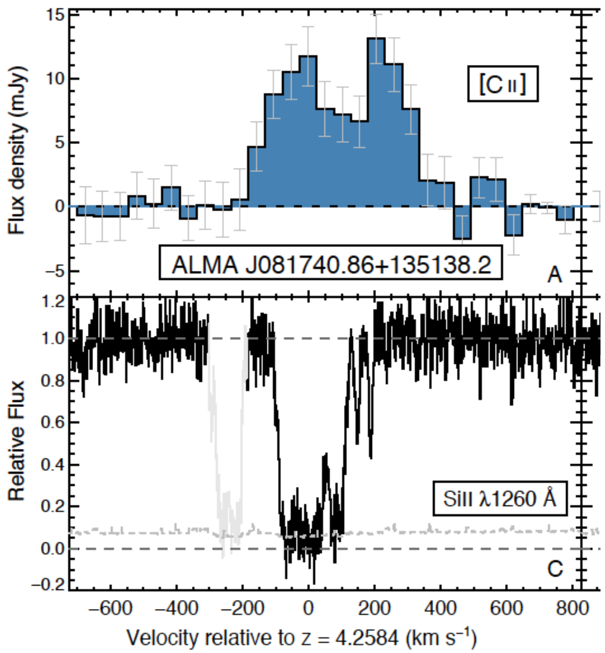
at z ~ 4

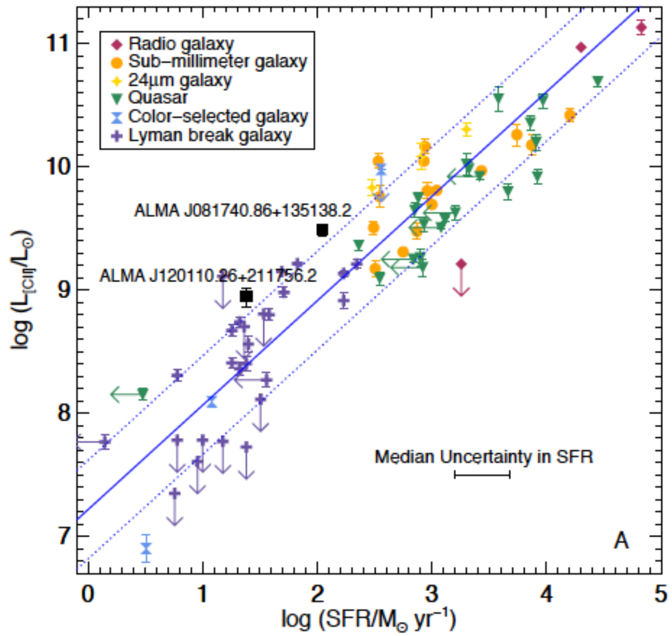
ALMA detection of the [CII] 158 μm, in two galaxies at z~ 4.26; 3.8

J08174+1351

Neeleman et al (2017)



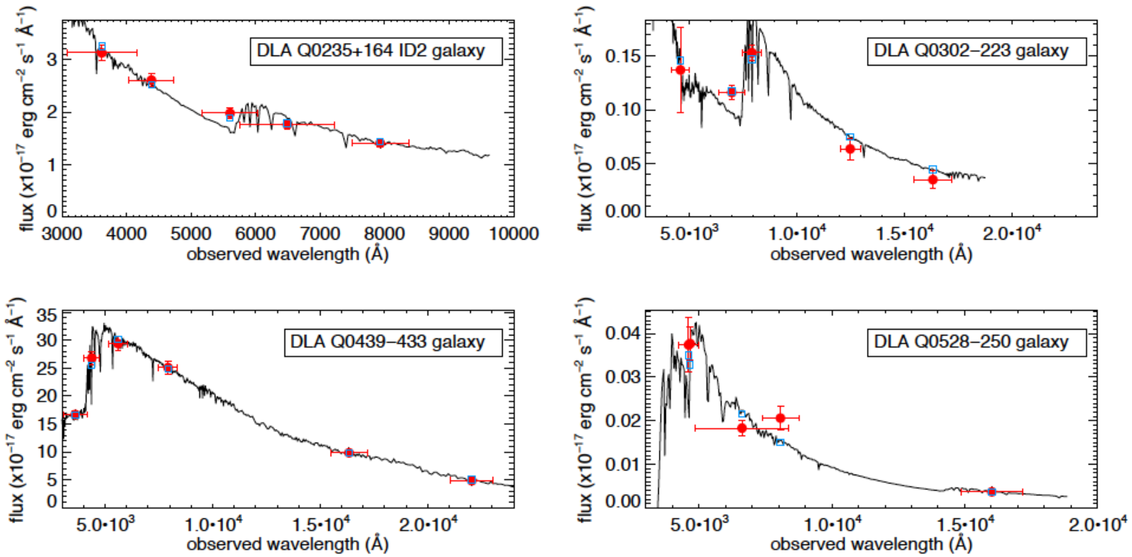


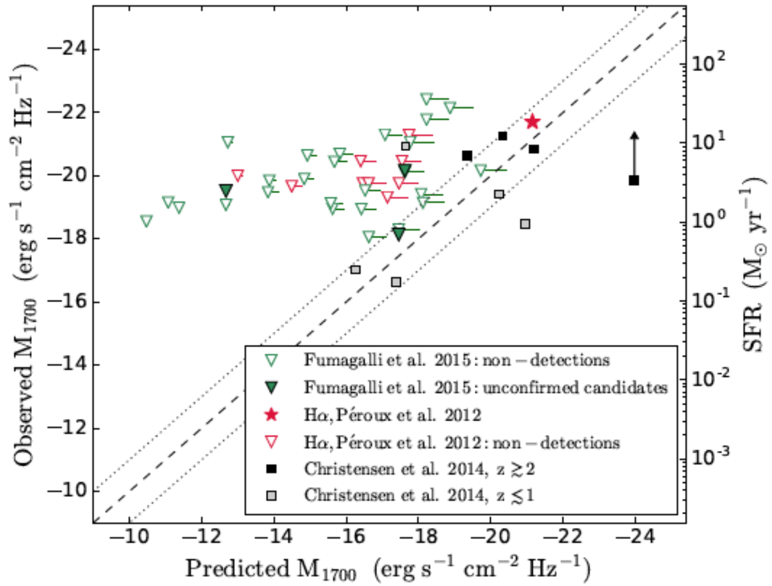


- impact parameter 6", ~40 Kpc, emission ~5Kpc,
- rotating disk the dynamical mass ~ 6×10^{10} $M_\odot$
- dust emission => SFR~100 $M_\odot$ yr^{-1} ~ LBG
- high metallicity DLAs [M/H]~-1, massive end of the DLA

imaging the continuum of DLA host galaxies

few DLA host high-z galaxies have being imaged in the continuum
(Christensen et al 2014, Fumagalli et al 2015)





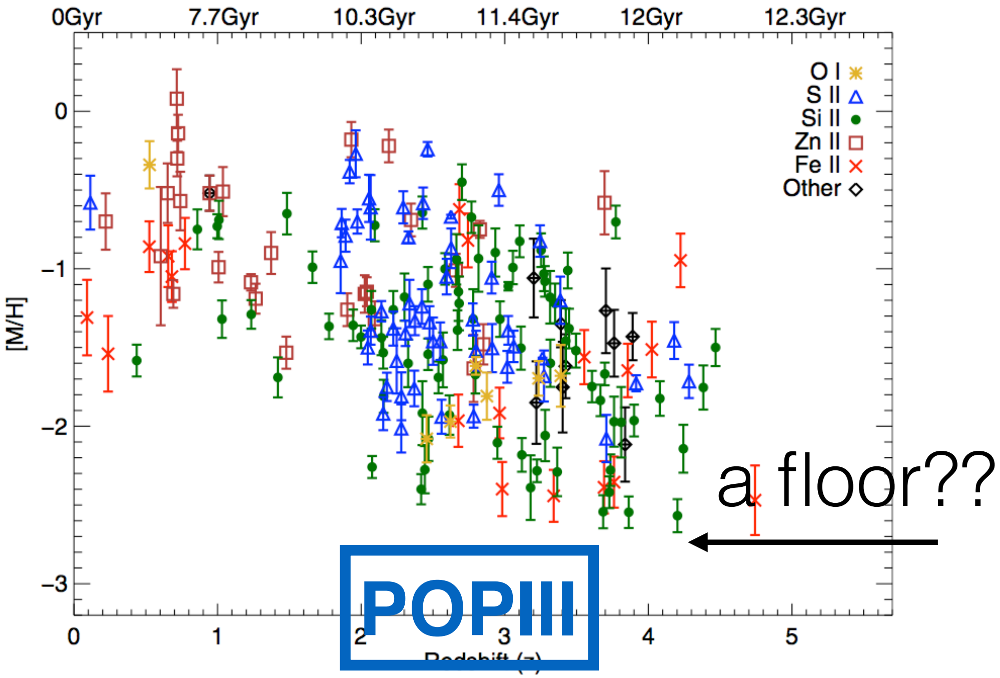
based on the SED => mass-metallicity relation

SFR ~ few $M_\odot$ yr^{-1}

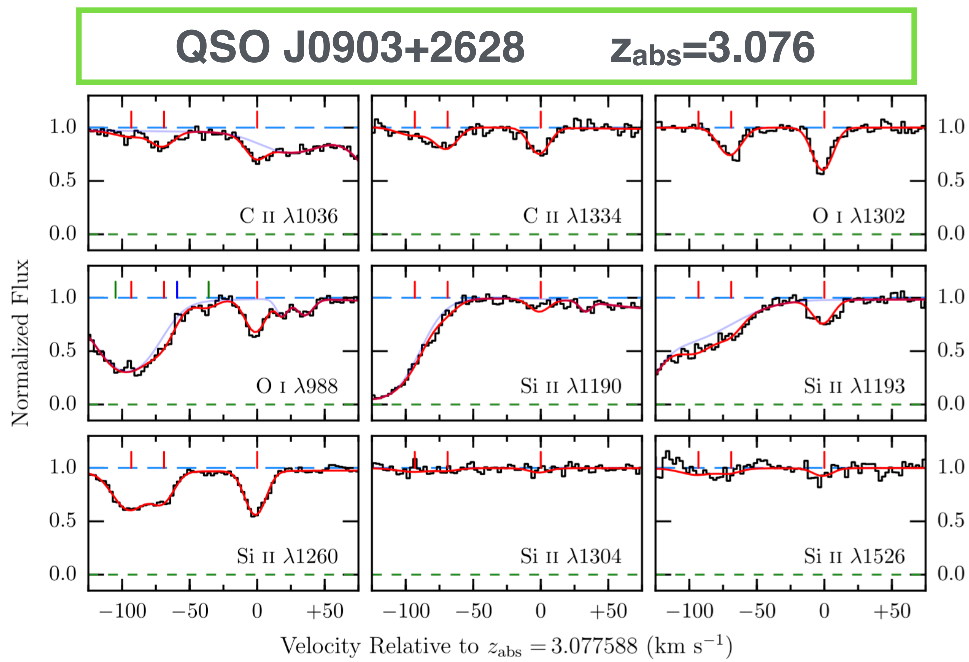
- M_{DLA} span from 10^6 to 10^{11} , with average 10^8 $M_\odot$
- L_{DLA} span from the L_{LBG} down for 8 mag
- SFR_{DLA} from 0.1 to 10 $M_\odot$ yr^{-1} (possibly lower)

in agreement with
cosmological simulations

DLA and first stars



Cooke et al 2017



Ellison et al 2010 J01140-0839 z_{abs}=3.7 **[C/H] =-3.05**
Dutta et al 2014 J0953-05 z_{abs}=4.2 **[C/H] =-3.05**
Cooke et al 2011 J1001+03 z_{abs}=3.0878 **[C/H] =-3.06**
Cooke et al 2016 z_{abs}= 2.5 [O/H]= -2.8, **[Fe/H]< -3.25**

[C/H] = -3.43
[O/H] = -3.05
[Si/H] = -3.21
[Fe/H] < -2.8

~ Halo Stars

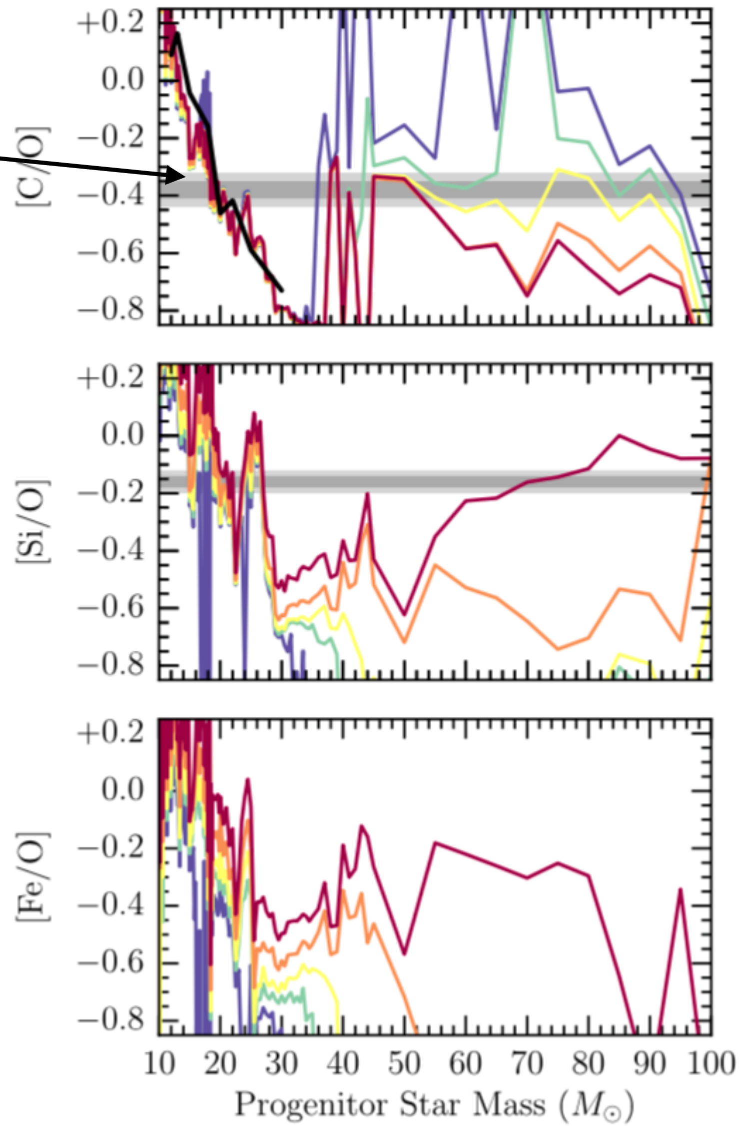
Caffau's star [C/H]< -3.8

probe early stellar nucleosynthesis

Smoking Gun of PopIII

abundances of metal-free stars as a function of progenitor mass and Kinetic Energy released by the SN explosion. With the PopIII yields from Heger & Woosley (2010):

For $M < 30\ M_\odot$ C/O function of SN mass



Kinetic Energy: blue 1.8×10^{51}, (2.4,3,5) red 10×10^{51} erg

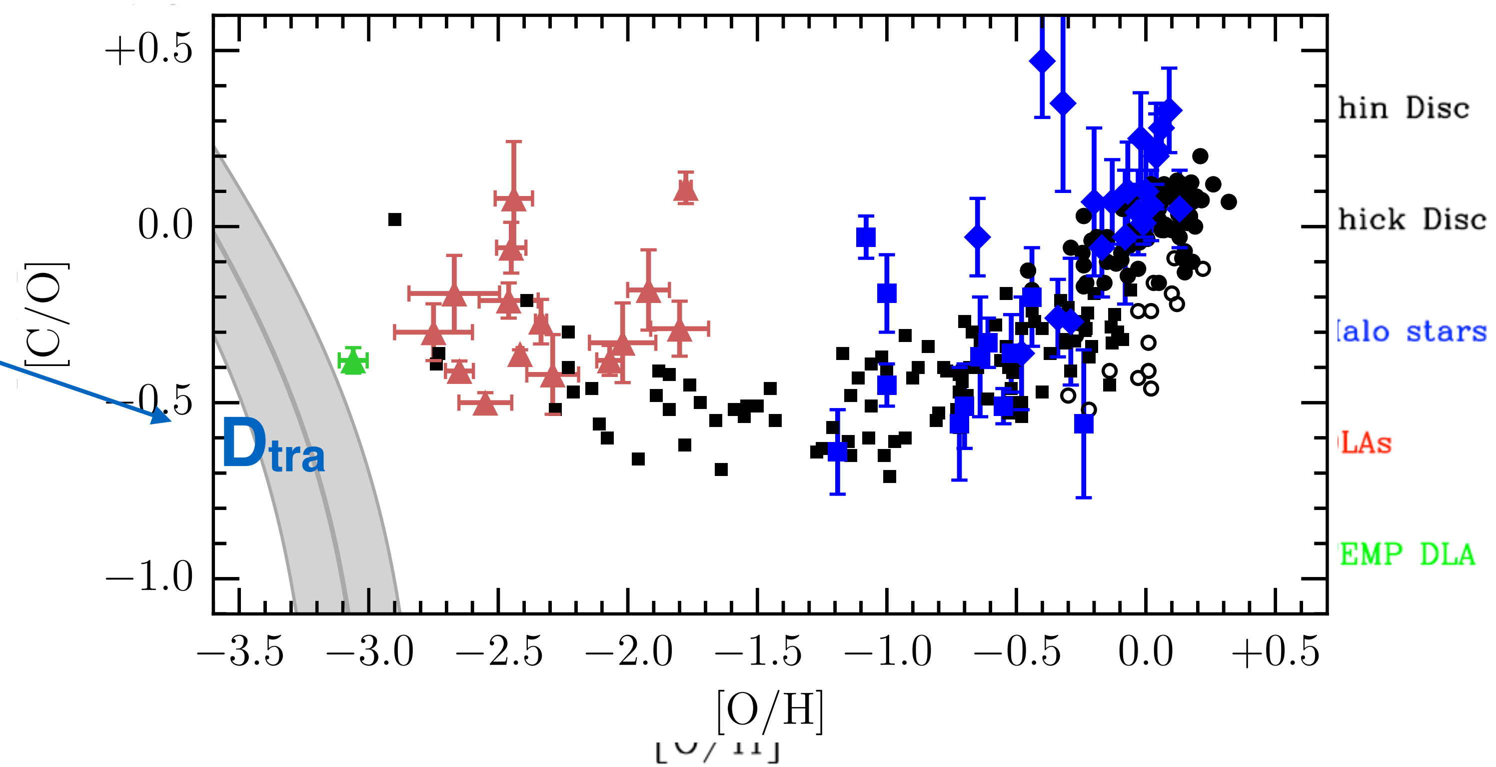
- No evidence for products of 140-260 $M_\odot$. Pair-instability SNae => [C/O]<-0.6, [Si/O]>0.2
- Assuming a single PopIII star, as progenitor the observed the progenitor is a CCSN of => 20.5 $M_\odot$

[C/O] evolution

CII 1036, 1334 A and OI 1302 strongly saturated, measures at [Fe/H]< -2.0

D$_{tra}$: transition discriminant for CII,OI cooling to form small mass stars

(cfr Caffau's lecture)



- **close to D$_{tra}$ ~ precursor of a "pristine" galaxy**, i.e. not yet small mass stars formed

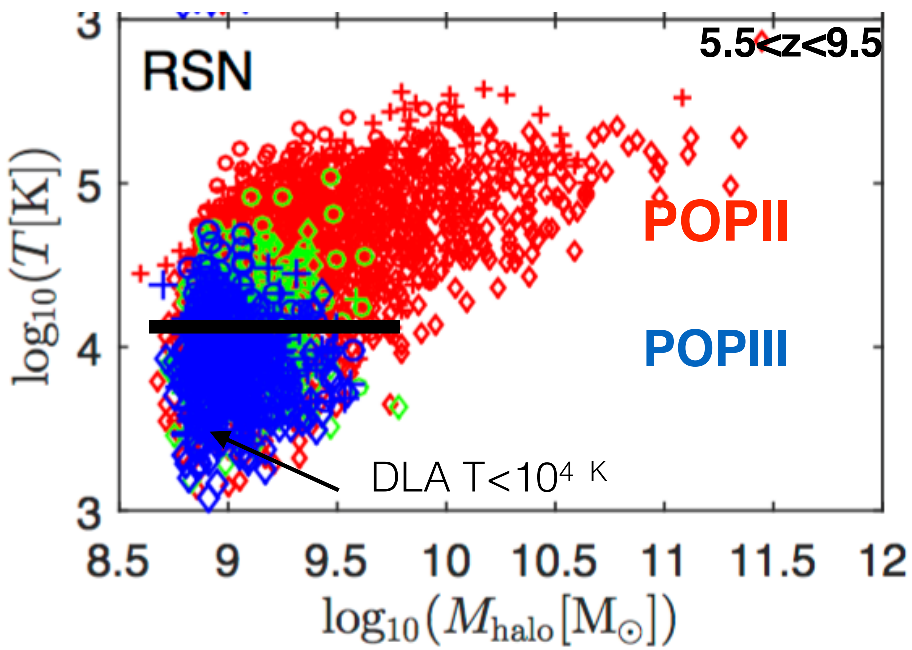
- **[C/Fe] ~ 0, no evidence of C enhancement** (In the Galaxy: CEMP: stars [Fe/H]<-2 with [C/Fe]>+1.0, fraction > 30%, to note old value of [C/Fe] = +1.5 Cooke et al 2012 shown in error). Why?

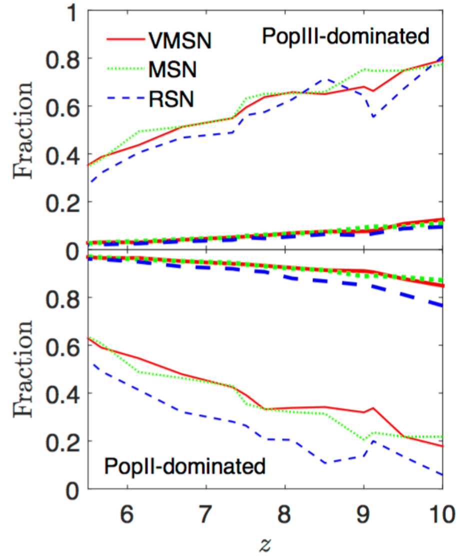
- **intrinsic dispersion**: 1) different progenitors 2) weak SN with different mixir

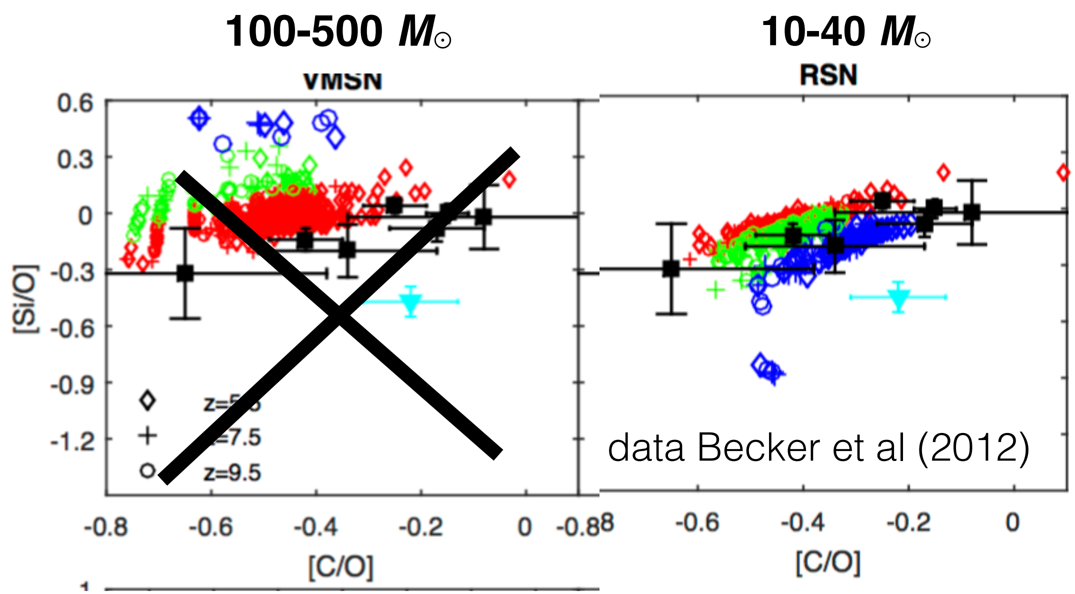
POPIII gas at high z

when do we expect to see the POPIII gas?

hydrodinamical simulations with Gadget-2, Ma et al (2017)







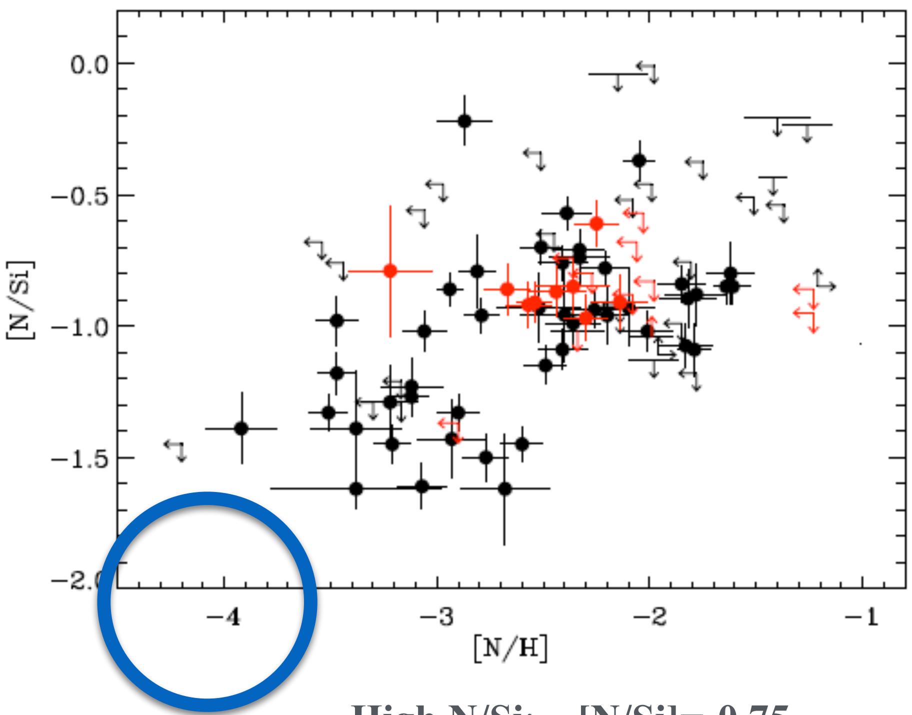
at z~5 ~40% POPIII
$M < 10^{9.6}$
[M/H]< -3.0
SFR <$10^{-1.5}$ $M_\odot$ yr^{-1}

Nitrogen

special nucleosynthesis:

Main producers: Intermediate Mass Stars 4 -8 $M_\odot$ AGB
Secondary element: CNO cycle main process but require C and O
At low metallicities could be primary: from C,O made by AGB and transported by TP in the H-burning shell.

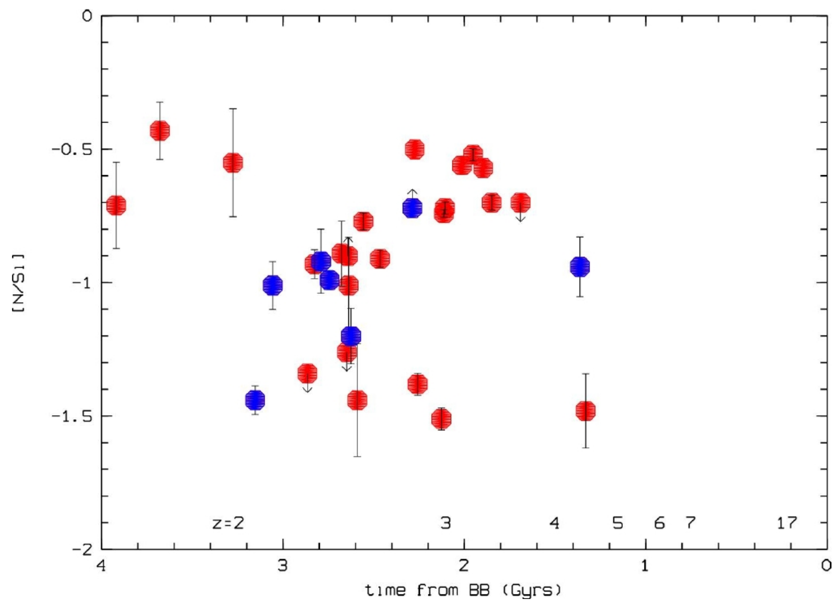
NI in the forest: NI 1134.1 1134.4 1134.9 Å NI 1199.0 1200.2 1200.7 Å (Molaro et al 1996)



bimodal?

High N/Si: [N/Si]=-0.75
Low N/Si : [N/Si]= -1.45

Zafar et al 2015



low N/Si young systems?
produced by massive stars (> 8 $M_\odot$)?
rotating models (Maynet &Maeder 2008)

Smoking gun of PopIII?

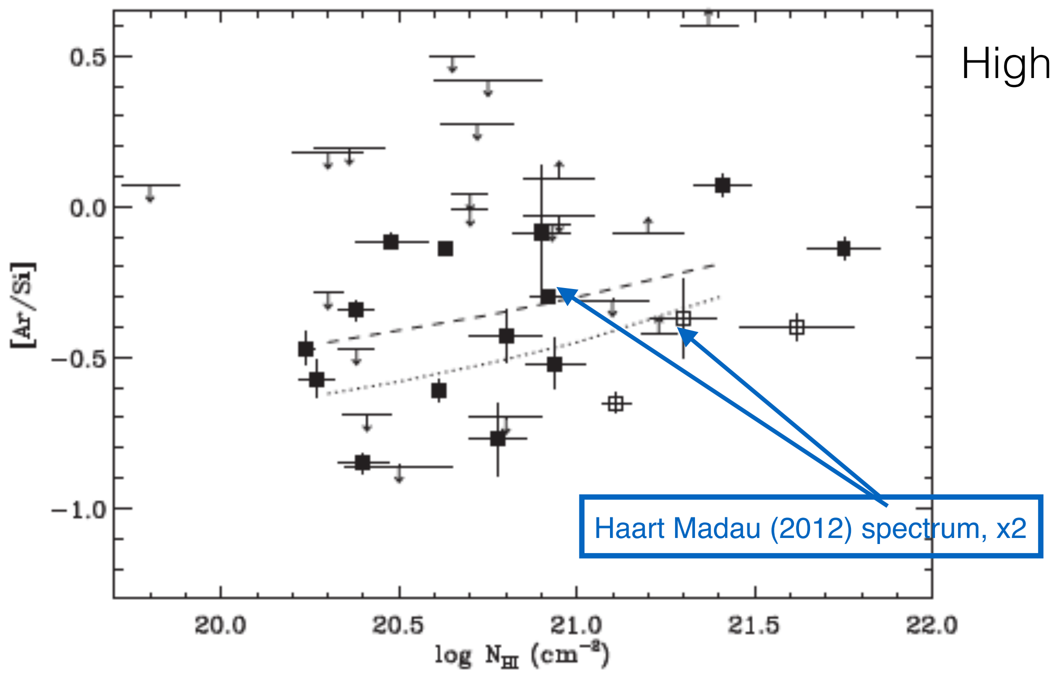
High and low N/α at **all** z;
High N/Si z=4.4 => onset star formation at z > 7 (for 500 Myr delay)

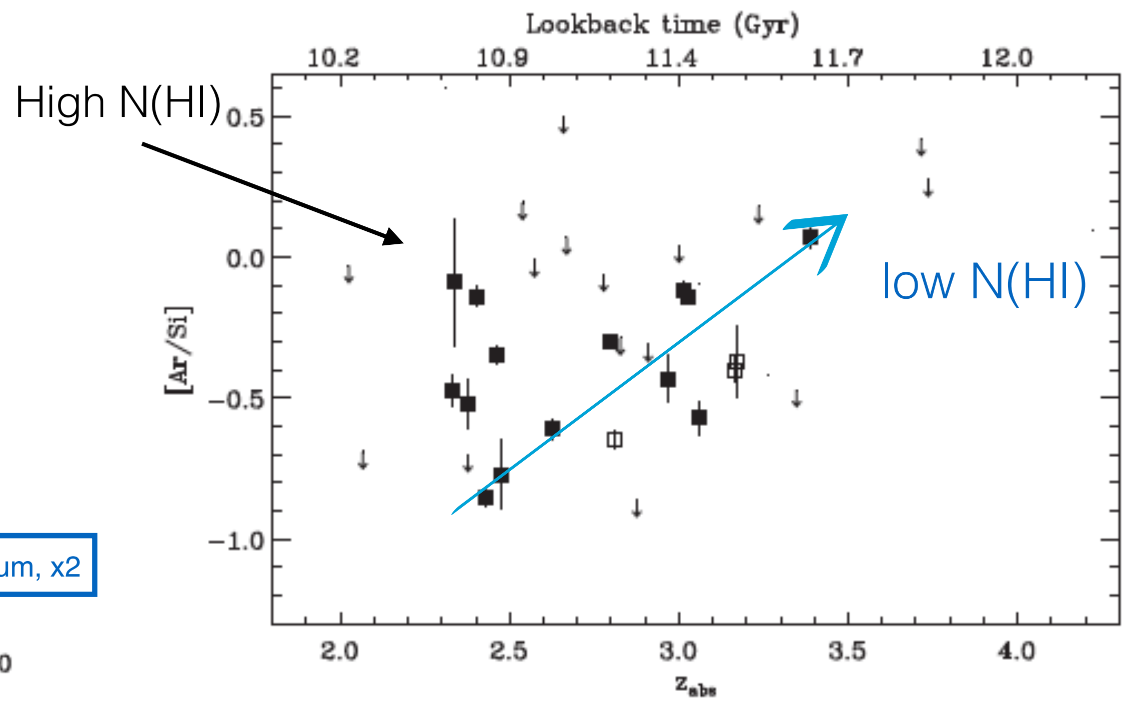
Argon

- ArI transitions: 1048, 1066 Å nucleosynthesis: α-element, non-refractory
- not measured in stars! no information on its chemical evolution
- Milky Way: [ArI/OI] = -0.23 ± 0.11
- IP= 15.76 eV, but photoionization cross section >> HI (Sofia & Jenkins 1998, Jenkins 2013)

Ar is sensitive to the radiation field

Zafar et al (2015)





[ArI/OI] = -0.4 ± 0.36, large dispersion
more deficient than the MW!

complete HeII (IP=54 eV) re-ionization at z~ 3

Conclusions (lesson I)

- DLA galaxies are high z counterparts of local galaxies, but spanning a wide range of properties

- DLA allow to study the universal neutral gas evolution. But no evidence of conversion of gas into stars.

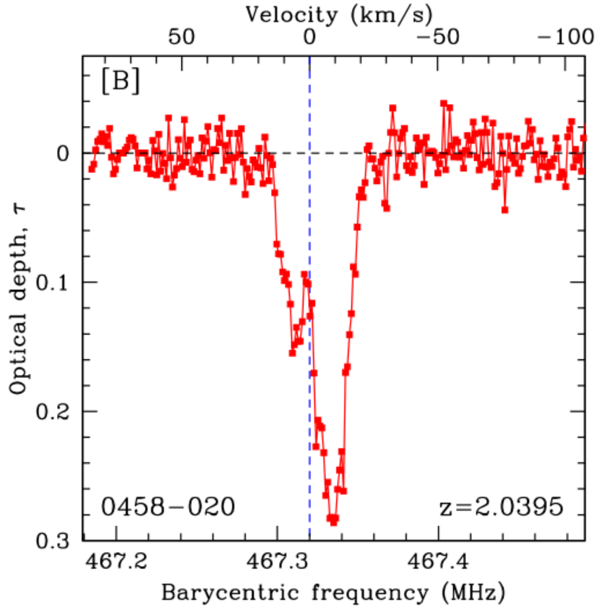
- DLA allow study of the chemistry in the 90% of the universe. Relative abundances of alpha-over iron-peak elements can be used to infer the kind of galaxies but the precise value remain controversial (though it is fair to say more similar to dwarf galaxies than protospirals)

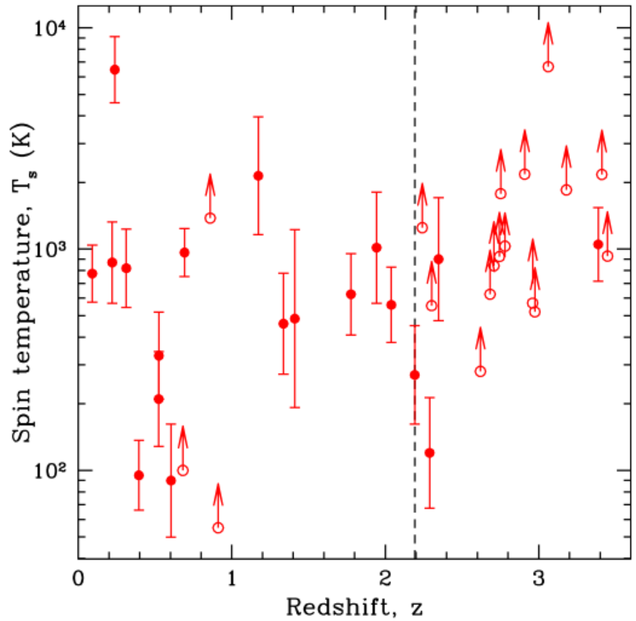
- The low metallicity tail of DLA is reaching levels where popIII tars yields can be probed

temperature of DLA by 21 cm

Karnekar et al 2014

37 DLAs





- Ts ~ 1000 K
- Ts higher at high z
- Ts higher at low [Fe/H]