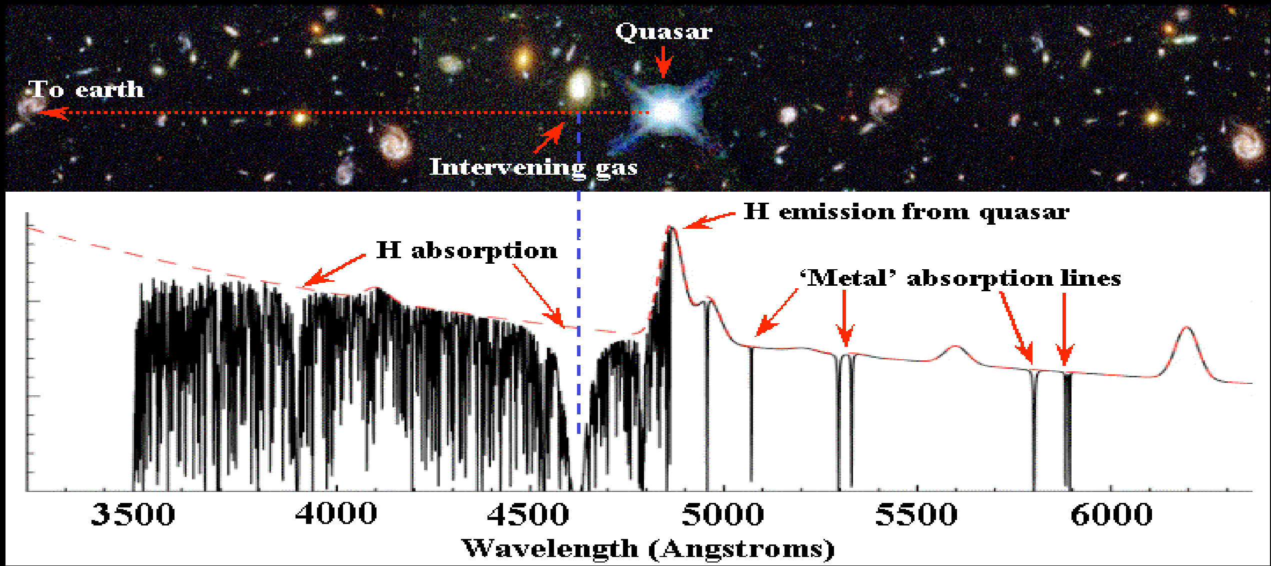
Metals, Dust and Diffuse Interstellar Bands in High Redshift Galaxies



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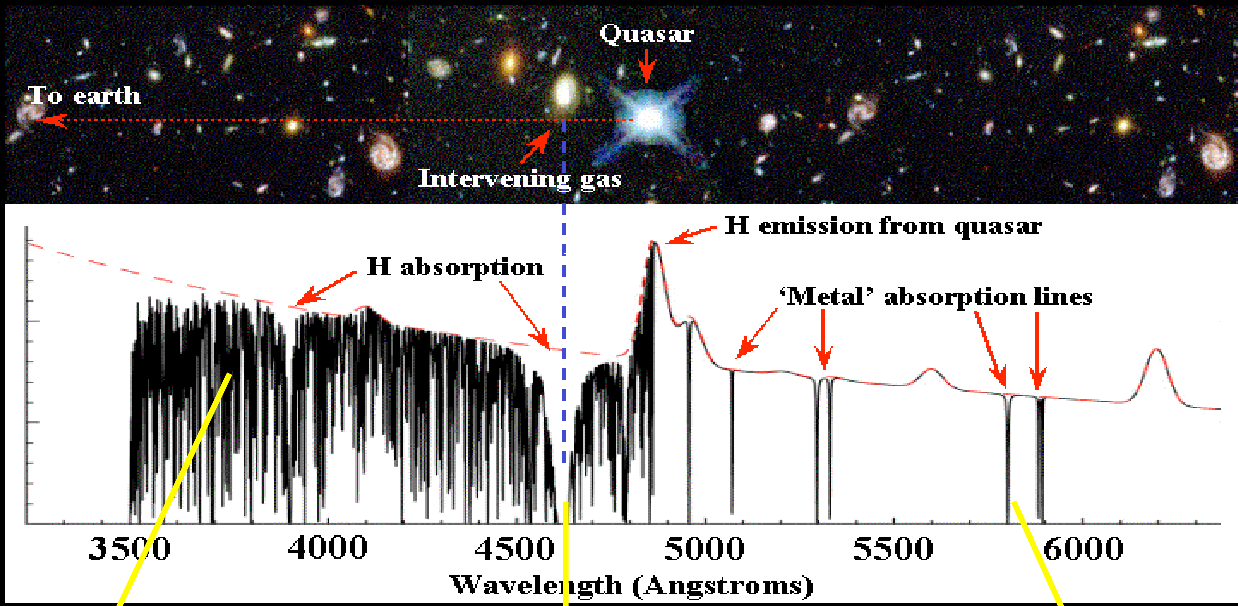
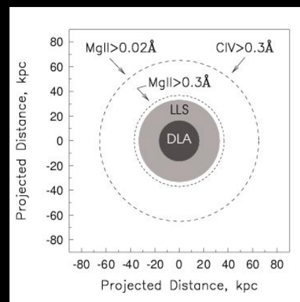


- Lyα forest: the IGM.
- N(HI) < 10^{17} atoms cm^{-2}
- Contains most of the baryons at z~3.

- Damped Lyman α systems
- N(HI) > 2×10^{20} atoms cm^{-2}
- Contain most of the *neutral* gas at any redshift.

- Metal selected absorbers
- N(HI) > 10^{17} atoms cm^{-2}
- Mostly associated with galaxies.



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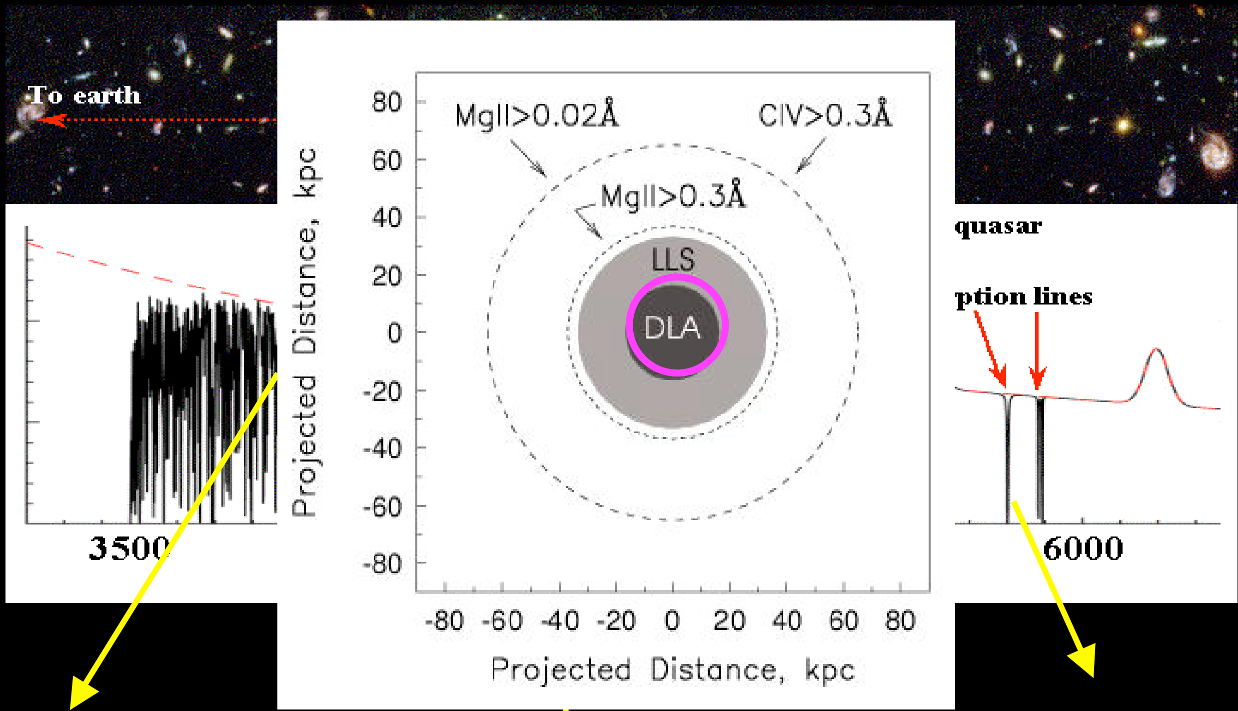

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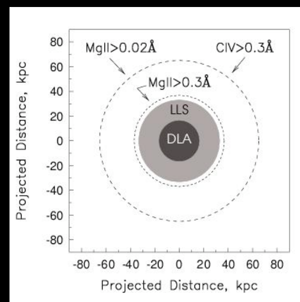

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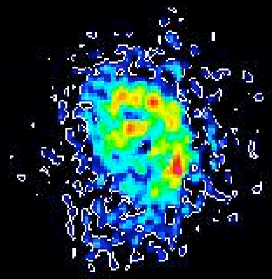
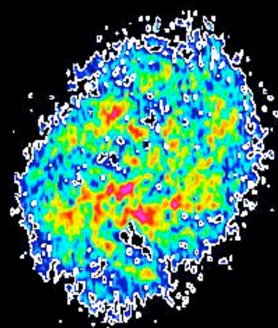
What galaxies make up the DLA population?

z=0: everything with gas!

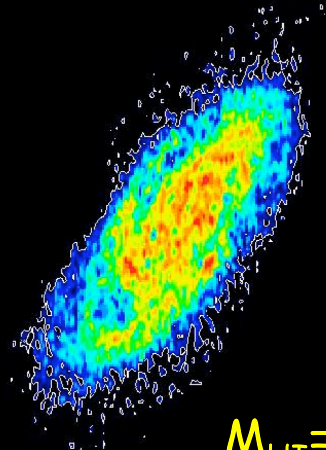
Zwaan et al. (2005)



$M_{HI}=10^8 M_\odot$



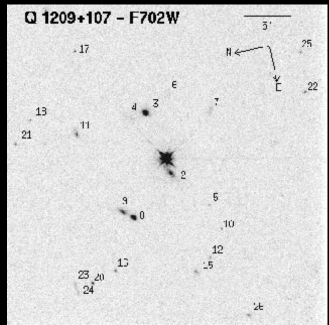
$M_{HI}=10^9 M_\odot$

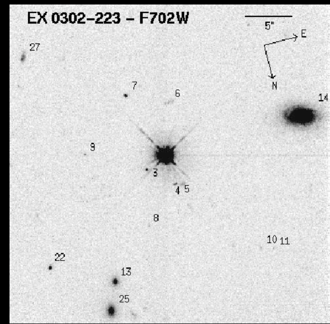


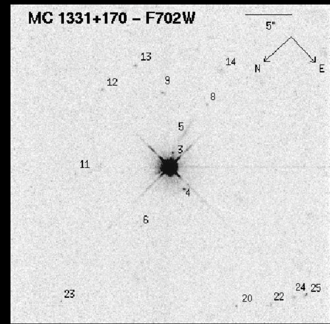
$M_{HI}=10^{10} M_\odot$

z=1: many things..

Le Brun et al. (1997)

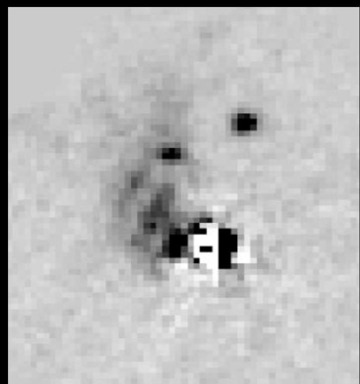


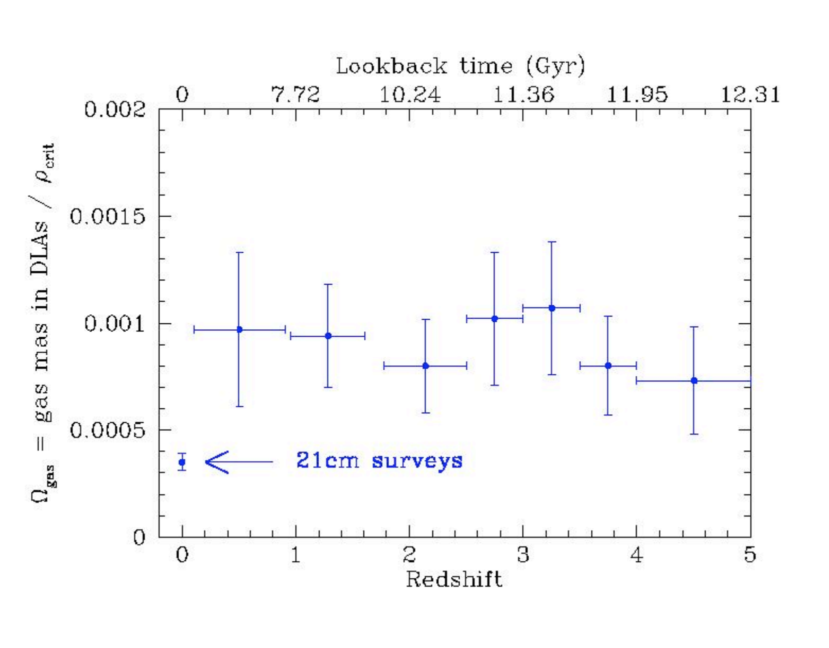




z=3: hard to say...

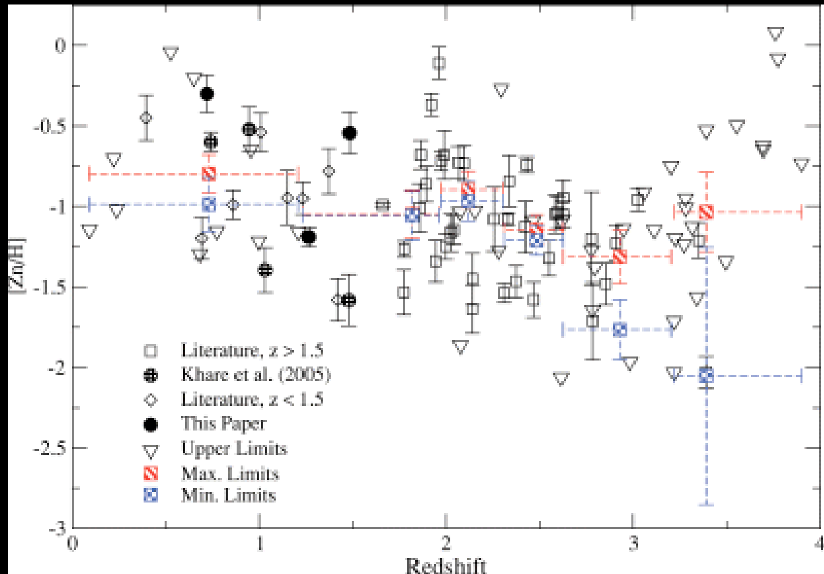
Weatherly et al. (2005)





DLAs allow us to probe neutral gas reservoirs out to very high redshifts without concerns of Malmquist bias.

500 DLAs from the SDSS, Prochaska, Herbert-Fort & Wolfe (2005)



Up to 20 different chemical elements can be measured per DLA providing insight into galactic chemical evolution and the cosmic build-up of metals.

Meiring et al. (2006).

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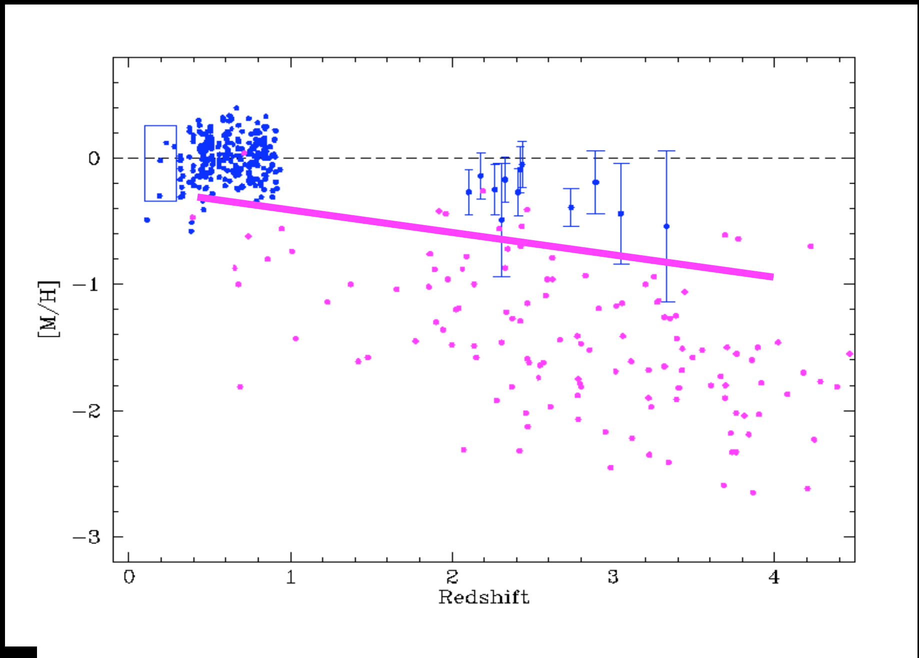
If DLAs are fair galaxy probes how do we explain…



- Anti-correlation of N(HI) and [Zn/H], e.g. Prantzos & Boissier (2000)
- Lack of marked [M/H] evolution, e.g. Pettini et al. (2000)
- Systematic difference between DLA and emission line galaxy metallicities e.g. Ellison, Mallen-Ornelas & Kewley (2005)

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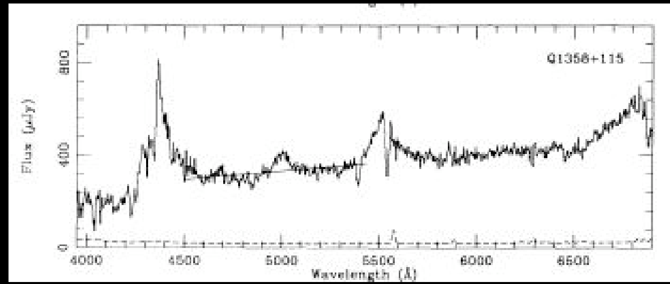
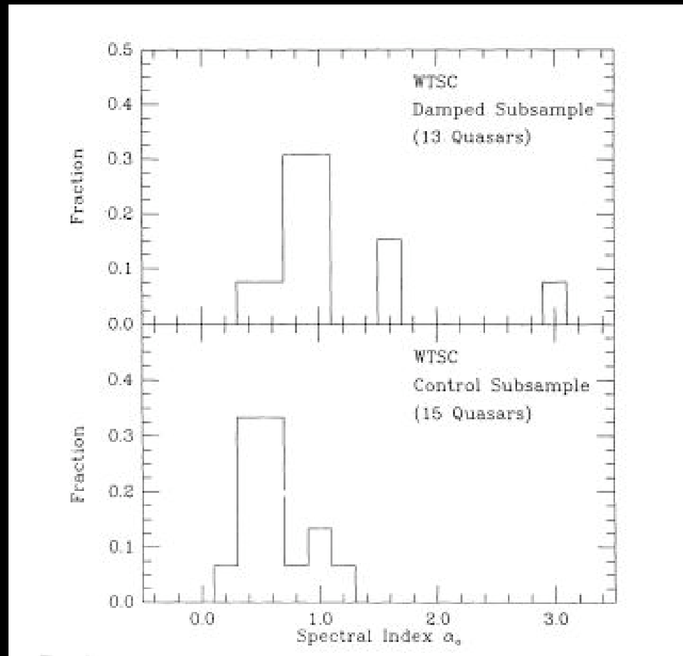
Galaxy Bias Due to Dust?

Evidence from both observations and theory that metal-rich DLAs are missed by optical surveys.



Pei, Fall & Bechtold (1991) found that QSOs with intervening DLAs had systematically (redder) steeper slopes.



Several theoretical works have predicted that dusty DLAs will be omitted from optical surveys (e.g. Churches et al. 2004; Trenti & Stiavelli 2006)

Implication: our surveys are biased against star-forming galaxies at all redshifts.

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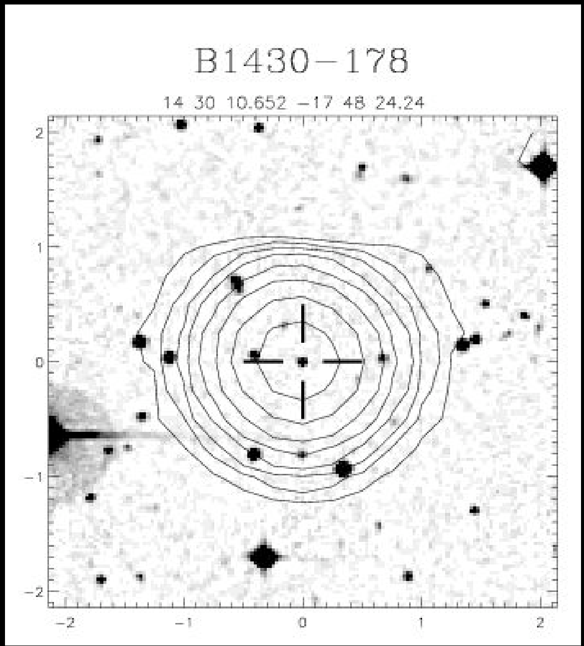
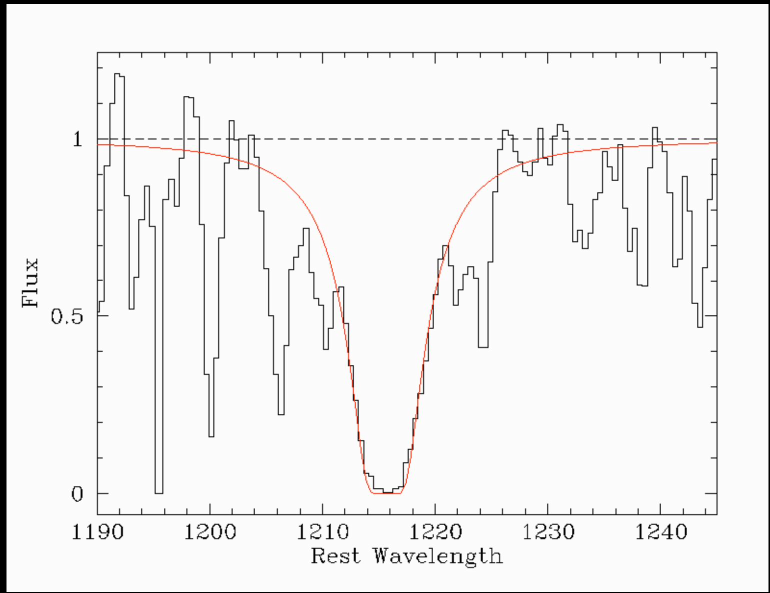
The Complete Optical and Radio Absorption Line System (CORALS) Survey:

Strategy: Select radio loud quasars from the PKS catalogs (>0.25 Jy) and obtain complete optical identifications. Obtain moderate resolution optical spectroscopy for *every* QSO regardless of optical magnitude.





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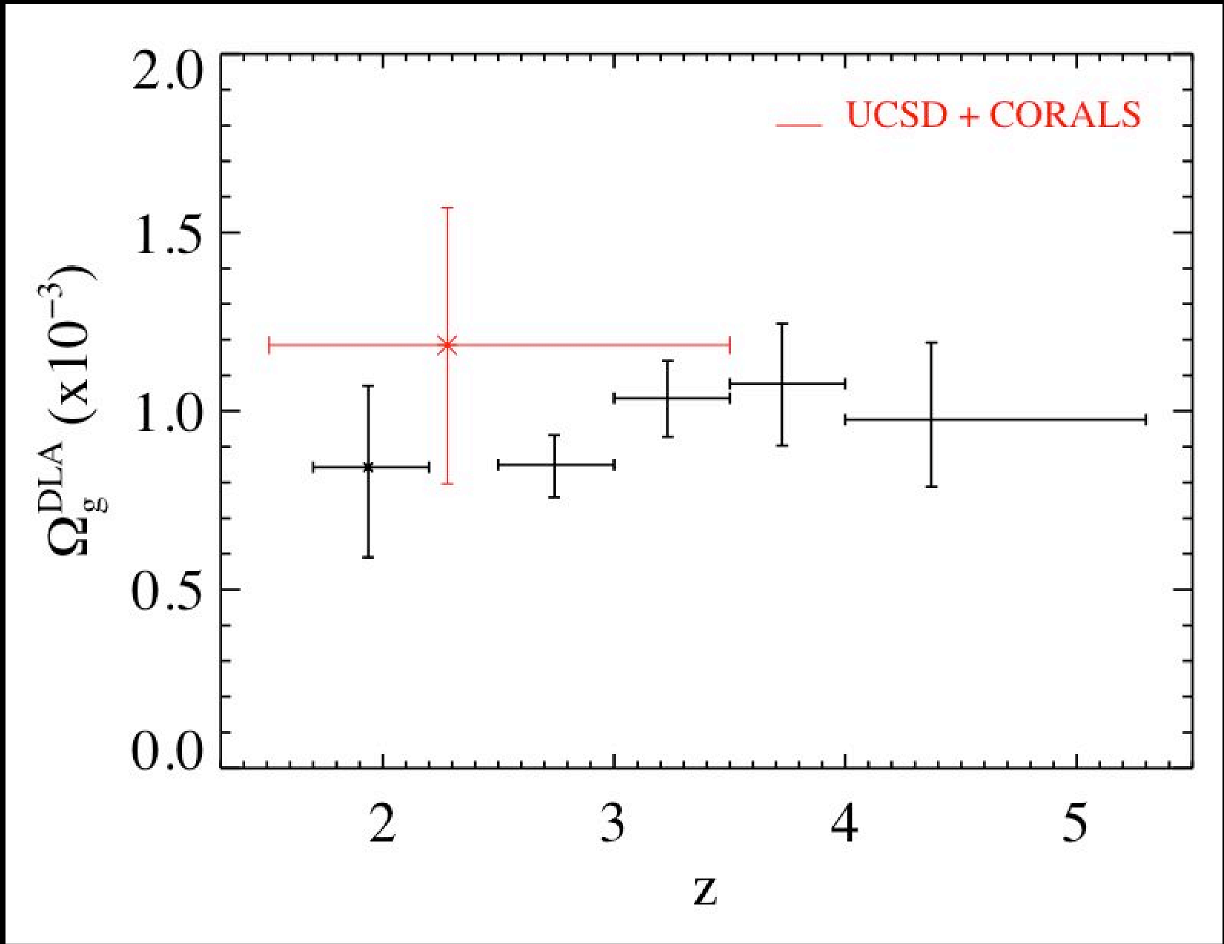

Total mass density of neutral gas in optically complete surveys such as CORALS (plus UCSD follow-up), show consistent amounts of neutral gas.

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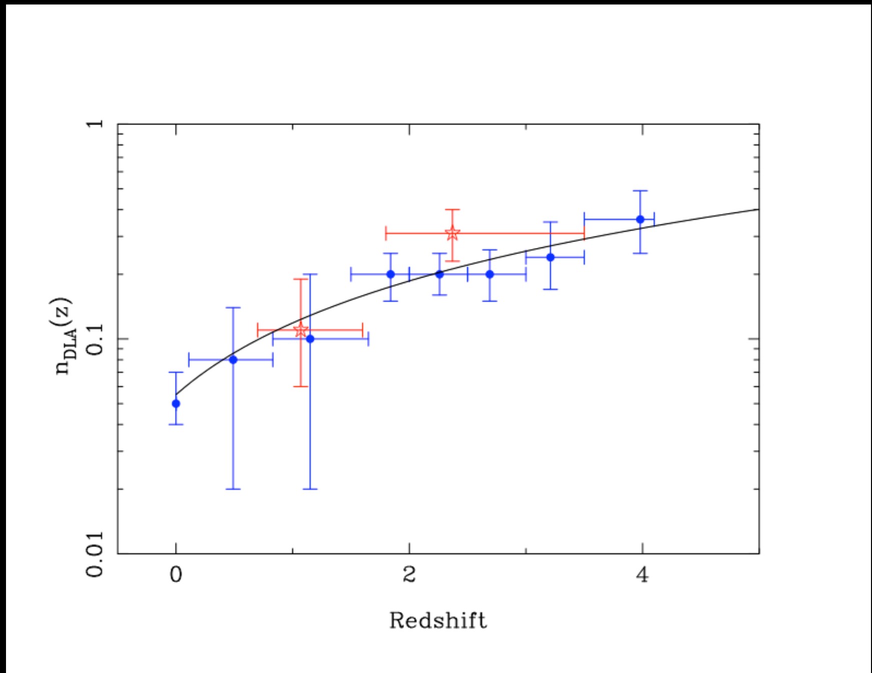

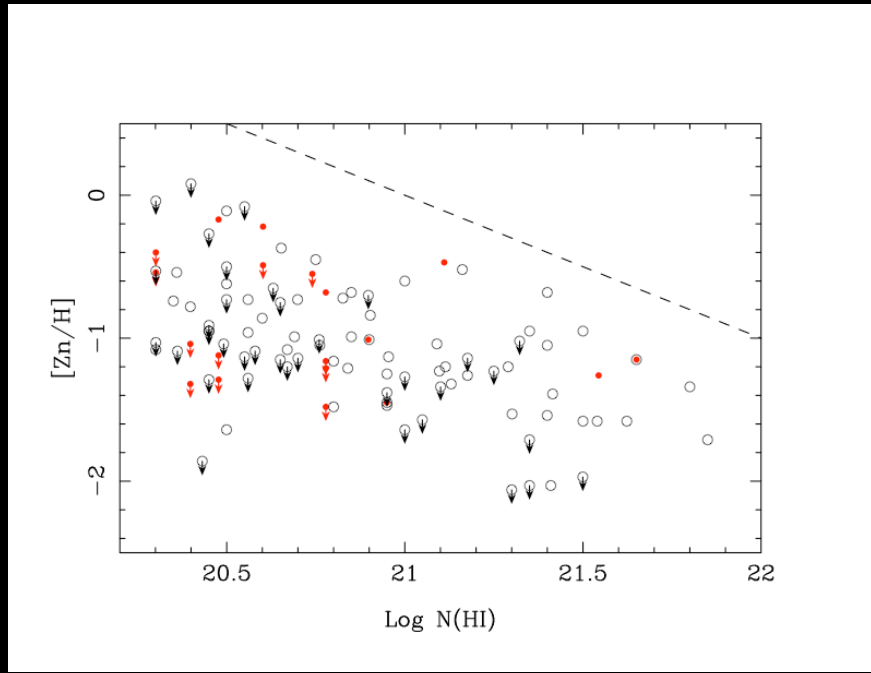

- Number of absorbers same in CORALS as other surveys
- Metallicities very similar and no high Z high N(HI) systems
- Dust reddening is small: E(B-V) < 0.04

Ellison et al (2001, 2004, 2005), Akerman et al (2004)

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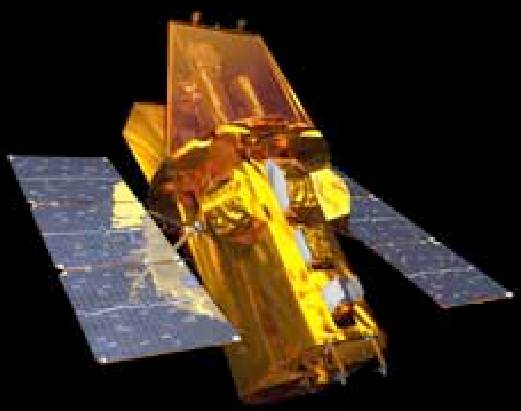
A complementary test of dust bias with GRBs

GRBs can be used as alternative probes of intervening galaxies. At their brightest, they outshine QSOs by 2 order of magnitude.

In order to exploit this, we need fast optical follow-up: Swift.



γ-ray flash detected, trigger X-ray and optical telescopes

↓ ~ 2 minutes

UVOT observations yield accurate optical position

↓ < 1 minute

Coordinates sent as an alert that can be received by cell phone

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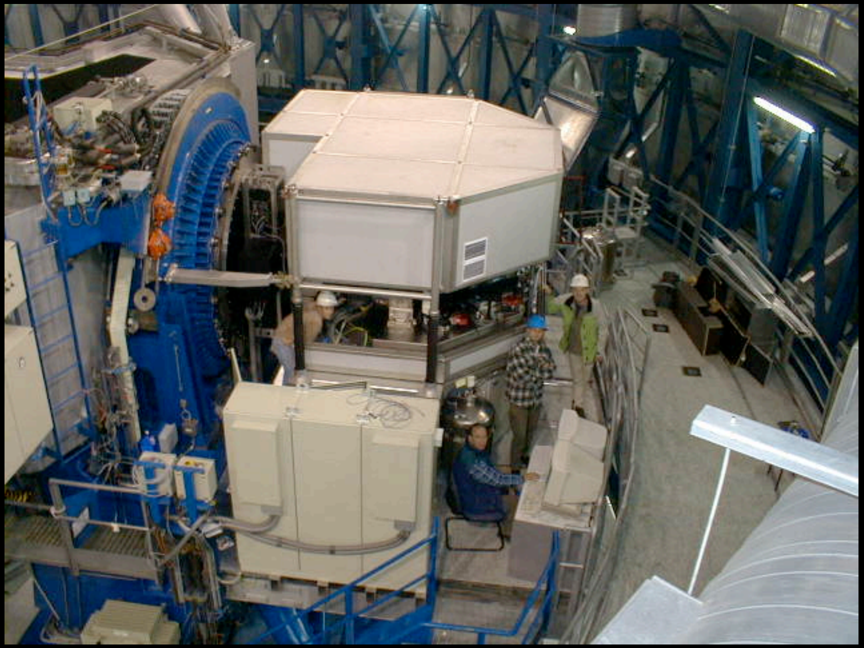
A complementary test of dust bias with GRBs

To take advantage of the Swift triggers, an ESO team commissioned an automated rapid response mode at the VLT. Using this mode, we can be integrating on a GRB afterglow in less than 10 minutes from the Swift trigger.



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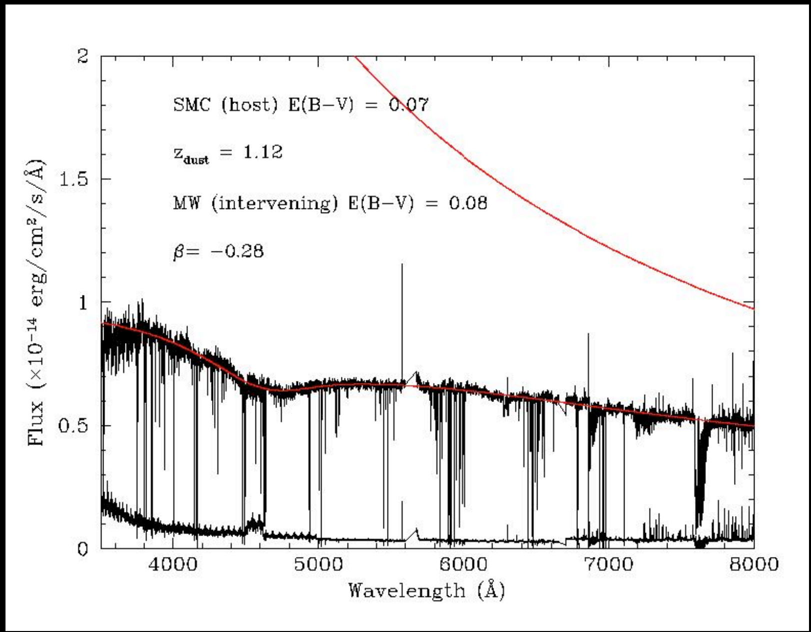
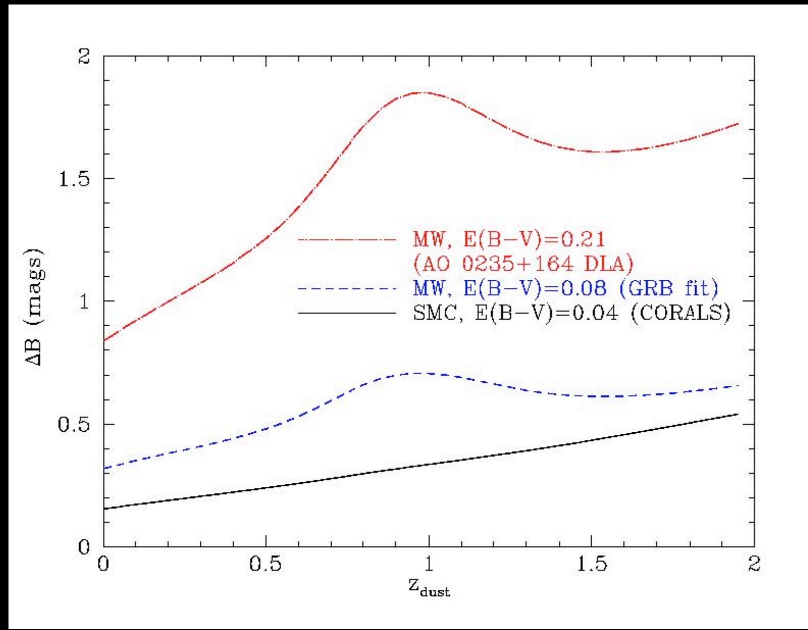
A complementary test of dust bias with GRBs

Observations of a z=1.5 GRB with V~14 at the VLT.





2175 Å bump detected in intervening absorber at z=1.12 with E(B-V)=0.08 (recall that most DLAs have E(B-V)< 0.04). Even this does not give a reddening above 0.5 mags

Ellison et al. (2006).

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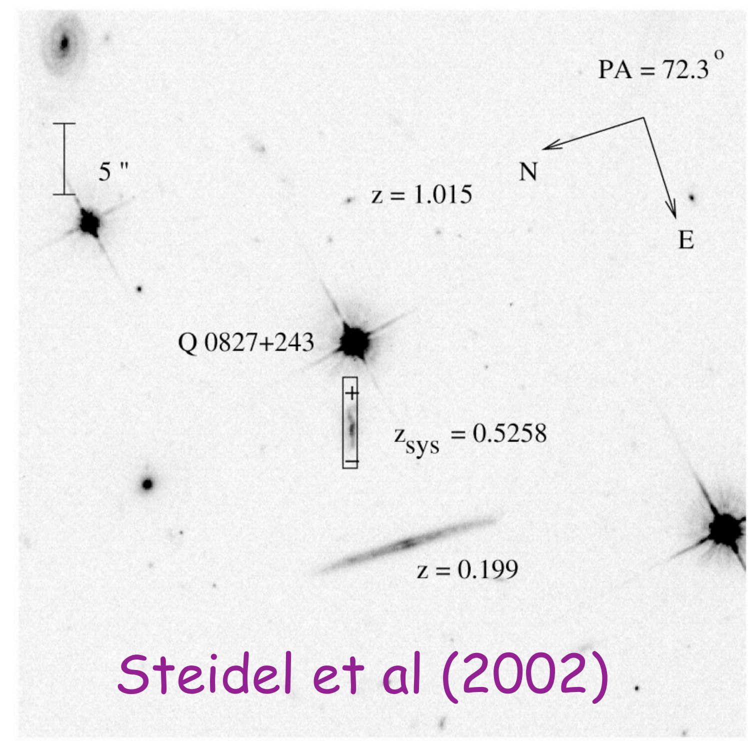
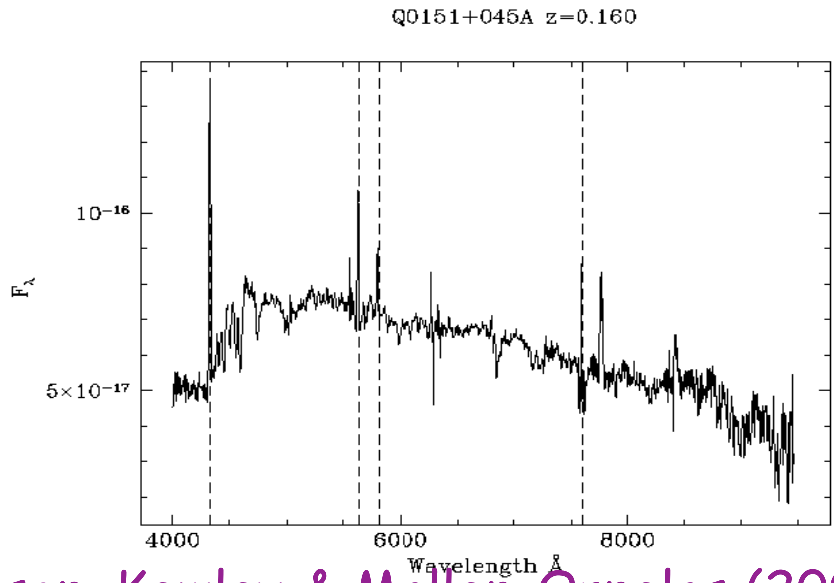
No significant dust bias, so no reason that DLAs should be metal poor compared with local emission line galaxies.



Steidel et al (2002)



Ellison, Kewley & Mallen-Ornelas (2005)

Is it fair to compare the two? What is the emission line metallicity of an absorption selected galaxy?

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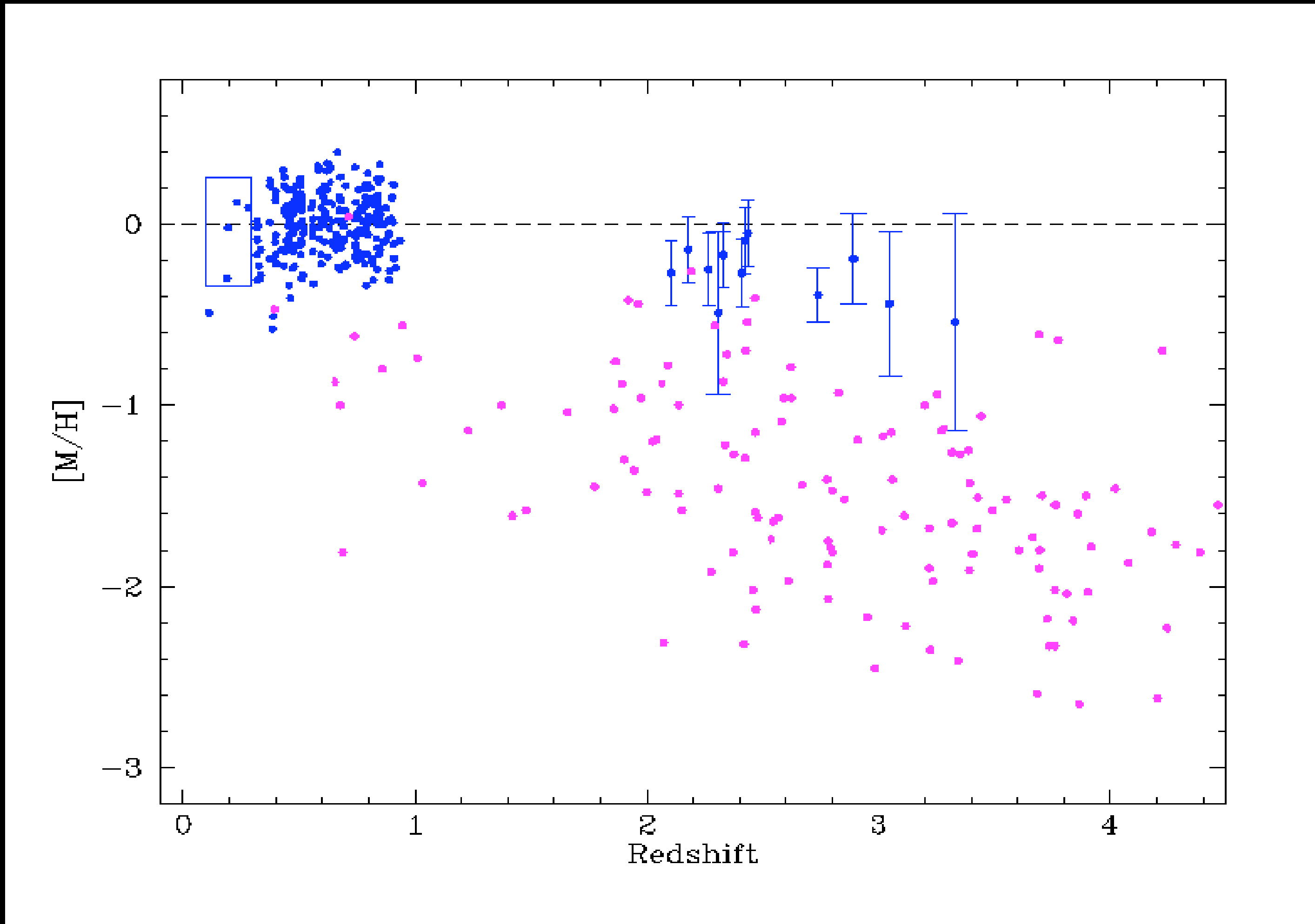

ELGs (●): Relatively high metallicities at all redshifts

DLAs (●): Metal-poor (typically < 1/10 solar) at all redshifts

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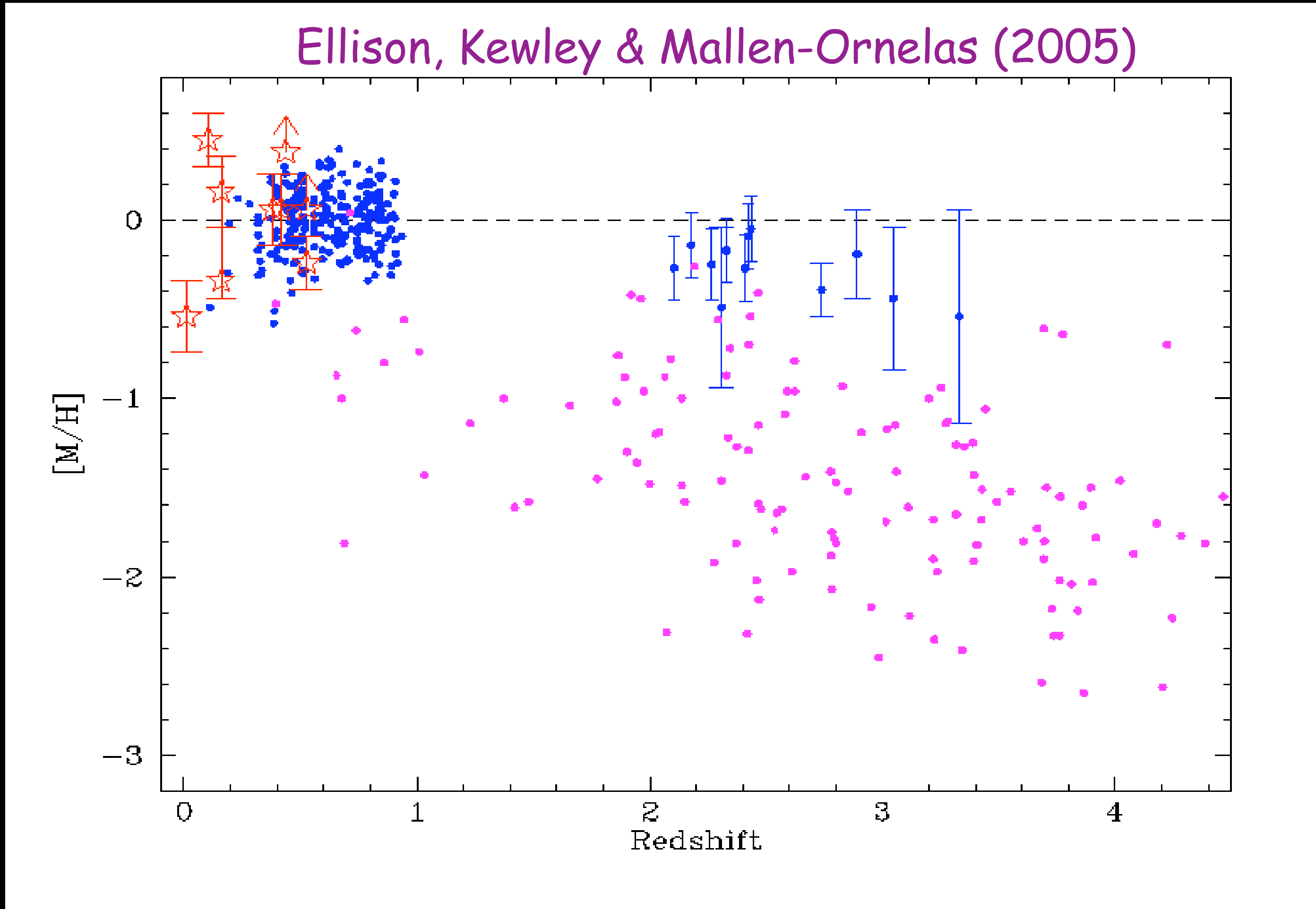
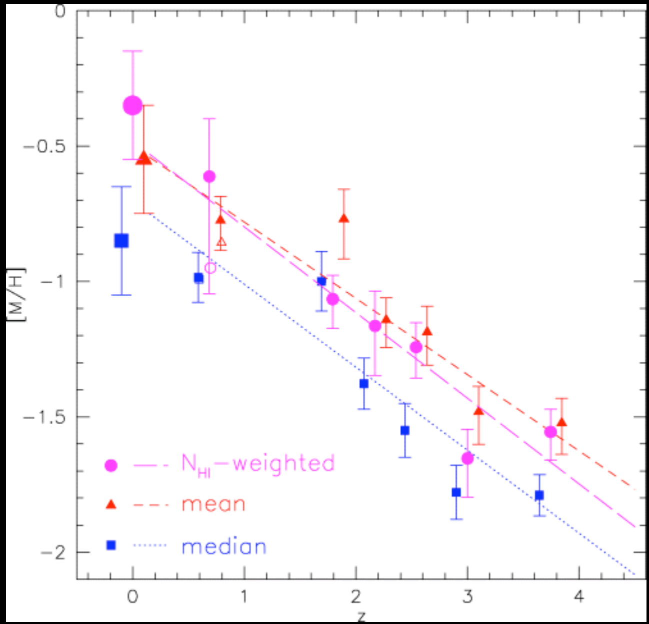


ELGs (●): Relatively high metallicities at all redshifts

DLAs (●): Metal-poor (typically < 1/10 solar) at all redshifts

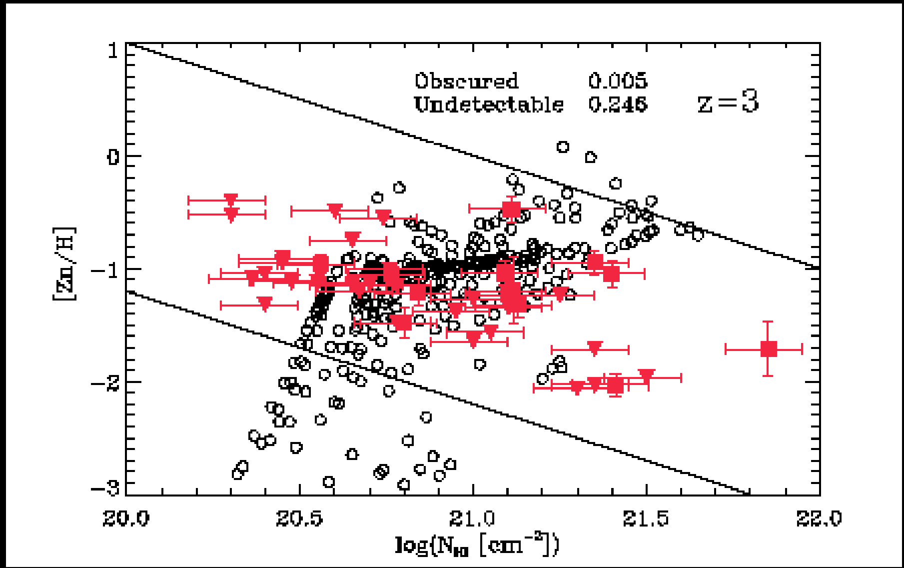
Absorption selected galaxies in emission (☆): ~ solar at z~0.5

Understanding DLA metallicities:



Survey of z=0 DLAs (21cm WHISP sample, Zwaan et al 2005) predicts that metallicity is sub-solar, consistent with traditional QSO DLA measurements.

Simulations indicate that high N(HI), high Z are likely to be rare (e.g. Johansson & Efstathiou 2006). Hence the anti-correlation need not be due to dust bias.



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Understanding DLA metallicities:

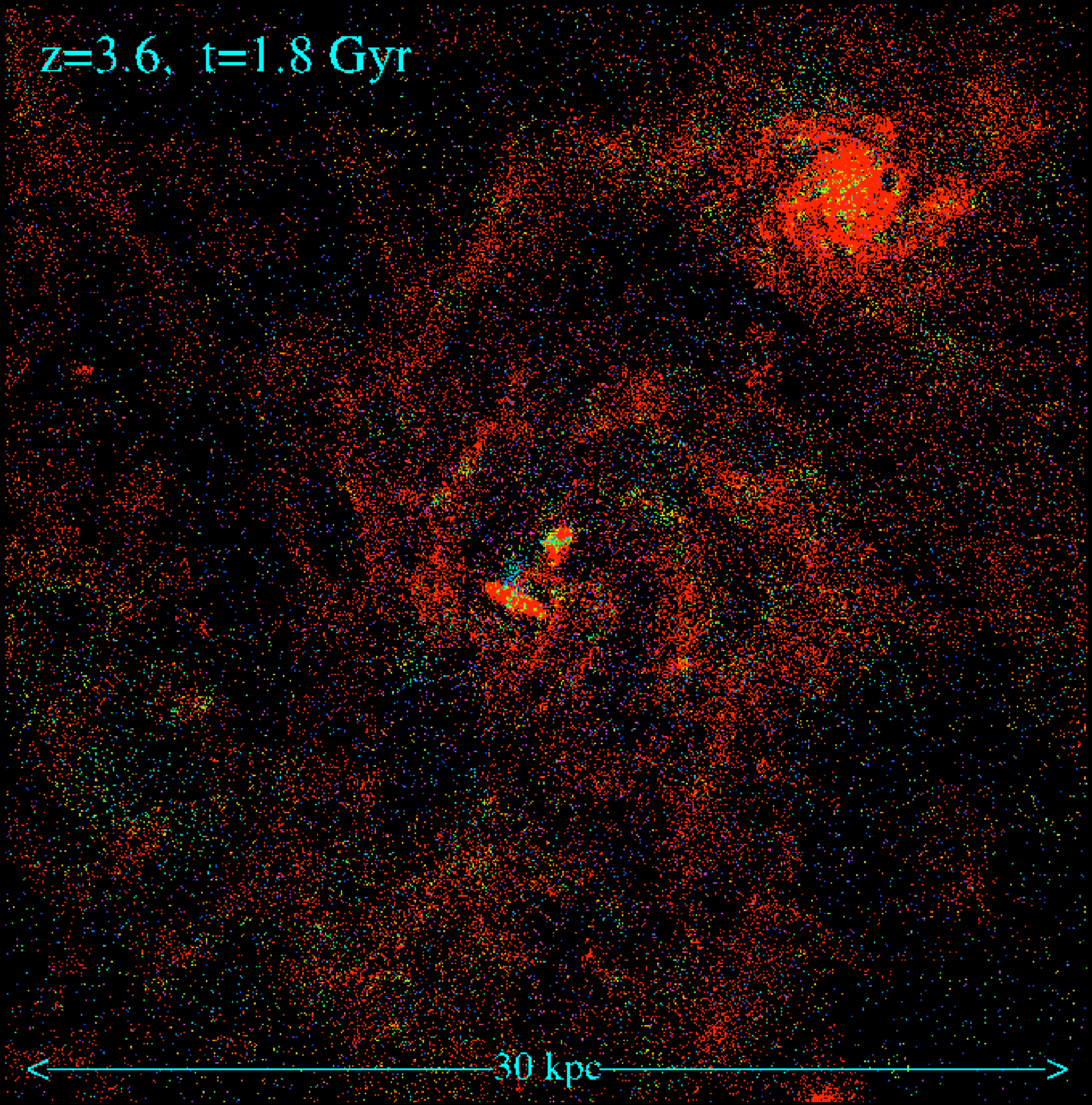

Image credit:
J. Sommer-Larsen

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Bringing it all together:

- DLAs are galaxies and contain the bulk of HI gas.

- DLAs appear to be a fair probe of galaxies, with no dust bias, weighted by gas cross-section.

- The star formation in these galaxies occurs in confined regions within larger gas halos.

- Most lines of sight therefore intersect galaxies away from the bulk of active star formation, so absorption metallicities are low.

- Their morphologies are therefore likely to be a mixed bag, although the more abundant dwarf galaxies probably dominate the cross section.

In this picture, metal-rich DLAs should exist, but they are rare. Is it possible to find them in a systematic way?

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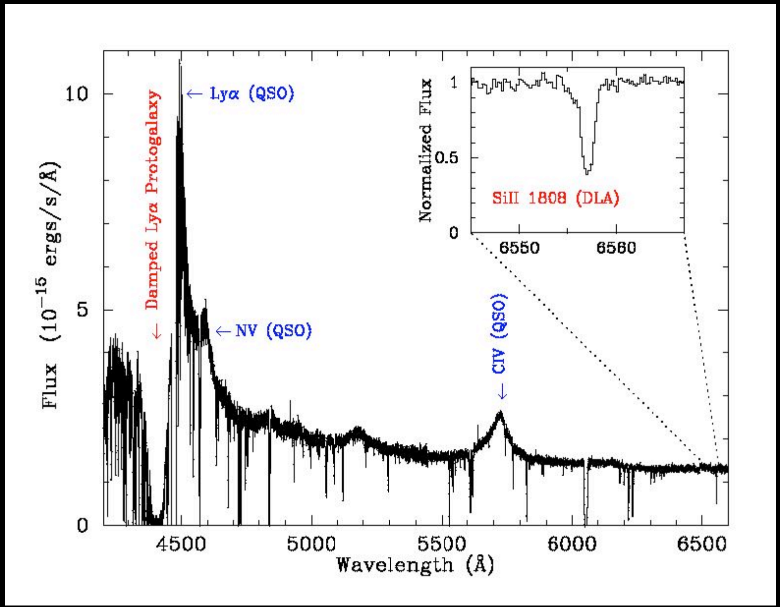
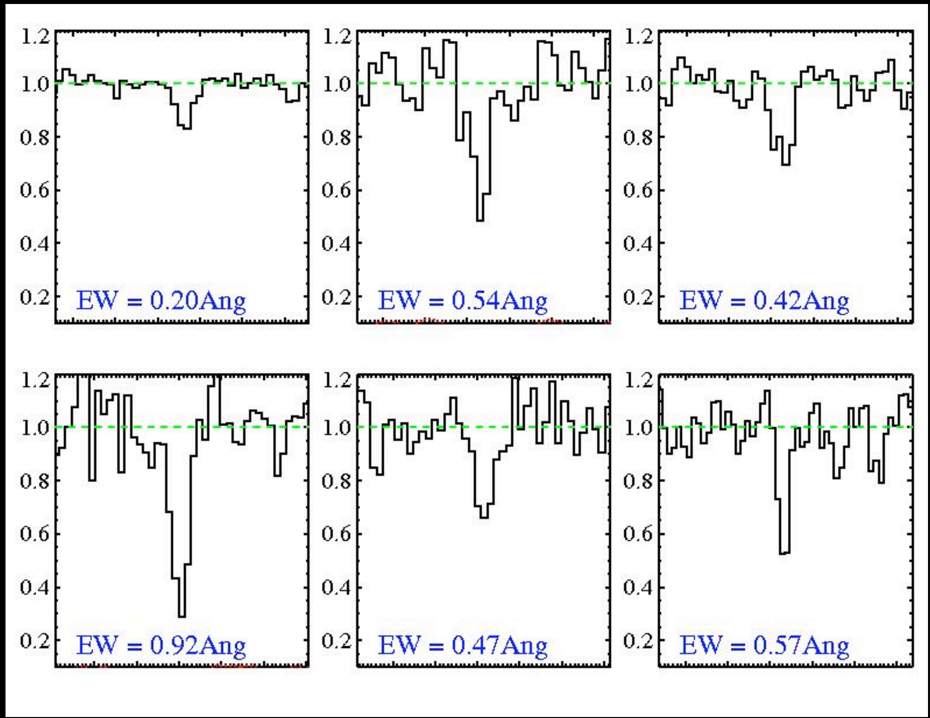
Selecting metal strong DLAs (Herbert-Fort et al. 2006)



Automated search through SDSS to identify DLAs with strong associated metal lines



The metal lines can be seen even in the relatively low S/N, low resolution SDSS spectra.

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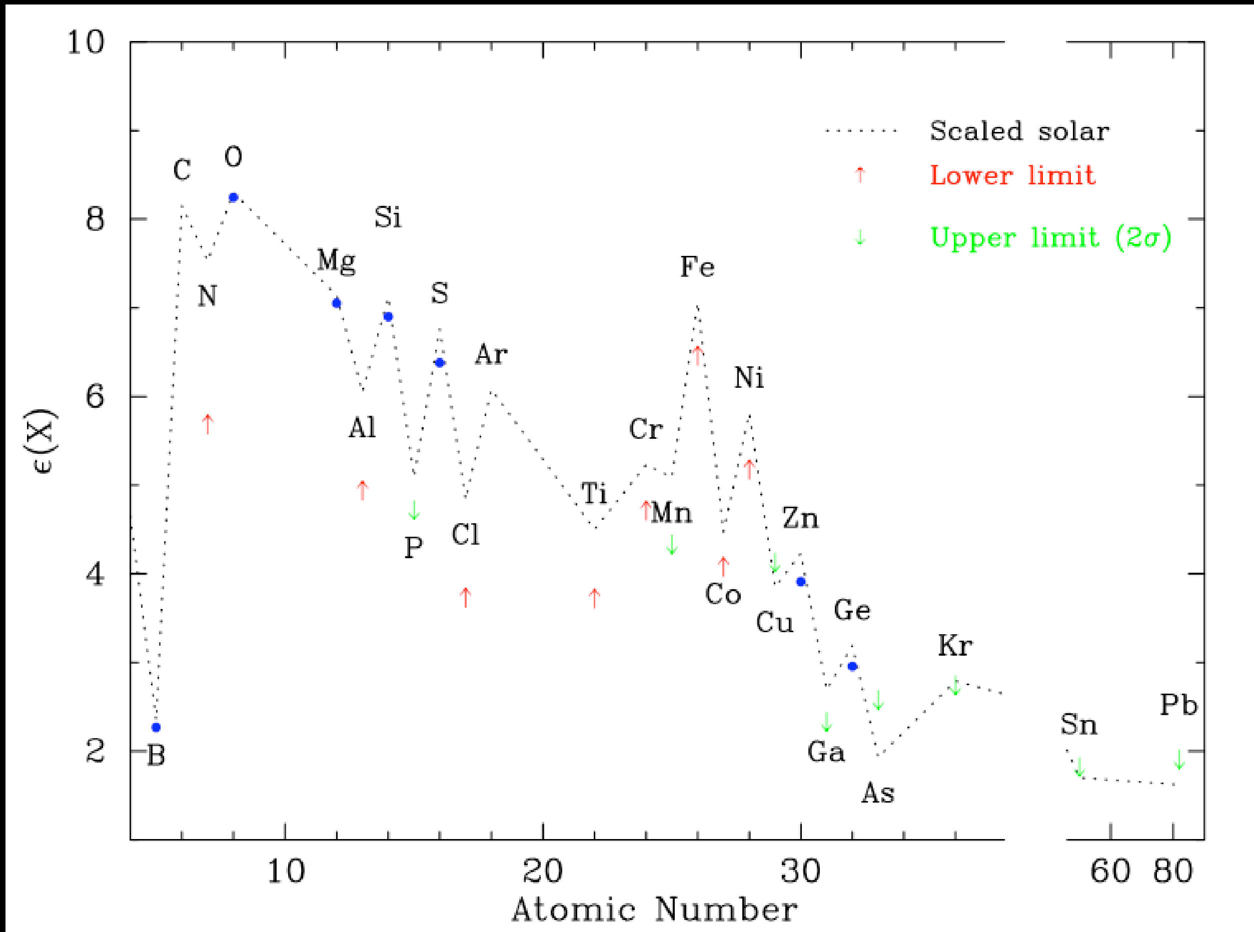
Follow-up with Keck HIRES

Prochaska et al. (2003)



In the metal-strong DLAs we are detecting some rare species for the first time outside of the local universe (and in some cases, the Milky Way), e.g. Ge, B, Ga, Kr, F, Cl and Cu.

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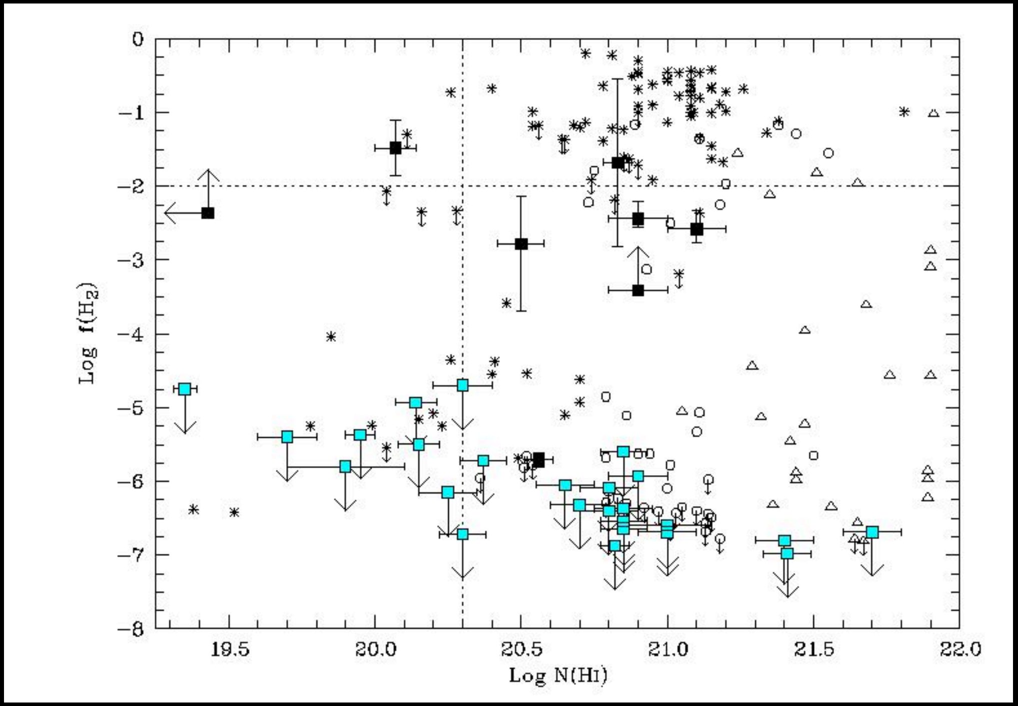
The search for molecular hydrogen

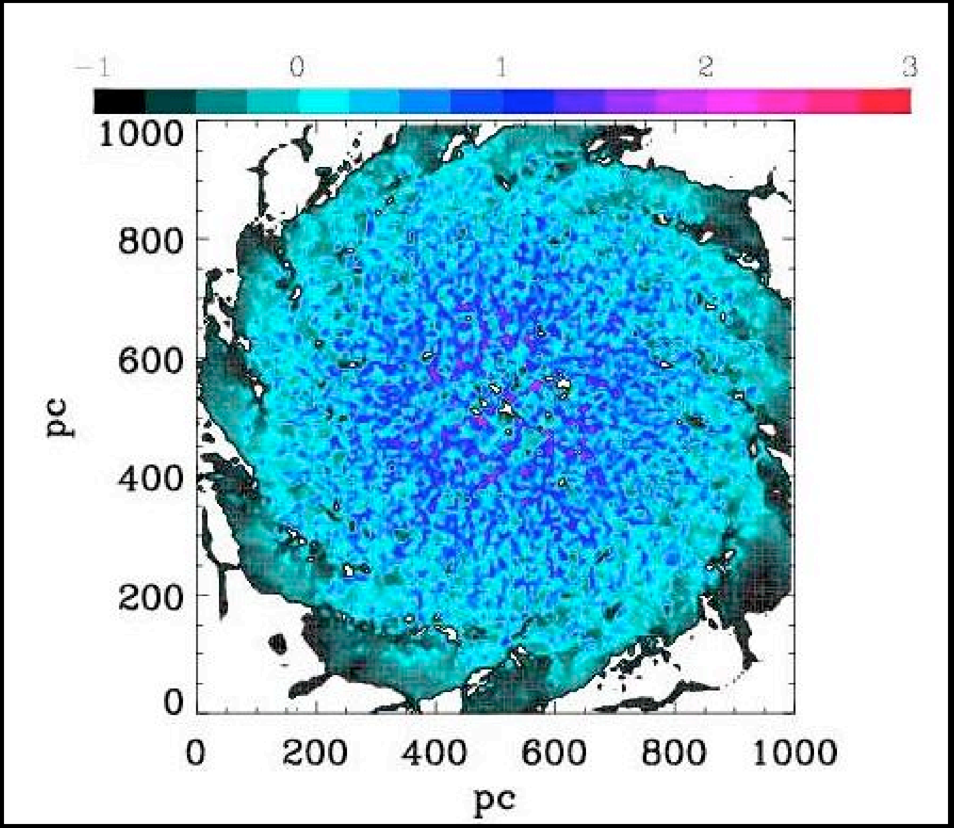
At log N(HI) >20.5, sightlines in the Milky Way have high fractions of H_2. Not so in DLAs - only 25% of DLAs studied have H_2, and generally the fractions are low.



Ledoux et al. (2003)

The search for molecular hydrogen

Is this because H_2 is much clumpier than HI, as suggested by simulations? Or is it due to low metallicities in DLAs?



Hirashita et al (2003)

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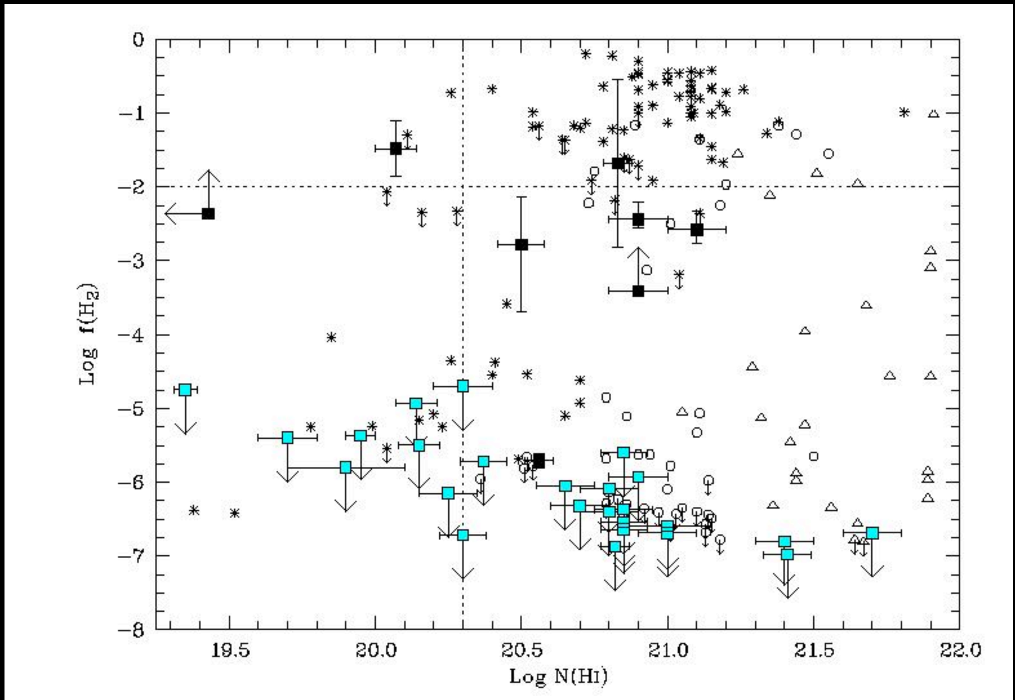
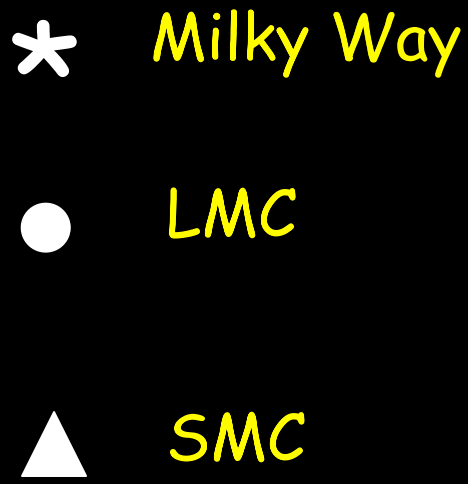
The search for molecular hydrogen

Observational test: if metallicity is the key, then galaxies with metallicities close to the LMC/SMC should have similar H_2 fractions, e.g. ~50% of sightlines should have $f(H_2) \sim 10^{-2} - 10^{-3}$.





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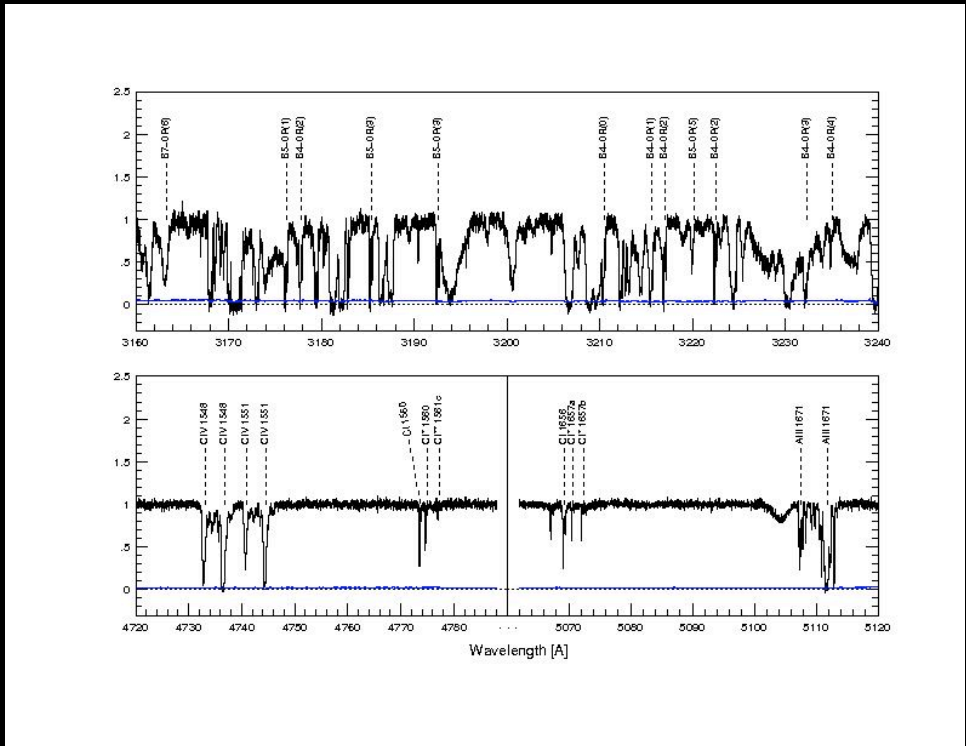
The search for molecular hydrogen

Pilot sample of 5 metal-strong DLAs observed with Keck in Aug. 2006, 3/5 show strong H_2 with fractions ~ 10^{-2}-10^{-3}. Other science that can be done with these detections:



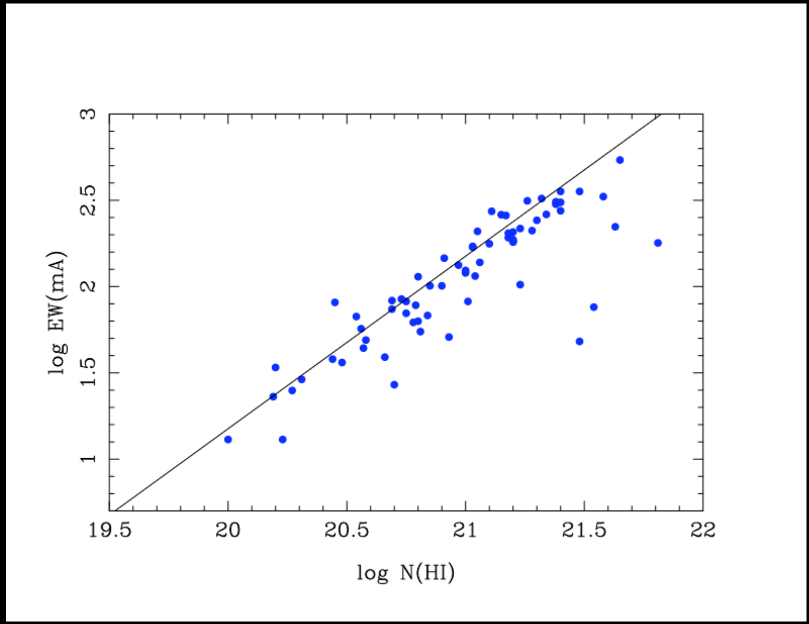
Milutinovic, Ellison et al. in preparation

- Variation of m_p/m_e, since molecular lines are a test of molecular reduced mass.
- Measurement of temperatures and densities from multiple J (rotational) levels.
- CII^* detections give SFR, can compare with energies determined from different J states.

Organic molecules: Diffuse Interstellar Bands

Over 100 (mostly) broad absorption lines seen in sightlines towards reddened stars. No definitive identification for any of the DIB carriers.

Correlation of some DIB strengths with N(HI), and some DIBs correlate well with each other ("families"), possibly the same carrier?



Very few extragalactic DIB measurements, only LMC, SMC and a very few sightlines in nearby galaxies.

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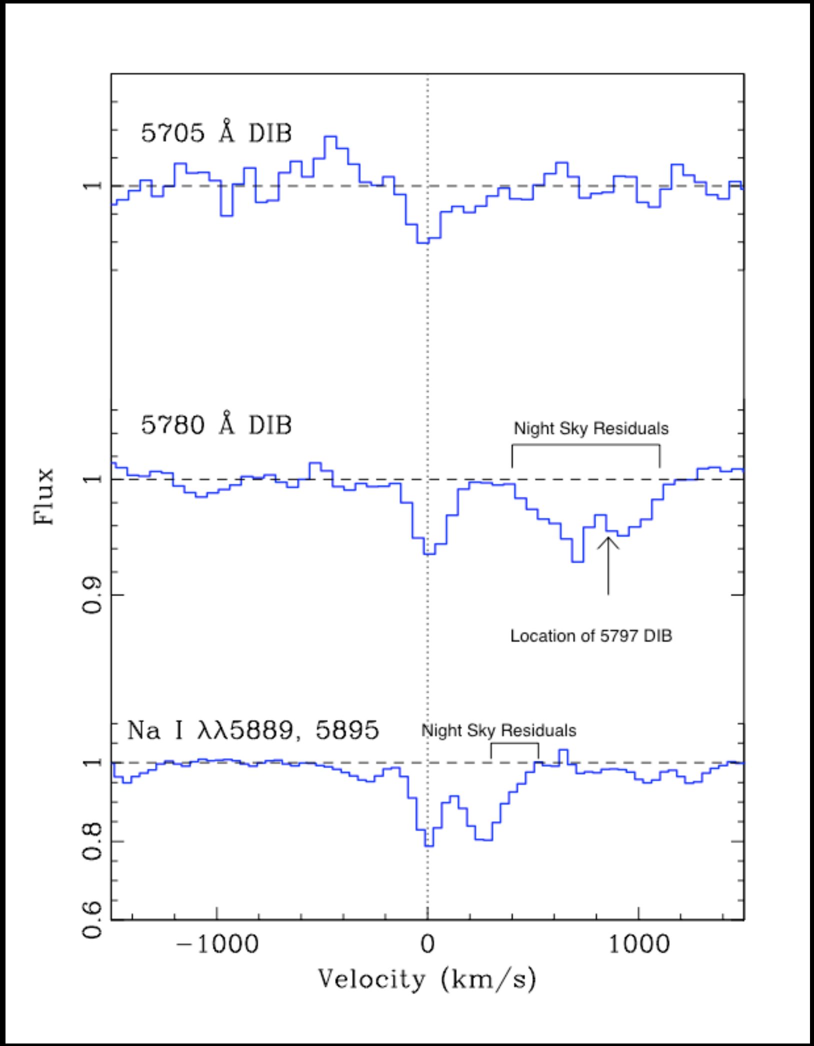
First Detection of DIBs at Cosmological Distances

<u>Target Details</u>
QSO 0235+164
DLA @ z_{abs} = 0.524
N(HI) = 21.70

<u>Observing details</u>
VLT/FORS
2.3 hours, S/N ~ 100
FWHM ~ 5 Å



B. York, Ellison et al (2006)

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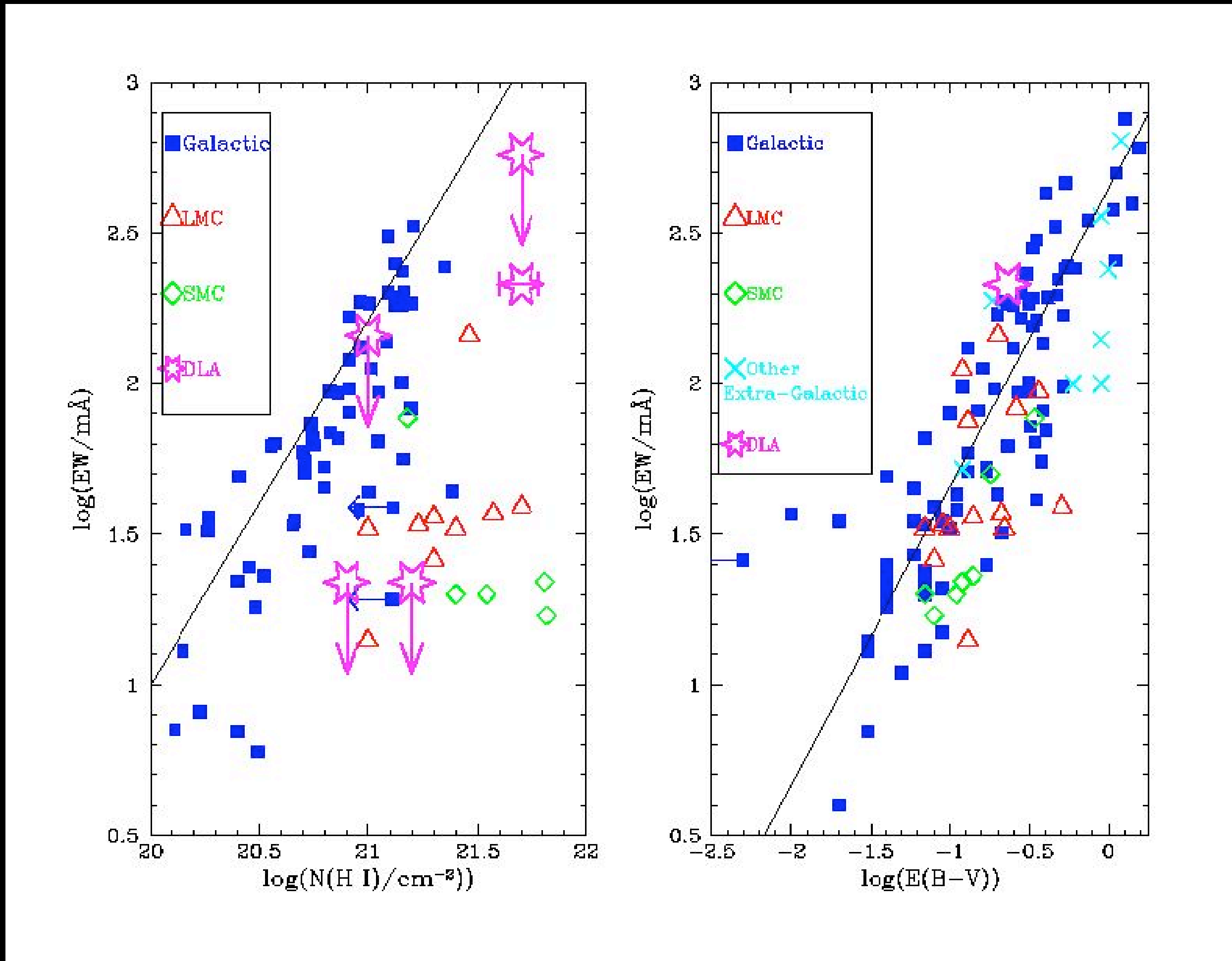

No correlation between 5780 DIB strength and N(HI), but good correlation with E(B-V). Since E(B-V) is usually low in DLAs, we expect very few to show DIBs.

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Summary

• No evidence that dust has caused a significant observational bias against metal-rich DLAs. DLA galaxies are characterised by low E(B-V) and metallicities ~ 1/10 solar at z~2.5.

• However, when the central parts of absorption galaxies are observed in emission, they can have solar metallicities and follow the luminosity-metallicity relation.

• About 5% of DLAs have very strong metal lines. These absorbers can be used to find rare elements and find sightlines rich in molecules

• Detection of DIBs at z~0.5: these organic compounds already present 5 billion years ago. DIB strengths different to Galaxy - dependent on metallicity and environment.

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