Damped Lyman Alpha Systens

There is an excellent review in the 2005 ARA&A by Wolfe, Prochaska & Gawiser.

1 History

We have already traced the historical discovery of QALs in general and discussed the observations that led them to be associated with intervening structures. We have also seen that the single power distribution in N(HI) led many (e.g. Tytler 1987) to infer that they belonged to a single population, ranging from the IGM to galaxy halos. We have (somewhat artifically) distinguished between different types of absorbers based on either their N(HI), or the metal lines associated with them. We have also made a cartoon of the structures we believe these absorbers to be associated with. However, there is some ambiguity here. For example, CIV can apparently be associated with galactic halos, but may also be associated with the IGM. In the mid 1980s Art Wolfe pioneered the search for absorbers that would be unambiguously associated with massive galaxies, the progenitors of Milky Way type disks. At this time, CDM hierarchical galaxy formation was in its infancy, so researchers saw no reason why they couldn't trace MW disks back to redshift of 3 or so.

Wolfe really wanted to find *disks*, how to do this? He considered various options e.g. 21 cm, but this was not suitable because of the small wavelength coverage of radio detectors. Also, at that time, there were no really good low frequency receivers for high z studies, not to mention that they were not sensitive enough to do these observations at high z (and we're still a generation of radio telescopes away from that). Instead, Wolfe went for the Lyα approach. He placed the cut-off at N(HI) $\geq 2 \times 10^{20}$ atoms cm^{-2} for two reasons:

1. Observations of local disks showed that N(HI) declined from $\sim 10^{21}$ in the centres of galaxies to about 2×10^{20} at 1–2 Holmberg radii (the radius at which the surface brightness is 26.5 mag/arc^2 in B) and beyond this the N(HI) dropped sharply

2. The resolution of the original spectrographic surveys was typically 10 Å so only broad features were resolved.

3. The 2×10^{20} limit means that most of the gas in the 'cloud' will be neutral, according to ionization models. This is handy for doing chemical abundances and tracing the total neutral gas content.

Due to the lowish resolution, early DLA surveys relied on EW cuts, and then followed up as many of their candidates as possible at higher resolution. Few DLAs were missed this way since the damping curve gives us

$$EW = 7.3 \times \sqrt{NHI/10^{20}} \tag{1}$$

but there were many blends. Nonetheless, these early surveys provided the first statistics for DLAs and the foundations which are still largely followed today.

The idea that DLAs were associated specifically with disks persisted for a good decade and drove the iterpretation behind the research. For example, signatures in the gas kinematics and chemistry which were similar to the MW were quickly pounced on as synonymous with disk absorption. In the

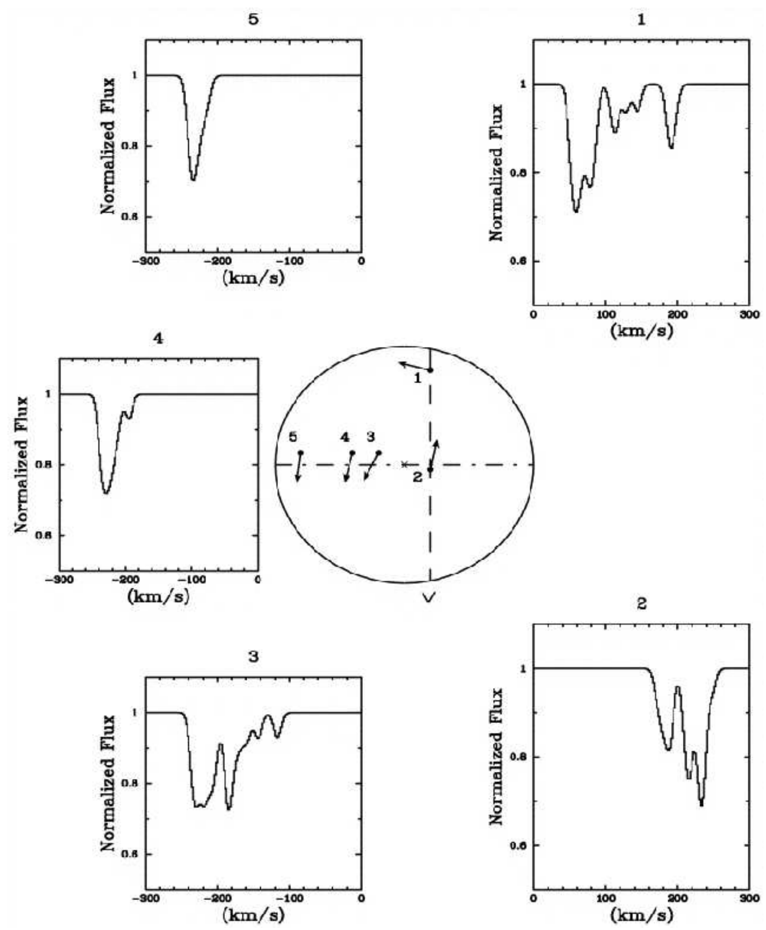

Figure 1: Models of asymmetric absorption profiles in a disk model.

mid-1990s Art Wolfe and his then grad student, Jason Prochaska strongly supported disk absorption based on the 'edge-leading' profile asymmetries. By this time, however, a hierarchical sequence of galaxy formation was largely accepted and it was hard to reconcile large disks in place already by $z \sim 3$. An alternative origin for the asymmetric profiles was put forward by Rauch et al (1996) who suggested that infalling proto-galactic clumps could produce the same profiles. In fact, any number of scenarios could reproduce these profiles.

2 Gas Content of DLAs

Because of the shape of f(N), the Lyα forest absorbers are the most numerous, but the DLAs contain most of the HI. A cosmologically interesting quantity is Ω_{DLA}, the mass density of neutral gas expressed as a fraction of the critical density

$$\Omega_{DLA} = \frac{H_0 \mu m_H}{c \rho_{crit}} \int_{N_{min}}^{N_{max}} N f(N) dN \tag{2}$$

where μ is the mean molecular weight and accounts for the 25% mass fraction in He. Including the power law CDDF with index $-\beta$ and normalization α

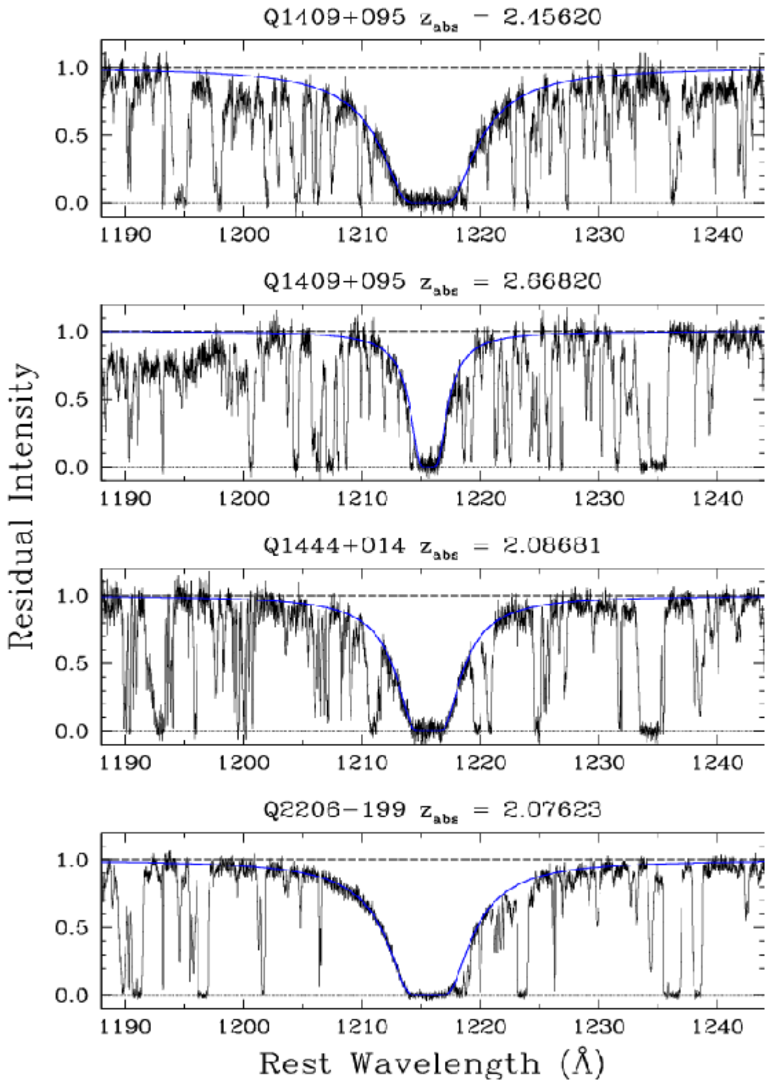

Figure 2: DLA profiles at high resolution as observed with UVES on the VLT and fits to the damping wings.

$$\Omega_{DLA} = \frac{H_0 \mu m_H}{c\rho_{crit}} \int_{N_{min}}^{N_{max}} \alpha N_{HI}^{-\beta+1} dN \tag{3}$$

$$\Omega_{DLA} = \frac{H_0 \mu m_H}{c\rho_{crit}} \alpha/(2-\beta)[N_{HI}^{2-\beta}]_{N_{min}}^{N_{max}} \tag{4}$$

So for $\beta < 2$ the integral diverges at the high N(HI) end and Ω is dominated by high column density systems. Note that Ω_{DLA} does not depend on the size or shape of the absorber, everything is contributed to the integral (but ionized gas is not accounted for). In practice, we don't want to assume a CDDF so instead we use

$$\Omega_{DLA} = \frac{H_0 \mu m_H}{c\rho_{crit}} \frac{\Sigma N_{HI}}{\Delta X} \tag{5}$$

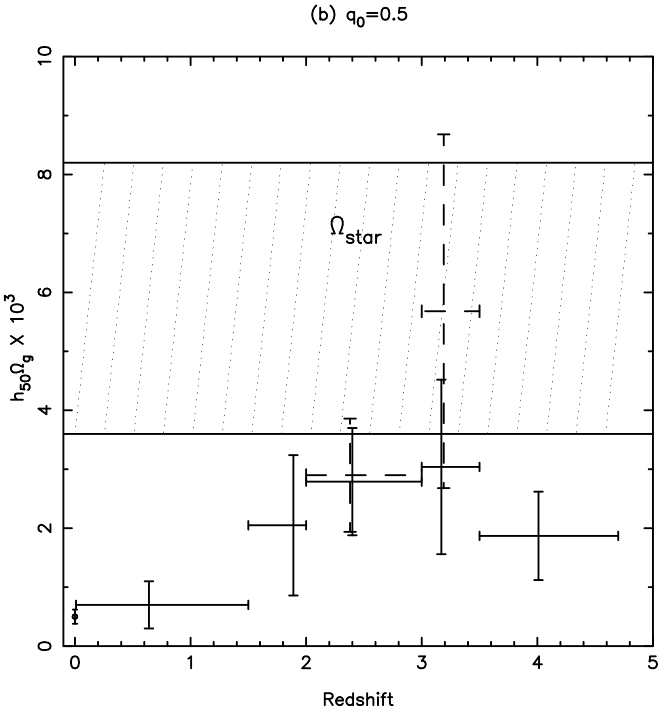

Figure 3: Early determinations of Ω_{DLA} found evidence for evolution (Storrie-Lombardi et al. 1996).

Intriguingly, surveys in the mid-1990s found an evolution in Ω_{DLA} that hinted that the gas in DLAs may be turned into all the stars by $z = 0$. However, the picture has changed a lot in the last few years. First, we have much better statistics at low redshift, thanks to concerted HST surveys. Also, it has been shown that at high z, the sub-DLAs start to contribute significantly to the total gas. The evolution in Ω_{DLA} has effectively disappeared!! But now there is a large gap between the $z = 0$ point and the next point in redshift – very rapid evolution?

That $z = 0$ point is determined by taking into account only spiral galaxies. Is this realistic? Blind surveys of local 21cm *emission* can produce samples that are analogous to DLA surveys since there is a direct correlation between the brightness temperature measured and the N(HI) (in the optically thin case). Blind surveys such as HIPASS and ADBS find that the probability distribution function is almost flat for range of luminosities. The dN/dz in blind surveys is in good agreement with a no evolution model out to higher redshifts. However, Ω_{DLA} is still a factor of 5 down, although error bars on low z DLAs are still very large.

Note that $\Omega_{DLA} \sim 0.03\Omega_b h$; a large fraction of the cosmological baryons are probably as ionized gas in the IGM.

2.1 21cm Absorption

The ground level term for neutral hydrogen, $1s^2S_{1/2}$ has quantum numbers n=1, l=m=0, s=1/2, J=L+S=1/2. However, because the proton and electron are both spin 1/2 fermions[1] the electron's

[1]Fermions are odd half integer spin particles

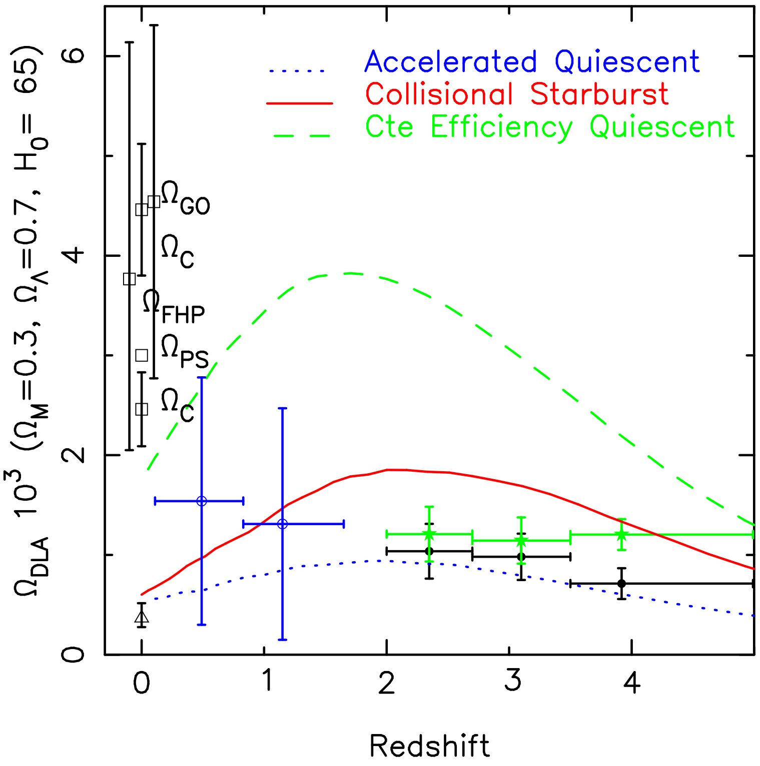

Figure 4: Gas content in DLAs as a function of redshift - little sign of evolution, but a clear deficit at $z = 0$ (Peroux et al 2003).

angular momentum, J, combines with the proton's nuclear angular momentum, I. The total angular momentum, F=I+J can have the value 0, 1. Therefore, two energy levels can exist, caused by this hyperfine (sometimes called 'spin-flip') splitting. The statistical weights are given by g=2F+1=1, 3. The energy difference corresponds to a wavelength of 21.1cm (1420 MHz).

Radiative transitions are forbidden (because both states have l=0) and since the transition probability is inversely proportional to λ^3, the lifetime for radiative decay is 11 million years! Although the transition probability is tiny, column densities in the ISM are very large. Since the excitation temperature for the 21cm transition is only 0.07K, the Boltzmann distribution holds and the temperature is the spin tempertaure, T_s. The population levels are therefore populated by collisions, ensuring that $T_s \sim T_k$. The optical depth at the line centre is

$$\tau = 5.2 \times 10^{-19} \frac{N(H)}{T_s \Delta V} \tag{6}$$

See http://www.mpifr-bonn.mpg.de/staff/epolehampton/thesis/node95.html for full maths. 21cm can be seen in emission or absorption, depending on the strength of the background continuum. At any frequency, the observed brightness temperature T_B is

$$\Delta T_B = (T_s - T_0)\{1 - exp[-\tau(\nu)]\} \tag{7}$$

where T_0 is the brightness temperature of the continuum. If T_0=0 and $\tau(\nu) << 1$, this equation simplifies to $T_B = T_s \tau(\nu)$. Combining with Eqn 6, we can see that the brightness temperature is

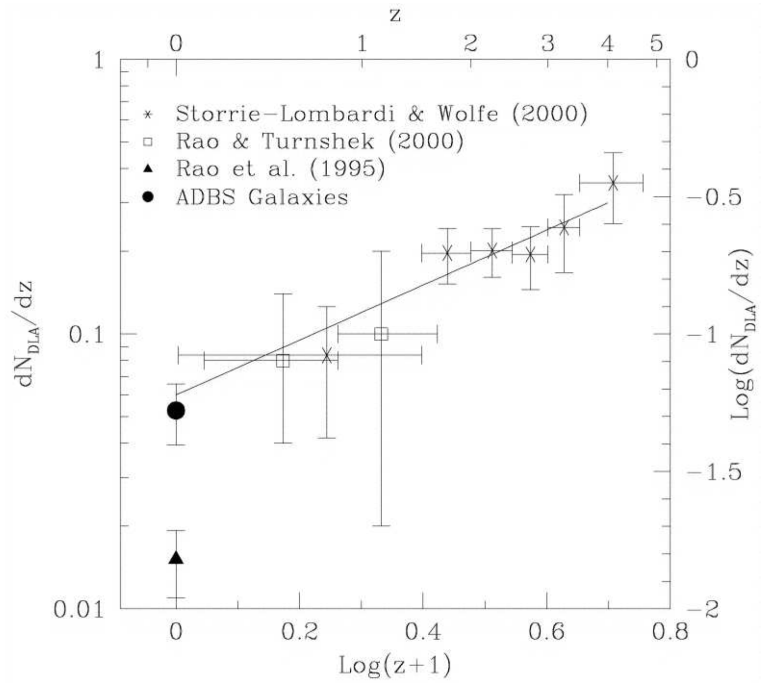

Figure 5: The number density of DLAs from $z = 0$ blind HI surveys, like the ADBS, find that n(z) AKA dN/dz of local absorbers is consistent with a no evolution model of high z absorbers (Rosenberg & Schneider 2003).

therefore a direct measure of the column density of neutral hydrogen *in the optically thin limit.* Low τ is usually ensured by the low oscillator strength of the transition (cf $\tau_{Ly\alpha}$). In fact, from Eqn 6 we find that since T and ΔV are, in practice, always larger than $\sim 50K$ and 10 km/s, the line only becomes optically thick above $\sim 10^{21}$ cm^{-2}.

If T_B in Eqn 7 is negative, we see absorption, i.e. when $T_s < T_0$ and the optical depth is large. In this case

$$N(HI) = \frac{1.823 \times 10^{18} \int T_s \tau(\nu) d\nu}{f} \tag{8}$$

I.e. the observed optical depth depends on column density *and* spin temperature. The f is covering factor, because the source maybe larger than the cloud.

21cm absorption can be observed in DLAs towards RLQs. Unlike the optical counterparts of QSOs, in the radio quasars can be extended and their projected area can be larger than the intervening absorber. In practice, f is often assumed to be 1 because we usually don't have high resolution maps of the QSO. For DLAs, we know the N(HI) accurately, so from 21cm measurements of τ we can infer a spin temperature. Because τ is inversely proportional to T_s, non-detections of 21cm absorption lead to *lower* limits on the spin temperature.

Measurements of these kinds require sensitive radio telescopes with good low frequency receivers. 21cm absorption occurs at

$$\nu(z) = 1420/(1 + z)\text{MHz} \tag{9}$$

Moreover, a site that is free from RFI is required – at low frequencies this is a real problem from TVs and mobile phones (NB ironically, it is therefore still better to observe at night, even at radio wavelengths!!). Two telescopes that have made a big impact are the GBT and the GMRT. Results from survey of Kanekar & Chengalur:

1. At low z ($z < 0.7$) DLAs with a range of temperatures are found, inlcuding 'low' values of a few hundred K, as found in local spirals.

2. DLAs at low z which have low T_s are usually associated with spirals.

3. At higer redshifts, there is an absence of cold gas, although covering fraction may affect the results by a factor of 2–3.

4. No 21cm detection at $z > 2$ and the typical limits are a few 1000K.

5. Tentative anti-correlation between metallicity and T_s

Much work can be done in this area because sample size still small. This is mainly because most QSOs (90%) are RQQ. Also, there are only certain frequency ranges which are possible to observe in

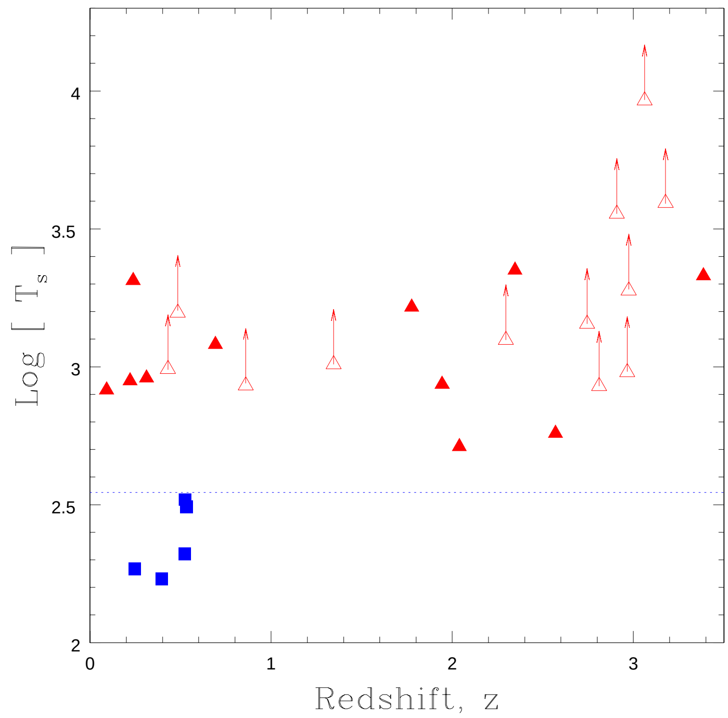

Figure 6: Spin temperatures as a function of redshift in DLAs.

2.2 Molecular Gas

Molecular gas is ubiquitous in the MW and is essential for star formation. We measure f the fraction of H_2 as

$$f = \frac{2N(H_2)}{[2N(H_2) + N(HI)]} \tag{10}$$

In the Galaxy, f undergoes a sharp transition at N(HI)$\sim 4 \times 10^{20}$. Above this value, typical H_2 fractions are 10^{-1}, below this value it's $< 10^{-4}$. We might therefore expect that detecting H_2 in DLAs would be quite easy. However, the rest-frame UV transitions are hard to detect because they are in the Lyα forest. The pay-off is that we can use large ground based telescopes.

Large survey for H_2 with UVES on the VLT. Only detections in 5/23 cases, with most of the lower limits at the level of $f < 10^{-5}$. Molecular fractions in DLAs closer to LMC and SMC than MW. Even when H_2 is detected, the typical fraction is about 10 less than in the MW (but similar to SMC and LMC) at about 10^{-2}. Why so little molecular gas? Two obvious reasons: dust content and cross section.

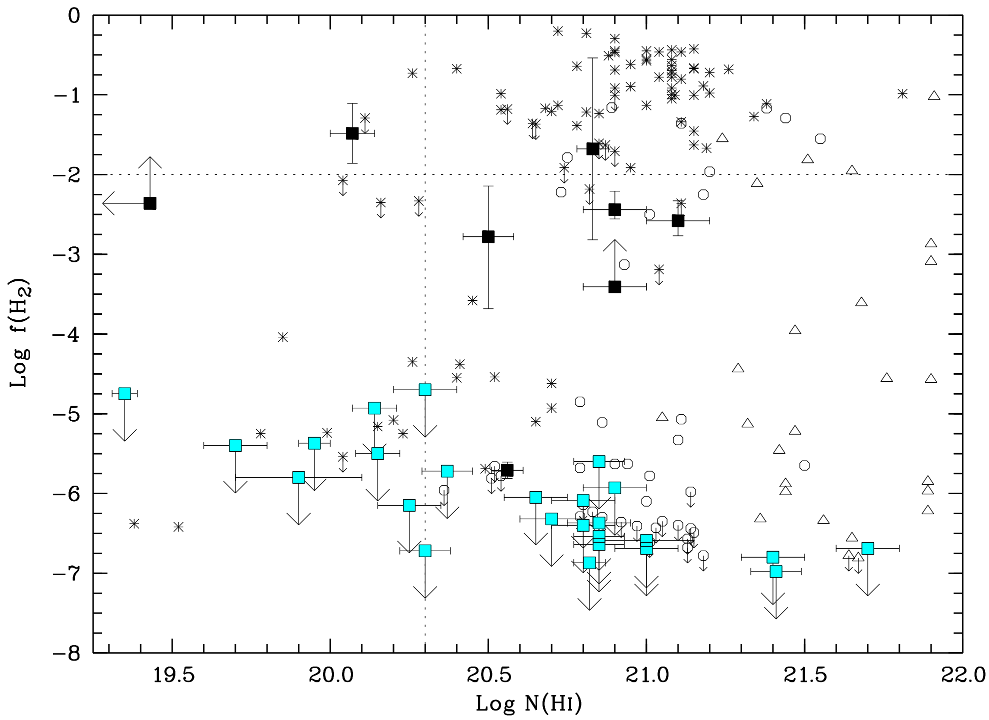

Figure 7: Molecular gas in DLAs as a function of N(HI) (Ledoux et al 2003)

H_2 forms on the surfaces of dust and is destroyed by photo-dissociation.

$$f \propto \frac{\kappa n_H^3}{J_\nu} \tag{11}$$

where κ is the dust-to-gas ratio. We have already seen that δ is the dust:metals ratio and can be measured, for example, from

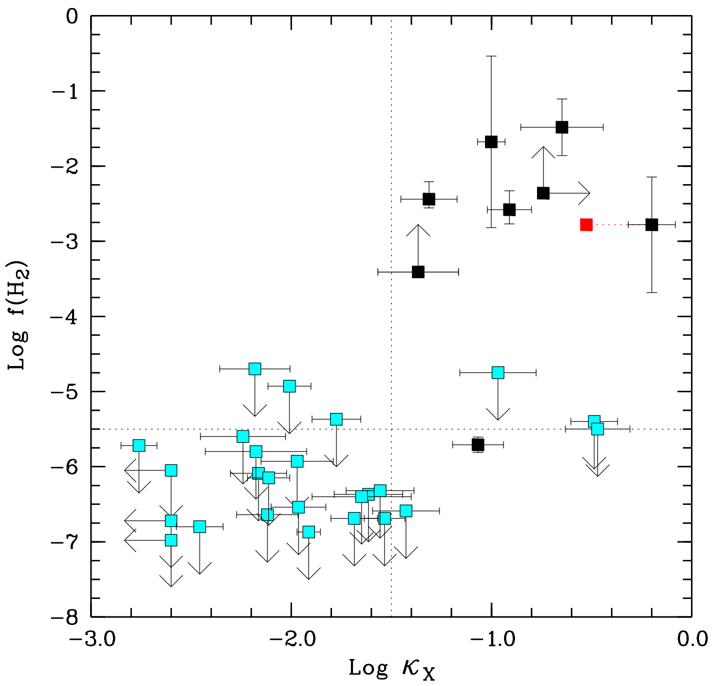

Figure 8: Molecular gas in DLAs as a function of dust to gas ratio, κ (Ledoux et al 2003)

$$\delta = 1 - 10^{[Cr/Zn]} \tag{12}$$

The dust:gas ratio is simply dust:metals $\times$ metals:gas. This latter term is simply the metallicity, e.g. [Zn/H]. So

$$\kappa = 10^{[Zn/H]} \times (1 - 10^{[Cr/Zn]}) \tag{13}$$

and measures how many atoms are in the gas versus dust phase. There is a positive correlation between κ and f, as expected, in DLAs. Also, H_2 is very clumpy: Hirashita et al (2003) estimate that the covering fraction of $f > 10^{-6}$ gas is $< 10\%$.

3 Metals and Dust in DLAs

Measuring chemical abundances in DLAs is probably *the* most important application of QALs. It allows us to trace the metal (and therefore star formation) history of galaxies back to $z \sim 5$, and possibly beyond. This is far past the era at which we can measure metallicities in stars (local galaxies only) and nebular abundances (currently restricted to $z < 1$). Moreover, very accurate abundances can be obtained because the methodology is simple. I.e. determine N(HI) from damping wings (accurate) and N(X) from the first ionised state of a weak metal line (accurate). In stars you have to determine surface gravities, effective temperatures, model for NLTE effects and 3D turbulence in the atmospheres. Nebular abundances usually rely on empirical calibrations. Typical errors in [X/H] are ~ 0.1 dex, with the main uncertainties due to dust and ionization.

3.1 Zinc

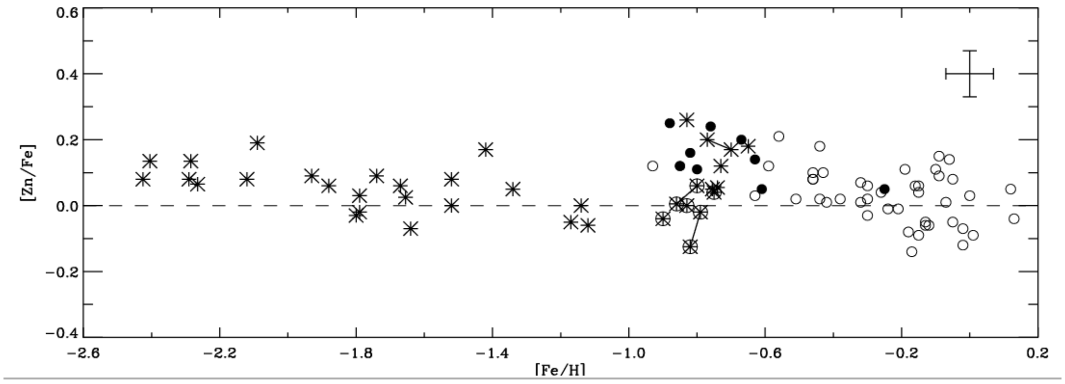

Figure 9: Zn traces Fe in Galactic stars.

When we talk about the 'metallicity' of a star, we have usually chosen some reference element; in stars this is Fe. However, Fe is highly depleted in the ISM, so we need a proxy. Proxies are often used in abundance work, and are based on the premise that certain elements trace each other due to common nucleosynthetic pathways. There are several Fe-peak elements which trace Fe (e.g. Co, Ni and Cr), but these are all depleted as well. Zn is often labelled an Fe-peak element, although its exact formation mechnism is still debated. Nonetheless, it does trace Zn, and is not depleted, so is a good proxy for Fe.

People still debate whether or not there is evolution in metallicity and this depends somewhat on how you plot the points. For example, some authors restrict themselves to using only Zn, whilst others try to use additional proxies, such as Si and O. Also, distinguish mean metallicity and weighted mean (which has cosmic significance)

$$[< Zn/H >] = log[\frac{\Sigma N(HI)}{\Sigma N(Zn)}] - log[N(Zn)/N(H)]_{\odot} \tag{14}$$

Evolution is, at most, mild and reaches around 1/10 solar by $z \sim 0.5$.

The metallicity distribution is very different to the MW disk and is probably closer to a combination of the halo plus thick disk. All the thin disk stars have [Fe/H] > -1.0, whereas such 'high' enrichment is rare for DLAs.

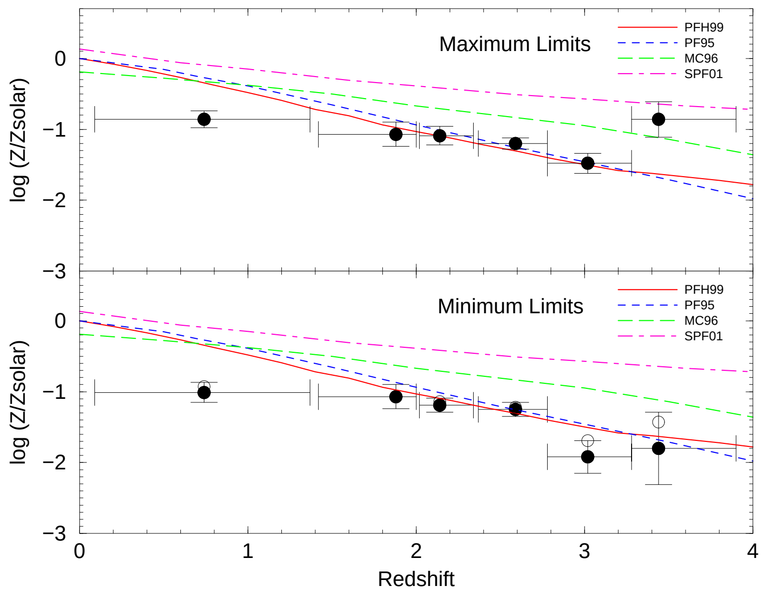

Figure 10: Metallicity as traced by Zn in DLAs as a function of redshift from Kulkarni et al (2004).

3.2 Dust Bias in DLAs

One explanation for the lack of evolution in metallicity is that very enriched systems have a lot of dust so obscure any background QSO. I.e. optical samples of QSOs suffer from dust bias. This is also supported by an apparent anti-correlation between metallicity and N(HI). The explanation here is that high N(HI), high [Zn/H] will have the most extinction and be missed in most surveys.

More observational evidence comes from look at properties of QSOs with and without DLAs, such as their spectral indices. Work in the early 1990s indicated that spectral indices were steeper in QSOs with DLAs, an indication of reddening. Many theoretical models of DLAs have supported the idea of a dust bias with the suggestion that up to 70% of QSOs may be missed by optically selected QSO samples.

Test this idea with a radio selected sample of QSOs (where dust isn't an issue) and get complete optical IDs. The Complete Optical and Radio Absorption Line System (CORALS) survey of Ellison et al. (2001) did just this. Determine statistics of this 'complete' sample and compare with previous work. Ω_{DLA} is reasonable agreement, higher by at most a factor of 2, n(z) also consistent within the errors. However, possible trend of statistics with QSO magnitude indicates that there may be an Eddington bias.

Perhaps this is not surprising at high z, since most of the star formation (and so, plausibly, metal and dust production) occured at $1 < z < 2$, so perhaps any dust bias is going to be more serious at low redshift. Can't easily repeat CORALS at $z < 1.5$ since we need HST, and even this is too small a telescope for a complete optical survey. Instead, use MgII absorbers to infer the statistics of DLAs. Again, the number density is in excellent agreement with previous samples. Overall, no sign of lots of missing absorbers over the range $0.6 < z < 3.5$.

However, this doesn't tell us anything about the metal content, perhaps the DLAs in CORALS are particularly metal rich. Turns out not to be the case, and none of the CORALS DLAs have [Zn/H] and N(HI) values that puts them in the forbidden 'dusty' part of the anti-correlation of

Prantzos & Boissier (2000).

So what about the observational 'evidence' that there is a dust bias in DLAs? Turns out that the work on spectral indices has not been reproduced in larger, homogeneous samples like the SDSS. Murphy & Liske (2004) found no evidence for a change in slope and have a much more sensitive limit than previous work – E(B−V) < 0.02 (3σ). Test this further by looking at optical and IR colours of CORALS QSOs. $B - K$ colours more sensitive to dust than spectral indices (wider wavelength range) and CORALS is a complete survey whereas SDSS is magnitude limited.

Mild statistical evidence for redder colours in QSOs with DLAs. Modelling this reddening gives an E(B−V) which is in agreement with the SDSS studies.

Overall, dust seems to have a minor effect on DLA detection, so why are their metallicities so low? Could be because random QSO sightlines are more likely to probe the outer edges of galaxies where the metallicity is lower. When we measure nebula abundances in galaxies our results are weighted by the star-light and we probe the inner regions of the galaxy which are likely more metal rich. If we measure the emission line abundances of galaxies selected in absorption (whose impact parameters are $\sim$ 20 kpc) their abundances are more in line with expectations.

3.3 Alpha Elements

Alpha elements are those built up by the addition of alpha particles (He nuclei) and are usually associated with massive star formation. Examples are O, Si, S, Mg and Ca. Most Fe-peak elements are made during the SNIa explosion of lower mass stars. The timescales are quite different – 10^9 vs 10^7 years so ratio of $[\alpha/\mathrm{Fe}]$ is a rough chronometer of SF activity. Signature over-abundance in MW disk at low metallicities is sign of first massive stars. $[\alpha/\mathrm{Fe}]$ is super-solar in DLAs, but this could well be due to dust, although Prochaska has argued that the 'plateau' at low abundance is a real over-abundance. Use non-refractory elements like [S/Zn] - these DLA points are all around solar.

This is very similar to patterns in local dwarf galaxies and can be explained by a bursting history.

3.4 Nitrogen

Like the α elements, N can be used as a chronometer. The idea here is that N has two different formation sites which are associated with different timescales. ^{14}N is mostly formed from ^{12}C as a by-product of the CNO cycle. If the seed C atoms are produced *in-situ* by the triple alpha process, then the resulting N is referred to as primary. If the seed nuclei were already present in the star, then the N is secondary. If the N is secondary, then its abundance depends on the initial O abundance. If N is primary, then it is independent of initial composition. Primary N dominates at low metallicities because there has been little previous star formation to make the seed nuclei.

The main source of primary N is thought to be IMS with $4 < M < 7$ solar masses. If this is the case, then there should be a time delay between the time at which O is produced and primary N at low metallicities. The expected time delay is about 250 Myrs, so we expect DLAs which have just undergone a burst of SF to have N/O below the primary plateau. DLAs show a range of N/O, many below the primary level. In fact, it is surprising that so many show such low N/O considering that the time delay is relatively short; we'd only expect about 1/7 DLAs to have N/O < -1.5. Possible solutions to this require extending the time delay by increasing importance in the production of primary N in lower mass stars. Possibilites include models which account for:

1. Including rotation in stellar yield models enhances mixing between the H-burning and He-burning layers which produces a significant contribution of N in 2–5 solar mass stars
2. Metallicity dependent yields. If stellar interiors are hotter in metal-poor stars, then N can be fused at relatively low masses, cf more metal rich stars.

4 Association with Galaxies

This lecture has been based on the premise that DLAs trace galaxies, but do we have any direct evidence for this? Yes – the galaxies responsible for DLAs are now being found, but this is hard work because they are quite faint and close to a bright QSO. About a dozen DLAs have spectroscopically confirmed galaxy counterparts at $z < 1$. The most important result of these surveys is that they have confirmed that DLAs come from a wide range of galaxy types, ranging from dwarfs, to LSBs to spirals.

It is interesting to see how our picture of galaxies in absorption compares with that in emission. We already saw that, in many cases, the kinematics of the gas matches the rotation curve of the disk. Recently, there have been the first determinations of emission line abundances - solar, cf the sub-solar values as seen in absorption. Random lines of sight are perhaps not a good tracer of the bulk of metals because they preferentially penetrate the galaxy at large impact parameters.

Future prospects: GRBs provide very biased sightlines, but can equally well probe the intervening gas. With Swift, it is possible to observe e.g. with UVES the optical afterglow when it is still very bright. Once faded, we will have a much better view of the galaxies than is ever going to be possible with QSOs.

4.1 Primordial Abundances

QALs as a test for SBBN. The standard model of the BB assumes (amongst other things)

- 'normal' physical laws
- Small degree of matter anti-matter asymmetry
- Gravitation as described by GR
- Thermal equilibrium i.e. particles with $mc^2 < kT$ are present in comparable numbers to photons
- Homogeneous and isotropic conditions (the cosmological principle).

Non-standard versions of BBN include a different value of G, non-standard neutrino properties (long lives, large masses) and asymmetries in neutrino flavour.

When the universe is less than ~ 1 second old its temperature is > 1 MeV neutrons and protons are in thermal (Boltzmann) equilibrium.

$$n(n)/n(p) = exp(-\Delta mc^2/kT) = exp(-1.29MeV/kT) \tag{15}$$

Electroweak interactions regulate the number of p and n:

$n + e^+ \rightleftharpoons p\overline{\nu_e}$
$p + e^- \rightleftharpoons n + \nu_e$
$n \rightleftharpoons p + e^- + \nu_e$

As the universe expands, the (matter) density drops and can be expressed as a function of time

$$\rho = \frac{3}{32\pi G t^2} \tag{16}$$

We can also write down an equation for energy density (in radiation), which is a function of temperature

$$\rho c^2 = c^2 \sigma \rho_i = 1/2 g_* a T_\gamma^4 \tag{17}$$

g_* counts the number of spin degrees of freedom of a particle (=1 for neutrinos because of their helicity). Whilst the weak interactions between p and n continue $T_\nu = T_\gamma$, because of thermal equilibrium. Combining the eqns 16 and 17 and including particle constants we get

$$kT = 0.8 t^{1/2} MeV \tag{18}$$

As the temperature falls, at some point it drops below $(m_n - m_p) - m_e$. I.e. $kT < (m_n - m_p) - m_e = 0.8$ MeV, which occurs at about 1 second. At this point the reactions slow down rapidily so that the n and p de-couple and are 'frozen out' in a ratio given by

$$n(n)/n(p) = exp(-1.29/0.8) = 0.20 \tag{19}$$

i.e. n:p is 1:5. Then the only reaction that significantly affects the number of p and n is neutron decay

$n \rightarrow p + e^- + \overline{\nu_e}$

The half life of a neutron is 615 seconds. Without further reactions to preserve the numbers of neutrons, the universe would be pure H! The reaction that preserves neutrons is the formation of the deuteron (deuterium [heavy hydrogen] nucleus i.e. p+n).

$p + n \rightleftharpoons d + \gamma$

This reaction is effective only when the universe has cooled sufficiently that photons don't disassociate all the deuterons, i.e. after about 300 s (kT $\sim$ 0.1 MeV). At this point the n:p ratio has dropped by $\exp[-300 \times ln2/615] = 0.71$ to 0.14 or 1:7.

Now He can form. Because the binding energy of these nuclei is >> 0.1 MeV, the reactions only go one way.

$d + n \rightarrow^3 H + \gamma$
$^3H + p \rightarrow^4 He + \gamma$
$d + p \rightarrow^3 He + \gamma$

$^3He + n \rightarrow ^4 He + \gamma$

A second chain that leads to Helium production is

$d + d \rightarrow ^3 He + n$
$d + d \rightarrow ^3 H + p$
$^3H + p \rightarrow ^4 He + n$
$^3He + p \rightarrow ^4 He + p$

I.e. the net reaction is $d + d \rightarrow ^4 He + \gamma$. Since virtually all n are used in the production of He the n:p ratio gives an approximate estimate of the He mass fraction. With n neutrons you can make $n/2$ He atoms (mass = 4 amu). Total mass of everything is n+p, so:

$$Y_p = \frac{0.5 \times n \times 4}{(n+p)} = \frac{2n}{n+p} = 0.25 \tag{20}$$

If the half life of the neutron had been much shorter than the time it takes for stable nuclei to form, all the neutrons would have decayed before nucleosynthesis had begun. An important point here is that how far nucleosynthesis proceeds before the reactions are frozen out depends on

$$\eta = \frac{n_b}{n_\gamma} = constant \sim 10^{-10} - 10^{-9} \tag{21}$$

Definition: baryons are composed of quarks, e.g. protons and neutrons. All baryons are also hadrons (the other hadron component is the meson). Combined with the background temperature, η (in units of 10^{-10}) tells us about the cosmological baryon density today:

$$\Omega_b h^2 = 3.65 \times 10^{-3} \eta_{-10} \tag{22}$$

D/H (and other light element ratios) can be used to infer baryon content of universe. Difficult observation because need high resolution ($\Delta v = 82$ km/s) and UV spectrograph for local measurements. The D/H ratio can be measured locally, but suffers astration. In local bubble, D/H seems relatively constant, but this value is still lower than high redshift values. At high z astration may be lower, and D/H lines shifted into optical. However, there is still some scatter and concern of blending with other Lyα lines. Dust maybe the source of local scatter? In general, the high z D/H values give Ω_b values that are in excellent agreement with CMB experiments. However, there maybe some discrepancy between DLAs and LLS, possibly due to ionization corrections in the latter.

4.2 Variations in the Fine Structure Constant

The fine structure constant is defined as having

$$\alpha = \frac{e^2}{\hbar c} \tag{23}$$

and it tells us about the way that photons and electrons interact in atoms. I.e. the separation of doublets is governed by α. The exact dependence of the doublet separation for a redshift dependent α depends on a parameter, q which is calculated theoretically using many-body methods, see

Murphy, Webb & Flambaum (2003) for more details. If ω_z is the wave number[2] of a transition at high redshift and ω_0 is the lab value, we write

$$\omega_z = \omega_0 + q_1 \times [(\frac{\alpha_z}{\alpha_0})^2 - 1] \tag{24}$$

i.e. if $\alpha_z \neq \alpha_0$ the wavelengths shift. Sometimes a doublet gets closer together, sometimes further apart, and sometimes the change is small, it depends on the atomic structure.

The idea of using doublets has been around for almost 40 years, with people mostly using CIV, SiIV or MgII. Using this method changes in the fine structure constant on the order 10^{-5} have been inferred (α lower in the past). The many multiplet method uses many lines together and looks for shifts between the ratios of 'anchor' lines and 'susceptible' lines. Lines shift in different directions, giving more leverage.

Murphy & Webb have continued to support a change in α, but the case is not closed. Other analyses have reported no shift, but there are still systematics such as differential doublet saturation to be considered.

[2]Recall that wave number can be expressed either as $k = 2\pi/\lambda$ or $\omega = 2\pi c/\lambda$

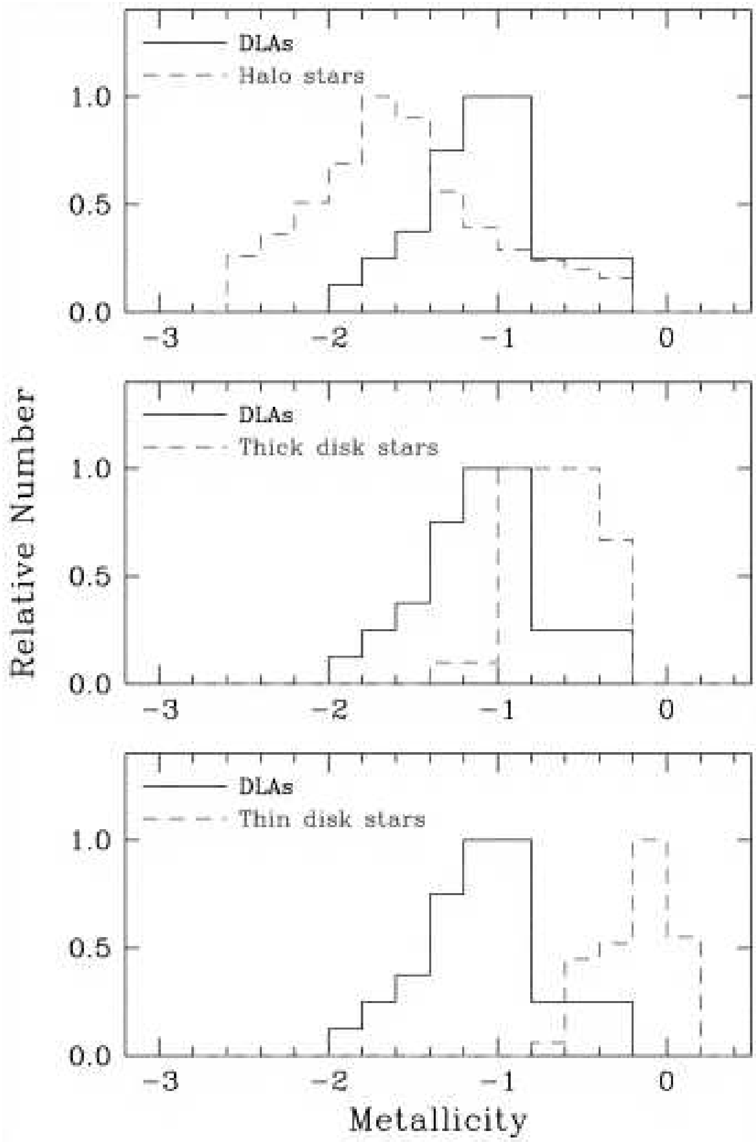

Figure 11: Metallicity distribution not similar to Galactic disk, closer to halo? (Pettini et al 1997).

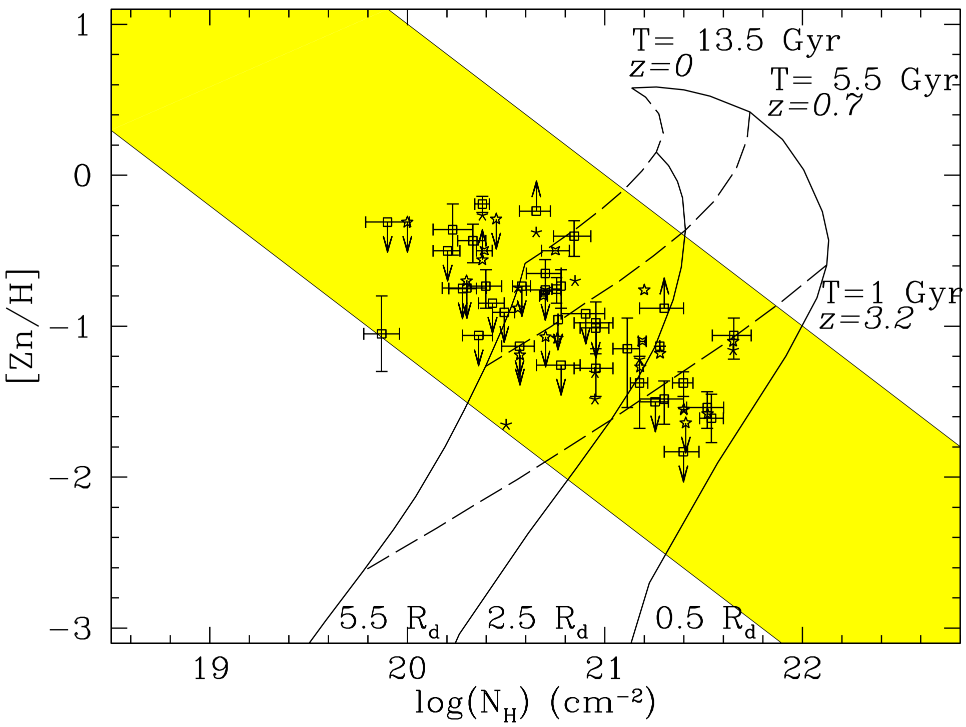

Figure 12: Anti-correlation between [Zn/H] and N(HI) – evidence for dust bias in DLAs? Prantzos & Boissier (2000).

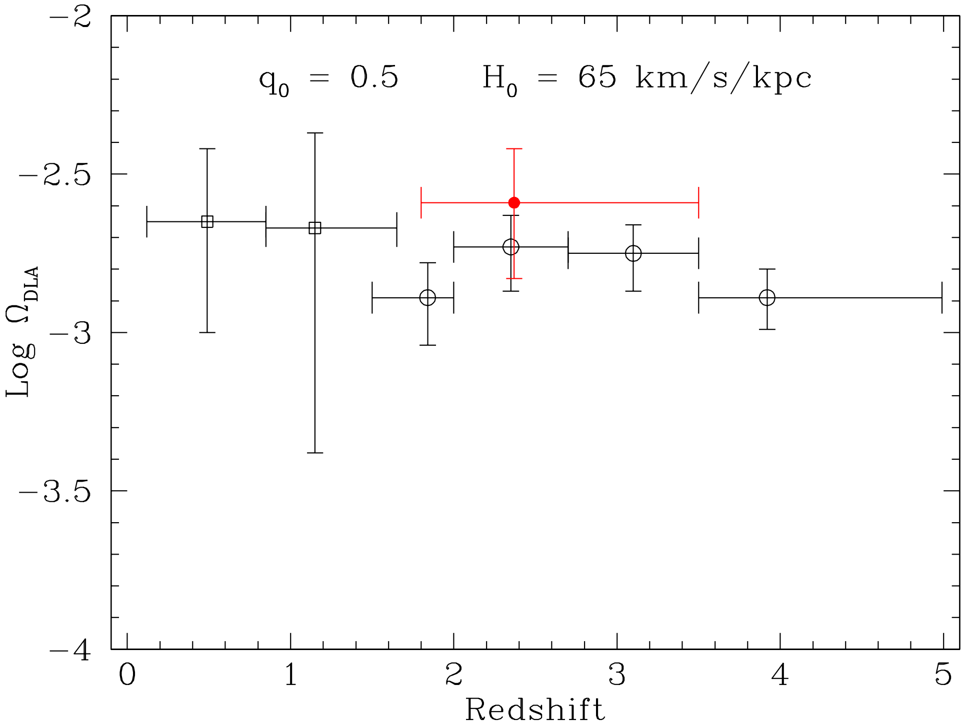

Figure 13: Neutral gas content of DLAs as a function of redshift. CORALS point (red) is in good agreement with previous surveys. Ellison et al (2001).

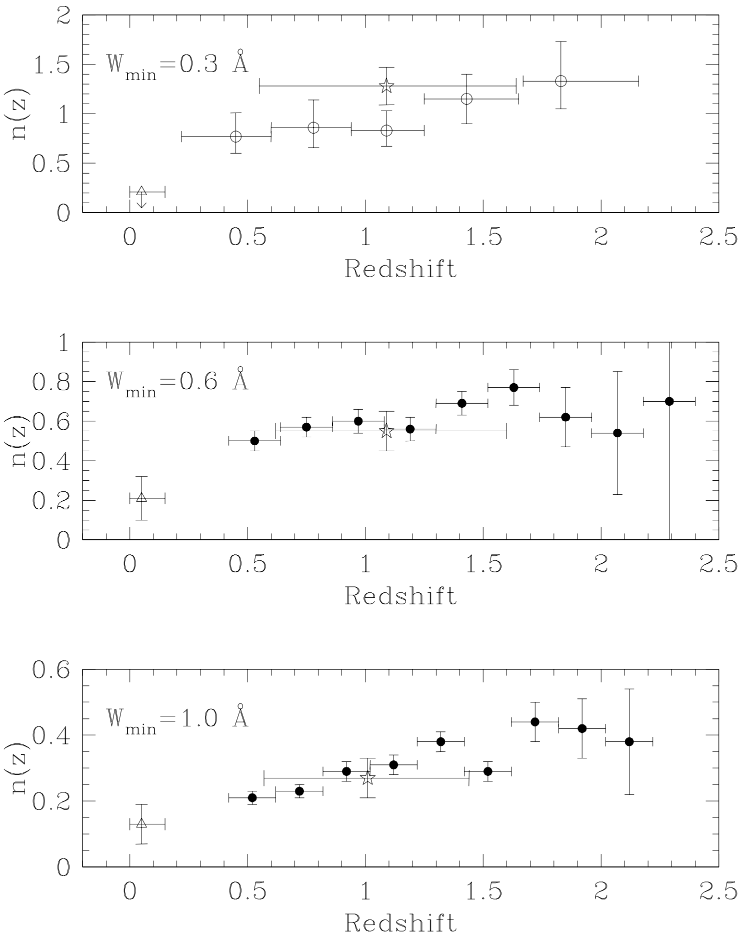

Figure 14: Number density of low z MgII systems as a function of redshift. CORALS point (star) is in good agreement with previous surveys. Ellison et al (2004).

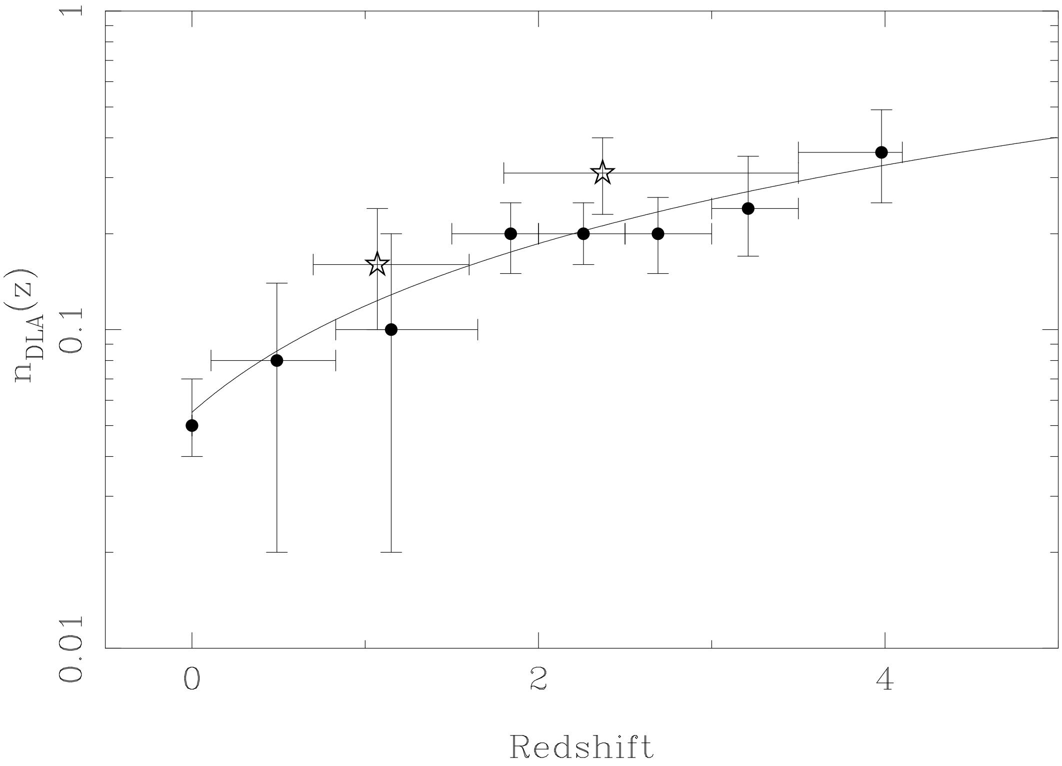

Figure 15: Number density of DLAs in both high and low z CORALS surveys (stars) compared with previous surveys. Ellison et al (2004).

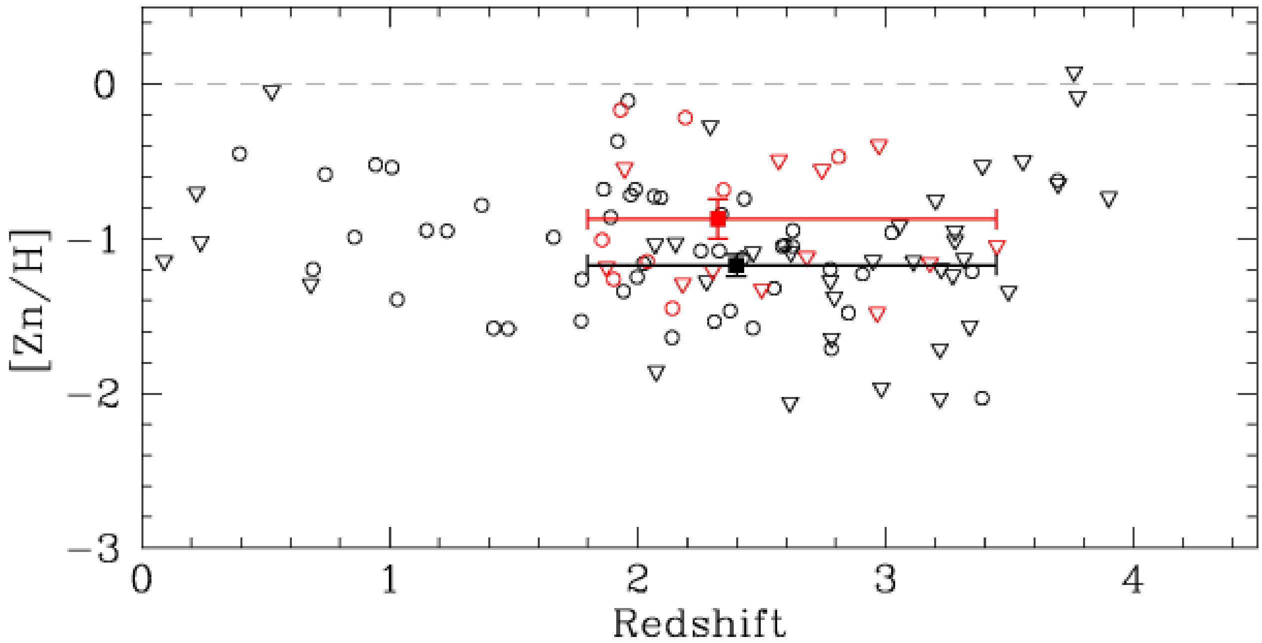

Figure 16: Metallicities of CORALS DLAs (and binned, weighted averages) compared with previous samples. Akerman et al. (2005).

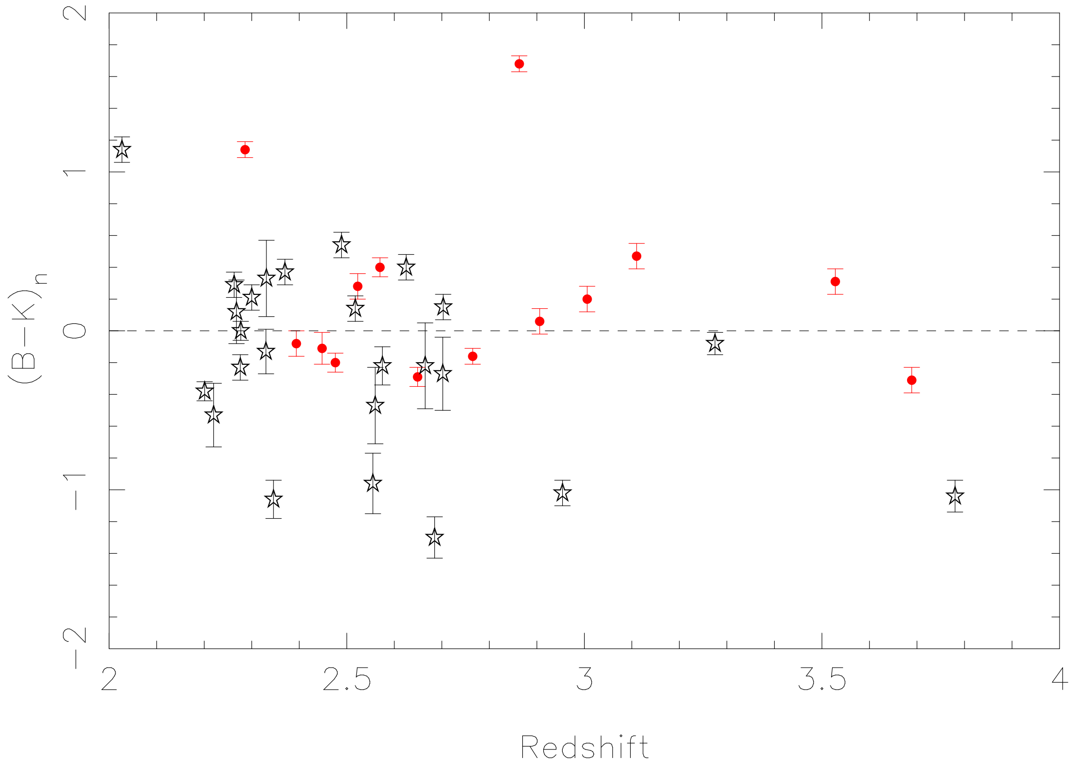

Figure 17: B−K colours of QSOS with (red dots) and without (stars) DLAs. There is marginal statistical evidence that the former are redder, Ellison, Hall & Lira (2005).

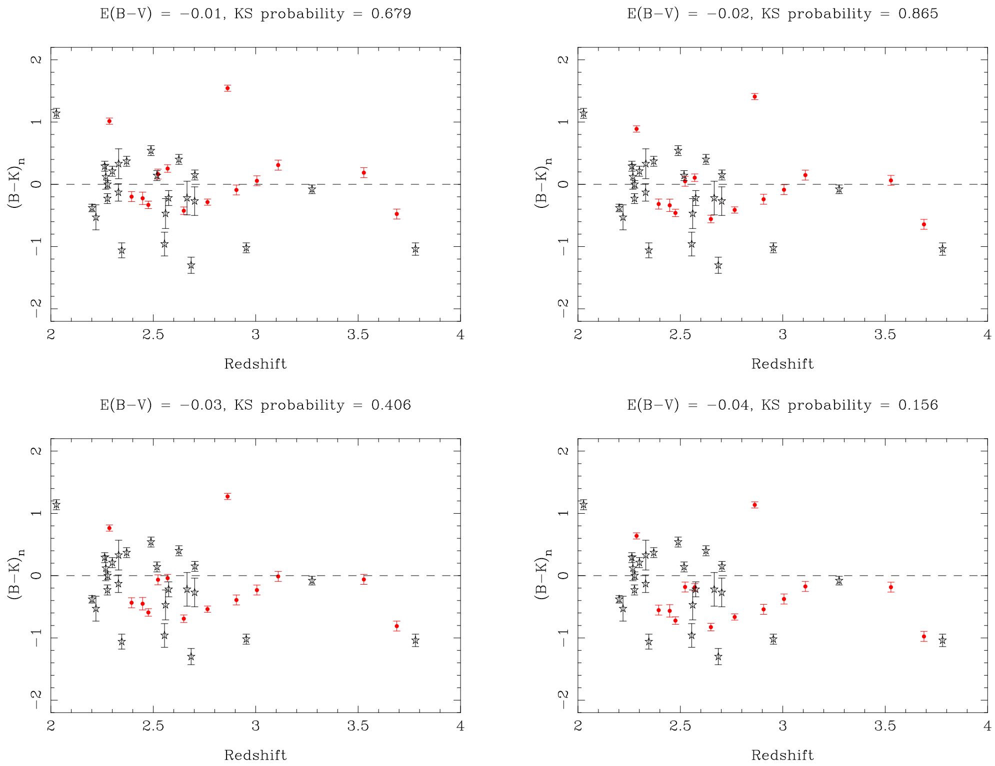

Figure 18: Estimating the reddening in DLAs by removing effect of dust according to an SMC extinction law and calculating the KS probability that the colours are drawn from the same distribution as QSOs without DLAs. Ellison, Hall & Lira (2005).

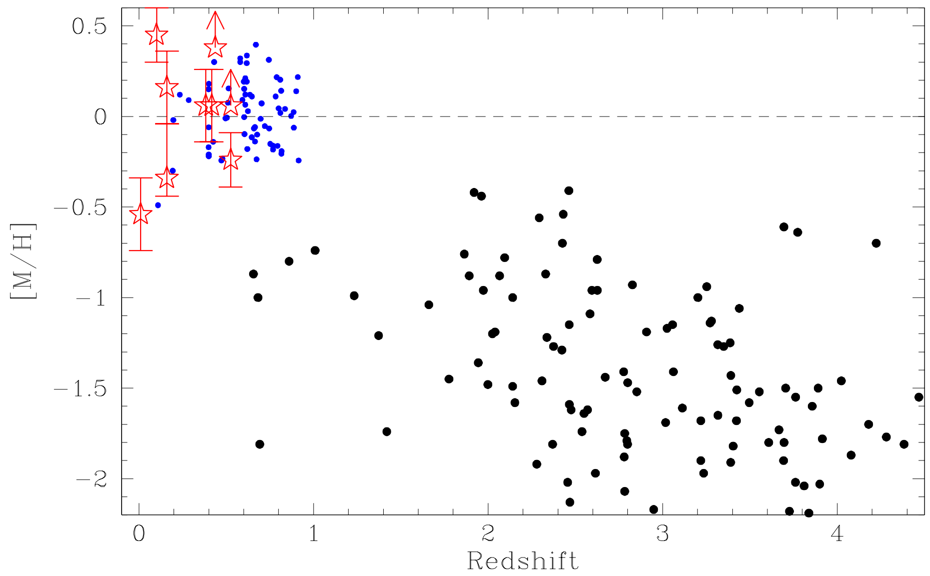

Figure 19: Perhaps DLA metallicities (black dots) are low compared to emission line metallicities of galaxies (blue dots) because they probe the outer parts of galaxies? Emission line metallicities of a handful of DLA galaxies (red stars) have relatively high values, Ellison, Kewley & Mallen-Ornelas (2005).

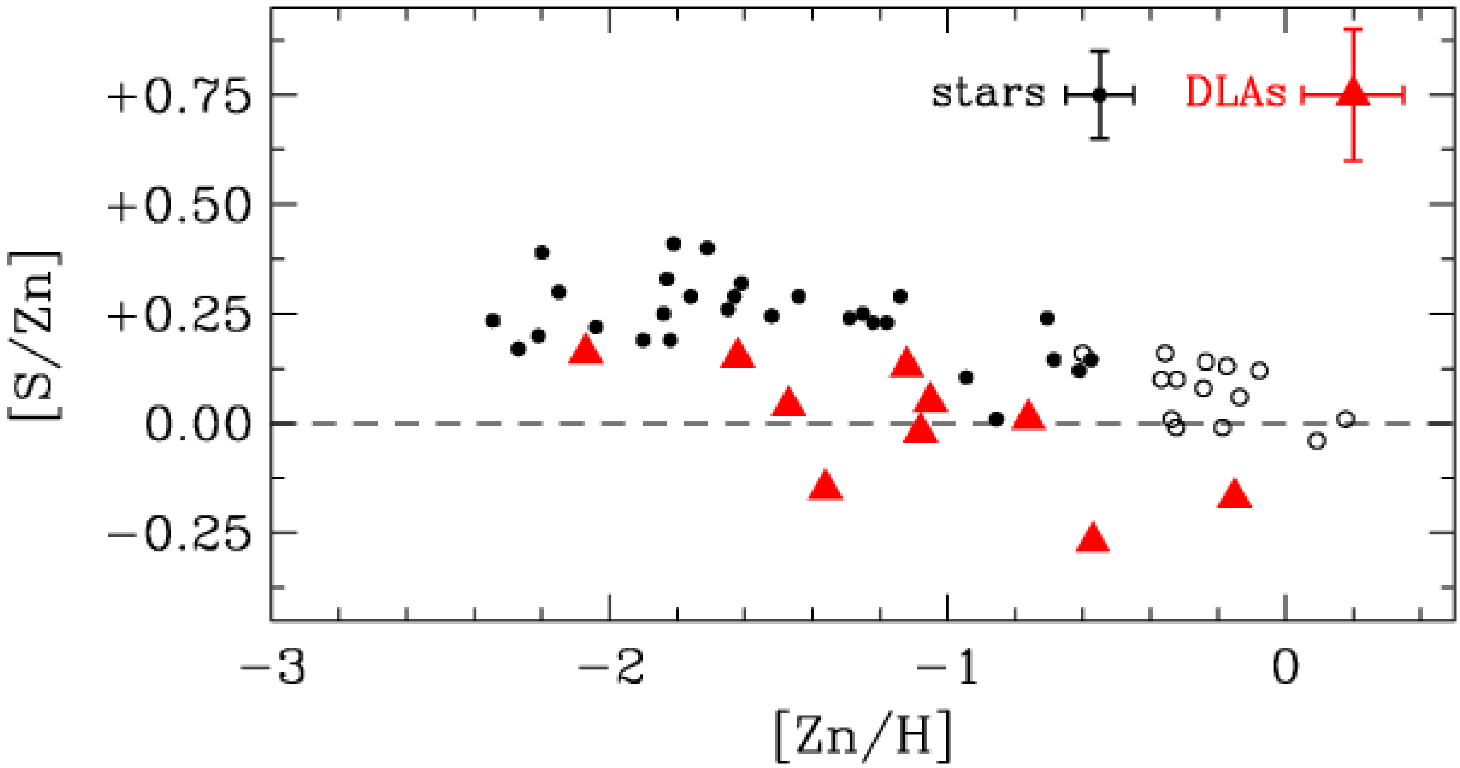

Figure 20: Alpha element enhancement in DLAs as measured by S/Zn ratios, 2 elements unaffected by dust depletion.

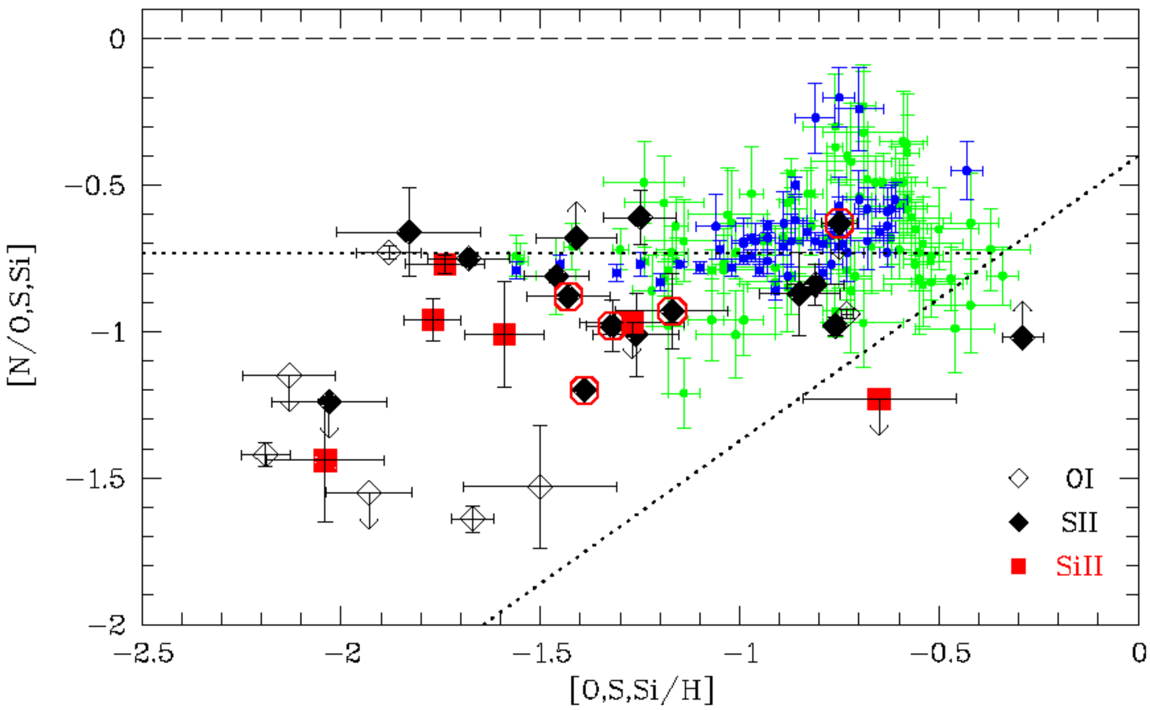

Figure 21: N/α in DLAs (large points) and galaxies (small points) from Wolfe, Prochaska & Gawiser (2005).

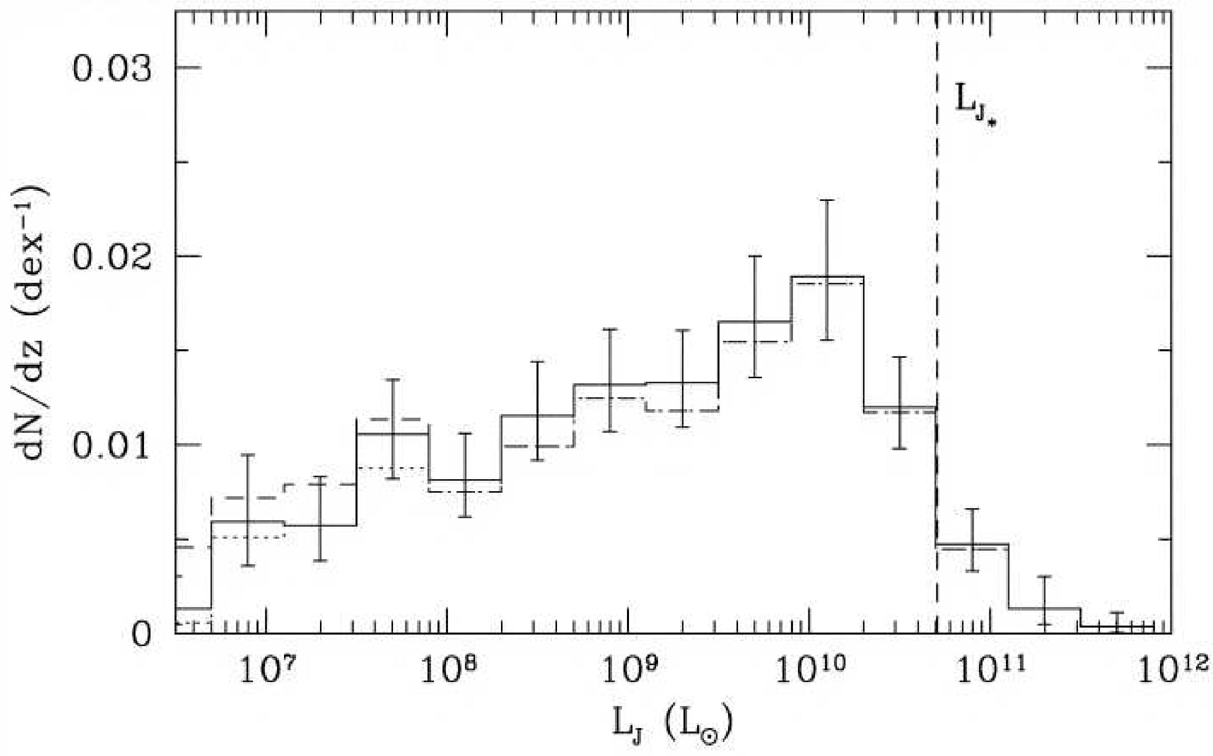

Figure 22: Galaxies in the local ADB survey of Rosenberg & Schneider (2003) have luminosities that have a relatively flat distribution, i.e. there is a high chance that a random DLA is a dwarf.

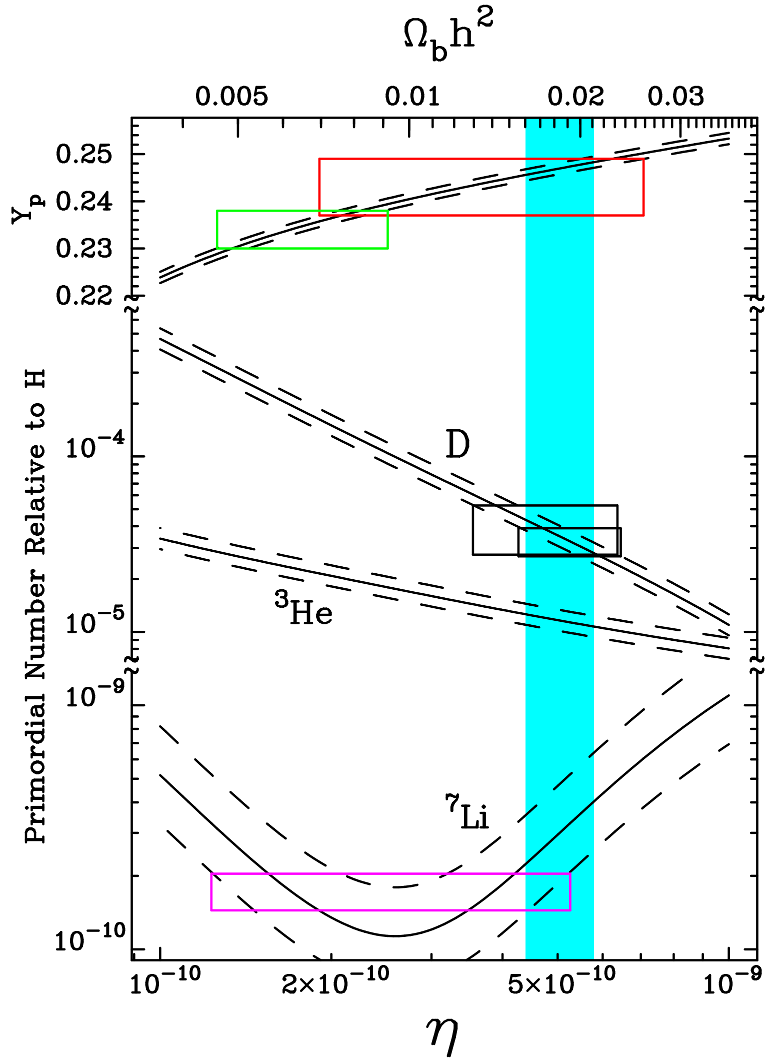

Figure 23: Relation between light element abundances, η and Ω_b. Widths of lines represent theoretical uncertainties.

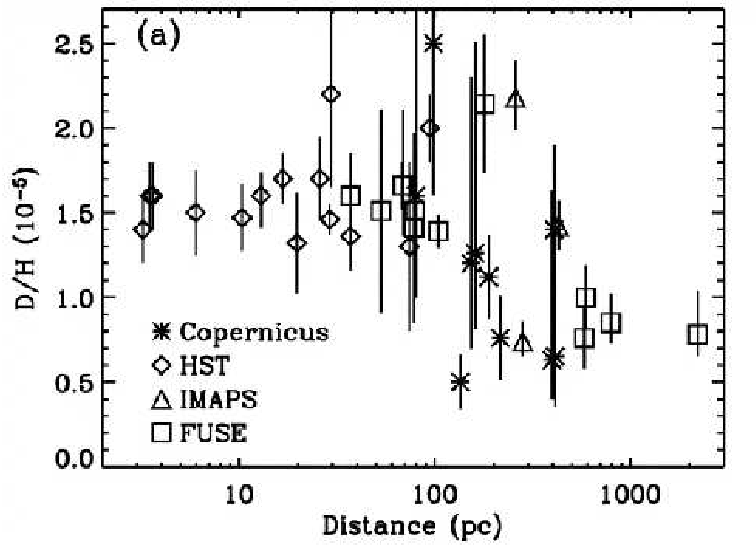

Figure 24: There is an almost constant D/H in the local bubble, but a large scatter in the LISM.

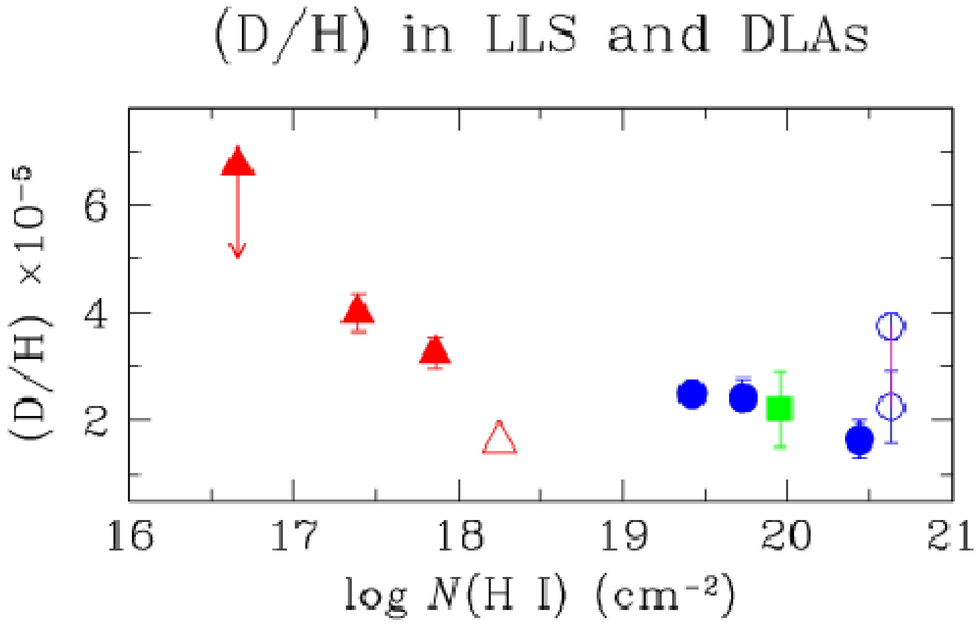

Figure 25: DLA D/H ratios give $\Omega_b = 0.044 \pm 0.004$ in excellent agreement with the CMB value of $\Omega_b = 0.046 \pm 0.010$.

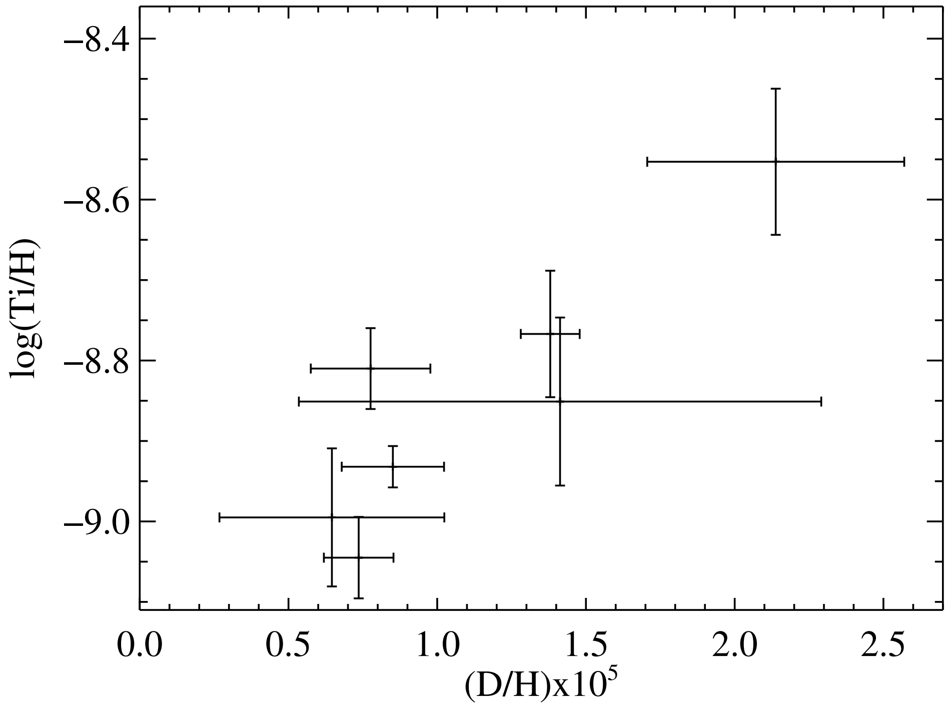

Figure 26: Dust depletion correlates with D/H abundance?

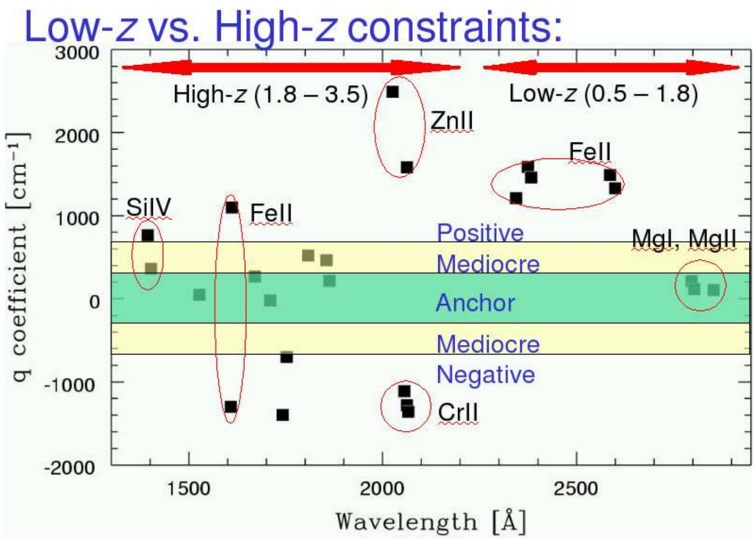

Figure 27:

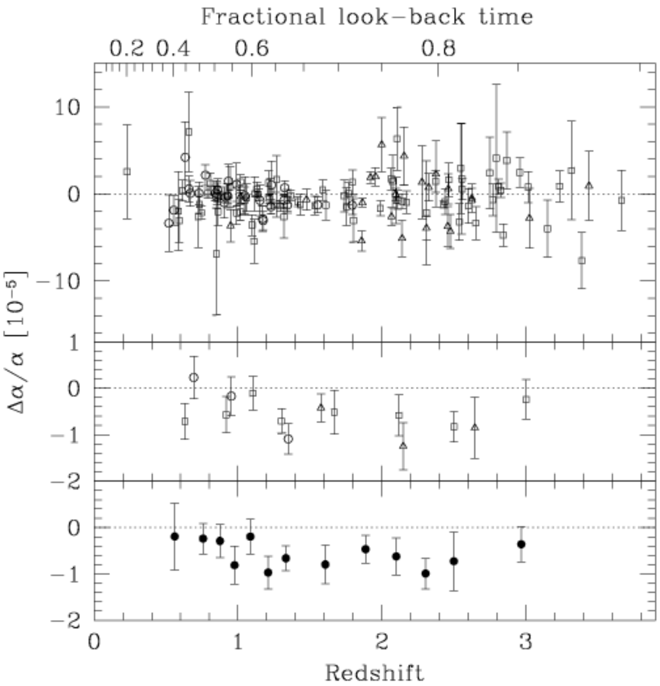

Figure 28: Constraints on change in α from the alkali doublet method