Probing galaxies through quasar absorption lines.

1) QSO absorption line background and jargon
   - curve of growth and Voigt profiles
   - naming conventions
   - physical motivations

2) Damped Lyman alpha systems (DLAs) properties
   - neutral gas content
   - chemical abundances
   - molecular gas

3) The nature of DLAs and sub-DLAs
   - imaging of DLAs
   - scaling relations and physical properties
   - the role of sub-DLAs

Goals - to give bakground of the topic, some cornerstone results and connect with comtemporary view of galaxy evolution.

Additional (optional) reading

- Annual review by Wolfe et al. (2005)

- QSO absorption line text book in preparation by Chris Churchill (fairly complete draft at astronomy.nmsu.edu/cwc)

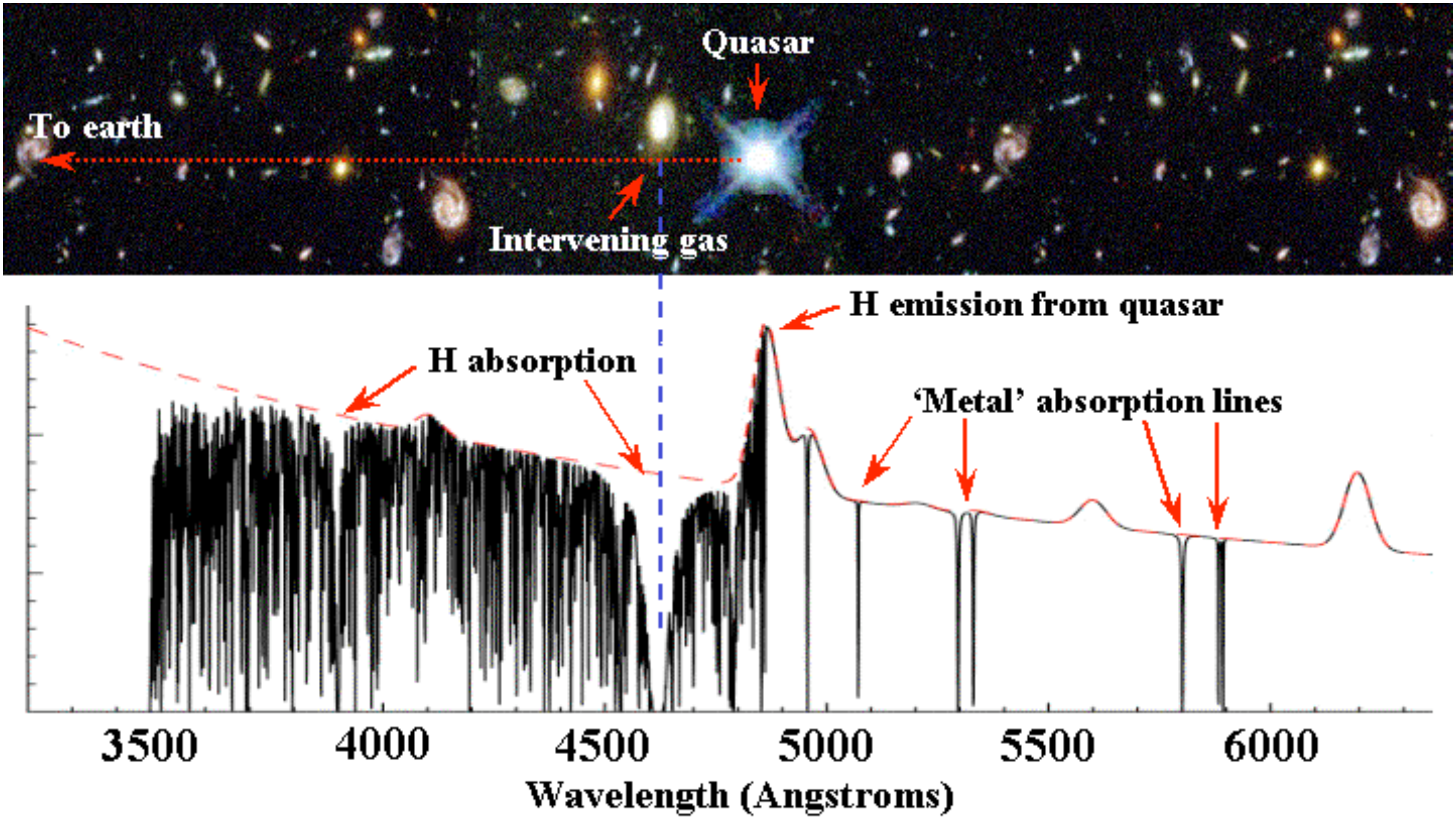
- Some lectures on astro-ph:
  - Petitjean astro-ph/9810418
  - Bechtold astro-ph/0112521
  - Pettini astro-ph/0603066, 0303072

- My lecture notes from previous ISM course: www.astro.uvic.ca/~sara/A503.html

- These slides will be available at www.astro.uvic.ca/~sara

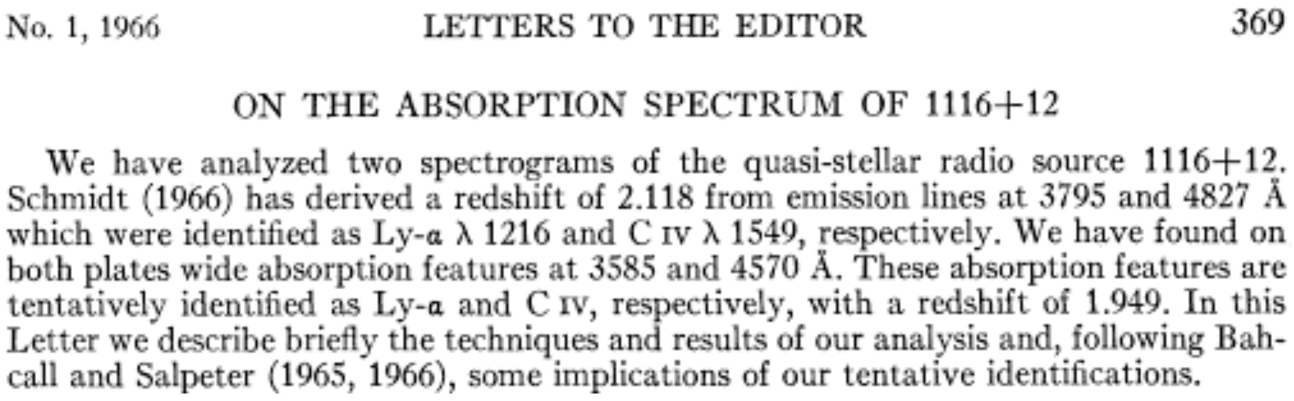
Part I:
QSO absorption line background and jargon

What are QSO absorption lines?



Absorption lines superimposed on the QSO's spectrum due to intervening *gas* in the IGM and galaxies.

A little bit of (ancient) history



No. 1, 1966 LETTERS TO THE EDITOR 369

ON THE ABSORPTION SPECTRUM OF 1116+12

We have analyzed two spectrograms of the quasi-stellar radio source 1116+12. Schmidt (1966) has derived a redshift of 2.118 from emission lines at 3795 and 4827 Å which were identified as Ly-α λ 1216 and C IV λ 1549, respectively. We have found on both plates wide absorption features at 3585 and 4570 Å. These absorption features are tentatively identified as Ly-α and C IV, respectively, with a redshift of 1.949. In this Letter we describe briefly the techniques and results of our analysis and, following Bahcall and Salpeter (1965, 1966), some implications of our tentative identifications.

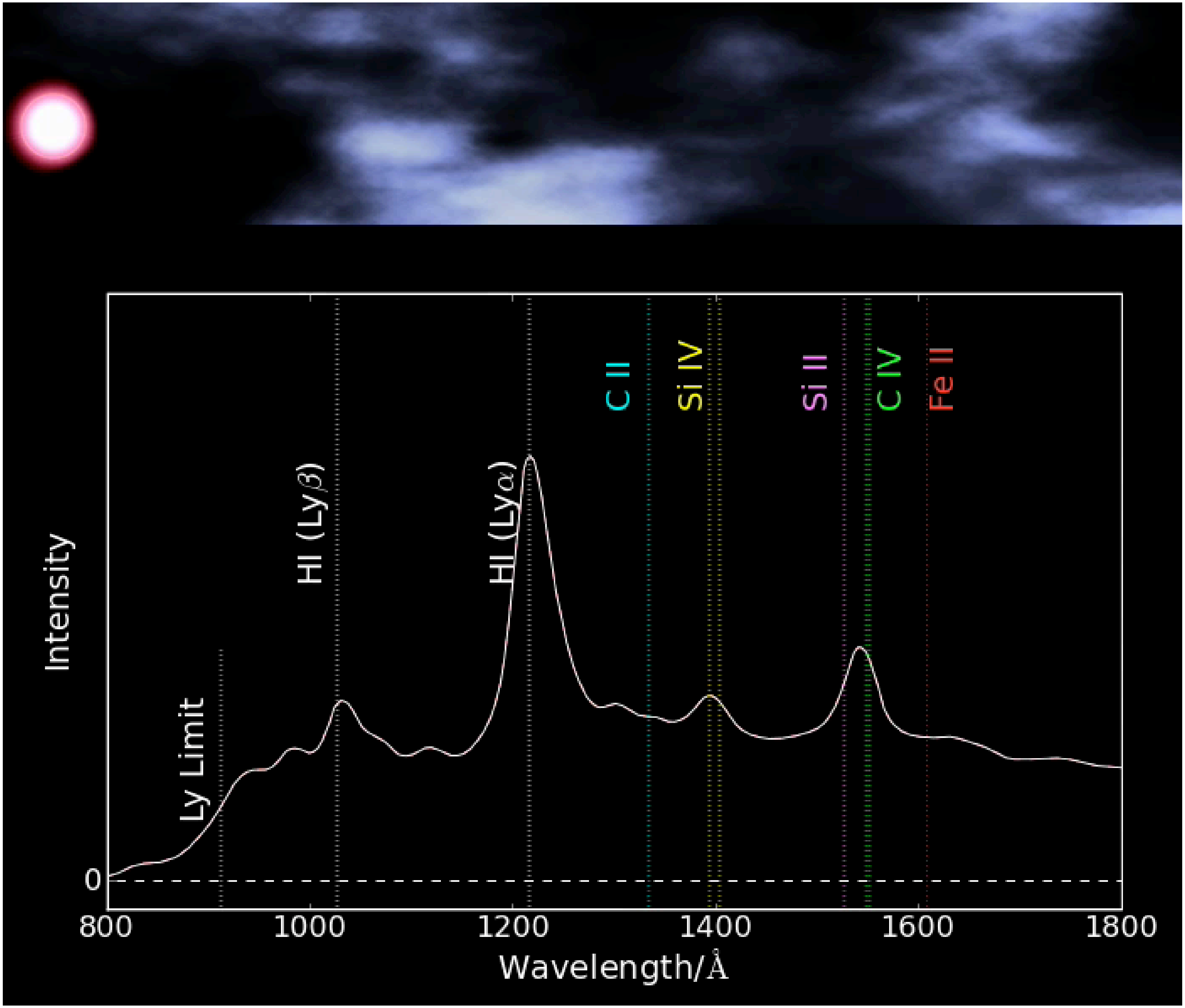
Bahcall, Peterson & Schmidt (1966)

Intervening or ejected? Evidence from Lyα forest:

1. If ejected, redshifts correspond to ejection velocities

$$\beta = \frac{v_{ej}}{c} = \frac{(1+z_e)^2 - (1+z_a)^2}{(1+z_e)^2 + (1+z_a)^2}$$

2. Same line density from QSO to QSO and not a strong function of redshift
3. Closely separated projected pairs showed common absorption.

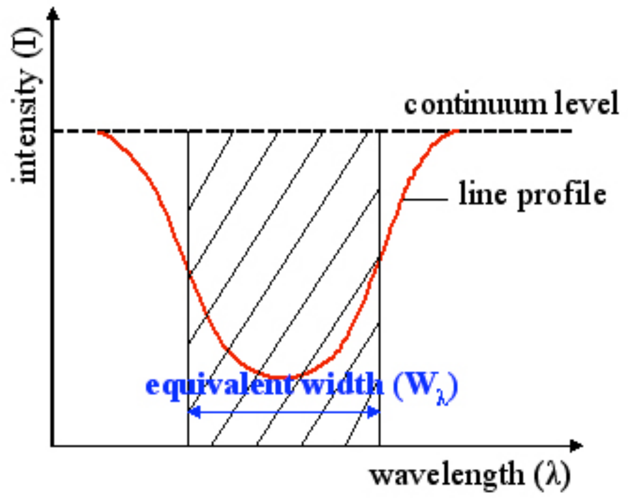

Intensity
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800
Wavelength/Å

Line formation and properties I: a primer on terms

Redshift: The observed wavelength of a line is $(1+z) \times \lambda_{rest}$

Equivalent width:

$$EW = \int \frac{I_0 - I_\lambda d\lambda}{I_0}$$



measured in Angstroms

$Ew_{obs} = Ew_{rest} \times (1+z)$

Ews are usually used when the spectral line is *unresolved* and have positive values for absorption lines and negative values for emission lines.

Line formation and properties I: a primer on terms

Column density: $N = 1.13 \times 10^{20} \frac{W(\lambda)}{\lambda_0^2 f}$

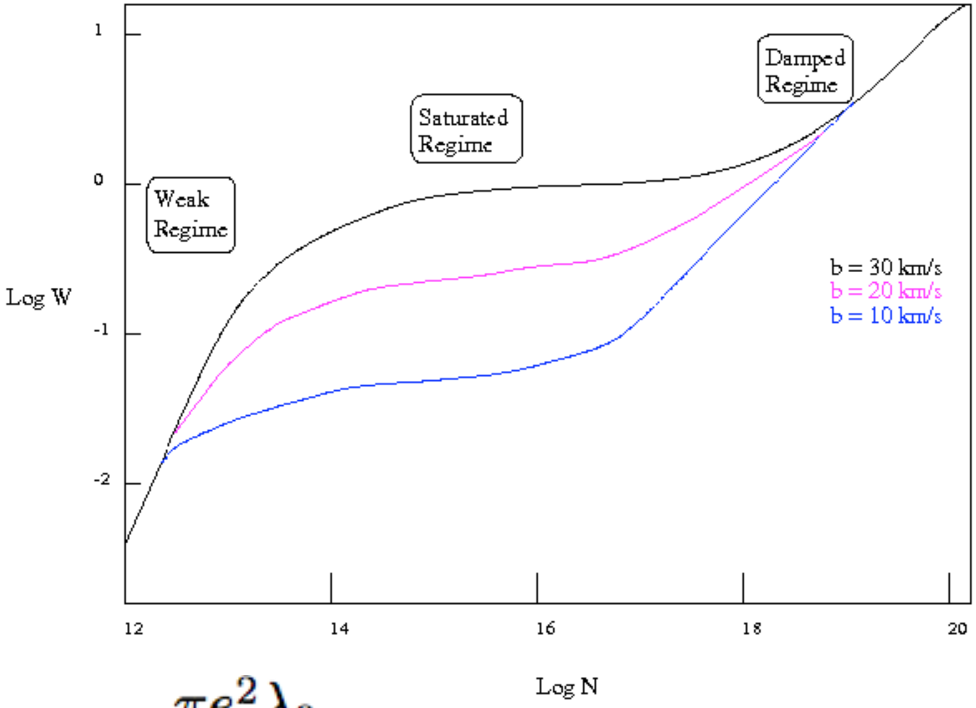
This is only applicable when the line is unsaturated. Measured in atoms cm^{-2}.

Doppler parameter: $b = \sqrt{\frac{2kT}{m} + b^2_{turbulent}}$ in km/s

Since Doppler parameter (or b-value) is a measure of line width it can also be expressed in terms of FWHM or σ

$$b = \sqrt{2}\sigma = \frac{FWHM}{2\sqrt{ln2}}$$

Line formation and properties II: The curve of growth



The curve of growth shows the connection between EW and N. Three regimes, of which only two have unique conversions between EW and N.

$$W(\lambda) = \frac{\pi e^2 \lambda_0}{m_e c^2} N \lambda_0 f$$

Unsaturated (linear) regime

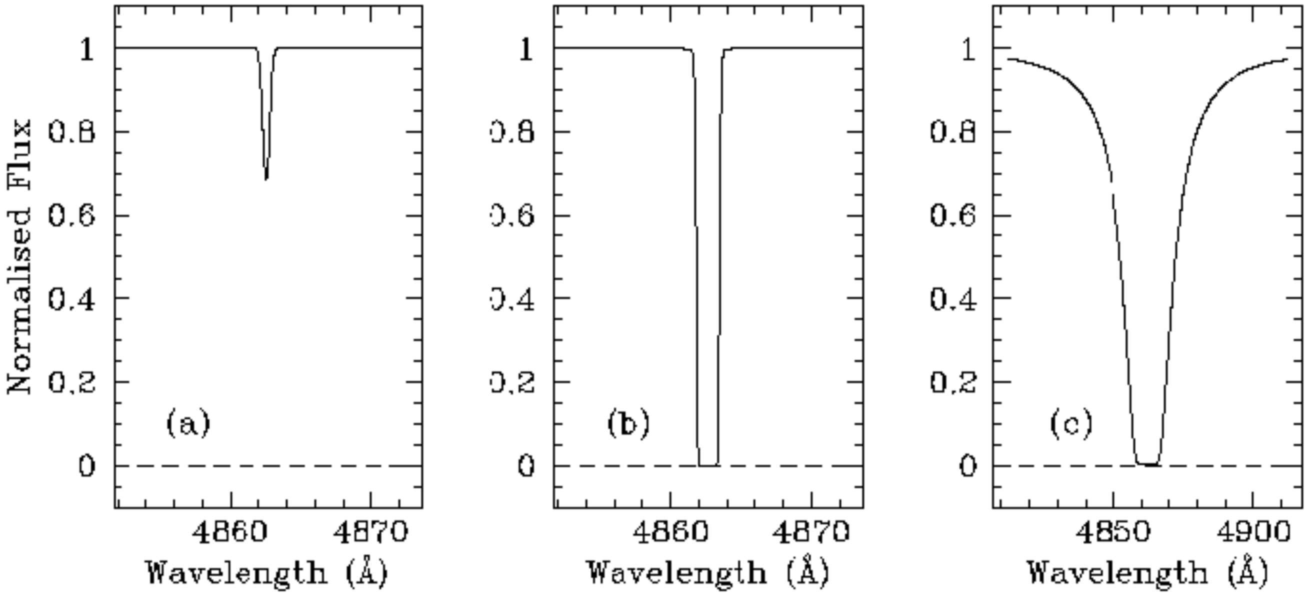
$$W(\lambda) \sim \frac{2b\lambda_0}{c} \sqrt{\ln\left(\frac{\pi^{0.5} e^2 N \lambda_0 f}{m_e c b}\right)}$$

Saturated regime

$$W(\lambda) \sim \frac{\lambda_0^{1.5}}{c} \sqrt{\frac{e^2}{m_e c} N \lambda_0 f \Gamma}$$

Damped regime

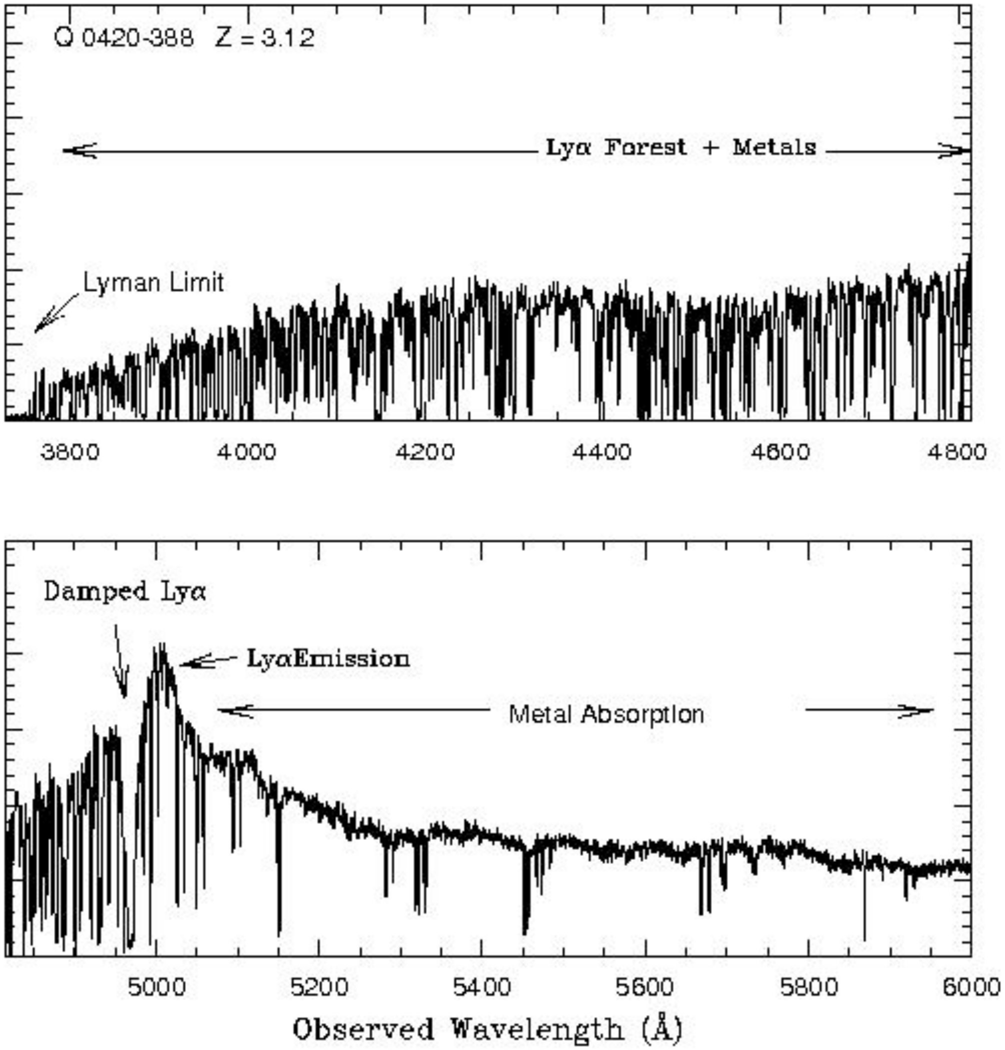
Line formation and properties III: Voigt profiles



The voigt profile is a convolution of a Maxwellian (thermal) profile and a Lorentzian (quantum mechanically damped) profile. The VP is generated analytically e.g. Humlicek (1979). Voigt profiles usually fit in high resolution data.

More details on line formation in lecture 1 of ISM course: www.astro.uvic.ca/~sara/A503.html

The QSO absorption line zoo



The different types of absorbers are named for the features through which they are identified. E.g.

CIV, MgII, CaII absorbers identified by their metal lines.

DLAs, sub-DLAs and Lyman limit systems identified by their HI properties.

Absorber	Log N(HI)	Signature	What is it?
Lyα forest	11 - 17.5 cm^{-2}	Lyα 1216 A	IGM
CIV system	> 14 cm^{-2} ?	CIV 1548 A	IGM/galaxy
MgII system	> 17 cm^{-2}	Mg II 2796 A	Galaxy halo
Lyman limit systems	> 17.5 cm^{-2}	Lyman limit at 912 A	Galaxy halo
Sub-DLA	19 - 20.3 cm^{-2}	Weak Lyα damping wings	Halo?Massive galaxy?
DLA	> 20.3 cm^{-2}	Lyα damping wings	Galaxy
CaII system	> 19 cm^{-2} ?	CaII 3935 A	High density gas?

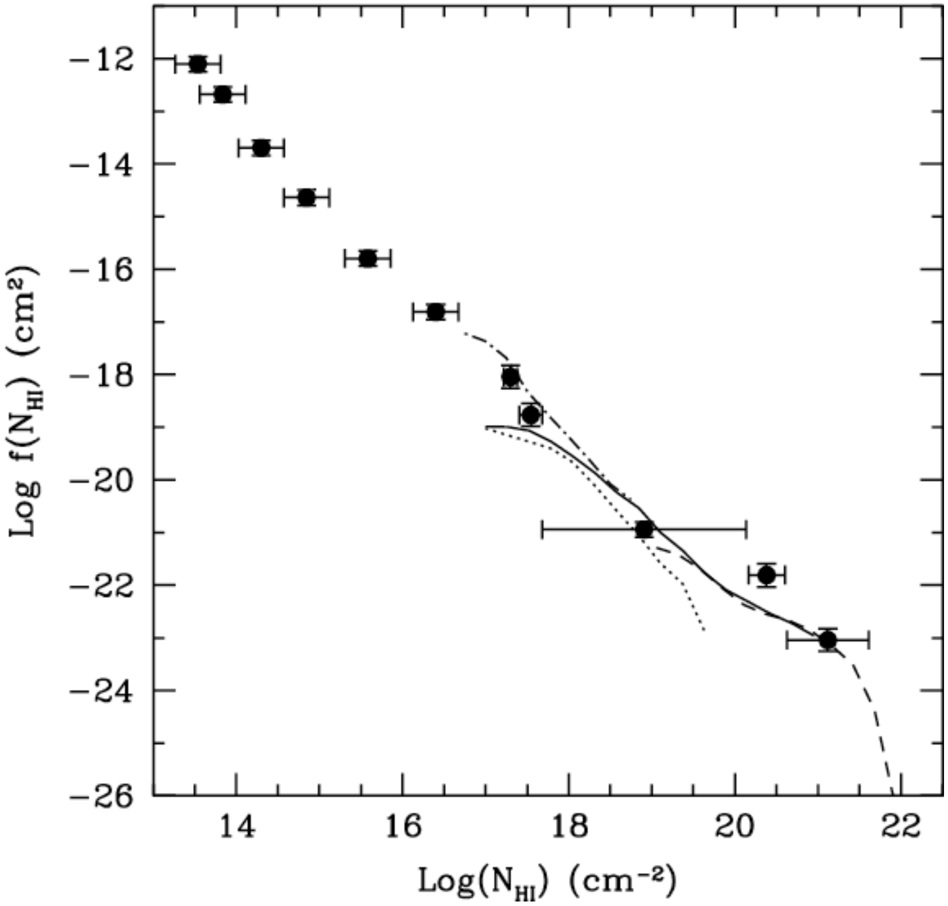
The importance of DLAs (and why 2 x 10^{20} cm^{-2}?)

The family of QSO absorbers is connected through the column density distribution function which is fairly well modelled with a single power law.

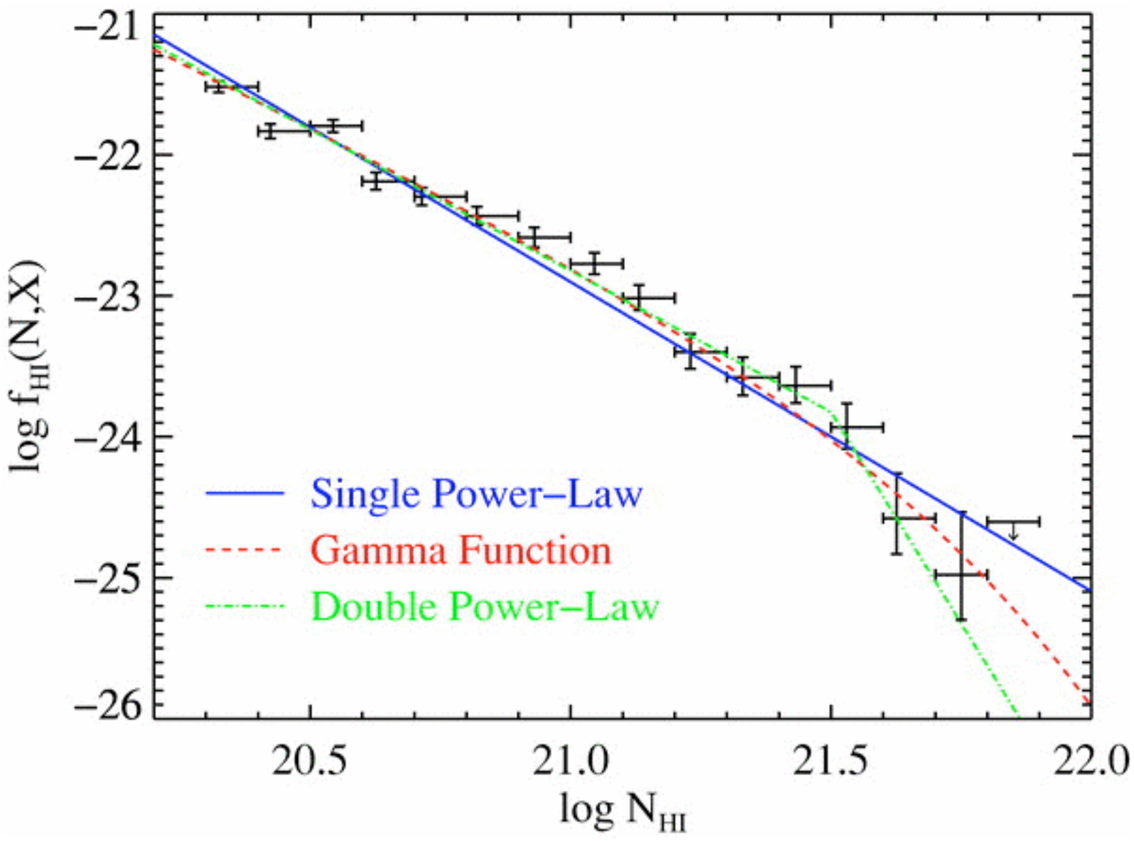
$$f(NHI) = A.N(HI)^{-\beta}$$

where $\beta \sim 1.5$

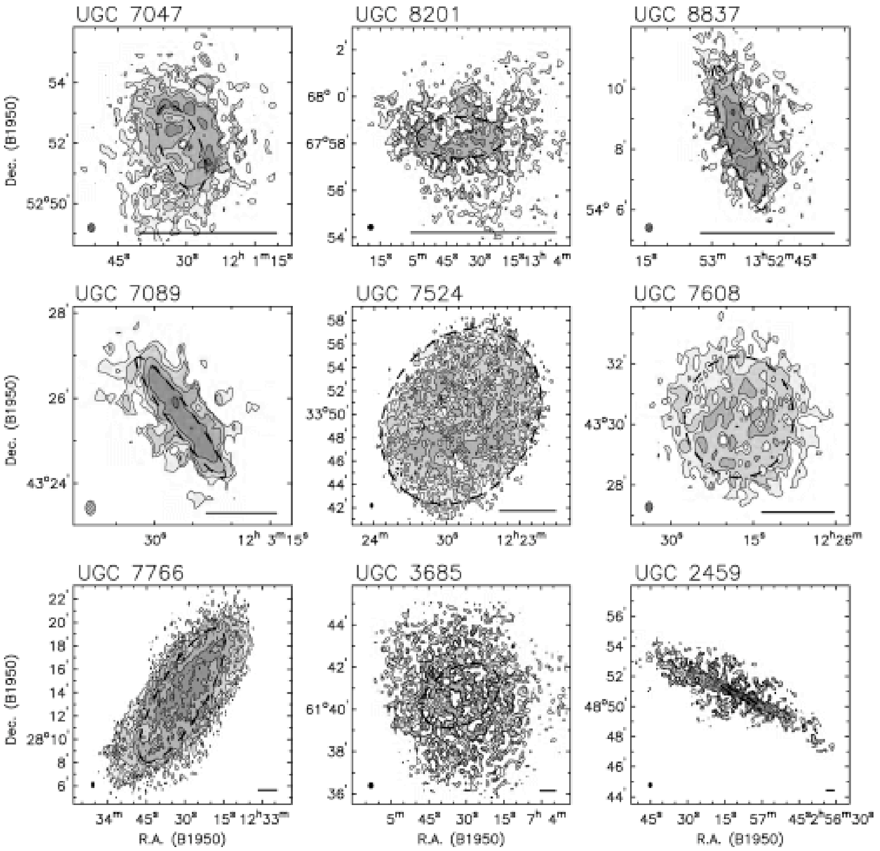
Since $\beta < 2$, this means that although the number density is dominated by the forest, the total HI mass is dominated by DLAs.



A closer look at the DLA portion of f(N) shows a turnover to $\beta >> 2$ at log N(HI) > 21.5, showing convergence at these high column densities.



In the days before CDM, it was expected that large disk galaxies could exist already at high z. The first DLA surveys were designed to detect these "Milky Way progenitors". 21cm surveys impractical.

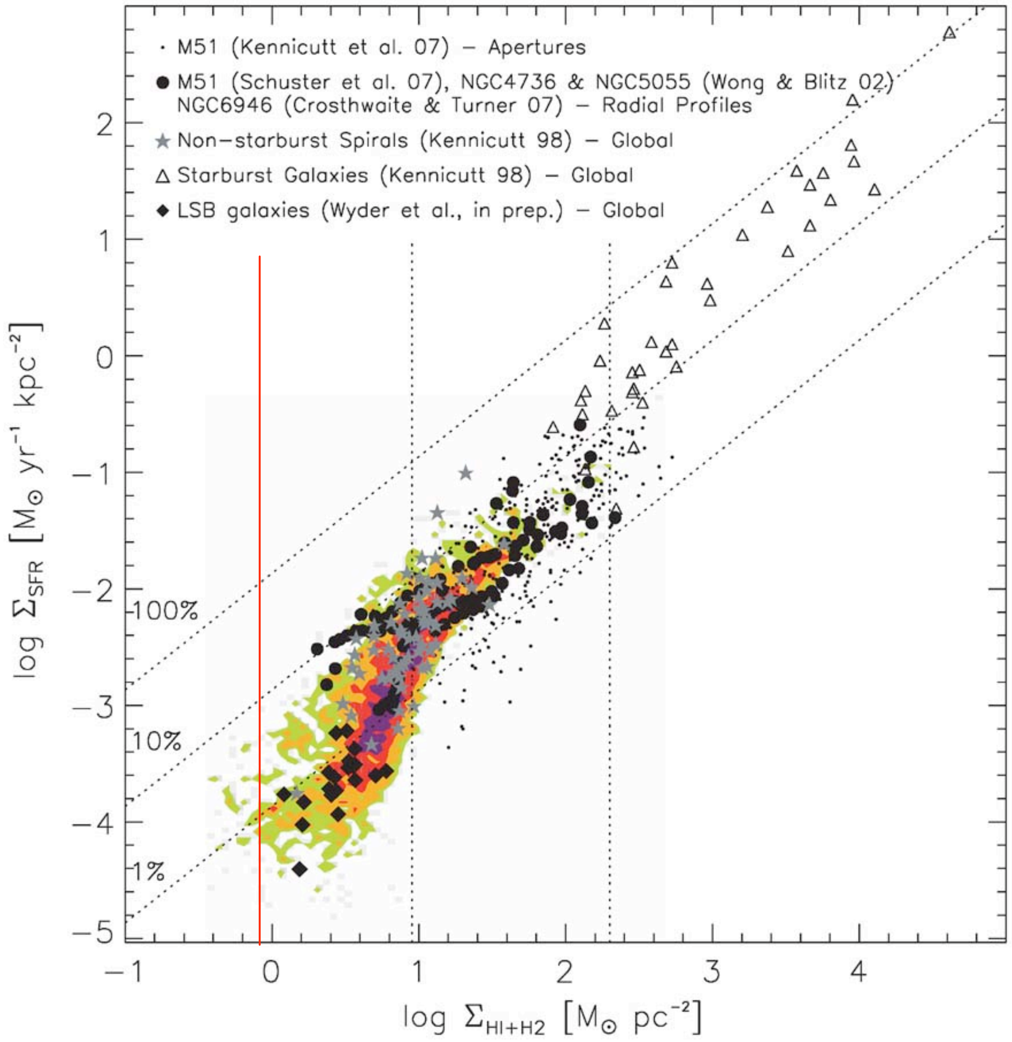


Radio surveys of local 21cm emission showed a sharp decline in HI at 2×10^{20} cm^{-2}. From the cog:

$$EW_{rest} = 7.3 \times \sqrt{NHI/10^{20}}$$

for damped lines - easily detected in low resolution spectra. Finally, at log N(HI) > 2×10^{20} cm^{-2} the gas is mostly neutral. However, sub-DLAs may play a role… see later.

Connection between HI and star formation



Total gas seemed to correlate with star formation, with little star formation occuring below the DLA cut-off.

$N(HI)=2\times10^{20}$ atoms cm^{-2} = 0.8 solar masses pc^{-2}.

Part II:

Damped Lyman alpha systems (DLAs) and their observational properties.

The neutral gas content of DLAs

Mass of neutral gas expressed as a fraction of the closure density of the universe:

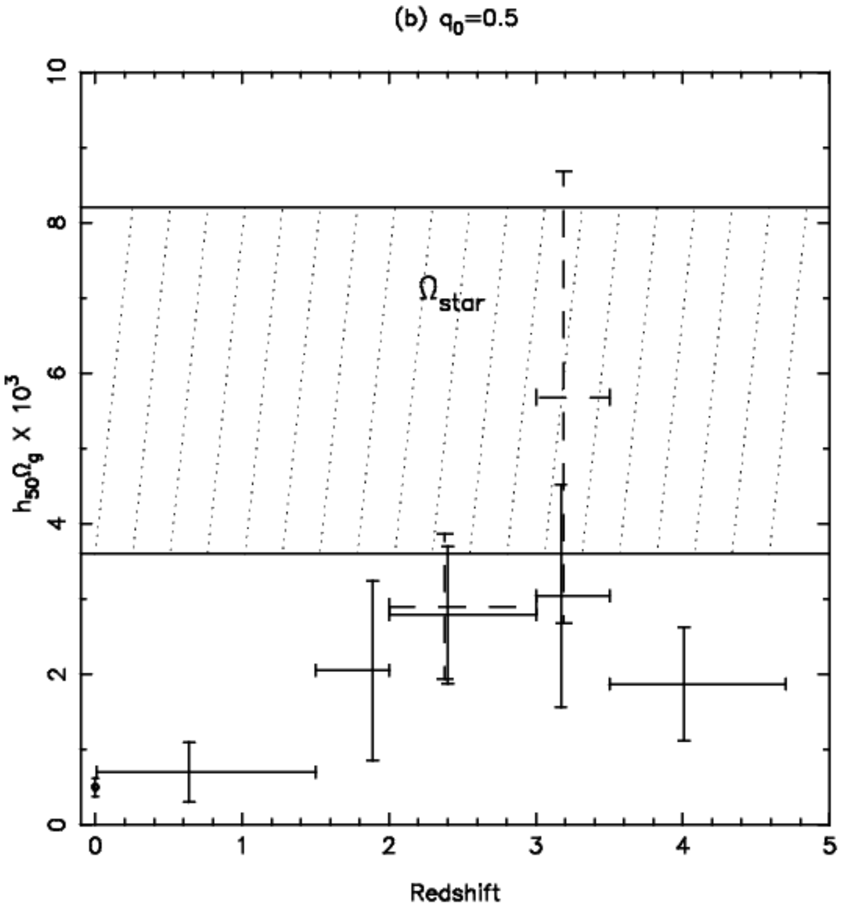
$$\Omega_{DLA} = \frac{H_0 \mu m_H}{c \rho_{crit}} \int_{N_{min}}^{N_{max}} N f(N) dN$$

In practice this is evaluated by summing the N(HI) in surveys over given redshift ranges:

$$\Omega(z)_{DLA} = \frac{H_0 \mu m_H}{c \rho_{crit}} \frac{\Sigma N_{HI}}{\Delta X(z)}$$

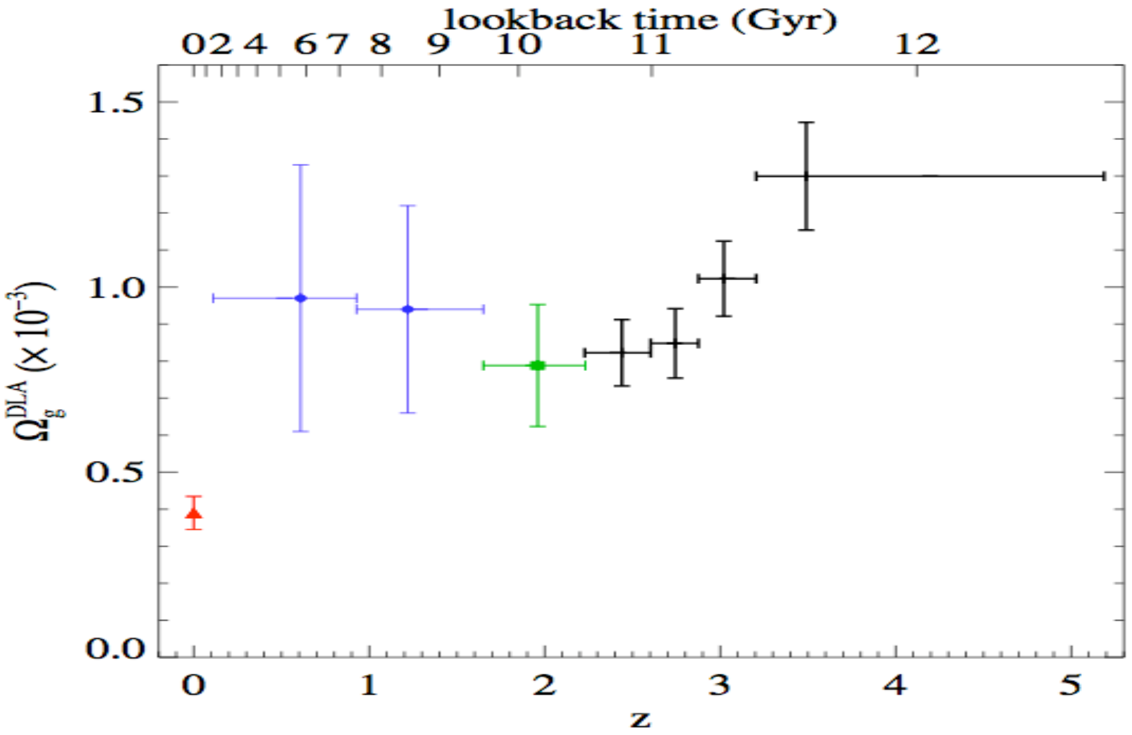
$$dX/dz = (1+z)^2[(1+z)^2(1+z\Omega_m) - z(z+2)\Omega_\Lambda]^{-1/2}$$

The picture 10 years ago (it all made some sense)

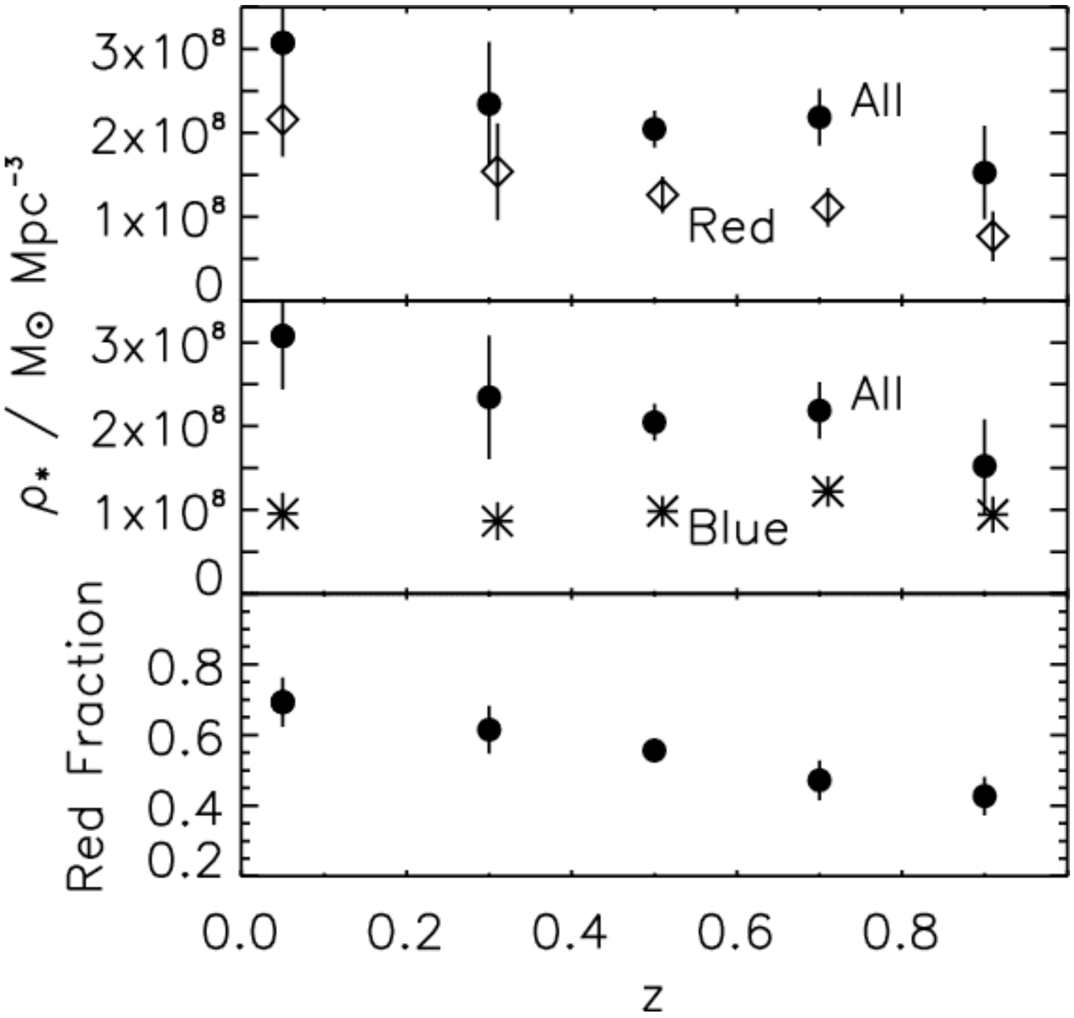


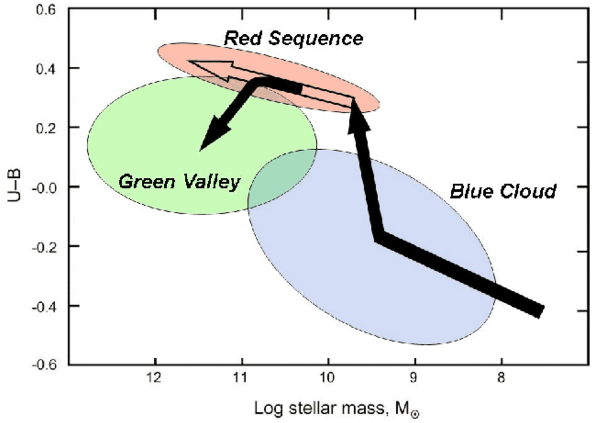
Interpretation: neutral gas is accumulated in galaxies at high z, it is then "used up" by star formation.
Implication: DLAs contain all the neutral gas for star formation.

The picture now (a lot has changed!)



Very little evolution in $\Omega(z)_{DLA}$. Low z values (blue) have increased, and z=0 value now accounts for the full HI mass function (not just spirals). The closed box model of gas into stars no longer holds (perhaps not surprising) and that gas must be constantly replenished.



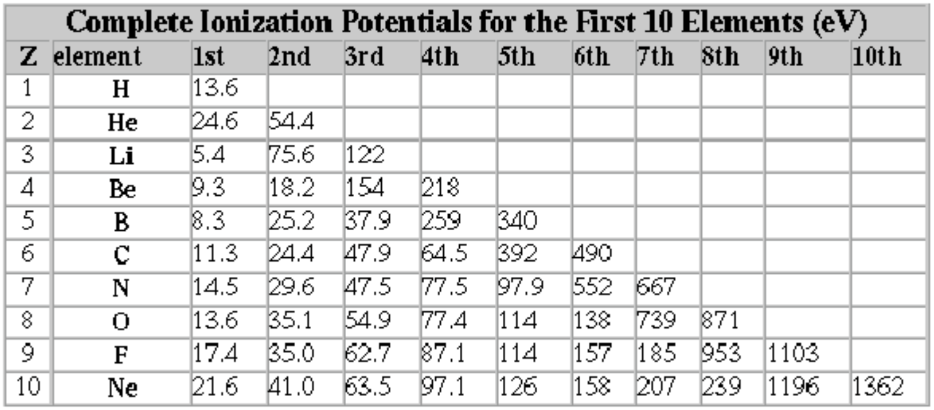


Constant replenishment of gas in star-forming galaxies supported by lack of mass evolution on the blue cloud.

Chemical abundances of DLAs

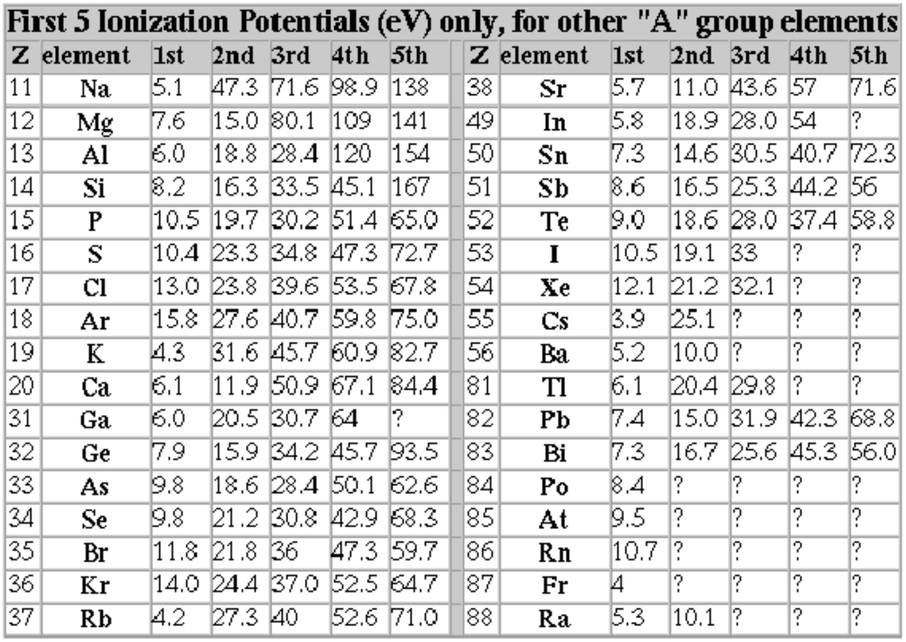
The definition: $[X/H] = log(N(X)/N(H)) - log(N(X)_{\odot}/N(H)_{\odot})$

I.e. we use abundances relative to solar on a log scale.
We also assume that N(XII) = N(X) and N(HI)=N(H). This works because the ionzation potential of XII is usually >13.6 eV and these photons are shielded by HI.



Complete Ionization Potentials for the First 10 Elements (eV)

Z	element	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	H	13.6									
2	He	24.6	54.4								
3	Li	5.4	75.6	122							
4	Be	9.3	18.2	154	218						
5	B	8.3	25.2	37.9	259	340					
6	C	11.3	24.4	47.9	64.5	392	490				
7	N	14.5	29.6	47.5	77.5	97.9	552	667			
8	O	13.6	35.1	54.9	77.4	114	138	739	871		
9	F	17.4	35.0	62.7	87.1	114	157	185	953	1103	
10	Ne	21.6	41.0	63.5	97.1	126	158	207	239	1196	1362



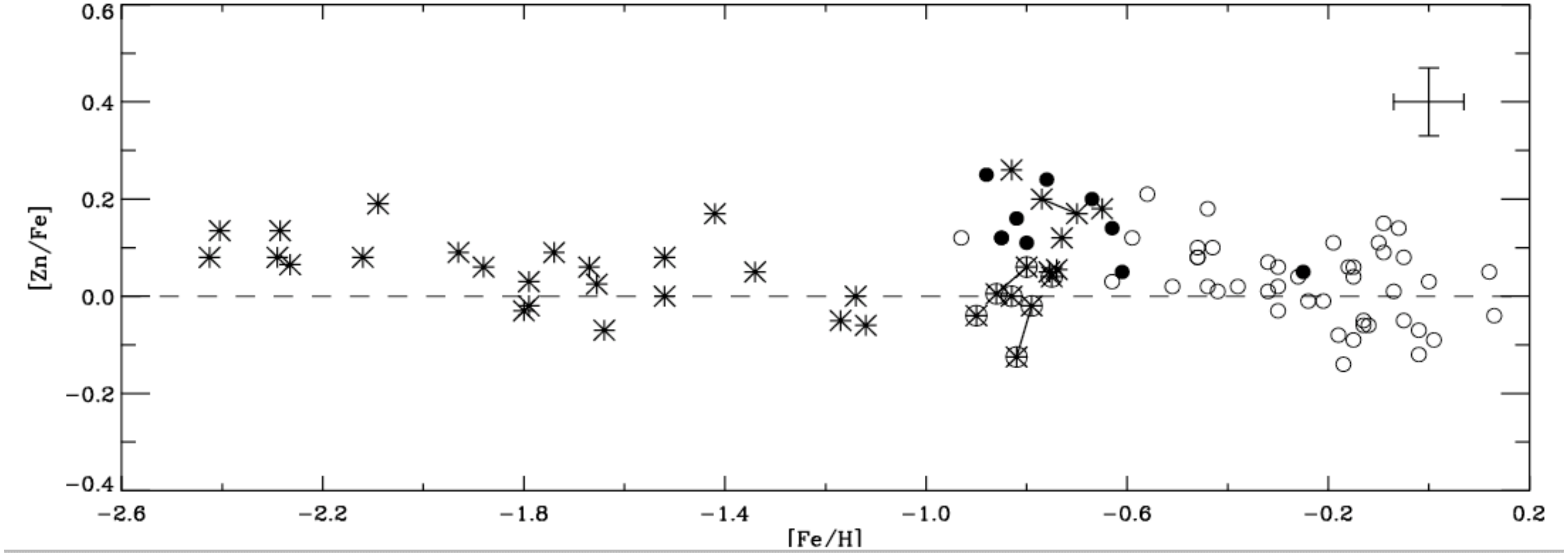
First 5 Ionization Potentials (eV) only, for other "A" group elements

Z	element	1st	2nd	3rd	4th	5th	Z	element	1st	2nd	3rd	4th	5th
11	Na	5.1	47.3	71.6	98.9	138	38	Sr	5.7	11.0	43.6	57	71.6
12	Mg	7.6	15.0	80.1	109	141	49	In	5.8	18.9	28.0	54	?
13	Al	6.0	18.8	28.4	120	154	50	Sn	7.3	14.6	30.5	40.7	72.3
14	Si	8.2	16.3	33.5	45.1	167	51	Sb	8.6	16.5	25.3	44.2	56
15	P	10.5	19.7	30.2	51.4	65.0	52	Te	9.0	18.6	28.0	37.4	58.8
16	S	10.4	23.3	34.8	47.3	72.7	53	I	10.5	19.1	33	?	?
17	Cl	13.0	23.8	39.6	53.5	67.8	54	Xe	12.1	21.2	32.1	?	?
18	Ar	15.8	27.6	40.7	59.8	75.0	55	Cs	3.9	25.1	?	?	?
19	K	4.3	31.6	45.7	60.9	82.7	56	Ba	5.2	10.0	?	?	?
20	Ca	6.1	11.9	50.9	67.1	84.4	81	Tl	6.1	20.4	29.8	?	?
31	Ga	6.0	20.5	30.7	64	?	82	Pb	7.4	15.0	31.9	42.3	68.8
32	Ge	7.9	15.9	34.2	45.7	93.5	83	Bi	7.3	16.7	25.6	45.3	56.0
33	As	9.8	18.6	28.4	50.1	62.6	84	Po	8.4	?	?	?	?
34	Se	9.8	21.2	30.8	42.9	68.3	85	At	9.5	?	?	?	?
35	Br	11.8	21.8	36	47.3	59.7	86	Rn	10.7	?	?	?	?
36	Kr	14.0	24.4	37.0	52.5	64.7	87	Fr	4	?	?	?	?
37	Rb	4.2	27.3	40	52.6	71.0	88	Ra	5.3	10.1	?	?	?

Chemical abundances of DLAs

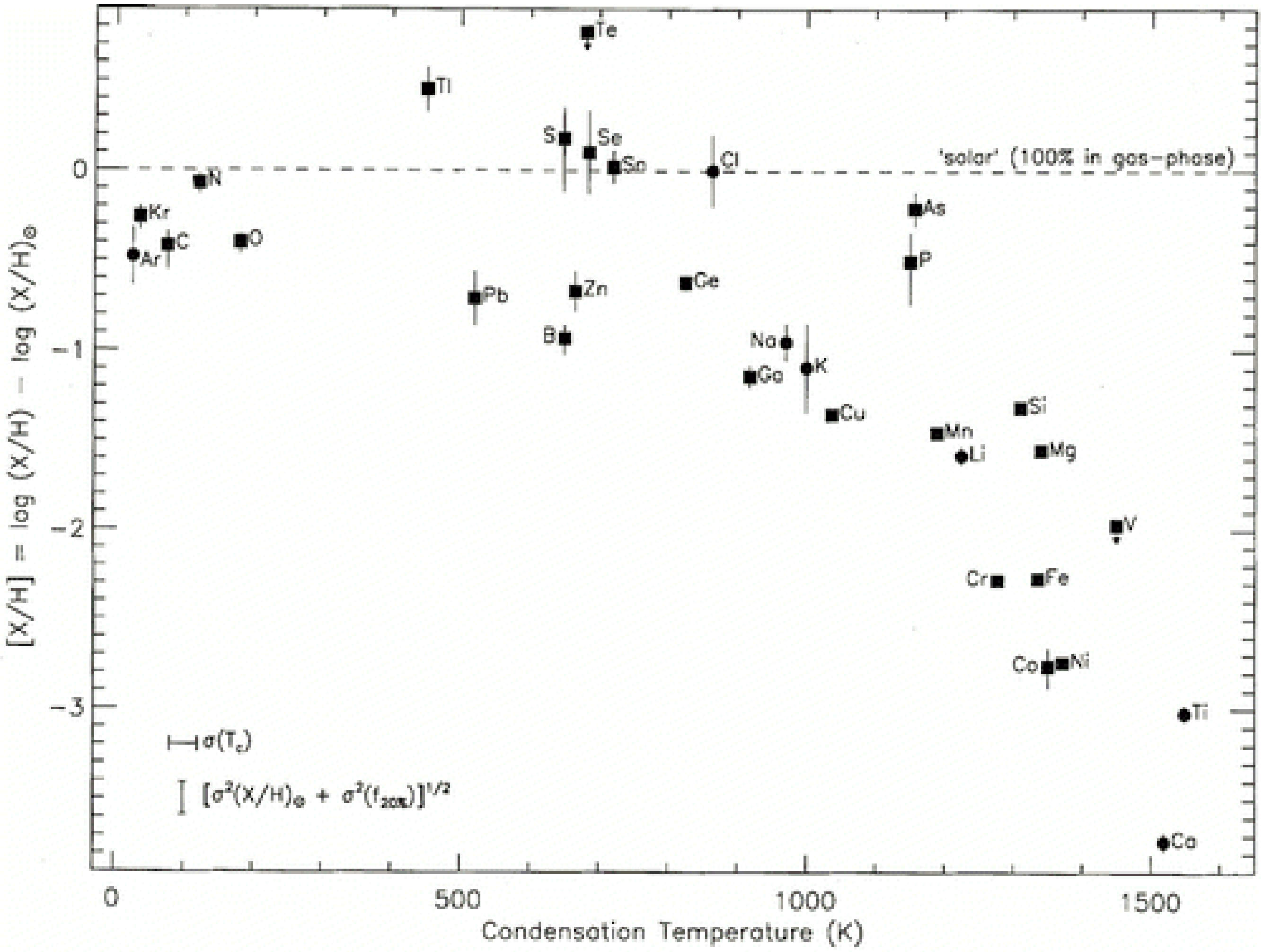
The definition: $[X/H] = log(N(X)/N(H)) - log(N(X)_{\odot}/N(H)_{\odot})$

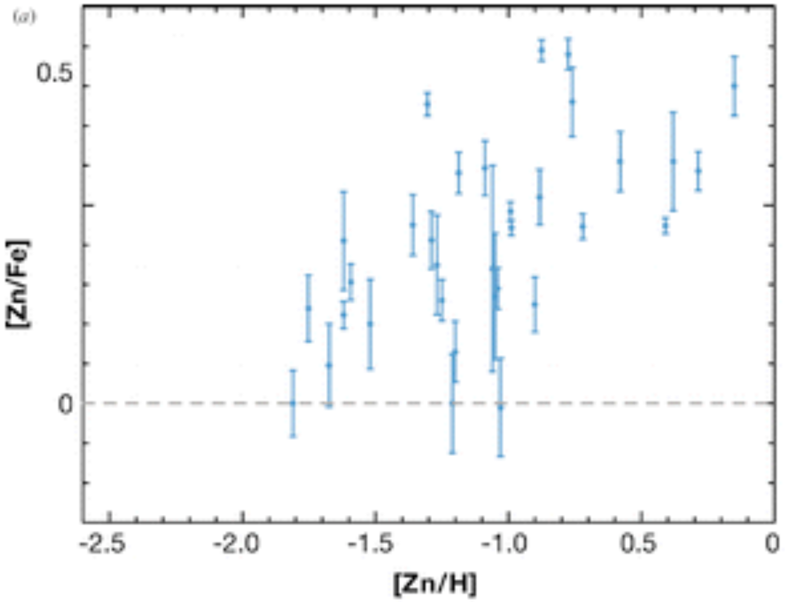
Definition of metallicity depends on field - usually O/H for galaxies and [Fe/H] for stars.



DLA work uses Zn - tracks Fe in stars and is relatively undepleted.

Galactic depletion patterns

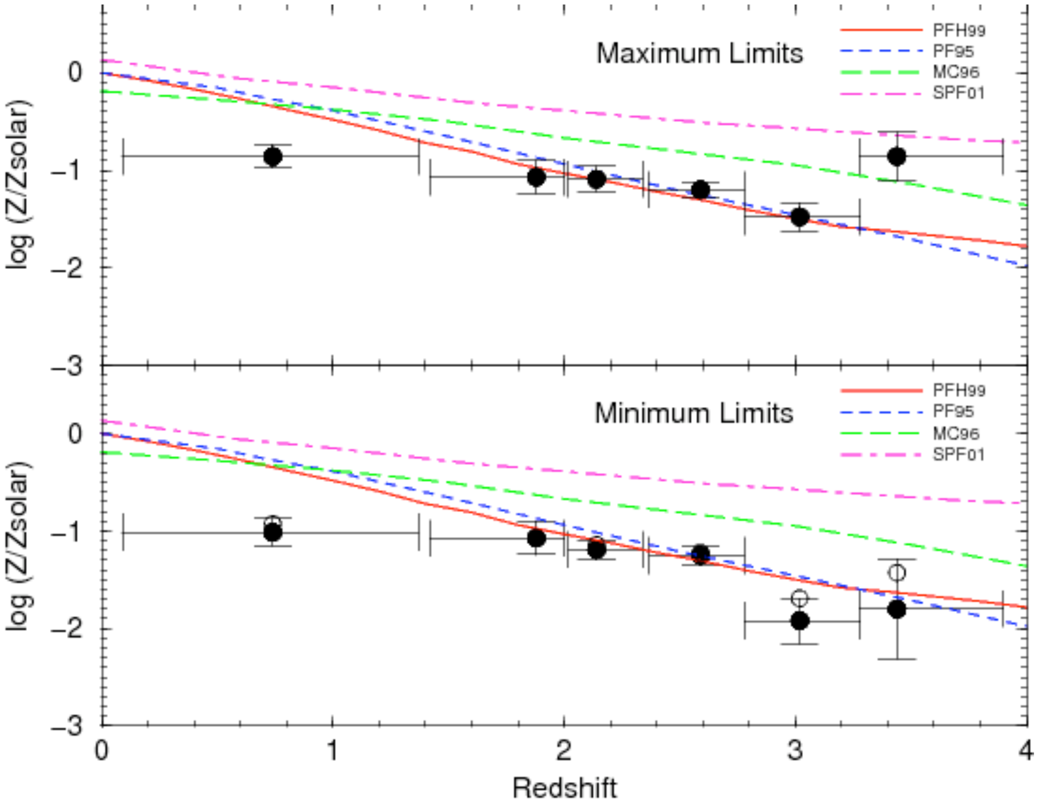




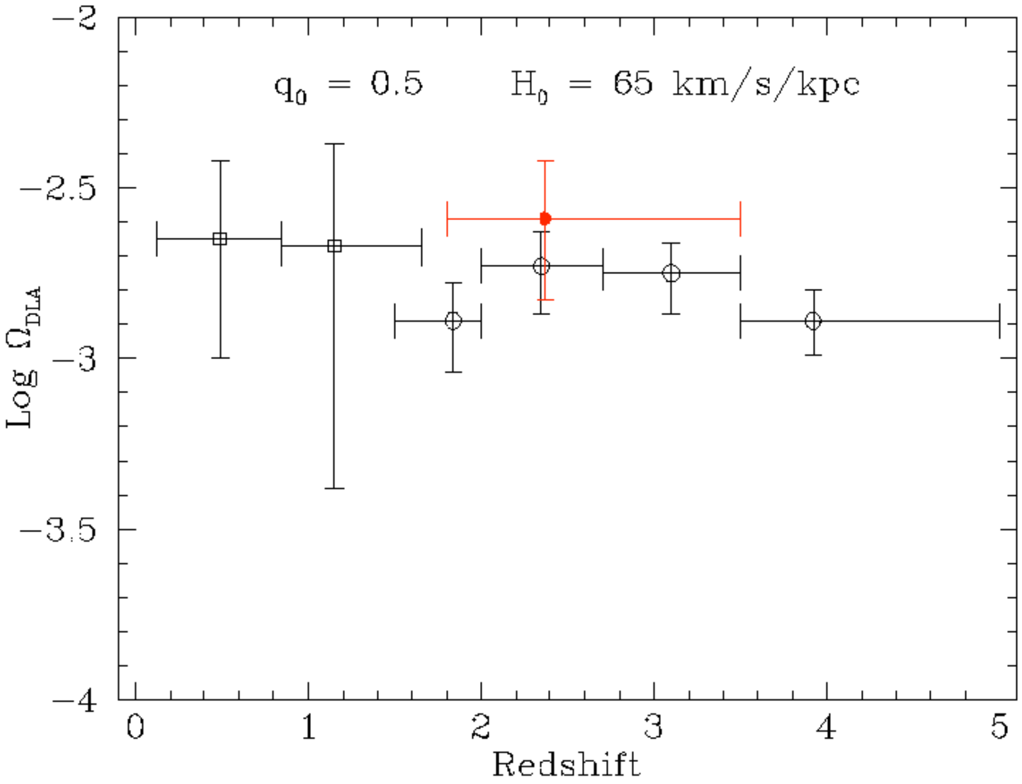
Dust depletion seems to get worse as metallicity increases. [Zn/Fe] corrections can't simply be applied to other elements, therefore care must be taken when interpreting abundances.

Metallicity evolution (or lack thereof)

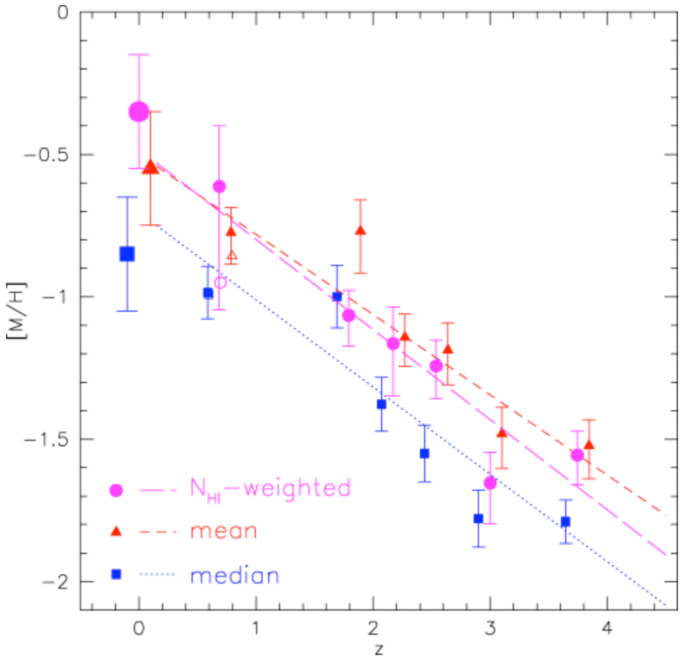
The finding that DLAs dominate the gas in galaxies led to the expectation that their metallicities would reach solar values by z~0. Not the case - and evolution is very flat.

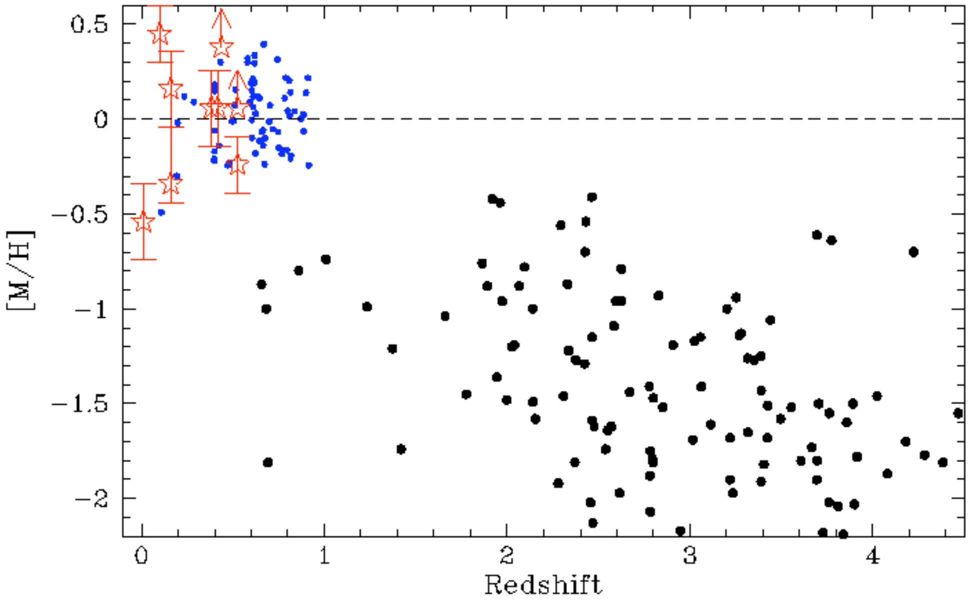


For many years, the possibility of dust bias was mooted. This could result in “missing” DLAs (particularly metal-rich, dusty ones) from surveys. Surveys of DLAs towards radio-loud QSOs show this is not the case.

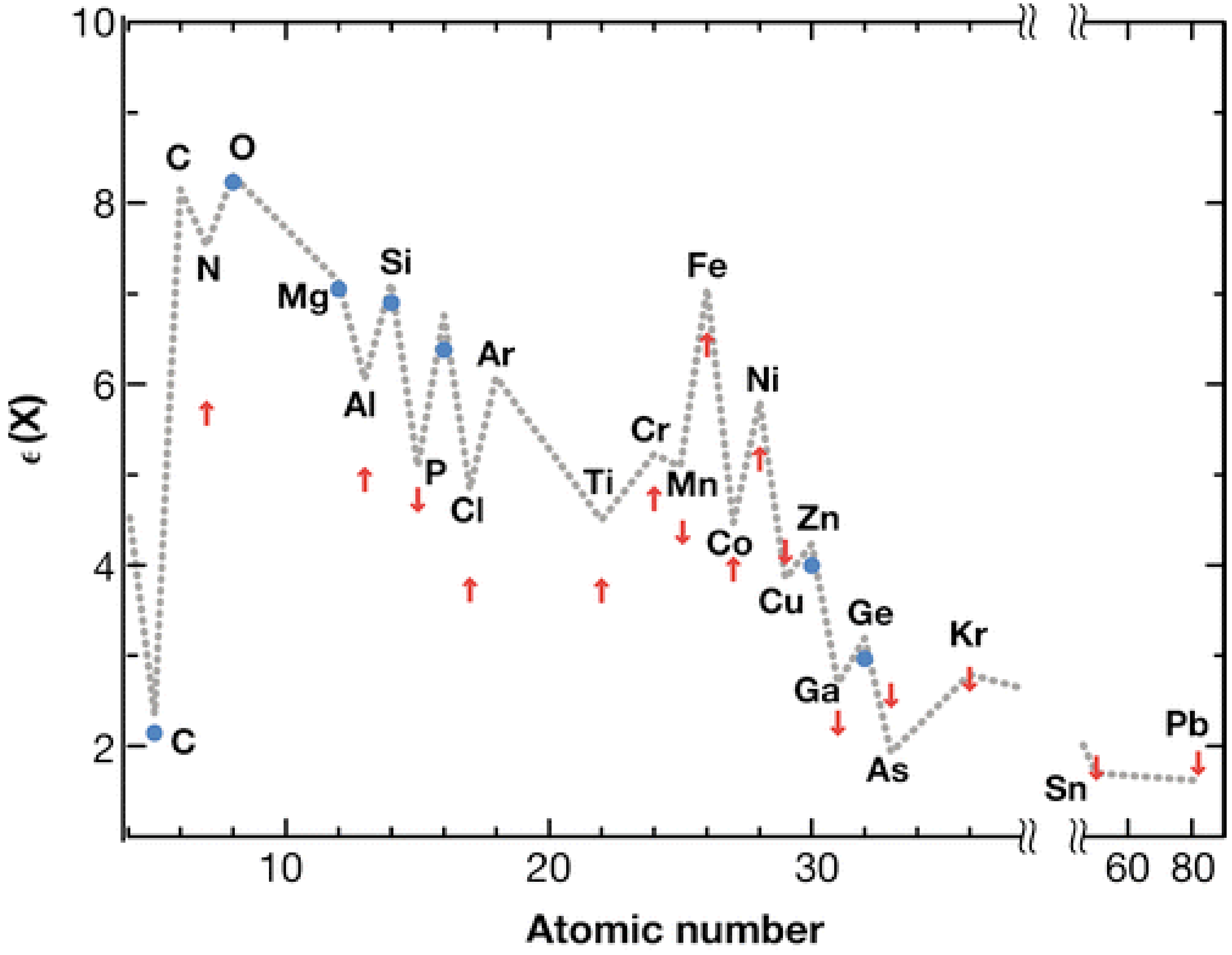


Should we really expect the metallicity to reach solar by z~0? Modelling of 21cm in local galaxies suggests not, since much of the local "DLAs" are low mass, low metallicity galaxies.





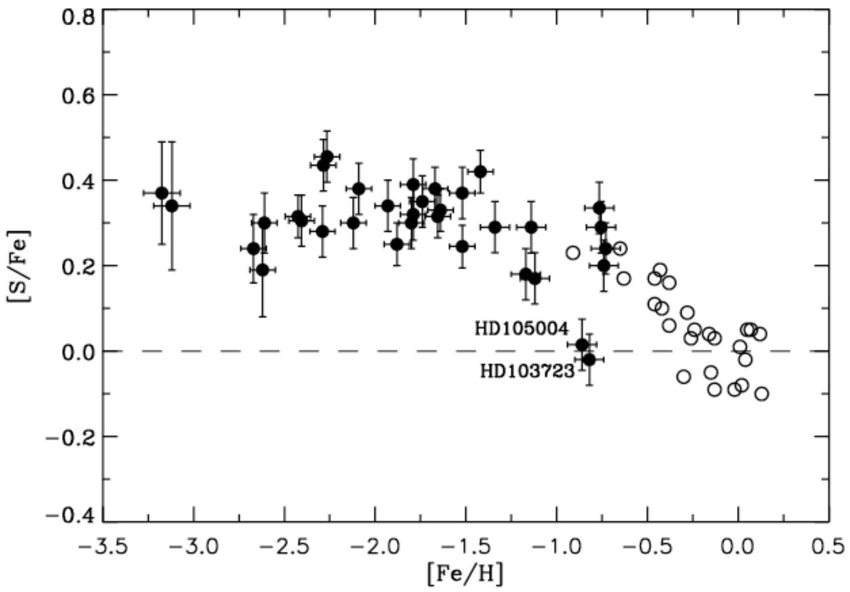
Also, the absorption cross-section is dominated by the outer parts of galaxies. Solar metallicities are only seen in the inner parts usually probed by nebular emission.



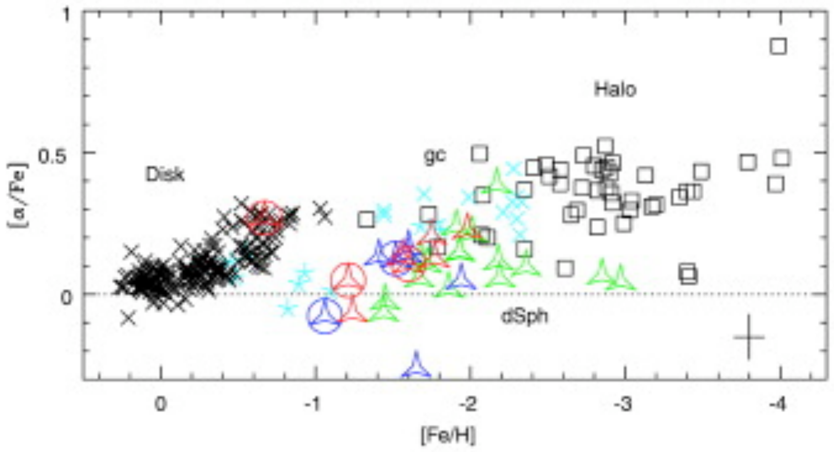
Wolfe, AM et al. 2005
Annu. Rev. Astron. Astrophys. 43: 861–918

Over 20 chemical elements can be measured in DLAs, comparison with local stellar populations can give insight into star formation history.

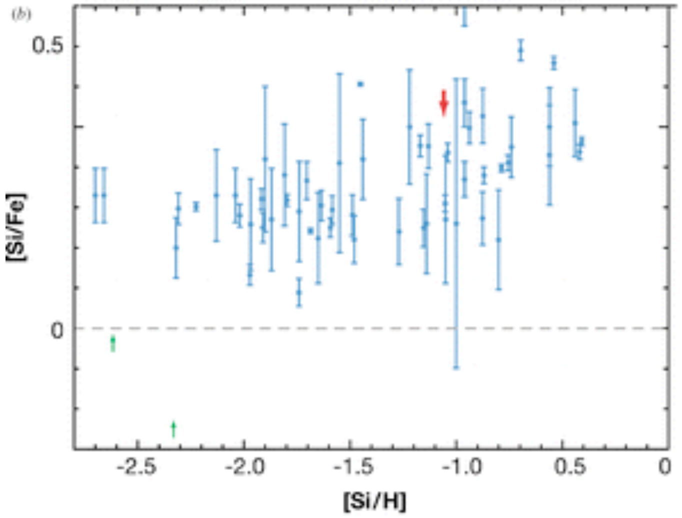
Alpha element abundances - cosmic clock and galaxy diagnostic

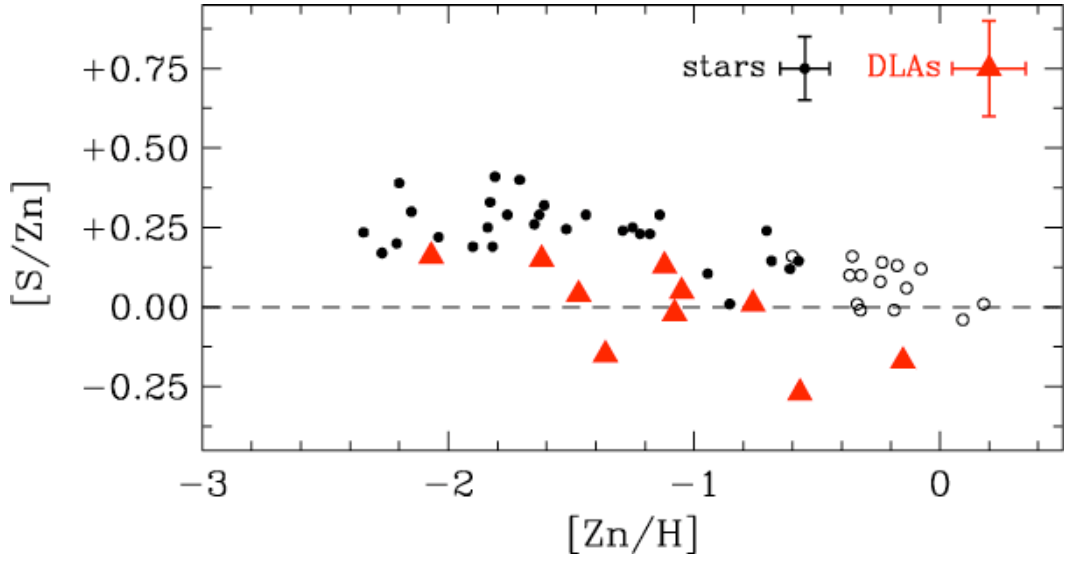


In the Milky Way, [α/Fe] increases at low [Fe/H] as contributions from SNII become more important.



Dwarf galaxies don't have such a strong [α/Fe] enhancement, perhaps due to low SFR or bursty histories.

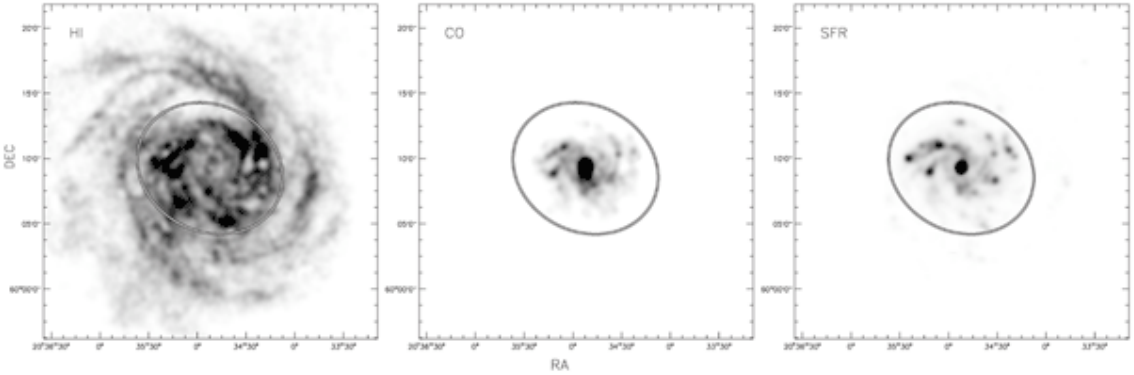




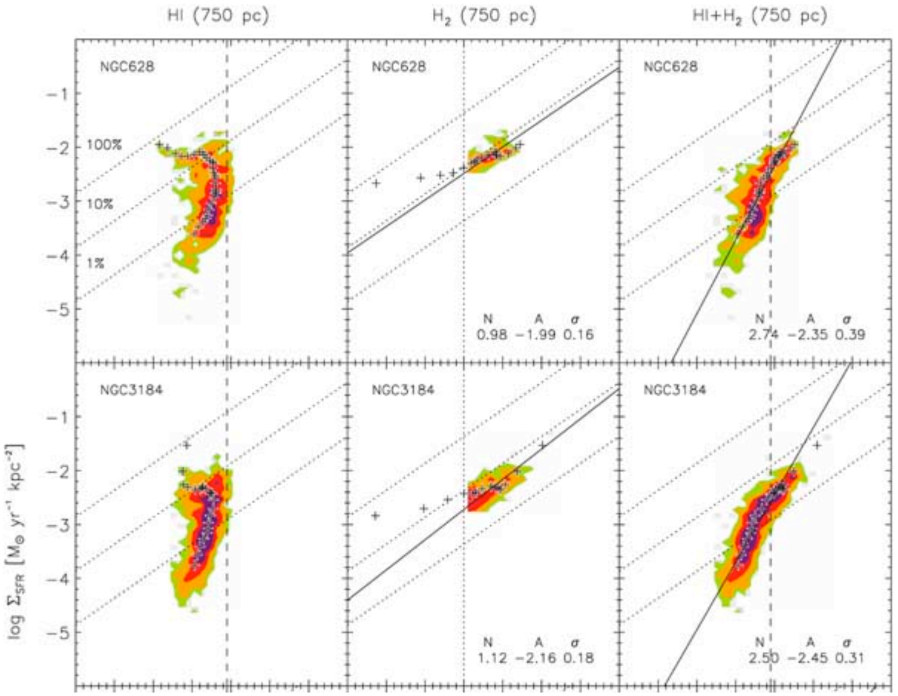
Conflicting evidence in DLAs? [Si/Fe] (which will be affected by dust depletion) suggests a minimum enhancement of 0.3 dex - is this the nucleosynthetic contribution? [S/Zn] (unaffected by depletion) suggests no enhancement. This could be due to problems in the assumption that Zn is a faithful tracer of Fe, since [Zn/Fe] ~ 0.1-0.2 for some thick disk stars. LTE corrections may also reduce stellar [S/Zn] values.

Molecular gas in DLAs

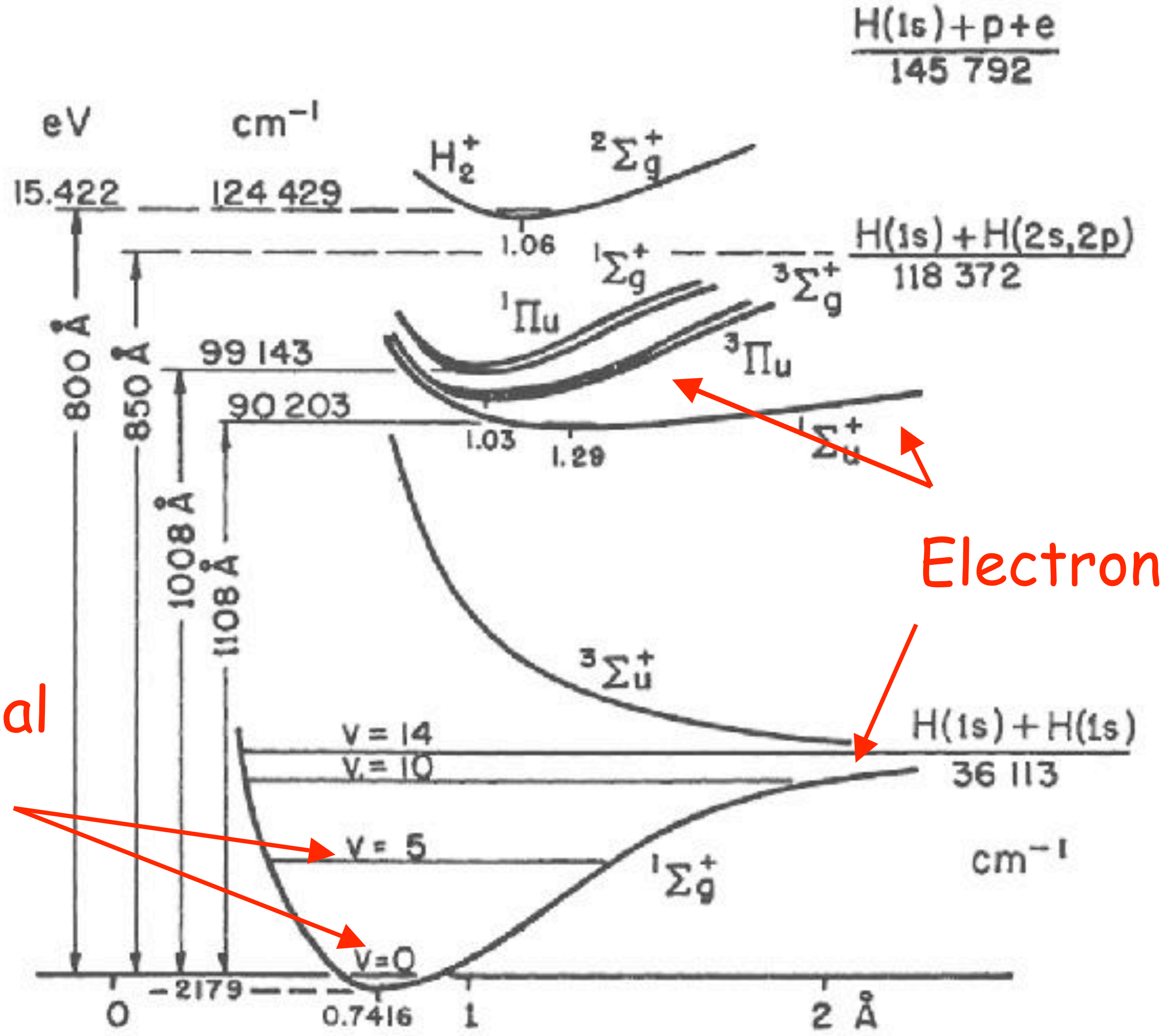
Molecular gas is important because it tells us where stars are forming.



The Kennicutt-Schmidt law of star formation is largely independent of HI, but SFR correlates tightly with H_2. Locally, H_2 is inferred from CO, in DLAs, we can measure it directly.



Molecular gas in DLAs



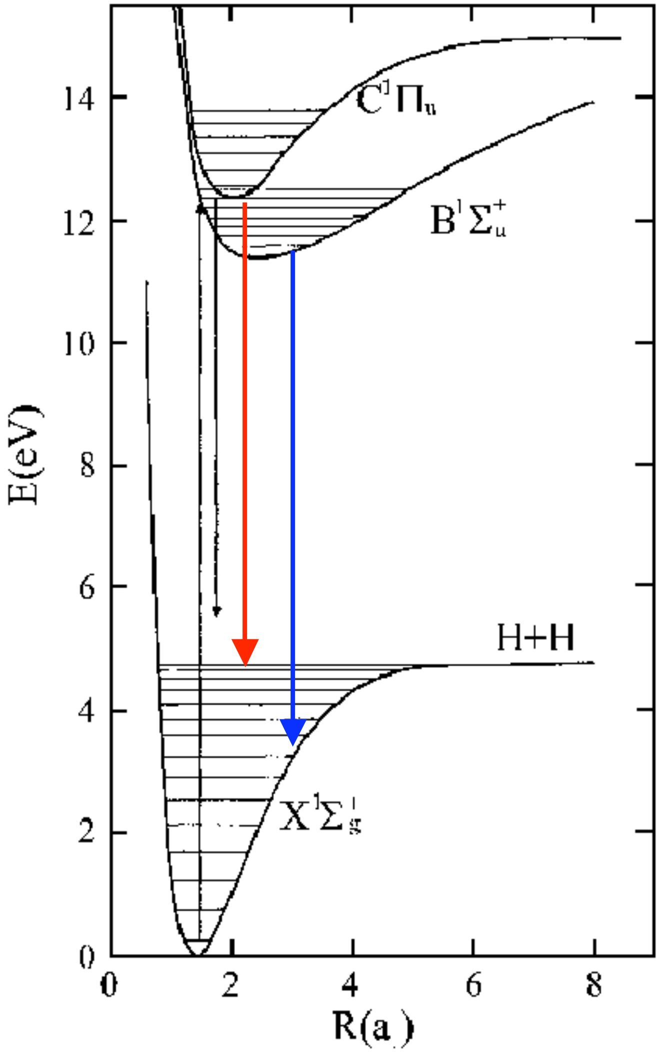
Electronic states

Vibrational states

Vibrational states further divided in rotational (J) states

Molecular gas in DLAs

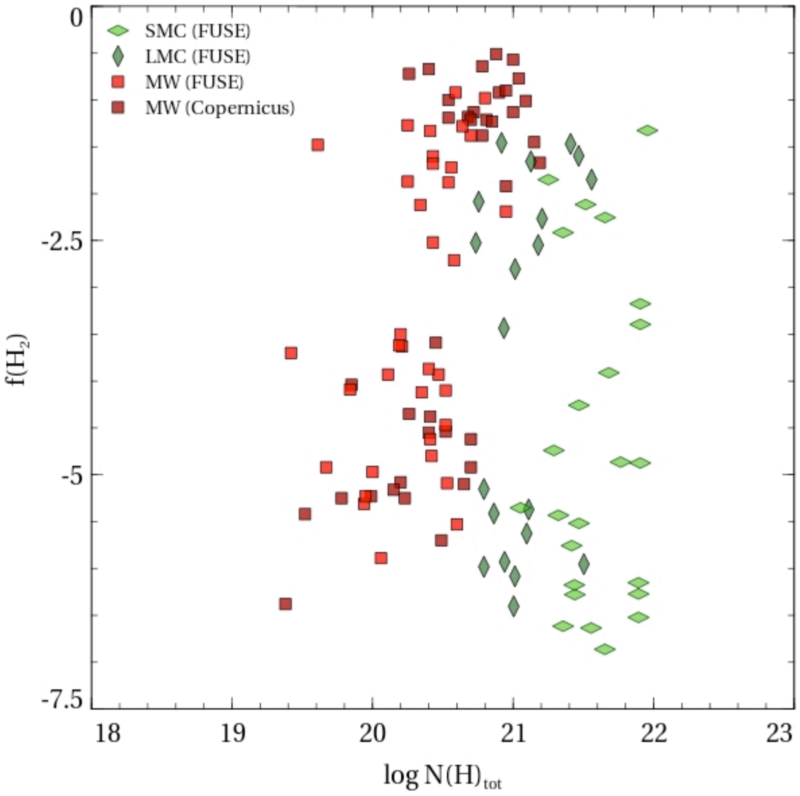
Werner band,
E>11.2eV,
λ<1108 A.



Lyman band,
E>12.3eV,
λ<1008 A.

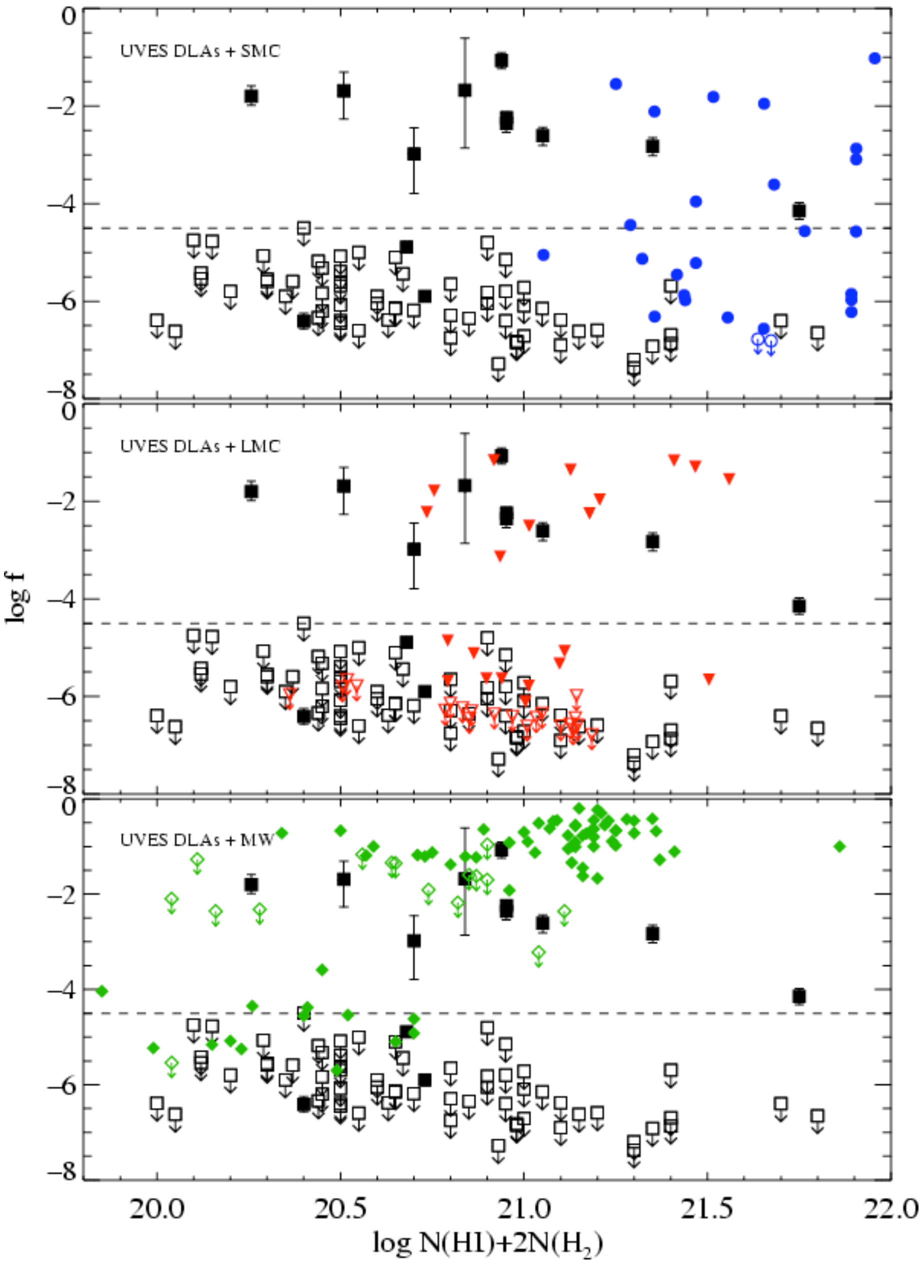
Molecular gas in DLAs

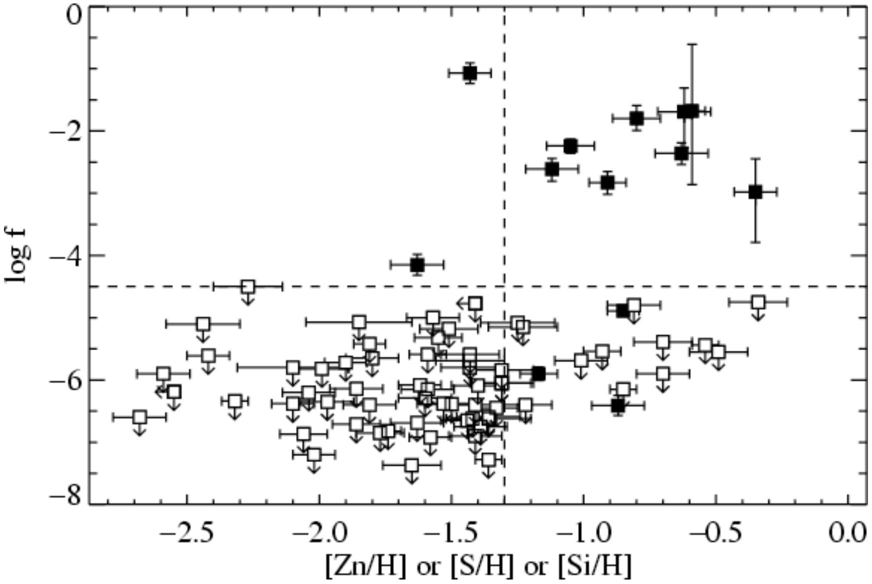
If DLAs are the regions of high z star formation, we expect to see some molecular gas at high N(HI).

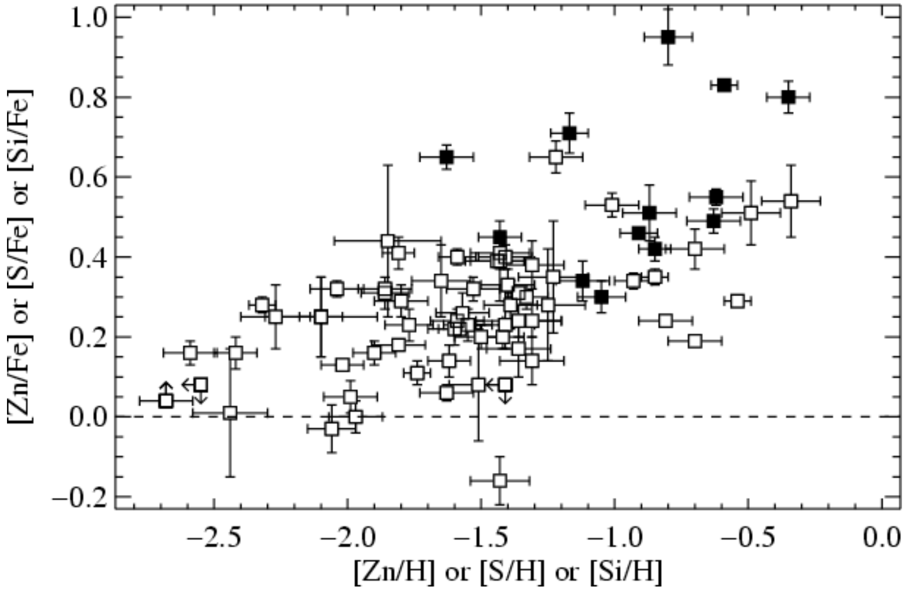


$$f = \frac{2N(H_2)}{[2N(H_2) + N(HI)]}$$

DLAs do not seem to harbour as much H_2 as the MW - neither by molecular fraction, nor by occurence. More similar to LMC. Possible effects of enhanced radiation or suppressed metallicity?



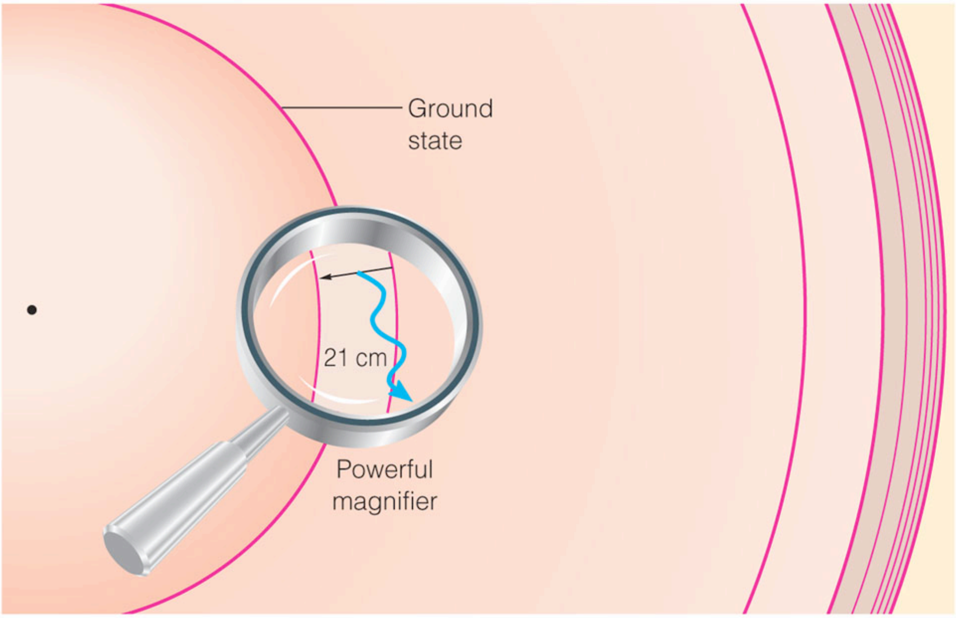


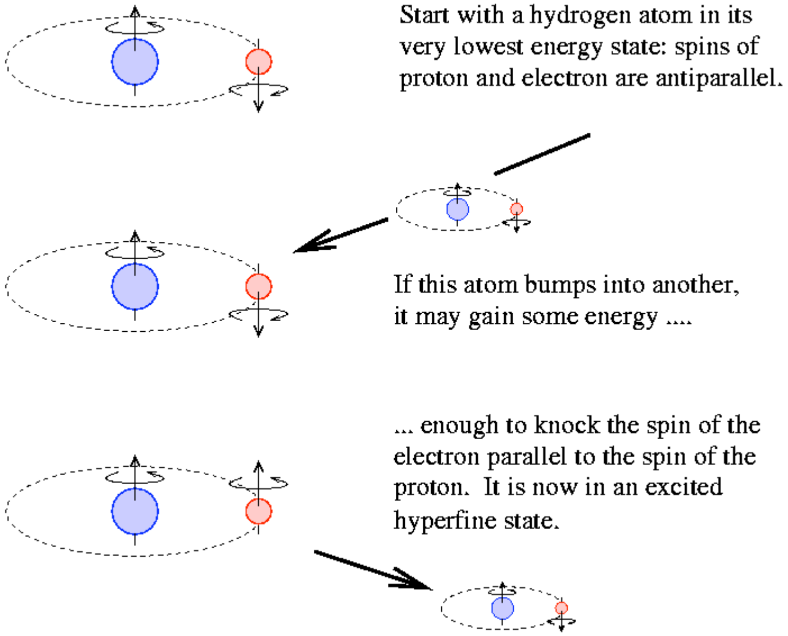


Both metallicity and dust seem to be important in the detection of molecules.

Most recently - a couple pf HD detections and the first detection of CO in a DLA.

DLA spin temperatures





Start with a hydrogen atom in its very lowest energy state: spins of proton and electron are antiparallel.

If this atom bumps into another, it may gain some energy ....

... enough to knock the spin of the electron parallel to the spin of the proton. It is now in an excited hyperfine state.

Radiative decay lifetime for hyperfine transition is 11 Myrs. Since the excitation temperature for the transition is 0.07 K, Boltzmann equilbrium is achieved. Spin temperature is the name given to the temperature measured through this spin-flip transition and since levels are populated by collisions $T_s \sim T_k$.

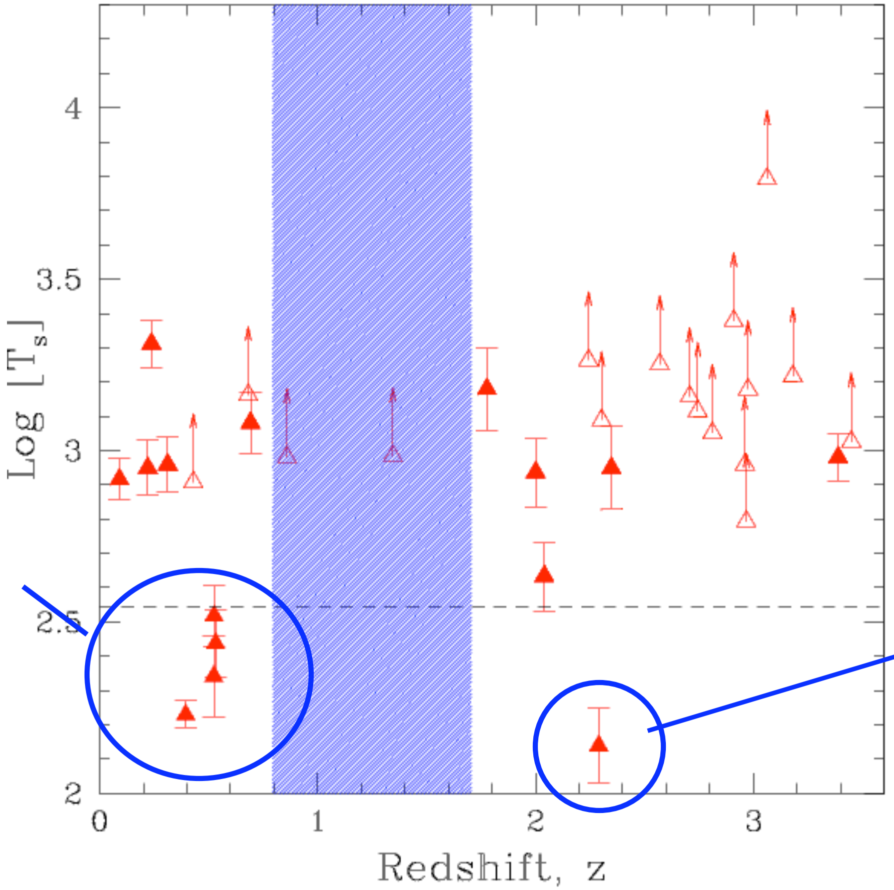
In practice, the spin temperature is obtained by integrating the optical depth over the velocity (or frequency) profile. There is also a dependence on covering fraction, f.

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

If N(HI) is known from Lya observations, then combining this with the 21cm optical depth yields the spin temperature.

In practice, T_s is the column density weighted harmonic mean. E.g. For 90% of gas at 8000K and 10% of gas at 100 K (typical values for the CNM and WNM) the $T_s \sim 900$ K.

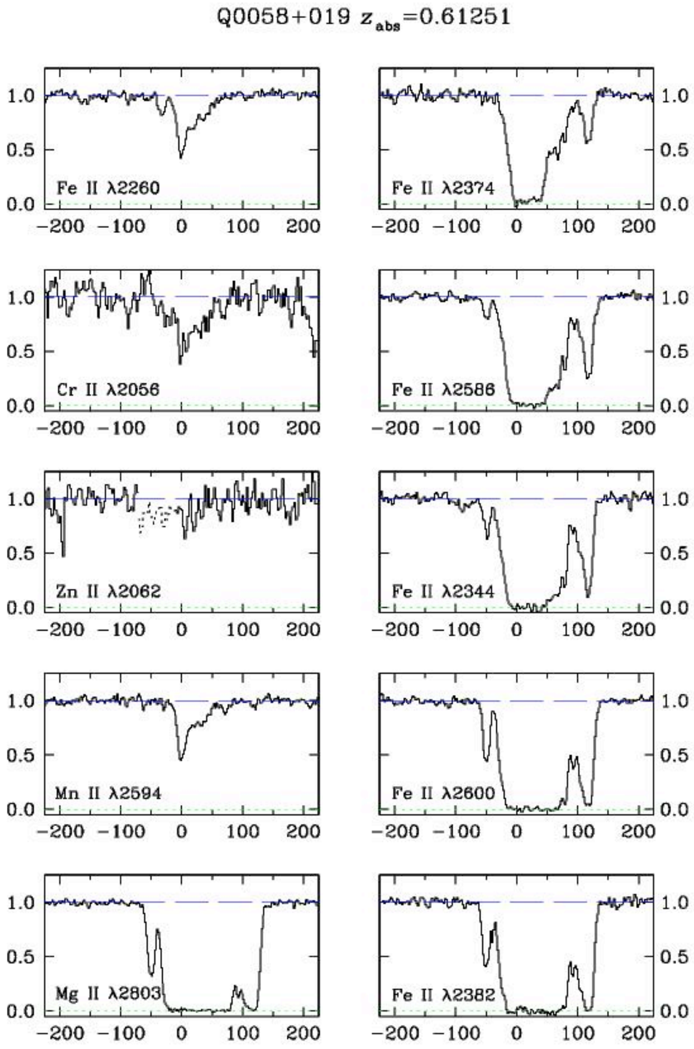
The Milky Way typically has T_s values ~100-300 K whereas dwarf galaxies tend to have T_s > 1000 K. DLAs tend to have high T_s which argues for some contribution from the WNM.

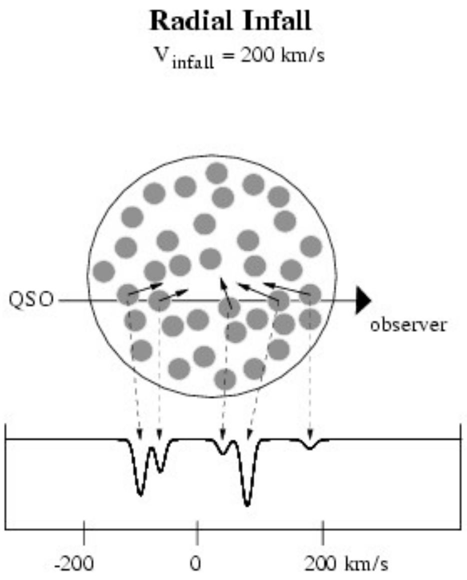


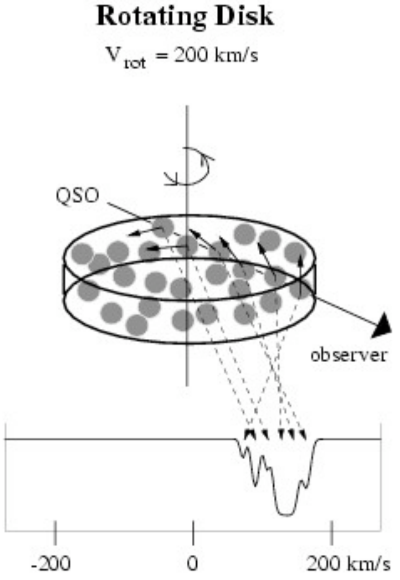
Confirmed Spiral galaxies

Brian York's discovery: only low T_s at high z

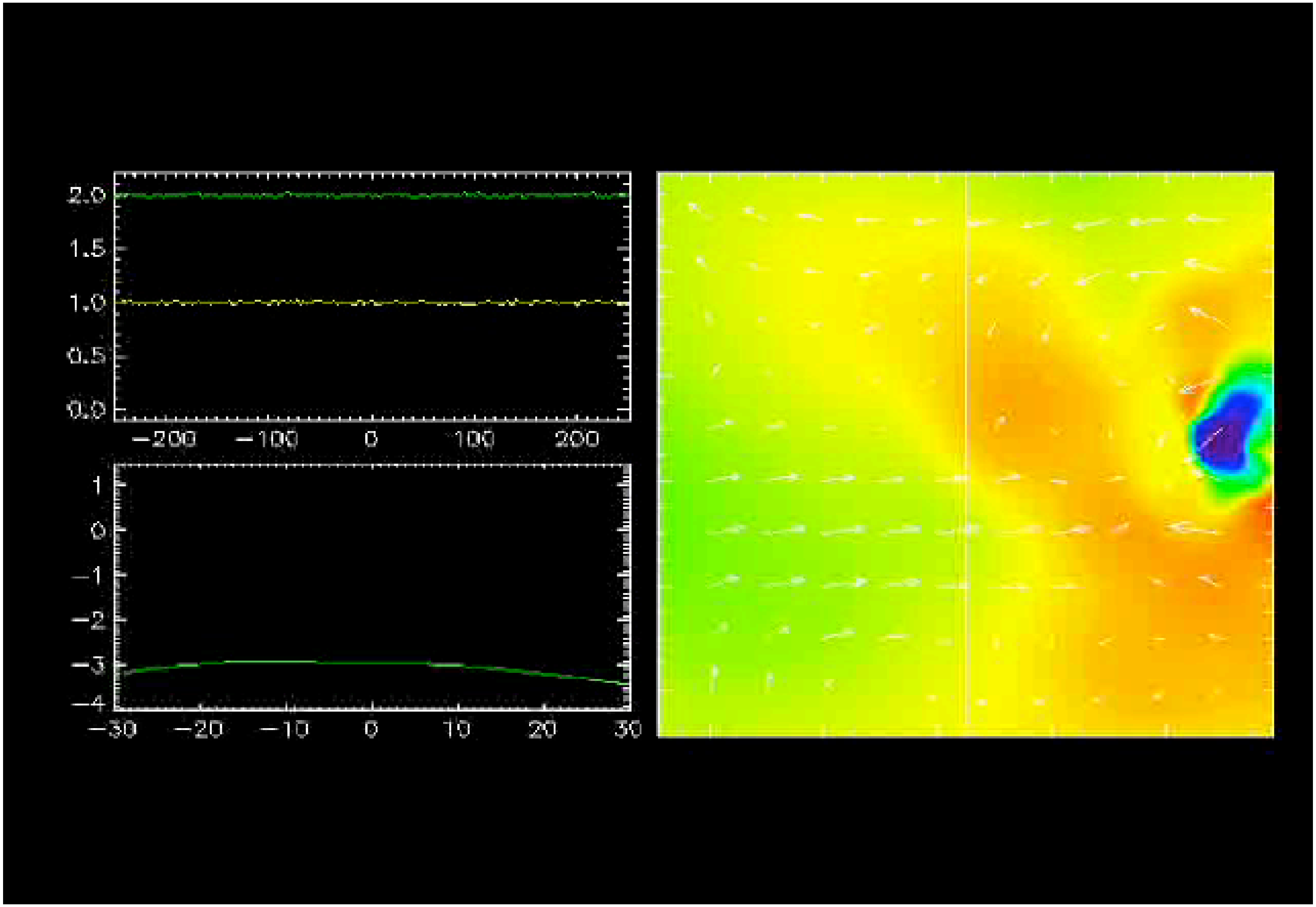
DLA kinematics







Edge-leading asymmetry a signature of disks?



Merging protogalactic clumps also have edge-leading asymetry

Bringing it all together - what are the DLAs anyway?

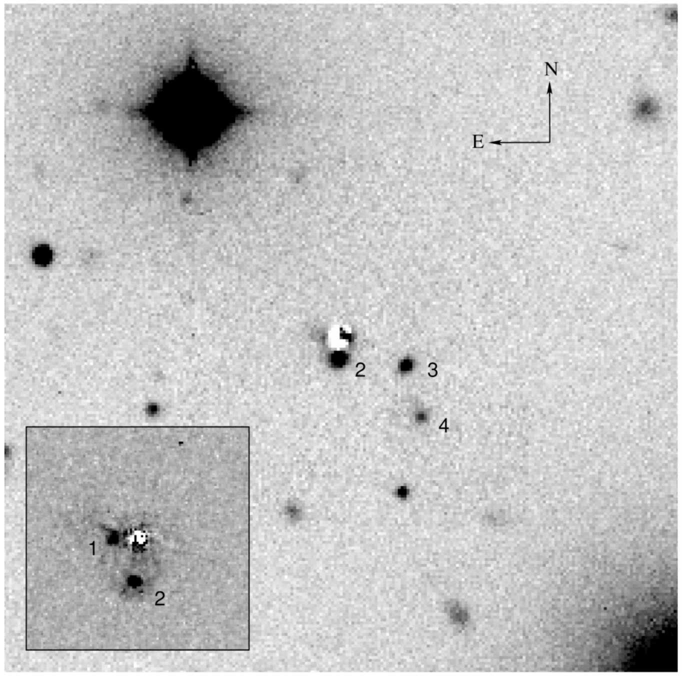
Summary of properties:

- Dominate the HI content at all redshifts
- Are relatively metal poor (~1/30 solar at z~2)
- Have some dust, but not as much as most MW sightlines
- May have a slight alpha enhancement, but less than MW
- Only a few sightlines have H_2, although the incidence increases with metallicity and dust content
- Kinematics may be indicative of rotation, but the signature is ambiguous.
- Spin temperatures are generally high.

But what do they *look* like?

Part III:
The nature of DLAs and how other absorbers fit into the picture.

Direct imaging of DLA galaxies



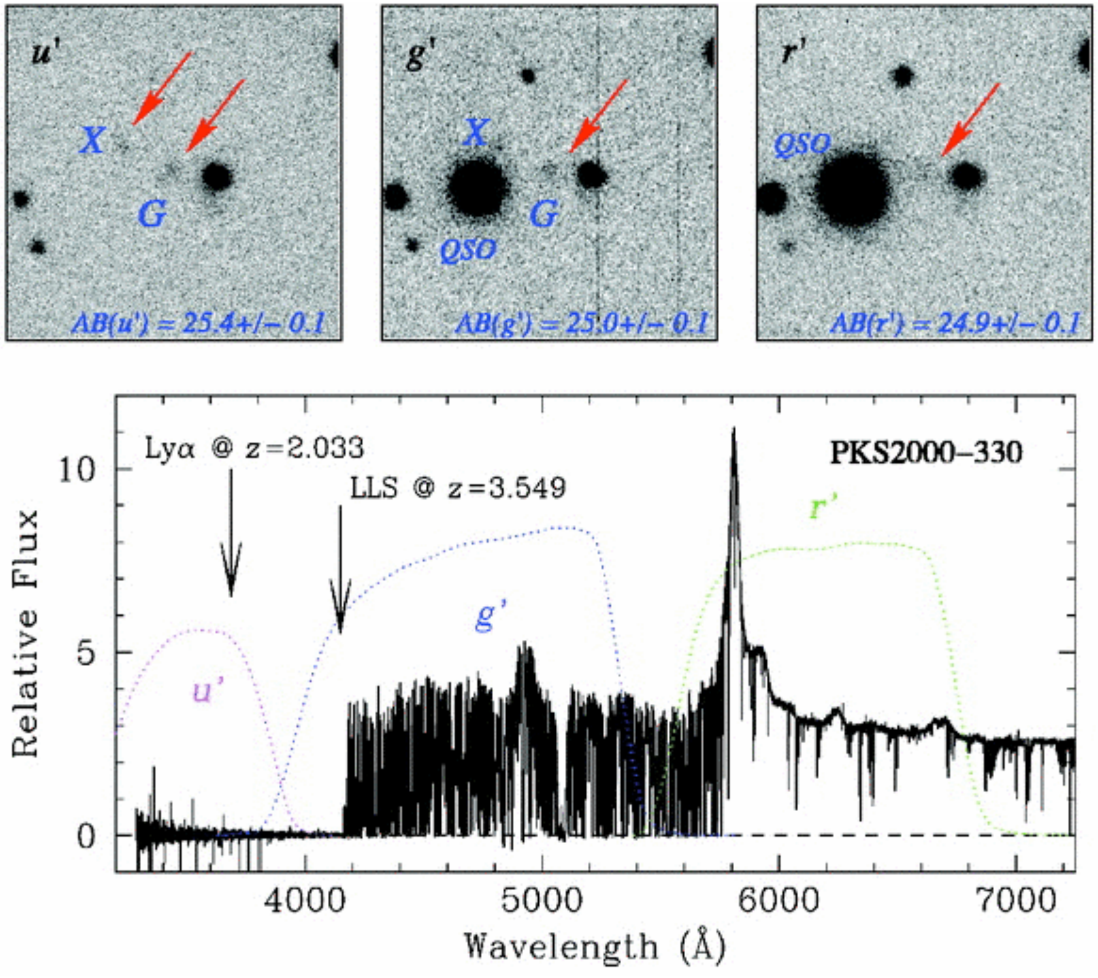
Direct imaging of DLAs is challenging due to a combination of factors.

1) The glare of the QSO
2) The small separation between galaxy and QSO
3) The high redshift (and thus, faintness) of the DLA

Nonetheless, a number of imaging programs have identified galaxies at the redshift of the DLA. They find that DLA galaxies are drawn from a smorgasbord of morphologies. However, the problem remains that there are often multiple galaxies at the right redshift, and how do you know that the real one is still yet to be detected?

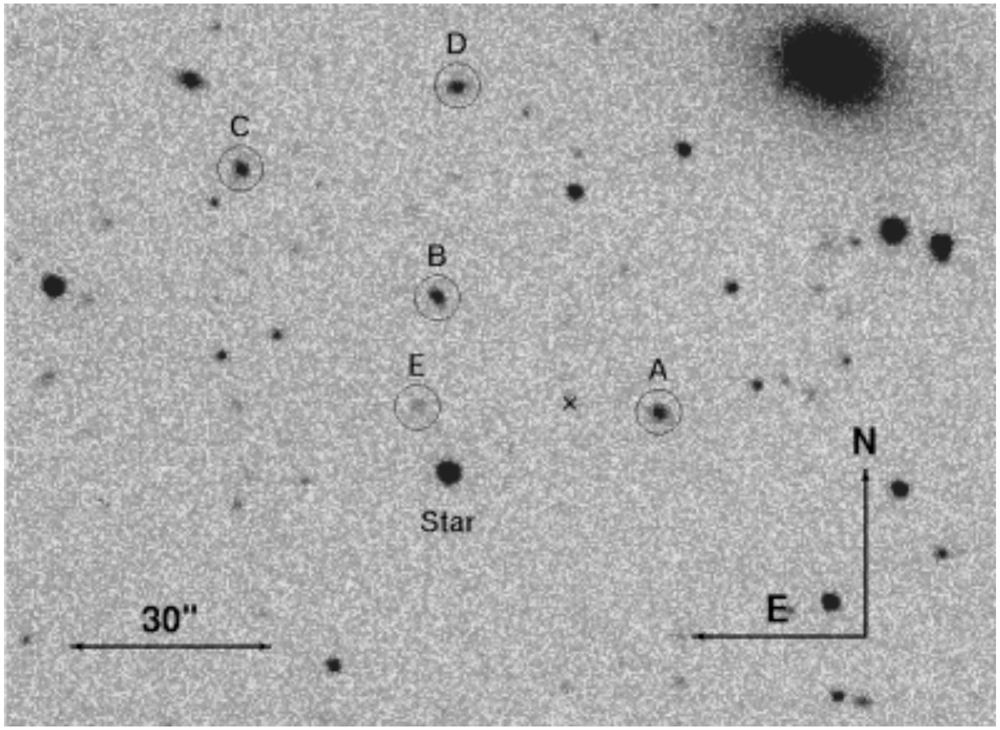
Direct imaging - a few clever tricks

1) Imaging below the Lyman limit. Select DLA candidates (based on strong MgII) and image at λ_r<912 A of a higher z LLS. This provides a natural blocking filter.



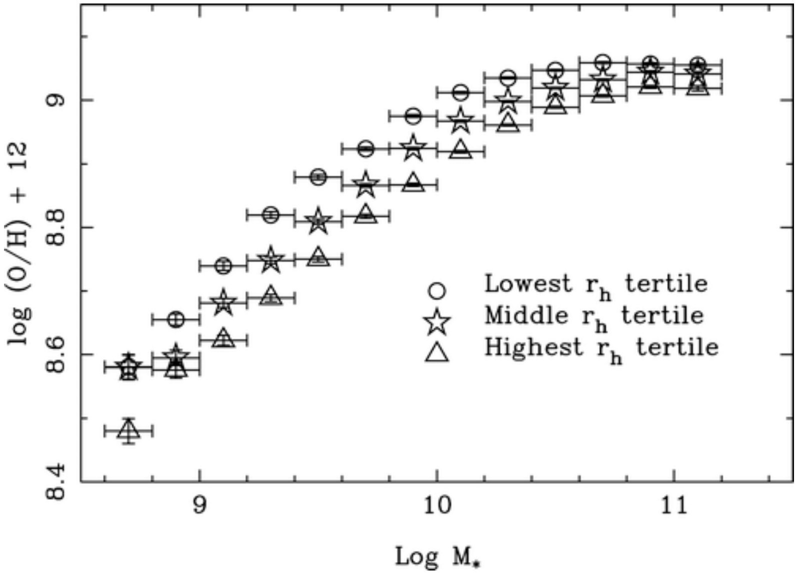
Direct imaging - a few clever tricks

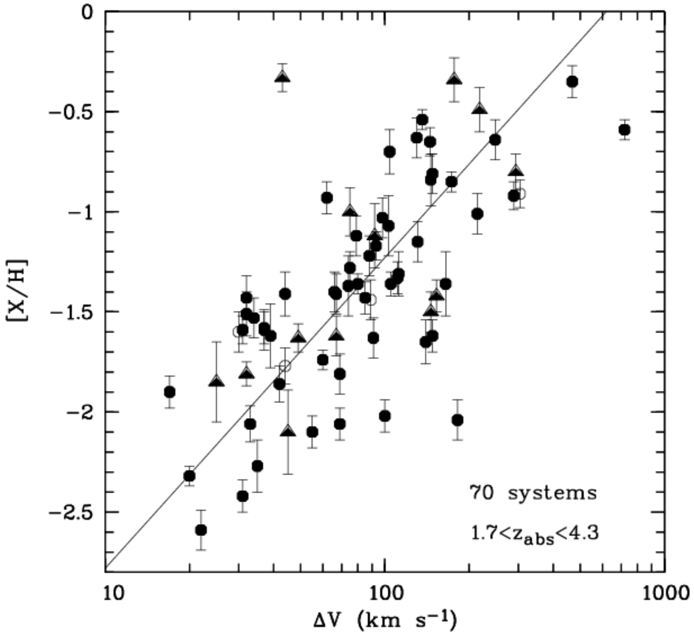
2) Imaging of a GRB field once the optical afterglow has faded. This avoids the problem of glare, but the issue of unambiguous identification is impossible to circumvent.



Clues from the mass-metallicity relation?

Beautiful MZR in the general galaxy population with scatter contributed by galaxy properties and environment.

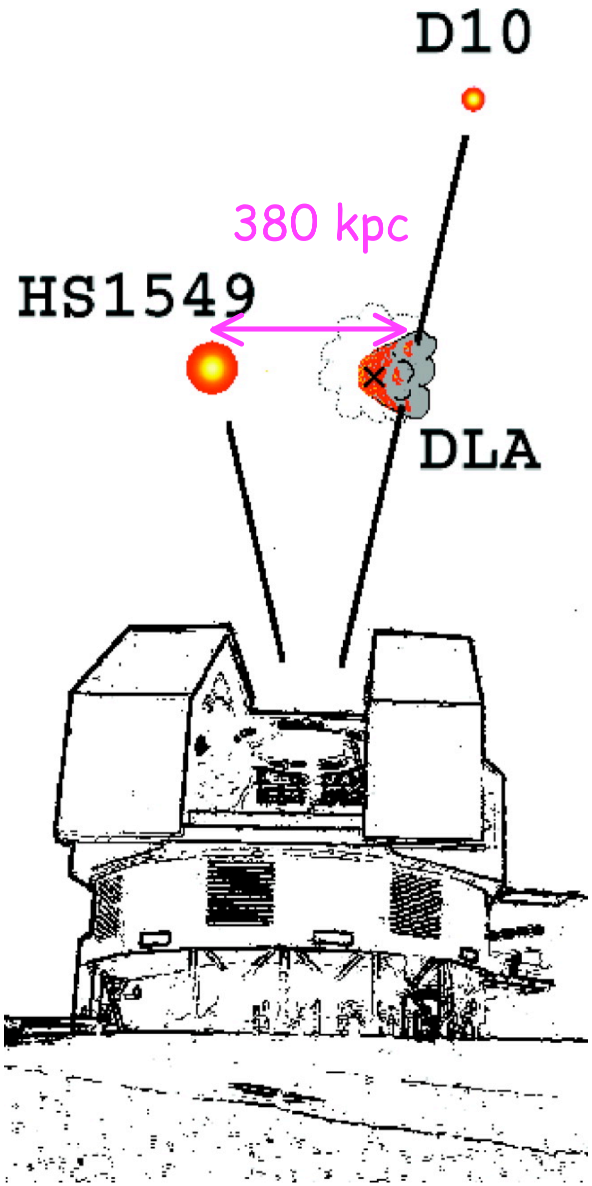


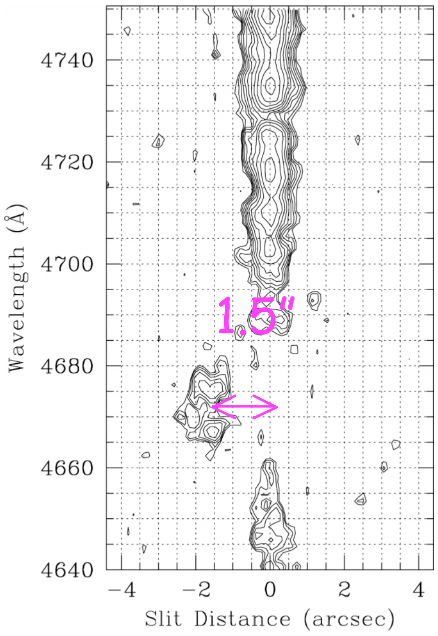


If velocity spread is assumed to be indicative of mass, a similar relation may exist in DLAs. More evidence that DLAs represent a wide range of galaxy types?

Are there other physical properties that can be measured?

The sizes of DLAs



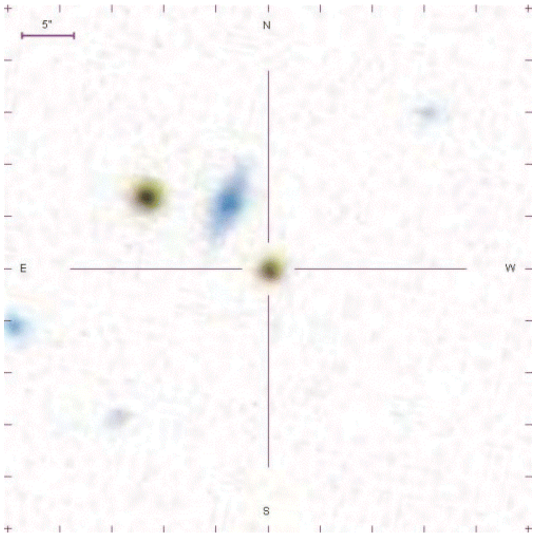


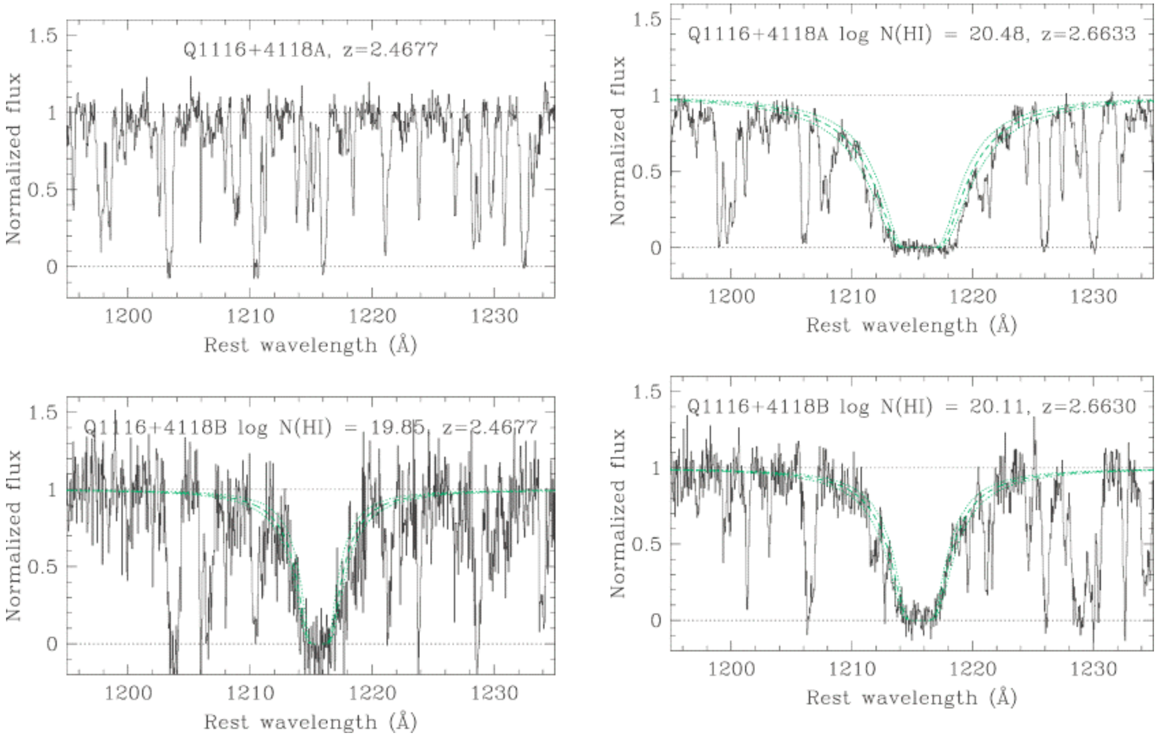
In one case fluorescence has been detected. The separation of the 2 sightlines at the redshift of the DLA is 380 kpc (proper).

Separation of fluorescence from QSO gives a lower limit to the size of the absorbing galaxy: 1.5" -> 12 kpc.

The sizes of DLAs

The size of DLAs can be inferred even if the galaxy is not directly detected, e.g. through lensed or pairs of QSOs.

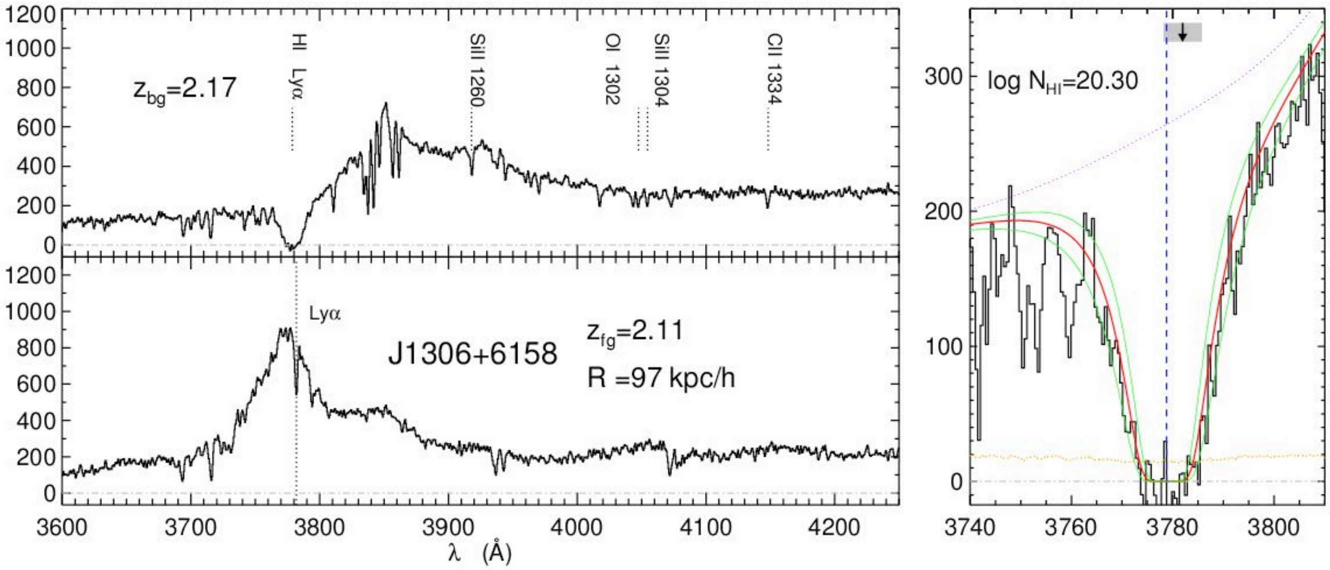




But the interpretation is not always obvious. In this pair, the separation is over 100 kpc, so the coincident absorption is unlikely to be due to the same galaxy. Clustering?

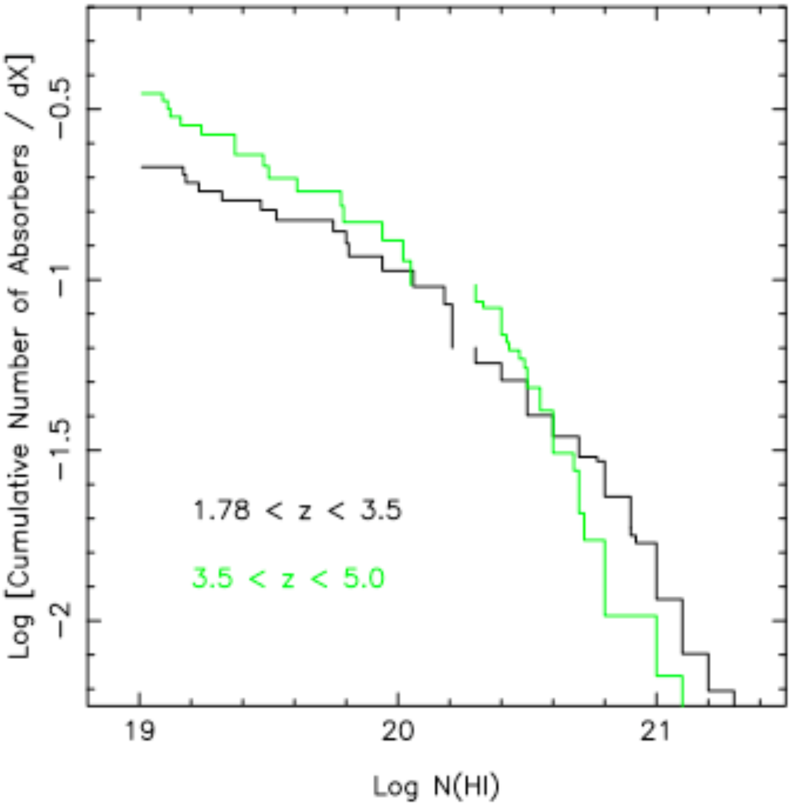
Clustering in DLAs

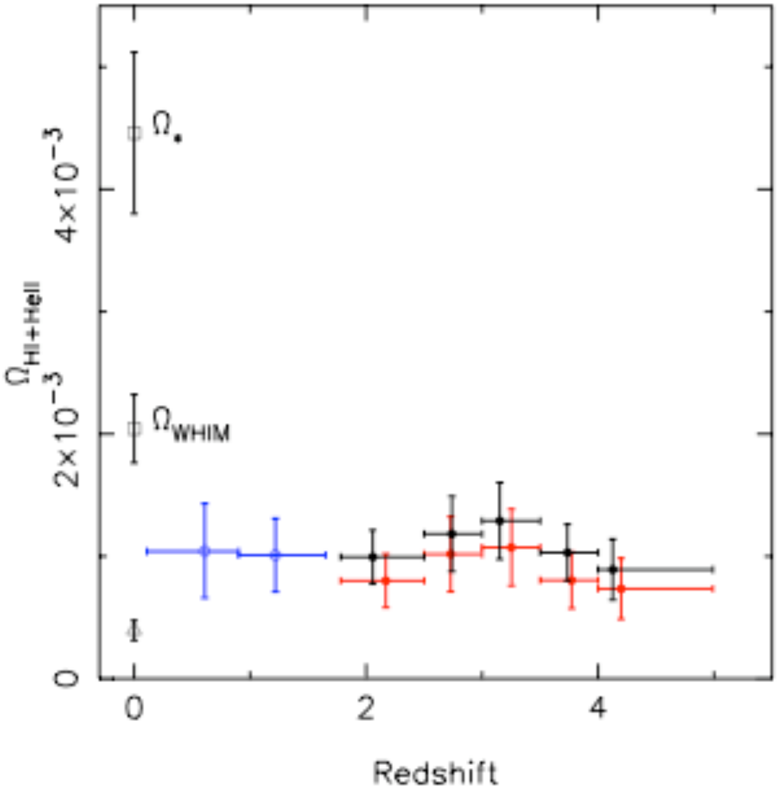
Proximate DLAs (within 3000 km/s of the QSO) are 2-4 times more common than intervening DLAs.Clustering in transverse absorbers: 50% of background QSOs show N(HI) > 10^{19} in absorption at the redshift of the foreground QSO when R < 150 kpc: a clustering signal 4-20 stronger than that seen in PDLAs.



Recent additions to the QAL zoo: sub-DLAs

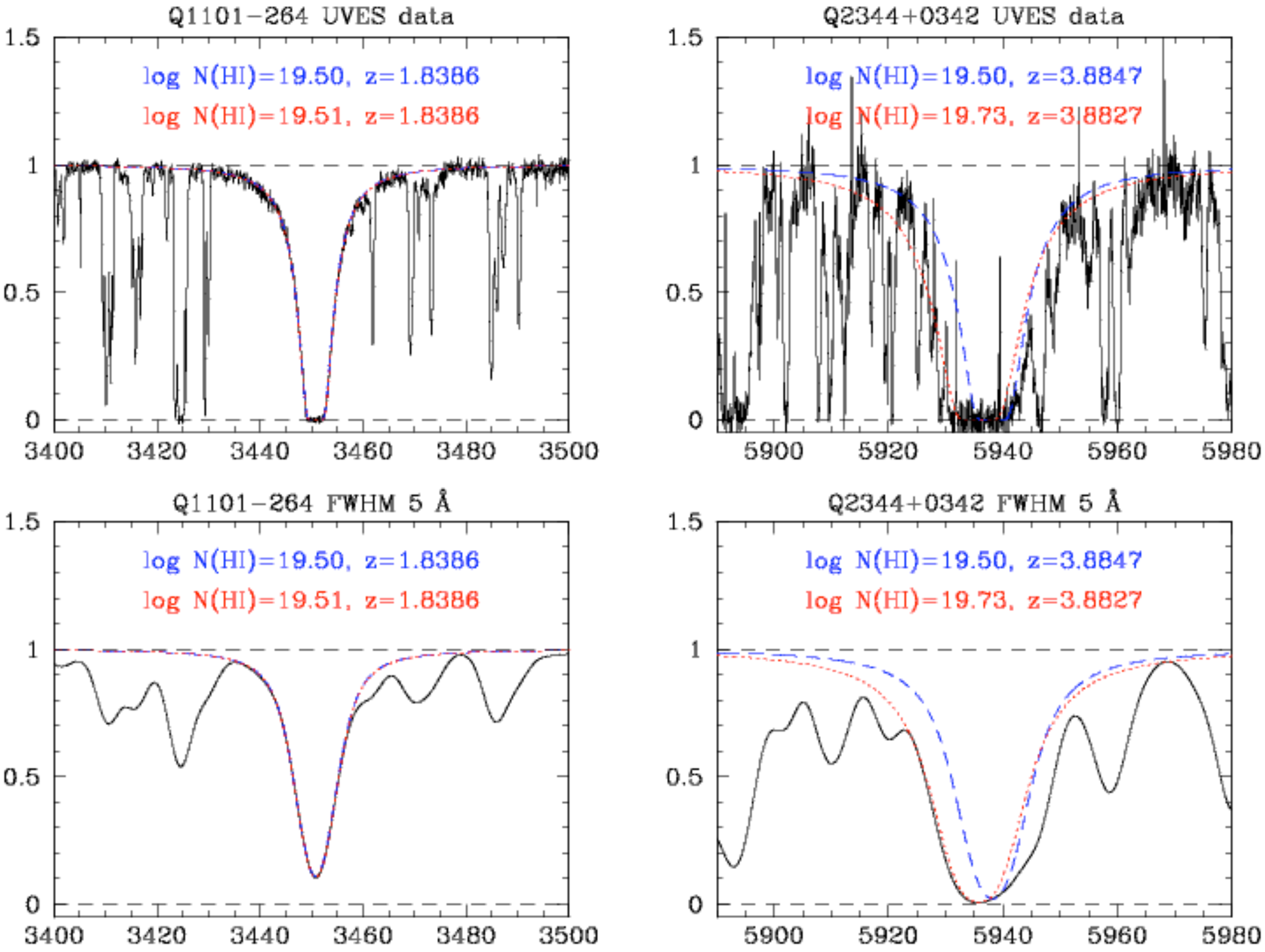
The contribution from sub-DLAs (19.0 < log N(HI) < 20.3) may be important, particularly at high z, but this is hotly (bitterly) debated. Sub-DLAs probably contain a significant fraction of ionized gas.





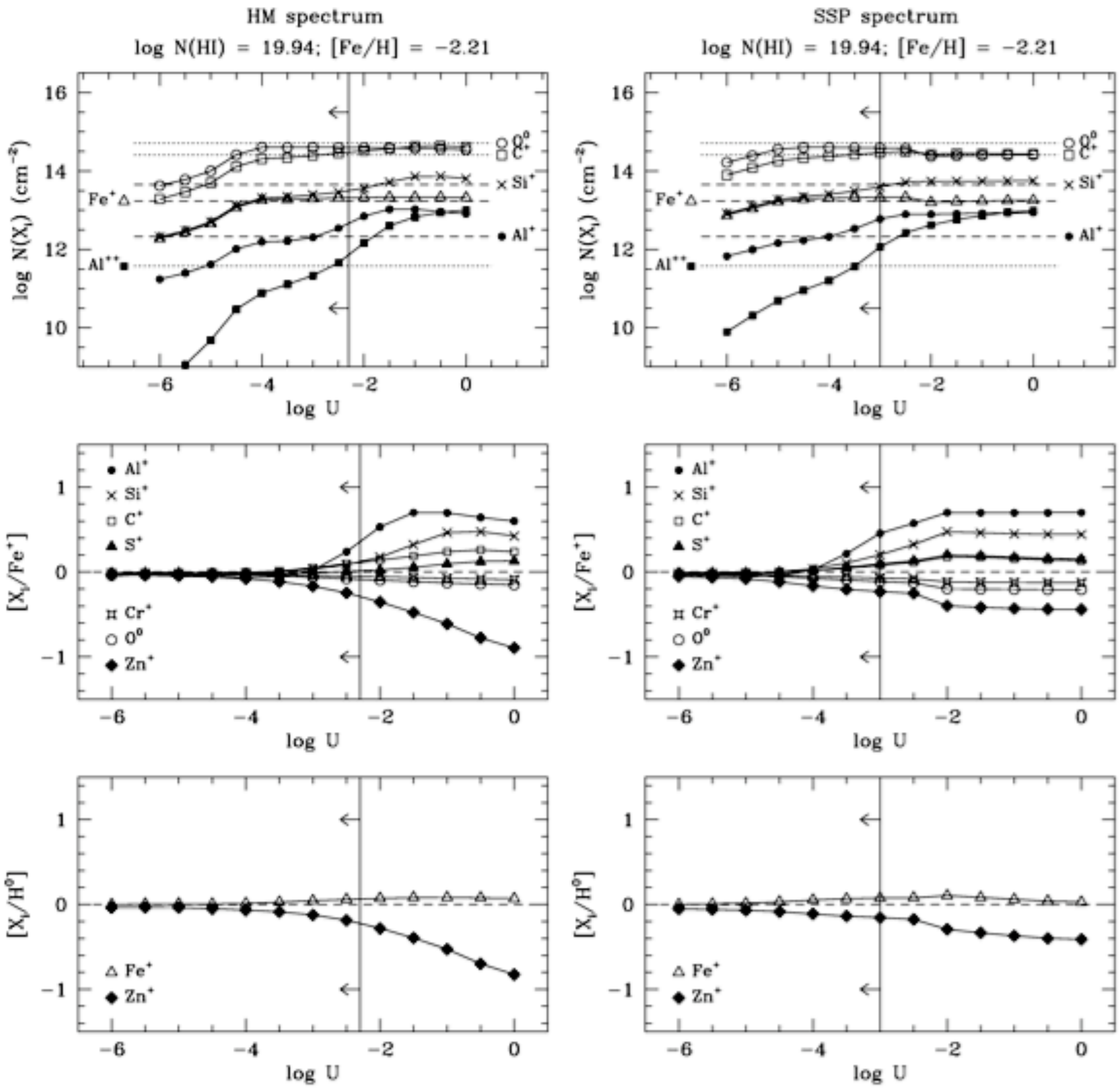
Sub-DLAs: some caveats

In order to determine N(HI) accurately, you need to be able to resolve the damping wings. For sub-DLAs, this really requires high resolution data.

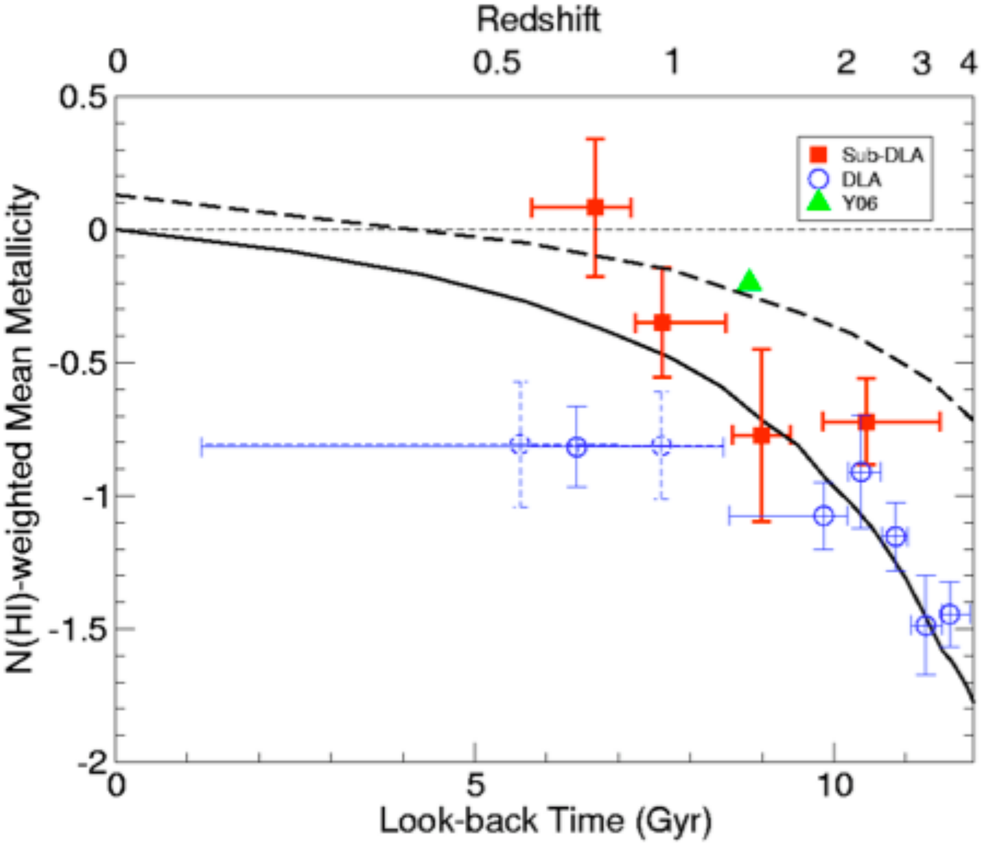


Sub-DLAs: some caveats

In order to determine [X/H] accurately, we must consider ionization corrections. There is considerable debate about the magnitude and direction of these corrections!



Sub-DLA metallicities are systematically higher than DLAs, and several sub-DLAs have abundances in excess of the solar value at z~2! The evolution also appears to be steeper than for DLAs.



High metallicities might mean high mass? Or selection bias?

Some open questions

- What is the nature of the sub-DLAs and why are they more metal-rich?

- What is the nature of the DLAs that are clustered around the QSO?

- What happens to Ω_{DLA} at $0<z<1$? How to reconcile high values at $z\sim2$ with local 21cm values.

- At what epoch is DLA gas assembled?

- Are we missing metals?

- Can we start to overlap 21cm studies with absorption?

Other applications of QAL

- Testing Big Bang nucleosynthesis through primordial D/H abundances

- Probing the redshift change of fundamental constants

- Tracing the enrichment of the intergalactic medium

- Finding `real-time' expansion of the universe

- Signatures of re-ionization

- Measuring the size of structures in the IGM

- Measuring the strength of the UV background radiation