Evolution of Metals and Dust in Galaxies: Damped and Sub- damped Lyman Alpha Quasar Absorbers from SDSS

Varsha P. Kulkarni
University of South Carolina

Collaborators

Joseph Meiring (Univ. of South Carolina)
Celine Peroux (Marseille)
Donald G. York (Univ. of Chicago)
Pushpa Khare (Utkal Univ.)
Giovanni Vladilo (Trieste)
James T. Lauroesch (Univ. of Louisville)
Arlin Crotts (Columbia Univ.)
Debopam Som (Univ. of South Carolina)

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Motivation

- History of element formation closely linked to history of star formation and gas consumption
- Metal content of a galaxy is a unique tracer of star formation and feedback processes

- So, we aim to measure chemical composition of galaxies at a range of redshifts

BUT… hard to study chemical composition of distant galaxies from just their emitted light.

- An alternative approach: Look for absorption signatures against bright background sources (e.g., quasars).

- Absorption line strengths depend on just the amount of gas along the sightline, not on galaxy luminosity. So expect to get a less biased picture than flux-limited imaging surveys, in principle.

A Typical Quasar Spectrum

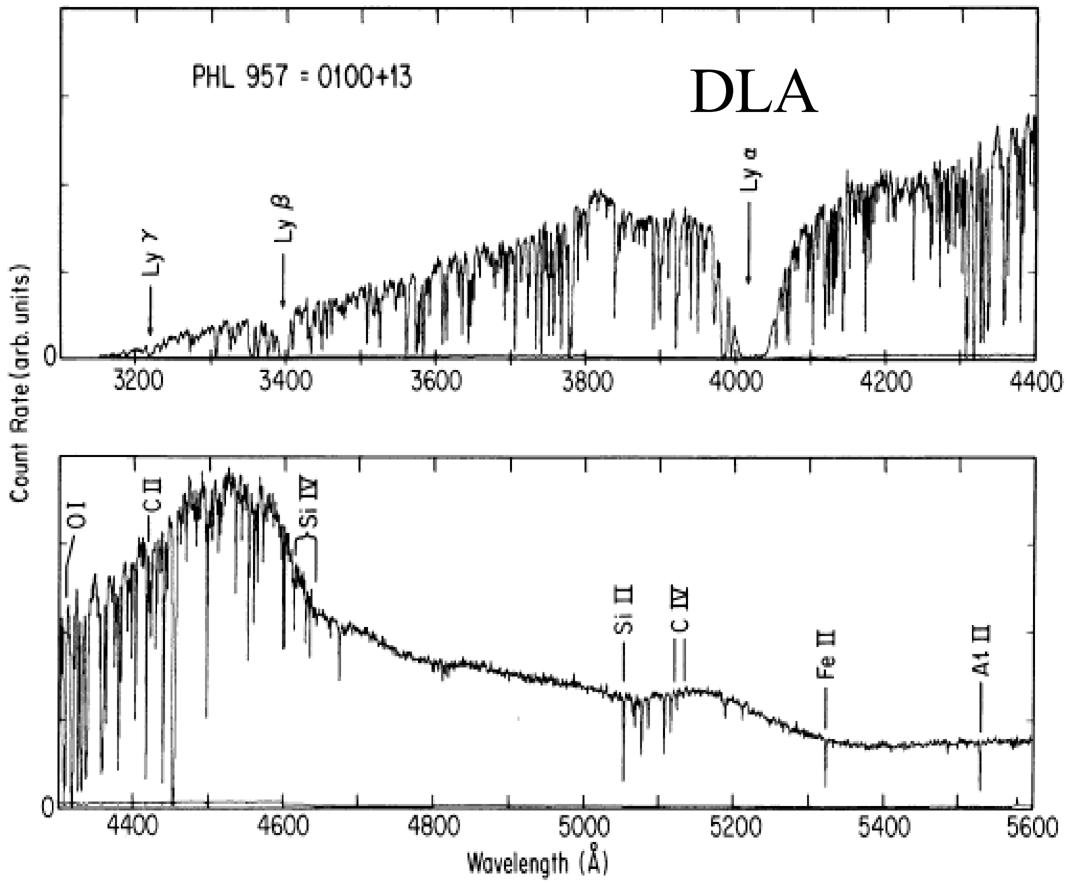
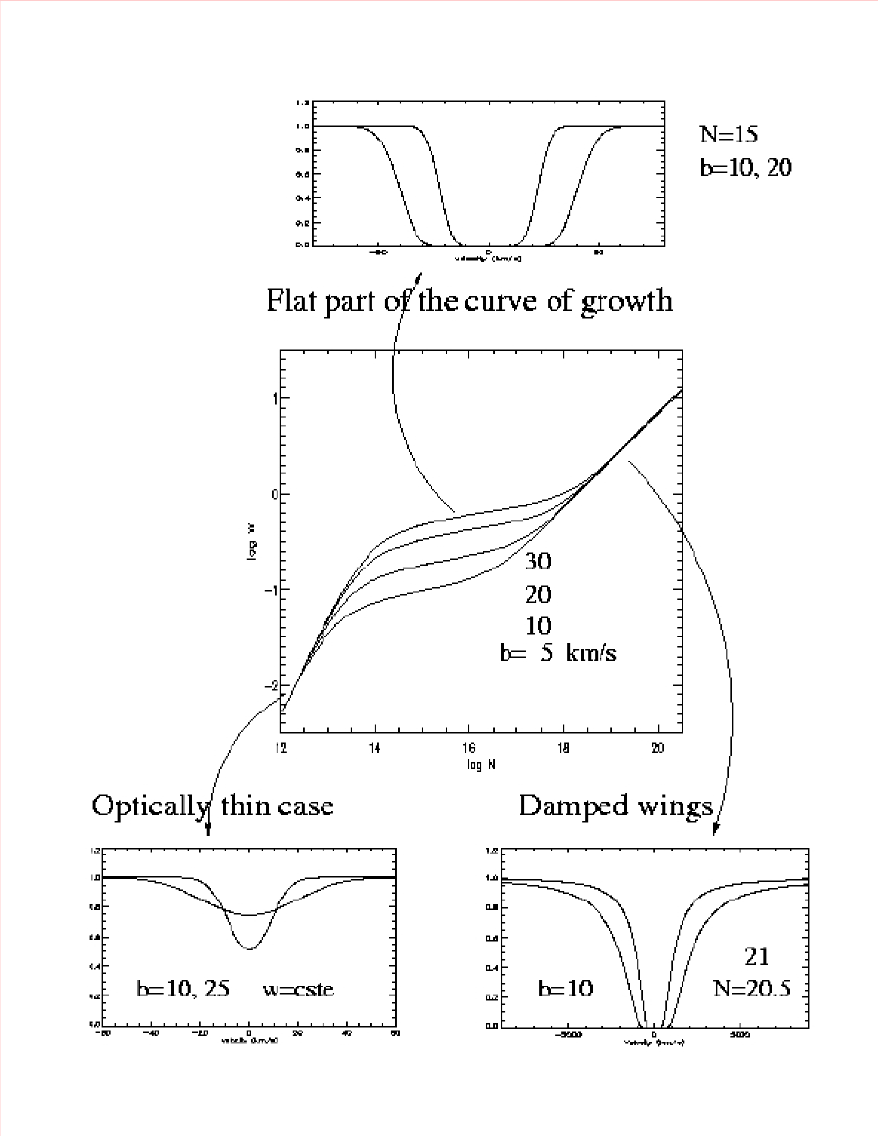


FIG. 1.—1 Å resolution spectrum of PHL 957 obtained with the MMT spectrograph. No attempt has been made to flux calibrate the data so the overall shape of the continuum reflects the wavelength dependent sensitivity of the instrument and atmospheric extinction. The lower curve presents the 1 σ level as derived from count statistics in the object and night sky spectra (plus dark emission). Discontinuities in the error spectrum indicate the edges of individual observations. Absorption lines longward of the Lyman-α forest in the $z = 2.309$ system are marked.

Black, Chaffee, & Foltz 1987



Ly-alpha Forest:

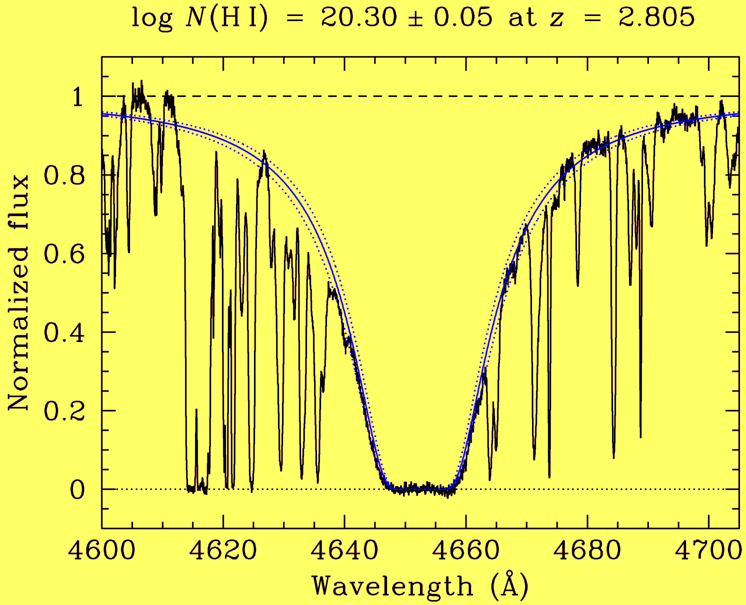
Optically thin, highly ionized;
Trace intergalactic gas or gas in outer regions of galaxies

Damped Ly-alpha Absorbers:

Optically thick, largely neutral
Trace interstellar matter in galaxies

Damped Lyman-Alpha (DLA) Absorbers

Neutral Hydrogen Column Density N(H I) $\geq 2 \times 10^{20}$ cm^{-2}



Sub-Damped Lyman-Alpha (sub-DLA) Absorbers

Neutral Hydrogen Column Density $10^{19} \leq$ N(H I) $< 2 \times 10^{20}$ cm^{-2}

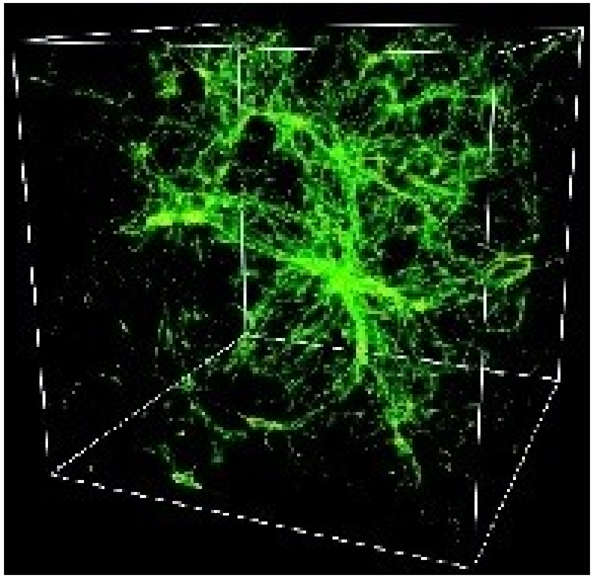
- Weaker than the classical DLAs, but show damping wings
- Sometimes also called "super Lyman-limit systems"

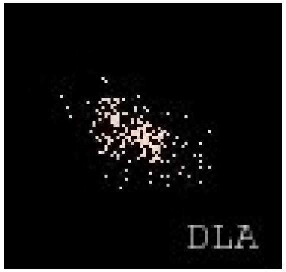
Most previous studies focussed on DLAs, not sub-DLAs.

DLAs as Probes of Metal Enrichment and Star Formation in Galaxies

• DLAs and sub-DLAs contribute a large fraction of H I in galaxies, and are the best existing probes of element abundances in distant galaxies over ~90% of cosmic history. So expected to shed light on the history of metal production and star formation in galaxies.

• DLAs are predicted to correlate with regions of star formation in numerical simulations of galaxy formation (e.g. Cen et al. 2003, Nagamine et al. 2004).





Metallicity Indicators

Use Zn to trace metallicity:

- nearly undepleted on ISM dust grains
- dominant ion Zn II has 2 lines that are usually unsaturated and lie outside the Ly-alpha forest.

- Use Cr/Zn, Fe/Zn etc. to trace dust content.

Evolution of Metallicity

- • Most cosmic chemical evolution models predict rise in global mean interstellar metallicity of galaxies with time, from low values at high z to near-solar values at z=0
- (e.g., *Pei & Fall 1995; Malaney & Chaboyer 1996;*
- *Pei, Fall, & Hauser 1999; Somerville et al. 2001*).

• Mass-weighted mean metallicity of nearby galaxies is indeed near-solar (e.g., *Kulkarni & Fall 2002; Fukugita & Peebles 2004*).

- **• Do DLA data show rise of global metallicity with time progressing to ~solar value at z~0?**

So does the DLA global metallicity evolve?

A Bit of History:

- Considerable debate existed over this issue (e.g., Pettini et al. 1999; Prochaska & Wolfe 1999; Prochaska et al. 2001; Savaglio 2001)

- Data could support evolution at ~2-3 e level but were also consistent with no evolution (Kulkarni & Fall 2002; Prochaska et al. 2003)

What made the DLA Z(z) relation uncertain?

- **Main Problem:** very few measurements existed at low z

  --Zn II e □2026, 2062 lines lie in UV for z < 0.6, in blue for 0.6 < z < 1.5

  --DLA Ly-alpha lines lie in UV for z < 1.6

- Need access to UV/ blue-efficient spectrographs

Why is Z(z) at z < 1.5 important?

F z < 1.5 is ~ 70% of the age of the Universe!

F Cosmic star formation rate was much higher at 1 < z < 1.5 than at z~0. So metallicity at low z should be higher

Can also clarify the relation of DLAs to present-day galaxies.

It was difficult to make much progress until the past few years, since not enough absorbers with z < 1.5 were known.

SDSS has greatly expanded the sample of low-z DLAs.

Abundances in SDSS DLAs at z < 1.5

(*Khare et al. 2004; Meiring et al. 2006; Pe'roux et al. 2006a; Meiring et al. 2007*)

- **Sample:** DLAs at 0.6 < z < 1.5 toward SDSS quasars with Mg II-selected absorbers with N(HI) measured from HST spectra (e.g., Rao et al. 2006)

- **Data:** Ground-based spectra obtained with

  --VLT Ultraviolet-Visual Echelle Spectrograph (UVES),

  --Magellan Inamori Kyocera Echelle (MIKE),

  --Multiple Mirror Telescope (MMT) Blue Channel

- Spectral resolution F5 km/s (UVES), 12 km/s (MIKE), 75 km/s (MMT)--high S/N enables detection of Zn, Cr, Fe, Mn, Ni, Si, etc.

Together with HST data, we have tripled the z < 1.5 DLA Zn sample and quadrupled the z < 1 sample

The "Missing Metals Problem" for DLAs

Most models predict the mean global metallicity in galaxies to rise with time, reaching solar level by now.

But DLA global metallicity is considerably subsolar even at low z!

119 DLAs at $0.1 < z < 3.9$

(Kulkarni et al. 2007 and references therein)

- Most DLAs at $z < 1.5$ appear to have low metallicities!
- Global mean metallicity of DLAs seems to evolve slowly at best for $0 < z < 4$, at $\lesssim$ 0.2 dex per unit redshift

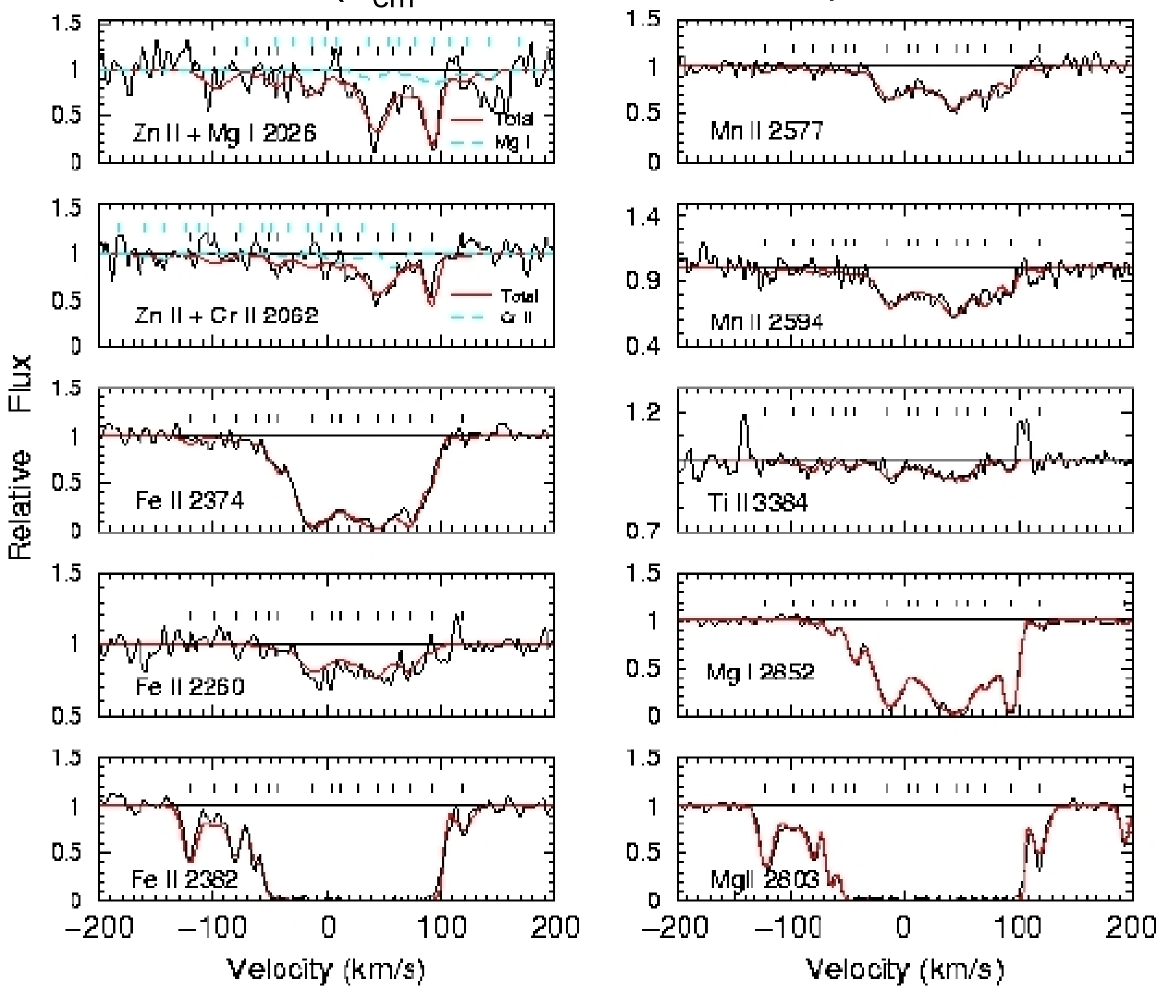
Missing Metals Problem (cont'd.)

- DLAs, Ly-alpha forest, Lyman-break galaxies, sub-mm galaxies at z=2.5 together show ~ 40-50% of metals expected from global star formation history.
- Have we overlooked some sites of metals?
- *Could sub-DLAs be more metal-rich than DLAs?*

SDSSJ1323-0021: One of the most metal-rich absorbers known

(Pe'roux et al 2006b; ESO Press Release, New Scientist blurb)

(z_{em}=1.39; zabs=0.72)



- Hint of metal-rich nature from MMT data (Khare et al. 2004)
- But need high resolution to check for saturation, and resolve blends of Zn II lines with Mg I, Cr II lines
- ESO DDT observations taken with VLT-2/UVES (4.7 km/s resolution)
- Confirmed strong Zn II Zn/H > 3.8 times solar! *Even if N(H I) were higher by 0.2-0.3 dex, still Zn/H > 2 solar!*

"A galaxy with 2-4 times solar metallicity at z~0.7 (6.3 Gyr ago!)

"Large Zn/Cr, Zn/Fe : Very Dusty!

A Survey of Sub-DLA Metallicities at z< 1.5

(Meiring et al. 2007; Meiring et al. 2008a; Peroux et al. 2008; Meiring et al. 2008b, to be submitted)

- Sub-DLAs at $0.7 < z < 1.5$, with N(HI) determined from archival HST UV spectra

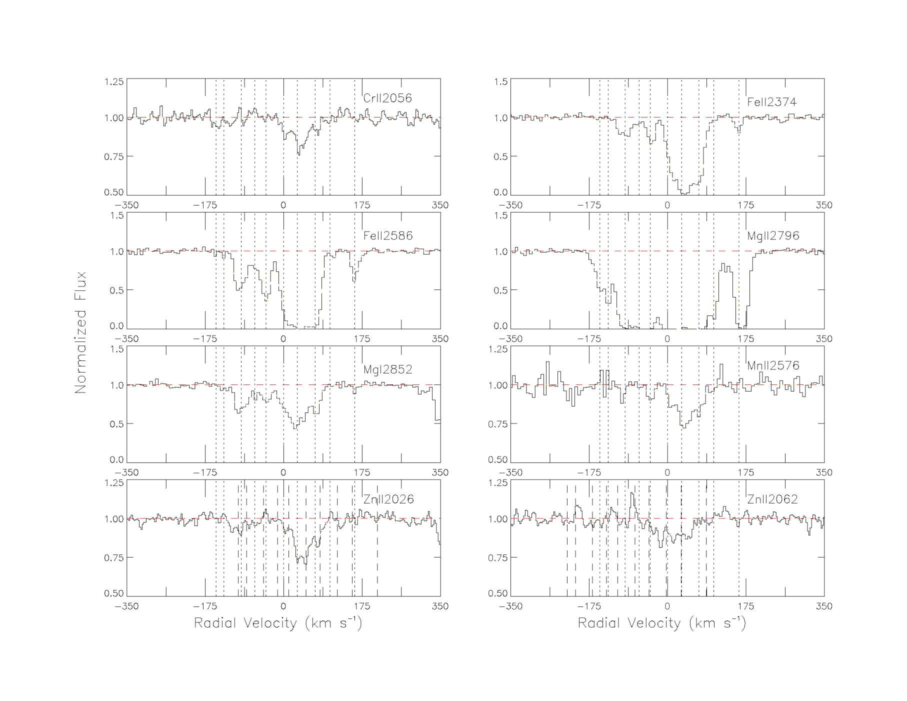
- 32 systems observed so far with adequate S/N using VLT UVES or Magellan MIKE (4.7-12 km/s resolution) + 2 observed with MMT

- Increased the sample of sub-DLA Zn measurements at $z < 1.5$ by a factor of ≈ 8

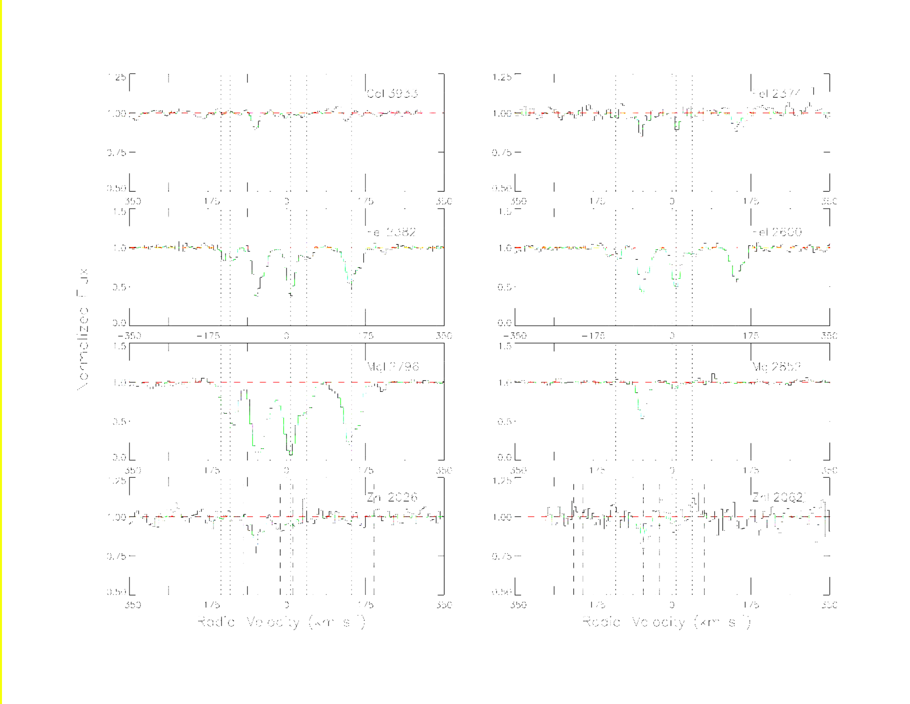
More Metal-rich Sub-DLAs

- We have now found several more metal-rich sub-DLAs at $0.7 < z < 1.5$ (5 supersolar, 8 between -0.5 and 0 dex)

A near-solar system at z_{abs}=1.41



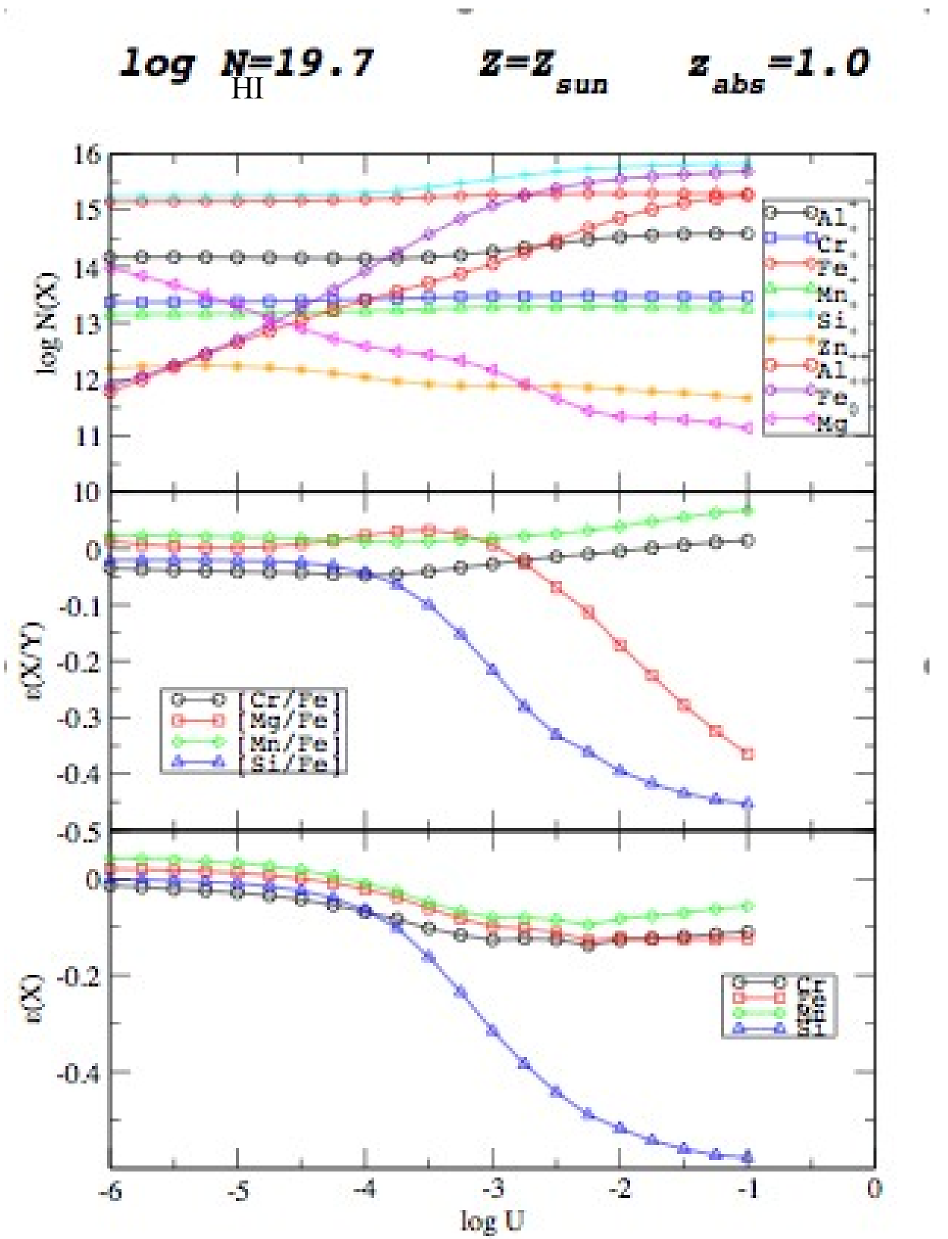
A super-solar system at z_{abs}=0.91



(Meiring et al. 2007, MNRAS, 376, 557)

- But not all sub-DLAs are metal-rich

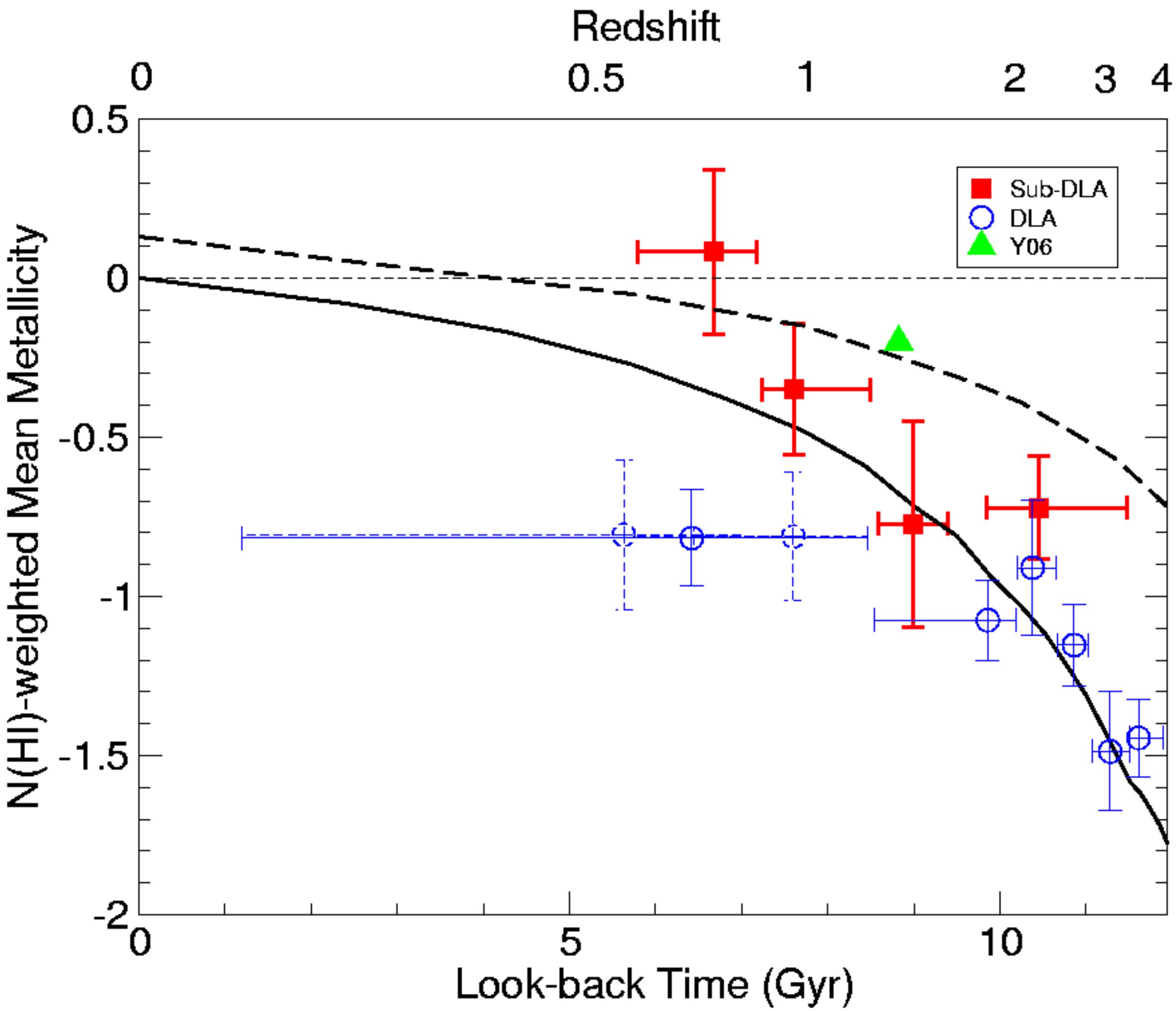
- High metallicities do not seem to be caused by ionization
- Examined ionization effects with CLOUDY photoionization grids
- Sub-DLAs with low N(HI) may have more ionized gas, but abundances seem ok within ~ 0.2 dex



Usually find log U < -3

Metallicity Evolution of Sub-DLAs

(Kulkarni et al. 2007, ApJ, 661, 88; Meiring et al. 2008b to be submitted)



- 52 Sub-DLAs with 0.6 < z < 3.2
- 119 DLAs with 0.1 < z < 3.9
- Sub-DLA global mean metallicity seems higher and faster-evolving than that of DLAs, at least at z < 1.5

The role of Sub-DLAs in Cosmic Metal Budget (*Kulkarni et al. 2007, ApJ, 661, 88; Khare et al. 2007, A&A, 464, 481; Meiring et al. 2008b, to be submitted)*

Fraction of metal-rich sub-DLAs seems higher. If a significant population of metal-rich sub-DLAs is found, sub-DLAs could help to reduce the Missing Metals Problem.

Comoving metal density in sub-DLAs, in units of F □ $_\odot$⊙□ $_{\text{baryons}}$ **x** $_\odot$

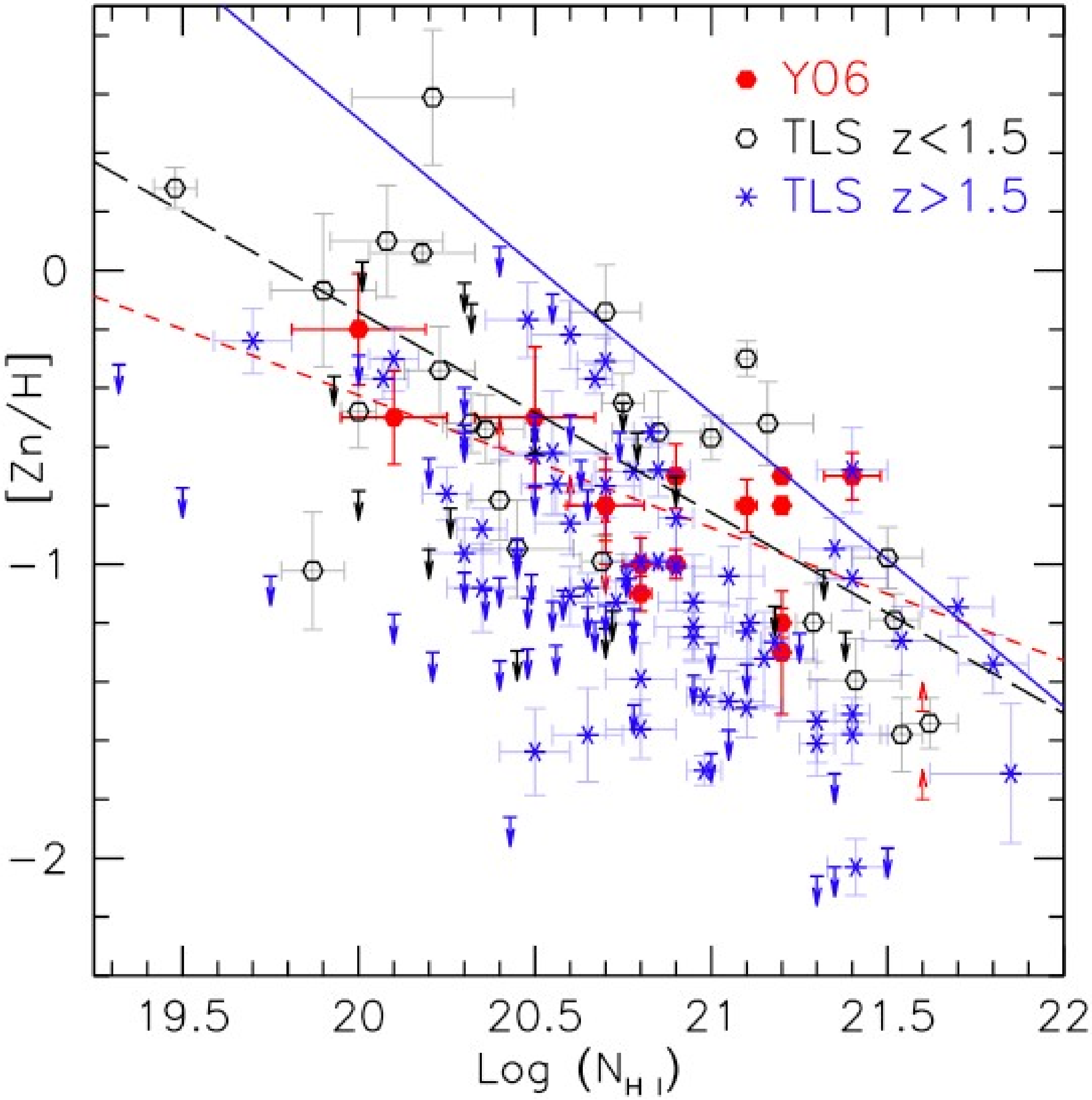
- At low z, $F_z^{\text{sub-DLAs}} \approx f \times Z_\odot \times F_{F □}^{\text{sub-DLAs}}$/F □ $_\odot$⊙□ **f x 22.9 x $\Omega_{\text{H I}}^{\text{sub-}}$** **where f = ionization fraction of the gas (in the range~ 1-10).**
- **Given that sub-DLA mean metallicity is ~7 times larger than that of DLAs at low z, and assuming $\Omega_{\text{H I}}^{\text{sub-DLAs}} / \Omega_{\text{H I}}^{\text{DLAs}}$ is similar at low and high z (~0.21),**

$\Omega_z^{\text{sub-DLAs}} / \Omega_z^{\text{DLAs}}$ = f x 1.5 (or larger if $\Omega_{\text{H I}}^{\text{sub-DLAs}} / \Omega_{\text{H I}}^{\text{DLAs}}$ is higher).

Sub-DLAs may contribute several times more than DLAs at low z!

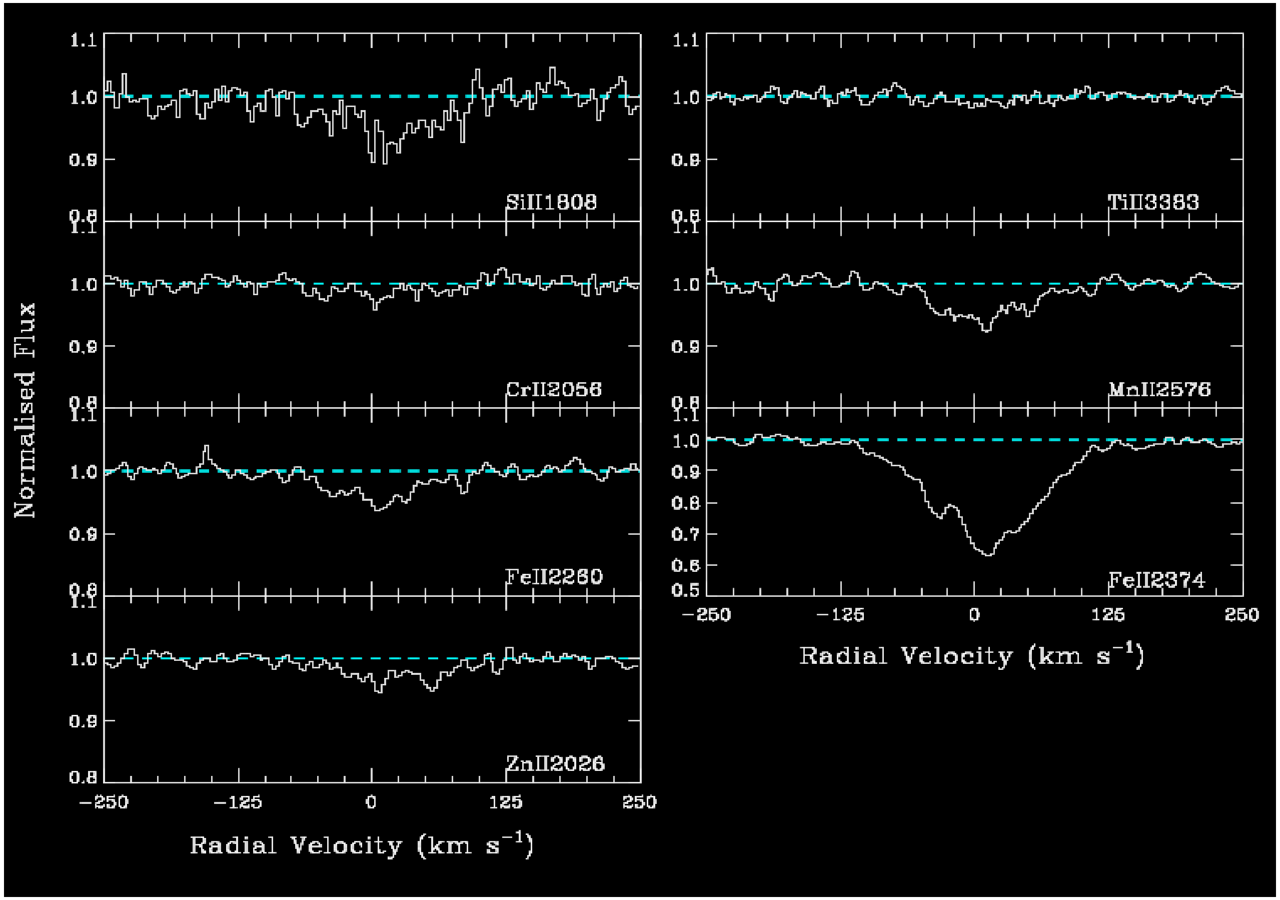
- **At high z, sub-DLAs contribute at least 32% of DLAs to Ω_z**

Metallicity vs. N(HI)



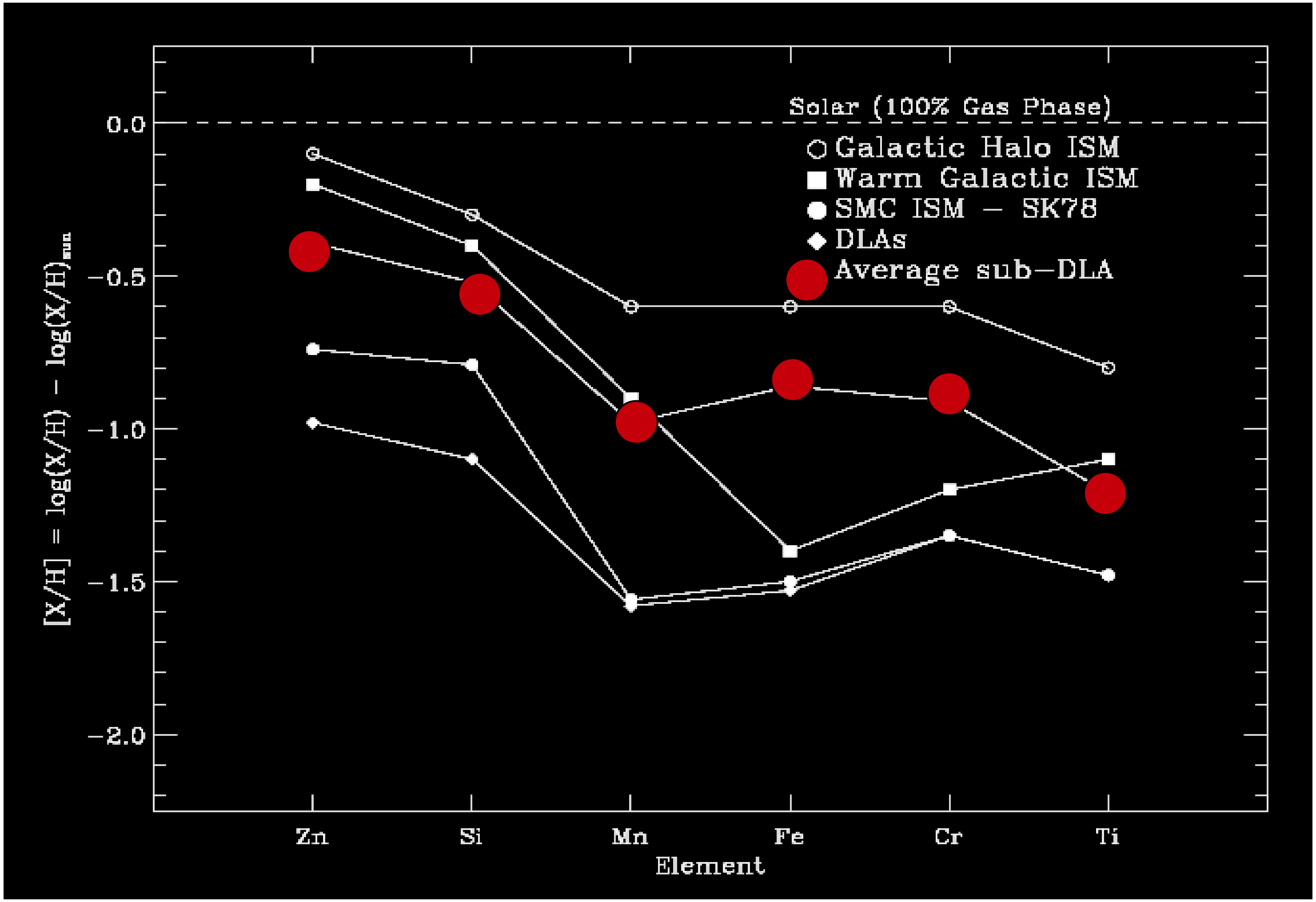
- Probably not just a dust obscuration effect (Khare et al. 2007)
- Note some objects above the blue line (what was suspected to be an obscuration limit by Boisse et al. 1998)
- Similar trend for log N(HI) < 17 systems: (e.g., Misawa et al. 2008)

An Average Sub-DLA Spectrum



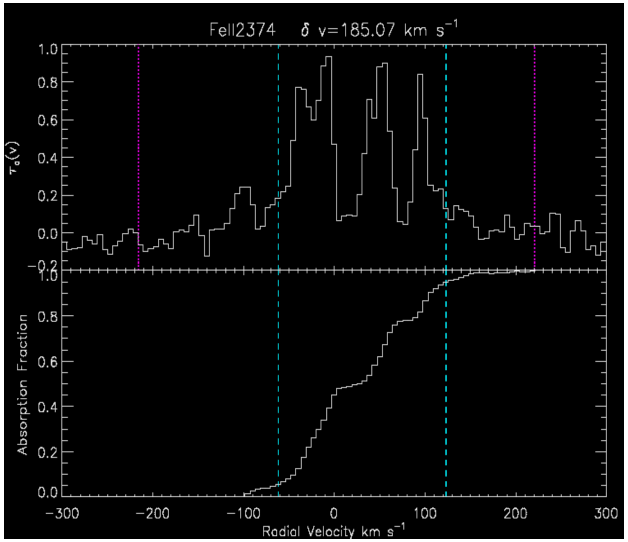
Result of shifting our individual spectra to absorber rest-frames and combining.

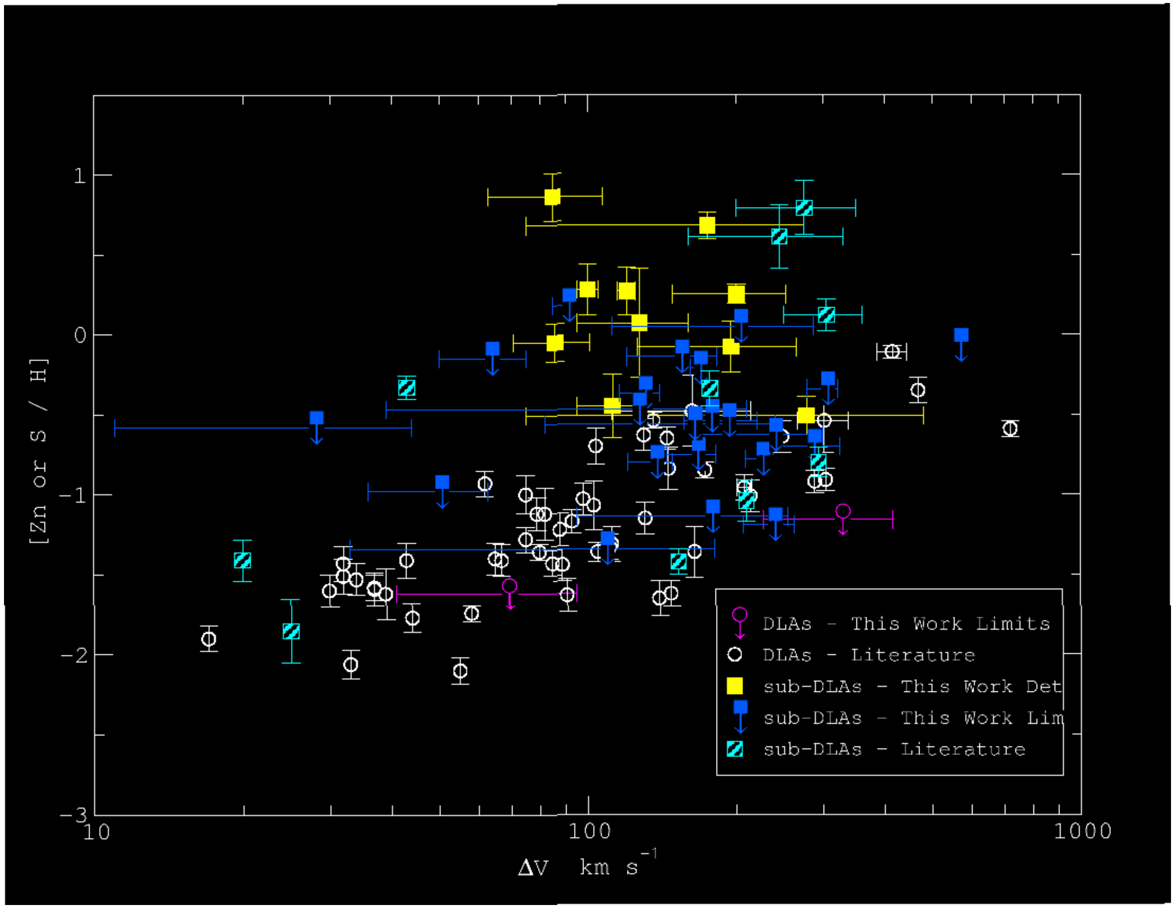
Sub-DLA Element Abundances compared to Local ISM Abundances



Metallicity *vs.* Velocity Width

Δv = velocity width enclosing inner 90% of absorption (integrating over AOD profile)





Sub-DLAs appear to have larger velocity widths on average than DLAs

Nature of Sub-DLAs and DLAs

- Sub-DLAs and DLAs may be distinct populations
- Larger velocity width, higher metallicity for sub-DLAs could mean sub-DLAs trace more massive galaxies than DLAs
- Or the metal-rich sub-DLAs may trace outflows
- Dust selection effects (bias against metal-rich dusty systems) may also be less for sub-DLAs than for DLAs
- On the other hand, there may be some "intermixing" of the two populations with time (e.g., a DLA may turn into a sub-DLA after gas consumption/stripping)

CONCLUSIONS

- Most DLAs at z < 1.5 appear to be metal-poor (<l□10-20% solar). Global mean metallicity of DLAs appears to evolve slowly, in contrast with predictions based on cosmic chemical evolution models and global star formation history from galaxy imaging surveys.

- But some sub-DLAs seem to be very metal-rich. We have discovered several near-solar/supersolar systems at 0.7 < z < 1.5!

- Sub-DLAs at z < 1.5 seem distinct from DLAs (more metal-rich, wider velocity spreads on average). Sub-DLAs may arise in more massive galaxies than DLAs.

- Sub-DLAs may contribute more than DLAs at z < 1.5 to cosmic metal budget, and may help to reduce the Missing Metals Problem in part.

FUTURE WORK

POTENTIAL SELECTION EFFECTS:

---Small number statistics?

Need abundances in many more absorbers, especially sub-DLAs.

--- Role of dust?

Need abundances in dusty DLAs to study element depletions, nature of dust.

--- Star formation rates? Morphologies?

Need high-resolution imaging , integral field spectroscopy for accurate morphology and SFR measurements

THE END