Probing Dust at High Redshifts with Quasar Absorption Systems

Varsha P. Kulkarni
University of South Carolina

COLLABORATORS

Monique C. Aller, Debopam Som (University of South Carolina)
Donald G. York (University of Chicago)
Celine Peroux (Laboratoire d'Astrophysique de Marseille)
Giovanni Vladilo (Osservatorio Astronomico di **Trieste)**
Daniel E. Welty (University Of Illinois)
Joseph Meiring (University of Massachusetts)
James Lauroesch (University of Louisville)
Pushpa Khare (Utkal University)

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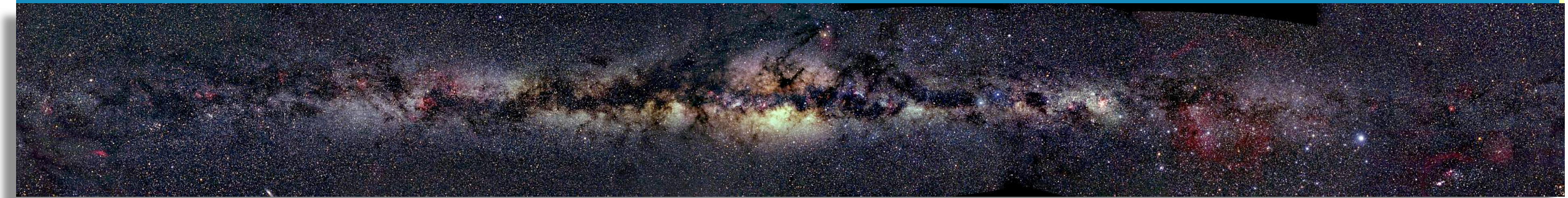


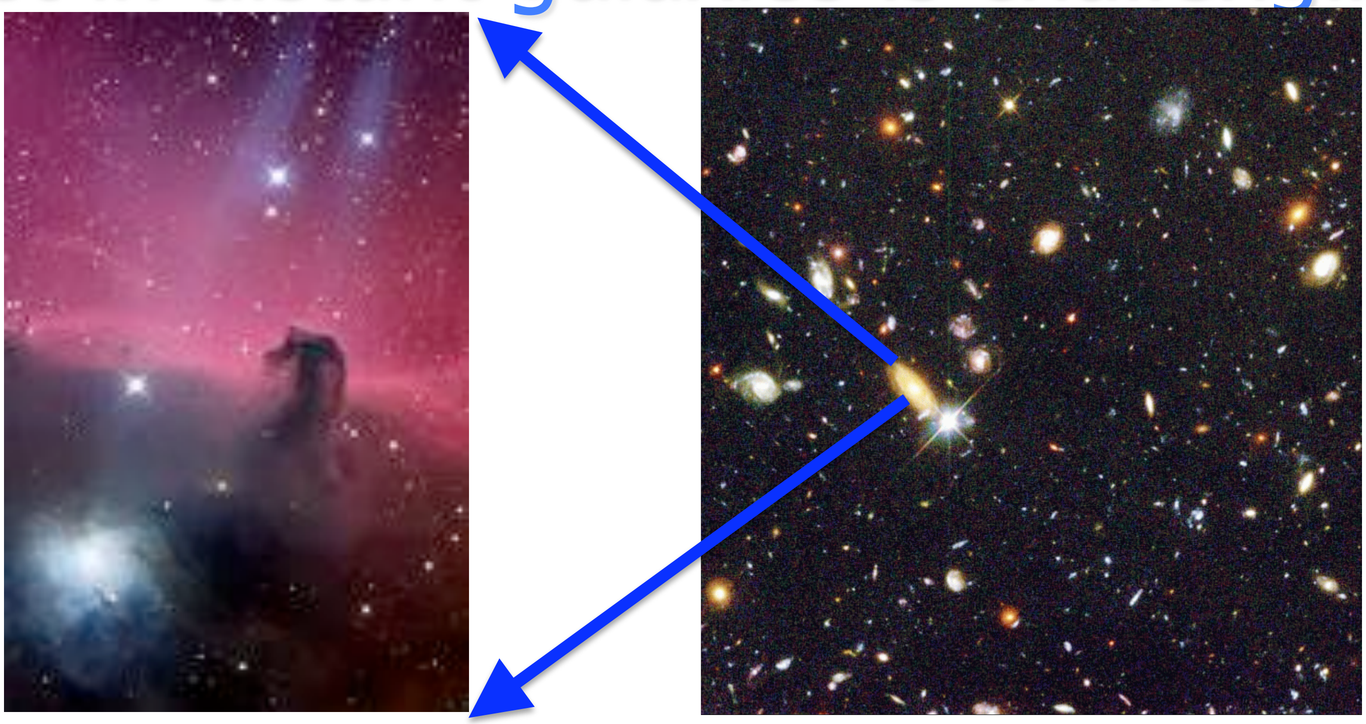
OUTLINE

- Introduction
- Tracing dust in quasar absorbers:
  - * Element Depletions
  - * Extinction Curves
  - * Dust Spectral Features
    - -carbonaceous dust
    - -silicate dust
- Conclusions

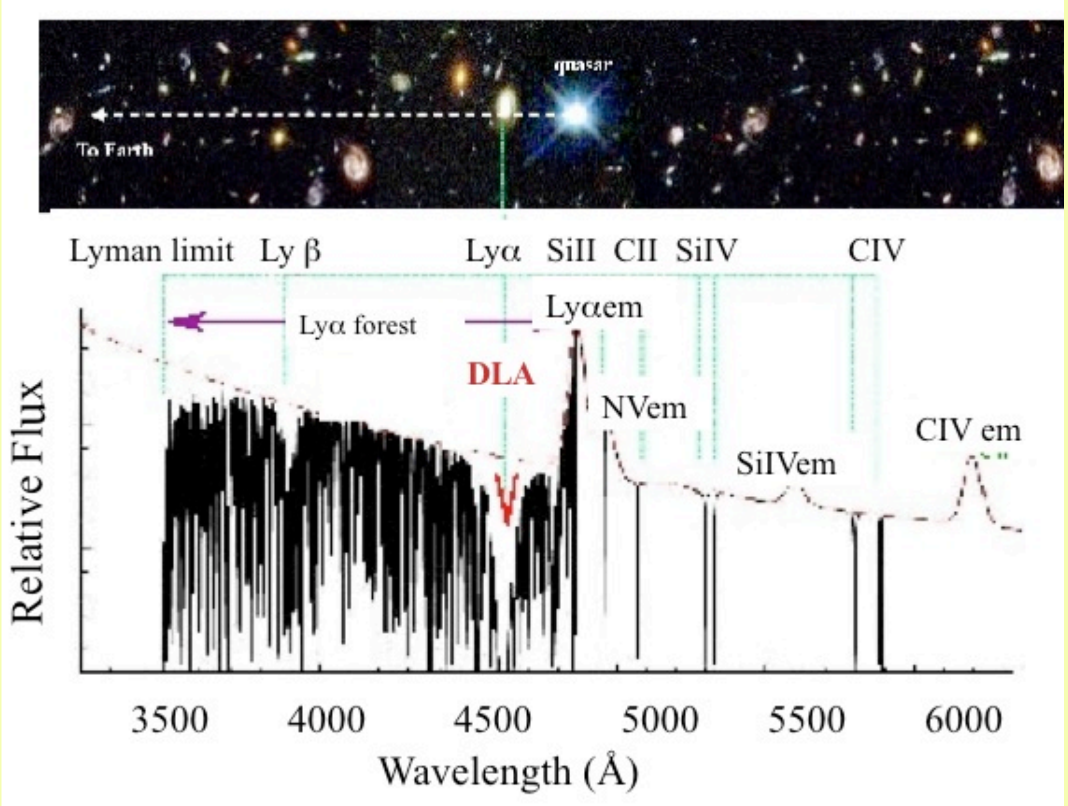
Why do we care about dust in distant galaxies?

- Dust affects view of distant universe (and hence estimates of size and expansion of the universe).
- Affects composition of ISM gas by locking up some part of heavy elements; hence affects determination of cosmic chemical evolution.

But detailed imaging studies of interstellar dust in distant galaxies is challenging!



Probing Interstellar Dust with Quasar Spectra

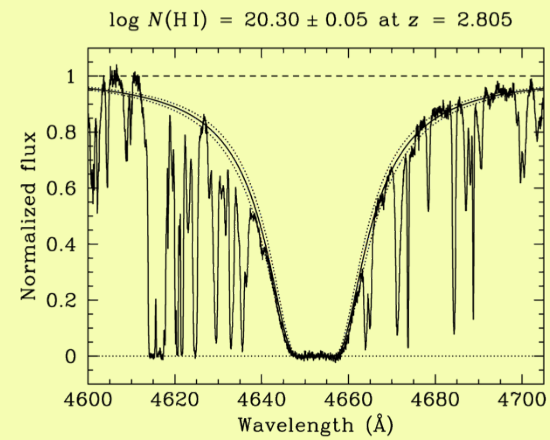


- Quasar absorption lines offer probes of galaxy chemical evolution over > 90% of cosmic history.

- Absorption line strengths depend on just the amount of matter along the sightline, not on galaxy luminosity.
- So expect to get a more unbiased picture than flux-limited imaging surveys.

Damped Lyman-Alpha Absorbers (DLAs)

Neutral Hydrogen Column Density N(H I) ≥ 2×10^{20} cm^{-2}



Sub-damped Lyman-Alpha Absorbers (sub-DLAs)

Neutral Hydrogen Column Density 10^{19} ≤ N(H I) < 2×10^{20} cm^{-2}

- Weaker than the classical DLAs, but show damping wings.

DLAs and sub-DLAs contain a large fraction of the neutral hydrogen in galaxies and offer best probes of chemical composition for distant galaxies!

Quasar Absorbers as Probes of Cosmic Chemical Evolution

- Most cosmic chemical evolution models predict a rise in global mean interstellar metallicity of galaxies with time, from low values at high z to near-solar values at z=0.

- But most DLAs appear to be metal-poor, even at low redshifts! (e.g., Kulkarni et al. 2005, 2007a, 2010a).

- A large fraction of DLAs also appear to have low star formation rates based on emission line searches (e.g., Kulkarni et al. 2006, Peroux et al. 2011 and references therein).

Dust in Quasar Absorbers

- Dust offers a partial explanation of low metallicities and low SFRs of DLAs (e.g., Fall & Pei 1993, Boisse et al. 1998).

- Dusty DLAs may hide ~17% of the total metal content at z~2, and more at lower z (e.g., Bouche et al. 2005).

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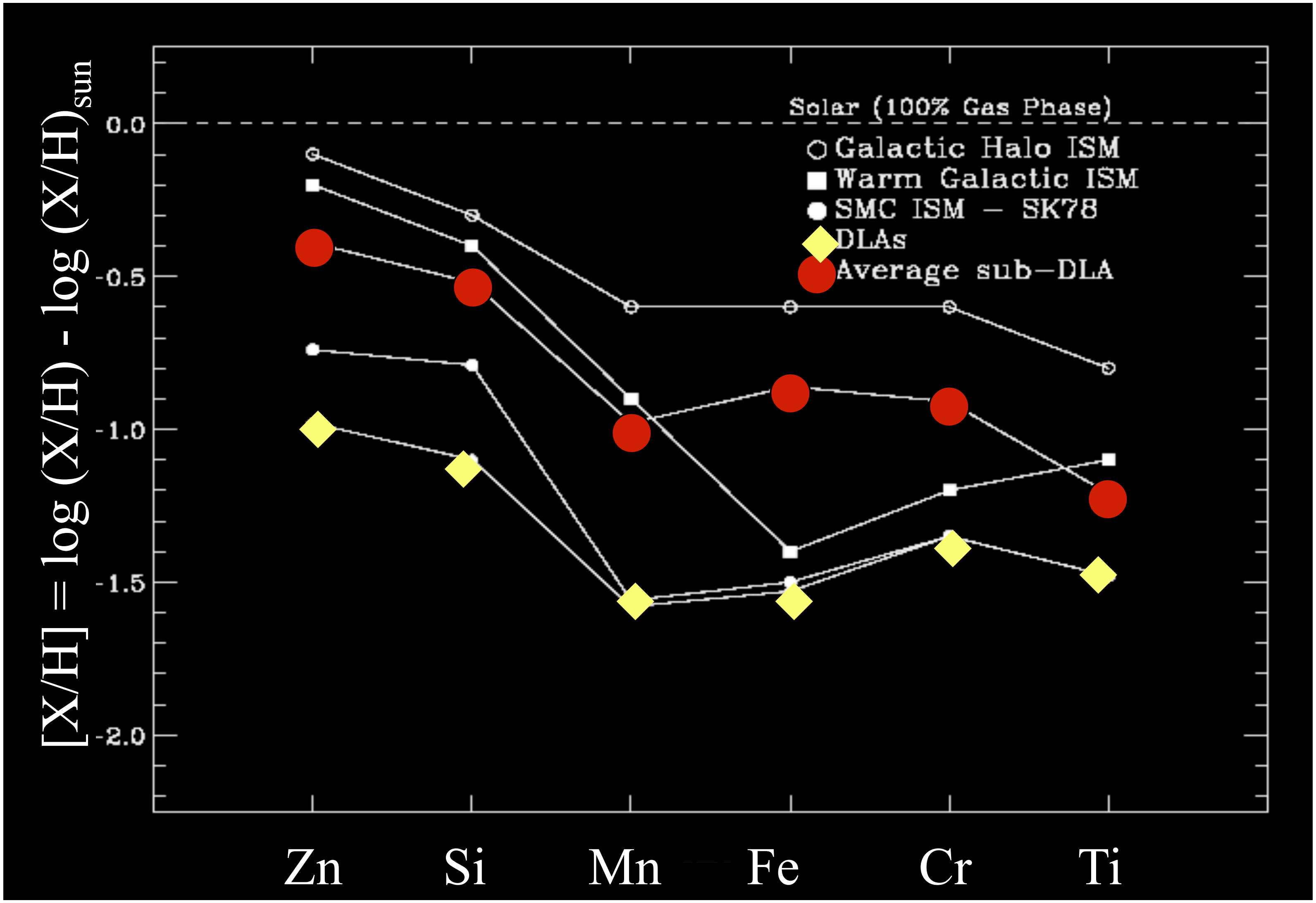
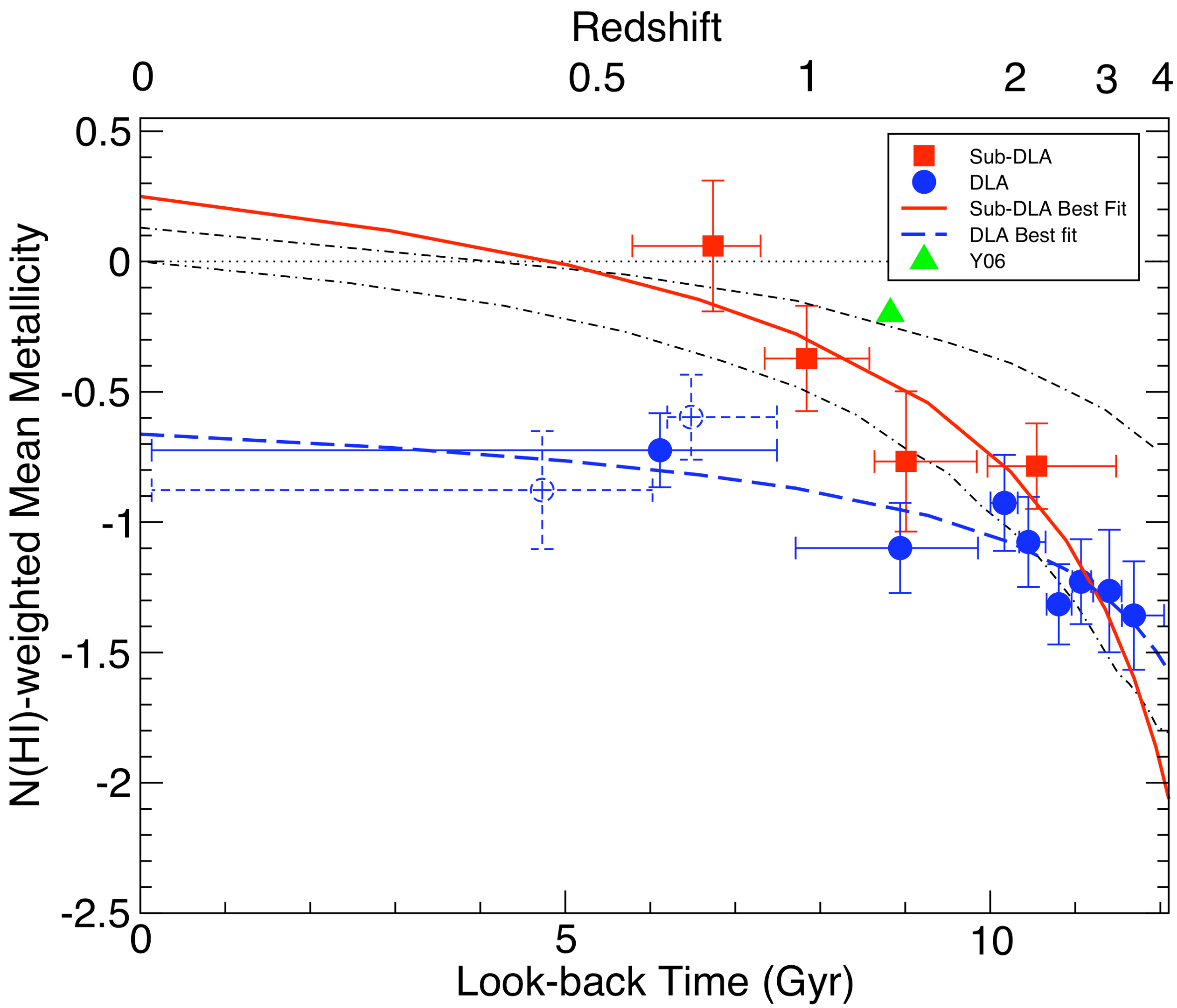
Element Depletions

Measure an almost undepleted element (e.g., Zn) and other depleted elements.



Metallicity Evolution of DLAs and Sub-DLAs

(e.g., Kulkarni et al. 2007, 2010, Prochaska et al. 2007)

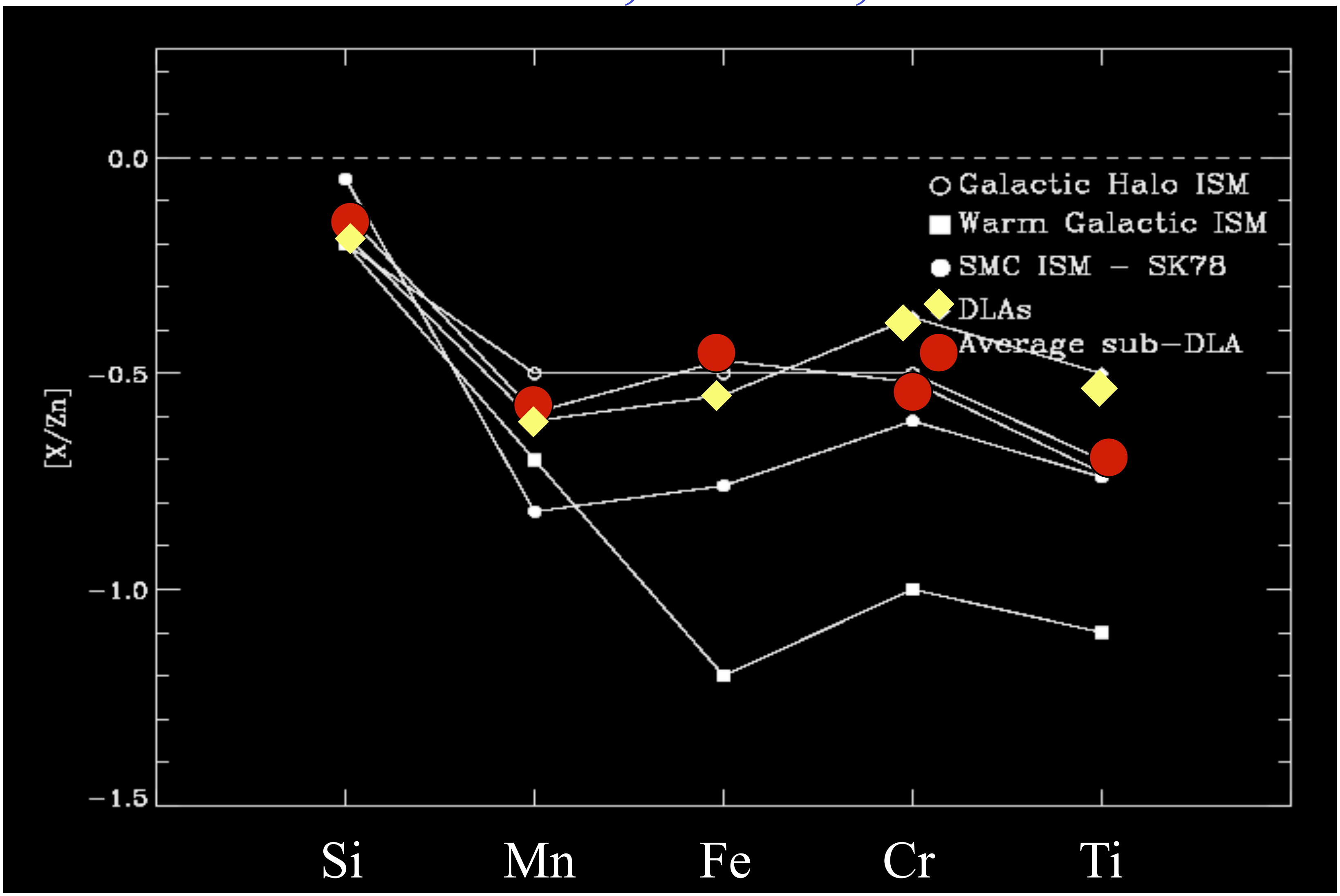


DLAs appear to be metal-poor on average at all z

Sub-DLAs appear to be more metal-rich and faster evolving

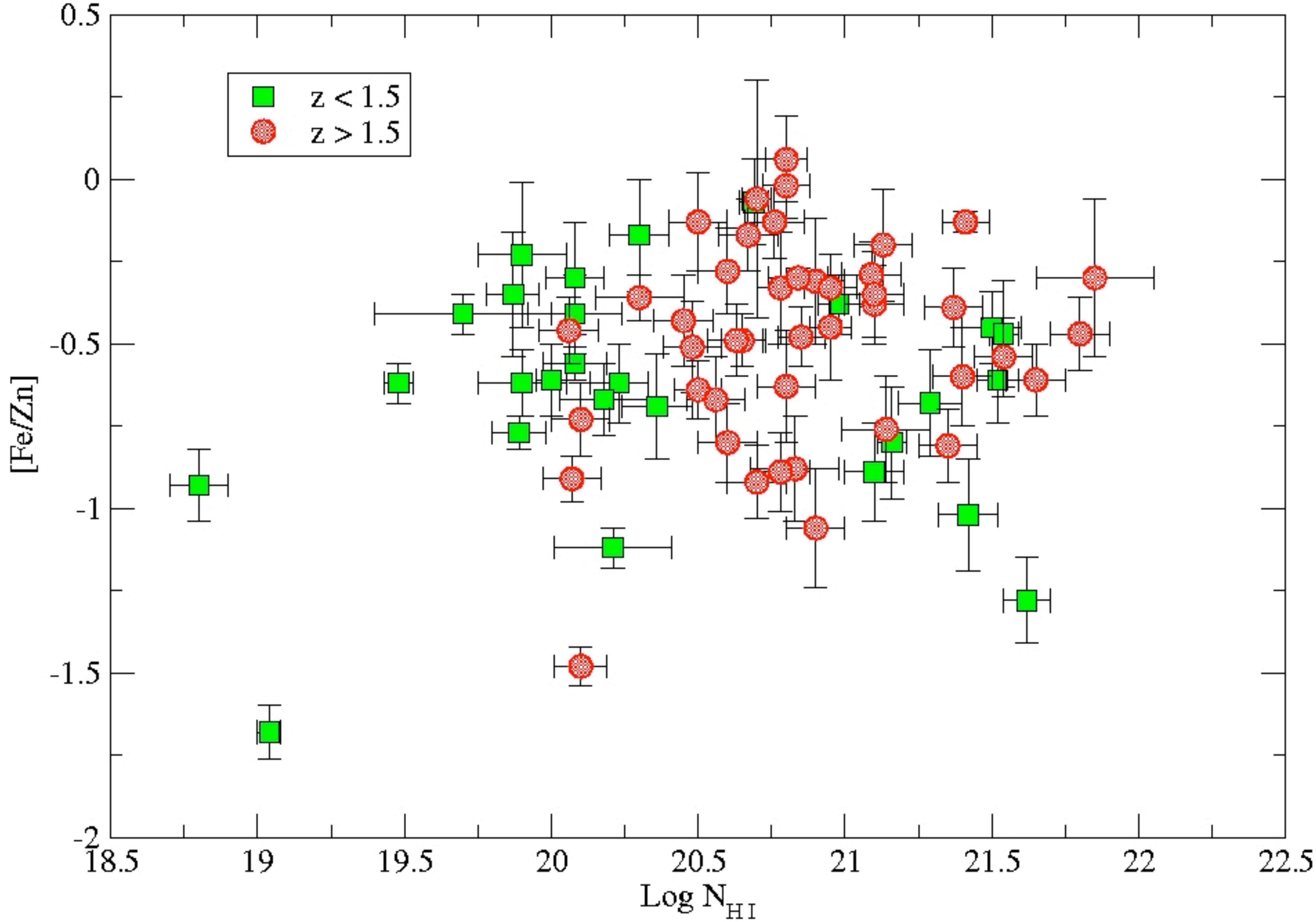
Z(z) from Zn, S is 0.5-0.6 dex above that from Fe for both DLAs and sub-DLAs.

Relative Abundance Patterns: sub-DLAs, DLAs, ISM



Relative pattern similar in DLAs, sub-DLAs, and Galactic halo ISM

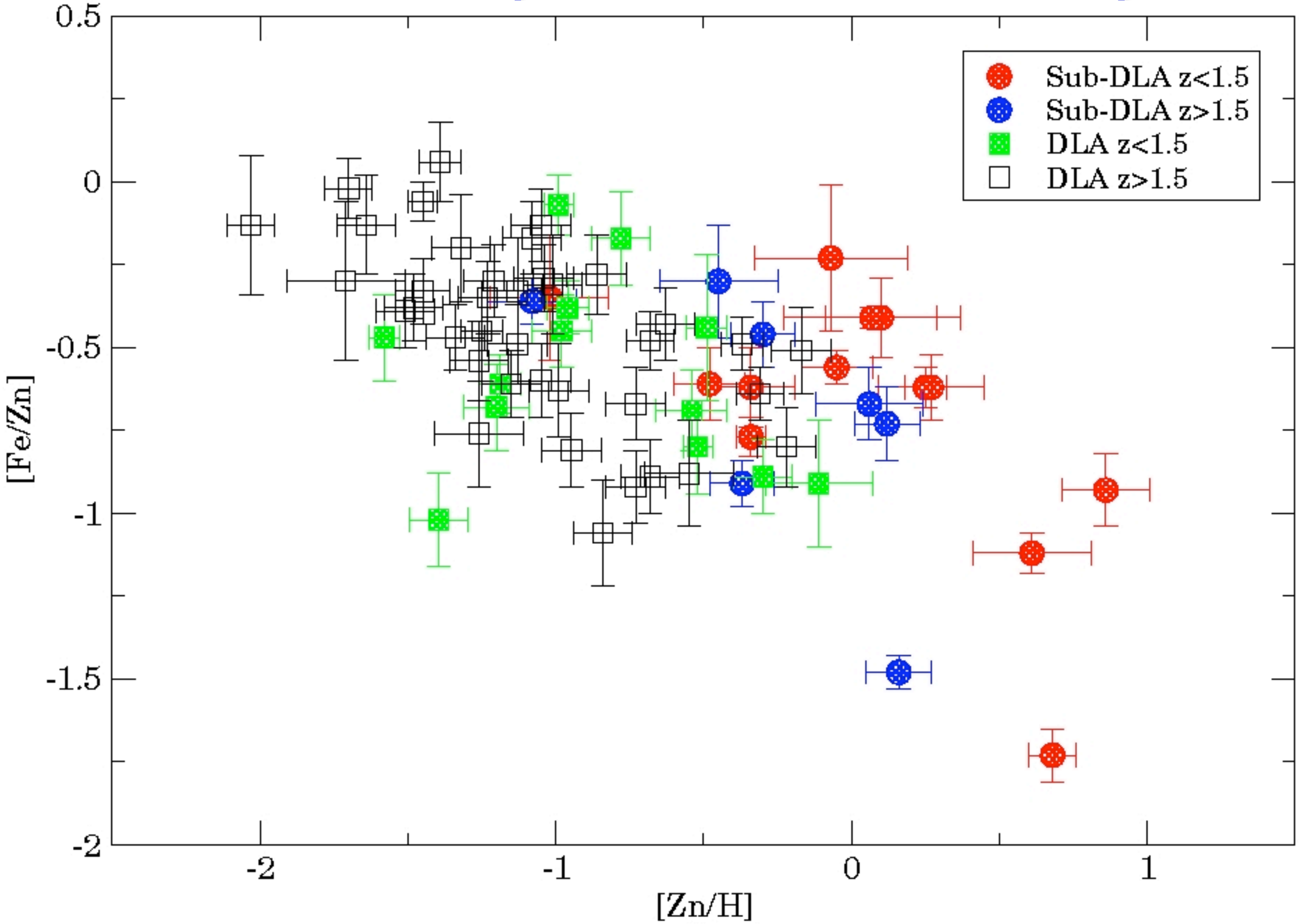
Dust Depletion vs. H I Content and Redshift



Depletion does not seem to depend on H I content or redshift.

(e.g., Meiring et al. 2009, MNRAS, 397, 2037; also Ledoux et al. 2006)

Dust Depletion vs. Metallicity



Depletion does anti-correlate with metallicity ([Zn/H]).
(e.g., Meiring et al. 2009, MNRAS, 397, 2037)

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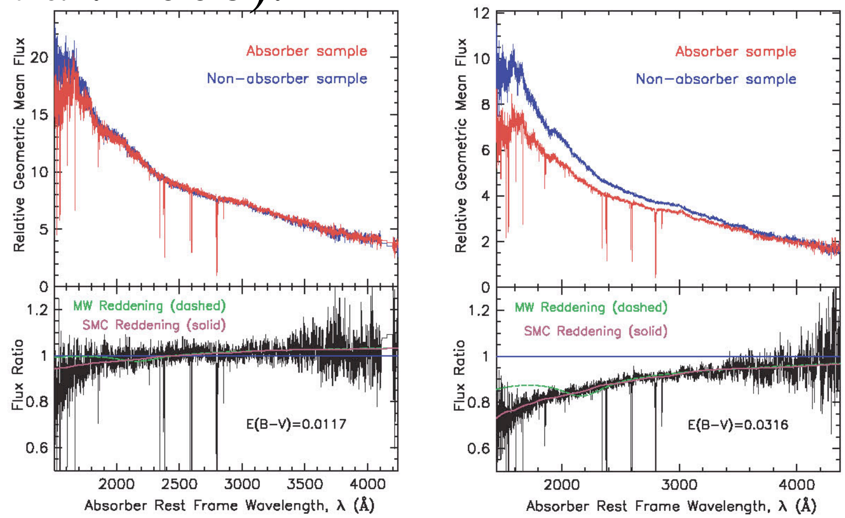
Extinction Curves

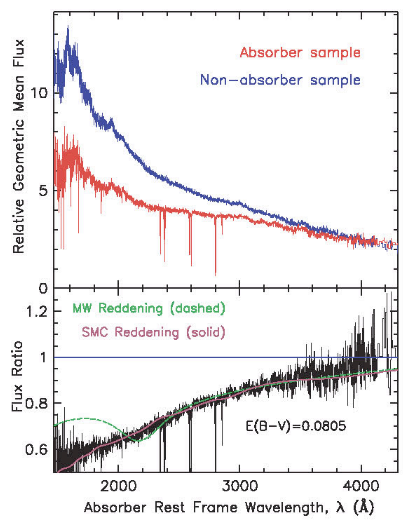
Compare quasars with and without absorbers to determine E(B-V). (e.g., Pei et al. 1991; York et al. 2006).

Mean Extinction Curve at 1 < z < 2: 809 SDSS Mg II absorbers



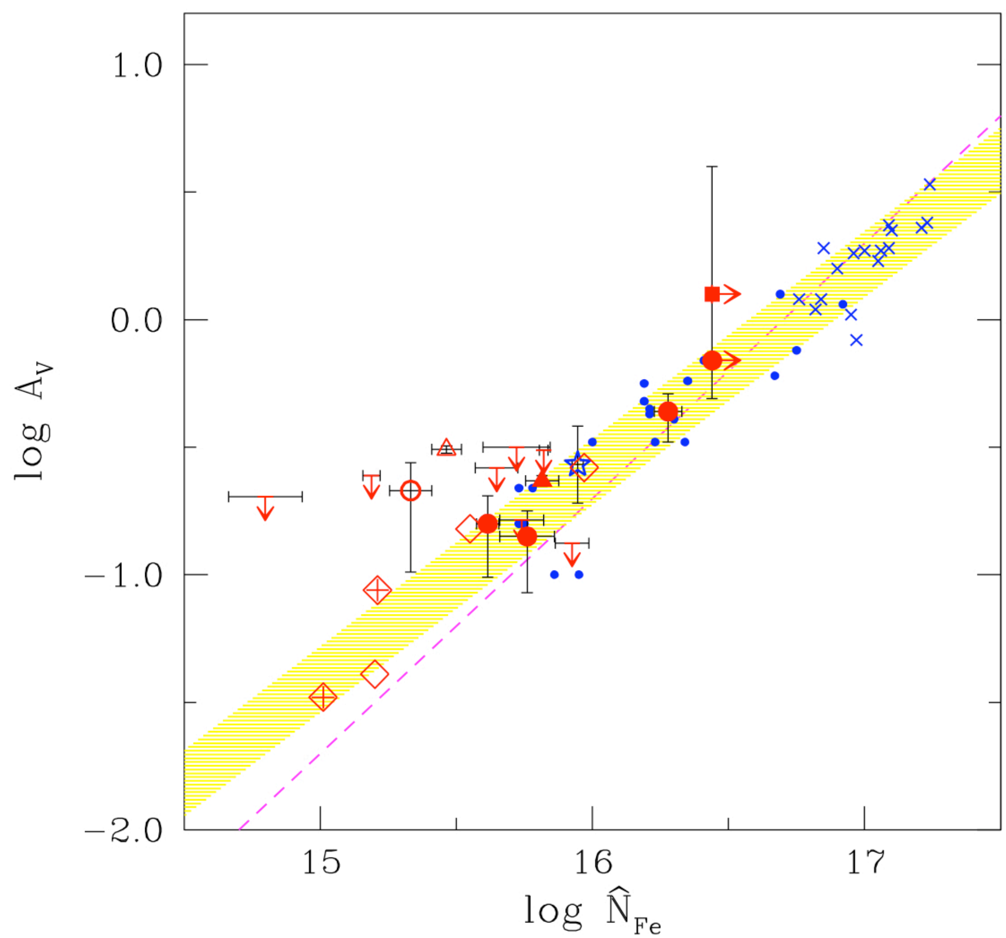
SMC curve found to be the best fit.

E(B-V)=0.01-0.09 depending on Mg II line strengths etc.



York et al. (2006), MNRAS, 367, 945

Extinction vs. Metal Column



Mean extinction per Fe atom in dust for DLAs is similar to that for Milky Way ISM. (Vladilo et al. 2006, A&A, 454, 151).

Dots and Crosses: MW ISM
Other symbols: DLAs

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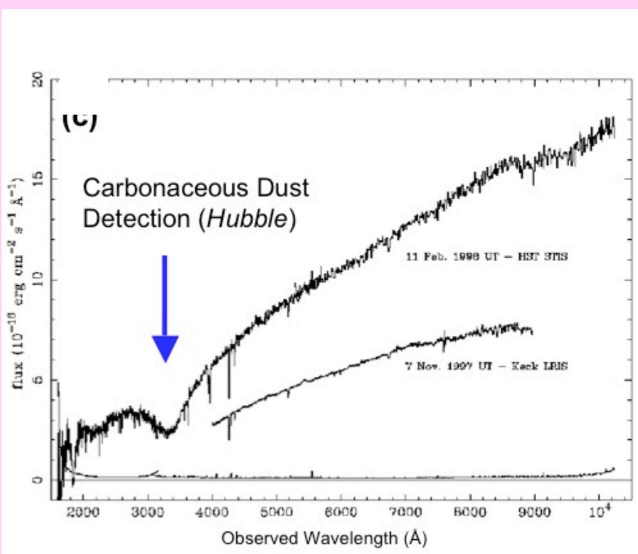
Dust Spectral Features

Carbonaceous Absorption: The 2175 Å Bump

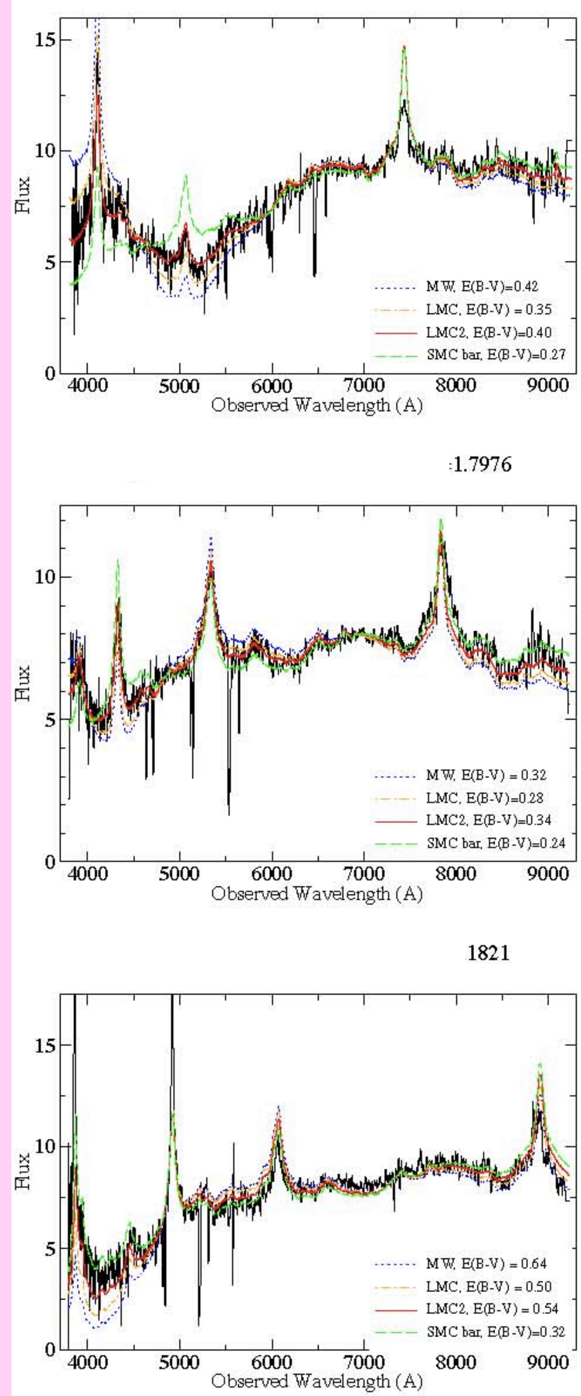
Most quasar absorbers do NOT show the 2175 Å bump (e.g. York et al. 2006).

A small number of absorbers are known to have the bump [e.g., Junkkarinen et al. (2004); Srianand et al. (2008); Noterdaeme et al. (2009, last talk); Kulkarni et al. (2011); Peng et al. (2011)].

Dusty systems may be the link between Lyman-break galaxies and metal-poor DLAs!



Junkkarinen et al. (2004)



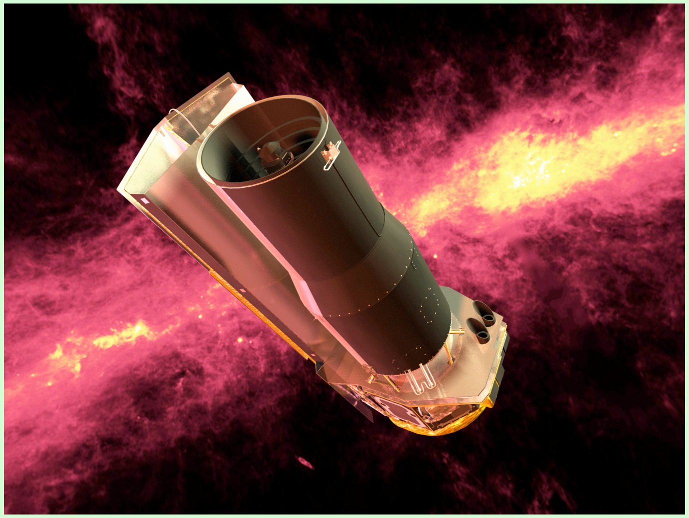
Kulkarni et al. (2011)

Silicate Absorption

- Silicates comprise ~70% of core mass of interstellar dust grains, but were not probed in previous DLA studies (which searched for the 2175 Å feature, believed to arise in carbonaceous dust).

- We have been carrying out a search for the silicate features in quasar spectra at the redshifts of known absorbers.

- Spitzer IRS provided the sensitivity, spectral coverage, and resolution to search for the redshifted strong silicate feature at 9.7 μm rest frame (Si-O stretching vibrations).



First Silicate Detection in a DLA

(Kulkarni et al 2007, ApJL, 663, 81)

• DLA at z=0.52 toward AO 0235+164:

log N_{HI} = 21.7; also a 21-cm absorber and an X-ray absorber

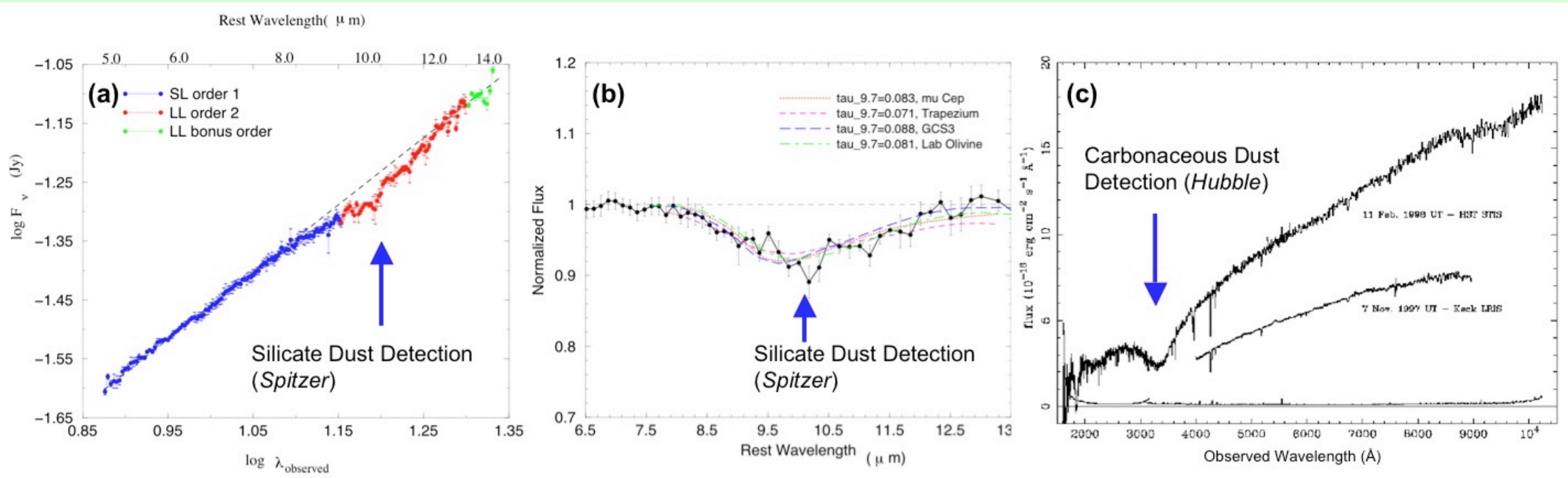
• Known to be dusty from optical, UV data (Junkkarinen et al. 2004;York et al. 2006b):

--strong 2175 Å bump,

--diffuse interstellar bands (4428, 5705, 5780 Å),

--reddened quasar

• So excellent place to search for silicates.



Spitzer Data for Four More Absorbers at $0.4 < z_{abs} < 1.3$

(Kulkarni et al. 2011, ApJ, 726, 14)

Target Selection:

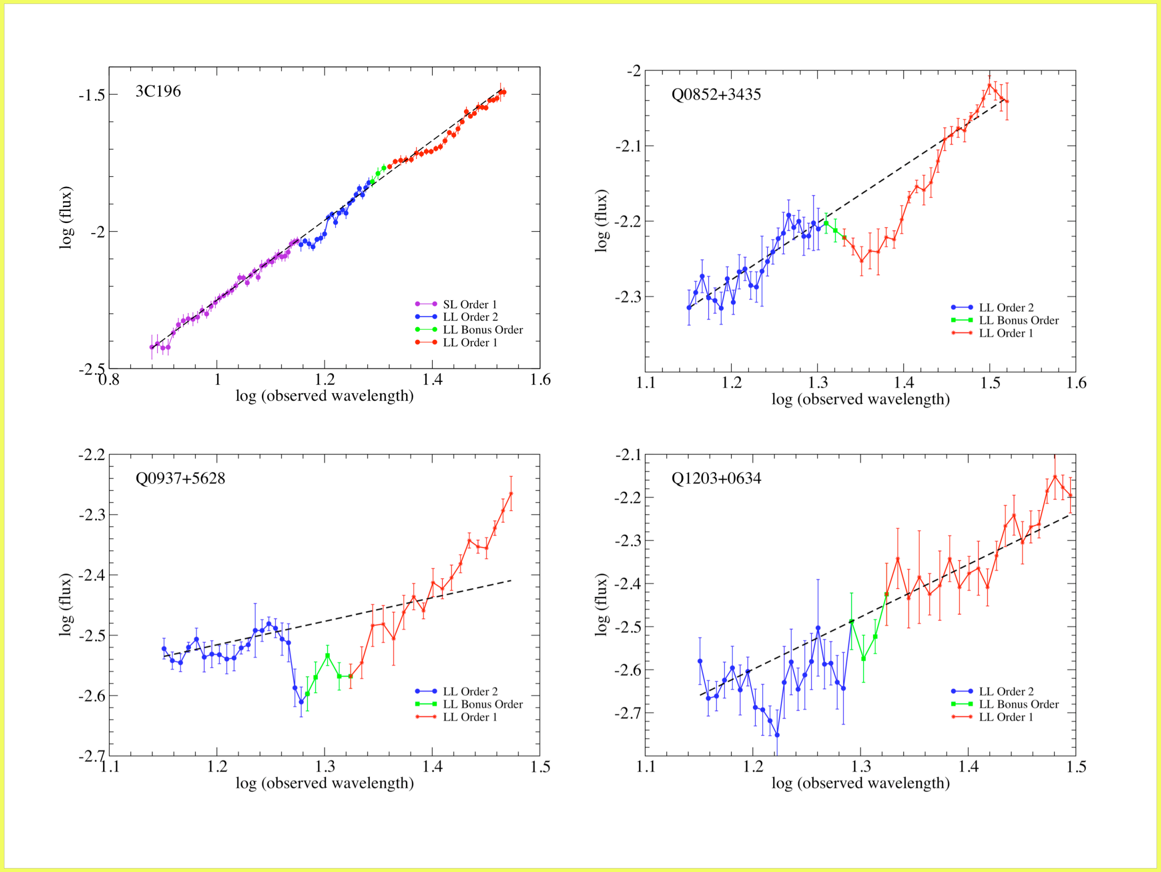
★ Substantial reddening of background quasar

★At least 2 signatures of dusty/cold gas:
2175 Å bump, strong depletion, 21-cm absorption etc.

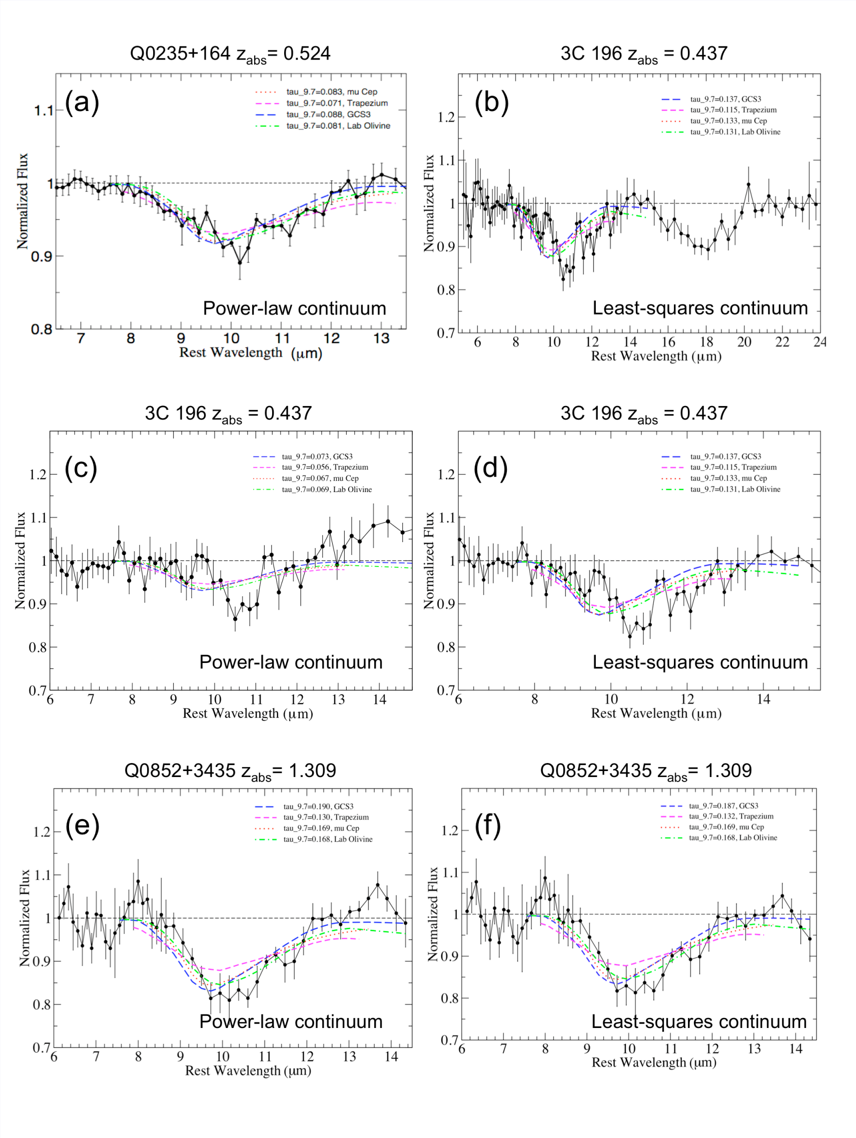
Observations: Spitzer IRS staring mode data with LL1, LL2, SL1

IRS spectra binned by a factor of 3 and fitted with power-law continuum.

Features centered at ~10 μm in absorber rest frame, with rest equivalent widths of 0.21-0.58 μm (6-10 σ significant in 3 out of 4 objects, 3.6 σ in 4th object.)



Comparison with Some Template Silicate Absorption Profiles



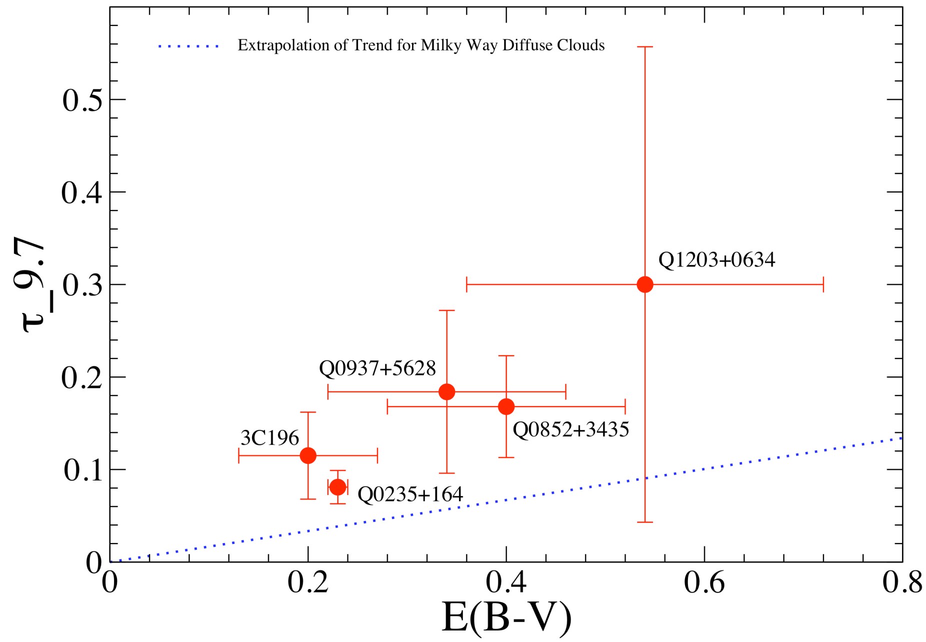
Four silicate absorption templates fitted for each system:

GCS3 (Galactic Center Source), Trapezium (molecular cloud), μCep (diffuse cloud), and Laboratory Amorphous Olivine.

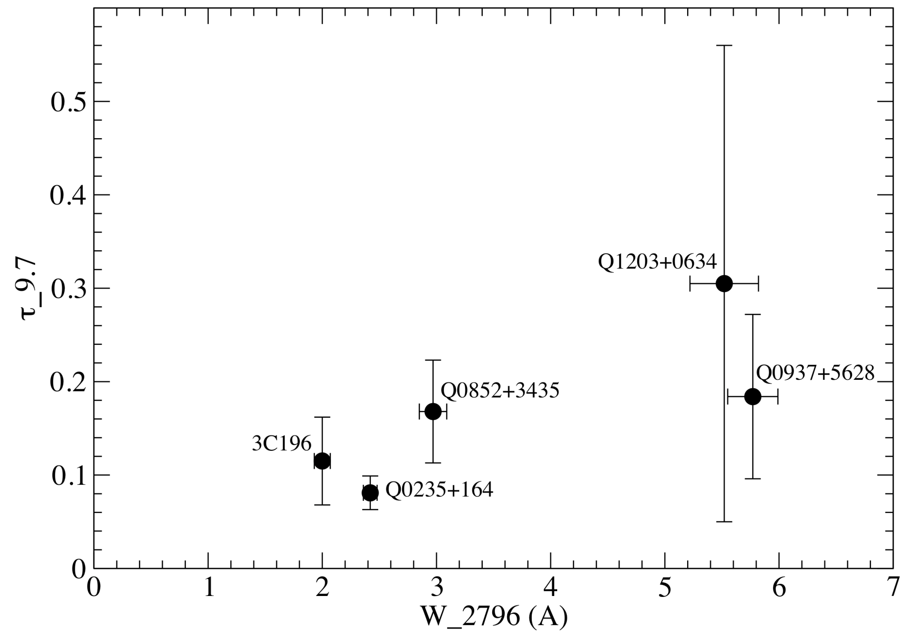
Amorphous olivine provides the best fit among these.

All features show peak optical depth a little longward of 9.7 mm—probably because of differences in structure and composition of grains.

Silicate Absorption vs. Reddening



Silicate Absorption vs. Mg II line strength

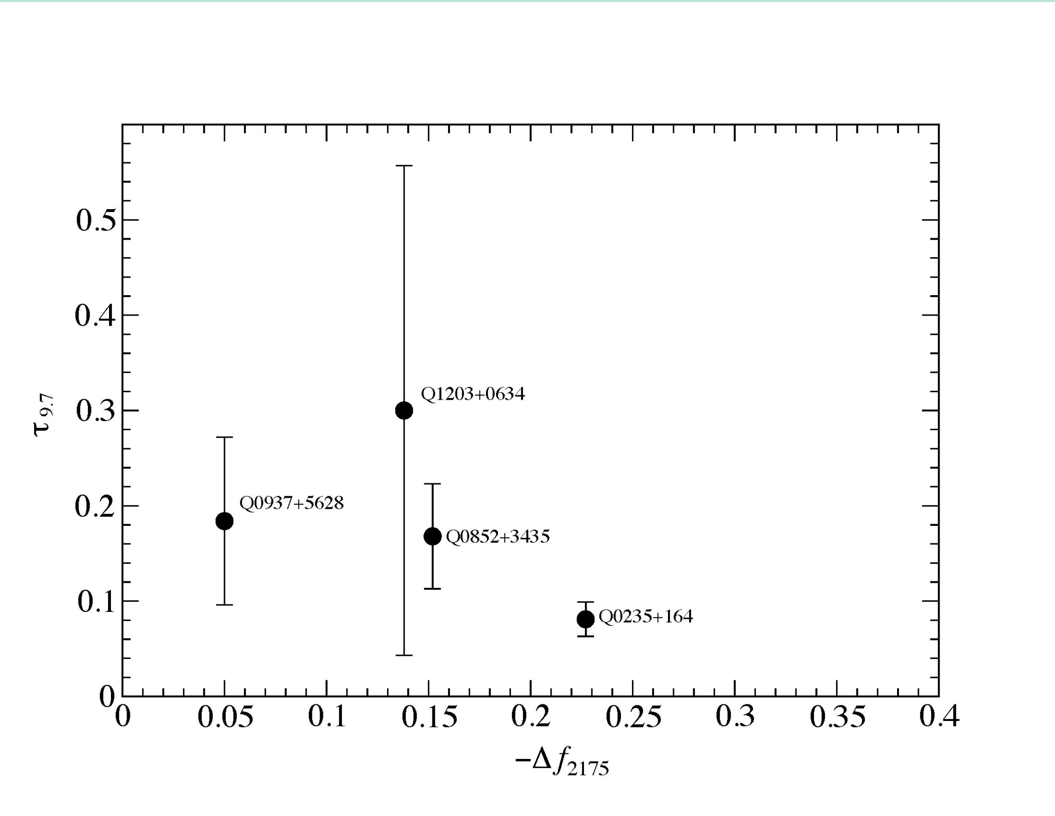


Silicate absorption strength appears to rise with reddening (96% probability of real correlation)

$\tau_{9.7}$/E(B-V) higher than that for Milky Way diffuse clouds (e.g., Whittet 1987)!

Silicate absorption strength may rise with Mg II strength

Silicate vs. Carbonaceous Dust

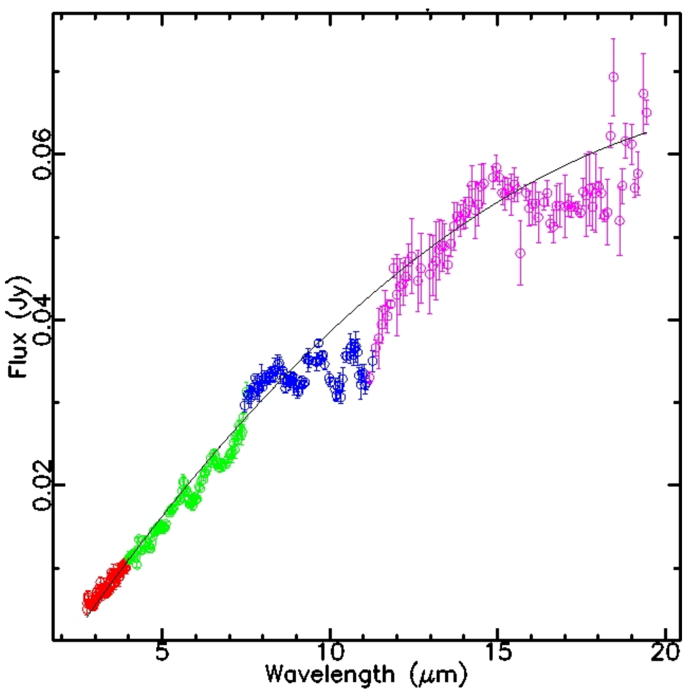


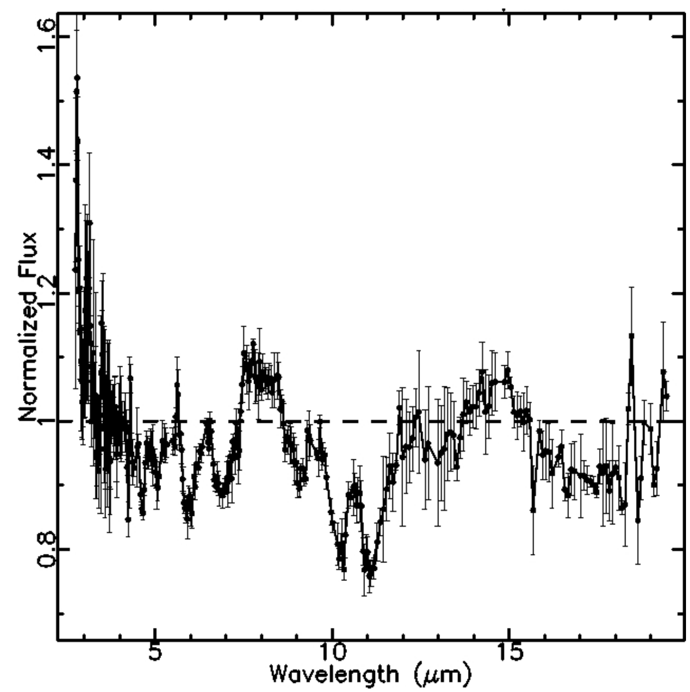
Possible anti-correlation between silicate and carbonaceous optical depths? (though sample is too small)!

Difference between O-rich dust vs. C-rich dust?

Another Detection: Strong Silicate Dust Absorption at z=0.9 (Aller et al. 2011)

Strong quasar absorber with prior indication of cold gas.

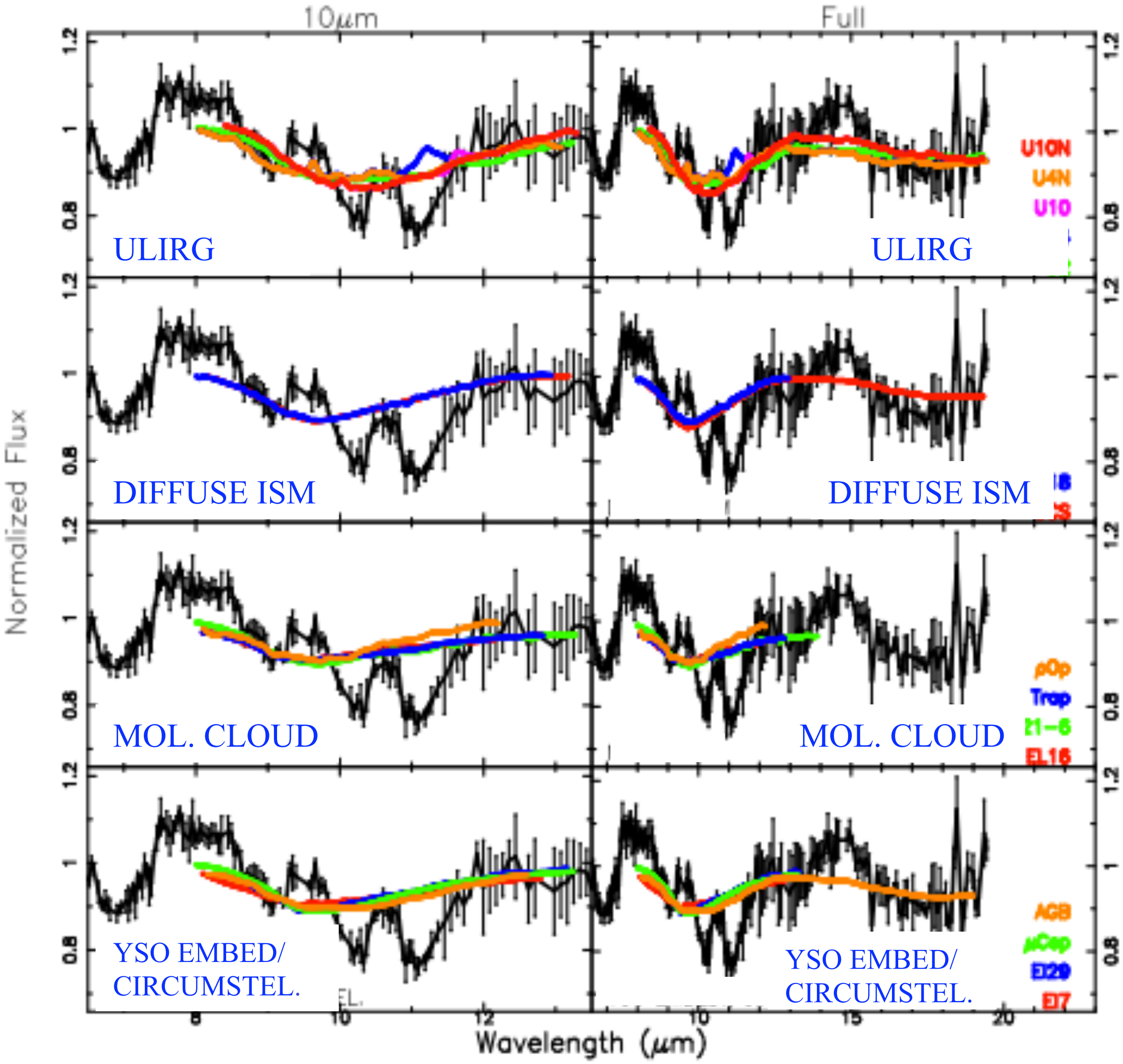




Left: IRS spectrum in absorber rest-frame wavelength: red-SL2; green-SL1; blue-LL2; and magenta-LL1.

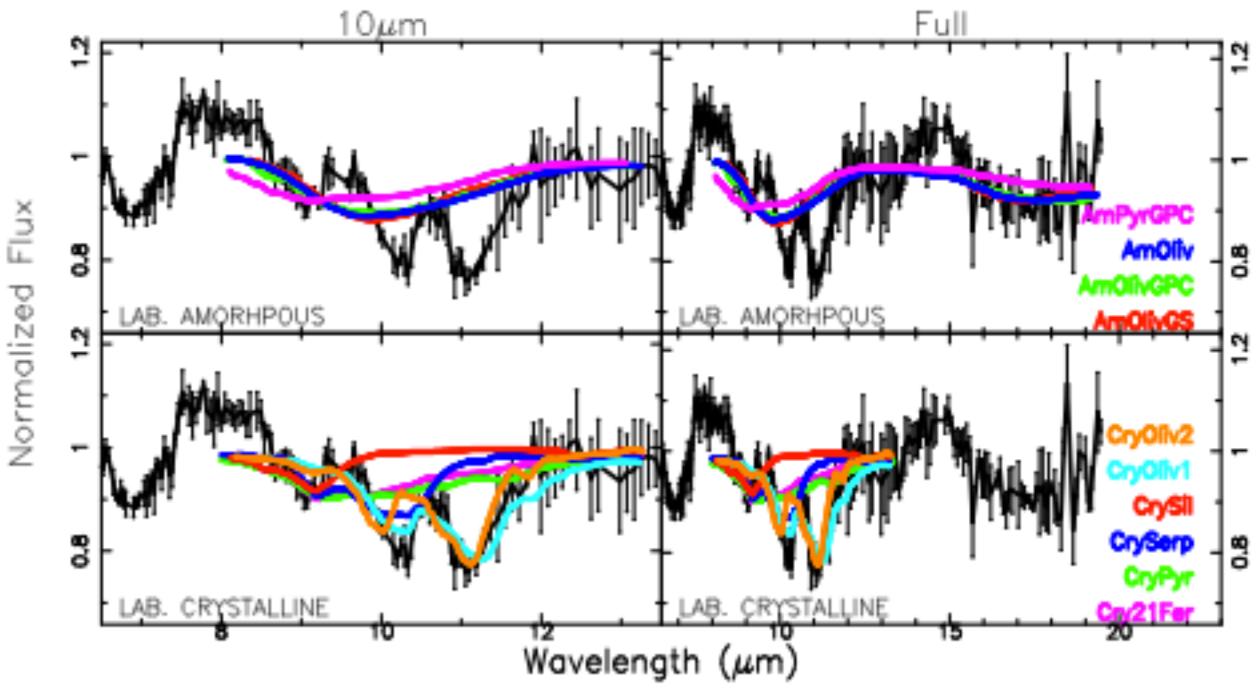
Right: The resultant normalized spectrum.

Fits with Observed Silicate Templates



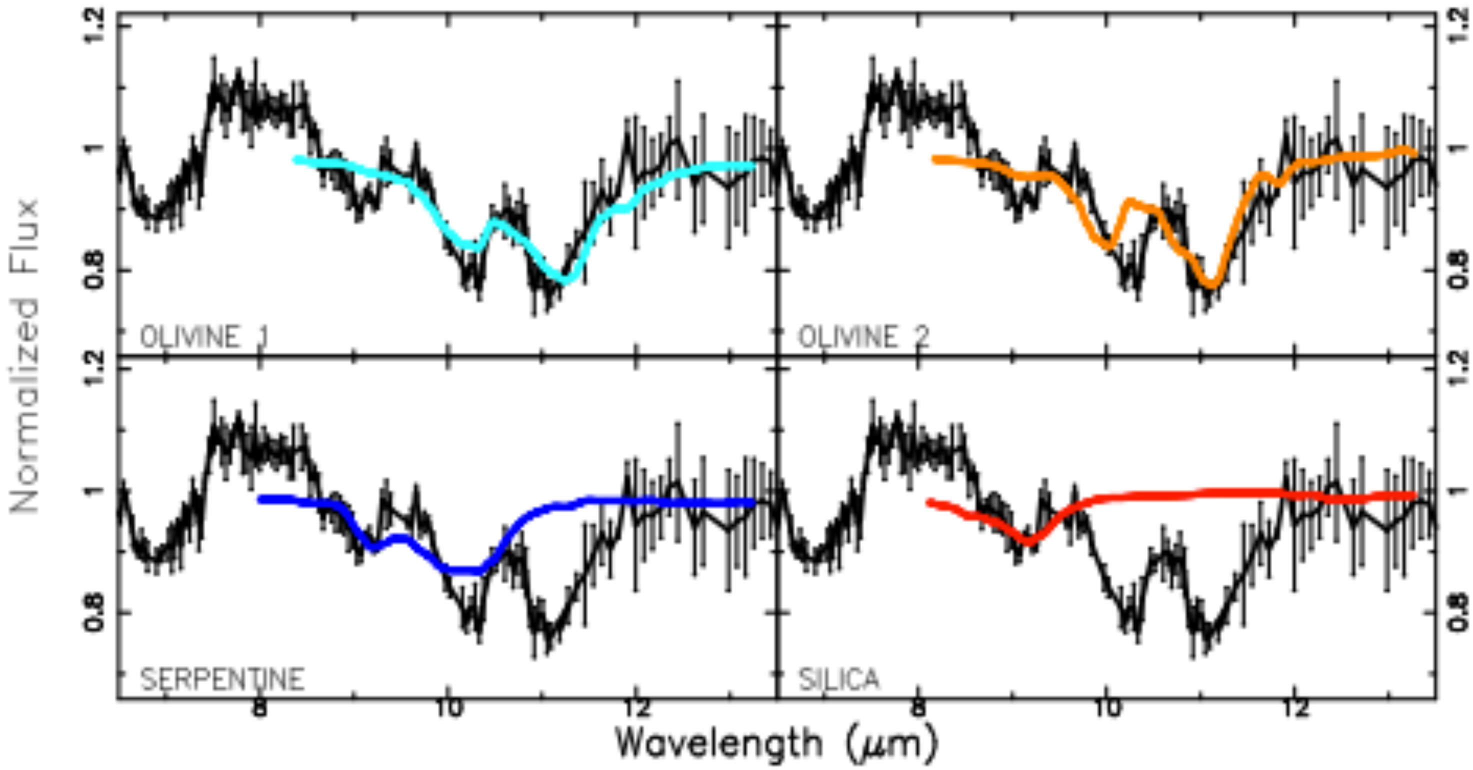
None of the astrophysically observed optical depth profiles replicate the structure in the 10 μm region seen in our data.

Fits with Laboratory Silicate Templates



The only profiles which reproduce the strong double- peaked profile within the 10 μm silicate feature region are the crystalline olivines.

Crystalline silicates at z=0.9?

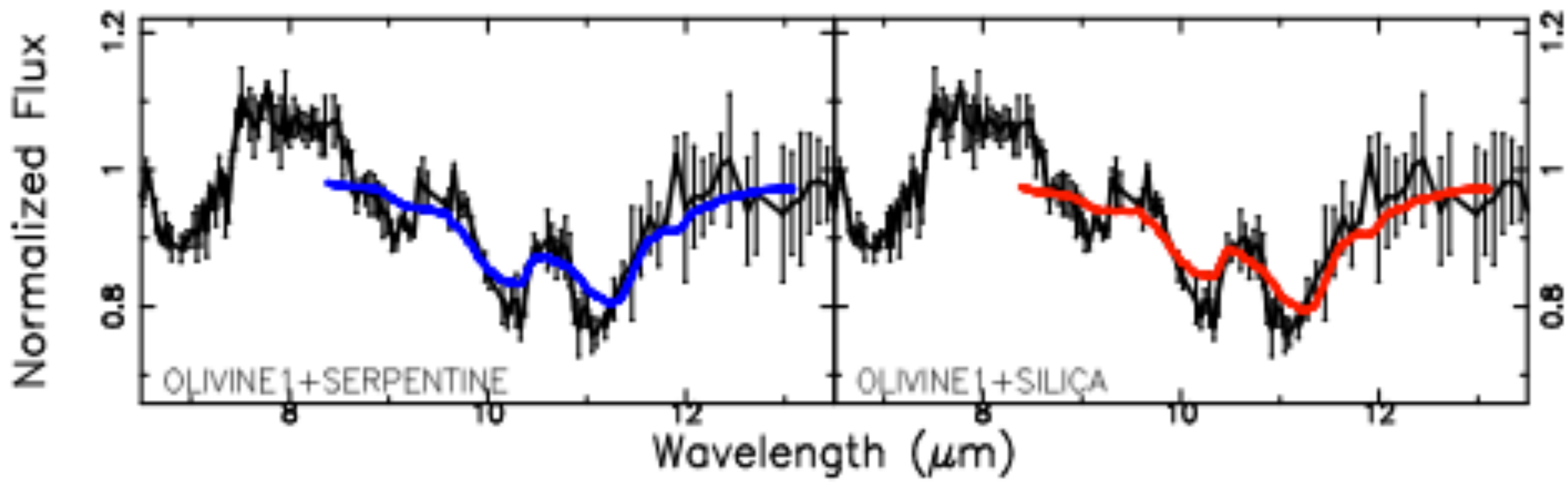


Crystalline Olivine Templates from Bowey & Adamson (2002)

Olivine 1 provides a slightly better fit than olivine 2, but neither reproduces the leftmost feature.

The leftmost feature could be fit by serpentine or by silica.

Bi-variate fits

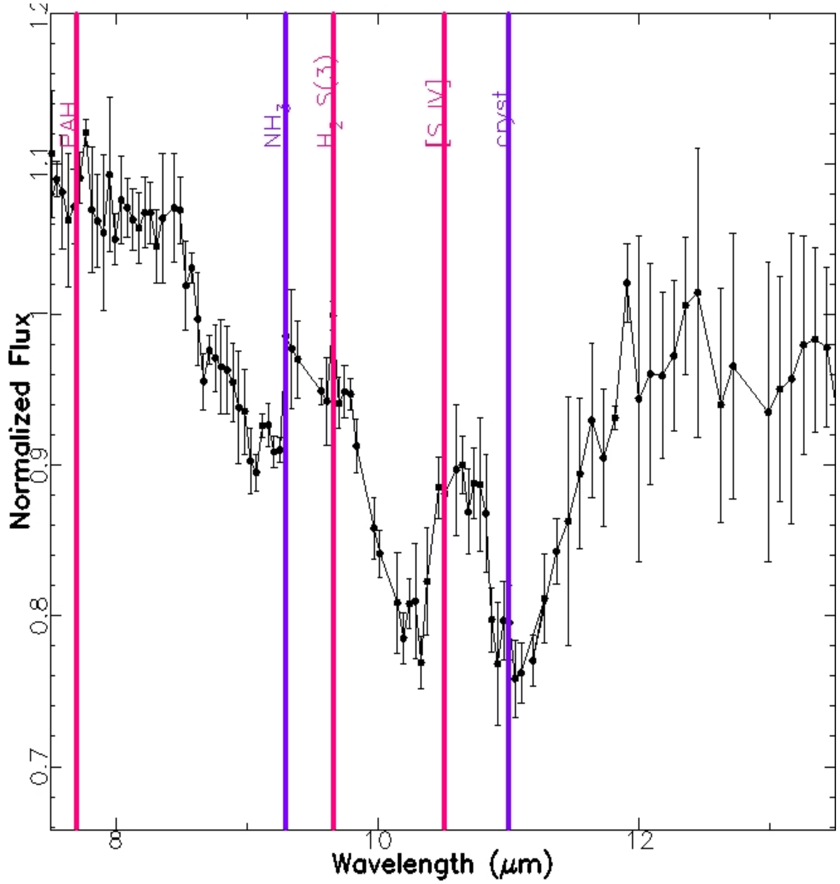


These two combinations formally produce the best fits, although only slightly better than the pure olivine 1 profile.

We may be seeing a mixture of crystalline olivine and serpentine or silica.

How would crystalline material form and be sustained in the cold absorbing gas? Caused by an unusual star-forming environment in the absorber?

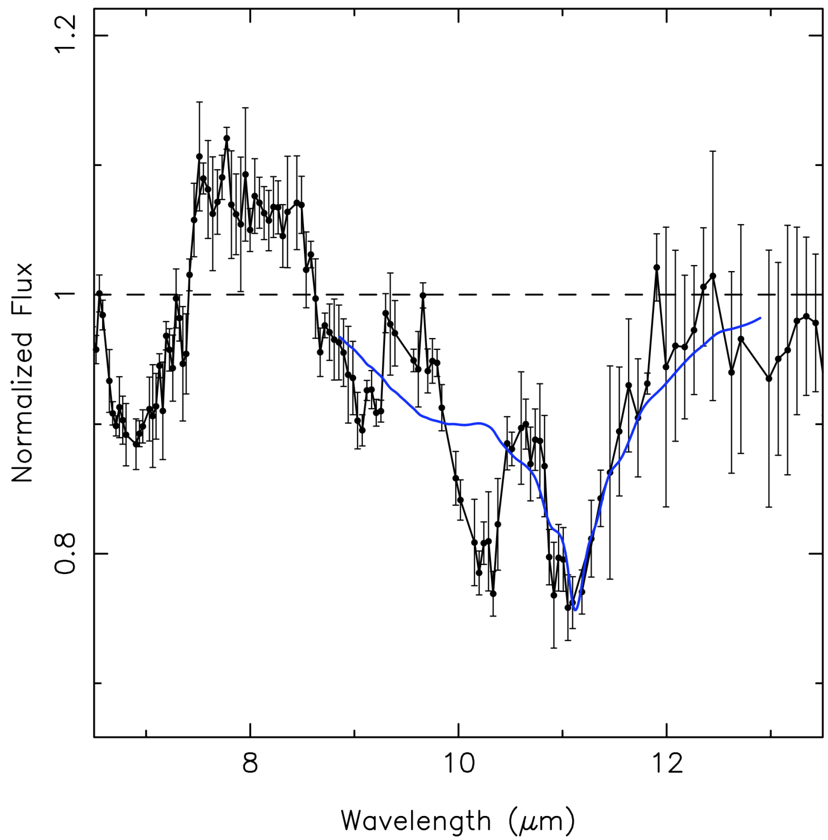
Alternatives to Crystalline Silicates?



Normalized flux profile, overlaid with emission (pink) and absorption (purple) molecular and atomic transitions detected in other astrophysical objects.

Perhaps these features could be invoked, together with a broad amorphous silicate absorption feature, to explain the structure?? But strong emission features in the absorbing galaxy seem unlikely.

Some SiC Absorption?



Last feature could be SiC, but amorphous olivine + SiC cannot explain the two left features.

May be crystalline olivine + SiC.

Again, combination of emission lines + amorphous olivine + SiC cannot be ruled out, but emission lines not expected in cold, absorbing gas.

CONCLUSIONS

- **Quasar absorbers allow us to study dust in distant metal-poor galaxies via depletion patterns, extinction curves, and dust spectral features.**

- **Most absorbers appear to have SMC-like extinction curve.**

- **Some dusty absorbers show the 2175 Å bump.**

- **We have detected the silicate 10 μm absorption feature in several quasar absorbers at $0.4 < z < 1.3$.**

- **Higher silicate optical depth/reddening ratio than that for Galactic diffuse clouds. Different grain size distributions? Different grain structures or compositions?**

- **$\tau_{9.7}$ may be correlated with Mg II strength**

- **In one absorber at z=0.9, we may be seeing crystalline silicates.**