Observations of Element Depletions and Extinction Curves due to Dust in Distant Galaxies

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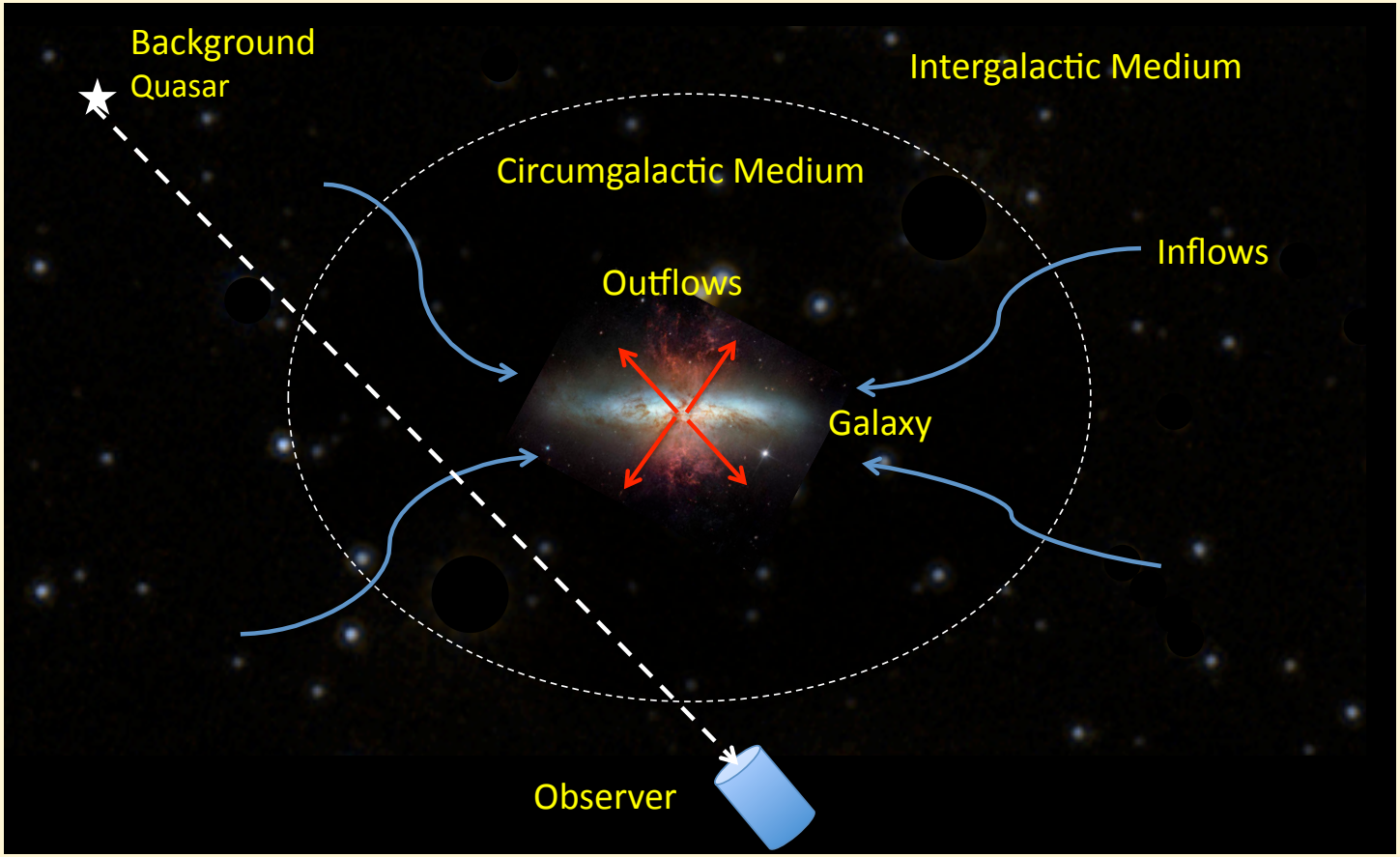
Searching for Distant Dust

What do *normal* distant galaxies show for the usual dust signatures of

★ element depletions?

★ extinction/reddening?

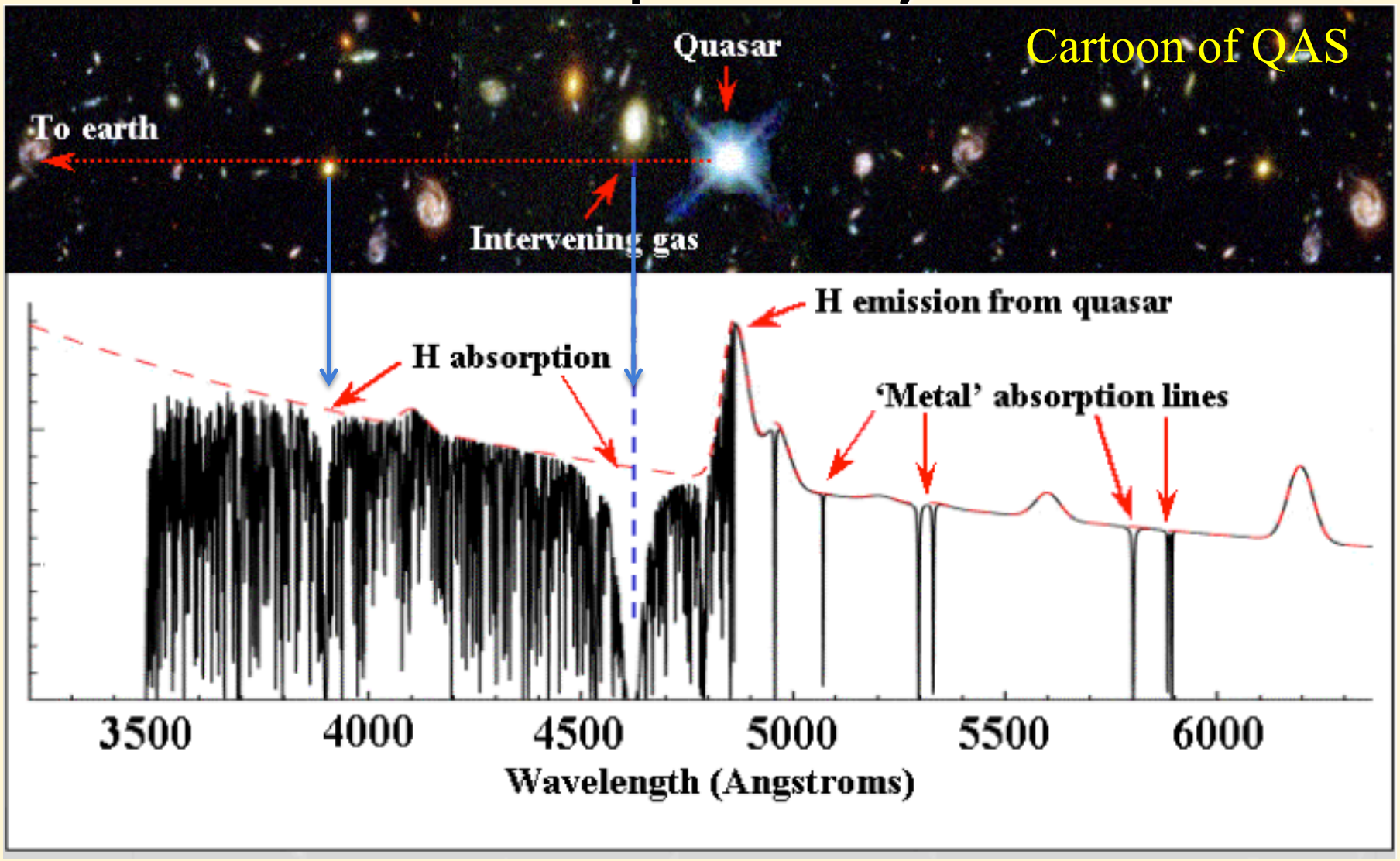
★ spectral features?



Selection independent of galaxy luminosity, SFR, nuclear activity etc.

Can probe a wide metallicity range
(< 0.01 solar to super-solar)

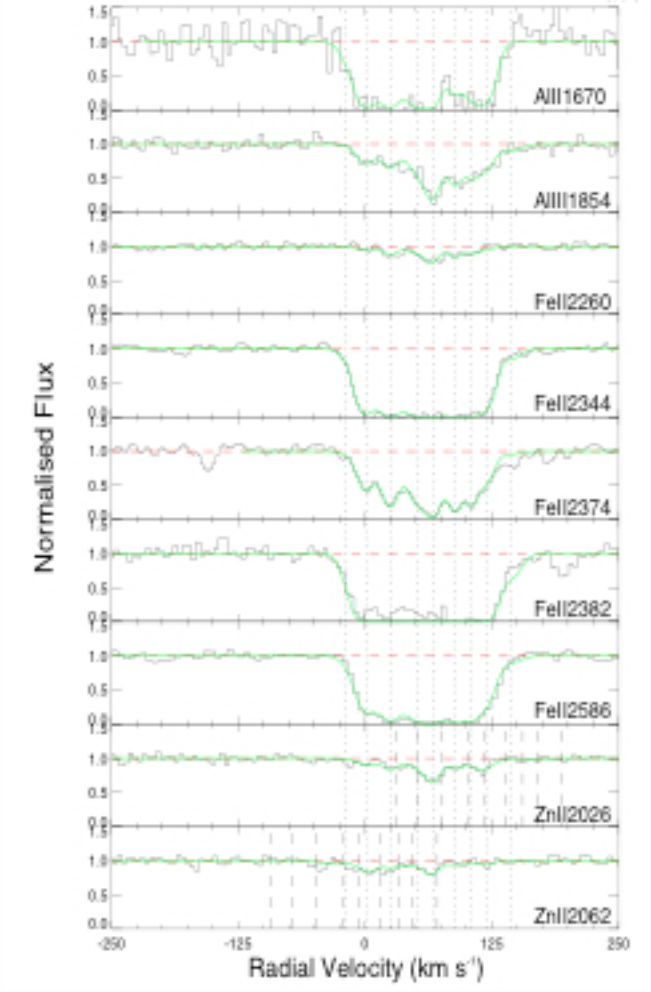
Quasar Absorption Systems (QASs)

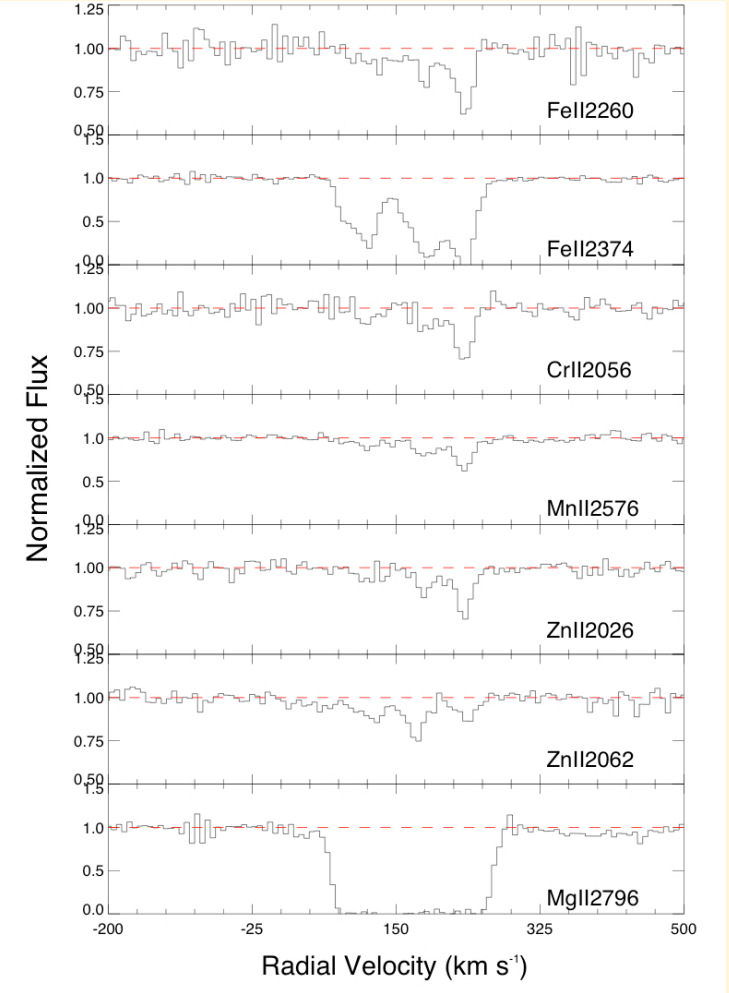


Especially important: DLAs $N(H\ I) \geq 2 \times 10^{20}$ cm^{-2} and
Sub-DLAs: $10^{19} \leq N(H\ I) < 2 \times 10^{20}$ cm^{-2}

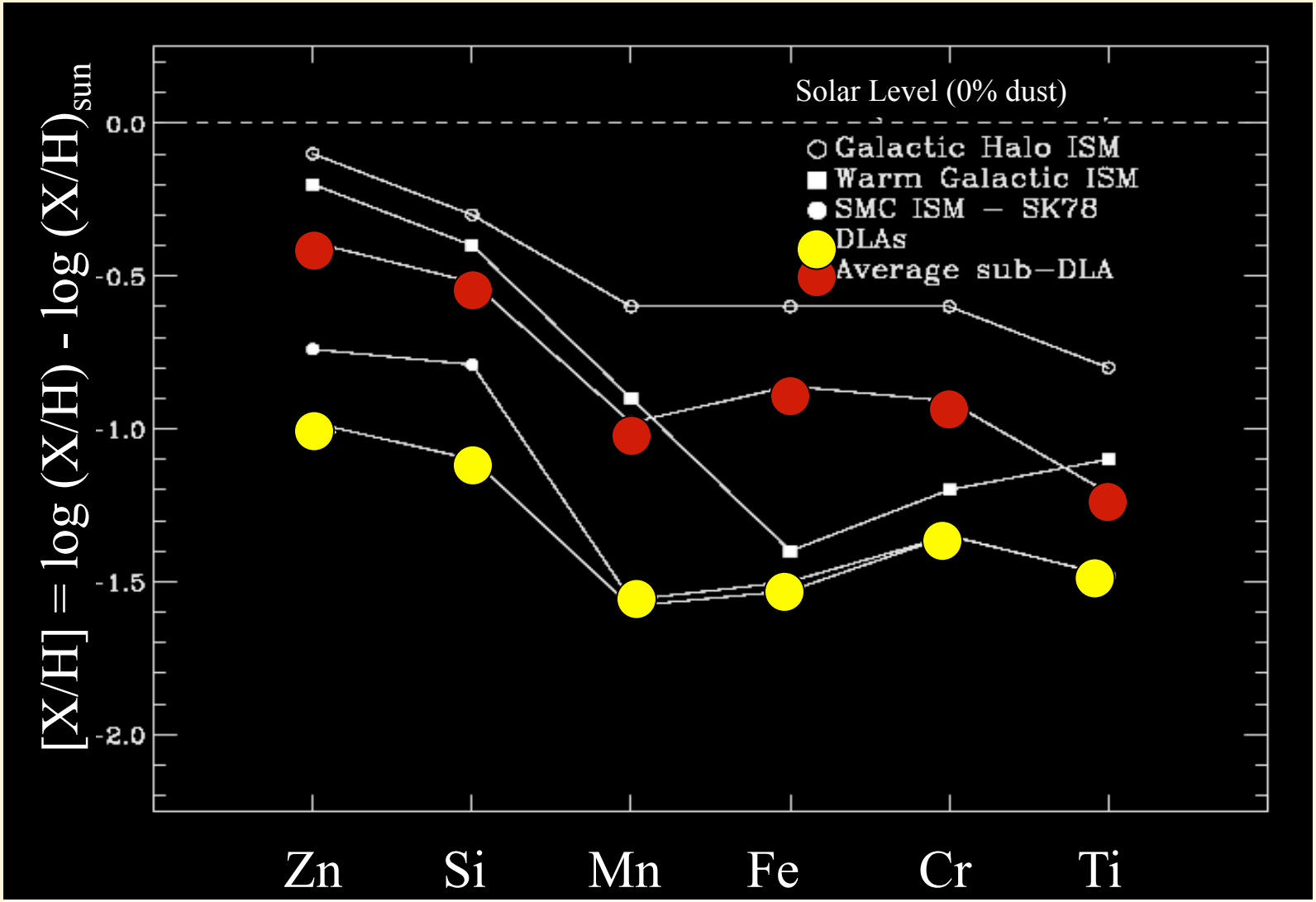
How do we measure element depletions?

We measure rest-frame optical/UV absorption lines from both volatile and refractory elements.

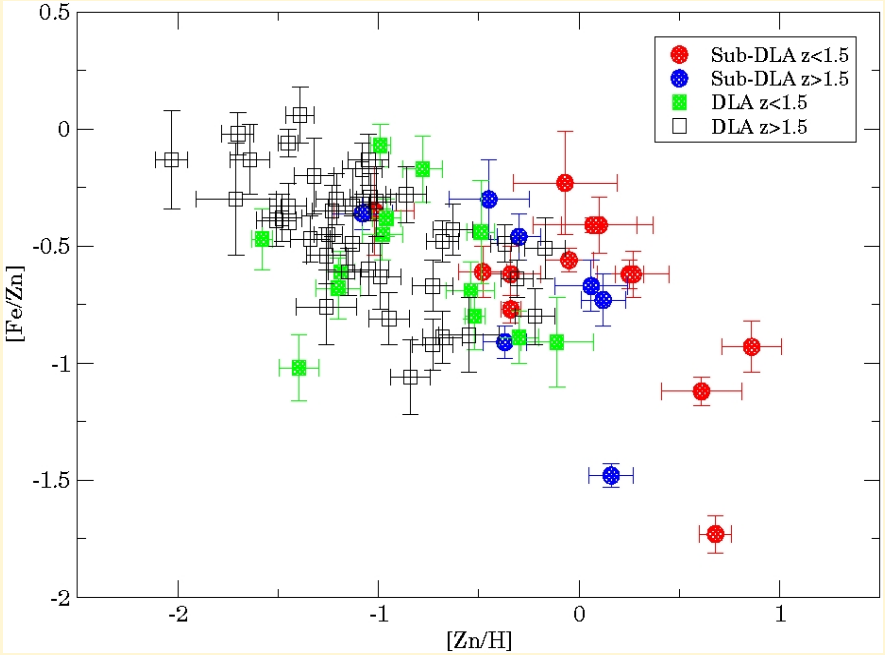


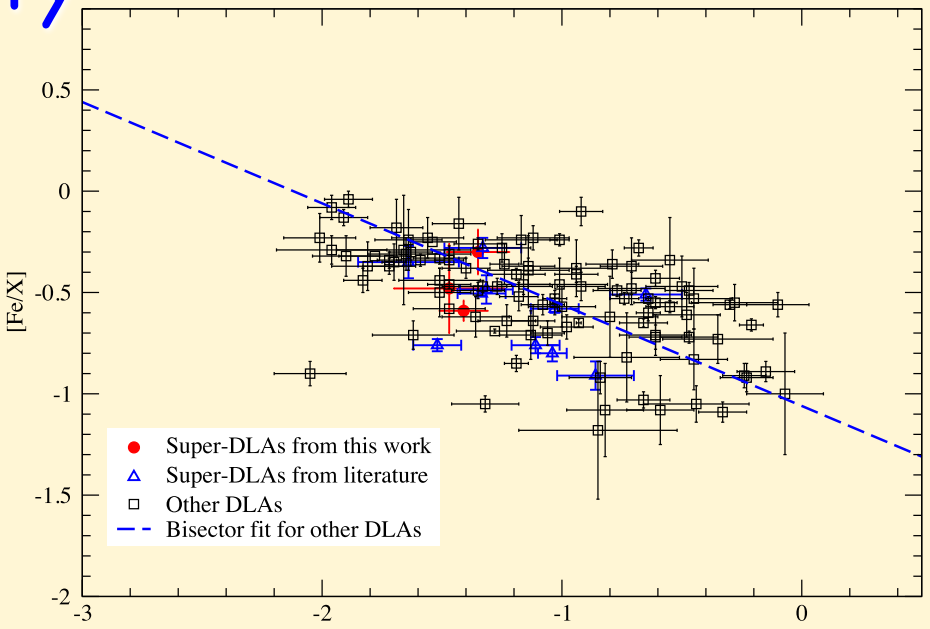


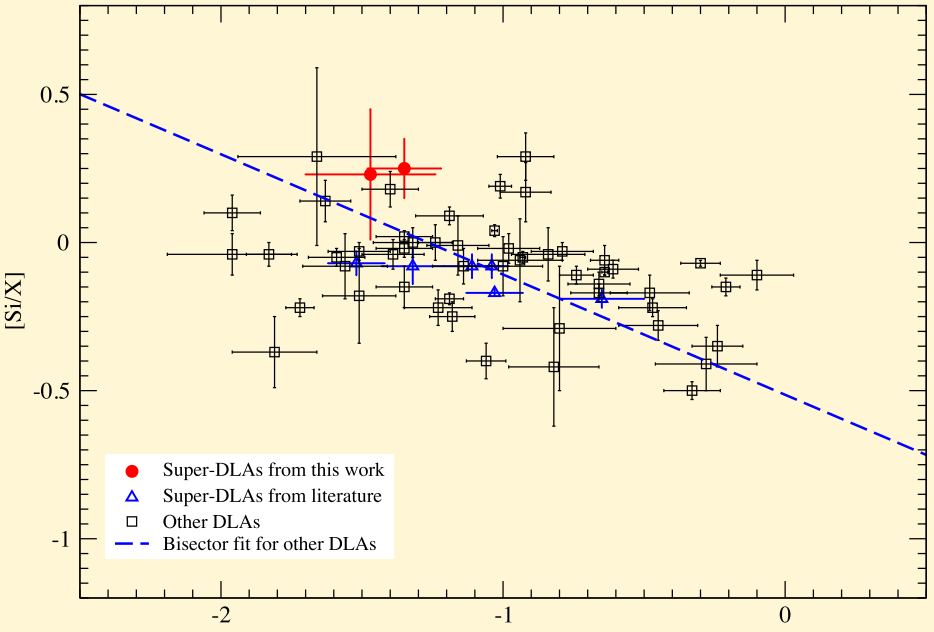
Distant galaxies show depletions of elements.



Depletion vs. Metallicity







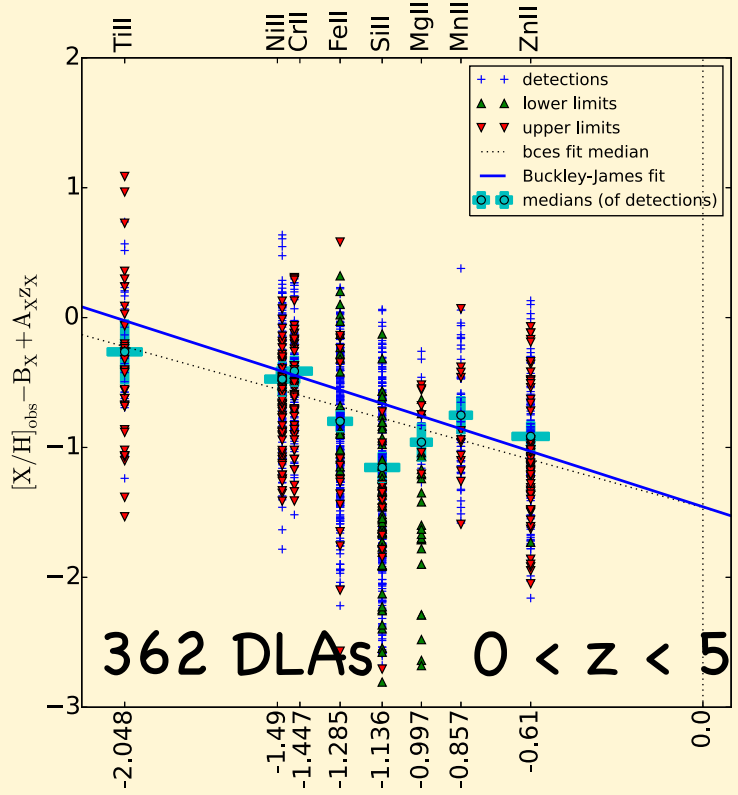
Depletion is more severe at higher metallicity (e.g., Ledoux et al. 2003, Meiring et al. 2006, 2009; Kulkarni et al. 2015)

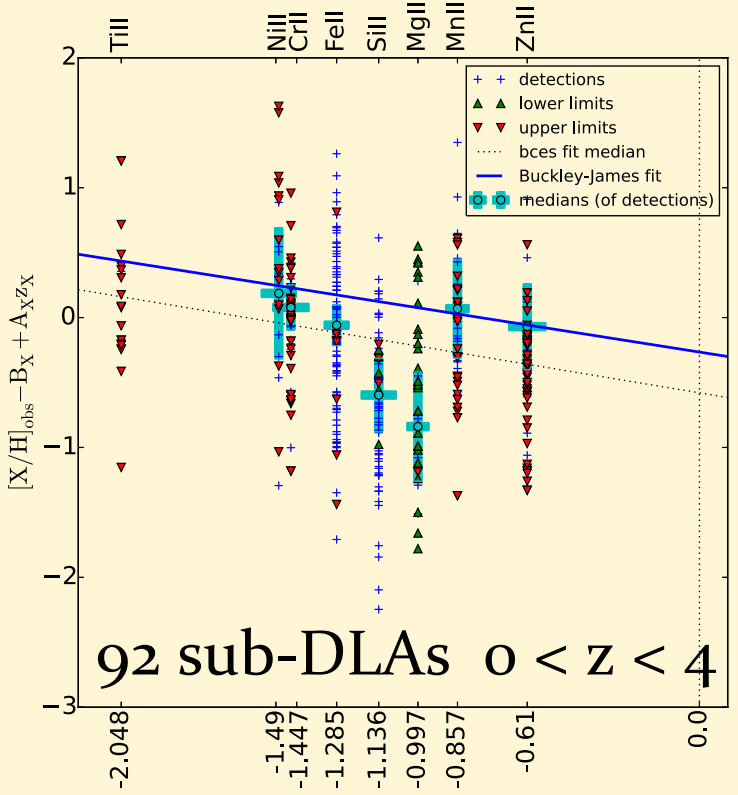
Kulkarni et al. 2015

[X/H]

Depletions at High Redshift (DLA, Sub-DLAs)

Jenkins (2009) approach for DLAs, sub-DLAs (Quiret et al. 2016)





$[X_{gas}/H]_{fit} = B_X + A_X(F_* - z_X)$ where F_* = line of sight depletion factor

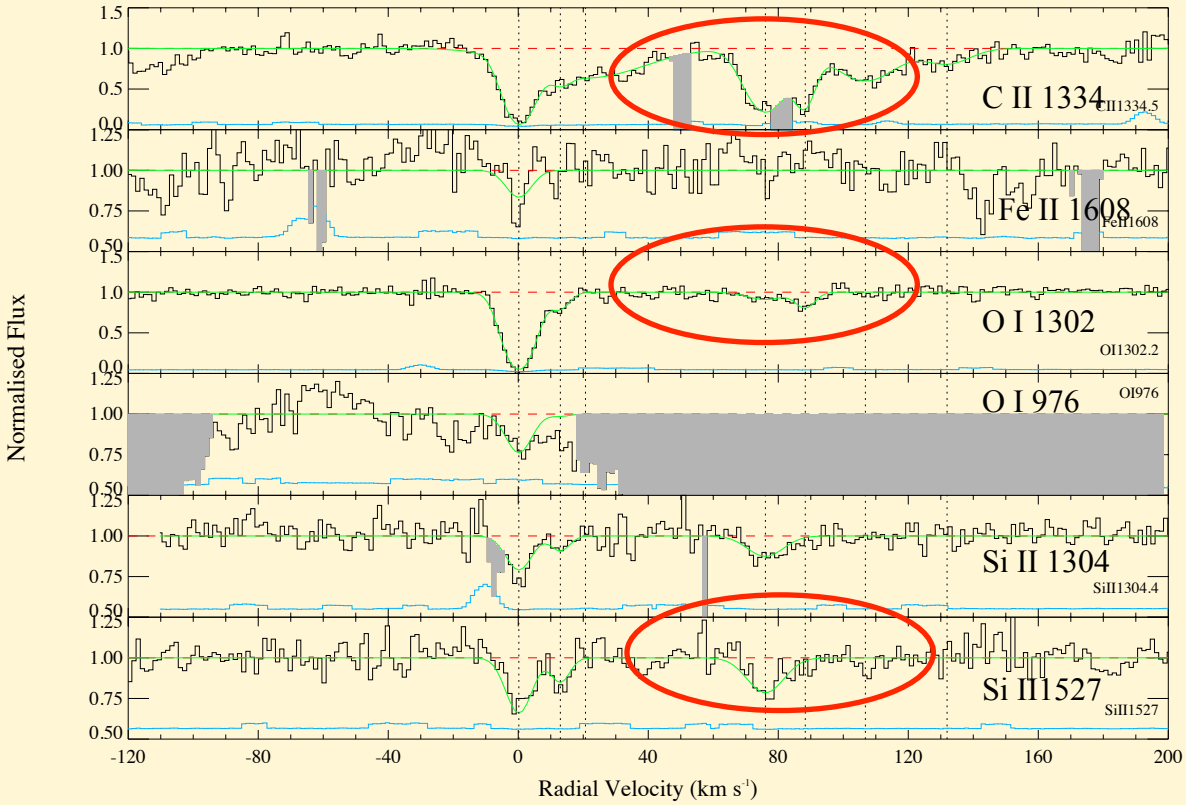
Median F_* = -0.70 ±0.06 for DLAs, -0.34 ±0.19 for sub-DLAs

Lower than F_* = 0.12 for warm disk ISM, -0.28 for halo ISM, -0.1 for warm ionized medium in MW.

Much less dust than in MW, greater ionization?

An Interesting Case of Dust Depletion at z=5

Morrison et al. (2016)



1/100 solar metallicity

Si/O < 1/3 solar overall

Significant depletion

[Si/O] = -0.50±0.08

[Fe/O] = -0.58±0.14

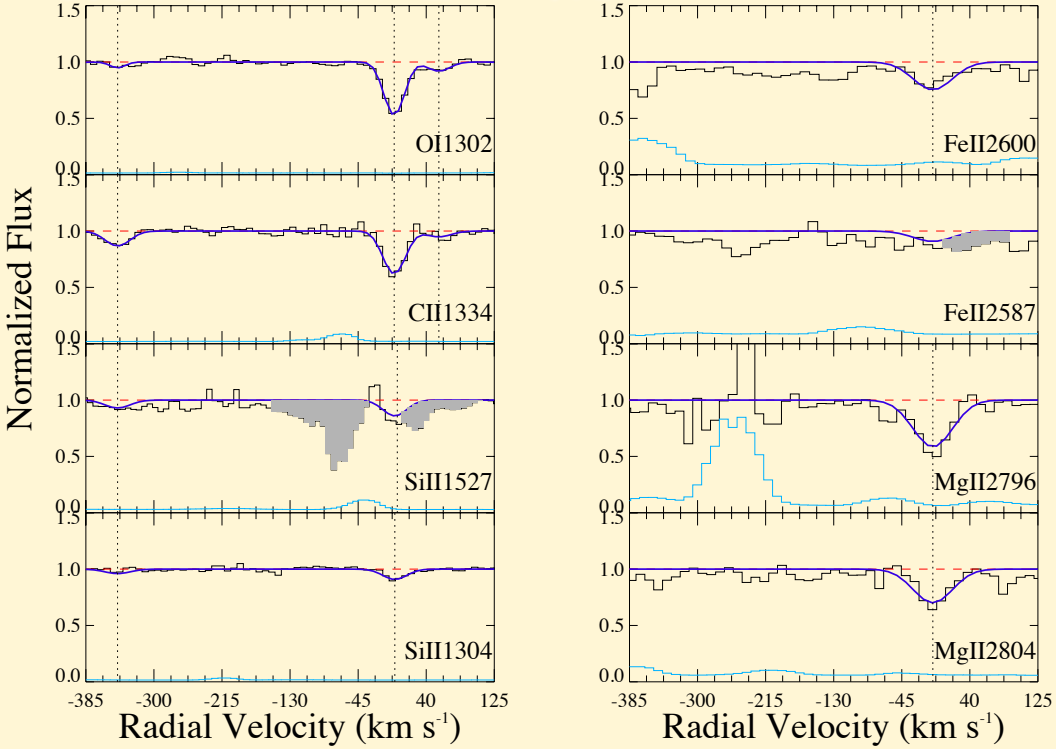
Factor of ~20-30 difference in abundance ratios in different velocity components

➔differences in depletion?

Expanding the z~5 Sample

Poudel et al. 2018; Poudel et al. 2019, submitted

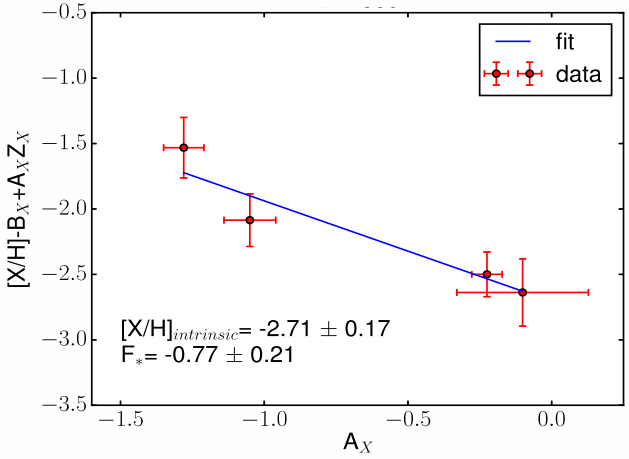
- Absorbers at z=4.81-5.34 discovered in SDSS
- VLT X-shooter, Magellan MIKE, and Keck ESI spectra resolve the Ly-α forest better than SDSS spectra
- Measured abundances of O, C, Si, Fe
- More than tripled the measurements of weakly depleted elements at z > 4.5



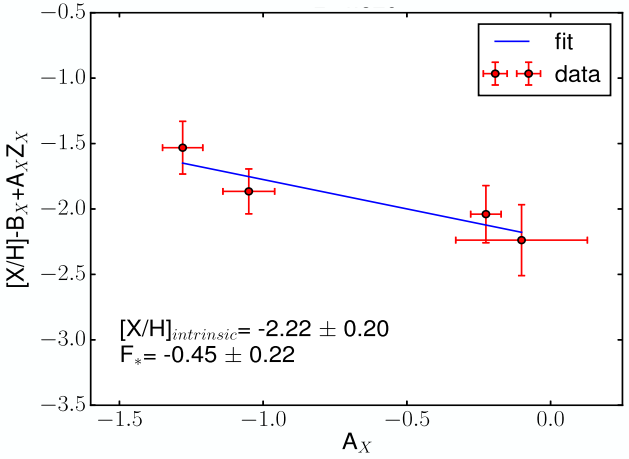
z=4.81 Sub-DLA
log N_{HI}=20.10+/-0.15

F* in Some Absorbers at z~5

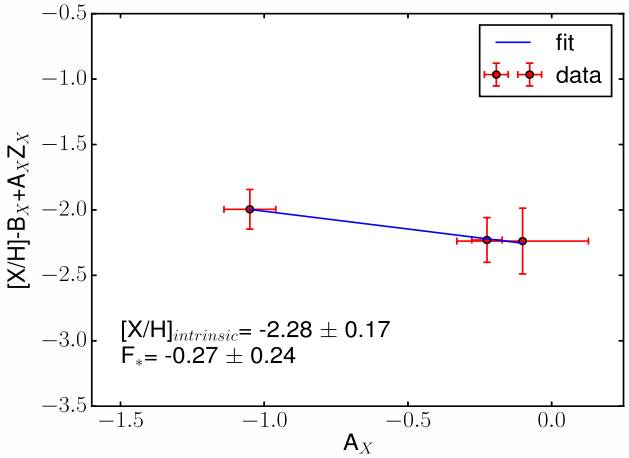
z=4.81



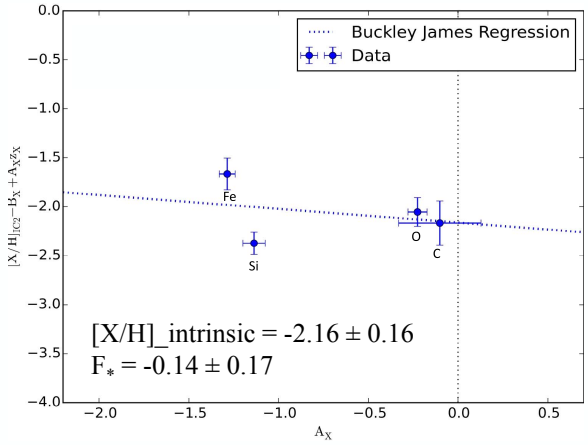
z=4.83



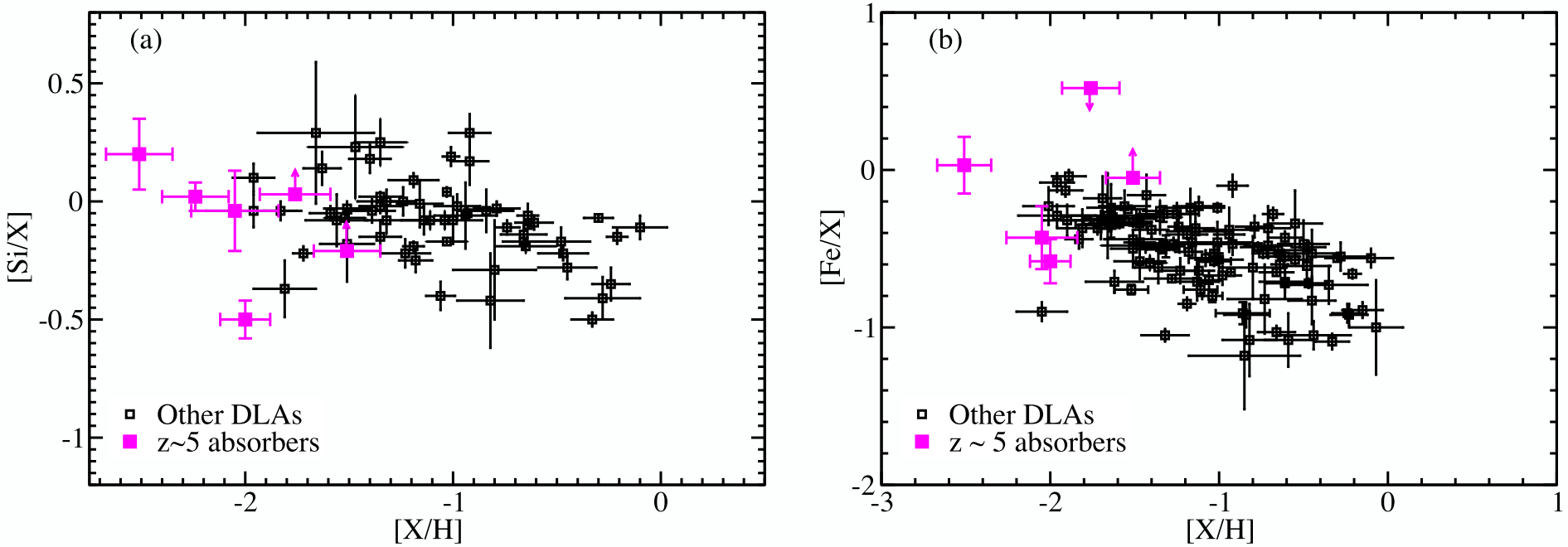
z=5.34



z=4.98



Depletion vs. Metallicity at z~5

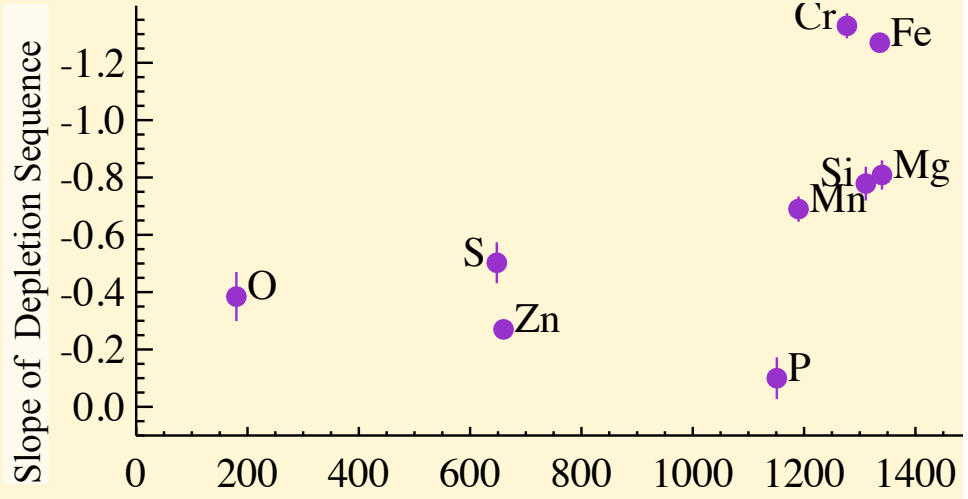


Some z~5 absorbers show substantial depletion of Si, Fe.

Not surprising that Si, Fe are depleted…

Consistent with De Cia et al. (2016, 2018) conclusions

Element Depletions in DLAs

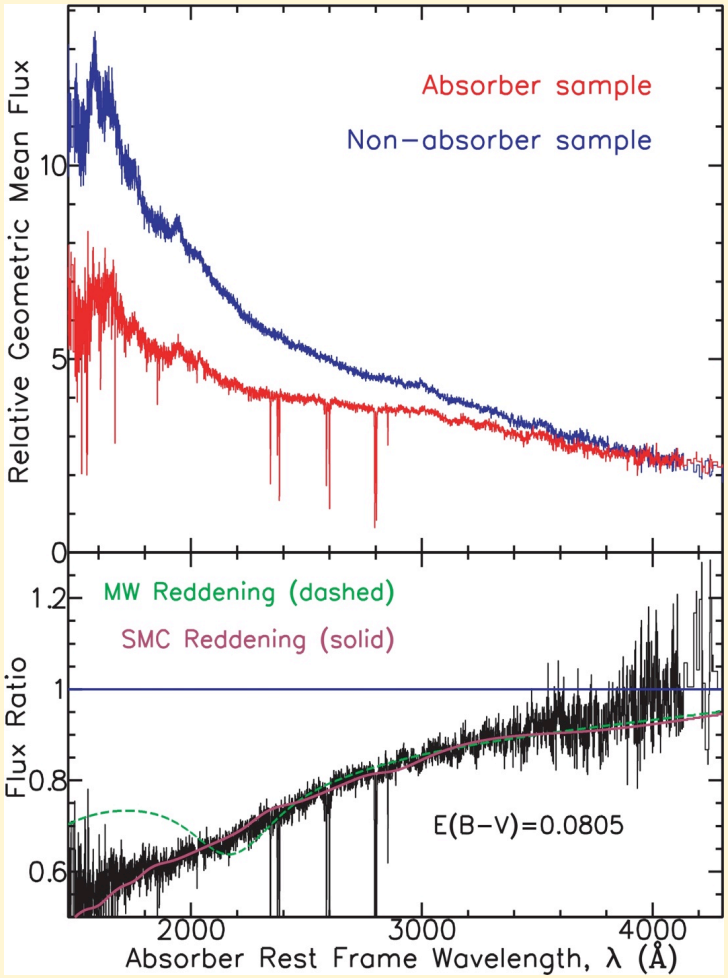


De Cia et al. (2016)

Even in DLAs, depletion is more severe for refractory elements like Si and Fe, than for volatiles like O, S….

Even at z~5!

Extinction Curves for Absorption-Selected Galaxies



Distant galaxies also redden spectra of background quasars.

Most of these distant galaxies show small but statistically significant amount of reddening.

York et al. (2006)

Extinction Curve fitting for SDSS DLAs/sub-DLAs

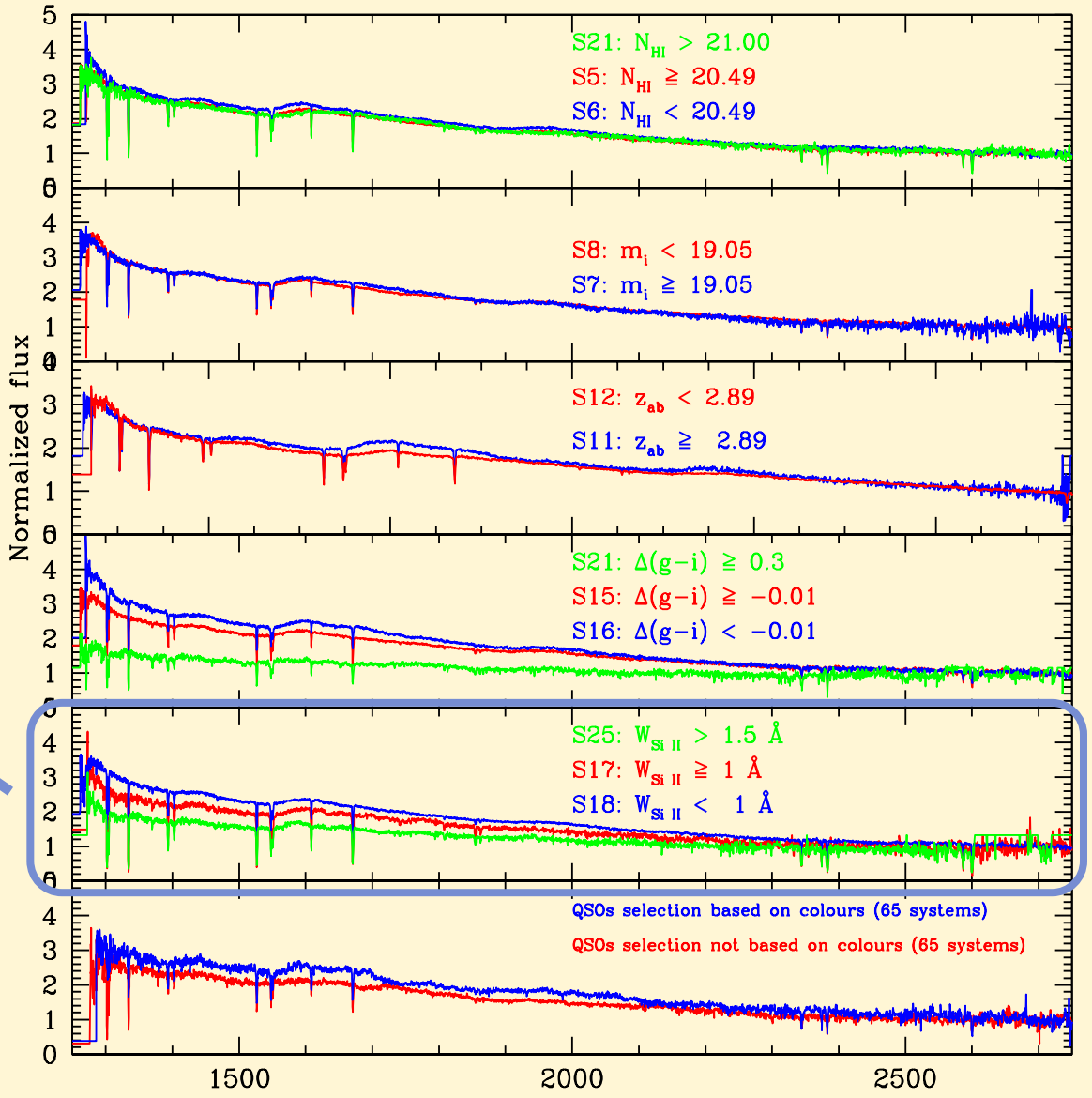
- Khare et al. (2012)
- 1084 systems with $2.1<z<5.2$, log $N_{HI}>20.0$

Stronger reddening for systems with stronger gas-phase Si lines

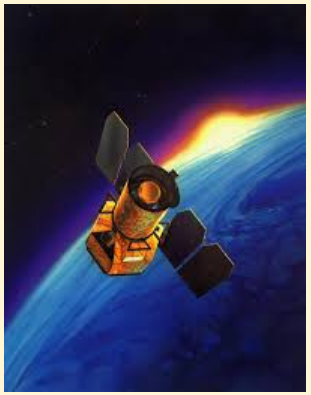
(E_{B-v} = 0.0097 for $W_{Si\ II\ 1526} \geq 1.0$ Å

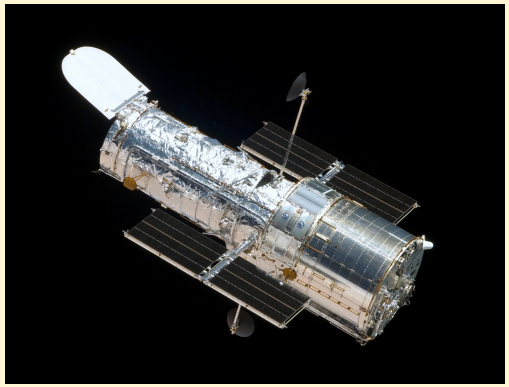
vs.

E_{B-v} = 0.0039 for $W_{Si\ II\ 1526} < 1.0$ Å.)



Sample for Study of Extinction Curves in Individual Distant Galaxies





72 quasars at 0.2 < z < 2 with foreground absorbers

66 with spectra available

SDSS, HST, Spitzer

Flux calibrated spectra

Photometry

General Method

Generate SEDs using available data

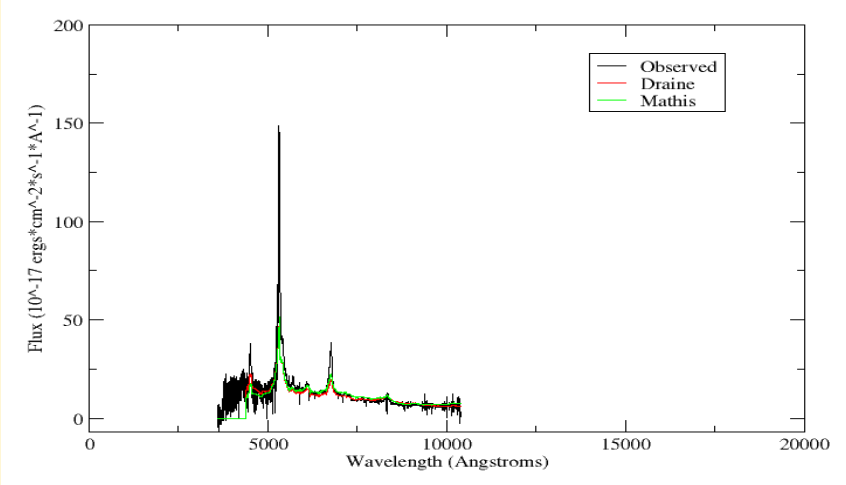
Use template of unreddened quasar composite spectra (e.g., Selsing et al. 2015, Hernan-Caballero et al. 2016)

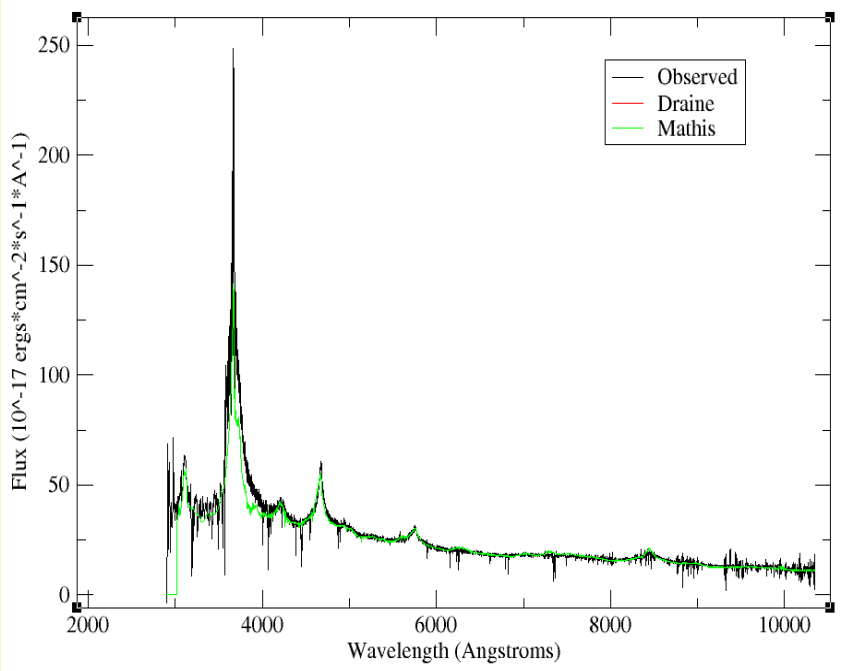
Shift the template to the quasar's redshift

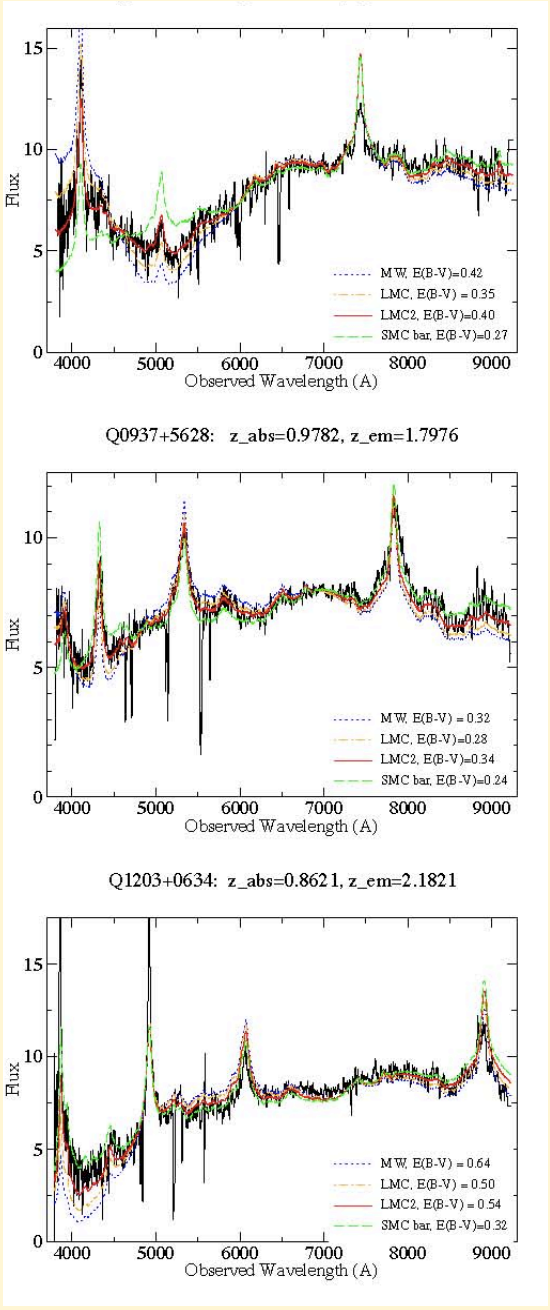
Redden using extinction curves at the absorber redshift and compare to observed spectrum

Find best-fitting E(B-V) and normalization factor

Examples: Fitting (UV, Visible)

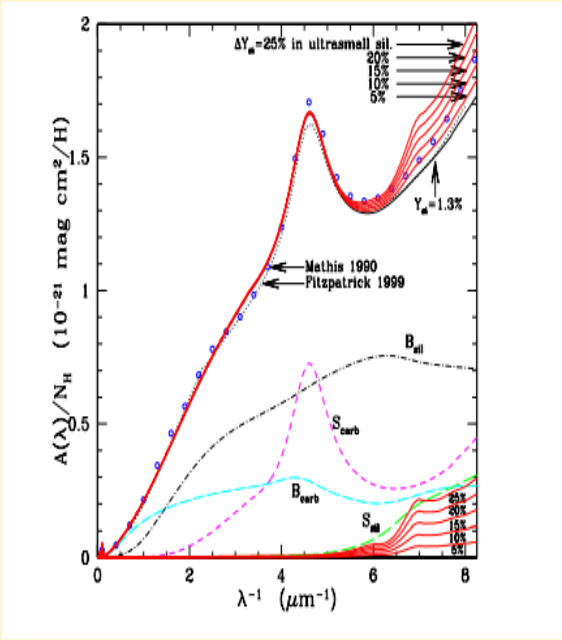






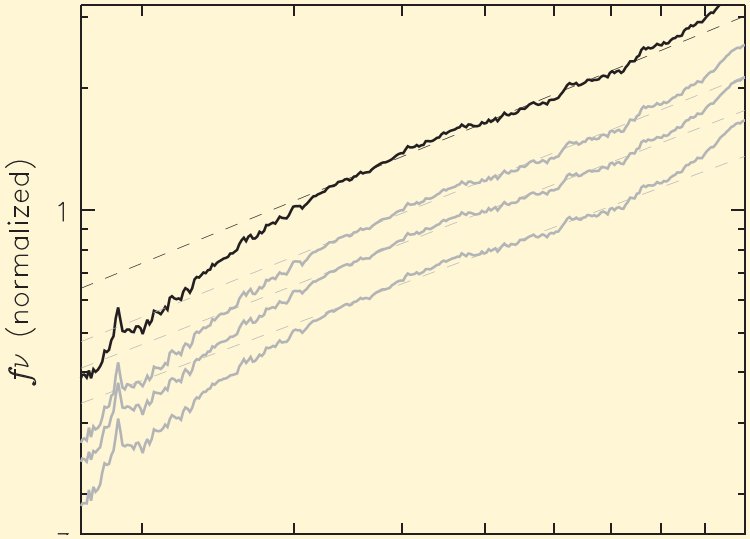
Fitting (IR)

IR Extinction curves from Draine 2001 and Cardelli, Clayton, Mathis 1989



Draine 2001 MW extinction curves.
Uppermost solid red line is the curve used.

Hernan-Caballero et al. 2016 composite spectrum used as the template



Does not fit well for some sources

Exploring other templates specific to different types of AGN

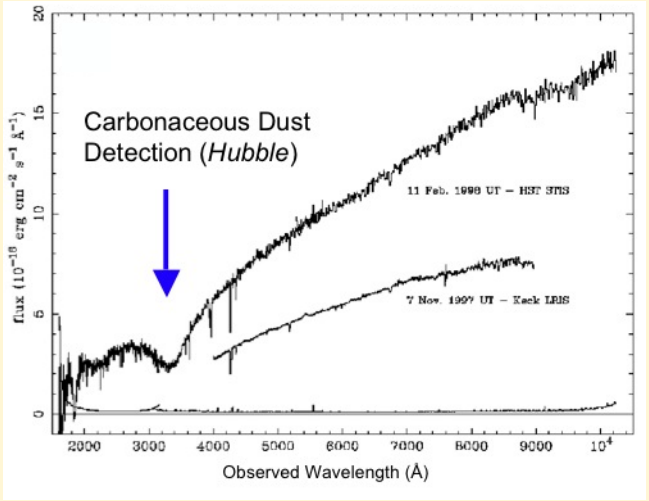
(More in Monique Aller's talk tomorrow)

Dust Spectral Features

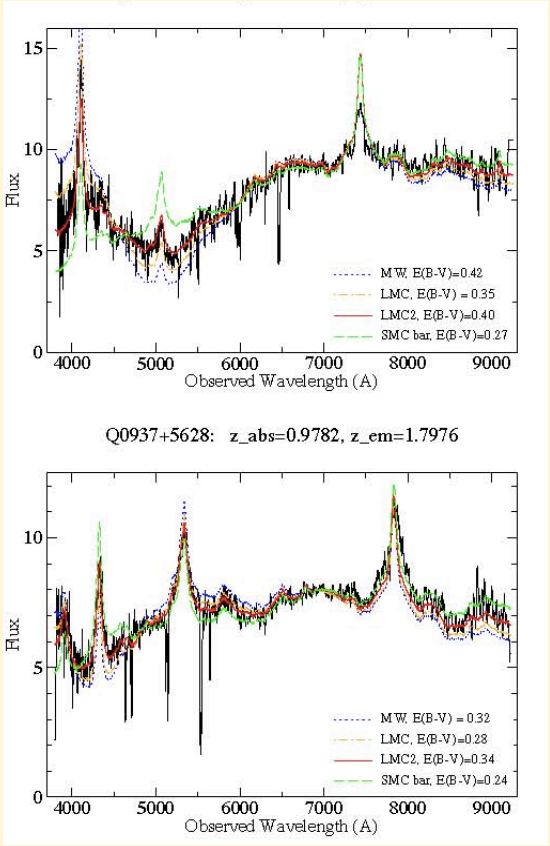
Carbonaceous Absorption: The 2175 Å Bump

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

A small number of absorbers show the bump (e.g., Junkkarinen et al. 2004; Srianand et al. 2008; Noterdaeme et al. 2009; Kulkarni et al. 2011; Ma et al. 2017, 2018)



Junkkarinen et al. (2004)

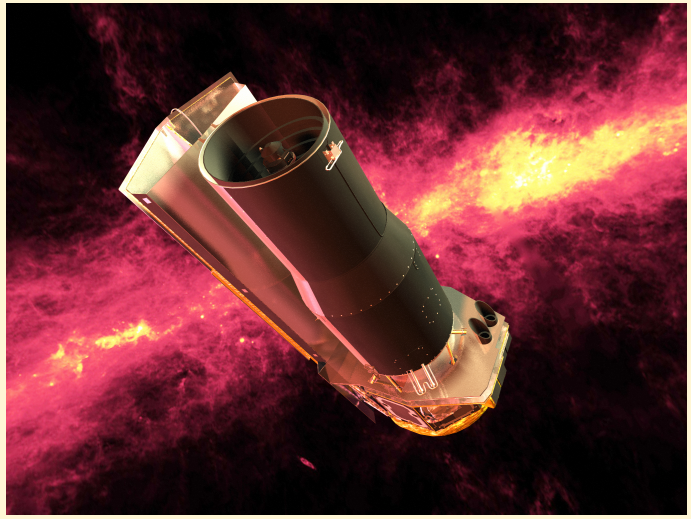


Silicate Dust in Distant Galaxies

- Most past studies of dust spectral features in quasar absorbers focused on the 2175 Å feature and ignored the silicate dust.

- We have been carrying out a search for the 10, 18 μm silicate features in quasar spectra in known absorbers at $z < 1.4$ selected to have abundant gas and dust.

- Search for the redshifted silicate features at 10 μm and 18 μm using our observations and archival data from Spitzer IRS
(e.g., Kulkarni et al. 2007, 2011, 2016, Aller et al. 2012, 2014, 2019 in prep)



More on this tomorrow in Monique Aller's talk

CONCLUSIONS

- Depletions of elements clearly present in galaxies selected by absorption in the spectra of background quasars

- F_* for DLAs is lower than for Milky Way halo gas.

- Some absorbers show Si, Fe depletion even at z~5

- Extinction is small but significant for DLAs.

- Often fitted best with SMC-like extinction curves.

But some objects are dustier with 2175 A bump and silicates.

Ongoing/Future work

- Expanding metallicity, dust measurements
- Enlarging the sample at z>4.5
- Extinction curve fits in IR
- Expanding silicate sample
- Improvements to key atomic data needed for accurate metallicity, depletion measurements—in progress with Kisielius, Ferland (e.g., Kisielius et al. 2014, 2015), compilation of latest atomic data by Cashman et al. 2017)

(~22% of the lines have uncertainties of > 0.1 dex in oscillator strengths , which is larger than the typical measurement uncertainties in metal column densities)