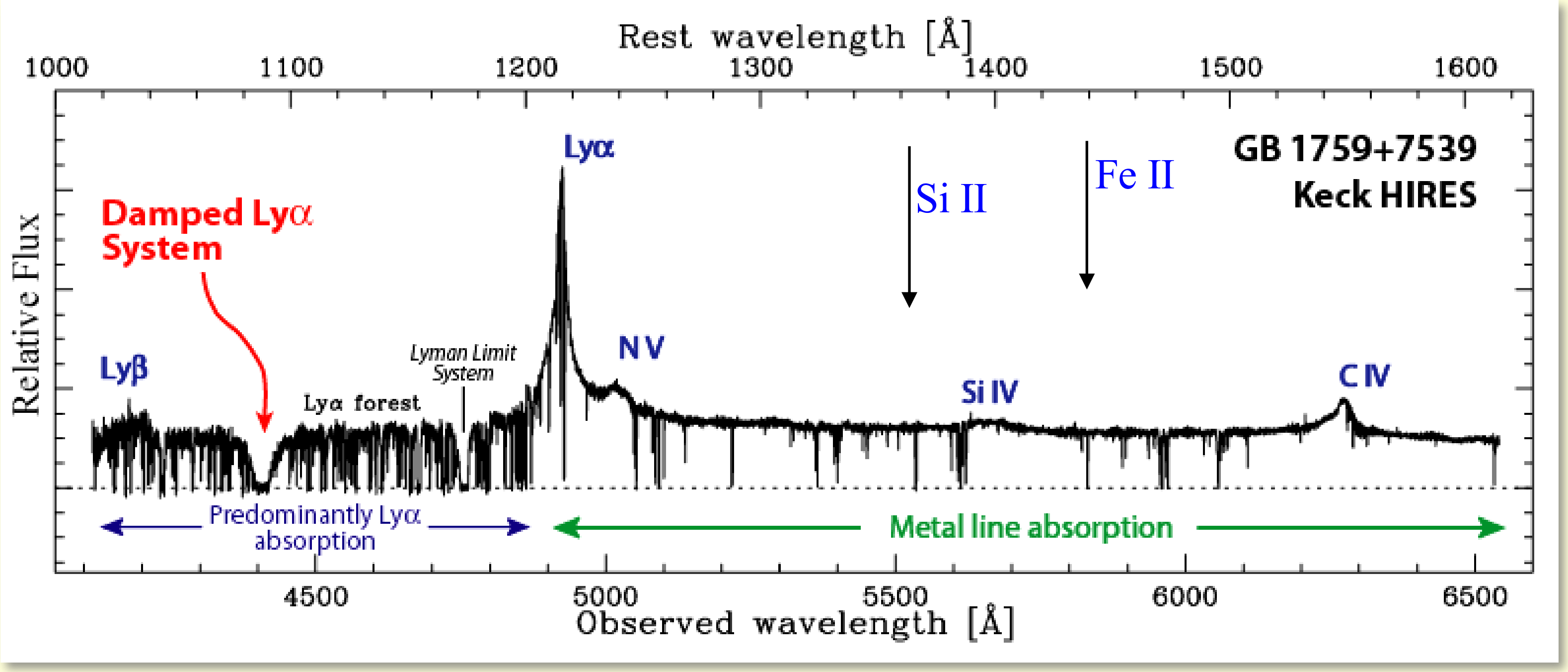
Metallicity and Kinematic Evolution of Damped Lyα Systems to z~5

Art Wolfe

Marc Rafelski: IPAC
Marcel Neeleman: UCSD
J. Xavier Prochaska: UCSC

Damped Lyα Absorption Systems

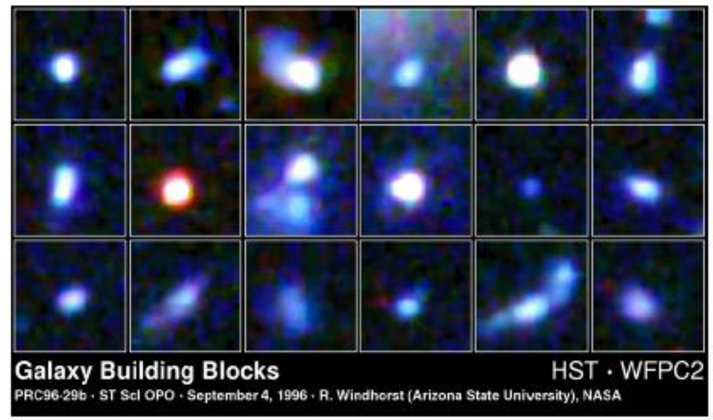


- Definition of Damped Lyα System (DLA): $N(HI) \geq 2 \times 10^{20}$ cm^{-2}
- Distinguishing characteristics of DLAs :
  - (1) Gas is Neutral
  - (2) Metallicity is low: [M/H]=-1.5
- DLAs dominate the neutral-gas content of the Universe out to z=5
- DLAs cover 1/3 of the sky at z=[2.5,3.5]
- $\Omega_{gas} \approx 0.5\Omega_{visible}$

What are DLAs?

A long standing debate

or



Haehnelt (2012)

How are DLAs Related to Galaxies?

- Do DLA metallicities resemble those of known stellar populations?
- Size, Mass of Galaxies Hosting DLAs?
- Origin of DLA kinematics?
- Do DLAs exhibit a mass-metallicity relation?

Outline

- Results of Survey for high-redshift ($z=4-5.2$) DLAs: Metal Abundances

- DLA Kinematics: velocity-interval distribution, and its relation to metal abundances and redshift

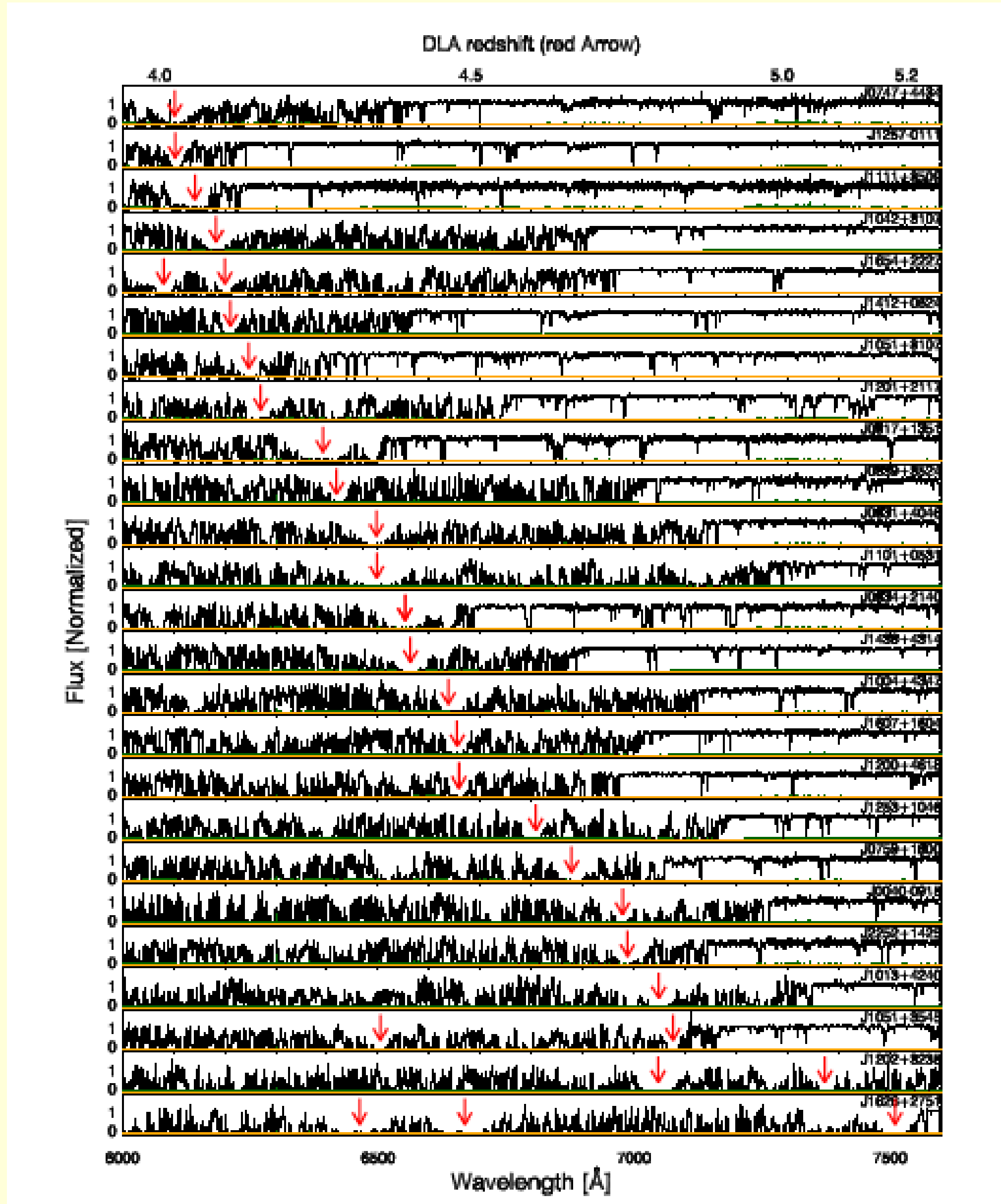
1. Keck ESI Survey for DLAs at $z_{abs} > 4$:

--Metal Abundances of DLAs

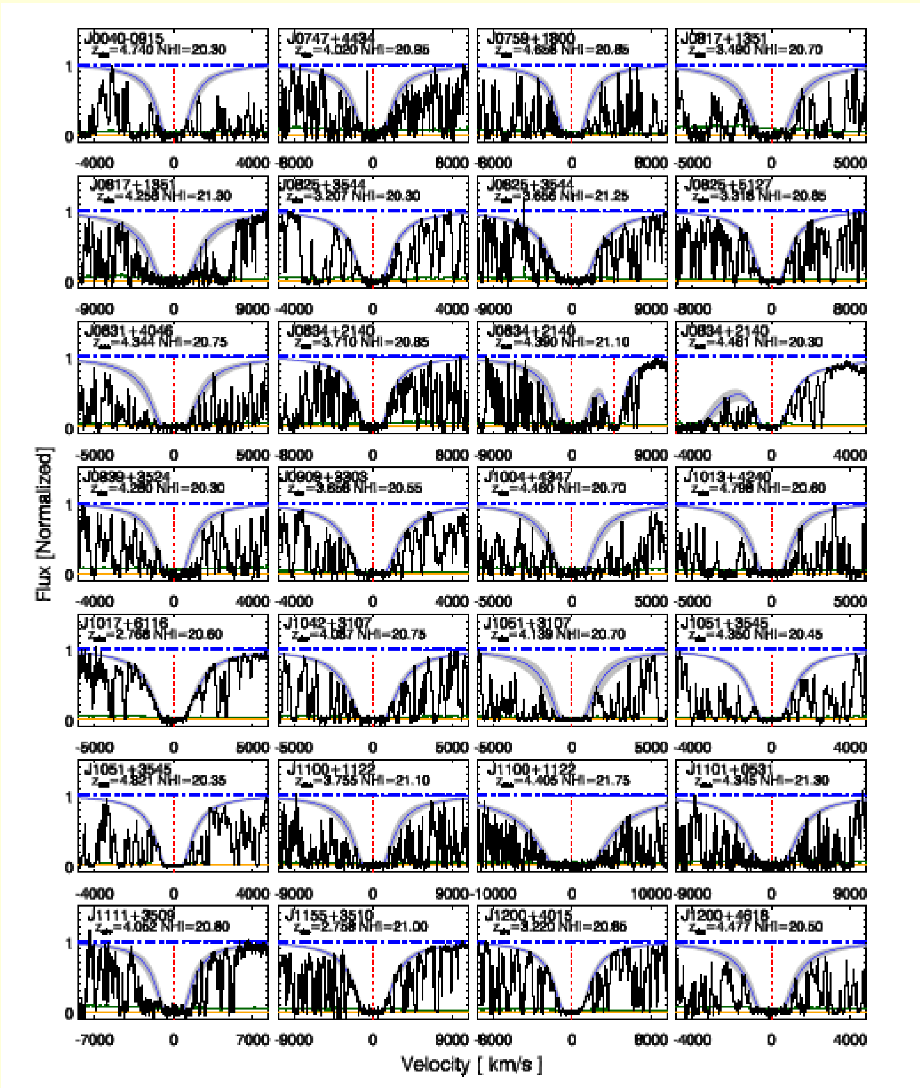
(Rafelski, Wolfe, & Prochaska 2012)

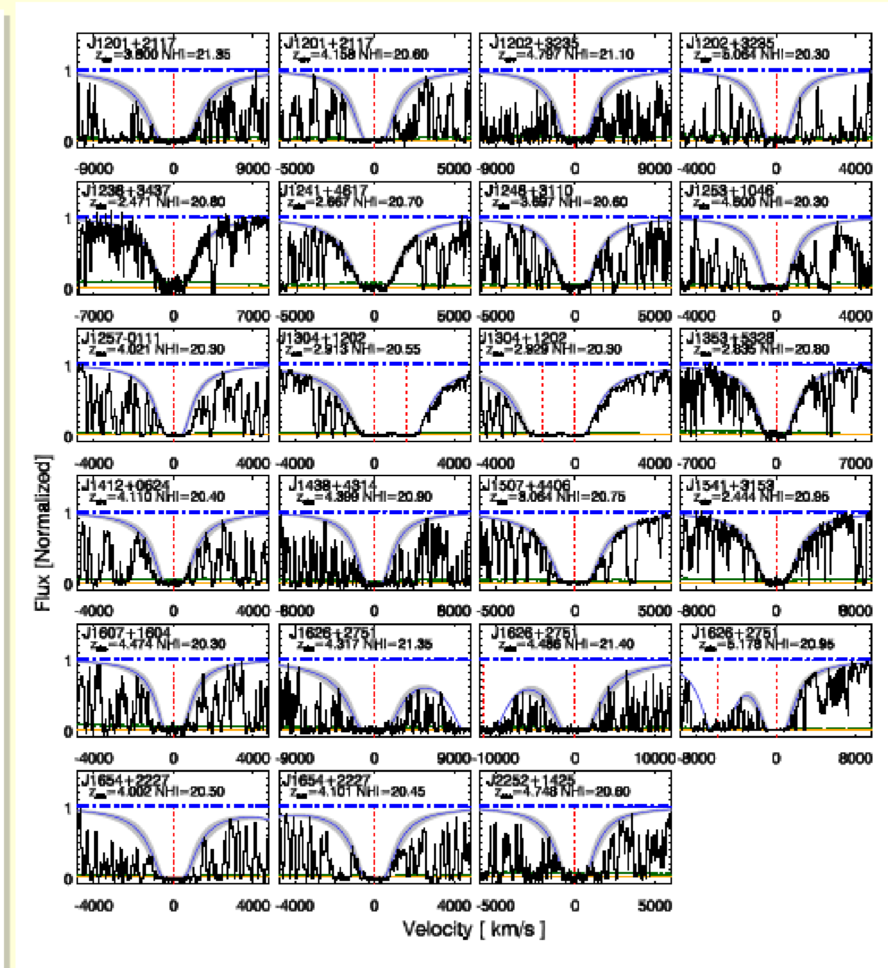
ESI Survey for high-z DLAs

- 25 quasar spectra
- 30 DLAs with $z > 4$



Gallery of ESI Damped Lyα Profiles



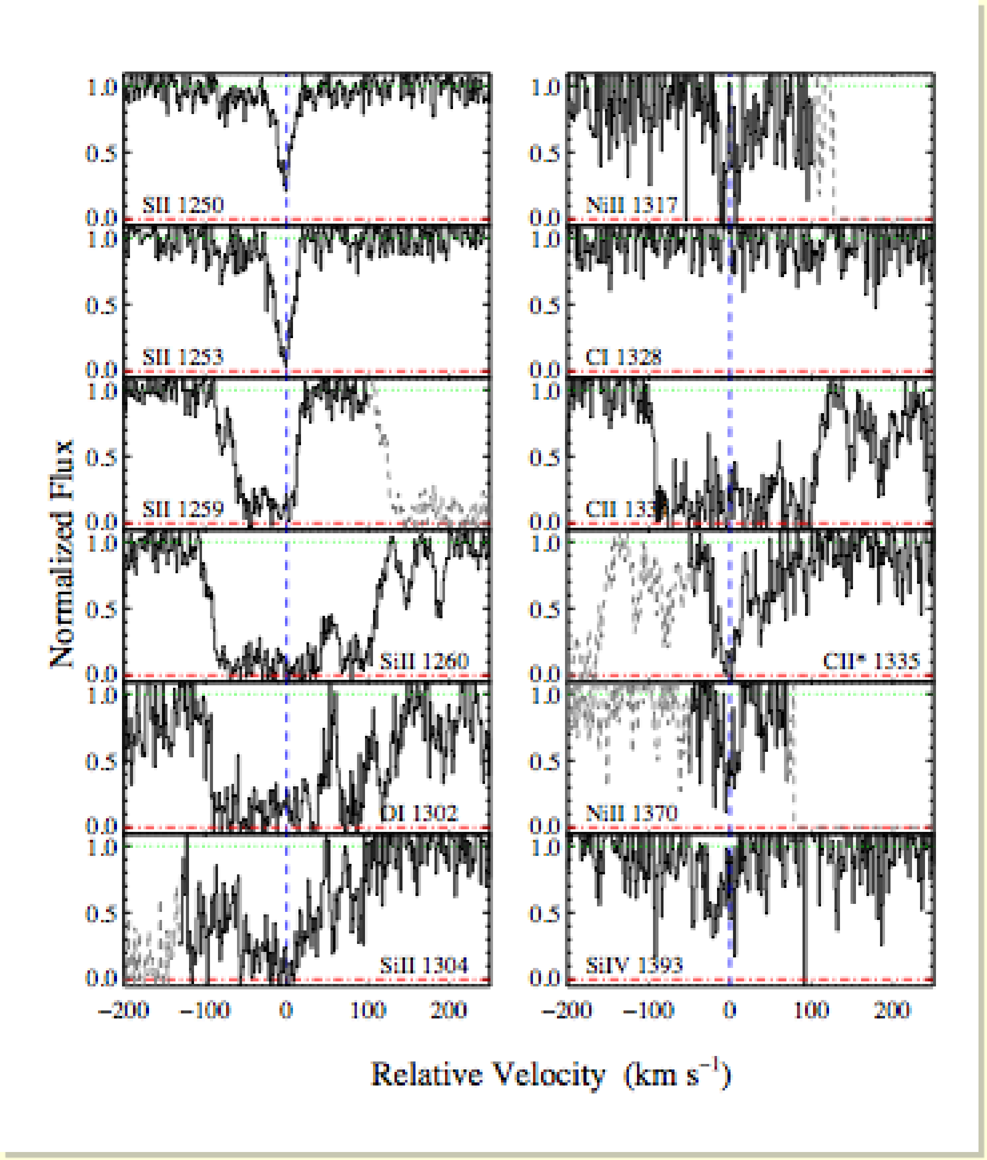


DLA Metal Abundances

- Based on H I and low-ion column densities

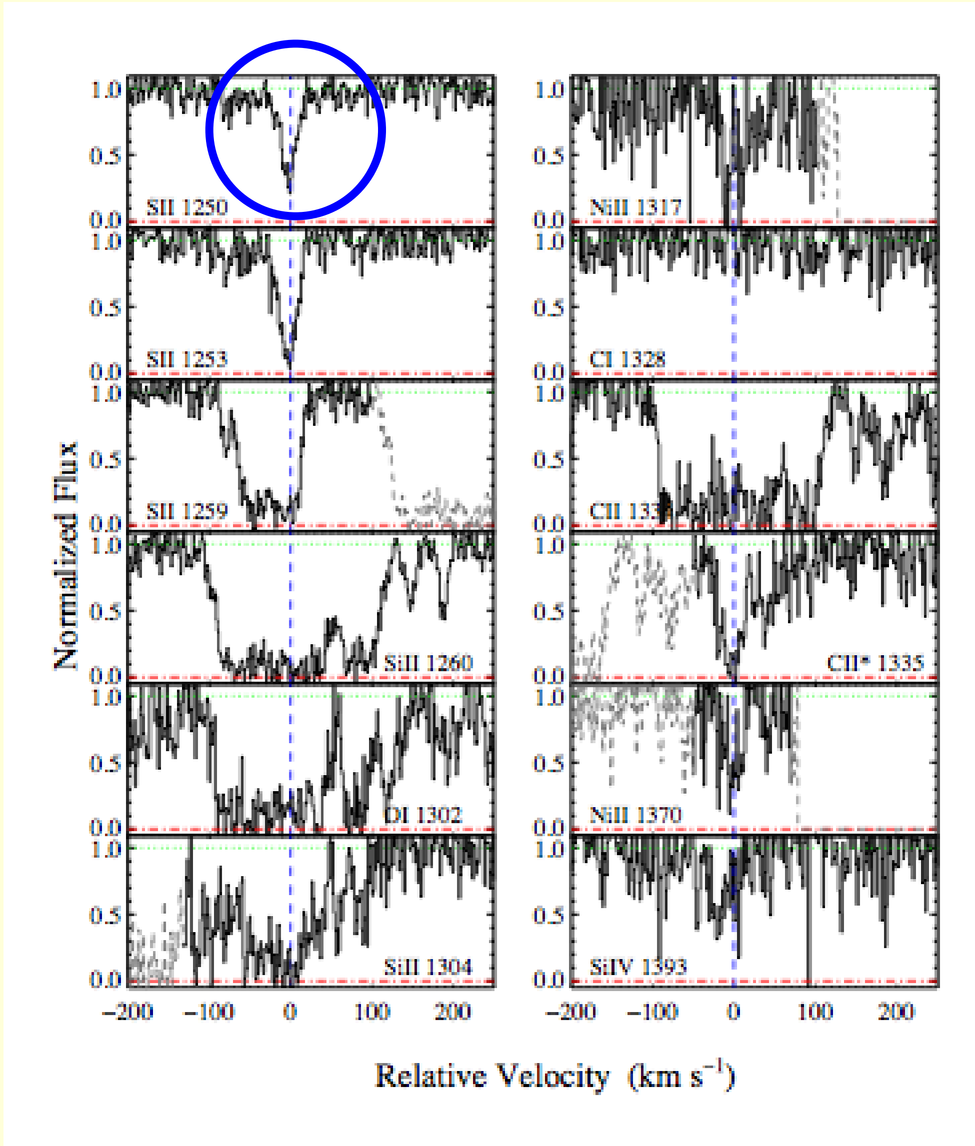
- No ionization corrections required since $(X/H)=(X^+/H^0)$
  - --Ionization potential of $X^+ > 1$ Ryd and of $X^0 < 1$ Ryd
  - --Thus starlight ($h\nu < 1$ Ryd) can photo-ionize X^0 to X^+
  - -- But X^+ shielded from photo-ionization

DLA-J0817+13, z=4.2584: HIRES velocity profiles

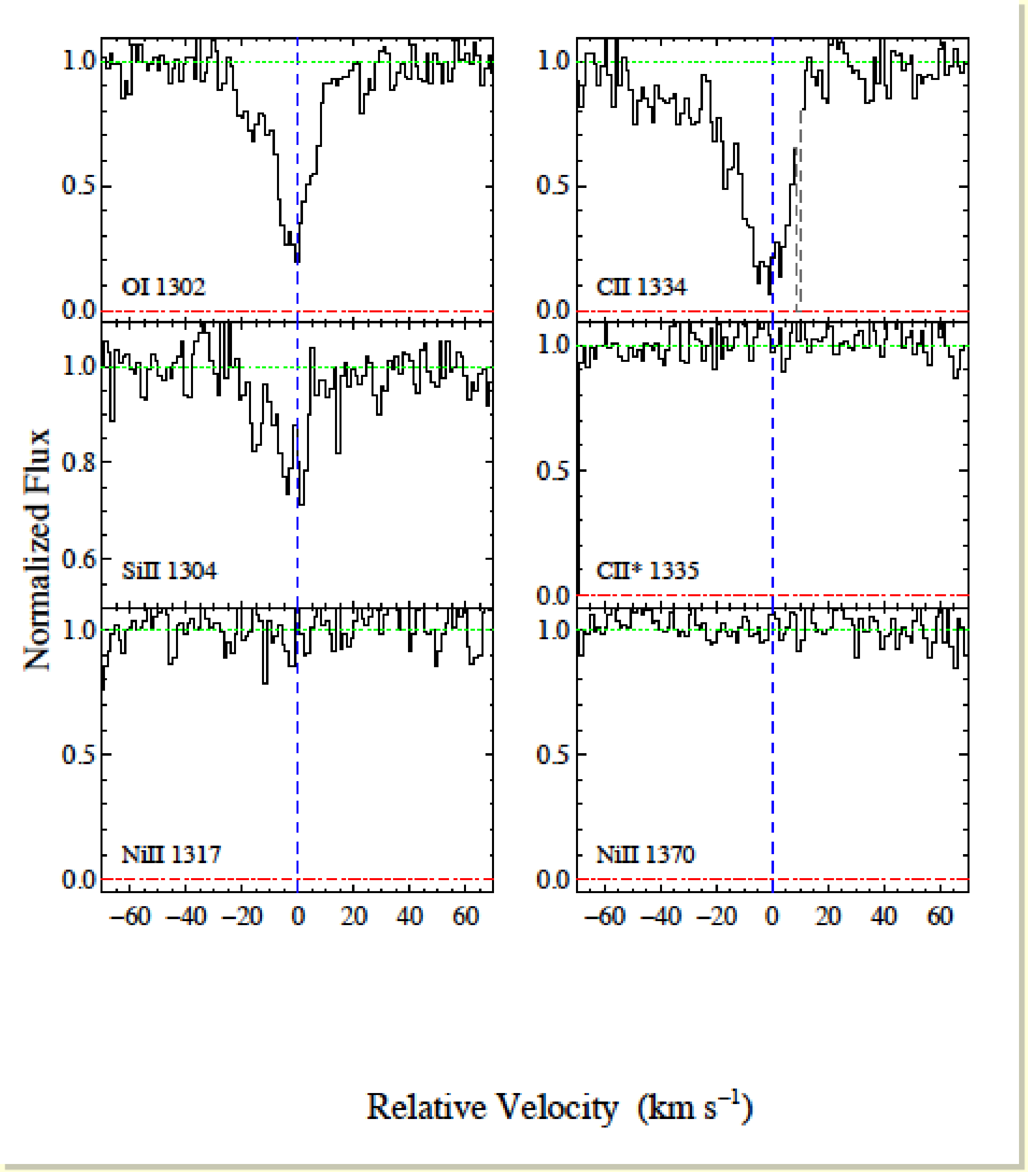


DLA-J0817+13, z=4.2584, [M/H]=-1.15±0.15

Metal Abundance
SII



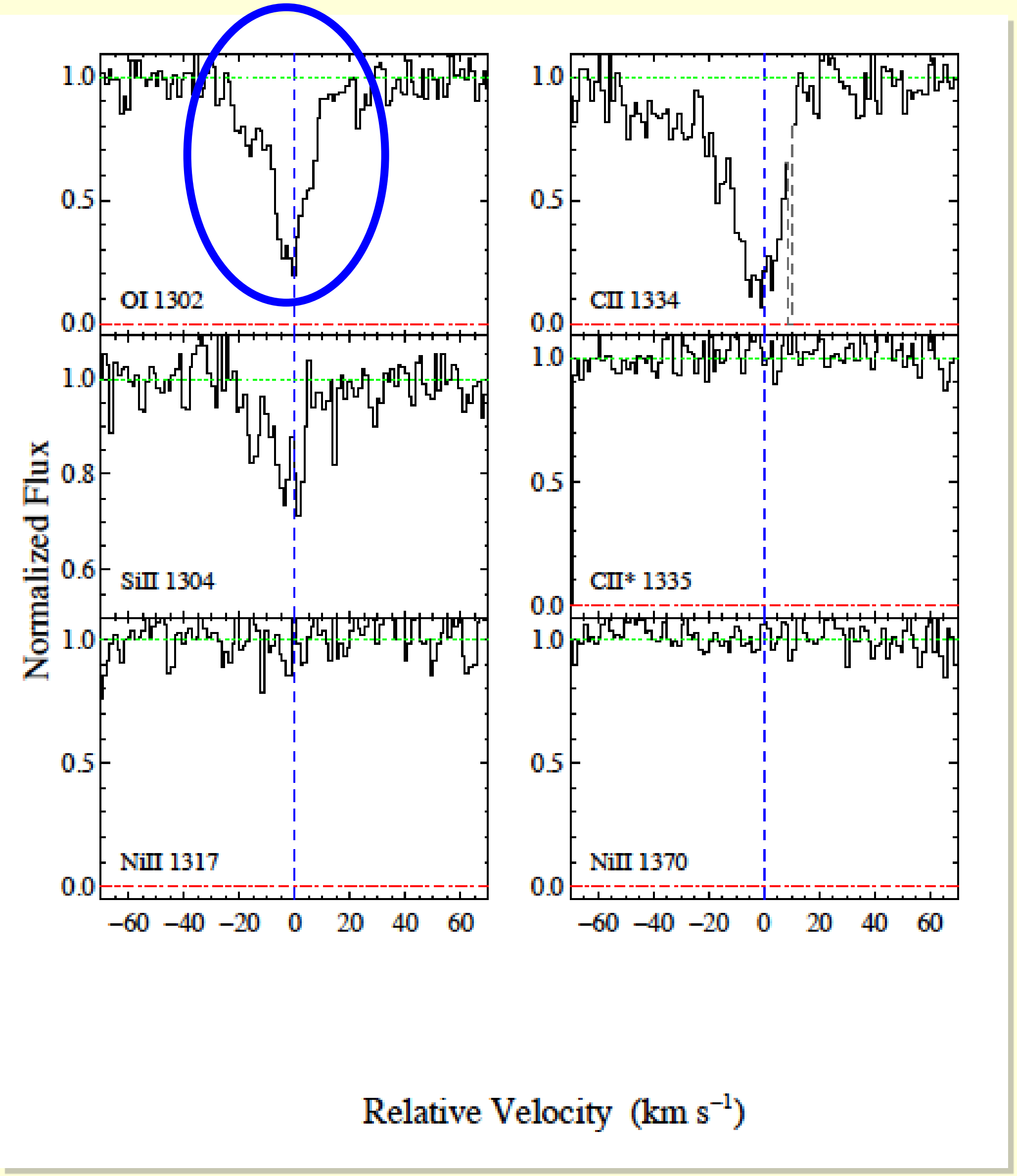
DLA-J1203+32, z=5.0647



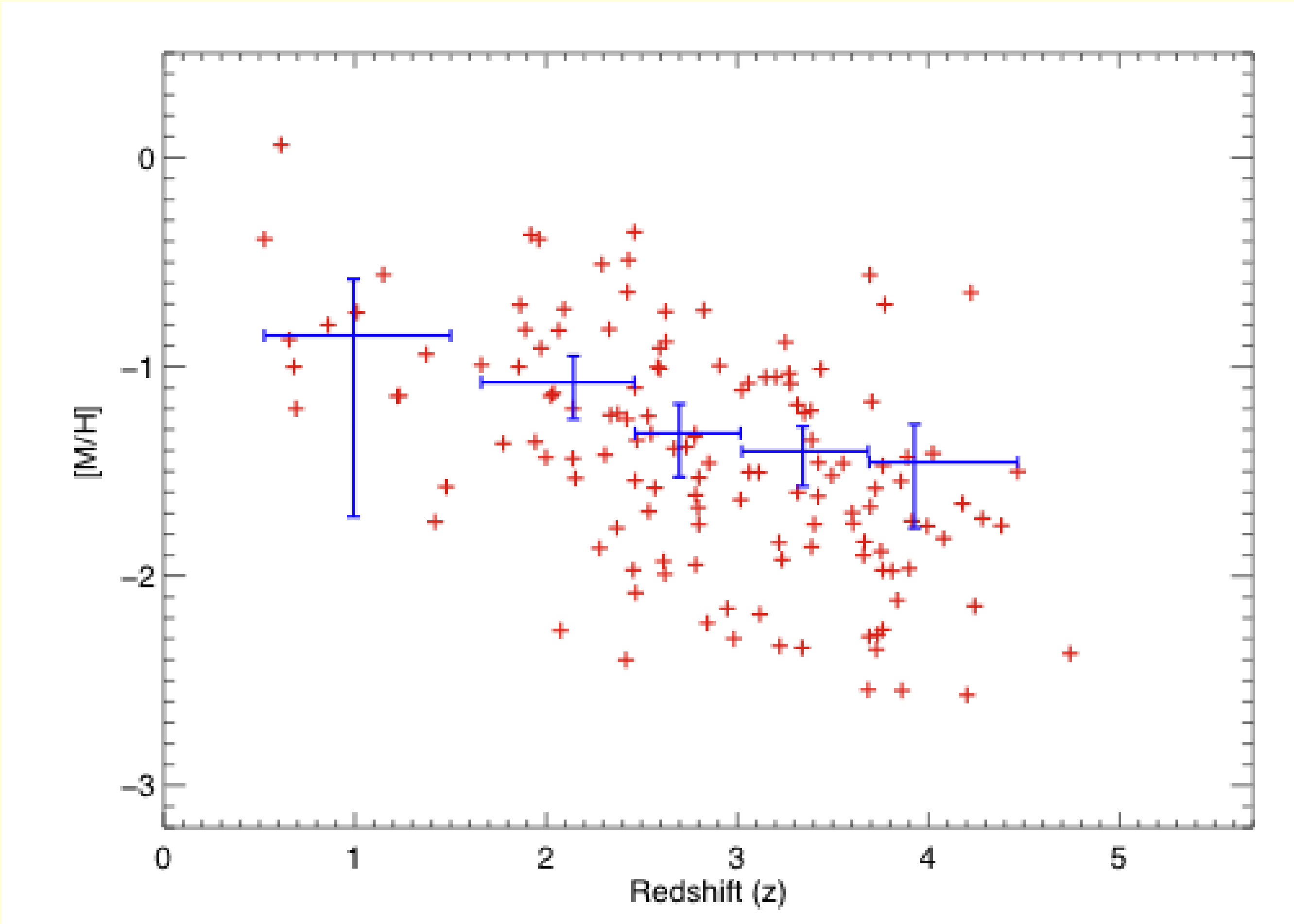
DLA-J1203+32, z=5.0647, [M/H]=-2.66±0.16

Metal Abundance

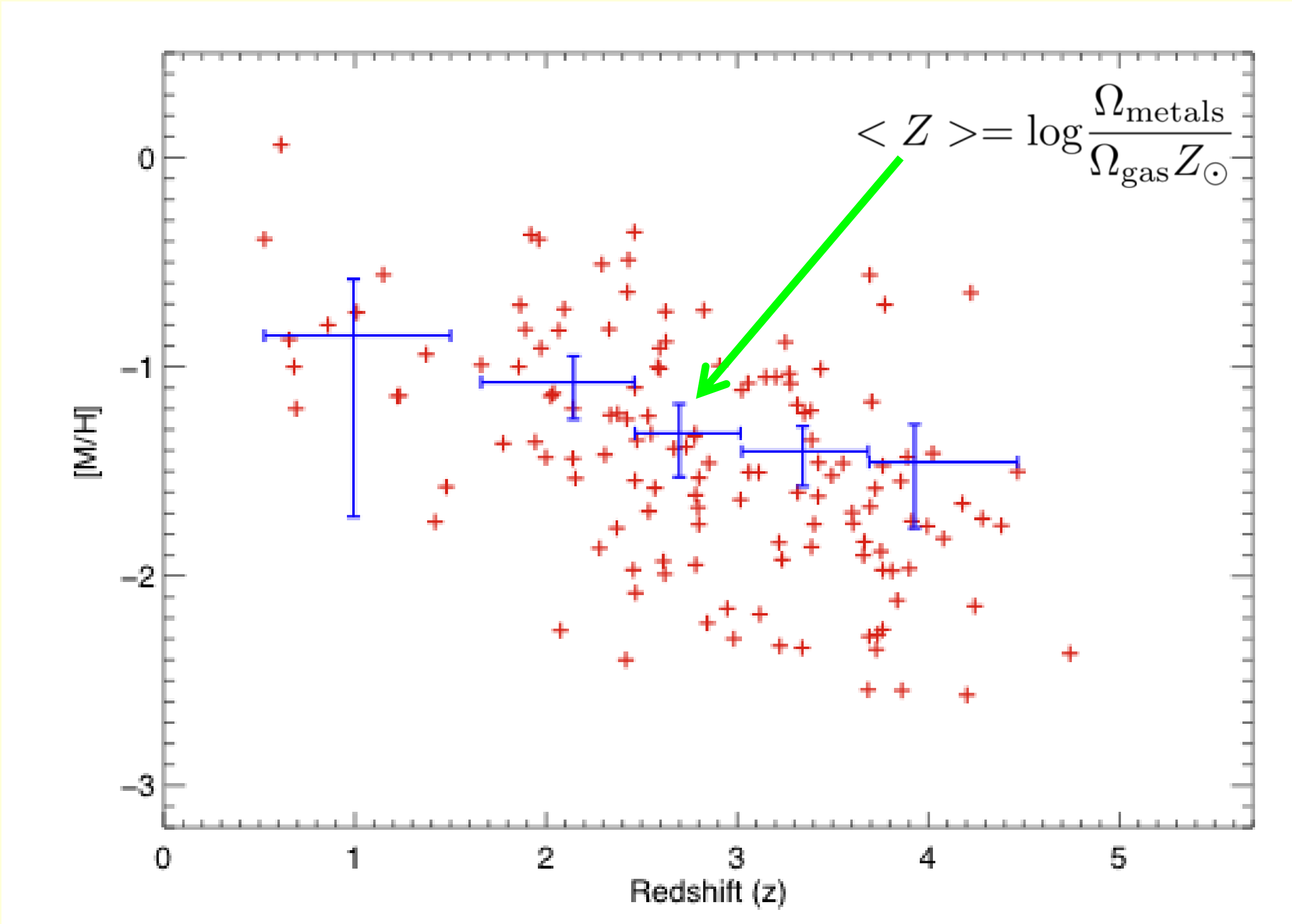
OI



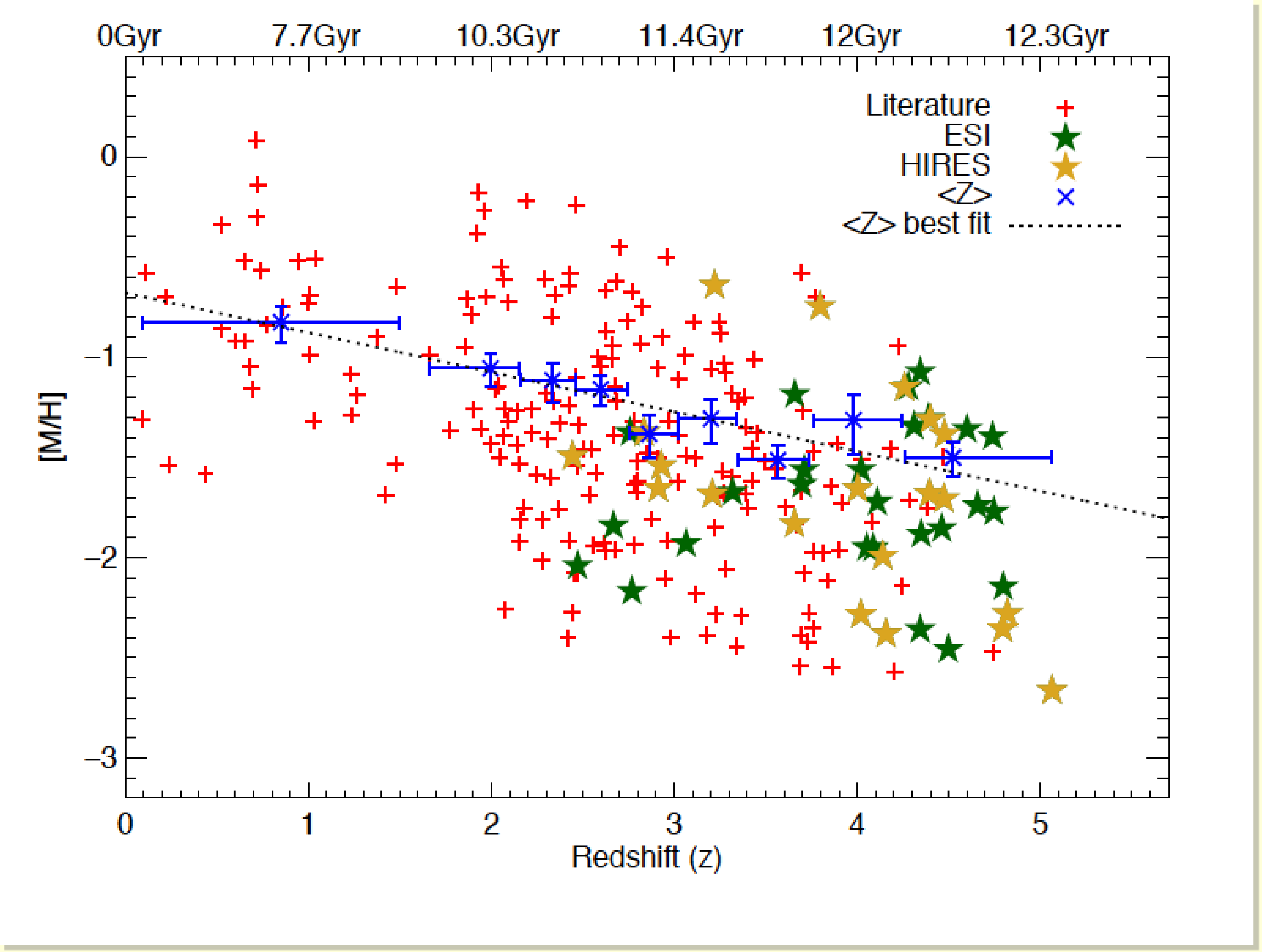
Metal Abundances and <Z> versus redshift (2004 sample)



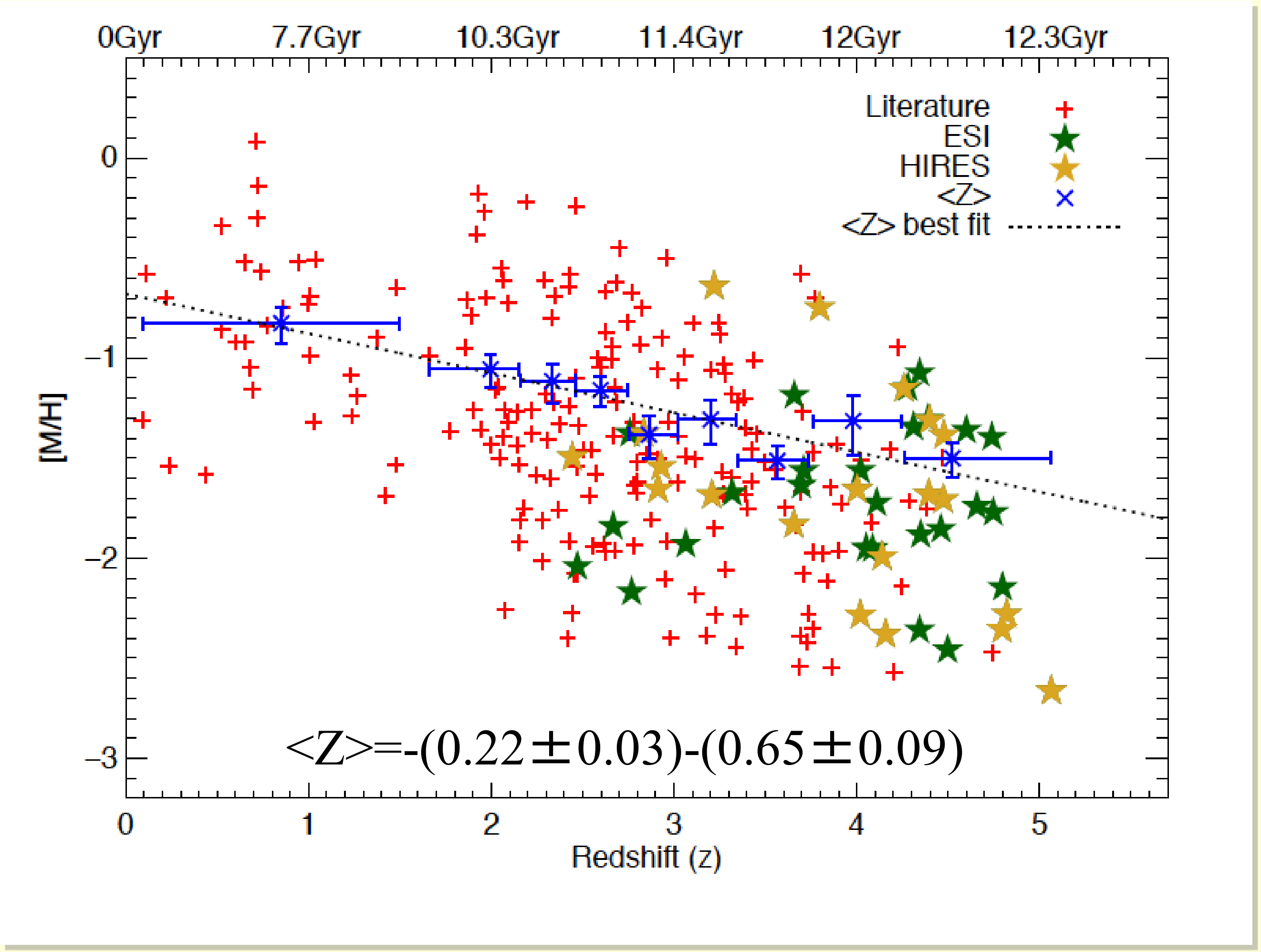
Metal Abundances and <Z> versus redshift (Prochaska etal 2003)



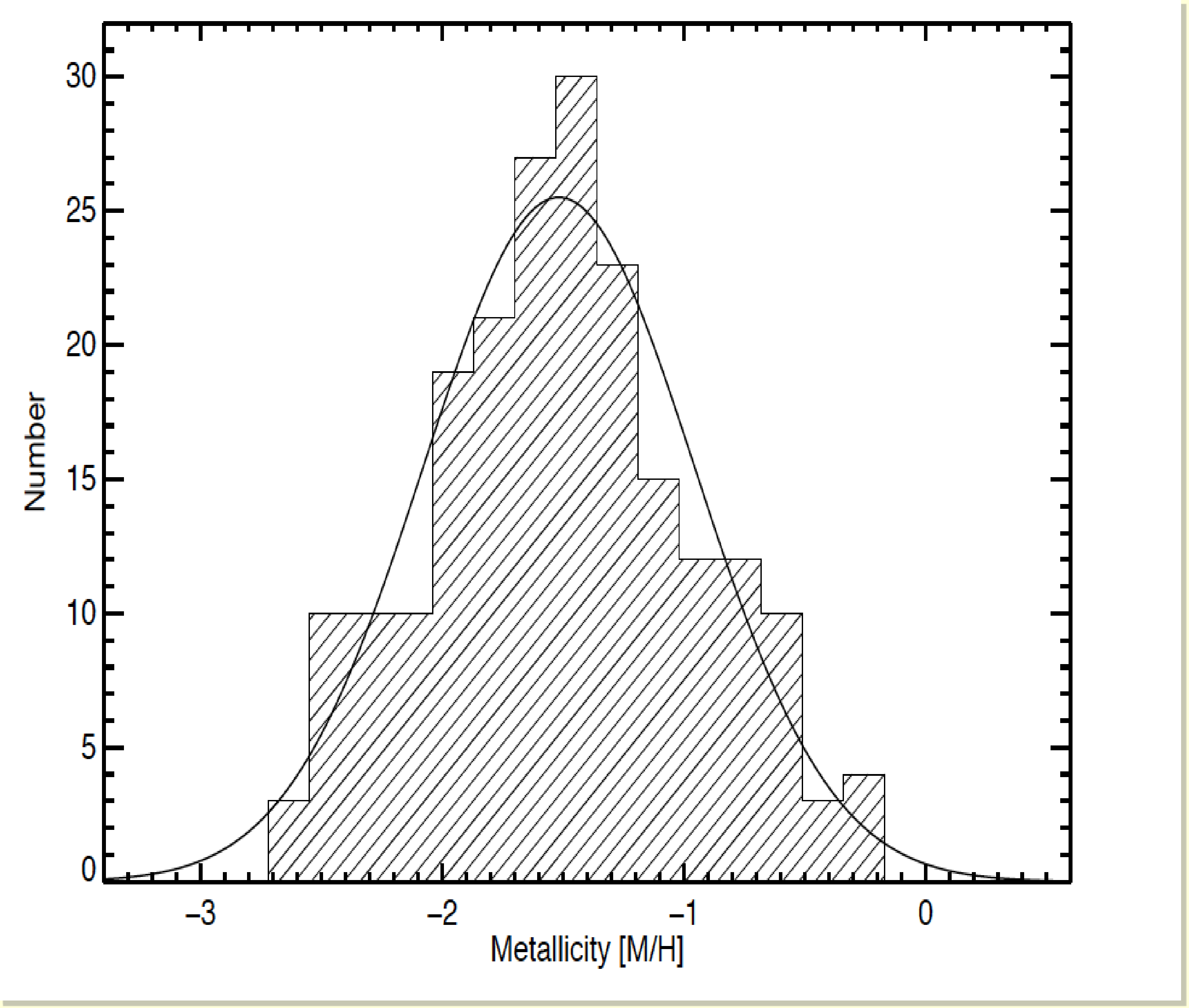
Metal Abundances and <Z> versus Redshift (Rafelski etal 2012)



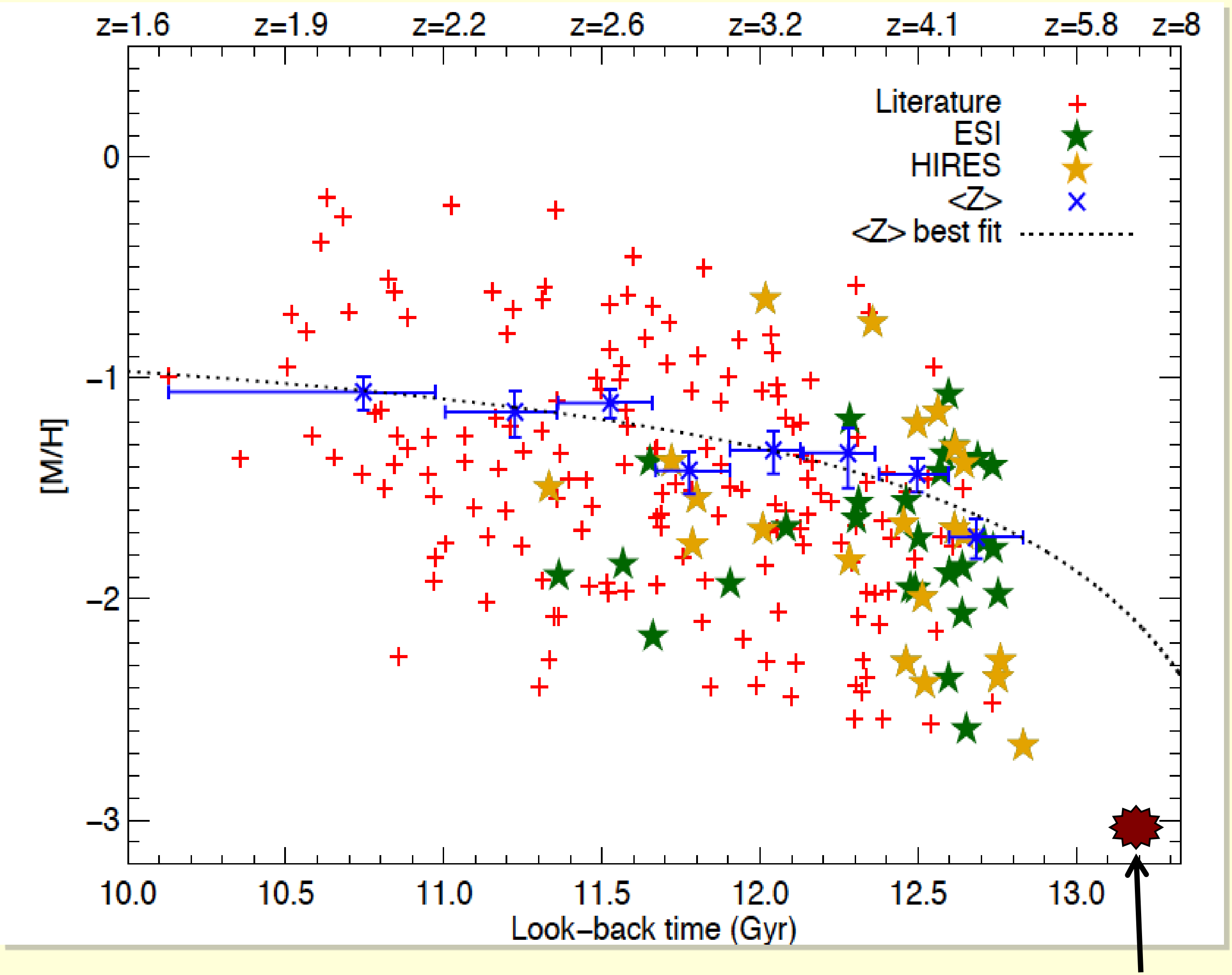
Metal Abundances and <Z> vs Redshift (Rafelski etal ’12)



Mean [M/H]=-1.50, $\sigma_{[M/H]}$ =0.55

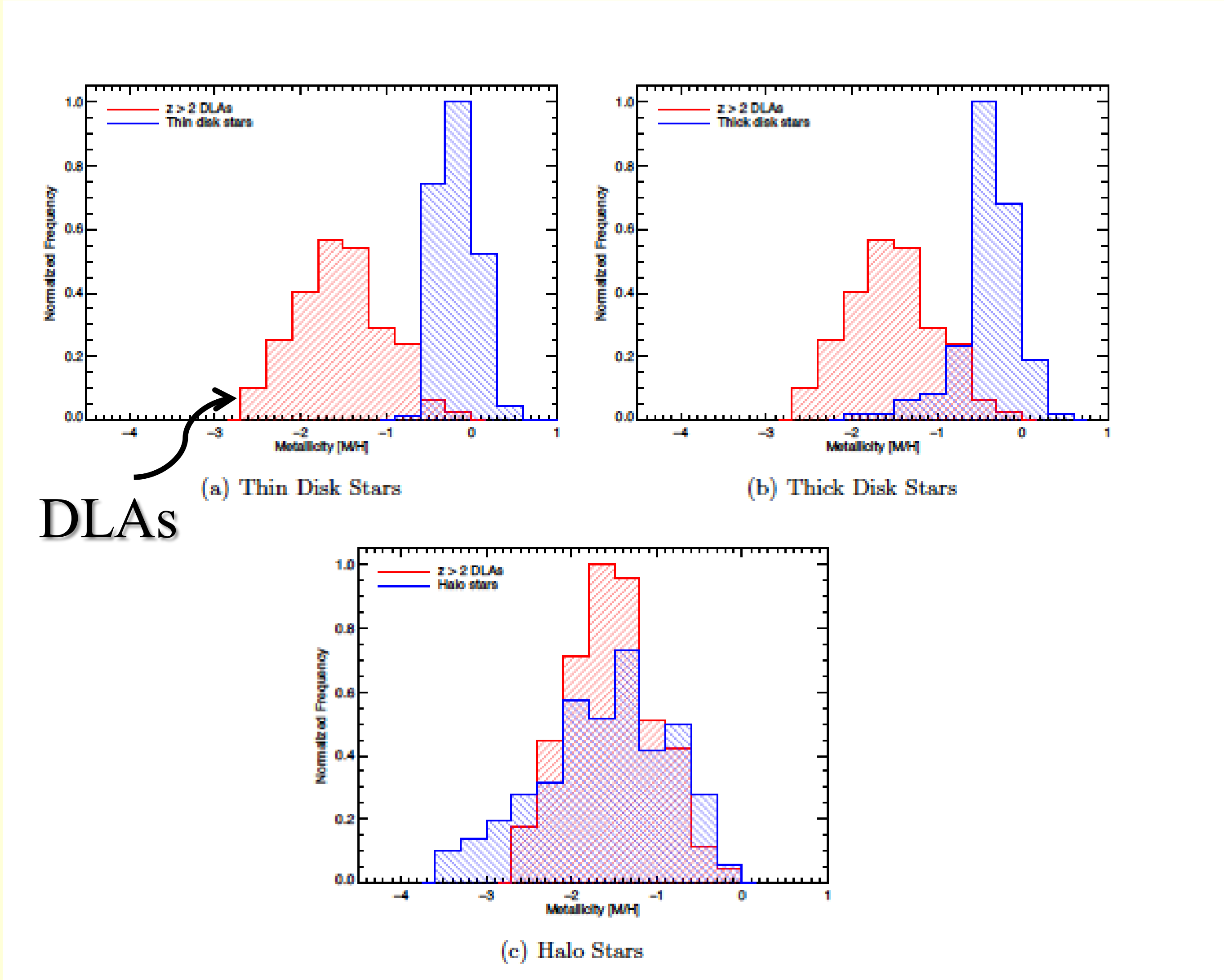


Metal Abundances versus look-back time



Predicted "floor"

Abundance Histograms: DLAs and Stellar Populations

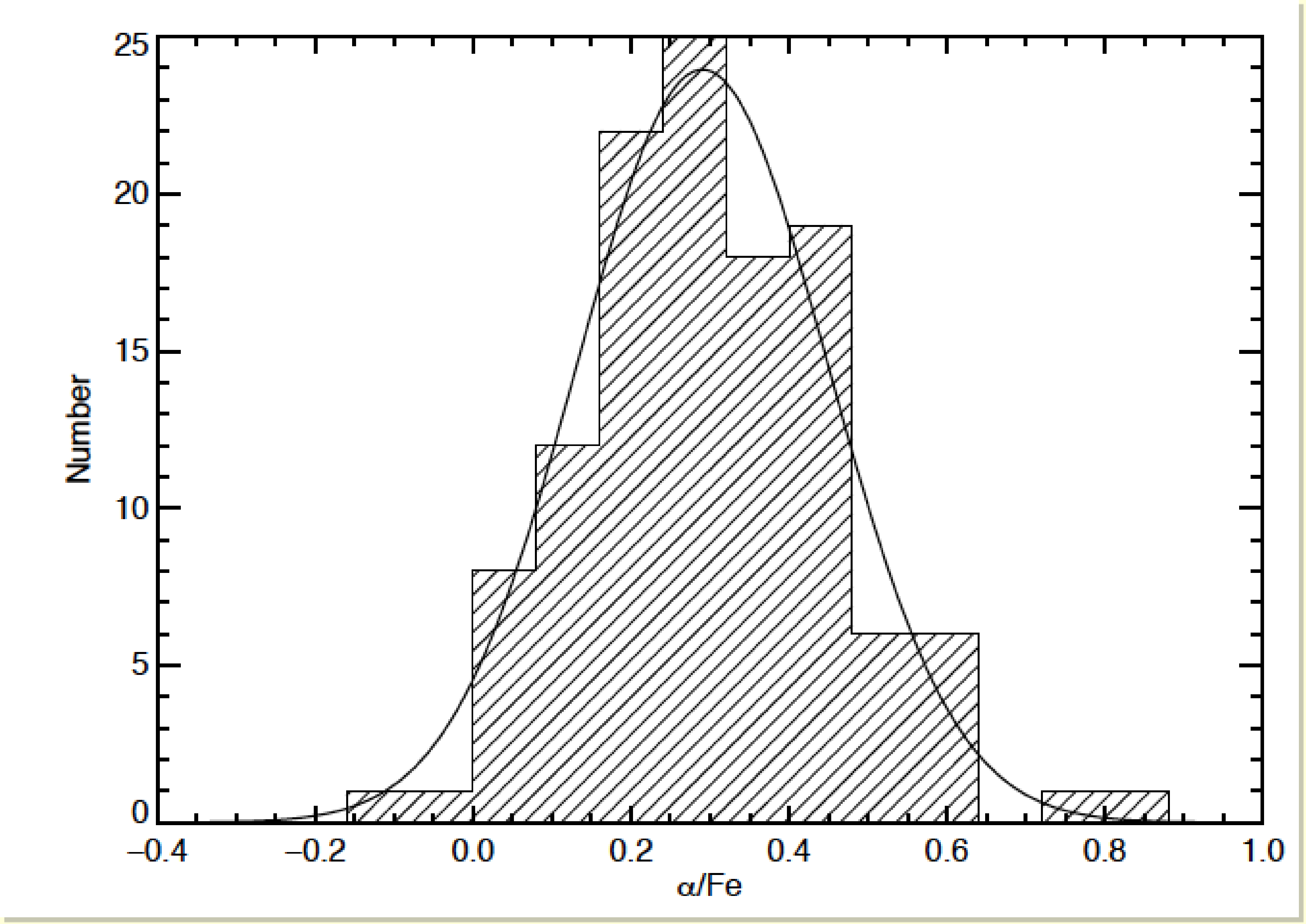


(a) Thin Disk Stars

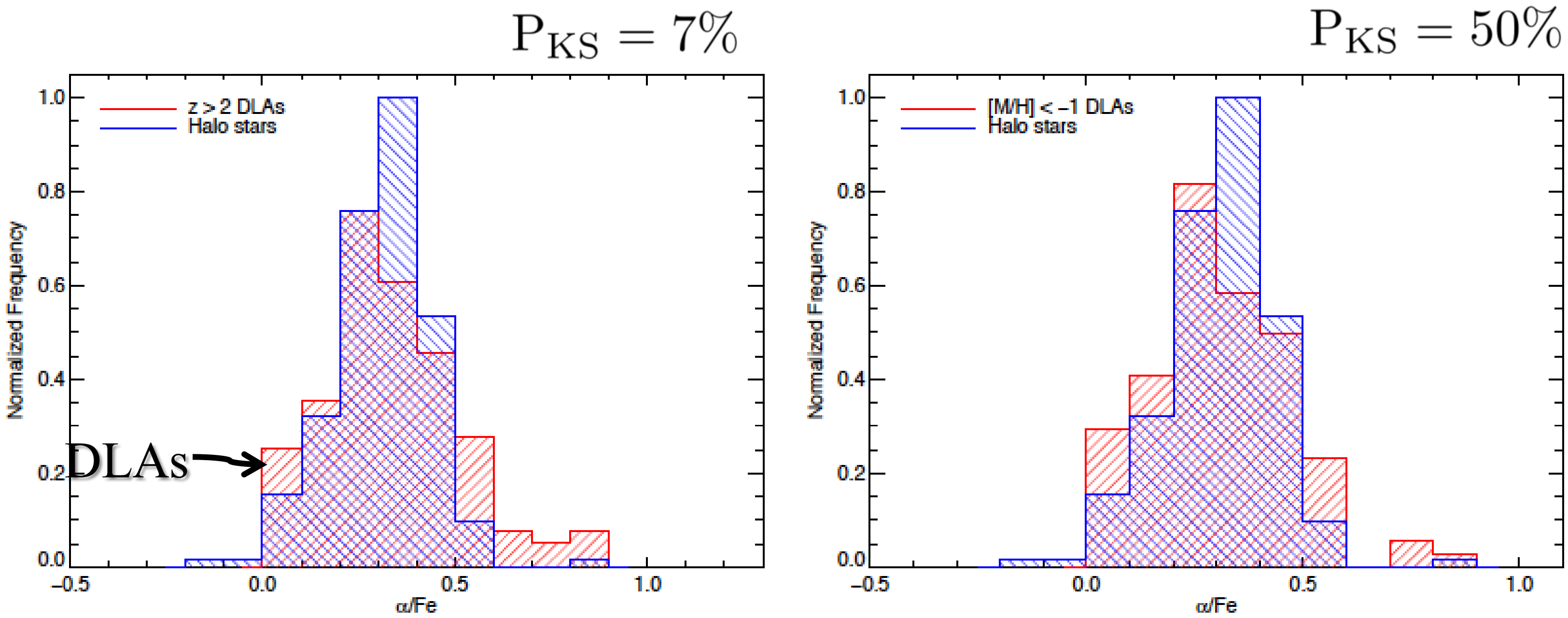
(b) Thick Disk Stars

(c) Halo Stars

[α/Fe] Distribution: DLAs are α Enhanced



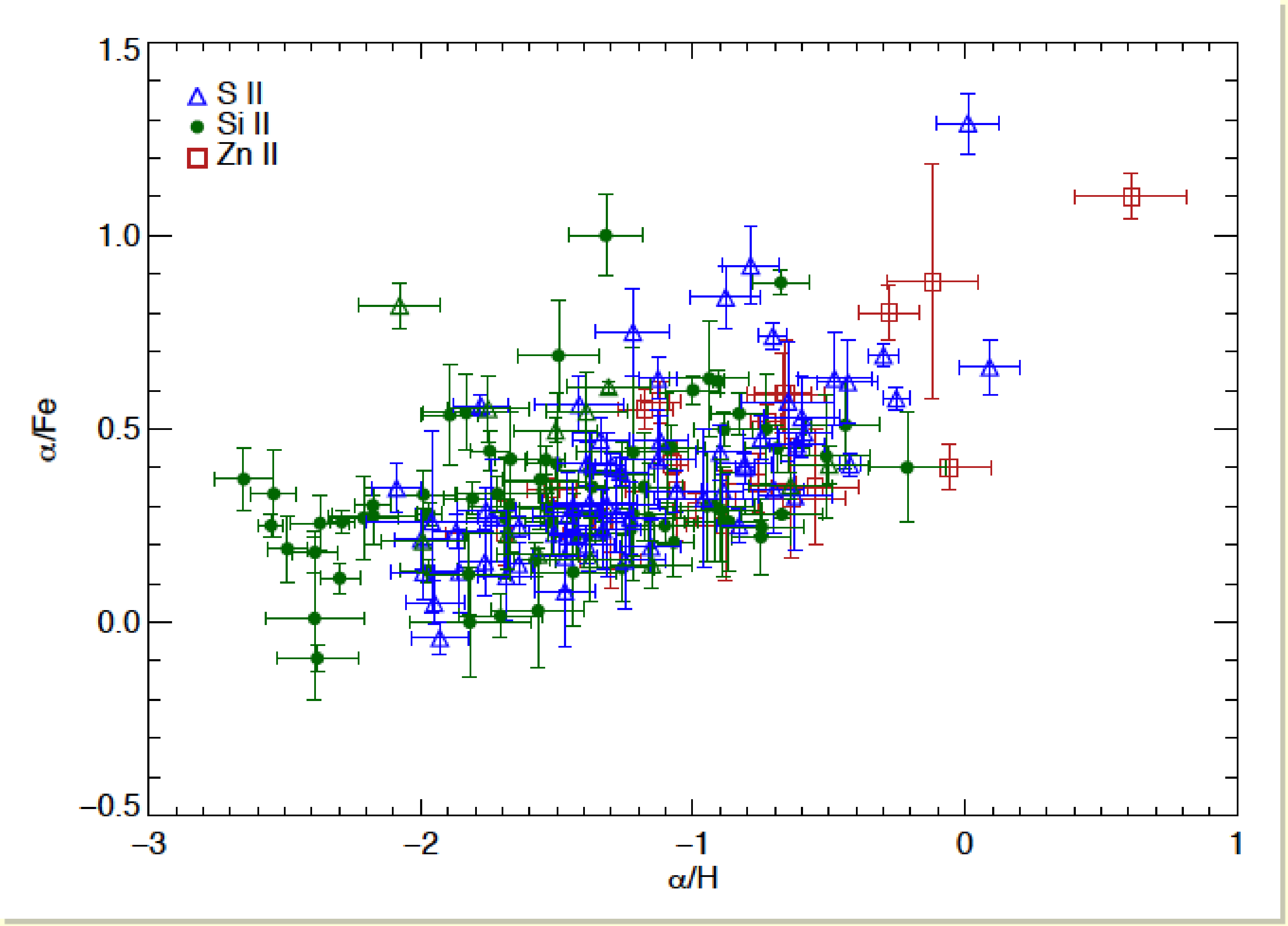
[α/Fe] Distribution Consistent with Halo Stars



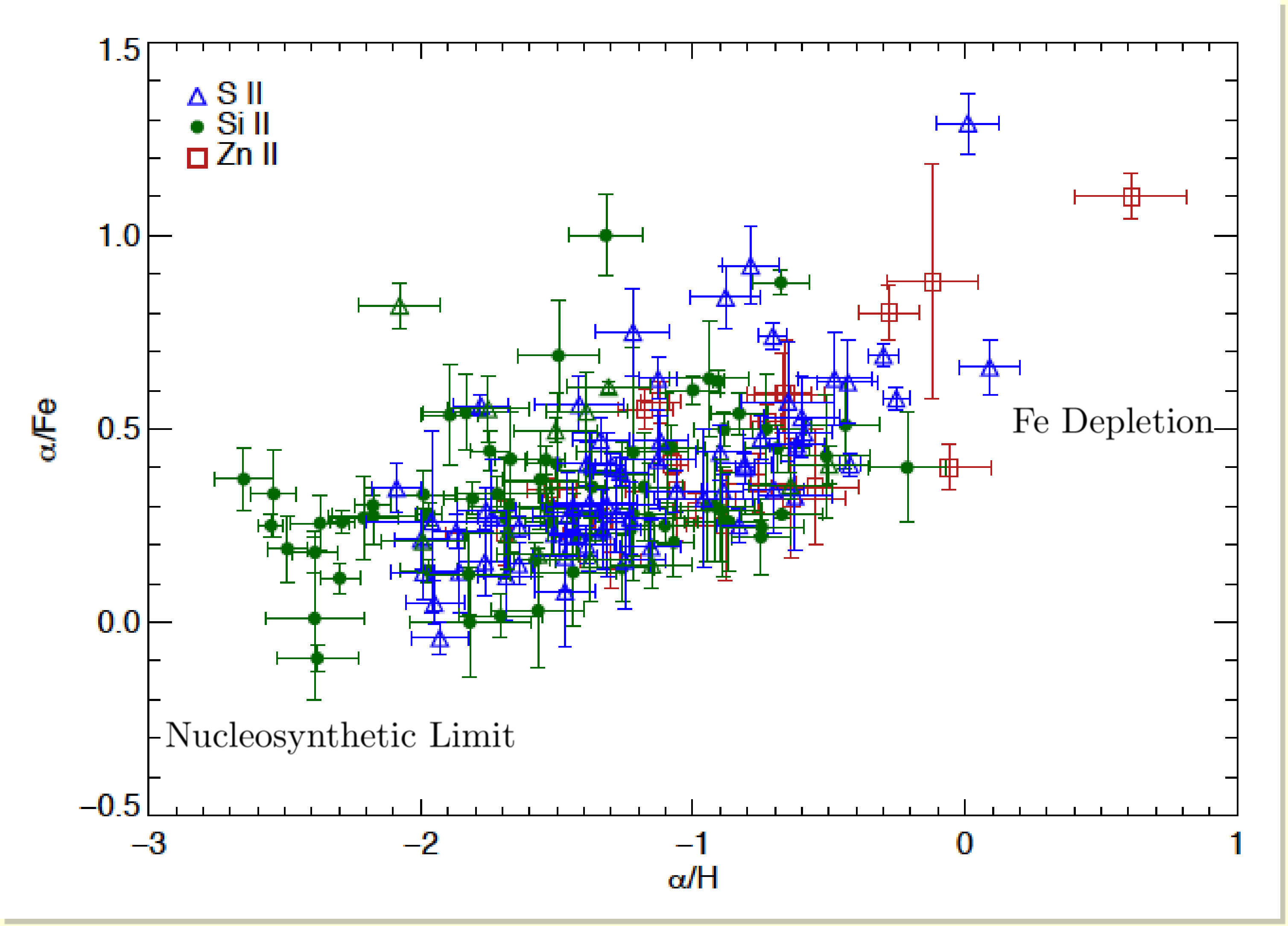
(a) $z > 2$ DLAs

(b) $z > 2$ and [M/H] < -1 DLAs

Dependence of [α/Fe] on Metal Abundance

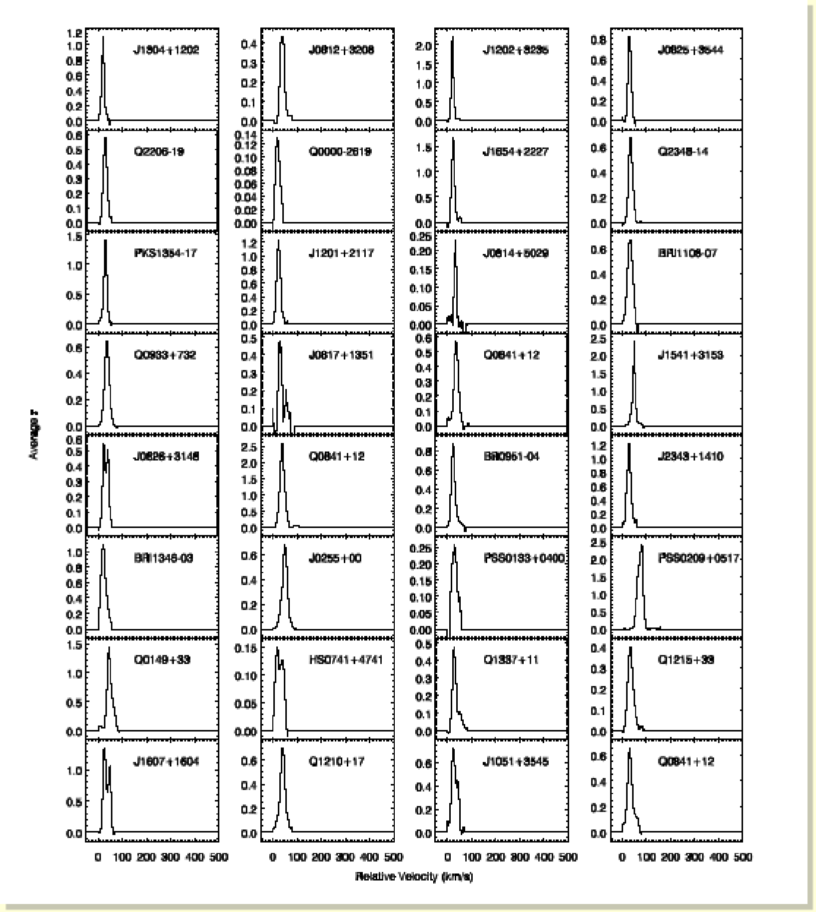


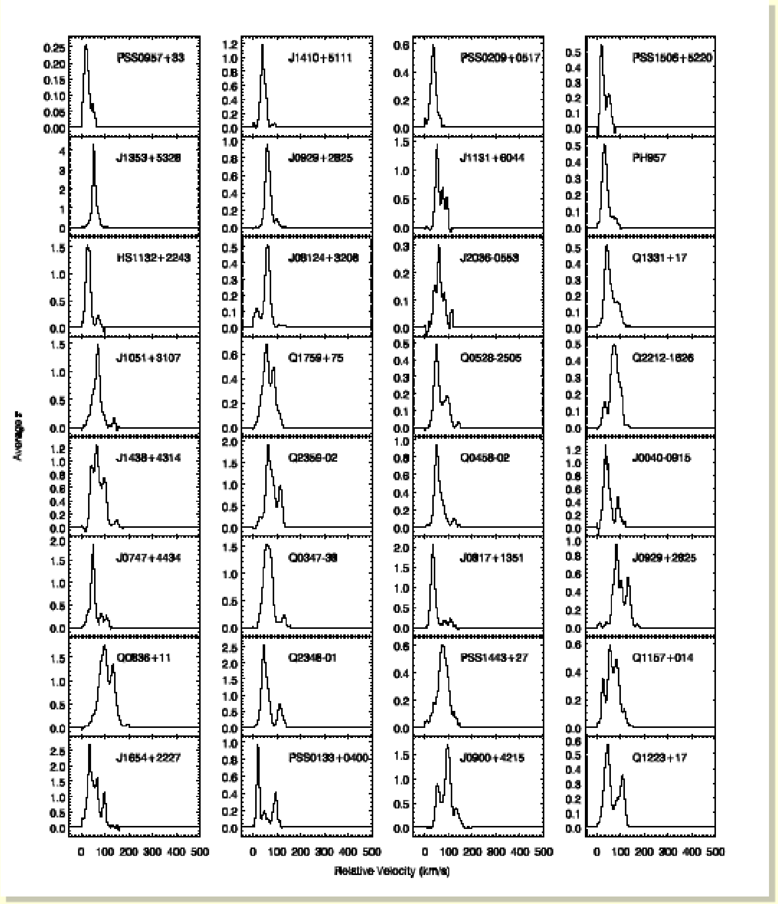
Dependence of [α/Fe] on Metal Abundance

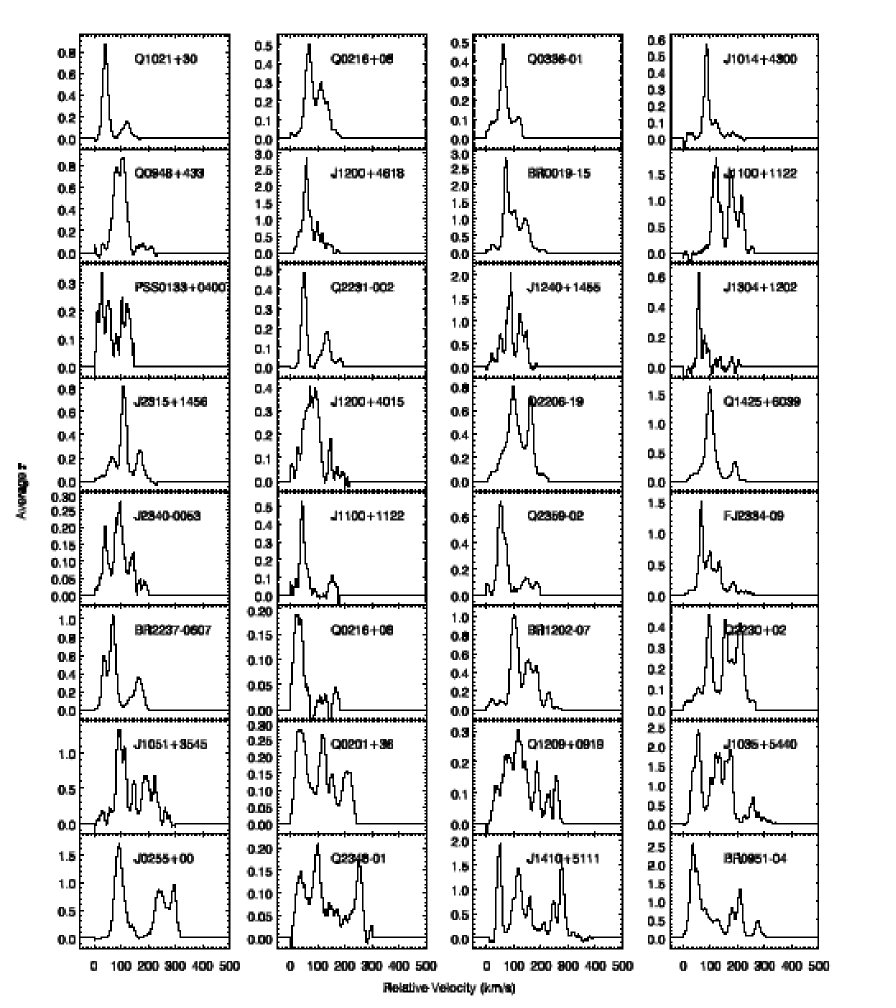


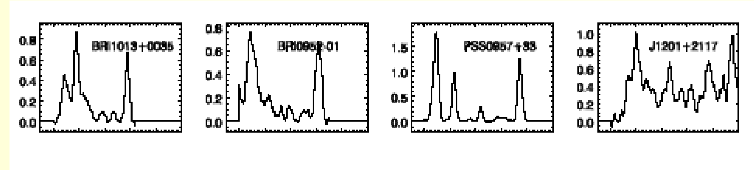
2. Keck HIRES study of DLA kinematics
(Neeleman, Wolfe, Prochaska & Rafelski 2012)

Low-ion (Si II, Zn II, etc.) optical depth profiles

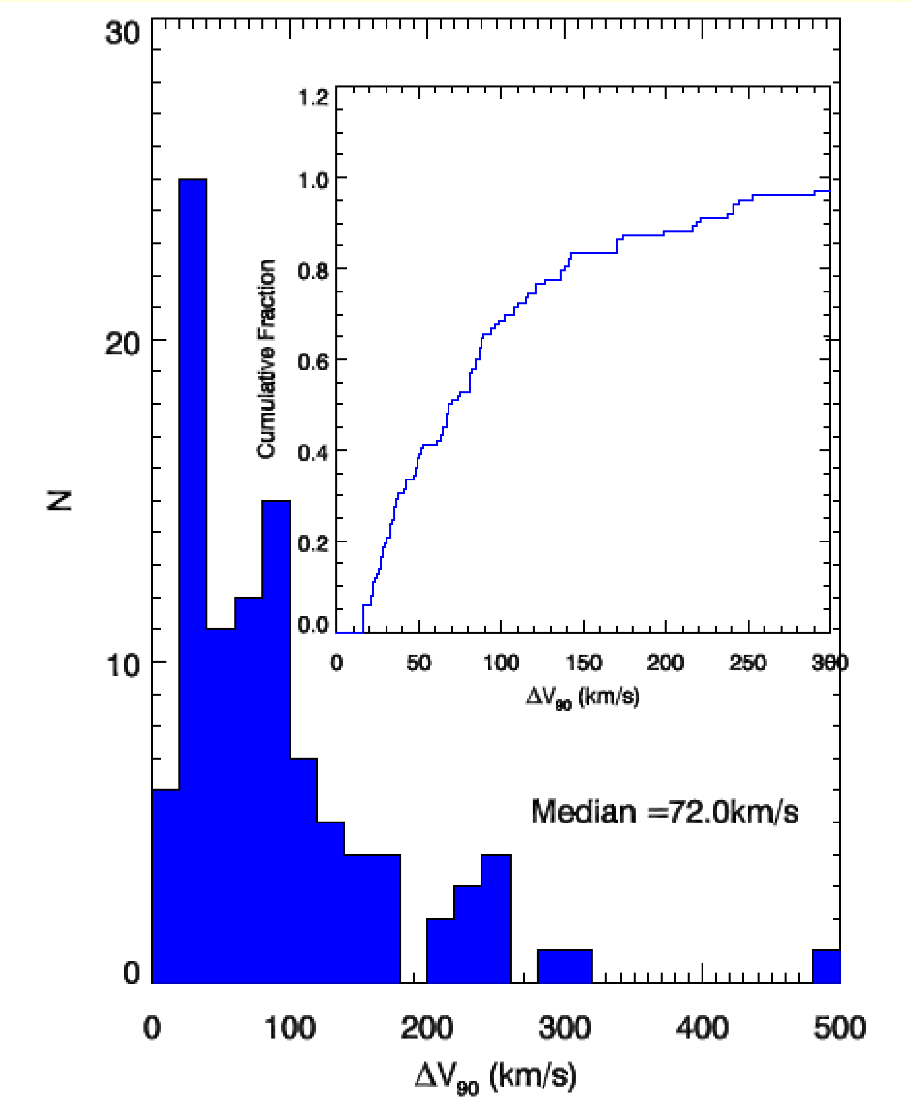





Q1021+30
Q0216+08
J1014+4300
Q0948+433
J1200+4618
BR0019-15
J1100+1122
PSS0133+0400
Q2231-002
J1240+1455
J1304+1202
J2315+1456
J1200+4015
Q2206-19
Q1425+6039
J2340-0053
J1100+1122
Q2359-02
FJ2334-09
BR2237-0607
Q0216+08
BRI1202-07
Q2230+02
J1051+3545
Q0201+36
Q1209+0919
J1035+5440
J0255+00
Q2348-01
J1410+5111
BR0951-04
Average τ
Relative Velocity (km/s)

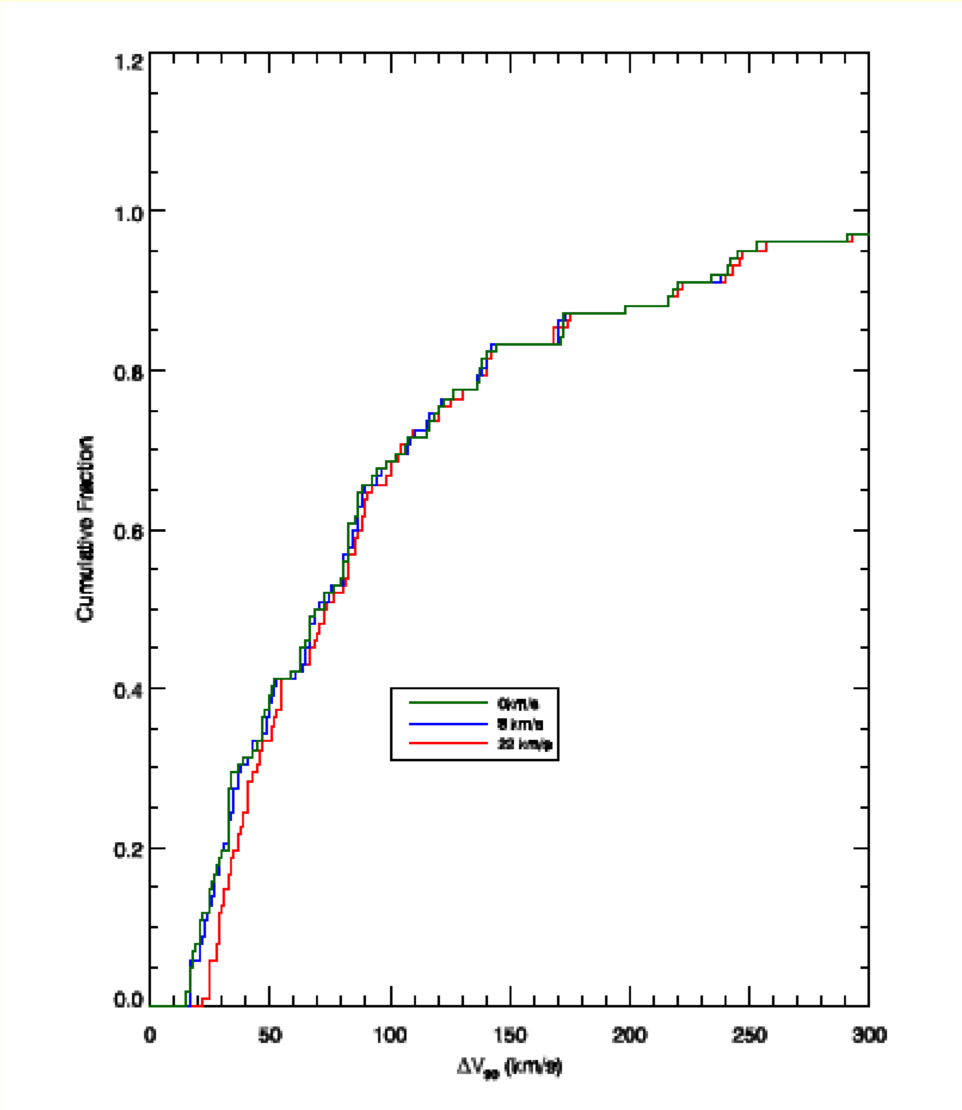

BRI1013+0035
PSS0957+33
J1201+2117

Velocity Width Distribution



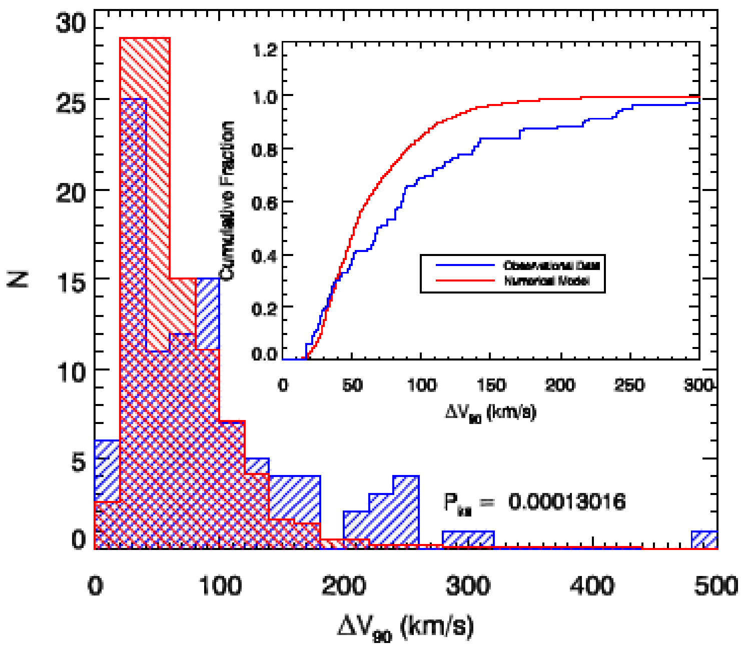
- 102 HIRES profiles
- Δv_{90} : velocity width enclosing 90% of central integrated optical depth
- Median Δv_{90} = 72 km s^{-1}

Kinematic Floor: $\Delta v_{90} \geq 18$ km s^{-1}



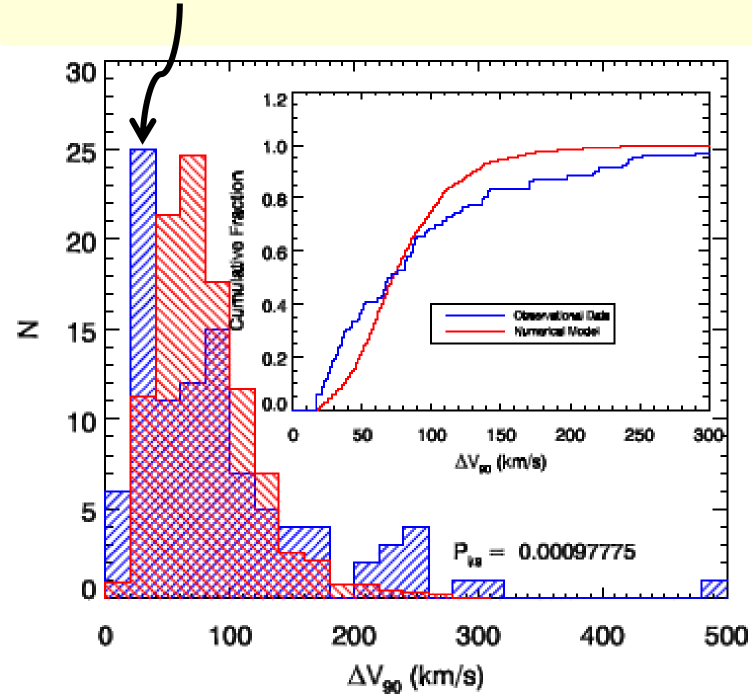
- Threshold circular velocity $v_c > 30$ kms^{-1}
- Limit on velocity dispersion $\sigma_v = 6$ kms^{-1}
- T < 3700 K

Comparison between ΛCDM simulations (red) and HIRES data (blue) reveals a problem



(a) Pontzen et al. 2008

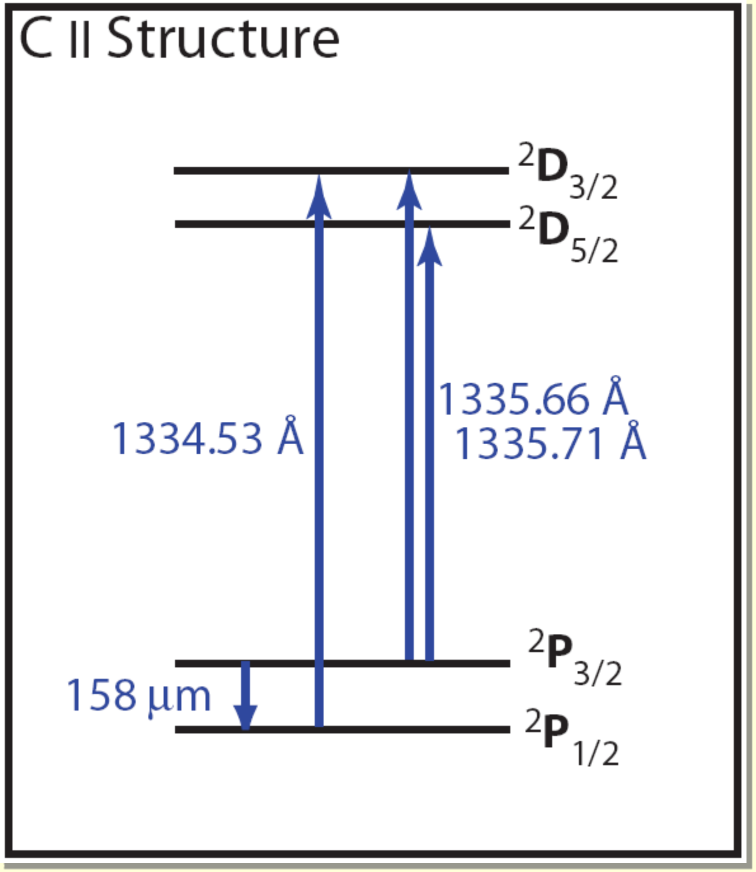
DLAs



(b) Tescari et al. 2009

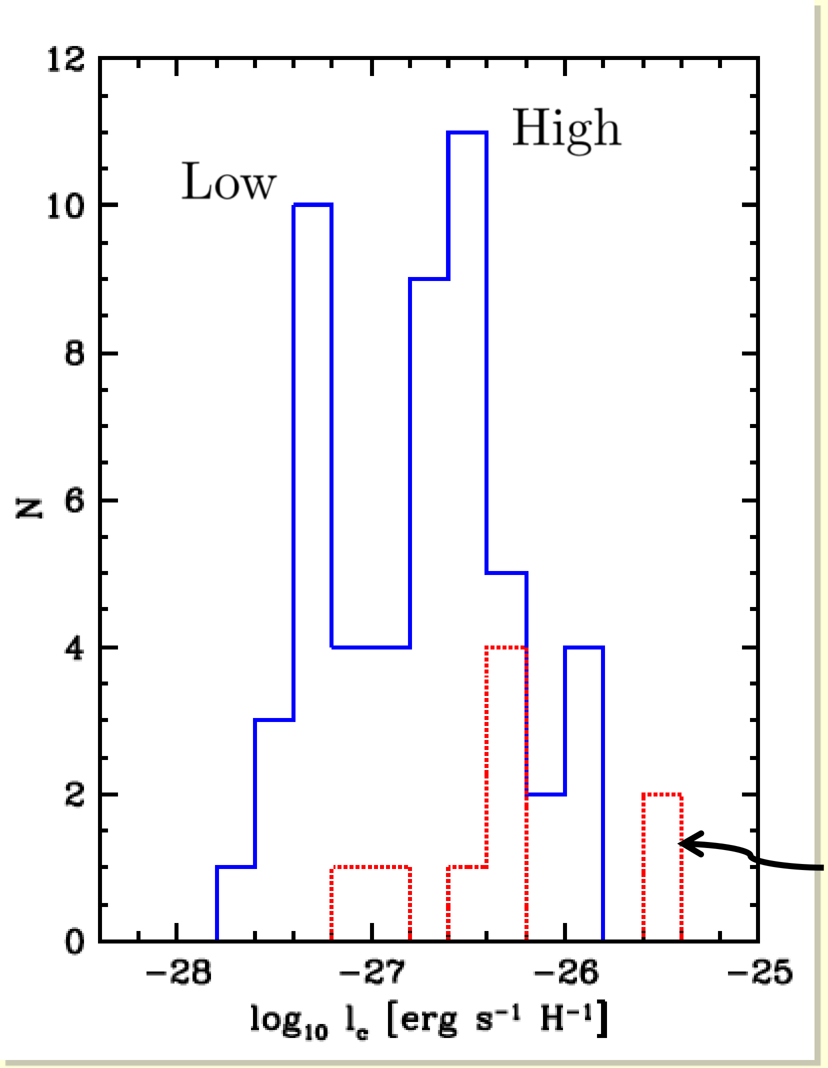
Divide DLA sample with respect to
[C II] 158 μm cooling rates per atom, l_c

CII* Absorption provides measure of gas cooling rates in DLAs



$$l_c = n\Lambda_{[C\,II]} \sim \frac{N(\mathrm{C\,II*})}{N(\mathrm{H\,I})} h\nu_{21} A_{21}$$

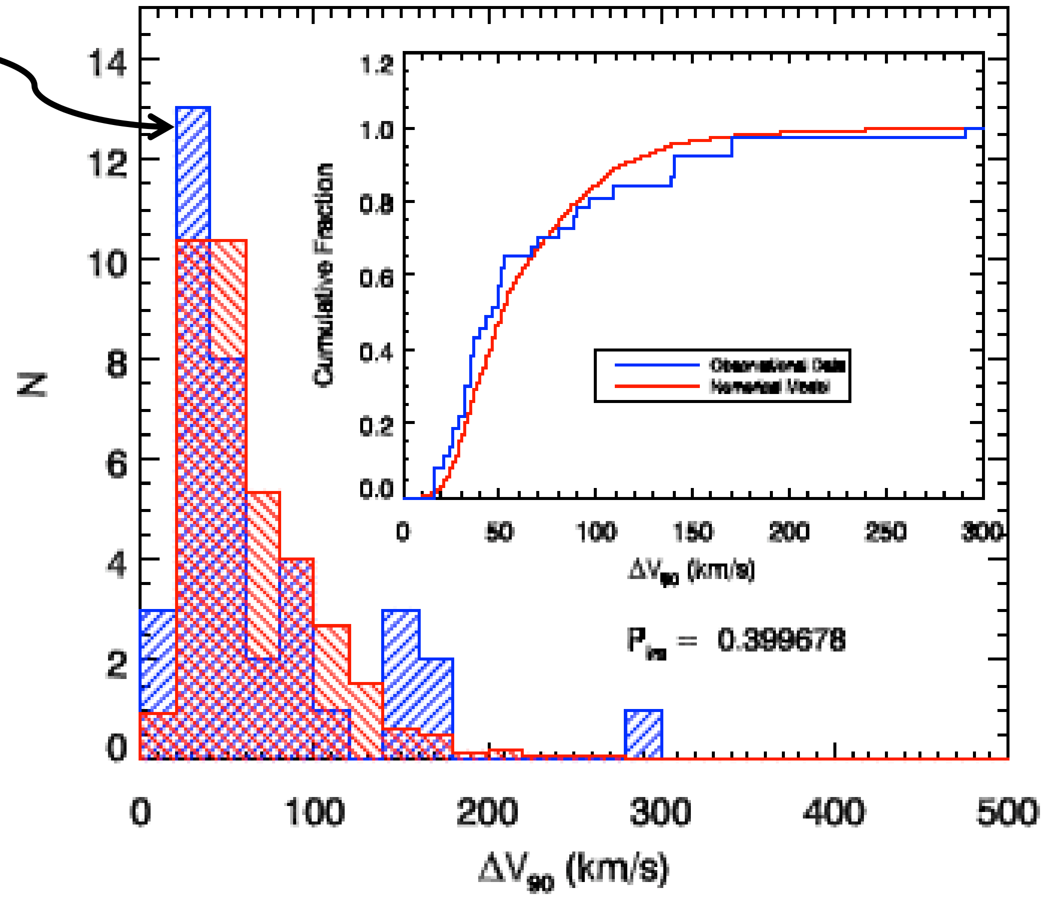
--Bimodality between "high-cool" and "low-cool" DLAs



lower limits

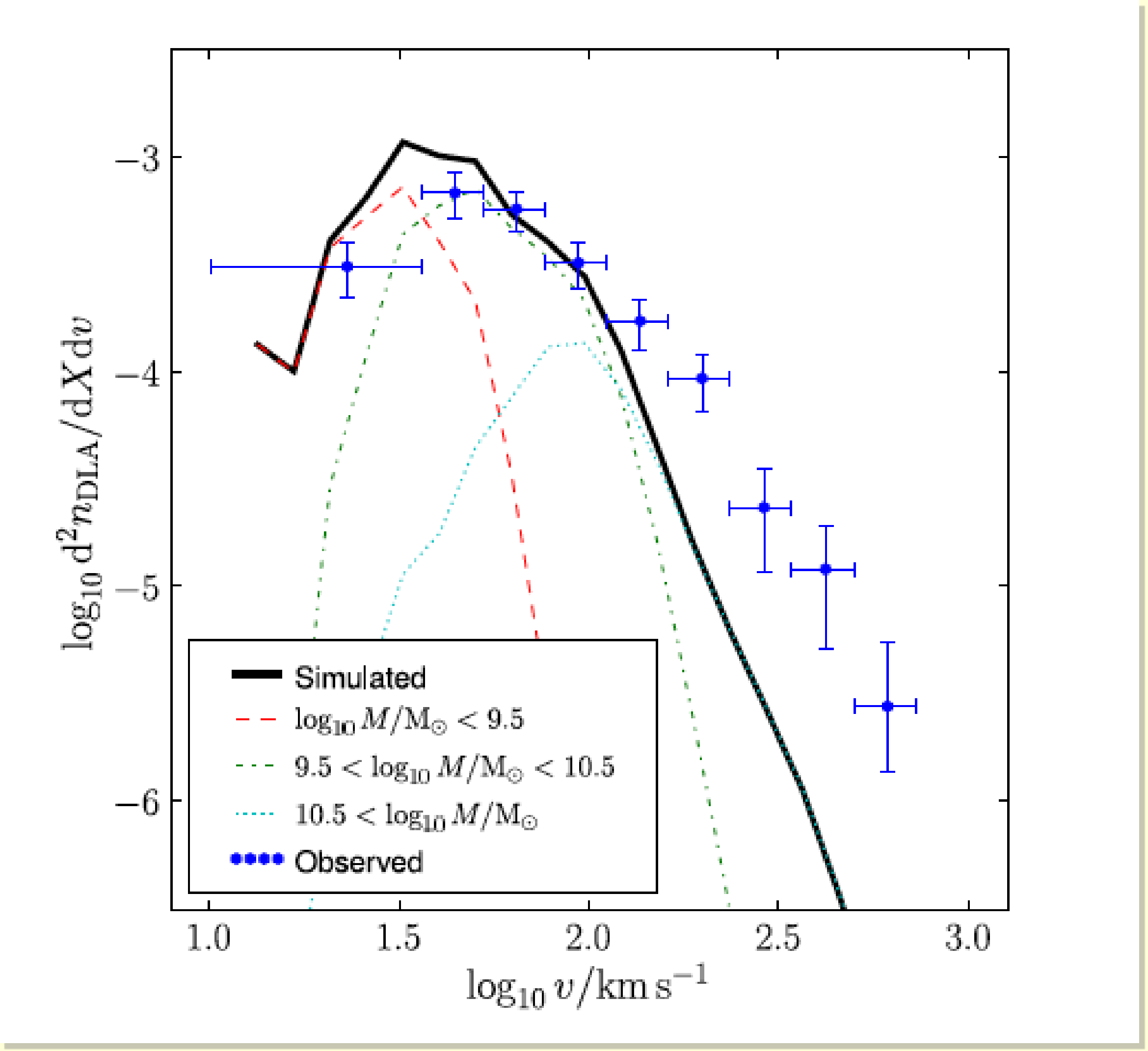
Pontzen *etal* (2008) model (red) consistent with kinematics of "low cool" DLAs (blue)

data

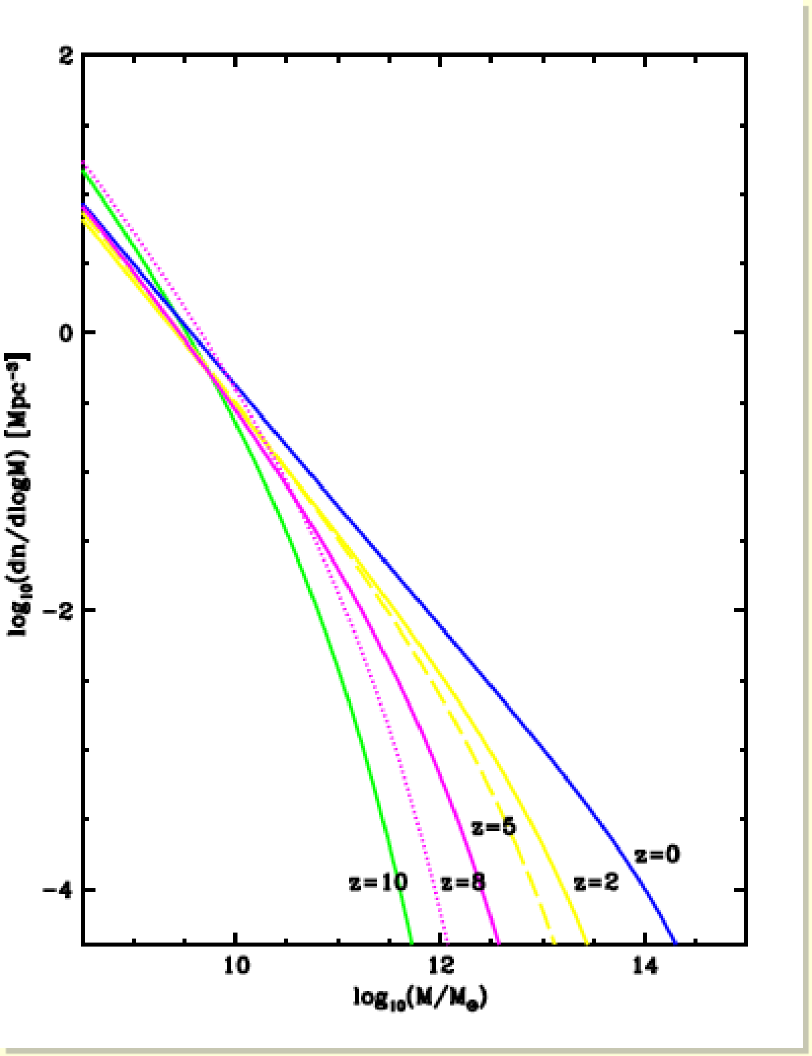


Median Velocity =50 kms^{-1}

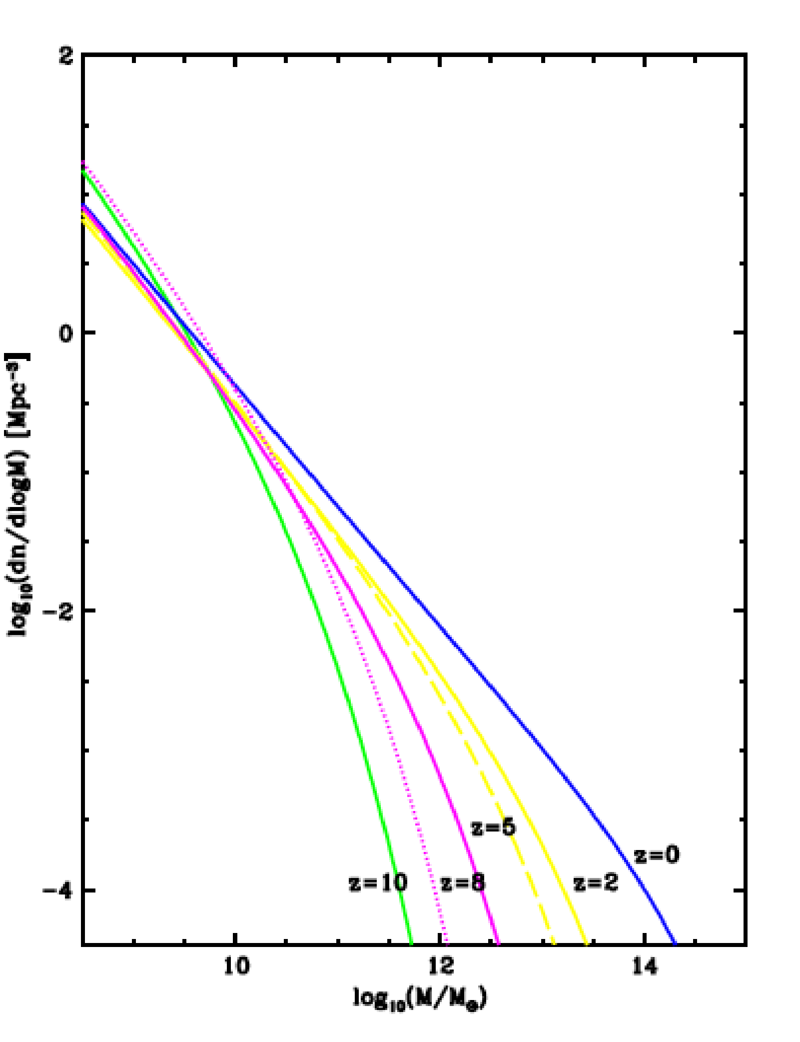
DLA incidence as function of Δv_{90} for different ranges of DLA halo masses (Pontzen *etal* '08)

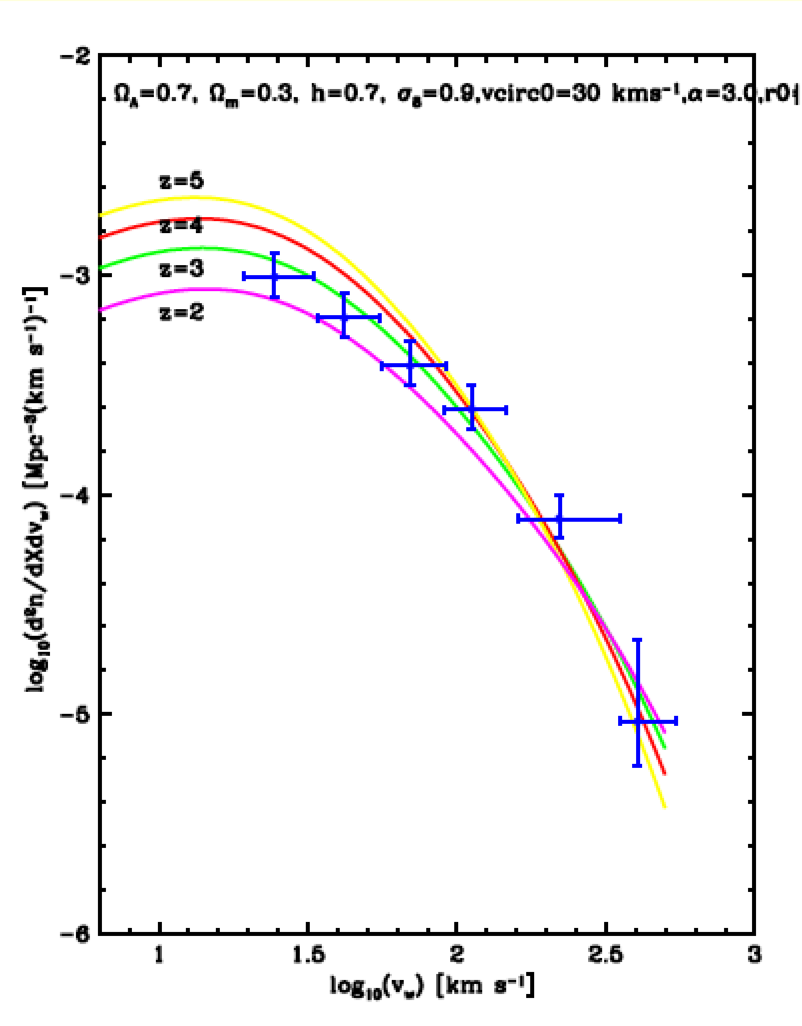


Evolution of halo mass function implies decrease of the circular velocity, v_c , with redshift

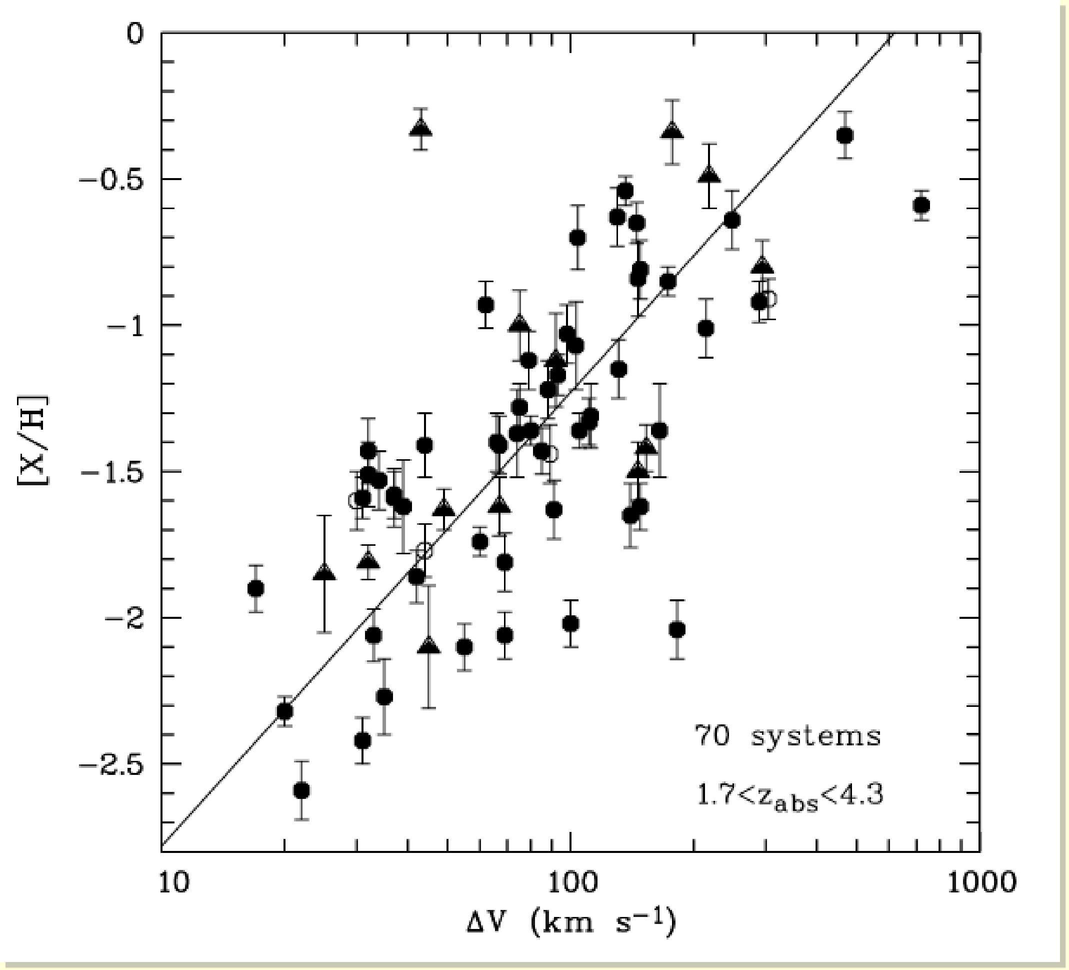


$$\frac{d^2n}{dXdv_w} = \int p(v_w|v_c(M))(\sigma(v_c(M)))(dn/\mathrm{dlog}M)d\mathrm{log}M$$

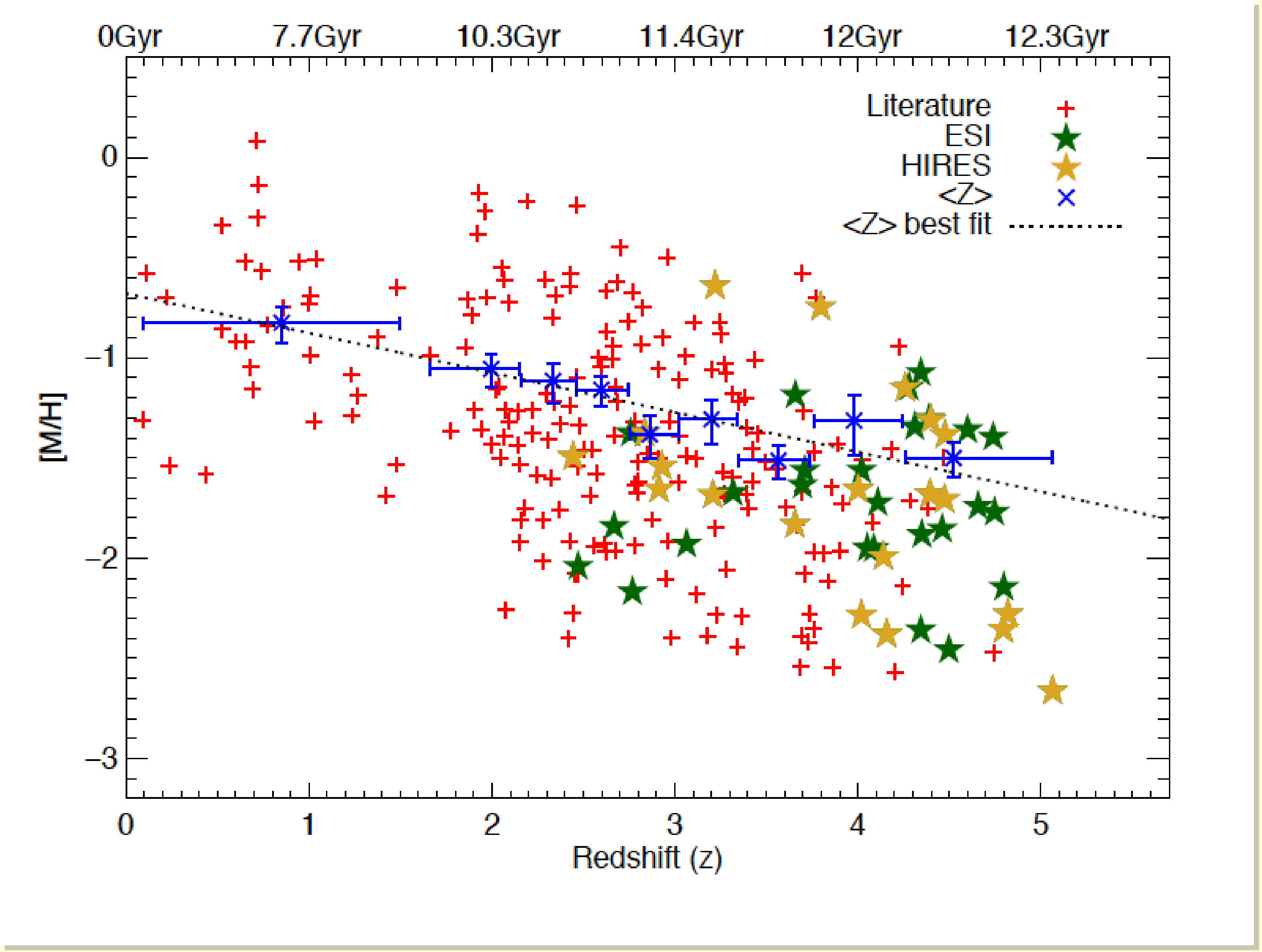




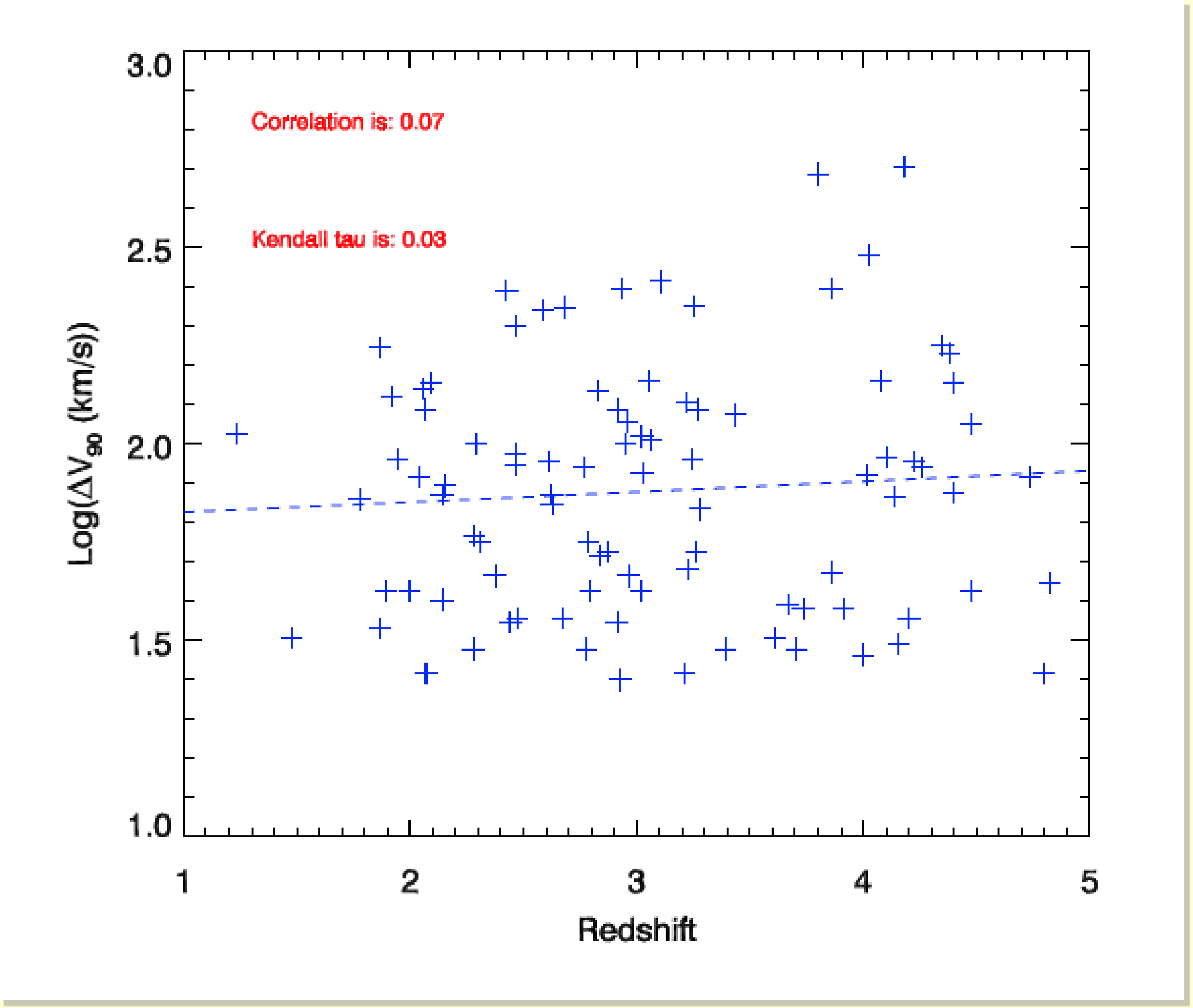
Indirect observational evidence for decline of Δv_{90} with z (Ledoux *etal* 2006)



Correlation between [M/H] and z further suggest Δv_{90} should decline with z



But evidence for evolution of Δv_{90} with z is weak at best



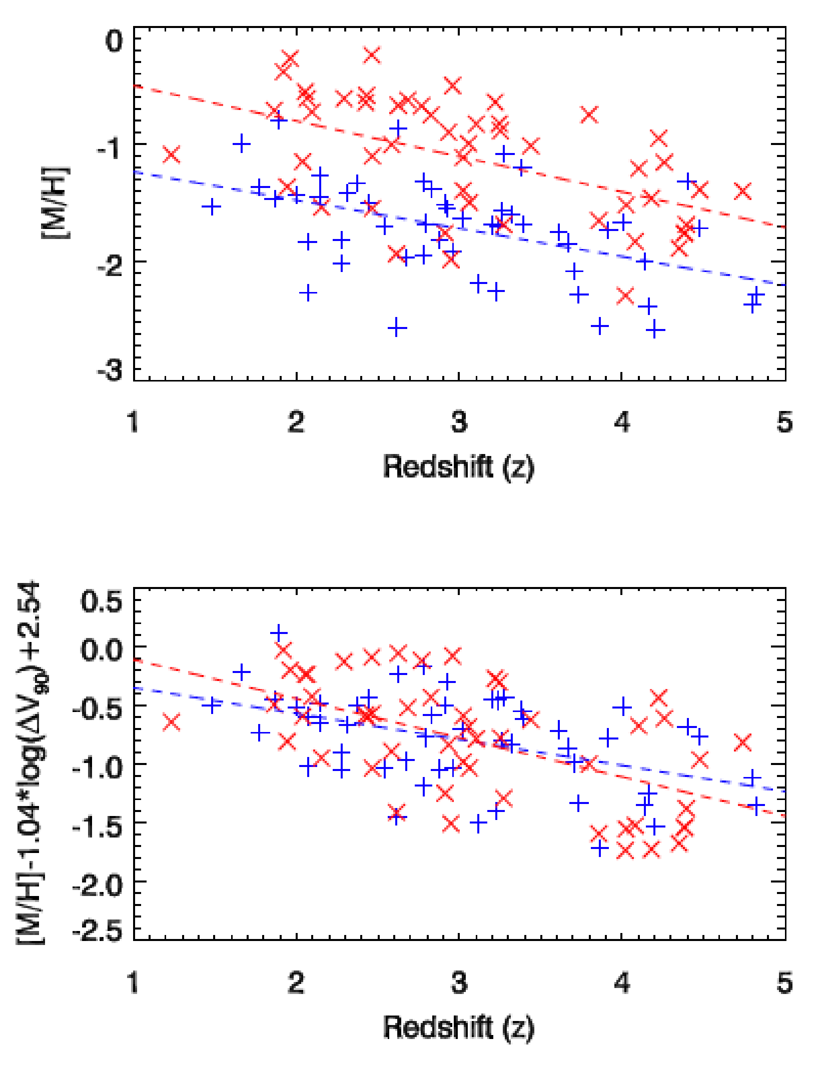
Fundamental Plane

- Two weakly correlated variables, Δv_{90} and z
- But Δv_{90} strongly correlated with [M/H]
- Redshift z strongly correlated with [M/H]
- Analogous to fundamental plane for elliptical galaxies where σ_v and μ are uncorrelated, but each are strongly correlated with r_e

$$[M/H] = -2.54{\pm}0.27 + 1.04{\pm}0.12 \cdot \log\Delta v_{90} - 0.26{\pm}0.04 \cdot z$$

Tilted

Edge-on

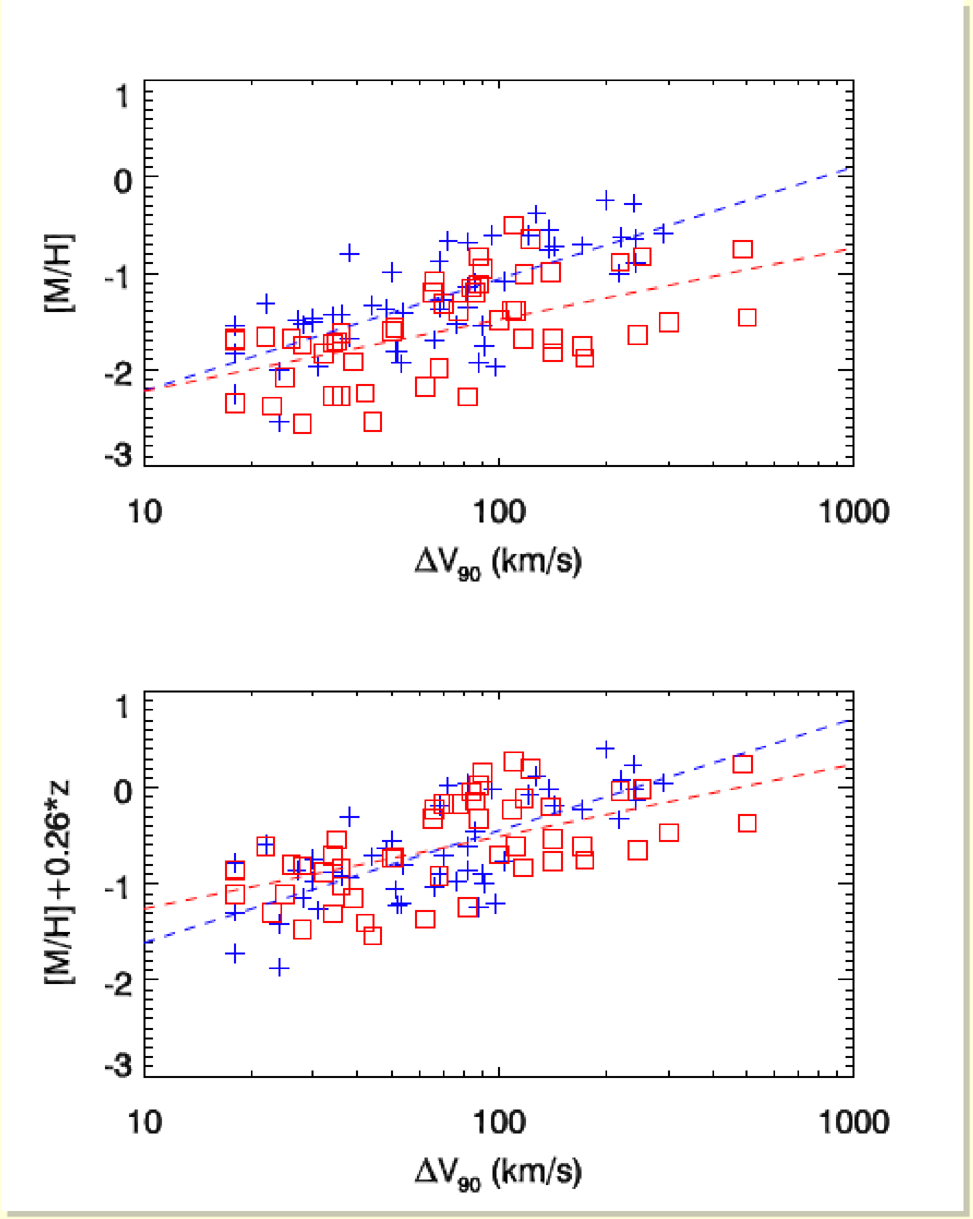


× : Δv_{90} >72 km/s

\+ : Δv_{90} <72 km/s

Tilted

Edge-on



+ :z < 2.95

□ : z > 2.95

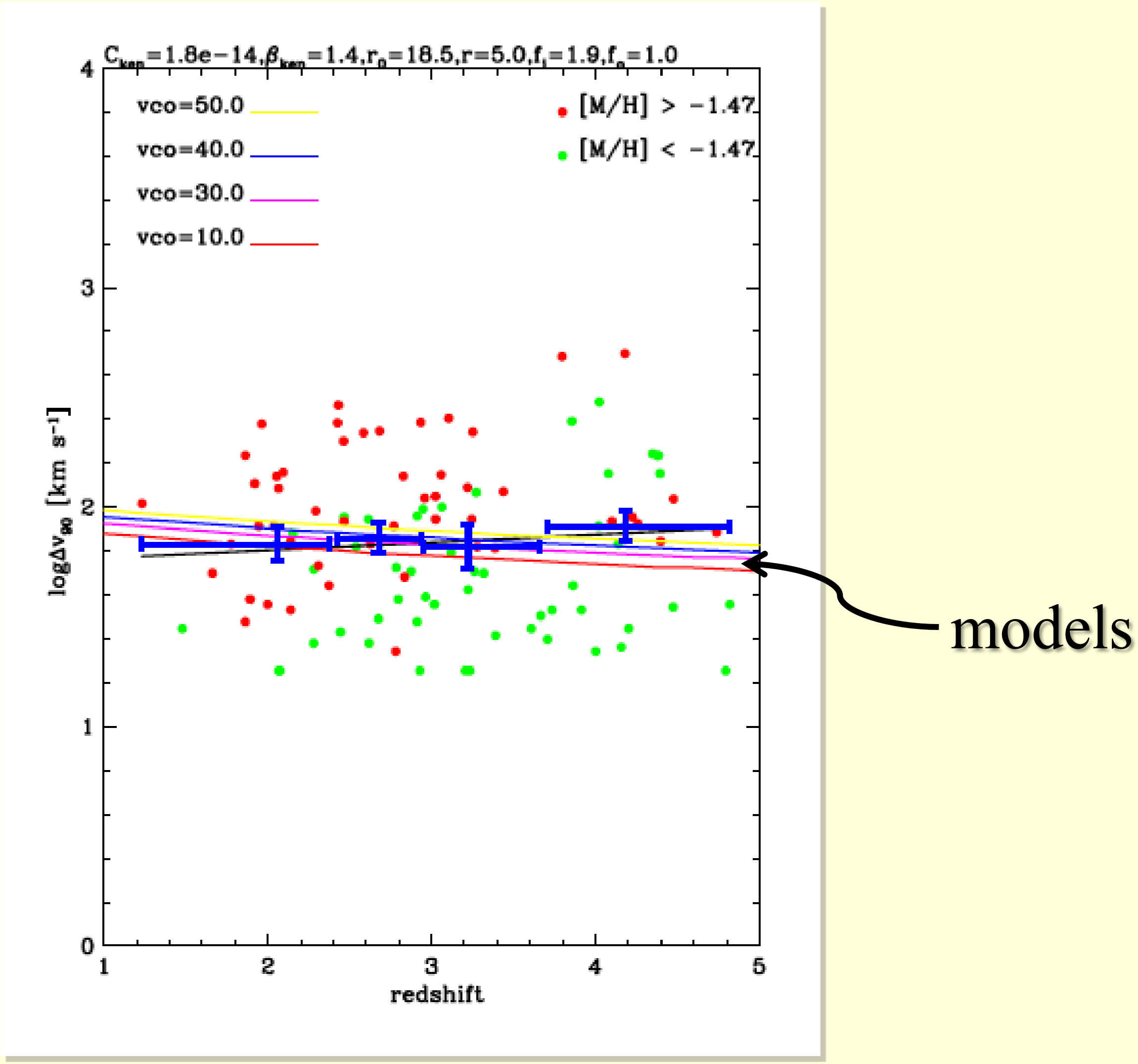
Model Predictions

- Kinematic Model (Barnes and Haehnelt 2008)
- Chemical Evolution (Erb 2006)

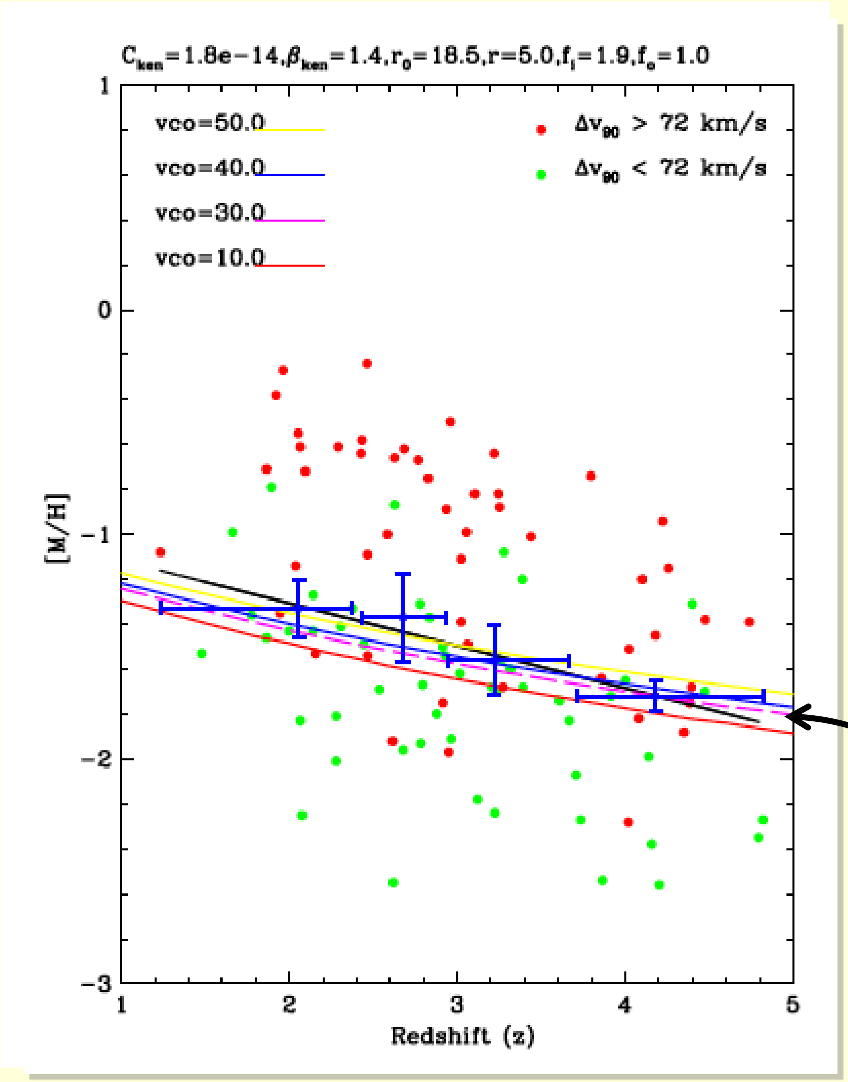
--Kennicutt-Schmidt Law (with reduced SFR efficiency)

--Tinsley type model with inflow and outflow

Model Predictions: velocity width vs z

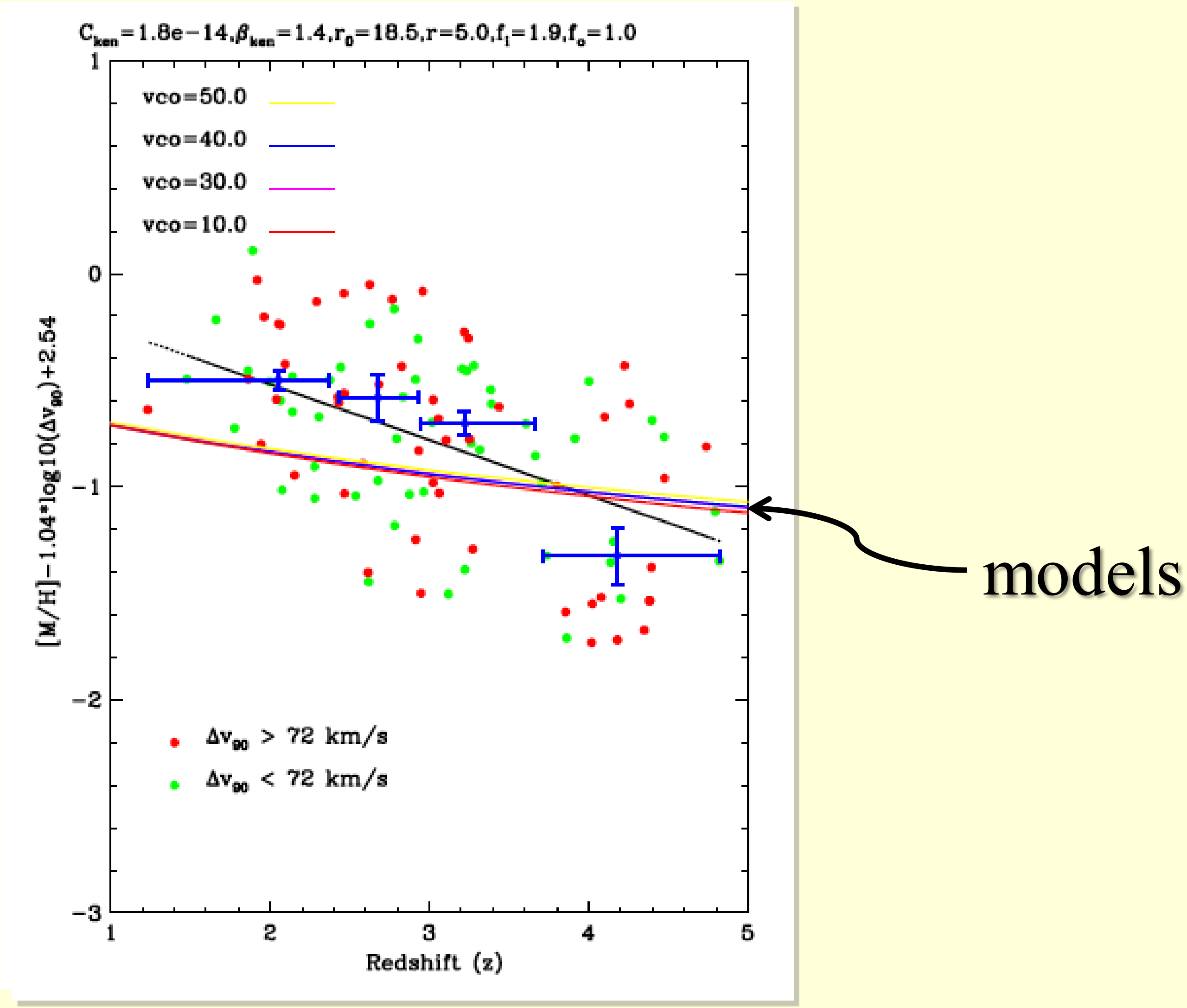


Model Predictions: metallicity vs z



models

Model Predictions: plane parameter vs z



Results of Survey for DLAs with z>4

- Robust evidence for linear decrease of <Z> with z for z=[1,5].
- Large Dispersion in [M/H] ($\sigma_{[M/H]}$ =0.55) at all z
- Distribution of [M/H] and [α/Fe] like halo stars
- Metallicity "floor" at [M/H] =-3

DLA Kinematics

- v_c > 30 km s^{-1} for halos hosting DLAs
- Simulations reproduce kinematics of "low-cool" DLAs
- Possible detection of fundamental plane in which [M/H] is a function of Δv_{90} and z
- Predicts a mass-metallicity relation with a zero-point metallicity that decreases with z
- Δv_{90} may increase with redshift