A Fundamental Plane for DLAs

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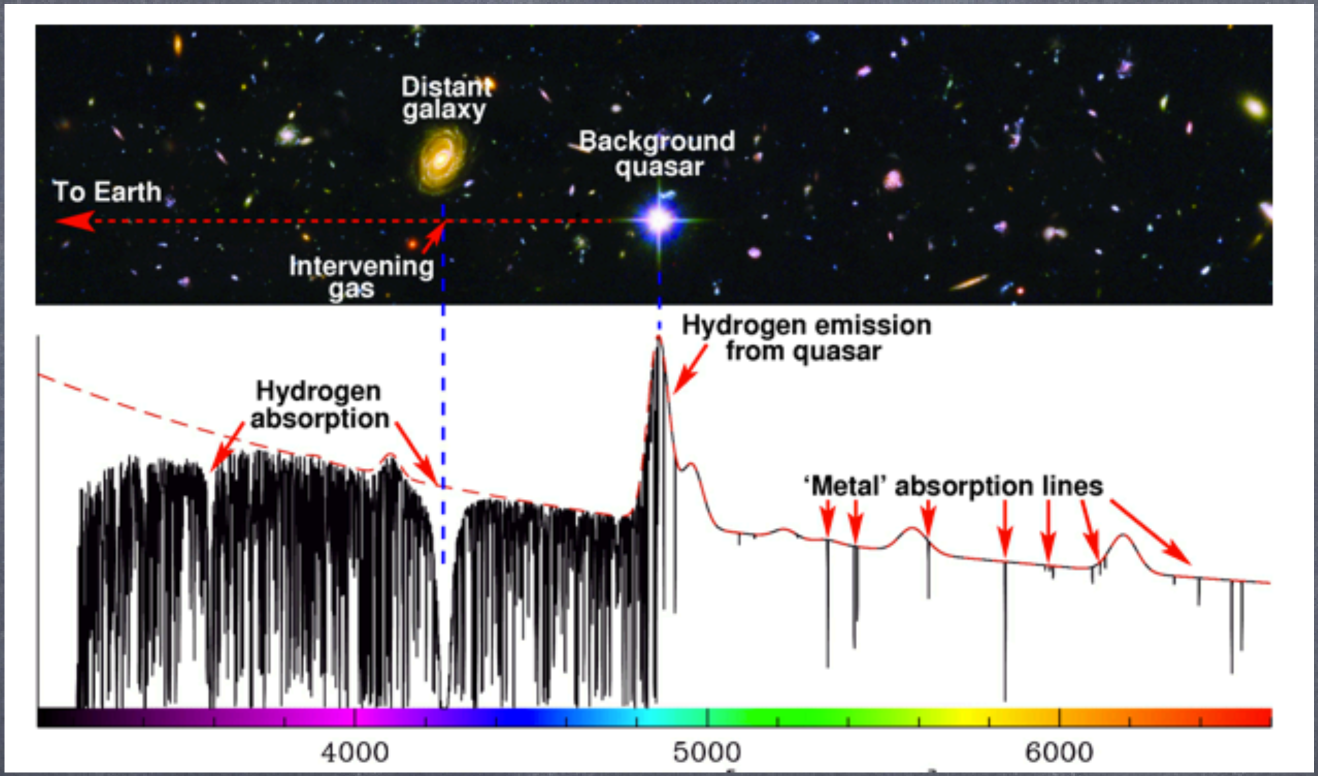
Outline

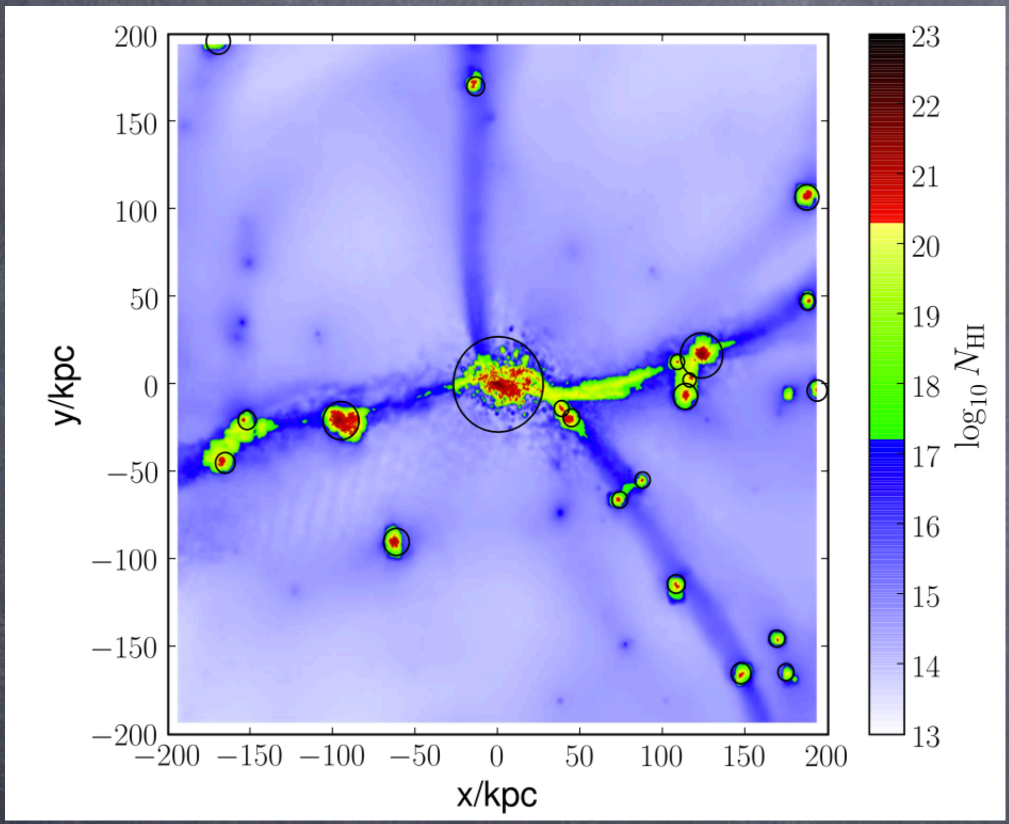
- What are the main parameters we can measure for DLAs, and what do their distributions tell us?
- What correlations exist between these parameters?
- What is the fundamental plane, and what does it physically tell us?
- How can the fundamental plane constrain numerical simulations of galaxy formation?

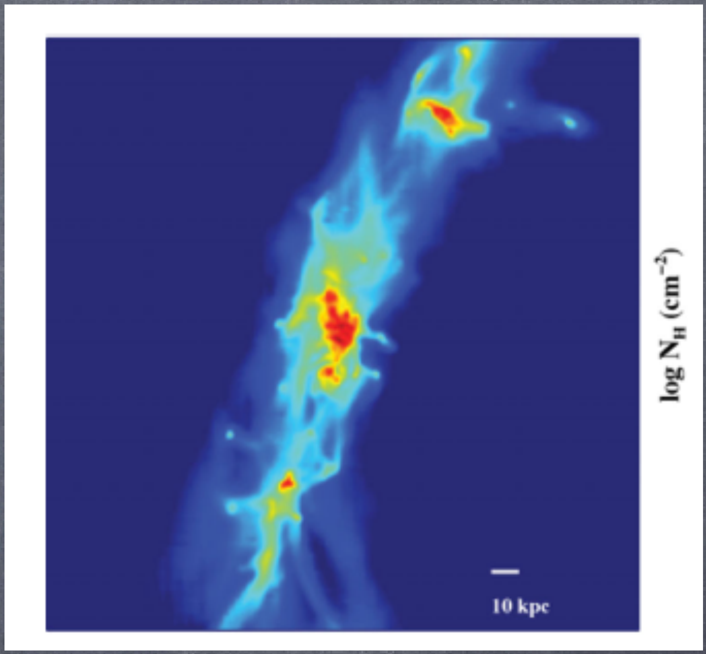
What are DLAs?



- DLAs are layers of gas with an H I column density of 2×10^{20} cm^{-2}.

What are DLAs?





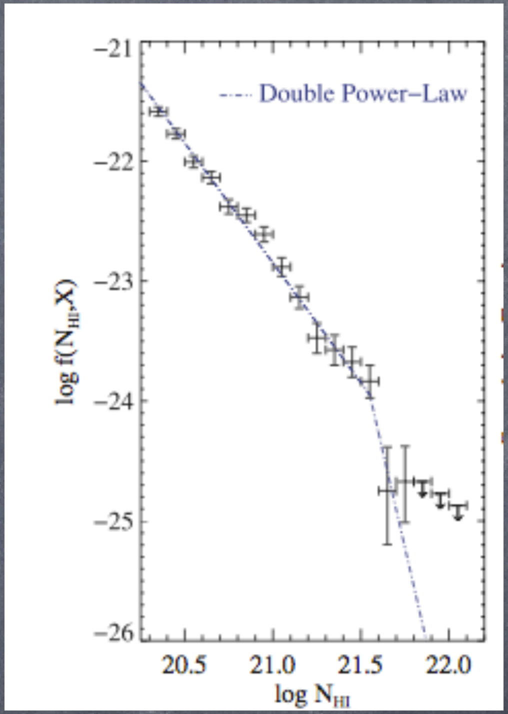
Pontzen et al. 2008

Fumagalli et al. 2011

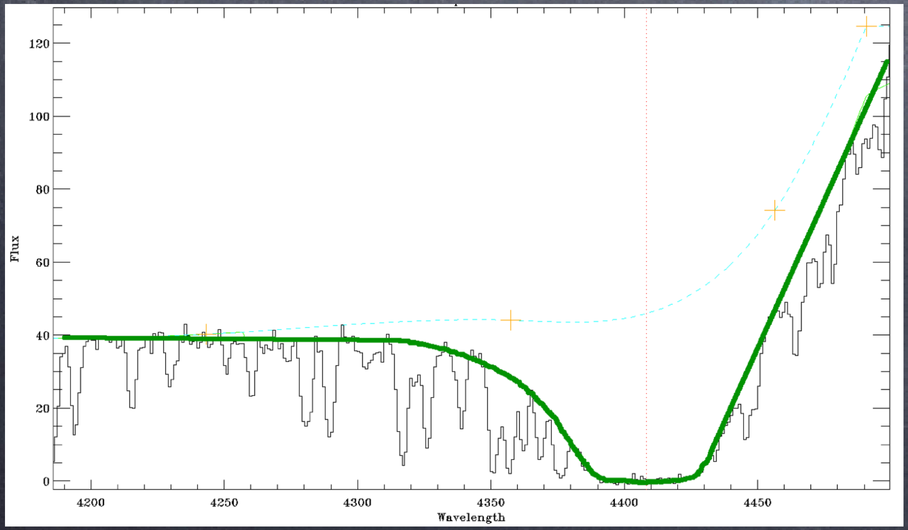
DLAs are associated with galaxies

What Properties of DLAs Do We Measure?

- Redshift and H I column density.
- The distribution of these properties will give $f(N_{HI},X)$

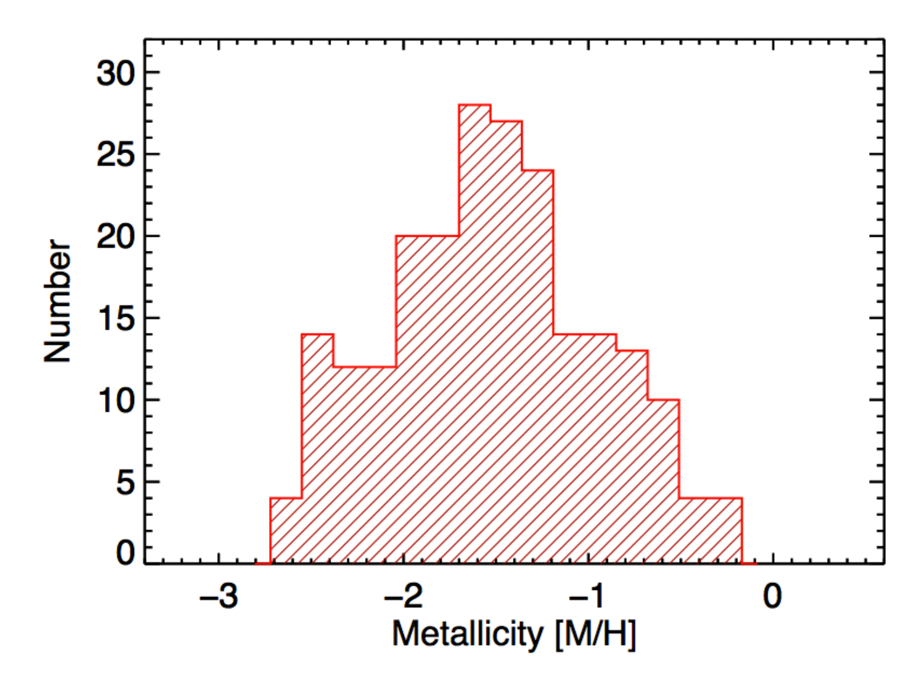


Prochaska & Wolfe 2009



What Properties of DLAs Do We Measure?

- Metallicity
- Metallicity distribution shows that DLAs are metal poor, with an average metallicity of -1.57.

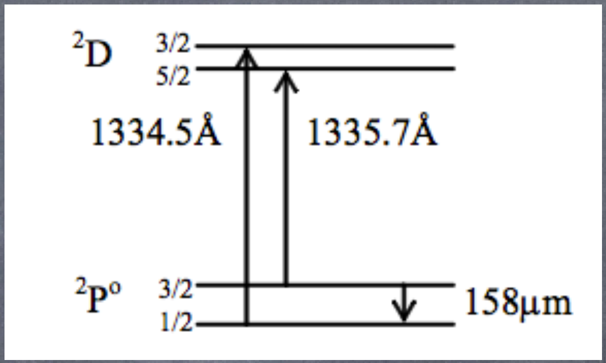


Rafelski et al. 2012

What Properties of DLAs Do We Measure?

- The cooling rate of the gas, ℓ_c. Defined by:

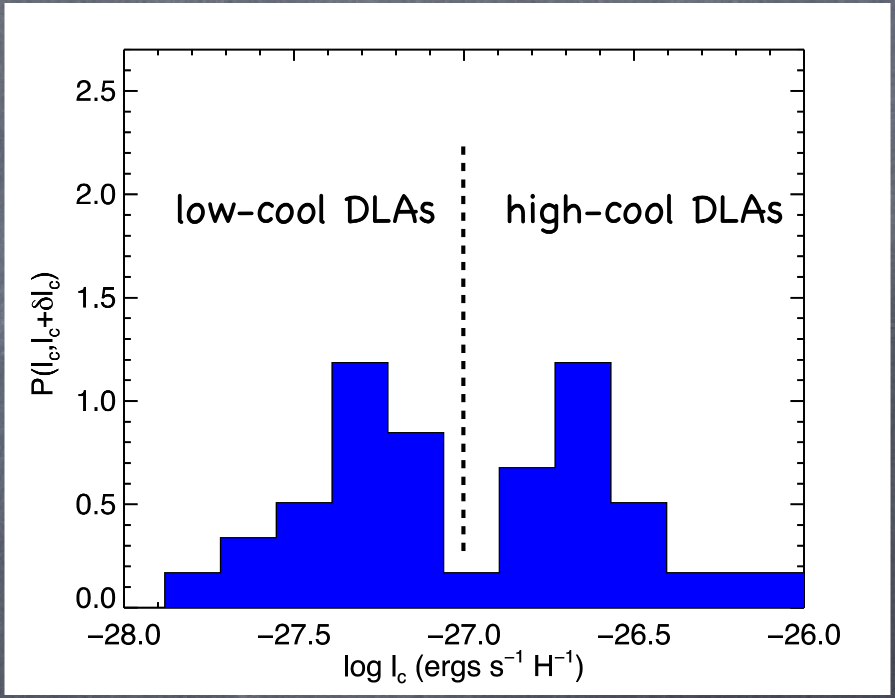
$$\ell_c = \frac{N(\mathrm{CII}^*)}{\mathrm{N_{HI}}} A_{ul} h\nu_{ul}$$



- The 158 micron line is the dominant coolant in the neutral ISM.
- The state responsible for the 158 micron line also produces the CII* λ1335.7 line.

What Properties of DLAs Do We Measure?

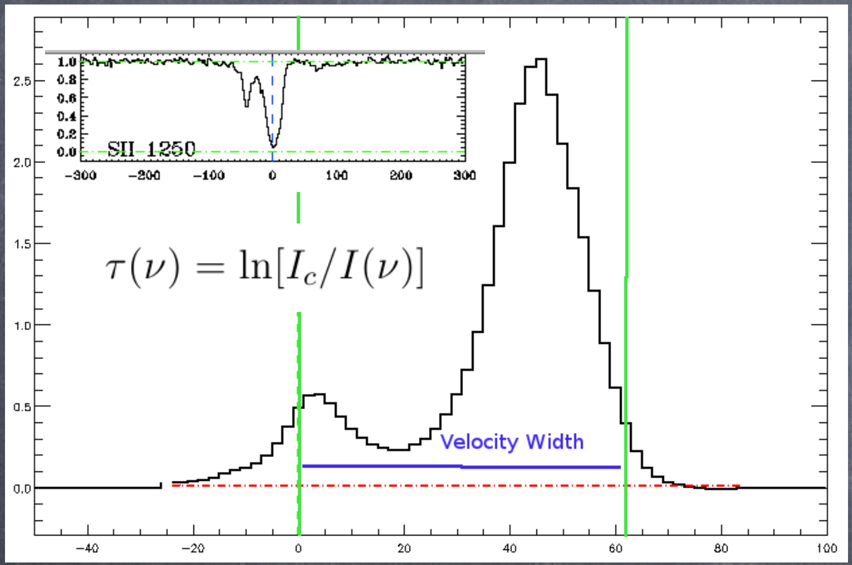
- The distribution is bimodal, allowing the DLA sample to be apportioned into two subsamples.
- Wolfe et al. 2008 asserts that low-cool DLAs are embedded in low mass halos and high-cool DLAs in higher mass halos.



Wolfe et al. 2008; Neeleman et al. 2013

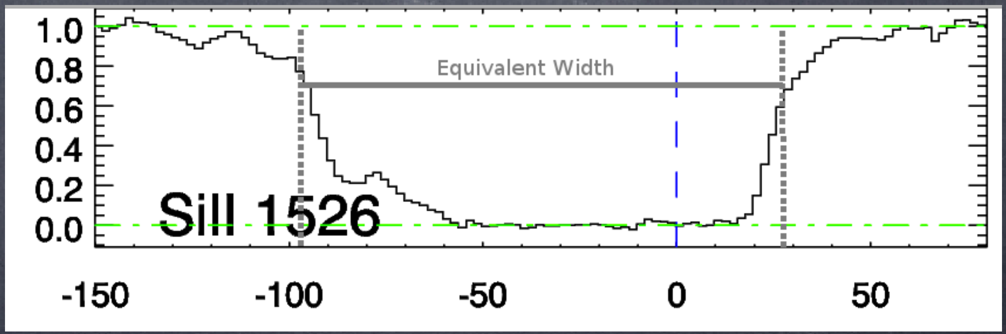
What Properties of DLAs Do We Measure?

The kinematics, in particular:

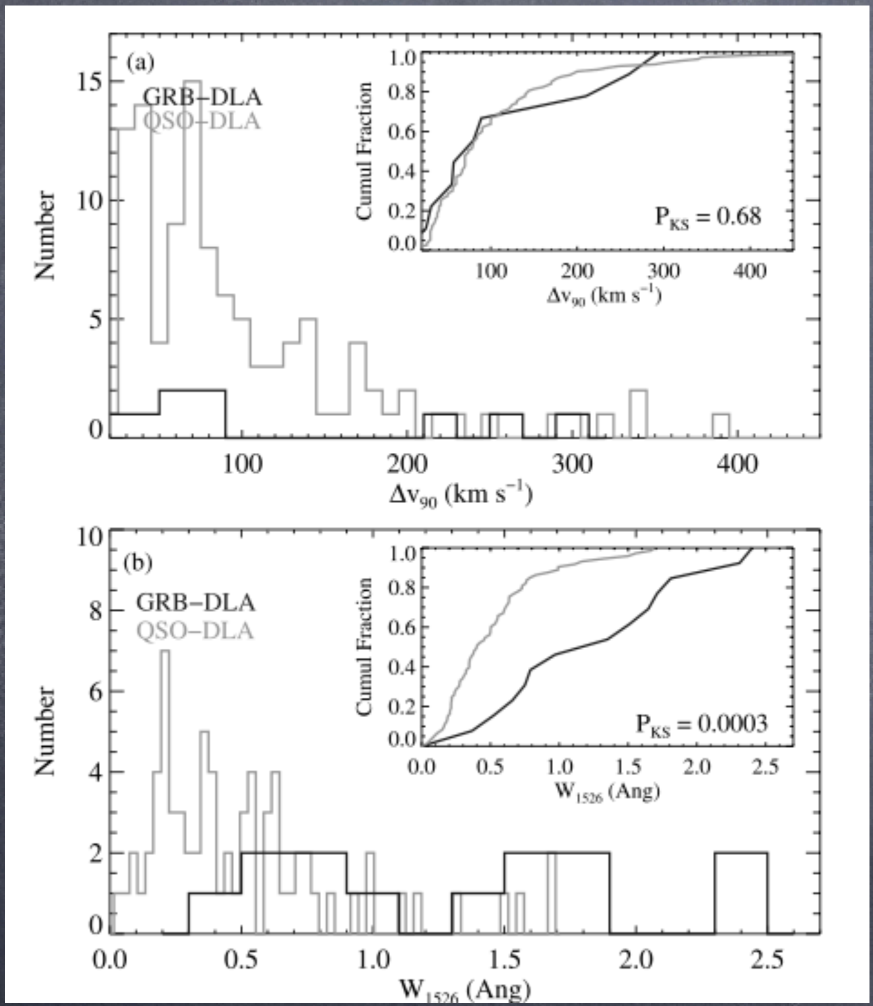


- The velocity width, ΔV_{90}, is the velocity interval which contains 90% of the integrated flux that is absorbed by the DLA.

- W_{1526} is the rest equivalent width of the Si II 1526 line.



What Properties of DLAs Do We Measure?



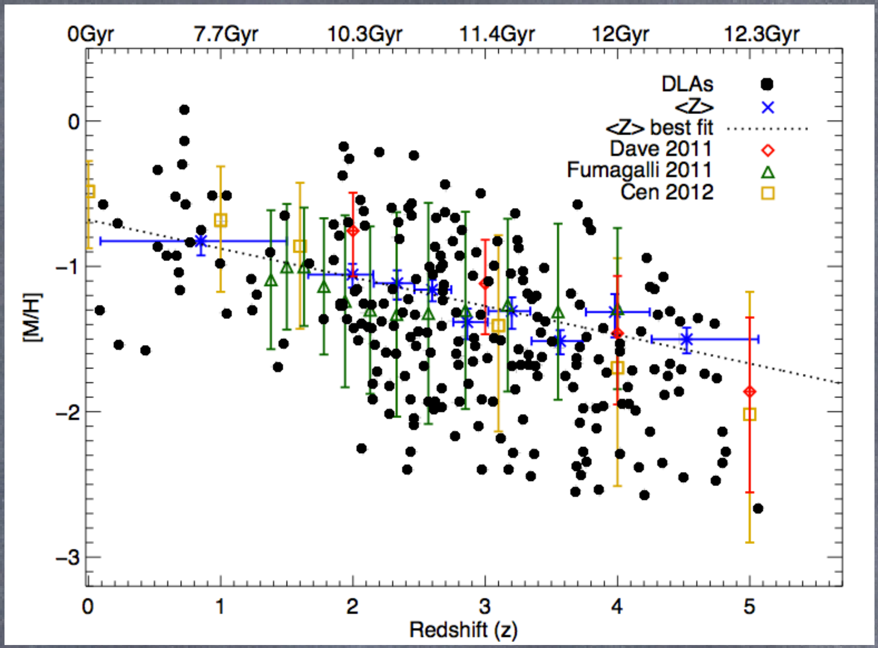
Prochaska et al. 2008

- The distributions show DLAs with large kinematics
- Furthermore, many DLAs have a velocity width greater than 100 km/s

What Next?

- Distributions provide a wide variety of observational data, which help in the understanding of DLAs.
- Next step: correlations. These correlations can provide additional information about the gas in galaxies at high redshift.

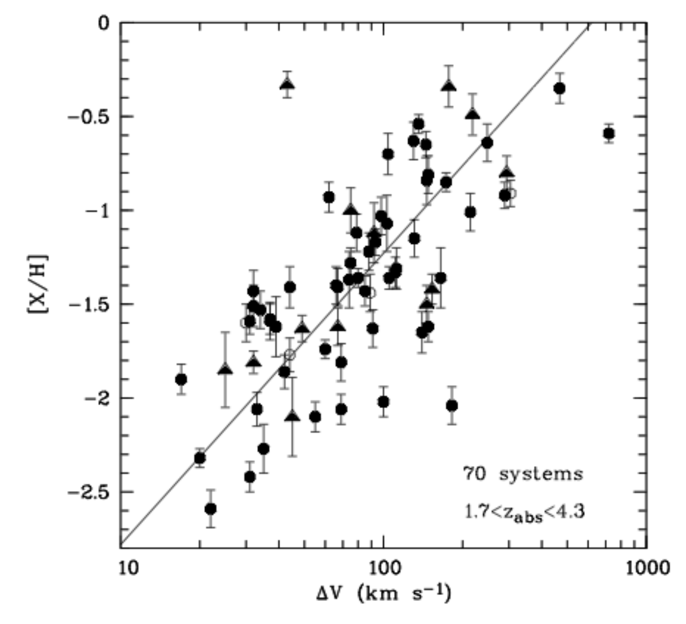
Correlations

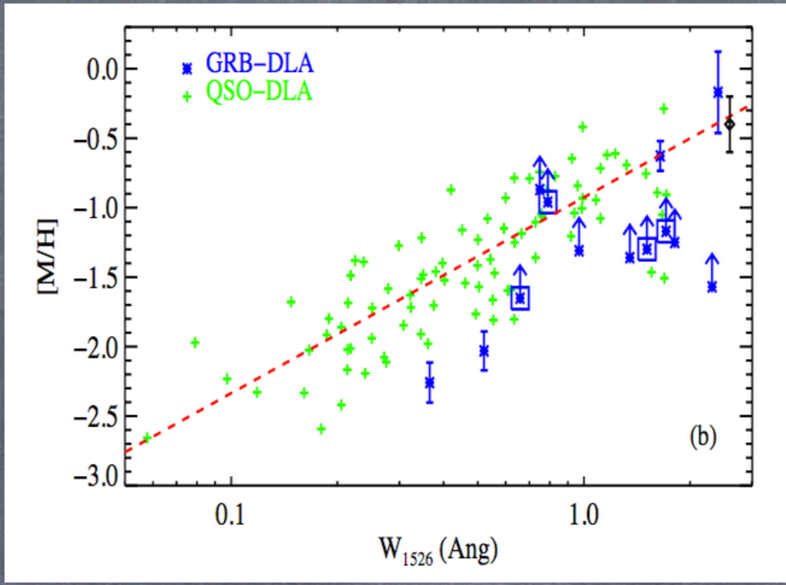


Rafelski et al. 2012

- Redshift-Metallicity Correlation shows that metallicity decreases with increasing redshift.
- This correlation will be further explored in the talk by M. Rafelski.

Correlations



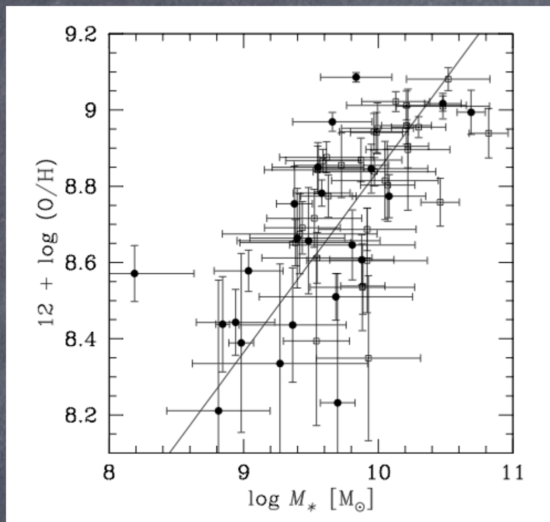


Ledoux et al. 2006

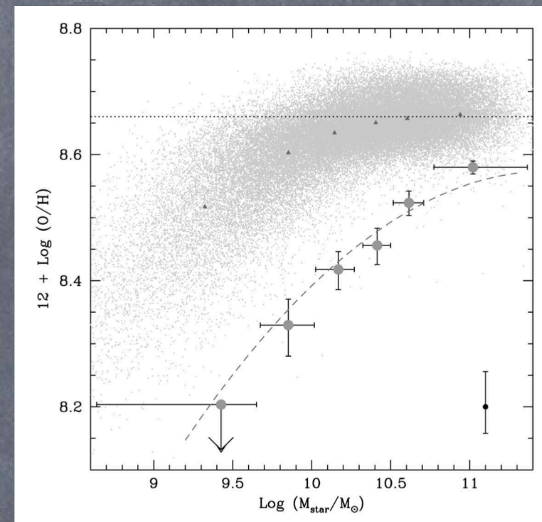
Prochaska et al. 2008

- Correlation between metallicity and the kinematic parameters.
- This correlation is believed to be due an underlying mass-metallicity correlation.

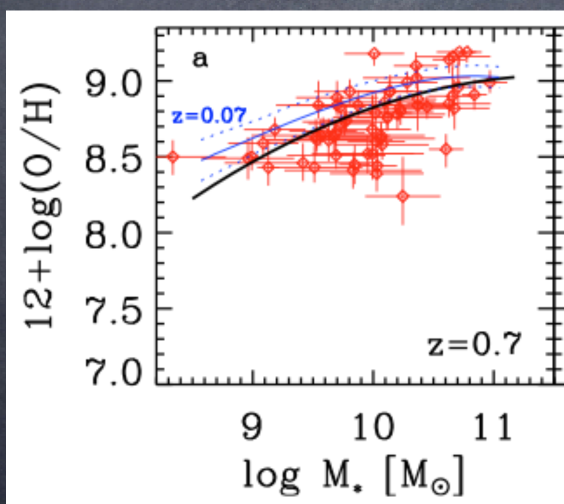
Correlations



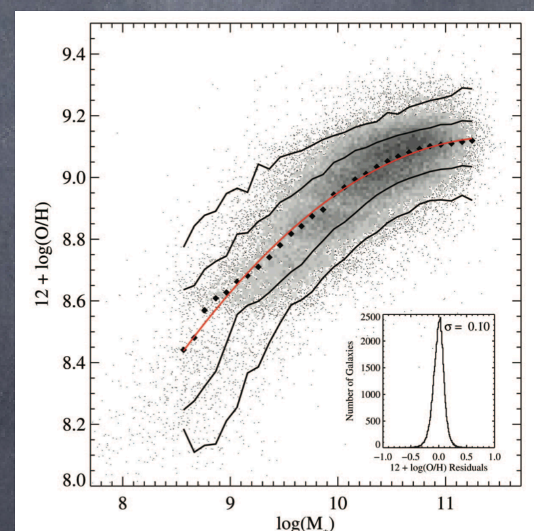
Savaglio et al. 2005



Erb et al. 2006



Maiolino et al. 2008



Tremonti et al. 2004

Can we do more?

- Distributions

  $\Downarrow$ need more data points

- Correlations

  $\Downarrow$ need more data points

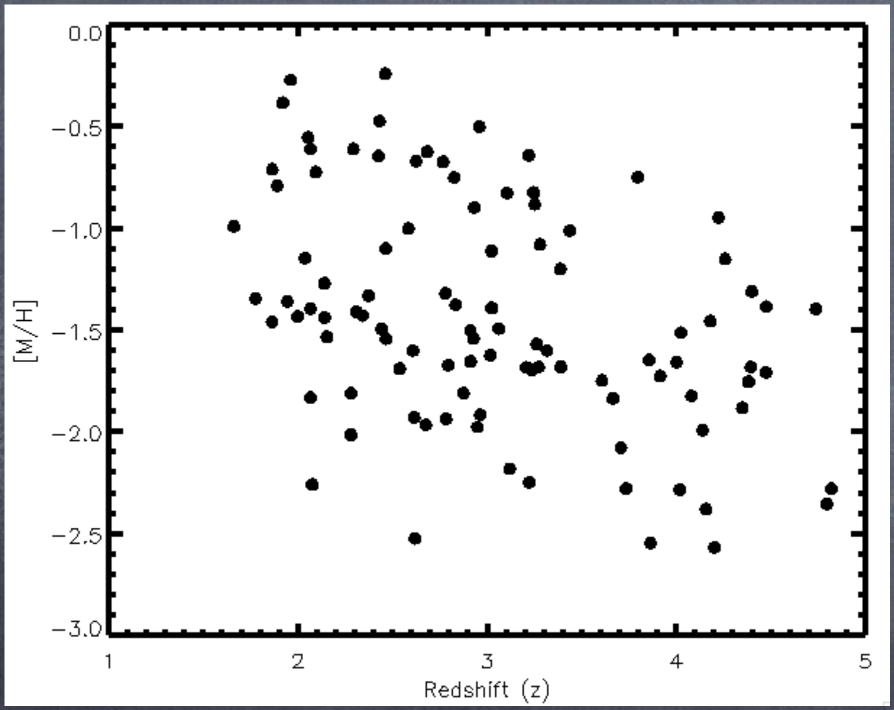
- Multi-parameter correlations, such as planar equations

The Sample

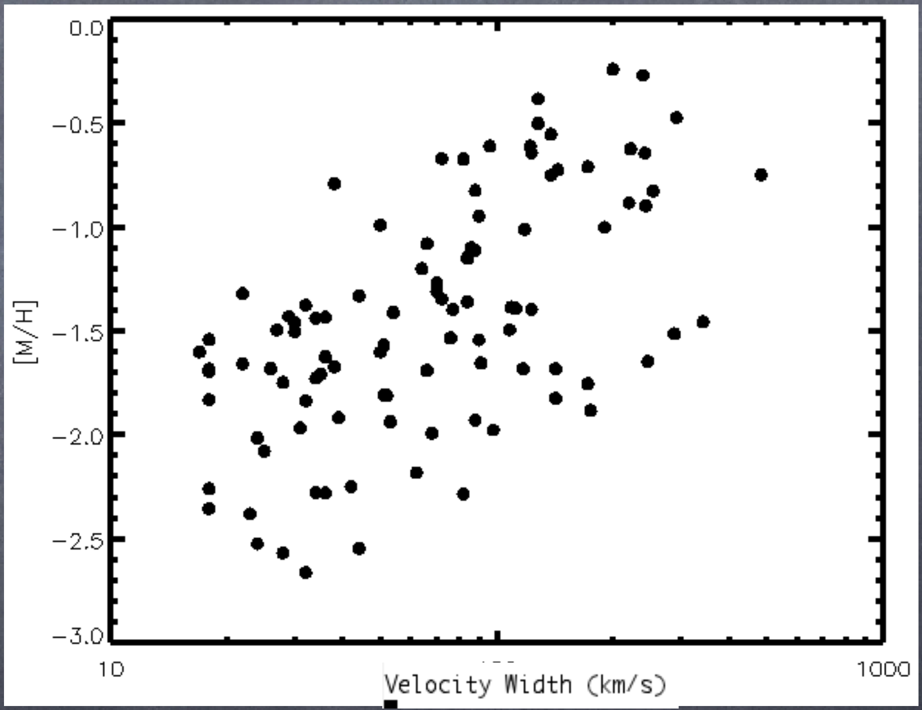
- 100 unbiased DLAs with high resolution spectra taken with a single instrument (HIRES/Keck)

- Last sample of HIRES-only DLAs had only 35 DLAs, the increase allows for three parameter correlations

Three-Parameter Correlations

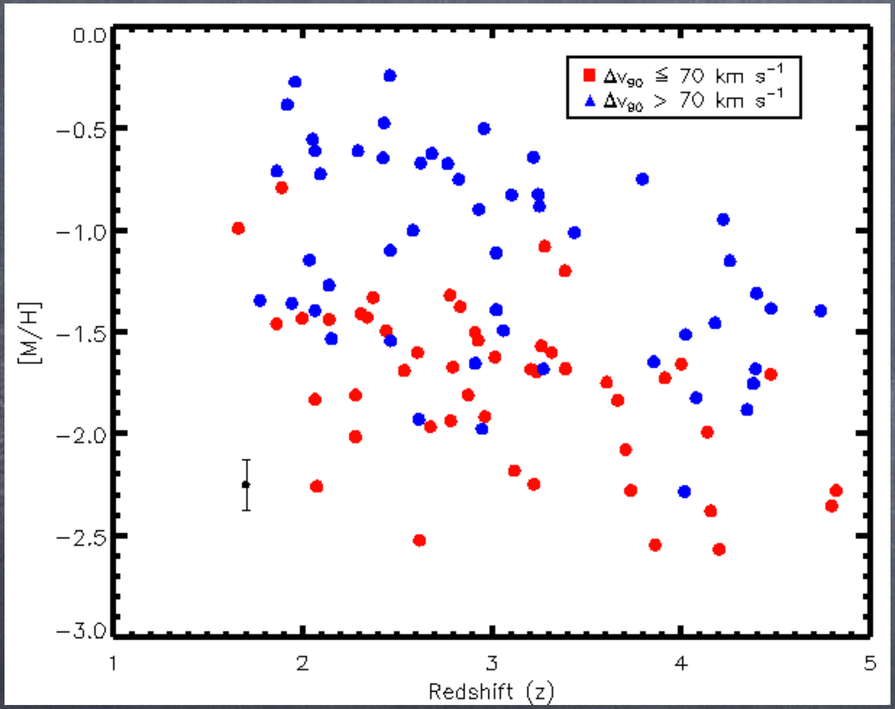


Metallicity-Redshift Correlation



Metallicity-Velocity Width Correlation

Three-Parameter Correlations



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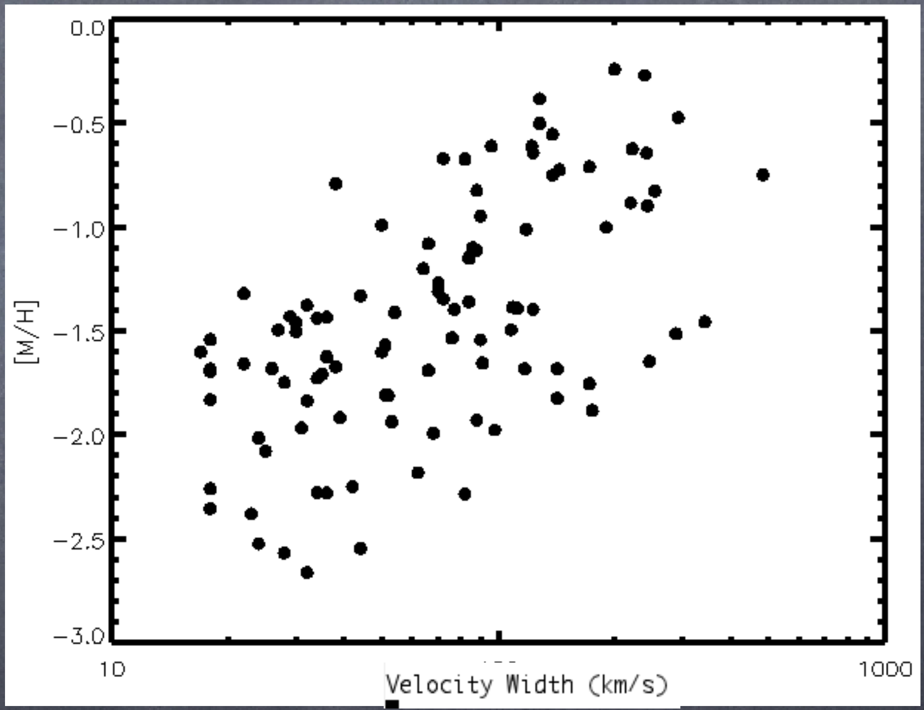

Metallicity-Velocity Width Correlation

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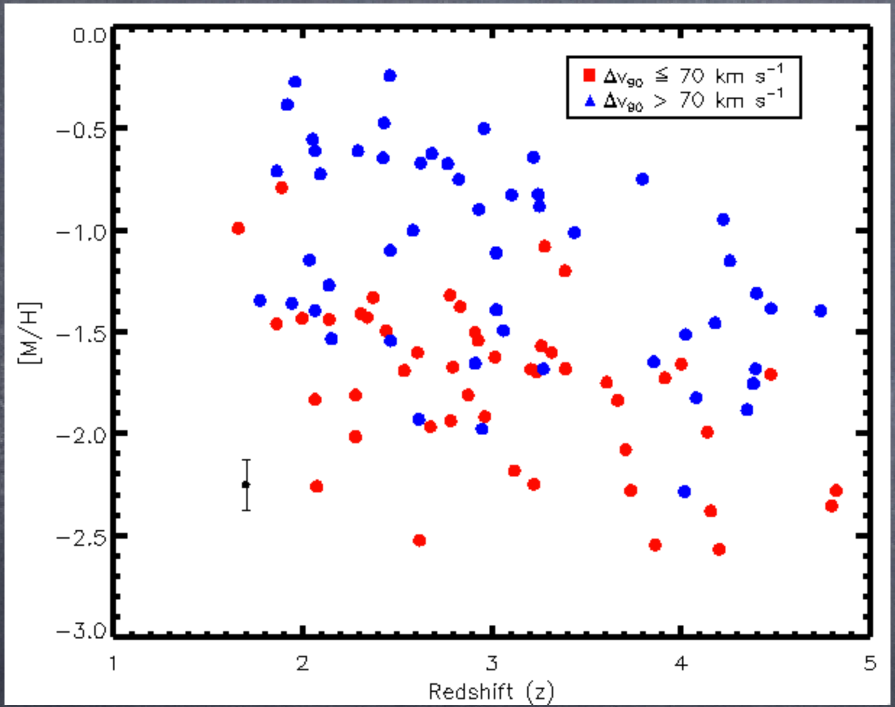
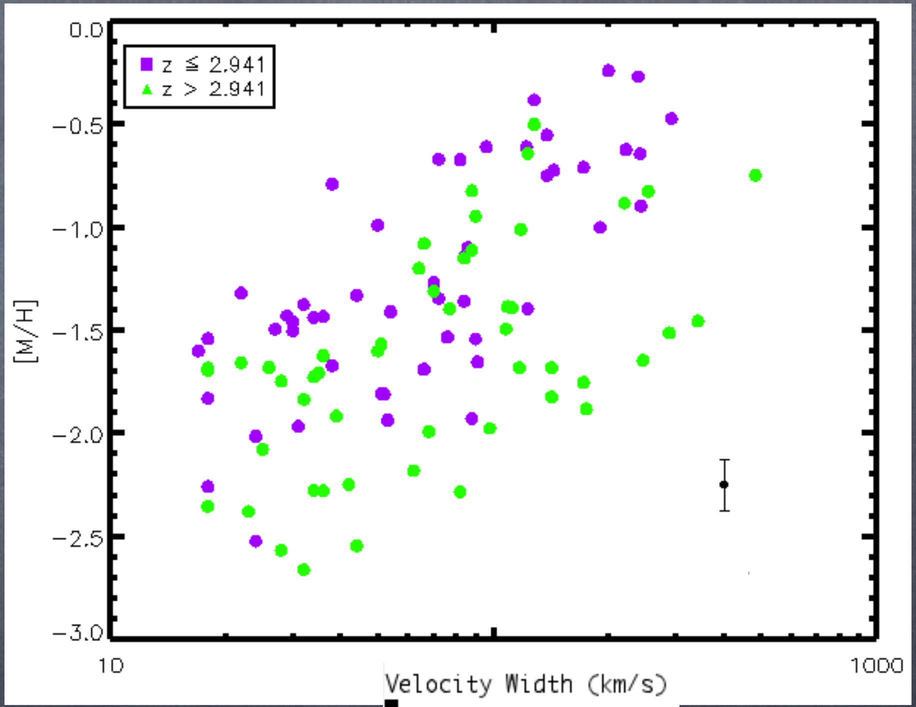
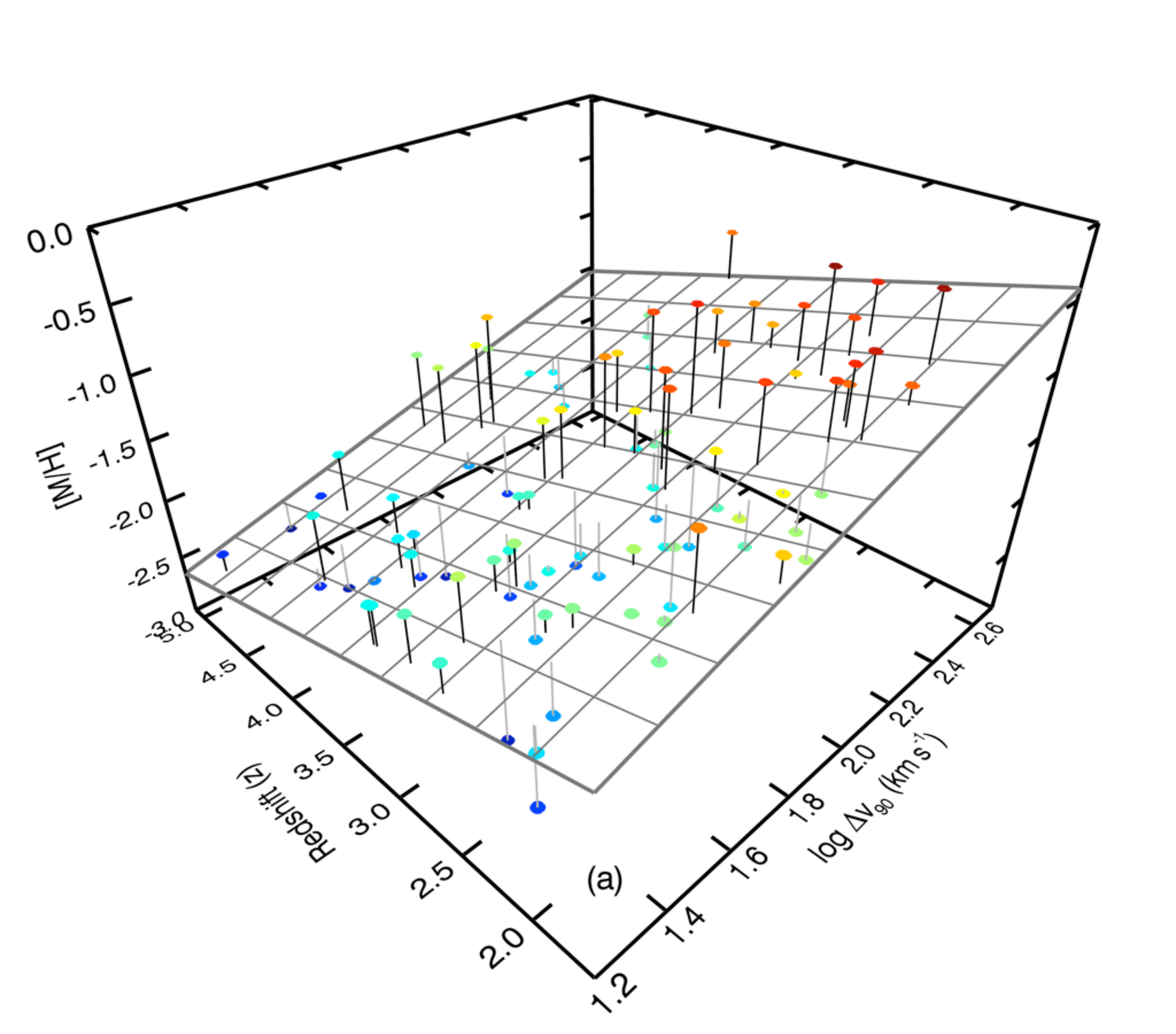


Metallicity-Redshift Correlation

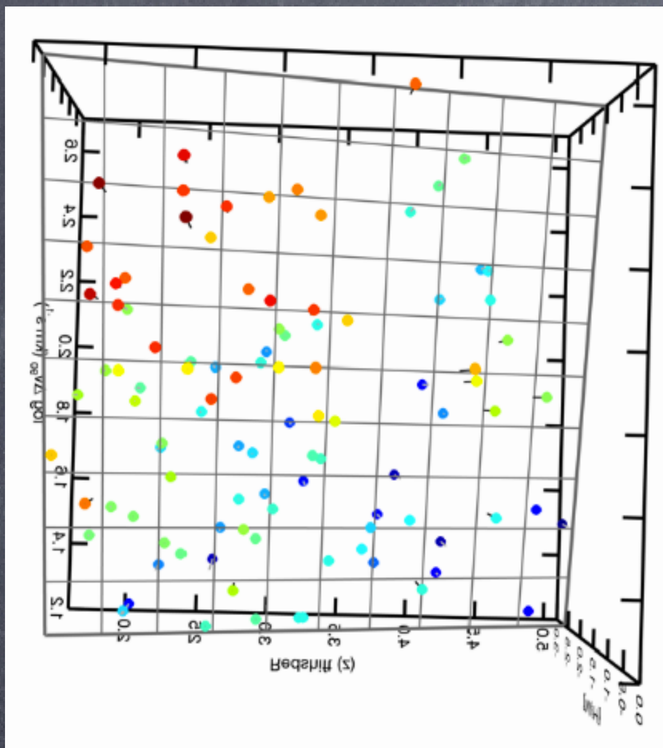


Metallicity-Velocity Width Correlation

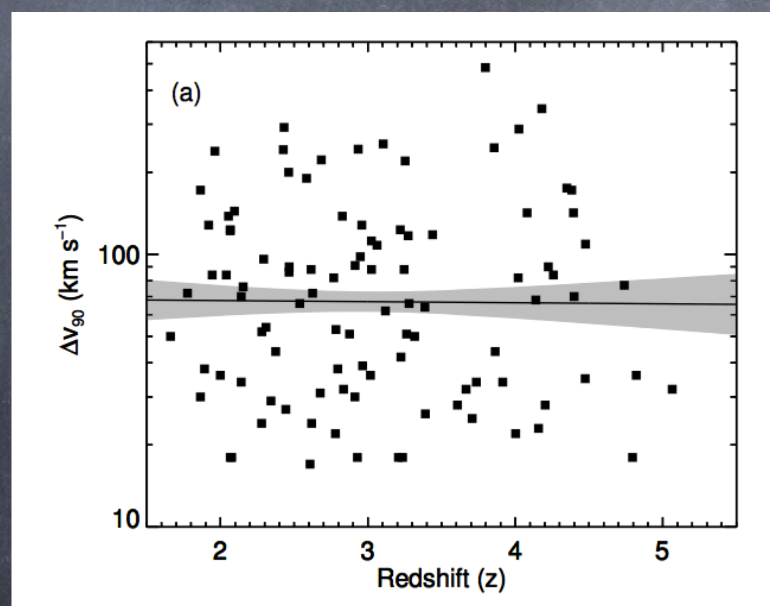
Fundamental Plane



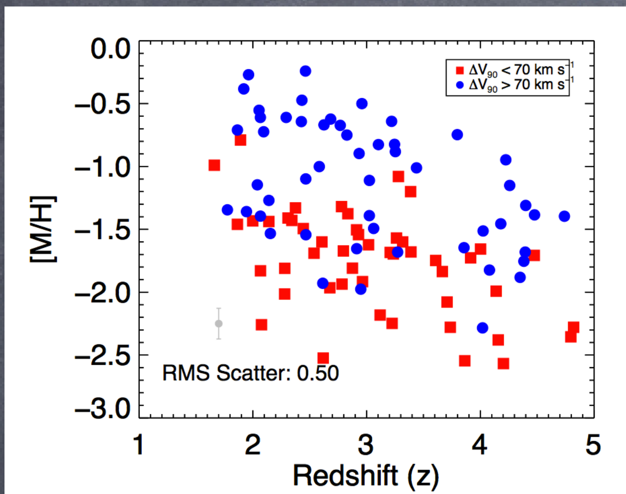
Fundamental Plane



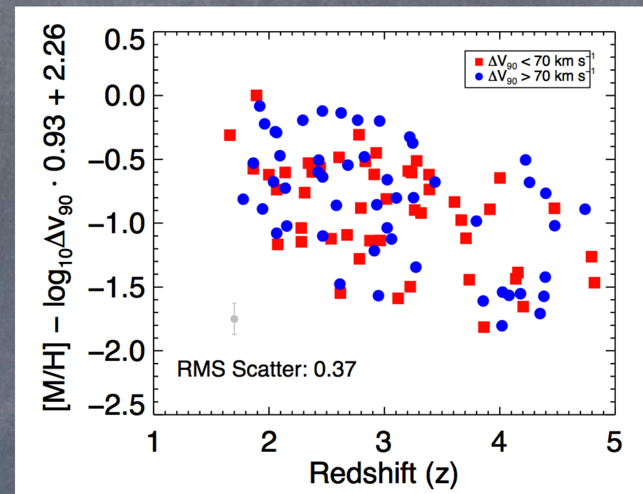
- Its existence is due to the lack of correlation between redshift and the velocity width.



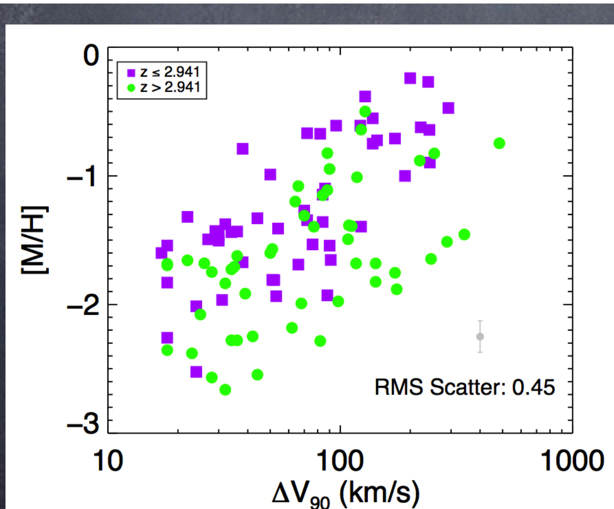
Fundamental Plane



$\Rightarrow$



$$[M/H] = (-1.9\pm0.5) + (0.74\pm0.21)\cdot\log\Delta v_{90} - (0.32\pm0.06)\cdot z$$



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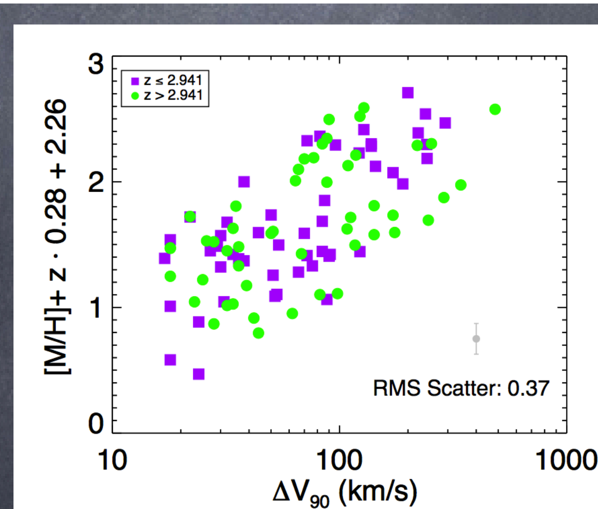
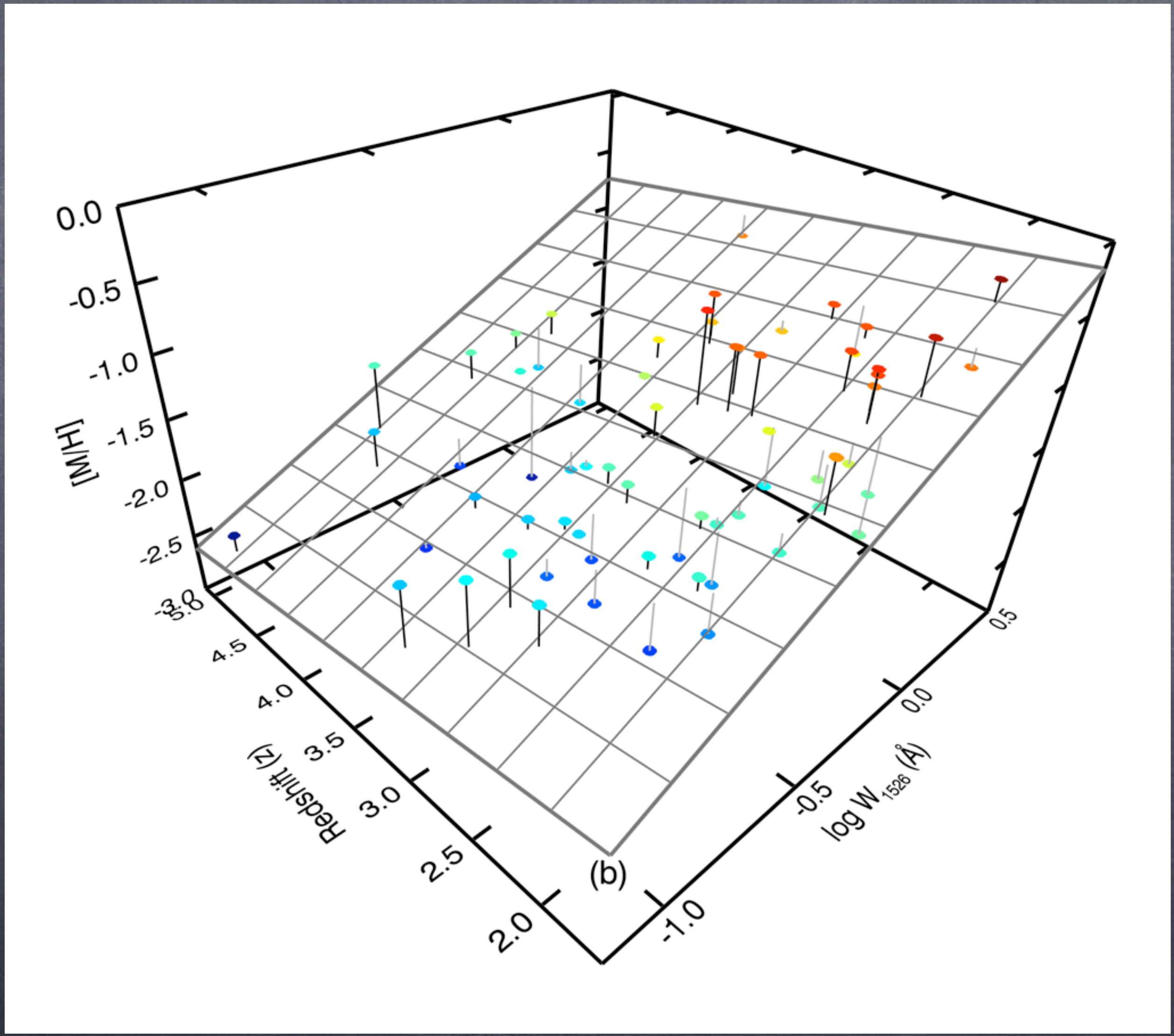
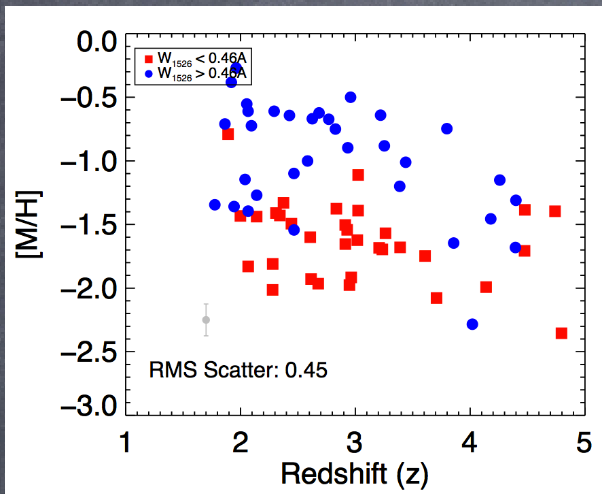


Second Fundamental Plane



Fundamental Plane



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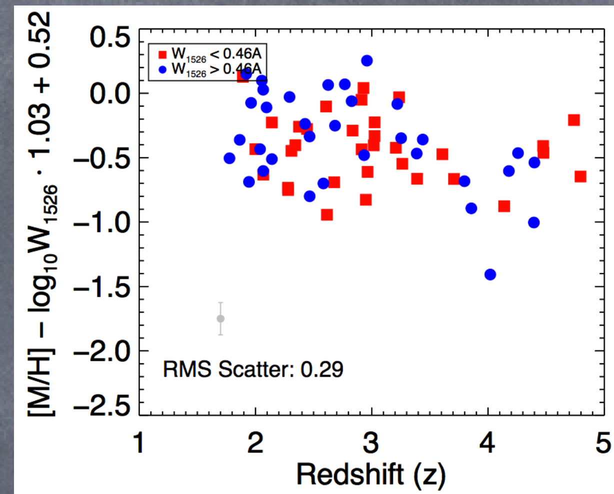
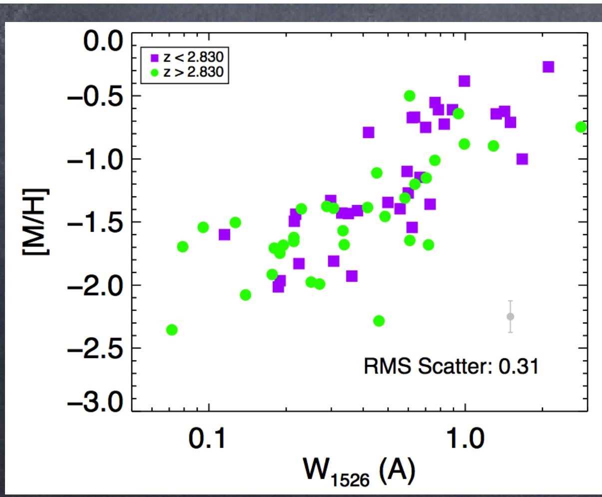


$$[\mathrm{M/H}] = (-0.47\pm0.14) + (1.1\pm0.3)\cdot\log \mathrm{W}_{1526} - (0.16\pm0.06)\cdot z$$



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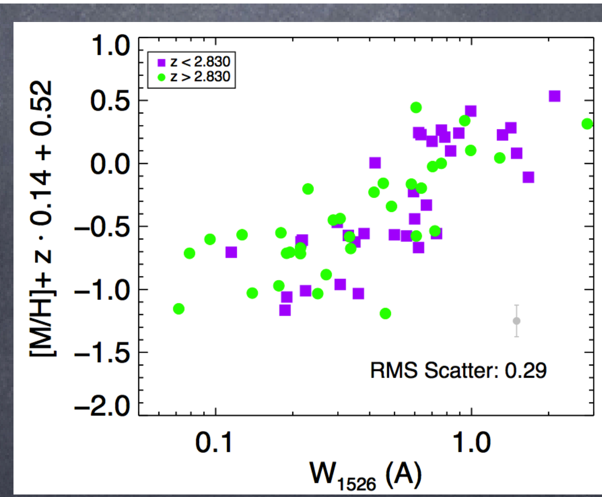
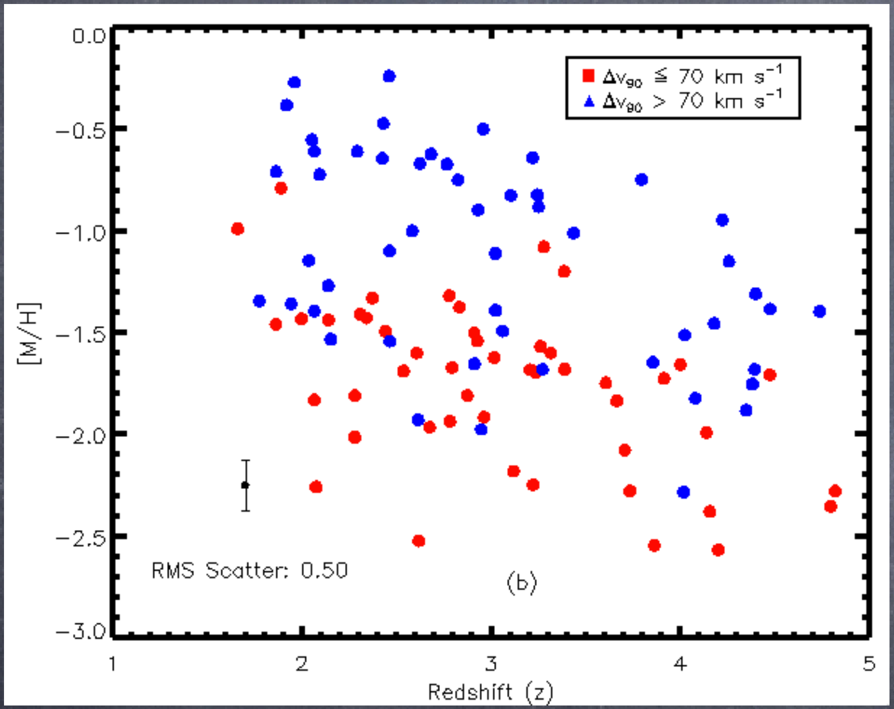


What is the physical reason for the existence of this plane?



- 1) At each redshift we find DLAs in a wide variety of dark matter halo masses.

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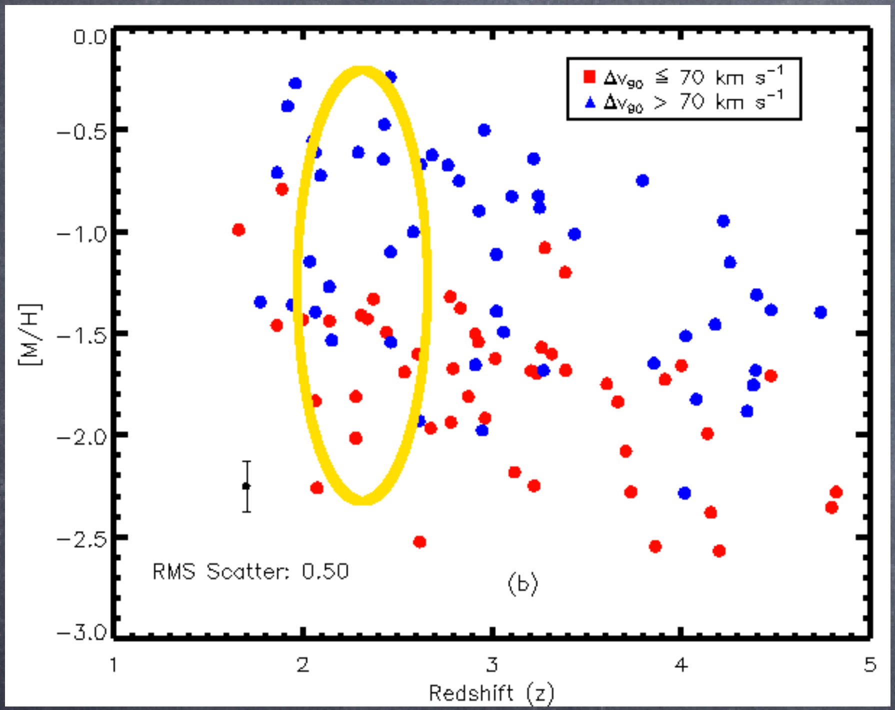

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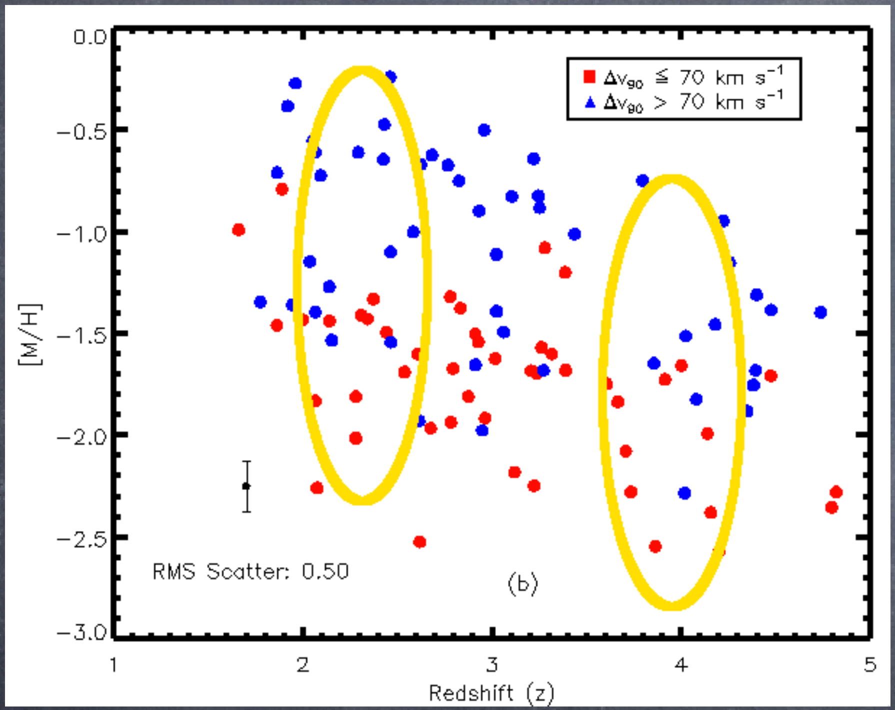

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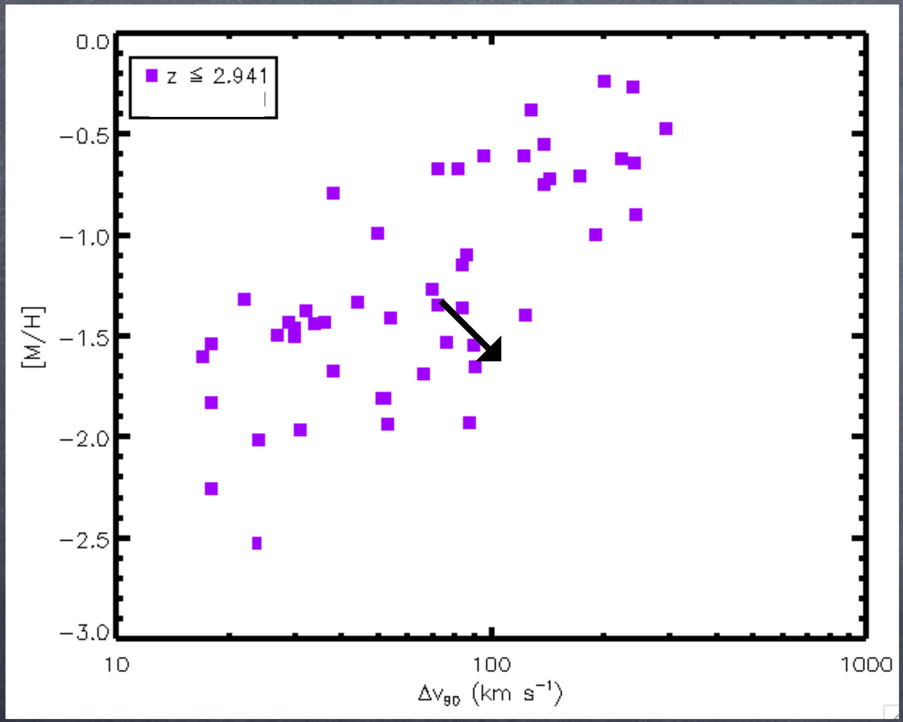

- 2) The kinematics-metallicity correlation evolves with redshift.

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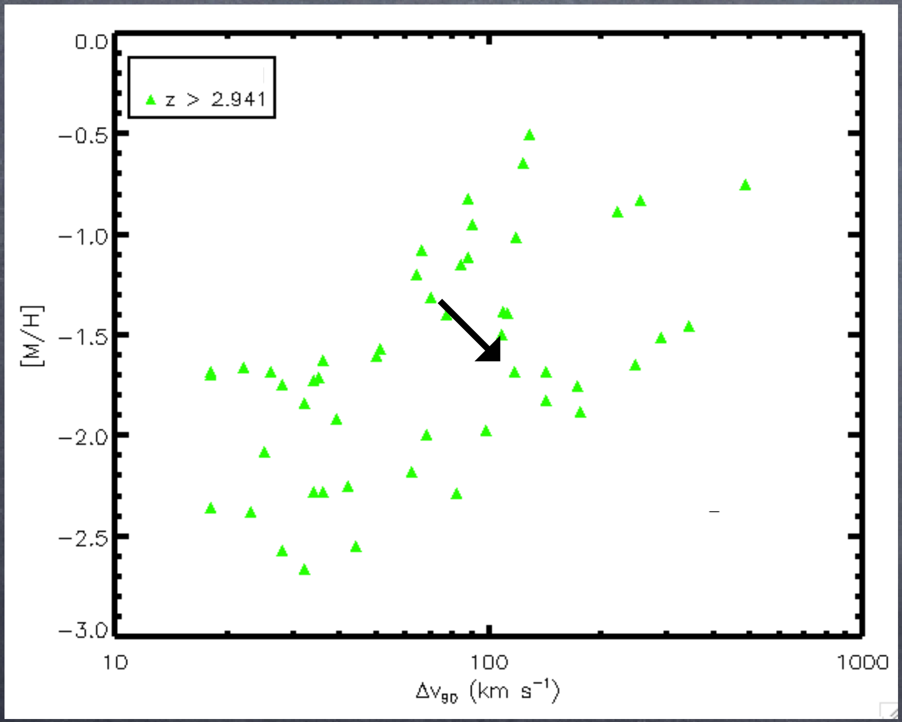

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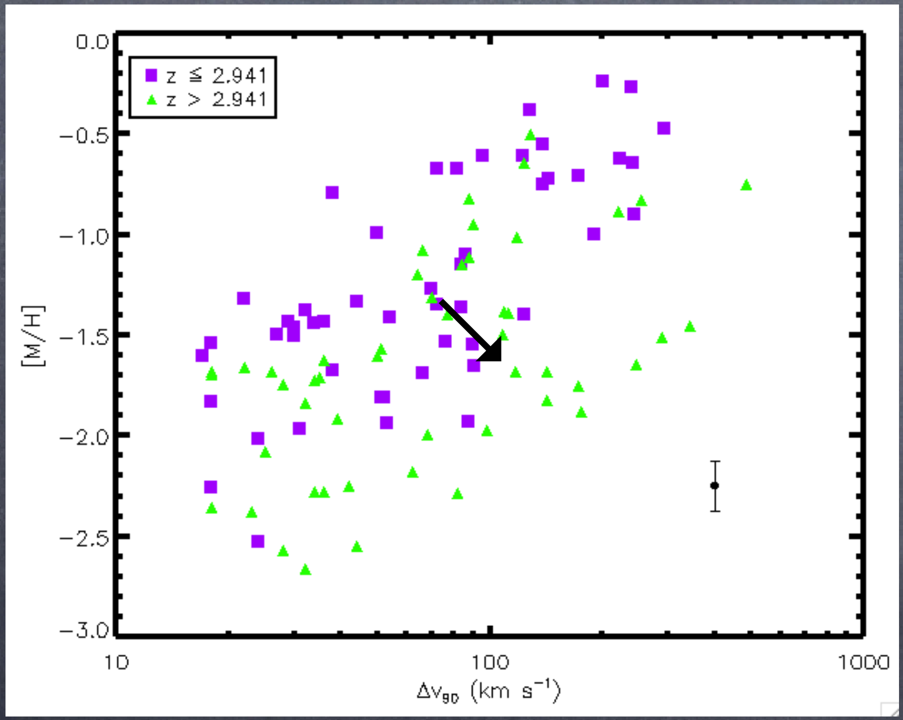
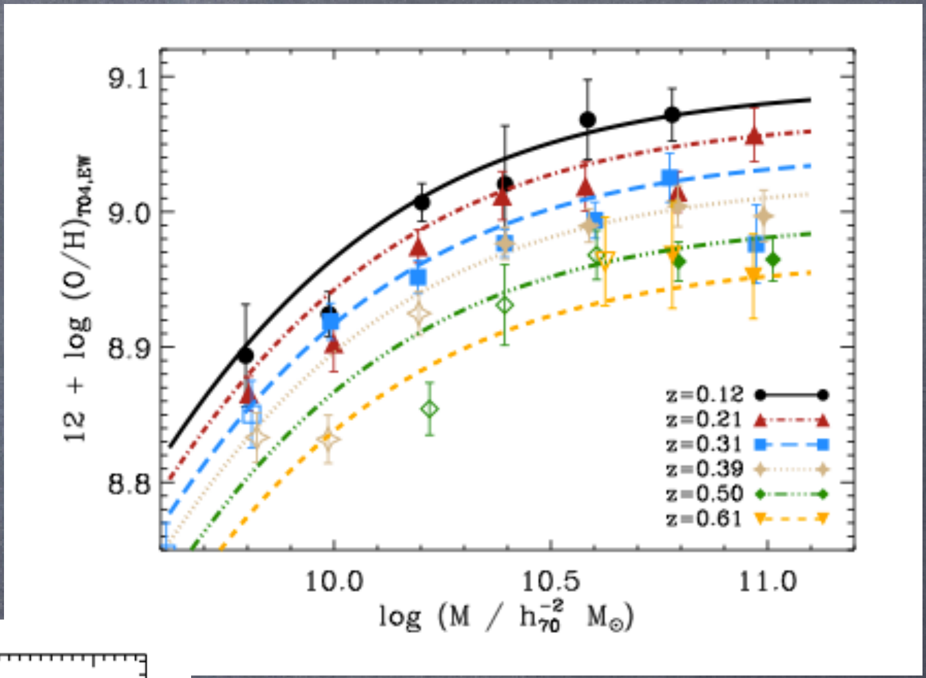


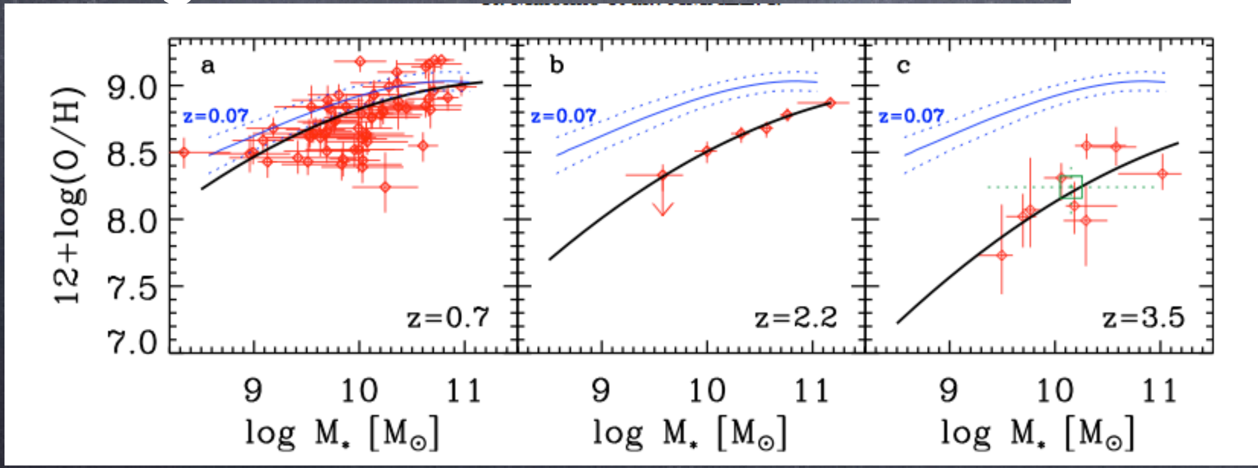
- 2) The kinematics-metallicity correlation evolves with redshift.

Evolution of the mass-metallicity correlation

- A similar evolution is seen for the mass-metallicity relation for galaxies.
- 0.3 dex/redshift for both DLAs and star-forming galaxies.



Moustakas et al. 2012

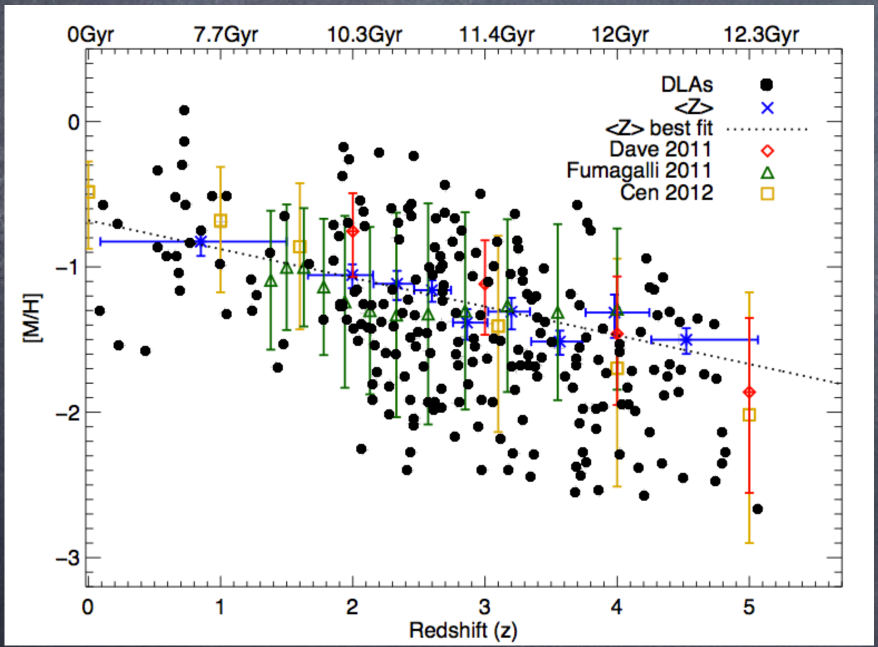


Maiolino et al. 2008

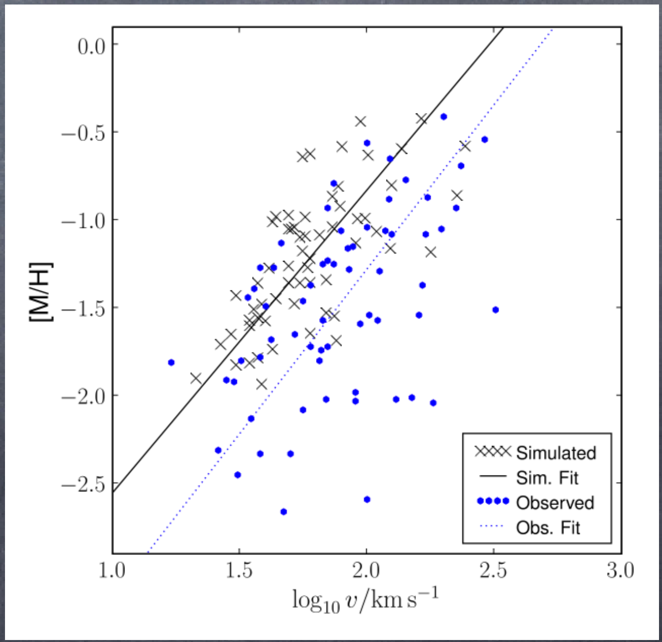
How does the fundamental plane constrain numerical models?

1) Both correlations should be reproduced simultaneously. according to:

$$[M/H] = (-1.9\pm0.5) + (0.74\pm0.21)\cdot\log\Delta v_{90} - (0.32\pm0.06)\cdot z$$



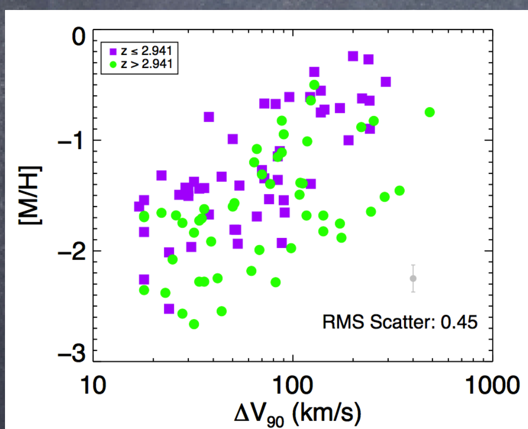
Rafelski et al. 2012



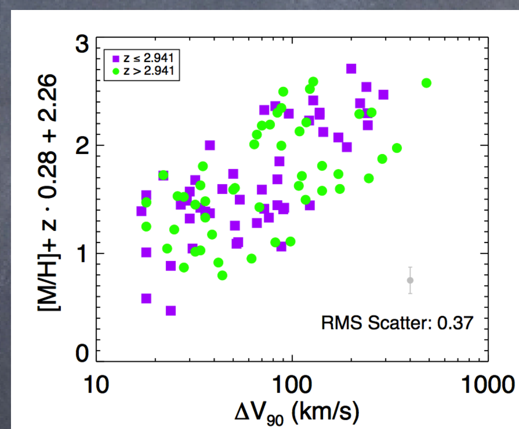
Pontzen et al. 2008

How does the fundamental plane constrain numerical models?

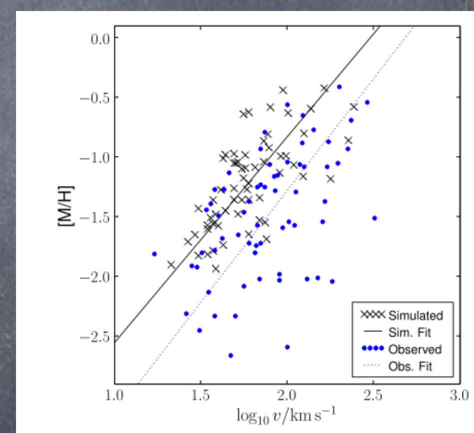
2) The scatter in the numerical simulations needs to be smaller than previously expected.



scatter ~ 0.45 dex



scatter ~ 0.37 dex



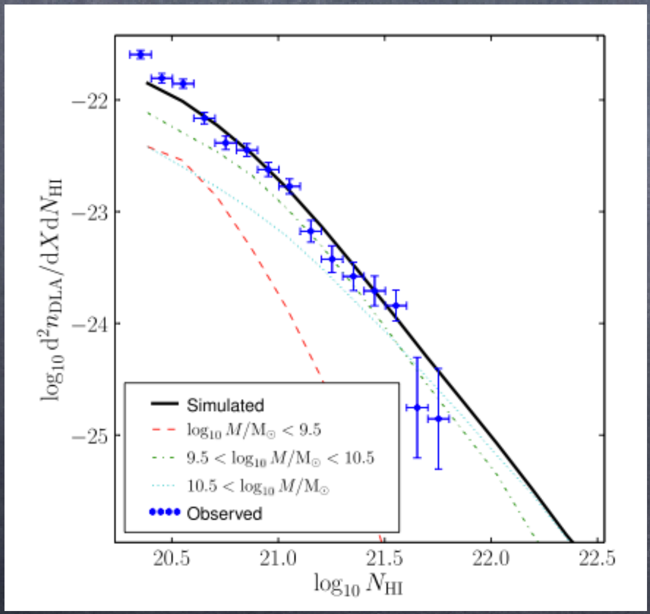
Pontzen et al. 2008

scatter ~ 0.27 dex

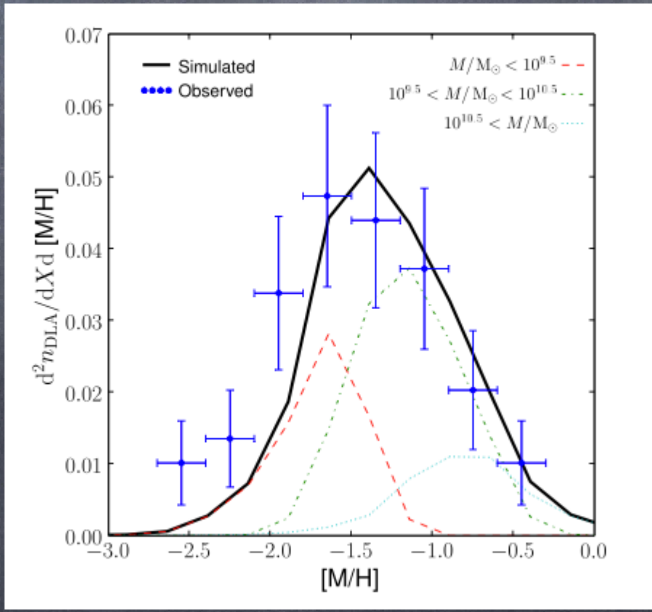
How does the fundamental plane constrain numerical models?

3) Any numerical model will need to populate all of the plane (the distributions need to match)

$f(N_{HI},X)$

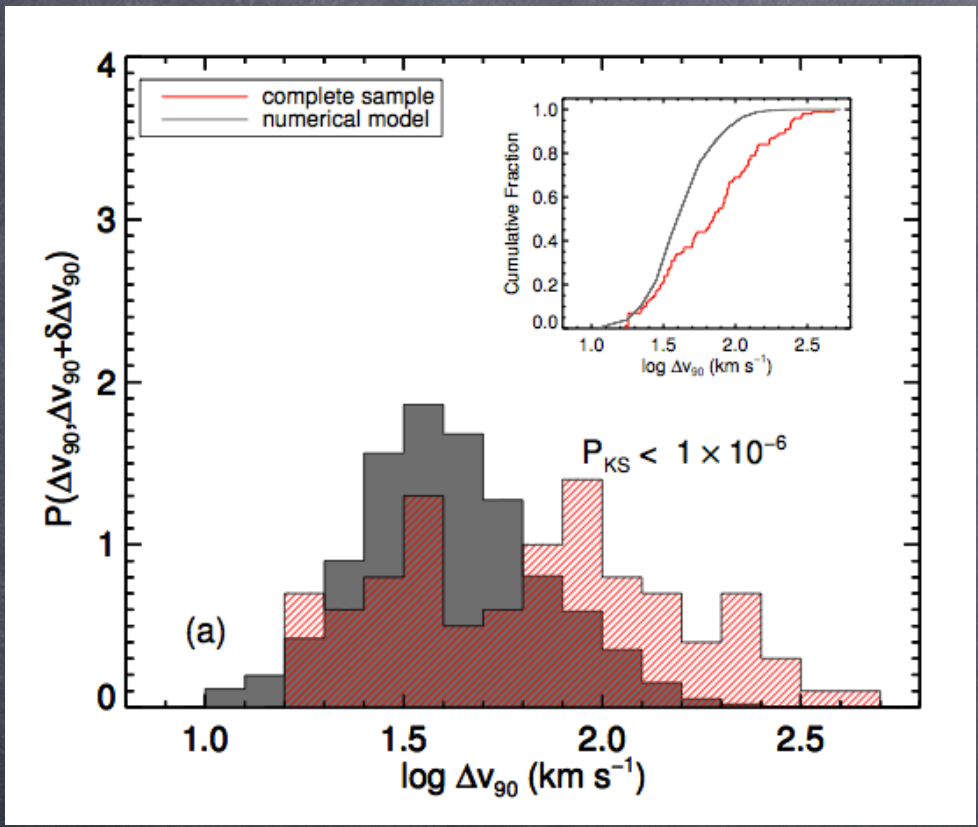


[M/H]



Pontzen et al. 2008

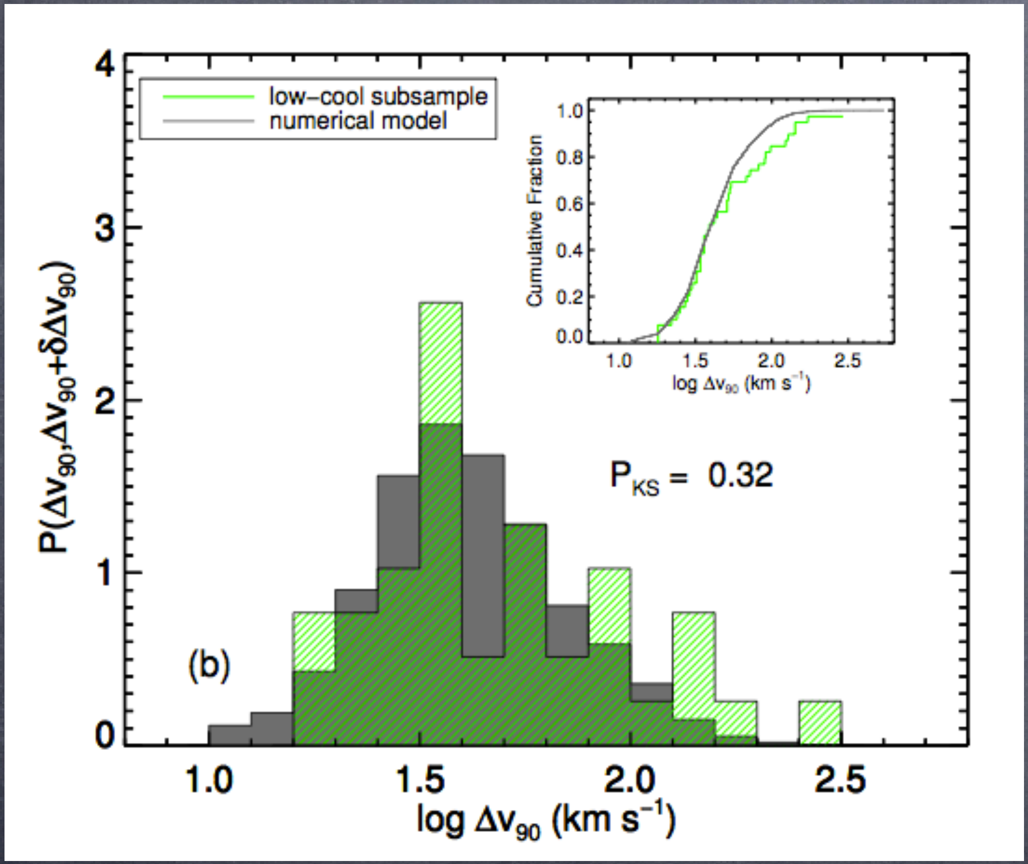
The Velocity Width Distribution



- The distribution has a large 'tail' toward high velocity width systems
- The median velocity width is high (~ 70 km/s)

Need relatively more DLAs in massive dark matter halos

The Velocity Width Distribution



- The simulations reproduce the velocity width distribution of the low cool DLAs
- This supports the hypothesis that simulations do not produce enough DLAs in massive halos.

Galactic scale outflows could provide the solution.

Summary

- The distributions and correlations between the parameters measured for DLAs provide information about the gas surrounding galaxies at high redshift.
- The existence of a fundamental plane between redshift, metallicity and ΔV_{90} indicates that the kinematics-metallicity relationship for DLAs is evolving with redshift in a similar manner as is seen for the mass-metallicity relationship for star-forming galaxies.
- Currently, simulations are able to simulate parts of the fundamental plane, but not all of the plane. This is thought to be due to the inability in reproducing enough DLAs in massive dark matter halos.