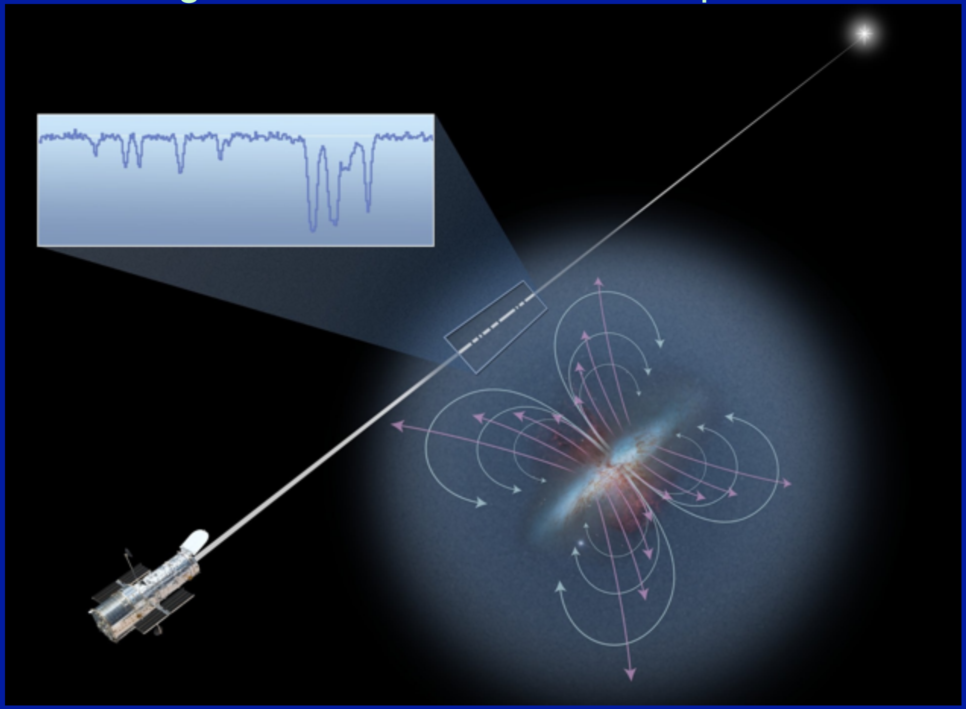
Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Evidence that the Cool/Warm CGM is Self-Similar with Halo Mass

Chris Churchill
New Mexico State University

Collaborators:
Nikki Nielsen (NMSU)
Glenn Kacprzak (Swinburne)
Sebastian Trujillo-Gomez (NMSU)
Michael Murphy (Swinburne)

Probing the CGM with QSO Absorption Lines



Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

MgII λλ2796,2803

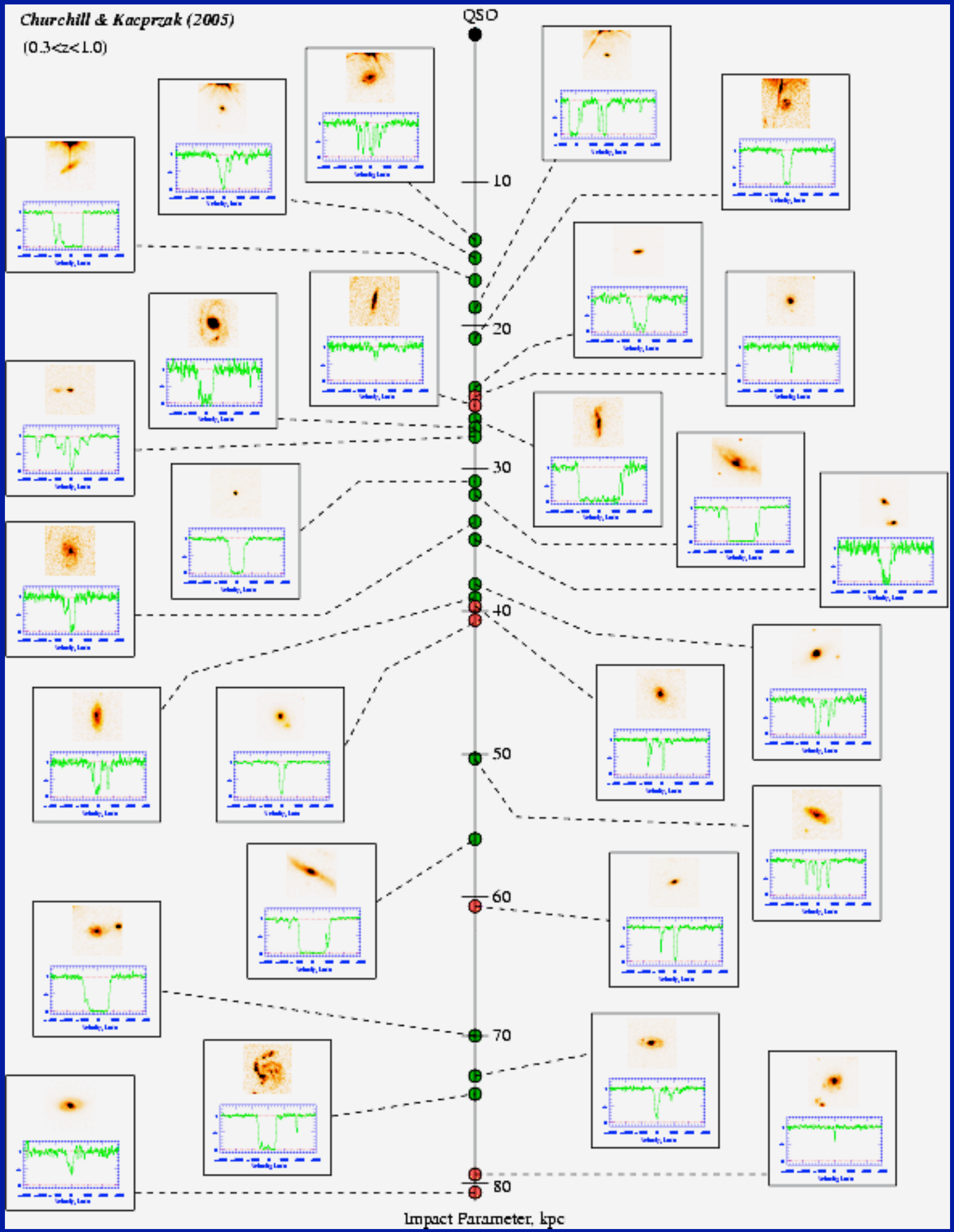
Very strong resonance doublet observable from the ground for z=0.2 to z=2.5

Established since 1991 to probe metal-enriched CGM gas out to ~150 kpc or more

Detects gas structures over five+ decades of N(HI), from $10^{15.5}$ to $10^{21.5}$ cm^{-2}

- wide range of astronomical phenomenon: winds, filamentary infall, co-rotating accretion..

For z<1, galaxies easily observed with 3-4 meter class telescopes



Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

MAGIICAT

MgII Absorber-Galaxy Catalog

Nielsen+ (2013) MAGIICAT I: arXiv:1304.6716
MAGIICAT II: arXiv:1211.1380

http://astronomy.nmsu.edu/cwc/Group/magiicat/

- 182 spectroscopically identified galaxies
- $0.07 < z < 1.1$
- $D < 200$ kpc of background quasars
- MgII coverage in optical quasar spectra
- standardized to ΛCDM "737" cosmology

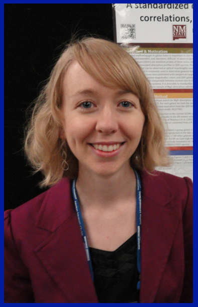
Masses Paper (Letter):
Churchill, C.W., Nielsen, N.M, Kacprzak, G.G., & Trujillo-Gomez, S. 2013, ApJ, 763, L42

Orientation Paper:
Kacprzak, G.G., Churchill, C.W., & Nielsen, N.M, 2012, ApJ, 760, L7

Major contributions from surveys

Steidel+ 1994
Bergeron+ 1997
Chen+ 2010
Kacprzak+ 2011

2 decades of data… compiled, standardized, and analyzed …



Nikki Nielsen

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

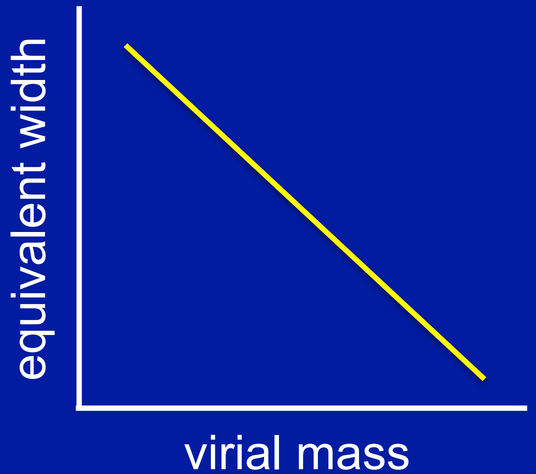
Expectations with virial mass

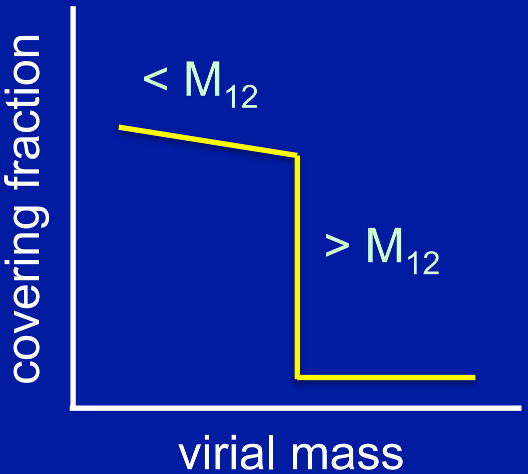
Halos with $M_h > M_{12}$ dominated by hot mode accretion; MgII should not survive
- smaller $W_r(2796)$
- vanishing covering fraction

Halos with $M_h < M_{12}$ dominated by cold mode accretion; MgII should survive
- larger $W_r(2796)$
- large covering fraction

$M_{12} = 10^{12}\ M_\odot$

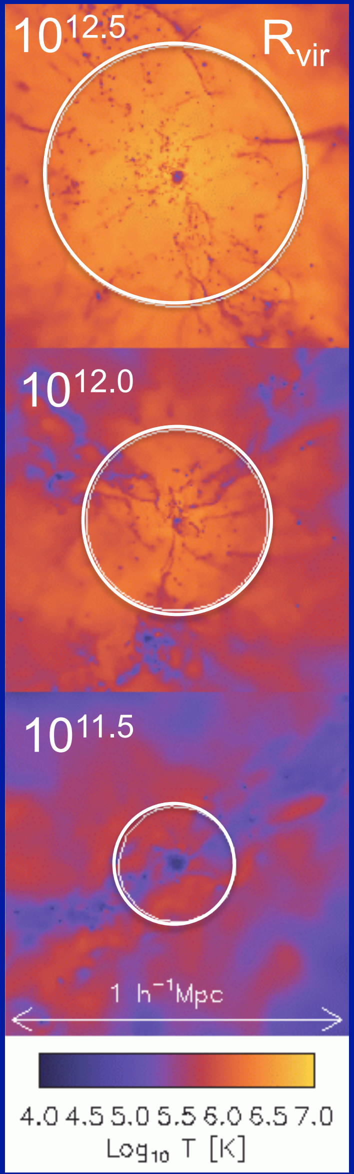
"Cold" = cool/warm gas $T<10^{4\text{-}5}$ K
MgII typically in $T=3\times10^4$ K gas





Theory/Simulations
- Birnboim/Dekel 03,06
- Keres+ 05,09
- Van de Voort+ 11,12
- + many others

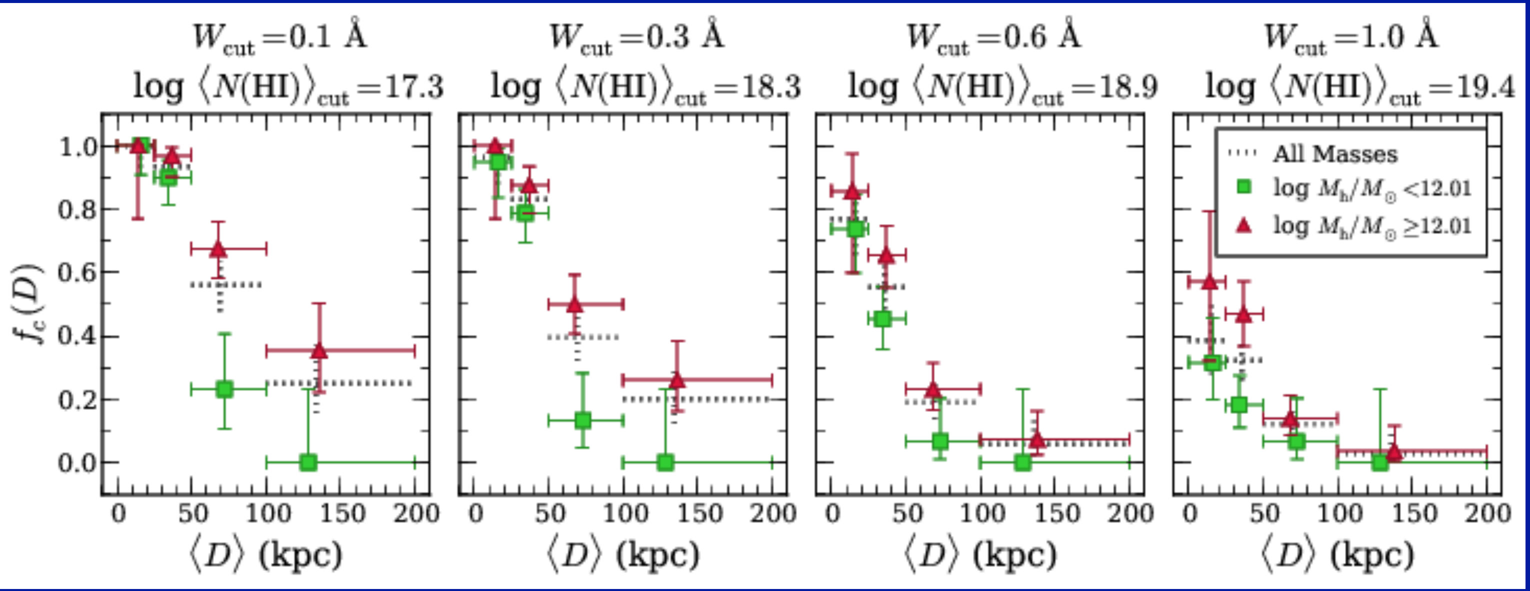
Halo Models
- Mo & Miralde-Escude (1996)
- Chen & Tinker (2010)
- Maller & Bullock (2004)
- + others



van de Voort + Schaye (2011)

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Observations of MgII covering fraction and virial mass

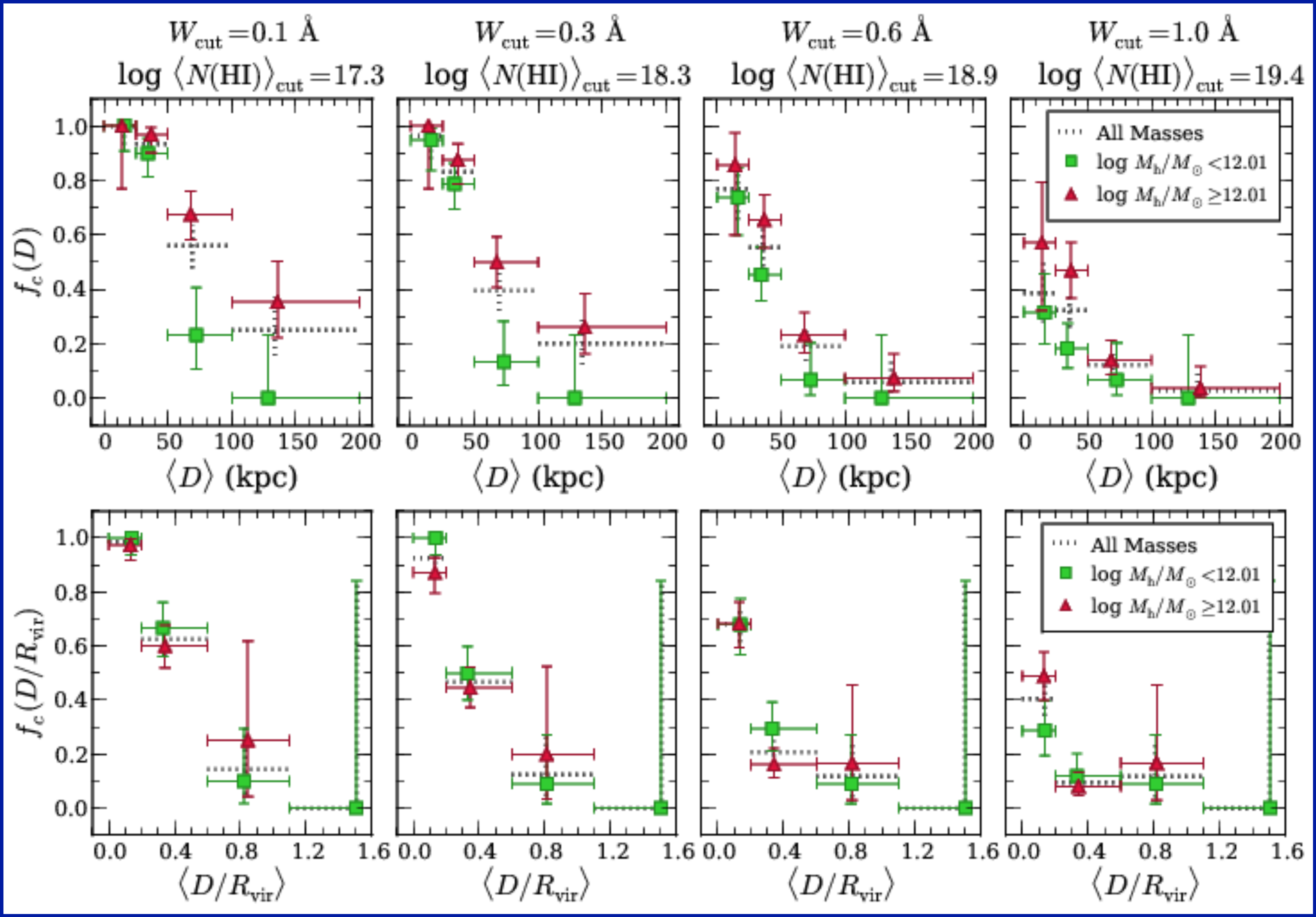


- Covering fraction decreases with increasing impact parameter (D)
- Higher mass halos have larger $f_c(D)$ for $W_r>0.1$ and $W_r>0.3$ Ang absorption
- The $f_c(D)$ is similar for $W_r>0.6$ Ang absorption
- The $f_c(D)$ is higher at smaller D for $W_r>1.0$ Ang
- Low mass halos exhibit $f_c(D)=0$ for D>100 kpc

Define $\eta_v = D/R_{vir}$

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Observations of MgII covering fraction and virial mass

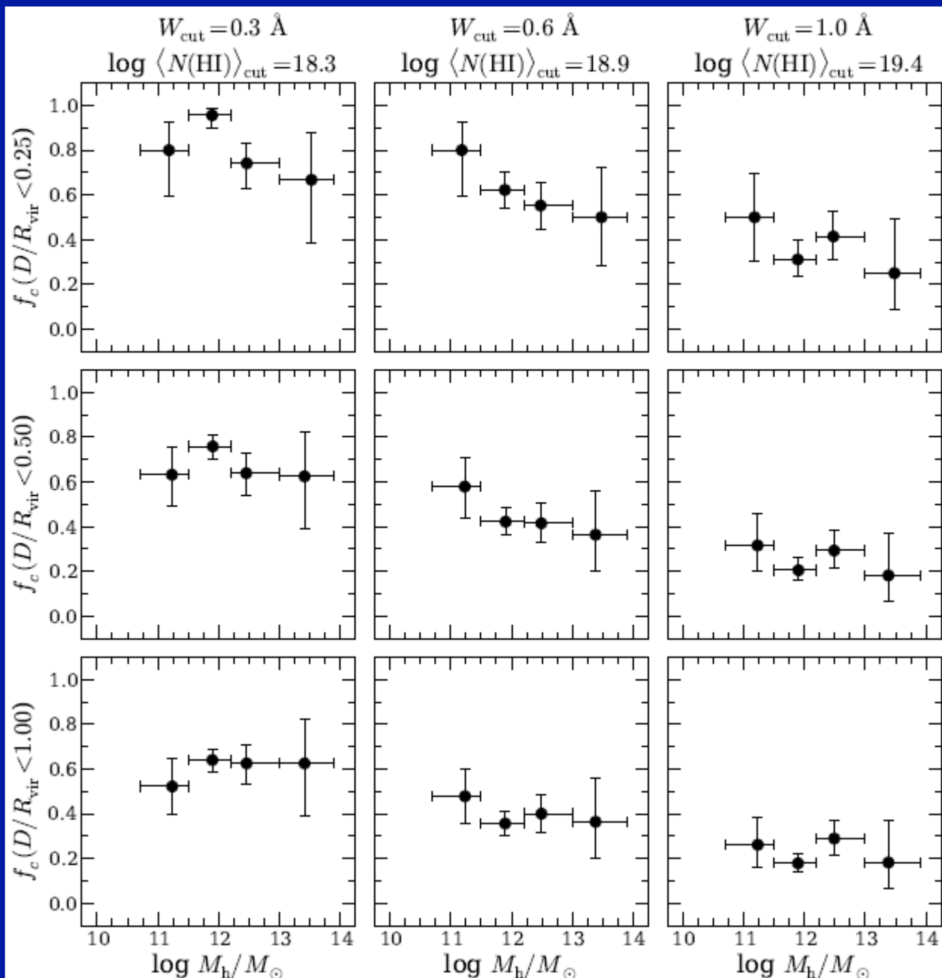


$f_c(\eta_v)$ is "self-similar" with halo mass

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

MgII covering fraction vs. halo mass

$f_c(\eta_v)$ as a function of virial mass



$\eta_v <$ 0.25

$\eta_v <$ 0.50

$\eta_v <$ 1.0

$f_c(\eta_v)$ decreases with increasing $W_r(2796)$ absorption threshold

No precipitous drop in $f_c(\eta_v)$ for $M_h > M_{12}$

Covering fraction is effectively constant with virial mass out to virial radius

TENSION:

Chen/Tinker (2010)

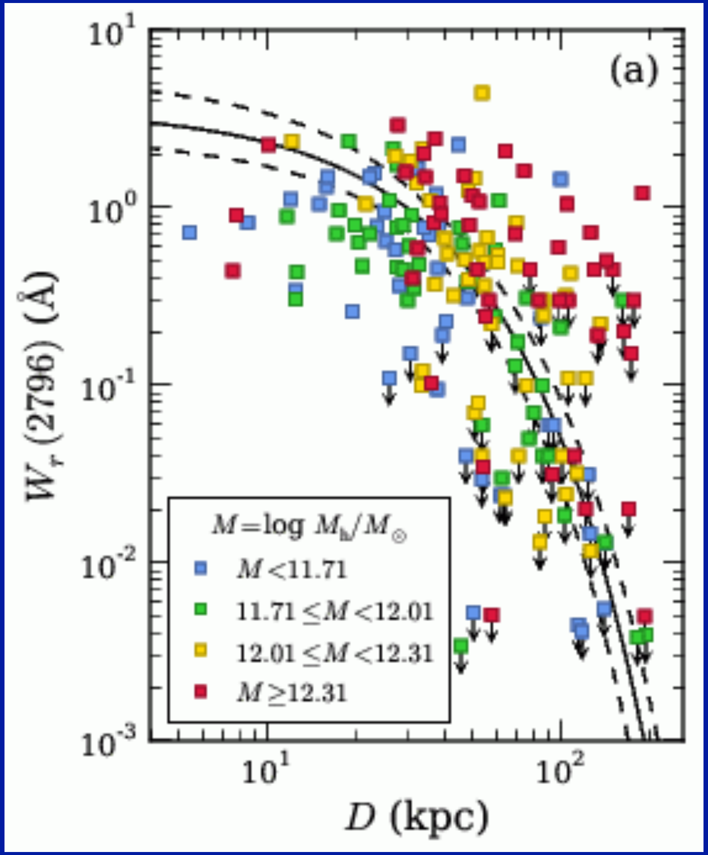
Maller/Bullock (2004)

Stewart (2011)

Winds? Recycling?

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

The W_r-D plane



- ~8 σ anti-correlation
- much scatter

WHAT IS SOURCE OF SCATTER?

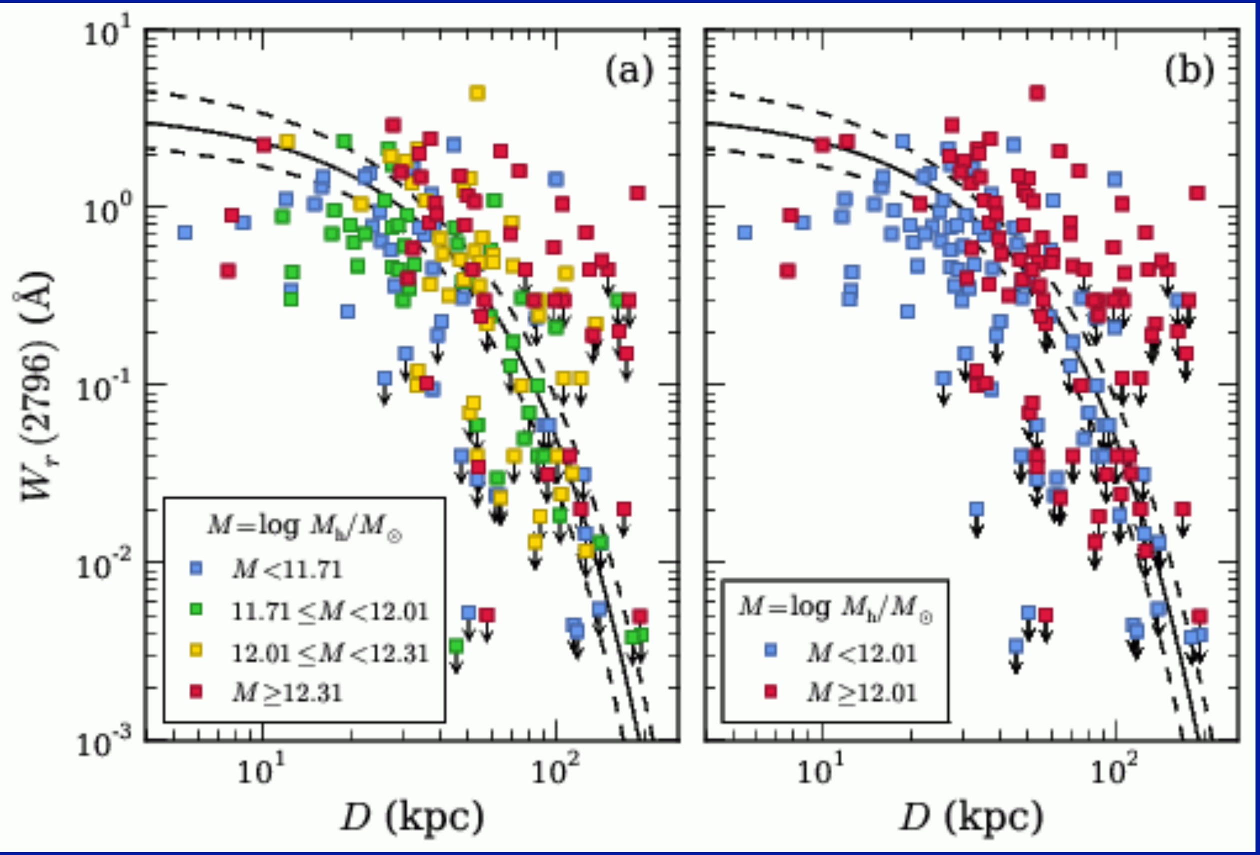
Inclination..........(Kacprzak+ 2011)
M_B, sSFR...................(Chen+ 2010)

SYSTEMATIC
VIRIAL MASS SEGREGATION

higher mass halos exhibits a larger MgII absorption strength at greater D, on average

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

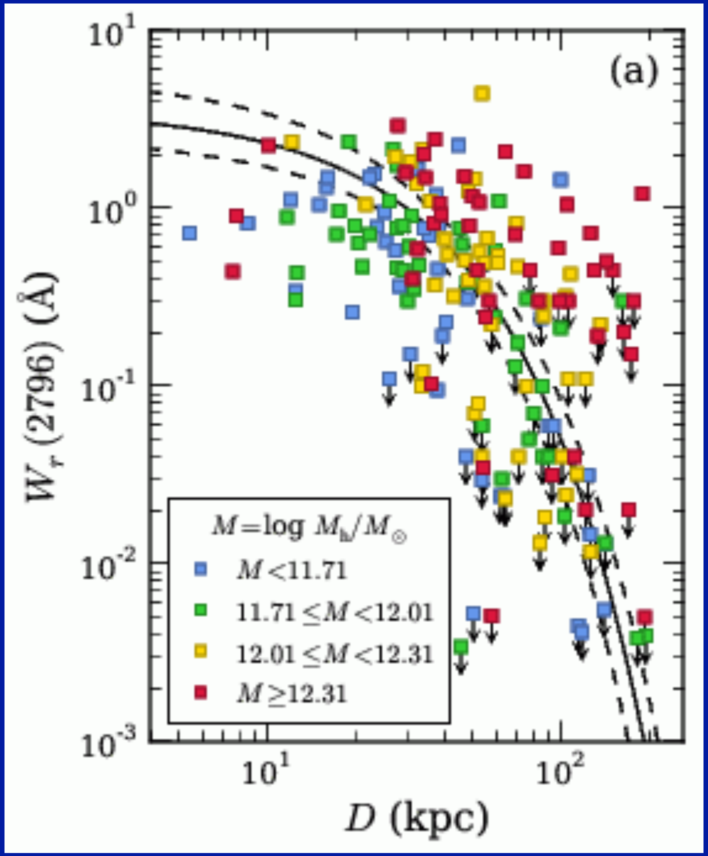
The W_r-D plane



Clearer if sample split at median halo mass… 2DKS test yields 4σ

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

The W_r-D plane



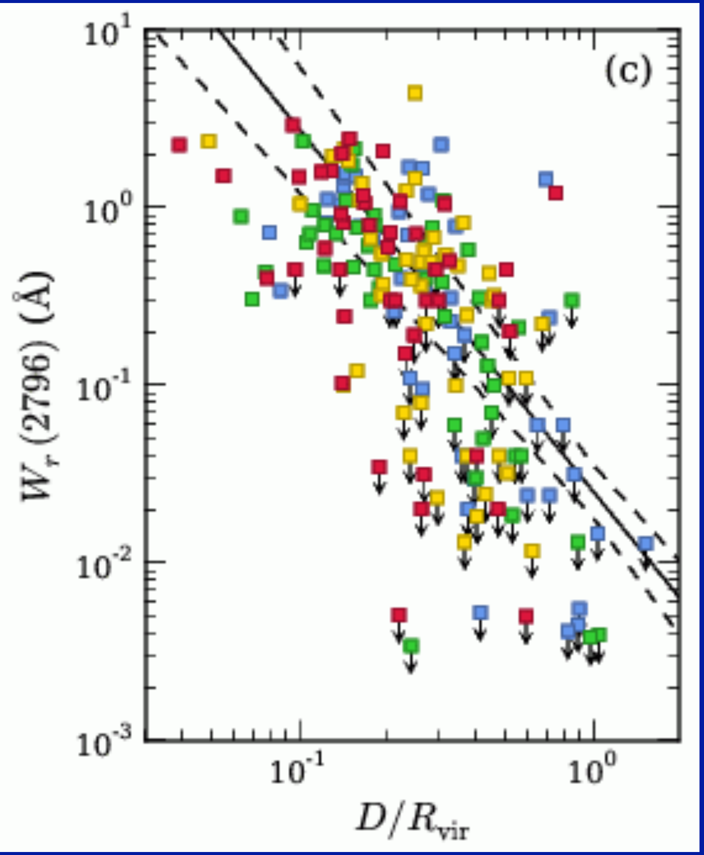
$R_{vir} \sim M_h^{1/3}$

IS THE FRACTIONAL PROJECTED DISTANCE RELATIVE TO THE VIRIAL RADIUS, $\eta_v = D/R_{vir}$, A FUNDAMENTAL PARAMETER?

Does the W_r-η_v plane provide the fundamental insight into the behavior of the CGM with projected galactocentric distance?

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

The W_r-η_v (D/R_{vir}) plane



The projected $W_r(2796)$-η_v profile is a tight inverse square power law out to the virial radius

$$W_r(2796) \sim \eta_v^{-2}$$

The scatter is reduced at the 13σ significance level and there is no systematic segregation of virial mass. The projected profile is the same regardless of virial mass.

SELF-SIMILARITY OF THE CGM

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Behavior of $W_r(2796)$ with M_h and D

$R_{vir} \sim M_h^{1/3}$ ← General scaling

$W_r(2796) \sim \eta_v^{-2}$ ← Fit to $W_r(2796)$ vs D/R_{vir}

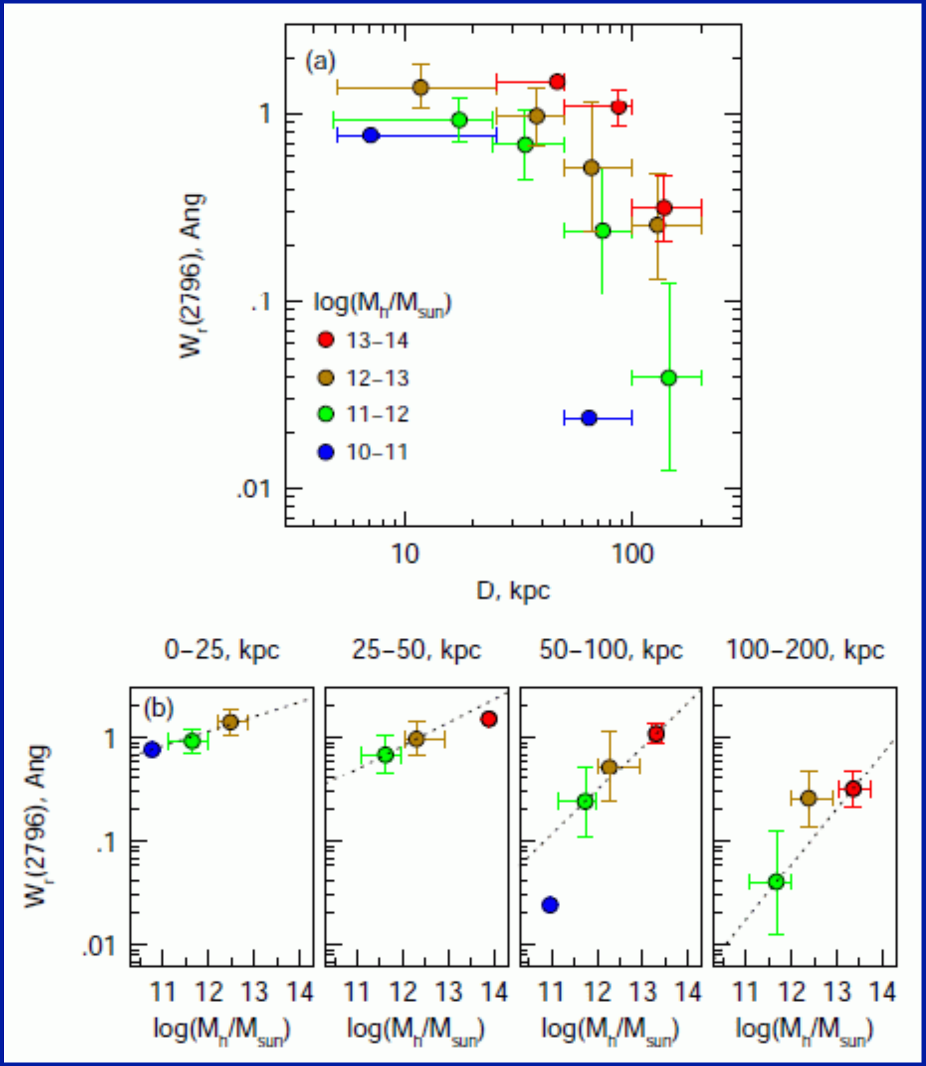
$W_r(2796) \sim D^{-2} M_h^{2/3}$ ← Deduced

We would expect to see that at fixed impact parameter

$W_r(2796)$ will *increase* with virial mass

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Mean $W_r(2796)$ vs. D in M_h decades



In finite impact parameter ranges, the mean $W_r(2796)$ is larger in higher mass halos

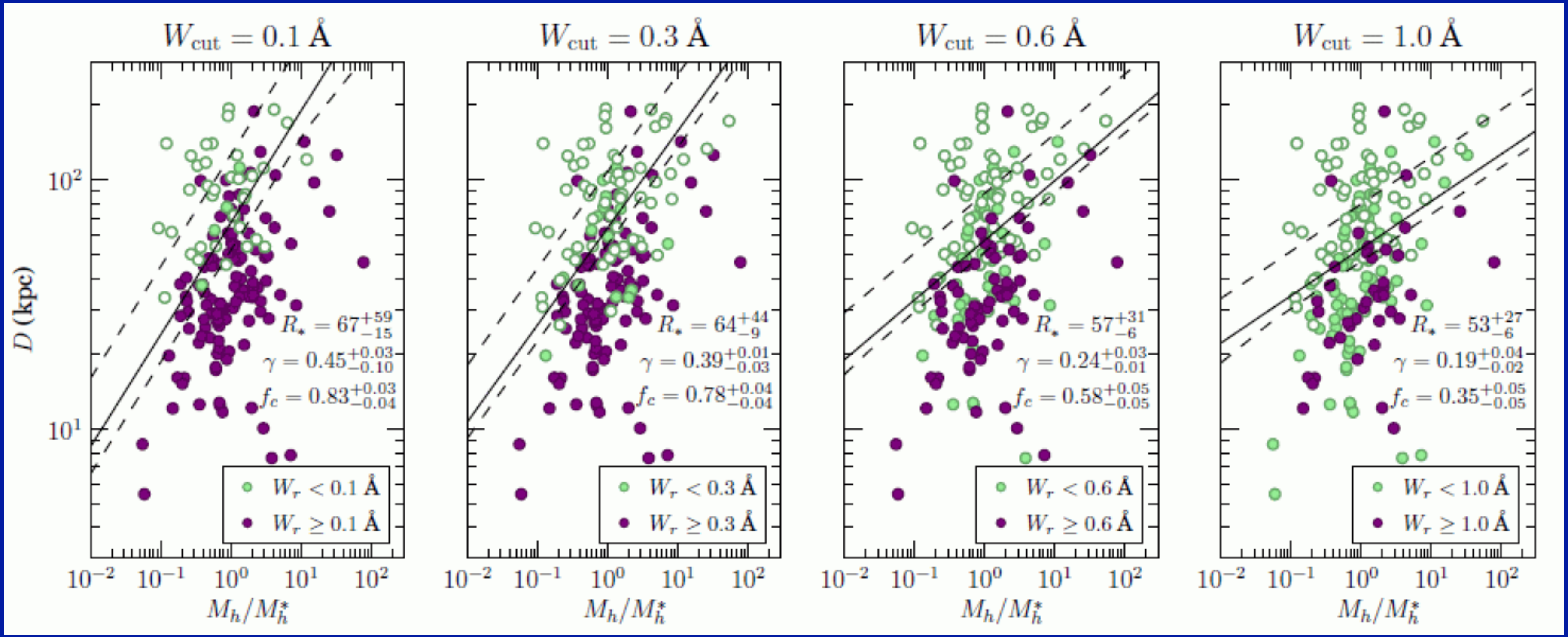
The mean $W_r(2796)$ shows power law dependence with halo mass

The fits are to the unbinned data and include upper limits

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

$R(M_h)$ – "absorption radius"

$$R(M_h) = R_*(M_h/M_*)^{\gamma}$$



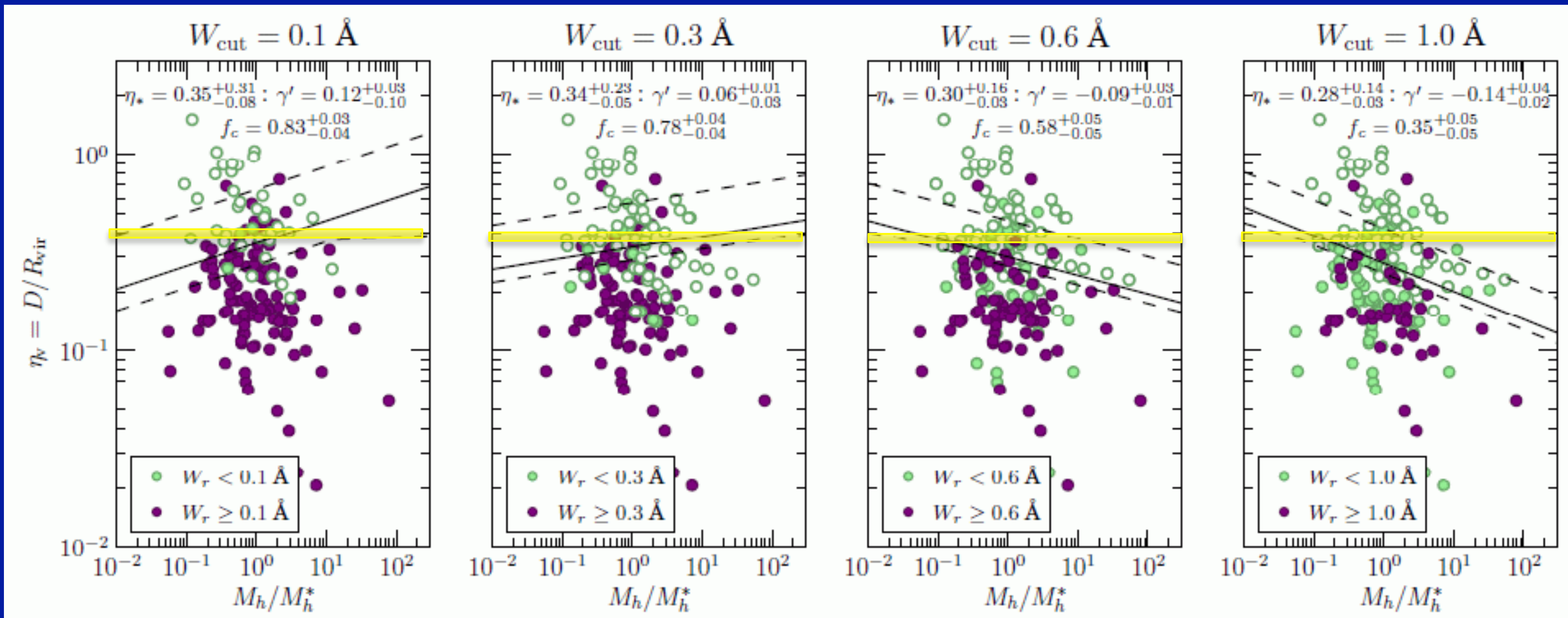
The absorption radius is more extended around higher mass galaxies.

The decrease in R_* and γ with increasing absorption threshold reflects decreasing covering fraction with higher absorption threshold

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

$\eta_v(M_h)$ – "mass-weighted absorption envelope"

$$\eta(M_h) = \eta_*(M_h/M_*)^{\gamma'}$$

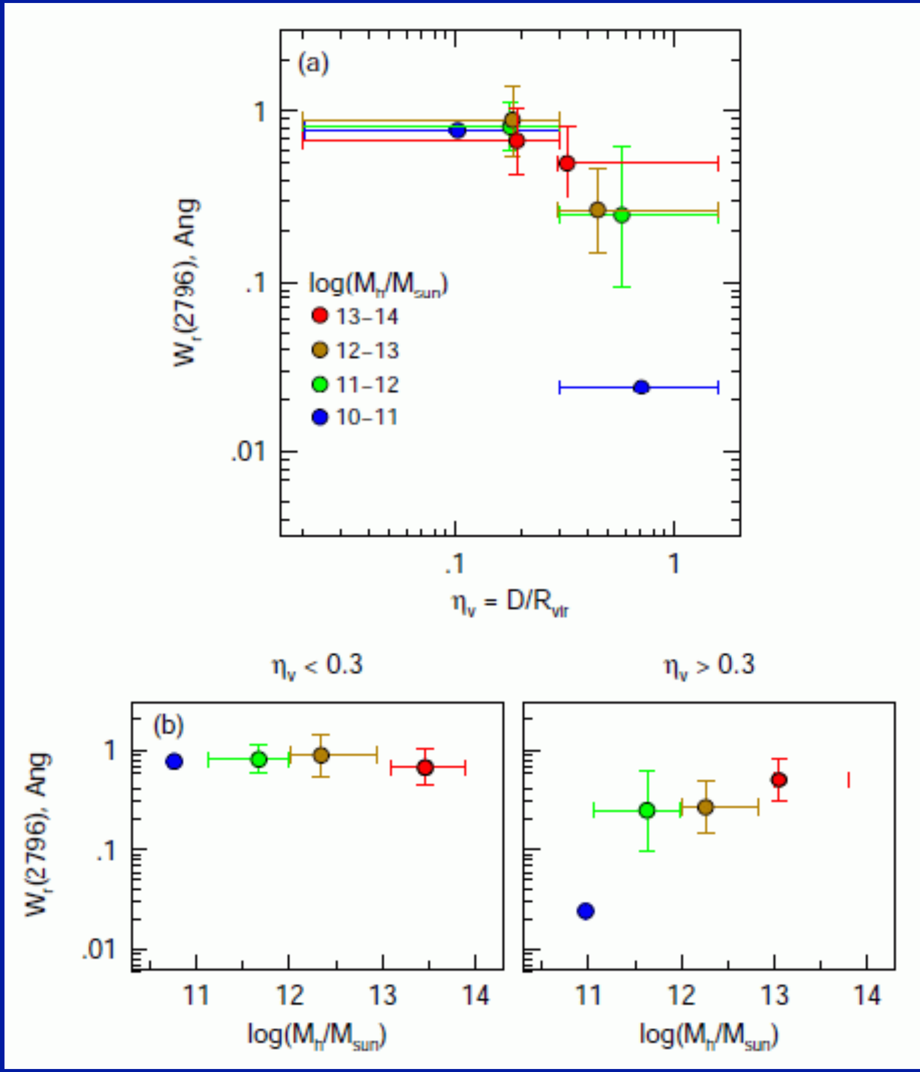


Very flat dependence with virial mass
η_*~0.3 for all absorption thresholds

Majority of cool/warm absorbing gas arises within inner 30% of virial radius

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Mean $W_r(2796)$ vs. η_v in M_h decades



For $\eta_v < 0.3$, the mean $W_r(2796)$ is independent of virial mass

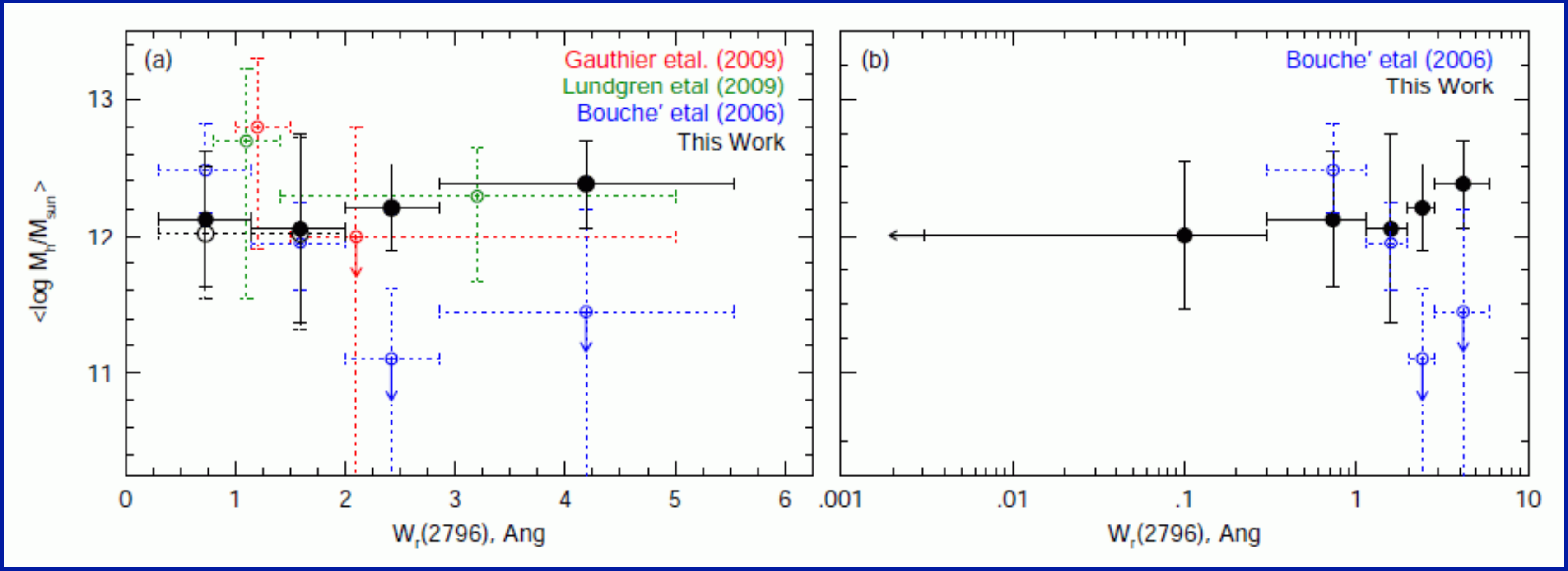
Consistent with a $W_r(2796)$ radial profile independent of virial mass

For $\eta_v > 0.3$, the mean $W_r(2796)$ is suggestive of being independent of virial mass, but is less definitive

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Mean $W_r(2796)$ vs mean M_h

Using LRG absorber cross-correlation techniques, several teams have suggested a general anti-correlation between $W_r(2796)$ and virial mass

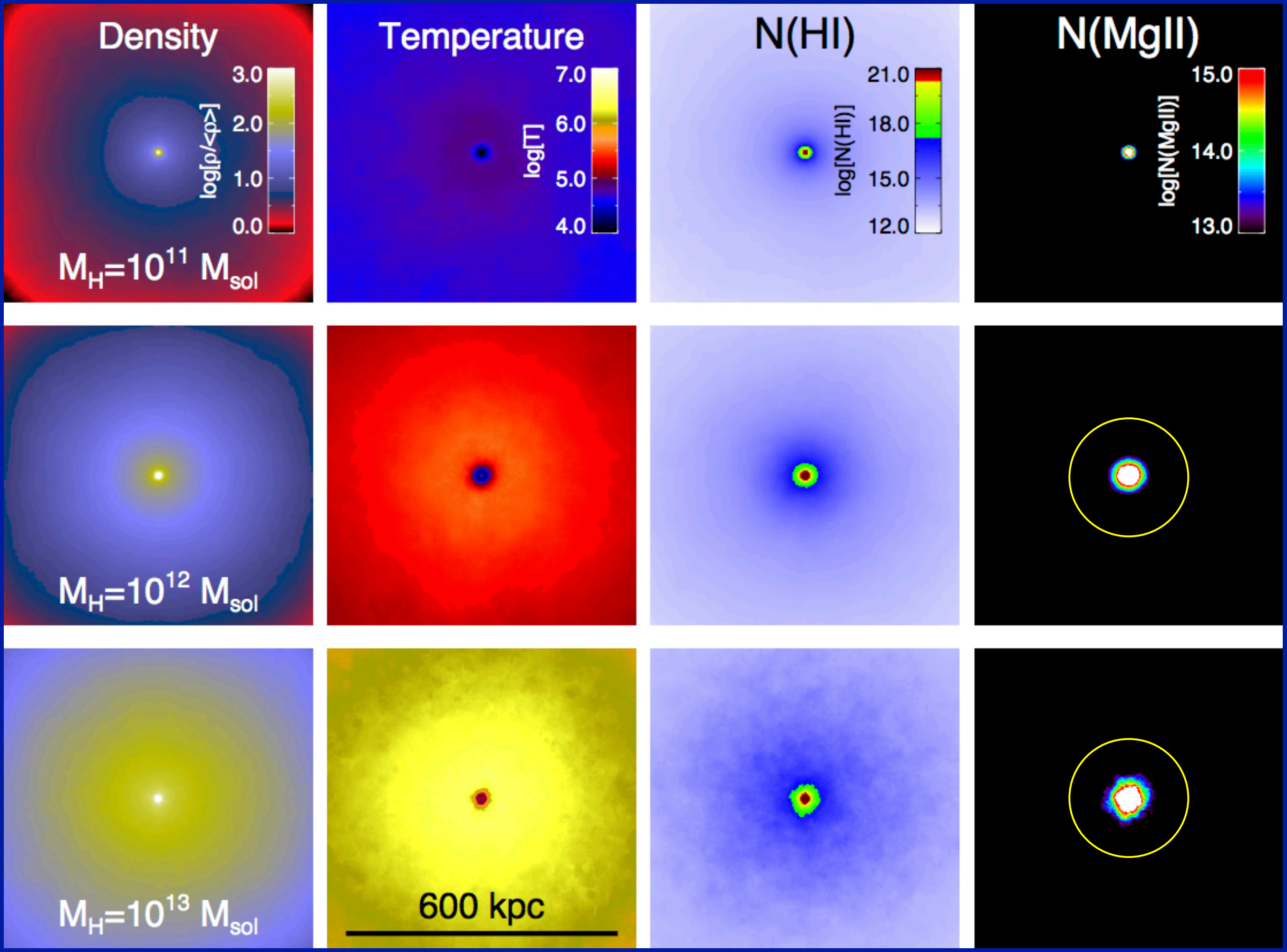


There is no correlation or anti-correlation between mean $W_r(2796)$ and virial mass when all impact parameters are included;

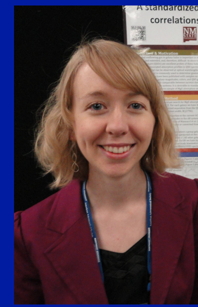
even down to the smallest absorbing structures (panel b)

Work by Amanda Ford 2013

N(MgII) halo sizes vs mean M_h



MgII CGM Kinematics



Paper IV: Nikki Nielsen+, in prep

check it out!

For ~75 of the galaxies, the MgII absorption is measured with HIRES/Keck or UVES/VLT high-resolution spectra; ~50 are detections that provide kinematics at ~6 km s^{-1} resolution

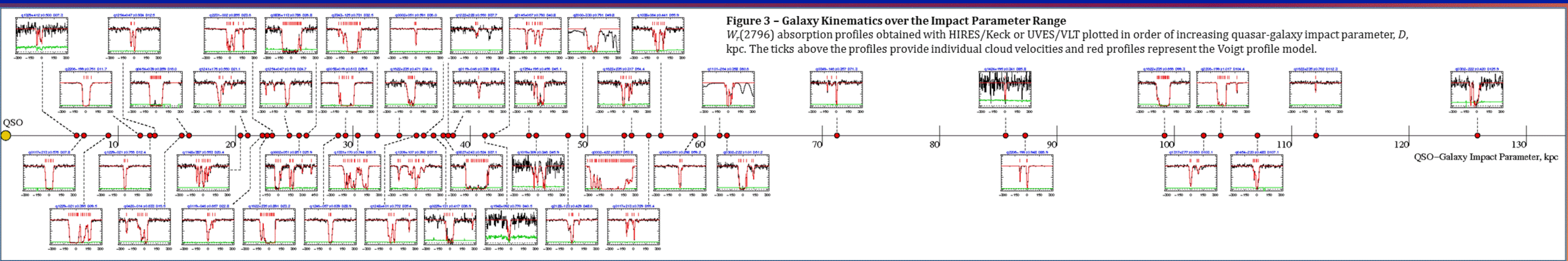


Figure 3 – Galaxy Kinematics over the Impact Parameter Range
$W_r(2796)$ absorption profiles obtained with HIRES/Keck or UVES/VLT plotted in order of increasing quasar-galaxy impact parameter, *D*, kpc. The ticks above the profiles provide individual cloud velocities and red profiles represent the Voigt profile model.

All profiles have been Voigt Profile modeled -> column densities, b parameters, velocities

Will exam: galaxy

impact parameter

f(N) distribution — $\eta_v = D/R_{vir}$

f(b) distribution — with — luminosity

f(Δv) distribution — color

virial mass

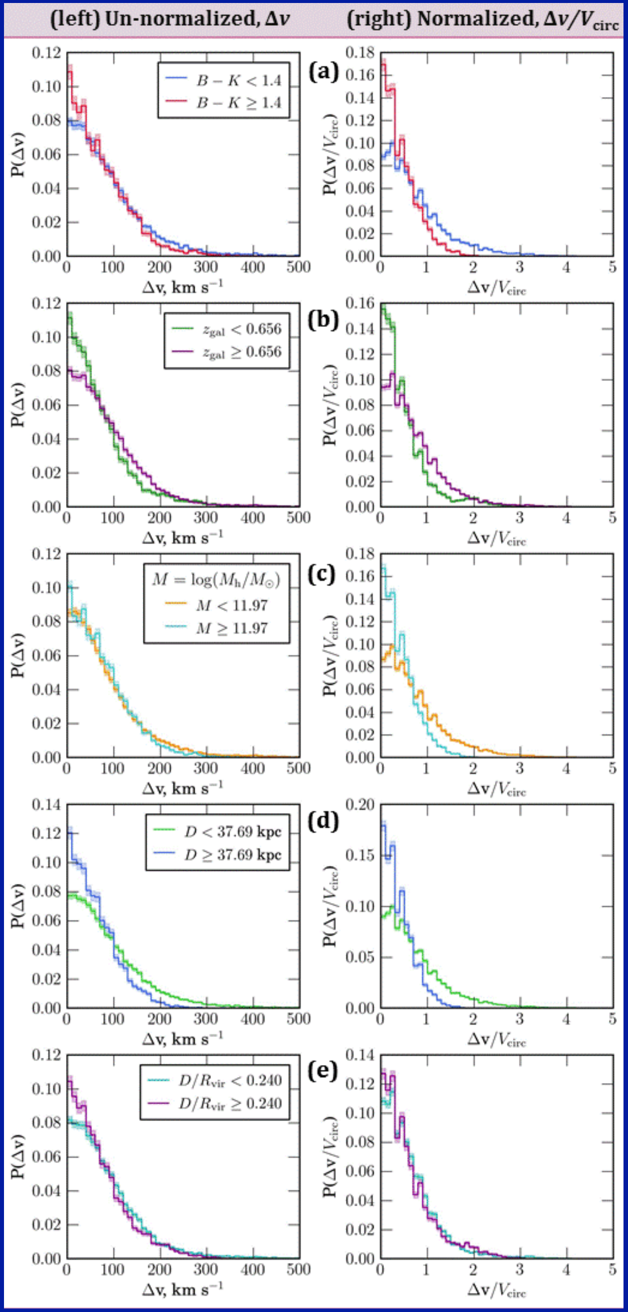
redshift

Paper IV: Nielsen+, in prep

TPCF, f(Δv)

TPCF = two-point correlation function

cloud-cloud Δv



Bluer galaxies have higher velocity dispersion relative to V_{circ} (mass normalized)

Higher z galaxies have higher velocity dispersion (absolute and mass normalized)

Lower M_h galaxies have higher velocity dispersion, but only when mass normalized

Inner regions of CGM has higher velocity dispersion (absolute and mass normalized)

Velocity dispersion independent of η_v= D/R_{vir} for both absolute and mass normalized cases!

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

Self-Similarity of the CGM

MgII absorption is alive and well in high mass halos; the covering fraction is fairly invariant with virial mass, though decreases with increasing absorption threshold

The extend of the cool/warm CGM increases with virial mass

The D/R_{vir} radial behavior of the covering fraction is identical for the low halo mass and high halo mass subsample; the mean absorption strength depends pimarily on its location relative to the virial radius

Most MgII absorbing gas in the CGM arises with D/Rvir < 0.3, and in this region the mean absorption strength is independent of virial mass

In finite impact parameter ranges, MgII absorption strength <u>increases</u> with halo mass; we do not confirm the anti-correlation between mean absorption strength and virial mass from cross-correlation studies

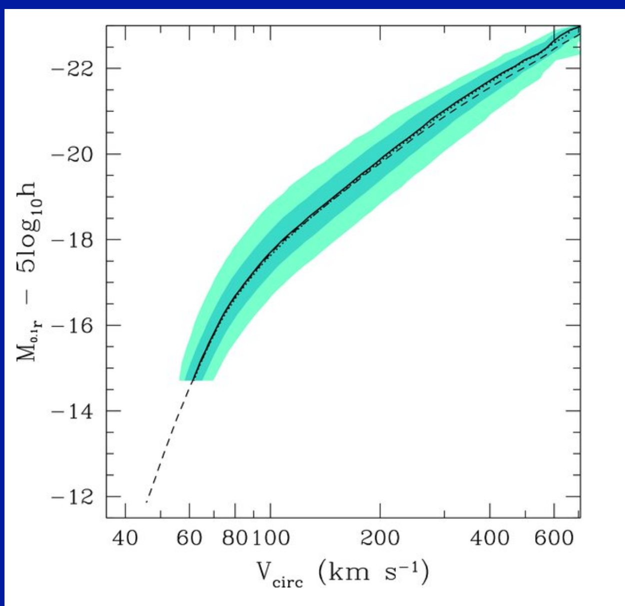
The TPCF indicates that the gas velocity dispersion is independent of virial mass

Possible additional material follows

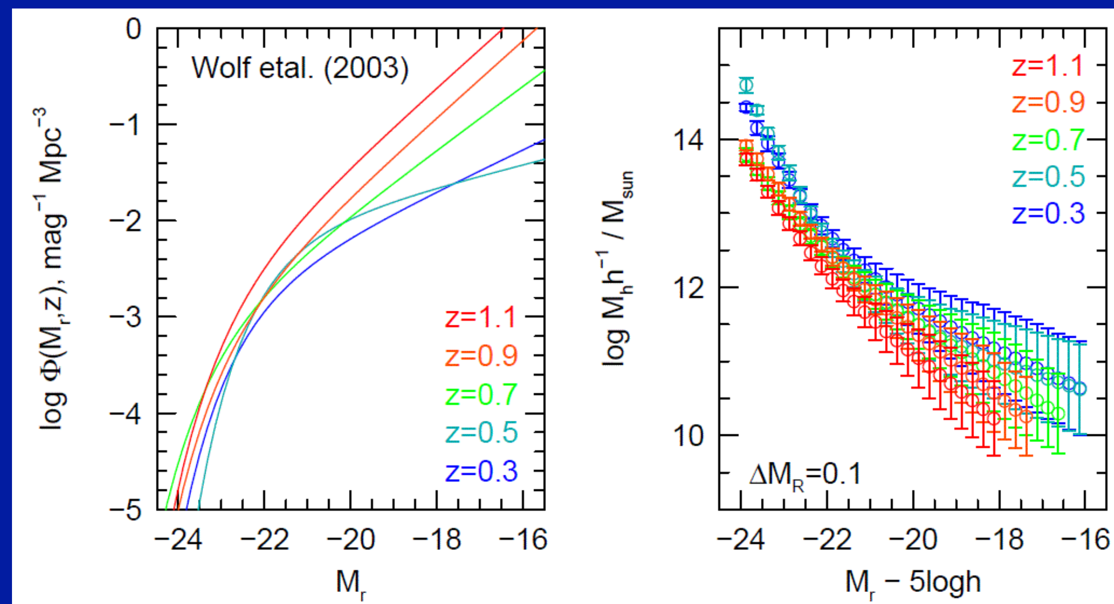
Halo masses – halo abundance matching

"HAM" maps galaxy luminosity to halo mass in a monotonic fashion, reproducing the luminosity function by construction. Following Trujillo-Gomez et al. (2011), we adopt the maximum circular velocity, V_c^{max} , and solve for the unique relation n ($<M_r$) = n ($>V_c^{max}$), from the Bolshoi simulations (Klypin etal 2011).

M_r vs V_c^{max}



$\Phi(M_r,z)$ vs M_r $M_h(z)$ vs M_r



The halos were matched in the five redshift bins (z = 0. 3, 0. 5, 0. 7, 0. 9, 1. 1) of the COMBO-17 r –band luminosity functions (Wolf etal 2003)

Pap I (2013, ApJ, 763, L42); Pap II (arXiv:1308.2618)

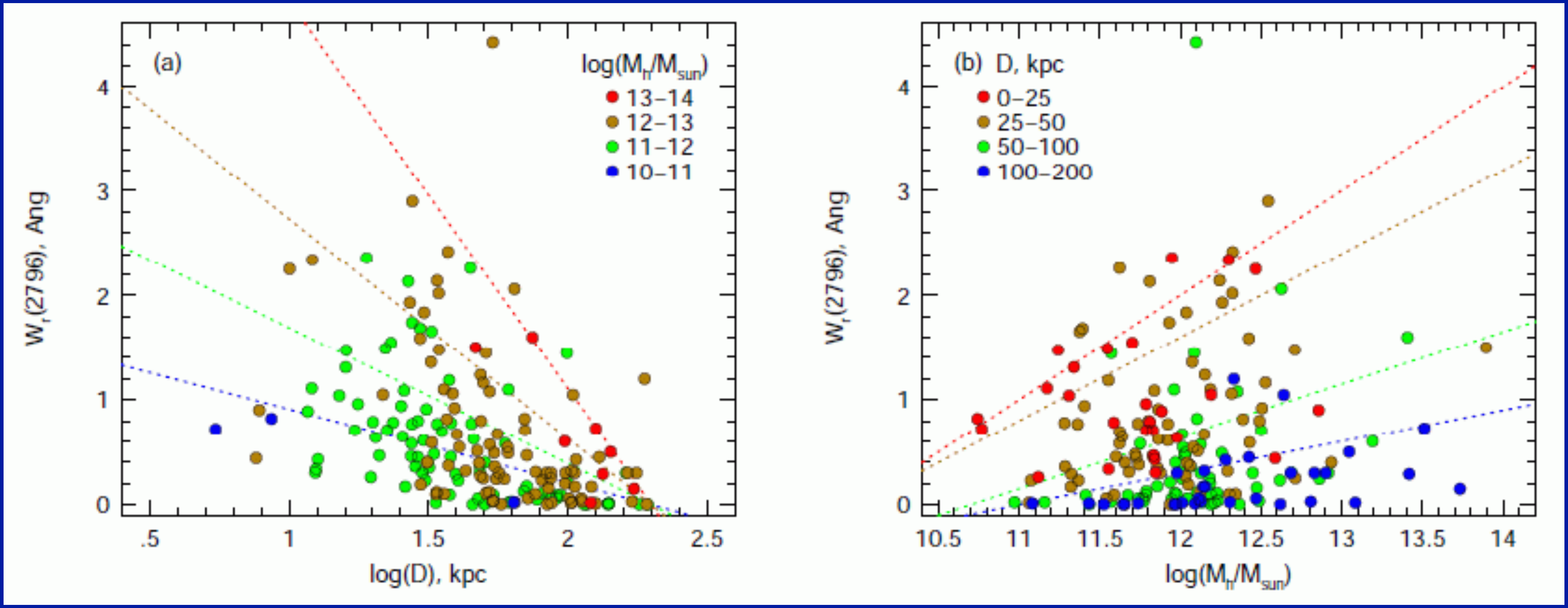
W_r(2796), M_h , and D

"upper envelope" of W_r(2796) steepens with halo mass

W_r(2796)-D plane

W_r(2796) increases with halo mass in finite D ranges

Wr(2796)-M_h plane



MgII absorption strength knows about both virial mass AND impact parameter

- decreasing with D for fixed M_h
- Increasing with M_h for fixed D