THE SELF-SIMILARITY OF THE CIRCUMGALACTIC MEDIUM WITH GALAXY VIRIAL MASS: IMPLICATIONS FOR COLD-MODE ACCRETION

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ABSTRACT
We apply halo abundance matching to obtain galaxy virial masses, $M_h$, and radii, $R_{vir}$, for 183 “isolated” galaxies from the “Mg II Absorber-Galaxy Catalog.” All galaxies have spectroscopic redshifts ($0.07 \leq z \leq 1.12$) and their circumgalactic medium (CGM) is probed in Mg II absorption within projected galactocentric distances $D \leq 200$ kpc. We examine the behavior of equivalent width, $W_r(2796)$, and covering fraction, $f_c$, as a function of $D$, $D/R_{vir}$, and $M_h$. Bifurcating the sample at the median mass log $M_h/M_\odot = 12$, we find (1) systematic segregation of $M_h$ on the $W_r(2796)$–$D$ plane ($4.0\sigma$); high-mass halos are found at higher $D$ with larger $W_r(2796)$ compared to low-mass halos. On the $W_r(2796)$–$D/R_{vir}$ plane, mass segregation vanishes and we find $W_r(2796) \propto (D/R_{vir})^{-2}$ ($8.9\sigma$). (2) High-mass halos have larger $f_c$ at a given $D$, whereas $f_c$ is independent of $M_h$ at all $D/R_{vir}$. (3) $f_c$ is constant with $M_h$ over the range $10.7 \leq \log M_h/M_\odot \leq 13.9$ within a given $D$ or $D/R_{vir}$. The combined results suggest the Mg II absorbing CGM is self-similar with halo mass, even above log $M_h/M_\odot \approx 12$, where cold mode accretion is predicted to be quenched. If theory is correct, either outflows or sub-halos must contribute to absorption in high-mass halos such that low- and high-mass halos are observationally indistinguishable using Mg II absorption strength once impact parameter is scaled by halo mass. Alternatively, the data may indicate predictions of a universal shut down of cold-mode accretion in high-mass halos may require revision.

Key words: galaxies: halos – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

Direct observation of the circumgalactic medium (CGM) is important for exposing the link between the intergalactic medium and galaxies, and the processes governing their star formation histories, stellar masses, luminosities, and morphologies. The CGM harbors a reservoir of chemically enriched gas with a mass that may rival the gas reservoir in galaxies (Tumlinson et al. 2011). The Mg II λ2796, 2803 absorption doublet observed in quasar spectra is an ideal probe of the CGM (see Churchill et al. 2005 for a review); it traces low-ionization gas over the broad range $10^{6.5} \leq N$(HII) $\leq 10^{21.5}$ cm$^{-2}$ (Churchill et al. 1999, 2000; Rao & Turnshek 2000; Rigby et al. 2002) and is detected out to projected distances of ~150 proper kpc (Kacprzak et al. 2008; Chen et al. 2010a; Churchill et al. 2012a; Nielsen et al. 2012).

In general, the CGM is a complex dynamical region affected by accretion, winds, and mergers. Two distinct modes of accretion are theorized to operate, “hot” or “cold,” where the mode depends on whether the halo mass, $M_h$, is above or below a critical threshold $M_{crit}$, where log $M_{crit}/M_\odot \approx 12$ (e.g., Birnboim & Dekel 2003; Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Stewart et al. 2011; van de Voort et al. 2011). Cold-mode accretion is predicted in $M_h < M_{crit}$ halos, whereas hot mode is predicted in $M_h > M_{crit}$ halos. Though some observations provide plausible evidence for cold-mode accretion at $z < 1$ (Kacprzak et al. 2011, 2012; Ribaudo et al. 2011; Thom et al. 2011), the baryonic mass in the cold mode is expected to diminish with decreasing redshift.

If accretion dominates, the distribution of absorber equivalent widths, $W_r(2796)$, and the absorption covering fraction, $f_c$, are predicted to markedly decline in $M_h > M_{crit}$ halos. If a large reservoir of cold gas ($T \approx 10^4$–$10^5$ K) is present in the CGM of $M_h > M_{crit}$ halos, it could imply outflows (cf., Stewart et al. 2011). Indeed, winds are commonly observed in Mg II absorption (e.g., Tremonti et al. 2007; Martin & Bouché 2009; Weiner et al. 2009; Rubin et al. 2010; Martin et al. 2012). Alternatively, the increased number of sub-halos associated with higher mass halos (Klypin et al. 2011) could counteract the predicted behavior of $W_r(2796)$ and $f_c$.

To observationally examine the validity of the hot/cold accretion theoretical paradigm, we require the halo masses of galaxies associated with absorption systems. A robust method for determining these masses is the parameterless halo abundance matching technique (e.g., Conroy et al. 2006; Conroy & Wechsler 2009; Behroozi et al. 2010; Trujillo-Gomez et al. 2011; Rodriguez-Puebla et al. 2012). The method has been extremely successful at reproducing the two-point correlation function with redshift, luminosity, and stellar mass (Conroy et al. 2006; Trujillo-Gomez et al. 2011), the galaxy velocity function, and the luminosity–velocity and baryonic Tully–Fisher relations (Trujillo-Gomez et al. 2011).

In this Letter, we explore the connection between $M_h$ and the Mg II absorbing CGM and show that the “cold” CGM is self-similar with halo mass over the mass range $10.7 \leq \log M_h/M_\odot \leq 13.9$. For this work, we define halo mass as the galaxy virial mass, including dark matter and baryons. In Section 2 we describe our galaxy sample and our method to estimate each galaxy’s halo mass. We present our findings in Section 3. In Section 4, we summarize and provide concluding remarks. Throughout, we adopt a $h = 0.70$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ flat cosmology.

2. THE SAMPLE, VIRAL MASSES, AND VIRIAL RADII

Our sample comprises 183 “isolated” galaxies from the “Mg II Absorber-Galaxy Catalog” (MAGiCAT; Nielsen et al. 2013). Each galaxy has a spectroscopic redshift ($0.07 \leq z \leq 1.12$).
The impact parameter range is 5.4 ≤ D ≤ 194 kpc. The ranges of the AB absolute B- and K-band magnitudes are −16.1 ≥ M_B ≥ −23.1 and −16.9 ≥ M_K ≥ −25.3, with rest-frame B−K colors 0.04 ≤ B − K ≤ 4.09. Including 3σ upper limits, the rest-frame Mg II λ2796 equivalent widths have the range 0.0034 ≤ W_r(2796) ≤ 2.90 Å with one system at W_r(2796) = 4.42 Å.

The M_b for each galaxy was obtained by abundance matching halos in the Bolshoi N-body cosmological simulation (Klypin et al. 2011) to the observed r-band luminosity function (LF) from the COMBO-17 survey (Wolf et al. 2003). In short, the method links the luminosity of galaxies to halo properties in a monotonic fashion, reproducing the LF by construction. Following Trujillo-Gomez et al. (2011), we adopt the maximum circular velocity, V_{max}, and solve for the unique relation n(c(M)) = n(<V_{max}), which properly accounts for the depth of the potential well and is unambiguously defined for both central halos and sub-halos.

The halos were matched in the five redshift bins centered at z = 0.3, 0.5, 0.7, 0.9, 1.1 of the COMBO-17 r-band LF. The galaxy r-band absolute magnitudes, M_r, were determined by k-correcting (e.g., Kim et al. 1996) the R, SDSS r, or Hubble Space Telescope/WFPC F702W observed magnitudes using the actual filter response curves. We employed Coleman et al. (1980) spectral energy distribution (SED) templates from Bolzonella et al. (2000). The adopted SED for each galaxy was obtained by matching its observed color to the redshifted SEDs. The resulting range of M_r is −15.1 ≥ M_r ≥ −22.7.

Scatter between M_h and M_r originates from scatter in the M_h−V_{max} relation due to different formation times of halos with similar mass. After mapping M_h to M_r, we account for this scatter by computing the average M_h in a ΔM_h = 0.1 bin centered on the M_r of the galaxy. Thus, each derived M_h is interpreted as the average halo mass of a galaxy with M_r. Varying the bin size ΔM_h had virtually no systematic effect or change in the scatter of each mass estimate.

The primary uncertainty in the derived M_h is the observed LF. Tests bracketing reasonable extremes of possible systematic errors in the measured LF yield M_h that are qualitatively unchanged. Full details of our methods and uncertainties are described in Churchill et al. (2013). The masses have the range 20.74 ≤ log M_h/M_⊙ ≤ 13.89 with median log M_h/M_⊙ = 12.01. Including systematics and scatter, the uncertainties are δ log M_h ≥ 0.1 at log M_h/M_⊙ = 10 increasing quasi-linearly to δ log M_h ≥ 0.35 at log M_h/M_⊙ = 13.

We obtain the virial radius, R_vir, for each galaxy using the formulae of Bryan & Norman (1998):

\[ R_v^3 = \frac{3}{4\pi} \frac{M_h}{\rho_c \Delta_c(z)} \]

\[ \Delta_c(z) = \frac{(18\pi^2 + 82x - 39x^2)}{1 + x}, \]

where \( x = \frac{1}{1 + z} \). The resulting radii have the range 70 ≤ R_vir ≤ 840 proper kpc with uncertainty of δR_vir/R_vir ≈ 0.1, where the uncertainty in each R_vir accounts for the standard deviation in the average virial mass assigned to each galaxy.

3. RESULTS

3.1. W_r(2796) versus D and D/R_vir

The observed anti-correlation between W_r(2796) and D is firmly established (e.g., Nielsen et al. 2012 and references therein). However, there is significant scatter in the relation. The source of the scatter has been investigated assuming a “second parameter,” i.e., galaxy luminosity (Kacprzak et al. 2008; Chen et al. 2010a), stellar mass or specific star formation rate (Chen et al. 2010b), morphology (Kacprzak et al. 2007), or geometry and orientation (Bouché et al. 2011; Kacprzak et al. 2011).

We divided the sample into halo mass quartiles. In Figure 1(a), we plot W_r(2796) versus D with points colored by mass (see legend). The curve is a log-linear fit (Nielsen et al. 2012). Generally, the highest-mass halos (yellow and red points) segregate above the fitted curve, whereas the lowest-mass halos (blue and green points) segregate below the fitted curve.

In Figure 1(b), we plot the data split by the median mass: the high-mass subsample (red points) has log M_h/M_⊙ ≥ 12.01, and the low-mass subsample (blue points) has log M_h/M_⊙ < 12.01. A two-dimensional Kolmogorov–Smirnov (KS) test yields a
In summary, there is significant systematic mass segregation on the average Mg ii absorber CGM. Further insight is provided by the behavior of the covering fraction of the Mg ii absorbing CGM, which has been investigated in some detail (Kacprzak et al. 2008; Chen et al. 2010a; Nielsen et al. 2012). Nielsen et al. (2012) showed a dependence on galaxy B-band luminosity in that higher luminosity galaxies have higher covering fractions at a given impact parameter than lower luminosity galaxies. Since luminosity is a proxy for mass, their result motivates an examination of the covering fractions as a function of \(M_{\mathrm{h}}\).

In the upper panels of Figure 2, we present \(f_c(D)\), the CGM covering fraction in an impact parameter bin having

4.2σ significance that the null hypothesis the two subsamples have identical \(W_{(2796)}-D\) distributions is ruled out. Excluding galaxies with upper limits on \(W_{(2796)}\) (absorbers only), the significance is 4.0σ. Clearly, there is significant mass segregation in the \(W_{(2796)}-D\) distribution, such that lower mass halos cluster toward smaller \(W_{(2796)}\) and \(D\), whereas higher mass halos cluster toward larger values.

Since halo mass is a correlated source of scatter on the \(W_{(2796)}-D\) plane, we examine \(W_{(2796)}\) versus \(D/R_{\mathrm{vir}}\), since \(R_{\mathrm{vir}} \propto (M_{\mathrm{h}})^{1/3}\). We plot these data in Figure 1(c). The solid line is the fit \(\log W_{(2796)} = \alpha_1 \log (D/R_{\mathrm{vir}}) + \alpha_2\), using the Expectation Maximization-Likelihood method (Wolzetz 1979; Isobe et al. 1986), which accounts for upper limits. The fit is normalized to the mean \(W_{(2796)}\) of absorbing galaxies at \(D/R_{\mathrm{vir}} = 0.3\). We obtained \(\alpha_1 = -2.04 \pm 0.21\) and \(\alpha_2 = -1.60 \pm 0.15\). The dashed lines are 1σ uncertainty curves.

A BHK-\(\tau\) non-parametric rank correlation test (Brown et al. 1974; Isobe et al. 1986), which accounts for upper limits, yielded an 8.2σ significance for the anti-correlation between \(W_{(2796)}\) and \(D\) (Nielsen et al. 2012). Using the BHK-\(\tau\) test, we find that \(W_{(2796)}\) is anti-correlated with \(D/R_{\mathrm{vir}}\) at a 8.9σ significance. Relative to the fits, the variance of the data on the \(W_{(2796)}-D\) plane is reduced from 0.50 to 0.11 on the \(W_{(2796)}-D/R_{\mathrm{vir}}\) plane (absorbers only). An \(F\)-test comparing the individual variances, \(\log W_{\text{fit}} - \log W_{\text{obs}}^2\), in both planes yielded probability \(P(F) = 1 \times 10^{-10}\) that their distributions are drawn from the same parent population; the scatter is significantly reduced in the \(W_{(2796)}-D/R_{\mathrm{vir}}\) plane. Furthermore, the distribution of halo masses about the fit has been homogenized. A two-dimensional KS test comparing the distributions of the low- and high-mass subsamples is consistent with their being drawn from the same parent distribution (1.3σ).

In summary, there is significant systematic mass segregation on the \(W_{(2796)}-D\) plane. However, on the \(W_{(2796)}-D/R_{\mathrm{vir}}\) plane, the scatter about the fit is reduced with very high significance; the anti-correlation is highly significant and the segregation by mass vanishes. The data suggest that the Mg ii absorbing CGM is strongly linked to halo mass such that \(W_{(2796)} \propto (D/R_{\mathrm{vir}})^{-3}\). Interestingly, the CGM exhibits substantial “patchiness” for \(D/R_{\mathrm{vir}} \geq 0.2\), where the relative number of sight lines with non-detections begins to increase. To investigate if this may be connected to galaxy properties, we performed KS tests to compare the colors and luminosities of absorbing galaxies and non-absorbing galaxies with \(W_{(2796)} < 0.1\) Å and \(D/R_{\mathrm{vir}} \geq 0.2\); we find no statistical differences.

3.2. Covering Fraction versus D and D/R_{\mathrm{vir}}

Further insight is provided by the behavior of the covering fraction of the Mg ii absorbing CGM, which has been investigated in some detail (Kacprzak et al. 2008; Chen et al. 2010a; Nielsen et al. 2012). Nielsen et al. (2012) showed a dependence on galaxy B-band luminosity in that higher luminosity galaxies have higher covering fractions at a given impact parameter than lower luminosity galaxies. Since luminosity is a proxy for mass, their result motivates an examination of the covering fractions as a function of \(M_{\mathrm{h}}\).
Figure 3. Covering fraction, $f_c(\leq D)$ vs. log $M_h/M_\odot$ for $W_r(2796) \geq W_{cut}$ inside impact parameter $D$. Each $W_{cut}$ corresponds to a mean minimum log $N(\text{H}I)$. Both proper (black points) and comoving (open blue points) coordinates are shown. Top: $D \leq 50$ kpc. Middle: $D \leq 100$ kpc. Bottom: $D \leq 200$ kpc. Contrary to theoretical expectations for cold-mode accretion, we find that $f_c(\leq D)$ does not vanish for $M_h \geq M_{cut}$. (A color version of this figure is available in the online journal.)

$W_r(2796) \geq W_{cut}$. The uncertainties for all covering fractions presented in this work were computed using binomial statistics. We computed $f_c(D)$ for the high-mass (red triangles) and low-mass (green squares) subsamples and for the full sample (dashed bars). Generally, high-mass halos have larger $f_c(D)$ at $D > 50$ kpc with increasing significance as $W_{cut}$ is lowered. Note that, for $D > 100$ kpc, low-mass halos have $f_c(D) = 0$ for all $W_{cut}$, whereas high-mass halos have $f_c(D) \approx 0.9$. In the lower panels of Figure 2, we plot $f_c(D/R_{vir})$, the CGM covering fraction in a $D/R_{vir}$ bin with $W_r(2796) \geq W_{cut}$. We find that $f_c(D/R_{vir})$ for high- and low-mass halos are statistically identical; $f_c(D/R_{vir})$ has no mass dependence for all $W_{cut}$ at all $D/R_{vir}$.

Using the median fit between $W_r(2796)$ and $N(\text{H}I)$ obtained by Ménard & Chelouche (2009), each $W_{cut}$ converts to a mean minimum neutral hydrogen column density. However, we caution that we extrapolated below the minimum $W_r(2796)$ of their fit (0.5 Å).

The combined behavior of $f_c(D)$ and $f_c(D/R_{vir})$ strongly suggests that the Mg ii absorbing CGM is self-similar with halo mass over the range $10.7 \leq \log M_h/M_\odot \leq 13.9$. If so, in a fixed $D$ bin, the higher $f_c(D)$ values for higher mass halos are naturally explained by the fact that the CGM of higher mass halos is probed at smaller $D/R_{vir}$, whereas lower mass halos are probed at larger $D/R_{vir}$.

3.3. Covering Fraction versus $M_h$

In Figure 3, we present $f_c(\leq D)$ versus $M_h$, where $f_c(\leq D)$ is the CGM covering fraction within impact parameter $D$ with $W_r(2796) \geq W_{cut}$. We computed $f_c(\leq D)$ for both proper coordinates (black points) and for comoving coordinates (open blue points). The behavior of $f_c(\leq D)$ is not sensitive to the choice of coordinates. We find that $f_c(\leq D)$ shows no definitive trend with $M_h$, being consistent with a constant value within errors. We also computed $f_c(\leq D/R_{vir})$, the CGM covering fraction within $D/R_{vir}$ with $W_r(2796) \geq W_{cut}$. We plot $f_c(\leq D/R_{vir})$ versus $M_h$ in Figure 4. Again, a suggestion of self-similarity of the Mg ii absorbing CGM is apparent; $f_c(\leq D/R_{vir})$ is effectively constant with halo mass within errors, primarily depending on $W_{cut}$ and the $D/R_{vir}$ cut. Though a suggestion decreasing $f_c(\leq D/R_{vir})$ with increasing $M_h$ is visually apparent, non-parametric rank correlation tests indicate that no correlation with $M_h$ is consistent with the data (null hypothesis satisfied within $0.2\sigma$–$0.9\sigma$).
Most importantly, we point out that neither \( f_c(\leq D/R_{\text{vir}}) \) nor \( f_c(\leq D/R_{\text{vir}}) \) rapidly decline or vanish for \( M_h > M_{\text{crit}} \). This behavior is in conflict with theoretical predictions in which cold-mode accretion diminishes for \( M_h > M_{\text{crit}} \) (cf., Birnboim & Dekel 2003; Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Stewart et al. 2011; van de Voort et al. 2011), either implying alternative origins for a ubiquitous Mg \( \II \) absorbing CGM or that cold-mode accretion persists above \( M_{\text{crit}} \).

4. DISCUSSION AND CONCLUSIONS

We applied the halo abundance matching technique to determine the galaxy virial masses, \( M_h \), for 183 “isolated” galaxies from MAGuCAT (Nielsen et al. 2013). We report four main results.

1. To a significant degree, the substantial scatter about the \( W_r(2796) - D \) anti-correlation is explained by a systematic segregation of halo mass on the \( W_r(2796) - D \) plane. With 4.0σ significance, the high-mass halos exhibit larger \( W_r(2796) \) at greater \( D \) compared to the low-mass halos. The significance of the \( W_r(2796) - D/R_{\text{vir}} \) anti-correlation is 8.9σ and the data indicate \( W_r(2796) \propto (D/R_{\text{vir}})^{-2} \). On the \( W_r(2796) - D/R_{\text{vir}} \) plane, systematic halo mass segregation vanishes and the scatter is reduced with very high significance. These results suggest that Mg \( \II \) absorption strength is strongly linked to \( D/R_{\text{vir}} \) via halo mass.

2. For all \( W_{\text{cut}} \) and \( D/R_{\text{vir}} \) there is no dependence of the covering fraction \( f_c(\leq D/R_{\text{vir}}) \) on \( M_h \), whereas for smaller \( W_{\text{cut}} \) and \( D > 50 \text{ kpc} \), \( f_c(D) \) is higher for the high-mass halos. Since \( f_c(\leq D/R_{\text{vir}}) \) decreases with increasing \( D/R_{\text{vir}} \), the \( M_h \) dependence of \( f_c(D) \) can be explained by the fact that at a fixed \( D \), higher mass halos are probed at smaller \( D/R_{\text{vir}} \) and lower mass halos are probed at larger \( D/R_{\text{vir}} \). The combined behavior of \( W_r(2796) \) versus \( D/R_{\text{vir}} \), \( f_c(D) \), and \( f_c(\leq D/R_{\text{vir}}) \) strongly suggests that the Mg \( \II \) absorbing CGM is self-similar with halo mass over the range \( 10.7 \leq \log M_h/\odot \leq 13.9 \).

3. The covering fraction \( f_c(\leq D) \) is constant with \( M_h \). Similarly, the covering fraction \( f_c(\leq D/R_{\text{vir}}) \) is a constant with \( M_h \) for all \( W_{\text{cut}} \) and \( D/R_{\text{vir}} \) cuts. The magnitude of the covering fraction depends only on \( W_{\text{cut}} \) and the \( D \) and \( D/R_{\text{vir}} \) cuts, decreasing with increasing \( W_{\text{cut}} \) for fixed \( D \) and with increasing \( D \) cut for fixed \( W_{\text{cut}} \). The lack of dependence of \( f_c(\leq D/R_{\text{vir}}) \) with \( M_h \) further supports our conclusion of the self-similarity of the Mg \( \II \) absorbing CGM with halo mass.

4. Neither \( f_c(\leq D) \) nor \( f_c(\leq D/R_{\text{vir}}) \) precipitously drop for \( M_h \geq M_{\text{crit}} \). This behavior is in direct conflict with
If cold-mode accretion substantially diminishes above some $M_{\text{crit}}$ (Birnboim & Dekel 2003; Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Stewart et al. 2011; van de Voort et al. 2011), our results imply that the Mg II absorbing CGM must be sustained by other mechanisms in $M_h > M_{\text{crit}}$ halos. A most obvious candidate is outflows, which are observed in starburst galaxies (e.g., Tremonti et al. 2007; Martin & Bouché 2009; Weiner et al. 2009; Rubin et al. 2010; Martin et al. 2012). On average, this would imply that, in high-mass halos, the dynamical and cooling times of non-escaping wind material are balanced with the wind cycling timescale such that their cold gas reservoirs are more or less observationally indistinguishable from the cold accretion reservoirs of low-mass halos. Simulations indicate recycling timescales on the order of 0.5–1.0 Gyr that decrease with increasing $M_h$ (Oppenheimer et al. 2010; Stewart et al. 2011). Thus, galaxies in higher mass halos with quiescent star formation for longer than $10^9$ yr would not be expected to have detectable Mg II or strong H I absorption (cf., Churchill et al. 2012b).

On the other hand, since the number of sub-halos increases in proportion to halo mass (Klypin et al. 2011), it is plausible that absorption from sub-halos counteracts our ability to observe the cutoff of cold-mode accretion in the central halos with $M_h \geq M_{\text{crit}}$. Alternatively, the theoretical prediction that cold-mode accretion universally diminishes in higher mass halos may not be correct.

Since $R_{\text{vir}} \propto (M_h/\Delta)^{1/3}$ and $W_r(2796) \propto (D/R_{\text{vir}})^{-2}$, we deduce that $W_r(2796) \propto D^{-2}(M_h/\Delta)^{2/3}$ over the range $10.7 \leq M_h \leq 13.9$. That is, $W_r(2796) \propto D^{-2}$ for fixed $M_h$ and $W_r(2796) \propto (M_h/\Delta)^{2/3}$ for fixed $D$. This behavior is consistent with the halo mass segregation we observe on the $W_r(2796)$–$D$ plane, and is corroborated by the $W_r(2796)$–stellar mass correlation reported by Martin et al. (2012) for starburst galaxies and the stellar mass dependence on the halo cross section of Mg II absorbing gas (Chen et al. 2010b). However, it is contrary to the global $W_r(2796)$–$M_h$ anti-correlation reported by Bouché et al. (2006) and Gauthier et al. (2009) based upon cross-correlation techniques. We explore implications of this discrepancy in Churchill et al. (2013).

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