STELLAR MASS VERSUS STELLAR VELOCITY DISPERSION: WHICH IS BETTER FOR LINKING GALAXIES TO THEIR DARK MATTER HALOS?

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Received 2012 October 19; accepted 2012 November 21; published 2012 December 12

ABSTRACT

It was recently suggested that compared to its stellar mass ($M_*$), the central stellar velocity dispersion ($\sigma_*$) of a galaxy might be a better indicator for its host dark matter halo mass. Here we test this hypothesis by estimating the dark matter halo mass for central galaxies in groups as a function of $M_*$ and $\sigma_*$. For this we have estimated the redshift-space cross-correlation function (CCF) between the central galaxies at given $M_*$ and $\sigma_*$ and a reference galaxy sample, from which we determine both the projected CCF, $w_p(r_p)$, and the velocity dispersion profile. A halo mass is then obtained from the average velocity dispersion within the virial radius. At fixed $M_*$, we find very weak or no correlation between halo mass and $\sigma_*$. In contrast, strong mass dependence is clearly seen even when $\sigma_*$ is limited to a narrow range. Our results thus firmly demonstrate that the stellar mass of central galaxies is still a good (if not the best) indicator for dark matter halo mass, better than the stellar velocity dispersion. The dependence of galaxy clustering on $\sigma_*$ at fixed $M_*$, as recently discovered by Wake et al., may be attributed to satellite galaxies, for which the tidal stripping occurring within halos has stronger effect on stellar mass than on central stellar velocity dispersion.

Key words: dark matter – galaxies: halos – large-scale structure of universe – methods: statistical

Online-only material: color figures

1. INTRODUCTION

The stellar mass of central galaxies in dark matter halos is believed to be strongly correlated with the dark matter mass of their halos. This relationship has been extensively studied in recent years using a variety of observational probes including galaxy clustering, satellite kinematics, gravitational lensing, and group/cycle catalogs. It has also formed the basis for most (if not all) of the current physical/statistical models that aim at populating dark matter halos with galaxies, such as semi-analytic models, halo occupation distribution models, and subhalo abundance matching models. These studies have well established that the stellar mass–halo mass relation for central galaxies can be described by a double power-law form with a relatively small scatter of $\sim 0.16$ dex (e.g., van den Bosch et al. 2004; Wang et al. 2006, 2007; Yang et al. 2007, 2012, 2009; More et al. 2009, 2011; Behroozi et al. 2010; Moster et al. 2010; Guo et al. 2010; Li et al. 2012).

Using data from the Sloan Digital Sky Survey (SDSS; York et al. 2000), Wake et al. (2012) recently showed that when compared to stellar mass ($M_*$), the central stellar velocity dispersion ($\sigma_*$) of galaxies is more closely related to their clustering properties. This led the authors to suggest that $\sigma_*$ might be better than $M_*$, since mass models of dark matter halos are already several halo mass or assembly history. On the other hand, the authors pointed out, their finding cannot rule out the possibility that the correlation of dark matter halos with $M_*$ is still tighter than that with $\sigma_*$. It is known that satellite galaxies may well deviate from the stellar mass–halo mass relation of central galaxies, due to the stripping of their outer regions by tidal interactions with their host halos, which has a stronger effect on $M_*$ than on $\sigma_*$. This motivates our work, in which we attempt to discriminate between these possibilities by directly measuring the dark matter halo mass for central galaxies of different stellar masses and stellar velocity dispersions. For this we first estimate the cross-correlation function (CCF) in redshift space between a reference sample of galaxies and the central galaxies of groups with given $M_*$ and $\sigma_*$. We then estimate the velocity dispersion profile (VDP) of satellite galaxies around the central galaxies by modeling the redshift distortion in the CCF, from which we determine an average mass for the dark matter halos in which the central galaxies reside. In a recent paper (Li et al. 2012, hereafter Paper I), we have shown that for central galaxies with different luminosities and masses, the dark matter halo masses measured in this way are in good agreement with the results obtained by Mandelbaum et al. (2006) from weak-lensing analysis of the SDSS data. When compared to the galaxy–galaxy cross-correlations probed in Wake et al. (2012), the cross-correlation between galaxies and group central galaxies enables us to directly probe the central galaxy–halo mass relation, thus avoiding the effect of satellite galaxies. In addition, the velocity dispersion of satellite galaxies is caused by the local gravitational field, thus it is a more direct measure of dark matter halo mass than the clustering amplitude adopted in Wake et al. (2012).

Throughout we assume a Λ cold dark matter cosmology model with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and $h = 0.7$.

2. DATA AND METHODOLOGY

We apply our analysis to the SDSS galaxy group catalog of Yang et al. (2007). This is a catalog of local galaxy groups with $0.01 < z < 0.2$ and is constructed from a mpA dr72 of the New York University Value-Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005) using a halo-based group finding algorithm developed by Yang et al. (2005). The stellar mass of each galaxy, $M_*$, accompanies the NYU-VAGC release,
which is estimated by Blanton & Roweis (2007) from the SDSS redshift and photometric data, assuming a universal stellar initial mass function of Chabrier (2003). We use the “total masses” instead of the “Petrosian masses,” obtained by correcting the latter using SDSS “model magnitudes” (see Li & White 2009 and Guo et al. 2010 for details). The central stellar velocity dispersion ($\sigma_\ast$) is available for each galaxy from the SDSS spectroscopy, measured within the 3rd diameter fiber. We have corrected $\sigma_\ast$ to an aperture of one-eighth of the galaxy effective radius following Cappellari et al. (2006) and Wake et al. (2012).

As in Paper I, we define the most massive galaxy in each group as its central galaxy. It has been suggested that the brightest cluster galaxies (BCGs), or the most massive galaxies adopted here, may be not exactly located at their halo center. However, a recent study by von der Linden et al. (2012) showed that such offsets are small in general; the average offset between X-ray centroids and BCGs is $\sim 20$ kpc. We use all the central galaxies of which the host groups have three or more member galaxies. This leads to a number of $\sim 16,000$ central galaxies. We divide the central galaxies into 14 samples according to their stellar mass and central velocity dispersion. In Figure 1 we plot the distribution of all the central galaxies in our samples in the plane of $M_\ast$ and $\sigma_\ast$. The regions of the different samples are indicated by the boxes, while the average mass and velocity dispersion of each sample are marked with a cross. This selection scheme gives us at least two $\sigma_\ast (M_\ast)$ samples at a given $M_\ast$ ($\sigma_\ast$), enabling us to study the dependence of clustering and halo mass on one of the two parameters while fixing the other. Our samples cover similar $M_\ast$ and $\sigma_\ast$ ranges as those considered in Wake et al. (2012).

For each of the 14 central galaxy samples, we begin by estimating the redshift-space CCF, $\xi^{(\delta)}(r_p, \pi)$, with respect to a reference galaxy sample selected from the NYU-VAGC sample dr72. The reference sample consists of about half a million galaxies with $r$-band apparent magnitudes $r < 17.6$ and absolute magnitudes $-24 < M_r < -16$, and redshifts in the range $0.01 < z < 0.2$. Details of the sample selection can be found in Paper I. We then obtain the projected CCF, $w_p(r_p)$, by integrating $\xi^{(\delta)}(r_p, \pi)$ over the line of sight separation $\pi$. Next, we model the real-space CCF $\xi_{cg}(r)$ with a combination of a Navarro et al. (1997) profile and a biased linear autocorrelation function of dark matter, and we determine an accurate description of $\xi_{cg}(r)$ by fitting the Abel transform of the model to the observed $w_p(r_p)$. The one-dimensional VDP of galaxies around the central galaxies in each sample is then estimated by comparing $\xi^{(\delta)}(r_p, \pi)$ with $\xi_{cg}(r)$, through modeling the redshift distortion in $\xi^{(\delta)}(r_p, \pi)$. Finally, we use $N$-body cosmological simulations to calibrate the relationship between the so-obtained velocity dispersion and the dark matter halo mass, with which we determine a halo mass for each of our central galaxy sample. Details of our methodology as well as the reference sample and simulations used for the computation and calibration can be found in Paper I. In this work we estimate errors on all the measurements using the bootstrap resampling technique (Barrow et al. 1984).

3. RESULTS

In Figure 2, we show the projected CCFs determined in the way described above for some of our samples. We plot the results for samples of different $\sigma_\ast$ but fixed $M_\ast$ in the upper panels, and the results for samples of different $M_\ast$ but fixed $\sigma_\ast$ in the lower panels. At fixed stellar mass, the projected CCF shows no or very weak dependence on $\sigma_\ast$; this is true for all the masses considered ($10.3 < \log(M_\ast/M_\odot) < 11.8$) and at all scales probed ($\sim 15$ kpc < $r_p$ < $\sim 30$ Mpc). In contrast, the projected CCF at fixed $\sigma_\ast$ shows significant and systematic trends with mass, in both amplitude and slope, and this is true for all the $\sigma_\ast$ bins. The CCF amplitude increases with increasing mass at all scales above $\sim 100$ kpc. This reflects the tight correlation between the stellar mass of the central galaxies and their dark matter halo mass, which clearly holds even when the central stellar velocity dispersion of the galaxies is limited to a narrow range. Moreover, the one-halo term below $\sim 1$ Mpc shows steeper slopes at lower masses and flatter slopes at higher masses, implying more centrally concentrated distribution of satellite galaxies in less-massive halos (see Paper I for detailed discussion).

In Figure 3, we show the VDP of satellite galaxies around our central galaxies, $\sigma_\ast$, measured as a function of the projected separation $r_p$ for different $M_\ast$ and $\sigma_\ast$ samples. Similarly, we see significant mass dependence at fixed $\sigma_\ast$ but very weak or no dependence of the VDP on $\sigma_\ast$ at a given mass. We would like to point out two interesting trends that can be read from the lower panels of the figure. First, at scales smaller than $\sim 1$ Mpc, the velocity dispersion increases with increasing central galaxy mass, with more remarkable effect at higher masses. The velocity dispersion of galaxies in a group or cluster is caused by the local gravitational field and so, when compared to the large-scale amplitude of CCFs, it provides a more direct and reliable measure of the mass of the host dark matter halo. Thus, the dependence of the small-scale $\sigma_\ast$ on $M_\ast$ at fixed $\sigma_\ast$ shows again that the stellar mass of central galaxies is more tightly correlated with halo mass than their central stellar velocity dispersion is. Second, at lower masses ($\lesssim 10^{11} M_\odot$), a mass-dependent shift is seen in the transition scale where the velocity dispersion starts to deviate from a flat slope and increase.
to form a bump at around 1 Mpc. As shown in Paper I (see their Figure 4), the transition occurs at around the virial radius of the host dark matter halo. Therefore, the fact that the transition is seen at larger scales for higher stellar masses at fixed $\sigma_*$ reflects the tight correlation between the central galaxy mass and the virial radius of its host dark matter halo, and thus the halo mass.

We have estimated a halo mass for each central galaxy sample based on a relation between the velocity dispersion measured in our methodology and the dark matter halo mass, as described in Section 2. This relation was calibrated in Paper I with the help of a set of high-resolution $N$-body simulations with the concordance $\Lambda$ cold dark matter cosmology. In Figure 4, we plot the halo mass estimated in this way as functions of both stellar mass (left panel) and central stellar velocity dispersion (right panel). The results for the samples of different $M_*$ and $\sigma_*$ are plotted in colorful symbols, with the size of the symbols being scaled by the halo mass. For comparison, we have performed the same analysis for a set of $M_*$ intervals without further dividing the galaxies in each interval into subsamples of $\sigma_*$, and a set of $\sigma_*$ intervals without further dividing the galaxies into subsamples of $M_*$. This gives an average relation between halo mass and $M_*$, and between halo mass and $\sigma_*$. The results are plotted as solid triangles connected with solid lines in the figure.

The figure reveals two facts: (1) both $M_*$ and $\sigma_*$ are correlated with halo mass and (2) the correlation between $M_*$ and halo mass is much tighter than the correlation between $\sigma_*$ and halo mass. The rms scatter of the different $\sigma_*$ samples around the average relation between halo mass and $M_*$ is 15.2% or 0.06 dex, compared to 73.2% or 0.24 dex for the different $M_*$ samples around the average relation between halo mass and $\sigma_*$. We finish this section by highlighting the stronger dependence of halo mass on $M_*$ than on $\sigma_*$ in Figure 1, where we indicate the halo mass of each sample by the size of a red circle.

4. SUMMARY AND DISCUSSION

Using data from the SDSS Data Release 7 (DR7), we have derived the VDPs for galaxy groups with central galaxies of different stellar masses ($M_*$) and stellar velocity dispersions ($\sigma_*$). From these we have obtained estimates of the dark matter halo mass for the central galaxies, and investigated the correlation of halo mass for central galaxies with $M_*$ and $\sigma_*$. At fixed $M_*$, we find very weak or no correlation between halo mass and $\sigma_*$. In contrast, strong mass dependence is clearly seen even when $\sigma_*$ is limited to a narrow range.

Wake et al. (2012) recently investigated the CCFs between galaxies of given $M_*$ and $\sigma_*$ and the parent sample, finding $\sigma_*$ to be more closely related than $M_*$ to the large-scale amplitude of the correlation functions. The authors suggested three possible explanations: (1) halo mass for central galaxies is more closely related to $\sigma_*$ than to $M_*$, (2) halo age (or concentration) for central galaxies is more closely related to $\sigma_*$ than to $M_*$, and (3) halo properties are still more tightly related to $M_*$ than to $\sigma_*$, and the dependence of clustering on $\sigma_*$ at fixed $M_*$ is attributed to
Figure 3. Velocity dispersion profile measured for the SDSS DR7 galaxy groups with central galaxies of different stellar masses ($M_*$) and stellar velocity dispersion ($\sigma_*$), as indicated in each panel.

(A color version of this figure is available in the online journal.)

Figure 4. Dark matter halo mass as function of galaxy stellar mass ($M_*$, left panel) and stellar velocity dispersion ($\sigma_*$, right panel), measured for the central galaxies of groups in the SDSS DR7. The colorful symbols are for the samples selected on the $M_*$ vs. $\sigma_*$ plane as shown in Figure 1. The solid triangles connected with the line in each panel are for samples selected only by $M_*$ (left panel) or $\sigma_*$ (right panel).

(A color version of this figure is available in the online journal.)
the contribution of satellite galaxies that deviate from the stellar mass–halo mass relation of centrals.

Our measurements of CCFs between galaxies and central galaxies and VDPs, as well as the inferred halo masses, are all consistent with the third possibility being the correct or the most compelling explanation. As discussed in Wake et al. (2012), tidal stripping may reduce the size and mass of a satellite galaxy as it orbits in its parent halo. This process has a stronger effect on stellar mass than on central stellar velocity dispersion, and is stronger in more massive halos. Therefore, at fixed stellar mass, galaxies of higher \( \sigma^* \) are more likely the satellites in higher mass halos, thus clustering more strongly than those of lower \( \sigma^* \). At fixed \( \sigma^* \), galaxies of higher mass are more likely the satellites in lower mass halos, thus lowering down the clustering amplitude and canceling out the mass dependence to some extent.

As can be seen from the right-hand panel of Figure 4, the stellar velocity dispersion of central galaxies is indeed correlated with halo mass, as expected, but with much larger scatter when compared to stellar mass. It is clear that the mass of dark matter halos is correlated more tightly with the stellar mass \( (M_\ast) \) of their central galaxy than with the central stellar velocity dispersion (\( \sigma^* \)) of the galaxy. Once the stellar mass is fixed, the central velocity dispersion shows little correlation with halo mass. Our results thus firmly rule out the other two possibilities proposed by Wake et al. (2012).

C.L. thanks David Wake for helpful discussion, and acknowledges the support of the 100 Talents Program of Chinese Academy of Sciences (CAS), Shanghai Pujian Programme (no. 11PJ1411600), and the exchange program between Max Planck Society and CAS. This work is sponsored by NSFC (11173045, 11233005, 10878001, 11033006, 11121062) and the CAS/SAFEA International Partnership Program for Creative Research Teams (KJCX2-YW-T23). This work has made use of data from the SDSS and SDSS-II. The SDSS Web Site is http://www.sdss.org/.

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