ON THE INTERMEDIATE-REDSHIF T CENTRAL STELLAR MASS-HALO MASS RELATION, AND IMPLICATIONS FOR THE EVOLUTION OF THE MOST MASSIVE GALAXIES SINCE Z ~ 1

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ABSTRACT

The stellar mass-halo mass relation is a key constraint in all semi-analytic, numerical, and semi-empirical models of galaxy formation and evolution. However, its exact shape and redshift dependence remain debated. Several recent works support a relation in the local Universe steeper than previously thought. Based on the comparisons with a variety of data on massive central galaxies, we show that this steepening holds up to z ~ 1, for stellar masses $M_{\text{star}} \gtrsim 2 \times 10^{11} M_{\odot}$. Specifically, we find significant evidence for a high-mass end slope of $\beta \gtrsim 0.35 - 0.70$, instead of the usual $\beta \lesssim 0.20 - 0.30$ reported by a number of previous results. When including the independent constraints from the recent BOSS clustering measurements, the data, independent of any systematic errors in stellar masses, tend to favor a model with a very small scatter ($\lesssim 0.15$ dex) in stellar mass at fixed halo mass, in the redshift range $z < 0.8$ and for $M_{\text{star}} > 3 \times 10^{11} M_{\odot}$, suggesting a close connection between massive galaxies and host halos even at relatively recent epochs. We discuss the implications of our results with respect to the evolution of the most massive galaxies since $z \sim 1$.

Subject headings: cosmology: theory – galaxies: statistics – galaxies: evolution

1. INTRODUCTION

Probing the exact relation between stellar mass and host halo mass is one of the hottest topics in present-day cosmology (Leauthaud et al. 2012; Yang et al. 2012; Behroozi et al. 2013; Moster et al. 2013; Reddick et al. 2013). Such mapping can possibly shed light on the complex and still poorly understood physical processes that govern galaxy evolution (e.g.,

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Silk et al. 2013), as well as unveil key properties of the underlying dark matter cosmological model (e.g., Weinberg et al. 2013).

Constraining the statistical and environmental evolution of massive galaxies, especially those of $M_{\text{star}} \gtrsim (2 - 3) \times 10^{11} M_{\odot}$, is particularly meaningful. A number of independent observations are showing that galaxies above this mass scale tend to depart from simple extrapolations of the scaling relations characterizing their lower-mass counterparts, having larger sizes, more prolate shapes, and redder colors (e.g., van der Wel et al. 2009; Bernardi et al. 2011).

However, the galaxy-halo mapping for massive galaxies as inferred from abundance matching between the stellar and halo mass functions, is still under debate. One of the main uncertainties relies on a proper determination of the stellar mass function (e.g., Bernardi et al. 2013; Muzzin et al. 2013). For example, the constant number density evolution of the massive galaxies derived by, e.g., Carollo et al. (2013) at $z \lesssim 1$, is in disagreement with other measurements at similar redshifts (Maraston et al. 2013; Muzzin et al. 2013).

In this letter, we provide additional, key constraints to the $M_{\text{star}} - M_{\text{halo}}$ relation for massive central galaxies at $0 < z < 1$ using direct stellar and host halo mass measurements of the Brightest Cluster Galaxies (BCGs), as well as accurate galaxy clustering measurements at $0.4 < z < 0.8$. The galaxy clustering measurements are used to infer the host halo mass distributions through the halo occupation distribution (HOD) models (e.g., Zheng et al. 2007), and thus provide a powerful tool to break the degeneracies inherent to the abundance matching techniques.

In the following we will adopt a cosmology with parameters $\Omega_{\text{m}} = 0.30$, $\Omega_{\Lambda} = 0.70$, $n_s = 1$, and $\sigma_8 = 0.8$, to match the one assumed in our reference stellar mass functions and halo occupation measurements. We will adopt the Chabrier Initial Mass Function (IMF: Chabrier 2003) as

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Behroozi et al. (2010). At any redshift of interest, we first fit
in Eq. 1 makes very little difference in the halo mass range of
interest here, e.g., $M_{200c} \gtrsim 10^{13} M_{\odot}$. Eq. 1 includes the subhalo
term $\Phi_{h}(> M_{200c}, z)$ with unstripped mass $M_{200c}$, which we
take from Behroozi et al. (2013). Neglecting the satellite term
in Eq. 1 makes very little difference in the halo mass range of
interest here, e.g., $M_{200c} \gtrsim 10^{13} M_{\odot}$.

It is instead much more relevant to adopt the proper intrinsic
scatter $\Sigma$ in stellar mass at fixed halo mass, ideally constrained
from independent datasets, as larger values of $\Sigma$ induce a flat-
ter $M_{\text{star}} - M_{\text{halo}}$ relation above the break. Eq. 1 does not
assume any scatter between stellar and halo mass, however one
straightforward way to include it is as follows (see also, e.g.,
Behroozi et al. 2010). At any redshift of interest, we first fit
the parameters of a two-power law relation defined as

$$ M_{\text{star}} = M_{\text{star}}^{0} \left( \frac{M_{200c}^{0}}{M_{200c}} \right) \alpha \left[ 1 + \left( \frac{M_{200c}^{0}}{M_{200c}} \right)^{\gamma} \right]^{-1} $$

(2)

to the raw output of Eq. 1. We then choose a value for the
intrinsic scatter $\Sigma$, and generate a large galaxy catalog by as-
signing to each (sub)halo extracted from the total halo mass
function, a galaxy with stellar mass derived from a Gaussian
distribution with mean given by the logarithm of Eq. 2 and
dispersion $\Sigma$ (in dex). We finally vary $\gamma$ in Eq. 2 to tune
the high mass-end slope $\beta = \alpha - \gamma$ until the input stellar mass func-
tion in Eq. 1 is fully reproduced.

3. DATA

The data on BCGs in groups and clusters considered in
this letter are derived at $z = 0.1$ from X-rays (Kravtsov et al.
2014), at $0.2 < z < 1$ from X-ray and weak lensing
in COSMOS (Finoguenov et al. 2007; George et al. 2011;
Huertas-Company et al. 2013b), at $0.8 < z < 1.4$ from
IR (SpARCS; Lidman et al. 2012; van der Burg et al. 2013)
and X-ray data (Strazzullo et al. 2010; Raichoor et al. 2011;
Rettura et al. 2011), and at $z \approx 1$ from the Cl1604 supercluster
and other structures from the ORELSE survey (Ascaso et al.
2014).

As for clustering, we utilize the massive galaxies at the me-
dian redshift of $z \approx 0.6$ from the CMASS sample of the Sloan
Digital Sky Survey-III (SDSS-III) Baryon Oscillation Spec-
troscopic Survey (BOSS; Dawson et al. 2013). Stellar masses
are from the Portsmouth SED-fitting (Maraston et al. 2013),
originally derived assuming a Kroupa IMF (Kroupa 2001).
The host halo masses for these massive galaxies are estimated
through the HOD modeling of the projected-space two-point
correlation functions on scales from $0.1 h^{-1}$Mpc to $60 h^{-1}$Mpc,
faithfully following the method laid out in Guo et al. (2014).

4. RESULTS

4.1. The number density of massive galaxies

The first step towards defining a more secure mapping be-
tween stars and halos relies on properly measuring the stellar
mass function of galaxies. The left panel of Fig. 1 shows the
cumulative number density of galaxies from Bernardi et al.
(2013) for the SDSS-DR7 main galaxy sample ($z \lesssim 0.2$; solid,
red line). We used their estimate based on Sérsic-exponential
light profile, which is considered by the authors to be the
most realistic one to describe SDSS data (Bernardi et al.
2014). When compared to the COSMOS/UltraVISTA data by
Muzzin et al. (2013) (long-dashed line), at the average red-
shift of $z = 0.75$, or the BOSS estimate from Guo et al. (2014)
(star), or even the BOSS determination of the stellar mass
function by Maraston et al. (2013) (diamonds), it would im-
ply at face value a significant increase in the number density
of massive galaxies towards low redshifts.

The right panel of Fig. 1 focuses on the number density
evolution of galaxies above $M_{\text{star}} \gtrsim 4 \times 10^{11} M_{\odot}$. For
completeness, this panel also reports the measurements inferred
by Moustakas et al. (2013) and Carollo et al. (2013), which
would instead suggest a negligible evolution since $z \lesssim 1$.
Moustakas et al. (2013) is well consistent with the stellar
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**Fig. 2.** Median stellar mass as a function of halo mass relation for central galaxies at $z = 0.1, 0.4, 0.7, 1.1$, clockwise from the upper left panel, respectively. The red, dot-dashed and red, dotted lines are derived from the Bernardi et al. (2013) stellar mass function, assumed constant at all redshifts above $\log M_{\text{star}} \gtrsim 10^{11} M_\odot$, with an intrinsic scatter of $\Sigma = 0.25$ and $\Sigma = 0$ dex, respectively. The solid line and gray area mark the Moster et al. (2013) median relation and its $1-\sigma$ uncertainty region, respectively. The blue, dashed line is the result by Yang et al. (2012). All the data are as labeled. The filled circles mark the median stellar mass-halo mass in the COSMOS data, while the red square the median in the IR/X-ray plus Ascaso et al. (2014) and other associated data.

Overall, most of the recent estimates of the stellar-halo mass relation tend to be discrepant with respect to direct central galaxy mass measurements in groups and clusters. All the available data collected in this work in fact, although with a large dispersion, tend to lie, on average, above the Moster et al. (2013) uncertainty region, implying a steeper stellar-halo mass relation, with the high-mass end slope (Eq. 2) increasing from $\beta \lesssim 0.2 - 0.3$ to $\beta \gtrsim 0.35 - 0.70$.)

**4.2. The stellar mass-halo mass relation**

Fig. 2 shows the median stellar mass as a function of host halo mass relation for central galaxies evaluated at $z = 0.1$ (upper left), $z = 0.4$ (upper right), $z = 0.7$ (lower left), $z = 1.1$ (lower right), for different models. The dot-dashed, red lines are obtained by inserting in Eq. 1 the Bernardi et al. (2013) stellar mass function, only valid at $z > 0.2$, with an intrinsic scatter of $\Sigma = 0.15$ dex. For completeness, we compare these results with three mappings from the recent literature, the Moster et al. (2013) median relation (solid, black lines), and the model inclusive of the total intra-cluster light. Other recent works mostly lie within the Moster et al. (2013) uncertainty region (e.g., Leauthaud et al. 2012). For completeness, we also show with purple dotted lines, the Behroozi et al. (2013) model inclusive of the total intra-cluster light.

Overall, the right panel of Fig. 1 brackets the possible evolutionary paths since $z \lesssim 1.0$ for the number density of massive galaxies, from a non evolving scenario (black, long-dashed line), to a fast evolving one (orange, dashed line). Most relevant measurements broadly fall within these sequences (e.g., Ilbert et al. 2013). The exact determination of the evolution and normalization of the high-mass end of the stellar mass function is limited by photometric and spectral systematics in the determination of stellar masses, as well as possible incompleteness and/or cosmic variance issues (e.g., Marchesini et al. 2009; Bernardi et al. 2013, 2013; Ilbert et al. 2013; Muzzin et al. 2013). In the following, we will evaluate the stellar mass-halo mass relation considering both of these extreme cases, and, by direct comparison with independent data sets, namely large scale clustering, set constraints on plausible evolutionary paths for the most massive galaxies in light of current estimates of the stellar mass function.
Such a discrepancy was already emphasized at $z < 0.3$ by some groups (e.g., Kravtsov et al. 2014; Shankar et al. 2014). Kravtsov et al. (2014), in particular, recomputed abundance matching with the Bernardi et al. (2013) stellar mass function, finding a steeper relation above $M_{\text{star}} \gtrsim 10^{11} M_\odot$, broadly consistent with their direct nine BCG stellar and halo mass measurements (orange stars). Our own determinations of the stellar-halo mass relation via Eq. [1] based on the local Bernardi et al. (2013) stellar mass function without scatter (dotted, red lines in Fig. 2), are at $z = 0.1$ broadly consistent with the Kravtsov et al. (2014) and Gonzalez et al. (2013) data at very high masses.

One of the primary causes of the discrepancies can be ascribed to the adoption of different input stellar mass functions. In particular, the Bernardi et al. (2013) stellar mass function, based on improved sky subtractions and modeling of the central galaxy light profile, is characterized by a significant boost in the abundance of the most massive galaxies, which in turn induces a steepening of the stellar-halo mass relation. Other factors contribute to the differences in Fig. 2 (Moster et al. 2013), for example, took care in deconvolving their adopted stellar mass function by some systematic errors before applying Eq. [1] thus producing a flattening in the high-mass end of their inferred stellar mass-halo mass relation.

4.3. Independent constraints from clustering

Fig. 2 also reveals that at $z \sim 0.3-0.6$, a clear degeneracy exists between a model based on Muzzin et al. (2013), with an intrinsic scatter in stellar mass at fixed halo mass of $\Sigma = 0.15$ dex (long-dashed, orange lines), and the one based on the $z = 0.1$ Bernardi et al. (2013) stellar mass function with $\Sigma = 0.25$ dex (dot-dashed, red lines). In fact, both models can potentially reproduce the COSMOS data, though the latter with larger scatter would imply a constant number density at least up to $z \sim 0.8$, at variance with the former. Irrespective of uncertainties on stellar masses, we discuss in this section how to use clustering to set a secure upper limit to $\Sigma$.

Fig. 3 displays with gray bands the Guo et al. (2014) HOD host halo mass distributions for central galaxies with stellar mass above log $M_{\text{star}} > 11.50$ (Kroupa IMF) at $z = 0.5$ (left) and $z = 0.7$ (right) inferred from the BOSS CMASS clustering measurements (Sect. 5). For the stellar mass of interest here, the galaxy sample is almost complete and the tiny fraction of missing galaxies due to the CMASS sample selections have negligible effects on the clustering measurements (Maraston et al. 2013; Guo et al. 2014). We compare the BOSS results with the abundance matching model based on Muzzin et al. (2013) stellar mass function, which perfectly matches the cumulative number density adopted by Guo et al. (2014) (left panel of Fig. 1). At each redshift of interest we generate a mock halo catalog extracted from the halo mass function, and populate the halos with galaxies through the stellar mass-halo mass relation based on Muzzin et al. (2013) with a given dispersion $\Sigma$.

Our results are shown in Fig. 3 for three different values of the scatter $\Sigma = 0.15, 0.20, 0.25$ dex, as labeled. Consistently with the reference HOD model, all our mock catalogs have halo masses defined as 200 times the background density at the redshift of interest, and matched to the stellar mass cut in BOSS. Models based on smaller scatter than $\Sigma > 0.15$ dex, inevitably map galaxies at fixed stellar mass to host halos significantly lower than that inferred from clustering measurements. A larger scatter tends to overall flatten the $M_{\text{star}} - M_{\text{halo}}$ relation above the break. However, increasing the scatter also includes lower-mass, more numerous halos in samples defined by stellar mass thresholds, thus effectively lowering the median halo mass at fixed stellar mass.

The lower scatter of $\Sigma = 0.15$ dex is fully consistent with the inferred scatter $\sigma_{\log M_{\text{halo}}} (\sim 0.62$ at $z = 0.5$ and $\sim 0.76$ at $z = 0.7$) in the HOD model, which describes the scatter in the host halo mass distribution for the stellar mass sample. The scatter $\sigma_{\log M_{\text{halo}}}$ can be converted into $\Sigma$ through $\Sigma = \rho \sigma_{\log M_{\text{halo}}}/\sqrt{2} \sim 0.17$ when assuming a power-law relation of $M_{\text{halo}} \propto M_{\text{star}}^\beta$ (Zheng et al. 2007), with $p \sim 0.35$ as found for Muzzin et al. (2013, cfr. Fig. 2). Our results of a low satellite population in abundance matching, e.g., redshift of infall, effect of environment, etc... (e.g., Maraston et al. 2013; Yang et al. 2012), we here discuss predictions for only central galaxies, and focus on the large-scale clustering and bias. The fraction of satellites in our stellar mass range is anyway very small (Guo et al. 2014).
Our result on a low scatter in the stellar-halo mass relation is independent of systematics in stellar masses, at least up to $z \sim 0.8$.

Our results can potentially set valuable constraints to the viable evolutionary paths of massive galaxies.

We first take the Bernardi et al. (2013) stellar mass function as the $z \sim 0$ reference, as it well matches all local data on massive BCGs (upper left panel of Fig. 2). A steadily decreasing number density of massive galaxies at $0.3 < z < 0.8$ (e.g., Muzzin et al. 2013, right panel of Fig. 1), would then, at face value, be consistent with most of the available constraints on the group and cluster centrals, keeping $\Sigma \lesssim 0.15$ dex to match the HOD halo mass distributions inferred from the BOSS clustering measurements (Fig. 3).

Another extreme case is forcing the Bernardi et al. (2013) number density of massive galaxies to be constant up to $z \sim 1$ (e.g., Carollo et al. 2013, right panel of Fig. 1). However, the latter model, coupled to the need for a negligible scatter $\Sigma$, would imply a systematic overestimate of a factor of $\gtrsim 5$ in the median BCG stellar mass, as currently measured in clusters at $z \gtrsim 0.8$ for $\log M_{200}/M_\odot \gtrsim 14.5$ (red dotted line versus red square in the bottom right panel of Fig. 2), and an overestimate of a factor $\sim 2$ of the total stellar plus intracluster light model by Behroozi et al. (2013; purple dotted lines in Fig. 2).

Irrespective of the systematics in the stellar mass function, current BCG mass determinations and HOD clustering measurements, may favor an increase of a factor of a few since $z \lesssim 1$ in the number density of the most massive galaxies. This can be partly induced by a parallel growth in the median stellar mass. Independent semi-empirical studies indeed suggest an increase in stellar mass by a factor of $\sim 2$ since $z \lesssim 1$ (Zheng et al. 2007, Lidman et al. 2013, Ascaso et al. 2014, Marchesini et al. 2014, e.g.). As supported by state-of-the-art hierarchical galaxy evolution models (e.g., De Lucia et al. 2006, Shankar et al. 2013), a non-negligible contribution to this mass growth can be explained by minor and major mergers. The latter, in particular, might be the ones responsible for the steepening in the high mass-end of the scaling relations characterizing early-type galaxies (e.g., Bernardi et al. 2011b).

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5. DISCUSSION
In this letter we found significant evidence for:

- a low scatter $\Sigma \lesssim 0.15$ dex in stellar mass at fixed host halo mass, at least up to $z \sim 0.8$.

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