The intriguing life of massive galaxies
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Further evidence for large central mass-to-light ratios in massive early-type galaxies

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Abstract. We studied the stellar populations, distribution of dark matter, and dynamical structure of a sample of 25 early-type galaxies in the Coma and Abell 262 clusters. We derived dynamical mass-to-light ratios and dark matter densities from orbit-based dynamical models, complemented by the ages, metallicities, and α-element abundances of the galaxies from single stellar population models. Most of the galaxies have a significant detection of dark matter and their halos are about 10 times denser than in spirals of the same stellar mass. Calibrating dark matter densities to cosmological simulations we find assembly redshifts $z_{\rm DM} \approx 1-3$. The dynamical mass that follows the light is larger than expected for a Kroupa stellar initial mass function, especially in galaxies with high velocity dispersion $\sigma_{\rm eff}$ inside the effective radius $r_{\rm eff}$. We now have 5 of 25 galaxies where mass follows light to $1-3\,r_{\rm eff}$, the dynamical mass-to-light ratio of all the mass that follows the light is large ($\approx 8-10$ in the Kron-Cousins R band), the dark matter fraction is negligible to $1-3\,r_{\rm eff}$. This could indicate a 'massive' initial mass function in massive early-type galaxies. Alternatively, some of the dark matter in massive galaxies could follow the light very closely suggesting a significant degeneracy between luminous and dark matter.

Keywords. galaxies: abundances, galaxies: elliptical and lenticular, cD, galaxies: formation, galaxies: kinematics and dynamics, galaxies: stellar content.

1. Introduction

In the past years we studied the stellar populations, mass distribution, and orbital structure of a sample of early-type galaxies in the Coma cluster with the aim of constraining the epoch and mechanism of their assembly.

The surface-brightness distribution was obtained from ground-based and *HST* data. The stellar rotation, velocity dispersion, and the H_3 and H_4 coefficients of the line-of-sight velocity distribution were measured along the major axis, minor axis, and an intermediate axis. In addition, the line index profiles of Mg, Fe and Hβ were derived (Mehlert *et al.* 2000; Wegner *et al.* 2002; Corsini *et al.* 2008). Axisymmetric orbit-based dynamical models were used to derive the mass-to-light ratio Υ_* of all the mass that follows the light and the dark matter (DM) halo parameters in 17 galaxies (Thomas *et al.* 2005, 2007a,b, 2009a,b). The comparison with masses derived through strong gravitational lensing for early-type galaxies with similar velocity dispersion and the analysis of the ionized-gas kinematics gave valuable consistency checks for the total mass distribution predicted by dynamical modeling (Thomas *et al.* 2011). The line-strength indices were analyzed by single stellar-population models to derive the age, metallicity, α-element abundance, and mass-to-light ratio $\Upsilon_{\rm Kroupa}$ (or $\Upsilon_{\rm Salpeter}$ depending on the adopted initial mass function, IMF) of the galaxies (Mehlert *et al.* 2003).

More recently, we have performed the same dynamical analysis for 8 early-type galaxies of the nearby cluster Abell 262 (Wegner *et al.* 2012). The latter is far less densely populated than the Coma cluster and it is comparable to the Virgo cluster. Moreover, while galaxies in Coma were selected to be mostly flattened, the Abell 262 galaxies we measured appear predominantly round on the sky.

2. Results

2.1. *Evidence for halo mass not associated to the light*

In the Coma galaxy sample, the statistical significance for DM halos is over 95% for 8 (out of 17) galaxies (Thomas *et al.* 2007b), whereas the Abell 262 sample reveals 4 (out of 8) galaxies of this kind (Wegner *et al.* 2012). In Coma, we found only one galaxy (GMP 1990) with $f_{\rm halo} \approx 0$, i.e., with a negligible halo-mass fraction of the total mass inside $r_{\rm eff}$. This is also the case of 4 galaxies in Abell 262 (NGC 703, NGC 708, NGC 712, and UGC 1308). The evidence for a DM component in addition to mass that follows light is not directly connected to the spatial extent of the kinematic data, degree of rotation, or flattening of the system. There is no relationship with the age, metallicity, and α-element abundance of the stellar populations.

We cannot discriminate between cuspy and logarithmic halos based on the quality of the kinematic fits, except for NGC 703 where the logarithmic halo fits better. Still, the majority of cluster early-type galaxies have $2-10$ times denser halos than local spirals (e.g., Persic *et al.* 1996), implying a $1.3-2.2$ times higher $(1+z_{\rm DM})$ assuming $\langle \rho_{\rm DM} \rangle \sim (1+z_{\rm DM})^3$, where $z_{\rm DM}$ is the formation redshift of the DM halos. Thus, if spirals typically formed at $z_{\rm DM} \approx 1$, then cluster early-type galaxies assembled at $z_{\rm DM} \approx 1.6-3.4$.

Averaging over all galaxies, we find that a fraction of $\langle f_{\rm halo} \rangle = 0.2$ of the total mass inside $r_{\rm eff}$ is in a DM halo distinct from the light. Similar fractions come from other dynamical studies employing spherical models (e.g., Gerhard *et al.* 2001). The Coma and Abell 262 galaxies show an anti-correlation between $\Upsilon_*/\Upsilon_{\rm Kroupa}$, i.e. the ratio between the dynamical and stellar population mass-to-light ratios, and $f_{\rm halo}$ (Fig. 1, left panel). Galaxies where the dynamical mass following the light significantly exceeds the Kroupa value ($\Upsilon_*/\Upsilon_{\rm Kroupa} > 3$) seem to lack matter following the halo distribution inside $r_{\rm eff}$ ($\langle f_{\rm halo} \rangle \approx 0$). In contrast, in galaxies near the Kroupa limit ($\Upsilon_*/\Upsilon_{\rm Kroupa} < 1.4$), the dark-halo mass fraction is at its maximum ($\langle f_{\rm halo} \rangle = 0.3$).

2.2. *Mass that follows the light*

As far as the mass-to-light ratios are concerned, the galaxies of Coma and Abell 262 follow a similar trend. While the dynamically determined Υ_* increases strongly with $\sigma_{\rm eff}$, i.e., the velocity dispersion averaged within $r_{\rm eff}$ (Fig. 1, right top panel), the stellar population models indicate an almost constant $\Upsilon_{\rm Kroupa}$ (Fig. 1, right middle panel). This implies that the ratio $\Upsilon_*/\Upsilon_{\rm Kroupa}$ increases with $\sigma_{\rm eff}$ (Fig. 1, right bottom panel). Around $\sigma_{\rm eff} \approx 200$ km s^{-1} the distribution of $\Upsilon_*/\Upsilon_{\rm Kroupa}$ has a sharp cutoff with almost no galaxies below $\Upsilon_*/\Upsilon_{\rm Kroupa} = 1$. For $\sigma_{\rm eff} \gtrsim 250$ km s^{-1} the lower bound of $\Upsilon_*/\Upsilon_{\rm Kroupa}$ increases to $\Upsilon_*/\Upsilon_{\rm Kroupa} \gtrsim 2$ at $\sigma_{\rm eff} \approx 300$ km s^{-1}. Similar trends are also observed in the SAURON sample with dynamical models lacking a separate DM halo (Cappellari

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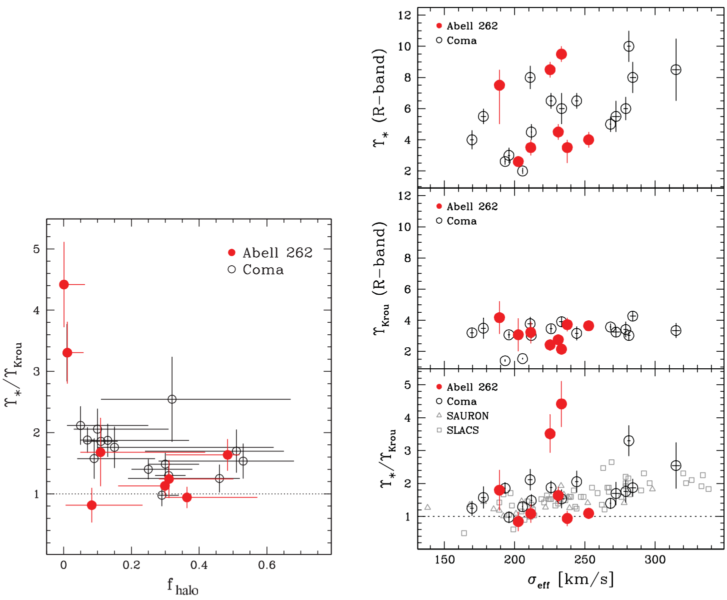

Figure 1. Left: Ratio of dynamical Υ_* to stellar-population $\Upsilon_{\rm Kroupa}$ as a function of $f_{\rm halo}$, i.e., the halo-mass fraction of the total mass inside $r_{\rm eff}$, for galaxies in Coma (open circles, Thomas *et al.* 2011) and Abell 262 (filled circles, Wegner *et al.* 2012). $r_{\rm eff}$. $\Upsilon_*/\Upsilon_{\rm Kroupa} = 1.6$ corresponds to a Salpeter IMF. Right: Dynamical Υ_* (upper panel), stellar-population $\Upsilon_{\rm Kroupa}$ (middle panel), and their ratio (bottom panel) as a function of the effective velocity dispersion, $\sigma_{\rm eff}$. In the bottom panel, Coma and Abell 262 galaxies are compared to SLACS (open squares, Treu *et al.* 2010) and SAURON galaxies (open triangles, Cappellari *et al.* 2006).

et al. 2006), in SLACS galaxies with combined dynamical and lensing analysis (Treu *et al.* 2010) and, recently, in the ATLAS3d survey with dynamical models including a DM halo (Cappellari *et al.* 2012).

3. Discussion

Fig. 1 provides strong evidence for large central Υ_* in massive early-type galaxies. However, in all gravity-based methods, there is a fundamental degeneracy concerning the interpretation of mass-to-light ratios. Such methods cannot uniquely discriminate between luminous and dark matter once they follow similar radial distributions. The distinction is always based on the assumption that the mass density profile of the DM differs from that of the luminous matter.

One extreme point of view is the assumption that the stellar masses in early-type galaxies are maximal and correspond to Υ_*. The immediate consequence is that the stellar IMF in early-type galaxies is not universal, varying from Kroupa-like at low velocity dispersions to Salpeter (or steeper) in the most massive galaxies (see Auger *et al.* 2010, Thomas *et al.* 2011, and Cappellari *et al.* 2012, for a detailed discussion). Recent attempts to measure the stellar IMF directly from near-infrared observations point in the same direction (see Conroy & van Dokkum 2012, and references therein). However, we also find the galaxies with the largest $\Upsilon_*/\Upsilon_{\rm Kroupa}$ have the lowest halo-mass fractions inside $r_{\rm eff}$ and vice versa. A possible explanation for this finding is a DM distribution that follows the light very closely in massive galaxies and contaminates the measured Υ_*, while it is

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more distinct from the light in lower-mass systems. This has been suggested elsewhere as a signature of violent relaxation.

One option to further constrain the mass-decomposition of gravity-based models is to incorporate predictions from cosmological simulations that confine the maximum amount of DM that can be plausibly attached to a galaxy of a given stellar mass. Since adiabatic contraction increases the amount of DM in the galaxy center, it could be in principle a viable mechanism to lower the required stellar masses towards a Kroupa IMF (Napolitano *et al.* 2010, but see also Cappellari *et al.* 2012). An immediate consequence is that some of the mass that follows the light is actually DM, increasing the DM fraction to about 50% of the total mass inside $r_{\rm eff}$.

Since the (decontracted) average halo density scales with the mean density of the universe at the assembly epoch, we derived the dark-halo assembly redshift $z_{\rm DM}$ for Coma (Thomas et al. 2011) and Abell 262 galaxies (Wegner et al. 2012). We compared the values of $z_{\rm DM}$ to the star-formation redshifts z_* calculated from the stellar-population ages. For the majority of galaxies $z_{\rm DM} \approx z_*$ and their assembly seems to have stopped before $z_{\rm DM} \approx 1$. The stars of some galaxies appear to be younger than the halo, which indicates a secondary star-formation episode after the main halo assembly. The photometric and kinematic properties of the remaining galaxies suggest they are the remnants of gas-poor binary mergers and their progenitors formed close to the $z_{\rm DM} = z_*$ relation. Without trying to overinterpret the result given the assumptions, it seems that Kroupa IMF allows us to explain the formation redshifts of our galaxies. In addition, galaxies in Coma and Abell 262 – where the dynamical mass that follows the light is in excess of a Kroupa stellar population – do not differ in terms of their stellar population ages, metallicities and α-element abundances from galaxies where this is not the case.

Taken at face value, our dynamical mass models are therefore as consistent with a universal IMF, as they are with a variable IMF. If the IMF indeed varies from galaxy to galaxy according to the average star-formation rate (Conroy & van Dokkum 2012) then the assumption of a constant stellar mass-to-light ratio *inside* a galaxy should be relaxed in future dynamical and lensing models.

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