Dark Matter and IMF normalization in Virgo dwarf early-type galaxies

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ABSTRACT
In this work we analyze the dark matter (DM) fraction, \( f_{DM} \), and mass-to-light ratio mismatch parameter, \( \delta_{IMF} \) (computed with respect to a Milky-Way-like IMF), for a sample of 39 dwarf early-type galaxies (dEs) in the Virgo cluster. Both \( f_{DM} \) and \( \delta_{IMF} \) are estimated within the central (one effective radius) galaxy regions, with a Jeans dynamical analysis that relies on galaxy velocity dispersions, structural parameters, and stellar mass-to-light ratios from the SMAKCED survey. In this first attempt to constrain, simultaneously, the IMF normalization and the dark matter content, we explore the impact of different assumptions on the DM model profile. On average, for a NFW profile, the \( \delta_{IMF} \) is consistent with a Chabrier-like normalization (\( \delta_{IMF} \sim 1 \)), with \( f_{DM} \sim 0.35 \). One of the main results of the present work is that for at least a few systems the \( \delta_{IMF} \) is heavier than the Milky-Way-like value (i.e. either top- or bottom-heavy). When introducing tangential anisotropy, larger \( \delta_{IMF} \) and smaller \( f_{DM} \) are derived. Adopting a steeper concentration–mass relation than that from simulations, we find lower \( \delta_{IMF} \) (\( \lesssim 1 \)) and larger \( f_{DM} \). A constant \( M/L \) profile with null \( f_{DM} \) gives the heaviest \( \delta_{IMF} \) (\( \sim 2 \)). In the MONDian framework, we find consistent results to those for our reference NFW model. If confirmed, the large scatter of \( \delta_{IMF} \) for dEs would provide (further) evidence for a non-universal IMF in early-type systems. On average, our reference \( f_{DM} \) estimates are consistent with those found for low-\( \sigma_e \) (\( \sim 100 \text{ km s}^{-1} \)) early-type galaxies (ETGs). Furthermore, we find \( f_{DM} \) consistent with values from the SMAKCED survey, and find a double-value behavior of \( f_{DM} \) with stellar mass, which mirrors the trend of dynamical \( M/L \) and global star formation efficiency (from abundance matching estimates) with mass.

Key words: galaxies: evolution – galaxies: general – galaxies: elliptical and lenticular, cD

1 INTRODUCTION
Dark matter (DM) is a ubiquitous component of the universe and dominates the mass density of virialized objects as galaxies and clusters of galaxies. The current scenario of galaxy evolution predicts that structures form bottom-up, i.e. the smallest haloes form first, and then, larger and more massive haloes are created from the merging of such smaller objects. Within this scenario, numerical simulations of (DM only) structure formation within the standard ΛCDM framework have provided accurate predictions on the DM density distribution from dwarf to massive galaxies, up to bigger structures, such as clusters of galaxies (Navarro et al. 1996; Bullock et al. 2001; Macciò et al. 2008). However, more realistic models have been produced to evaluate the effect of baryons on the DM distribution (e.g., Gnedin et al. 2004).

No model of galaxy formation can be complete without an understanding of how dwarf galaxies form, as these systems are the closest objects, in the nearby Universe, to the building blocks of present, more massive, galaxies. Their shallow potential wells make them susceptible to a large variety of processes, from supernova feedback, to externally induced effects, such as photoionization and heating from cosmic UV background, as well as environmental processes, such as tidal interactions and ram-pressure stripping (Dekel & Birnboim 2006; Recchi 2014). This makes dwarf galaxies challenging to model, but at the same time, excellent laboratories to test important ingredients of astrophysics.

Providing a picture of the formation and evolution of dwarf galaxies implies to understand the origin of their
luminous and dark mass components. In this regard, together with age and metallicity, the stellar Initial Mass Function (IMF) is a key stellar ingredient, as varying the IMF can lead to variations of a factor of \(\sim 2\) into the mass scale of galaxies. Direct counts in the Milky Way (MW) have originally characterized the IMF as a power-law mass-distribution, \(dN/dM \propto M^{-\alpha}\), with \(\alpha \sim 2.35\) (Salpeter 1955), and subsequently refined it to flatten at lower masses \((M \lesssim 0.5M_\odot; Kroupa 2001; Chabrier 2003)\). The IMF has been initially considered as universal across galaxy types and cosmic time, mostly because of a lack of evidence of IMF variations among stellar clusters and OB associations in our Galaxy. This assumption has been recently questioned by a loud chorus of dynamical, lensing, and stellar population studies, finding evidence for systematic IMF variations in massive early-type galaxies (ETGs; Treu et al. 2010; Thomas et al. 2011; Conroy & van Dokkum 2012; Cappellari et al. 2012; Spiniello et al. 2012; Wegner et al. 2012; Dutton et al. 2013; Ferreras et al. 2013; Goudfrooij & Krukissen 2013; La Barbera et al. 2013; Tortora et al. 2013; Weidner et al. 2013; Goudfrooij & Krukissen 2014; Shu et al. 2014; Tortora et al. 2014a,b). These independent lines of evidence are interpreted with an excess of low-mass stars in high- (relative to low-)mass ETGs, implying lower DM fractions in these systems than found under the assumption of a universal, MW-like, distribution (e.g., Cappellari et al. 2012; Tortora et al. 2013). However, evidence for a heavier IMF normalization, than the MW-like one, has been recently questioned for three nearby massive galaxies by Smith (2013) and Smith et al. (2013), based on a lensing analysis of low-redshift ETGs.

Previous works of the DM and stellar mass distribution in galaxies have focused on the study of intermediate-luminosity and bright ETGs, with stellar masses \(M_* \gtrsim 10^{10} M_\odot\). At lower mass scales, most of the analysis have assumed universal IMF: e.g. Geha et al. (2002), who have fitted long-slit spectroscopy for six dwarf ellipticals (dE), Ry s et al. (2014), who have performed the full dynamical modelling of 2D kinematic data of 12 dEs, Toloba et al. (2014a,b), who use virial theorem to model effective velocity dispersion for a sample of 39 dEs. In contrast, there are very few analyses of the IMF, see, e.g., the direct constraints in ultra-faint dwarf galaxies around the Milky Way (Geha et al. 2013). Moreover, to date, no detailed dynamical analysis has been performed to characterize both the DM content and IMF normalization (i.e. the stellar mass-to-light ratio normalized to that expected for a MW-like distribution) at these low masses, e.g. in dEs. As more massive ETGs, dEs are an ideal target for this kind of study, as they are dominated by old halo stars, have negligible star formation rate at present, and little dust content (de Looze et al. 2014; Toloba et al. 2014), making the computation of mass-to-light ratios less affected by systematics.

In this paper, we fill the above-mentioned gap, studying the central mass distribution of 39 Virgo dEs, drawn from Toloba et al. (2014), hereafter T+14), in the stellar mass range \(\sim 10^8 - 10^9 M_\odot\). We fit the central dynamics using various (stellar and DM) mass distribution profiles, comparing our findings with results for massive systems. The layout of the paper is the following. In Section 2 we describe the datasample and our dynamical method. In Section 3 we discuss the results of the paper. Conclusions are drawn in Section 4.

## 2 SAMPLES AND DATA ANALYSIS

### 2.1 Dataset

We analyze a sample of 39 dEs in the magnitude range \(-19 < M_e < -16\), selected from the Virgo Cluster Catalog (VCC, Binggeli et al. 1985) to have high surface brightness with respect to the dwarf galaxy population (Janz & Lisker 2009). Albeit incomplete in luminosity, this sample is representative of the early-type population in this magnitude range (T+14).

The analysis relies on the following data:

- **Single Sérsic fit.** The structural parameters are taken from Table 4 of T+14, where the \(R_e\) from the growth curve fit and the Sérsic index from the single Sérsic fit are from Janz et al. (2014). The \(R_e\)'s of the growth curve fits match reasonably well those from direct single-Sérsic fits. For 9 systems without a measured value of \(n\) (as they had no fit with a single Sérsic component or are not present in Janz et al. 2014), we have adopted \(n = 1\), testing the impact for different choices of this parameter (see Section 3). Although only 8 out of the 39 SMAKCED dEs are best fitted with a single (relative to a double) Sérsic profile (see below), to allow a more homogeneous comparison with massive ETGs from the SPIDER sample (La Barbera et al. 2010), we adopt single-component parameters as our reference case throughout the present work.

- **Double Sérsic fit.** Data for the inner and outer Sérsic components are taken from Table 5 in Janz et al. (2014), for the 33 (out of SMAKCED sample of 39) dEs analyzed in that work. Out of these 33 dEs, 25 objects are better described by multiple components, with 19 galaxies being described by a double Sérsic fit and 6 by a single Sérsic profile plus a lens.

- **Effective velocity dispersions, \(\sigma_v\).** computed within an ellipse of semi-major axis length of one \(R_{maj}\) (T+14). The \(\sigma_v\)'s have been computed by T+14 by flux-averaging both rotation velocity and velocity dispersion within each galaxy isophote, hence accounting for both ordered and random motions in each system.

- **Age and metallicity estimates** are taken from Table 5 of T+14, which have fitted relevant Lick spectral indices – measured within the \(R_{maj}\) ellipse – with Vazdekis et al. (2012) simple stellar population (SSP) models. Using exponentially...
declining star formation histories, T+14 have demonstrated that the stellar masses are, on average, fairly consistent with the SSP estimates, but the scatter is larger. For four galaxies (VCC 0170, VCC 0781, VCC 1304 and VCC 1684) Hβ and/or Hα are found in emission. The emission lines are narrower than absorption lines, thus the two components can be decoupled (see Toloba et al. 2014 for details). Although they do not find any significant emission in any of the other galaxies, they cannot rule out the possibility of them having some emission. Thus, for galaxies with undetected emission features the estimated ages (and stellar masses) would be taken as upper limits. See Section 3.1 for further details.

2.2 Analysis

For each galaxy, we obtain the stellar H-band mass-to-light (M/L) ratio, Υ_{SSP}, using the best fitted age and metallicity from T+14, and the simple stellar population (SSP) models of Vazdekis et al. (2012), for a Kroupa IMF. These Υ_{SSP} are converted to those for a Chabrier IMF, by subtracting 0.05 dex (i.e. the difference in normalization between the Kroupa and Chabrier IMFs). Under the assumption of a radially constant Υ_{SSP}, the deprojected mass profile of the stellar component is written as M_*(r) = Υ_{SSP} J_*(r), with Υ = Υ_{SSP}. To derive the light profile J_*(r), we perform a deprojection, under the assumption of spherical symmetry, of the H-band S´ersic profiles (from the galaxy structural parameters, see above). Dynamical (DM + light) mass estimates are obtained by fitting the observed σ with spherical, isotropic Jeans equations (Tortora et al. 2009). To account for the fact that σ is averaged within an elliptic aperture, while we rely on spherical models, we calculate the 3D velocity dispersion from the radial Jeans equation at the circularized (geometric) effective radius, R_e = qR_{maj}. The dynamical (i.e. total) mass distribution of galaxies is computed by adopting either single-component (i.e. a radially constant dynamical M/L) or two-component profiles (i.e. stellar component plus DM halo) with the stellar Υ, being a free fitting parameter, or fixed to Υ_{SSP} (in case some other quantity, e.g. concentration, is let free to vary, see the different cases described below).

Thus, after the mass model is chosen and the predicted velocity dispersion, σ_v^2(p), from the Jeans equation, is derived, the equation σ_v^2(p) = σ_v is solved with respect to the free parameter p. The uncertainties on the best-fitting parameter p and derived quantities are obtained by shifting the input parameters (i.e. σ_v, R_e, n, M_*) according to their errors a number of times and considering the distributions of corresponding best-fitting solutions.

2.3 Mass models

We rely only on velocity dispersions measured within a single aperture, which does not allow us to constrain the shape of the DM profile in detail. To this effect, we explore a variety of models, analyzing several plausible assumptions.

The range of models considered in this study are summarized in Table I. Numerical collisionless N-body simulations have provided clues on the formation and the evolution of DM haloes, finding that the DM density of the haloes (from dwarf galaxies to clusters) is independent of halo mass and well described by a double power-law relation with a cusp at the center (Navarro et al. 1996, 1997, Moore et al. 1998). Thus, it is a natural choice to start from this theoretical motivated class of DM profiles.

As reference case, we adopt the two-component mass profile NFW (see Table I), given by a S´ersic-based stellar mass distribution (with p = Υ, as a free parameter) and a standard DM halo with a Navarro et al. (1996, NFW, hereafter) density profile. We relate virial mass, M_{vir}, to concentration, c_{vir}, with the mean trend for a WMAP5 cosmology (for relaxed halos in Macciò et al. 2008), while the M_{vir} - M relation is assumed from Moster et al. (2010, M+10 hereafter), which extends down to stellar masses of \sim 10^8 M_⊙.

The model NFWf-multi is used to study the impact of varying the parametrization of the galaxy light distribution. For galaxies whose light distribution is better fitted by a multiple, rather than a single, component according to Janz et al. (2014), we describe the stellar component with double-S´ersic fit parameters.

Following Tortora et al. (2014a), we also explore how our results depend on the assumed c_{vir} - M_{vir} relation. In particular, since for higher mass galaxies (than those analyzed in the present work), some studies suggest higher concentrations than those from simulations (Booote et al. 2007, Leier et al. 2012, hereafter LFS12), we also consider “high-concentration” models (NFWf-hc), with c_{vir} = 20, in contrast to the typical value of \sim 12 predicted for our dEs from the Macciò et al. (2008) relation (for M_\sim 10^9 M_⊙ and M_{vir} \sim 10^{13} M_⊙). We refer to these models as “high-concentration” NFW models, NFWf-hc. Moreover, the impact of cosmological framework on the theoretical c_{vir} - M_{vir} relation is analyzed with models NFWf-WMAP1 and NFWf-WMAP3, which use WMAP1 and WMAP3 results from N-body simulations in Macciò et al. (2008). Notice that WMAP1 predictions are very similar to the c_{vir} - M_{vir} based on the first release of Planck cosmological parameters (Dutton & Macciò 2014)

A possible source of systematics is the hypothesis of isotropic stellar orbits, as spatially resolved stellar kinematics for a handful of dEs has been found to be better modelled with tangential anisotropies, rather than isotropy (e.g. Geha et al. 2003). Although a detailed analysis of galaxy anisotropies is far from being trivial, and is certainly beyond the scope of the present work, we have estimated the impact of anisotropy on our inferences. To this effect, in our list of models (Table I), we have also included three cases corresponding to radially constant anisotropy β in the Jeans equations (see also Tortora et al. 2009, 2014): a “mild” tangential anisotropy, β = -0.4, (NFWf-mild-tan-β), a “strong” tangential anisotropy, β = -1, (NFWf-strong-tan-β) and a “mild” radial anisotropy, β = 0.4 (NFWf-mild-rad-β).

To further explore the effect of mass modelling, as well as the impact of adopting alternative theories of gravity on our results, we also consider the following models.

- cMLf. In contrast to the DM haloes predicted by N-body simulations, a different class of models relies on the
assumption that total mass follows the light distribution, i.e. constant \( M/L \) models with \( \rho_{\text{SL}} = \Upsilon_{\text{tot},J^*} \). Thus, we adopt a no-DM model with constant \( M/L \) profile, defined to have a total mass distribution \( \rho_{\text{noDM}} = \Upsilon_{J}, \) with \( \Upsilon_{J} \) as the only free fitting parameter.

- **MOND.** A modified Newtonian gravitational acceleration model, in the regime of low acceleration, according to the MOND theory (Milgrom 1983; Begeman et al. 1991), has become an alternative theory to reproduce galactic dynamics without DM. The acceleration as a function of the radius \( r \), \( g(r) \), is given by \( g(r) = g_n(r) \), where \( x = g(r)/a_0 \), \( a_0 \) is the MOND acceleration constant (which sets the transition from the Newtonian to the low acceleration regime), \( g_n \) is the Newtonian acceleration, and \( \mu(x) \) is an empirical function interpolating between the two regimes. We adopt the following expressions: a) \( \mu_1(x) = x/(1 + x) \) (MOND1, Famaey & Binney 2005; Angus 2008) and b) \( \mu_2(x) = x/\sqrt{1 + x^2} \), which has been the first one successfully tested with observations (MOND2, Sanders & McGaugh 2002). A constant \( M/L \) profile with a free \( \Upsilon_{J} \) is adopted for the total mass distribution (see Tortora et al. 2014 for further details).

To complete our large model portfolio, we also adopt two models with \( \Upsilon_{J} = \Upsilon_{\text{SSP}} \), with a fixed Chabrier IMF normalization:

- **NFfC.** A NFW model, adopting the same \( M_{\text{vir}}-M_{*} \) relation used for NFfW, but dismissing the \( c_{\text{vir}} - M_{\text{vir}} \) relation, and leaving \( c_{\text{vir}} \) as a free parameter.

3 IMF MISMATCH AND DM FRACTIONS

The final products of our analysis are the SSP \( M/L, \Upsilon_{\text{SSP}} \), the dynamically-determined stellar and total \( M/L \)'s, \( \Upsilon_{J} \) and \( \Upsilon_{\text{dyn}}, \) the inferred mismatch parameter \( \delta_{\text{IMF}} \) for models with free IMF normalization, defined as \( \delta_{\text{IMF}} \equiv \Upsilon_{J}/\Upsilon_{\text{SSP}}, \) and effective DM fraction, \( f_{\text{DM}} \equiv 1 - \Upsilon_{J}/\Upsilon_{\text{dyn}}. \)

In Figure 1 we plot the results of our analysis. In the left panel, we plot \( \delta_{\text{IMF}} \) vs. \( f_{\text{DM}} \) for our reference NFfW model (cytan symbols), while the median \( \delta_{\text{IMF}} \), computed for the whole sample of dEs, versus the median \( f_{\text{DM}}, \) are shown in the right panel, for all models listed in Table 1 (error bars show the 16-84th percentile scatter in the data). For the “standard” NFfW, in two cases (i.e. VCC 0009 and VCC 1355) the model fails to fit the data. Only 50% of the sample is fitted by the “high-concentration” model, NFfW-hc. For NFfW-WMAP1, VCC 0009 is the only galaxy for which the model fails, while for NFfW-WMAP3 the model fails for VCC 0009, VCC 0170, VCC 0308 and VCC 1355. The “fixed IMF” models (NFfC and cMLC) only fail for VCC 1910. On the other hand, MOND and cMLC models allow all galaxies to be fitted. The two-component (or Chabrier IMF-fixed) models fail to reproduce the data as the mass from the assumed DM model (or from the Chabrier IMF-based model) is larger than the total mass allowed by the observed \( \sigma_e \). This is not contem- plated in the cMLC and MONDian models, for which it is always possible to find a \( \Upsilon_{J} \), reproducing the data.

In the next sections we will discuss the \( \delta_{\text{IMF}} \) and \( f_{\text{DM}} \) estimates for each galaxy in the sample and then we will study the impact of mass model comparing the median and
the standard error of the median calculated over the sample

\[ \delta \]

distribution of the models in Table 1. We also determine the

\[ \delta \]

standard error of the median by the factor 1.253 [Harding et al. 2013].

\[ \delta \]

Figure 2. Effective radius (top-) and galaxy velocity dispersion (bottom-panels) versus \( M_{\text{Chab}} \). Different points are color-coded according to \( \delta_{\text{IMF}} \) (left panels) and \( f_{\text{DM}} \) (right panels), respectively (see labels in the top panels). The model NFW is adopted. Large and small dots correspond to SMACKED dEs and bright SPIDER ETGs, respectively. Structural parameters for the SPIDER ETGs have been measured in the K band, roughly matching the H-band photometry of SMACKED dEs.

Table 1. Mass models adopted in this study. Column 1 reports the label of each model. Columns 2, 3 and 4 list the main model ingredients, while columns 5 and 6 give the corresponding IMF normalization, \( \delta_{\text{IMF}} \), and DM content, \( f_{\text{DM}} \), estimates from our dynamical analysis. Median, 16-84th percentiles of the sample distribution and the standard error of the median are shown.

| ID | Model | \( M_{\text{dm}} - c_{\text{eff}} \) | IMF | Results | \( \log \delta_{\text{IMF}} \) | \( f_{\text{DM}} \) |
|----|-------|-------------------------------|-----|---------|----------------|----------------|
| NFW | NFW + Sérsic | M + 10 - WMAP5 | free | 0.13 \( ^{+0.25}_{-0.06} \) \( ^{+0.06}_{-0.06} \) | 0.35 \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW-multi | NFW + 2 Sérsic | M + 10 - WMAP5 | free | 0.05 \( ^{+0.03}_{-0.03} \) \( ^{+0.04}_{-0.04} \) | 0.39 \( ^{+0.05}_{-0.05} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW-bc | NFW + Sérsic | M + 10 - c_{eff} = 20 | free | \( -0.21^{+0.03}_{-0.02} \) \( ^{+0.13}_{-0.12} \) | \( 0.7^{+0.21}_{-0.22} \) \( ^{+0.05}_{-0.05} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW MILAP1 | NFW + Sérsic | M + 10 - WMAP1 | free | \( 0.0^{+0.0}_{-0.0} \) \( ^{+0.00}_{-0.00} \) | \( 0.47^{+0.16}_{-0.16} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW MILAP3 | NFW + Sérsic | M + 10 - WMAP3 | free | \( 0.20^{+0.04}_{-0.04} \) \( ^{+0.09}_{-0.09} \) | \( 0.29^{+0.05}_{-0.05} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW-mild-tan-\( \beta \) | NFW + Sérsic + \( \beta = 0.4 \) | M + 10 - WMAP5 | free | \( 0.20^{+0.04}_{-0.04} \) \( ^{+0.05}_{-0.05} \) | \( 0.32^{+0.03}_{-0.03} \) \( ^{+0.03}_{-0.03} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW-strong-tan-\( \beta \) | NFW + Sérsic + \( \beta = 0.4 \) | M + 10 - WMAP5 | free | \( 0.20^{+0.04}_{-0.04} \) \( ^{+0.05}_{-0.05} \) | \( 0.32^{+0.03}_{-0.03} \) \( ^{+0.03}_{-0.03} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFW-mild-rad-\( \beta \) | NFW + Sérsic + \( \beta = 0.4 \) | M + 10 - WMAP5 | free | \( 0.20^{+0.04}_{-0.04} \) \( ^{+0.05}_{-0.05} \) | \( 0.32^{+0.03}_{-0.03} \) \( ^{+0.03}_{-0.03} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| cMLf | constant | \( M/L \) | free | \( 0.13^{+0.02}_{-0.02} \) \( ^{+0.05}_{-0.05} \) | \( 0.3^{+0.05}_{-0.05} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| cMLf M01 | \( \mu_{1} + \text{constant} \) | \( M/L \) | free | \( 0.06^{+0.02}_{-0.02} \) \( ^{+0.05}_{-0.05} \) | \( 0.3^{+0.05}_{-0.05} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| cMLf M02 | \( \mu_{2} + \text{constant} \) | \( M/L \) | free | \( 0.20^{+0.04}_{-0.04} \) \( ^{+0.05}_{-0.05} \) | \( 0.32^{+0.03}_{-0.03} \) \( ^{+0.03}_{-0.03} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| NFWC | NFW + Sérsic | M + 10 - c_{eff} free | Chabrier | 0 | \( 0.60^{+0.16}_{-0.05} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
| cMLC | constant | \( M/L \) | free | \( 0.23^{+0.04}_{-0.04} \) \( ^{+0.05}_{-0.05} \) | \( 0.3^{+0.05}_{-0.05} \) \( ^{+0.04}_{-0.04} \) | 0.03 \( ^{+0.05}_{-0.05} \) |
3.1 NFW and systematics in light profile

Our reference NFWf model produces, on average, $\delta_{\text{IMF}} \sim 1.3$ (log $\delta_{\text{IMF}} \sim 0.1$ dex) and $f_{\text{DM}} \sim 0.35$. The large scatter in $\delta_{\text{IMF}}$ (see points in the left panel and gray scatter bar in the right panel of Figure 4) is due to the fact that while most galaxies turn out to have an IMF normalization consistent with a MW-like distribution (log $\delta_{\text{IMF}} \sim 0$), a significant fraction of them ($\sim 30\%$) have a super-Salpeter IMF normalization (i.e. $\delta_{\text{IMF}} > 1.8$). DM fractions are, on average, in the range $0.2$ to $0.6$, consistent with independent estimates for “normal” (as opposed to dwarf) ETGs (see below). The standard error of the median is $\sim 0.04$ for $f_{\text{DM}}$ and $\sim 0.05$ dex for $\delta_{\text{IMF}}$.

Adopting $10\%$ uncertainties on $R_e$ and $n$, and propagating the uncertainties on age and metallicity from Table 5 in T+14, we find 1σ average errors on $\delta_{\text{IMF}}$ and $f_{\text{DM}}$ of $\sim 0.15$ dex and $\sim 0.05$, respectively. Taking the uncertainties into account, we find that some dEs have $\delta_{\text{IMF}}$ inconsistent (heavier than) a Chabrier IMF normalization. In particular, at the 3σ level, the galaxies VCC0397, VCC0750 and VCC1684 have $\delta_{\text{IMF}} > 1.8$, while VCC0523, VCC0781, VCC1122 and VCC1528 have $\delta_{\text{IMF}} > 1$ (but $< 1.8$). Assuming $30\%$ (rather than $10\%$) uncertainties on both $R_e$ and $n$, the error on $\delta_{\text{IMF}}$ is almost unchanged, while for $f_{\text{DM}}$ is of $\sim 0.1$ and we find that, at 3σ, VCC0750 and VCC1684 still have $\delta_{\text{IMF}} > 1.8$, while VCC0397 and VCC0781 have $1 < \delta_{\text{IMF}} < 1.8$. Note that to these larger $\delta_{\text{IMF}}$ correspond smaller DM fractions, with $f_{\text{DM}} < 0.2 – 0.3$. Thus, while for most galaxies our results are consistent with a MW-like normalization, our analysis suggests that for at least a few dEs, the $M/L$ detected from previous studies (e.g. T+14) might be partly accounted for by heavier IMF normalization, rather than large DM fractions in the galaxy central regions.

Note that a $\delta_{\text{IMF}}$ larger than one can be due to either a bottom-heavy (due to a larger fraction of dwarf relative to giant stars) or a top-heavy IMF (because of the large fraction of stellar remnants from evolved massive stars). This degeneracy has been broken in ETGs, by studying gravity-sensitive features in the integrated light of galaxies. Such spectroscopic approach allows one to constrain the mass fraction of dwarf-to-giant stars in the IMF, rather than its overall normalization, in contrast to dynamical and lensing methods (Conrow & van Dokkum 2012, Spiniello et al. 2012, La Barbera et al. 2014). Indications of top-heavy IMFs are found from a) galaxy number counts (Baugh et al. 2005), b) in ultra compact dwarfs, based on the large fraction of low-mass X-ray binaries found (Dabringhausen et al. 2012), c) in the MW center (e.g., Bartko et al. 2010) or d) in Galactic globular clusters (e.g., Prantzos & Charbonnel 2003). In addition, galaxy formation models reproduce the observed Intra-Cluster medium if a top-heavy IMF is adopted (Nagashima et al. 2003). Studies of gravity-sensitive features in dEs are still missing, thus, we cannot exclude a top-heavy IMF in these systems.

As mentioned in Section 2 Sérsic indices are measured only for 30, out of 39, dEs analyzed in this work. For systems with no available $n$, we have adopted $n = 1$. To test the effect of this assumption, we have varied the Sérsic $n$ from 0.5 to 2, which is a “conservative” range, encompassing the observed values, for the SMACKED sample of dEs. For the 7 (out of 9) systems where the NFWf fits do not fail, the impact of changing the $n$ is shown in the left panel of Figure 4 (see dark-green lines), which show how the $\delta_{\text{IMF}}$ and $f_{\text{DM}}$ values change when the $n$ is varied. Larger Sérsic indices correspond to smaller $\delta_{\text{IMF}}$ and larger $f_{\text{DM}}$. We find, on average, a mild variation of $\sim 0.05$ dex on both $\delta_{\text{IMF}}$ and $f_{\text{DM}}$, with negligible impact on median values for the whole sample. We have further tested the effect of the $n = 1$ assumption on the galaxies with a measured Sérsic index, by varying it to $n = 1$. On average, the variation is 0.03 for $f_{\text{DM}}$ and $-0.02$ dex for $\delta_{\text{IMF}}$.

We have also tested the impact of different parametrization of the light on our dynamical estimates. The model NFWf-multi replaces the single Sérsic profile with the double Sérsic parametrization for those systems which are better fitted by the latter model. The results over the whole sample for both NFWf and NFWf-multi models are plotted in the left panel of Figure 4 to highlight the effect of a refined description of the light distribution in our dynamical analysis. The galaxies with the largest $f_{\text{DM}}$ are the most affected. However, the medians computed over the whole sample are almost unchanged with respect to the reference NFWf (see right panel of Figure 4).

As we have mentioned in Section 2, galactic nuclei, if present, are excluded in the fit of the light distribution of the SMACKED dEs. It is important to quantify the impact on our results if these nuclei are included in the analysis. Because it is not trivial to extract the amount of light due to the nuclei from T+14, we rely on estimates from independent literature. 9 out of the 39 galaxies are shared with Paudel et al. (2011), who has provided estimates of nuclear fluxes, $f_{\text{nuc}}$, at $r < 2r_e$ and total ones, $f_{\text{tot}}$ (their Table 1), finding that the nuclei account for $< 2\%$ of the total flux. Assuming that this limit can be extended to the whole SMACKED sample, we have included in our modelling procedure a constant mass distribution with flux $f_{\text{nuc}}$ at $r < 2r_e$. We find that the impact on our results is negligible, since the $\delta_{\text{IMF}}$ gets smaller by 0.02 dex, while the $f_{\text{DM}}$ are left unchanged. The $\delta_{\text{IMF}}$ would get smaller by more than 0.1 dex for nuclei which account for more than 10% of the total flux. However, such prominent nuclei are not observed.

Finally, correcting for not detected emission lines would make the ages and stellar masses smaller, getting $f_{\text{DM}}$ and $\delta_{\text{IMF}}$ larger. To provide a quantification of this effect we have augmented the measured $H_\beta$ index by its error (which we use to estimate the impact of emission), and matched it with Vazdekis et al. (2012) model predictions, deriving younger stellar populations. We have also taken into account metallicity change due to age variation, using the model predictions on the $[Mg/Fe]$–$H_\beta$ plane. On average, stellar masses and $\delta_{\text{IMF}}$ get smaller and larger by $\sim 0.05$ dex, respectively, and $f_{\text{DM}}$ is larger by $\sim 0.07$.

3.2 DM mass model degeneracy

We start discussing the impact of different $c_{\text{vir}} - M_{\text{vir}}$ relations. We notice that for “high-concentration” NFW models, NFWf-hc, the best-fitting $T_e$ is significantly lower than that for a Chabrier IMF (i.e. $\delta_{\text{IMF}} < 1$). As already discussed, a value as high as $c_{\text{vir}} = 20$ is able to describe only $\sim 50\%$ of the SMACKED dEs. These models predict too much mass in the center than what is allowed by the measured $\sigma_v$. Together with the fact that the Chabrier IMF...
gives the minimum normalization with respect to either top- or bottom-heavier distributions (when other relevant stellar population parameters, such as age and metallicity, are fixed), this result suggests that high concentration models are generally disfavoured for SMAKCED dEs. Since only 50% of the sample is fitted, the standard errors of the median get higher, i.e. $\sim 0.05$ for $f_{\Delta DM}$ and $\sim 0.13$ dex for $\delta_{\Delta IMF}$. For what concerns different theoretical predictions for the DM frameworks are equivalent to reproduce the dynamics of the central galaxy regions (Tortora et al. 2014b). In particular, for $f_{DM}$ the highest $\delta_{\Delta IMF}$ and smaller DM fractions (see Figure 1). The right panel in Figure 1 illustrates the effect of anisotropy on our sample results (see open red symbols), with respect to our reference NFWf model (filled red square). For tangential anisotropy (e.g. Goha et al. 2002), we obtain larger dynamical masses (see also Tortora et al. 2012), larger $\delta_{\Delta IMF}$ and smaller $f_{\Delta DM}$ with respect to the NFWf isotropic case. In particular, for $\beta = -0.4$ ($\beta = -1$) $\delta_{\Delta IMF}$ gets larger by $\sim 0.09$ ($\sim 0.15$) and $f_{\Delta DM}$ is smaller by $\sim 0.03$ ($\sim 0.05$). For the sake of completeness, we also consider here results when radial anisotropy is assumed. This provides smaller $\delta_{\Delta IMF}$ (by $\sim 0.11$) and larger DM content (by $\sim 0.05$). Overall, we conclude that the effect of anisotropy is not negligible, especially for what concerns $\delta_{\Delta IMF}$, while for $f_{\Delta DM}$ the results remain constrained within the typical error budget of our models, even with the more “extreme” assumption (e.g. $\beta = -1$).

The highest $\delta_{\Delta IMF}$ are obtained, as expected, by the model with no DM, i.e. cMLf (filled blue square and error bar in Figure 1), where $\delta_{\Delta IMF}$ is significantly larger than the NFWf case ($\delta_{\Delta IMF} > 1.5$), with $\sim 80\%$ of galaxies nominally consistent with a super-Salpeter IMF normalization. When assuming tangential anisotropy, all galaxies in this model would turn out to have super-Salpeter normalization.

For what concerns models with modified gravity, median results are shown in Figure 1 as open blue (MOND1) and violet squares (MOND2), respectively. The $\delta_{\Delta IMF}$'s differ by $\sim 0.14$ dex between the two cases, bracketing results for the NFWf. However, within uncertainties the two models give consistent results. Thus for dEs we confirm the same conclusions as for more massive ETGs, i.e. that the MOND and DM frameworks are equivalent to reproduce the dynamics of the central galaxy regions (Tortora et al. 2014b).

Finally, Figure 1 shows $f_{DM}$ estimates for the two models with fixed Chabrier IMF, i.e. $\sigma_{\scalebox{0.9}{FWC}}$ and cMLC, respectively. As expected, because of the intrinsically lower stellar $M/L$ normalization, the $f_{DM}$ are much larger ( $\geq 0.4$, with an average of $\sim 0.6$) than the NFWf model.

3.3 Comparison with literature

As a comparison with independent results, Figure 1 also plots $f_{DM}$ estimates from Table 8 of T+14 (black cross and arrow in the right panel in Figure 1). They adopt a Kroupa IMF to describe the stellar component and use the virial relation $M_{\text{dyn}} \propto K(n)\sigma^2 R_e$, with $K = 3.63$, corresponding to a Sersic profile with $n \sim 2$ (Cappellari et al. 2003). After correcting their stellar masses to a Chabrier IMF, we obtain a median $f_{DM}$ value of $0.52^{+0.16}_{-0.15}$, which can be compared with our results for the cMLC model. A difference of $\Delta f_{DM} \sim 0.1$ is found (see Figure 1). This discrepancy is due to the fact that 1) T+14 adopt a different definition, with respect to our work, for the total and stellar mass within $1 R_e$, as dynamical masses are estimated within a sphere with radius $R_e$ (following the virial definition), while stellar masses are calculated within a projected cylinder with radius $R_e$; 2) the average Sersic index of the T14 sample is $n \sim 1.5$, and not $n \sim 2$ (as they assume to compute the $K(n)$). Note that the $K(n)$ tends to decrease with $n$ (Bertin et al. 2002). Correcting for these different assumptions, $M_{\text{dyn}}$ become larger and smaller masses within $1 R_e$ are smaller, making the median $f_{DM}$ value larger and identical to our cMLC estimate (this effect is outlined by the black horizontal arrow in the right panel in Figure 1). This agreement is expected if the same data and mass model are adopted.

We have also performed a comparison of our cMLC $f_{DM}$ with the values derived by means of a complete Jeans dynamical modelling (JAM) of the 2D kinematics in Rys et al. (2014). After the cross-matching, 6 galaxies are left. Looking at their face values, Rys et al. (2014) $f_{DM}$ are, on average, larger by $\sim 0.1$. These JAM values look quite similar to the virial predictions, which assume the same $K$-value of massive ETGs in Cappellari et al. (2006). If we normalize these mass definitions to our cMLC model, the discrepancy is even larger (by $\sim 0.2$). However, we find that this discrepancy is possibly related to inhomogeneity between the SMAKCED and Rys et al. (2014) data sets as differences in a) wavebands used to calculate structural parameters and $M/L$ (H-band in SMAKCED vs. r-band in Rys et al. 2014), b) stellar mass determinations, since absorption lines are fitted with Vazdekis et al. (2012) models in SMAKCED survey and color-to-$Y$ formula from Bell et al. (2003) is used in Rys et al. (2014), and c) estimated velocity dispersions. A complete understanding of these sources of systematics is beyond the scope of the present work.

3.4 Comparison with massive ETGs

In this section, we discuss our results for dEs into the broader framework of the continuity of intrinsic properties of spheroidal systems, comparing the finding for dEs with those for a local ($0.05 < z < 0.095$), complete, sample of $\sim 4300$ giant ETGs drawn from the SPIDER survey (see La Barbera et al. 2011 and Tortora et al. 2012 for further details about sample selection). The SPIDER dataset includes stellar masses derived from the fit of stellar population synthesis (SPS) models to optical+near-infrared photometry (Swindle et al. 2011), galaxy structural parameters (effective radius $R_e$ and Sersic index $n$; using 2DPHOT, La Barbera et al. 2008), homogeneously derived from $g$ through $K$ wavebands, and SDSS central-aperture velocity dispersions, $\sigma_{Ap}$. SPIDER ETGs are defined as luminous bulge dominated systems, featuring passive spectra in the central SDSS fiber aperture (La Barbera et al. 2010). The dynamical analysis, presented in our previous papers for

$^4$ Note that these stellar masses are consistent with ones obtained adopting absorption lines (Swindle et al. 2011).
SPIDER ETGs (Tortora et al. 2013; Tortora et al. 2014a), is similar to that carried out for dEs in the present work. In particular, we have derived DM content and IMF normalization for SPIDER ETGs using the NFW profile, i.e. assuming the NFW+Sérsic profile, with the same $c_{vir}$–$M_{vir}$ and $M_{*}$–$M_{vir}$ relations as for dEs.

The results for dE and luminous ETGs are compared in Figure 2 where $R_e$ and $M_*$ are plotted as a function of $M_*$ (see also T+14), and colour-coded in terms of $\delta_{DM}$ and $f_{DM}$ (left- and right-panels), respectively. The figure shows the well-known shallower $R_e-M_*$ and $\sigma_e-M_*$ relations for dEs, with respect to the relations for luminous ETGs (Matković & Guzmán 2003; Woo et al. 2008; Toloba et al. 2012). Note that dEs have an almost constant $R_e$ with respect to $M_*$, with no dependence of $\delta_{DM}$ on $R_e$ at fixed stellar mass (see big dots with different colors in the top-left panel of Figure 2). On the contrary, in the $\sigma_e-M_*$ plot (bottom-left panel), larger $\delta_{DM}$ correspond to larger $\sigma_e$. Notice that this is expected in our one-parameter NFW models, as dEs have almost constant $R_e$, and at fixed $M_*$, the only way to match a higher $\sigma_e$ is thus to have a larger (smaller) $\delta_{DM}$ ($f_{DM}$, see bottom-right panel). For what concerns the behaviour with $f_{DM}$ (right panels of the Figure), we also notice that both dEs and luminous ETGs have effective DM fractions driven by $R_e$, since bigger galaxies have larger $\delta_{DM}$ (see also Napolitano et al. 2010; Tortora et al. 2012).

The trends of $\delta_{IMF}$ and $f_{DM}$ with $M_*$ and $\sigma_e$ are plotted more explicitly for dEs and luminous ETGs, in Figure 3 (red and black symbols, respectively). The $\delta_{IMF}$ ($f_{DM}$) appears to increase (decrease) with $\sigma_e$ (panels (a) and (c)) consistent with what seen in Figure 2 while no significant correlation of both $f_{DM}$ and $\delta_{DM}$ is seen with $M_{\star, Chab}$ (panels (b) and (d)). However, we remind the reader that although representative of the population of dEs, SMAGCED sample is certainly incomplete with respect to $M_*$ and $\sigma_e$. Further analysis, based on spatially extended kinematical data (i.e. 2D spectroscopy) and complete galaxy samples, are required to pinpoint the intrinsic correlations of DM and IMF normalization with galaxy parameters in dEs.

For what concerns median values of $\delta_{IMF}$ and $f_{DM}$ (red dots and errorbars in Figure 3), we see that in the $\delta_{IMF}$–$M_*$ diagram (panel (b)), the median $\delta_{IMF}$ for dEs is consistent, overall, with that for ETGs. This is due to the fact that while most dEs have $\delta_{IMF}$ consistent with a MW-like normalization, a significant fraction of them exhibit a Salpeter or super-Salpeter normalization (Section 2). In fact, when looking at the $\delta_{IMF}$–$\sigma_e$ plot (panel (a)), we see that dEs tend to have, on average, slightly higher IMF normalization than the lowest $\sigma_e$ ETGs (whose normalization is fully consistent with the MW-like distribution). Interestingly, the trend of $f_{DM}$ with $M_*$ (panel (d)) points to a double-value behaviour of DM content with stellar mass in ETGs, with larger $f_{DM}$ in most massive ETGs ($M_*>10^{11} M_\odot$) and dEs ($M_*>10^9 M_\odot$), and a minimum at $M_* \sim 10^{10} M_\odot$.

To have some further hints of the $f_{DM}$ trends, we have constructed toy mass models, based on our reference NFW model by computing stellar mass profiles according to either a Chabrier or a Salpeter IMF, and adopting the mean size and $n$-mass relations of dEs and massive ETGs, respectively. Results for the $f_{DM}$ trends are shown in the bottom panels of Figure 3. At fixed IMF, such toy-models predict a double-value trend for the $f_{DM}$ as a function of both $\sigma_e$ and $M_{\star, Chab}$ (panel c and d). In the $f_{DM}$–$M_*$ diagram (panel d), this trend matches quite well the observations for both dEs and ETGs. In contrast, for the $f_{DM}$–$\sigma_e$ diagram, the toy-models give a good match to dEs (although some overall variation of $\delta_{IMF}$ is required to exactly match the trend, as also seen in panel a), while there is a clear mismatch in the case of massive ETGs, where toy models predict an increasing trend of $f_{DM}$ while the inferred $f_{DM}$ tends to mildly decrease with $\sigma_e$. As seen in panel a, this disagreement is due to the fact that toy models assume a constant IMF normalization, while data imply a strong trend of $\delta_{IMF}$ with $\sigma_e$. In summary, our toy-models also support a double-value behaviour in the $f_{DM}$–$M_*$ correlation.

We have also verified that the double-value trend of $f_{DM}$ does not depend critically on our assumptions of a given $M_{vir}$–$M_*$ relation. In fact, a similar result is found when considering the cMLC model.

The U-shape behaviour of $f_{DM}$ with $M_*$ in early-type systems can be understood as a result of different feedback mechanisms in these systems at different mass scales. In lowest mass galaxies (dEs), star-formation is likely inhibited by (e.g.) supernovae feedback. This becomes less important at increasing galaxy mass (Dekel & Birnboim 2006; Cattaneo et al. 2008). However, at the highest $M_*$, additional processes, such as dry merging, AGN feedback or halomass quenching further inhibit gas cooling, and decrease star-formation efficiency again (Dekel & Birnboim 2006). Hence, the lowest- and highest-mass galaxies are expected to have the lowest star-formation efficiency, and thus, under the assumption of a universal DM distribution, the highest DM content. The $f_{DM}$ trend in dEs and luminous ETGs adds up to other well known correlations in ETGs, such as the trends of total $M/L$ and star formation efficiency (Benson et al. 2003; Marinoni & Hudson 2002; van den Bosch et al. 2007; Comov & Wechsler 2009; M+10), the U-shape of half-light dynamical $M/L$ (Wolf et al. 2010; Toloba et al. 2011), $\mu_e - R_e$ (Capaccioli et al. 1992; Kormendy et al. 2000) and size-mass (Shen et al. 2003; Hyde & Bernardi 2009) relations, the trends of optical colour and metallicity gradients (Spolaor et al. 2010; Kuntschner et al. 2010; Tortora et al. 2011), as well as DM gradients (Napolitano et al. 2003) with galaxy mass.

4 DISCUSSIONS AND CONCLUSIONS

In this work, we have performed an isotropic Jeans dynamical analysis for 39 dwarf ellipticals in the Virgo cluster, from T+14. For the first time, we have studied the IMF normalization and the effective DM content using a suite of fixed DM profiles and the stellar $M/L$ as a free-fitting parameter. We have also performed the analysis with MOND, modified-gravity, models. The main results are shown in Figure 1 where we find that, on average, using a NFW profile and standard $c_{vir}$–$M_{vir}$ relation from N-body simulations (NFW model in Table 1), dEs have $\log \delta_{IMF} = 0.11^{+0.33}_{-0.27}$ with error $\sim 0.05$ dex (i.e. consistent with a Chabrier-like IMF normalization) and $f_{DM} = 0.35^{+0.27}_{-0.12}$ with error $\sim 0.03$. A constant-

5 Median and 16-84th percentiles of the sample distribution are shown, together with the standard error.
IMF and DM in dEs

$M/L$, with no-DM content (the cMLC model), maximizes the stellar mass content (i.e. the $\delta_{\text{DM}}$), pointing to super-Salpeter IMF normalizations. In the MOND scenario, using two standard interpolating functions (MOND1, Famaey & Binney 2005; MOND2, Sanders & McGaugh 2002) we find results which encompass the NFW predictions, in agreement with results for massive ETGs (Tortora et al. 2010). For completeness, we have also analyzed the cases of a universal Chabrier IMF (NFWC and cMLC), which provide larger effective DM fractions when compared to our reference model with free IMF normalization, NFWf. The derived DM fractions for the NFWC model are fully consistent with the estimates in Toloba et al. (2014), if stellar and dynamical masses are homogeneously defined. We have also analyzed the impact of several further assumption, such as light-profile parametrization, velocity dispersion anisotropy, and assumptions on the $c_{\text{vir}}-M_{\text{vir}}$ relation. In particular, at the mass scale of dEs, our data seem to disfavour a $c_{\text{vir}}-M_{\text{vir}}$ relation steeper than that from simulations, as it might be the case for more massive halos (see e.g. Leier et al. 2012), while if tangential anisotropy is assumed (see e.g. Geha et al. 2002), we obtain larger $\delta_{\text{DM}}$ and smaller $f_{\text{DM}}$ with respect to the reference isotropic case (on the contrary, radial anisotropy produces larger $f_{\text{DM}}$ and smaller $\delta_{\text{DM}}$). Although most of dEs have $\delta_{\text{DM}}$ consistent with a MW-like normalization, for the reference NFWf model, we also find evidence that some dEs might have $\delta_{\text{DM}} > 1$ or $> 1.8$ at high statistical significance, i.e. an IMF which is heavier that a Chabrier- or Salpeter-like distribution.

In Figures 2 and 3 we have compared results for dEs with those for massive ETGs from the SPIDER sample (La Barbera et al. 2010; Tortora et al. 2013, 2013). We find some hints that $\delta_{\text{DM}}$ might increase with $\sigma_e$, as in more massive ETGs (Tortora et al. 2013, 2014). However, spatially extended kinematical data (i.e. 2D spectroscopy) and complete galaxy samples are required to confirm if this trend is real, rather than due to sample incompleteness. Moreover, we find that, on average, dEs tend to have slightly higher IMF normalization than ETGs at lowest $\sigma_e$ ($\sim 100$ km s$^{-1}$), whose IMF normalization is fully consistent with a MW-like distribution.

The trend of $f_{\text{DM}}$ with $M_*$ suggests a double-value behaviour, with largest $f_{\text{DM}}$ in most massive ETGs ($M_* \gtrsim 10^{11} M_\odot$) and dEs ($M_* \sim 10^9 M_\odot$), and a minimum at $M_* \sim 2-3 \times 10^{10} M_\odot$. These trends mirror those of the dynamical $M/L$ (Wolf et al. 2010; Toloba et al. 2011), and of total star formation efficiency with respect to mass (Benson et al. 2000; Marinoni & Hudson 2002; van den Bosch et al. 2007; Conroy & Wechsler 2009, M+10), which are the result of the interplay among different physical processes, such as SN feedback at lowest galaxy masses, and AGN feedback, galaxy merging and halo mass heating in the most massive ETGs (Tortora et al. 2010).

In this paper, we have performed a first attempt to constrain, simultaneously, the IMF normalization and dark matter content of low-mass (dwarf) early-type galaxies, finding for at least a few systems that the $\delta_{\text{DM}}$ is heavier than the MW-like value. Since such a “heavy” $\delta_{\text{DM}}$ could be due to either a bottom- or a top- heavy distribution, a natural follow-up of the present work would be to study gravity-sensitive features in the integrated light of galaxies, which have provided, so far, important constraints to the
IMF slope of massive ETGs [Conroy & van Dokkum, 2012; Ferreras et al., 2013; La Barbera et al., 2014]. In fact, a similar analysis is currently lacking for dE’s. In the future, it will be also necessary to apply the present analysis to large and complete samples including a variety of stellar systems, such as dwarf ellipticals, dwarf spheroidals, ultra-compact dwarfs, and late-type galaxies, to achieve a complete picture of how the dark matter and stellar components have been assembled along the whole galaxy mass sequence.

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