Central mass-to-light ratios and dark matter fractions in early-type galaxies

C. Tortora¹,²⋆, N.R. Napolitano², A.J. Romanowsky³, M. Capaccioli⁴,⁵, G. Covone⁴,⁶

¹ INAF – Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 - Catania, Italy
² INAF – Osservatorio Astronomico di Capodimonte, Salita Moiariello, 16, 80131 - Napoli, Italy
³ UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
⁴ Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Compl. Univ. Monte S. Angelo, 80126 - Napoli, Italy
⁵ INAF – VSTceN, Salita Moiariello 16, 80131 - Napoli, Italy
⁶ INFN – Sezione di Napoli

Accepted Received

ABSTRACT

Dynamical studies of local elliptical galaxies and the Fundamental Plane point to a strong dependence of the total mass-to-light ratio on luminosity with a relation of the form \(M/L \propto L^\gamma\). The “tilt” \(\gamma\) may be caused by various factors, including stellar population properties (metallicity, age and star formation history), IMF, rotational support, luminosity profile non-homology and dark matter (DM) fraction. We evaluate the impact of all these factors using a large uniform dataset of local early-type galaxies from Prugniel & Simien (1996). We take particular care in estimating the stellar masses, using a general star formation history, and comparing different population synthesis models. We find that the stellar \(M/L\) contributes little to the tilt. We estimate the total \(M/L\) using simple Jeans dynamical models, and find that adopting accurate luminosity profiles is important but does not remove the need for an additional tilt component, which we ascribe to DM. We survey trends of the DM fraction within one effective radius, finding it to be roughly constant for galaxies fainter than \(M_B \sim -20.5\), and increasing with luminosity for the brighter galaxies; we detect no significant differences among S0s and fast- and slow-rotating ellipticals. We construct simplified cosmological mass models and find general consistency, where the DM transition point is caused by a change in the relation between luminosity and effective radius. A more refined model with varying galaxy star formation efficiency suggests a transition from total mass profiles (including DM) of faint galaxies distributed similarly to the light, to near-isothermal profiles for the bright galaxies. These conclusions are sensitive to various systematic uncertainties which we investigate in detail, but are consistent with the results of dynamics studies at larger radii.

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

1 INTRODUCTION

Early-type galaxies (ETGs) are the most massive stellar systems in the Universe, containing much of the cosmic budget of visible and dark matter (DM). They include elliptical (E) and lenticular (S0) galaxies and form a nearly uniform class of objects: usually red, old and with only traces of cold gas and active star formation. The striking regularities in their properties include strong correlations between size (e.g. the effective radius, \(R_{\text{eff}}\)) and the surface brightness therein (\(I_{\text{eff}}\); Kormendy [1977]), and between kinematics (the central velocity dispersion \(\sigma_0\)) and luminosity (\(L_\text{eff}\); Faber & Jackson [1976] hereafter FJ).

The two relations above merge into the so-called Fundamental Plane (FP; Djorgovski & Davis [1987], Dressler et al [1987]), i.e. a relation between the (logarithm of) \(\sigma_0\), \(R_{\text{eff}}\) and \(I_{\text{eff}}\) of ETGs. The FP can be interpreted in terms of the virial theorem of relaxed systems, according to which \(2T + U = 0\) where \(U\) is the potential energy and \(T\) the kinetic energy. This can be re-written in terms of observed
quantities as approximately \( L \propto \sigma^2 R_{\text{eff}} \). However, the FP is found observationally to be \( L \propto \sigma^2 R_{\text{eff}}^\alpha \) with \( \alpha \neq 1 \) and \( \eta \neq 2 \), i.e. a different orientation of the plane in the space of the logarithmic quantities with respect to the virial prediction. This tilt of the FP provides insight for the formation and structure of ETGs, and can be interpreted as a variation of the total mass-to-light ratio \( (M/L) \) with \( L \) (Dressler et al. 1987) with the simplest parametrization as a power law, \( M/L \propto L^\gamma \). The slope, \( \gamma \), of this relation could be driven by one or more different factors: a variation in stellar \( M/L \) (due to metallicity or age gradient or change in IMF), a variation in the DM content, non-homology, rotational support, etc. (see e.g. Busarello et al. 1997; D’Onofrio et al. 2006; Graves 2009). It is of considerable importance to disentangle these factors using high-quality data at low redshift, in order to use the FP as a guide to galaxy evolution in different environments and cosmic epochs (e.g. Kochanek et al. 2000; Bernardi et al. 2003; Reda et al. 2005; van Dokkum & van der Marel 2007).

Many studies over the years have attempted to decode the FP tilt (e.g. Renzini & Ciotti 1993; Horth & Madsen 1995; Renzini & Calura 1998; Prugniel & Simien 1996; hereafter PS96; Graham & Colless 1997; Graham 1998; Scodeggio et al. 1998; Mobasher et al. 1999; Bertin et al. 2002; Nickol et al. 2002; Riciputi et al. 2005; di Serego Alighieri et al. 2006; Bolton et al. 2007; Gargiulo et al. 2009). The emerging consensus is that stellar populations account for a minor fraction of the tilt (e.g. Trujillo, Burkert & Bell 2004) hereafter T+B; Cappellari et al. 2006; hereafter C+06; Proctor et al. 2008; La Barbera et al. 2008; Graves 2009); see however Jun & Im 2008), with the major contributor yet to be firmly identified—which would have ramifications for galaxy formation models (e.g. Capelato et al. 1995; Levine & Aguilã 1996; Kritsuk 1997; Bekki 1998; Ferreras & Silk 2000; Mathews & Brighenti 2000; Chiosi & Carraro 2002; Dantas et al. 2003; Bolatto et al. 2003; Gonzalez-Garcia & von Albedo 2003; Nickol et al. 2003; Evstigneeva et al. 2004; Aceves & Velazquez 2005; Onorbe et al. 2005, 2006; Bowler-Kolesin et al. 2005; Dekel & Cox 2006; Robertson et al. 2006; Shankar et al. 2006; Almeida et al. 2007; Hopkins et al. 2008).

An additional complication is that the tilted FP may not be flat, with claims made for curvature (Zaritsky et al. 1996, hereafter PS96; Graham & Colless 1997; Graham 1998; D’Onofrio et al. 2006; Graves 2009). As discussed in PS96, the colours (extinction- and K-corrected) are measured within 1 \( R_{\text{eff}} \) and \( V \)-band magnitudes, while the differences of \( U - B \) are measured within 1 \( R_{\text{eff}} \), the central velocity dispersions \( \sigma_0 \) are recovered from long slit spectra and \( V_{\text{max}} \) is defined as the quadratic sum of the maximum rotation on the major and minor axes. Since we are interested in fitting spectral energy distributions (SEDs), we select galaxies with at least two measured colours (most of the selected galaxies have four colours). Selecting also for galaxies brighter than \( M_B = -16 \), we recover \( \approx 400 \) galaxies among which, following the PS96 classification, \( \approx 55\% \) are bona fide Es (their subsample 1), \( \approx 30\% \) are type S0 and Sa (their subsample 2).

2 SAMPLE

Our data-set of local ETGs is drawn from PS96. This is currently one of the largest homogeneous samples of local ETGs available in the literature containing both photometry and kinematics of the galaxy central regions, and the only one including information on the peak rotation velocity \( (V_{\text{max}}) \). As discussed in PS96, the colours (extinction- and K-corrected) are measured within 1 \( R_{\text{eff}} \), the central velocity dispersions \( \sigma_0 \) are recovered from long slit spectra and \( V_{\text{max}} \) is defined as the quadratic sum of the maximum rotation on the major and minor axes. Since we are interested in fitting spectral energy distributions (SEDs), we select galaxies with at least two measured colours (most of the selected galaxies have four colours). Selecting also for galaxies brighter than \( M_B = -16 \), we recover \( \approx 400 \) galaxies among which, following the PS96 classification, \( \approx 55\% \) are bona fide Es (their subsample 1), \( \approx 30\% \) are type S0 and Sa (their subsample

1 Downloadable at http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/309/749.

2 The authors do not report detailed information about their measurement set-up but, as extensively adopted in literature analyses of this dataset, we will interpret \( \sigma_0 \) as the luminosity-weighted velocity dispersion within a circular aperture of radius \( R_{\text{eff}}/8 \).

3 Apparent total magnitudes are on average slightly brighter than those in RC3 catalog (de Vaucouleurs et al. 1991) by \( -0.05 \pm 0.1 \) mag, while the differences of \( B - V \) and \( U - B \) colours with those in RC3 are 0.00 \( \pm 0.03 \) and \( -0.02 \pm 0.03 \).
5), and the remaining ≈ 15% are dusty objects, interacting galaxies, dwarf spheroidals, compact, dwarf, low-luminosity and peculiar ellipticals, etc. (subsamples 2, 3, 4 and 6). For the main purposes of this paper, we will use subsample 1 (hereafter “Es”) and 5 (hereafter “S0s”), thus incorporating 335 galaxies, or ≈ 85% of the PS96 sample.

In all the following, we use a cosmological model with \((\Omega_m, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)\), where \(h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}\) (Spergel et al. 2003), corresponding to a universe age of \(t_{\text{uni}} = 13.5 \text{ Gyr}\).

E galaxies populate a restricted region in the colour-magnitude diagram, the so-called “red sequence”, with a colour range of \(B - V \approx 0.9 - 1\). S0s span a wider range of colours (i.e., \(B - V \approx 0.7 - 1\)) and are fainter than Es on average. The two subsamples follow similar FJ relations \(L \propto \sigma_0^2\)5, including a characteristic magnitude \((M_B \sim -20.5)\) where the relation clearly changes its slope (see left panel of Fig. 1). For the E sample, \(\eta = 2.9 \pm 0.5\) and 5.6 ± 1.2 for the faint and bright galaxies, respectively.

This FJ “dichotomy” has been reported elsewhere (Matković & Guzmán 2004; Forbes et al. 2008), and seems related to systematic changes seen in other optical properties, e.g. the Kormendy relation (Capaccioli et al. 1992; Nigroche-Netro et al. 2003), the Sersic (1968) index (Caon, Capaccioli & D’Onofrio 1993; Prugniel & Simien 1997), hereafter PS97; Graham 1998; Graham & Guzman 2003) and the size-magnitude relation (Shen et al. 2003; Bernardi et al. 2007; Lauer et al. 2007; Desroches et al. 2007; Hyde & Bernardi 2008a). The latter relation is illustrated for our sample Es in the right panel of Fig. 1 where the faint and bright galaxies have fitted slopes of 0.85 ± 0.07 and 0.43 ± 0.11, respectively.

We will see that a characteristic luminosity scale is also found to characterize other correlations of ETG parameters.

3 STELLAR MASS-TO-LIGHT RATIO

One of the key aspects of our analysis is determining each sample galaxy’s stellar \(M/L\), \(\Upsilon_*\), which we do by fitting model SEDs to the observed galaxy colours. Although photometric modelling may seem less powerful than detailed spectroscopic fits, most spectroscopic samples are restricted to the very central regions of galaxies and may be very biased indicators of the stellar populations on scales of \(\sim R_{\text{eff}}\).

In Section 3.1 we describe the modelling procedure and present the recovered stellar populations properties for the sample galaxies. We report the implications for the size-mass relation in Section 3.2 and for trends in \(\Upsilon_*\) in Section 3.3.

3.1 Stellar populations modelling procedure

We create a set of synthetic stellar spectra using the prescription of Bruzual & Charlot (2003, hereafter BC03), which encompasses a wide range of initial metallicities and ages. A Salpeter (1955) or Chabrier (2001, 2002, 2003) initial mass function (IMF) is assumed, with initial masses \(m\) in the range 0.1 – 100. The two IMFs do not influence the colours, but basically affect the \(\Upsilon_*\) estimates, which are \(\approx 1.8\) times larger with a Salpeter IMF than with a Chabrier IMF.

To generate a more general and realistic star formation history (SFH), we convolve the BC03 “single burst” models with an exponentially-decaying star formation (SF) rate with time \(t \propto e^{-t/\tau}\), where \(\tau\) is a characteristic time scale. The choice of BC03 is dictated mostly by its versatility.

---

5 The distance scale is critical for normalizing the luminosities and \(M/Ls\). The distance moduli \((m - M)\) from PS96, rescaled to \(h = 0.7\), are on average lower than those reported in the RC3 catalog (de Vaucouleurs et al. 1991) by \(-0.11^{+0.26}_{-0.23}\) mag (uncertainties are 25th and 75th percentiles), while agreeing closely with estimates from Zouy et al. (2001) (shifted by \(-0.06\) mag to correct to the Cepheid distance scale; Jensen et al. 2003) which differs by \(0.06^{+0.18}_{-0.16}\) mag.
and ability to span the stellar parameter space (metallicities and ages) but it is not the only prescription available on the market. We test for the presence of any modelling systems by mainly checking two different popular prescriptions, [Bell & de Jong (2001), hereafter BdJ01] and [Maraston (2005), hereafter M05] in Appendix A.

For each galaxy, we fit synthetic spectra to the observed colours ($U - B$, $B - V$, $V - R$, and $V - I$, after convolving the spectra with the appropriate filter bandpass functions), allowing us to estimate the age ($t_{\text{gal}}$), metallicity ($Z$), $\tau$, $\Upsilon_{*,B}$ and hence the stellar mass, $M_* = \Upsilon_{*,B} \times L_B$ (hereafter we will always quote luminosity and $M/L$ values in the $B$-band, even if not specified). In detail, we build a set of synthetic colours with $Z \in (0.008, 0.02, 0.05 \pm 0.05) \%$, $\tau \in (0.1 - 5)$ Gyr, and $t_{\text{gal}}$ up to $10^{10}$ yr. The fitting procedure consists of generating 100 Monte Carlo realizations of the observed galaxy colour sets assuming Gaussian errors of 0.05 mag per colour, and minimizing a $\chi^2$ statistic between the modelled and observed colours for each realization. The overall best-fit model parameters and their uncertainties are defined as the median and scatter of these 100 best fits.

Our synthetic modelling procedure is more general than the extensively used “simple stellar population” (SSP) model where a galaxy is approximated as experiencing a single burst of star formation (i.e., $\tau = 0$; [Trager et al. 2003; Maraston 2005, see also Appendix A]). Instead we leave $t_{\text{gal}}$, $\tau$ and $Z$ all as free parameters in order to better represent the wide variety of SFH expected both observationally and theoretically (see e.g. De Lucia et al. 2006; Noeske et al. 2007). The allowed ranges in the parameters will then be larger than in the more simplified SSP case because of the well known degeneracies among them (Gavazzi et al. 2002, BC03).

To test the reliability of our modelling technique and the intrinsic parameter scatter, and to check for the presence of spuriously-generated correlations, we run a suite of Monte Carlo simulations. We extract 100 simulated galaxy spectra from our BC03 SED libraries with random $t_{\text{gal}}$, $Z$ and $\tau$ (i.e. with no correlation among these parameters), and apply our generalized fit procedure—comparing the recovered parameters with the input model values. We find that $\Upsilon_*$ is recovered well, with a scatter of $\sim 10\%$ (see Fig. 2). Similar consistency is found for $t_{\text{gal}}$, $Z$ and $\tau$, which have on average larger scatter: $\sim 20\%$, $\sim 30\%$ and $\sim 30\%$ respectively. We check for spurious correlations using a Spearman rank test ([Press et al. 1992]), finding that $\tau$ vs $t_{\text{gal}}$ show no correlation at the 95% confidence level, but that $t_{\text{gal}}$ and $Z$ are weakly correlated, which is a common effect in stellar populations analyses. However, this $t_{\text{gal}}$--$Z$ degeneracy does not affect the $\Upsilon_*$ inference, which is our primary concern.

After fitting the real data for the complete sample of 335 galaxies, we show some relations between model parameters and other observed galaxy quantities in Fig. 3. From this Figure it is evident that the metallicity is generally solar or super-solar ($Z \gtrsim 0.02$) and on average only weakly dependent on other properties such as luminosity -- which is fortunate since the BC03 stellar libraries include only a few reference values for $Z$. More striking are the strong correlations involving $t_{\text{gal}}$ and $\tau$, such that the brighter, more massive galaxies formed their stars on average on shorter timescales than the fainter, less massive galaxies, while the younger galaxies also had shorter SF timescales (this does not mean that the brighter galaxies are younger, and if the S0s are included, the opposite is clearly true).

Similar findings on the SFHs of ETGs have been found in observational ([Gavazzi et al. 2002, Thomas et al. 2005] and theoretical ([De Lucia et al. 2006; Romeo et al. 2008]) analyses. We will consider this subject in detail in a subsequent paper ([Napolitano et al. 2009a, in prep.], and for now summarize some basic parameters. The bright ETGs ($M_B \lesssim -20.5$) have a median $\tau \approx 0.5$ Gyr, while the faint ETGs have $\tau \approx 1$ Gyr. The Es have similar properties, while the S0s have on average more protracted SFHs ($\tau \sim 1$--1.5 Gyr). The median $\Upsilon_*$ for the ETGs is $6.9 \pm 2 \Upsilon_\odot$ ($3.8 \pm 1.1 \Upsilon_\odot$) for a Salpeter (Chabrier) IMF, where the quoted errors are the 1 $\sigma$ scatter. The S0s have only slightly smaller median $\Upsilon_*$ than the Es: $6.2 \Upsilon_\odot$ ($3.4 \Upsilon_\odot$) and $7.1 \Upsilon_\odot$ ($3.9 \Upsilon_\odot$), respectively. However, the two samples differ more strongly in the distribution of $\Upsilon_*$, where the Es have a fairly symmetric distribution about the mean, while the S0s have a pronounced tail to low $\Upsilon_*$, such that the mean value of $5.8 \Upsilon_\odot$ ($3.2 \Upsilon_\odot$) differs from the median estimate.

3.2 Size-mass relations

An indirect way to test our derived $\Upsilon_*$ values is to check how the implied scaling relation between size and stellar
mass compares to previously established results. Expressing the size-luminosity relation as $R_{\text{eff}} \propto L^{\alpha_L}$, we find a slope for the Es of $\alpha_L = 0.70 \pm 0.06$, which is slightly steeper than some literature findings of $0.54 \pm 0.03$ (Pahre et al. 1998; Bernardi et al. 2003; Mamon & Lokas 2005). However, this slope is very sensitive to the range of luminosities fitted, since we see a difference between the “faint” and “bright” subsamples (see Section 3.2 and right panel of Fig. 1).

For the size-mass relation $R_{\text{eff}} \propto M^{\alpha_M}$, we obtain $\alpha_M = 0.65 \pm 0.05$ overall (Fig. 2), consistent with previous estimates for low-redshift galaxies of typically $\sim 0.6$ (Bernardi et al. 2003; Shen et al. 2003; Mamon & Lokas 2003; N+05). This correlation also bends at a characteristic mass scale of $M_{\star} \sim 10^{11.1} M_{\odot}$, with $\alpha_M = 0.36 \pm 0.13$ and $0.73 \pm 0.12$ for the faint and bright galaxies, respectively (cf. Shen et al. 2003). We find the S0s to have on average smaller $R_{\text{eff}}$ than Es of the same mass, and similar $\alpha_M$ at high masses, but flattening to $\sim 0$ at low masses.

3.3 Luminosity dependence of $\Upsilon_\star$

The central regions of ETGs are probably dominated by the stellar mass, so it is of critical importance to ascertain the fraction of the FP tilt that is connected to the stellar population properties. We focus on the relation $\Upsilon_\star \propto L_B^{\gamma_\star}$ in log-log space, fitting to weighted medians of binned data values, with results that are stable to changes in the binning (Fig. 4). For the overall ETG sample, we find a slope of $\gamma_\star = 0.06 \pm 0.01$; the Es have $\gamma_\star = 0.02 \pm 0.01$, and S0s have $\gamma_\star = 0.17 \pm 0.03$, although this steeper slope is driven by the very faintest galaxies ($M_B > -19$).

Before taking these results at face value, we investigate possible dependencies on modelling systematics. Changing the IMF from Salpeter to Chabrier does not affect $\gamma_\star$, but only the overall normalization of $\Upsilon_\star$. Adopting a simplified model with $t_{\text{gal}}$ as the only free parameter, with $\tau \sim 0.75$ Gyr and $Z \sim Z_{\odot}$ fixed to the median values for the whole sample (see Section 3.1), the $\Upsilon_\star$ steepens for the faint galaxies and flattens for the bright ones, with an over-
all result of \( \gamma_* \sim 0.16 \) (Appendix A). An even more simplified SSP model with \( \tau = 0 \) yields about the same \( \gamma_* \sim 0.18 \). Thus, we see that allowing for the variations of SF timescales (and metallicity) within the sample is critical to accurately deriving the \( \Upsilon_* \) trends with luminosity. An additional complication, only partially addressed by our model’s protracted exponential SFH, is multiple bursts of SF in a single galaxy which, if corrected for, would probably flatten the slope even further (cf. section 4.7 of C+06).

We now consider alternative stellar populations basis models. As detailed in Appendix A, adopting the BJ01 or M05 models with the same assumptions would imply shallower and steeper \( \Upsilon_* \) slopes, respectively. This turns out to be the dominant source of uncertainty in the analysis, although the uncertainty is largest for the faintest galaxies (\( M_B \gtrsim -20.5 \)), and the \( \Upsilon_* \) estimates more stable for the brighter galaxies.

How do our results compare to previous work? As mentioned in Section 4, most recent studies agree that \( \gamma_* \) is a relatively small contributor to the total \( \gamma \) of the FP. E.g. PS96 inferred from the same data set that \( \gamma_* \sim 0.1 \), and T+04 found using very different data and techniques that \( \gamma_* = 0.07 \pm 0.01 \) in the \( B \)-band. This general consistency is encouraging, but it should be kept in mind that as just discussed, there remain significant uncertainties in the modelling.

The foregoing conclusions are based upon a universal IMF, but there are suspicions that the IMF may vary with time or environment (e.g. \cite{vanDokkum2008,Dave2008}). \cite{RenziniCiotti1993} pointed out that a variation in the IMF with luminosity could easily account for the FP tilt. Here we illustrate this point again with a simple toy model, wherein the faint galaxies have a Chabrier IMF, and the bright ones a Salpeter IMF (a more realistic scenario would have the IMF changing smoothly with luminosity). The implied \( \Upsilon_* \) slope would be \( \gamma_* \sim 0.3 \) (Fig. 3), which as we will see would be enough to explain the FP tilt with no further ingredients (e.g. no DM).

We lastly examine the correlation of \( \Upsilon_* \) with velocity dispersion: \( \Upsilon_* \propto \sigma^\gamma \). The fitted slope is \( \gamma_* \sim 0.2 \) for both Es and S0s (Fig. 7). The steepness of this trend relative to \( \gamma_* \) suggests that the stellar populations of galaxies are more strongly linked to their dynamical masses than to their luminosities. This issue will be considered in more detail in the following Sections, and as part of a separate analysis in \cite{Napolitano2009}.

### 4 DYNAMICAL MASS

Besides \( \Upsilon_* \), the other fundamental quantity we want to determine is the total dynamical \( M/L, \Upsilon_{dyn} \). The usual way the dynamical mass is calculated in FP studies is with the virial relation

\[
M = \frac{K \sigma^2 r}{G},
\]

where \( G \) is the gravitational constant and \( K \) is a pressure correction coefficient (or virial coefficient; e.g.
We outline the modelling methods in Section 4.1, present results based on luminosity profile homology in Section 4.2 and on more general profiles in Section 4.3.

4.1 Dynamical methods

The basic approach of our dynamical models is to take the observed luminosity profile for each galaxy, along with a parameterized mass model, and solve for the projected velocity dispersion $\sigma_0$ within a central aperture. The mass model parameters are then optimized to match the observed value for $\sigma_0$.

In detail, the steps are the following:

(i) We parameterize the luminosity profile $j_*(r)$ by either a (deprojected) [de Vaucouleurs (1948) profile or a more general Sérsic (1968) model (Caon, Capaccioli & D’Onofrio 1993)], which fully takes into account any non-homologies in the stellar density distributions. The functional form for $j_*(r)$ is specified in Appendix B of PS97.

(ii) We adopt a simplified form for the total cumulative dynamical mass profile $M(r)$ which is either a constant-$M/L$ profile $M(r) = Y_0 L(r)$ (including the cases where DM is missing or has a cored distribution; see Burkert 1995, Napolitano et al. 2009a), or a singular isothermal sphere (SIS), where $M(r) \propto \sigma^4_{\text{SIS}}$. The latter choice is motivated by evidence from strong gravitational lensing for near-SIS profiles in the central regions of ETGs (e.g. Kochanek 1991, Koopmans et al. 2006). These two alternatives bracket the plausible range of mass profiles.

(iii) We solve the Jeans equation:

$$\frac{d (j_* \sigma_r^2)}{dr} + 2 \frac{\beta(r)}{r} j_* \sigma_r^2 = -j_* (r) \frac{GM(r)}{r^2},$$

where $\beta = 1 - \sigma_r^2/\sigma^2$ is the anisotropy. This model assumes spherical symmetry and no rotation (cf. Mamon & Lokas 2003). For simplicity we also assume isotropy ($\beta = 0$), in which case the Jeans Eq. (2) can be transformed to:

$$\sigma_r^2(r) = \frac{1}{j_*(r)} \int_r^{\infty} \frac{GM(s)}{s^2} ds .$$

(iv) We project Eq. (8) to obtain the line-of-sight velocity dispersion:

$$\sigma_{\text{los}}^2(R) = \frac{2}{I(R)} \int_R^{\infty} \frac{j_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}},$$

where

$$I(R) = 2 \int_R^{\infty} \frac{j_* r dr}{\sqrt{r^2 - R^2}}$$

is the projected density profile.

(v) We integrate $\sigma_{\text{los}}$ within a fixed aperture $R_{\text{eff}}$ to obtain the aperture velocity dispersion, $\sigma_{\text{Ap}}$ using the Equation:

$$\sigma_{\text{Ap}}^2(R) = \frac{1}{L(R)} \int_0^{R_{\text{eff}}/8} 2\pi S I(S) \sigma_{\text{los}}^2(S) dS ,$$

where

$$L(R) = \int_0^R 2\pi S I(S) dS$$

is the luminosity within the projected radius $R_R$. We check that using an aperture of $R_{\text{eff}}/10$ would leave the
We fit the model $\sigma_{Ap}$ to the observed $\sigma_0$ and iterate the preceding steps, varying the free parameters in Eq. (3) (i.e. $\sigma_{SIS}$ or $\Upsilon_0$). The resulting best-fit mass profile then provides the total spherical mass-to-light ratio within an effective radius $\Upsilon_{\text{dyn}}(R_{\text{eff}})$ (which is coincident with $\Upsilon_0$ in the case of the constant-$M/L$ model).

This procedure does not take into account certain factors that could in principle alter the final mass estimates. Firstly, the mass model does not include a central black hole, but we calculate the effect to be negligible. More importantly, real galaxies are neither spherical nor isotropic in general. We will check the impact of these simplifications later, but here begin with a first-order correction to the isotropic results.

Detailed dynamical models of nearby galaxies have shown that their central stellar parts are close to isotropic after subtracting the rotational component (e.g. G+01; C+06; Capparelli et al. 2007). The observed $\sigma_{Ap}$ does incorporate both the projected rotation and dispersion components of the specific kinetic energy ($\sigma_{Ap}^2 = v_{\text{rms}}^2 = v^2 + \sigma^2$), and the Jeans equations could in principle be reformulated along these lines. However, for many galaxies the rotation is so dominant that it is preferable to include it as an additional, separate term, which would require additional assumptions about the rotation field of each galaxy, and would best entail a non-spherical treatment anyway — all of which is beyond the scope of the current paper.

Here we adopt a heuristic correction to the observed dispersion in order to approximately account for rotational effects. Following PS94, we parameterize the corrected $\sigma_{Ap}$ by $\sigma_{Ap}^2 = \sigma_{Ap,\text{rot}}^2 + \sigma_{\text{rot}}^2$ to estimate $\delta_{\text{rot}}$ we have performed Monte Carlo simulations as in Napolitano et al. (2001), beginning with a suite of analytical spherical stellar+DM models as described in N+01. For each model with a fixed gravitational potential, we assume isotropy and an additional rotational component that increases with radius, then solve the Jeans equations and project to $\sigma_{Ap}$. Finally we examine the factor $\delta_{\text{rot}}$ that relates the rotating and non-rotating "measurements" $\sigma_{Ap}$, finding this simple approximation:

$$\delta_{\text{rot}} \approx 1 + 0.05 \frac{V_{\text{max}}}{\sigma_0},$$

which is calculated for an aperture of 1 $R_{\text{eff}}$ and turns out to be valid for a large range of galaxy masses. We therefore apply this correction to the observed $\sigma_{Ap}$ before matching to the models in step (vi) above. The correction increases the inferred $\Upsilon_{\text{dyn}}$ values since rotation at $\sim R_{\text{eff}}$ coupled with the $\beta = 0$ assumption depresses the central $\sigma_r$ for a given mass profile: a rotational component must be subtracted from the right hand side of Eq. (3).

The trend with luminosity for the rotation correction in our galaxy sample is shown in Fig. 8, implying $\Upsilon_{\text{dyn}}$ corrections of $\sim 1\%$ for the brightest Es, and $\sim 6\%$ for the faintest S0s (as is well known, rotation is a stronger factor on average among fainter ETGs). When plotting results for all galaxies in the sample we use the median ($V_{\text{max}}/\sigma_0$)-$L_B$ trend to estimate their $\delta_{\text{rot}}$. Where possible, we also classify the Es as fast- or slow-rotators, using $V_{\text{max}}/\sigma_0 = 0.25$ as the demarcation — a simple scheme that matches the more robust conclusions of C+06 in more than 90% of the overlapping cases.

### 4.2 Results from homologous luminosity profiles

We can now derive $\Upsilon_{\text{dyn}}$, starting with the simplest case where we assume no rotation, and a homologous model for the luminosity distribution $j_\Upsilon(r)$: an $R^{1/4}$ profile which is completely determined by the known $L_B$ and $R_{\text{eff}}$ for every galaxy. For the mass profile we assume initially the SIS model. Fitting the $\sigma_0$ data, we show the mass-luminosity results in Fig. 9 (left panel). Binning the data, we fit the median relation $\Upsilon_{\text{dyn}} \propto L_B^{0.21 \pm 0.01}$ and find $\gamma_{\text{dyn}} = 0.21 \pm 0.01$. This is identical to the one for the E subsample alone, $\gamma_{\text{dyn}} = 0.21 \pm 0.01$ (see Table I). The S0s show a larger scatter and have a global slope of $\gamma_{\text{dyn}} = 0.18 \pm 0.03$, which steepens for faint galaxies ($M_B > -20.5$, $\gamma_{\text{dyn}} \sim 0.3$) and appears to flatten or even decrease at higher luminosities ($\gamma_{\text{dyn}} \leq 0$). These slope results are scarcely changed by including the rotational correction (see Table I), although the
normalization of Υ_{dyn} is increased for the S0s (see Fig. 9, right), an issue to which we will return in §5.

Previous dynamical studies of ETGs using j_∗ homology have found a variety of tilt slopes, ranging from γ_{dyn} ~ 0.1 to ~ 0.3 (e.g., Jorgensen et al. 1993; Bernardi et al. 2003; Padmanabhan et al. 2004; T+04). The average of the literature B-band values in Table 1 of PS96 yields γ_{dyn} = 0.25 ± 0.05, consistent with our result.

Now considering the other extreme assumption for the mass model, constant-M/L, the extrapolation to R_{eff} after fitting to σ_0 changes the Υ_{dyn} normalization, corresponding to K = 2.05 at R_{eff} in Eq. (1) for SIS, and K = 1.93 for constant-M/L. The slope of the Υ_{dyn}-L_B relation is on the other hand unchanged (see Table 1). The K difference does raise the interesting possibility of mass profile non-homology, e.g. a systematic change with luminosity. As with the IMF toy model in Section 3.3, we can consider an arbitrary case where the faintest galaxies have constant-M/L profiles, and the brightest ones have SIS. This would increase Υ_{dyn} by ~ 0.02, i.e. mass non-homology does not appear to be a significant contributor to the FP tilt, assuming j_∗ homology.

### 4.3 Results from generalized luminosity profiles

We next relax the j_∗ homology assumption, allowing for more realistic luminosity profiles based on the S´ersic law, with surface brightness profiles expressed as:

$$\mu(R) \propto C - (R/R_{eff})^{1/n},$$

where $C$ is a constant and $n$ is an index of profile curvature which correlates with luminosity, such that the brighter galaxies have higher $n$ (less curved profiles; e.g., Caon, Capaccioli & D’Onofrio 1993; Graham 1995; Graham & Guzmán 2003; Mamon & Lokas 2005; Kormendy et al. 2008). As illustrated by Eq. (2), for a given dispersion profile, changing the shape of $j_*(r)$ will affect the inferred mass. Thus it is important to explore the impact of $j_*$ non-homology on Υ_{dyn}, which may be expressed as a trend with luminosity $K = K(nL_B)$. This is all a fancy way to say that accurate dynamical results require accurate luminosity profile models.

The n-L_B correlation has been investigated for our galaxy sample by PS97. From the overall ETG sample in their fig. 5, we define a simple relation where $n \sim L_B^{0.6}$ for $M_B > -20$, and $n = 4$ for all the brighter galaxies. This

---

**Figure 9.** Dynamical M/L in B-band within R_{eff} as a function of luminosity assuming j_∗ homology and an SIS total mass profile. Red squares and blue stars denote E and S0 galaxies, respectively. Points with error bars are the median values and ±25% scatter for the galaxies in luminosity bins. Left panel: No rotation assumed. Linear best fits to the binned data are overplotted as straight lines. Right panel: Correction made for rotational support.

**Table 1.** Slope of M/L–L_B relation for Es and S0s and different dynamical models (the S´ersic profiles assume the n-L_B relation discussed in the text). The first five rows are the slope for the total (dynamical) mass, and the last row due to stars only, as derived with our stellar-populations model (Section 3). §The faintest S0s have a steeper slope than the brighter ones (see Fig. 5). Uncertainties on slopes are the 1σ scatter computed by a bootstrap method.

| Model               | γ_E  | γ_S0 | γ_tot    |
|---------------------|------|------|----------|
| R^{1/4}+SIS         | 0.21±0.01 | 0.18±0.03 | 0.21±0.01 |
| R^{1/4}+SIS+rot     | 0.20±0.01 | 0.18±0.03 | 0.20±0.01 |
| R^{1/4}+const-M/L+rot | 0.20±0.01 | 0.18±0.03 | 0.20±0.01 |
| S´ersic+SIS+rot     | 0.21±0.01 | 0.20±0.03 | 0.21±0.01 |
| S´ersic+const-M/L+rot | 0.19±0.01 | 0.19±0.03 | 0.13±0.02 |
| Stars               | 0.02±0.01 | 0.17±0.03 | 0.06±0.01 |

14 PS97 noted that at least one other study found higher values of $n$ for the brightest galaxies, but commented that those results were more sensitive to the outer profiles than to the central regions of relevance here. Similar concerns might apply to the recent smaller galaxy sample of Kormendy et al. (2008), but it is beyond the scope of our paper to re-investigate $n$ dependencies in detail. If $n$ were systematically higher for the brighter galaxies, then these systems’ Υ_{dyn} results would be lower (cf. next footnote). Note also that the R_{eff} values that we use were obtained by
relation also applies for the E subsample, and we assume that it does for the S0s as well.

We now use the $n-L_B$ relation to construct the $j_\star (r)$ Sérsic profile for each galaxy as needed for the dynamical modeling (Section 4.1). Since we have examined the effects of rotation in Section 4.2, we will here skip over the simplified case of no rotation. The resulting $\Upsilon_{\text{dyn}}$ values for both SIS and constant-$M/L$ cases are summarized in Table 1 and Fig. 10. For the SIS case, relaxing the $j_\star$ homology slightly changes the slope $\gamma_{\text{dyn}}$. However, in the constant-$M/L$ case, both the luminosity and mass profiles are affected, and significant differences arise. The masses are increased for the fainter galaxies causing the $\Upsilon_{\text{dyn}}$ slope to become shallower overall ($\gamma_{\text{dyn}} = 0.13 \pm 0.02$), and even constant at lower luminosities ($\gamma_{\text{dyn}} = 0.05 \pm 0.04$ and $0.23 \pm 0.02$ for the faint and bright Es, respectively). The Es and S0s are again not noticeably different in their region of luminosity overlap. In Appendix B we investigate systematic uncertainties in these results, whose impact we will consider in the next section.

Now reviewing the results of this and the previous Sections, with the $j_\star$ homology assumption, the steep $\Upsilon_{\text{dyn}}$ slope relative to $\Upsilon_\star$ ($\gamma_{\text{dyn}} = 0.20$ vs $\gamma_\star = 0.06$) would imply that $\sim 75\%$ of the FP tilt is related to DM content or some other factor. Including the (realistic) $j_\star$ non-homologies changes the picture somewhat: if all galaxies have SIS mass profiles, the previous conclusion is unchanged.

If they have steeper mass profiles, then the dynamical contribution to the tilt decreases, and for the fainter galaxies may even disappear.

Thus our results suggest overall that DM contributes to the tilt for the brightest galaxies, while the contribution for the fainter galaxies is unclear but probably less. This conclusion differs from that of T+04, who found using similar Sérsic models and assuming constant-$M/L$, no need for a correlation between DM fraction and luminosity.

Their galaxy sample is fainter and much smaller, so their results are actually consistent with ours in general. The exception is for the brightest galaxies, where the higher $n$-values of T+04 lead to less tilt than we find. In any case, it should be noted that reproducing the FP tilt without DM variation is not a unique solution, and as we have shown, DM could still be a primary driver of the tilt.

5 DARK MATTER FRACTIONS

Having analyzed the trends for stellar and total mass in our galaxy sample, we now examine the implications for DM content. We define the DM fraction within the three-dimensional radius $r = 1 R_{\text{eff}}$ by:

$$f_{\text{DM}} = \frac{M_{\text{tot}} - M_\star}{M_{\text{tot}}} = 1 - \frac{\Upsilon_\star}{\Upsilon_{\text{dyn}}},$$

where for physically meaningful results we should have $\Upsilon_\star \leq \Upsilon_{\text{dyn}}$ and thus $f_{\text{DM}} \geq 0$. Strictly speaking, our derived $\Upsilon_\star$ should be deprojected before computing $f_{\text{DM}}$, but we do not have the information necessary to do so. Given the negative colour gradients in ETGs, we expect the deprojected $\Upsilon_\star$ to be somewhat higher than in projection, and thus the true $f_{\text{DM}}$ to be somewhat lower. For this reason and especially because of the large IMF uncertainty, the absolute values for $f_{\text{DM}}$ are not definitive, but instead the relative variations are more robust and are the focus of our study.

We now consider the $f_{\text{DM}}$ trends found for our galaxy sample, taking as a default the $\Upsilon_\star$ estimates from the gener-
alized ($t_{gal}, \tau, Z$) BC03-based stellar populations model, and the $\Upsilon_{dyn}$ estimates from the dynamical models using generalized luminosity profiles (Section 4.3). As shown in Fig. 11, $f_{DM}$ increases with luminosity in the E galaxy subsample, but is constant or even decreasing for the S0s. The combined ETG sample has $f_{DM}$ increasing overall, but with the hint of a slope change at $M_B \sim -20.5$, from roughly constant at faint magnitudes to steeply increasing for brighter objects; the trends for the S0s and the correspondingly fainter Es are roughly consistent. These conclusions are valid for both bracketing mass profile cases (SIS and constant-$M/L$), although the slope change is less apparent for the SIS model. To quantify this breakdown, we have measured the slopes of $\gamma_{DM}$ of $f_{DM}$-$L_B$ relation for the two models, and found that $\gamma_{DM} \sim 0.5$ for $L_B \geq 10.4 L_\odot$ and $\gamma_{DM} \sim 0$ for $L_B \leq 10.4 L_\odot$, clearly inconsistent within the errors.

The trends with luminosity are mirrored by similar correlations with the velocity dispersion as we show in Fig. 12. Here the slope is steeper in general because of the combined effect of the $\Upsilon_\ast$-$\sigma$ correlation shown in Fig. 7 and the stronger dependence between $\Upsilon_{dyn}$ and $\sigma_0$.

The DM fraction is typically $f_{DM} \sim 0.3$ assuming a Salpeter IMF, with a broad range for individual galaxies from $\sim 0$ to $\sim 0.9$ (rms scatter of $\sim 0.15$). About 15% of the galaxies have, within the errors, $f_{DM} < 0$ (typically those with low surface brightness $\mu_{eff}$), an unphysical result which may indicate that the Salpeter IMF is inaccurate (cf. C+06); adopting a Chabrier IMF would imply more DM, with $f_{DM} \sim 0.6$ typically, and only a tiny handful of galaxies with $f_{DM} < 0$. Changing the IMF also flattens slightly the luminosity dependence of $f_{DM}$, since this quantity is not directly proportional to $\Upsilon_\ast$. 

---

**Figure 11.** Trends of DM fraction with luminosity, using SIS and constant-$M/L$ mass models (left and right panels, respectively). Symbols are as in Figs. [9][10][11].

**Figure 12.** Trends of DM fraction with velocity dispersion, using SIS and constant-$M/L$ mass models (left and right panels, respectively). Symbols are as in Figs. [9][10][11].
We next look for any DM differences between the fast-rotator and slow-rotator Es, following the classification in Section 4.1. However, as shown in Fig. 13 there is no discernible difference; slow and rotators typically have $f_{DM}$ $\sim$ 0.35 and $\sim$ 0.25, respectively, but this is consistent with a simple luminosity effect, since fast rotators are fainter on average than slow rotators. This result appears contrary to the finding of C+06 (based on more detailed dynamical models and somewhat different stellar populations constraints for a much smaller galaxy sample) that there is an $f_{DM}$ discontinuity between slow and fast rotators.

We also compare S0s in Fig. 13, where it appears that their declining trend of $f_{DM}$ with luminosity is inconsistent with the Es in the same luminosity range. However, we caution that our spherical dynamical models are most questionable for the S0s, so the overall situation appears consistent with a continuous trend of $f_{DM}$ with luminosity for all ETGs, independent of morphology and rotation. For the rest of the paper, we will therefore generally lump all these ETG subclasses together as one population.

Before continuing further, we check once more the effects of systematic uncertainties, as detailed in Appendix C. Despite the uncertainties, our default model is consistent with results on DM content at larger radii, and we therefore consider the overall mild increase of $f_{DM}$ to be robust, with the inflection at intermediate luminosities perhaps less so.

How do our results compare to previous studies of DM trends in ETG centres? The analysis most similar to ours is from T+04. As discussed in Section 3.3 they found no indication of a correlation between $f_{DM}$ and luminosity, but their sample was primarily of faint galaxies, where we also found the correlation is weak. If we adopted higher Sérsic indices for the brightest galaxies, the correlation would also weaken for them, but this scenario would seemingly be inconsistent with large-radius tracers of DM (see App. C). Borriello et al. (2003) modelled a large sample of ETGs dynamically and claimed that the flatness of the FP would not permit centrally-concentrated DM halos as predicted by cosmological models. Their results imply $\gamma_{c} = 0.27 \pm 0.04$, thereby explaining all the tilt through the stellar populations — in flat contradiction to our $\gamma_{c} = 0.06 \pm 0.01$. This is mainly the consequence of their choices to not allow for a systematic variation of the virial DM fraction with luminosity in their model, and to use homologous $j_{c}(r)$ profiles which we have seen produce misleading results.

Finally, Padmanabhan et al. (2004) analyzed a large sample of SDSS ETGs, using a combination of stellar populations and dynamical models. Although the different redshift ranges make comparisons not straightforward, their results do appear roughly equivalent to ours, with $\gamma_{c} \sim 0$ and $\gamma_{dyn} \sim 0.17$, and even a hint of a flattening of the $f_{DM}$ slope at lower luminosities. Note however that they used an inaccurate homologous $j_{c}(r)$ profile.

6 IMPLICATIONS: DARK MATTER AND GALAXY FORMATION

The trends we have seen for $f_{DM}$ as a function of luminosity could provide fresh clues to galaxy formation. The most basic interpretation of central DM variations is that they reflect variations in total DM within the virial radius. Assuming that the Universal baryon fraction is roughly conserved from galaxy to galaxy, the implication is then that higher $f_{DM}$ means lower efficiencies of star formation $\epsilon_{SF}$. In this respect, the trends we find are qualitatively expected. Both observations and theory point to a universal U-shaped trend of $\epsilon_{SF}$ (or equivalently virial $M/L$) with luminosity, and a peak efficiency at $M_{*} \sim 10^{11} M_{\odot}$ (e.g. Benson et al. 2000; Marinoni & Hudson 2002; N+05; van den Bosch et al. 2007).

Physically, the lowest-mass galaxies are least able to retain their primordial gas content long enough to form many stars, since their gravitational potential wells are not deep enough to prevent ejection from supernovae feedback. More massive galaxies are increasingly able to inhibit feedback...
and form more stars, but at a certain mass scale, additional processes kick in such as AGN feedback, inhibiting gas cooling and decreasing $\epsilon_{\text{SF}}$ again (e.g. Cattaneo et al. 2004; Shankar et al. 2006; Kaviraj et al. 2007; Tortora et al. 2008). Thus, the lowest-mass and the highest-mass galaxies are the most DM-dominated. Our current galaxy sample does not extend faint enough to discern any $U$-shape, but the change we see in the $f_{\text{DM}}$ trend below scales of $M_B \sim -20.5$ or $M_\ast \sim 10^{11} M_\odot$ does coincide with the generically expected minimum of DM content. The consistencies of the trends for the ETG sub-types (S0s, fast-rotator Es, slow-rotator Es) suggest that the dominant driver of star formation is mass, not angular momentum.

It is of course a stretch to draw firm conclusions about virial quantities based on data from scales $\ll R_{\text{eff}}$. The central DM content that we are actually probing may be decoupled from the baryon content in several ways: the central DM density reflects the ambient density at the time of initial halo collapse; the baryons could have interacted with the DM and changed its distribution; and the $f_{\text{DM}}$ quantity that we measure is somewhat dependent on the particular values of $R_{\text{eff}}$ for the stars rather than simply probing the DM properties. To allow for such effects, and to provide quantitative marks for comparison to cosmological theory, we now consider the properties of the DM alone, in terms of its average density within some small radius, $\langle \rho_{\text{DM}} \rangle$.

In order to make critical comparisons with a literature study discussed below, we estimate $\langle \rho_{\text{DM}} \rangle$ within $2 R_{\text{eff}}$, extrapolating our usual models outwards in radius. We present this result vs stellar mass for the whole ETG sample in Fig. [14] using a Salpeter IMF and alternatively the SIS or constant-$M/L$ mass profile. Although these bracketing mass profiles gave similar results for $f_{\text{DM}}$ within $1 R_{\text{eff}}$, at $2 R_{\text{eff}}$ they start to diverge more, giving noticeably different results for $\langle \rho_{\text{DM}} \rangle$. The less massive galaxies have increasingly dense DM halos, apparently reaching a plateau of $\langle \rho_{\text{DM}} \rangle \sim 0.05 M_\odot$ pc$^{-3}$ at masses below $\log M_\ast/M_\odot \sim 11$.

As a reality check, we compare the results for flattened ETGs in the Coma cluster from Thomas et al. (2008), hereafter T+08, who used detailed three-integral axisymmetric dynamical models of stellar kinematics to decompose the galaxies into their stellar and DM mass components. Their $\langle \rho_{\text{DM}} \rangle$ values from their NFW halo model match up remarkably well with our SIS-based results. T+08 fitted their data with a logarithmic density-mass trend which would imply very high central $\langle \rho_{\text{DM}} \rangle$ for the faintest galaxies. However, as we can see in the Figure, such conclusions would involve extrapolating outside the mass range covered by the data, and in fact the T+08 results do show some sign of the density plateau at small masses which we find.

Now we calculate predictions from $\Lambda$CDM cosmological models, adopting an NFW density profile, and the Bullock et al. (2001) mass-concentration relation, as discussed in N+05. The final parameter in this model is the mass ratio between stars and DM within the virial radius, taking plausible values of alternatively $M_\ast/M_{\text{vir}} = 0.1$ or 0.01 (corresponding to $\epsilon_{\text{SF}} \sim 6\%$ or $\sim 60\%$, respectively, for a baryon fraction of 0.16; see N+05 and Spergel et al. 2003). The results for $\langle \rho_{\text{DM}} \rangle$ are shown in Fig. [14] where the model predictions are seen to be fairly consistent with the observations, including the bend in the $\langle \rho_{\text{DM}} \rangle$ trend at similar galaxy masses. This bend is not caused by anything intrinsic to the DM itself, but by the radius adopted for measuring the density. As shown in Fig. [13] (right panel), the mass-$R_{\text{eff}}$ relation for ETGs has a bend, which probably explains not only the density trends seen in this section but also the $f_{\text{DM}}$ results of the previous section. For bright galaxies, $R_{\text{eff}}$ increases rapidly with mass, probing quickly into regions contain more DM, at lower averaged densities. Fainter galaxies have less quickly varying $R_{\text{eff}}$ which thus tracks the slowly-varying DM scale radius more closely, so that the observable DM properties are roughly constant.

In more detail, the $\epsilon_{\text{SF}} = 60\%$ theoretical case coincides roughly with our observational findings assuming a constant-$M/L$ profile, and the $\epsilon_{\text{SF}} = 6\%$ case coincides nicely with our SIS-based findings. However, neither of these cases is plausible observationally or theoretically for the full range of galaxy masses. Our final case invokes a transition from high $\epsilon_{\text{SF}}$ for the faint galaxies to low $\epsilon_{\text{SF}}$ for the bright galaxies, which is generically expected from various lines of evidence. More specifically, motivated by the findings of N+05 based on radially-extended dynamical studies of ETGs (see also e.g. Napolitano et al. 2009a), we assume that the bright galaxies have $\epsilon_{\text{SF}}$ decreasing steadily from 60% to 16% in the mass range of $0.01 \leq R_{\text{eff}} \leq 12 M_\odot$; the faint galaxies have a constant $\epsilon_{\text{SF}} = 90\%$. As shown in Fig. [13] this model would be consistent with our SIS findings at the bright end, and with constant-$M/L$ at the faint end. However, the NFW-based models themselves would have roughly SIS profiles for the entire range of luminosity, which means this set of model assumptions is not self-consistent.
It is beyond the scope of this paper to explore the possible combinations of DM parameters that would be fully consistent with the data, but we speculate that the low-luminosity objects have low-concentration DM haloes. Note that changing the IMF to Chabrier would not significantly change these conclusions, since the data curves would shift up and to the left in Fig. [13].

7 CONCLUSIONS

The relative amounts of dark and luminous mass in ETGs is crucial information for understanding the internal structure of these systems and their formation mechanisms. In this paper we have analyzed both the stellar and dynamical $M/L$ in the central regions of one of the largest homogeneous samples of local early-type galaxies, provided by PS96.

We estimate the stellar content by accurate population synthesis models of several observed colours using the BC03 prescription. We measure dynamical masses using the observed central velocity dispersion $\sigma_0$ and several simplifying assumptions in the Jeans equations.

We find that the stellar $M/L$, $\Upsilon_*$, has a shallow trend with luminosity with a slope $\sim 0.06$ for the whole ETG sample (with S0s showing a steeper trend than the Es: see Table [1]). Dynamical $M/L$, on the other hand, have a slope for the $M/L \propto L_B$ relation of is $0.21 \pm 0.01$ when considering ETGs as a (photometrical and kinematical) homologous galaxy family, i.e. fully consistent with results derived in local galaxies’ $B$-band FP.

For the non-homology case (i.e. assuming the S´ersic profile for the light distribution and differential rotation within $R_{\text{eff}}$), we find that using the SIS model as the total mass distribution does not much affect the $M/L$ slope and thus not the FP tilt either. On the contrary, non-homology can account for as much as $\sim 40\%$ if considering the constant--$M/L$ model, and even more (up to $80\%$) for the faint systems.

A further $30\%$ (i.e. $0.06/0.21$) is provided by the $\Upsilon_*$ slope. The residual contribution to the $M/L \propto L_B$ slope ($\sim 70\%$ for the SIS model and $30\%$ for constant--$M/L$) is mainly due to a variation with luminosity of their DM fraction.

It must be stressed that this average budget of $\gamma$ contributions masks a more complicated distribution with luminosity. For instance, for the bright/massive galaxies (i.e. $\log L_B \gtrsim 10.4 L_\odot$ and $\log M_* \gtrsim 11.3 M_\odot$) which have a quasi-$R^{1/4}$ profile and little or no rotation, the effect of the non-homologies is minimal and the slope of the $M/L \propto L_B$ remains steeper than the faint systems where non-homologies can account for almost all the slope $\gamma$. This, obviously, relates to the trend of the DM fractions discussed in Section [13].

Here we have seen that $f_{\text{DM}}$ is strongly varying with luminosity and mass. In particular, we observe a dichotomy in DM content of bright and faint Es: galaxy brighter than $M_B \sim -20.5$ and more massive than $\log M_* \sim 11 - 11.3 M_\odot$ have an increasingly larger $f_{\text{DM}}$ while galaxies lying below these luminous and mass scales invert the trend, such that $f_{\text{DM}}$ is constant or marginally decreasing with luminosity and mass. When separating the E sample into “slow” and “fast” rotators it is evident that this two-fold trend is mainly found in the fast rotator systems (see Fig. [13]). These two kinematical varieties do not show large differences in their $f_{\text{DM}}$ properties. In particular, we do not find significant evidence for systematically lower $f_{\text{DM}}(R_{\text{eff}})$ for the fast rotator variety (C+06), although with a large scatter one might make such a conclusion using a small statistical sample. The inclusion of the ellipticity and orbital anisotropy would increase the steepness of the faint/less massive sample, but would leave unaffected the bright/massive galaxy range, still maintaining the dichotomy (Fig. [C1] bottom right). As an alternative to a variable DM content, we have briefly analyzed the effect of a change in IMF as a function of luminosity (see Fig. [5]), which could also explain the FP tilt.

The $f_{\text{DM}}$ dichotomy adds to other well known ETG correlations as found in the $\mu_e - R_{\text{eff}}$ relation, FJ, size-luminosity (or size-mass) relations and in the correlations of S´ersic index with both galaxy size and luminosity, as discussed in Sections [21], [32] and [14] (Capaccioli et al. 1992, Prugniel & Simien 1991, Shen et al. 2003, Matkovi´c & Guzmán 2005, etc.). Our results mirror the DM content in the outskirts of galaxies, where variations of virial $M/L$ as a function of mass and luminosity have been found both in simulations and observational analysis (Benson et al. 2000, Marinoni & Hudson 2002, van den Bosch et al. 2007). A similar dichotomy in DM content is not observed for S0s, which are generally fainter and less massive than Es and are strongly affected by rotational support (influencing the normalization of $\Upsilon_\text{dyn}$). They have a slightly higher DM fraction and show a monotonically decreasing trend with mass and luminosity, consistent with what is known for spiral galaxies (Persic, Salucci & Ashman 1993).

A continuity in DM content of galaxy as a function of amount of rotational support is possibly shown in Fig. [13] where we plot DM fractions as a function of luminosity for slow and fast rotators and lenticulars.

Looking at the average central DM density, $\langle \rho_{\text{DM}} \rangle$, we have found that this quantity has a fairly small scatter within the ETG sample. Albeit model dependent – the S´ersic+SIS model providing $\langle \rho_{\text{DM}} \rangle$ which are $0.2 - 0.4$ dex larger than the ones obtained with the constant--$M/L$ – the overall trend of the galaxy distribution decreases monotonically with the stellar mass and luminosity in good agreement with independent results obtained by Thomas et al. (2008) for ellipticals in the Coma cluster. Our larger statistical sample, though, has allowed us to discern the presence of a “knee” in the distribution (around the usual mass/luminosity scale at $\log M_* \sim 11 M_\odot$ and $\log L_B \sim 10.4 L_\odot$) where the relation of the more massive/luminous galaxies bends to a steeper slope than the one followed by the less massive/luminous systems. We have shown that this “knee” can be explained with the change of the slope in the $R_{\text{eff}} - M_*$ relation at $\log M_* \sim 11 M_\odot$.

As a robust estimator of the central DM density, $\langle \rho_{\text{DM}} \rangle$ can be compared against the expected values for standard NFW profiles. The match found is broadly good, with the results obtained assuming the S´ersic+SIS model favoring high dark-to-luminous mass ratios, i.e. lower star formation efficiencies, while the constant--$M/L$ models fit lower $M_{\text{vir}}/M_*$ values, i.e. higher efficiencies. In order to match up with the picture where galaxies have star formation efficiencies varying with the stellar mass (Benson et al. 2001, Dekel & Birnboim 2006), we have shown that the DM density characteristics should change with the mass with low mass systems being surrounded by more “cored” haloes.
(well approximated by the constant-$M/L$ models) and high mass systems by “cusped” haloes (here reproduced by the Sérsic+SIS profile).

This DM non-homology could be a possible explanation of the “anomalously” low halo concentration parameters recently found modeling intermediate luminosity galaxies, compared to the giant ellipticals showing “regular” concentration as expected from the ΛCDM simulations (Napolitano et al. 2009a). In this respect a model like the Einasto profile (Einasto 1965, but see also Navarro et al. 2004, 2008, Cardone et al. 2005, Graham et al. 2006) or a phenomenological model including a wide range of innermost density slopes (Tortora et al. 2007) provides suitable working hypotheses to test on larger data sample with extended kinematics (e.g. Atlas3D) or the PN.S Elliptical Galaxy Survey: Douglas et al. 2007; Napolitano et al. 2009b). In this respect a model like the “central models. NRN has been funded by CORDIS within FP6

We thank the anonymous referee for his/her kind report. We also thank Michele Cappellari for fruitful discussions and Claudia Maraston for providing us with her synthetic spec-

ACKNOWLEDGMENTS

We thank the anonymous referee for his/her kind report. We also thank Michele Cappellari for fruitful discussions and Claudia Maraston for providing us with her synthetic spectral models. NRN has been funded by CORDIS within FP6

REFERENCES

Aceves, H., & Velázquez, H. 2005, MNRAS, 360, L50 Almeida, C., Baugh, C. M., & Lacey, C. G. 2007, MNRAS, 376, 1711 Bekki, K. 1998, ApJ, 496, 713 Bell, E. F. & de Jong, R. S. 2001, ApJ, 550, 212B (BdJ01) Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289 Benson, A.J., Cole, S., Frenk, C.S., Baugh, C.M., Lacey, C.G., 2000, MNRAS, 311, 793 Bergond, G., Zepf, S. E., Romanowsky, A. J., Sharples, R. M., & Rhode, K. L., 2006, A&A, 448, 155 Bernardi M. et al., 2003, AJ, 125, 1849 Bernardi, M., Hyde, J. B., Sheth, R. K., Miller, C. J., & Nichol, R. C. 2007, AJ, 133, 1741 Bertin G., Ciotti L., Del Principe M., 2002, A&A, 386, 149 Binney, J. & Tremaine, S. 1987, Galactic Dynamics, Prince-ton Univ. Press., Princeton. Bolton, A. S., Burles, S. Koopmans, L. V. E., Treu, T., Monstakas, L. A. 2006, ApJ, 638, 703B Bolton, A. S., Burles, S., Treu, T., Koopmans, L. V. E., & Monstakas, L. A. 2007, ApJ, 665, L105 Bolton, A. S., Treu, T., Koopmans, L. V. E., Gavazzi, R., Monstakas, L. A., Burles, S., Schlegel, D. J., & Whyt, R. 2008, ApJ, 684, 248 Borriello, A., Salucci, P. & Danese, L. 2003, MNRAS, 341, 1109

Boyland-Kolchin, M., Ma, C.-P., & Quataert, E. 2005, MN-

RAS, 362, 184 Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2006, MN-

RAS, 369, 1081 Bruzual, A. G. & Charlot, S. 2003, MNRAS, 344, 1000 Bruzual, G. 2007, ASPC, 374, 303 Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack, J. R., & Dekel, A. 2001, MNRAS, 321, 559 Busarello, G., Capaccioli, M., Capozziello, S., Longo, G., & Puddu, E. 1997, A&A, 320, 415 Burkert, A. 1995, ApJ, 447L, 25B Capaccioli, M., Caon, N., & D’Onofrio, M., 1992, MNRAS, 259, 323 Caon, N., Capaccioli, M. & D’Onofrio, M., 1993, MNRAS, 265, 1013 Capaccioli, M., Napolitano, N. R., & Arnaboldi, M., 2002, ArXiv Astrophysics e-prints, arXiv:astro-ph/0211323 Capelato, H. V., de Carvalho, R. R., & Carlberg, R. G. 1995, ApJ, 451, 525 Cappellari, M. et al. 2006, MNRAS, 366, 1126 (C+06) Cappellari, M. et al. 2007, MNRAS, 379, 418 Cardone, V. F., Delpidipalumbo, E. & Tortora, C. 2005, MNRAS, 358, 1325 Cattaneo, A., Dekel, A., Devriendt, J., Guiderdoni, B., & Blaizot, J., 2006, MNRAS, 370, 1651 Chabrier, G. 2001, ApJ, 554, 1274 Chabrier, G. 2001, ApJ, 567, 304 Chabrier, G. 2003, PASP, 115, 763 Chiosi, C., & Carraro, G. 2002, MNRAS, 335, 335 Coccato, L., et al. 2009, MNRAS, in press, arXiv:0811.3203 Couroy, C., Gunn, J. E., & White, M. 2008, arXiv:0809.4261 Covone G., Paolillo M., Napolitano N. R., Capaccioli, M., Longo G., Kneib J.-P. et al. 2009, ApJ, 691, 531 Dantas, C. C., Capelato, H. V., Ribeiro, A. L. B., & de Carvalho, R. R. 2003, MNRAS, 340, 398 Davé, R. 2008, MNRAS, 385, 147 Dekel, A., & Birnboim,Y. 2006, MNRAS, 368, 2 Dekel, A., & Cox, T. J. 2006, MNRAS, 370, 1445 De Lorenzi, F et al., 2008, MNRAS, in press, arXiv:0804.3350 Debattista, V. P., Pannella, M., & Mendez, R. H. 2008, MNRAS, 385, 1729 De Lorenzi, F. et al., 2008, MNRAS, in press, arXiv:0804.3350 De Lucia, G., Springel, V., White, S. D. M., Croton, D., Kauffmann, G. 2006, MNRAS, 366, 499D Desroches, L.-B., Quataert, E., Ma, C.-P., & West, A. A. 2007, MNRAS, 377, 402 de Vaucouleurs, G. 1948, Ann. d’ Ap., 11, 247 de Vaucouleurs G., de Vaucouleurs A., Corwin H.G. Jr., et al., 1991, Third Reference Catalogue of Bright Galaxies (RC3) di Serego Alighieri, S., Lanzoni, B., Jørgensen, I. 2006, A&A, 451, 345 Djorgovski, S. & Davis, M. 1987, ApJ, 313, 59D D’Onofrio, M., Valentinuzzi, T., Secco, L., Caimmi, R., & Bindoni, D. 2006, New Astronomy Review, 50, 447 D’Onofrio, M., et al. 2008, ApJ, 685, 875 Douglas, N. G., Napolitano, N. R., Romanowsky, A.J., et al., 2007, ApJ, 664, 257 Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L.,
APPENDIX A: SYSTEMATIC EFFECTS IN THE STELLAR POPULATIONS MODELS

Here we examine the role of systematic uncertainties in the stellar populations results, using different assumptions and basis models (sec. also, similar analysis in [Rettura et al. 2008, Kannappan & Gawiser 2007] and [Conroy et al. 2008]). First we consider our default model based on BC03, using three different parameterizations for the SFH. In our reference model, $\tau$ and $Z$ (as well as $t_{gal}$) are free parameters fitted to each galaxy; a more simplified model has fixed $\tau$ for the whole sample; an even simpler SSP model has $\tau=0$ and $Z=Z_\odot$. The impact of these differences is shown in Fig. A1 (left panel), the distributions of $\Upsilon_*$ in all these models are fairly similar, except in the simplest case which shows a stronger tail to low values of $\Upsilon_*$. The difference stems from M05 predicting $\tau=1$ Gyr and $Z=Z_\odot$ corresponding to typical values for the whole sample; an even simpler SSP model has $\tau=0$ and $Z=Z_\odot$. As shown in Fig. A1, the distributions of $\Upsilon_*$ in all these models are fairly similar, except in the simplest case which shows a stronger tail to low values of $\Upsilon_*$. The impact of these differences is shown in Fig. A2 (left panel), where it can be seen that overly restrictive modelling assumptions compensate with large variations in $\Upsilon_*$ and thus steeper values for $\gamma_*$. The differences from M05 are most prominent in the near-infrared, but not substantially for $\Upsilon_*$.

Next we compare basis model variations, starting with BC03 and M05. The different input stellar models and treatments of the thermally-pulsing asymptotic giant branch phase (TP-AGB) lead to different $\Upsilon_*$ predictions for the same colours (Maraston et al. 2006). Comparisons of some parameters derived from the two models with solar metallicity, given the same colour data, are made in Fig. A2 (right panels). The inferred ages agree very well for older populations, with M05 returning ages up to ~10% higher than BC03, while for younger populations, up to ~30% lower. The difference stems from M05 predicting $V-R$ and $V-I$ to be redder for young populations and bluer for old, while $B-V$ is redder for all ages. The implications for $\Upsilon_*$ are

17 Recent preliminary updates of the BC03 models have included an improved TP-AGB treatment [Bruzual 2007, Eminian et al. 2008]. The colours and $\Upsilon_*$ predictions are altered, particularly in the near-infrared, but not substantially for $Z \geq 0.4 Z_\odot$. These new models are more similar to M05 than BC03 but for old ages resemble BC03 [McGrath et al. 2007].
Figure A1. Distributions of recovered $\Upsilon_*$ from PS96 galaxy sample, for different stellar populations models and assumptions. Top left: BC03+Salpeter model with different parameter assumptions: $\tau = 0$ and $Z = Z_\odot$ (red); $\tau = 0.75$ Gyr and $Z = Z_\odot$ (blue); and $\tau$ and $Z$ free to vary (green). Top right: BC03 and M05 models compared, assuming $\tau = 0$ and $Z = Z_\odot$. The main panel shows a Salpeter IMF, with BC03 in blue and M05 in orange; the inset panel shows a lower-mass IMF, with BC03+Chabrier in red, and M05+Kroupa in green. Bottom left: BC03 and M05 models compared (solid and dashed lines, respectively), with $Z$ free to vary. Bottom right: BC03 and BJ01 models compared, assuming $\tau = 0$ and $Z = Z_\odot$. The solid black lines show BJ01, and blue shows BC03, in both cases with a Salpeter IMF. Lower-mass IMFs are also shown: red is BC03 with Chabrier IMF, short-dashed black is BJ01 with “scaled” Salpeter IMF, long-dashed black is BJ01 with “modified” Salpeter IMF, solid dark grey is BJ01 with Scalo IMF, dashed light grey is BJ01 with “top-light” IMF slope, and dot-dashed light grey is BdJ01 with “top-heavy” IMF slope (the latter two cases using the PEGASE prescription).

that agreement is good for $\Upsilon_* \gtrsim 6 \, \Upsilon_\odot$, while for lower values the M05 predictions are smaller by up to a factor of two. The extension of the M05 results to smaller values of $\Upsilon_*$ can also be seen in Fig. A1. The final impact of these systematic differences on the trend of $\Upsilon_*$ with luminosity is shown in Fig. A2 (left panel): M05 yields a more steeply increasing trend.

We finally examine the SSP models from BJ01. BJ01 predict a tight correlation between $\Upsilon_*$ and galaxy colour\(^{18}\) using relations for the three colours $B - V$, $B - R$ and $V - I$ and minimizing a $\chi^2$ function we determine the best fitted $\Upsilon_*$ for the BdJ01 prescriptions which are shown in Fig. A1 (left panel).

Assuming a Salpeter IMF, the use of different stellar prescriptions (BC03 vs BdJ01) has a negligible effect on the bulk of the $\Upsilon_*$ distribution (e.g. solid black lines and blue ones in the Figure). Some of the assumed IMFs in BdJ01 (“scaled” and “modified” Salpeter and the Scalo prescription for further details see BJ01) predict lower $\Upsilon_*$, with the Scaled Salpeter and Scalo IMFs giving similar results of the BC03+Chabrier one (red curves in the same Figure). Finally, using BJ01 results for PEGASE (Fioc & Rocca-Volmerage 1997) prescription we obtain that: 1) a top-heavy IMF with a slope $-0.85$ gives $\Upsilon_*$ values which are in the between of the Kroupa (2001) IMF (or Chabrier or Scalo) and Salpeter IMF predictions, while 2) a top-light IMF with a slope $-1.85$ give much larger $\Upsilon_*$ values. Note that distributions using directly BC03 (red and blue lines in left panel of Fig. A1) have a larger spread around the peak distribution than the BdJ01 results.

\(^{18}\) This was obtained for spiral galaxies but it has been proven to work for ETGs as well (BJ01, Bell et al. 2003)
BJ01 results have been plotted in middle panel of Fig. A2 like grey points. The slope of the relation shown in this figure is unchanged if we use the various prescriptions analyzed in the paper above (see distributions using a Salpeter IMF in left panel of Fig. A1); on the contrary, a little change in the zero point is observed.

As a final test, we compare results using different models and data on the same galaxies. As a stellar synthesis model, C+06 fit single burst models (using stellar prescription in Vazdekis et al. 1996), to some line-strength indices. Their estimates are on average 20% larger than ours (with a scatter of 17%). This discrepancy could not be fixed by fitting Vazdekis et al. (1996) or BC03 SSP models to our galaxy colours. Some systematics can be ascribed, partially, to the extrapolation of line-strength indices (and velocity dispersion) from the very central regions to the effective radius, if some change in the average stellar population is present and unaccounted.

APPENDIX B: INDEPENDENT CHECKS ON DYNAMICAL MASSES

Given the simplifications of our Jeans models used to derive the dynamical masses (spherical quasi-isotropic models), we test here using independent results whether our methods have introduced any systematic bias for $T_{\text{dyn}}$. Our first cross-check is with C+06, who constructed detailed two-dimensional models of nearby ETGs. Our sample has 18 galaxies in common with theirs. The main differences between the two datasets are: 1) our distance moduli are on average larger (0.05 mag) than C+06 but consistent within the scatter; 2) our effective radii are on average 5% larger with a median scatter of 16%; 3) the central velocity dispersions from C+06 are lower than the PS96 values by $6 \pm 15$ km s$^{-1}$ (see Emsellem et al. 2004).

C+06 constructed flattened, axisymmetric, constant $M/L$ dynamical models, using both two-integral Jeans models and three-integral Schwarzschild (1979) orbit models. Their luminosity models are multi-Gaussian expansions of the observed surface brightness profiles, and thus quite non-homologous. Converting our constant- $M/L$ Sérsic-based $T_{\text{dyn}}$ results to the $I$-band and to the C+06 distances, we compare to their results in Fig. A1. The masses are broadly consistent, with a systematic trend for ours to be higher by $\sim 20\%$.

There are several possible reasons for this residual discrepancy, including rotation, orbital anisotropy variations, and galaxy flattening – all of which were handled in rigorous detail by C+06 but not by our models. Based on the results of Cappellari et al. (2007), the anisotropy effect should not correlate strongly with luminosity, but rotation and flattening probably do. We also compare our modelled values of $\sigma_v$ (the velocity dispersion integrated over a 1 $R_{\text{eff}}$ aperture, another 7 from their sample did not have measured $I-L$ colours available for making a proper comparison between their $I$-band and our $B$-band $T_{\text{dyn}}$ results.
folding in the rotational contribution) with their observed values, to see if our extrapolation from the central aperture could be generating the discrepancy. However, our $\sigma_e$ values turn out to be lower by $13^{+9}_{-6}$ km s$^{-1}$, which goes the wrong way to explain our higher masses.

Next we consider the detailed spherical dynamical models of G+01, with 16 galaxies in common. After shifting to the same distance scale, our $Y_{\text{dyn}}$ values at $R_{\text{eff}}$ are $27\% \pm 8\%$ lower on average than theirs. Since their sample was focussed on round galaxies, we suspect again that flattening is playing a key role in the accuracy of our results, but that we have been able to largely compensate for its effects in our simplified modelling.

Finally we turn to the dynamical results of van der Marel & van Dokkum (2007, hereafter MD07), who compiled $Y_{\text{dyn}}$ for 60 local galaxies from the literature (van der Marel 1991; Magorrian et al. 1998; Kronawitter et al. 2000; Gebhardt et al. 2003; C+06). The original works made use of various types and quality of data and dynamical models, but should in general be superior to ours. The $Y_{\text{dyn}}$ values are combined after homogenizing the distances and cosmology, and converting to the same distance scale, our $Y_{\text{dyn}}$ values at $R_{\text{eff}}$ are $27\% \pm 8\%$ lower on average than theirs. Since their sample was focussed on round galaxies, we suspect again that flattening is playing a key role in the accuracy of our results, but that we have been able to largely compensate for its effects in our simplified modelling.

**APPENDIX C: SYSTEMATIC UNCERTAINTIES FOR DARK MATTER FRACTION**

We consider finally how various systematic uncertainties could impact the $f_{DM}$ determinations. We first consider the stellar populations models. As detailed in Appendix A, the model prescription that is used can have a noticeable effect on the $Y_*$ trends. We show in Fig. C1 (upper left panel) the differences engendered in $f_{DM}$ by adopting different models. Among the most plausible models, the results are roughly consistent, but the trend of $f_{DM}$ with luminosity tends to flatten or steepen with the use of M05 or BJ01, respectively, rather than BC03.

We next consider uncertainties in the dynamical models, starting with the assumed mass profile. As shown in Fig. C1 (upper right panel), the bracketing models of SIS and constant-$M/L$ produce similar results for $f_{DM}$. Testing the possibility that our $n = 4$ Sérsic index for the bright Es is inaccurate, we alternatively take the higher $n = 6$ relation from Caon, Capaccioli & D’Onofrio (1993) as reported in PS97, and find that in a constant-$M/L$ case, $Y_{\text{dyn}}$ for the brighter galaxies decreases and the overall $f_{DM}$ trend is constant with luminosity (Fig. C1 bottom left panel). However, an SIS profile is probably a better match for these galaxies, and in this case, changing $n$ would not affect the results. Finally, we try to calibrate out the inaccuracies in our simplified Jeans modelling, based on the MD07 results, and find that the $Y_{\text{dyn}}$ values for the fainter galaxies might actually be lower, and the $f_{DM}$ slope with luminosity therefore steeper (Fig. C1 bottom right panel).

To quantify the effect of ellipticity ($\epsilon$) on our estimates, we have also selected E galaxies with $\epsilon < 0.3$ (as derived by RC3). For these systems, the results are still consistent with an increasing (flat) trend of $f_{DM}$ with luminosity for bright (faint) galaxies.

In summary, there are several potential competing sys-
Central M/L and DM fraction in early-type galaxies

Figure C1. Effects of systematic modelling uncertainties on DM fractions, for the overall EG sample. Unless otherwise stated, the mass model is constant-M/L, and the IMF is Salpeter. Top left panel: Changing the stellar populations basis model (see left panel in Fig. A2 for line definitions). Top right panel: Changing the dynamical mass model from SIS (black) to constant-M/L (grey). Bottom left panel: Changing the Sérsic index $n$ in the dynamical modelling (black: PS97 values; grey: Caon, Capaccioli & D’Onofrio (1993) values). Bottom right panel: Calibrating the dynamical models using MD07 (black: original; grey: recalibrated). Here a Chabrier IMF is used to avoid negative $f_{DM}$ values.

Systematic effects, and it is not clear which one might win out in biasing the $f_{DM}$ slope. Given this uncertainty, we carry out a different, critical test of confidence in our results. Finding results in the literature for the mass content of galaxies in our sample at large radii, we construct the M/L-gradient parameter $\nabla \Upsilon$ introduced by N+05. This simple but powerful metric is calculated from dynamical measurements of $M/L$ at inner and outer radii by the following formula:

$$\nabla \Upsilon = \frac{R_{\text{eff}}}{R_{\text{out}} - R_{\text{in}}} \left( \frac{\Upsilon_{\text{out}}}{\Upsilon_{\text{in}}} - 1 \right).$$

(C1)

Given the longer lever arm, $\nabla \Upsilon$ when available tells us with greater security whether or not an object is rich or poor in DM. We compare $f_{DM}$ and $\nabla \Upsilon$ in Fig. C2 and confirm that high-$f_{DM}$ objects from the current paper generally have high halo DM content in the literature while low-$f_{DM}$ have small $\nabla \Upsilon$ consistent with a lower global DM content.

No attempt is made here to decompose the M/L measurements into stars and DM, i.e. to determine $f_{DM}$. Instead, the broad premise is that $\Upsilon_{\text{dyn}}$ increases more rapidly with radius in galaxies with higher $f_{DM}$. 

20
Figure C2. M/L-gradient parameter based on extended dynamics, compared to central DM fraction (default SIS model with Chabrier IMF). Red and blue dots are E and S0 galaxies. Most of the data are taken from N+05, with several updates and additions from more recent literature (Teodorescu et al. 2005; Schuberth et al. 2006; Douglas et al. 2007; Weijmans et al. 2008; Napolitano et al. 2009b; Romanowsky et al. 2009; Kumar et al. 2009).