The slope of the mass profile and the tilt of the fundamental plane in early-type galaxies

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ABSTRACT

We present a survey, using the Chandra X-ray observatory, of the central gravitating mass profiles in a sample of 10 galaxies, groups and clusters, spanning ~2 orders of magnitude in virial mass. We find the total mass distributions from ~0.2–10Re, where Re is the optical effective radius of the central galaxy, are remarkably similar to powerlaw density profiles. The negative logarithmic slope of the mass density profiles, α, systematically varies with Re, from α ≳2, for systems with Re ~4 kpc to α ≳1.2 for systems with Re ≥ 30 kpc. Departures from hydrostatic equilibrium are likely to be small and cannot easily explain this trend. We show that the conspiracy between the baryonic (Sersic) and dark matter (NFW/ Einasto) components required to maintain a powerlaw total mass distribution naturally predicts an anti-correlation between α and Re that is very close to what is observed. The systematic variation of α with Re implies a dark matter fraction within Re that varies systematically with the properties of the galaxy in such a manner as to reproduce, without fine tuning, the observed tilt of the fundamental plane. We speculate that establishing a nearly powerlaw total mass distribution is therefore a fundamental feature of galaxy formation and the primary factor which determines the tilt of the fundamental plane.

Key words: Xrays: galaxies— galaxies: elliptical and lenticular, cD— galaxies: ISM— dark matter— galaxies: fundamental parameters

1 INTRODUCTION

The global optical properties of giant elliptical galaxies are often parametrized by three key quantities, the effective (half-light) radius (Re) of the stellar light, the mean surface brightness (or luminosity) and the central line-of-sight velocity dispersion (σ0). In this three-dimensional parameter space, they occupy a narrow “fundamental” plane (Dressler et al. 1987; Djorgovski & Davis 1987), the orientation of which differs significantly from naive expectations from the virial theorem (assuming homology and a constant mass-to-light ratio, γ). The relative importance which deviations from homology, variations in the stellar population properties and changing dark matter fractions play in producing this “tilt” have been hotly debated (e.g. Renzini & Ciotti 1993; Firth & Madsen 1993; Ciotti et al. 1994; Prugniel & Simien 1997; Graham & Colless 1997; Gerhard et al. 2001; Padmanabhan et al. 2004; Trujillo et al. 2004; Cappellari et al. 2006; Bolton et al. 2006; Tortora et al. 2006 and references therein), with recent work tending to emphasize the importance of dark matter (e.g. Cappellari et al. 2006; Bolton et al. 2007). To maintain the thinness of the fundamental plane, however, the dark matter fraction within ~Re must be tightly correlated with the optical properties of the galaxy (e.g. Ciotti et al. 1996).

Strong observational evidence for the existence of massive dark matter halos around early-type galaxies has been provided by independent observational constraints from X-ray studies, lensing and stellar dynamics (e.g. Humphrey et al. 2000, hereafter H06; Mathews & Brighenti 2006 and references therein; Kochanek 1993; Grillitsch et al. 1999; Gavazzi et al. 2007; Gerhard et al. 2001; Thomas et al. 2007). Although the total mass distribution within Re is dominated by the stars, the dark matter fraction is non-negligible, and stellar dynamics and lensing studies (most of which are restricted to within ~Re) suggest that it establishes a conspiracy with the luminous matter to produce total mass density (ρm) profiles close to ρm ∝ R−2 (where R is the radius), i.e. the “singular isothermal sphere” (e.g. Kochanek 1993; Treu & Koopmans 2004; Koopmans et al. 2006, 2009; Kronawitter et al. 2006). This “bulge-halo conspiracy” is similar to that which establishes flat rotation curves in disk galaxies.

Total mass distributions approximately consistent with ρm ∝ R−2 have long been reported from hydrostatic X-ray analysis of nearby elliptical galaxies at scales much larger than Re (e.g. Trinchieri et al. 1988; Thomas 1986; Serlemitsos et al. 1993; Nulsen & Bohringer 1997; Kim & Fabian et al. 1994; Mathews & Brighenti 1997; Malaguti et al. 2000). This “bulge-halo conspiracy” is similar to that which establishes flat rotation curves in disk galaxies.

In recent years, however, a number of studies have reported departures from hydrostatic equilibrium in nearby elliptical galaxies. For example, Gavazzi et al. (1997) and Simmerling et al. (2005) find departures from hydrostatic pressure equilibrium for nearby elliptical galaxies at scales ~Re. Departures from hydrostatic equilibrium are likely to be small and cannot easily explain this trend. We show that the conspiracy between the baryonic (Sersic) and dark matter (NFW/ Einasto) components required to maintain a powerlaw total mass distribution naturally predicts an anti-correlation between α and Re that is very close to what is observed. The systematic variation of α with Re implies a dark matter fraction within Re that varies systematically with the properties of the galaxy in such a manner as to reproduce, without fine tuning, the observed tilt of the fundamental plane. We speculate that establishing a nearly powerlaw total mass distribution is therefore a fundamental feature of galaxy formation and the primary factor which determines the tilt of the fundamental plane.

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et al. (2003) and Zappacosta et al. (2006) studied the very unexpected for the dark matter potential to be preferred over some other mass distributions. With the improved capabilities of Chandra and XMM, much tighter constraints on radial mass profiles have now been reported for a wider array of galaxies (e.g., Humphrey et al. 2006, 2007, 2009b; Fukazawa et al. 2006; O’Sullivan & Ponman 2007; O’Sullivan et al. 2007; Buote 2002), which similarly resemble $\rho_m \propto R^{-\alpha}$ (as pointed out by Cavazza et al. 2007), although not exactly so over all radial scales (Romanowsky et al. 2009). Fukazawa et al. (2006) fitted a model of the form $\rho_m \propto R^{-\alpha}$ to the combined mass profiles of their galaxy sample outside 10 kpc, finding $\alpha = 1.67 \pm 0.33$.

At the scale of massive galaxy clusters, hydrostatic X-ray analysis has revealed much less cuspy mass distributions ($\alpha \sim 1.4$; e.g., Buote & Lewin 2004; Voigt & Fabian 2006; Abazajian et al. 2005; David et al. 2001; Lewis et al. 2004; 2003; 2009 and Zappacosta et al. 2006) studied the very relaxed clusters A2029 and A2589, finding that the total mass profiles were in good agreement with the NFW shape expected for the dark matter only, once again suggesting some kind of conspiracy between the luminous and dark matter to produce an approximately powerlaw total mass distribution in the core of the system. Stellar dynamics and lensing studies of clusters have, similarly, found less cuspy mass distributions in the core of the system. Stellar dynamics and lensing studies of clusters have, similarly, found less cuspy mass distributions in the core of the system.

In order to investigate this disparate behaviour at different mass scales, in this paper we carry out a uniform X-ray analysis of a sample of relaxed galaxies, groups and clusters to investigate the shape of the innermost mass distributions. X-ray analysis is ideally suited for this study, since it allows straightforward mass measurements in individual systems over a wide radial range, from the baryon dominated regime ($R \lesssim R_e$) to regions where the dark matter dominates the gravitating mass ($R \gtrsim R_e$), thus providing adequate leverage to elucidate any conspiracy between these different components. For relaxed systems, hydrostatic equilibrium is believed to be an excellent approximation, with nonthermal effects contributing no more than 20% of the total pressure (e.g., Charazov et al. 2008; Nagai et al. 2007; Piffaretti & Valdarini 2005; Humphrey et al. 2009a, hereafter H09). In our previous papers (H06, H09; Gastaldello et al. 2007; Zappacosta et al. 2006) we have carried out detailed decompositions of the mass distribution of these systems into baryonic and non-baryonic components. We have not, however, investigated in detail the relationship between these two components. In light of the apparent conspiracies between them at both cluster and galaxy scales, in this present paper, we adopt the more pragmatic approach of examining whether the inner part of the mass profile can be modelled as a powerlaw, and investigating whether its slope varies systematically.

Throughout this work, we assume a cosmology of $H_0=70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m=0.3$ and $\Lambda=0.7$. All error-bars, unless stated otherwise, correspond to 1-$\sigma$ confidence regions.

### Table 1

Properties of the galaxies, groups and clusters in our sample. We list the K-band effective radius of the central galaxy ($R_e$) obtained from the 2MASS database (Jarrett 2000), except for the clusters, for which we report (1) the V-band $R_e$ from Malumuth & Kirshner (1989) and (2) the R-band $R_e$ from Zanin et al. 1993. We quote luminosity distances for each object, based on the redshift in the NED database, except those marked “*”, which were based on the surface brightness fluctuations study of Tonry et al. (2001), see H09, H09. Deprojected density and temperature profiles were taken from the listed reference (Ref). Where the data are unpublished or were re-reduced in the present work, we list the Chandra observation identifiers (ObsID) and net exposure time (Exp). References: (1) H09, (2) Humphrey et al. (2009b), (3) Humphrey et al. (2009), (4) F. Gastaldello (2009, priv. comm.); Gastaldello et al. (2007), (5) W. Liu (2009, priv. comm.); Liu et al. (2009).

| Object        | $R_e$ (kpc) | Distance (Mpc) | ObsID | Exp (ks) | Ref |
|---------------|------------|----------------|-------|----------|-----|
| NGC 1332      | 2.7        | 21.3$^*$       | ...   | ...      | (1) |
| NGC 720       | 3.1        | 25.7$^*$       | 7062,7372 | 99 (2) |     |
| ...           | ...        | ...            | ...   | ...      |     |
| ES0552-020    | 16         | 138            | 3206  | 19 ...   |     |
| ABELL 2589    | 33$^*$     | 183            | 7190  | 52 ...   |     |
| ABELL 2029    | 76$^*$     | 350            | 4977  | 77 ...   | (5) |

### 2 DATA ANALYSIS

#### 2.1 The sample

We chose a sample of 9 objects, spanning ~2 orders of magnitude in virial mass ($M_{vir}$) from the survey of morphologically relaxed, X-ray luminous systems by Buote et al. (2007). We supplemented this sample with NGC 1332, which has the smallest $R_e$ of the relaxed systems we have previously studied for X-ray mass analysis (H06, H09). We focused on Chandra data, since high spatial resolution is essential to study in detail the inner part of the X-ray halo. As we require coverage from $\lesssim R_e$ to several times $R_e$, we only considered objects which had deep enough data to enable spectra to be obtained in at least two annuli within $R_e$. Unfortunately, most nearby galaxy clusters which are morphologically relaxed on large scales also exhibit significant AGN-induced cavities in the core which complicate the analysis. Therefore, we only included two clusters which have been shown to be relaxed at both large and small scales (Lewis et al. 2002; Zappacosta et al. 2006). The properties of the sample and the archival data we used are summarized in Table 1.

#### 2.2 The Slope of the Mass Profile

The Chandra data were reduced and analysed to provide deprojected temperature and density profiles, as outlined in H09. For NGC 1332, NGC 4361 and NGC 4649 the data are described in H09 and Humphrey et al. (2008). We will discuss in more detail the NGC 720 data in Humphrey et al. (2009b) and the A 2029 data in Liu et al. (2009). For RXJ1159+5531, we used the deprojected profiles described...
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Figure 1. Radial mass profiles for each object, arbitrarily scaled for clarity. The solid lines are the best-fitting profiles determined from our “forward fitting” analysis of the temperature and density profiles, while the data-points are determined from the more “traditional” method (§ 2.2). We stress that the models are not fitted to these data-points but are derived independently.

In Gastaldello et al. (2007, provided by F. Gastaldello 2009, priv. comm.),

Under the hydrostatic approximation, we transformed these density and temperature data into mass constraints by two complementary approaches. First, the “traditional” method involves parametrizing these profiles with arbitrary models (for more details on these models, see H09; Humphrey et al. 2008; Gastaldello et al. 2007), which are then differentiated and inserted into the equation of hydrostatic equilibrium (e.g. Mathews 1978). An advantage of this method is that it makes no a priori assumption about the form of the mass distribution. By evaluating the resulting mass model at a number of radii (corresponding to each spectral extraction region) we obtained the mass “data-points” shown for each system in Fig 1. Error-bars were estimated via a Monte Carlo technique (Lewis et al. 2003). We here focus only on the central part of these data; based on experimentation, we considered the mass within 10R_e or 200 kpc, whichever is smaller. Over this radial range, the profiles are all approximately powerlaw in form, but the exact slope varies from object to object.

We find overall good agreement with previously published mass profiles (H09; H03; Gastaldello et al. 2007; Zappacosta et al. 2008; Lewis et al. 2003), although for ES0552-020 the normalization is ~0.1 dex higher than that found by Gastaldello et al. (2007), using XMM data. Nevertheless, this discrepancy is comparable with our estimated systematic error for this object (§ 2.3), and will not affect our conclusions.

Since the traditional method relies on the adoption of ad hoc temperature and density profiles, this can lead to significant systematic errors in the recovered mass distribution (e.g. H09). Furthermore, the individual “data-points” are all correlated, which makes it difficult to interpret a fit made directly through them. Therefore, to be more quantitative, we fitted the mass distribution using the “forward fitting” method described in Humphrey et al. (2008). This involves solving the equation of hydrostatic equilibrium to compute temperature and density profile models, given parametrized mass and entropy profiles. Since the entropy profile must rise monotonically, we parametrized it as a constant plus a powerlaw with one or two breaks added, as needed. For the stellar plus dark mass distribution, we adopted a powerlaw, corresponding to \( \rho_m \propto R^{-\alpha} \), i.e.

\[
M(< R) = M_{75} \left( \frac{R}{75 \text{kpc}} \right)^{3-\alpha}
\]

where \( M \) is the mass enclosed within radius \( R \). \( M_{75} \) and \( \alpha \) were parameters of the fit. An additional gas mass component was included self-consistently in the calculation, but is generally small in the fitted radial range. We fitted only the inner parts of the density and temperature profiles, as described above, freely varying \( M_{75} \), \( \alpha \), the parameters describing the entropy profile and a term related to the gas pressure at a suitable reference radius (H09). Following H09, parameter space was explored with a Bayesian Monte Carlo method assuming flat priors (see § 2.3 for the impact of

\footnote{Specifically, the nested sampling algorithm of Feroz & Hobson (2008).}
Table 2. Marginalized best-fitting values of the powerlaw slope ($\alpha$) and normalization ($M_{75}$) for each object in the sample. We list both the marginalized value and the 1-$\sigma$ statistical errors (“Best”) and an estimate of the systematic uncertainty (“Sys.”) due to various data-analysis choices (§2.4). We stress this should not be added in quadrature with the statistical errors. Also shown is the $\chi^2$ per degree of freedom (dof) for each fit to the temperature and density profiles.

| Object   | $\alpha$     | $\Delta \alpha$ | $\log M_{75}$ | $\Delta \log M_{75}$ | $\chi^2$/dof |
|----------|--------------|----------------|---------------|----------------------|--------------|
|          | Best         | Sys.           | Best          | Sys.                 |              |
| NGC 1332 | 2.05$^{+0.05}_{-0.06}$ | $\pm0.04$ | $12.15^{+0.12}_{-0.11}$ | $\pm0.07$ | 16/6          |
| NGC 720  | 1.91$^{+0.05}_{-0.07}$ | $\pm0.02$ | $12.34^{+0.08}_{-0.07}$ | $\pm0.03$ | 5.7/8         |
| NGC 4649 | 1.97$^{+0.03}_{-0.03}$ | $\pm0.03$ | $12.48^{+0.08}_{-0.07}$ | $\pm0.03$ | 30/22         |
| NGC 4261 | 2.01$^{+0.03}_{-0.03}$ | $\pm0.04$ | $12.37^{+0.09}_{-0.05}$ | $\pm0.09$ | 6.5/2         |
| RXJ1159  | 1.67$^{+0.11}_{-0.10}$ | $\pm0.06$ | $12.82^{+0.10}_{-0.10}$ | $\pm0.07$ | 9.3/4         |
| MKW4     | 1.66$^{+0.03}_{-0.03}$ | $\pm0.03$ | $12.84^{+0.03}_{-0.03}$ | $\pm0.06$ | 26/18         |
| AWN4     | 1.64$^{+0.12}_{-0.11}$ | $\pm0.08$ | $12.88^{+0.03}_{-0.02}$ | $\pm0.02$ | 15/12         |
| ESO552  | 1.38$^{+0.11}_{-0.18}$ | $\pm0.09$ | $12.81^{+0.07}_{-0.07}$ | $\pm0.06$ | 9.6/10        |
| A 2589   | 1.24$^{+0.17}_{-0.10}$ | $\pm0.27$ | $12.88^{+0.03}_{-0.03}$ | $\pm0.12$ | 19/17         |
| A 2029   | 1.24$^{+0.05}_{-0.06}$ | $\pm0.22$ | $13.17^{+0.01}_{-0.11}$ | $\pm0.11$ | 23/8          |

2.3 Systematic Errors

As in all studies of dark matter in early-type galaxies, regardless of the specific method, our work involved a number of arbitrary analysis choices. In this section, we describe how sensitive our results are to the various choices we made. For a more detailed discussion of these various systematic error assessments, see BH07.

We first examined how the choice of priors might be influencing our results by replacing each of the flat priors we adopted by priors which were flat in logarithmic space (we replaced the flat prior on $\log M_{75}$ with one which is flat on $M_{75}$). These choices typically had a smaller effect than the statistical errors. Next we investigated the sensitivity of our spectral-fitting results to our treatment of the Chandra background by using the standard “background template” spectra, suitably renormalized to match the data at energies $\gtrsim 10$ keV, instead of the more robust, modelled background adopted by default. To assess the importance of the radial range we fitted, we tried reducing it by $\sim 20\%$ for each object. We experimented with spectral-fitting over different energy ranges (0.4–7.0 keV, 0.5–2.0 keV and 0.7–7.0 keV, in addition to our default, 0.5–7.0 keV), varying the neutral galactic column density by 25%, and the distance by 30% (for the NGC objects, we instead varied the distance by the statistical error on their distance measurements in BH07). In Table 2 we list the largest change in the marginalized parameter values arising due to these choices. None of these systematic errors are large enough to affect our conclusions.

3 DISCUSSION

3.1 A luminous-dark matter conspiracy

In general, the stars are believed to dominate the gravitational potential within $\sim R_e$, with the dark matter dominating outside this scale (e.g. Brighenti & Mathews 1997).
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Figure 2. Left: Variation of the marginalized $\alpha$ as a function of $R_e$, from our data (circles), showing a strong anti-correlation. We overlay (stars) the lensing data of Koopmans et al. (2006), which is computed at scales smaller than $\sim R_e$ and plotted versus $R_e$. For a strictly fair comparison with our work, their data may need to be shifted slightly to the left (given differences in the adopted photometric bands). We also overlay the predictions of our toy model (solid line; § 3.2) and an estimate of the model uncertainty (dotted lines). To indicate how changing the Sérsic index ($n$) of the stellar light component affects our model, we have annotated each model line with the corresponding value of $n$. Right: Marginalized 1-σ joint confidence contours for $\alpha$ and $M_75$ for each object. We overlay the predictions of our toy model, combined with the K-band Kormendy relation (solid line), and an estimate of the uncertainty in the model (dotted lines).

Gerhard et al. (2001); in particular, we have shown this for the systems studied here (Hoekstra et al. 2007; Lewis et al. 2003; Buote & Lewis 2004; Zappacosta et al. 2006). Therefore, the approximately powerlaw mass distributions shown in Fig. 1 indicate an apparent conspiracy between the luminous and dark matter to produce a scale-free total mass distribution, at least within $\sim 10 R_e$.

At much larger scales, there is evidence that the profiles deviate from this simple shape (e.g. Lewis et al. 2003; Vikhlinin et al. 2006; Humphrey et al. 2008; Gastaldello et al. 2007; Romanowsky et al. 2009). Nevertheless, in the inner regions of the systems, this effect is similar to the “bulge-halo” conspiracy found at much smaller scales ($\lesssim R_e$) in lensing and stellar dynamics studies (e.g. Treu & Koopmans 2004; Koopmans et al. 2006, 2009). It is important to appreciate that the observed powerlaw mass profiles cannot simply arise from the arbitrary superposition of any reasonable stellar and dark mass components. To illustrate this quantitatively, we simulated a powerlaw-like mass profile and fitted it with a model comprising Sérsic and dark matter components (as described in detail in § 2.2). For any given galaxy luminosity, we found that both $R_e$ and the normalization of the dark matter component cannot vary by more than $\sim 25\%$ from their “best” values while maintaining mean absolute fractional deviations between the model and data of less than $10\%$ (as indicated by our fits in § 2.2).

The origin of this conspiracy is unclear, but it is likely tied to the complex interaction of baryons and dark matter in the centres of galaxies (for example, Robertson et al. 2006 point out the importance of gas physics in maintaining the tilt of the fundamental plane, which may be related to this conspiracy; § 2.2.3). Unfortunately these processes are very poorly understood; the predicted central dark matter density cusps due to “adiabatic contraction” (Blumenthal et al. 1986; Gnedin et al. 2004) have not been observationally confirmed (e.g. Humphrey et al. 2006; Zappacosta et al. 2006; Gnedin et al. 2007; Dutton et al. 2007), suggesting that other effects, such as dynamical friction, may be important (e.g. El-Zant et al. 2004; Dutton et al. 2007; Abadi et al. 2009). It is unclear, therefore, that any model is so far robustly predicting a powerlaw total mass distribution arising from these effects.

Since the data were not all fitted over the same physical scales, it is important to assess whether the systematic variation in $\alpha$ we observe is simply an artefact of these different fit ranges. In Fig. 3 we show the mass profiles of three representative systems with different $R_e$, arbitrarily scaled for clarity, and shown as a function of physical radius (left) and fraction of the virial radius (right; deduced from the virial masses reported in Buote et al. 2007). In conjunction with Fig. 1 (which shows the same profiles as a function of fraction of $R_e$), it is immediately clear that throughout overlapping radial scales the slopes of the three mass distributions are all very different, so that the fit range is unlikely to be the cause of the trends observed in Fig. 1.

Although all of the systems we considered are morphologically relaxed, which should eliminate objects with the largest departures from hydrostatic equilibrium, it is still important to consider whether deviations from hydrostatic equilibrium could be responsible for the observed trends. In order to affect the shape of the mass profile, any source of nonthermal pressure must vary radially in a finely balanced manner, given that the gas pressure profile is consistent with a powerlaw mass density profile (Fig 1) that varies systematically with the host properties (Fig 2). For the cluster A 2589, Zappacosta et al. (2006) concluded that, if the true mass distribution is much cuspler than inferred from the X-rays (for example, an unmodified NFW plus a stellar mass component), no plausible source of turbulent or magnetic pressure could make the X-ray measurements imply such a flat total density profile. H09 carried out full mass decompositions for three of our galaxies, finding stellar...
mass to light ratios in excellent agreement with the predictions of stellar population synthesis models, suggesting that nonthermal pressure is very small (≤ 10–20%) within Re. This was further supported by the good agreement between the X-ray constraints on the central black hole masses, and those obtained from optical methods for these objects. Furthermore, nine of our objects were included in the sample of Buote et al. (2007), who showed that their dark matter halos inferred from X-ray mass analysis approximately exhibit the relationship between halo “concentration” (c_{vir}) and total mass predicted from numerical structure formation simulations. This supports the idea that the shapes of the mass profiles for these systems are not significantly in error due to non-hydrostatic effects.

In their survey of 15 lensing systems, Koopmans et al. (2006) found that α ranged from ~1.8–2.4, while the Re spanned ~2–17 kpc. In the left hand panel of Fig. 2 we overlay their measured α versus Re. We find that they are roughly consistent with the points from our X-ray sample, but at given Re, α is generally larger. For strict consistency with our adopted photometric bands, their data may need to be adjusted, however. Since Re in the K-band is typically smaller than in bluer bands (as an illustration of this effect, for the galaxies in the catalogue of La Barbera et al. 2008 we find that that Re is on average ~50% larger in the K-band than the K-band), this would likely involve shifting the Koopmans et al. to the left, bringing them into better agreement with our results. By inspection, there is a slight hint in their data of the anti-correlation we observe between α and Re, although it is not statistically significant. However, since their fits were all restricted to regions ≤ 0.9Re, where the stellar mass dominates the potential, they are more likely to have been subject to local curvature in the mass distribution than the X-ray data were, given the better radial coverage of the latter.

3.2 Decomposing the mass profiles: a toy model

To investigate quantitatively the implications of the apparent conspiracy between dark and luminous mass components implied by Fig. 2, we constructed a simple toy model by decomposing a pure powerlaw mass distribution into an NFW (Navarro et al. 1997) dark matter profile plus a de Vaucouleurs stellar mass component (using the deprojected Sersic approximation of Prugniel & Simien 1997 and fixing the Sersic index, n = 4). In our previous work (Buote et al. 2007; Koopmans et al. 2007; Gastaldello et al. 2008), we have shown that decompositions of this type for the systems studied in the present work give parameters for the NFW model which are consistent with theory. The measured NFW concentration parameters are slightly higher than predicted median from N-body simulations, but this can be reasonably attributed to relaxed X-ray selected systems having formed early. To perform the decomposition, we first constructed a set of mass “data-points” from the powerlaw model in 10 approximately logarithmically-spaced bins between ~0.4–200 kpc, which we then fitted with the two-component model by minimizing the rms of the fractional residuals. The normalization and scale radius of the dark matter component were allowed to vary freely, as were Re and the normalization of the stellar model. We allowed the slope of the input mass distribution to vary systematically from α = 2.2 to α = 1.35. Below this limit, we found that the derived relationships (discussed below) became non-monotonic, which may represent the limitations of our simple parametrization rather than any physical insight, and so we prefer not to discuss this regime. While one might a priori expect significant degeneracies in this decomposition given the number of free parameters, in fact the shapes of the Sersic and NFW mass profiles are sufficiently different that we found a unique decomposition for any input powerlaw, at least for the range of profiles and models we investigated.

We show an example simulated profile, and the best-fitting dark and stellar mass components, in Fig. 3, clearly illustrating how they can conspire to produce an approximately scale-free model.

We overlay in Fig. 3 (left panel) the best-fitting relation between Re and α obtained from our simple mass decompositions (solid line), which can be approximated to better than 1% by α = 2.31 − 0.54 log Re. Without any fine tuning, it clearly captures the overall behaviour of the observed data reasonably well. Since the stellar light profiles of real galaxies may not be exactly de Vaucouleurs in form, we have also experimented with varying the Sersic index, n, from 3–5. Similarly, the NFW model used to parameterize the dark matter halo over the fitting range and may not be strictly correct if the baryonic and non-baryonic components interact gravitationally. Therefore, we have tried replacing it with the revised mass model of Navarro et al. (2004), allowing the mass slope index to fit freely and thus provide more freedom in parameterizing the radial distribution of dark matter. The dotted lines in Fig. 4 bound the range of recovered relations, given these changes, which clearly bracket the observed data. In practice, the impact of changing the stellar light profile dominated this estimate of our model uncertainty.

Since our simple toy model can be freely renormalized,
we cannot use it alone to make any explicit predictions for the relationship between $\alpha$ and $M_{75}$. One way to make further progress, however, is to exploit the "Kormendy relation" between a galaxy's luminosity and $R_e$ (Kormendy 1977). For a given stellar mass-to-light ratio ($\gamma_*$), $M_{75}$ must be adjusted to keep the stellar component consistent with the Kormendy relation while maintaining the powerlaw total mass distribution for a given $\alpha$ (and hence $R_e$). We adopted a form for this relation which is appropriate for our data, estimated from the K-band galaxy luminosities and $R_e$ tabulated by Gastaldello et al. (2007) and H06. We found a mean relation $\log L/L_\odot = 10.95 + 0.79 \log R_e$, with an intrinsic scatter of $\sim 0.11$ dex, where $L$ is the total luminosity of the galaxy in the K-band and $L_\odot$ is the luminosity of the Sun, assuming a K-band absolute Solar magnitude of 3.41. We assumed $\gamma_* = 1$, appropriate for an old stellar population (e.g. Maraston 2005). In Fig 3 (right panel) we overlay the predictions of this simple model (solid line), and an estimate of the range of uncertainty, which factors in the effects of varying the Sersic index of the stellar light by $\pm 1$, the intrinsic scatter in the Kormendy relation and a $\pm 50\%$ variation in $\gamma_*$ (which dominates the error budget). Clearly the model captures the overall behaviour of the data fairly well.

To verify that our model is self-consistent, it is important to determine if the parameters of the fitted dark matter model it predicts are reasonable. Since the toy model cannot be used alone to set the normalization of the mass profile, to do this we considered the simple model, folding in the Kormendy relation, described above. Starting with the $\alpha$-$M_{75}$ relation predicted by this model, we simulated corresponding powerlaw mass profiles, and decomposed them into Sersic and dark matter components. We found monotonic relations between $M_{vir}$ and $\alpha$ and between NFW $c_{vir}$ and $\alpha$, allowing us to recast this as a $c_{vir}$-$M_{vir}$ relation, which we can approximate by $c_{vir} = c_{14} (M_{vir}/10^{14} M_\odot)^{-\beta}$, where $c_{14} = 10$ and $\beta = 0.17$. This is very close to the best-fitting $c_{vir}$-$M_{vir}$ relation found by Duote et al. (2007), for which $c_{14} = 9.0 \pm 0.4$ and $\beta = 0.172 \pm 0.026$. Exploring the estimated range of uncertainty on the model linking $\alpha$ and $M_{75}$, we found $c_{14}$ to lie in the range 6–16 and $\beta$ from 0.13–0.18. The total range of $M_{vir}$ spanned by our predicted $c_{vir}$-$M_{vir}$ relation ($\sim 12.5 < \log_{10} M_{vir} < 15.0$) is similar to the range spanned by the systems in our sample. It appears, therefore, that the parameters of the NFW component implied by our simple model are appropriate for the kinds of system studied in this work.

### 3.3 Implications for the fundamental plane

The existence of a conspiracy between the dark and luminous matter to produce a powerlaw total mass profile should have implications for the tilt of the fundamental plane. The fundamental plane may be written in the form

$$\log R_e = A \log \sigma_0 + B \mu + \text{const.}$$

where $\sigma_0$ is the central velocity dispersion, $\mu$ is the mean surface brightness within $R_e$, and $A$ and $B$ are proportionality constants. One way to gain insight into this relation is to interpret it in terms of the scalar virial theorem (e.g. Binney & Tremaine 2008). We can write this in the form:

$$\log R_e = 2 \log \sigma_0 - \log \left( \frac{L_{1/2}}{\pi R_e^2} \right) - \log \gamma + 5.47$$

Here $R_e$ is in kpc, $\sigma_0$ is in km s$^{-1}$, $L_{1/2}$ is (approximately) the light within $R_e$ (in Solar units) and $\gamma = \gamma_* \gamma_m$ is the mass to light (M/L) ratio in Solar units, where $\gamma_*$ is the stellar M/L ratio and $\gamma_m$ the ratio of total mass to stellar mass within $R_e$. The value of the additive constant on the right hand side is useful only in setting the absolute normalization of $\gamma_*$ and does not affect our conclusions. For convenience we chose to determine it from the theoretical relation of Wolf et al. (2009), since this implies a mean $\gamma_*$ of $\sim 1$ for the La Barbera et al. (2008) galaxy sample (see below), which is consistent with the expectations for an old stellar population. Alternative, empirical relations have been found by Cappellari et al. (2004) assuming mass follows light) and Bolton et al. (2007, assuming a singular isothermal sphere mass distribution), which would imply lower $\gamma_*$, by as much as $\sim 40\%$ (for the Cappellari et al. relation). Nevertheless, for our work the absolute value of $\gamma_*$ is unimportant, and so this choice does not affect our conclusions.

In the K-band, assuming the absolute Solar magnitude is 3.41 and neglecting cosmological effects, we can write $\log(L_{1/2}/\pi R_e^2) \simeq 16.00 - 0.4 \mu$, and hence

$$\log R_e = 2 \log \sigma_0 + 0.4 \mu - \log \gamma - 10.53$$

If structural non-homology does not significantly affect this equation, the tilt of the fundamental plane arises through the dependence of $\gamma$ on the other properties of the galaxy. Eliminating $\sigma_0$ between Eqns 2 and 3 and rearranging, we

\[2\] We replaced the total velocity dispersion in their relation with the central velocity dispersion, which is only strictly valid for a flat velocity dispersion profile.
obtain:
\[
\log \gamma = \left( \frac{2}{A} - 1 \right) \log R_e - \left( \frac{2B}{A} - 0.4 \right) \mu + \text{const.}
\]
\[
= (0.33 \pm 0.04) \log R_e + (0.007 \pm 0.011) \mu + \text{const.}
\]
\[
\simeq (0.33 \pm 0.04) \log R_e + \text{const.}
\]  

(4)

where we have used the “log \( \sigma_8 \) fit” values for \( A \) and \( B \) from the recent K-band analysis of La Barbera et al. (2005). The \( \mu \) term is consistent with zero, within the error, suggesting that the tilt of the fundamental plane can arise if \( \gamma \) depends only on \( R_e \), which is exactly the prediction of the toy model, as we discuss below. Nevertheless, since the \( \mu \) term may be non-negligible, to obtain a more accurate assessment of how \( \gamma \) varies with \( R_e \), we computed \( \log \gamma \) directly from the data of La Barbera et al., by using Eqn 3. We grouped these data into a series of narrow \( R \) bins, within each of which we calculated the mean \( \gamma \) and its error (by applying the central limit theorem to the scatter of the data), as shown in Fig 4.

We can use our toy model not only to predict the relationship between \( R_e \) and \( \alpha \), but also the dark matter fraction within \( R_e \) (and hence \( \gamma_m \)), as is immediately clear from inspection of Fig 4. Since the dark matter fraction does not depend on the overall normalization of the mass profile, we do not need to fold in any other relations (such as the Kormendy relation). Furthermore, since we find that \( R_e \) varies monotonically with \( \alpha \) (Fig 3), it is possible to recast this as a relation between \( \gamma_m \) and \( R_e \). We show the resulting relation (roughly \( \log \gamma_m \simeq -0.03 \log R_e + 0.32 (\log R_e)^2 \)) in Fig 4, along with an estimate of the uncertainty that arises from varying the Sersic index by \( \pm 1 \), or adopting the Navarro et al. (2004) model for the dark matter profile. It is immediately clear that there is good agreement between the model and the La Barbera et al. (2005) data, implying the mean \( \gamma_m \simeq 1 \), as noted above. Since the stellar populations of early-type galaxies (and hence \( \gamma_m \)) do not strongly vary with \( R_e \) (at least for \( R_e \lesssim 1 \) kpc; Graves et al. 2009), this suggests that assuming the ubiquity of approximately powerlaw density profiles (supported by Fig 3) is sufficient (albeit not necessary) to explain the tilt of the fundamental plane. While it is possible that not all giant early-type galaxies have density profiles which so closely resemble a powerlaw (although we are not aware of any convincing such counter-examples found by X-ray methods), to lie on the fundamental plane, Fig 4 indicates that their \( \gamma_m \) must still vary with \( R_e \) in a very similar way to the predictions of the toy model. Nevertheless, since it is actually the flattening of the density profile with increasing \( R_e \) that is responsible for the \( \gamma_m-R_e \) relation predicted by the toy model, it is plausible that similar flattening of the mass distributions in a system without a powerlaw-like mass distribution might produce approximately the same trend.

One intriguing prediction of our toy model is that the relationship between \( \log \gamma_m \) and \( \log R_e \) has some curvature, which would also imply curvature in the fundamental plane. There is, in fact, some evidence that brightest cluster galaxies (BCGs) may not lie on the same fundamental plane as smaller systems (e.g. Oegerle & Hoessel 1991; von der Linden et al. 2007; Bernardi et al. 2004), but it is not clear

that the observed behaviour could be explained in terms of the predicted curvature. Indeed, there is a hint that the observed \( \gamma \) versus \( R_e \) relation begins to deviate from our simple predictions at \( R_e \gtrsim 20 \) kpc (Fig 4), which may arise due to deviations from structural homology among BCGs, or it may represent the limitations of our simple model.

To make a more quantitative comparison between the traditional fundamental plane and our toy model, we adopted a linear approximation for the toy model relationship between \( \gamma_m \) and \( R_e \) (\( \log \gamma_m \simeq -0.11 + 0.37 \log R_e \)); this is accurate to about \( \pm 0.03 \) dex over the range \( 0.2 < \log R_e < 1.0 \), as shown in Fig 4, assuming \( \gamma_m = 1 \). Substituting this into Eqn 3 (assuming \( \gamma_m \) is constant) and rearranging into the form of of the model, we found \( A=1.46 \) and \( B=0.29 \). These are in good agreement with recent K-band measurements of the fundamental plane (A\( \sim \)1.46 and B\( \sim \)0.30–0.33; La Barbera et al. 2005; Jun & Im 2008; Mobasher et al. 1999; Zahid et al. 2004).

Pahre et al. 1995), repeating the analysis, but allowing the Sersic index to vary by \( \pm 1 \), or using the alternative dark matter model of Navarro et al. (2004), we obtained \( A \) in the range \( \sim 1.2-1.6 \) and \( B=0.23-0.31 \). Thus, assuming only a powerlaw total mass distribution, we can clearly reproduce the shape of the K-band fundamental plane, without any fine-tuning of the model parameters. We therefore speculate that the establishment of a powerlaw total mass distribution is a fundamental feature of galaxy formation and the principal factor in determining the tilt of the fundamental plane. Since the relative importance of gas-rich and “dry” merging for the assembly of present-day giant ellipticals is still under debate (e.g. Hopkins et al. 2008; Naab et al. 2009; Nipoti et al. 2009), the requirement of producing a nearly powerlaw total mass distribution in the core of low-redshift systems will therefore be a key test of these models.

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3 for consistency with our X-ray analysis, we ignored those systems with logR_e \( \lesssim 0.2 \).
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