The age dependence of the size-stellar mass relation and some implications

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ABSTRACT

We use a sample of about 48,000 SDSS early-type galaxies to show that older galaxies have smaller half-light radii R_e and larger velocity dispersions σ than younger ones of the same stellar mass M_{star}. We use the age-corrected luminosity L_r^{corr} as a proxy for M_{star} to minimize biases: below $L_r^{corr} \sim 10^{11} L_\odot$, galaxies with age $\sim$ 11 Gyrs have R_e smaller by 40% and σ larger by 25%, compared to galaxies that are 4 Gyrs younger. The sizes and velocity dispersions of more luminous galaxies vary by less than 15%, whatever their age, a challenge for current galaxy formation models. A closer check reveals that the lowering in the dispersion is caused by older galaxies that show a significant departure from the R_e–L_r^{corr} and σ–L_r^{corr} relations at high L_r^{corr}. Such features might find an explanation in models where more massive galaxies undergo more minor mergers than less massive galaxies at late times, thus causing a break in the homology. In terms of the Fundamental Plane of early-type galaxies, the data indicate that all galaxies show a significant and similar increase in the dynamical-to-stellar mass ratio with increasing mass, independent of their age. However, older galaxies have smaller M_{dyn}/M_{star} ratios than objects which formed more recently. These findings may suggest that lower mass galaxies and, at fixed stellar mass, higher redshift galaxies, formed from gas-richer progenitors, thus underwent more dissipation and contraction.

Key words: galaxies: structure – galaxies: formation – galaxies: evolution – cosmology: theory

1 INTRODUCTION

The formation and evolution of galaxies is still hotly debated. The cooling of baryons in dark matter halos should form compact and dense self-supporting, rotating stellar and gaseous disks (e.g., Fall & Efstathiou 1980; Navarro & Steinmetz 2000; Governato et al. 2007). Later major mergers between disk galaxies have then been proposed as the main routes to form elliptical galaxies (e.g., Toomre & Toomre 1972). Several detailed numerical simulations (e.g., Barnes & Hernquist 1991; Boylan-Kolchin et al. 2006; Dekel & Cox 2006; Robertson et al. 2006; Burkert et al. 2008; Hopkins et al. 2008) have shown that many dynamical and photometrical properties of the remnant spheroidal galaxies can be explained simply in terms of the merging of progenitors having varying levels of gas-richness. Galaxies which form from gas-

rich, dissipative, mergers result in more compact remnants with larger velocity dispersions.

On the other hand, in a pure monolithic model of galaxy formation (e.g., Eggen et al. 1962), stars are formed in a single burst of star formation from gas falling towards the center, and the evolution is passive thereafter. Although there is clear evidence for a red and dead population of massive early-type galaxies (see Renzini 2006 for a review), hierarchical merging could still have played some role at late times. The metallicities of typical early-type galaxies are well reproduced in models with frequent minor mergers at moderate redshifts (e.g., Bournaud et al. 2007; Naab & Ostriker 2009) and are not much affected by later dry mergers (Pipino & Matteucci 2008). The sizes and velocity dispersions of BCGs in the local Universe are evolving in a manner which suggests frequent minor dry mergers as recently as 1 Gyr ago (Bernardi 2009). The clustering and number density of massive galaxies in the Sloan Digital Sky Survey (SDSS), the 2dF-SDSS LRG and QSO Survey (2SLAQ), the NOAO Deep Wide-Field Survey and in DEEP2 also suggest that some merging events involving massive galaxies must

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have occurred since redshift $z \sim 1$ (e.g., Bundy et al. 2007; White et al. 2007; Wake et al. 2008), but that the majority of the stellar mass had already been assembled by this time.

In addition, there is now growing evidence that massive galaxies at $z \sim 2$ are much smaller and denser than their local counterparts of the same stellar mass (e.g., Trujillo et al. 2006; van Dokkum et al. 2008; Cimatti et al. 2008; Saracco et al. 2008). These observations are in line with the idea that high–redshift galaxies formed in a denser universe, and therefore from baryonic clumps which collapsed in denser, more gas-rich environments, which, in turn, induced more dissipation, more compact remnants and higher velocity dispersions. However, similarly compact galaxies to those observed at high-redshift do not exist in the local universe, raising the question of what process or processes have acted to increase the sizes of these objects to make them consistent with the larger sizes we see at late times (e.g., van Dokkum et al. 2008).

In this Letter, we present evidence that the sizes of early-type galaxies are difficult to reconcile with a pure monolithic model, at least for the most massive galaxies. In § 2 we describe the data set and present the measurements on which our conclusions are based. We discuss our results and their implications in § 4. Where necessary, we set the cosmological parameters $\Omega_m = 0.30$, $\Omega_\Lambda = 0.70$, and $h \equiv H_0/100 \, \mathrm{km \, s^{-1} \, Mpc^{-1}} = 0.7$.

2 DATA

We use the SDSS-based sample of early-type galaxies from Hyde & Bernardi (2008a) who give a prescription for how to correct the SDSS photometric parameters for known sky subtraction problems which affect objects with large apparent brightnesses. The sample, which contains about 48,000 early-type galaxies, is distributed within the redshift range $0.013 < z < 0.3$, which corresponds to a maximum lookback time of 3.5 Gyr. The galaxies in the sample have apparent magnitudes $14.5 \lesssim m_r \lesssim 17.5$ (based on deVaucouleur fits to the surface brightness profiles), axis ratios $b/a > 0.6$, and ages greater than 2 Gyr. To study the bulk of the early-type population of local galaxies, we remove the Brightest Cluster Galaxies (BCGs) from our sample, as they might have had unusual formation histories (see Bernardi 2009). This was done by matching the Hyde & Bernardi (2008a) sample to the maxBCG (Koester et al. 2007) and C4 (Miller et al. 2005) cluster samples (this procedure should remove most of the BCGs although some contamination could still be present). Our results do not vary significantly if BCGs were not excluded. The luminosities we report are estimated by first correcting the absolute magnitudes for evolution to $z = 0$ (following Hyde & Bernardi 2008a, we add $0.9z$ to the observed magnitudes), and then setting $\log(L_r/L_\odot) = -0.4(M_r - 4.62)$ (Blanton et al. 2001). Estimated stellar masses and ages for these objects are from Gallazzi et al. (2005).

3 RESULTS

We divide the sample into bins of different ages, as labeled in the top left panel of Fig. 1, chosen so as to provide at least 2,000 galaxies in each bin. For each age bin, we further divide the sample into nine equally-spaced bins in luminosity, and plot only bins with more than 5 galaxies. We compute the median size, velocity dispersion, and mass-to-light ratio in each bin of redshift and luminosity. Uncertainties on these median quantities are approximated by the square root of the variance divided by the square root of the number of sources in the bin. Finally, we only consider galaxies older than 5 Gyrs in our final sample, in order to minimize contamination from objects for which the luminosity- and mass-weighted ages might differ substantially.

The top panels in Figure 1 show the $R_e - L_r$ and $\sigma - L_r$ relations for galaxies of different ages. For $L_r < 10^{11} L_\odot$, lines of constant age run parallel to the $\sigma - L_r$ relation, with older galaxies being offset to larger σ. This is remarkably consistent with previous expectations which were based on a *very* different analysis (Forbes & Ponman 1999; Bernardi et al. 2005). Even more remarkable is the fact that the $R_e - L_r$ relation is almost independent of age. The age estimate is noisy, so one might have worried that this has erased any age-dependence in the $R_e - L_r$ relation. However, this is unlikely to be the case, since the $\sigma - L_r$ relation does vary for galaxies of different age.

Because the luminosity changes as the stellar population ages (typically as $L_r \propto t^{-0.75}$), we would have liked to replace L_r with the stellar mass M_{star}, and study the $R_e - M_{\mathrm{star}}$ and $\sigma - M_{\mathrm{star}}$ relations instead. However, such plots are complicated by the fact that the SDSS is magnitude limited and because the age and M_{star} estimates are highly correlated. The flux limit will tend to select brighter sources at fixed M_{star}, thus scattering sources to lower M_{star}/L ratios and to younger ages with respect to their true ones, given the intrinsic correlations in the errors. Therefore, the oldest objects corresponding to a given M_{star} may be missing. However, the correct spread in ages at fixed L is reproduced if luminosities are taken as independent variables (we refer the reader to the full analysis presented in Appendix A of Bernardi 2009 for more discussion). Therefore, we correct each luminosity for its fading with age by setting

$$\log L_r^{\mathrm{corr}} = \log L_r + 0.75 \log(t/5.5 \, \mathrm{Gyrs}), \qquad (1)$$

where t is the age. Bernardi (2009) shows that L_r^{corr} defined in this way is a good proxy for M_{star}.

Fig. 1c shows the R_e-L_r^{corr} relation for galaxies of different ages. To produce Figs. 1c and 1d we first rebin the whole sample in the new grid of luminosities L_r^{corr} and then recompute the correlations, although we also note that a simple median rescaling of the curves in Fig. 1a and 1b via Eq. (1) would yield similar results. In contrast to the R_e-L_r relation shown in Fig. 1a, there is now a clear trend with age: at fixed $L_r^{\mathrm{corr}} \propto M_{\mathrm{star}}$, younger galaxies tend to have larger sizes. At $\log(L_r^{\mathrm{corr}}/L_\odot) \sim 10.5$, the offset is ~ 0.15 dex; it decreases to $\lesssim 0.1$ dex at higher L_r^{corr}. Fig. 1d shows instead that the σ-L_r^{corr} relation is less age dependent than the $\sigma - L_r$ relation in Fig. 1b. At $\log(L_r^{\mathrm{corr}}/L_\odot) \sim 10.5$, the spread in velocity dispersions is < 0.1 dex, and it decreases to $\lesssim 0.05$ dex at larger L_r^{corr}. Above $\log(L_r^{\mathrm{corr}}/L_\odot) \sim 11$, the relation is curved – older galaxies have a lower σ than expected from extrapolating the σ-L_r^{corr} relation defined at lower luminosities to higher L_r^{corr}. More specifically, we find that a fit to the sample of young galaxies with age $t < 6$ Gyr yields a slope in the R_e-L_r^{corr} relation of ~ 0.52 (long-dashed
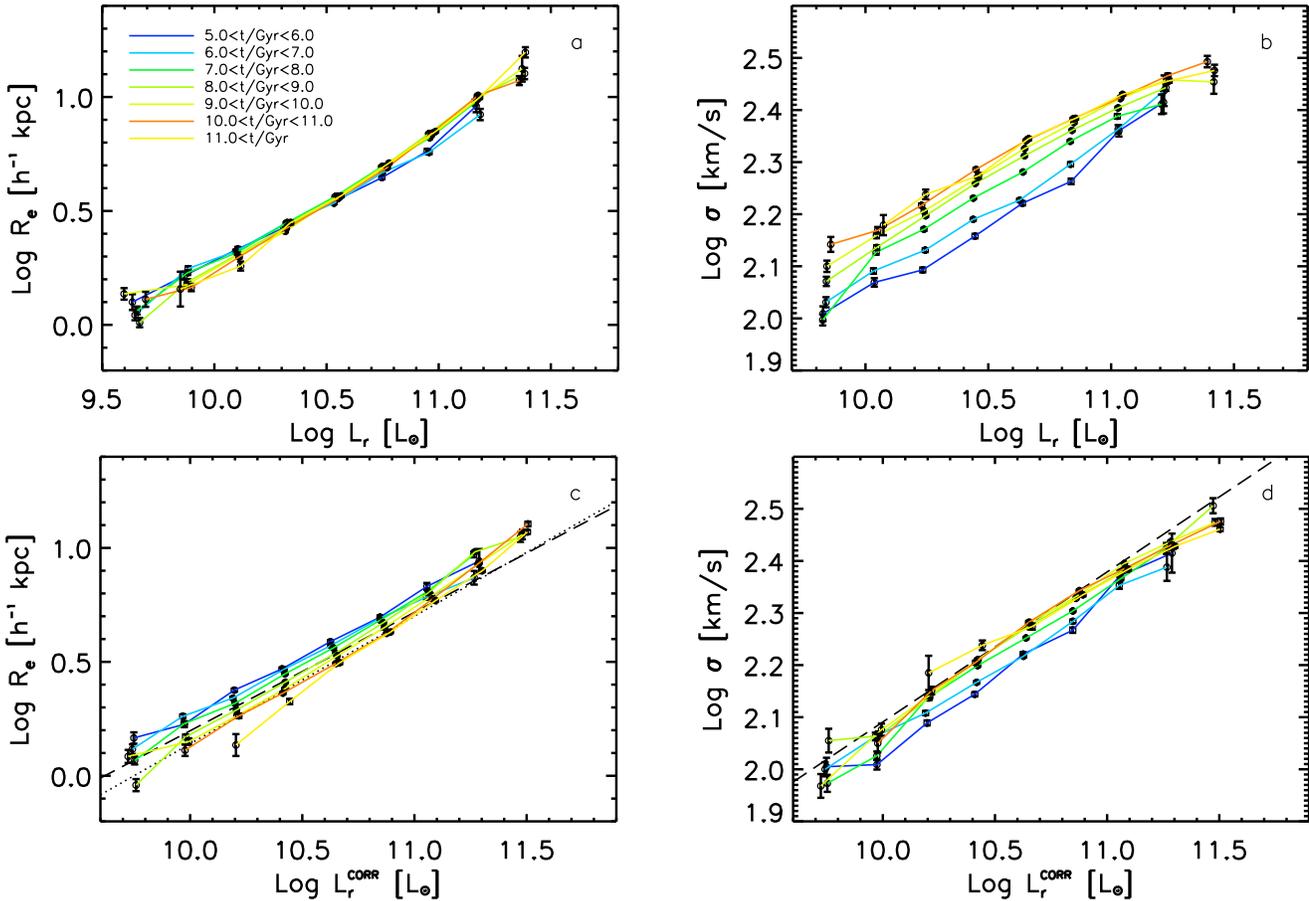
Figure 1. *Top*: size R_e (*left*) and velocity dispersion σ (*right*) as a function of r-band luminosity L_r, for galaxies of different ages, as labeled. *Bottom*: Same as top panels, but after correcting luminosity for age effects, so that it is a proxy for stellar mass. The *long-dashed* lines in Figs. 1c and 1d are the fits to the R_e-L_r^{corr} and σ-L_r^{corr} correlations to the subsample of galaxies with age $t < 6$ Gyr, displaced in normalization to match the locus defined by older galaxies. The *dotted* line in Fig. 1c, with arbitrary normalization, has a slope of 0.56 as derived by Shen et al. (2003) fitting the R_e-L_r^{corr} relation to the whole sample of SDSS early-type galaxies.

line in Fig. 1c), very close to the slope of 0.56 derived by Shen et al. (2003) fitting the R_e-L_r^{corr} relation to the whole sample of SDSS early-type galaxies (dotted line). (Both the dashed and dotted lines in Figs. 1c and 1d are displaced in normalization to match the locus defined by older galaxies.) Fig. 1c shows that very old ($t > 9$ Gyr) galaxies tend to follow an R_e-L_r^{corr} relation with a very similar slope, although more massive ($\log(L_r^{\mathrm{corr}}/\mathrm{L}_\odot) \gtrsim 11$) systems show a systematic and significant deviation, of up to $\Delta \log R_e \sim 0.1$ dex, from the extrapolation of such a straight line. Analogously, Fig. 1c shows that the same subsample of old and massive galaxies, also show a significant departure of $\Delta \log \sigma \sim 0.05$ dex above $\log(L_r^{\mathrm{corr}}/\mathrm{L}_\odot) \gtrsim 11$ from the straight, long-dashed line of slope ~ 0.29, derived from fitting the σ-L_r^{corr} relation calibrated on younger galaxies only. In the overall, this curvature is similar to that found for BCGs, for which it is even more evident Bernardi (2009). We stress here that this gradual steepening and corresponding flattening in the relations, are present in galaxies of a fixed age, thus mirroring a clear break in the homology when moving from lower to more massive systems.

4 DISCUSSION AND CONCLUSIONS

In the simplest galaxy evolution models, the age of the stellar population reflects the time of assembly of the galaxy. Hence, older galaxies are expected to have smaller sizes and larger velocity dispersions than their younger counterparts of the same M_{star}, both because the high-redshift Universe was denser, and because the objects at that time are thought to have formed from gas-richer progenitors. However, the differences observed between the sizes of old and young galaxies in our sample are far less than what expected given the evolution $R_e \propto (1 + z)^{-1}$ at fixed stellar mass which would result if the galaxy density is proportional to the density of the universe. For example, galaxies as old as 12 Gyr ($z \sim 4$), should be displaced by $\Delta \log R_e \sim 0.5$ (i.e., a factor of ~ 3) downwards with respect to the younger galaxies in our sample. So the absence, in our data, of a strong age-dependent trend with size, rules these models out.

A more elaborate model postulates that although the sizes were initially smaller (so as to be consistent with the $z \sim 2$ observations mentioned in the Introduction), they have since evolved, while the stellar mass has remained unchanged (Fan et al. 2008). This model exploits the fact that the epoch when early-type galaxies were

forming stars is close to that when AGNs were most active (e.g., Cattaneo & Bernardi 2003; Granato et al. 2004; Haiman et al. 2007; Shankar et al. 2008, 2009a). So, in this model, AGN activity is assumed to expel gas from the central regions; the sudden reduction of mass in the core makes the surrounding stellar distribution puff up, increasing the size. Because the objects are assumed to eventually settle back into virial equilibrium at these larger sizes, with no change in mass, this model also predicts that the velocity dispersions decrease from their initial values, but that the age-dependence in the σ-$M_{\rm star}$ relation is not erased.

The Fan et al. (2008) model was calibrated to reconcile the differences between the $z \sim 2$ and local R_e-$M_{\rm star}$ relations. At lower $M_{\rm star}$, it predicts that younger galaxies should be larger by $\sim 0.15-0.2$ dex, in good agreement with our Fig. 1c. At higher masses, we find an offset of $\lesssim 0.1$ dex, which is less than the ~ 0.3 dex they predict. They also predict that σ should be larger for older galaxies: they find an increase of ~ 0.15 dex in σ when moving from younger to older galaxies at large masses, with slightly smaller trends at lower masses. While we are in qualitative agreement with their predictions, our results point to a much smaller offset, especially at $\log(L_r^{\rm corr}/{\rm L}_\odot) \gtrsim 11$. However, given the systematic uncertainties in computing the profile and luminosity-dependent normalization coefficients in the virial relations (see Fan et al. 2008 for details), it is difficult to make detailed comparisons with their predictions. Only ad-hoc numerical simulations will be able to further probe their model.

In hierarchical models, the stellar population can be older than the time at which the total mass was assembled into one system (e.g., Bower et al. 2006; De Lucia et al. 2006). This is accomplished by making dense progenitors through wet (gas rich) mergers at high redshift, followed by a sequence of dry, dissipationless mergers which serve to reduce the densities (e.g., Kormendy et al. 2008). However, this evolution in sizes cannot be directly tested from Fig. 1c, which shows galaxies only in their present form. On the other hand, the observed break in the $\sigma-L_r^{\rm corr}$ relation (Fig. 1d), when combined with the steepening in the $R_e-L_r^{\rm corr}$ relation (Fig. 1c), might be a signature that minor mergers played a role in the mass assembly of at least the most massive objects.

Preliminary results from Shankar et al. (2009b, and references therein) show that major dry mergers are uncommon for intermediate mass galaxies, with even the most massive galaxies experiencing one such event at most. Early-type galaxies, born at $z \sim 2$ and with $z = 0$ mass $M_{\rm star} \gtrsim 3 \times 10^{10}{\rm M}_\odot$, undergo at least $3-7$ minor dry mergers, with the number increasing with $M_{\rm star}$. As sketched by Bernardi (2009), and theoretically discussed by, e.g., Ciotti (2008, and references therein), repeated minor mergers of mass ratio $f < 1$ can enable the remnants to increase their masses by a factor $(1 + f)$, the sizes by a factor of $(1 + 2f)$, and to decrease σ^2 by a factor of $(1 - f)$, thus without changing the virial product $\sigma^2 R_e$ much. For example, even 5 minor mergers with f as low as $f \approx 0.2$, would be capable of increasing the sizes by a factor of ~ 5, and the stellar mass by just a factor of 2.5. Ad-hoc, recent numerical simulations are showing that this can actually be possible Naab et al. (e.g., 2009, and references therein). This steep and fast evolution in the R_e-$M_{\rm star}$ plane is another way to efficiently puff-up the high-z, compact galaxies. The main challenge
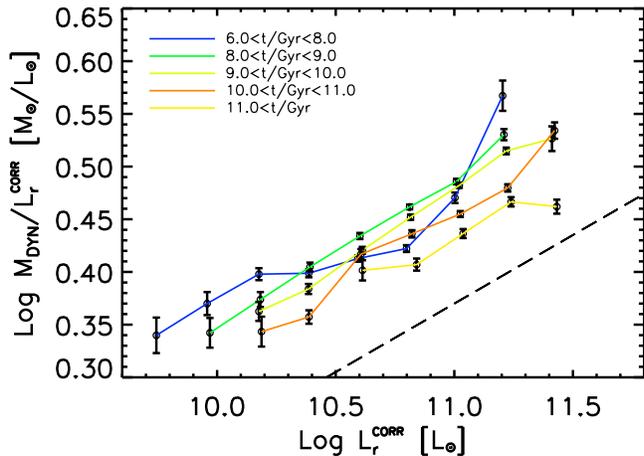

Figure 2. Dynamical mass-to-light ratio as a function of age-corrected luminosity for galaxies of different ages, as labeled. Irrespective of age, we find that all galaxies show a significant tilt.

for hierarchical models would then be to grow *all* galaxies of different ages coherently on a similar size-luminosity relation, as we see it today (see Shankar et al. 2009b). Also, hierarchical models tend to produce too large size dispersions at fixed galaxy luminosity, at variance with our data (Gonzalez et al. 2008, but see also Khochfar & Silk 2006). Nevertheless, a late evolution driven by minor mergers in the most massive and older galaxies, that preferentially sit in richer environments, might explain the gradual steepening of the size-mass relation at high $L_r^{\rm corr}$ and the corresponding curvature at high σ.

Before concluding, we would like to discuss our findings in the context of the Fundamental Plane relation $R_e \propto \sigma^a I^b$ (FP, e.g. Djorgovski & Davis 1987. Observations suggest that $a \sim 1.43 \pm 0.05$ and $b = -0.79 \pm 0.02$ with small scatter (e.g., Hyde & Bernardi 2008b). The fact that $(a, b) \neq (2, -1)$ is sometimes called the 'tilt', and is thought to reflect the fact that $M_{\rm dyn}/L_r$ or $M_{\rm star}/L_r$ is not constant (e.g., D'Onofrio et al. 2006; Hyde & Bernardi 2008b). The idea is that if

$$\sigma^2 \propto \frac{M_{\rm dyn}}{R_e} \propto \left(\frac{M_{\rm dyn}}{L_r} \right) I_r R_e \propto L_r^\gamma I_r R_e, \qquad (2)$$

then

$$R_e \propto \sigma^{2/(2\gamma+1)} I_r^{-(\gamma+1)/(2\gamma+1)}, \qquad (3)$$

with I_r the surface brightness of the galaxy. Previous work has shown that $\gamma > 0$ if L_r is the optical luminosity. In the discussion which follows, we consider the effect of replacing L_r with $L_r^{\rm corr}$. Figure A5 in Bernardi (2009) shows that $M_{\rm star}/L_r^{\rm corr}$ vs $L_r^{\rm corr}$ is flat for these galaxies, so this should be equivalent to studying the stellar mass Fundamental Plane (e.g., Hyde & Bernardi 2008b).

Fig. 2 shows $M_{\rm dyn}/L_r^{\rm corr}$ versus $L_r^{\rm corr}$, for galaxies of different bins in formation time. (We define the dynamical mass as $(M_{\rm dyn}/M_\odot) = 10^{10} (\sigma/200 \, {\rm km \, s}^{-1})^2 (R_e/{\rm h}^{-1} \, {\rm kpc})$, and only show bins in which there were more than 100 galaxies.) It is clear that the relation is not flat: except for the bin with the most recent formation time (which may be contaminated by selection effects and/or errors in age of the type discussed by Bernardi 2009), the 'tilt' is $\gamma \approx 0.13$ (long-dashed line in Fig. 2), and it is approximately *independent*

of age. Under the reasonable assumption of a universal DM profile (e.g., Navarro et al. 1997), the tilts reported in Fig. 2 suggest that less massive galaxies are more concentrated, possibly due to more dissipation, thus inducing more contraction and a lower dark matter fraction within R_e. Note that, as discussed in § 2, all R_e in SDSS are calibrated with deVaucouleur fits (i.e., with a Sérsic index $n = 4$), thus the non-homology seen in Fig. 2 should principally derive from actual dynamical mass variations with stellar mass and not, for example, from non-homology effects in the light distributions (e.g., Tortora et al. 2009, and references therein). Moreover, Fig. 2 also shows that, at fixed L_r^{corr}, galaxies which formed earlier tend to have smaller $M_{\mathrm{dyn}}/L_r^{\mathrm{corr}}$ than younger ones. This offset is mainly driven by the smaller sizes R_e associated to older galaxies, as expected if the latter were formed in a denser and gas-richer environment.

Finally, note that setting $\gamma = 1/4$ in equation (3) would make the Fundamental Plane relation $R_e \propto \sigma^{1.33} I_{\mathrm{corr}}^{-0.83}$ for populations of a fixed formation time. However, because of the dependence of the zero-point of the $M_{\mathrm{dyn}}/L_r^{\mathrm{corr}} - L_r^{\mathrm{corr}}$ relation on formation time, the slope γ becomes shallower if one averages over a range of formation times. A smaller value of the tilt γ means that the FP coefficient a should be larger when one averages over the full early-type population than when one restricts the study to a small range of formation times. All the galaxies in a cluster tend to have similar formation times (e.g. Bernardi 2009). This suggests that the FP computed for a single cluster should have greater 'tilt' (the coefficient a should be further from 2) than the FP for the full population. So it is interesting that $a \approx 1.6$ for the full population (Hyde & Bernardi 2008b). Perhaps this is why the traditional FP, with I_r instead of I_{corr}, has $a \sim 1.43 \pm 0.05$ for SDSS early-types (Bernardi et al. 2003; Hyde & Bernardi 2008b), whereas $a \sim 1.24 \pm 0.07$ for the Coma cluster is smaller (e.g., Jorgensen et al. 1996).

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