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TRANSVERSE DISSECTIONS OF THE FUNDAMENTAL PLANES OF ELLIPTICAL GALAXIES AND CLUSTERS OF GALAXIES

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ABSTRACT

Seen edge-on, the fundamental plane (FP) of elliptical galaxies is very thin and tilted, which corresponds to a very small dispersion ($\lesssim 12\%$) of the M/L ratio at each location on the FP, and to a trend by a factor ~ 3 of M/L along the FP, respectively. In this *Letter* we investigate two possible origins of the tilt: a systematic change of the stellar initial mass function (IMF), and a trend in the relative distributions of the bright and dark matter. In both cases we find that major changes in either the IMF or the bright/dark matter relative distributions are required along the FP to account for its tilt, while its constant thickness requires an extremely small dispersion in the IMF or in the bright/dark matter distribution at every location on the FP. In both cases fine-tuning seems required to account for the tilt and yet preserve the small, constant thickness of the FP. We suggest observations that may distinguish between the two options. Also clusters of galaxies appear to define an equally thin but untilted FP (i.e., M/L = constant). We discuss some implication of the existence of such cluster FPs for galaxy formation and cluster evolution.

Subject headings: dark matter — galaxies: clustering — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: fundamental parameters

1. INTRODUCTION

There are three main global observables of elliptical galaxies: the central velocity dispersion σ_*, the effective radius R_e, and the mean effective surface brightness I_e. Elliptical galaxies do not uniformly populate this three-dimensional parameter space; rather, they are confined to a narrow plane (Dressler et al. 1987; Djorgovski & Davis 1987), thus called the fundamental plane (FP). Bender, Burstein, & Faber (1992, hereafter BBF) have introduced an orthogonal coordinate system (κ_1, κ_2, κ_3), with each of the new variables being a linear combination of $\log \sigma_*^2$, $\log R_e$, and $\log I_e$. In the new space, the κ_1-κ_3 plane provides an almost edge-on view of the FP. In this *Letter* we follow some of the implications of three observed properties of the BBF sample of Virgo and Coma cluster ellipticals (their Fig. 1): (1) the FP is remarkably thin, with a 1 σ dispersion $\sigma(\kappa_3) \simeq \pm 0.05$ (R. Bender, private communication); (2) this thickness is constant along the FP; and (3) the tilt of the FP corresponds to the κ_3 increase $\Delta\kappa_3 \simeq 0.3$ from faint to bright galaxies. Since $\log M/L = 3^{1/2}\kappa_3 + \text{const}$, the narrowness and tilt of the FP imply a very small galaxy-to-galaxy variation of the mass-to-light ratio M/L for given mass or luminosity, and a trend $M/L \propto L^{1/5} \propto M^{1/6}$ (see also Kormendy 1987), corresponding to a range by a factor ~ 3 for the BBF galaxies.

Several factors contribute to broadening the FP in the κ_3 direction: errors, projection effects, deviations from the standard surface brightness distribution (the $R^{1/4}$ law), and finally intrinsic galaxy-to-galaxy variations of M/L. The BBF observed dispersion of κ_3 implies a dispersion $\sigma(M/L) \lesssim 18\%$. However, if one discards disky and peculiar ellipticals, the upper limit to the true, intrinsic dispersion is only $\sim 12\%$ (R. Bender, private communication). Part of this could still be due to projection effects, as a mix of prolate galaxies is seen at different viewing angles. This effect may be as large as $\Delta\kappa_3 = \pm 0.025$ (A. Burkert, private communication), although Jorgensen et al. (1993) argue that galaxies rather project *along* the FP.

Belonging to a FP seems not an exclusive property of cluster elliptical galaxies: Schaeffer et al. (1993) have provided evidence that other systems—such as globular clusters and clusters of galaxies—also define their own FP. This latter result refers to a rather small sample of only 16, yet best studied, Abell clusters of galaxies. This is certainly a much smaller sample than that defining the FP for ellipticals, and a larger database is needed before reaching firm conclusions. Three requirements are necessary for a class of hot dynamical systems to flatten about a FP: (1) to be (nearly) virialized, (2) to have similar structures, and (3) to exhibit a small dispersion of M/L for any given total mass of the system (e.g., Kormendy & Djorgovski 1989, and references therein). Globular clusters and ellipticals certainly meet the first requirements, and the Schaeffer et al. finding indicates that rich clusters of galaxies may not be far from being well virialized, too. That the three kinds of systems meet the second requirement is also well known: the success of King or de Vaucouleurs profiles in fitting their radial distributions testifies to this. Concerning the third condition, globulars are well known to have $M/L \simeq 1$, while in this *Letter* we consider some implications of the FP constraints on M/L for cluster ellipticals and clusters of galaxies.

In § 2 we discuss the implications of the above properties of the FP for the stellar initial mass function (IMF) in the sample galaxies, under the assumption that the dark matter in a galaxy does not affect σ_*. This assumption is relaxed in § 3, where we explore under which conditions the observed trend of M/L can be ascribed to a trend in the relative distribution of the bright and dark components. With the caveat above, in § 4 we briefly discuss some implications for galaxy formation of the suggested existence of a FP for clusters of galaxies. Our conclusions are summarized in § 5.

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2. THE TILT OF THE FUNDAMENTAL PLANE WITHOUT DARK MATTER

Part of the FP tilt is certainly due to a metallicity effect, brighter galaxies being more metal rich and then *redder* than fainter galaxies. However, this effect accounts for only a minor fraction of the observed tilt (Dressler et al. 1987), and Djorgovski & Santiago (1993, hereafter DS) demonstrate that the trend of M/L with L is somewhat reduced at longer wavelength, but persists to the K band (and thus to the bolometric). That metallicity alone is not sufficient to produce the tilt is confirmed by model stellar populations (e.g., Buzzoni 1989), which for the metallicity range of BBF galaxies show a M_*/L_B variation 3–4 times smaller than the observed tilt, along with a vanishingly small trend of M_*/L_K. DS rather argue that the M/L trend could be produced by a systematic trend of the IMF with galaxy luminosity (metallicity), a possibility that we explore further in this section, where we assume that M/L as inferred from κ_3 is *not* affected by the presence of a dark matter halo, i.e., $M/L = M_*/L$.

The stellar M_*/L ratio is obtained by convolving the present stellar mass M with the IMF, with $M = M_i$ for the initial mass $M_i < M_{TO}$ (the turnoff mass), and $M = M_R$, the remnant mass for $M_i \geq M_{TO}$. We adopt $M_{TO} = 0.85\ M_\odot$, appropriate for a 15 Gyr old population. For $0.85 < M_i < 8.5\ M_\odot$ we adopt $M_R = 0.077 M_i + 0.48$. For $M_i > 8.5\ M_\odot$ stars are assumed to leave 1.4 $M_\odot$ neutron stars. We also explore the case $M_R = \frac{1}{2} M_i$ for $M_i > 40\ M_\odot$, so as to mimic the case of most massive stars leaving massive black holes. For the IMF we adopt $\psi(M_i) = 2.9 L_B M_i^{-(1+x)}$, where L_B is the blue luminosity of the population and the normalization factor 2.9 is appropriate for an age of 15 Gyr and near solar metallicity (Ciotti et al. 1991; Renzini 1993). The stellar M/L ratio then becomes

$$\frac{M_*}{L_B} = 2.9 \int_{M_{inf}}^{100} M M_i^{-(1+x)}\, dM_i\,, \qquad (1)$$

where M_{inf} is the minimum stellar mass. We explore both the case of a single-slope IMF, and the case of the multislope IMF favored by Scalo (1986), for which $x = 1.7$ for $M_i > 2\ M_\odot$, $= 1.35$ for $0.3 < M_i < 2\ M_\odot$ (where the normalization factor 2.9 is applied), and $= -1$ (i.e., a flat IMF) for $M_i < 0.3\ M_\odot$, but we also treat x as a parameter for $M_i < 0.3\ M_\odot$. We further assume that the faintest galaxies displayed in Figure 1 of BBF have $M_*/L_B = 5$, a typical value for faint ellipticals (with $H_0 = 50$). The tilt of the FP thus implies $M_*/L_B \simeq 15$ for the brightest BBF galaxies.

Figure 1 shows M_*/L_B versus M_{inf}. We first notice that—in the case of a single-slope IMF—for no value of x values of M_*/L_B as small as 5 are obtained, unless M_{inf} is unrealistically high. Reducing the slope does not help: for x below ~ 0.65 the M/L ratio increases again, since then the mass in remnants increases more than the mass in lower main-sequence stars is reduced. Only with a multislope IMF a low M_*/L_B can be realized: one which is rather flat below M_{TO} and rather steep above can work, i.e., the IMF is neither top-heavy nor bottom-heavy. This is why Scalo's multislope IMF shown in Figure 1*b* works much better: with $M_*/L_B \simeq 4$ for $M_{inf} = 0.1\ M_\odot$, the generally adopted value. A modified Scalo IMF with $x \simeq 0$ for $M_i \lesssim 0.3\ M_\odot$ and $M_{inf} = 0.1\ M_\odot$ gives the required $M_*/L_B \simeq 5$. Very important is to notice that for the parameter combinations giving $M_*/L_B \simeq 5$, the M/L ratio is fairly insensitive to variations of both M_{inf} and x, i.e., galaxy-to-galaxy differences up to $\sim 50\%$ in M_{inf} and $\Delta x \simeq 0.5$ in the lower main sequence would result in variations of M_*/L_B less than $\sim 12\%$, *consistent with the observed narrowness of the FP at low luminosities.*

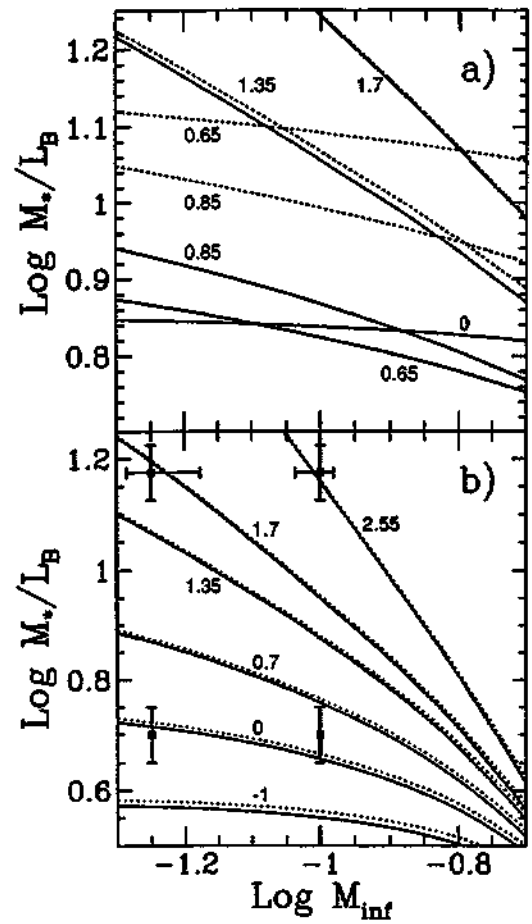

FIG. 1.—The stellar mass-to-light ratio as a function of the minimum stellar mass for several choices of the IMF slope x. Panel (*a*) refers to a single-slope IMF, while panel (*b*) refers to Scalo's multislope IMF with x being varied only below 0.3 $M_\odot$. The dotted line corresponds to the option of massive stars leaving black hole remnants rather than neutron star remnants as detailed in the text. The *error boxes* correspond to the constraints imposed by tilt and thickness of the fundamental plane at low (*lower boxes*) and high luminosities (*upper boxes*), for two choices of M_{inf}.

We now turn to the FP tilt. Figure 1 shows that M_*/L_B is insensitive to variations of M_{inf} for the flat IMF required to give $M_*/L_B \simeq 5$ in low-luminosity ellipticals; only for a steep IMF the M/L ratio is sensitive to M_{inf}. We conclude that a mere variation of M_{inf} with a constant IMF slope cannot account for the observed trend. Hence, a variation of slope is required, by an amount Δx which depends on the adopted M_{inf}. For the *canonical* $M_{inf} = 0.1\ M_\odot$, x should increase from ~ 0 to ~ 2.5. Even for $M_{inf} = 0.05\ M_\odot$, x has to increase from ~ 0 to ~ 1.7, in order to get the factor of 3 increase in M_*/L_B. These values of Δx are appreciably larger than those estimated by DS.

Figure 1*a* also shows the effect of assuming that massive stars leave black hole (BH) remnants as detailed above. This has an effect only for rather flat IMFs. The trend in M_*/L_B can be produced even at constant (flat) IMF slope, provided there were a systematic *decrease* in the critical mass for BH formation with *increasing* stellar metallicity. We find rather unattractive this formal *solution*, as just in most metal-rich galaxies, metals would be lost behind the horizon of the events, rather than used to increase the metallicity of subsequent stellar gen-

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erations. We conclude that *a major change of IMF slope in the lower main sequence is necessary to account for the FP tilt.*

There remains to consider the thickness of the FP at high luminosity. Figure 1*b* shows that in order to preserve the $\sim 12\%$ upper limit on $\sigma(M_*/L_B)$, the galaxy to galaxy dispersion in $M_{\rm inf}$ and x should now be extremely small, $\lesssim \pm 10\%$ and $\lesssim \pm 0.15$, respectively. *With a larger dispersion, the edge-on view of the FP would rather look like a wedge* (with the wide side at high-luminosity, large κ_1), rather than a strip of constant thickness. This is a result of the nonlinear behavior of log M_*/L_B as a function of x and $M_{\rm inf}$. Such very small galaxy-to-galaxy dispersion, coupled to a large systematic variation of x is a rather demanding constraint, and we conclude that fine-tuning is required to produce the observed tilt of the FP, while preserving its constant thickness: the IMF should be virtually universal for given galaxy mass, and yet exhibit a large trend with galaxy mass.

Besides the IMF, M/L is also a function of age, because so is the luminosity. Thus, the small thickness of the FP implies a small dispersion in the age of the bulk stellar content of cluster elliptical galaxies (Renzini 1993). If the 12% scatter in M/L is ascribed to a scatter in luminosity, rather than to mass, we get a tight constraint on the age dispersion, with an upper limit of only 1.5 Gyr if galaxies are older than ~ 10 Gyr and $x = 1.35$ for $M \sim M_{\rm TO}$. Such small age dispersion is in perfect agreement with the similarly tight limit that is independently set by the tightness of the color-σ relation for Virgo and Coma ellipticals (Bower, Lucey, & Ellis 1992).

Figure 1 shows that the present M_*/L_B ratio is rather insensitive to variations of the IMF for $M > M_{\rm TO}$. Could ellipticals have had vastly different IMF slopes for $M > M_{\rm TO}$, and yet have the same M_*/L_B today? No doubt an algebraic solution could be found, but we consider this as an extremely unlikely possibility. Indeed, the IMF slope for $M > M_{\rm TO}$ directly controls the past rate of luminosity evolution of stellar populations, and thus were the upper IMF different from galaxy to galaxy having the same present M_*/L_B, then galaxies would have had in the past different luminosities and M/L ratios: the existence of the FP would just be a transient event, a privilege of the present epoch. The argument can be put in quantitative terms (Renzini 1993), and if one insists that for the last ~ 14 Gyr the FP has been as tight as it is now, then dispersions larger than $\sigma(x) \simeq 0.1$ in the upper IMF cannot be tolerated. It is also easy to realize that with a systematic trend in the upper IMF slope with galaxy mass, *the FP would rotate with lookback time*, i.e., the tilt of the FP would be a function of redshift, a potentially observable effect.

3. THE TILT OF THE FUNDAMENTAL PLANE WITH DARK MATTER

Alternatively, the trend of M/L_B could be produced by a systematic variation of the dark matter contribution to the central velocity dispersion, i.e., to a variation in either the dark to bright matter ratio $R = M_{\rm DM}/M_*$, or in the relative distribution of the two kinds of matter, such as exemplified by a change of $\beta = R_H/R_e$ (R_H being the effective radius of the dark matter halo), or some combination thereof. We approximate the dark and bright matter distributions with Plummer spheres with different effective radii. This allows us to work analytically, while a more refined treatment is not necessary for our present purposes. The M/L ratio inferred from the κ_3 coordinate of the FP then becomes

$$\frac{M}{L_B} = \frac{M_*}{L_B}\left[1 + \frac{2R(\beta + 3)}{\beta(\beta + 1)^3}\right]. \qquad (2)$$

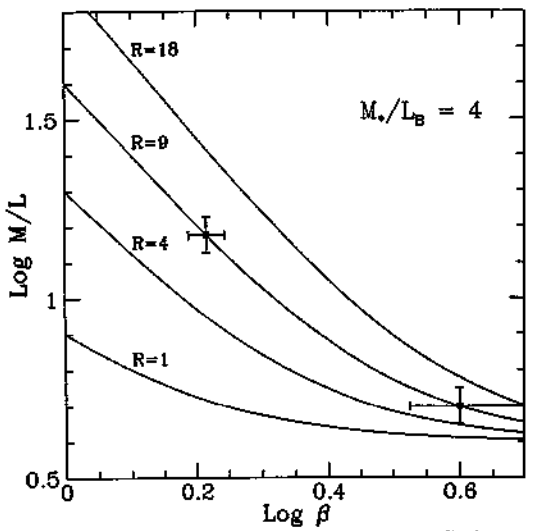

FIG. 2.—The total M/L as a function of $\beta = R_H/R_e$, the ratio of the dark to the bright matter effective radii, for several values of the dark-to-bright mass ratio R, and for a stellar $M_*/L_B = 4$. For the case $R = 9$, the constraints imposed by the tilt and thickness of the fundamental plane at low (*lower box*) and high luminosities (*upper box*) are indicated.

Assuming $M_*/L_B = \text{const}$, the whole tilt of the FP is ascribed to a trend in the term within square brackets. Since the variation is of a factor of 3, the minimum amount of dark matter in bright ($M/L_B = 15$) galaxies is at least ~ 2 times the bright matter. This is a very conservative lower limit, holding for $\beta = 1$ in $M/L_B = 15$ galaxies, and $\beta \gg 1$ in low M/L_B galaxies.

Figure 2 shows M/L_B versus β for several values of R, and for $M_*/L_B = 4$, the value appropriate to the Scalo IMF. Of course, the variation of log β required to produce the factor of 3 tilt is smaller, the larger the dark-to-bright matter ratio R. For example, for $R = 9$, one needs $\Delta \log \beta \simeq 0.4$, i.e., a variation of R_H/R_e of roughly a factor of 2.5. Note that the run of log M/L_B with log β is nonlinear, and therefore a constant dispersion of log β produces a *wedge* effect on the thickness of the FP. This effect can be buried in the noise if the dispersion in log β is sufficiently small to give $\sigma(\log M/L) \lesssim 0.05$ for $M/L \simeq 15$ galaxies, which requires $\sigma(\log \beta) \lesssim 0.05$: once again fine-tuning is required to produce the FP tilt while keeping its narrow thickness.

Of some concern is the fact that the curvature of the lines in Figure 2 may produce a *warped* FP, unless such curvature is balanced by the actual relation linking β to κ_1 (or galaxy mass). We choose not to follow this aspect any further, since at such level of detail more appropriate mass distributions may be needed, and anisotropy effects may be relevant. Incidentally, we note that an appropriate systematic trend of orbital anisotropy can reduce from a factor ~ 3 to ~ 2 the change in M/L implied by the FP tilt: anisotropy alone cannot explain the tilt.

4. THE FUNDAMENTAL PLANE FOR CLUSTERS OF GALAXIES

Transformation from the observed cluster luminosity, effective radius, and core velocity dispersion into the κ_1, κ_2, κ_3 coordinate system is possible for clusters as it is for galaxies. For the Schaeffer et al. sample of 16 Abell clusters, this gives a remarkably constant κ_3 while κ_1 varies by a factor of 10, with a remarkably small dispersion $\sigma(\kappa_3)/\kappa_3 \lesssim 0.07$ (A. Cappi, private communication). This means that *the cluster FP is not tilted* and translates into an upper limit 1 σ dispersion $\sim 0.07(3)^{1/2} = 12\%$ in M/L, remarkably similar to that found

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among Virgo and Coma true ellipticals. Yet, the physical processes involved in determining the cluster and the galaxy M/L ratios are certainly different. For clusters $M/L = (M_{DM} + M_{ICM} + M_*)/L$, where M_{DM} and M_{ICM} are the mass of dark matter in the cluster and the mass of the intracluster medium, respectively. The total cluster M/L is ~ 200 (Schaeffer et al. 1993), for the stellar contribution we take $M_*/L_V \simeq 5$, while from X-ray data, Arnaud et al. (1992) obtain that M_{ICM}/L_V increases with cluster luminosity:

$$\frac{M_{ICM}}{L_V} \simeq 70\left(\frac{L_V}{10^{13}\ L_\odot}\right)^{0.5\pm0.25}. \quad (3)$$

For example, for the cluster A2256, combining data from Arnaud et al. (1992) and Henry, Briel, & Nulsen (1993) one has $M/L_V = 200$ and $M_{ICM}/L_V = 36$, and therefore with $M_*/L_V \simeq 5$ one has $M_{DM}/L_V = 160$, with most of the visible (baryonic) matter being in the ICM rather than inside galaxies. The constancy of $\kappa_3 \propto M/L$ implies $M_{DM}/M_* \sim$ const, and therefore from equation (3) it follows that $M_{ICM}/M_{DM} \propto M_{DM}^{0.5}$: apparently more massive clusters were either more successful in collecting baryons, or in keeping them. The constancy of the ICM iron mass-to-light ratio (Renzini et al. 1993) indicates that—contrary to small groups—rich clusters are unlikely to have suffered a major outgassing since their formation; otherwise, a fraction of the ICM iron would have been lost as well. We conclude that richer clusters have collected more baryons per unit of dark matter mass, rather than lost less baryonic gas. Yet, in spite of a disposal of a larger amount of baryonic raw material, richer clusters had to be *less* efficient in condensing baryons into galaxies and stars, and did so precisely to the extent required to keep $M/L \sim M_{DM}/M_*$ constant, as dictated by the contancy of κ_3. Clearly, $\kappa_3 \simeq$ const—and the existence itself of a cluster FP—may be more the result of the gas-dynamical and dissipational processes leading to galaxy and star formation, rather than the result of just dissipationless hierarchical clustering.

5. DISCUSSION AND CONCLUSIONS

In this *Letter* we have concentrated on two possiblities for the production of the apparent trend of M/L of cluster ellipticals with luminosity: a systematic variation of the IMF, and a systematic variation of the dark and bright matter distributions. In both cases we find that rather major changes are required. Moreover, the constant, small thickness of the FP imposes that at any point on the FP the galaxy-to-galaxy dispersion in either the IMF slope or in the ratio β of the dark to bright matter effective radius to be of the order of $\sim 10\%$ of the whole range required to produce the observed tilt. On this ground we do not find one possible origin of the tilt more attractive than the other (in this sense they are both unattractive). Guzmán, Lucey, & Bower (1993, hereafter GLB) argue that a bottom-heavy IMF for giant, metal-rich galaxies goes the wrong way with respect to the need of producing the observed metal enrichment, and favor a dark matter origin of the FP tilt. The lower surface brightness of bright ellipticals may indeed suggest lower values of R_H/R_e (see also Navarro 1993). However, the size of the FP tilt implies that the central dynamics of ellipticals should turn from stellar dominated to fully dark matter dominated with increasing luminosity, certainly a nontrivial difference. This intriguing alternative may be solved by observations. Signature of an IMF origin of the tilt would be the rotation of the FP with lookback time. Signature of a dark matter origin would be a systematic trend along the FP of the stellar velocity dispersion as a function of radial distance from the center: *the radial gradient of σ_* should be steep at the faint end of the FP, flat at the bright end (for β = const), or vice versa (for R = const).* Existing observations (e.g., Kormendy & Richstone 1992; Saglia et al. 1993) do not suggest large amounts of dark matter for $r < R_e$, but a thorough exploration of the FP remains to be done.

The apparently constant M/L of clusters of galaxies sets a strong constraint on the ability of clusters of collecting baryonic gas, and on their efficiency of converting it into galaxies and stars. The tightness of the cluster FP speaks of a high uniformity and synchronization in the galaxy formation process in rich clusters, and indicates that the excess baryons in richer clusters were perhaps collected *after* the completion of galaxy formation. Baryons apparently stick easier to clusters than do collisionless particles.

The discovery of the FP for ellipticals was soon perceived as relevant to our understanding of galaxy formation, and soon the FP has been used to map galaxy distances and deviations from the Hubble flow. In this *Letter* we have confined ourselves to a less ambitious approach, simply considering two possible origins of the tilt of the FP. If the stellar IMF is the cause of the tilt, then the FP tells perhaps more about star formation than about galaxy formation. On the other hand, if dark matter is the origin of the tilt than the FP may tell on the (variable) amount of concentration experienced by the dissipational baryonic component relative to the dissipationless component (see also BBF; GLB). Perhaps we may have even more to learn about galaxy formation from the face-on mapping of the FP—which is not uniformly populated (GLB)—and from the discovery that rich clusters of galaxies may also lie on a FP.

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