THE FUNDAMENTAL PLANE OF MASSIVE QUIESCENT GALAXIES OUT TO Z ~ 2

JESSE VAN DE SANDE1, MARISKA KRIEK2, MARJIN FRANK1, RACHEL BEZANSON3, AND PIETER G. VAN DOKKUM4

1 Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
2 Astronomy Department, University of California at Berkeley, Berkeley, CA 94720, USA
3 Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
4 Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA

Abstract
The Fundamental Plane (FP) of early-type galaxies, relating the effective radius, velocity dispersion, and surface brightness, has long been recognized as a unique tool for analyzing galaxy structure and evolution. With the discovery of distant quiescent galaxies and the introduction of high sensitivity near-infrared spectrographs, it is now possible to explore the FP out to z ~ 2. In this Letter we study the evolution of the FP out to z ~ 2 using kinematic measurements of massive quiescent galaxies (M* > 10^{11} M_☉). We find preliminary evidence for the existence of an FP out to z ~ 2. The scatter of the FP, however, increases from z ~ 0 to z ~ 2, even when taking into account the larger measurement uncertainties at higher redshifts. We find a strong evolution of the zero point from z ~ 2 to z ~ 0: Δ log_{10} M/L_e ∝ (-0.49 ± 0.03) z. In order to assess whether our spectroscopic sample is representative of the early-type galaxy population at all redshifts, we compare their rest-frame g – z colors with those from a larger mass complete sample of quiescent galaxies. At z > 1 we find that the spectroscopic sample is bluer. We use the color offsets to estimate a mass-to-light ratio (M/L) correction. The implied FP zero point evolution after correction is significantly smaller: Δ log_{10} M/L_e ∝ (-0.39 ± 0.02) z. This is consistent with an apparent formation redshift of z_{form} = 6.62^{+1.19}_{-1.41} for the underlying population, ignoring the effects of progenitor bias. A more complete spectroscopic sample is required at z ~ 2 to properly measure the M/L evolution from the FP evolution.

Key words: galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: stellar content – galaxies: structure

Online-only material: color figures

1. INTRODUCTION
The Fundamental Plane (FP) of early-type galaxies is the empirical relation between the effective radius r_e, stellar velocity dispersion within one effective radius σ_e, and the average surface brightness within one effective radius I_e (e.g., Djorgovski & Davis 1987; Dressler et al. 1987; Jorgensen et al. 1996). Traditionally, the offset in the FP is interpreted as the mass-to-light ratio (M/L) evolution of galaxies (e.g., Faber et al. 1987), under the assumption that early-type galaxies form a homologous family, and that all the evolution is caused by the change in luminosity. Holden et al. (2010) indeed suggested that this assumption is correct, finding that out to z ~ 1 the slope of the FP does not change. By extending M/L evolutionary studies to higher redshifts, it is possible to put constraints on the formation epoch of massive galaxies.

The evolution of the M/L has been studied extensively out to z ~ 1.3 (e.g., van Dokkum & van der Marel 2007; Holden et al. 2010). The general consensus is that the evolution of the M/L appears to evolve as Δ ln M/L_B ∝ z. With recent studies showing that the first massive, quiescent galaxies were already in place when the universe was only ~3 Gyr old (e.g., Kriek et al. 2006; Williams et al. 2009), the question arises of whether the FP already existed at this early epoch and how the M/L evolved.

With the advent of new NIR spectrographs, such as VLT-X-SHOOTER and Keck-MOSFIRE, it is now possible to obtain rest-frame optical spectra of quiescent galaxies out to z ~ 2. For example, in van de Sande et al. (2011, 2013) we obtained stellar kinematic measurements for five massive quiescent galaxies at 1.4 < z < 2.1 (see also Toft et al. 2012; Belli et al. 2014b). Combined with high-resolution imaging and multi-wavelength catalogs, these recently acquired kinematic measurements enable the extension of FP studies beyond z ~ 1.3.

In this Letter, we explore the existence of an FP at z ~ 2, and use the FP to measure the evolution of the M/L from z ~ 2 to the present day for massive quiescent galaxies. In a parallel study, Bezanson et al. (2013b) presented the mass FP evolution. Throughout the Letter we assume a ΛCDM cosmology with Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s^{-1} Mpc^{-1}. All broadband data are given in the AB-based photometric system.

2. DATA
For the work presented in this Letter, we use a variety of data sets, which all contain accurate kinematic measurements of individual galaxies and high quality broadband photometric catalogs. For more details see Table 1 and van de Sande et al. (2014). All velocity dispersions presented here are aperture corrected to one effective radius following the method as described in van de Sande et al. (2013).

Stellar masses are derived using the FAST code (Kriek et al. 2009). We use the Bruzual & Charlot (2003) Stellar Population Synthesis (SPS) models and assume an exponentially declining star formation history, the Calzetti et al. (2000) dust attenuation law; and the Chabrier (2003) stellar initial mass function. For galaxies in the Sloan Digital Sky Survey (SDSS), stellar masses are from the MPA-JHU DR7 release which are based on Brinchmann et al. (2004).

5 http://www.mpa-garching.mpg.de/SDSS/DR7/
The photometry and thus also the stellar mass are corrected for missing flux using the best-fit Sérsic luminosity (Taylor et al. 2010). Effective radii and other structural parameters, such as Sérsic index and axis ratio, are determined using two-dimensional Sérsic fits with GALFIT (Peng et al. 2010). The effective radii are circularized, i.e., \( r_e = \sqrt{ab} \). All rest-frame fluxes, including those for the SDSS sample, are calculated using the photometric redshift code EAZY (v46; Brammer et al. 2008).

We derive the average surface brightness within one \( r_e \) (\( I_e \), in units of \( L_{\odot}\,\text{pc}^{-2} \)) by dividing the total luminosity in the rest-frame g-band by \( 2\pi r_e^2 \). Absolute g-band magnitudes are calculated with \( M_{\odot} = 5.14 \), which we derive from the solar spectrum taken from the CALSPEC database.6

We adopt a mass limit (\( M_\ast > 10^{11}M_\odot \)) to homogenize the final sample. We note, however, that our sample remains relatively heterogeneous and in particular the higher redshift samples are biased toward the brightest galaxies (see also Section 4). We furthermore use the \( U - V \) versus \( V - J \) rest-frame color selection criteria to remove star-forming galaxies from our sample (e.g., Wuyts et al. 2007; Williams et al. 2009). Quiescent galaxies are selected to have \( U - V > (V - J) \times 0.88 + 0.59 \). This criterion is slightly different from previous work, as we do not require that \( U - V > 1.3 \) or \( V - J < 1.5 \). The latter criteria remove post-starburst galaxies and very old galaxies, respectively.

### 3. THE FUNDAMENTAL PLANE

The FP is traditionally written as:

\[
\log_{10} I_e = a \log_{10} \sigma_e + b \log_{10} L_{e,g} + c_1
\]

with \( r_e \) in kpc, \( \sigma_e \) in km s\(^{-1}\), and \( L_{e,g} \) in \( L_{\odot}\,\text{pc}^{-2} \). In this Letter, we adopt the slope from Jorgensen et al. (1996), i.e., \( a = 1.20 \), and \( b = -0.83 \). While detailed studies on galaxies in the SDSS have shown that the slope is steeper, i.e., \( a = 1.404, b = -0.76 \) (Hyde & Bernardi 2009), we nonetheless adopt the Jorgensen et al. (1996) values for an easier comparison with previous high-redshift studies. We do not fit the slope ourselves at high redshift, as our sample is too small and biased at \( z > 1 \). However, we note that Holden et al. (2010) find the same slope of the FP at \( z \sim 1 \) as Jorgensen et al. (1996).

While the projection of the FP along the effective radius is most often shown, the projection along \( \log_{10} I_e \) directly shows the evolution in the \( M/L \), which is thought to be the main driver in the evolution of the FP zero point. The top row in Figure 1 shows the following projection:

\[
\log_{10} I_e = a \log_{10} \sigma_e + b \log_{10} L_{e,g} + c_1
\]

with \( a = 1.45, b = -1.20 \), and \( c_1 = -0.11 \). We determine the zero point \( c_1 \) using a least-square fit, using the IDL function MPFIT (Markwardt 2009). The zero point evolves rapidly with redshift: 0.30, 0.54, 0.96 dex, at \( z \sim 0.75, z \sim 1.25, z \sim 2.00 \), respectively.

The top row in Figure 1 suggests that the FP exists out to \( z \sim 2 \). However, to quantify the existence of an FP, we consider the scatter before and after the fit, i.e., the rms scatter in \( I_e \) versus the scatter in \( (a \log_{10} \sigma_e + b \log_{10} L_{e,g}) - \log_{10} I_e \) or \( \Delta \log_{10} I_e \). For example, for galaxies in the SDSS for which we know the FP exists, the scatter in \( \log_{10} I_e \) is 0.26 ± 0.003 dex before the fit, while after the fit, we measure \( \Delta \log_{10} I_e = 0.13 \pm 0.002 \) dex. At \( z = 2 \) we find a decrease as well, from \( \log_{10} I_e = 0.33 \pm 0.04 \) dex, before the fit, to \( \Delta \log_{10} I_e = 0.25 \pm 0.04 \) after the fit. This hints at the existence of an FP at \( z \sim 2 \), although the scatter in dex is almost twice as high compared to \( z \sim 0 \).

We use Monte Carlo simulations to determine if the scatter could be due to measurement uncertainties alone. We find that scatter induced by observational errors is 0.14 dex at \( z \sim 2 \), resulting in an intrinsic scatter of 0.20 dex. Compared to the FP scatter at \( z \sim 0 \), the intrinsic scatter at \( z \sim 2 \) is still higher. The larger scatter could have been caused by the large range in age and the bias toward post-starburst galaxies.

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6 http://www.stsci.edu/hst/observatory/cdbs/calspec.html

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### Table 1

| Survey and Field | \( N_{\text{gal}} \) | \( z \) | Spectroscopy | Telescope and Instrument | Photometric Catalog | Structural Parameters |
|------------------|-----------------|--------|-------------|--------------------------|-------------------|----------------------|
| SDSS DR7         | 4621            | 0.05 < \( z < 0.07 \) | Abazajian et al. (2009) | SDSS          | Blanton et al. (2005) | Simard et al. (2011) |
| NMBS-COSMOS      | 3               | 0.7 < \( z < 0.9 \) | Bezanson et al. (2013b) | Keck-DEIMOS    | Skelton et al. (2014) | Bezanson et al. (2011) |
|                  |                 |        |              |                          | Whitaker et al. (2011) |                      |
| UKIDSS-UDS       | 10              | 0.6 < \( z < 0.7 \) | Bezanson et al. (2013b) | Keck-DEIMOS    | Skelton et al. (2014) | van der Wel et al. (2012) |
|                  | 1               | 0.83   | Wuyts et al. (2004) | Keck-LRIS      | Förster Schreiber et al. (2006) |
| MS 1054-0321     | 8               | \( z = 0.83 \) | Wuyts et al. (2004) | Keck-LRIS      | Förster Schreiber et al. (2006) |
| GOODS-S          | 7               | 0.9 < \( z < 1.2 \) | van der Wel et al. (2005) | VLT-FORS2      | Skelton et al. (2014) | van der Wel et al. (2012) |
| GOODS-N          | 1               | \( z = 1.315 \) | Newman et al. (2010) | Keck-LRIS      | Skelton et al. (2014) | van der Wel et al. (2012) |
| EGS              | 8               | 1.0 < \( z < 1.3 \) | Belli et al. (2014a) | Keck-LRIS      | Skelton et al. (2014) | van der Wel et al. (2012) |
| COSMOS           | 6               | 1.1 < \( z < 1.3 \) | Belli et al. (2014a) | Keck-LRIS      | Skelton et al. (2014) | van der Wel et al. (2012) |
| GOODS-S          | 1               | \( z = 1.419 \) | Belli et al. (2014a) | Keck-LRIS      | Skelton et al. (2014) | van der Wel et al. (2012) |
| NMBS-COSMOS      | 4               | 1.2 < \( z < 1.5 \) | Bezanson et al. (2013a) | Keck-LRIS      | Whitaker et al. (2011) | Bezanson et al. (2013a) |
| NMBS-AEGIS       | 2               | 1.4 < \( z < 1.6 \) | Bezanson et al. (2013a) | Keck-LRIS      | Whitaker et al. (2011) | Bezanson et al. (2013a) |
| NMBS-COSMOS      | 1               | 1.6 < \( z < 2.1 \) | van de Sande et al. (2013) | VLT-XSHOOTER | van de Sande et al. (2013) |
| UKIDSS-UDS       | 1               | 1.4 < \( z < 2.1 \) | van de Sande et al. (2013) | VLT-XSHOOTER | van de Sande et al. (2013) |
| COSMOS           | 1               | 1.823  | Ondera et al. (2012) | Subaru-MOIRCS | Muzzin et al. (2013a) | Ondera et al. (2012) |
| MUSYCLG          | 1               | 2.286  | van Dokkum et al. (2009) | Gemini-GNIRS | Blanc et al. (2008) | van Dokkum et al. (2009) |
| COSMOS           | 2               | 2.1 < \( z < 2.3 \) | Belli et al. (2014b) | Keck-MOSFIRE | Skelton et al. (2014) | Belli et al. (2014b) |
increasingly bluer than the reference sample, indicating a rather strong selection bias. 

(b) log$_{10}$ $B_{\text{r}}$ was selected spectroscopic sample to a larger photometric and more complete sample. The Astrophysical Journal Letters 793:L31 (6pp), 2014 October 1 

Figure 1. Edge-on projections of the FP of massive quiescent galaxies ($M_*>10^{11}M_\odot$) from low to high redshift. Top: at $z>0.5$ galaxies no longer fall on the SDSS FP (dotted line), with the dashed line indicating the best-fit relation. The rms scatter increases from $z\sim 0$ to $z \sim 2$, and cannot be explained by larger measurement errors at $z>1$ alone. Bottom: similar as top row, but now including a color correction applied to all galaxies in our spectroscopic sample, to fix the sample bias toward bright young galaxies (see Section 4). With the correction applied, we find that the scatter around the FP now reduces for the three high-redshift bins, implying that a tight FP exists out to $z \sim 2$.

(A color version of this figure is available in the online journal.)

Figure 2. Redshift evolution of rest-frame $g-z$ color and $M/L$ correction from color offset. (a) $(g-z)_{\text{rest-frame}}$ colors for our high-redshift spectroscopic sample compared to a larger and more complete photometric sample from the 3D-HST survey with a similar mass selection as shown by the large gray circles. The gray area indicates the $1-\sigma$ scatter. For the reference sample we measure that $(g-z)_{\text{rest-frame}}$ evolves as $-0.16z$ (dashed gray line). At $z>1$ the spectroscopic sample becomes increasingly bluer than the reference sample, indicating a rather strong selection bias. (b) log$_{10} M/L_g$ vs. rest-frame $g-z$ color. Massive galaxies from the SDSS are shown by the gray contour, which encloses 68% of all galaxies. The green line shows an M11 model, and the dashed black line shows the linear approximation to the model ($\log_{10} M/L \propto 1.29 (g-z)_{\text{rest-frame}}$). We use the model approximation to correct the $M/L$ using the color offset. The correction is demonstrated with arrows for the galaxy with the lowest $M/L$ and bluest color. (c) Corrected $M/L$s and $g-z$ colors. The correction is small for most low-redshift galaxies ($\sim 0.2$ dex), while the galaxies at $z>1.5$ have larger corrections of $\sim 0.2$--$1.0$ dex.

(A color version of this figure is available in the online journal.)

4. CORRECTING FOR SAMPLE BIAS

In order to explain the larger scatter in the FP of our high-redshift sample, we compare the rest-frame $g-z$ colors of our spectroscopic sample to a larger photometric and more complete galaxy sample. We use galaxies from the 3D-HST survey (v4.1; Brammer et al. 2012; Skelton et al. 2014), which were selected to be massive ($M_*>10^{11}M_\odot$), non-star-forming according to their $U-V$ versus $V-J$ colors (see Section 2), and have a reduced $\chi^2<5$ for the best-fit stellar population model to their spectral energy distribution. Rest-frame fluxes for the reference sample were derived with EAZY, in a similar fashion as for the spectroscopic sample and are based on photometric redshifts.

In Figure 2(a) we show the comparison of the rest-frame $g-z$ color as a function of redshift. The reference sample is binned in redshift, with the median of each bin shown as a big gray circle. The dashed line shows the best fit of the color as a function of redshift: $(g-z)_f = -0.16z + 1.49$. There is very little difference between the reference and the spectroscopic sample at $0<z<1$, while at $z>1$ the spectroscopic sample becomes...
increasingly bluer compared to the median of the reference sample. At \( z > 1.4 \) we furthermore see a large spread in colors where some galaxies follow the median of the galaxy population, while other galaxies are offset by more than 0.5 mag.

All spectroscopic samples are relatively blue at higher redshifts, as it is easier to obtain high signal-to-noise spectra for quiescent galaxies compared to the much fainter older quiescent galaxies. In order to estimate the effect of this bias, we use the color difference with the reference sample to calculate a \( M/L \) correction for the individual galaxies in our spectroscopic sample.

First, we measure the relative evolution of the \( M/L \) from the FP as shown in the top panels of Figure 1, under the assumption that \( a \) and \( b \) do not evolve with redshift:

\[
\Delta \log_{10} M/L = c_z - c_0. \tag{3}
\]

Here \( c_0 \) is the FP zero point at redshift zero, while \( c_z \) is determined from the residuals from the FP for each individual galaxy at redshift \( z \):

\[
c_z = \left( a \log_{10} \sigma_e + b \log_{10} I_e \right) - \log_{10} I_e \tag{4}
\]

Note that we have \( \Delta \log_{10} M/L = \Delta \log_{10} I_e \).

Next, we use the relation between the rest-frame \( g - z \) color and the derived \( \Delta \log_{10} M/L \) as shown in Figure 2(b) to derive the \( M/L \) correction. There is a correlation between the color and \( M/L \), where the bluest galaxies have the lowest \( M/L \). This correlation is also predicted by SPS models, on which we base our \( M/L \) correction. In Figure 2(b) we show a Maraston & Strömbäck (2011, Ma11) solar metallicity model (green line), with a truncated star formation history and constant star formation for the first 0.5 Gyr. Different ages in this model are indicated on the green line by the circle (0.3 Gyr), diamond (1.0 Gyr), and triangle (10 Gyr). We approximate the Ma11 model by a simple linear fit: \( \Delta \log_{10} M/L \propto 1.29(g - z)_\text{rest} \) (dashed black line). We use this fit to estimate the \( M/L \) correction.

As an example, we highlight the bluest galaxy in our sample, NMBS-Cos-7447 at \( z \sim 1.8 \). In Figure 2(a), the black arrow indicates the color offset to the \( (g - z)_{\text{rest-frame}} \) color–redshift relation. The same galaxy has an extremely low \( M/L \) as is clear from Figure 2(b). Here the vertical arrow is again the color offset of this galaxy, but the horizontal arrow now points toward the \( M/L \) that the galaxy would have if it would fall on the color–redshift relation from Figure 2(a). The \( M/L \) correction that we apply to this individual galaxy is therefore the length of the horizontal arrow. In other words, for each galaxy we lower the \( M/L \) by 1.29 times the color offset, where the factor 1.29 comes from the linear fit to the Ma11 model (dashed line). We note, however, that a steeper \( M/L \) versus color relation yields larger \( M/L \) corrections, and thus impacts the \( M/L \) evolution in Section 5. We show the corrected colors and \( M/L \) for the entire sample in Figure 2(c). The rest-frame \( g - z \) color and \( M/L \) of the spectroscopic sample is now similar to that of the reference sample.

With the \( M/L \) (or \( \Delta \log_{10} I_e \)) correction applied, we can return to the FP which is shown in the bottom row of Figure 1. As before, the dashed colored lines indicate the best-fit FP with the following zero points in each redshift bin: 0.30, 0.53, and 0.62 dex, from low to high redshift. Note that the \( z \sim 2 \) zero point is significantly lower than before the correction. The scatter around the FP is greatly reduced for all three redshift bins. In particular for the highest redshift bin, which had the largest spread in \( (g - z)_{\text{rest}} \) color, the scatter has decreased by almost a factor two. More quantitatively, the scatter after the FP fit is \( \Delta \log_{10} I_e = 0.11 \pm 0.02, 0.13 \pm 0.02, 0.13 \pm 0.03 \) from low to high redshift, respectively. We note that the small scatter is most likely a lower limit, as we do not include the intrinsic color scatter in our analysis.

5. Evolution of the \( M/L \)

In Figure 3 we show the \( M/L \) as derived from the FP offset relative to \( z \sim 0 \), as a function of redshift for all galaxies. We indicate the different zero points from Figure 1 as dashed lines. The red solid line is a linear least-square fit to all data, which describes the evolution of the \( M/L : \Delta \log_{10} M/L_e \propto (-0.49 \pm 0.03)z \). Here we have anchored the fit to the median of the \( z \sim 0 \) SDSS galaxies. When excluding SDSS from the fit, the evolution is more rapid: \( \Delta \log_{10} M/L_e \propto (-0.61 \pm 0.09)z \).
The evolution is similar to a previous result by van Dokkum & van der Marel (2007), who find that the $M/L \propto (−0.555 \pm 0.042)z$ in the rest-frame $B$ band. Here, the effect of using a slightly bluer rest-frame filter makes very little difference, i.e., our measured $M/L$ evolution in the rest-frame $B$ band is only slightly faster as compared to the $g$ band: $\Delta \log_{10} M/L_B \propto (−0.53 \pm 0.03)z$.

For a fair comparison with previous studies, we also restrict the fit to $z < 1.4$ and find a slower evolution than other studies: $\Delta \log_{10} M/L_g \propto (−0.45 \pm 0.01)z$. This suggests that the relatively fast evolution of the entire sample is mainly driven by galaxies at $z > 1.4$. This is furthermore evident from Figure 3(a) in which almost all $z > 1.4$ galaxies fall below the best fit for the entire sample.

Figure 3(b) shows the $M/L$ evolution with redshift, with the $M/L$ correction included. This time, we find a milder evolution in the $M/L$ than before: $\Delta \log_{10} M/L_g \propto (−0.39 \pm 0.02)z$, shown by the red line. Our corrected $M/L$ evolution is similar to previous studies by e.g., van Dokkum & Stanford (2003) $(-0.46 \pm 0.039)$, and Holden et al. (2005) $(-0.426 \pm 0.04)$, but slower than the evolution found by van Dokkum & van der Marel (2007) $(-0.555 \pm 0.04)$, and Holden et al. (2010) $(-0.60 \pm 0.04)$. If we would have used a steeper $M/L$ versus color relation for the correction, (e.g., $\log_{10} M/L_g \propto 1.80(g − z_{\text{rest-frame}})$ the $M/L$ evolution would be slower: $\Delta \log_{10} M/L_g \propto (−0.36 \pm 0.03)z$.

We also show the single burst Ma11 model from Figure 2, with a formation redshift of infinity. Using the same Ma11 model, we fit the average formation redshift of the biased sample (Figure 3(a)), and estimate $z_{\text{form}} = 3.29_{-0.55}^{+0.55}$. For our corrected sample (Figure 3(b)) we estimate the apparent $z_{\text{form}} = 6.62_{-1.44}^{+3.19}$. The large difference highlights the strong selection bias in the sample. Both estimates ignore the progenitor bias, which is very strong given the fact that the number density of massive galaxies changes by a factor of $\sim 10$ from $z \sim 2$ to $z \sim 0$ (Muzzin et al. 2013b). Therefore, the corrected $z_{\text{form}}$ should be regarded as an upper limit for a mass-complete sample that is not supplemented by newly quenched galaxies at later times. We note that we would find a lower $z_{\text{form}}$ if we were to include progenitor bias in our analysis, or if we would use an evolving mass limit in our sample-selection. A more detailed study of this effect would require a mass-complete spectroscopic sample.

### 6. DISCUSSION

In Section 4 we have corrected our sample for the bias toward young quiescent galaxies. In this correction we assume that all quiescent galaxies at a particular redshift have the same color and thus the same age. This assumption is an oversimplification, and the scatter in the FP is actually partly due to age variations (e.g., Graves et al. 2009). Furthermore, the age variations of quiescent galaxies may increase with redshift as shown by Whitaker et al. (2010). Thus, it is very likely that the scatter in the FP will be induced by larger age variations at higher redshifts.

Because we apply the same correction at all redshifts, we do show that the scatter in the FP due to variation in properties other than age (e.g., evolution in stellar mass, size, velocity dispersion, and metallicity) is approximately constant over time. However, our $M/L$ evolution is not necessarily the $M/L$ evolution of progenitors and descendants of a fixed population as the masses, sizes, and velocity dispersions of these galaxies likely evolve systematically with redshift. Using a simple model, we can estimate the effect of structural evolution on the FP and $M/L$ evolution. Given that mass evolves as $\Delta \log_{10} M/M_\odot \sim 0.15z$ (van Dokkum et al. 2010), we find that $\Delta M/L \sim M^2$, and $\Delta M/L \sim M^{-0.49}$ in van de Sande et al. (2013). Thus, if mass grows by a factor $f$, the $M/L$ evolution (from Equations (3) and (4)) including structural evolution can be written as follows:

$$\Delta \log_{10} M/L \simeq a \log_{10}(f^{-0.5} \sigma_e) + b \log_{10}(f^2 \sigma_e) - \log_{10}(f^{-3} I_e)$$

(5)

The bias in the $M/L$ evolution induced by structural evolution can therefore be approximated by $(-0.5a + 2b + 3) \log_{10} f$. Assuming a mass growth factor of 0.3 dex, we find that the offset in the $M/L$ due to structural evolution is small: $\sim 0.04$ dex. We note that if velocity dispersion does not evolve, this effect is larger: $\sim 0.2$ dex.

### 7. CONCLUSION

In this Letter, we have used stellar kinematic and structural measurements of massive quiescent galaxies ($M_\ast > 10^{11} M_\odot$) out to $z \sim 2$ to study the evolution of the rest-frame $g$-band FP. We utilize this empirical relation between the size, stellar velocity dispersion, and the surface brightness, to constrain the evolution of the $M/L$.

We find preliminary evidence for the existence of an FP out to $z \sim 2$, but with larger scatter as compared to the present-day FP for massive quiescent galaxies from the SDSS. There is a rapid evolution of the FP zero point from $z \sim 0$ to $z \sim 2$: $\Delta \log_{10} M/L_g \propto (−0.49 \pm 0.03)z$. Furthermore, we find that the $M/L_g$ evolution for galaxies at $z > 1.4$ is faster than for galaxies at $z < 1.4$.

The larger scatter and fast evolution can be explained by the fact that our spectroscopic sample becomes increasingly bluer at high redshift compared to a mass complete sample of quiescent galaxies. We calculate the color difference between the galaxies and the mass complete sample, and estimate the systematic effect on the $M/L$.

With this correction applied, the evolution of the $M/L$, as derived from the FP, is slower: $\Delta \log_{10} M/L_g \propto (−0.39 \pm 0.02)z$. A simple model, ignoring progenitor bias, would imply a formation redshift of $z_{\text{form}} = 6.62_{-1.44}^{+3.19}$ for a mass complete sample. The difference between the evolution of our observed sample and the underlying population highlights the need for a more detailed study of a mass complete spectroscopic sample.

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