Galaxy properties as revealed by MaNGA. I. Constraints on IMF and $M_*/L$ gradients in ellipticals

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ABSTRACT

We estimate ages, metallicities, $\alpha$-element abundance ratios and stellar initial mass functions of elliptical (E) and S0 galaxies from the MaNGA-DR15 survey. We stack spectra and use a variety of single stellar population synthesis models to interpret the absorption line strengths in these spectra. We quantify how these properties vary across the population, as well as with galactocentric distance. This paper is the first of a series and is based on a sample of pure elliptical galaxies at $z \leq 0.08$. We show that the properties of the inner regions of Es with the largest luminosity ($L_r$) and central velocity dispersion ($\sigma_0$) are consistent with those associated with the commonly used Salpeter IMF, whereas a Kroupa-like IMF is a better description at $\sim 0.8 R_e$ (assuming [Ti/Fe] variations are limited). For these galaxies the stellar mass-to-light ratio decreases at most by a factor of 2 from the central regions to $R_e$. In contrast, for lower $L_r$ and $\sigma_0$ galaxies, the IMF is shallower and $M_*/L_r$ in the central regions is similar to the outskirts. Although a factor of 2 is smaller than previous reports based on a handful of galaxies, it is still large enough to matter for dynamical mass estimates. Accounting self-consistently for these gradients when estimating both $M_*$ and $M_{\text{dyn}}$ brings the two into good agreement: gradients reduce $M_{\text{dyn}}$ by $\sim 0.2$ dex while only slightly increasing the $M_*$ inferred using a Kroupa IMF. This is a different resolution of the $M_* - M_{\text{dyn}}$ discrepancy than has been followed in the recent literature where $M_*$ of massive galaxies is increased by adopting a Salpeter IMF while leaving $M_{\text{dyn}}$ unchanged. A companion paper discusses how stellar population differences are even more pronounced if one separates slow from fast rotators.

Key words: galaxies: fundamental parameters – galaxies: spectroscopy – galaxies: structure

1 INTRODUCTION

The spectrum of a galaxy is a linear combination of the spectra of its stars. Stellar spectra depend on mass, age and chemical composition, so a galaxy’s spectrum encodes information about its stellar mass, the mean age of its stars, more detailed information about its star formation history (single-burst, episodic, time-scales), its chemical composition (metallicity, $\alpha$-element abundance ratios, dust content) and the IMF (which describes the mix of stars formed in each episode). Decades of work have shown how to decode this ‘fossil record’ (Worthey 1994; Trager et al. 1998; Kauffmann et al. 2003; Bernardi et al. 2006; Panter et al. 2007; Graves et al. 2009). We now know that the mix of stars in galaxies varies across the galaxy population, over and above the obvious variations with morphology across the Hubble sequence.

In this and the following papers of this series, we focus almost exclusively on early-type galaxies (Es and S0s) since late-type galaxies (Spirals) have gas and dust which complicate the spectral analysis. In fact, in this paper, we only study Es (we study S0s in Dominguez Sanchez et al. in prep.). However, even amongst Es, the stellar populations depend on other global properties such as velocity disper-
In addition to varying across the early-type galaxy population, there are stellar population gradients even within a single galaxy. Although this has been known for some time – color gradients in galaxies have been quantified for decades (e.g. Tortora et al. 2011, and references therein) – we are now on the cusp of a revolution in the study of gradients. This is because of the advent of Integral Field Units (IFUs) which provide spatially resolved spectroscopy for galaxies. The SAURON (Emsellem et al. 2004) and Atlas3D (Cappellari et al. 2011) surveys of a decade ago provided estimates of kinematic gradients (i.e., rotation curves and velocity dispersion profiles) in tens to hundreds of early-type galaxies, each sampled by tens to hundreds of spaxels. At the moment, the MaNGA survey (Mapping Nearby Galaxies at Apache Point Observatory; Bundy et al. 2015; Law et al. 2015; Wake et al. 2017; Westfall et al. 2019) provides this, as well as sufficiently high quality spectra to determine chemical abundance gradients, for about two thousand early-types, each sampled by hundreds to thousands of spaxels.

Why do gradients matter? Perhaps the crudest measure of the inhomogeneous distribution within a galaxy is the correlation between stellar population and distance from the center: the stellar population gradient. This is expected to constrain and separate its star formation history from its assembly history (e.g. inside-out or outside-in? in-situ or ex-situ?). But, most importantly, stellar population gradients affect how we estimate the stellar mass of a galaxy (Bernardi et al. 2018b and references therein). Stellar masses are the bricks which build the bridge that connects galaxy formation models to dark matter halos and hence to cosmology. Reliable stellar mass estimates are crucial for reconciling the stellar mass density today with that inferred from the integrated star formation rate. They also impact discussions of the efficiency of feedback from active galactic nuclei in the quasar and/or radio modes, and the response of the dark matter halo to galaxy formation.

There are currently two distinct methods for estimating the mass in stars. One exploits the fact that the light from a galaxy is simply a linear combination of the light from its stars. So, by finding that linear combination of stellar spectra – each with its own mass-to-light ratio (e.g., in the optical, young massive stars have small mass-to-light ratios) – which best-fits the observed spectrum, one can constrain the overall mass-to-light ratio of the galaxy. We will refer to this as \( M_*/L_r \). In this approach, the stellar mass is obtained by multiplying the estimated \( M_*/L_r \) by the observed \( L_r \) to yield \( M_* \).

The other method uses the motions of the stars to constrain their collective mass. Typically, this estimate is based on the Jeans equation, and requires some assumption about the distribution of dark matter, which is expected to dominate the mass far from the center, and some knowledge of the orbital anisotropies. We will refer to this mass estimate as \( M^{\text{dyn}}_* \). The most widely cited dynamical mass estimates (Cappellari et al. 2013a,b) are based on the additional assumption that the shape of the light profile traces the shape of the stellar mass profile – i.e., that the stellar mass-to-light ratio is constant (the total mass-to-light ratio is not constant, of course, because dark matter dominates on large scales). This is an assumption of convenience – it has no physical motivation. In this approach, the value of \( M^{\text{dyn}}_*/L_r \) is determined by matching the observed velocity dispersion, rather than by matching detailed features of the spectrum.

Thus, roughly speaking, \( M^{\text{dyn}}_* \) depends on the shape of the fitted light profile, but not on its amplitude, whereas the stellar population based estimate \( M_* \) depends more on the total light \( L_\text{r} \), than on the detailed profile shape. In this respect, comparing \( M_* \) and \( M^{\text{dyn}}_* \) is attractive, since it nicely separates out two distinct sources of uncertainty. In addition, \( M_* \) depends on assumptions about the dust content, the IMF of the stellar population and so on, whereas \( M^{\text{dyn}}_* \) (in principle) does not. On the other hand, \( M_* \) does not depend on the dark matter distribution or orbital anisotropies, whereas \( M^{\text{dyn}}_* \) does. These two estimates are thought to provide two distinct routes – albeit with rather different systematic biases – to the same underlying physical quantity. It has been shown for some time that, if one assumes the same IMF within a galaxy and across the population, then \( M^{\text{dyn}}_*/M_\text{SP} \) varies across the early-types population (e.g. Bender et al. 1992; Bernardi et al. 2003; Shankar & Bernardi 2009; Cappellari et al. 2013b; Li et al. 2017; Bernardi et al. 2018a). This discrepancy between the \( M_\text{SP} \) and the \( M_* \) estimates has driven many to conclude that the IMF is Salpeter, or even super-Salpeter, in massive galaxies (e.g. Cappellari et al. 2013b; Li et al. 2017; Bernardi et al. 2018a).

Of course, if gradients are important, then the stellar light and matter profiles have different shapes. This implies that the Jeans equation-based \( M^{\text{dyn}}_* \) estimates currently in the literature are incorrect, because they are based on the assumption that the true stellar mass-to-light ratio is independent of distance from the center. While this has been known for some time, the conventional wisdom had been that this is a small effect. This is based on analyses which assume that the IMF within a galaxy is fixed, and in this case the stellar population derived \( M_*/L_r \) is about 20% larger in the center than it is within \( r_e/2 \) (i.e. half the projected half-light radius). However, recent work suggests that if the IMF is also allowed to vary when fitting the spectrum, then the \( M_*/L_r \) difference may be as large as a factor of 3 (van Dokkum et al. 2017). As Bernardi et al. (2018b) note, if \( M_*/L_r \) gradients really are this large, then \( M^{\text{dyn}}_* \) estimates currently in the literature must be revised downwards.

It is not obvious that a factor of 3 is realistic. The van Dokkum et al. (2017) analysis was based on a handful of objects. This is in part because determining the IMF is not an easy task: changes in the IMF only lead to rather subtle effects on the spectrum (Conroy & van Dokkum 2012; La Barbera et al. 2013; Martín-Navarro et al. 2015; La Barbera et al. 2016; Tang & Worthey 2017), some of which are degenerate with other stellar population differences (e.g., star formation histories, chemical abundances, etc.). High signal-to-noise spectra are required to disentangle IMF gradients from these other effects. The MaNGA survey (Bundy et al. 2015) provides an IFU sample that is an order of magnitude larger compared to what is currently available.

Parikh et al. (2018) describe a first attempt at estimating IMF gradients in the MaNGA sample based on a stacking analysis of the spectra. However, the sample size available at the time (1700 galaxies versus ~ 4600 in the current MaNGA data release) meant that they were only able to measure rather approximate trends across the population. They divided the sample into three bins of stellar...
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| SELECTION OF GALAXIES |
|------------------------|
| Condition             | Observations | Galaxies |
| Es                    | 1052         | 1028     |
| FLAG_FIT ≠ 3          | 1002         | 982      |
| No contamination      | 814          | 797      |

Table 1. The number of galaxies in our sample of Es, as described in the text.

2 DATA

2.1 MaNGA survey

The MaNGA survey (Bundy et al. 2015) is a component of the Sloan Digital Sky Survey IV (Blanton et al. 2017; hereafter SDSS IV). MaNGA uses integral field units (IFUs) to measure multiple spectra across ~10000 nearby galaxies (see Wake et al. 2017, for the sample selection). The IFU observations enable the construction of detailed kinematic and chemical composition maps of each galaxy (Westfall et al. 2019). In this work, we use the MaNGA DR15 (Aguado et al. 2019), which provides observations for ~4600 galaxies. MaNGA DR15 includes datacubes with spectral information in the wavelength range 360-10000 nm and spatial sampling of 1-2 kpc thanks to an observational strategy which includes dithering (see Westfall et al. 2019 for more details). Apart from the observed spectra, DR15 also provides kinematic maps (stellar velocity and velocity dispersion), as well as emission and absorption line estimates for each spectrum.

The photometric parameters used throughout this work come from the PyMorph Photometric Value Added Catalogue (MPP-VAC) presented in Fischer et al. (2019). The MPP-VAC provides photometric parameters from Sérsic and Sérsic + Exponential fits to the 2D surface brightness profiles of the MaNGA DR15 galaxy sample (4672 entries for 4599 unique galaxies) in the SDSS g, r, and i bands. In addition to total magnitudes, effective radii, Sérsic indices, axis ratios b/a, etc., MPP-VAC also includes a flagging system (FLAG_FIT) which indicates the preferred fit model (Sérsic or Sérsic + Exponential). In this work, for each galaxy, we use the best-fit parameters in the SDSS r-band for the model indicated by FLAG_FIT. When FLAG_FIT = 0 — i.e., no preference between Sérsic or Sérsic + Exponential fits — we use the values returned by the latter.

The MPP-VAC provides two estimates of the total magnitudes and sizes: One corresponds to integrating the best fitting surface brightness profiles to infinity, and the other to truncating these profiles at 7R_e. (The scale which contains half this ‘truncated’ light is slightly smaller than the ‘untruncated’ R_e.) For most of the analysis in this paper, we use the ‘truncated’ magnitudes and sizes.

2.2 Sample selection and binning

This paper and its companion (Paper II) use a sample of pure E galaxies to study their properties as a function of global parameters (i.e. absolute magnitude, central velocity dispersion and half-light radius) as well as galactocentric distance (i.e. their gradients). A third paper in this series analyzes the properties of S0 galaxies (Domínguez Sánchez et al. in prep.). Since Es have neither complex star formation histories nor multiple structural components (such as spiral arms or bars) we assume that they can be well approximated by a single stellar population (SSP).

To select a pure sample of Es we use the companion morphological catalog to MPP-VAC (Fischer et al. 2019, MRLM-VAC). The MRLM-VAC provides morphological properties (e.g., TType, presence of bar, edge-on galaxies, etc.) derived from supervised Deep Learning algorithms based on Convolutional Neural Networks. Details on the Deep Learning model architecture, training and testing procedures are given in Domínguez Sánchez et al. (2018). We require TType ≤ 0 and P_s0 ≤ 0.5 to select our sample of Es from the MRLM-VAC (which includes 4672 observations for 4599 unique galaxies). The first condition selects early-type galaxies (1948 observations for 1908 galaxies) as opposed to late-type galaxies, and the second selects Es (1052 observations for 1028 galaxies) rather than S0s (see Table 1). About ~22% of the MaNGA DR15 galaxies are Es.

Since we require of accurate photometry and kinematics, we remove from our sample galaxies with FLAG_FIT=3 from MPP-VAC (i.e., no available photometric parameters), as well as galaxies with unreliable spectra due to contamination by neighbors (removed after visual inspection). We also limited our sample selection to galaxies with z ≤ 0.08, for the reasons we discuss in Section 2.3.

Figure 1 shows the relation between central velocity dispersion σ_0 and absolute magnitude M_r for the whole E sample (small grey dots). We divide the low redshift (z ≤ 0.08) E sample into four bins based on M_r and σ_0 (colored sym-
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Figure 1. Distribution of central velocity dispersion $\sigma_0$ and absolute magnitude $M_r$ in our sample (grey dots). Blue, green, yellow and red dots show the objects with $z \leq 0.08$ which we assign to bins B00, B10, B11 and B21 described in Table 2.

BINNING OF GALAXIES

| Bin   | $M_r$ [mag] | $\log_{10} \sigma_0$ [km s$^{-1}$] | Galaxies all $z$ | Galaxies $z \leq 0.08$ |
|-------|-------------|------------------------------------|------------------|-------------------------|
| B00   | $-21.5$, $-22.5$ | 2.20, 2.30                          | 74               | 70                      |
| B10   | $-21.5$, $-22.5$ | 2.30, 2.40                          | 133              | 121                     |
| B11   | $-22.5$, $-23.5$ | 2.30, 2.40                          | 138              | 52                      |
| B21   | $-22.5$, $-23.5$ | 2.40, 2.50                          | 164              | 60                      |

Table 2. Number of galaxies in each bin with and without redshift cut.

To measure absorption features accurately, spectra must have high SN ($\geq 100$). As we discuss in Section 2.3, this requires that we create stacked spectra. Our bin sizes were chosen with this requirement on SN in mind. The bin limits, as well as the number of galaxies in each bin are given in Table 2. For galaxies with repeated observations we only use the best S/N observation for each one. Note that $M_r = -22.5$ is close to the critical luminosity at which various scaling relations change slope (Bernardi et al. 2011). This corresponds to a stellar mass of $2 \times 10^{11} M_\odot$ if the IMF is Chabrier (2003). In Section 4, we show that the IMF is not Chabrier, and use our results to provide a better estimate of the translation from $L$ to $M_\star$.

2.3 Stacked spectra and Lick indices

We would like to measure radial gradients of Lick indices reliably. This requires SN greater than 100. As Figure 2 shows, the typical S/N in a spaxel lies well-below this value. Therefore, we must work with stacked spectra. We generate these by stacking together the spectra of galaxies in the same bin (see Table 2). For each galaxy, we use all the spaxels from the MAPS-VOR10-GAU-MILESHC files that have SN $\geq 5$. However, as we are interested in measuring gradients from the central regions out to about $R_e$ for each bin, we would like to make stacks for a narrow range in projected distance $R$ for each bin. Figure 3 shows the joint distribution of angular size and redshift for the Es in bins B00, B10, B11 and B21. Small vertical lines show the median $z$ for each bin if we include all objects (dashed), or if we restrict the sample to $z \leq 0.08$ (solid). There are very few B00 or B10 objects at $z \geq 0.08$. The same galaxy, if placed at $z \leq 0.05$, will be covered by many more spaxels than if it is at higher $z$. For the largest galaxies, the IFU may not cover the entire region within $R_e$; this is particularly a concern for bins B11 and B21. We will return to this point later.

Figure 3 shows that there are almost no B00 or B10 objects at $z \geq 0.08$ (see also Table 2). For these, the sample is essentially volume limited. The small vertical lines in Fig-
fit in the MPP-VAC). The radial to our results for the four bins in Figure 4. z this higher z and have z > R/R each Figure 4 shows the number of spaxels which contribute to (dashed), or if we restrict the sample to z ≤ R/R 0.9 Gyrs. While this does not seem dramatic, note that the bins B11 and B21 the median looktime is reduced from 1.2 to significantly.

We also limit our analysis to 0.8 R/R e 0.8, reduces lookback time systematics significantly. We try an alternative stacking procedure: constructing radial stacks for each galaxy and then stacking the galaxies corresponding to each bin described in Table 2 together. With this methodology, each galaxy contributes equally to the final stack; however, it has the disadvantage of penalizing the galaxies with the larger SN (larger number of spaxels or higher surface brightness). The results presented in the following sections (based on the stacks derived using all the available spaxels) are consistent with the results obtained by stacking the radial stacks of individual galaxies, with the latter being slightly more noisy.

Once we have created the stacks, we smooth them to a resolution of 300 km s⁻¹ and we measure the Lick indices. Table 3 lists the Lick indices which play an important role in this paper. To illustrate the quality of the stacks, Figure 5 shows the stacked spectra for the objects in bin B10 for a range of R/R e. The spectra have been offset vertically for clarity. The right panels of Figure 5 show zoom-ins around the Lick indices discussed in the following sections. These panels show clear trends of index-strength with distance from the center, which we quantify shortly.

Figure 6 shows the signal-to-noise profiles for the Lick indices measured from the stacked spectra. This shows that our stacks have S/N ≫ 100 on all scales we explore in this paper.
Table 3. Lick indices used in this work and their corresponding definitions: (1) Trager et al. (1998), (2) La Barbera et al. (2013). TiO1 and TiO2 are discussed in the Appendix.

2.4 Comparing stacks with median spaxel values

2.4.1 Velocity dispersion profiles

Figure 7 shows velocity dispersion profiles for our four $\sigma_0$ and $M_r$ bins. In both panels, filled circles connected by a line show the value from each stack (note that here the stacks are not smoothed to 300 km s$^{-1}$). In the top panel, the thinner lines with crosses show the median of the individual spaxels, with the hashed region showing the range which includes 68% of the objects around the median. The two agree to within about 10%. Aside from showing the expected trend that $\sigma$ increases from blue to yellow to red, with green being similar to yellow (see Figure 1), both estimates show clearly that $\sigma$ decreases approximately as $\sigma(R) \propto R^{-0.1}$.

The estimated $\sigma(< R)$, shown as filled squares in the bottom panel of figure 7, is slightly shallower, $\sigma(R) \propto R^{-0.06}$, and agrees with previous work on individual spectra (e.g. Jorgensen et al. 1995). In contrast, Parikh et al. (2018) report flat $\sigma(R)$ profiles for their stacks. We get flatter profiles if we neglect to subtract the effects of rotation from the spaxels before stacking (triangles in the bottom panel),
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Figure 7. Top: Velocity dispersion profiles for the four bins defined in Table 2, estimated from our stacked spectra (circles connected by solid lines) and from the median of the velocity dispersion measurements made on the individual spaxels themselves (crosses connected by dotted lines; the hashed region shows the range which includes 68% of the objects around the median). Bottom: Velocity dispersion profiles estimated from our stacked spectra in radial bins before (triangles) and after (circles) correcting the individual spaxels for rotation (i.e. using equation 1 with $v = 0$ and $v \neq 0$, respectively) and from the cumulative stacks (squares) obtained after correcting for rotational velocity (i.e. $v \neq 0$ in equation 1).

but strongly believe that rotation should be removed before doing any analysis.

2.4.2 Line-index strength profiles

Figure 8 shows a similar analysis to Figure 7 but for the line-indices in our four bins. I.e. for each $R$ and bin, symbols show the Lick index strength measured from the stacked spectrum, and solid lines show the median of the line-index measurements for the individual spaxels (here too the stacks are not smoothed to 300 km s$^{-1}$). We detect clear changes in line strength with $R/R_e$: Whereas H$\beta$ decreases towards the center, the Fe, Mg and TiO lines all increase. In what follows, we present results based on TiO2$_{SDSS}$, and comment on TiO2 and TiO1 in the Appendix.

Figure 8. Line-index strength as a function of projected radius for the four bins defined in Table 2, estimated from our stacked spectra (symbols), and from the median of the measurements made on the spaxels themselves (solid lines). Dashed lines show the region which encloses 68% of the spaxels at each $R/R_e$.

Figure 9. Median observed (dashed) and emission-corrected (solid) H$\beta$ absorption line strength in our stacked spectra. We use the emission corrected lines throughout.

Before moving on, it is worth making three points. First, because bin B10 has similar $\sigma_0$ to bin B11, and similar $L_r$ to bin B00, it is curious that it has H$\beta$ and Mg$b$ more similar to bin B21 (see top panels of Figure 8). At least for H$\beta$, one might worry that something may be systematically wrong with our emission correction for this bin. To address this, Figure 9 shows the observed and emission corrected line strengths in our four bins (smoothed to 300 km s$^{-1}$). The correction does not appear to be systematically different for B10 than for the other bins: the correction for B10 is smaller than for B00 but larger than for B11 and B21. We conclude that the anomalously weak H$\beta$ for B10 is not an artifact.

Second, for Fe, we found we had to treat bin B11 slightly differently from the others. Whereas the peak of the distribution of Fe> 0 values measured in the spaxels is in good
agreement with the value we measure from our stack (so this is the value we use when plotting the yellow solid line), there are a large number of spaxels in which Fe ≃ 0. This number is large enough that the median is biased low if we include the Fe ≃ 0 values. We are not sure what causes this, but believe that the measurement from the stacked spectrum is more reliable. Third, while the agreement between the symbols and the solid lines is reassuring (for all bins and scales), even small differences matter quite a lot. E.g., as we will see below, even differences in Fe of 0.1 Å matter. In general, the discrepancies are larger in the outer regions, where the S/N of the individual spaxels is smaller, so we have more confidence in the values measured from the stacks.

3 COMPARISON WITH STELLAR POPULATION MODELS

In this section we use the Lick indices listed in Table 3 that we measured in our stacked spectra. As it is conventional, we work with

\[ \langle \text{Fe} \rangle \equiv \frac{(\text{Fe}5270 + \text{Fe}5335)}{2} \]

and

\[ [\text{MgFe}] \equiv \sqrt{\text{Mg}b - \langle \text{Fe} \rangle}. \]

We find clear differences between \( \sigma_0 \) and \( L_r \) bins, as well as strong gradients within each bin (Figure 8). Rather than studying these individually, we instead work with Lick-index pairs. This is because it has long been known that, for a fixed IMF, a plot of \( H_\beta - [\text{MgFe}] \) is a good age-metallicity indicator (Worthey 1994), whereas \( \langle \text{Fe} \rangle - [\text{MgFe}] \) is a diagnostic of the \( \alpha/\text{Fe} \) enhancement ratio (Trager et al. 1998).

3.1 Stellar population models

In what follows, we will use the MILES-Padova models with BiModal IMFs to interpret our measurements. The Appendix discusses why, and describes what happens if we use a number of alternatives: MILES-BaSTI, MILES-Padova with UniModal IMFs, as well as models from Tang & Worthey (2017) and Thomas et al. (2011).

The MILES models (Vazdekis et al. 2010) use the MILES stellar library to provide SSPs for the full optical spectral range (3540-7409 Å) at high resolution (FWHM=2.3 Å) for a wide range of ages, metallicities and IMFs. The model spectra are stored in air wavelengths. There are two sets of isochrones available: Padova00 (Girardi et al. 2000) and BaSTI (Pietrinferni et al. 2004, 2006). The Padova00 isochrones are given at base \([\alpha/\text{Fe}]\), while the BaSTI isochrones provide three different \([\alpha/\text{Fe}] = (\text{base}, \text{solar and } 0.4)\). Unfortunately, the BaSTI isochrones return unrealistic ages for our measurements (see Appendix), so in the following analysis we use the Padova00 isochrones.

The Padova00 isochrones also include the later stages of stellar evolution, using a simple synthetic prescription for incorporating the thermally pulsing AGB regime to the point of complete envelope ejection. The range of initial stellar masses extends from 0.15 to 7\( M_\odot \). We use the Lick indices provided by the webtool server\(^1\) at 300 km s\(^{-1}\) resolution. To account for \([\alpha/\text{Fe}]\), we derive an \( \alpha \)-enhancement correction from the BaSTI isochrones which we then apply to the Padova00 MILES models:

\[
I_{\text{Padova}}(\text{age}, Z, \text{IMF}, \alpha) = I_{\text{Padova}}(\text{age}, Z, \text{IMF}, \text{baseFe}) \times \frac{I_{\text{BaSTI}}(\text{age}, Z, \text{IMF}, \alpha)}{I_{\text{BaSTI}}(\text{age}, Z, \text{IMF}, \text{baseFe})}.
\]

This correction is small for \([\text{MgFe}]\) and the TiO-based indices since variation in the \( \alpha \)-enhancement has little effect on those indices.

The available IMFs for the MILES models used include the Unimodal and Bimodal shapes described in Vazdekis et al. (1996), the Kroupa-universal and revised- Kroupa (2001) and the Chabrier (2003) IMFs. The unimodal IMF is a power-law function characterized by its slope as a free parameter. The standard Salpeter (1955) IMF is obtained when the slope value is 1.3. On the other hand, the bimodal IMF is similar to the unimodal for stars with masses above 0.6\(M_\odot\), but decreasing the number of the stars with lower masses by means of a transition to a shallower slope. Its slope is the only free parameter (as in the unimodal case). The IMF slopes (\(\Gamma\)) range from 0.3 to 3.5. We use the range of \(\Gamma = [0.8-2.5]\) for the unimodal and \(\Gamma = [0.8-3.5]\) for the bimodal IMFs.

3.2 Age, metallicity and \([\alpha/\text{Fe}]\) given an IMF

The two panels in Figure 10 show the age-metallicity diagnostic plots. In this and following figures, the grids in age, metallicity and \( \alpha \)-enhancement are refined by interpolating the models. In short, for each index, we fix all the parameters (age, Z, IMF, \([\alpha/\text{Fe}]\)), except the one we want to refine, and then we interpolate the index value to the new sampling. We use spacing intervals of 1 Gyr for the age, 0.05 for \([\text{M/H}]\) and 0.1 for \([\alpha/\text{Fe}]\). To guide the eye, the two thick solid lines for each model show lines of fixed age (10 Gyr) and metallicity (solar).

In each panel, each of the four \( \sigma_0-L_r \) bins are represented by ten points: these show measurements of the index strength in bins of 0.1R/ from the center. There are clear well-defined radial gradients in the measured \( H_\beta, \langle \text{Fe} \rangle \) and \([\text{MgFe}]\) line strengths: the central regions have smaller \( H_\beta, \text{[MgFe]} \) and larger \( \langle \text{Fe} \rangle \). As we noted before, the trend with \( \sigma_0 \) and \( L_r \) is less clear. Whereas the blue, yellow and red samples, (B00, B11, and B21) which have successively larger \( \sigma_0 \) are also ordered in \( H_\beta \), the green symbols (B10) have substantially smaller \( H_\beta \). For now, we wish to use SSPs to interpret these gradients before turning to global trends with \( \sigma_0 \) and \( L_r \). The anomalous behavior of the green symbols (B10) is studied in more details in our companion paper (Paper II).

Each panel of Figure 10 also shows two different MILES-Padova SSP model grids having BiModal IMFs as labelled. For reference, the BiModal IMF with slope 1.3 is very similar to a Kroupa IMF. These grids show that, for a given IMF, the central regions are older, more metal-rich and enhanced, whatever the value of \( \sigma_0 \) and \( L_r \). The age estimates

\(^1\) http://www.iac.es/proyecto/miles/pages/webtools/tune-ssp-models.php
Figure 10. Hβ-[MgFe] and <Fe>-[MgFe] index diagrams. Symbols show measured gradients in line strength in each bin, and differences between bins. Dotted lines show age-metallicity grids for two SSP models, which have very different IMFs, to illustrate how such diagrams can be used to estimate IMF-dependent age, metallicity and enhancement factors. Both the data and the models have been smoothed to a common resolution of 300 km s$^{-1}$.

In the top panel, the grids depend very weakly on [$\alpha$/Fe]; we set [$\alpha$/Fe] = 0.25, which the bottom panel indicates is reasonable. Grids have spacing intervals of 1 Gyr, 0.05 and 0.1 for the age, [M/H] and [$\alpha$/Fe], respectively. To guide the eye, the two thick solid lines for each model show lines of fixed age (10 Gyrs) and metallicity (solar). IMF depend weakly on the IMF; the metallicity estimates less-so. Moreover, the relative age differences between bins depend even less on IMF.

We quantify this more precisely as follows. For each IMF, we find the triple of age, metallicity and [$\alpha$/Fe] which best describes the measured Hβ, [MgFe] and <Fe> line strengths. Here ‘best’ means that we minimize a distance between measured and predicted index strengths. Whereas the usual procedure (e.g. La Barbera et al. 2013; Martin-Navarro et al. 2015) normalizes each separations by the associated measurement error for the index, this is not quite appropriate. E.g., if models span a large range of values in one index and only a small range in another, then the best-fit distance would be determined by the index with the largest range of values. We account for this by first normalizing distances by the typical range spanned by models – fortunately, in practice, this does not vary strongly between indices (except for the TiO1 and TiO2 indices). Strictly speaking, because we have sampled the models on a grid, this procedure has merely found the nearest triple to our measurements: we then search for the other seven models which define the cube that encloses our measurements, and use (tri-)linear interpolation from these values to determine the age, metallicity and [$\alpha$/Fe] values which we use below.

3.3 Allowing IMF variations

To address the question of whether, in addition to age, metallicity or [$\alpha$/Fe] gradients within a galaxy, there are IMF gradients as well, we turn to the TiO2$_{SDSS}$-[MgFe] index. Recent work (La Barbera et al. 2013, 2016; Martin-Navarro et al. 2015; Tang & Worthey 2017) has shown that, with some care, TiO2$_{SDSS}$-[MgFe] can be used as an IMF diagnostic. (We discuss other TiO-related indices in the Appendix.) Figure 11 illustrates our methodology. As in the previous figures, symbols show our measurements and dotted lines show SSP age-metallicity grids for [$\alpha$/Fe]=0.25 and a wide range of IMF slopes, to illustrate how this diagram can be used to discriminate between IMFs.

Figure 11. TiO2$_{SDSS}$-[MgFe] index diagram, showing gradients in line strength in each bin, and differences between bins. Dotted lines show age-metallicity grids for [$\alpha$/Fe]=0.25 and a range of IMF slopes, to illustrate how this diagram can be used to discriminate between IMFs.
**ASSUMPTION 1** Same IMF for all galaxies; no gradients
**ASSUMPTION 2** IMF can vary with $\sigma$ and $L_r$; no gradients
**ASSUMPTION 3** Variable IMF + gradients; $[\text{Ti/Fe}] = [\alpha/\text{Fe}]$
**ASSUMPTION 4** Variable IMF + gradients; $[\text{Ti/Fe}] = 0$

| ASSUMPTION | RANGENOTE |
|------------|-----------|
| 1          | Same IMF for all galaxies; no gradients |
| 2          | IMF can vary with $\sigma$ and $L_r$; no gradients |
| 3          | Variable IMF + gradients; $[\text{Ti/Fe}] = [\alpha/\text{Fe}]$ |
| 4          | Variable IMF + gradients; $[\text{Ti/Fe}] = 0$ |

Table 4. List of assumptions about $[\text{Ti/Fe}]$ and IMF variations.

In principle, for each IMF-dependent triple, the associated SSP model predicts the TiO$_2$SDSS line strength, and hence a position on the TiO$_2$SDSS-[MgFe] diagram, which can be compared with that observed. For example, Figure 10 indicates that, for the largest $\sigma$ bin (red symbols) the smallest $R$ (smallest H$_\beta$) has an age of about 10 Gyrs and [M/H]=-0.15 if the IMF has slope 2.8, but age 12 Gyrs and [M/H]=0.1 if the IMF has slope 1.3. Figure 11 shows that this point, which has the largest measured TiO$_2$SDSS of all the red symbols, lies very far above the IMF-1.3 grid, and quite far above the IMF-2.8 grid as well. Evidently, an even more extreme IMF is preferred, although matching the age and metallicity well will be non-trivial.

### 3.4 The $[\text{Ti/Fe}]$ enhancement

It is well-known that the $[\alpha/\text{Fe}]$ abundance ratio in Es can be enhanced relative to solar, and this constrains the timescale of star formation (Thomas et al. 2005). Other elements such as Na, Ca, Ti are produced in a variety of processes at different times as a galaxy evolves, including AGB star winds, Type Ia and Type II supernovae, and can therefore be used to further constrain the physics of galaxy formation and evolution. In particular, just as $[\alpha/\text{Fe}]$ may be different from solar, so too can these other elements. In particular, the TiO elements are sensitive to the abundance of low-mass stars, so are indicators of the IMF slope. However, the predicted line strengths depend on the underlying [Ti/Fe] enhancement: the model grids shown in Figure 11 assume $[\text{Ti/Fe}] = 0$.

Fortunately, changing [Ti/Fe] makes no significant difference to the H$_\beta$-[MgFe] and <Fe>-[MgFe] grids shown before. However, it does affect the predicted TiO$_2$SDSS. Following La Barbera et al. (2013) we calibrate this as follows. Conroy & van Dokkum (2012) provide spectra for models having a Chabrier IMF, solar metallicity, and an age of 13.5 Gyr, for three choices of $[\text{Ti/Fe}] = (-0.3, 0, +0.3)$. We smooth these to our resolution ($300 \text{ km s}^{-1}$) and then measure the TiO-related indices given in Table 3. (The other lines, e.g., [MgFe], are essentially unchanged.) For each index, e.g., TiO$_2$SDSS, we measure two slopes: one describes how the index strength changes as [Ti/Fe] increases from 0 to 0.3, and the other how it changes as [Ti/Fe] decreases from 0 to −0.3. We use these linear fits to extrapolate beyond 0.3 or −0.3 if necessary in what follows. Because [MgFe] does not depend on [Ti/Fe], in effect, changing [Ti/Fe] shifts the model grids vertically in Figure 11. Since changing the IMF also shifts the model grids (primarily) vertically, and the intrinsic value of [Ti/Fe] is unknown, there is, potentially, a strong degeneracy between the IMF and [Ti/Fe]. Therefore, we have explored a few alternative, extreme procedures.

First, suppose we assume that all galaxies do indeed have $[\text{Ti/Fe}] = 0$ (see Table 4 and right-hand panel in Figure 12; we refer to this as ASSUMPTION 4). Then Figure 11 implies large IMF gradients within a galaxy, as well as large IMF changes across the population (largest $\sigma$ will have largest IMF slopes). If instead, we assume all galaxies have the same IMF (left-hand panel in Figure 12; hereafter ASSUMPTION 1), then the strong radial gradient in TiO$_2$SDSS shown by our measurements must be attributed to large gradients in [Ti/Fe] since each IMF grid (for a fixed [Ti/Fe] abundance) only spans a narrow range of TiO$_2$SDSS values. These gradients are shown in the left-hand panel of Figure 12, where we set the IMF slope to 2.3 (as Figure 11 suggests this grid lies in the middle of our data). This is unsatisfactory because it is known that $[\alpha/\text{Fe}]$ does not show extreme gradients within a galaxy or trends across the population (e.g. with $\sigma$, e.g. Martín-Navarro et al. 2018; Parikh et al. 2018, 2019), so it is not obvious why [Ti/Fe] would.

A milder version of this allows a different IMF for each ($L$, $\sigma$) pair (hereafter ASSUMPTION 2). In this case, we require that [Ti/Fe] spans a similar range across all bins. The changing symbols in the second panel from the left of
Figure 13. Inferred IMF gradients in our four bins allowing a variable IMF and assuming [Ti/Fe]=[α/Fe] (left) or [Ti/Fe]=0 (right). Different symbols represent different IMFs as in Figure 12, but the actual value of IMF slope shown is got by interpolating between the two best-fitting IMF models.

Figure 12 indicate that, as a result, the IMF differs in each bin. We use the symbol to indicate the model with the closest IMF (for bins B00, B10, B11 and B21 this slope is 1.5, 2.0, 2.3 and 2.5). In order to span a similar range of [Ti/Fe], the IMF (for bins B00, B10, B11 and B21 this slope is 1.5, 2.0, 2.3 and 2.5). In order to span a similar range of [Ti/Fe], the IMF slope must increase as $\sigma_0$ increases: The blue and green bins have the same $L_r$, but different $\sigma_0$; they have different IMFs. This is also true of the yellow and red bins. (On the other hand, although the green and yellow bins have the same $\sigma_0$, they have different IMFs.) The increase of IMF slope with $\sigma_0$ is in qualitative agreement with many other recent studies (e.g. La Barbera et al. 2013; Martín-Navarro et al. 2015). (Recall that a Kroupa IMF corresponds to slope 1.3.) However, even in this case, the implied radial gradients in [Ti/Fe] are still rather large.

If we assume that [Ti/Fe] scales as [α/Fe] (e.g. Parikh et al. 2019; hereafter ASSUMPTION 3) then IMF gradients are required to explain much of the observed TiO2SDSS line-strengths. The second panel from the right of Figure 12 shows the inferred [Ti/Fe] is much weaker than for the other two choices, and the fact that multiple symbols are needed for each $\sigma_0$, $L_r$ bin indicates that the IMF changes with radius.

Figure 13 shows the change in the IMF slope associated with this case (ASSUMPTION 3) and if we had simply set [Ti/Fe]=0 (ASSUMPTION 4). We use a different symbol for each IMF, as in the previous figure. However, the IMF slope we show is got from interpolating between the two closest-fitting IMF models. The IMF is, on average, more bottom heavy for large $\sigma_0$ or $L_r$, and it is more bottom heavy in the central regions. It is interesting to compare this figure with Figure 5 in Martín-Navarro et al. (2015). We are in agreement with their [Ti/Fe]-corrected analysis showing that BiModal IMF slopes are Kroupa like at $1R_e$, but steeper in the central regions. However, they find central slopes of $\sim 3$ which are slightly larger than our value of 2.5. (Their analysis is based on two galaxies whose velocity dispersion profiles are similar to the largest $\sigma_0$ bin in our sample.)

3.5 Age, metallicity and [α/Fe] gradients

We turn now to galaxy ages, metallicities, [α/Fe] and $M_*/L_r$ values, paying particular attention to the robustness of our conclusions with respect to changes in the assumed [Ti/Fe]. Figure 14 shows the age, metallicity, [α/Fe] and $M_*/L_r$ gradients associated with these scenarios. There are clear trends for age, metallicity and [α/Fe] to increase with $\sigma_0$ across the population (bin B10 is peculiar, as we discuss shortly). Whereas metallicity increases strongly towards the central regions in all four bins, this is less true for age: moreover, ASSUMPTIONS 3 and 4, which allow for IMF gradients, show weaker age gradients (especially for bins B10 and B21). Indeed, for Bin B21 (red symbols) there is almost a degeneracy between age and IMF, with the central regions (largest $\sigma$ values) preferring younger ages but more bottom-heavy IMFs.

In general, gradients in [α/Fe] are weak, with a tendency to increase towards the outer regions. This is consistent with previous work (e.g. Vaughan et al. 2018). However, we find that this trend depends on the models used: [α/Fe] increases towards the center when using the TMJ models (see Appendix A2).

Perhaps the most striking point is the anomalous behavior of the green symbols (B10). While age and metallicity tend to increase as $\sigma_0$ increases (from B00 to B11 to B21) the galaxies in bin B10 (green symbols) are the oldest, even though they are neither the most luminous, nor the ones with the largest $\sigma_0$. They also have [α/Fe] similar to B21 (red symbols) and enhanced relative to B11 (yellow), even though their $\sigma_0$ is the same as B11. These results are clearly visible in all panels, whatever we assume about [Ti/Fe]. Note that, because we were careful to restrict the sample to $z \leq 0.08$, this age difference is not a consequence of lookback time differences between the B10 and the other samples. These anomalies are discussed in more detail in our companion paper (Paper II).

3.6 $M_*/L_r$ gradients with varying IMF

Finally, we turn to the question of $M_*/L_r$ gradients. ASSUMPTIONS 1 and 2, in which there are no IMF gradients, show weaker age gradients (especially for bins B10 and B21). Indeed, for Bin B21 (red symbols) there is almost a degeneracy between age and IMF, with the central regions (largest $\sigma$ values) preferring younger ages but more bottom-heavy IMFs. In general, gradients in [α/Fe] are weak, with a tendency to increase towards the outer regions. This is consistent with previous work (e.g. Vaughan et al. 2018). However, we find that this trend depends on the models used: [α/Fe] increases towards the center when using the TMJ models (see Appendix A2).

Perhaps the most striking point is the anomalous behavior of the green symbols (B10). While age and metallicity tend to increase as $\sigma_0$ increases (from B00 to B11 to B21) the galaxies in bin B10 (green symbols) are the oldest, even though they are neither the most luminous, nor the ones with the largest $\sigma_0$. They also have [α/Fe] similar to B21 (red symbols) and enhanced relative to B11 (yellow), even though their $\sigma_0$ is the same as B11. These results are clearly visible in all panels, whatever we assume about [Ti/Fe]. Note that, because we were careful to restrict the sample to $z \leq 0.08$, this age difference is not a consequence of lookback time differences between the B10 and the other samples. These anomalies are discussed in more detail in our companion paper (Paper II).
Figure 14. Inferred age, metallicity, $[\alpha/\text{Fe}]$ and $M_*/L_r$ gradients in our $\sigma_0$ and $L_r$ bins associated with our four assumptions regarding $[\text{Ti/Fe}]$: that all galaxies have the same IMF (BiModal with slope 2.3 on all scales (left)); that all galaxies in a bin have the same IMF on all scales, but this IMF may change from one bin to another (second from left); allowing a variable IMF and assuming $[\text{Ti/Fe}] = [\alpha/\text{Fe}]$ (second from right); allowing a variable IMF and assuming that $[\text{Ti/Fe}]=0$ for all galaxies (right). Legend in the top left panel shows which symbol represents each IMF.

(i.e. we estimated ages, metallicities, $[\alpha/\text{Fe}]$ using ASSUMPTION 1 with IMF fixed to Salpeter). Note that in this case, the $M_*/L_r$ of bin B10 is more similar to that of bin B21 in contrast with the results of Figure 15. The right panel shows the result of repeating the analysis, but with the IMF fixed to Kroupa, and then dividing the $M_*/L_r$ which is returned by that for Salpeter (shown in the left hand panel). This ratio is about 0.7 for all bins and scales, indicating that the $M_*/L_r$ gradient for Kroupa is just like that for Salpeter – only the overall normalization is smaller.

Figure 17 shows the ratio of the $M_*/L_r$ values in the bottom right panels of Figure 15 (i.e. ASSUMPTION 3) to that shown in the left panel of Figure 16 (i.e. fixed Salpeter IMF) versus radius (left panel) and metallicity (right panel). This ratio is scale-dependent for the ellipticals with the largest $L_r$ and $\sigma_0$ in the central regions the $M_*/L_r$ estimate from our ASSUMPTION 3 is similar (or slightly higher) than that inferred by using a Salpeter IMF, decreasing to a Kroupa-like value by $\sim 0.8 R/R_e$. On the other hand, for lower $L_r$ and $\sigma_0$ ellipticals, $M_*/L_r$ of the central regions is similar to the outskirts and consistent with the value inferred if one uses a Kroupa IMF. It is worth noting that the Kroupa value is a reasonable approximation to $M_*/L_r$ at $0.8 R/R_e$ for all our bins (except B10), despite the fact that the IMF itself is not the same in all our bins (Figure 13).

The right hand panel of Figure 16 shows that this ratio is tightly correlated with metallicity, and varies only weakly across the population. This agrees with previous work: E.g. Martín-Navarro et al. (2015) argue that the IMF slope is approximately equal to $2.2+3[M/H]$ for the BiModal models we are using here. However, as we discuss in Appendix A, the precise scaling with $[M/H]$ is model dependent.
Figure 15. Inferred age, metallicity, [α/Fe] and $M_*/L_r$ gradients versus galactocentric distance in our $\sigma_0$ and $L_r$ bins associated with ASSUMPTION 2 (left) and ASSUMPTION 3 (right) regarding [Ti/Fe] (see text for details).

Figure 16. Left: $M_*/L_r$ if the IMF is fixed to Salpeter on all scales for all galaxies. Right: Ratio of $M_*/L_r$ to that for Salpeter, if the IMF is fixed to Kroupa for all scales for all galaxies.

4 EFFECT OF GRADIENTS ON STELLAR POPULATION AND DYNAMICAL MASS ESTIMATES

The $M_*/L_r$ gradients shown in the previous section are considerably smaller than those quoted by van Dokkum et al. (2017). Nevertheless, the analysis in Bernardi et al. (2018b) suggests that they are just large enough to matter for dynamical (Jeans-equation based) estimates of the stellar mass. Therefore, we now check if gradients are necessary to reconcile stellar population and dynamical mass estimates.

We define the stellar mass of a galaxy as the sum over its circularized surface brightness profile weighted by the $M_*/L_r$ profile corresponding to its bin in $L_r$ and $\sigma_0$ (see, e.g., bottom panels of Figure 15):

$$M_* \equiv 2\pi \sum_i \Delta R_i R_i I(R_i) (M_*/L_r)_i.$$  \hspace{1cm} (3)

As a result, the $M_*/L_r$ estimate depends on what we assumed about the IMF. Since our $M_*/L_r$ estimates only extend to about $R_e$ or so, and Figure 16 suggests that the Kroupa value is a reasonable approximation at 0.8 $R/R_e$ for all our bins except B10, we simply assume this remains true beyond $R_e$, and set $M_*/L_r$ to be that for Kroupa at large $R$.

To begin, we first check that our integrated $M_*/L_r$ estimates are consistent with previous work (comparing integrated $M_*/L_r$ rather than $M_*$ estimates themselves removes systematics associated with the total luminosity $L_r$, see Bernardi et al. 2013, 2017a,b; Fischer et al. 2017). Mendel et al. (2014) provide $M_*$ and $L_r$, and hence $M_*/L_r$ estimates for these galaxies which are based on the assumption that the IMF is Chabrier across the population and that there are no gradients. The closest IMF in our study is Kroupa, and it is well-known that $M_*/L_r$ from Chabrier differs from that

Figure 17. Ratio of $M_*/L_r$ shown in the bottom panels of Figure 15 to that for Salpeter (left panel of Figure 16) as a function of radius (left) and metallicity (right).

Figure 18. Comparison of integrated $M_*/L_r$ estimates. Left hand panel shows the values from Mendel et al. (2014) (shifted by 0.05 since Chabrier IMF based values differ from those from Kroupa IMF by 0.05 dex). Right hand panel shows the ratio of estimates from ASSUMPTION 1 (same IMF for all galaxies; lower and upper set of symbols show results for fixed Kroupa and Salpeter IMFs) to ASSUMPTION 3 (IMF varies within a galaxy and across the population).
for Kroupa by 0.05 dex (e.g. Bernardi et al. 2010). Therefore, the left hand panel of Figure 18 shows the ratio of the Mendel estimates, shifted by this amount, to our ASSUMPTION 1 Kroupa estimates. For ease of comparison with the results which follow, we show (the log of) this ratio as a function of $M_\star$ estimate returned by using the $M_\star/L_\star$ profiles of ASSUMPTION 3 (in which the IMF varies within a galaxy and across the population). The agreement with Mendel et al. (2014) is rather good considering that our estimate for each galaxy is obtained by using the average $M_\star/L_\star$ profile for its bin (this contributes to some of the scatter in Figure 18).

Having established consistency with the literature, the right hand panel compares our ASSUMPTION 1 estimates for two different IMF choices – Kroupa and Salpeter – with those from our ASSUMPTION 3. If gradients did not matter, then the symbols would lie along the dashed lines shown. The larger $L_\star$ bins (orange and red) are clearly offset below: for these more massive objects, gradients act to slightly increase the estimated stellar mass. The effect is small because gradients are mainly present in the inner regions which contribute less than half the mass.

Gradients are expected to affect dynamical mass estimates more dramatically (Bernardi et al. 2018b). On dimensional grounds $M_{\text{dyn}} \propto R_\star \sigma^2/G$, so the estimate depends on the scale on which $\sigma$ is measured and the constant of proportionality. In what follows, we use the central value $\sigma_0$ which is typically about 12% larger than $\sigma_e$, the value averaged within the projected radius $R_e$ (e.g. Figure 7), and we explore three choices for the proportionality factor. Since this factor depends on the Sersic profile, here we show galaxies with $\text{FLAG\_FIT}=1$ ($\sim 64\%$ of our E sample), i.e. whose photometry is better described by a single Sersic profile (see Fischer et al. 2019 for details). Finally, it is conventional (Cappellari et al. 2013b; Li et al. 2017) to show the ratio $M_{\text{dyn}}/M_\star$ as a function of $\sigma_e$. In what follows, we always use $M_\star$ from ASSUMPTION 3; i.e., our $M_\star$ values include the effects of gradients.

In the left hand panel of Figure 19 we set $M_{\text{dyn}} = 4R_\star \sigma^2_e/G \approx 5R_\star \sigma^2_e/G$ (e.g. McDermid et al. 2015). Notice that, on average $\log_{10}(M_{\text{dyn}}/M_\star) \approx 0.2$ dex. Comparison with Figure 18 suggests that, $M_{\text{dyn}}$ would approximately equal $M_\star$ if the IMF were Salpeter. The dashed line shows that, in fact, $M_{\text{dyn}}/M_\star$ is not constant, but increases with $\sigma_e$. For comparison, the dot-dashed line shows the $M_{\text{dyn}}/M_\star-\sigma_e$ scaling determined by Li et al. (2017) (which ignored the effects of IMF gradients), shifted slightly to crudely account for the fact that, for their default IMF (Salpeter) $\Delta \sim 0.14$ in Figure 18. The dashed lines is shifted upwards by $\sim 0.1$ dex compared to the dot-dashed line.

The middle panel sets $M_{\text{dyn}} = k(n,R) R_\star \sigma^2_e/G$, with $k(n, R)$ given by Table 1 of Bernardi et al. (2018a), where $n$ is the Sersic index of a single-component fit to the light profile and $R = 0.1R_\star$. This $M_{\text{dyn}}$ estimate accounts for the fact that galaxies have different light profiles, but assumes that $M_\star/L_\star$ is constant. It further assumes that velocity dispersions are isotropic and the mass on sufficiently small scales is dominated by stellar rather than dark matter, and therefore normalizes the resulting Jeans-equation estimate to match the observed $\sigma_0$. (Thus, $M_{\text{dyn}}$ for each galaxy uses its $R_\star$, $\sigma_0$, and light profile.) These $M_{\text{dyn}}$ values also are about 0.2 dex larger than our ASSUMPTION 3 based stellar mass estimates, and the scaling with $\sigma_e$ is still present. In this case the $M_{\text{dyn}}/M_\star-\sigma_e$ correlation is in good agreement with Li et al. (2017). This establishes consistency between ours and previous work, which has driven many to conclude that the IMF is Salpeter, or even super-Salpeter, at large $\sigma_e$ (e.g. Cappellari et al. 2013b; Li et al. 2017). I.e., previous work argues that the discrepancy between the ATLAS$^{3D}$ $M_{\text{dyn}}$ estimator and $M_\star$ (based on a fixed IMF) is removed by increasing $M_\star$ (i.e., by changing the default IMF choice in a $\sigma_e$-dependent way). However, as we noted in the context of Figure 16, our analysis suggests that Salpeter-like bottom-heavy IMFs are only really seen in the central regions, so it is not obvious that this reconciliation of $M_{\text{dyn}}$ and $M_\star$ is self-consistent.

Of course, this comparison is unfair since ASSUMPTION 3 indicates that $M_\star/L_\star$ gradients are present, espe-
entially in the more massive galaxies. For these galaxies, the IMF may be Salpeter-like in the central regions, but (except for bin B10) it is more Kroupa-like at $R_e$ (and, we assume, beyond). The right hand panel shows the result of including the $M_*/L_e$ gradients shown in Figure 15— and otherwise following the same methodology which was used for the middle panel— when estimating $M_{\text{dyn}}$ (see Bernardi et al. 2018b). In this case, $M_{\text{dyn}}$ for each galaxy uses its own $R_e$, $\sigma_0$, and light profile shape, but all galaxies in a bin have the same $M_*/L_e$ profile (c.f. Figure 15). Comparison with the other two panels shows that accounting for $M_*/L_e$ gradients reduces the $M_{\text{dyn}}$ estimate by $\sim 0.2 \text{ dex}$ and brings it into good agreement with the stellar population based $M_e$. Moreover, the correlation with $\sigma$ is removed (dashed line is much flatter). Thus, our analysis, which accounts self-consistently for the same gradients when estimating both $M_e$ and $M_{\text{dyn}}$, brings the two into agreement by reducing $M_{\text{dyn}}$ significantly and increasing $M_e$ slightly, rather than from increasing $M_e$ and leaving $M_{\text{dyn}}$ unchanged. This is a different resolution of the $M_*/M_{\text{dyn}}$ discrepancy than has been followed in the recent literature.

We end this section with two words of caution. First, the IMF and $M_*/L_e$ values we derive are light- rather than mass-weighted estimates. Second, they are strongly dependent on the SSP models used. While our general age and metallicity trends are quite robust regardless of the model (even for the peculiar bin B10), the IMF and $M_*/L_e$ values obtained using (our extension of) the TMJ models are significantly larger than those shown here (see Appendix A for a more detailed comparison, and Figures A5 and A6 in particular). This raises the question of whether it is possible to constrain the absolute value of $M_e/L_e$. This may be possible because the larger (IMF and) $M_*/L_e$ values associated with the TMJ models imply larger $M_e$ values. This would not be problematic were it not for the fact that these models also produce strong gradients (Figure A6), the effect of which is to decrease the associated $M_{\text{dyn}}$. As a result, they have $M_e > M_{\text{dyn}}$, which is unreasonable. Thus, it may be that requiring $M_e \approx M_{\text{dyn}}$ provides a useful constraint on single stellar population models.

5 CONCLUSIONS

We measured a number of Lick indices (Table 3) using stacked spectra of $\sim 300$ MaNGA elliptical galaxies at $z \leq 0.08$ (Figures 5). Each stack covers a narrow range in $\sigma_0$ and $L_e$ (Figure 1 and Table 2). In each bin, we found significant radial gradients in the line strengths (Figure 8). We used SSP models to interpret the differences between bins, and the radial gradients within each bin (Figures 10 and 11).

- Age, metallicity and $[\alpha/\text{Fe}]$ generally increase with $\sigma_0$ (and $L_e$). However, galaxies with $\sigma_0$ between about 200 – 250 km s$^{-1}$ and $M_e$ between $\sim 21.5$ and $\sim 22.5$ (approximately $5 \times 10^{10} M_\odot$) tend to be anomalously old, metal poor and $[\alpha/\text{Fe}]$-enhanced (Figure 14). We discuss a plausible explanation for this in our companion paper (Paper II).

- Within a bin, galaxies are older and more metal rich towards the center. Whether or not they are more $[\alpha/\text{Fe}]$-enhanced towards the center is model-dependent: MILES-based models have much weaker gradients than TMJ (compare Figures 15 and A6). These conclusions are qualitatively unchanged if we assume all galaxies have the same IMF, or if the IMF can vary across the population but is fixed within a galaxy (i.e. there are no IMF gradients), or if we allow IMF gradients (Figure 14). However, age gradients are weaker if we allow IMF gradients. In addition, the inferred $[\text{Ti}/\text{Fe}]$ depends significantly on these assumptions (Figure 12).

- If IMF variations are required (because $[\text{Ti}/\text{Fe}]$ variations are limited), the data indicate that the IMF is increasingly bottom-heavy (has a steeper slope) than the often-used Kroupa IMF towards the central regions (Figure 13) and tends to be more bottom-heavy for the largest $L_e$ and $\sigma_0$ galaxies.

- It is important to fit for all stellar population properties, including the IMF, when determining $M_*/L_e$. The $M_*/L_e$ ratio, and its dependence on distance from the center, is sensitive to IMF variations and other population gradients. Analyses which do not allow IMF-gradients imply a $\sim 30\%$ increase in $M_*/L_e$ from $R_e$ to the central regions (Figures 15 and 16), and suggest that $M_*/L_e$ is the same function of $\sigma$ within a galaxy as it is of $\sigma_0$ across the population (Figures 14). If IMF-gradients are allowed, then this difference can be as large as a factor of 2, and the scaling with $\sigma$ within a galaxy differs from that across the population (Figures 14 and 15). We find a factor of $\sim 2$ decrease from the central regions to $R_e$ for the largest $L_e$ and $\sigma_0$ galaxies. However, at lower $L_e$ and $\sigma_0$, the IMF is shallower and the $M_*/L_e$ of central regions is similar to the outskirts (Figures 15 and 17).

- Although the $M_*/L_e$ gradients we find are weaker than some recent estimates, they are strong enough to impact Jeans-equation analyses of the dynamical mass of elliptical galaxies. Ignoring gradients makes $M_{\text{dyn}}$ about $0.2 \text{ dex}$ larger than the stellar population estimate of the stellar mass (Figure 18). Accounting self-consistently for these gradients when estimating both $M_e$ and $M_{\text{dyn}}$ brings the two into good agreement (Figure 19): gradients reduce $M_{\text{dyn}}$ by $\sim 0.2 \text{ dex}$ while only slightly increasing the $M_e$ inferred using a Kroupa IMF. This is a different resolution of the $M_*/M_{\text{dyn}}$ discrepancy that has been followed in the recent literature where $M_e$ is increased while leaving $M_{\text{dyn}}$ unchanged. In addition, requiring $M_e \leq M_{\text{dyn}}$ provides a useful constraint on single stellar population models.

As Bernardi et al. (2018b) note, our resolution of the $M_*/M_{\text{dyn}}$ discrepancy affects estimates of the stellar mass density: the larger values implied by previous $M_{\text{dyn}}$ analyses will result in overestimates. Now that we have better determined how $M_*/L$ gradients vary over the population, it would be interesting to revisit Jeans equation analyses with these more realistic gradients to constrain the dark matter content and anisotropic velocity dispersions in elliptical galaxies (e.g. Chae et al. 2018, 2019).

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APPENDIX A: OTHER SSPS AND IMF-INDICATORS

The main text presented results based on the MILES-Padova SSPs with a wide range of IMFs (what they call BiModal), and used TiO2SSS as the primary IMF-diagnostic. Here

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w show what is possible with other SSPs, and other TiO indicators.

A1 Other SSPs
Figure A1 shows the $H_{\alpha}$-[MgFe] grids associated with the MILES-BaSTI as opposed to the MILES-Padova models. These grids assign ages in excess of 15 Gyr to the oldest galaxies in our sample. This is unreasonable, and is why we work with the MILES-Padova models in the main text.

Figure A2 compares the MILES-Padova UniModal, Tang & Worthey (2017) and Thomas et al. (2011) models (TW and TMJ hereafter), all for $[\alpha/Fe]=0$. Although it is known that $[\alpha/Fe] \neq 0$, for TW only $[\alpha/Fe]=0$ grids are currently available. Fortunately, changing $[\alpha/Fe]$ does not make a dramatic difference for the ages and metallicities. The MILES and TW grids are for the same two IMFs: the top-center panel shows that the TW grids imply subsolar metallicities for all but the center-most parts of all four bins. The bottom left panel shows that the MILES Uni-modal grids cover our measurements; the only reason we used the BiModal grids in the main text is that the BiModal grids provide more closely spaced IMFs. The bottom-center panel shows that the TW grids just barely cover our measurements; unfortunately, only $[\alpha/Fe]=0$ is available for these models, but we know that $[\alpha/Fe]=0$ is not realistic. This is why we have not used these models further. Note, in addition, that these TiO2SDSS-[MgFe] grids slope up and to the right; this is qualitatively different from the MILES models.

The TMJ models are available only for two IMFs: Kroupa and Salpeter. Comparison of the top right panel of Figure A2 with Figure 10 shows that the TMJ models return older ages and higher metallicities (we show shortly that they also return higher $[\alpha/Fe]$). Nevertheless, the relative differences between the $(\sigma_0, L_{r})$ bins is similar. In particular, galaxies in the intermediate $\sigma_0$ but small $L_{r}$ bin (green symbols) are found to be older than those in the two bins having higher-$L_{r}$ (yellow and red symbols).

The bottom panel shows TiO2SDSS-[MgFe]. Here, both TMJ model grids lie so far from the measurements that it is difficult to justify using the TMJ models without somehow incorporating additional IMFs. If these TMJ-Kroupa grids agreed with the MILES-BiModal-1.3 grids shown in the main text, then there would be some justification for assuming that the MILES-based results are likely to be unbiased. Unfortunately, this is not the case: even though the Kroupa and MILES-BiModal-1.3 IMFs are the same, the TMJ-Kroupa and MILES-BiModal-1.3 model grids differ. Not only are they offset in TiO2SDSS strength, but the response of TiO2SDSS strength to changes in age and metallicity is weaker for TMJ: as a result, each TMJ grid spans a narrower range of TiO2SDSS values.

For completeness, Figure A3 shows some of the results obtained using the MILES-Padova UniModal (instead of BiModal) models: (left) the IMF slope gradients inferred by using a variable IMF (i.e. ASSUMPTION 3); (middle) the corresponding $M_*/L_{r}$ gradients; (right) the ratio of $M_{e}/L_{r}$ to that for Salpeter. The inferred properties are similar to those obtained from the BiModal models except that the $M_{e}/L_{r}$ tend to be higher (compare with Figures 15 and 17). At $R/R_{e}=0.8$, the IMFs are all shallower than Salpeter (left) but the $M_{e}/L_{r}$ values are not very different from Salpeter (right). In addition, at $R/R_{e} \sim 0.4$ the IMFs in the two low-$L$ bins (blue and green) are different from the two at higher-$L$ (yellow and red), but the $M_{e}/L_{r}$ values are similar. Clearly, gradients in IMF slope alone are not good indicators of $M_{e}/L_{r}$ gradients.

A2 MILES-extended TMJ models
In an attempt to extend the reach of the TMJ models, we have transferred the MILES IMF grids to TMJ as follows. We find the offsets of each MILES grid point from its respective MILES-BiModal-1.3 point and apply these to the TMJ-Kroupa point. We then scale the range covered by each grid by the same factor by which MILES and TMJ differ for Kroupa. The two panels in Figure A4 show the result, but we caution that because this procedure is not fully self-consistent, the results which follow are suggestive only. This is why they are not in the main text. Comparison with right-hand panels of Figure A2 shows that now the extended-TMJ models completely cover the $H_{\alpha}$-[MgFe] and TiO2SDSS-[MgFe] measurements. From these we can infer age, metallicity, $[\alpha/Fe]$ and IMF-gradients (although we have used the various assumptions listed in Table 4 about how $[Ti/Fe]$ varies across the population, here we show the results from ASSUMPTION 3), and finally, $M_{e}/L_{r}$ gradients, shown in Figures A5–A6. (Of course, the $M_{e}/L_{r}$ values actually come from MILES, but, at least for the Kroupa and Salpeter IMFs, they are similar to TMJ.)

The biggest qualitative difference with respect to the MILES models is $[\alpha/Fe]$: Here the gradients are much stronger; $[\alpha/Fe]$ correlates tightly with $\sigma$, both within a galaxy and across the population. In addition, the inferred ages are younger, and the $M_{e}/L_{r}$ values and IMF slopes are significantly larger than the MILES-based ones presented in the main text. As we note in the main text, the larger $M_{e}/L_{r}$ values would not be problematic if these models did not produce strong gradients (Figure A6), the effect of which is to decrease the associated $M_{\text{dyn}}$. As a result, they have
Figure A2. Same as Figures 10 and 11 but for the MILES-Padova UniModal models (left), the TW models (middle) with the same IMFs, and the TMJ models (right).

Figure A3. Left: IMF slope gradients (similar to left panel of Figure 13) inferred by using a variable IMF (ASSUMPTION 3) but using the MILES-Padova UniModal (instead of BiModal) models. Middle: Corresponding $M_\star/L_r$ gradients (similar to bottom right panel of Figure 15). Right: Ratio of $M_\star/L_r$ inferred by using a variable IMF to that for Salpeter (similar to left panel of Figure 17).

$M_\star > M_{dyn}$, which is unreasonable. This is another reason why we did not present these extended-TMJ models in the main text.

A3 Other TiO indicators

The main text used TiO$_2$$_{SDSS}$ (defined in La Barbera et al. 2013) as an IMF indicator. This is a modified version of the TiO$_2$ index of Trager et al. (1998), in which the red sideband is re-defined to minimize deviation between the models and data (see Appendix A of La Barbera et al. 2013 for a more detailed discussion). Although recent IMF studies focus on TiO$_2$$_{SDSS}$ instead of TiO2 (e.g., Martín-Navarro et al. 2015; Tang & Worthey 2017), we have repeated all the analyses in the main text using TiO2 and TiO1 as well. As for TiO$_2$$_{SDSS}$, it is necessary to calibrate the response of these indices to the [Ti/Fe] enhancement.

TiO2: The TiO2 analysis returns higher [Ti/Fe] and higher IMF slopes (left panel in Figure A7), which translate into larger $M_\star/L_r$ values (middle and left panels in Figure A7), with overall slightly larger $M_\star/L_r$ gradients.

TiO1: The TiO1-based analysis is more complicated. Figure A8 shows the TiO1-[MgFe] grids for the same MILES-Padova models shown in the main text, for the TW models,
Figure A4. Lick-index diagnostic diagrams with TMJ-model grids obtained by extending TMJ-Kroupa to other BiModal IMFs using the MILES-Padova BiModal IMF models presented in the main text.

Figure A5. Inferred gradients of the IMF slope (left panel) and the ratio of $M_*/L_r$ to that for Salpeter (right panel) for our four bins assuming [Ti/Fe]=[$\alpha$/Fe] but using the MILES-extended TMJ models (same as left panel of Figure 13). and for the TMJ models discussed in the previous section (recall that, for these models, only the Kroupa and Salpeter IMFs are really from TMJ; all the other IMFs were obtained by shifting and scaling the MILES-models). The most striking point is that the MILES-Padova models, which cover the observed range of TiO2 SDSS, all lie well-above most of the measurements. The discrepancy cannot be removed by appealing to [Ti/Fe]; for the same IMF to match TiO1 and TiO2 SDSS requires different [Ti/Fe], which is unphysical. This is also true of the TW models. In contrast, the TMJ models fare much better. This is because the starting point for these models – the Kroupa and Salpeter models – lie below the TiO1 measurements, just as they do for TiO2 SDSS (compare Figure A2). The net result is that TiO1 implies slightly lower IMF slopes but otherwise the same trends as the TiO2 SDSS trends presented earlier.

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Figure A7. Left: the IMF slope gradients (same as in Figure 13) but using TiO2 (instead of TiO2$_{SDSS}$) as the IMF sensitive index. Middle: $M_*/L_r$ gradients from ASSUMPTION 3 using TiO2 (instead of TiO2$_{SDSS}$). Right: the ratio of $M_*/L_r$ inferred by using TiO2 to that for Salpeter.

Figure A8. TiO1-[MgFe] index diagram, showing gradients in line strength in each bin, and differences between bins. Dotted lines show age-metallicity grids for [$\alpha$/Fe]=0.25 and a range of IMF slopes, to illustrate how this diagram can be used to discriminate between IMFs. Left panel uses the same MILES-Padova models shown in the main text; middle panel shows the TW models; right panel shows the TMJ models, extended to other IMFs using the method described in Appendix A2.