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The similar stellar populations of quiescent spiral and elliptical galaxies

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ABSTRACT

We compare the stellar population properties in the central regions of visually classified non-star-forming spiral and elliptical galaxies from Galaxy Zoo and Sloan Digital Sky Survey (SDSS) Data Release 7. The galaxies lie in the redshift range $0.04 < z < 0.1$ and have stellar masses larger than $\log M_* = 10.4$. We select only face-on spiral galaxies in order to avoid contamination by light from the disc in the SDSS fibre and enabling the robust visual identification of spiral structure. Overall, we find that galaxies with larger central stellar velocity dispersions, regardless of morphological type, have older ages, higher metallicities and an increased overabundance of α-elements. Age and α-enhancement, at fixed velocity dispersion, do not depend on morphological type. The only parameter that, at a given velocity dispersion, correlates with morphological type is metallicity, where the metallicity of the bulges of spiral galaxies is 0.07 dex higher than that of the ellipticals. However, for galaxies with a given total stellar mass, this dependence on morphology disappears. Under the assumption that, for our sample, the velocity dispersion traces the mass of the bulge alone, as opposed to the total mass (bulge+disc) of the galaxy, our results imply that the formation epoch of galaxy and the duration of its star-forming period are linked to the mass of the bulge. The extent to which metals are retained within the galaxy, and not removed as a result of outflows, is determined by the total mass of the galaxy.

Key words: galaxies: bulges – galaxies: general – galaxies: spiral – galaxies: statistics.

1 INTRODUCTION

Galaxies in the local Universe come, broadly speaking, in two flavours: objects with blue and red optical colours tend to inhabit different regions of the colour–magnitude diagram (Strateva et al. 2001), with blue galaxies showing a large spread in colour and red galaxies following a relatively tight sequence. This so-called red sequence has been observed up to $z \simeq 2$ and has grown in mass by a factor of $\sim$2 since $z = 1$, although the evolution in the massive end of the distribution remains controversial (Bell et al. 2004; Heavens et al. 2004; Cimatti, Daddi & Renzini 2006; Faber et al. 2007; Robaina et al. 2010). As galaxies with red stellar populations typically show low levels of star formation[1] (SF), the mechanism needed to add stellar mass to the red sequence must imply the migration of a certain number of objects from the blue cloud to the red sequence (Brinchmann & Ellis 2000; Bell et al. 2007; Walcher et al. 2008) by quenching their SF.

While galaxies on the blue cloud show predominantly disc-like light profiles, the red sequence is dominated by objects with more concentrated light distributions (Blanton et al. 2003). Further evidence on the relation between SF quenching and galaxy structure is provided by Bell (2008), who found that red and dead stellar populations tend to inhabit galaxies with concentrated light profiles. Detailed studies of the shape of quiescent galaxies show that spheroidal systems are overwhelmingly dominant at masses larger than 1–2 $\times$ 10^{11} $M_{\odot}$, but a large contribution of red discs is observed below that critical mass (van der Wel et al. 2009; Masters et al. 2010), in good agreement with the results by Bundy et al. (2010) on the migration of disc galaxies to the red sequence. More recently, Holden et al. (2012) reported that at all redshifts $z < 1$ the relative fraction of disc and early-type galaxies added to the red sequence at a given stellar mass is approximately constant. Taking all these previous results together, it is clear that SF quenching in disc galaxies without the need of dramatic morphological perturbations is a valid and frequent mechanism – although not dominant – to move galaxies from the blue cloud to the red sequence.

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[1] A fraction of galaxies in the red sequence at all redshifts are red because of dust obscuration rather than truly red and dead populations. This fraction decreases towards both lower redshift and high stellar mass.

For this reason, red disc galaxies have drawn the attention of the extragalactic community. In the late 1970s, van den Bergh (1976) reported the existence of passive galaxies with spiral morphology in the Virgo Cluster, and later studies confirmed the existence of a population of quiescent disc galaxies in dense environments (i.e. Poggianti et al. 1999). More recently, Wolf et al. (2009) showed that in an intermediate-mass cluster environment red spiral galaxies are equivalent to the actively star-forming blue spirals, but with lower SF and a higher fraction of dust obscuration. These galaxies also tend to display stronger bar features than their blue counterparts (Hoyle et al. 2011a). A hint on the origin of these systems is also provided by Bamford et al. (2009) and Skibba et al. (2009), who found by using visually classified Sloan Digital Sky Survey (SDSS) galaxies from Galaxy Zoo (GZ) that the relation between optical colour and environment is more significant than the well-known morphology–density relation (Dressler 1980).

Decades of studies have shaped solid knowledge of the stellar populations of red-sequence galaxies. These galaxies follow several tight scaling relations linking their stellar population properties to their mass and their dynamical and structural properties, such as the colour–magnitude relation (Faber 1973; Gonzalez, Faber & Worthey 1993), the relation between absorption index strengths and velocity dispersion (Bender, Burstein & Faber 1993; Chang et al. 2006; Kelson et al. 2006) and the Fundamental Plane (Djorgovski & Davis 1987; Bernardi et al. 2003). The physical drive of these relations is an increase in all of metallicity, element abundance ratios and stellar age with galaxy mass or velocity dispersion (Trager et al. 2000; Kuntschner et al. 2001; Thomas et al. 2005; Gallazzi et al. 2006; Tojeiro & Percival 2010). Indeed, stellar population properties seem to be more fundamentally correlated with stellar velocity dispersion than with galaxy mass (Graves, Faber & Schiavon 2009). The picture that emerges is that present-day elliptical galaxies with deeper potential wells have reached a higher degree of chemical enrichment and have formed their stars at earlier epochs and on shorter time-scales. Moreover, the small intrinsic scatter in the observed scaling relations is associated primarily with variations in stellar age and, to a lesser degree, in chemical abundances, putting additional constraints on the variety of SFHs that present-day elliptical galaxies of similar mass have undergone (e.g. Jimenez et al. 2005, 2007; Gallazzi et al. 2006; Graves, Faber & Schiavon 2010).

An additional parameter that influences the star formation history (SFH), hence the stellar populations, of elliptical galaxies is their environment. While the slope of the scaling relations is independent of the environment, small variations in their zero-point and scatter have been observed, indicating both that the fraction of galaxies with younger stellar populations (‘rejuvenated’) increases in low-density environments (Thomas et al. 2010) and that at fixed mass galaxies in denser environments tend to be older than their low-density counterparts (Clemens et al. 2006; Cooper et al. 2010; Hoyle, Jimenez & Verde 2011b).

On the other hand, relatively few works (see e.g. Proctor & Sansom 2002; Thomas & Davies 2006; Kuntschner et al. 2010; Falcon-Barroso et al. 2011) have analysed the stellar populations and scaling relations of different morphological types, in particular, among red-sequence galaxies. Thomas & Davies (2006) re-analysed the sample of spiral bulges (from Sa to Sbc) of Proctor & Sansom (2002) and found that the bulges of spiral galaxies have similar stellar populations to elliptical galaxies at fixed velocity dispersion. Early-type spiral galaxies also seem to follow the same Fundamental Plane as ellipticals, albeit with larger scatter (Falcon-Barroso et al. 2011).

However, these works generally do not distinguish galaxies on the basis of their SF activity. In this work, we are specifically interested in comparing the stellar populations of galaxies that are quiescent but differ in morphology, namely quiescent spirals against elliptical galaxies. The primary focus of Masters et al. (2010) was on the characterization of red spirals and the comparison with blue spirals, but a detailed comparison of the stellar populations in quiescent spiral and early-type galaxies could shed some light on the processes by which they are formed and subsequently quenched. In particular, given the differences found between red and blue spirals in Masters et al. (2010), it would be extremely important to learn whether the stars in spiral galaxies can follow an evolutionary path similar to those in spheroidal systems even when the morphological evolution of their host galaxies is dramatically different, as that would put constraints on the mechanisms driving the SFHs of passive galaxies in the Universe.

In this paper, we study the stellar populations in the central regions of a sample of truly passive spiral galaxies at $z \lesssim 0.1$ from SDSS and compare them to those in quiescent ellipticals. We choose to do so by comparing the ages, total metallicities ([Z/H]) and, in particular, the α-enhancement of their populations. In order to assemble a statistically significant galaxy sample we use data products from the New York University-Value Added Catalog (NYU-VAC; Blanton et al. 2003) and visual morphology estimates from the GZ project (Lintott et al. 2008, 2011). We also model the stellar populations in SDSS Data Release 7 (DR7) quiescent galaxies, following the method described in Gallazzi et al. (2005, 2006, hereafter G05 and G06, respectively), to obtain stellar masses, r-band weighted ages, [Z/H] and $\Delta \mathrm{Mg}_b/\langle \mathrm{Fe} \rangle$ – a tracer of the α-enhancement. We end up with a sample of $\sim$1000 quiescent spiral and $\sim$14 700 passive early-type galaxies.

This paper is organized as follows. In Section 2 we describe the sample selection and the parameters we use to characterize the stellar populations. In Section 3 we present our results and discuss possible evolutionary paths. Finally, in Section 4, we present our conclusions.

Throughout this paper we use $\Omega_{\mathrm{m}0} = 0.3$, $\Omega_{\Lambda 0} = 0.7$ and $h_{100} = 0.7$. All magnitudes are in the AB photometric system.

2 SAMPLE SELECTION AND METHOD

Galaxies are drawn from the SDSS DR7 (Abazajian et al. 2009). In particular, we make use of the publicly available NYU-VAC released by Blanton et al. (2005). We select galaxies in the redshift range $0.04 < z < 0.1$ and masses $\log M_* > 10.4\,\mathrm{M}_{\odot}$. The magnitude limit in the SDSS spectroscopy places the lower mass limit for red galaxies at $z \sim 0.1$ approximately at $\log M_* = 10.6\,\mathrm{M}_{\odot}$, although we choose to work with galaxies slightly below that limit. Nonetheless, we warn the reader that our sample is incomplete by $\sim$20 per cent below $\log M_* = 10.6\,\mathrm{M}_{\odot}$ at the highest redshift probed here. We make use of NYU-VAC k-corrected photometry, spectroscopic redshifts and light-profile fitting parameters in the r band.

Stellar masses, metallicities and r-band light-weighted ages for SDSS DR7 galaxies have been estimated in the same way as for previous releases and as described in G05, to which we refer the reader for a full description. Briefly, estimates of the stellar population parameters are obtained by comparing the observed stellar absorption features (corrected for emission lines) with those predicted by a comprehensive library of model spectra based on Bruzual & Charlot (2003) Single Stellar Populations (SSPs) convolved with Monte Carlo SFHs. A comparison between the new SDSS DR7 parameters and those of SDSS DR4 from G05 and G06 provides no systematic offset and a typical dispersion at the level of ∼0.1 dex in light-weighted age, stellar mass and metallicity for galaxies with red, *quiescent* stellar populations, well below the typical error budget in those measurements. In this work, we correct the estimated galaxy ages to $z = 0$ by adding the lookback time at the redshift of the galaxy under the assumption of passive evolution (which is very reasonable for our sample of quiescent galaxies).

In addition to the aforementioned stellar population parameters we focus on the α-enhancement. In spite of the name, the effect is more a lack of iron rather than an excess of α-elements. This lack of iron is produced when the SF time-scale of a galaxy is short. Core-collapse supernovae enrich the medium with α-elements in scales of a few tenths of Myr, while the Fe-enrichment is due to Type Ia supernova explosions. If a significant fraction of the stars are formed in a period shorter than the ∼1 Gyr needed by Type Ia supernova progenitors to evolve, the stars would show a chemical composition with higher α/Fe abundance ratios than those in stellar populations formed with longer time-scales.

As a tracer of the α-enhancement in the stellar populations of our sample we use the semi-empirical [α/Fe] indicator adopted by G06, namely $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ which is the difference between the observed $\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle$ absorption index[2] and that of the scaled-solar BC03 model that best fits [α/Fe]-independent features. G06 have tested, through comparison with Thomas et al. (2003) models with variable abundance ratios, that $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ correlates linearly with the abundance ratio [α/Fe] independently of age and metallicity (except for metallicities below 30 per cent solar, which is lower than the range covered by our sample). In particular, we confirm such proportionality over the metallicity and age range spanned by our sample ($0.5 < Z/\mathrm{Z}_\odot < 2$ and age older than 3 Gyr) with the differential models presented in Walcher et al. (2009) based on the theoretical Coelho et al. (2007) models calibrated on to either BC03 or Vazdekis et al. (2010). We stress that the values of $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ should not be directly translated into values of [α/Fe], i.e. the proportionality constant between $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ and [α/Fe] is not 1 and is likely model dependent.

2.1 Quiescent stellar populations

As we want to compare spiral and elliptical galaxies with *quiescent* stellar populations – and specifically not galaxies reddened by dust obscuration – we select galaxies without Hα emission from their spectra. Nonetheless, two effects can endanger the reliability of this selection: (a) large levels of dust obscuration might cause the absence of Hα detections even in the presence of SF and (b) the 3 arcsec diameter of the SDSS fibre might not be large enough, in many cases, to sample a representative fraction of the stellar populations present in the galaxy. This would be specially concerning in the case of galaxies with quiescent bulges and star-forming discs. These problems might be alleviated by the inclusion of an additional criterion. It has been shown that galaxies dominated by passive (i.e. non-star-forming) populations tend to be found in a particular region of a colour–colour plot in which one of the colours bracket the 4000 Å break and the other falls redwards of that spectral feature (Williams et al. 2009; Holden et al. 2012).[3] In such a diagram red-passive and red-obscured galaxies are distinguished by the different imprint imposed by age and dust on the galaxy's spectral energy distributions. We show the SDSS derived $u - r$ colour versus $r - z$ colour diagram of the galaxy sample in Fig. 1. From the comparison between both panels, it is clear that elliptical and spiral galaxies without Hα emission present a different distribution. More than 90 per cent of elliptical galaxies lie on the region of the diagram where quiescent stellar populations cluster while spirals present a larger dispersion, both towards the bluer $u - r$ colour, probably indicating different stellar populations in the centre and outskirts of the galaxy, and towards the redder $r - z$ values, implying larger levels of obscuration by dust. Therefore, we decide to use for this study only those galaxies without notable Hα emission *and* quiescent stellar populations over the whole galaxy by selecting them in the $u - r$ versus $r - z$ diagram. The green line in both panels of Fig. 1 shows the selection box used here. We have been very conservative in the definition of the boundaries between star forming and non-star forming. If we were to select galaxies at ∼1σ from the centre of the quiescent clump, we would include several massive spiral galaxies with residual levels of SF, detected at different colours in the disc and bulge in a visual inspection. The reason is that the galaxies in our sample span more than 1 dex in stellar mass, and the boundary between blue cloud and red sequence is mass (or magnitude) dependent (Fig. 2). Then, we decide to include galaxies 0.04 mag redder in $u - r$ than the 1σ boundary. This shift is arbitrary, but help us to make sure that the galaxies we study are, indeed, quiescent.

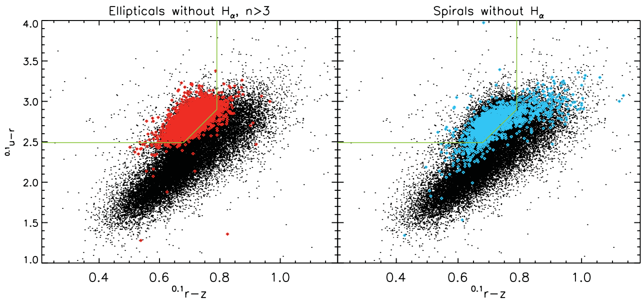

Figure 1. Colour–colour diagram of SDSS DR7 galaxies with $\log(M_*/\mathrm{M}_\odot) > 10.4$ at $0.04 < z < 0.1$. Left-hand panel: elliptical galaxies with no Hα emission and Sérsic index $n > 3$ are shown with red symbols. Right-hand panel: spiral galaxies with no Hα emission are shown with blue symbols. The green solid line in both panels defines the box used to select galaxies with quiescent stellar populations. This work concentrates on the comparison between objects shown as blue and red points within the selection box.

Our sample selection differs from that in previous studies making use of GZ data (Masters et al. 2010) in the sense that we do not only select by optical colour, but specifically reject any galaxy with hints of recent SF.

2.2 Systematic error checks

The main aim of this work is to perform a differential analysis between the stellar populations of quiescent spiral and elliptical galaxies. In order to identify these particular morphological types we use visual classifications released by the GZ collaboration (Lintott et al. 2008, 2011). Initially, we select galaxies with a debiased probability $P_{\mathrm{debiased}} > 0.8$ (Bamford et al. 2009) of being either spiral or elliptical (spiral arms or the presence of and edge-on disc is required in the GZ classification in order to assign a galaxy to the category of spiral). However, there are some relevant caveats one should take into account when using this catalogue: (a) quiescent galaxies have red optical colours and a higher Mass-to-light

[2] ⟨Fe⟩ is the average of the Fe5270 and Fe5335 index strengths.

[3] A similar method but using a combination of optical and ultraviolet colours has been successfully applied to the selection of red, old, disc galaxies by Wolf et al. (2009).

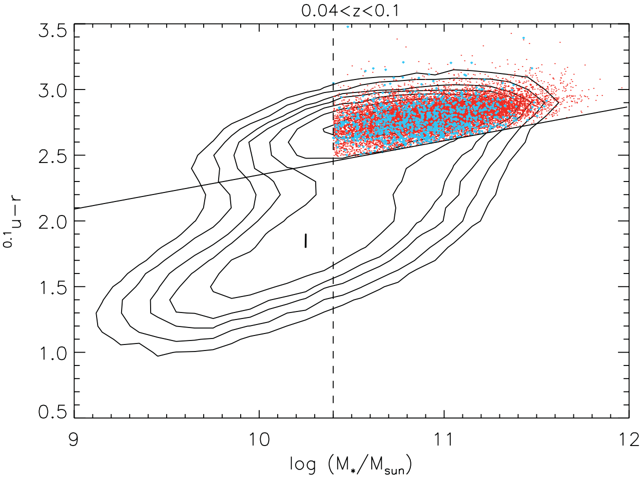

Figure 2. Colour–stellar mass relation for SDSS DR7 galaxies at $0.04 < z < 0.1$. Contours show the density of galaxies in that redshift slice. The blue points represent our final sample of ∼1000 quiescent spiral galaxies, while the red points show our final sample of ∼19 000 quiescent ellipticals. The vertical dashed line corresponds to our adopted lower mass limit of $\log(M_*/\mathrm{M}_\odot) = 10.4$. The solid line corresponds to our adopted definition of red-sequence galaxies.

(M/L) ratio than star-forming galaxies, implying that for galaxies at the same mass, it is intrinsically more difficult to classify a red galaxy than a blue one, (b) quiescent spiral galaxies usually lack the strong structure present in star-forming spirals. This makes it even harder to recognize spiral patterns,[4] and (c) the definition of 'Combined Spiral' used in GZ catalogue includes both face-on disc galaxies with obvious spiral arms *and* edge-on discs for which the spiral structure is not detectable even when present. The higher the redshift and the lower the stellar mass, the harder it is to clearly identify the spiral structure in a disc galaxy, even when present. All those problems could lead to a relatively high number of potential misclassifications, which are partially corrected for when calculating the debiased probability (see Bamford et al. 2009 for further details). Nonetheless, as we show in Fig. 3, there is a clear bias present when studying quiescent galaxies. For a complete sample of spirals the projected axis ratio distribution should be approximately flat at values larger than the intrinsic thickness. We check for this by plotting the axis ratio (b/a) versus galaxy stellar mass of the GZ-selected spirals with quiescent stellar populations. Truly face-on disc galaxies would fall close to $b/a = 1$, while those seen edge-on would appear somewhere in the range $0.1 < b/a < 0.5$ (depending on the intrinsic thickness of the disc and bulge contribution). Alternatively, in the absence of any bias the distribution with b/a should be homogeneous at all masses. Instead we observe a deficit of low-inclination spirals at low masses. In order to guarantee the homogeneity of the spiral galaxy sample, we use only low-inclination galaxies ($b/a \geq 0.5$). While this does not guarantee that we are completely down to our mass limit of $\log M_* = 10.4$, we can be sure that the morphological selection is homogeneous by including in the sample only those spiral galaxies with visible arms.

In this work, we follow the GZ nomenclature, that is we call 'ellipticals' those galaxies which have a probability of being elliptical >0.8. However, this category includes many galaxies with bulge-to-total ratio (B/T) lower than those of purely bulge-dominated objects and potentially, some misclassified face-on, smooth discs.

[4] Both Masters et al. (2010) and the present study use galaxies with visible spiral patterns.

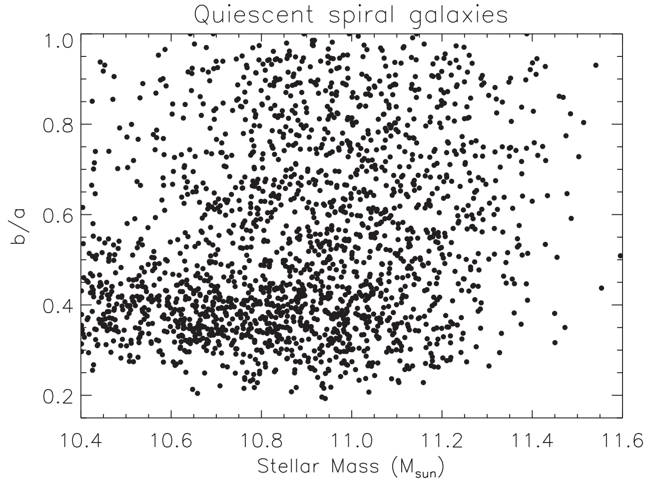

Figure 3. Axis ratio (r band) versus galaxy stellar mass for our quiescent spiral galaxies as classified in GZ ($P_{\rm CS} > 0.8$). The majority of relatively low inclination ($b/a > 0.5$), lower mass quiescent spirals are not confidently assigned to the 'spiral' category in the GZ catalogue.

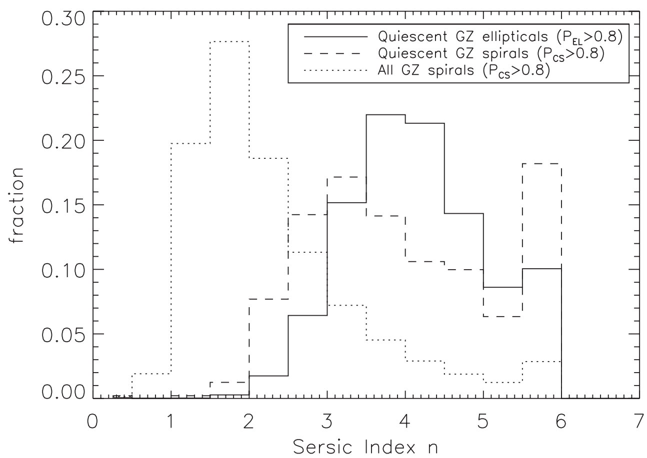

Figure 4. Sérsic index distribution of quiescent elliptical, quiescent spiral and all spiral galaxies in the DR7 spectroscopic catalogue. Only galaxies with debiased probability $P_{\rm debiased} > 0.8$ are selected in all three cases. Quiescent spiral galaxies show a distribution closer to that of early types than that of 'normal' spirals.

Large, massive, low-inclination spiral galaxies would be more likely to get an accurate classification than small, low-mass counterparts. This is a matter of concern because potential systematic differences in the sizes and spiral structure of low- and high-inclination disc galaxies could jeopardize a proper comparison: the 3 arcsec diameter of SDSS spectrograph fibre would sample systematically different physical radii in galaxies observed under different angles.

We show the Sérsic index distributions of quiescent ellipticals, quiescent spirals and all the spirals in our catalogue, selected by a debiased probability $P_{\rm debiased} > 0.8$ of having the respective morphological type in Fig. 4. Notably, quiescent spiral galaxies present a different Sérsic distribution than star-forming spiral galaxies – dominated by blue discs – peaking at $n \simeq 4$ instead of a lower value of $n \sim 1.5$–2 of blue spirals. This is indicative of the presence of large bulges in these objects. We note that introducing a further cut in n to select elliptical galaxies (i.e. selecting only elliptical galaxies with $n > 3$) makes no difference to our final results.

Ideally, we would compare the stellar populations in the *bulges* of spiral and elliptical galaxies, as in the works by Proctor & Sansom (2002) and Thomas & Davies (2006), but given the degeneracy between B/T, physical size and angular distance evolution and the fixed size of the SDSS spectrograph fibre we will be probing the stellar populations in the *central regions*, that are indeed dominated by the bulge. Given the typical high Sérsic index of quiescent spirals, it is very likely that the light within R_e is dominated by a prominent bulge. Nonetheless, we cannot discard some contribution from stellar populations in the inner disc, although we deem it to be a second-order effect since we specifically select galaxies with quiescent stellar populations *all over* the galaxy. We will also test our main results for a subsample of galaxies for which we know the light in the fibre to be bulge dominated.

While we focus on the comparison between elliptical and face-on spiral galaxies, we will also show in some of our plots a third group of galaxies, composed of edge-on quiescent discs selected from the NYU-VAC to have $b/a < 0.4$ – and no constraint in GZ visual classification. When comparing this with the two aforementioned samples (edge- and face-on quiescent discs), the reader should bear in mind that in many cases the amount of light originated by the discs' stellar populations in edge-on objects will be larger than in the case of the GZ face-on quiescent spiral sample.

As a summary of our sample selection, we use SDSS DR7 galaxies at $0.04 < z < 0.1$ with $\log M_*/\mathrm{M}_\odot > 10.4$. Objects are selected to show optical $u - r$ colour compatible with red sequence galaxies, no Hα emission in the spectra. Additionally, we select them photometrically to be quiescent in the $u - r$ versus $r - z$ diagram following Williams et al. (2009) and Holden et al. (2012). All objects must have debiased probability $P > 0.8$ of being either spiral or elliptical in the GZ catalogue. Furthermore, we include only those spiral galaxies with low ellipticity ($b/a > 0.5$). We will show for comparison purposes edge-on quiescent disc galaxies selected from the NYU-VAC to have $b/a < 0.4$. This leaves us with a sample of approximately 14 700 early-type galaxies and 1000 face-on spirals.

3 RESULTS

In this paper, we perform a *differential* analysis of the stellar populations in the central regions of quiescent spiral and elliptical galaxies. We compare, in particular, the metallicity, α-enhancement (traced by the excess of $\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle$) and r-band light-weighted age of those two groups of galaxies over the redshift range $0.04 < z < 0.1$ and with stellar masses $\log(M_*/\mathrm{M}_\odot) > 10.4$.

In Fig. 5 we show the median values of those quantities in bins of stellar mass. The metallicity in all three subsamples is remarkably similar over the whole mass range explored in this paper. They are compatible within the 1σ typical dispersion, shown as the large error bar on the right-hand side of the plot, and the positions of the mean of both distributions are indistinguishable. The error in the position of the mean is denoted by the error in every mass bin.

While the fact that massive elliptical galaxies are α-enhanced is well established in the literature (Worthey, Faber & Gonzalez 1992; Thomas, Maraston & Bender 2003; Thomas et al. 2005; G06), we find at very high statistical significance, that *at all masses*, the central regions of quiescent spiral galaxies also show an important excess of α-elements with respect to Fe, and follow a trend with mass similar to that of the ellipticals. Both populations are largely overlapping, but in this case, the position of the mean seems to be shifted down by $\sim$0.1. Light-weighted ages of quiescent spirals seem to be, on average, 400 Myr younger than those of ellipticals. Nonetheless, errors in the measurements, modelling and derivation of parameters could add-up an error similar to such a small difference. If we are conservative and assume that the typical observational error in $\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle$ always work in the direction of increasing the recovered enhancement [i.e. if we consider as true enhanced only those galaxies with $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle) > 0.2$], we can make sure that the bulk of elliptical galaxies at all the masses probed here possesses, indeed, a super solar α/Fe ratio. Quiescent spiral galaxies above $10^{10.6}$ M$_\odot$ are also unequivocally α-enhanced.

The total stellar mass of a galaxy is a good tracer of its properties, but as we study the stellar populations in the *central regions* of the object, we perform a similar exercise in Fig. 6, except that this time we show the metallicity, α-enhancement and age of the stellar populations as a function of the measured velocity dispersion (σ_v) in the central region of the galaxy.

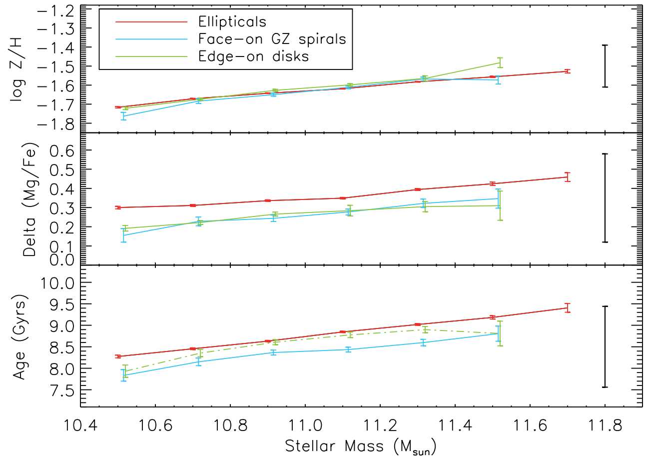

Figure 5. Top panel: metallicity versus stellar mass. The metallicity in the central regions of quiescent spiral (dashed line) and elliptical (solid line) galaxies is identical. Middle panel: excess of Mg_b over Fe with respect to BC03 models. The α-enhancement is very similar in the two populations. There is a small shift in $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ present in quiescent spirals with respect to ellipticals. The two groups are largely overlapping, as shown by the 1σ error bar on the right, which represents the dispersion in the distribution. Bottom panel: r-band light-weighted age versus stellar mass. Again, quiescent spiral and elliptical galaxies are very similar, with a very weak trend of spirals showing slightly younger stellar populations. The large error bar in all three panels shows the typical 1σ dispersion.

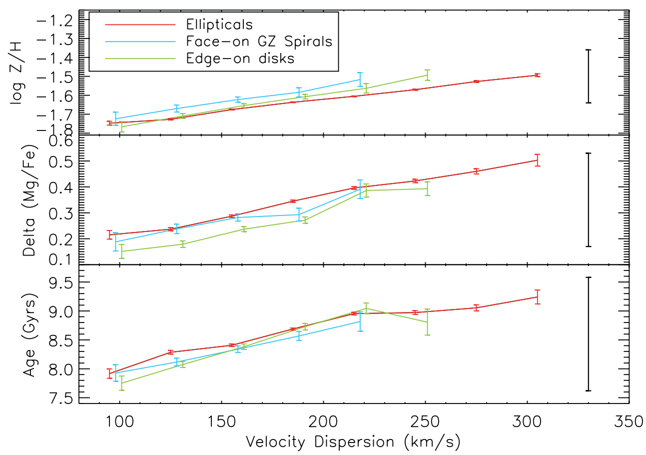

Figure 6. Stellar population properties as a function of the central σ_v. Lines and error bars are the same as in Fig. 5.

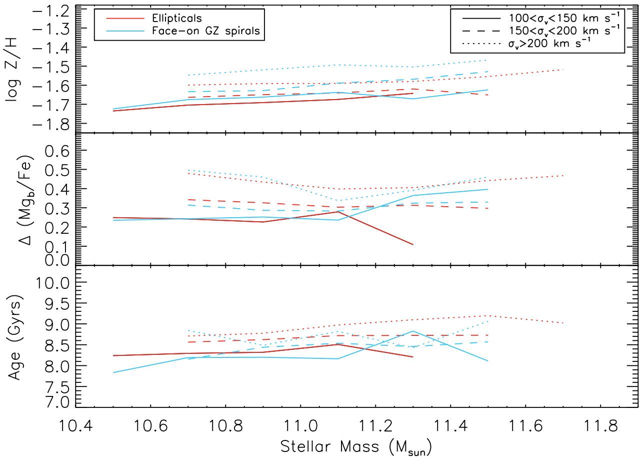

Figure 7. Stellar population properties as a function of total stellar mass, in bins of velocity dispersion. Trends with stellar mass are almost non-existent, in comparison with Fig. 5, implying that the central velocity dispersion (a good proxy for the bulge's mass) and not *total* stellar mass is the observable with the strongest correlation with stellar population parameters.

Velocity dispersion is not completely free from the influence of the mass distribution of the galaxy in the outer regions, i.e. outside the fibre coverage, but has the advantage of being a direct measurement of the dynamical properties in the region of the galaxy under study and also less uncertainties related to modelling than total stellar mass. Nonetheless, while these quiescent spiral galaxies have prominent bulges, as interpreted from their high Sérsic indexes, and are studied at radii smaller than their R_e, in some cases there will be some non-negligible contribution from the disc inside the fibre.

In this case, the median metallicity in the central regions of quiescent spirals is higher than that in early types. The measured $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ and light-weighted ages of spirals are consistent with the stellar populations of ellipticals at a given σ_v. The fact that at a given σ_v all the three physical quantities re-scale in the same way with respect to ellipticals when comparing to Fig. 5, indicates that the main source of the differences between those plots is the different B/T in ellipticals and spirals. This makes us question which is the parameter which correlates the strongest with stellar populations: total stellar mass or bulge mass (central velocity dispersion).

As shown in Fig. 7, we repeat the exercise performed in Figs 5 and 6 but studying trends with stellar mass *in bins* of σ_v. In this case, there are only very weak (if at all) correlations between the age and α-enhancement in our galaxies and their total stellar mass, implying that the velocity dispersion correlates the strongest with these parameters. However, it seems that there is a residual correlation between the metallicity and the stellar mass even when we factor out σ_v – [Z/H] increases monotonically with stellar mass in all bins of σ_v and for both morphological types.

We will from now on assume that central velocity dispersion is a good proxy for the mass of the bulge. The calculation of the mass of the bulge from a direct measurement of σ_v can be, in principle, affected by the orbits of stars in the disc. However, Cappellari et al. (2006) use SAURON data to show that central σ_v is proportional to $\sqrt{M}$ and weakly dependent on the orbital distributions. In addition, we select only relatively face-on spiral galaxies, minimizing the impact of the disc's rotation on the σ_v measurement.

The difference in total stellar mass, at a given bulge mass, must come mainly from the disc. The lack of a trend in age and α-overabundance with total stellar mass, at fixed velocity dispersion, indicates that the stellar mass of the disc is not relevant in shaping these physical parameters. Instead, the residual trend in metallicity with total stellar mass at a given bulge mass implies that the extra mass of the disc might be relevant for the total metal content retained by the galaxy.

We now quantify the statistical significance of any possible difference between spirals and ellipticals by studying not only the median values of metallicity, $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle)$ and age, but also the whole distribution of these parameters in bins of σ_v. We show these distributions in Fig. 8, where we have split our galaxy samples in three bins of central velocity dispersion. Using the two-sided Kolmogorov–Smirnov (KS) test, we find that the bulges of quiescent spirals are more metal-rich than elliptical galaxies at fixed σ_v with high confidence (probability of the two samples to be drawn from the same distribution $P \sim 10^{-3}$). The difference in the median values is at the level of ∼0.07 dex. While there are some differences in α-enhancement and age (at least in some of the σ_v bins), their statistical significance is not large, so physical interpretation is unnecessary, especially considering the typical uncertainties affecting the measurements.

Gallazzi et al. (2008) identified the systematic uncertainties affecting the derivation of the stellar population parameters. The main contributions to the error budget in the case of metallicity are the lack of variation of [α/Fe] in BC03 models, and to the choice of priors according to which the model library produces a galaxy's SFH.[5] A combination of both factors can add an error of up to 0.046 dex in [Z/H], which is more than half of the difference we find between passive spirals and ellipticals. However, the fact that we see the same trend in all bins of σ_v and the different shape of the distributions in Fig. 8 make us believe that there is a physical difference between the two galaxy samples. Moreover, we have shown that [α/Fe] of spiral bulges and ellipticals are indistinguishable at fixed velocity dispersion; thus, any bias introduced by α/Fe would affect their total metallicity in a similar way and have negligible effect on our differential analysis.

So far, we have performed a differential analysis of the stellar populations in the *central regions* of spiral and elliptical galaxies, but we cannot guarantee that all the light in the SDSS spectrograph fibre does indeed come from the bulge. In order to minimize this potential contamination from disc light we have chosen to work only with galaxies hosting *quiescent* discs, with stellar populations more similar to those in red and dead ellipticals than those in star-forming discs. Furthermore, it is possible to only select galaxies for which the light in the fibre is dominated by the stars in the *bulge*. In order to do this, we use the catalogue by Simard et al. (2011), who have performed a bulge-disc decomposition for galaxies in the SDSS. We now choose only those galaxies for which at least 80 per cent of the light in the fibre is originated by bulge stars and repeat the analysis shown in Fig. 8. It is worth noting that the total number of elliptical (spiral) galaxies is reduced by 10 per cent (52 per cent).

We show the results of this exercise in Fig. 9. Once again the metallicity seems to be the only discrepant quantity between the bulges of passive spirals and ellipticals at high significance ($P \sim 10^{-3}$ in all three bins). The distribution of age and α-enhancement in both galaxy samples are relatively similar. Visual inspection of the distributions, as well as the KS test probabilities, shows that the statistical evidence for a difference between the samples is inconclusive. High spatial resolution and 3D spectroscopy, rather than increasing sample size, would be more likely to test this conclusively.

[5] We refer the reader to Gallazzi et al. (2008) for a full discussion on systematic uncertainties in the modelling.

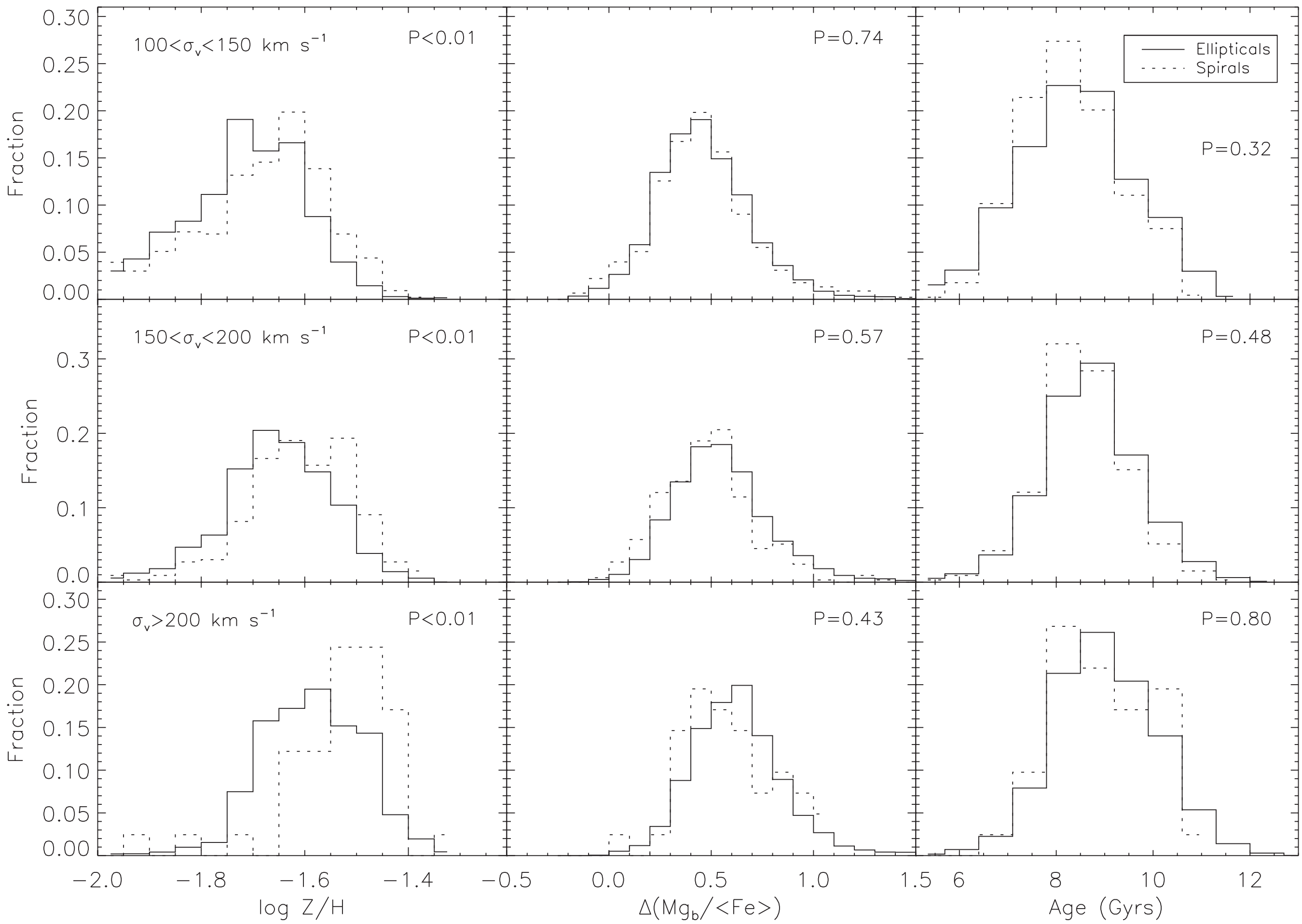

Figure 8. Distributions of metallicity, $\Delta(\mathrm{Mg}_b/\langle\mathrm{Fe}\rangle$ and light-weighted age in different bins of central velocity dispersion for quiescent spiral (dotted line) and elliptical (solid line) galaxies. The probability of both samples to be drawn from the same distribution, obtained from a two-sided KS test, is shown in each panel. Bulges of quiescent spiral galaxies have higher metallicity than ellipticals with the same σ_v at high confidence. α-enhancement and age differences between the two samples are only marginally detected when combining the three bins in σ_v. See the text for more details.

Our findings point to a scenario in which the stellar population properties in the bulges of quiescent spiral and elliptical galaxies scale with the central velocity dispersion. We find the youngest, less metallic, less α-enhanced objects to be those with the lower values of σ_v. This result is in good qualitative agreement with that of Thomas & Davies (2006), despite a notable difference in sample selection and aperture definition. The main difference between the two works is the statistical significance reached because we use a sample ~50 times larger. Our larger sample size could also be driving our main discrepancy. While they find *Z*/H, α-enhancement and age of spiral bulges to be equivalent to those in ellipticals at a given velocity dispersion, we find that the metallicity in bulges of quiescent spirals is higher than in elliptical galaxies.

However, it seems that the metallicity of those stellar populations *also* correlates with the total stellar mass of the galaxy. We know that there is a fundamental correlation between the mass of a galaxy and its metal content (i.e. Tremonti et al. 2004; G05), and that its origin is likely due to the higher capacity of more massive systems to retain metals in the presence of outflows.

Taken together, our results imply that the formation epoch of galaxies and the duration of their star-forming period are linked to the mass of the bulge. The extent to which metals are retained within the galaxy, not being removed as a result of outflows, is determined by the total mass of the galaxy.

Masters et al. (2010) studied the stellar populations of red spirals, finding them to be systematically older and with less recent SF activity than blue spiral galaxies. Combining their results with those presented here, imply a scenario in which SFHs of red spirals are more similar to those of ellipticals than those of star-forming spirals.

We are very conservative in the selection of quiescent galaxies, so it is possible that a population of disc-like, low-level star formers do exist (and that is precisely what Wolf et al. 2009 and others report). However, a late quenching of the SF in disc galaxies could be reconciled with our results if, in spite of the relatively homogeneous colour and lack of SF at $z \le 0.1$, there are radial gradients present in the stellar populations ages. In other words, if these galaxies grow inside out (Barden et al. 2005) and the centre of the objects, where the bulk of the stellar populations reside, was assembled at $z > 1$, the SF per unit mass might be small enough to not to leave behind a strong imprint in the global colours of the object by $z \le 0.1$, and make it into our sample.

Kuntschner et al. (2006) make use of SAURON survey data in order to study the stellar populations of 48 early-type galaxies. They find that the flattened component identified in fast-rotators does

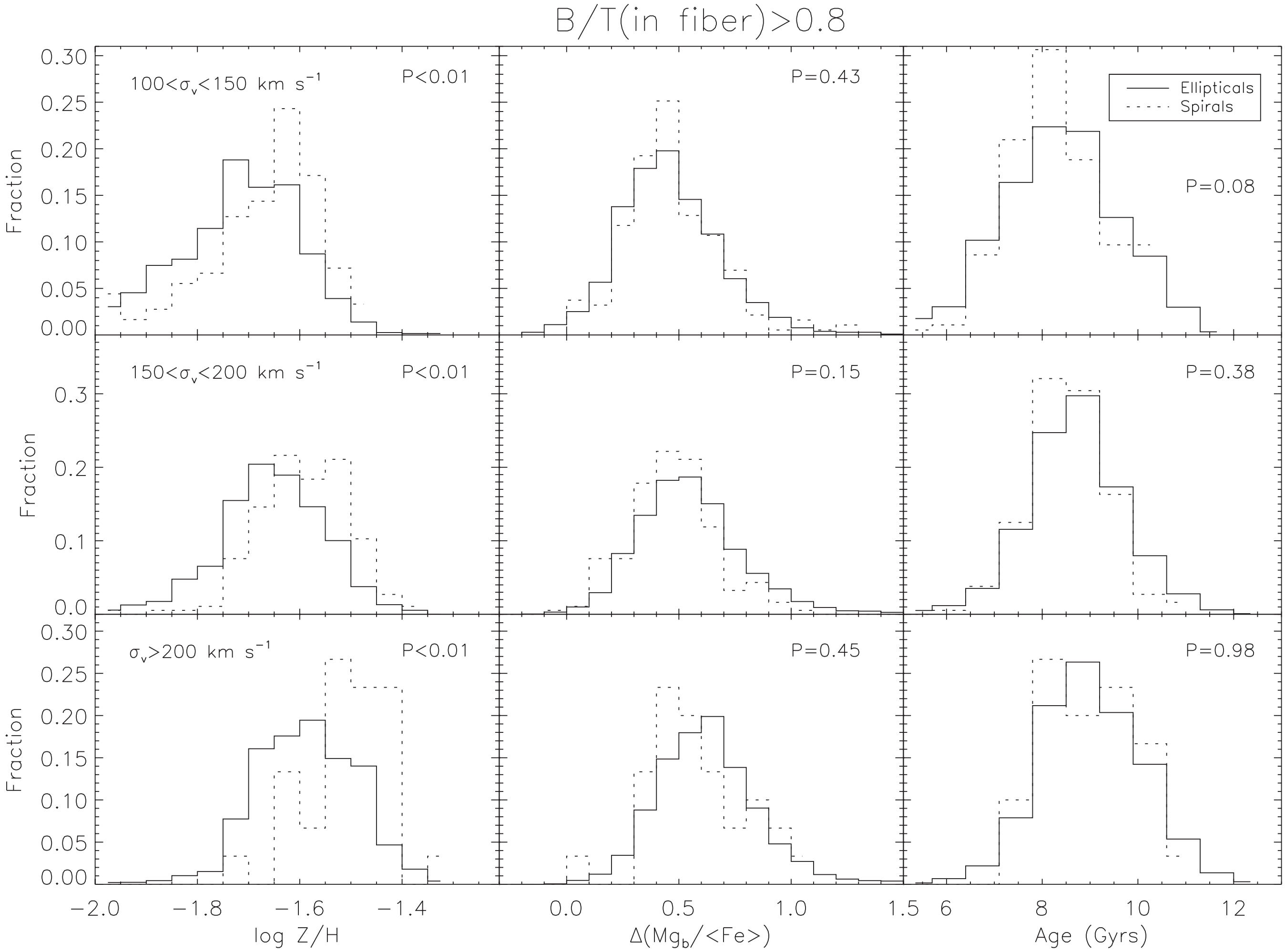

Figure 9. The same distributions as in Fig. 8 but using only galaxies with B/T > 0.8 in the fibre – at least 80 per cent of the light contributing in the spectrum is produced by stars in the bulge.

actually show an increase in the metallicity and a mildly depressed [α/Fe] ratio with respect to the main body of the galaxy. Unfortunately their maps do not typically cover regions much larger than R_e, nor later morphological types than S0s. Future surveys, like the recently started Calar Alto Large Integral Field Area survey, will provide 3D spectroscopy over the full optical extent of a statistically significant sample of galaxies of all morphological types (Sánchez et al. 2012), allowing the study of the stellar populations of quiescent spirals at larger radii.

Assuming that similar α-enhancements imply similar SF time-scales, it seems reasonable to believe that whatever the reason is after the shorter typical SF time-scales in elliptical galaxies, it is very likely that the stars in the bulges of quiescent spirals share a common formation mode with those in ellipticals. Furthermore, the fact that the light-weighted ages are similar at a given $\sigma_{\rm v}$ implies that the epoch of the SF shut-off must also be placed at the same epoch, and any subsequent episode of SF must have happened at a lookback time high enough for any trace of young stellar populations to have disappeared by today.

We would like to recall that while at stellar masses above 1–$2 \times 10^{11}\,{\rm M}_{\odot}$ the contribution of passive discs to the growth of the red sequence is very small (van der Wel et al. 2009), probably because of a merger-dominated formation history at those masses (van der Wel et al. 2009; Robaina et al. 2010), there are many passive discs contributing to such a growth since $z \sim 1$ (Bundy et al. 2010; Holden et al. 2012) at lower masses. Therefore, it will be very important to understand when and how do spiral galaxies without notable SF activity in the local Universe stopped forming stars. Future models of galaxy formation and evolution would have to be able to reproduce the small difference in metallicity.

4 CONCLUSIONS

We have assembled a sample of galaxies with morphological classifications from GZ and photometry and light-profile fit parameters from the SDSS DR7 and NYU-VAC. We perform a comparison between the stellar populations in the central regions of low-inclination quiescent spiral galaxies and those in elliptical galaxies over the redshift range $0.04 < z < 0.1$ and for galaxies with stellar masses above $10^{10.4}\,{\rm M}_{\odot}$. Specifically, we compare their r-band light-weighted ages, stellar metallicities and α-enhancement [as traced by $\Delta({\rm Mg}_b/\langle{\rm Fe}\rangle)$], derived as in G05 and G06. The main results of this analysis are as follows.

(i) Central velocity dispersion is the observable with the strongest correlation with stellar population parameters. When we fix $\sigma_{\rm v}$ we find no dependence of light-weighted age or α-enhancement with total stellar mass for both elliptical and quiescent spiral galaxies.

In the case of passive spirals, if we assume that central velocity dispersion is a good proxy for the bulge's mass, this implies that these parameters are independent of the disc's stellar mass. However, there is a residual correlation between [Z/H] and stellar mass even if we factor out central σ_v.

(ii) The metallicity of the stars in the bulges is higher in passive spirals than in ellipticals, at a given central velocity dispersion, by ~0.07 dex. On the other hand, median values and distributions of age and α-enhancement are statistically compatible in both galaxy samples. This, together with the residual correlation found between metallicity and total stellar mass (bulge+disc), indicates a higher capacity of more massive systems to retain their metals during the process of SF.

(iii) Our results are in good qualitative agreement with those of Thomas & Davies (2006) in the case of age and α-enhancement despite notable differences in sample selection and aperture definition. Our finding of a lower [Z/H] in quiescent ellipticals is likely a cause, given how small the difference is, of sample size.

(iv) As we are very strict with our criteria for selecting *passive* stellar populations, we are certainly not including in our sample all galaxies in transition from star formers to passive red. It is possible that our sample selection criteria are leaving out slightly less red disc galaxies with low levels of SF and younger stellar populations, even if they are already on the red sequence. Models of galaxy formation have to account for a very large range in structural and morphological properties among galaxies with similar stellar ages and SF time-scales.

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