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The VIMOS Public Extragalactic Redshift Survey (VIPERS) ⋆

The coevolution of galaxy morphology and colour to $z \sim 1$

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ABSTRACT

Context. Understanding how galaxy properties evolve is one of the challenges of extragalactic astrophysics. One possible approach is to statistically analyse large samples of galaxies: to this aim galaxies must be separated in different classes sharing the same characteristics. Therefore, the study of the separation of galaxy types and of the evolution of the specific parameters used in the classification are fundamental to understand galaxy evolution.

Aims. We explore the evolution of the statistical distribution of galaxy morphological properties and colours over the redshift range $0.5 < z < 1$, combining high-quality imaging data from the CFHT Legacy Survey with the large number of redshifts and extended photometry from the VIPERS survey.

Methods. Galaxy structural parameters are measured by fitting Sérsic profiles to i-band images and then combined with absolute magnitudes, colours and redshifts, to trace the evolution in a multi-parameter space. We analyse, using a new method, the combination of colours and structural parameters of early- and late-type galaxies in luminosity–redshift space.

Results. We found that both the rest-frame colour distributions in the (U-B) vs. (B-V) plane and the Sérsic index distributions are well fitted by a sum of two Gaussians, with a remarkable consistency of red-spheroidal and blue-disky galaxy populations, over the explored redshift ($0.5 < z < 1$) and luminosity ($-1.5 < B - B_* < 1.0$) ranges. The combination of the UBV rest-frame colour and Sérsic index n as a function of redshift and luminosity allows us to present the structure of early- and late-type galaxies and their evolution. We found that early type galaxies display only a slow change of their concentrations since $z \sim 1$; it is already established by $z \sim 1$ and depends much more strongly on their luminosities. In contrast, late-type galaxies get clearly more concentrated with cosmic time since $z \sim 1$, with only little evolution in colour, which remains dependent mainly on their luminosity. This flipped luminosity (mass) and redshift dependence likely reflects different evolutionary tracks of early- and late-type galaxies before and after $z \sim 1$.

Conclusions. The combination of rest-frame colours and Sérsic index n as a function of redshift and luminosity leads to a precise statistical description of the structure of galaxies and their evolution. Additionally, the proposed method provides a robust way to split galaxies into early and late types.

Key words. cosmology: observations, galaxies: general, structure, evolution, statistics

1. Introduction

The human eye and brain have evolved to be able to rapidly pick up underlying similarities and subtle differences amongst a set of objects (even unconsciously) allowing them to be efficiently and reliably identified and ordered into categories. As for galaxy studies it is common use to divide sources into populations according to specific galaxy properties. Hubble (1926) provides the first statistical classification of extragalactic nebulae based on their shapes. Since then the Hubble tuning fork has been used to divide galaxies into ellipticals, spirals and irregulars, with various degrees of complexity and details. The original classification scheme went through various modifications and found its definitive exposition in Sandage (1961). Still, the well-defined galaxy segregation observed in the local universe starts to lose its discriminatory power when moving to higher redshifts where galaxies have more irregular and diverse shapes, and new classification schemes should be introduced (e.g. van der Wel et al. 2007; Kartaltepe et al. 2015).

Due to the impressive amount of photometric data produced by large galaxy surveys, it is necessary to move from human classifiers to automatic techniques. The standard approach is to identify a series of parameters which correlate with the visual morphology of a galaxy and to define the parameter–space which best identifies a specific morphological type (e.g. Abraham et al. 1996; Conselice et al. 2000; Lotz et al. 2008). Among the non-

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parametric diagnostics of galaxy structure the more traditionally used are galaxy asymmetry, concentration, Gini coefficient, the 2nd-order moment of the brightest 20% of galaxy pixels, clumpiness (or smoothness) and ellipticity (Abraham et al. 2003; Lotz et al. 2004). A widely used parametric description of the galaxy light profile is based on the exponent of the Sérsic law fit to the galaxy surface brightness distribution (Sérsic 1963). The Sérsic index n, that quantifies the concentration of the light, has been commonly used as a selection criterion to divide early and late–type galaxies in many investigations (e.g. Driver et al. 2006 applied $n = 2$ to the galaxies from Millennium Galaxy Catalogue; Cassata et al. 2011 used $n = 2$ on the high-z HST galaxies). Ravindranath et al. (2004) analysed a sample of nearby galaxies with visual morphologies determined by Frei et al. (1996) artificially redshifted to $z = 0.5$ and 1.0, and found that the single Sérsic profile index $n = 2$ well separates early- and late-type galaxies, even in the presence of dust or star forming regions.

Alongside the rather qualitative classification criteria at the basis of the Hubble-Sandage system, a more quantitative interpretation related to how physical parameters (e.g. stellar mass, specific angular momentum, ages, cold gas fraction, etc.) vary along the Hubble sequence, can be developed (see Roberts & Haynes 1994, for an extensive review). Hubble's early-type galaxies (ellipticals and lenticulars) are usually redder in optical colours, more luminous and massive, with older stellar populations, and smaller reservoirs of gas and dust; conversely, late-type galaxies (spirals and irregular galaxies) are generally less massive, show younger stellar populations and have bluer colours (e.g. de Vaucouleurs 1961; Roberts & Haynes 1994; Kennicutt 1998; Bell et al. 2004; Bundy et al. 2005, 2006; Haynes & Giovanelli 1984; Noordermeer et al. 2005). Many studies suggest that these correlations hold at least up to $z \sim 1$ (Fritz et al. 2009; Fritz & Ziegler 2009; Pozzetti et al. 2010; Bolzonella et al. 2010; Kovač et al. 2010; Tasca et al. 2009). In particular, the morphology-colour correlation is traced back to at least up to $z \sim 2$ (e.g. Bassett et al. 2013).

Similarly to what is seen in the distribution of morphological types, galaxy rest-frame colours tend to segregate into a bimodal distribution. This is best evidenced by the colour–magnitude (or colour–stellar mass) diagram, in which two clear loci are preferentially occupied by the blue and the red populations, known respectively as the "blue cloud" (or sometimes "blue sequence") and the "red sequence". Galaxy colours reflect the ages and star formation histories of the mean galaxy stellar population. To understand the origin of the observed colour bimodality would therefore help to shed light on the main galaxy evolution mechanisms at play and their relative timescales. It is now commonly accepted that the total stellar mass within the blue cloud shows very little growth since $z \sim 1$, while the red sequence has grown by at least a factor ~ 2 (e.g. Cimatti et al. 2006; Arnouts et al. 2007). The most popular scenario invoked to explain the growth of red galaxies is a migration of a significant fraction of star-forming systems from the blue cloud to the red sequence, due to different quenching processes. Observational studies of high-mass (central) galaxies prefer a self-regulated mass quenching, while quenching in low-mass (satellite) galaxies has likely been mainly due to environmental and/or merging influences (e.g. Peng et al. 2010, 2012; Wetzel et al. 2014).

When a narrow luminosity bin is considered, the resulting distribution of colours can be described fairly well as a sum of two Gauss functions, although it has also been shown that an additional, intermediate population, inhabiting the so-called "green valley" between the two main sequences, may also be required (Wyder et al. 2007; Mendez et al. 2011; Schawinski et al. 2009; Coppa et al. 2011; Loh et al. 2010; Lackner & Gunn 2012; Brammer et al. 2009). These objects are commonly thought to represent a transition phase from the blue cloud to the red sequence, showing the star formation quenching mechanism at work (Pozzetti et al. 2010). Arnouts et al. (2013) found that actively star–forming and quiescent galaxies segregate themselves particularly well in the $NUV - r$ versus $r - K$ plane. More recently Moutard et al. (2016), using the multi–wavelength information collected in the VIPERS region, reported a locus in the $NUVrK$ diagram inhabited by massive galaxies with a variety of morphologies probably transiting from the star forming to the quiescent populations. A similar behavior is observed out to $z = 1.3$ (Coppa et al. 2011) and the "green valley" population is still present when using different rest-frame colours, such as $U - B$ (Nandra et al. 2007; Yan et al. 2011), $U - V$ (Brammer et al. 2009; Moresco et al. 2010) and $NUV - r$ (Wyder et al. 2007; Fritz et al. 2014).

Understanding the physical processes responsible for the observed bimodality in morphology and colour and its dependence on the galaxy environment is a major challenge in the field of galaxy evolution (e.g. Tasca et al. 2009). To shed some light on how the progenitors of galaxies in the local universe have acquired their shapes and physical properties, large surveys, as well as the classification of galaxies at different epochs, are needed. The VIMOS Public Extragalactic Survey (VIPERS; Guzzo & The Vipers Team 2013) fulfills these requirements over the redshift range $0.5 < z < 1.2$. VIPERS is a spectroscopic redshift survey which provides on one side a unique combination of volume and density, and on the other side excellent 5–band photometric coverage with the Canada–France–Hawaii Telescope Legacy Survey Wide (CFHTLS-Wide), suitable to obtain galaxy morphologies, colours and rest-frame spectral energy distributions (SEDs), from which physical properties such as stellar mass can be derived (e.g. Fritz et al. 2014).

The purpose of this work is to develop a robust method to classify galaxies from intermediate redshift range in order to analyse their colour and morphological observational parameters from ground-based observations.

This paper is organized as follows. In Sect. 2 we summarize the data used. In Sect. 3, we describe the method of bimodality analysis using galaxy colour and redshift and discuss the evolutionary trends in colour bimodality. In Sect. 4 we present the methodology of measurement of Sérsic parameters of the VIPERS galaxies from the CFHTLS images, discuss the bimodality of the Sérsic index distribution and present evolutionary effects on the Sérsic index. In Sect. 5 we compare our results with the published relations involving the measurement of the Sérsic index. In Sect. 6 we introduce a new method to classify galaxies, fully exploiting the 2D distribution in the colour-shape plane as a function of rest-frame magnitude and redshift. In Sect. 7 we discuss the implication for the evolution of early- and late-type galaxies of this new classification scheme and we summarise our results in Sect. 8. In Appendix. A and B we show the tests of reliability of the Sérsic function profile fitting procedure.

For clarity, for the remainder of this article when describing the two main galaxy populations we will call them red and blue when they have been selected simply according to their colours, spheroid-like and disc-like when selected solely based upon their Sérsic index, and early-type and late-type when the populations are selected from both colour and morphology.

In our analysis all magnitudes are given in the AB photometric system. Throughout the cosmological model with a matter density parameter $\Omega_m = 0.3$, cosmological constant density parameter $\Omega_\Lambda = 0.7$ and Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} is assumed.

2. Data

2.1. The VIPERS project

The VIMOS Public Extragalactic Redshift Survey (VIPERS) is an ESO Large Programme aimed at measuring redshifts for $\sim 10^5$ galaxies at $0.5 < z \lesssim 1.2$, to accurately and robustly measure clustering, the growth of structure (through redshift-space distortions), and galaxy properties at an epoch when the Universe was about half its current age. Spectroscopic targets were first selected to a limit of $i < 22.5$ in two fields (namely W1 and W4) of the Canada-France-Hawaii Telescope Legacy Survey Wide (CFHTLS T0005 release, Mellier et al. 2008), further applying a simple and robust *gri* colour pre-selection to effectively remove galaxies at $z < 0.5$. Spectra have been observed with the VIMOS multi-object spectrograph (Le Fèvre et al. 2003) at moderate resolution ($R = 210$) using the LR Red grism. This provides a wavelength coverage of 5500 – 9500 Å and a typical radial velocity error of 141 km s^{-1}. Coupled to the "short-slits" observing strategy described in Scodeggio et al. (2009), the colour pre-selection allows us to double the galaxy sampling rate (which is ∼ 40% in the redshift range of interest) with respect to a pure magnitude-limited sample.

At the same time, the total area (about 24 deg^2) and the depth of VIPERS result in a large volume, $5{\times}10^7$ h^{-3} Mpc^3, analogous to that of the local 2dFGRS. Such combination of sampling and depth is unique among current redshift surveys at $z > 0.5$. Further details on the design of VIPERS, along with its data products, can be found in Guzzo et al. (2014).

In the present paper, we investigate the morphological properties of galaxies in the VIPERS Public Data Release 1 (PDR-1, see Garilli et al. 2014), and their interplay with rest-frame colours. This catalogue[1] includes 55 358 galaxies with spectroscopic redshifts (z_{spec}) over about 10 deg^2.

Besides the spectroscopic redshift, each galaxy in the PDR-1 catalogue is provided with u, g, r, i, z apparent magnitudes, as estimated by the Terapix team using `SExtractor` (Bertin & Arnouts 1996). These (MAG_AUTO) magnitudes are part of the CFHTLS-T0005 data release and were derived in double image mode in order to match the same aperture in all bands.

2.2. Photometric data

From the PDR-1 catalogue we selected only galaxies with redshifts measured with the highest reliability, i.e. with quality flag $z_{flag} = [2, 3, 4, 9]$ according to the classification presented in Guzzo et al. (2014) [2]. Moreover, due to small numbers of high-redshift galaxies we restrict our analysis to $z_{spec} \leq 0.95$, reducing the samples to 20 208 and 18 299 galaxies in the W1 and W4 fields respectively.

All spectrophotometric rest-frame properties of the VIPERS galaxies were derived using the SED fitting program Hyperzmass (Bolzonella et al. 2010). Absolute magnitudes were derived using the apparent magnitude that most closely resembles the observed photometric passband, shifted to the redshift of the galaxy under consideration, before applying colour and k-corrections

[1] The PDR-1 catalogue is fully available to the public through the official website http://vipers.inaf.it

[2] The same flag scheme was used in previous spectroscopic surveys as VVDS (Le Fèvre et al. 2013) and zCOSMOS (Lilly et al. 2007).

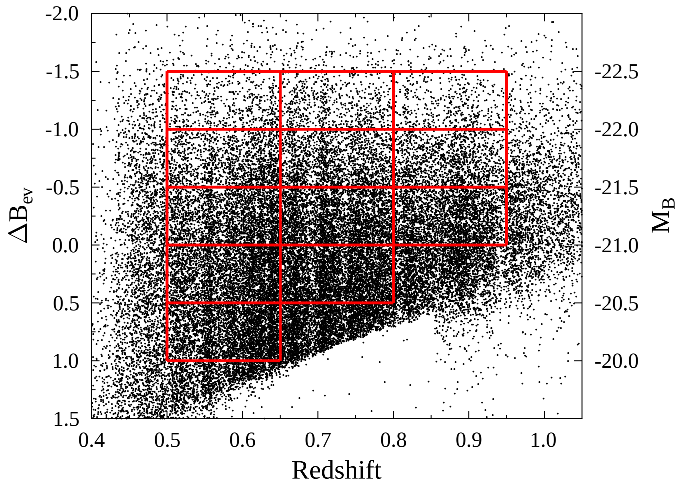

Fig. 1: Distribution of ΔB_{ev} as defined in Eq. 1 for galaxies in the VIPERS sample as a function of redshift z. The red lines enclose the selected sub-samples of galaxies. The right-side vertical axis shows the values of the absolute magnitude M_B for a fixed redshift $z = 0.7$.

derived from the best-fit SED (see details in Fritz et al. 2014). To investigate the dependence of morphology and colour of galaxies on their redshift, we corrected their absolute magnitudes to account for their intrinsic evolution, as derived from the characteristic luminosity parameter (L^*) of the luminosity function (LF) in the Schechter (1976)'s equation. For this purpose, we used the global B-band LF in the redshift range from $z = 0.5$ to 1.3 presented in Table 3 of Fritz et al. (2014). These data have been used to compute the linear approximation of evolution with redshift of the characteristic magnitude B_{ev} and to define the ΔB_{ev} luminosity by the equation:

$$\Delta B_{ev} = M_B - B_{ev}(z) = M_B + 19.90 + 1.59z\,. \quad (1)$$

Considering the evolution of the whole galaxy population, without division them into the blue and red populations, we found a slightly steeper B_{ev} evolution than reported in other studies (e.g. Faber et al. 2007). They found that in the redshift range $0 < z < 1$ the characteristic magnitude B_{ev} evolves in z with a slope -1.23 ± 0.29, whereas our study gives -1.59 ± 0.20. However, the results are consistent within 1σ uncertainties.

In Figure 1 we present the distribution of rest-frame ΔB_{ev} as a function of redshift for the VIPERS galaxies. The left-side vertical axis shows the ΔB_{ev} value, whereas the right-side one gives the absolute magnitude M_B at the mean VIPERS redshift $z = 0.7$. As expected, due to selection effects, we progressively lose the faint population to higher redshifts, leaving only the brighter objects. In the present study we considered 12 volume limited sub-samples represented by the red boxes in Fig. 1. Each subsample is statistically complete, spans $\Delta B_{ev} = 0.5$ magnitudes and a redshift range $\Delta z = 0.15$.

2.3. CFHTLS imaging

The morphological analysis has been based on the study of the 2D surface brightness profile of the VIPERS galaxies. To model the light profile of galaxies in the VIPERS PDR-1 we use CCD images in the i-band from eighteen W1 and eleven W4 CFHTLS fields covering 28 deg^2 of the VIPERS project. While the VIPERS PDR-1 catalogue is based on the Terapix T0005 release, for the analysis of the structural parameters we use a more recent version of the CFHTLS data (i.e. T0006, Goranova et al. 2009). A full description of the CFHTLS data processing including calibration, stacking and mosaicing is provided in Mellier et al. (2008) and Goranova et al. (2009). The public data from Terapix T0006 are organised in $1^\circ \times 1^\circ$ fields and have a pixel scale of $0.186''$. The mean seeing, i.e. full width at half maximum (FWHM) of stellar sources, depends on the filter of the CFHTLS images and is equal to $0.85''$, $0.78''$, $0.72''$, $0.64''$, $0.68''$ in the $u, g, r, i/y$ (the filter i broke in 2006 and it was replaced by a similar, but not identical, filter, called y) and z-bands, respectively (Goranova et al. 2009).

To secure the quality of the derived morphological parameters, we used CCD tiles in the i photometric band where the mean FWHM is smallest. Objects were extracted by independently running `SExtractor` on the CFHTLS tiles in the T0006 release. This means that the centroid of photometric sources can be slightly different from the coordinates of the corresponding VIPERS spectroscopic objects. We associated spectroscopic and photometric sources on the basis of their relative (projected) distance, assuming a maximum matching radius equal to $1''$. For 98.6% of the objects the distance between the VIPERS galaxy (i.e., its position according to T0005) and the one in the T0006 release is less than $0.3''$, and for only 0.3% objects it is larger than $0.5''$. Objects with distance larger than $1''$ were excluded from the present analysis.

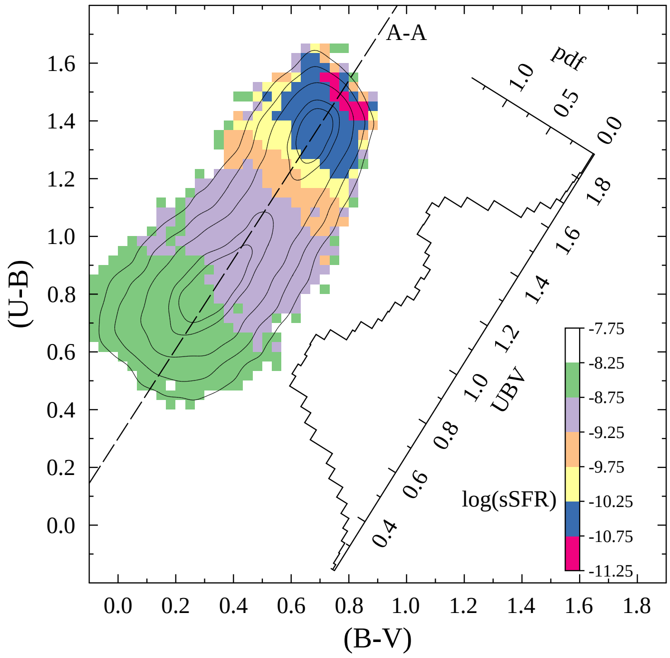

Fig. 2: Density of the VIPERS galaxies in the rest-frame $(U-B)$ versus $(B-V)$ colour-colour diagram. The contour lines show the galaxy density distribution in five equally spaced levels from 10% to 99% of the maximum value. The histogram shows the galaxy number density distribution projected along the line $A-A$ connecting the two maxima of this distribution. The colours show the median sSFR 1/yr values of galaxies derived from SED fitting in seven equally spaced logarithmic bins.

3. Rest-frame colours

3.1. Galaxy colour – based classification

To probe the colour distribution of VIPERS galaxies we use the rest-frame $(U-B)$ versus $(B-V)$ colour-colour plot, based on the absolute magnitudes derived in Fritz et al. (2014).

The isodensity contour lines presented in Fig. 2 show an evident bimodality in the rest-frame colours, with two well separated peaks. We define the combined colour UBV by projecting the galaxy rest-frame colours along the $A-A$ dashed line that connects the two density peaks of Fig. 2. In this way the separation of the red and blue populations is even more prominent than using the one-dimensional analysis, i.e. based only on $(U-B)$ or $(B-V)$ rest-frame colours. The dashed line that defines the combined UBV rest-frame colour is described by the following equation:

$$UBV = (B-V) \times \cos(\theta) - (U-B) \times \sin(\theta), \qquad (2)$$

where $\theta = 58.08^\circ$ is the slope of the $A-A$ line. The UBV rest-frame colour separation of the two peaks along the the UBV line is equal to 0.71, to be compared with 0.61 and 0.37 when it is projected on the $(U-B)$ and $(B-V)$ axes, respectively.

Figure 2 is colour coded by the median specific Star Formation Rate (sSFR is defined as the star formation rate per unit stellar mass of a galaxy) of galaxies inside a given small range of $(U-V)$ and $(B-V)$ colours. The sSFRs are derived via SED fitting. Values of constant sSFR are almost perpendicular to the line connecting the two colours peaks ($A-A$ line), with values of sSFR steadily decreasing with UBV rest-frame colour along the line $A-A$. The correlation between the UBV colours and sSFR is therefore clearly evident, with blue colours corresponding to higher values of sSFR and red galaxies being mostly quiescent. It is also noticeable how this correlation is stronger than the one with $(U-B)$ or $(B-V)$ colours used independently. The local minimum of the UBV probability distribution function corresponds to a value of sSFR $\approx 10^{-10}\,\mathrm{yr}^{-1}$, which is the value adopted by Davidzon et al. (2016) to separate active and passive galaxies at these redshifts. Therefore, even if in the following analysis we will use the colour UBV, we should keep in mind that this parameter can be considered a good proxy of sSFR.

3.2. Galaxy colour bimodality

To investigate the dependence of the UBV rest-frame bimodality on galaxy luminosity and redshift we have computed the distribution of the combined rest-frame colour UBV defined in Eq. 2 in each of the subsamples shown in Fig. 1, i.e. five equally-sized bins in $\Delta B_{\rm ev}$ of width 0.5 mag and three bins in redshift each of width 0.15 in z ($0.50 < z \leq 0.65$, $0.65 < z \leq 0.80$ and $0.80 < z \leq 0.95$). The results are presented in Fig. 3. The bimodality is a persistent feature over the whole luminosity-redshift range explored. The shape of the PDF, however changes. The red population (the red line) is dominant at bright luminosities, whereas the blue population (blue line) becomes increasingly important in the faintest magnitude bins. As already mentioned in Sect. 1, many studies have reported and described this colour bimodality in galaxies out to $z \sim 2$ (e.g Strateva et al. 2001; Blanton et al. 2003; Baldry et al. 2004; Bell et al. 2004; Willmer et al. 2006; Faber et al. 2007; Blanton & Berlind 2007; Fritz et al. 2014).

The optical colour distribution is in general well modeled by the sum of two Gauss functions (Strateva et al. 2001; Baldry et al. 2004; Ball et al. 2008). Figure 3 also shows that the UBV rest-frame colour distribution is well approximated by the sum of two Gaussians (the brown curves), in agreement with previous

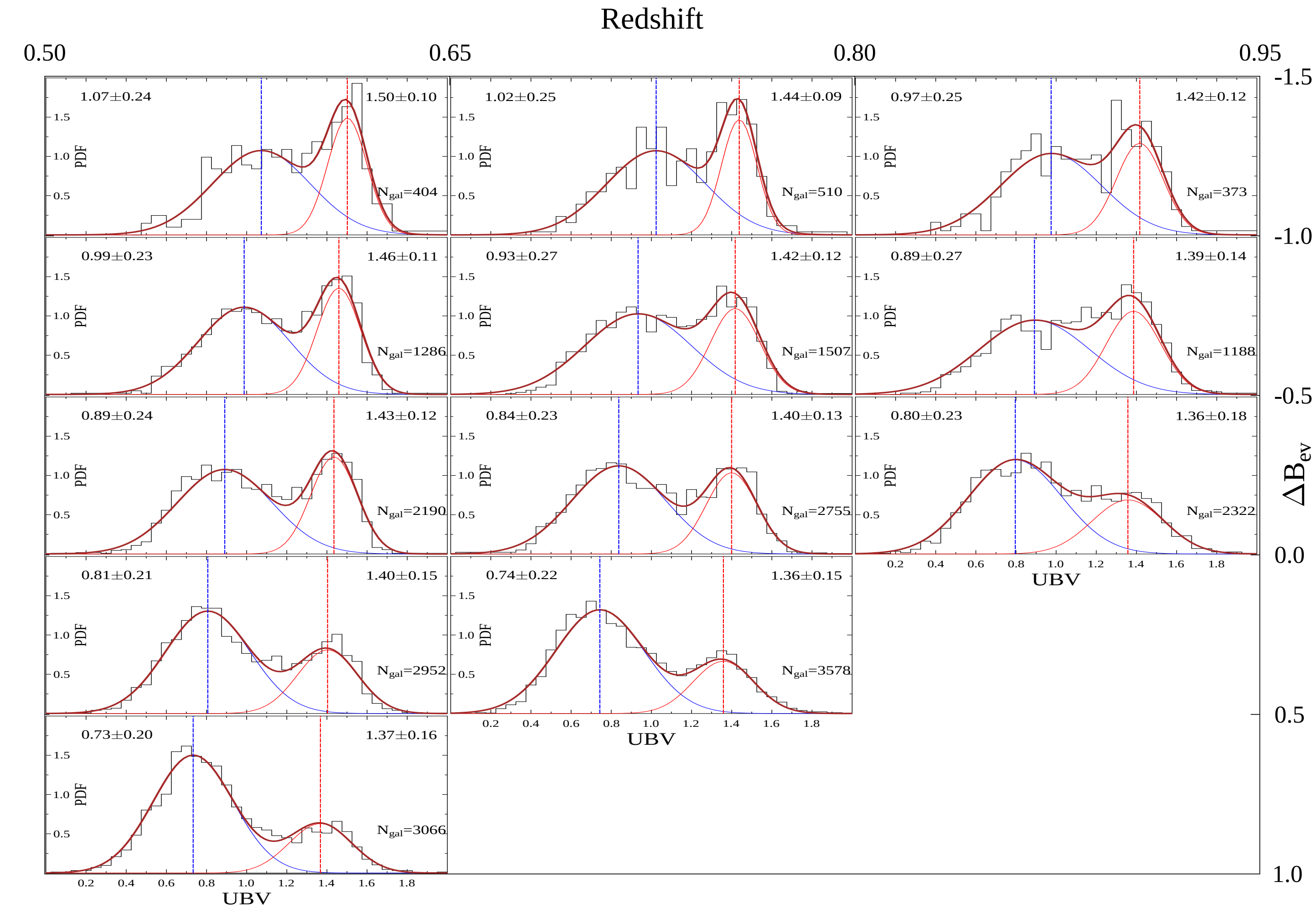

Fig. 3: UBV rest-frame colour distributions (black histograms) of VIPERS galaxies in different redshift (increasing from left to right) and luminosity (from top to bottom) bins. The blue and red curves represent the Gaussian components fitting the colour distribution of the two galaxy populations, and the vertical dashed lines mark the maxima of the Gauss functions. The solid brown line shows the sum of the two Gaussians. The central values and 1σ widths of the Gaussians for the blue and red galaxy populations are labeled in each panel, in the top left and right respectively. The number of galaxies considered in each bin is also shown in the bottom right of each panel.

results (e.g. Baldry et al. 2004) Similar results are also found in e.g. Ball et al. (2008), González et al. (2009).

The mean and the dispersion of each Gaussian component (the blue and red curves) depend on magnitude and redshift. The blue objects are characterised by a larger dispersion in colour than the red ones, which justifies the terms blue cloud and red sequence generally used to characterize the two populations.

The local minimum is thought to be populated by objects that are evolving from star forming to quiescent galaxies. We did not find a significant excess of objects between the two main galaxy populations with respect to the sum of the two Gauss functions, meaning that there is no statistical evidence of a third population of objects. This is at variance with the results of other analyses which claim to find an excess of objects in the region between the two peaks (e.g. Wyder et al. 2007; Mendez et al. 2011; Schawinski et al. 2009; Coppa et al. 2011; Loh et al. 2010; Lackner & Gunn 2012; Brammer et al. 2009). This excess of galaxies is usually found in the distribution of several colour indices, such as $U - B$ (Nandra et al. 2007; Yan et al. 2011), $U - V$ (Brammer et al. 2009; Moresco et al. 2010) and $NUV - r$ (Wyder et al. 2007; Fritz et al. 2014). In particular, Wyder et al. (2007) show that the $NUV - r$ colour distribution is not strictly the sum of two Gaussians, and Coppa et al. (2011), using zCOSMOS data in the redshift range $0.5 < z < 1.3$, reported a third galaxy population located between the blue and red populations. The lack of the third galaxy population located between two Gaussians peaks is possibly related with the fine size of luminosity and redshift bins used in this study. The excess of galaxies with respect to the the sum of the two Gaussians appears when using a coarser grid redshift or luminosity. Moreover, the UBV rest-frame colour, being an excellent proxy to sSFR, is more efficient at separating different galaxy populations and less prone contaminant objects that could populate the intermediate colours.

While in the local Universe the colour-magnitude diagram is effective at dividing galaxies into different populations (e.g. Strateva et al. 2001; Baldry et al. 2004; Wyder et al. 2007), to study distant galaxies it becomes important to consider how the selection depends also on galaxy luminosity and redshift (Bell et al. 2004). Exploring the effects of the luminosity and redshifts in the VIPERS sample, we reveal the systematic blueing of both the blue and red populations moving towards fainter magnitudes at fixed redshift (blue and red vertical lines in Fig. 3). Quantitatively, the blue cloud moves from $UBV = 1.07$ to 0.73 and the red sequence from $UBV = 1.50$ to 1.37 at $z = [0.50, 0.65]$ for values of $\Delta B_{\rm ev}$ increasing from −1.5 to 1.0. Similar trends in the analysis of the $u-r$ rest-frame colour have been found in the low redshift universe by Ball et al. (2008) and Mendez et al. (2011) using the SDSS galaxy sample. Moreover, both populations in Fig. 3 evolve toward bluer colours moving to higher redshifts.

The positions of the Gaussian maxima of the red and blue populations can be described by the following formalism:

$$UBV_{\rm b} = 1.06(\pm0.02) - 0.36(\pm0.03)z - 0.18(\pm0.01)\Delta B_{\rm ev} \quad (3)$$

$$UBV_{\rm r} = 1.56(\pm0.02) - 0.26(\pm0.02)z - 0.06(\pm0.01)\Delta B_{\rm ev} \quad (4)$$

where z is the redshift, $\Delta B_{\rm ev}$ is the distance from the evolving characteristic luminosity as defined in Eq. 1, and $UBV_{\rm b}$ and $UBV_{\rm r}$ are the central positions of the blue and red galaxy distributions, respectively. The quoted errors on the coefficients were estimated through a bootstrap procedure using 1000 resamplings.

4. Sérsic index

4.1. Estimation of Sérsic parameters

To derive the surface brightness parameters of VIPERS galaxies, we have performed a 2D fit of the observed galaxy i-band light distribution with a PSF-convolved Sérsic model. We used the single component Sérsic (1963) profile given by the equation:

$$I(r) = I_e \exp\left\{-b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]\right\}, \quad (5)$$

where r_e is the radius enclosing half of the total light of the galaxy, I_e is the mean surface brightness at r_e, and b_n is a normalization factor, which is chosen in such a way that r_e corresponds to the half-light radius (Graham & Driver 2005). This parametrization well describes the light distributions of elliptical, spiral and irregular galaxies (see e.g. Trujillo et al. 2001a). The detailed analytical properties of Eq. (5) are discussed e.g. by Ciotti & Bertin (1999), Trujillo et al. (2001b), Graham & Driver (2005).

To perform the fit we used the code GALFIT (Peng et al. 2002). The fitting procedure of GALFIT provides the value of the semi-major axis (a_e), the axial ratio (b/a) of the profile, from which the circularised effective radius ($r_e = a_e\sqrt{b/a}$) is derived, as well as the Sérsic index n, and the apparent magnitude of the modeled galaxy.

We used the CFHTLS-T0006 images of VIPERS targets, and divided each 1° × 1° tile into postage stamps centred on each VIPERS galaxy (see some examples in Fig. 4). To define the size of the postage stamps, we rely on the `SExtractor` parameters, which describe the ellipse associated to a given i-band detection, namely $R_{\rm K}$ (KRON_RADIUS), A, B (A_IMAGE, B_IMAGE) and θ (THETA_IMAGE). The centre of each postage stamp coincides with the centroid of the `SExtractor` ellipse, while its sides (Δx and Δy) are four times larger than the projected total dimension of the ellipse on the x and y axis, i.e.

$$\Delta x = 8R_{\rm K}\sqrt{(A\cos\theta)^2 + (B\sin\theta)^2},$$
$$\Delta y = 8R_{\rm K}\sqrt{(A\sin\theta)^2 + (B\cos\theta)^2}. \quad (6)$$

These sizes ensure that each postage stamp has sufficient object-free pixels to estimate the background emission, which plays an important role in galaxy image fitting.

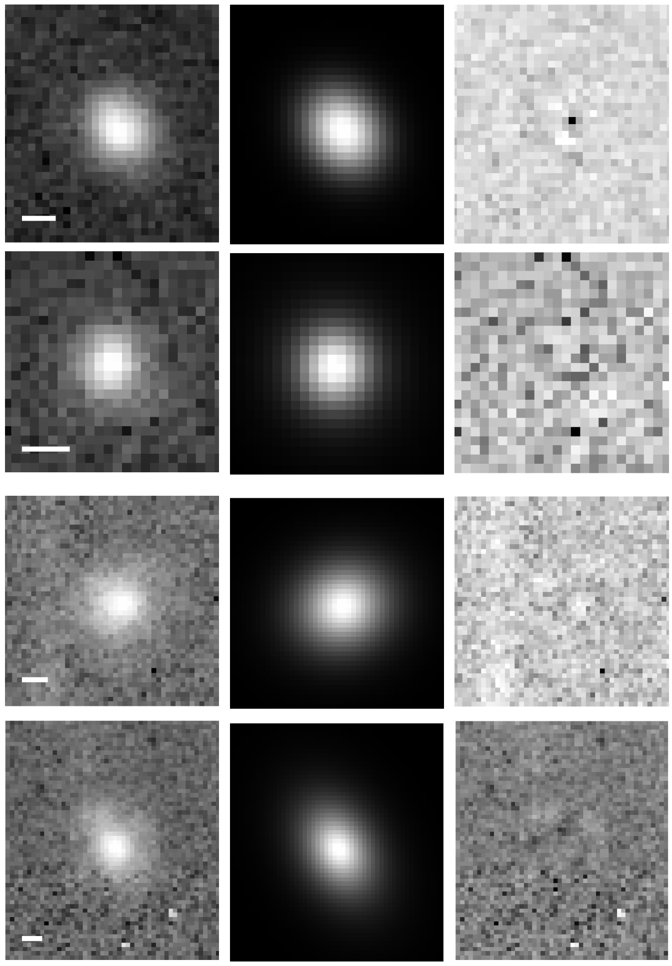

Fig. 4: Four examples of the GALFIT image decomposition procedure. Left column: postage stamps with observed galaxies; middle column: best-fit PSF-convolved Sérsic model to each galaxy; right column: residual images. The small horizontal bars in the left column correspond to 1″.

There are two main approaches to estimating the level of background emission. In the first procedure the background is characterised independently of the analysis of the target object, computed *a priori* e.g. from an annular region surrounding the galaxy (Barden et al. 2005; Häussler et al. 2007; Guo et al. 2009; Fritz et al. 2009; Fritz & Ziegler 2009). In the second method the background is a free parameter that can vary during the GALFIT fitting (Mosleh et al. 2013; Cassata et al. 2011). The Sérsic parameters presented in this paper were obtained adopting this second approach. When the area of the postage stamp is ≈ 10 times larger than the target galaxy and the sky-background variance is uniform, the two methodologies to estimate the background are equivalent (Cassata et al. 2011; Mosleh et al. 2013). These conditions are satisfied in our data.

Postage stamps centred on each galaxy were extracted from the CFHTLS tiles, and SExtractor run to detect all of the objects contained therein. In the fitting procedure, all of the other objects within the postage stamp are masked, unless the aperture ellipse of a secondary object, increased by a factor 1.5, overlaps with that of the main target. In that case, the two (or more) photometric sources are fitted simultaneously to get the best values of the Sérsic profile parameters. The values MAG_AUTO, FLUX_RADIUS, A_IMAGE, B_IMAGE, THETA_IMAGE obtained by SExtractor were used as a first guess of r_e, position angle, ellipticity, and magnitude in GALFIT. In the absence of an estimate of the Sérsic index n, the initial value of this parameter in GALFIT fit was set to $n = 1.7$ for all galaxies.

GALFIT requires a local Point Spread Function (PSF) for each postage stamp to convolve the Sérsic model. The PSF model is generated at the centre of each galaxy using a 2D Chebyshev approximation of the elliptical Moffat function parameters. A detailed description of the PSF construction is given in Appendix B.

Figure 4 shows some examples of the fit performed by GALFIT for VIPERS galaxies. The original image of the galaxy, the best-fit PSF-convolved Sérsic model of each galaxy, and the residual map (real image - model) are shown.

More details about our morphological analysis and the reliability of GALFIT results are presented in Appendix A. Briefly, we added 4000 artificial galaxies to the CFHTLS images with structural parameters generated from the Sérsic indices, magnitudes and effective radii obtained by GALFIT for a randomly-selected subset of the VIPERS galaxies used in this analysis. From these tests we estimate uncertainties in our measurements of n of $|\Delta n|/n = 0.16$ at the 68% level, and 0.33 at the 95% level (i.e. for 95% of galaxies in our sample), while the effective radii are accurate to within 4.4% and 12% for 68% and 95% of our sample respectively. Our tests also confirm that any bias in the n measurements is negligible.

To analyse the galaxies with the best quality Sérsic function parameters obtained from the data we selected only the objects with reduced χ^2 (χ^2_{DoF}) values smaller than 1.2, following Peng et al. (2002). This removes only 4% galaxies in the extreme high-end tail of the χ^2_{DoF} distribution, with the vast majority of fits producing χ^2_{DoF} values in the range 0.9–1.15. We also discarded 261 objects with $n < 0.2$: low values of the Sérsic index imply a lower accuracy in the approximation of the Sérsic b_n normalization factor (Ciotti & Bertin 1999) and introduces a small bias on the distribution of the disk-like profiles, but it is negligible when compared to the error bars of the fitted Sersic index. Similar low-n cuts are commonly used in other studies.

After removing 5707 (12%) bad fitted by GALFIT objects, we obtained our final sample, constituted by 38 620 galaxies. Finally, the volume-limited sample of objects presented in Fig. 1 consists of 22 131 galaxies.

4.2. Sérsic index bimodality

Figure 5 shows the Sérsic index distribution of VIPERS galaxies in the same luminosity and redshift bins as used in Sect. 3.2 for the UBV colour. Since the Sérsic index, n, appears as an exponent in Eq. 5 defining the Sérsic profile (Driver et al. 2006, 2011), a logarithmic-spaced x-axis is used to optimise the analysis and visualisation of the wide range of n values.

Similarly to the UBV histograms shown in Fig. 3, the Sérsic index distribution is bimodal in many of the redshift–luminosity bins. We thus fit each Sérsic index distribution as a sum of two Gauss functions in $\log n$, with one Gaussian component considered to represent the disk-like population (blue curves), and a second to represent the spheroid-like galaxy population (red curves). The sum of the two Gaussian fits (solid brown curves) describes well the Sérsic index distribution at all redshifts and luminosities explored here. Even though for galaxies fainter than the characteristic luminosity of the LF, i.e. $\Delta B_{\rm ev} > 0.0$, the global distribution is not so evidently bimodal, nonetheless it is well reproduced by the sum of the two Gauss functions.

The vertical blue and red dashed lines in Fig. 5 show the central values of the two Gaussian components for each redshift and luminosity bin. Comparing the locations of these lines from panel to panel, we see that the mean Sérsic indices of both disk-like and spheroid-like galaxy populations vary systematically with luminosity and redshift. In particular, both disk-like and spheroid-like populations become increasingly concentrated with increasing luminosity and decreasing redshift.

We find that the best two-dimensional linear fit of these positions in the redshift z versus $\Delta B_{\rm ev}$ luminosity plane is well described by the following equations:

$$\log n_{\rm d} = 0.04(\pm0.01) - 0.16(\pm0.01)z - 0.07(\pm0.01)\Delta B_{\rm ev} \quad (7)$$

$$\log n_{\rm s} = 0.47(\pm0.01) - 0.03(\pm0.01)z - 0.09(\pm0.01)\Delta B_{\rm ev} \quad (8)$$

where $\Delta B_{\rm ev}$ is the luminosity given by Eq. 1 and $n_{\rm d}$ and $n_{\rm s}$ are the mean Sérsic indices of the disc-like and spheroid-like galaxy populations. The errors of the best-fit coefficients were estimated by a bootstrap procedure using 1000 resamplings.

The Sérsic index $n = 1$, commonly used to model the light profile of the disk-like galaxies, is well in the range [0.81,1.11] spanned by the average Sérsic indexes measured within the analysed redshift-luminosity space limits. For spheroid-like galaxies we find mean values in the range [2.42, 3.69], lower than the typical value used to describe nearby elliptical galaxies (i.e., $n = 4$, see de Vaucouleurs 1948). Other authors have reported similar Sérsic indices for early-type galaxies, e.g. $\langle n \rangle = 3.0$ (D'Onofrio 2001), $\langle n \rangle = 3.3$ (Padmanabhan et al. 2004), $n > 2.5$ (Eales et al. 2015; Griffith et al. 2012). Moreover, the tests presented in the Appendix ensure that the Sérsic parameters we have obtained are reliable and that the bias in the estimate of n is negligible for all the redshift and luminosity bins considered in this analysis.

5. Comparison with literature

Previous studies have shown that the Sérsic index of galaxies depends on both their absolute magnitude and redshift (e.g Graham & Guzmán 2003; Tamm & Tenjes 2006; van Dokkum et al. 2010, 2013; Patel et al. 2013; Buitrago et al. 2013). To compare our results with other works Eqs. 7 and 8 are combined with Eq.1 to obtain the following relations:

$$\log n_{\rm d} = -(M_B + 19.30 + 3.74z)/13.75 \quad (9)$$

$$\log n_{\rm s} = -(M_B + 14.87 + 1.87z)/10.68 \quad (10)$$

where the dependence on absolute magnitude is made explicit. The relation between galaxy luminosity and Sérsic index has been reported in many studies for spheroid-like galaxies (e.g. Young & Currie 1994; Graham & Guzmán 2003; Ferrarese et al. 2006). Moreover, a link between structural parameters and luminosity has also been studied by Cross et al. (2004) for E/S0 galaxies in the redshift range from $z = 0.5$ to 1. Equations 9 and 10 show that fainter disc and spheroidal galaxies have lower value of the Sérsic index than the luminous ones and that this relation depends on redshift.

The dependence of Sérsic index on redshift has been analysed in many studies (e.g. Tamm & Tenjes 2006; van Dokkum et al. 2010, 2013; Patel et al. 2013; Buitrago et al. 2013). Figure 6 shows the Sérsic index-redshift relations for both disc-like and spheroid-like populations within VIPERS for three absolute magnitude values and the comparisons with previous studies. In the next sections we analyse in detail the comparison for the two classes of galaxies.

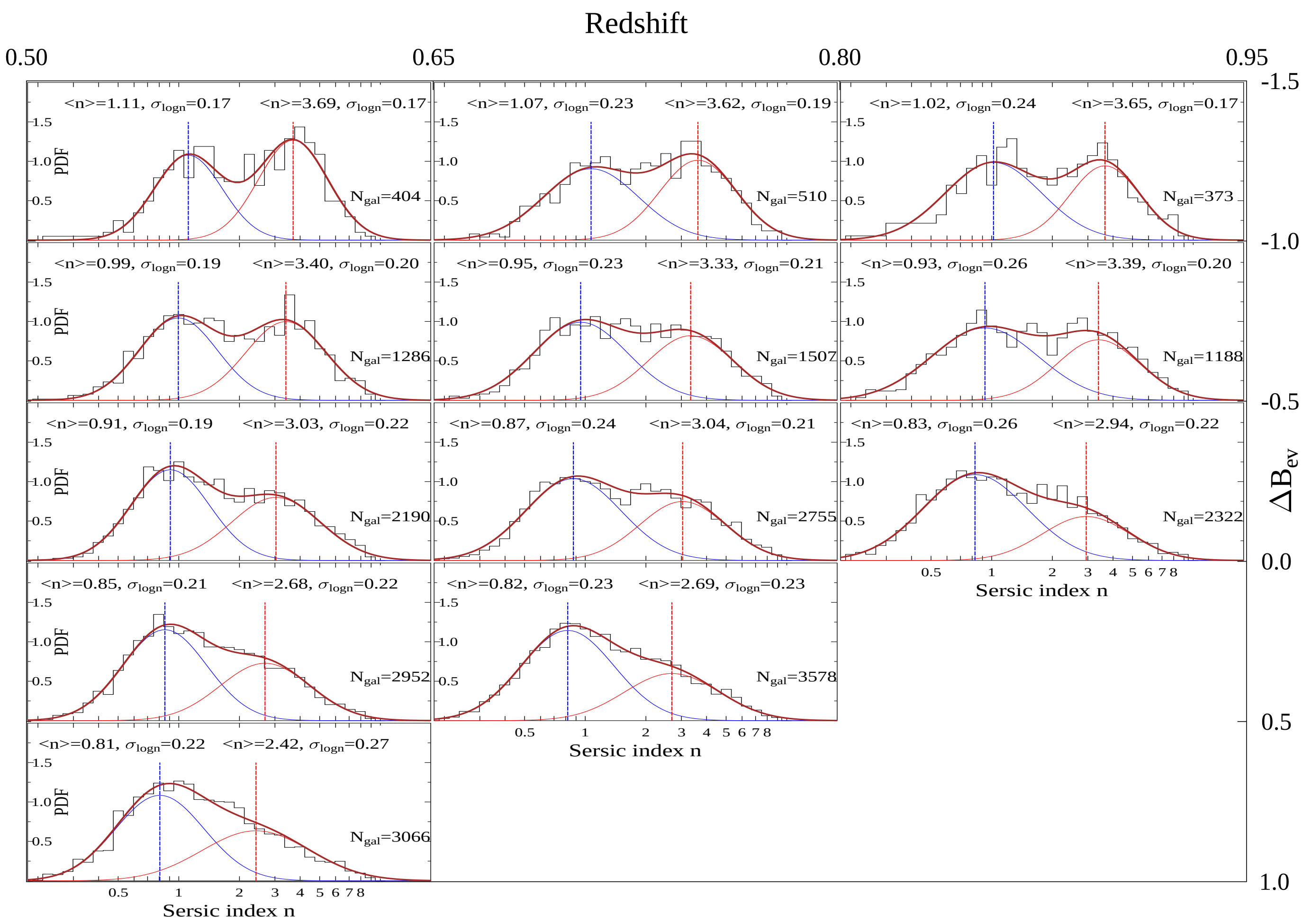

Fig. 5: The Sérsic index distribution (black histograms) for different redshift (from left to right) and $\Delta B_{\rm ev}$ luminosity bins (from top to bottom). The blue and red solid lines show the Gaussian fits to the disc-like and spheroid-like populations, respectively. The vertical dashed lines mark the central values of each Gaussian. The sum of the two Gaussian fits is shown as a solid brown line. The central values $\langle n \rangle$ of the Gauss functions, their 1σ widths, and the total number of galaxies in each bin are shown in each panel.

5.1. Spheroid-like galaxies

Patel et al. (2013) computed structural parameters of massive galaxies in high-resolution HST imaging from the CANDELS and COSMOS surveys, and measured the evolution of the Sérsic index of galaxies in the redshift range $0.25 < z < 3$, after splitting them into quiescent and star-forming populations on the basis of their rest-frame UVJ colours.

The solid red lines show the Sérsic index-redshift relations for spheroid-like populations described by Eq. 10 for three values of B-band absolute magnitude. The solid red circles in Fig. 6 show the median Sérsic indices for quiescent galaxies with $\log(M/M_{\odot}) > 10.5$ in four redshift bins, while the orange dashed line indicates their best-fit Sérsic index–redshift relation over the redshift range $0 < z < 2.5$ of the form $n \propto (1+z)^{-0.50(\pm0.18)}$. The exponent of this relation is consistent with our fit, $n \propto (1+z)^{-0.64}$, we obtain for our brightest ($M_B = -22$) spheroid-like galaxies, which also fulfill their criterion $\log(M/M_{\odot}) > 10.5$.

van Dokkum et al. (2010) measured the Sérsic index parameter from stacked rest-frame R-band (observed J, H-band) images from NEWFIRM Medium Band Survey. They selected a sample at a given constant cumulative number density, which results in their use of a stellar mass limit which evolves with redshift. The stellar mass limit of their selection at our mean redshift $z \sim 0.7$ is $\log(M/M_{\odot}) > 11.35$ and does not vary considerably (< 0.07 dex) in the redshift range we are exploring, $0.5 < z < 0.95$. At these large stellar masses the galaxy population is dominated by quiescent objects. Rather than fitting Sérsic profiles to each individual galaxy, and measuring the mean of the distribution, van Dokkum et al. (2010) created deconvolved stacked images of massive galaxies within bins of redshift and fitted Sérsic functions to the stacked radial surface density profile, the results of which are shown as brown triangles in Fig. 6. They measure a best-fit evolution for the Sérsic index of the form $n = 6.0 \times (1+z)^{-0.95}$ over the range $0 < z < 2$ 0<z<2, presented with the brown line in this plot. The redshift evolution is faster than in Patel et al. (2013), perhaps reflecting the contamination by non-quiescent objects or systematics in measuring Sérsic indices from stacked images, but in good agreement with our results in the common z-range.

Buitrago et al. (2013) estimated quantitative and visual morphologies from HST images of a sample drawn from the DEEP2 and GOODS surveys, combined with a local sample based on SDSS imaging. Their sample of massive $\log(M/M_{\odot}) > 11$ galaxies was then subdivided into early- and late-type galaxies on the basis of the visual classification. The mean Sérsic indices of

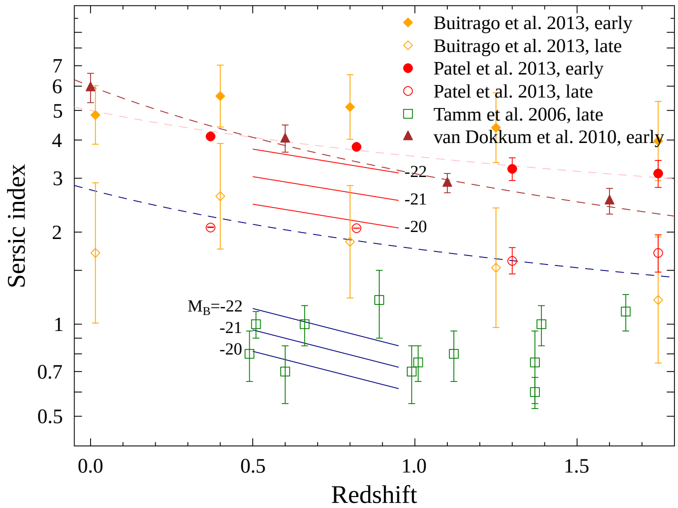

Fig. 6: Sérsic index – redshift relation: VIPERS results are presented as red and blue solid lines for spheroid- and disc-like galaxies respectively for three values of B-band absolute magnitude. Patel et al. (2013)'s results for quiescent and star-forming objects with $\log(M/M_\odot) > 10.5$ are shown as red filled and empty circles and dashed orange and blue lines. The relation found by van Dokkum et al. (2010) for a constant comoving number density sample is plotted in brown (short-dashed line and triangles). Buitrago et al. (2013)'s results for a sample visually classified into early- and late-type galaxies is shown as orange filled and empty diamonds, while disc-galaxies measured by Tamm & Tenjes (2006) are represented by green squares.

visually-selected early-types in bins of redshift are displayed as magenta crosses, and show the same gradual increase in n with time, albeit systematically shifted to higher Sérsic index values by $\Delta n \sim 1.5$. Despite of the different selection criteria, the evolution of the Sérsic index for bright spheroid-like is in good agreement with the relations found in literature for massive quiescent galaxies.

5.2. Disk-like galaxies

The Sérsic index – redshift relation for disc-like galaxies given by Eq. 9 is presented in Fig. 6 by the dark blue lines, and for $M_B = -22$ mag can be written as $n_\mathrm{d} = 1.65(1+z)^{-0.98}$. The dependence of the n-redshift relation on absolute magnitude is smaller for disc-like galaxies than for spheroid-like ones, while its evolution with cosmic time is faster for disc-like galaxies than for spheroid-like ones.

Patel et al. (2013) and Buitrago et al. (2013) found similar, decreasing trends. However, their relations are significantly offset from our results by $\Delta n \sim 1$, probably reflecting the fact that they used selection criteria very different from ours (i.e. star-forming galaxies in Patel et al. 2013 and very massive visually classified late-type galaxies in Buitrago et al. 2013). In particular, we found that the characteristic stellar mass, estimated from the mass – luminosity relation, of our disc-like sample corresponds to a selection of stellar masses smaller than $\log(M/M_\odot) = 10.5$.

For a much more meaningful comparison we turned to the Tamm & Tenjes (2006) sample who measured the Sérsic profile of 22 galaxies in the HDF-S using a selection similar to ours, as they have only considered disk-like galaxies (with $n < 2$) in absolute magnitude range $-17 < M_B < -22$. It is therefore reassuring that theirs results are consistent with ours, as shown in Fig. 6.

Comparing our results with previous work, we find a general good agreement of the evolution of the Sérsic index for spheroid-like galaxies with the ones for quiescent and early-type galaxies. Instead, galaxies defined as star-forming are characterised by larger values of Sérsic index when compared to disk-like ones.

6. Sérsic index – colour distribution

In Sects. 3.2 and 4.2 we independently analysed the UBV rest-frame colour and the logarithm of the Sérsic index n of the VIPERS galaxies as a function of the redshift z and ΔB_ev luminosity. Both parameters show a bimodal distribution. Using the local galaxy sample of the Millennium Galaxy Catalogue, Driver et al. (2006) showed not only that both colour and Sérsic index are characterised by bimodal distributions, but that two well-separated populations exist on the $u - r$ rest-frame colour versus $\log(n)$ plane.

To investigate whether this is still true at high redshift we have repeated Driver et al. (2006) analysis in each of our subsamples. The results are shown in Fig. 7. The colours in each surface density map of this plot are normalised to have values in the range 0–1, so that 1 (dark red colour) is the peak density in each bin. The joint probability distribution of UBV rest-frame colour and Sérsic index n is clearly bimodal in all panels, with two well separated peaks and indicates the presence of two different populations that we identify with early- and late-type galaxies.

The plot shows that the distribution of the late-type galaxies are centred at the Sérsic index value $n \approx 1$ and the rest-frame colour $UBV \approx 0.8$, while those of the early-type galaxies are centred at $UBV \sim 1.4$ and $2.5 < n < 4$. The latter peak appears somewhat elongated along the n-axis and moves towards larger values of the Sérsic index (from $n \sim 2.5$ to 4) with cosmic time, i.e. galaxies become more concentrated at lower redshift. The two peaks are separated by the local minimum located at $UBV \sim 1.2$, corresponding to sSFR $10^{-10}\mathrm{yr}^{-1}$ (see Fig. 2); a value that is often used to separate active from passive objects (e.g. Davidzon et al. 2016). From these plots we see that a more effective separation can be done using the combined Sérsic index n and UBV rest-frame colour information.

We fitted the joint probability distribution of Sérsic index and UBV colour in each redshift-luminosity bin with the sum of two 2D-Gaussians. The iso-density contour lines are separated in step of 0.2 the surface distribution density. The dashed circle around each peak shows the 0.5σ level of each 2D-Gaussian.

We do not include a covariance term for the Gauss functions, to avoid artificially creating apparent correlations between UBV and n within the single populations due to the presence of the second population.

In addition to the dominant populations of early- and late-type galaxies, Fig.7 shows that a fraction of blue galaxies have large values of the Sérsic index ($n \gtrsim 2$), while conversely some red galaxies have a Sérsic index $n \approx 1$, typical of disc-like objects. We postpone a thorough investigation of these peculiar objects to a future analysis.

Moreover, Fig. 7 gives us information on the galaxy morphological type fraction in each luminosity/redshift bin. It shows that the most luminous bins are dominated by early-type galaxies, whereas the late-like galaxies dominate the less luminous subsamples.

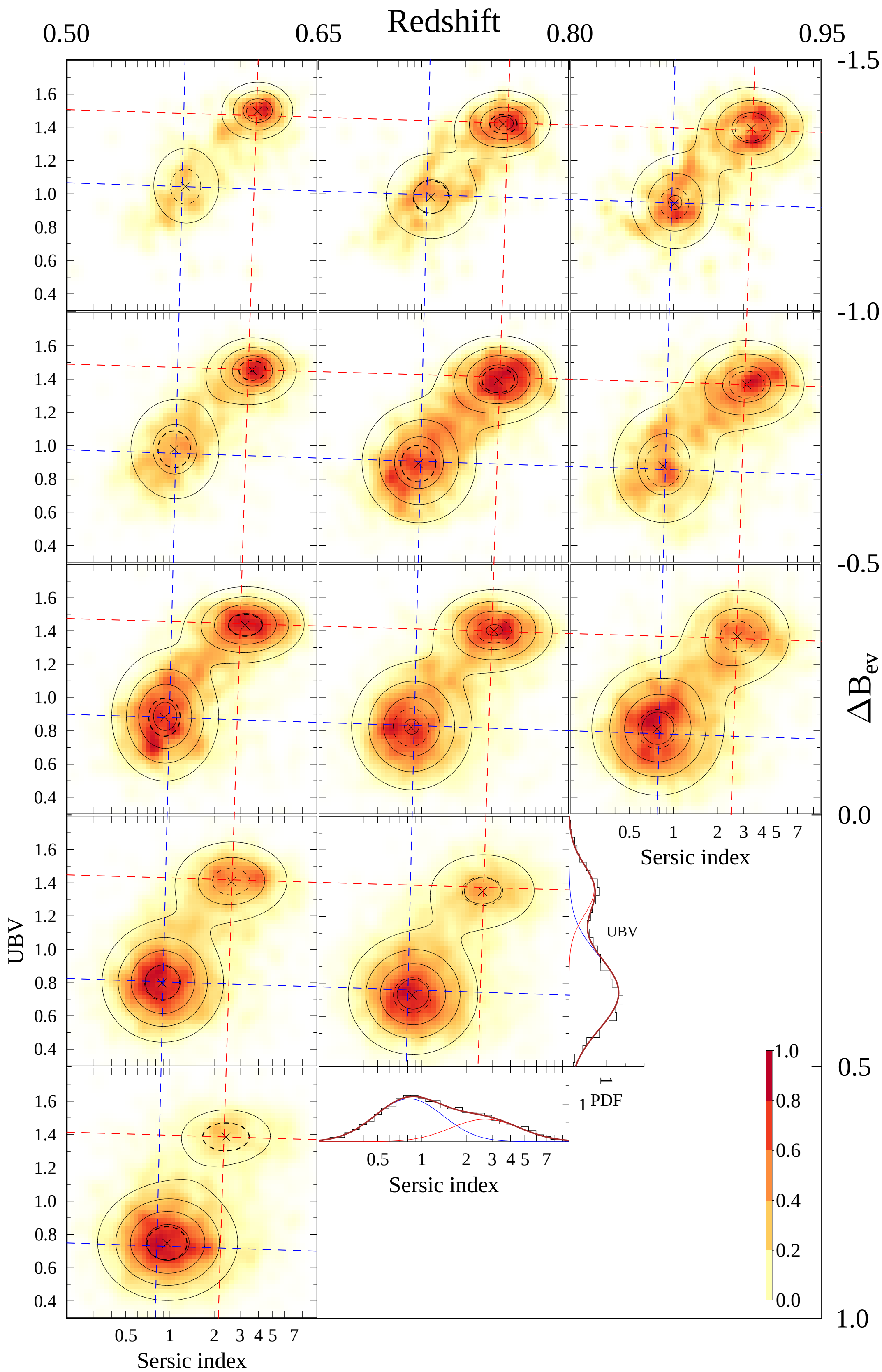

Fig. 7: UBV rest-frame colour vs Sérsic index n distribution. Each panel shows the colour coded galaxy surface density distribution map of the VIPERS galaxies in each redshift and $\Delta B_{\rm ev}$ luminosity bin. The colour bar presented in the bottom right corner gives the normalised galaxy surface density. The contour lines show in steps of 0.2 the density values obtained from the two Gaussians bivariate fitting procedure. The blue and red dashed lines show the 2-dimensional model whereas the crosses identify the positions of the centre of the given galaxy population. The dashed lines around the peaks shows the value of 0.5σ of the Gaussian fit. The histograms present the galaxy distributions projected on the Sérsic index and UBV colour axes, at the bin z = [0.65, 0.80] and $\Delta B_{\rm ev}$ = [0.5, 0.0].

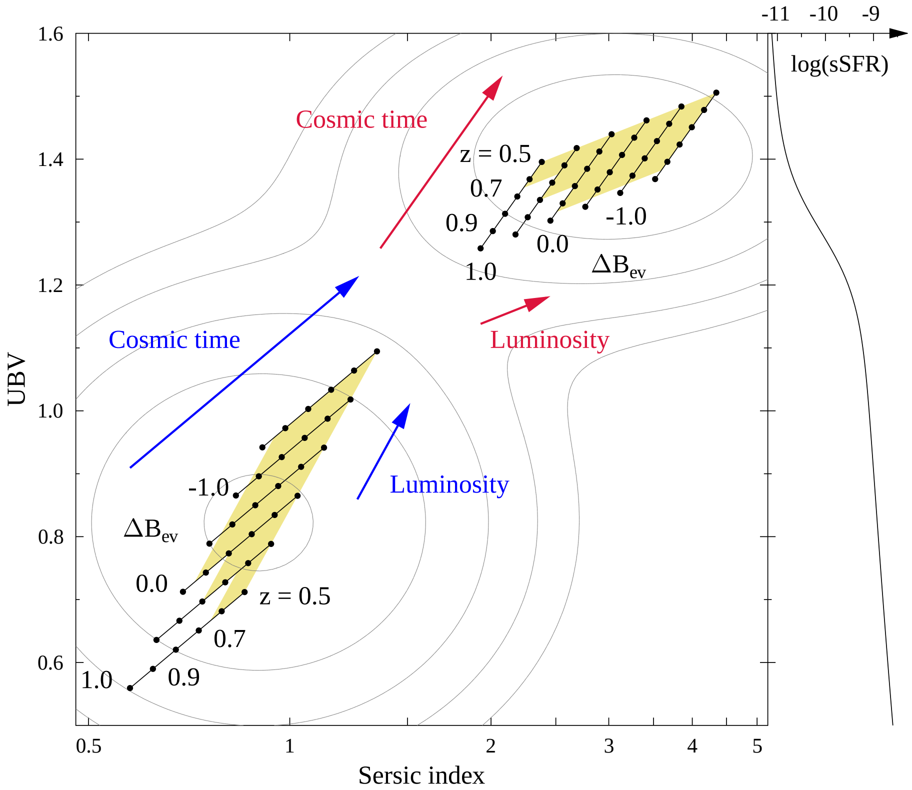

Fig. 8. *UBV* rest-frame colour versus Sérsic index $\log(n)$ relation of late-type (lower left corner) and early-type (upper right corner) galaxies. Dots indicate redshift from $z = 0.5$ to 1.0 in steps of 0.1. Black solid lines connect the values of $\Delta B_{\rm ev}$ from -1.5 to 1 in 0.5 magnitude steps. The arrows show the direction of the redshift and luminosity galaxy evolution. The right plot presents the *UBV* colour versus sSFR relation. The 0.2 dex background contour lines show the bivariate number density of all studied VIPERS galaxies in our sample ($0.5 < z < 0.95$). The yellow coloured regions mark the analysed redshift and luminosity limits, as presented in Fig. 1 and 7.

6.1. Early-type galaxies in the n–UBV plane

The galaxy surface distributions presented in Fig. 7 show that the positions of early- and late-type galaxy populations change with both redshift and luminosity.

Fitting the sum of two 2D Gauss functions to the distributions in each bin we obtain the positions of the population centres ($\log(n)$, UBV). Using these positions we determined the empirical relation connecting the galaxy population centre with $\Delta B_{\rm ev}$ and redshift. Our results in Sects.3.2 and 4.2 showed that the *UBV* rest-frame colour and the Sérsic index $\log(n)$ are well reproduced by a linear dependence on redshift and luminosity. We thus fit the position of the early-type galaxy population centre ($\log(n_{\rm e})$, $UBV_{\rm e}$) in Fig. 7 with a two-dimensional linear function, obtaining the following set of equations describing the central position of this galaxy population as a function of redshift and luminosity:

$$UBV_{\rm e} = 1.58(\pm0.02) - 0.27(\pm0.03)z - 0.04(\pm0.01)\Delta B_{\rm ev} \quad (11)$$

$$\log(n_{\rm e}) = 0.57(\pm0.03) - 0.18(\pm0.04)z - 0.10(\pm0.01)\Delta B_{\rm ev}, \quad (12)$$

where $\Delta B_{\rm ev}$ is given by Eq. 1. The errors of the fitted coefficients were estimated by a bootstrap procedure using 1000 resamples.

The relations given by Eqs. 11 and 12 were used to compute the central *UBV* and n values for the early-type galaxy populations in each redshift and luminosity bin and are shown as crosses in Fig. 7. Comparing these positions with the shape of the higher density contour lines and the 0.5σ widths of the 2D Gaussian fits (marked as dashed ellipses) we find that the simple linear approximation given above well predicts the observed peak position of the early-type galaxy population. The mean distance between the maxima positions from data and linear model is smaller than 0.1σ.

6.2. Late-type galaxies in the n–UBV plane

The same procedure was also applied to the late-type galaxy distributions. The following set of equations describes the central position ($UBV_{\rm l}$, $\log(n_{\rm l})$) of the late-type galaxy population as a function of redshift and luminosity:

$$UBV_{\rm l} = 1.02(\pm0.03) - 0.31(\pm0.05)z - 0.15(\pm0.01)\Delta B_{\rm ev} \quad (13)$$

$$\log(n_{\rm l}) = 0.18(\pm0.03) - 0.34(\pm0.04)z - 0.08(\pm0.01)\Delta B_{\rm ev}. \quad (14)$$

The crosses in Fig. 7 show the position of the late-type galaxies distribution centre given by Eqs. 13 and 14. The plot shows that our linear model well reproduces the positions of galaxy density maxima, with distance from the maxima computed from data smaller than 0.1σ.

6.3. Comparison of 1D to 2D approximation

In Sects.3.2 and 4.2 we focussed our attention on the 1D distributions of the Sérsic index and *UBV* rest-frame colour. It is worth comparing those results with the ones obtained from the 2D approximation. We find that both approaches give almost the same results for the *UBV* rest-frame colour position of the galaxy populations centres. The 1D relations given by Eqs. 3 and 4 and the 2D ones presented by Eqs. 11, 13 are consistent with each other within $\pm1\sigma$ of the fitted parameters.

However, some significant differences occur in the approximation of the Sérsic index $\log(n)$ positions. The coefficients representing the redshift dependence in the 1D relations given by Eqs. 7, 8 and the 2D ones presented by Eqs. 12, 14 are different, with the redshift dependence in the 1D representation being significantly shallower than the one obtained with the 2D analysis. The origin of this difference is evident when comparing Figs. 7 and Fig. 5: the 2D galaxy distribution very well separates both galaxy populations for all $\Delta B_{\rm ev}$ luminosity and redshift bins. In contrast, in the 1D projection of the Sérsic index log(n) these distributions partially overlap each other, especially for the less luminous disc- and spheroid-like galaxy populations, as clearly seen in the histograms presented in Fig. 5. Because of this, the results obtained with the 2D approach are much better determined and more robust than those obtained with the 1D analysis.

7. Sersic index – UBV colour coevolution

The analysis presented in the previous sections provides a quantitative description of the Sérsic index – UBV colour relation and its dependence on redshift and the galaxy luminosity. Figure 8 makes use of Eqs. 11, 12, 13 and 14 to present these dependencies on the Sérsic index versus UBV colour plane. Dots represent values given by the equations presented in the previous sections, for redshift from $z = 0.5$ to 1.0 in steps of 0.1, and black lines connect points corresponding to the fixed values of $\Delta B_{\rm ev}$ ranging from -1.5 to 1.0 in steps of 0.5 mag. Contour lines represent the galaxy surface density of the whole VIPERS galaxy sample studied in this paper, in steps of 0.2 dex. The coloured regions highlight the redshift and luminosity limits presented in Figs. 1 and 7. The blue and red arrows indicate the change of values of UBV and Sérsic index log(n) as a function of redshift and luminosity. In Sec. 3.1 we show that the UBV rest-frame colour is well correlated with the sSFR. The approximate relation of UBV colour versus sSFR is presented on the right side of Fig. 8.

The UBV rest-frame colour versus log(n) diagram allows to make a division, at the intermediate redshift $z \approx 0.7$, between the late-type galaxies (presumably, disk-like and blue, mostly star-forming) with $UBV < 1.2$ and $n < 1.5$ and early-type galaxies (presumably, spheroidal and red, mostly quiescent) for which $UBV > 1.2$ and $n > 1.5$.

Figure 8 visually connects four galaxy parameters and allows to present the coevolution of the properties of galaxies belonging to the early- and late-type classes. In fact, from this figure it is already clear that the evolution of the relation between UBV and n is markedly different for early- and late-type galaxies, like also other studies found (e.g. Blanton et al. 2003). We also find that the Sérsic index n of both main morphological galaxy types - disk-like and spheroidal - increases both with their luminosity and cosmic time. This result is consistent with observations and numerical simulations (e.g. Conselice 2003; Conselice et al. 2005; Treu et al. 2005; Bundy et al. 2005; Brook et al. 2006; Aceves et al. 2006; Hopkins et al. 2007).

7.1. Early-type galaxies

The results presented in the previous sections allow us to give a general overview of the colours and structural properties of early-type galaxies (ETGs). Figure 8 shows explicitly the effect of evolution and luminosity on the colours and structural properties of ETGs. Firstly, it confirms that ETGs simultaneously become redder and more concentrated *both* with cosmic time and increasing luminosity (presumably correlated with stellar mass) (Trujillo et al. 2001b; Graham & Guzmán 2003; Tamm & Tenjes 2006; van Dokkum et al. 2010, 2013; Patel et al. 2013; Buitrago et al. 2013). However, the effects of increasing luminosity and cosmic time on early-type galaxies act in different directions. This means that we cannot take a low-luminosity early-type galaxy at $z = 1.0$, and simply wait a few Gyr for it to become as red *and* as concentrated as its high-luminosity counterpart was at $z = 1.0$. At $z = 1.0$, we see that a low-luminosity ($\Delta B_{\rm ev} = +1.0$) red galaxy is 0.10 mag bluer in UBV and 0.6 times less concentrated than its 10 times more luminous ($\Delta B_{\rm ev} = -1.5$) red counterpart.

Following a galaxy evolutionary track, we see that while a galaxy can rapidly redden to match its high-luminosity counterpart by $z = 0.63$, over the same time-scale it only marginally increases its concentration by a factor equal to 1.17, i.e. only a quarter of the amount needed to match that of high-luminosity ETGs at $z = 1.0$. Indeed, even at $z = 0$ (assuming an extrapolation of the linear trends) its Sérsic index will not have increased sufficiently.

Low-luminosity early-types are known to have later formation epochs and more extended bursts of star formation than their high-luminosity counterparts and have delayed star formation histories (e.g. Thomas et al. 2005). The delayed star formation can be also seen tentatively from the plot in Fig. 8, where low luminosity galaxies seem to have on average larger values of sSFR than brighter ones at a fixed redshift.

The results presented here confirm that while it is possible to account for this delay by matching low-luminosity ETGs observed at lower redshifts to higher mass ETGs seen at earlier epochs, and to first order to have stellar populations of equivalent ages (although the metallicities will differ), the lower-luminosity ETGs will still have quite different structural properties, being much less concentrated at fixed stellar age. This fundamental difference likely reflects the less active merger history of lower luminosity (mass) ETGs (e.g. Rodriguez-Gomez et al. 2016; Lacey & Cole 1993; Aceves et al. 2006; De Lucia et al. 2006), meaning they cannot build up the more extended stellar halos of high-mass ETGs.

If we assume that the increase in n is due to major mergers (e.g Aceves et al. 2006) and the continual accretion of material onto the outskirts of the galaxy, the trends of Figure 8 suggest that low-luminosity ETGs do not undergo sufficient minor mergers at late epochs to “catch up” the much more active merger history of high-mass ETGs at $z > 1$.

7.2. Late-type galaxies

At first sight, Figure 8 suggests that late-type galaxies (LTGs) show very similar trends to early-type, becoming simultaneously redder and more concentrated, both with cosmic time (decreasing z) and increasing luminosity. Moreover, the evolution from $z = 1$ to $z = 0.5$ in the UBV vs. log(n) plane is similar in magnitude and direction to that of the early-type population, leaving the separation between the two populations virtually unchanged, as is presented in Fig. 7. Hence, the bimodality appears to neither strengthen or weaken with time, at least for the redshift range studied here.

Interestingly however, the relative impacts of time and luminosity on UBV colour and log(n) appear to have flipped in comparison to that seen among the ETGs. The concentration of LTGs is most dependent on cosmic time, while UBV colour increases mostly with luminosity. At $z = 1.0$, a low-luminosity LTG ($\Delta B_{\rm ev} = +1.0$) is 0.375 mag bluer and 1.6 times less concentrated than its 10 times more luminous counterpart ($\Delta B_{\rm ev} = -1.5$). By following its evolutionary track, it is able to change its structure sufficiently rapidly to match the Sérsic index of its high-luminosity counterpart by $z = 0.41$, but over this same time period it is only expected to become 0.18 mag redder, half of that required to match the UBV colour of the high-luminosity LTG at $z = 1$.

Given the well known systematic decline in specific-SFRs among LTGs over $0 < z < 1$, in which both high- and low-luminosity (stellar mass) spirals see their star formation drop exponentially and in step (e.g. Noeske et al. 2007; Zheng et al. 2007), it is intersting to note that their structural parameters are changing more rapidly than their colours, while UBV colour is more dependent on luminosity. It should in fact be easier to make a spiral galaxy redder by reducing star formation, than an early-type galaxy, as the response to a reduction in star formation is greatest when the galaxy is initially blue (see e.g. Fig. 2 and the right plot of Fig. 8). One explanation could be that the large change in UBV colour with luminosity among LTGs reflects more the increased reddening due to dust in massive spirals rather than a decrease in specific-SFR.

Theoretically, it is expected that the bulge fraction of merger remnants increases with the decreasing gas fraction of the progenitors (e.g. Robertson et al. 2006; Hopkins et al. 2009). The higher luminosity (mass) disk-like galaxies have a higher bulge fraction due to major- and intermediate-mass ratio mergers. The dense luminous part of galaxies are undisturbed during this process and luminous material dominates the central regions of mergers' remnants (Barnes & Hernquist 1992) and their Sérsic index value increases, as is shown in this study.

8. Summary

In this paper we presented the coevolution of the galaxy morphological properties and colours over the redshift range from $z = 0.5$ to 1 combining high-quality imaging data from the CFHT Legacy Survey with the large number of redshift and extended photometry from the VIPERS survey. We used this new dataset to investigate the coevolution of galaxy Sérsic index and UBV rest-frame colour. The galaxy structural parameters were measured by GALFIT fitting the Sérsic profile to the i–band CFHTLS T0006 images. To do this, the PSF of the images was precisely estimated and approximated over the whole of each $1° \times 1°$ tile. The resultant parameters were carefully tested by a set of different methods which confirms the good quality of the fits and reliability of their fitted values. Our results can be summarized as follows:

- We find a clear bimodality of the UBV rest-frame colour and Sérsic index distribution, very well approximated by a sum of two Gaussians over the explored redshift and luminosity ranges. We parametrised the position of the two maxima in UBV and n distributions as a function of luminosity and redshift. This parametrization allow us to analyse the colours and structural parameters of the red and blue, or the spheroidal and disk-like galaxies based on their location in the luminosity–redshift space.
- The 1D and 2D methods show the evident bimodality both of the UBV rest-frame colour and Sérsic index distribution up to redshift $z = 1$.
- The combination of the UBV rest-frame colour and Sérsic index n as a function of redshift and luminosity leads to a precise statistical description of the structure of galaxies and their evolution. Our method of analysis connects four galaxy parameters, i.e. UBV colour, Sérsic index, luminosity and redshift, and allows to present the coevolution of the properties of galaxies belonging to the early- and late-type classes together with their evolution.
- We find that both early- and late-type galaxies simultaneously become redder and more concentrated both with cosmic time and increasing luminosity (stellar mass). Early type galaxies, however, display only a slow change of their concentrations since $z \sim 1$; it is already established by $z \sim 1$ and depends much more strongly on their luminosities. In contrast, late-type galaxies get clearly more concentrated with cosmic time since $z \sim 1$, with only little evolution in colour, which remains dependent mainly on their luminosity. This flipped luminosity (mass) and redshift dependence likely reflects different evolutionary tracks of early- and late-type galaxies before and after $z \sim 1$.

We demonstrated that the method presented in this paper is an improvement manner to separate early- and late-type galaxies, and to study how their colour and morphology depend on luminosity and redshift. This can be used in further investigation of galaxy evolution.

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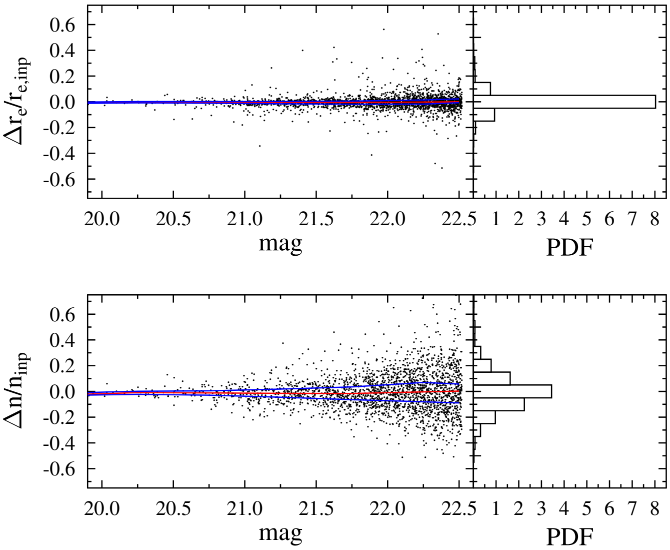

Fig. A.1: Distribution of the fractional deviation of the Sérsic index n and the effective radius r_e as a function of the apparent magnitude. test_n_re_2

Appendix A: Tests of the GALFIT results

To assess the robustness of the presented galaxy profile fitting procedure we perform simulations similar to ones presented in the literature (Häussler et al. 2007; Longhetti et al. 2007; Guo et al. 2009; Pannella et al. 2009; Mosleh et al. 2013). To estimate the accuracy of the results obtained from GALFIT, we applied exactly the same fitting procedure as that used for the real objects to a set of $\sim$ 4000 (i.e. $\sim$10% of a real sample) artificial galaxies.

The simulated objects were generated using the Sérsic parameters from the GALFIT output of the randomly selected VIPERS galaxies. This way gives more realistic shape of the galaxy light profile than the randomly generated parameters of the Sérsic parameters and allows us to compare both results for each single object.

Each simulated profile was added to a different background image. To construct the background we applied the method similar to that proposed by Longhetti et al. (2007). The background image has been obtained by mosaicing different portions of the object-free regions of the CFHTLS tile into one large image. Then the generated profile of each galaxy was superimposed on the randomly selected region of the background. The advantage of this method is that the background retains the same noise characteristic as the real CCD image. Finally the galaxy profile was convolved with the PSF of the shape generated at the galaxy position.

Simulated images of galaxies prepared in this way were analysed by SExtractor and GALFIT using the same procedure as done for the real objects. The results of our tests are presented in Fig. A.2. The top row shows the relation between the input and output parameter values, whereas the bottom one presents the estimated uncertainty of the Sérsic profile parameters, i.e. the half-light radius r_e in pixels, Sérsic index n, axis ratio b/a and apparent magnitude m. The red lines in the bottom figures show the median and the blue lines indicate the 1σ scatter around the median, defined as that which encloses 68% of the points.

The tests results presented in Fig. A.2 show that the galaxy apparent magnitude m is the best recovered Sérsic function parameter in the simulation and the accuracy of its value decreases for the less luminous galaxies. Similar results from GIM2D and GALFIT were obtained by Pannella et al. (2009).

Simulations show that the error of recovered value of the half-light radius r_e is larger for the smaller galaxies. However, even in this case the difference between input and output parameters presented in Fig A.2 is less than 10%. The small systematic differences between those values was also reported in other studies (Häussler et al. 2007; Longhetti et al. 2007; Guo et al. 2009). Moreover, we found that the axis ratio b/a of the galaxy light profile is robust. The uncertainty of this parameter is in the order of a few percent.

The analysis shows that the Sérsic index n is also well recovered. However, in this case we observe a larger fractional deviation scatter around the median than for mentioned previous two parameters. Figure A.2 shows that the fractional deviation of the Sérsic index n is almost uniformly distributed over the n. Similar scatter of the reconstructed parameters is also reported in other studies (Häussler et al. 2007; Longhetti et al. 2007; Guo et al. 2009).

The carried out simulations show a good agreement between the input and output Sérsic function parameters. The 1σ deviation of values (i.e. containing 68% of points) about the parameter median is narrow, and for majority of the tested objects the error of recovered parameters are less than 10%.

In the study of the distant galaxies the typical size of galaxy registered on the CCD images is small and can influence their estimated light profile parameters. In the next tests we verify the accuracy of the Sérsic index n and half-light radius r_e as a function of the apparent magnitude. The results are shown in Figure A.1. As expected, this figure shows that faint galaxies exhibit larger random uncertainties in their Sérsic index $\Delta n/n_{\mathrm{inp}}$ and half-light radius $\Delta r_e/r_{e,\mathrm{inp}}$.

Figure A.1 shows that in both cases the error of recovered parameters is smaller for the luminous galaxies and as expected systematically increases for faint objects. For faint galaxies the external part of the objects can fall under the sky surface brightness and this effect can lead to increases of the value of Sérsic index n. The test shows no systematic. The distribution of errors in the whole analysed luminosity range is symmetric.

The last test we present shows the fractional difference of the Sérsic index as a function of redshift and luminosity. To do this we applied the same binning as was used in our analysis and presented in Fig. 3, 5 and 7, to estimate the reliability of our study.

The simulated $\sim$ 4000 objects were generated using the Sérsic parameters from the GALFIT output as described in the first test. Galaxies are then divided into redshift-luminosity samples to compute mean and standard deviation of the distributions of the fractional difference $\Delta n/n_{\mathrm{inp}}$.

Figure A.3 presents the results and shows histograms and median value with the ±34% scatter around the median. The histograms show that the accuracy of the Sérsic index n estimation decreases both with redshift and luminosity. The most accurate value of n we get is for the nearby and most luminous galaxies. As expected, faint galaxies exhibit larger random uncertainties in their Sérsic index n parameter, what is consistent with the previous test. The histograms and numerical values presented in Fig. A.3 show no systematic deviation of the Sérsic index fitted to the galaxy images. The tests we presented show that Sérsic function parameters computed by GALFIT from CFHTLS CCD images of the VIPERS galaxies are robust.

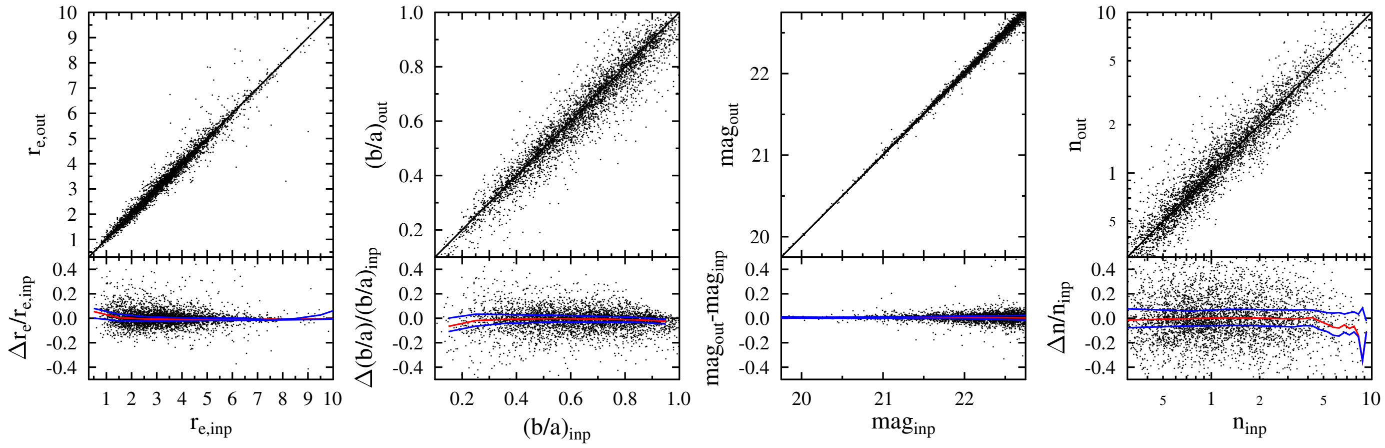

Fig. A.2: The comparison between Sérsic parameters of ~ 4000 simulated galaxies and their recovered values. Bottom plots show the fractional deviation of the parameters as a function of the half-light radius r_e in pixels, minor to major axis ratio b/a, apparent magnitude m and Sérsic index n. The red line shows the median whereas the blue line denotes the 1σ scatter around the median, defined to enclose 68% of the points at a given input value.

Appendix B: Modeling of the PSF

The CFHTLS images were obtained with MegaCam at the prime-focus with wide-field corrector (Boulade et al. 2000). However, while the corrector is optimised to produce a uniformly high quality image of the whole field of view, it also introduces large-scale non-linear geometrical distortions (Cuillandre et al. 1996). This effect together with the seeing significantly disturb the isotropy of the PSF and have to be corrected before any further measurements are done from the images.

The elliptical Point Spread Function for the CFHTLS images can be approximated by the Moffat (1969) function

$$I(r) = I_0 \left(1 + \left(\frac{r}{\alpha}\right)^2\right)^{-\beta}, \tag{B.1}$$

where I_0 is the central luminosity, β is the profile shape parameter and α is the half-light radius of the profile.

To construct a proper PSF for the VIPERS galaxies across the whole $1° \times 1°$ CCD field we carefully selected stars from each CFHTLS tile. The stars were taken from the stellar branch of the SExtractor (Bertin & Arnouts 1996) MAG_AUTO versus FWHM_IMAGE diagram within the apparent magnitude range from 18 to 22 mag. Figure B.1 presents two examples of this diagram computed from images with good and bad quality. In the first plot the vertical region dominated by the point-like objects is sharp wheres in the second one it is significanty wider. To remove small and distorted stars, the objects with SExtractor ISOAREA_IMAGE $\leq$ 10 pixels and ELLIPTICITY > 0.2 were rejected from the analysis. The visual inspection of the CCD images confirmed that these criteria very well select isolated and non-distorted point-like objects.

The average number of stars used for the approximation of the Moffat parameters, and uniformly distributed in each of $1° \times 1°$ CFHTLS tile, is ~ 2000 and varies from field to field (between ~ 1000 and ~ 3500).

However, the applied method might be somewhat restrictive. Because of the image distortion presented in some CFHTLS tiles there are regions where no PSF stars were selected by this algorithm, as shown in the top-left plot in Fig. B.2. This occurs mainly in the regions close to the tile border covering about 2% of the total VIPERS area. Since the quality of the PSF plays such an important role in the GALFIT image deconvolution we excluded galaxies from these regions from the presented analysis.

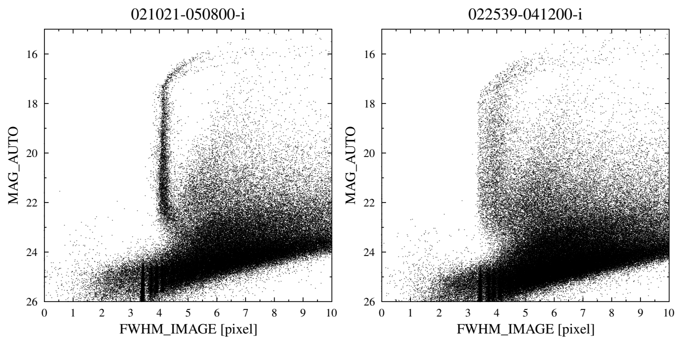

Fig. B.1: MAG_AUTO versus FWHM_IMAGE plot used to select PSF candidate objects for two CFHTLS tiles with good (left panel) and worse (right panel) image quality.

In the next step, a Moffat function was fitted to the images of stars extracted from the CFHTLS tiles in the form of the postage stamps of size 35x35 pixels each, which is more than 10 times larger than the FWHM. Then, for each CFHTLS tile of size of $1° \times 1°$, the fitted parameters of the Moffat function were approximated by the two-dimensional Chebyshev polynomial. The Chebyshev approximation was used due to its numerical stability and the smallest maximum deviation from the approximated function (Dahlquist & Bjorck 1974). We have checked polynomials of degree from 5 to 11 and found that polynominal degree of 7 best approximates the Moffat function parmeters across the CFHTLS tile. In this way, we obtained an analytical form of how each of the Moffat function parameters vary across the whole field, which allowed us to compute the PSF at the position of every galaxy in the tile.

The first verification of our PSF modeling was performed using the whisker plot (Van Waerbeke et al. 2000; Tewes et al. 2012). This diagram demonstrates how the ellipticity e and the orientation θ of PSF stars vary across the field. Each selected star is represented by a line whose length represents the star elliptic-

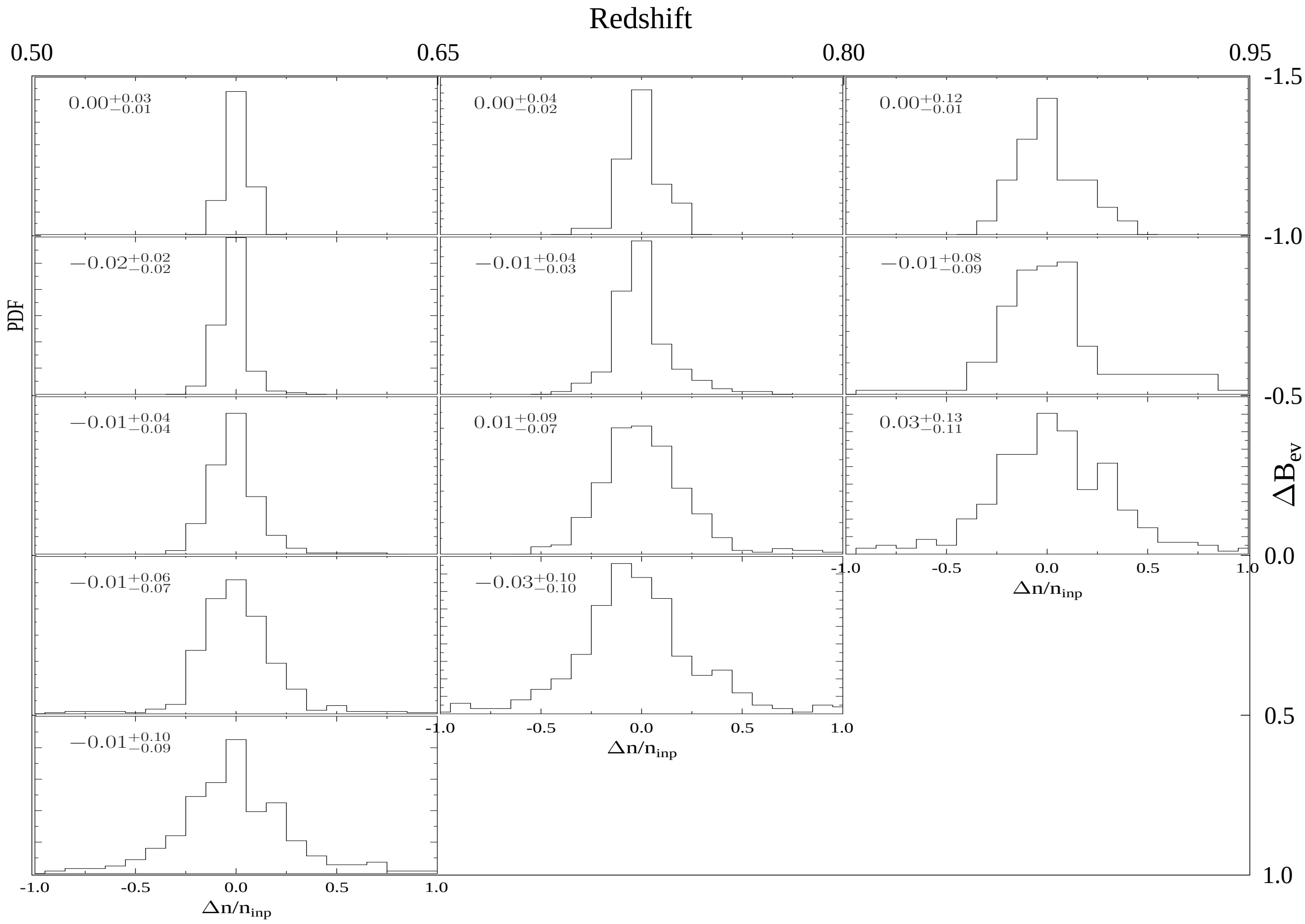

Fig. A.3: Distribution of the fractional deviation of the Sérsic index n as a function of redshift and luminosity. In each bin the histogram of the fractional difference $\Delta n/n_{\mathrm{inp}}$ with their median and 1σ uncertainties around the median (i.e. the 16th and 84th percentile of values) are shown.

ity e, and is orientated to match the position angle of the star's major axis. The colour of each line represent the i-band magnitude of the star. The first plot in the top row of Figure B.2 shows a strong anisotropy of observed stars which should be corrected for. To do this, we applied the complex ellipticities (Tewes et al. 2012) defined by

$$e = \frac{\epsilon - 1}{\epsilon + 1}\exp(i2\theta) = |e|\left(\cos(2\theta) + i\sin(2\theta)\right) = e_1 + i \cdot e_2, \quad \text{(B.2)}$$

where the elongation is defined as $\epsilon = b/a$. This representation is commonly used in anisotropy determination in gravitational lensing analysis (Holhjem et al. 2009; Van Waerbeke et al. 2000).

We performed a 3σ clipping procedure on the corrected stellar complex ellipticities e_1 and e_2 (Tewes et al. 2012), which removed most of the stars whose shape was deformed. After this procedure, for each tile the parameters of the Moffat function were approximated again by the two-dimensional Chebyshev polynomial degree of 7. This iteration leads us to the final analytical approximation of the PSF coefficients used to reconstruct the PSF at the position of each VIPERS galaxy.

As an example of the method described above, Fig. B.2 presents the selected plots obtained from the final Moffat function parameters for the lower quality CFHTLS_022539-041200 tile in $i-$band. The diagrams in the second row of the figure were obtained from our global PSF approximation. The plots presented in the first and second rows show very good correlations between the observed and approximated results. The last row in Fig. B.2 shows the PSFs of stars after the correction for anisotropy. One can observe that the field corrected for telescope anisotropy is almost uniform, which confirms the high quality of our PSF approximation. Even for a tile with an image distortion as high as the one presented in this example, our method accurately maps the variation of the PSF across the whole field of view. This precise modeling plays a vital role in the successful galaxy image decomposition by GALFIT.

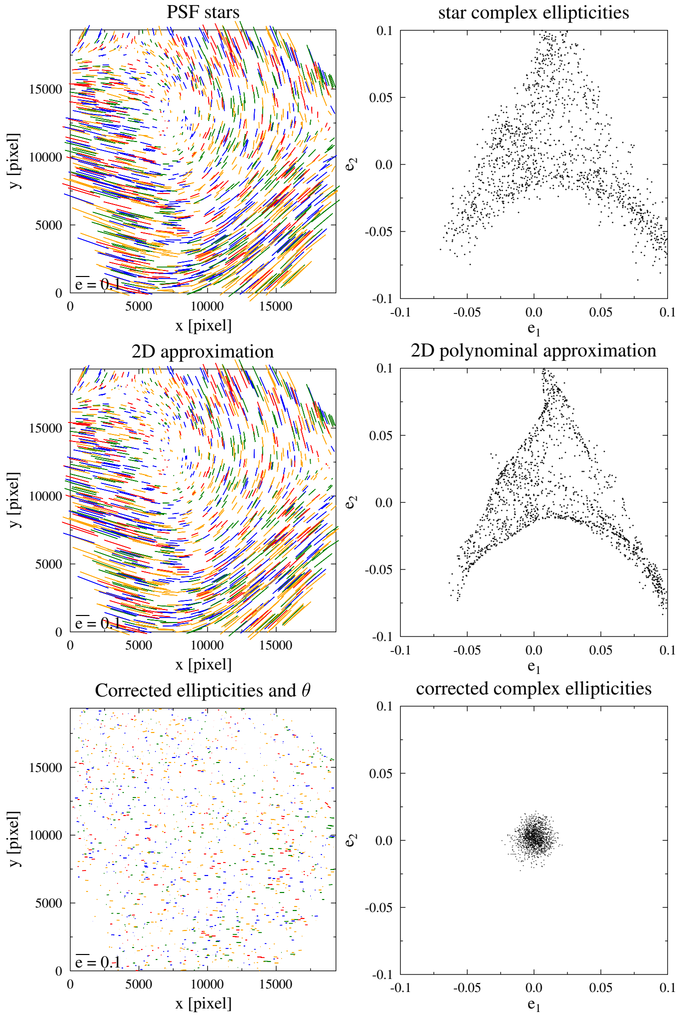

Fig. B.2: Whisker plot (left column) and the complex ellipticities (right column) obtained from the PSF parameters for the 022539-041200 tile in the *i*-band. The upper panels show the results obtained from uncorrected star ellipticities, the middle panels – from the 2D polynomial approximation of the Moffat parameters and the bottom panels – the final results after the correction for the anisotropy was applied. The small bar at the left-bottom corner of all left panels shows the ellipticity $e = 0.1$. Apparent *i* magnitudes are marked by colours: values of 18-19 mag by red, values of 19-20 mag by green, values of 20-21 mag by blue, and values of 21-22 mag by orange.