PASSIVELY EVOLVING EARLY-TYPE GALAXIES AT 1.4 < z < 2.5 IN THE HUBBLE ULTRA DEEP FIELD


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ABSTRACT

We report on a complete sample of 7 luminous early-type galaxies in the Hubble Ultra Deep Field (UDF) with spectroscopic redshifts between 1.39 and 2.47 and to K_{AB} < 23. Using the BzK selection criterion we have pre-selected a set of objects over the UDF which fulfill the photometric conditions for being passively evolving galaxies at z > 1.4. Low-resolution spectra of these objects have been extracted from the HST+ACS grism data taken over the UDF by the GRAPES project. Redshift for the 7 galaxies have been identified based on the UV feature at rest frame 2640 < λ < 2850 Å. This feature is mainly due to a combination of FeII, MgI and MgII absorptions which are characteristic of stellar populations dominated by stars older than ~ 0.5 Gyr. The redshift identification and the passively evolving nature of these galaxies is further supported by the photometric redshifts and by the overall spectral energy distribution (SED), with the ultradeep HST+ACS/NICMOS imaging revealing compact morphologies typical of elliptical/early-type galaxies. From the SED we derive stellar masses of \( \geq 10^{11} M_\odot \) and ages of \( \sim 1 \) Gyr. Their space density at \(< z > = 1.7 \) appears to be roughly a factor of 2–3 smaller than that of their local counterparts, further supporting the notion that such massive and old galaxies are already ubiquitous at early cosmic times. Much smaller effective radii are derived for some of the objects compared to local massive ellipticals, which may be due to morphological K corrections, evolution, or the presence of a central point-like source. Nuclear activity is indeed present in a subset of the galaxies, as revealed by them being hard X-ray sources, hinting to AGN activity having played a role in discontinuing star formation.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: early-types — galaxies: high-redshift — cosmology: observations

1. INTRODUCTION

In the local universe, as accurately measured by the SDSS (e.g., Baldry et al. 2004), passive early type galaxies with stellar masses larger than \( 10^{11} M_\odot \) dominate the counts of most massive galaxies, being a factor of 3 more numerous than late type galaxies above this mass threshold. About 1/3 of all the stars in galaxies in the local universe are hosted by such objects (Baldry et al. 2004). The process by which these galaxies formed is still unclear. At least some of them may have formed at relatively high redshifts, in a process that, for its rapidity, is reminiscent of the monolithic collapse scenario (Eggen, Lynden-Bell & Sandage 1962). On the other hand, others may have been assembled at relatively recent epochs, through merging of smaller subunits (Toomre 1977). The formation of massive spheroids is a central problem of current theories of galaxy formation (e.g., Loeb & Peebles 2003; Gao et al. 2004).

It is now well established that up to \( z \sim 1 \) a significant population of red passively evolving early-type galaxies can be found in the field among extremely red objects (EROs; Cimatti et al. 2002a; Yan et al. 2004; see McCarthy et al. 2004 for a review), together with dust reddened systems. The EROs are highly clustered (Daddi et al. 2000a; McCarthy et al. 2001; Roche et al. 2003; Miyazaki et al. 2003; Brown et al. 2005; Georgakakis et al. 2005) as expected for the progenitors of local massive ellipticals (Daddi et al. 2001; Moustakas & Somerville 2002). The space density of \( z \sim 1 \) early-type galaxies is at least within a factor of 2 of the local value (Daddi et al. 2000b; Pozzetti et al. 2003; Bell et al. 2004; Caputi et al. 2004) implying a modest evolution from \( z = 1 \), especially for the most massive ones. Their stars appear fairly old (\( \sim 3 \) Gyr), suggesting even higher formation redshifts \( z \sim 2 \) (Cimatti et al. 2002a; Treu et al. 2005).

On the other hand, physically motivated galaxy formation models based on hierarchical clustering within the ΛCDM framework (Cole et al. 2001; Kauffmann et al. 1999; Somerville et al. 2001) have been so far unable to account for the large space density of \( z > 1 \) red galaxies (Daddi et al. 2000b; Smith et al. 2001; Firth et al. 2002; Somerville et al. 2004; Glazebrook et al. 2004). These models result in widespread merging and associated star-formation activity of massive galaxies at relatively low-redshifts, and it is currently not fully clear what physical mechanism needs to be involved in order to terminate star-formation and produce the red colors of passive galaxies. Feedback processes, e.g., from the onset of AGN activity, seem to be a promising tool to achieve that (Granato et al. 2001; 2004; Springel et al. 2004). This strengthens the necessity to simultaneously trace the formation of galaxies and AGN activity to understand the link be-
between assembly of stellar mass in galaxies and the growth of supermassive black holes (Mageronian et al. 1998; Ferrarese & Merritt 2000).

As little evolution in massive (> 10^{11} M_\odot) field early-type galaxies is detected up to z = 1, it is necessary to push the investigation to the highest possible redshifts in order to further constrain the formation of early type galaxies. Crucial questions to ask are: up to which redshift do passively evolving early-type galaxies exist?, which is their space density as a function of z?, what is their clustering? and what is the environment they live in (i.e. cluster vs field)? Studying the highest redshift massive and passive objects, i.e. those presumably closest to the formation or assembly epoch, could in principle also reveal useful information to understand the physical processes by which these galaxies were formed.

For almost a decade the unique example of spectroscopically confirmed high-z passive galaxy beyond z ~ 1.5 has been 53W091 at z = 1.55 (Dunlop et al. 1996; Spinrad et al. 1997). This objects was preselected for being a radio-galaxy, hence it was virtually selected over the whole sky. Its very red colors suggested fairly old stellar populations, although with some controversies about detailed age (see e.g., Nolan et al. 2001 and references therein). The North and South Hubble Deep Fields with their extremely deep imaging data prompted searches for z > 1.5 passive galaxy candidates (Treu et al. 1999; Stiavelli et al. 1999; Broadhurst & Bouwens 2000; Benitez et al. 1999), however none of such objects was eventually spectroscopically confirmed. That is due to the faintness of the candidates in the optical domains and because optical spectroscopy from the ground is hampered by the presence of strong OH sky emission lines at the wavelengths where the main spectral features are redshifted. Now, over fields of a few tens to a few hundreds arcmin^2, three groups have recently presented the discovery of several high-z passive galaxies. Cimatti et al. (2004) reports 4 passive galaxies spectroscopically confirmed at 1.6 < z < 1.9 in the K20 survey, from a region within the GOODS-South field. The ACS imaging revealed their compact early-type galaxy like morphologies. McCarthy et al. (2004) have redshifts for 20 passive objects in 1.3 < z < 2.15 (of which 8 at z > 1.5) from the Gemini Deep Field Survey. Saracco et al. 2005 confirm 7 very massive old galaxies at 1.3 < z < 1.7 from low-resolution near-IR spectroscopy. The latter two studies both lack HST morphology information.

While it is now established that a significant population of passive galaxies exist up to z ~ 2 at least, the availability of the Hubble Ultra Deep Field (UDF) dataset, with ultimately deep and high spatial resolution optical and near-IR imaging offers a unique possibility for studying these high-z passive galaxies in some detail. As a part of our Grism ACS Program for Extragalactic Science (GRAPES), we have collected about 50 HST orbits of ACS+G800L grism spectroscopy on the UDF (Pizgkal et al. 2004, 2004 hereafter). As discussed in more detail further in the paper, the HST+ACS spectroscopy allows us to obtain much higher S/N ratios on the continuum than reachable from the ground. In this paper, we have taken advantage of the GRAPES spectra to present spectroscopic confirmation for a sample of 7 early-type galaxies at 1.4 < z < 2.5 in the UDF, and used the available multiwavelength datasets to study their properties.

The paper is organized as follows: in Sect. 2 we comment on the usefulness of low resolution spectra of passive galaxies and a new spectral index is defined for their characterization. Sect. 3 discusses the color selection of z > 1.4 passive galaxy candidates. In Sect. 4 redshift identifications are presented and discussed in detail. Morphological parameters of the 7 objects are derived in Sect. 5. Stellar population properties, including stellar masses and ages, are estimated in Sect. 6. The issue of space density evolution of passive early-type galaxies to z = 2.5 is discussed in Sect. 7, while in Sect. 8 the evolution of morphology is discussed. Sect. 9 presents the X-ray detection of two of the galaxies in our sample. Summary and conclusions are given in Sect. 10.

We assume a Salpeter IMF from 0.1 and 100 M_\odot, and a WMAP flat cosmology with Ω_m = 0.7, Ω_m = 0.27, and h = H_0/[km s^{-1} Mpc^{-1}] = 0.71 (Spergel et al. 2003).

2. UV SPECTRA OF PASSIVE GALAXIES: THE M_guv FEATURE

The low resolution of the HST grism spectra does not allow us to detect individual absorption or emission lines (if not for large equivalent widths, Xu et al. 2005) whose identification generally yields redshift measurements in higher resolution spectroscopy. Nevertheless the GRAPES spectra are well suited for the identification of broad, low resolution spectral features like the strong breaks that are commonly found among old stellar populations. Fig. 1 shows rest frame UV spectra (the region generally accessible to GRAPES HST+ACS for 1.4 < z < 2.5 objects) from Bruzual & Charlot (2003) spectral synthesis models and from Kurucz models of stars (Kurucz et al. 1979), smoothed to the typical resolution of our data. While the 4000Å break and the 3600Å Balmer break rapidly disappear beyond 1μm for z > 1.4, there are other strong age dependent features in the UV that are detectable in relatively low resolution spectra. The most prominent one is a bump in the region 2640-2850Å that is due to the combination of several strong absorption lines, including MgII2800 that is the strongest one. The typical shape of this region was first used by Spinrad et al. (1996) to measure the redshift of the z = 1.55 passive galaxy, and more recently also by Cimatti et al. (2004) and McCarthy et al. (2004). We have dubbed this feature the M_guv feature, and defined the M_guv index as:

\[
M_{guv} = \frac{2 \times (f_{2725} - f_{2625})}{f_{2625} + f_{2825}}
\]

where the integration ranges (see Fig. 1) are defined in Å. The M_guv feature is found to be almost independent of the spectral resolution for R > 50, the typical rest-frame resolution of the spectra discussed in this paper, and on dust extinction. Fig. 2 shows the age dependence of the M_guv feature for passive as well as actively star-forming galaxies. The M_guv feature is a key fingerprint of the presence of passively evolving stellar populations because it is not present in young dust reddened star-forming galaxies (Fig. 1 and 2), which can still produce similarly red overall colors for high dust extinction. Its secure detection therefore allows one to establish the nature of the sources by breaking the age/dusty degeneracy among red sources, as well as the measurement of the galaxy redshift.

3. PASSIVE z > 1.4 GALAXIES: SAMPLE SELECTION

In order to search for high-redshift, passively evolving galaxies among the > 10000 galaxies detected in the UDF, we relied on their peculiar color properties. Candidates of z > 1.4 passively evolving galaxies were pre-selected following the criteria outlined by Daddi et al. (2004b). These were calibrated on the complete K20 survey spectra database that
Passive $z > 1.4$ galaxies in the UDF

FIG. 1.— The mid-UV spectral energy distribution of galaxies from the Bruzual & Charlot (2003) library (left) and of stars from the Kurucz database (right), smoothed to $\sim 50$ Å rest frame resolution, similar to the HST spectra of the objects analysed in this paper. Old simple stellar population (SSP) galaxies or low mass stars have very red spectra and a characteristic signature with a peak and a dip in the region 2640–2850Å, mainly due to a combination of FeII, MgI and MgII absorptions lines. This MgUV feature appears after a few 100 Myr of passive evolution (visible in A-type stars or later) and gets stronger as age increase (notice the 2 order of magnitude UV continuum dimming for SSP galaxies from 0.2 to 2.0 Gyr). Star-forming galaxies with large reddening (dot-dashed line in the left panel) can reach similarly red continua in case of very high reddening, but are distinguished from the former because of the lack of any strong spectral feature in the UV, like OB-type stars. The vertical lines (both panels) show the 3 windows used for the measurement of the MgUV index (Eq. 1).

FIG. 2.— The age dependence of the MgUV index (Eq. 1). The three solid lines correspond to SSP models for three different metallicities $(0.4Z_{\odot}, Z_{\odot}, 2.5Z_{\odot})$; higher metallicity produce a larger MgUV index at fixed age for most of the age range). The dotted line is for a constant star-formation model with $(B-V) = 1.2$. The MgUV index is almost independent on reddening and on the resolution of the spectra for $R > 50$, the typical rest-frame resolution of our GRAPES spectra.

includes the $z > 1.4$ passive and star-forming galaxies described in Cimatti et al. (2004) and Daddi et al. (2004a). Defining the color difference: $B_zK \equiv (z-K)_{AB} - (B-z)_{AB}$, the candidate $z \sim 2$ passive galaxies can be located with $B_zK < -0.2 \cap (z-K)_{AB} > 2.5$ (Daddi et al. 2004b).

Objects satisfying the above condition were retained as a primary sample. However, based on Fig. 8 (bottom-left diagram) of Daddi et al. (2004b), also galaxies having $z - K > 2.5$ and $B_zK > -0.2$ were considered for detailed analysis, as young "proto-ellipticals" could be in principle located at $B_zK > -0.2$. Moreover, despite the extreme depth of $B$-band UDF imaging the errors on $B-z$ colors are found to be large for many red objects with $z - K > 2.5$.

This pre-selection criteria require $B$, $z$, and $K$-band imaging. We have used the deep VLT+ISAAC $K$-band images over the GOODS field (Fig. 3) (Vandame et al. 2005 in preparation), and the ultra-deep ACS images of the UDF for the $B$- and $z$-bands (Beckwith et al. 2005 in preparation). Galaxies were selected over the area of about 12 arcmin$^2$, where deep ACS images are available, requiring total magnitudes $K_{AB} < 23$ as measured by SExtractor MAG_AUTO (Bertin & Arnouts 1996). This is ~1 mag fainter than reached by the K20 survey, while the area is a factor ~3 smaller than the K20/GOODS area that is contiguous and in part overlapping with the UDF area analysed here (Fig. 3).

Fig. 4 show the resulting $B_zK$ diagram. In order to increase the accuracy of the color measurements we have not attempted to reduce the ACS resolution to the much poorer 0.5" seeing of the K-band data. For the ACS bands we used SExtractor MAG_AUTO measured in consistent apertures defined in the $z$-band (double image mode). SExtractor MAG_AUTO measurements were used also for the K-band (single image mode). This results in a different physical aperture of the magnitudes in the optical versus near-IR bands. However, we

9 Available at "http://www.eso.org/science/goods/releases/20040430/"
10 Available at "http://archive.stsci.edu/prepds/udf_hlsp.html"
verified that the resulting $z-K$ was not biased (at least within $\sim 0.05$ mags on average) with respect to seeing matched $z-K$ magnitudes for objects in common to the catalog of Daddi et al. (2004b). There are 20 objects with $z-K > 2.5$ of which 7 have also $B_zK < -0.2$.

4. ANALYSIS: REDSHIFTS AND SPECTRA

To measure the redshifts of the selected candidates, we have used all the available information including high quality HST low resolution optical spectra and the multicolor photometric data available for the UDF, as discussed in the next two sections.

4.1. ACS-HST low-resolution spectroscopy

The ACS-HST grism 800L data, obtained as part of the GRAPES project, cover the wavelength range 5000-11000Å with maximum efficiency around 7000-8000Å. The spectral dispersion is about 40Å/pixel. The low sky background at these wavelengths from space allow HST grism data to be taken in slitless mode, so that all UDF objects are simultaneously observed in the GRAPES data. The effective spectral resolution depends on the spatial size of the objects. For unresolved sources the spectral dispersion translates into a resolution of $R \approx 100$ at 8000Å, while extended sources have lower resolution spectra. Thanks to the absence of OH sky emission lines and the exquisite spatial resolution of HST, the GRAPES low-resolution spectroscopy allows us to reach relatively high S/N ratios on the continuum. For compact galaxies, like the ones considered in this paper, one gets $S/N \sim 10$ at 8000Å over a 100Å region for $i_{AB} \sim 25.5$, for the $10^5$s integration time of the GRAPES data. This is significantly better than what can be reached from the ground with red-optimized CCDs on 8-10m class telescopes with similar integration times, except for the narrow spectral windows free of OH sky emission lines.

The seven passive early-type galaxies with proposed redshift $1.4 \leq z \leq 2.5$ are shown with large symbols. Five occupy the region with $B_zK < -0.2$ as expected (Daddi et al. 2004b), while two bluer objects are also identified.

Full details of GRAPES grism data reduction and calibration are given in P04. As slitless spectroscopy can imply spectra superposition from neighboring sources, the data were obtained at five independent position angles to minimize this effect. Narrow extraction windows (see P04) were used to maximize the S/N ratio of the resulting spectra. The 5 epoch spectra were co-added, avoiding regions contaminated by neighboring objects, as described in P04.

4.2. Spectral analysis

The 20 red galaxies selected as described in Sect. 3 were inspected by looking for the $M_{gUV}$ feature described above, and to their overall spectral shape. Some of the spectra had too low S/N ratio to be useful because the objects are too faint in the optical. Seven objects were retained as likely $z \gtrsim 1.4$ passive objects identifications, five of these having $B_zK < -0.2$. Spectra for these seven galaxies are shown in Fig. 5. The five single epoch spectra of each object were inspected to verify that the detected features were persistent and not due to obviuous spurious artifacts.

In order to objectively identify the redshift of the objects, and to exclude possible features misidentification, we cross correlated the spectra with galaxy templates from the Bruzual & Charlot (2003) library before definitively assigning redshifts. The model templates were convolved with the line spread functions computed from the light profiles of the galaxies to reproduce the actual spectral resolution of the data. Note that this fitting approach is rather conservative because most of the continuum region of the spectra with no detected features have no strong effect on the fitting and reduce the impact of the regions where the actual features are, i.e. it dilutes the signal by giving equal weight to all data in the spectral range.

Two classes of models were adopted for the spectral fits in
order to bracket the general cases of old and passive galaxies versus strongly dust reddened galaxies. For old galaxies we considered simple stellar populations (SSP) and a model with exponentially declining SFR with timescale $\tau = 0.3$ Gyr. Ages less than the age of the universe at each redshift were required and a maximum reddening of $E(B-V) < 0.2$ was allowed. We considered solar and 40% solar metallicity. For dusty galaxies we used constant star-formation rate models with unlimited dust reddening and solar metallicity.

In all seven cases, except for #3523, the models for old passive galaxies converge to the solution guessed by eye, with the $M_{UV}$ feature correctly identified. In most cases dusty models provide a worse fit to the data, however, differences are not large and all reduced $\chi^2$ are below 1 and acceptable. The minima of reduced $\chi^2$ being all below 1 might actually suggest that some significant degree of correlation (e.g., due to the reduction process, P04) is present in the data. Results of the spectral fitting are summarized in Table 1, where in all cases the $z_{\text{spec}}$ is quoted for the best fitting old/passive galaxy model, as justified from the results of the next section. Detailed description of redshift assignment for individual objects is described in Sect. 4.4, following the analysis of the SEDs and photometric redshifts.

4.3. Spectral energy distributions and photometric redshifts

To further constrain the redshift identifications we used the extremely high-quality imaging available on the UDF area. This includes the BVIc ACS imaging and the J and H NICMOS imaging. ISAAC J and K band data were also used, the J-band filter of ISAAC being much narrower than the NICMOS one, as well as V and R from FORS2 that have central wavelengths that are quite different from the ones of the ACS bands. To match ground based and HST datasets we proceeded as discussed in Sect. 3. It was checked that over the common range the photometric SEDs and the HST low resolution spectra were consistent. The SED of the seven $z > 1.4$ early-type galaxies candidates are shown in Fig. 6. The same range of model parameters as for the spectral fitting was used, corresponding to the two classes of old/passive versus dusty models. The hyperz code (Bolzonella et al. 2000) was used for the model fitting and to derive photometric redshifts. A lower limit of 0.05 mags was used for the photometric errors in all the bands, in order to account for photometric zero-point uncertainties and possible residual uncertainties in the

11 practically, for the intrinsically bluest models, $E(B-V) \lesssim 1.5$ is more than sufficient to provide SEDs as red or redder than the data at any redshifts match of the different datasets.

Results of the SED fitting and photometric measurements are summarized in Table 1. SED fitting in all cases result in significantly better fits for models of old/passive galaxies with respect to those for dusty objects, rejecting dusty models at more than $3\sigma$ confidence levels (Avni 1976) in all cases. Best fits have generally acceptable reduced $\chi^2$ and indeed look reasonable by eye inspection. The agreement between the photometric redshifts and the spectroscopic redshifts, derived from the spectral fitting with old stellar populations, is very good with 6 out of 7 objects having $|z_{\text{spec}} - z_{\text{pho}}| < 0.1$. 4.4. Redshifts and redshifts quality classes for individual objects

Based on the results of SED and spectral fitting, we assigned redshifts and redshifts quality classes (A for good-confidence redshifts, B for less secure ones) for individual objects. A quality “A” redshift is assigned when the $M_{UV}$ feature appears well detected, and when the photometric and spectroscopic redshifts are in good agreement (i.e., within $\Delta z = 0.1$).

• #8238: $z = 1.39$, Class = B.
  The SED and spectral fitting agree within $\Delta z = 0.13$, the spectrum is consistent with the presence of the 4000Å break and of the $M_{UV}$ feature.
• #4950: $z = 1.55$, Class = A.
  The SED and spectral fitting agree very closely with $\Delta z = 0.02$, the spectrum clearly shows the $M_{UV}$ feature. The rise toward the UV below 6000Å is consistently present also in the photometry. This object is also part of the K20 survey (Cimatti et al. 2002b) with a measured redshift of $z = 1.553$. A weak [OII]3727 emission line is detected in the K20 survey spectrum.
• #1025: $z = 1.73$, Class = A.
  The SED and spectral fitting agree extremely closely with $\Delta z = 0.01$. The spectrum, that is fairly blue especially at $\lambda < 2500Å$, shows the characteristic $M_{UV}$ feature. The upturn in the blue spectra is consistent with what expected for A-type stars (Fig. 1). This source is detected in the X-rays (Giacconi et al. 2002; Alexander et al. 2003; see Sect. 9).
  Zheng et al. (2004) propose $1.47 < z_{\text{pho}} < 1.58$, reasonably consistent with our spectroscopic redshift.
• #3523: $z = 1.76$, Class = B.
  The spectrum would suggest $z \sim 1.1$ as the best fitting old galaxy solution by placing the 4000Å break around 9000Å
and the CaII H&K lines in the dip at 8700Å. The above solution is not consistent with the photometric SED, as at $z \approx 1.1$ no reasonably good fit could be obtained. A secondary solution from spectral fitting, with nearly the same $\chi^2$ of the best one, is found at $z = 1.76$, in very good agreement with the photometric redshift within $\Delta z = 0.04$. We propose the latter solution as the spectroscopic redshift for this galaxy. The $M_{\text{GUV}}$ feature is not evident, although the spectrum is consistent at least with the presence of a 2900Å break. The proposed redshift thus relies strongly on the overall SED and spectral fitting. The absorption like spectral features at 8900Å and 9200Å are to be considered spurious noise features for our proposed redshift. Yan et al. (2004) suggest this is an old galaxy at $z_{\text{phot}} = 1.6$, in good agreement with the redshift proposed here.

- #3650: $z = 1.91$, Class = A.

The SED and spectral fitting agree extremely closely with $\Delta z = 0.01$. The $M_{\text{GUV}}$ feature is very evident.

- #3574: $z = 1.98$, Class = A.

The SED and spectral fitting agree closely with $\Delta z = 0.04$. 
The spectrum shows the $M_{B_{UV}}$ feature. Yan et al. (2004) propose this is an old galaxy at $z_{\text{phot}} = 1.9$, in excellent agreement with our spectroscopic redshift.

- #1446: $z = 2.47$, Class = B. 
The SED and spectral fitting are in fair agreement at best with $\Delta z \sim 0.4$. The spectrum has a strong feature at 9200Å that in the spectral fitting with old models is identified with the $M_{B_{UV}}$ feature. Emission line identification algorithms described in Xu et al. (2005), however, pick up the feature as a possible emission line. If the feature is an emission line we find best fitting $\lambda \sim 9230\text{Å}, \text{FWHM}\sim160\text{Å}$ and $\text{EW}\sim150\text{Å}$. The large FWHM and EW would suggest an AGN emission line. This would be possible as the object is a hard X-ray source (Giacconi et al. 2002; Alexander et al. 2004), although no strong emission line is detected in the FORS spectra described by Szokoly et al. (2004). We tried to fit its photometric SED with reddened QSO/AGN templates but the fit still significantly prefers old/passive models. As the SED drops in the B-band, the only plausible AGN line identification would be [CIII] $\lambda 1909$ at $z = 3.83$, with the Lyman-break producing the B-band drop. Zheng et al. (2004) propose a photometric redshift $4.13 < z_{\text{phot}} < 4.35$, not far from that. For $z = 3.83$ one would expect to detect an even stronger CIV $\lambda 1550$ emission at about 7500Å that instead is not present. For $z = 3.83$ it would be difficult also to explain the overall shape of the SED with, e.g., the break between the J- and H-bands. Chen & Marzke (2004) propose this object is a dusty galaxy with $z_{\text{phot}} = 3.43$, not consistently with our analysis, while Yan et al. (2004) propose this is an old galaxy at $z_{\text{phot}} = 2.8$.

The spectral and photometric properties show that we can distinguish two classes of objects among our sources. Objects #4950 and #1025 have in fact significant B-band excess flux with respect to the others (see Fig. 4 and Fig. 8) suggesting the presence of hotter stars. These two objects will be discussed in more details in Sect. 6.2.

4.5. Discussion of redshift identifications

The proposed redshifts are based on low resolution spectra that, we recall, do not allow to detect individual absorption or emission lines as ordinarily done for redshift identifications of faint galaxy spectroscopy. Therefore, we cannot exclude with full confidence that, in a minority of the cases, our identifications might be somehow mistaken. We believe, however, that identifications are generally reliable, because: (1) the spectral fitting routine generally converge to the solution guessed by visual inspection of the spectra, when using tem-
plates for passive galaxies; (2) the photometric redshift estimated with the high-quality UDF data are in very good agreement with the proposed spectroscopic redshifts with median $z_{\text{spec}} - z_{\text{phot}} = 0.04$ only; (3) there is an overall consistent picture as signatures of old stellar populations are seen in the spectra, the SEDs strongly argue for passive stellar populations and morphologies of early-type galaxies are recovered, as discussed in the next section.

As an additional test, we verified the location of the seven sources in the Pozzetti & Mannucci (2000) diagram, Fig. 7. The $R - K$ versus $J - K$ colors of the sources are consistent with those expected for passively evolving galaxies up to $z \lesssim 2$. The only due exception is object #1446 with much redder $J - K$ color and proposed $z = 2.47$, a redshift at which the above diagnostic may not apply. We verified that using the criterion proposed by Pozzetti & Mannucci (2000) for $z > 2$, involving the J-, H- and K-bands, also the object #1446 would be classified as a passive red galaxy. We also verified, for further overall consistency, that best fitting models of the SEDs produce good fits to the HST grism spectra.

4.6. Sample completeness

The completeness of the $z \gtrsim 1.4$ sample of passive galaxies was investigated. We checked if additional passive $z \gtrsim 1.4$ galaxies could be found among bluer objects with $2.2 < z - K < 2.5$. It may be expected that toward the lowest $z \sim 1.4$ range of redshifts some early type galaxy could have $z - K < 2.5$ (either intrinsically or because of the errors in the photometry). No convincing case could be found. Among the remaining unidentified galaxies with $z - K > 2.5$ there are 3 more objects with compact morphology that are not in our sample with proposed spectroscopic redshift. One of these is #869, which is a $z = 3.064$ type 2 QSO (Szokoly et al. 2004), with no distinctive feature in our GRAPES spectrum. The other two are UDF #8363 and #5056, and have noisy spectra with no feature identifiable and photometric redshifts 2.30 and 1.43, respectively. These might be additional passive $z > 1.4$ objects. Their $BzK$ colors are consistent with the $BzK < -0.2$ region (object #8363 is the reddest one in $z - K$ with a lower limit to $B - z$, Fig. 4).

There are 10 more galaxies with $z - K > 2.5$ that remain unidentified in GRAPES spectra, and have irregular, diffuse and sometimes merging-like morphologies, reminiscent of the $z \sim 2$ star-forming galaxies (having also similar colors and magnitudes) shown in Daddi et al. (2004a,b). Only one of these has formally $BzK < -0.2$. The fact that we cannot detect features of old stars in these objects could be an observational bias as the S/N of the spectra for these extended and diffuse galaxies is generally low. However, they might be more likely genuine dust reddened star-forming galaxies. An analysis of the stacked X-ray and radio emission of galaxies with similarly $z - K$ colors and having $BzK < -0.2$ in the K20 survey suggests that these objects are mainly vigorous dust reddened starbursts at $z > 1.4$ (Daddi et al. 2004a,b).

In summary, there are at most only two reasonable additional candidates passive $z > 1.4$ galaxies, that are compact and have the expected $BzK$ colors. These are less luminous than the ones for which we propose a spectroscopic redshift. Additional passive objects might still be present among the galaxies with irregular morphology, although no object with similar properties is currently known both at high and low redshift.

4.7. Redshift clustering

We mention in passing the few evidences of redshift clustering that can be drawn from the redshifts of our sample. For these objects, the correlation length $r_0$ might be comparable or even higher than for typical EROs at $z \sim 1$ ($r_0 \sim 10$ $h^{-1}$ Mpc; Daddi et al. 2001; McCarthy et al. 2001; Brown et al. 2005), as these could be the truly first collapsed massive galaxies. This should translate in significant pairings between ours and to other galaxies, e.g. to those in the K20 region (Fig. 3). In fact, the $z = 1.91$ galaxy is at the same redshift of the Cimatti et al. (2004) $z = 1.903$ elliptical and also to that of the $z = 1.901$ near-IR bright galaxy in Daddi et al. (2004b). The $z = 1.73$ and $z = 1.76$ galaxies in our sample may actually be at the same redshift given the errors, presumably $z = 1.73$ where two other near-IR bright massive star-forming galaxies also lie (Daddi et al. 2004b). Also at $z = 1.55$ and $z = 1.39$ other massive star-forming galaxies are found in the K20 survey. Similarly, 3 out of 4 of the $z > 1.5$ early-type galaxies by Cimatti et al. (2004) are at $z \sim 1.61$, and strong pairing is observed also in the McCarthy et al. (2004) sample.

5. ANALYSIS: MORPHOLOGY

We inspected by eye the morphological appearance of the 7 galaxies with proposed spectroscopic confirmation as old high-$z$ stellar populations. Fig. 8 show the available HST imaging (see also the color images of the objects in Fig. 5). All objects look very compact and regular. Object #4950 appears a bulge dominated nearly face-on spiral, i.e. an S0, with perhaps evidence of merging or cannibalism in the blue bands. Object #1446 is the most elongated one and might be an early spiral or an S0 galaxy. The other objects are visually classified as E/S0 systems. In order to provide a more quantitative estimate of the morphology we used CAS and Sérsic profile fitting.
5.1. CAS analysis

The concentration and asymmetry of all the galaxies having $z - K > 2.5$ were measured in the $i$-band, corresponding to about 3000 Å rest-frame for $z \sim 2$ (similar results would be obtained in the $z$-band). Parameters definitions consistent with those given in Conselice (2003) were used. Fig. 9 shows the resulting measurements. Objects with proposed spectroscopic confirmation as $z > 1.4$ passive galaxies tend to have high concentrations and low asymmetry (see also Tab. 2). In general, these objects occupy a range of values consistent with those of early-type galaxies: for example all have concentrations $C > 2.6$, a value marking the boundary between early- and late-type galaxies in the local universe (Strateva et al. 2001; see also Conselice 2003). The asymmetries are generally low: $\lesssim 0.2$ in all cases.
5.2. Sérsic profile fitting

We used GALFIT (Peng et al. 2002) to model the light profile of the 7 objects with proposed redshift confirmation. Both i-band and z-band analyses were performed for a cross check of the results and to test for possible color trends. The PSF was derived for each band by averaging stellar objects in the field (Pirzkal et al. 2005). All the z \(> 1.4\) passive galaxies are resolved. We fitted Sérsic (1968) profiles of the form:

\[
\mu(r) = \mu_e e^{-\kappa \left(\frac{r}{r_e}\right)^{1/n}}
\]

where \(r_e\) is the effective radius, \(\mu_e\) is the effective surface brightness, \(n\) is the free Sérsic index, and \(\kappa\) is determined from \(n\) in order for half of the integrated flux to be within \(r_e\). Results are summarized in Table 2. The Sérsic profile fitting also allowed us to derive the total magnitudes, as listed in Table 1. The quoted uncertainties are purely statistical and fitting also allowed us to derive the total magnitudes, as listed in Table 2. The Sérsic profile fitting also allowed us to derive the total magnitudes, as listed in Table 1. The quoted uncertainties are purely statistical and derived by GALFIT on the basis of the image noise. Notice that the errors on the parameters are correlated. For example, fitting with a larger \(n\) generally implies larger \(r_e\) and brighter total magnitudes.

The Sérsic index \(n\) is generally found consistent within the estimated noise between the \(i\)- and \(z\)-bands. Derived values are in the range of 2.8–9 with many of them close to the de Vaucouleurs value of \(n = 4\), typical of E/S0 systems, with the exception of the object with the highest estimated redshift (1446) having \(n \approx 1\), that is consistent with the presence of an exponential disk and may be an early-type spiral or perhaps an S0 galaxy. This galaxy is reminiscent of the \(z = 2.5\) evolved disk galaxy discussed by Stockton et al. (2004). For object 4950 the Sérsic fit leaves strong residuals, corresponding to features visible in the B-band (see Fig. 8). Nevertheless, the \(z\)-band light appears to be dominated by a regular spheroid with \(n \approx 4\). A fit in the \(i\)-band was not attempted for this object.

Table 2. Morphological parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>C</th>
<th>A</th>
<th>n</th>
<th>(r_e) pix</th>
<th>(r_e) kpc</th>
<th>b/a</th>
<th>n</th>
<th>(r_e) pix</th>
<th>(r_e) kpc</th>
<th>b/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>8239</td>
<td>E/S0</td>
<td>3.09</td>
<td>0.11</td>
<td>8.2</td>
<td>\pm 1.5</td>
<td>11 \pm 4.7</td>
<td>2.8</td>
<td>\pm 1.2</td>
<td>0.89</td>
<td>5.8 \pm 1.0</td>
<td>4.7</td>
</tr>
<tr>
<td>4950</td>
<td>Sa+M?</td>
<td>3.57</td>
<td>0.18</td>
<td>4.3</td>
<td>\pm 0.4</td>
<td>22 \pm 3.7</td>
<td>5.6</td>
<td>\pm 0.9</td>
<td>0.60</td>
<td>–</td>
<td>1.2</td>
</tr>
<tr>
<td>1025</td>
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<td>0.12</td>
<td>4.2</td>
<td>\pm 0.5</td>
<td>2.9 \pm 0.3</td>
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<td>\pm 0.1</td>
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<td>5.0 \pm 0.7</td>
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<tr>
<td>3523</td>
<td>E/S0</td>
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<td>\pm 1.6</td>
<td>11 \pm 4.3</td>
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<td>\pm 1.1</td>
<td>0.74</td>
<td>9.7 \pm 2.0</td>
<td>16</td>
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<td>5.4 \pm 0.8</td>
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<td>2.5 \pm 0.2</td>
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<td>\pm 0.05</td>
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<td>\pm 0.12</td>
<td>0.35</td>
<td>1.4 \pm 0.3</td>
<td>3.9</td>
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6. RESULTS: STELLAR POPULATIONS OF z \(> 1.4\) EARLY-TYPE GALAXIES

In order to derive the characteristic stellar population properties of the seven \(z > 1.4\) galaxies we compared the photometric SEDs (with deep imaging data in 10 bands from B to \(K\), as described in Sect. 4.3, see also Fig. 6) to stellar population synthesis models from the Bruzual & Charlot (2003) library, at the (fixed) spectroscopic redshift of each source. We base our physical parameter estimates mainly on the photometric SEDs rather than on the spectra because of the much wider wavelength range spanned by the former. In particular we would expect the rest-frame UV photometry, including the very deep \(B\)-band images, to strongly constrain the presence or lack thereof of young stellar populations. The near-IR bands provide instead a census of the past star-formation.

A more extended library than the one adopted in Sect. 4.3 was used in this case, including models with 0.2, 0.4, 1.0 and 2.5 solar metallicity. Reddening is restricted to be \(E(B-V) < 0.2\) (we use a Calzetti et al. 2000 law). Some small amount of
dust reddening are sometimes found also among local early-type galaxies (e.g., Goudfrooij & de Jong 1996), and could be more often present at these high redshifts as we are observing more closely to the star-formation epoch. For the star-formation history we adopted SSP models and exponentially decreasing models with SFR histories, zero for SSP models, and the actual duration of star-formation phase, assumed to be equal to $t$ for exponential SF timescales in early-type galaxies. Limiting to the 5 objects with no $B$-band excess flux, we find that the SSP and $t = 0.1$ Gyr models provide much better fits to the SEDs than models with $t = 0.3$ or 1 Gyr. Exponentially declining star-formation histories with $t \geq 0.3$ Gyr are clearly inappropriate for these objects as they strongly overproduce the rest-frame UV fluxes. A similar result was found by McCarthy et al. (2004) and may seem to imply relatively short formation timescales (e.g. less than 0.3 Gyr). This appears to be consistent with the $\alpha$-enhancement found to be typical of elliptical galaxies at $z = 0$, that also suggests short formation timescales (e.g., Thomas, Maraston & Bender 2002; Thomas et al. 2005). However, the failure of models with $t \geq 0.3$ Gyr may not be due to their long formation timescales, but to the exponentially declining tail of star-formation. Physical reasons, like the feedback from supernovae explosions or from the onset of AGN activity (Granato et al. 2004), suggests that in more physically motivated models the SF might be completely stopped by such feedback. The “truncated” models that we considered allow us to explore this possibility, and check whether much longer SF timescales are consistent with our data. In fact, these “truncated” models produce acceptable fits to the SEDs even for the case of 2-Gyr lasting star-formation. In conclusion, the available portion of the SED

### Table 3. Stellar populations properties

<table>
<thead>
<tr>
<th>ID</th>
<th>$z_{\text{spec}}$</th>
<th>Class</th>
<th>$\chi^2_{\nu,m}$</th>
<th>$\text{P}(\chi^2_{\nu,m})$</th>
<th>$M_B$</th>
<th>U-B$_{\text{rest}}$</th>
<th>B-V$_{\text{rest}}$</th>
<th>$M_*/L_B$</th>
<th>$M_{\text{pass}}$</th>
<th>$\tau_{\text{pass}}$</th>
<th>$S_{\text{type}}$</th>
<th>$M_{\text{AGN}}$</th>
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<tr>
<td>8238</td>
<td>1.39</td>
<td>B</td>
<td>1.5</td>
<td>13</td>
<td>-20.98</td>
<td>0.23</td>
<td>0.91</td>
<td>1.0–2.4</td>
<td>2.5–6.2</td>
<td>0.5–4.5</td>
<td>&gt; 1.6</td>
<td>F5</td>
</tr>
<tr>
<td>4950</td>
<td>1.55</td>
<td>A</td>
<td>1.2</td>
<td>30</td>
<td>-22.86</td>
<td>0.19</td>
<td>0.76</td>
<td>2.9–7.3</td>
<td>1.3–3.4</td>
<td>0.6–2.5</td>
<td>1.8–3.7</td>
<td>F0</td>
</tr>
<tr>
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<td>1.73</td>
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<td>0.7</td>
<td>68</td>
<td>-21.76</td>
<td>0.19</td>
<td>0.76</td>
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<tr>
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<td>A</td>
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<td>0.2</td>
<td>0.68</td>
<td>0.5–0.9</td>
<td>0.16</td>
<td>0.5–0.9</td>
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<td>0.5–1.2</td>
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<td>2.47</td>
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<td>0.59</td>
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<td>0.3–0.7</td>
<td>2.8–3.2</td>
<td>2.5 ± 0.6</td>
<td>F5</td>
</tr>
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</table>

*Note.* $\chi^2_{\nu,m}$ is the reduced $\chi^2$ of the best fits. Ranges for $M_B$ and $\text{Age}_{\text{pass}}$ (and thus for $M_*/L_B$ and $\tau_{\text{pass}}$) are given at the 95% confidence level. $U-V$ and $B-V$ colors are derived from the best fitting model.

#### 6.1. Formation and ages of $z \gtrsim 1.4$ early-type galaxies

In order to characterize the evolutionary status of these objects, we estimated the quantity $\text{Age}_{\text{pass}}$ as the time elapsed since the onset of the passive evolution (i.e., since the end of the last major burst of star-formation). This is defined as the difference between the model age and the duration of the star-formation phase, assumed to be equal to $t$ for exponential SF histories, zero for SSP models, and the actual duration of the burst for truncated star-formation models. Table 3 shows that $\text{Age}_{\text{pass}}$ estimates are typically in the range of 0.5–1.5 Gyr, suggesting that the onset of passive evolution started at $\text{Age}_{\text{pass}} \sim 2–3.5$ in most cases.

It is interesting to investigate what types of SF histories yield acceptable fits to the SEDs, as this could constrain the SF timescales in early-type galaxies. Limiting to the 5 objects with no $B$-band excess flux, we find that the SSP and $t = 0.1$ Gyr models provide much better fits to the SEDs than models with $t = 0.3$ or 1 Gyr. Exponentially declining star-formation histories with $t \geq 0.3$ Gyr are clearly inappropriate for these objects as they strongly overproduce the rest-frame UV fluxes. A similar result was found by McCarthy et al. (2004) and may seem to imply relatively short formation timescales (e.g. less than 0.3 Gyr). This appears to be consistent with the $\alpha$-enhancement found to be typical of elliptical galaxies at $z = 0$, that also suggests short formation timescales (e.g., Thomas, Maraston & Bender 2002; Thomas et al. 2005). However, the failure of models with $t \geq 0.3$ Gyr may not be due to their long formation timescales, but to the exponentially declining tail of star-formation. Physical reasons, like the feedback from supernovae explosions or from the onset of AGN activity (Granato et al. 2004), suggests that in more physically motivated models the SF might be completely stopped by such feedback. The “truncated” models that we considered allow us to explore this possibility, and check whether much longer SF timescales are consistent with our data. In fact, these “truncated” models produce acceptable fits to the SEDs even for the case of 2-Gyr lasting star-formation. In conclusion, the available portion of the SED
and the presence of the $M_{B_{UV}}$ feature allow us to set strong constraints on $\text{Age}_{\text{pass,}}$, but not on the previous duration of the SF activity. Rest-frame near-IR data from Spitzer could help constraining also this latter quantity.

The fits with $\tau = 0.1$ Gyr models allow us to derive limits to the maximum amount of ongoing SFR in these passive galaxies, as these models have some residual SF at any time. For the 5 objects one gets residual SFR $\lesssim 0.1 M_{\odot}\text{yr}^{-1}$ with the $\tau = 0.1$ Gyr models. Even if continuing at this level for a full Hubble time to $z = 0$, this would increase the galaxies masses by less than 1%. Of course, we neglect here the possibility of completely dust extincted SF that we would not detect anyway in the optical-IR.

Further constraint on the formation processes of early-type galaxies can be obtained from the comparison with theoretical simulations. For example Hernandez & Lee (2004) estimated the relaxation time-scales of elliptical galaxies formed as the result of the merger of two equal size disks, and the Press-Schechter probability of such a merger to happen in practice. For early-type galaxies with stellar masses similar to the ones that we derive, i.e. $M_* \sim 10^{11} M_{\odot}$, they suggest that if such objects are found at $z \gtrsim 1.6$, as we do, it is highly unlikely that they have formed through mergers of equal-size spirals.

6.2. Blue excess early-type galaxies

We now come back to the two objects with B-band flux excess, #4950 and #1025. It is perhaps surprising that $\text{Age}_{\text{pass}}$ measurements for these two objects are not distinguishable from the ones of the other redder galaxies. However, unlike for the other five galaxies, these two bluest early-type objects can only be fitted by the $\tau = 0.3$ Gyr models, which seem to produce the correct balance between old and younger stars. The residual SFRs of the best-fitting $\tau = 0.3$ Gyr models is $5-10 M_{\odot}\text{yr}^{-1}$ for #4950 and about half of that for #1025. This is revealed for #4950 also by the detection of a weak $\text{[OH]}\lambda 3727$ emission in the K20 survey spectrum.

These two objects have $B-Z > -0.2$ because of their relatively blue $B-z$ color (see Fig. 4). Passively evolving galaxies shortly after the quenching of SF are expected to show similar colors (Daddi et al. 2004b), but on the other hand the blue $B-z$ colors may also be due to a secondary burst of starformation, involving a small fraction of the total stellar mass.

This is most likely the case of the galaxy #4950. Its morphology changes strongly from the $B$-band to the $z$-band (Fig. 8 and 10). The $B$-band light is fairly irregular with a significant substructure of 3–4 blobs. It is unlikely that such a clumpy structure is a bar, as these are typically more regular. The blobs visible in the $B$-band may be instead due to an ongoing merger or cannibalism of smaller galaxies or satellites. The $z$-band light distribution is instead more regular and appears typical of a spheroid. A feature looking like spiral arms or perhaps a ring is also detected at a distance of about 5 kpc from the center, that is significantly less luminous than the central light both in $B$ and $z$-bands. From the spectrum we find additional evidence for composite stellar populations. The best stellar template fit is in fact an F0, but best fits with A5 and F2 stars are found when limiting the fit to below or above 2800 Å rest frame, respectively. The $B$-bright clumps may have been formed or accreted after the $z$-band spheroid was in place.

The morphology of object #1025 is instead regular from the $B$-band to the $z$-band with no obvious changes. Sérsic profile fits were obtained for this object also in the $V$- and $B$-bands, finding that it is consistent with an high Sérsic index $n \sim 4$ in all ACS bands. There is instead a trend of decreasing effective radius with decreasing wavelength that appears significant, possibly due to the presence of a color gradient (Sect. 8). In the HST grism spectrum we find that no change is detected when fitting templates of stars below or above 2800 Å rest-frame only, and an A3 type star spectrum dominates the light consistently in the $2000 \AA < \lambda < 3600 \AA$ range. There is therefore no strong evidence in this object for the coexistence of two clearly distinct stellar populations, although the fact that a simple SSP model cannot reproduce its SED implies at least a somewhat extended SF timescale. This object appears to be an early-type galaxy observed very closely to some significant star-formation event, when early A-type stars (rather than F-type stars found in all the others passive objects) were still dominating its UV SED. Broadhurst & Bouwens (2000) discussed the observational lack of known early-type galaxies with A-type dominated stellar populations, our object being perhaps the first known case. The relatively short lifetime of A-type stars, of order of a few hundreds Myr at most, may be the actual reason why these objects are rare.

FIG. 10.— Comparison of the surface brightness distribution for object #4950 in the $B$- and $z$-band. The same range of fluxes ($\text{f}$) are plotted for the two objects. The peak of the $z$-band image corresponds to a relative dip in the $B$-band, that it is instead dominated by two blobs separated by $\sim 1$ kpc (0.7) from the galaxy center. The $z$-band surface brightness profile clearly shows the central cusp and extended wings typical of de Vaucouleurs galaxies. The faint spiral arms, or ring, are not visible in these images. See also Fig. 8 and the color inset in Fig. 5 for comparison.
The recent star-formation event may actually be the one when most of the stars in this spheroid were formed. Object #1025 would then represent the closest known link between passively evolving F-star dominated early-type galaxies and the as yet not established nature of the main formation event. The relaxed morphology at this early stage would imply a fairly short dynamical relaxation timescale. If the star-formation event is a secondary one, involving only a fraction of the mass, this objects might instead be similar to the E+A galaxies found at lower redshift (Dressler et al. 1983). This single object in the 1.4 < z < 2 redshift range corresponds, however, to a volume density that is 2 to 3 orders of magnitude higher than the local density of E+A galaxies above similar luminosities (Quintero et al. 2004). The fraction of E+A galaxies in the present sample (one out of seven) would also be higher then the just 1% that is found locally (Quintero et al. 2004).

7. RESULTS: EVIDENCE FOR A DECLINING NUMBER DENSITY OF EARLY-TYPE GALAXIES AT z ⪈ 1.4

An important question to address is how the abundance of z ⪈ 1.4 passive early-type galaxies compares to the local value, and to the populations of star-forming galaxies at the same redshifts.

As the majority of our sample galaxies, and all of the class "A" ones, are located at z < 2, we consider the 1.39 < z < 2.00 redshift range for this comparison. Over the 12.2 arcmin\(^2\) selection area this redshift range includes a volume of \(\sim 20000\) Mpc\(^3\). Summing up the galaxy stellar masses estimated in Sect. 6 we obtain a total stellar mass in the range of 7–16 \(\times 10^{11}\) M\(_{\odot}\), and a stellar mass density in the range of 3.4–8 \(\times 10^{-4}\) M\(_{\odot}\) Mpc\(^{-3}\) for an average redshift \(z \approx 1.7\). The 6 early-type galaxies with 1.39 < z < 2.00 correspond to a number density of 3.4 \(\times 10^{-4}\) Mpc\(^{-3}\).

7.1. Evolution from z \approx 2 to z = 0

The masses of these 6 galaxies are all close to or larger than \(10^{11}\) M\(_{\odot}\), and we can assume our sample to be reasonably complete above such a mass threshold for passive early-type galaxies down to \(K_{AB} = 23\). In the local universe, the number density and the stellar mass density of passively evolving galaxies with \(M_{*} > 10^{11}\) M\(_{\odot}\) are about \(9 \times 10^{-4}\) Mpc\(^{-3}\) and 1.3 \(\times 10^{-3}\) M\(_{\odot}\) Mpc\(^{-3}\), respectively (Baldry et al. 2004\(^\ast\)). Thus our sample of early-type galaxies in 1.39 < z < 2.00 accounts, at face value, for \(\sim 35\%\) of the number density of \(M_{*} > 10^{11}\) M\(_{\odot}\) passive galaxies in the local universe, and for a fraction of \(\sim 25–60\%\) of the relative stellar mass density. Notice that at z = 0 about \(75\%\) of all \(M_{*} > 10^{11}\) M\(_{\odot}\) galaxies are classified as passive early-type galaxies (Baldry et al. 2004). We therefore infer at z = 1.7 a decrease in the number density of massive early-type galaxies by at most of a factor of 3, if limiting to z < 2. The inferred fractions would be further divided by a factor of 2 if using all the volume in 1.39 < z < 2.47.

A major limit of these calculations is represented by cosmic variance, because of the small volume probed by UDF. All our passive galaxies are EROs with R – K > 5.3 (Table 1), which are strongly clustered populations (Daddi et al. 2000; McCarthy et al. 2001). Clustering can produce strong fluctuations in the number density of objects over small volumes, which most likely result in an underestimate of the true densities as averaged over large volumes (Daddi et al. 2000). If one assume that these z > 1.4 galaxies have the correlation length of EROs, i.e. \(r_{0} \sim 10 h^{-1}\) Mpc (Daddi et al. 2001; 2003), one finds that even at the 1\(\sigma\) level the true number density (and thus the stellar mass density) of passive galaxies could be within half and twice that estimated from our sample, or between 20\% and 80\% of the local value.

It is clear that similar searches on much larger and independent areas would be important to measure the number density evolution with some reasonable accuracy. The UDF dataset is likely to remain unique in its depth and quality for many years to come, but our result confirms that reliable estimates on the abundance of z > 1.4 passive early-type galaxies might be obtained by using the BzK photometric criteria only (Fig. 4; Daddi et al. 2004b), even without complete spectroscopic follow-up. In fact, in the UDF the sky density of the brightest (K/VAB < 20) candidate z > 1.4 early-type galaxies satisfying conditions z – K > 2.5 and BzK < –0.2 is not much smaller than that found in a \(\sim 30\) times wider field survey (Kong et al. in preparation). So, the densities derived over the UDF field should not dramatically underestimate the true values.

7.2. Passive objects at even higher redshifts?

The highest redshift passive object that we recover is at z = 2.47, although with "B" class redshift, while all the others lie at z < 2. Therefore, it is important to ask is whether the paucity of z > 2 passive galaxies is due to the limiting magnitude of the sample (i.e. they exist but are fainter) or to passive galaxies getting rarer and rarer. Indeed, some of the galaxies in our sample are consistent with having started pure passive evolution only at z ⪈ 2.

We have used a V/V\(_{\text{max}}\) test to try to shed light on the issue. For each of our objects we compute the maximum redshifts at which it would still be part of the sample (i.e. with \(K_{AB} < 23\), Kron magnitudes, and z – K > 2.5). We use the best fitting Bruzual & Charlot models to compute K-corrections, and z = 1.39 as the lower redshift boundary. The result is that the six objects would be still in the sample at least up to z = 3.3 (when \#8238 would drop out) and up to z = 4.6 (when finally also \#3650 would drop out). With \(V/V_{\text{max}} > 0.14 \pm 0.04\) and a maximum V/V\(_{\text{max}} = 0.35\) for \#1446, an uniform V/V\(_{\text{max}}\) distribution is rejected at the 99.7\% level, based on a Kolmogorov-Smirnov test.

There is therefore strong evidence for evolution, especially beyond z = 2. This means that if galaxies with masses and SEDs (i.e. ages) similar to the ones that we see at z < 2 = 1.7 were present at higher redshifts we would have detected them out to z ~ 4 (and with z – K > 2.5). These results underscore a rapid disappearance of truly passive systems at redshifts z ⪈ 2. This does not mean that massive galaxies where not present at earlier epochs, but that if existing they were mostly likely still actively star-forming. Notice that at z = 4 the Universe is already \(\sim 1.6\) Gyr old and in principle there would have been time to produce passively evolving galaxies with ages similar to the ones we see at 1.4 < z < 2.5.

Of course, clustering can bias also this < V/V\(_{\text{max}}\) test. For example, by chance the UDF may lack a cluster-like structure with many similar galaxies at z ⪈ 2. On the other hand, a similar < V/V\(_{\text{max}}\) test in the sky contiguous K20 survey region suggests that the K-band luminous BzK-selected starbursts galaxies are evolving positively in number over the same redshift range (Daddi et al. 2004b). These BzK starbursts are massive (stellar masses \(\sim 10^{11}\) M\(_{\odot}\)) and plausible.
candidates for being precursors to early-type galaxies. Therefore it appears that while the number density of passive galaxies is dropping with increasing $z$, that of their immediate likely precursors is somewhat increasing, as expected. It is worth emphasizing that these two $< V/V_{\text{max}} >$ tests were performed basically on the same sky area, and therefore they should be affected by clustering in a similar way.

7.3. The fraction of $z > 1.4$ stellar mass in passive objects

It is interesting to estimate what fraction of the mass, or of the most massive galaxies, is in passive galaxies at the probed redshifts $1.4 < z < 2.5$. Galaxies with $BzK > -0.2$ are in most cases star-forming objects at $1.4 < z < 2.5$ (Daddi et al. 2004), thus spanning the same redshift range of the detected passive galaxies. We can thus simply compare the sample of $BzK > -0.2$ galaxies selected to $K_{\text{AB}} = 23$ to the current sample of passive objects to the same limiting magnitude. We used the (SED-fit based) $K$-band magnitude versus stellar mass relation calibrated in Daddi et al. (2004b). For the passive galaxies in our sample this relation provides fairly good estimates of the stellar masses, fully consistent with those listed in Table 3. As star-forming galaxies in $1.4 < z < 2.5$ we consider all $BzK > -0.2$ sources, i.e. 43 objects when excluding the 2 passive "blue" objects and any source with X-ray detection as likely an AGN. Of these 6 have estimated stellar mass $M_\star \gtrsim 10^{11} M_\odot$, producing a total stellar mass of order of $5 \times 10^{11} M_\odot$, or up to $10 \times 10^{11} M_\odot$ for those above an estimated stellar mass limit of $M_\star > 0.5 \times 10^{11} M_\odot$. These figures are similar to the ones derived above for passive objects in the same redshift and mass ranges. This supports earlier hints that at $1.4 < z < 2.0$ roughly $50\%$ is in passive galaxies and roughly $50\%$ is in vigorous star-forming galaxies, for objects with stellar masses $M_\star \gtrsim 10^{11} M_\odot$ (Cimatti et al. 2004; McCarthy et al. 2004). By summing together the similar stellar mass densities contributions from passive and star-forming galaxies at $1.4 < z < 2$ having $M_\star \gtrsim 10^{11} M_\odot$, one gets fairly close to the local value from the SDSS (Baldry et al. 2004). However, the uncertainties due to small number statistics and clustering, and in the estimates of stellar masses are both at least a factor of $\sim 2$. The evolution of most massive galaxies is not easily detectable up to $z = 2$, and therefore it is arguably not very strong.

7.4. Comparison to $\Lambda$CDM theoretical predictions

McCarthy et al. (2004) and Cimatti et al. (2004) already pointed out that the existence of $z > 1.4$ passive early-type galaxies in such relatively high number is at odd with current predictions of semi-analytic models of galaxy formation and evolution, that predict the passive evolution phase to be established much later, if ever. This is similar to the reported failure to accounts for EROs number counts even at $z \sim 1$ (e.g., Daddi et al. 2000; Firth et al. 2002). These conclusions are supported also by the present findings.

For example, among the early semi-analytic models, the simulations $^{14}$ by Kauffmann et al. (1999) predict a number density at $z = 1.46$ of galaxies with $(B-V)_{\text{rest}} > 0.6$ (Table 3) and stellar masses $M_\star > 10^{11} M_\odot$ that is about a factor $\sim 50\%$ of 10 lower than recovered here in the UDF, and by $z \sim 2$ such objects should have virtually disappeared. Nevertheless, it is interesting that these models do predict that at least some galaxies exist with the colors and masses of the ones we observe (Fig. 11), and that a hint for a bimodal color distribution is already in place in the models at these redshifts. On the other hand, there appear to be too few massive galaxies in these simulations, either passive or star forming (Daddi et al. 2004a,b; Fontana et al. 2004). Among the more recent generation of models, those by Somerville et al. (2004) are quite successful in predicting the number density of massive galaxies at high redshift, but fail to produce the bimodal color distribution even at low redshift. Similarly, the hydrodynamical simulations of Nagamine et al. (2005a,b) appear to match the statistic of $z = 2$ massive galaxies but are less successful in reproducing the abundance of $z \sim 2$ old and passive galaxies. There is now general agreement that one of the problems with the models is their tendency to sustain star formation in massive DM halos all the way to low redshifts, and intense theoretical efforts are currently under way in the attempt to cope with these discrepancies. A strong AGN feedback appears to be a viable way for switching off star formation in massive galaxies at $z \gtrsim 2$ (e.g., Granato et al. 2004).

8. RESULTS: MORPHOLOGY EVOLUTION OF EARLY TYPE GALAXIES TO $z > 1.4$

The morphological properties of our sample of $z > 1.4$ passive early-type galaxies were compared to those of the corresponding local populations.

Fig. 12 shows the B-band rest-frame Kormendy (1977) relation for our objects compared to a local sample of early-type galaxies in the Coma cluster (Joergensen et al. 1995).
Similarly, about half of $z \sim 1$ massive early-type galaxies from the K20 survey, shown in Fig. 12, have sizes of about 1 kpc that are smaller than their local massive counterparts. Small sizes of K20 early-type galaxies were also inferred by Cassata et al. (2005) for the higher redshift sample of 4 early-type galaxies at $z \geq 1.5$, i.e., $r_e = 1–3$ kpc, measured on ACS $z$-band data as in this work. Waddington et al. (2002) showed that their two $z \sim 1.5$ radio-selected early-type galaxies have too small sizes (3 kpc), as compared to lower redshift samples. Stanford et al. (2004) present a rest-frame $B$-band morphological analysis of early-type galaxies to $z = 1.4$ in the Hubble Deep Field North based on HST+NICMOS, showing indeed a trend of significantly smaller sizes of luminous galaxies with respect to local massive counterparts (see their Fig. 16). An analogous result might be noticed in Fig. 4 of Gebhardt et al. (2003).

Therefore, it appears well established observationally that some fraction of high redshift passive early-type galaxies appear significantly smaller than their likely $z = 0$ descendants. While this is similar to the well known trend of size reduction with redshift for star-forming galaxies (e.g., Ferguson et al. 2004), this effect had not been highlighted and/or discussed previously for early-type galaxies, if not for the 2 radio-galaxies of Waddington et al. (2002). It is somehow surprising because one would expect that these massive galaxies, that are already undergoing passive evolution, should evolve smoothly into local massive ellipticals with no major change in their properties if not for aging of the stellar populations. The availability of the ultradeep UDF imaging might allow us to better constrain and understand this issue.

We tried to investigate the possible reasons for this effect on our sample of $z > 1.4$ early-type galaxies. The small effective radii we derive with the Sérsic fitting might be due to the presence of an unresolved nuclear component, e.g., from an AGN. Actually, two of the four objects with small $r_e$ are detected in X-rays (see Section 9). For the two compact objects with the highest S/N ratio in the $z$-band imaging (#1025 and #3650) we attempted fitting their surface brightness profiles with two component models, Sérsic plus a point-like source. The resulting best fit is still dominated by the Sérsic component, but its $r_e$ is not significantly increased with respect to the one component fits, just a lower Sérsic index $n$ is derived. However, when forcing $r_e$ to be large, a good fit with $r_e \approx$ few kpc can be obtained, consistently with the local objects, and still with large $n$ values. In this case the nuclear source is about 2 magnitudes fainter than the spheroid, in agreement with the fact that the optical SEDs and spectra appear dominated by stellar light (Sect. 4 and 6). If this is the reason of the small radii, it would imply a widespread nuclear activity, or relics of nuclear starbursts, in $z \sim 1.4–2$ early-type galaxies.

We notice, however, that 4 out of the 7 objects have very small effective radii, $r_e < 1$ kpc, and passive evolution would bring them in a region of the $r_e - \mu_e$ diagram where very few local galaxies are found. Moreover, local galaxies with $r_e < 1$ kpc tend to be much less massive than our $z > 1.4$ objects. Similarly, the stellar surface mass density $\mu_e$ of the 4 galaxies, defined as $\mu_e = M_*/(2\pi r_e^2)$, is more than a factor $\approx 10$ higher than that of local galaxies with similar stellar masses (Kauffmann et al. 2004). All in all, the $z > 1.4$ $r_e < 1$ kpc objects cannot be the progenitors of the $z = 0$, low-mass galaxies with similar effective radii.

![FIG. 12.— The B-band rest-frame Kormendy (1977) relation for the 1.4 < $z$ < 2.5 early-type galaxies (filled circles with error bars), compared to Coma early type galaxies taken from Joergensen et al. (1995) converted to the B-band (empty squares), and to 0.7 < $z$ < 1.2 early-type galaxies from the K20 survey (crosses, from di Serego Alighieri et al. 2005, in preparation). Observed values for our objects are derived from the $z$-band measurements. The average effective brightness $<\mu_e>$ were corrected for cosmological surface brightness dimming and bandpass shift (observed $z$-band to rest $B$-band), but not for the (relatively uncertain) passive evolution dimming to $z = 0$.](image-url)
A possible mechanism for size evolution would be substantial satellite engulfment by the massive red galaxies as they evolve to lower redshifts, which would imply an additional growth of their stellar mass. Object #4950 might be an example of this process in act. Confirmation of this scenario would require the detection of large concentrations of satellite galaxies in the vicinity of the passive z > 1.4 galaxies. This option might be tested in the future by using the ultradeep UDF data.

In relation to the morphological K-correction option, we note that blue cores are not uncommon already among 0.5 < z < 1 ellipticals (Menanteau et al. 2001, 2004), and that the observed z-band corresponds to 2600–3800 Å in the rest frame for 1.4 < z < 2.5 (so somewhat bluer than the 4300 Å of the B-band). The most direct way to check this option would be to obtain Sérsic profile fits in the NICMOS F110W and F160W bands, bracketing the rest-frame B-band for 1.4 < z < 2.5. However, this is technically difficult, mainly due to the large 0.2" pixel size of NICMOS (a factor of 4 larger than the ACS pixels) corresponding to ~ 2 kpc at z ~ 2. Attempting such fits is beyond the scope of the present work. What we checked instead was the trend of $r_e$ with wavelength, within the range covered by the ACS data. We constructed $i$–$z$ color maps of all our z > 1.4 galaxies (Fig. 13), but among the 4 objects with $r_e < 1$ kpc only #1025 shows a quite prominent blue core. This objects also exhibits a strong trend of $r_e$ with wavelength, as shown in Fig. 14, while a Sérsic profile consistent with $n \sim 4$ is found in all the ACS bands. An extrapolation would give $r_e$ larger by 50% in the rest-frame B-band with respect to that measured in the observed z-band. Still, this increase would not suffice to bring this object at $z = 0$ on the populated part of the Kormendy relation, as that would need an increase by a factor ~ 3. Yet, we cannot presently rule-out the possibility that $r_e$ may change more steeply with wavelength, especially beyond the 4000 Å break. We finally note that small $r_e$ values in the rest-frame B-band are common among early-type galaxies to z = 1.4 (Stanford et al. 2004), which outlines the existence of this problem also when using B-band rest-frame measurements. A final assessment of why some high-z ellipticals have such small effective radii and how they relate to local E/S0 galaxies is left to future investigations.

9. RESULTS: THE X-RAY PROPERTIES OF z > 1.4 EARLY-TYPE GALAXIES

Two of the 7 z > 1.4 early-type galaxies discussed here are detected in the 1 Msec Chandra X-ray observation (Giacconi et al. 2002), and their properties are reported in Table 4. The two sources are both very hard (HR > 0.4) and both of them were discussed also by Padovani et al. (2004) as possible QSO2 candidates.

Object #1446 is close to the detection limit with ~ 20 net counts, almost all from the hard band (HR > 0.42), and we estimate its luminosity to be $L_{2-10keV} = 2.2 \times 10^{43}$ erg s$^{-1}$. Object #1025 is detected with ~ 90 net counts, thus allowing a rough spectral analysis. Fig. 15 shows the X-ray spectrum of the object along with an absorbed power-law at the source redshift. The best fit rest frame column density id $N_H = 5 \times 10^{23}$ cm$^{-2}$; and the corresponding unabsorbed X–ray luminosity is $L_{2-10keV} = 8 \times 10^{43}$ erg s$^{-1}$. Given the high column density and the X–ray luminosity close to $10^{44}$ erg s$^{-1}$ this object can be classified as an X–ray QSO2. It is intriguing that the optical spectrum appears to be dominated by stellar light, that may imply that the obscuring torus is blocking also most of

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15 The luminosities derived by Padovani et al. (2004) are larger than those inferred here given that these authors put these objects at slightly higher redshifts.
the emission in the optical and near-IR domains. An excess emission with respect to the power-law continuum is present at $\sim 2.3 - 2.4$ keV. This would be consistent with the presence of a redshifted 6.4 keV Fe Kα emission line. Indeed, when a Gaussian line is added to the model spectrum, the fit improves and suggests a redshift $z = 1.71$, in excellent agreement with the redshift measured in the optical/near-IR, and a rest-frame line equivalent width of $\sim 350$ eV, similar to what found in obscured X-ray sources (e.g., Brusa et al. 2005b; Maccacaro et al. 2005).

Both sources have large X-ray to optical flux ratios (X/O). Coupled with the analysis of Mignoli et al. (2004), that suggest that most of the hosts of hard X-ray AGN with large X/O and R-K $> 5$ are spheroids at $z > 1$, this imply a close connection between hard X-ray sources and high-redshift early-type galaxies.

Although based on two objects only, the fraction of AGNs in $z \sim 2$ these early-type galaxies is at face value $\sim 30\%$. This is larger than that observed for the X-ray–type sample of $z \sim 1$ EROS discussed by Brusa et al. (2002; no X-ray emission was revealed in a sample of 8 sources), and much larger than the $\sim 1\%$ value observed locally. This is similar to the fraction of AGN among EROS at the probed K magnitudes (Alexander et al. 2002; Brusa et al. 2005a) underlining again the possible close connection between the formation of AGN and early-type galaxies.

### Table 4. X-ray emission properties

<table>
<thead>
<tr>
<th>ID (G02)</th>
<th>ID (A03)</th>
<th>$z$</th>
<th>$F_{\text{soft}}$ cgs</th>
<th>$F_{\text{hard}}$ cgs</th>
<th>$N_H$ cm$^{-2}$</th>
<th>$L_{\text{2-10 keV}}$ cgs</th>
<th>X/O</th>
<th>X/K</th>
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</thead>
<tbody>
<tr>
<td>1025</td>
<td>256</td>
<td>255</td>
<td>1.73</td>
<td>$0.9 \times 10^{-16}$</td>
<td>$4.1 \times 10^{-15}$</td>
<td>$\sim 5 \times 10^{23}$</td>
<td>8 $\times 10^{43}$</td>
<td>12</td>
</tr>
<tr>
<td>1446</td>
<td>605</td>
<td>243</td>
<td>2.47</td>
<td>$&lt; 0.4 \times 10^{-16}$</td>
<td>$4.6 \times 10^{-16}$</td>
<td>(HR $&gt; 0.42$)</td>
<td>$2 \times 10^{43}$</td>
<td>5</td>
</tr>
</tbody>
</table>

### 10. Summary and Conclusions

Based on the $BzK$ two-color selection criterion meant to identify $z > 1.4$ passively evolving galaxies, a sample of seven objects has been identified in the UDF for which AGC grism spectra confirm both the high redshift ($1.4 \lesssim z \lesssim 2.5$) and the current absence (or very low) ongoing star formation. The analysis conducted over the ultradeep ACS imaging further shows that the objects are morphologically early-type galaxies.

The redshifts are derived from the identification of the spectral feature at the rest-frame $2640 < \lambda < 2850$ Å due mainly to MgI and MgII absorptions in late A- and F-type stars, and which shows up prominently only in synthetic stellar populations with no (or very low) star formation in the last $\sim 0.5$ Gyr.

The SEDs and ACS grism spectra of 5 of the objects are best reproduced by a star formation history initiated $\gtrsim 1.5$ Gyr before, and completely discontinued over the last $\sim 0.5 - 1.5$ Gyr, implying that the passive evolution started at $z \gtrsim 2 - 3.5$. In the other cases a similar age constraint is inferred, but the spectra are best reproduced by an exponentially declining SFR, with $\tau \sim 0.3$ Gyr.

The overall spectral energy distributions of the objects indicate stellar masses in excess of $\sim 10^{11} M_\odot$ and we infer that the comoving volume density of such massive, early-type galaxies at $< z > \sim 1.7$ is about $1/3$ of the local value. The uncertainty in the derived fraction is dominated by cosmic variance, given the small field covered by the UDF. Allowing for the expected clustering of these galaxies we infer that at the $1\sigma$ level such fraction could be as low as $\sim 20\%$ or as high as $\sim 80\%$. Clearly, the exploration of wider fields is necessary to accurately pinpoint the actual decrease with redshifts of the number density of massive galaxies which are passively evolving. However, a $V/V_{\text{max}}$ test indicates that beyond $z \sim 2$ this number density is likely to drop very rapidly.

One intriguing aspect of the present findings is the quite small effective radii derived from the ACS $z$-band images, which in 4 out of 7 cases are less than 1 kpc. Given their high mass, the passive evolution of such very compact objects will bring them in a region of the Kormendy relation (or, equivalently, of the fundamental plane) which is depopulated at $z = 0$. We discuss various possibilities to explain this apparent paradox, including a morphological K-correction (e.g., due to the possible presence of blue cores in these galaxies), or of an AGN point-like source biasing the $r_C$ measurements, or eventually some evolutionary effects such as if the observed galaxies were still subject to further growth at lower redshifts. While we mention hints favoring one or another option, the existing data do not allow to reach any firm conclusion on this specific issue.

Finally, we point out that while in the local universe most of the most massive galaxies are passively evolving giant ellipticals, the present data – combined with previous evidence

![Image of X-ray spectrum of #1025 from Chandra.](https://example.com/figure15.png)
in a partly overlapping field (Daddi et al. 2004a,b) – indicates that by z ∼ 2 passively-evolving and seemingly vigorous starbursts galaxies occur in comparable numbers among most massive galaxies. This remains a major challenge for the current theoretical simulations of galaxy formation to reproduce.

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