

# CANDELS: The correlation between galaxy morphology and star formation activity at $z \sim 2$

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## ABSTRACT

We discuss the state of the assembly of the Hubble Sequence in the mix of bright galaxies at redshift  $1.4 < z \leq 2.5$  with a large sample of 1,671 galaxies down to  $H_{AB} \sim 26$ , selected from the HST/ACS and WFC3 images of the GOODS–South field obtained as part of the GOODS and CANDELS observations. We investigate the relationship between the star formation properties and morphology using various parametric diagnostics, such as the *Sérsic* light profile, Gini ( $G$ ),  $M_{20}$ , Concentration ( $C$ ), Asymmetry ( $A$ ) and multiplicity ( $\Psi$ ) parameters. Our sample clearly separates into massive, red and passive galaxies versus less massive, blue and star forming ones, and this dichotomy correlates very well with the galaxies’ morphological properties. Star-forming galaxies show a broad variety of morphological features, including clumpy structures and bulges mixed with faint low surface brightness features, generally characterized by disky-type light profiles. Passively evolving galaxies, on the other hand, very often have compact light distribution and morphology typical of today’s spheroidal systems. We also find that artificially redshifted local galaxies have a similar distribution with  $z \sim 2$  galaxies in a  $G$ – $M_{20}$  plane. Visual inspection between the rest-frame optical and UV images show that there is a generally weak morphological k-correction for galaxies at  $z \sim 2$ , but the comparison with non-parametric measures show that galaxies in the rest-frame UV are somewhat clumpier than rest-frame optical. Similar general trends are observed in the local universe among massive galaxies, suggesting that the backbone of the Hubble sequence was already in place at  $z \sim 2$ .

*Subject headings:* galaxies: evolution – galaxies: high-redshift –galaxies:

## 1. Introduction

Galaxy morphology in the local universe provides significant information about the formation and evolution of galaxies. Massive galaxies in the nearby universe are well described by the Hubble sequence, which correlates with the dominance of galaxy’s central bulge, surface brightness and colors. Hubble types are also broadly correlated with physical parameters, such as the star formation rate and dynamical properties (Roberts& Haynes 1994; Blanton et al. 2003). In the classical picture, late-type spiral galaxies are active star-forming structures with flattened, gas rich, rotationally supported exponential disks, while early-type galaxies are more luminous, massive and quiescent systems, supported by stellar velocity dispersion and have smooth elliptical isophotes with a so-called “de Vaucouleurs” (or similar) light profile. In a color-magnitude (or mass) diagram of the local universe, the early- and late-type galaxies occupy two distinct regions, known as the red sequence and blue cloud, respectively (Blanton et al. 2003, Baldry et al. 2004). The red sequence consists of mostly non-star-forming galaxies with a bulge dominated structure and colors indicative of an old stellar population. In contrast, the galaxies lying in the blue cloud have different star formation properties, including blue star-forming stellar populations and mostly disk-like structures.

The key question of how and over what time-scale the Hubble Sequence has formed remains unanswered. At a basic level, exploring the origin of the Hubble sequence can simply be done by investigating if high-redshift galaxies have distributions of morphological types (early- and late-type) and star-forming properties that resemble those in the nearby universe. Several surveys that have used the Hubble Space Telescope (HST) have observed that the properties of galaxies at  $z \sim 1$  are broadly consistent with those in the local universe (Bell et al. 2004: GEMS, Papovich et al. 2005: HDFN, Cassata et al. 2007 : COSMOS). However, the morphological analysis is still controversial at the peak epoch of star-formation

activity ( $z \sim 2 - 3$ ). Until relatively recently, most studies of galaxy morphologies at  $z > 2$  have been performed at rest-frame ultraviolet (UV) wavelengths using optical imagers (such as HST/WFPC2 and HST/ACS). These works found that irregular or peculiar structures appear more common, and traditional Hubble types do not appear to be present at these epochs (Giavalisco et al. 1996a,b; Steidel et al. 1996; Lowenthal et al. 1997; Lotz et al. 2004; Papovich et al. 2005; Lotz et al. 2006; Ravindranath et al. 2006; Law et al. 2007; Conselice et al. 2008). This is generally explained as due to the fact that UV radiation predominantly traces emission from the star-forming regions (Dickinson 2000), which tend to be more clumped and irregularly distributed than older stellar populations, and also by the fact that quenched galaxies were missing from the optical images. The rest-frame optical regime is a better probe of the overall stellar distribution in galaxies, and early near-infrared (NIR) observations with *HST* and NICMOS of star-forming galaxies at  $z > 2$  from UV selected samples found that their morphology remains generally compact and disturbed also at rest-frame optical wavelengths and bear no obvious morphological similarities to lower redshift galaxies (Papovich et al. 2005; Conselice et al. 2008). Interestingly, however, Kriek et al. (2009) showed that 19 spectroscopically confirmed massive galaxies ( $> 10^{10.5} M_{\odot}$ ) at  $z \sim 2.3$  are clearly separated into two classes as a blue cloud with large star-forming galaxies, and a red sequence with compact quiescent galaxies. Unlike late-type galaxies, early-type galaxies (ETGs) have been used to investigate the cosmic history of massive galaxies in many studies (e.g. Renzini (2006), and references therein) due to their simple elliptical morphologies and passively evolving stellar populations. At  $z < 1$ , there is general consensus that the majority of massive ETGs ( $M > 10^{11} M_{\odot}$ ) were already in place at  $z \sim 0.8$ , with a number density comparable to that of local galaxies (Cimatti et al. 2002; Im et al. 2002). A number of studies have reported the emergence of massive and compact galaxies by  $z \sim 2 - 3$ , which are already quenched ETGs (Cimatti et al. 2004; Daddi et al. 2005; Trujillo et al. 2006, 2007; van Dokkum et al. 2008; Cassata et al. 2008; Valentinuzzi

et al. 2010; Cassata et al. 2010). The number density of these galaxies rapidly increases, by a factor of five, from  $z \sim 2$  to  $z \sim 1$ , and they are up to 5 times more compact in size than local ones with similar mass (Cassata et al. 2011, 2013). Recent works have suggested, however, that a large fraction of, and possibly even all, massive, quiescent galaxies at  $z \sim 2$  are disk dominated (van der Wel et al. 2011). While the observation of such disks at  $z > 2$  is based on morphological analysis alone, typically distribution of apparent elongation, with no dynamical measures at present, the existence a sizeable fraction of compact disks at  $z > 2$  among massive, passive galaxies (van Dokkum et al. 2011; Wang et al. 2012; Bruce et al. 2012) suggests that the physical mechanism responsible for quenching star-formation may be distinct from the process responsible for morphological transformation.

Recently, studies of the morphologies of  $z \sim 2$  galaxies have advanced using the high resolution NIR Wide-Field Camera 3 (WFC3). Szomoru et al. (2011) found a variety of galaxy morphologies, ranging from large, blue, disk-like galaxies to compact, red, early-type galaxies at  $z \sim 2$  with 16 massive galaxies in the Hubble Ultra Deep Field (HUDF). Cameron et al. (2011) also studied the rest-frame UV and optical morphologies with  $1.5 < z < 3.5$  galaxies determined by the YHVz color-color selection in the HUDF and the Early Release Science (ERS) field, and confirmed previous studies by showing in particular the presence of regular disk galaxies, which have been missing in previous studies, either because they are not detected at the available sensitivity or because their appearance is irregular at rest-frame UV wavelengths. The results from these studies are generally interpreted as possible evidence at  $z \sim 2$ , at least among the brightest galaxies at that epoch, of the general correlations between spectral types and morphology that today define the Hubble Sequence. The most important limitations of these works are that they are based on very small samples, which are not statistically significant (less than 20 galaxies) and not homogeneously selected, and their morphological analysis was restricted to only *Sérsic* profile fitting or visual classifications.

Significant improvements are now possible using larger samples of panchromatic images from the CANDELS (Cosmic Assembly Near-infrared Extragalactic Legacy Survey) observations. Wuyts et al. (2011) investigated how the structure of galaxies (*Sérsic* index and size) depends on galaxy position in the SFR–stellar mass diagrams since  $z \sim 2.5$ , specifically showing strong trends of specific star formation rate (SSFR) with *Sérsic* index using large data sets combined in 4 different fields, COSMOS, UDS, GOODS-South and North. Although the *Sérsic* index, measured by fitting a single *Sérsic* profile to a galaxy, is the most common approach to analyzing galaxy morphology, it is also useful to study morphologies with non-parametric measures such as Gini ( $G$ ) (Abraham et al. 2003),  $M_{20}$  (Lotz et al. 2004), multiplicity ( $\Psi$ ) (Law et al. 2007) and CAS (Abraham et al. 1996, Conselice et al. 2003) since not all galaxies are described by smooth and symmetric profiles. In a recent CANDELS paper, Wang et al. (2012) used Gini ( $G$ ),  $M_{20}$  and visual classifications to identify a correlation between morphologies and star-formation status at  $z \sim 2$ , showing two distinct populations, bulge-dominated quiescent galaxies, and disk or irregular star-forming galaxies, though they only use massive galaxies ( $M > 10^{11} M_{\odot}$ ). Recent panchromatic surveys such as CANDELS hold the promise of significant progress in investigating galaxy structures at high redshift because they combine sensitive *HST* morphology at rest-frame UV and optical wavelengths with the depth and accuracy of space-borne photometry. The CANDELS project also adds coverage of a substantial amount of sky, which results in samples whose size and dynamic range in mass are about one order of magnitude, or more, larger than in previous works. In this study, we extend previous results using a statistically significant sample (1,671 galaxies) down to a lower mass limit ( $M > 10^9 M_{\odot}$  at  $z \sim 1.4$  and  $10^{10} M_{\odot}$  at  $z \sim 2.5$ , specifically for passive galaxies) and using various morphological parameters (non-parametric diagnostics such as  $G$ ,  $M_{20}$ ,  $\Psi$ , Concentration (C) and Asymmetry (A), and the parametric *Sérsic* light profiles, characterized by the *Sérsic* index ( $n$ ) and half-light radius  $R_e$ ), as well as visual

inspection.

The combination of high–angular resolution and sensitivity afforded by the *HST*/ACS and WFC3 images with the relatively large size of the sample allows us to probe in a statistical fashion the correlations between galaxy structures and star–formation activity at  $z \sim 2$ , i.e. the epoch when the cosmic star–formation activity reached its peak, to their counterparts in the local universe. The structure of this paper is as follows. The optical and infrared data and selection of our galaxy sample are introduced in Section 2. The rest–frame color and mass distributions are described in Section 3. We present the analysis of galaxy morphologies in the rest–frame optical using the distribution of non–parametric approaches, as well as *Sérsic* index and half–light radius in Section 4. Comparison with galaxies from the local universe is shown in Section 5 and the results of a comparison of rest–frame UV morphologies with rest–frame optical are presented in Section 6. Finally, we conclude with a discussion of our results and compare them to other studies in Section 7 and summarize our results in Section 8.

## 2. Data and Sample Selection

All the data used in this work come from the observations acquired during the GOODS (Giavalisco et al. 2004) and CANDELS (Grogin et al. 2012; Koekemoer et al. 2012) projects in the GOODS–South field, including both space–born (Chandra, Hubble and Spitzer) as well as ground–based (VLT) data. The CANDELS *HST* observations, including the details of the data acquisition, reduction and calibration, source identification and photometry extraction, are thoroughly described elsewhere (see Grogin et al. 2012; Koekemoer et al. 2012; Guo et al. 2013); here we briefly review key features of the WFC3 images that are relevant to this work. The *HST* component of CANDELS consists of a Multi–Cycle Treasury program to image five distinct fields (GOODS–North and –South, EGS, UDS

and COSMOS) using both WFC3 and ACS. The whole project is organized as a two-tier Deep+Wide survey. The CANDELS/Deep survey covers about 125 square arc minutes to  $\sim 10$ -orbit depth within GOODS-North and -South (Giavalisco et al. 2004) at F105W(Y), F125W(J) and F160W(H), while the Wide survey covers a total of  $\sim 800$  square arc minutes to  $\sim 2$ -orbit depth within all five CANDELS fields. In this study, we use the 4-epoch (about 2 orbits) CANDELS F160W(H-band) imaging that covers about 115 square arc minutes ( $\sim 2/3$  of the whole GOODS-S) including the GOODS-S deep region, plus the ERS (Windhorst et al. 2011). This survey has a  $5\sigma$  limiting depth of  $H_{AB} = 27.7$ , and a drizzled pixel scale of  $0.06''$ . A number of photometric catalogs exist based on CANDELS data, and here we use one where sources have been detected using the package SExtractor (Bertin et al. 1996) in the WFC3 H-band images, and multi-wavelength photometry has been obtained using a software package with an object template-fitting method (TFIT, Laidler et al. 2007). This catalog includes photometry from the *HST*/ ACS and WFC3 images in the BVizYJH bands; from VLT/VIMOS U and VLT/ISAAC Ks images; and from the Spitzer/IRAC images at 3.6, 4.5, 5.8 and  $8.0 \mu\text{m}$  (Guo et al. 2013).

We identify galaxies at  $1.4 < z \leq 2.5$  with a broad range of star-formation properties, from passive to star forming, and with different levels of dust obscuration using photometric redshifts and SSFR estimated by fitting the CANDELS broad-band rest-frame UV/optical/NIR spectral energy distribution (SED) to spectral population synthesis models (hereafter, SED sample). Additionally, for comparison, we also select samples of galaxies using the BzK technique, a color selection based on the (B-z) vs. (z-K) color-color diagram, widely used to identify galaxies at  $z \sim 2$  relatively independently of their star-formation activity and dust obscuration properties (Daddi et al. 2004, 2007). While characterized by some contamination by AGNs and low-redshift interlopers, as well as incompleteness to very young and dust-free star-forming galaxies (see Daddi et al. (2004)), the BzK selection is overall quite effective and particularly economic in that it only requires the

acquisition of three photometric bands. In contrast, the SED selection is observationally much more expensive because it requires a large number of photometric bands to yield robust photometric redshifts as well as robust measures of the stellar population properties, i.e. stellar mass, star-formation rate, dust obscuration and age of the dominant stellar population. For the same reason, however, it is less prone to the effects of photometric scatter and characterized by a higher degree of completeness than the BzK criterion.

In view of the fact that in CANDELS the two GOODS fields have deeper and fully panchromatic images relative to the other fields of the survey, here we use the SED sample as our primary data set for our study, and compare it with the BzK sample to test if they yield similar conclusions about the general morphological properties of the galaxies mix at  $z \sim 2$ . Such a comparison, which at this level of sensitivity can only be made in the GOODS fields, is particularly useful for those other fields where data for selecting galaxies by means of SED fitting are not available or do not have sufficient wavelength coverage and/or sensitivity for accurate results. In our particular case, since the BzK sample is based on the ground-based K-band images, which are significantly shallower ( $5\sigma$  limiting magnitudes of  $K_s=24.4$ ) than the WFC3 images, the depth, and hence the size, of the sample is smaller than the SED one. However, since the efficiency and simplicity of the BzK selection criteria offer a distinct advantage in other fields of the CANDELS survey, where the rich complement of photometry of the GOODS-South field is not available, the knowledge of the relative performance and possible limitations of both selection criteria will be very useful.

## **2.1. The Galaxy Mix at $z \sim 2$ : Photometric Redshift and SED-fitting selection**

Measures of the stellar mass, star-formation rate, dust obscuration and age of the dominant stellar population have been obtained by Guo et al. (2013) using the TFIT

panchromatic catalog of the GOODS–South field (see also Guo et al. 2011, 2012, where key results and features of the SED fitting have been discussed). Prior to carrying out the SED fitting, photometric redshifts have been measured for all galaxies from the 13–band UVVizYJHKsI<sub>1</sub>I<sub>2</sub>I<sub>3</sub>I<sub>4</sub> photometry using the PEGASE 2.0 spectral library templates (Fioc & Rocca-Volmerange 1997), as well as the available sample of 152 spectroscopic redshifts (about 4% of our final sample) as a training set. In the redshift range considered here the CANDELS photometric redshifts are of good quality, as verified by comparing them against available spectroscopic ones. This comparison yields a mean and scatter (  $1\sigma$  deviation after  $3\sigma$  clipping) in our photometric redshift measurement of 0.0005 and 0.03, respectively.

The properties of the dominant stellar populations are subsequently derived by fitting the observed SED to the spectral population synthesis models by fixing the redshift to the photometrically derived value and using the redshift probability function,  $P(z)$ , to calculate the errors from a Monte Carlo bootstrap. The multi–band photometry is fit to the updated version of the Bruzual & Charlot (2003) spectral population synthesis library with a Salpeter initial mass function. We use either a constant star formation history or an exponentially declining one ( $e^{-t/\tau}$ ), depending on which functions result in a smaller  $\chi^2$  with the data. The Calzetti law (Calzetti et al. 2000) is used for the dust obscuration model together with the Madau (1995) prescription for the opacity of Inter galactic medium (IGM) (see Guo et al. 2013 for a full description of the procedure). In the redshift range  $1.4 < z \leq 2.5$ , arbitrarily (but inconsequentially) chosen to reproduce that of the BzK selection criteria (see Daddi et al. (2007)), the photo–z plus SED fitting procedures yield 3,542 galaxies with signal to noise ratio in the H-band  $(S/N)_H > 10$  (hereafter, SED sample).

Star–forming and passive galaxies are defined based on the measure of the SSFR, namely the ratio of the star–formation rate to the stellar mass. Specifically, we define

passive galaxies as those with  $SSFR < 0.01 \text{ Gyr}^{-1}$ , and using this criterion we find 105 passive galaxies and 3,437 star-forming ones out of the 3,539 comprising the SED sample. Thus, with our cut on the SSFR, 3% of all galaxies at  $z \sim 2$  are classified as passive.

## 2.2. The Galaxy Mix at $z \sim 2$ : The BzK Selection

We have constructed the BzK sample by adopting the BzK color-color selection by Daddi et al. (2004), where galaxies of various “spectral types” are identified by their position in the  $(B - z)$  versus  $(z - K)$  color-color diagram. The BzK selection is widely used to investigate the evolution of galaxies at  $z \sim 2$  (Daddi et al. 2005; Reddy et al. 2005; Daddi et al. 2007; Lin et al. 2012; Fang et al. 2012; Yuma et al. 2012). To the extent that the average obscuration properties of the star-forming galaxies are well described by the Calzetti (2000) obscuration law, this rest UV/Optical color selection is sensitive to galaxies at  $1.4 < z \leq 2.5$  with a significantly broader range of dust obscuration than the UV selection alone (e.g. Reddy et al. 2009, 2010; also Guo et al. 2011 for a discussion). It is also sensitive to passively evolving galaxies in a similar redshift range, which the UV selection misses altogether. As in any selection of distant galaxies that is based on colors, however, the details of the redshift distribution of the selected galaxies depend on the relative sensitivity of the images and the shape of the adopted bandpasses.

The original BzK criteria were implemented using a sample where source detections were carried out in the K-band images, since these had sufficient sensitivity and were such that every galaxy detected at least in the z-band was detected in the K one with higher S/N. Since this is not the case with our data, where the *HST*/ACS z-band image is much deeper than the ground-based VLT/ISAAC Ks band image even for the reddest SED considered here, we construct our BzK samples from the ACS z-band selected source catalog (Giavalisco et al. 2004), where we further require  $(S/N)_K > 7.0$  in the K-band

and  $(S/N)_z > 10.0$  in the  $z$ -band to ensure robust color measurements. We then use the selection criteria introduced by Daddi et al. (2004) as shown in Figure 1:

$$BzK \equiv (z - K) - (B - z) \geq -0.2 \quad \text{for star-forming galaxies (sBzKs) and}$$

$$BzK < -0.2 \cap (z - K) > 2.5 \quad \text{for passively evolving galaxies (pBzKs)}$$

Out of a total of 1,043 BzK galaxies, we find 981 sBzKs (blue circles in Figure 1) and 62 pBzKs (red circles), namely 6% of the sample is made of passive galaxies. This fraction is twice as large as the one of the SED sample, and the reason is that the BzK selection defines galaxies as passive solely based on their colors, while in the SED sample galaxies are defined as passive based on the SSFR. If the threshold were defined as  $SSR < 0.16 \text{ Gyr}^{-1}$ , then the SED sample and BzK would both have the same 6% fraction of passive galaxies. Finally, it is important to keep in mind that all BzK galaxies also have detection in the WFC3/F160w CANDELS images, which we have used to analyze their rest-frame optical morphology.

Compared to the SED selection, the BzK selection is relatively easy and economical to implement, requiring only three photometric bands, and it is largely independent of dust reddening. The combination of photometric scatter (which depends on the sensitivity of the data) and the intrinsic variance of galaxies' SED, however, result in some degree of contamination by interlopers (i.e. galaxies that are not in the targeted redshift range) as well as of incompleteness, namely loss of galaxies that are scattered away from the selection windows. For the same reasons, the separation between passive galaxies and star-forming ones suffers from scatter, in the sense that dust-reddened star-forming galaxies might be observed in the selection window of passive ones and vice versa (see, e.g. Daddi et al. 2004, 2005, 2007).

To diminish the contamination by interlopers from outside the redshift range considered here and how it affects our morphological analysis, we can use the photometric redshift to

restrict our sample to galaxies with  $1.4 < z \leq 2.5$ . This further cut serves two purposes. First, it filters away the high- $z$  tail of our BzK sample, which very likely results from the combination of the relatively shallow depth of the ACS B-band images, and the fact that the sample is  $z$ -band selected. The cut also serves the purpose of creating our reference cosmic epoch to assess the state of galaxy morphology evolution. This leaves a final BzK sample of 736 galaxies down to  $H \sim 25$ , of which 46 are classified as passively evolving (pBzK), i.e. 6.3% of the sample, and 690 are star-forming (sBzK) galaxies. We explicitly note that using the photometric redshifts to eliminate likely interlopers has left the passive fraction essentially unchanged. In the following we will refer to this photo- $z$  filtered sample simply as the “BzK sample”, while the original sample will be called the “pure BzK” one. The top panel of the Figure 2 compares the photometric redshift distribution of the BzK sample to that of the whole H-band selected TFIT sample (e.g. SED sample not restricted by redshift), while the bottom one shows the number counts of the SED sample, of the two BzK samples, and also of the whole H-band selected TFIT sample for comparison. It can be seen from the photometric redshift histograms that the redshift distribution of BzKs is tapered at both ends of the corresponding selection window as a result of the color cuts built in the selection criteria. Clearly, this is not presented in the SED sample. It can also be seen that the number counts of the SED and BzK samples are very similar in shape, especially at  $H < 25$ , the former being slightly larger than the latter simply due to the larger completeness and the fact that the redshift distribution is not set by color cuts. Since the magnitude (mass) distribution is not similar especially at the faint end, we cut BzK and SED samples with  $M > 10^9 M_\odot$  ( $H \lesssim 26$  : over the 90% completeness limit of the CANDELS  $H$  band in the GOODS-S Deep field) to study and compare the morphologies directly. As we shall see later, the morphological properties of the SED and BzK samples are essentially identical, suggesting they are both representative of the mix of bright galaxies at  $z \sim 2$ .

### 3. Color-mass diagram at $z \sim 2$

In Figure 3, we report the distribution of rest-frame U–V (3730Å– 6030Å) color versus stellar mass for the BzK (left) and SED (right) samples. The blue crosses and red circles represent the star-forming (sBzK) and passive (pBzK) galaxies, respectively. The rest-frame colors are measured using the best-fitting SED template, which is scaled to pass through the closest observed photometric point for each rest-frame wavelength we consider to derive the k-correction and subsequently the rest-frame magnitude. Figure 3 shows that there is a distinct difference in the color-mass diagram between star-forming and passive galaxies. In both our samples, the colors of passive galaxies (pBzKs) span a much smaller range than those of star-forming ones (sBzKs). An important question to answer, therefore, is whether or not the limited excursion of the intrinsic colors of the pBzKs is simply the result of their selection and not due to the characteristics of their SED. After all, these galaxies are selected specifically to be red, namely to have the observed colors expected from passively evolving galaxies (or galaxies with a relatively small specific star formation rate) observed at  $1.4 < z \leq 2.5$ . To test this possibility, we have compared the scatter of the observed colors and of the intrinsic colors of our pBzK sample in bins of both apparent and absolute magnitude, which is shown in Figure 4. As it can be seen, the scatter *always* increases when going from the intrinsic colors to the observed ones, as one would expect in a sample with a relatively large dispersion of redshift. Moreover, the pBzKs occupy a significantly smaller range of stellar mass, and, at the same time, the two types occupy a disjoint range of SSFR (color-coding of points at Figure 3). Taken all together, this is evidence that while pBzKs are selected to be red, thus covering a restricted range of both the *observed* B-z and z-K colors, their *intrinsic* colors are all very similar, since they span a range significantly smaller than the observed ones, denoting a similarity of physical properties. This conclusion is further reinforced by their small range of mass, since the color selection does not in principle set any restrictions on the stellar mass.

We note that although our star-forming and passive samples separate well in Figure 3, a small fraction of massive star-forming galaxies overlap with the passive ones. The majority of those massive star-forming galaxies are red due to UV colors which are reddened by dust, and similar trends are observed in the red sequence at  $z \sim 0$  (Baldry et al. 2006). In the BzK sample, 11 red sBzKs with  $SSFR < 0.01^{-2} \text{ Gyr}^{-1}$  are all massive ( $M > 10^{10} M_{\odot}$ ) and generally red (rest-frame  $U - V > 1.3$  except two galaxies with  $U - V > 1.0$ ). They are visually characterized by compact structures, with the exception of one having large size ( $R_e = 3.5$  kpc) and a light profile characteristic of an exponential disk ( $n = 1.34$ ). These could be passive galaxies that are not classified as such by the BzK criterion either because of photometric scatter in the photometric measures or because of the galaxies’ intrinsic SED variations (see Section 2.2).

We find 70 (50 for the BzK sample) X-ray detected galaxies among our sample, marked as diamond symbols in Figure 3. Most of them (86% :SED sample, 90%: BzK sample) are star-forming galaxies (sBzKs), and those X-ray detected galaxies are generally massive and compact. We do not exclude them from further study since they also follow a similar trend in the color-mass diagram, and have similar morphologies as non X-ray detected galaxies.

#### 4. Morphological Classification Using Non-parametric Approaches

In order to investigate further the morphologies of galaxies within  $1.4 < z \leq 2.5$ , we turn next to several non-parametric morphological diagnostics such as the Gini parameter ( $G$ ), the second-order moment of the brightest 20% of the galaxy pixels ( $M_{20}$ ) and the multiplicity parameter ( $\Psi$ ). Many studies have used these parameters to quantify galaxy morphology (Lotz et al. 2004; Abraham et al. 2007; Law et al. 2007; Overzier et al. 2010; Law et al. 2012; Wang et al. 2012) locally and at high redshift, generally showing that they are an effective and automated way to measure galaxy morphologies for large samples.

These parameters quantify the spatial distribution of galaxy flux among the pixels, without assuming a particular analytic function for the galaxy’s light distribution. Thus they may be a better characterization of the morphology of irregulars, as well as standard Hubble-type galaxies (Lotz et al. 2004, Hereafter, LPM04). Before measuring these parameters, we need to identify the pixels belonging to each galaxy. For each galaxy, we calculate the “elliptical Petrosian radius”,  $a_p$ , which is defined like the Petrosian radius (Petrosian 1976) but uses ellipses instead of circles (LPM04). We use the segmentation map generated by SExtractor when making the H-band detections (Guo et al. 2013), and use the ellipticities and position of peak flux determined by SExtractor for each galaxy. We then set the semi-major axis  $a_p$  to the value where the ratio of the surface brightness at  $a_p$  to the mean surface brightness within  $a_p$  is equal to 0.2. The surface brightness at each elliptical aperture,  $a$ , is measured as the mean surface brightness within an elliptical annulus from  $0.8a$  to  $1.2a$ . There are 10 galaxies in the SED sample and one sBzK whose images comprise less than 28 pixels (corresponding to a circle with a radius of 3 pixels), which we have excluded from further analysis. Note again that we use galaxies with  $M > 10^9 M_\odot$  from both samples for our morphology analysis, which leaves us with 46 pBzKs and 669 sBzKs, and 104 passive and 1567 star-forming galaxies of the SED sample.

Using the SED and BzK samples with stellar mass  $> 10^9 M_\odot$ , we first compute the G parameter defined in LPM04, which measures the cumulative distribution function of a galaxy’s pixel values (light). Therefore, G of 1 would mean all light is in one pixel while G of 0 would mean every pixel has an equal share. Hence, G is used to distinguish between the galaxies for which fluxes are concentrated within a small region or uniformly diffuse. We also compute the  $M_{20}$  parameter, which traces the spatial distribution of any bright nuclei, bars, spiral arms, and off-center star clusters. Typically, galaxies with high values ( $M_{20} \geq -1.1$ ) are extended objects with double or multiple nuclei, whereas low values ( $M_{20} \leq -1.6$ ) are relatively smooth with a bright nucleus (see LPM04 for a

detailed explanation of  $M_{20}$ ). The third non-parametric coefficient is the multiplicity  $\Psi$  (Law et al. 2007), designed to discriminate between sources based on how "multiple" the source appears. Galaxies with lower  $\Psi$  are compact galaxies with generally one nuclei while irregular galaxies with multiple clumps have higher  $\Psi$  (Law et al. 2007) (the definitions of each diagnostic are presented in the above references).

#### 4.1. Rest-frame Optical Morphology

Figure 5 shows the relative distribution of the  $G$ ,  $M_{20}$  and  $\Psi$  for star-forming and passive galaxies of the BzK and SED samples (blue and red histogram, respectively). The  $G$  values are mostly in the range 0.3 – 0.7 with a mean of 0.43 for star-forming galaxies (0.48 for sBzKs) and 0.53 for passive ones (0.58 for pBzKs). Passive galaxies are shifted to higher  $G$  than star-forming ones. The majority of pBzKs (90%) and about 70% of passive galaxies have  $G > 0.5$ . The mean values of the  $M_{20}$  for star-forming (sBzK) and passive (pBzK) galaxies are -1.47 (-1.54) and -1.68 (-1.73), respectively. The middle panel of Figure 5 shows that the passive galaxies (pBzKs) have lower values and show a peak at  $\sim -1.7$  while the star-forming ones (sBzKs) exist in a wide range of  $M_{20}$  values that are slightly skewed to higher  $M_{20}$ . Lastly, the  $\Psi$  values of star-forming galaxies (sBzKs) have a range of values up to  $\sim 5$ , but most of the passive galaxies (SED: 90% , BzK: 94% ) have  $\Psi < 1.0$ . Law et al. (2012) find that spectroscopically confirmed star-forming galaxies at  $z=1.5-3.6$  have  $\Psi < 1$  for isolated regular galaxies,  $1 < \Psi < 2$  for sources that show some morphological irregularities, and larger values for sources having multiple clumps that are separated. Therefore, all passive galaxies (pBzKs) tend to be dominated by one main clump while star-forming ones (sBzKs) can have two or more significant components in addition to a main nucleation. There is some degree of correlation between the  $G$  and  $M_{20}$ ,  $\Psi$  measurements (see Figure 6). The passive galaxies (pBzKs) reside in a narrow

region with higher  $G$  and lower  $M_{20}$  and  $\Psi$  indicating that they consist of one bright central source. In contrast with passive galaxies (pBzKs), star-forming ones (sBzKs) with lower  $G$  have higher  $M_{20}$  and  $\Psi$  because galaxies with diffuse morphology tend to have a spread out flux distribution. Figure 5 and 6 also show that there is an overlap in the distributions of morphological parameters of star-forming galaxies and passive ones. For example, there are star-forming galaxies with high  $G$  and low  $\Psi$  or  $M_{20}$  that are located in same region where the bulk of passive galaxies are observed, and vice versa.

To illustrate and further explore these galaxies in the overlapped region, we have chosen star-forming galaxies with  $G > 0.6$  and passive galaxies with  $G < 0.5$  for visual inspection and classification. We indeed found that the star-forming galaxies can generally be classified as blue spheroids and the passive ones as red disks. In agreement with Law et al. (2007), the 35 star-forming galaxies with high  $G$  visually appear as compact structures in Figure 7. Note that all these images have S/N ratio per pixel ( $S/N_{pp}$ ) greater than 2.5, the threshold used in LPM04 for reliable measurements, and most of them (85%) are relatively bluer than normal passive galaxies. About 40% of star-forming galaxies in the sample of Law et al. (2012) were visually classified as such compact structures as well. Among passive galaxies in the SED sample, 10 of them have  $S/N_{pp} < 2.5$ , and all have  $G < 0.5$ . This indicates that we cannot measure reliable morphology due to the low  $S/N_{pp}$  ratio. In Figure 8, we show the 25 passive galaxies with  $G < 0.5$  and  $S/N_{pp} > 2.5$ . Most of them have smooth structures, and some are elongated or have secondary structures. They are intrinsically red with rest-frame  $(U - V) > 1.5$ , and 16 galaxies are massive ( $M > 10^{10} M_{\odot}$ ). Red (passive) disks at high redshift have also been recently studied by other groups. For example, Wang et al. (2012) found that 30% in quiescent galaxies of their sample with  $M > 10^{11} M_{\odot}$  at  $1.5 \leq z \leq 2.5$  can be morphologically classified as disks. This is generally consistent with the findings presented here, although we note that due to their low  $S/N_{pp}$ , some of our “passive disks” might actually be morphological mis-classifications or even be

dust-obscured star-forming galaxies. Finally, we observe that, overall, the BzK and the SED samples have essentially identical distributions of morphological parameters, although the SED sample includes galaxies with lower  $G$ , namely those with  $S/N_{pp} < 2.5$ , which is the result of their lower surface brightness.

In addition to  $G$ ,  $M_{20}$  and  $\Psi$ , we measure the Concentration ( $C$ ) and Asymmetry ( $A$ ) of our samples. The concentration index  $C$  (Abraham et al. 1996; Conselice 2003) measures the concentration of flux. Typical values of  $C$  range from  $\sim 1$  for the least compact to  $\sim 5$  for most compact galaxies. Note that asymmetry  $A$  (Schade et al. 1995; Abraham et al. 1996; Conselice et al. 2000) compute the 180 degree rotational asymmetric light distribution of all galaxy and hence the most symmetric galaxies have  $A = 0$ . We present the distribution of  $C$  and  $A$  for the BzK (left) and SED (right) samples in Figure 9. As expected, the passive galaxies (pBzKs) are more similar to ellipticals in their  $C$  and  $A$  values, while the star-forming ones (sBzKs) are more spiral and merger-like. In the  $C - A$  plane, passive galaxies (pBzKs) are different from star-forming ones (sBzKs), but the difference is not as significant compared to the difference in  $G - M_{20}$  and  $\Psi$ . As expected, the distribution of  $C$  and  $A$  for both samples are similar as shown in the previous figures.

In summary, the distributions of the non-parametric morphological diagnostics that we have considered here for both the BzK and SED samples are essentially the same in each spectral type class. Star-forming and passive galaxies clearly show different distributions of non-parametric morphological measures, and they are separated well in  $G - M_{20}$  and  $\Psi$  spaces. Passive galaxies (pBzKs) are mostly compact, spheroidal structures, and the majority of star-forming ones (sBzKs) are somewhat extended or have multiple clumps, similar to disks or irregular galaxies in the Local universe. These results agree with those of Wang et al. (2012) who also studied the morphologies of massive galaxies ( $M > 10^{11} M_{\odot}$ ) at  $z \sim 2$  with  $G$ ,  $M_{20}$  and visual classifications. They found that the quiescent galaxies are

bulge dominated and star-forming galaxies have disks or irregular morphologies visually as well as in the  $G$  and  $M_{20}$  analysis. We extend their study with a larger sample down to a lower mass limit, and obtain almost the same conclusion about galaxy morphologies at  $z \sim 2$ .

In Appendix A, we investigate the robustness of non-parametric measures ( $G$ ,  $M_{20}$  and  $\Psi$ ), mainly used in this study for morphological analysis, using GOODS-S and the Hubble Ultra Deep Field (UDF) images in the H-band. The UDF overlaps part of the GOODS-S imaging, but goes much deeper ( $5 \sigma$  depth of 28.8), and thus offers an opportunity to test the dependence of parameters on the signal-to-noise per pixel ( $S/N_{pp}$ ). We show that any difference between the two different fields, which have different exposure times, is relatively small for three parameters, with the scatter in measured properties increasing as S/N decrease. We find that most ( $> 90\%$ ) of BzK galaxies have  $S/N_{pp} > 2.5$ , and  $\sim 70\%$  of the SED sample have  $S/N_{pp} > 2.5$ . We note that we do not exclude galaxies with  $S/N_{pp} < 2.5$  since they rarely change our results in this study.

#### 4.2. $G$ , $M_{20}$ and $\Psi$ vs. *Sérsic* Index and $R_e$

*Sérsic* index and half-light radius ( $R_e$ ) have been successfully used to characterize galaxy morphology in many previous works, both at low and high redshift (low-z: Blanton et al. 2003, Driver et al. 2006; mid-z: Cheung et al. 2012; high-z: Ravindranath et al. 2006, Bell et al. 2012). Recently, Bell et al. (2012) and Wuyts et al. (2011) show that the *Sérsic* index correlates well with quiescence in galaxies at  $z \lesssim 2$ . Therefore, we investigate how galaxy morphologies with  $G$ ,  $M_{20}$  and  $\Psi$  correlate with *Sérsic* index ( $n$ ) and  $R_e$ . We use the *Sérsic* index and  $R_e$  (van der Wel et al. 2012) obtained by fitting a *Sérsic* profile to the galaxy image using GALFIT (Peng et al. 2002). Passive galaxies in both samples have  $\langle n \rangle \sim 3.0$ , and over 96% of them have  $n > 1.0$ , with 50% having  $n > 2.5$ . In contrast,

star-forming galaxies have  $\langle n \rangle \sim 1.5$ , with 85% of them having  $n < 2.5$ . This suggests that the majority of star-forming (sBzK) galaxies have disk-like (exponential light profile) or irregular structure with a light profile shallower than an exponential one. In contrast, all passive galaxies (pBzKs) have a dominant bulge including some bulge+disk structures. A similar analysis of morphologies at  $z < 2.5$  using the *Sérsic* index in the SFR-mass diagram was carried out by Wuyts et al. (2011), who found that the main sequence (MS) consists of star-forming galaxies with near exponential profiles, and passive galaxies below the MS have higher *Sérsic* indices close to a de Vaucouleur profile ( $n = 4$ ). Szomoru et al. (2011) also reported similar results with 16 massive galaxies at  $z \sim 2$ , and found that star-forming galaxies have diskier (low  $n$ ) profiles than passive galaxies. We present the distribution of  $G$ ,  $M_{20}$  and  $\Psi$  as a function of *Sérsic* index in two different mass bins divided by a threshold mass,  $M_{th} = 1 \times 10^{10} M_{\odot}$  in Figure 10 (SED sample) and 11 (BzK sample).

In both samples, we find that there are significant correlations between *Sérsic* index and  $G$ ,  $M_{20}$  and  $\Psi$ , with galaxies with high  $n$  having high  $G$  and low  $M_{20}$ ,  $\Psi$ , and vice versa. As we have already noted in Figure 3, most of the passive galaxies (pBzKs) have masses greater than  $1 \times 10^{10} M_{\odot}$ , and the majority of star-forming galaxies (78%) and 70% for sBzKs have  $M < 1 \times 10^{10} M_{\odot}$ . In massive systems ( $M \geq 1 \times 10^{10} M_{\odot}$ ), the two populations show a well-separated bimodal distribution in their morphologies and colors (see Figures 10 and 11). Red passive galaxies (pBzKs) show spheroidal-like structures with high  $n$ ,  $G$  and low  $M_{20}$ ,  $\Psi$ , while blue star-forming ones (sBzKs) exhibit a larger variety of morphologies, but mainly have low  $n$ ,  $G$  and high  $M_{20}$ ,  $\Psi$ . There are some star-forming galaxies (sBzKs) with high *Sérsic* index ( $n > 2.5$ , vertical dotted line in Figure 10, 11). They follow mostly the same trend in morphologies with higher  $G$  and lower  $M_{20}$ ,  $\Psi$ , indicating the presence of a bright center (see the blue spheroids in Figure 7). Bell et al. (2012) showed examples of such systems in their sample, and found that those appear to be spheroidal-like structures, but in many cases also have significant asymmetries, or faint secondary sources and tidal

tails. A loose relation between non-parametric measures and *Sérsic* index is observed for massive galaxies in the right panel of Figure 10, 11, but not for low mass galaxies at all. This means that the commonly used *Sérsic* index is not enough to study morphology of those galaxies. Therefore, it is important to use the non-parametric diagnostics in addition to the *Sérsic* profile to quantify the morphology of galaxies towards the low end of the mass distribution.

In Figure 12 (SED sample) and 13 (BzK sample), we plot the non-parametric measures as a function of  $R_e$  in both small and large mass systems to see how the size varies along with spectral type and stellar masses. We find that  $R_e$  also correlates well with all the non-parametric measures in general, as galaxies with low  $G$  and high  $M_{20}$ ,  $\Psi$  have smaller sizes and relatively low *Sérsic* Index ( $n < 2.5$ : Empty symbols) in both samples. Overall, star-forming galaxies (sBzKs) tend to have larger half-light radii than passive ones (pBzKs), even in the case of massive systems ( $M \geq 1 \times 10^{10} M_\odot$ ) and about half of passive (pBzK) galaxies show very compact morphologies, with  $r_e < 1 \text{ kpc}$ . This is consistent with previous results, which find that passive galaxies are more compact than star-forming galaxies at  $z \sim 2$  (Toft et al. 2009; Wuyts et al. 2011; Cassata et al. 2011), and the same general trend is observed at  $z \sim 0$  among massive galaxies (Williams et al. 2010).

## 5. Comparison with the Local Universe

The strong correlation between galaxy color (and SFR) and morphology shown in the previous sections is reminiscent of the Hubble sequence at  $z = 0$ . However, to understand if actually the Hubble sequence is in place at  $z \sim 2$ , it is important to examine how galaxy morphologies at  $z \sim 2$  differ from the local galaxies. In general, comparing morphological parameters of local galaxies, which are observed at relatively high resolutions to their counterparts in high- $z$  samples, whose resolution is lower, is not straightforward because

because most morphological diagnostics do depend on the resolution. A fortunate case, however, is that of the comparison between local galaxies at redshift  $0.05 < z < 0.1$  from the SDSS survey to galaxies at  $z \sim 1$  observed with *HST*, since the difference of angular diameter distance at these two redshifts nearly perfectly compensates for the difference in the angular resolution of the two instrumental configuration (Nair & Abraham 2010). At this purpose, we should also keep in mind that in our adopted cosmology, the fractional variation of the angular diameter distance in the redshift range  $1.4 < z < 2.5$  is only  $\approx 5\%$ . Furthermore, even though  $G$  and  $M_{20}$  measures are robust given the resolution of the observation, particularly if the data is deep enough to allow the Petrosian radius to be used to measure the parameters (Abraham et al. 2007), we should nonetheless be careful when directly comparing the  $G$  and  $M_{20}$  from observations with different resolutions (LPM04; Lisker et al. 2008). Therefore, in this study, we compare the  $z \sim 2$  galaxy morphologies in the SED and BzK samples to those of the local galaxy sample of LPM04 after we simulate how they would appear in the CANDELS images if they were observed at redshift  $z \sim 2$ . For this reason, we have used the B-band and g-band images of the local galaxies (Frei et al. 1996; Abazajian et al. 2003), which at this redshift correspond to the H band (for details about the local galaxy observations, see LPM04). We have restricted the comparative analysis with the high-redshift galaxies to only those at  $2.0 < z \leq 2.5$  to minimize the possible effects of the morphological K-correction. Furthermore, we have only considered galaxies within a magnitude range of  $0 \leq (M_B - M_*) \leq 4$  (LPM04), where we take  $M_* = -20.1$  (Blanton et al. 2003b) for local galaxies, and  $M_* = -22.9$  for galaxies at  $z \geq 2$  (Shapley et al. 2001), assuming that the local galaxies were brighter in the past but did not evolve morphologically (LPM04).

In this simulation, we first modify the angular sizes and surface brightness of local galaxy images to account for distance and cosmological effects. The images are rebinned to the pixel scale of the galaxies observed at  $z = 2.3$  (WFC3 pixel size is  $0.06''$ ) and the

flux in each pixel is rescaled so that the total magnitude of the galaxy corresponds to some preassigned value, for example to that of an  $M^*$  galaxy at  $z = 2.3$ . The modified images are then convolved with the WFC3 PSF and, lastly, we add Poisson noise appropriate to the WFC3/NIR observations using the IRAF task MKNOISE.

In Figure 14, we present the  $G$ ,  $M_{20}$  and  $\Psi$  measured from the redshifted modified local galaxy images. The measures of the redshifted galaxies (from the left, 1st and 2nd panels) are quite different from those of the original local galaxy images (3rd panel). This is in agreement with LPM04, who conclude that  $z \sim 2$  Lyman Break Galaxies (LBGs) do not have morphologies identical to local galaxies. Overall, the distributions of galaxies at  $z \sim 2.3$  in both samples and that of the redshifted local galaxies are similar in  $G$ - $M_{20}$  space, as shown in the 1st and 2nd panel of Figure 14, but the high-redshift star-forming galaxies have a broader distribution of  $M_{20}$  for a given value of  $G$  than the redshifted local late types. This trend is reflected in the  $G$ - $\Psi$  plane (in the bottom panels), which shows lower  $\Psi$  values for the redshifted local galaxies. Large and luminous star-forming disks are mostly responsible for this excess of galaxies with higher  $M_{20}$  and broader (slightly higher) distribution of  $\Psi$ , another manifestation of the fact that disks at  $z \sim 2$  are not simply scaled-up versions of the local ones in terms of star-formation rates, but are intrinsically different (e.g. Papovich et al. 2005, Law et al. 2007). Comparatively, the  $z \sim 2$  passive galaxies have  $G$  and  $M_{20}$  values that are much more similar to those observed for the present-day E/S0 galaxies. Overall, the qualitative similarity of values, shapes and trends of the distributions of morphological parameters at low and high redshift suggests that the Hubble sequence is essentially in place at  $z \sim 2$ .

Our comparative study also shows that while the morphology of the oldest systems at any epoch, i.e. the passively evolving galaxies, in general changes relatively little from  $z \sim 0$  to the present, at least as traced by our diagnostics, disks galaxies underwent strong

structural evolution over the same cosmic period. A noticeable exception is the evolution of the size of massive ellipticals, which at  $z \sim 2$  were dominated by very compact galaxies, which had stellar density up to two order magnitudes higher than today’s counterparts of similar mass, while at present such systems have essentially disappeared (see Cassata et al. (2011, 2013)). Also, it is interesting to note that Huang et al. (2013) find that at even higher redshifts, i.e.  $4 < z < 5$ , the size distribution of star-forming galaxies is significantly larger than that predicted from the spin parameter distribution observed in cosmological N-body simulations, a marked difference from local disks which follow the simulation predictions very well.

## 6. Comparison With Rest-Frame UV

It is important to compare the rest-frame UV and optical morphologies, since the former traces the spatial distribution of star formation, and thus contains information on how, and where, galaxies grow in mass and evolve morphologically, while the latter traces the structure of their stellar components. With the CANDELS images we can study the relation between rest-frame optical (5300 Å) and UV (2800 Å) morphology with a large sample. Since non-parametric measures can vary systematically with the PSF and pixel size of the images as the resolution decreases (Lotz et al. 2004; Law et al. 2012), we made a version of the ACS z-band image which is PSF-matched to the WFC3 H-band one (by convolution with an ad-hoc kernel) and which we have re-binned to the same pixel scale of 0.06”/pixel. To make a meaningful comparison, we use the same segmentation map and the “elliptical Petrosian radius” estimated from the H-band image and apply it to the PSF matched z-band image to measure the  $G$ ,  $M_{20}$  and  $\Psi$  in the rest-frame UV. In Figure 15 we compare the  $G$ ,  $M_{20}$  and  $\Psi$  of the BzK and SED samples in the UV and optical rest-frames (passive (pBzK) and star-forming (sBzK) galaxies in red and blue, respectively). What

we find from our measurements is that all three parameters are different between the H- and z-bands in general. First, the H-band derived  $G$  is higher for both passive (pBzKs) and star-forming (sBzKs) galaxies at  $z \sim 2$ . The values of  $M_{20}$  at the two wavelengths are well correlated for both populations, but generally the z-band measurements have slightly higher values. In particular, we find that the scatter increases as  $M_{20}$  increases. This means that galaxies are clumpier in the z-band and the difference in  $M_{20}$  between the two bands is bigger in the case of multi-clump structures (e.g. higher  $M_{20}$ ). The  $\Psi$  values from the H-band and z-band for star-forming (sBzK) galaxies are well correlated, while most of the passive ones (pBzKs) in the z-band have higher  $\Psi$  value than in the H-band. We compute the fractional differences of the three parameters between optical and UV defined as  $f(M_{20}) = [M_{20}(z) - M_{20}(H)]/M_{20}(z)$ , shown in the insets of Figure 15 to check for offsets from the linear correlation. Negative  $M_{20}$ , positive  $G$  and  $\Psi$  imply that parameters in the z-band are higher than the ones in the H-band.

Overall, in the rest-frame UV, galaxies appear to have higher  $\Psi$  and  $M_{20}$  and lower  $G$  values than in the rest-frame optical since observations in the rest-frame UV show more fragmented structures than the rest-frame optical, especially for star-forming galaxies. We additionally find that the passive galaxies (pBzKs) in the rest-frame optical tend to have a higher  $G$  and lower  $\Psi$  and  $M_{20}$  than in the rest-frame UV because the rest-frame optical light from old stellar populations is typically more concentrated than that from younger stellar populations, consistent with the result from Guo et al. (2011) that the inner region of passive galaxies at  $z \sim 2$  have a redder color gradient. A similar trend was noted by Wuyts et al. (2012), who found that the median galaxy size and  $M_{20}$  are reduced (less clumpy), while  $G$  and  $C$  increase from rest-frame 2800 Å and U band to the optical, using star-forming galaxies at  $0.5 < z < 2.5$ .

Sample images of galaxies in both rest-frame optical and UV are shown in Figure 16 to

visually present the morphological differences between passive and star-forming galaxies and to see how nonparametric measures are correlated with the visual classifications. We have selected 16 galaxies (eight pBzKs and eight sBzKs) included in both BzK and SED samples. These images have relatively smooth and regular morphologies in both bands. The eight images for each spectral type are sorted by their H-band magnitude, with the brightest one located at the bottom and decreasing upward, and non-parametric statistics and redshifts of each galaxy labeled. This figure illustrates the good correspondence between the measured parameters and the visual morphologies of the galaxies. Most sBzKs are extended, and exhibit a broad range of morphologies, from isolated systems with a central bulge and galaxies with bulge and disk components, to irregular systems with multi-clumps. The pBzKs have morphologies similar to those of present day spheroids, bulges and ellipticals. Visually, the sBzKs appear clumpier in the rest-frame UV compared to optical, showing a dependence on wavelength with the exception of a few isolated cases, while pBzKs look very similar in both wavelengths. Overall, visual inspection shows that the morphological types in both bands are generally similar, in agreement with Cassata et al. (2010) who found that passive galaxies ( $SSFR < 0.01 \text{ Gyr}^{-1}$ ) have a “weak morphological K-correction”, with size being smaller in the rest-frame optical than in the UV. However, the comparison with non-parametric measures show that galaxies in the rest-frame UV are somewhat clumpier than rest-frame optical for both galaxy populations. For star-forming galaxies at  $z > 1.5$ , Bond et al. (2011) and Law et al. (2012) measured the internal color dispersion (ICD), and found that the morphological differences between the rest-frame UV and optical are typically small. However, the argument that the majority of ICDs for star-forming galaxies are larger than those for passive galaxies (Bond et al. 2011) is not consistent with our finding of relatively large offset for pBzKs in Figure 15. Since most of our pBzKs ( $\sim 80\%$ ) are massive ( $M > 3 \times 10^{10} M_{\odot}$ ), one possibility is that high mass galaxies tend to exhibit greater morphological differences with large ICD (Law et al. 2012). Furthermore, pBzKs

are typically brighter and rather compact at rest-frame optical wavelengths, which results in higher  $G$  and lower  $M_{20}$  and  $\Psi$  than in the rest-frame UV. On the other hand, Szomoru et al. (2011) found a strong dependence of the morphology on wavelength in a visual study of 16 massive galaxies at  $z \sim 2$ .

## 7. Discussion

In this section we briefly compare our measures of the morphologies of the mix of galaxy populations in the redshift range  $1.4 < z \leq 2.5$  to the predictions of theoretical models. In particular, we discuss the evidence that the bimodal distribution of galaxies in the color-mass (or luminosity) diagram, namely the “red sequence” and “blue cloud”, has already started to appear at  $z \sim 2$ , and compare it with existing measures at lower redshift. The reliability of our non-parametric measures,  $G$ ,  $M_{20}$  and  $\Psi$  and their performance in quantifying the morphology of galaxies at  $z \sim 2$ , especially for less massive ones, are also discussed. Lastly, we discuss the comparison between BzK and SED selected samples.

### 7.1. Comparison to the predictions of theoretical models

Our analysis of the various morphological indicators, both parametric and non-parametric ones, as well as a simple visual inspection (e.g. Figure 16), have shown that star-forming galaxies (sBzKs) exhibit a broad variety of morphological structures, ranging from galaxies with a predominant disk morphology and varying degree of bulge-to-disk ratio to irregular (clumpy) structures to very compact and relatively regular galaxies. Generally, the mix of star-forming galaxies at  $z \sim 2$  looks rather different from its counterpart in the local universe, showing a much larger fraction of irregular and disturbed morphologies, especially among massive and luminous galaxies, although bright galaxies that closely

resemble local spirals are also observed. We do observe luminous, clumpy galaxies whose light profile is consistent with a disk (of course, we do not have dynamical information on these galaxies) and whose overall morphology is in broad qualitative agreement with the theoretical predictions of violent disk instability (VDI, Dekel et al. 2009a) as seen in high-resolution hydrodynamic cosmological simulations (Ceverino et al. 2010). These simulations show that galaxy disks are built up by accretion of continuous, intense, cold streams of gas that dissipate angular momentum in a thick, toomry-unstable disk, where star-forming clumps form. Subsequently, clumps migrate toward the center and edge, giving rise to bulges and pseudo-bulges. Observations of the star-formation rate, stellar mass and age of the clumps, as well as their average radial dependence relative to the center of the galaxies are also broadly consistent with this scenario (e.g. Guo et al. 2011).

On the other hand, passive galaxies (pBzKs) are mostly spheroidal-like, comparatively more regular and compact structures, a fact that has been consistently observed in previous works (Daddi et al. 2005; Franx et al. 2008; van Dokkum et al. 2008; Cassata et al. 2010, 2011). It is important to keep in mind, however, that there is scant spectroscopic information on the dynamical properties of these galaxies, namely whether they are primarily supported by velocity dispersion or by rotation. While the modicus of spectroscopic observations currently available (van Dokkum et al. 2011; Onodera et al. 2011) is certainly consistent with the high-redshift passive galaxies being spheroids, a significant or even dominant contribution by rotation cannot be ruled out given the limited angular resolution of the existing spectra, and some have indeed proposed that a significant fraction or maybe even most (van der Wel et al. 2011; Bruce et al. 2012) of these galaxies are actually compact rotating disks. From the theory point of view, there are three distinct scenarios for the formation of the compact spheroids, namely major mergers, multiple minor mergers or the migration of clumps driven by violent disk instabilities (Dekel et al. 2009b; Genzel et al. 2011) to the disks center, building a massive bulge. Cosmological hydrodynamical

simulations indicate that these processes, operating alone or in combination, can form compact spheroids. In most cases, the inner parts of the compact spheroids formed by VDI are rotating, and the outer parts are non-rotating, formed mostly by minor mergers. While the observed morphological properties of galaxies certainly include cases that are broadly consistent with these scenarios, it is clear that to make progress comparisons between the dynamical properties of the galaxies and the predictions of the simulations are necessary. These, however, require spectroscopic observations with sensitivity and spatial resolution that are not currently available.

In general very compact and massive galaxies are thought to be the result of a highly dissipative process, either a major wet merger (e.g. Wuyts et al. 2010) or direct accretion of cold gas. Accretion of cold gas from the inter-galactic medium (Birnboim & Dekel 2003; Keres et al. 2005; Dekel & Birnboim 2006) can lead to the formation of compact, massive galaxies, either via VDI in a compact disk (Dekel et al. 2009b) or via direct accretion of the gas traveling directly to the galaxy center rapidly and forming stars in-situ (Johansson et al. 2012). Quenching of the star formation subsequently takes place late when the supply of gas is halted. The simulations suggest that cold accretion is naturally interrupted in dark matter halos more massive  $\approx 10^{12} M_{\odot}$  once the shocked halo gas become too hot to allow the cold flows to penetrate the halo before they themselves get shock-heated (Dekel & Birnboim 2006), leading the formation of a massive compact passive galaxy. Additional feedback mechanisms from star-formation itself (Diamond-Stanic et al. 2012) and AGN (Springel 2005) can also contribute to suppress the accretion of cold gas.

As mentioned earlier, Bruce et al. (2012) have studied the morphologies of massive galaxies at  $1 < z < 3$  in the CANDELS-UDF field using *Sérsic* and bulge+disc models, finding that at  $z > 2$  massive galaxies are dominated by disk-like structures and 25-40% of quiescent galaxies have disk-dominated morphologies. Following their classification of

disks, namely  $n < 2.5$  (even though they also use bulge- to-total H-band flux ratio), we find that about 50% of our passive galaxies (with  $SSFR < 0.01 \text{ Gyr}^{-1}$ ) have exponential light profiles with  $n < 2.5$ , i.e consistent with exponential disks. These roughly classified passive disks have mostly  $G > 0.5$ ,  $M_{20} < 1.45$ ,  $\Psi < 1.0$ , suggesting that they generally are not clumpy structures, and their morphology is characterized by a central bright nucleus surrounded by low surface brightness features. The presence of passive disks seems inconsistent with models where galaxy morphology transforms from a disk structure into a bulge followed by quenching of star formation as the galaxy evolves. The existence of passive disks is, however, predicted by hydrodynamic simulations (Keres et al. 2005; Dekel & Birnboim 2008), which show that these structures form when cold gas inflows are halted, thus quenching star formation without the transformation of morphology. For example, (Williams et al. 2013) argue that the morphological properties and volume density of massive, compact passive galaxies at  $z \sim 2$  and those of compact star-forming galaxies at  $z > 3$  are generally consistent with such a scenario.

## 7.2. Bimodal color distribution at $z < 2.5$

In this study, to the extent that passive and star-forming galaxies can effectively be identified by means of broad-band colors, e.g. either the BzK selection criteria or via SED fitting, we have shown that passive (pBzK) and star-forming (sBzK) galaxies occupy regions of the rest-frame U-V and stellar mass diagram (e.g. Figure 3) that are essentially the same as the “red sequence” and “blue cloud” observed in the local universe (e.g. Blanton et al. 2003, Bell et al. 2004). Passive galaxies (pBzKs) are intrinsically red and massive, whereas, star-forming galaxies (sBzKs) are generally bluer and have lower mass than passive (pBzK) ones (with the exception of about 7% red massive sBzKs). The majority of the exceptions are massive dusty star-forming galaxies, and are largely redder than low mass star-forming

galaxies (sBzKs) at  $z \sim 2$ . Thus, they can contaminate the red sequence sample by a significant fraction, if selected based only on a single rest-frame (U-V) color (Brammer et al. 2009), since most of the UV emission from high-redshift star formation is at least somewhat obscured by dust.

An intriguing property of this color-mass diagram is the lack of passive galaxies with mass  $M < 10^{10} M_{\odot}$ . To a minor extent, this is the result of incompleteness, since passive galaxies with lower mass, and hence luminosity, become harder to detect. From the simulation using model galaxies in the GOODS-S Deep field mosaics, we confirm that the early-type galaxies with “de Vaucouleurs” light profile (*Sérsic* Index = 4) are 90% complete with  $H < 26$ . Clearly, however, such a small incompleteness alone cannot explain the lack of low-mass passive galaxies at  $z \sim 2$ , and in fact such low-mass galaxies are actually detected by the SED selection, as shown in the right panel of Figure 3 which illustrates how massive red galaxies are rarely star-forming, and more actively star-forming galaxies are bluer and have lower masses. Furthermore, obscured star-forming galaxies in the same redshift range and with similar rest-frame (U-V) colors are detected in significantly larger number even at lower masses, as the right panel of the figure shows. This fact strongly suggests that the quenching of star-formation at this epoch is tightly correlated with the mass of the galaxies, with the most massive ones being significantly more likely to cease their star formation activity. At mass  $M < 10^{10} M_{\odot}$ , galaxies appear much less likely to stop forming stars, a fact that has been observed by other groups. For example, Kauffmann et al.(2003) and Bell et al.(2007) observed that at  $z < 1$  the stellar mass value of about  $3 \times 10^{10} M_{\odot}$  appears to be the transition mass point between galaxies that belong to the blue cloud (younger stellar populations) and those of the red sequence.

There is evidence that this transition mass between quenched and star-forming galaxies has evolved significantly over cosmic time (Bundy et al. 2007) further supporting the

downsizing scenario whereby more massive galaxies appear to quench first, and subsequently lower mass galaxies quench later. At high redshift, quenching appears to depend on galaxy stellar mass, perhaps through some internal process that is tied to the total mass of the galaxy of which the stellar one is a good proxy in passive systems, whereas later, environmental processes can contribute to galaxy quenching and can affect lower-mass galaxies (e.g. Peng et al 2010, Peng et al 2012). This process effectively builds up the lower-mass end of the red sequence over time by quenching lower-mass star-forming galaxies later when environmental processes become more influential. Our observed deficiency of lower-mass passive galaxies at  $z \sim 2$  is consistent with this scenario and the implied mechanisms by which galaxies quench their star-formation.

Results from other deep extragalactic surveys have provided constraints on the buildup of stellar mass locked up in the red sequence, by studying how the bimodality of galaxy properties has changed over cosmic time. For example, using the COMBO-17 and DEEP2 surveys, (Bell et al. 2004; Faber et al. 2007) have studied the evolution in the rest-frame color bimodality of galaxy samples out to  $z \sim 1$ , finding evidence that the buildup of the red sequence must be accounted for by a combination of merging of galaxies already on the red sequence, as well as migration of star-forming galaxies that have quenched. Recently, Brammer et al (2011) extended the study of rest-frame color bimodality in galaxies to higher redshift, showing that star-forming and passive galaxies are still robustly separated in color over the redshift range  $0.4 < z < 2.2$ , and coming to the similar conclusion that the growth of the red sequence must come from both merging and migration, particularly for galaxies above the apparent quenching threshold,  $M > 3 \times 10M_{\odot}$ . In this context, a possibility is that that the morphological bimodality we have observed in this study may imply that some degree of morphological transformation must accompany the quenching of star-forming galaxies at  $z < 1.4$ , if they are to match the properties of the red sequence after quenching. Regardless of the dominant mechanisms building the red sequence, and

weather or not the dominant mechanisms evolve with redshift, our result suggests that the process was already underway at redshift 2. In other words, at this epoch, the formation of the Hubble sequence is already underway. Further detailed study of the evolution of morphological properties of galaxies as a function of mass and star-formation properties will be required to identify the specific mechanisms contributing to the growth of the red sequence.

### 7.3. The reliability of non-parametric measures

We mainly use the  $G$ ,  $M_{20}$  and  $\Psi$  to study the morphologies of galaxies at  $z \sim 2$ . Those non-parametric measures are widely used to study galaxy morphologies at high redshift, especially for large samples (Law et al. 2007; Conselice et al. 2008; Law et al. 2012; Wang et al. 2012). We investigate the robustness of the  $G$ ,  $M_{20}$  and  $\Psi$  parameters in relation to the SNR in Appendix A and show that any differences in the estimated parameters for the same galaxies observed in the GOODS-S and UDF images, whose only difference is the vastly different total exposure time, are relatively small. Most of the galaxies in our samples (above 90% of BzK and 70% of SED selected galaxies) have reliable morphological measurements with  $S/N_{pp} > 2.5$  at  $z \sim 2$ . Moreover, the good correspondence between those parameters and visual inspection (in Figure 16), as well as model-dependent parameters indicates that our  $G$ ,  $M_{20}$  and  $\Psi$  measures are not biased by low signal-to-noise. We note that *Sérsic* index alone is generally not sufficient to quantify the morphology of low mass galaxies since we find no correlation between *Sérsic* index and non-parametric measures in the lower mass systems ( $M < 10^{10} M_{\odot}$ ). Also non-parametric measures more effectively characterize the morphology of irregular galaxies (LPM04). Therefore, it is crucial to use non-parametric diagnostics instead of, or at least in parallel with, the commonly used *Sérsic* profile to study the morphology of lower mass galaxies and to explore the origin of

the Hubble sequence at  $z \sim 2$ , and epoch when many galaxies appear irregular.

#### 7.4. The good performance of the BzK-selected sample

Both the BzK and SED samples show very similar morphological distributions in all the analysis done here. The comparison of the two samples confirms that they are similarly representative of the mix of bright galaxies at  $z \sim 2$ . We additionally compare the distribution of morphological parameters for the 136 spectroscopically confirmed BzK galaxies (8 pBzKs and 128 sBzKs, specz sample) to the parent distribution (BzK sample). As expected, the relative distributions of  $G$ ,  $M_{20}$  and  $\Psi$  are similar to our parent sample, and the median values of each parameter are almost the same, with the exception of  $G$  in the case of sBzKs. The average  $G$  value of BzKs in the specz sample is slightly higher, since over 70% of the specz sample are bright and massive ( $M > 1 \times 10^{10} M_{\odot}$ ) galaxies, which tend to have higher  $G$ . Thus, in conclusion, the very similar results derived from both samples proves the effectiveness of the BzK selection criteria in sampling the full diversity of the mix of massive galaxies at  $z \sim 2$ , at least as far as the morphological properties of relatively massive galaxies are considered. The BzK selection will be particularly effective, for example, in the other three CANDELS fields where the broad-band photometry is neither as deep or as broad in wavelength as in the two GOODS fields.

## 8. Summary

In this paper we have explored general trends between galaxy morphology and broad-band spectral types at  $z \sim 2$  using the *HST*/WFC3 H-band images taken in the GOODS–South field as part of the CANDELS survey, in combination with the existing GOODS ACS z-band images, as well as sensitivity–matched images at other wavelengths

that are part of the GOODS data products (Giavalisco et al. 2004). Combining the deep and high-resolution NIR data to optical data, we are able to study the dependence of morphologies on wavelengths and expand the scope of previous studies of galaxy morphologies at the same redshift (Kriek et al. 2009; Cameron et al. 2011; Szomoru et al. 2011; Wang et al. 2012) with significantly larger sample size and lower mass limit ( $> 10^9 M_\odot$ ). The galaxies of our primary sample are selected in the redshift range  $1.4 < z < 2.5$  to cover a broad range of spectral types (star-formation properties and dust obscuration) using SED fitting to spectral population synthesis models (SED sample). For comparative reasons we also selected galaxies using the BzK criterion which culled galaxies in the same redshift range and with essentially identical spectral properties, modulo a large contamination from interlopers and AGN. Analyses of the two samples show consistent results suggesting that the BzK and SED selection criteria are equivalent in sampling the mix of spectral types at  $z \sim 2$ . We investigate the rest-frame optical morphologies using five non-parametric approaches, mainly  $G$ ,  $M_{20}$  and  $\Psi$  in addition to  $C$  and  $A$ , and two model-dependent parameters obtained by fitting *Sérsic* profiles, namely  $n$  and  $R_e$ . The major findings of this study are presented below.

1. In the rest-frame (U-V) color and mass diagram, our sample clearly separates into red massive passive galaxies with low SSFR and blue star-forming ones with less massive, high SSFR occupying the same regions in the color-mass diagram as the galaxies observed in the local universe.
2. We find that galaxies with different spectral types are distinctly classified morphologically as two populations, especially for massive systems ( $> 10^{10} M_\odot$ ): 1) star-forming galaxies are heterogeneous, with mixed features including bulges, disks, and irregular (or clumpy) structures, with relatively low  $G$ ,  $n$  and high  $M_{20}$ ,  $\Psi$ ; 2) passive galaxies are spheroidal-like compact structures with higher  $G$ ,  $n$  and lower

$M_{20}$  and  $\Psi$ . Generally, the sizes of star-forming galaxies are larger than passive ones, even in massive systems, but some have very compact morphologies, with  $R_e < 1kpc$ . We confirm using a variety of measures that star formation activity is correlated with morphology at  $z \sim 2$ , with the passive galaxies looking similar to local passive ones although smaller, while star-forming galaxies show considerably more morphological diversity than massive star-forming galaxies on the Hubble sequence today.

3. We show that the morphological analysis only using the *Sérsic* index is not sufficient to characterize differences in morphologies especially for lower mass galaxies ( $M < 10^{10} M_{\odot}$ ). Therefore we conclude that it is important to use non-parametric measures to investigate the morphologies of high redshift galaxies in a broad range of stellar masses. In this study, the combination of large samples with a suite of morphological diagnostics, both parametric and non-parametric ones, as well as visual inspections, gives us a significantly improved description of the state of galaxy morphologies at  $z \sim 2$  and its correlations with the spectral type, i.e. mostly the star-formation activity, expanding the significance and the scope of previous studies which were based on much smaller samples and only massive galaxies at the same epoch (Kriek et al. 2009; Cameron et al. 2011; Szomoru et al. 2011; Wang et al. 2012).
4. Generally,  $z \sim 2$  galaxies show a similar trend in morphologies with those measured from the redshifted images of local galaxies, even though many of the star-forming galaxies have  $M_{20}$  values higher than seen for galaxies in the local sample. The passive galaxies at  $z \sim 2$  have  $G$  and  $M_{20}$  values that are much more similar to those observed for the present-day E/S0 galaxies.
5. Comparison of visual images between the rest-frame optical and near UV show that the morphological k-correction is generally weak, however, the comparison with non-parametric measures indicates that galaxies observed in the rest-frame UV are

slightly clumpier, with lower  $G$  and higher  $M_{20}$  and  $\Psi$ , than rest-frame optical.

Taken all together, our results show that the correlations between morphology as traced by a suite of common diagnostics, and broad-band UV/Optical spectral types of the mix of relatively massive galaxies (i.e.  $M > 10^9 M_{\odot}$ ) at  $z \sim 2$  are quantitatively and qualitatively similar to those observed for their counterparts in the local universe. We interpret these results as evidence that the backbone of the Hubble Sequence observed today was already in place at  $z \sim 2$ .

This work is based on observations taken by the CANDELS Multi-Cycle Treasury Program with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

### A. Robustness of Parameter Estimations

The reliability of model-independent parameters has been tested and discussed by many previous studies (Lotz et al. 2006; Lisker 2008; Andrae et al. 2011; Law et al. 2012). These parameters are robust for large bright sources (with high signal-to-noise ratio) in general, but it can be unreliable for small faint sources. In particular, the  $G$  value is very sensitive to the signal-to-noise ratio (LPM04 and Lisker et al. 2008). Our galaxy sample goes deeper ( $H < 26$ ), and to lower stellar mass limits ( $\sim 10^9 M_{\odot}$ ) than other works that study morphologies at  $z \sim 2$  (e.g. Kriek et al. 2009, Szomoru et al. 2011, Wang et al. 2012). Therefore, it is crucial to understand how noise and other limitations affect parameters we use here. We test the dependence of the parameters,  $G$ ,  $M_{20}$  and  $\Psi$ , on the signal-to-noise ratio, i.e., the depth of an image. HST/UDF WFC3 imaging data, which differ only in exposure time from GOODS-S data, is an ideal comparison dataset for investigating the effect of the different image depth on these parameters. Previously, Lisker et al. 2008

tested the dependence of signal-to-noise on  $G$ ,  $M_{20}$  in the UDF and GOODS-S using  $i$ -band images. To investigate how this affects our measurements with the NIR WFC3 images, we use the UDF and shallower GOODS-S F160W (H-band) data (both with 60mas pixel scales) and select 959 sources in the UDF image using GOODS-S source catalog. Then, we estimate  $a_p$  from the GOODS-S H-band image, and use it to measure the parameters for both the UDF and GOODS-S images. The final sample is 520 objects which have stellarity  $\leq 0.8$ , after excluding sources for which the number of pixels within  $a_p$  is less than 28 pixels (same exclusion with Lisker 2008). Signal-to-noise ratio per pixel ( $S/N_{pp}$ ) is defined as

$$S/N_{pp} = \frac{1}{N_{pix}} \sum_i^{N_{pix}} \frac{f_i t_{exp}}{\sqrt{rms_i t_{exp} + f_i t_{exp}}} \quad (A1)$$

where,  $N_{pix}$  indicates the total number of pixels within the  $a_p$ ,  $t_{exp}$  is the total image exposure time.  $f_i$  and  $rms_i$  are the pixel values in the drizzled image and rms image, respectively. The strong dependence of  $G$ ,  $M_{20}$ ,  $\Psi$  on the  $S/N_{pp}$  are shown in figures 17, 18, and 19, respectively. The two top panels in figure 17 present how values of  $G$  vary with  $S/N_{pp}$  in the GOODS-S (red circles) and UDF (blue circles). Obviously, the UDF has a higher  $S/N_{pp}$  (difference of depth is about 1.8 mag), but the overall trend of  $G$  looks similar to that for GOODS-S. Both  $G$  values overlap almost exactly when we move the Gini of the UDF to the relatively small median difference (-0.03) shown in the bottom left panel. However, the  $G$  of galaxies with different exposure times is dependent on the  $S/N_{pp}$  as shown in the bottom right panel. The difference of in  $G$  between the UDF and GOODS-S decrease as  $S/N_{pp}$  increases.  $M_{20}$  and  $\Psi$  also follows the same trend and distribution as  $G$  as shown in figure 18 and 19, but with small median differences of about 0.01 and 0.11, respectively. Consequently, the model-independent parameters depend on signal-to-noise ratio, but the difference between two fields with different exposure times are less significant than Lisker (2008). LPM04 find that  $G$  and  $M_{20}$  are reliable for galaxy images with  $S/N_{pp} \gtrsim 2.5$  (vertical dashed line on the bottom right panel in each figure). Given this

threshold in reliability, we investigate how this may affect our results by measuring the  $S/N_{pp}$  of each galaxy. We find over 90% of BzK sample and 70% of SED sample having  $S/N_{pp} \geq 2.5$ , which excludes some faint star-forming galaxies and passive galaxies with low  $G$  from our sample. Repeating our analysis with these faint objects removed doesn't change the results. Therefore, we confirm that the results from our measurements did not suffer from this  $S/N$  effect.

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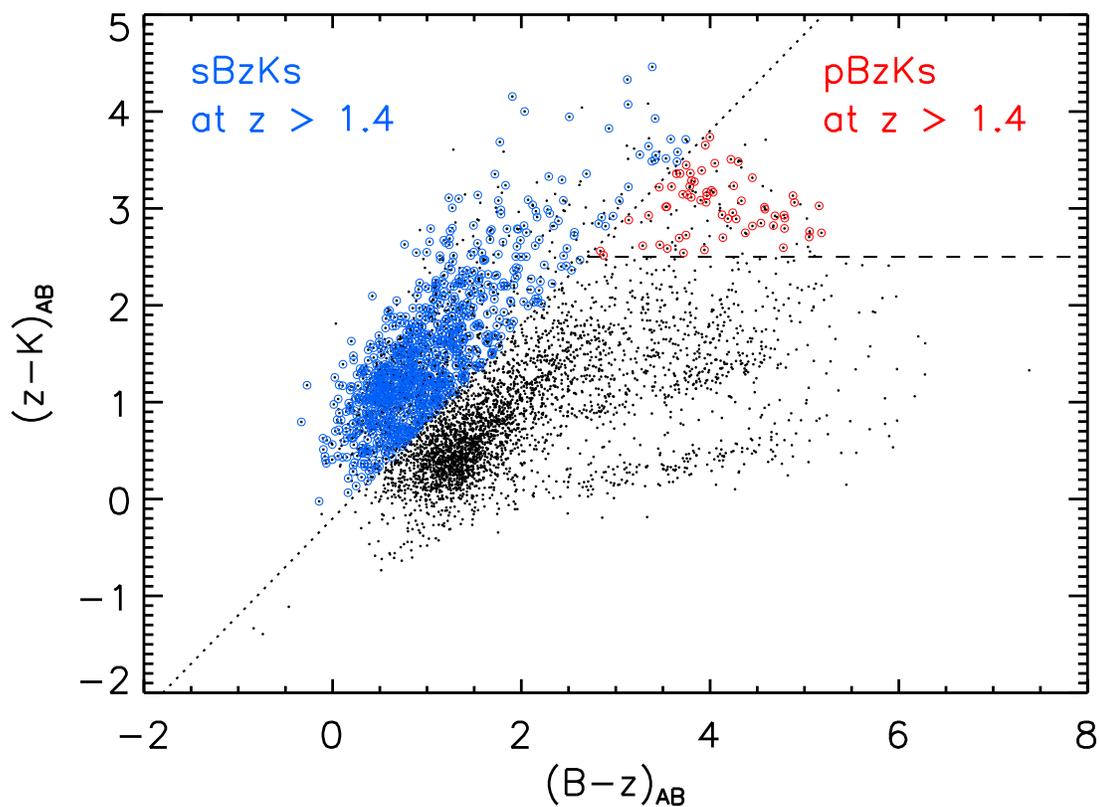


Fig. 1.—  $(z-K)$  vs.  $(B-z)$  diagram for the  $z$ -band selected sources in the GOODS- South field of the HST/ACS [black points] with  $S/N_k > 7$  and  $S/N_z > 10$ . Sources above the dotted line are classified as the star-forming galaxies [sBzKs] and sources between the dotted and dashed lines are the passively evolving galaxies [pBzKs]. 1043 BzK galaxies are detected in WFC3/F160w (H-band) observation, using epoch 4 of the CANDELS. The blue and red circles identify these 981 sBzKs and 62 pBzKs, respectively [BzK sample].

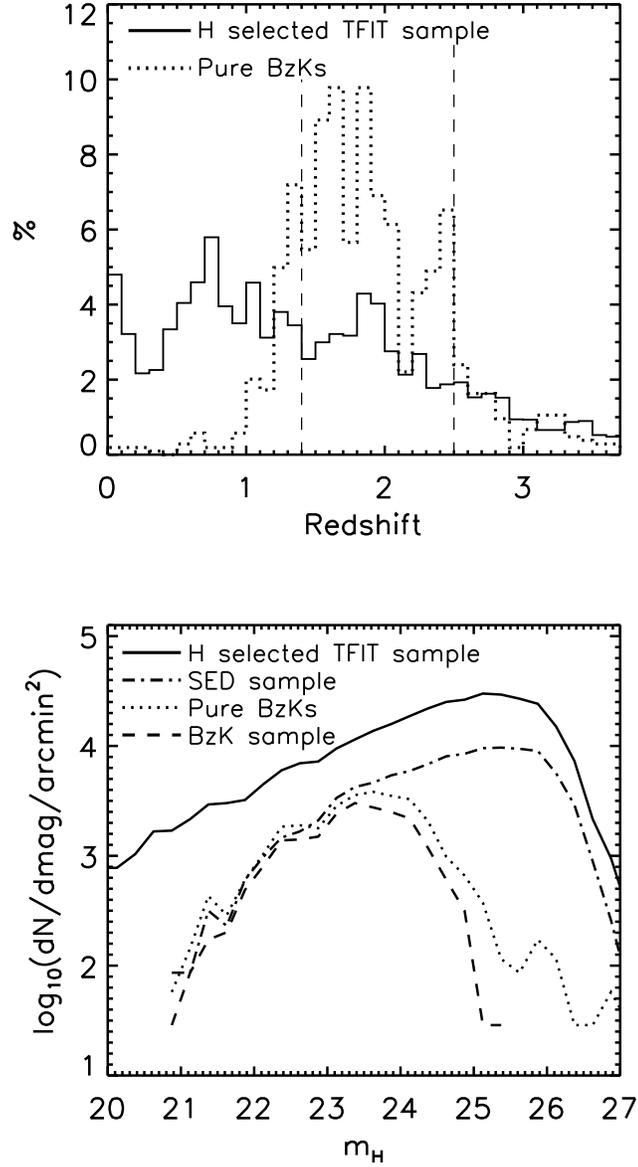


Fig. 2.— Comparison of the photometric redshift distribution of the BzK sample to that of the SED sample (Top) and the number counts of SED sample, of the two BzK samples, and also of the whole H–band selected TFIT sample for comparison (Bottom). The thick solid line represents the H–band selected TFIT sample (e.g. SED sample without redshift limitation), and dotted line represents the “Pure BzK”. The redshift window,  $1.4 < z \leq 2.5$ , is described as vertical dashed lines in the top panel. In the Bottom panel, the dot and dash dot lines are for the BzK sample (BzKs at  $z \sim 2$ ) and SED sample, respectively.

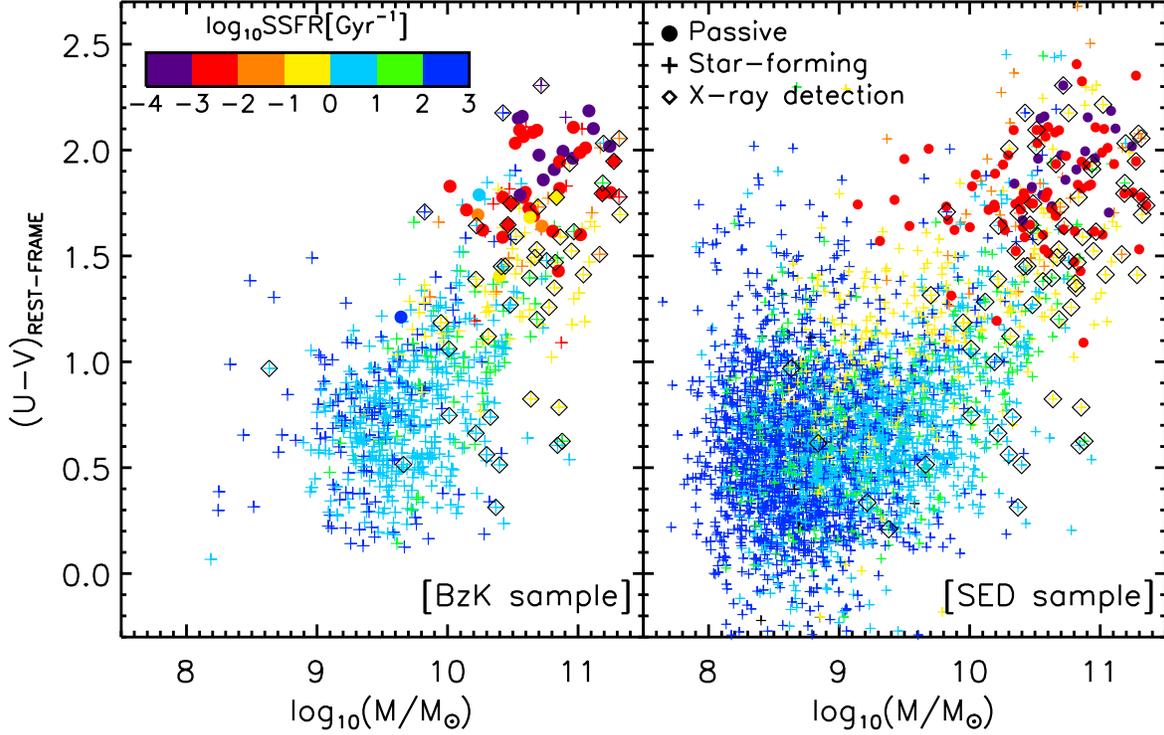


Fig. 3.— The rest-frame U-V color versus Stellar mass for galaxies of both BzK (left) and SED (right) samples at  $z \sim 2$ . The crosses and circles represent the star-forming (sBzKs) and passive (pBzKs), respectively. The rest-frame colors of the passive (pBzK) galaxies span a much smaller range than star-forming (sBzK) ones, with the two samples having distinct color distributions. The color-coding reflects the specific star formation rate (SSFR) defined as star formation rate divided by stellar mass (right panel). Most massive pBzKs have  $SSFR < 0.01 \text{ Gyr}^{-1}$  which means they are rarely star-forming and intrinsically red in contrast to blue sBzKs with higher SSFR and lower mass. Diamond symbols represent the 70 x-ray detected galaxies (50 for BzK sample).

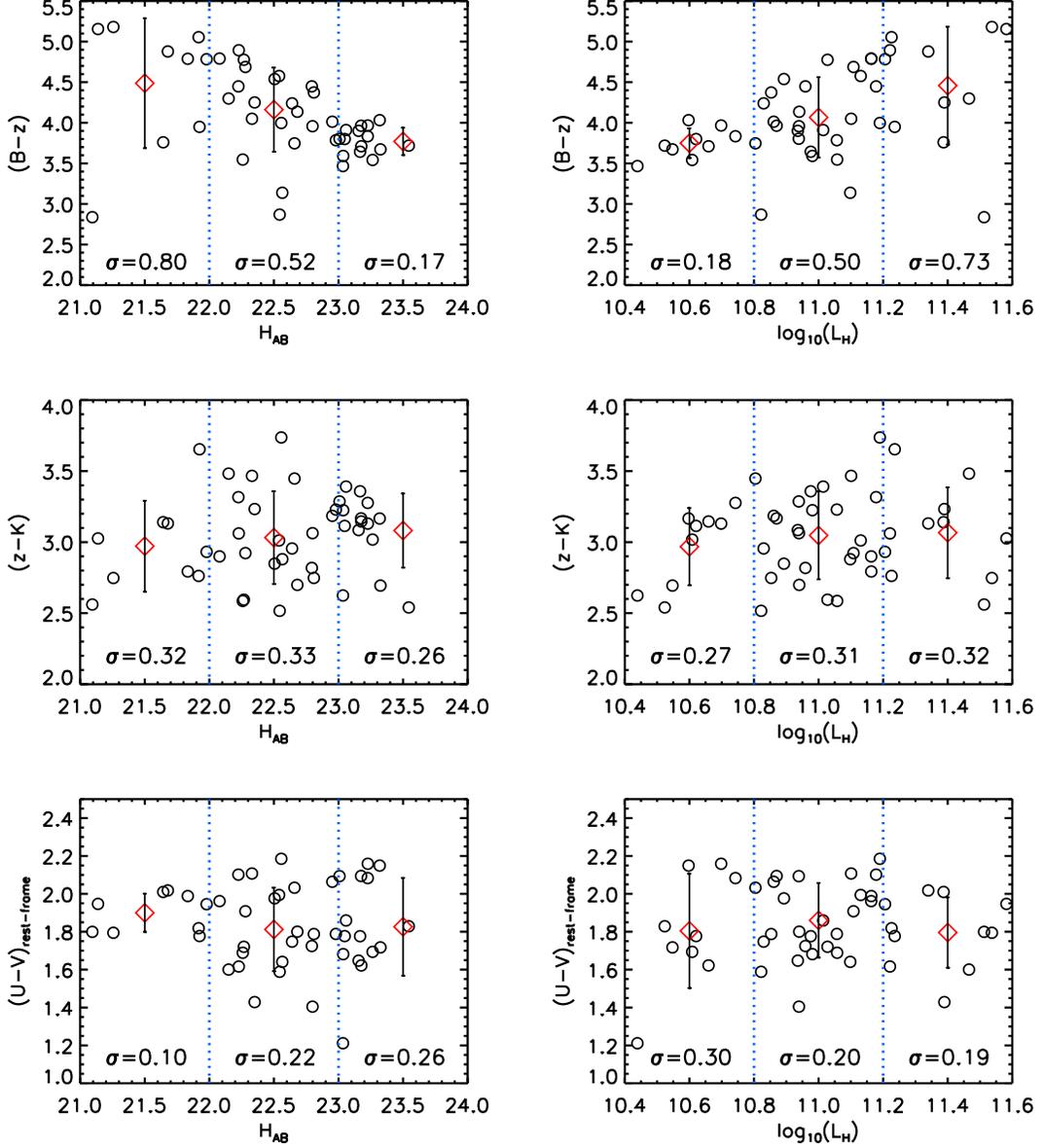


Fig. 4.— The observed colors (B-z and z-K) and rest-frame color (U-V) versus apparent ( $H_{AB}$ ) and absolute magnitudes ( $\log(L_H)$ ) for pBzK galaxies. The  $\sigma$  values and error bars represent the standard deviation of colors.

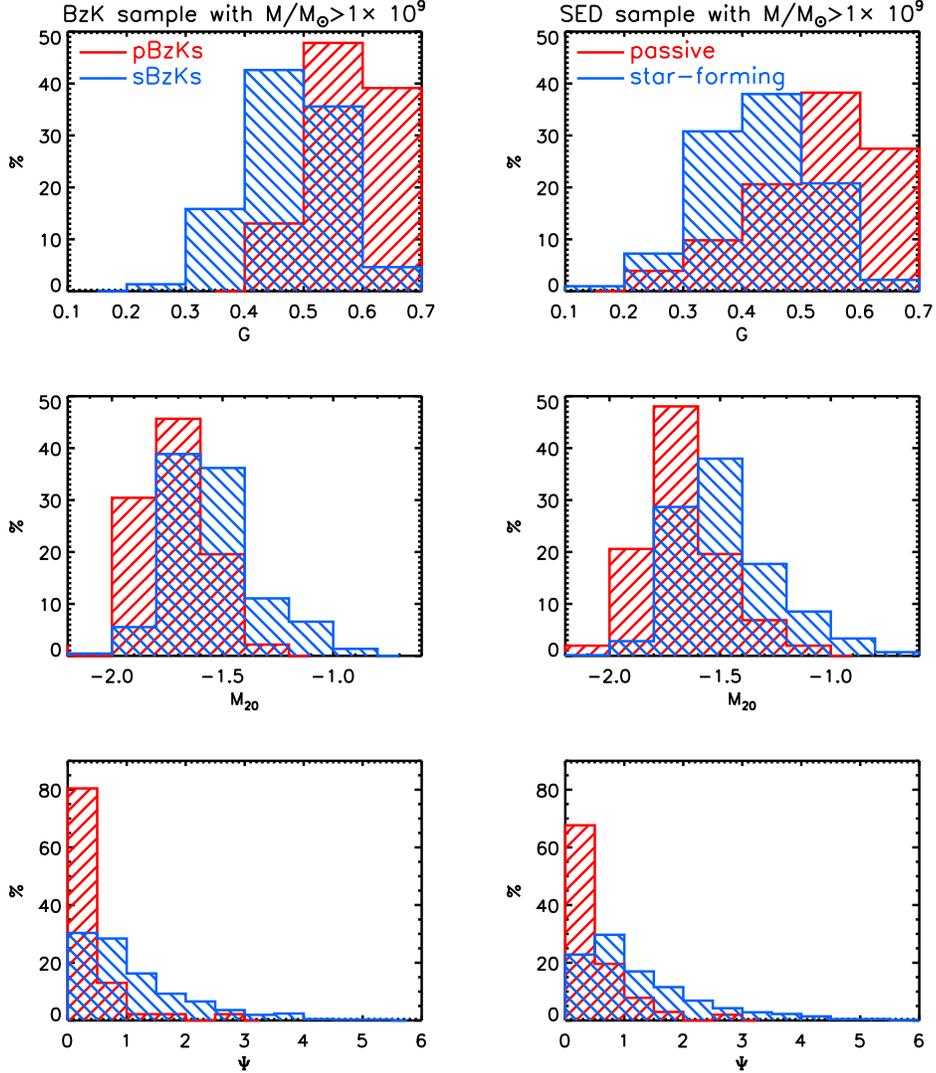


Fig. 5.— Relative distributions of  $G$  (top),  $M_{20}$  (middle) and  $\Psi$  (bottom) for BzK (left) and SED samples (right) having  $M > 10^9 M_{\odot}$ . Red and blue histograms represent the pBzK (passive) and sBzK (star-forming) galaxies, respectively. Overall, both samples show similar morphological distribution in three parameters, such as passive (pBzK) galaxies have higher  $G$  and lower  $M_{20}$  and  $\Psi$  in contrast to star-forming (sBzK) galaxies. This is consistent with the passive galaxies being compact and relatively smooth, while the star-forming ones are more extended and have more fine-scale structures.

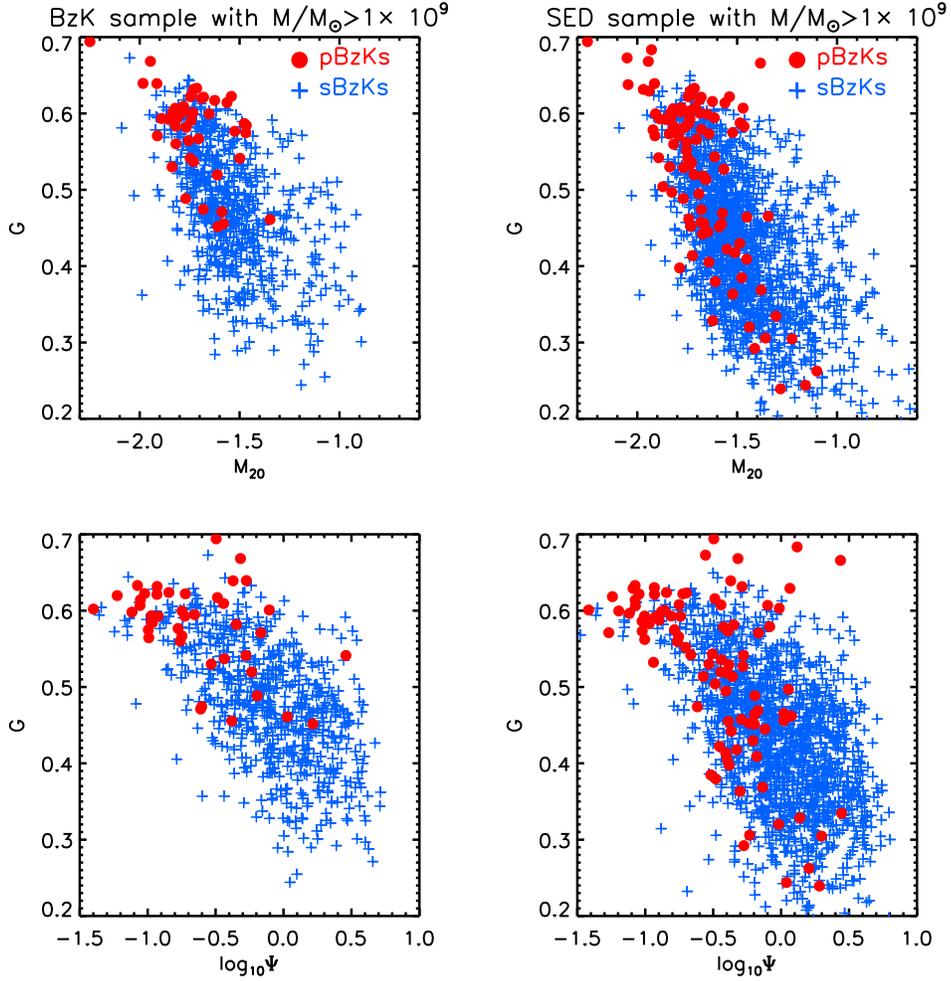


Fig. 6.— Distribution of  $G$  vs.  $M_{20}$  (top) and  $\Psi$  (bottom) for BzK (left) and SED (right) samples having  $M > 10^9 M_{\odot}$ . In both samples, there are clear morphological differences between passive galaxies and star-forming ones also seen in figure [5]. However, in  $G - M_{20}$  and  $G - \Psi$  spaces, some star-forming galaxies show a similar morphological trend as passive one and several passive galaxies in the SED sample have lower  $G$  and higher  $M_{20}$  and  $\Psi$  like star-forming ones.

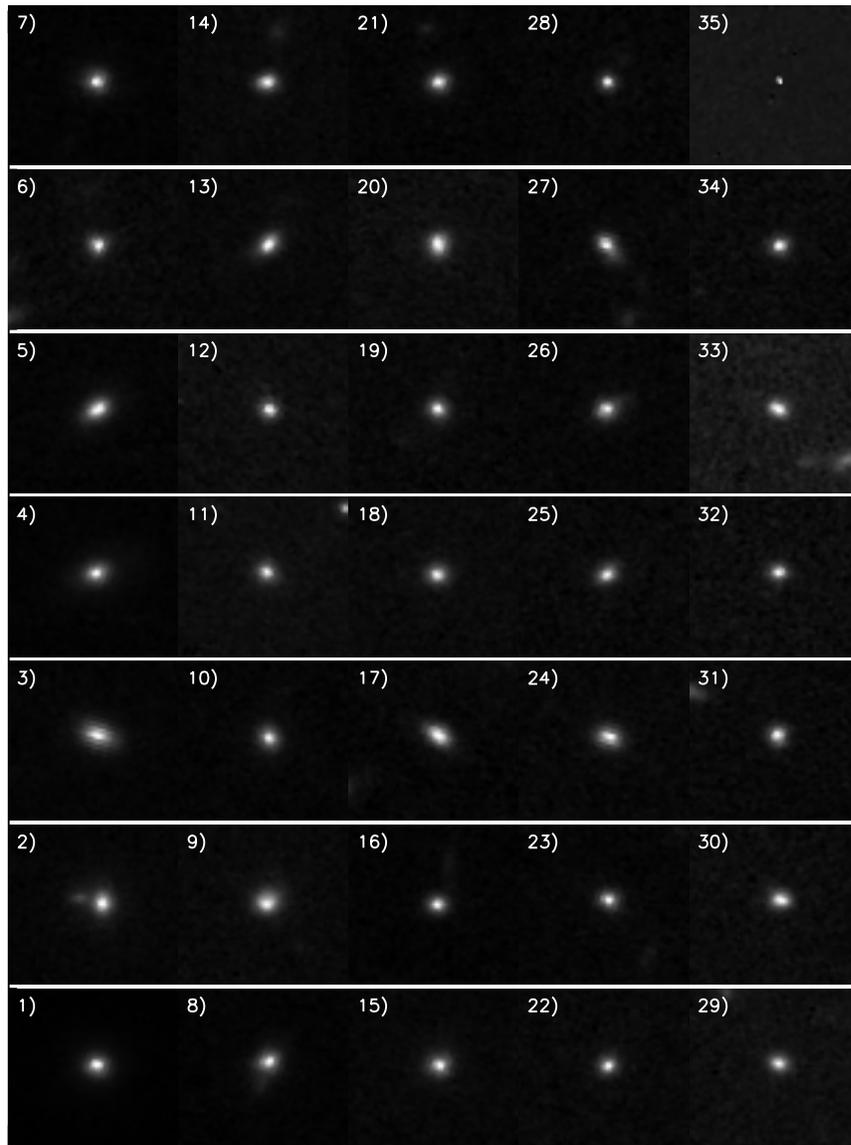


Fig. 7.— Postage stamps of 35 star-forming galaxies ( in SED sample) with  $G > 0.6$ . Each postage stamp is  $3.6 \times 3.6 \text{ arcsec}^2$  and all images have been linearly scaled. The number in each stamp indicates the order of H-band magnitude, i.e. number 1 galaxy is the brightest one. As one can see, all star-forming galaxies with high  $G$  show spheroid-like structures with a bright clump.

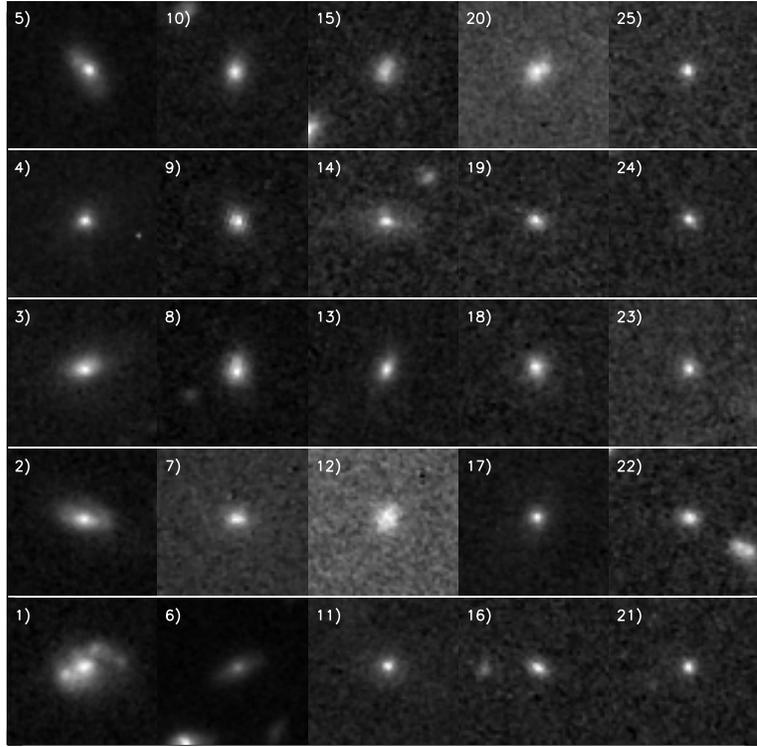


Fig. 8.— Postage stamps of 25 passive galaxies ( in SED sample) with  $G < 0.5$  (Image stamp size, image scaling and magnitude order follow the same properties of Figure 7). Among 35 passive galaxies with  $G > 0.5$ , 10 galaxies are excluded due to the low signal-to-noise ratio per pixel,  $S/N_{p,p} < 2.5$ . Those galaxies are all red and show extended structures as an example of red (passive) disks.

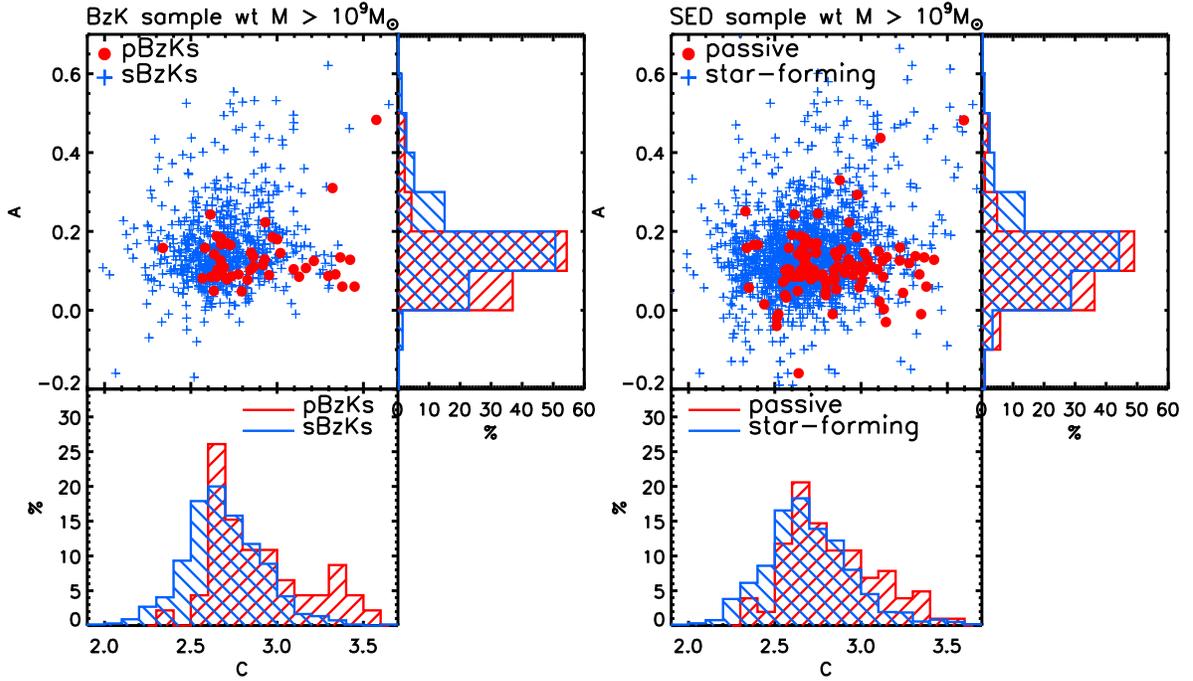


Fig. 9.— The plot of Asymmetry[A] vs. Concentration[C] for BzK(left) and SED (right) samples having  $M > 10^9 M_\odot$  and the histograms of each parameter. The passive galaxies (pBzKs) are more spheroidal like in their C and A values, while star-forming galaxies (sBzKs) are more spiral and merger like. Passive galaxies (pBzKs) are different in C-A plane than the star-forming ones (sBzKs) although the difference is not huge compared to  $G - M_{20}$  and  $-\Psi$ .

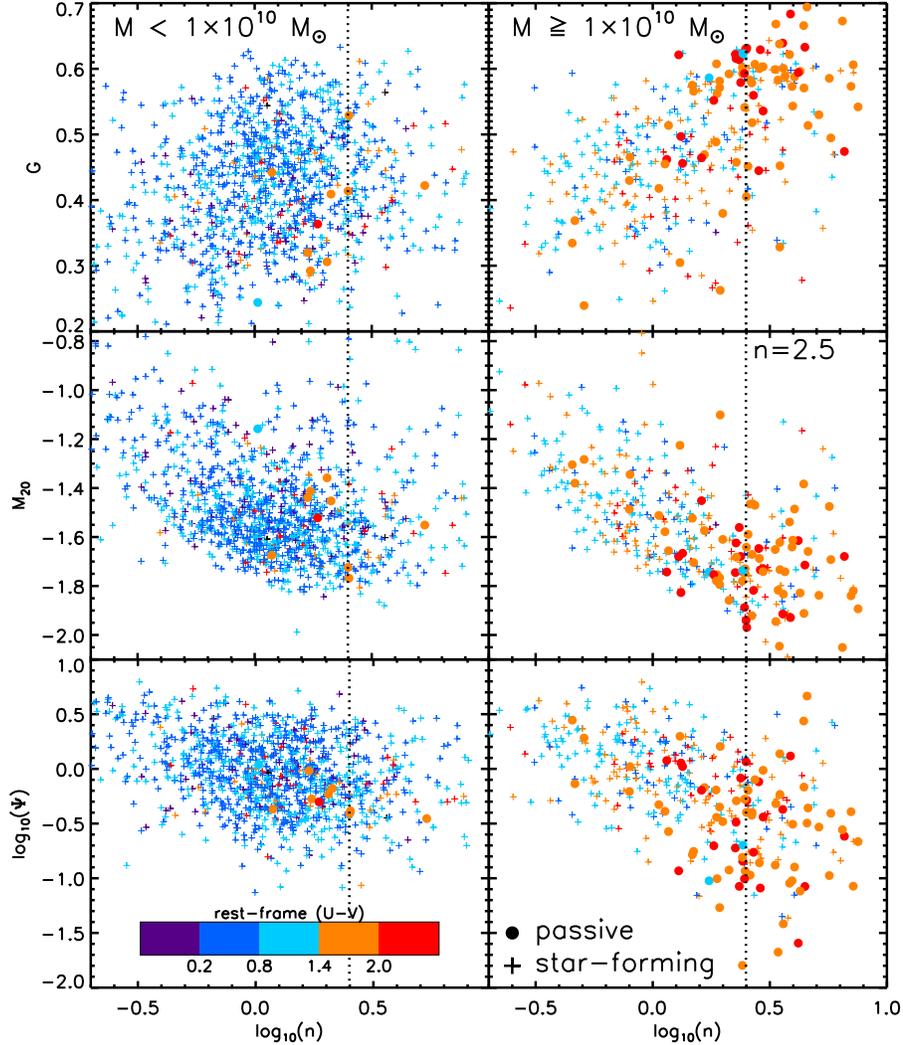


Fig. 10.— The distribution of morphological parameters as a function of *Sérsic* index ( $n$ ) for the SED sample with  $M > 10^9 M_{\odot}$  in two different mass bins divided by a mass threshold,  $M_{th} = 10^{10} M_{\odot}$ . The color-coding represents the rest-frame (U-V) color of galaxies, and the dotted vertical line is for  $n = 2.5$ . About 96% passive galaxies (circles) are more massive than  $M_{th}$ , while about 78% of star-forming ones (crosses) have mass,  $M < M_{th}$ . Star-forming galaxies dominated by low  $n$ , especially at  $M < M_{th}$  and passive ones mostly have higher  $n$ . Redder galaxies (mostly passive galaxies) tend to have higher  $G$  and lower  $M_{20}$  and  $\Psi$  in the massive system.

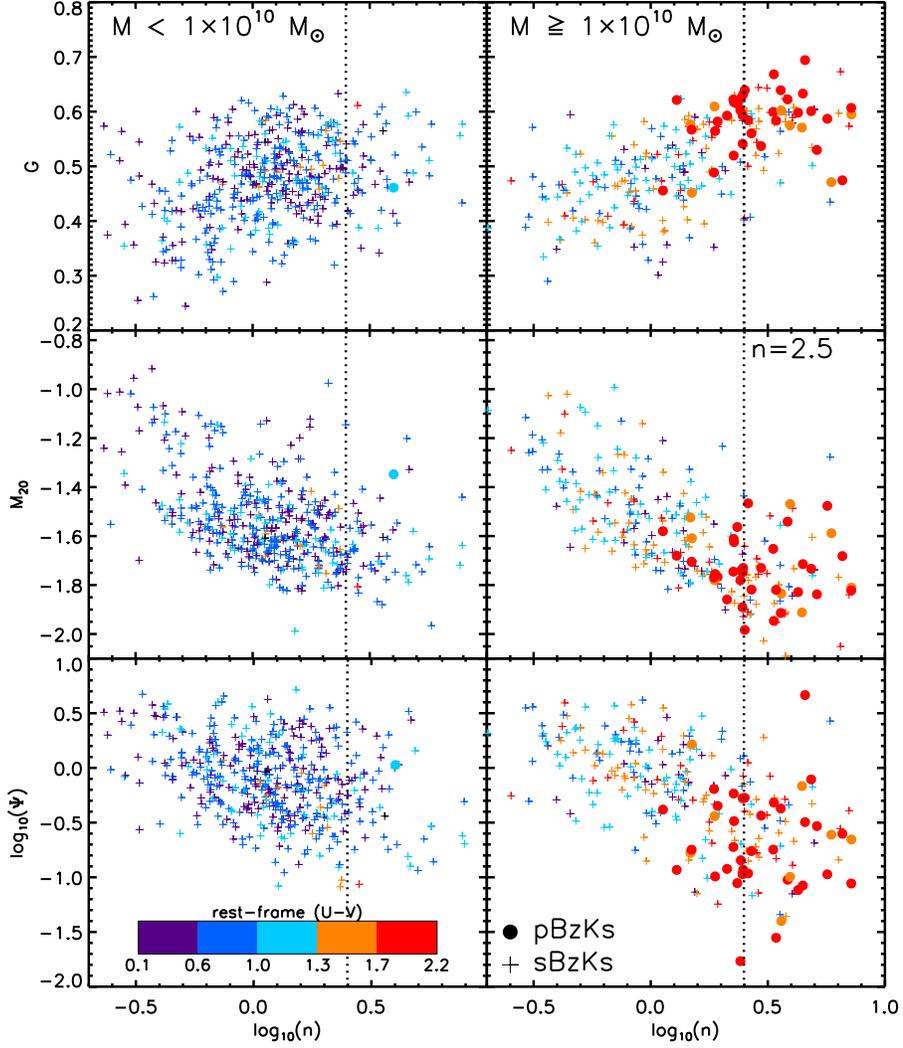


Fig. 11.— The distribution of morphological parameters as a function of *Sérsic* index ( $n$ ) for the BzK sample with  $M > 10^9 M_{\odot}$  in two different mass bins divided by a mass threshold,  $M_{th} = 10^{10} M_{\odot}$ . The color-coding represents the rest-frame  $(U-V)$  color of BzK sample, and the dotted vertical line is for  $n = 2.5$ . All pBzKs (circles) are more massive than  $M_{th}$ , while about 70% of sBzKs (crosses) have mass,  $M < M_{th}$ . sBzKs dominated by low  $n$  and pBzKs mostly have higher  $n$ . The morphologies and rest-frame colors are well separated, especially in the massive systems.

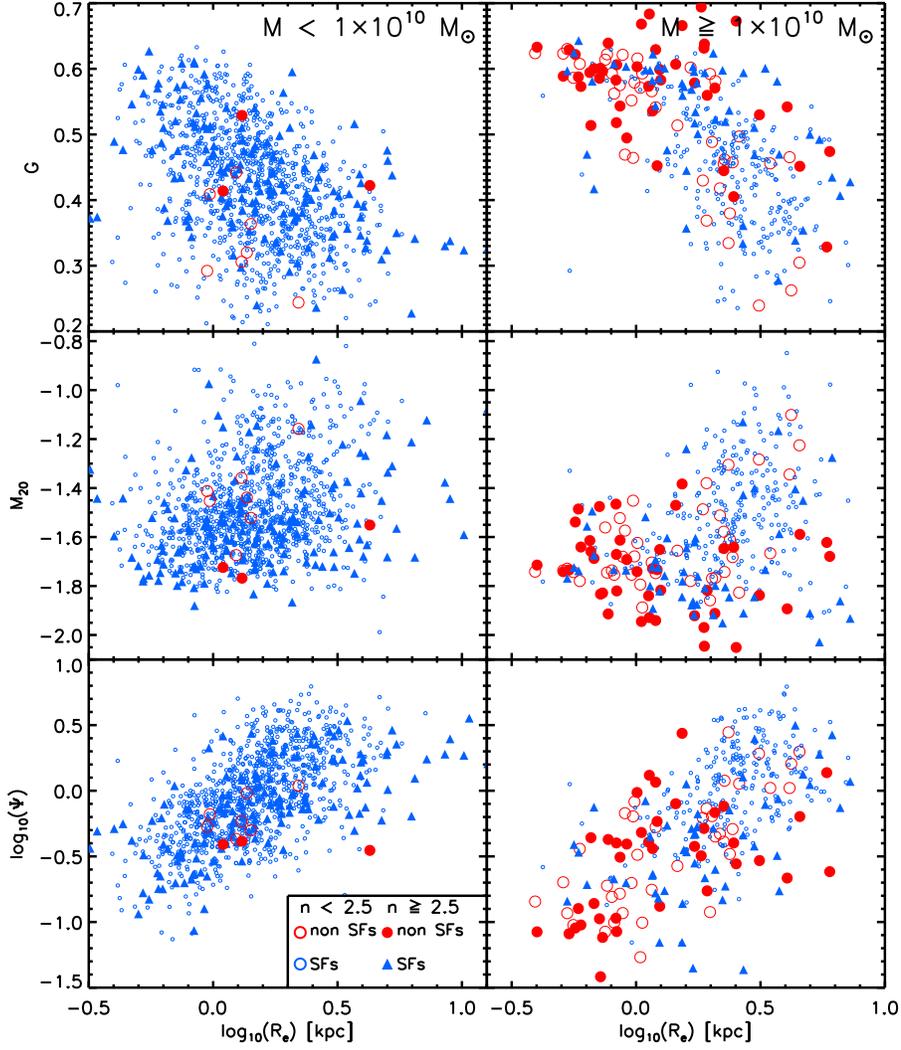


Fig. 12.— The distribution of morphological parameters as a function of half-light radius ( $R_e$ ) for the SED sample with  $M > 10^9 M_{\odot}$  in two different mass bins divided by a mass threshold,  $M_{th} = 10^{10} M_{\odot}$ . Open symbols show the galaxies with  $n < 2.5$  and filled symbols show galaxies with  $n \geq 2.5$ . Star-forming and passive galaxies are expressed as blue and red colors, respectively. Overall, star-forming galaxies tend to have larger effective radii than passive ones, even in the case of massive systems,  $M > M_{th}$ , and a half of passive galaxies show very compact morphologies, with  $R_e < 1 \text{ kpc}$ . Galaxies with smaller  $R_e$  tend to have a compact structure with high  $G$  and low  $\Psi$ .

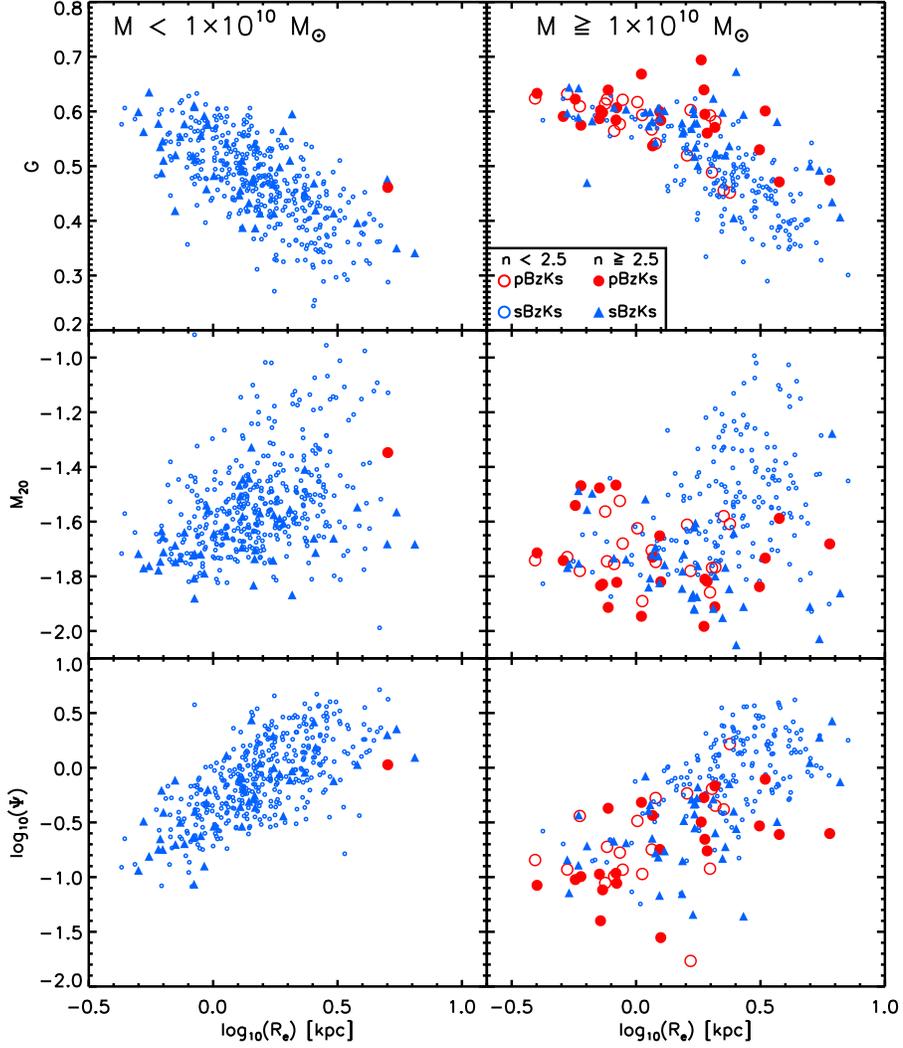


Fig. 13.— The distribution of morphological parameters as a function of half-light radius ( $R_e$ ) for the BzK sample with  $M > 10^9 M_{\odot}$  in two different mass bins divided by a mass threshold,  $M_{th} = 10^{10} M_{\odot}$ . Open symbols show the galaxies with  $n < 2.5$  and filled symbols show galaxies with  $n > 2.5$ . sBzKs and pBzKs are expressed as blue and red colors, respectively. The statistics of  $R_e$  and overall morphological distributions are same with SED sample of Figure 12.

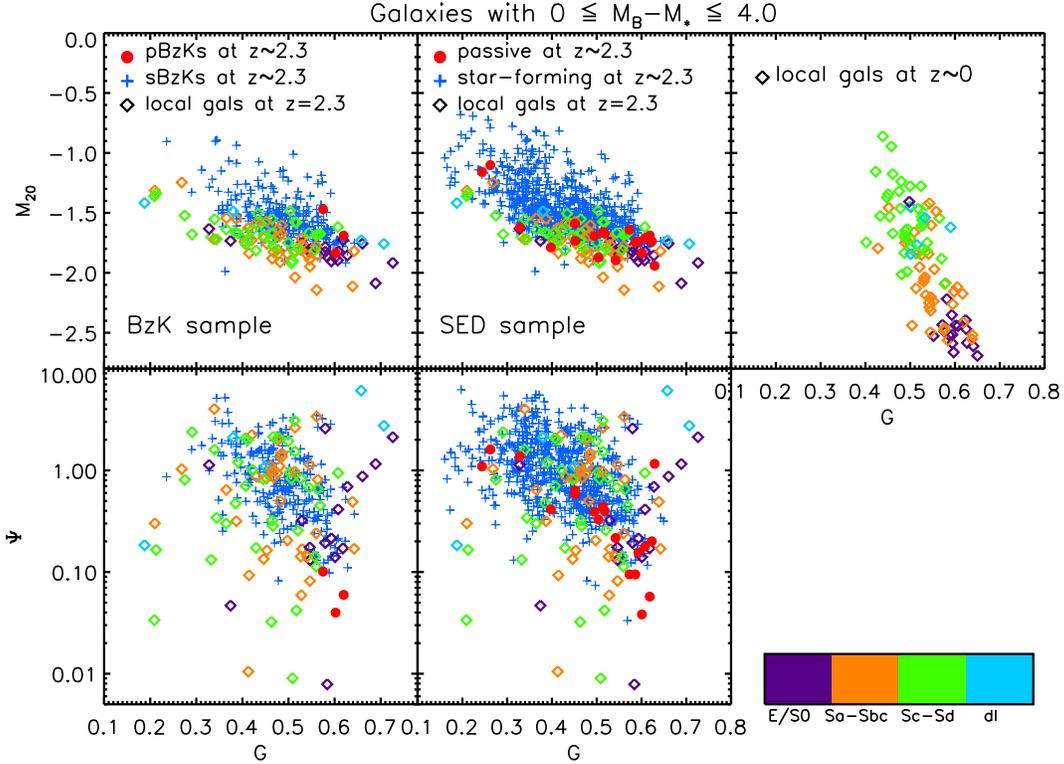


Fig. 14.—  $G$  vs.  $M_{20}$  and  $\Psi$  for the galaxies at  $z \sim 2.3$  and local galaxies from LPM04. We compare the morphologies of BzK [from left: 1st panel] and SED sample [2nd panel] in WFC3 H-band with degraded B/g-band image of local galaxies. To reduce the effect of any morphological k-correction, we compare only the galaxies with redshifts  $2.0 < z \leq 2.5$ . Local galaxies are selected to lie in the same  $M_B - M_*$  range ( $0.0 \leq (M_B - M_*) \leq 4.0$ ) as the  $z \sim 2.3$  sample, assuming  $M_* = -20.1$  locally and  $M_* = -22.9$  at  $z \geq 2$ . The 3rd panel shows observed morphologies of normal local galaxy types expressed by the following colors (violet: E/S0, magenta: Sa-Sbc, green: Sc-Sd, light blue: dl). Comparison between passive and star-forming galaxies in each sample (red dots and blue crosses, respectively) at  $2.0 < z \leq 2.5$  and the morphologies of redshifted local galaxies at the WFC3 H-band image resolution are described on the 1st and 2nd panels. Overall, galaxies at  $z \sim 2.3$  tend to have similar distribution in  $G - M_{20}$  space with redshifted local galaxies even though there are many galaxies with higher  $M_{20}$  for their  $G$  than for any of the local ones.

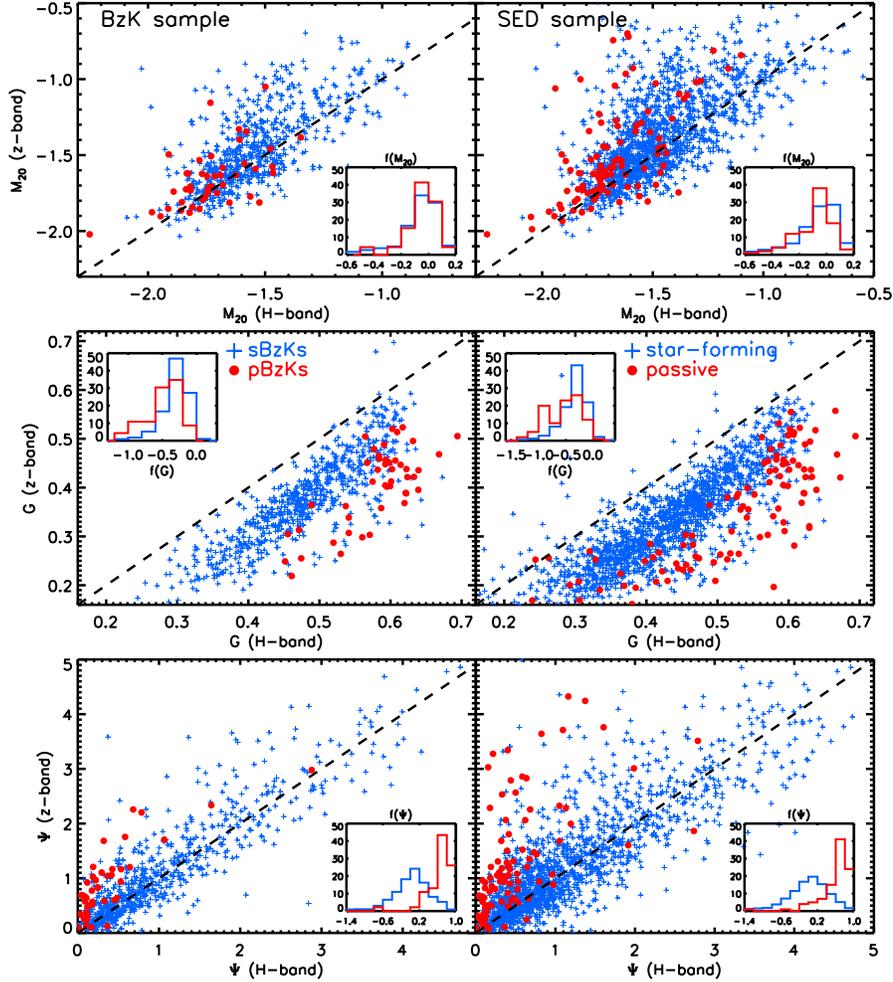


Fig. 15.— Comparison of the morphological parameters for galaxies at  $z \sim 2$  between the rest-frame UV (z-band) and optical (H-band) [BzK: left, SED: right]. The top, middle and bottom panels show  $M_{20}$ ,  $G$  and  $\Psi$ , respectively. Blue crosses and red circles represent the sBzKs (star-forming) and pBzKs (passive), respectively, and a dotted black line in each panel shows a linear correlation. The inset in each panel show the distribution of the fractional differences ( $f$ ) of the parameters in the two rest-frame bands defined as  $f(M_{20}) = [M_{20}(z) - M_{20}(H)]/M_{20}(z)$ . Negative  $f(M_{20})$  and positive  $f(G)$ ,  $f(\Psi)$  means that parameters are bigger in the z-band in each plot.

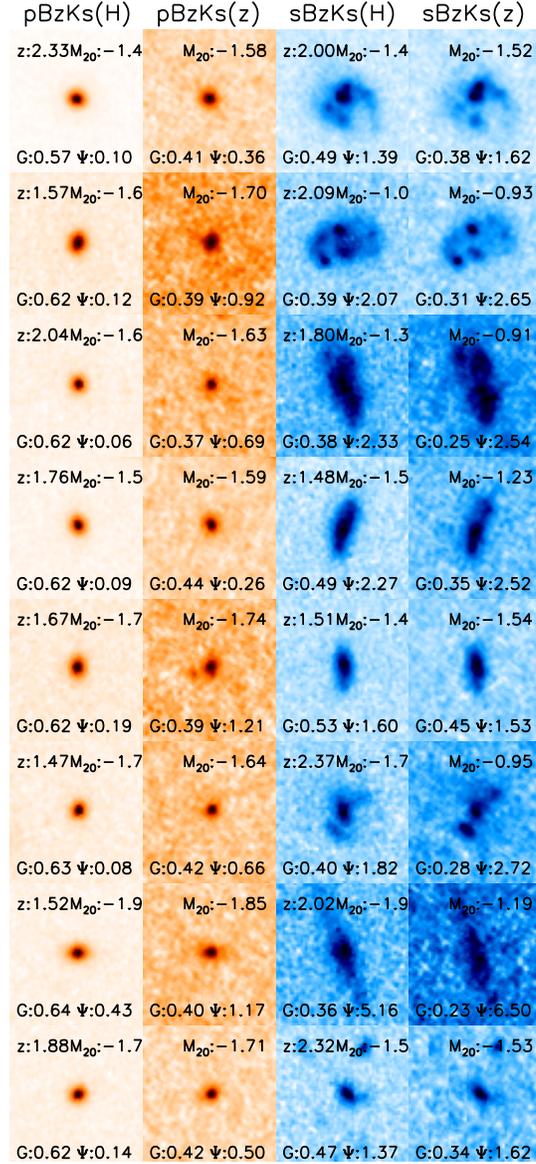


Fig. 16.— Postage stamps of 16 galaxies which are selected in both BzK and SED samples, including 8 pBzKs (1st & 2nd columns) and 8 sBzKs (3rd & 4th columns) in the rest-frame optical (WFC3 H-band: 1st & 3rd) and UV (ACS z-band: 2nd & 4th). The galaxy images are ordered by decreasing magnitude from top to bottom (the eighth galaxy is the brightest one at each column). Each postage stamp is  $3.6 \times 3.6 \text{ arcsec}^2$  and labels indicate the redshifts ( $z$ ) and morphological parameters. Star-forming galaxies show a variety of morphologies, while all passive galaxies show bulge-like structures. The morphology between  $z$  and H-band of passive galaxies are almost identical, but this is not the case for star-forming ones.

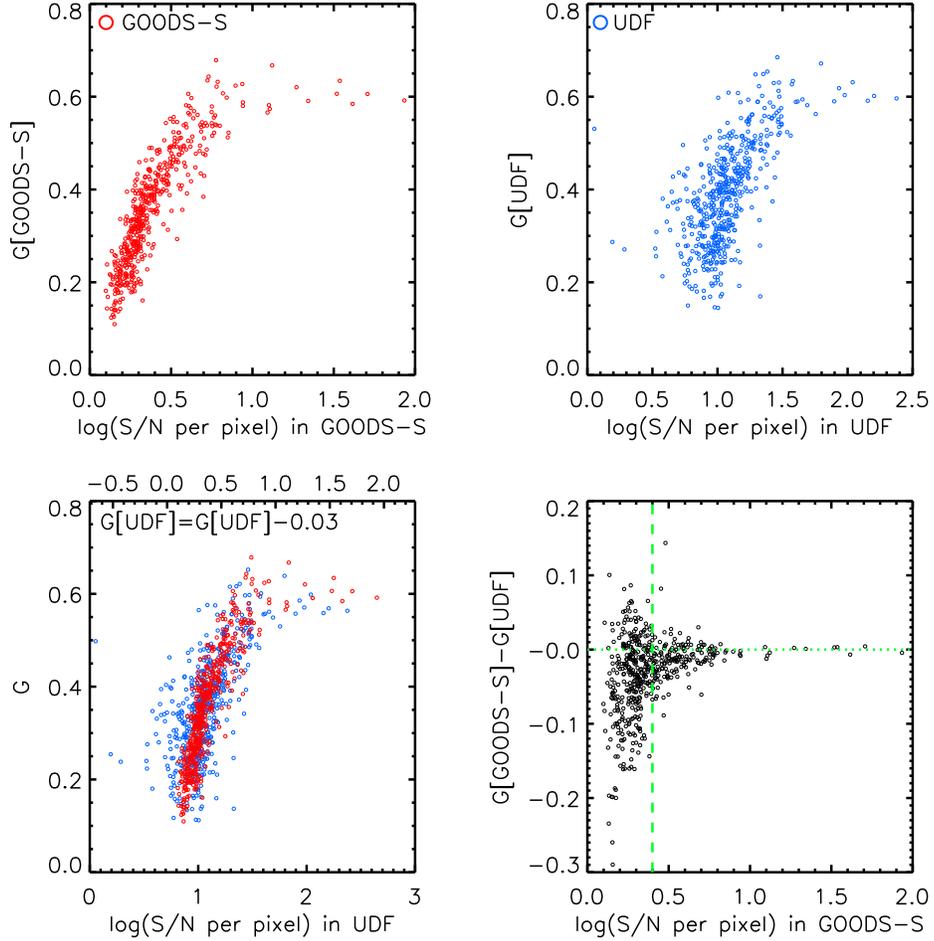


Fig. 17.— Gini vs. logarithmic signal-to-noise per pixel for the same galaxies imaged with differing image depths in UDF (blue) and GOODS-S (red). In the bottom left panel, we have shifted G values in UDF with a median of differences,  $(G[GOODS] - G[UDF]) = -0.03$ . The bottom right panel is the plot of  $\log(S/N \text{ per pixel})$  vs. the difference in G between GOODS and UDF. The green dashed line at  $\log(S/N \text{ per pixel})=2.5$  indicates the signal-to-noise limit for robust measures discussed in the text.

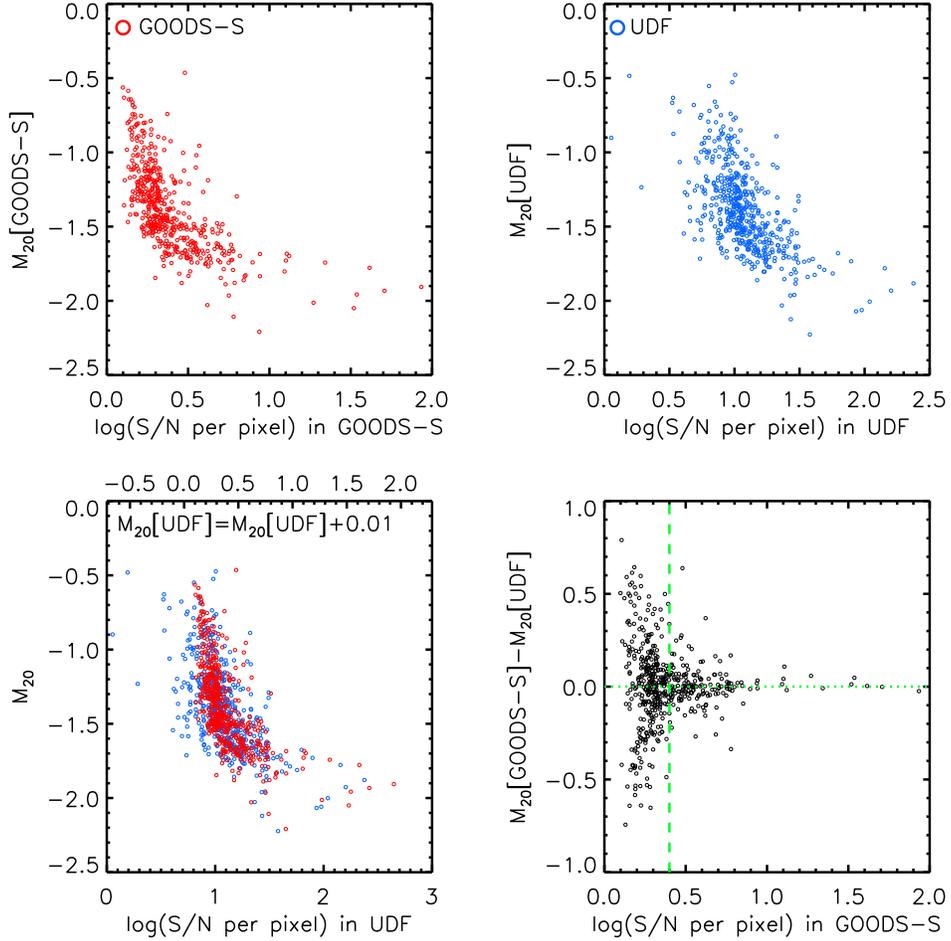


Fig. 18.—  $M_{20}$  vs. logarithmic signal-to-noise per pixel for the same galaxies imaged with differing image depths in UDF (blue) and GOODS-S (red). In the bottom left panel, we have shifted  $M_{20}$  values in UDF with a median of differences,  $(M_{20}[\text{GOODS}] - M_{20}[\text{UDF}]) = 0.01$ . The bottom right panel is the plot of  $\log(\text{S/N per pixel})$  vs. the difference in  $M_{20}$  between GOODS and UDF. The green dashed line at  $\log(\text{S/N per pixel})=2.5$  indicates the signal-to-noise limit for robust measures discussed in the text.

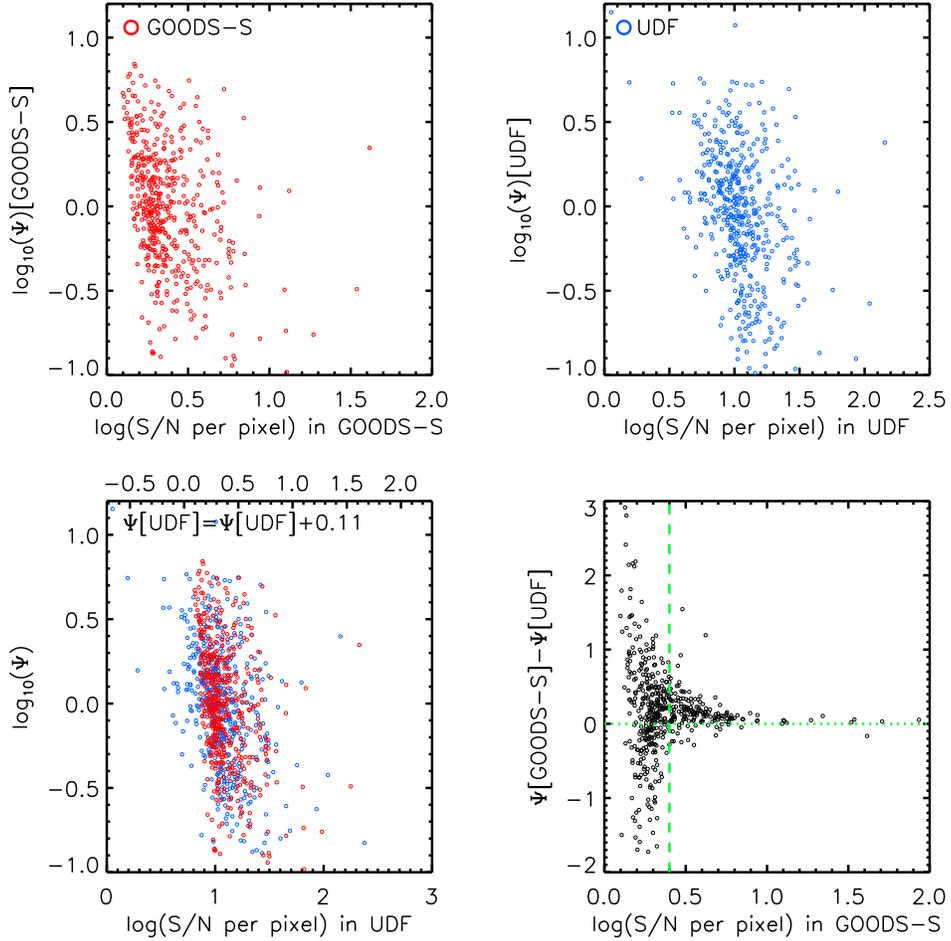


Fig. 19.—  $\Psi$  vs. logarithmic signal-to-noise per pixel for the same galaxies imaged with differing image depths in UDF (blue) and GOODS-S (red). In the bottom left panel, we have shifted  $\Psi$  values in UDF with a median of differences,  $(\Psi[\text{GOODS}] - \Psi[\text{UDF}]) = 0.11$ . The bottom right panel is the plot of  $\log(\text{S/N per pixel})$  vs. the difference in  $\Psi$  between GOODS and UDF. The green dashed line at  $\log(\text{S/N per pixel})=2.5$  indicates the signal-to-noise limit for robust measures discussed in the text.