GREEN VALLEY GALAXIES

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SUMMARY: The "green valley" is a wide region separating the blue and the red peaks in the ultraviolet-optical color magnitude diagram, first revealed using *GALEX* UV photometry. The term was coined by Christopher Martin (Caltech), in 2005. Green valley highlights the discriminating power of UV to very low relative levels of ongoing star formation, to which the optical colors, including $u - r$, are insensitive. It corresponds to massive galaxies below the star-forming, "main" sequence, and therefore represents a critical tool for the study of the quenching of star formation and its possible resurgence in otherwise quiescent galaxies. This article reviews the results pertaining to (predominantly disk) morphology, structure, environment, dust content and gas properties of green valley galaxies in the local universe. Their relationship to AGN is also discussed. Attention is given to biases emerging from defining the "green valley" using optical colors. We review various evolutionary scenarios and we present evidence for a new one, the *quasi-static* view of the green valley, in which the majority (but not all) of galaxies currently in the green valley were only partially quenched in the distant past and now participate in a slow cosmic decline of star formation, which also drives down the activity on the main sequence, presumably as a result of the dwindling accretion/cooling onto galaxy disks. This emerging synthetic picture is based on the findings from Fang et al. (2012), Salim et al. (2012) and Martin et al. (2007), as well as other results.

Key words. galaxies: evolution – ultraviolet: galaxies

1. INTRODUCTION

The dichotomy between spiral and elliptical galaxies has been established at the start of the extragalactic astronomy (Hubble 1926). The dichotomy consists of contrasts in morphology (spiral arms vs. featureless), color (blue vs. red), kinematics (rotational vs. pressure supported), typical luminosity (lower vs. higher), clustering (lower vs. higher density environments), etc. Many of these differences are the result of, or are related to the variations in the cold gas content, which in turn lead to very different levels of star formation (SF). Early-type galaxies (ETGs), which include ellipticals and disk-bearing lenticulars (S0), were traditionally considered to represent a quiescent population, although individual exceptions were known, particularly among S0s. The formation history of galaxies of different morphological types remains one of the central questions in current research efforts.

The new angle on the old question of galaxy dichotomy was provided with the advent of the Sloan Digital Sky Survey (SDSS, York et al. 2000). With its vast spectroscopic survey of galaxies in the local universe ($z \sim 0.1$, Strauss et al. 2002) and accurate optical photometry in five bands, SDSS enabled robust statistical analysis of galaxy populations. A color-magnitude diagram (CMD) constructed with SDSS photometry revealed that *field* galaxies formed two peaks in their optical color distribution (Strateva et al. 2001, Baldry et al. 2004). The narrower red peak was previously studied primarily in galaxy clusters, and was known as the *red sequence*. SDSS

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highlighted that the red sequence, and consequently the ETGs that are found in it, are abundant in non-cluster environments. The wider blue peak in optical color distribution became known as the *blue cloud*. The physical differences between two populations were thoroughly explored and quantified by Kauffmann et al. (2003a) who found that the red peak galaxies have, on average, older stellar populations, higher surface stellar mass densities, and dominate at stellar masses above $10^{10.5} M_\odot$.

This *bimodality* in color distributions thus became a central point in studies of local galaxies, but also at higher redshifts. Bell et al. (2004) and Faber et al. (2007) reported that the luminosity function of red-sequence galaxies has increased by a factor of two or more since $z \sim 1$. This result would suggest that the build-up of the red sequence (and thus, presumably, of ETGs) is a process that is ongoing at the present epoch. This scenario would be at odds with the traditional picture in which ETGs (especially ellipticals) have formed, and, therefore, stopped forming stars and became red, very early in the history of the universe. This traditional picture, supported by ample observational evidence (e.g. Trager et al. 2000), has its roots in the monolithic collapse scenario of Eggen, Linden and Bell (1962), which has subsequently been replaced with the hierarchical formation scenario (e.g. Kauffmann et al. 2006) in which mergers of disk galaxies provide a natural formation mechanism for elliptical galaxies (e.g. Barnes and Hernquist 1996). If mergers continue to be important in the latter epochs of the universe, as some numerical simulations suggested, then they would open the door for the late-epoch formation of ETGs and explain the reported growth of the red sequence. And if ETGs continue to be formed today, then there should exist galaxies that are currently in the process of transformation. Such galaxies would have properties that are in between those of the late and early-type galaxies. For example, they should have some SF, but most of the former activity would have ceased, i.e. their *specific star formation rate* (SSFR), or star formation rate (SFR) per unit stellar mass (SFR/M_*), would be lower than that of late-type galaxies of the same mass. The optical bimodality recognizes only actively star-forming and quiescent galaxies. So, how can such transitional population be identified on a large scale?

One promising approach is to utilize the *ultraviolet* (UV) photometry. UV covers the peak of the blackbody emission of young (< 100 Myr) stars, which means that even relatively small amounts of SF will stand out in the UV in contrast to the optical emission that is dominated by older stars. Furthermore, the UV emission, being produced by short-lived stars, will more closely reflect the *current* SF,

unlike the optical emission (even in U band) which is produced by stars that live in excess of a Gyr (Kennicutt 1998). UV observations require observations from space. In 2003 NASA launched *Galaxy Evolution Explorer*, or *GALEX* (Martin et al. 2005), a small space telescope dedicated to mapping the sky in two ultraviolet bandpasses: far-UV (FUV, $\lambda_{\rm eff} = 1550$ Å), and near-UV (NUV, $\lambda_{\rm eff} = 2300$ Å). Over its mision lifetime of ten years, *GALEX* observed much of the sky. Of special significance is its medium-deep imaging survey (MIS) of several thousand square degrees, which largely overlaps with the SDSS. It is the synergy between *GALEX* with SDSS that led to the discovery of the "green valley".
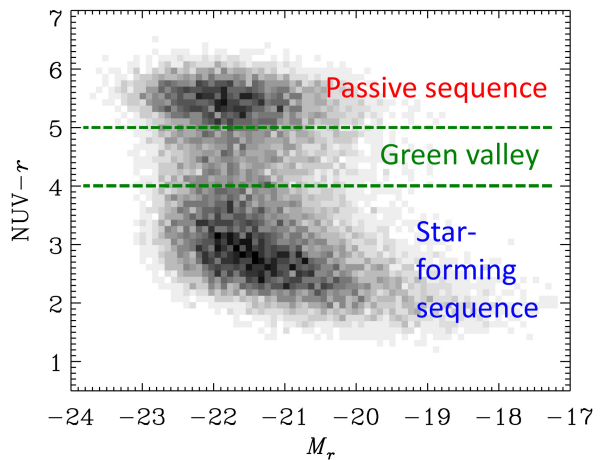

Fig. 1. *Ultraviolet-optical color magnitude diagram showing the ranges of NUV−r colors that correspond to actively star-forming galaxies, the green valley, and passive galaxies. This figure and Figs. 3 and 4 are based on the $z < 0.22$ GALEX/SDSS sample and data from Salim et al. (2007).*

2. GREEN VALLEY DEFINED

Green valley is a *wide* and relatively flat (hence, "the valley") region in the *UV-optical* CMD that lies between the peaks formed by star-forming and passive galaxies, respectively (Fig. 1).[1] The term *green valley* was coined by D. Christopher Martin, the principal investigator of *GALEX*, at the team meeting held in October 2005. The green valley was initially described in a series of *GALEX* papers. Wyder et al. (2007) defined it as a feature of CMD; Martin et al. (2007) discussed its possible evolutionary status, and Salim et al. (2007) explored its relation to active galactic nuclei (AGN). Schiminovich et al. (2007) studied its role in the morphological evolution.[2]

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[1] To avoid the confusion with its usual definition that pertains to optical colors, we will refer to red galaxies in the UV-optical CMD as the *passive sequence*, rather than the red sequence.

[2] Ironically, of the four aforementioned papers that appeared in the special volume of *The Astrophysical Journal* dedicated to *GALEX*, only Martin et al. did not mention the green valley by name, presumably because the term was considered too informal when the paper was submitted in early 2006. The other three papers were completed later in 2006 or 2007, by which time the term became adopted within the team.
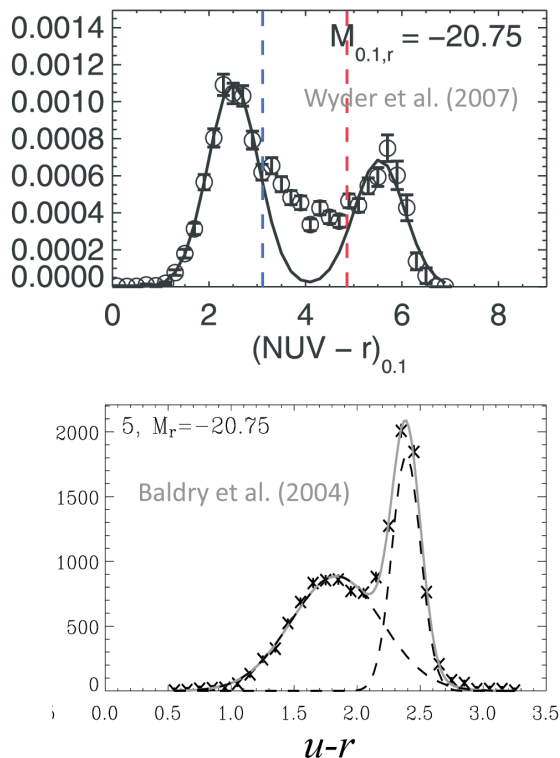
Fig. 2. *UV-optical (NUV−r; upper panel) and optical (u − r; lower panel) color distributions of galaxies with $M_r = -20.75$. Distributions represent slices of volume-corrected color-magnitude diagrams. NUV−r distribution has widely separated peaks and the excess population defined as the green valley (vertical dashed lines). In u−r the blue peak is wide (the "blue cloud") and overlaps with the red peak ("red sequence"), and the entire distribution can be modeled with two Gaussians. Adapted from Wyder et al. (2007) and Baldry et al. (2004).*

Wyder et al. (2007) defined the green valley as an *excess population* that is left over when the rest-frame UV-optical color distribution (in slices of optical absolute magnitude) is modeled as the sum of two Gaussians (Fig. 2a). The wide separation between the peaks and the presence of an excess population between them stands in stark contrast to the optical color distribution, which can be fully decomposed, at every absolute magnitude, into a sum of two Gaussian distributions (Baldry et al. 2004). This is true not only for $g - r$ color, but also for $u - r$ (Fig. 2b). Wyder et al. (2007) pointed out that the existence of the green valley argues for a continuum of properties from star-forming to quiescent galaxies that is hidden under the strict bimodality presented by optical CMDs. The green valley is most conspicuous when the rest-frame NUV magnitude (throughout the article we refer to rest-frame magnitudes and colors) is combined with some optical band, usually r (Fig. 1).

The physical significance of the green valley is that it represents a simple tool to identify transitional galaxies.[3] Transitional galaxies have lower SSFRs than actively star-forming galaxies of the same mass (Fig. 3). The latter lie on the star-forming ("main") sequence (Salim et al. 2007, Noeske et al. 2007). SSFR is a proxy for the star formation history and the evolutionary stage that the galaxy is in. The characteristic SSFR of normal SF is mass-dependent (Fig. 3). We define the onset of the transitional region to be at SSFR below that of massive Sbc galaxies (Salim et al. in prep.), i.e. log SSFR < -10.8 in units of Solar mass per year. Sbc's are the earliest galaxy type in which no classical bulge is present (Fisher and Drory 2008), so SF is expected to proceed normally (without being quenched), and yet Sbc's extend to the massive end of the stellar mass distribution. The lower end of the transitional range is more difficult to determine because the accuracy of SSFRs rapidly deteriorates below the star-forming sequence. At log SSFR $= -11.8$, our adopted lower limit, the majority of galaxies no longer show evidence for SF in UV images. Below this value, the SSFRs in Figs. 3 and 4 should be considered upper limits because SED model libraries, having exponentially declining SF histories with the shortest e-folding time of 1 Gyr, do not contain models with arbitrarily low SSFRs. This also means that the "actual" distribution of galaxies in log SSFR may not have two peaks, rather there would be the peak from the SF sequence and the tail of galaxies that extend towards ever lower SSFRs (Schiminovich et al. 2007). The bimodality seen in color distributions is simply because red colors have a finite limit, i.e. they saturate.

To summarize, transitional galaxies in the local universe can be defined as:

$$-11.8 < \log(\mathrm{SFR}/M_*) < -10.8.$$

Note that there is no evidence that these boundaries should include mass dependence for $\log M_* > 9$.

To illustrate the critical difference between UV-optical and optical colors in relation to transitional galaxies, in Fig. 4 we show a variety of colors plotted against the SSFR. Fig. 4b shows that NUV−r, even though not corrected for dust extinction, correlates well with SSFR over four orders of magnitude (Salim et al. 2005). The green valley in NUV−r can be defined as:

$$4 < \mathrm{NUV} - r < 5.$$

To make the above cut based on color better reflect the transitional galaxies it is recommended to remove dusty star-forming galaxies. This can be easily achieved by selecting face-on systems, e.g. with a cut $b/a > 0.65$ (Fang et al. 2012), or by introducing an additional cut based on $r - J$ color (Bundy et al. 2010 modification of Williams et al. 2009 method). Of course, it is best to, if possible, completely forgo the selection based on color and use dust-corrected SSFRs instead (e.g. from SDSS MPA/JHU online catalog.)

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[3]We distinguish between *transitional* and *transiting* galaxies, because the latter implies an evolutionary scenario.
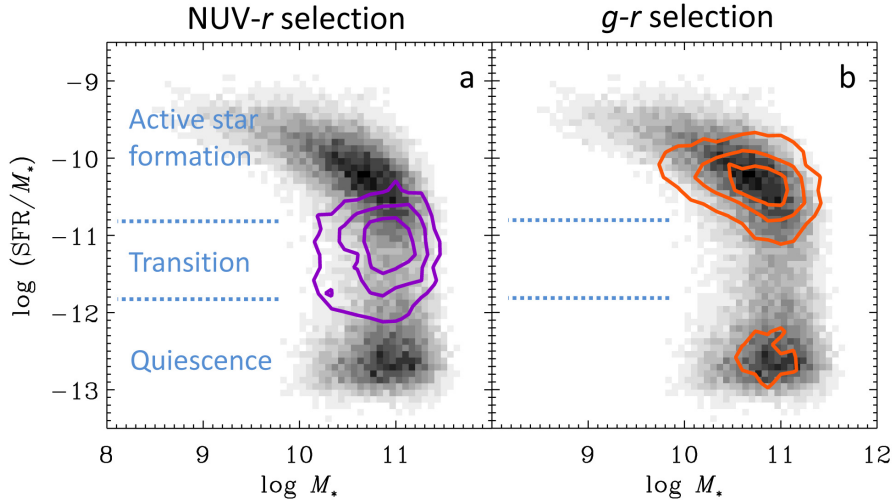
Fig. 3. *Specific SFR vs. stellar mass diagram highlighting the transition region below the star-forming sequence. Overlaid contours show the location of galaxies selected using: (a) intermediate NUV−r colors (i.e. the green valley), and (b) intermediate g − r colors. The latter avoids the transition region and selects massive galaxies on the "main" sequence. SFRs in this figure are dust-corrected and have been determined using Bayesian SED fitting involving up to seven bands (FUV to z).*

Fig. 4a shows FUV−r vs. log SSFR. The correlation with SSFR persists but is somewhat less tight. More importantly, at MIS depth *GALEX* FUV detection ($> 3\sigma$) rate of SDSS spectroscopic sample is only 57% , while it is 85% in NUV. Therefore, NUV is a more useful choice. At a given SSFR, the spread in colors (optical or UV-optical) of star-forming galaxies is mostly due to various amounts of intrinsic dust reddening (and for quiescent galaxies due to variations in stellar metallicity).[4]

The correlation between the color and the SSFR changes dramatically when the UV band is replaced with an optical u band (3550Å, Fig. 4c). Now the galaxies with transitional SSFRs have the same range of colors as the completely quiescent galaxies. Situation with $g − r$ colors is very similar: transitional and quiescent galaxies have the same colors, i.e. they both lie within the red sequence (Fig. 4d). The insensitivity of optical colors, including $u − r$, to recent SF has been pointed out in a number of papers (e.g. Kauffmann et al. 2007, Fig. 1; Schawinski et al. 2007a, Fig. 6; Kaviraj et al. 2007a, Fig. 11; Woo et al. 2013).

Fig. 4d shows that the optical red sequence also includes galaxies that lie at the tip of the blue cloud. That the blue cloud and the red sequence overlap in optical colors can also be seen in Baldry et al. (2004) color distributions, reproduced in Fig. 2b. Masters et al. (2010) reported a large number of spiral galaxies with red optical colors and proposed that they were "passive spirals", presumably with little or no SF. However, Cortese (2012) showed using UV and mid-IR SFRs that all "passive spirals"

are actually on the massive end of the star-forming sequence, having SFRs no different from other galaxies of that mass. They conclude that, especially at high masses, optical colors cannot distinguish between actively star-forming and passive galaxy. For the same reason it is not appropriate to quenching fractions with optical colors, as highlighted by Woo et al. (2013). To quote Kauffmann et al. (2007), *"ultraviolet ... leads to a very different accounting of which galaxies in the local universe are truly "red and dead""*.

In Fig. 3a we show where the green valley galaxies selected by UV-optical color ($4 < \text{NUV}−r < 5$, no dust corrections) lie on SSFR vs. stellar mass diagram (purple contours). As expected, they correspond to galaxies that lie mostly below the star-forming sequence. A number of studies, presumably out of convenience, define the green valley as a region of intermediate colors in the *optical CMD*. For example, Lackner and Gunn (2012) define "green valley" to be a 0.1 mag wide band in $g − r$ CMD that lies adjacent to the red sequence. Fig. 3b shows the location of these "pseudo" green valley galaxies on SSFR–M_* diagram. It occupies the massive end of the star-forming sequence and completely avoids the transitional region that starts below it. It even includes some quiescent galaxies. The reason for this "contamination" can be seen in Fig. 4d where the orange dividing line corresponds to Lackner and Gunn split at $M_r = -22$. Some studies consider the green valley not to be a region at all but the *dividing line* (the minimum) between the blue and the red peaks, again in the optical CMDs.

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[4]This explains why including the absolute magnitude (with which both the dust extinction and metallicity correlate) as the third axis in $g − r$ vs. NUV−r diagram reduces the scatter in the color-color plane of Chilingarian and Zolotukhin (2011).
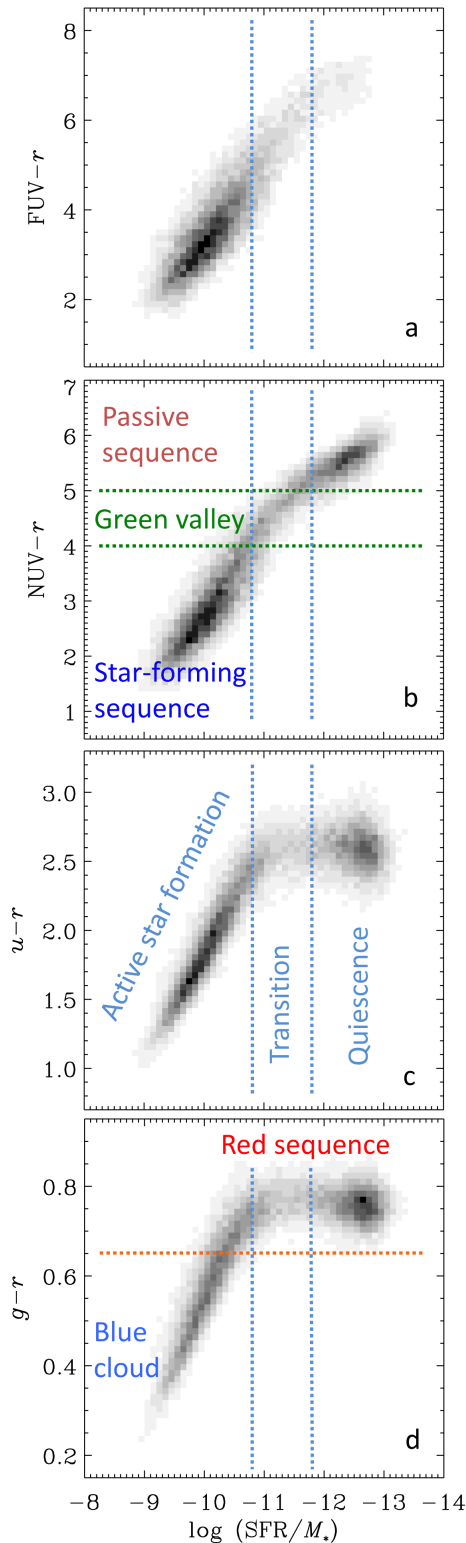
Fig. 4. *Relationship between the rest-frame colors (no dust correction) and dust-corrected specific SFRs. Panels a and b employ UV-optical colors and demonstrate good correlation with the specific SFR. In panels c and d optical colors are tightly correlated with specific SFR for normally star-forming galaxies but become degenerate for low specific SFRs.*

The green valley can alternatively be defined with photometric bands other than NUV and r as long as they correlate to recent SF and stellar mass, respectively. For example, Haines et al. (2011) use the ratio of 24 μm flux to K-band flux. Some such mid-IR equivalents of the green valley were even given new names (Mid-infrared Canyon, Walker et al. 2013; Infrared Transition Zone, Alatalo et al. 2014). Confusion arises when mid-IR green valleys are compared and found to be different from the (pseudo) "green valley" defined with *optical* colors. A comparison with the actual green valley would have revealed that mid-infrared colors isolate very similar population.

In the rest of this article we will primarily discuss the results of the studies that define the green valley using UV-optical colors, IR colors, or utilize SSFRs directly. Furthermore, we will focus on galaxies in the local universe ($z < 0.3$) with $M > 10^9 M_\odot$, i.e. the non-dwarf population that is more likely to consist of central galaxies in their dark matter halos. High-redshift results are presented separately in Section 3.6. Due to space limitations we will omit case studies. For a more general overview of galaxy properties in the local universe please refer to Blanton and Moustakas (2009).

3. PROPERTIES OF GREEN VALLEY GALAXIES

3.1. Morphology and structure

Green valley galaxies are predominantly *bulge-dominated, disk galaxies*. In Fig. 5 we show optical images (*gri* composites) of a sample of nearest ($10 < D < 25$ Mpc) green valley galaxies observed by SDSS and *GALEX*, selected to be evenly distributed over a range of masses ($9.3 < \log M_* < 11.4$). Their red appearance is consistent with red-sequence optical color (Fig. 4d). For comparison, a lower-mass blue-cloud galaxy is shown in the inset of the first image. Most galaxies in Fig. 5 do not look like either the typical late-type galaxies (with conspicuous and well-defined spiral arms), or like the typical early-type galaxies (with smooth light profiles). Instead, they do look like a hybrid class, with often prominent dust lanes, rings or disturbed outer profiles. Even in galaxies that look like featureless S0s, the SF is actually present in the disk, but requires UV imaging to be seen (Salim et al. 2010, 2012). Formally, the great majority of green valley galaxies are classified as S0 through Sb in RC3 or Hyperleda catalogs. While most S0s are fully quiescent, some 20% lie in the green valley. On the other hand, Sb galaxies are primarily found on the star-forming sequence, but some enter the green valley (Salim et al. in prep). M31, an Sb galaxy with NUV$-r = 4.5$ (transformed from Gil de Paz et al. 2007), lies in the green valley (Mutch et al. 2011), but the Milky Way (Sbc), having $\log$ SSFR ~ -10.5, does not, despite relatively red optical colors. No single Hubble type, or even a subtype is found only in the green valley. In this se-
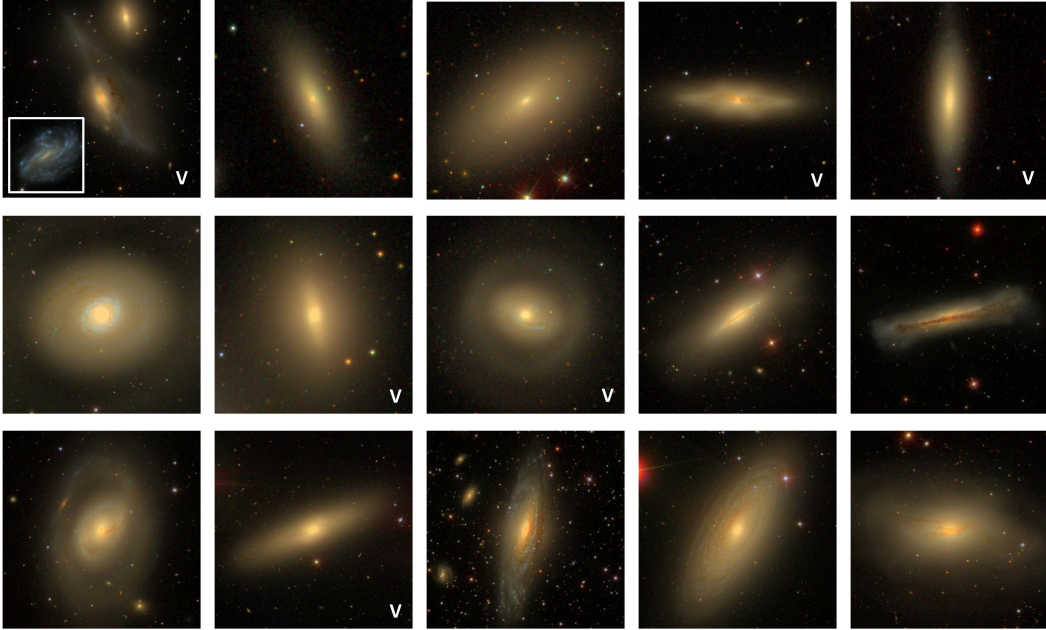
Fig. 5. *A collage of SDSS images (gri composites) of some of the nearest (D < 25Mpc) green valley galaxies, spanning the mass range from $\log M_* = 9.3$ (upper left) to $\log M_* = 11.4$ (lower right). Green valley is composed of optically red, mostly disk galaxies (S0-Sb) displaying a variety of morphological features. "V" denotes Virgo Cluster members. Inset shows a late-type spiral, for color comparison. From Salim et al. (in prep.)*

nse, the green valley reflects the composition of the optical red sequence in which it is located. The red sequence includes almost all Sa's and the majority of Sb spirals (e.g. Gil de Paz et al. 2007, Fig. 5.) *The red sequence should not be equated with early-type galaxies, which, in turn, must not be equated with the spheroids (elliptical galaxies).*

While pure spheroids are to be found in the green valley at higher masses ($\log M_* > 11$), there is a lack of evidence that they have ongoing SF, i.e. they scatter mostly into the green valley from the passive side. Salim et al. (2012) studied a sample of 30 green valley galaxies with deep optical imaging from the ground and FUV follow-up with the *Hubble Space Telescope (HST)*. Whenever a wide-spread SF was present in *HST* images (3/4 of the sample), the galaxy would have an optical disk. They also found that the fraction of SDSS ETGs (i.e. bulge-dominated disks and spheroids) that have extended SF (and are therefore found in the green valley) declines above $\log M_* > 10.9$, which is where spheroids begin to dominate over disk ETGs. The star-forming fraction also declines with optical light concentration index, another feature of pure spheroids. The Hubble classification places pure spheroids in the *elliptical* category. Consequently, ellipticals should be rare in the green valley. This is difficult to verify with SDSS imaging, which at $z \sim 0.1$ lacks the requisite resolution and depth for robust classification, resulting in many S0s appearing like ellipticals, but the detailed surveys of nearby ETGs (e.g. ATLAS^{3D}) also find

almost no evidence of SF in galaxies classified as elliptical (Young et al. 2011). A notable exception is NGC 5173 (E1), the most HI-rich known elliptical, which probably owes its patchy star-forming regions to a particularly gas-rich merger (Vader and Vigroux 1991). Yi et al. (2005) were the first to point out that as many as 15% of ETGs lie in the green valley and could therefore represent cases of ongoing SF. Kaviraj et al. (2007a), also using *GALEX* photometry, estimated that 30% of ETGs had 1–3% of stars younger than 1 Gyr. These results were sometimes interpreted to mean that there is a large fraction of *ellipticals* with ongoing SF, but recent results paint a more nuanced picture in which the SF in ETGs is restricted to disk galaxies (S0s), and is largely absent from massive ellipticals, whether they are slow or fast rotators.

It should be mentioned that the *UV upturn* phenomenon in ETGs (Code and Welch 1979) due to the old stellar populations (presumably, horizontal branch stars) does not produce colors bluer than $NUV - r = 5.4$ (Burstein et al. 1988, Schawinski et al. 2007a) so it cannot, by itself, bring an ETG into a green valley. Furthermore, even in the absence of high-resolution UV imaging, the UV upturn is relatively easy to distinguish from SF when the UV color (i.e. FUV−NUV) is available because galaxies with the UV upturn show an anti-correlation between the UV and optical color (Donas et al. 2007, Gil de Paz et al. 2007).

Discussion in this section does not pertain to very rare E+A galaxies, which also have elliptical morphology and sometimes have green valley colors (Kaviraj et al. 2007b). We will discuss them in Section 4.

In terms of the quantitative structural morphology, Schiminovich et al. (2007) showed that the green valley galaxies have Sersic indices that are halfway (in logarithm) between those of star-forming and passive galaxies. Furthermore, they report that the average Sersic indices increase with mass for every type of galaxy. Because the Sersic index, even in i band, can be affected by younger stars in the disk (Fang et al. 2013), it is more physically instructive to look at the stellar mass surface density profiles, which also place green valley galaxies between star-forming and passive (Schiminovich et al. 2007). However, when the mass surface density is considered only in the central 1 kpc, i.e. the bulge, both the green valley and passive galaxies have remarkably similar densities at the given mass (Fang et al. 2013).

The UV morphology of green valley galaxies has been less studied than the optical morphology, mostly because of relatively poor (5 arcsec) resolution of *GALEX* images. Salim et al. (2012) used FUV imaging with *HST*, and found that the rings of various shapes and sizes are the most common UV feature, and are typically not conspicuous or visible in optical images. In some cases the rings or SF features extend well beyond the optical extent of the disk, making these galaxies similar to giant low surface brightness galaxies such as Malin 2 and UGC6614, or resembling extreme UV disks (Thilker et al. 2007, Lemonias et al. 2011), that may be the signpost of intense accretion from the intergalactic medium (IGM). In rare cases the outer rings experience very intense SF (e.g. Hoag's object, Finkelman et al. 2011), the colors of which alone would place them on the star-forming sequence. More typically, the color profiles of green-valley ETGs are bluer at larger radii within the contiguous disk, with colors approaching those of actively star-forming galaxies, but with very low surface brightnesses ($\mu_r > 24$ mag arcsec^{-1}, Fang et al. 2012), making these regions of the disk very different from those of actively star-forming galaxies.

3.2. Dust and the measurement of SFRs

Measurement of dust-corrected SFRs is quite challenging for green valley galaxies due to their low SSFRs. Emission-line diagnostics (Hα, [OII]) are not very useful because (a) equivalent widths of green valley galaxies are small, (b) green valley galaxies often contain an AGN or a LINER ($\sim 50\%$, Martin et al. 2007), which contaminates line emission, (c) if spectra cover only the central regions, as in the case of SDSS fibers, many green valley galaxies will not have emission lines because the SF may be absent in the bulge (Salim et al. 2012). Estimating SFRs and dust extinction using the mid-infrared emission (alone, or in combination with the UV) is also of lim-

ited use. In red sequence galaxies, most of the dust heating in the mid-IR will be due to intermediate-age (~ 1 Gyr) or older stellar populations (Cortese et al. 2008), so the estimates of SFR based on mid-IR luminosity will be one to two orders of magnitude too high (Salim et al. 2009, Hayward et al. 2014). Dust corrections affecting the FUV ($A_{\rm FUV}$) can be determined from a correlation with the UV slope (β) or UV color (Calzetti et al. 1994). The method works very well for starburst galaxies (Meurer et al. 1999) and can also be adapted for use with normal star-forming galaxies (e.g. Buat et al. 2005, Seibert et al. 2005, Salim et al. 2007). However, the dust-to-UV color correlation breaks down for green valley galaxies where the UV color is primarily sensitive to the age of the stellar population (e.g. Gil de Paz 2007). The most promising approach is to utilize full UV-optical SED, which allows breaking of the age-dust degeneracy (Kaviraj et al. 2007c). This can be achieved by fitting the observed SED to models that include a range of dust attenuations and SF histories. Note that the SED fitting should not extend to rest-frame near-IR bands, since those are not well reproduced in the current stellar population synthesis models (e.g. Taylor et al. 2011).

It should be mentioned that the level of SF is small in green valley galaxies only in relative terms. A $10^{11} M_\odot$ galaxy sitting in the middle of the green valley (log SSFR$= -11.3$), would have a SFR of 0.5 $M_\odot$yr^{-1}, which is ten times higher than SFR of M33 (Wilson et al. 1991).

Schiminovich et al. (2007) found that the dust attenuation of green valley galaxies is between that of star-forming and truly passive galaxies. This trend is consistent with the picture in which dust and SFR are correlated. Agius et al. (2013) find that sub-mm detected ETGs tend to be found in the green valley. Also, Hinz et al. (2012) report that most of the dust in an outer-ring S0 galaxy NGC 1291 lies within the star-forming ring, which is responsible for making it a green-valley galaxy. There have been some results that spurred the notion that the observed green valley is composed only of dusty SF galaxies, suggesting that the physical green valley did not exist. That this is not the case was pointed out already in Wyder et al. (2007), who presented a dust-corrected CMD, and is obvious from Figs. 3 and 4 that do not show a gap in SSFRs.

3.3. Environment and clustering

Whether the reasons for a galaxy getting into the green valley are internal or external i.e. due to the effects of the environment, is of critical importance. Schawinski et al. (2007a) studied passive and green valley galaxies that conform to early-type morphology and have no AGN activity. They found that ETGs tend to be somewhat bluer (in NUV−r) in lower-density environments i.e. in the field vs. in groups or clusters. Also, the fraction of ETGs in the green valley was higher for the field. They also show that these differences are not due to denser environments having more massive galaxies, which tend to

be more quiescent. They suggested that the change is possibly due to ram pressure stripping in denser environments, but the results are also consistent with other scenarios that prevent the gas from reaching the galaxy. Crossett et al. (2014) found that the fraction of red-sequence galaxies that have blue NUV$-r$ colors (i.e. scatter into the green valley) is higher at cluster outskirts, again consistent with environmental effects. They also indicated that cluster green valley galaxies showed optical spiral structure but it was not checked if the spirals in cluster green valleys were more common than in field green valley. They find that $\sim 10\%$ of cluster red-sequence galaxies have some SF, which is 2–3 times lower fraction than in the field (see Section 3.1.)

While the dependence of green-valley fractions on environment may be suggestive of a quenching mechanism, it is not clear that the gas-stripping by environment is sufficient to drive the galaxy towards quiescence. Observational results are mixed. In a study of green valley populations in Virgo cluster compared with the nearby field sample, Hughes and Cortese (2009) reported an intriguing result that the Sa and (unspecified number of) *later* green valley galaxies are primarily found in the cluster, but not in the field. Furthermore, all Virgo cluster green-valley galaxies were HI deficient. These results suggest that the gas stripping in dense environments is critical for galaxy quenching but it is not clear how relevant the HI deficiency is considering the lack of correlation with H_2 deficiency in clusters (Boselli et al. 2014). In contrast, Haines et al. (2011) report that the late-type (Sb and later) galaxies are rare in green valleys of clusters. This forms a part of a bigger question of the existence and the importance of "late-type" (small bulge) S0s (Kormendy and Bender 2012).

The analyses of clustering of the general population of galaxies (Heinis et al. 2009, Loh et al. 2010) revealed that green valley galaxies have some clustering properties similar to passive galaxies (detachment from the Hubble flow), while most are between star-forming and passive, suggesting that if green valley galaxies are a transiting population, they must also change their environment.

3.4. Active Galactic Nuclei

Co-evolution of supermassive black holes and galaxies is one of the central questions in studies of galaxy evolution today (Kormendy and Ho 2013, Heckman and Best 2014). Even relatively low-luminosity AGN may have a role in regulating SF, or in maintaining the quiescence of a passive galaxy (e.g. Croton et al. 2006).

Martin et al. (2007) showed that the *fraction* of galaxies that are classified as AGN using the Baldwin-Peterson-Terlevich (BPT) diagram, peaks at the intermediate UV-optical colors, at $\sim 50\%$, and suggested a connection with quenching of SF, supported by an anti-correlation, albeit weak, between AGN strength and the rate of quenching. Salim et al. (2007) extended this analysis by considering BPT AGN and non-AGN at the same stellar mass, and found that AGN, both the raw numbers and *number*

densities actually peak in the star-forming sequence, with the tail towards the green valley. Furthermore, they emphasized the difference between strong AGN ($L[\text{OIII}] > 10^7 L_\odot$), which lie entirely on the massive end of the star-forming sequence, and the weak AGN, which are mostly found on the star-forming sequence but also extend to the passive sequence (Fig. 6). They present a picture in which AGN may be responsible for a *gradual* suppression of SF of galaxies on the star-forming sequence, and argue against sporadically fed AGN through minor gas-rich mergers. The result of Martin et al. that the AGN fractions peak in the green valley can be reconciled with their numbers peaking on the SF sequence by the fact that in the green valley the BPT method is sensitive to LINERs, which may not represent active nuclei, but may arise from excitations from hot evolved populations (Stasinska et al. 2008).
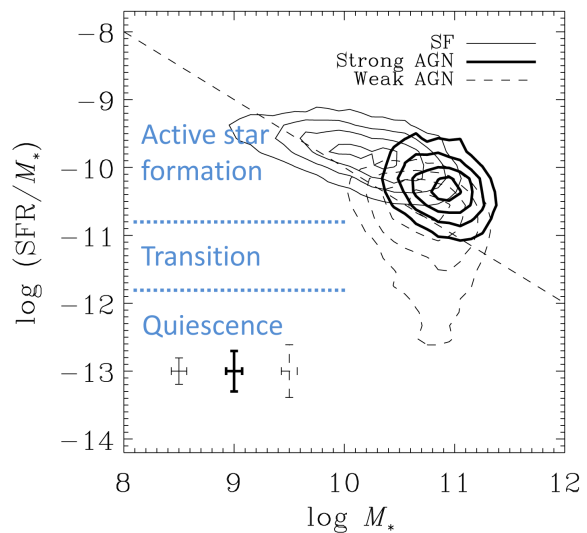

Fig. 6. *Specific SFR vs. stellar mass diagram showing the locations of galaxies selected from the BPT diagram to be star-forming (thick solid contours), strong AGN ($L[\text{OIII}] > 10^7 L_\odot$), and weak AGN ($L[\text{OIII}] < 10^7 L_\odot$). AGN are selected to lie above the Kauffmann et al. (2003b) demarkation line on the BPT diagram. Strong BPT AGN lie on the star-forming sequence, as well as many weak ones. The latter extend through the transition region (the green valley). Adapted from Salim et al. (2007).*

Martin et al. (2007) results are sometimes misinterpreted to mean that AGN *numbers* peak in the green valley, spurring criticism that for AGN quenching to be viable they should not peak in the green valley (e.g. Schawinski et al. 2009). The confusion regarding whether AGN are found among the actively star-forming galaxies was further compounded because there are numerous studies that define the "green valley" using *optical* colors (e.g. Nandra et al. 2007, Silverman et al. 2008, Schawinski et al. 2007b, 2009, 2010, Treister et al. 2009, Vasudevan et al. 2009, Cardamone et al. 2010, Mendez et al. 2013, Smolcic 2009), and which consequently find that AGN peak at intermediate colors (especially the

more luminous ones selected by X rays or the mid-IR slope). However, massive, normal star-forming galaxies intrinsically can only have intermediate optical colors (Fig. 4b), so these studies actually confirm that AGN are mostly on the star-forming sequence. The conclusion is that, when interpreted correctly, both the UV and the optical studies present consistent evidence (see also Rosario et al. 2013).

It is important to point out that the BPT selection of AGN in the local universe needs to include all galaxies lying above the empirical demarcation line of Kauffmann et al. (2003b) and not only galaxies that lie above the Kewley et al. (2001) line of maximum theoretical SF (Juneau et al. 2014). Selecting only the latter biases the sample towards low-luminosity AGN (Fig. 2 in Kauffmann et al. 2003b), which, on average, have lower SSFRs (Kewley et al. 2006). AGN that lie between the two lines are often called SF/AGN composites, but it should be kept in mind that all galaxies on the AGN branch (AGN mixing sequence) can have SF to some extent, and that being above the Kewley et al. line is irrelevant.

That BPT identifies AGN with specific SFRs as high as those of non-AGN (at a given mass) argues against significant incompleteness or bias of the BPT technique (above some threshold of AGN luminosity) due to SF contamination (see also Fig. 6 in Kauffmann et al. 2003b). This claim is further supported by the fact that AGN found by other methods (e.g. X-rays, radio), also fall within the AGN branch of the BPT diagram (Yan et al. 2011, Juneau et al. 2011).

Most AGN studies in the context of the green valley population pertain to the more common Type 2 AGN, whose central engine is not sufficiently strong to affect the global color of the host, or is so oriented that it is sufficiently obscured by the dust. The vast majority of AGN belong to Type 2, even if LINERs are not considered to be AGN. Type 1 AGN (QSOs, Seyfert 1s) on the other hand have broad emission lines and contribute to continuum emission. Trump et al. (2013) remove the central sources of broad-line AGN to study host colors, and find that such AGN prefer optically bluer hosts, in line with the results for luminous Type 2 AGN.

3.5. Gas properties

Gas content of green valley galaxies, both atomic and molecular, and its relation to galaxies on either side of the green valley provides important clues to understanding the origin of this population. *GALEX* Arecibo SDSS Survey (GASS; Catinella et al. 2010) obtained HI measurements for ~ 1000 galaxies with $0.025 < z < 0.05$ and $M_* > 10^{10} M_\odot$, with special emphasis on transitional galaxies. Producing a survey of HI that would not be biased towards gas-rich systems is challenging, and GASS attempts to reduce the effect of these biases by careful selection and analysis. Unlike galaxies on the passive sequence, almost all green valley galaxies are detected in GASS. Gas fraction ($M_{\rm HI}/M_*$) correlates with NUV$-r$ color (Catinella et al. 2012), suggest-

ing that the green-valley phase is not due to the abrupt change in the gas reservoir. Remarkably, GASS showed that the SF efficiency is nearly the same in the green valley and outside of it (Schiminovich et al. 2010), suggesting that whatever mechanism regulates the gas supply also regulates the SF.

Fabello et al. (2011) find that the SF efficiency based on stacked HI data from ALFALFA survey does not seem to depend on the bulge fraction, thus disfavoring the morphological quenching scenario of Martig et al. (2009). One should keep in mind that the model of Martig et al. (2009) in which the bulge suppresses SF without removing the gas is strictly applicable only to the inner-disk *molecular* gas, and Crocker et al. (2011) do find that some ETGs with molecular gas do not have SF (based on their UV-optical color). More generally, however, the H_2 fraction, like the HI fraction, does correlate with NUV$-r$ color (Saintonge et al. 2011), so it is difficult to claim that morphology regulates SF without also affecting the gas content.

3.6. Green valley at higher redshifts

Because the green valley is defined relative to the star-forming sequence (Section 2), which is shifting towards higher SSFRs with redshift (e.g. Speagle et al. 2014), it is appropriate to also have redshift-dependent cuts on SSFR and/or UV-optical color. For $\langle z \rangle \sim 0.8$ sample, Salim et al. (2009) use green valley limits of $-11 < \log(SFR/M_*) < -10$ and $3.5 < {\rm NUV} - r < 4.5$, which match very well with the Moustakas et al. (2013) division between the SF and passive galaxies that shifts in log SSFR as $1.33z$.

Bundy et al. (2010) followed the morphology of the green valley and passive sequence to $z \sim 1.2$ and reported that the fraction of disk galaxies, especially at higher masses, was greater in the past, suggesting that some of them merge into spheroids while being green/passive. Mendez et al. (2011) found, using quantitative morphological parameters (CAS, bulge-to-total ratio, Gini/M_{20}) that the green valley at $0.4 < z < 1.2$, is mostly composed of disk galaxies intermediate between star-forming and passive galaxies, with even lower merger fractions than those measured for blue galaxies, suggesting that the mergers are not important for quenching at those redshifts. These results do not differ essentially from those in the local universe.

Goncalves et al. (2012) obtained spectra of green valley galaxies at $z \sim 0.8$ which suggest that the transiting rate used to be higher in the past, and involved more massive galaxies i.e. that the massive end of the passive sequence was put in place earlier, representing another aspect of "downsizing".

E+A galaxies, which represent an interesting green-valley population locally (Section 4), have also been identified at $0.5 < z < 1.2$, and were found to reside in dense environments (like quiescent galaxies). Their number densities, however, are comparable to those of E+As at low redshift (Vergani et al. 2010).

4. EVOLUTIONARY PICTURE

In this section we overview various evolutionary scenarios for the green valley, and propose the "quasi-static" model as a synthesis view.

Green valley (modulo dust) is most often portrayed as the population of galaxies transiting, at the present epoch, from active SF to quiescence on a relatively fast timescale (< 1 Gyr) i.e. as galaxies that have *recently* been quenched or are undergoing quenching. The picture that has emerged over the last seven years is both different and more complex.

From the methodological point of view it should be said that the studies that discuss the migration of galaxies through the *optical* CMD will be of limited use for understanding the quenching mechanisms in massive galaxies. This is because the different locations within the (dust-corrected) blue cloud simply represent various levels of SSFR of galaxies that are actively star-forming (see Fig. 4d), with many of the massive star-forming galaxies already in the red sequence. In other words, the transition to quiescence for massive (non-satellite) galaxies happens *within* the optical red sequence, "under the radar" of optical CMDs. Optical colors are instead useful for the study of normal, pre-quenching SF, as evidenced by the tight correlation betwen optical colors and SSFR (Figs. 4c, d).

Before evaluating various scenarios for the origin of green valley population, we assess the evidence that (a) there should exist a substantial transit from active SF to quiescence, and (b) that this transit should produce spheroids (ellipticals). Recent results show that when the evolution of the mass function of star-forming and quiescent galaxies is determined using the actual SSFRs and from areas that minimize cosmic variance, there is essentially no evolution in the massive end ($M_* > 10^{10.5} M_\odot$) of quiescent galaxies since $z \sim 0.8$ (Moustakas et al. 2013). This implies that ellipticals, which dominate at these masses, have already been in place at that epoch, which is consistent with numerous studies that fail to find sufficient number of major mergers at the present epoch to sustain the formation of new ellipticals (e.g. Lotz 2008), and with the classical picture of ellipticals as an ancient population. Thus, the flux of galaxies through the green valley may be much smaller than previously thought based on the optical red sequence luminosity functions, and may be limited to lower mass galaxies.

An often laid out the argument for rapid (< 1 Gyr) transition through the green valley comes from the relative paucity of galaxies that are found there. However, the green-valley crossing time is impossible to be determined based on the number density of galaxies alone. Martin et al. (2007) used SF history-sensitive spectral indices Hδ_A and $D_n(4000)$ to roughly determine the quenching rates in the green valley and have found (their Fig. 13) that the quenching timescales span the entire range probed, from some with just 50 Myr to the majority (50%) with 2 Gyr. This latter timescale corresponds to green-valley crossing times of at least 2.5 Gyr. They estimate that the total transiting time from activity

to quiescence is as long as ~ 6 Gyr (their Section 6.1.2). Note that this does not mean that most transiting galaxies move slowly, only that the slow ones will be overrepresented in the green valley: *"Galaxies with faster quench rates will spend less time in the transition region, and the fact that the majority of galaxies are found to have low quench rates in the transition zone does not mean that the majority of galaxies undergo slow quenches."* (Martin et al. 2007.)

That the green valley may be mostly *static* was proposed in Salim et al. (2012) and Fang et al. (2012) on the basis of the detailed investigation of the UV morphologies and star-formation histories of a sample of green valley ETGs. Morphologies were found to be consistent with the smooth, gradual star formation. Most SF were found to take place in the outer regions of optically red, old disks. SF histories of these outer disks, do not differ from those of actively star-forming galaxies, i.e. there is no evidence of a fast decline or fast rise. Note that in this quasi-static scenario there is no reason for SFRs of green valley galaxies to stay constant over cosmic epochs. They may still decline slowly for the same reasons that drive the decline of SF on the main sequence e.g. the drop in the overall accretion rate (e.g. van de Voort et al. 2011). *Thereefore, most (but certainly not all) galaxies currently in the green valley are not moving rapidly through it, rather, it is the green valley (as the region below the star-forming sequence) that moves slowly towards lower SSFRs.*

Suggestions have been made that some green valley galaxies may come *from* the passive sequence, following the resumption of (steady) gas accretion from the IGM (Thilker et al. 2010). Salim et al. (2012) append this scenario by suggesting that the galaxy may move between the low-level SF and quiescence depending on the duty cycle of a (Type 2) AGN. The connection between the fueling of SF and of AGN has been shown in Kauffmann et al. (2007), who exploited the fact that SDSS fibers capture the bulge region of the galaxy, while the photometry is global, to explore age gradients in bulge-dominated green valley galaxies. They found that what leads to intermediate UV-optical colors is the SF in the extended disk, whereas the bulges can be young or old. On the other hand, old disks rarely have young bulges. This suggests that the gas source is an outer reservoir, rather than the gas from a merging galaxy, which usually ends up in the centers of the galaxies (e.g. Peirani et al. 2010), though interactions may help bring the gas there. *The outer reservoir fuels disk SF and occasionally also reaches the central black hole. The resulting activity may lead to prevention of further accretion by some feedback process and results in (temporary) shutting down of SF.* This connection between the green valley and the passive sequence is supported by the Fang et al. (2013) result that the two groups of galaxies are structurally very similar. Depending on the duration of AGN/SF cycles and the prevalence of feedback, this scenario may for all practical purposes be observationally indistinguishable from the more general static picture.

In contrast to this relatively steady-state picture, a scenario has been proposed by Kaviraj et al. (2009) that the green valley is made up entirely of otherwise passive galaxies that recently underwent a minor gas-rich merger. They support this scenario with numerical simulations of merging populations. While there is little doubt that minor mergers involving quiescent galaxies and gas-rich galaxies do occur, and may not be uncommon (e.g. the upper left image in Fig. 5, or Crockett et al. 2011), it is unlikely, from the morphologies and SF histories, that such cases are responsible for the majority of the green valley.

The idea of an external source of gas for green valley galaxies has been challenged on the account of the measurements of the metal abundance, which for some star-forming rings around S0 galaxies is close to solar (Bresolin 2013, Ilyina et al. 2014). At face value these results argue against accretion from IGM, or at least the accretion of pristine gas. However, in the quasi-static scenario the accretion is a slow process during which substantial enrichment may be possible. The main alternative to the fueling of green valley SF through the accretion of external gas is that it is sustained by internal gas from mass loss. It dates back to Faber and Gallagher (1976), when the ubiquity of gas in and around ETGs was not well established. Kaviraj et al. (2007a) claimed that the recycled gas from mass loss is insufficient to produce SF observed in green valley galaxies, however, it may provide some fuel (Leitner and Kravtsov 2011). Since the mass loss should follow stellar light, and the SF in green valley mostly happens in the outer disk, this avenue is plausible if the gas is transported, e.g. by secular action of a bar (Schwarz 1984). Since mass loss is universal, the question arises as to why are not all barred S0 galaxies star-forming?

Detailed discussion of the processes that initiated the quenching and brought the galaxy into the green valley in the first place is outside of the scope of this review. Green valley galaxies cannot simply be more quiescent versions of star-forming galaxies, because their structure is different (more centrally concentrated) than that of galaxies on the main sequence of the same mass (Schiminovich et al. 2007, Fang et al. 2013). Therefore, the simple fading mechanisms, due to, for example, gas exhaustion or gas starvation cannot explain why galaxies leave the star-forming sequence. Recent work places importance to the build up of the bulge (e.g. Bell 2008, Cheung et al. 2012), rather than the so called halo quenching (Dekel and Birnboim 2006, Woo et al. 2013). This makes both the ejective AGN feedback (e.g. Cattaneo et al. 2006) and the morphological quenching (Martig et al. 2009) viable options. *The quasi-static model of the green valley informs us that after it was initiated, the quenching does not always proceed to full quiescence, and therefore many of the present-day green valley galaxies may have been quenched, but only partially, early in the history of the universe.*

Finally, we touch upon E+A and related galaxies, which may represent the only true fast-transiting population. E+As (Dressler and Gunn 1983, Yang et al. 2008) are characterized by the lack of [OII] and Balmer emission lines, i.e. no current SF, but with deep Hδ features, signaling the presence of relatively young A stars. They must have experienced a strong burst of SF in which a significant fraction of mass has formed over a short period of time (< 0.1 Gyr; Kaviraj et al. 2007b), possibly induced by a major gas-rich merger. As a result, E+As retain their very blue optical colors ($0.2 < g-r < 0.5$), but due to the lack of *current* SF lie offset in NUV$-r$ colors towards the red, with many (but not all) of E+As lying in the green valley. They occupy a region to the right of the star-forming sequence in Fig. 4d (see also Kaviraj et al. 2007b). Chilingarian and Zolotukhin (2012) show tracks of *truncated* SF histories that pass through similar regions as those occupied by E+As. Optically blue ETGs of Kannappan et al. (2009) and McIntosh et al. (2013) may also represent a population with truncated SF histories, but without having experienced the burst prior to the cessation of SF. E+As and related galaxies therefore represent the true, fast-transiting green-valley population, but they are very rare compared to "normal" green valley galaxies and not representative of it as a whole. However, due to their fast transit times (Chilingarian and Zolotukhin 2011), they may be an important source of quiescent galaxies over cosmic times (Yesuf et al. 2014), possibly sufficient to explain the moderate low-mass passive sequence buildup, which the masses of E+As match well.

Green valley represents an exciting development made possible by wide-area UV surveys. The ability to identify and study galaxies with low, but non-zero specific SFRs has already led to important advances in our understanding of galaxy evolution.

REFERENCES

Agius, N. K. et al.: 2013, *Mon. Not. R. Astron. Soc.*, **431**, 1929.
Alatalo, K., Cales, S. L., Appleton, P. N., Kewley, L. J., Lacy, M., Lisenfeld, U., Nyland, K., Rich, J. A.: 2014, *Astrophys. J.*, **794**, L13.
Baldry, I. K., Glazebrook, K., Brinkmann, J., Ivezić, Ž., Lupton, R. H., Nichol, R. C., Szalay, A. S.: 2004, *Astrophys. J.*, **600**, 681.
Barnes, J. E., Hernquist, L.: 1996, *Astrophys. J.*, **471**, 115.
Bell, E. F. et al.: 2004, *Astrophys. J.*, **608**, 752.
Bell, E. F.: 2008, *Astrophys. J.*, **682**, 355.
Blanton, M. R., Moustakas, J.: 2009, *Annu. Rev. Astron. Astrophys.*, **47**, 159.

Boselli, A., Cortese, L., Boquien, M., Boissier, S., Catinella, B., Gavazzi, G., Lagos, C., Saintonge, A.: 2014, *Astron. Astrophys*, **564**, A67.

Bresolin, F.: 2013, *Astrophys. J.*, **772**, L23.

Buat, V. et al.: 2005, *Astrophys. J.*, **619**, L51.

Bundy, K. et al.: 2010, *Astrophys. J.*, **719**, 1969.

Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., Lauer, T. R.: 1988, *Astrophys. J.*, **328**, 440.

Calzetti, D., Kinney, A. L., Storchi-Bergmann, T.: 1994, *Astrophys. J.*, **429**, 582.

Cardamone, C. N., Urry, C. M., Schawinski, K., Treister, E., Brammer, G., Gawiser, E.: 2010, *Astrophys. J.*, **721**, L38.

Catinella, B. et al.: 2010, *Mon. Not. R. Astron. Soc.*, **403**, 683.

Catinella, B. et al.: 2012, *Astron. Astrophys*, **544**, A65.

Cattaneo, A., Dekel, A., Devriendt, J., Guiderdoni, B., Blaizot, J.: 2006, *Mon. Not. R. Astron. Soc.*, **370**, 1651.

Cheung, E. et al.: 2012, *Astrophys. J.*, **760**, 131.

Chilingarian, I. V., Zolotukhin, I. Y.: 2012, *Mon. Not. R. Astron. Soc.*, **419**, 1727.

Code, A. D., Welch, G. A.: 1979, *Astrophys. J.*, **228**, 95.

Cortese, L., Boselli, A., Franzetti, P., Decarli, R., Gavazzi, G., Boissier, S., Buat, V.: 2008, *Mon. Not. R. Astron. Soc.*, **386**, 1157.

Cortese, L.: 2012, *Astron. Astrophys*, **543**, A132.

Crocker, A. F., Bureau, M., Young, L. M., Combes, F.: 2011, *Mon. Not. R. Astron. Soc.*, **410**, 1197.

Crockett, R. M. et al.: 2011, *Astrophys. J.*, **727**, 115.

Crossett, J. P., Pimbblet K. A., Stott, J. P., Jones, D. H.: 2014, *Mon. Not. R. Astron. Soc.*, **437**, 2521.

Croton, D. J. et al.: 2006, *Mon. Not. R. Astron. Soc.*, **365**, 11.

Dekel, A., Birnboim, Y.: 2006, *Mon. Not. R. Astron. Soc.*, **368**, 2.

Donas, J. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 597.

Dressler, A., Gunn, J. E.: 1983, *Astrophys. J.*, **270**, 7.

Eggen, O. J., Lynden-Bell, D., Sandage, A. R.: 1962, *Astrophys. J.*, **136**, 748.

Fabello, S., Catinella, B., Giovanelli, R., Kauffmann, G., Haynes, M. P., Heckman, T. M., Schiminovich, D.: 2011, *Mon. Not. R. Astron. Soc.*, **411**, 993.

Faber, S. M. et al.: 2007, *Astrophys. J.*, **665**, 265.

Faber, S. M., Gallagher, J. S.: 1976, *Astrophys. J.*, **204**, 365.

Fang, J. J., Faber, S. M., Koo, D. C., Dekel, A.: 2013, *Astrophys. J.*, **776**, 63.

Fang, J. J., Faber, S. M., Salim, S., Graves, G. J., Rich, R. M.: 2012, *Astrophys. J.*, **761**, 23.

Finkelman, I., Moiseev, A., Brosch, N., Katkov, I.: 2011, *Mon. Not. R. Astron. Soc.*, **418**, 1834.

Fisher, D. B., Drory, N.: 2008, *Astron. J.*, **136**, 773.

Gil, de, Paz, A. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 185.

Gonçalves, T. S., Martin, D. C., Menéndez-Delmestre, K., Wyder, T. K., Koekemoer, A.: 2012, *Astrophys. J.*, **759**, 67.

Haines, C. P., Busarello, G., Merluzzi, P., Smith, R. J., Raychaudhury, S., Mercurio, A., Smith, G. P.: 2011, *Mon. Not. R. Astron. Soc.*, **412**, 145.

Haines, C. P. et al.: 2011, *Mon. Not. R. Astron. Soc.*, **417**, 2831.

Heckman, T. M., Best, P. N.: 2014, *Annu. Rev. Astron. Astrophys.*, **52**, 589.

Heinis, S. et al.: 2009, *Astrophys. J.*, **698**, 1838.

Hinz, J. L. et al.: 2012, *Astrophys. J.*, **756**, 75.

Hubble, E. P.: 1926, *Astrophys. J.*, **64**, 321.

Hughes, T. M., Cortese, L.: 2009, *Mon. Not. R. Astron. Soc.*, **396**, L41.

Ilyina, M. A., Sil'chenko, O. K., Afanasiev, V. L.: 2014, *Mon. Not. R. Astron. Soc.*, **439**, 334.

Juneau, S., Dickinson, M., Alexander, D. M., Salim, S.: 2011, *Astrophys. J.*, **736**, 104.

Juneau, S. et al.: 2014, *Astrophys. J.*, **788**, 88.

Kannappan, S. J., Guie, J. M., Baker, A. J.: 2009, *Astron. J.*, **138**, 579.

Kauffmann, G. et al.: 2003, *Mon. Not. R. Astron. Soc.*, **341**, 33.

Kauffmann, G. et al.: 2003, *Mon. Not. R. Astron. Soc.*, **341**, 54.

Kauffmann, G. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 357.

Kauffmann, G., Heckman, T. M., De, Lucia, G., Brinchmann, J., Charlot, S., Tremonti, C., White, S. D. M., Brinkmann, J.: 2006, *Mon. Not. R. Astron. Soc.*, **367**, 1394.

Kaviraj, S. et al.: 2007a, *Astrophys. J. Suppl. Series*, **173**, 619.

Kaviraj, S., Kirkby, L. A., Silk, J., Sarzi, M.: 2007b, *Mon. Not. R. Astron. Soc.*, **382**, 960.

Kaviraj, S., Peirani, S., Khochfar, S., Silk, J., Kay, S.: 2009, *Mon. Not. R. Astron. Soc.*, **394**, 1713.

Kaviraj, S., Rey, S.-C., Rich, R. M., Yoon, S.-J., Yi, S. K.: 2007c, *Mon. Not. R. Astron. Soc.*, **381**, L74.

Kennicutt, R. C., Jr.: 1998, *Annu. Rev. Astron. Astrophys.*, **36**, 189.

Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., Trevena, J.: 2001, *Astrophys. J.*, **556**, 121.

Kewley, L. J., Groves, B., Kauffmann, G., Heckman, T.: 2006, *Mon. Not. R. Astron. Soc.*, **372**, 961.

Kormendy, J., Bender, R.: 2012, *Astrophys. J. Suppl. Series*, **198**, 2.

Kormendy, J., Ho, L. C.: 2013, *Annu. Rev. Astron. Astrophys.*, **51**, 511.

Lackner, C. N., Gunn, J. E.: 2012, *Mon. Not. R. Astron. Soc.*, **421**, 2277.

Leitner, S. N., Kravtsov, A. V.: 2011, *Astrophys. J.*, **734**, 48.

Lemonias, J. J. et al.: 2011, *Astrophys. J.*, **733**, 74.

Loh, Y.-S. et al.: 2010, *Mon. Not. R. Astron. Soc.*, **407**, 55.

Lotz, J. M. et al.: 2008, *Astrophys. J.*, **672**, 177.

Martig, M., Bournaud, F., Teyssier, R., Dekel, A.: 2009, *Astrophys. J.*, **707**, 250.

Martin, D. C. et al.: 2005, *Astrophys. J.*, **619**, L1.

Martin, D. C. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 342.

Masters, K. L. et al.: 2010, *Mon. Not. R. Astron. Soc.*, **405**, 783.

McIntosh, D. H. et al.: 2014, *Mon. Not. R. Astron. Soc.*, **442**, 533.

Mendez, A. J., Coil, A. L., Lotz, J., Salim, S., Moustakas, J., Simard, L.: 2011, *Astrophys. J.*, **736**, 110.

Mendez, A. J. et al.: 2013, *Astrophys. J.*, **770**, 40.

Meurer, G. R., Heckman, T. M., Calzetti, D.: 1999, *Astrophys. J.*, **521**, 64.

Moustakas, J. et al.: 2013, *Astrophys. J.*, **767**, 50.

Mutch, S. J., Croton, D. J., Poole, G. B.: 2011, *Astrophys. J.*, **736**, 84.

Nandra, K. et al.: 2007, *Astrophys. J.*, **660**, L11.

Noeske, K. G. et al.: 2007, *Astrophys. J.*, **660**, L43.

Peirani, S., Crockett, R. M., Geen, S., Khochfar, S., Kaviraj, S., Silk, J.: 2010, *Mon. Not. R. Astron. Soc.*, **405**, 2327.

Rosario, D. J. et al.: 2013, *Astrophys. J.*, **771**, 63.

Saintonge, A. et al.: 2011, *Mon. Not. R. Astron. Soc.*, **415**, 32.

Salim, S. et al.: 2005, *Astrophys. J.*, **619**, L39.

Salim, S. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 267.

Salim, S. et al.: 2009, *Astrophys. J.*, **700**, 161.

Salim, S., Fang, J. J., Rich, R. M., Faber, S. M., Thilker, D. A.: 2012, *Astrophys. J.*, **755**, 105.

Salim, S., Rich, R. M.: 2010, *Astrophys. J.*, **714**, L290.

Schawinski, K. et al.: 2007a, *Astrophys. J. Suppl. Series*, **173**, 512.

Schawinski, K. et al.: 2007b, *Mon. Not. R. Astron. Soc.*, **381**, L74.

Schawinski, K., Virani, S., Simmons, B., Urry, C. M., Treister, E., Kaviraj, S., Kushkuley, B.: 2009, *Astrophys. J.*, **692**, L19.

Schawinski, K. et al: 2010, *Astrophys. J.*, **711**, 284.

Schiminovich, D. et al..: 2010, *Mon. Not. R. Astron. Soc.*, **408**, 919.

Schiminovich, D. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 315.

Schwarz, M. P.: 1984, *Mon. Not. R. Astron. Soc.*, **209**, 93.

Seibert, M. et al.: 2005, *Astrophys. J.*, **619**, L55.

Silverman, J. D. et al.: 2008, *Astrophys. J.*, **675**, 1025.

Smolčić, V.: 2009, *Astrophys. J.*, **699**, L43.

Speagle, J. S., Steinhardt, C. L., Capak, P. L., Silverman, J. D.: 2014, *Astrophys. J. Suppl. Series*, **214**, 15.

Stasińska, G., Vale, Asari, N., Cid, Fernandes, R., Gomes, J. M., Schlickmann, M., Mateus, A., Schoenell, W., Sodré, L., Jr., Seagal, Collaboration: 2008, *Mon. Not. R. Astron. Soc.*, **391**, L29.

Strateva, I. et al..: 2001, *Astron. J.*, **122**, 1861.

Strauss, M. A. et al.: 2002, *Astron. J.*, **124**, 1810.

Taylor, E. N. et al.: 2011, *Mon. Not. R. Astron. Soc.*, **418**, 1587.

Thilker, D. A. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 538.

Thilker, D. A. et al.: 2010, *Astrophys. J.*, **714**, L171.

Trager, S. C., Faber, S. M., Worthey, G., González, J. J.: 2000, *Astron. J.*, **120**, 165.

Treister, E. et al.: 2009, *Astrophys. J.*, **693**, 1713.

Trump, J. R., Hsu, A. D., Fang, J. J., Faber, S. M., Koo, D. C., Kocevski, D. D.: 2013, *Astrophys. J.*, **763**, 133.

Vader, J. P., Vigroux, L.: 1991, *Astron. Astrophys*, **246**, 32.

van, de, Voort, F., Schaye, J., Booth, C. M., Haas, M. R., Dalla, Vecchia, C.: 2011, *Mon. Not. R. Astron. Soc.*, **414**, 2458.

Vasudevan, R. V., Mushotzky, R. F., Winter, L. M., Fabian, A. C.: 2009, *Mon. Not. R. Astron. Soc.*, **399**, 1553.

Vergani, D. et al.: 2010, *Astron. Astrophys*, **509**, A42.

Walker, L. M. et al.: 2013, *Astrophys. J.*, **775**, 129.

Williams, R. J., Quadri, R. F., Franx, M., van, Dokkum, P., Labbé, I.: 2009, *Astrophys. J.*, **691**, 1879.

Wilson, C. D., Scoville, N.: 1991, *Astrophys. J.*, **370**, 184.

Woo, J. et al: 2013, *Mon. Not. R. Astron. Soc.*, **428**, 3306.

Wyder, T. K. et al.: 2007, *Astrophys. J. Suppl. Series*, **173**, 293.

Yan, R. et al.: 2011, *Astrophys. J.*, **728**, 38.

Yang, Y., Zabludoff, A. I., Zaritsky, D., Mihos, J. C.: 2008, *Astrophys. J.*, **688**, 945.

Yesuf, H. M., Faber, S. M., Trump, J. R., Koo, D. C., Fang, J. J., Liu, F. S., Wild, V., Hayward, C. C.: 2014, *Astrophys. J.*, **792**, 84.

Yi, S. K. et al.: 2005, *Astrophys. J.*, **619**, L111.

York, D. G. et al.: 2000, *Astron. J.*, **120**, 1579.

Young, L. M. et al.: 2011, *Mon. Not. R. Astron. Soc.*, **414**, 940.

ГАЛАКСИЈЕ У ЗЕЛЕНОЈ ДОЛИНИ

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"Зелена долина" је назив за широку област која раздваја плави и црвени максимум галаксија на ултраљубичасто-оптичком дијаграму магнитуда-боја, и први пут је откривена помоћу сателита за UV област *GALEX*. Зелена долина указује на моћ ултраљубичастог дела спектра за разлучивање галаксија са веома ниским релативним нивоом формирања звезда, на које оптичке боје нису осетљиве. Зелена долина је важан инструмент за изучавање процеса гашења формирања звезда и његовог потенцијалног поновног јављања у пасивним галаксијама. У овом чланку је дат преглед резултата везаних за морфологију, структуру, околину, прашину и гас у овим галаксијама у локалном свемиру. Разматра се и однос према активним галактичким језгрима. Дат је преглед разних еволуционих могућности и предлаже се нов, квази-статички модел по којем је већина галаксија које су сада у зеленој долини имала делимичну супресију формирања звезда у далекој прошлости и сада се налази у фази спорог опадања стопе формирања звезда, која доводи и до опадања активности код галаксија главног низа, вероватно услед смањене акреције на диск галаксије.