Chapter I

Introduction and Summary

1 Statement of the Problem

Galaxy formation and evolution is the mother of all astronomical problems. It takes as its starting point the description of the basic contents of the universe from cosmology, and seeks ultimately to explain the formation of stars and planets within galaxies, including the creation of the basic elements necessary for life. In this way, it links the two big questions — how did the universe begin; and what are the origins of life?

In its scale and complexity, galaxy formation and evolution is a diabolical problem. A complete, from–first–principles description involves physical processes that occur on scales ranging from many megaparsecs down to hundreds of kilometers, and indeed down to the scales of molecules, nuclei, and electrons. There is broad consensus on a general, qualitative picture of how galaxies form, and what physical processes are likely to be the most important in governing their evolution. Driven by gravitational pressure, minute fluctuations in the post-inflation, dark–plus–baryonic density field grow into a froth of filamentary structures and voids. As overdensities become gravitationally unstable, they collapse and condense to form individual, virialized halos — the cradles for future galaxies. In the course of collapse, thermal pressure separates the baryonic gas from the dark matter. Gas accretion onto and into the dark halo is then regulated by the cooling efficiency of the gas. As the gas density increases, so too does the cooling rate. At a certain point, too cold and dense for thermal pressure to withstand its self-gravity, the gas now begins to fragment and collapse. Once the gas density in the centers of smallest fragments becomes high enough to ignite fusion, a star is born. Somewhere along the way, a supermassive black hole develops in the center of each halo. Both the stars and the black hole then drive kinetic and/or energetic 'feedback' processes, which can incite, disrupt, or prevent further gas accretion and star formation. If the feedback is strong enough, galaxies can also affect their surrounding environment, and thus other galaxies. Further, as cosmic structure formation continues around them, galaxies can also grow through successive mergers. Tidal interactions between galaxies can also be important in triggering star formation, or in stripping gas out of galaxies. But virtually none of these processes are well understood individually, much less how they relate to one another.

The most successful approach to the problem has been through the use of 'semi-analytic' models (see Baugh, 2006, for an introductory overview; it should also be noted that with continued advances in computational power, cosmological hydrodynamical simulations are becoming practicable; see, e.g., Naab et al., 2006, Schaye et al., 2009). The basic idea behind semi-analytic modeling is to take the results of large-volume N-body simulations of structure formation within the framework of ΛCDM cosmology (see the review of Springel, Frenk & White, 2006), and then combine them with empirical, analytic 'laws' that describe the halo- and galaxy-scale physical processes that influence the baryons. In this way, semi-analytic models generate 'predictions' for the global properties of individual galaxies. Where the results differ from the observed universe, the assumptions underpinning the model are then refined to reduce the discrepancy. Given the large uncertainties and many approximations in these models, theorists have no shortage of knobs and levers with which to fine-tune their results.

Pedagogically, the virtue of this approach is that, by identifying precisely how changing the model assumptions affects the outcome, it provides a means of probing the relative importance of different physical processes at different scales or stages of evolution. But these models are not, strictly speaking, predictive. Instead, they focus on *post hoc* modifications to the assumptions underpinning the models in order to obtain consistency. Rather than a complete physical explanation of the process of galaxy evolution, the models thus aim for a consistent description of the evolving properties of the galaxy population (see, e.g., Croton et al., 2006; Bower, McCarthy & Benson, 2008; Somerville et al., 2008). The 'best' models are those that simultaneously reproduce the largest number of qualitatively different aspects of the observed galaxy population with the smallest amount of tuning.

The field of galaxy formation and evolution is thus largely observation driven, and likely to remain so for quite a while. In this context, the goal of this thesis is to provide new observational constraints on the evolution of galaxies with which to challenge these kinds of models. In particular, *this thesis is focused on the evolution of massive galaxies — in terms of their number, star formation activity, and structure — over 10 Gyr of cosmic history.*

2 Technical Background — The basic requirements of a modern lookback survey

Lookback Surveys and Observational Cosmology

Because the speed of light is finite, it takes time for light to travel from one place to another. Thus, when you look over great distances, you see parts of the universe that are actually younger than here and now. Observing galaxies over a range of distances thus provides a kind of time-ordered series of momentary glimpses into the lives of individual galaxies at different points in the history of the universe. *Through comparisons between the statistical properties of the galaxy population across a range of distances, 'lookback' surveys provide a means of directly observing the evolution of galaxies over cosmic time.*

As in most of astronomy, the technical crux of any lookback survey is determining the distances to individual sources. In our expanding universe, the cosmic expansion history is imprinted on every photon: as photons stream through space they are caught up in the expansion and redshifted. The farther and longer they travel, the greater the effect. As a distance indicator, redshifts by themselves provide only a relative distance measurement; the precise relation between redshift and distance (or, equally, lookback time) depends on the cosmic expansion history.

The major advances in observational cosmology made between 1998 and 2003 thus revolutionized the field of lookback survey science. This revolution began in the late 1990s with the first solid evidence for dark energy, which came from supernova 'standard candle' measurements (e.g., Riess et al., 1998; Perlmutter et al., 1999), and culminated with the announcement of the first results from a small microwave satellite called the Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al., 2003). In combination with these kinds of supernovae results, the Hubble key project measurement of the Hubble constant (Freedman et al., 2001), and clustering measurements based on nearby galaxies (e.g., Verde et al., 2002) and the Lyman-α forest (e.g., Croft et al., 2002), the WMAP data allowed the determination of the basic cosmological parameters to within $\lesssim 5$ % (Spergel et al. 2003; Verde et al. 2003; see also Spergel et al. 2005; Dunkley et al. 2009; Komatsu et al. 2009). Taken together, these results established the 'concordance cosmology' as a standard model.

Prior to this, the interpretation of lookback surveys was hampered by a degeneracy between evolutionary and cosmological effects; the emergence of the concordance cosmology broke this degeneracy. 'Precision' cosmology is thus a key enabling factor for quantitative studies of the evolution galaxies in terms of their global physical properties. It provides the crucial information needed to translate from observed quantities to intrinsic ones: from fluxes to absolute luminosities, from apparent to physical sizes, and from number counts to comoving densities.

Spectroscopic Galaxy Redshift Surveys at High and Low Redshift

At least for large distances, the most robust and reliable distance indicator is a spectroscopic measure of redshift. While the advent of relatively sensitive CCD detectors made it possible, for the first time, to obtain spectra for relatively faint, distant galaxies, it was only with the multiplexing power of multiobject spectrographs that spectroscopic lookback surveys became practicable. By the early 1990s, based on samples of tens to hundreds of galaxies, the first strong evidence had begun to emerge for significant differences between 'high redshift' galaxies ($z \lesssim 0.5$, with a mean redshift of 0.1) and those in the local universe — that is, the first signs of evolution (see Koo & Kron, 1992, for a review of these results). In the mid 1990s, the sensitivity of newly commissioned 10 m-class telescopes pushed the frontiers of high redshift science. In 1996, for example, Cowie et al. used the LRIS spectrograph on Keck to assemble a sample of nearly 400 galaxies in the range $0.2 \lesssim z \lesssim 1.7$. Over the following five years, the DEEP survey (Vogt et al., 2005; Weiner et al., 2005) obtained 658 redshifts for galaxies with a median redshift of 0.65. 2002 marked a second generational change and a watershed for spectroscopic lookback surveys. In this year, two major surveys began, both using a new generation of multiobject spectrographs mounted on 10 m-class telescopes. Using DEIMOS on Keck, the aim of DEEP-2 was to collect more than 50000 $z \gtrsim 0.7$ galaxies (Davis et al., 2003; Faber et al., in preparation). They collected 8000 spectra in their first year of operation. The goal of the VIMOS VLT Deep Survey (VVDS; Le Fèvre et al., 2005) was to collect on the order of 135000 redshifts; they obtained 10000 in their first year.

Since evolution can only be inferred from statistical differences between the high– and low–redshift galaxy populations, *local galaxy surveys provide the crucial 'control' sample with which to compare higher redshift results.* Just as multiobject spectrographs led to an explosion in our knowledge of the high-redshift universe, our knowledge and understanding of the local universe has been revolutionized by a succession of ambitious spectroscopic surveys. The Las Campanas Redshift Survey (LCRS; Shectman et al., 1996) collected more than 26000 redshifts between 1988 and 1994. Between 1995 and 2002, the Two Degree Field Galaxy Redshift Survey (2dF GRS; Colless et al., 2001, 2003) collected approximately 220000 galaxy redshifts. Using a dedicated telescope, the Sloan Digital Sky Survey (SDSS; York et al., 2000; Strauss et al., 2002) began in 2000, aiming to collect 1000000 redshifts over five years. The survey has since been extended, and is ongoing.

As an aside, it is worth reflecting on the pace of these developments. In their 1991 review of 'Redshift Surveys of Galaxies', Giovanelli & Haynes remark that '[b]y any standards of human activity, the redshift industry is among the most successful, as it can boast a sustained growth rate in excess of 10 % per year over its whole 80-year history, and has the potential to maintain its growth for the foreseeable future.' It 1980, the combined total of spectroscopic redshifts, including multiple determinations for individual objects, was on the order of 8000 (Palumbo, Tanzella-Nitti, & Vettolani, 1983). Had we sustained 10 % year-on-year growth, we would expect to now have something like 145000 redshifts. This number is comparable to the average *annual* output of SDSS.[1] The impact of multiobject spectrographs on observational cosmology cannot be understated.

Photometric Redshifts

The generic problem with spectroscopic surveys remains that, in comparison to photometric imaging, they are observationally expensive. Moreover, with current technologies, spectroscopy is limited to objects brighter than $I \sim 24$ and $K \sim 20$ (see, e.g., Fernández-Soto et al., 2001; Cimatti et al., 2002; Kriek et al., 2006, 2008a). This limitation became especially important with the launch of the *Hubble Space Telescope* (*HST*), and in particular following the Hubble Deep Field (HDF) project (Williams et al., 1996). Given that spectroscopy was impossible, how best to those galaxies at the edge of the observable universe?

[1] Between them, the SDSS and the AAO are responsible for approximately 85 % of all redshifts ever collected (Driver et al., 2009).

As an alternative to spectroscopy, it is possible to derive an approximate redshift the photometric spectral energy distribution (SED). Rather than emission or absorption lines, these photometric redshift techniques rely on broad spectral shape and gross features like the Balmer/4000 Å or Lyman breaks to constrain a galaxy's redshift (see, e.g., Connolly et al., 1995; Steidel, Pettini & Hamilton, 1995). The idea of photometric redshifts was presented by Baum (1962), who used the technique to measure distances to several clusters in the range $0.1 \lesssim z \lesssim 0.5$.[2] Baum's measurements were based on photometry in nine broad bands, including two near infrared filters, coadded for 2–4 galaxies per cluster. In this way, he found a redshift of 0.44 ± 0.03 for the cluster 3C295; the modern value is 0.46. By 1985, using stellar population synthesis models to fit optical SEDs, Koo had achieved a photometric redshift accuracy of $\Delta z \sim 0.04$ for $z \lesssim 0.5$ and $\Delta z \sim 0.06$ for $z \sim 0.6$, thereby extending the idea of photometric redshifts to the general galaxy population (see also, e.g., Loh & Spillar, 1986). In this way, photometric redshifts — or "phot-zs" — provide a kind of "poor person's redshift machine" (Koo, 1985).

At least in principle, photometric redshifts also offer a means of probing those very faint galaxies for which spectroscopy is impractical. It is important to note, however, spectroscopic redshifts are still needed for a representative subsample to test the validity of the photometric determinations (see, e.g., Connolly et al., 1995; Brammer et al., 2008, but see also Quadri & Williams, 2009, who present an empirical test of photometric redshift accuracy using galaxy pairs.). This fact explains why photometric redshifts were not widely used until *after* large spectroscopic surveys were completed. Further, even with a good "spec-z" comparison sample, no guarantees can be made on the reliability of any individual galaxy's phot-z. Photometric redshift surveys can thus extend and complement spectroscopic surveys, but they do not eliminate the need for spec-zs for a large and representative sample (see, e.g., Fernández-Soto et al., 2001).

The use of photometric redshifts makes it possible to analyze vastly larger samples of galaxies, albeit with significant uncertainties. Phot-zs thus became the default means of analyzing the HDF data in particular (see, e.g., Subbaroo et al., 1996; Gwyn & Hartwick, 1996; Sawicki, Lin & Yee, 1997; Connolly et al., 1997), and high-redshift galaxies in general. The successes in the HDF (see, e.g., Hogg et al., 1999; Fernández-Soto et al., 2001) spurred a number of efforts to develop and apply new photometric redshift estimation techniques (e.g., Csabai et al., 2000; Bolzonella, Miralles & Pello, 2000; Benítez, 2000; Firth, Lahov & Somerville, 2003; Vanzella et al., 2004). But there is one project that deserves special mention here: by combining optical photometry in 5 broad- and 12 medium-band (roughly equivalent to $R \sim 10$ spectroscopy), the COMBO-17 survey achieved a photometric redshift accuracy of $\Delta z/(1+z) \sim 0.02$ for 25000 galaxies $z \lesssim 1$ galaxies (Wolf et al., 2003, 2004). In terms of the successful application of photometric redshift techniques, this survey probably contributed more than any other to the acceptance and adoption of photometric redshift techniques as a legitimate means of analyzing large, representative samples of high-redshift galaxies.

[2]See also Stebbins & Whitford 1948, who, pursuing an observing program devised by Hubble and Baade, derived "a relation between color index and red shift for extragalactic nebulae".

Stellar Mass Estimation

Photometric redshift techniques require a set of template spectra with which to fit the observed SEDs of individual galaxies. By using empirical templates (*i.e.*, spectra of galaxies of known spectral type), the best fit template can then be used to provide an approximate spectral classification. The alternative is to use synthetic spectra based on stellar population models (e.g., Le Borgne & Rocca-Volmerange, 2002; Bruzual & Charlot, 2003; Maraston, 2005). The advantage to this approach is that each template can be associated with a stellar mass-to-light ratio.

Using a large library of synthetic stellar population spectral templates that span a wide enough range of possible star formation histories, it is thus possible to derive stellar mass estimates from galaxy SEDs — and, equally, star formation rates, mean stellar ages and the other essential stellar population parameters of interest for quantifying the evolution of the galaxy population (Tinsley & Gunn, 1976; Tinsley, 1978). While these techniques are conceptually related to photometric redshifts, they are obviously not specific to photometric surveys. As an important example, Kauffmann et al. (2003a,b) used spectral diagnostics to derive stellar mass estimates for SDSS galaxies (see also, e.g. Heavens, Jiminez & Lahov, 2000; Panter, Heavens & Jiminez, 2003).

The accuracy of these techniques is limited by (at least) three important factors. Firstly, they depend on accurate stellar population models, including a broad enough range of (parametric) star formation histories to describe the full diversity of real galaxies (see, e.g., Charlot, Worthey & Bressan, 1996; Maraston et al., 2006; Kannappan & Gawiser, 2007; Conroy, Gunn & White, 2009). Secondly, and related to this point, there is the issue of the stellar initial mass function (IMF). The shape of the IMF — and how or whether it varies with, e.g., star formation rates, environment, and redshift — is still a major unknown (see, e.g., Salpeter, 1955; Kroupa, 2002; Hopkins & Beacom, 2006; van Dokkum, 2008; Cerviño & Valls-Gabaud, 2008). Finally, the accuracy of stellar mass estimates is fundamentally limited by generic degeneracies between the observable properties of different stellar populations with different mass-to-light ratios (see, e.g. Rix & Rieke, 1993; Brinchmann & Ellis, 2000; Bell & de Jong, 2001; Gallazzi & Bell, 2009).

The Critical Importance of Near Infrared (NIR) data

Most of the broad spectral features on which modern SED-fitting algorithms rely fall in the restframe optical (Connolly et al., 1995). For $z \gtrsim 1$, these features are redshifted beyond the observers' optical window and into the near infrared (NIR). For this reason, NIR imaging is a critical requirement for studies of the $z \gtrsim 1$ galaxy population: *deep NIR observations are the key to opening the door to the $z \gtrsim 1$ universe* (see, e.g., Hogg et al., 1997; Rudnick et al., 2001; Labbé et al., 2003; Förster-Schreiber et al., 2006).

There is a second reason why having NIR data is crucial. A galaxy's restframe ultraviolet emission is dominated by hot, bright, young stars. This means that optically selected galaxy samples at $z \gg 1$ become progressively more biased towards star forming galaxies. By selecting in the observed NIR, galaxies are selected on their restframe optical emission, which is dominated by the longer lived, main sequence stars that typically constitute the bulk of a galaxy's mass. That is, NIR-selected samples of $z \gtrsim 1$ galaxies offer a practical means of constructing mass-limited samples of distant galaxies, and so to get a representative census of the massive galaxy population. (this point is discussed further below; see also, e.g., Adelberger & Steidel, 2000; Cimatti et al., 2002; Labbé et al., 2003; van Dokkum et al., 2006).

The Essential Ingredients

Hence it was my good fortune that by the time I began work on this thesis in 2004, a series of technological, technical, and conceptual innovations had led to a true Kuhn-ian revolution in the science of galaxy formation and evolution (Kuhn, 1962). These included: the explosion of high– and low–redshift spectroscopic redshift surveys afforded by massively-multiplexing multiobject spectrographs; the increased sensitivity and resolution of 10 m class telescopes and space based observatories; the maturation and acceptance of techniques for estimating both photometric redshifts and stellar mass-to-light ratios; the advent of wide-field NIR imagers; and the establishment of the concordance cosmology as a standard model for cosmology. Together, these developments provided all the necessary requirements for detailed, quantitative studies of the general galaxy population in terms of their luminosities, stellar masses, star formation, sizes, structures, and morphologies.

Further, using these kinds of surveys, both the cosmic star formation history (Lilly et al., 1996; Madau et al., 1996; Hopkins, 2004, and references therein; Bowens et al. 2007, Bouwens et al. 2009) and the buildup of stellar mass (e.g., Fontana et al., 2004, Drory et al., 2005, Fontana et al., 2006, Arnouts et al., 2007, Pozzetti et al., 2007, Pérez-González et al., 2008, Marchesini et al., 2009; see also Trentham, Wilkins & Hopkins 2008) have now been constrained out to $z \sim 5$; that is, over approximately 90 % of cosmic history.

3 Galaxy Formation and Evolution – What we have learned

Round Ones and Flat Ones; Red Ones and Blue Ones; Old Ones and Young Ones — A dichotomy among z ∼ 0 galaxies

Even before galaxies came to be known as 'galaxies', it was recognized that 'extragalactic nebulae' fell into two broad classes (Hubble, 1926). This classification was originally made on the basis of structure: the distinction was between 'late type' galaxies, which showed conspicuous spiral arm structures and/or a bright nuclear region, and smooth, featureless elliptical 'early type' galaxies. (At lower masses, irregular and peculiar galaxies are an important third class; in what follows, I will ignore these galaxies.) The two classes of galaxies have since been shown to have rather different properties. First, in general, elliptical galaxies have redder colors than spirals (Strateva et al., 2001; Blanton et al., 2003; Driver et al., 2006). This reflects the fact that early type galaxies tend to be dominated by relatively old stellar populations, whereas late type galaxies tend to be actively forming new stars (Kauffmann et al., 2003b; Brinchmann et al., 2004; Wyder et al., 2007). Early type galaxies tend to lie preferentially in higher density environments (Blanton et al., 2005; Baldry et al., 2006; van der Wel et al., 2008). Further, the most massive and/or luminous galaxies tend to be early type (Strateva et al., 2001; Kauffmann et al., 2003b).

The emergent picture, then, is of a population of 'developed' massive, quiescent, centrally-concentrated, and old elliptical or spheroidal galaxies that are found in more dense environments, as distinct from the less massive, star forming, 'developing' disk-dominated population that dominates in the field and in small groups (see, e.g., Ellis et al., 2005; Conselice, 2006). That is, the two different classes of galaxies appear to correspond to distinct evolutionary states. *Elucidating the nature of and physical basis for the difference between developed and developing galaxies is a major challenge for cosmological models of galaxy formation and evolution.*

The Central Importance of Stellar Mass

Within each of these populations, however, galaxies are remarkably well behaved. Although the basic, global properties of individual galaxies — for example, luminosity, mass, size, local density, star formation rate, mean stellar age, metallicity, and gas content — vary by orders of magnitudes, there exist very tight and well-defined correlations between essentially all of these properties for each of these two classes (see, e.g., Minkowski, 1962; Faber & Jackson, 1976; Tully & Fisher, 1977; Sandage & Visvanathan, 1978; Dressler, 1980; Djorgovsky & Davis, 1987; Dressler et al., 1987; Magorrian, 1998). Presumably, key information about the physical processes governing galaxies' formation and evolutionary histories are encoded in the slope of, and scatter around, these relations.

One of the most important insights gleaned from the SDSS has been to confirm the idea that most, if not all, of these relations can be understood as being primarily a sequence in mass (e.g. Kauffmann et al., 2003b; Shen et al., 2003; Blanton et al., 2005; Baldry et al., 2006; Gallazzi et al., 2006). Given a galaxy's stellar mass, it is thus possible to predict a wide variety of global properties with a remarkable degree of accuracy. Moreover, Kauffmann et al. (2003b) have shown that the distinction between developing and developed galaxies coincides with an apparent 'transition mass' of $\sim 3 \times 10^{10}$ $M_\odot$; above this limit, most galaxies are quiescent, early type galaxies (see also, e.g., Blanton et al., 2005). In this sense, stellar mass appears to be a fundamental parameter in determining — or at least describing — a galaxy's current state of evolution. (Although see, e.g., Kauffmann et al., 2006; Franx et al., 2008; Graves, Faber & Schiavon, 2009, who argue that stellar surface density or velocity dispersion may be a more fundamental parameter in describing this transition.)

By observing changes in the scaling relations between stellar mass and other global galaxy properties, we can therefore hope to learn something about the processes that shape the lives of galaxies. In particular, we would like to determine when and why these relations first come about, as well as when and how galaxies make the transition from developing to developed.

Star Formation Quenching and the Transition From Blue to Red

In a landmark study based on the COMBO-17 photometric redshift survey, Bell et al. (2004b) showed that the distinct color–magnitude relations for red and blue galaxies[3] are already in place at $z \sim 1$ (see also, e.g. Im et al., 2002; Tanaka et al., 2005; Weiner et al., 2005; Willmer et al., 2006; De Lucia et al., 2007). As in the local universe, the 'red sequence' is dominated by largely quiescent, structurally early type galaxies (Bell et al., 2004a; Holden et al., 2008). The morphology–density relation seen locally is also in place by this time (van der Wel et al., 2007), as is the 'fundamental plane' relation (a relation between dynamical mass and surface brightness) for early type galaxies (Treu et al., 2002; van der Wel et al., 2004; di Serego Alighieri et al., 2005). Further, both the color–magnitude relation for red galaxies and the fundamental plane for early type galaxies evolve in a manner that is consistent with passive fading of an old ($z \gtrsim 2$) stellar population (see, e.g., Bell et al., 2004b; van der Wel et al., 2004; Cimatti, Daddi & Renzini, 2006).

That is, the galaxy population at $z \sim 1$ appears to be qualitatively similar to that of the present day. But this is not to say that nothing has changed. The total mass density of red sequence galaxies has roughly doubled between $z \sim 1$ and the present (Borch et al., 2006; Faber et al., 2007; Brown et al., 2008). At the same time, that total mass density of blue galaxies, which are actively star forming, remains more or less constant (Borch et al., 2006; Arnouts et al., 2007; Bell et al., 2007). We are thus faced with a rather curious situation: the number of passive galaxies grows continually over time, while the combined stellar mass of actively star forming galaxies remains unchanged.

These results have been accommodated within the ΛCDM paradigm through the postulation of a 'quenching' mechanism, which acts to disrupt star formation in massive galaxies, thereby inciting a transition from blue to red. While the physical basis for this *ad hoc* inclusion to cosmological models of galaxy evolution is not understood, a number of candidates have been proposed, including the prevention of gas accretion onto high mass halos by shock heating (e.g., Dekel & Birnboim, 2006; Cattaneo et al, 2006, 2008; van den Bosch et al., 2008) and energetic or kinetic feedback from active galactic nuclei (e.g. Croton et al., 2006; Bower et al., 2006; Menci et al, 2006; Somerville et al., 2008; Bower, McCarthy & Benson, 2008), possibly triggered by a merger event. This quenching mechanism is also required to get the right number of massive galaxies at high redshift (see, e.g., Cattaneo et al, 2006; Menci et al, 2006)

Quantifying the evolution in the red/blue fraction among massive galaxies thus provides basic observational constraints on the mechanism whereby star formation is quenched. In so doing, it offers a potential means of constraining the relative

[3]Here and in what follows, 'red' is often used as a proxy for 'quiescent' and/or 'early-type'. There is considerable — but not total — overlap between galaxy samples selected by morphology (*i.e.*, early-/late-type), photometry (*i.e.*, red/blue), and spectroscopy (*i.e.*, quiescent/star forming). In this sense, it reasonable, but not strictly accurate, to use the terms red, quiescent, and early type (or blue, star forming, and late type) as if they were interchangeable. However, it is still unclear which which of these distinctions is/are the most 'fundamental' (see, e.g. Blanton et al., 2005).

importance of AGN feedback, mergers, and gas accretion in regulating the star formation process in particular, and in galaxy evolution in general.

The Situation at High Redshift

Without the luxury of spectroscopic redshifts for representative samples of high redshift galaxies, the pioneering studies of the high redshift universe relied on samples selected on the basis of observed colors.[4] In particular, the Lyman-break selection criterion proposed by Steidel et al. (1993, 1996, 1999, 2003) was shown to be an efficient means of selecting galaxies at $z \gtrsim 3$. This selection works by isolating the sharp spectral break caused by absorption of UV photons between Lyman-α (1216 Å) and the Lyman limit (912 Å) by hydrogen atoms in the IGM. Their small sizes (Steidel, Pettini & Hamilton, 1995; Giavalisco, Steidel & Macchetto, 1996), relatively strong clustering (Adelberger et al., 1998; Giavalisco et al., 1998; Giavalisco & Dickinson, 2001), moderate star formation rates (see, e.g. Adelberger & Steidel, 2000; Pettini et al., 2001; Papovich, Dickinson & Ferguson, 2001), and relatively low masses (Sawicki & Yee, 1998; Shapley et al., 2001) were all consistent with the idea that these Lyman Break Galaxies (LBGs) being 'primordial' massive galaxies (see, e.g., Giavalisco & Dickinson, 2001; Giavalisco, 2002).

While this color selection was deliberately targeted towards high-redshift galaxies, by selecting on the basis of a restframe UV feature, it was also implicitly limited to star forming galaxies with little or no dust obscuration (see, e.g. Adelberger & Steidel, 2000). Using a NIR color selection criterion, which is based on the restframe optical Balmer and 4000 Å breaks in the spectra of old stellar populations, Franx et al. (2003) identified a nearly completely disjoint population of Distant Red Galaxies (DRGs). These galaxies were quickly spectroscopically confirmed to lie mostly at $z \gtrsim 2.3$ van Dokkum et al. (2003, 2004), and to be more massive, older, and dustier than the LBGs (van Dokkum et al., 2004; Förster-Schreiber et al., 2004; Labbé et al., 2005).

The discovery of the DRG population had two important implications. First, the fact that many DRGs were found to have genuinely old stellar populations significantly pushed back the epoch of formation for massive galaxies. It had been shown that a decent fraction of Extremely Red Objects (EROs, selected on the basis of their optical–minus–NIR colors; see McCarthy 2004 and references therein) were evolved and quiescent galaxies at $z \lesssim 1.3$, and quiescent galaxies at $1.4 \lesssim z \lesssim 2$ had been found in spectroscopic surveys (e.g. Cimatti et al., 2004; Glazebrook et al., 2004; McCarthy et al., 2004; Daddi et al., 2004, 2005). But the DRGs provided evidence for the emergence of significant numbers of massive, evolved galaxies in the first 2–3 Gyr of the history of the universe.

[4] Color selection techniques had in fact been an important part of moderate- and high-redshift spectroscopic studies since the mid 1990s. It was quickly realized that purely flux-limited samples were an inefficient means of isolating distant galaxies: most faint galaxies are nearby, low luminosity galaxies (see, e.g. Lilly et al., 1996; Ellis et al., 1996; Cowie et al., 1996). In the context of the earlier discussion of photometric versus spectroscopic redshifts, as well as in what follows, these kinds of color selection techniques can be thought of as an extremely crude photometric redshift. The same can be said of the 'red sequence cluster method' of identifying massive, red sequence galaxies in clusters (Gladders & Yee, 2000, 2005).

Secondly, particularly given that DRGs were found to exist in numbers comparable to the LBGs, these results also showed that the use of the Lyman break technique in particular, and color-selected samples in general, could yield a badly biased and significantly incomplete view of the high redshift universe (Labbé et al., 2003, 2005; Reddy et al., 2005; van Dokkum et al., 2006). *To get a fairer picture of the high redshift universe, what was needed was a complete sample of galaxies selected by stellar mass*; van Dokkum et al. (2006) showed that this could be done efficiently on the basis of photometric redshifts, using NIR-selected galaxy samples.

Old Galaxies in the Young Universe

By obtaining very deep, restframe optical spectra of a mass-limited sample of $z \sim 2.3$ galaxies, Kriek et al. (2006, 2008a) made a significant advance on previous photometric and spectroscopic studies of high redshift galaxies. These galaxies were K-selected, and were selected to have photometric redshifts greater than 2 (11 out of 36 of these galaxies were selected from an early version of the data presented in Chapter II). On the basis of their spectra, roughly half of these galaxies were shown unambiguously to have evolved stellar populations, and little or no ongoing star formation. Further, there was the tantalizing suggestion that the passive galaxies may already follow a red sequence (Kriek et al., 2008b; see also the recent results by Williams et al., 2009; Brammer et al., 2009). In other words, *a significant number of the massive galaxies at $z \sim 2.3$ have stellar populations that are consistent with their being "fully formed" massive galaxies.* (At least some) massive galaxies form or assemble their stars very early on in the history of the universe — and in a very short time.

The Continued Evolution of Quiescent Galaxies

Within the paradigm of hierarchical structure formation, the most massive objects are expected to be both young *and* old. They are old in the sense that they are expected to form preferentially from the highest overdensities, which are the first to collapse. On the other hand, since large structures form through successive mergers between smaller progenitors, the most massive galaxies are expected to have assembled only relatively recently, and in this sense are quite young. There is thus a crucial distinction to be made between a galaxy's mean stellar age, and its formation age; *i.e.*, the time since it first assumed its present form. With the introduction of a quenching mechanism, the models thus 'predict' that these massive galaxies will continue to grow through accretion and/or minor and major mergers, even after their star formation has effectively ceased (see, e.g., De Lucia et al., 2006).

With this in mind, there is (at least) one important difference between the $z \sim 2.3$ galaxies and local galaxies of the same stellar mass: the high redshift galaxies are much smaller. Using a combination of *HST* and Keck laser guide-star assisted adaptive optics imaging, van Dokkum (2008) measured sizes for 9 out of the 11 quiescent galaxies in the Kriek et al. (2006) sample. They found sizes on the order of 3–10 times smaller than typical galaxies of the same mass in the local universe. These galaxies have physical surface densities (measured within the central kiloparsec) that are 2–3 times higher than their local counterparts (Bezanson et al., 2009). As further confirmation of the remarkable compactness of these galaxies, van Dokkum, Kriek & Franx (2009) measured a velocity dispersion of 510^{+165}_{-95} km/s for one of these galaxies (see also the $z \sim 1.6$ results of Glazebrook, 2009). This work confirmed and consolidated the work of a number of authors, including Daddi et al. (2005), Trujillo et al. (2006), Trujillo et al. (2007), Zirm et al. (2007), and Toft et al. (2007). Similarly compact galaxies have since been found at $1 < z < 2$ by Cimatti et al. (2008) and Damjanov et al. (2009; see also Longhetti et al., 2007; Saracco et al., 2009), as well as at $1.7 < z < 3.0$ by Buitrago et al. (2008).

The observation that massive galaxies at high redshift are so much smaller than their local counterparts implies that each of these massive galaxies have to significantly grow in size in order to match the properties of galaxies found in the local universe. Theoretical candidates for the physical processes that drive this strong size evolution include a combination of accretion and mergers (van der Wel et al., 2009; Hopkins et al., 2009), and kinetic feedback from AGN (Fan et al., 2008). In this way, *confirming and quantifying the $z \lesssim 2.3$ size evolution of massive galaxies has the potential to provide constraints on the recent merger histories of massive galaxies, and thus the relative importance of mergers in galaxy growth.*

4 This Thesis

With all of the above as background, the three key questions addressed in this thesis are:

- When are massive galaxies formed?
- When is star formation quenched in massive galaxies?
- What happens to these galaxies after their star formation has ended?

A recurring theme throughout this work is the importance of systematic errors. Those who know me will be aware of my predilection for asking, “What could possibly go wrong?”; this is a question that appears more than once in what follows. While not nearly as glamorous or inspiring as being able to conclude that, say, at least half of all massive galaxies were formed in the last 7 Gyr, the results connected to error analysis are at least as important as the more ‘astronomical’ results — if not more so. It is only through detailed error analysis that we can learn exactly how well we know what we think we know.

4.1 The Rise of Red Galaxies

The first two of these key questions are addressed in Chapters II and III. This work is based on a NIR-selected catalog of the Extended Chandra Deep Field South (ECDFS), based on photometry in ten broadband filters compiled as part of the MUtiwavelength Survey by Yale–Chile (MUSYC; Gawiser et al., 2006). This catalog is based on publicly available optical imaging obtained from a number of different sources (Hildebrandt et al., 2006, and references therein), supplemented by original optical and NIR data taken by the MUSYC team. The ECDFS is one of the premier sites for deep field galaxy evolution studies, with observations spanning the UV to the radio. The additional of NIR data fills a crucial gap in the wavelength coverage of this important field. Particularly in concert with the many existing and upcoming survey projects targeting the ECDFS (see references given in Chapter II), the MUSYC NIR-selected catalog provides an outstanding laboratory for $z \gtrsim 1$ galaxy studies.

Chapter II is devoted to the integration of these different datasets into a mutually consistent whole. The resultant catalog comprises over 10000 reliable detections above our nominal selection and completeness limit of $K^{\mathrm{AB}} = 22$ over an effective survey area of 818 square arcmin, including nearly 9000 high-redshift galaxies, and an approximately complete sample of nearly 1300 $M_* > 10^{11}$ $\mathrm{M}_\odot$ galaxies at $z_{\mathrm{phot}} < 1.8$. In order to maximize the legacy value of the data, the data calibrations have been extensively tested through both internal consistency checks and external comparisons to existing surveys. In particular, we found a major calibration error in the COMBO-17 data of the ECDFS, which has since been corrected (Wolf et al., 2008)

The MUSYC ECDFS catalogs have been made freely and publicly available, including the reduced images, ten band photometry, a comprehensive compilation of spectroscopic redshifts from literature sources, state of the art photometric redshift determinations, and restframe photometry. This restframe photometry has been derived using an IDL implementation of an algorithm described by Rudnick et al. (2003), which I developed and tested. This utility, dubbed InterRest, has also been made freely available. The imaging data have since been incorporated into the FIREWORKS (Wuyts et al., 2008) catalog of the GOODS region, and form the backbone of the *Spitzer* Infrared MUSYC Public LEgacy (SIMPLE) survey (Damen et al., 2009), which adds extremely deep *Spitzer Space Telescope* data for the full field.

In **Chapter III**, the MUSYC data are used to construct the color–magnitude and color–stellar mass diagrams for $z \lesssim 2$. A red sequence is detected out to at least $z \sim 1.2$, but beyond this point, the NIR data are not deep enough to distinguish distinct red and blue populations. The $z \lesssim 1.2$ color evolution of the red sequence is consistent with the passive fading of old stars, with no evidence of evolution in the scatter around the color-magnitude or color-mass relations (see also Ruhland et al., 2009). But this is not to say that the red sequence does not evolve as a population: the number density of red galaxies grows by a factor of at least 5 between $z \approx 2$ and the present, and by a factor of at least 2 after $z \approx 1$. In contrast, the total number density of massive galaxies is approximately constant over $0 < z < 1$.

Our results link the $z \lesssim 1$ results of, e.g., Bell et al. (2004b) and Faber et al. (2007) to the $z \sim 2.3$ results of Kriek et al. (2006, 2008a,b). Bridging this $1 \lesssim z \lesssim 2$ gap is of particular interest since the cosmic star formation rate drops by an order of magnitude in this interval (see, e.g., Hopkins, 2004; Nagmine et al., 2006; Panter et al., 2007; Tresse et al., 2007; Pérez-Gonzaléz et al., 2008). This is also the era in which massive galaxies first emerge in large numbers (Juneau et al., 2005; Borch et al., 2006; Fontana et al., 2006; Pozzetti et al., 2007). These results are also complementary to studies that consider the mean star formation rate as a function of stellar mass (e.g., Juneau et al., 2005; Zheng et al., 2007; Damen et al., 2009a).

Since all passive galaxies are red, but not all red galaxies are passive, the results presented in Chapter III can be used to place an upper limit on the number of massive galaxies that have had their star formation effectively quenched. We therefore conclude that *at most 20 % of all local massive, red sequence galaxies had finished their star formation by $z \sim 2$, and that at least 50 % stopped forming stars only after $z \sim 1$.* Whatever the mechanism that is responsible for quenching star formation in massive galaxies, this is when it operates.

This work was the first of its kind to include a detailed investigation of the systematic uncertainties associated with these kinds of measurements. By systematically varying individual aspects of the experimental design, we were able to directly quantify the relative importance of a number of effects, including data calibration, photometric methods, photometric redshift uncertainties, errors in stellar mass estimates, and field-to-field variance. This allows us to identify the most important sources of systematic error or uncertainty; these are, in order: 1.) systematic differences in the analysis of the high-redshift galaxies and the $z \sim 0$ comparison sample; 2.) details of the photometric redshift calculation; and 3.) the basic photometric calibration of the data. Each of these sources of systematic uncertainty outweighs the statistical uncertainties, including those due to field–to–field variance. We also show that, for example, the choice of templates for the photometric redshift calculation, random photometric redshift errors, and systematic errors in the stellar mass estimates are not dominant sources of uncertainty.

By identifying and focusing on the most important sources of error and uncertainty, we have minimized our vulnerability to these effects, and so provide a more robust result than previous studies. Bearing this in mind, Chapter III also includes a complementary analysis that, while model dependent, is largely immune to the three most important sources of systematic errors. These results agree remarkably well with those from our more sophisticated analysis based on photometric redshifts. To the extent that these two analyses are consistent, this gives some confidence that we may in fact have the important systematic effects 'under control'.

Quantifying the systematic uncertainties associated with each different aspect of our experimental design is not only useful in interpreting our specific results, but also as a guide for the design of future surveys and experiments. In terms of future work, it is highly significant that, even for this relatively modest-sized field, systematic uncertainties outweigh the statistical errors, even after accounting for the effects of field-to-field variance (see also Marchesini et al., 2009). This implies that *future surveys will require better analysis as much as better data in order to improve on the results given in Chapter III.*

4.2 (No) Compact Galaxies in the Local Universe

Chapter IV addresses the third key question: what happens to galaxies after they finish their star formation? Specifically, we test the claim that the passive galaxies observed at $z \sim 2.3$ have to undergo significant structural evolution in order to match the $z \sim 0$ galaxy population by using data from the SDSS to look for local red sequence galaxies with comparable sizes and masses. Even more specifically, Chapter IV considers the possibility that such massive, compact galaxies might be missing from the SDSS catalog due to selection effects.

As part of the SDSS spectroscopic target selection algorithm, there are two selection criteria that exclude high surface brightness objects; these are intended to ensure against saturation and cross-talk in the spectroscopic detectors (Strauss et al., 2002). We show that this makes incompleteness a concern for bright and compact galaxies at *low* redshifts: even if red sequence galaxies with the sizes and masses seen at $z \sim 2.3$ were to exist $z \lesssim 0.05$, they would be not be selected as SDSS spectroscopic targets. For this reason, we look for massive, red sequence, compact galaxy candidates in the range $0.066 < z < 0.10$, where SDSS should be $\gtrsim 50$ % complete, and still be able to adequate resolve such compact galaxies.

If the $z \sim 2.3$ galaxies were not to evolve in either size or number density, we would expect to have found on the order of ~ 6500 such galaxies within this sample. Instead, after discarding those galaxies with obvious reasons to distrust their size and/or mass measurements, and after corroborating the size and mass measurements of the remainder of the sample based on their velocity dispersions, we find no (0) galaxies that are consistent with being passively evolved versions of the $z \sim 2.3$ galaxies. Chapter IV also includes a search for massive, compact galaxies in the SDSS photometric sample, for which selection effects should not be a concern; again, we find no plausible candidates. Massive, compact, red sequence galaxies are not just missing from the SDSS catalogs, they are simply not there to be found in the local universe.

This confirms the conclusions of van Dokkum (2008): *massive galaxies must undergo significant structural evolution after $z \sim 2$, even after their star formation has effectively ended.* The mechanism for this size evolution is not clear. However, using a simple statistical argument, we suggest that the fact that each and every one of the $z \sim 2.3$ galaxies must evolve in size implies this growth cannot be explained by a highly stochastic mechanism like major mergers.

4.3 Estimating Galaxies' Masses

The connection between observations and theory of galaxy evolution hinges on our ability to make the link between galaxies' observed SEDs and their intrinsic stellar populations (or, conversely, to predict SEDs for galaxies in the models given their star formation histories). As described above, these estimates are plagued by a number of different kinds of random and systematic uncertainties. The primary goal of **Chapter V** is to test our ability to derive robust stellar mass estimates from five band optical SEDs for galaxies in the local universe. Specifically, we compare stellar mass estimates to estimates of total mass based on galaxy dynamics, derived using the latest generation of SED-fit stellar mass-to-light ratios and the most robust size and flux measurements available for galaxies in the SDSS.

We find very good correspondence between stellar and dynamical mass estimates, but only provided that we account for non-homology (*i.e.* structural differences among galaxies) when deriving the dynamical mass estimates. In particular, we find no statistically significant trends in the stellar-to-dynamical mass ratio as a function of spectroscopic stellar population indicators, or as a function of derived stellar population parameters. Nor do we find any significant trends as a function of direct observables (e.g., apparent magnitude or size), which would indicate a bias in these measurements. Further, we find no appreciable difference between the relation between stellar– and dynamical–mass estimates for galaxies in different states of activity. Because both of these mass estimates are model-dependent, neither one offers a truly solid basis for comparison; the very good consistency thus provides very strong circumstantial evidence — but not proof beyond a reasonable doubt — that there are no significant biases in either mass estimate, including the models used to derive them. With this caveat, we conclude that, at 99 % confidence, *across a broad range of stellar populations, the systematic, differential errors in stellar mass estimates based on five band optical photometry are less than 0.12 dex (40 %).*

We also find a rather mild mass-dependence for the stellar-to-dynamical mass ratio. This same trend is seen for subsamples of galaxies with the same structures; this observation is thus independent of the model used to account for structure and dynamical non-homologies. This implies a relatively small variation in the dark–to–baryonic mass ratios of galaxies as a function of mass, at least among the most massive galaxies. Moreover, at fixed mass, the observed scatter in stellar-to-dynamical mass ratios is small; the intrinsic variations in the dark-to-baryonic mass ratios among galaxies of the same mass may be as small as 0.04 dex ($\sim$ 10 %).

5 Outlook

While our knowledge and understanding of the galaxy population and its evolution has exploded since the early 1990s, the past five or ten years has seen the establishment of galaxy formation and evolution as a mature science. One very important sign of this is the growing awareness of the importance of systematic errors. This awareness extends to interpretation of the theoretical models (see, e.g. Schaye & Dalla Vecchia, 2008; Wiersma, Schaye & Smith, 2009; Booth & Schaye, 2009). On the observers' side, this awareness is particularly apparent in connection with stellar mass estimates (see, e.g., van der Wel et al., 2006; Kannappan & Gawiser, 2007; Wuyts et al., 2007; Kriek et al., 2008a; Wuyts et al., 2009; Marchesini et al., 2009; Conroy, Gunn & White, 2009, Chapters III and V). Continued refinement of stellar evolution models will help to reduce the uncertainties in high redshift science. (Although there remains the question as to just how universal the stellar IMF is; the IMF is the new cosmology.)

In this sense, the upcoming NIR multiobject spectrographs will be extremely valuable. By providing spectroscopic redshifts for large numbers of $z \gtrsim 1$ galaxies, they will allow significantly more robust redshift and stellar mass determinations for galaxies at $1 \lesssim z \lesssim 2$. The results of the NEWFIRM medium band photometric redshift survey (van Dokkum et al., 2009; Brammer et al., 2009) are also likely to be important in this regard. However, given the maturity of SED-fitting techniques, these results seem more likely to extend and refine our present knowledge than they are to overturn it. (Here, it is relevant that the results presented in Chapter III are dominated by systematic errors in the data analysis, rather than random uncertainties associated with statistical or measurement errors, and in particular that stellar mass estimates are not a dominant source of uncertainty.) In this sense, NIR spectrographs seem less likely to revolutionize our understanding of the $z \gtrsim 1.5$ universe in the same way as our understanding of the $0 \lesssim z \lesssim 1.5$ universe has been by optical spectra. That said, obtaining dynamical estimates of the total masses of $z \lesssim 2$ galaxies will provide important new consistency checks on stellar mass estimates, and in particular constraints on any redshift dependency in the IMF.

There are a number of instruments and observatories planned for the next decade that promise to provide qualitatively new information on the properties of high redshift galaxies. With ALMA, it will be possible to probe the molecular gas content of high redshift galaxies; ASKAP, MEERCAT, and the SKA will do the same for atomic gas. These telescopes will thus provide a means of exploring evolution in the process of star formation. LOFAR will map massively star forming galaxies and AGN out to $z \gtrsim 2$ As well as being able to push further down the luminosity function at lower redshifts, the next generation of space telescopes, including the JWST, should open a window to the $z \gtrsim 5$ universe.

In the meantime, however, the challenge remains to disentangle the relative importance AGN feedback, secular evolutionary processes, and environmental effects in the evolution of massive galaxies, and in particular which of these is/are responsible for the quenching of star formation and the structural transformation from disk to elliptical. Given the recent explosion of survey projects, in terms of both number and scope, the prospects for making progress on these questions with the data presently available are excellent. In particular, there have been several recent works that argue that environmental effects play a far less important role triggering star formation than previously thought (e.g., van der Wel et al., 2008; van den Bosch et al., 2009; Pasquali et al., 2009). There are also indications that only a small fraction of the total cosmic star formation can be directly linked to merger events (e.g., Noeske et al., 2009; Robaina et al., 2009). Further exploration of these results may be very revealing.

The most immediately obvious way of determining which processes are the most relevant in driving the transition from blue to red and from late to early type morphologies is still through observing the evolution in galaxy demographics. Two key questions are: the extent to which the quenching of star formation and the morphological transition is coupled, and how the AGN activity of the red/blue early-/late-type populations compare. If it can be shown, for example, that the quenching of star formation happens before the morphological transition (or vice versa), that would imply that these two transitions are the products of distinct physical processes (see, e.g. Pozzetti et al., 2009). Another possibility is that, for example, if the peak of AGN activity was shown to occur only *after* the quenching of star formation, this might rule out AGN feedback as the primary quenching mechanism (in this context, see the recent results by Brown et al., 2009; Wild et al., 2009).

In all of this, morphology remains a relatively unexplored dimension of parameter space. Each of the major processes have rather different morphological signatures: for example, secular star formation in galaxies is clumpy, but largely symmetric; mergers and interactions induce strong asymmetries. In this sense, a comprehensive morphological census of the high- and low-redshift galaxy populations may also to qualitatively new constraints on the relative importance of the different processes thought to underpin the evolution of galaxies. This would require the development of new, non-parameteric measures of morphology (see, e.g., Conselice, 2003; Lotz, Primack & Madauo, 2004; Kelly & McKay, 2005; Abraham et al., 2007; Heurtas-Company et al., 2008).

These questions will only be resolved using very large, representative samples of galaxies at $z \gg 0$. The SDSS has greatly expanded and concretized our knowledge and understanding of the local galaxy population: what is needed is a similar sized survey with redshift resolution. By obtaining both optical spectra and subarcsec-resolution optical and NIR imaging for 250000 $z \lesssim 0.5$ galaxies, the GAMA survey Driver et al. (2009) may go a long way towards addressing these issues. Ultimately, however, what we would really like is an SDSS-sized sample of galaxies at $z \sim 1$ or even $z \sim 2$, with diffraction-limited NIR imaging and spectra obtained using a 30 m-class telescope.

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