PROCEEDINGS OF SCIENCE

arXiv:1212.5641v1 [astro-ph.CO] 22 Dec 2012

Galaxy Formation: Where Do We Stand?

Christopher J. Conselice*
Centre for Astronomy and Particle Theory
University of Nottingham, United Kingdom
E-mail: conselice@nottingham.ac.uk

This paper presents a review of the topic of galaxy formation and evolution, focusing on basic features of galaxies, and how these observables reveal how galaxies and their stars assemble over cosmic time. I give an overview of the observed properties of galaxies in the nearby universe and for those at higher redshifts up to $z \sim 10$. This includes a discussion of the major processes in which galaxies assemble and how we can now observe these - including the merger history of galaxies, the gas accretion and star formation rates. I show that for the most massive galaxies mergers and accretion are about equally important in the galaxy formation process between $z = 1-3$, while this likely differs for lower mass systems. I also discuss the mass differential evolution for galaxies, as well as how environment can affect galaxy evolution, although mass is the primary criteria for driving evolution. I also discuss how we are beginning to measure the dark matter content of galaxies at different epochs as measured through kinematics and clustering. Finally, I review how observables of galaxies, and the observed galaxy formation process, compares with predictions from simulations of galaxy formation, finding significant discrepancies in the abundances of massive galaxies and the merger history. I conclude by examining prospects for the future using JWST, Euclid, SKA, and the ELTs in addressing outstanding issues.

VIII International Workshop on the Dark Side of the Universe,
June 10-15, 2012
Rio de Janeiro, Brazil

*Speaker.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike Licence.

1. Introduction

Anyone trying to understand the formation of the universe must consider galaxies. Often used as a tracer population of the underlying matter, it is becoming clear that the history and physics of the formation of galaxies is a critical aspect for obtaining a full picture of the evolution of the universe. Yet we are really just starting to understand this, and uncertainties in our measurements of evolution remain large, although significant progress has been made in outlining the basic problem.

What is better understood is the observations of galaxies, which ultimately should reveal how the galaxies themselves have formed and evolved. In the local universe we have a solid understanding of the galaxy population based on large surveys such as SDSS and GAMA (e.g., Driver et al. 2011). Galaxies which are elliptical/passive along with spirals that have active star formation dominate the local population. The stellar and luminosity functions of nearby galaxies are also well measured (e.g., Loveday et al. 2012) and we now understand when the stars in these galaxies were formed based on detailed stellar population analyses.

What we do not yet understand is how or when these galaxies assembled. There has however been significant progress on addressing some of the issues related to this in the last 10-15 years. For example, the first measurements of galaxy properties at high redshift showed that the star formation rate is larger at higher redshifts than at lower redshifts (e.g., Madau et al. 1998), but this only reveals when stars form, not necessarily when galaxies assemble. We have some idea of this through observing the merger history of galaxies (e.g., Le Fevre et al. 2000; Conselice et al. 2003, 2008; Hammer et al. 2009; Lotz et al. 2008; 2011; Bluck et al. 2009, 2012; Man et al. 2012; Lopez-Sanjuan et al. 2012), and other modes such as gas accretion are now also being measured (e.g., Conselice et al. 2012). It is also important to realise that the questions of when the stars form in galaxies we see today, and when the galaxies themselves form, are distinct. It is also important to remember that these issues often must be addressed separately.

Traditionally the approach taken towards understanding the physics behind galaxy formation is to use galaxy observables, such as luminosity/mass functions, relations between observables, such as velocities and luminosities to test models. These models, starting with simple collapse ones (Eggen et al. 1962) implement basic physics, and subsequently predict the observables. This is now a large industry, and theory has revealed many clues towards understanding how galaxy formation has occurred, although as we discuss later (§5) there are still significant problems with theory matching galaxy observables.

Overall, in this review I place galaxy studies into three different classes: (1) Observables (i.e., measured or derived directly from telescopes) - this includes galaxy masses, luminosities, internal velocities, sizes, morphologies, etc. (2) Measuring galaxy history, i.e., how does the mass assembly/star formation, merging, and evolution in scaling relationship occur? (3) Finally, physics - what are the mechanisms driving the history of the observed assembly? An important side question is whether we have identified all of these processes. Within this framework the observables are first needed, then the history of the galaxy formation can be derived, which influences and leads into our understanding of the physics. Each of these three are active areas of research and can and often help guide the development of the other two.

This review will describe the observations of galaxies up to redshifts of $z \sim 10$, and how we are now able to measure the history of galaxy formation in detail up to at least $z = 3$, but only currently

for the most massive systems with log $M_* > 11$. For these systems we are obtaining a good idea of the formation mechanisms of galaxies. We demonstrate this through measuring the merger history of these galaxies, and the amount of cold gas accreted from the intergalactic medium at redshifts $1 < z < 3$. We show that these two processes are about equal in importance, and that minor mergers are as important as major mergers in forming galaxies. We also discuss how well theory is able to reproduce some of these properties, and discuss significant issues that still needing addressing. We use a standard cosmology of $H_0 = 70$ km s^{-1} Mpc^{-1}, and $\Omega_m = 1 - \Omega_\lambda = 0.3$ throughout.

2. Observations

2.1 Nearby Galaxies

Nearby galaxies at $z < 0.3$ have been studied in detail since the 1920s, and in many ways we know the most about galaxy properties and observables from examining nearby systems. What we know is that 75% of galaxies brighter than $M_B = -20$ are spiral or disk in morphology, with 22% SO/elliptical, and the remaining 2% are peculiar/irregular (Conselice 2006). Being nearby and thus relatively easy to study, many properties of nearby galaxies have been measured in detail, including their stellar mass and luminosity functions (e.g., Loveday et al. 2012; Taylor et al. 2011), as well as their detailed surface brightness distributions and internal kinematics (e.g., Cappellari et al. 2011; Kelvin et al. 2012).

Perhaps the most useful observation that can be performed on nearby galaxies in terms of their formation histories is to study in detail their stellar populations through absorption lines (e.g.,

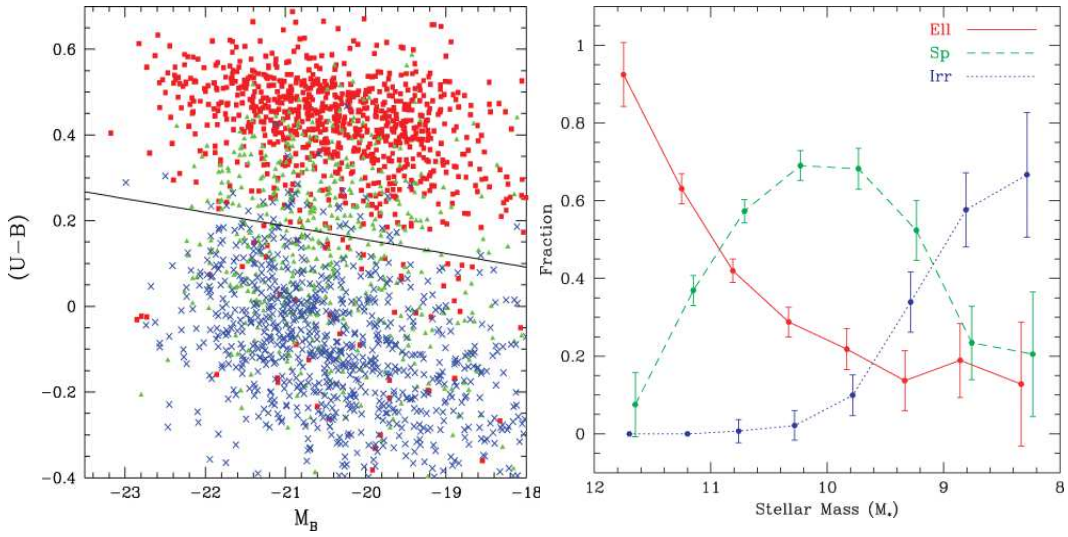

Figure 1: Plots showing basic features of the nearby galaxy population as a function of stellar mass. The left panel shows the colour-mass diagram for nearby systems, showing a clear differential between red galaxies on the red sequence and blue galaxies in the blue cloud. This correlates very strongly at $z = 0$ with galaxy morphology with ellipticals found in the red sequence (red points) and spirals/mergers (blue points) in the blue cloud. The right panel shows the distribution of morphology as a function of stellar mass in the nearby universe, with a smooth transition from early to late types at lower masses (Conselice 2006).

Trager et al. 2000; Thomas et al. 2005). These studies have found that the formation history of the stars in galaxies depends strongly upon their stellar mass, and less so on their environment. The most massive systems are dominated by old stars, such that single stellar population ages of their stellar masses are older than 5 Gyr (Trager et al. 2000). By comparing absorption line strengths to models, it can be shown that the most massive galaxies also contain the most α enriched stellar populations, demonstrating a quick formation for the stellar populations within these massive galaxies (e.g., Thomas et al. 2005). The stars in lower mass systems form later, although this may not be the case in the densest environments. There is furthermore a lack of strong environmental effects, such that galaxies in the most dense areas appear to have similar ages as those in lower densities. The effects of environment appear to be less important, and progressively so at higher redshifts (e.g., Grützbauch et al. 2011a,b; §4.2).

This is also seen in the distribution of morphology and star formation in the local universe as a function of stellar mass, whereby the lowest mass galaxies are the most likely to have a spiral or irregular morphology, and higher star formation rates and bluer colours (e.g., Baldry et al. 2006; Conselice 2006; see Fig. 1). There is in fact a very strong correlation such that the value of a galaxy's stellar mass, averaged over all environments, is a strong predictor for the morphology and star formation histories of individual galaxies.

In terms of galaxy evolution, another important insight that local galaxies provides is a nearby benchmark by which we can gauge how galaxy properties have changed as a function of redshift. In this review, I focus on the evolution of galaxy masses, morphologies, and kinematics. I do not provide a detailed study of other features of nearby galaxies here, such as how galaxy clustering or environment correlates with the properties or evolution of nearby galaxies, although see e.g., Kauffmann et al. (2004) for a discussion of this.

2.2 Distant Galaxies: The Universe at $z > 1$

The epoch of high redshift studies of galaxies began in earnest due to deep Hubble Space Tele-

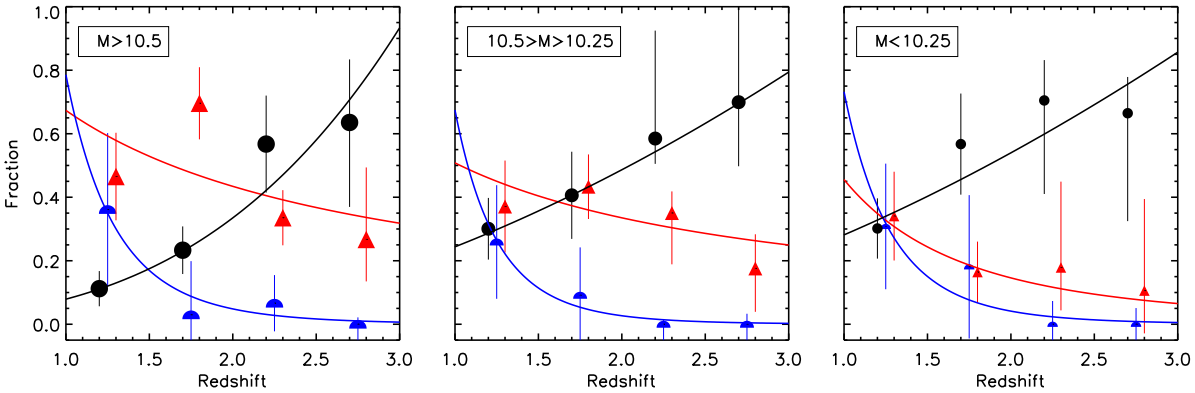

Figure 2: Morphological evolution of the galaxy population from Mortlock et al. (2013). The black lines are for galaxies classified as peculiar (as in Conselice et al. 2011b), and the red lines are for galaxies classified as ellipticals and the blue lines those as disks. These have been corrected for redshift effects by determining how structure changes due to redshift effects as detailed in simulations (see Mortlock et al. 2013). There is a clear evolution in structure, such that the most massive galaxies form 'normal' Hubble types before lower mass systems.

scope observations (e.g., Ferguson et al. 2000), and with the first 8-10m telescope observations of Lyman-break galaxies (LBGs) (Steidel et al. 1996), both quickly leading to the first measurements of the star formation history of galaxies (e.g., Madau et al. 1996). Since that time, observations with the HST have pushed observations of LBGs up to $z = 8$ and perhaps beyond (Yan et al. 2012) up to $z = 10$ (e.g., Coe et al. 2012). While we are still detecting galaxies at progressively higher redshifts, and have unlikely seen the first galaxies yet, we are able to make observations of these systems, during the $\sim$13 Gyr time period when most galaxy assembly has occurred.

The observables that are most commonly investigated for galaxies beyond the local universe are similar to what we can measure for nearby galaxies, including: masses, luminosities, morphologies, sizes, kinematics and clustering, as well as derived quantities such as star formation rates and gas masses. Observationally is makes sense to divide high redshift galaxies into four epochs, largely for observationally reasons. These are: $z < 1$, $1 < z < 3$, $3 < z < 6$ and $z > 6$. Each of these epochs is studied in slightly different ways, and obviously we know progressively less about the more distant and earlier epochs.

The universe up to $z \sim 1$ (at half its current age) in many ways 'looks' similar to the universe today. It is still uncertain what fraction of the stellar mass was assembled by $z = 1$, but it is likely more than half (e.g., Mortlock et al. 2011). The morphologies of $z = 1$ galaxies are also very similar to those that we see in the local universe with a similar fraction of different types (e.g., Conselice et al. 2005a), however these galaxies have more of a clumpy structure overlayed on their primary Hubble types (spirals, ellipticals) (e.g, Elmegreen et al. 2007).

At higher redshifts, particularly at $z > 2$ the universe of galaxies is quite different from today. In general, galaxies are bluer, smaller, more asymmetric, and contain higher star formation rates. Attempts to understand the evolution of this includes: measuring luminosity and mass functions (e.g., Bouwens et al. 2011); evolution of stellar populations and colours (e.g., Finkelstein et al. 2012); morphological evolution, including sizes and surface brightness profile evolution (e.g., Conselice et al. 2005a; 2008; 2011; Buitrago et al. 2011; Weinzirl et al. 2012); clustering evolution (e.g., Foucaud et al. 2011) and star formation evolution (e.g., Bouwens et al. 2010). Also, $z > 1$ systems have smaller radii at a given mass than local galaxies at the same stellar mass (e.g., Trujillo et al. 2007; Buitrago et al. 2008), suggesting some evolution throughout time to increase the sizes of galaxies by some still uncertain process (Ownsworth et al. 2012). See these papers for details of these various issues.

As one example, Figure 2 shows the morphological evolution for galaxies from the CANDELS survey (Mortlock et al. 2013 in prep), demonstrating how there is both a redshift and stellar mass dependence on morphology. As can be seen at $z = 3$ the morphological fraction is dominated by galaxies that appear peculiar in appearance (the black circles and lines), while at lower redshifts, towards $z = 1$ the classical Hubble type galaxies - those identifiable as disks or ellipticals start to become the dominant population (e.g., Buitrago et al. 2011). The other interesting feature of this evolution is that there is a mass dependence such that this 'transition' from peculiar to normal galaxy is at higher redshifts for higher mass galaxies. This transition redshift is $z = 2.22 \pm 0.87$ for $\log M_* > 10.5$ galaxies, $z = 1.75 \pm 0.76$ for $10.25 < \log M_* < 10.5$ galaxies, and $z = 1.73 \pm 0.56$ for $\log M_* < 10.25$ systems.

There is also strong star formation evolution from $z = 0$ to $z = 1$, such that the total star formation rate density averaged over all galaxies at $z \sim 1$ is a few times higher per co-moving

volume element than in today's universe (e.g., Bouwens et al. 2010). However, the star formation rate peaks and is roughly constant at a given stellar mass between $1 < z < 3$ (Fig. 3), such that a typical massive galaxy will double its stellar mass due to this star formation over the epoch $1 < z < 3$, and lower mass galaxies grow even larger. Later we investigate the relative role of this star formation in growing the stellar masses of galaxies, and what this reveals about their formation (§3). At even higher redshifts the total star formation density declines at $z > 3$ up to $z \sim 7$ (Bouwens et al. 2010) although the specific star formation rate for the most massive galaxies is relatively constant (Stark et al. 2009), suggesting some star formation regulation process might be at work.

Perhaps the most basic way to address when galaxies form is however to compare the stellar mass distribution of distant galaxies to that of galaxies in the nearby universe. This is particularly the case for the most massive systems, as these form before low mass galaxies (e.g., Bundy et al. 2006; Mortlock et al. 2011), and are the easiest galaxies to simulate in computers and are thus an invaluable test of galaxy formation models (e.g., Conselice et al. 2011b). Massive galaxies have been studied in detail using various surveys from the Hubble Space Telescope within deep pointed surveys (Mortlock et al. 2011), as well wider area surveys using imaging from telescopes such as UKIRT within the UKIDSS Ultra Deep Survey (Hartley et al. 2010).

There is a strong signature of galaxy 'downsizing' in almost all galaxy properties up to at least $z = 3$, such that the highest mass galaxies tend to 'shut down' formation modes, including AGN, before the lower mass galaxies. Essentially this means that high mass galaxies finish forming

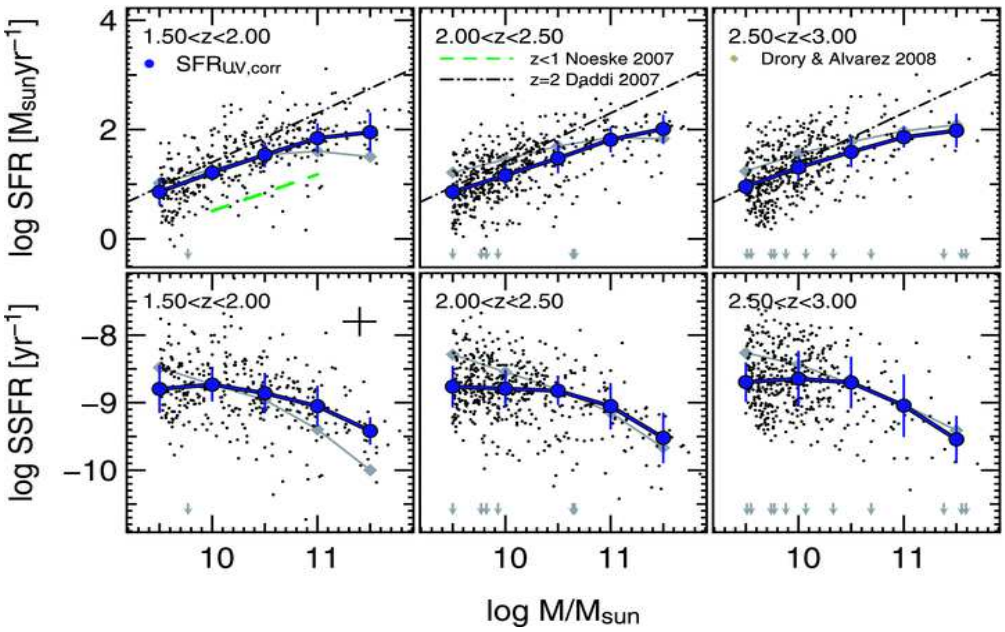

Figure 3: Relation between stellar mass and star formation rate for galaxies from $\log M_* = 9.5 - 12$. The star formation rate increases with stellar mass, on average, during this epoch although the specific star formation rate drops at higher masses. The star formation relation with mass is also fairly constant during this epoch (from Bauer et al. 2011).

before lower mass ones. For example, when examining the abundances of massive galaxies with $M_* > 10^{11}$ $M_\odot$, the measured number densities up to $z \sim 1-2$ are similar to what is found in the local universe, at the same stellar mass limit (e.g., Conselice et al. 2011b; Mortlock et al. 2011). Therefore to study the properties of the the most massive galaxies and to examine their formation observationally we must go to higher redshifts, namely at $z > 2$.

Recent results have accomplish this by examining the most massive systems at $1.5 < z < 3$ with Hubble Space Telescope surveys that can resolve these systems. This includes the CANDELS survey (Grogin et al. 2011) and the GOODS NICMOS Survey (GNS; Conselice et al. 2011b). Recent results from these surveys have shown that the formation modes for the most massive galaxies are dominated by mergers (Bluck et al. 2009; 2012), and the accretion of gas from the intergalactic medium (Conselice et al. 2012) with the bulk of this formation occurring at $z > 1$ (Mortlock et al. 2011). We explain below the reasoning behind these results, and how others have found similar conclusions. The below analysis has only been carried out for the highest mass galaxies so far, although in the future lower mass systems can be analysed in a similar way using deeper data.

3. Empirical Galaxy Formation

3.1 The Role of Mergers up to $z = 3$

Galaxy assembly is a combination of at least three processes. These are: merging with existing galaxies; the accretion of cold gas from the intergalactic medium; and the conversion of in-situ initial gas into stars in a galaxy over time. Understanding the relative role of these processes, and how these vary as a function of stellar mass and environment, is one of the major goals of extragalactic astronomy.

We now have some idea about the role of mergers in galaxy assembly (e.g., Conselice et al. 2003; Lotz et al. 2008; Bluck et al. 2012). While mergers can dominate much of the evolution within galaxies, including triggering star formation and AGN, instigating morphological changes, etc., we are mainly interested here in how it builds up the stellar masses of galaxies over time.

The amount of stellar mass added to a galaxy due to the merger process is given by the integral over the merger history, based on the fraction of galaxies merging, and the time-scale for mergers (e.g., Bluck et al. 2009; 2012). Bluck et al. (2012) and Conselice et al. (2012) carry out this integration using the observed merger history measured directly from the GNS sample of massive galaxies at $1.5 < z < 3$ (Fig. 4), and the modeled time-scale for mergers (e.g., Bluck et al. 2009; 2012).

Using pairs of galaxies and galaxies involved in merging, as seen through the CAS system, we can now measure accurately the merger history up to $z = 3$ (e.g., Bluck et al. 2012 and references within). The total amount of stellar mass accreted into a galaxy is a double integral over the redshift range of interest (z_1 to z_2 corresponding to look-back times t_1 and t_2), and over the stellar masses which we probe (M_1 to M_2), which for the GNS, sensitive down to $M_* = 10^{9.5}$ $M_\odot$, can be expressed as,

$$M_{*,M} = \int_{t_1}^{t_2} \int_{M_1}^{M_2} M_* \times \frac{f'_m(z, M_*)}{\tau_m(M_*)} dM_* dz, \quad (3.1)$$

where $\tau_{\rm m}(M_*)$ is the merger time-scale, which depends on the stellar mass of the merging pair (Bluck et al. 2012). The total integration of the amount of mass assembled through merging gives $M_{*,M}/M_*(0) = 0.56 \pm 0.15$, where $M_*(0)$ is the initial average stellar mass of the GNS massive galaxy sample. This is the fractional amount of stellar mass added due to both major and minor mergers for systems with stellar mass ratios down to 1:100 for the average massive GNS galaxy after following a merger adjusted constant co-moving density (Conselice et al. 2012).

However, to fully understand the total baryonic mass assembly of galaxies due to the merger process, we also need to account for how much gas mass is brought into these systems through mergers. This is calculated by integrating the amount of gas in these merging systems using an empirical fit to the relationship between the gas mass fraction, $\mu_{\rm gas}$, and the stellar mass found at $z = 2-3$. Overall the lower mass galaxies contribute the bulk of the gaseous mass from mergers, whereas most of the stellar mass accreted in mergers arises from higher mass ratio mergers. We show this relative role of mergers in Figure 4. This relation can then be used to calculate for the GNS sample how much gas mass is added due to merging, finding $M_{g,M}/M_*(0) = M_{*,M}/M_*(0) \times f_g = 0.57 \pm 0.15$. Over the redshift interval $z = 0-3$ major and minor mergers are roughly equal in terms of importance in building up galaxies.

The high number of minor mergers is also a solution to the size problem in massive galaxies. When examining the effective radii of massive galaxies at redshifts $z > 0.5$ they are much smaller than galaxies of similar masses in today's universe (e.g., Buitrago et al. 2008; Trujillo et al. 2007; Weinzirl et al. 2011). How these galaxies expand to become the large galaxies we see today is not well understood. However, by examining the number of minor mergers we observe from $z = 3$ down, and by using simple physics, it is possible to show that these mergers provide enough mass at the right locations to expand the measured sizes of galaxies by up to a factor of five (Bluck et al. 2012). This is therefore likely the solution to the problem of how galaxies can be so compact at high redshift, but still have significantly high stellar masses (see also Ownsworth et al. 2012).

3.2 Gas Accretion From the Intergalactic Medium

One important observation of high redshift massive galaxies with $\log M_* > 11\ M_\odot$ is that these systems have an average star formation rate that is relatively constant at $1.5 < z < 3$, and declines at $z < 1.5$ (Fig. 3). This star formation increases the stellar mass within these systems by an amount which approximately doubles it. This is a high star formation rate, and the amount of gas mass accreted due to merging, plus the original amount of gas is not enough to sustain the star formation present (Papovich et al. 2011; Conselice et al. 2012).

We can show, based on this, that the amount of gas accreted into a massive GNS galaxies is $M_{g,A}/M_*(0) = 0.70 \pm 0.22$ (Conselice et al. 2012), such that an amount of mass on the order the entire initial stellar mass of a massive galaxy is added over time outside of mergers to form stars during $1.5 < z < 3$, a time span of ~ 2 Gyr. This reveals a net gas accretion, which is then turned into stars, of $61 \pm 19\,M_\odot\,{\rm yr}^{-1}$. When considering that these galaxies have outflows (e.g., Weiner et al. 2009) that could easily double the amount of gas mass needed to be accreted from the IGM (e.g., Faucher-Giguere et al. 2011) we find that the gross inflow rate increasing to: $\dot{M}_{\rm acc} = 96 \pm 19\,M_\odot\,{\rm yr}^{-1}$.

The result of this is that gas accretion accounts for 49±20% of the stellar matter added to galaxies from $1.5 < z < 3$. Mergers account for the remainder of the mass assembly, with 1/2 of

this minor mergers and 1/2 of this major mergers (Bluck et al. 2012). Gas accretion however is responsible for 66±20% of all new star formation during this epoch within log $M_* > 11$ galaxies. Overall this implies that gas accretion into massive galaxies at early epochs is potentially a major formation method, and dominates over mergers as a formation mechanism for new stars. This is however a first estimate of this quantity, and future studies with wider and deeper surveys will measure this number with more accuracy in the future.

This measured gas accretion rate is roughly consistent with theoretical calculations which predict a similar amount of gas accretion (e.g., Murali et al. 2002; Dekel et al. 2009). Some of the first predictions of the gas accretion by Murali et al. (2002) found a gas accretion rate of $\dot{M}_{\rm g,A} \sim 40$ $M_\odot\,{\rm yr}^{-1}$, while more recent work suggests higher rates of $\dot{M}_{\rm g,A} \sim 100$ $M_\odot\,{\rm yr}^{-1}$ (e.g., Dekel et al. 2009; Faucher-Giguere et al. 2011). These first results on measuring cold gas accretion are in general agreement with these models, although this measurement should be redone for larger samples and at lower masses to determine the role of mergers vs. accretion as a function of stellar mass.

4. Role of Environment

4.1 Galaxy Clustering and Dark Matter Halos

One of the new frontiers of studying galaxies and their evolution is to examine how they cluster together, and what this reveals of their halo masses, as well as their environment. The summary of how this evolution occurs is shown in Figure 5 based on results from Foucaud et al. (2010). In

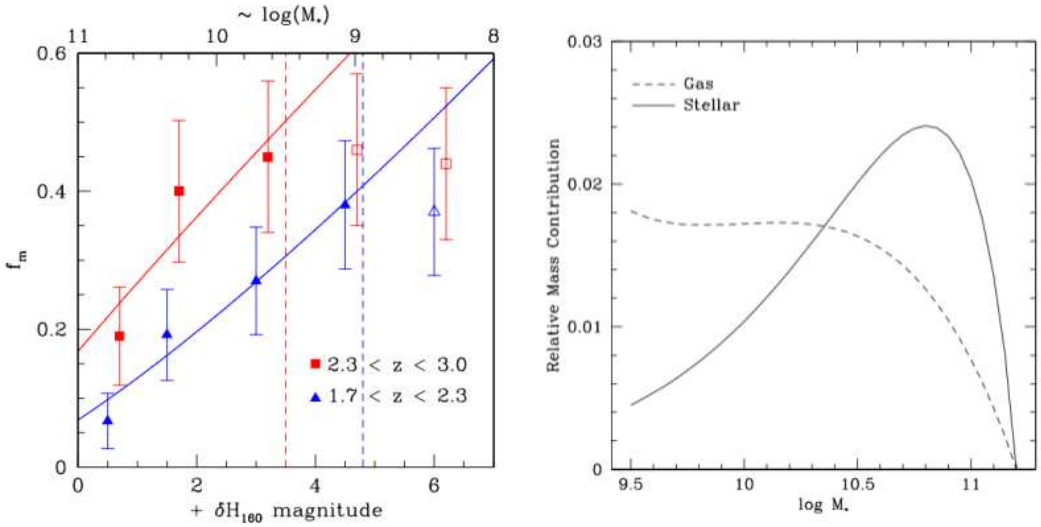

Figure 4: Plots showing the role of mergers, both major and minor, and gas accretion in forming galaxies at $z = 1-3$. The left panel shows the merger fraction for systems with stellar masses log $M_* > 11$. Shown at the top of the left panel are the stellar masses of the lower mass galaxies merging with these massive galaxies down to log $M_* = 9.5$, demonstrating that minor mergers are more common than major mergers (Bluck et al. 2012). The right panel shows the relative amounts of mass added to these massive galaxies due to mergers, revealing that most of the gas is brought in by lower mass galaxies while higher mass galaxies add most of the stellar mass (Conselice et al. 2012.)

general the most massive galaxies are the most clustered, with correlation lengths of $r_0 = 10$-15 h^{-1} Mpc from redshifts $0.5 < z < 2$ (Hartley et al. 2010). Interestingly, there does not appear to be a strong trend with redshift, such that the most stellar massive systems have the highest clustering values up to $z = 2$. At higher redshifts, the clustering strength increases at a fixed stellar mass, such that the most massive halos assemble their stellar mass before lower mass ones.

The clustering strengths of these galaxies can be converted into halo masses by matching the abundances of galaxies selected by stellar mass into a corresponding halo mass from N-body simulations within a given cosmology (e.g., Mo & White 2002). Using this method it is therefore possible to determine how the stellar to total mass ratio evolves for ensembles of galaxies as selected through their stellar mass. When comparing total masses to stellar masses the most massive systems have the lowest stellar to total mass ratios (Fig. 5). This implies that something is either shutting off star formation within the most massive galaxies, or more likely that halo masses contain sub-halos which contribute to their total masses. Systems with total masses $M_{halo} > 10^{13}$ $M_{\odot}$ have stellar mass to halo mass ratios of < 0.01 while this ratio goes down to ~ 0.1 for systems with $M_{halo} \sim 10^{11}$ $M_{\odot}$, although we know that dwarf systems also have very low M_*/M_{halo} ratio (Penny et al. 2009).

Related to the stronger clustering at higher redshifts, it is also clear that at fixed stellar mass, the ratio of stellar to halo mass increases at lower redshifts at a given halo mass. This implies that there is a halo downsizing, such that the most massive halos form stars first, and only after a few Gyr do lower mass halos form enough stars for their systems to enter the same stellar mass selection. This thereby lowers the ratio of stellar to halo mass, given that these late comers to a given mass bin are in lower mass halos, which lowers the clustering strength of the population selected by this stellar mass range. Note however, that is it not clear if this is a general result or simply for galaxies selected by stellar mass. For example disk galaxies up to $z = 1.4$ shows very little evolution in the stellar mass to total mass ratios (Conselice et al. 2005b), or alternatively in the stellar mass Tully-Fisher relation (e.g., Conselice et al. 2005b; Miller et al. 2011).

Integral field spectroscopy for $z > 1$ systems has also revealed important clues about the nature of these high redshift galaxies (Förster Schreiber et al. 2009). These studies typically find an equal distribution of systems which are: 1. rotationally dominated, 2. mergers and 3. systems that have high velocity dispersions, but which are very compact. The true nature of these systems has yet to be revealed, but clearly the kinematics of distant galaxies shows significant differences from galaxies in the local universe. More IFU studies of larger samples of galaxies are currently needed, as there are at most only a few hundred IFU spectra measured for $z > 1$ galaxies thus far.

4.2 Environment vs. Mass - Which Dominates?

Since galaxies were first studied, and especially since the paper by Dressler (1980) there has been a recurring question of the role of environment in driving galaxy formation/evolution. It is clear that in the local universe disk galaxies are more likely found in low density environments, while early-type systems are found in denser ones (e.g., Dressler 1980). However, this effect is most pronounced in extreme environments, and it is not clear beyond these extremely dense environments how, say a modestly dense environment would affect galaxy evolution over a very low density environment.

This was examined in detail by Grützbauch et al. (2011a,b) who looked at galaxy colours and star formation rates as a function of both environmental density as well as a function of stellar mass and redshift. What was very clear is that while there is some environmental effect, such that galaxies are redder in denser areas (Grüzbauch et al. 2011a), this effect is most pronounced at lower redshifts, typically at $z < 1$. At redshifts higher than this the effects of environment are very minimal (e.g., Grüzbauch et al. 2011a).

On the flip-side of this, when comparing galaxy colours and star formation rates with stellar masses, there is a much stronger correlation, such that the most galaxies have red colours compared to lower mass galaxies, as well as having a higher star formation rate at higher redshift (Grützbauch et al. 2011b; Fig. 6). There is also very little trend in galaxy properties with the overall halo mass in which a galaxy is located, demonstrating that environment, as measured by the number of nearby galaxies and the total mass of the group/cluster a galaxy is located has very little effect on the observed properties of galaxies. This is consistent with there being very little trend in age or star formation history for local galaxies as measured through stellar spectra fitting (e.g., Thomas et al. 2005; §2.1).

These correlations show that the stellar mass, or likely the halo mass of an individual galaxy is the overall most important aspect for how these systems form and evolve. This is possibly related to the fact that galaxies with higher masses have more massive black holes, and that AGNs are significantly active during this epoch, depositing 35 times the binding energy into the galaxy over $1 < z < 3$ on average (e.g., Bluck et al. 2011). Larger black holes produce more energy back

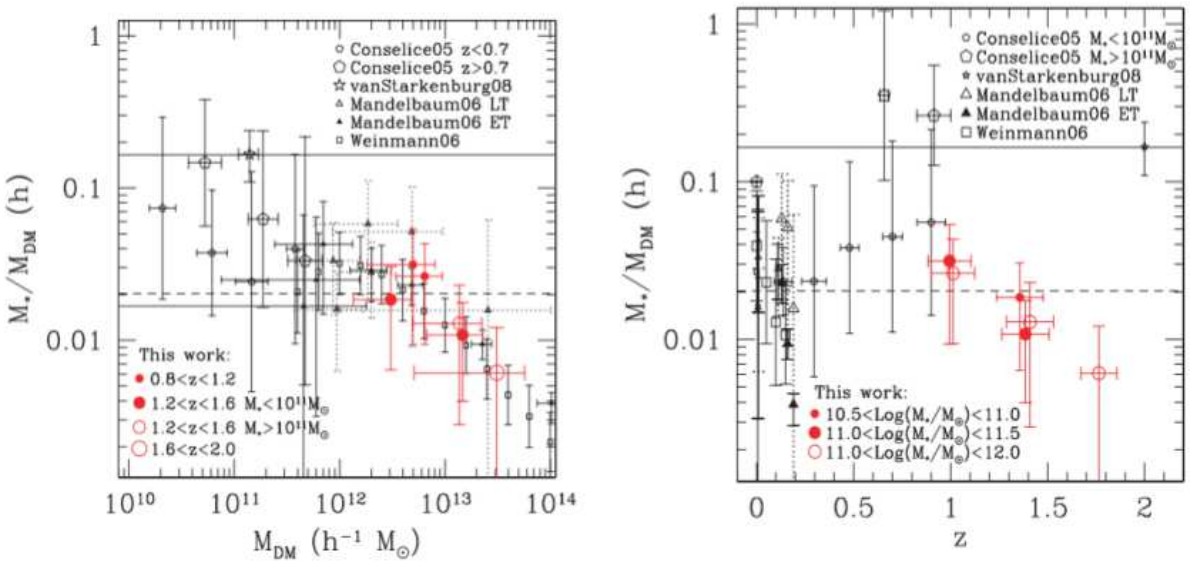

Figure 5: The relationship between the halo mass and the ratio of stellar to halo mass (left panel), as well as this ratio of masses as a function of redshift (right panel) (Foucaud et al. 2010). As shown, the amount of stellar mass relative to dark matter mass declines at higher redshifts for systems with larger halo masses. Furthermore, there is some evidence that the highest mass halos are populated earlier than low mass ones, with the result being that for a given stellar mass selection there is a higher ratio of stellar to dark matter mass at lower redshifts.

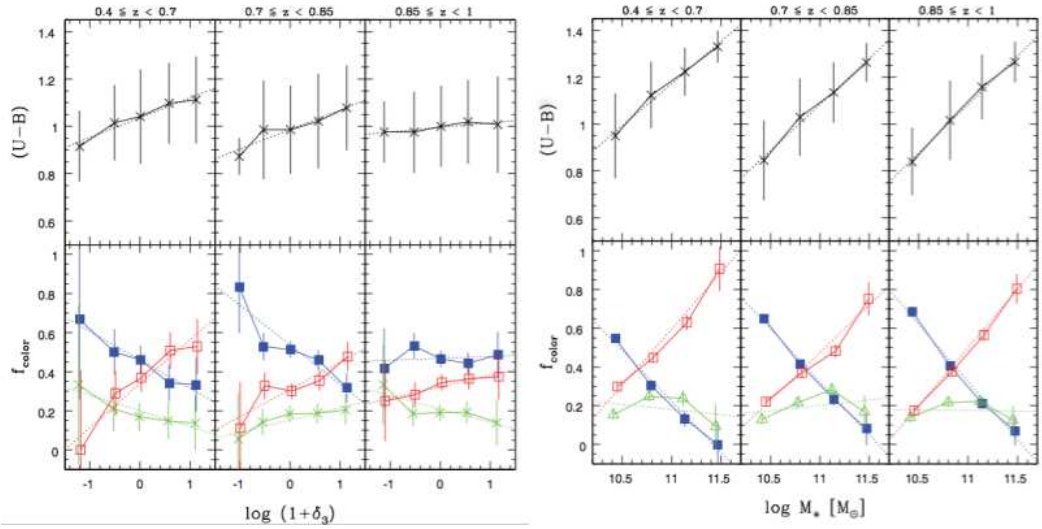

Figure 6: The right panel and left panels show the relationship between galaxy rest-frame colour and environment (as measured through $1+\sigma$) and stellar mass (Grützbauch et al. 2011a). This relations are also shown as a function of redshift in three panels. The left panels shows how the relationship between environment and colour such that there is very little trend between these, while the right panel shows that there is a strong correlation between the stellar mass and colour, such that higher mass galaxies are always on average redder than lower mass systems. This strong trend continues up to $z-3$ (e.g., Grützbauch et al. 2011b).

into their host galaxies, and this is possibly the reason why mass is such as defining characteristic of galaxies. This may also explain how downsizing occurs first for the most massive galaxies, although finding direct proof that AGN/black holes have a significant effect on gas and star formation in galaxies remains elusive.

5. How Well Does Theory Predict Galaxy Evolution?

Understanding how galaxy formation occurs was initially first calculated using the ages of different stellar populations in the Galaxy (Eggen et al. 1965), and the default initial assumption was that galaxies formed like stars in a monolithic-type collapse. In the 1980s the first computer simulations of structure formation showed that a universe dominated by Cold Dark Matter (CDM) matched observations of galaxy clustering on large scales (Davis et al. 1985), and that within this framework galaxy assembly should be hierarchical (Blumenthal et al. 1984).

The situation today is that there are many simulations that are used to predict properties of the galaxy population, and how it evolves through time. Significant success has been reached when predicting the properties and scaling relationships of galaxies, yet problems still exist (e.g., Guo et al. 2011). While there are famous problems such as the satellite and the CDM dark matter profile problem, there are also issues when examining how the evolution of galaxies occurs, and trying to match this with the theory.

I focus here on the much less well known problems of CDM in predicting galaxy evolution at high-redshift. While semi-analytical CDM models can predict local galaxy properties well (e.g., Bower et al. 2006; Guo et al. 2011), there are very significant differences between observations

and theory when probing at higher redshift. One of these is that most semi-analytical simulations are not able to reproduce the abundances, or the formation history of massive galaxies through mergers (e.g., Conselice et al. 2007; Bertone & Conselice 2009; Marchesini et al. 2010; Guo et al. 2011; for further information on problems in other galaxy predictions using CDM see e.g., Guo et al. 2011).

Specifically, the number densities of massive galaxies with $\log M_* > 11$ are under-predicted in CDM galaxy formation models at $z > 2$ (e.g., Conselice et al. 2007; Marchesini et al. 2010; Guo et al. 2011; Fig. 7). The difference with CDM models can be up to a factor of 10 or higher up to $z = 2$. While some CDM models attempt to get around the star formation downsizing through merging existing, but quiescent, galaxies at $z < 1$ (De Lucia et al. 2006), these systems are clearly already well formed by this time. To further investigate the problem of matching observables with theory requires that we investigate how the formation process of galaxies occurs, and whether models can reproduce these known formation modes. One of major methods for doing this is to investigate how well CDM models can reproduce the formation history of galaxies as seen through processes such as merging.

For example, Bertone & Conselice (2009) compare the merger history of galaxies to the predictions from the Millennium simulation. This comparison shows that the Millennium simulation underpredicts the number of major mergers by a similar order of magnitude (factor of 10) that it underpredicts the abundances of galaxies (Fig. 7). The reasons for this are unclear, but may relate to either underlying cosmological assumptions, or the way in which baryons are implement

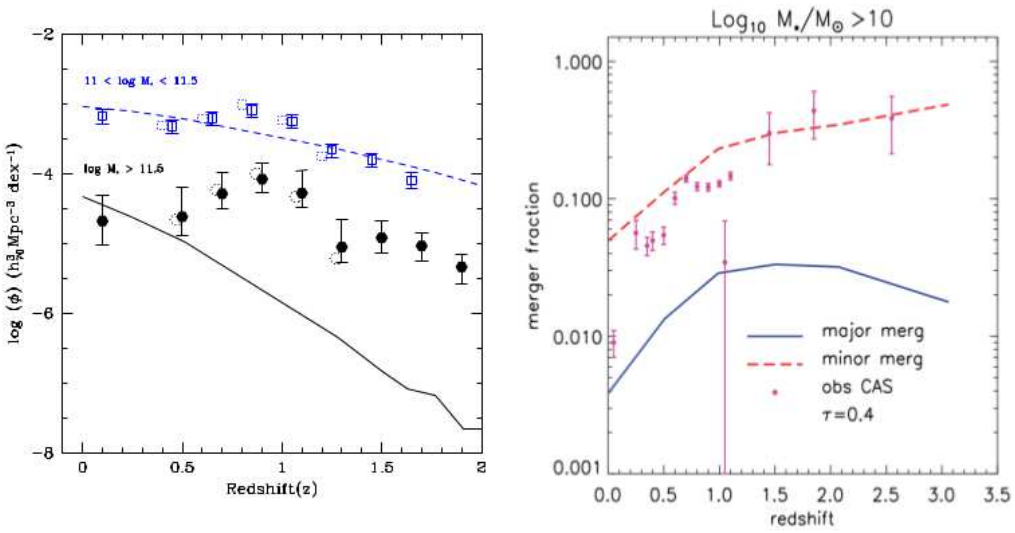

Figure 7: Plot showing issues with CDM simulation results. The left panel show the evolution of the number densities for galaxies with stellar masses between $M_* = 10^{11} - 10^{11.5}$ $M_\odot$ and galaxies with $M_* > 10^{11.5}$ $M_\odot$. For the most massive systems there is a significant difference in the numbers of massive galaxies and the CDM prediction from the semi-analytical Millennium simulation, up to a factor of 100 (Conselice et al. 2007). The right panel shows the comparison between the major merger history and simulations based on CDM (Bertone & Conselice 2009). The blue solid line shows the prediction for the same quantities as the points, demonstrating values that are significantly lower than the observations.

in these simulations. Future work, including investigating the underlying role of dark matter, and other cosmological features, will have to be included in future theoretical research on how galaxies form.

6. Summary and Outlook for the Future

The basic ideas presented in this review is that we can observationally determine how galaxy formation occurs, and do not have to rely on comparing basic observables to models to understand this history. I have shown how we now have some understanding for how the most massive galaxies with $M_* > 10^{11}$ $M_\odot$ assembled their stellar mass and baryons at $z < 3$ – showing that likely mergers and gas accretion are equally important during this epoch. Observations of higher redshift galaxies are still very new, especially in terms of having stellar mass completed samples, although progress will be quickly made with surveys such as CANDELS, UKIDSS UDS and VISTA.

While we have learned quite a bit about the history of the formation of massive galaxies, probing the star formation and merger rates, there is still a significant amount regarding galaxies that we are still just starting to explore. Some of these outstanding issues that have not been fully addressed, include: how disk galaxies and their structures (spiral arms, bars) form, and what the nature of massive galaxies themselves are at $z > 2$, as these systems are not analogs to any local galaxies in almost every way.

Deep and wide field surveys such as with Euclid and WFIRST will carry out large imaging surveys that will address the problem of galaxy evolution in great detail, providing the large and deep fields that Hubble and ground based telescopes cannot provide. However, what is also needed is kinematic measurements alongside structural measurements to truly decipher the nature of distant galaxies. We are just starting to scratch the surface of what can be done, but in the near future instruments such as KMOS on the VLT, and in the future the ELTs will provide large numbers of IFU spectra through surveys.

We have also not yet detected the first galaxies to form, although we are pushing the limits (e.g., Yan et al. 2012). JWST and the ELTs will provide a deep probe of the universe such that we will likely see the first galaxies and perhaps stars forming, especially utilising the benefits of gravitational lensing (e.g., Coe et al. 2012). The next generation of radio telescopes, such as SKA and its precursors will furthermore allow us to measure the still largely uncertain properties of gas within distant galaxies, including the important question of how the gas content evolves with time. This will allow us to complete our physical and empirical knowledge of galaxy formation.

I thank my collaborators, students and post-docs for allowing me to include some of their work in this review, and for the numerous discussions that have significantly increased my understanding of the topic of galaxy formation. This includes: Alice Mortlock, Asa Bluck, Fernando Buitrago, Matt Hilton, Ignacio Trujillo, Shardha Jogee, Tim Weinzirl, Will Hartley, Jamie Ownsworth, Ruth Grützbauch, Seb Foucaud, Omar Almaini, Amanda Bauer and Ken Duncan. Support for some of the research presented here came from STFC, NASA, NSF and the Leverhulme Trust.

References

Baldry, I., et al. 2006, MNRAS, 373, 469

Bauer, A.E. et al. 2011, MNRAS, 417, 289

Bertone, S., Conselice, C.J. 2009, MNRAS, 396, 2345

Bluck, A., et al. 2009, MNRAS, 394, 51L

Bluck, A., et al. 2011, MNRAS, 410, 1174

Bluck, A., et al. 2012, ApJ, 747, 34

Blumenthal, G., Faber, S., Primack, J., Rees, M. 1984, Nature, 311, 517

Bouwens, R. et al. 2011, ApJ, 737, 90

Bouwens, R., et al. 2010, ApJ, 725, 1587

Bower, R.G., et al. 2006, MNRAS, 370, 645

Buitrago, F. et al. 2008, ApJ, 687, 61

Buitrago, F. et al. 2011, arXiv:1111.6993

Bundy, K., et al. 2006, ApJ, 651, 120

Cappellari, M. et al. 2011, MNRAS, 413, 813

Coe, D. et al. 2012, arXiv:1211.3663

Conselice, C.J., Bershady, M.A., Dickinson, M., Papovich, C. 2003, AJ, 126, 1183

Conselice, C.J., Blackburne, Papovich, C. 2005a, ApJ, 620, 564

Conselice, C.J., et al. 2005b, ApJ, 628, 160

Conselice, C.J. 2006, MNRAS, 373, 1389

Conselice, C.J., et al. 2007, MNRAS, 381, 962

Conselice, C.J., et al. 2008, MNRAS, 386, 909

Conselice, C.J., et al. 2011a, MNRAS, 417, 2770

Conselice, C.J., et al. 2011b, MNRAS, 413, 80

Conselice, C.J., et al. 2012, arXiv:1206.6995

Davis, M., Efstathiou, G., Frenk, C., White, S. 1985, ApJ, 292, 371

De Lucia, G., et al. 2006, MNRAS, 366, 499

Dekel, A. et al. 2009, Nature, 457, 451

Driver, S., et al. 2011, MNRAS, 413, 971

Dressler, A. 1980, ApJ, 236, 351

Elmegreen, D.M., et al. 2007, ApJ, 658, 763

Eggen, O., Lyden-Bell, D., Sandage, A. 1962, ApJ, 136, 748

Faucher-Giguére, C.-A. 2011, MNRAS, 417, 2982

Ferguson, H., Dickinson, M., Williams, R. 2000, ARA&A, 38, 667

Finkelstein, S. et al. 2012, ApJ, 756, 164

Förster Schreiber, N. et al. 2009, ApJ, 706, 1364

Foucaud, S. et al. MNRAS, 2010, 406, 147

Grogin, N., et al. 2011, ApJS, 197, 35

Grützbauch, R., et al. 2011a, MNRAS, 411, 929

Grützbauch, R., et al. 2011b, MNRAS, 418, 938

Guo, Q., et al. 2011, MNRAS, 413, 101

Hammer, F., et al. 2009, A&A, 507, 1313

Hartley, W.G., et al. 2010, MNRAS, 407, 1212

Kauffmann, G., et al. 2004, MNRAS, 353, 713

Kelvin, L. 2012, MNRAS, 421, 1007

Le Fevre, O., et al. 2000, MNRAS, 311, 565

Lopez-Sanjuan, C., et al. 2012, A&A, 548, 7

Lotz, J., et al. 2008, ApJ, 672, 177

Lotz, J., et al. 2011, ApJ, 742, 103

Loveday, J., et al. 2012, MNRAS, 420, 1239

Madau, P., et al. 1996, MNRAS, 283, 1388

Marchesini, D., et al. 2010, ApJ, 725, 1277

Man, A., Toft, S., Zirm, A., Wuyts, S., van der Wel, A. 2012, ApJ, 744, 85

Mortlock, A. et al. 2011, MNRAS, 413, 2845

Miller, S.H., et al. 2011, ApJ, 741, 115

Murali, C. et al. 2002, ApJ, 571, 1

Mo, H.J., White, S.D.M. 1996, MNRAS, 282, 347

Ownsworth, J.R., Conselice, C.J., Mortlock, A., Hartley, W., Buitrago, F. 2012, MNRAS, 426, 764

Papovich, C., et al. 2011, MNRAS, 412, 1123

Penny, S.J., Conselice, C.J., de Reijcke, S., Held, E. 2009, MNRAS, 393, 1054

Stark, D.P., et al. 2009, ApJ, 697, 1493

Steidel, C. et al. 1996, ApJ, 462, 17

Taylor, E., et al. 2011, MNRAS, 418, 1587

Thomas, D., Maraston, C., Bender, R., de Oliveira, C. 2005, ApJ, 621, 673

Trager, S.C., et al. 2000, AJ, 119, 1645

Trujillo, I., et al. 2007, MNRAS, 382, 109

Weiner, B.J., et al. 2009, ApJ, 692, 187

Weinzirl, T., et al. 2012, ApJ, 743, 87

Yan, H., et al. 2012, arXiv:1112.6406