The Buildup of Early-Type Galaxies: Measuring the Formation and Assembly of Stellar Mass Since $z \sim 2.5$

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Executive Summary

Most of the stars in the universe today reside in massive spheroidal systems such as elliptical galaxies, S0 galaxies and massive spiral bulges (Fukugita, Peebles & Hogan 1998.) Over the past decade, we have found (1) that the epoch of formation of the stars in elliptical and S0 galaxies depends on galaxy mass, (2) that these galaxies probably have undergone significant structural evolution in the past 10 Gyrs and (3) that there is an important coupling between the growth of the mass of the galaxy and the growth of the super-massive black hole in the center. The key time of vigorous star-formation, black hole growth, and mass assembly happens at $z > 1.5$, a redshift difficult to observe with modern instrumentation. With 30-m optical/near-IR telescopes (GSMT), we can directly observe the star-formation of the progenitors of early-type galaxies at $z = 1.5 - 2.5$. Such observations will enable us to establish the aging and buildup of the stellar populations, and to time the growth of the black holes and how that relates to galaxy growth. More directly, we will assess what galaxies formed the majority of stellar mass, when and how that stellar mass was assembled into the early-type galaxy population we see today, and what processes stopped further star-formation. Answering these questions will result in us establishing how the bulge dominated galaxies, especially elliptical and S0's, we observe today came to be.

1. Early-type Galaxy Assembly

The traditional formation model for a spheroid has been binary mergers of spiral galaxies (e.g., Toomre & Toomre 1972). Modern high resolution simulations find that, in general, the result of the merger of two spiral galaxies looks mostly like an elliptical or S0 with some rotational support while mergers free of cold gas produce rounder, more slowly rotating remnants (Cox et al. 2006, Roberston et al. 2006). The assembly of $z = 0$ $L^\star$ spheroidal galaxies through mergers, especially those in the most massive dark matter halos, has been a key component in many of the semi-analytic models of galaxy formation. Because massive dark matter halos assemble through mergers relatively late in the history of the universe, a model where early-type galaxy formation is driven by mergers predict significant mass assembly at relatively late times (De Lucia et al. 2006.)

In contrast, some recent hydrodynamic simulations show that the large amount of dense gas present at high redshift can lead to the formation of spheroid-dominated galaxies (Naab et al. 2007, Dekel et al. 2009.) This rapid formation, where most of the stellar mass is assembled early, has some observational support. Recent galaxy surveys have found that the mass function of galaxies with $> 10^{11}$ $M_\odot$ changes little from $z \simeq 1$ until today (Brown et al. 2007, as one example) while the lower mass galaxies have significantly evolved (Brown et al. 2007; Faber et al. 2007). Studies combining models of dark matter assembly with the observations of galaxy distribution functions, often called Halo Occupation Distribution models, find that these galaxies with $> 10^{11}$ $M_\odot$ at $z = 0$ have assembled 80% of their stellar mass by $z = 1$ (Brown et al. 2008, Conroy & Wechsler 2009.)

In the next sections, we will outline the recent research in the evolution of spheroidal dominated galaxies. The observed properties and evolution of the $z < 1$ early-type population show that both significant mass assembly and star-formation occurring between $z = 1.5$ and $z = 2.5$. At these redshifts, the majority of all stars were likely formed, there was sig-

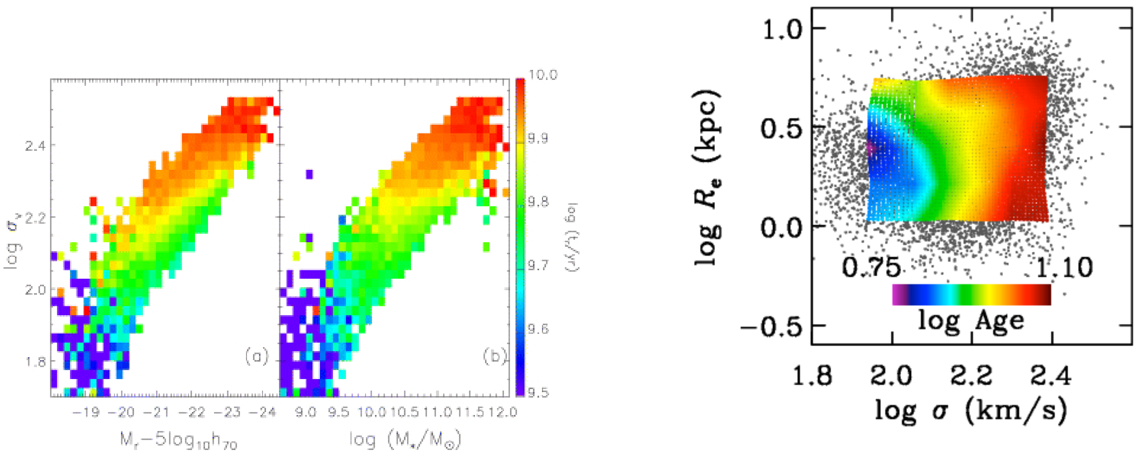

Figure 1: *Left:* Galaxy age in $\log_{10}$ years shown as a function of both M_r (a) or stellar mass (b) and velocity dispersion from Gallazzi et al. (2006). The colors indicate stellar population ages, the x-axis shows either the M_r or the stellar mass, and the y-axis shows the velocity dispersion. At a given stellar mass, galaxies with larger dispersions (i.e., deeper potential wells) formed their stars at earlier epochs. *Right:* The distribution of stellar population ages in $\log_{10}$ Gyrs, in color, as a function of velocity dispersion and radius from the sample of Graves et al. (2009). The dots show the sizes and dispersions of individual galaxies. On top of the dots is the log of the average population age of the galaxies in that part of the size-dispersion plane shown in color. The lines of constant age appear to be roughly parallel to lines of constant velocity dispersion. Graves et al. (2009) concludes from this, and other results, that the velocity dispersion is the important variable for determining the formation epoch of the population.

nificant black hole mass growth, and there is evidence, from the structure of these galaxies, that substantial mass assembly occurred.

1.1 When Did the Stars in Spheroids Form?

Elliptical and S0 galaxies in both the field and in clusters of galaxies, are clear examples of the trend that more massive galaxies have older populations of stars. The overall trend of increasing stellar population age for higher mass early-type galaxies has been found using models of the stellar populations fit to the spectra of local elliptical and S0 galaxies. We illustrate this in Figure 1. Both Gallazzi et al. (2006) and Graves et al. (2009) find that the age of the stellar populations in a early-type galaxy depends on its velocity dispersion. From these results, a galaxy with $\sigma \simeq 170 - 200$ km s^{-1} or 10^{11} M$_\odot$, formed the majority of its stars around $z \simeq 2$. Graves et al. (2009) find that the velocity dispersion, more than the mass, is the most important determinant of the population age. Dark matter halos that formed earlier are predicted to be denser and, therefore, have a higher dispersion than those that formed later. The correlation between dispersion and stellar population age could be clue that the majority of star formation occurred at a similar time as the dark matter halo formation.

The fundamental plane of elliptical and S0 galaxies uses measurements of the velocity dispersion and surface brightness profile to estimate the mass-to-light ratio (M/L) of a galaxy. The evolution in M/L is rapid for young stellar populations, then slows as the population ages. As we observe closer to the epoch of formation, the pace of the evolution in the M/L should increase. In Figure 2, we show a number of measurements of the M/L as a function of mass and redshift. As seen at low redshift, there is an overall trend where

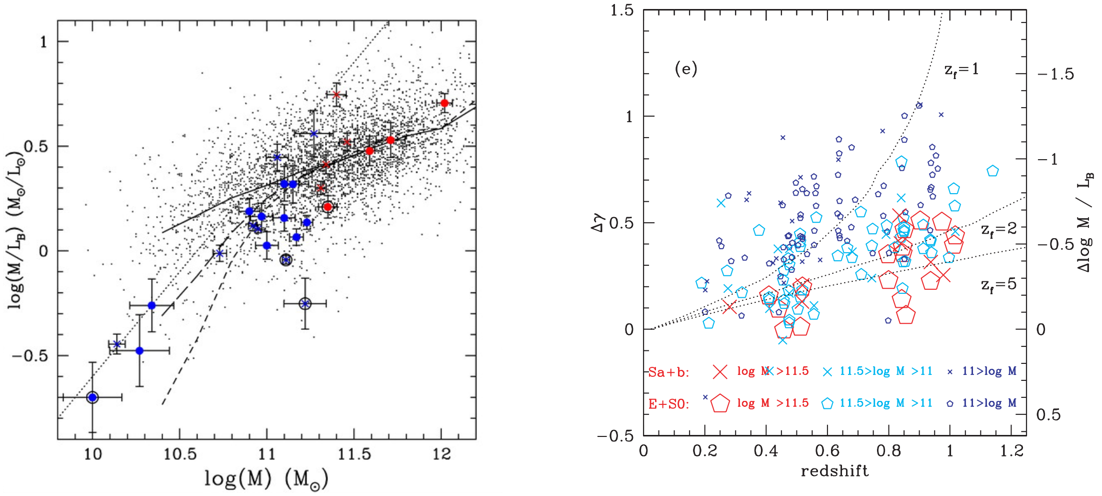

Figure 2: *Left:* the mass-to-light ratio (M/L) of a large sample of field elliptical and S0 galaxies from the Sloan Digital Sky Survey (small dots) as compared with a sample of early-type galaxies at $z \simeq 1$ selected from the HST GOODS-S survey (large symbols with error bars; van der Wel et al. 2005.) The change in the M/L found for the galaxies around 10^{11} M$_\odot$ (blue points) , is much larger than that found for the 10^{12} M$_\odot$ galaxies (red points). This difference can only be explained by a more recent epoch of star-formation for at least a subsample of the lower mass galaxies. *Right:* Evolution with redshift in M/L for galaxies at different masses from Treu et al. (2005). Dotted lines show the evolution in M/L for populations with different star-formation epochs. A typical galaxy with a mass of 10^{11} M$_\odot$, a $L^\star$ early-type at $z = 0$, formed most of its stars at $z \simeq 1.5$.

the most massive galaxies have the slowest evolution in the M/L and thus appear to have the oldest stellar populations, regardless of the galaxy's environment (Treu et al. 2005; van der Wel et al. 2005; Holden et al. 2005).

By $z = 2$, we are now finding the galaxies that are the likely progenitors of the $z = 0$ and $z = 1$ early-type galaxies discussed above. Using a color criteria to select older stellar populations (Franx et al. 2003; van Dokkum et al. 2003), a population of passively evolving galaxies has been identified at $z = 2.3$. This population has galaxies with $> 10^{11}$ M$_\odot$, no star-formation and lie on the red-sequence (Kriek et al. 2008). At the same redshift, star-forming selected samples have also uncovered galaxies with both significant masses and a large population of relatively evolved stars (Shapley et al. 2005; Erb et al. 2006.) There are galaxies at $z \simeq 2$ with the right stellar populations to become elliptical and S0 galaxies at low redshift. These galaxies sit at the bottom of deep potential wells and will continue accrete gas. What prevents further significant star-formation between $z = 2.3$ and today?

1.2 The Black Hole Growth/Galaxy Growth Connection

The cores of all spheroidal-dominated galaxies appear to harbor super-massive black holes, with the mass of the black hole increasing with increasing galaxy mass (see Magorrian et al. 1998, Ferrarese & Merritt 2000; Gebhardt et al. 2000; see Novak 2006a for more thorough discussion.) The growth of the central black hole and the growth of a galaxy's bulge, or spheroidal component, are clearly connected. Recent semi-analytical models have succeeded in providing a theoretical framework for this connection using feed-back from the output of active galactic nuclei (AGN; Bower et al. 2006; Croton et al. 2006.) In these models, as gas falls to the center of the galaxy, fueling the black hole, the output of the black

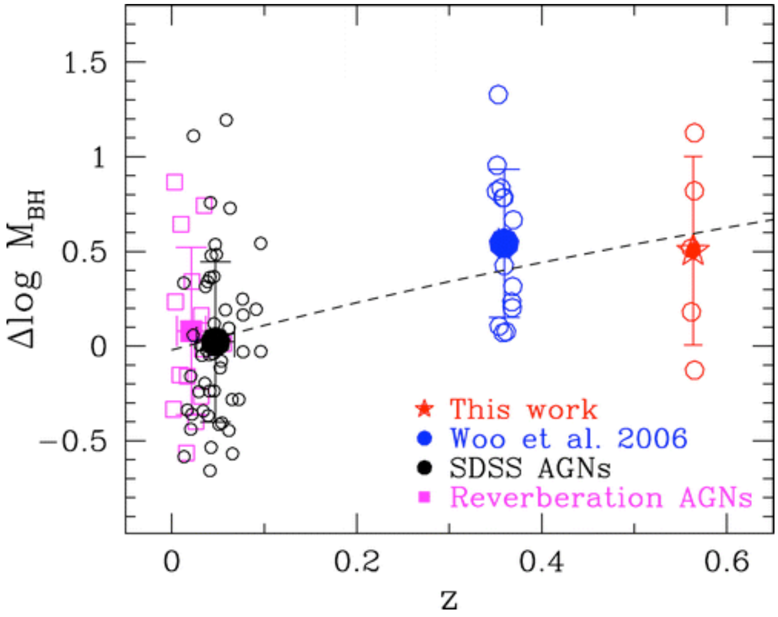

Figure 3: Offset of the black hole mass - galaxy mass relation as a function of redshift (Woo et al. 2008). The low redshift data (black points) and the high redshift data (blue and red points) all use the same black hole mass - optical line-widths relation. This relation is calibrated with the reverberation mapping measures of black hole masses, based on the local sample (magenta). At $z = 0.57$, the mass of the black hole for a given mass early-type galaxy grows by a factor of three, demonstrating that black hole growth happens before galaxy growth.

hole prevents further gas infall, thus "quenching" star-formation in the host galaxy as well as slowing further black hole growth.

In this model, the connection between black hole growth and galaxy growth would then be strong, with each regulating the other. The properties of emission lines in active galactic nuclei can be used to estimate black hole masses, when calibrated with more direct measurements at low redshift. Using the same fundamental plane measurements discussed above, various authors have found that the growth in mass of the galaxy trails behind the black hole growth (Woo et al. 2006; Peng et al. 2006; Woo et al. 2008; see Figure 3) and, even at $z = 3$ there is evidence that massive black-hole growth predates substantial star-formation in the host galaxy (Shields et al. 2006.) This raises two interesting questions. First, when did the black hole acquire the mass it has today? Likely, this occurred at a redshift of $z \simeq 2$, when 10^{11} $M_\odot$ galaxies have a large amount of AGN activity (Kriek et al. 2007) and QSO luminosity function peaks (e.g.; Richards et al. 2006). Second, if galaxies are less massive at a given black hole mass and black hole feedback is successful at shutting down star-formation, how did these galaxies grow in mass between $z \simeq 0.6$ and today?

1.3 Structural Evolution In Early-type Galaxies

Early-type galaxies are observed to undergo structural evolution between $z \simeq 2$ and today. Numerous authors have observed that at $z \simeq 2 - 3$, passively-evolving galaxies are smaller and denser than galaxies of the same mass are today (Trujillo et al. 2004, 2006; Daddi et al. 2005; Longhetti et al. 2007; Toft et al. 2007; Zirm et al. 2007; Cimatti et al. 2008; Franx et al. 2008; van Dokkum et al. 2008; Rettura et al. 2009) – see Figure 4 for examples. We show, in Figure 5, an summary plot of this evolution from van der Wel et al. (2008). This plot shows that the half-light radius of early-type galaxies at a fixed mass become smaller at higher redshifts with $r(z)/r(z=0) \propto (1+z)^{-1}$ in a smooth manner. The result is that the $z \simeq 2$ galaxies identified as the likely progenitors of today's $> L^{\star}$ early-type galaxies appear $\simeq 3-6\times$ smaller and $\simeq 20-200\times$ denser than the equivalent mass galaxies today.

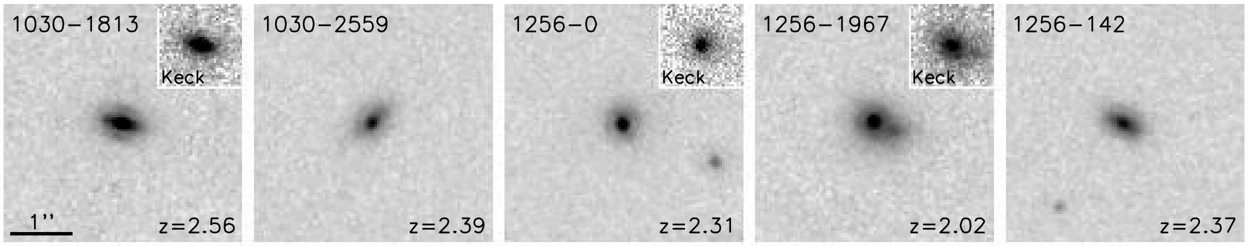

Figure 4: NICMOS Camera 2 images from van Dokkum et al. (2008) of 10^{11} $M_{\odot}$ galaxies at $z=2$. Each image is $\simeq$30 kpc on a side. Inset are three 1 hour K band Keck adaptive optics images compared to 2 hour NICMOS images. The sizes and surface brightness measurements from the Keck AO data agree well with those from the NICMOS data. Such AO observations will play an increasingly important role in the future. These distant galaxies are significant smaller, $\sim 1/3-1/6$ than the same mass galaxies today. We conclude that there must be significant changes in these galaxies, either mass assembly or structural evolution, between $z=2$ and today.

Simulations of early-type galaxy formation by merging, such as mentioned above (Cox et al. 2006; Robertson et al. 2006) show that the product of the merger of two galaxies strong depends on the size and gas content of the progenitor galaxies. The same simulations also show a dichotomy in the distribution of axial ratios of the products of mergers (Cox et al. 2006; Naab & Burkert 2006; Novak et al. 2006b; Burkert et al. 2008) with the gas rich mergers generating oblate spheroids and gas-poor mergers resulting in prolate triaxial systems. To date, studies of the axis ratio distribution of elliptical and S0 galaxies show no evolution, at least in clusters of galaxies at $z \simeq 1$ (Holden et al. 2009) but we expect significant changes at higher redshift, $z = 1.5-2.5$, when galaxies are observed smaller and denser at the same stellar mass.

2. Future Prospects: Observing Galaxy Assembly As it Happened

2.1 The Challenge

At both low and high redshift, we find evidence that the elliptical and S0 population is made of stars that formed around $z \simeq 2$. At that same redshift, we find evidence of black hole growth from studies of AGN in massive galaxies and we find that the likely progenitors of today's early-type galaxies are structurally different. The number density of galaxies at $z=2$ is 1/6 of the value we find today (Kriek et al. 2008), while by $z=1$ almost all of the population of massive galaxies is assembled (Brown et al. 2007). These results imply that very substantial amounts of mass assembly occurred between $z=2$ and $z=1$. What happened?

2.2 The Solution

We have the potential to directly observe the galaxy assembly process. The most impressive gains will come from GSMT 30-m class telescopes and adaptive optics. In Figure 4, we show adaptive optics images of $z=2.3$ early-type galaxies, taken in good conditions

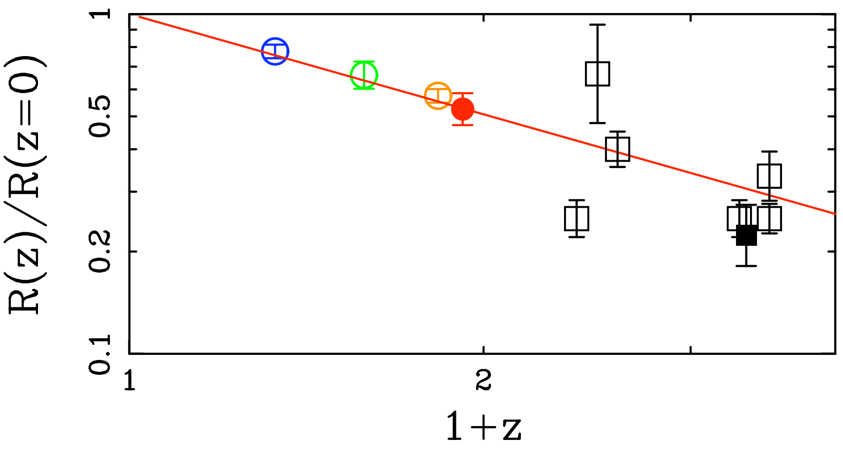

Figure 5: The sizes of galaxies with masses of 10^{11} $M_{\odot}$ as a function of redshift from van der Wel et al. (2008.) The solid red dot shows the ratio of the half-light radius of early-type galaxies from both field and cluster samples at $z \simeq 1$ to the half-light radius of galaxies of the same dynamical mass at $z = 0$. Open colored circles are a similar measurement made using a sample of cluster galaxies with stellar mass estimates. The higher redshift points (open black squares) are from the literature, with the solid square using the sample in Figure 4. For galaxies with masses of 10^{11} $M_{\odot}$, the galaxies half-light radius becomes smaller at higher redshift at a rate of $\propto (1+z)^{-1}$, shown with the red line.

but with a modest capability adaptive optics system on a 10-m telescope. Improvements in the capabilities of future adaptive optics system will concentrate a far higher fraction of the light in the diffraction limited core, thus providing higher signal-to-noise. The greatest advances will come from imaging and spectroscopy coupled with adaptive optics on 30-m class telescopes. A 30-m telescope will provide ≃20 milli-arcsecond images at 1.5-2.0μm, corresponding to ≃200 pc at z∼2. Current AO spectroscopic efforts can only measure the kinematic properties of star-forming regions of galaxies at $z = 2$ which have strong emission lines (e.g., Förster-Schreiber et al. 2006; Law et al. 2009). Studying the dynamics of the stellar populations is beyond their capabilities. Higher quality adaptive optics systems will provide detailed kinematics at sub-kpc resolution of the stars as well as higher quality imaging, surpassing the results from space telescopes (5× better resolution than JWST at 2μm). A 30-m class telescope with an advanced adaptive optics system could provide absorption line measurements of the velocity dispersions for all of the $z = 2.3$ galaxies in Figure 4 with one to two hour integrations.

Combining these capabilities will mean we can answer the following questions:

- When does the black hole grow? Can we show a direct causal link between AGN activity and the suppression of star-formation at $z \simeq 2$, when the early-type galaxy population formed most of its stars? Because galaxy stellar populations show a mass dependence, it is reasonable that the black hole mass growth may show a galaxy mass dependence. Testing mass-dependent cosmic evolution out to $z \simeq 2$ with a 30-m class telescope can lead us to understanding the role of black-hole mass in galaxy growth and regulating star-formation.

- Do the massive compact galaxies at high redshift have much higher velocity dispersions, as expected from their compact structure? Some models of early-type galaxy formation through merging predict much more oblate and rotationally supported galaxies at high redshift, while others predict the presence of a disk in all galaxies at high redshift. Absorption line velocity dispersions, shape measurements and measures of rotation are needed to test these predictions.

- What mode does the mass growth of the early-type galaxies happen? is the dominant form cold gas accretion or major mergers at $z \simeq 2$? The morphological properties and the dynamics of infalling gas, from AO spectroscopy, will provide direct measurements of these phenomena.

With a 30-m GSMT we could have the capability within 10 years to observe the assembly of the majority of the stellar mass in the universe today. We would observe where the stellar mass formed, what processes regulate star-formation, and how it was finally assembled into the massive elliptical and S0 galaxies we see today. The formation of these galaxies is one of the leading puzzles in astrophysics today, and the focus of a huge theoretical modeling effort. By the next decadal survey, this puzzle could be well along the path to being resolved.

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