Galaxy Evolution Studies with Deep, Wide-Field, Near-Infrared Surveys

A Whitepaper Submitted to the Decadal Survey Committee

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Executive Summary

The earliest phases of galaxy formation leave a vast array of imprints in the local universe in the form of bimodal galaxy properties, galaxy luminosity functions, large scale structure, and relations between galaxy morphology and density. Understanding the connection between these observables and the underlying build-up of dark matter halos lies at the core of understanding galaxy formation. In the next ten years, largely due to major advances in near-infrared detector development, we have the first opportunity to assemble a complete census of the most massive dark matter halos over a large fraction of the sky and a large fraction of cosmic history. Wide-area, near-infrared surveys can provide a census of all the stellar mass formed by galaxies up to $z \sim 5$. Using these data, we will identify the epoch during which the red-sequence of early-type galaxies formed, the (likely earlier) time that these massive galaxies formed their stars, the mechanisms that regulate star-formation in massive halos, and when the relation between morphology and density became established. More importantly, we will learn the physical mechanisms that govern these processes, such as gas accretion and the key role of active galactic nuclei in the formation of massive galaxies. Sensitive, wide-area, near-infrared surveys can address some of the most fundamental questions in galaxy formation:

- What are the relative timescales of galaxy formation and the formation of their constituent stellar populations?
- How does environment affect galaxy formation and evolution?
- What controls the star formation rate in galaxies?
- What is the relationship between dark matter halo mass and galaxy mass?

1 Introduction

Largely due to impressive *optical* surveys from the ground (e.g., SDSS, DEEP2) and from space (e.g., GOODS, COSMOS), the past decade of galaxy formation research has wrought a revolution by establishing the concordance between the growth of galaxies and dark matter halos. Over the past 12 billion years, the build-up of stellar mass has gone hand in hand with the build-up of large-scale structure and massive dark matter halos. However, despite this considerable progress on many fronts, we lack a clear physical understanding of galaxy formation. The fundamental mismatch between the luminosity function of galaxies and the mass function of dark matter halos teaches us that baryonic physics and feedback is vital to galaxy formation.

Understanding these formation processes will explain the strong dependence of galaxy luminosities and star-formation histories on the underlying dark matter halo mass. In effect, the physics of the formation of large halos and how these halos accrete gas determines much of the smaller scale physics, determining aspects such as star-formation histories, galaxy morphology and the growth of the supermassive black holes (SMBHs) in galaxy centers. In turn, these small scale physics regulate the larger-scale phenomena, turning off star formation in the most massive galaxies. How the evolution in galaxy properties, such as morphology or star-formation rate, depends on environment depends how these various feedback cycles are regulated.

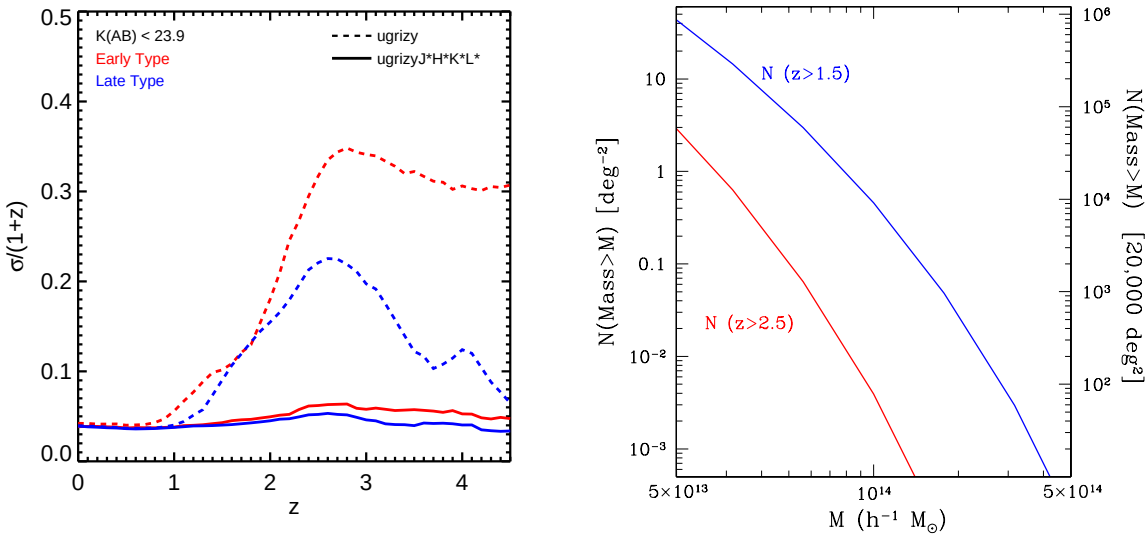

Figure 1: **(left)** Simulated photometric redshift accuracy for early-type (red) and late-type (blue) galaxies. The dashed lines show the expected performance for LSST alone. Solid lines include NIR data from *NIRSS*, a proposed deep-wide survey described briefly below (§6): NIR data vastly improve photometric redshift accuracies at $z > 1$. The simulations assume a 4% floor to these accuracies (Brodwin et al. 2006). **(right)** Predicted number of galaxy clusters as a function of halo masses for two redshift regimes, assuming $\sigma_8 = 0.82$, $\Omega_m = 0.27$, and $\Lambda = 0.73$.

To address these questions, deep, wide-area optical imaging surveys such as LSST and Pan-Starrs are being planned to operate in the next decade. To fully realize their enormous potential, similarly deep and wide-area near-infrared (NIR) imaging is essential. Complementary NIR surveys would provide two crucial enhancements for addressing the most important questions about galaxy formation and evolution: (1) the ability to obtain accurate photometric redshifts at $z > 1$, and (2) the ability to *select* galaxies at wavelengths that correlate with stellar mass and then to *measure* their ages and stellar masses. The necessity of obtaining deep-wide NIR imaging is illustrated in Figure 1 which shows the dramatic improvement in photometric redshifts at $z > 1$ when NIR data are used with optical photometry.

Below we discuss our ideas of how research on galaxy evolution needs to develop, and on the datasets needed to answer the most pressing questions for the next decade.

2 What are the relative timescales of galaxy formation and the formation of their constituent stellar populations?

Hierarchical galaxy formation scenarios imply that galaxy formation is a bottom-up process, proceeding from the agglomeration of small groups of stars into larger sub-galactic sizes before L^* galaxies are produced. The timescales of star formation and galaxy building have so far been difficult to ascertain. Galaxies at $z < 1$ are observed to divide into roughly two populations, strongly dependent upon their mass and current star formation rate (Hubble 1923, Kauffmann et al. 2003, Bell et al. 2004). Massive galaxies generally contain old, passively evolving stellar populations, while galaxies with ongoing star formation are less massive. This bimodality is clearly expressed in optical color-magnitude (CM) diagrams (CMDs). Luminous galaxies populate a tight "red sequence", and star-forming ones inhabit a wider

and fainter "blue cloud", a landscape that is observed at all times and in all environments from the present epoch out to at least $z \sim 1$.

The origin of this bimodality, and particularly of the red sequence, dominates much of the present discussion of galaxy formation. The central issues include: (1) when do stars form relative to the galaxies they end up in? (2) what kind of path in the CMD do galaxies trace over their evolutionary history? and (3) what physical mechanisms are responsible for the quenching of star formation which may allow galaxies to move from the blue cloud to the red sequence? Answering the first question would tell us whether galaxies are first quenched, and then grow in mass *along* the red sequence (*e.g.*, by dry mergers, in which there are no associated bursts of star formation – *e.g.*, van Dokkum 2005), or grow primarily through star formation and then quench directly onto their final position on the red sequence (*e.g.*, Faber et al. 2007).

Galaxy formation models are now able to reproduce the red sequence, at least at $z \simeq 0$, by positing that massive DM halos are able to form shock-heated, quasi-hydrostatic hot halos, which are suspectible to heating by AGN or other processes (e.g., Bower et al. 2006, Croton et al. 2006, Hopkins et al. 2008), while low-mass halos accrete gas in cold, dense filaments that cannot easily be heated (Dekel & Birnboim 2006). A prediction of this paradigm is that the critical mass separating "hot mode" halos from "cold mode" halos was larger in the past, so that at high redshift even very massive halos accrete much of their gas through cold, dense filaments that are likely impervious to AGN heating (Birnboim & Dekel 2007; Dekel et al. 2008). This means the models predict that *central* galaxies at $z \gtrsim 2$ are likely to be still forming stars, while some *satellite* galaxies in these halos may be quenched due to environmental processes. To test these predictions, large scale studies of the red sequence-blue cloud bimodality already undertaken at $z < 1$ by SDSS, GEMS and DEEP-2 must be extended to $z > 1$.

3 How does environment affect galaxy formation?

In the present epoch, there is a well-established correlation between galaxy morphology and both star formation rate and local galaxy density. In the lower density field environment, galaxies tend to be star-forming spirals, whereas elliptical galaxies with little or no recent star formation dominate the high density environments of galaxy clusters. The galaxy morphology-density relation persists to $z \sim 1$, at least, although there may be subtle changes in the mix of early and late galaxies towards higher redshifts. However, the denser environments such as galaxy clusters become increasingly rare at $z > 1$, where so far it has been impossible to carry out adequately large studies of the morphology-density and star formation-density relations. The expected numbers of clusters at the highest redshifts are shown in Figure 1 for half of the sky, making it clear that areas as large as ∼half of the sky must be surveyed to find sufficient numbers of the densest, most massive galaxy cluster environments at $z > 2$.

An important goal in the next decade will be to determine what happens to nascent galaxies in dense environments as they proceed from what we see in protoclusters at $z \sim 3$ to what we see in the well-defined red sequences of massive clusters at $z < 1$. It seems likely that the appearance of the red sequence will happen first in the densest environment and then spread to lower density environments such as groups before becoming established in the field. To carry out such a study, it is necessary to identify the full range of environments at $z > 2$, including massive galaxy clusters. A stellar mass selected galaxy cluster survey, where

candidates are identified via stellar-mass overdensities in a NIR selected galaxy sample using accurate photometric redshifts (Brodwin et al. 2006), should be effective as long as there are galaxies to be found within the dark matter halos. With this approach, the selection of a cluster candidate is *independent of the presence of a red-sequence* and of the presence of an ICM, and tied to the halo mass if the number of galaxies in a cluster scales with its dark matter halo mass.

The range in environment as a function of halo mass reaches $M > 10^{15}$ $M_\odot$ in the local universe. The greatest leverage in comparisons between galaxies in low and high density environments at $z \sim 0$ and $z \sim 3$ occurs if we sample a similar halo mass range at the higher redshifts. This requires a deep NIR imaging survey of most of the sky due to the fact that halos of mass $M > 10^{14}$ $M_\odot$ are exceedingly rare at $z > 2$ (Figure 1, right). The number of halos of mass greater than a few $\times 10^{14}$ $M_\odot$ expected per square degree in the concordance *WMAP* ΛCDM cosmology (Komatsu et al. 2008) is only $\sim 0.01\,\mathrm{deg}^{-2}$ at $z > 2$. Therefore, only a very large area survey would have the capability to *systematically* identify adequate samples of the first massive cluster scale objects at $z > 2$.

4 What controls the star formation in galaxies?

The relation between the central black-hole mass and the stellar mass of the bulge in galaxies indicates that active galactic nuclei play an important role in determining the star formation history of galaxies. Trying to understand the feedback processes due both to AGN and to other sources such as supernovae will be one of the key avenues towards a more complete understanding of what controls star formation during the building of stellar populations in galaxies over cosmic time. A key ingredient of this effort will be knowledge of the stellar masses of galaxies which means that we will need near-IR photometry.

Another important discovery from the past ∼decade is the way that the dependence of the star formation rate on environment appears to change with redshift. Elbaz et al. (2007) find that the star formation rate appears to increase with increasing local density at $z \sim 1$, though this study encompasses only the modest range of local galaxy density possible from a pencil-beam survey. Cooper et al. (2008), using the DEEP2 survey, show that in high density regions the fraction of luminous (L^*) galaxies on the red sequence increases from 5% at $z = 1.3$ to 15% at $z = 0.8$, but remains nearly constant (5%) over the same redshift range for galaxies in low local densities. Furthermore, much of the $1 < z < 3$ peak in cosmic star formation rate density (e.g., Dickinson et al. 2003) occurs in luminous or ultraluminous infrared galaxies (ULIRGS; Le Floc'h et al. 2005, Papovich et al. 2006) which at $z > 1$ have clustering amplitudes similar to those of galaxy clusters (Brodwin et al. 2007; Papovich et al. 2008), indicating they preferentially lie in rich environments. The implication is that even though at $z \sim 0$ dense environments such as galaxy clusters are virtually devoid of star formation, prodigious star formation rates associated with the assembly of massive galaxies occur in rich environments at $z \sim 2$ such as proto-clusters. This critical redshift is also the epoch where a transition in dominance of the modes of gas accretion onto galaxies is predicted to occur. These lines of evidence indicate that it will be necessary to identify and study the dense galaxy environments at high redshifts to gain a better understanding of the way that the peak star formation rate density appears to proceed from high to low density environments with decreasing redshift.

5 What is the relationship between halo mass and galaxy mass?

In this section we outline the generalized halo occupation distribution (HOD) approach to studying galaxy evolution with respect to dark matter halos that is complementary to the direct study of galaxies as described above. While galaxy formation and evolution are complicated because of baryon-related processes (gastrophysics), the formation and evolution of dark matter halos, which are dominated by gravity, are well understood with improving computational power and N-body simulations. By combining our knowledge of halo distributions (e.g., abundances and clustering) with the observed galaxy clustering, we are able to infer the relation between galaxies and dark matter halos within the HOD framework. The empirically inferred halo-galaxy at different redshifts would enable us to learn a great deal about galaxy formation and evolution and to constrain baryon-related processes. The advantages of having deep NIR data are that one can continue such analyses out to $z > 1$ while retaining a stellar-mass selected galaxy sample with excellent photometric redshifts.

The HOD (e.g., Jing et al. 1998, Peacock & Smith 2000, Seljak 2000, Scoccimarro et al. 2001, Berlind & Weinberg 2002) characterizes the galaxy-halo relation by the probability distribution of the number of galaxies of a given type in halos of a given mass, together with the spatial and velocity distributions of galaxies inside halos. HOD modeling, or the closely related "conditional luminosity function" (CLF) has been successfully applied to interpret galaxy clustering data from both low- and high-redshift galaxy surveys (Yang et al. 2005; Cooray 2006). It has proven to be a powerful tool for interpreting galaxy clustering and testing galaxy formation theory. With HODs inferred at multiple redshifts and the known theory of halo growth, informative constraints on galaxy evolution start to emerge (e.g., Zheng, Coil, & Zehavi 2007, White et al. 2007).

Galaxy properties probed in current HOD applications are mostly galaxy luminosity (stellar mass) and color. With a larger data set, we would be able to study the relations between the full range of observed properties for galaxies and dark matter halos, including luminosity, color, morphology, stellar mass, star formation rate, central/satellite status, and AGN activity (in different bands). These properties encode complementary information about galaxy formation and evolution. The joint distribution of these properties as a function of halo mass, if inferred from the data, would provide stringent tests on theories of galaxy formation. Linking these results at different redshifts would allow us to yield insights into the origin and evolution of the bimodal color distribution of galaxies, the feedback mechanisms, the role of mergers in star formation and AGN activities. To infer such joint distributions as a function of halo mass would require very large galaxy samples with accurate photometric redshifts that enable precise measurements of galaxy clustering at multiple redshifts for galaxy samples in fine bins of the multi-dimensional parameter space defined by the galaxy properties.

The combination of deep NIR with deep optical data from very wide area surveys would provide a unique opportunity to simultaneously conduct HOD analyses at multiple epochs in the range $0 < z < 5$. Using only optical data would restrict analyses to preferentially star-forming samples of galaxies at $z > 1$ due to the rest frame wavelengths being sampled. With the NIR data one would be able to address the following topics related to galaxy formation and evolution:

(1) Study the evolution of the relation between luminosity (stellar mass) and halo mass. It has been found that at $z < 1$, the relation between central galaxy stellar mass and host halo mass shows little evolution (Brown et al. 2008). If the relation persists up to $z \sim 3$, then

it would be possible to identify a remarkable scaling relation in galaxy formation. Otherwise, one would be able to identify a special epoch in galaxy formation and gain insights on the mechanism.

(2) Test the roles of hot and cold gas accretion in galaxy formation. One recent theoretical model (Dekel et al. 2008) predicts that the transition halo mass of cold to hot mode of accretion is expected to undergo rapid evolution at $z \sim 2$. This could be addressed through studying the evolution of the mass scales of halos hosting blue and red galaxies.

(3) Study galaxy evolution over the redshift range $0 < z < 3$. By combining the halo evolution and the inferred HODs at different epochs, it will be possible to establish an evolutionary link between galaxy populations at different redshifts. The growth history of central and satellite galaxies as a function of halo mass could be mapped out and the contributions from mergers and star formation could also be separated (Zheng et al. 2007). Together with HODs from lower redshift surveys (e.g., SDSS, AGES, DEEP2), our understanding of galaxy formation and evolution would be greatly enhanced.

6 Observational requirements

The science described above would require a very wide-deep NIR imaging survey, coupled with the planned optical imaging surveys such as LSST. Just as the near-IR UKIDSS, VISTA Hemisphere and VIKING surveys probe similar depths as the optical imaging surveys SDSS and DES to enable studies of galaxy evolution primary at $z < 1$ over large areas of sky, in the next decade we will need a NIR counterpart to the very deep optical data that will be obtained by e.g. LSST and Panstarrs-4. Extragalactic *Spitzer* surveys are limited to a few hundred deg^2 even in the warm mission era, and *WISE* will reach only to $z \sim 0.5$ for normal L* galaxies, so there is currently no mission that will enable us to fully exploit the very large area optical imaging surveys that will come online after 2010.

We describe briefly two projects which would meet these requirements. First, the *Near-IR Sky Surveyor (NIRSS)* is a concept for a medium-class NASA mission to conduct an all-sky NIR imaging survey. The mission would use a 1.4m class telescope to conduct a 2 year imaging survey in the JHKL bands, reaching 5σ depths $\sim 1\mu$Jy (~ 24 mag AB) in all four bands. Second, the Synoptic All-Sky Infrared (*SASIR*) survey is a concept that would use a new 6.5m telescope in San Pedro Martir, Mexico designed to repeatedly observe the infrared sky simultaneously in the $YJHK$ bands. With a FOV of $\sim$1 deg^2 per band, a 4 year survey would be able to observe $\sim$20,000 deg^2 roughly 10 times with a typical return time every 2 months. The 5 σ survey depth is expected to reach $0.6-1.5\mu$Jy ($24.5-23.4$ AB mag). SASIR is planned to be a privately funded, publically operated survey organized by the University of California in collaboration with astronomy institutions in Mexico (INAOE, UNAM).

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