Understanding Galaxy Assembly

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Introduction

Our present understanding of how galaxies form is based upon the idea that the visible portions of galaxies correspond to only a small subset of the total mass of a galaxy, most of which is contained by its dark matter halo. While a successful and elegant theoretical framework for dark matter halos exists, describing their growth via mergers from the initial fluctuations visible in the cosmic microwave background, it has proven incapable in predicting the visible properties of the galaxies themselves. The fundamental challenge is that the theory is phrased in terms dark matter, while our knowledge of galaxies is based on observations of light, as emitted by stars and gas. To relate theory and observables requires us to understand the process by which stars form in galaxies, and how the stellar and gas mass of a galaxy relates to its dark matter mass.

The central question that we pose in this white paper is: *how did galaxies evolve from primordial fluctuations to the well ordered but diverse population of disk and elliptical galaxies that we observe today?* Specific questions that are set for substantial progress in the coming decade are:

- When did the first galaxies form?
- How and when did galaxies assemble their stars and supermassive black holes?
- What triggers episodes of galaxy-scale star formation? What shuts them off?
- How do energetic feedback processes affect the galaxy formation process?
- What is the role of environment in driving galaxy formation?

Clearly, galaxy formation is a complex interplay of gravitational physics dominated by dark matter, baryonic physics of star formation, and high-energy physics near supermassive black holes. A comprehensive theory is still far away, so it is fair to say that progress will remain observationally driven for the foreseeable future. As we will show, many of the key observations are photon-starved with present 8-m class visible/near-IR telescopes and require investment in new facilities. Some observations will best be done from space with the James Webb Space Telescope, others can only be performed with future giant ground-based telescopes. A thoughtful strategy for progress will operate these facilities cooperatively.

Current state of progress

We will focus on the galaxy evolution in the key interval from redshift $z \sim 4$, when the first massive collapsed objects can be seen, to $z \sim 0.5$ when the assembly of massive galaxy structures is essentially complete and galaxies settled into their equilibrium shapes and dynamical states.
We have gleaned a fair amount of information from studies of the optical and infrared properties of modest sized samples of galaxies at $z > 1$. About half the stellar mass in present day galaxies was assembled in the $1 < z < 4$ interval (e.g., Marchesini et al. 2009), but there are substantial systematic uncertainties in the stellar mass determinations for individual galaxies, leaving the evolution and shape of the stellar mass function poorly constrained. In particular, current surveys do not probe low mass galaxies, the building blocks of modern systems, beyond z=1, as show in Figure 1 (left). Furthermore, the assumption of a Universal Initial Mass Function required to

infer stellar masses is increasingly disputed (Hoversten & Glazebrook 2008, Meurer et al. 2009, van Dokkum 2008a). Tracing accurate mass functions across cosmic time is necessary if we are to understand the relative importance of in-situ star formation versus mergers in galaxy assembly, and relate stellar mass assembly to the growth of dark matter.

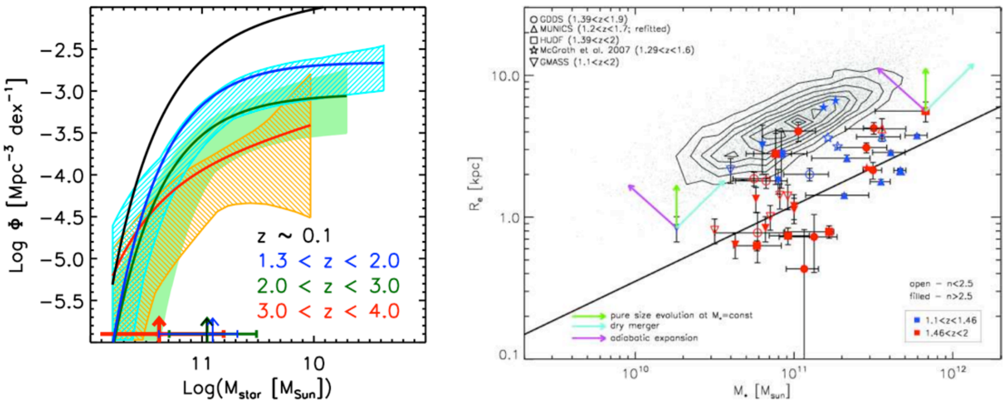

Figure 1. *(left)* The evolving galaxy stellar mass function from (Marchesini et al. 2009). Approximately 50% of the stellar mass was in place by z = 1, but large uncertainties remain beyond this redshift. *(right)* The mass radius relation for massive galaxies at 1 < z < 2 from Damjanov et al. (2009). The contours show the local population. Passive galaxies at z > 1 are a factor of 3 smaller than their present day counterparts and simple merger models have great difficulty in explaining the nearly pure size evolution apparent in the few Gyr between z ~ 2 and z ~ 1.

The shapes and sizes of galaxies provide an important independent probe of their dynamical and evolutionary state, e.g., through the classical scaling relations for spheroids, the fundamental plane and its projections. HST studies of spectroscopic samples from 8-m telescopes have shown that the correlation between stellar content and morphology seen locally (Kauffmann et al. 2003) is in place to z ~ 2 (e.g., Franx et al. 2008). One of the more remarkable discoveries in the past years concerns the small sizes and apparently high densities of massive quiescent galaxies at z > 1 (e.g., Daddi et al. 2005; van Dokkum et al. 2008b). In Figure 1 (right) we reproduce the mass-size relation for early-type galaxies from Damjanov et al. (2009). This plot appears to show dramatic evolution (by factors of 3) in the stellar mass density in galaxies over a relatively short interval of time. Such pure size-evolution is very difficult to explain in the context of dry merger models, which make galaxies more massive as well as bigger (e.g., Khochfar & Silk 2006), showing there are still fundamental problems in our picture of galaxy evolution. One clear, and untested, prediction emerges from dry merger models: the velocity dispersion should not evolve as mergers build objects (e.g, Ciotti et al. 2007).

The key to understanding the true dynamical state of galaxies and their evolution in the 1 < z < 4 interval are proper determinations of total (dynamical) masses. Clustering studies allows one to infer halo masses statistically (e.g., Adelberger et al. 2005), but not for individual galaxies. Accurate velocity dispersions are needed, which are currently achievable only for select bright star forming systems. In the case of the ultra-compact massive quiescent galaxies, velocity dispersion measurements are well beyond the capability of 8-m class telescopes.

While the robust determination of the evolving mass function may elucidate the growth of the halos that host galaxies, additional diagnostics are needed to relate this to the evolution of the stellar populations and interstellar matter (the “gastrophysics”). Studies of the star forming component have given a reasonable idea of the evolution of the integrated gas phase abundances to z ~ 3 (e.g. Erb et al. 2006). We have far less understanding of the photospheric abundances in galaxies at z > 1, with only tentative suggestions of (super-)solar abundances in massive early type galaxies at z ~ 1.5 (Halliday et al. 2008). The ages of the stellar constituents of even the most massive galaxies at z > 1 are also quite uncertain (e.g., Kriek et al. 2006). The key diagnostics lie in the rest-frame ultra-violet where flux densities drop precipitously once star formation has ceased. State of the art spectroscopy with 50-hour integrations on 8-m telescopes provide only crude ages for the passive galaxies to z ~ 2 (McCarthy et al. 2007).

What the coming decade can offer

The new generation of wide field near-IR imagers being developed for 8-m class telescopes will be sensitive enough to detect small stellar mass building blocks of galaxies up to z = 4 over a wide range of environments. Eight-meter telescopes, however, do not have the sensitivity or resolution to carry out the spectroscopy needed to understand the nature of the objects. The superior capabilities of JWST and GSMTs on the other hand will allow us to address the most urgent questions, of which we will discuss several here.

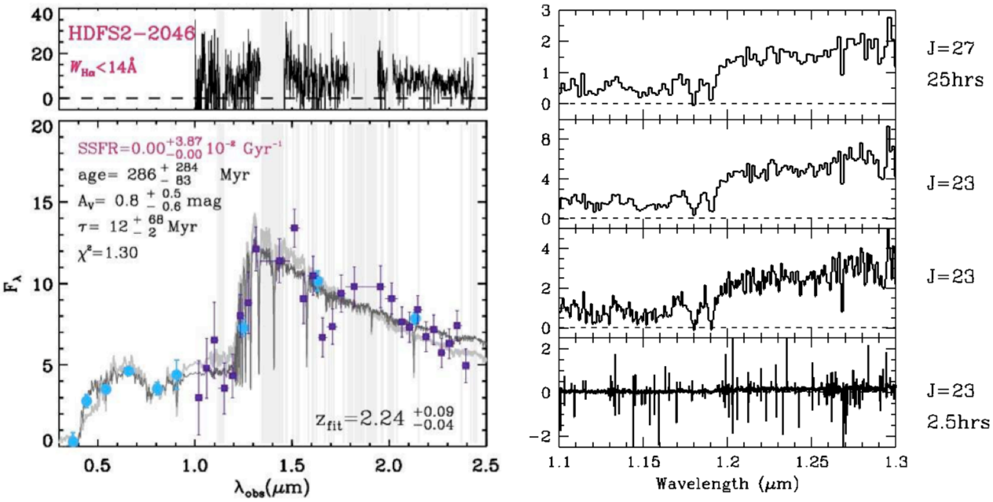

Figure 2. *(left)* State of the art near-IR spectrum of a massive red galaxy at z = 2.24 with GNIRS on Gemini. The upper panel is the raw sky subtracted spectrum, the lower panel shows the data binned *(purple squares)* and compared to a model SED. From Kriek et al. (2006). *(right)* Simulated spectra of a similar galaxy as observed with the 25-m GMT and its proposed near-IR multi-object spectrograph. The panels show (from bottom to top) the raw sky subtracted spectrum, a binned spectrum, a spectrum obtained with OH suppressing Bragg fibers and, last, a spectrum obtained with a noiseless photon counting detector and OH suppression.

Abundances and Stellar Populations: The near-IR regime is scientifically extremely rewarding beyond z = 1, providing a window on the familiar rest-frame optical spectral diagnostics that are crucial to constrain star formation rates, ages, kinematics, and abundances. Though gas phase metallicities have been measured for the brightest star-forming galaxies with current 8-m telescopes (Erb et al. 2006), *stellar* abundances, a fundamental measure of the history of galaxy assembly, are far more difficult to determine. The James Webb Telescope will revolutionize the study of gas-phase abundances in galaxies at intermediate and high redshifts. Absorption line indices sensitive to stellar populations and star-formation histories will also be essential to understanding mass assembly, the role of inflows and feedback from the IGM, and variations in the IMF. These investigations are beyond the reach of current facilities and require a GSMT-like telescope for progress, as is illustrated in the 8-m and simulated 25-m spectra in Figure 2.

Dynamical Mass Functions: Secure determinations of mass functions require dynamical masses for large numbers of objects over a range of masses. Significant progress depends on several key aspects: sufficient spectral resolution to resolve the velocity profile down to low masses (R > 3000), substantial multiplexing (> 50), and a large field of view. These requirements are well matched to the design specifications of planned instruments on GSMTs. Field of view is important for survey efficiency as it enables one to match target brightness, surface density on the sky, and depth, so that enough similarly bright sources are available. Fields of view of at least 5′ x 5′ are needed to efficiently sample the dynamical masses of galaxy populations at z > 2.

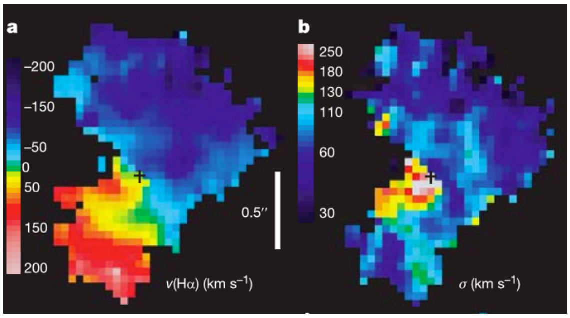

Figure 3. Velocity fields and dispersions from AO-assisted IFU observations with SINFONI on the VLT. The velocities are well fit by a smoothly rotating disk model. This object, however, has L ~ 5L* and is not representative of the bulk of the population. Typical z ~ 2 galaxies are both **fainter and smaller**. From Genzel et al. (2006).

Advanced Probes of Internal Properties: A major leap will be offered by the ability to probe the velocity fields and stellar populations of distant galaxies on scales of ~100 pc (~ 0.01" at z = 2). Currently we have access to crude global properties, but in the coming decade we will likely spatially deconstruct galaxies into their sub-galactic components. Such detail will help to finally address the age-old nature vs. nurture debate in galaxy formation theory (e.g. ELS, Toomre 1977), which remains with us until today. Modern semi-analytical models predict early assembly of massive galaxies driven by mergers (Croton et al. 2006), while hydrodynamic simulations suggest that today's ellipticals formed in a rapid collapse with only a small amount of mass added through mergers and accretion (Naab et al. 2007).

Current state-of-the-art high-spatial resolution IFU observations do not resolve the issue. Law et al. (2007) discuss objects at z ~ 3 dominated by kinematic dispersion and mergers whereas

Genzel et al. (2008) paint a picture of z ~ 2 massive rotating disks. Both pictures are likely incomplete: current observations are severely photon starved and can only see the brightest knots of star formation in the brightest galaxies. The example shown in Figure 3 is brighter than $5L^*$ and thus unlikely to be representative of the full population. The VLT and Keck simply do not have the required sensitivity, angular resolution, or both, to measure the dynamics of ordinary galaxies at z > 2. The James Webb telescope will provide rotation curves for many galaxies, but only on scales of a few kpc, to coarse to resolve the most compact structures. The next generation GSMTs, working at or near the diffraction limit can provide both the requisite sensitivity and resolution to unveil the internal dynamics of galaxies.

Synergies between JWST, ALMA, and GSMTs

Addressing the key questions in the big picture of galaxy assembly in the the next decade requires capabilities that exceed the design requirements of any single planned future facility. Rather, the new facilities operating jointly in a coordinated fashion will bring about the most dramatic progress. For example, GSMTs will benefit greatly from synergy with JWST. JWST has the advantage of a reduced background allowing unsurpassed survey speeds, detecting galaxies over the widest redshift range, and establishing redshifts and line luminosities from unresolved spectroscopy. From these samples, GSMTs with larger apertures, larger fields of view, and adaptive optics, will enable detailed follow up studies. These will include dynamical mass measurements for large numbers of sources and extremely detailed studies on the smaller spatial scales and higher spectral resolution than possible with JWST (see Figure 4).

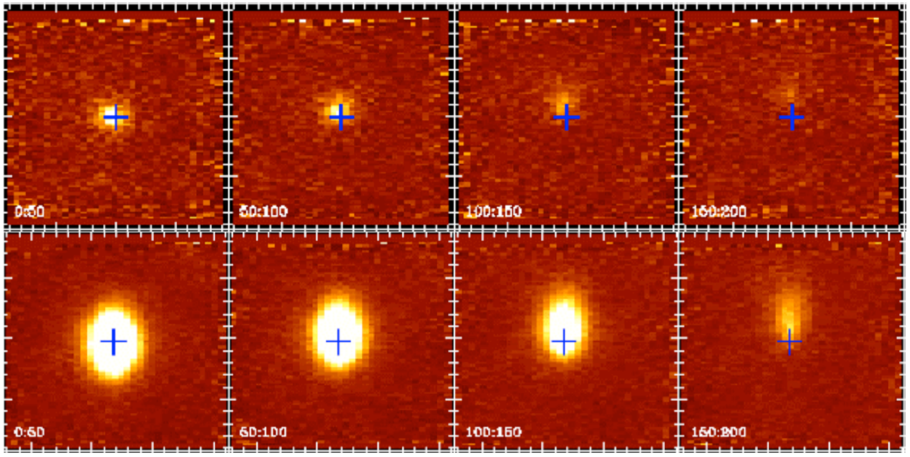

Figure 4. Simulated IFU Hα channel maps for a disk galaxy at z = 2.5. The upper panel shows simulated 50 km/s velocity channels for the NIFS instrument on the Gemini 8-m telescope. The bottom panel shows the same object as observed with a similar IFU on the GMT 25-m telescope. The gain is sensitivity allows one to probe fainter objects to larger radii or to sample on finer spatial scales. Each box is 2″on a side and 50 km/s wide.

In other respects, new facilities will offer completely complementary capabilities. Sub-mm surveys with ALMA, will uncover the dust-reprocessed emission from star formation and AGN to z = 10, and the cold molecular gas content and kinematics to z = 3. GSMTs will enable optical spectroscopy (rest-frame UV at 1.5 < z < 4), allowing the detection of a vast number astrophysically interesting ions that provide diagnostics of the shape of the stellar IMF, metallicity, stellar chemical abundances, and kinematics of the warm interstellar gas.

Summary

A full elucidation of the complex evolution of galaxies from seedlings at the earliest time to mature massive systems today requires highly detailed and sensitive observations to high redshift, well beyond current capabilities. The coming decade will bring revolutionary facilities, e.g., JWST, ALMA, and GSMTs, whose capabilities are strongly complementary in wavelength coverage, spatial and spectral resolution, and survey efficiency. In the table below we summarize how these facilities can work together to address the key questions raised in this white paper.

Science Question	Ground-based 8-m	JWST	ALMA	GSMTs
Global Mass Evolution	**Large area imaging surveys**	**Low mass end of distribution**	**-**	**Spectroscopy of large samples**
Internal Dynamics	**-**	**Large samples of line widths**	**Dynamics of cold gas**	**IFU studies at diffraction limit**
Stellar Populations	**Photometric samples**	**Low dispersion spectra**	**Obscured star formation**	**High resolution line indices**
Abundances	**Rare, bright objects**	**Nebular diagnostics**	**Molecular gas**	**Photospheric abundances**

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