Project Description
Galaxy Evolution in a Hierarchical Universe: Emerging Insights and Future Challenges

1. Overview of the Program

Contemporary galaxy formation models combine the well-established Λ Cold Dark Matter (ΛCDM) cosmology with baryonic physics to provide a general framework for galaxy evolution (e.g., Somerville & Primack 1999; Cole et al. 2000; Steinmetz & Navarro 2002; White et al. 2004; Springel et al 2005a,b; Springel & Hernquist 2005; Khochfar & Burkert 2005; Maller et al. 2006). However, the predictions on how galaxies evolve are not unique as they depend sensitively on the merger history of galaxies in the models, the baryonic physics (e.g., gas cooling, star formation (SF), and feedback from supernovae and AGN), and to some extent on the resolution of numerical resolutions (e.g., Mayer et al. 2008). In particular, the timescales and mechanisms through which the main baryonic components of galaxies – bulges, bars, and disks – assemble remain hotly debated. Furthermore, hierarchical models of galaxy evolution have been purported to exhibit several troubling inconsistencies with observations, including the angular momentum problem the sub-structure problem, and the problem of bulgeless galaxies (Navarro & Steinmetz 2000; Burkert & D'Onghia 2004; D'Onghia et al. 2006).

In order to glean direct insights into galaxy evolution, as well as test current models, my research program endeavors to set empirical constraints on the merger history, SF, and structural components of galaxies as a function of mass, redshift, and environment. This proposal focuses on three central themes, which are intimately related: *the structural assembly of galaxy components, particularly bulges, the problem of bulgeless galaxies, and the merger history of galaxies.*

In ΛCDM models of galaxy evolution, much attention has been directed at the assembly of bulges through major mergers. In a typical scenario, gas with low angular momentum settles in the inner regions of CDM halos where it forms small and dense protodisks (e.g., White & Rees 1978; Burkert & D'Onghia 2004). The subsequent major merger of these central stellar disks typically forms a classical bulge (e.g. Steinmetz & Navarro 2002; Naab & Burkert 2003; Burkert & Naab 2004; Mihos & Hernquist 1996), with a Sérsic index in the range $2 < n < 6$ (Hopkins et al. 2008, in prep.). A stellar disk subsequently forms around the bulge when hot gas in the halo cools, settles, and forms stars (Steinmetz & Navarro 2002; Burkert & Naab 2004).

However, often ignored are the roles played by minor mergers and secular processes in assembling bulges in a hierarchical Universe. During a minor merger, a tidally induced bar and/or direct tidal torques from the companion can drive gas into the inner kpc (e.g., Quinn et al. 1993; Hernquist & Mihos 1995; Jogee 2006 and references therein), where subsequent SF forms a compact high v/σ stellar component, or disky pseudobulge with $n \leq 2$. In addition, the stellar core of the satellite can sink to the central region. Secular scenarios, on the other hand, form bulges in *non-interacting* galaxies, via gas inflows driven by a stellar bar or globally oval structure (e.g., Kormendy 1993; Jogee 1999; Kormendy & Kennicutt 2004; Jogee, Scoville, & Kenney 2005), via vertical resonances and buckling instabilities in a stellar bar (Combes & Sanders 1981; Combes et al. 1990; Pfenniger & Norman 1990; Athanassoula 2005), and perhaps even via turbulence, dynamical friction and viscous processes at very early epochs (Genzel et al. 2008; Bournaud et al. 2008; Elmegreen et al. 2008).

In fact, we direly lack a quantitative assessment of the relative importance of different bulge formation pathways in spirals, and still cannot fully answer the following fundamental question: which of these three mechanisms account for most bulges in present-day massive spirals? An important first step is the study by Weinzirl, Jogee, Khochar, Burkert, & Kormendy (2008, hereafter WJKBK08; § 2.1A), which *rules out major mergers as the main pathway.* But many questions remain open regarding minor mergers and secular processes. A related thorny issue is that galaxies with no bulges (so-called bulgeless galaxies) are quite common in the local Universe (e.g., Böker et al. 2002; Carollo et al. 2007; Kautsch et al. 2006; Barazza, Jogee & Marinova 2008a, hereafter BJM08a; Kormendy & Fisher 2008). This prevalence of bulgeless galaxies has been coined the bulgeless galaxy problem, and even touted as a dramatic failure of ΛCDM models of galaxy evolution

In this proposal, we propose *a comprehensive exploration of the structural assembly of bulges, the properties of bulgeless galaxies, and the merger history of galaxies as a function of redshift out to* $z \sim 3$ *(lookback times* $T_{\rm b} \sim 11.5$ *Gyr*[1]*), and in different environments, ranging from fields to rich clusters* (§ 2.3 to § 2.5). Particularly exciting will be the opportunity to explore the properties of some of the most massive galaxies ($M_\star \geq 10^{11} M_\odot$) less than 3 Gyr after the Big bang, when the Universe was less than 16% of its present age (§ 2.5). We will use these observational constraints as a test-bed for hierarchical models of galaxy evolution. The PI has a long record of performing detailed comparisons with theoretical models or/and working closely with theorists in order to advance the concurrent development of the theoretical framework (e.g., Jogee et al. 1999, 2002a, 2002b, 2004, 2005, 2008b; Berentzen, Shlosman, & Jogee 2006; Heiderman, Jogee, et al. 2008; WJKBK08; § 2.1; Figs 1c and 2a).

While our proposed program may seem outlandishly ambitious, several key factors render it timely and feasible. Firstly, the PI is a a team member of five large science collaborations, namely GEMS (Rix et al. 2004), ACS-GOODS (Giavalisco et al 2004); Space Telescope Abell 901/902 Survey (STAGES; Gray et al. 2008, in prep.), the Coma Cluster HST ACS Treasury Survey (Carter et al. 2008); and NICMOS-GOODS (Conselice et al 2008, in prep.), and has access to the extensive reduced panchromatic ground-based, *HST*, *Spitzer*, and *Chandra* dataset. Furthermore, the PI and her research group are leading the science papers on barred galaxies in the GEMS, STAGES, Coma, and NICMOS-GOODS collaborations, as well as some of the papers on the history and impact of galaxy interactions. Thus, they have the necessary expertise for the proposed program. Finally, the PI and her students have already completed two extensive studies (WJKBK08; Jogee et al. 2008b; § 2.1), which develop the methodology, demonstrate the feasibility, and put forth some important results on the two core themes of this program: the assembly of of bulges and the merger history of galaxies.

Over the last 4 years, the PI has adopted a holistic approach to research, teaching, and education/outreach, and led two NASA-funded and one NSF-funded education and public outreach (EPO) programs (§3; See Chair's Letter). These have impacted tens of millions of people

[1]We assume a flat cosmology with $\Omega_{\rm m}$ = 1- Ω_λ = 0.3 and H_0 = 70 km s^{-1} Mpc^{-1} throughout.

and thousands of teachers and students, and culminated in a cutting-edge suite of activities and educational tools. Taking advantage of these extensive resources, we propose five timely teacher professional development workshops, focusing on exploring galaxies and the cosmos (§3).

The rest of the proposal is structured as follows. §2 presents our research program, §3 our EPO program, and §4 the results from prior NSF support.

2. Structural assembly and merger history of galaxies in a hierarchical Universe

2.1. Feasibility Tests and Recent Milestones from Two Pilot Studies

Below are highlights of two extensive studies (WJKBK08; Jogee et al. 2008b), which we conducted over the last two years. These studies act as a proof of concept for the proposed program since they develop the methodology that we will use, demonstrate the feasibility of the analysis, and put forth some important results on the two core themes of this program: the assembly of of bulges and the merger history of galaxies.

(A) Bulge n and B/T in High Mass Spirals: Constraints on the Origin of Bulges:

In the study by WJKBK08, we derived the bulge-to-total mass ratio (B/T) and bulge Sérsic index n by performing $2D$ bulge-disk-bar decomposition on H-band images of 146 bright, high mass, moderately inclined spirals. Most previous $2D$ decompositions have focused on two-component bulge-disk decomposition, and ignored the contribution of the bar even in strongly barred galaxies. However, as shown by this work and other recent studies (e.g., Laurikainen et al. 2005; Laurikainen et al. 2007; Reese et al. 2007), it is important to include the bar component in the $2D$ decomposition, in order to correctly estimate the bulge-to-total ratio (B/T) and disk properties. Interestingly, we find that as many as $\sim 56\%$ of high mass spirals have low $n \leq 2$ bulges: such bulges exist in barred and unbarred galaxies across all Hubble types (Fig. 1a). Furthermore a striking $\sim 66\%$ of high mass spirals have $B/T \leq 0.2$ (Figs. 1a and 1c). In addition we find that the frequency of stellar bars in galaxies with low $n \leq 2$ bulges is nearly two times higher than in spirals with classical bulges. This suggests there may be an intimate link between bars and disky pseudobulges.

Next we performed one of the first quantitative comparisons of the observed distribution of bulge B/T in high mass spirals to predictions from ΛCDM-based models of Khochfar & Burkert (2005) and Khochfar & Silk (2006). In these models, a bulge with a low $B/T \leq 0.2$ can exist in a galaxy with a past major merger, only if the last major merger occurred at $z > 2$ (lookback $>$ 10 Gyr; Fig. 1b). The predicted fraction of high mass spirals with a past major merger and a bulge with a present-day $B/T \leq 0.2$ is *a factor of over 15 smaller* than the observed fraction ($\sim$ 66%) of high mass spirals with $B/T \leq 0.2$. The comparisons *rule out major mergers as the main formation pathway for bulges in high mass spirals*, contrary to common perception.

In the models, the majority of low $B/T \leq 0.2$ bulges exist in systems that have experienced *only minor mergers, and no major mergers*. These bulges must be built instead via minor mergers and secular processes. So far, we explored one realization of the model focusing on bulges built via satellite stars in minor mergers (Fig. 1c). In paper II (Khochar et al. in prep.), future models will explore more realistic minor merger scenarios and secular processes.

(B) The history of galaxy mergers and its impact on SF over the last 7 Gyr:

In Jogee et al. (2008b), we present a comprehensive observational estimate of the frequency of interacting galaxies over $z \sim 0.24$–0.80 (lookback times of 3–7 Gyr), and the impact of these interactions on the SF of galaxies over this interval. Our study is based on *HST* ACS, COMBO-17, and Spitzer 24 μm data from the GEMS survey. We work with a large sample of ~ 3600 ($M \geq 1 \times 10^9$ $M_\odot$) galaxies and ~ 790 high mass ($M \geq 2.5 \times 10^{10}$ $M_\odot$) galaxies for robust number statistics.

We use two independent methods to identify strongly interacting galaxies: a tailored visual classification system complemented with spectrophotometric redshifts and stellar masses, as well as the CAS merger criterion ($A > 0.35$ and $A > S$; Conselice 2003), based on CAS asymmetry A and clumpiness S parameters. We find that for intermediate mass ($M \geq 1 \times 10^9$ $M_\odot$) galaxies, CAS can overestimate the merger fraction at $z > 0.5$ by a factor ~ 3. In effect, the CAS criterion misses about half of the visually-classified strongly interacting galaxies, but picks up a significant number of non-interacting dusty, star-forming galaxies. Thus, in the explorations of the merger fraction in the projects outlined in § 2.3 to § 2.5, we use a hybrid approach of a tailored visual classification, rather than a blind application of the CAS criterion.

While many earlier studies focused only on major mergers, we try to constrain the frequency of minor mergers as well. Among ~ 790 high mass ($M \geq 2.5 \times 10^{10}$ $M_\odot$) galaxies, the fraction of visually-classified interacting galaxies over $z \sim 0.24$–0.80, ranges from 9% $\pm$ 5% to 8% $\pm$ 2%. Lower limits on the major merger and minor merger fraction over this interval range from 1.1% to 3.5% , and 3.6% to 7.5%, respectively. This is *the first*, albeit approximate, empirical estimate of the frequency of minor mergers over the last 7 Gyr.

We also compare our empirical merger rate for high mass galaxies to predictions from different ΛCDM-based simulations of galaxy evolution, including the halo occupation distribution (HOD) models of Hopkins et al. (2007); semi-analytic models (SAMs) of Somerville et al. (2008), Bower et al. (2006), and Khochfar & Silk (2006); and smoothed particle hydrodynamics (SPH) cosmological simulations from Maller et al. (2006). To our knowledge, such extensive comparisons have not been attempted to date. *We find qualitative agreement between the observations and models, with the (major+minor) merger rate from different models bracketing the observed rate, and showing a factor of five dispersion (Fig. 2b).*

Finally, we explore the impact of interactions on SF. We find that the mean SFR of visibly interacting galaxies is only modestly enhanced compared to non-interacting galaxies over $z \sim 0.24$–0.80. Visibly interacting systems only account for a small fraction ($< 30\%$) of the cosmic SFR density over $T_{\rm b} \sim 3$–7 Gyr (Fig. 2b). This suggests that the behavior of the cosmic SFR density over the last 7 Gyr is predominantly shaped by non-interacting galaxies.

2.2. Central Questions

Building on the methodology and results presented in §2.1, we propose to tackle the following set of central questions in this research program:

(A) Do the frequency of bulgeless galaxies and the properties of bulges differ significantly between field and cluster environments (§ **2.3**)? What fraction of bulges are disky pseudobulges with low Sérsic index ($n \leq 2$), as opposed to classical bulges with $2 < n < 6$? Answers to this question provide an important test for hierarchical models of galaxy formation, which predict differences in the merger history as a function of galaxy morphology, mass, and environment (Cole et al. 2000).

(B) How does the frequency of bulgeless galaxies among field spirals change with redshift out to $z \sim 0.8$, when the Universe was half of its present age (**§ 2.4**)? Can hierarchical models even come close to reproducing the the frequency of bulgeless galaxies among high or low mass spirals as a function of redshift ? How do the SFRs and color of bulgeless galaxies compare to those of spirals with bulges, at a given stellar mass? What is the SF history and stellar populations of these systems? Do bulgeless galaxies host supermassive black holes (SMBHs), and if so, what are the implication for the origin of the tight relation between bulges and central BHs (Gebhardt et al. 2000; Ferrarese & Merritt 2000)?

(C) What are the properties of massive galaxies at ~ 1.5 to 3.0 (lookback times of 9.5-11.5 Gyr), when the Universe was a mere 16% to 30% of its present age (**§ 2.5**)? Are their rest-frame optical morphologies suggestive of interacting/merging systems, non-interacting relaxed systems, bulgeless disks, or assembling systems characterized by chains and clumps? How actively are they forming stars? Do these systems, particularly bulgeless ones, harbor SMBHS?

2.3. Bulge assembly and galaxy merger history in rich cluster environments

We will explore the issues in §2.2 (A) using the HST ACS Coma cluster Treasury survey (Carter et al 2008), on which the PI is a co-investigator. The survey provides high resolution (~ 50 pc at the distance of $\sim$100 Mpc) F475W and F81W images. While the ACS failure prevented the completion of the survey in the outskirt of the cluster, the core region has nearly complete coverage. As the richest and best studied local cluster, Coma will be used as the zero-redshift baseline for many studies of high-redshift clusters. We also have access to XMM-Newton data (Briel et al. 2001; Hornschemeier et al 2006), mid-UV and near-UV GALEX data (Hornschemeier private communication), VLA continuum maps (Miller et al. in preparation), and Spitzer IRAC (Jenkins et al. 2007) and MIPS (Bai et al. 2006) data.

We will identify flat superthin inclined bulgeless galaxies, defined as those with ellipticity $e > 0.8$ (Kautsch et al. 2006). An ellipse-fitting and analysis package has already been developed by Jogee et al. (2004) and consists of the following: (1) An iterative adaptive tool that automates the process of ellipse-fits such that a given fit adaptively 'learns' from previous fits; (2) An interactive analysis tool, where one can inspect the fitted ellipses overlaid on galaxy images, and then apply quantitative criteria to the radial profiles of ellipticity, PA, and surface brightness from ellipse fits, in order to identify and characterize the properties (ellipticity e, semi major axis a, PA, etc) of stellar bars and disks. Flat superthin galaxies can readily be identified by applying the criterion $e > 0.8$ to the outer disk ellipticity. We note that this ellipse-fitting and analysis package allows large samples to be efficiently analyzed, and has already been tested and applied to large samples locally and at intermediate redshifts: 1590 galaxies out to $z \sim 1$ in the GEMS survey (Jogee et al 2004); 260 optical and NIR images in the OSU survey of local bright spirals (Marinova & Jogee 2007); 2000 late-type SDSS disk galaxies at $0.01 \leq z < 0.03$ (BJM08a), 800 bright galaxies in the STAGES A901/902 supercluster survey at $z \sim 0.17$ (Marinova, Jogee, & the STAGES collaboration 2008); and 2256 disk galaxies in the EDisCS survey (White et al. 2005) of clusters at $z \sim 0.4$–1.0 (Barazza, Jablonka, Desai, Jogee & the EDisCS collaboration 2008b).

In addition to identifying flat superthin inclined bulgeless galaxies via ellipse fits, we will characterize the properties of the bulge, disk, and bar in *moderately inclined* ($i < 60°$) spirals by performing $2D$ bulge-disk-bar decomposition, as detailed in WJKBK08 (§ 2.1), on ACS I-band (F814W) images. We will use the bulge Sérsic index n in order to determine the relative distribution of low $n \leq 2$ pseudobulges and classical bulges with $n > 2$ in the core of the Coma cluster. This distribution will be compared with the field values from WJKBK08, as well as to model predictions. We will also investigate whether the host of pseudobulges are preferentially barred in clusters.

We will explore the stellar populations and color gradients in the bulge, disk, and bars of spirals in the Coma cluster. Complemented by K-band and IFU observations, the ACS F475W and F81W images can be used to interpret the observed color distributions in terms of ages and metallicities, using photometric techniques (James et al. 2006) and line indices (e.g., Poggianti et al. 2001; Sánchez-Blázquez et al. 2006). What are the relative ages and metallicities of pseudobulges compared to disks, and of pseudobulges compared to classical bulges?

We will also take advantage of the high resolution of the ACS data, as well as the X-ray observations from XMM-Newton and radio continuum data to investigate whether bulgeless galaxies and galaxies with very low bulge-to-total flux ratio harbor compact massive objects (CMO), such as supermassive black holes (SMBHs) and nuclear stellar clusters? It is well known by now that in bright ($M_{\rm B} <$ -20) galaxies, there is a tight correlations between the mass of the central SMBH and the properties of the bulge/spheroid component. In this context, the presence of SMBHs in flat superthin inclined bulgeless galaxies would present a challenge to several models postulating a symbiotic self-regulated growth of BH and bulges.

2.4. Bulgeless galaxies in field spirals over the last 7 Gyr

We will explore the issues in §2.2 (B) using the GEMS survey (Rix et al. 2004), which provides high resolution *HST* Advanced Camera for Surveys (ACS) images in the F606W and F850LP filters over an 800 arcmin^2 ($\sim 28' \times 28'$) field centered on the Chandra Deep Field-South (CDF-S). Accurate spectrophotometric redshifts [$\delta_{\rm z}/(1 + z) \sim 0.02$ down to $R_{\rm Vega} = 24$], and stellar masses (Borch et al. 2006) are available from the COMBO-17 project (Wolf et al. 2004). The effective point spread function (PSF) in a single F606W image is $\sim 0''.07$, corresponding to 260 pc at $z \sim 0.24$ and 520 pc at $z \sim 0.80$. In addition to *HST* ACS imaging, the GEMS field has panchromatic coverage which includes *Spitzer* (Papovich et al. 2004) and *Chandra* data (Alexander et al. 2003; Lehmer et al. 2005). The PI is a team member and has access to the survey data products, and multi-wavelength data.

We already know from visual classification of $\sim$ 3690 galaxies (Jogee et al 2008b) that many flat superthin inclined bulgeless galaxies are present over the redshift range $z \sim$ 0.24–0.8 (e.g., Fig. 2c). We will identify and quantitatively characterize these systems by using the same method outlined in §2.3, and applying the ellipse-fitting and analysis package developed by Jogee et al. (2004) to $\sim$ 3690 spirals of stellar mass $M_\star \geq 10^9 M_\odot$ over $z \sim$ 0.24–0.8. As described in §2.3, this methodology has already been tested and applied to large samples both locally and at intermediate redshifts, including 1590 galaxies out to $z \sim 1$ in the GEMS survey (Jogee et al 2004).

In order to assess how systematic effects, such as cosmological dimming, loss of spatial resolution, and selection biases affect the observed results, we will artificially redshift local flat superthin inclined bulgeless galaxies (e.g., from Kautch et al. 2006 and the Coma sample in §2.3) using the FERENGI software (Barden et al. 2008). While in WJKBK08, we focused on model-versus-data comparisons for high mass spirals at *local redshifts* ($z \leq 0.01$), here we will perform a more stringent test by comparing the observed frequency of bulgeless galaxies *as a function of redshift* versus model predictions.

A strategic advantage of using the GEMS sample is that we will be able to take advantage of the extensive study by Jogee et al. (2008b; see §2.1 B) of $\sim$ 3690 galaxies with $M_\star \geq 10^9 M_\odot$ over $z \sim$ 0.24–0.8. In particular, we can fold into our analysis their results on the frequency of interacting galaxies over $z \sim$ 0.24–0.80 (Fig. 2a). The derived merger frequency can be used to test the merger history in the models (Fig. 2a), along with their predictions on bulges. Additionally, the visual classes (S0, Sa, Sb-Sc, Sd, Irr) of the spirals will also be useful when comparing flat superthin inclined bulgeless galaxies to spirals with bulges.

The SFR (based on UV and Spitzer data) of the flat superthin inclined bulgeless galaxies will be compared to that of spirals with bulges. Using the public *Chandra* data, we will explore whether bulgeless galaxies are active and compare the frequency of bulgeless galaxies in active and non-active spirals. Finally, using the GALEX, Combo-17 UV to optical data, HST ACS images, and Spitzer IRAC data, constraints can be set on the ages and metallicities of these systems (James et al. 2006).

2.5. Assembly of Massive young galaxies within 3 Gyr after the Big Bang

While many large ACS surveys (e.g., GEMS, DEEP, GOODS, COSMOS, etc) have been conducted to date, even with the reddest ACS F850LP filter, we can only trace the rest-frame optical out to $z \sim 1$. At higher redshifts, we probe the rest-frame UV light, which traces young, massive stars, yielding little information on the underlying mass distribution. Thus, until now it has been difficult to robustly probe the structure and mass of galaxy components at early epochs.

We have recently completed a very large (180-orbits) deep NICMOS3 F160W GOODS survey (HST GO-11082), which probes the rest-frame optical light from galaxies over the interval $z \sim 1.5$ to 3.0, less than 3 Gyr after the Big Bang. This is an exciting era where the Universe was a mere 16% to 30% of its present age and numerous issues outlined in §2.2 (C) beg for an answer. The total area imaged in our program covers 1/3 of the ACS GOODS field and obtains data for 6500 objects down to a depth of F160W = 26.5(AB), with 3 orbits per pointing. The pointings were selected to target 60 very massive ($M_\star \geq 10^{11} M_\odot$) galaxies at $z > 2$ in the GOODS field. This constitutes one of the largest, if not the largest, sample of very massive galaxies at high redshifts. Furthermore within the area covered by our survey, there are also several hundred high mass ($M_\star \geq 10^{10} M_\odot$) objects.

The current NIC3 PSF ($0.3''$, corresponding to 2.5 kpc over $z \sim$ 1.5 to 3.0) is too coarse for carrying out robust $2D$ bulge-disk-bar decomposition (WJKBK08; § 2.1 A) of moderately inclined galaxies, but is adequate for quantifying the properties and fraction of flat superthin inclined bulgeless galaxies using the method based on ellipse fitting described in §2.3. If most bulges in massive spirals from through slow secular processes, there should be a high fraction of bulgeless galaxies at these epochs.

We will also classify the rest-frame optical morphologies of moderately inclined massive systems into different groups: interacting/merging systems, non-interacting fairly symmetric systems, bulgeless disks, or assembling systems characterized by chains and clumps. A hybrid approach based on tailored visual classification, and the CAS merger criterion will be used, as outlined in §2.1 B and Jogee et al (2008b). We will use an adaptation of the redshifting software FERENGI (Barden et al. 2008) to quantify redshift-dependent systematic effects, such as cosmological dimming and loss of spatial resolution. The morphologies are of particular interest given that recent studies show that many of the bright actively star-forming systems at $z > 2$ (Genzel et al. 2008) have turbulent rotating star forming rings/disks, plus central bulge/inner disk components, but show no signs of major mergers. This had led to the suggestion that secular processes in gas-rich proto-disks may be responsible for the stellar buildup observed in massive galaxies at $z \sim 2$ (Genzel et al. 2008; Bournaud et al. 2008). Using available UV-to-optical ground based SEDs, *Spitzer* data, and *Chandra* data for the GOODS field, we will also explore the SF and AGN activity among massive galaxies of different morphologies

We are also attempting to constrain the kinematics, dynamical state, rest-frame Hα emission, stellar population characteristics of these massive systems by requesting observing time for near-infrared long-slit spectroscopy (e.g., using GNIRS on Gemini-S). For systems that appear to be in virial equilibrium, the sizes from NIC3 images, combined with the velocity dispersions, will allow us to estimate their dynamical masses.

3. EPO: Exploring Galaxies and the Cosmos: A Teacher Professional Development Workshop

Over the last 4 years, the PI has strongly advocated a holistic approach to research, teaching, and education/outreach, while conducting scientific research in several large science collaborations (GEMS, STAGES, Coma ACS Treasury survey, and NICMOS-GOODS).

As the PI of the EPO program for the HST ACS Treasury Survey of the Coma cluster, she and her EPO team have produced 5 Stardate and 5 Universo radio programs on the Coma cluster, which aired in 2008 to a weekly audience of over ten million people; the StarDate and Universo Teacher's Guide, which are being distributed to thousands of teachers nationally; and class activities focusing on cluster galaxies. The Coma radio programs and HST images are being used in a ViewSpace program that will be shown in museums nationwide.

The PI has also led the EPO program 'Building a Bridge to Texas High School Science Teachers and Students', funded by NASA and NSF. She extended this effort by using a grant from UT's Division of Instructional Innovation and Assessment (DIIA) to develop the Galaxies and Cosmos Explorer Tool (GCET), an online tool (http://www.as.utexas.edu/gcet/; Jogee et al. 2007) to allow students to explore the evolution of galaxies over 8 billion years. The development of GCET was an interdisciplinary effort and the PI worked with graduate students from computer science (Achal Augustine) and DIIA (Aaron Smith), undergraduate astronomy student (Sarah Miller – now a 2008 Rhodes scholar), and astronomy educator Dr. Mary Kay Hemenway. GCET will also be used in a research class for 3rd/4th year undergraduates in 2009.

As the adviser for 72 Astronomy undergraduates and Dean's Scholars at UT Austin, the PI also joined forces with Computer Sciences, Math, and Physics to co-submit an interdisciplinary NSF STEM proposal (DUE-0807140) to help 1st/2nd year undergraduates achieve long term success in the STEM fields of Astronomy, Computer Sciences, Math and Physics, where women and minorities are under-represented. The proposal was just awarded $600,000 by NSF in 2008.

Proposed program : Building on our philosophy of integrating research, teaching, and education/outreach, we propose an EPO program that builds on our existing rich suite of activities and educational tools. We request funds to conduct 5 teacher professional development workshops focusing on exploring galaxies and the cosmos for high school teachers at McDonald Observatory. The goals of this five-year educational component are to (1) provide teacher professional development workshops for 75 teachers to offer them an experience to participate in galaxy activities in a classroom setting; (2) provide effective instructional activities on galaxies to high school teachers to use with their students

In each of years one through five, we will conduct a residential 3-day/2-night teacher's workshop for 15 teachers at the Observatory. The PI will participate in the planning of the workshop and materials and will attend a portion of the workshop annually to present her research, answer questions, and interact with the participating teachers.

Since 2001, McDonald Observatory has been presenting teacher professional development workshops (Hemenway & Redfield 2008) during the summer in Fort Davis, Texas, the beautiful mountainous site where the telescopes are located. For example, in the summer of 2008, McDonald Observatory is offering eight different professional development workshops. Examples of our teacher professional development recruiting webpage and a selection of photos from 2007 workshops are available on the McDonald Observatory webpage. Typically, during a summer our workshops will serve 120-150 teachers and we will have 80-100 teachers on a waiting list.

The workshops will align with the Texas Essential Knowledge and Skills[2] and the following National Science Education Standards[3] for content: 9-12 Science as Inquiry (abilities necessary to do scientific inquiry, understanding about scientific inquiry); History and Nature of Science (science as a human endeavor, historical perspectives, nature of scientific knowledge); Physical Science (interactions of energy and matter); Earth and Space Science (Origin and evolution of the universe); Science and Technology (understanding of science and technology, abilities of technical design)

The PI has already developed a rich suite of educational activities related to her research on galaxy evolution to be used in the professional development workshops. The activities include: *(1) The Galaxy Cosmos Explorer Tool (GCET)*: GCET is a web-based tool that encourages students to actively engage in quantitative analyses of *HST* images from the GEMS survey. The tool allows users to surf the cosmos and access ACS images of over 8,000 galaxies. Users can measure the size, determine the lookback time, perform morphological classification on images

[2]http://www.tea.state.tx.us/teks/

[3]http://www.nap.edu/html/nses/

in two rest-frame wavelengths, and gauge the different stellar populations present. Users can record their measurements, as well as reference information, such as coordinates and redshift, into Excel spreadsheets for further analysis. Other scaffolding activities have been created to help students build their understanding of galaxies in order to use the GCET tool. These include a Galaxy Classification Activity, a Multi-wave Length Astronomy Activity (Hemenway, Jogee, Fricke, Worhatch, & Ruberg, 2007), and a Lives of Stars Activity. A short course workshop has already been developed about the GCET tool and delivered at the Conference for the Advancement of Science Teachers in 2008, so we have experience presenting these materials already; *(2) Activities based on the HST ACS Treasury Survey of the Coma Cluster*: These are available in the StarDate/Universo Teacher Guide and online. Their contents are derived from the PI's work with HST ACS Treasury Survey of the Coma Cluster. All activities have been extensively tested in the classroom.

Additionally, a new high school activity, that is under development and will be completed over the next year, will use content from the deep GOODS-NICMOS survey, where the PI is a co-investigator. In addition to the classroom activities, the teachers will tour the observatory and share in the life of a research astronomer through mealtimes with the astronomers and tours of their telescope.

To meet our second goal of providing teachers with activities they can take back to the classroom, the new StarDate/Universo Teacher Guide[4] includes, among many activities, an activity on Stars and Galaxies, and the PI has StarDate radio programs online that can be used in conjunction with the Teacher Guide. (These are associated with and tied to the PI's research on the Coma Cluster.)

Other resources that will be produced over the next year can easily be integrated into the workshop content and/or the materials that teachers take back to the classroom. They include a DVD on careers in astronomy and a ViewSpace museum show about the Coma Cluster research. Teachers will receive all activities presented in the workshop and expanded versions of those activities on a CD-ROM to take back to their classroom. And finally, we arm teachers with materials they need to inspire their students to consider careers in science and technology when they get back to the classroom. Teachers take back our Department of Astronomy's undergraduate brochures, and posters to encourage students in STEM careers. Teachers also become acquainted with the 'What are Astronomers Doing?' website (Hemenway et al. 2004), which describes all the projects going on at the telescopes each week.

Target Audience: The target audience for this proposal is 9th to 12th grade science teachers who have traditionally underrepresented students. While we will recruit nationally for this workshop, it should be noted that the K-12 education population in Texas is inherently diverse. In 2005-6 (the most recent year for which Texas Education Agency has published statistics), 45% of Texas's 4.5 million students were Hispanic and 14.7% were Black. Almost 56% of Texas's students were economically disadvantaged. Texas has 1,227 school districts spread out in 7,956 campuses (including charter schools).

[4]The StarDate Universo Teacher Guide, Johnson, R. editor, The University of Texas McDonald Observatory, p. 30-37.

In Texas, the degree plans that most students will use, beginning with students who were high school freshmen in 2007-08, will require four years of science, instead of the three previously required. At the same time, by 2012-2013, Integrated Physics and Chemistry (IPC) will be phased out of the Texas high-school curriculum. A new state-mandated Earth and Space System Science course will be offered. In addition, fourth-year students have a state-approved course in Astronomy among those they can take. With these changes, Texas teachers and students will have a new need for access to standards-based content and to Astronomy experts, to help them effectively deal with the new curriculum, and the PI can help fulfill this need.

Evaluation: An outside evaluator, Dr. Cynthia Roberts-Gray with Third Coast Research and Development, will design and analyze the evaluation. A process and outcome evaluation is planned. We plan both a formative and summative evaluation (Frechtling & Sharp, 1997). The team will evaluate implementation to insure that the project is being carried out according to the timeline, determine whether key milestones are being met, and reflect on accomplishments. With the help of the evaluator, the team will formulate specific questions about outcomes achieved and lessons learned, and find appropriate methods to address these to serve both the needs of the project and NASA.

Formative evaluation will consist of daily opportunities for open-ended discussion of the content and pedagogy delivered within the activities. At the conclusion of the workshops, focus groups will form to reflect on the following themes: (1) How do the activities and experiences at the workshop support the participants' learning?; (2) How do the activities and experiences at the workshop support teaching? (3) Did the workshop provide an adequate range of resources to meet the needs of the participants? Two months after the workshop, the participants will receive a questionnaire concerning their implementation of the workshop experience. Four months after the workshop, a sample of participants will be interviewed concerning their impressions concerning the workshop and how they have implemented the workshop experience into their classrooms.

4. Prior NSF Support

The PI was awarded an NSF grant (NSF AST-0607748), entitled 'Bars and their Impact on Galaxy Evolution over the Last Eight Billion Years', for the period 09/1/2006 to 09/1/2009. Results from the first 2 years are outlined below.

Publications: From 2006 to 2008, we have produced 12 journal papers, with 7 of these led by the PI and members of her research group at UT (graduate students I. Marinova, A. Heiderman and T. Weinzirl, postdoc F. Barazza, and undergraduate Dean's scholars S. Miller and K. Penner). The journal papers include: (1) Marinova, I. & Jogee, S. 2007, ApJ, 659, 1176; (2) Barazza, F. D., Jogee, S., & Marinova, I. 2008a, ApJ, 675, 1194 (BJM08a); (3) Barazza, F. D., Jablonca, P., Desai, V., Jogee, S., Aragón-Salamanca, A., & the ESO Distant Clusters Survey (EDisCS) collaboration 2008b, ApJ, submitted; (4) Caldwell, J. A. R. et al. 2008, Apjs, 174, 136; (5) Carter, D., et al. 2008, ApJ, 672, 776; (6) Weinzirl, T., Jogee, S., Khochfar, S., Burkert, A., Kormendy, J. 2008, ApJ, submitted (arXiv:0807.0040; WJKBK08); (7) Jogee, S., et al. 2008b, ApJ, submitted; (8) Heiderman, A., Jogee, S., & the STAGES collaboration, 2008, ApJ, submitted; (9) Marinova, I., Jogee, S., & the STAGES collaboration, 2008, ApJ, submitted; (10) Gallazi, A. et al. 2008, ApJ, submitted; (11) Somerville, R. S. et al. 2008, ApJ, 672, 776;

(12) Heymans, C., et al. 2008, MNRAS, 385, 1431;

In addition, we produced 16 conference papers, which are listed in the reference section. All the papers were led by the PI, members of her research (Marinova, Heiderman, Weinzirl, Barazza, Miller, Penner), and EPO collaborators (Hemenway, Fricke) The contributions include a AAS Plenary lecture given by the PI (Jogee, S., 2007, BAAS, 211, #88.01), an invited talk at the 2008 IAU Symposium 254, and an invited talk at the conference on 'Galaxy and Black Hole Evolution: Towards a Unified View' (Jogee 2007).

Results from EPO program: The EPO program 'Building a Bridge to Texas High School Teachers and Students' supports the creation of a galaxy evolution activity using GEMS data, presenting teacher professional development workshops at the Conference for the Advancement of Science Teaching (CAST) to train teachers to use these activities, and conducting videoconferences with the classrooms of teachers who attend the professional development workshops. Additional funding from NASA/STScI and a FAST Tex (Faculty And Student Teams for Technology) grant for Instructional Innovation Techniques from UT have allowed us to create a total of five activities on galaxy evolution that can be used in a high school classroom over a one-week period. Each activity builds upon the knowledge gained in the previous activity. Advanced classes can enter into the five-step program at whatever knowledge level is appropriate.

The first of five activities focuses on the differences in galactic structures and how galaxies are classified. The second activity covers multiwavelength astronomy, Wien's Law, resolution, and the different galactic features that can be viewed in various wavelengths (Hemenway, Jogee, Fricke, Worhatch, & Ruberg, 2007). The third activity covers stellar evolution, focusing on colors and masses of different stars. The fourth activity will address cosmology, redshift, and the expansion of the Universe. The fifth activity provides instruction on how to use GCET (Jogee et al. 2007).

The first three of five activities are complete. We are still in the early stages of planning how to bring cosmology, redshift and expansion of the universe into the fourth activity and use the GOODS-NICMOS data. The fifth activity, a six-page student guide for using GCET has been created and field-tested with high-school teachers with positive results. It will be tested soon with students and then released for use.

A short-course workshop on GCET was presented at the November 2007 CAST meeting in Austin, Texas. Another workshop will be presented at a mini-CAST in 2008-2009. The PI will do the videoconferences with the classrooms of the teachers that attend the mini-CAST during the International Year of Astronomy (2009). And finally, we are working with Google Earth and Sky to make GCET available to Google users.

Results from the research program: Below is a summary of some of our results

(1) Establishing the $z \sim 0$ point for bars in the field: We complemented the GEMS study of bars over $z \sim 0.2$ to 1.0 (Jogee et al 2004) with two local studies (Marinova & Jogee 2007 and Barraza, Jogee, & Marinova 2008a) in order to nail down the rest-frame optical 'zero-redshift' point for bars. In Marinova & Jogee (2007), we found that the bar fraction is $\sim 44\%$ in the rest-frame B-band, where dust and SF obscure about 1/3 of the bars visible in the NIR. After applying to the local data, the same cutoffs in magnitude, bar size, and bar ellipticity ($e_{\rm bar} \geq 0.4$),

which are relevant for strong bars out to $z \sim 1$ in the GEMS survey, we find that the observed decline in the optical bar fraction from $36\% \pm 6\%$ to $24\% \pm 4\%$ over $z \sim 0.2$ to 1.0 in GEMS (Jogee et al. 2004) may in large part be due to redshift-dependent systematic effects. A similar result is obtained by Barraza, Jogee, & Marinova (2008a), where ~ 2000 late-type disk galaxies in SDSS at $0.01 \leq z < 0.03$ were analyzed using the bar analysis package and quantitative criteria established in Jogee et al. (2004). Interestingly we found that disk-dominated galaxies with no bulge or a very low B/T display a significantly higher optical bar fraction ($> 70\%$ vs 40%) than galaxies with prominent bulges. Furthermore, our study finds that $\sim 20\%$ of disk galaxies appear to be 'quasi-bulgeless', presenting a potential challenge to ΛCDM models.

2. Bars as a function of environment: While bars in the field have been widely studied, comparatively little is known about the frequency, properties, and impact of bars in rich clusters. Using the bar analysis package and quantitative approach established in Jogee et al (2004), we are currently exploring bars in clusters through three studies: a study of 800 bright galaxies in the STAGES A901/902 supercluster survey at $z \sim 0.17$ (Marinova, Jogee, & the STAGES collaboration 2008); a study of 500 galaxies in the ACS treasury survey of the rich Coma cluster at $z \sim 0.025$ (Weinzirl, Jogee, & the Coma collaboration, in prep.); and a study of 2256 disk galaxies in the EDisCS survey of clusters at $z \sim 0.4$–1.0 (Barazza, Jablonka, Desai, Jogee & the EDisCS collaboration 2008b). Our early results from the STAGES survey suggest that the optical bar fraction in the A901 and A902 clusters is similar to that of the field, and shows no significant trend with any local environment tracer (Marinova, Jogee, & the STAGES collaboration 2008).

3. Bulge n and B/T in High Mass Spirals: Constraints on the Origin of Bulges: The results of this paper (WJKBK08) are described in §2.1 A.

4. The history of galaxy mergers and its impact on SF over the last 7 Gyr: The results of this paper (Jogee et al 2008b) are described in §2.1 B.

5. Properties and Impact of Interacting Galaxies in the A901/02 Supercluster from STAGES: While the paper in (4) focuses on *field* galaxies, the study by Heiderman, Jogee & the STAGES collaboration (2008) explores galaxy interactions in the denser environments of *rich clusters* within the A901/02 supercluster at $z \sim 0.165$. Our findings are: (1) The fraction ($f_{\rm int}$) of strongly interacting galaxies is 0.049 ± 0.013, with at least 0.015 ± 0.005 being major interactions. (2) The strongly interacting galaxies lie outside the cluster core in the region between the core and viral radius. Based on comparison with N-body simulations, we suggest that this is due to groups being accreted by the A901/902 clusters; (3) The average SFR is enhanced by a factor of ~ 2 to 4 in strongly interacting galaxies compared to non-interacting galaxies. However, strongly interacting galaxies only contributes 20% of the total SFR density, while 80% comes from galaxies whose SFR is significantly depressed at a given stellar mass compared to field galaxies. The SFR depression is seen from the core out to the virial radius, implying that the driving mechanisms must be effective over a large range of radii.

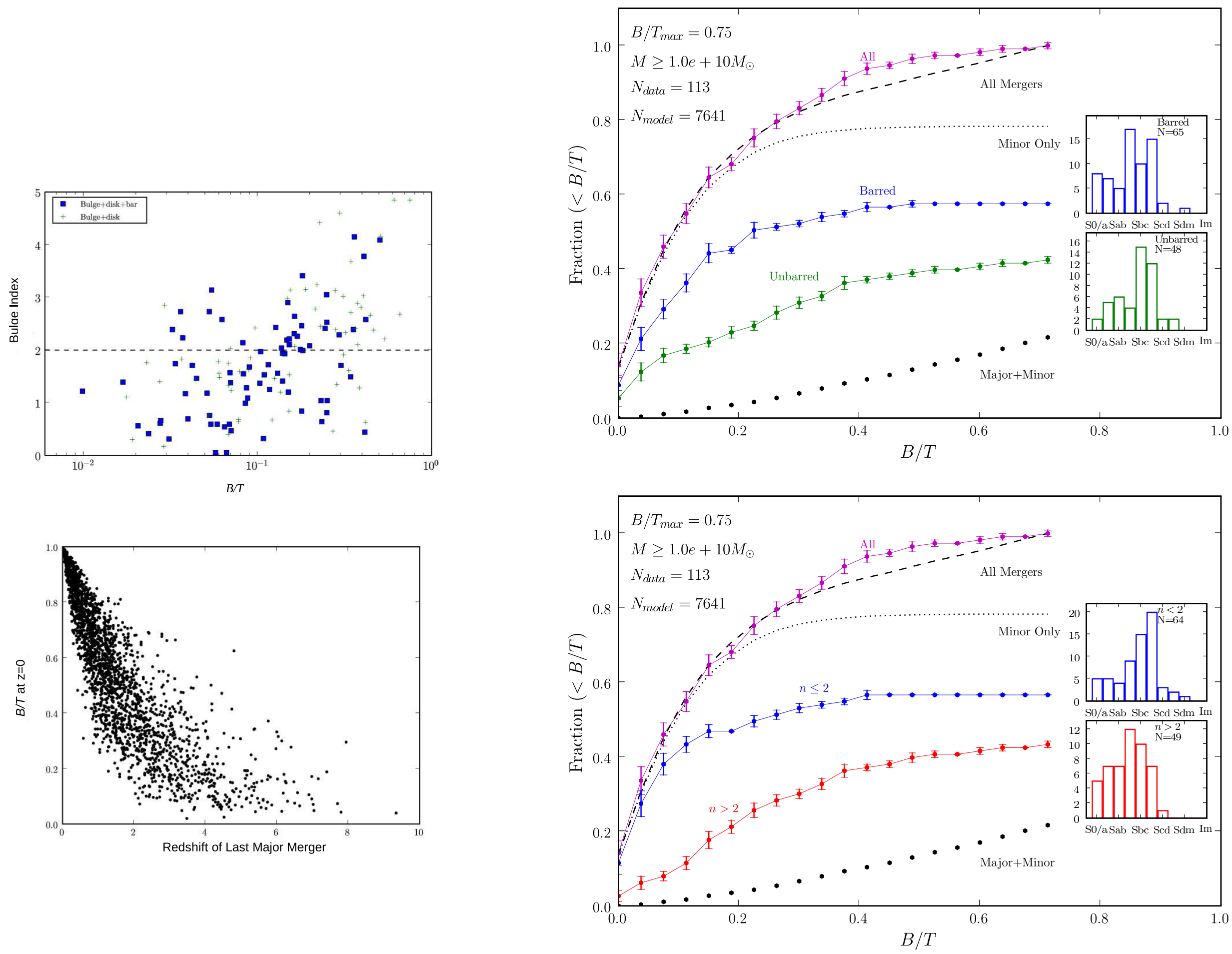

Fig. 1.— **(a) [Top Left]:** The empirical relation between B/T and bulge Sérsic index n is shown. The legend indicates the type of decomposition used. *As many as* 60% *of bright spirals have low* $n \leq 2$ *bulges: such bulges exist in barred and unbarred galaxies across all Hubble types, and their* B/T *ranges from 0.01 to 0.4, with most having* $B/T \leq 0.2$. **(b) [Bottom Left]:** For those galaxies that experienced a major merger in the ΛCDM-based models of galaxy evolution, the B/T of the remnant at $z \sim 0$ is plotted against the redshift z_{last} of the last major merger. Systems where the last major merger occurred at earlier times have had more time to grow a disk and thus have a lower B/T at $z \sim 0$. A galaxy with a past major merger can have $B/T \leq 0.2$ only if its last major merger occurred at $z > 2$ (lookback time > 10 Gyr). **(c) [Right]:** We compare the empirical distribution of bulge-to-total mass ratio to predictions from the models for high mass spirals. The y-axis shows the cumulative fraction F of galaxies with $B/T \leq$ a given value. The colored lines represent the data. The black dashed line shows F from all model galaxies, while the black dotted line and black dots show galaxies that experienced, respectively, *only past minor mergers* and *both major and minor mergers*. In the models, the fraction ($\sim 3\%$) of high mass spirals, which have undergone a past major merger and host a bulge with $B/T \leq 0.2$ is *a factor of over 15 smaller* than the observed fraction ($\sim 66\%$) of high mass spirals with $B/T \leq 0.2$. Thus, *bulges built via major mergers seriously fail to account for most of the low* $B/T \leq 0.2$ *bulges present in* $\sim$ *66% high mass spirals.* [All figures are from Weinzirl, Jogee, Khochar, Burkert, & Kormendy (2008). See §2.1A for details.]

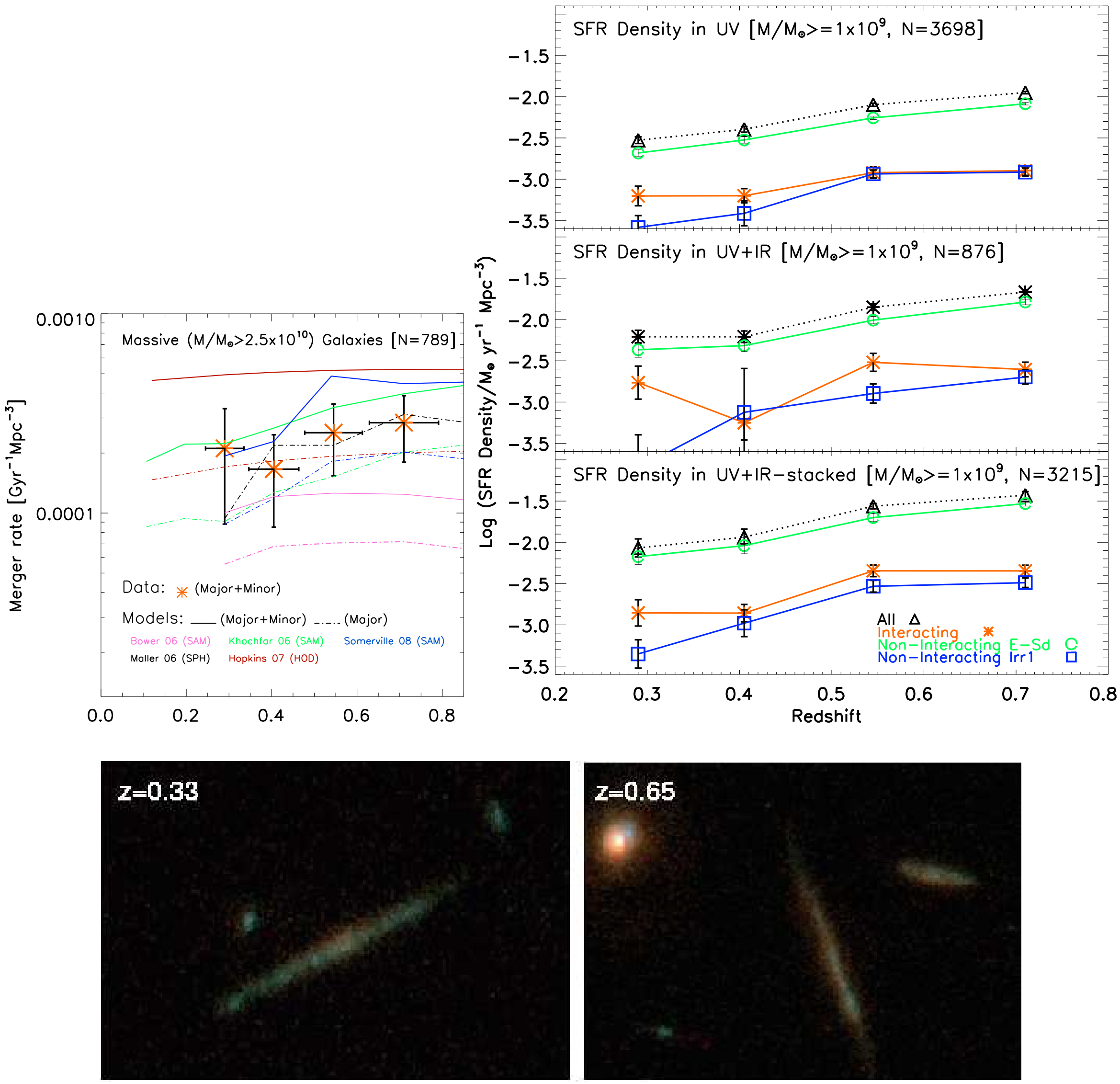

Fig. 2.— **(a) [Top Left]:** The empirical rate of galaxy mergers with mass ratio $M1/M2 > 1/10$ (orange stars) among high mass galaxies is compared to the rate of (major+minor) mergers (solid lines) predicted by different ΛCDM-based models of galaxy evolution over $z \sim 0.24$–0.80 or lookback times of $\sim$ 3–7 Gyr (from Jogee et al 2008b; §2.1B). **(b) [Top Right]:** We compare the contribution of interacting and non-interacting galaxies to the total SFR density for $M \geq 1.0 \times 10^9$ $M_\odot$ systems. The SFR density is shown based on UV (top panel), UV+IR (middle panel; based on only 876 galaxies with 24um detections), UV + stacked-IR (based on 3215 galaxies with 24um coverage) data. In all three cases, interacting galaxies only contribute a small fraction (typically below 30%) of the total SFR density over $z \sim 0.24$–0.80 (from Jogee et al 2008b; §2.1 B) **(c) [Bottom]:** Examples of superthin flat inclined bulgeless galaxies at different redshifts in GEMS. The image is a composite from F606W and F850LP (§2.4).