1 Background and Scientific Motivation

The theoretical research proposed here is especially timely because of two recent observational developments: (1) we finally are closing in on the true cosmological parameters; and (2) new observations at $z \sim 2$ are clarifying the processes by which most of the stars in the universe formed, and at $z \lesssim 1$ how present-day galaxies assembled.

(1) The evolution of structure in the universe on all scales larger than the central regions of galaxies appears to be governed by the dark matter distribution predicted by ΛCDM (e.g., Conroy et al. 2006; Komatsu et al. 2009; Primack 2009c), although there are issues concerning possible disagreements with ΛCDM on smaller scales (Primack 2009a,b). The cosmological parameter σ_8, the normalization of the fluctuation power spectrum on the cluster scale 8 h^{-1} Mpc, controls the growth of structure as a function of redshift. For example, σ_8^{-2} appears in the exponential in Press-Schechter-type expressions (e.g., Sheth & Tormen 2002) for the abundance of dark matter halos as a function of redshift. This crucial parameter was found in the first-year WMAP1 analysis (Spergel et al. 2003) to be $\sigma_8 = 0.9 \pm 0.1$, in the third-year WMAP3 analysis (Spergel et al. 2007) ≈ 0.75, and in the fifth-year WMAP5 analysis (Komatsu et al. 2009) 0.817 ± 0.026, including data on baryon acoustic oscillations (BAO) and type Ia supernovae (SN). "Considering a range of extended models, we continue to find that the standard ΛCDM model is consistently preferred by the data," according to WMAP5 (Dunkley et al. 2009). Much recent data (e.g., Rozo et al. 2009; Vikhlinin et al. 2009) agrees with the WMAP5 cosmological parameters. In addition, recent N-body simulations (Macciò et al. 2008) show that halos with the WMAP5 cosmological parameters agree better with galaxy-scale observations than with WMAP1 and WMAP3 paramaters. The Millennium Run (Springel et al. 2006) and Millennium II (Boylan-Kolchin et al. 2009) were done with the WMAP1 cosmological parameters. Our recently-completed Bolshoi simulation[1] was done with WMAP5 parameters, and also has much better mass and force resolution than the Millennium Run. **We propose to make the Bolshoi simulation the basis for better understanding of the dark matter backbone of structure formation and for a new generation of improved semi-analytic models (SAMs).**

(2) Recent observations of massive forming galaxies at $z \sim 2$ by Reinhard Genzel's group have shown that many of these galaxies have large rotating gaseous disks with bright clumps of star formation (Genzel et al. 2008). Recent hydrodynamic simulations by our group (Ceverino et al. 2009) - which for the first time resolve the relevant physical size, temperature, and density scales - are finding similar behavior (Genzel 2009) and also predicting other phenomena such as Lyman-α blobs (Goerdt et al.) that appear to be in agreement with observations. Meanwhile, large surveys such as DEEP2, AEGIS, and COSMOS are clarifying how galaxies assemble at $z \lesssim 1$ into the forms we see in the nearby universe.

The origin and evolution of galactic spheroids, which comprise approximately three-fourths of the stellar mass in the Universe (Fukugita & Peebles 2004), **is a key problem that is at last ripe for solution.** Although it is widely believed that many elliptical galaxies (Es) and most classical galactic bulges formed via galaxy mergers (Kormendy & Kennicutt 2004), co-I Dekel has proposed an alternative scenario for formation of massive Es at high redshift $z \gtrsim 2$ through instabilities in disks that formed via cold gas inflows (Dekel et al. 2008). These are the questions that our proposed research aims to answer in order to determine the key processes that produced the entire evolving population and spatial distribution of early-type galaxies:

- Which spheroids formed from mergers of two gas-rich disk galaxies, and which formed in other ways?

[1] `http://astronomy.nmsu.edu/aklypin/Bolshoi/`

- What was the nature of the progenitor galaxies that merged, when did these mergers occur, and how much gas dissipation and star formation was involved?
- What are the differences, for example in shapes and kinematics, between spheroids that formed via mergers vs. those that formed via instabilities in cold gas inflows?
- When did the supermassive black holes (SMBHs) associated with galactic spheroids grow by gas accretion producing bright AGN, and how did the AGN in turn affect the evolution of the resulting galaxies?
- What was the relative importance of AGN feedback vs. other processes such as the truncation of cold flows into galaxies in quenching star formation and producing the observed color bimodality of galaxies?
- What were the processes responsible for the changing properties of elliptical galaxies as a function of redshift, in particular for higher redshift ellipticals being smaller and denser?
- How are these high-redshift spheroids transformed into those that we see nearby?

It is well established that, locally, major interactions between galaxies are responsible for impressive bursts of star formation in Ultraluminous Infrared Galaxies (ULIRGs) such as Arp 220. However, their contribution to the total density of star formation nearby is small. At higher redshifts, the fraction of galaxies that emit the bulk of their energy at infrared wavelengths increases (e.g., Papovich et al. 2004; Le Floc'h et al. 2004). This was once believed to be the result of an expected rapid increase in the merger rate of galaxies towards higher redshifts, which appeared to be confirmed by observations showing an increased fraction of morphologically disturbed galaxies at higher redshift (e.g., Brinchmann & Ellis 2000; Conselice et al. 2003). However, *Spitzer* studies with much larger data sets indicate that the majority of the infrared-emitting galaxies at $z \sim 0.7$ are morphologically *normal* spiral galaxies (Bell et al. 2005; Melbourne et al. 2005). There is also evidence that the pair fraction does *not* evolve strongly out to $z \sim 1.2$ (Lin et al. 2004, 2007), and that the fraction of morphologically disturbed galaxies also does *not* evolve strongly out to $z \sim 1$ (Lotz et al. 2008a) or even $z \sim 4$ (Lotz et al. 2006), although the trends may be different for IR-selected galaxies (Shi et al. 2009). Observations also seem to imply that star formation at $z \sim 1$ is predominantly not "bursty" but rather proceeds at a rate that is fairly constant in time (Noeske et al. 2007), in apparent contradiction with a merger-driven starburst picture. Whether the increase in star formation with redshift is driven by frequent minor mergers, which may induce star formation without strong morphological disturbances or strong bursts, or by quiescent star formation in galaxies that are constantly being resupplied with new gas, is an outstanding question that we propose to address.

Perhaps the strongest evidence of the importance of major galaxy mergers is the rapid increase in the mass density of spheroids from $z \sim 1$ to the present (Bell et al. 2004; Faber et al. 2007). The observed merger rate (Lin et al. 2008; Lotz et al. 2008b, 2009a) suggests that these spheroids plausibly were created by the merging of galaxies, but the fraction of dissipationless vs. gas-rich mergers is uncertain. Only mergers involving disk galaxies can increase the total mass density of spheroids, although simulations show that disks can be regrown in gas-rich mergers (e.g., Springel & Hernquist 2005; Robertson et al. 2006). Mergers are also likely to be a key ingredient (Hopkins et al. 2008a) in the growing of SMBHs and in producing the observed $M_{\rm BH}$-σ relation (e.g. Tremaine et al. 2002). We have developed tools to determine the rates of both gas-rich ("wet") and gas-poor ("dry") mergers reliably out at least to $z \sim 1$ (see §2.4), and we propose to extend them to higher redshifts.

At long last, cosmological hydrodynamic simulations of galaxy formation, with higher resolution and better implementations of supernova feedback, are beginning to make realistic disk galaxies (Governato et al. 2007; Mayer et al. 2008; Ceverino & Klypin 2009). Hydrodynamic simulations of major mergers of gas-rich disk galaxies reproduce some key features of observed early-type galaxies (e.g., Barnes & Hernquist 1992; Cox et al. 2006a). Star formation in massive galaxies at high redshifts appears to convert gas into stars very efficiently (Genel et al. 2008). Major mergers may be responsible for the very luminous submillimeter galaxies, but infrared IFU observations suggest that much of the star formation at $z \gtrsim 2$ occurs in thick gaseous disks (Genzel et al. 2008; Shapiro et al. 2008). New hydrodynamic simulations of high-redshift galaxy formation by our group are showing that cold streams of gas can enter even rather massive galaxies at $z \gtrsim 2$, that these forming disks are unstable to clumping, and that such star-forming clumps merge to form stellar spheroids in such systems (Dekel et al. 2008, 2009; Ceverino et al. 2009). We address the relative importance of this mode of spheroid formation compared to binary mergers of gas-rich disks in §3.3-6 below.

A related question is the nature of the mechanism that shuts down star formation in galaxies and creates their bimodal color distribution (Bell et al. 2004; Baldry et al. 2006; Faber et al. 2007; Brammer et al. 2009). Hydrodynamic simulations of binary galaxy mergers including a model for AGN accretion and feedback (Springel et al. 2005b), in which the black hole accretes rapidly during the final coalescence of the galaxies and expels all gas from the system, reproduce the observed $M_{\rm BH}$-σ relation (Di Matteo et al. 2005). They also naturally result in a shutdown of star formation after the merger and the formation of a red remnant (Springel et al. 2005a) and appear to be consistent with observations of the QSO luminosity function (Hopkins et al. 2005 and subsequent papers, reviewed in Hopkins et al. 2008b,a).

Despite its successes, it is not clear that the Springel-Hernquist-Hopkins AGN model is fully consistent with the observations. In this model, the intrinsic luminosity of the AGN is strongly peaked at the time the galactic nuclei merge. At that time, feedback from the accreting black hole blows out the gas from the merging galaxies and terminates most growth of both $M_{\rm SMBH}$ and $M_{\rm spheroid}$. This cannot be the complete story. The SAM based on this model (Somerville et al. 2008b) does not produce the correct redshift distribution of bright quasars. SDSS data on nearby galaxies (Schawinski et al. 2007) and AEGIS data on $z \sim 1$ galaxies (Nandra et al. 2007; Georgakakis et al. 2008) show that much of the AGN activity occurs *after* the spheroid is already turning red. Furthermore, X-ray emission from AGN in galaxies at $z \sim 1$ seems to come mostly from early-type galaxies, not mergers (Pierce et al. 2007; Pierce 2009); and LINER-type emission, presumably connected to low-level AGN activity, is observed to originate from post-starburst galaxies whose gas and dust appear not to have been cleared out during the starburst phase (Graves et al. 2007). The DEEP2 survey has turned up a two multiple AGN and 35 velocity-offset AGN (Comerford et al. 2009) in post-starburst galaxies, favoring a merger origin for these galaxies but suggesting that many of the SMBHs in the merging galaxies have not yet themselves merged.

A different mechanism must be responsible for preventing star formation over longer periods. Heating of the IGM by sustained low-level AGN activity ("radio-mode" AGN feedback (Croton et al. 2006)) is one possibility; the shutting down of cold gas inflow due to a virial shock when the halo mass grows larger than approximately $10^{12}\,\mathrm{M}_\odot$ is another (Birnboim & Dekel 2003; Kereš et al. 2005; Birnboim et al. 2007; Dekel & Birnboim 2007).

The comparison between theory and observations is complicated by the difficulty of finding and identifying not only merging galaxies at high redshift, but also highly obscured AGN. The X-ray emission from these sources can be attenuated to the point that it becomes difficult to detect with current X-ray telescopes, but NuSTAR, scheduled for launch in 2011, should detect higher energy X-rays from even Compton-thick AGN. The infrared dust emission, on the other hand, is readily detected but can also originate in the highly obscured starbursts predicted by the merger picture.

In recent years, true multi-wavelength capabilities have become reality. The wavelength coverage of large galaxy surveys is increasing, and the AEGIS survey (Davis et al. 2007) has accumulated essentially panchromatic coverage including X-ray, far-ultraviolet, optical, near-infrared, mid-infrared, and radio wavelengths, with DEEP2 spectra of galaxies to $z \sim 1.4$. This will be extended to higher redshifts by the DEEP3 survey. The Herschel space telescope will extend wavelength coverage at far-infrared wavelengths out to redshifts around 2, and ALMA and SKA out to the epoch of reionization. Studies of galaxies that focus on single observables, like the luminosity function, are rapidly becoming outdated.

The challenge now is to measure the full multi-dimensional distribution of galaxies in *all* observables, and to develop a unified model of galaxy formation that can predict these quantities. To determine the role of galaxy mergers in fueling AGN and the buildup of spheroids compared to alternative mechanisms, more sophisticated methods for identifying merging galaxies in surveys are needed, utilizing all available observables. Creating such models and methods is a major goal of the research proposed here. We aim in particular to provide the main theoretical support for the DEEP3 and AEGIS surveys.

The research proposed here would accomplish the following:

- **Determine the ΛCDM gravitational backbone for structure formation** with current cosmological parameters by analyzing our Bolshoi simulation, running higher-resolution simulations of subregions, and determining halo properties and the halo merger tree (§3.1).
- Develop improved semi-analytic models (SAMs) based on the Bolshoi simulations and on our new analytic model of spheroid formation in order to **predict the properties of the evolving galaxy population** (§3.2).
- Develop improved hydrodynamic simulations of galaxy formation appropriate for higher redshifts, including **AGN, gas flow into galaxies, and environmental effects of large-scale structure** (§3.3-5).
- Use our improved Sunrise radiation transfer model (§2.2) and our new hydrodynamic simulations of galaxy formation (§2.1) to develop sophisticated **algorithms for identification and multiwavelength characterization of spheroid formation processes** in galaxy surveys (§3.5-6).
- Use **scientific visualization** to understand and illustrate the processes that govern galaxy formation and the evolution of structure in the universe (§3.7).
- All our models and outputs and all software developed will be **freely available**.

Our "Santa Cruz" style of running and analyzing simulations in close collaboration with observers builds on and extends our current research, detailed in Section 2. The proposed new research is described in more detail in Section 3, and the broader goals and impacts of our research in Section 4.

2 Our Recent and Current Work, and Proposed Continuations

This section describes our completed and ongoing research relevant to the present proposal, to provide a context for this proposal and to show that we are in a position to accomplish the proposed new work. We also describe proposed continuations of our current research.

2.1 Simulations of Early-type Galaxy Formation. We have done a large suite of high-resolution hydrodynamic simulations of binary galaxy mergers and compared them to observations in order to measure the rate of galaxy mergers out to redshifts $z \sim 1$. We have also initiated a program to simulate star formation in massive galaxies at higher redshifts, and as mentioned the results appear to be consistent with the latest observations.

Binary and multiple galaxy mergers. For the past several years, our group has been studying mergers of galaxies through high resolution hydrodynamic simulations of binary galaxy encounters, including star formation and supernova feedback. In our simulations, progenitorgalaxies are modeled as a stellar disk and bulge, a gas disk, and a dark-matter halo, with parameters chosen to match observed galaxies. Two of these galaxies are then placed on an approaching orbit, and the simulation is started. The simulations have typically used 170,000 particles per galaxy, with a smaller number of simulations using up to 1,700,000 particles per galaxy. They were run using the current version of the GADGET N-body/hydrodynamics code, including star formation and feedback. Using this method, a spatial resolution of $\sim 100\,\mathrm{pc}$ and a mass resolution of $\sim 10^6\,\mathrm{M}_\odot$ are attained.

Both as Primack's PhD student and during his subsequent postdoc at Harvard, our continuing Collaborator **T. J. Cox** ran a large suite of galaxy merger simulations that our group analyzed (Cox et al. 2004; Cox 2004; Cox et al. 2006b, 2008). We have also done an extensive study of the effects of different supernova feedback parameterizations (Cox et al. 2006b), and for the first time conducted an extensive study of minor as well as major mergers (Cox et al. 2008), investigating how the properties of the merger-induced starbursts depend on the mass ratios of the merging galaxies.

We store many complete snapshots for each set of initial conditions, and we use our *Sunrise* code (§2.3) to turn this detailed tracking of gas, star formation, and metals into images in every waveband from far-UV to far-IR, including a realistic treatment of the effects of dust. We "observe" these outputs as observers do real galaxies, including redshifting and seeing effects, and analyze the resulting images morphologically using several analysis tools (§2.4). We find that own Gini-M_{20} tool can detect minor mergers and gas-poor mergers. However, we find that close pairs (both in redshift and on the sky) are usually gas rich mergers, which also tend to produce morphologically Asymmetric galaxies. We measure the timespans over which merging galaxies will be observable as close pairs or as morphologically disturbed (Lotz et al. 2008c, 2009c,b,a). Combining this with AEGIS observations (Lotz et al. 2008b), we measure the actual rates of different types of mergers: gas rich vs. gas poor, and major vs. minor out to $z \sim 1$ (§2.4). Continuing this to higher redshifts (§3.3-6) is essential in order to determine the role of mergers in forming early-type galaxies.

We are comparing many properties of the merger remnants with observations of elliptical galaxies. One project concerned the radial dependence of the velocity dispersion in elliptical galaxies produced by mergers. A study led by Co-I Dekel refuted the argument that a low observed velocity dispersion in the outskirts of elliptical galaxies rules out the presence of a dark matter halo (Romanowsky et al. 2003). The low velocity dispersion is a natural outcome of the merging process, which naturally puts stars in the outer regions of the remnants on highly radial orbits via gravitational interactions with the merging galactic nuclei (Dekel et al. 2005).

Greg Novak (who finished his PhD with Primack in September 2008 and is now a postdoc at Princeton) studied the shapes of the merger remnants and their dark halos and found that the stellar minor axis and the halo major axis are almost always close to perpendicular. The elongation is along the merger axis, and the stellar minor axis is oriented close to the angular momentum axis, with much of this angular momentum typically arising from the orbital angular momentum of the merging galaxies. These predictions (Novak et al. 2006) are being tested by observations of weak gravitational lensing (Parker et al. 2007). Greg also compared with new strong lensing data on elliptical galaxies (Bolton et al. 2007), finding that our binary merger remnants agree with the data on Es with lower velocity dispersion σ_v but that Es with higher $\sigma_v \gtrsim 350$ km s^{-1} have higher central densities than are attained in binary mergers (Novak et al., in prep.). In agreement with the new SLACS lensing data (Bolton et al. 2008), we find that the total density in our simulations is very close to isothermal (r^{-2}) (Novak 2008).[2]

Novak also did a detailed kinemetry comparison of the binary merger remnants with integral field unit observations of early-type galaxies in the SAURON survey (Emsellem et al. 2004, 2007). Prelminary results reported in Novak's PhD thesis (Novak 2008) indicate that our binary, gas-rich

[2] `http://physics.ucsc.edu/~joel/Novak-thesis.pdf`

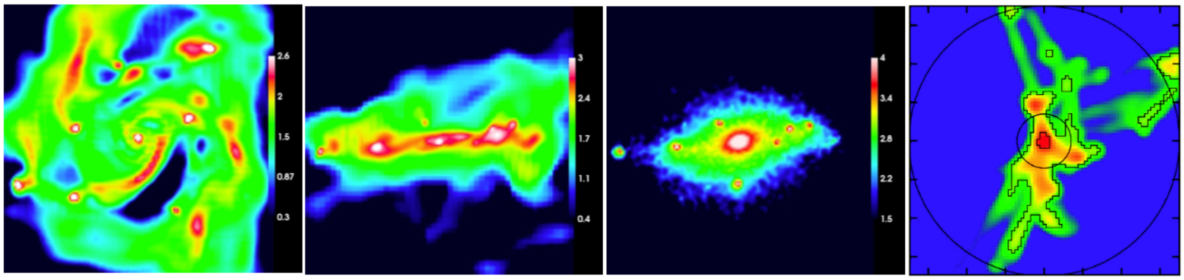

Figure 1: Gas surface density of a galaxy at $z \sim 2.3$ from a high-resolution cosmological simulation (Ceverino et al. 2009). The first three images are 10×10 kpc; the color code is log suface density in units of $M_\odot$ pc^{-2} (Ceverino et al. 2009). The face-on view (a) shows shows an extended disk broken into several giant clumps. The edge-on view (b) demonstrates that this is a well-defined gas disk, and the young stars in the giant clumps resemble observed "chain" galaxies (Elmegreen & Elmegreen 2006). The edge-on view of surface density of all stars (c) shows a large bulge formed by merging clumps that comprises about half of the stars. (d) Lyman α "observed" surface brightness (contours mark 10^{-18} and 10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}) from the simulation at $z = 2.3$ (Goerdt et al.). The outer circle shows the virial radius $R_{\rm vir} = 65$ kpc; the inner circle is $0.2R_{\rm vir}$. This resembles observed Lyman α blobs (see §3.4).

major mergers result in remnants that are very similar to the approximately 75% of SAURON ellipticals that are classified as "fast rotators" (Emsellem et al. 2007; Cappellari et al. 2007; Falcón-Barroso et al. 2008). However, the remaining ∼25% are slowly rotating, nearly spherical elliptical galaxies that are not produced in binary merger simulations.

A possible formation mechanism for these galaxies is multiple major or minor mergers (Weil & Hernquist 1996; Bournaud et al. 2007; Burkert et al. 2008; Naab et al. 2007; Novak 2008), that are expected to occur in dense regions at high redshifts. Novak ran an ambitious new series of simulations of multiple mergers to test this hypothesis (Novak 2008). A paper based on these and ongoing simulations will soon be submitted for publication. These simulations included both fully cosmological initial conditions and also simplified cases of interactions between many individual galaxies.

Spheroid formation from unstable gaseous disks. Although gaseous disks formed in at least three of the six cosmological cases that Novak ran, the stellar systems formed were predominantly spheroidal, partly because of mergers of dense clumps and partly because the changing stream configuration caused the disk orientation to change with time. The results of these ~ 100 parsec resolution simulations appear to be broadly similar to those that Dekel reported (Dekel et al. 2008). Galactic winds typically emerge from simulated galaxy mergers, driven by shocks and energy input from supernovas and AGN, and adiabatically expand. When galaxy mergers are simulated in realistic cosmological environments, these outflowing winds shock against the surrounding inflowing gas. We will see whether this may realistically account for the X-ray halos of observed galaxy groups containing elliptical galaxies.

Daniel Ceverino (who finished his PhD with Collaborator Klypin in 2008 and is now a postdoc with Co-I Dekel) did pathbreaking hydrodynamical simulations of processes in the galactic interstellar medium (ISM) using the Eulerian hydrodynamics + N-body Adaptive Refinement Tree (ART) code developed by Klypin in collaboration with his former PhD student Andrey Kravtsov (Kravtsov et al. 1997; Kravtsov 1999, 2003). The ART-hydro code properly models the multicomponent ISM. Since it includes the heating and cooling rates from radiative processes and molecular as well as line cooling, it can simulate temperatures down to ~ 100 K, densities $n_{\rm H} > 10^{-3}$ cm^{-3}, and reach the thermodynamic conditions of molecular clouds. Instead of using a sub-resolution model of a multi-phase medium as in (Springel & Hernquist 2003; Cox et al. 2006c) their code resolves it, and naturally produces hot bubbles, chimneys, and galactic winds. Another important ingredient is runaway stars: massive stars ejected from the molecular clouds where they form. (Although most massive stars are found in stellar clusters and OB associations, 10-30% are found in the field with velocities consistent with such an ejection scenario.) Such runaway stars become supernovas 10-100 pc from molecular clouds, which greatly facilitates feedback. Having understood key physical processes in (4 kpc)^3 simulations of the ISM of a disk galaxy with resolution of a few pc, Ceverino and Klypin next checked that the same processes occurred in simulations with the $\sim$ 35 pc resolution that their cosmological simulations could achieve. They found that the classic problems of disk galaxy formation – overcooling and loss of angular momentum resulting in unrealistically massive bulge formation – are avoided, with their simulated galaxies having nearly flat rotation curves (Ceverino & Klypin 2009). Finally they studied the effect of stellar feedback in galaxy formation at high redshift.

In ongoing cosmological simulations of the formation of the progenitors of massive elliptical galaxies at high redshift, run using Primack's allocations of supercomputer time, Ceverino has seen cold flows of gas into galaxies feeding unstable dense gas-rich disks that form giant clumps, each a few percent of the disk mass, in which stars form rapidly. The clumps migrate into a central bulge in $\sim$ 0.5 Gyr, but cold gas inflow can maintain this phenomenon for up to several Gyr. Figure 1 shows such a clumpy disk galaxy. The resulting unstable gaseous disks resemble those found by Genzel and collaborators (Genzel et al. 2008), but the merging clumps can build a massive stellar spheroid. A sufficiently large stellar spheroid can then stabilize the disk and largely prevent further star formation. The model thus predicts a galaxy bimodality already by $z \sim 3$, with star-forming disks and reddening spheroids (Dekel et al. 2009). The large gaseous disks in these simulations resemble those found in Novak's simulations mentioned above, which showed much less clump formation because these GADGET simulations could not cool to molecular cloud temperatures. Continuing the Ceverino simulations and comparing them to observations is a major focus of this proposal (§3.4-5)

2.2 Improving Semi-Analytic Models of Galaxy Formation. Our simulations of galaxy formation have led to improved SAMs by enabling us to model the properties of the sphroids formed in mergers and also by improving treatment of absorption and reradiation by dust.

Matt Covington (who finished his PhD with Primack in September 2008 and is now a postdoc at the University of Minnesota) created an analytic model of the properties of remnants from our galaxy merger simulations. Covington's physical merger model accurately predicts the stellar half-mass radius and velocity dispersion of the stellar spheroids produced by gas-rich binary mergers based on energy transfer from orbital to internal kinetic energy in the first close pass of the merger (Covington et al. 2008). It is a major improvement over the simplified model used in Cole et al. (2000), which does not take radiative energy losses into account. The model works for a wide range of merger mass ratios, and it also accurately predicts the properties of spheroids formed in gas-poor ("dry") mergers. The only inputs required are the properties of the progenitor galaxies and their orbits, and work is in progress to create a simplified model that effectively integrates over cosmologically representative orbits (§3.2).

Such analytic models are useful for gaining an intuitive understanding of which physical processes are important, and also for use in conjunction with semi-analytic models (SAMs). In order to predict the properties of the evolving population of spheroidal galaxies, we combined this analytic model with two different SAMs, Somerville's new one (Somerville et al. 2008b) and one based on the Millennium simulation (Croton et al. 2006). We used the SAMs to predict the properties of the disk galaxies involved in all the mergers (mass, disk size, bulge to disk ratio, and gas content) and we summed with proper weighting over the orbits from cosmological simulations (Benson 2005). Somerville's SAM has disks with size-mass relation evolution in good agreement (Somerville et al.

2008a) with observations from low redshifts (Shen et al. 2003) out to high redshifts (Trujillo et al. 2006). The resulting stellar spheroids have a size-mass relation evolution with nearly the observed slope and zero point, both for SDSS spheroids and those out to $z \sim 3$. The dispersion in the spheroid sizes is smaller than that of the disks because the larger disk galaxies were also more gas rich, and in mergers with increasing gas fraction more gas is driven to the center and forms smaller radius stellar systems. The increasing gas content and smaller sizes of higher redshift disks accounts for the smaller radius of the spheroids resulting from their mergers. Similar results were obtained for the Millennium SAM; the slope of the spheroid size-mass relation was an even better match to the observations, although the Millenium SAM's unrealistically large disks resulted in a zero-point offset that was corrected when the observed sizes were instead used in the model. Covington also found in his PhD thesis[3] that the merger-produced stellar spheroids lie in a Fundamental Plane offset from the virial plane by the observed "tilt," because of an increased central star/dark matter ratio in more massive galaxies. These encouraging results, which will soon be submitted for publication, suggest that mergers of gas-rich disks form a significant fraction of elliptical galaxies, at least the lower-mass ones. They also suggest that the scaling relations of stellar spheroids are a consequence of those of the disk galaxies from which they form. The most massive elliptical galaxies cannot be produced by binary mergers of disks because of the absence of sufficiently massive and metal-rich disks (Naab & Ostriker 2009). As we have already mentioned (see also §3.4-5), they are possibly produced by multiple overlapping mergers and/or cold flows producing unstable clumpy disks. However, an important question is why these more massive early-type galaxies also obey scaling relations like those of the less massive early-type galaxies that plausibly formed from binary major mergers.

In another project, Covington compared the kinematics of intermediate stages of our simulations with the Keck Observatory DEIMOS spectra of galaxies in the AEGIS survey. Although these AEGIS galaxies often had far lower rotation velocities for their stellar masses than the Tully-Fisher relation would predict, when their rotation velocities were added in quadrature to their velocity dispersions they were found to lie on a Tully-Fisher-like relation with remarkably little scatter (Kassin et al. 2007). When we mimic the AEGIS spectra by observing our simulations similarly, including seeing and using the same code to measure $V_{\rm rot}$ and σ as used to analyze the observed spectra, we find that intermediate stages of our galaxy mergers have kinematic properties very much like those observed (Covington PhD dissertation 2008; Covington et al., in prep.)– see Figure 2. Our simulations are helping us to interpret the observations in terms of the depth of the potentials in these galaxies. In particular, we have found that there is a close correlation between $S_{0.5} = (\sigma^2 + 0.5V_{\rm rot}^2)^{1/2}$ and the total enclosed mass if they are both evaluated at (for example) the radius that encloses 80% of the stellar mass. Moreover, we found that the kinematics can help to determine the merger stage; for example, the rotation velocity often drops dramatically for about 100 Myr just after the coalescence of the galaxy nuclei. However, to truly mimic the observations we are now including the effects of dust in calculating these simulated spectra (§3.3-6), which is possible with the new version of *Sunrise*.

Rudy Gilmore (who just finished his PhD with Primack in June 2009 and will be a postdoc at SISSA) did an extensive study of the extragalactic background light (EBL) and gamma-ray attenuation using SAMs, in collaboration with Rachel Somerville (Primack et al. 2008; Gilmore 2009). He also calculated the evolving UV EBL using SAMs and models of the evolving AGN contribution, including processing of the ionizing radiation by the IGM in collaboration with Haardt and Madau (Gilmore et al. 2009a). Gilmore and Primack, in collaboration with Francisco Prada, used this new model of the UV background and GRB data to calculate the response to GRBs *Fermi* and of ground-based Atmospheric Cherenkov Telescopes like MAGIC (Gilmore et al. 2009b). We

[3] `http://physics.ucsc.edu/~joel/Covington-PhD-thesis.pdf`

have major work in progress to improve the calculation of the EBL and to use gamma-ray data to constrain the cosmic history of star formation (§3.2).

2.3 The Radiation Transfer Model *Sunrise*. Hydrodynamic simulations alone cannot predict what the systems would look like when observed. Merger-driven starbursts, which are some of the most luminous galaxies in the local universe, are invariably highly extinguished by dust (Sanders & Mirabel 1996), so any attempt to compare the simulated galaxies with observations must take this into account. In order to calculate the effects of dust, we have developed the Monte-Carlo radiative-transfer code *Sunrise* (Jonsson 2004, 2006). Snapshots of the geometry of stars and gas in the hydro simulations, along with the star-formation history of the system, are saved at least 50 times throughout the merger. These are then used as inputs to the radiative-transfer calculation. Spectral energy distributions are calculated for pre-existing stars and for stars formed during the interaction, and this radiation is then propagated through the dusty interstellar medium of the simulated galaxies.

Using our *Sunrise* radiative-transfer code we have generated images of each simulated merger from many different viewpoints, in many wavelength bands, throughout the merger event. These images cover wavelengths from far-ultraviolet GALEX bands through optical ACS and ground-based filters and near-infrared NICMOS and the short-wavelength IRAC bands. Our simulations seem to replicate the properties of observed local starburst galaxies well (Jonsson et al. 2006). In particular, the simulations follow observed correlations between the IR/UV flux ratio and the ultraviolet spectral slope (Meurer et al. 1999; Goldader et al. 2002). Images and spectra of our simulations are available on a public web site[4], and our intent is to provide access to the science data as well so that other researchers can use the simulations for their own analyses.

The current version of *Sunrise* uses a "polychromatic" algorithm, where every Monte Carlo ray samples every wavelength (Jonsson 2006). This new algorithm makes it possible to calculate spectra of unprecedented spectral resolution. *Sunrise* has been adapted to use sub-resolution models of star-forming regions from the photoionization/dust code MAPPINGS III (Dopita et al. 2005). The emission from these star-forming regions includes emission lines, hot dust and PAH emission. Emission from diffuse dust is calculated self-consistently from the local radiation field, a calculation that we have sped up by two orders of magnitude using new Graphics Processing Units (GPUs) (**?**). Taking all these features into account, *Sunrise* can generate realistic spectra of the galaxy simulations (Jonsson et al. 2009). Collaborator Jonsson, who recently joined Lars Hernquist's group at Harvard, will continue to improve *Sunrise*.

2.4 Galaxy Merger Identification, Timescales, and Rates. For the purpose of comparing simulations to observations, we have developed non-parametric measures quantifying galaxy morphology (Lotz et al. 2004). These measures separate local "normal" galaxies and ULIRGs remarkably well, and an analysis of ACS images of the EGS indicates that the local distribution of morphologies is present also at higher redshift (Lotz et al. 2008a). This method was used to estimate the merger fraction and merger rates in the AEGIS data (Lotz et al. 2008d) However, a key obstacle to understanding the galaxy merger rate and its role in galaxy evolution is the difficulty in constraining the timescales of mergers. Theoretical estimates for galaxy merger timescales are quite crude, and it is difficult to quantify the efficiency of various observational methods in selecting mergers. The combination of galaxy merger simulations and a realistic radiative transfer model is essential for calibrating these timescales. In work with Collaborator Jennifer Lotz (NOAO), we have applied morphological merger detection algorithms to simulated images of equal-mass mergers. This study shows that the timescales during which mergers may be identified are strongly dependent on the methods used (Lotz et al. 2008c). We are finding, for example, that Close Pairs and Asym-

[4]`http://governator.ucsc.edu/simulations`

metry are primarily sensitive to gas-rich major mergers, while Gini-M_{20} can detect even gas-poor minor mergers that produce small morphological disturbances and little induced star formation. As we explained in §2.1, the good news is that this reconciles apparently divergent estimates of the galaxy merger rate as a function of redshift, and it allows us to estimate the rates of various types of mergers.

2.5 Roles of Active Galactic Nuclei. Primack's student **Christy Pierce** finished her PhD in March 2009 and is now a postdoc at Georgia Tech. Her dissertation (Pierce 2009) was on the morphological and color characteristics of AGN host galaxies out to $z \sim 1$ in the AEGIS data. Preliminary results were presented in (**?**), and detailed papers are now being submitted for publication. Identifying AGN using X-ray and radio emission and also optical spectra, Pierce showed that host galaxies of relatively bright AGN were usually early type galaxies rather than galaxy mergers. As we mentioned in §1, this does not seem entirely consistent with expectations from the Hopkins-Hernquist simulations. Pierce also found that only the brightest unobscured AGN change the central colors and morphologies significantly, so that our morphological classification tools are otherwise adequate to characterize AGN host galaxies (Pierce et al. 2009). We describe proposed research on AGN in galaxy formation in §3.5.

3 Proposed New Research

The goals of this project are ambitious, and our approach is correspondingly multi-pronged. We are analyzing our just-completed high-resolution Bolshoi cosmological simulation, in order to understand better the details of ΛCDM structure formation and to provide the basis for better semi-analytic models of the evolving galaxy population. Continuing the research just discussed, we are running and analyzing high-resolution hydrodynamical simulations to clarify key phenomena in star formation and its quenching in galaxy formation. We are developing models, tools, and algorithms for predicting the detailed appearance, spectra, and panchromatic spectral energy distributions of galaxies from these simulations, including highly obscured AGN. And we are using these models to gain an understanding of galaxy mergers, cold gas inflows leading to unstable disks, the interplay between AGN feeding and feedback, and how these processes shape the evolution of the galaxy population, especially by comparing with observations like the DEEP2/3 and AEGIS galaxy surveys. The specific questions we hope to answer were summarized in Section 1, Background and Scientific Motivation. Broadly, **we aim to clarify the processes governing star formation and its quenching in the formation of galactic spheroids, in order to understand the evolving population of early-type galaxies**. Here are details of the proposed research:

3.1 Bolshoi cosmological simulation. The Bolshoi simulation was run using the Adaptive Refinement Tree (ART) dissipationless code with 2048^3 particles in a comoving volume 250 h^{-1} Mpc on a side. The cosmological parameters were $h = 0.73$ and $\sigma_8 = 0.83$, consistent with WMAP5. The dynamic range was 262,000 and there were 400,000 major time steps. This simulation requred 6 million cpu-hours on 13824 cores and 12 Tb of RAM using early-user time on the new Pleiades machine at NASA Ames Research Center. The 1 $h^1 M_\odot$ mass per particle and the force resolution of 1 h^{-1} kpc are almost an order of magntude better than the Millennium run, and the 170 timesteps saved (representing 75 Tb of data) are more than three times greater than for the Millennium run. A mini-Bolshoi simulation was also run with 1024^3 particles in 1/8 the volume with the same resolution and cosmological parameters.

We are now in the process of analyzing these simulations. Halos have been identified at all timesteps using Klypin's BDM halo-finder and are being found using Springel's Subfind halo-finder (Springel et al. 2001). Merger trees are now being constructed with our Collaborator Risa Wechsler and her postdoc Michael Busha. The Bolshoi simulation provides information about halo properties (such as mass and subhalo radial density profiles, concentrations, shapes, and angular momenta) and halo mass accretion and merger rates in different cosmological environments, which will be useful for many astrophysical purposes including halo occupation distribution (HOD) analyses. To give just one example: in dissertation research on the shapes of dark matter halos led by Primack's former grad student Brandon Allgood (Allgood et al. 2006), we found that to determine halo shapes accurately at several radii $N_p > 7000$ particles are requred within the virial radius of the halo, which was achieved for halos with mass $> 9.3 \times 10^{11} h^{-1} M_\odot$ in a resimulated subregion of a larger simulation. The Bolshoi simulation has achieved better mass and force resolution in a volume 1000 times larger, and with the current best-fit cosmological parameters!

To study the distribution and evolution of satellite and dwarf galaxy halos in both typical and low-density environments, we plan to run **"sub-Bolshoi"** simulations of a number of subregions of the Bolshoi simulation with 64 times the mass resolution and force resolution of order 100 pc. These sub-Bolshoi runs will include hydrodynamic simulations of some of these subregions using the adaptive mesh ART-hydro code, including star and black hole formation and feedback.

Among the many applications of the Bolshoi simulation will be populating the backward light-cone and the creation of improved mock catalogs for redshift surveys, which Brian Gerke has agreed to do for the DEEP3 and AEGIS survey. Primack's grad students will all be involved in analyzing the Bolshoi simulation and applying these analyses to cosmological questions. Analyses will also be done by the Co-I and Collaborators and their grad students. Collaborators Bullock and Wechsler are former PhD students of Primack whose dissertation research established fundamental properties of dark matter halo concentrations (Bullock et al. 2001b), angular momenta (Bullock et al. 2001a; Vitvitska et al. 2002; Maller et al. 2002), and mass accretion history (Wechsler et al. 2002), and who have often subsequently collaborated with him with and Dekel and Klypin on such issues.

3.2 Improving semi-analytic models and predicting the evolution of the galactic spheroid population. In addition to using our Bolshoi simulation as the basis for a new generation of SAMs, we are incorporating our analytic merger model (Covington et al. 2008) into the SAMs. As we discussed in §2.2 above, we can now use the analytic model together with SAM calculations of merging galaxy properties (sizes, masses, bulge-to-total mass ratios, and gas content) and orbits to predict the stellar mass, age, and metallicity, stellar half-light radius, stellar velocity dispersion, and other properties of the resulting spheroids at various redshifts. The great advantage of incorporating the analytic model into SAMs is that this will allow prediction of correlations of spheroid properties, for example with environment, and also allow us to determine the evolution of individual objects – thus seeing, for example, what compact ellipticals at high redshift evolve into at lower redshifts. This project is high priority of our Collaboration with Rachel Somerville and Darren Croton, who are working with Primack and his grad students, especially Lauren Porter. Since her dissertation research with Primack (Somerville & Primack 1999; Somerville et al. 2001), Somerville has been an international leader in semi-analytic modeling of galaxy formation. Croton led the Millennium SAM (Croton et al. 2006).

In SAMs based on the Millennium run, most mergers involve "orphan galaxies," dark matter halos that have lost so many particles after they fall into a larger halo that they can no longer be identified by the halo finder. Such galaxies are assumed in these SAMs to merge onto the central galaxies in the larger halo after a residual merging time that is calculated by some variant of the classical dynamical friction formula, possibly including a model of stripping due to tidal interaction with the larger halo. **The uncertainties due to this approximate treatment will be largely avoided by the better mass and force resolution and the 170 saved timesteps of the**

Bolshoi simulation.

We anticipate that the merger orbits will depend on the environment of the dark matter halo and on redshift. At any redshift, the rare halos that are much higher in mass than the typical mass of collapsing halos are fed from several (often three) filaments, while the more typical halos lie along filaments and infall into them occurs primarily along the filament axis (Dekel et al. 2008). We will test whether this is the main reason why lower-mass elliptical galaxies are typically elongated (along their host filament) and rotating (perpendicular to the long axis), properties that we showed are predicted by binary major merger simulations (Novak et al. 2006), while more massive ellipticals are typically more spherical and non-rotating.

Primack's student Lauren Porte has already used Covington's analytic merger model together with outputs from the Croton and Somerville SAMs to model the entire early-type galaxy population produced by major mergs of gas-rich disk galaxies. She has been comparing these results with the beautiful analysis of SDSS data on early-type galaxies in Genevieve Graves's just-finished PhD dissertation supervised by Collaborator Sandra Faber. By analyzing coadded SDSS spectra of elliptical galaxies binned by stellar half-light radius R_e and velocity dispersion σ_v, Graves has found that their light-weighted ages and metallicities are mainly functions of σ_v rather than R_e (Graves et al. 2009b,a). Porter is finding a similar behavior of light-weighted metallicity, but she finds that stellar age is a function of R_e as well as σ_v since - as we mentioned above in discussing Covington's dissertation research (Covington 2008), now being prepared for publication - merging the smaller and more gas-rich disks typical at higher redshift produces smaller spheroids. Since our analytic merger model correctly predicts the results of dry as well as wet and minor as well as major mergers, Porter plans to extend this work by including all mergers predicted by the SAMs, including minor and dry mergers, to see whether doing this will reproduce the observed trends in elliptical galaxy stellar age and metallicity. De Lucia et al. found that half of a typical elliptical galaxy's mass is accreted below z 0.8, mostly in minor mergers (De Lucia et al. 2006; De Lucia & Blaizot 2007). Recent simulations suggest that several minor mergers can increase R_e by a factor of ~ 3 while only slightly decreasing σ_v (Naab et al. 2009).

By including the merger model in SAMs rather than postprocessing as Porter has done (§2.2), we can also predict environmental effects and compare to observations such as those indicating somewhat greater stellar ages of ellipticals in clusters compared to the field. We will also try to extend our analytic merger model to include the results of our new cosmologically based multi-merger and cold-flow hydrodynamnical simulations. Such analytic treatments are crucial to understand the simulations, rather than just treating them as black boxes, as well as to interpolate and extrapolate beyond specific cases simulated. Preliminary attempts at such an analytic understanding (Dekel et al. 2009) are encouraging. That will also allow these important galaxy-formation processes to be treated by SAMs, allowing prediction of the properties of the entire evolving galaxy population and comparisons to the growing observational data at higher redshifts.

Porter proposes to improve SAMs also by incorporating Type Ia as well as Type II supernovae, thus allowing us to predict the evolution of galaxy [Mg/H] and [Mg/Fe] as well as [Fe/H] and compare to observations. In addition, with Collaborator Somerville, Porter will further develop the ability to predict galaxy spectra in SAMs, continuing the program of (Trager & Somerville 2009). Comparing these spectra directly to observations using the Lick indices will avoid biases inherent in mass-weighted ages and metallicities. Porter's undergraduate senior thesis at Caltech with Andrew Benson was on Galform SAM models of elliptical galaxies, and in addition to the SAM research with Croton and Somerville, Porter and Benson plan to work with Primack on a Galform SAM based on Bolshoi. It will be illuminating to compare the predictions of all three SAMs in order to see the effects of the different assumptions they embody regarding gas cooling, star formation, feedback, and dust.

3.3 Running improved galaxy merger simulations and comparing to observations. We propose to extend our research described in §2.1 om three directions. One is to compare simulated with observed kinematics of stars and globular clusters (GCs) at larger radii; another is to model specific merging systems in order to constrain better the feedback and other uncertain parameters in the simulations. The third program, running cosmological adaptive-mesh hydrodynamic merger simulations, is discussed in §3.4.

Chris Moody, a UCSC grad student working with Primack, has been analyzing our binary and multiple galaxy merger remnants out to $\sim 5R_e$. We are working with UCSC observational astronomer Aaron Romanowsky to compare the simulated remnants with the stellar and GC kinematics data on nearby elliptical galaxies being obtained using powerful integral field unit spectrographs and multiobject spectrographs on large telescopes (e.g., Noordermeer et al. 2008). Keck/DEIMOS observations, for example, have not only provided kinematics of many GCs in nearby elliptical galaxies, but the residual starlight has allowed measurement of stellar kinematics to radii $\gtrsim 3R_e$. One galaxy classified as a fast rotator at $r \leq R_e$ is slower rotating and rounder at larger radius; another classified as an elliptical fast rotator at $r \leq R_e$ is more elliptical and an even faster rotator at large radius. Moody is finding that such kinematic decoupling between inner and outer radii is relatively common in both binary and multiple merger remnants, and he is now working to understand the origin of these phenomena in the merging galaxy properties and orbits. Moody is also gearing up to run his own galaxy merger simulations, with Collaborator T. J. Cox, to model specific merger systems.

In addition to IFU studies of early-type galaxies, IFU data are increasingly being obtained for galaxies that appear to be interacting or merging. For example, our Collaborator Jennifer Lotz has obtained such data on nearby galaxies using Sparsepak on the WYN telescope, a French group has obtained such data at $z \sim 0.6$ (Neichel et al. 2008), the DEEP team is obtaining such data using the OSIRIS detector at Keck Observatory, and Genzel's group is obtaining 2D IR spectra using the SINFONI instrument at Paranal Observatory (Genzel et al. 2008). Our group is in a unique position to make theoretical predictions to compare with these observations, including the important effects of dust using the new version of *Sunrise*. This work could be very helpful in clarifying the astrophysics that is operating in these star-forming systems.

3.4 Running state-of-the-art galaxy formation simulations and comparing to observations. Working with Collaborator Anatoly Klypin, with our current students and postdocs including Daniel Ceverino, and with Collaborator T. J. Cox, we propose to do an extensive series of new hydrodynamic simulations of the formation of early-type galaxies, including both binary and multiple mergers and the cold flow processes that may be increasingly important in high mass halos at high redshifts $z \gtrsim 2$. Some of these galaxy formation simulations will occur as part of our "sub-Bolshoi" hydrodyamical simulation program (§3.1), which will reach or exceed 100 pc resolution.

Earlier simulations by our group and others have included many binary mergers of galaxies modeled after nearby spirals, which typically have star formation rates (SFRs) of a few solar masses per year. But most stars formed in the high-redshift universe. Galaxies at redshift $z \gtrsim 1$ typically have SFRs an order of magnitude higher than nearby, reflecting the well known evolution in the SFR ("Madau plot") and the more recently discovered regularity in the specific star formation rates (SSFRs) of star-forming galaxies (Noeske et al. 2007). In our simple binary merger simulations we can increase the SFR somewhat by increasing the initial gas fraction in the disks, but the resulting efficient star formation rapidly depletes the denser gas in the central regions. As a result, a significant fraction of stars have formed even before the galaxies encounter each other. Such galaxy mergers turn a lower fraction of their initial gas into stars than galaxies that start with a lower gas fraction (Cox et al. 2006b). This is probably unrealistic. In order to have the observed sustained high SFRs, the simulated galaxies must be continuously resupplied with gas by the filaments within which they reside.

As we discussed in §2.1, Collaborator Klypin's former PhD student Daniel Ceverino, now a postdoc with Co-I Dekel, is performing the highest resolution cosmological hydro simulations of galaxy evolution including the gaseous environment. These new simulations not only treat galactic gas inflows and outflows realistically, they also naturally include multiple mergers and cold flows that are likely to form many of the more massive elliptical galaxies at high redshift, as shown for example by the argeement of the simulations in Figure 1 with the observations of the Genzel group. These simulations naturally predict many quantities that can be compared to observations, including the evolution of the star formation rate, metallicity, stellar mass, half-light radius, morphology, and kinematics including velocity dispersion and rotation. For example, we are finding that the central stellar spheroids are rapidly rotating down to $z \sim 1.3$ (as far as these high-resolution hydro simulations have yet run) when formed by merging of star forming clumps from unstable gaseous disks. We have sped up the code significantly, and we are learning how to get it to scale on larger supercomputers. This will allow us to run many galaxy simulations down to $z = 0$.

These high-resolution hydro simulations make predictions that can be compared to many of the new observations now becoming possible. For example, the gas flowing along filaments into these forming galaxies converts gravitational potential energy into Lyman α radiation (e.g., Dijkstra & Loeb 2009) as shown in Figure 1(d), with luminosity and morphology resembling observations (e.g., Matsuda et al. 2006, 2009). Comparing observed to simulated kinematics could help to discriminate between this galaxy formation scenario in which the gas is infalling vs. starburst models where the gas is outflowing.

We are working with our UCSC Collaborator Mark Krumholz to develop better treatments of feedback below the resolution scale, especially radiative feedback treated using ray-tracing, in order to improve our calculation of the star formation efficiency in mergers and in the star-forming clumps produced by disk instabilities (Figure 1). This may also enable us to explore the origin of globular clusters in forming elliptical galaxies. Primack will work with his student Moody to compare the kinematics and morphology of the simulated galaxies to observations, and with his student Porter to improve SAM treatment of galaxy formation at high redshift.

3.5 Using improved models to interpret observations of AGN in forming galaxies. Current hydrodynamic simulations of AGN in merging galaxies (Hopkins et al. 2008b,a) , mostly run by Collaborator T. J. Cox, have suggested that feedback from the rapidly accreting, obscured black hole will clear the merging galaxies of cold gas, shut down star formation, and for a short while uncover the bright AGN before it runs out of gas. This scenario predicts that bright AGNs should be in merging and interacting galaxies, with the peak AGN luminosity as the two galaxies are merging. In contrast, analysis of the SDSS spectra of nearby galaxies shows that bright AGN typically appear hundreds of Myr after the starburst (Wild et al. 2007), and our analysis of colors and morphology of X-ray emitting galaxies at $z \sim 1$ in the DEEP2 survey shows that they are mostly red-sequence(Nandra et al. 2007; Georgakakis et al. 2008) galaxies with early-type morphologies (Pierce et al. 2007; Pierce 2009), in apparent contradiction to the theoretical model. Data now becoming available at higher redshifts $z \gtrsim 2$ may agree better with the model. However, it remains unclear how SMBHs will be fueled in the multiple overlapping galaxy mergers that will be common at higher redshifts or where the main star formation occurs in clumps fed by cold flows. Primack's grad student Priya Kollipara is working with Daniel Ceverino to run new simulations like that shown in Figure 1, but **now including fueling and feedback from SMBHs** in order to explore these issues. For example, we are assuming that seed black holes exist in the star-forming clumps in unstable disk galaxies, and following the resulting SMBH fueling. Although we do not know how AGN jets couple to the surrounding gas, we do compute energy and momentum transfer from radiative feedback using ray-tracing techniques, working with Collaborator Mark Krumholz. We also plan to include recycled gas from stars as a source of fuel for star formation and AGN fueling (Ciotti & Ostriker 2007).

In order to draw strong conclusions, we will need to analyze the simulations in the same way as the observations. In binary mergers, for example, the brightest AGN phase is at the final coalescence of the two galaxies, when they quickly assume a spheroidal appearance and would not necessarily be morphologically classified as mergers. Using our improved *Sunrise* radiation transfer models, we can generate simulated observations of the simulations and correlate observables like morphology and X-ray luminosity with the intrinsic growth of the black hole.

These simulations can then be compared with multiwavelength data sets, especially those being assembled by the DEEP/AEGIS team, led by our Collaborator Sandra Faber, and those by Genzel's group. We know that the gravity of the spheroid can influence infall of gas toward the SMBH, and that feedback from the SMBH can affect star formation in the spheroid. The challenge is to develop methods to measure both star formation and SMBH mass growth quantitatively in all stages of galaxy evolution. Primack's finishing graduate student Christy Pierce has done part of this work in her just-finished dissertation (Pierce 2009). This includes estimating the effect of AGN on morphologies and colors of galaxies (Pierce et al. 2009). However, much work remains to be done to calculate the appearance and spectra of merging and postmerger galaxies including AGN from our new simulations, using our radiation transfer code *Sunrise*, and comparing them to multiwavelength observations. This project will be undertaken by UCSC grad student Priya Kollipara working with Primack and Collaborators Sandra Faber and Patrik Jonsson.

3.6 Understanding the role of cold flows in star formation and quenching. We will further study how efficiently cold flows penetrate through hot halos at high $z \gtrsim 2$ and thus can grow massive disks with high star formation rates even in massive halos. This is expected (Dekel & Birnboim 2006) because M_{shock} is much larger than the typical forming halo mass M_* at $z > 2$, while they are comparable at $z \lesssim 1$. The hypothesis is that rare halos (with $M >> M_*$) at $z > 2$ are fed by narrow, dense dark matter filaments. The gas riding these filaments cools rapidly and avoids the shock heating that occurs elsewhere in the halo. This has been demonstrated in a few simulations (Dekel et al. 2008), but it remains to be seen how common this phenomenon is in higher-resolution cosmological simulations and also whether the observed galaxies thought to exemplify this phenomenon actually have properties similar to those predicted by the simulations.

The properties of elliptical galaxies at $z \lesssim 2$ require a robust quenching of the cold gas supply for star formation above a threshold halo mass $M_{crit} \approx 10^{12} M_\odot$ (Dekel & Birnboim 2006; Croton et al. 2006; Cattaneo et al. 2006, 2008). Heating is also required in order to prevent cooling flows in cluster halos. AGN feedback is being considered, by us and others, as the source of quenching. However, as we mentioned above, how AGN feedback couples to the extended halo gas is a difficult open issue. However, bright quasars have short duty cycles and cannot provide the required long-term maintanence, and the characteristic halo mass M_{crit} does not seem to emerge from the black hole physics. Gaseous major mergers, suggested as the trigger for quenching via starbursts or quasar activation (Hopkins et al. 2007), also have a hard time explaining the characteristic mass, and it is not clear that their frequency and starburst efficiencies are sufficient (Cox et al. 2008).

We propose to examine in detail using hydrodynamical simulations several alternative quenching mechanisms. One possibility is **gravitational quenching**, in which the gravitational energy associated with cosmological baryon accretion into dark matter halos is the major source maintaining quenching of star formation (Dekel & Birnboim 2008). Analytic calculations and hydrodynamical simulations reveal the existence of a threshold halo mass $M_{shock} \sim 10^{12} M_\odot$ for a stable shock at the virial radius (Birnboim & Dekel 2003; Dekel & Birnboim 2006). In smaller halos, rapid cooling prevents the post-shock pressure from suporting the shock against gravitational collapse. The accreted gas flows cold into the inner halo, where it may eventually shock, build a disk, and form stars. When the halo mass grows above M_{shock}, a stable shock rapidly propagates outward toward the virial radius, halting the infalling gas and creating a hot, quasi-static medium at the virial temperature. This is a most natural trigger for quenching star formation in massive galaxies, which may explain the threshold mass and provide the hot gas necessary for *any* quenching mechanism. We propose to pursue a detailed investigation of this process.

An alternative possibility is **morphological quenching**,' whereby star formation in galactic disks becomes stabilized against fragmentation into star-forming clumps by the growth of a central stellar spheroid, as shown in Figure 1. In contrast with gravitational quenching and AGN feedback, which are limited to halos of total mass $\gtrsim 10^{12} M_{\odot}$, morphological quenching appears to be able to explain how field ellipticals can become red even in less massive halos. This process also needs to be explored via simulations compared to observations.

3.7 Scientific visualization. To really gain an understanding of the processes that occur when galaxies merge, it is essential to be able to efficiently study the simulations in a variety of ways, and especially to explore the temporal dimension which often is not represented well when studying isolated snapshots. For this purpose, our group is collaborating with Chris Henze (NASA Ames) whose visualization group has the experience and facilities for this work. Our simulation codes have been instrumented so simulations running on the Columbia supercomputer can be rendered and visualized in real time, and we are going to continue this collaboration to study our new simulations. The visualizations also make spectacular videos for explaining our science to the public, and Primack has proposed to NASA a collaboration with major planetariums to make the invisible universe visible. Such visualizations for education and public outreach are also a goal of the new University of California systemwide High-Performance Astro-Computing Center that Primack will lead.

4 Broader Goals and Impacts

Our group has a long history of openness, giving access to codes and simulation outputs to researchers interested in performing their own analyses or comparisons. Our *Sunrise* radiation-transfer code is free software, enabling everyone interested to use and modify it for their needs. This will continue to be true for the software and algorithms that will be developed as part of this proposal, to the benefit of the general research community. The development of *Sunrise* has led to a Collaboration between our group and two of the foremost galaxy simulation groups in the U.S., those of Hernquist (CfA) and Governato (U Washington).

We also have a long tradition of collaborating closely with observers, especially our DEEP/AEGIS colleagues. We host a galaxy formation workshop at UCSC each summer attended not only by our group and the DEEP team but also our Collaborators and others. These summer workshops have proven to be extremely productive — they allow us to discuss new data and results, share ideas, and generate new projects. Many visitors have attended, which has resulted in collaborations on various topics.

Opportunities for undergraduates to work on research projects as part of senior theses have been good, typically one or two projects every year (Jhirad 2004; Cottrell 2005; Favoloro 2005; Rocha 2006). One of the recent examples is Miguel Rocha, a Mexican immigrant who transfered to UCSC from a community college and whose work, supervised by Jonsson and Primack, resulted in a published paper (Rocha et al. 2008). He is currently a graduate student in astrophysics at UC Irvine.

PI Primack has given many popular talks to diverse audiences from the local Rotary club to major international conferences. He has written many articles for encyclopedias and popular magazines, and been interviewed by many print and broadcast journalists. Primack has also been teaching with Nancy Abrams a popular UCSC undergraduate course on "Cosmology and Culture" for a decade and a half. This led to their popular book, *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos*, published in the U.S. by Riverhead/Penguin and in the British Commonwealth by HarperCollins (2006), in French, Norwegian, and Portuguese translations (2008), with other translations in progress.[5] Primack developed "Einstein's Rocket" video games to teach key ideas of relativity; a java version is available on the UCSC Physics website.[6] Primack and his theorist colleagues are also collaborating with Chris Henze at NASA Ames, Mark SubbaRao at Adler Planetarium, Ryan Wyatt at Morrison Planetarium, and Martin Ratcliffe of Sky-Scan to make our simulation outputs available to planetariums worldwide, and to combine constrained simulations of the dark matter distribution in the nearby universe with astronomical images of galaxies to show how galaxies fit into the cosmic web. Primack has applied for NASA funding to support these Public Outreach efforts.

Co-I Dekel has been organizing Winter Schools in Cosmology, attended by many of the leading US graduate students and postdocs in the field (1995, 1997, 2003, ...). For the last 3 years he has been organizing a series of public lectures on science. He serves as the chief scientific advisor to the popular Israel science magazine Galileo, and has given many popular-science lectures.

Our simulations provide striking illustrations of our research,[7] Our animations have been featured in the NASA Spitzer Science Center video press releases,[8] and were attractions at supercomputing conferences SC04, SC06, and SC09, where they were presented by Primack's students. They were also featured in NERSC's 2004 and NASA Supercomputing Division's 2006 and 2008 Annual Reports. Visualizations of our simulations have been used to illustrate articles in magazines including *Astronomy* and *National Geographic*. A video submitted by Jonsson, Novak, and Primack of one of our galaxy merger simulations was a semifinalist in the 2008 NSF/Science Magazine Visualization Challenge. Further education and outreach efforts are described at the end of §3.7.

[5] Many reviews and print and broadcast interviews can be found at `http://viewfromthecenter.com` including a list of over 100 popular lectures during 2006-08.

[6] `http://physics.ucsc.edu/$\sim$snof/er.html`

[7] `http://sunrise.familjenjonsson.org/coolstuff.html`

[8] "Showcase: Andromeda, Beauty and the Beast" and "Exposing the Exploding Cigar Galaxy" at `http://www.spitzer.caltech.edu/features/hiddenuniverse`.

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