1 Scientific/Technical/Management – Introduction

Galaxy formation is so complicated that observations and theory cannot give us a clear picture of how galaxies form without working hand-in-hand. Fortunately, new observations at $z \gtrsim 1.5$ are clarifying the processes by which most of the stars in the universe formed, and at $z \lesssim 1.5$ how present-day galaxies assembled. And observations are finally closing in on the ΛCDM cosmological parameters, so that we have a definite cosmological framework within which to model galaxies.

The main goal of the proposed research is to provide theoretical support for two large HST legacy projects, the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS)[1] and the Advanced Camera for Surveys (ACS) Nearby Galaxy Survey Treasury (ANGST). CANDELS is designed to document the first third of galactic evolution from $z = 8$ to 1.5 via deep imaging of more than 250,000 galaxies with WFC3/IR and ACS. Five premier regions of the sky are selected; each has additional multi-wavelength data from Chandra, Spitzer, Herschel, and other observatories, plus extensive spectroscopy of the brighter galaxies. The use of five widely separated fields mitigates cosmic variance and yields statistically robust and complete samples of galaxies down to 10^9 solar masses out to $z \sim 8$. We propose to use our state-of-the-art hydrodynamics plus N-body code *hydroART* developed by Klypin in collaboration with his former PhD student Andrey Kravtsov (Kravtsov et al. 1997; Kravtsov 1999, 2003) to simulate hundreds of cosmological regions, containing many hundreds of large galaxies and thousands of satellite and dwarf galaxies (§2-3). We will use our *Sunrise* code (Jonsson 2006; Jonsson et al. 2006, 2010; Jonsson & Primack 2010) to make realistic images of these galaxies in many wavebands and at many times during their evolution to compare with the imaging and photometry from CANDELS and other programs (§4). We will also analyze these simulations to understand their implications for phenomena including metallicity evolution and Lyman alpha absorption and emission (§5). These simulations will also further the other main goal of this proposal, to support the ANGST survey, which is collecting HST data on the nearby dwarf and satellite galaxies that pose some of the greatest challenges for theory, including the abundance of such galaxies and the emptiness of voids (§6).

Our simulations reap the benefits of recent developments, including improved physical models and better codes and computers. The simulations are now increasingly realistic and produce simulated galaxies that look a lot like real ones. Improved computer hardware allows us to do mass production of galaxy simulations with extremely high resolution, currently 20-50 parsec. With hundreds of regions simulated we can also explore statistically such issues as effects of environment, the frequency and duration of major mergers and of disk instabilities and their relative importance in formation of galactic spheroids, how baryons cycle into and out of galaxies including the origin of galactic winds, and how star formation is regulated in star-forming galaxies and how it is prevented in most red-sequence galaxies.

We put special emphasis on understanding in simple terms the processes responsible for observed or simulated features, using "toy models" that capture the key elements of a complicated process. Examples in our previous work include toy models for halo structure (Bullock et al. 2001), halo growth (Wechsler et al. 2002), and radii of merger remnants (Covington et al. 2008). Toy models will be developed and applied for guiding the simulations

[1] http://candels.ucolick.org

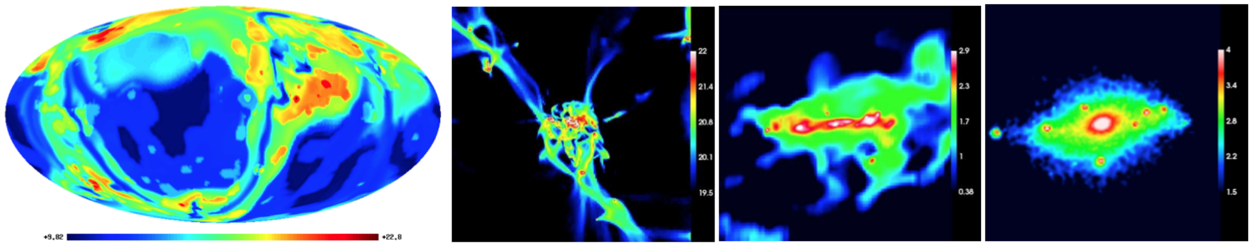

Figure 1: Streams into a forming galaxy at $z \sim 2.5$ in our cosmological *hydroART* simulations. **a** Entropy in a shell at 1.5 $R_{\rm vir}$, showing for the first time a low-entropy pancake (coherent blue line) surrounded by planar shocks (green-yellow). Three inflowing streams are embedded in the pancake. **(b)** Gas in a region 160 kpc across in the same simulation (Ceverino et al. 2009, resolution 70 pc), showing three narrow cold streams feeding a 10 kpc disk through a 30 kpc interphase region. **(c)** Edge-on closeup (10 kpc across) of this same gaseous disk, resembling observed "chain" galaxies (Elmegreen & Elmegreen 2006). **(d)** Edge-on view of surface density of all stars in this same disk, showing that about half the stars are in a large bulge formed by merging clumps.

and interpreting them.

In summary, our proposed research will:

- Provide cosmological hydrodynamical simulations of hundreds of large galaxies and thousands of small galaxies at all redshifts with a resolution of 20-50 pc – the largest and most extensive simulation suite of this kind.

- For each galaxy we will provide images generated with our radiative-transfer code *Sunrise* using the same wavebands as for observed galaxies.

In order to use observations and high-resolution simulations to predict the evolution of the entire galaxy population, the best approach remains semi-analytic models (SAMs). We have recently run the Bolshoi series of high-resolution cosmological simulations (Klypin et al. 2010; Trujillo-Gomez et al. 2010; Prada et al. 2011) with cosmological parameters set equal to the best current values. We are working with collaborators including Darren Croton and Rachel Somerville and Primack's graduate student Lauren Porter to run improved SAMs based on detailed merger trees from the Bolshoi simulation and our currently running miniBolshoi simulation, which will resolve the merger history and structure of thousands of Milky Way mass and smaller halos, with sub-halos complete to better than 15 km/s internal velocity. These SAMs will benefit from the insights gained from our new simulations compared with the latest observations. We are already including in these SAMs our new code which predicts, based on our earlier hydrodynamic simulations (e.g., Cox et al. 2008), the stellar radius and velocity dispersion of spheroids produced by mergers including the effects of dissipation, thus naturally accounting for the steep slope and small dispersion of the elliptical galaxy mass-radius relation (Covington 2008; Covington et al. 2008, 2011).

2 High-Resolution Hydrodynamic Simulations

We use the hydro+N-body cosmological code *hydroART* – see for example Fig. 1. Details of the feedback algorithm are given in Ceverino & Klypin (2009). The code now also includes effects of radiation pressure due to young massive stars. Molecular cooling was implemented by using equilibrium cooling rates down 100 K. We use a zoom-in technique to make our simulations. For this project we are using a 200 Mpc simulation box, which will be run dissipationlessly (N-body-only) to $z = 0$. At $z = 2$ we will identify all halos. A random fraction of the halos in each logarithmic bin will be chosen for hydro-reruns. Selection at $z = 2$ is important. Our zoom-in technique does not allow separate simulations of subhalos: the whole parent halo must be simulated. Unfortunately, we cannot afford the supercomputer time to simulate a cluster of galaxies down to 50 pc resolution with our full hydro code – it would require 10 billion particles. However, at $z = 2$ galaxies are not yet in large clusters and simulations can be done even for progenitors of present-day cluster ellipticals. (By running the N-body-only simulation to $z = 0$ we know where every "galaxy" will end up.) We typically run these simulations in a 20 Mpc region, with high resolution hydrodynamics only in the inner ~ 2 Mpc.

Our simulations (Ceverino & Klypin 2009; Ceverino et al. 2010) include a model of stellar feedback that minimizes ad hoc assumptions. This can be achieved only by doing what the real Universe does: formation of a dense (> 10 atoms cm^{-3}), cold ($T \approx 100$ K) molecular phase, where the star formation happens, and which is disrupted by young stars. Radiative feedback due to young stellar clusters has been recently implemented in our code. It follows the same line of ideas and motivation as in Hopkins et al. (2011), but we use a different implementation. We estimate the radiation energy of the most massive stars and assume that in dense regions of star formation this energy is either trapped or directly goes to momentum transfer to gas. In either case it results in additional pressure and finally produces gas momentum, which in turn increases the efficiency of stellar feedback without artificial termination of gas cooling (as in Governato et al. 2007; Brooks et al. 2007) or kicking wind particles (as in the GADGET code). This radiative feedback occurs only for a very short ~ 5 Myr period following the formation of the massive stars. Large galactic winds form naturally without assuming any artificial scheme.

AGN and stellar radiative feedback was not part of our earlier simulations (Dekel et al. 2009a,b; Ceverino et al. 2010), and that may have been the reason why they have perhaps too many large clumps. (Another reason may have been a selection effect – these systems were not in dense environments of large groups and clusters.) We will implement AGN feedback in a similar way as in Springel et al. (2005): a supermassive black hole (BH) accretes mass according to the Bondi-Hoyle-Lyttleton model with parameters set by gas around a massive particle playing the role of the BH. The BH growth is constrained by the Eddington limit. A few percent of the Eddington luminosity is channeled into the ISM. More realistically than earlier simulations (e.g., Springel et al. 2005; Hopkins et al. 2008b,a), we deposit the energy not to the internal gas energy (heat) but to pressure, thus mimicking the radiation pressure of AGN. Also more realistic is the fact that all of our simulations are cosmological, with each galaxy fed by gas from the cosmic web at least until they merge.

Simulation comparison is part of our proposed program. Dr. Ji-hoon Kim, who ran ENZO high-resolution hydrodynamical galaxy simulations as part of his dissertation research with Tom Abel, will be coming to UCSC as a postdoc, and he has agreed to run ENZO simulations of some of the same initial conditions as our *hydroART* simulations. Dekel's group will do a similar program using Teyssier's RAMSES code. We are eager to share our initial conditions and compare outputs with other groups running high-resolution hydrodynamical galaxy simulations, in order to help all of us improve our codes and understand better their successes and problems.

Radiation Transfer Models with Sunrise. In order to calculate the effects of stellar age, metallicity and dust, we will use the Monte-Carlo radiative-transfer code *Sunrise*. The spectral energy distribution of all stars in a given timestep is propagated through the dusty interstellar medium of the simulated galaxies. The current version of *Sunrise* uses a polychromatic algorithm (Jonsson 2006), where every Monte-Carlo ray samples every wavelength. This algorithm makes it possible to calculate spectra efficiently with unprecedented spectral resolution. *Sunrise* uses subgrid models of star-forming regions from the photoionization/dust code MAPPINGS-III (Jonsson et al. 2009). Emission from diffuse dust is calculated self-consistently from the local radiation field, allowing calculation of spectral energy distributions out to the far-IR for comparison with Spitzer and Herschel data.

One of the biggest advantages of CANDELS is the associated multi-wavelength observations, which cover wavelengths from the UV to the far IR and allow tracing both the regions of star-formation and the distribution of older stellar populations. We will generate a large library of *Sunrise*-generated images in all 7 wavelength of CANDELS for every simulated galaxy from many different directions – see Fig. 2 for examples. For each run we will choose at least 10 moments. This gives $\sim$ 10Tb of image data. Results of simulations will be organized in catalogs with each object having numerous attributes such as stellar mass, virial mass, spin parameter, Sersic index, concentration and clumpiness indexes (many of them), luminosities in different bands, and so on. The catalogs can be searched for specific properties. For example, one can find all galaxies with given stellar mass at given redshift. Each subsample will give you physical properties of the selected galaxies: their merging history, environment, and images in different bands, among other things.

From the $\sim$ 20 simulations run thus far and the $\sim$ 15 currently running, we know what resources are required. For each region of $\sim$ 2 Mpc including a "galaxy" of $\sim 10^{12} M_\odot$ mass and 1-2 million dark matter particles, it takes about 5K cpu-hours to run it to $z = 2$ and 30K to continue to $z = 0$, with additional time required for dense regions or higher resolution. We plan to spend at least 5M cpu-hours per year on such simulations. Within the first year or so, we expect to have 300 simulations run until $z = 2$, with about 100 of these continued until $z = 0$. In subsequent years we plan to do additional simulations of this resolution plus higher resolution simulations. The actual number of simulated galaxies is larger because each run produces not only selected galaxies, but also their neighbors and satellites. Additional computer time of $\sim$ 3M cpu-hours per year will be required to run *Sunrise* on many timesteps from these simulations, to produce realistic images including the effects of stellar evolution and dust scattering and absorption. Primack's grad student Chris Moody has created a pipeline to do these *Sunrise* calculations, The large number of objects is not an issue; we have expertise to handle very large data sets, as in our Bolshoi project.

Supercomputer Time. Our supercomputer allocations support our ambitious simulation program. Primack's allocation on NASA Advanced Supercomputing (NAS) machines was 13M cpu-hours in 2009-10 and 7M in 2010-11, which were used mainly for our Bolshoi cosmological simulations. Our current NAS allocation is 10M for 2011-12, which we will use mainly for the galaxy simulations in this proposal. The NAS Pleiaides supercomputer now has 3648 nodes, each with 12 Intel cores. Extensive additional time has been allocated to Primack for this project on the new NERSC Hopper-II machine at LBNL, which has 6384 nodes, each with 24 AMD cores. Our OpenMP *hydroART* code has been ported and tuned for these multicore nodes on both Pleiades and Hopper-II. We will continue to work closely with Dr. Christopher E. Henze and the NAS visualization team in order to visualize our galaxy simulations to help us understand them. Beyond mapping density and entropy, a special challenge is to study the 3D velocity field using advanced interactive procedures – e.g., for exposing the kinematics in the interfaces between streams, disk, and outflows.

Rapid Dissemination of Results. If the postdoc requested in this proposal is funded, we will be able to make the results of our simulations available very rapidly as they come from the supercomputers, along with tools to analyze them. This includes some raw data, catalogs of halos and "galaxies", and images simulated with Sunrise. The plan is to place all the data on a server at NMSU and give access to any astronomer who wants to use the data. A list of available simulation outputs will be available on our web server. Catalogs of halos and galaxies including various characteristics such as masses, colors, magnitudes, and profiles will also be accessible on the web. Raw data and images will be also stored on the data server. We can store ~ 20 snapshots for every model and 100 snapshots for most interesting 100 objects. We will also provide tools (codes) to read and analyze the results. The estimated amount of data is about 20-30Tb of disk space. We request funds ($20k) for the data server. In addition to large disk capacity it will have 48 cores and 32Gb ram – enough for basic analysis of the raw data and catalogs.

3 From the Cosmic Web into Galaxies

Fig. 1 shows how a massive high-z galaxy is fed by ~ 3 streams along filaments embedded in an extended Zel'dovich pancake. The simulations show that almost all the mass feeding a massive high-z galaxy comes along a few narrow streams, including all mergers. The bigger clumps represent gas-rich galaxies with stars and DM halos. The gas input is via a broad range of clump masses, hitting the galaxy as major mergers, minor mergers, or smoother flows. Smaller, "mini-minor" mergers are expected to join the rotating disk with the smooth component, though they could be more efficient in driving disk turbulence. We will measure the clump mass function in the streams, and deduce the galaxy **merger rate** as a function of mass ratio, z, $M_{\rm vir}$, and environment, for the gas, stellar and DM components – a major improvement over the controversial current estimates.

We will explore the way high-z massive galaxies are fed from the cosmic web using our cosmological simulations. The evolution of the streams as they plow their way in through the hot halo, their possible breakup into clumps prior to joining the disk, and their interaction with other streams and with the central disk, are all key issues for disk evolution and halo gas. Analyzing our simulations, we will develop algorithms to identify coherent pancakes and streams, in gas, stars and DM, and study the statistics of stream properties, including number and co-planarity, as a function of halo mass. Comparing the streaming rates of DM, gas and stars, we will quantify the statistics of accretion and merger rates, as constraints on disk growth and star formation. This will also lead to new physical recipes as a function of redshift, mass and environment, to be implemented in SAMs.

Fig. 1b, showing coherent streams in the outer halo (~ 100kpc) and the central disk (~ 10kpc), reveals a "messy" region of ~ 30kpc surrounding the disk. It involves a complex pattern of shocks, as well as gravitational, hydrodynamical, and thermal instabilities. The

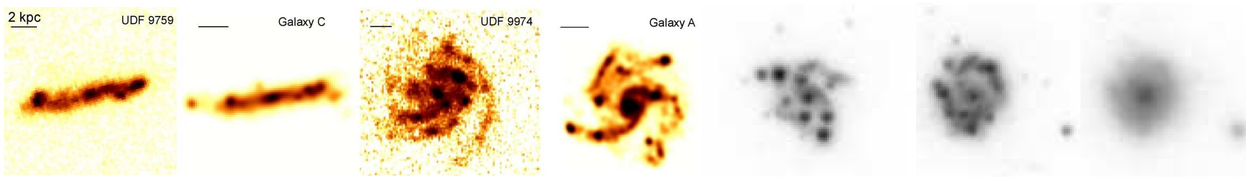

Figure 2: The stellar components of clumpy disks at $z \sim 2$: HST images compared to simulations "observed" with a similar color and PSF. **In brown:** two UDF galaxies versus two simulated disks, edge-on and face-on. **In b&w:** two I-band images of face-on simulated clumpy disks, and an H-band image of the adjacent "ring" galaxy, where the clumps have disappeared.

kinematics in this region is a key to understanding the **dissipation** of stream energy into turbulence and heat, and the **transfer of angular momentum** on the way to a rotating disk. We will explore the structure and kinematics of the interaction zone utilizing advanced interactive visualization tools The dense cold streams are highly supersonic with respect to the cold gas and marginally supersonic with respect to the pressure confining hot medium. We will study the development of **hydrodynamical instabilities** in such situations (missing from the literature!).

4 Understanding and Visualizing Disk Instabilities

A comparison of the predicted streaming rate into galaxies at $z \sim 2$ and the comparable observed star formation rate (SFR) in galaxies of $\sim 100\, M_\odot\, \mathrm{yr}^{-1}$ (Genzel et al. 2006, 2008) indicates that the SFR is governed by the net accretion to within a factor of order 2 (Dekel et al. 2009a). This is in agreement with the predicted steady state (Dekel et al. 2009b) emerging from mass conservation, $\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \dot{M}_*$, with $\dot{M}_* = \epsilon_{\rm sfr} M_{\rm gas}/t_{\rm ff}$, which implies an **attractor solution** $\dot{M}_* \rightarrow \dot{M}_{\rm acc}$, once all terms vary slowly. This can explain the decline of SFR from $z \sim 2$ to 0 (Noeske et al. 2007), and the associated decline of cosmological SFR density (Bouché et al. 2010). Using our simulations, we will test the validity of the attractor solution by comparing SFR and accretion rate as a function of time. We will study the spatial distribution of SFR in the different components of disk, clumps and bulge, and correlate it with the incoming streams, to explore the accretion-SFR connection.

The gas streaming into high-z disks induces violent gravitational instability, in agreement with observations showing transient features and giant clumps forming stars (Genzel et al. 2006; Elmegreen et al. 2009). Inward migration on an orbital timescale grows a bulge (Bournaud et al. 2007; Elmegreen et al. 2009). Our first high-resolution *hydroART* simulations (Ceverino et al. 2010) indeed revealed clumpy disks (Fig. 1). Instability analysis in a cosmological setting (Dekel et al. 2009b) predicted that a significant fraction of the $z \sim 2$ galaxies are clumpy disks with massive bulges in a steady state. We will generalize this analytic treatment, and study a suite of simulated galaxies spanning a range of masses to $z = 0$, with higher resolution and improved physics for a systematic comparison between theory and observations. CANDELS will provide multi-wavelength images of 250,000 high-z galaxies, to be confronted with the predicted morphologies. Fig. 2 shows a sample of HST images of clumpy $z \sim 1.5 - 3$ galaxies vs. simulated disks "observed" with similar wavelengths and PSFs, indicating a striking similarity.

Using Simulations to Help Guide high-z Galaxy Image Classification. A naive classification might have tagged all of these as ongoing mergers, but probably this is only true of some such images. While the simulated galaxies are often clumpy disks, preliminary analysis of CANDELS images suggests that these early simulations may have overproduced clumpy disks. We are eager to compare our large suite of improved simulations with the rapidly growing CANDELS data.

In some cases, the disk structure is obvious (e.g., the face-on "ring" 2nd from the right in Fig. 2) or can be deduced from the "chain" morphology (left pair), but in many cases the disk geometry is not easy to identify from the few dominant clumps (3rd from right, which is the same face-on disk to its left). This demonstrates the need for a new theory-motivated classification scheme for high-z galaxies. The H image of the face-on "ring" (right) demonstrates how the clumpy features could disappear in the red bands, arguing that the bluer images are better for identifying disk instability features.

Based on the simulations, we will develop a classification scheme that highlights the clumps, including their spatial distribution (concentration, eccentricity, asymmetry), color and SFR, and will distinguish between mergers and unstable disks. The simulated galaxies will be "observed" at the different HST bands, including dust extinction (via *Sunrise*), background noise, and PSFs. We will study the simulated evolution of the clumpy disks, the onset and termination of the instability phase, in comparison with CANDELS (with Co-I Faber and her student Mark Mozena, co-supervised by Primack). We will study in detail (a) disk size and thickness, (b) bulge-to-disk ratio, (c) density profile of stars, gas and SFR in the bulge and the disk, (d) disk kinematics and kinematic signatures of the clumps, (e) baryonic fraction, and (f) spatial distribution of metallicity.

This comparison of simulations with observations will also enable us to extend to higher redshifts our study of the rates of various types of mergers (major and minor, gas-rich and gas-poor) to redshift 1.5 (Lotz et al. 2009, Lotz et al. 2011, in final prep.), interpreting number counts of various morphologies in various redshift ranges using our measurements of observability timescales of these morphologies based on hydrodynamic simulations (Lotz et al. 2010a,b). Distinguishing between mergers and clumpy disks will hopefully be helped by the multiwavelength observations available in CANDELS.

Understanding the Instability of Cosmological Disks Our analytic study in Dekel et al. (2009b) was crudely valid at high z, when the disk was gas rich and the stars had a comparable velocity dispersion, $\sigma_\star \sim \sigma_{\rm g}$. We assumed input by accretion and draining by migration, while in Bouché et al. (2010) we assumed draining of gas into stars. In reality, the disk is a two-component system that gradually becomes star dominated as the accretion rate decays. The stellar dispersion, which remains high as the gas cools, now acts to stabilize the disk.

We will perform an **analytic** study of two-component disk instability including mass exchange between gas and stars, to capture the **transition** from a violently unstable disk to a more stable one at low z.

- We will explore the relevant parameter space to learn about the evolution of two-component disks in a cosmological context from instability to stability and vice versa.
- We will investigate potential drivers for the **disk turbulence** that maintains marginal instability with giant clumps and rapid migration, gravitational heating vs. stellar

feedback.

The formalism we use (Rafikov 2001) is based on a generalized Toomre Q_2 parameter derived from those of gas and stars and the ratio $\sigma_\star/\sigma_{\rm gas}$, and we seek a solution where **marginal instability** is regulated at $Q_2 \sim 1$. We require **mass conservation**, where the disk gas mass reacts to the accretion, migration, and SF (including feedback), $\dot{M}_{\rm g} = \dot{M}_{\rm acc} - \dot{M}_{\rm mig} - \dot{M}_*$. The SFR $\dot{M}_* = \epsilon_{\rm sfr} M_{\rm g}/t_{\rm ff}$, with an efficiency $\epsilon_{\rm sfr} \sim 0.01$, reflects the Kennicutt law (Krumholz et al. 2009a,b). The bulge growth is by migration from the disk and by merging of galaxies. The cosmological $\dot{M}_{\rm acc}$ is known, and $\dot{M}_{\rm mig}$ is computed as in Dekel et al. (2009b). **Energy conservation** constrains the growth of velocity dispersions by gravitational "heating" due to the inflow in the potential well, into the disk and within the disk, as the gas turbulence dissipates (Krumholz & Burkert 2010). A failure to obtain a solution where the gas pressure is larger than just its thermal component is interpreted as transition to stability.

Clump Structure. While the 70 pc resolution of our initial simulations (Ceverino et al. 2010) allowed us to uncover the disk fragmentation, it is only marginal. We need to resolve the clump substructure in order to trace the generation of internal turbulence and molecular cooling. With our improved *hydroART* code, we aim to simulate similar galaxies with ~ 10 pc resolution to $z \sim 2$ by the second year of this program, resolving sub-clumps comparable to star-forming molecular clouds with molecular cooling to < 100K and densities $> 10^4\,{\rm cm}^{-3}$. This will permit (a) a reliable measure of the clump population properties while grid-scale artificial fragmentation is under control, (b) a study of the internal structural and kinematic properties of the clumps, and (c) a reliable treatment of SF and feedback in them.

Molecular Hydrogen Dissociation Feedback Star formation (SF) is associated with molecular gas (Leroy et al. 2008). Since H_2 forms primarily on dust grains, the formation-dissociation balance is highly sensitive to the metal content. This leads to SF suppression in dwarf galaxies (Krumholz et al. 2009b), in DLAs (Gnedin et al. 2009; Gnedin & Kravtsov 2010), and perhaps in all very-high-z galaxies.

As an alternative to SN feedback (Dekel & Silk 1986) and stellar feedback from massive stars, radiation from main-sequence stars can shut down SF by dissociating the H_2 molecules. The H_2 fraction is $f_{H_2} \sim 1 - 0.02(Z_{-1}\Sigma_{-1})^{-1}$, where Z is in units of 0.1 solar (McKee & Krumholz 2010). This leads to a critical halo mass $M_{\rm dis} \sim 10^{11}{\rm M}_\odot$, which could vary in time and between galaxies, below which H_2 is dissociated. The dissociation feedback has the unique features that (a) the transition at $M_{\rm dis}$ is sharp (because a small f_{H_2} enhances the SFR, which increases f_{H_2} further), and (b) the dissociated gas is not ejected but rather put on hold until Z or Σ are high enough for SF to resume. A cutoff of SFR below $\sim 10^{11}{\rm M}_\odot$ is helpful in explaining the growth of SFR density from $z \sim 8$ to 2, and the downsizing of SF in galaxies (Bouché et al. 2010). With feature (b), the cutoff at $M_{\rm dis}$ helps explaining the specific SFR plateau at $z = 2-8$. With SF expert Krumholz, we will work out the role of dissociation through time, using theoretical and observational constraints on the evolution of Z and Σ.

A challenge will be to **implement molecules** in the *hydroART* code, avoiding costly time-dependent chemistry networks coupled to radiative transport (Robertson & Kravtsov 2008; Gnedin et al. 2009). We will use instead a successful analytic solution to the local H_2 fraction (Krumholz et al. 2009a; McKee & Krumholz 2010). We will run cosmological simulations including H_2 dissociation feedback, alongside with SN and stellar feedback, to study the role of each mechanism.

Morphological Quenching. In trying to understand early-type galaxies (ETGs), we must address the "quenching" mechanism responsible for the suppression of star formation. Since there is so little star formation in red galaxies, stellar and SN feedback cannot be important in preventing gas from forming stars and keeping red galaxies red. Mechanisms such as AGN feedback (Cattaneo et al. 2009, review), virial shock heating (Dekel & Birnboim 2006), and gravitational heating (Birnboim et al. 2007; Birnboim & Dekel 2010; Khochfar & Ostriker 2008), all refer to halos $\geq 10^{12}\mathrm{M}_{\odot}$. We seek a mechanism that could quench SFR also in **isolated red ETGs** that are centrals in smaller halos, which constitute $\sim 10\%$ of the dwarfs in SDSS. Given that much of the high-z SF is in unstable gas disks, it can be quenched when the disk becomes stable, e.g. because of the growth of a stellar **spheroid**, by mergers or by in-situ migration. This automatically links the color of a galaxy with its morphology; it does not require gas consumption, removal or termination of gas supply; and it can also work in small halos. We presented this concept of morphological quenching (MQ) in Martig et al. (2009), predicting the presence of stable gas disks in high-z ETGs. We plan to study MQ in detail using simulations, and come up with testable predictions, e.g., correlations between mass, bulge-to-disk ratio, SFR, gas surface density and environment.

Evolution to Low-z Spheroids We wish to relate the high-z star forming galaxies to their low-z descendants. The Ceverino et al. (2010) simulations ended at $z \sim 1.3$, by which most galaxies developed a large rotating spheroid. This motivates the hypothesis that wildly unstable disks develop into rotating spheroids (Rettura et al. 2010) or become thick stellar disks. We wish to investigate how later gas accretion, combined with feedback, leads to the thin disks of today's spirals, which are not violently unstable.

- We will push many simulations to $z = 0$ with a resolution of $\sim 20\,\mathrm{pc}$ or better by the second year of this project.
- These simulations will allow (a) testing the predicted transition to stability, (b) investigating our proposed mechanism of MQ, and (c) measuring the fractions of today's bulges that originate from disk clumps versus external mergers.
- Primack, grad student Chris Moody, our UCSC collaborator Aaron Romanowsky, and Dekel and HU postdoc Loren Hoffman will analyze the kinematic structure of our low-z simulated galaxies compared to nearby ETGs.

5 Observing Cold Streams via Lyman-α Emission and Absorption

The cold streams feeding high-z halos consist of hydrogen at $(1\text{–}5) \times 10^4$K, a natural extended source for Ly-α emission and absorption as an alternative to outflows (e.g., Furlanetto et al. 2005; Dijkstra & Loeb 2009; Goerdt et al. 2010; Faucher-Giguère et al. 2010; Fumagalli et al. 2011). The emission can result from collisional excitation or photo-ionization. The available energy sources are (a) gravitational energy released by the streaming into the potential well and (b) the UV radiation and winds from stars and AGN. Our high-resolution hydro simulations enable a computation of the Ly-α emission and absorption from these sources,

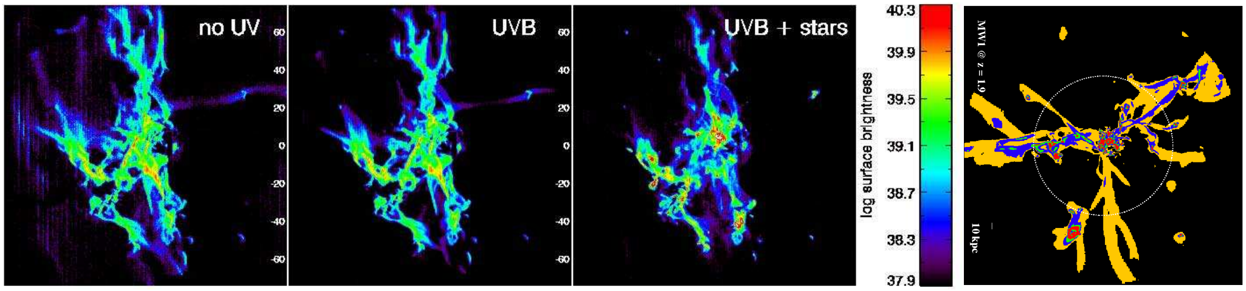

Figure 3: Preliminary results on Ly-α emission and absorption including radiative transfer (SENODA). Extended Ly-α emission from a simulated massive galaxy ($M_{\rm vir}\sim10^{12}{\rm M}_\odot$, $z=4.5$, box 150kpc). **(a)** CIE, no photo-ionization, with Ly-α multi-scattering. **(b)** With UV background ionizing the unshielded regions. **(c)** Including UV from stars and fluorescence. The total luminosity is $\sim10^{43}\,{\rm erg\,s^{-1}}$. **(d)** Neutral gas column density in a $10^{12}{\rm M}_\odot$ halo at $z=1.9$ out to $2R_{\rm vir}$ (Fumagalli et al. 2011). Neutral (red, DLA), neutral-ionized transition (green, SLLS), ionized optically thick (blue, LLS), and optically thin (yellow, MFP).

providing ways for detecting the cold streams and models for the origin of the observed systems.

Ly-α Emission. In Goerdt et al. (2010) we computed the emissivity due to collisional excitation from the simulated gas temperature, density, and approximate neutral fraction, assuming self-shielding against UV within the dense streams. The relevance of gravity emerges from the accretion rate, $\dot M\sim100\,M_\odot\,{\rm yr}^{-1}$, and the energy released per infalling mass $\sim V_{\rm vir}^2=GM_{\rm vir}/R_{\rm vir}$. For $V_{\rm vir}\sim300$ km/s, the power is $\dot M\,V^2\sim10^{43}$ erg/s, comparable to the luminosity of Ly-α blobs (LABs: Steidel et al. 2000; Matsuda et al. 2004, 2006, 2011). The predicted LABs resemble the observed ones, with a luminosity function in the right ball park; halos of $10^{12-13}{\rm M}_\odot$ at $z\sim3$ shine as LABs of $10^{42-44}\,{\rm erg\,s^{-1}}$ that extend to $50-100$kpc with a characteristic irregular morphology. However, Faucher-Giguère et al. (2010) showed that this calculation overestimated the Ly-α emission because the self-shielding assumption is inaccurate; a more detailed radiative transfer RT calculation is required. We now compute the Ly-α emission using full **radiative transport** (RT) in post-processing, justified by the short radiation-diffusion timescale. The RT is applied to the UV continuum from background and galactic sources and to the resonant line scattering. Local dust absorption is computed from density and metallicity. The RT calculation is being done with Dan Kasen utilizing the 3D Monte-Carlo RT code SEDONA (Kasen et al. 2006) – see Fig. 3.

In the **RT of ionizing radiation**, we consider UV from the cosmic background (Haardt & Madau 1996, 2011) and from local stars, include the scattering and absorption by HI and dust, and iteratively converge to ionization equilibrium.

In the **RT of Ly-α photons**, the emissivity due to thermal excitation is computed similarly to Goerdt et al. (2010) and the Ly-α due to fluorescence is computed from the photoionization rate determined by the UV transport routine. The RT code treats the multiple scattering and diffusion of the Ly-α photons from the line center to the wings before escaping. The density of **dust**, which absorbs and scatters both Ly-α and UV photons, is constructed from the simulated metallicity due to SNs, and its properties are read from Table 6 of Li & Draine (2001). Fig. 3abc shows a preliminary example from our analysis (Kasen et al., in prep.). The total Ly-α luminosity is $\sim10^{43}\,{\rm erg\,s^{-1}}$, only slightly affected by the line scattering, which spreads out the emission region. Dust reduces the Ly-α luminosity outside the inner 10 kpc by only a few percent. The UV background shuts down unshielded regions. The UV from stars does not make a drastic change to the overall luminosity and morphology, but now the luminosity from **fluorescence**, largely reduced by dust near the stars, is comparable to the gravity-driven CIE luminosity. The RT codes will be developed and passed through further cosmological tests (Iliev et al. 2006). The RT will be applied to our suite of simulations for accurate predictions of LAB properties including 2D spectroscopic maps of the double-peaked Ly-α line profiles, to be compared with current observations (Matsuda et al. 2011) and for stimulating new observations. This comparison aims at features that may distinguish between the models of cold streams and outflows — we expect the line profile to be dominated by the coherent streaming in halos $> 10^{12}\mathrm{M}_{\odot}$ at $z \geq 3$. We will also compute emission in other H lines and X-ray emission from the hot gas.

Ly-α Absorption. The cold streams also leave absorption imprints on the spectra of quasars and galaxies. We study how the simulated galaxies give rise to observed systems, classified by column density N_{HI} into DLA ($> 20.3\,\mathrm{cm}^{-2}$), SLLS ($19.0-20.3$), LLS ($17.2-19.0$), and MFP ($15.5-17.2$). In work led by UCSC grad student M. Fumagalli (with Prochaska and Primack), utilizing our RT analysis, we compute the HI fraction, and study the cross section of neutral and ionized gas as a function of redshift, mass, and location in disk, satellites, and streams. Our preliminary results (Fig. 3d; Fumagalli et al. 11) reveal a patchy structure, with neutral pockets of damped Ly-α (DLA) embedded in extended finger-like ionized components of lower column density SLLS+LLS systems. Within $2R_{\mathrm{vir}}$, the covering factor of optically thick gas is $< 10\%$ for LLS and 1% for DLA, but massive galaxies and their streams account for $> 30\%$ of the observed absorbers (the rest presumably coming from smaller galaxies or the IGM). We will pursue a statistical comparison with the observed systems, including predictions of detection rates for future all-sky surveys by ALMA and eventually the SKA. We will address the cold-stream signatures on the kinematics and metallicity of absorption systems, and study the relation between absorption and emission, e.g. LLSs and Ly-α emitters (Rahmani et al. 2010). In particular, Steidel et al. (2010) measured massive outflows in stacked spectra of $z \sim 3$ LBGs, which overwhelm the signal from inflows. An intense inflow should be there if it supplies the gas for the high SFR plus the massive outflows, but it is expected to be hidden in the stacked spectra because of the small sky coverage by the streams and their low metallicity. We will use the simulations to make quantitative predictions for metal absorption in the cold streams.

6 Giant and Dwarf Galaxies in the Local Volume

Galaxies in the Local Volume – a 10 Mpc region centered on our Milky Way – have special interest for observers and theorists. Observationally this is the region where dwarf galaxies can be studied. For theorists this is a challenging area because it is where the standard ΛCDM cosmology encounters some of its most serious challenges. We follow tradition and do not include the Local Group into the Local Volume. This still leaves lots of data and issues to address. We can broadly separate those issues into two domains: statistics of galaxies (e.g., abundance of dwarfs, emptiness of voids, motion of galaxies) and physics of individual galaxies (e.g., star formation rates, morphology, rotation curves).

The Local Volume does not have a high density environment of clusters and rich groups, but it is not a low-density region either: there is a slight overdensity of 1.4 of galaxies with $M_B = -17$ to -22 inside a sphere of 8 Mpc radius, and the sphere of 4 Mpc radius is overdense by a factor of 4 (Karachentsev et al. 2004; Tikhonov & Klypin 2009). However, the region has numerous voids of different sizes (Tikhonov & Karachentsev 2006; Tikhonov & Klypin 2009). Of particular interest is the region just outside of the Local Group: in the shell with radii 1-3.5 Mpc there are no bright galaxies, but there are dozens of dwarfs with $M_B = -8$ to -15.

There are two large observational samples of galaxies for the Local Volume. The Karachentsev et al. sample of galaxies is complete for galaxies in the 8 Mpc region down to $M_B = -10$. It has about 500 galaxies. The sample is being updated and by the end of summer 2011 it will have 800 galaxies inside the 10 Mpc sphere. Co-I Klypin is a PI of a Russian grant (no money to Klypin), which partially funds the effort. He will have access to the new catalog. Another sample is the Advanced Camera for Surveys (ACS) Nearby Galaxy Survey Treasury (ANGST),[2] which within the 3.8 Mpc region has about 70 galaxies, of which 60 are dwarfs (Dalcanton et al. 2009; Weisz et al. 2011; Williams et al. 2011). To our knowledge this is the only sample that gives CMD-based star formation rates (SFR) for galaxies outside the Local Group based on individual stars, not on broadband photometry. These first ANGST results show that the SFR for dwarfs does not evolve much over time. There are bumps and there is an enhancement at high-z, but on average the SFR is nearly flat in these dwarf galaxies, as opposed to larger spirals, which show a clear decline by a factor of 2-3 since $z = 2$. According to ANGST, half of the stars in the dwarfs was formed by $z = 2$. There are numerous publications on some individual galaxies in the region.

This is valuable information, which we plan to compare with two types of simulations: (1) hydrodynamical simulations of 100-200 dwarf galaxies to study the history of star formation and the dynamics of gas in dwarf galaxies and (2) cosmological N-body simulations to address the statistical issues. Hot issues and problems for the theory include:

- Star formation rates and global properties of dwarf galaxies.
- Abundance of dwarf galaxies with rotational velocities 25-50 km/s. Theory seems to predict too many such dwarfs (Trujillo-Gomez et al. 2010). Note that this is *not* the well-known satellite overabundance problem, which is for satellites with $V_{\rm circ} < 30$ km/s (e.g., Klypin et al. 1999; Kravtsov 2010). Instead, this is for isolated galaxies, not satellites, with larger $V_{\rm circ} = 30 - 50$ km/s (Tikhonov & Klypin 2009; Zwaan et al. 2010).

In addition to the old dwarf core-cusp problem (Primack 2009), there are questions such as the mass of "cold baryons" (= stars + cold gas) from simulations compared with the observed values. Cosmological hydro simulations by Avila-Reese et al. (2011) indicate that theoretical SFRs are a factor 3-10 too low. However, the resolution of the simulations was questionable and observed SFRs were taken from Salim et al. (2007) (UV from GALEX and SDSS photometry). For galaxies with stellar masses $M_* = 10^8 - 10^9 M_\odot$ the latter gives a factor of 3-5 higher SFR as compared with ANGST (Weisz et al. 2011). This likely observational discrepancy is related to very large incompleteness corrections in Salim et al.

[2] `http://www.nearbygalaxies.org//dashboard/home`

(2007). So, the discrepancy with the simulations may not be too bad. However, theoretical predictions are also very uncertain, and we plan to improve the accuracy of the simulations.

Hydrodynamical simulations: matching ANGST. Most of the galaxies in the ANGST and Karachentsev samples have absolute magnitudes $M_B = -10-$ to -15 and rotational velocities $25-50$ km/s (Tikhonov & Klypin 2009). Disk scale lengths vary: 0.3-1 kpc. Virial masses are expected to be in the range $M_{\rm vir} = 10^9 - 10^{10} M_\odot$. In order to resolve the galaxies we plan to reach the resolution of 10-20 pc and to have 1-2 million dark matter particles and by the end of the simulation a few million stellar particles, each with typical mass of $\sim 100\ M_\odot$ (there is no mass resolution issue for hydro in AMR codes). The dwarf galaxies are small and they require very high resolution, which means that we need substantial cpu resources – comparable with those of larger galaxies. We can make 100-200 simulations of this type with each having only few galaxies. The setup of the simulations is similar to larger galaxies: low-resolution runs followed by zoom-in re-simulations. Many such dwarf and satellite galaxies will already have been simulated at lower resolution in the neighborhoods of our larger simulated galaxies.

N-body simulations: Statistics of galaxies in the Karachentsev sample. By the time our proposed program starts we will have finished the "miniBolshoi" cosmological simulation with 5 billion particles, in a 200 Mpc simultion box that has 15 high-res spherical regions. The regions are selected from a low-res run and contain ~ 200 halos in the mass range $(1-2) \times 10^{12} M_\odot$. There are 12 regions that mimic the Local Volume: radius 10 Mpc; overdensity in the range (0.8-1.6); no massive halos with mass larger than $10^{13} M_\odot$. Two regions are large voids of radius 15 Mpc each. We expect to have about 5 million dwarf halos with circular velocities down to 10 km/s and force resolution of 100 pc. This setup is sufficient to address most of the statistical questions for the assembly and distribution of galaxies in the Karachentsev and ANGST samples. In addition, we will have ~ 200 Milky-Way objects each with $100-200$ satellites to study such effects as the frequency of large mergers in the past, accretion history and destruction of satellites, effect of presence or absence of M31, and so on.

7 Technical Plan

The PI, Joel Primack, will be responsible for overall management of the effort, and Co-Is Dekel, Faber, and Klypin and the Collaborators will constitute a management committee to consider all important issues. We will meet frequently, by phone and email, and at our annual summer workshop at UCSC.

The division of labor between the PI, Co-Is, and Collaborators will be that the NMSU team led by Co-I Klypin and including Collaborator Ceverino will be mainly responsible for improving the *hydroART* code and running the many galaxy simulations. The UCSC team including the proposed new postdoc will be mainly responsible for analyzing these new hydrodynamic simulations; developing improved analytic models based on the simulations; and using the radiative transfer code *Sunrise* with Collaborator Jonsson to make multi-wavelength comparisons between simulations and data in collaboration with Faber and the CANDELS team. The new postdoc will also lead the effort to archive the outputs from our galaxy simulations in catalogs that will be maximally useful to the astronomical community. Co-I Dekel will be involved in all this work, especially during his frequent visits to UCSC, and his Hebrew University team will run and analyze additional hydrodynamic simulations to explore star formation and quenching. Collaborator Krumholz will help improve the treatment of star formation and feedback in our hydrodynamic simulations and analytic analyses. Collaborator Somerville and her team will work with Primack and his grad student Porter to use our Bolshoi merger trees for improved SAMs based on our new simulations.

As mentioned in §2, we have large allocations of supercomputer time to carry out the proposed research. At UCSC we also share the Pleiades astrophysics computer, with more than 800 processors; as a Co-I, Primack is entitled to 0.7 million node-hours per year. We have adequate workstations at UCSC to analyze the outputs from these supercomputer simulations, although we request modest funds for maintenance and connection fees. NMSU requests funds for a new computer/server system to host and distribute the outputs from our *hydroART* simulations to all interested astronomers.

Milestones: During the first year, 2012, we plan to run more than 200 simulations focussed on forming galaxies, with approximately 1/3 of these carried to low redshift. We will also begin detailed comparisons with observations. We will also run ~ 10 new higher resolution cosmological galaxy formation simulations to produce more detailed information about dwarf galaxies and to clarify the details of our many lower-resolution simulations, and analyze several of them using *Sunrise* to allow detailed multiwavelength comparisons with observations. We will also compare our *hydroART* simulations with high-resolution simulations using other codes. During 2013 we plan to run and analyze hundreds of 10-50 pc high-resolution cosmological hydrodynamical simulations, and continue code development to include additional physical phenomena. By 2014 CANDELS and other surveys will have greatly added to the available data on galaxy formation out to high redshift, and we will critically compare our theoretical models with this data treasure trove in order to answer the questions discussed throughout this proposal.

Broader Impacts: This research supports NASA's goal of discovering the structure and evolution of the universe, and it is relevant to interpreting observations by NASA missions including Hubble, Spitzer, Chandra, and Fermi, and to preparing for future missions including JWST.

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. This will continue to be true for the outputs, software, and algorithms that will be developed as part of this proposal, to the benefit of the general research community. In particular, we are working with Alex Szalay and the Virtual Astronomical Observatory (VAO) to make multiple outputs from our simulations and SAMs available in the most useful manner.

We also have a long tradition of collaborating closely with observers, especially our DEEP/AEGIS/CANDELS colleagues. We host a galaxy formation workshop at UCSC each summer attended not only by our group and members of the CANDELS team but also our Collaborators and others. These summer workshops allow us to discuss new data and results, share ideas, and generate new projects. The programs for our 2009 and 2010 workshops include slides from more than 50 talks each.[3] [4]

The new University of California systemwide High-Performance AstroComputing center (UC-HIPACC), which Primack directs, will host an international Astro-Computing school

[3] `http://physics.ucsc.edu/SCGW09/SCGF_program.html`

[4] `http://hipacc.ucsc.edu/GalaxyWorkshop2010.html`

every summer and two research conferences per year, and support education and public outreach efforts. The 2010 school, at UCSC, was on galaxy simulations, directed by Co-I Klypin. The 2011 school, at Berkeley and LBNL and directed by Peter Nugent and Dan Kasen, is on supernovae and other topics in explosive astrophysics. The 2012 school will be on astroinformatics, hosted by Mike Norman at UCSD and directed by Alex Szalay.

Our research has broadened the opportunities for underrepresented groups. Many of our former grad students, including several women, are now leading researchers. Primack's current grad students involved in the research discussed in this proposal include a Black woman (Lauren Porter) and a Hispanic man (Christopher Moody), and one of Klypin's grad students (Sebastian Trujillo-Gomez) is also Hispanic.

Primack has been teaching with Nancy Abrams a popular UCSC undergraduate course on "Cosmology and Culture" since 1995. This led to their popular book, *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos* (Riverhead/Penguin, 2006) with many foreign editions.[5] Their new book, *The New Universe and the Human Future: How a Shared Cosmology Could Transform the World* (Yale University Press, 2011) with linked videos at a new website,[6] was based on their multimedia Terry Lectures at Yale in 2009.[7] Primack also developed "Einstein's Rocket" video games to teach key ideas of relativity; a java version is available on the UCSC Physics website[8] and a free iPhone/iPad app is in development.

Our simulations provide striking illustrations of our research,[9] and have been featured in a recent National Geographic TV special,[10] NASA Spitzer Science Center video press releases,[11] and at supercomputing conferences SC04, SC06, SC09, and SC10, where they were presented by Primack's students. They were also featured on the NERSC website,[12] and in NERSC's and NASA Supercomputing Division's Annual Reports. Visualizations of our simulations have been used to illustrate articles in magazines including *Astronomy*, *National Geographic*, and *Science*. A video[13] submitted by Jonsson, Novak, and Primack of one of our galaxy merger simulations was a semifinalist in the 2008 NSF/Science Magazine Visualization Challenge. Primack and his colleagues are also collaborating with Chris Henze at NASA Ames, Mark SubbaRao at Adler Planetarium, and Ryan Wyatt at Morrison Planetarium to create dome and 3D shows that explain how dark and luminous matter interact to produce galaxies and the large scale structure of the Universe, and to make our simulation outputs available to planetariums and other educational venues worldwide. Primack is Co-I on a 2011 NASA EPOESS proposal to support these Education and Public Outreach efforts.

[5] Many reviews and print and broadcast interviews can be found at `http://viewfromthecenter.com` including a list of over 80 popular lectures during 2006-2011.

[6] `http://new-universe.org`

[7] `http://new-universe.org/TerryLectures.html`

[8] `http://physics.ucsc.edu/~snof/er.html`

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

[10] `http://channel.nationalgeographic.com/episode/inside-the-milky-way-4605/Overview`

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

[12] `http://www.lbl.gov/cs/Archive/news032210.html`

[13] `http://www.youtube.com/watch?v=agqLEbOFT2A`

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