# HEC Annual Report of Research Accomplishments

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1. SMD-09-1131
2. Report Period: 05/01/09 to 04/30/10
3. Title: High Resolution Cosmological Simulations and Galaxy Evolution>
4. Principal Investigator: Joel Primack, University of California Santa Cruz (UCSC), joel@scipp.ucsc.edu

5. Co-Investigators:

Anatoly Klypin, New Mexico State University
Patrik Jonsson, Harvard-Smithsonian Center for Astrophysics

6. Collaborating Organizations:

In addition to the Co-Investigators, our important collaborators on these projects include Thomas J. Cox, Carnegie Observatory, Pasadena, California; Darren Croton, Swinburne University, Melbourne, Australia; Avishai Dekel, Hebrew University, Jerusalem, Israel; Sandra Faber, UCSC; Rachel Somerville, Space Telescope Science Institute; and Risa Wechsler, Stanford University. All of these people are regularly at UCSC for research meetings and workshops in connection with this project.

7. Project Goals and Objectives:

We used the NAS computational facilities to simulate large cosmological regions with high resolution using our Adaptive Refinement Tree (**ART**) code, and also to simulate small regions to study galaxy evolution and interactions using the codes **ART-hydro** and **GADGET**. The large simulations trace galaxy population evolution. The galaxy simulations examine both the dark matter halos hosting galaxies and the effects of galaxy interactions, including detailed treatment of the scattering, absorption, and reradiation of starlight by interstellar dust using our powerful radiative transfer code **Sunrise**. We are doing significant new code development including use of GPUs, in addition to novel simulations. Our simulations permit creation of detailed images and videos of simulated galaxies in various wavebands for comparison with observations of real galaxies, and also for education and outreach, in collaboration with Chris Henze and his visualization group. Our simulations facilitate theoretical interpretation of data from the largest galaxy surveys, SDSS and DEEP, and they support numerous NASA missions, including HST, Spitzer, GALEX, Chandra, and JWST.

## 8. Project Description:

There were three main projects during this report period:

(1) completion and analysis of the giant cosmological simulation Bolshoi and preparation of follow-on simulations,

(2) running several extremely high resolution hydrodynamic simulations of galaxy formation, and

(3) visualizing our simulations, including use of our Sunrise code to model the appearance of galaxies including effects of radiative transfer and dust

(1) The Bolshoi simulation is the first large dissipationless ΛCDM cosmological simulation run with the current (WMAP5 and WMAP7) cosmological parameters. Its volume is (250 $h^{-1}$ Mpc)$^3$ and its force and mass resolution are nearly an order of magnitude better than the leading Millennium Run simulation. The first detailed paper analyzing Bolshoi [1] has been submitted, and a second major paper will be submitted in a week or so [2]. We have found all halos and subhalos with maximum circular velocity greater than 50 km/s in all 180 stored timesteps (typically about 10 million halos in each timestep). Our collaborator Prof. Risa Wechsler of Stanford, Primack's former PhD student, and her team have created detailed merger trees, tracing the entire merging history of the halos. We are working with three of the leading semi-analytic modeling groups in the world to populate all these halos with galaxies according to the best current simulations, and to compare the resulting predictions of the evolving galaxy population with the available observational data. We plan to make our outputs available to the entire community.

We have successfully set up initial conditions to run two important new Bolshoi-type simulations, which we are starting to run.

(a) One of the important new results from Bolshoi is that the abundance of halos that could host galaxies at high redshifts $z$ ~ 10 is overestimated by an order of magnitude by the standard Sheth-Tormen approximation, which poses a challenge in understanding how the universe is ionized. To clarify the evolution and nature of the first halos, we are running a new large multi-mass-scale Bolshoi-size simulation in which low mass particles, representing a large fraction of all the simulation particles, are put into the regions where the first halos form, while the remaining higher-mass particles fill the rest of the volume and provide the correct tidal forces in the high-res regions. This will allow us to achieve two orders of magnitude higher mass resolution and an order of magnitude better force resolution.

(b) A similar method will be used to simulate the entire evolution of ~10 typical regions (not in voids or including clusters), each ~10 Mpc across. This will provide statistics on the evolution of halos hosting ~100 Milky-Way-size galaxies, with the entire history of subhalos hosting ~$10^3$ potential satellites resolved in each Milky-Way-size halo. The existing Via Lactea and Aquarius simulations have higher resolution on a small number of Milky-Way-size halos. Since they show that there is a lot of variation between halos, we are running this new cosmological Bolshoi-size simulation to acquire a statistical sample of such halos and see how environment influences the resulting halo substructure.

(2) Recent observations with the latest instruments, including Integral Field Unit spectrographs on the Keck and Very Large Telescopes, are showing that a significant fraction of galaxies at redshifts $z \sim 2.5$ have thick disks with big clumps of vigorous star formation. Our new ART-hydro simulations of early galaxy evolution are being run by Klypin's former PhD student Daniel Ceverino, who is now a postdoc with Avishai Dekel. Our simulations, with very high resolution ~70 parsecs, show that cold streams of gas flow down cosmic dark matter filaments and produce unstable disk galaxies that appear to resemble closely these observations. These simulations are the best that we know of in the world to date. Our articles this year [3], [4] reported on simulations run last year on the Bassi computer at NERSC, which were featured on the NERSC website (http://www.lbl.gov/cs/Archive/news032210.html). We have been running more ambitious simulations on the NAS Schirra machine, whose architecture is ideal for our OpenMP ART-hydro code. We are now analyzing the outputs and writing papers reporting the results and comparisons with observations. Ceverino and Primack's graduate student Priya Kollipara are improving the code to include radiative feedback from star clusters and active galactic nuclei (AGN).

(3) We have run Sunrise on Columbia to process thousands of views of galaxy merger simulations. We have completed a series of papers [5], [6], [7] that determine the timescales over which various morphological signatures will be visible, and this is allowing us to convert the observed counts of galaxies exhibiting these signatures into accurate measurements of the rates of various types of galaxy mergers [8]. The Sunrise code has been improved in several ways [9]. Jonsson and Primack published a paper [10] on using graphics processor units (GPUs) to greatly speed up calculations of the Sunrise code.

## 9. Project URL (if any): http://astronomy.nmsu.edu/aklypin/Bolshoi/

## 10. Relevance of Work to NASA:

The evolving galaxy population is observed at many wavelengths by NASA missions including HST, Spitzer, GALEX, Chandra, and the simulations we are doing at NAS predict properties of these galaxies and help to interpret these observations. In particular, this work is particularly relevant to the new Multi-Cycle Treasury (MCT) award of over 900 orbits of HST time to a project led by our UCSC collaborator Sandra Faber. The new high-resolution simulations of the dark matter halos hosting the first forming galaxies that we have set up and begun to run will be crucial for predicting observations by James Webb Space Telescope (JWST) and other new instruments.

Our simulations are also the basis for visualizations that were featured by the NASA team at the November 2009 SuperComputing conference (SC09) in Portland, OR. A visualization by Chris Henze of a fly-through through part of the final timestep of the Bolshoi simulation was the focus of a segment that was filmed at NASA Ames Research

Center on November 24, 2009, for a 2010 National Geographic channel TV special. We and the NAS visualization team are working with the Adler Planetarium in Chicago and the Morrison Planetarium in San Francisco on major planetarium shows that will subsequently be used at many other planetariums.

## 11. Computational Approach:

*codes run*: Adaptive Refinement Tree (ART), ART-hydro, GADGET, Sunrise

## 12. Results:

*<Include key milestones and progress made toward them.>*

• Update halo finding code for large simulations – done Aug/09
• Visualize Bolshoi simulation – first results Oct/09
• Finish Bolshoi halo catalogs – done February/10
• First journal paper on Bolshoi – [1] submitted February/10
• Finish Bolshoi halo merger trees – done April/10
• Use Sunrise code to model galaxy appearance – many simulations processed, others in progress
• Use Bolshoi simulation to compare predicted and observed galaxy luminosity-velocity relations – paper submitted May/10
• Use high-resolution galaxy simulations to clarify how galactic spheroids form at high redshift – in progress
• Run higher-res Bolshoi-type simulations to z=0 – initial conditions complete Apr/10
• Run several high-res galaxy simulations to z=0 – expect to reach z=0 by about June/10

## 13. Scientific or Engineering Impact:

• Analysis of our Bolshoi simulation, the most ambitious cosmological simulation yet, run on Pleiades using the latest cosmological parameters, will enable improved understanding of evolution of the galaxy population and of large scale structure.

• Our high-resolution ART-hydro hydrodynamic galaxy formation simulations, run on Schirra, are clarifying how galaxies form and evolve.

• Our Sunrise visualizations of the appearance and spectra of galaxies run on Columbia, together with observations of galaxies with various morphological signatures, are allowing the first accurate calculations of the rates of galaxy mergers of various types. This is clarifying the origin of galactic spheroids, which host most of the stellar mass in the universe and also host supermassive black holes.

For more details and references please see answer 8. above.

## 14. Computational Technology Accomplishments:

The Bolshoi simulation took 6 million cpu-hours on Pleiades. The ART code scaled well to 13824 cores.

A factor of ~100 speedup of the simultaneous computation of many wavelengths by our Sunrise code was achieved ("polychromatic" version of the code) – see reference [10] in Section 18 below by Jonsson, Groves, and Cox.

Jonsson and Primack published a paper [10] on using Nvidia graphics processor units (GPUs) to greatly speed up calculations of the Sunrise code. Chris Henze plans to purchase 128 advanced Nvidia GPUs for the main NAS visualization computer, which could be very useful for such calculations.

## 15. Impact of HEC Resources on Project:

Pleiades was essential for the ambitious Bolshoi simulations, and Schirra is the best architecture for the OpenMP ART-hydro code used for our very high-resolution hydrodynamic galaxy simulations.

We benefitted greatly from working with Chris Henze and the NAS visualization team on visualizations that clarify the meaning of outputs from our simulations, and also in using them for education and public outreach.

## 16. Future plans for use of HEC Resources:

Pleiades will continue to be essential for our continuations of the Bolshoi cosmological simulations described in 8(1) (a) and (b) above. The large nodes of Schirra are essential for the OpenMP high-resolution ART-hydro calculations of galaxy formation and evolution described in 8(2) above. Our GADGET and Sunrise calculations have been optimized on Columbia.

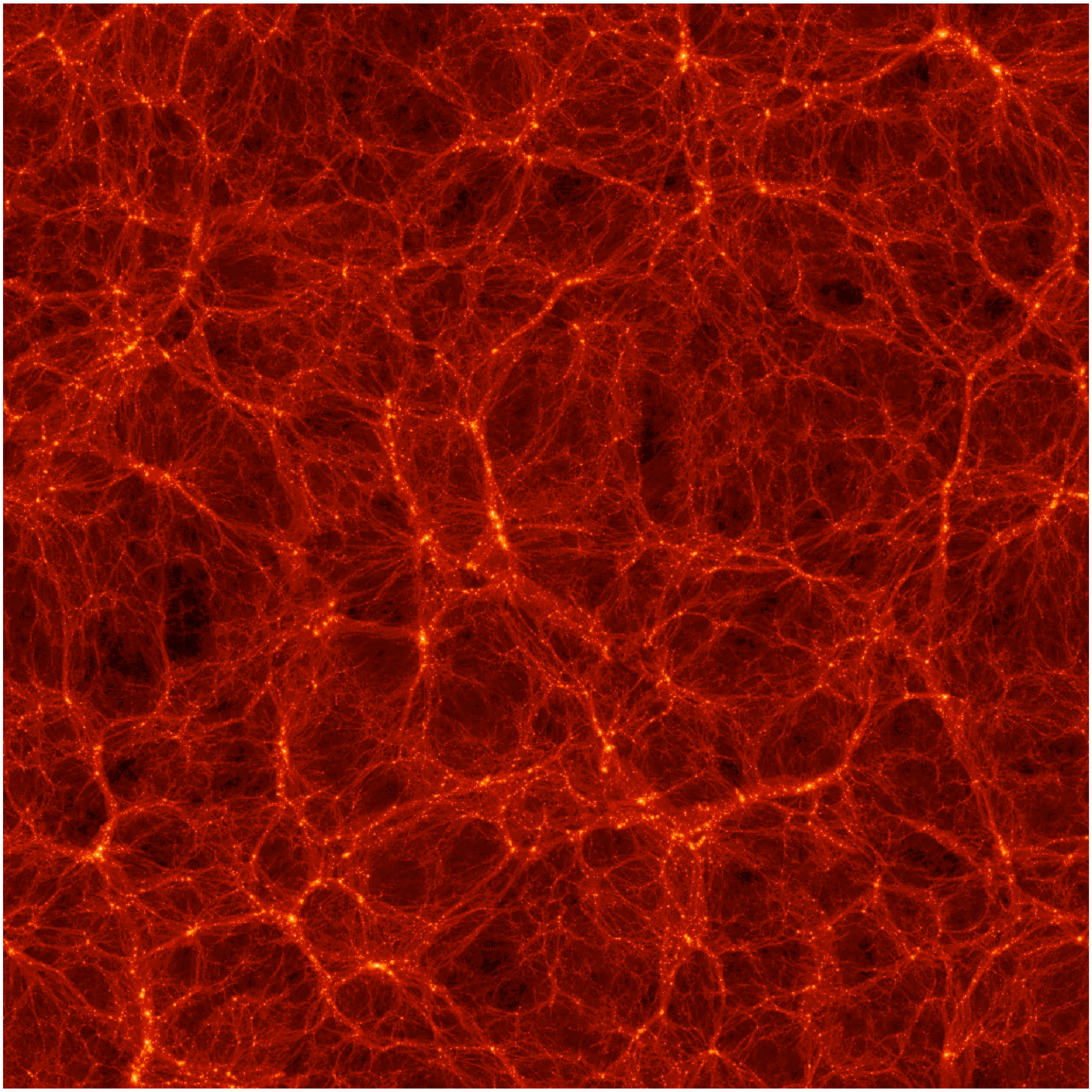
We expect to continue to benefit greatly from working with Chris Henze and the NAS visualization team to understand better the outputs from our simulations, and also to use them for education and public outreach.

## 17. Include at least one representative picture, graphic, or movie with caption.

*<Insert, attach, or upload in e-Books.>*

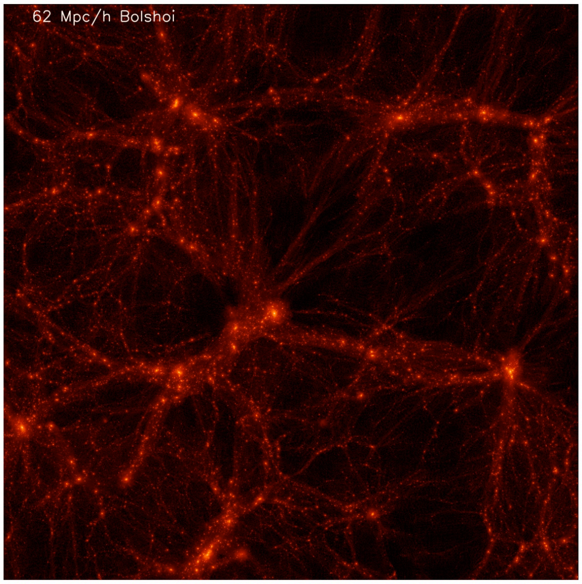
Note that there are many relevant figures in the articles cited in Section 18 below, especially numbers 1), 5), and 6).
Chris Henze made a beautiful visualization video of a fly-through of a 30 Mpc/h region of the final ($z$ = 0) timestep of the Bolshoi simulation, including a rich cluster halo. It's at http://people.nas.nasa.gov/~chenze/Bolshoi/bolshoi_01.mpg

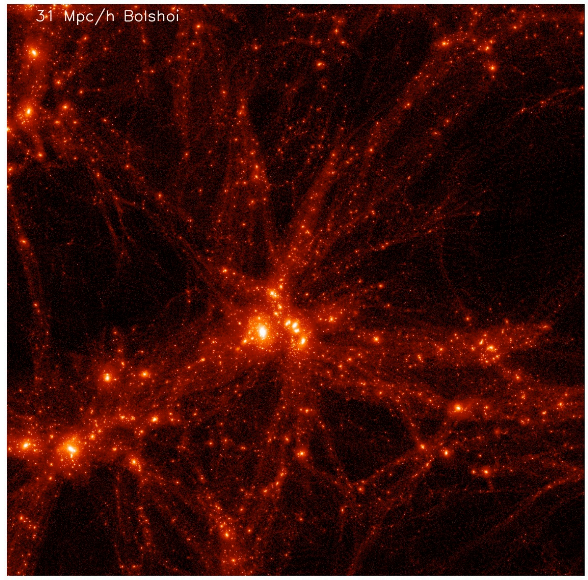
Below are visualizations of the final timestep from the Bolshoi simulation on successively smaller scales.

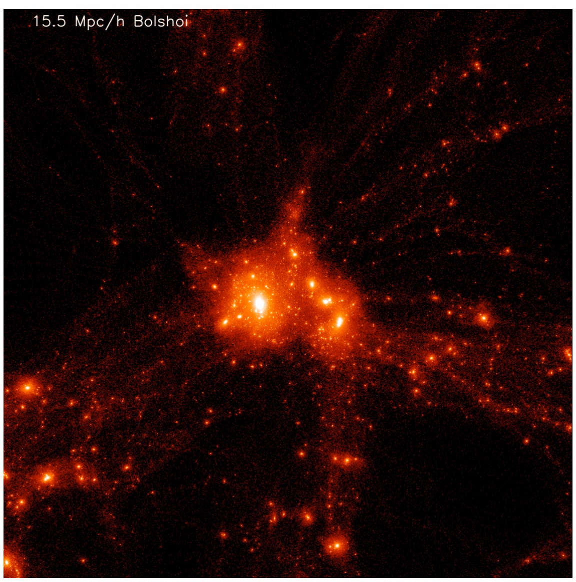


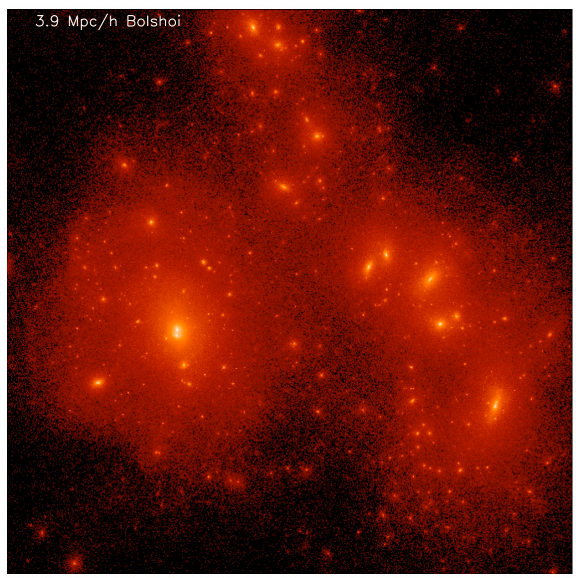
Slice of the entire Bolshoi simulation at redshift $z$ = 0: 250x250x10 $h^{-1}$ Mpc.

The following figures are slices of the simulation at redshift $z = 0$ of width 62, 31, 15.5, and 3.9 $h^{-1}$ Mpc.




## 18. Publications which cite this project*:*

*<Give citation and abstract for each. Include URL if available.*
*Identify which are refereed.*
*Place an asterisk (*) before publications that acknowledge HEC Resource use.>*

1) * “Halos and galaxies in the standard cosmological model: results from the Bolshoi simulation,” by Anatoly Klypin, Sebastian Trujillo-Gomez, and Joel R. Primack, submitted to ApJ, arXiv:1002.3660 (February 2010).

Abstract: We present the first results from the new Bolshoi N-body cosmological LCDM simulation that uses cosmological parameters favored by current observations. The Bolshoi simulation was done in a volume 250Mpc on a side using 8 billion particles with mass and force resolution adequate to follow subhalos down to a completeness limit of Vcirc=50km/ s circular velocity. Using excellent statistics of halos and subhalos (10M at every moment and 50M over the whole history) we present accurate approximations for statistics such as the halo mass function, the concentrations for distinct halos and subhalos, abundance of halos as function of their circular velocity, the abundance and the spatial distribution of subhalos. We find that at high redshifts the concentration falls to a minimum of about 3.8 and then rises slightly for higher values of halo mass. We find that while the Sheth-Tormen approximation for the mass function of halos found by spherical overdensity is accurate at low redshifts, it over-predicts the abundance of halos by nearly an order of magnitude by $z$=10. We find that the number of subhalos scales with the circular velocity of the host halo as ${V_{host}}^{0.5}$, and that subhalos have nearly the same radial distribution as dark matter particles at radii 0.3-2 times the host halo virial radius. The subhalo velocity function $n(>V)$ behaves as $V^{-3}$. We give normalization of this relation for different masses and redshifts. Finally, we use an abundance-matching procedure to assign r-band luminosities to dark matter halos as a function of halo $V_{circ}$, and find that the luminosity-velocity relation is in remarkably good agreement with the observed Tully-Fisher relation for galaxies in the range 50-200 km/s.

2) * "The galaxies that inhabit dark matter halos: scaling relations and abundance in the ΛCDM cosmology," by Sebastian Trujillo-Gomez, Anatoly A. Klypin, Joel Primack, and Aaron J. Romanowsky, about to be submitted (May 2010).

3) "High-redshift clumpy discs and bulges in cosmological simulations," by Daniel Ceverino, Avishai Dekel, and Frederic Bournaud, MNRAS, in press, arXiv:0907.3271 (July 2009).

Abstract: We analyse the first cosmological simulations that recover the fragmentation of high-redshift galactic discs driven by cold streams. The fragmentation is recovered owing to an AMR resolution better than 70pc with cooling below $10^4$K. We study three typical star-forming galaxies in haloes of ~$5 \times 10^{11} M_{solar}$ at $z \approx 2.3$ when they were not undergoing a major merger. The steady gas supply by cold streams leads to gravitationally unstable, turbulent discs, which fragment into giant clumps and transient features on a dynamical time-scale. The disc clumps are not associated with dark-matter haloes. The clumpy discs are self-regulated by gravity in a marginally unstable state. Clump migration and angular-momentum transfer on an orbital time-scale help the growth of a central bulge with a mass comparable to the disc. The continuous gas input keeps the system of clumpy disc and bulge in a near steady state for several Gyr. The average star formation rate, much of which occurs in the clumps, follows the gas accretion rate of ~45 $M_{solar}\ yr^{-1}$. The simulated galaxies resemble in many ways the observed star-forming galaxies at high redshift. Their properties are consistent with the simple theoretical framework presented in Dekel, Sari & Ceverino. In particular, a two-component analysis reveals that the simulated discs are indeed marginally unstable, and the time evolution

confirms the robustness of the clumpy configuration in a cosmological steady state. By $z \sim 1$, the simulated systems are stabilized by a dominant stellar spheroid, demonstrating the process of `morphological quenching' of star formation. We demonstrate that the disc fragmentation is not a numerical artefact once the Jeans length is kept larger than nearly seven resolution elements, i.e. beyond the standard Truelove criterion.

4) "Gravity-Driven Lyman-Alpha Blobs from Cold Streams into Galaxies," by T. Goerdt, A. Dekel, A. Sternberg, D. Ceverino, R. Teyssier, and J. R. Primack, submitted to MNRAS, arXiv: 0911.5566 (November 2009). Abstract: We use high-res cosmological hydro AMR simulations to predict the hydrogen Lalpha emission from the cold gas streams that fed galaxies in massive haloes at high z. The local emissivities due to collisional excitation are calculated from the simulated gas properties, while photoionization is less important. The Lyalpha surface density is mapped assuming that 85% of the Lalpha photons are observed. Typical haloes of mass $M\mathrm{v} \sim 10^{12\text{-}13}$ $M_{sun}$ at $z \sim 3$ emit as Lyalpha blobs (LABs) with luminosities $10^{43\text{-}44}$ erg/s and 50-100 kpc extent. Most of the Lyalpha comes from the extended, narrow, partly clumpy, inflowing, cold streams of (1-5)x$10^4$K that feed the galaxy. Dust absorption is negligible in the streams. The predicted LAB morphology is irregular, with dense clumps and elongated extensions. The area contained within isophotes with surface brightnesses of $2.2\mathrm{x}10^{-18}$ erg $s^{-1}$ $cm^{-2}$ $arcsec^{-2}$ is ~20-200 $arcsec^{-2}$. The linewidth is expected to range from a few hundreds to above 1000 km/s with a large variance. The typical Lalpha surface brightness profile is proportional to $r^{-1.2}$. The Lyalpha emission in our simulations is powered by the gravitational energy gained by the streaming into the halo potential well, while the UV background contributes <20%. A toy model of gravitational heating explains the simulated results. The simulated LABs are similar in luminosity, morphology and extent to the observed LABs, and they have distinct kinematic features. The predicted luminosity function is consistent with observations, and the predicted areas and linewidths reproduce the observed scaling relations. The LABs can be regarded as direct detections of the cold streams that drive galaxy evolution at high z. This mechanism for producing LABs appears inevitable in most high-z galaxies.

5) * "Galaxy merger morphologies and time-scales from simulations of equal-mass gas-rich disc mergers," by Jennifer Lotz, Patrik Jonsson, T. J. Cox, and Joel R. Primack, MNRAS, 391, 1137 (2008). Abstract: A key obstacle to understanding the galaxy merger rate and its role in galaxy evolution is the difficulty in constraining the merger properties and time-scales from instantaneous snapshots of the real Universe. The most common way to identify galaxy mergers is by morphology, yet current theoretical calculations of the time-scales for galaxy disturbances are quite crude. We present a morphological analysis of a large suite of GADGET N-body/hydrodynamical equal-mass gas-rich disc galaxy mergers which have been processed through the Monte Carlo radiative transfer code SUNRISE. With the resulting images, we examine the dependence of quantitative morphology (G, $M_{20}$, C, A) in the SDSS g band on merger stage, dust, viewing angle, orbital parameters, gas properties, supernova feedback and total mass. We find that mergers appear

most disturbed in G - $M_{20}$ and asymmetry at the first pass and at the final coalescence of their nuclei, but can have normal quantitative morphologies at other merger stages. The merger observability time-scales depend on the method used to identify the merger as well as the gas fraction, pericentric distance and relative orientation of the merging galaxies. Enhanced star formation peaks after and lasts significantly longer than strong morphological disturbances. Despite their massive bulges, the majority of merger remnants appear disc-like and dusty in g-band light because of the presence of a low-mass star-forming disc.

6) * "The effect of gas fraction on the morphology and time-scales of disc galaxy mergers," by Jennifer Lotz, Patrik Jonsson, T. J. Cox, and Joel R. Primack, MNRAS, in press, arXiv: 0912.1593 (Dec 2009). Abstract: Gas-rich galaxy mergers are more easily identified by their disturbed morphologies than mergers with less gas. Because the typical gas fraction of galaxy mergers is expected to increase with redshift, the under-counting of low gas-fraction mergers may bias morphological estimates of the evolution of galaxy merger rate. To understand the magnitude of this bias, we explore the effect of gas fraction on the morphologies of a series of simulated disc galaxy mergers. With the resulting g-band images, we determine how the time-scale for identifying major and minor galaxy mergers via close projected pairs and quantitative morphology (the Gini coefficient G, the second-order moment of the brightest 20 per cent of the light $M_{20}$ and asymmetry A) depends on baryonic gas fraction $f_{gas}$. Strong asymmetries last significantly longer in high gas-fraction mergers of all mass ratios, with time-scales ranging from <=300Myr for $f_{gas}$ ~ 20 per cent to >=1Gyr for $f_{gas}$ ~ 50 per cent. Therefore, the strong evolution with redshift observed in the fraction of asymmetric galaxies may reflect evolution in the gas properties of galaxies rather than the global galaxy merger rate. On the other hand, the time-scale for identifying a galaxy merger via G-$M_{20}$ is weakly dependent on gas fraction (~200-400Myr), consistent with the weak evolution observed for G-$M_{20}$ mergers.

7) * "The effect of mass ratio on the morphology and time-scales of disc galaxy mergers," by Jennifer Lotz, Patrik Jonsson, T. J. Cox, and Joel R. Primack, MNRAS, in press, arXiv: 0912.1590 (Dec 2009). Abstract: The majority of galaxy mergers are expected to be minor mergers. The observational signatures of minor mergers are not well understood; thus, there exist few constraints on the minor merger rate. This paper seeks to address this gap in our understanding by determining if and when minor mergers exhibit disturbed morphologies and how they differ from the morphology of major mergers. We simulate a series of unequal-mass moderate gas-fraction disc galaxy mergers. With the resulting g-band images, we determine how the time-scale for identifying galaxy mergers via projected separation and quantitative morphology (the Gini coefficient G, asymmetry A and the second-order moment of the brightest 20 per cent of the light $M_{20}$) depends on the merger mass ratio, relative orientations and orbital parameters. We find that G-$M_{20}$ is as sensitive to 9:1 baryonic mass ratio mergers as 1:1 mergers, with observability time-scales of ~0.2-0.4 Gyr. In contrast, asymmetry finds mergers with baryonic mass ratios between 4:1 and 1:1 (assuming local disc galaxy gas fractions). Asymmetry time-

scales for moderate gas-fraction major disc mergers are ~0.2-0.4 Gyr and less than 0.06 Gyr for moderate gas-fraction minor mergers. The relative orientations and orbits have little effect on the time-scales for morphological disturbances. Observational studies of close pairs often select major mergers by choosing paired galaxies with similar luminosities and/or stellar masses. Therefore, the various ways of finding galaxy mergers (G-$M_{20}$, A, close pairs) are sensitive to galaxy mergers of different mass ratios. By comparing the frequency of mergers selected by different techniques, one may place empirical constraints on the major and minor galaxy merger rates.

8) * "Galaxy merger morphologies and time-scales from simulations and observations," by Jennifer Lotz, Patrik Jonsson, T. J. Cox, and Joel R. Primack, to be submitted to MNRAS (May 2010).

9) * "High-Resolution Panchromatic Spectral Models of Galaxies including Photoionisation and Dust," by Patrik Jonsson, Brent Groves, and T. J. Cox, MNRAS, in press, arXiv:0906.2156 (June 2009). Abstract: An updated version of the dust radiation transfer code Sunrise, including models for star-forming regions and a self-consistent calculation of the spatially dependent dust and PAH emission, is presented. Given a hydrodynamic simulation of a galaxy, this model can calculate a realistic 2-dimensional ultraviolet--submillimeter spectral energy distribution of the galaxy, including emission lines from HII regions, from any viewpoint. To model the emission from star-forming regions, the MAPPINGSIII photoionization code is used. The high wavelength resolution (~ 1000 wavelengths) is made possible by the polychromatic Monte-Carlo algorithm employed by Sunrise. From the 2-D spectral energy distributions, images in any filter bands or integrated galaxy SEDs can be created. Using a suite of hydrodynamic simulations of disc galaxies, the output broad-band images and spectral energy distributions are compared with observed galaxies from the multiwavelength SINGS and SLUGS galaxy surveys. Overall, the output spectral energy distributions show a good match with observed galaxies in colours ranging from GALEX far-UV to SCUBA submillimeter wavelengths. The only possible exception is the 160 micron/850 micron colour, which the simulations underestimate by a factor "of order 5" compared to the SINGS sample. However, the simulations here agree with the SLUGS galaxies, which consistently have significantly larger amounts of cold dust than the SINGS galaxies. The Sunrise model can be used to generate simulated observations of arbitrary hydrodynamic galaxy simulations. In this way, predictions of galaxy formation theories can be directly tested against observations of galaxies.

10) "Accelerating dust temperature calculations with graphics-processing units," by Patrik Jonsson and Joel Primack, New Astronomy, 15, 509 (August 2010), arXiv: 0907.3768. Abstract: When calculating the infrared spectral energy distributions (SEDs) of galaxies in radiation-transfer models, the calculation of dust grain temperatures is generally the most time-consuming part of the calculation. Because of its highly parallel nature, this calculation is perfectly suited for massively parallel general-purpose graphics-processing units (GPUs). This paper presents an

implementation of the calculation of dust grain equilibrium temperatures on GPUs in the Monte-Carlo radiation transfer code SUNRISE, using the CUDA API. The GPU can perform this calculation 69 times faster than the eight CPU cores, showing great potential for accelerating calculations of galaxy SEDs.

## 19. Presentations resulting from this project:

1) Joel Primack, invited presentation on cosmological visualizations for public outreach, Astro-Viz 2009 meeting at California Academy of Sciences, May 2009.
2) Joel Primack, Keck Institute for Space Sciences (KISS) program on dark matter, Caltech, July 2009.
3) Michael Busha, “A Statistical Analysis of the Massive Subhalo Population in Milky Way Mass Halos,” UCSC Galaxy Workshop, August 2010 (http://physics.ucsc.edu/SCGW09/scgf09-busha.pdf)
4) Joel Primack, Terry Lectures (http://www.yale.edu/terrylecture/thisyear.html) and Astronomy Colloquium, Yale University, October 2009.
5) Nina McCurdy, presenting results from our Bolshoi and galaxy simulations, SuperComputing 2009 (SC09) conference, Portland, OR (November 2009) (http://www.nas.nasa.gov/SC09/BirthofUniverse_Backgrounder.html)
6) Joel Primack, “Successes of and challenges to the ‘double dark’ (dark matter and dark energy)/Lambda cold dark matter theory,” Opening talk at Dark Matter 2010, Marina del Rey, Los Angeles, CA, February 2010 (http://www.physics.ucla.edu/hep/dm10/talks/primack.pdf)
7) Joel Primack,” EBL with GRB and Blazars,” invited lecture at The View from 5 AU conference, Beckman Center, UC Irvine, March 2010 (http://physics.uci.edu/5AU/Primack.pdf)

## 20. Media references which discuss this project:

(None yet.)

## 21. Number of New Technology Reports filed as a result of this work:

(None yet.)