DRAFT PROPOSAL: Public Outreach via Cosmological Simulation Visualizations

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Proposal Summary

The visible material in the universe -- stars, gas, dust, planets, etc. -- accounts for only about 0.5% of the cosmic density. The remaining 99.5% of the universe is invisible. Most of it is dark matter (~23%) and dark energy (~72%), with non-luminous baryons making up ~4%. In order to describe the evolution and structure of the universe, it is essential to show the distribution of dark matter and the relationship of dark matter to visible structures. We propose to make visualizations of state-of-the-art simulations of cosmology and galaxy formation, and distribute them to planetariums and other outreach venues. Our cosmological simulations show the evolution of the dark matter cosmic web that forms the backbone along which galaxies and clusters form. Our galaxy formation and galaxy merger simulations show galaxies realistically, using our Sunrise code to simulate both stellar evolution and reprocessing of light by dust. We propose to work with the NASA Ames Research Center visualization team to visualize the simulations, and with the Adler and Morrison Planetariums to plan the visualizations including developing methods to show the multicomponent universe, to try the visualizations out on public audiences and evaluate their successes and needs for improvement, and to make them available to digital planetariums worldwide. We will also make videos based on these visualizations available to other venues, including on the web. These new visualizations will enrich the materials available to show how astrophysicists are calculating the physical processes that result in observed properties of galaxies and of the large scale structure of the universe. The visualizations will show how invisible dark matter shapes the visible universe. Astronomical observations represent snapshots of particular moments in time; it is the role of astrophysical theory to produce movies that link these snapshots together into a coherent physical theory.

1. Introduction

In the 1920's the Carl Zeiss optical works developed the first planetarium star projectors and Max Adler funded the construction of the first planetarium in the western hemisphere, known today as Chicago's Adler Planetarium. The Adler Planetarium, consisting of a Zeiss optical projector showing stars and constellations on a dome overhead, opened its doors on May 12, 1930. This was a year after Edwin P. Hubble reported the relationship between the speed and distance of galaxies moving away from the Milky Way, and three years before Fritz Zwicky pointed out that the high line-of-sight velocities of galaxies in the Coma cluster implied that most of the gravitating material in the cluster is nonluminous "dark matter." Starting with Evans & Southerland's vector graphics planetarium projectors in the 1980's, planetariums have installed increasingly advanced digital projectors, which permit high-resolution dome-filling displays of data including the 2dF and SDSS galaxy distributions and R. Brent Tully's collection of data and images of nearby galaxies. Planetariums have also begun to install 3D theaters. Material shown on these venues however, is comprised solely of luminous objects and represents just a tiny fraction of the cosmic density. Planetariums have yet to project dark matter simulations onto their domes, and to show how dark matter and dark energy shape the evolution and structure of the universe on both large scales and galaxy scales.

Thirty years ago, the review by Faber & Gallagher (1979) convinced most astronomers that dark matter is the dominant form of mass in the universe, and soon after that Blumenthal, Faber, Primack & Rees (1984) proposed the Cold Dark Matter (CDM) theory. Since then many astrophysicists have developed CDM theory and run simulations of versions of CDM with different cosmological parameters. The NASA *Cosmic Background Explorer* (*COBE*) discovery in 1992 of the fluctuations in the Cosmic Background Radiation confirmed a key prediction of CDM.

By 1998, multiple lines of observational evidence pointed to a universe dominated by dark energy and dark matter. Since the releases, beginning in 2003, of NASA *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data along with other ground and space-based observations and the large 2dF and SDSS redshift surveys, the cosmological parameters have become known with increasing precision. The Cosmic Background Radiation and the large-scale distribution of galaxies are both consistent with the predictions of the ΛCDM theory (i.e., CDM with a large cosmological constant Λ or other form of dark energy); indeed the standard ΛCDM model with the simplest cosmic inflation models is a better fit to the data than a variety of extended models (Dunkley et al. 2009). The visible material in the universe – stars, luminous gas, light-absorbing dust, planets, etc. – accounts for only about 0.5% of the cosmic density. The remaining 99.5% of the universe is invisible, mostly dark matter (~23%) and dark energy (~72%), with non-luminous baryons making up ~4% (Hinshaw et al. 2009, Table 6). Even though we do not yet know the true nature of the dark matter or the dark energy, we now know enough about their effects to be able to work out in detail the history of structure formation in the universe. And computer simulations are not just playing an essential role in developing scientific understanding, they can be used to create visualizations that are as beautiful as they are educational.

In order to describe the evolution and structure of the universe, it is essential to show the distribution of dark matter and the relationship of dark matter to visible structures. The aim of the present proposal is to bring this invisible universe to the astronomy-interested public through planetariums and other venues. This involves several aspects, including developing a visual language to show several dark and luminous components, along with evaluations to determine how well diverse audiences understand visualizations incorporating various visual conventions; and developing a digital pipeline to translate outputs from high-resolution simulations into software for planetarium presentations. Our key visualization projects are (1) large cosmological simulations, (2) constrained cosmological simulations of the Local Supercluster, and (3) simulations of galaxy formation including galaxy mergers. Once all of these have been translated into digital planetarium software, it will be relatively easy to produce not only dome shows including preprogrammed 5-7 minute modules with supporting documentation, but also flat-screen 2D and 3D presentations. These projects and the digital pipeline that we will develop to create them will open the door for a wider range of astronomical visualizations in the future. We propose to create an advisory committee of astronomers and planetarium experts to advise us on all these projects, with annual meetings; and in years two and three of the project we propose to organize workshops and other activities to explain the new material to potential users. We also propose to make much of this new visualization, outreach, and background material available to astronomers, educators, and the public via a new website.

2. Key Visualization Projects

Our three key visualization projects are (1) the Bolshoi Simulation, the latest and most ambitious large cosmological simulation, including associated semi-analytic models of the evolving galaxy population; (2) constrained simulations of the Local Universe; and high-resolution hydrodynamic simulations of galaxy formation including galaxy mergers. All of these visualizations can be used for digital planetarium shows, 2D and 3D theater presentations, and videos. (Our main collaborators on each project are listed.)

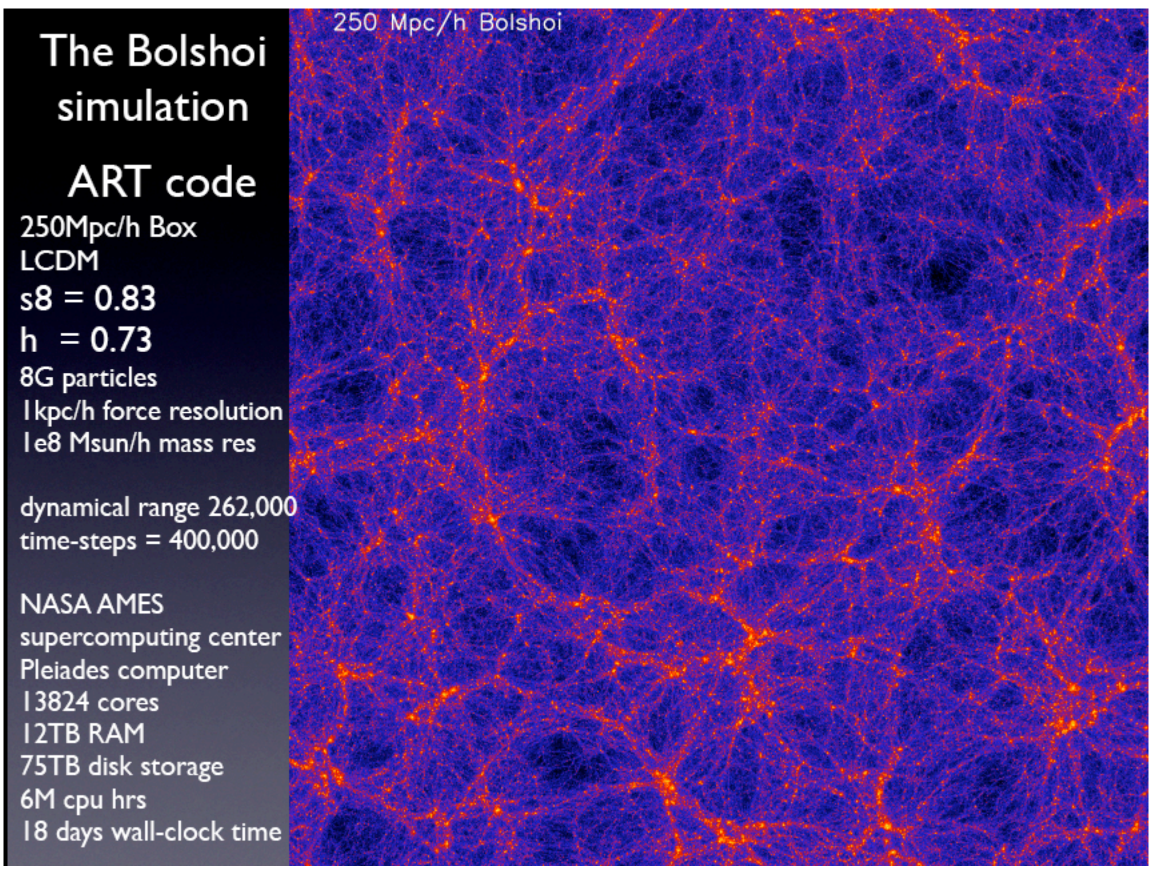

Figure 1. Final ($z = 0$) timestep of the Bolshoi Simulation, showing a slice 10 h^{-1} Mpc thick by 250 h^{-1} Mpc square.

2.1.1 Bolshoi Simulation (cosmological ΛCDM simulation using 8 billion particles with WMAP5 parameters in a volume 250 h^{-1} Mpc on a side; bolshoi means "big" in Russian). This simulation finished in April 2009. It used about 6 million cpu-hours of early-user time on the new Pleiades supercomputer at NASA Ames Research Center, the fourth fastest supercomputer in the world on the June 2009 list of the top 500 supercomputers. We saved about 150 timesteps, which required ~75 Tb of storage. PI Primack has received a new allocation of more than 3 million cpu-hours of Pleiades time to simulate subvolumes at 64x better mass resolution, and we may visualize evolution of some of these subvolumes. (Key collaborators: Anatoly Klypin, New Mexico State University; Chris Henze, NASA Ames.)

The Millennium Run simulation (Springel et al. 2006) has been the leading large cosmological simulation for the past several years, and it has been the basis for many cosmological studies. Our new Bolshoi simulation has nearly an order of magnitude better mass and force resolution than Millennium. Moreover, the Millennium simulation was based on the WMAP1 cosmological parameters (Spergel et al. 2003), while the Bolshoi simulation is based on the WMAP5 parameters (Hinshaw et al. 2009), which are a more precise match to the best available cosmological data. Figure 1 shows the density distribution of dark matter in a slice of the final timestep of the Bolshoi Simulation.

Proposed Bolshoi visualizations for public outreach include both fly-throughs and zoom-ins of the final (redshift $z = 0$) timestep, showing the cosmic web and its substructure. We are now finding the dark matter halos in each timestep using both spherical and friends-of-friends halo finders. It will also be illuminating to visualize the evolution of the merger tree, showing how dark matter halos merge and coalesce, and we are working with Collaborator Henze to develop new methods to do this.

2.1.2 Bolshoi Semi-Analytic Models. We are now calculating the halo merger tree from the Bolshoi halo catalog, in collaboration with Primack's former PhD student Prof. Risa Wechsler and her group at Stanford University. The merger tree will be the basis for state-of-the-art Semi-Analytic Models (SAMs) of the evolution of the galaxy population. This would allow us to paste appropriate pictures of galaxies on the evolving dark matter simulation, and we could fly though regions of the simulated universe including these galaxy images both at earlier epochs and at the present epoch. (Key SAM collaborators: Primack's former students Rachel Somerville, Space Telescope Science Institute, and Darren Croton, Swinburne University, Melbourne, Australia. The SAM based on the Millennium Run simulation is Croton et al. 2006.)

2.2.1 Local Universe Simulation. This is a GADGET cosmological ΛCDM simulation using ~1 billion particles in a volume 64/h Mpc on a side, constrained so that a "Local Group" and "Virgo Cluster" and other nearby structures are near the middle. Thousands

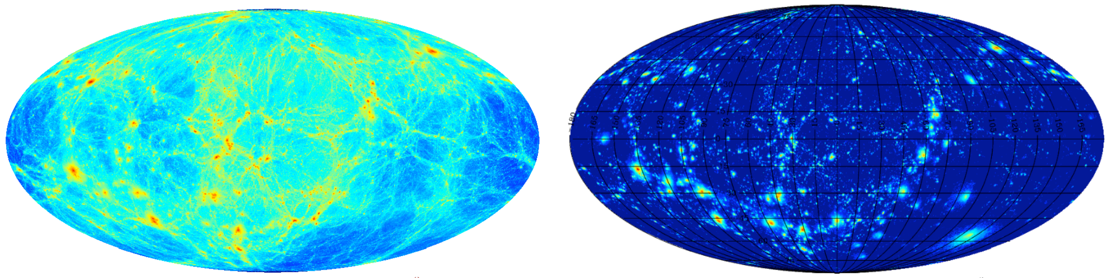

Figure 2. Local Universe Simulation: ((left) Dark Matter Sky; (right) Dark Matter Annihilation Gamma-Ray Sky.

of timesteps can be stored so that we can visualize the evolution of structure from the Big Bang to the present. We can also do fly-throughs and zoom-ins, both as the simulation evolves and at the present epoch. Although the constraints don't exactly reproduce the local universe, the simulation should be close enough to reality that it would be illuminating to overplot in 3D the local galaxies (e.g., the Tully Catalog) and isodensity contours representing high and low densities. The moderately high density regions are the filamentary "cosmic web" and the bright nearby galaxies should lie in the filaments. In addition, we plan to fly through 3D maps of simulated gamma ray production by dark matter annihilation (proportional to dark matter density squared). The left panel in Figure 2 is a 2D map (Mollweide projection) of the dark matter distribution (DM density divided by r^2) projected onto the sphere around us, while the right panel is the predicted gamma ray sky from annihilation in nearby galaxies (DM density squared divided by r^2). (Key collaborators: Francisco Prada, Institute of Astrophysics of Andalusia, Spain, and his group; and Chris Henze and his group at NASA Ames.)

2.2.2 Future of the Local Universe. This is the same Local Universe simulation, continued into the far future assuming that the dark energy is a cosmological constant. This can be visualized both in co-moving coordinates (overall appearance of the volume doesn't change much, but on small scales structures fall together) and in physical coordinates (the local region becomes increasingly empty, and in ~100 billion years even the Virgo Cluster leaves the horizon of the Local Group). The main recent papers on this are Nagamine & Loeb (2003) and Busha et al. (2003, 2007). (Key collaborators: same as Local Universe Simulation, and also Michael Busha, postdoc with Prof. Risa Wechsler at Stanford University.)

2.2.3 How Structures Form in the Expanding Universe – visualizing how higher-than-average density fluctuations reach a maximum radius, then stop expanding and undergo gravitational collapse, while the rest of the universe continues to expand around them. This is the basis of our modern understanding of the evolution of the universe, and the goal of this project is to devise visualizations that will help both students and the general public to understand this key process. For example, particles that will be bound into a particular halo at $z = 0$ can be color coded and followed from early times until the present. (Key personnel: Nina McCurdy, UCSC.)

2.3. High Resolution Hydrodynamic Simulations of Galaxy Formation.

2.3.1 Galaxy Merger Simulations. Galaxy mergers are thought to be the main way that disk galaxies are transformed into galactic spheroids, which now host supermassive black holes and most of the stellar mass in the universe (Fukugita & Peebles 2004). Primack's group has run a wide range of high-resolution GADGET hydrodynamical simulations of major and minor galaxy mergers, including gas cooling and heating, star formation, supernova feedback, and the effects of dust (Cox et al. 2006, 2008; Novak et al. 2006, Novak 2008). Hernquist's group at Harvard has run many similar simulations including the accretion by and feedback from supermassive black holes (reviewed in Hopkins et al. 2008). Most of these simulations were carried out by Primack's former grad student Collaborator T. J. Cox. The calculated visual appearance of a major merger shown in Figure 3 includes stellar evolution and dust absorption and reradiation treated by the state-of-the-art Sunrise code (Jonsson 2006, Jonsson et al. 2006, 2009). We have stored thousands of timesteps for some of these simulations and we plan to continue this simulation program supported by other grants, so that we can visualize the entire process from any vantage point including the view from a star in one of the merging galaxies. It

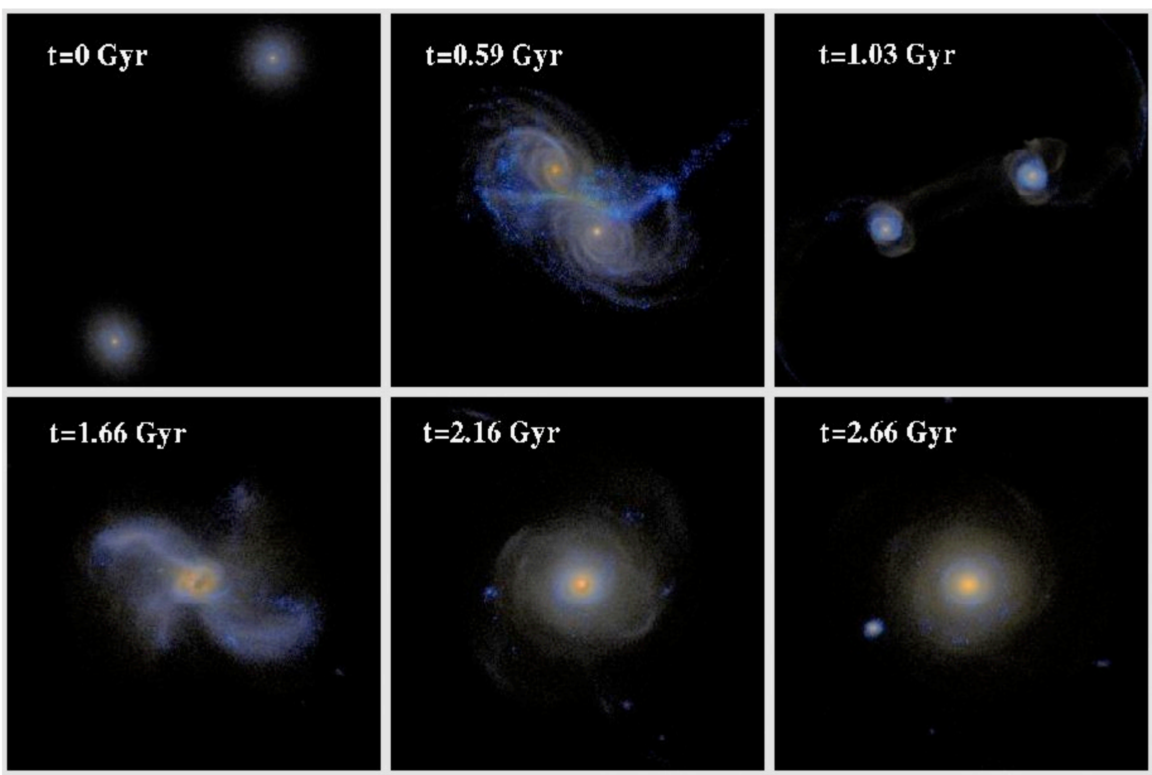

Figure 3. Composite color images including dust extinction for a high-resolution hydrodynamic galaxy major merger simulation. Time since the start of the simulation in given in the upper left corner of each image. (Top row) Initial pre-merger galaxies, first pass, maximal separation after the first pass. (Bottom row) Merger of the nuclei, 0.5 Gyr after the merger, remnant at 1 Gyr after the merger. The field of view at 0 Gyr and 1.03 Gyr is 200 kpc, while the field of view for the other images is 100 kpc. Star-forming regions appear blue, while the dust-enshrouded star-forming nuclei appear red. (From Lotz et al. 2008.)

will be challenging to visualize all the components: old and newly formed stars, gas density and temperature, metallicity, and dark matter density; and also kinematics. In the galaxy merger video by Patrik Jonsson, Greg Novak, and Joel Primack selected as a finalist in the 2008 Science Magazine – NSF Visualization Challenge, we alternated between showing the optical appearance and the gas distribution during a galaxy merger, but we will seek to discover more accessible methods of showing the multiple components. Galaxy merger simulations may be especially appropriate for 3D theater displays, since the galaxies are recognizable at most merger stages. (Key collaborators: Primack's former grad students Patrik Jonsson (now a postdoc at UCSC, moving to Harvard in September 2009), T. J. Cox (now working with Lars Hernquist at Harvard, moving in September 2009 to Carnegie Observatories), and Greg Novak (now a postdoc with Jeremiah Ostriker at Princeton), and Primack's current grad students.)

2.3.2 Very High Resolution Simulations of Forming Galaxies. Daniel Ceverino started these high-resolution adaptive mesh hydrodynamic simulations as a PhD student with Collaborator Anatoly Klypin (using PI Primack's supercomputer time and Klypin's ART-hydro code running in Open MP). Ceverino is running even more ambitious simulations as a postdoc with Primack's long-term collaborator Avishai Dekel, now using Primack's allocations on the Schirra and Columbia computers at NASA Ames. Visualizations will be crucial to help us understand the formation and evolution of these galaxies in cosmological simulations, and compare the simulations to observations. These are among the highest resolution and most realistic galaxy formation simulations now being done, and they suggest that the process of star-forming clump formation in gaseous galactic disks fed by cold streams at high redshift $z > 2$ followed by clump merging onto central spheroids may be the main formation mechanism of massive galactic spheroids (Dekel et al. 2008, Dekel, Sari, & Ceverino 2009). (Key collaborators: Daniel Ceverino, Avishai Dekel, and Anatoly Klypin.)

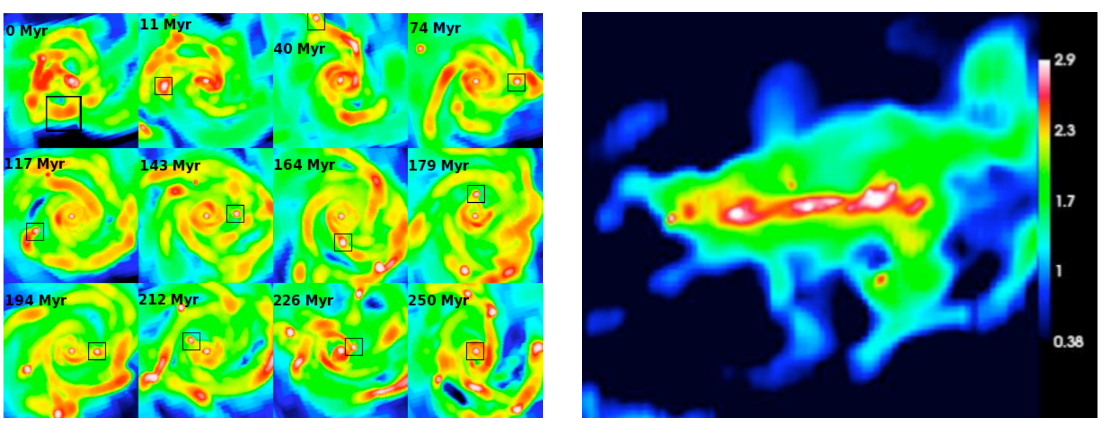

Figure 4. (Left) Evolution of gas disk at $z \sim 2$, showing a clump (boxed) merging onto central spheroid. (Right) Side view of a timestep of the same simulation. The region shown is 15 kpc across. Color code is log surface density in $M_{\odot}/pc^2$.

2.4 Additional Visualization Projects. Once we have established a pipeline to move our simulations into will be relatively easy to translate other cosmological simulations into the formats used by digital planetarium software. The following are two other examples of such simulations.

2.4.1 Evolution and Substructure of a Milky Way Size Dark Matter Halo. Via Lactea I was the first billion particle simulation of a dark matter halo of the size that hosts our own galaxy was run by Piero Madau's UCSC group (Diemand et al. 2007), and their more recent 4 billion particle Via Lactea II simulation (Diemand et al. 2008) is competitive with the European Aquarius simulation (Springel et al. 2008).

2.4.2 Massive Star Formation. Mark Krumholz (UCSC) is doing state-of-the-art hydrodynamical simulations that are answering the question of how stars ~100 times the mass of the sun form, and why most are in binary systems with similar–mass stars (Krumholz et al. 2009).

3.1 Why Planetariums? Planetariums used to show mainly the nearby stars in the night sky. With the advent of digital projectors they have greatly expanded their content by including various sky surveys (Sloan digital sky survey, Tully galaxy data set, etc.). However, planetariums have yet to project dark matter simulations onto the dome for a public audience. While exploring static environments provide a wealth of information about the current shape of the universe, they present only a snapshot of the latest moment in the story of our cosmology. Visualizations of cosmological simulations can tell a more complete story by visualizing the evolution of the cosmic web.

With scientific advancement comes the responsibility to include the general public by integrating new discoveries into the story of the cosmos. Planetariums provide the perfect venue to do just that, since they have both the best equipment and the most interested audience. The fact that the audience is self-selected means that they are personally invested in the material. By conveying the excitement within the scientific community, beautiful simulation visualizations will undoubtedly inspire future scientists, and in particular future astronomers and physicists.

Digital planetariums are also the most ambitious venue, since digital planetarium software makes extending our productions to 3D theaters, flat screens, and the internet will be comparatively easy.

3.2 Roles of Adler and Morrison Planetariums. These planetariums will be crucial in developing a visual language for displaying dark matter as well as visible matter (stars, gas, and dust), and working with PI Primack and his scientific collaborators and with Collaborator Chris Henze and the NASA Ames visualization group to make compelling visualizations of our multicomponent simulations. In addition to their domes, both Adler and Morrison Planetariums have 3D theaters where we can try 3D visualizations on various audiences. After these audiences have seen the shows in various formats, we will systematically evaluate how well our visualizations are able to communicate the three dimensional appearance of the universe on various size scales and its evolution through cosmic time.

3.3 Making visualizations. The first part of this project will be devoted to translating the simulations into formats compatible with systems used for video, digital Planetarium and

3D theater systems. Simulations were originally created for research purposes, and are too large for standard display systems, where the number of dynamic objects is currently limited to about 10^5. The number of particles thus must be greatly reduced. Therefore a large part of the preliminary process will be determining how to best sub-sample the current data in such a way that maintains the most interested and valuable characteristics of the simulation. Part of the work in preparing visualizations will also be interpolating between the saved timesteps.

We need to see what visualizations work best in 3D. The merging of two galaxies looks very different from various vantage points. Merger simulations often show the event several times from different perspective but fail entire three dimensional experience into a single animation. Adapting the current merger simulations to 3D theater will allow for a more complete and powerful experience. (talk about how this will be enriching for scientists and the public alike).

More critical will be deciding what material to present and how to present it so that it will be understood by diverse audiences. How can we show the dark matter and visible matter simultaneously without confusing the audience? How can we show motion? What sort of color codes convey information without confusion.

Real-Time vs. Pre-Rendered shows. We plan on producing both Real-Time and Pre-Rendered shows to be distributed to planetariums. The Pre-Rendered material will also be useful in video form for other applications including education and science museums. Real-Time shows would require providing a data set that can be used both to create shows and to hold live (exploration) sessions. Pre-rendered shows, or "show in a can" would demand less compatibility and would therefore be compatible with a larger variety of systems. These shows would be in 5 to 7 minute blocks designed to explore the most illuminating aspect/components of the simulations.

3.3 Dissemination. The next part of the proposed project will be devoted to creating a dissemination process and continuing to evaluate the success of the productions.
Other possibilities include producing DVDs or Blu-Ray disks and distributing them to both formal and informal science education institutions.

3.4 Plans and Methodology for Evaluation of Visualizations

Visualizations have the potential to move and educate audiences. However, it is an open question as to whether a visualization of content that is unfamiliar to any given audience will be meaningful to this audience, especially without appropriate guidance. Studies show, particularly in the area of cosmology, that the general public does not have extensive background knowledge or understandings and often have pervasive misconceptions about content. Absent appropriate foundational understandings, audiences may not be able to relate to the visualizations or may misinterpret them.

Evaluation work undertaken at the Adler Planetarium will be formative in nature. Evaluator Michelle Nichols, using her experience in visitor evaluation in the museum setting and taking advantage of the facilities at the Adler's Space Visualization Laboratory, will work with small groups of visitors to ascertain how they interpret portions of visualizations or entire visualizations. This will be done first without, and then with some guidance from museum staff about what these visualizations represent, and help with any difficult concepts. Audiences' initial reactions, impressions and questions about visualizations given without guidance will inform what guidance is offered. When guidance is offered, again audience reactions will be recorded to see if their understanding of the visualizations is enhanced.

This data about what guidance is appropriate to facilitate understanding will be available to partners to use in several ways: first it can inform subsequent iterations of visualizations, possibly suggesting additional content or different approaches to the visualization. Second, it will be available to be included in accompanying materials for end users of these visualizations. As such it can inform voiceover scripts for planetarium shows, or notes for lectures or other educational programs given that use these visualizations.

4. Proposed Advisory Committee with some suggested members, perhaps including the following people Donna Cox (NCSA), Frank Summers (STScI), Derrick Pitts (Franklin Institute Fels Planetarium), Ian McLennan (Vancouver), Shawn Laatsch (Hilo Planetarium), Tom Abel (Stanford), and Andrey Kravtsov (UChicago). Plans to meet annually, perhaps in conjunction with AstroViz and/or Planetarium meetings. *to be finished*

6. Management Plan, Division of Labor, and Timeline including how this proposal responds to NASA's missions *to be finished*

Management: The PI and Co-Is will constitute a management committee to consider all major issues.

Timeline: 2010 – create initial planetarium versions of key projects, begin trials and evaluations, first meeting of advisory committee. 2011 – finish first versions of key projects for evaluation and limited distribution, first presentations to planetariums at relevant conferences. 2012 – finish final versions of projects including supplementary materials, launch major distribution effort, workshops for planetarium staff, outreach to other venues.

Staff: Nina McCurdy will play a crucial role in various aspects of this proposed project. Nina's academic background in physics, combined with the knowledge and vocabulary she has gained through her personal explorations of the visual arts, makes her a valuable liaison between the scientific, artistic, and planetarium communities. Nina will work closely with the Adler and the Morrison planetarium, as well as any other institutions/sites that this project extends to. She will be deeply familiar with the scientific concepts of the simulations and will help the planetarium teams design the most meaningful and effective explorations of them. Nina will also be creating simulations and will have a range of involvement in projects described earlier. In addition, Nina will be the project's web master. She, along with possibly one other artist, will create a website making our productions publicly available and thereby extending our outreach to a much wider audience.

Evaluator: Michelle Nichols, Adler Planetarium. It will be necessary to have a professional evaluator on the team. Once the material (or test materials) has been distributed, this person will be in charge of working with the various institutions to scientifically assess the effectiveness of the productions.

(Separate sections) Budget and Justification *to be done*

Capabilities of DigitalSky 2 (how much of this should we include?)

At its core, DigitalSky 2 is a digital planetarium instrument, but its capabilities far exceed those of any classical planetarium projector. With DigitalSky 2 the user can move freely through a 3D universe viewing endless astronomical phenomenon and employing advanced teaching aids. Astronomical bodies can draw trails as they move through the sky and planets can zoom in with full motion and 3D texturing as they come into the foreground.

DigitalSky 2 also provides dramatic multimedia capabilities allowing still image and video clips to be inserted anywhere on the dome and manipulated freely in real time. 3D objects may also be imported into DigitalSky 2 allowing them to move through space and behave as part of the 3D environment in any presentation. DigitalSky 2 is truly a complete planetarium solution. The classic array of auxiliary effects projectors will never again be required as virtually any phenomenon can be incorporated directly into the DigitalSky 2 simulation.

The DigitalSky 2 user interface has been developed based on Sky-Skan's decades of experience in the planetarium industry. A familiar "manual console" page allows users to access traditional earth bound planetarium controls in the same way they have operated optical-mechanical instruments. A 3-axis joystick facilitates navigating the more complex 3D models. For the most complex sequences an automation scripting language allows all functions to be pre-defined and accessed at the click of a button. Whether manual or pre-scripted operation is desired, DigitalSky 2 insulates the user from the standard Windows GUI making live presentations simple.