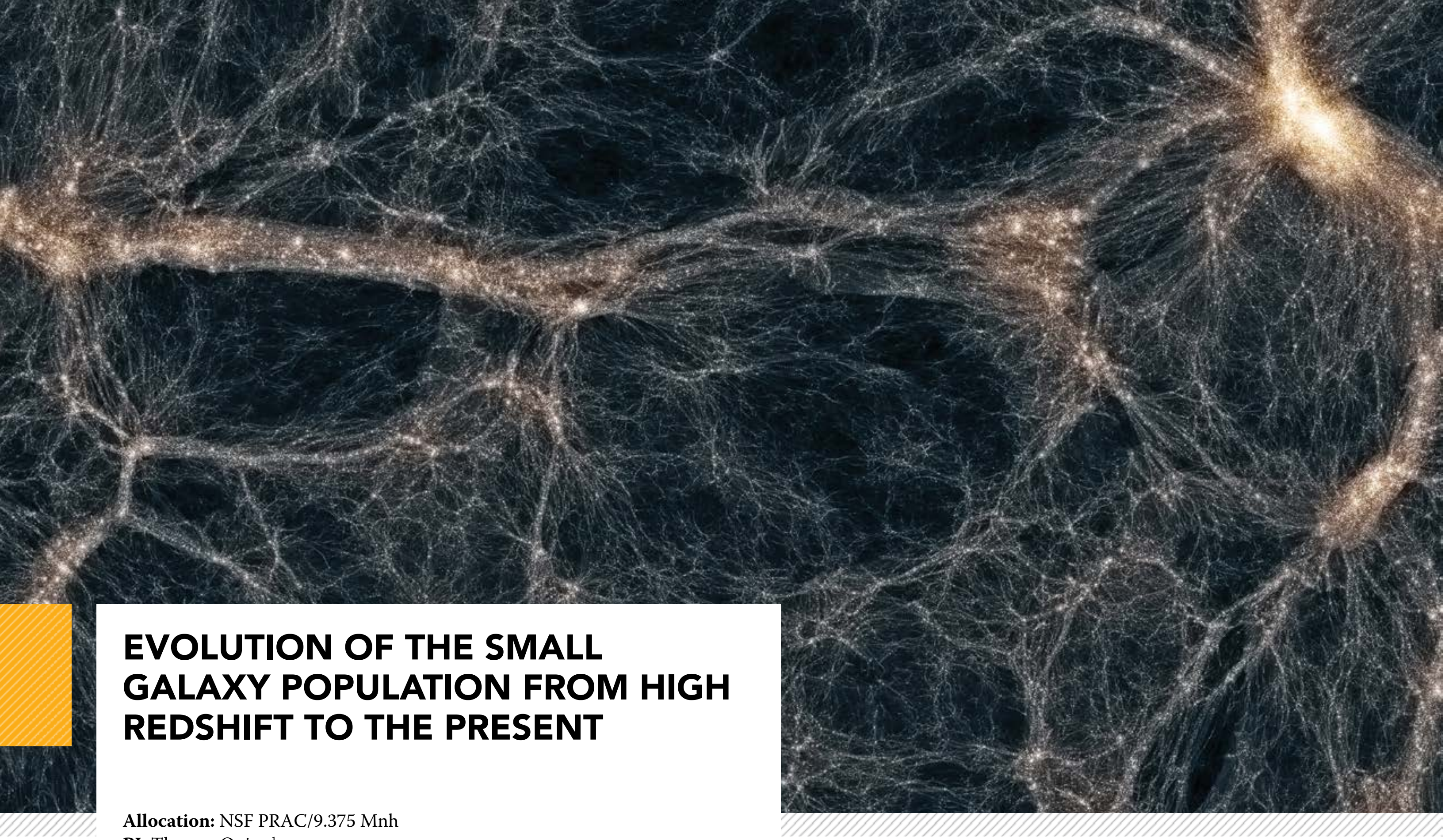

EVOLUTION OF THE SMALL GALAXY POPULATION FROM HIGH REDSHIFT TO THE PRESENT

Allocation: NSF PRAC/9.375 Mnh
PI: Thomas Quinn[1]
Co-PI: Fabio Governato[1]
Collaborators: Lauren Anderson[1], Michael Tremmel[1], Charlotte Christensen[3], Sanjay Kale[4], Lucasz Weslowski[4], Harshitha Menon[4], Gengbin Zheng[5]

[1]University of Washington
[2]University of Arizona
[3]Grinnell College
[4]University of Illinois at Urbana-Champaign
[5]National Center for Supercomputing Applications

FIGURE 1 (BACKGROUND): A slice of a 24-billion-particle simulation of the present-day dark matter in a 25 Mpc volume of the universe. The object in the upper right is roughly the size of our local group of galaxies and is resolved with several hundred million particles.

EXECUTIVE SUMMARY:

Creating robust models of the formation and evolution of galaxies requires the simulation of a cosmologically significant volume with sufficient resolution and subgrid physics to model individual star-forming regions within galaxies. This project aims to do this modeling with the specific goal of interpreting Hubble Space Telescope observations of high-redshift galaxies. We are using the highly scalable N-body/smooth particle hydrodynamics code ChaNGa, based on the Charm++ runtime system on Blue Waters, to perform a simulation of a 25 million parsecs cubed volume of the universe with a physically motivated star formation/supernovae feedback model. This past year's accomplishments include using a pathfinding simulation at one-tenth the needed resolution, which we will use to study overall star formation histories and luminosity functions. This simulation is also being used to tune the feedback model to accurately model galaxy morphologies over a range of masses.

INTRODUCTION

The cold dark matter (CDM) paradigm for structure formation has had many successes over a large range of scales, from cosmic microwave background fluctuations on the scale of the horizon to the formation and clustering of individual galaxies. However, at the low end of the galaxy luminosity function, the CDM theory and observations are somewhat at odds. In particular, the existence of bulgeless, cored small galaxies is not a natural prediction of CDM.

However, these are the scales where the baryonic physics of gas cooling, star formation, and feedback can significantly impact the overall mass of the galaxy. Furthermore, accurately modeling the star formation process requires a spatial resolution of order 100 parsecs or less in order to resolve the molecular star-forming regions of the interstellar medium. On the other hand, survey volumes addressing small galaxies, including recently approved Hubble Space Telescope (HST) programs, are over 10,000 cubic Mpc. Only with large simulations can we do proper comparisons with these programs to address the following basic issues of the CDM model:

- Does the standard ΛCDM model produce the correct number densities of galaxies as a function of mass or luminosity?
- What is the overall star formation history of the universe?
- How do these galaxies relate to the galaxies we can study in detail in the local universe?

METHODS & RESULTS

We used the highly scalable N-body/smooth particle hydrodynamics code ChaNGa to simulate the volumes surveyed by HST with sufficient resolution to make robust predictions of the luminosity function, star formation rate, and morphologies appropriate for these surveys. The results of the simulations were processed by our parallel data reduction pipeline that creates simulated observations. These results can be directly compared with results from observational programs.

Preliminary results from our low-resolution simulations indicated that we can reproduce the high-redshift galaxy luminosity functions observed by HST. The simulations also predicted the numbers of galaxies fainter than those observed so far. Depending on how much UV radiation can escape from these low-mass galaxies, there may be enough stellar radiation from these low-mass galaxies to completely reionize the intergalactic medium.

WHY BLUE WATERS?

The mass and spatial resolution required to reliably model galaxy morphology were set by our published resolution tests. Therefore the size of the simulation we perform was set by the sub-volume of the universe we wish to model. HST surveys of high-redshift, star-forming galaxies cover a volume comparable to a cube 25 Mpc on a side. This volume will not only allow us to make direct comparisons with HST surveys, but also enhance their scientific return by understanding how those surveyed galaxies will evolve to the present.

This volume and our required resolution result in a total of 24 billion particles. This is just over an order of magnitude larger than simulations that we could run on other resources to which we have access. A sustained petascale facility like Blue Waters was required for this simulation.

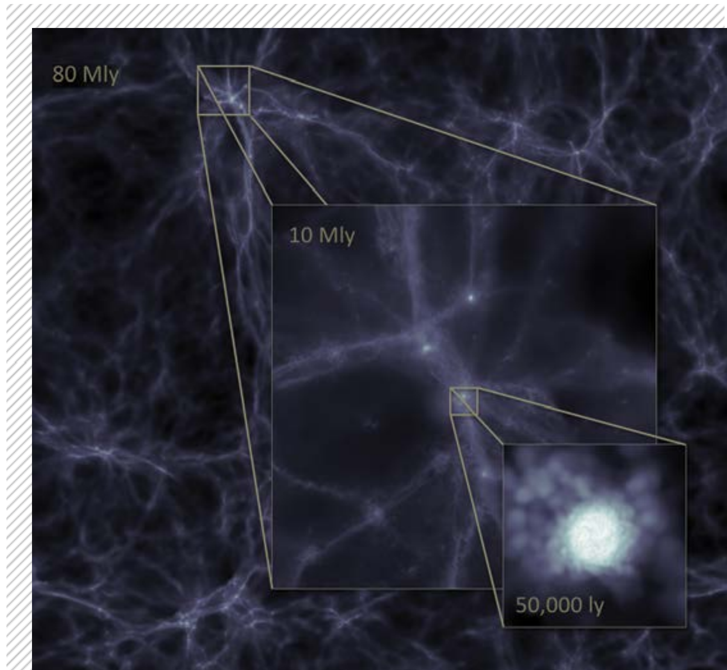

FIGURE 2: A zoom-in on one of the galaxies in a gas dynamical simulation of a 25 Mpc volume of the universe. The zoom-in shows how the disk morphology of an individual galaxy is resolved within this volume.

Nevertheless, this simulation was still a compromise. For example, if we wish to understand how high-redshift galaxies are influencing the surrounding intergalactic gas, a much larger volume is needed. Intergalactic gas is studied in absorption from observations of background quasars using the HST Cosmic Origins Spectrograph. Statistical samples of this gas require a volume of order 60 Mpc on a side, over an order of magnitude larger than our current simulation. Only with this size of simulation will we be able to understand the extent to which star formation, supernovae, and active galactic nuclei in individual galaxies influence the surrounding gas, and to conduct a proper census of the majority of the baryonic matter in the universe. The next generation of Track-1 computational resources will be required for this simulation.

PUBLICATIONS

Governato, F., et al., Faint dwarfs as a test of DM models: WDM versus CDM. *Mon. Not. R. Astron. Soc.*, 448 (2015), 792, doi:10.1093/mnras/stu2720.

Menon, H., et al., Adaptive techniques for clustered N-body cosmological simulations. *Comput. Astrophys. Cosmol.*, 2 (2015), 1, doi:10.1186/s40668-015-0007-9.