Interim Report for Blue Waters GLCPC Project Allocation

1. Project Information

Project title: Pushing the Dynamic Range: Simulating the Co-Evolution of Galaxies and Black Holes

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2. Executive Summary

We are performing high-resolution cosmological hydrodynamic simulations following the formation and evolution of massive galaxies from the Big Bang to the present time. We are focusing on galaxies more massive than the Milky Way (up to the mass scale of galaxy groups) while at the same time including enough resolution to explicitly model the interstellar medium of galaxies and the effects of feedback from stars. We will use the simulations to study the co-evolution of galaxies and their supermassive black holes. By pushing the dynamic range of cosmological zoom-in simulations by about an order of magnitude relative to the current state of the art, these new simulations will enable a wide range of other scientific investigations, such as studies of the gaseous halos of massive galaxies, and will thus have legacy value.

3. Description of Research Activities and Results

Key challenges: The principal challenge in simulating the co-evolution of galaxies and supermassive black holes (SMBHs) is the extreme dynamic range involved. This is an important problem because observations indicate a close connection between the growth of SMBHs and the evolution of their host galaxies. For example, the masses of SMBHs correlate tightly with the stellar bulges of galaxies. The cosmic history of SMBH growth also roughly tracks the cosmic star formation history. Furthermore, SMBHs appear crucial to explain the properties of the most massive galaxies, which are observed to have stopped forming stars long ago. However, the physical mechanisms driving this connection remain largely unknown. This is because the huge dynamic range of physical scales involved has so far made it extremely challenging to simultaneously simulate all the relevant dynamics. This is especially the case since observed galaxy-black hole scaling relations indicate that, relative to stars, SMBHs become energetically dominant in the high-mass galaxies that are the most computationally demanding to simulate at high resolution.

Why it matters: Simulating the growth of SMBHs in cosmological simulations will enable us to answer several frontier questions in astrophysics, including: What is the origin of galaxy-black hole scaling relations? How is active galactic nucleus (AGN) activity triggered? What is the impact of AGN feedback on galaxy evolution? What are the effects of stellar feedback on SMBH growth?

The simulations proposed here will have a legacy value by enabling detailed investigations of other timely questions in galaxy formation. For example, our simulations will enable us to simulate galaxy groups with resolution sufficient to resolve the interstellar medium (ISM) of individual galaxies and the effects of stellar feedback.

Why Blue Waters: The Blue Waters capabilities are essential to simulate at high resolution the massive galaxies in which most SMBH growth occurs, from the Big Bang to the present time. Pushing our simulations to the scale of the current runs represents an order-of-magnitude increase in computational demands relative to our previous simulations and will thus enable us to test and optimize the scaling of cosmological zoom-in simulations in a new regime. Since a version of our GIZMO simulation code is publicly available, this optimization will benefit the community at large.

Accomplishments: This is an interim report on our first six months of using Blue Waters. During these first six months:

- We set up our GIZMO simulation code on Blue Waters and familiarized ourselves with the compute environment.
- We carried out scaling tests to determine the maximum number of cores to which GIZMO scales well for our particular problem on Blue Waters. We also experimented extensively with different mixtures of simulation parameters and identified optimal MPI-OpenMP combinations.
- We started evolving two large, production-quality simulations of massive galaxies including SMBHs (one including a new subgrid model for metal diffusion by unresolved turbulence).

Up to the mid-point of our first-year allocation, we have used 21% of our allocated CPU time. Although this is significantly less than 50%, this is largely because of the (human) time initially invested for scaling tests on Blue Waters. Now that we have begun evolving production-quality simulations, we anticipate using the remainder of our allocation at a higher rate in the latter half of the year. Thinking forward, we anticipate proposing for a renewal of our Blue Waters allocation for the following year and migrating much of our research to Blue Waters.

One interesting preliminary result of our present runs is that our massive galaxies appear to be developing very high density "cores." This is a potentially important finding, which could have implications for the formation of nuclear star clusters and/or the fueling of SMBHs. Previous cosmological simulations of galaxies of this mass generally did not have enough resolution to predict the formation of such high density cores. We are analyzing in more detail these unexpected high-density cores in order to understand their scientific implications.

From the computational perspective, these high-density cores are a challenge because the strong clustering of matter and short dynamical times that result make evolving the high-density cores extremely computationally demanding. This scientifically interesting result is therefore forcing us to develop new strategies for evolving the new simulations to later cosmic times. We are actively working on the next steps.

This summer, we submitted for publication to MNRAS Letters a first paper on the growth of SMBHs in cosmological simulations with the FIRE stellar feedback model (see below). This article is a preview of the kind of analysis that we will be doing on our Blue Waters simulations. This article is based on pilot simulations of massive galaxies similar to the ones that we are currently evolving using Blue Waters, but were stopped at high redshift (early cosmic time). With Blue Waters, we are pushing to evolve similar galaxies but all the way to the present time.

4. Publications

1. Anglés-Alcázar, D., **Faucher-Giguère, C.-A.**, Quataert, E., Hopkins, P. F., Feldmann, R., Torrey, P., Wetzel, A., & Kereš, D., "Black Holes on FIRE: Stellar Feedback Limits Early Feeding of Galactic Nuclei," submitted to MNRAS Letters [arXiv:1707.03832].