THE EVOLUTION OF THE HALO MASS FUNCTION IN AN ACCELERATED UNIVERSE

Allocation: Exploratory/50 Knh
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EXECUTIVE SUMMARY

We live in an accelerated expanding universe that is dominated by a cosmological constant, or the value of the energy density of the vacuum of space, also known as "dark energy." This dark energy acts as a negative pressure pushing everything away and making the universe expand at faster rates. In the distant future, dark energy will completely dominate the evolution of large-scale structures. Based on a simple theoretical criterion, we can determine the limits of gravitationally bound, dark-matter halos in their critical shells for virialized haloes. (A system is virialized when the potential energy is twice the negative kinetic energy.) 70 billion years into the future, this predicts that the density inside the last bound shell has to be twice the critical density of the universe at that time. Using Blue Waters, we applied this criterion far into the future by using N-body simulations of dark matter particles, where all of the halos are fully virialized and "frozen" in the cosmic web. This simulation produced a halo mass function that reaches an asymptotic form, from which we can extract useful information to constrain the large-scale structures we observe today and put constraints on current cosmological models.

RESEARCH CHALLENGE

Recent observations suggest that we live in an expanding, zero-curvature universe dominated by a cosmological constant. This vacuum energy density, the so-called dark energy, appears to dominate the expansion rate of the universe today. In the present cosmological scenario, the universe transitioned from a matter-dominated stage to a dark-energy-dominated, accelerating stage at redshift $z \approx 0.7$. During the period of time when the universe was substantially dominated by matter density over dark-energy density, decelerating its expansion, the formation and evolution of structures were driven only by gravitational instability of matter concentrations, producing structures that grew over time. At later times, when dark energy came to govern the dynamics of the universe, accelerating its expansion, the formation of structures slowed down. At those times, massive structures much denser than the dark energy will not be much affected by this acceleration and will remain gravitationally bound. As they evolve into the future, these structures will be fully virialized: They will be spherical, and they will stop accreting mass so they will be "frozen" in the future cosmic web.

By using simulations of the future evolution of dark matter particles, it is possible to place constraints on the bounds of superstructures by following the mass evolution of the biggest clusters found at redshift $z = 0$ (present day) in the simulation. However, due to resolution limitations in previous studies, a complete understanding of the evolution of mid-size halos based, among other properties, on local environments in a universe with a cosmological constant still remains incomplete. We wanted to understand how the mass of these structures evolves with time and how we can use that information to put constraints on today's cosmological models of structure formation.

METHODS & CODES

We carried out several dark matter particle N-body simulations from very far in the past, when the universe was only 2% of its current size, to the future, where the universe will be 100 times its current size, in order to understand the evolution of dark matter haloes. Since our simulations included only dark matter particles, we evolved them in time using the parallel tree N-body/smoothed particle hydrodynamics (SPH) code GADGET-2 [1], which is the main software used. Only the tree code was used for this simulation. These simulations started at redshift $z = 40$ and evolved until the scale factor reached 100, which is about five times the current age of the universe and with a size 100 times larger.

Our main bottleneck is the gravitational force computation that GADGET-2 completes for each timestep, but since our simulation is well within the XE compute node's peak performance limits, this was not an issue. All of the runtime libraries needed for the GADGET-2 simulation are already included in Blue Waters' software and packages list: hdf5 (for writing the output files), mpich2 (for communication), and fftw (for tree force computation).

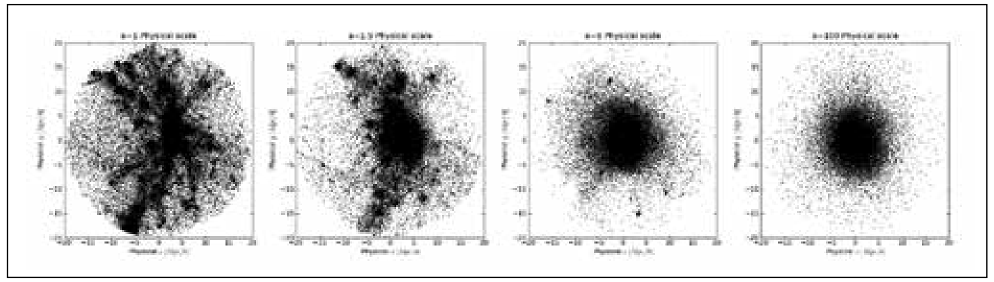

Figure 1: The particles that eventually in the future will collapse into a massive, virialized, and spherical halo. From left to right: a=1 (present), a=1.5, a=8 and a=100 (future). We see that the differences increase with the scale factor, and the structures at a=100 appear physically isolated.

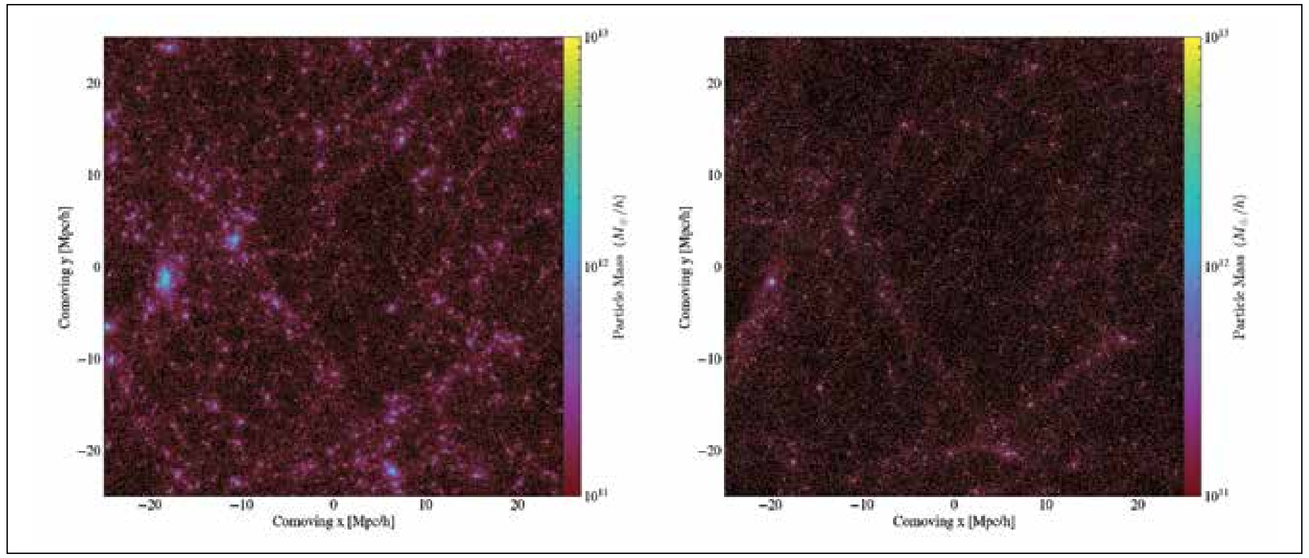

Figure 2: A slice of one of the simulations for the same 50 megaparsec/hour (Mpc/h) region at the present (a=0, left) and in the distant future (a=100, right). Halos are more spherical and well defined in the future; everything is virialized, and no more mass accretion is occurring.

RESULTS & IMPACT

Using Blue Waters, we were able to run several simulations at different scales; given the exploratory nature of our allocation, we are still processing and analyzing the data generated.

We can see from Fig. 1 that even the largest haloes in the future with close to 80,000 particles are very spherical and virialized, where only the dark energy is dominating the evolution and no more mass is being accreted to these structures. Fig. 2 shows a small section of one of the simulations where we can see the same effect but at larger scales; we can still see the web-like structure, but all the haloes are more concentrated after evolving into the future. The left panel shows the same structures as seen today; the right panel shows them in the future when the universe is 100 times larger (note that the units are scaled for the visualization).

We have created over 100 snapshots per simulation and are planning to study the evolution of these structures in much more detail. We plan to extend previous work on simulated future evolution of structures to smaller halos as well as to use different cosmological parameters. Initial results show that the halos stop accreting mass when the universe is twice today's size. After that point, all structures will be defined and will reach a stable, virialized configuration.

WHY BLUE WATERS

N-body dark matter simulations at scale require the use of a high-performance computing resource that is multicore, scalable, stable, and has high bandwidth with low-latency interconnect communication, especially when running large simulations on the order of 1 billion particles. Parallel I/O access to data is also a requirement. Blue Waters provides all of the above in addition to a very helpful dashboard and outstanding help and technical support, which makes it a perfect platform for running such simulations.