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Density Profiles and Substructure of Dark Matter Halos: Converging Results at Ultra-High Numerical Resolution

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Abstract

Can dissipationless *N*-body simulations be used to reliably determine the structural and substructure properties of dark matter halos? A large simulation of a galaxy cluster in a cold dark matter universe is used to increase the force and mass resolution of current "high-resolution simulations" by almost an order of magnitude to examine the convergence of the important physical quantities. The cluster contains ~5 million particles within the final virial radius, $R_{vir} \simeq$ 2 Mpc (with H_0 = 50 km s^{-1} Mpc^{-1}), and is simulated using a force resolution of 1.0 kpc (0.05% of R_{vir}); the final virial mass is 4.3×10^{14} $M_☉$, equivalent to a circular velocity of v_{circ} $(GM/R)^{1/2} \simeq$ 1000 km s^{-1} at the virial radius. The central density profile has a logarithmic slope of -1.5, identical to lower resolution studies of the same halo, indicating that the profiles measured from simulations of this resolution have converged to the "physical" limit down to scales of a few kpc (~0.2% of $R_{\rm vir}$). In addition, the abundance and properties of substructure are consistent with those derived from lower resolution runs; from small to large galaxy scales ($v_{\rm circ}$ > 100 km s^{-1}, $m > 10^{11}$ $M_{\odot}$), the circular velocity function and the mass function of substructures can be approximated by power laws with slopes of ~-4 and ~-2, respectively. At the current resolution, overmerging (a numerical effect that leads to structureless virialized halos in low-resolution N-body simulations) seems to be globally unimportant for substructure halos with circular velocities of $v_{\rm circ}$ > 100 km s^{-1} (~10% of the cluster's $v_{\rm circ}$). We can identify subhalos orbiting in the very central region of the cluster ($R \lesssim$ 100 kpc), and we can trace most of the cluster progenitors from high redshift to the present. The object at the cluster center (the dark matter analog of a cD galaxy) is assembled between $z = 3$ and $z = 1$ from the merging of a dozen halos with $v_{\rm circ} \gtrsim$ 300 km s^{-1}. Tidal stripping and halo-halo collisions decrease the mean circular velocity of the substructure halos by ≈20% over a 5 billion yr period. We use the sample of 2000 substructure halos to explore the possibility of biases using galactic tracers in clusters: the velocity dispersions of the halos globally agree with the dark matter within $\lesssim$10%, but the halos are spatially antibiased, and in the very central region of the cluster ($R/R_{\rm vir} < 0.3$) they show positive velocity bias ($b_v \equiv \sigma_{v3D,\rm halos}/\sigma_{v3D,\rm DM} \simeq$ 1.2-1.3); however, this effect appears to depend on numerical resolution.

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