Are halo profiles and concentrations universal?

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[Profiles: 1401.1216 - Concentrations: 1407.4730]

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Are halo density profiles universal?

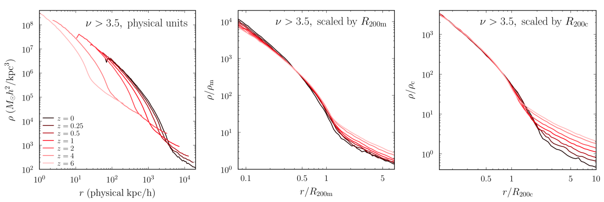


Figure 1: The median density profiles of very massive halos of fixed ν at different redshifts. In physical units (left), the profiles vary across redshifts. When radii are rescaled by some spherical overdensity radius, R_Δ, and the corresponding reference density, ρ_m or ρ_c, the inner density profiles become nearly universal.

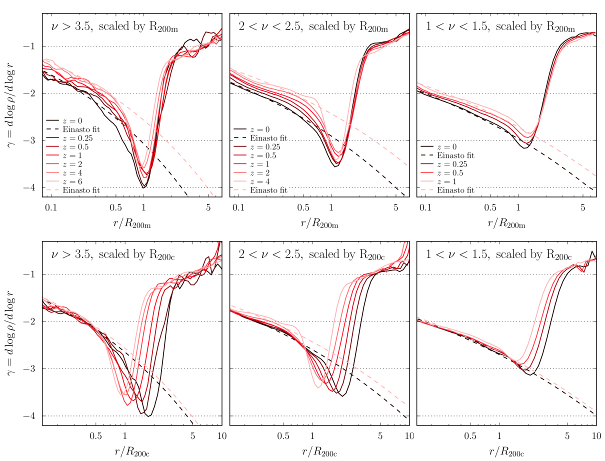


Figure 2: The exact redshift scaling is easier to see in the logarithmic slope of the density profiles, shown here for three bins in peak height which, at z=0, correspond to very massive clusters ($M > 10^{15}$ $M_\odot$/h, left), more common clusters ($M \sim 10^{14}$ $M_\odot$/h, center), and galaxy to group scale halos ($M \sim 10^{12\text{-}13}$ $M_\odot$/h, right). The radii are scaled by R_{200m} in the top row and by R_{200c} in the bottom row. **The inner region ($r < R_{200c}$) is most self-similar in units of R_{200c}, whereas the outer region ($r > R_{200m}$) is most self-similar in units of R_{200m}.** Scaling with R_{vir} and ρ_{vir} gives intermediate results. The self-similarity of the inner (outer) regions in units of R_{200c} (R_{200m}) holds for all halo masses, not only the most massive clusters. The steepening of the profiles around R_{200m} in massive halos is caused by their higher accretion rate (see Diemer & Kravtsov 2014a for details).

Abstract

Numerous theoretical arguments and simulation results indicate that the density profiles of halos are closely related to their mass assembly history. The latter is expected to be a universal function of peak height, $\nu = \delta_c/\sigma(M)$. Thus, we expect that the density profiles of halos with a fixed ν are close to universal, as long as radii and densities are expressed in the proper units.

We analyze a large suite of cosmological simulations to test how well this expectation holds in a hierarchical cosmology. We find that at fixed ν, the inner density profiles are most universal in units of R_{200c}, while the outer profiles are most universal in units of R_{200m}, where a radius R_Δ is defined to enclose an overdensity Δ wrt. the mean or critical density of the universe. In addition, Figure 2 demonstrates that the outer profiles are not universal, but exhibit a systematic variation with ν. This variation is caused by the different mass accretion rates of halos.

We also show that the relation between concentration, c, and ν is most universal when c is defined as $c_{200c}=R_{200c}/r_s$. However, sizeable deviations from universality in the c_{200c}-ν relation remain. We show that these deviations can be explained as a residual dependence of concentration on the local slope of the matter power spectrum, n. We construct a universal function of only two variables, $c_{200c}(\nu,n)$, that accurately describes concentrations across 22 orders of magnitude in mass and over a wide range of redshifts and cosmologies.

Are halo concentrations universal?

Concentration exhibits a non-trivial dependence on mass, redshift, and cosmological parameters. However, it has been shown that the relation between c and peak height, ν, is almost universal with redshift (e.g., Prada et al. 2012).

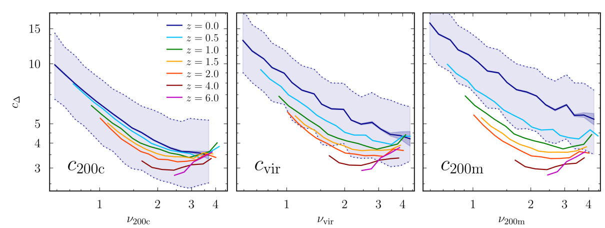


Figure 3: The c-ν relation for three definitions of the virial radius. Clearly, the **c_{200c}-ν relation is most universal with redshift**, while the other definitions, c_{vir} and c_{200m}, experience a spurious evolution at low redshift, namely when dark energy becomes important and ρ_m or ρ_c diverge. This evolution is related to the density profiles shown in Figure 2: at low z, halos are mostly in the slow accretion regime (e.g., Zhao et al. 2003), meaning that r_s barely changes, and $c_\Delta = R_\Delta / r_s \sim R_\Delta$. As we show on the left, the inner parts of density profiles at fixed ν are most universal in redshift when radii are rescaled by R_{200c}, leading to a more universal c_{200c}-ν relation.

A universal model for halo concentrations

The concentration-peak height relation is almost universal with redshift, but not quite (see center column). Thus, we are looking for a second parameter besides ν that affects concentration.

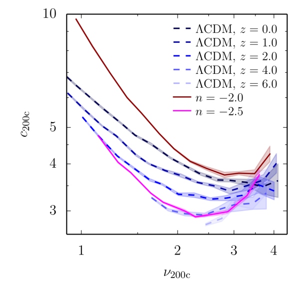
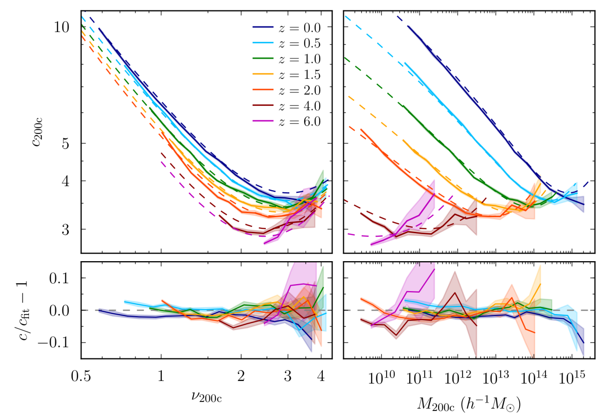


Figure 4: The c-ν relation in two self-similar cosmologies with Ω_m=1 and power-law spectra of slopes n=-2 and n=-2.5. Clearly, n has a large impact on concentration. The ΛCDM relations lie in between n=-2 and n=-2.5, roughly the range of n in a ΛCDM power spectrum.

Thus, we postulate that n is a second parameter influencing concentration, and that **concentration can be expressed as a universal function, c(ν,n)**. We fit our simulations results with such a function, namely a double power-law whose normalization and location of the minimum vary with n.

Figure 5: With only seven free parameters, this model fits ΛCDM concentrations to about 5% accuracy from z=0 to z=6 (the solid lines show simulation results, the dashed lines our model). The model also describes the concentrations in self-similar cosmologies, as well as those of Earth-mass halos at z=30. We provide a python code to evaluate our model at **www.benediktdiemer.com/code**.



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