A universal model for halo concentrations

Benedikt Diemer [1,2,3] and Andrey V. Kravtsov [2,3,4]

ApJ 799, 108 • arXiv 1407.4730 • python code at benediktdiemer.com/code

Abstract

Numerous theoretical arguments and simulation results indicate that the density profiles of halos (and hence their concentrations) are closely related to their mass assembly history which is expected to be a universal function of peak height, $\nu=\delta_c/\sigma(M)$. Thus, we expect that concentration, c, should be close to universal, i.e. independent of redshift and cosmology, at fixed ν.

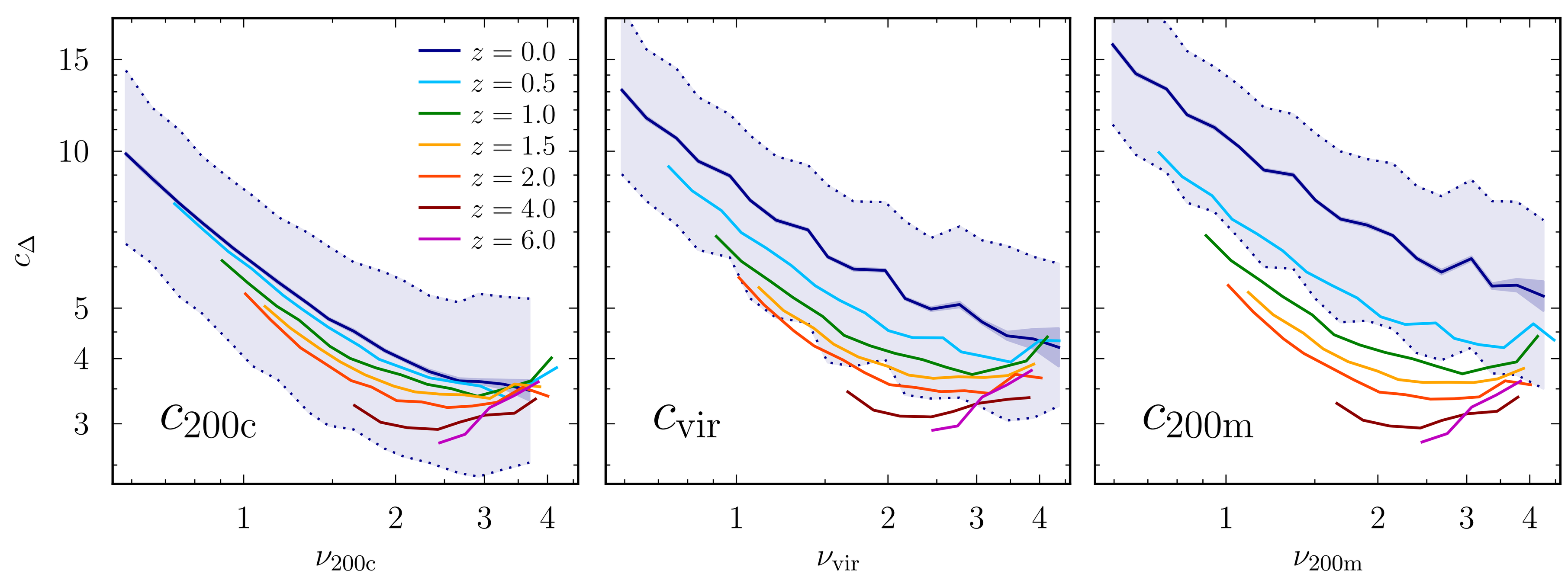
Analyzing a large suite of cosmological simulations, we find that, at fixed ν, the inner density profiles are most universal across redshift in units of R_{200c}. This implies that the relation between c and ν is most universal when c is defined as $c_{200c}=R_{200c}/r_s$. However, sizeable deviations from universality in the c_{200c}-ν relation remain.

We show that these deviations can be explained by 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.

Our model differs from all other models in the literature. For example, our model predicts an upturn at high masses (contrary to models based on halo samples where unrelaxed halos are excluded), and very low concentrations where the power spectrum is steep.

Are 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). The figure below shows the c-ν relation for three definitions of the virial radius. 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.



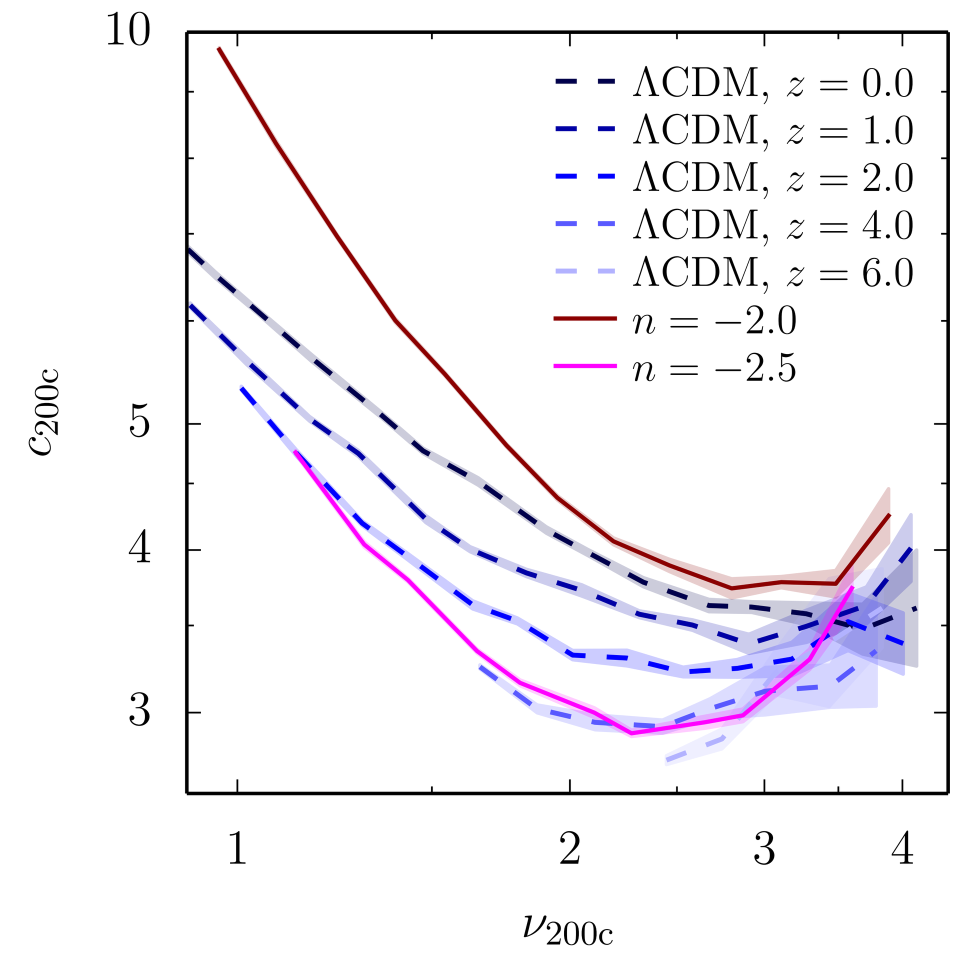
What parameters influence concentration?

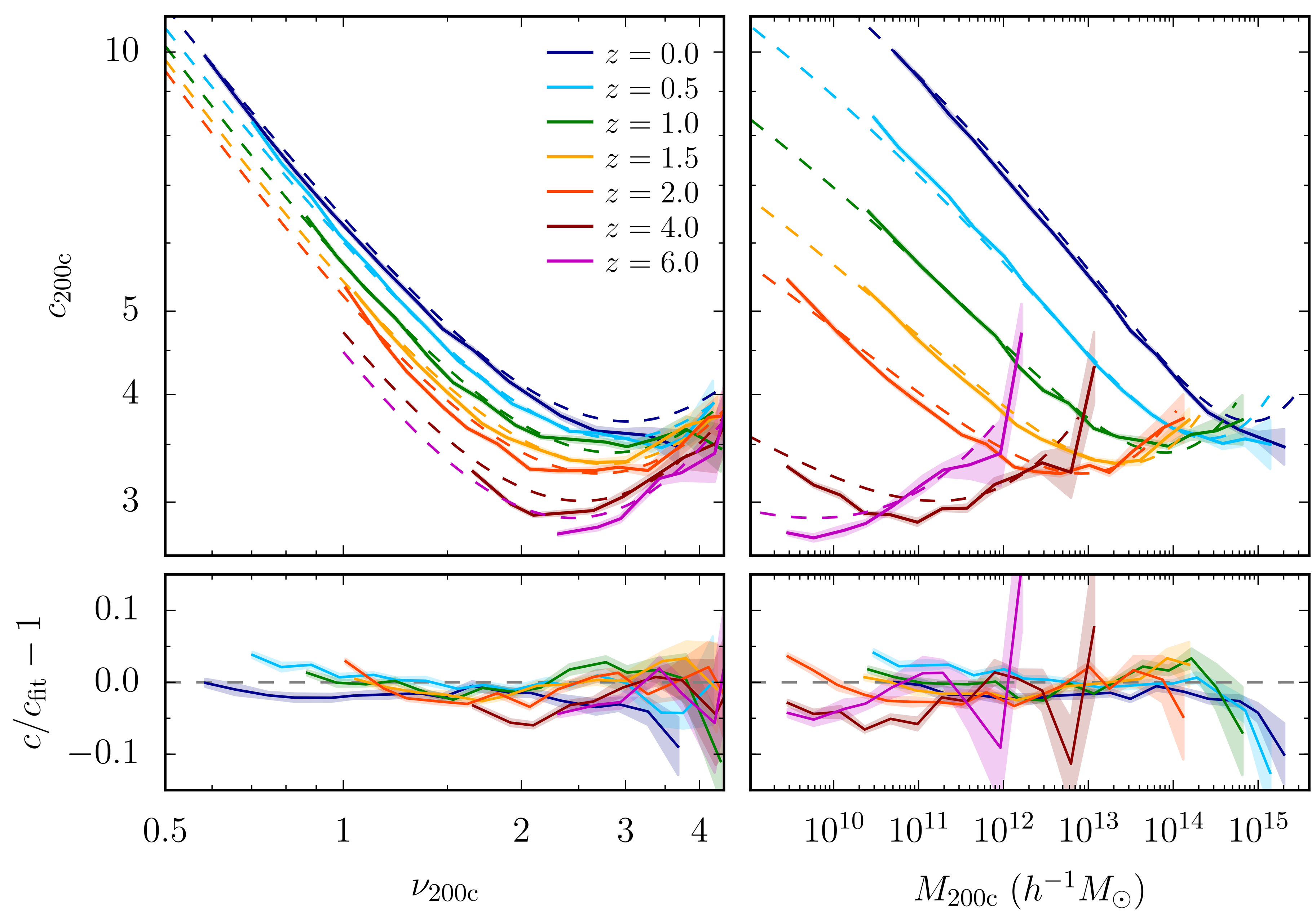
Given the remaining non-universality in the c-ν relation, we are looking for a second parameter besides ν that affects concentration. When comparing the c-ν relation in two self-similar cosmologies with $\Omega_m=1$ and power-law spectra with slopes $n=-2$ and $n=-2.5$ (maroon and pink lines in the top right figure).

Clearly, n has a large impact on c at fixed ν. The ΛCDM relations lie in between the $n=-2$ and $n=-2.5$ curves, 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 of only peak height and the power spectrum slope.

A universal model

We fit our simulation results with a function $c_{200c}(\nu,n)$, namely a double power law whose normalization and location of the minimum vary with n. With only seven free parameters, this model fits ΛCDM concentrations to about 5% accuracy from $z=0$ to $z=6$ (figure below; the solid lines show simulation results, the dashed lines our model). We provide the python code colossus to evaluate our model for arbitrary cosmology, halo mass, redshift, and mass definition.

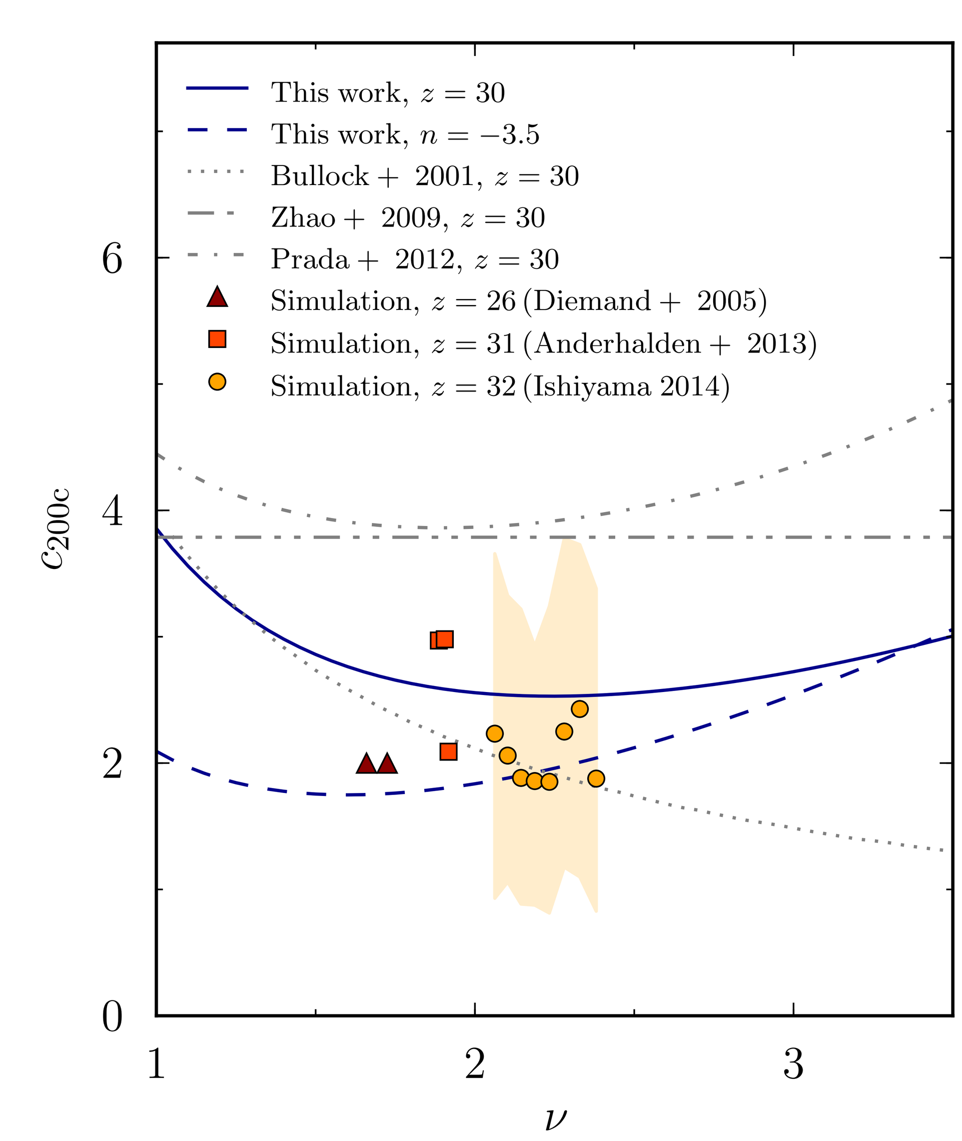




Model predictions at high masses and redshifts

Our model makes some noteworthy predictions. First, c increases at large peak heights (see also Prada et al. 2012). This upturn is due to unrelaxed halos (Ludlow et al. 2012), meaning models based on halo samples where unrelaxed halos were excluded do not show this upturn (e.g., Correa et al. 2015).

Second, out model predicts that concentration decreases for very steep power spectra, without a particular floor value. This prediction can be tested in Earth-mass halos at $z\sim30$ (blue lines in the figure to the right). Such halos have been shown to have extremely low concentration, in agreement with our model.



THE UNIVERSITY OF CHICAGO
Harvard-Smithsonian Center for Astrophysics
KICP Kavli Institute for Cosmological Physics at The University of Chicago
THE KAVLI FOUNDATION

1) ITC Fellow, Harvard-Smithsonian Center for Astrophysics; benedikt.diemer@cfa.harvard.edu
2) Department of Astronomy and Astrophysics, The University of Chicago
3) Kavli Institute for Cosmological Physics
4) Enrico Fermi Institute, The University of Chicago

References

- Correa et al. 2015, MNRAS 452, 1217
- Diemer & Kravtsov 2015, ApJ 799, 108
- Ludlow et al. 2012, MNRAS 427, 1322
- Prada et al. 2012, MNRAS 423, 3018
- Zhao et al. 2003, MNRAS 339, 12