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Simulating the dark side of the Universe

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Introduction

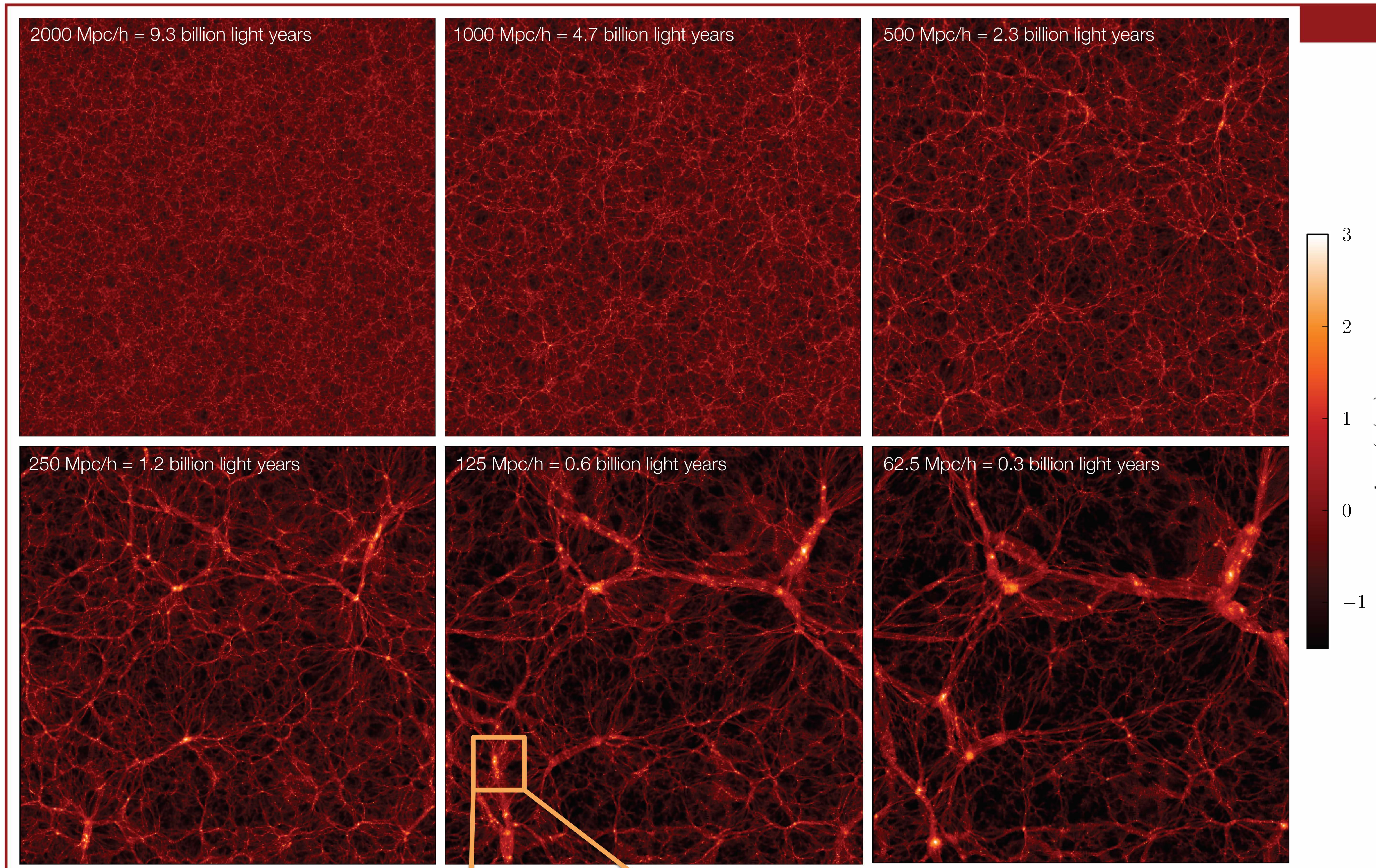
About 80% of the matter in the universe consists of one or many particles that remain to be identified, so-called **dark matter**. Its existence can only be inferred from its gravitational effects, but we believe that it interacts weakly, or not at all, with itself and with "normal" matter, and only feels the force of gravity. Thus, we can model the dark matter as a large collection of virtual particles in a box that contains a representative part of the Universe.

The initial distribution of the matter, relatively soon after the big bang, was almost uniform, but with slight ripples which are related to the ripples we observe in the cosmic microwave background. Gravity then makes the initial ripples collapse into a pattern called the **cosmic web**. At the intersection of filaments, the dark maffer forms dense objects called **halos** which are of great importance because they host **galaxies** such as our own Milky Way. In fact, our dark matter halo is much more extended than the stars in our galaxy itself.

We run large simulations to connect the evolution and shape of halos to their cosmic environment. In particular, we focus on halo density profiles, and devise meaningful, physical models to describe them.

References

- Diemer & Kravtsov, *Dependence of the outer density profiles of halos on their mass accretion rate*, 2014, arXiv:1401:1216
- Diemer & Kravtsov, *A universal model for halo concentrations*, 2014, arXiv:1407.4730



N-body simulations

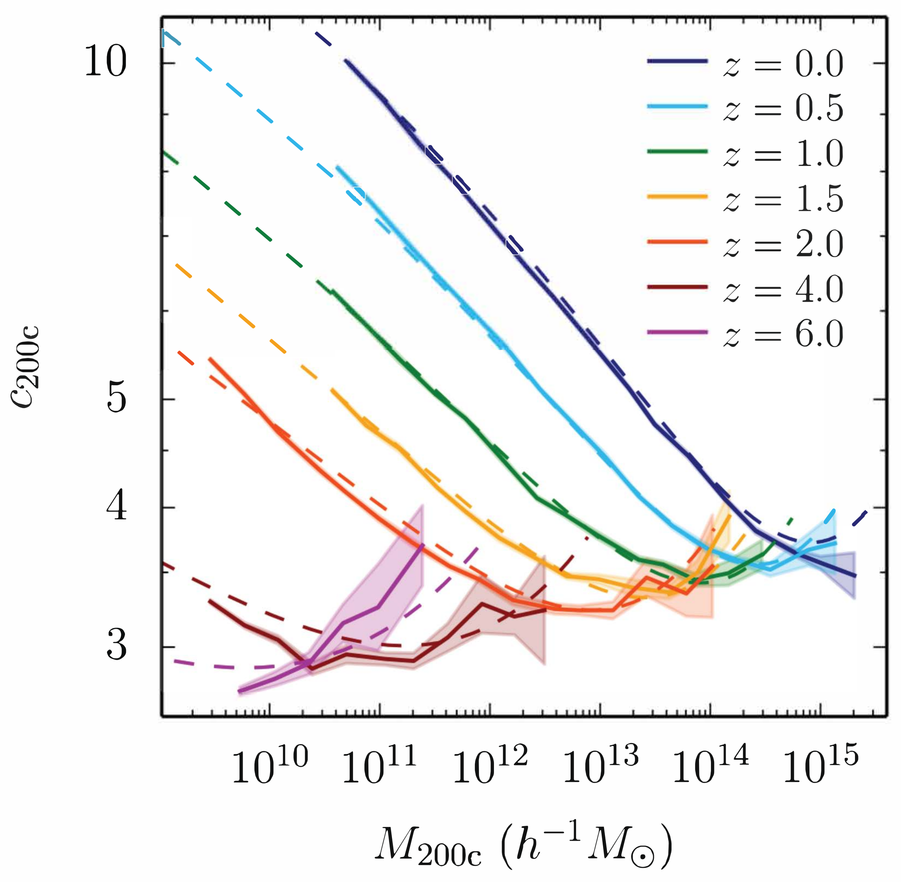
The images show the **density of dark matter** in our simulated universes at the **current time**. The density is expressed in units of the average density of the universe, meaning the brightest spots are 1000 times denser than the average, and the darkest spots about 5% of the average.

Each image corresponds to a box of different size. On large scales, the universe is almost uniform (top left), but when we "zoom in", we discover more and more structure. The structures in the small boxes look similar because the same random seeds were used for each box, but they have vastly different sizes.

Even in the smallest box (bottom right), the Milky Way galaxy would be smaller than a single pixel.

Each simulation contains 1 billion dark matter particles, meaning that storing a single snapshot demands 30GB of disk space, or 3TB for the 100 snapshots we stored for each run. All our simulations were run on 32 to 64 nodes of the RCC Midway cluster, and consumed about one million CPU hours in total.

Halo concentration

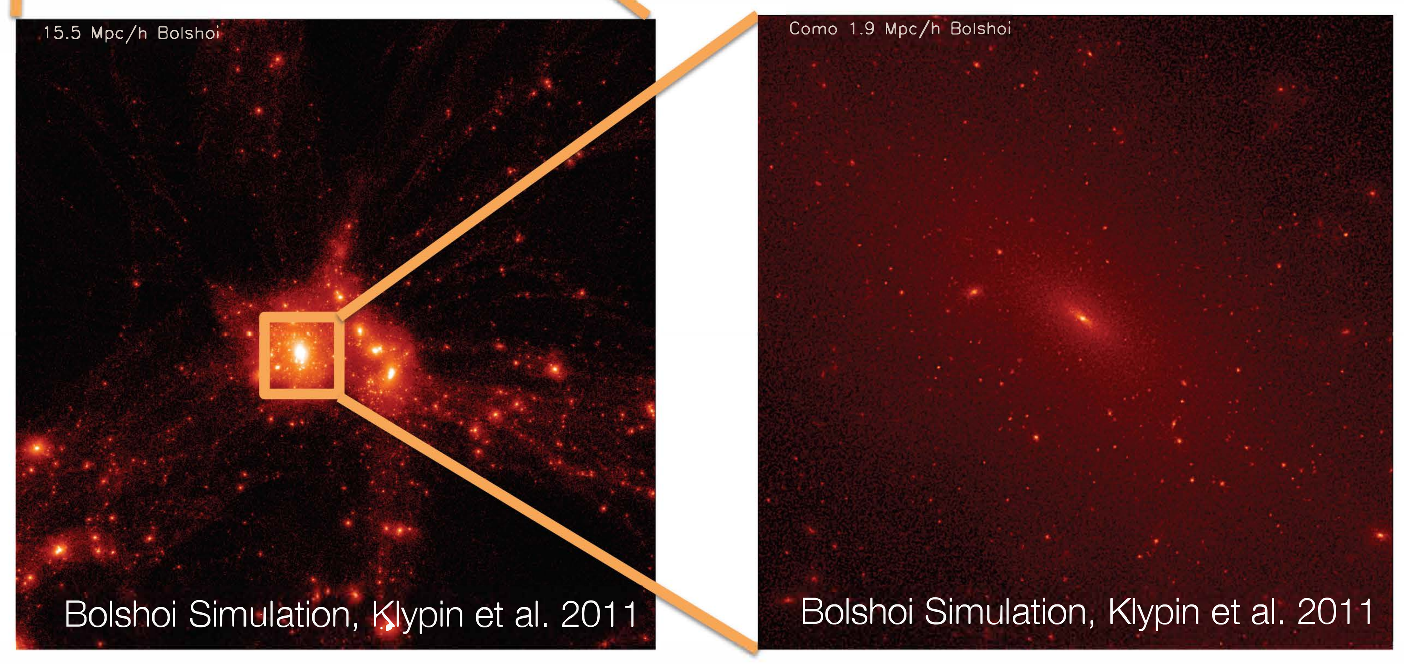


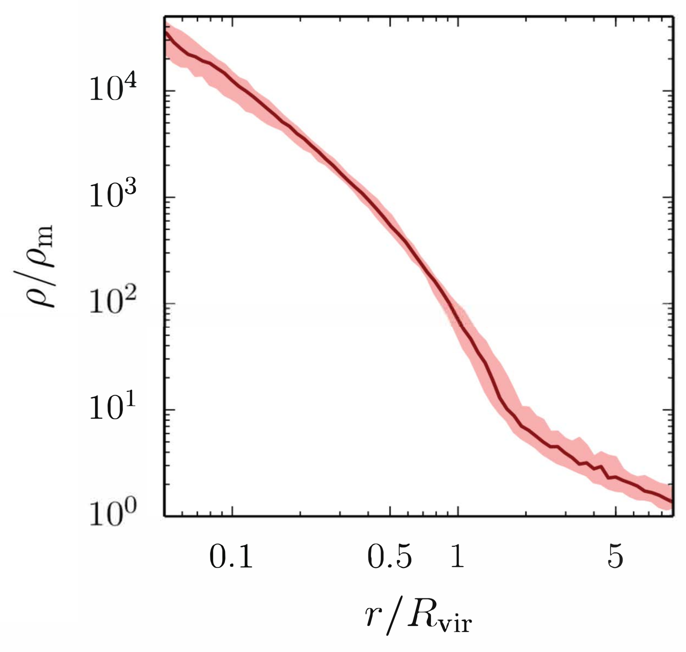
A very important characteristic of dark matter halos is how centrally concentrated they are. This concentration parameter is increasingly being measured in observations, and it is critical to have an accurate theoretical description for halo concentrations.

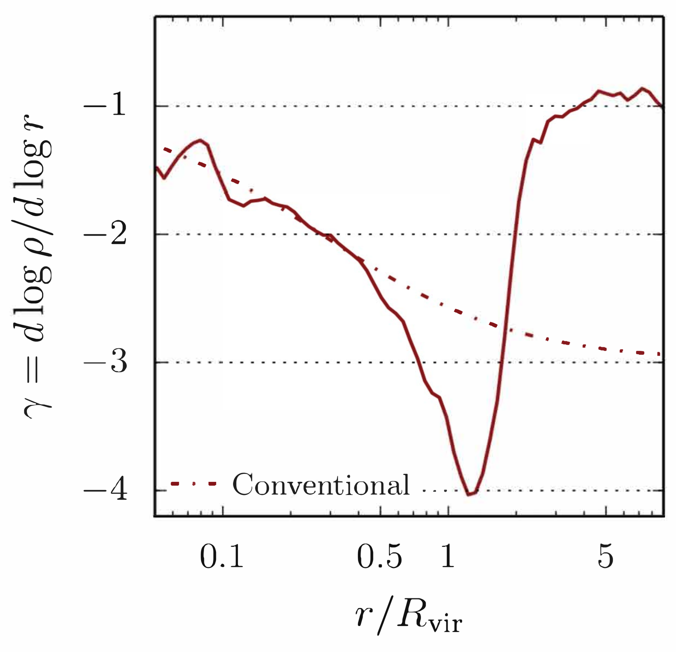
However, concentration depends on halo mass and time in a complicated way as shown on the left; the colors indicate different cosmic times.

We have proposed a new model for this relation, plotted with dashed lines. This model represents one of the most general and accurate predictions of simulated concentrations to date.

The density profiles of dark matter halos







The images above show the dark matter density in a large cluster of galaxies (left) and in the central halo in a cluster (right). The images are not actual zooms of the larger images, but illustrate the size scales. The plots on the right show the average density profile of very large halos, and its slope. We show that the profile of halos depends on the rate at which they accrete new matter. The faster they grow, the steeper the profile. This dependence was not captured by the conventionally assumed profile (dot-dashed line). The steepest point in the profiles represents a natural edge of the halo, in contrast to the classical wisdom that halos have no well-defined outer boundary.