CAUSTIC RINGS AND COLD DARK MATTER

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The hierarchical cold dark matter (CDM) model for structure formation is a well defined and testable model. Direct detection is the best technique for confirming the model yet predictions for the energy and density distribution of particles on earth remain inadequate. Axially symmetric collapse of collisionless dark matter can leave observable caustic rings in phase space and this model is frequently used to make experimental predictions (Sikivie 1999). Such cold collapses inevitably suffer from radial orbit instabilities that produce unrealistic bar-like halos. Moreover, this model bears no relation to the hierarchical growth of CDM galactic halos which form via a complicated sequence of mergers and violent relaxation. This process destroys any symmetry and phase wraps existing caustics on a scale comparable to the first objects to collapse. Since axions can cluster on microscopic scales and free streaming of neutralinos only erases structure smaller than $\sim 100(GeV/m_{CDM})$ A.U., the dynamical effects of caustics in the Galactic halo are expected to be negligible.

1 Introduction

Revealing the nature of dark matter is fundamental to cosmology and particle physics. A combination of observations and theory suggests that the dark matter consists of non-baryonic particles, and in this large class of hierarchical cosmogonic models a universe dominated by cold dark matter (CDM) remains plausible albeit with some potential problems on small scales.

The only convincing method for confirming the existence of non-baryonic dark matter is by direct detection. Many such experiments are in progress and are beginning to probe the parameter space allowed by cosmological and particle physics constraints (e.g. DAMA, CDMS). Direct and indirect detection experiments are highly sensitive to the local density of particles and their velocity distribution. For example, the flux of gamma-rays on Earth from neutralino annihilations in the galactic halo depends on the amount of substructure in the dark matter (e.g. Bergstrom etal 1999). It is therefore crucial to understand the phase space structure of galactic halos in hierarchical models in order that experiments can be fine tuned to search for the appropriate signals, and that event rates or modulation effects can be correctly interpreted (Ullio etal 2000).

Many of the ongoing dark matter searches adopt the principle that CDM particles passing through the solar system have a smooth continuous density distribution with isotropic Maxwellian velocities. Other halos models have been studied e.g. Sikivie (1992, 1999), who assume axially symmetric and cold collapse of matter to infer the presence of caustic rings in the solar neighbourhood. We can now use the results of high resolution computer simulations of structure formation within a CDM universe to examine these assumptions more carefully.

2 Collisionless dark matter halos

2.1 Axially symmetric cold collapse

Caustics are singularities in phase space (e.g. Hogan 1999). For example, it may be possible to observe a radial caustic in the galaxy distribution surrounding clusters as material on the turnaround shell is projected onto the zero velocity surface. Physical singularities in density can occur, for example as shells of material turnaround during the collapse of a dark matter halo. Spherical symmetry gives rise to shells and a singularity at the halo center whereas axial symmetry produces a sequence of caustic rings.

Under certain conditions dynamically significant caustics are a theoretical possibility. Sikivie has calculated the radial positions and structure of caustic rings that occur during cold and axially symmetric collapse. Predictions from this model are often used to calculate rates for direct and indirect detection experiments therefore its assumptions should be critically examined.

Cold initial conditions are essential for the formation of narrow caustics otherwise they will be smeared out over a radial scalelength $\approx R_{200}\sigma_{infall}/\sigma_{halo}$. Here R_{200} is the virialised extent of the halo and σ_{infall} is the velocity dispersion of infalling material. In order to achieve a significant density enhancement, the infalling shells must have a velocity dispersion $< 10\%$ of the velocity dispersion of the final halo. Unfortunately such a cold collapse is globally unstable to the radial orbit instability (Aguilar and Merritt 1990). This is demonstrated in Figure 1 which shows the gravitational collapse of 10^7 particles with initial velocity dispersion 10% of the final velocity dispersion. As the central region virialises the bar instability creates a prolate mass distribution with an axial ratio larger than 2:1. This is incompatible with observational constraints on halo shapes.

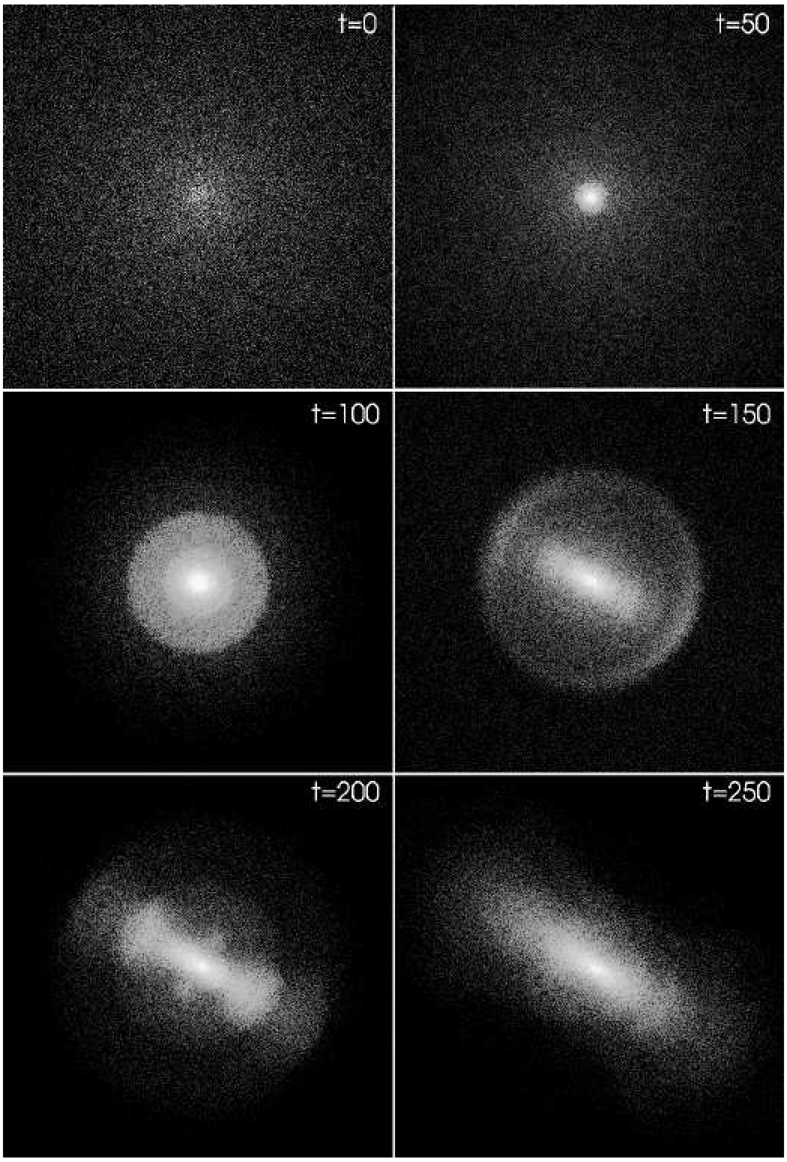

Figure 1. The collapse of a cold, collisionless sphere. The final structure is a highly flattened prolate system that results from a radial orbit instability.

2.2 Hierarchical growth

CDM halos form via a series of many mergers and accretions of dark matter clumps along highly filamentary mass distributions. The assumptions of symmetry and locally cold flows is an incorrect over-simplification of the true hierarchical growth.

At a given point in a CDM halo, the "smooth" dark matter background arises from material that has been tidally stripped from less massive halos. The infalling background of CDM is a hierarchy of tiny halos that are unresolved in current numerical simulations. Globally, the fraction of CDM in bound objects is expected to be 100%, whereas current simulations that can resolve just one level of the hierarchy find a value of $\sim 50\%$.

If the power spectrum was cutoff on small scales, e.g. warm or hot dark matter, then locally cold material would fall onto halos giving rise to caustic structures. These features would be phase wrapped only a few times and it is possible that they have observable consequences. The power spectrum of fluctuations in the CDM model allows small dense dark matter halos to collapse at very early epochs – the cutoff scale from the free streaming of neutralinos is approximately $10^{-12}M_{\odot}$. The first halos to collapse will have prominent caustics although on a tiny scale compared to the solar system. Infalling material will be scattered by various processes such as tidal fields and halo-halo encounters which smear out the caustic sheets of CDM mini-halos (e.g. Tremaine 1999, Helmi and White 1999).

We have used numerical simulations to investigate the structure of dark matter halos across a range of mass scales from $10^7M_{\odot}$ to $10^{15}M_{\odot}$. Rather than run many simulations at low resolution we have simulated several at very high resolution. One of the key results that we find is that substructure within hierarchical models is essentially scale free. The distribution and orbital properties of "halos-within-halos" is independent of halo mass – CDM galaxy halos contain literally thousands of halos more massive than those that surround the dwarf satellite galaxies in our own halo, Draco and Ursa-Minor.

Figure 2 shows the formation of a single CDM halo resolved with 10^6 particles and force resolution $< 0.001R_{200}$. The substructure visible within the CDM halo in Figure 2 is nearly self-similar. If we could zoom into a single subhalo it would appear like a scaled version of the entire system.

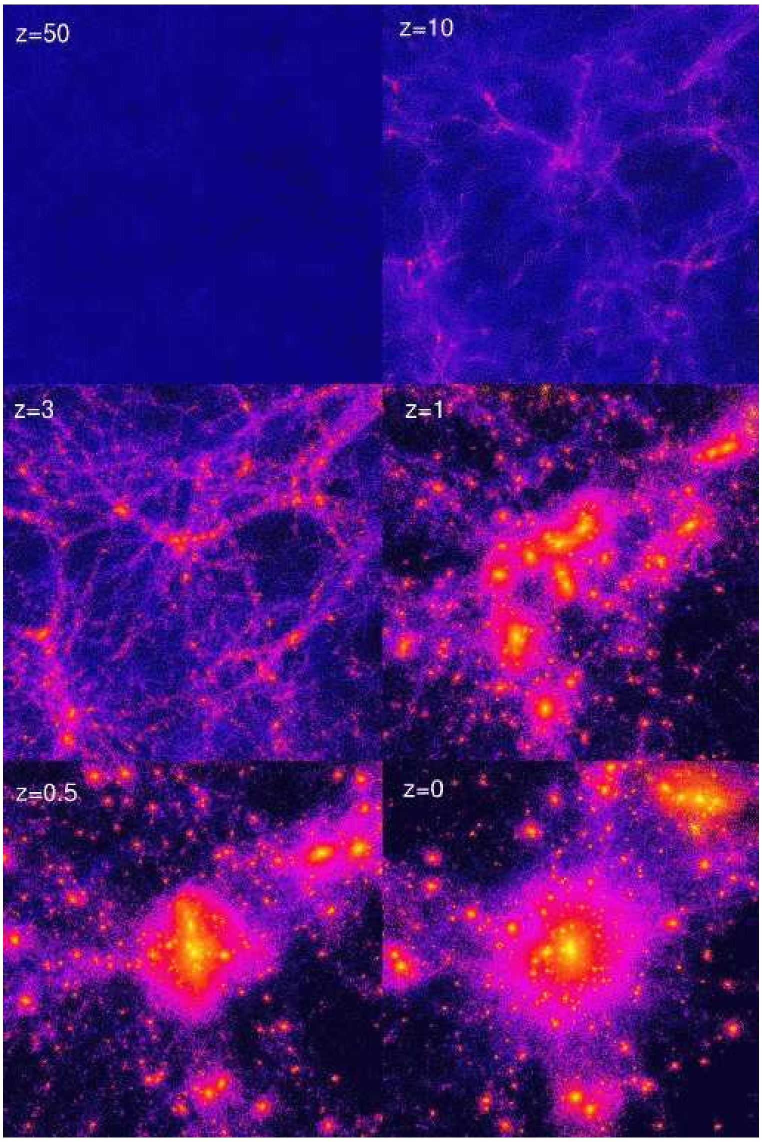

Figure 2. The hierarchical collapse of a CDM halo. The grey scale shows the local density of dark matter at the indicated redshifts. The size of each panel is 4 comoving Mpc for H=50 km/s/Mpc.

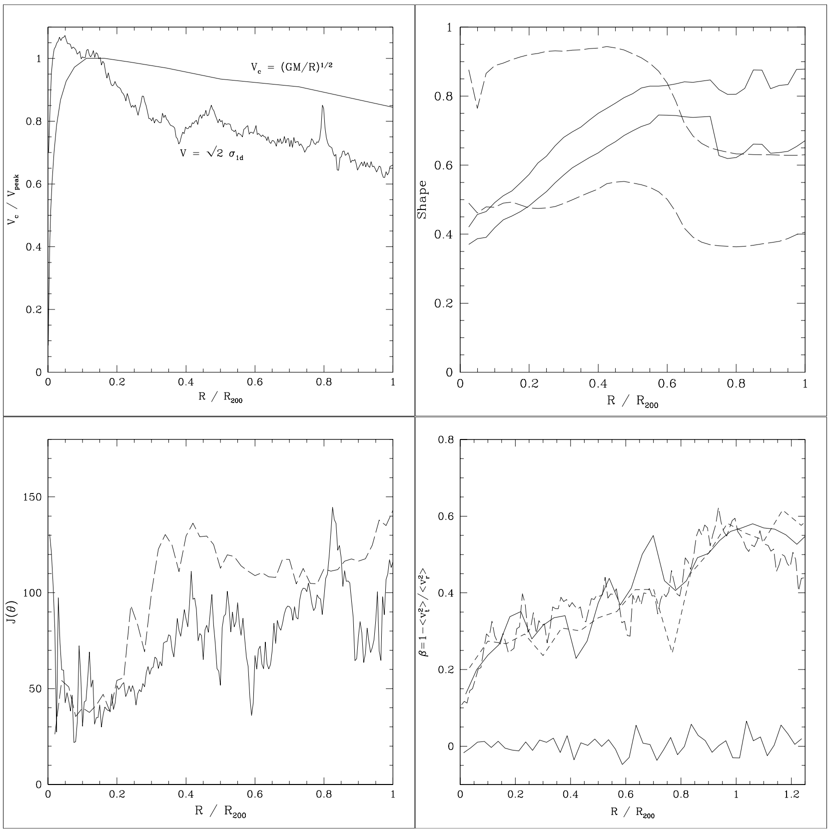

Figure 3. From top left to bottom right we plot the spherically averaged rotation curve and and 1d velocity dispersion profile of a CDM halo, the short to long axis ratios of two CDM halos, the angular momentum vector of these two halos and the anisotropy parameter within a single halo simulated at different resolutions. From these plots it is clear that the global properties of halos are complex and axial symmetry is not preserved.

Finally, we show the structure in velocity space as a function of location within a CDM halo. We have taken 3 cubes at different positions in the halo that are smooth in density space. Each cube contains 2000 particles and has no bound subhalos within them as can been seen in the central panels. The left panel shows the histogram of one component of the distribution of particle speeds in each cube – the curve shows a Maxwellian distribution with σ set equal to the spherically averaged value at $0.1R_{200}$. The right panels show the x and y components of velocity plotted against each other. In the outer halo streams of tidally stripped particles have made just one or two complete orbits and they remain very distinct and cold features in velocity space. As one moves from the outer to the inner halo, the streams are significantly more wound up in phase space and the velocity distribution becomes close to a Maxwellian. However this is purely a resolution effect since higher resolution would resolve smaller halos and a network of cold streams at the solar radius.

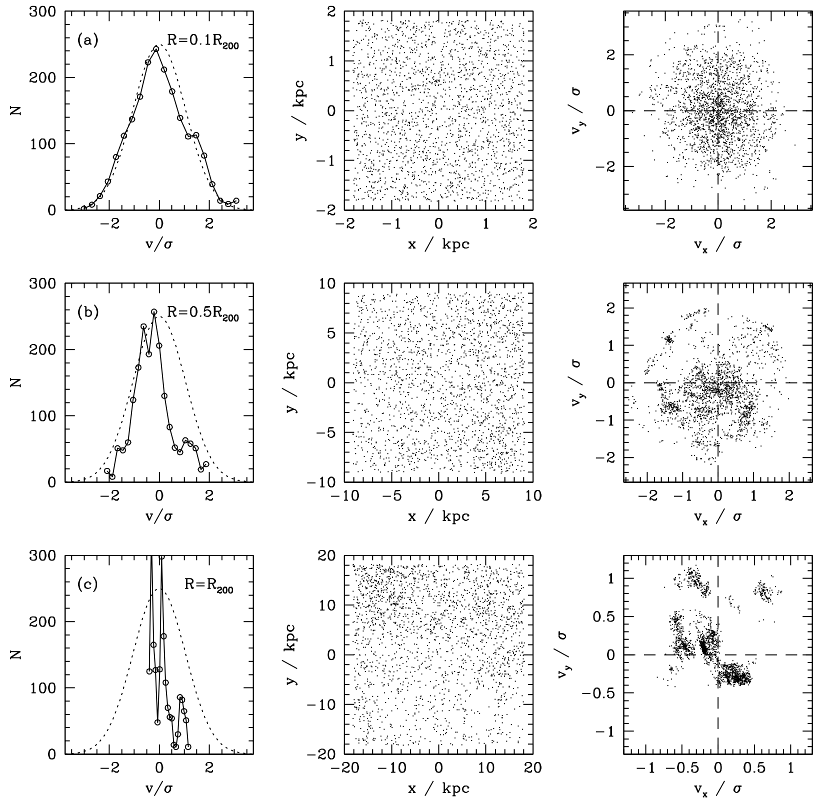

Figure 6. The left panels show velocity histograms of particles extracted from small patches of the halo where the particles are smoothly distributed in density space (center panel) but show complex velocity distributions (right panels).

3 Summary

We have presented preliminary results from simulations of CDM halos that are the highest resolution possible using todays supercomputers. These simulations have just begun to resolve sub-kiloparsec scales, giving rise to several important predictions on the global structure and substructure of collisionless dark matter halos. The steep central cusps and abundant dark matter substructure of CDM halos are fundamental and testable predictions.

The phase space structure of halos resulting from complex merger histories are just begining to be resolved with current simulations. We find that tidally stripped debris leaves characteristic structure in phase space and the velocity distributions depends sensitively on the location of the observer within triaxial CDM halos (Evans etal 2000, Ullio etal 2000). However, a great deal of work remains to determine the rate and energy distribution of CDM particles through a detector $\sim 1m^3$ (Copi & Krauss 2001).

The prominence of caustics depends crucially on the small scale power spectrum. Detectable caustic rings require very special initial conditions that are incompatible with the CDM paradigm – namely axial symmetry and locally cold velocity fields.

Future simulations and analytic work will be able to answer the key questions: Is there a smooth component of dark matter on the scale of the solar system? Is the earth likely to be passing through a single cold tidal stream or the superposition of many such streams?

References

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