The fine-scale structure of dark matter halos

Simon White
Max Planck Institute for Astrophysics

Princeton
December 2009
The dark matter structure of $\Lambda$CDM halos

A rich galaxy cluster halo  
Springel et al 2001

A 'Milky Way' halo  
Power et al 2002
• Halos extend to \(\sim 10\) times the 'visible' radius of galaxies and contain \(\sim 10\) times the mass in the visible regions.

• Halos are not spherical but approximate triaxial ellipsoids -- more prolate than oblate -- axial ratios greater than two are common.

• "Cuspy" density profiles with outwardly increasing slopes
  -- \(\frac{d \ln \rho}{d \ln r} = \gamma\) with \(\gamma < -2.5\) at large \(r\)
  -- \(\gamma > -1.2\) at small \(r\).

• Substantial numbers of self-bound subhalos contain \(\sim 10\%\) of the halo's mass and have \(\frac{d N}{d M} \sim M^{-1.8}\).

  Most substructure mass is in most massive subhalos.
Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below
Halo assembly for neutralino ΛCDM

- Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below
Halo assembly for neutralino ΛCDM

- Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below

- They form at high redshift and thus are dense and resistant to later tidal disruption
Halo assembly for neutralino ΛCDM

- Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below
- They form at high redshift and thus are dense and resistant to later tidal disruption
Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below.

They form at high redshift and thus are dense and resistant to later tidal disruption.

The mass is primarily in small halos at redshifts $z \geq 15$. 
Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below.

They form at high redshift and thus are dense and resistant to later tidal disruption.

The mass is primarily in small halos at redshifts $z \geq 15$. 
Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below.

They form at high redshift and thus are dense and resistant to later tidal disruption.

The mass is primarily in small halos at redshifts $z \geq 15$.

Structure builds up from small (e.g. Earth mass) to large (e.g. Milky Way halo mass) by a sequence of mergers.
Halo assembly for neutralino ΛCDM

- Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below
- They form at high redshift and thus are dense and resistant to later tidal disruption
- The mass is primarily in small halos at redshifts \( z \geq 15 \)
- Structure builds up from small (e.g. Earth mass) to large (e.g. Milky Way halo mass) by a sequence of mergers
Overdensity vs smoothing at a given position

If the density field is smoothed using a sharp filter in $k$-space, then each step in the random walk is independent of all earlier steps.

A Markov process

The walks shown at positions A and B are equally probable.
At an early time $\tau_1$

A is part of a quite massive halo

B is part of a very low mass halo or no halo at all
Overdensity vs smoothing at a given position

Later, at time $\tau_2$
A's halo has grown slightly by accretion
B is now part of a moderately massive halo
Overdensity vs smoothing at a given position

A bit later, time $\tau_3$,
A's halo has grown further by accretion.

B's halo has merged again and is now more massive than A's halo.
Overdensity vs smoothing at a given position

Still later, e.g. $\tau_4$

A and B are part of halos which follow identical merging/accretion histories

On scale X they are embedded in a high density region.

On larger scale Y in a low density region
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25, \Omega_\Lambda = 0.75, n=1, \sigma_8 = 0.9$

Angulo & White 2009

The linear power spectrum in “power per octave” form

Assumes a 100GeV wimp following Green et al (2004)
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2009

Variance of linear density fluctuation within spheres containing mass $M$, extrapolated to $z = 0$

As $M \to 0$, $S(M) \to 720$
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by $\sqrt{720}$, then they represent complete halo assembly histories for random CDM particles.

An ensemble of walks thus represents the probability distribution of assembly histories.
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2009

Distribution of the masses of the first generation halos for a random set of dark matter particles

The median is $10^{-2}$ to $1.0 \ M_\odot$

For 10% of the mass the first halo has $M > 10^7 M_\odot$

Direct simulation will become possible around 2035
EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2009

Collapse redshift distribution of the first generation halos for a random set of dark matter particles

The median is $z = 10$ to 13

For 10% of the mass the first halo collapses at $z > 34$

For 1% at $z > 55$
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo & White 2009

Total mass fraction in halos

At $z = 0$ about 5% (Sph) or 20% (Ell) of the mass is still diffuse

Beyond $z = 50$ almost all the mass is diffuse

Only at $z < 13$ (Sph) or $z < 8$ (Ell) is most of the dark matter in halos
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2009

The typical mass element in a “Milky Way” halo goes through $\sim 5$ “infall events” where its halo falls into a halo bigger than itself.

Typically only one of these is as part of a halo with $M > 10^8 M_\odot$
EPS halo assembly: conclusions

- The typical first generation halo is much more massive than the free-streaming mass limit

- First generation halos typically form quite late $z \lesssim 13$

- Most mass is diffuse (part of no halo) beyond $z = 13$

- Halo growth occurs mainly by accretion of much smaller halos

- There are typically few (~5) “generations” of halos, only 1 or 0 predecessors with $M > 10^8 M_\odot$ for most particles in a “MW” halo

  Low mass “first” halos are little denser, and so not much more resistant to tidal destruction than much more massive early halos
The Aquarius halos

Springel et al 2008
"Milky Way" halo

$z = 1.5$

$N_{200} = 3 \times 10^6$
“Milky Way” halo

$z = 1.5$

$N_{200} = 94 \times 10^6$
"Milky Way" halo

$z = 1.5$

$N_{200} = 750 \times 10^6$
How well do density profiles converge?

Aquarius Project: Springel et al. 2008
How well do density profiles converge?

Aquarius Project: Springel et al 2008

Graph showing the convergence of density profiles for different samples labeled as Aq-A-1 to Aq-A-5 at z = 0.0.
How well does substructure converge?

Springel et al 2008
How uniform are subhalo populations?

For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass.

The Via Lactea simulations differ significantly, at least VL-I.
Scatter in the number of subhalos with $M_{\text{sub}} > \mu M_{\text{halo}}$ is Poisson for $\mu > 0.005$ but is $\sim 18\%$ for $\mu < 0.001$. 

Statistics of Milky Way-mass halos

Boylan-Kolchin et al 2009
All mass subhalos are similarly distributed.

A small fraction of the inner mass in subhalos.

<<1% of the mass near the Sun is in subhalos.
Substructure: conclusions

- Substructure is primarily in the outermost parts of halos.
- The radial distribution of subhalos is almost mass-independent.
- Subhalo populations scale (almost) with the mass of the host.
- The total mass in subhalos converges only weakly at small masses.
- Subhalos contain a very small mass fraction in the inner halo.
Maybe Dark Matter can be detected in a laboratory

Xenon Dark Matter detection experiment at Gran Sasso

External view of Gran Sasso Laboratory
Local density in the inner halo compared to a smooth ellipsoidal model

- Estimate a density $\rho$ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The $rms$ scatter about the smooth model for the remaining points is only about 4%

Vogelsberger et al 2008
Local velocity distribution

- Velocity histograms for particles in a typical \((2\text{kpc})^3\) box at \(R = 8 \text{kpc}\)
- Distributions are smooth, near-Gaussian and different in different directions
- No individual streams are visible
Energy space features – fossils of formation

The energy distribution within (2 kpc)$^3$ boxes shows bumps which

-- repeat from box to box

-- are stable over Gyr timescales

-- repeat in simulations of the same object at varying resolution

-- are different in simulations of different objects

These are potentially observable fossils of the formation process
Conclusions for direct detection experiments

- With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by < 20%

- The local velocity distribution of DM particles is similar to a trivariate Gaussian with no measurable “lumpiness” due to individual DM streams

- The energy distribution of DM particles should contain broad features with ~20% amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

Dark matter astronomy
Maybe the annihilation of Dark Matter will be seen by Fermi?
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008

$M < < r > > M_{200}$, $L(<r) / L_{200}$, $L_{\text{sub}}(<r) / L_{200}$

$r$ [kpc]

$> 10^5 M_\odot$

$> 10^8 M_\odot$

main halo L

main halo M

satellite L
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008
Milky Way halo seen in DM annihilation radiation
Milky Way halo seen in DM annihilation radiation

emission from resolved subhalos (SubSm+SubSub)
Milky Way halo seen in DM annihilation radiation

unresolved subhalo emission (MainUn)

-0.50 \leq \text{Log(Intensity)} \leq 2.0
Milky Way halo seen in DM annihilation radiation
Conclusions about clumping and annihilation

- Subhalos increase the MW's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun.

- The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~1.5).

- Individual subhalos have lower S/N for detection than the main halo.

- The highest S/N known subhalo should be the LMC, but smaller subhalos without stars are likely to have higher S/N.
Caustics in self-similar spherical halo growth

Bertschinger 1985

Graphs showing:
- Comoving radius vs. time for a single shell
- Velocity vs. position at a given time
- Mass vs. radius
- Radial density profile
Simulation from self-similar spherical initial conditions

Vogelsberger et al 2009

The radial orbit instability leads to a system which is strongly prolate in the inner nonlinear regions.
Simulation from self-similar spherical initial conditions

Geodesic deviation equation \rightarrow phase-space structure local to each particle

Vogelsberger et al 2009

Number of caustic passages
Simulation from self-similar spherical initial conditions

Radial density profile

Vogelsberger et al 2009

Median density of streams associated with individual particles
Simulation from self-similar spherical initial conditions

Vogelsberger et al 2009

Maximum density at caustic passage assuming a standard neutralino WIMP with a mass of 100 GeV

Median and quartiles plotted at each radius for the simulation

Except for the outermost caustic the maximum density at caustic passage is lower in 3d than in the similarity solution
Caustic crossing counts in a ΛCDM Milky Way halo

Vogelsberger & White 2010
Caustic crossing counts in a $\Lambda$CDM Milky Way halo

Vogelsberger & White 2010
Conclusions about caustics and annihilation

- Caustics are less significant in realistic three-dimensional situations than in one-dimensional similarity solutions.

- Particles in the inner regions of halos (e.g. $r \sim 10\text{kpc}$ in the MW) have typically passed through several hundred caustics with low stream densities and weak caustics.

- The annihilation luminosity from caustics is a small fraction of the total (e.g. $\sim 4\%$ of that beyond $10\text{kpc}$ for a MW model).

- If annihilation radiation is detected from external galaxies (e.g. M31) only the outermost caustic is likely to be visible.
Myths about small-scale structure and DM detection

- Halo DM is mostly in small (e.g. Earth mass?) clumps → direct detectors typically live in low density regions

- DM streams → non-Maxwellian, “clumpy” $f(v)$ → direct detectors will see an irregular velocity distribution

- Small (Earth-mass?) clumps dominate observable annihilation signal

- Dwarf Spheroidals/subhalos are best targets for detecting annihilation (and are boosted by sub-substructure)

- Smooth halo annihilation emission is dominated by caustics
Myths about small-scale structure and DM detection

- Halo DM is mostly in small (e.g. Earth mass?) clumps. Direct detectors typically live in low density regions.
- DM streams are non-Maxwellian, “clumpy” $f(v)$. Direct detectors will see an irregular velocity distribution.
- Small (Earth-mass?) clumps dominate observable annihilation signal.
- Dwarf Spheroidals/subhalos are best targets for detecting annihilation (and are boosted by sub-substructure).
- Smooth halo annihilation emission is dominated by caustics.
EPS statistics for the standard $\Lambda$CDM cosmology

Millennium Simulation cosmology: \[ \Omega_m = 0.25, \quad \Omega_\Lambda = 0.75, \quad n = 1, \quad \sigma_8 = 0.9 \]

Angulo et al 2009

The typical mass element in a “Milky Way” halo goes through 3.5 “major mergers” where the two halos are within a factor of 3 in mass.

The majority of these occur when the element is part of the larger halo.