Substructure

- The best evidence for a hierarchical structure formation
- The distribution and properties of substructure contains information about the entire hierarchy and history of merging galaxies
- This includes information about the properties and nature of dark matter
- Substructures in large halos is likely the host for galaxies

Substructure studies only a decade old

first serious substructure studies in 1998:
resolving substructure in simulations

self-similar substructure

substructure identification

- new generation of halo finders: BDM (like SO with substructure), subfind (a hierarchical fof), Denmax, etc.
- typically, find all density peaks, use velocity information to remove unbound particles. halo properites only use bound particles.
- virial radius (and mass) are not meaningful, because the structures don’t extend that far out. maximum circular velocity is often used as a mass proxy.

Formation of a galaxy-sized halo in LCDM, \( M_{\text{vir}} = 3 \times 10^{12} \hbar^{-1} \text{Msun} \); \( R_{\text{vir}} = 293 \hbar^{-1} \text{kpc} \).

Abundance of subhalos in a given halo

is determined by competition between accretion of new subhalos and disruption of old subhalos

disruption = loss of identity via merging with other halos or significant mass loss due to tidal stripping
CDM halos typically contain $f_{\text{SUB}} \approx 2-15\%$ of their masses bound up in subhalos.

The multiplicity of subhalos scales roughly as $dn/dm \sim m^{-\alpha}$ with $\alpha \approx 1.7 - 1.95$.

$N(m) \sim m^{-0.7 - 0.95}$.

Biggest subhalos are typically a few percent of the host mass.

The multiplicity of subhalos scales roughly as $dn/dV_{\text{MAX}} \sim V_{\text{MAX}}^{-\beta}$ with $\beta \approx 3.7$.

$N(V_{\text{MAX}}) \sim V_{\text{MAX}}^{-2.7}$.

Biggest subhalos have typically $V_{\text{SAT}}/V_{\text{HOST}} \approx 1/4$.

Small deviation from self-similar scaling (Zentner, et al. 2005)

Fraction of halos of a given mass that are substructure. For galaxy size halos, 15-25% at all z.

Krautso, Berlind, Wechsler et al 2004
the subhalo mass function is sensitive to formation time; especially its accretion history in the last Gyr.

average SHMF is a one parameter family which depends on M/M*

the mass fraction of subs with m/M > 10^-4

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formation of the smallest structures

one of the first objects to form, at z~60.

smooth halo with a cuspy density profile.

earth mass 10^8-6, size of the solar system.

10^15 of these inside the galactic halo

the same MW-sized halo viewed

substructure aligns with major axis

substructure aligns with major axis

Halo Substructure has anisotropic distribution

Zentner et al. 2005; Liebeskind et al. 2005

The same MW-sized halo viewed

substructure aligns with major axis

substructure aligns with major axis
Compared to the dark matter, subhalos are distributed preferentially at large halo-centric radii. e.g., Colin et al. 2000; Kravtsov et al. 2004; Zentner et al. 2005; Diemand et al. 2005 …

The radial distribution of subhalos depends on how subhalos are selected. Nagai & Kravtsov 2005

What processes affect substructure?

- Orbit decays by dynamical friction: central merger.
- Tidal forces act to disrupt the accreted halo.

Galaxies can lose orbital energy due to a gravitational drag force:

\[
F_{DF} = \frac{4\pi \ln(\Lambda) G^2 M_{\text{sat}}^2 \rho(r)}{V_{\text{orb}}^2} \left[ \text{erf}(x) - \frac{2X}{\sqrt{\pi}} \exp(-X^2) \right]
\]

Chandrasekar 1943
**Tidal stripping of subhalos: three examples**

Kravtsov, Gnedin & Klypin 2004

- **Tidal Force**
- **Vmax** and grav. bound mass
- **Distance to the host**

\[
V_m = \text{max of } \text{circ velocity curve} = (GM(<r)/r)^{1/2}
\]

**can do this analytically**

**calculate Orbits & Mass Loss in the Host Potential**

**Simple Example Orbits:**

- Massive Subhalos & Subhalos on Low Angular Momentum Orbits Lose Mass Quickly
  - e.g. Zentner et al. 2005; Taylor & Navarro

**present day subhalo mass and Vmax are affected by tidal stripping**

and average effect depends on radius

this introduces a bias in spatial and velocity distributions of subhalos selected using current mass or Vmax

[Nagai & Kravtsov 2005]
analytic model can reproduce this: can use to study other models and to push resolution.

Shift in the balance of power: Accretion vs. destruction

Typical Merger & Mass loss timescales are
\[ t_{\text{dyn}} \sim (3-4 \text{ Gyr})/(1+z)^{3/2} \]


The MW has 11 luminous satellites within what is thought to be roughly its virial radius (~300 kpc/\( h \)) and Andromeda has 13.

Simulations show ~200 dark matter subhalos with similar velocity structures around MW-size halo.
the substructure problem

- hide it (halos, but no galaxies)
- destroy it (SIDM)
- never make it in the first place (WDM)

The amount of primordial power on scales relevant for galaxy formation is not well constrained ($< Mpc$ and scale-invariance is almost always assumed)

Suppression of small-scale power from dark matter produced through decays (Feng et al. 2003; Cembranos et al. 2005).

Suppression of small-scale power via models of non-thermal, sterile neutrino dark matter (Abazajian 2005; Asaka et al. 2005).

Warm Dark Matter has two effects:

Suppression of Linear Power Spectrum due to free-streaming on scales with $k_{F S} \propto (m/keV)^{-4/3}$

High densities limited by finite "Phase-Packing" because initial phase-space density is relatively low, $Q = \rho/(\sqrt{\pi}) \propto 10^{-24} (\text{M}_\odot/\text{pc}^3/\text{km}^3/\text{s}^3) \propto 10^{-4} Q_X$

- The amount of primordial power on scales relevant for galaxy formation is not well constrained $\lambda < \text{Mpc}$ and scale-invariance is almost always assumed.

fraction of mass in substructure depends on DM properties.

- Bullock, Kravtsov & Weinberg 2000
- Somerville 2002

number of surviving subhalos depends on tidal disruption & dynamical friction, number which are visible galaxies depends on redshift of reionization

- Bullock, Kravtsov & Weinberg 2000
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Example Cumulative Velocity Functions

- WMAP-like
  - $n = 0.84$
- TILT
  - $n = 0.95$
- Almost WDM-like P(k) but no primordial velocities

see also Kazantzidis et al. 2004; Wilkinson et al. 2004; Lokas et al. 2005
what is $v_{\text{max}}$ for subhalos?
very hard to tell.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{halo_distribution.png}
\caption{Two halos that may (approximately) host Carina based on $v_{\text{LOS}}$.}
\end{figure}


the KGK solution: all of the surviving satellites were once substantially larger, all small halos have been suppressed.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{halo_vmax.png}
\caption{Number of Satellite vs. $V_{\text{max}}$.}
\end{figure}


lensing

level of anomalies will scale with amount of substructure.

Dalal & Kochanek:

$0.006 < f_{\text{sat}} < 0.07$
(even more than sims!)

lots of technical issues
(including both in the lens modeling and in the substructure modeling)

In the absence of substructure, a close pair of images like A&B in the diagram should be equally bright (Mao & Schneider 1998).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{lensing.png}
\caption{In the absence of substructure, a close pair of images like A&B in the diagram should be equally bright (Mao & Schneider 1998).}
\end{figure}

tidal streams in M31

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{tidal_streams.png}
\caption{Tidal streams in M31}
\end{figure}

Marlow et al. 1999

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Substructure Summary

- Substructures are ubiquitous in CDM.
- Simulations have now characterized the properties of substructures fairly well.
- Mass function of substructure is roughly self-similar.
- The number of substructures is a trade-off between accretion (the halo merging rate) and destruction (dynamical friction; tidal stripping).
- Abundance & properties may constrain small scale power spectrum (inflation; DM physics), but much work is still needed.
- Lensing & stellar structure may be ways of probing dark and disrupted substructures.