Dark Matter Substructure and The Clustering Crisis

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Either of these methods can be applied analytically, using the halo model, or numerically, by directly populating halos and subhalos in numerical simulations.

Latter is generally considered more accurate, more flexible, and with the development of **Halotools™**, almost as fast as the analytical method. see Hearin+16
SHAM spin-off: Empirical Modeling

Apply SHAM at different redshifts, using $\Phi(M_\star, z)$
Combine with halo merger trees $\Rightarrow$ SFR($M_\star, z$)

Yang+09; Conroy & Wechsler 09; Moster+10; Yang+12; Behroozi+13a,b; Moster+13; Wang+13; Bethermin+13; Lu+14

Behroozi et al., 2013

Yang, Mo, vdB et al. 2012
Moster+13, Behroozi+13 and Yang+12, which all fit $\Phi(M^*,z)$, underpredict clustering on small scales, especially at low stellar mass...

- Same holds for standard SHAM based on $M_{\text{peak}}$
- $V_{\text{peak}}$ based SHAM nicely fits clustering data (see also Reddick+13)
The Clustering Crisis

- $V_{\text{peak}}$ SHAM implicitly assumes NO evolution in the $V_{\text{peak}}(M^*)$ relation with redshift (i.e., no $z_{\text{peak}}$ dependence).

- Using average $V_{\text{max}}(z)$ histories of vdBosch+14, we can infer the average stellar mass growth histories implied.

- These are very different from those implied by Moster+13, Behroozi+13, or Yang+12, and are thus inconsistent with $\Phi(M^*,z)$

Models that fit the clustering don’t fit the evolution in the stellar mass function, and vice versa
The Clustering Crisis

Problem is with satellites. Either models need more sub-halos (orphans) or satellites need to be more massive...

Solutions to the Clustering Crisis

- Satellite galaxies continue to grow in stellar mass after accretion. This by itself is not enough to solve the problem.

- Assembly bias: satellites at accretion have already overgrown their stellar mass compared to centrals.

- There is too much subhalo disruption in numerical simulations, by roughly a factor two. Need for `orphans'.
Subhalo Disruption in Bolshoi

- Fractional Disruption Rate $\approx 13$ percent per Gyr
- Only $\sim 35$ percent of subhaloes accreted at $z=1$ survive to $z=0$
- Is tidal disruption real or numerical artifact?
  If real, what are the physical conditions for disruption?
What if ALL disruption is numerical?

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Turning off disruption in model reveals its impact

Without disruption, abundance of subhalos is boosted by factor \(~2\), roughly independent of mass or maximum circular velocity.

This would solve the Clustering Crisis
The Evolution of Dark Matter Substructure

- Tidal Stripping
- Impulsive Heating
- Force Softening
- Two-Body Relaxation
- Harassment
- Dynamical Friction
- Limiting Mass Resolution
Disruption occurs preferentially at small halo-centric radii, for subhalos on more radial orbits, and at first or second pericentric passage.

However, disruption is NOT biased with respect to the number of particles in the subhalo...

What causes this disruption???

Based on Bolshoi + Rockstar
Subhalo Disruption in the Bolshoi Simulation

Three modes of disruption in Bolshoi

Withering: subhaloes whose mass is stripped below mass resolution.

Merging ($D_m$): subhaloes that merge with host halo; driven by dynamical friction.

Disintegration ($D_d$): subhaloes that seem to `spontaneously' disintegrate close to pericenter...

Examples of $D_d$ subhalos the last 0.8Gyr prior to disruption. All these examples have $N_p > 5000$ at disruption.

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As first pointed out by Hayashi+03, instantaneous stripping of outer layers of NFW halo can leave a remnant with positive binding energy.

For an isotropic NFW halo ($\beta=0$), the core has positive binding energy if $r_{\text{cut}} < r_{\text{bind}} = 0.77 \ r_s$. (corresponding core mass is $\sim 0.08 \ M_{\text{vir}}$)

Hayashi+03 therefore suggest that subhaloes will spontaneously disintegrate once their tidal radius, $r_{\text{tid}}$ becomes smaller than $r_{\text{cut}}$. 
Does Stripping cause Disruption? NO!

As first pointed out by Hayashi+03, instantaneous stripping of outer layers of NFW halo can leave a remnant with positive binding energy.

However, contrary to their claim, this does NOT result in disruption...
Simulate NFW halo orbiting on **circular** orbit inside **static** potential of host halo.

- No impulsive (tidal) heating
- No dynamical friction

**Naive Prediction:**
all matter outside of tidal radius will be stripped of over time...

**More `Sophisticated’ Prediction:**
all matter with an apocenter $r_{apo} > r_t$ will be stripped of over time...
$r_{orb} = 0.1 \ r_{vir,h}$

$r_t = 0.11 \ r_s$
Simulate NFW halo orbiting on circular orbit inside static potential of host halo.

- Analytical predictions fail to predict amount of mass stripped
- Mass loss continues for >50 Gyr

\[N = 10^5\]
\[c_h = 5\]
\[c_s = 10\]
\[M_h = 10^3 m_s\]
Tidal Stripping on Circular Orbits

Disruption for $r_{\text{orb}} < 0.15 r_{\text{vir}}$ .......or numerical artefacts?

vdB, 2016, in prep.
$r_{\text{orb}} = 0.1 r_{\text{vir,h}}$
Tuning the Softening Length

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\( \varepsilon \) too large ➢ force bias ➢ central cusp unresolved

\( \varepsilon \) too small ➢ force noise ➢ artificial large-angle deflections ➢ isothermal core

\( \varepsilon_{\text{opt}} \approx 0.05 \)

vdB+16, in prep.
Force Softening

Mass evolution and disruption extremely sensitive to softening length
As subhalo loose mass, its optimal softening length decreases
Adaptive, individual softening may be required (e.g., Iannuzzi & Dolag 11; Hobbs+15)

\[ \varepsilon = 0.01 \quad \varepsilon = 0.03 \quad \varepsilon = 0.05 \quad \varepsilon = 0.07 \quad \varepsilon = 0.09 \quad \varepsilon = 0.11 \]

\[ \varepsilon_{\text{opt}} \propto r_{\text{half}} N^{-1/3} \]
Towards Numerical Convergence

$r_{orb}=0.1$
$c_h=5$
$c_s=10$
$M_h=10^3 m_s$

$N=1,000,000$
$N=300,000$
$N=100,000$
$N=30,000$
Towards Numerical Convergence

\[ r_{\text{orb}} = 0.1 \]
\[ c_h = 5 \]
\[ c_s = 10 \]
\[ M_h = 10^3 m_s \]

In order to suppress discreteness noise: \( N > 10^6 \)
In order to suppress artificial disruption: \( \epsilon < 0.005 \)
Towards Numerical Convergence

Ability to resolve dynamics is a strong function of:
- number of particles
- force softening
- strength of tidal field

$r_{\text{orb}} = 0.5$
$c_h = 5$
$c_s = 10$
$M_h = 10^3 m_s$
What about Tidal (Impulsive) Heating?

We model tidal heating by integrating the impulse approximation along the subhalo’s orbit using detailed model of Gnedin, Hernquist & Ostriker (1999).

We add adiabatic correction using the model of Weinberg (1994) and Gnedin & Ostriker (1999).

We apply this method to Monte-Carlo realizations of a NFW subhalo on a typical orbit in a NFW host halo, and compute $\Delta E$ for each individual DM particle.

- Impulsive heating injects large amounts of energy.
- Central region is unaffected and remains bound.
- Material that becomes unbound due to tidal heating, is anyways stripped of due to tidal force.

Impulsive, tidal heating is sub-dominant

vdB, 2016, in prep.
What about Tidal (Impulsive) Heating?

- **Two-body relaxation** due to interactions of subhalo particles with (hotter) host halo particles is similar to that due to interactions with (colder) subhalo particles.  
  [Despite claims to the contrary; Carlberg 1994; van Kampen 1995, 2000]

- **Impulsive heating** due to encounters with hotter (overly massive) host halo particles has similar (negligible) impact as two-body relaxation  
  [Despite claims to the contrary; Moore, Katz & Lake 1996]

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**CAUTION:**  
\[ E_{\text{tot}} \neq \sum E_i \]
Conclusions

⭐ **Clustering Crisis:** Halo Occupation Models that fit clustering, do not fit $\Phi(M_*,z)$ and vice versa

Solution requires at least one of the following
- very significant satellite growth after accretion
- assembly bias; $M_{*,\text{sat}}(M_h,z_{\text{acc}}) > M_{*,\text{cen}}(M_h,z_{\text{acc}})$
- orphans (i.e., more satellites than subhalos)

⭐ **Subhalo Disruption:** resolving dynamics of subhalos requires
- huge $N$ (to suppress discreteness noise)
- small softening length ($\sim 1/10$ of that for isolated halos)

⭐ **Current generation of cosmological simulations still suffers from severe overmerging.**
- serious road-block for small-scale cosmology program
- serious road-block for understanding galaxy formation
Conclusions

★ What causes subhalo disruption?
  ● Dynamical friction (physical)
  ● Inadequate force resolution (numerical)
  ● Discreteness noise (numerical)

★ In absence of dynamical friction, subhaloes never disrupt.

★ How to proceed?

Only hope is to characterize shortcomings of N-body simulations, and complement simulation results with semi-analytical model.