

Illuminating numerical complexity with physical simplicity--

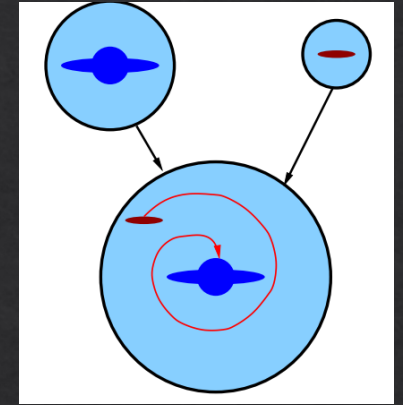
Universal laws of subhalos arising from unbiased accretion

Jiaxin Han (韩家信)

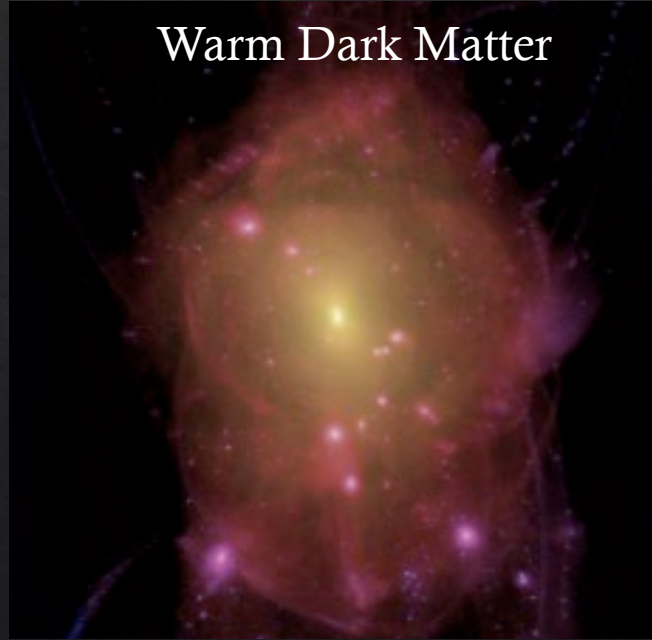
Shanghai Jiao Tong University

Subhalo -- debris of halo merger

- Encodes small scale cosmological information
- Carrier of satellite galaxies

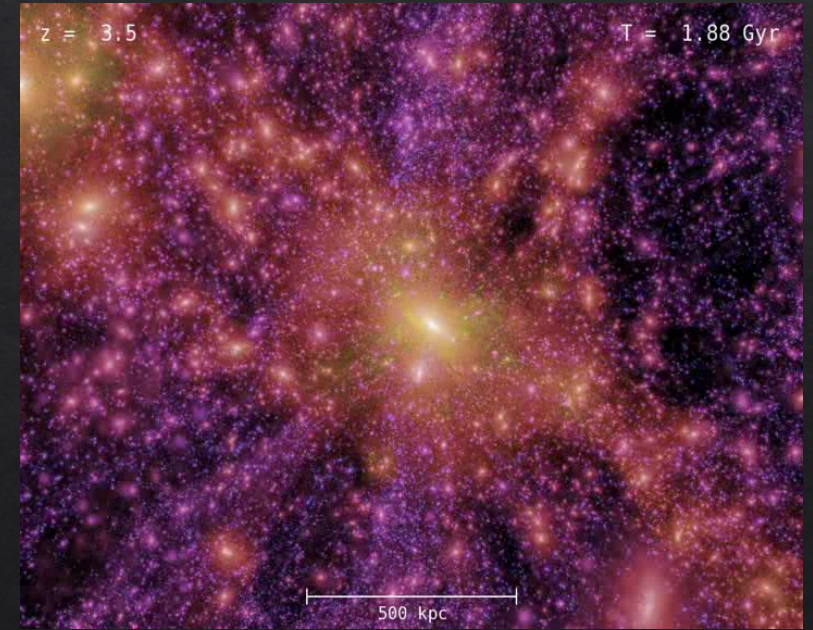


Cold Dark Matter



Warm Dark Matter

Lovell+2014



Springel+ 2008

Universal laws on subhalo distribution

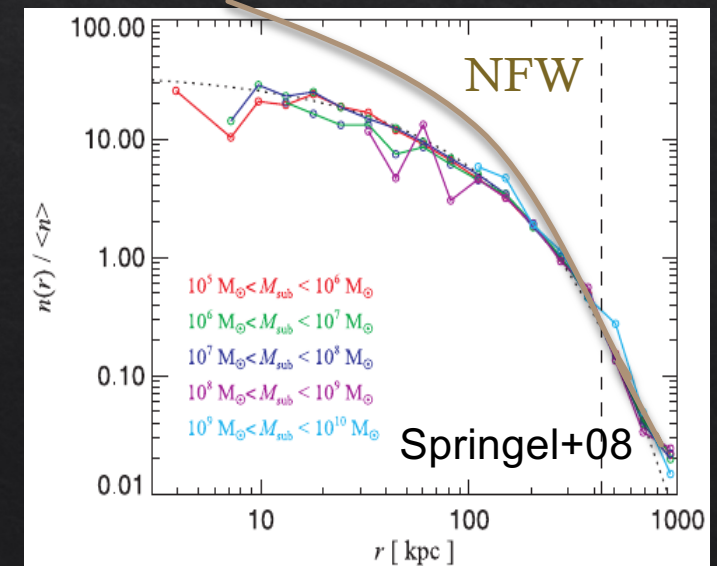
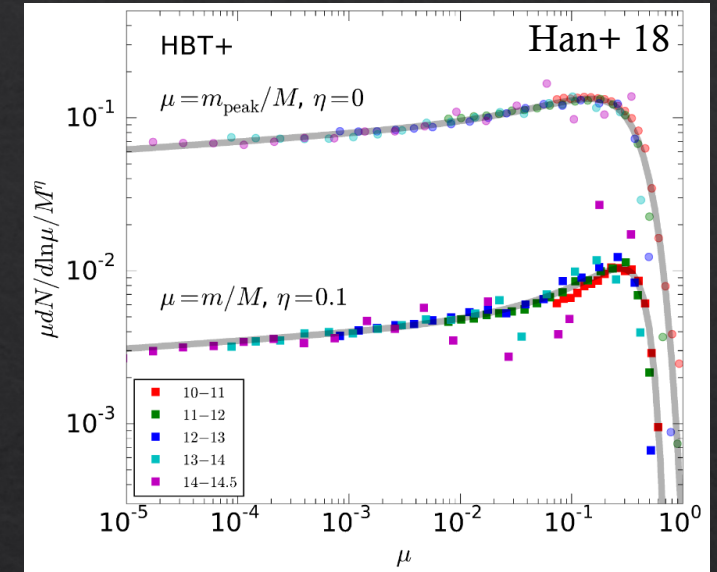
- ◇ Subhalo mass functions
 - ◇ (Double) Schechter form
 - ◇ Largely independent on host halo mass
 - ◇ Probably also universal across redshift, cosmology, hierarchy ?
- ◇ Subhalo radial distribution
 - ◇ Mass independent
 - ◇ Flatter than NFW

Can we understand these laws?

-Yes, **unbiased accretion**

What do we learn from them?

- Origin, dynamics, mass loss, disruption, hierarchy, cosmology & dark matter



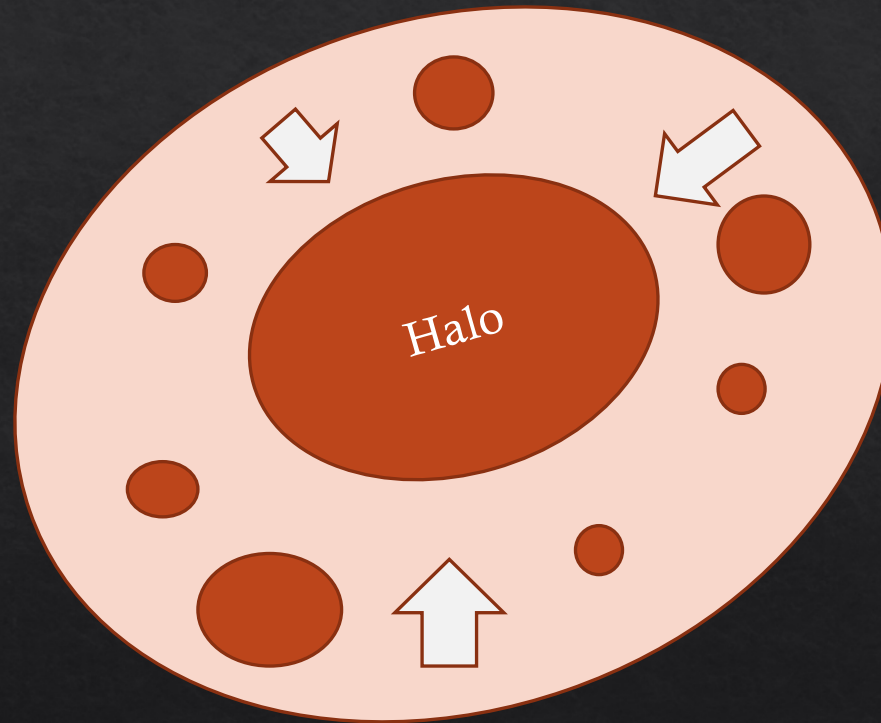
Unbiased accretion

Halos and diffuse matter are accreted indiscriminately

Subhalo progenitors fall in on similar orbits as matter



Subhalo spatial distribution



Subhalo progenitors fall in in proportion to matter



Subhalo mass distribution

Han et al. 2016

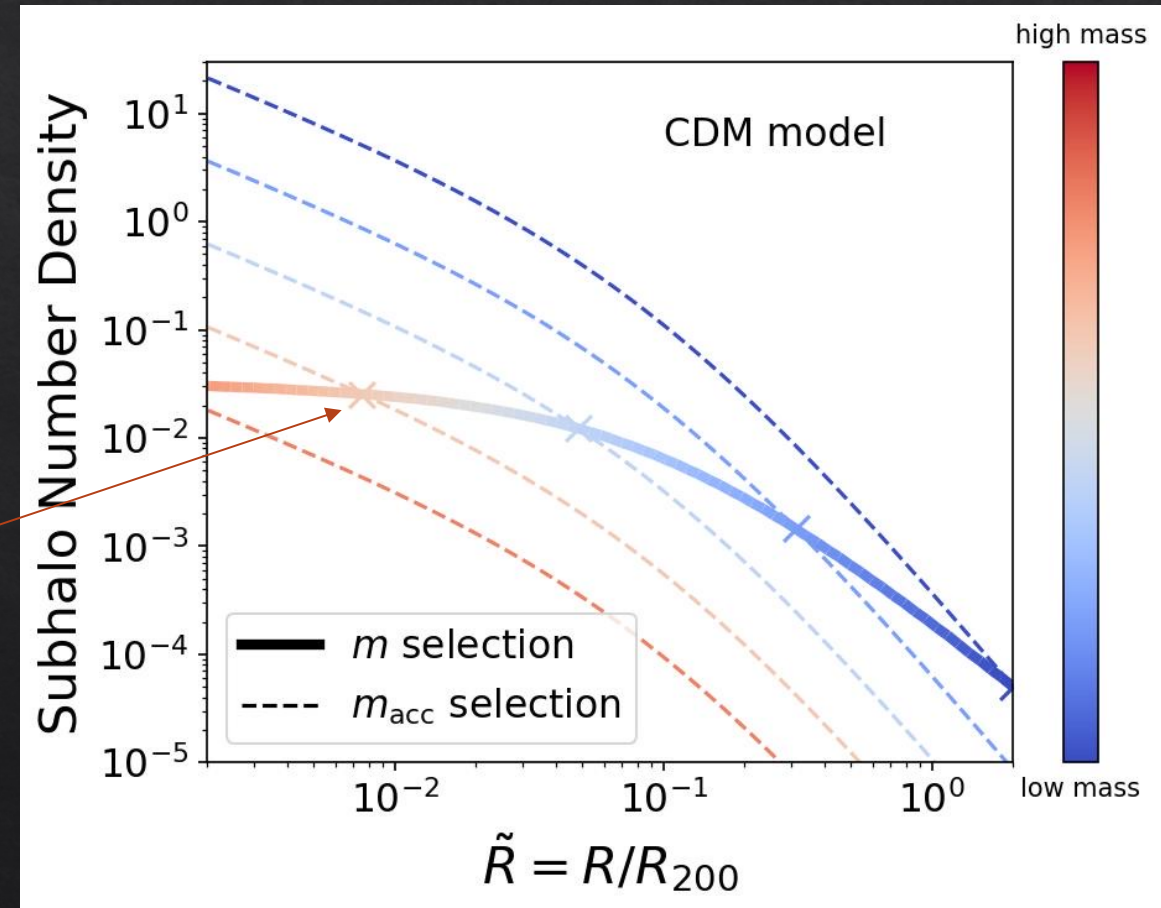
Modelling subhalo radial distribution

- ◇ Unbiased accretion: subhalos at fixed infall mass follow host density profile (NFW)
- ◇ Simulations usually measure subhalo distribution at fixed final mass

Tidal stripping:

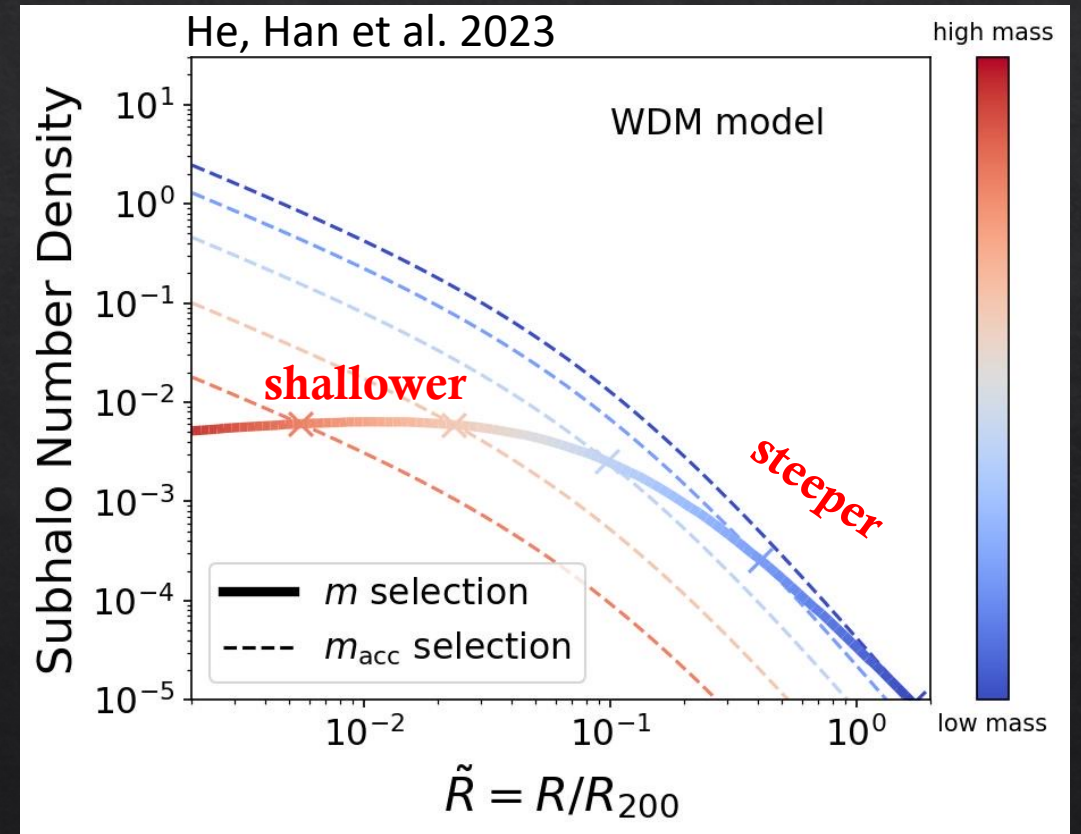
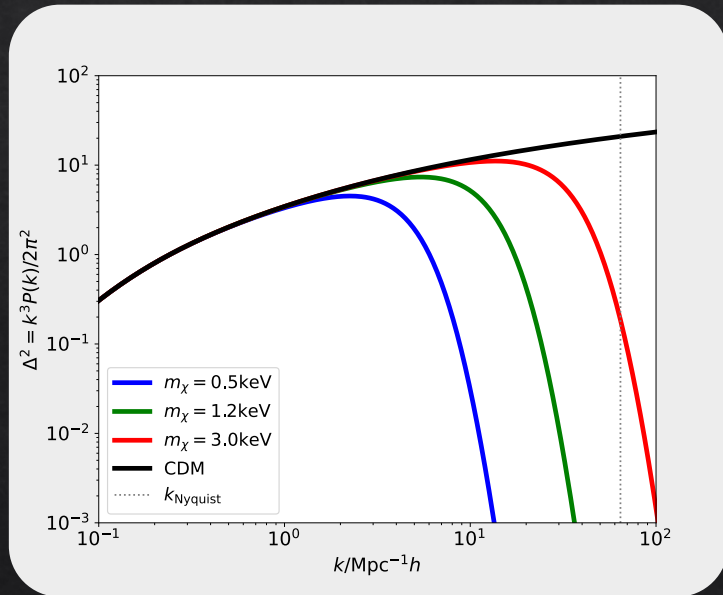
same final mass map to different infall mass at different radius

Han et al. 2016



Extending to Warm Dark Matter

- ◇ WDM has suppressed small scale power
 - ◇ Suppressed mass function at low mass end
 - ◇ Lower concentration at low mass end → stronger tidal stripping



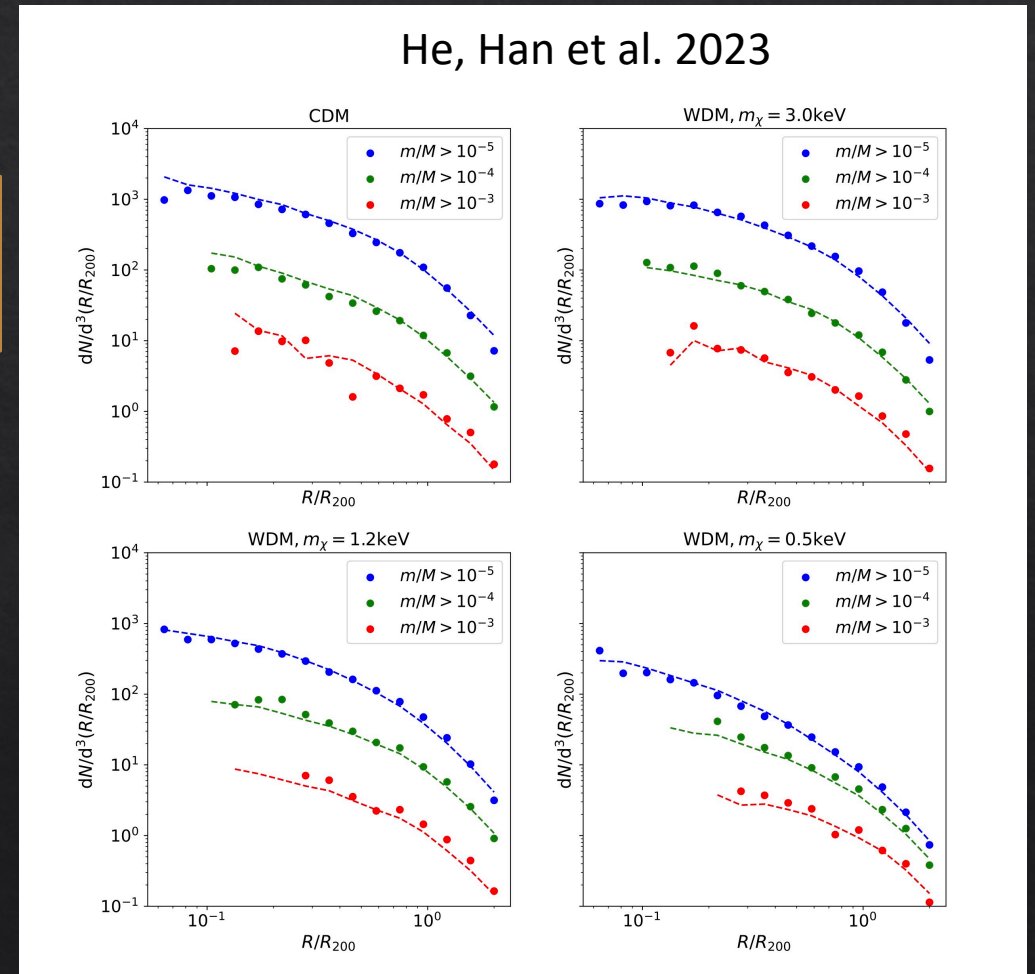
Universal subhalo radial and mass distribution

- ◇ Analytical model:

$$dN(m, m_{acc}, R) = \underbrace{dN(m_{acc})}_{\text{Progenitor mass function}} \times \underbrace{dP(m|m_{acc}, R)}_{\text{mass loss}} \times \underbrace{\tilde{\rho}(R)}_{\text{host density profile}}$$

Progenitor mass function mass loss host density profile

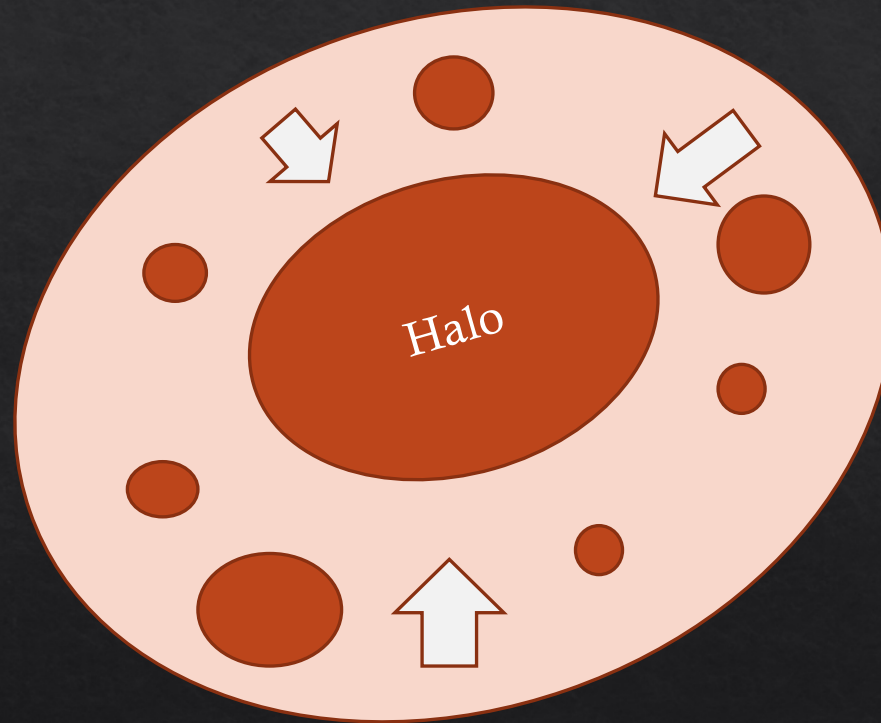
- ◇ Predicts final mass function from progenitor mass function
- ◇ ~50% of subhalos are disrupted
- ◇ Python sampler:
 - ◇ SubGen, SubGen2 on github
 - ◇ To generate subhalo samples for any halo in CDM/WDM



Unbiased accretion

Halos and diffuse matter are accreted indiscriminately

Subhalo progenitors fall in on similar orbits as matter



Subhalo progenitors fall in in proportion to matter



Halo merger rate proportional to halo growth rate

Universal specific halo merger rate

◆ The merger rate per unit mass growth, $f(\xi)$, is universal

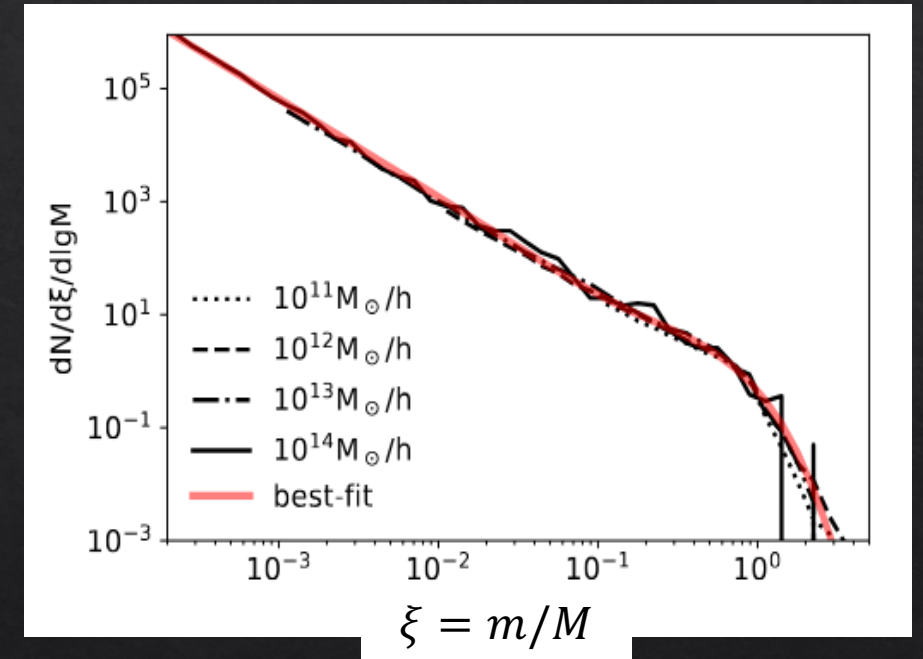
◆ Across host mass, redshift and cosmology

$$dN_{\text{merge}}/d\xi/d\log M_h = (a_1\xi^{b_1} + a_2\xi^{b_2}) \exp(c\xi^d),$$

◆ **Nontrivial**: Previous works have to introduce detailed mass, redshift and cosmology dependences, when not working with the specific merger rate

◆ Predict a universal **progenitor mass function**, $g(\xi)$

◆ Equivalence: $f(\xi) = -\frac{dg(\xi)}{d\xi}$

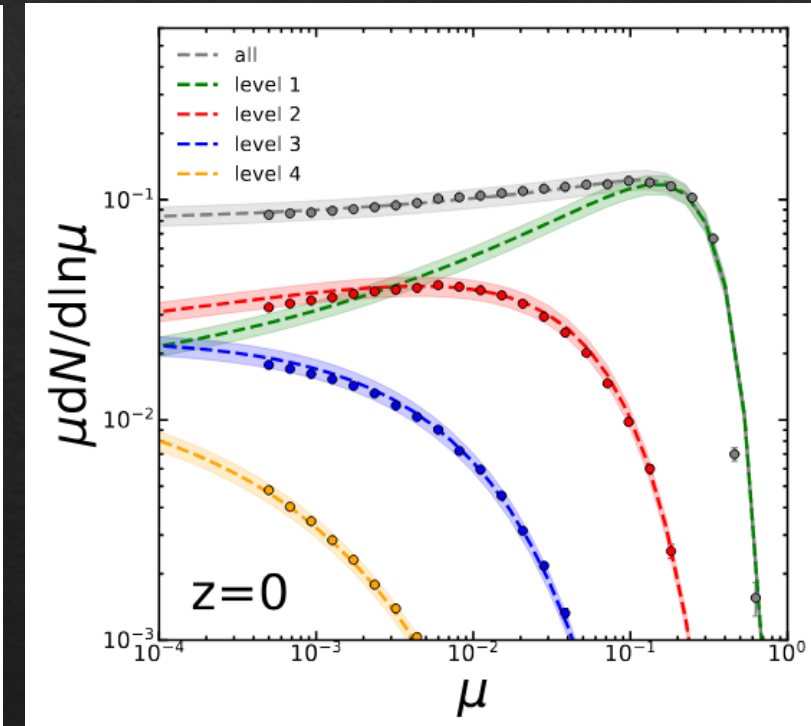
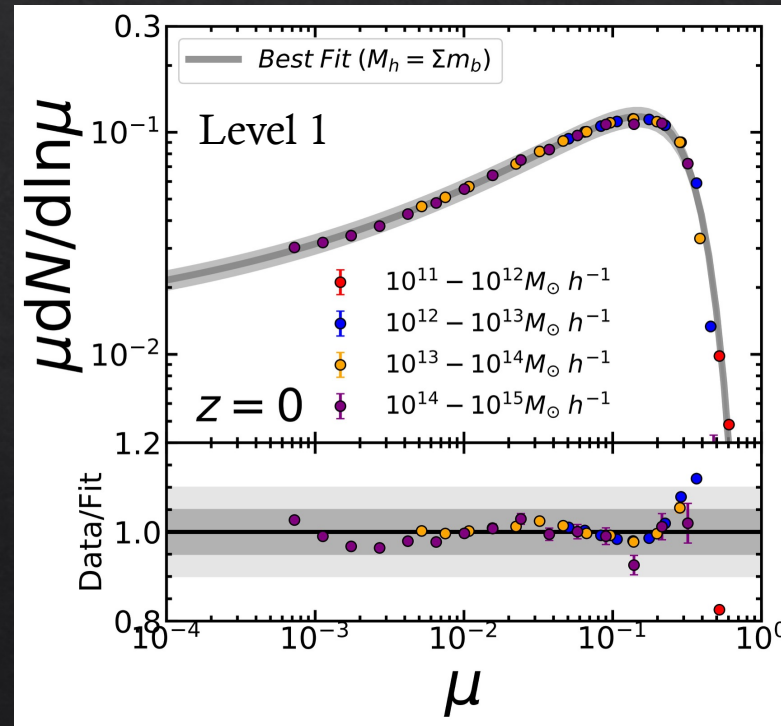
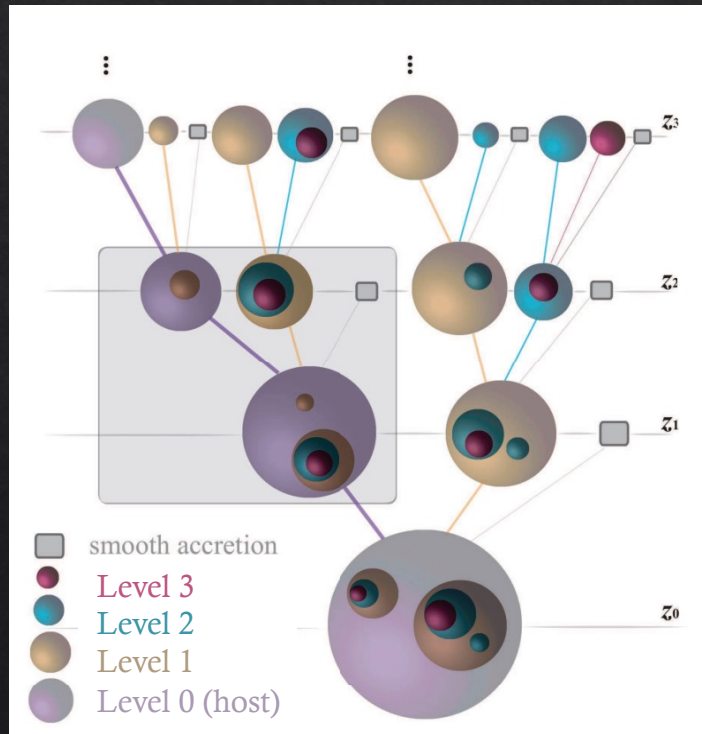


Dong, Zhao, Han+ 2022

Universal PMF across levels

Hierarchical merger leads to different levels of progenitors (and subhalos)

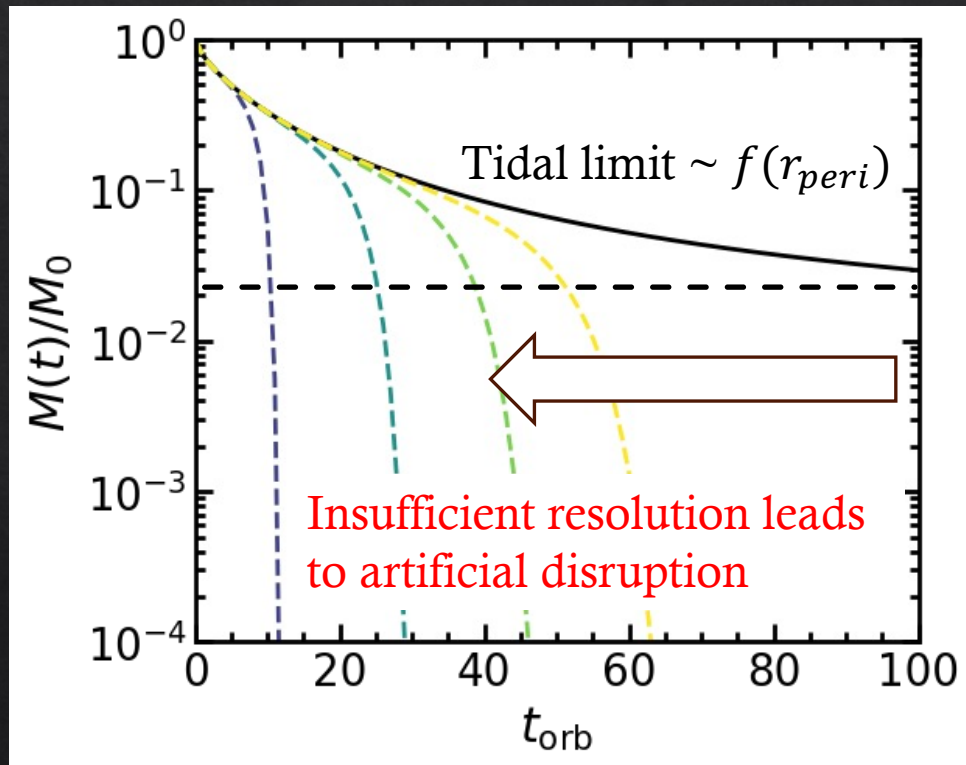
Level- n PMF = n -th convolution of Level-1 PMF



Merger rate only models the PMF of level-1 subhalos

Jiang, Han+2025

Artificial Disruption



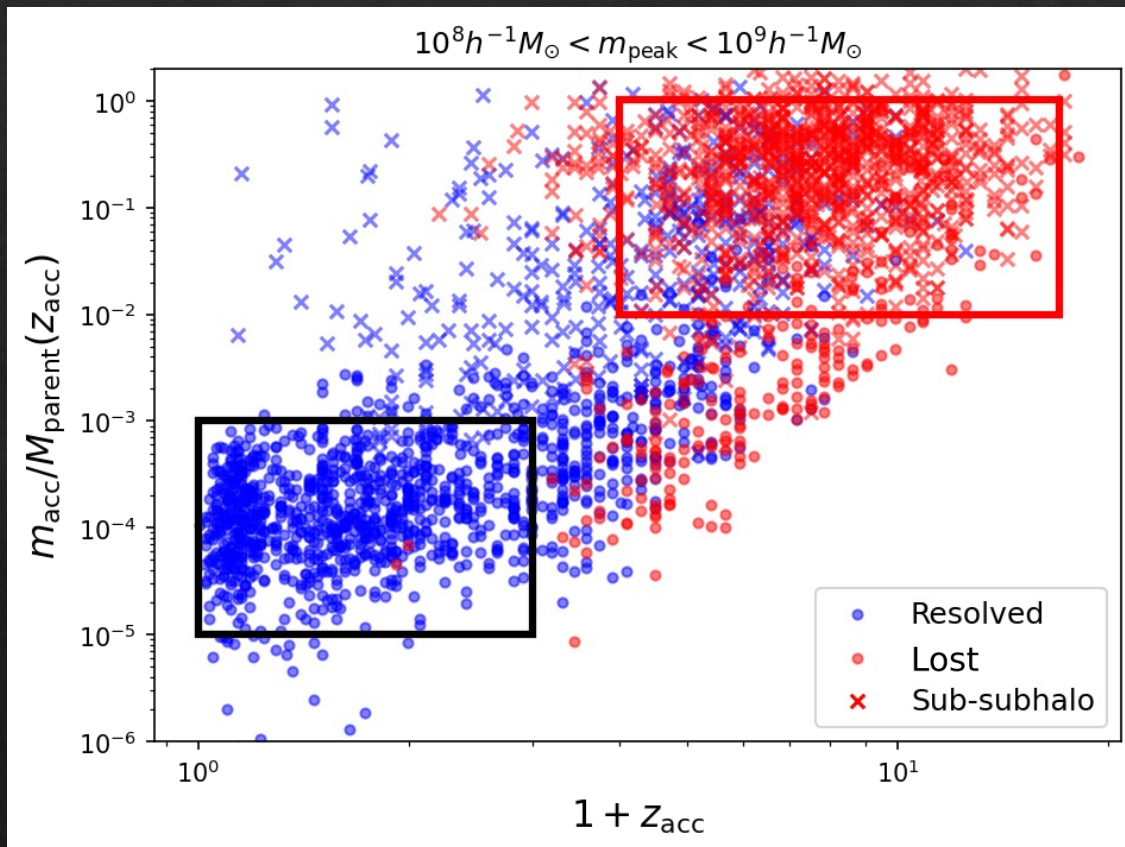
van den Bosch et al. 2018 Errani et al. 2021

- ◇ CDM subhalos never fully disrupt in theory
 - ◇ Artificial disruption at insufficient resolution
 - ◇ Fake convergence at insufficient softening
- ◇ $\sim 50\%$ subhalos disrupt in simulations
 - ◇ Converges with resolution

Current simulations are suffering from significant artificial disruption?

Origins of surviving vs disrupted subhalos

- Theoretical studies on artificial disruption pertains only to the surviving condition, and they indeed remain resolved!

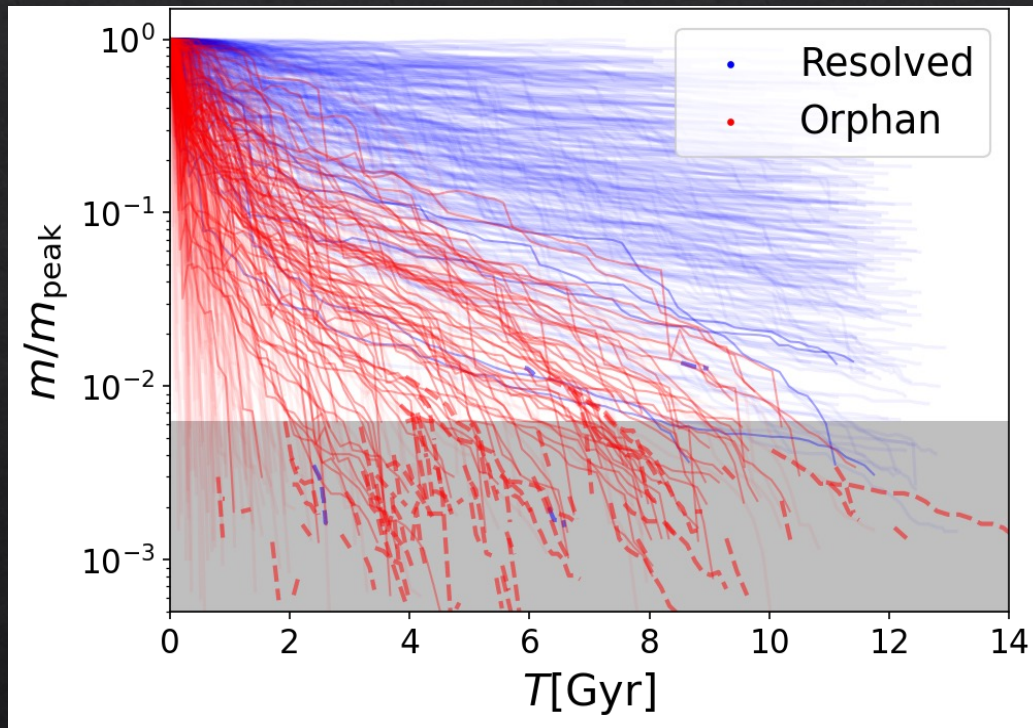


Disrupted	Surviving
High redshift	Low redshift
Major merger	Minor merger
High level sub	Level-1 sub
Rapid host growth	Slow host growth

He, Han & Li 2025

Origins of surviving vs disrupted subhalos

- Disrupted subhalos experience extreme mass loss **for a physical reason**
- Current simulations are **safe** from artificial disruption



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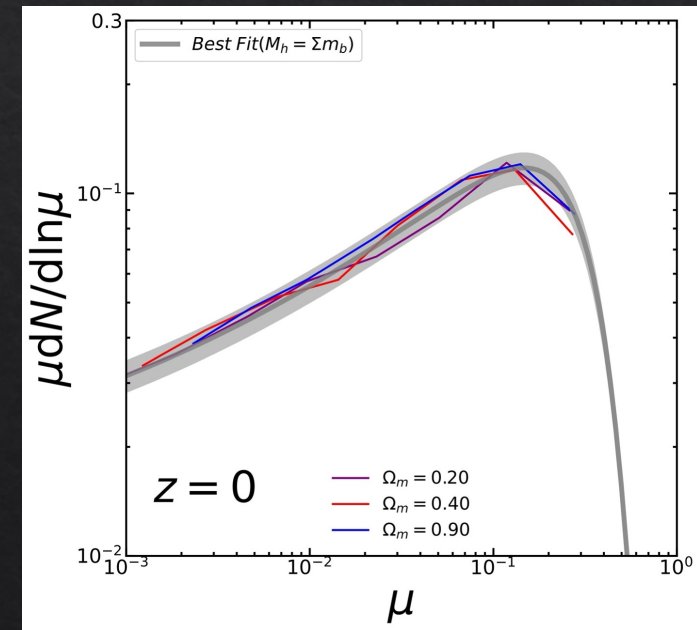
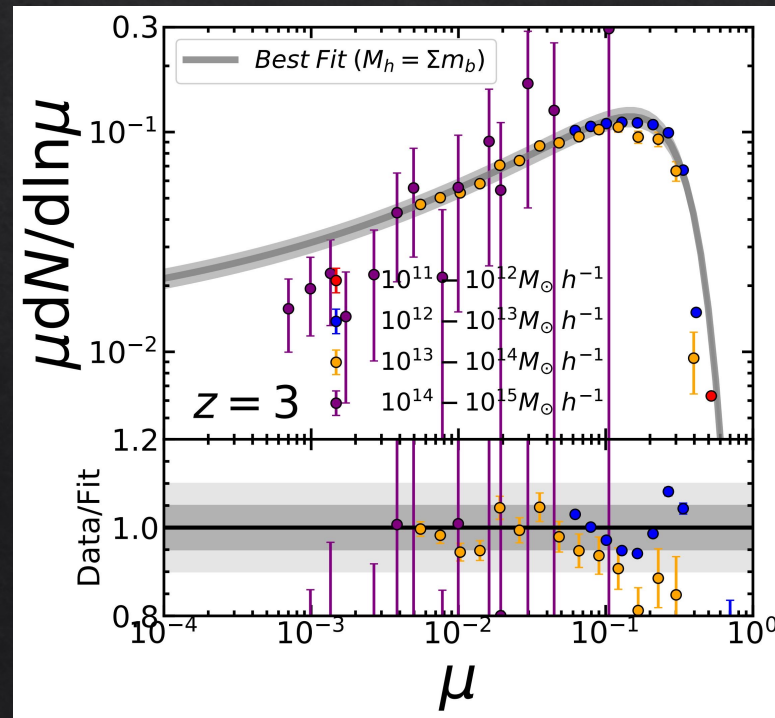
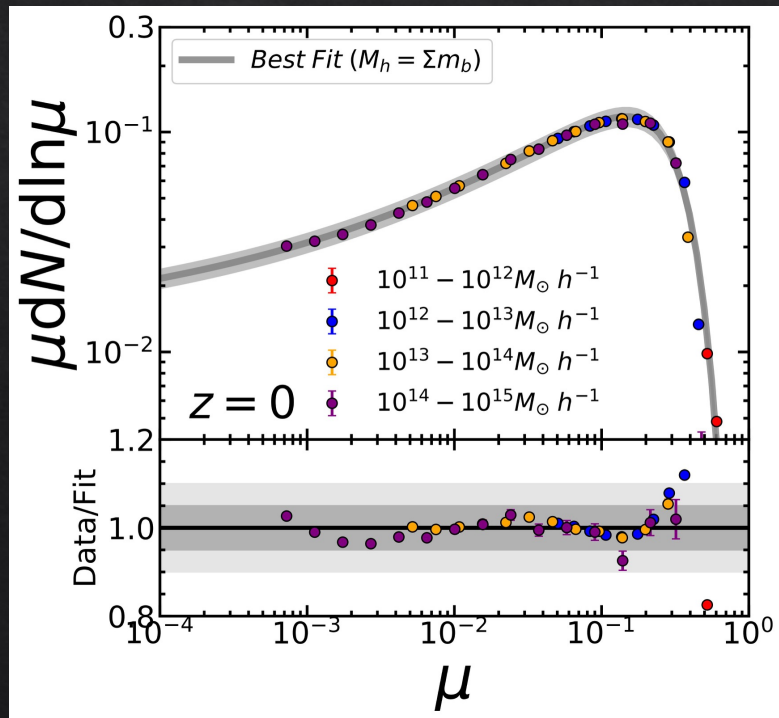
He, Han & Li 2025

Summary

- ◇ **(sub)halos and diffuse matter are accreted onto halos in an “unbiased” way**
- ◇ Similar dynamics
 - ◇ Leads to radial distribution of subhalos following host profile at fixed infall mass
 - ◇ Tidal stripping leads to a modification to the profile at fixed final mass
 - ◇ WDM subhalos are distributed differently due to different infall mass function and mass loss rate
- ◇ Proportional accretion rate
 - ◇ Universal specific merger rate
 - ◇ Universal subhalo peak mass function at any level
 - ◇ High level subhalos dominate the low mass subhalo population
 - ◇ “Disrupted” subhalos in cosmological simulations can be understood arising from their hierarchical origin

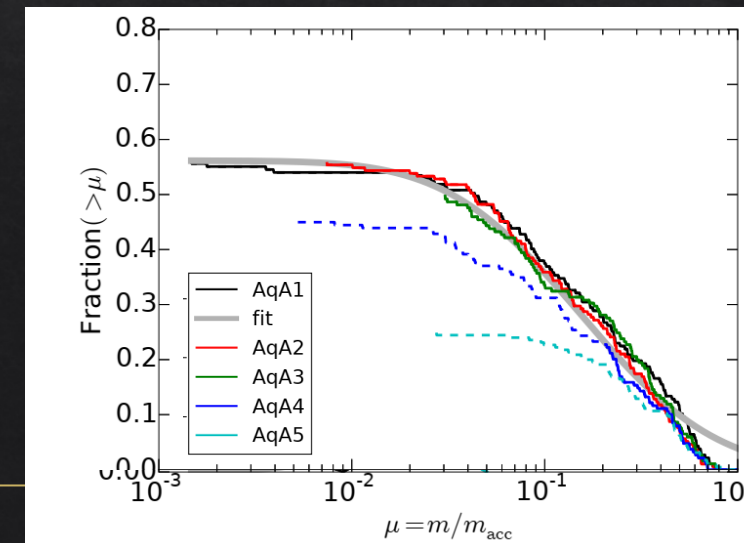
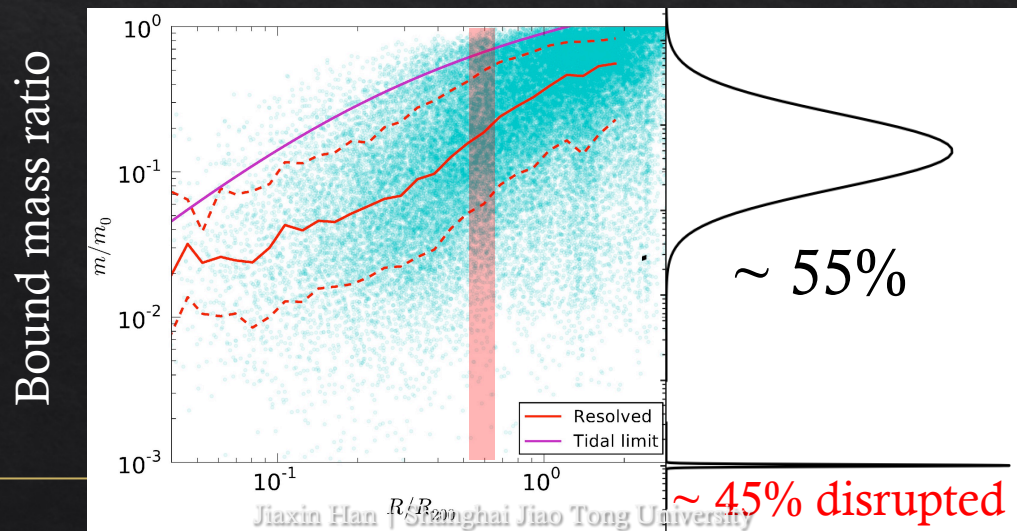
Universal Subhalo Peak Mass Function

- ◇ The progenitor mass function (or Peak MF) has to be universal as well
- ◇ Verified to 10% in simulations across mass, redshift and cosmology
 - ◇ Well fit by the same double-Schechter function



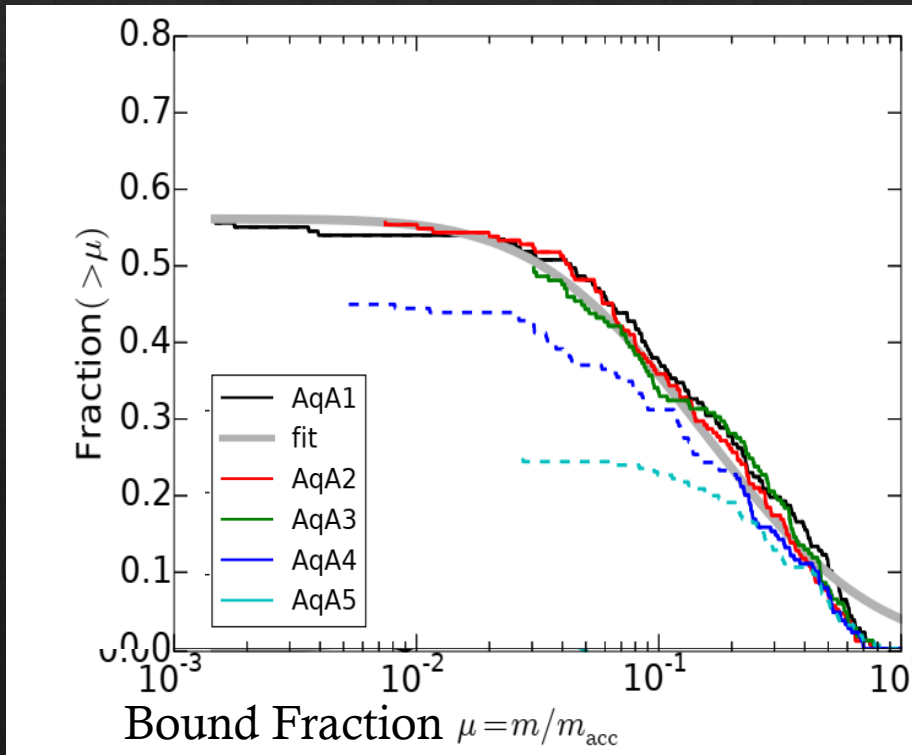
Tidal Stripping and Disruption

- ◇ Mass loss
 - ◇ Mean: $\frac{m}{m_{acc}} \propto r^{-\beta}$, Lognormal scatter
- ◇ Disruption: $\sim 45\%$ subhalos remain disrupted at the highest resolution
 - ◇ Converges with increasing resolution, **Physical?**
 - ◇ Recent theoretical studies suggest CDM subhalos never disrupt (e.g., van den Bosch et al. 2018, Errani & Penarrubia 2021). **Artificial?**



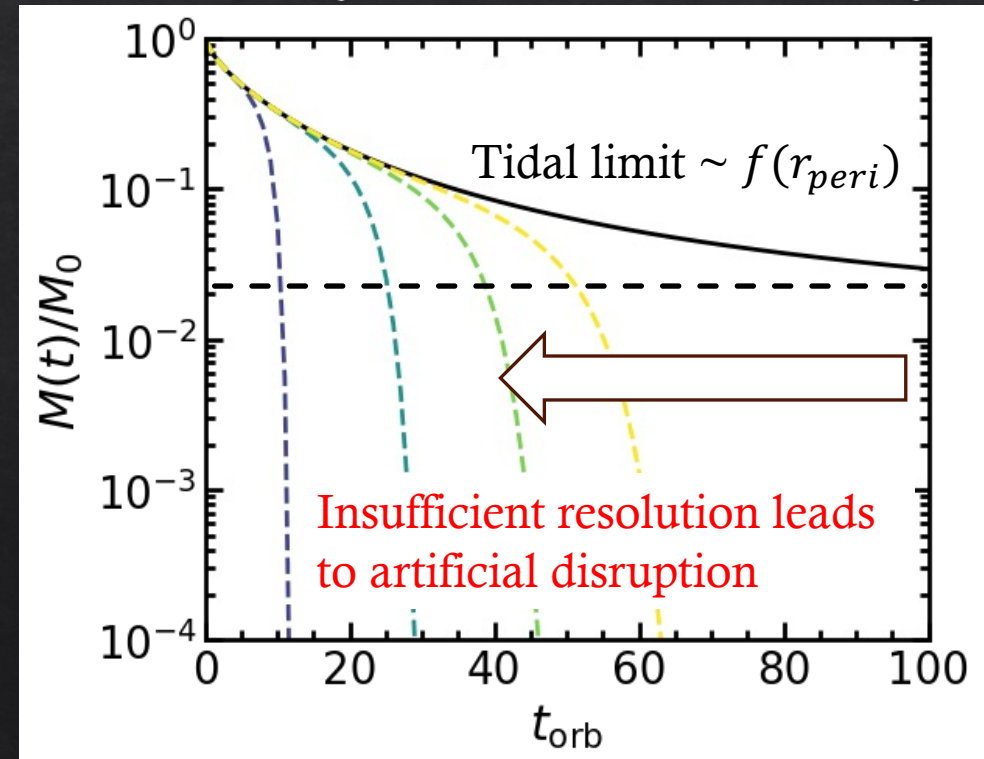
Artificial Disruption

- ◇ ~50% subhalos disrupt in simulations
 - ◇ Converges with resolution



Han et al. 2016

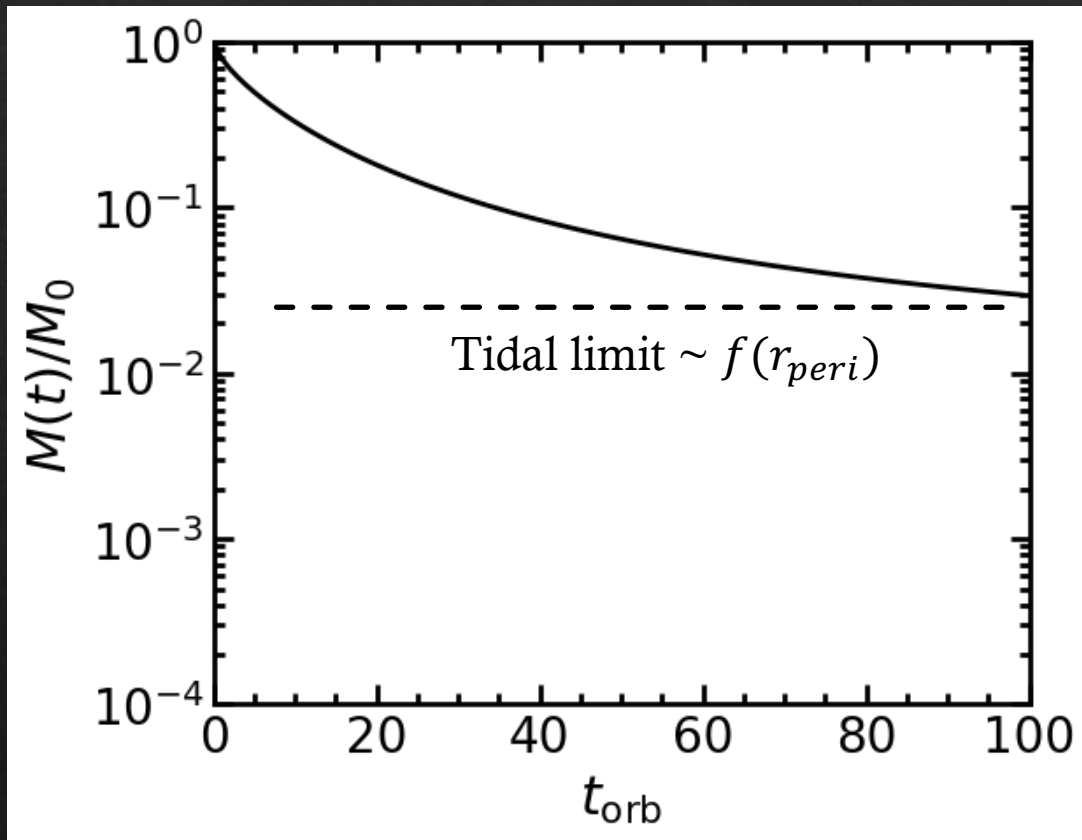
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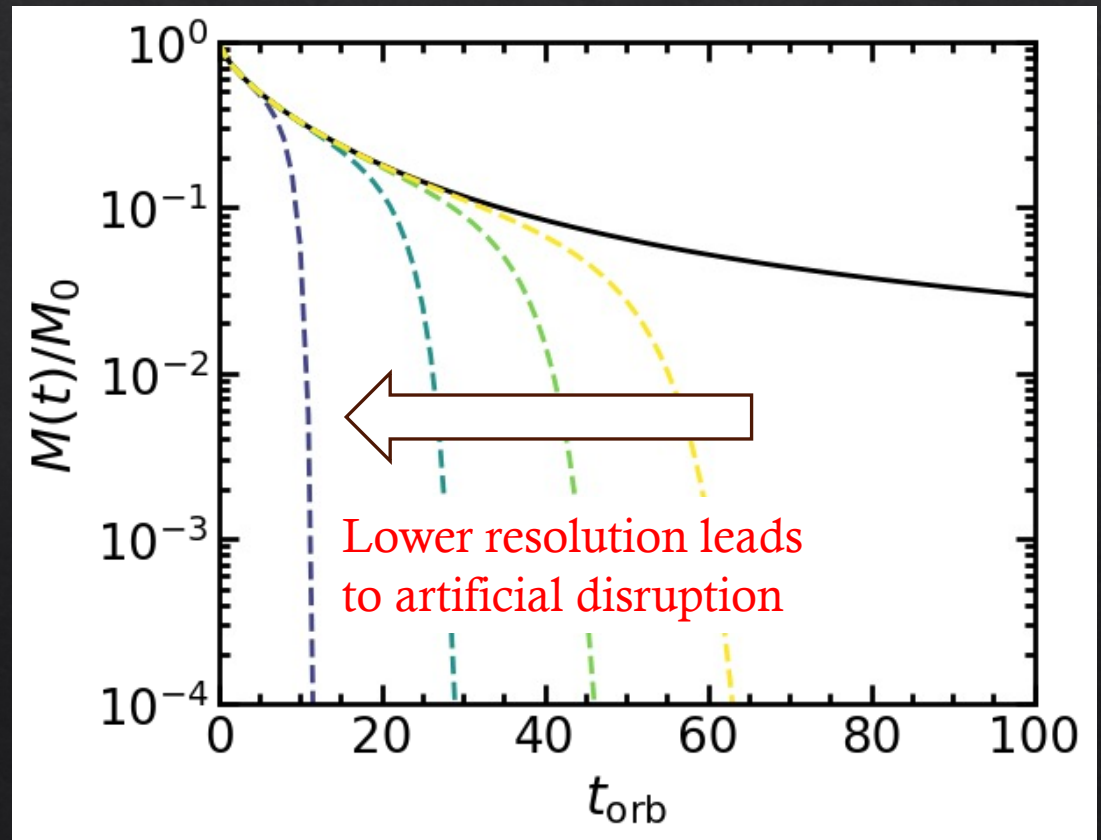
van den Bosch et al. 2018 Errani et al. 2021

Artificial Disruption

- ◆ Theoretical studies predict that CDM subhalos should not disrupt



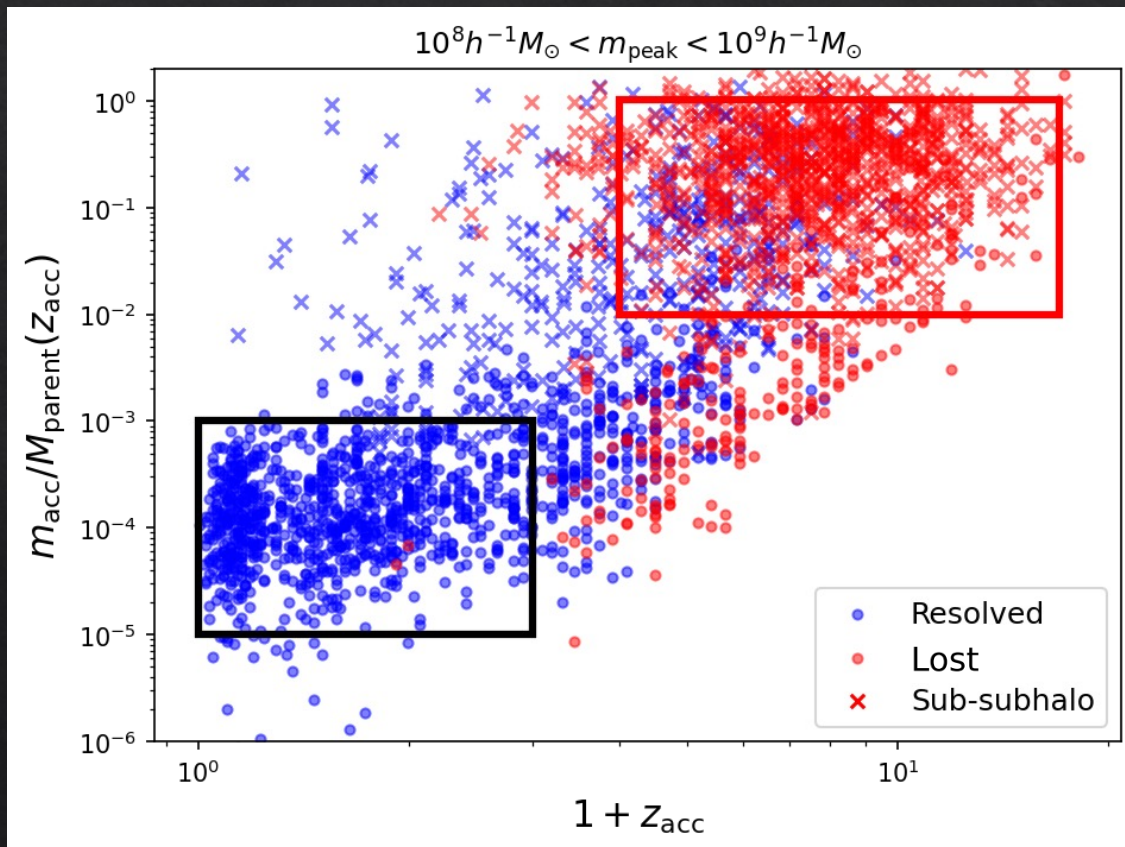
Errani et al. 2021, Stucker et al. 2023



van den Bosch et al. 2018

Origins of surviving vs disrupted subhalos

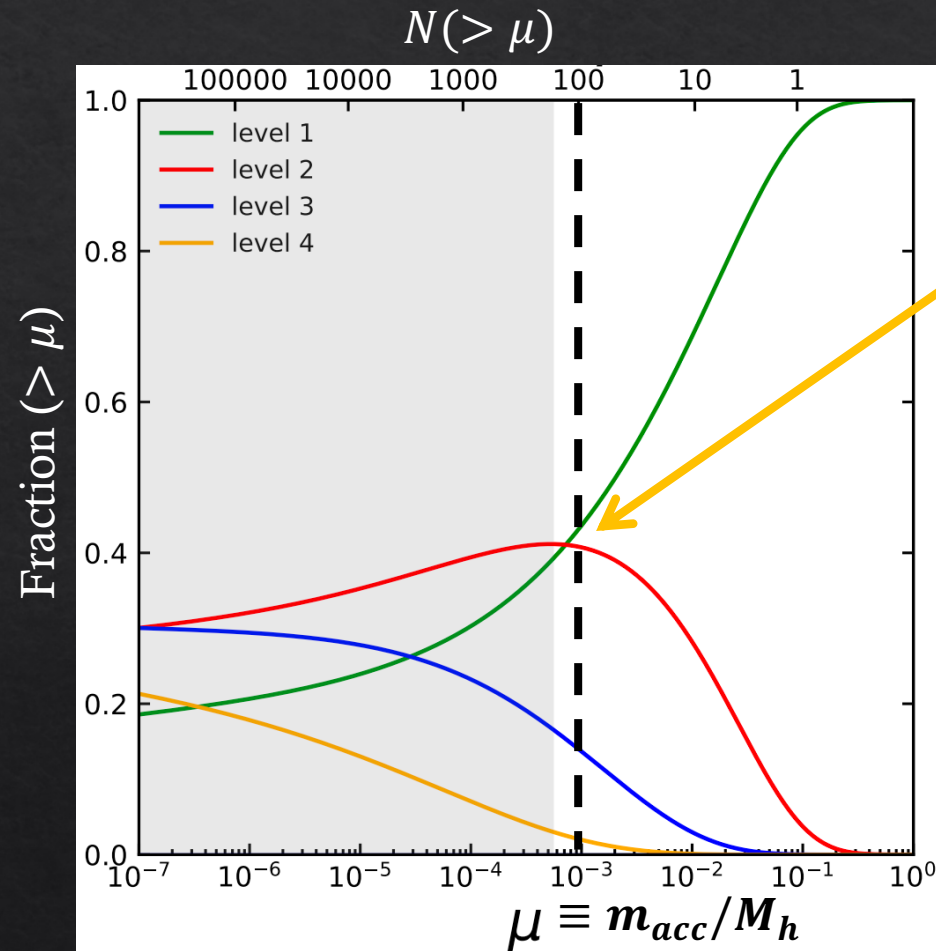
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The hierarchy composition of subhalos

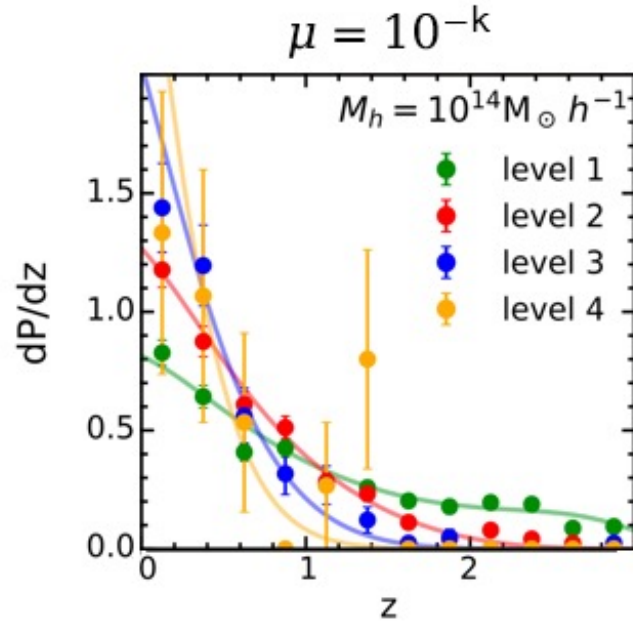
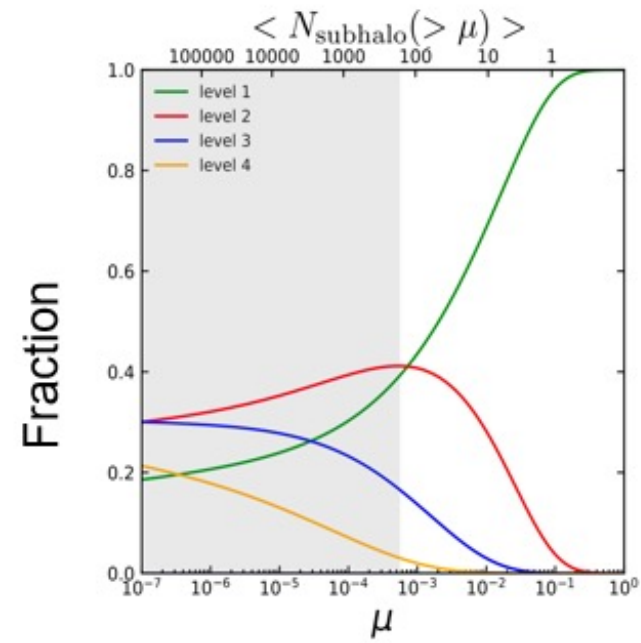
Pre-processing is important!



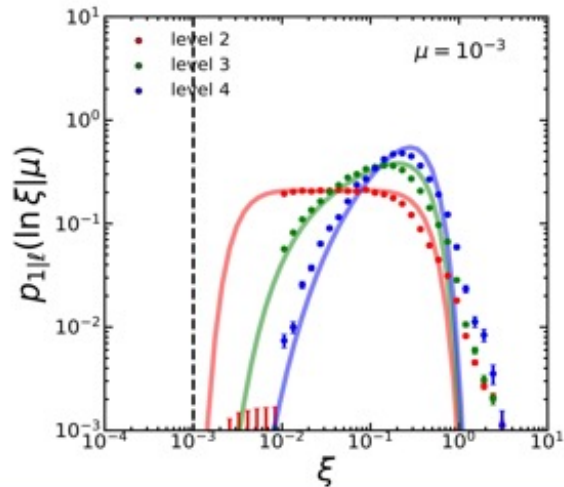
Only **40%** of the top 100 progenitors originate from **direct mergers** with main halos.

Composition of the subhalo population

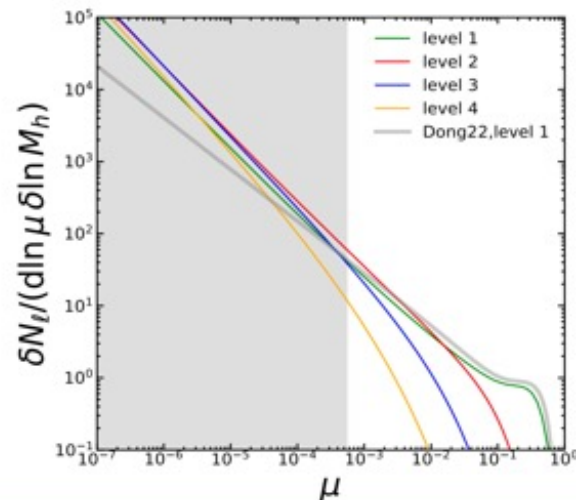
Accretion redshift



Initial merger ratio



Subhalo accretion rate



- **Higher level** progenitors dominate at progressively lower mass.
- Majority of high-level ones are first accreted in **major mergers**.
- High-level subhalos are acquired more **recently**.
- ...