Model for WDM Subhalo Distribution

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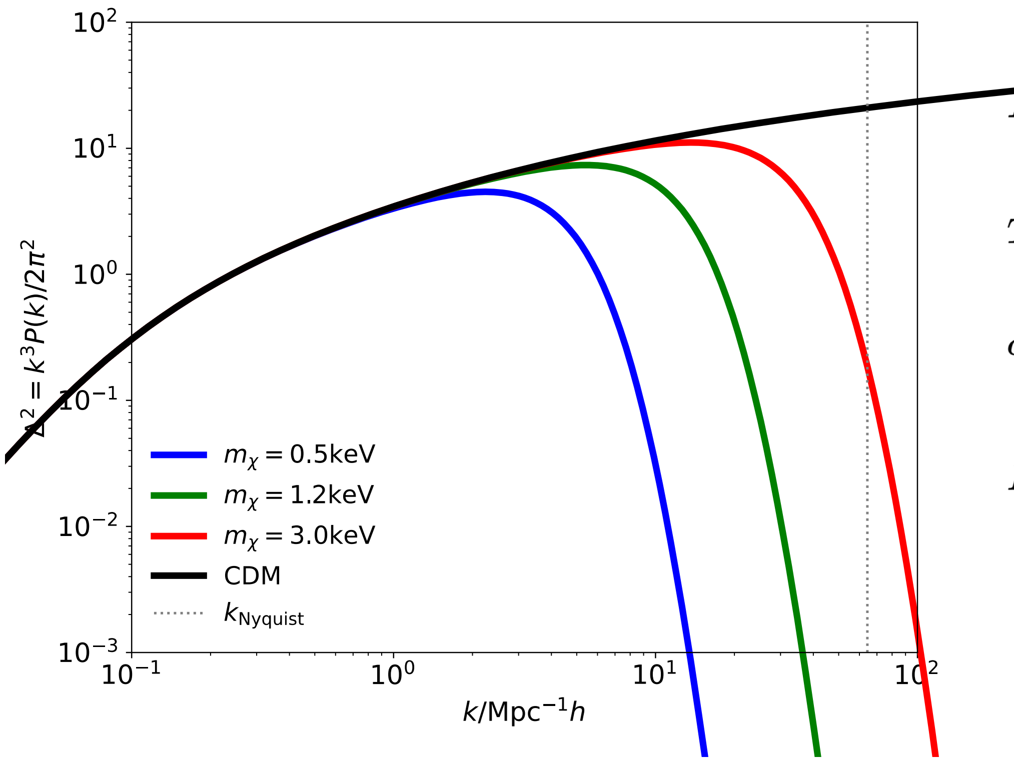
Power Spectrum of WDM



$$P_{\mathrm{WDM}}(k) = T^2(k) P_{\mathrm{CDM}}(k)$$

$$T(k) = \left(1 + (\alpha k)^{2v}\right)^{-5/v}$$

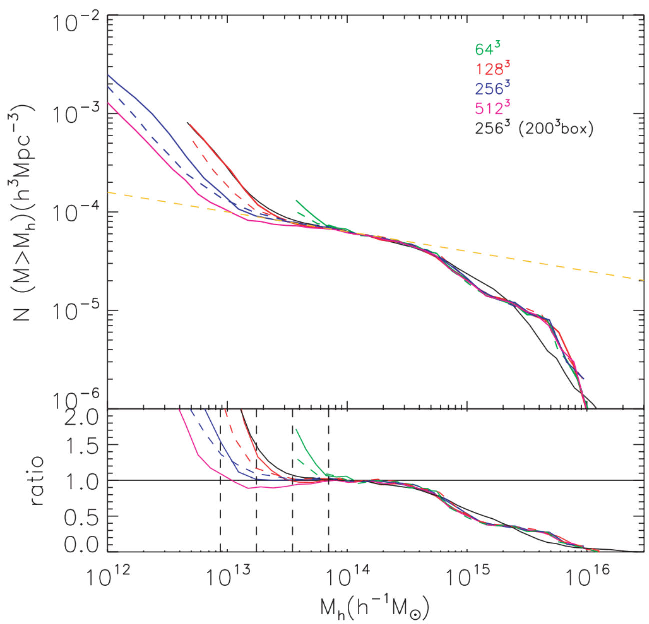
$$\alpha = 0.049 \left(\frac{m_{\mathrm{WDM}}}{1\mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_{\mathrm{WDM}}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

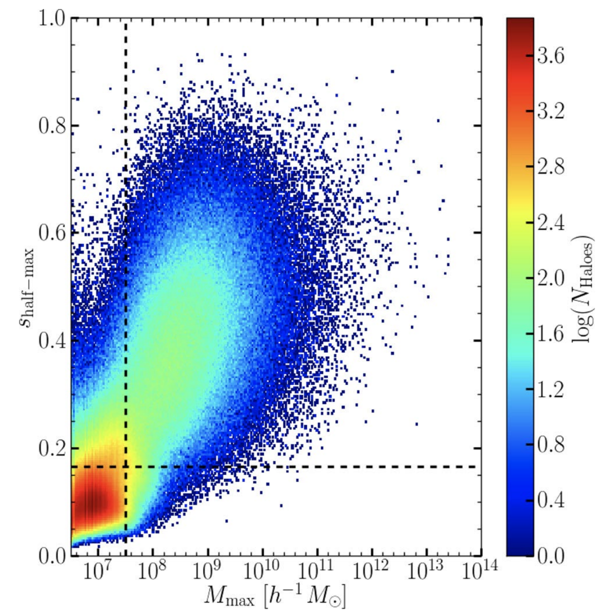
$$M_{\mathrm{hm}} = \frac{4\pi}{3}\rho_0 \left(\frac{\pi}{k_{\mathrm{hm}}}\right)^3$$

The matter power spectrum of WDM will be suppressed at small scale compared with CDM case.

Simulation and Spurious Halos

m_χ	Lbox[Mpc]	N_{sub}	$\mathrm{M_{hm}}[\mathrm{h^{-1}M_\odot}]$	$\mathrm{M_{lim}}[\mathrm{h^{-1}M_\odot}]$
CDM	100	2291533		
0.5keV	100	120781	1.1×10^{11}	8.6×10^{9}
1.2keV	100	453445	5.4×10^{9}	1.5×10^{9}
3.0keV	100	1284579	2.3×10^{8}	2.3×10^{8}



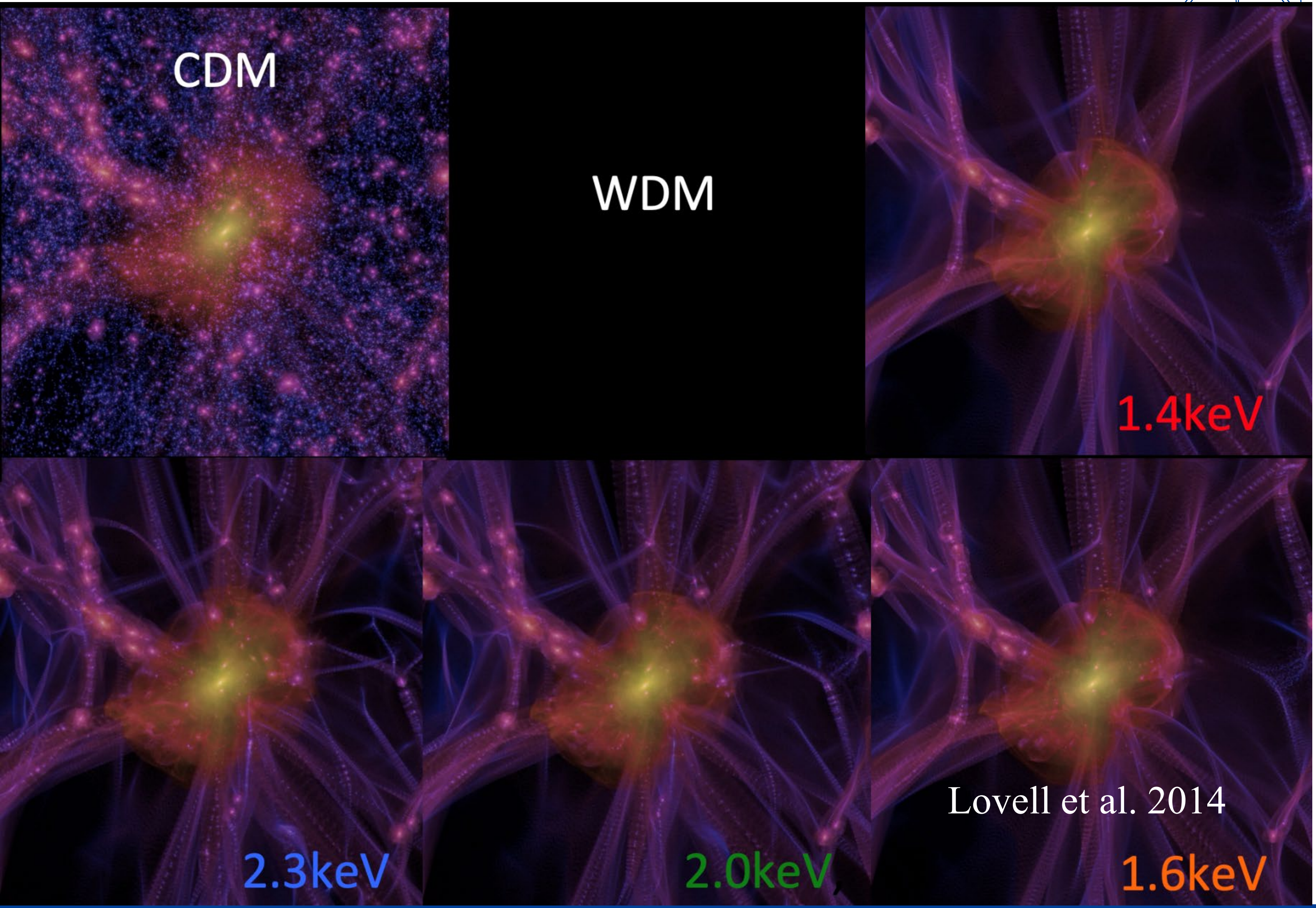


Bose et al. 2016

$$M_{\rm lim} = 10.1\bar{\rho} d k_{\rm peak}^{-2}$$

Wang et al. 2007

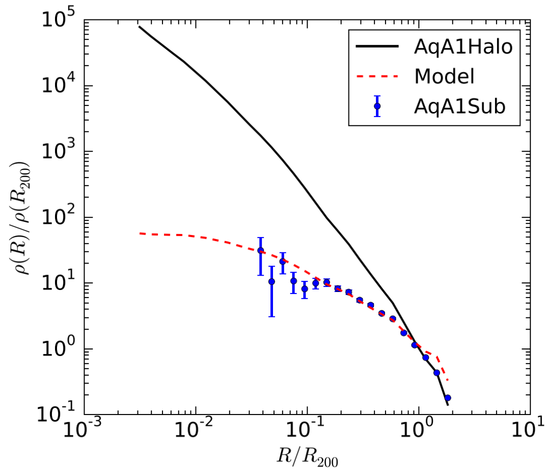
Warm Dark Matter



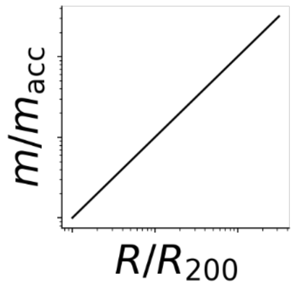
Model Framework

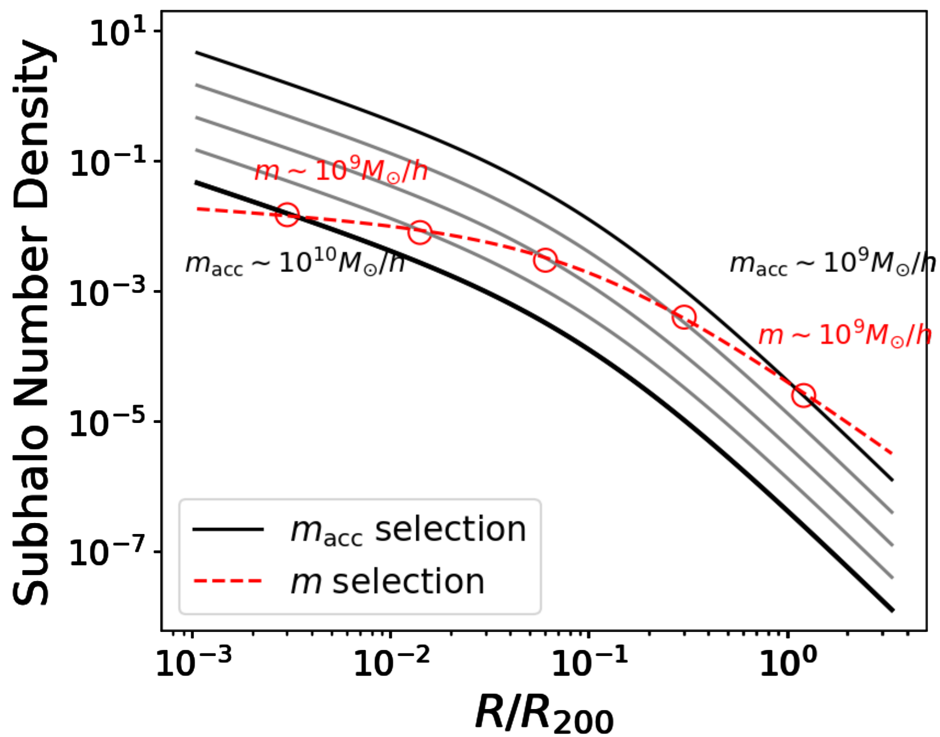
The spatial distribution of the subhalo should trace the halo density profile.

"anti-bias": subhalo final number density is less centrally concentrated



Halo Density Profile





Model Framework

$$\mathrm{d}N(m, m_{\rm acc}, R) = \mathrm{d}N(m_{\rm acc}) \times \mathrm{d}P(m \mid m_{\rm acc}, R) \times \tilde{\rho}(R)$$

Unevolved subhalo mass function

$$\frac{\mathrm{d}N}{\mathrm{d}\ln m_{\rm acc}} \propto m_{\rm acc}^{-\alpha}$$

Mass loss and disruption by tidal effects

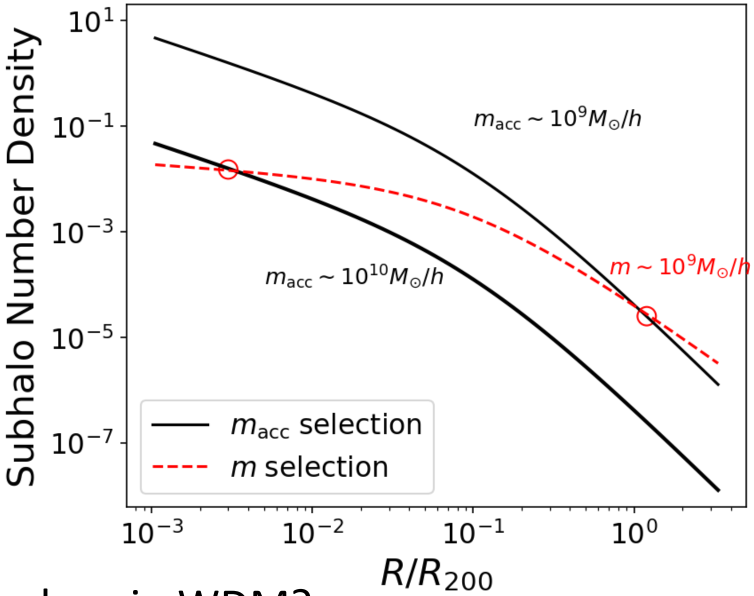
$$\frac{m}{m_{\rm acc}} \propto R^{\beta}$$

Unevolved spatial distribution

$$\frac{\mathrm{d}N(R \mid m_{\rm acc})}{\mathrm{d}^3 R} \propto \rho(R)$$

Unevolved and final subhalo mass functions have the same power-index

Leading a mass-independent spatial distribution



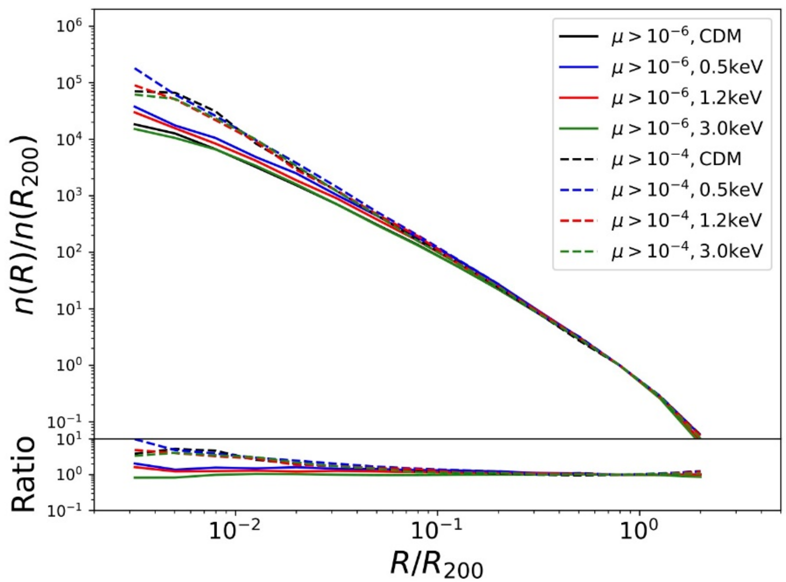
Q: Can the CDM model explain the distribution of subhaloes in WDM?

Unevolved spatial distribution

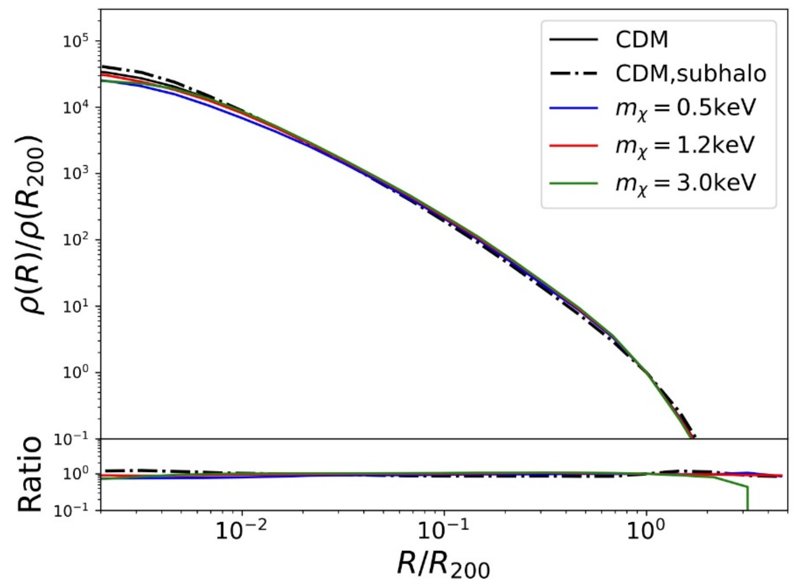
The number density profile of accreted subhalos traces the halo density profile.

$$\tilde{n}_{\rm sub}(R|m_{\rm acc}) \sim \tilde{\rho}_{\rm DM}(R)$$

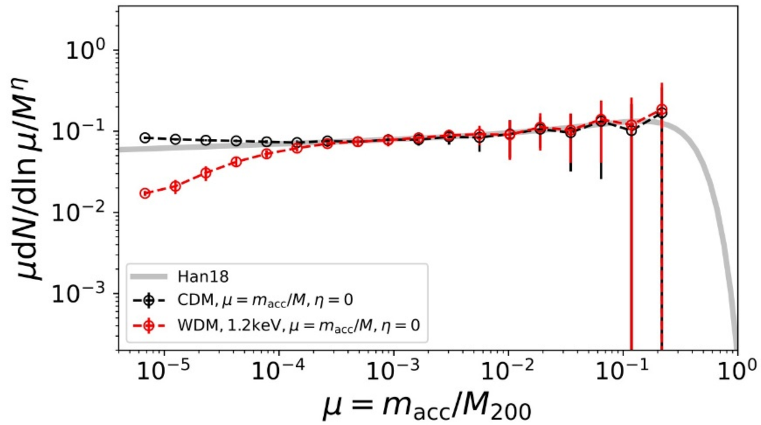
Unevolved spatial distribution



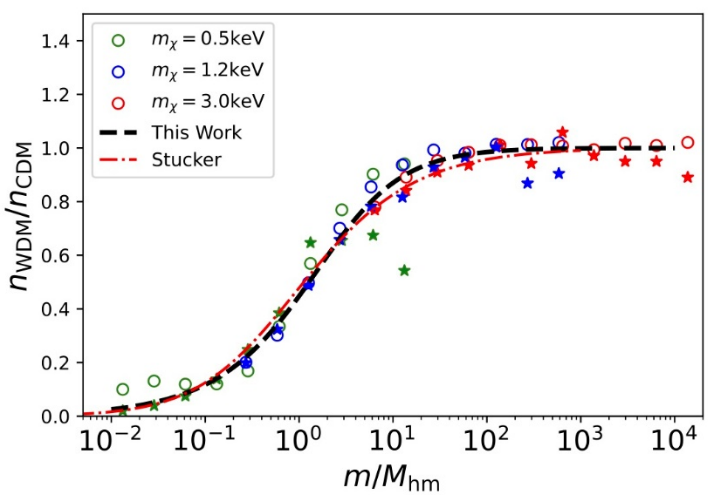
Halo density profile



Unevolved subhalo mass function



The subhalo mass function of WDM is suppressed at the scale below $M_{\rm hm}$ in contrast to CDM.



$$\frac{n_X(M)}{n_{\rm CDM}(M)} \simeq \left(1 + \left(a\frac{M_{\rm hm}}{M}\right)^b\right)^c$$ Stucker et al. 2021

○ : unevolved mass function

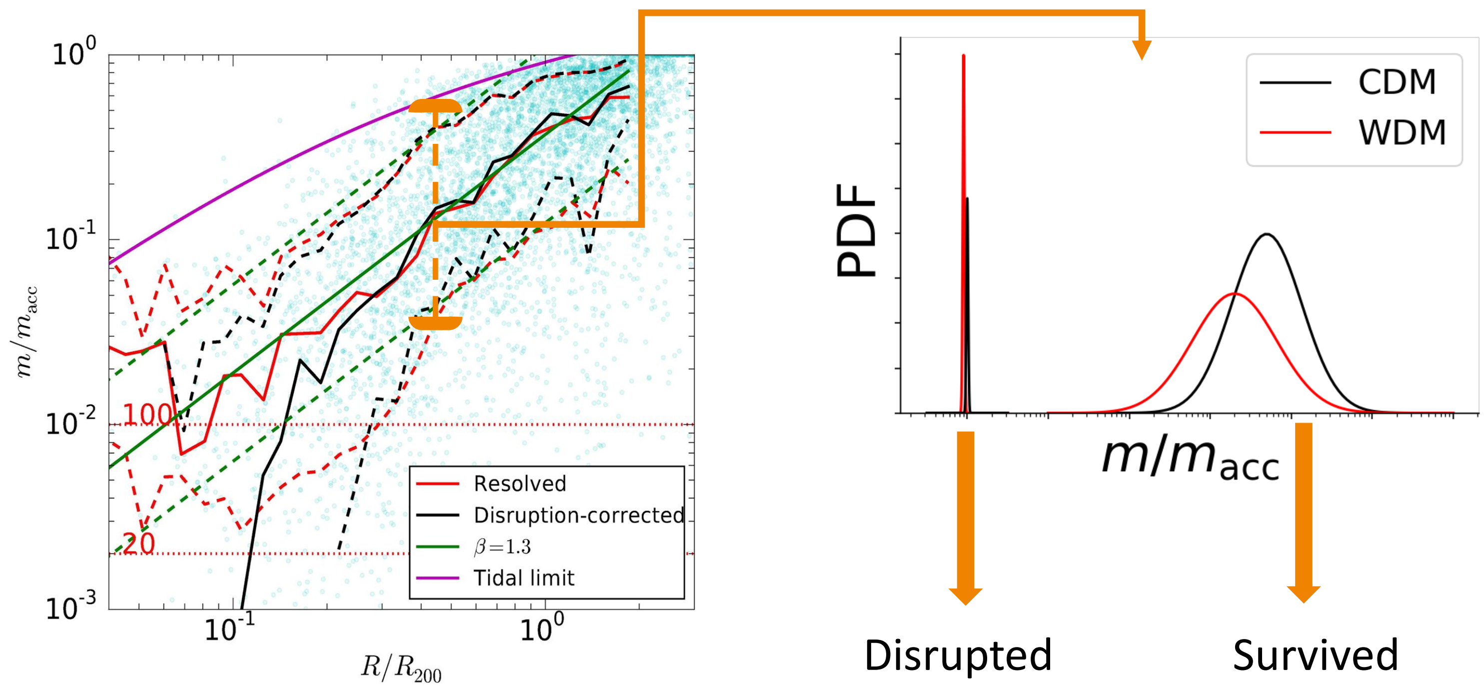
★ : evolved mass function

$a = 2.3$

$b = 1$

$c = -0.68$

Tidal Stripping

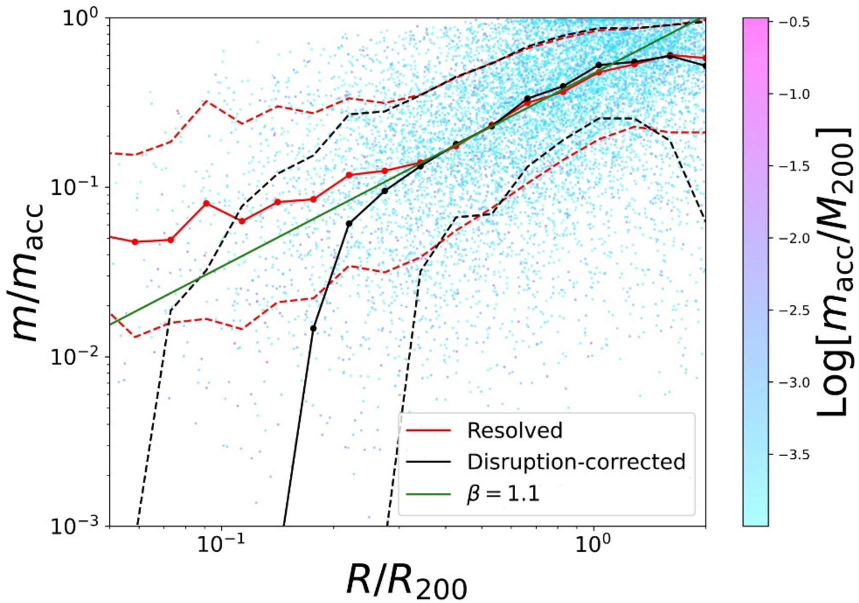


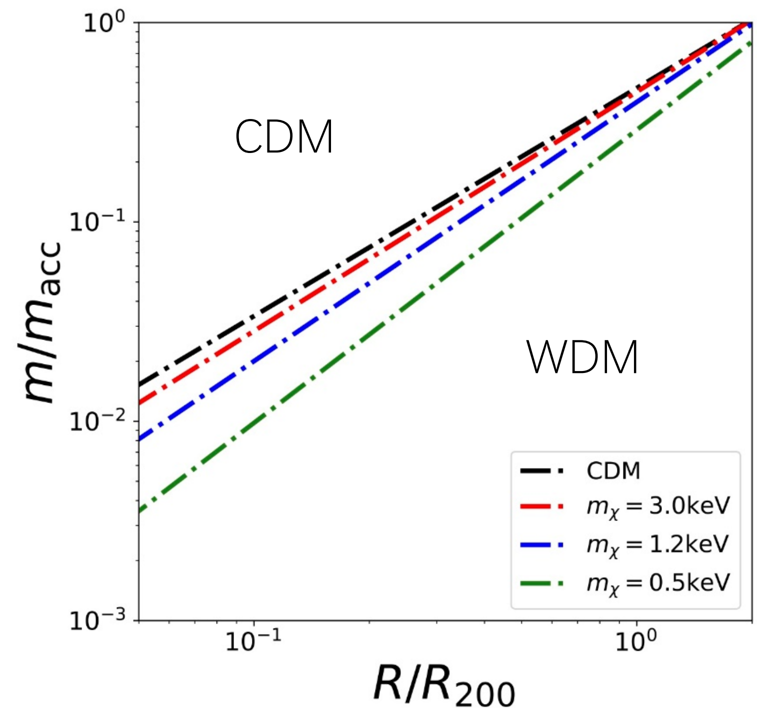
$$\bar{\mu}(R) = \mu_{\star}\left(\frac{R}{R_{200}}\right)^{\beta}$$

The ratio between the final mass and infall mass of a given subhalo is approximately proportional to the halo-centric radius, and the scatter follows the lognormal distribution

Survival fraction depends on subhalo mass, more WDM subhaloes below $M_{\rm hm}$ are disrupted.

Mass Stripping In WDM

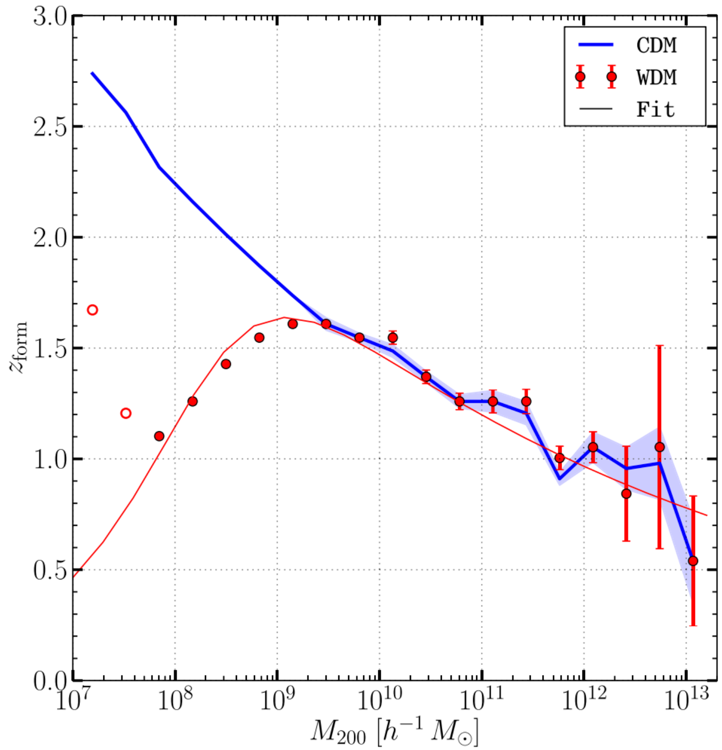




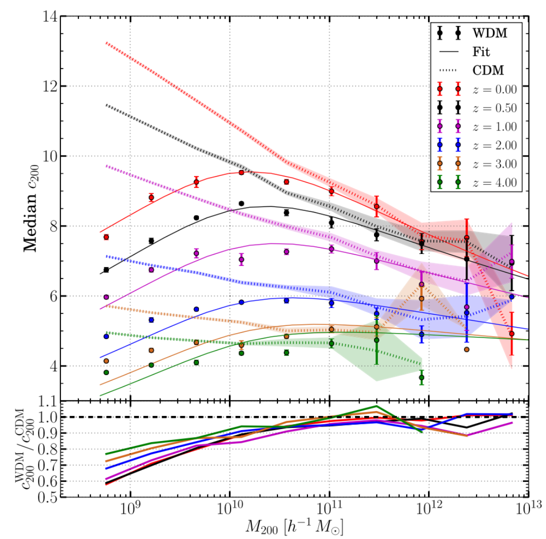
Stronger tidal stripping on WDM subhaloes

Vulnerable to the tidal effects

Halo Concentration



$$\frac{c_{200}^{\rm WDM}}{c_{200}^{\rm CDM}} = \left(1 + \gamma_1 \frac{M_{\rm hm}}{M_{200}}\right)^{-\gamma_2} \times (1+z)^{\beta(z)}$$

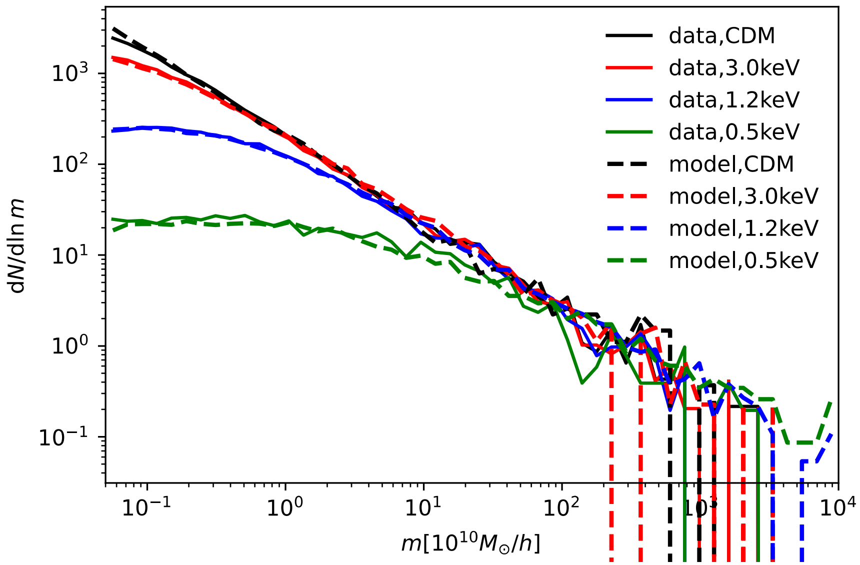


Later formation time of WDM halos leads to lower concentration.

Bose et al. 2016

MCMC Realization

m_χ/keV	$M_{hm}/h^{-1}M_\odot$	μ_*	β	σ
CDM	~	0.48	1.12	0.99
3.0	2.3×10^8	0.46	1.2	1.01
1.2	5.4×10^9	0.42	1.3	1.1
0.5	1.1×10^{11}	0.29	1.45	1.25



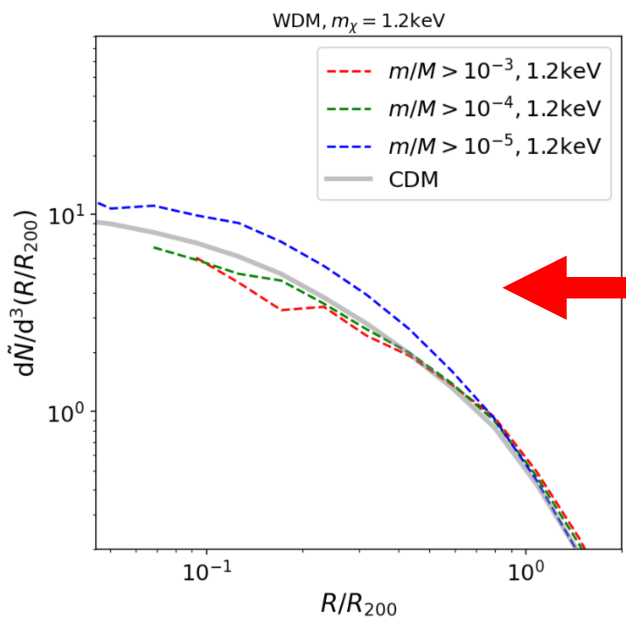
$$\frac{\mathrm{d}N(m,R)}{\mathrm{d}\ln m\,\mathrm{d}^3R} \sim \tilde{\rho}(R)\int_{m_{\min}}^{m_{\max}} f_s(m_{acc})\left[\frac{m_{acc}}{m_0}\right]^{-\alpha}\left(1+\left(\kappa\frac{M_{hm}}{m_{acc}}\right)^{\eta}\right)^{\gamma} \times \exp\left[-\frac{1}{2}\left(\frac{\ln\mu-\ln\bar{\mu}(R)}{\sigma}\right)^2\right]\mathrm{d}\ln m_{acc}$$

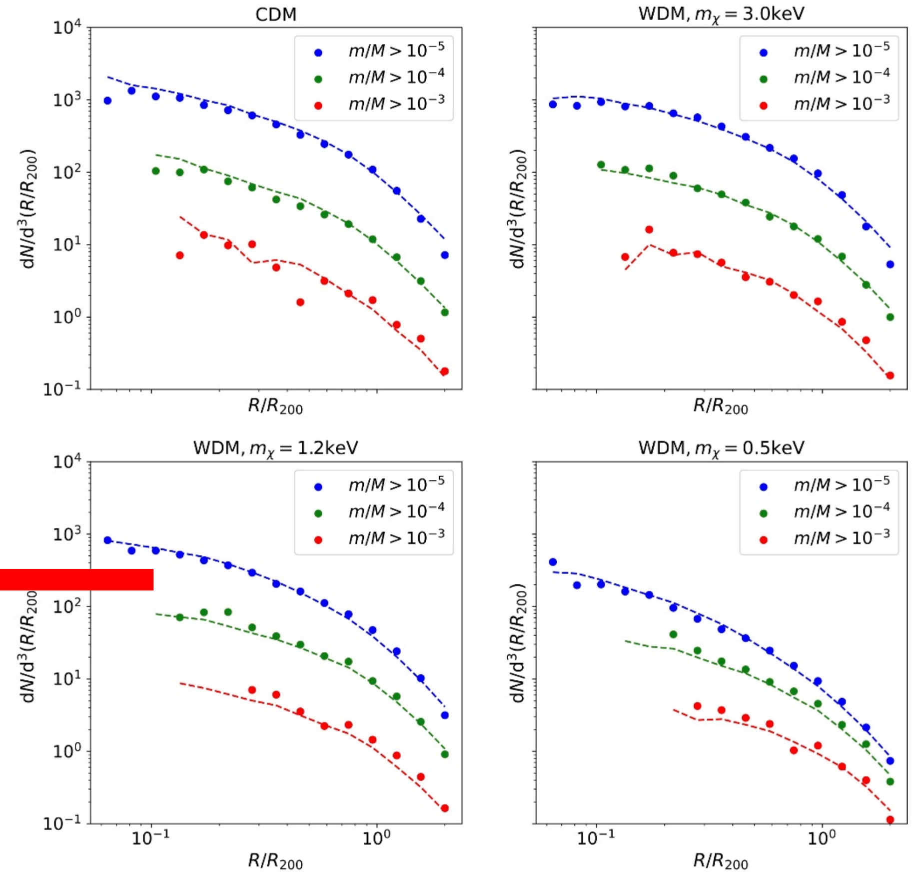
Model Predictions

$$\frac{\mathrm{d}N(m,R)}{\mathrm{d}\ln m} \propto m^{-\alpha} R^{\gamma} \rho(R)$$

Scaled radial number density

depends on both subhalo mass and WDM particle mass.





Summary

- We use a series of high-resolution CDM and WDM simulations to extend the CDM subhalo distribution model to the WDM situation.
- In contrast to the power-law form in CDM, the unevolved subhalo mass function for WDM is suppressed at the low mass end due to the cut-off in the power spectrum.
- WDM subhaloes are more vulnerable to tidal stripping and disruption due to their lower concentrations at accretion time.
- These differences result in a mass-dependent spatial distribution of WDM subhaloes which also depends on the WDM particle mass.