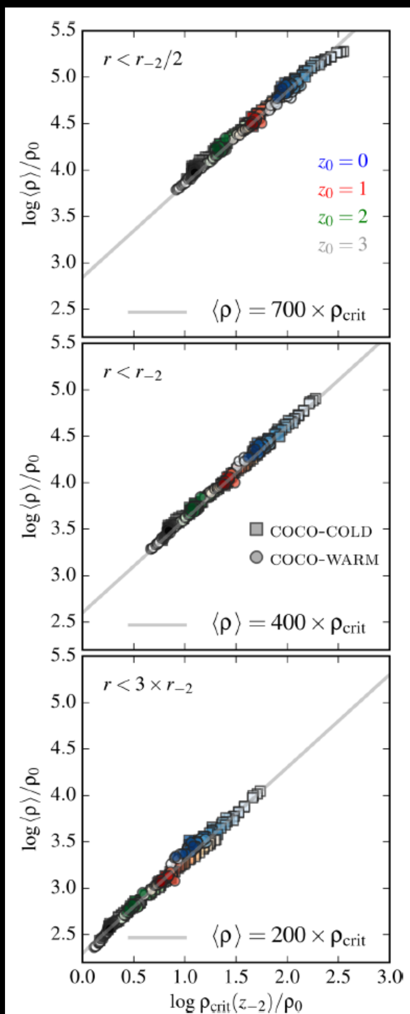
One Theorist's Tool Wishlist for Small Scale Structure

Semi-Analytical Modeling Frameworks (DMO)

KITP CDM18, April 19, 2018

Sheldon Campbell (UC Irvine)

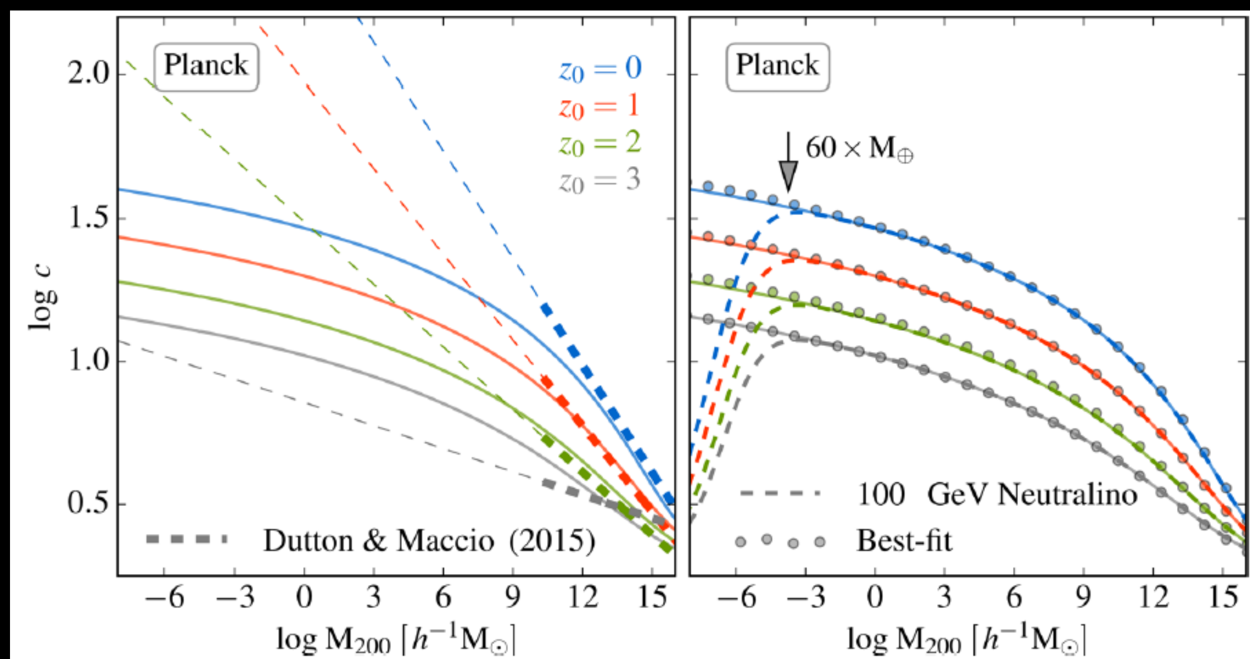
Recent Tools 1: Physical Reasoning for Low Mass Halo Extrapolation?



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **460**, 1214–1232 (2016) doi:10.1093/mnras/stw1046
Advance Access publication 2016 May 3

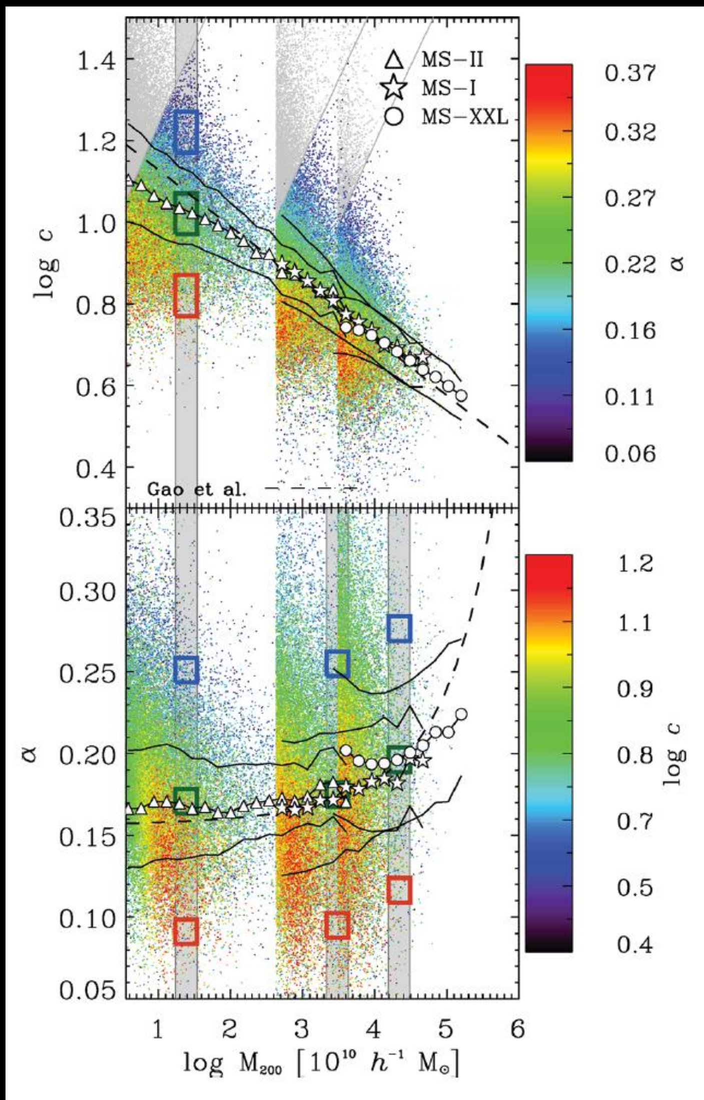
The mass–concentration–redshift relation of cold and warm dark matter haloes

Aaron D. Ludlow,[1★] Sownak Bose,[1] Raúl E. Angulo,[2] Lan Wang,[3] Wojciech A. Hellwing,[1,4,5] Julio F. Navarro,[6†] Shaun Cole[1] and Carlos S. Frenk[1]

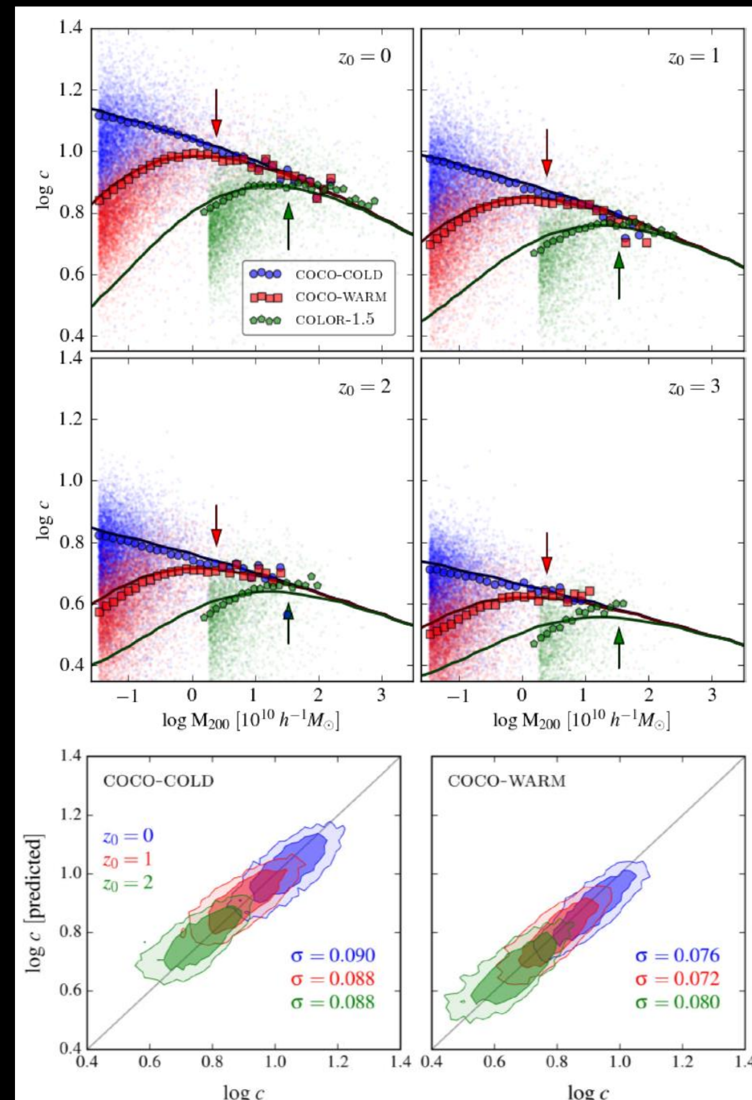


Need Characterization of Scatter

Ludlow+ 2013



Ludlow+ 2016



Recent Tools 2: Universal Subhalo Mass Functions

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **457**, 1208–1223 (2016) doi:10.1093/mnras/stv2900

A unified model for the spatial and mass distribution of subhaloes

Jiaxin Han,[1★] Shaun Cole,[1★] Carlos S. Frenk[1] and Yipeng Jing[2,3]

- Parametrize by subhalo profile at infall (unevolved mass function).
- Modularize subhalo evolution over all orbits & satellite histories (fixed subhalo mass m and position R).
- A natural separation of dependencies:

$$n_{\rm sub}(R, m, m_{\rm acc}, z_{\rm acc}, c_{\rm acc} | M_{\rm host}) \equiv \frac{dN_{\rm sub}}{d^3R \; d{\rm ln}m \; d{\rm ln}m_{\rm acc} \; dz_{\rm acc} \; dc_{\rm acc}}(R, \ln m, \ln m_{\rm acc}, z_{\rm acc}, c_{\rm acc})$$

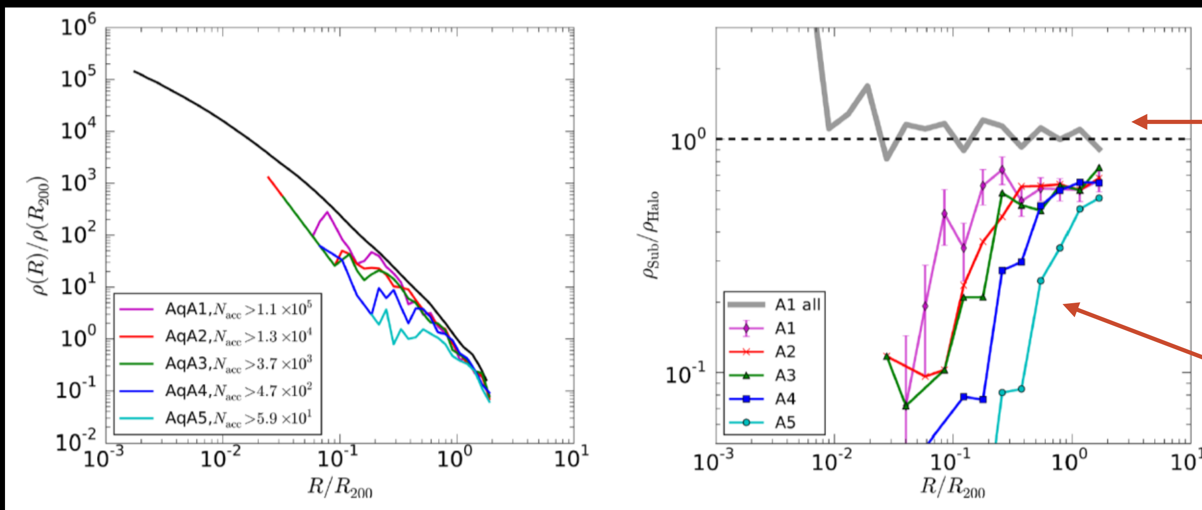
$$= \frac{dN_{\rm sub}}{d^3R \; d{\rm ln}m_{\rm acc} \; dz_{\rm acc} \; dc_{\rm acc}}(R, \ln m_{\rm acc}, z_{\rm acc}, c_{\rm acc} \mid M_{\rm host}) \times T_{\rm ev}(\ln m \mid R, \ln m_{\rm acc}, \ldots)$$

Unevolved Subhalo Mass Function
- distribution of accreted subhalos, independent of their tidal evolution.

Evolution Transfer Function
- what is distribution of subhalo masses at R with given infall time and structure?

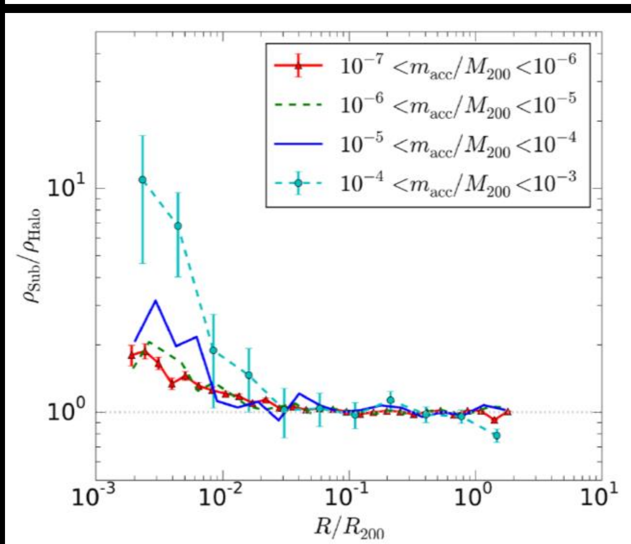
Subhalo Mass Functions: Unevolved Spatial Distribution

Radial distribution is the same as all the other accreted collisionless test masses.



all accreted subhalos

subhalos with $\frac{m_{acc}}{M_{host}} > 10^{-4}$ and resolved at z=0, convergence for $R \gtrsim 0.3\ R_{200}$.



Effect independent of accreted mass for $R \gtrsim 0.03\ R_{200}$.

$$\frac{dN_{sub}}{d^3R\ d\ln m_{acc}\ dz_{acc}\ dc_{acc}} \propto \rho_{host}(R)$$

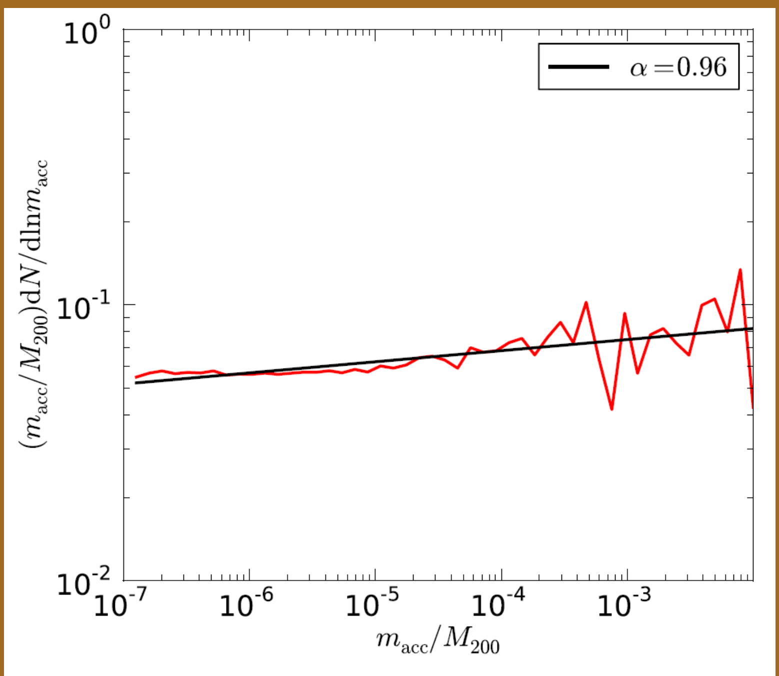
Unevolved Subhalo Mass Function

$$\frac{dN_{\mathrm{sub}}}{d^3R\, d\ln m_{\mathrm{acc}}\, dz_{\mathrm{acc}}\, dc_{\mathrm{acc}}} = A_{\mathrm{acc}} \frac{M_{\mathrm{host}}}{m_0} \left(\frac{m_{\mathrm{acc}}}{m_0}\right)^{-0.95} \frac{\rho_{\mathrm{host}}(R)}{M_{\mathrm{host}}}\, P(z_{\mathrm{acc}}|m_{\mathrm{acc}})\, P(c_{\mathrm{acc}}|m_{\mathrm{acc}}, z_{\mathrm{acc}})$$

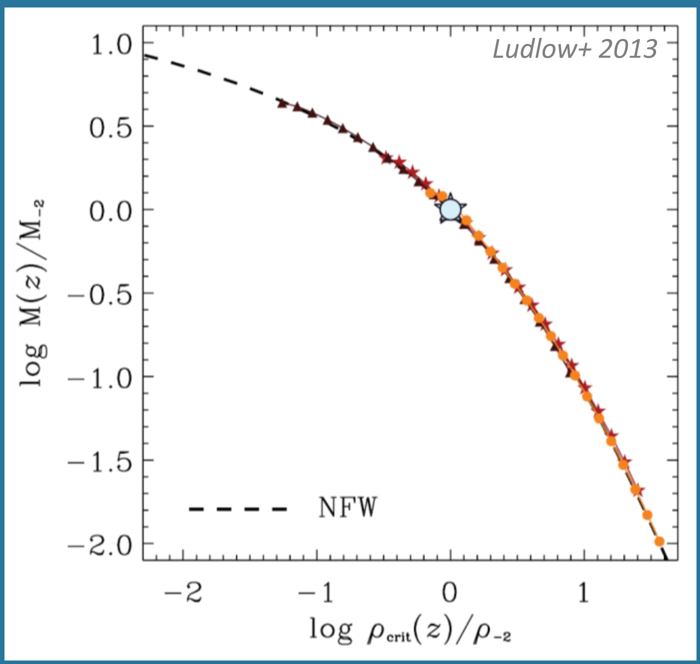
Field Halo Concentration Distribution

Constrained Field Halo MF

Inclusive Subhalo MF



Host Accretion History

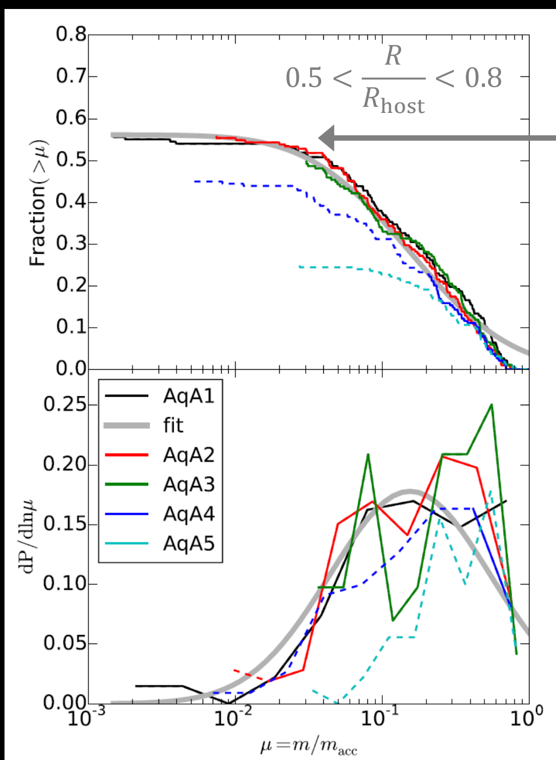


Evolution Transfer Function for CDM

$$T_{\rm ev}(\ln m \mid R, \ln m_{\rm acc}, z_{\rm acc}, c_{\rm acc}, M_{\rm host})$$

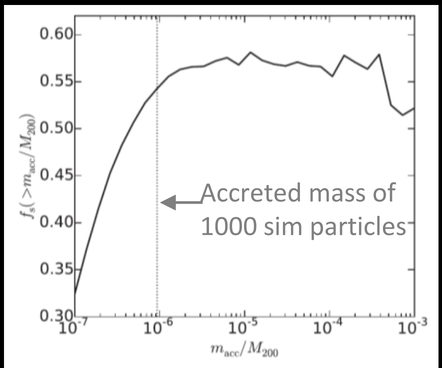
Key observation in Han+ 2017:

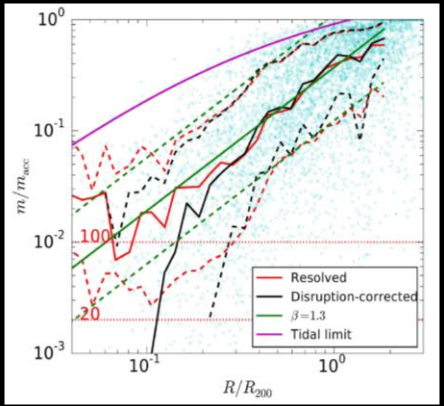
$\frac{m}{m_{\rm acc}}$ is approximately log-Gaussian distributed at each R.



Cumulative distribution saturates at subhalo survival fraction $f_s \simeq 0.55$.

There is no detectable mass or R dependence of f_s or distribution width σ.





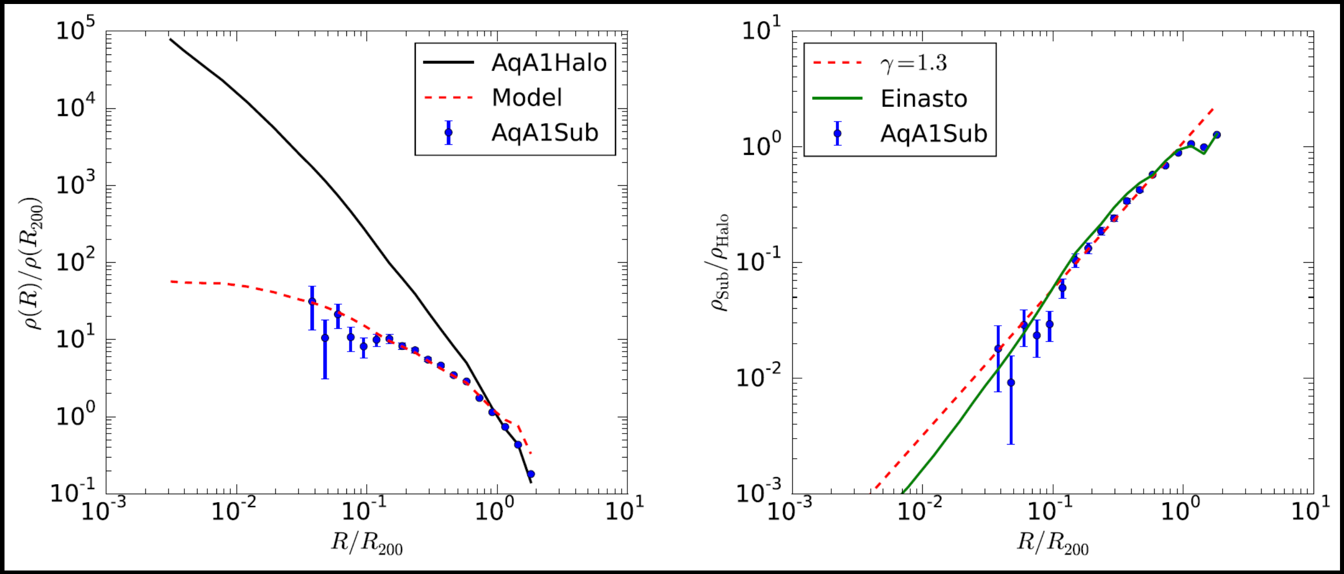
Evolution Transfer Function for CDM

$$T_{\mathrm{ev}}(\ln m \mid R, \ln m_{\mathrm{acc}}, z_{\mathrm{acc}}, c_{\mathrm{acc}}, M_{\mathrm{host}}) \simeq \frac{f_s}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\left(\ln \frac{m}{m_{\mathrm{acc}}} - \ln \bar{\mu}(R)\right)^2}{2\sigma^2}\right]$$

The only detectable radial dependence is in the mean mass loss

$$\bar{\mu}(R) = \mu_* \left(\frac{R}{R_{\mathrm{host}}}\right)^{\beta}.$$

This and the host density profile generate the total MF radial dependence.



Toy Small Scale Structure CDM Model

1. $P(z_{\rm acc}|m_{\rm acc}) = \delta(z_{\rm acc} - z_0)$ All substructure accreted at the same redshift.

2. $P(c_{\rm acc}|m_{\rm acc}, z_0) = \delta(c_{\rm acc} - \bar{c}(m_{\rm acc}, z_0))$ Neglect scatter in the concentration relation.

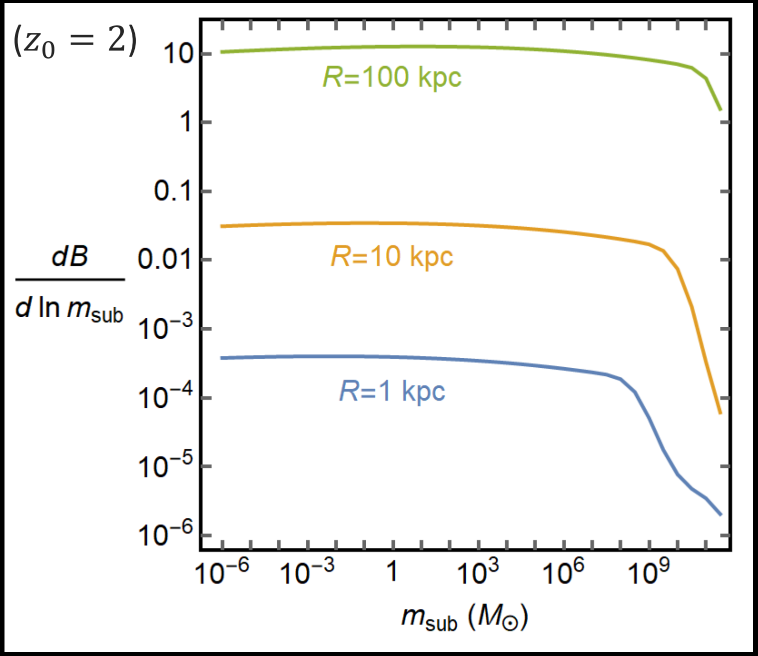
3. Use a truncation model: density profile is the same as infall, but the virial radius is truncated to reduce the mass from $m_{\rm acc}$ to m.

Dark Matter Annihilation Substructure Boost Factors

Define boost B at position R: $\langle \rho^2(R) \rangle = \langle \rho(R) \rangle^2 \, [1 + B(R)]$

$$B(R) = \int d\ln m \, d\ln m_{\mathrm{acc}} \, d^3 R_{\mathrm{sub}} \, n_{\mathrm{sub}}(R, m, m_{\mathrm{acc}}) \left[\frac{\rho_{\mathrm{sub}}(|\boldsymbol{R} - \boldsymbol{R}_{\mathrm{sub}}|, m, m_{\mathrm{acc}})}{\rho_{\mathrm{host}}(R)} \right]^2$$

Contributions of each subhalo mass to $B(R)$ at different positions in a $10^{12}\ M_\odot$ halo.

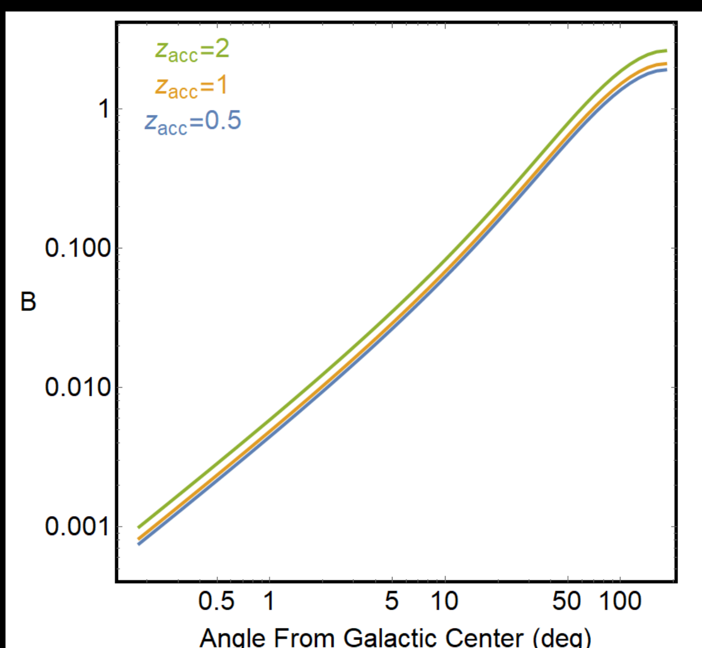


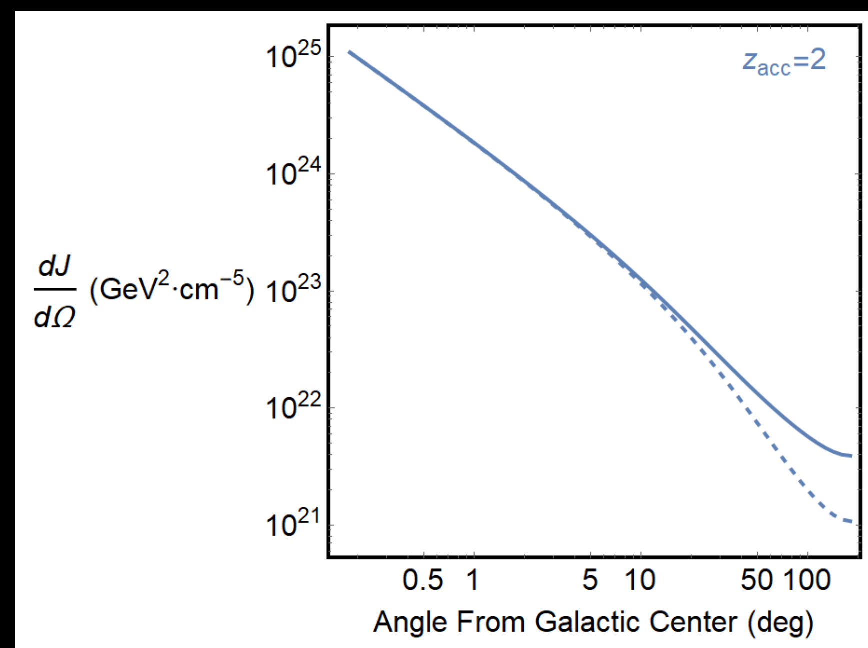
Dark Matter Annihilation Substructure Boost Factors

Similarly for Milky Way J-factors along each line of sight.

$$\frac{dJ}{d\Omega}(\boldsymbol{n}) = \int ds\, \rho^2(s, \boldsymbol{n})$$

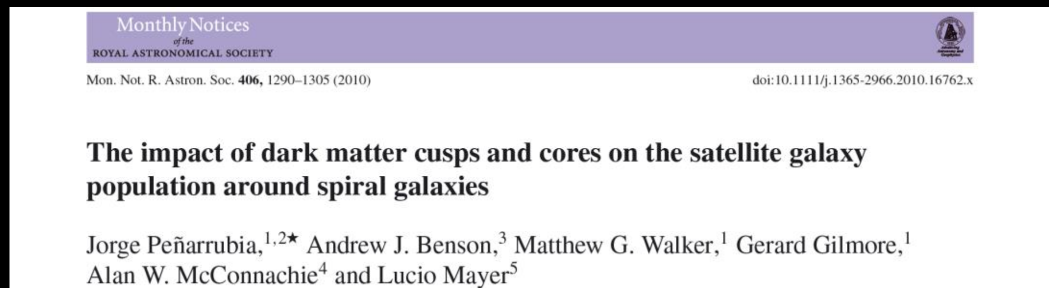
$$\frac{dJ_{\text{tot}}}{d\Omega}(\boldsymbol{n}) = \frac{dJ_{\text{host}}}{d\Omega}(\boldsymbol{n})\,[1 + B(\boldsymbol{n})]$$





Recent Tools 3: Subhalo Tidal Tracks

Model tidal mass loss as dominated by tidal shock at pericenter passage (closest approach).



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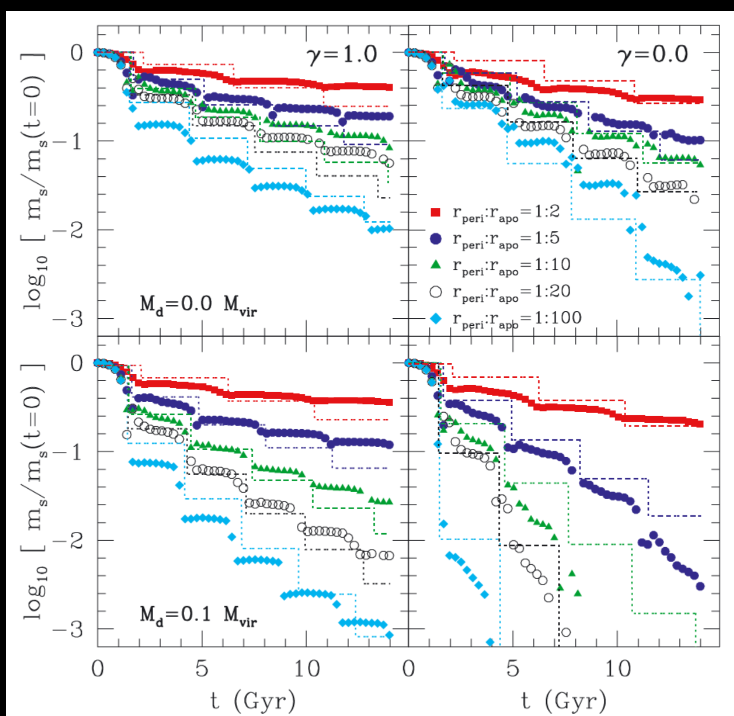
Mon. Not. R. Astron. Soc. **406,** 1290–1305 (2010) doi:10.1111/j.1365-2966.2010.16762.x

The impact of dark matter cusps and cores on the satellite galaxy population around spiral galaxies

Jorge Peñarrubia,[1,2★] Andrew J. Benson,[3] Matthew G. Walker,[1] Gerard Gilmore,[1] Alan W. McConnachie[4] and Lucio Mayer[5]



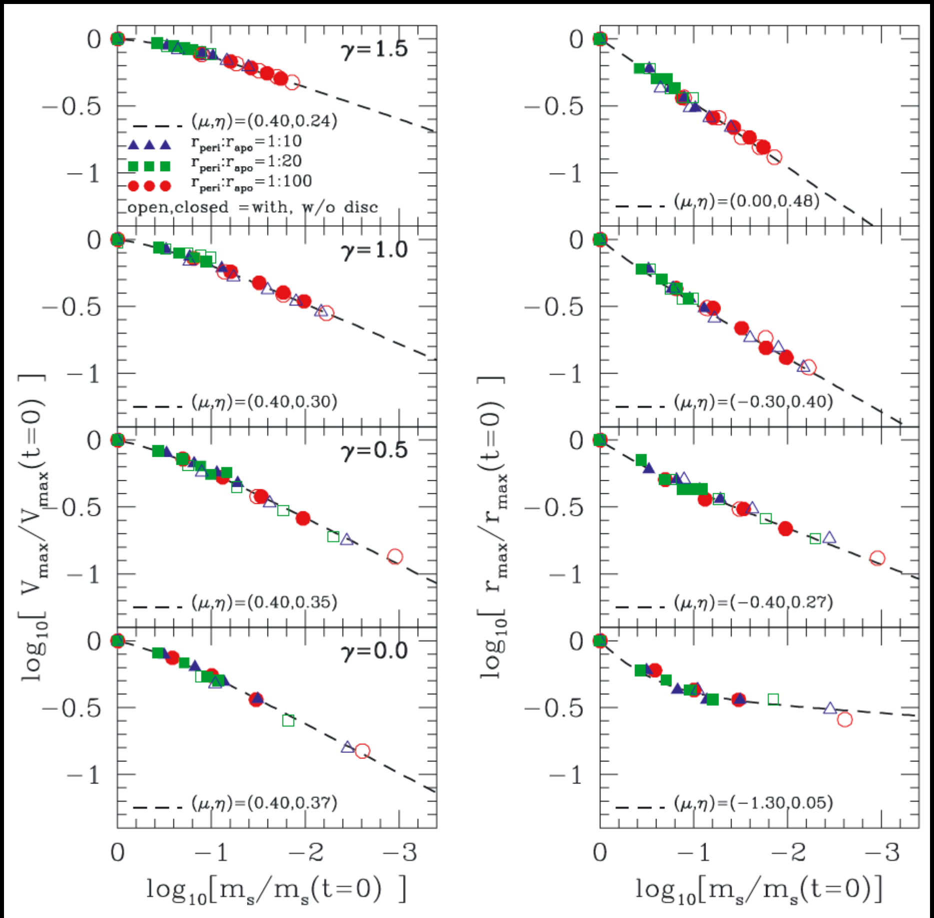
$r_{\mathrm{apo}} = 0.7\, R_{\mathrm{vir}}$

Dots: Subhalo mass in simulation.
Dashes: Model's mass loss after peri pass.

Model: Truncate the subhalo at its tidal radius.

$$r_t \simeq \left(\frac{m_{\mathrm{sub}}(< r_t)}{\omega^2 - \frac{d^2\Phi_{\mathrm{host}}}{dr^2}} \right)^{1/3}$$

Tidal Tracks: Modified subhalo profile depends only on mass loss and γ.



$$y(x) = \frac{2^{\mu} x^{\eta}}{(1+x)^{\mu}}$$

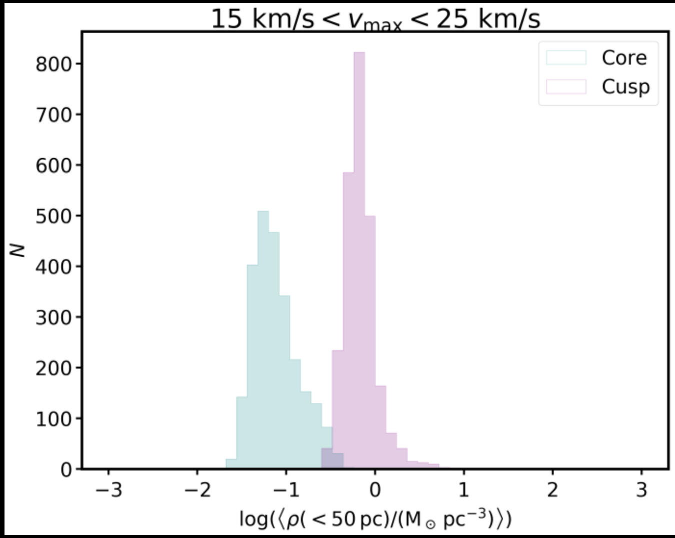
x is $\frac{m}{m_{\mathrm{acc}}}$

y is $\frac{V_{\max}}{V_{\max,\mathrm{acc}}}$ or $\frac{r_{\max}}{r_{\max,\mathrm{acc}}}$

Example Application: Properties of Dwarf Satellites

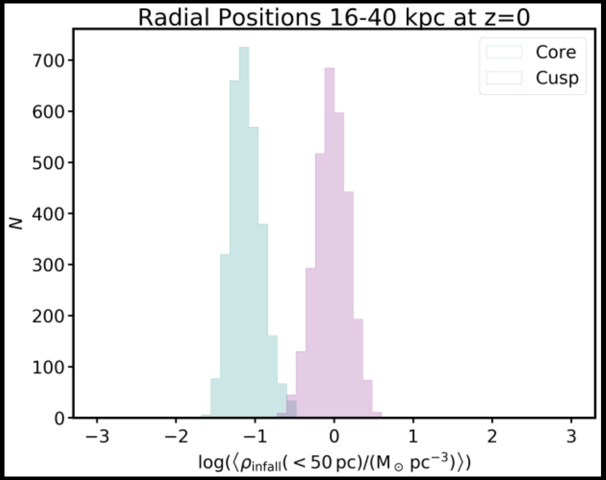
- Sample subhalo orbit histories from simulations (e.g., Elvis, Aquarius, …)
- Sample halo mass function for infall halos at infall redshift of each history.
- Use reionization model to estimate fraction of subhalos that are without stars.

What is this model's distribution (within 200 kpc) of satellite inner densities (within 50 pc) with profiles $15\ \mathrm{km/s} < v_{\mathrm{max}} < 25\ \mathrm{km/s}$?



Example Application: Properties of Dwarf Satellites

Distribution of satellite inner densities for satellites located $16\ \mathrm{kpc} < R_{\mathrm{sub}} < 40\ \mathrm{kpc}$?



Distribution of infall masses for these objects.