CDM subhalo concentrations and implications for DM annihilation signals

[based on: arXiv:1603.04057]

Ángeles Moliné - Centro de Física Teórica de Partículas

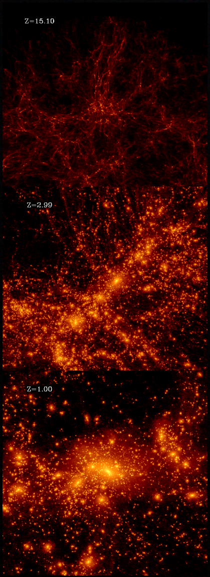
In collaboration with M. Sánchez-Conde, Sergio Palomares-Ruiz and F. Prada

MultiDark Galaxies Workshop

La Plata, September 27, 2016

ΛCDM paradigm

In the standard theoretical framework for structure formation, the Universe is dominated by a cosmological constant and cold, collisionless dark matter.

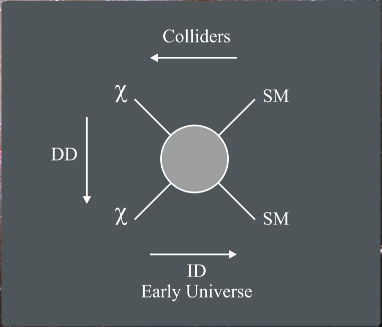


- Small density perturbations grow via gravitational instability, forming bound structures
  $\longrightarrow$ *DM halos*
- Galaxies form hierarchically, with low-mass halos collapsing earlier and merging to form larger and larger systems over time
- The galaxies are embedded in massive, extended DM halos teeming with self-bound substructure $\longrightarrow$ *subhalos*

Dark Matter detection

A good candidate for dark matter is a weakly interacting massive particle(WIMP), with mass lying from the GeV to the TeV scale.

- Direct detection: The WIMPs that pass through the Earth can be detected by their interaction with matter. The experiments measure the recoil energy of nuclei produced by dark matter scattering.
- Indirect detection: The way to indirectly detect DM is via annihilations or decay products as gamma-rays, antimatter and neutrinos.
- Collider experiments: produce dark matter particles from the collision of SM paticles.



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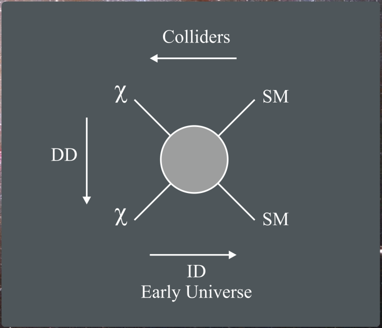
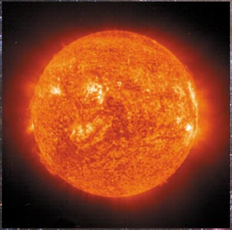
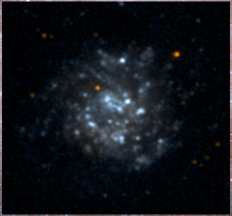


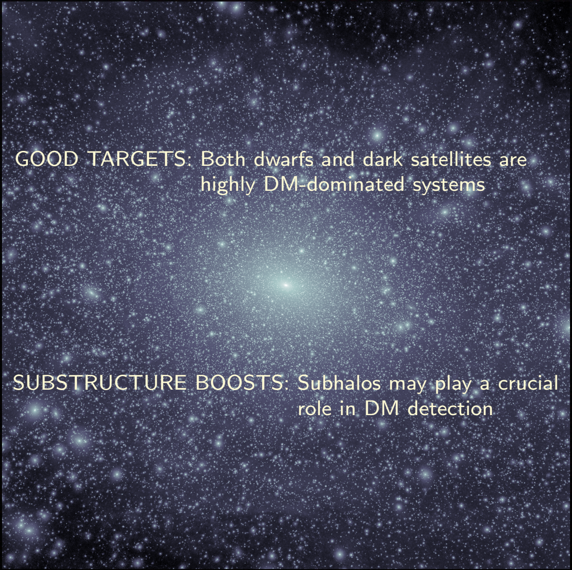
Indirect detection:

Signals are expected from the center of the our galaxy, the whole halo, halo substructure, dwarf galaxies, other astrophysical object such as Sun, etc.





Subhalos:



Diemand et al. 2008 - The Via Lactea Project

The estimate of the diffuse extragalactic flux of neutrinos of flavour α due to dark matter annihilations:

$$\frac{d\phi_{\nu_\alpha}}{dE_0} = \underbrace{\frac{\rho_{\mathrm{m},0}^2}{2} \int \frac{dz}{H(z)}\, \xi^2(z)}_{\text{astrophysics}}\ \underbrace{\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2} \sum_{\beta,i} |U_{\alpha,i}|^2\, |U_{\beta,i}|^2 \sum_j \mathrm{Br}_j \frac{dN_{\nu_\beta,j}(E_0(1+z))}{dE}}_{\text{particle physics}},$$

astrophysics particle physics

with,

$\langle\sigma v\rangle$: the annihilation cross section multiplied by velocity,

$\frac{dN_{\nu_\beta,j}}{dE}$: the differential energy spectrum for the number of neutrinos of flavour β at emission,

Br_j: branching ratio of channel j, U: the leptonic mixing matrix,

$\rho_{\mathrm{m},0}$: the dark matter background density, $E = E_0(1+z)$

$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$, H_0: the Hubble constant,

$\xi^2(z)$: the enhancement of the annihilation signal arising due to the clustering of DM into halos and subhalos.

$\xi^2(z)$ description:

$$\xi^2(z) = \frac{\Delta(z)\,\rho_c(z)}{\rho_{m,0}} \int_{M_{min}} dM \,\frac{M}{\rho_{m,0}}\,\frac{dn(M,z)}{dM} \int dc\, P(c)\, \xi^2_{M}(M,c;z)$$

$\xi^2_M(M,z)$ gives the average enhancement in the flux due to a generic halo

$$\xi^2_{M}(M,c;z) \propto \frac{\int 4\pi r^2 \rho^2(r;M,c)\,dr}{(\int 4\pi r^2 \rho(r;M,c)\,dr)^2}\ ,$$

c: the concentration parameter, $P(c)$: the distribution of concentration parameters

$$c(M,z) = \frac{r_\Delta}{r_s}; \qquad \rho_{NFW}(r/r_s) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}, \quad r_s : \text{scale radius}$$

DM halo at redshift z is characterized by one parameter Δ:

$$M = \frac{4\pi}{3}\Delta\,\bar{\rho}(z) r^3_\Delta; \qquad \Delta = cte \ \text{ or } \ \Delta = \Delta_{vir}(z)\,.$$

Δ: the overdensity with respect to the mean density of the universe, $\bar{\rho}(z)$.

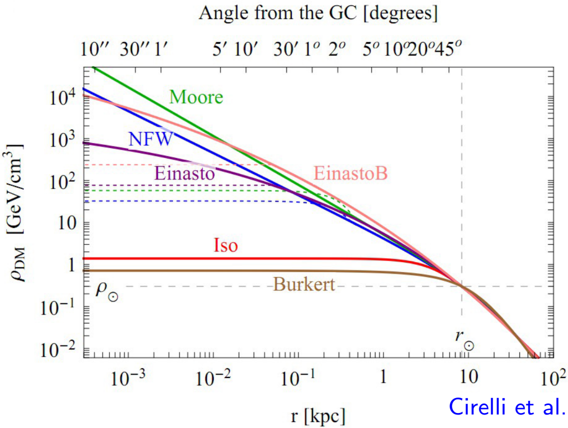
$\xi^2(z)$ description:

$\xi^2(z) = \frac{\Delta(z)}{\rho_m}$

$\xi^2_M(M, z)$ gives the

c: the concentration p ... ers

$c(M, z) =$ ... s



Cirelli et al., 2012

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The presence of substructure could produce an enhancement (or boost) over the expected signal from the smooth distribution of DM in the host halo

$$\xi^2(z) = \frac{\Delta(z)\,\rho_{\rm c}(z)}{\rho_{\rm m,0}} \int_{M_{\rm min}} dM \,\frac{M}{\rho_{\rm m,0}} \frac{dn(M,z)}{dM} \left[1 + B(M)\right] \xi^2_{\rm M}(M,c;z)$$

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- DM annihilation boost factor from substructure

$$B(M) = \frac{4\,\pi\,R^3_{vir}}{\mathcal{L}_{smooth}(M)} \int_{M_{min}}^{M} \int_0^1 \frac{dn(m,x_{sub})}{dm}\,\mathcal{L}(m,x_{sub})\,x^2_{sub}\,dx_{sub}\,dm$$

- Subhalo luminosity

$$\mathcal{L}(m,x_{sub}) \equiv \int_0^{R_{sub}} \rho^2_{sub}(r)\,4\,\pi\,r^2\,dr, \qquad x_{sub} = \frac{R_{sub}}{R_\Delta}$$

$$\propto \rho^2_s\,r^3_s \propto m\,\frac{c^3(m,x_{sub})}{f^2\,(c(m,x_{sub}))}$$

$f(c) = \ln(1+c) - c/(1+c)$

$dn/dm \propto (m/M)^{-\alpha}$: subhalo mass function

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- Subhalo luminosity

$$\mathcal{L}(m, x_{\rm sub}) \quad \equiv \quad \int_0^{R_{\rm sub}} \rho^2_{\rm sub}(r) \, 4\,\pi\, r^2 \, dr, \qquad x_{\rm sub} = \frac{R_{\rm sub}}{R_\Delta}$$

$$\propto \quad \rho_s^2 \, r_s^3 \propto m \, \frac{c^3(m, x_{sub})}{f^2\,(c(m, x_{sub}))}$$ $\longrightarrow$ very sensitive to subhalo concentration!

$f(c) = \ln(1 + c) - c/(1 + c)$

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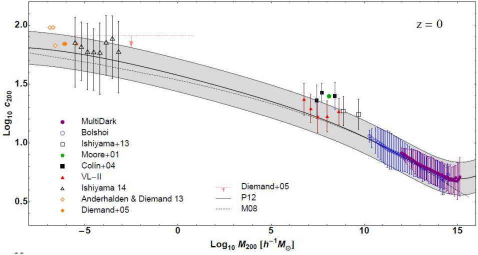
(Sub)halo internal structure: The Concentration Parameter

$$\boxed{c^{halo} \neq c^{subhalo}} \ (?)$$

- c_Δ



Sánchez-Conde & Prada, 2014

$$c_\Delta = \frac{R_{\rm vir}}{r_s} \quad \text{(NFW)}$$

r_s: scale radius
$R_{\rm vir}$: virial radius

$$M_{\rm vir} = \frac{4\pi}{3} \Delta\, \bar{\rho}(z) R_{vir}^3$$

Δ: overdensity with respect to the mean density of the universe

- c_V

$$c_V = \frac{\bar{\rho}(R_{\rm max})}{\rho_c} = 2\left(\frac{V_{\rm max}}{H_0 R_{\rm max}}\right)^2$$

$R_{\rm max}$: radius of peak circular velocity
$V_{\rm max}$: maximum circular velocity

⇒ more robust definition for subhalos
⇒ independent of a density profile

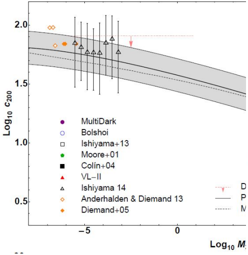
- c_V - c_Δ

$$c_V = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\rm max}/r_s)}{f(c_\Delta)} \Delta, \qquad m_\Delta = \frac{f(c_\Delta)}{f(2.163)} \frac{R_{\rm max} V_{\rm max}^2}{G}.$$

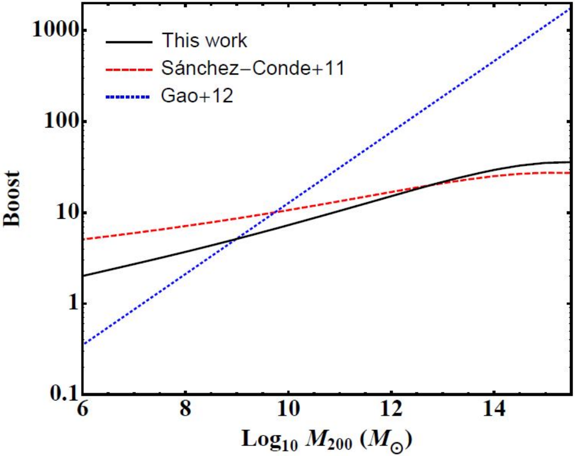
(Sub)halo internal structure: The Concentration Parameter

$$c^{halo} \neq c^{subhalo}$$ (?)

- c_Δ



Sánchez-Conde &



Sánchez-Conde & Prada, 2014

- c_V

$$c_V = \frac{\bar{\rho}(R_{ma}}{\rho_c}$$

$R_{\max}$: radius of peak circu
$V_{\max}$: maximum circular

or

- c_V - c_Δ

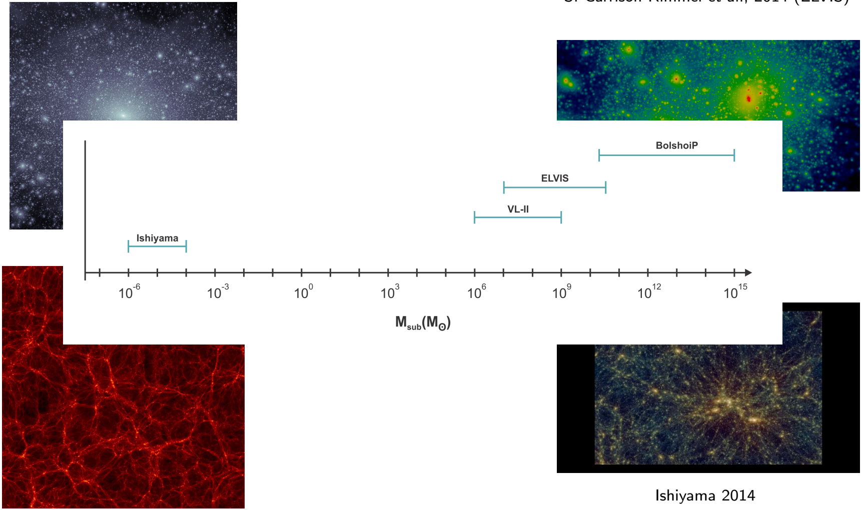
$$c_V = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\max}/r_s)}{f(c_\Delta)} \Delta\,, \qquad m_\Delta = \frac{f(c_\Delta)}{f(2.163)} \frac{R_{\max}\, V^2_{\max}}{G}\,.$$

Our work

Simulations

J. Diemand et al., 2008 (VL II)

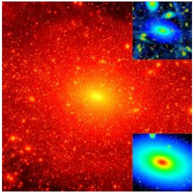
S. Garrison-Kimmel et al., 2014 (ELVIS)



Ishiyama 2014

Anatoly Klypin et al. (BolshoiP)

VL-II

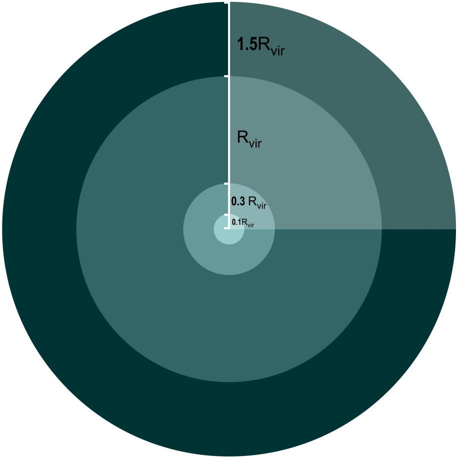


J. Diemand et al., 2008

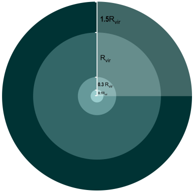
Via Lactea simulations follow the formation and evolution of a Milky-Way-size halo.

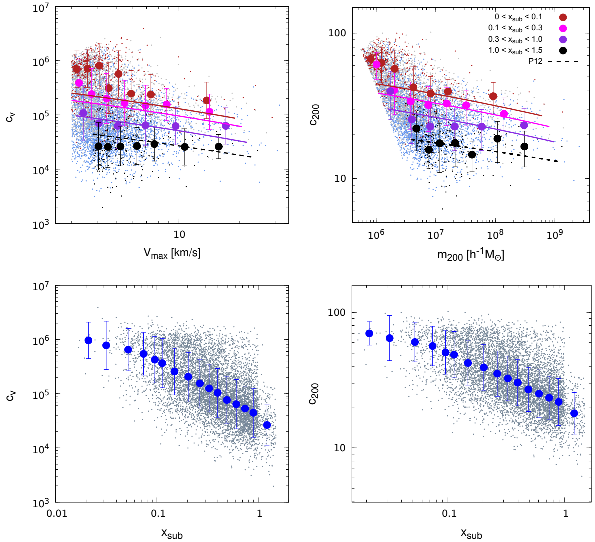
- VL-II employs just over one billion $4100\ M_{\odot}$ particles to model the formation of a M_{200}=1.93 x $10^{12}\ M_{\odot}$ halo and its substructure.
- Resolve about 53000 individual subhalos within the host halo's r_{200}=402 kpc
- VL-II adopted ΛCDM parameters from the WMAP 3 year data release.

We have obtained the medians of c_V and c_{200} in three radial bins



Results - VL II





- Only subhalos larger than V_{max} =3 km s^{-1} are included
- We have obtained the medians of c$_V$ and c$_{200}$ in three radial bins
- We have considered a calibration bin to compare the halos with subhalos concentrations
- A calibration bin has been included beyond Rvir to estimate field halo concentrations using the same simulation
- Median subhalo concentration increases towards the halo center for subhalos of the same mass
- Subhalo concentrations are signifcantly larger than those of field halos

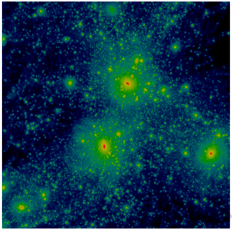
Bin 1: 182 sub, Bin 2: 2156 sub, Bin 3: 4576 sub, C B: 218 sub.

ELVIS: Exploring the Local Volume in Simulations

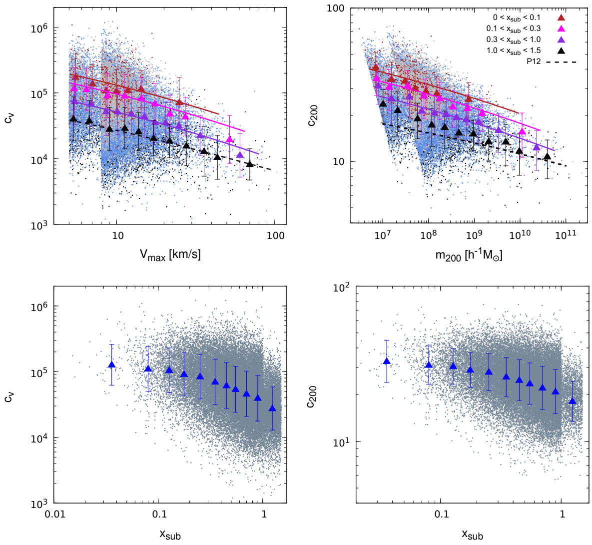
S. Garrison-Kimmel et al., 2014

- ELVIS is a set of high-resolution simulations that model the Local Group
- The suite contains 48 Galaxy-size haloes and three halos of higher resolution, each within volumes that span 2-5 Mpc in size with particle mass m_p=1.9 x 10^5 $M_\odot$
- Half of the Galaxy haloes are in paired configurations, the other half haloes are isolated, mass-matched analogs
- ELVIS has adopted WMAP 7 cosmological parameters.

Thelma (Bottom) & Louise (Top)



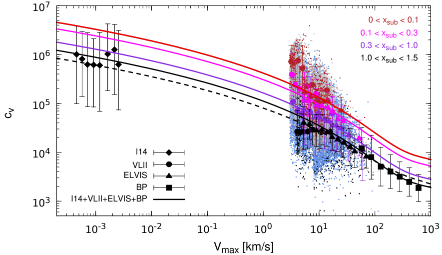
Results - ELVIS



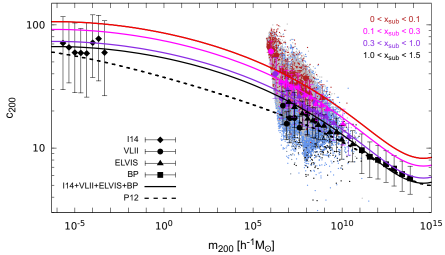
- We create a single simulation data set containing both the 48 halos and the 3 with higher resolution
- For the suit of the high resolution halos, only subhalos larger than $V_{max} = 5$ km s^{-1} are included and for the other 48 halos we consider all data provided by the simulation ($V_{max} > 8$ km s^{-1}).
- We implemented three radial bins and a calibration bin, as it was done with VL-II
- We have obtained median subhalo concentrations in three radial bins
- Median subhalo concentration increases towards the halo center for subhalos of the same mass
- Subhalo concentrations are signifcantly larger than those of field halos

Bin 1: 86 sub, Bin 2: 4442 sub, Bin 3: 17592 sub, C B: 5282 sub.

Results - Parametrizations for the median subhalo concentrations



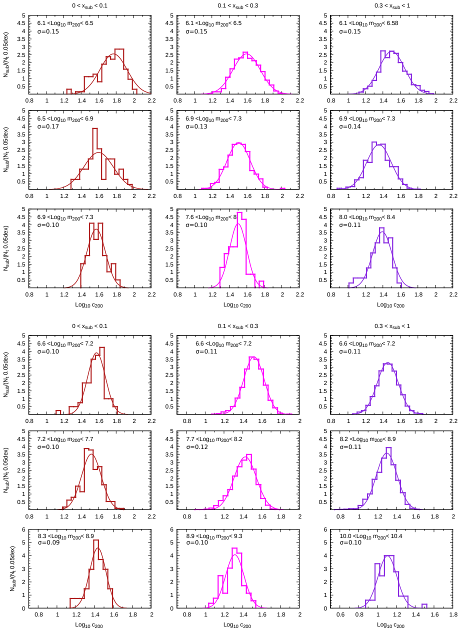
$$c_V(V_{max}, x_{sub}) = c_0 \left[1 + \sum_{i=1}^{3}\left[a_i \log\left(\frac{V_{max}}{10\,\mathrm{km/s}}\right)\right]^i\right] \cdot [1 + b \log(x_{sub})]$$



$$c_{200}(m_{200}, x_{sub}) = c_0 \left[1 + \sum_{i=1}^{3}\left[a_i \log\left(\frac{m_{200}}{10^8 h^{-1} M_\odot}\right)\right]^i\right] [1 + b \log(x_{sub})]$$

- Good agreement between VL-II and ELVIS except in the innermost regions
- Field halo concentrations agree well with expectations.

Scatter of the c_{200} concentration parameter: log-normal distribution



VL-II

$\sigma_{\log c_{200}} \sim 0.13$

ELVIS

$\sigma_{\log c_{200}} \sim 0.11$

Results - Boost

Subhalos suffer from
tidal forces
within their host halos $\longrightarrow$ are expected to be truncated at some radius $r_t < r_\Delta$

$\searrow$

subhalo luminosity must be truncated at r_t
instead of r_Δ

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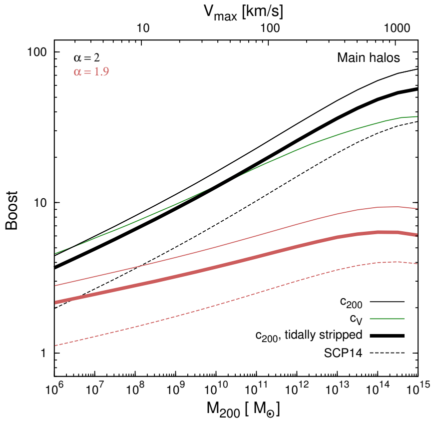

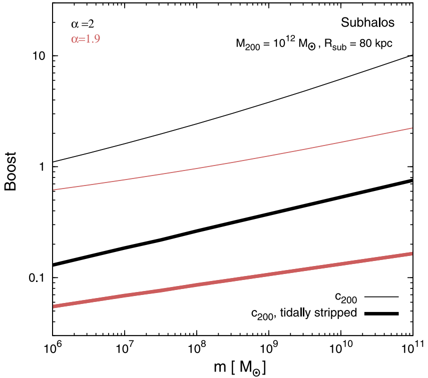

Summary

- Study subhalo properties as a function of the distance to the host halo center and subhalo mass
- Used a concentration parameter independent of a density profile $(c_{\rm V})$
- Subhalo concentration increases towards the halo center for subhalos of the same mass and are significantly larger than those of field halos
- Provide a set of fits that, including both mass and radial dependences, accurately describe the subhalo structure and its role on the search for DM via its annihilation products
- Improved the model in Sánchez-Conde and Prada (2014).
- In order to improve these analysis, it exists a clear need to have more information about the properties of halos and subhalos in a larger range of mass and redshifts

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Thank you