Subhalo properties in an interacting dark matter scenario

[based on arXiv:1907.12531]

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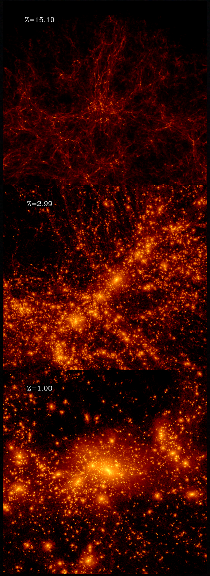
ΛCDM paradigm

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*

Is the ΛCDM the right answer?

Is the ΛCDM the right answer?

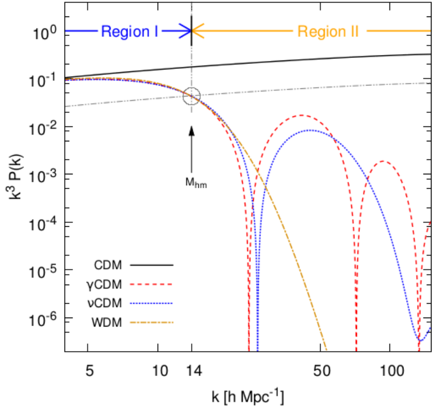
- Absence of a overwhelming DM signal for CDM and the lack of evidence in collider experiments
- Profiles of Galaxy Haloes: halo mass profiles with cuspy cores and low outer density while lensing and dynamical observations indicate a central core of constant density and a flattish high dark mass density outer profile (e.g. Broadhurst et al., 2005, Frenk and White, 2012)
- *"Too big to fail problem"*: dwarf galaxies are expected to be hosted by halos that are significantly more massive than indicated by the measured galactic velocity (e.g. Boylan-Kolchin et al., 2011)
- *"Milky Way satellite problem"*: The abundance of dark matter substructures predicted by numerical simulations of structure formation exceeds significantly the number of satellite galaxies observed around the Milky Way and Andromeda (e.g. Klypin et al., 1999, Kim et al. 2018).

Interacting Dark Matter (IDM)

Interactions between dark matter and radiation (photons or neutrinos) $\Longrightarrow$ the DM remains coupled to the radiation in the early Universe until the latter is diluted enough as the Universe expands for the DM to become decoupled

$\Downarrow$

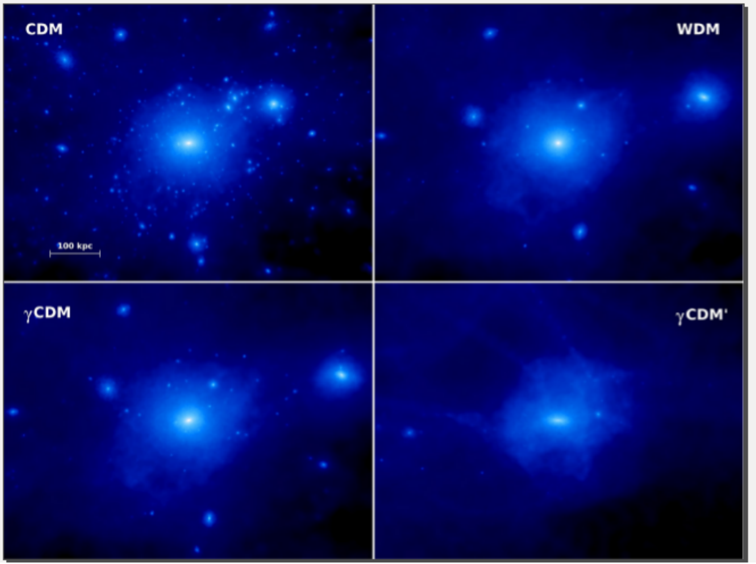
primordial perturbations are suppressed below a certain scale



- significant differences about the number of low-mass DM halos and their properties
- suppress density fluctuations on small mass scales ($M \propto 1/k^3$)
- The collisional damping of primordial DM fluctuations induces a damped oscillating linear matter power spectrum.

Schewtschenko et al., 2015

Alternative scenarios



Bœhm et al., 2014

The contribution to the diffuse $\gamma-$ray emission arising from the annihilation of DM particles of all haloes at all cosmological distances is given by:

$$\frac{d\phi_\gamma(E_0)}{dE_0} = \frac{\langle\sigma v\rangle}{2}\frac{\rho^2_{\mathrm{m},0}}{m^2_{\mathrm{DM}}}\int\frac{dz}{H(z)}\,\xi^2(z)\,e^{-\tau(E_0,z)}\sum_i \mathrm{Br}_i\frac{dN_{\gamma,i}(E_0(1+z))}{dE}\ ,$$

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 γ-rays at emission,

Br_j: branching ratio of channel j,

$\tau(E_0,z)$: optical depth of attenuation of $\gamma-$rays in the extragalactic background light

$\rho_{\mathrm{m},0}$: 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

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

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:

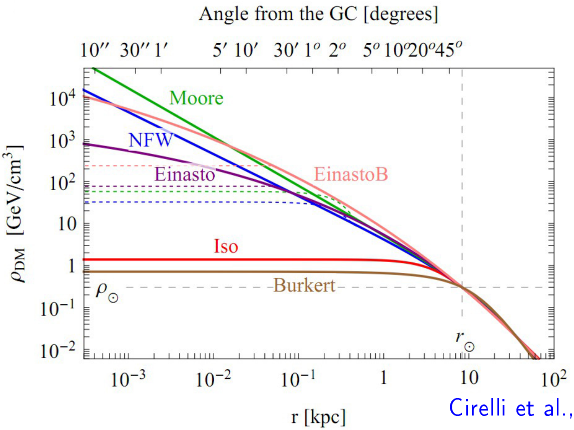
$$M = \frac{4\pi}{3} \Delta\, \bar{\rho}(z) r^3_\Delta; \qquad \Delta = cte \ \text{ or } \ \Delta = \Delta_{vir}(z)\,.$$

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



Cirelli et al., 2012

c: the concentration p ... ers

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

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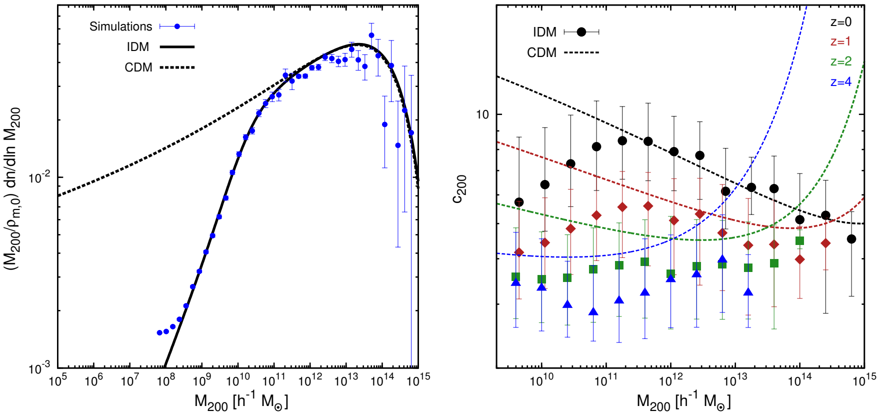
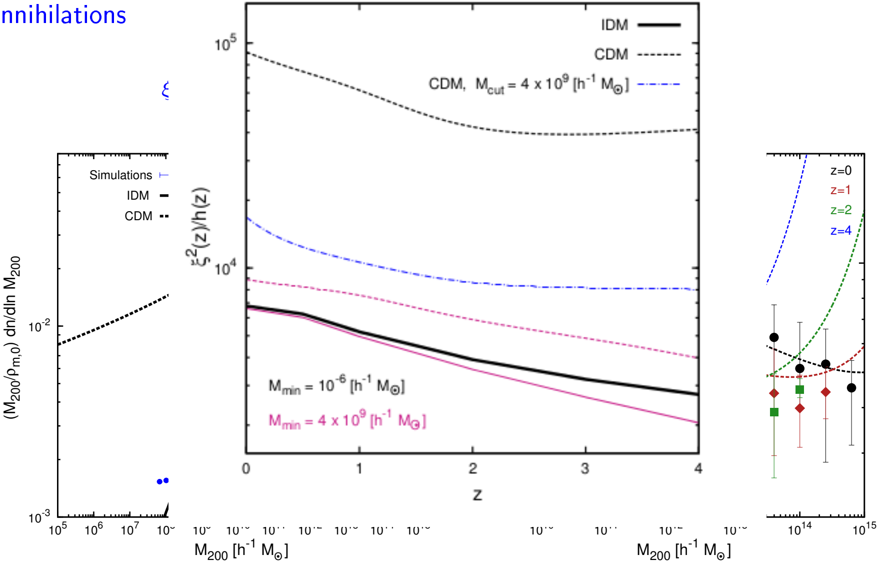
Interacting DM: The impact on DM isotropic extragalactic flux from DM annihilations

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



Moliné et al., 2016

Interacting DM: The impact on DM isotropic extragalactic flux from DM annihilations



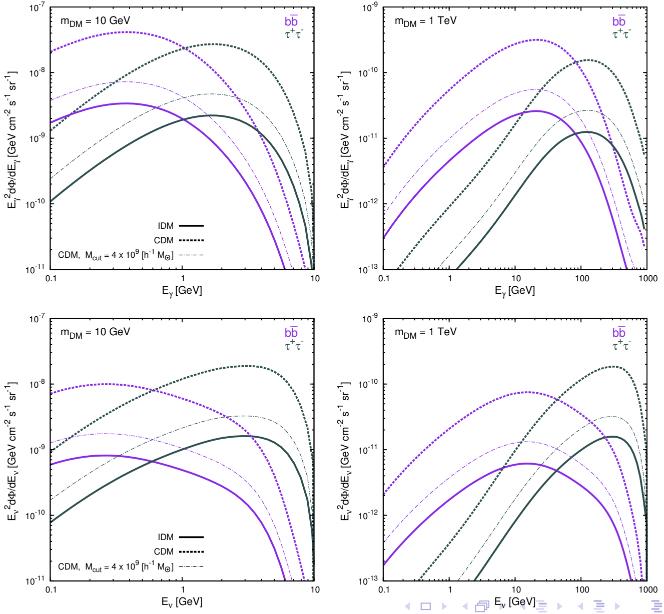
Moliné et al., 2016

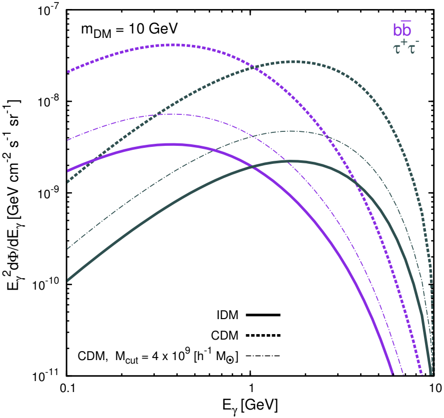
Extragalactic fluxes

Moliné et al., 2016

γ-rays

neutrinos





Moliné et al., 2016

- The extragalactic isotropic signal has a similar energy dependence to that in the ΛCDM model, but the overall normalization is reduced
- This could lead one to misinterpret possible evidence for models beyond the ΛCDM as being due to CDM particles annihilating with a much weaker cross section than expected (!)

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

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

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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

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

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

$\longrightarrow$ very sensitive to subhalo concentration!

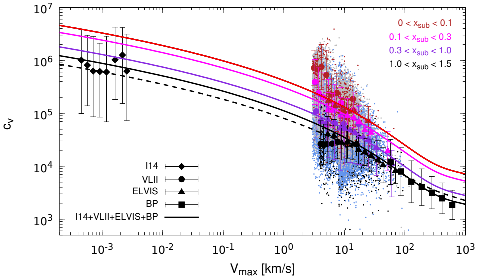
$f(c) = \ln(1+c) - c/(1+c)$

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

(Sub)halo internal structure: The Concentration Parameter

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

- c_Δ



Moliné, 2017

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

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

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

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

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

N-body Simulations: Full-volume & zoom-in

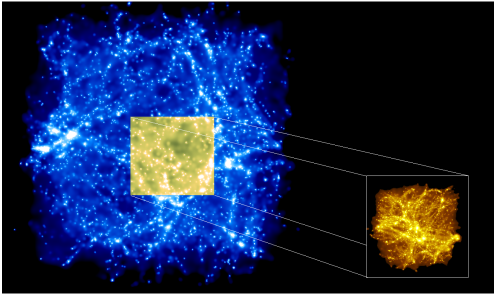
$\sigma/\sigma_{\rm Th} = 2 \times 10^{-9}(m_{\rm DM}/{\rm GeV})$, $z_{ini} = 127$, $\Delta = 200$, WMAP7.

Box

- 100 Mpc
- $m_{\rm Part} = 1.96 \times 10^8\ {\rm M}_\odot/h$

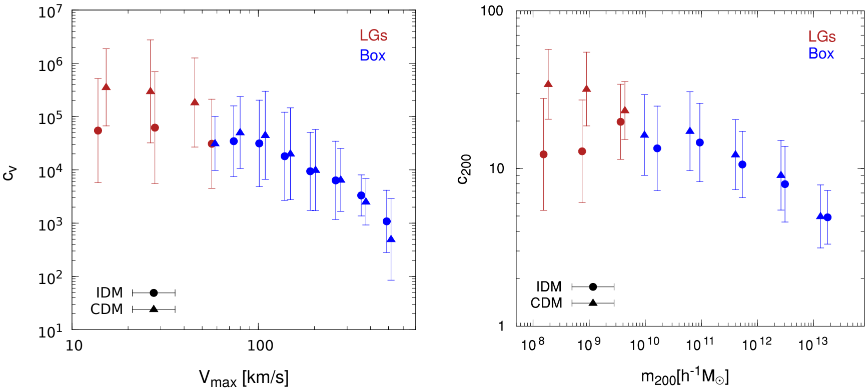
4 Local Groups

- $m_{\rm Part} = 4.85 \times 10^5\ {\rm M}_\odot/h$



courtesy from Jascha Schewtschenko

Subhalo concentrations

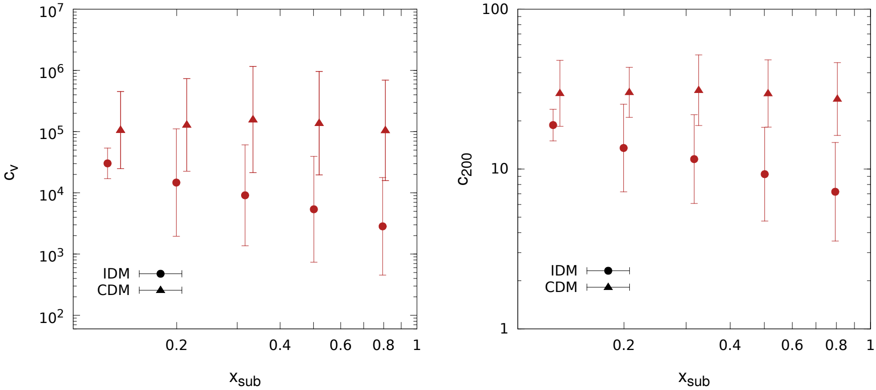


- Significantly lower median value of both c_V and c_{200} in the low bins of $V_{\max}$ and m_{200} for IDM compared to CDM
- This reduction in concentration originates from the later collapse of the low-mass DM haloes and subhalos in the IDM model (similar to the effect seen in WDM simulations, e.g. Lovell et al. 2011)

Moliné et al., 2019

Galaxies 2019, 7(4), 80, arXiv:1907.12531

Subhalo concentrations



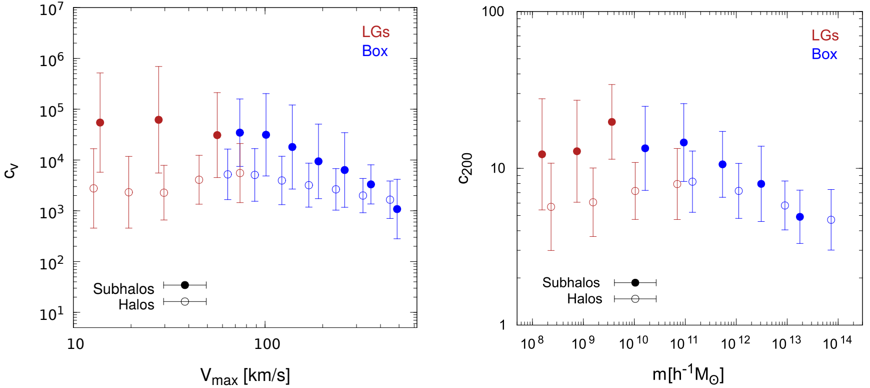
- Significantly lower median value for concentrations in all radial bins for IDM compared to CDM

Moliné et al., 2019

Galaxies 2019, 7(4), 80, arXiv:1907.12531

IDM subhalo and halo concentrations

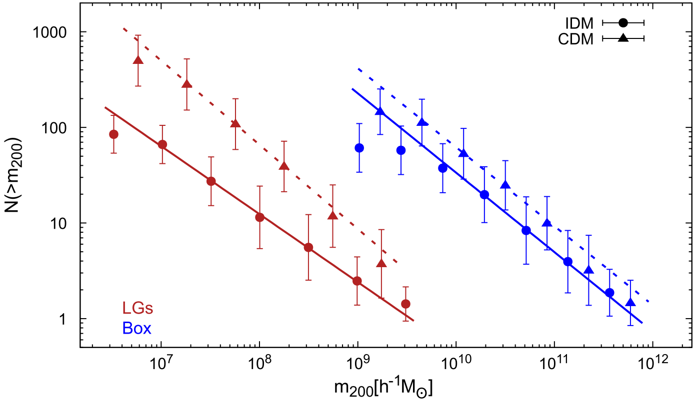
$$\boxed{c^{halo} \neq c^{subhalo}} \ (?)$$



Subhalo concentrations are larger than those of field halos as in CDM model

Moliné et al., 2019

Subhalo abundances

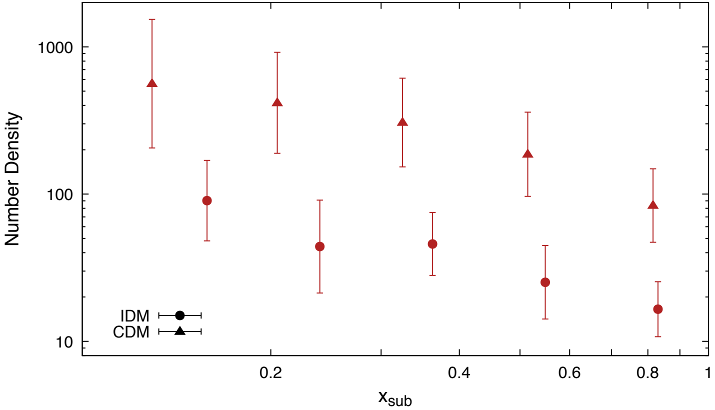


- LGs: Mean $N(>\mathrm{m}_{200})$ values for IDM subhalos are almost a factor ~ 10 lower than those of CDM, this factor decreasing towards large subhalo masses ($\gamma^{IDM} = -0.7$).
- Box: the differences among the two considered cosmologies are not statistically significant anymore ($\gamma^{IDM} = -0.83$).

Moliné et al., 2019

Galaxies 2019, 7(4), 80, arXiv:1907.12531

Radial distribution



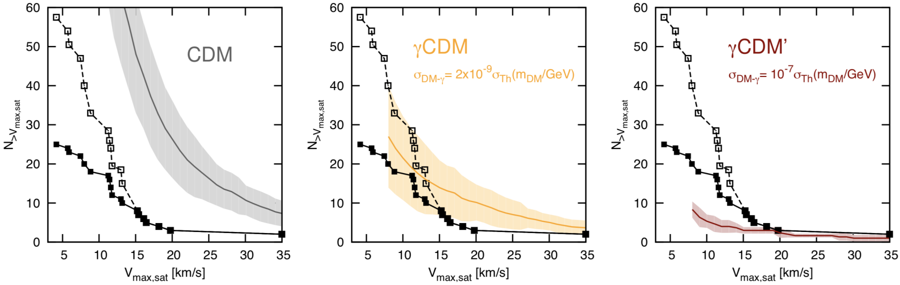
- the radial number density of IDM subhalos increases towards the center of the host halo as in the CDM case but is significantly lower at all host radii.

Moliné et al., 2019

Galaxies formation with IDM models

In collaboration with G. Yepes, M. Sánchez-Conde, J. Stadler, C. Boehm, A. Aguirre Santaella, M. V. Varo García

Satellite galaxy abundance in a MW-like DM halo



Bœhm et al., 2014, arXiv: 1404.7012

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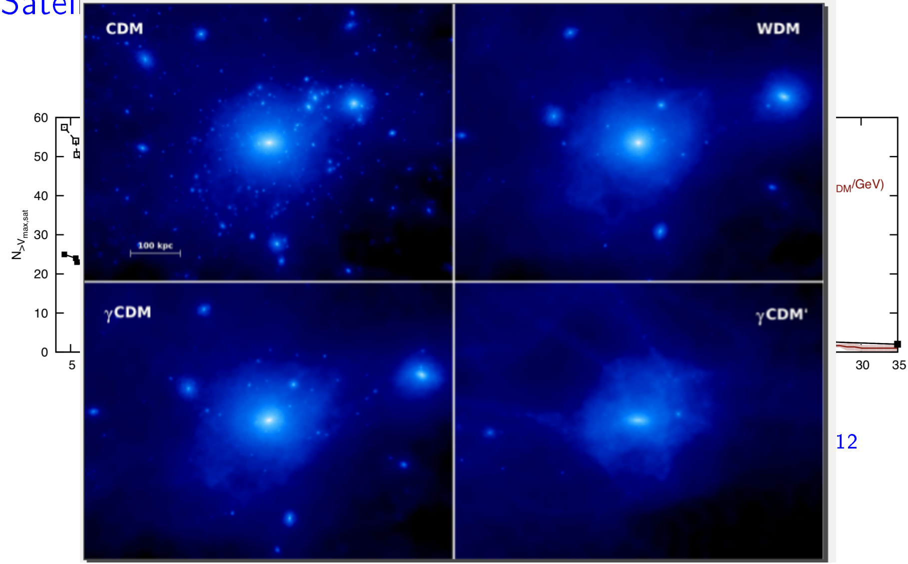

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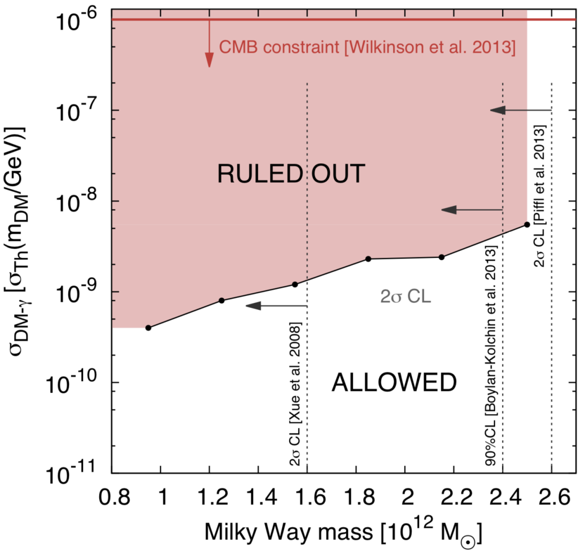
Constraints in the γCDM cross sections

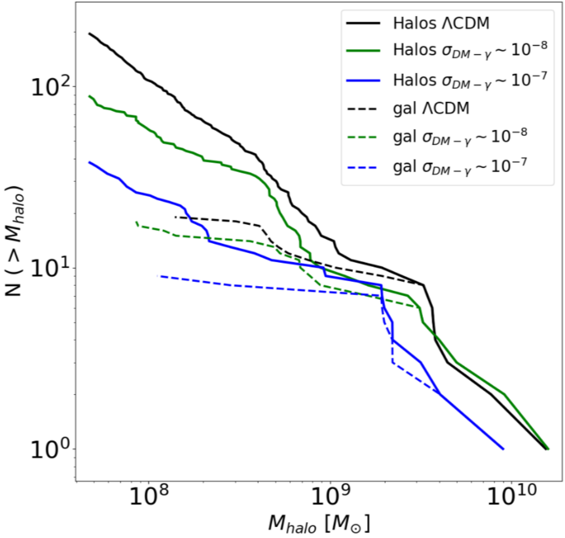


CLUES Simulation (Constrained Local UniversE Simulations)

2 LGs with different host halo masses:

- N = 4096^3 particles (Dark Matter + baryonic physics)
- IDM: 2 γCDM cross sections: $\sigma/\sigma_{\rm Th} = 10^{-9}, 10^{-10}\,[m_{\rm DM}/{\rm GeV}]$
- CDM

Preliminary results



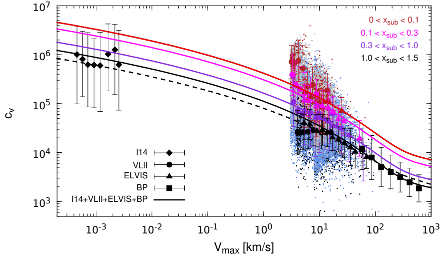
Summary

- We have investigated DM subhalo properties in models where the linear matter power spectrum is suppressed at small scales due to DM interactions with radiation (photons or neutrinos)
- Both for IDM halos and subhalos we observed a significant reduction of the concentrations in the lower mass range and at all radii for subhalos.
- When comparing our results for IDM halos and subhalos of the same mass, the IDM subhalos are more concentrated than field halos
- We find a significantly smaller number of subhalos in IDM with respect to that observed in our CDM simulations which can help alleviate alleged tensions between standard CDM predictions and observations at small mass scales
- These results has a direct application on studies aimed at the indirect detection of DM. The role of halo substructure in DM searches will be less important in IDM scenarios than in CDM, given the fact that both the IDM subhalo concentrations and abundances are lower compared with the CDM case.
- Yet, it will not be not negligible, as we also find in our IDM simulations larger concentrations for subhalos with respect to field halos of the same mass.
- We expect to improve our previous analyses using hydrodynamic simulations.

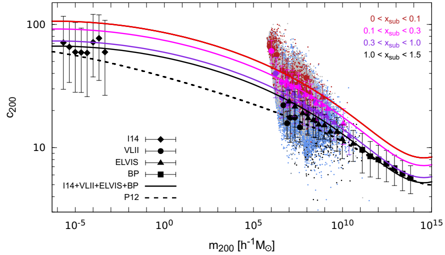
Thank you!

Back up

Results - Parametrizations for the median subhalo concentrations



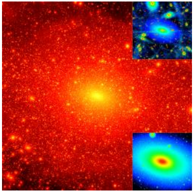
$$c_{\rm V}(V_{\rm max}, x_{\rm sub}) = c_0 \left[1 + \sum_{i=1}^{3} \left[a_i \log\left(\frac{V_{\rm max}}{10\,{\rm km/s}}\right)\right]^i\right] \cdot [1 + b\log(x_{\rm sub})]$$



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

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

VL-II



J. Diemand et al., 2008

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

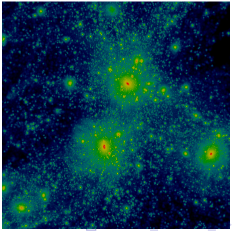
- VL-II employs just over one billion $4100\ M_{\odot}$ particles to model the formation of a M_{200}=1.93 x $10^{12}\ M_{\odot}$ halo and its substructure.
- Resolve about 53000 individual subhalos within the host halo's r_{200}=402 kpc
- VL-II adopted ΛCDM parameters from the WMAP 3 year data release.

ELVIS: Exploring the Local Volume in Simulations

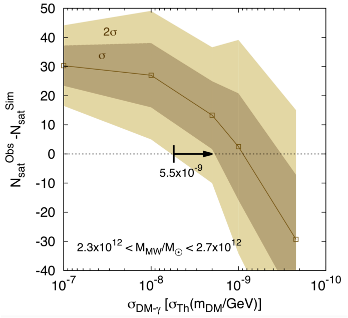
S. Garrison-Kimmel et al., 2014

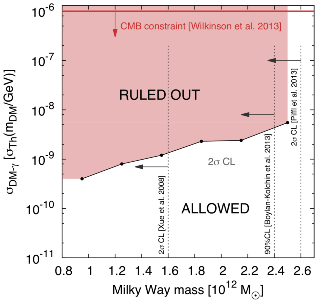
- ELVIS is a set of high-resolution simulations that model the Local Group
- The suite contains 48 Galaxy-size haloes and three halos of higher resolution, each within volumes that span 2-5 Mpc in size with particle mass m_p=1.9 x 10^5 $M_\odot$
- Half of the Galaxy haloes are in paired configurations,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

Thelma (Bottom) & Louise (Top)



Constraints on the γCDM cross section





The interactions between dark matter and photons (or alternatively neutrinos) result in additional terms in the linerized Euler equations governing the evolution of the cosmic components

$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}\left(\theta_b - \theta_\gamma\right) \ , \\
\dot{\theta}_\gamma &= k^2\psi + \left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) k^2 \delta_b - \dot{\kappa}\left(\theta_\gamma - \Theta_b\right) - C_{\gamma-\mathrm{dm}} \ , \\
\dot{\theta}_{\mathrm{dm}} &= k^2\psi - \mathcal{H}\theta_{\mathrm{dm}} - C_{\mathrm{dm}-\gamma} \ ,
\end{aligned}$$

ψ the gravitational potential, $\mathcal{H}$ the conformal Hubble rate and θ and σ the velocity divergence and anisotropic stress potential associated with the respective baryon, photon and DM fluid.

$\dot{\kappa} \equiv a\sigma_{\mathrm{Th}} c n_e$ the Thomson scattering rate with respect to conformal time, $R \equiv (3/4)(\rho_b/\rho_\gamma)$ is a pre-factor to ensure momentum conservation.

$$C_{\mathrm{dm}-\gamma} = \dot{\mu}\left(\Theta_{\mathrm{dm}} - \Theta_\gamma\right) \tag{1}$$

$\dot{\mu} \equiv a\sigma_{\mathrm{dm}-\gamma} c n_{\mathrm{dm}}$, $\sigma_{\mathrm{dm}-\gamma}$ the elastic scattering cross-section between dark matter and photons, and $S \equiv (3/4)(\rho_{\mathrm{dm}}/\rho_\gamma)$ as the scaling of the counter term in the momentum transfer.