Implications of simulated MW-like haloes for DM direct detection

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Based on work in progress with F. Calore, M. Lovell, G. Bertone, M. Schaller, and C. Frenk
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- local DM density: $\rho_\chi \sim 0.3 \text{ GeV cm}^{-3}$
- typical DM velocity: $\bar{v} \sim 220 \text{ km/s}$
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- typical DM velocity: $\bar{v} \simeq 220 \text{ km/s}$

Numerical simulations of galaxy formation predict dark matter velocity distributions which can deviate from a Maxwellian.
Dark matter direct detection

- Strong tension between hints for a signal and exclusion limits:

  ![Graph showing dark matter direct detection results](image)

  - LUX (90%)
  - SuperCDMS (90%)
  - CDMS-Si (68% & 90%)
  - DAMA (90% & 3σ)

- These kinds of plots assume the **Standard Halo Model** and a specific DM-nucleus interaction.
Our aim

- Identify Milky Way-like galaxies from simulated halos, by taking into account observational constraints on the Milky Way (MW).
- Extract the local DM density and velocity distribution for the selected MW analogues.
- Analyze the data from direct detection experiments, using the predicted local DM distributions of the selected haloes.
Identifying Milky Way analogues

- Usually a simulated halo is classified as *MW-like* if it satisfies the *MW mass constraint*, which has a large uncertainty. We show that the mass constraint is not enough to define a MW-like galaxy.
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- We consider simulated haloes with $5 \times 10^{11} < M_{200}/M_\odot < 10^{14}$, and select the galaxies which most closely resemble the MW by the following criteria:
  - Rotation curve from simulation fits well the observed MW kinematical data.
  - The total stellar mass of the simulated galaxies is within the $3\sigma$ observed MW range: $4.5 \times 10^{10} < M_*/M_\odot < 8.3 \times 10^{10}$.
Observations vs. simulations

- **Numerical Simulations**: The EAGLE hydrodynamic simulations (DM + baryons) at two different resolutions.

<table>
<thead>
<tr>
<th>Name</th>
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<tr>
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Observations vs. simulations

Initial sets of haloes:
EAGLE IR: 2411 | EAGLE HR: 61 | APOSTLE IR: 24

Haloes which have correct total stellar mass:
EAGLE IR: 335 | EAGLE HR: 12 | APOSTLE IR: 2
Goodness of fit to the observed data:

\[ \chi^2 / (N - 1) \]

\[ \log(M_{200} / M_\odot) \]

\[ N = 2687 \] is the total number of observational data points used.

- Minimum of the reduced \( \chi^2 \) occurs within the \( 3\sigma \) measured range of the MW total stellar mass. \( \Rightarrow \) haloes with correct MW stellar mass have rotation curves which match well the observations.
Observations vs. simulations

Goodness of fit to the observed data:

\[
\chi^2/(N-1) = \frac{\sum (O_i - E_i)^2}{N - \text{df}}
\]

\[
\log\left(\frac{M_{200}}{M_\odot}\right)
\]

\[
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- Minimum of the reduced \(\chi^2\) occurs within the 3\(\sigma\) measured range of the MW total stellar mass. \(\Rightarrow\) haloes with correct MW stellar mass have rotation curves which match well the observations.

- We focus only on the selected EAGLE HR and APOSTLE IR haloes due to higher resolution.
Spherically averaged DM density profiles:

- **Dark matter density profiles**
  - Spherically averaged DM density profiles: 
    - $\rho_{DM}[GeV/cm^3] = 2.8 \times \epsilon = 0.98$ kpc
    - $\rho_{DM}[GeV/cm^3] = 2.8 \times \epsilon = 0.87$ kpc

- Need the DM density at the position of the Sun.
- Consider a torus aligned with the stellar disc with $7 \text{kpc} < R < 9 \text{kpc}$, and $-1 \text{kpc} < z < 1 \text{kpc}$.
- EAGLE HR: local $\rho_{DM} = 0.42 - 0.73$ GeV cm$^{-3}$.
- APOSTLE IR: local $\rho_{DM} = 0.41 - 0.54$ GeV cm$^{-3}$.

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Local speed distributions

In the galactic rest frame:
Local speed distributions

In the galactic rest frame:

- Comparison to dark matter only (DMO) simulations:
The differential event rate (event/keV/kg/day):

\[ R(E_R, t) = \frac{\rho \chi}{m \chi m_A} \int_{v > v_m} d^3 v \frac{d\sigma_A}{dE_R} v f_{\text{det}}(v, t) \]

where \( v_m = \sqrt{m_A E_R / (2 \mu^2 \chi A)} \) is the minimum WIMP speed required to produce a recoil energy \( E_R \).
The differential event rate

- The differential event rate (event/keV/kg/day):

\[
R(E_R, t) = \frac{\rho_\chi}{m_\chi m_A} \frac{1}{m_A} \int_{v>v_m} d^3 v \frac{d\sigma_A}{dE_R} v f_{\text{det}}(v, t)
\]

where \(v_m = \sqrt{m_A E_R/(2\mu^2\chi_A)}\) is the minimum WIMP speed required to produce a recoil energy \(E_R\).

- For the standard spin-independent and spin-dependent scattering:

\[
R(E_R, t) = \sigma_0 \frac{F^2(E_R)}{2m_\chi \mu^2} \rho_\chi \eta(v_m, t)
\]

where

\[
\eta(v_m, t) \equiv \int_{v>v_m} d^3 v \frac{f_{\text{det}}(v, t)}{v}
\]

halo integral
The halo integral

\[ \eta(v_{\min}) \quad \text{(km/s)}^{-1} \]

\[ \nu_{\min} \quad \text{[km/s]} \]

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Implications for direct detection

- Assuming the SHM:
Implications for direct detection

- Comparing with simulated MW-like haloes (smallest $\rho_{DM}$):

![Graph showing direct detection implications](image)

- $\chi(\rho_{DM})$
- $\sigma_{SI} (cm^2)$
- $m_\chi (GeV)$

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Implications for direct detection

- Comparing with simulated MW-like haloes (largest $\rho_{DM}$):

![Graph showing the sensitivity of direct detection experiments to the mass of the dark matter particle ($m_\chi$) and the scattering cross-section ($\sigma_{SI}$) for different experiments (LUX, SuperCDMS, CDMS-Si, DAMA).]
Implications for direct detection

- Comparing with simulated MW-like haloes (largest $\rho_{DM}$):

- Halo-to-halo uncertainty larger than the 1\(\sigma\) uncertainty from each halo.

- Overall difference with SHM mainly due to the different local DM density of the simulated haloes.
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Haloes with velocity distributions closest and farthest from SHM Maxwellian:

Fix local $\rho_{DM} = 0.3$ GeV cm$^{-3}$.
Effect of the velocity distribution

- Haloes with velocity distributions closest and farthest from SHM Maxwellian:

  Fix local \( \rho_{DM} = 0.3 \text{ GeV cm}^{-3} \)

- Shift in the low WIMP mass region persists, where experiments probe the high velocity tail of the distribution.

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Summary

- We identified simulated haloes which satisfy observational properties of the Milky Way, besides the uncertain mass constraint. Haloes are MW-like if:
  - good fit to observed MW rotation curve.
  - stellar mass in the $3\sigma$ observed MW stellar mass range.

The local velocity distribution of the selected haloes can deviate substantially from the SHM Maxwellian with an excess at higher speeds. \Rightarrow shift of allowed regions and exclusion limits at low WIMP masses.

The local DM density: $\rho_{\text{DM}} = 0.41 - 0.73 \, \text{GeV cm}^{-3}$. \Rightarrow overall shift of the allowed regions and exclusion limits for all masses.
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Additional slides
Velocity distribution components

Distributions of radial, azimuthal, and vertical velocity components:

![Graphs showing distributions of radial, azimuthal, and vertical velocity components.](image-url)