Predictions of hydrodynamic simulations for direct dark matter detection

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Based on work done 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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Numerical simulations of galaxy formation predict dark matter velocity distributions which can deviate from a Maxwellian.
Strong tension between hints for a signal and exclusion limits:

- 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.
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Identifying Milky Way analogues

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- We demonstrate 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.
  
  - The galaxies contain a substantial stellar disc component.
Numerical Simulations: The EAGLE hydrodynamic simulations (DM + baryons) at intermediate (IR) and high resolutions (HR).

<table>
<thead>
<tr>
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<th>N</th>
<th>$m_g$ ($M_\odot$)</th>
<th>$m_{dm}$ ($M_\odot$)</th>
</tr>
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<td>HR</td>
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Observations vs. simulations

- **Numerical Simulations**: The EAGLE hydrodynamic simulations (DM + baryons) at intermediate (IR) and high resolutions (HR).

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- **Observational data**: extensive compilation of MW rotation curve measurements from: [Iocco, Pato, Bertone, 1502.03821].
Rotation curve and stellar mass criteria:

- Initial set of simulated haloes satisfying our halo mass constraint: 2411 in the IR; 61 in the HR runs.

- Haloes which lie in the 3σ observed range of the MW total stellar mass: 335 in the IR, and 12 in the HR runs.
Observations vs. simulations

Goodness of fit to the observed data:

\[
\chi^2/(N - 1) = 11.8, 12.0, 12.2, 12.4, 12.6, 12.8, 13.0
\]

\[
\log(M_{200}/M_\odot) = 10^{10}, 10^{11}
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M_* [M_\odot] = 10^2, 10^3, 10^4
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\[
N = 2687 \text{ is the total number of observational data points used.}
\]

- The minimum of the reduced $\chi^2$ naturally 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.
Select simulated galaxies whose stellar kinematics show a disc component, rather than ellipticals or undergoing mergers.

Characterize the morphology of each simulated galaxy by looking for evidence of coherent rotation. Distinguish between discs and spheroids (comprises bulges and stellar haloes).
Morphology of simulated haloes

- Select simulated galaxies whose stellar kinematics show a disc component, rather than ellipticals or undergoing mergers.

- Characterize the morphology of each simulated galaxy by looking for evidence of coherent rotation. \( \Rightarrow \) distinguish between discs and spheroids (comprises bulges and stellar haloes).

- Haloes satisfying all criteria: 10 in the IR, and 2 in the HR runs.
Spherically averaged DM density profiles:

\[ \rho_{\text{DM}}(R) = 2.8 \times e^{-R/1.96\text{kpc}} \]

\[ \rho_{\text{DM}}(R) = 2.8 \times e^{-R/0.98\text{kpc}} \]

Need the DM density at the position of the Sun.

Consider a torus aligned with the stellar disc with 7 kpc < R < 9 kpc, and −1 kpc < z < 1 kpc.

IR haloes: local \( \rho_{\text{DM}} = 0.55 - 0.84 \text{GeV cm}^{-3} \).

HR haloes: local \( \rho_{\text{DM}} = 0.44 - 0.65 \text{GeV cm}^{-3} \).
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Local speed distributions

In the galactic rest frame:

- \( \chi^2 = 11.1 \)
- \( \chi^2 = 19.8 \)

Comparison to dark matter only (DMO) simulations:

- \( \chi^2 = 5.4 \)
- \( \chi^2 = 8.2 \)
Local speed distributions

In the galactic rest frame:

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

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

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

Need the velocity distributions in the detector reference frame:

\[
f_{\text{det}}(v, t) = f_{\text{gal}}(v + v_s + v_e(t))
\]

Sun’s velocity wrt the Galaxy: \(v_s \approx (0, v_{\text{sim}}, 0) + (11.10, 12.24, 7.25) \text{ km/s} \)

\(v_{\text{sim}}\): rotational velocity of star particles in simulations.

Earth’s velocity: \(v_e \approx 30 \text{ km/s} \)
The halo integral

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

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

where

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

halo integral
Implications for direct detection

- Assuming the SHM:

\[ \chi(\sigma_{\text{SI}}) \]

\[ m_\chi \text{ (GeV)} \]

\[ \sigma_{\text{SI}} \text{ (cm}^2) \]

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Implications for direct detection

- Comparing with simulated MW-like haloes:
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![Graph showing direct detection results with LUX, SuperCDMS, CDMS-Si, and DAMA points]

- Halo-to-halo uncertainty larger than the 1σ uncertainty from each halo.
- Overall difference with SHM mainly due to the different local DM density of the simulated haloes.
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Implications for direct detection

- Comparing with simulated MW-like haloes:

  - 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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Effect of the velocity distribution

- We fix the local $\rho_{DM} = 0.3$ GeV cm$^{-3}$ for the simulated haloes.

- Shift in the low WIMP mass region persists, where experiments probe the high velocity tail of the distribution.
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.
- show a dominant disc in the stellar component.
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The local velocity distribution of the selected haloes deviates 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: $\rho_{\text{DM}} = 0.44 - 0.65 \text{ GeV cm}^{-3}$. $\Rightarrow$ overall shift of the allowed regions and exclusion limits for all masses.
Additional slides
Due to the motion of the Earth around the Sun, the velocity distribution in the Earth’s frame changes in a year.

\[ f_{\text{det}}(\mathbf{v}, t) = f_{\text{sun}}(\mathbf{v} + \mathbf{v}_e(t)) = f_{\text{gal}}(\mathbf{v} + \mathbf{v}_s + \mathbf{v}_e(t)) \]
The velocity distribution depends on the halo model.

In the SHM, a truncated Maxwellian velocity distribution is assumed

\[ f_{\text{gal}}(v) \approx \begin{cases} N \exp\left(-\frac{v^2}{\bar{v}^2}\right) & v < v_{\text{esc}} \\ 0 & v \geq v_{\text{esc}} \end{cases} \]

with \( \bar{v} \approx 220 \text{ km/s} \), \( v_{\text{esc}} = 550 \text{ km/s} \).

DM distribution could be very different from Maxwellian:

- Most likely both smooth and un-virialized (streams and debris flows) components.
- the smooth component may not be Maxwellian.
Local speed distributions

Distributions of radial, azimuthal, and vertical velocity components:
Local speed distributions

Comparison with Maxwellian matched to peak:

\[
HR \quad \frac{\langle v \rangle}{\langle v \rangle - \langle v \rangle} \\
HR DMO
\]