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

Dark matter halo

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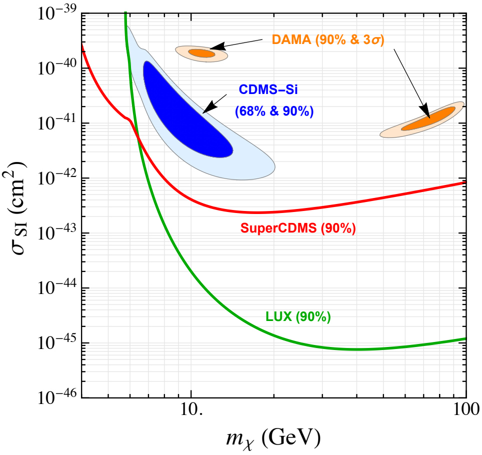
  - local DM density: $\rho_\chi \sim 0.3$ GeV cm^{-3}
  - typical DM velocity: $\bar{v} \simeq 220$ km/s
- Numerical simulations of galaxy formation predict dark matter velocity distributions which can deviate from a Maxwellian.

Dark matter direct detection

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



- 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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- 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 3σ 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.

Name	L (Mpc)	N	$m_{\rm g}$ $(M_\odot)$	$m_{\rm dm}$ $(M_\odot)$
EAGLE IR	100	6.8×10^9	1.81×10^6	9.70×10^6
EAGLE HR	25	8.5×10^8	2.26×10^5	1.21×10^6
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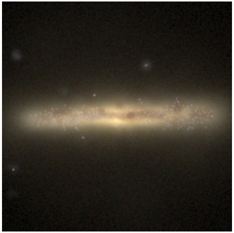

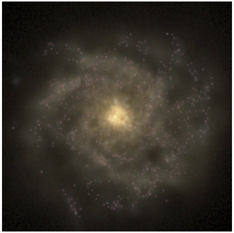

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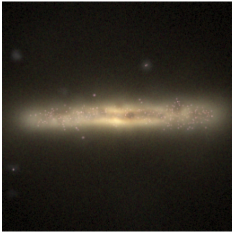
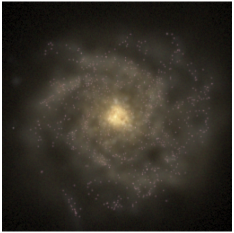
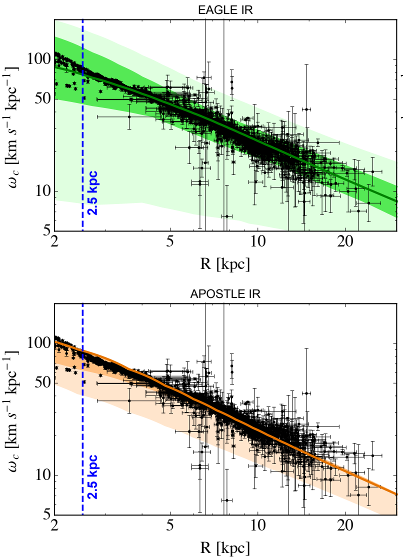




- **Observational data**: extensive compilation of MW rotation curve measurements from: [Iocco, Pato, Bertone, 1502.03821].

Observations vs. simulations



Initial sets of haloes:

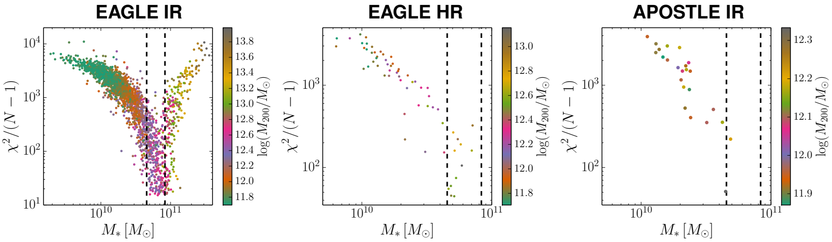
EAGLE IR: 2411 | **EAGLE HR: 61** |
APOSTLE IR: 24

Haloes which have correct total stellar mass:

EAGLE IR: 335 | **EAGLE HR: 12** |
APOSTLE IR: 2

Observations vs. simulations

Goodness of fit to the observed data:



$N = 2687$ is the total number of observational data points used.

- Minimum of the reduced χ^2 occurs within the 3σ measured range of the MW total stellar mass. $\Rightarrow$ haloes with correct MW stellar mass have rotation curves which match well the observations.

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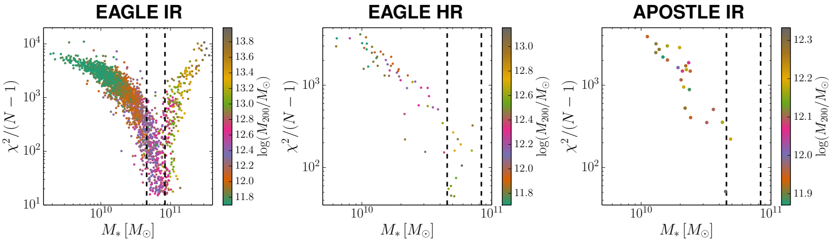

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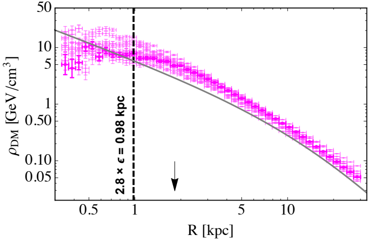
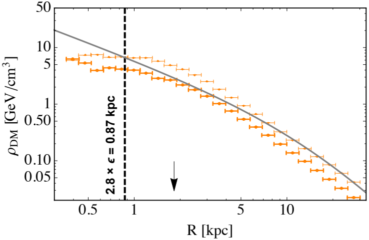
- Minimum of the reduced χ^2 occurs within the 3σ measured range of the MW total stellar mass. $\Rightarrow$ haloes with correct MW stellar mass have rotation curves which match well the observations.
- We focus only on the selected **EAGLE HR** and **APOSTLE IR** haloes due to higher resolution.

Dark matter density profiles

- Spherically averaged DM density profiles:





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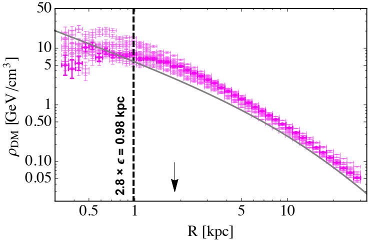
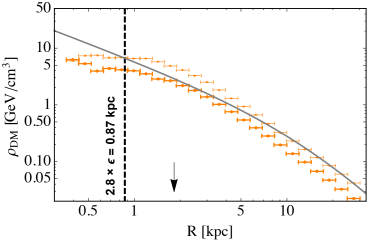
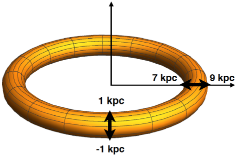




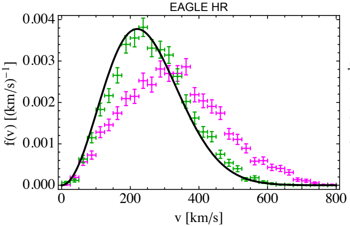
- Need the DM density at the position of the Sun.
- Consider a torus aligned with the stellar disc with $7\ \mathrm{kpc} < R < 9\ \mathrm{kpc}$, and $-1\ \mathrm{kpc} < z < 1\ \mathrm{kpc}$.

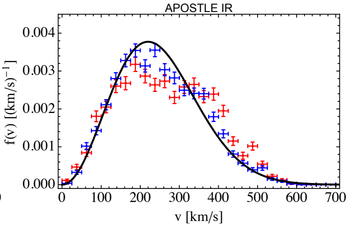
EAGLE HR: local $\rho_{\mathrm{DM}} = 0.42 - 0.73$ GeV cm^{-3}.
APOSTLE IR: local $\rho_{\mathrm{DM}} = 0.41 - 0.54$ GeV cm^{-3}.



Local speed distributions

In the galactic rest frame:





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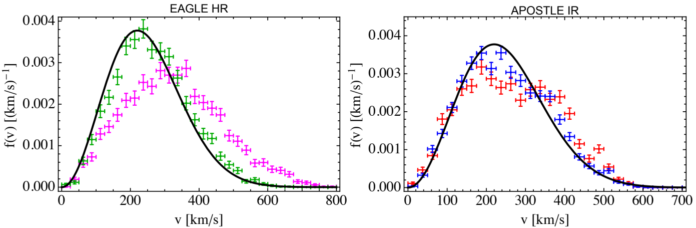
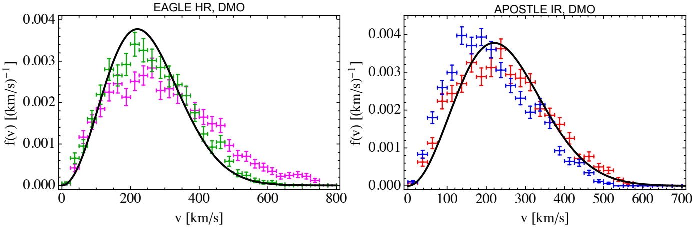


- Comparison to dark matter only (DMO) simulations:



The differential event rate

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

$$R(E_R, t) = \frac{\rho_\chi}{m_\chi} \frac{1}{m_A} \int_{v>v_m} d^3v \frac{d\sigma_A}{dE_R} \; v \; f_{\rm det}(\mathbf{v}, t)$$

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.

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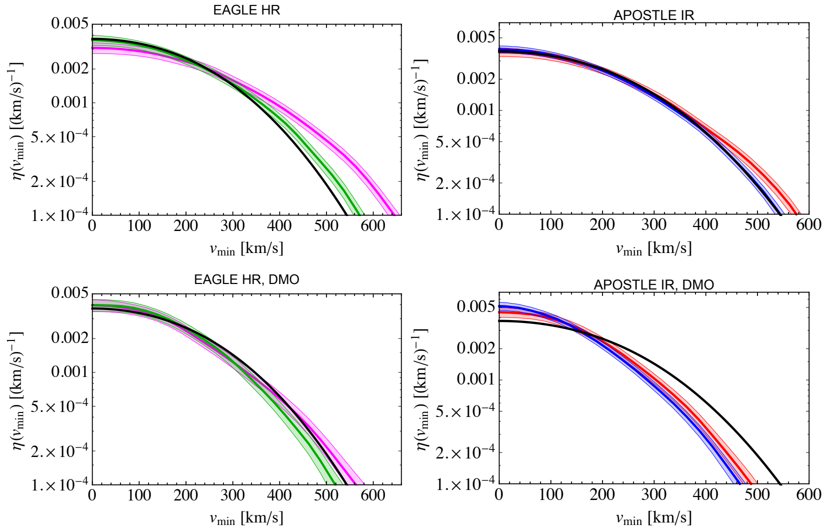
- For the standard spin-independent and spin-dependent scattering:

$$R(E_R, t) = \underbrace{\frac{\sigma_0 \; F^2(E_R)}{2 m_\chi \mu_{\chi A}^2}}_{\text{particle physics}} \; \underbrace{\rho_\chi \; \eta(v_m, t)}_{\text{astrophysics}}$$

where

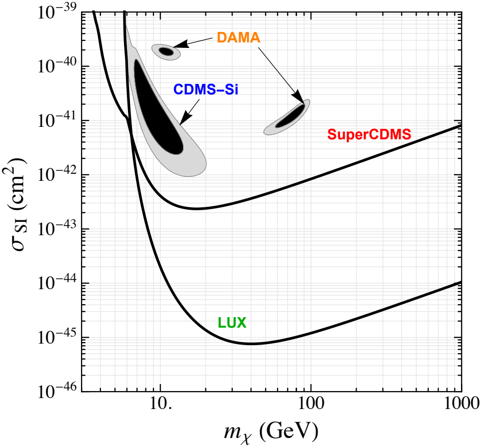
$$\boxed{\eta(v_m, t) \equiv \int_{v > v_m} d^3 v \; \frac{f_{\rm det}(\mathbf{v}, t)}{v}} \qquad \text{halo integral}$$

The halo integral



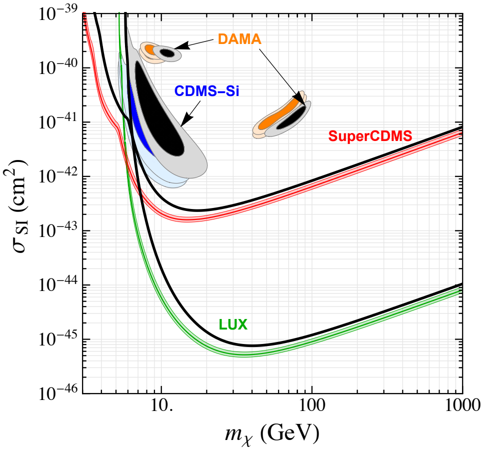
Implications for direct detection

- Assuming the SHM:



Implications for direct detection

- Comparing with simulated MW-like haloes (smallest ρ_{DM}):



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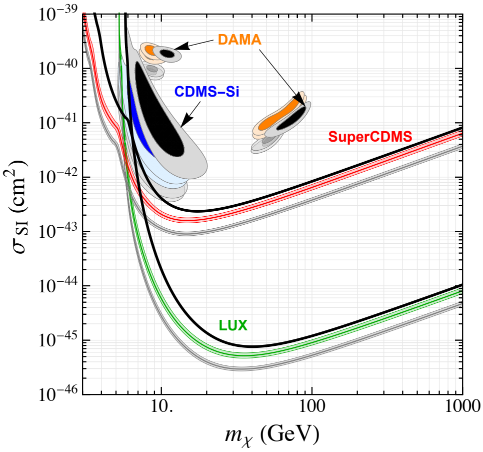
- Comparing with simulated MW-like haloes (largest ρ_{DM}):



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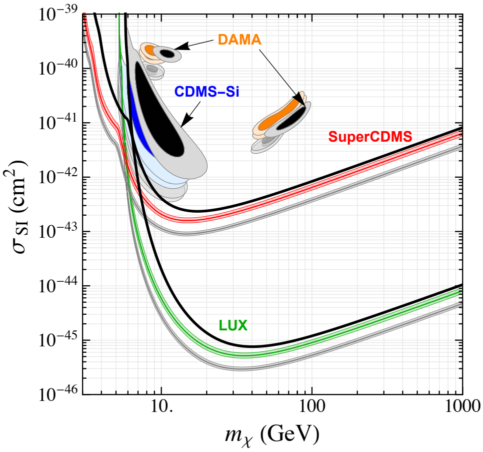

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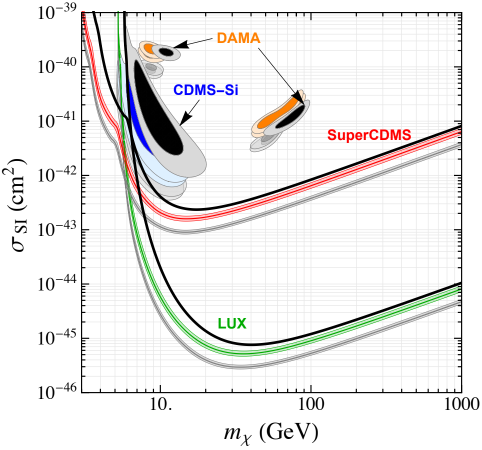
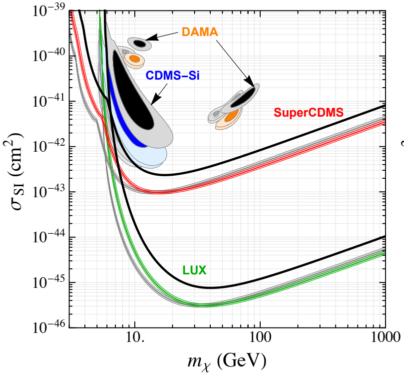


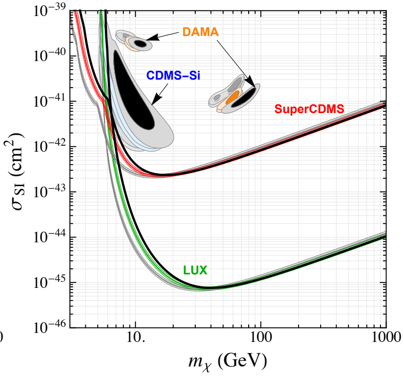
- Halo-to-halo uncertainty larger than the 1σ uncertainty from each halo.
- Overall difference with SHM mainly due to the different local DM density of the simulated haloes.

Effect of the velocity distribution

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

Fix local $\rho_{\rm DM} = 0.3$ GeV cm^{-3}





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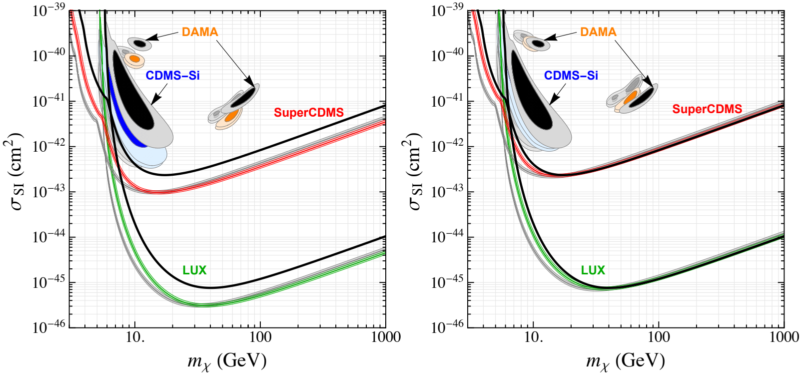

- Shift in the low WIMP mass region persists, where experiments probe the high velocity tail of the distribution.

Summary

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- 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: $\rho_{\rm DM} = 0.41 - 0.73$ GeV cm^{-3}. $\Rightarrow$ overall shift of the allowed regions and exclusion limits for all masses.

Additional slides

Velocity distribution components

Distributions of radial, azimuthal, and vertical velocity components: