Hydrodynamic simulations and dark matter direct detection

Nassim Bozorgnia

GRAPPA Institute
University of Amsterdam

Based on work done with F. Calore, M. Lovell, G. Bertone, and the EAGLE team
arXiv: 1601.04707

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Outline

- Dark matter direct detection
- Hints for a signal versus constraints
- DM distribution from hydrodynamic simulations
  - Identifying Milky Way analogues
  - Local DM density and velocity distribution
- Analysis of direct detection data
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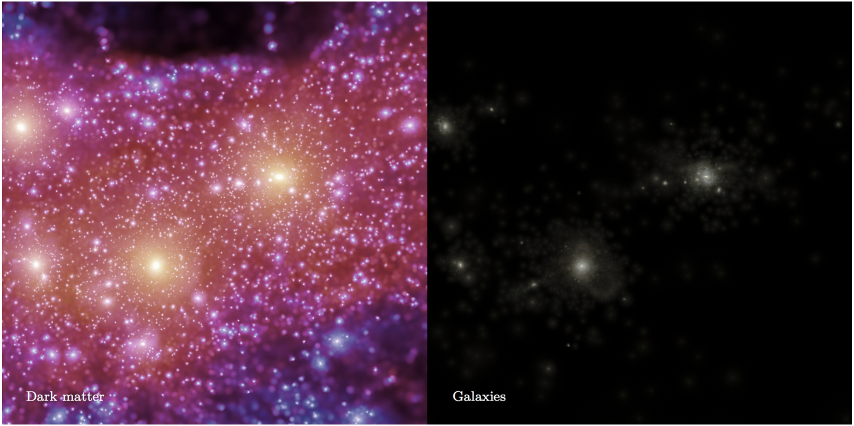
Dark matter halo



APOSTLE Simulations, 1511.01098

Dark matter halo

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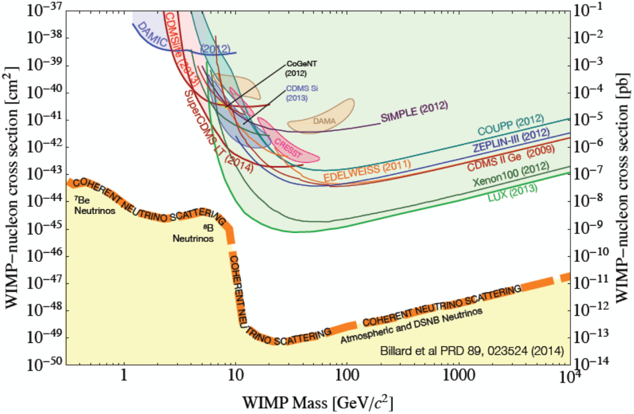
  - local DM density: $\rho_\chi \sim 0.3$ GeV cm^{-3}
  - typical DM velocity: $\bar{v} \simeq 220$ km/s
- Numerical simulations of galaxy formation predict dark matter velocity distributions which can deviate from a Maxwellian.

Dark matter direct detection

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



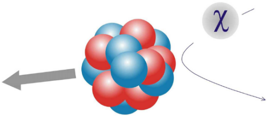
- These kinds of plots assume the Standard Halo Model and a specific DM-nucleus interaction.

Our aim

- Use high resolution hydrodynamic simulations to determine the local DM distribution.
- 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.

Direct detection principles

- Look for energy deposited in low-background detectors by the scattering of WIMPs in the dark halo of our galaxy.
- WIMP-nucleus collision:



- Elastic recoil energy:

$$E_R = \frac{2\mu_{\chi A}^2 v^2}{m_A} \cos^2 \theta_{\rm lab}$$

$\theta_{\rm lab}$: angle of the nuclear recoil relative to the initial WIMP direction

- Minimum WIMP speed required to produce a recoil energy E_R:

$$v_m = \sqrt{\frac{m_A E_R}{2\mu_{\chi A}^2}}$$

The differential event rate

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

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

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

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

where

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

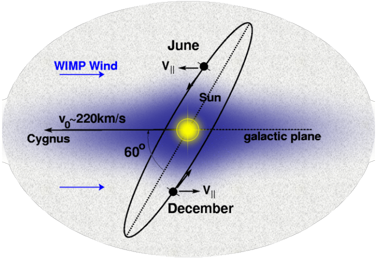
Astrophysical uncertainties

- Local DM density: normalization factor in the event rate.
- DM velocity distribution: enters in the halo integral. $\Rightarrow$ Different experiments (energy threshold, target nuclei) probe different DM speed ranges, and thus their dependence on the DM velocity distribution varies.

Annual modulation

- Due to the motion of the Earth around the Sun, the velocity distribution in the Earth's frame changes in a year.

Max in June
Min in Dec



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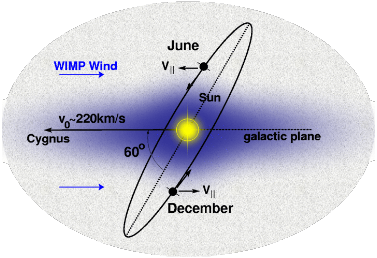

$$f_{\rm det}(\mathbf{v}, t) = f_{\rm sun}(\mathbf{v} + \mathbf{v}_e(t)) = f_{\rm gal}(\mathbf{v} + \mathbf{v}_s + \mathbf{v}_e(t))$$

Sun's velocity wrt the Galaxy: $\mathbf{v}_s \approx (0, 220, 0) + (10, 13, 7)$ km/s

Earth's velocity: $v_e \approx 30$ km/s

Dark matter velocity distribution

- What is $f_{\rm gal}(\mathbf{v})$? The answer depends on the halo model.

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with $\bar{v} \simeq 220$ km/s, $v_{\rm esc} \simeq 550$ km/s.

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- DM distribution could be very different from Maxwellian:
  - Most likely both smooth and un-virialized components.
  - the smooth component may not be Maxwellian.

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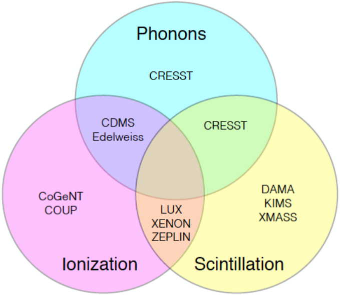
Hints for a signal versus constraints



- We consider data from four experiments:

  Hints for a signal:

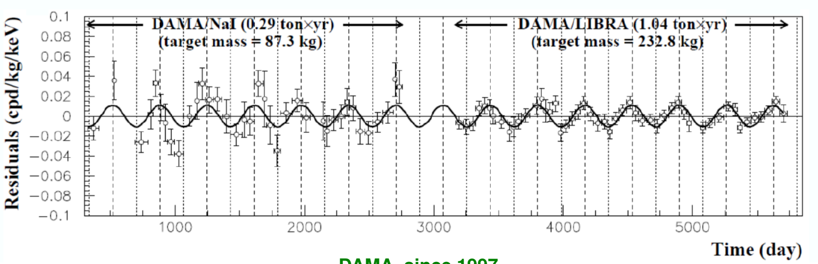
  - **DAMA:** scintillation (NaI)
  - **CDMS-Si:** ionization + phonons (Si)

  Null results:

  - **LUX:** scintillation + ionization (Xe)
  - **SuperCDMS:** ionization + phonons (Ge)

DAMA annual modulation signal

- NaI detectors; 9.3σ modulation signal; 1.33 ton yr (14 yrs)

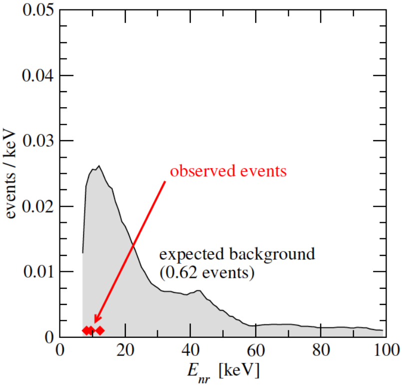


DAMA, since 1997

- Two possible WIMP masses: $m_\chi \sim 10$ GeV, $m_\chi \sim 80$ GeV

CDMS-Si excess of events

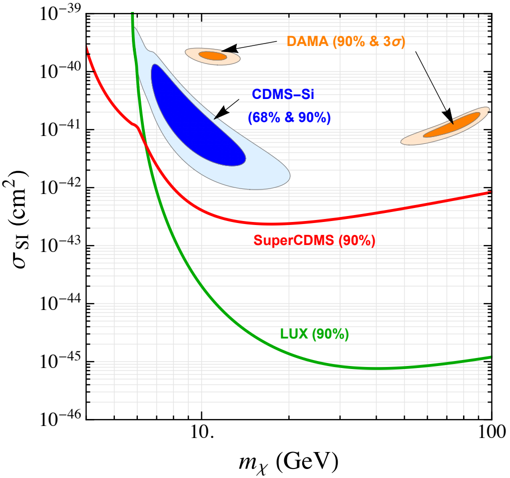
- 140.2 kg day in 8 Si detectors. Observed 3 events against expected background of 0.62 events.
- WIMP $+$ background hypothesis favored over the known background estimate at $\sim 3\sigma$.



- Maximum likelihood at $m_\chi = 8.6$ GeV

Constraint from LUX and SuperCDMS

- Assuming the Standard Halo Model and spin-independent elastic scattering:



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- We use the **EAGLE** and **APOSTLE** hydrodynamic simulations (**DM** + **baryons**).

Name	L (Mpc)	N	$m_{\rm g}$ ($\mathrm{M}_\odot$)	$m_{\rm dm}$ ($\mathrm{M}_\odot$)
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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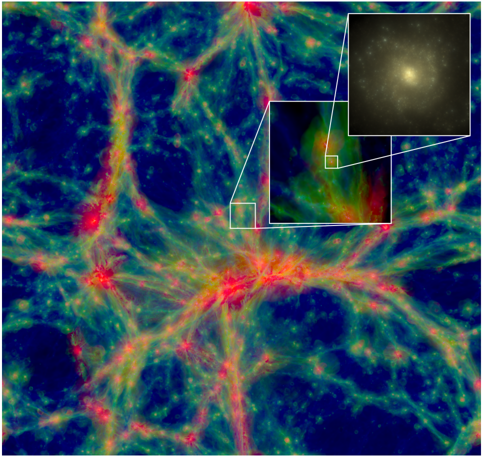
- **APOSTLE IR**: zoomed simulations of Local Group-analogue systems, comparable in resolution to **EAGLE HR**.
- These simulations are calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.
- Companion dark matter only (DMO) simulations were run assuming all the matter content is collisionless.

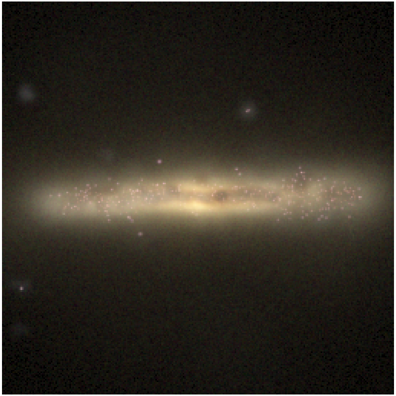
EAGLE simulations

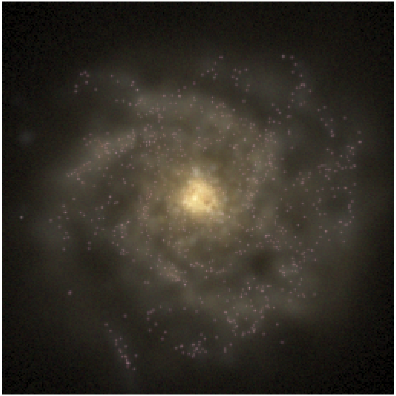


EAGLE project, 1407.7040

Intergalactic gas: blue $\Rightarrow$ green $\Rightarrow$ red with increasing temperature.

Milky Way analogues





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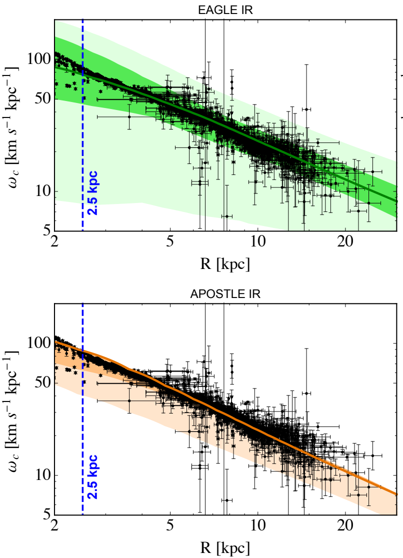
- Consider simulated haloes with $5 \times 10^{11} < M_{200}/\mathrm{M}_\odot < 2 \times 10^{13}$ and select the galaxies which most closely resemble the MW by the following criteria:

  - Rotation curve from simulation fits well the observed MW kinematical data from: [Iocco, Pato, Bertone, 1502.03821].
  - The total stellar mass of the simulated galaxies is within the 3σ observed MW range: $4.5 \times 10^{10} < M_*/\mathrm{M}_\odot < 8.3 \times 10^{10}$.

Observations vs. simulations



Initial sets of haloes:

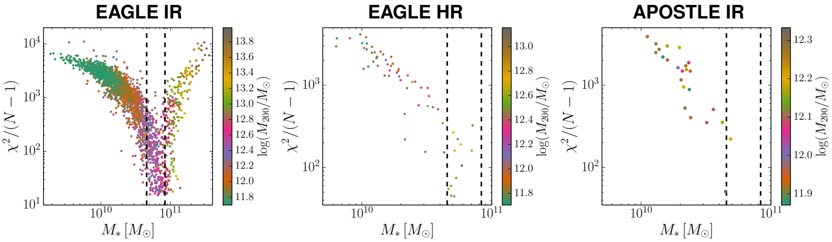
EAGLE IR: 2411 | **EAGLE HR: 61** | **APOSTLE IR: 24**

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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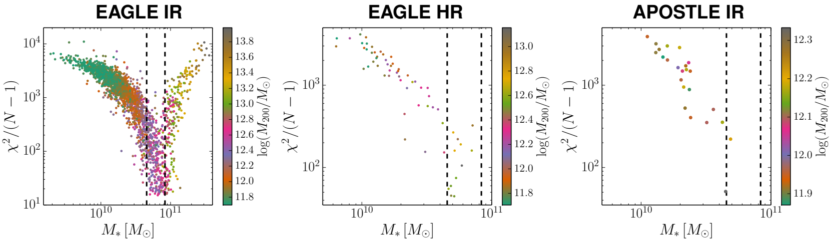

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- Minimum of the reduced χ^2 occurs within the 3σ measured range of the MW total stellar mass. $\Rightarrow$ haloes with correct MW stellar mass have rotation curves which match well the observations.
- We focus only on the selected **EAGLE HR** and **APOSTLE IR** haloes due to higher resolution $\Rightarrow$ total of **14** MW analogues.

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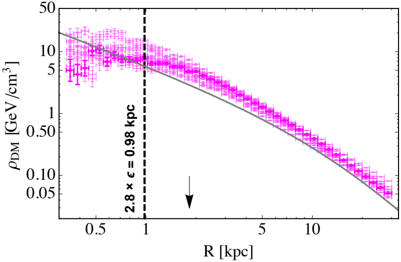
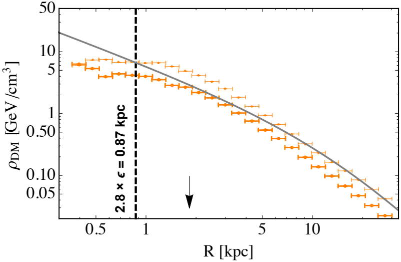
Dark matter density profiles

- **Spherically averaged** DM density profiles derived from mass enclosed in a given spherical shell between R and $R + \delta R$:





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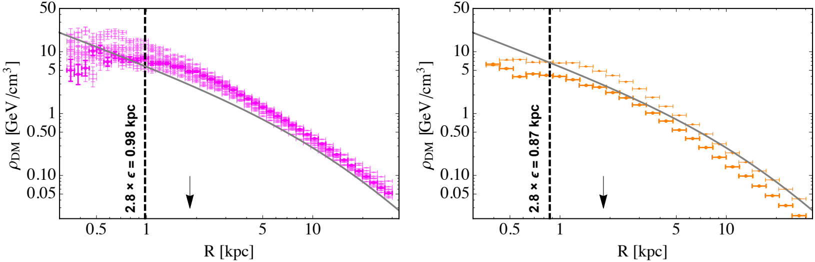
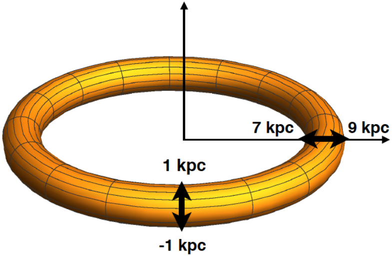


- In the inner 1.5 – 2 kpc: DM density shallower than NFW.
- Between 1.5 – 6/8 kpc: baryons lead to a steepening of the DM profile.

Local dark matter density

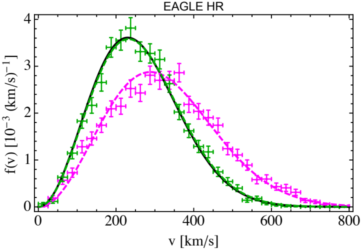
- Need the DM density at the position of the Sun.
- Consider a torus aligned with the stellar disc with $7\ \mathrm{kpc} < R < 9\ \mathrm{kpc}$, and $-1\ \mathrm{kpc} < z < 1\ \mathrm{kpc}$.



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

Local DM speed distribution

In the galactic rest frame:



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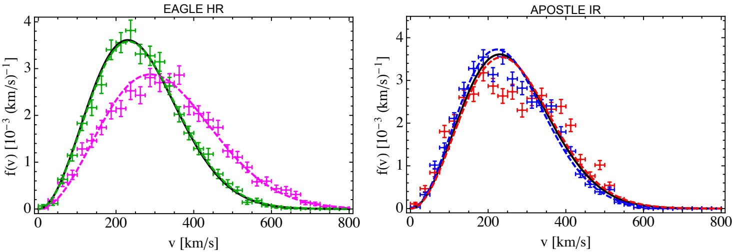
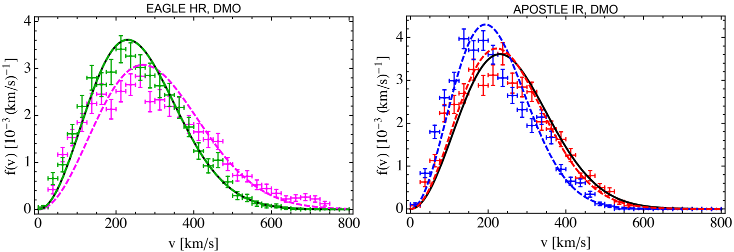


- Comparison to DMO simulations:



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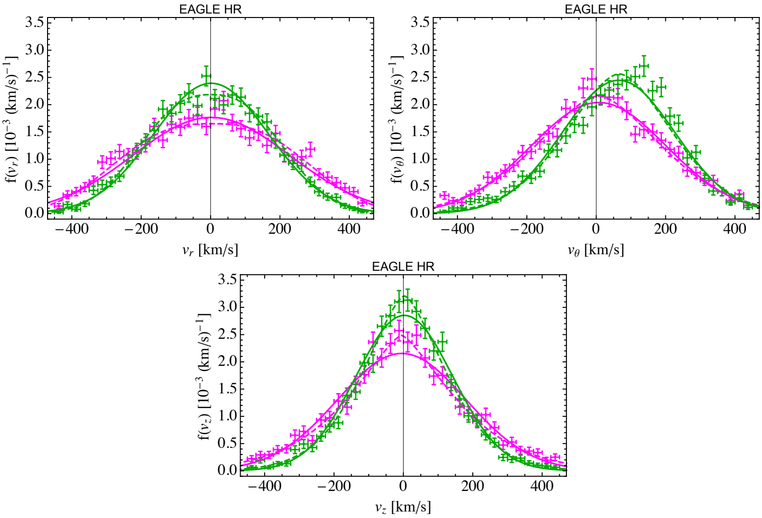
- The Maxwellian distribution with a free peak provides a better fit to most haloes in the hydrodynamic simulations compared to their DMO counterparts.
- The best fit peak speed of the Maxwellian distribution in the hydrodynamic simulations: 223 – 289 km/s.

Components of the velocity distribution

Distributions of radial, azimuthal, and vertical velocity components:



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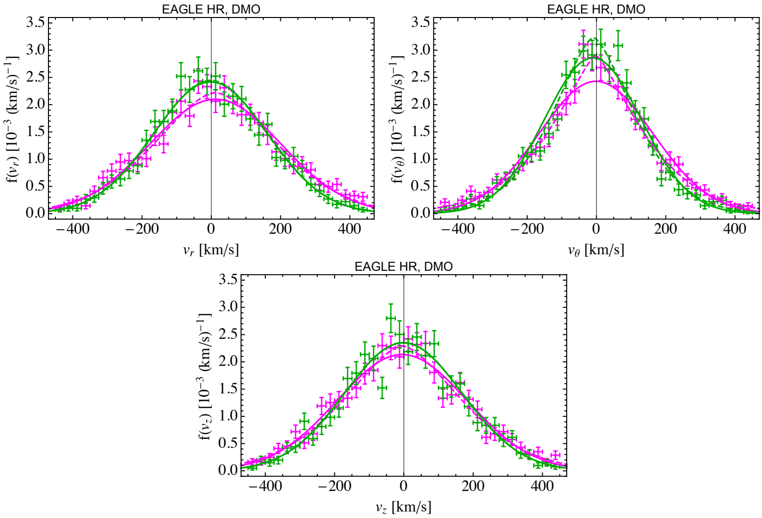

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- Four haloes have a significant positive mean **azimuthal** speed ($\mu > 20$ km$/$s). The DMO counterparts of these haloes don't show evidence of rotation.
- Is this pointing to the existence of a "dark disc"?
  - Among the four rotating haloes, two haloes have a rotating DM component in the disc with mean velocity comparable (within 50 km$/$s) to that of the stars.
  - Hint for the existence of a co-rotating dark disc in two out of 14 MW-like haloes. $\Rightarrow$ dark discs are relatively rare in our halo sample.

The halo integral

- The halo integral parametrizes the astrophysics dependence of the event rate,

$$\eta(v_m, t) \equiv \int_{v>v_m} d^3v \, \frac{f_{\rm det}(\mathbf{v}, t)}{v}, \quad R(E_R, t) = \frac{\rho_\chi \sigma_0 \, F^2(E_R)}{2 m_\chi \mu_{\chi A}^2} \, \eta(v_m, t)$$

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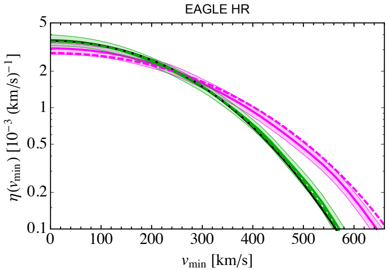
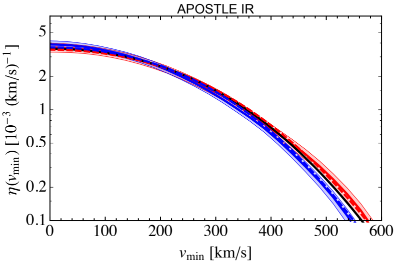
Sun's velocity wrt the Galaxy: $\mathbf{v}_s \approx (0, v_\star, 0) + (11.10, 12.24, 7.25)$ km/s

$v_\star$: local circular speed for the **simulated halo**.

The halo integral





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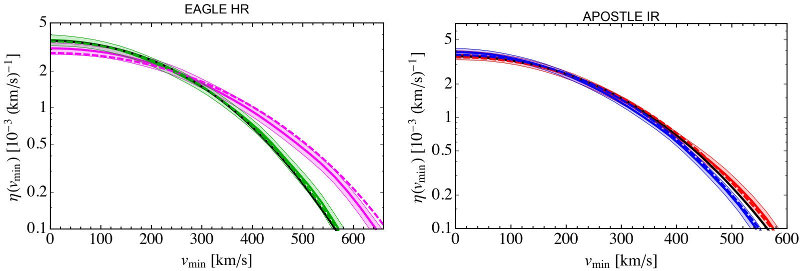

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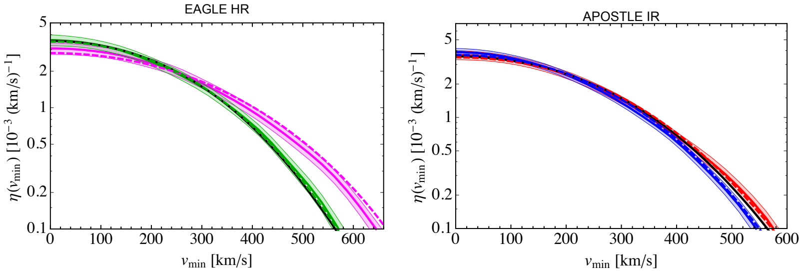
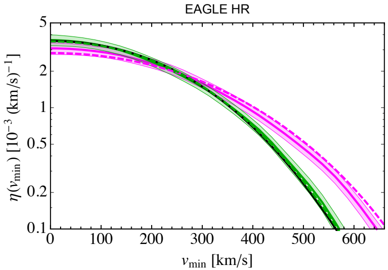
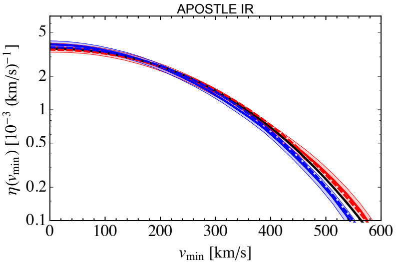


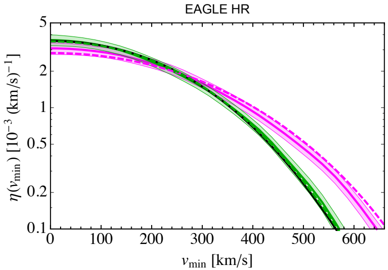
- Significant halo-to-halo scatter in the halo integrals.
- Halo integrals for the best fit Maxwellian velocity distribution (peak speed 223 – 289 km/s) fall within the 1σ uncertainty band of the halo integrals of the simulated haloes.

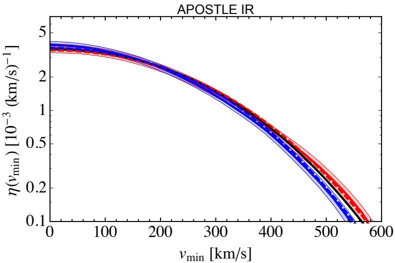
The halo integral



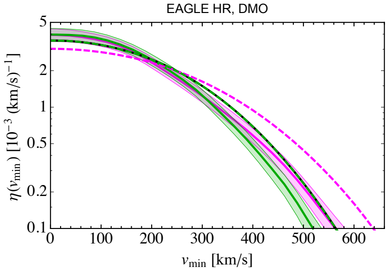


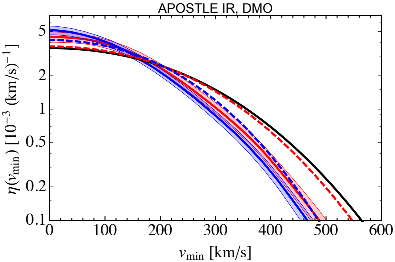
- Significant halo-to-halo scatter in the halo integrals.
- Halo integrals for the best fit Maxwellian velocity distribution (peak speed 223 – 289 km/s) fall within the 1σ uncertainty band of the halo integrals of the simulated haloes.
- Difference between simulated haloes and SHM Maxwellian due to the different peak speed of the DM velocity distribution.





- Comparison to DMO simulations:

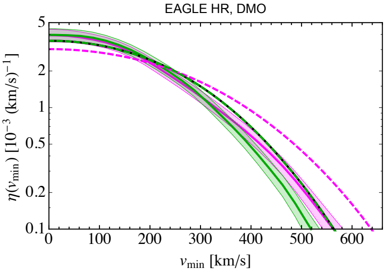


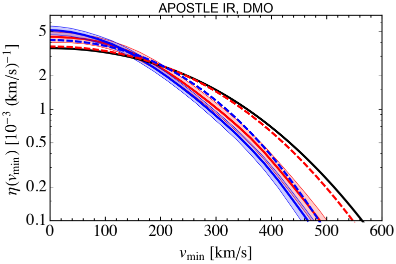


The halo integral

- Including baryons in the simulations results in a shift of the tails of the halo integrals to higher velocities with respect to the DMO case.

- Speed distributions of DMO haloes not captured well by a Maxwellian. Large deficits at the peak, and an excess at low and very high velocities compared to the best fit Maxwellian. $\Rightarrow$ Halo integrals of DMO haloes quite different from best fit Maxwellian halo integrals.





The halo integral

- Two other recent works studying implications of hydrodynamic simulations for direct detection:
  - Kelso et al. 1601.04725
  - Sloane et al. 1601.05402

- Our results agree in that halo integrals and hence direct detection event rates obtained from a Maxwellian velocity distribution with a free peak speed are similar to those obtained directly from the simulated haloes.

The halo integral

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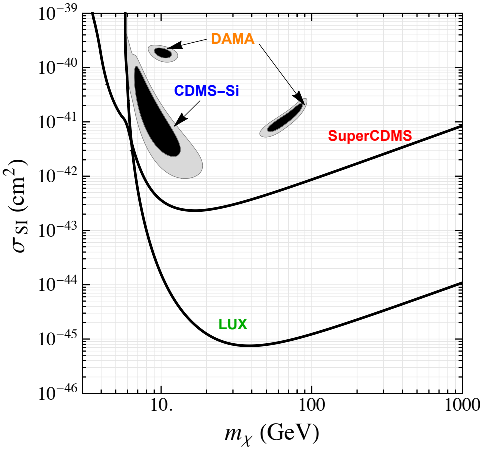
- Our results agree in that halo integrals and hence direct detection event rates obtained from a Maxwellian velocity distribution with a free peak speed are similar to those obtained directly from the simulated haloes.
- A Maxwellian velocity distribution with a peak speed constrained by hydrodynamic simulations could be used by the community in the analysis of direct detection data.

Outline

- Dark matter direct detection
- Hints for a signal versus constraints
- DM distribution from hydrodynamic simulations
  - Identifying Milky Way analogues
  - Local DM density and velocity distribution
- Analysis of direct detection data
- Summary

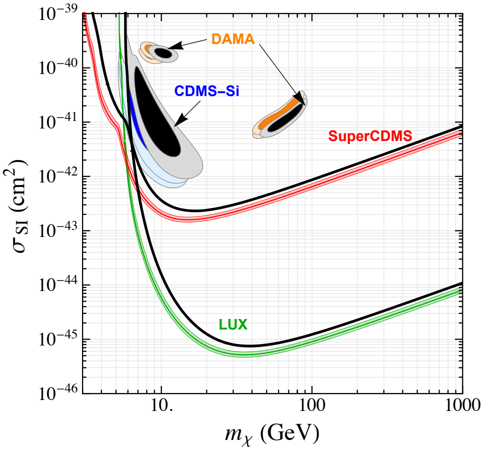
Implications for direct detection

- Assuming the SHM:



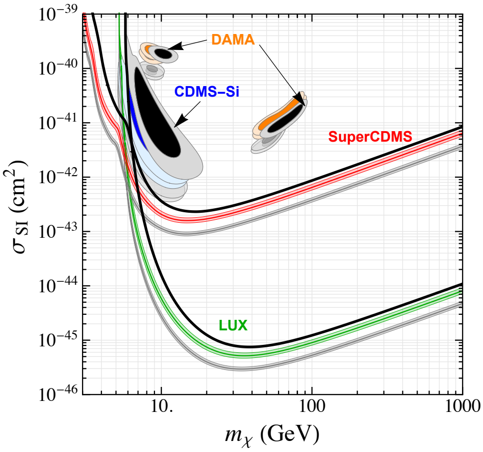
Implications for direct detection

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



Implications for direct detection

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



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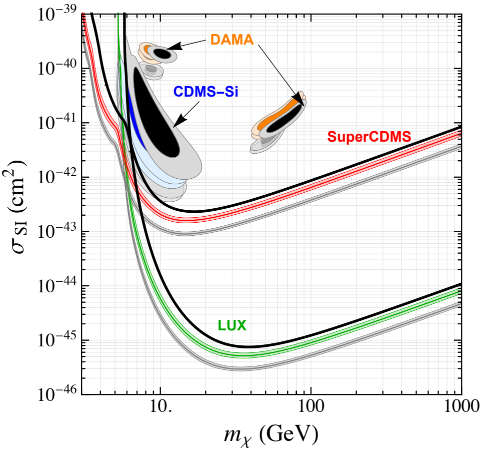

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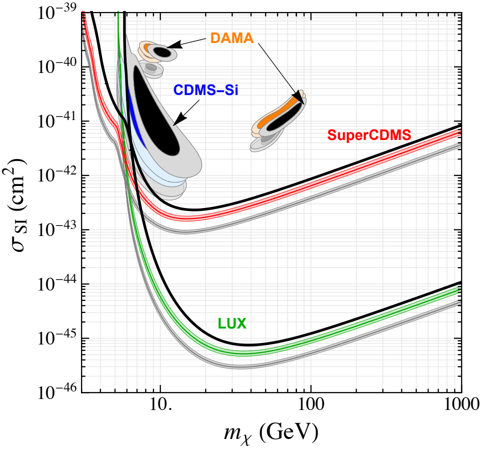
Implications for direct detection

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

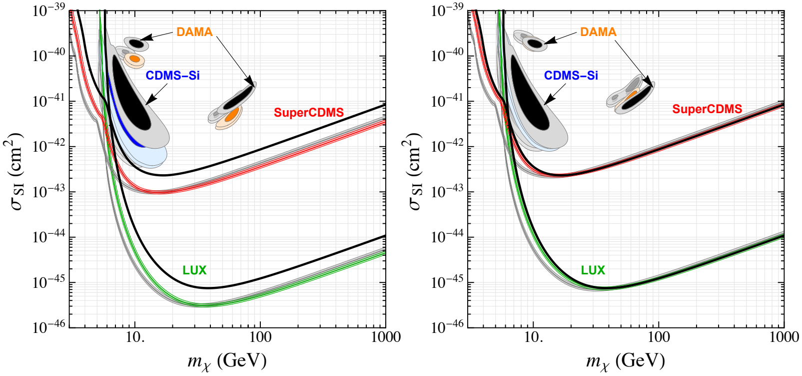


- Halo-to-halo uncertainty larger than the 1σ uncertainty from each halo.
- Overall difference with SHM mainly due to the different local DM density of the simulated haloes.

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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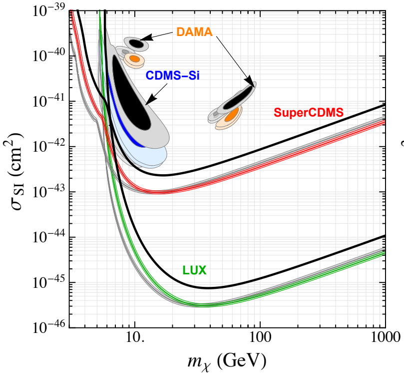

- Shift in the low WIMP mass region persists, where experiments probe the high velocity tail of the distribution.

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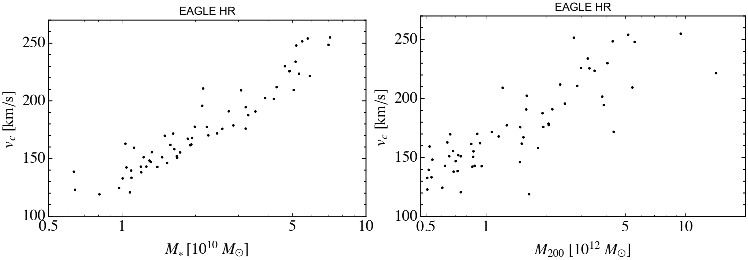
- Shift in the allowed regions and exclusion limits occurs in the same direction. $\Rightarrow$ compatibility between different experiments is not improved.

Additional slides

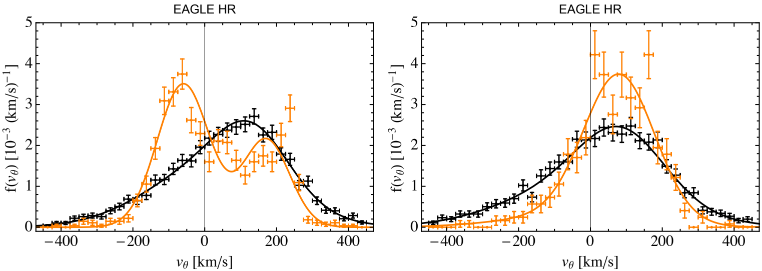
Selection criteria



- $M_\star$ strongly correlated with v_c at 8 kpc, while the correlation of M_{200} with v_c is weaker.
- $M_\star(R < 8\ \mathrm{kpc}) = (0.5 - 0.9)M_\star$.
- $M_{\mathrm{tot}}(R < 8\ \mathrm{kpc}) = (0.01 - 0.1)M_{200}$.
- Over the small halo mass range probed, little correlation between $M_{\mathrm{DM}}(R < 8\ \mathrm{kpc})$ and M_{200}.

Velocity distribution azimuthal components

DM and stellar velocity distributions:



- Fit with a double Gaussian. Difference in the mean speed of second Gaussian between DM and stars is 35 km/s in the left, and 7 km/s in the right panel.
- Fraction of second Gaussian is 32% in the left panel and 43% in the right panel.