Predictions of hydrodynamic simulations for direct dark matter detection

Nassim Bozorgnia

GRAPPA Institute
University of Amsterdam

Based on work done with F. Calore, M. Lovell, G. Bertone, M. Schaller, and C. Frenk

GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

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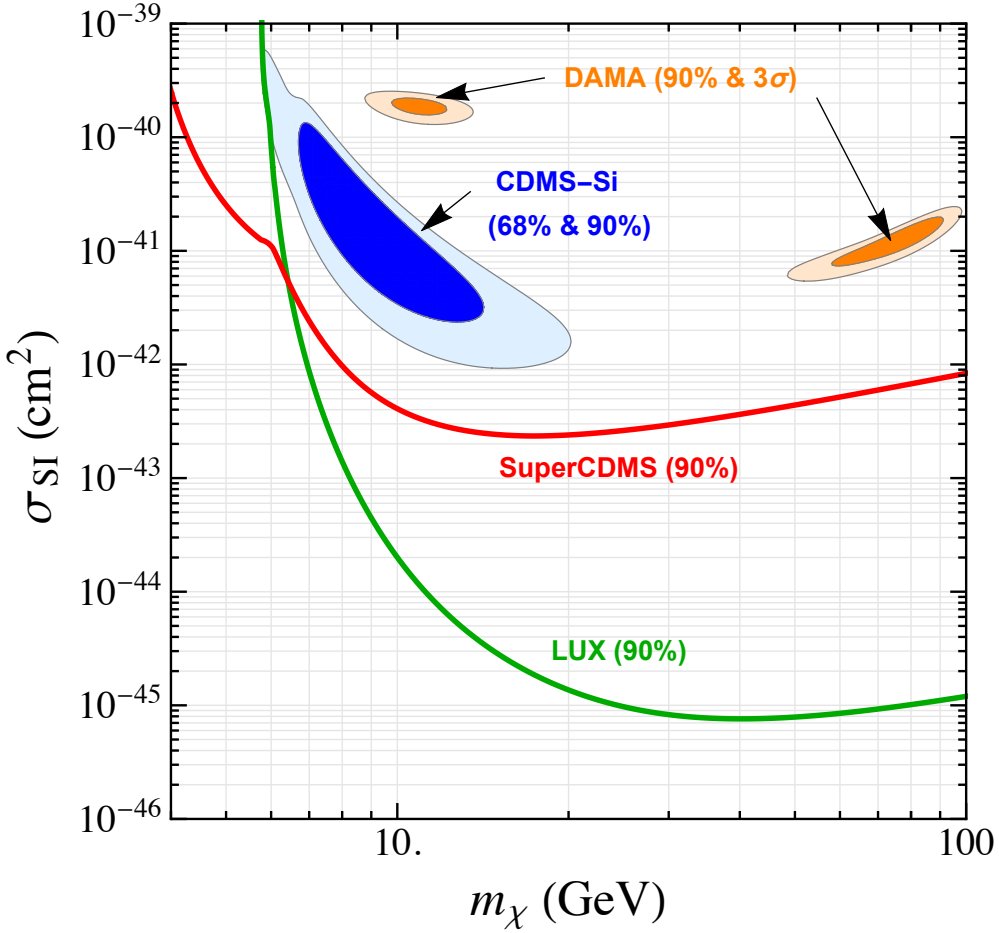
  - local DM density: $\rho_\chi \sim 0.3$ GeV cm^{-3}
  - typical DM velocity: $\bar{v} \simeq 220$ km/s
- Numerical simulations of galaxy formation predict dark matter velocity distributions which can deviate from a Maxwellian.

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 demonstrate that the mass constraint is not enough to define a MW-like galaxy.
- 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.
  - The galaxies contain a substantial stellar disc component.

Observations vs. simulations

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

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

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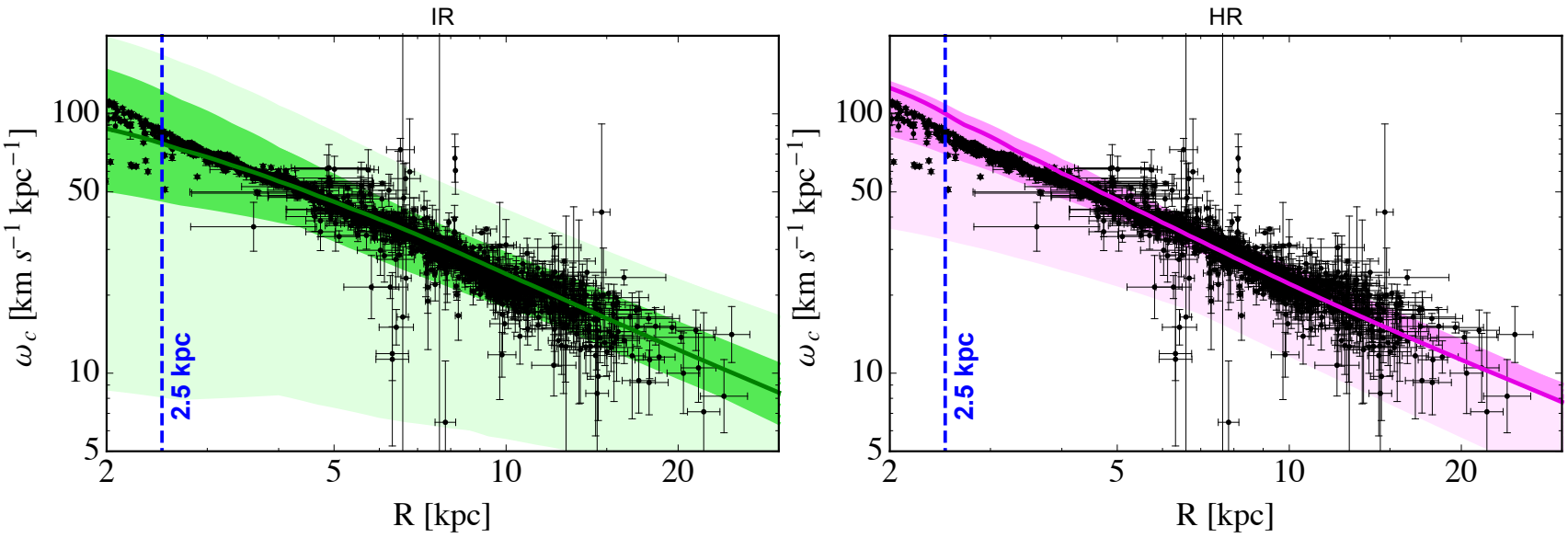
- **Observational data**: extensive compilation of MW rotation curve measurements from: **[Iocco, Pato, Bertone, 1502.03821]**.

Observations vs. simulations

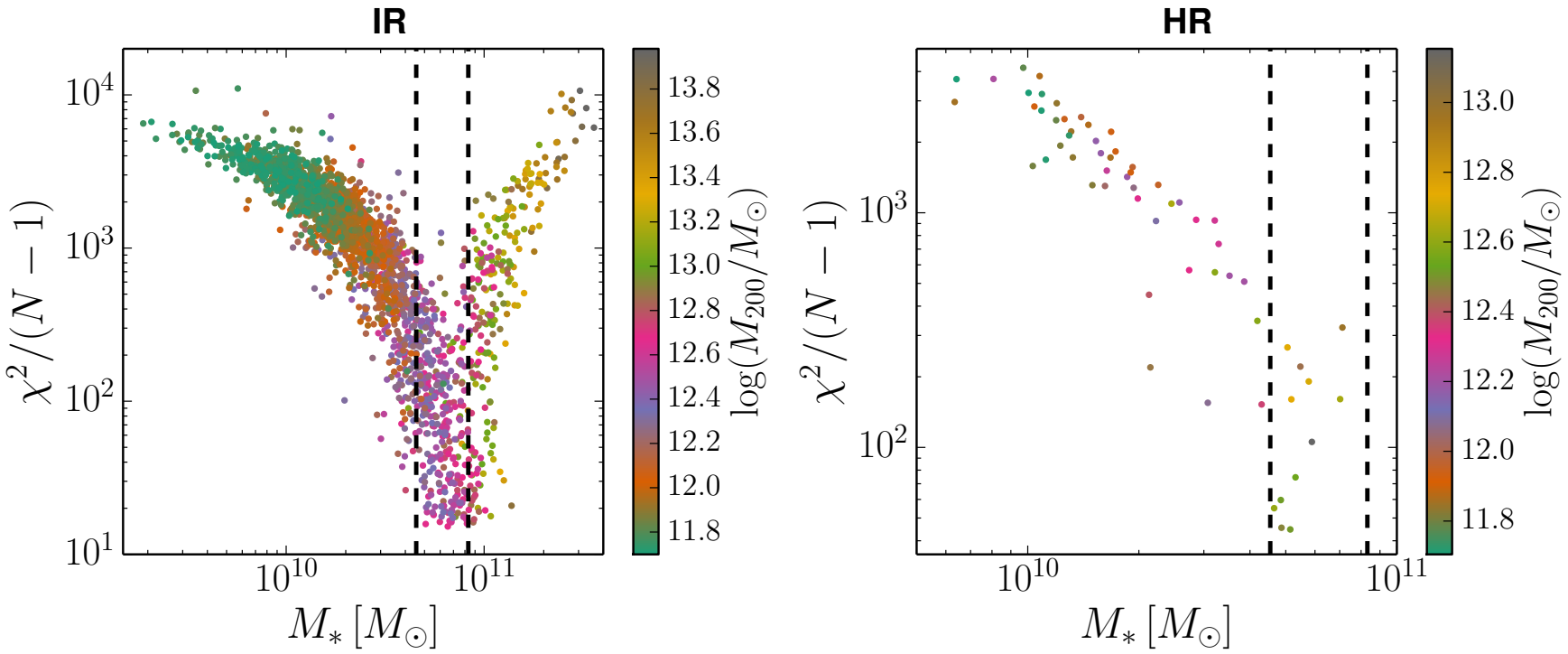
Rotation curve and stellar mass criteria:



- 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:



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

- The minimum of the reduced χ^2 naturally 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.

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).

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- Select simulated galaxies whose stellar kinematics show a disc component, rather than ellipticals or undergoing mergers.
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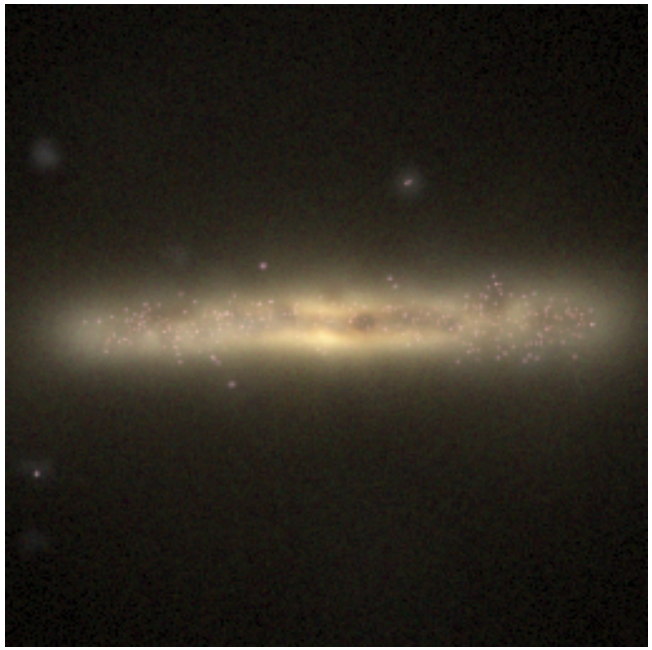
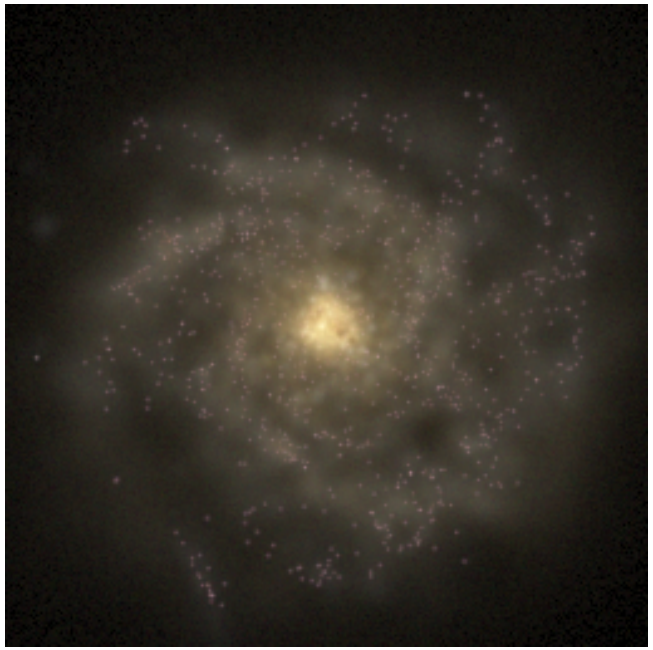
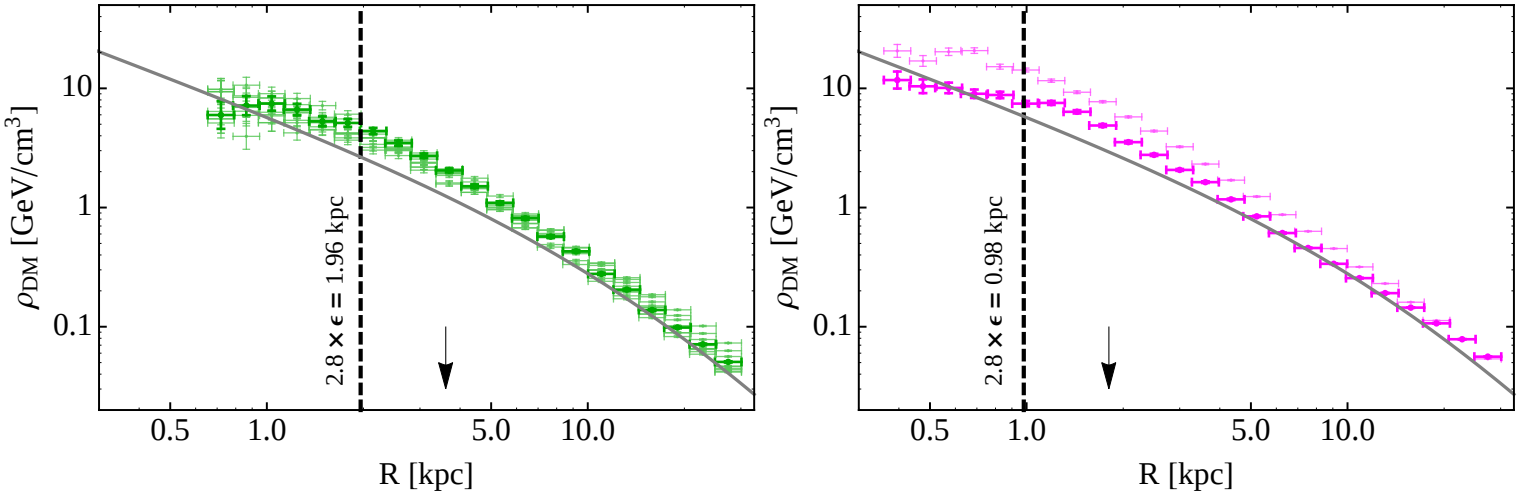
- Haloes satisfying all criteria: **10** in the **IR**, and **2** in the **HR** runs.





Dark matter density profiles

- Spherically averaged DM density profiles:



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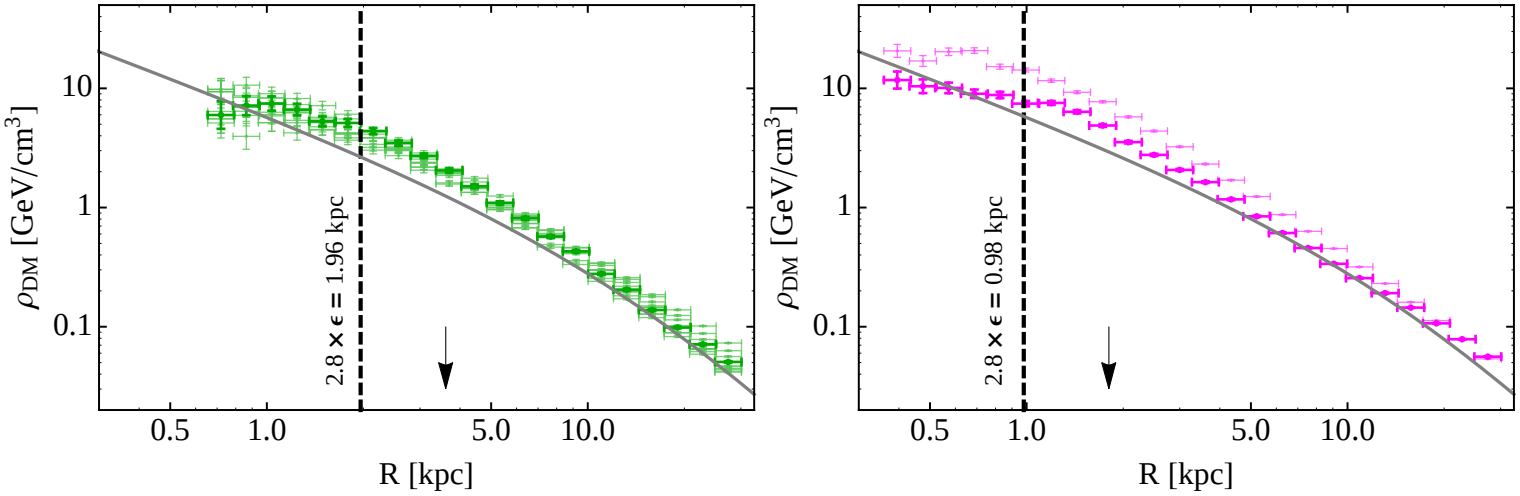
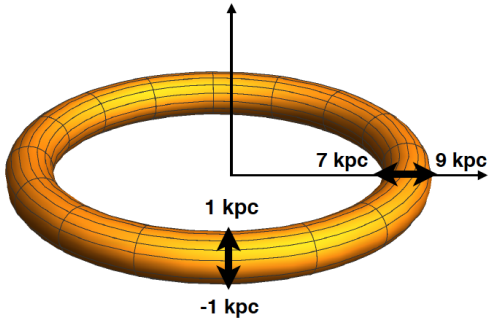


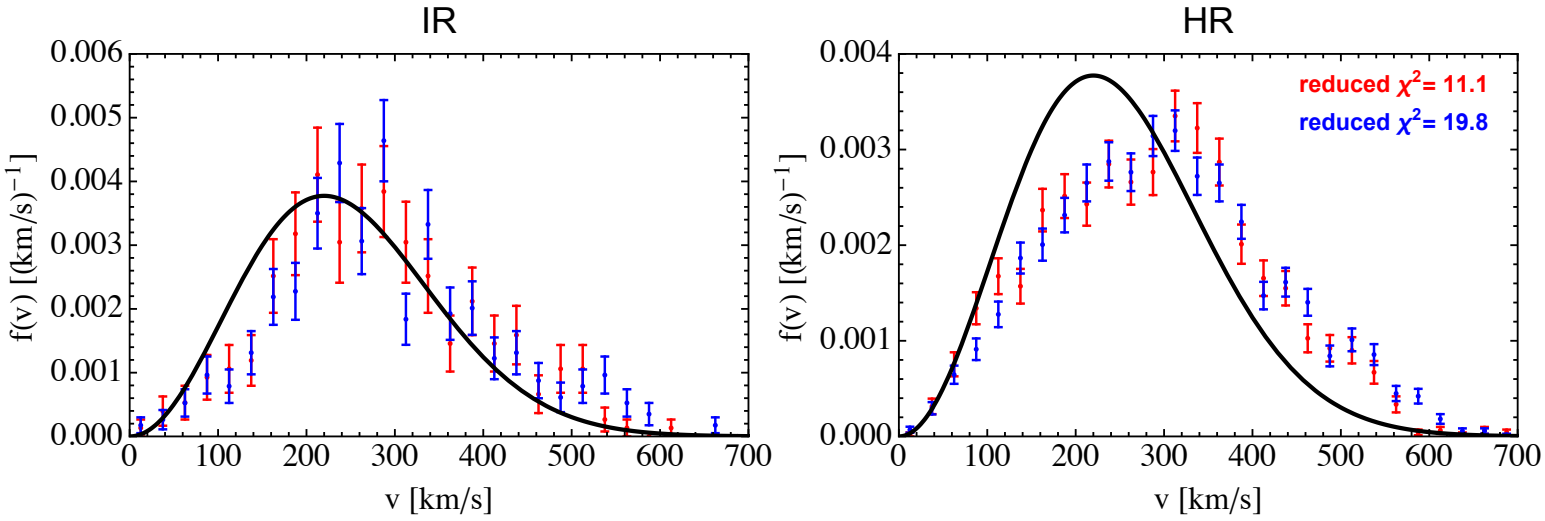
- Need the DM density at the position of the Sun.
- Consider a torus aligned with the stellar disc with $7\ \mathrm{kpc} < R < 9\ \mathrm{kpc}$, and $-1\ \mathrm{kpc} < z < 1\ \mathrm{kpc}$.

  IR haloes: local $\rho_{\mathrm{DM}} = 0.55 - 0.84$ GeV cm^{-3}.
  HR haloes: local $\rho_{\mathrm{DM}} = 0.44 - 0.65$ GeV cm^{-3}.



Local speed distributions

In the galactic rest frame:



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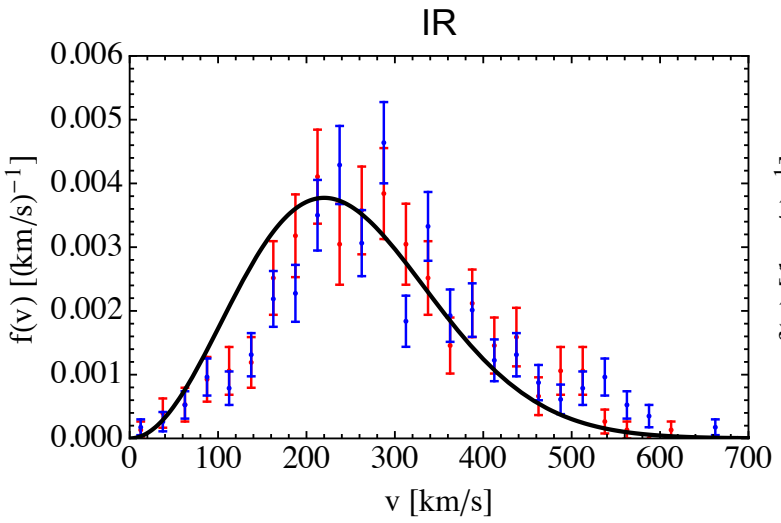
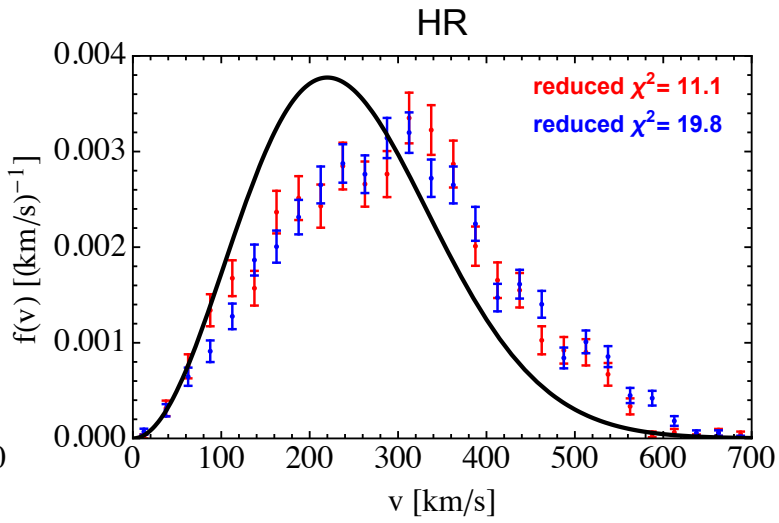
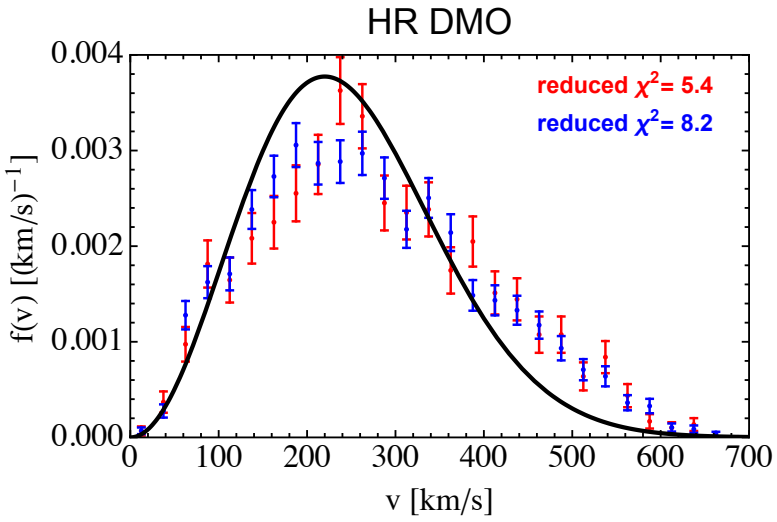




- Comparison to dark matter only (DMO) simulations:



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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- Need the velocity distributions in the detector reference frame:

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

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

$v_{\rm sim}$: rotational velocity of star particles in simulations.

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

The halo integral

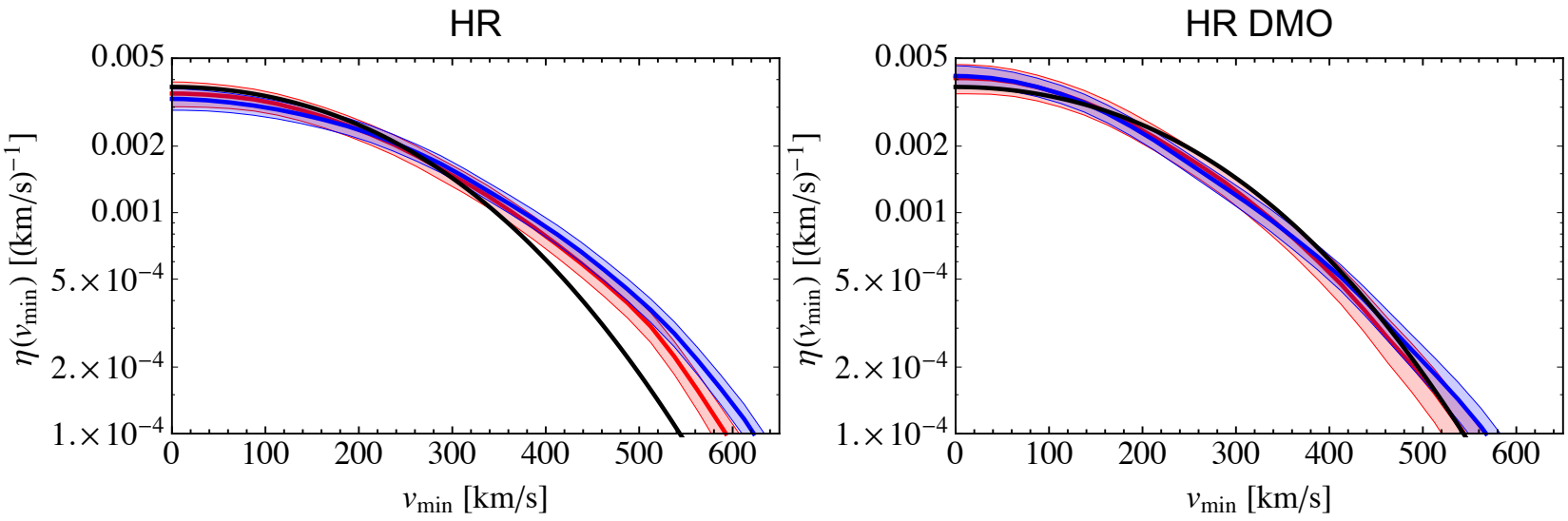
- For the standard spin-independent and spin-dependent scattering:

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

where

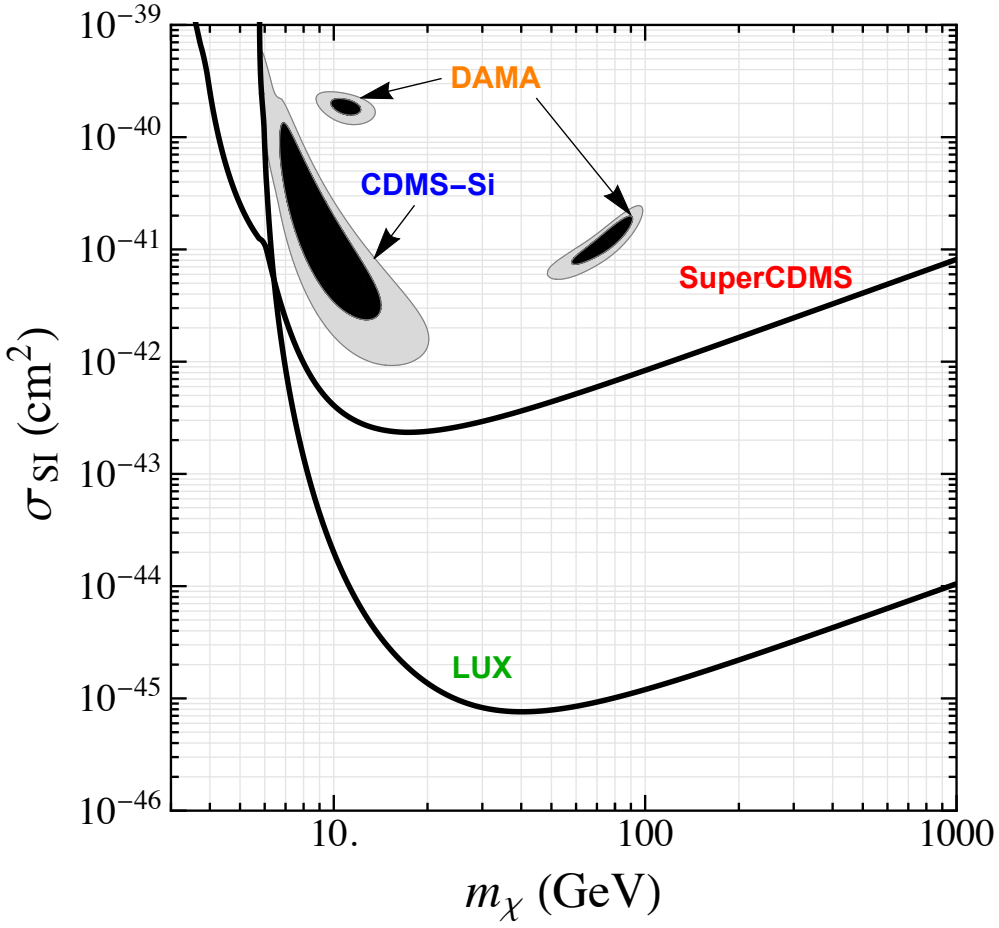
$$\boxed{\eta(v_m, t) \equiv \int_{v > v_m} d^3 v \, \frac{f_{\rm det}(\mathbf{v}, t)}{v}}$$

halo integral



Implications for direct detection

- Assuming the SHM:



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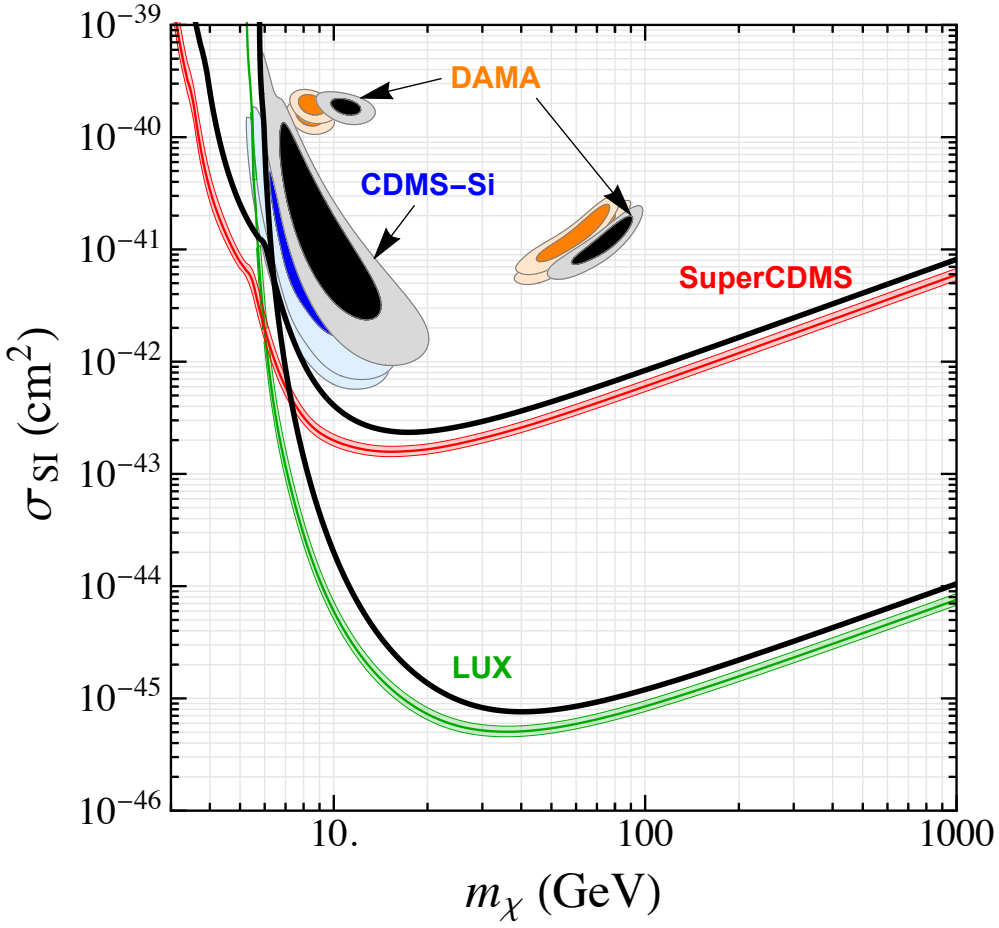

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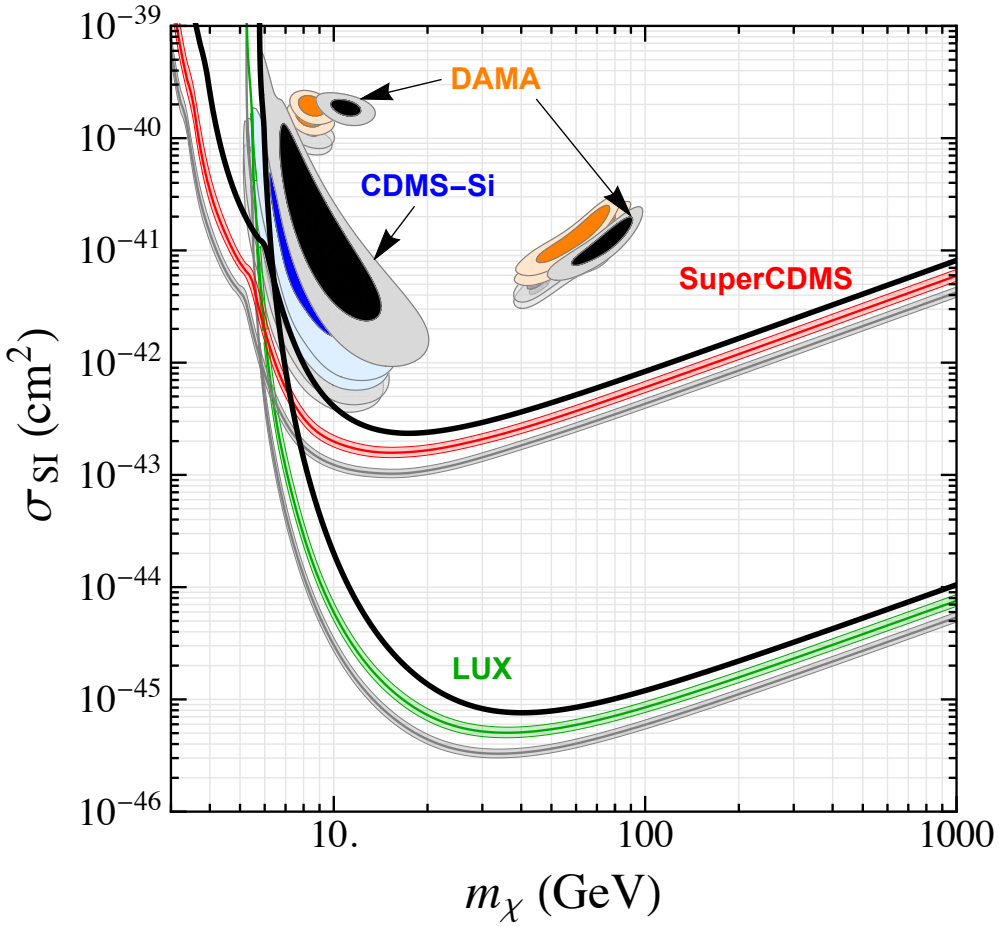

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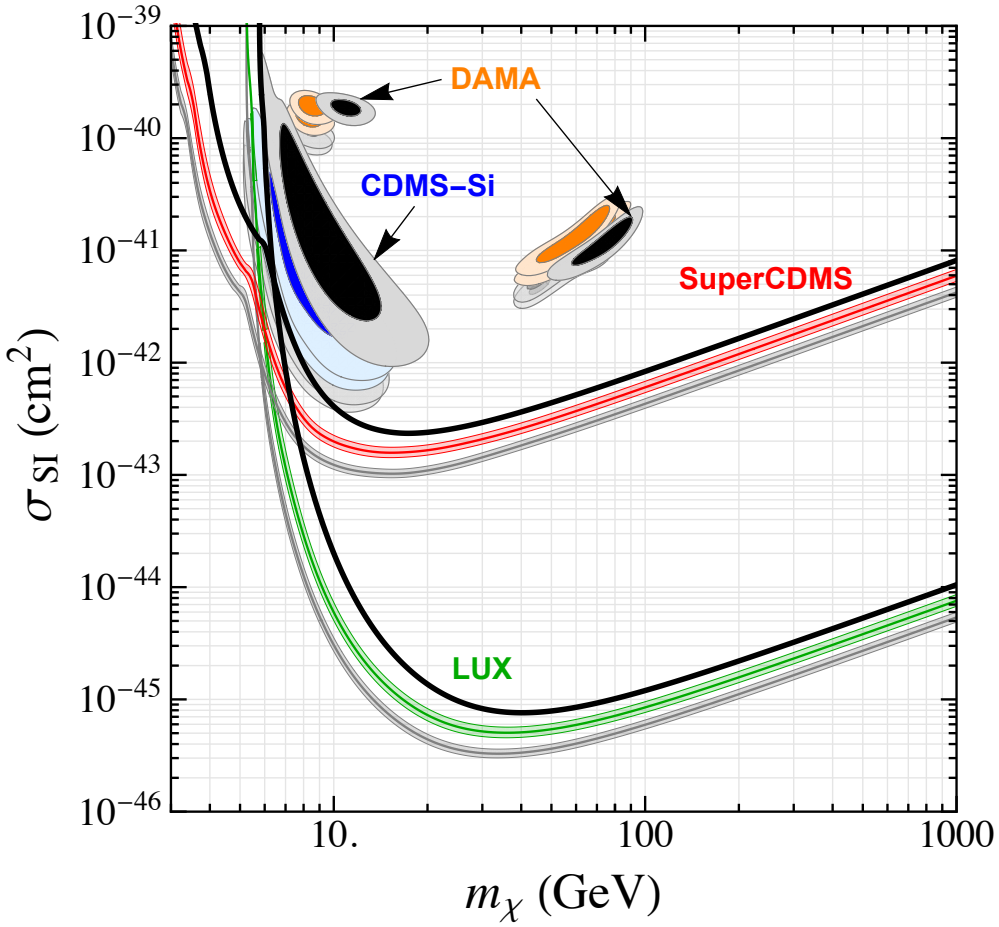

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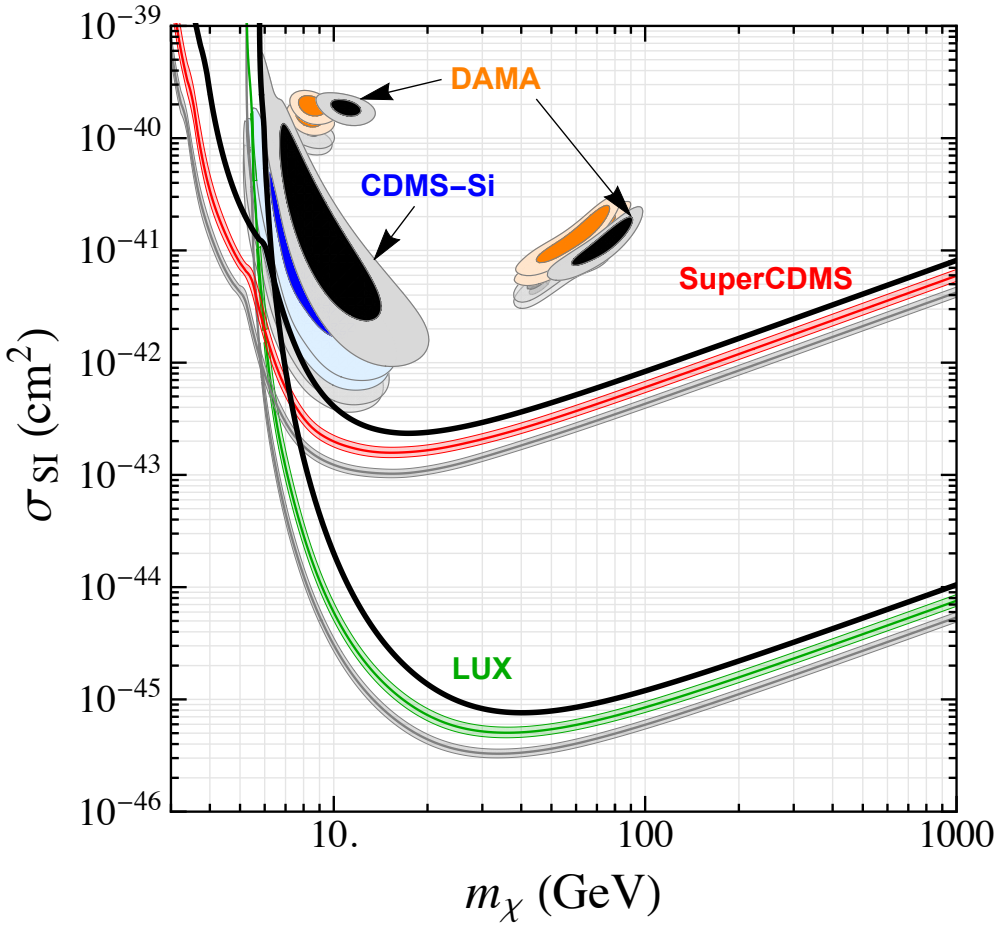
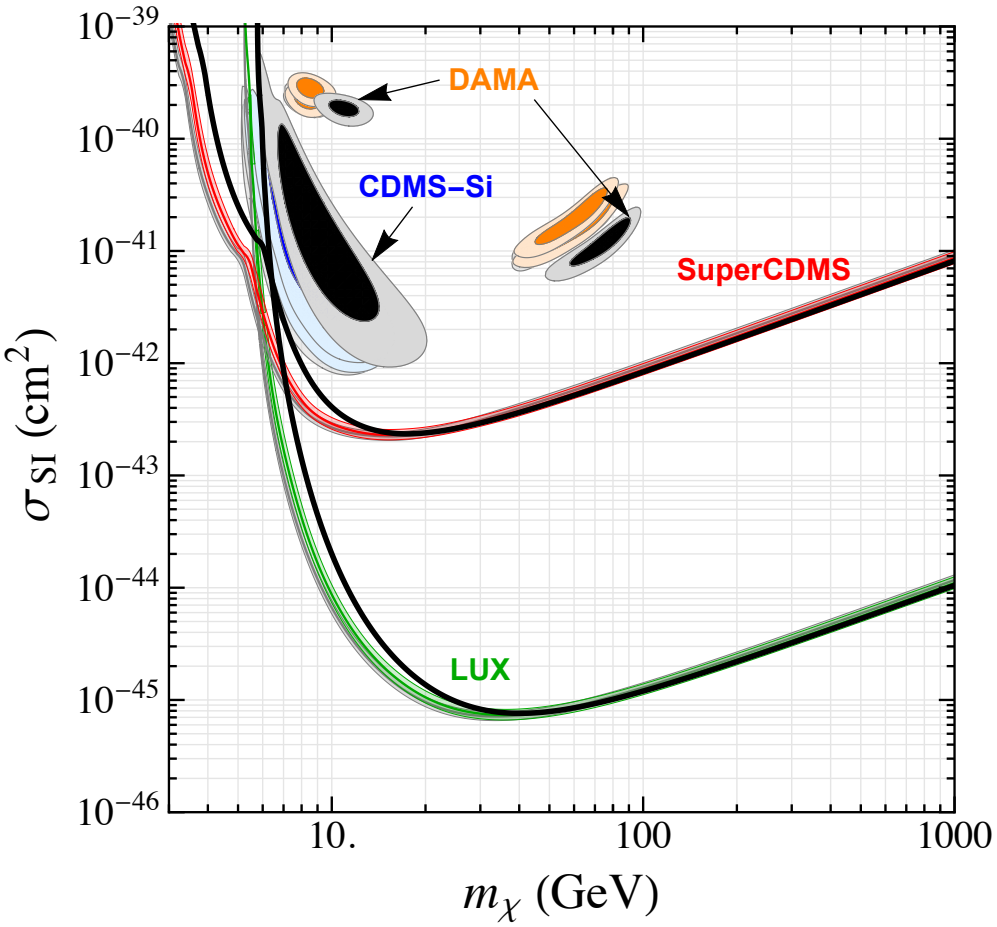


- Halo-to-halo uncertainty larger than the 1σ uncertainty from each halo.
- Overall difference with SHM mainly due to the different local DM density of the simulated haloes.

Effect of the velocity distribution

- We fix the local $\rho_{\rm DM} = 0.3$ 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.

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.
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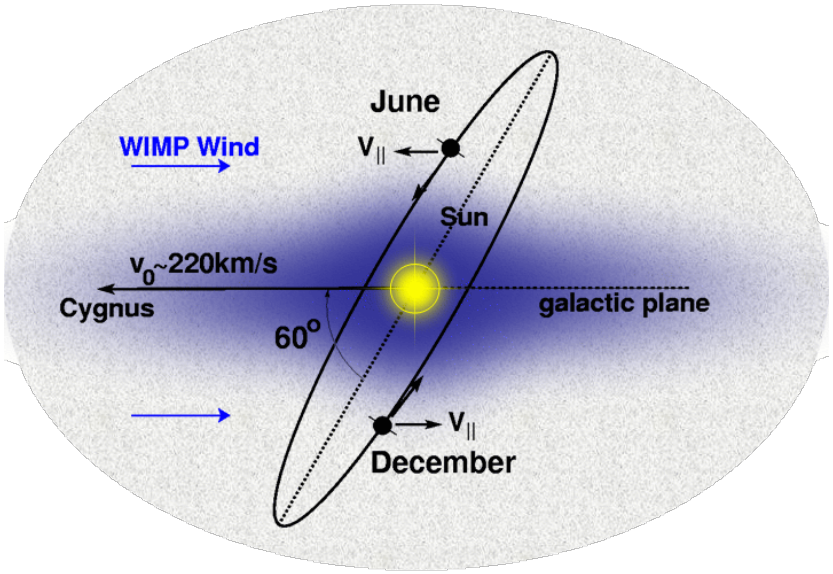
- The local velocity distribution of the selected haloes deviates substantially from the SHM Maxwellian with an excess at higher speeds. $\Rightarrow$ shift of allowed regions and exclusion limits at low WIMP masses.
- The local DM density: $\rho_{\rm DM} = 0.44 - 0.65$ GeV cm^{-3}. $\Rightarrow$ overall shift of the allowed regions and exclusion limits for all masses.

Additional slides

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



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

Velocity distribution $f_{\rm gal}(\mathbf{v})$

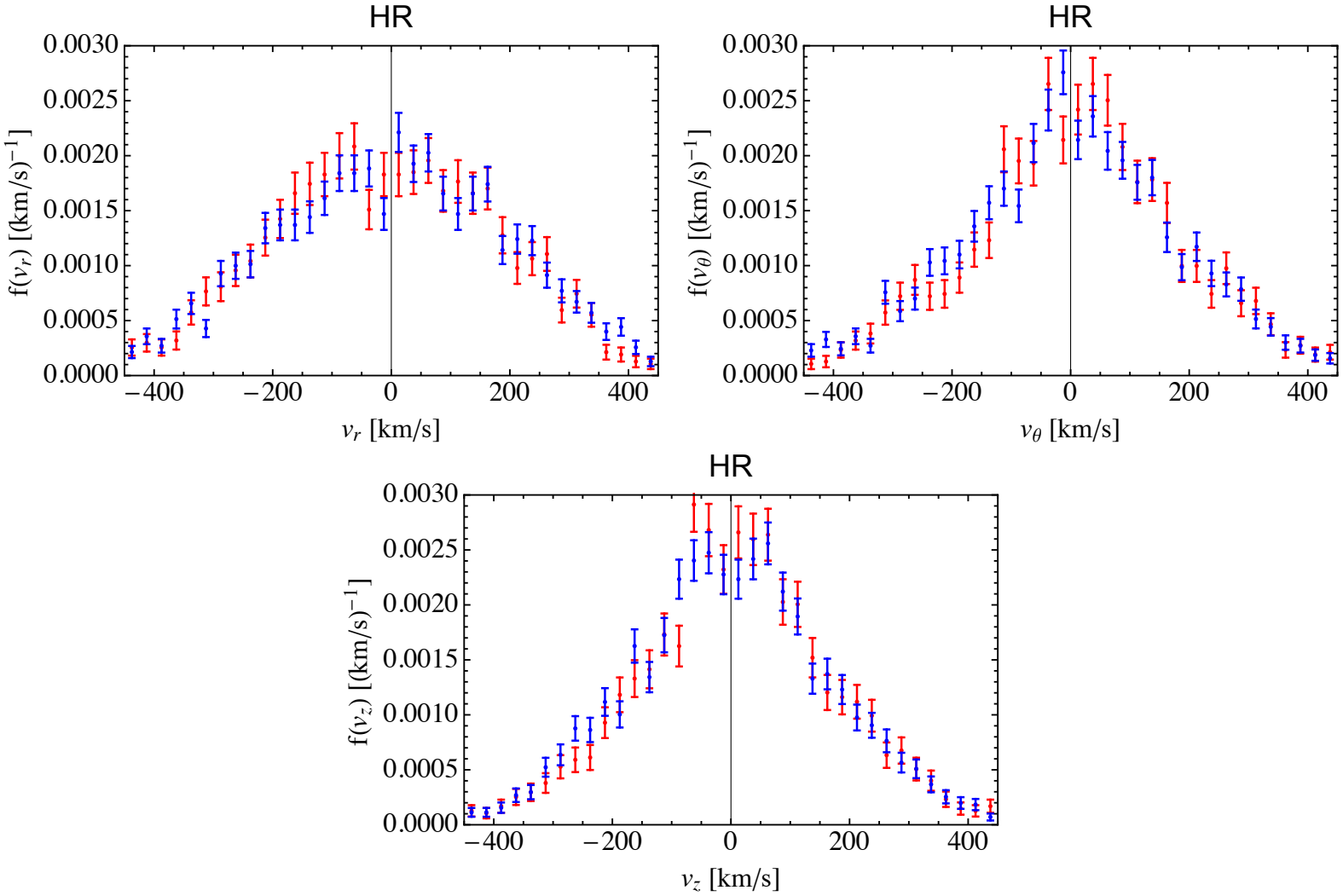
- The velocity distribution depends on the halo model.
- In the SHM, a truncated Maxwellian velocity distribution is assumed

$$f_{\rm gal}(\mathbf{v}) \approx \begin{cases} N \exp(-\mathbf{v}^2/\bar{v}^2) & v < v_{\rm esc} \\ 0 & v \geq v_{\rm esc} \end{cases}$$

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