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Direct Detection for Self-Interacting Dark Matter models

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Outline

1. Introduction
2. Identifying Milky Way-like halos
3. DM Density Profile
4. DM Speed Distribution
5. Transforming to Detectors Frame
6. Comparison of cross-section models
7. Summary & Conclusion

Aim of the project

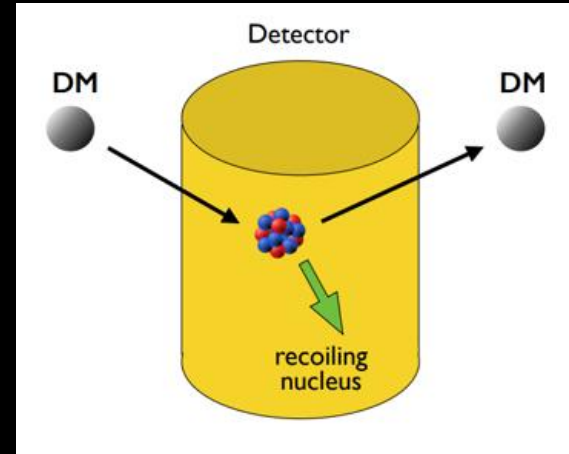
- Dark matter direct detection event rate depends on the local dark matter distribution
- What is the local dark matter distribution for self-interacting dark matter (SIDM)?
- Use cosmological simulations of SIDM to answer this question

Direct detection of dark matter

- measuring the recoil energy of nuclei after interaction with DM particle
- Event rate determines the DM mass and cross section:

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v > v_{\min}} d^3v \frac{d\sigma_{\chi N}}{dE_R} v f_{\text{det}}(\mathbf{v}, t)$$

- Astrophysical input in the event rate: DM density and velocity distribution in solar neighborhood



Question

Why is the velocity distribution of dark matter in the detector frame?

Why can't we just use the galactic dark matter velocity distribution?

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v > v_{\min}} d^3v \frac{d\sigma_{\chi N}}{dE_R} v f_{det}(\mathbf{v}, t)$$

← velocity distribution

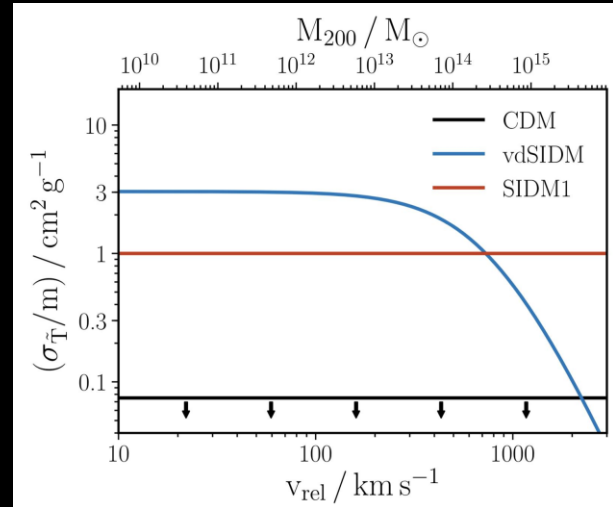
answer

The experiments take place on the earth
→ velocity distribution for the earth is needed



Self-interacting dark matter

- Self-interacting dark matter (SIDM) is an alternative to collisionless cold dark matter (CDM)
- SIDM cross section:
 - Constant (e.g. SIDM1)
 - Velocity-dependent (vdSIDM)

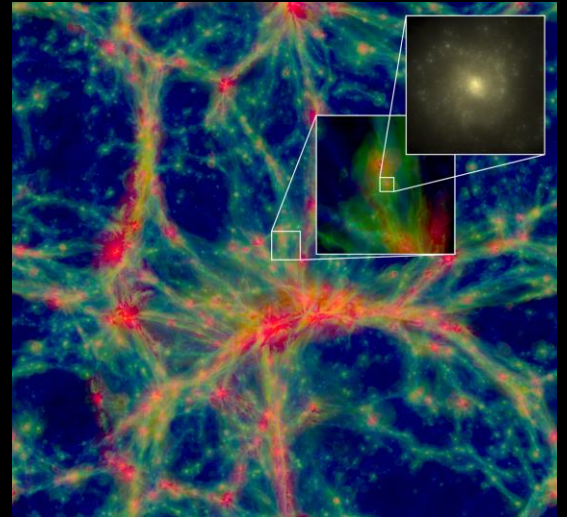


[Robertson et al., 2020]

Cosmological simulations

collisionless dark matter (CDM) vs. self-interacting dark matter (SIDM) vs. SIDM + Baryons

- simulations → constrain the local DM distribution
→ better assumptions about DM properties
- Quantify the difference between const. and vd-cross section for SIDM+baryons models
- Analyze 652 simulated Milky Way sized halos from the EAGLE project



[EAGLE project]

Identifying Milky Way-like halos

- 1. Halo mass: $M_{200} = [0.5 - 500] \cdot 10^{12} M_{\odot}$
- 1. Stellar mass: $M_{\star} = [4.5 - 8.3] \cdot 10^{10} M_{\odot}$
- 1. Rotation curve → compare to observations
- 1. Halo structure → excluding halos with large substructures near the solar circle

652 simulated halos



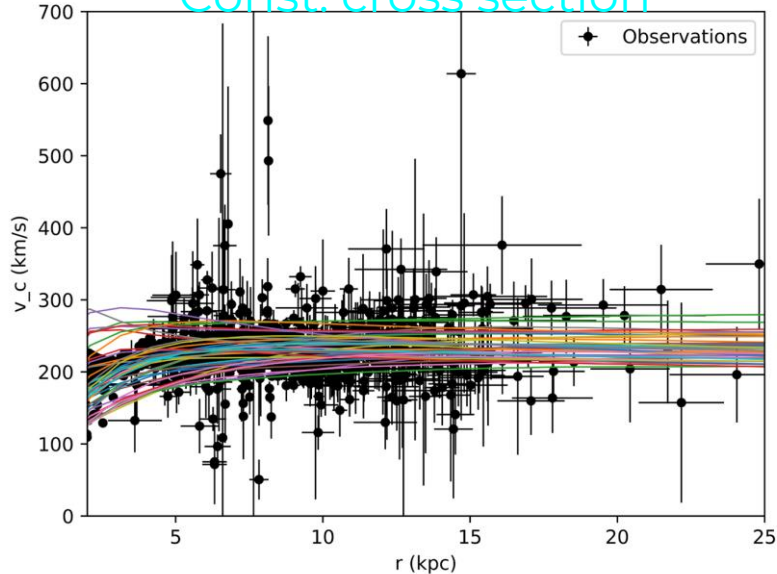
79 MW-like halos

38 const. cross section halos
41 vd.- cross section halos

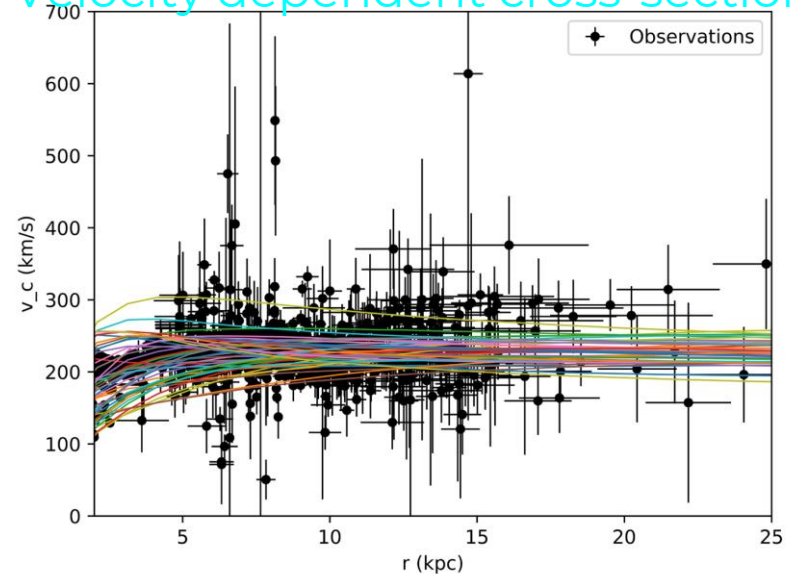
Total rotation curves

appear to be in good agreement \rightarrow no halos excluded based on their rotation curve

Const. cross section



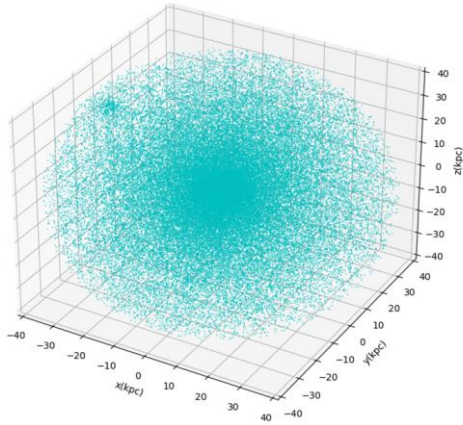
Velocity dependent cross-section



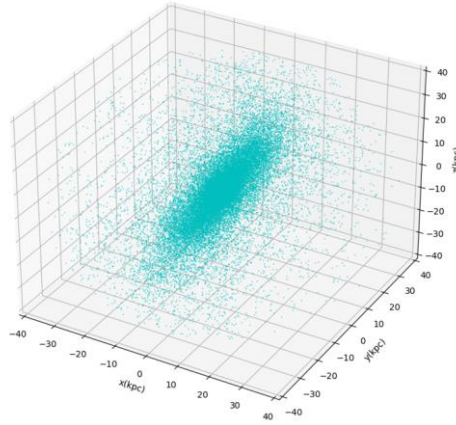
Simulation frame

(x,y,z) axes are in random directions → transform to a new reference frame

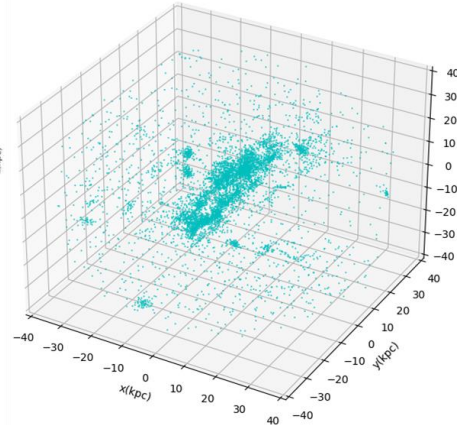
Dark matter



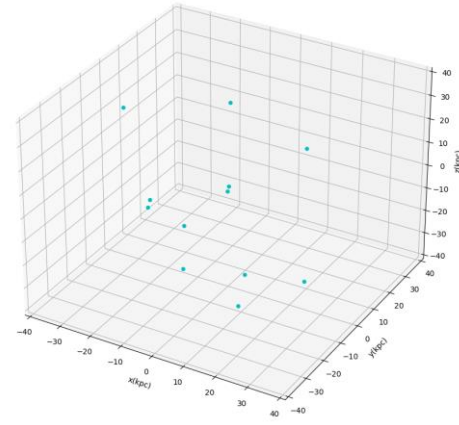
Stars



Gas



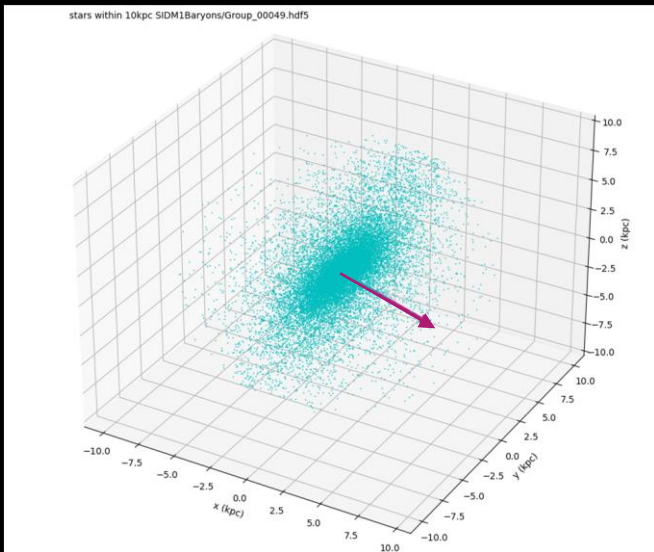
Black holes



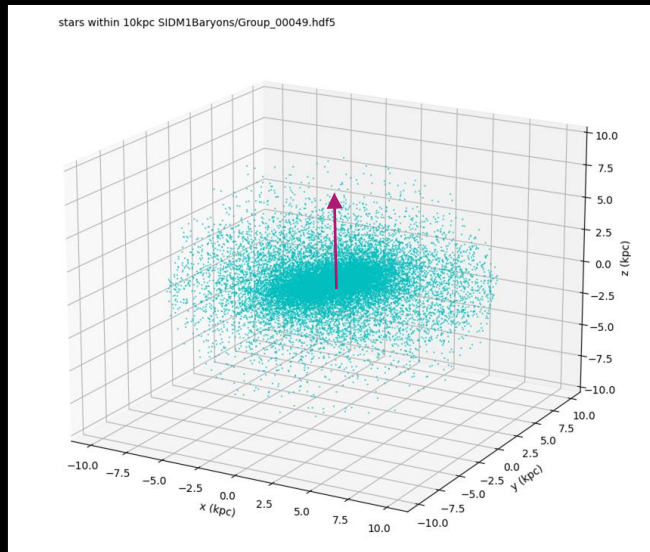
Defining the stellar disk

aligning the z' -axis with the direction of the angular momentum of the stars within 10 kpc

simulation frame (x,y,z)



galactic frame (x',y',z')

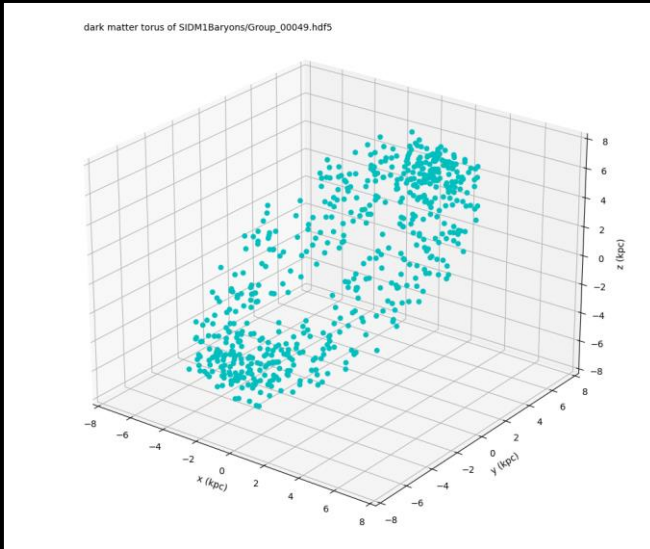


Defining the solar circle

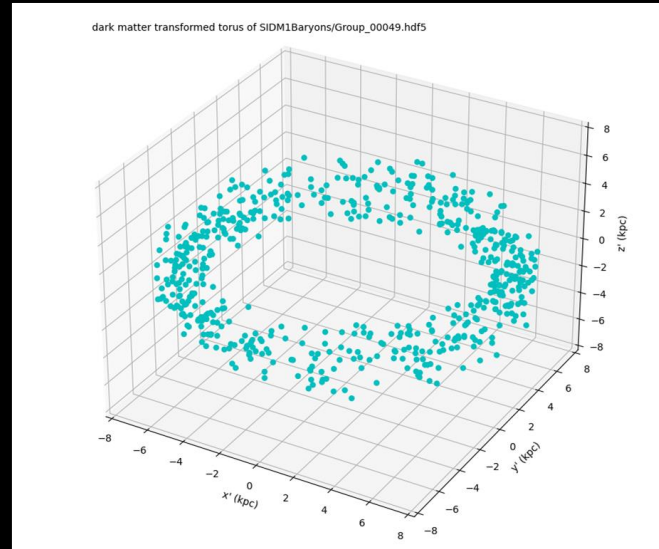
solar circle: $r=8\text{kpc}$

→ cylindrical shell with an inner and outer radius of 7kpc and 9kpc and a height extending from -2 kpc to 2 kpc

Simulation frame (x,y,z)



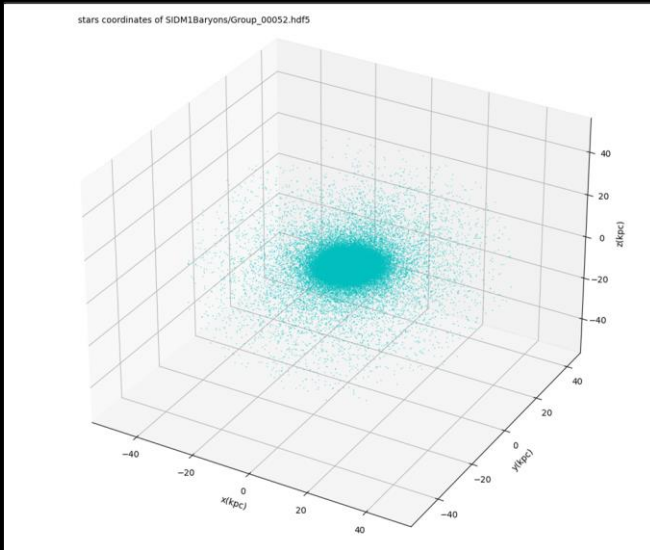
Galactic frame (x',y',z')



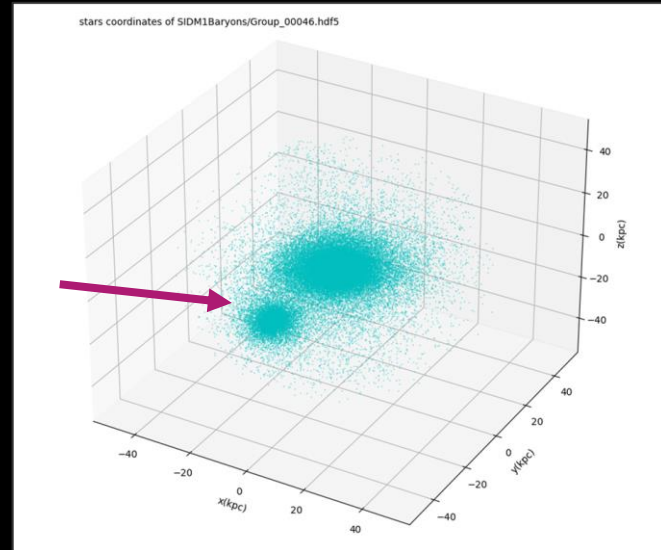
Excluding halos with substructures

excluded halos with substructures near the solar circle
-> focus on the smooth halo

No substructures

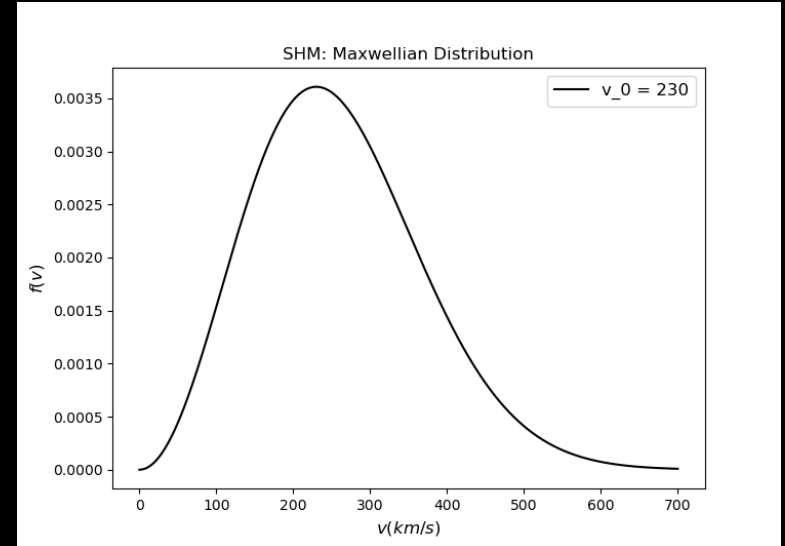


With a substructure



Standard Halo Model

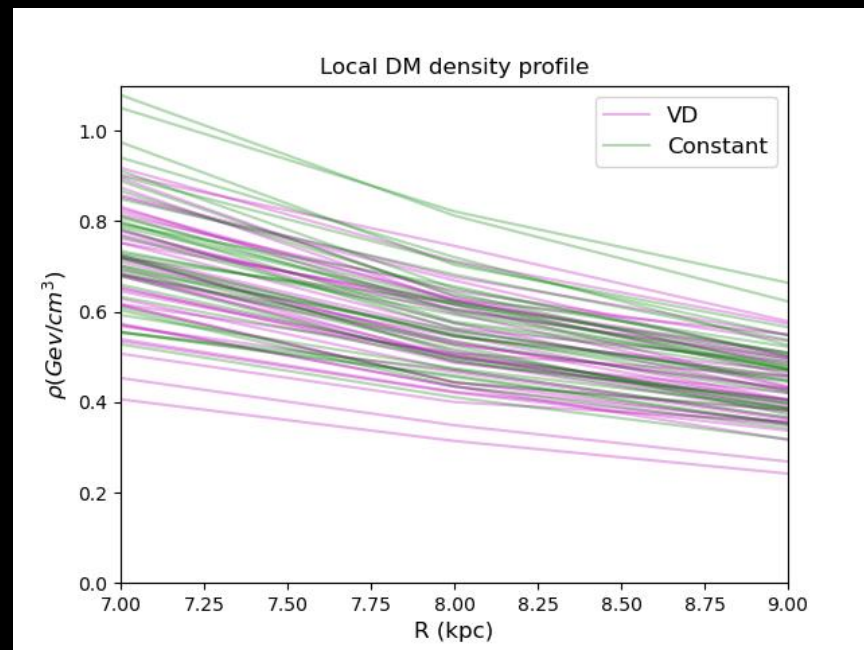
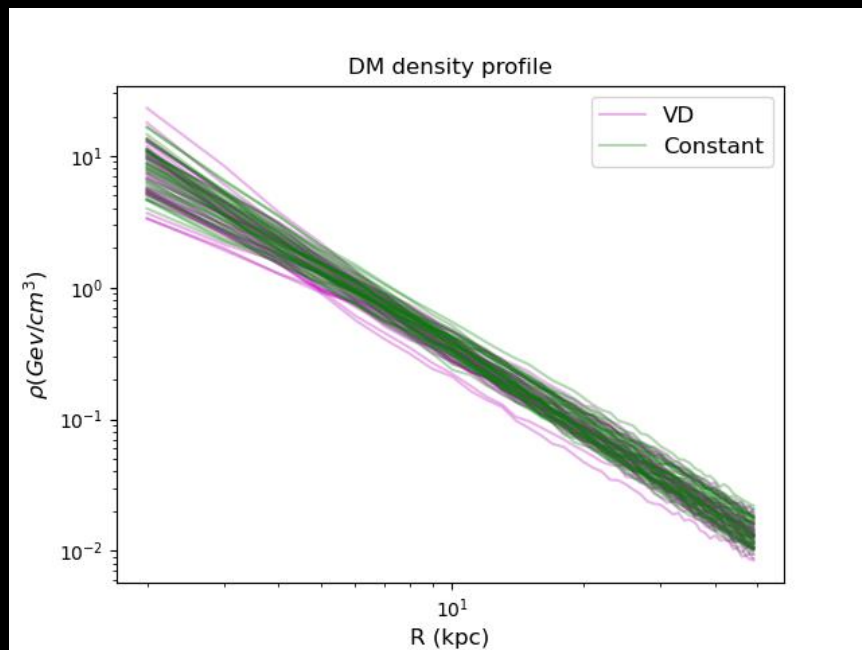
- Spherical and Isothermal
- Follows isotropic Maxwellian speed distribution
- Has density of 0.3 GeV/cm^3
- Most probable speed of 230 km/s



Density Profile

Vel. Dep. Cross Section	Constant Cross Section
$\rho = [0.29 - 0.67] \text{ GeV/cm}^3$	$\rho = [0.34 - 0.78] \text{ GeV/cm}^3$

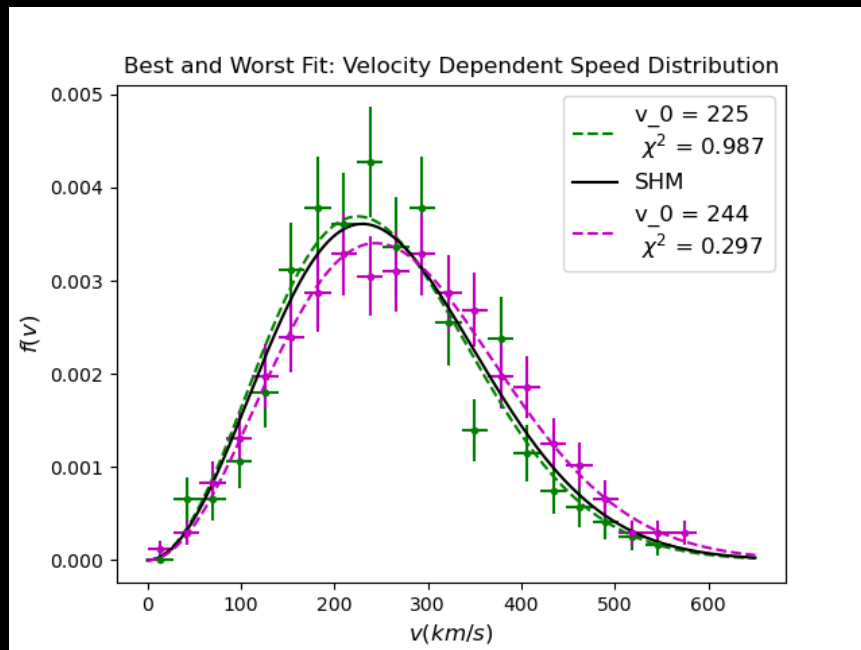
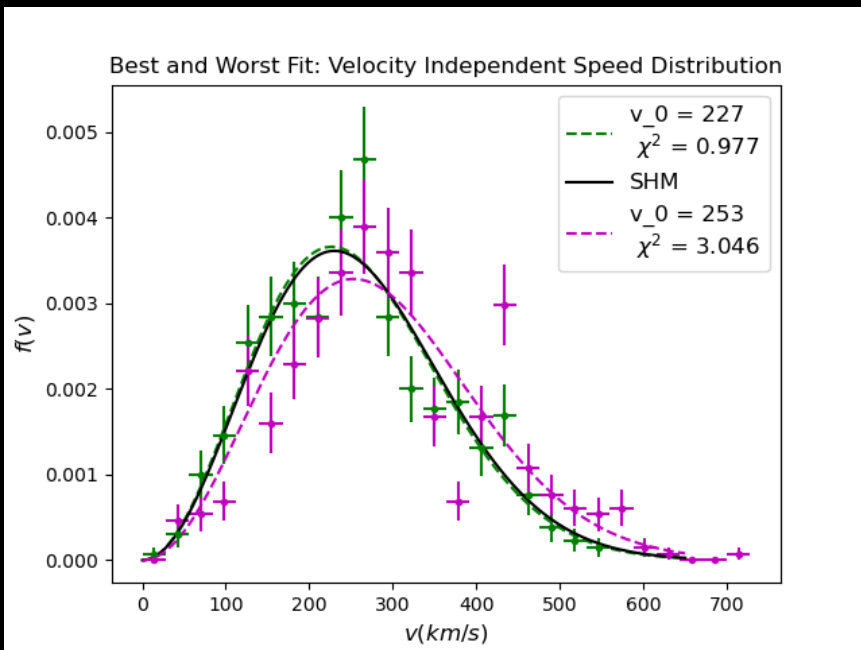
- Constant cross section shifted upwards \rightarrow higher density \rightarrow greater event rate



Local DM Speed Distribution in the Galactic Frame

- DM speed distribution is fitted with a standard Maxwellian distribution
- The velocity dependent haloes are closer to the SHM

$$f(|\mathbf{v}|) \propto |\mathbf{v}|^2 \exp[-(|\mathbf{v}|/v_0)^2]$$



Comparing Speed Distributions

Vel. Dep. Cross Section

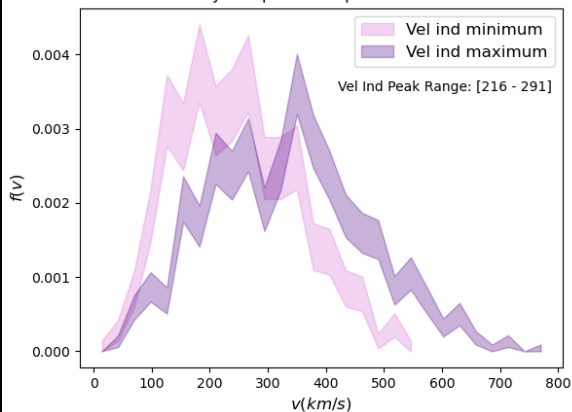
Constant Cross Section

$v_{\text{peak}} = [206 - 270] \text{ km/s}$

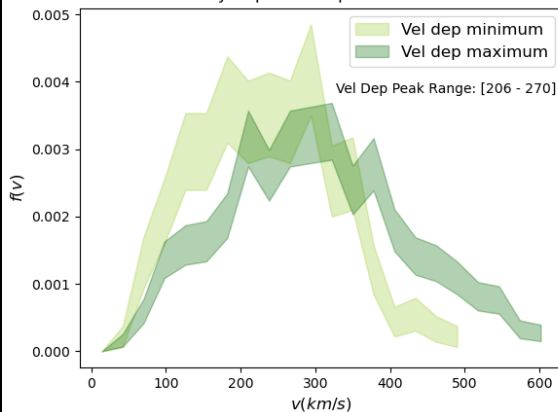
$v_{\text{peak}} = [216 - 291] \text{ km/s}$

- The velocity independent peak speed is shifted to the right

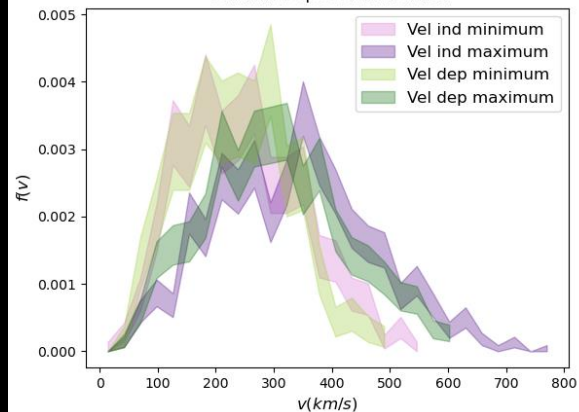
Velocity Independent Speed Distribution



Velocity Dependent Speed Distribution



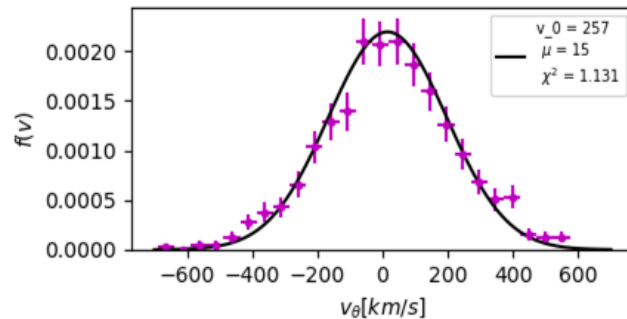
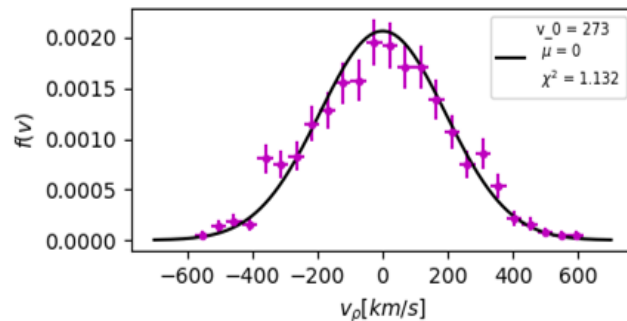
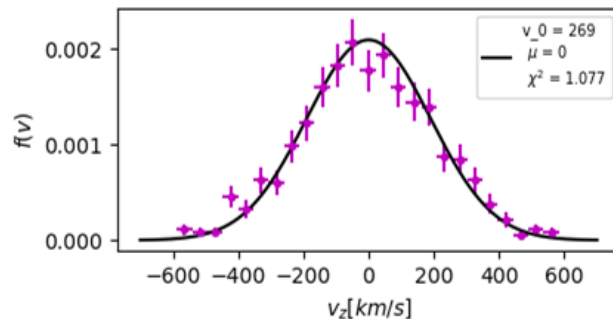
Combined Speed Distribution



Component Dist.

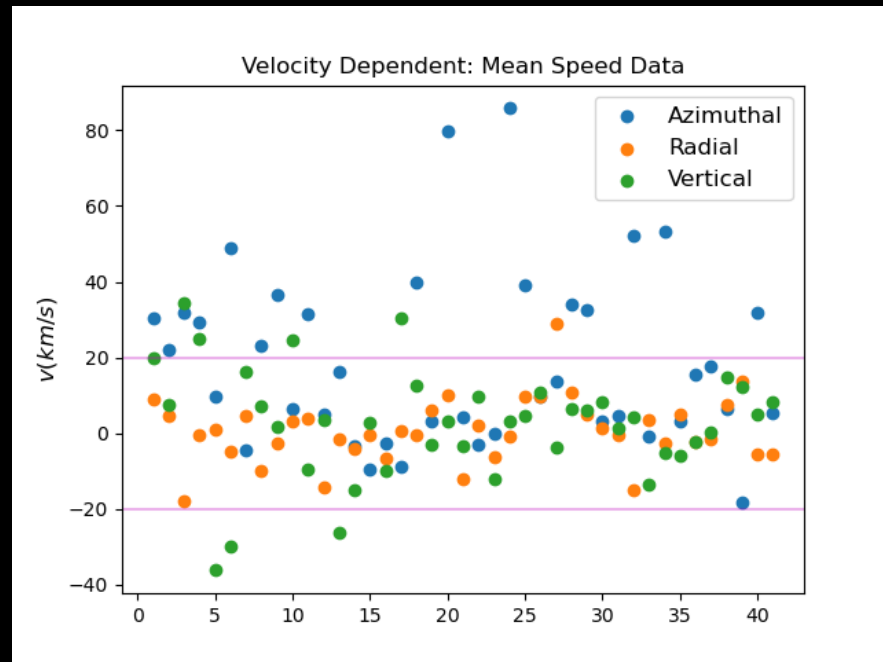
- The velocity distribution is plotted for the vertical, radial and azimuthal components
- The best fit was a Gaussian distribution

$$f(v_i) = \frac{1}{\sqrt{\pi}v_0} \exp \left[-(v_i - \mu)^2 / v_0^2 \right]$$



Component Dist.

- Radial and vertical \rightarrow mostly ranged between $[-20 - 20]$ km/s
- Azimuthal component shifted \rightarrow significant rotation of the DM particles along the galactic disk



Transforming to the detectors frame

- Transform the DM velocities from galactic to the detectors frame by

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

← Earth's velocity w.r.t the sun

$$\mathbf{v}_s = \mathbf{v}_c + \mathbf{v}_{\text{pec}}$$

Sun's velocity w.r.t the galactic frame

Circular velocity

Peculiar velocity

Question

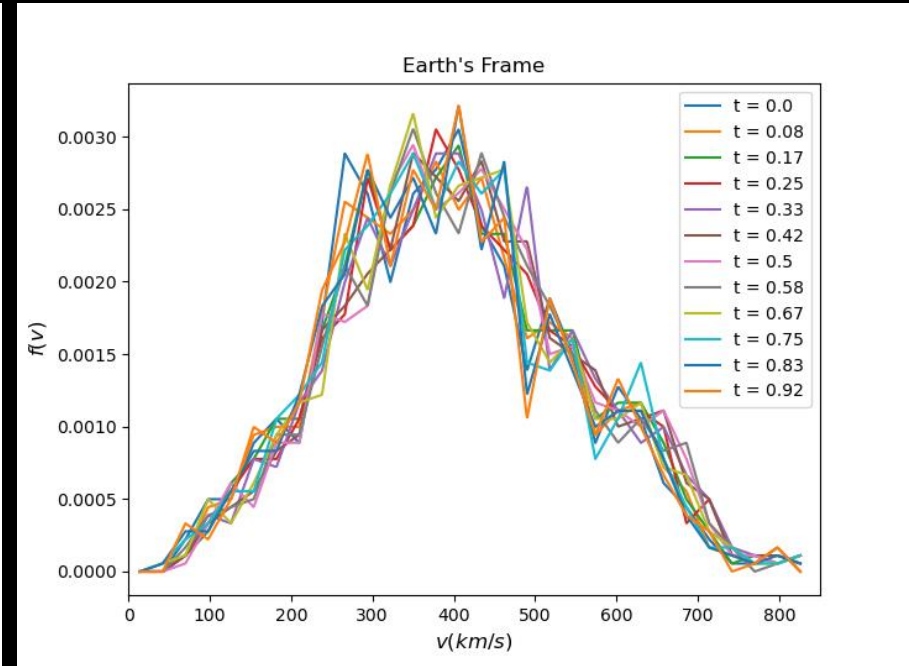
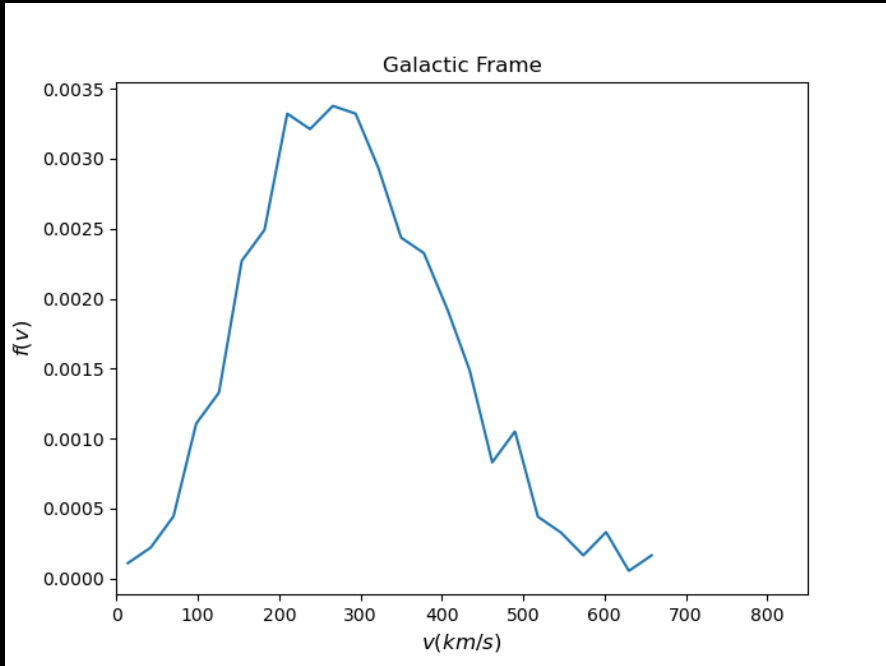
Why is $v_e(t)$ expressed as a function of time?



answer

- Annual variation of Earth's velocity w.r.t the sun
- $V_e(t)$ → time dependence for the event rates equation

Transformation of Speed Distribution



$$\frac{dR}{dE_R} \propto \rho_\chi \eta(v_{\min}, t)$$

Event rate depends on local DM density and DM velocity distribution

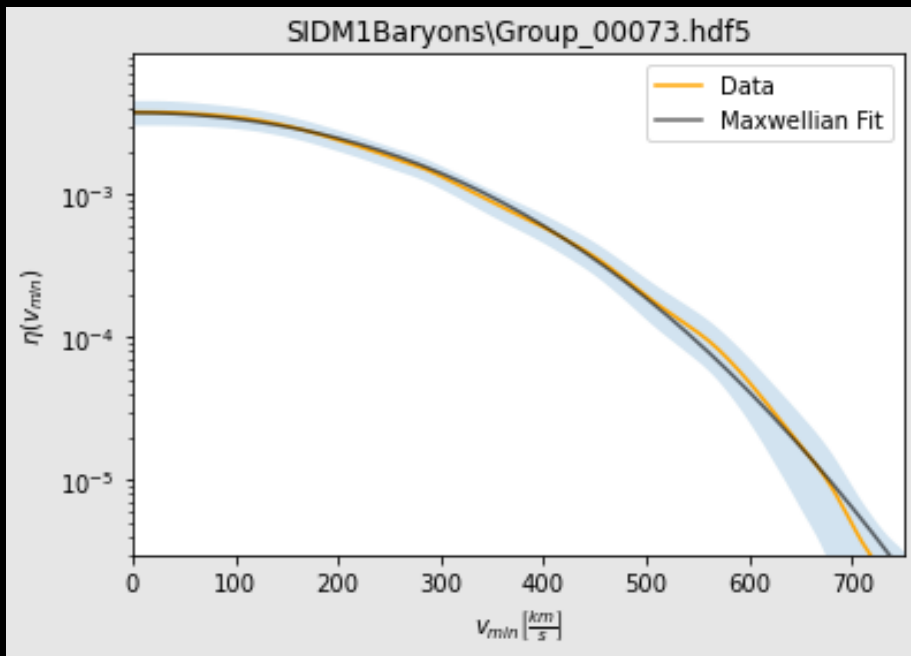
DM velocity distribution \rightarrow Halo Integral

$$\eta(v_{\min}, t) \equiv \int_{v > v_{\min}} d^3v \frac{f_{\text{det}}(\mathbf{v}, t)}{v}$$

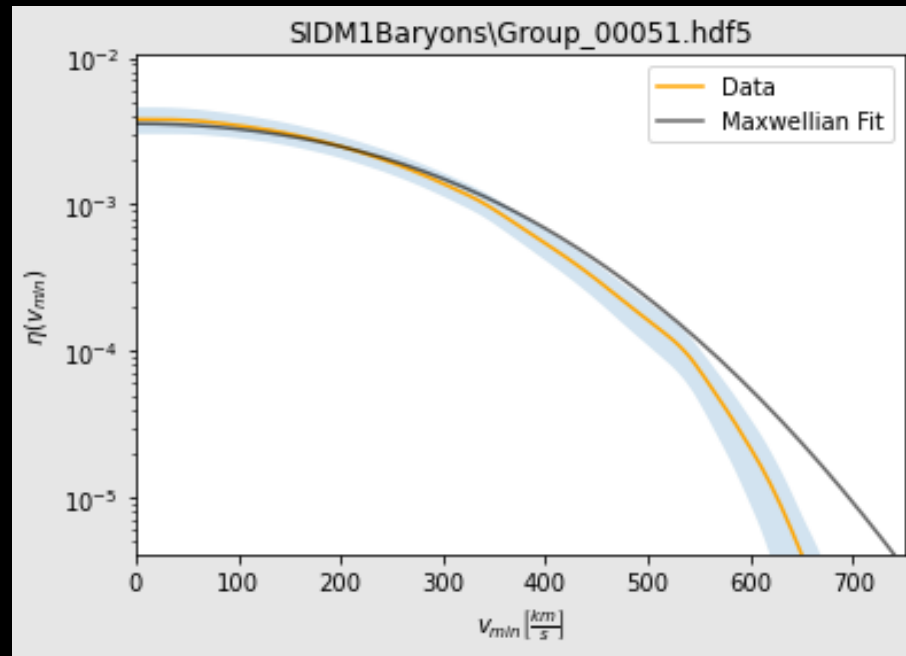
Halo Integral plots

- Eliminate time dependency
 - Mean of all months
- Compare
 - Data
 - Maxwellian distribution fit (Analytical solution)
 - SHM (Maxwellian with $v_0 = 230$ km/s)

Constant cross-section Halo Integral

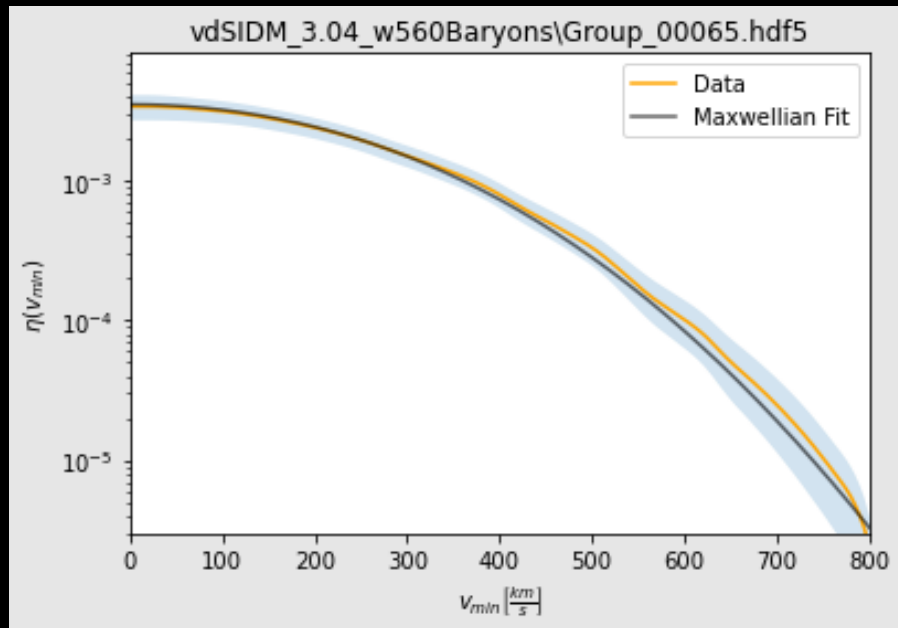


Best Data Maxwell match

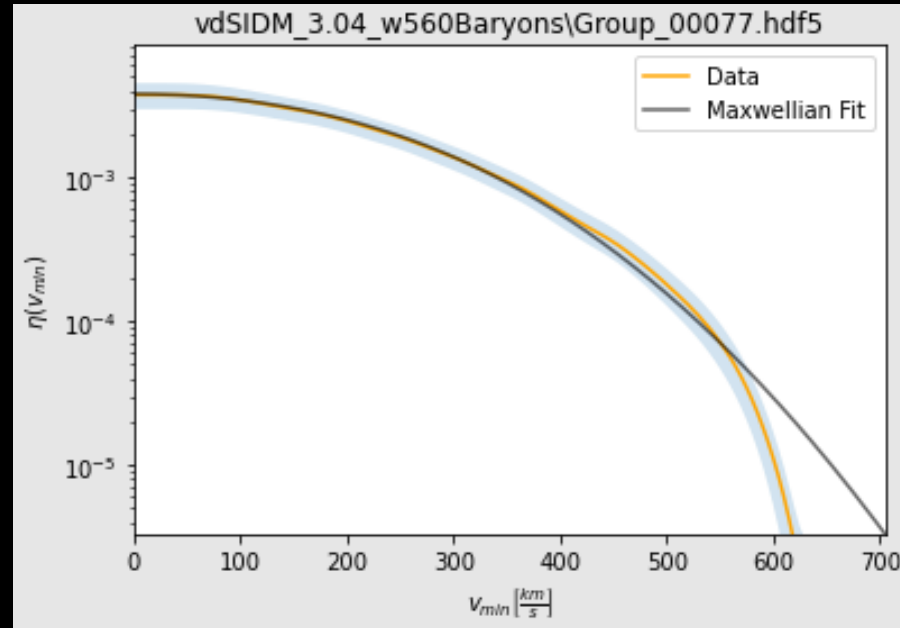


Worst Data Maxwell match

Velocity dependent cross-section Halo Integral



Best Data Maxwell match

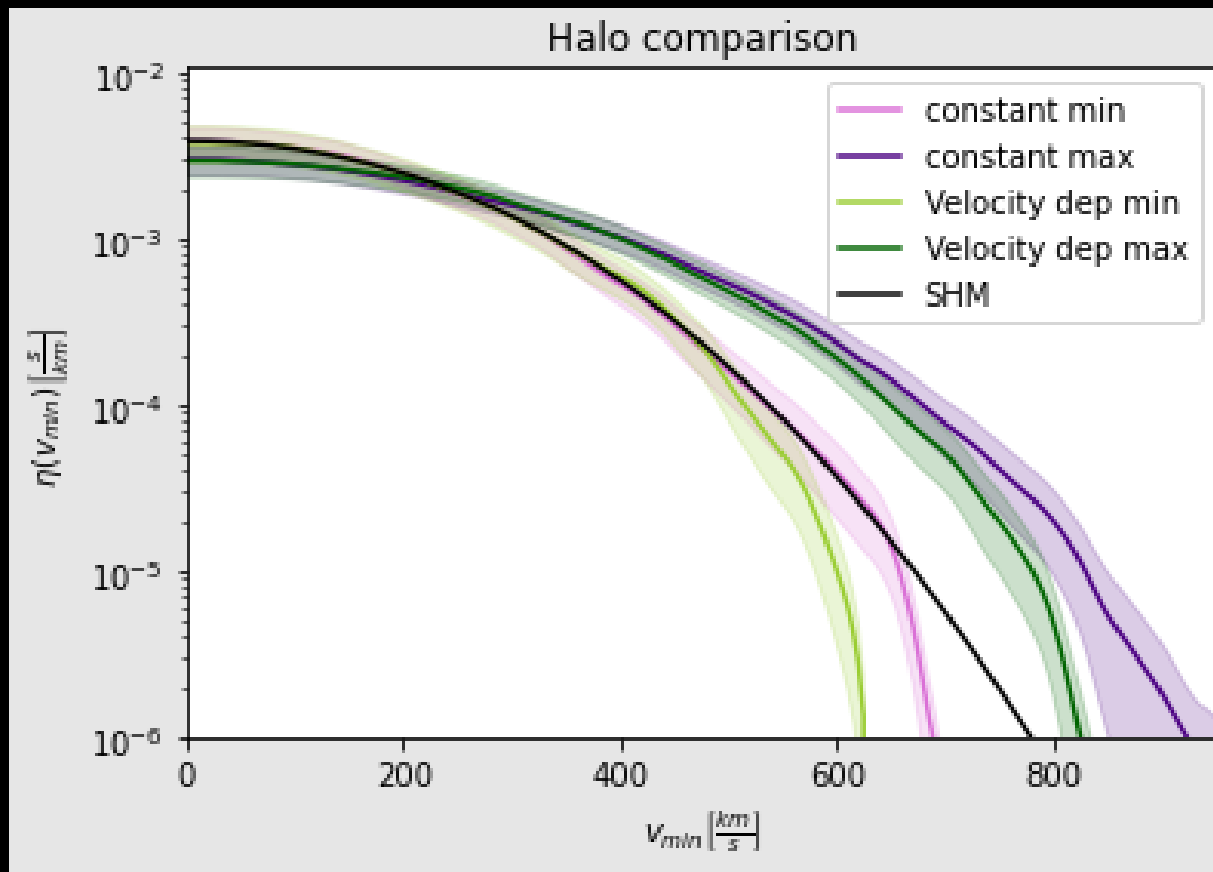


Worst Data Maxwell match

Determining goodness of Maxwellian ansatz

- High velocity tails of analytic solution within $\pm 1\sigma$ range of data solution
 - Constant: 12/38
 - Velocity dependent: 14/41
- Maxwellian is not a good ansatz for halo integrals for most simulations

Model comparison



Model comparison

- Halo Integral for velocity dependent model is shifted to the left
 - Lower v_{\min}
- Constant model has larger v_{\min}

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_{\chi T}^2}} \quad \mu_{\chi T} = \frac{m_{\chi} m_T}{(m_{\chi} + m_T)}$$

Q: How does the shift of a halo integral to larger v_{\min} affect the DM mass?

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_{\chi T}^2}} \quad \mu_{\chi T} = \frac{m_{\chi} m_T}{(m_{\chi} + m_T)}$$

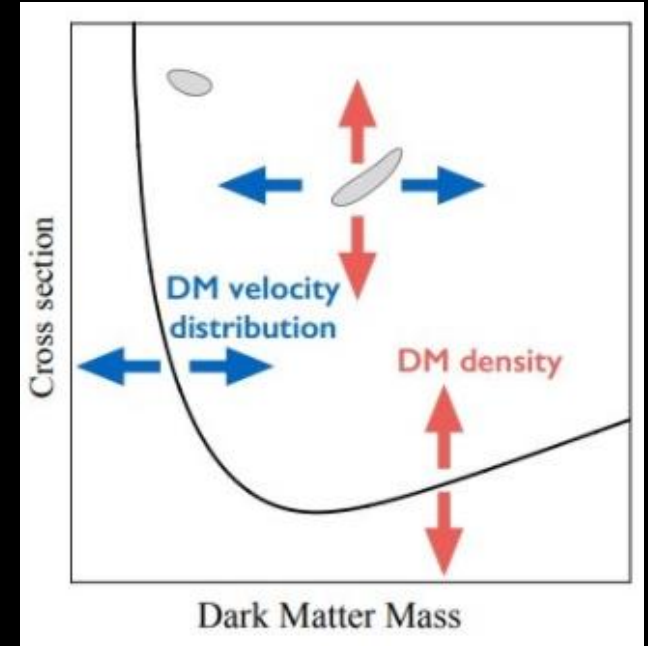
Q: How does the shift of a halo integral to larger v_{\min} affect the DM mass?

→ Increases sensitivity to probe lower DM masses

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_{\chi T}^2}} \quad \mu_{\chi T} = \frac{m_{\chi} m_T}{(m_{\chi} + m_T)}$$

Exclusion limits for DM mass and cross-section

- CDM case
- Affects the exclusion limits and regions for DM mass and cross-section
 - Changes interpretation of direct detection experiments



CDM case [lecture 2, Bozorgnia]

Summary

- Used halo simulations including SIDM and Baryons
- Identified Milky Way-like halos
- Transformed coordinates to galactic frame
- Selected particles in our neighborhood (torus)
- Fit data to Maxwell speed distribution
- Transformed to Earth's frame
- Computed Halo Integral

Conclusion

- Density
 - Constant [0.34 - 0.78] GeV/cm^3
 - Vel. dep. [0.29 - 0.67] GeV/cm^3
- Fitted peak speed
 - Constant [216 - 291] km/s
 - Vel. dep. [206 - 270] km/s

Conclusion

- Maxwellian is not a good ansatz for SIDM:
 - Constant cross section: 12/38
 - Velocity dependent cross section: 14/41
- Both models and SHM match for small v_{\min}
 - Significant differences for large v_{\min}
- Shift to larger v_{\min} for constant cross-section
 - Larger v_{\min} → Smaller DM mass → Affects the exclusion limits and regions for DM mass and cross-section

Future prospects

- What are the effects of baryons on the results for both SIDM models
- Use a stricter criteria for MW-like haloes
- What other fitting functions can we use to get a better result
- Compare our results to CDM
- Look at exclusion limits for the DM mass and cross section plane

Thank you for
your attention!

Backup slides

Velocities in the Earth's frame

- $\mathbf{v_E(t)} = \mathbf{v_c} + \mathbf{v_{pec}} + \mathbf{v_e(t)}$
- $\mathbf{v_{pec}}$ is sun's peculiar velocity w. r. t. Local Standard of Rest velocity
 - $\approx (11.1, 12.24, 7.25) \text{ km/s}$
- $\mathbf{v_c}$ is sun's circular velocity
 - Computed from mass enclosed within 8 kPc
- $\mathbf{v_e(t)}$ is earth's velocity w. r. t. the sun
 - Circular ansatz
 - t represents time normalized for one year

$$\mathbf{v}_e(t) = v_e[\mathbf{e}_1 \sin \lambda(t) - \mathbf{e}_2 \cos \lambda(t)]$$

$$\lambda(t) = 2\pi(t - 0.218)$$

