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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

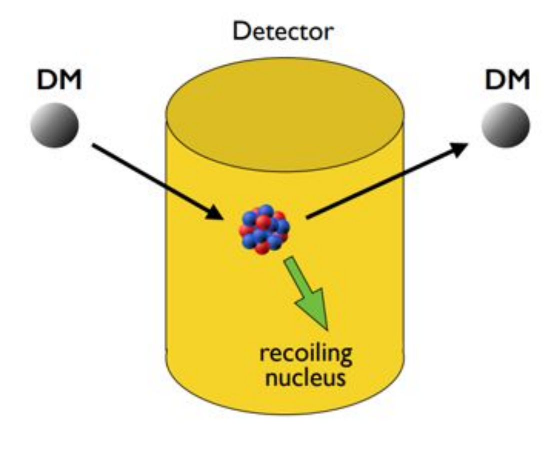
Direct detection of dark matter

- measuring the recoil energy of nuclei after interaction with DM particle

- Event rate determines the DM mass and cross section:

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

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



[Explore Lecture 2, Bozorgnia]

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

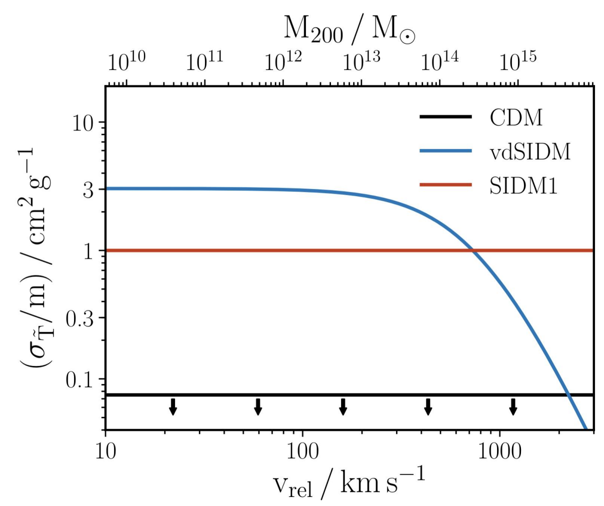
answer ⇒ The experiments take place on the earth
→ velocity distribution for the earth is needed

[NASA]

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]

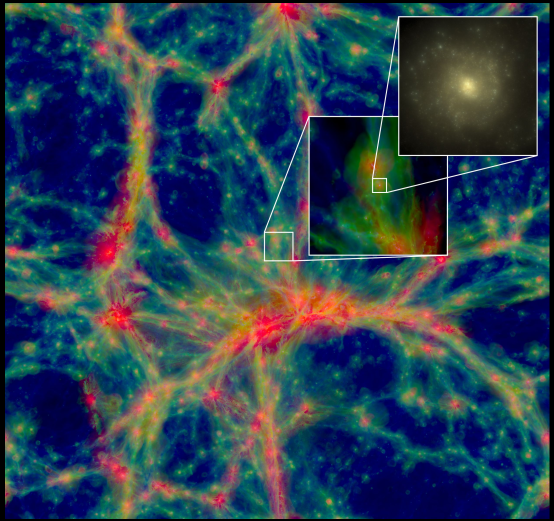
Cosmological simulations

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

652 simulated halos

↓

79 MW-like halos

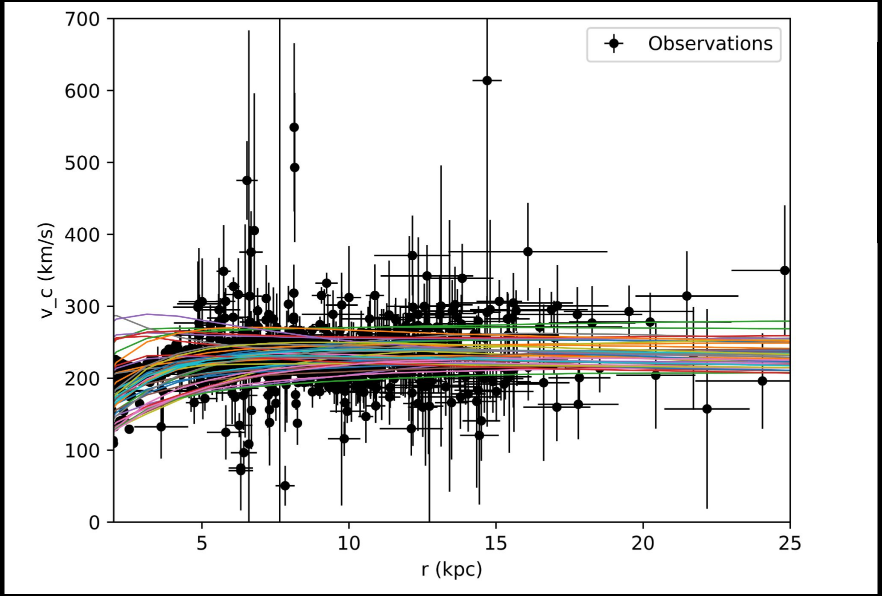
38 const. cross section halos
41 vd.- cross section halos

THE EAGLE SIMULATION
THE EVOLUTION AND ASSEMBLEY OF GALAXIES AND THEIR ENVIROMENT

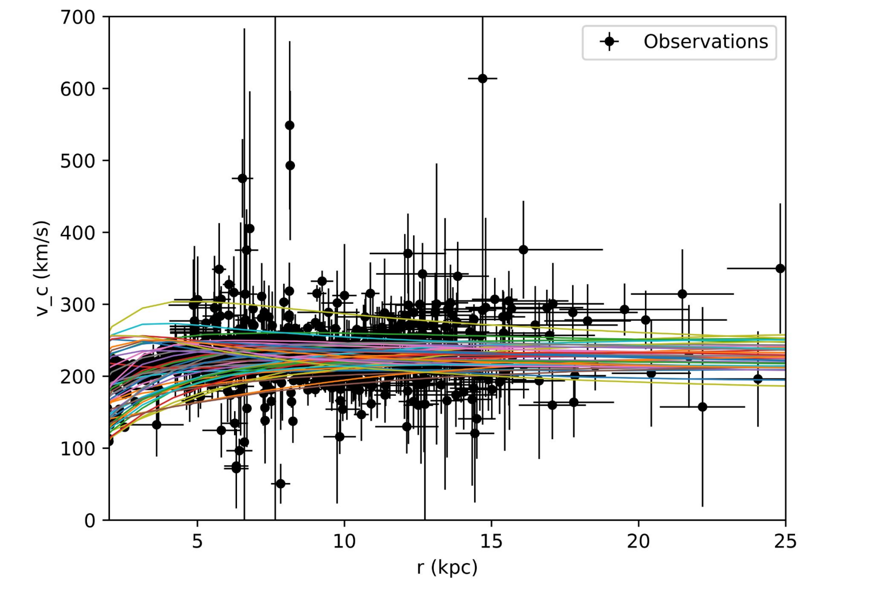
Total rotation curves

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

Const. cross section



Velocity dependent cross-section

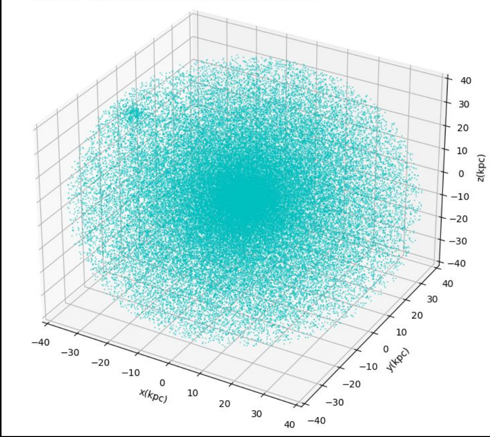


[Credit for the observational data: Iocco et al., 2015]

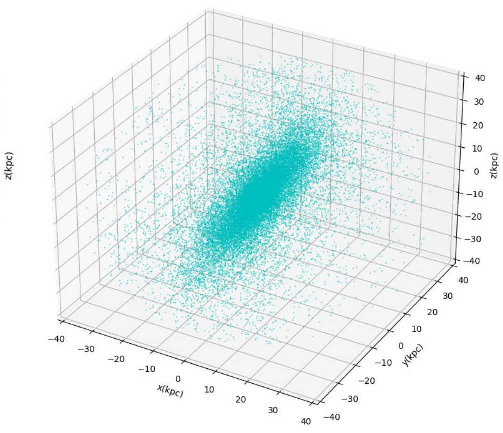
Simulation frame

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

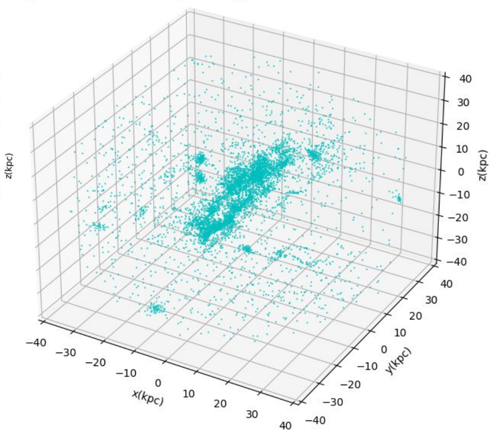
Dark matter



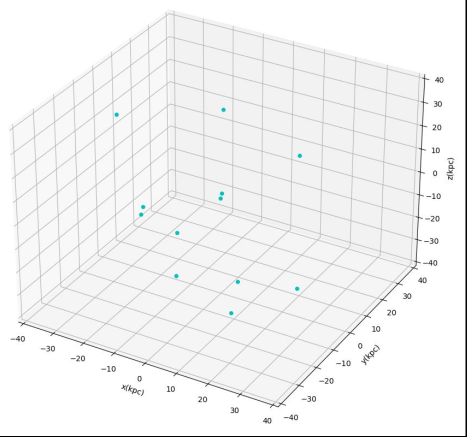
Stars



Gas



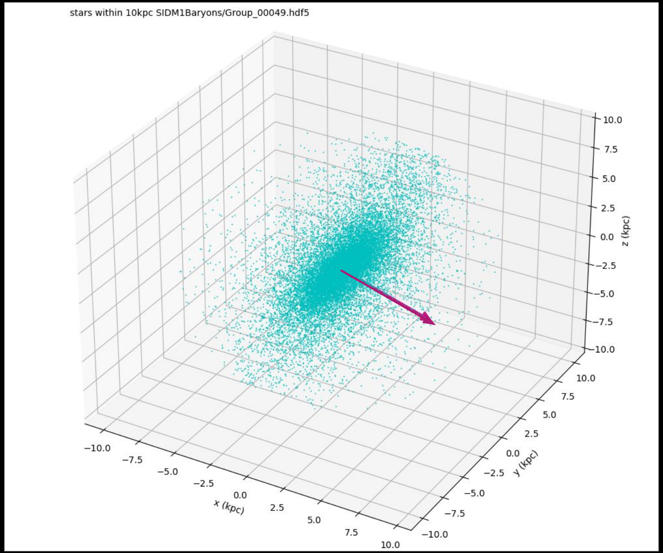
Black holes



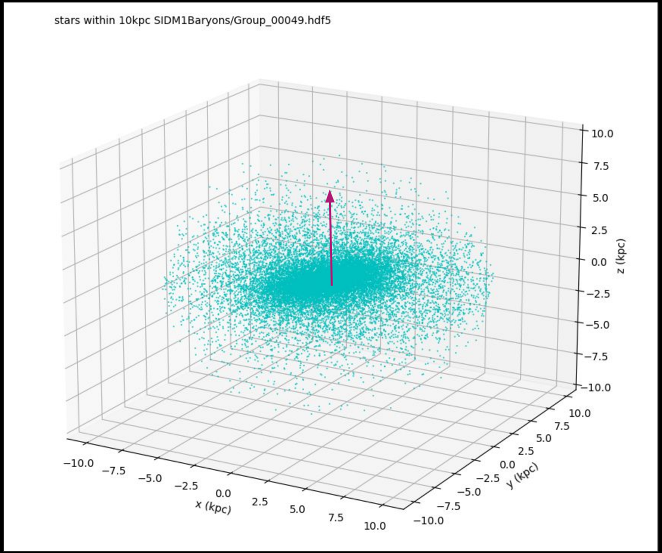
Defining the stellar disk

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’)

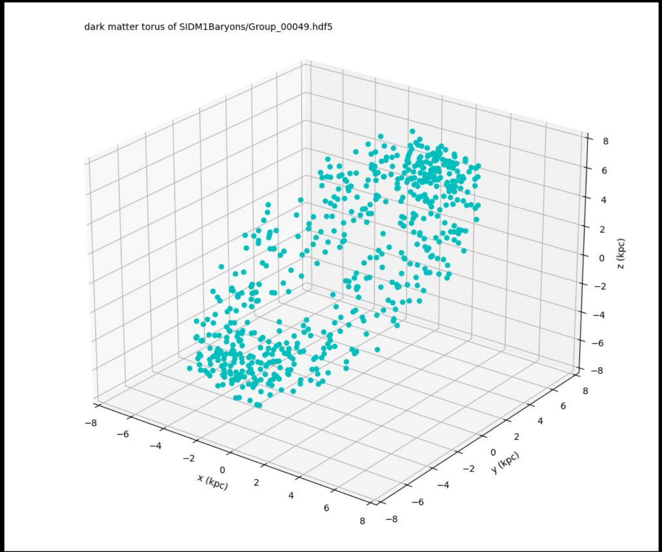


Defining the solar circle

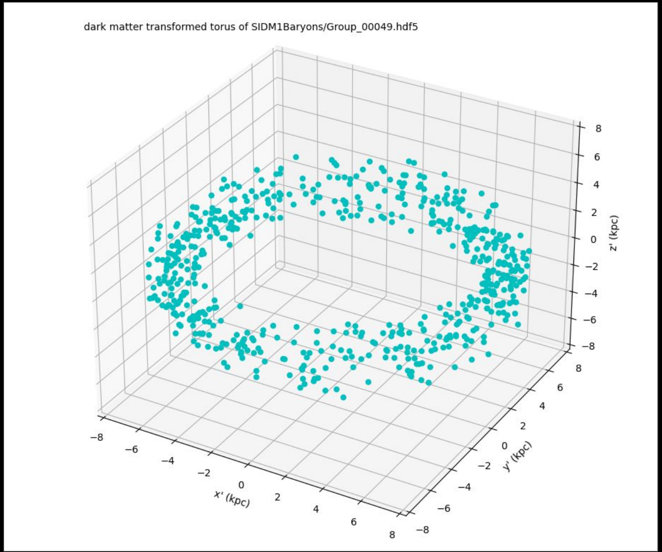
solar circle: r=8kpc

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

Simulation frame (x,y,z)



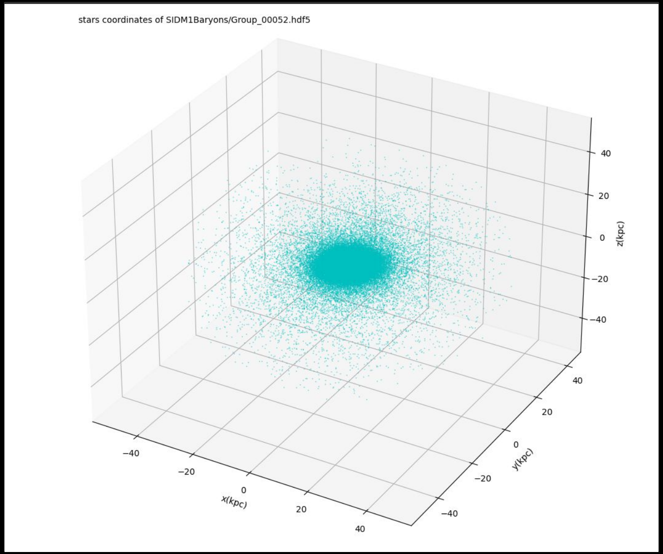
Galactic frame (x',y',z')



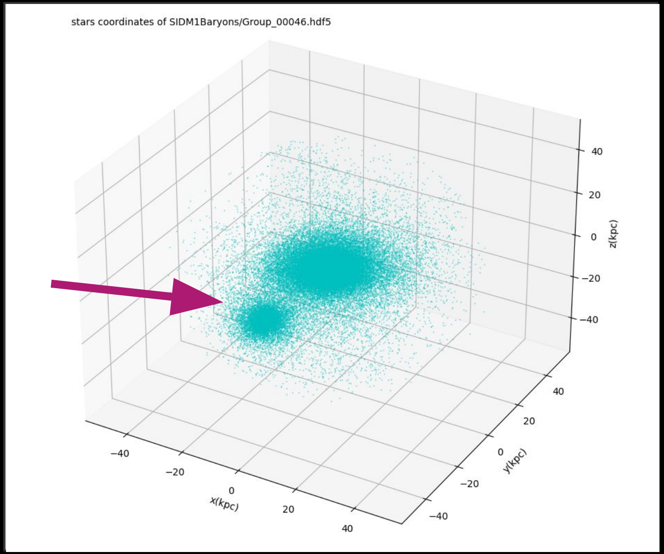
Excluding halos with substructures

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

No substructures

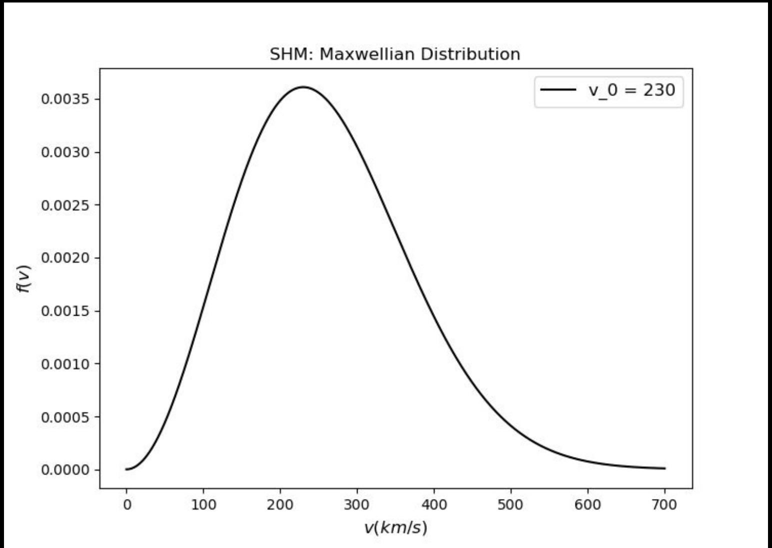


With a substructure



Standard Halo Model

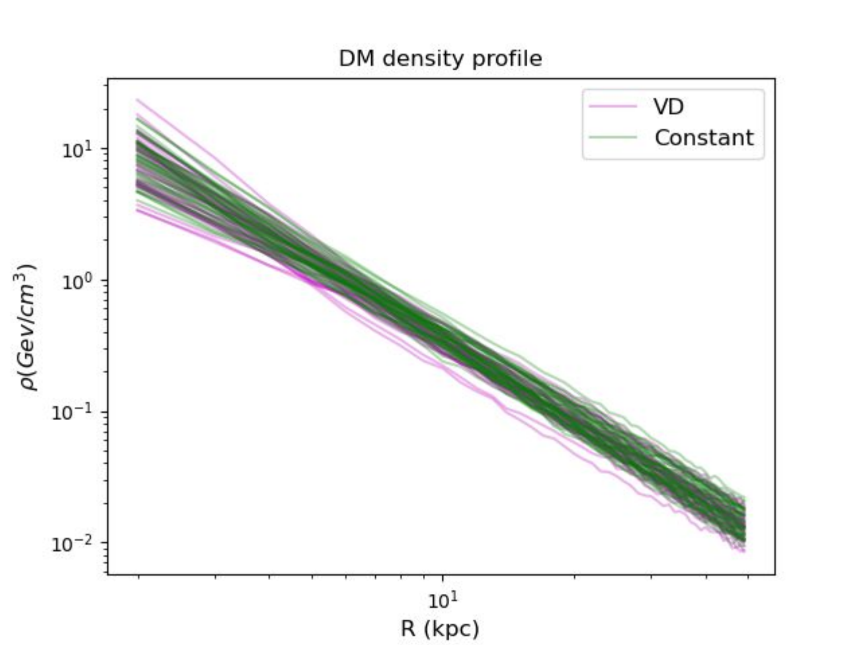
- Spherical and Isothermal
- Follows isotropic Maxwellian speed distribution
- Has density of 0.3 Gev/cm^3
- Most probable speed of 230 km/s

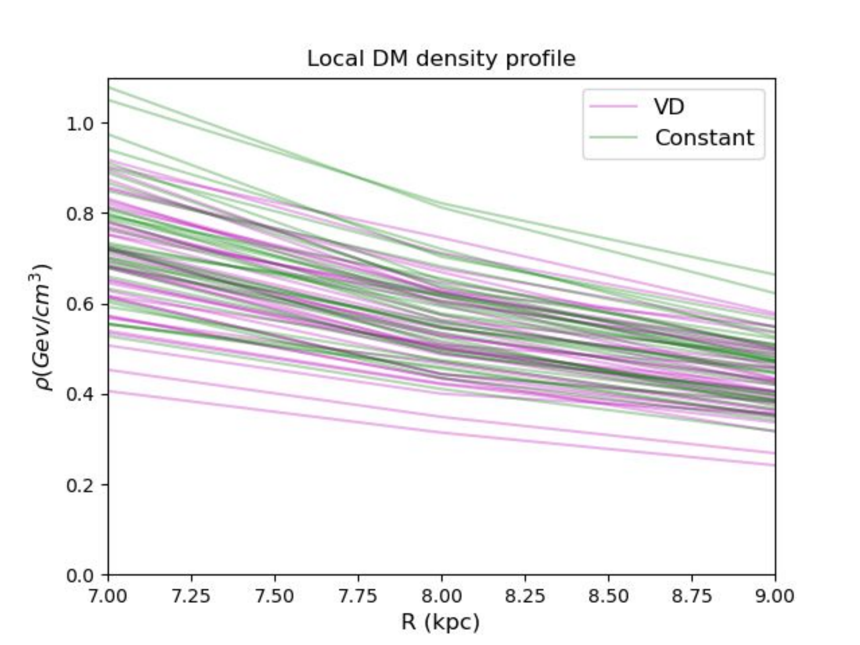


Density Profile

Vel. Dep. Cross Section	Constant Cross Section
ρ = [0.29 - 0.67] Gev/cm^3	ρ = [0.34 - 0.78] Gev/cm^3

- Constant cross section shifted upwards → higher density → greater event rate



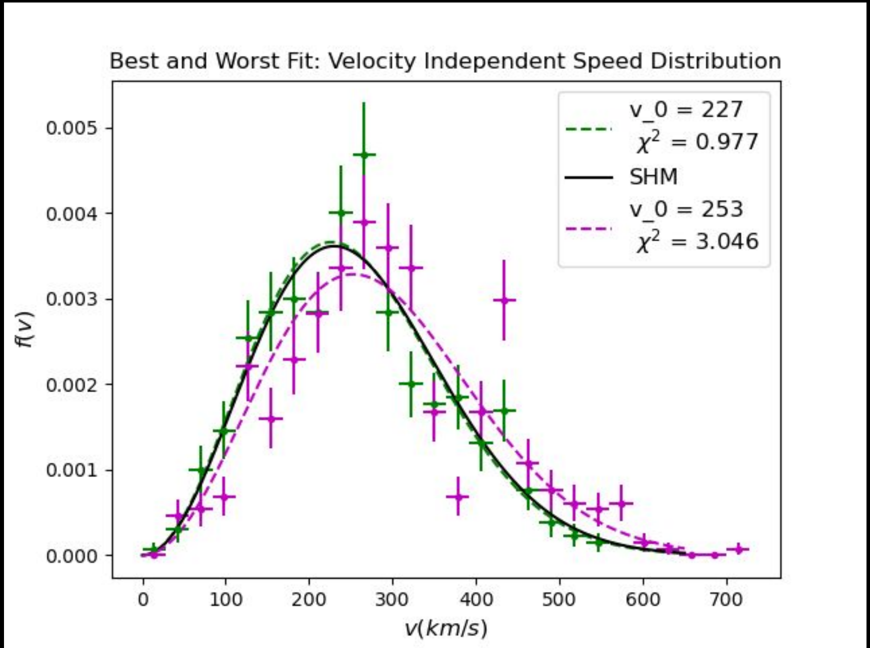


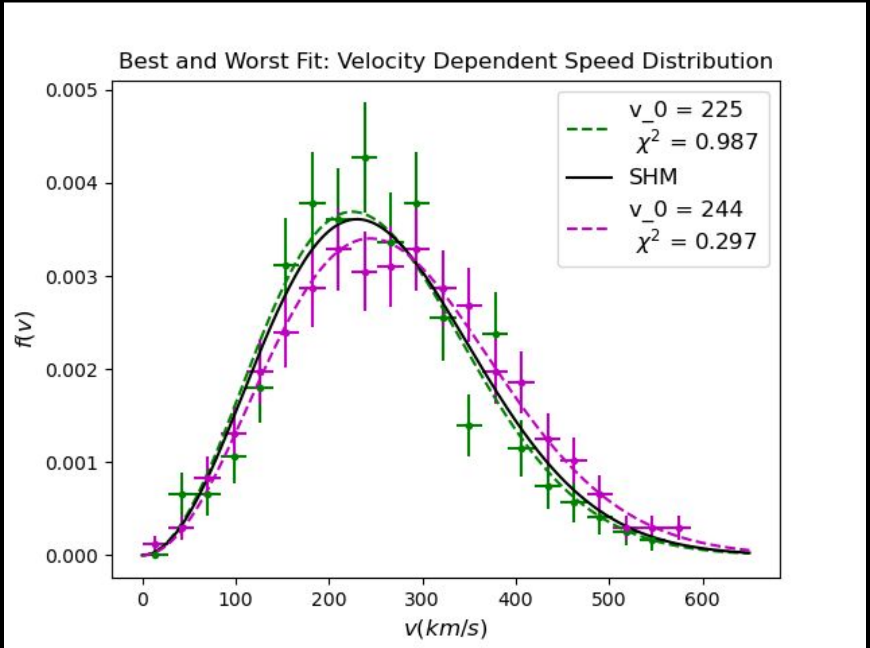
Local DM Speed Distribution in the Galactic Frame

- DM speed distribution is fitted with a standard Maxwellian distribution

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

- The velocity dependent haloes are closer to the SHM

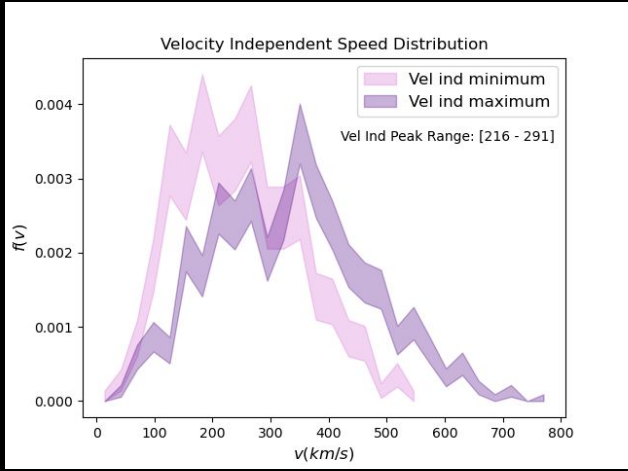


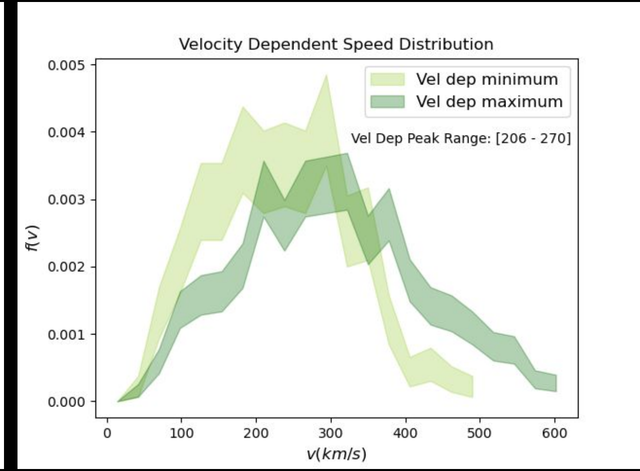


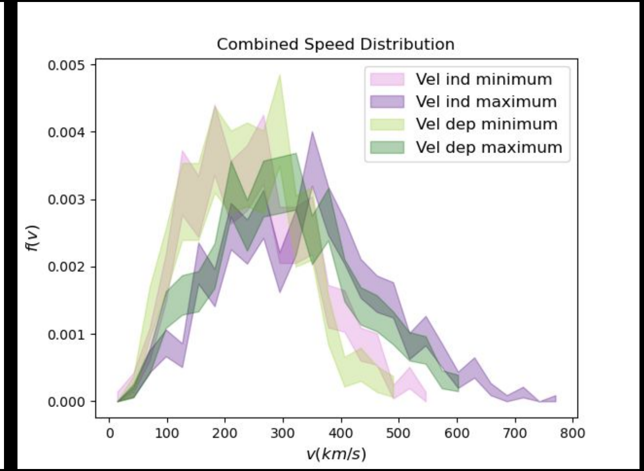
Comparing Speed Distributions

Vel. Dep. Cross Section	Constant Cross Section
v_{peak} = [206 - 270] km/s	v_{peak} = [216 - 291] km/s

- The velocity independent peak speed is shifted to the right





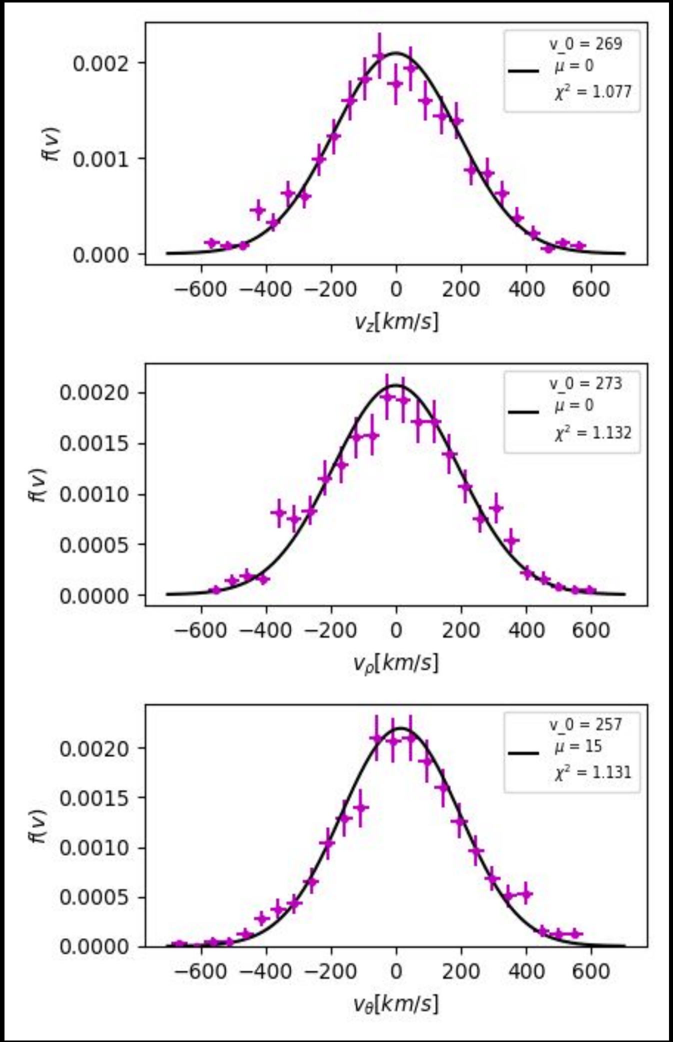


Component Dist.

- The velocity distribution is plotted for the vertical, radial and azimuthal components

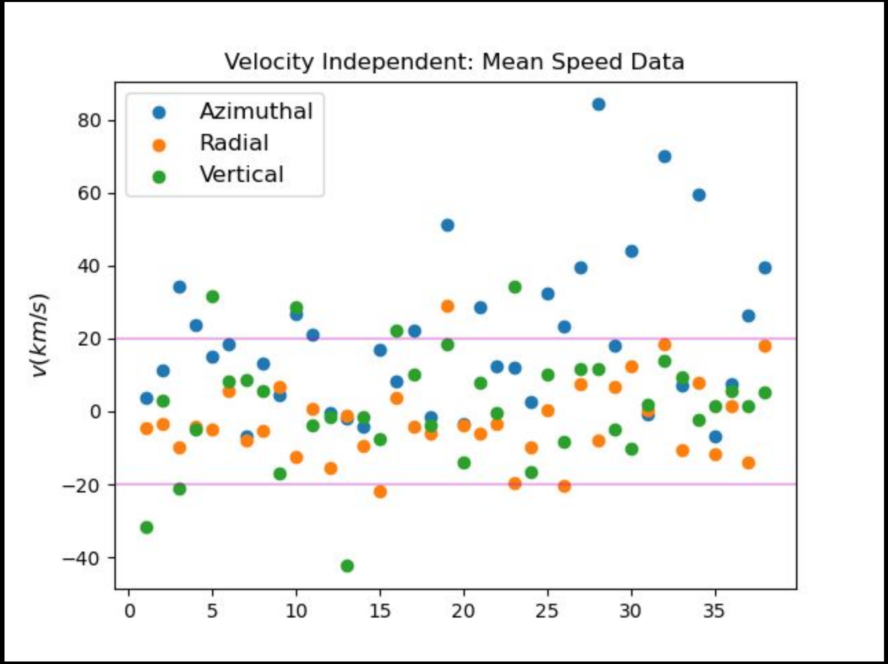
- The best fit was a Gaussian distribution

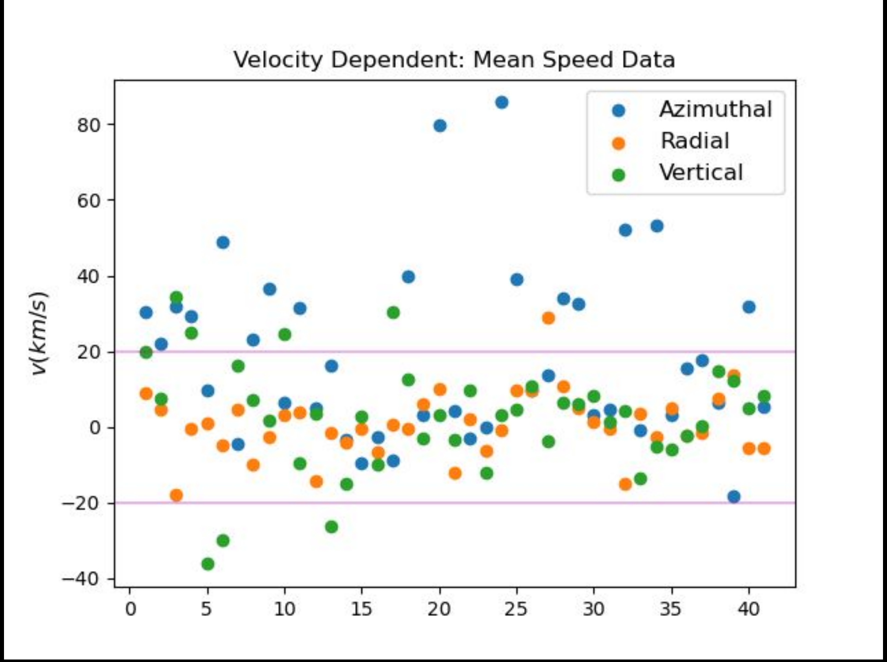
$$f(v_i) = \frac{1}{\sqrt{\pi} v_0} \exp\left[-(v_i - \mu)^2 / v_0^2\right]$$



Component Dist.

- Radial and vertical → mostly ranged between [-20 - 20] km/s
- Azimuthal component shifted -> 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

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

Earth's velocity w.r.t the sun

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

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

Circular velocity

Peculiar velocity

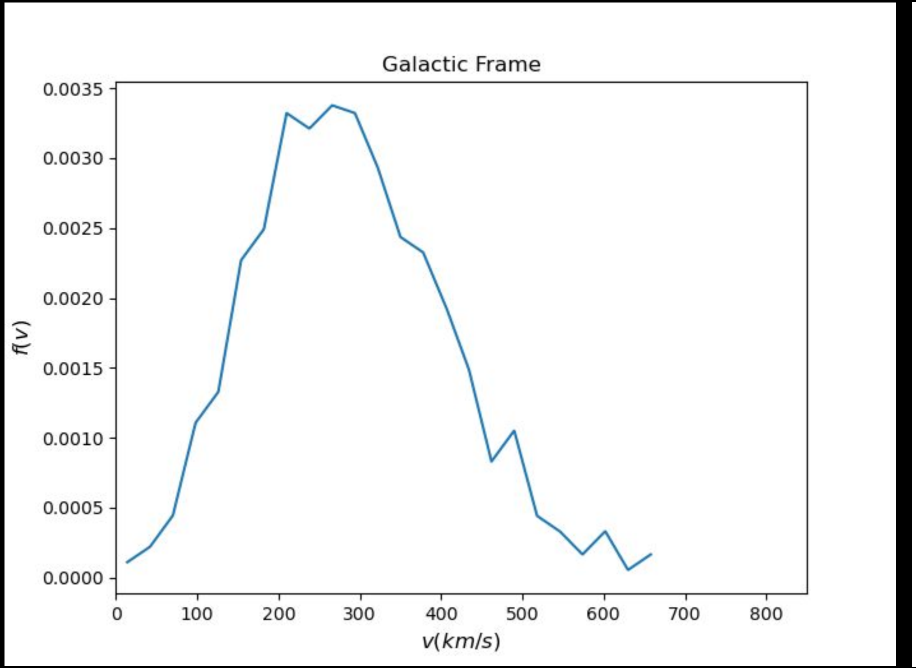
Question

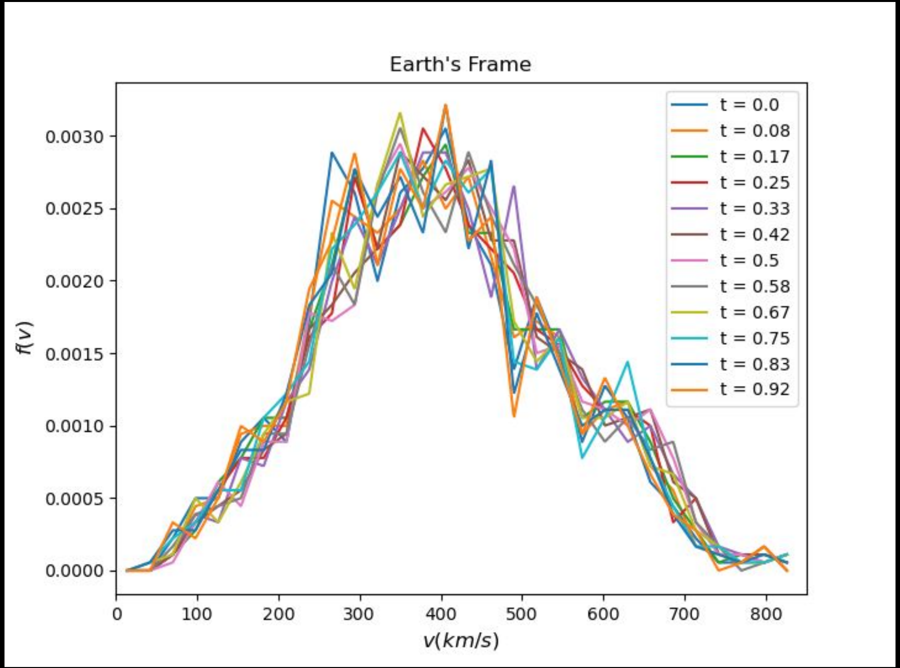
Why is $v_e(t)$ expressed as a function of time?

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 → Halo Integral

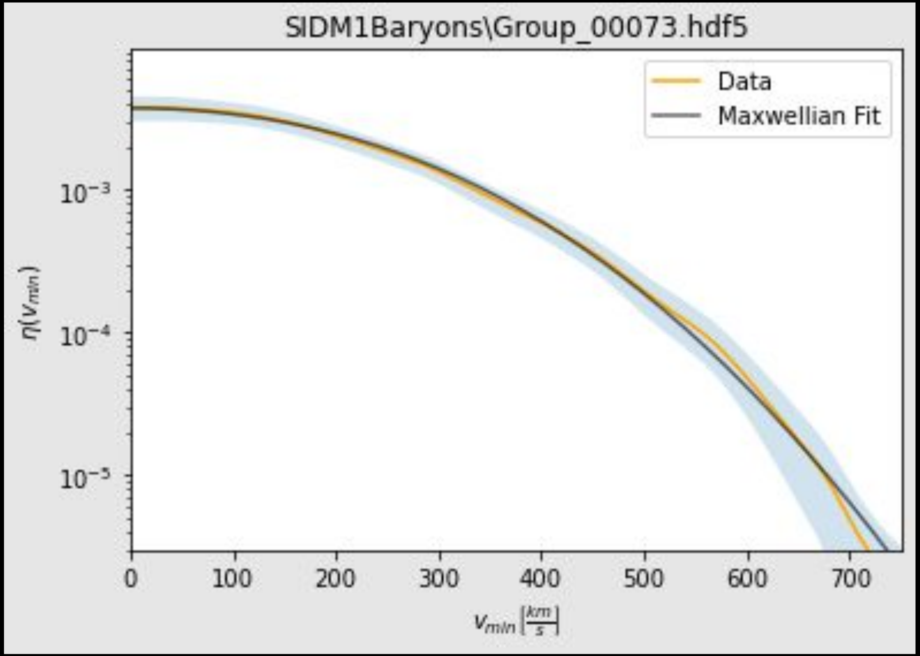
$$\eta(v_{\min}, t) \equiv \int_{v>v_{\min}} d^3v \, \frac{f_{\rm det}(\mathbf{v}, t)}{v}$$

Halo Integral plots

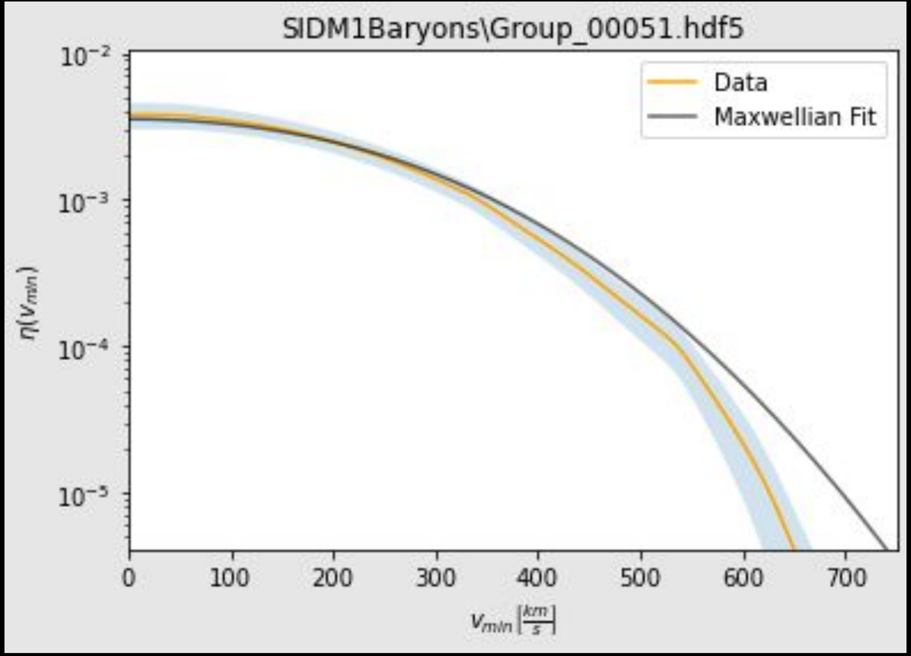
- Eliminate time dependency
  - Mean of all months

- Compare
  - Data
  - Maxwellian distribution fit (Analytical solution)
  - SHM (Maxwellian with v_0 = 230 km/s)

Constant cross-section Halo Integral

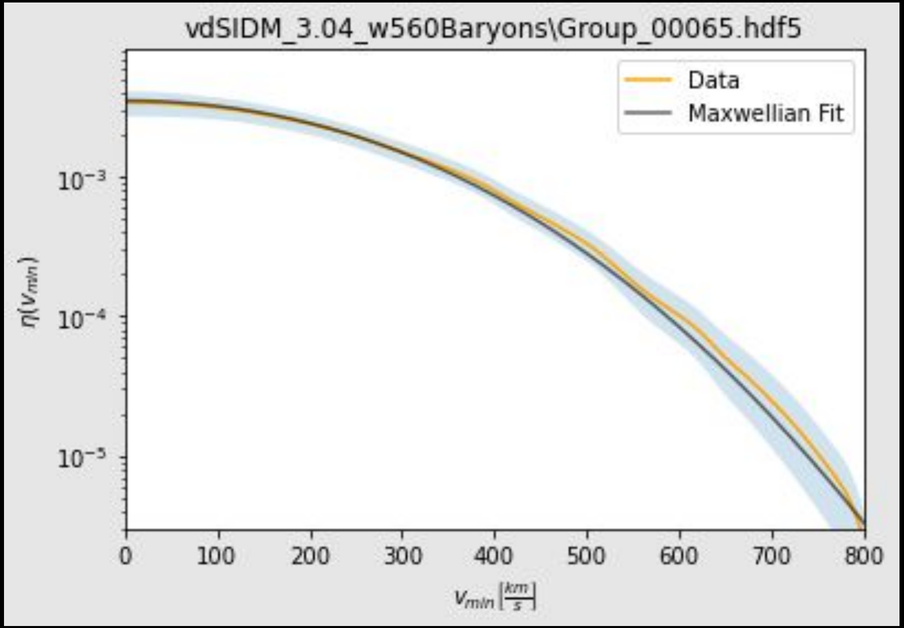


Best Data Maxwell match

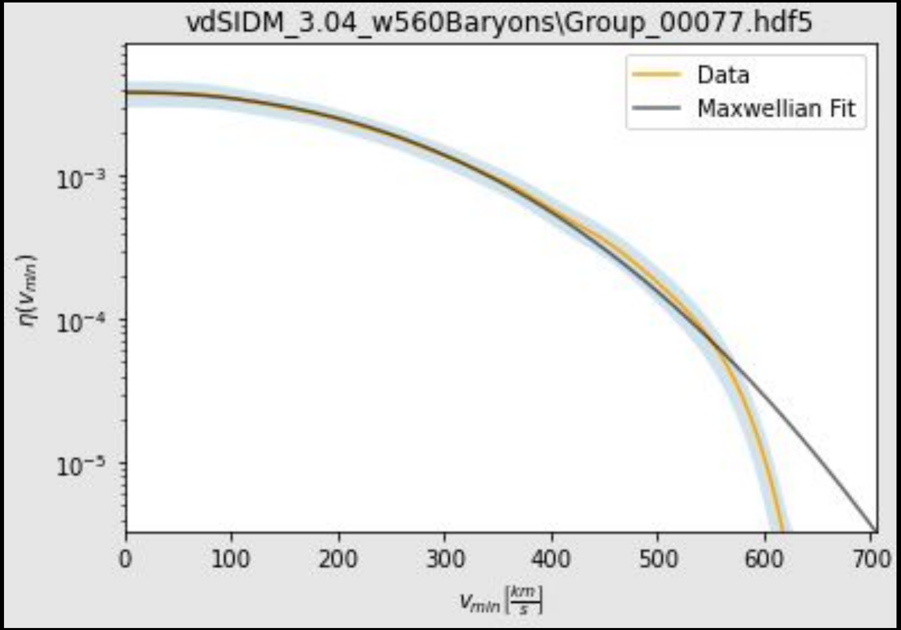


Worst Data Maxwell match

Velocity dependent cross-section Halo Integral



Best Data Maxwell match



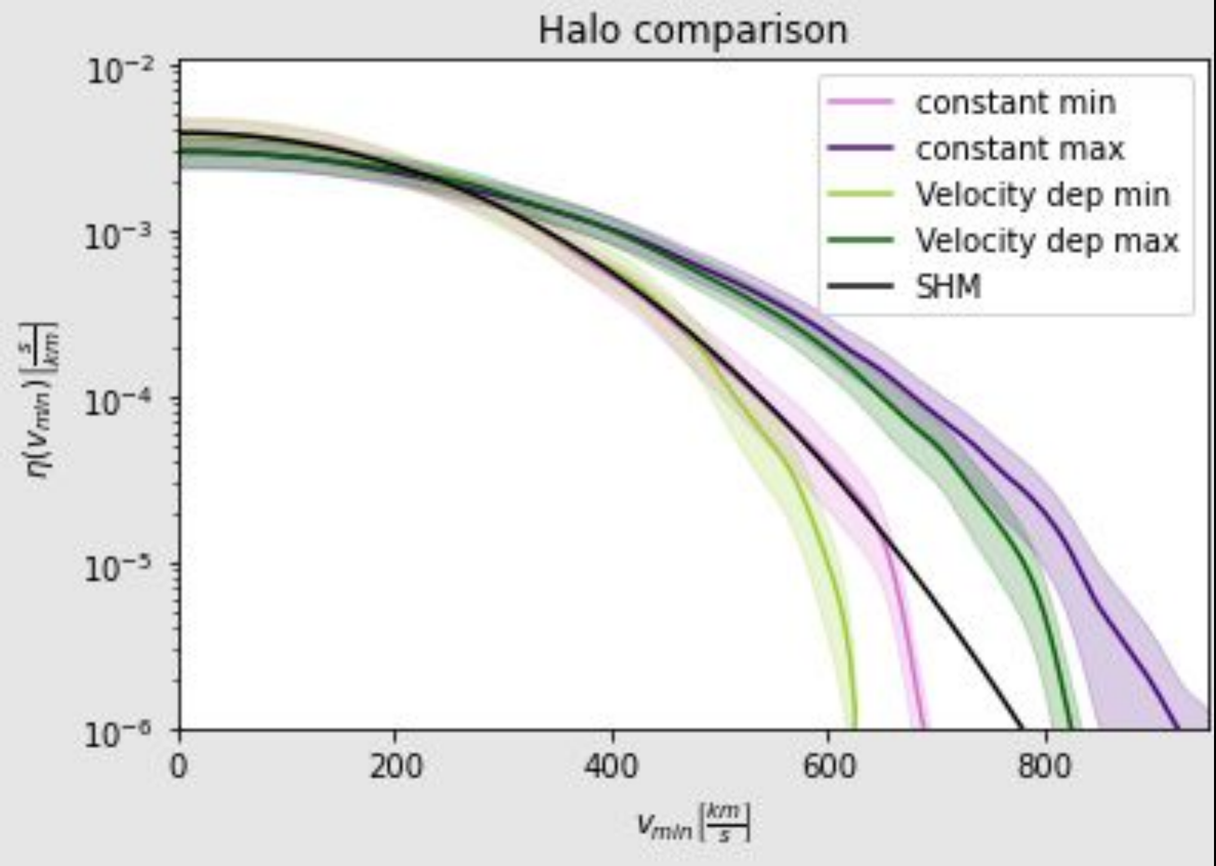
Worst Data Maxwell match

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}

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

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

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

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

→ Increases sensitivity to probe lower DM masses

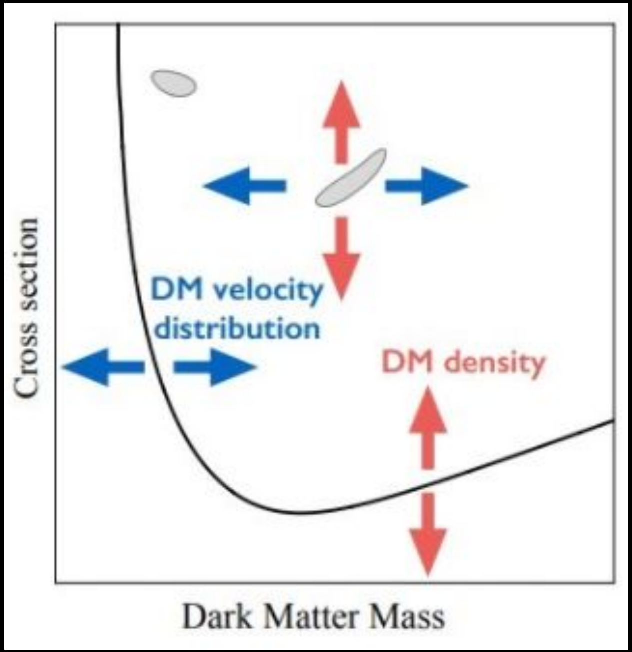
$$v_{\text{min}} = \sqrt{\frac{m_T E_R}{2\mu_{\chi T}^2}} \qquad \mu_{\chi T} = \frac{m_\chi m_T}{(m_\chi + m_T)}$$

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
  - ≈ (11.1, 12.24, 7.25) 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

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

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