



Introduction

We investigate the predicted detection rates of dark matter particles in direct detection experiments influenced by the Milky Way's structure and in particular its dark matter halo. We focus on refinements to the standard halo model (SHM) [1] arising from the recent discovery of the Gaia Sausage Enceladus (GSE), a highly radially anisotropic stellar structure believed to be the remnant of a dwarf galaxy merger [2][3]. This discovery was made possible by the Gaia mission [4], which provides unprecedentedly precise measurements of the positions and velocities of billions of stars in the Milky Way, revealing some stars with much higher eccentricities leftover from this merger. Building on previous work [5], which incorporated the GSE into the SHM, we implement a more realistic treatment of the GSE's velocity distribution. To achieve this, we utilize the AGAMA code [6], a powerful software library for building self-consistent galaxy models based on distribution functions. This allows us to incorporate the latest observational constraints, including those from the Gaia satellite, into our prediction of dark matter scattering rates.

Dark Matter as an Astroparticle

Dark matter (DM) is usually assumed to be a non-baryonic, electromagnetically neutral, and non-collisional component that constitutes approximately 26.4% of the universe's critical density and 84.4% of its total matter density. Despite alternative theories such as modified gravity, DM is essential for explaining the correct spectrum of density perturbations, the anisotropy power spectrum of the cosmic microwave background (CMB), and observations from weak lensing and X-ray data of galaxy cluster.

The mass of DM candidates ranges from as low as 10^{-22} eV to several solar masses. Although usually assumed to be electrically neutral, milli-charged scenarios are considered with stringent observational limit. Laboratory detection efforts include direct detection experiments using cryogenic detectors, noble liquids, and room temperature scintillators, among others, alongside searches at accelerators and colliders.

Astrophysical detection is based on indirect evidence from gamma rays, neutrinos, cosmic-ray antimatter, and multi-wavelength studies, with additional constraints from stellar physics and cosmological data. Primordial black holes are also explored as potential macroscopic DM candidates through gravitational lensing and their impact on the CMB [7].

Galactocentric Velocity Distribution

Having established realistic parameters of the Milky Way model in AGAMA, based on the framework from Binney & Vasiliev (2023)[8], we conducted a simulation and determined the velocity distribution function of the DM halo. Similarly, we constructed the velocity distribution for the GSE component and for a self-consistent combined model with 80% Halo and 20% GSE contribution. From here on we call the combined model the self-consistent AGAMA Halo Model (scAHM). We plot the 1D velocity distribution functions for the components and the combined model normalized to have a unit integral over the velocity space in Figure 1.

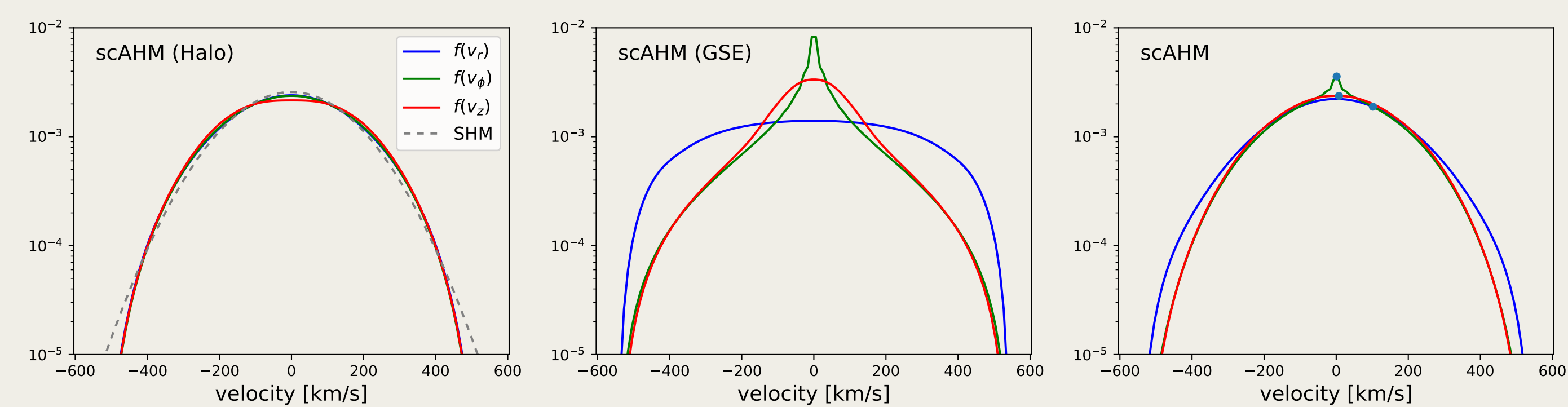


Figure 1. Distribution functions of the halo component (left) and GSE component (middle) and the combined case (80/20 Halo/GSE) referred to as scAHM. The blue dot (right panel) represents the velocity components of a particle with a specific speed of $|\vec{v}| = 260$ km/s and direction in the heliocentric reference frame shown in Figure 2. Note that the SHM distribution function, plotted on top of the halo component, is simply an isotropic 3D Gaussian.

The most striking difference between the component's velocity distributions is the strongly non-Gaussian shape of the GSE component. These features arise from the highly eccentric orbits of stars associated with the GSE, reflecting its origin in a dwarf galaxy merger. The deviation is particularly pronounced in the radial velocity component (blue curve), extending to high velocity tails, as well as the azimuthal (green curve) and vertical (red curve) velocity components peaking around zero reflecting the radial anisotropy. Combining the smooth Halo with the asymmetric GSE dilutes the prominence of the non-Gaussian features but does not erase them entirely.

Heliocentric Sky Map

Having the velocity distribution functions (radial, tangential and vertical) of DM halo particles, we can depict the sky in different reference systems – heliocentric and geocentric. For instance, the velocity of the Sun with respect to the galactic centre is $v = 240$ km/s. For comparison, Earth's velocity around the Sun is ~ 30 km/s. In Figure 2 we show a sky map of recoil directions expected from dark matter interactions coming in with a velocity of $|\vec{v}| = 260$ km/s across the sky in the heliocentric system.

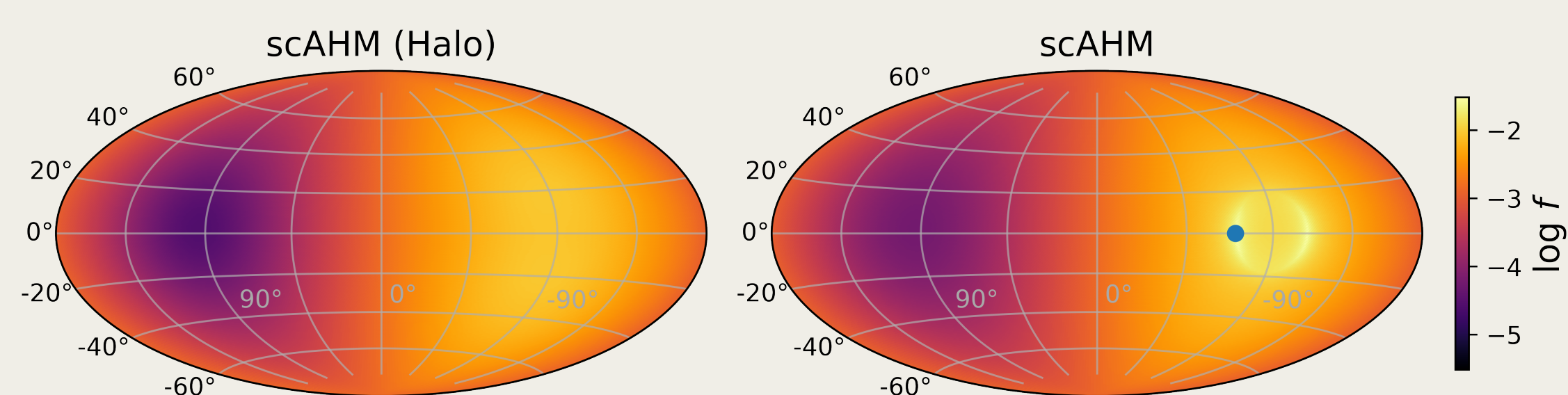


Figure 2. Recoil directions $f(\vec{v}, \varphi, \theta)$ across the sky (φ, θ) in the heliocentric system of the SHM model (isotropic Gaussian) and the scAHM model at $|\vec{v}| = 260$ km/s. The blue dot shows a specific position in the sky map related to the velocity components as shown in Figure 1.

For scAHM, the anisotropy of the velocity distribution results in an increase of one order of magnitude into a ring-shaped structure with its centre opposite to the moving direction of the Sun compared to the simple SHM model, which is built from a 3D isotropic Gaussian velocity distribution. The ring-shaped structure directly arises from the unique characteristics of the GSE's velocity distribution (see right panel of Figure 1): The GSE's velocity distribution shows a sharp peak in the tangential component (green curve in Figure 1) around zero. This means a significant portion of the GSE stars move in highly eccentric orbits. When we view recoils from Earth, the preferred radial motion translates into a higher probability of detecting DM candidates arriving from a ring-like structure opposite to the moving direction of the sun. Note, the radius of the ring depends on the chosen velocity slice v and is only visible if the velocity is close to the moving speed of the Sun around the galactic centre.

Seasonal Dependence of Scattering Rates

Following Evans et. al (2019) [5], we assume DM consists of spin-independent weakly interacting massive particles (WIMP) and calculate the differential scattering rate $\frac{dR(t)}{dE_r}$, given by,

$$\frac{dR(t)}{dE_r} = N_T \frac{\rho_0}{m_\chi} \int_{v>v_{min}} v f(\vec{v} + \vec{v}_E(t)) d^3v. \quad (1)$$

The relevant parameters are the number of target nuclei N_T , the assumed DM mass m_χ , the DM speed in the reference frame of the Earth $v = |\vec{v}|$, the minimum DM speed that could induce a recoil of energy v_{min} , the DM nucleus scattering cross section $\frac{d\sigma_r(c, E_r)}{dE_r}$, and finally, the velocity distribution function f in Earth's reference frame that is calculated using the self-consistent AGAMA model of our galaxy. We find that the maximal seasonal variation (Earth orbiting the Sun) occurs between early June and early December. In Figure 3 we show the results for different target nuclei and assumed DM masses measured in June and December.

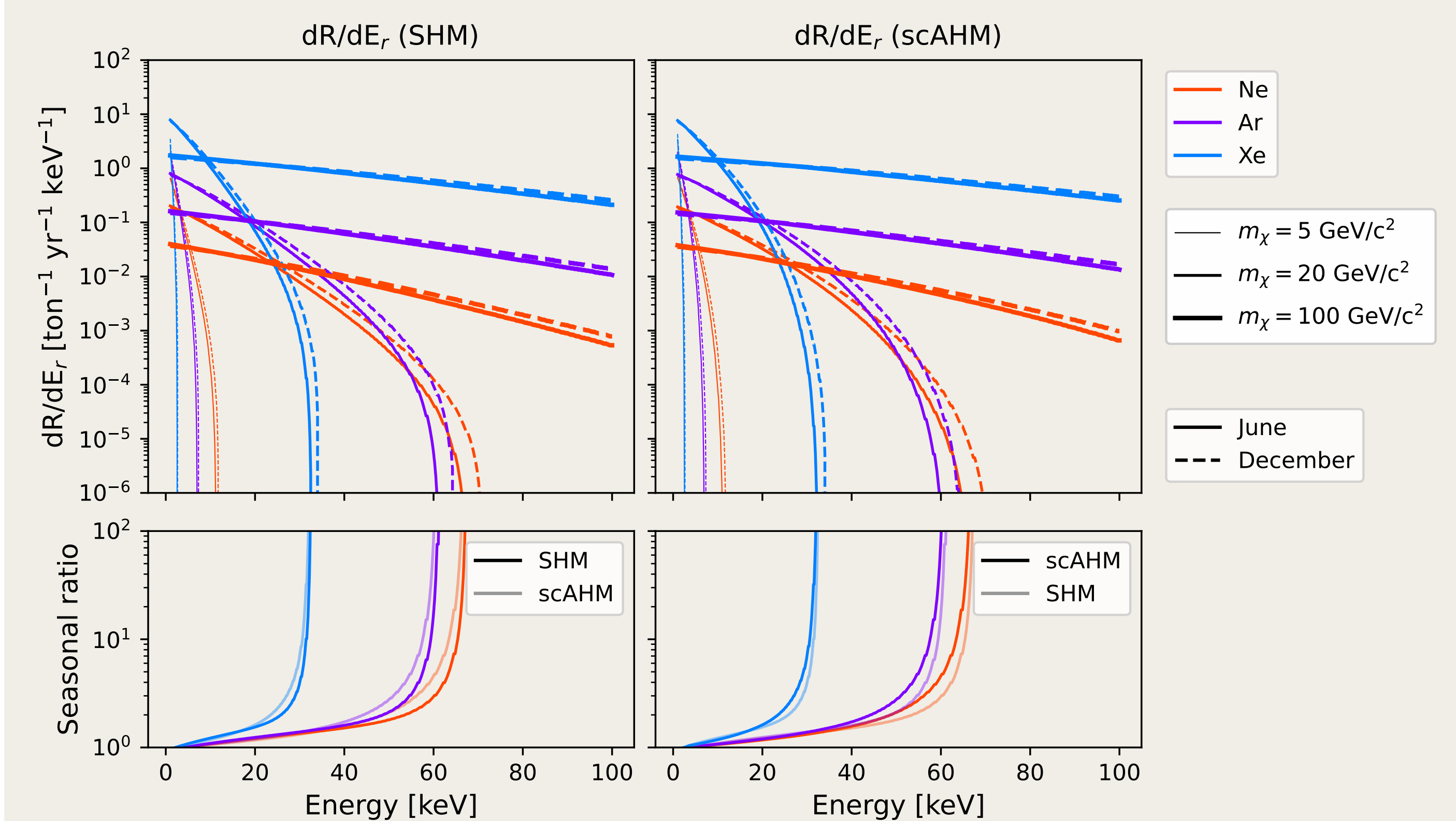


Figure 3. Differential scattering rate $\frac{dR(t)}{dE_r}$ (top row) as a function of energy for the Halo (left) and scAHM (right) models. The seasonal variation is shown with solid and dashed lines, different colours show different target nuclei, and the linewidth represents the assumed DM particle mass. The bottom row shows the ratio of $\frac{dR(t)}{dE_r}$ between June and December for $m_\chi = 20$ GeV/ c^2 .

We only find a small difference between the Halo and scAHM model. The seasonal ratio between June and December varies slightly for both cases. The prominent ring-shaped feature seen in Figure 2 in the scAHM model is smoothed out in the overall recoil energy distribution.

Event Rates for Different Experiments

Integration of $\frac{dR}{dE_r}$ over dE_r yields the following detection rates.

Table 1. Calculated DM detection rates using Xenon as the detector material

m_χ [GeV/ c^2]	R_{Halo} [1/yr/ton]		R_{scAHM} [1/yr/ton]	
	June	December	June	December
5	1.04	0.74	1.28	0.912
20	39.1	35.9	41.7	38.8
100	77.8	75.2	80.2	78.2

Conclusion

Despite the differences in the velocity distribution, the overall impact on the expected WIMP detection rates is relatively modest (in other words: the Sausage is not that spicy). The Gaia Sausage component leads to a slight decrease in event rates at high recoil energies. This is counterbalanced by a slight increase in overall event rates due to changes in other halo parameters. The seasonal modulation signal is slightly enhanced by the inclusion of the GSE, particularly for heavier WIMPs. However, Figure 2 shows, that for certain directions the recoils are expected to be one order of magnitude higher for scAHM compared to SHM. If detectors become sensitive to the direction and velocity of WIMPs we may be able to measure this deviation (in other words: the Sausage is only spicy if you bite from the right side).

References

- [1] Andrzej K. Drukier, Katherine Freese, and David N. Spergel. "Detecting cold dark-matter candidates". In: *Phys. Rev. D* 33 (1986), pp. 3495–3508. DOI: 10.1103/PhysRevD.33.3495.
- [2] Amina Helmi et al. "The merger that led to the formation of the Milky Way's inner stellar halo and thick disk". In: *Nature* 563.7729 (2018), pp. 85–88. DOI: 10.1038/s41586-018-0625-x.
- [3] V. Belokurov et al. "Co-formation of the disc and the stellar halo". In: *MNRAS* 478.1 (2018), pp. 611–619. DOI: 10.1093/mnras/sty982.
- [4] T. Prusti et al. "The Gaia Mission". In: *Astron. Astrophys.* 595. Gaia Data Release 1 (2016), A1. DOI: 10.1051/0004-6361/201629272.
- [5] N. Wyn Evans, Ciaran A. J. O'Hare, and Christopher McCabe. "Refinement of the standard halo model for dark matter searches in light of the Gaia Sausage". In: *Phys. Rev. D* 99 (2019), p. 023012. DOI: 10.1103/PhysRevD.99.023012.
- [6] Eugene Vasiliev. "AGAMA: action-based galaxy modelling architecture". In: *MNRAS* 482.2 (2018), pp. 1525–1544.
- [7] S. Navas et al. "Review of Particle Physics". In: *Phys. Rev. D* 110 (2024), p. 030001. DOI: 10.1103/PhysRevD.110.030001.
- [8] James Binney and Eugene Vasiliev. "Self-consistent models of our Galaxy". In: *MNRAS* 520.2 (), pp. 1832–1847. DOI: 10.1093/mnras/stad094. arXiv: 2206.03523 [astro-ph.GA].