Dependence of the WIMP Angular Kinetic–Energy Distribution on the Solar Galactic Orbital Velocity

CHUNG-LIN SHAN

Preparatory Office of the Supporting Center for Taiwan Independent Researchers
P.O.BOX 21 National Chiao Tung University, Hsinchu City 30099, Taiwan, R.O.C.

E-mail: clshan@tir.tw

Abstract

In this article, we study in a little more detail the angular kinetic–energy distribution of halo Weakly Interacting Massive Particles (WIMPs) and consider two simple modifications with the Solar Galactic orbital velocity in our Monte Carlo simulations of the 3-dimensional WIMP velocity as the first trial of future investigations on distinguishing models of the Galactic structure of Dark Matter particles by using directional direct detection data.
1 Introduction

Directional direct Dark Matter (DM) detection experiments aim to measure 3-dimensional information (recoil tracks and/or head–tail senses) of target nuclei scattered by halo Weakly Interacting Massive Particles (WIMPs) [1, 2]. This could provide a practical way for discriminating WIMP singles from neutrino–nucleus scattering backgrounds (the so–called “neutrino floor”) [3, 4, 5].

In our earlier works [6, 7], we investigated the angular distributions of the direction (flux) as well as the accumulated and the average kinetic energies of the Monte Carlo–simulated 3-dimensional WIMP velocity in different celestial coordinate systems. While, in the Equatorial coordinate system, the anisotropy and the directionality (clockwise rotated annual modulation) of the distribution patterns of the 3-D WIMP direction/kinetic energy could be clearly observed, two significant characteristics of the patterns of the “average” WIMP kinetic energy have also been discovered.

Firstly, the (main) hot–points of the angular distribution patterns of the average WIMP kinetic energy appearing approximately in the straight area between the longitude of 90°W and 0° and below the latitude of 15°S could not coincide with the hot–points of the patterns of the WIMP flux and the accumulated kinetic energy spreading obliquely from the center to the southwest part of the sky [7]. Secondly, two extra hot–points close to the center and at the southwestern corner of the sky could also be observed in the distribution patterns of the average WIMP kinetic energy. Accompanied with the annual modulation of the distribution patterns, these two hot–points would even show a clearly seasonal appearance [7].

So far we have theoretical explanations for neither the pattern difference nor the (seasonal) appearance of the extra hot–points. Nevertheless, in order to understand in more detail their contributions to our future study on the Galactic structure of DM particles by using directional direct detection data, in this article, we investigate the dependence of the angular distribution of the WIMP average kinetic energy on the Solar Galactic orbital velocity.

In the next section, we will consider two modifications of the standard Galactic halo model used in our simulations and discuss the corresponding distribution patterns of the 3-D WIMP average kinetic energy. Then we conclude in Sec. 3.

2 Two modifications of the standard Galactic halo model

In our Monte Carlo simulations of the 3-dimensional information on the WIMP velocity, the simple Maxwellian velocity distribution function truncated at the Galactic escape velocity has been adopted for the radial component in the Galactic coordinate system [8]:

\[ f_{G,r}(v) = f_{1,Gau}(v) = \left[ \left( \frac{\sqrt{\pi}}{4} \right) \text{erf} \left( \frac{v_{\text{esc}}}{v_0} \right) - \left( \frac{v_{\text{esc}}}{2v_0} \right) e^{-v_{\text{esc}}^2/v_0^2} \right]^{-1} \left( \frac{v^2}{v_0^2} \right) e^{-v^2/v_0^2}, \]

for \( v \leq v_{\text{esc}} \), and \( f_{G,r}(v > v_{\text{esc}}) = 0 \). Here \( v_0 \) is the Solar orbital velocity around the Galactic center, \( v_{\text{esc}} \) is the escape velocity from our Galaxy at the position of the Solar system and has been set as 550 km/s in our simulations [9]. Moreover, for the angular component of the 3-D WIMP velocity, a simple isotropic distribution in the Galactic coordinate system has been considered [6].

Meanwhile, each generated 3-D WIMP velocity (including the measuring time) will be transformed from the Galactic frame through the Ecliptic and the Equatorial frames to the laboratory frame (see Ref. [6] for details). For the transformation between the Galactic and the Ecliptic
coordinate systems, the moving velocity of the Solar system in the Galaxy \(v_{\odot,G} \simeq 220\ \text{km/s}\) has been adopted\(^1\).

In this article, as the first trial of future investigations on distinguishing models of the Galactic structure of Dark Matter particles by using directional direct detection data, we consider two simple scenarios with the Solar Galactic orbital velocity in our simulations and discuss the effects on the angular distribution patterns of the average kinetic energy of halo WIMPs in the Equatorial coordinate systems.

2.1 Varying \(v_{\odot,G}\) and \(v_0\) simultaneously

We consider at first the modifications of the Galactic orbital velocity of the Solar system \(v_{\odot,G}\) and, correspondingly, the value of the parameter \(v_0\) appearing in our generating distribution (1).

In the upper (a) frame of Figs. 1 to 5, we show the angular distributions of the 3-D WIMP average kinetic energy in the Equatorial coordinate system with 500 total events on average (Poisson–distributed) in one experiment in one entire year and in each 60-day observation period of four advanced seasons [6], binned into \(12 \times 12\) bins for the longitude and latitude directions, respectively. 5,000 experiments with five values of \(v_{\odot,G} = v_0 = 180, 200, 220, 240,\) and \(260\ \text{km/s}\) have been simulated. The comparison standard with \(v_{\odot,G} = v_0 = 220\ \text{km/s}\) is given in Figs. 3(a).

In each plot, the dark–green star indicates the theoretical main direction of the WIMP wind (the opposite direction of the Galactic movement of the Solar system) in the Equatorial coordinate system: \(42.00^\circ\text{S}, 50.70^\circ\text{W}\). Additionally, in the plot simulated for each season, we also put a blue–yellow point to indicate the opposite direction of the Earth’s velocity relative to the Dark Matter halo on the central date of each observation period\(^2\). Moreover, the horizontal color bar on the top of each plot indicates the mean value of the average kinetic energy (averaged over all simulated experiments) in each angular bin in unit of the all–sky average value\(^3\).

By comparing our simulation results, one would find that the difference between the distribution patterns (with each pair of the simultaneously varied \(v_{\odot,G}\) and \(v_0\)) is not significant. This would indicate that, as long as we adopt the (actual) Solar orbital velocity \(v_{\odot,G}\) for the parameter \(v_0\) in the generating velocity distribution (1), the angular distribution of the average WIMP kinetic energy would depend only slightly on \(v_{\odot,G}\) and could be a characteristic of the considered simple Maxwellian halo model. Certainly, with quantitative information about the (average) WIMP kinetic energy, the angular (average–)kinetic–energy distribution could provide a more precise value of \(v_{\odot,G}\) as well as the reliability of our halo model.

2.2 Fixing \(v_{\odot,G}\) but varying \(v_0\)

Now, we consider a practical scenario in which the Solar orbital velocity is fixed as \(v_{\odot,G} = 220\ \text{km/s}\), while the parameter \(v_0\) in our generating velocity distribution (1) varies alone from \(180\ \text{km/s}\) to \(260\ \text{km/s}\), as a pre–study of the sensitivity of the angular distribution of the average WIMP kinetic energy for distinguishing predictions of different halo models.

---

\(^1\)Note that, although \(v_0\) in Eq. (1) should theoretically be the same quantity as \(v_{\odot,G}\), in this work we handle \(v_{\odot,G}\) as the astronornical measurement but \(v_0\) is purely a tunable parameter in the simple Maxwellian halo model.

\(^2\)Note that the direction (the right ascensions and the declinations) of the Earth’s velocity relative to the DM halo depends on the Solar orbital velocity \(v_{\odot,G}\). Detailed calculations can be found in Appendix A of Ref. [6].

\(^3\)Note that the all–sky average value of the average WIMP kinetic energy depends (strongly) on the Earth’s relative velocity to the DM halo and in turn the Solar orbital velocity \(v_{\odot,G}\). Hence, the distribution pattern in each plot is not normalized by the same standard, but show only the relative strength in each single case with the specified \(v_{\odot,G}\) and/or \(v_0\) value and the observation period.
Figure 1: The angular distributions of the WIMP average kinetic energy in the Equatorial coordinate system with 500 total events on average in one entire year and in each 60-day observation period of four advanced seasons [6]. (a) $v_{\odot, G} = v_0 = 180$ km/s; (b) $v_{\odot, G} = 220$ km/s and $v_0 = 180$ km/s. See the text for further details.

We show in the lower (b) frame of Figs. 1 to 5 the angular distributions of the 3-D WIMP average kinetic energy with fixed $v_{\odot, G} = 220$ km/s and five values of $v_0 = 180$, 200, 220, 240, and 260 km/s, respectively, in the Equatorial coordinate system. Again, 500 total events on average in one entire year and in each 60-day observation period of four advanced seasons has
Figure 2: As in Figs. 1, except that $v_{\odot,G} = v_0 = 200$ km/s (a) as well as $v_{\odot,G} = 220$ km/s and $v_0 = 200$ km/s (b) have been simulated.

been considered and the comparison standard with $v_{\odot,G} = v_0 = 220$ km/s is given in Figs. 3(b).

In contrast to the small difference between the distribution patterns with the simultaneously varied $v_{\odot,G}$ and $v_0$ shown previously, the angular distributions with the fixed $v_{\odot,G}$ and the varied $v_0$ show a significantly clear variation: the most energetic directions of incident WIMPs (the red hot–points) spread with the increased $v_0$, even though the all–sky average value in each plot increases already strongly with the increased $v_0$. This indicates that, even without quantitative
Figure 3: As in Figs. 1, except that the results with $v_{\odot,G} = v_0 = 220$ km/s have been given in both of the upper and lower frames as the comparison standard (figures from Ref. [7]).

Information about the (average) WIMP kinetic energy, the angular distribution pattern of the average WIMP kinetic energy should already be sensitive to the value of the parameter $v_0$ in the generating WIMP velocity distribution (1) and, in turn, would be useful for distinguishing models of the structure of halo Dark Matter.
Figure 4: As in Figs. 1, except that $v_{\odot,G} = v_0 = 240$ km/s (a) as well as $v_{\odot,G} = 220$ km/s and $v_0 = 240$ km/s (b) have been simulated.

3 Summary

In this article, we investigated the dependence of the angular distribution of the WIMP average kinetic energy on the Galactic orbital velocity of the Solar system, as the first trial of future investigations on distinguishing models of the Galactic structure of Dark Matter particles by using directional direct detection data.
Figure 5: As in Figs. 1, except that $v_{\odot,G} = v_0 = 260$ km/s (a) as well as $v_{\odot,G} = 220$ km/s and $v_0 = 260$ km/s (b) have been simulated.

Two simple scenarios with the Solar Galactic orbital velocity have been considered. At first we modified the Solar orbital velocity in the transformation between the Galactic and the Ecliptic coordinate systems and the parameter $v_0$ appearing in our generating distribution for the radial component of the 3-D WIMP velocity in the Galactic coordinate system simultaneously. Our simulations indicate that the simulated angular distribution of the average WIMP kinetic energy would depend only slightly on the Solar orbital velocity and could be a characteristic of
the considered (simple Maxwellian) halo model. On the other hand, we considered also the scenario in which the Solar orbital velocity is fixed, while the parameter $v_0$ in our generating distribution for the 3-D WIMP Galactic velocity varies. The spread of the most energetic directions of incident WIMPs in the simulated angular distributions with the increased $v_0$ indicates that, even without quantitative information about the (average) WIMP kinetic energy, the angular average–kinetic–energy distribution should already be sensitive to the value of the parameter $v_0$ and would be useful for distinguishing models of the structure of halo Dark Matter.

**Acknowledgments**

The author would like to thank the friendly hospitality of the Institute of Physics at the National Chiao Tung University during the finalization of this article.

**References**

[1] S. Ahlen et al., “The Case for a Directional Dark Matter Detector and the Status of Current Experimental Efforts”, *Int. J. Mod. Phys.* **A25**, 1–51 (2010), arXiv:0911.0323 [astro-ph.CO].

[2] F. Mayet et al., “A Review of the Discovery Reach of Directional Dark Matter Detection”, *Phys. Rept.* **627**, 1–49 (2016), arXiv:1602.03781 [astro-ph.CO].

[3] C. A. J. O’Hare, A. M. Green, J. Billard, E. Figueroa–Feliciano and L. E. Strigari, “Readout Strategies for Directional Dark Matter Detection beyond the Neutrino Background”, *Phys. Rev.* **D92**, 063518 (2015), arXiv:1505.08061 [astro-ph.CO].

[4] C. A. J. O’Hare, B. J. Kavanagh and A. M. Green, “Time–Integrated Directional Detection of Dark Matter”, *Phys. Rev.* **D96**, 083011 (2017), arXiv:1708.02959 [astro-ph.CO].

[5] C. A. J. O’Hare, “Can we Overcome the Neutrino Floor at High Masses?”, *Phys. Rev.* **D102**, 063024 (2020), arXiv:2002.07499 [astro-ph.CO].

[6] C.-L. Shan, “Simulations of the 3-Dimensional Velocity Distribution of Halo Weakly Interacting Massive Particles for Directional Dark Matter Detection Experiments”, arXiv:1905.11279 [astro-ph.HE] (2019), in publication.

[7] C.-L. Shan, “Simulations of the Angular Kinetic–Energy Distribution of Halo Weakly Interacting Massive Particles for Directional Dark Matter Detection Experiments”, in publication.

[8] G. Jungman, M. Kamionkowski and K. Griest, “Supersymmetric Dark Matter”, *Phys. Rep.* **267**, 195–373 (1996), arXiv:hep-ph/9506380.

[9] P. A. Zyla et al. (Particle Data Group), “The Review of Particle Physics 2020”, *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020), 2. Astrophysical Constants and Parameters.