Simulations of the Angular Kinetic-Energy Distribution of Halo Weakly Interacting Massive Particles for Directional Dark Matter Detection Experiments

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Research Article

Keywords: Dark Matter, WIMP, direct detection, directionality

Posted Date: February 4th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1328248/v1>

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March 2020

Simulations of the Angular Kinetic–Energy Distribution of Halo Weakly Interacting Massive Particles for Directional Dark Matter Detection Experiments

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Abstract

In this paper, as the second step of our study on developing data analysis procedures for using 3-dimensional information offered by directional Dark Matter detection experiments in the future, we investigate the patterns of the angular distribution of the Monte Carlo-generated 3-D kinetic energy of halo Weakly Interacting Massive Particles (WIMPs) in different celestial coordinate systems. We will demonstrate the “directionality” of the angular distributions of the 3-D WIMP kinetic energy by both of their annual and diurnal modulations. For readers’ reference, the angular distribution patterns of the 3-D WIMP kinetic energy in the “laboratory (location)–dependent” reference frames of several underground laboratories are given in the Appendix.

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Figure 1: The sketches of the basic concepts of directional Dark Matter detection: (a) the diurnal modulation of the main direction of incident WIMPs, the so-called “directionality” of the WIMP wind, for a laboratory located in the Northern Hemisphere (in Summer); (b) except of the directionality of the WIMP wind, the event number of WIMP signals observed at a laboratory located in the Southern Hemisphere (in Winter) could also have the diurnal modulation caused by the Earth’s shielding of the WIMP flux. The darkened/lightened (left/right-hand) spheres indicate that the laboratory of interest is in the night/day.

1 Introduction

So far Weakly Interacting Massive Particles (WIMPs) χ arising in several extensions of the Standard Model of particle physics are still one of the most favorite candidates for cosmological Dark Matter (DM). In the last (more than) three decades, a large number of experiments has been built and is being planned to search for different WIMP candidates by direct detection of the scattering recoil energy of ambient WIMPs off target nuclei in low-background underground laboratory detectors (see Refs. [1, 2, 3, 4, 5, 6] for reviews).

Besides the non-directional direct detection experiments measuring only recoil energies deposited in detectors, the “directional” detection of Galactic DM particles has been proposed more than one decade to be a promising experimental strategy for discriminating signals from backgrounds by using additional 3-dimensional information (recoil tracks and/or head-tail senses) of (elastic) WIMP-nucleus scattering events (see Refs. [7, 8, 9, 10, 11, 12, 13]). Several experimental collaborations investigate different detector materials and techniques and have achieved recently great progress [11, 13].

The basic concept of directional Dark Matter detection is based on the rotation of the Earth. As sketched in Figs. 1, there are two kinds of possible “diurnal” modulation of WIMP signals to observe: the diurnal modulation of the main incident direction of Galactic WIMPs, the so-called “directionality” of the WIMP wind, as well as that of the number (scattering rate) of WIMP events caused by Earth’s shielding of the WIMP flux. Directional DM detection experiments aim hence, as the first step, to identify positive *modulated anisotropic* WIMP signals and discriminate them from theoretically (approximately) isotropic background events.

As the preparation for our future study on the development of data analysis procedures for using and/or combining 3-D information offered by directional detection experiments to, e.g., reconstruct the 3-dimensional WIMP velocity distribution, in our previous paper [14], we

investigated the patterns of the angular distribution of the Monte Carlo-generated 3-dimensional WIMP velocity in different celestial coordinate systems as well as applied the Bayesian fitting technique to reconstruct the radial distribution (magnitude) of the 3-D WIMP velocity. Not only the diurnal modulation of the angular WIMP velocity distribution mentioned above, we demonstrated also the possible “annual” modulations of both of the angular and the radial distributions of the 3-D WIMP velocity.

However, besides recoil energies, what one could measure (directly) in directional detection experiments is recoil tracks and in turn recoil angles (and recoil senses) of scattered nuclei. Therefore, in this paper, as the second step of our study on developing analysis methods for directional DM detection experiments, we consider the angular distribution patterns of the (generated and transformed) 3-D WIMP kinetic energy in different celestial coordinate systems, which should help us to study (statistically) the angular distribution of the recoil energy of scattered nuclei later.

The remainder of this paper is organized as follows. In Sec. 2, we review briefly the event generation process based on the Monte Carlo method. Then, in Secs. 3 and 4, we present the (annual/diurnal modulated) patterns of the angular kinetic-energy distribution of Galactic WIMPs in different celestial coordinate systems one by one. We conclude in Sec. 5. Some technical details for our analyses and a summary of the laboratory-dependent simulation results will be given in Appendix.

2 Event generation

In this section, we review briefly the event generation of the 3-dimensional WIMP velocity (the magnitude and the direction as well as the measuring time) in the *Galactic* coordinate system based on the Monte Carlo method. As in Ref. [14], these generated 3-D WIMP velocities will be transformed into different celestial coordinate systems for data analyses presented in Secs. 3 and 4 as well as in Appendix B.

All tools needed for understanding our simulations and analyses presented in this paper: our definitions of different celestial coordinate systems as well as the transformation formulae and matrices between these coordinate systems, can be found in Appendix A and Ref. [14].

2.1 Radial component of the 3-D WIMP velocity distribution

For generating the radial component (magnitude) of the 3-D WIMP velocity in the Galactic coordinate system, we consider the simple Maxwellian velocity distribution truncated at the Galactic escape velocity [1]:

$$f_{1,\text{Gau}}(v) = \begin{cases} N_{\text{Gau}} \left(\frac{v^2}{v_0^3} \right) e^{-v^2/v_0^2}, & \text{for } v \leq v_{\text{esc}}, \\ 0, & \text{for } v > v_{\text{esc}}, \end{cases} \quad (1)$$

with the normalization constant

$$N_{\text{Gau}} = \left[\left(\frac{\sqrt{\pi}}{4} \right) \text{erf} \left(\frac{v_{\text{esc}}}{v_0} \right) - \left(\frac{v_{\text{esc}}}{2v_0} \right) e^{-v_{\text{esc}}^2/v_0^2} \right]^{-1}, \quad (2)$$

where $v_0 \simeq 220$ km/s is the Solar orbital speed around the Galactic center and 498 km/s $< v_{\text{esc}} < 608$ km/s is the escape velocity from our Galaxy at the position of the Solar system [15].

2.2 Angular component of the 3-D WIMP velocity distribution

Since the simplest model of the Galactic Dark Matter halo is assumed to be isothermal, spherical and isotropic, the angular distribution of the 3-D WIMP velocity in the Galactic coordinate system has been considered to be isotropic and thus the velocity directions (i.e., the ϕ - and θ -angles in the longitude and the latitude directions, respectively) are generated with a constant probability in our simulations:

$$f_{\phi,G}(\phi) = 1, \quad \phi \in (-\pi, \pi], \quad (3)$$

and

$$f_{\theta,G}(\theta) = 1, \quad \theta \in [-\pi/2, \pi/2]. \quad (4)$$

2.3 Measuring time and observation periods/shifts of WIMP events

Since, in the Galactic point of view, WIMP–nucleus scattering events should be observed randomly and constantly, in our simulations we considered a constant probability for generating the measuring UTC (Coordinated Universal Time) time of the recorded WIMP signals:

$$f_{t,G}(t) = 1, \quad t \in [t_{\text{start}}, t_{\text{end}}]. \quad (5)$$

Moreover, as discussed in detail in Ref. [14], two options for the observation periods were considered in our simulations for demonstrating the annual modulation of the angular distribution of the 3-D WIMP kinetic energy. The first one is the natural choice of four normal seasons with the central dates on the March 21st (79.0 day), the June 20th (170.25 day), the September 19th (261.50 day), and the December 19th (352.75 day), respectively. Meanwhile, considering the relative velocity of the Earth to the Galactic Dark Matter halo should be the maximum (minimum), when its orbital velocity is (anti-)parallel to the projection of the direction of the Solar movement on the Ecliptic plane around the 21st of May (140.74 day) (the 20th of November, 323.24 day), the second option is four “advanced” seasons (~ 30 days earlier) with the central dates on the February 19th (49.49 day), the May 21st (140.74 day), the August 20th (231.99 day), and the November 20th (323.24 day), respectively¹.

For each season of these two options, we considered a 60-day (± 30 days) observation period and each pair of the corresponding season has thus an overlap of around 30 days. In Table 1, we list, including the normal and the advanced seasons, four different options for the observation periods in a 365-day year considered in our simulations presented in this paper.

On the other hand, for demonstrating the (originally proposed) directionality (diurnal modulation) of the angular WIMP kinetic-energy distribution, we considered four observation intervals of 4 hours (± 2 hours) at the central (*local*, not the UTC) times of 0 o’clock, 6 o’clock, 12 o’clock, and 18 o’clock, respectively (see Table 2), in the 60-day periods centered on the January 26th ($25.16 = 390.16$ day) and the July 27th (207.66 day), respectively (see Table 1) [14].

3 Angular distributions of the 3-D WIMP kinetic energy in different coordinate systems

In Ref. [14], we discussed the angular distributions of the (generated and transformed) 3-D WIMP velocities in different celestial coordinate systems, which show only the anisotropy and the

¹Note that, in our simulations presented in this paper, we considered simply a 365-day year and the few extra hours in an actual Solar year has been neglected.

Option	Central date (day)	Period (day)
One entire year	—	0 – 365
Four normal seasons	79.0	49.0 – 109.0
	170.25	140.25 – 200.25
	261.50	231.50 – 291.50
	352.75	322.75 – 382.75 (= 17.75)
Four advanced seasons	49.49	19.49 – 79.49
	140.74	110.74 – 170.74
	231.99	201.99 – 261.99
	323.24	293.24 – 353.24
For diurnal modulation	207.66	177.66 – 237.66
	390.16 (= 25.16)	360.16 – 420.16 (= 55.16)

Table 1: Four options for the observation periods in a 365-day year considered in our simulations presented in this paper. Note that the last option is considered only for demonstrating the diurnal modulation of the angular WIMP kinetic-energy distribution.

directionality of the incident *flux* of Galactic WIMPs. For the study on the angular distribution of the recoil energy of scattered nuclei, we consider in this and the next sections the angular distributions of the 3-D WIMP kinetic energy in different coordinate systems by summing up the *squared magnitudes* of the 3-D WIMP velocities in different angular bins.

In this section, we present at first the angular distribution of the “accumulated” WIMP kinetic energy in the “laboratory-independent” Equatorial coordinate system and then in the “laboratory-dependent” horizontal and laboratory coordinate systems. 50 and 500 total events in (one daily shift of) one observation period (365 days/year, 60 days/season, or 4 hours/shift $\times$ 60 days) on average in one experiment for one laboratory have been simulated. 5,000 experiments have been simulated.

Option	Central time (hour)	Interval (hour)
One entire day	—	0 – 24
Four daily shifts	0	0 – 2, 22 – 24
	6	4 – 8
	12	10 – 14
	18	16 – 20

Table 2: Two options for the observation intervals in a 24-hour day considered for demonstrating the diurnal modulation of the angular WIMP kinetic-energy distribution.

Figure 2: The angular distribution of the 3-D WIMP kinetic energy in the Equatorial coordinate system. One entire year (0 to 365 day) has been considered. 50 total events on average in one experiment have been simulated and binned into 6×6 bins for the longitude and latitude directions, respectively. The dark-green star indicates the theoretical main direction of incident WIMPs in the Equatorial coordinate system [16]: 42.00°S , 50.70°W . The horizontal color bar on the top of the plot indicates the mean value of the accumulated kinetic energy (averaged over all simulated experiments) in each angular bin in unit of the all-sky average value.

As readers' reference, a summary of the angular distributions of the simulated 3-D WIMP kinetic energy observed in the horizontal and laboratory coordinate systems of different underground laboratories will be given in Appendix B.

3.1 Angular WIMP kinetic-energy distribution in the Equatorial frame

In this subsection, we present at first the angular distribution of the transformed 3-D WIMP kinetic energies in the Equatorial coordinate system².

In Figs. 2 and 3, we show the angular distributions of the 3-D WIMP kinetic energy in the Equatorial coordinate system. One entire year (0 to 365 day) has been considered. 50 and 500 total events on average in one experiment have been simulated and binned into 6×6 bins and 12×12 bins for the longitude and latitude directions, respectively. The dark-green star in each plot indicates the theoretical main direction of incident WIMPs in the Equatorial coordinate

²Note that the Equatorial coordinate system defined in our simulations moves orbitally around (and also approximately linearly with) the Sun, but doesn't rotate (see Appendix A). Thus the axis directions of the Equatorial coordinate system are fixed.

Figure 3: As in Fig. 2, except that 500 total events on average in one entire year have been simulated and binned into 12×12 bins for the longitude and latitude directions, respectively.

system [16]: 42.00°S , 50.70°W . The horizontal color bar on the top of the plot indicates the mean value of the accumulated kinetic energy (averaged over all simulated experiments) in each angular bin in unit of the all-sky average value.

Comparing with the angular distributions of the WIMP flux in the Equatorial coordinate system discussed in Ref. [14], one can find first that two sets of the distribution patterns look very similar: the highest-kinetic-energy (dark-red and purple) bins spread also from the center to the southwest part of the sky, whereas the WIMP kinetic energy would be the lowest in the most part of the northern and the eastern sky. This demonstrates that both angular distributions could be used for identifying the anisotropy of the incident direction of Galactic WIMPs. More precisely, the distribution pattern of the 3-D WIMP kinetic energy would be, due to the weight of the squared velocity, more enhanced and more concentrated on the theoretical main direction of the WIMP wind.

On the other hand, one can find from both of Figs. 2 and 3 that, comparing to the deviations of the highest-WIMP-flux bins from the theoretical main WIMP direction discussed in Ref. [14], the deviations of the highest-kinetic-energy bins seem to be reduced and, with $\mathcal{O}(500)$ total WIMP events and a higher analysis resolution, the hot-point could now cover the theoretical main WIMP direction.

3.1.1 Annual modulation of the angular kinetic-energy distribution in the Equatorial frame

Moreover, in order to demonstrate the annual modulation of the angular distribution pattern of the 3-D WIMP kinetic energy, we show from Figs. 4 to 7 the angular WIMP kinetic-energy

(a) 49.0 – 109.0 day

(b) 140.25 – 200.25 day

(c) 231.50 – 291.50 day

(d) 322.75 – 382.75 day

Figure 4: The angular distributions of the 3-D WIMP kinetic energy in the Equatorial coordinate system with 50 total events on average for each 60-day observation period of four *normal* seasons listed in Table 1. Besides the dark-green star indicating the theoretical direction of the WIMP wind, the blue-yellow point in each plot indicates the opposite direction of the Earth’s velocity relative to the Dark Matter halo on the central date of the observation period [14].

distributions in the Equatorial coordinate system with 50 and 500 total events on average in each 60-day observation period of four normal and four advanced seasons³ listed in Table 1, respectively. In each plot, besides the dark-green star indicating the theoretical direction of the WIMP wind, 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 the observation period [14].

By comparing the plots in four normal and four advanced seasons as well as each pair of the corresponding plots in the normal and the advanced seasons carefully, one could confirm the clockwise annual modulation of the distribution patterns of the 3-D WIMP kinetic energy, which indeed follows the movement of the blue-yellow point indicating the instantaneous theoretical main direction of incident WIMPs. As concluded in Ref. [14], this could be, besides the

³This means although that ~ 300 (or even $\sim 3,000$) total WIMP events in one year would be required, considering the laboratory-independence of the Equatorial coordinate system, one could in practice collect the events observed at several underground laboratories together for the analyses.

(a) 49.0 – 109.0 day

(b) 140.25 – 200.25 day

(c) 231.50 – 291.50 day

(d) 322.75 – 382.75 day

Figure 5: As in Figs. 4, except that 500 total events on average in each 60-day observation period of four normal seasons have been simulated.

pure anisotropy of the WIMP flux/kinetic energy, the second (important) characteristic for discriminating directional WIMP signals from any (unexpected) backgrounds with some specified incoming directions.

3.2 Angular WIMP kinetic–energy distribution in the horizontal frame

In this subsection, we present the angular distribution of the transformed 3-D WIMP kinetic energies in the horizontal coordinate system⁴.

Here we show only the annual modulation of the angular kinetic–energy distributions observed at the Kamioka and the SUPL laboratories. More simulation results and discussions for other underground laboratories will be given in Appendix B.

Figure 6: As in Figs. 4, except that four observation periods of the *advanced* seasons listed in Table 1 have been considered.

3.2.1 Annual modulation of the angular kinetic-energy distribution in the horizontal frame

In Figs. 8 and 9, we show the angular distributions of the 3-D WIMP kinetic energy with 50 and 500 total events on average in one entire year and in each 60-day observation period of four *advanced* seasons in the horizontal coordinate system of the Kamioka laboratory (36.43°N , 137.31°E), as a demonstration for an underground laboratory located in the Northern Hemisphere.

As observed in Sec. 3.1, firstly, the angular WIMP kinetic-energy distributions would be very similar to, but more enhanced and more concentrated than the angular distributions of the WIMP flux shown in Ref. [14]. Hence, both of them could be used for identifying the directionality of the WIMP wind.

Moreover, in order to demonstrate the *location*-dependence of (the annual modulation of) the angular distribution pattern of the 3-D WIMP kinetic energy, in Figs. 10 and 11 we show also the angular kinetic-energy distributions in the horizontal coordinate system of the SUPL

⁴Note that the horizontal coordinate system defined in our simulations not only moves orbitally around (and also approximately linearly with) the Sun, but also rotates daily and discretely (see Appendix A).

(a) 19.49 – 79.49 day

(b) 110.74 – 170.74 day

(c) 201.99 – 261.99 day

(d) 293.24 – 353.24 day

Figure 7: As in Figs. 6, except that 500 total events on average in each 60-day observation period of four advanced seasons have been simulated.

laboratory (37.07°S , 142.81°E), which is so far the unique functionable underground laboratory in the Southern Hemisphere.

As discussed particularly in Ref. [17], the Kamioka and the SUPL laboratories are located at the almost-symmetric positions with respect to the Equatorial plane in the Northern and the Southern Hemisphere, respectively. This means that, with a 12-hour time difference in the same day or a 6-month difference in a year, the horizontal coordinate systems of two laboratories should have a common x -axis (pointing towards north) and the difference between two frames is a 180° -rotation around the common x -axis. Therefore, the annual modulations of the angular kinetic-energy distribution pattern observed at such a pair of laboratories show clearly a 6-month difference with a 180° -rotated symmetry around the center.

More demonstrations for the location-dependence of the annual modulation of the angular WIMP kinetic-energy distribution with other (pairs of) underground laboratories can be found in Appendix B.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 8: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the Kamioka laboratory (36.43°N , 137.31°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four *advanced* seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 9: As in Figs. 8, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 10: As in Figs. 8, 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated, except that the SUPL laboratory (37.07°S , 142.81°E) has been considered.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 11: As in Figs. 10, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

3.3 Angular WIMP kinetic–energy distribution in the laboratory frame

In this subsection, we present the angular distribution of the transformed 3-D WIMP kinetic energies in the laboratory coordinate system⁵.

Here we show only the diurnal modulation of the angular kinetic–energy distributions observed at the Kamioka and the SUPL laboratories. More simulation results and discussions for other underground laboratories can be found in Appendix B.

3.3.1 Diurnal modulation of the angular kinetic–energy distribution in the laboratory frame

In Figs. 12 and 13, we show the angular distributions of the 3-D WIMP kinetic energy observed at the Kamioka laboratory in four 4-hour daily shifts listed in Table 2⁶ in the 60-day observation periods of 177.66 – 237.66 day and 360.16 – 420.16 (= 55.16) day with 50 and 500 total events on average, respectively.

As discussed in Ref. [14], by comparing the upper and lower four plots with each other, the approximate 12-hour shift of the angular kinetic–energy distribution patterns in two observation periods with a half–year time difference could be clearly identified. Meanwhile, by comparing Figs. 12 and 13 with Figs. 8 and 9, one could also find the similarity between the diurnal modulation of the angular kinetic–energy distribution in the laboratory coordinate system in each observation period and the annual modulation of the distribution pattern in the horizontal coordinate system.

Moreover, as in Sec. 3.2.1, in order to demonstrate the location–dependence of the diurnal modulation of the angular WIMP kinetic–energy distribution, in Figs. 14 and 15 we show also the angular kinetic–energy distributions observed at the SUPL laboratory in four 4-hour daily shifts in the periods of 177.66 – 237.66 day and 360.16 – 420.16 (= 55.16) day. As discussed particularly in Ref. [17] and shown in Sec. 3.2.1, by comparing Figs. 14 and 15 with Figs. 12 and 13, one can also clearly find the characteristic 12-hour difference and 180°–rotation around the center between two sets of the distribution patterns observed in the laboratory coordinate system of two laboratories.

In Appendix B, one can find more simulation results and comparisons of the diurnal modulation of the angular WIMP kinetic–energy distribution for other underground laboratories.

4 Angular distributions of the average WIMP kinetic energy in different coordinate systems

In the previous section, we have demonstrated the angular distributions of the “accumulated” WIMP kinetic energy in different celestial coordinate systems. As discussed already, since they are simply the sum of the squared magnitudes of the 3-D WIMP velocities in different angular bins, these distributions look very similar to, but more enhanced and concentrated than the angular distributions of the WIMP flux presented in Ref. [14]. This is expectable: the much more WIMPs (from one specified direction), the (much) higher the accumulated kinetic energy.

⁵Note that the laboratory coordinate system defined in our simulations not only moves orbitally around (and also approximately linearly with) the Sun, but also rotates continuously (see Appendix A).

⁶Note that, in the simulations of the diurnal modulation of the angular WIMP kinetic–energy distribution presented in this paper, we have re–calculated the local time of each simulated event of the considered laboratory from the generated measuring UTC time.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure 12: The angular distributions of the 3-D WIMP kinetic energy observed at the Kamioka laboratory in four daily shifts in the observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h), respectively. 50 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

(a) 177.66 - 237.66 day, 22 - 2 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 2 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure 13: As in Figs. 12, except that 500 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure 14: As in Figs. 12, 50 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated, except that the SUPL laboratory has been considered.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure 15: As in Figs. 14, except that 500 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

Figure 16: The angular distribution of the average WIMP kinetic energy in the Equatorial coordinate system. One entire year with 50 total events on average has been considered. The theoretical main direction of incident WIMPs has been given here as the dark-green star again. All simulation setup are the same as in Fig. 2. Note that the horizontal color bar used here indicates the mean value of the average kinetic energy (per WIMP) (averaged then over all simulated experiments) in each angular bin in unit of the all-sky average value.

Thus, in this section, we would like to remove the effect of the factor of the event number and consider the angular distributions of the “average” WIMP kinetic energy in different celestial coordinate systems, as the second indicator of (the annual/diurnal modulation of) the angular distribution pattern of the strength (and the direction) of the incident velocity of Galactic WIMPs. We present the angular average-kinetic-energy distribution (divided by the event number in each angular bin) in the Equatorial at first and then in the horizontal and the laboratory coordinate systems in detail.

In Appendix B, more simulation results of the angular distributions of the average WIMP kinetic energy observed in the horizontal and laboratory coordinate systems of different underground laboratories will be summarized as readers’ reference.

4.1 Angular average-kinetic-energy distribution in the Equatorial frame

In this subsection, we present at first the angular distribution of the transformed 3-D kinetic energies per WIMP in the Equatorial coordinate system.

In Figs. 16 and 17, we show the angular distributions of the average WIMP kinetic energy in the Equatorial coordinate system with 50 and 500 total events on average in one entire year.

Figure 17: As in Fig. 16, except that 500 total events on average in one entire year have been simulated. Two extra (red) hot-points close to the center and at the southwestern corner of the sky can be seen clearly here.

The horizontal color bar on the top of the plot indicates now the mean value of the average kinetic energy (per WIMP) (averaged then over all simulated experiments) in each angular bin in unit of the all-sky average value.

One can find at first that, even with only $\mathcal{O}(50)$ WIMP events, the highest-average-kinetic-energy (red) bin(s) could precisely cover the (dark-green) theoretical main direction of incident WIMPs. However, one would also find in Fig. 16 that, with only $\mathcal{O}(50)$ WIMP events and a rather low analysis resolution, the angular average-kinetic-energy distribution seems not to decrease monotonically from the (red) hot-point around the theoretical main WIMP direction.

Nevertheless, with a raised event number of $\mathcal{O}(500)$ WIMPs and a higher analysis resolution, one can find in Fig. 17 that, the second-highest-average-kinetic-energy (yellow) bins would indeed be around the hot-point. Meanwhile, two (unexpected) extra hot-points close to the center and at the southwestern corner of the sky would appear clearly now.

Moreover, it would also be interesting to remark that, while the highest-*accumulated*-kinetic-energy bins shown in Fig. 3 spread obliquely from the center to the southwest part of the sky, the highest-*average*-kinetic-energy bins in Fig. 17 appear in the approximately straight area between the longitude of 90°W and 0° and from the latitude of 15°S to 75°S (see also Figs. 19 and 21)⁷.

⁷As yet we have no straightforward explanations for the extra hot-points and the pattern difference nor an idea whether they could help us to understand the Galactic structure of Dark Matter particles.

(a) 49.0 – 109.0 day

(b) 140.25 – 200.25 day

(c) 231.50 – 291.50 day

(d) 322.75 – 382.75 day

Figure 18: The angular distributions of the average WIMP kinetic energy in the Equatorial coordinate system with 50 total events on average in each 60-day observation period of four *normal* seasons. All simulation setup and notations are the same as in Figs. 4.

4.1.1 Annual modulation of the angular average-kinetic-energy distribution in the Equatorial frame

Now we show from Figs. 18 to 21 the angular average-kinetic-energy distributions in the Equatorial coordinate system with 50 and 500 total events on average in each 60-day observation period of four normal and four advanced seasons, respectively. Again, besides the dark-green star indicating the theoretical direction of the WIMP wind, we also put the blue-yellow point in each plot to indicate the instantaneous theoretical main direction of incident WIMPs.

One can find firstly that, basically, the (main) hot-point could always cover the (instantaneous) theoretical main WIMP direction. Meanwhile, the clockwise annual modulation of the distribution patterns following the movement of the instantaneous main WIMP direction could also be identified and even more clearly (cf. Figs. 5 and 7). Moreover, as found in Fig. 17, the (main) hot-points appear in the approximately straight areas between the longitude of 90°W and 0° and below the latitude of 15°S .

Very interestingly, it can be found in Figs. 19 and 21 that two extra hot-points discovered in Fig. 17 would now show a clearly *seasonal* appearance; in particular, in the plots of the *advanced*

(a) 49.0 – 109.0 day

(b) 140.25 – 200.25 day

(c) 231.50 – 291.50 day

(d) 322.75 – 382.75 day

Figure 19: As in Figs. 18, except that 500 total events on average in each 60-day observation period of four normal seasons have been simulated.

seasons.

4.2 Angular average-kinetic-energy distribution in the horizontal frame

In this subsection, we present the angular distribution of the transformed 3-D kinetic energies per WIMP in the horizontal coordinate system.

Here we show only the annual modulation of the angular average-kinetic-energy distributions observed at the Kamioka and the SUPL laboratories. More simulation results and discussions for other underground laboratories will be given in Appendix B.

4.2.1 Annual modulation of the angular average-kinetic-energy distribution in the horizontal frame

In Figs. 22 and 23, we show first the angular average-kinetic-energy distributions with 50 and 500 total events on average in one entire year and in each 60-day observation period of four advanced seasons in the horizontal coordinate system of the Kamioka laboratory. Then, as in

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 19.49 - 79.49 day, 50 events

(a) 19.49 - 79.49 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 110.74 - 170.74 day, 50 events

(b) 110.74 - 170.74 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 201.99 - 261.99 day, 50 events

(c) 201.99 - 261.99 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 293.24 - 353.24 day, 50 events

(d) 293.24 - 353.24 day

Figure 20: As in Figs. 18, except that four observation periods of the *advanced* seasons have been considered.

Sec. 3.2.1, we show also the angular average-kinetic-energy distributions observed at the SUPL laboratory in Figs. 24 and 25.

First, by comparing the distribution patterns with only $\mathcal{O}(50)$ WIMP events shown in Figs. 22 and 24 to those with $\mathcal{O}(500)$ events in Figs. 23 and 25, the importance of the total number of the observed events (at one laboratory!) and the analysis resolution for this demonstration can be seen clearly.

Moreover, while the basic distribution patterns of the average WIMP kinetic-energy observed at the Kamioka and the SUPL laboratories would still show the similarity with the characteristic 180° -rotation around the center with the half-year time difference, the appearances and the locations (directions) of the hot-points of the average-kinetic-energy distributions of two laboratories seem not to be correspondent with each other. This can be found more clearly when there are only $\mathcal{O}(50)$ analyzed events.

On the other hand, as discussed in Sec. 4.1, by comparing Figs. 22 to 25 with Figs. 8 to 11, one can find again that the hot-points of the distribution patterns of the accumulated and the average WIMP kinetic energy observed at both laboratories would not coincide with each other.

More demonstrations for the location-dependence of the annual modulation of the angular

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 19.49 - 79.49 day, 500 events

(a) 19.49 – 79.49 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 110.74 - 170.74 day, 500 events

(b) 110.74 – 170.74 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 201.99 - 261.99 day, 500 events

(c) 201.99 – 261.99 day

Angular distribution of the kinetic energy per WIMP in the Equatorial frame, 293.24 - 353.24 day, 500 events

(d) 293.24 – 353.24 day

Figure 21: As in Figs. 20, except that 500 total events on average in each 60-day observation period of four advanced seasons have been simulated. A *seasonal* appearance of *each* of two extra hot-points found in Fig. 17 can be seen clearly here (more representative than in Figs. 19).

WIMP average-kinetic-energy distribution with other (pairs of) underground laboratories can be found in Appendix B.

4.3 Angular average-kinetic-energy distribution in the laboratory frame

In this subsection, we present the angular distribution of the transformed 3-D kinetic energies per WIMP in the laboratory coordinate system.

Here we show only the diurnal modulation of the angular average-kinetic-energy distributions observed at the Kamioka and the SUPL laboratories. More simulation results and discussions for other underground laboratories can be found in Appendix B.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 22: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the Kamioka laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 0 - 365 day, 500 events, at Kamioka

(a) 0 – 365 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 19.49 - 79.49 day, 500 events, at Kamioka

(b) 19.49 – 79.49 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 110.74 - 170.74 day, 500 events, at Kamioka

(c) 110.74 – 170.74 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 201.99 - 261.99 day, 500 events, at Kamioka

(d) 201.99 – 261.99 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 293.24 - 353.24 day, 500 events, at Kamioka

(e) 293.24 – 353.24 day

Figure 23: As in Figs. 22, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 24: As in Figs. 22, 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated, except that the SUPL laboratory has been considered.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure 25: As in Figs. 24, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

4.3.1 Diurnal modulation of the angular average-kinetic-energy distribution in the laboratory frame

In Figs. 26 and 27, we show first the angular average-kinetic-energy distributions observed at the Kamioka laboratory in four 4-hour daily shifts in the 60-day observation periods of 177.66 – 237.66 day and 360.16 – 420.16 (= 55.16) day with 50 and 500 total events on average, respectively. Then, as in Sec. 3.3.1, we show also the angular average-kinetic-energy distributions observed at the SUPL laboratory in Figs. 28 and 29.

Interestingly, while the similarity with the characteristic 180° -rotation around the center with the half-year time difference between the angular distributions of the average WIMP kinetic energy observed at the Kamioka and the SUPL laboratories could be seen here clearly: not only the basic distribution patterns, but also the locations of the hot-points, the similarity with the approximate 12-hour shift between the distribution patterns observed at each laboratory in two periods with a half-year time difference seems not to hold so well as we found in Sec. 3.3.1 (and Ref. [14]).

Note that, as mentioned in Sec. 4.2.1, the comparisons of Figs. 26 and 28 with Figs. 27 and 29 show that, for identifying the hot-points in the distribution patterns of the average WIMP kinetic energy, $\mathcal{O}(500)$ recorded WIMP events in each 4-hour daily shift in the 60-day observation period would be required⁸.

In Appendix B, one can find more simulation results and comparisons of the diurnal modulation of the angular WIMP average-kinetic-energy distribution for other underground laboratories.

5 Summary

In this paper, as the second step of our development of data analysis procedures for using and/or combining 3-dimensional information offered by directional Dark Matter detection experiments, we investigated the angular distributions of the 3-dimensional WIMP kinetic energy observed in different celestial coordinate systems (of different underground laboratories).

We considered at first the angular distributions of the “accumulated” kinetic energy of the Monte Carlo-simulated WIMP events. Our simulations show that, with $\mathcal{O}(50)$ total events collected through one entire (or several) year(s) (recorded probably by detectors at several underground laboratories), the anisotropy of the kinetic-energy distribution of incident WIMPs in the Equatorial coordinate system could already be identified; the distribution pattern of the 3-D WIMP kinetic energy would even be more enhanced and more concentrated on the theoretical direction of the WIMP wind, compared with the angular distribution of the WIMP flux presented in our earlier work [14].

Moreover, the clockwise rotated “annual” modulation of the distribution patterns of the 3-D WIMP kinetic energy, following the movement of the instantaneous main incident direction of Galactic WIMPs, demonstrated in our earlier work [14] could also be confirmed roughly with only $\mathcal{O}(50)$ and clearly with $\mathcal{O}(500)$ total WIMP events accumulated in each observation period of a few tens of days. As we already concluded in Ref. [14], *this would be, besides the pure anisotropy of the WIMP velocity(flux)/kinetic energy, the second (important) characteristic for identifying directional WIMP signals and discriminating from any (unexpected) backgrounds with some specified incoming directions.*

⁸This means in turn that in one laboratory our detector(s) would need to have an ability of observing at least $\mathcal{O}(10,000)$ WIMP events per year!

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure 26: The angular distributions of the average WIMP kinetic energy observed at the Kamioka laboratory in four daily shifts in the observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h), respectively. 50 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure 27: As in Figs. 26, except that 500 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure 28: As in Figs. 26, 50 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated, except that the SUPL laboratory has been considered.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure 29: As in Figs. 28, except that 500 total events on average in each 4-hour daily shift in the 60-day observation period have been simulated.

In addition, we discussed also the location–dependence of the annual and the diurnal modulations of the angular distribution patterns of the 3-D WIMP kinetic energy in our laboratory–dependent horizontal and laboratory coordinate systems (of different underground laboratories), as demonstrated in Refs. [14, 17].

On the other hand, in order to remove the effect of the angular distribution of the WIMP flux, we considered also the angular distributions of the “average” WIMP kinetic energy. While both of the anisotropy and the clockwise annual modulation of the distribution patterns of the average WIMP kinetic energy could still be identified clearly, two interesting phenomena were also discovered.

Firstly, with $\mathcal{O}(500)$ WIMP events (and a higher analysis resolution), two extra hot–points close to the center and at the southwestern corner of the sky would appear clearly. And, accompanied with the annual modulation of the angular WIMP average–kinetic–energy distribution, these two hot–points would show a seasonal appearance.

Secondly, the hot–points of the angular distributions of the accumulated and the average WIMP kinetic energy would not coincide with each other: while the hot–points of the accumulated–kinetic–energy distributions spread obliquely from the center to the southwest part of the sky, those of the average–kinetic–energy distributions appear in the approximately straight area between the longitude of 90°W and 0° and below the latitude of 15°S .

Possible theoretical explanations for both of (the seasonal appearance of) the extra hot–points and the pattern difference as well as their contributions to our understanding on and/or reconstruction of the Galactic structure of Dark Matter particles would need more investigation.

In our simulations presented in this paper, 50 and 500 total WIMP events on average in (one daily shift of) one observation period (365 days/year, 60 days/season, or 4 hours/shift $\times$ 60 days) have been considered. In this and probably the next decades, even only $\mathcal{O}(50)$ total WIMP signals (per year) to observe would be a strong challenge for all (non–)directional direct Dark Matter detection experiments. Fortunately, the recorded 3-D velocity information of WIMP signals offered by different underground laboratories could (in principle) be transformed to all laboratory–independent (Galactic, Ecliptic, and Equatorial) coordinate systems for our analyses.

As the second step, once enough WIMP events could be observed in one laboratory, (the location–dependence of) (the annual and the diurnal modulations of) the angular distributions of the 3-D WIMP kinetic energy in the laboratory–dependent (horizontal and laboratory) coordinate systems could then be demonstrated.

Regarding the observation periods considered in our simulations presented in this paper, we used several approximations about the Earth’s orbital motion in the Solar system. First, the Earth’s orbit around the Sun is perfectly circular on the Ecliptic plane and the orbital speed is thus a constant. Second, the date of the vernal equinox is exactly fixed at the end of the 79th day (the May 20th) of a 365-day year and the few extra hours in an actual Solar year have been neglected. Nevertheless, considering the very low WIMP scattering event rate and thus only a few tens of total (combined) WIMP events required in at least a few tens of days (an overall event rate of $\lesssim 1$ event/day) for the first–phase analyses, these approximations should be acceptable.

In summary, we went one step further for our study on (the analyses of) the angular distribution of the recoil energy of the scattered target nucleus, what one could in practice observe in directional Dark Matter detection experiments. Hopefully, this and more works achieved in the future could help us to understand the 3-dimensional (velocity) distribution of Galactic Dark Matter particles as well as provide useful information for indirect detection experiments.

Figure A1: The sketch of the definitions of and the relative orientations between the (black) Galactic, the (red) Ecliptic, and the (blue) Equatorial coordinate systems (on the date of the vernal equinox). While the magenta circular band indicates an approximate path of the orbital motion of the Solar system in the Galaxy and the blue circular band the Earth’s orbit around the Sun, the additional (golden) arrows indicate the direction of the movement of the Solar system around the Galactic center. Note that the moving direction of the Solar system is not parallel to, but only approximately along the $\mathbf{Y}_G$ -axis of the Galactic coordinate system (with an included angle of $8.87^\circ = 35.48^\text{m}$), nor on the (approximate) Galactic plane (0.60° above) [14]. See the text for the detailed definitions of these coordinate systems.

Acknowledgments

The author would like to thank the friendly hospitality of the School of Physics at the Sun Yat-Sen University during the finalization of this work. The author would also appreciate particularly the kindly long-term academic and administrative support by the Institute of Physics at the National Chiao Tung University.

A Our definitions of the celestial coordinate systems

In this section, we give our definitions of three “laboratory-independent” (Galactic, Ecliptic, and Equatorial) and two “laboratory-dependent” (horizontal and laboratory) coordinate systems used in our simulations and analyses. The detailed derivations and discussions of the analytic and/or the numerical forms of all transformation matrices between these celestial coordinate systems can be found in Appendix A of Ref. [14].

A.1 Definitions of the laboratory-independent coordinate systems

In Fig. A1, we sketch the relative orientations between the Galactic, the Ecliptic and the Equatorial coordinate systems (on the date of the vernal equinox⁹).

⁹Note that, in our simulations presented in this paper, the date of the vernal equinox has been fixed exactly at the end of the 79th day (the May 20th) of a 365-day year.

Figure A2: The sketches of the definition of the (dark-green) horizontal (a) and the definition of the (dark-green) laboratory (b) coordinate systems, respectively. A (light-green) Earth coordinate system is also given here [14]. ϕ_{Lab} and θ_{Lab} indicate the longitude and the latitude of the location of the laboratory of interest, respectively, whereas ωt_{PM} the rotated angle of the (yellow) Prime Meridian around the Earth's north polar axis from 12 midnight (the beginning) of (the UTC time of) each single day. See the text for the detailed definitions.

First, for our simulations presented in this paper, the Galactic coordinate system is defined as follows: the origin is at the (approximate) Galactic Center (GC), (not the center of the Sun), the primary direction (the $\mathbf{X}_G$ -axis) points from the Solar center to GC, and the $\mathbf{Z}_G$ -axis points to the Galactic North Pole (GNP). The right-handed convention is used for defining the $\mathbf{Y}_G$ -axis and the fundamental ($\mathbf{X}_G - \mathbf{Y}_G$) plane is the approximate Galactic plane. Note that, as shown in Fig. A1, the moving direction of the Solar system (golden arrows) towards the CYGNUS constellation is *not parallel to*, but only *approximately along* the $\mathbf{Y}_G$ -axis of the Galactic coordinate system (with an included angle of $8.87^\circ = 35.48^\text{m}$), *nor on* the (approximate) Galactic plane (0.60° above).

Meanwhile, the Ecliptic and the Equatorial coordinate systems are defined as follows: their origins are located at the center of the Sun and that of the Earth, respectively, the common primary direction (the $\mathbf{X}_S/\mathbf{X}_{\text{Eq}}$ -axis) is the direction pointing from the Solar center to that of the Earth at 12 midnight (the *end*) of the date of the vernal equinox, the $\mathbf{Z}_S$ - and the $\mathbf{Z}_{\text{Eq}}$ -axes are perpendicular to the (yellow) Ecliptic or the (blue) Equatorial plane, respectively, and their $\mathbf{Y}_S$ - and $\mathbf{Y}_{\text{Eq}}$ -axes are then defined as usual by the right-handed convention. Note that, the Ecliptic and the Equatorial coordinate systems only move, but do not rotate with the Sun nor with the Earth.

A.2 Definitions of the laboratory-dependent coordinate systems

On the other hand, as sketched in Figs. A2, for demonstrating the annual modulation of the angular distribution of the 3-D WIMP kinetic energy measured in a specified underground laboratory, we defined first the horizontal coordinate system with the origin at the geographic location of the laboratory of interest at 12 midnight (the *beginning*) of (the UTC time of) each single day, the primary direction (the $\mathbf{X}_H$ -axis) and the $\mathbf{Z}_H$ -axis pointing towards north and the zenith, respectively, and the right-handed convention for defining the $\mathbf{Y}_H$ -axis. Note that, for

Coordinate system	Movement	Rotation	Style
Galactic	$\times$	$\times^\dagger$	—
Ecliptic	$\checkmark$	$\times$	Orbital $\rightarrow$ approximately linear
Equatorial	$\checkmark$	$\times$	Linear + orbital $\rightarrow$ spiral
Horizontal	$\times^\ddagger$	$\checkmark$	Daily and discrete
Laboratory	$\times^\ddagger$	$\checkmark$	Instantaneous and continuous

Table A1: The styles of the movement and the rotation of all celestial coordinate systems defined in our simulations presented in this paper.

† : The tiny angle swept by the connection between the Solar and the Galactic centers during the orbital motion of the Solar system in the Galaxy is ignored here.

‡ : Fixed on the Earth and combined *additionally* with the “linear + orbital $\rightarrow$ spiral” movement of the Equatorial coordinate system.

each single “Solar” day, our horizontal coordinate system is fixed at 12 midnight (the beginning) of the day and thus changes daily and discretely (see Table A1).

Moreover, for identifying the diurnal modulation of the angular WIMP kinetic-energy distribution, we also defined the laboratory coordinate system by taking into account the *instantaneous* measuring time of each recorded WIMP scattering event. This means that our laboratory coordinate system is defined basically the same as the horizontal coordinate system, but rotates with the laboratory of interest around the Earth’s north polar ($\mathbf{Z}_{\text{Eq}}$ -)axis instantaneously by an angle of ωt_{PM} , where we defined

$$\omega \equiv \frac{2\pi}{1 \text{ day}}, \quad (\text{A1})$$

and t_{PM} indicates the fractional part of the measuring UTC time t of each recorded WIMP event in unit of day. Note that, our laboratory coordinate system changes (rotates around the Earth’s north polar axis) *event by event*.

In Table A1, we summarize the styles of the movement and the rotation of all celestial coordinate systems defined in our simulations presented in this paper. Note that, except of the “linear + orbital $\rightarrow$ spiral” motion of the Equatorial coordinate system, the horizontal and the laboratory coordinate systems are fixed on the Earth and only rotate around the Earth’s north polar axis.

B Angular distributions of the 3-D WIMP kinetic energy observed at the known underground laboratories

As in Ref. [14], for readers’ reference, we summarize in this section the angular distributions of the 3-D WIMP kinetic energy in two laboratory-dependent (horizontal and laboratory) coordinate systems at the locations of several underground laboratories.

For each laboratory, we provide the following figures:

- the angular distributions of the 3-D WIMP (average) kinetic energy in the horizontal coordinate system of the laboratory in one entire year and in the 60-day observation periods of four advanced seasons on the central date of 49.49 day, 140.74 day, 231.99 day, and 323.24 day, respectively;
- the angular distributions of the 3-D WIMP (average) kinetic energy in the laboratory coordinate system of the laboratory in four 4-hour daily shifts in two 60-day observation periods with the central dates of 207.66 day and 25.16 (= 390.16) day.

50 and 500 total WIMP events on average in (one daily shift of) one observation period (365 days/year, 60 days/season, or 4 hours/shift $\times$ 60 days) have been simulated. Remind that, in the simulations of the diurnal modulation of the angular WIMP (average-)kinetic-energy distribution presented here, we have re-calculated the local time of each simulated event of the considered laboratory from the generated measuring UTC time.

Moreover, as discussed particularly in Ref. [17] and demonstrated in Secs. 3 and 4, the angular distribution patterns of the 3-D WIMP flux and (average) kinetic energy observed in the laboratory-dependent coordinate systems of several pairs of underground laboratories could be used as cross checks of the observation of the directionality of the main incident direction of Galactic WIMPs:

- Cf. 1. The CJPL (28.15°N, 101.71°E) and the ANDES (30.19°S, 69.82°W) laboratories, located at the almost-opposite positions with respect to the Earth's center: the angular distributions observed in the *same* periods would have similar patterns, but with a 180°-rotation around the center;
- Cf. 2. The Kamioka (36.43°N, 137.31°E) and the SUPL (37.07°S, 142.81°E) laboratories, located at the almost-symmetric positions with respect to the Equatorial plane in the Northern and the Southern Hemisphere: the angular distributions observed in the periods with a *half-year* time difference would have similar patterns, but with a 180°-rotation around the center;
- Cf. 3. The North-American DUSEL (44.35°N, 103.75°W) and SNOLAB (46.47°N, 81.19°W) laboratories and the European Boulby (54.55°N, 0.82°W), Callio (63.66°N, 26.04°E), LNGS (42.45°N, 13.58°E), LSC (42.81°N, 0.56°W), and LSM (45.14°N, 6.70°E) laboratories, located at the approximately equal latitude¹⁰ with an $\sim 90^\circ$ (more precisely, between $\sim 80^\circ$ and $\sim 130^\circ$) longitude difference: the angular distributions observed in the periods with a *3-month* time difference would have alike patterns.

In practice, one can consider more corresponding pairs of laboratories. First, the locations of the CJPL and the Kamioka laboratories are relatively close. So one can treat them as in the common East-Asian (EAs) Group and the first two comparisons (Cfs. 1 and 2) given above would be (approximately) held for both two laboratories. Hence,

- Cf. 1. The angular distributions of the East-Asian laboratories and the distribution of the South-American (SAm) ANDES laboratory observed in the same periods would have similar patterns, but a 180°-rotation around the center;

¹⁰The locations of the Boulby and the Callio laboratories are more northern, but our observations can still be (approximately) held.

Figure A3: The sketch of the comparisons of the angular distribution patterns of the 3-D WIMP flux and (average) kinetic energy observed in the horizontal coordinate system of all pairs of laboratory groups. See the text for detailed explanations.

- Cf. 2. The angular distributions of the East-Asian laboratories and the distribution of the South-Pacific (SPa) SUPL laboratory observed in the periods with a half-year time difference would have similar patterns, but a 180° -rotation around the center.

Moreover, similar to the combinations of the North-American (NAm) and the European (Eu) laboratories in Cf. 3 above, one can expect that (see Fig. A3 and Table A2)

- Cf. 4. The angular distributions of the European laboratories and those of the East-Asian laboratories observed in the periods with a *3-month* time difference would have alike patterns;
- Cf. 5. The angular distributions of the North-American laboratories and those of the East-Asian laboratories observed in the periods with a *half-year* time difference would have similar patterns;
- Cf. 6. The angular distributions of two Southern-Hemispheric ANDES and SUPL laboratories observed in the periods with a *half-year* time difference would also have similar patterns.

Finally, similar to the combinations of the East-Asian laboratories with the ANDES and the SUPL laboratories, we can also expect that

- Cf. 7. The angular distributions of the North-American laboratories and that of the (SPa) SUPL laboratory observed in the *same* periods would have similar patterns, but a 180° -rotation around the center;
- Cf. 8. The angular distributions of the North-American laboratories and that of the (SAm) ANDES laboratory observed in the periods with a *half-year* time difference would have similar patterns, but a 180° -rotation around the center;

as well as

Laboratory group	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
North–America (NAm)	Alike	Cf. 3 3-month earlier	Cf. 5 half–year difference	Cf. 8 half–year difference <small>+180°–rotation</small>	Cf. 7 Alike <small>+180°–rotation</small>
Europe (Eu)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier <small>+180°–rotation</small>	Cf. 9 3-month later <small>+180°–rotation</small>
East–Asian (EAs)	Cf. 5 half–year difference	Cf. 4 3-month later	Alike	Cf. 1 Alike <small>+180°–rotation</small>	Cf. 2 half–year difference <small>+180°–rotation</small>
South–America (SAm)	Cf. 8 half–year difference <small>+180°–rotation</small>	Cf. 10 3-month later <small>+180°–rotation</small>	Cf. 1 Alike <small>+180°–rotation</small>	Alike	Cf. 6 half–year difference
South–Pacific (SPa)	Cf. 7 Alike <small>+180°–rotation</small>	Cf. 9 3-month earlier <small>+180°–rotation</small>	Cf. 2 half–year difference <small>+180°–rotation</small>	Cf. 6 half–year difference	Alike

Table A2: The summary of the comparisons of the angular distribution patterns of the 3-D WIMP flux and (average) kinetic energy observed in the horizontal coordinate system of all pairs of laboratory groups.

Cf. 9. The angular distributions of the European laboratories and that of the (SPa) SUPL laboratory observed in the periods with a *3-month* time difference would have similar patterns, but a 180°–rotation around the center;

Cf. 10. The angular distribution of European laboratories and that of the (SAm) ANDES laboratory observed in the periods with a *3-month* time difference would have similar patterns, but a 180°–rotation around the center.

We sketch in Fig. A3 the comparisons of the angular distribution patterns of the 3-D WIMP flux and (average) kinetic energy observed in the horizontal coordinate system of all pairs of laboratory groups discussed in Ref. [17] and extended here:

- The (light–)red double–arrows indicate that the similar distribution patterns observed at the pair of laboratories appear in two observation periods (daily–shifts) with a half–year (12-hour) time difference;

- The (light-)blue arrows indicate that the similar distribution patterns observed at the pair of laboratories appear in two observation periods (daily-shifts) with a 3-month (6-hour) time difference, where the arrow directions indicate the directions of the time flow (from the laboratory in the previous period (shift) to the laboratory in the next period (shift));
- The (light-)green bars indicate that the similar distribution patterns observed at the pair of laboratories appear in the same observation periods (daily-shifts);
- The light-red double-arrows, the light-blue arrows, and the light-green bars indicate that there is a $+180^\circ$ -rotation between the similar distribution patterns observed at the pair of laboratories.

A summary of these comparisons of the angular distribution patterns is also given in Table A2.

B.1 Agua Negra Deep Experiment Site (ANDES)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
ANDES (30.19°S, 69.82°W)	Cf. 8 half-year difference +180°-rotation	Cf. 10 3-month later +180°-rotation	Cf. 1 Alike +180°-rotation	Alike	Cf. 6 half-year difference

Table A3: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the ANDES laboratory (30.19°S, 69.82°W) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A4: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the ANDES laboratory (30.19°S , 69.82°W). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A5: As in Figs. A4, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A6: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the ANDES laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A7: As in Figs. A6, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A8: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the ANDES laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A4.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A9: As in Figs. A8, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A5.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A10: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the ANDES laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A6.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A11: As in Figs. A10, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A7.

B.2 Boulby Laboratory

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
Boulby (54.55°N, 0.82°W)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier +180°-rotation	Cf. 9 3-month later +180°-rotation

Table A4: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the Boulby laboratory (54.55°N, 0.82°W) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A12: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the Boulby laboratory (54.55°N , 0.82°W). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A13: As in Figs. A12, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A14: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the Boulby laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A15: As in Figs. A14, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A16: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the Boulby laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A12.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A17: As in Figs. A16, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A13.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A18: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the Boulby laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A14.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A19: As in Figs. A18, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A15.

B.3 Callio Laboratory

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
Callio (63.66°N, 26.04°E)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier +180°-rotation	Cf. 9 3-month later +180°-rotation

Table A5: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the Callio laboratory (63.66°N, 26.04°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A20: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the Callio laboratory (63.66°N , 26.04°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A21: As in Figs. A20, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A22: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the Callio laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A23: As in Figs. A22, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A24: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the Callio laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A20.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A25: As in Figs. A24, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A21.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A26: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the Callo laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A22.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A27: As in Figs. A26, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A23.

B.4 China Jinping Underground Laboratory (CJPL)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
CJPL (28.15°N, 101.71°E)	Cf. 5 half-year difference	Cf. 4 3-month later	Alike	Cf. 1 Alike +180°-rotation	Cf. 2 half-year difference +180°-rotation

Table A6: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the CJPL laboratory (28.15°N, 101.71°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A28: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the CJPL laboratory (28.15°N , 101.71°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A29: As in Figs. A28, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A30: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the CJPL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A31: As in Figs. A30, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A32: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the CJPL laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A28.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A33: As in Figs. A32, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A29.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A34: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the CJPL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A30.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A35: As in Figs. A34, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A31.

B.5 Deep Underground Science and Engineering Laboratory (DUSEL)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
DUSEL (44.35°N, 103.75°W)	Alike	Cf. 3 3-month earlier	Cf. 5 half-year difference	Cf. 8 half-year difference +180°-rotation	Cf. 7 Alike +180°-rotation

Table A7: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the DUSEL laboratory (44.35°N, 103.75°W) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A36: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the DUSEL laboratory (44.35°N , 103.75°W). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A37: As in Figs. A36, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 - 237.66 day, 22 - 2 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 2 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A38: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the DUSEL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated.

(a) 177.66 – 237.66 day, 22 – 24 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 24 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A39: As in Figs. A38, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A40: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the DUSEL laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A36.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A41: As in Figs. A40, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A37.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A42: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the DUSEL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A38.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A43: As in Figs. A42, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A39.

B.6 Kamioka Observatory

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
Kamioka (36.43°N, 137.31°E)	Cf. 5 half-year difference	Cf. 4 3-month later	Alike	Cf. 1 Alike +180°-rotation	Cf. 2 half-year difference +180°-rotation

Table A8: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the Kamioka laboratory (36.43°N, 137.31°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A44: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the Kamioka laboratory (36.43°N , 137.31°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A45: As in Figs. A44, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A46: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the Kamioka laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A47: As in Figs. A46, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A48: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the Kamioka laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A44.

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 0 - 365 day, 500 events, at Kamioka

(a) 0 - 365 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 19.49 - 79.49 day, 500 events, at Kamioka

(b) 19.49 - 79.49 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 110.74 - 170.74 day, 500 events, at Kamioka

(c) 110.74 - 170.74 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 201.99 - 261.99 day, 500 events, at Kamioka

(d) 201.99 - 261.99 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 293.24 - 353.24 day, 500 events, at Kamioka

(e) 293.24 - 353.24 day

Figure A49: As in Figs. A48, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b - e) have been simulated. All simulation setup are the same as in Figs. A45.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A50: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the Kamioka laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A46.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A51: As in Figs. A50, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A47.

B.7 Laboratori Nazionali del Gran Sasso (LNGS)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
LNGS (42.45°N, 13.58°E)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier +180°-rotation	Cf. 9 3-month later +180°-rotation

Table A9: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the LNGS laboratory (42.45°N, 13.58°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A52: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the LNGS laboratory (42.45°N , 13.58°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A53: As in Figs. A52, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A54: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the LNGS laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 – 237.66 day, 22 – 24 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 24 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A55: As in Figs. A54, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A56: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the LNGS laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A52.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A57: As in Figs. A56, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A53.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A58: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the LNGS laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A54.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A59: As in Figs. A58, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A55.

B.8 Laboratoire Souterrain Canfranc (LSC)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
LSC (42.81°N, 0.56°W)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier <small>+180°-rotation</small>	Cf. 9 3-month later <small>+180°-rotation</small>

Table A10: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the LSC laboratory (42.81°N, 0.56°W) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A60: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the LSC laboratory (42.81°N , 0.56°W). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A61: As in Figs. A60, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A62: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the LSC laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A63: As in Figs. A62, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A64: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the LSC laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A60.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A65: As in Figs. A64, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A61.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A66: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the LSC laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A62.

(a) 177.66 - 237.66 day, 22 - 2 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 2 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A67: As in Figs. A66, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A63.

B.9 Laboratoire Souterrain de Modane (LSM)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
LSM (45.14°N, 6.70°E)	Cf. 3 3-month later	Alike	Cf. 4 3-month earlier	Cf. 10 3-month earlier <small>+180°-rotation</small>	Cf. 9 3-month later <small>+180°-rotation</small>

Table A11: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the LSM laboratory (45.14°N, 6.70°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A68: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the LSM laboratory (45.14°N , 6.70°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A69: As in Figs. A68, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A70: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the LSM laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A71: As in Figs. A70, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A72: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the LSM laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A68.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A73: As in Figs. A72, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A69.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A74: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the LSM laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A70.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A75: As in Figs. A74, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A71.

B.10 Sudbury Neutrino Observatory (SNOLAB)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
SNOLAB (46.47°N, 81.19°W)	Alike	Cf. 3 3-month earlier	Cf. 5 half-year difference	Cf. 8 half-year difference +180°-rotation	Cf. 7 Alike +180°-rotation

Table A12: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the SNOLAB laboratory (46.47°N, 81.19°W) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A76: The angular distributions of the 3-D WIMP kinetic energy in the horizontal coordinate system of the SNOLAB laboratory (46.47°N, 81.19°W). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A77: As in Figs. A76, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A78: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the SNOLAB laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 2 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 2 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A79: As in Figs. A78, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A80: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the SNOLAB laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A76.

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 0 - 365 day, 500 events, at SNOLAB

(a) 0 – 365 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 19.49 - 79.49 day, 500 events, at SNOLAB

(b) 19.49 – 79.49 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 110.74 - 170.74 day, 500 events, at SNOLAB

(c) 110.74 – 170.74 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 201.99 - 261.99 day, 500 events, at SNOLAB

(d) 201.99 – 261.99 day

Angular distribution of the kinetic energy per WIMP in the horizontal frame, 293.24 - 353.24 day, 500 events, at SNOLAB

(e) 293.24 – 353.24 day

Figure A81: As in Figs. A80, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A77.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A82: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the SNOLAB laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 – 237.66 day (a – d) and 360.16 – 420.16 (= 55.16) day (e – h) have been simulated. All simulation setup are the same as in Fig. A78.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A83: As in Figs. A82, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A79.

B.11 Stawell Underground Physics Laboratory (SUPL)

Laboratory	Compared laboratory groups				
	NAm	Eu	EAs	SAm	SPa
SUPL (37.07°S, 142.81°E)	Cf. 7 Alike <small>+180°-rotation</small>	Cf. 9 3-month earlier <small>+180°-rotation</small>	Cf. 2 half-year difference <small>+180°-rotation</small>	Cf. 6 half-year difference	Alike

Table A13: The comparisons of the angular distribution patterns of the 3-D WIMP (flux and) (average) kinetic energy observed in the horizontal coordinate system of the SUPL laboratory (37.07°S, 142.81°E) with those observed at the other laboratory groups. All notations in the above sketch are the same as in Fig. A3.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A84: The angular distributions of the 3-D WIMP kinetic energy in the horizontal co-ordinate system of the SUPL laboratory (37.07°S , 142.81°E). 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A85: As in Figs. A84, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A86: The angular distributions of the 3-D WIMP kinetic energy in the laboratory coordinate system of the SUPL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated.

(a) 177.66 - 237.66 day, 22 - 2 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 2 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A87: As in Figs. A86, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A88: The angular distributions of the average WIMP kinetic energy in the horizontal coordinate system of the SUPL laboratory. 50 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A84.

(a) 0 – 365 day

(b) 19.49 – 79.49 day

(c) 110.74 – 170.74 day

(d) 201.99 – 261.99 day

(e) 293.24 – 353.24 day

Figure A89: As in Figs. A88, except that 500 total events on average in one entire year (a) and in each 60-day observation period of four advanced seasons (b – e) have been simulated. All simulation setup are the same as in Figs. A85.

(a) 177.66 - 237.66 day, 22 - 24 hour

(b) 177.66 - 237.66 day, 4 - 8 hour

(c) 177.66 - 237.66 day, 10 - 14 hour

(d) 177.66 - 237.66 day, 16 - 20 hour

(e) 360.16 - 420.16 day, 22 - 24 hour

(f) 360.16 - 420.16 day, 4 - 8 hour

(g) 360.16 - 420.16 day, 10 - 14 hour

(h) 360.16 - 420.16 day, 16 - 20 hour

Figure A90: The angular distributions of the average WIMP kinetic energy in the laboratory coordinate system of the SUPL laboratory. 50 total events on average in each 4-hour daily shift in the 60-day observation periods of 177.66 - 237.66 day (a - d) and 360.16 - 420.16 (= 55.16) day (e - h) have been simulated. All simulation setup are the same as in Fig. A86.

(a) 177.66 – 237.66 day, 22 – 2 hour

(b) 177.66 – 237.66 day, 4 – 8 hour

(c) 177.66 – 237.66 day, 10 – 14 hour

(d) 177.66 – 237.66 day, 16 – 20 hour

(e) 360.16 – 420.16 day, 22 – 2 hour

(f) 360.16 – 420.16 day, 4 – 8 hour

(g) 360.16 – 420.16 day, 10 – 14 hour

(h) 360.16 – 420.16 day, 16 – 20 hour

Figure A91: As in Figs. A90, except that 500 total events on average in each 4-hour daily shift in the 60-day observation periods have been simulated. All simulation setup are the same as in Fig. A87.

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