Annual and diurnal modulations of the angular distribution of the 3-D WIMP velocity observed at an underground laboratory

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Abstract. In this article, I present our (Monte Carlo) simulation results of the angular distribution of the 3-dimensional WIMP velocity, in particular, a possible “annual” modulation and the diurnal modulation proposed in literature, for different underground laboratories.

1. Introduction
Directional direct Dark Matter detection experiments aim to identify the diurnal modulation of nuclear scattering signals induced by halo Weakly Interacting Massive Particles (WIMPs) coming (mainly) from the CYGNUS constellation. There are two kinds of diurnal modulation:

- Directionality: the diurnal modulation of the (main) incident direction of WIMP events; for a laboratory located in the Northern Hemisphere in Summer, the most WIMP events should come from the zenith around the midnight and from the north around the noon.
- Flux shielding: the diurnal modulation of the number (scattering rate) of WIMP events; for a laboratory located in the Southern Hemisphere in Winter, the WIMP flux could be reduced in the day.

1.1. Event generation in the Galactic coordinate system
For generating 3-D WIMP velocities in the Galactic coordinate system, we consider the simplest model of an isothermal, spherical and isotropic Dark Matter halo.

- The radial velocity distribution is the simple Maxwellian velocity distribution:

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

for \( v \leq v_{\text{esc}} \), and \( f_{1,Gau}(v > v_{\text{esc}}) = 0 \).
2. Angular distribution of the 3-D WIMP velocity

In this section, I present the angular distribution patterns of the 3-dimensional WIMP velocity transformed to the laboratory–independent Equatorial coordinate system as well as the laboratory–dependent horizontal and laboratory coordinate systems (see Ref. [1] for their definitions). 500 total events on average in one experiment in each (4-hour daily shift of each) 60-day observation period have been generated and 5,000 experiments (for one laboratory) have been simulated (See Ref. [1] for details).

2.1. Annual modulation in the Equatorial coordinate system

Considering the very low event rate of one direct Dark Matter detector, especially a direction–sensitive TPC detector, we can, as the first step for identifying the directionality of incident WIMPs, combine WIMP events observed at different laboratories in the laboratory–independent Equatorial coordinate system:

Here the dark–green star (in all four plots) indicates the theoretical direction of the WIMP wind in the Equatorial coordinate system: 42.00°S, 50.70°W, while the blue–yellow point (in each plot) indicates the opposite direction of the Earth’s relative velocity to the Dark Matter halo on the central date of each observation period (see Ref. [1] for the detailed calculations).

It can be found that, firstly, the average event numbers from the center to the southwest part could be at least 11.4 times or even 16 times larger than the most part of the sky ($\gtrsim 13.9$ (19.4) events/bin against $\lesssim 1.2$ events/bin among 500 total events). This would hence be a clear identification of the anisotropy of the main direction of incident WIMPs. Secondly, the distribution patterns in four plots variate slightly and this variation follows indeed the circular clockwise movement of the blue–yellow point. This would be, besides the pure “directionality” of the WIMP wind, a second (important) characteristic for identifying directional WIMP signals and discriminating from any (unexpected) backgrounds from some specified incoming directions.

2.2. Annual modulation in the horizontal coordinate system

Once more and more WIMP events can be recorded in different laboratories, we can consider to demonstrate the angular distribution patterns of the 3-D WIMP velocity observed in the horizontal coordinate system of the laboratory of interest. Below are the angular WIMP velocity distribution observed in the horizontal coordinate systems of the Kamioka (36.43°N, 137.31°E) and the SUPL (37.07°S, 142.81°E) laboratories, respectively.
While SUPL is so far the unique functionable underground laboratory in the Southern Hemisphere, the Kamioka laboratory is located at the almost–symmetric point with respect to the Equatorial plane. 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 $\mathbf{X}_H$–axis (pointing towards north) and the difference between two frames is a $180^\circ$–rotation around the common $\mathbf{X}_H$–axis. Therefore, their angular distribution patterns show a 6-month difference with a $180^\circ$–rotated symmetry around the center.

2.3. Diurnal modulation in the laboratory coordinate system

Finally, I present the diurnal modulation of the angular WIMP velocity distributions observed in the laboratory coordinate system of the Kamioka laboratory around 25.16 day and 207.66 day, respectively. From left to right, the simulated 4-hour event–measuring time are around midnight, morning, noon, and evening, respectively.

It can be found firstly that, by comparing these two sets of plots in two observation periods with a half–year time difference with each other, the angular distribution patterns show indeed a 12-hour shift. Moreover, the variations of the diurnal modulation of the angular distribution patterns in both periods look similar to the annual modulation shown before.

3. Conclusions

In this article, I have demonstrated (the annual and diurnal modulations of) the directionality of the angular distribution of the Monte Carlo–generated 3-D WIMP velocity. For the first step with only a few observed WIMP events, one can combine events observed at different laboratories in the location–independent Equatorial coordinate system to identify the (variation of the) directionality of the WIMP wind. Once more and more WIMP events can be recorded in different laboratories, we can then compare the angular WIMP velocity distribution patterns in the horizontal coordinate systems of different laboratories.

References

[1] Shan C-L 2019 Simulations of the 3-Dimensional Velocity Distribution of Halo Weakly Interacting Massive Particles for Directional Dark Matter Detection Experiments (Preprint 1905.11279)