PROCEEDINGS OF SCIENCE

Earth-Scattering Induced Modulation in Low-Threshold Dark Matter Experiments

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In recent years, the threshold of Dark Matter search experiments has been lowered, enabling the search for Dark Matter-electron scattering. In the region of interest for mass and cross-section that current experiments can reach, the propagation of particles from the Dark Matter wind through the Earth can produce a (sideral) daily modulation in the observed signal. We explore the modulation signal expected in different materials and show how a significant improvement in the current sensitivity can be obtained in the lower mass region by searching for that daily modulation. Depending on the mediator, mass, and cross-section of interest, we study the dependence of the sensitivity on the latitude of the experiment.

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1. Introduction

In order to properly describe numerous astrophysical observations, the addition to a non barionic supplementary form of matter seems hard to avoid. The Dark Matter could appear under many forms. One currently researched well-motivated candidate is a MeV scale dark matter particle that would interact with standard model particles through a mediator [1]. At these low energies, the constraints to the dark matter cross-section are limited, and, in the region of interest being explored by current experiments, the cross-section is high enough for the Earth not to be transparent to those particles. As such, given the apparent dark matter wind produced by the movement of the solar system in our galaxy, the propagation of a fraction of the dark matter flux reaching a detector will suffer scattering and energy loss as it goes through the Earth.

In this document, we will study the propagation of the dark matter flux through the Earth using a modified version of DaMaSCUS (Sec. 2), determining for the ultralight and heavy mediator case the observed dark matter velocities as a function of the isodetection angle, the angle between the position of a detector on Earth and the incoming dark matter wind. We will then convert these velocity distributions into expected event rates on Silicon, Xenon or Argon targets (Sec. 3). We will show that the rate variation with isodetection angle can be modelled by an almost universal sigmoid functional shape and discuss some of its properties. We will then derive how this rate modulation can be used in specific currently running experiments using Silicon, Xenon and Argon (Sec. 4). We will finally conclude on the use and prospects for this method in the near future.

2. Dark Matter propagation in Earth

We modified the DaMaSCUS code to properly take into account MeV particles propagation in the Earth, including screening effects. The new code can be found in [2]. The code still outputs the velocity distribution of dark matter particles after propagating through the earth, as a function of the isodetection angle, angle between the position of the detector on the Earth and the incoming dark matter wind. An isodetection angle of 0 degrees correspond to a detector receiving the dark matter wind directly from above, an angle of 90 degrees means the wind is coming from the horizon, while an angle of 180 degrees means the wind has to go through the Earth diameter to reach the detector. It is important to note that given the direction of movement of the solar system in the galaxy (roughly towards the constellation of Cygnus), a detector located around 40 degrees of latitude north (where most underground laboratories and dark matter experiments are, in SNOLAB, Gran Sasso, Modane...) will observe the dark matter wind during a (sideral) day from an isodetection angle minimum close to 0 to a maximum close to 90 degrees, while a detector in the southern hemisphere (in SUPL for example) will observe the wind from isoangles roughly 90 degrees to 180 degrees. Examples of dark matter velocities are shown in Fig.1 for both heavy and ultralight mediator, at different cross-sections, where the Earth effect is strong or where it starts fading. Simulations were run over a wide range of cross-section at energies of 0.6, 1, 1.45, 2.6, 5, 10, 100 and 1000 MeV. The fine range of energies simulated at close to 1 MeV correspond to the region of interest for Silicon detectors, where the initial focus of our study was put. We then expanded the simulated range to higher masses to explore the prospects for Xenon or Argon detectors.

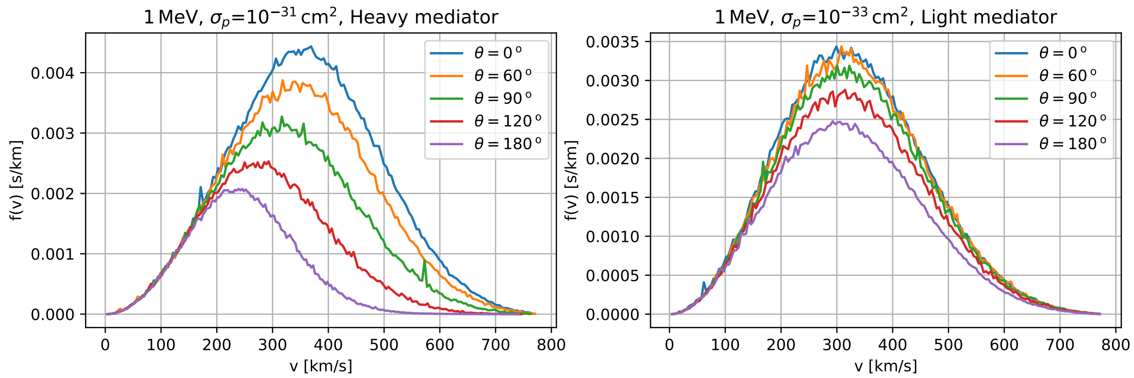

Figure 1: Velocity distribution for a 1 MeV, $\sigma_p = 10^{-31}$ cm^2 heavy mediator (left) and a 1 MeV, $\sigma_p = 10^{-33}$ cm^2 light mediator (right) dark matter candidate for different isodetection angles θ, from 0° to 180°. In the latter case, the Earth is becoming transparent and only a mild isodetection angle dependence can be observed.

3. Signal modulation in Silicon, Xenon and Argon

Once the velocity distributions have been simulated, we computed the signal expected for Silicon, Xenon and Argon targets. For both mediators, all 3 targets, and over the full range simulated, the rate evolution with isodetection angle is very well described by a sigmoid. We adjust each simulation with the following function:

$$r(\theta) = \bar{r} - \frac{A}{2} \tanh\left(\frac{\theta - \theta_0}{\lambda}\right)$$

where $\bar{r}$ is the average rate of event, A is the modulation amplitude (in rate of event), λ describes the slope of the rate modulation, and θ_0 is the position of the inflexion point of the curve. A will be the obvious important parameter, determining when the Earth becomes transparent and the rate change becomes too small to be observable for experiments. Another interesting parameter is θ_0. At high cross-sections, when the Earth is strongly opaque, θ_0 will be lower than 90 degrees by a few tens of degrees, meaning on a significant portion of the Earth (the southern part) the flux will be strongly attenuated, even when coming from the horizon. In these conditions, an experiment in the northern hemisphere will observe a larger event rate modulation than one in the southern hemisphere (note than in fraction of change, the detector in the southern hemisphere will suffer a close to 100% modulation, but in absolute terms, which is the relevant parameter from the detector signal point of view, the modulation will be smaller than in the north).

Once we determined the values of the 4 adjusted parameters, $\bar{r}$, A, θ_0 and λ, for each mediator, energy, cross-section and target, we can then interpolate the parameters to get the expected event rate variation with isodetection angle for any configuration. The evolution of these parameters is important to understand the final discrimination power of an experiment using the modulation to search for a dark matter signal. Examples of event rates obtained at different signal bins can be seen in Fig.2, together with some discussion of the fitted parameters evolution.

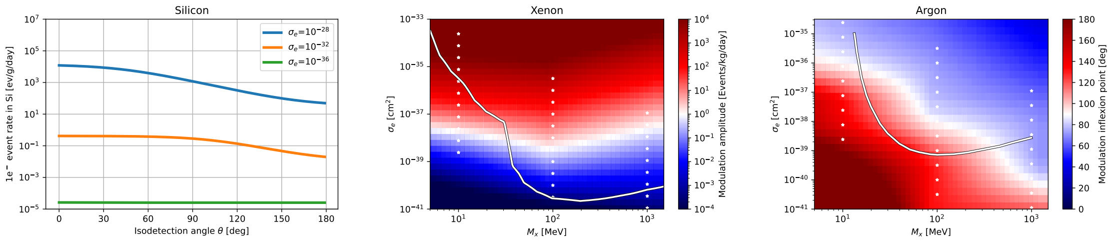

Figure 2: Left: 1 e$^-$ event rate in silicon for a 1 MeV dark matter particle interacting via a heavy mediator at different cross-sections. As the cross-section lowers, the total event rate is reduced, but in addition the modulation changes: as the Earth becomes transparent, the modulation amplitude is reduced, and the inflexion point moves towards the south (higher θ values). Center: evolution of the modulation amplitude for a Xenon target. The stars are the simulated data points and the lines corresponds to the current world leading limits for Xenon experiments [3, 4]. Right: evolution of the inflexion point for an Argon target, together with the DarkSide50 current exclusion limits [5]. In most of the unexplored space of parameters, the inflexion point is above 90°, meaning an experiment in the southern hemisphere would reach a better sensitivity.

4. Application to existing Dark Matter search experiments

In the case of Silicon, we had already used a preliminary version of these simulations in 2021 to get the first modulation based MeV-scale limits by checking the non observation of a 1 e$^-$ rate modulation in a skipper CCD with the DM^2 experiment [6]. Here we repeat this method, also recently applied by the DAMIC-M experiment (although with a different earth propagation code) [7]. We determine the expected limit obtained with a 100 g.day experiment (current skipper CCD experiments) and a 30 kg.year experiment (future expected experiments), considering both a detector at 40 degrees of latitude north (SNOLAB, Modane) or south (Bariloche, where we operated DM^2), and a background rate at 1 e$^-$ of 450 events per gram per day, the current state of the art noise level. The modulated limits are significantly better than the direct limits in the lower energy mass range. Moving to the southern hemisphere also translates in a significant improvement of the limits. The DAMIC-M modulation limits are close to the 100 g.day limit (the background rate in DAMIC-M is slightly higher than the one taken here, explaining the slightly worse limit). All these limits can be seen in Fig.3.

For the Xenon and Argon case, we just indicate here the expected event modulation at the current best limits reached by these experiments in Fig.4. In order to assess the true potential of the method, a proper knowledge of the stability of the event rate over sidereal days, and over the data taking period, are necessary and out of the scope of this study. We nonetheless note that in both cases the expected daily modulation is still strong at the limits published, and we expect therefore that significantly improved exclusion limits could be placed in case no modulations are found in the Xenon and Argon experimental data.

5. Perspectives

We have shown that for light dark matter dark sector models the propagation of the dark matter wind through the Earth induces a daily modulation that provides a tool to potentially improve exclusion limits, especially close to threshold, for any detector currently in operation. It already

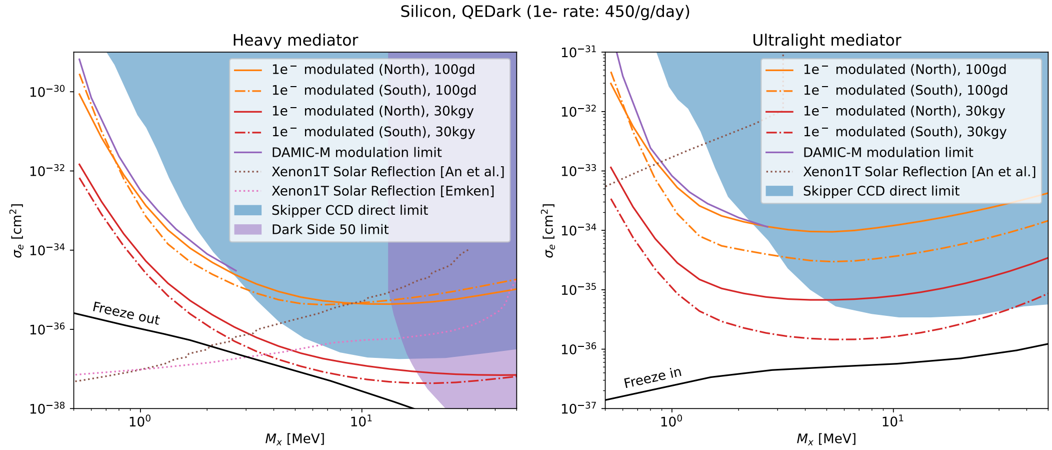

Figure 3: Exclusion limits assuming no modulation is observed in a silicon skipper CCD experiment. See text for details.

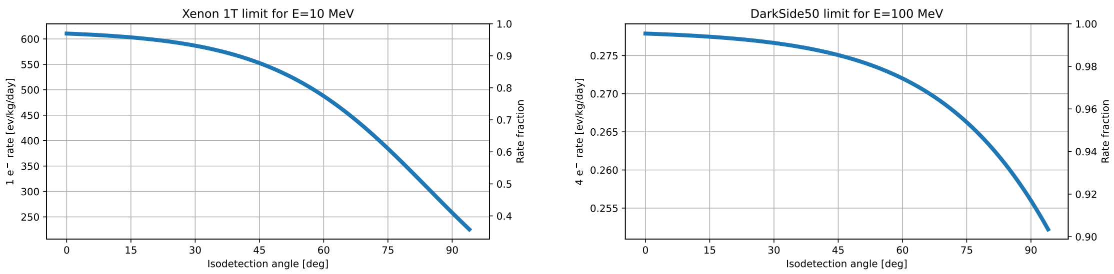

Figure 4: Expected event rate variation with isodetection angle for the heavy mediator case, taking the current limit for Xenon1T at 10 MeV and DarkSide50 at 100 MeV for the lowest energy bin considered in the respective publications.

provides the best limit for the ultralight mediator case in the 1 – 2.5 MeV energy range [7]. While the current parameter space would provide a larger modulation in the southern hemisphere, significant modulations are still expected for northern hemisphere detectors. Finally, should a dark matter signal be observed in the parameter space discussed in this work, the sidereal daily modulation would provide a smoking gun signal to discriminate dark matter from eventual unexpected background.

References

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[7] DAMIC-M collaboration, *Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M*, arXiv:2307.07251 [hep-ex]