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Recent progress in the search for light Dark Matter particles in South America: DM^2 and CONNIE

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The recent development of highly sensitive solid-state detectors such as Skipper CCDs has achieved single-electron event resolution, allowing the search for rare interactions with an energy threshold as low as 1.2 eV. In addition, models of dark matter (DM) with masses of a few (1–5) MeV interacting with electrons predict a diurnal modulation of single-electron events in such detectors. This modulation would be enhanced in the southern hemisphere because the DM wind comes from 40 degrees north. The DM^2 experiment aims to probe this region of the parameter space in Bariloche, southern Argentina, and has been recently upgraded with a 3 g prototype Skipper CCD. The CONNIE experiment uses two Skipper CCDs to search for CEvNS with nuclear reactor neutrinos, but it can also probe dark matter models in the aforementioned region of the parameter space. In this paper, a short description of the expected diurnal modulation of DM is given. Current status, data, results and future perspectives for DM searches in both experiments are discussed.

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1. Introduction

In recent years, the lack of signal in dark matter (DM) direct detection experiments that search for particles of masses O(GeV) interacting via nuclear recoil has motivated a paradigm shift. New searches target lighter particles with masses in the MeV range interacting with electrons. In particular, the SENSEI [1] and DAMIC-M [2] experiments have set the most stringent limits for such candidates between $[0.5 - 1000]$ MeV by using the Skipper CCD technology.

Skipper CCDs are Charge-Coupled Devices with an improved readout stage that allows to take multiple samples of the charge stored in each pixel, therefore reducing the readout noise by a factor of (number of samples)$^{1/2}$. Thus, the minimum signal that can be collected is that required to produce an electron-hole pair in silicon, 1.2 eV. A DM particle in the region of interest interacting with an electron in the silicon bulk will leave a signature of a few $(1-4)$ electrons of charge [3]. The drawback is that to achieve such extreme sensitivity, it is necessary to take several hundred samples per pixel, which ultimately leads to a large increase in the readout time. A common strategy to mitigate this is to do a $N \times M$ hardware binning, *i.e.*, to sum the charge of N pixels in the horizontal direction and M pixels in the vertical direction, and read only this sum.

Although many Latin American scientists are involved in the development, commissioning, and operation of Skipper CCDs, the world-leading experiments are located in North America and Europe. In this work, we present two experiments located in South America that search for low energy interactions: DM^2, in Bariloche, Argentina and CONNIE, in Angra dos Reis, Brazil. Both experiments are located at the surface, which means that there is a high cosmic background. However, a DM signal could be detected above this background if we look for a diurnal modulation of events.

2. Diurnal modulation of Dark Matter

The Earth has a peculiar velocity with respect to the rest frame of the DM halo, and from the Earth frame this means that there is a preferred direction in the DM velocity distribution – the DM wind. Standing at the Earth's surface, we see this wind coming on average from 40° N. Due to the Earth's rotation, this direction varies throughout the day. The angle between the DM wind direction and the normal to the surface is called "isodetection angle", or isoangle. An isoangle of 0° means that the DM wind is coming directly from above, 90° means it is coming from the horizon, and 180° means it is coming from below. Fig. 1a shows the extremes of the range of isoangles that are scanned at Bariloche, close to 90° at one point during the day and close to 180° twelve hours later. A detector located in the northern hemisphere will scan lower isoangles, while a detector located in the southern hemisphere will scan higher isoangles, as shown in Fig. 1b.

In turn, a high isoangle means that the DM particles have to cross part or all of the Earth's crust to reach the detector. For a DM particle with mass and cross section in the region of interest, this means that it has a chance to interact with nuclei or electrons in the Earth's crust and thus lose energy or scatter away. This phenomenon creates a diurnal modulation in the flux of particles reaching the detector, which ultimately translates into a modulation of events. This modulation can be used to search for a signal above an irreducible background, such as the low-energy background seen in Skipper CCDs.

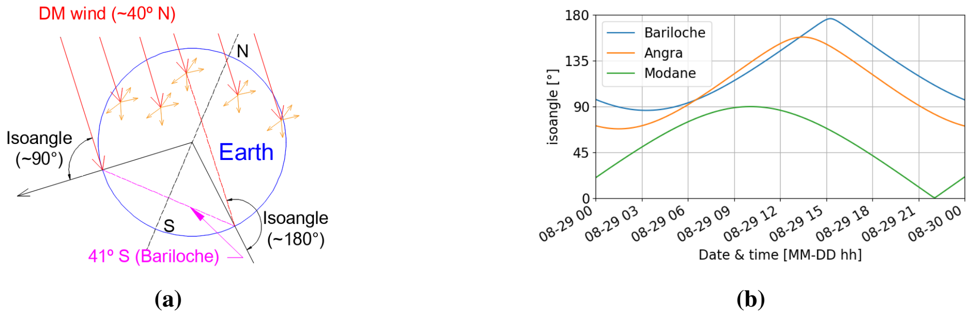

Figure 1: (a) Schematic of the DM wind and isoangle in Bariloche at two different times of the day. (b) Daily variation of isoangles at the sites of different experiments: Bariloche (DM^2), Angra (CONNIE) and Modane (DAMIC-M).

3. DM^2 and CONNIE

The Dark Matter Daily Modulation experiment (DM^2) is a direct detection experiment located in the city of Bariloche in southern Argentina. A 6150×1536 pixel, 675 μm thick Skipper CCD is mounted inside a steel vacuum chamber and cooled down to $\sim$ 105 K using a cold finger and liquid nitrogen. There is no additional shielding. The Skipper CCD is controlled by a Low Threshold Acquisition (LTA) board [4], which exchanges data with a Raspberry Pi computer. The experiment was first operated in 2020 with a 0.1 g prototype detector, demonstrating the feasibility of a diurnal modulation search with surface-level detector [5]. The detector was replaced by a 3 g prototype provided by the DAMIC-M collaboration in early 2023, and after several commissioning runs, a 6.69 g.day science run was used to produce the results presented below.

The COherent Neutrino-Nucleus Interaction Experiment (CONNIE) searches for CEvNS interactions of nuclear reactor neutrinos with Skipper CCDs. It is located at the Angra-II nuclear power plant in Angra dos Reis, Brazil. There are two 682×1222 pixel, 675 μm thick Skipper CCDs mounted in a copper box surrounded by a lead and polyethylene shield 30 m away from the reactor core (for more details see [6]). The shield blocks both radiation coming from the reactor and cosmic rays, making it possible to search for possible incoming DM particles. A 0.9 g.day science run was selected to apply the diurnal modulation analysis and obtain the rejection limits presented below.

4. Data analysis and results

Due to the different detector sizes and backgrounds, there were different approaches to data acquisition in each experiment. In DM^2, each pixel was read 650 times, but since the goal was to reduce the exposure time as much as possible, a 10×10 hardware binning was used. A defect in the active region of the CCD injected a large number of single-electron events in one half of the detector, so only half of the detection mass was used for this study. Each image was acquired in continuous readout mode and sequentially, so the exposure time of each image is the same as the readout time, 25 minutes and 45 seconds. On the other hand, the CONNIE images have no hardware binning and 400 samples per pixel. The readout was also continuous, but a cleaning procedure was performed between sucessive images, so that the total exposure time was half of the readout time,

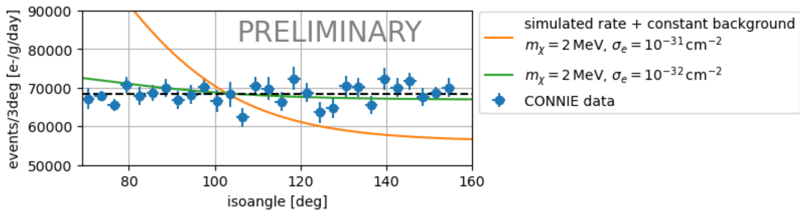

Figure 2: CONNIE single-electron events versus isoangle (blue dots). In orange and green are the expected rates for a 2 MeV DM candidate with two different cross sections.

about 1 hour. One of the detectors proved to have a higher single-electron rate than the other, so only the images coming from the cleaner CCD were used for the analysis.

Masks were applied to the images to eliminate single-electron pixels spatially correlated to cosmically induced events. In the case of DM^2, a high-energy mask was applied to all pixels with more than 100 electrons of charge ($\sim$ 370 eV) and two adjacent pixels in both the vertical and horizontal directions. This reduces the total event rate by $\sim$ 10%. The number of pixels with zero, one and two electrons was then counted and used to calculate the final event rate. Since 100 pixels were summed, the probability of two single-electron events accumulating was not negligible, and the pixels with two electrons are counted as two separate single-electron events. In CONNIE, the high-energy mask applies to all pixels with at least 4 electrons of charge and extends to 10 neighboring pixels in the two dimensions. An additional Serial Register Event (SRE) mask was applied to discard events generated near the serial register of the CCD that produce a long tail of single-electron pixels. Only the pixels with zero and one electrons were counted to calculate the single-electron rate.

An isoangle was assigned to each image by looking at the date and time when the image was taken and following the steps described in [7] to calculate the Earth's velocity in the galactic frame. Then the galactic coordinates were entered into the Python package `astropy` [8] to get the altitude h at which the wind arrives, and the isoangle was set to $90° - h$. Finally, an average rate was calculated for each isoangle bin, and the data were compared with simulations of Dark Matter propagating through the Earth. An example of this procedure is shown in Fig. 2. A 90% C.L. upper bound for the DM mass and DM-e$^-$ interaction cross section was obtained assuming both heavy and ultra-light mediators, yielding the results shown in Fig. 3. The results are preliminary, since a finer tuning of the simulations is needed for these specific masses and cross sections, but it can be seen that there is an improvement of two orders of magnitude in σ_e compared to the previous DM^2 limits (thin green line) and of four orders of magnitude compared to protoSENSEI (orange line). This even improves the limits obtained by the DAMIC-M "direct" search (dashed red line), although recent results searching for the same diurnal modulation [9] have given stronger limits that are an order of magnitude lower than ours (solid red line).

5. Future perspectives

The limits set with CONNIE offer promising perspectives for the DM diurnal modulation search in the near future. The single-electron rate is low thanks to the shielding, and it is stable

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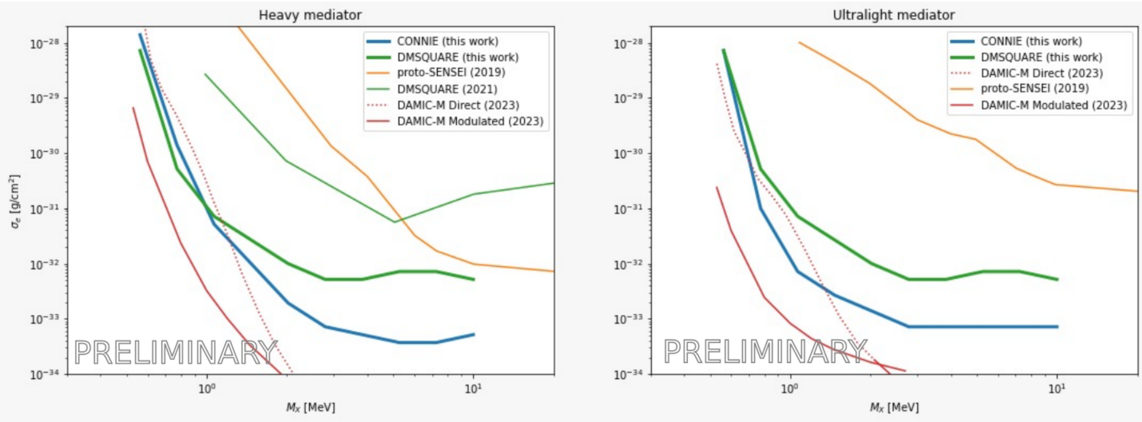

Figure 3: Preliminary 90% CL upper bounds on DM-electron interactions through a heavy (left) and ultra-light (right) dark photon mediator for DM^2 (green, thick line) and CONNIE (blue line), compared to similar experiments.

enough to perform longer searches, scanning the same isoangles in different seasons. This will allow other diurnal modulation effects, especially solar modulation, to be ruled out with sufficient statistical power. Further studies are underway to include the noisier CCD and other science runs in the data analysis. There are also plans to install a MultiChip Module (MCM) designed for the Oscura experiment [10], which will increase the detection mass. Efforts in DM^2 will be made to obtain more stable data. An upgrade of the electronics is underway to reduce the spurious charge produced by the CCD clocking. We expect to improve the limits obtained by both CONNIE and DM^2 in the near future, and to apply similar analyses to upcoming experiments.

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