

# Effects of Diurnal Modulation in Direct Cold Dark Matter Searches. The Experiment in Sierra Grande

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## Abstract

Description and some details about the experiment to be conducted at Sierra Grande, Argentina are presented. The potential advantages of using the Earth as an absorber to produce diurnal modulation effects in cold dark matter searches are given.

## I. INTRODUCTION

By now there is compelling evidence that most of the mass in the Universe is dark [1]. The hardest evidence comes from:

1. the flat rotation curves at galaxy scales (measured in spiral galaxies) [2],
2. the anomalous line-of-sight velocities, greater than the escape velocity, at the level of clusters of galaxies, [3]
3. the formation of structures in the early universe and the growth of perturbations [4],  
and

4. gravitational lensing (Einstein rings) of very distant systems. [5]

From the measurements of mass to light ratios at different length scales a few conclusions are drawn:

1. The density of luminous matter,  $\rho_{lum}$ , is of the order of 1% of the critical density; *i.e.*  $\Omega_{lum} \equiv \rho_{lum}/\rho_c \approx 0.01$  ( $\rho_c \approx 2.6h_{50}^2 \text{ keV cm}^{-3}$ ),
2. up to the largest scales measured, namely that of clusters of galaxies, the dark matter density (non-emitters from the x-ray end of the electromagnetic spectrum down to radio waves) is between 20 to 40 times larger than the luminous matter,  $20\Omega_{lum} \lesssim \Omega_{DM} = \rho_{DM}/\rho_c \lesssim 40\Omega_{lum}$
3. at galactic scales the density of matter in units of the critical density is such that  $\Omega_G = \rho_G/\rho_c \lesssim 0.18$ , and
4. for scales up to a few Mpc the density of matter (luminous + dark) is of the order of 40% of  $\rho_c$  ( $\Omega_{DM+Lum} \approx 0.4$ ).

Further evidence to bear in mind comes from big bang nucleosynthesis (BBN) which successfully accounts for the abundances of the primordially synthesized light nuclei [6]. BBN places an upper limit for the present baryon abundance in the Universe at  $\Omega_B \lesssim 0.16$ . This bound and that of point 1. above indicate that most of the baryons in the Universe could well be dark. Furthermore the BBN bound together with point 3. suggest that at galactic scales most of the dark matter might be baryonic.

Baryonic candidates are not in shortage and they are extensively analyzed in Ref. [4]. Experiments aimed at looking at these massive compact halo objects (MACHO's) are currently under way [7]. Concurrently, the search for non-baryonic dark matter, either directly or indirectly, has already produced some results. Thus, in Fig. 1, we show the exclusion plot (at 95% C.L.) in the cross-section versus mass-of-the-candidate plane, obtained with two semiconductor detectors of very low background, the COSME II detector at Canfranc (Spain) and the TWIN detectors at Homestake (USA). These detectors have already imposed stringent bounds on the type of DM particle one should be expecting. In the figure we also include the cross section for a heavy Dirac neutrino as a function of its mass. Neutrinos are the prototypical non-baryonic candidates but the list of candidates is not exhausted by them and includes others, so far, unobserved objects such as: axions [8], the lightest supersymmetric partner (neutralino) [9] and particles obtained from grand unified theories with unbroken U(1) symmetries [10]. Semiconductor detectors generate a signal by collecting either the ionization, the photons or the phonons produced by the detector atoms recoiling after being struck by the particle. Because of this process they are best suited to detect candidates that scatter elastically and coherently from the components of the detector with

masses near the mass of the detector atoms, where the energy deposited by the candidate will be the largest. This type of candidates, with masses a few GeV and larger and with interactions weaker than strong and electromagnetic, go usually under the generic name of weakly interacting massive particles (WIMP's). A typical example is the aforementioned heavy Dirac neutrino which we use next to illustrate the expected interaction cross section. A Dirac neutrino with vector couplings to  $Z$  bosons and which scatters elastically from nuclei by  $Z$  exchange has a cross section given by

$$\frac{d\sigma}{dT} = \frac{G^2}{8\pi} \frac{M_R^2}{T_{max}} \left[ Z(1 - 4\sin^4\theta_W) - N \right]^2 \underbrace{\exp \left\{ -\frac{2M_N T R^2}{3\hbar^2} \right\}}_{\text{loss of coherence}} \quad (1.1)$$

with  $T_{max}$  the maximum recoil energy of the target nucleus of mass  $M_N$ ,  $M_R$  is the reduced mass,  $Z$  and  $N$  the number of protons and neutrons in the target nucleus, respectively, and  $\theta_W$  the weak mixing angle.  $G^2 = G_F^2 (G_f/G_w)^2$  is a generic coupling constant arbitrarily scaled and which for neutrinos satisfies  $G_f = G_w$ ;  $G_F$  is the Fermi coupling constant ( $G_F^2 \approx (290\text{GeV})^{-1} = 5.24 \times 10^{-38} \text{ cm}^{-2}$ ). For comparison we note that, for neutral technibaryons or strongly coupled  $U(1)'$   $(G_f/G_w)^2 \approx 10$ ; for sneutrinos  $(G_f/G_w)^2 \approx 2$ , and for neutralinos  $(G_f/G_w)^2 \approx 10^{-1} - 10^{-3}$ . The *loss of coherence* factor in (1.1) takes into account the depletion in the elastic cross section due to scattering processes where the momentum transfer is larger than the inverse radius of the target nucleus.

The detection rate, integrated in energy, is given by the product

$$\text{Rate} = \mathcal{N} \times \Phi \times \sigma \quad (1.2)$$

where  $\mathcal{N}$  is the number of target nuclei,  $\Phi$  is the dark matter flux ( $\Phi = n \langle v \rangle$  with  $n$  the number density of DM particles and  $\langle v \rangle$  their mean velocity) and  $\sigma$  is the integrated cross section. This cross section for a particular bin of deposited energy in the detector  $E_{dep}$  has to be convoluted with the velocity distribution of DM particles in the Earth. Thus, the rate of detected events per energy interval is expressed in the form

$$R_{E_{dep}} = \mathcal{N} N \times \underbrace{\frac{\rho_{halo}}{m_\delta}}_n \times \lim_{\Delta T \rightarrow 0} \left\{ \Delta T \int_{v_{min}(m_\delta, T)}^{v_{max}} f(v) v \frac{d\sigma(v, T)}{dT} dv \right\} \quad (1.3)$$

where the three unknown parameters to be determined are: the halo density  $\rho_{halo}$ , the DM particle mass  $m_\delta$ , and the strength  $G$  of the interaction cross section  $d\sigma/dT$  (see Eq.(1.1)). To this rate one has to apply a relative efficiency factor (REF) which is a function of  $E_{dep}$  and depends on the type of detector used.

Direct searches typically employ the signal-to-noise method in order to place bounds on potential candidates and their interactions. The basic idea is to calculate the ratio of observed to expected rates and to exclude, for a given candidate mass, all cross sections

larger than this ratio according to some chosen statistical criterion. This is shown in Fig. 2 where actual data from the COSME II detector are shown as a function of  $E_{dep}$ . Three curves are drawn corresponding to Dirac neutrinos of masses 10 GeV, 100 GeV and 2 TeV. The 100 GeV mass curve greatly exceeds the observed rate, whereas the other two could well be hidden in the background. Notice that the lightest candidate (dotted line) being lighter than the target nucleus can only deposit a limited amount of energy in head-on collisions (near the threshold of the detector). The heaviest candidate, on the other hand, deposits energy on a broader interval. Thus, for a given detector material, there is an optimum DM candidate which has the largest detection rate; it corresponds to that with a mass in the neighborhood of the detector mass. As described, the signal-to-noise method is limited by its definition since it can only set limits but cannot signal the existence of DM particles. *The sensitivity of any direct search would be greatly enhanced by a well understood modulation of the expected signal.*

Two types of modulation of the signal have been proposed so far: First, the *annual modulation* due to the relative velocity of the Earth with respect to the galactic halo. In this method one expects to observe differences in the rate of detection originating on the motion of the Earth around the Sun which, at some time of the year, adds to the orbital motion of the Sun about the center of the galaxy ( $\vec{V}_{Sun} \approx 250 \pm 25$  km/s plus a peculiar component of  $\approx 16.5$  km/s) and six months later subtracts from the same velocity ( $\vec{V}_{Earth} \approx 30$  km/s). The predicted modulation, of the order  $\approx 4-6\%$ , affects detection rates and energy spectra. Second, *diurnal modulation* due to the elastic scattering of the cold DM particles on the constituent nuclei of the Earth. In this method for some values of the masses and coupling constants of the CDM particles sizable effects in detection rates and energy spectra are anticipated so long as the detector is placed in a favorable geographical location. This last method, originally proposed by Collar and Avignone [13] in 1992, is the underlying idea behind the Sierra Grande experiment, that we describe next.

## II. DIURNAL MODULATION AND THE SIERRA GRANDE EXPERIMENT

Figure 3 depicts schematically the Earth crossed out by two axes; a polar axis  $\hat{Z}$  of rotation about itself, and a translation axis  $\hat{V}$  denoting the motion of the planet on the galactic plane following the Sun. The dark matter halo is assumed at rest in the galactic coordinate system with a Maxwellian distribution of velocities for its components, and a dispersion velocity  $\vec{v}_{disp}$  of approximately 270 km/s. A cutoff at the tail of the distribution, given by the escape velocity from the galaxy  $\vec{v}_{esc} \approx 650$  km/s [14] is also assumed. For a detector on the Earth one has to add to the velocity distribution of the DM particles the component due to the motion of the planet around the center of the galaxy. This defines naturally a set of rings (isodetection rings) on the surface of the Earth along which the CDM

flux and velocity distribution will be the same. As the Earth rotates about  $\hat{Z}$ , a detector located at a given point on it will rotate through many values of the angle  $\theta$  in the figure, and hence the counting rate and velocity distribution will be modulated according to how much the elastic scattering of the WIMPs on nuclei in the mantle and core affect their exit points and velocities. This will depend on their masses and coupling constants.

If the scattering of the DM particle with the Earth is considerable, the greater modulation would be achieved by a detector that manages to get close to the  $\theta \approx 180^\circ$  isodetection ring where the probability of at least one scattering is the largest. Calculations by Collar and Avignone [15] indicate that such optimal geographic location corresponds to a detector sitting between  $35$  and  $40^\circ$  South latitude.

An idea about the angles swept by the proposed experiment at Sierra Grande and other laboratories with similar detectors can be gleaned by looking at Fig. 4. Three sites with detectors in the northern hemisphere, Canfranc in the border between Spain and France, Homestake in the USA and Baksan in Siberia, Russia, reach in the optimum case to  $\theta = 100^\circ$ . The Sierra Grande experiment, on the other hand, begins at  $\theta = 80^\circ$  and reaches up to  $\theta \approx 180^\circ$ . Even in the absence of scattering the geometry depicted in Fig. 3 gives rise to a modulation of the incoming and outgoing fluxes with respect to  $\theta$  in the way shown in Fig. 5. In this situation, a detector sensitive to events coming in or out of the Earth could well be used to identify CDM particles. Associated with the incoming or outgoing fluxes there is a mean velocity of the DM particles, which follows a pattern similar to the one shown above (Fig. 6).

Next step we consider the more realistic situation of particles penetrating a sphere with a known density profile. We choose a value of the incoming flux  $\Phi_{in}$  and the incoming velocity  $\vec{v}_{in}$  for a very large number of trials, and follow the trajectory of each particle through the Earth as it scatters and loses energy. For this, we model the Earth (see Fig. 7) according to its elemental content and geological data and obtain values for the outgoing flux  $\Phi_{out}$  and the outgoing velocity  $\vec{v}_{out}$  at each isodetection ring  $\theta$ . Once this is done we recompute the modified values of  $n$  and  $f(v)$  of Eq.(1.3) and calculate the expected rate for each ring  $R(\theta)$ . One such calculation is shown in Fig. 8 for a candidate with  $m_\delta = 7$  GeV and a coupling constant  $G_f = 31G_w$ . To get an idea of the expected scattering probability we notice that for the average density of the Earth

$$\langle \rho \rangle = 1.82 \times 10^{23} \text{ nuclei/cm}^3$$

and the average cross section

$$\langle \sigma \rangle \approx 10^{-32} \text{ cm}^2$$

the probability that a DM scatters from one of the Earth constituents is

$$P = 1 - \exp\{-2R_\oplus \langle \rho \rangle \langle \sigma \rangle\} \approx 0.9 \quad (2.1)$$

For the realistic case considered above the advantages of placing a detector in the southern hemisphere become clear by looking at Fig. 9. In part *a*) of the figure we show the expected flux of DM particles (obtained by Monte Carlo) divided by the expected flux, for several different masses and coupling constants. The shaded areas on top of the figure illustrate the  $\theta$ -bins one could use to compare detection rates. The experiment at Canfranc sees a very smooth variation in the flux after crossing all available  $\theta$ -bands. The one in Sierra Grande, however, sweeps across those values of  $\theta$  where the modulation is at its largest. The same reasoning applies to the bottom part of the figure where we show the mean velocity of particles reaching the detector as a function of the angle  $\theta$ .

### A. The experiment in Sierra Grande

To search for diurnal modulation effects as described in the previous section a collaboration between the laboratory TANDAR, Argentina, the University of South Carolina and Pacific Northwest Laboratory in the USA, and the University of Zaragoza in Spain, has been set up. The site of the experiment is an iron mine (not active since mid 1991) located in Sierra Grande, province of Rio Negro, some 1,250 km south of Buenos Aires, Argentina at  $41^\circ$  South  $66^\circ$  West. The mine, that though inactive has not been abandoned, possesses a central shaft that reaches a depth of 420 meters with an accompanying downward gallery that spirals all the way down to the bottom of the mine. Further 70 km of horizontal galleries are intended for the exploitation of the mineral. Formerly a state company, the provincial administration which now runs the mine has granted for the experiment an easy accessible area at approximately 360 m deep ( $\approx 1,000$  mwe) where the detector and all accessory equipment will be installed.

The planned detector is a 1 kg hyperpure crystal of natural Germanium ( $\gtrsim 92\%$  spin-zero nuclei) built by Princeton Gamma-Tech. The cryostat and related low background technology has been developed by the people at Pacific Northwest Laboratory, Richland, Seattle, and the whole setup is similar to others used by the same group for double beta decay and DM experiments in different laboratories. The data taking will be the standard of a nuclear physics experiment and will be performed on what is called an event by event basis, namely for each event one records its energy and time tags its arrival in order to associate the time with the corresponding angle  $\theta$ . When enough statistics is collected, for each energy bin  $i$ , the data are summed which correspond to an interval in angle where the counting rate was low  $\Delta\theta_2$  and subtracted from the collected data at an angle region where the counting rate was high  $\Delta\theta_1$ . The difference in the number of events between these two  $\theta$ -regions  $R_i = N(\Delta\theta_2) - N(\Delta\theta_1)$  is called the *residual* for energy bin  $i$ ; if a statistically significant deviation from zero shows up in  $R_i$  it will be indicating the presence of a DM particle in a limited region of the  $(m_\delta, G)$  plane, the precise value depending on the statistics collected.

One nice feature of this sort of analysis is that since there is a subtraction involved, the statistical error bars decrease as more data are considered whereas in the signal-to-noise method the error bars are, at best, as good as those of the unknown background.

In Fig. 10 we show a Monte Carlo residuals spectrum for a 1 TeV heavy Dirac neutrino assuming a background similar to those already achieved by existing detectors. The dashed curve is the theoretical result. One point to mention that in all calculations the density of the halo has been kept fixed at  $\rho_{halo} = 0.4 \text{ GeV cm}^{-3}$  which is the most often quoted value. Uncertainties in this number, which have been risen [16] (specially towards smaller densities), will move upwards the excluded region in Fig. 1 and make this sort of analysis even more relevant.

### III. CONCLUSIONS

For some ranges of masses and coupling constants, CDM particles can suffer significant scattering with the Earth that could result in experimentally observable modulation in existing detectors. Subtracting energy spectra for different times of the day increases the sensitivity for placing bounds on certain CDM candidates. A “real effect” would result in a positive signal over the nature ( $m_\delta, G$ ) of CDM particles. The planned experiment in Sierra Grande–Argentina is the first attempt to exploit this diurnal modulation effect.

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## FIGURES

FIG. 1. Exclusion plot (95% C.L.) for the mass and elastic cross section on Ge for dark matter particles. The solid line corresponds to the weak interaction cross section (heavy Dirac neutrino).

FIG. 2. The normalized raw spectra from the COSME II detector presently operated by the UZ/PNL/USC collaboration. The expected detection rates for different heavy Dirac neutrinos in the galactic halo are also shown (ref.[11]).

FIG. 3. The geometry of the diurnal modulation method; shown are the velocity of the Earth through the galactic halo,  $\widehat{V}$ , the Earth's axis of rotation  $\widehat{Z}$ , and the isodetection rings on which the CDM distribution and flux is uniform (ref.[12]).

FIG. 4. Bands in the angle  $\theta$  of Fig. 3 swept by three different detectors in the northern hemisphere, and by the proposed experiment in Sierra Grande (from [12]).

FIG. 5. Incoming and outgoing fluxes as function of the isodetection rings location (from [12]). No scattering with the Earth.

FIG. 6. Similar to Fig. 5 but plotting the mean velocity as function of  $\theta$ .

FIG. 7. Cross section of the density profile of the Earth indicating the relative abundances.

FIG. 8. Comparison of the normalized fluxes into and out of the Earth without scattering with the flux out and total flux with scattering in the Earth. The chosen CDM candidate has a mass  $m_\delta = 7$  GeV and  $G_f^2 = 1000 G_w^2$ .

FIG. 9. a) Sample calculations of the flux of scattered CDM particles normalized to the flux without scattering for 4 values of mass and coupling constant. b) same as a) but for mean velocities. In both figures the regions in  $\theta$  crossed by the COSME II detector and the Sierra Grande experiment are shown.

FIG. 10. Simulated experimental residual for CDM consisting of heavy Dirac neutrinos. The detector modelled here is COSME II which cannot reject these candidates using conventional exclusion techniques.