WIMP's signal and predictions for the new ANDES laboratory??

O. Civitarese[1*], K. J. Fushimi[2] and M. E. Mosquera[1,2]
[1]*Dept. of Physics, University of La Plata, c.c. 67 1900, La Plata, Argentina.* and
[2]*Facultad de Ciencias Astronómicas y Geofísicas,*
University of La Plata. Paseo del Bosque S/N 1900, La Plata, Argentina.

In this work we have analyzed the DAMA-LIBRA modulation data considering that the interactions between the WIMP and the Na and/or I nucleus of the detector and the Ge-type detector. We have made predictions to observation of modulation for the future laboratory to be built in San Juan, Argentina, if the detector is either a NaI detector or a Ge detector. We have found that the annual modulation does not change but, the diurnal modulation is modified by a factor 1.17 or 1.29 at the maximum value for a NaI or Ge detector respectively.

PACS numbers: 95.35.+d

I. INTRODUCTION

The observations of Zwicky [1] and Rubin and Ford [2] established the existence of a "dark matter", and therefore a series of problems in order to understand the nature and properties of this new kind of matter. The detection of the dark matter is crucial to solve some of the actual cosmological problems.

Nowadays, we know that the Universe is composed by ordinary matter, dark matter and dark energy, and that the amount of barionic density matter can be determined with great accuracy around 5% [3–5]. The rest of the Universe composition is 23% dark matter and 72% dark energy.

The most probably candidate for dark matter is the WIMP (Weakly Interacting Massive Particle). This particle massive (the mass ranges from 1 GeV to 10 TeV [6]) is electrically neutral, can interact weakly and gravitational with the ordinary matter but do not suffer neither electromagnetic nor strong interactions. It is assume that the dark matter in the Galactic Halo is composed mostly by WIMPs with a velocity distribution function of Maxwell-Boltzmann [6]. As a consequence of the Earth annual movement around the Sun, a time variable flux of dark matter (annual modulation) might be measure and, therefore, some properties of the WIMPs should be obtained.

There are several efforts to experimentally determine the annual modulation of the WIMP signal, and two kinds of detection, namely direct detection [7, 8] (e. g. DAMA [9, 10], CRESST [11], CoGeNT [12, 13], CDMS [14, 15], XENON [16], etc.), and indirect detection [17, 18] (e. g. IceCube [19], ANTARES [20], Fermi-LAT [21], HESS [22], among others).

The direct detection experiments generally are located in underground laboratories, and they measure the recoil energy of a nucleus when a WIMP hits it. It is important to have the same kind of detector in two or more locations since, as we shall shown, the diurnal modulation amplitude signal depends on the location of the laboratory. For this reason, in this work we compare two detectors, DAMA (a NaI detector) and CoGeNT (composed of Ge) with an equal possible detector to be located in ANDES laboratory (Agua Negra Deep Experimental Site). The ANDES laboratory will be settle in San Juan, Argentina, under the ANDES mountain range at a deep of 1700 m [23].

The paper is organized as follows. In Section II we describe the formalism in order to computed the annual and diurnal modulation rates and in Section III we show how the diurnal modulation depends on the location of the detector and predictions for the possible new laboratory in San Juan, Argentina are presented. Finally, conclusions are drawn in section IV.

II. FORMALISM

The recoil rate of the interaction between the WIMP and the detector nucleus can be written as [24]

$$\frac{dR}{dE_{\rm nr}} \;=\; \frac{2\rho_\chi}{m_\chi}\int d^3v v f(\vec{v},t)\frac{d\sigma}{dq^2}(q^2,v)\,, \tag{1}$$

where $E_{\rm nr}=\frac{\mu^2 v^2}{M}(1-\cos\theta)$ is the recoil energy (μ stands for the reduced mass of the system WIMP-nuclei, and θ is the dispersion angle), $\rho_\chi = 0.3\,{\rm GeV\,cm^{-3}}$ is the local mass density of dark matter, m_χ the WIMP's mass, $f(\vec{v},t)$ represents the WIMP's velocity distribution and v is the WIMP velocity with respect to the detector nuclei. The cross section can be written as

$$\frac{d\sigma}{dq^2}(q^2,v)=\frac{\sigma_0}{4\mu^2 v^2}\left(F(q)\right)^2\,. \tag{2}$$

In the previous equation, $q=\sqrt{2ME_{\rm nr}}$ represent the transfer momentum (M is the nucleus mass), σ_0 the cross section at zero transfer momentum and $F(q)$ stands for the nuclear form factor.

Calling

$$\eta \;=\; \int \frac{f(\vec{v},t)}{v}d^3v\,, \tag{3}$$

*Corresponding author
e-mail: osvaldo.civitarese@fisica.unlp.edu.ar

the recoil rate of Eq. (1) is

$$\frac{dR}{dE_{\rm nr}} = \frac{2\rho_\chi}{m_\chi}\frac{\sigma_0}{4\mu^2}\left(F(q)\right)^2\eta\,. \tag{4}$$

The calculation of each one of the different terms in the Eq. (4) are discussed in the next sections.

A. Halo component

In order to obtain the velocity distribution of the WIMPs, we have assumed that the model for the dark matter halo is the Standard Halo Model [25], and, therefore, the velocity distribution correspond to a Maxwell-Boltzmann distribution [24, 26]

$$f(\vec{v}) = \begin{cases} \frac{1}{N(\pi v_0^2)^{\frac{3}{2}}}e^{-|\vec{v}|^2/v_0^2} & |\vec{v}| < v_{\rm esc} \\ 0 & |\vec{v}| > v_{\rm esc} \end{cases}, \tag{5}$$

$$N = {\rm erf}\left[\frac{v_{\rm esc}}{v_0}\right] - \frac{2}{\sqrt{\pi}}\frac{v_{\rm esc}}{v_0}e^{-\left(\frac{v_{\rm esc}}{v_0}\right)^2}, \tag{6}$$

where N is the normalization factor, erf$[x]$ is the error function and $v_{\rm esc}$ and v_0 are the escape velocity for the WIMPs and the velocity of the Sun. In this work we considered $v_{\rm esc} = 544\,$km/s [27] and $v_0 = 220\,$km/s [26]. Therefore, if one includes the laboratory velocity ($\vec{v}_{\rm lab}$), the integral of the Eq. (3) to be solve is

$$\eta = \frac{1}{N(\pi {v_0}^2)^{3/2}}\int\frac{e^{-(\vec{v}+\vec{v}_{\rm lab})^2/v_0^2}}{v}d^3v\,. \tag{7}$$

Finally, η can be written as

$$\eta = \begin{cases} \frac{1}{2Nv_{\rm lab}}\left({\rm erf}\left[\frac{v_{\rm lab}+v_{\rm min}}{v_0}\right] - {\rm erf}\left[\frac{v_{\rm min}-v_{\rm lab}}{v_0}\right]\right) & v_{\rm min} < v_{\rm esc} - v_{\rm lab} \\ \frac{1}{2Nv_{\rm lab}}\left({\rm erf}\left[\frac{v_{\rm esc}}{v_0}\right] - {\rm erf}\left[\frac{v_{\rm min}-v_{\rm lab}}{v_0}\right]\right) & v_{\rm esc} - v_{\rm lab} < v_{\rm min} < v_{\rm esc} + v_{\rm lab} \\ 0 & v_{\rm min} > v_{\rm esc} + v_{\rm lab} \end{cases}. \tag{8}$$

In the previous equation, the WIMP's minimal velocity needed to produce a nucleus' recoil is [28]

$$v_{\rm min} = \sqrt{\frac{E_{\rm nr}(m_\chi + M)^2}{2Mm_\chi^2}}\,. \tag{9}$$

B. Laboratory velocity $v_{\rm lab} = |\vec{v}_{\rm lab}|$

The laboratory is located in certain place of the Earth, therefore its velocity can be written as

$$\begin{aligned} \vec{v}_{\rm lab} &= \vec{v}_\odot^{\,G} + \vec{v}_\oplus(t,t')\,, \\ \vec{v}_\odot^{\,G} &= \vec{v}_\odot + \vec{v}_{\rm LSR}\,, \\ \vec{v}_\oplus(t,t') &= \vec{v}_{\rm rev}(t) + \vec{v}_{\rm rot}(t')\,, \end{aligned} \tag{10}$$

where $\vec{v}_\odot^{\,G}$ is the Sun's velocity with respect to the galactic system, that can be written as the sum of the peculiar velocity of the Sun with respect to the Local Standard of Rest (LSR), $\vec{v}_\odot^{\,G} = (9, 12, 7)$ km/s [29], and the LSR's velocity $\vec{v}_{\rm LSR} = (0, 220 \pm 50, 0)$ km/s [29] (both in the Galactic system [42]). The term $\vec{v}_\oplus(t,t')$ is the sum of the orbital velocity of the Earth $\vec{v}_{\rm rev}(t)$ and the rotational velocity $\vec{v}_{\rm rot}(t')$. The time t is expressed in sidereal days, and t' in sidereal hours.

If we consider the mean orbital velocity as $v_{\rm rev}^\oplus = 29.8\,$km/s [29], the annual velocity can be written as

$$\begin{aligned} \vec{v}_{\rm rev}(t) = v_{\rm rev}^\oplus \Big[&\varepsilon_1^{\rm eclip}\sin(w_{\rm rev}(t - t_{\rm eq})) \\ &- \varepsilon_2^{\rm eclip}\cos(w_{\rm rev}(t - t_{\rm eq}))\Big]\,. \end{aligned} \tag{11}$$

In the previous equation $w_{\rm rev}$ is the orbital frequency, $t_{\rm eq}$ is the sidereal time of the march equinox and, in the galactic system,

$$\begin{aligned} \varepsilon_1^{\rm eclip} &= (-0.055, 0.494, -0.867)\,, \\ \varepsilon_2^{\rm eclip} &= (-0.993, -0.112, -2.58\times 10^{-4})\,, \\ \varepsilon_3^{\rm eclip} &= (-0.097, 0.862, 0.497)\,. \end{aligned} \tag{12}$$

In Fig. 1 we shown the different components of the orbital velocity as a function of sidereal time.

The Earth rotational velocity is written as

$$\begin{aligned} \vec{v}_{\rm rot}(t') = v_{\rm rot}^\oplus\,[&\varepsilon_1^{\rm ecu}\sin(w_{\rm rot}(t' + t_0)) \\ &- \varepsilon_2^{\rm ecu}\cos(w_{\rm rot}(t' + t_0))]\,, \end{aligned} \tag{13}$$

where $v_{\rm rot}^\oplus = V_{\rm ecu}\cos(\phi_0)$, $V_{\rm ecu} = 0.4655\,$km/s is the rotational velocity in the Equator [29], ϕ_0 is the laboratory latitude. The frequency is $w_{\rm rot}$ and t_0 corresponds to the time associated to the laboratory longitude λ_0. The versor in the galactic system are

$$\begin{aligned} \varepsilon_1^{\rm ecu} &= (-0.055, 0.494, -0.867)\,, \\ \varepsilon_2^{\rm ecu} &= (-0.873, -0.446, -0.198)\,, \\ \varepsilon_3^{\rm ecu} &= (-0.485, 0.746, 0.456)\,. \end{aligned} \tag{14}$$

In Fig. 2 we shown the different components of the rotational velocity as a function of sidereal time for two

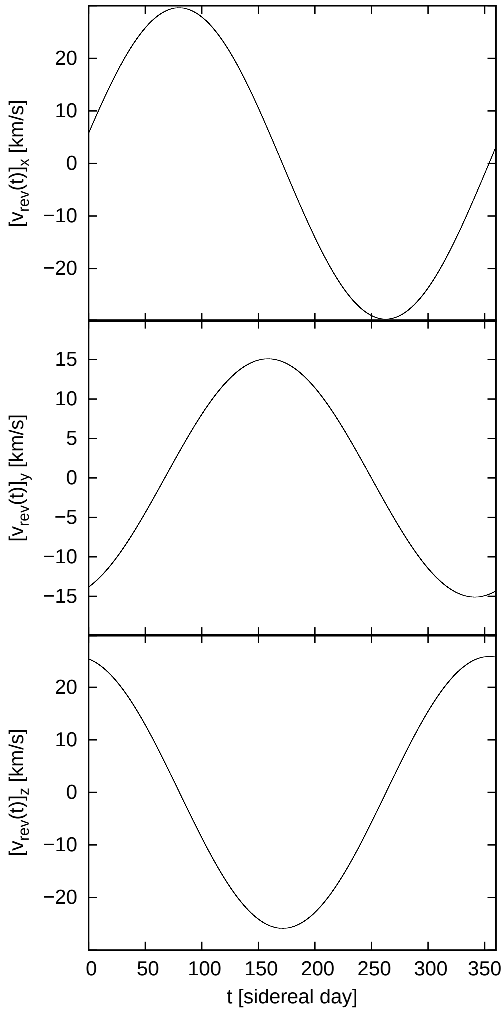

FIG. 1: Orbital velocity of the laboratory as a function of the sidereal time.

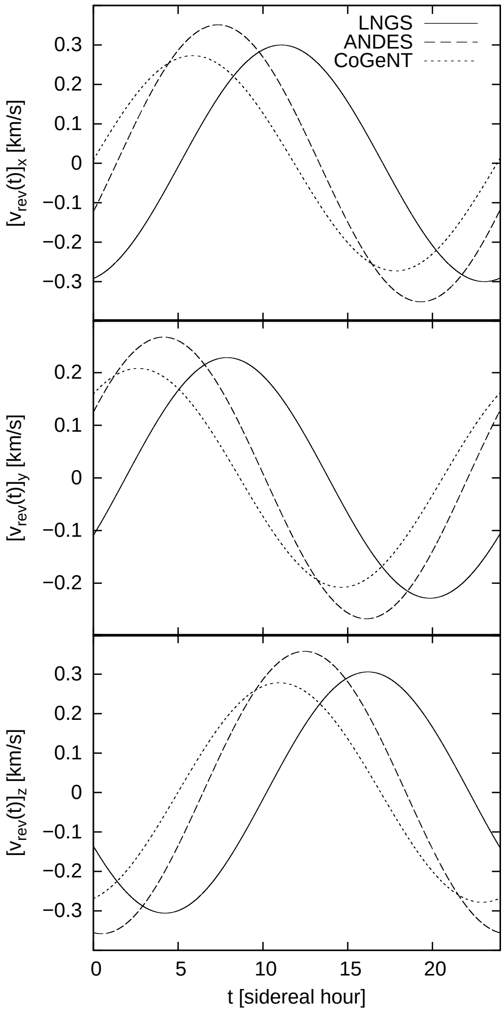

FIG. 2: Rotational velocity of the laboratory as a function of the sidereal time. Solid line: LNGS laboratory; dashed line: ANDES laboratory; dotted-line: SUL laboratory.

Laboratory	ϕ_0	λ_0
LNGS	$42°27'$ N	$13°34'$ E
CoGeNT	$47°48'$ N	$92°14'$ W
ANDES	$30°15'$ S	$69°53'$ W

TABLE I: Longitude and latitude of the LNGS, SUL and ANDES laboratories.

laboratories, the LNGS (Laboratori Nazionali del Gran Sasso) located in Italy [29, 30], the CoGeNT detector located at Soudan Underground Laboratory (SUL) in USA [31] CITA and the future ANDES (Agua Negra Deep Experimental Site) in San Juan, Argentine [23, 32–34] (the longitude and latitude of each laboratory is presented in Table I).

Finally, the laboratory velocity can be written as

$$\begin{aligned} v_{\rm lab} &\simeq |\tilde{\vec{v}}^G_\odot| + v^\oplus_{\rm rev} A_{\rm m}\cos(w_{\rm rev}(t-\tilde{t_0})) \\ &\quad + v^\oplus_{\rm rot} A_{\rm d}\cos(w_{\rm rot}(t'-t_{\rm d}))\,, \end{aligned} \tag{15}$$

where $\check{v}_{\rm lab} = \frac{\vec{v}_{\rm lab}}{|\vec{v}_{\rm lab}|}$, $|\tilde{\vec{v}}^G_\odot| = |\vec{v}^G_\odot| + \frac{1}{2}\frac{|\vec{v}_{\rm rev}|^2}{|\vec{v}^G_\odot|}$, $\tilde{t_0} = t_{\rm eq} + \frac{\beta_{\rm m}}{w_{\rm rev}}$, $A_{\rm m} = 0.488$, $\beta_{\rm m} = 1.260\,{\rm rad}$, $t_{\rm d} = \frac{\beta_{\rm d}}{w_{\rm rot}} - t_0$, $A_{\rm d} = 0.6712$ and $\beta_{\rm d} = 3.9070\,{\rm rad}$ [29].

In Figures 3 and 4 we present the laboratory velocity, for each site, as function of the sidereal time.

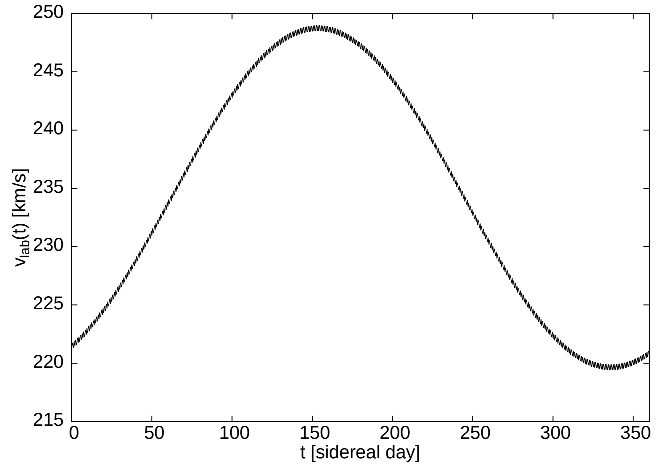

FIG. 3: Laboratory velocity as function of the sidereal time. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

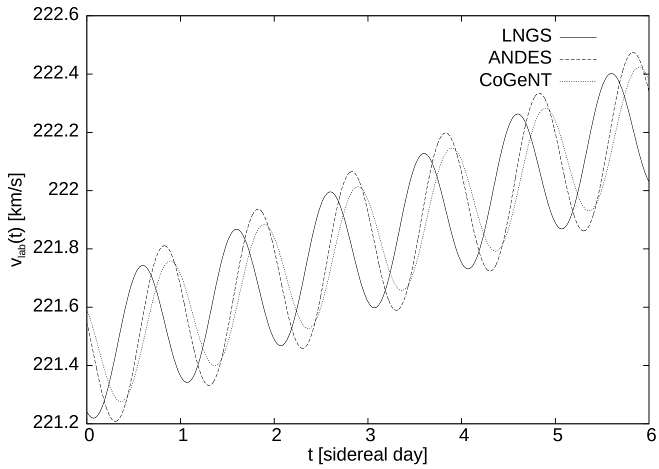

FIG. 4: Laboratory velocity as function of the sidereal time. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

C. Nuclear form factor

In this work, we have considered the spin-independent cross section

$$\sigma_0^{\rm SI} \;=\; \frac{4}{\pi}\mu^2 \left[{\rm Z}\ {\rm f}_p + ({\rm A}-{\rm Z}){\rm f}_n\right]^2 , \qquad (16)$$

where Z is the proton number, $A-Z$ the neutron number, f_p and f_n are the coupling factors. The nuclear form factor can be defined as [35]

$$F(q) \;=\; \frac{4\pi}{A}\int_0^\infty \frac{r}{q}\rho(r)\sin(qr)dr\,, \qquad (17)$$

where $\rho(r)$ is the nuclear density

$$\rho(r) \;=\; \frac{\rho_0}{1+e^{\frac{(r-R_0)}{a}}}\,. \qquad (18)$$

where the nuclear parameter are the usual ones, $a \simeq 0.65\,\mathrm{fm}$, $R_0 = 1.12A^{\frac{1}{3}}\,\mathrm{fm}$ y $\rho_0 = 0.17\,\mathrm{fm}^{-3}$ [36].

In order to obtain an analytic expression of the form factor, we have performed an expansion of $\sin(qr)$, leaving to

$$F_{\rm WS}(q) \;=\; \frac{4\pi\rho_0}{A}\sum_{k=1}\frac{(-1)^{k+1}q^{2k-2}}{a(2k-1)!}\int_{-\frac{R_0}{a}}^\infty \frac{(az+R_0)^{2k}}{1+e^z}dz\,. \qquad (19)$$

The integral of the last expression can be divided into two, after considered $(za+R_0)^{2k} = \sum_{j=0}^{2k}\frac{(2k)!}{j!(2k-j)!}a^{2k-j}R_0^j z^{2k-j}$

$$\int_{-\frac{R_0}{a}}^\infty \frac{z^{2k-j}}{1+e^z}dz \;=\; \int_0^\infty \frac{z^{2k-j}}{1+e^z}dz + \int_{\frac{-R_0}{a}}^0 \frac{z^{2k-j}}{1+e^z}dz\,.$$

After performing a serial expansion, we integrated the two expressions and obtained

$$F_{\rm WS}(q) \;=\; \frac{4\pi\rho_0 a^3}{A}\sum_{k=1}\frac{(aq)^{2k-2}}{(2k-1)!}\sum_{j=0}^{2k}\frac{(2k)!}{(2k-j)!j!}\left(\frac{R_0}{a}\right)^j\left\{\sum_{n=1}^\infty\frac{(-1)^{n+k}}{n^{2k-j+1}}\Gamma(2k-j+1)+(-1)^{j+k+1}\frac{(\frac{R_0}{a})^{2k-j+1}}{2k-j+1}\right.$$
$$\left. +\sum_{n=1}^\infty\frac{(-1)^{n-j+k+1}}{n^{2k-j+1}}\left[\Gamma(2k-j+1)-\Gamma\left(2k-j+1,\frac{nR_0}{a}\right)\right]\right\}. \qquad (20)$$

The form factor obtained using a Woods-Saxon density is similar to the empirical form factor of Helm [37]

$$F_{\rm H}(q) \;=\; 3e^{-q^2s^2/2}\frac{\sin(qr_n)-qr_n\cos(qr_n)}{(qr_n)^3} \qquad (21)$$

where $s \simeq 0.9\,\mathrm{fm}$, $r_n^2 = c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2$, $a \simeq 0.52\,\mathrm{fm}$ and $c \simeq \left(1.23A^{1/3} - 0.6\right)$ fm [38].

D. Annual and diurnal modulation rates

We can write the recoil rate in terms of the annual and diurnal modulation rates as

$$\begin{aligned}\frac{dR}{dE_{\rm nr}} &= S_0 + S_{\rm m}(E_{\rm nr})\cos(w_{\rm rev}(t-\tilde{t_0})) \\ &\quad + S_{\rm d}(E_{\rm nr})\cos(w_{\rm rot}(t'-t_{\rm d}))\,, \end{aligned} \tag{22}$$

where the annual modulation can be computed as

$$S_{\rm m}(E_{\rm nr}) = \frac{\rho_\chi}{m_\chi}\frac{\sigma_0}{2\mu^2}\left(F(q)\right)^2 v_{\rm rev}^{\oplus} A_{\rm m}\frac{\partial\eta}{\partial v_{\rm lab}}\bigg|_{\tilde{t_0};t_{\rm d}}\,, \tag{23}$$

and the diurnal modulation is

$$S_{\rm d}(E_{\rm nr}) = \frac{\rho_\chi}{m_\chi}\frac{\sigma_0}{2\mu^2}\left(F(q)\right)^2 v_{\rm rot}^{\oplus} A_{\rm d}\frac{\partial\eta}{\partial v_{\rm lab}}\bigg|_{\tilde{t_0};t_{\rm d}}\,. \tag{24}$$

The average modulation amplitude are defined as

$$< S_{\rm m} > = \frac{1}{E_2 - E_1}\int_{E_1}^{E_2} S_{\rm m}(E_{\rm nr})dE_{\rm nr}\,, \tag{25}$$

$$< S_{\rm d} > = \frac{1}{E_2 - E_1}\int_{E_1}^{E_2} S_{\rm d}(E_{\rm nr})dE_{\rm nr}\,. \tag{26}$$

III. RESULTS

In this work we consider the best fit values obtained by the different collaborations of the WIMP's mass and the cross section in order to compute the diurnal modulation of the possible detector to be located in ANDES laboratory.

As we can see from Eq. (24), the recoil rate depends on the location of the detector. The phase of the diurnal modulation amplitude (namely $t_{\rm d} = \frac{\beta_{\rm d}}{w_{\rm rot}} - t_0$ of Eq. (22)) depends on the longitude of the experimental site, meanwhile, the latitude changes the value of the amplitude of the diurnal modulation, thought its dependence with $v_{\rm rot}^{\oplus} = V_{\rm ecu}\cos(\phi_0)$. For this reason, in this section we present same predictions of the average diurnal modulation amplitude if either a NaI type detector or a Ge detector is located the ANDES laboratory [33].

A. NaI detector

In order to compute the average diurnal modulation amplitude, we use the parameters obtained in Ref. [24, 39], that is $m_\chi = 11\,\mathrm{GeV}$, and $\sigma_0^{\rm SI} = 2\times10^{-14}\,\mathrm{fm}^2$ (scattering only with the sodium nuclei).

In Figure 5 we show the diurnal modulation amplitude as a function of the recoil energy for the interaction of a WIMP with the Na nuclei of the detector. We have considered that the two laboratories would have the same detector. As one can notice, the diurnal modulation amplitude is large for the ANDES detector, due to the location (in particular the latitude) of the experimental site. For the I nuclei, the diurnal modulation has the same effect due to the detector's location. The annual modulation amplitude is the same for the two laboratories.

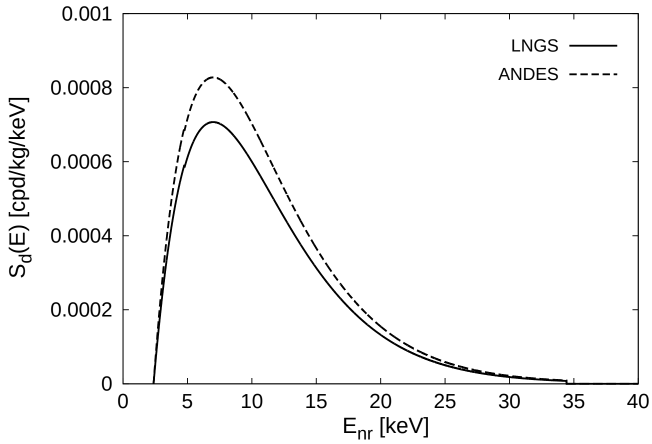

FIG. 5: Diurnal modulation amplitude as a function of the recoil energy. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

In order to contrast the experimental data and the theoretical results, one have to perform a correction to the recoil energy due to a quenching factor (that is the energy that the detector measures is not the total recoil energy) as $E = QE_{\rm nr}$. In this case, for the sodium $Q_{Na} = 0.3$ [40].

In Figure 6 we present the diurnal modulation as a function of the sidereal time (in days) for an energy detector of 2 keV for the two laboratories. As one can see, there exists a noticeably phase shift and the amplitude is larger for the ANDES laboratory. ACA NO SE CUAL DE LOS DOS GRAFICOS DEJAR EL 6 o EL 7

In Figure 8 we present the results for the LNGS and ANDES experimental sites for the average modulation amplitude as a function of the detector energy. As one can see, the value of the possible measurements on ANDES are larger than LNGS ones, by a factor of the order of 1.17.

B. Ge detector

For the Ge-type detector, we use the parameters obtained in Ref. [41], that is $m_\chi = 10\,\mathrm{GeV}$, and $\sigma_0^{\rm SI} = 10^{-15}\,\mathrm{fm}^2$.

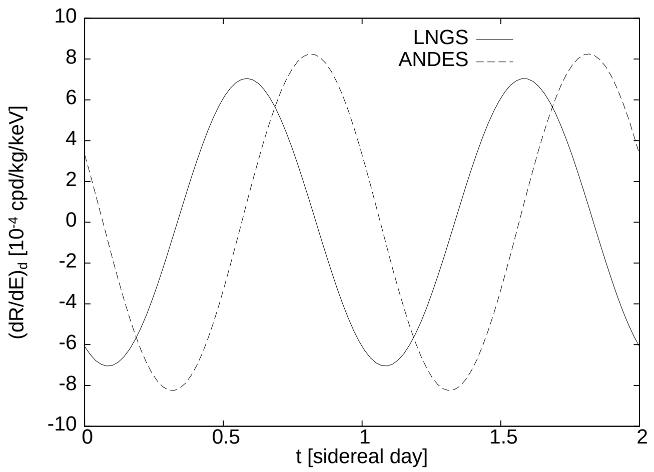

FIG. 6: Diurnal modulation amplitude as a function of the sidereal time. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

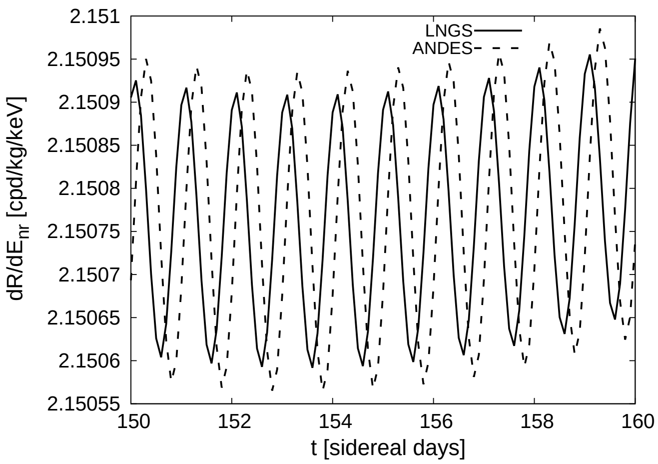

FIG. 7: Rate as a function of the sidereal time. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

The two different diurnal modulation amplitude for the SUL laboratory and the ANDES laboratory is presented in Figure 9, as a function of the recoil energy. Once again, the diurnal modulation amplitude is large for the ANDES detector.

To determine the average diurnal modulation amplitude we need the quenching factor for Ge, $Q_{Ge} = 0.2$ [39] and the response function

$$\epsilon\,(E) \;=\; 0.66 - \frac{E}{50\,\mathrm{keV}}\,, \tag{27}$$

where the energy E correspond to the detector energy [39]. This function has to be considered when one perform the integral of the Eq. (26).

In Figure 10 the diurnal modulation as a function of the sidereal time (in days) for an energy detector of 2 keV is presented. Once again, there exists a phase shift and the amplitude is larger for the ANDES laboratory. ACA NO SE CUAL DE LOS DOS GRAFICOS DEJAR EL 10 o EL 11

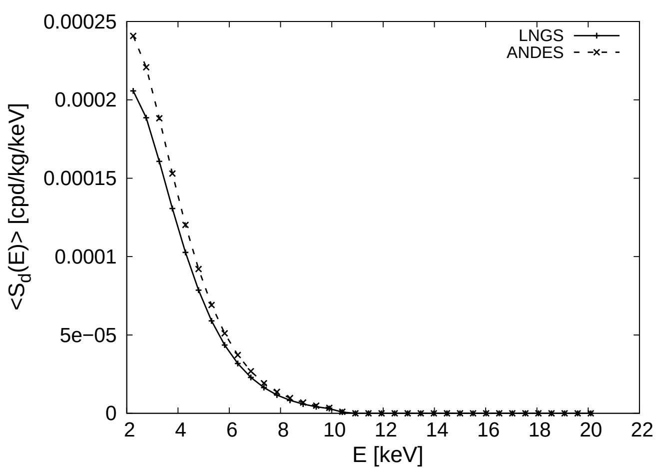

FIG. 8: Possible measurements on ANDES and LNGS experimental sites, considering only sodium recoil. Solid line: LNGS laboratory; dashed line: ANDES laboratory.

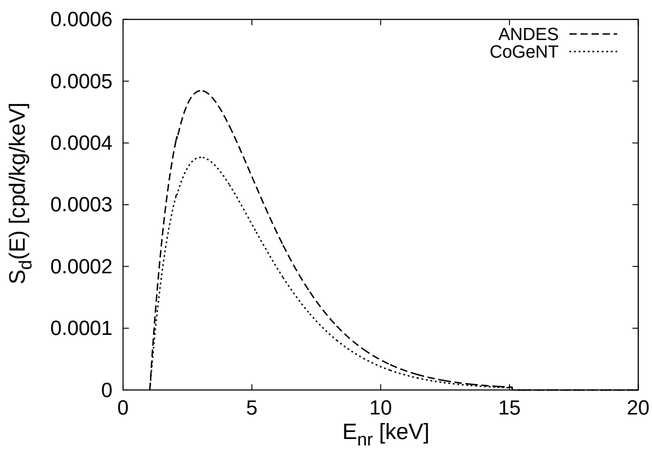

FIG. 9: Diurnal modulation amplitude as a function of the recoil energy. Dotted line: SUL laboratory (Ge detector); dashed line: ANDES laboratory.

In Figure 12 we present the results for the SUL and ANDES experimental sites for the average modulation amplitude as a function of the detector energy. The value of the possible measurements on ANDES are larger by a factor of the order of 1.29.

IV. CONCLUSIONS

In this work, we have computed the recoil rate of the scattering of a WIMP with a nucleus in a certain detector. We have considered two different detectors and, we have also shown that for the best values of the mass and cross section, the diurnal modulation amplitude depends

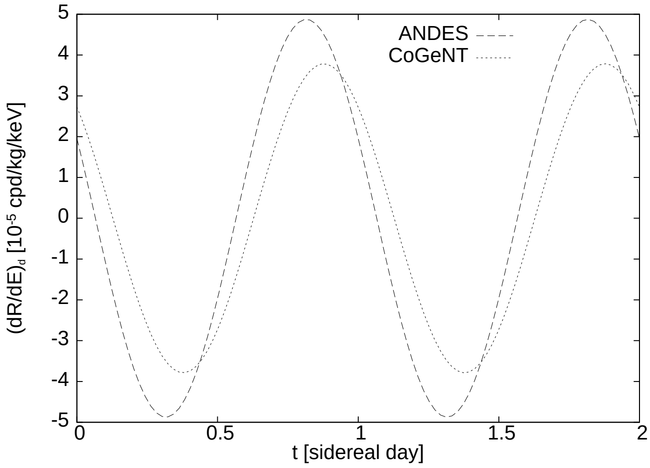

FIG. 10: Diurnal modulation amplitude as a function of the sidereal time. Dotted line: SUL laboratory (Ge detector); dashed line: ANDES laboratory.

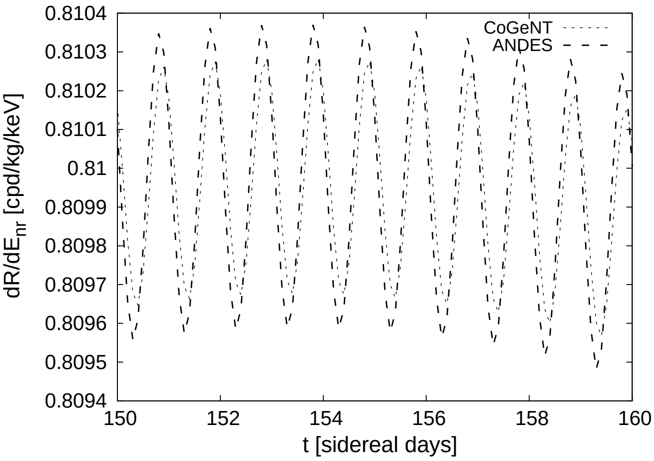

FIG. 11: Rate as a function of the sidereal time. Dotted line: SUL laboratory (Ge detector); dashed line: ANDES laboratory.

on the location of the detector in the Earth. We have compared the results of the current experiments and the future WIMP's detector to be located in the Agua Negra Deep Experimental Site for two different kinds of detectors. We have found that the value of the average diurnal modulation, for a NaI detector, is larger than the measure in DAMA-LIBRA by a factor 1.17, meanwhile for the Ge detector is almost 1.29. This factors correspond to the rate of the latitude's cosine of the two detectors.

Acknowledgments

Support for this work was provided by the National Research Council (CONICET) of Argentina, and by the ANPCYT of Argentina. O. C. and M. E. M. are members of the Scientific Research Career of the CONICET.

[1] F. Zwicky, Helv. Phys. Acta **6**, 110 (1933).
[2] V. C. Rubin and W. K. Ford, Jr., Astrophys. J. **159**, 379 (1970).
[3] P. A. R. Ade et al, ArXiv e-prints 1502.01589 (2015).
[4] C. L. Bennett et al., Astrophys. J. Suppl. **208**, 20 (2013).
[5] G. Hinshaw et al., Astrophys. J. Suppl. **208**, 19 (2031).
[6] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996).
[7] M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985).
[8] I. Wasserman, Phys. Rev. D **33**, 2071 (1986).
[9] R. Bernabei et al., Nucl. Instrum. Meth. A **592**, 297 (2008).
[10] R. Bernabei et al., Eur. Phys. J. C **67**, 39 (2010).
[11] G. Angloher et al., Eur. Phys. J. C **72**, 1971 (2012).
[12] C. E. Aalseth et al., Phys. Rev. D **88**, 012002 (2013).
[13] C. E. Aalseth et al., Phys. Rev. Lett. **106**, 131301 (2011).
[14] D. S. Akerib et al., Phys. Rev. D **72**, 052009 (2005).
[15] Z. Ahmed et al., Phys. Rev. Lett. **106**, 131302 (2011).
[16] E. Aprile et al., Astropar. Phys. **34**, 679 (2011).
[17] J. Silk, K. Olive and M. Srednicki, Phys. Rev. Lett. **55**, 257 (1985).
[18] T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D **34**, 2206 (1986).
[19] A. Achterberg et al, Astropart. Phys. **26**, 155 (2006).
[20] M. Ageron et al, ArXiv e-prints 1104.1607 (2011).
[21] W. B. Atwood et al., Astrophys. J. **679**, 1071 (2009).
[22] F. Aharonian et al, Astron. Astrophys. **457**, 899 (2006).
[23] http://andeslab.org/index.php
[24] K. Freese, M. Lisanti and C. Savage, ArXiv e-prints 1209.3339 (2012).
[25] K. Freese, J. Frieman and A. Gould, Phys. Rev. D **37**, 3388 (1988).
[26] G. Jungman, M. Kamionkowski and K. Griest, Phys.

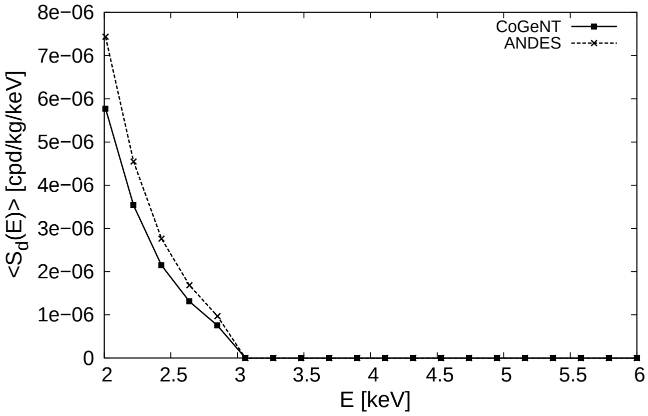

FIG. 12: Possible measurements on ANDES and SUL experimental sites. Dotted line: SUL laboratory (Ge detector); dashed line: ANDES laboratory.

Rept. **267**, 195 (1996).

[27] G. B. Gelmini, ArXiv e-prints 1502.01320 (2015).

[28] A. M. Green, Phys. Rev. D **68**, 023004 (2003); Erratum: Phys. Rev. D **69**, 109902(2004).

[29] R. Bernabei et al., Eur. Phys. J. C **74**, 2827, (2014).

[30] https://www.lngs.infn.it/en

[31] http://cogent.pnnl.gov/

[32] P. A. N. Machado, T. Mühlbeier, H. Nunokawa and R. Zukanovich Funchal, Phys. Rev. D **86**, 125001 (2012).

[33] O. Civitarese, Nuclear and Particle Physics Proceedings **267**, 377 (2015).

[34] X. Bertou, Eur. Phys. J. Plus **127**, 1 (2012).

[35] Y.-Z. Chen et al., Commun. Theor. Phys. **55**, 1059 (2011).

[36] A. Bohr and B. Mottelson, Nuclear Structure vol. I, W. A. Benjamin Inc., M. A, (1975).

[37] R. H. Helm, Phys. Rev. **104**, 1466 (1956).

[38] J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).

[39] C. Savage, G. Gelmini, P. Gondolo and K. Freese, JCAP **0904**, 010 (2009).

[40] R. Bernabei et al., Phys. Lett. B **424**, 195 (1998).

[41] C. E. Aalseth et al., ArXiv e-prints 1401.6234 (2014).

[42] In the Galactic system, the x-axes is pointing to the Galactic Center and the z-axe to the Galactic North Pole.