*Conference Proceedings Paper*

# Dark matter annual modulation results from the ANAIS-112 experiment

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Published: date
Academic Editor: name

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**Abstract:** An annual modulation in the interaction rate of galactic dark matter particles is foreseen due to the Earth's movement around the Sun; the DAMA/LIBRA observation of a modulation signal compatible with expectations is intriguing the community for twenty years. The ANAIS-112 experiment, with a target of 112.5 kg of NaI(Tl), is running smoothly at the Canfranc Underground Laboratory (Spain) since 2017, aiming to test this observation using the same detection technique and target. Results on the modulation search from two years of data (220.7 kg·y) have been presented and the analysis of three years (313.6 kg·y) is underway. Under the hypothesis of modulation, the deduced amplitudes from best fits are in all cases compatible with zero for the two energy regions at [2-6] and [1-6] keV; the results agree with the expected sensitivity for the considered exposure, which fully supports the goal of achieving a 3σ sensitivity to explore the DAMA/LIBRA result for a five-year operation. Here, the ANAIS-112 set-up and performance will be briefly reminded and the annual modulation results and prospects will be discussed.

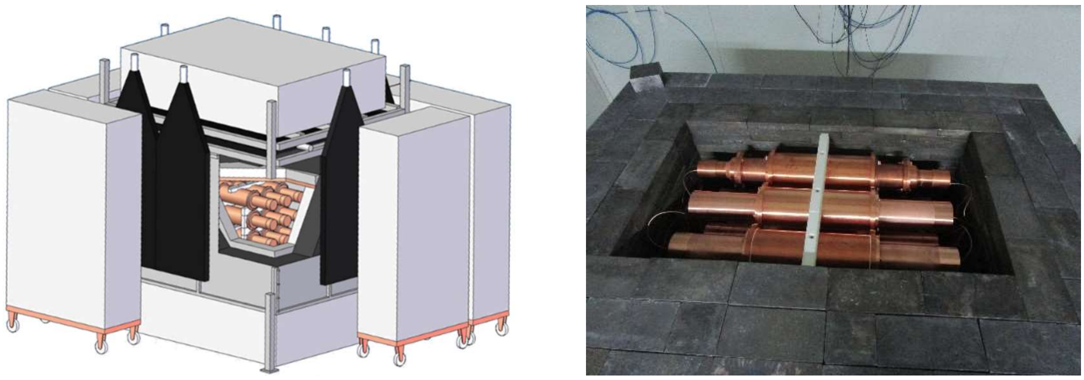
**Keywords:** dark matter; WIMPs; direct detection; annual modulation; NaI scintillators

## 1. Introduction

The direct detection of dark matter particles, like the so-called Weakly Interacting Massive Particles (WIMPs), which could populate the galactic halo, is mainly based on their elastic scattering off target nuclei in suitable detectors [1]. As the Earth moves around the Sun, the relative velocity between the detector and the dark matter particles follows a time variation giving rise to a modulation in the expected rate of interaction with well-defined features [2]. The DAMA/LIBRA experiment, taking data with about 250 kg of NaI(Tl) detectors at the Gran Sasso Underground Laboratory in Italy, has reported the presence of an annual modulation signal with all the expected properties at a confidence level of 12.9σ, from an exposure of 2.46 t·y accumulated over two decades [3,4]. Taking into account the results presented by other direct detection experiments using different targets (see for instance [1]), a tension appears if considering the DAMA/LIBRA signal as due to dark matter, assuming common but also more generic interaction or halo models. In this context, to prove or disprove the DAMA/LIBRA observation in a model-independent way and using the same target and technique would be essential and this is the goal of the ANAIS experiment [5]. Other projects all over the world have undertaken this task too, like COSINE-100 (also taking data and with first annual modulation results for an exposure of 97.7 kg·y released [6]) and SABRE [7], PICOLON [8] and COSINUS [9], being in preparation.

## 2. Experiment

The ANAIS-112 experiment, located at the Canfranc Underground Laboratory (LSC), in Spain, started the data-taking phase in August, 2017. A full description of the set-up, shown in Figure 1, can be found in [10]. ANAIS-112 includes an array of 3x3 NaI(Tl) scintillators, with a crystal mass of 12.5 kg each, having a total mass of 112.5 kg. ANAIS detectors were manufactured by the Alpha Spectra Inc. company in Colorado (US) and two Hamamatsu photomultipliers (PMTs), model R12669SEL2, were coupled to each crystal through quartz windows at the LSC clean room. The copper enclosure has a Mylar window (allowing to perform low energy calibration using external sources) and detectors have shown an outstanding optical quality; together with the high-efficiency of the PMTs used, this has allowed to achieve a light collection of ~15 photoelectrons (phe) per keV for all the detector units [11]. The shielding of ANAIS-112 is made of 10 cm of archaeological lead followed by 20 cm of low activity lead against the external gamma radiation, a box filled with radon-free $N_2$ gas to avoid radon intrusion being under overpressure and 40 cm of polyethylene and water to moderate neutrons. Sixteen plastic scintillators acting as active veto cover the sides and top of the set-up to tag residual muons. The LSC facilities are placed at a depth of 2450 m.w.e..



(**a**) (**b**)

**Figure 1.** Set-up of the ANAIS-112 experiment: (**a**) Schematic view showing the nine modules and the full shielding; (**b**) Picture taken during ANAIS-112 commissioning with detectors, lead shielding and calibration system visible.

The ANAIS-112 hardware and software for data acquisition, fine-tuned in the previous operation of s¡ prototypes, is also described in [10]. The PMT electric pulses taken from the detectors are processed for trigger and for signals at both high and low energy. The waveform of the low-energy signal is recorded at 2 GS/s. For each PMT, the trigger is at phe level; the coincidence (logical AND) in a 200 ns window of the two PMT signals from a module gives the acquisition trigger. Every two weeks, measurements with $^{109}$Cd sources are made for calibration and correction of potential gain drifts, if necessary. An accurate calibration in the low energy range down to the threshold is performed by considering both the information from the $^{109}$Cd calibration measurements with that from $^{40}$K and $^{22}$Na emissions from crystal contaminations corresponding to 3.2 and 0.87 keV (identified by the coincidences with the corresponding high-energy gammas). Even though triggering with virtually 100% efficiency below 1 keV[1] has been shown by observing $^{22}$Na events,

[1] All the energies given in the paper correspond to electron equivalent energies.

the analysis threshold has been set at 1 keV; due to the selection criteria established for the rejection of non-scintillation events, the acceptance efficiencies decrease up to ~15% at 1 keV.

## 3. Results

In the analysis protocol of ANAIS-112, the energy distribution of single-hit events (those depositing energy at only one detector) in the region of interest is blinded. After the first year of data taking and before performing the first annual modulation analysis, 10% of acquired events (randomly chosen) were unblinded in order to perform the final tuning of the procedures for event rejection [10], to make a complete background analysis and characterization [12] and to evaluate the experiment sensitivity [13].

Background models have been developed for each one of the nine ANAIS-112 detectors based on the quantified radioactivity of the different components, independently estimated following several approaches [12,14]. The spectra measured in different energy regions and conditions are well reproduced in the models. The measured, efficiency-corrected background level is 3.58±0.02 c/keV/kg/day from 1 to 6 keV; the bulk contamination of NaI(Tl) crystals was identified as the main background source, being contributions of $^{210}$Pb and $^{40}$K and of cosmogenic $^{22}$Na and $^{3}$H the most relevant ones [15,16].

Results on annual modulation from ANAIS-112 data were firstly presented after unblinding 1.5 years of data, corresponding to an exposure of 157.55 kg·y, applying the designed analysis protocol [5]. Using the same procedure, a new modulation analysis was performed for the first 2 years of data taken until the beginning of September 2019, corresponding to 220.69 kg·y [17]. This model-independent analysis carried out is intended to search for modulation in the energy regions, [1-6] keV and [2,6] keV, analyzed by DAMA/LIBRA. A least-squared fit is made considering the measured rate R over the time t, summing all modules, as:

$$R(t) = R_0 + R_1\, exp(-t/\tau) + S_m\, cos(\omega(t- t_0)), \tag{1}$$

where $R_0$ and $R_1$ are free. The $\tau$ parameter is fixed from the time evolution given by the background model for the considered energy region. The period and phase, related to $\omega$ and $t_0$, are fixed as 1 y and maximum at June, 2$^{nd}$ , following the predictions for a standard galactic halo. The modulation amplitude, $S_m$, is set to zero when considering the null hypothesis. Figure 2 presents the fit of the counting rate to Equation 1 for the two considered energy regions. Results are consistent with the null hypothesis; the best fits for the amplitude under the modulation hypothesis are $S_m$ = -0.0029 ± 0.0050 c/keV/kg/day and $S_m$ = -0.0036 ± 0.0054 c/keV/kg/day for the [2-6] and [1-6] keV energy regions, respectively. These values are compatible at 1$\sigma$ with the absence of modulation and incompatible with DAMA/LIBRA result at ~2.6$\sigma$. Now, the analysis of the first 3 years of data accumulated (corresponding to 313.6 kg·y) is underway.

## 4. Discussion

Figure 3 compares these results obtained from ANAIS-112 data for the modulation amplitude $S_m$ to those obtained by DAMA/LIBRA [3]; in addition, the estimated sensitivity of ANAIS-112 at different confidence levels is depicted.

The obtained results from the analysis of ANAIS-112 two-year data fully confirm the sensitivity prospects previously evaluated [13], being at 2$\sigma$ level for 2 years. This supports the achievement of 3$\sigma$ for 5 years of data, as shown in Figure 4, which presents the ANAIS-112 projected sensitivity to DAMA/LIBRA (in units of $\sigma$ C.L) as a function of time. This sensitivity is quoted as the ratio between the measured DAMA/LIBRA modulation and the standard deviation on $S_m$ from ANAIS-112.

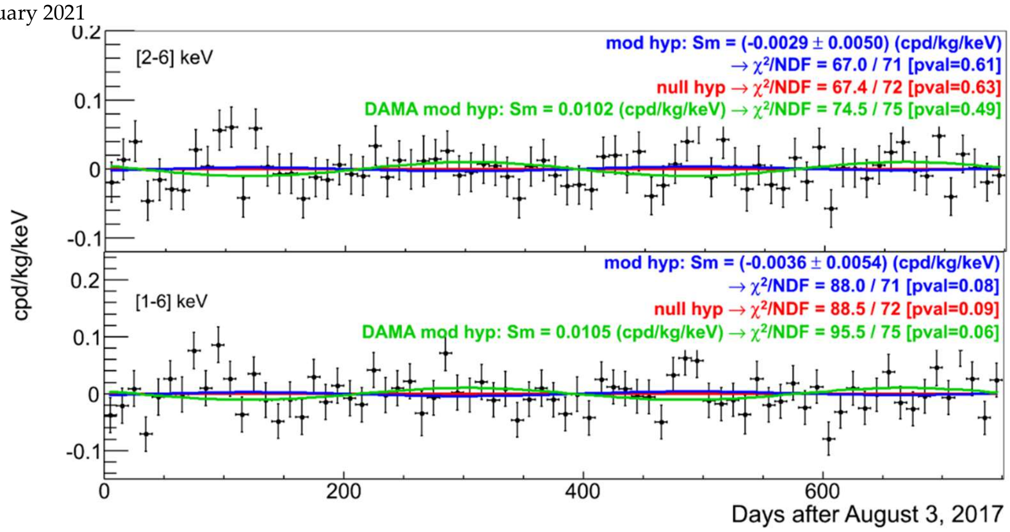



**Figure 2.** Results of the fit of ANAIS-112 data for first 2 years to Equation 1 in the two energy regions of [1-6] and [2-6] keV in the modulation (blue) and null hypothesis (red). The non-modulated components have been subtracted after fitting. DAMA/LIBRA results are shown too (in green) for comparison.

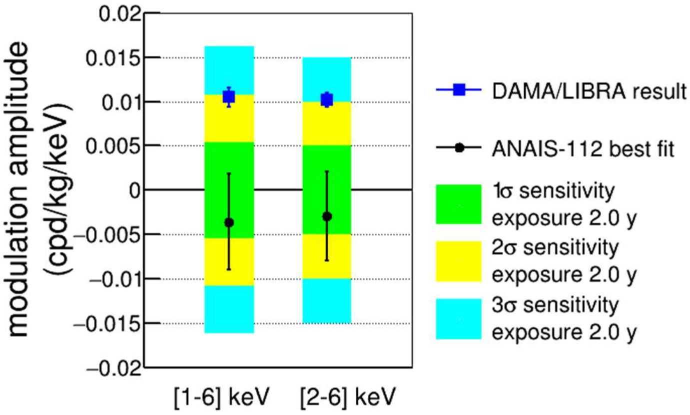



**Figure 3.** Comparison between ANAIS-112 best fit for the annual modulation amplitude $S_m$ from the first 2 years of data and DAMA/LIBRA result [3], for the two considered energy regions. The estimated sensitivity is presented too at several confidence levels as coloured bands: 1σ (green), 2σ (yellow) and 3σ (cyan).

## 5. Conclusions

The ANAIS-112 experiment aims at the confirmation or refutation of the annual modulation signal observed over two decades by the DAMA/LIBRA experiment at the Gran Sasso Underground Laboratory. It operates at the Canfranc Underground Laboratory with 112.5 kg of NaI(Tl) crystals and the data taking for the dark matter search is progressing smoothly since 2017. For the first 2 years of data collected (220.69 kg·y), the modulation amplitudes derived for the [2-6] and [1-6] keV energy regions ($S_m$ = -0.0029 ± 0.0050 c/keV/kg/day and $S_m$ = -0.0036 ± 0.0054 c/keV/kg/day, respectively) are compatible with modulation absence and incompatible with DAMA/LIBRA observation at 2.6σ, being the experimental sensitivity at 2σ. The preliminary analysis of the first 3 years of data (313.6 kg·y) seem to corroborate these conclusions; the publication of these results is in preparation. Being fully confirmed the ANAIS-112 sensitivity prospects, the cability of testing DAMA/LIBRA at

3σ when collected 5 years of data (expected for August 2022) is guaranteed, which will shed light to the long-standing DAMA/LIBRA conundrum.

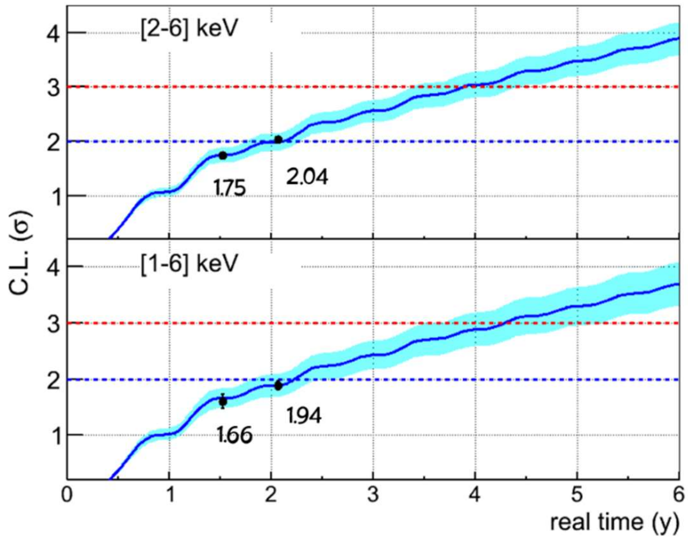



**Figure 4.** ANAIS-112 sensitivity to DAMA/LIBRA signal in units of σ C.L. as a function of time. Cyan bands show the 68% C.L. DAMA/LIBRA uncertainty in the modulation amplitude. Black dots and numbers give the experimental sensitivities obtained in the two ANAIS-112 annual modulation analysis carried out, for 1.5 and 2 years.

**Acknowledgments:** This work has been financially supported by the Spanish Ministerio de Economía y Competitividad and the European Regional Development Fund (MINECO-FEDER) under grants FPA2017-83133-P; the Spanish Agencia Estatal de Investigación under grant PID2019-104374GB-I00; the Consolider-Ingenio 2010 Programme under grants MultiDark CSD2009-00064 and CPAN CSD2007-00042; the LSC Consortium; and the Gobierno de Aragón and the European Social Fund (Group in Nuclear and Astroparticle Physics and I. Coarasa predoctoral grant). We thank the support of the Spanish Red Consolider MultiDark FPA2017-90566-REDC. Authors would like to acknowledge the use of Servicio General de Apoyo a la Investigación-SAI, Universidad de Zaragoza and technical support from LSC and GIFNA staff.

**Author Contributions:** A.O. and ML.S. designed the experiment; J.A., MA.O., A.O., A.S., ML.S. and P.V. commissioned the experiment; J.A., D.C., M.M., MA.O., Y.O., A.O. and ML.S. performed calibration and maintenance of the experiment; MA.O., M.M. and ML.S. developed analysis tools; I.C., M.M, J.P. and ML.S. analyzed the data; S.C. and P.V. developed background simulation codes; E.G., A.O. and J.P. performed radiopurity measurements; I.C., E.G., M.M., and J.P. contributed to sensitivity estimates; S.C. prepared the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

## Abbreviations

The following abbreviations are used in this manuscript:

ANAIS: Annual modulation with NAIs Scintillators
COSINUS: Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches
DAMA/LIBRA: DArk MAtter/Large sodium Iodide Bulk for RAre processes
LSC: "Laboratorio Subterráneo de Canfranc" (Canfranc Underground Laboratory)
phe: photoelectron
PICOLON: Pure Inorganic Crystal Observatory for LOw-energy Neutr(al)ino

PMT: Photomultiplier Tube
SABRE: Sodium-iodide with Active Background REjection
WIMP: Weakly Interacting Massive Particle

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