PROCEEDINGS OF SCIENCE

A combined search for dark matter with COSINE-100 and ANAIS-112

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The evidence for the existence of dark matter from astrophysical observations is strong. However, there has not been a conclusive direct detection of dark matter that does not rely on gravitational interaction with visible matter. One experiment, DAMA, claims to have observed an annual modulation signal in a sodium-iodide-based detector consistent with that expected from dark matter. COSINE-100 and ANAIS-112, two leading sodium-iodide dark matter experiments, were designed to test DAMA's claim directly using the same target material. COSINE-100, located at Yangyang Underground Laboratory in South Korea, and ANAIS-112, located at Canfranc Underground Laboratory, have been taking data since 2016 and 2017, respectively. The two experiments have similar sensitivity and have thus far published results independently. In this contribution, I will discuss our efforts to combine the data from the two experiments for increased search sensitivity and share its results.

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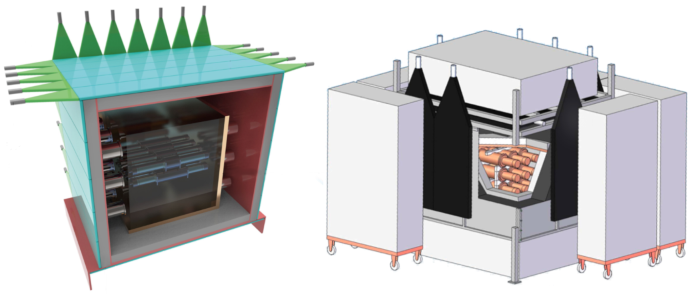

Figure 1: Left: COSINE-100 detector. Right: ANAIS-112 detector.

1. COSINE-100 and ANAIS-112 Experiments

The Universe is expected to be 27% dark matter as unaccounted for by standard model particle physics [1]. One way to search for dark matter is to look for its scattering off of atomic nuclei [2]. In addition, we can look for an annual modulation of this signature induced by the variation in its scattering rate due to the relative motion of the Sun and the Earth [3]. DAMA/LIBRA reports the discovery of a modulation signal with a significance of 12.9σ [4]. However, their results are incompatible with other dark matter direct detection experiments [5].

COSINE-100 [6] and ANAIS-112 [7] are two experiments explicitly designed to test DAMA by using the same target material, NaI(Tl). COSINE-100 and ANAIS-112 crystals were grown by the same producer, Alpha Spectra Inc., using similar raw powder materials. The COSINE-100 experiment collected physics data between October 16, 2016 and March 14, 2023 at the Yangyang underground laboratory (Y2L) in Korea. COSINE-100 consisted of five low background NaI(Tl) detectors for a total active mass of 61.3 kg. The COSINE-100 detector is described in Ref. [8] and visualized by the left panel of Figure 1. ANAIS-112 began taking data in August 3, 2017 at the Laboratorio Subterráneo de Canfranc (LSC) in Spain, ANAIS-112 consists of nine NaI(Tl) crystals, 12.5 kg each, for an active mass of 112.5 kg. The ANAIS-112 detector is described in Ref. [7] and visualized by the right panel of Figure 1.

ANAIS-112 and COSINE-100 have published results from annual modulation analyses using the first three years of data [9, 10] and six years of data [11, 12]. The datasets for both experiments' dark matter annual modulation searches are made available open access through Origin Excellence Cluster's Dark Matter Data Center [13]. Their results are compatible with the no modulation hypothesis to varying sensitivities.

I present here the proceedings for a talk given at the COST Action COSMIC WISPers Training School in Annecy, France during September 2025 on the combined analysis of data from ANAIS-112 and COSINE-100. Additionally, we compare these results with those from a simple (weighted) combination of the best-fit values, finding them to be compatible.

2. Combining Data

As shown in Ref. [14], both experiments are compatible and the weighted average of both results for three-year exposure provides a statistically equivalent result to a full combined analysis.

Therefore, we can use this to find the expected exclusion of DAMA/LIBRA when combining the latest results for the 6-years datasets of COSINE-100 [12] and ANAIS-112 [11].

The rigorous method, detailed in Ref. [14], includes fitting of each experiment's rate with their respective background models before performing a simultaneous fit across the datasets for the annual modulation signal.

ANAIS-112 publishes their three-year dataset with various background models, namely the MC-PDF model and the single exponential model. Though the MC-PDF model offers one fewer nuisance parameter, the alternative single exponential decay was found to be a good fit and the sensitivity achieved by the single exponential model matches well that of the MC-PDF's [15]. The single exponential model used in ANAIS is:

$$\phi_{bkgd}(t_i) = (1 - f) + f e^{-t_i/\tau} \tag{1}$$

where the two free parameters are the overall scaling factor, f, and time-dependent backgrounds effective decay time constant, τ. The exponential function is used to model the ANAIS-112 backgrounds in this combined analysis, as it is straightforward to implement and yields statistically equivalent results. The analysis of the ANAIS-112 three-year data following this model yields a non-statistically significant difference with the modulation search results in Ref. [9] and observes no change in sensitivity.

The background model published by COSINE-100 in Ref. [16] uses a sum of eight exponential decays, resulting from ^{3}H, ^{22}Na, ^{109}Cd, ^{210}Pb in the bulk of the NaI crystal, ^{210}Pb on nearby surfaces, ^{113}Sn, ^{121m}Te, and ^{127m}Te, plus a constant "flat" term which accounts for the long-lived isotopes:

$$R_i\,(t \mid \alpha_i, \beta_i) = \alpha_i + \sum_{k=1}^{N_{bkgd}} \beta^{i}_{0,k} e^{-\lambda_k t}, \tag{2}$$

where α_i is the flat component of the i^{th} crystal, $\beta_{0,k}$ is the initial rate at $t = 0$ of the k^{th} short-lived radioisotope, and λ_k is the decay constant of that component. The thorough modeling of these components is described in Refs. [8, 16, 17].

3. Annual Modulation Search

After the residuals from COSINE-100 and ANAIS-112 are obtained from the background subtraction procedures, they are simultaneously fit for the annual modulation signal. In the standard halo dark matter model, the rate of scattering events in the background subtracted residuals is expected to be:

$$R(t) = S_m \cos(\omega(t - t_0)), \tag{3}$$

where $\omega = \frac{2\pi}{T}$ for the period of $T = 1$ year, t_0 is the phase (fixed to June 2), and S_m is a modulation amplitude. We used 15-day bins for both experiments with January 1, 2016 as the common start date for $t = 0$, reaching a total exposure of 485 kg·yr for the combined 3-year datasets. The exposure for the combined 6-year datasets is 984 kg·yr. Figures 2 and 3 demonstrate the invariability of results from chosen statistical methods alongside the modulation best fit value for the 3-year and 6-year combined datasets respectively.

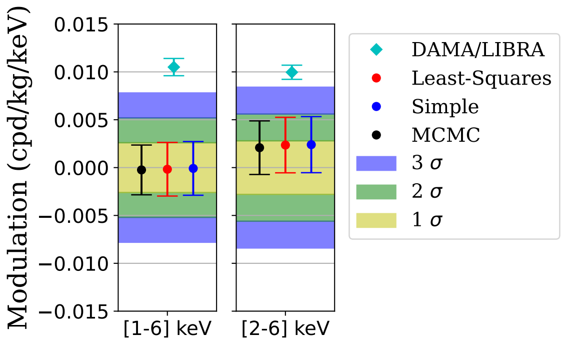

Figure 2: Best-fit amplitudes for the 1–6 and 2–6 keV regions where the colored bands show the combined sensitivity. There is remarkable compatibility between results of the MCMC, Least-Squares fit, as well as the simple combination of the COSINE-100 and ANAIS-112 independent results. Figure from Ref. [14].

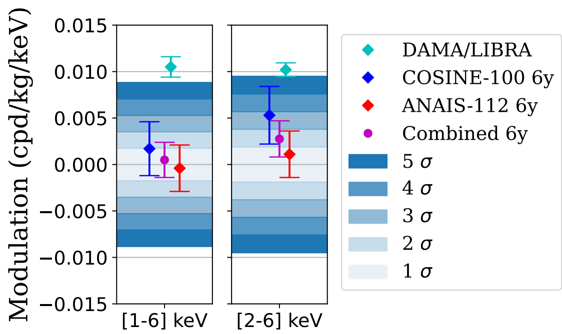

Figure 3: Simple combination results of the COSINE-100 full dataset [12] and ANAIS-112 6-year [11] annual modulation searches. The colored bands show the sensitivity region for 6-year data from both experiments combined in 1σ (lightest blue) to 5σ (darkest blue). Figure from Ref. [14].

4. Results

Careful consideration for possible systematics is undergone in the direct combination of the residual rates obtained by the subtraction of the fitted respective background models for the COSINE-100 and ANAIS-112 3-year datasets [14]. Best fit values obtained for the modulation amplitudes are -0.0002 ± 0.0026 cpd/kg/keV in the 1–6 keV and 0.0021 ± 0.0028 cpd/kg/keV in the 2–6 keV energy regions. These results are incompatible with DAMA/LIBRA's assertion for their observation of annual modulation at 3.7σ and 2.6σ, respectively. Furthermore, a simple combination of the newly released 6-years datasets from COSINE-100 and ANAIS-112 find values consistent with no modulation at 0.0005 ± 0.0019 cpd/kg/keV in the 1–6 keV and 0.0027 ± 0.0021 cpd/kg/keV in the 2–6 keV energy regions with 4.7σ and 3.5σ respective exclusions of DAMA/LIBRA [14].

These results demonstrate that, through open access of data and background modeling techniques, NaI(Tl) experiments can reasonably combine to improve search sensitivities for dark matter as a community and have shown that no modulation consistent with DAMA/LIBRA is observed in NaI(Tl) detectors.

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