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Combined Annual Modulation Dark Matter Search with COSINE-100 and ANAIS-112

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The annual modulation signal, claimed to be consistent with dark matter as observed by DAMA/LIBRA in a sodium-iodide based detector, has persisted for over two decades. COSINE-100 and ANAIS-112 were designed to test the 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 in Spain, have been taking data since 2016 and 2017, respectively. Each experiment published its respective results independently. In this Letter, we present the results of an annual modulation search as a test of the signal observed by DAMA/LIBRA with the first three respective years of data from COSINE-100 and ANAIS-112. Using a Markov Chain Monte Carlo method, we find best fit values for modulation amplitude

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of -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 not compatible with DAMA/LIBRA's assertion for their observation of annual modulation at 3.7σ and 2.6σ, respectively. Performing a simple combination of the newly released 6-year datasets from both experiments finds 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 the DAMA/LIBRA signal.

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The energy content of the Universe is expected, based on cosmological observations, to be 27 percent dark matter, which is unaccounted for by standard model particle physics [1]. Many theories exist that could explain the nature of a dark matter particle. The weakly interacting massive particle (WIMP) is particularly compelling as it fulfills strong theory motivations and, given controlled uncertainties from astronomical input, could be realized by direct detection experiments alone [2].

One way to search for WIMPs and WIMP-like particles is to look for their scattering off of atomic nuclei [3]. In addition, we can look for an annual modulation of this signature induced by the variation in their scattering rate due to the relative motion of the Sun and the Earth [4].

The DAMA/NaI Collaboration first claimed observing an annual modulation in their data in 1997 [5]. Since then, they have mounted a new experiment, DAMA/LIBRA, which now reports a modulation with a significance of 12.9σ [6]. Their results contradict other direct detection dark matter experiments in the most conventional scenarios for the dark matter particle and halo models [7], as well as the energy dependence of the signal expected by the WIMP spin-independent isospin conserving case in the standard halo model [8]. Attempts to explain these contradictions with alternative dark matter models or detector effects have not been successful [6,9].

COSINE-100 [10] and ANAIS-112 [11] are two experiments explicitly designed to test DAMA by using the same target material, NaI(Tl), which removes all dependencies in the particle and halo model that affect the comparison between experiments using different target nuclei. COSINE-100 and ANAIS-112 crystals were grown by the same producer, Alpha Spectra Inc., using similar raw powder materials. Detector design is also very similar in both experiments. The first crystals were produced in 2012 for the ANAIS experiment.

In addition to using the same target material, good control of systematics in the calibration of the detectors within the region of interest is mandatory. The most relevant caveat associated with the response of the NaI(Tl) detectors comes from the uncertainties in the knowledge of the quenching factors (QFs) for the scintillation of nuclear recoils in NaI(Tl), the ratio of light yields from a nuclear recoil with respect to an electron recoil of the same energy. Thought to be an intrinsic property of the material, the sodium and iodine QFs generally have been found to be consistent across many independent measurements for crystals grown from various powders and techniques, but with a relatively high dispersion. In addition, the most recent measurements show a steady decrease at low recoil energies within the region of interest for the testing of the DAMA/LIBRA result [12–15]. Recently, these QFs for sodium recoils have been found to vary with the calibration methods applied [14], which could explain some of the dispersion in the values obtained by the different measurements. However, the QFs reported by DAMA/LIBRA are assumed by the collaboration to be energy independent, and the values are significantly higher [16].

At present, it cannot be ruled out that differences in the QFs could be found for different crystals, depending on the impurities content, crystalline properties, Tallium doping, etc. This being the case, the comparison between COSINE-100, ANAIS-112, and DAMA/LIBRA would require a good knowledge of the QFs for sodium and iodine recoils in all the experiments. COSINE-100 and ANAIS-112 have carried out dedicated measurements of the QFs for their crystals [14,15], and address the analysis of this discrepancy in their recent 6-year dataset publications [17,18].

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 detectors were shielded by 700 m rock overburden (1800 mwe), 2200 L of liquid scintillator, copper, lead, and plastic scintillator muon veto panels. The liquid scintillator is an additional veto at low energies, allowing COSINE-100 to conduct dark matter searches between 2–3 cpd/kg/keV background rates in the energy region of interest [19]. The COSINE-100 detector is described in Ref. [20]. COSINE-100's signal selection efficiency is 85% at 1.0 keV and approaches unity at 2 keV [21].

ANAIS-112 began taking data in August 3, 2017 at the Laboratorio Subterráneo de Canfranc (LSC) in Spain, under a rock overburden of 2450 mwe ANAIS-112 will continue in operation until the end of 2025. ANAIS-112 consists of nine NaI(Tl) crystals, 12.5 kg each, for an active mass of 112.5 kg. The shielding is composed of archaeological lead, low-activity lead, an antiradon box, active muon vetoes, polyethylene bricks, and water tanks [11,22]. The background rate in the region of interest amounts to 2.0–4.7 cpd/kg/keV, depending on the crystal, and

TABLE I. Comparison of annual modulation search results of COSINE-100, ANAIS-112, and their combined search with the 3-year datasets found by this Letter. These values reflect the decision of the background model and include our reanalysis for the COSINE-100 3-year dataset using the updated background model [25]. The least-squares (LS) frequentist method is shown beside the MCMC Bayesian method. All results show the modulation amplitude in cpd/kg/keV for the frequency and phase-fixed scenario.

Configuration	1–6 keV	2–6 keV
COSINE-100 (this)	0.0052 ± 0.0042	0.0067 ± 0.0047
ANAIS-112 (this)	-0.0040 ± 0.0037	-0.0002 ± 0.0037
Combined MCMC	-0.0002 ± 0.0026	0.0021 ± 0.0028
Combined LS	-0.0002 ± 0.0028	0.0023 ± 0.0029
Combined simple	-0.0001 ± 0.0028	0.0024 ± 0.0029

efficiencies around 95% in the 1–6 keV energy region have been checked with ^{109}Cd and ^{252}Cf periodical calibrations [17].

With ANAIS-112's higher active mass and COSINE-100's lower background rate because of the liquid scintillator veto, the two experiments have similar sensitivities. ANAIS-112 and COSINE-100 have published results from the first three years of data, corresponding to live times of 2.78 years and 2.58 years, respectively [21,23]. Both experiments find no modulation to support the DAMA/LIBRA dark matter claim, and their results are displayed in Table I. The datasets for both experiments' dark matter annual modulation search are made available open access through Origin Excellence Cluster's Dark Matter Data Center [24]. Recently, COSINE-100 and ANAIS-112 have released modulation searches with datasets corresponding to 5.85 years [18] and 5.56 years live time [17], respectively. Both results are compatible with the no modulation case.

Here, we present a combined analysis of the first three years of data from ANAIS-112 and COSINE-100 using all the information available on the time distribution of the rates, efficiencies, and background modeling for both experiments and compare the Bayesian and frequentist approaches. Additionally, we compare these results with those from a simple (weighted) combination of the best-fit values, finding them to be compatible. We also present the simple combination of the six-year results as an indication of what can be expected when the data are released and analyzed by the methods described here.

Computation of residuals—Because of the numerous factors each experiment must individually account for, the best way to directly combine datasets is to compute the residuals of each crystal detector for each experiment and then, perform a combined fit to those data.

Each experiment has provided its measured event rate with the respective crystal detector live times and efficiencies. For the modulation search, we are interested in the single-hit selected events as random coincidences of dark matter and background signals are negligible. We have seen from Ref. [26] that an incomplete description of time-dependent backgrounds can artificially induce modulation signals. As such, each experiment has conducted a thorough investigation of time-dependent backgrounds [27,28]. Included in these models is crucial information about the radioactive background content of the experiments where, in the region of interest, the dominant components are ^{210}Pb on the crystal surface and, in the crystal bulk, ^{3}H and ^{40}K.

ANAIS-112 background model—ANAIS-112 has explored different techniques for the background modeling in the annual modulation analysis for the 3-year dataset, including a single exponential decay and Monte-Carlo (MC) probability density function (PDF) models, both added to a constant component [29,30]. The MC PDF background model used by ANAIS is built by the addition of all the background contributions identified in the ANAIS-112 background model developed in Ref. [31] and updated with the three-year data and improved analysis methods developed in Refs. [28,29]. This MC PDF takes into account for each energy region the evolution in time of each contribution, according to the lifetimes of each parent isotope. Further updating is in progress using the available six-year data.

Though the MC PDF model offers one fewer nuisance parameter, the alternative single exponential decay was found to be a good fit with $\chi^2 \approx 129/107$ and $115/107$ in the 1–6 and 2–6 keV regions, respectively, for the modulation hypothesis [29]. The sensitivity achieved by the single exponential model matches well that of the MC PDF's. The single exponential model used in ANAIS is

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

where the two free parameters are the overall scaling factor, f, and time-dependent background 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 3-year data following this model yields a nonstatistically significant difference with the modulation search results in Ref. [23] and observes no change in sensitivity.

COSINE-100 background model—The COSINE-100 time-dependent background model 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 near-by surfaces, ^{113}Sn, ^{127m}Te, and ^{127m}Te, plus a constant "flat" term which accounts for the long-lived isotopes:

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

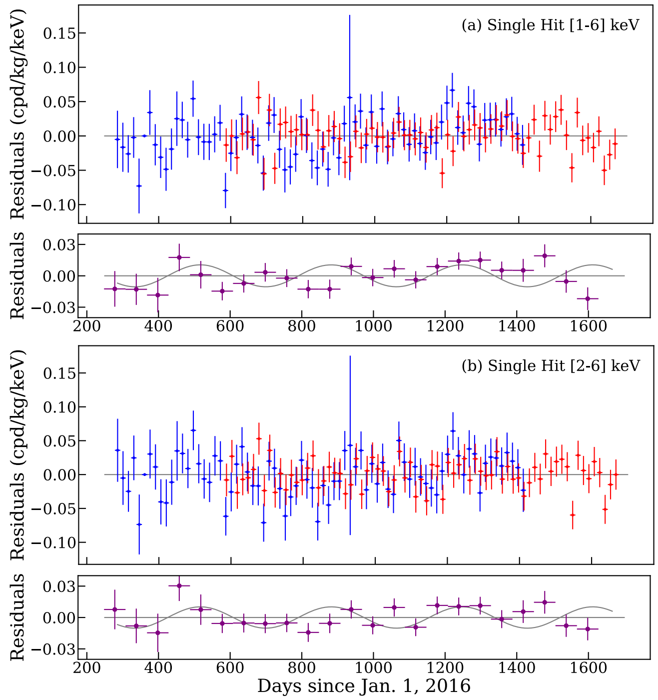

FIG. 1. The background subtracted residuals for COSINE-100 (blue) and ANAIS-112 (red), for a total exposure of 485 kg · yr in energy ranges of (a) 1–6 and (b) 2–6 keV. The subplots show their combined data in time bins of 2 months (purple) where a gray curve is drawn to visually compare the DAMA modulation signal.

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. [20,25,27]. It is worth noting that the surface-^{210}Pb component has an "effective" half-life of a computed 33.8 ± 8 years due to it being replenished from the ^{222}Rn decay chain [25].

Additionally, this Letter uses the updated background model from COSINE-100 in Ref. [25]. We reanalyze the 3-year data and find a slight, nonstatistically significant, difference with the previous COSINE-100 3-year modulation search results in Ref. [21], and observe no change in sensitivity (see Table I).

Annual modulation search—Residuals retrieved from subtracting modeled backgrounds are plotted together in Fig. 1. 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. Residuals from COSINE-100 and ANAIS-112 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

$$R(t) = S_m \cos[\omega(t - t_0)], \qquad (3)$$

TABLE II. Comparison of annual modulation search results from COSINE-100 [21], ANAIS-112 [23], and DAMA/LIBRA [6]. All results show the modulation amplitude in cpd/kg/keV for the frequency and phase-fixed scenario.

Configuration	1–6 keV	2–6 keV
COSINE-100 [21]	0.0067 ± 0.0042	0.0050 ± 0.0047
ANAIS-112 [23]	-0.0013 ± 0.0037	0.0031 ± 0.0037
DAMA/LIBRA [6]	0.0105 ± 0.0011	0.0102 ± 0.0008

where $\omega = (2\pi/T)$ for the period of $T = 1$ yr, t_0 is the phase (fixed to June 2), and S_m is a modulation amplitude. DAMA/LIBRA reports a modulation amplitude of $S_m = 0.0105 \pm 0.0011$ (0.0102 ± 0.0008) cpd/kg/keV in the 1–6 (2–6 keV) energy region [6]. It is also possible to simultaneously fit the background models of the respective experiments along the modulation function, bypassing the need to compute residuals, which retrieves equivalent results.

Bayesian vs frequentist—We carried out both a χ^2 minimization of the least-squares (i.e., frequentist) method and Markov chain Monte Carlo (MCMC, i.e., Bayesian) analysis to fit the data shown in Fig. 1 with Eq. (3). While each analysis method has its benefits and drawbacks, we illustrate here that both methods give consistent results for the annual modulation search using the COSINE-100 and ANAIS-112 datasets. The COSINE Collaboration uses a Bayesian approach to modulation search, while the ANAIS Collaboration has performed a frequentist method using χ^2 minimization [21,23].

The annual modulation results of COSINE-100, ANAIS-112, their combined search, and the comparison of statistical methods are summarized in Table I. The previously published values of COSINE-100 [21], ANAIS-112 [23], and DAMA/LIBRA [6] are displayed in Table II for comparison. Despite the differences in background models with the previously published searches, the sensitivities found for COSINE-100 and ANAIS-112 by this Letter are unchanged.

Figure 2 displays the results for the analysis performed via the least-squares and MCMC method, as well as the simple combination of the two independent experiments' results. The simultaneous fit of the 3-year datasets from COSINE-100 and ANAIS-112 to Eq. (3) finds no modulation, with MCMC best-fit amplitudes at -0.0002 ± 0.0026 cpd/kg/keV and 0.0021 ± 0.0028 cpd/kg/keV, for 1–6 and 2–6 keV, respectively. These values are compatible with the amplitudes found by the least-squares fit as well as the simple combination of the COSINE-100 and ANAIS-112 independent results.

Method verification through simulations—A comprehensive investigation for the biases of the analysis is conducted by employing a pseudostudy to quantify the impact of systematics. COSINE-100 and ANAIS-112 have

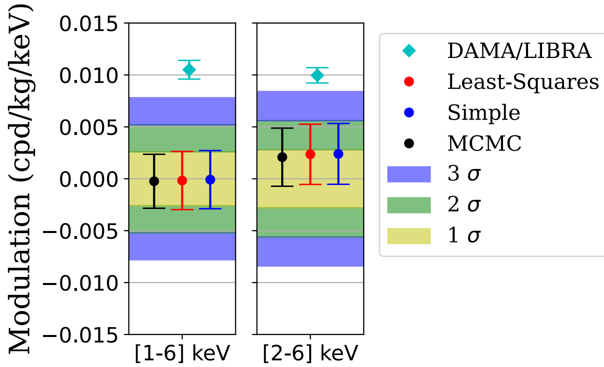

FIG. 2. Best-fit amplitudes for the 1–6 and 2–6 keV regions where the colored bands show the combined sensitivity. There is remarkable compatibility between results of the MCMC, least-squares fit, as well as the simple combination of the COSINE-100 and ANAIS-112 independent results.

each performed their own pseudostudies and found no relevant biases [21,29]. Since the method for fitting the modulation to residuals is specific to this Letter, we present the results for the bias investigation by pseudostudy for this method.

We simulated the data for each crystal in both experiments by taking the COSINE and ANAIS background models described in Eqs. (1) and (2), inject various amplitudes for the dark matter signal, and vary them with a Poisson distribution to mimic a counting experiment.

Data generated from the background model produces a simulated experiment for the null hypothesis case without the dark matter signal. We build ensembles by injecting the dark matter signal with varying S_m amplitudes of ± 0.0025, ± 0.005, ± 0.0075, and the DAMA/LIBRA signal, ± 0.0105 cpd/kg/keV, with fixed phase (June 2) and period (1 yr). Including the no modulation case, this gives a total of 9 ensembles. Approximately 10 000 pseudoexperiments were generated per ensemble to quantify potential biases, defined as the difference between the injected signal and the fit result. For all ensembles, mean biases were found to be negligible.

Figure 3 shows the bias distribution for the 10 000 experiments of the null hypothesis and the DAMA/LIBRA modulation cases in the top panel. The bottom panel shows the pull distribution which is computed by dividing the bias by the fit uncertainty and characterizes the error bias. These are compatible with the standard normal distribution and reflect that the sensitivity of the experiment(s) is therefore compatible with the spread of the pseudomodulation results. Table III lists this value in the last column and shows the corresponding results for the mean bias for the null hypothesis and DAMA/LIBRA modulation cases.

Towards 1 ton yr combined exposure—COSINE-100 has recently released its search for annual modulation with the full dataset, utilizing an exposure of 358 kg · yr [18]. Likewise, ANAIS-112 has recently released their 6-year

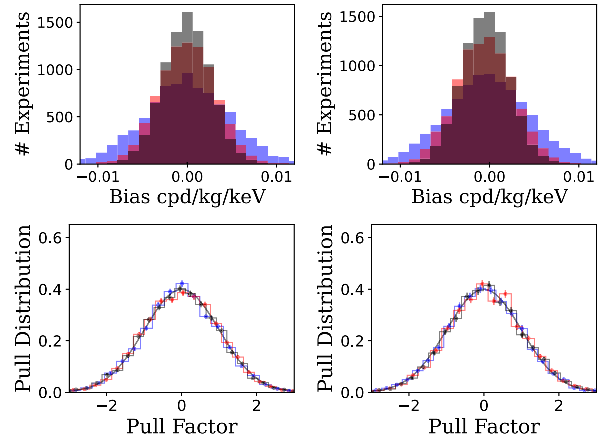

FIG. 3. (Top) Distribution of the bias between best-fit and injected modulation amplitudes in the 1–6 keV region for null hypothesis (top left) and DAMA modulation (top right) cases. (Bottom) Pull distributions for the 1–6 keV (bottom left) and 2–6 keV region (bottom right) where all are compatible with $\mu = 0$ and $\sigma = 1$ (gray curve). The blue, red, and black shaded regions correspond to COSINE-100, ANAIS-112, and their combined analysis, respectively. See Table III for reported numerical values for the mean biases.

dataset with an exposure of 626 kg · yr [17]. The procedures of this Letter have shown that the data from the two experiments are compatible and that their results can be combined; the direct combination of results provides a similar value to the thorough analysis which can utilize either MCMC or χ^2 minimization.

The simple combination for the combined exposure of 984 kg · yr results in modulation values of 0.0005 ± 0.0019 cpd/kg/keV in the 1–6 keV and 0.0027 ± 0.0019 cpd/kg/keV in the 2–6 keV energy regions.

TABLE III. Bias in $\times 10^{-4}$ cpd/kg/keV (defined as the difference of the injected signal and the fit result), found by the fitting procedures derived from simulation for the no modulation case and the DAMA/LIBRA modulation in the 1–6 keV and 2–6 keV energy regions. The bias listed for ANAIS-112 corresponds to the background model from Eq. (1) as reported in Ref. [29] and the COSINE-100 bias uses the updated background model from Ref. [25]. The last column shows the standard deviation in $\times 10^{-4}$ cpd/kg/keV of the pseudostudy modulations.

1–6 keV	Bias [$S_m = 0$]	Bias [DAMA S_m]	σ_{Sm}
COSINE-100	-0.2 ± 0.4	-3.9 ± 0.3	47 ± 4
ANAIS-112	-0.4 ± 0.2	-4.7 ± 0.2	35 ± 3
Combined	-0.3 ± 0.2	-3.8 ± 0.2	28 ± 2
2–6 keV			
COSINE-100	-0.3 ± 0.4	-4.3 ± 0.4	52 ± 5
ANAIS-112	-0.3 ± 0.2	-4.7 ± 0.3	35 ± 3
Combined	-0.2 ± 0.2	-4.4 ± 0.2	29 ± 3

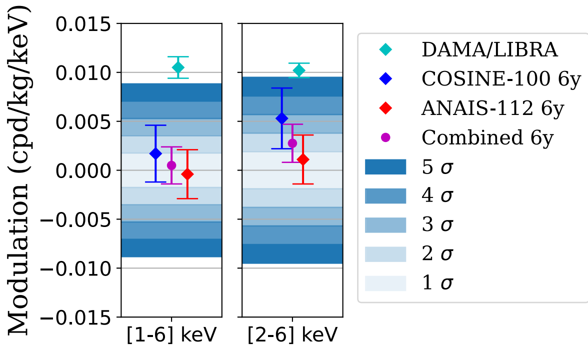

FIG. 4. Simple combination results of the COSINE-100 full dataset [18] and ANAIS-112 6-year [17] annual modulation searches. The colored bands show the sensitivity region for 6-year data from both experiments combined in 1σ (lightest blue) to 5σ (darkest blue).

These values are incompatible with the DAMA/LIBRA signal to significances of 4.7σ and 3.5σ, respectively, as illustrated by Fig. 4. This result strongly challenges the interpretation of the DAMA/LIBRA modulation in terms of galactic dark matter. A thorough combined analysis will be performed when the full ANAIS-112 dataset is available.

Conclusions—The methods described in this Letter demonstrate the compatibility of the COSINE-100 and ANAIS-112 experiments. The direct combination of the residual rates obtained by the implementation of the respective background models show careful consideration for possible systematics. Using the MCMC method, we find best fit values on the combined 3-year datasets from COSINE-100 and ANAIS-112 with modulation amplitude of -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-year datasets from COSINE-100 and ANAIS-112 finds 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 the DAMA/LIBRA signal.

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Data availability—The data that support the findings of this Letter are openly available [24].

[1] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **641**, A6 (2020); **652**, C4(E) (2021).
[2] G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, S. Profumo, and F. S. Queiroz, Eur. Phys. J. C **78**, 203 (2018).
[3] M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985).
[4] K. Freese, J. A. Frieman, and A. Gould, Phys. Rev. D **37**, 3388 (1988).
[5] R. Bernabei, P. Belli, F. Cappella, R. Cerulli, F. Montecchia, F. Nozzoli, A. Incicchitti, D. Prosperi, C. Dai, H. Kuang, J. Ma, and Z. Ye, Int. J. Mod. Phys. D **13**, 2127 (2004).
[6] R. Bernabei *et al.*, Prog. Part. Nucl. Phys. **114**, 103810 (2020).
[7] M. Schumann, J. Phys. G **46**, 103003 (2019).
[8] S. Baum, K. Freese, and C. Kelso, Phys. Lett. B **789**, 262 (2019).
[9] R. Bernabei *et al.*, Eur. Phys. J. C **74**, 3196 (2014).
[10] G. Adhikari *et al.*, Eur. Phys. J. C **78**, 107 (2018).
[11] J. Amaré *et al.*, Eur. Phys. J. C **79**, 228 (2019).
[12] H. W. Joo, H. S. Park, J. H. Kim, S. K. Kim, Y. D. Kim, H. S. Lee, and S. H. Kim, Astropart. Phys. **108**, 50 (2019).
[13] L. J. Bignell *et al.*, J. Instrum. **16**, P07034 (2021).
[14] D. Cintas *et al.*, Phys. Rev. C **110**, 014613 (2024).
[15] S. H. Lee *et al.*, Phys. Rev. C **110**, 014614 (2024).
[16] R. Bernabei *et al.*, Phys. Lett. B **389**, 757 (1996).
[17] J. Amaré *et al.*, Phys. Rev. Lett. **135**, 051001 (2025).
[18] N. Carlin *et al.*, arXiv:2409.13226.
[19] G. Adhikari *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **1006**, 165431 (2021).
[20] P. Adhikari *et al.* (COSINE-100 Collaboration), Eur. Phys. J. C **78**, 490 (2018).
[21] G. Adhikari *et al.* (COSINE-100 Collaboration), Phys. Rev. D **106**, 052005 (2022).
[22] I. Coarasa *et al.*, J. Cosmol. Astropart. Phys. 11 (2022) 048; 06 (2023) E01.
[23] I. Coarasa *et al.*, Commun. Phys. **7**, 345 (2024).
[24] O. E. Cluster, Dark Matter Data Center (2024), https://www.origins-cluster.de/odsl/dark-matter-data-center.
[25] G. H. Yu *et al.* (COSINE-100 Collaboration), Eur. Phys. J. C **85**, 32 (2025).

[26] G. Adhikari *et al.* (COSINE-100 Collaboration), Sci. Rep. **13**, 4676 (2023).
[27] G. Adhikari *et al.* (COSINE-100 Collaboration), Eur. Phys. J. C **81**, 837 (2021).
[28] J. Amaré *et al.*, J. Phys. Conf. Ser. **2156**, 012175 (2021).
[29] J. Amaré *et al.*, Phys. Rev. D **103**, 102005 (2021).
[30] I. Coarasa Casas, ANAIS-112. Searching for the annual modulation of dark matter with a 112.5 kg NaI(Tl) detector at the Canfranc Underground Laboratory., Ph.D. thesis, Zaragoza University, 2021.
[31] J. Amaré, S. Cebrián, I. Coarasa *et al.*, Eur. Phys. J. C **79**, 412 (2019).