

ANAIS-112: the most sensitive experiment to test the DAMA/LIBRA signal in a model independent way

Iván Coarasa on

behalf of the **ANAIS team** icoarasa@unizar.es

> 15th International Workshop on the Identification of Dark Matter 2024

8 July - 12 July

L'Aquila, Italy



Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza



Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

The ANAIS experiment

ANAIS (<u>Annual modulation with Nal(Tl) scintillators</u>) intends to provide a model
 GOAL independent test of the signal reported by DAMA/LIBRA, using the same target and technique, but different experimental approach and environmental conditions



Projected sensitivity: 3σ in 5 years data-taking



ANAIS-112 SET-UP

- 9 ultrapure NaI(Tl) crystals 12.5 kg (**112.5 kg**) in 3 × 3
- Cylindrical modules coupled to 2 high QE PMTs (~40%)





On 3 August 2017, data collection starts

SHIELDING

DAMA/LIBRA

- Gamma shielding: \geq 10 cm of OFHC Cu + 15 cm of Pb
- Anti-Rn: Plexiglas box fluxed with N₂ gas
- Neutron shielding: 10/40 cm Polyethylene/paraffin + 1.5 mm Cd foils

ANAIS-112

- Gamma shielding: 10 cm of ancient Pb + 20 cm of Pb
- Anti-Rn: metallic box fluxed with N₂ gas
- Neutron shielding: 40 cm Polyethylene/water tanks
- Active muon vetoes: 16 scintillator plastics



MUON VETO



In ANAIS, we flag every muon that cross the shielding

We set a (configurable) dead-time after every passage

DAMA/LIBRA has no muon veto





 $\Phi_{\mu} \ (m^{-2} \, s^{-1})$

10²

100

10⁻²

Surface

OROVILLE (USA)

IMB (USA)

SOUDAN (USA)

KAMIOKA (Jap / BOL

do not fulfill the DM requisites Not enough muon-induced fast neutrons to account for the signal

 μ flux @LSC

=10 $\times \mu$ flux @LNGS

LNGS

HOMESTAKE (USA)

SUDBURY (Canada)

BAKSAN (Russia)

5000

6000

But still some open questions:

- (Delayed) effect of muons in PMTs?
- Slow phosphorescence in Nal?

I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

NaI(Tl) scintillating detectors

DAMA/LIBRA

- 25 crystals, 10.2×10.2×25.4 cm³, 9.7 kg each
- Saint Gobain, Kyropoulos method with a Pt crucible
- PMTs phase1: ETL 9265-B53/FL and 9302-A/FL (QE~30%)
- PMTs phase2: Hamamatsu R6233MOD (QE~38%)
- Light guides: 10 cm Suprasil B

ANAIS-112

- 9 cylindrical crystals, 12 cm $\phi \times 30$ cm, 12.5 kg each
- Alpha Spectra (same as COSINE)
- PMTs: Hamamatsu R12669SEL2 (QE~40%)
- Quartz windows (no light guides)



LIGHT COLLECTION

DAMA/LIBRA



- DAMA/LIBRA-phase1 showed a very good linearity between the calibration with the 59.5 keV line of ²⁴¹Am and the tagged 3.2 keV line of ⁴⁰K
- In DAMA/LIBRA-phase2, a slight non-linearity is observed (it gives a shift of about 0.2 keV at the software energy threshold and vanishes above 15 keV)

Prog. Part. Nucl. Phys. 114 (2020) 103810

I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

ANAIS-112



In ANAIS non proportionality is observed < 25 keV (20%)



LOW ENERGY CALIBRATION - ROI [1-6] keV

Guides

for ¹⁰⁹Cd

sources

Mylar

window

Guides for ²⁴¹Am sources



DAMA/LIBRA

- Periodical calibrations every ~10 days with a ²⁴¹Am source (30.4 keV (composite), 59.5 keV). Linear calibration down to threshold
- Linearity check and corrected @ 3.2 keV with whole statistics



I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

ANAIS-112

- Detectors equipped with a Mylar window
- Calibration with ¹⁰⁹Cd sources (11.9, 22.6 and 88.0 keV) every two weeks for gain correction
 - Calibration in the ROI with internal bulk contaminants ²²Na (0.9 keV) and ⁴⁰K (3.2 keV) with whole statistics



Non proportionality < 25 keV (20%)



Linear calibration in 2 ranges:

- 1-10 keV [ROI]
 - 10-100 keV

EVENT SELECTION AND EFFICIENCY

ANAIS-112

DAMA/LIBRA



NR QUENCHING FACTORS Required for the WIMP interpretation

DAMA/LIBRA



I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

ANAIS-112

Monochromatic neutron source at TUNL (Duke Univ.)

Five small NaI(Tl) crystals from AS (different powder qualities) measured in same set-up @TUNL

- **Compatible** values for the 5 crystals
- Noticeable differences for different energy calibrations (Nal non-linearity)



D. Cintas et al., arXiv:2402.12480 (2024), Accepted in Phys. Rev. C



Robust agreement between on-site neutron calibrations and TUNL measurements when QF(E) is considered

Data-taking overview





Annual modulation results



ANAIS–112 modulation results:

- 1.5 y: Phys. Rev. Lett. 123, 031301 (2019)
- 2 y: J. Phys. Conf. Ser. 1468, 012014 (2020)
- 3 y: Phys. Rev. D 103, 102005 (2021)

(keV)		S _m (counts/keV/kg/day)		
	ANAIS-112	COSINE-100 (*)	DAMA/LIBRA (†)	
[1-6]	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011	
[2-6]	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008	
0.02 0.015 0.01 0.000 0 (cbd/keV) 0 0.00- 0.010 -0.015		 COSINE result COSINE result DAMA/LIBRA result ANAIS-112 best fit 10 sensitivity exposure 3.0 y 20 sensitivity exposure 3.0 y 30 sensitivity exposure 3.0 y 	ANAIS: $\sim 2.5\sigma$ sensitivity	

Annual modulation results



<u>ANAIS-112 modulation results:</u>

- 1.5 y: Phys. Rev. Lett. 123, 031301 (2019)
- 2 y: J. Phys. Conf. Ser. 1468, 012014 (2020)
- 3 y: Phys. Rev. D 103, 102005 (2021)

NEW DATA RELEASE: 3y + ML(*) arxiv 2404.17348 (submitted to Comm. Phys.)

(*) Based on JCAP11(2022)048

About 95% of live time

Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

Improved filtering protocols with ML techniques

The region of interest (1-6 keV) is dominated by **non-bulk scintillation events**

Improve the "bulk scintillation" event selection with ML techniques based on BDT

Training populations

Signal events: dedicated on-site neutron calibrations with ²⁵²Cf source **Noise events:** blank module similar to ANAIS-112 modules, but without NaI(Tl) crystal





Performance of using ML for event selection in: JCAP11(2022)048 and JCAP06(2023)E01 Reanalysis of 3 years data in: *arXiv*:2404.17348 (Apr. 2024), Submitted to Comm. Phys.

Improved filtering protocols with ML techniques

Following JCAP11(2022)048



Annual modulation analysis strategy

Focus on **model independent** analysis searching for modulation

- ➔ In order to better compare with DAMA/LIBRA results
 - Juse the same energy regions ([1-6] keV, [2-6] keV)
 - → Fix period 1 year and phase to June 2nd
- → Simultaneous fit of the 9 detectors in 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i \mu_i)^2 / \sigma_i^2$, where the expected number of events μ_i for detector *d* in time bin *i* is given by:

$$\mu_{i,d} = \left[R_{0,d} \left(1 + f_d \phi_{bkg,d}^{MC}(t_i) \right) + \mathbf{S}_m \cos(\omega(t_i - t_0)) \right] M_d \Delta E \Delta t$$

Annual modulation analysis strategy

Focus on **model independent** analysis searching for modulation

- \rightarrow In order to better compare with DAMA/LIBRA results
 - → use the same energy regions ([1-6] keV, [2-6] keV)
 - Fix period 1 year and phase to June 2nd
- → Simultaneous fit of the 9 detectors in 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i \mu_i)^2 / \sigma_i^2$, where the expected number of events μ_i for detector d in time bin i is given by:



$2.5\sigma \rightarrow 2.8\sigma$

Improved 3-year results [1-6] keV

arXiv:2404.17348

Null hyp χ²/ndf: 993.38/972 [p_{ini}=0.310]

Mod hyp χ^2 /ndf: 992.68/971 [p_{val}=0.307] S_m = (-0.0031±0.0037) (cpd/kg/keV)



PRD103(2021)102005

Mod hyp χ^2 /ndf: 1075.15/971 [p_{val}=0.011] S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)

Null hyp χ^2 /ndf: 1075.81/972 [p_{val}=0.011]



3-year annual modulation with BDT cut





Best fit modulation amplitudes **compatible with zero** at ~ 1σ Best fit **incompatible with DAMA/LIBRA** at 3.7 (2.6) σ for [1-6] ([2-6]) keV **Sensitivity with 3 years data:** 2.8 σ for [1-6] and [2-6] keV

Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

Stability checks before 6-year unblinding

Event selection efficiency stability



Stability checks before 6-year unblinding

Evolution of control populations

0.9 keV (²²Na) and 3.2 keV (⁴⁰K) selected by coincidence. BDT cut and efficiency corrected (trigger+BDT)



Annual modulation results with 6 years



Annual modulation results with 6 years





Best fit modulation amplitudes **compatible with zero** at ~ 1σ Best fit **incompatible with DAMA/LIBRA** at 3.9 (2.9) σ for [1-6] ([2-6]) keV **Sensitivity with 6 years data: 4.2 (4.1)** σ **for [1-6] ([2-6]) keV**

 5σ sensitivity in late 2025

I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

Ρ

R

Ε

Μ

Ν

Α

R

Υ

Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

New parallel DAQ system in ANAIS-112

To better understand (and eventually remove) anomalous events appearing at low energy with asymmetric light-sharing

- Extending the digitization window from 1.25 to 8 μs and free of dead time (ANOD, Anais NO Dead time)
- ANOD is working smoothly since winter 2023 (CAEN DT5730, 8 channels)
- By now, only 4 crystals (8 PMTs) are readout, but very promising results! We have acquired a VX2730 CAEN card (32 channels, 14 bit, 500 MS/s, memory 83 MS/ch) that will allow to digitize the 9 detectors + blank module (delivery expected this summer)

Improving the background model

Understanding the background evolution is essential for the modulation fit

- Using the full non-blinded information [9 detectors, >6 years]
- Adding full PMT description + surface components
- Multiparametric fit to the different components present in the bkg model



ANAIS+

Replacing the PMTs by SiPMs (at low T)

See J. Apilluelo's talk at 17:10 (Parallel 1)



Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline



The ANAIS-112 experiment

Improved results on annual modulation with 3 years





Annual modulation results with 6 years

Next steps



Summary and outlook

Summary and outlook

- ANAIS—112 is leading the international efforts in the independent test of the DAMA/LIBRA signal, working properly
 after 7 years of data-taking
- Low-energy event selection and sensitivity have been improved with machine-learning techniques
- Preliminary results for 6 years: ANAIS–112 is compatible with the absence of modulation and incompatible with the DAMA/LIBRA signal at 4σ (3σ) in [1-6] keV ([2-6] keV), for a sensitivity of 4.2σ (4.1σ) at [1-6] keV ([2-6] keV)
- 5σ sensitivity in late 2025
- ANAIS has carried out QF measurements, pointing to values lower than those of DAMA. Disagreement still to be comprehended. Understanding the response of NaI(Tl) crystals to nuclear recoils is crucial in the model independent comparison with DAMA/LIBRA
- **New parallel DAQ** in ANAIS working since winter 2023 for 4 crystals. Promising results for improving PSD event selection. 9 crystals + blank this summer
- Plan to improve our **background model** with the accumulated exposure
- ANAIS—112/COSINE—100 working to combine results. Preliminary results in S. Hollick's talk at 15:20 (Parallel 1)
- **Open Data Policy**: ANAIS-112 3-year annual modulation analysis and the reanalysis can be downloaded at https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais. 6 years in the near future

Thank you for your attention!

ANAIS research team

J. Amaré, J. Apilluelo, S. Cebrián, D. Cintas, <u>I. Coarasa</u>, E. García, M. Martínez, Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, M. L. Sarsa











ANAIS experiment operation is presently financially supported by MICIU/AEI/10.13039/501100011033 (Grants No. PID2022-138357NB-C21 and PID2019-104374GB-I00), and Unión Europea NextGenerationEU/PRTR (AstroHEP) and the Gobierno de Aragón. Funding from Grant FPA2017-83133-P, Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, the Gobierno de Aragón and the LSC Consortium made possible the setting-up of the detectors. The technical support from LSC and GIFNA staff as well as from Servicios de Apoyo a la Investigación de la Universidad de Zaragoza (SAIs) is warmly acknowledged.

Backup

Annual modulation results with 5 years



I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

Toy MC for efficiency analysis

- 2000 Toy MC carried out with ANAIS background + DAMA/LIBRA modulation
- Updated to include variations in the efficiency around the mean value of different size
- We recover in all cases the right modulation amplitude enlarging the standard deviation



I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

Ρ

R

Ε

Μ

Ν

Α

R

Y

[1-6] keV

Toy MC for efficiency analysis

- 2000 Toy MC carried out with ANAIS background + DAMA/LIBRA modulation
- Updated to include variations in the efficiency around the mean value of different size
- We recover in all cases the right modulation amplitude enlarging the standard deviation
- The Chi2 value is strongly sensitive to this efficiency "variation". **Our analysis suggests is <3% [1-6] keV**



I. Coarasa, IDM 2024 – Parallel session, L'Aquila (Italy), 09/07/2024

Ρ

R

Ε

Μ

Ν

Α

R

[1-6] keV