From ANAIS–112 to ANAIS+: eight years of dark matter search at the Canfranc Underground Laboratory

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Light Dark World 2025
16-19 September 2025, Madrid

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

MultiDark
Multimessenger Approach for Dark Matter Detection

Outline

1. Dark matter annual modulation and DAMA positive signal
2. ANAIS–112 analysis and results from 6 years
3. ANAIS–112 status and prospects
4. Beyond ANAIS–112: ANAIS+
5. Summary and outlook

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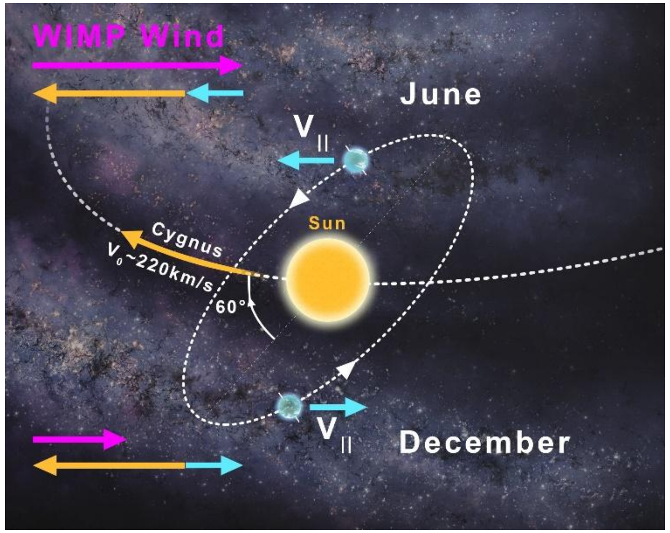
Dark matter annual modulation



Due to the revolution of the Earth around the Sun, the speed of dark matter particles in the Milky Way's halo relative to Earth **varies seasonally**, producing an **annual modulation** in the rate of nuclear recoil events in detectors

$$R(t) \approx S_0 + S_m \cdot \cos\omega(t - t_0)$$

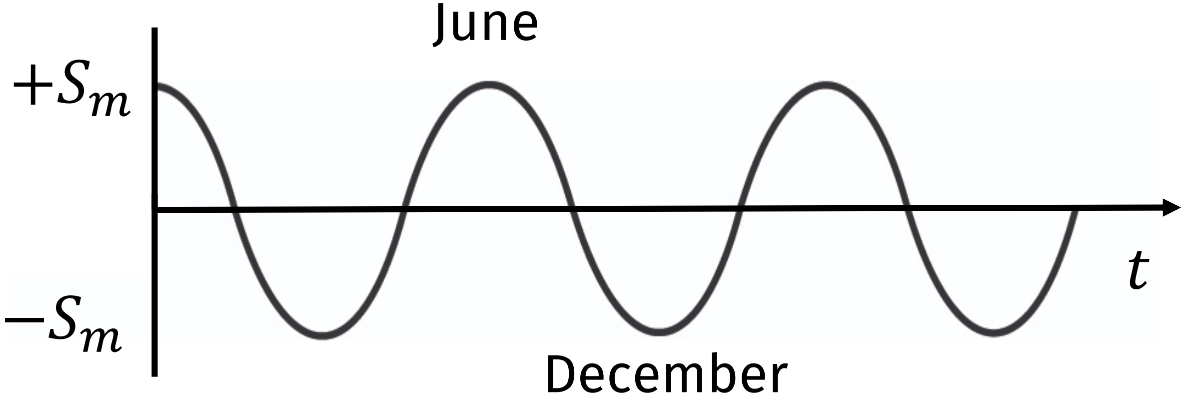
where $\omega = 2\pi/365\ \mathrm{d}^{-1}$, $t_0 = 152.5$ d

Detection rate would have a cosine behaviour with a yearly period and maximum around June 2nd

Only at low energy

Single-hit events

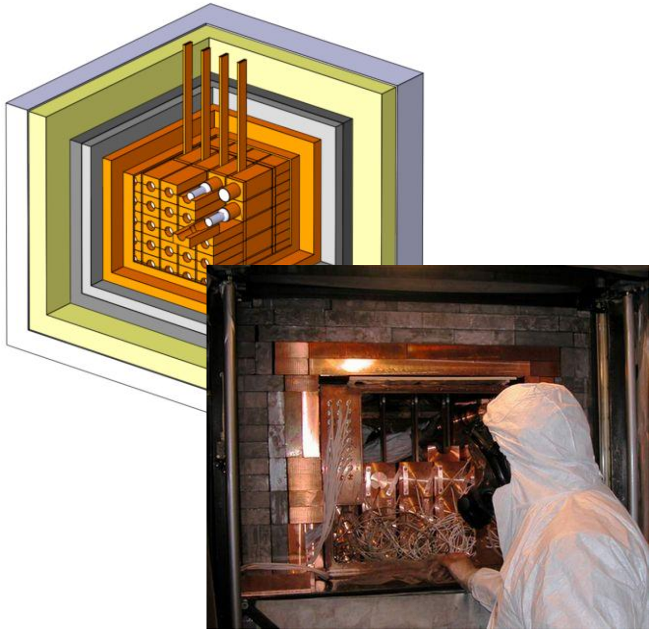
$S_m/S_0 \lesssim 7\%$



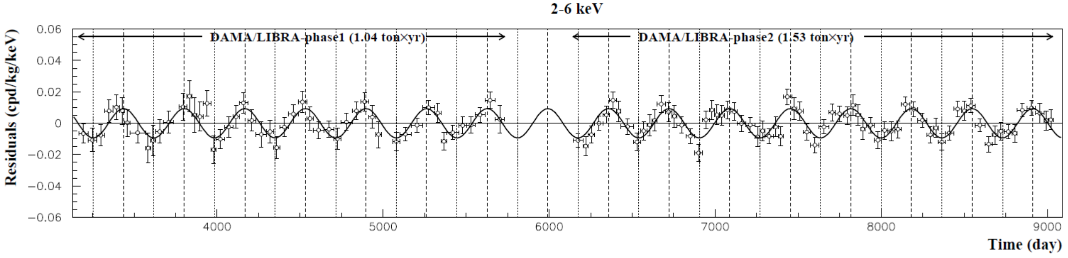
DAMA/NaI and DAMA/LIBRA positive signal

DAMA experiment using NaI(Tl) @LNGS (1995-2024)

Exp. phase	Period	Mass (kg)	Annual cycles	Exposure (t×y)
DAMA/NaI	1995-2002	9×9.7	7	0.29
DAMA/LIBRA-phase1	2003-2010	25×9.7	7	1.04
DAMA/LIBRA-phase2 [Higher *QE* PMTs]	2011-2024 (2019)	25×9.7	14 (8 released)	--- (1.53)

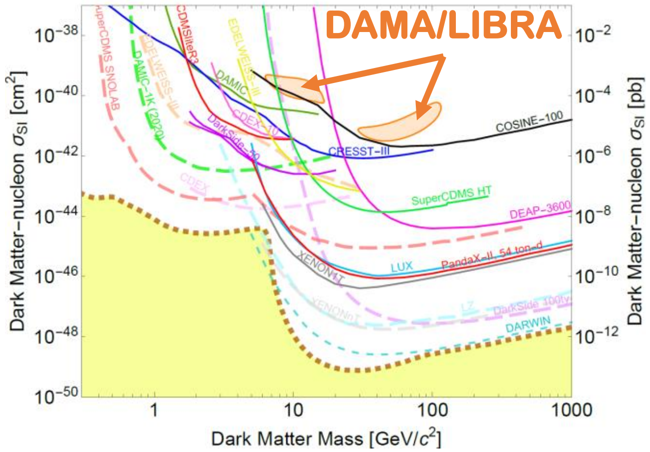


DAMA clearly observes an **annual modulation** compatible with DM **at more than 13σ**



R. Bernabei et al., Nucl. Phys. At. Energy 22 (2021) 329-342

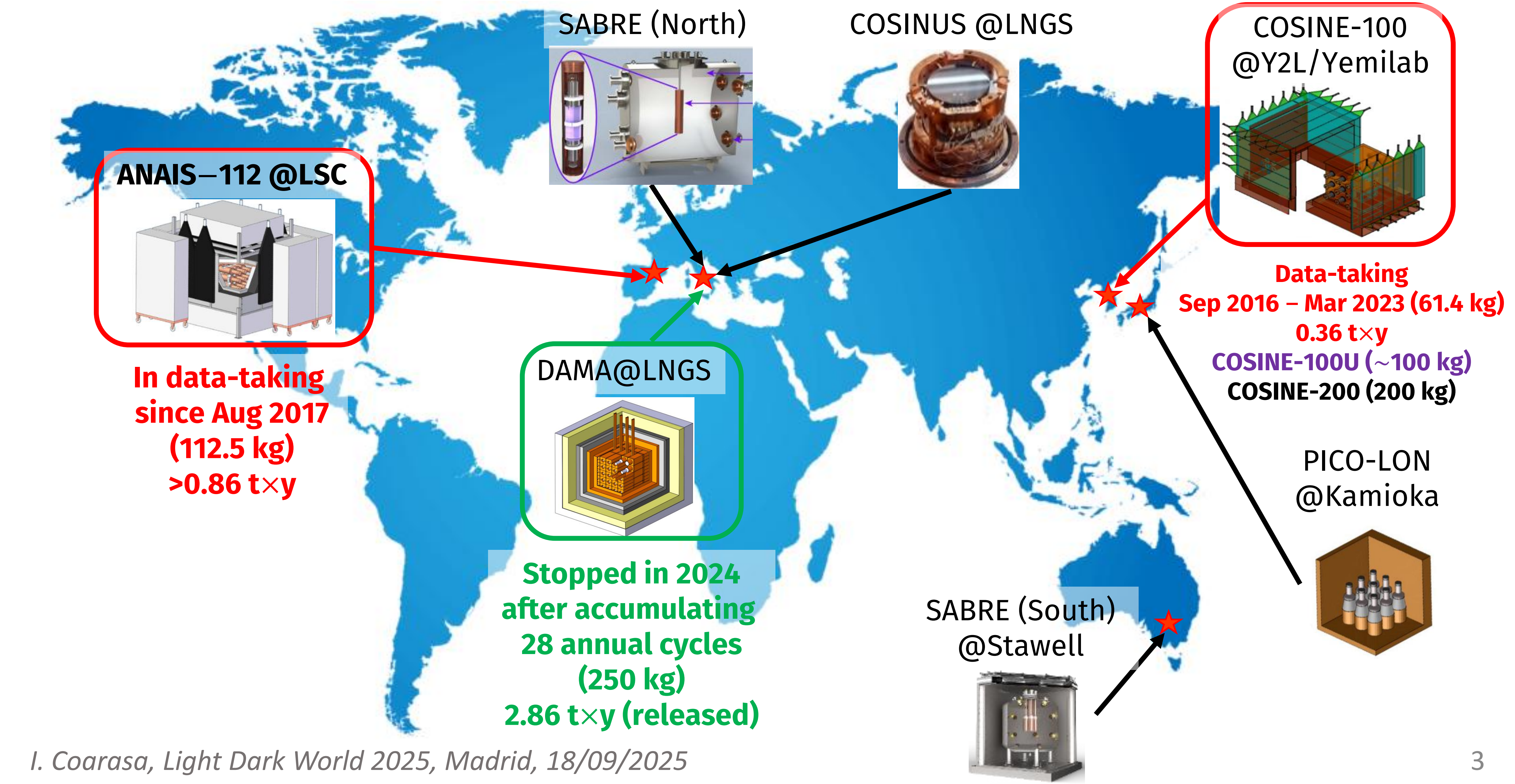
STRONG TENSION



Other very sensitive experiments do not see the signal, but the comparison is **model dependent**

A model independent test is needed using the same target

Other NaI experiments around the world



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The ANAIS experiment

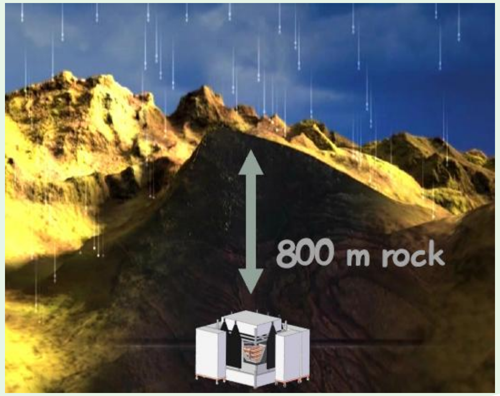
GOAL

ANAIS (*Annual modulation with NaI(Tl) scintillators*) intends to provide a **model 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

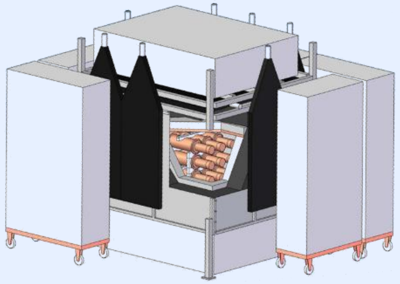
WHERE

At the **Canfranc Underground Laboratory**, LSC @ SPAIN (under 2450 m.w.e.)



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%)

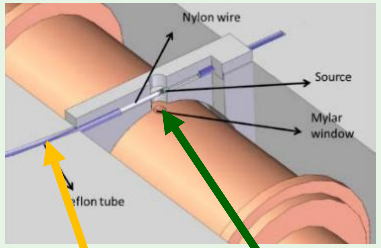


On 3 August 2017, data collection starts

Low energy calibration

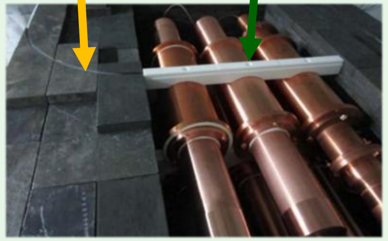
ROI [1-6] keV

Linear calibration in 10-100 keV

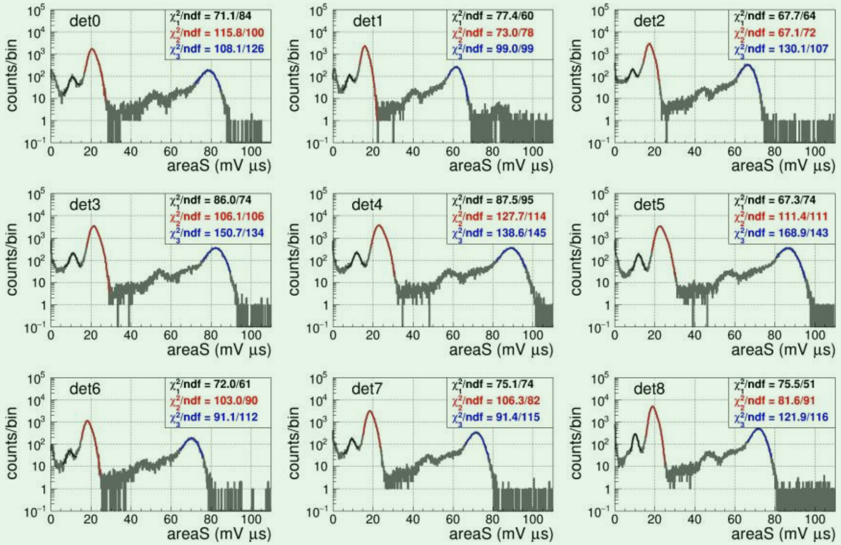


Guides for ^{109}Cd sources

Mylar window



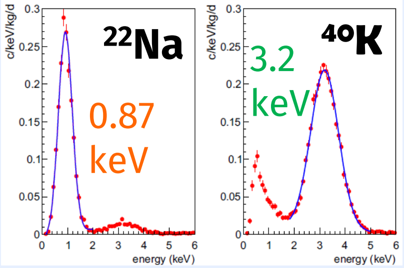
- Detectors equipped with a Mylar window
- Calibration with ^{109}Cd sources (11.9, 22.6 and 88.0 keV) every two weeks for gain correction

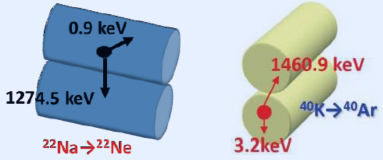


Linear calibration in 1-10 keV [ROI]

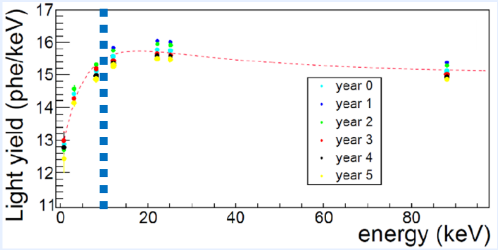
- Calibration in the ROI with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) with whole statistics

Coincidence events





Non proportionality < 25 keV (20%)



ANAIS–112 analysis and results from 6 years

The analysis of 6 years of data from the ANAIS experiment and its results can be found in:

[Physical Review Letters 135(2025)051001]

Towards a Robust Model-Independent Test of the DAMA/LIBRA Dark Matter Signal: ANAIS-112 Results with Six Years of Data

Julio Amaré,[1,2] Jaime Apilluelo,[1,2] Susana Cebrián,[1,2] David Cintas,[1,2] Iván Coarasa,[1,2,*] Eduardo García,[1,2] María Martínez,[1,2] Ysrael Ortigoza,[1,2,3] Alfonso Ortiz de Solórzano,[1,2] Tamara Pardo,[1,2] Jorge Puimedón,[1,2] María Luisa Sarsa,[1,2,†] and Carmen Seoane[1,2]

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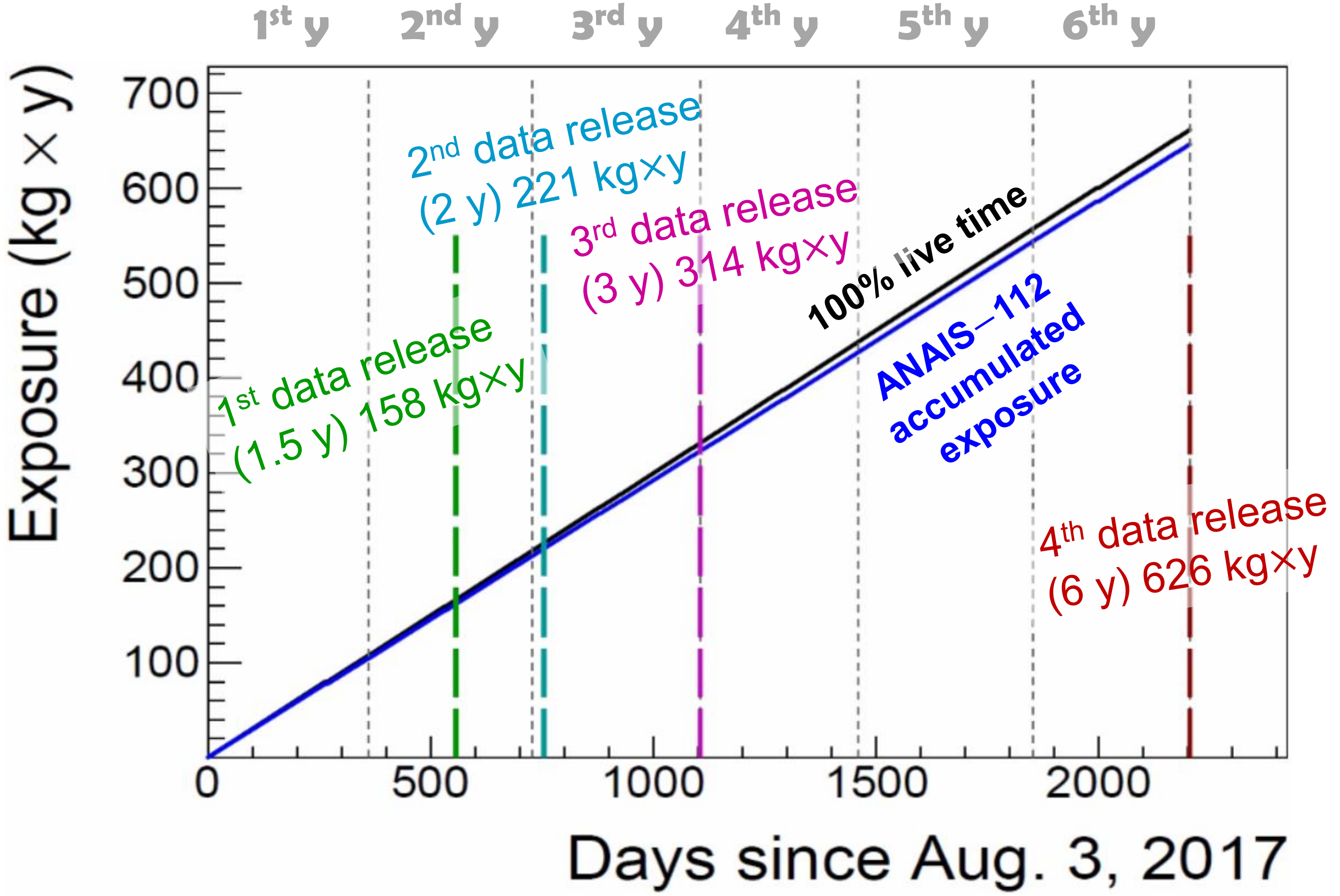
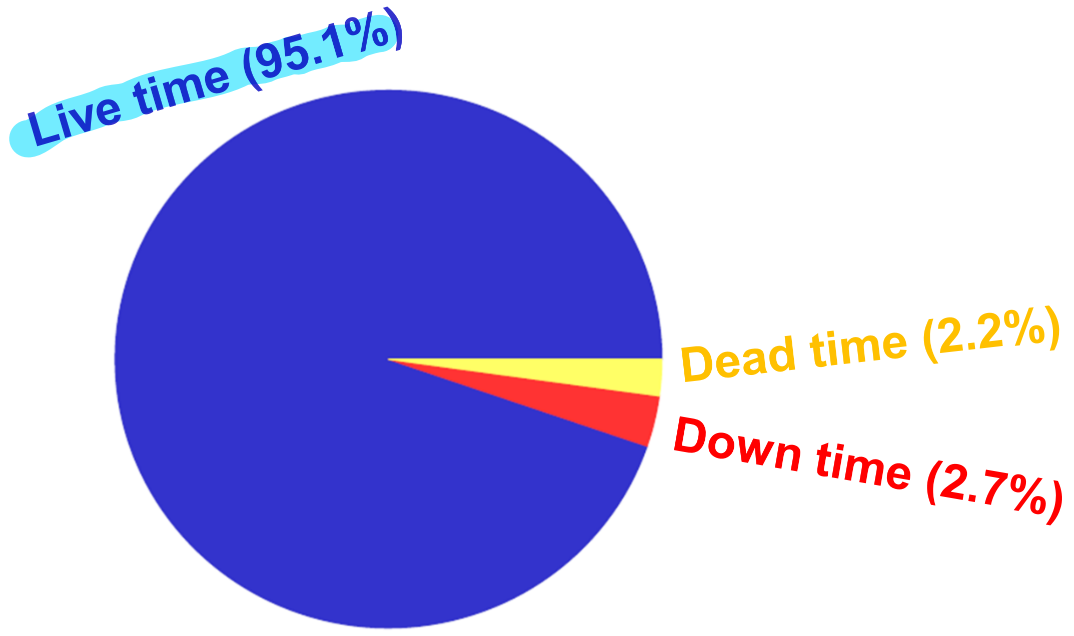
The most sensitive results to date with the same target material, NaI(Tl), as DAMA/LIBRA

ANAIS–112 analysis: six-year data-taking overview



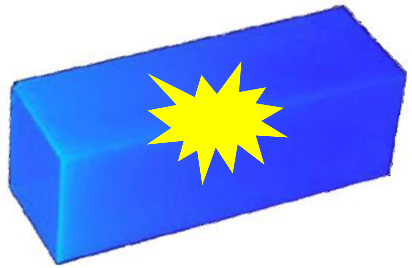
ANAIS–112 accumulated exposure from Aug. 3, 2017 to Aug. 17, 2023



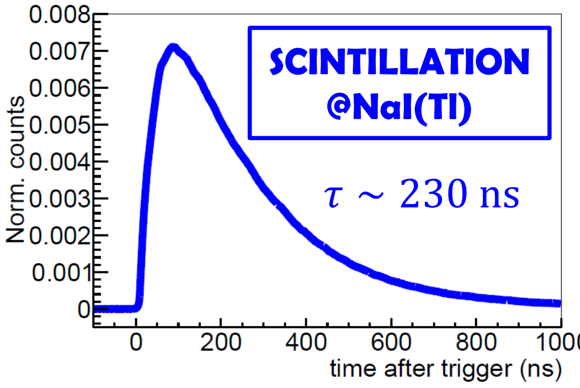
ANAIS–112 analysis: event selection

What do we expect to see?

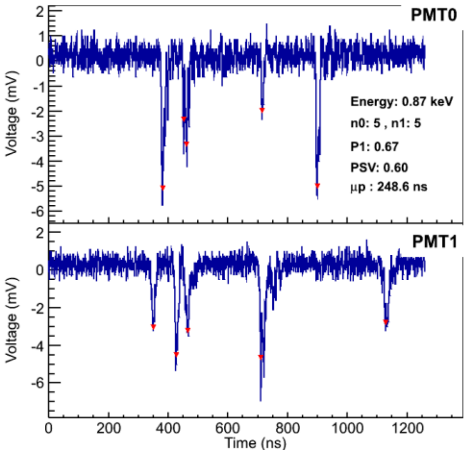
Scintillation light in the NaI(Tl) crystal (bulk)



Expected signal

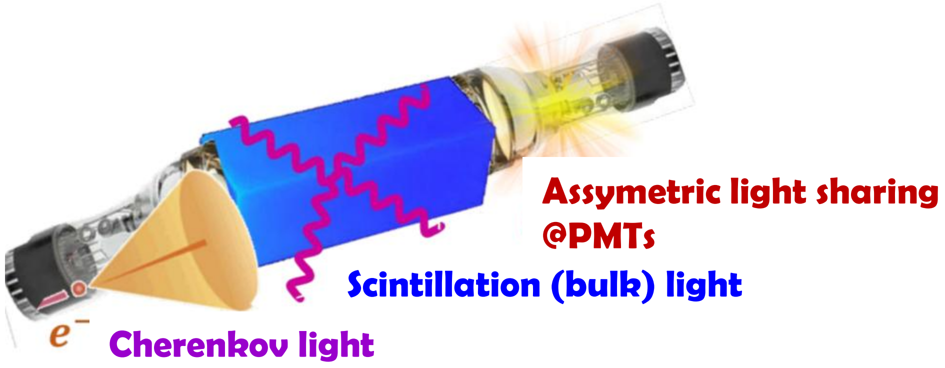


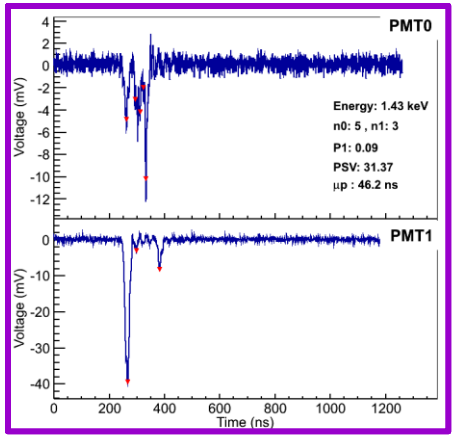
… but at low energy (15 phe/keV)

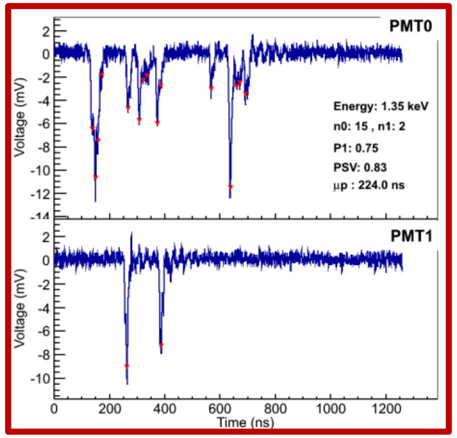


What do we actually see?

Scintillation light + light emitted in the materials surrounding the NaI(Tl) crystal







ANAIS–112 analysis: event selection and efficiency

Event selection improved with ML techniques based on BDT *JCAP11(2022)048 and JCAP06(2023)E01*

Training populations

Signal events: dedicated on-site neutron calibrations with ^{252}Cf source [1-2] keV
Noise events: blank module similar to ANAIS–112 modules, but without NaI(Tl) crystal

Balanced training populations (>30 000 evts), split 70% (30%) for training (test)

Blank module

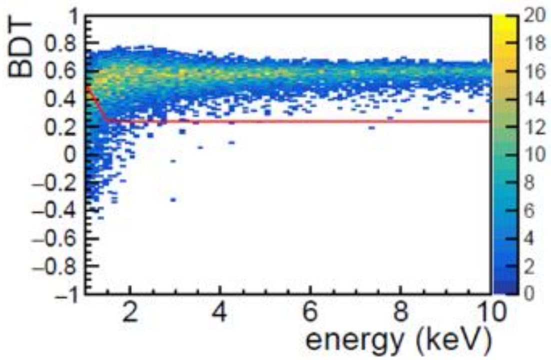
15 training parameters

Standard analysis (4) $P_1 = \frac{\sum_{100\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)}$ $\mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i}$ n_0, n_1

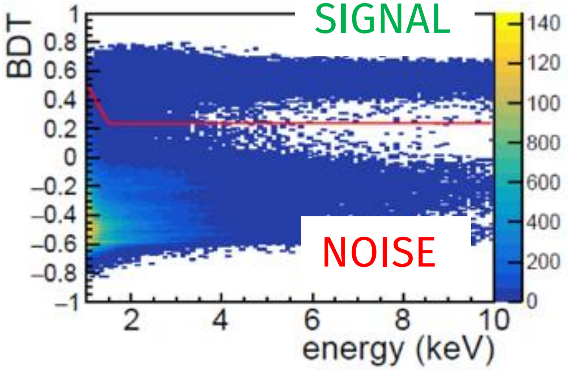
New parameters (11) $P_2 = \frac{\sum_{0\ \mathrm{ns}}^{50\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)}$ $Asyphe = \frac{nphe_0 - nphe_1}{nphe_0 + nphe_1}$ $CAP_x = \frac{\sum_{0\ \mathrm{ns}}^{x\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{t_{max}} A(t)}$ $x = 50, 100, 200, 300, 400, 500, 600, 700, 800$ ns

BDT cut defined for every detector and energy bin

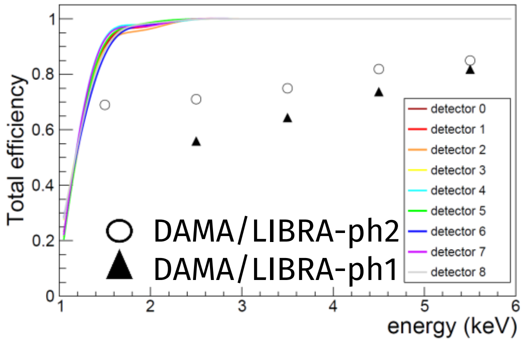
Neutron calibration



Background



Efficiency



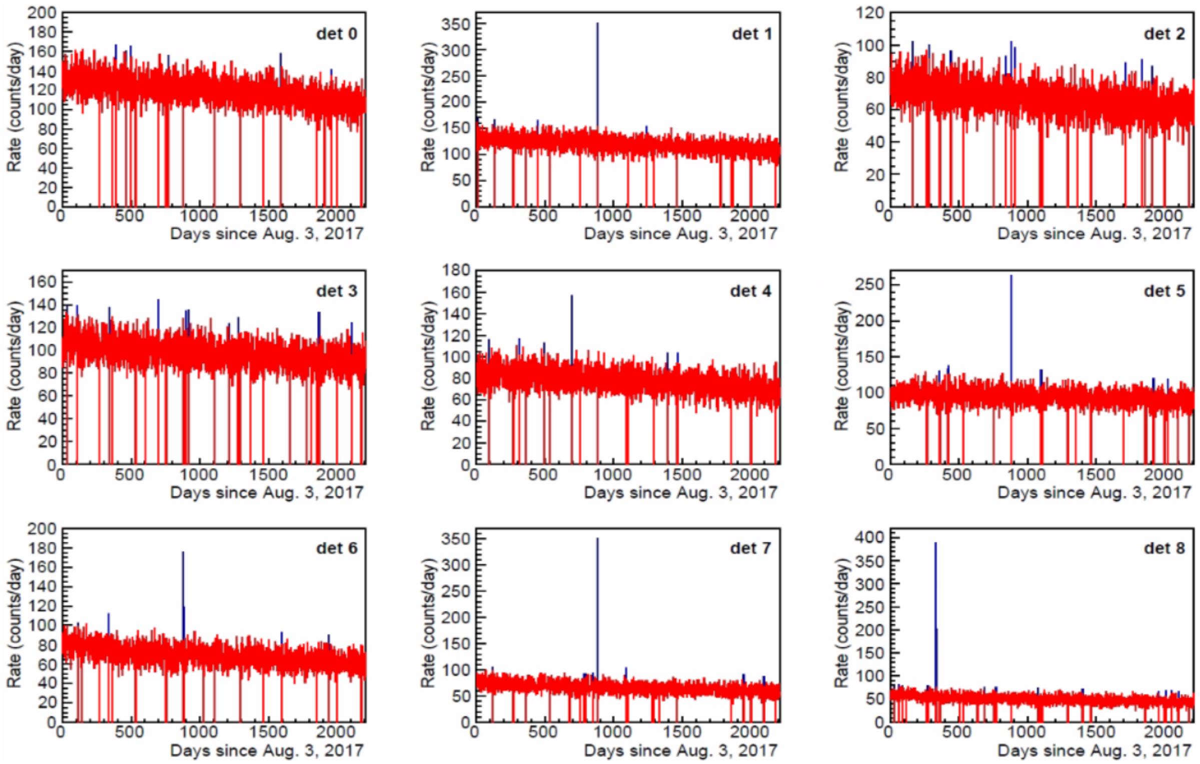
↑30% in efficiency [1-2] keV

↓20% in background [1-2] keV

Efficiency better than DAMA/LIBRA above 1.5 keV, but sharply decreasing below, **limiting the analysis energy threshold to 1 keV**

ANAIS–112 analysis: event selection

1) BDT cut to select low-energy bulk scintillation events — *JCAP11(2022)048 and JCAP06(2023)E01*
2) Rejection of high-trigger rate periods — *Comm. Phys. 7(2024)345*
3) Removal 1 s after a muon passage
4) Single-hit events (multiplicity=1)



Events filtered with BDT <3 keV

+ Cut in trigger rate

Live time 95.1%
Veto cut −2.6%
Rate cut −0.4%

Exposure
646.55 kg×y

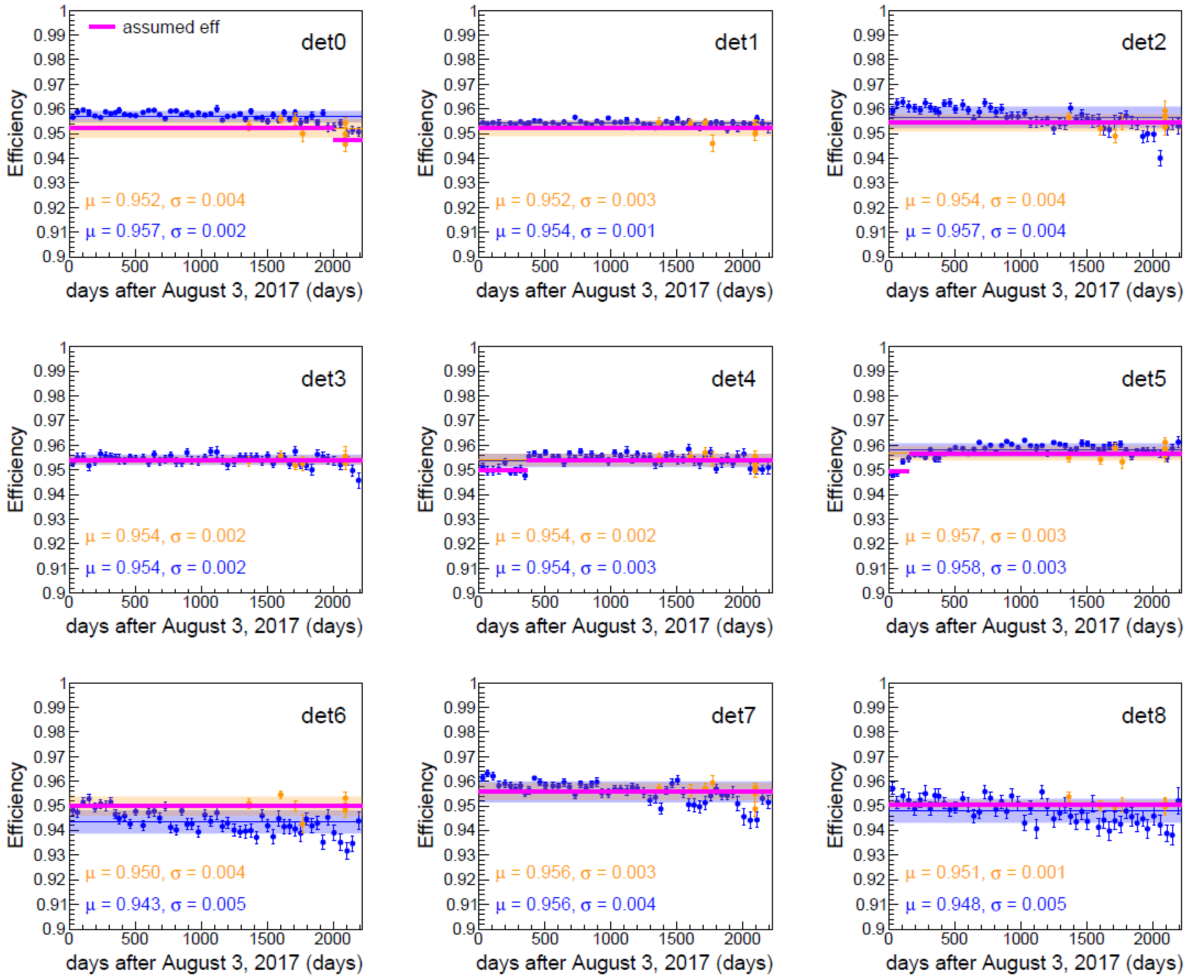
→

Effective exposure
625.75 kg×y

ANAIS–112 analysis: stability checks

Event selection efficiency stability

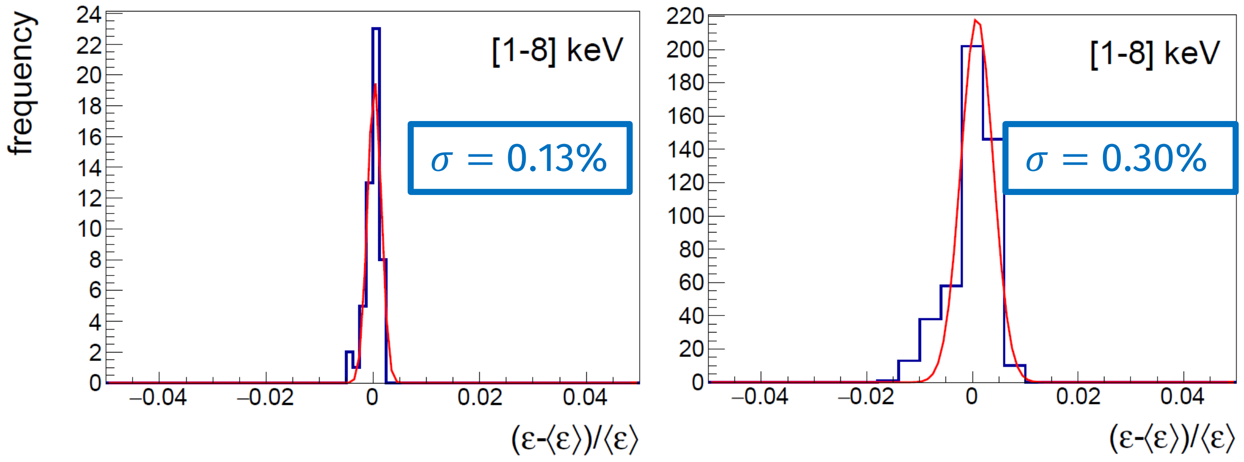
^{109}Cd calibration and ^{252}Cf neutron calibration

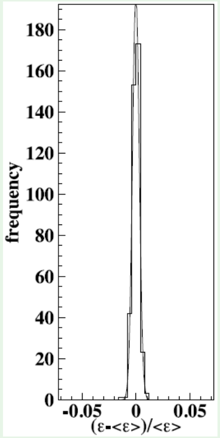


det4 & det 5: change in HV after 1 year

det 0: change in gain PMT0 after 5 year

Averaging all detectors | Considering independently





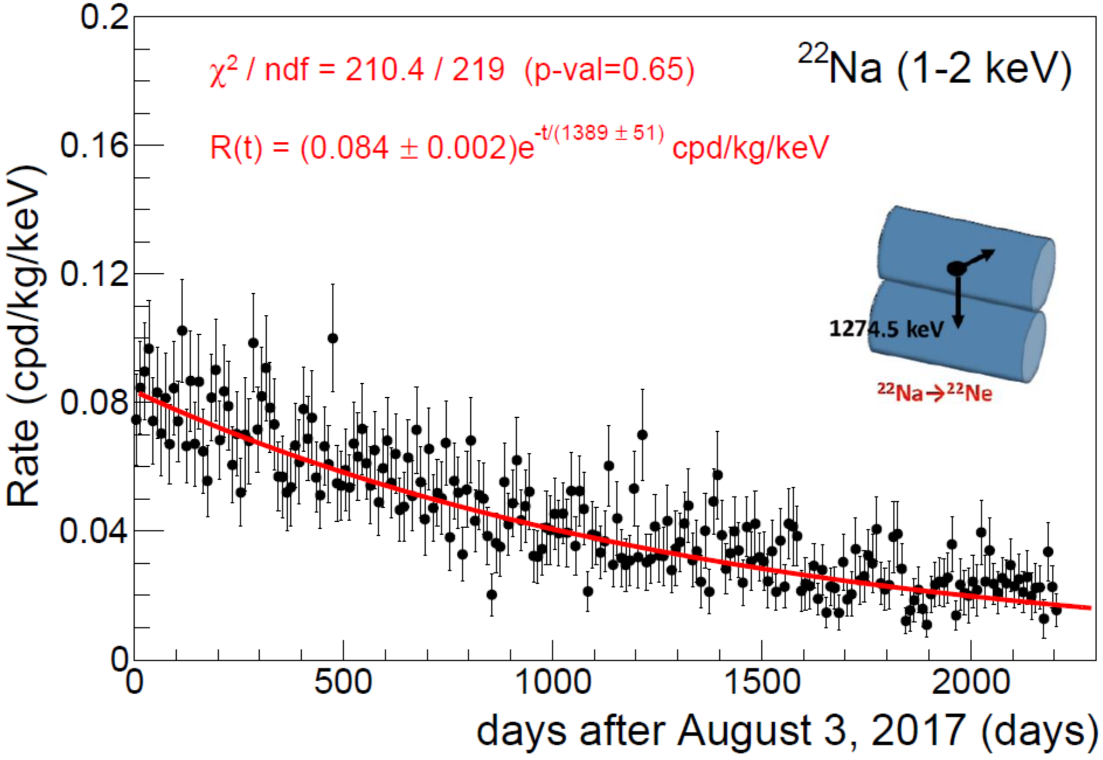
DAMA/LIBRA-phase2 reports a similar spread $\sigma = \mathbf{0.30\%}$ in [1-8] keV

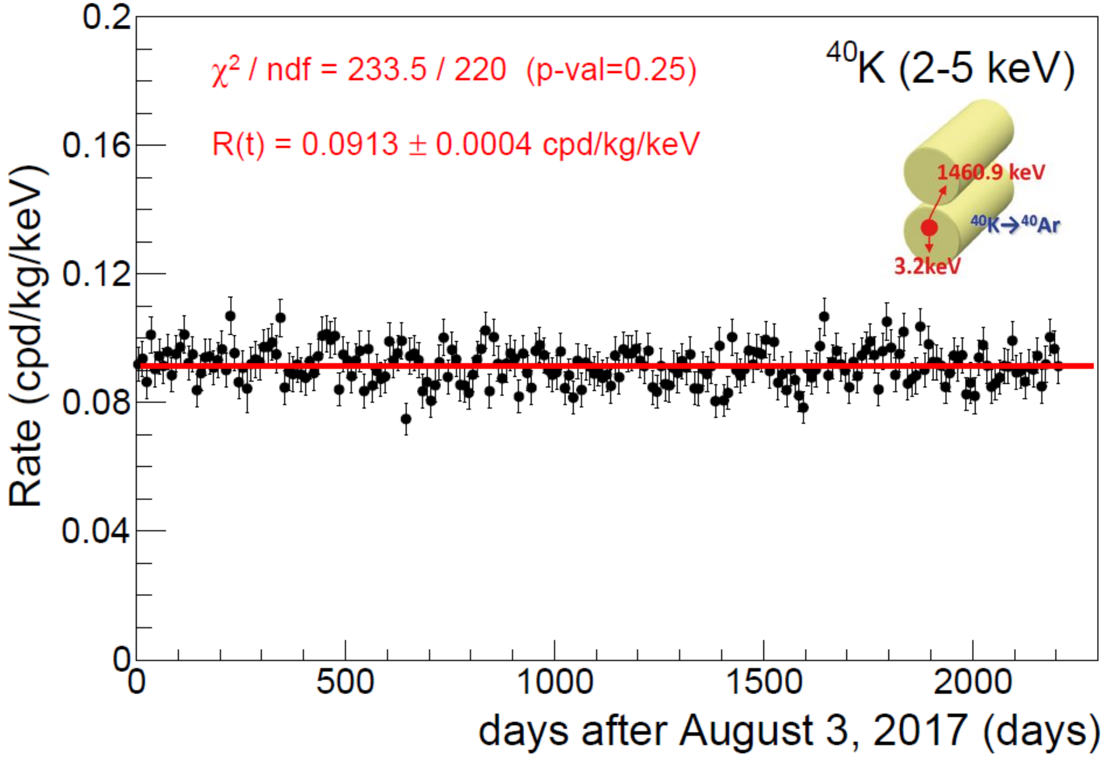
Prog. Part. Nucl. Phys. 114 (2020) 103810

ANAIS–112 analysis: stability checks

Evolution of control populations

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





$\tau_{fit} = 1389 \pm 51$ days

$\boldsymbol{\tau_{22Na} = 1369}$ **days**

ANAIS–112 analysis: annual modulation strategy

Following PRD103(2021)102005

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

- ➔ 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 45-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:

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

ANAIS–112 analysis: annual modulation strategy

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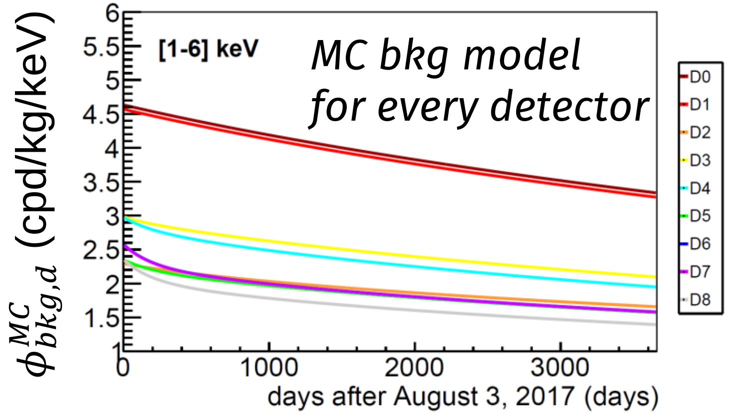
Decaying background, modeled by MC



Constant background (DM and residual noise)

Modulation signal (fixed period and phase)

19 free parameters: $R_{0,d}, f_d, S_m$

Annual modulation results with 6 years

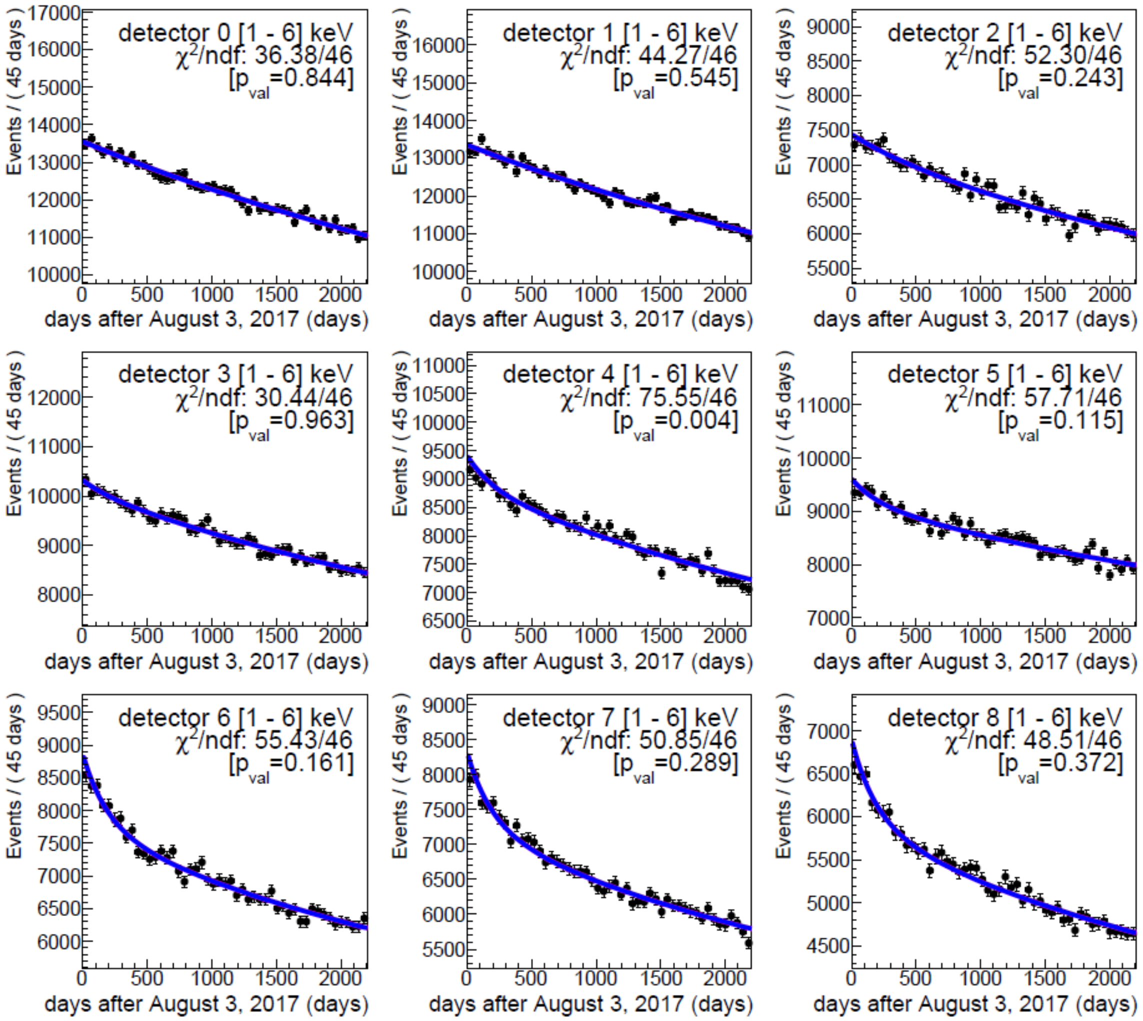
625.75 kg × y

[1-6] keV: **4.2σ**

Null hyp χ^2/ndf: 451.34/423 [p_{val}=0.164]

Mod hyp χ^2/ndf: 451.31/422 [p_{val}=0.156]

S_m = (-0.0004 ± 0.0025) (cpd/kg/keV)

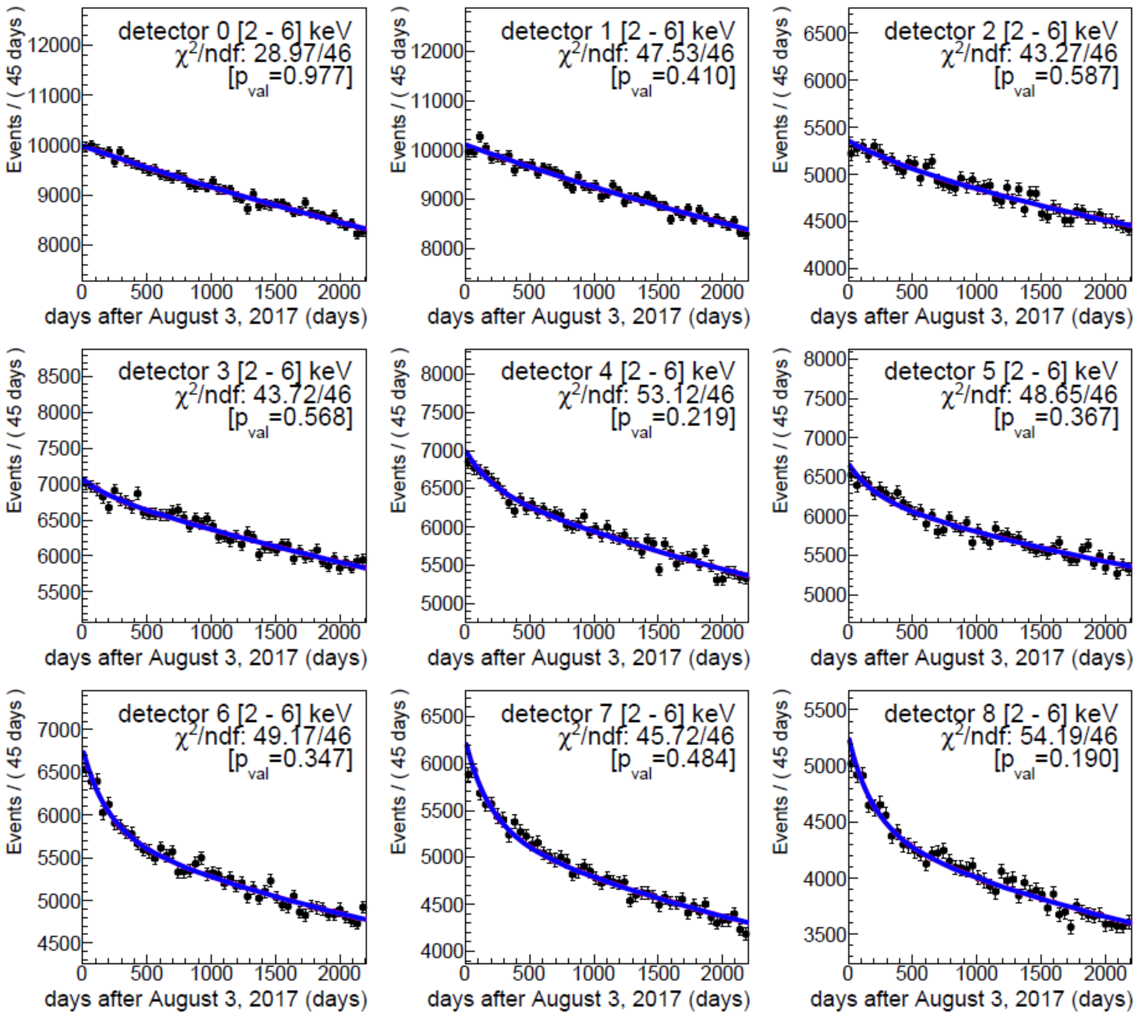


[2-6] keV: **4.1σ**

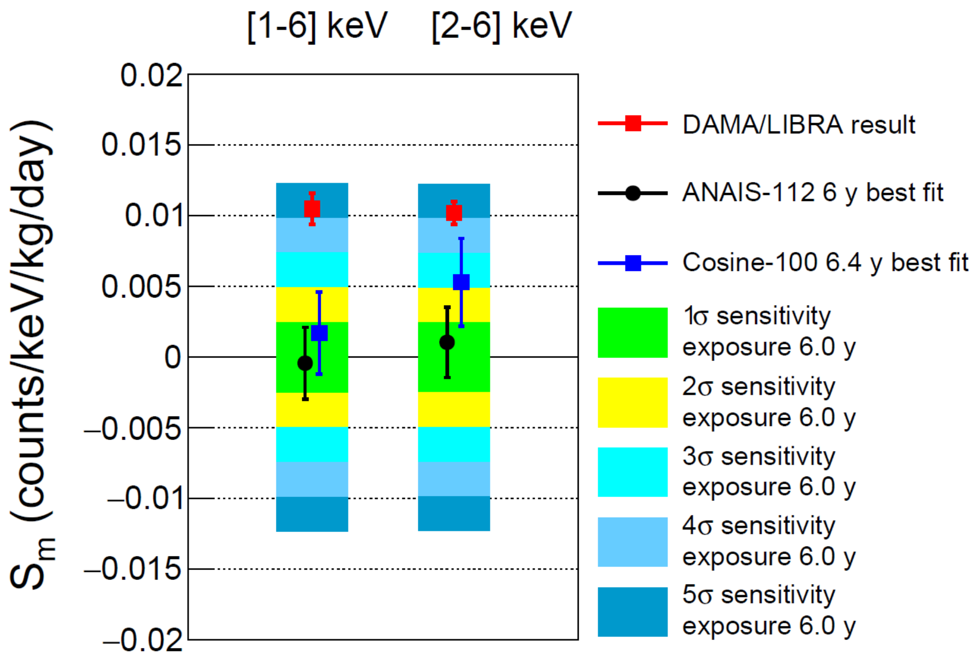
Null hyp χ^2/ndf: 414.46/423 [p_{val}=0.607]

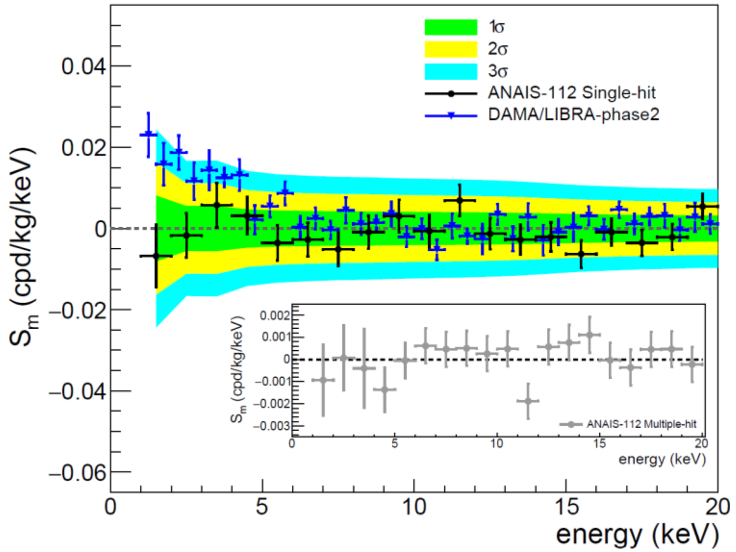
Mod hyp χ^2/ndf: 414.28/422 [p_{val}=0.596]

S_m = (0.0011 ± 0.0025) (cpd/kg/keV)



Annual modulation results with 6 years





ANAIS−112

Best fit modulation amplitudes **compatible with zero** at 1σ

Incompatible with DAMA/LIBRA at 4.0 (3.5) σ for [1-6] ([2-6]) keV

Sensitivity with 6 years data: 4.2 (4.1) σ for [1-6] ([2-6]) keV

COSINE−100 full dataset *Sci. Adv. 11(2025)eadv6503*

Incompatible with DAMA/LIBRA at 2.8 (1.5) σ for [1-6] ([2-6]) keV

Sensitivity: 3.6 (3.3) σ for [1-6] ([2-6]) keV

The modulation amplitude was analyzed **keV by keV from 1 to 20 keV** for single- and multiple-hit events, showing **no modulation in all bins**

Annual modulation results: study of systematics

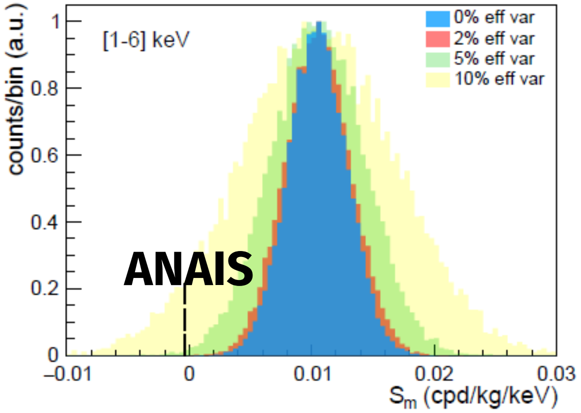
20000 MC pseudo-experiments with ANAIS parameters (background evolution and measured efficiencies), with and without adding the modulation observed by DAMA/LIBRA

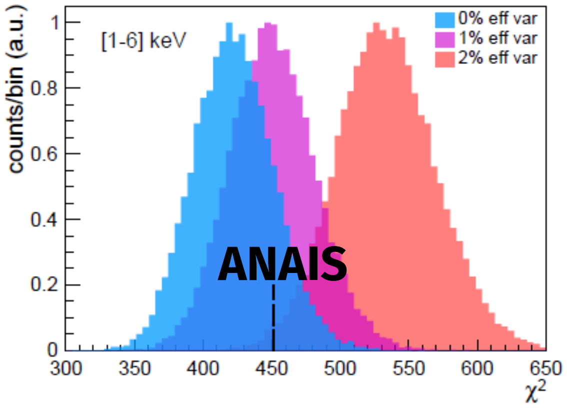
Fit bias study

No bias is observed and similar standard deviations than found in the ANAIS–112 6-year results

Efficiency stability study

- ➔ Including variations in efficiency around mean value
  - We recover in all cases the right modulation amplitude enlarging the standard deviation
  - The χ^2 distribution point at efficiency fluctuations **well below 2%**, which do not compromise the significance of our result





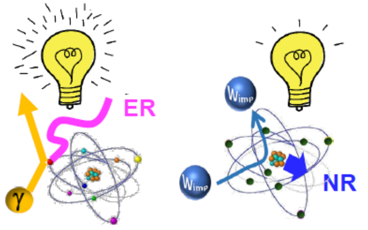
- ➔ Introducing a linear dependence with time (decreasing or increasing)
- ➔ Introducing an annual modulation or antimodulation

At the level of the variations observed in our efficiencies

NEGLIGIBLE

Annual modulation results: considering differences in QF

Under the hypothesis that the **QF may vary among crystals** (growing method, Tl concentration, impurities…), the **keVee** energy regions where the signal appears can differ across NaI experiments



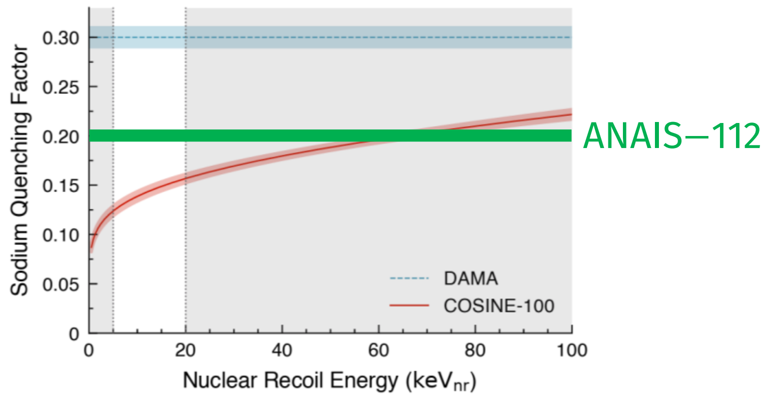
$$QF = \frac{L_{NR}}{L_{ER}}$$

Comparison in terms of **Na-NR energy**, assuming

DAMA/LIBRA $QF_{Na} = 0.30$ *Phys. Lett. B 389(1996)757–766*

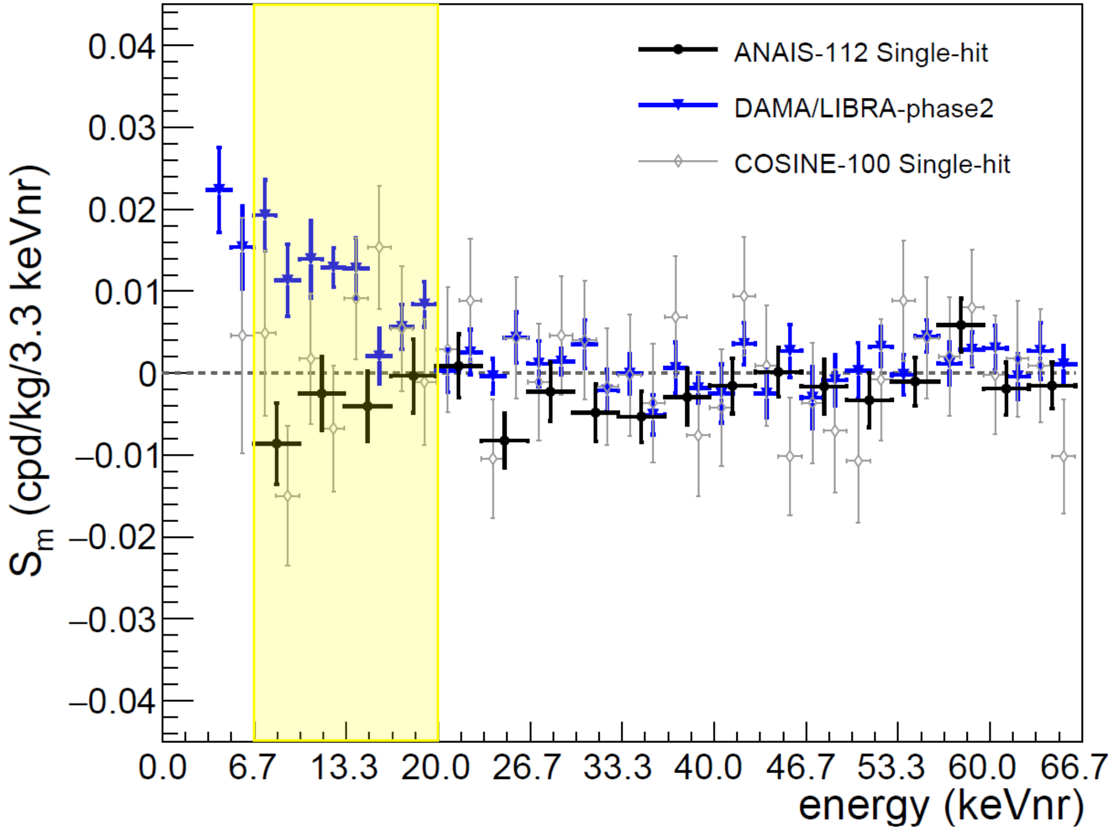
ANAIS−112 $QF_{Na} = 0.20$ *Phys. Rev. C 110(2024)014613*

COSINE−100 *Sci. Adv. 11(2025)eadv6503*



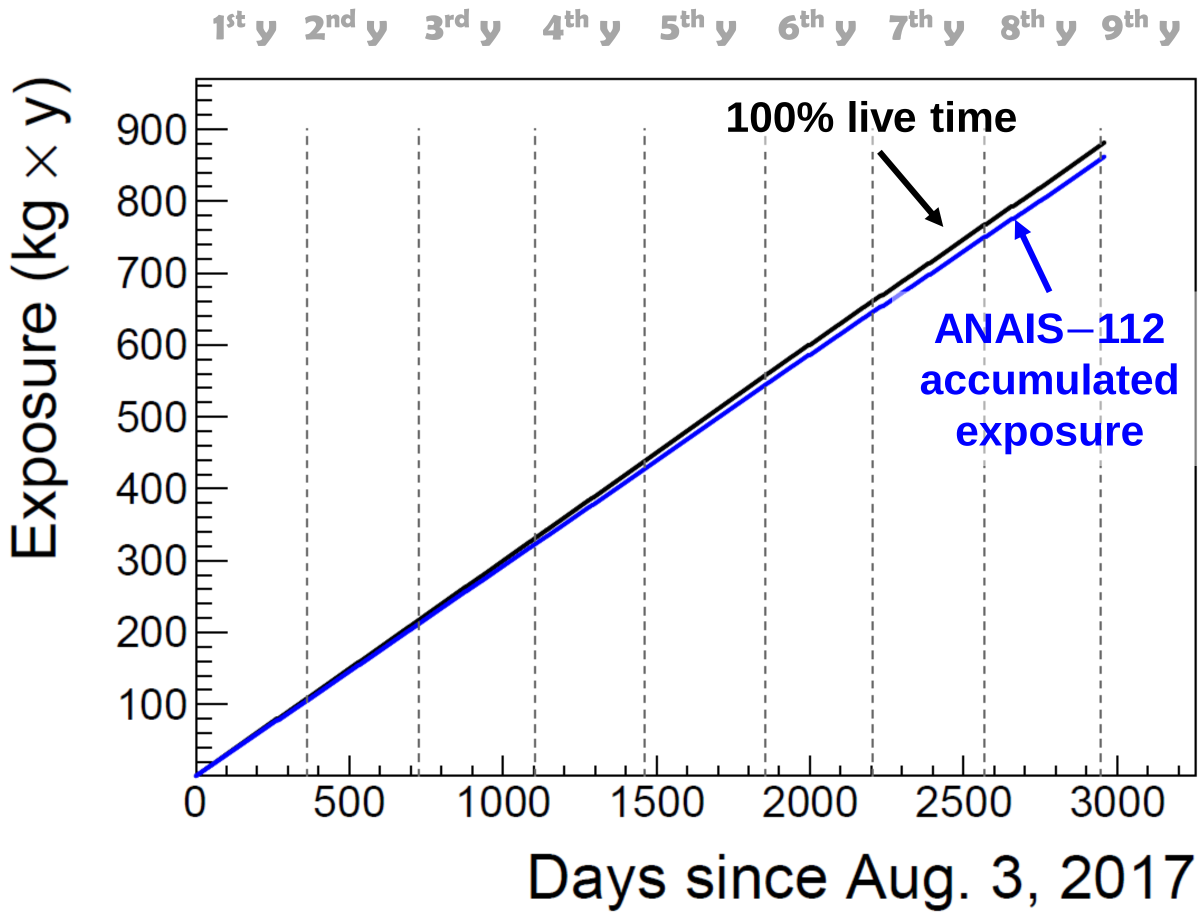
$$[6.7 - 20]\ \text{keVnr} = \begin{cases} [2-6]\ \text{keVee} & \text{DAMA} \\ [1.3-4]\ \text{keVee} & \text{ANAIS} \end{cases}$$

ANAIS compatible with no modulation and **incompatible with DAMA/LIBRA at 4.2 σ** (4.4 σ sensitivity)



Outline

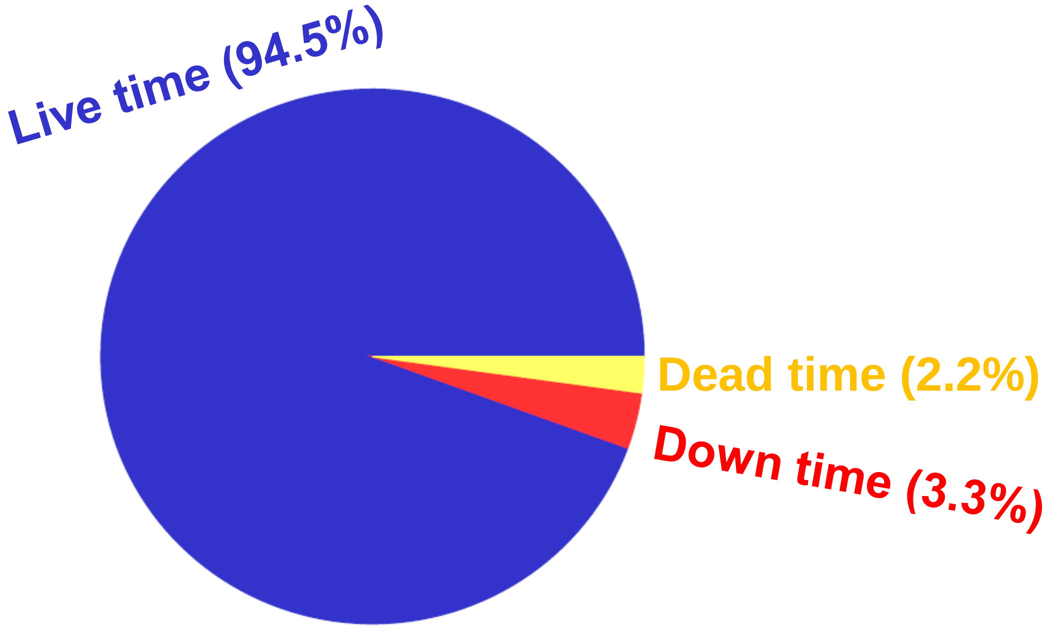
ANAIS–112 status: data-taking overview



About 95% of live time

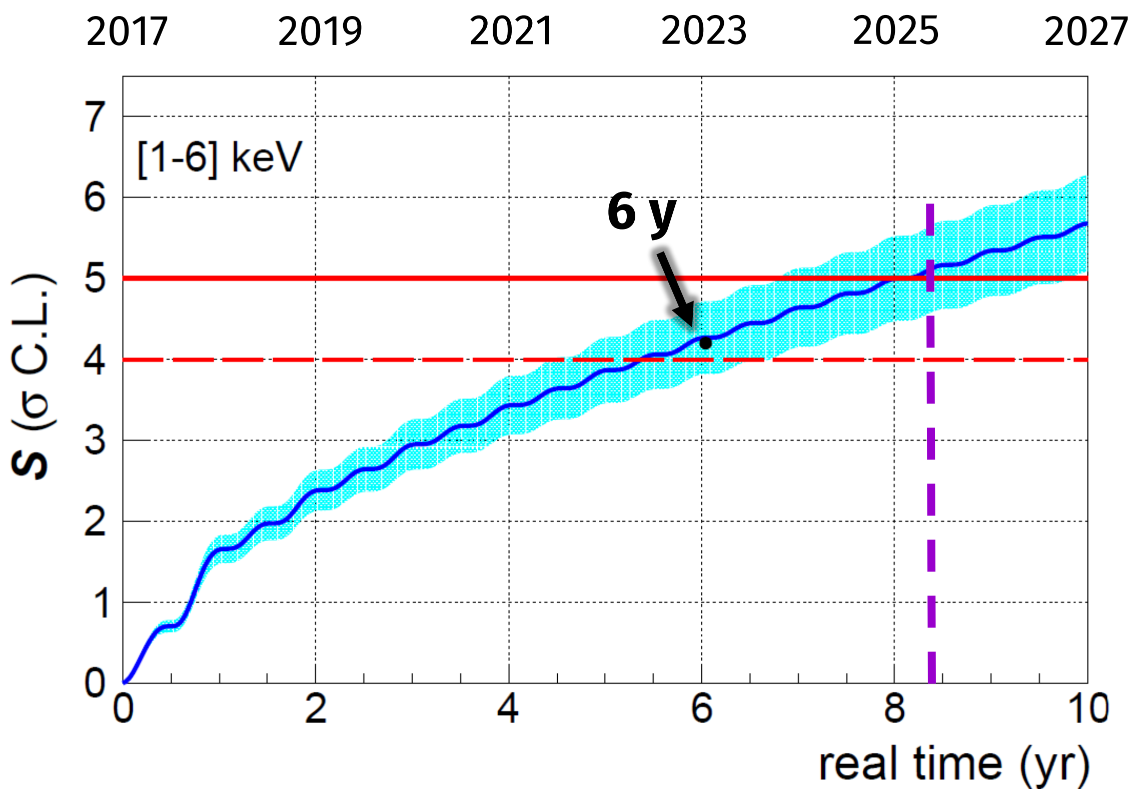
ANAIS–112 accumulated exposure

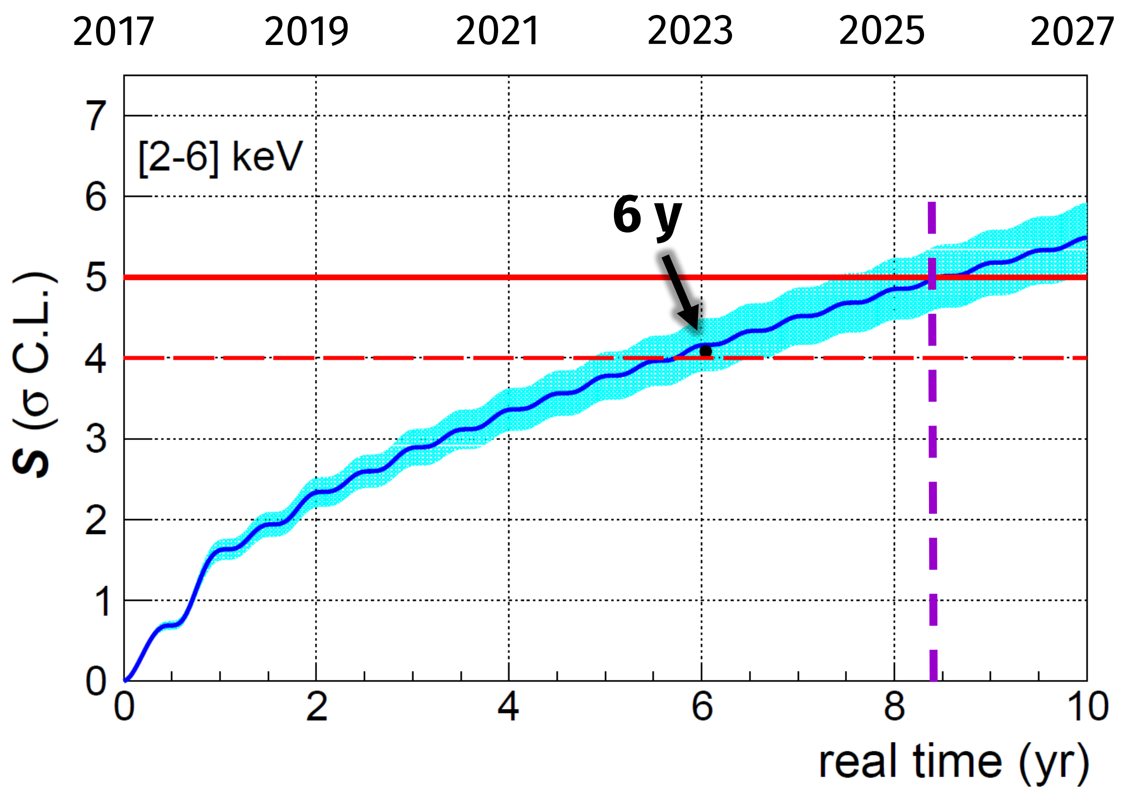
862.46 kg×y
@ Sep. 10, 2025



Eight-year exposure has already been completed this August

ANAIS–112 sensitivity prospects





5σ sensitivity in late 2025

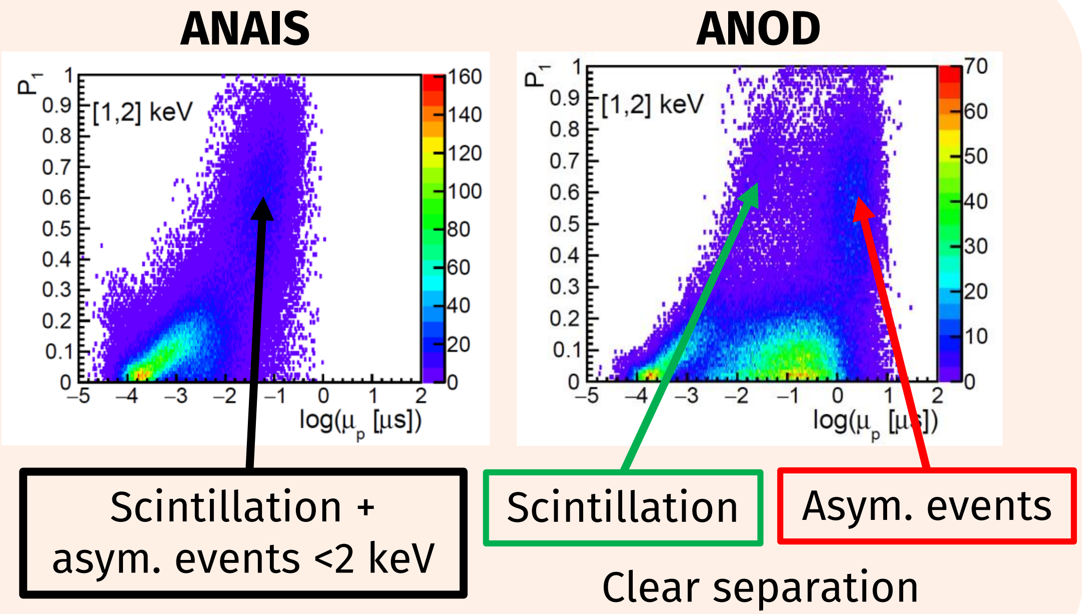
(Scheduled end date of data taking)

Work in progress

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)
- Since winter 2024, and thanks to a VX2730 CAEN card (32 channels, 14 bit, 500 MS/s, memory 83 MS/ch), we are able to digitize the 9 detectors + blank module (18 PMTs). Work in progress, but **very promising results**!



Clear separation in the mean time!

Improving the background model

Understanding the background evolution is essential for the modulation fit

- Using the full non-blinded information [9 detectors, >8 years]
- Adding full PMT description + surface components
- **Multiparametric fit** to the different components present in the bkg model

Improving ML training populations

Simulating pulses through the response function of ANAIS—112 detectors

Testing QF with on-site neutron calibrations

Outline

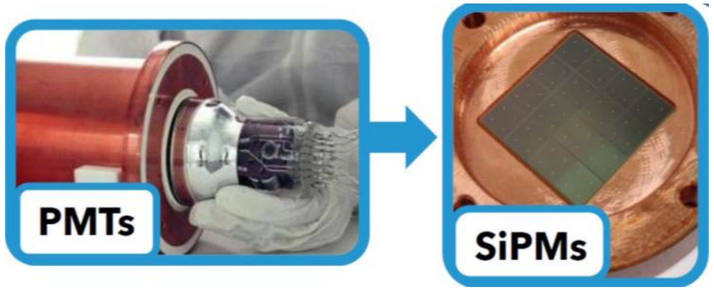
1. Dark matter annual modulation and DAMA positive signal
2. ANAIS–112 analysis and results from 6 years
3. ANAIS–112 status and prospects
4. Beyond ANAIS–112: ANAIS+
5. Summary and outlook

Beyond ANAIS–112: ANAIS+

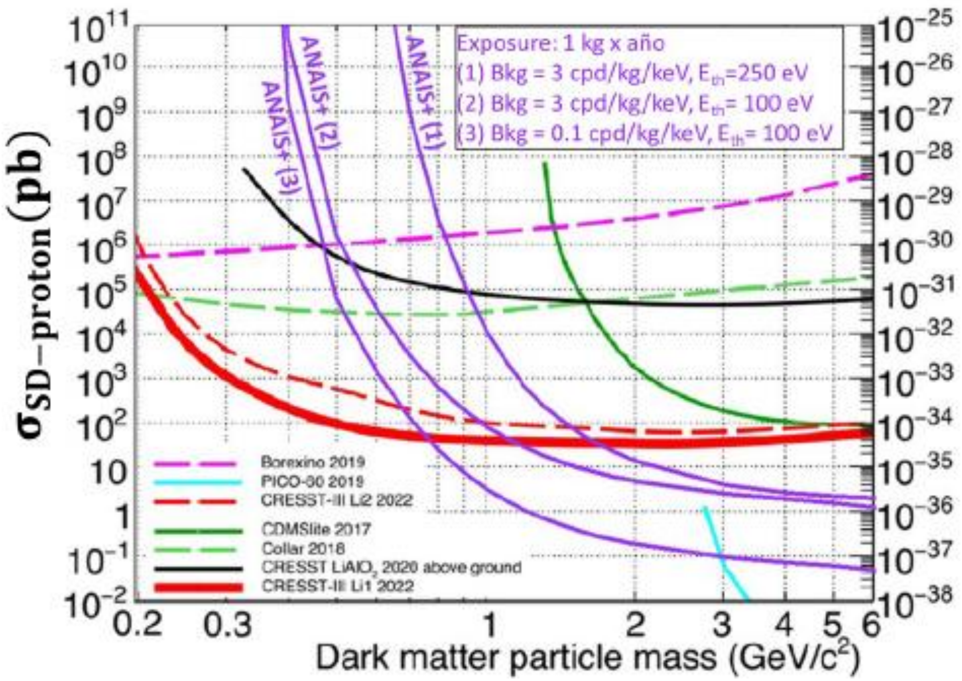
Motivation

➔ PMTs limit our energy threshold. Replacing the PMTs by **SiPMs (at low T)** could allow a **reduction in the energy threshold**, giving a better sensitivity and reducing some systematic effects on the comparison with DAMA/LIBRA

➔ Very sensitive to light WIMPs (SI, SD) and even neutrino coherent scattering

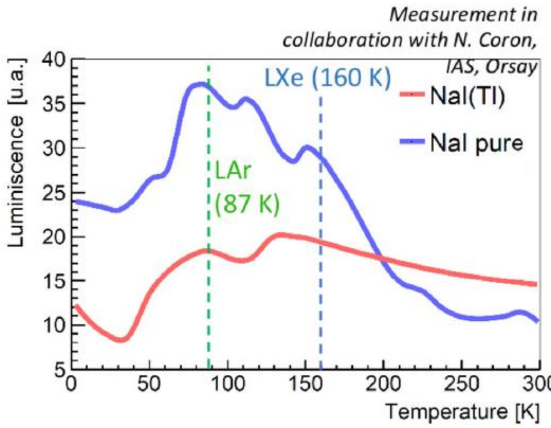


Energy threshold ~100 eV could be achieved



Not considering Migdal

Low exposure, reasonable bkg feasible if combined with radiopure crystals built at the new LSC facility and using a LAr bath as active veto



- High QE (~40%)
- High radiopurity (lower bkg)
- Low operating voltage $\mathcal{O}(10\ V)$
- But high dark current at room T (0.1-1 MHz/mm² vs 100-1000 Hz PMTs)

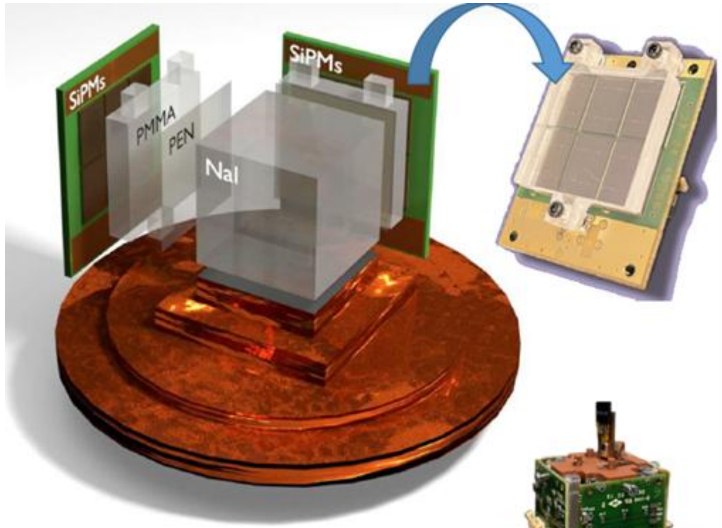
WORK AT LOW T

BONUS: Undoped NaI is a very good scintillator at low T

Beyond ANAIS–112: ANAIS+

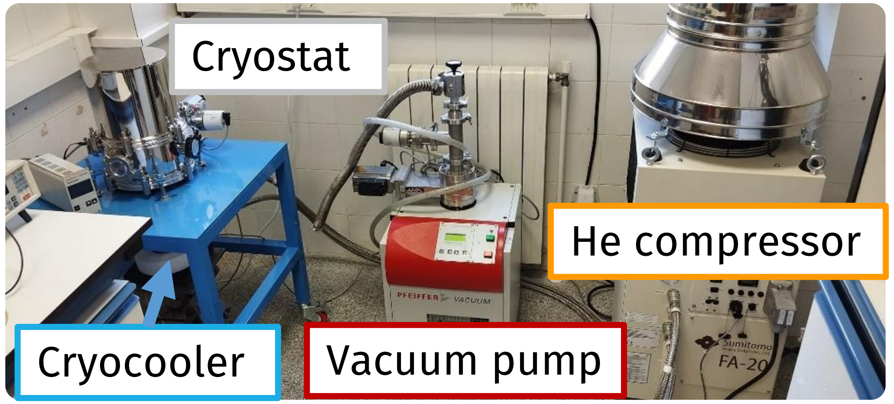
ANAIS+ prototypes

- Cubic NaI **scintillator crystal** $(1'' \times 1'' \times 1'')$
- **4 faces** covered by SiPMs arrays (**6 SiPM/side summed up**)
- SiPMs have been designed and are being produced at **LNGS**
- **PMMA** pieces to **protect** the SiPMs **bonding wires**
- **PEN** (polyethylene naphthalate) wavelength shifter ($\lambda_{emission} \approx 420$ nm)
- **First prototype** built and **being tested** (30-300 K)
- Medium term: **test in LAr at LSC**



Cryogenic installation at U. Zaragoza

- Cryocooler Sumitomo CH-104 (34 W at 77 K)
- He Sumitomo Compressor FA-20
- Capability to reach **T < 40 K**



Plan de Recuperación, Transformación y Resiliencia

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

INFN LNGS

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline

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Summary and outlook

- ANAIS–112 is leading the international efforts in the **independent test** of the DAMA/LIBRA signal, working properly after 8 years of data-taking
- Results for 6 years: ANAIS–112 is compatible with the absence of modulation and incompatible with the DAMA signal at **4.0σ** (**3.5σ**) in [1-6] keV ([2-6] keV), for a sensitivity of 4.2σ (4.1σ) at [1-6] keV ([2-6] keV) PRL 135(2025)051001
- **5σ sensitivity in late 2025** *(scheduled end date of data taking)*

- **New parallel DAQ** in ANAIS working since winter 2023 for 4 crystals and since winter 2024 for 9 crystals + blank. Promising results for improving PSD event selection
- Determining the **quenching factor** by comparing on-site neutron calibrations with G4 simulations *Paper soon*
- Building an **improved background model** with the accumulated exposure *Paper soon*
- ANAIS–112/COSINE–100 working to **combine results**. First three years compatible with the absence of modulation and incompatible with DAMA at **3.7σ** (**2.6σ**) in [1-6] keV ([2-6] keV) PRL135(2025)121002

- Within the **ANAIS+** framework, **NaI+SiPM** technology could lower the energy threshold to ~100 eV at low temperature, enabling searches for **light WIMPs**

- **Open Data Policy**: ANAIS–112 3- and 6-year annual modulation analyses (data and scripts) can be downloaded at https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais

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Thank you for your attention!

ANAIS research team
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Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

GOBIERNO DE ARAGON

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea
NextGenerationEU

MultiDark
Multimessenger Approach for Dark Matter Detection

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Backup

Toy MC for efficiency analysis

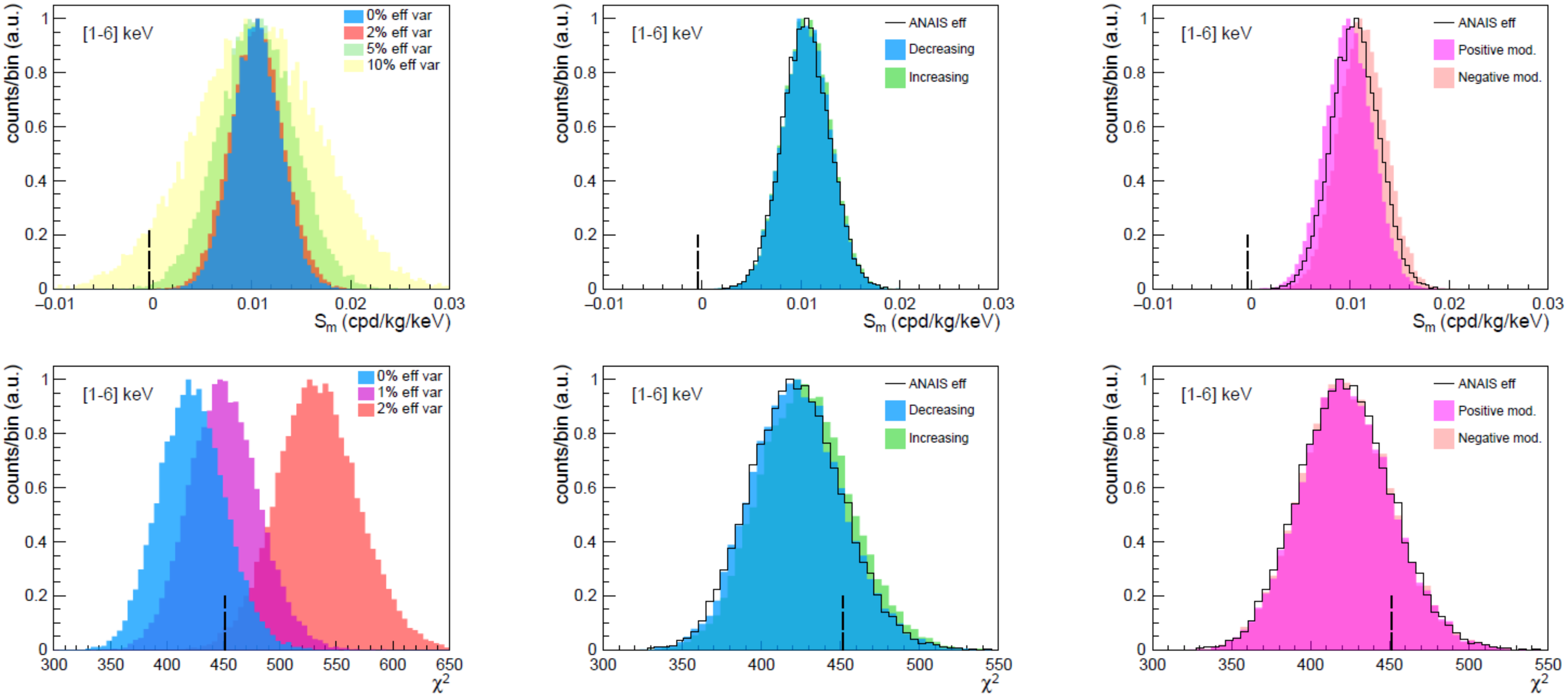
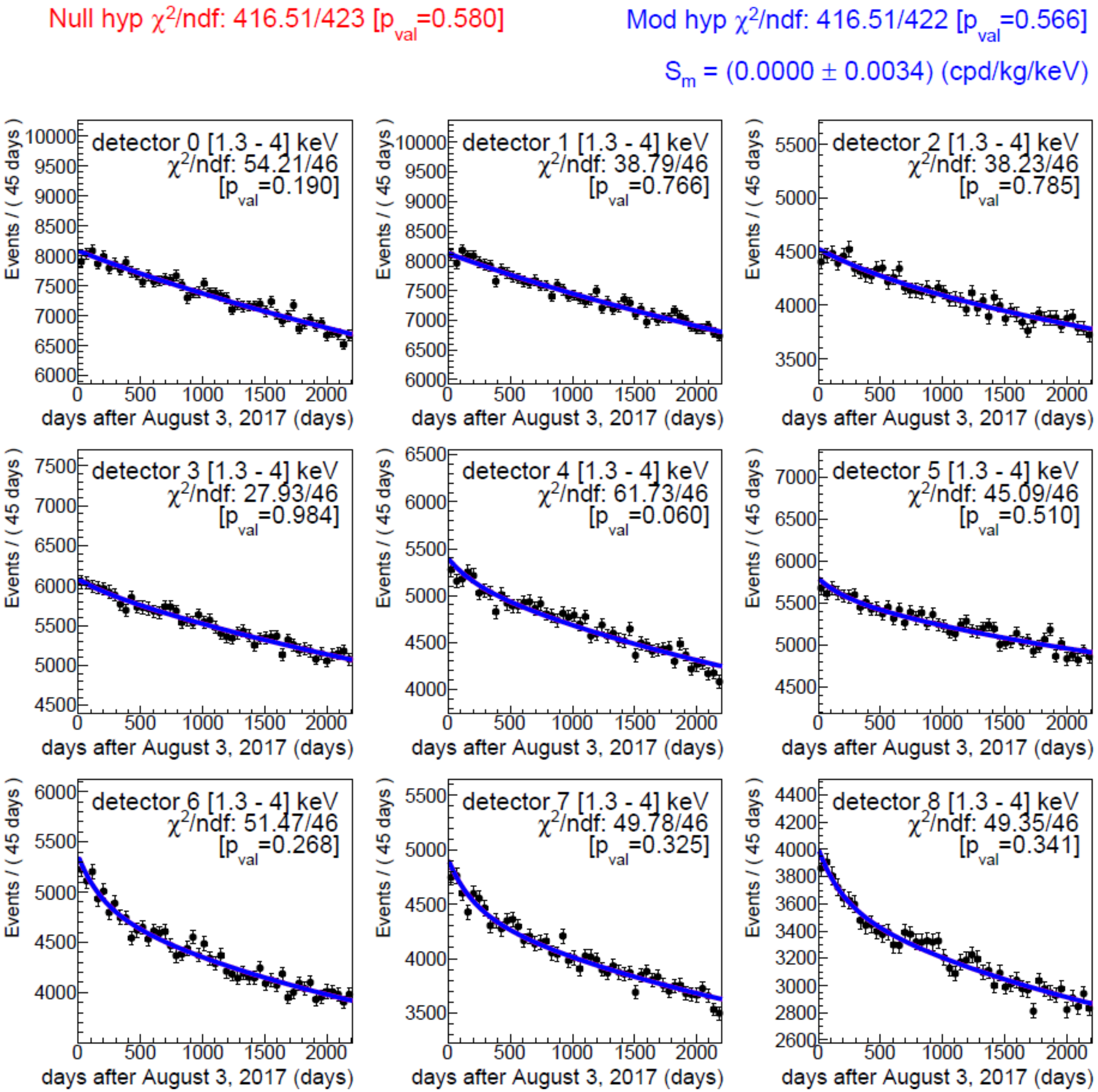


FIG. 4. Results of 20 000 toy MC simulations using the updated ANAIS–112 experimental features for 6 years, adding the modulation observed by DAMA/LIBRA. Upper panels: distribution of modulation amplitudes recovered in the [1–6] keV energy region for fluctuations in the efficiency of 0, 2, 5 and 10% (left panel); for efficiencies with a 0.6% linear variation with time in all detectors, decreasing and increasing (middle panel) and for annually modulated (or antimodulated) efficiencies in 2 modules at 0.1% and constant for the rest (right panel). Lower panels: corresponding χ^2 value distribution of the fits (ndf=422). The ANAIS–112 result is shown as dashed line in all the panels.

Annual modulation results in [1.3-4] keV



$[6.7-20]\ \mathrm{keV_{nr}}$

$S_m = (0.0 \pm 2.3)\ \mathrm{cpd/ton/3.3\ keV_{nr}}$

Annual modulation residuals in [1-6] keV

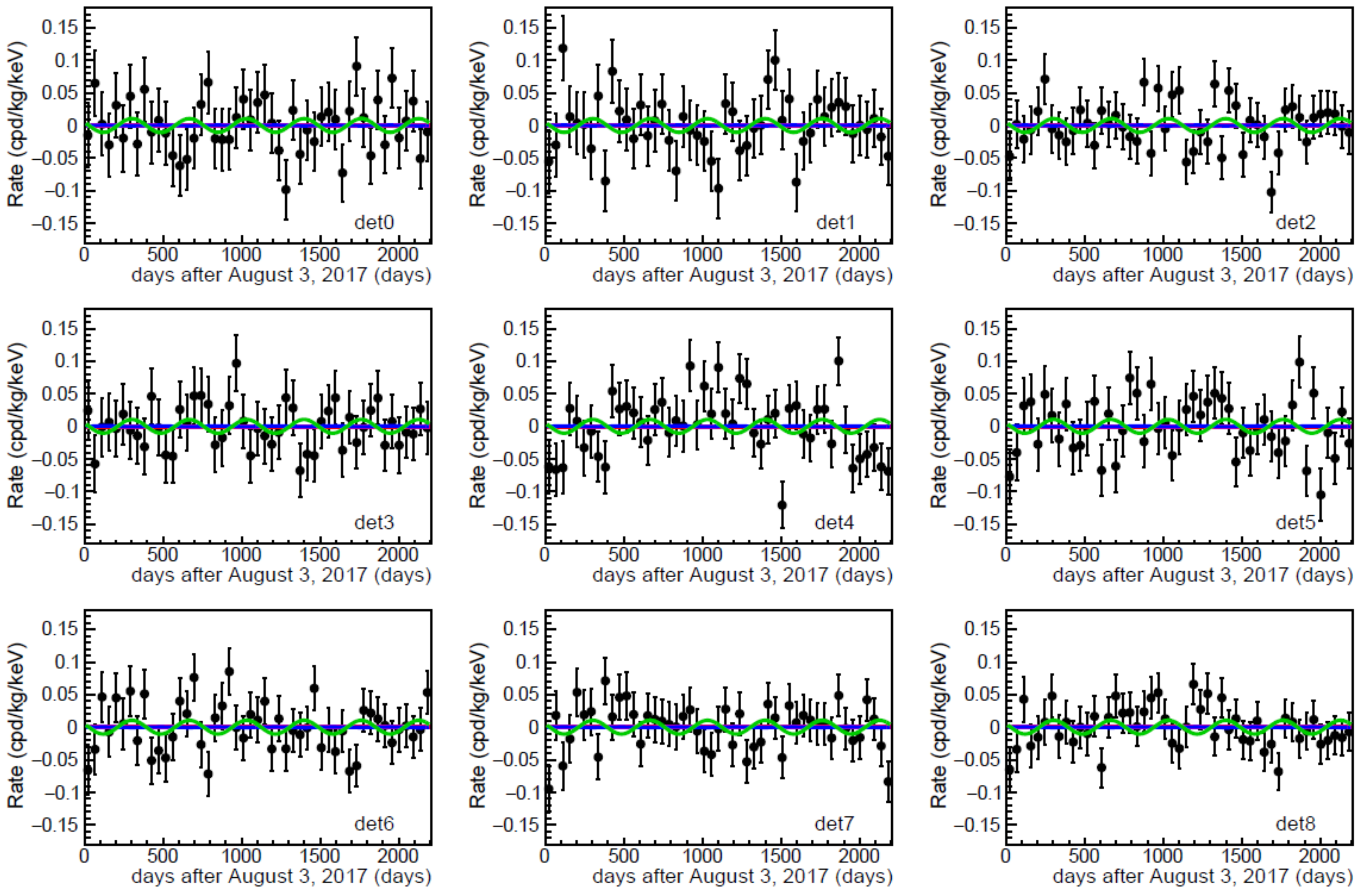


FIG. 8. Fit results for the data from the nine modules in the [1–6] keV energy region after subtracting the non-modulated term from Eq. 2. Blue and red lines are the result of the fit for the modulation and null hypothesis, respectively, after subtracting the non-modulated term from Eq. 2. The modulation observed by DAMA/LIBRA is shown in green.

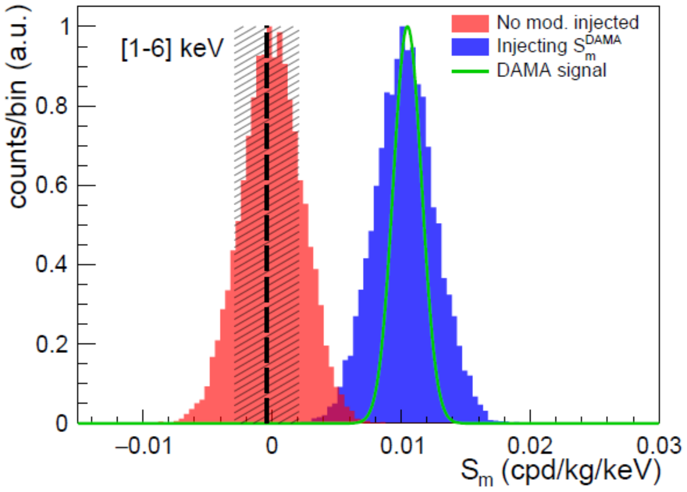


FIG. 5. Distribution of the modulation amplitudes recovered in the [1–6] keV energy region with (blue) and without (red) injecting the DAMA/LIBRA signal in 10 000 toy MC simulations. The ANAIS–112 result is represented by the dashed black line, with the uncertainty shown as a pattern of black lines, and The DAMA/LIBRA signal is displayed in green.