Updated results on annual modulation with three years of data from ANAIS-112, present status and prospects

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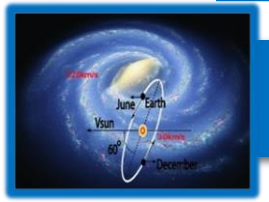
SUSY 2024
Theory meets Experiment
Madrid, 10 – 14 June 2024

CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

MultiDark
Multimessenger Approach for Dark Matter Detection

Outline

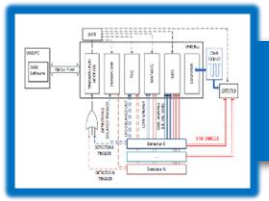


Dark matter annual modulation and DAMA positive signal

ANAIS–112: Annual modulation results with 3 years

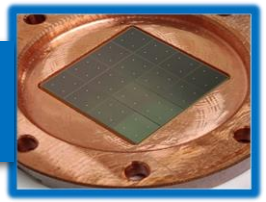
Preparing the 6-year unblinding

Na & I quenching factors



New DAQ system in ANAIS–112

Beyond ANAIS–112: ANAIS+



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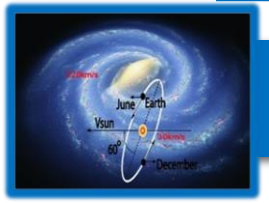

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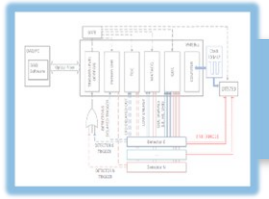

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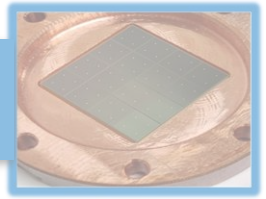
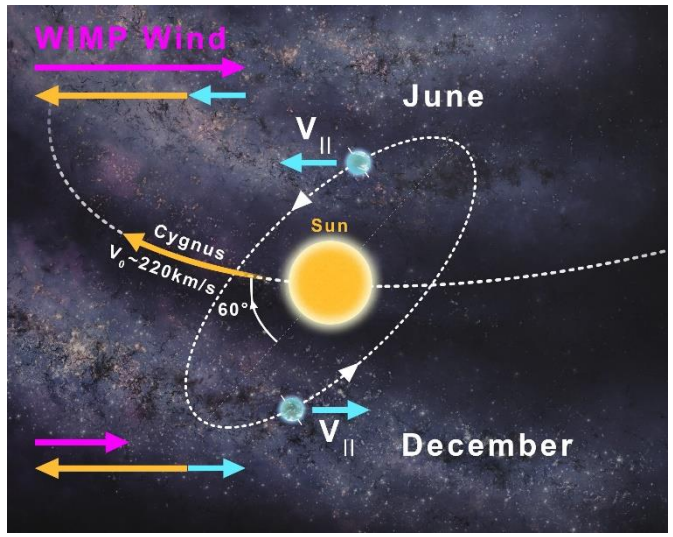
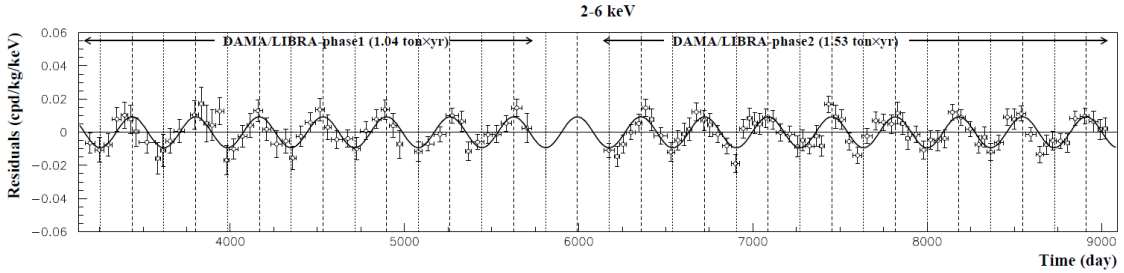


Dark matter annual modulation & DAMA/LIBRA positive signal



DAMA/NaI and DAMA/LIBRA @LNGS (since 1995)



Cosine behaviour: $T = 1$ y, $\phi = 02$/Jun

Only at low energy

Single-hit events

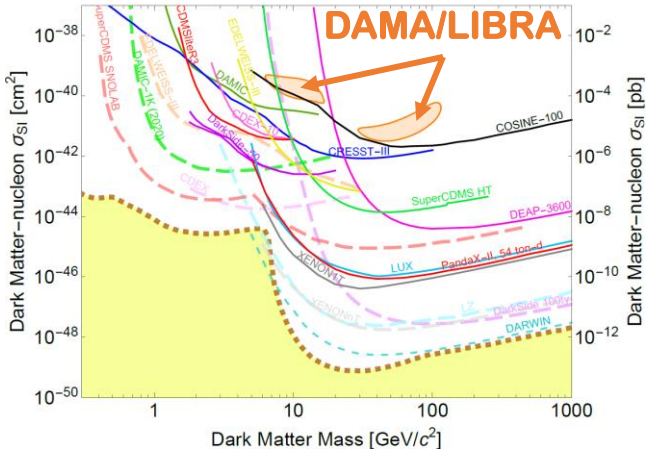
$S_m/S_0 \lesssim 7\%$

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

DAMA/NaI: 100 kg NaI(Tl) [1995-2002]
DAMA/LIBRA: 250 kg NaI(Tl) [2003-today]

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

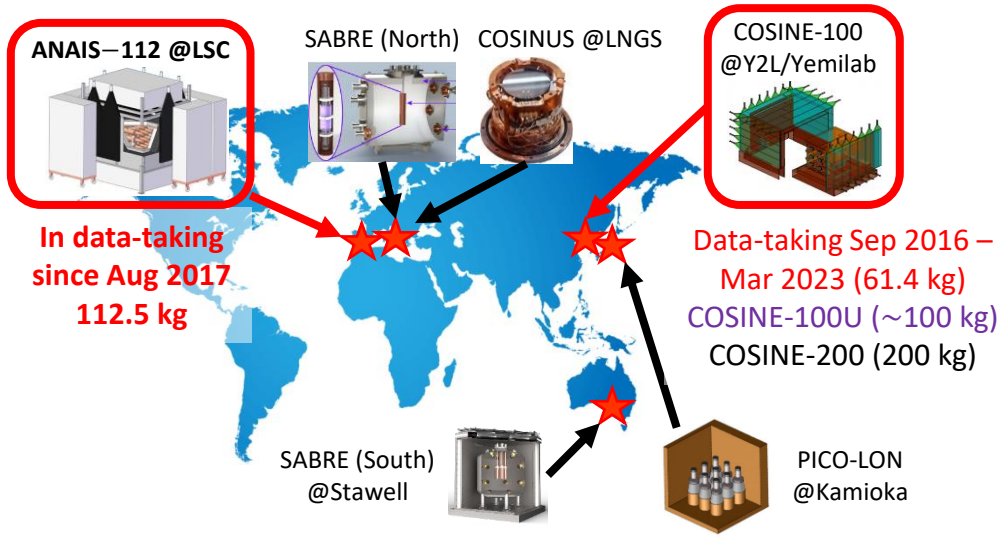
STRONG TENSION



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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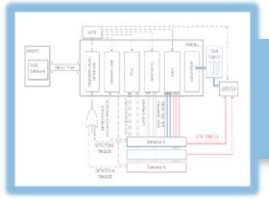

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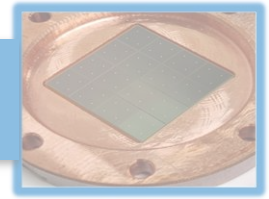


The ANAIS experiment

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** at the **Canfranc Underground Laboratory** (Spain)

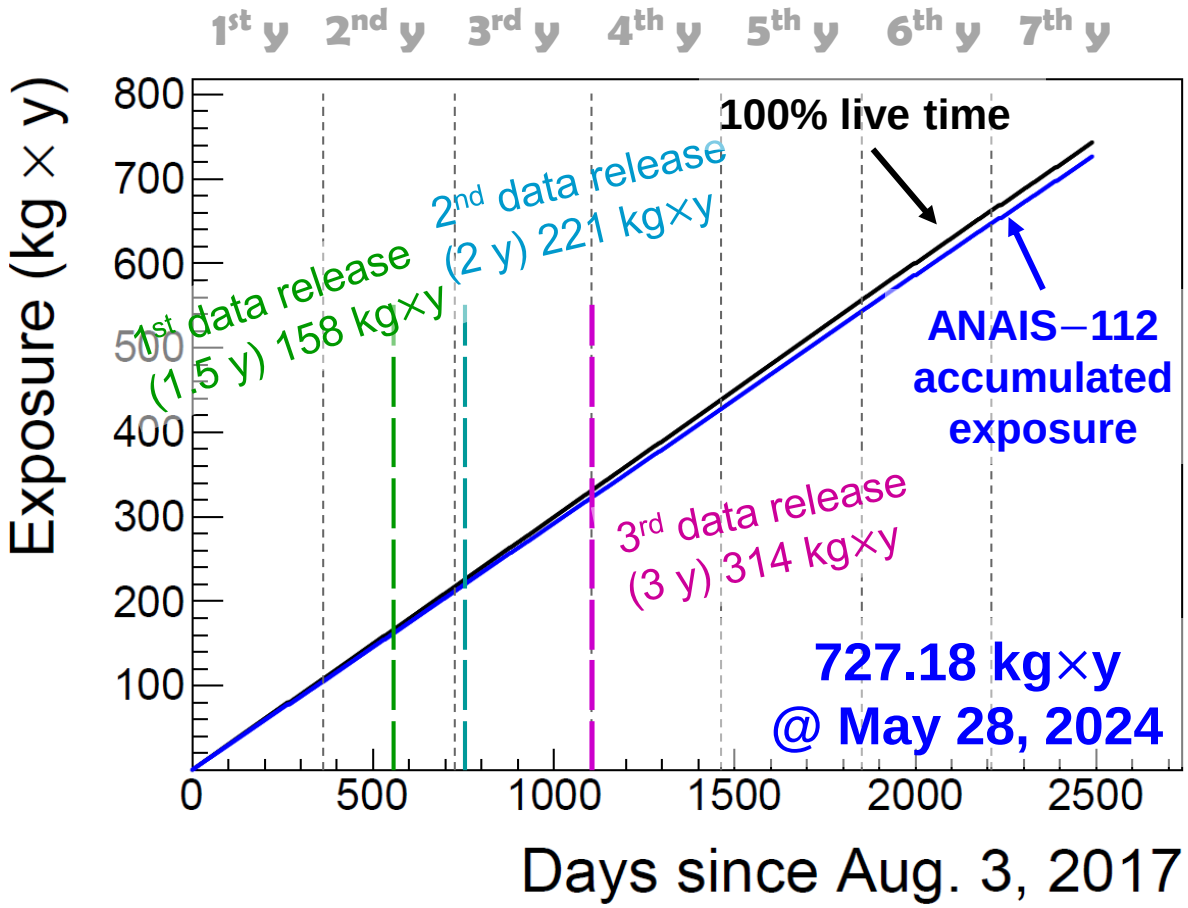
Projected sensitivity: 3σ in 5 years data-taking

ANAIS–112 experimental 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%)
- Mylar window allows external calibration
- Outstanding light collection of ~15 phe/keV
- **On 3 August 2017, data collection starts**
- First 3-year data results published

6-year data analysis ONGOING. Results soon

Annual modulation results



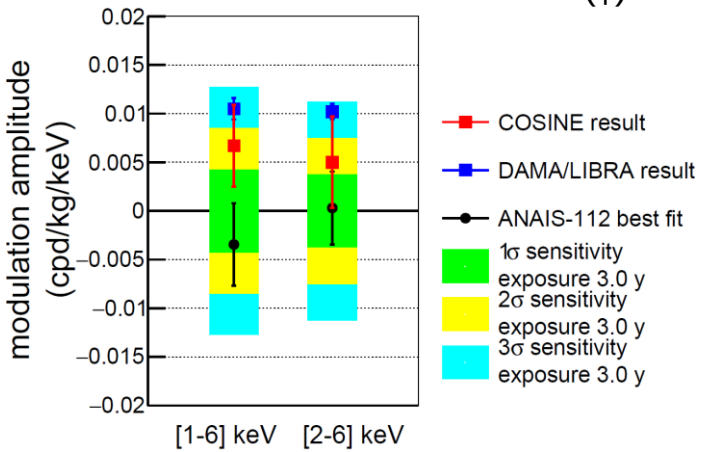
About 95% of live time

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)

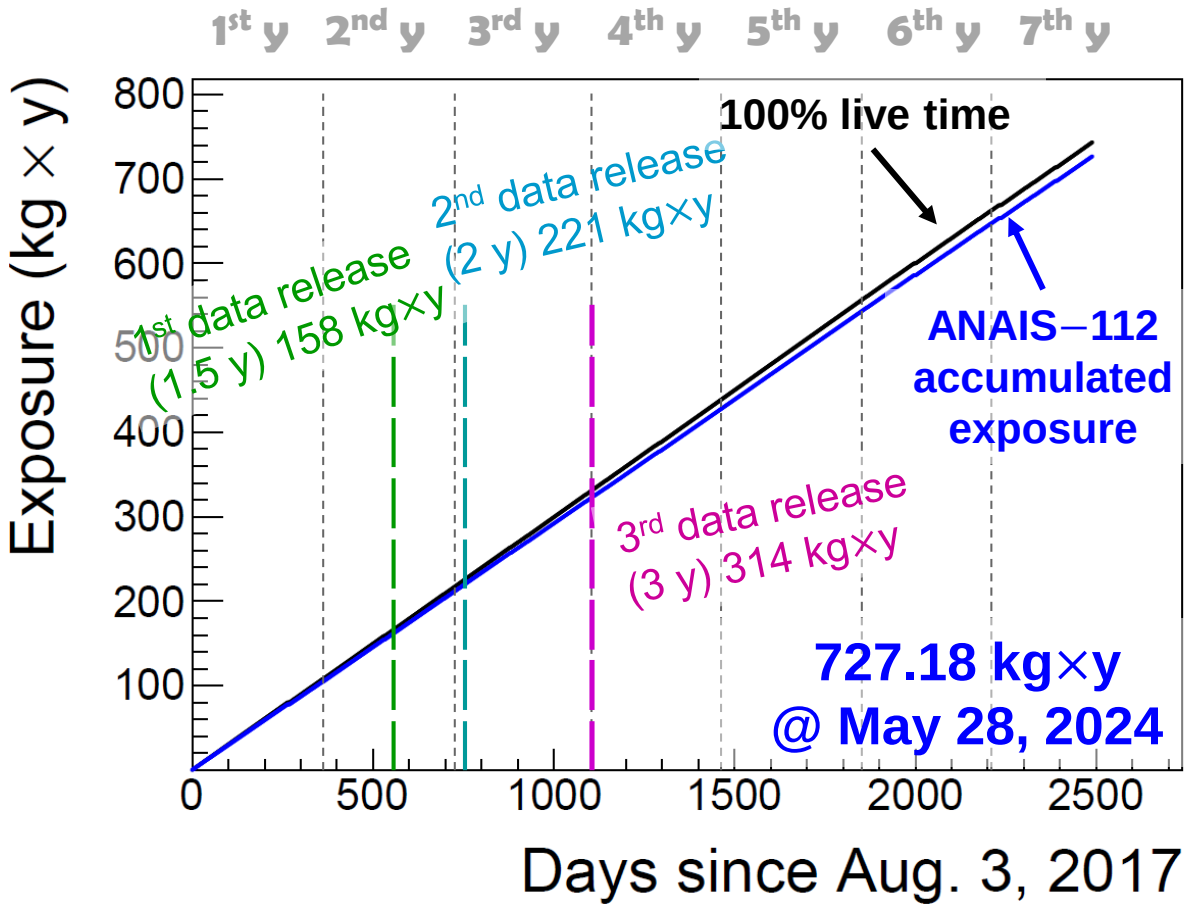
E (keV)	S_m (counts/keV/kg/day)		
	ANAIS−112	COSINE−100 (*)	DAMA/LIBRA (†)
[1-6]	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011
[2-6]	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008

(*) PRD 106, 052005 (2022)
(†) PPNP 114, 103810 (2020)



ANAIS: ~ 2.5σ sensitivity

Annual modulation results



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

(*) Based on JCAP11(2022)048

Improved filtering protocol with ML techniques

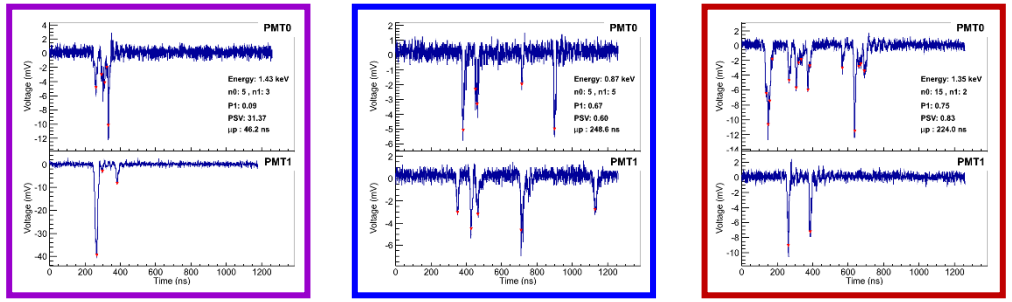
The region of interest (1-6 keV) is dominated by **non-bulk scintillation events**

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

Training populations

Signal events: dedicated on-site neutron calibrations with ^{252}Cf source

Noise events: blank module similar to ANAIS−112 modules, but without NaI(Tl) crystal



Training parameters (15)

BDT

Standard analysis (4)

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

$$P_2 = \frac{\sum_{0\ \mathrm{ns}}^{50\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)} \qquad Asynphe = \frac{nphe_0 - nphe_1}{nphe_0 + nphe_1}$$

$$CAP_x = \frac{\sum_{0\ \mathrm{ns}}^{x\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{t_{max}} A(t)}$$

$$x = 50, 100, 200, 300, 400, 500, 600, 700, 800\ \mathrm{ns}$$

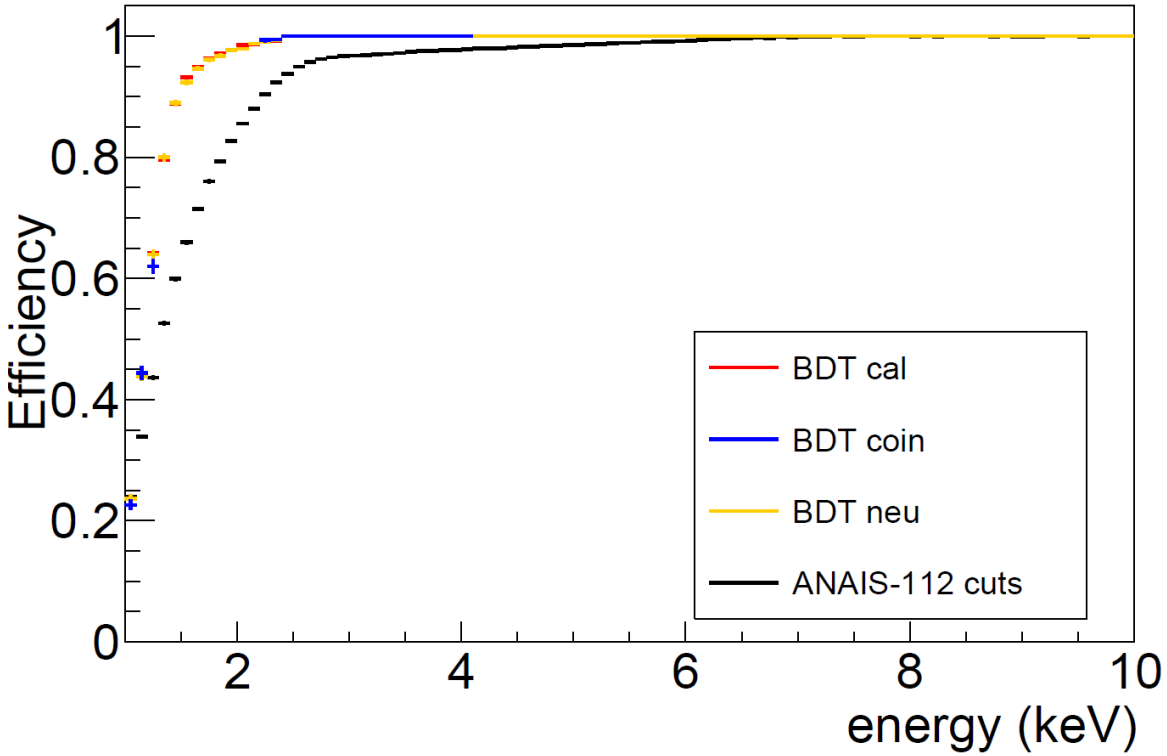
Performance of using ML for event selection in: *JCAP11(2022)048 and JCAP06(2023)E01*

Reanalysis of 3 years data in: *arXiv:2404.17348 (Apr. 2024), Submitted to Comm. Phys.*

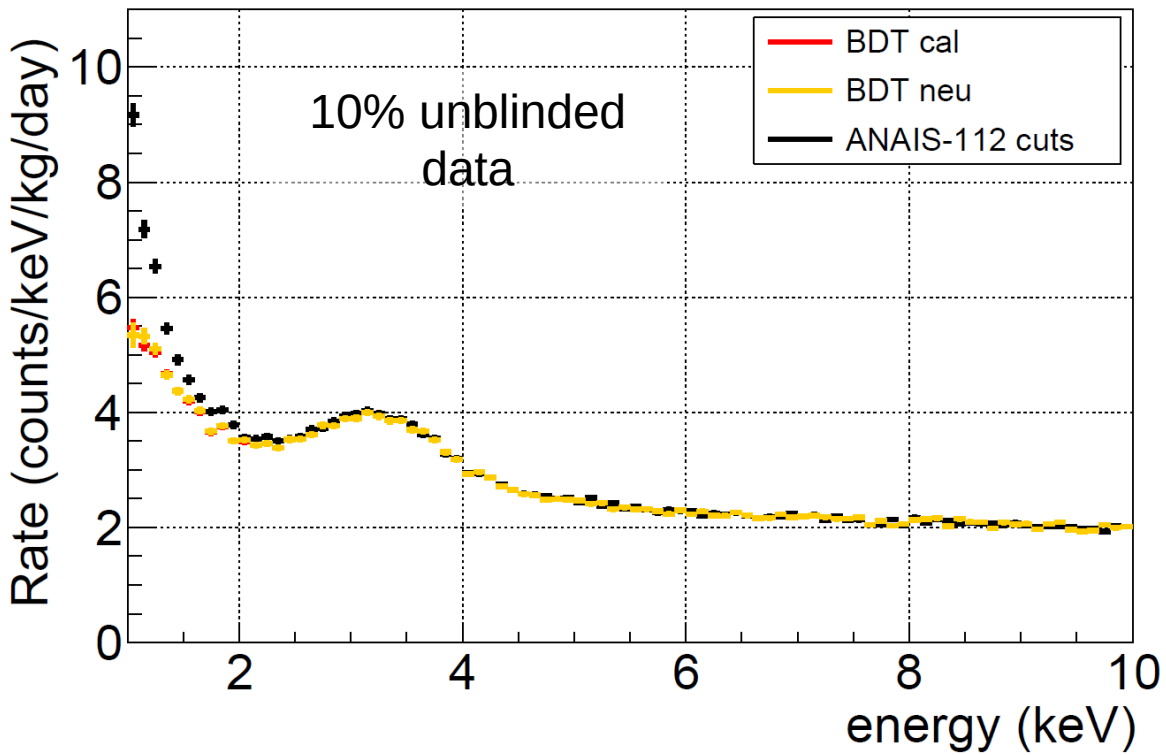
Improved filtering protocol with ML techniques

Following JCAP11(2022)048

Acceptance efficiency



Efficiency-corrected background



~30% improvement in efficiency in [1-2] keV

~18% background reduction in [1-2] keV

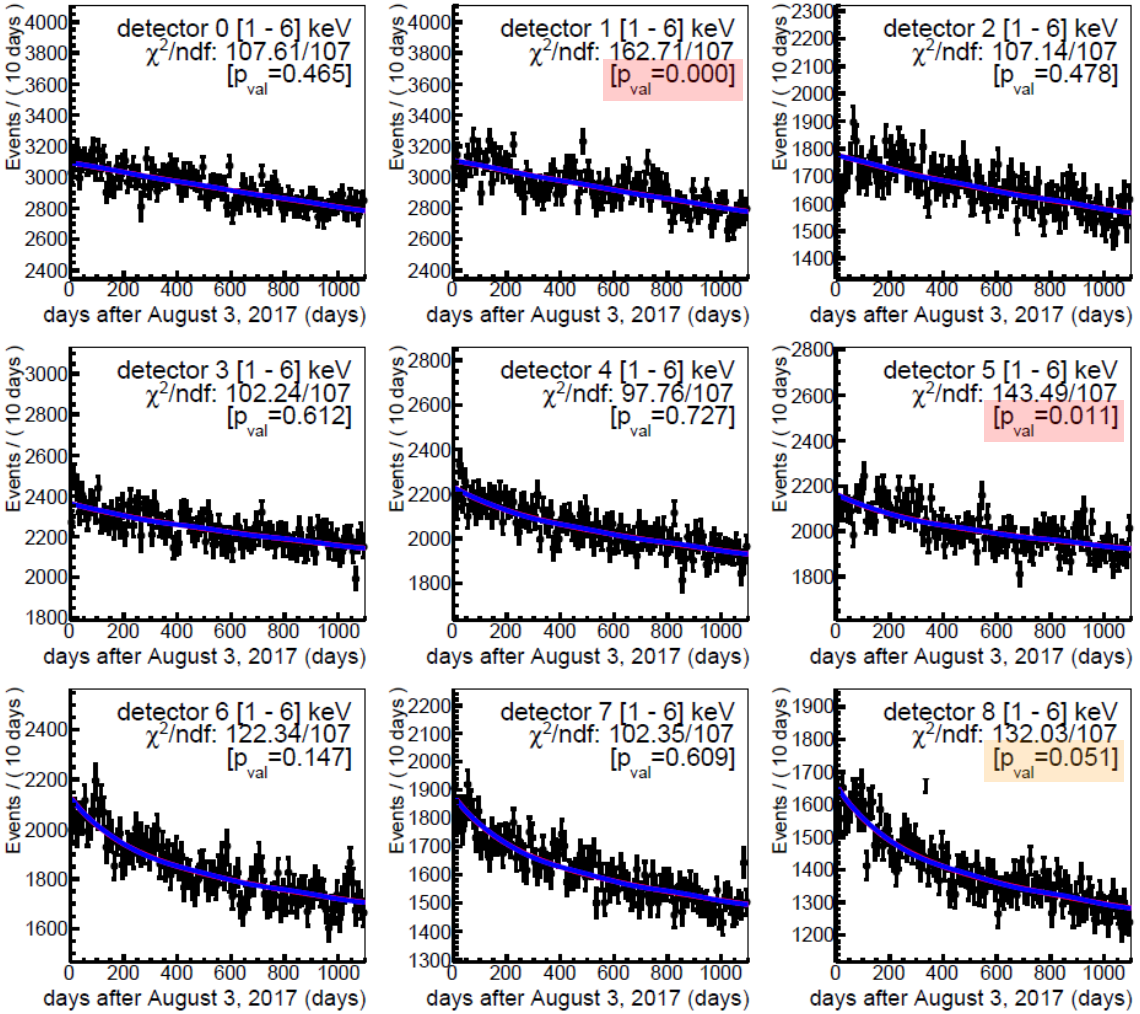
Improved 3-year results [1-6] keV

PRD103(2021)102005

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

Mod hyp χ^2/ndf: 1075.15/971 [p_{val}=0.011]

S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)

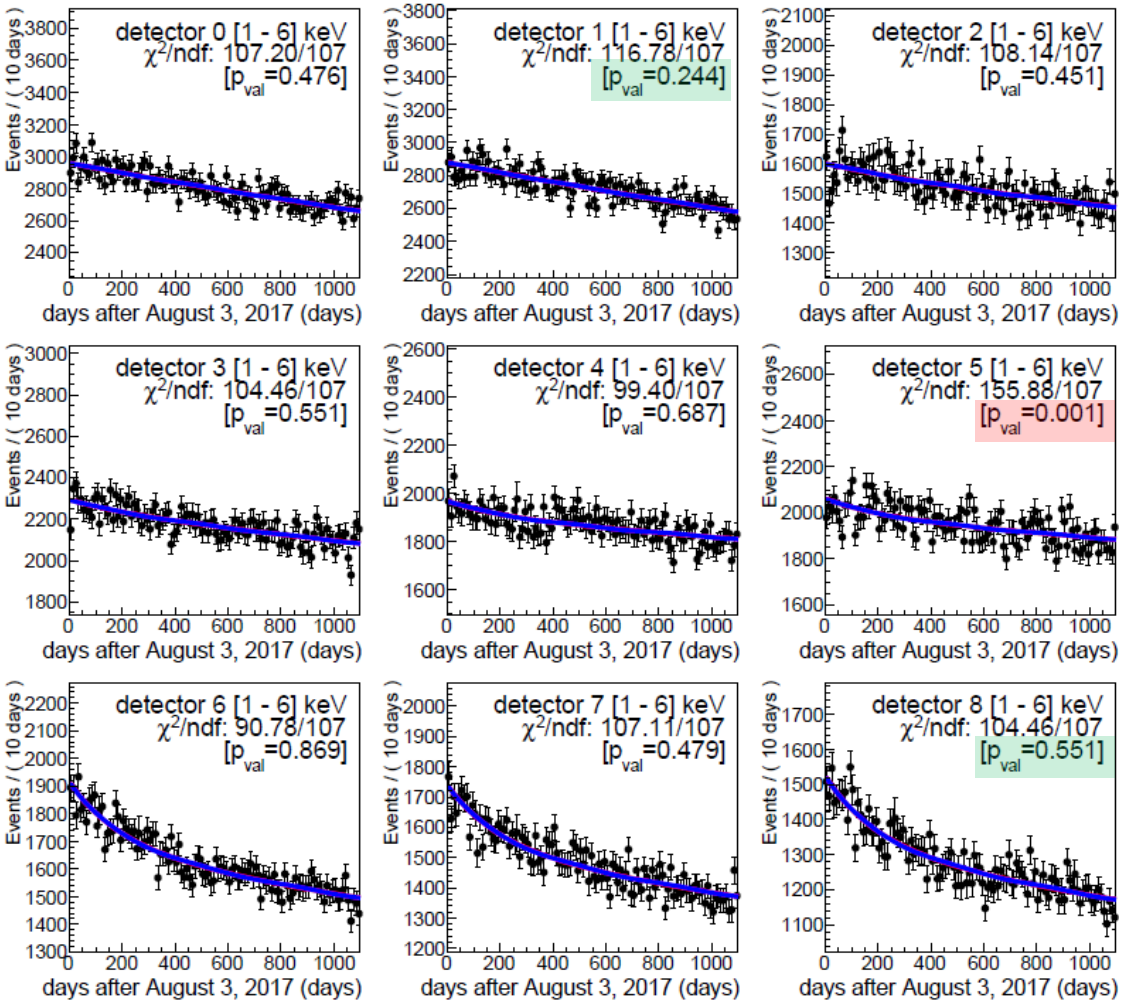


arXiv:2404.17348

Null hyp χ^2/ndf: 993.38/972 [p_{val}=0.310]

Mod hyp χ^2/ndf: 992.68/971 [p_{val}=0.307]

S_m = (-0.0031 ± 0.0037) (cpd/kg/keV)



Improved 3-year results [1-6] keV

$2.5\sigma \rightarrow 2.8\sigma$

PRD103(2021)102005

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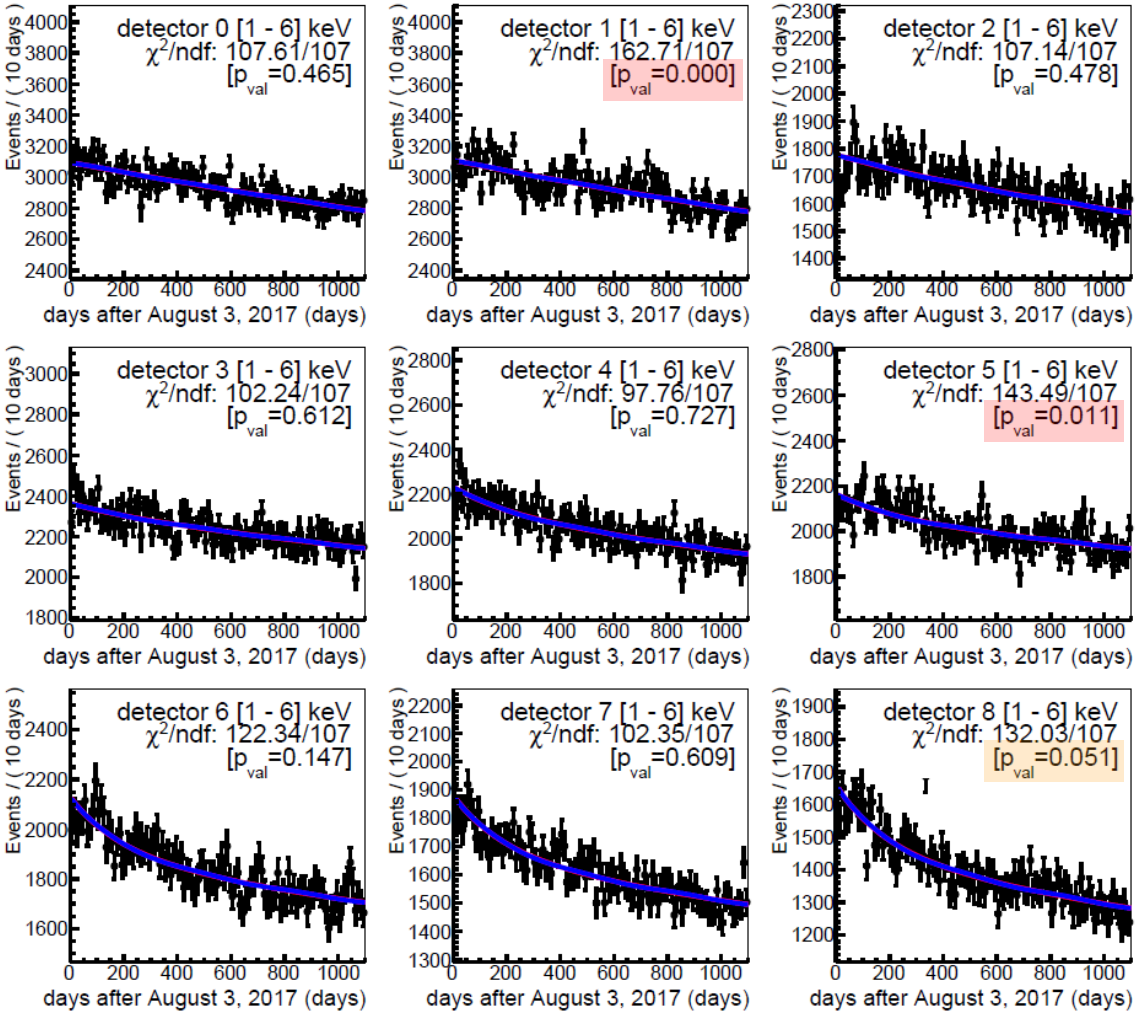

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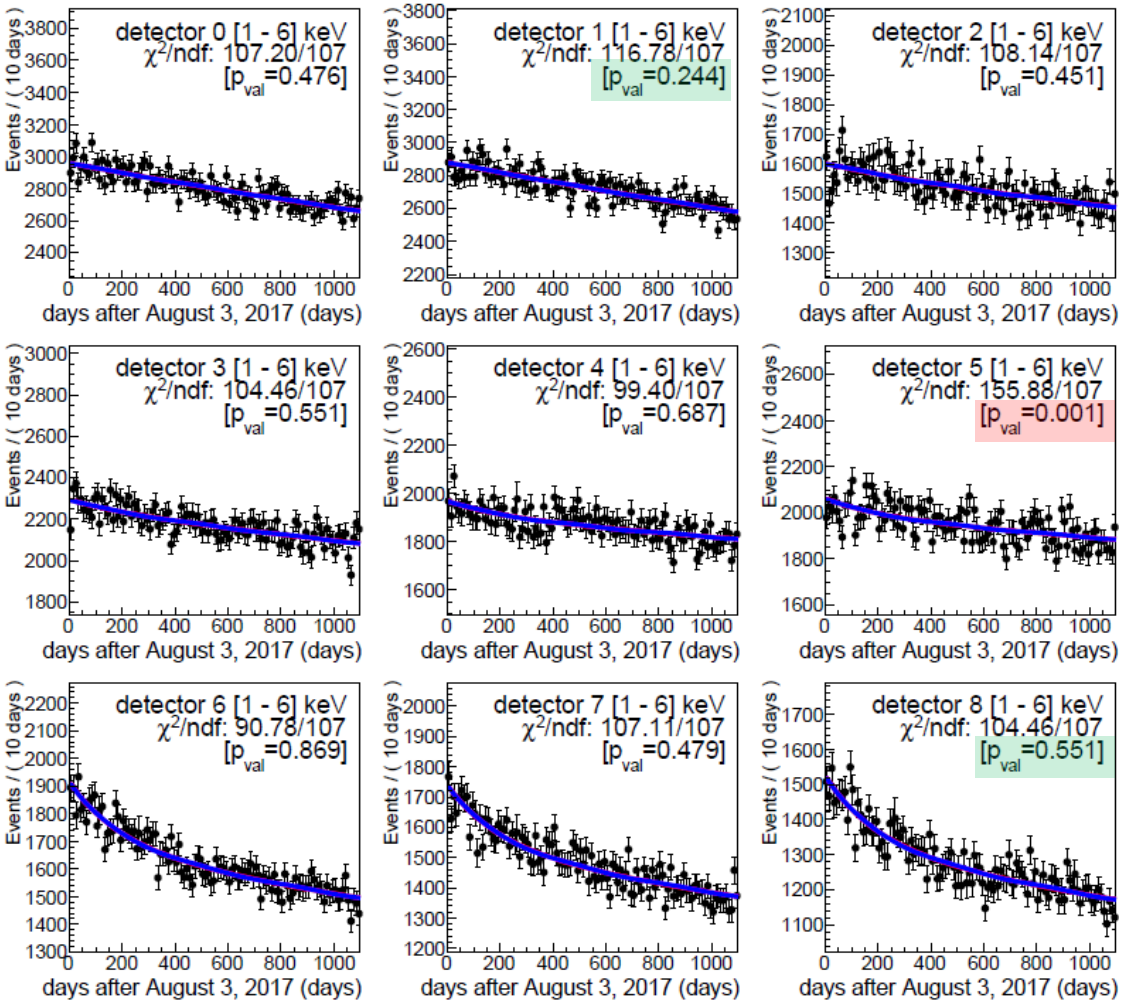
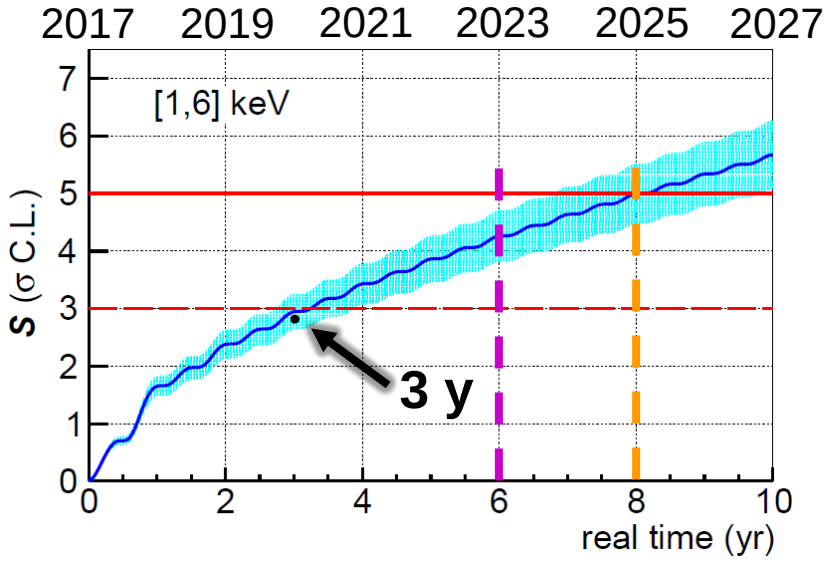
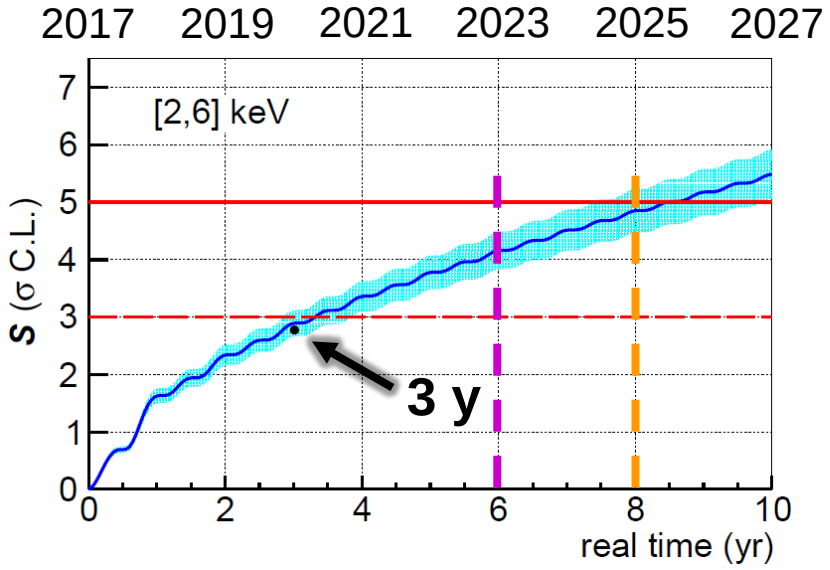
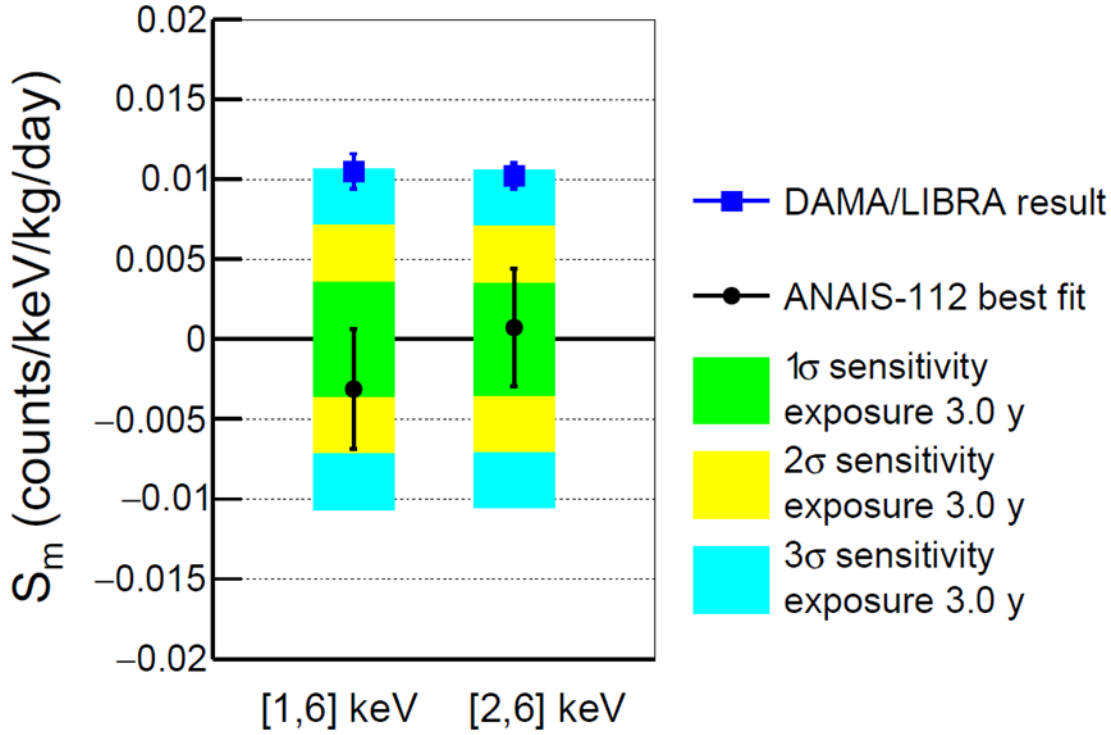


3-year annual modulation with BDT cut







Best fit modulation amplitudes **compatible with zero** at $\sim 1\sigma$

Best fit **incompatible with DAMA/LIBRA** at 3.7 (2.6) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.8σ for [1-6] and [2-6] keV

>4σ sensitivity with 6 y (NEXT RELEASE) **5σ sensitivity in late 2025**

ANAIS–112 3-year data public

➔ Thanks to the support of the **Dark Matter Data Center**, funded by the ORIGINS excellence cluster, 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

- ➔ Background model
- ➔ Efficiency
- ➔ Live time
- ➔ Event data at ROI
- ➔ Fitting routines

ANAIS-112 Three Year

Detector Module	ANAIS-112
Material	NaI(Tl)
Technology	3 × 3 Array of NaI(Tl) scintillating crystals D0-D8 using two Photo Multiplier Tubes (PMTs) each to detect scintillation light signal.
Fiducial Mass	12.5 Kg each. Total 112.5 Kg
Total Live Time	1013.83 days **Sec III of PhysRevD.103.102005 misquotes this as 1018.6 days. The last bin, bin 111, live time: 4.74 days, was not considered for the analysis in this publication.)
Threshold	1 keV (Electron equivalent energy. All energies are in keVee, aliased by keV)
Acceptance Region	1-6 keV and 2-6 keV
Average Resolution	$\sigma = (-0.008 \pm 0.001) + (0.378 \pm 0.002) \times \sqrt{E(keV)}$

ANAIS provides a JuPyter Notebook with examples of how to plot the data in these datasets and to run the RooFit macro for fitting the data.
Launch a Binder session with the notebook preloaded: launch binder

Download full repository as tar.gz: GitLab

If you use this dataset, please cite:
PhysRevD.103.102005
arXiv:2103.01175 [astro-ph.IM]

Resources | Visualize

ANAIS-112 Three Year Reanalysis with event selection using ML

Detector Module	ANAIS-112
Material	NaI(Tl)
Technology	3 × 3 Array of NaI(Tl) scintillating crystals D0-D8 using two Photo Multiplier Tubes (PMTs) each to detect scintillation light signal.
Fiducial Mass	12.5 Kg each. Total 112.5 Kg
Live Time temporal distribution	see files ANAIS112liveTime_3y_10days_D?.csv -> for every detector(0-8) Live time D0: 1006.49 days Live time D1: 1010.82 days Live time D2: 1003.29 days Live time D3: 1004.40 days Live time D4: 1006.07 days Live time D5: 1007.29 days Live time D6: 1006.32 days Live time D7: 1008.13 days Live time D8: 1002.33 days
Threshold	1 keV (Electron equivalent energy. All energies are in keVee, aliased by keV)
Exposure	Total: 323.35 kg-yr Effective: 312.12 kg-yr after muon and rate cuts
Average Resolution	$\sigma = (-0.008 \pm 0.001) + (0.378 \pm 0.002) \times \sqrt{E(keV)}$

Download full repository as tar.gz: GitLab

If you use this dataset, please cite:
I. Coarasa et al JCAP11(2022)048
arXiv:2404.17348 [astro-ph.IM]

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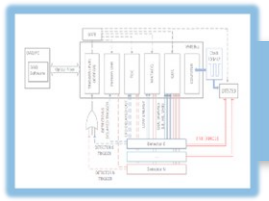

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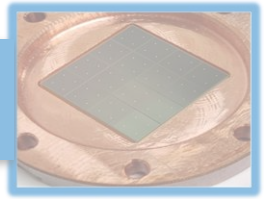
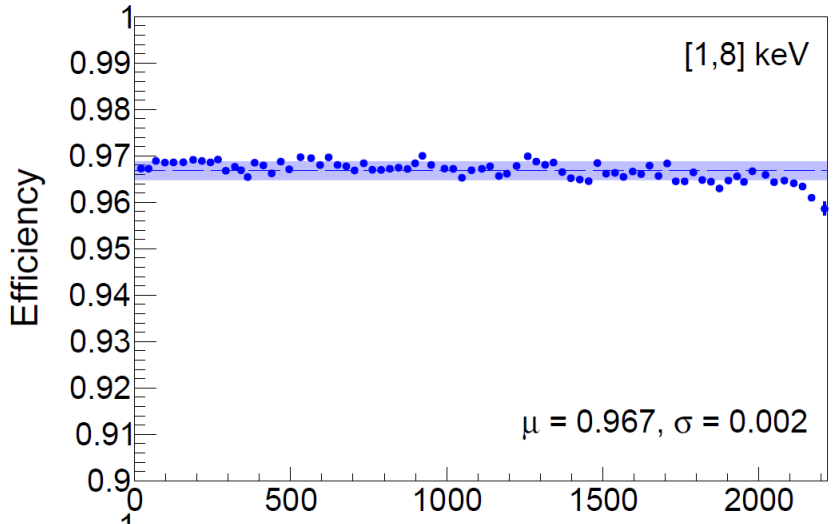
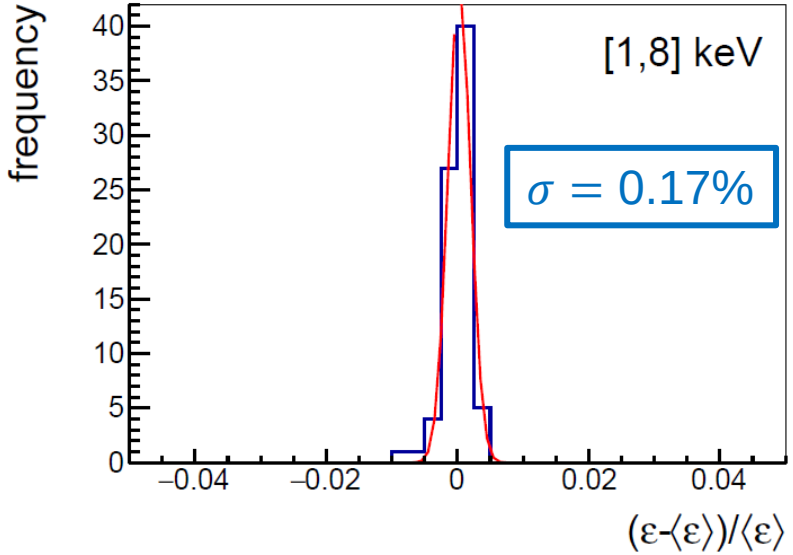


Preparing the 6-year unblinding

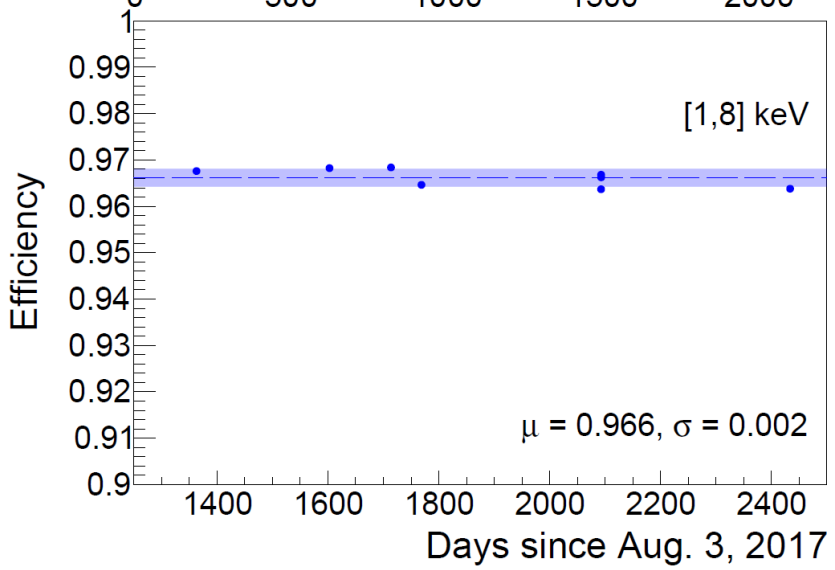
Event selection efficiency stability

Efficiency calculated from ^{109}Cd calibrations





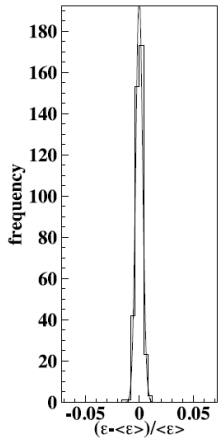
Efficiency calculated from **neutron** calibrations



DAMA/LIBRA-phase2 reports

σ = **0.30%** in [1-8] keV

We are more stable than DAMA/LIBRA

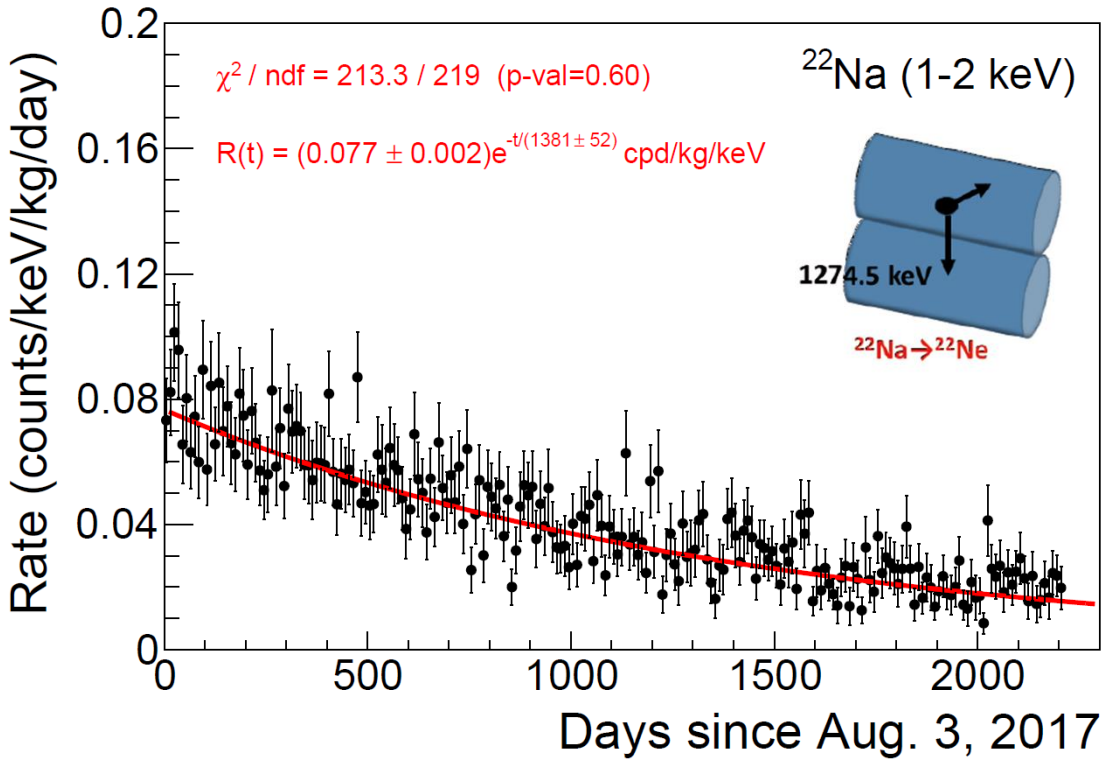


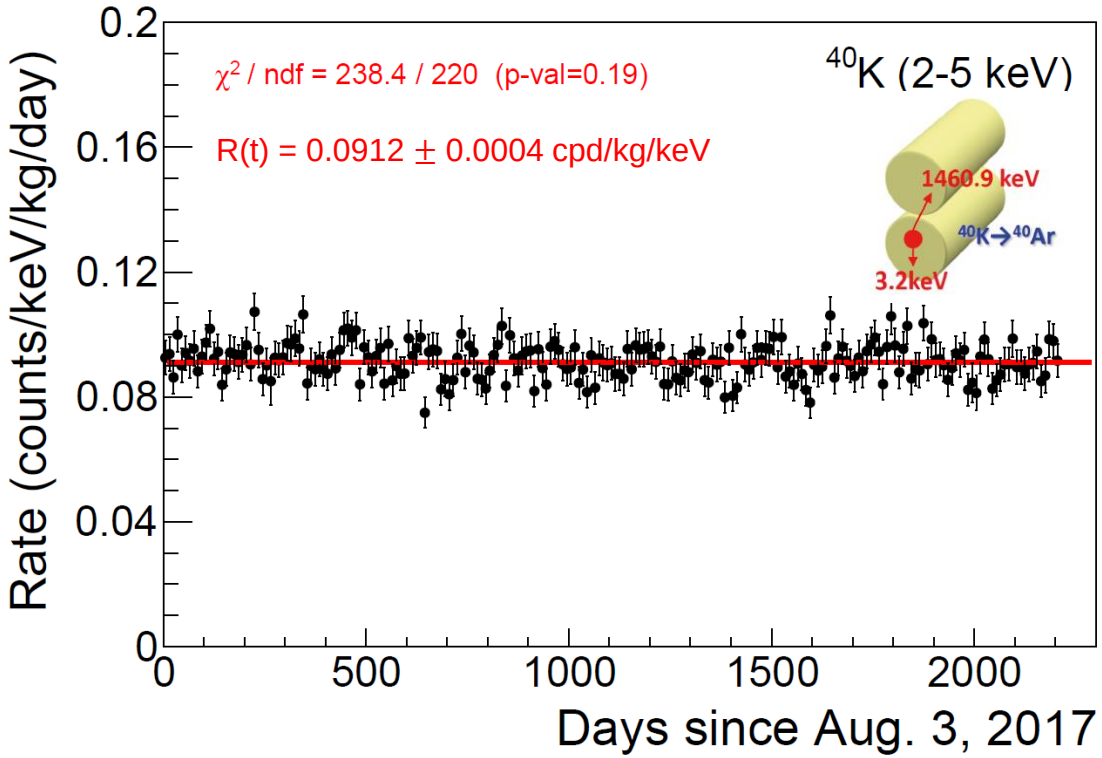
R. Bernabei et al., Prog. Part. Nucl. Phys. 114 (2020) 103810

Preparing the 6-year unblinding

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)





$\tau_{fit} = 1381 \pm 52$ days

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

Preparing the 6-year unblinding

Improving the background model

Understanding the background evolution is essential for the modulation fit

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

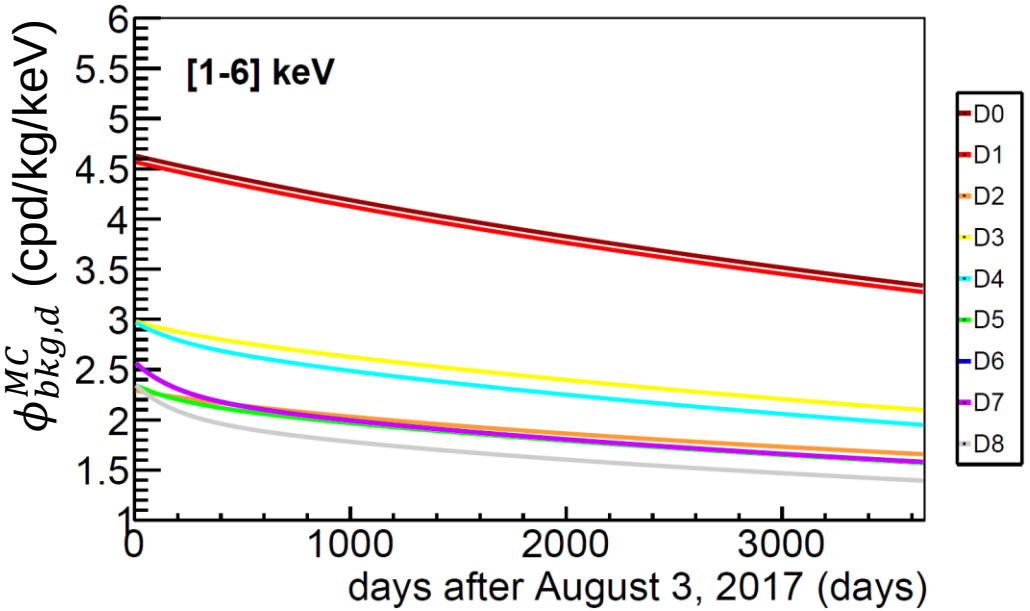
9 crystals (^{40}K, ^{210}Pb, ^{232}Th, ^{238}U, ^{235}U, ^{3}H, ^{22}Na, ^{109}Cd, ^{113}Sn, I's, Te's)

18 PMTs (^{40}K, ^{226}Ra, ^{232}Th, ^{238}U, ^{235}U)

Others: 9 Cu housing, 18 SiPads, 18 Quartz windows (^{40}K, ^{226}Ra, ^{232}Th, ^{238}U)

+ Air inside the shielding (^{222}Rn)

+ Roman lead (^{210}Pb)



6 years analysis with ML techniques and new background model is almost finished

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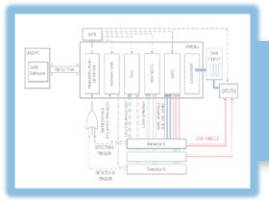
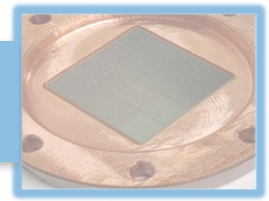


New DAQ system in ANAIS–112

Beyond ANAIS–112: ANAIS+



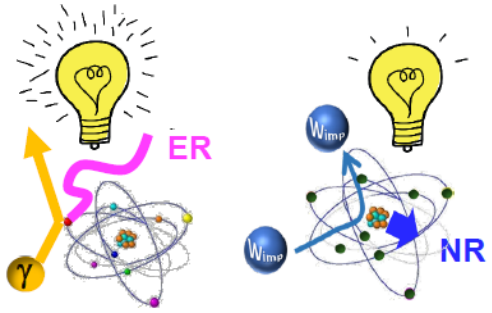
NR Quenching factor measurements

Is this really a model independent test of the DAMAI/LIBRA result?

Direct comparison in **electron recoil energy**, but the **nuclear recoil energy** is **quenched** and the quenching factor (Q) could depend on crystal properties

➔ A large number of measurements for the Q of NaI detectors

➔ Still too many uncertainties in the Q values and energy dependences

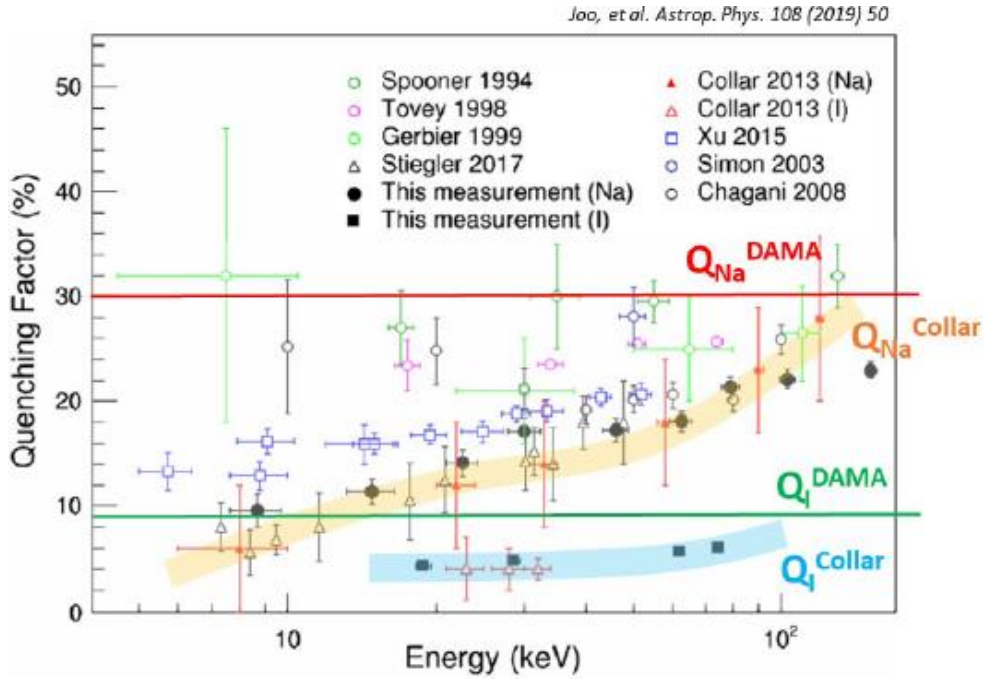


In a scintillator, an **ER** produces much more light than a **NR** of the same energy!

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

$Q_{Na}^{DAMA} = 30\%$

$Q_{I}^{DAMA} = \ 9\%$



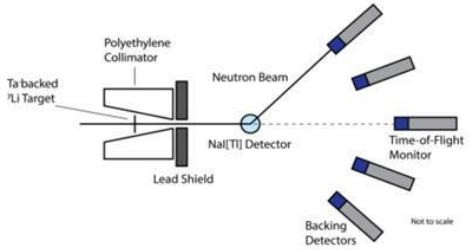
The response of different detectors to DM particles could differ if Q is different

NR Quenching factor measurements

Q determination for ANAIS−112 crystals is ongoing: two approaches are followed in parallel

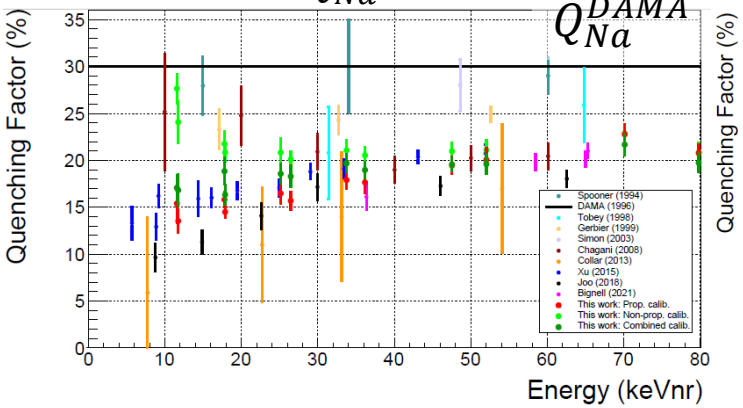
Monochromatic neutron source at TUNL (Duke Univ.)

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

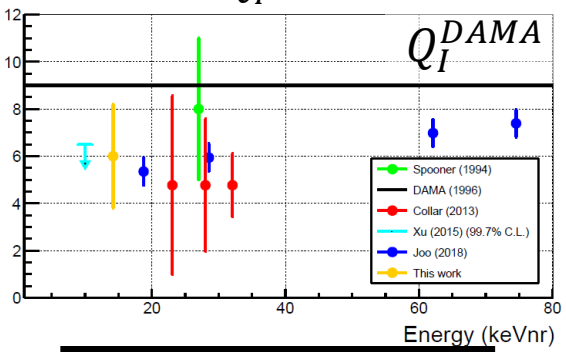


➔ **Compatible** values for the 5 crystals
➔ Noticeable differences for different energy calibrations (**NaI non-linearity**)
➔ **Lower QF** than **DAMA/LIBRA** measurement

Results for Q_{Na}



Results for Q_I



$$Q_{Na} = (21.2 \pm 0.8)\%$$
$$Q_I = (6.0 \pm 2.2)\%$$

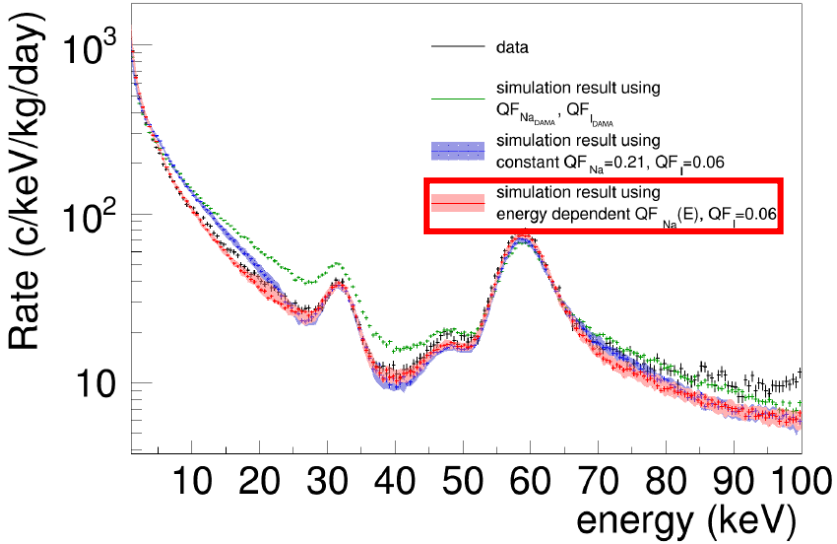
D. Cintas et al., arXiv:2402.12480 (Feb. 2024), Submitted to Phys. Rev. C

On-site neutron calibrations with ^{252}Cf source

Method: Compare calibration data with MC simulation, assuming a certain QF (energy dependent)

Eight calibration runs since April 2021 using a **^{252}Cf neutron source** at different positions in the ANAIS−112 set-up

➔ **Very sensitive** to the QF
➔ **DAMA/LIBRA QF not compatible** with ANAIS data
➔ Robust agreement with TUNL measurements (QF(E) favored)



[Analysis almost finished Paper soon]

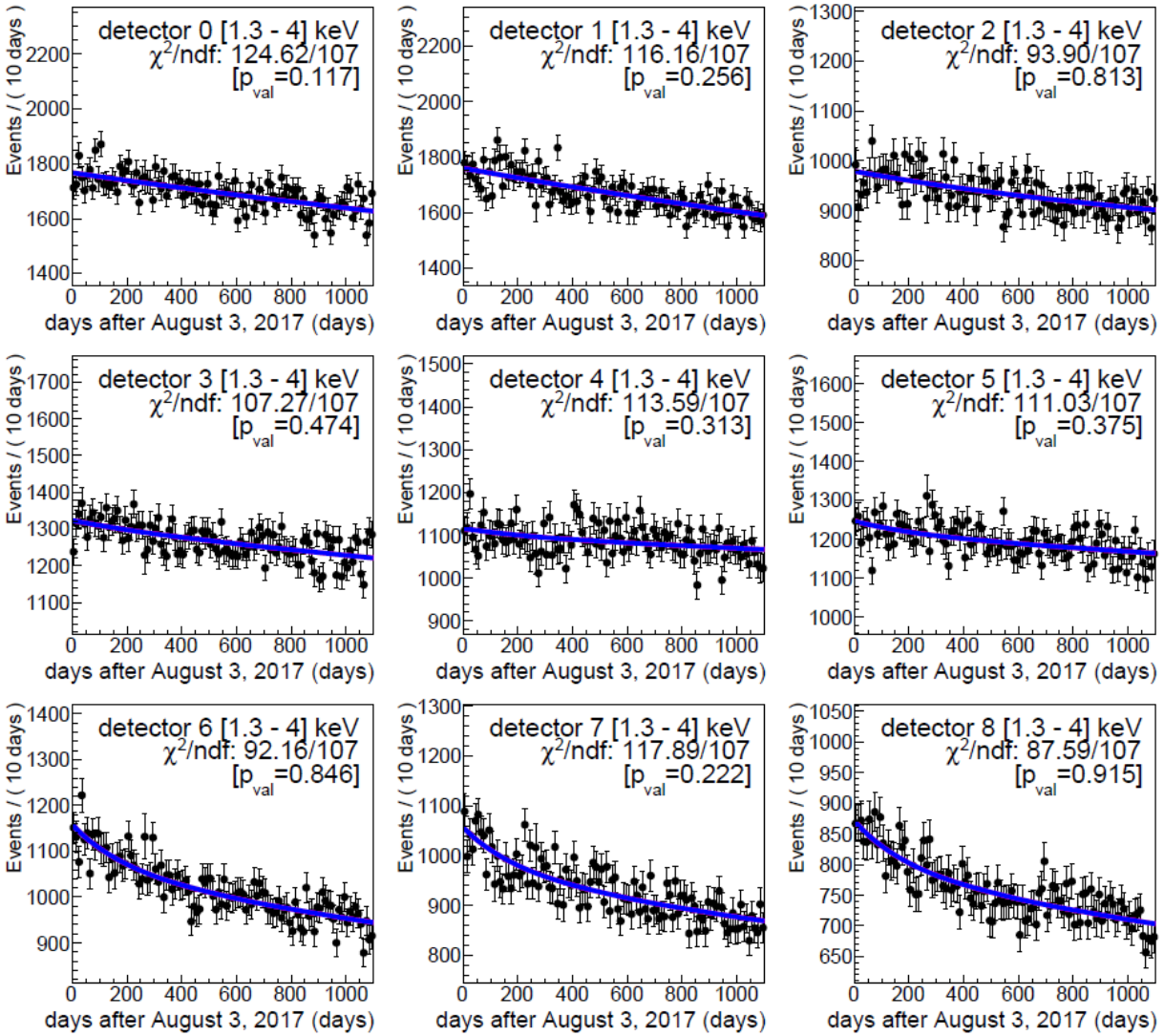
T. Pardo et al., PoS(TAUP2023)078

3-year annual modulation analysis in 1.3 – 4 keV

Null hyp χ^2/ndf: 963.18/972 [p_{val}=0.574]

Mod hyp χ^2/ndf: 963.16/971 [p_{val}=0.565]

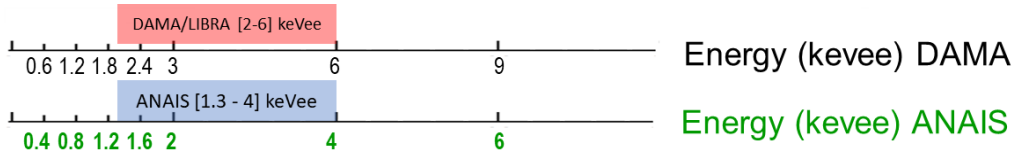
S_m = (-0.0006 ± 0.0050) (cpd/kg/keV)



Supposing:

➔ $Q_{Na} = 0.30, Q_I = 0.09$ in DAMA/LIBRA

➔ $Q_{Na} = 0.20, Q_I = 0.06$ in ANAIS–112



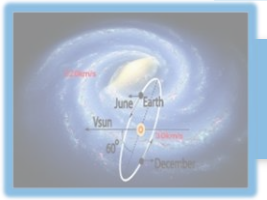
DAMA $[2-6]$ keV $\longrightarrow$ ANAIS $[1.3-4]$ keV

Best fit modulation amplitude $S_m = (-0.0006 \pm 0.0050)$ counts/keV/kg/day **compatible with zero** at 1σ

Best fit **incompatible with DAMA/LIBRA** at 2.2σ

Sensitivity with 3 years data: 2σ

Outline

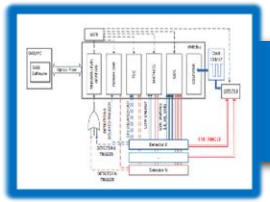


Dark matter annual modulation and DAMA positive signal

ANAIS–112: Annual modulation results with 3 years

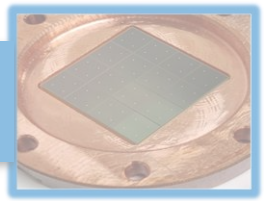
Preparing the 6-year unblinding

Na & I quenching factors



New DAQ system in ANAIS–112

Beyond ANAIS–112: ANAIS+

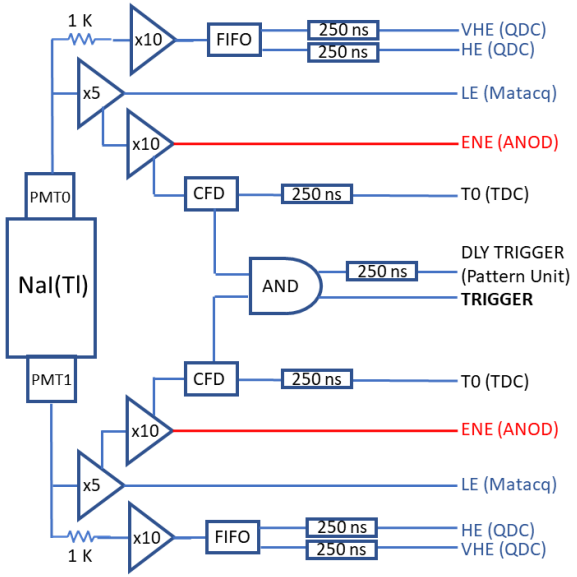


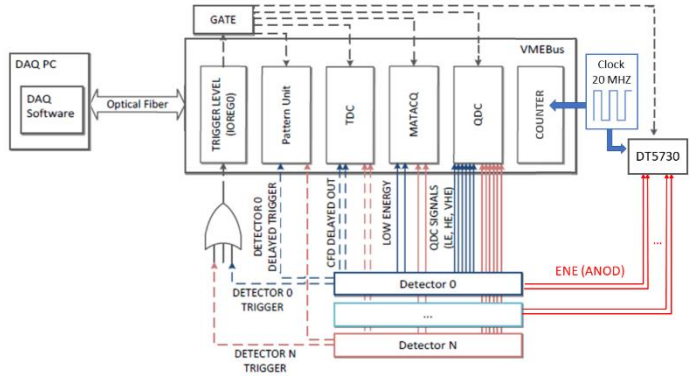
New DAQ system in ANAIS–112

To better understand (and eventually remove) the asymmetric events of still unknown origin

ANAIS–112 DAQ system

➔ Individual PMT signals digitized and fully processed
➔ Trigger at phe level for each PMT signal
➔ AND coincidence in 200 ns window
➔ Redundant energy conversion by QDC
➔ Trigger in OR mode among modules
➔ Electronics at air-conditioned-room to decouple from temperature fluctuations
➔ Muon detection system: tag every muon event to offline processing





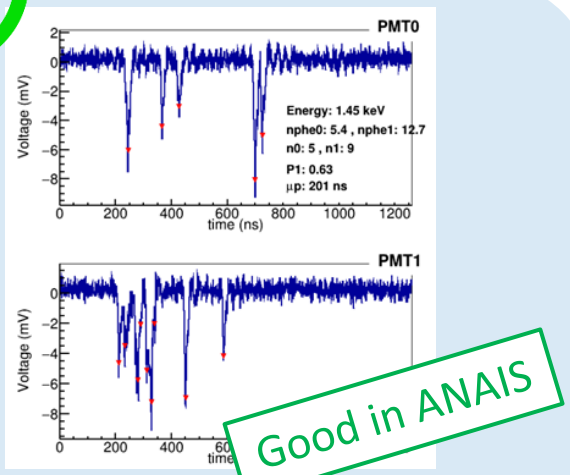
ANAIS-112 digitization performed by CAEN V1729A (MATACQ chip)
14 bits, 2 GS/s, 1.25 μs window
3–4 ms dead time per event

Plan de Recuperación, Transformación y Resiliencia

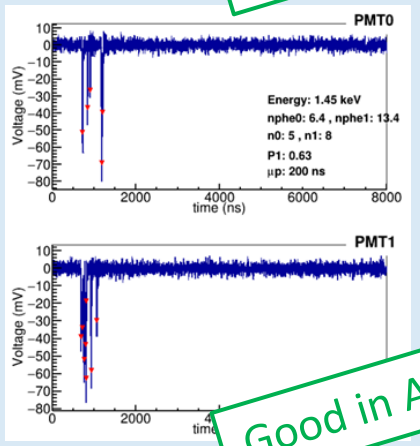
New DAQ system in parallel (ANOD, Anais NO Dead time)
CAEN DT5730 **(8 channels)** → 4 modules
14 bits, 500 MS/s → 8 μs window
Internal buffer: 640 kS/ch
No dead time for rates <100 Hz

New DAQ system in ANAIS–112

To better understand (and eventually remove) the asymmetric events of still unknown origin



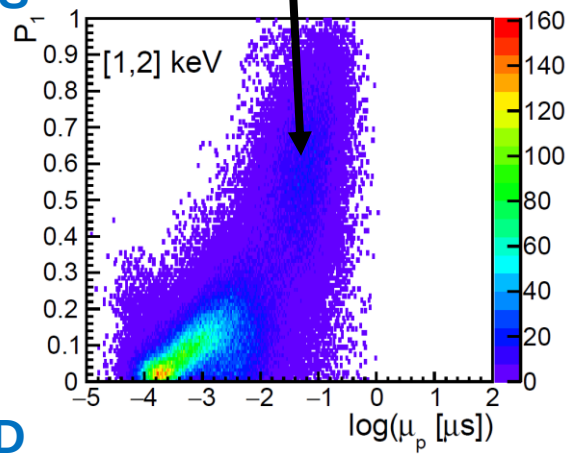
Good in ANAIS



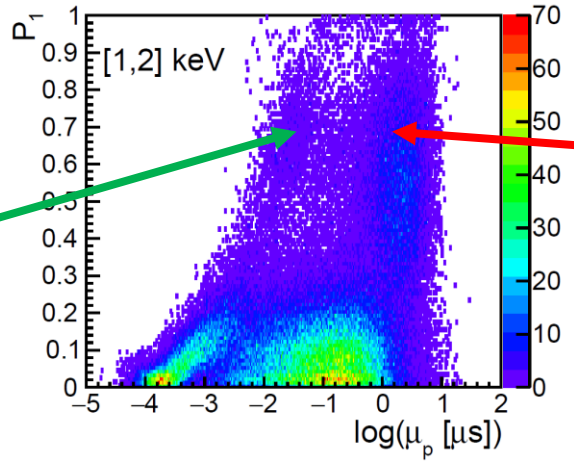
Good in ANOD

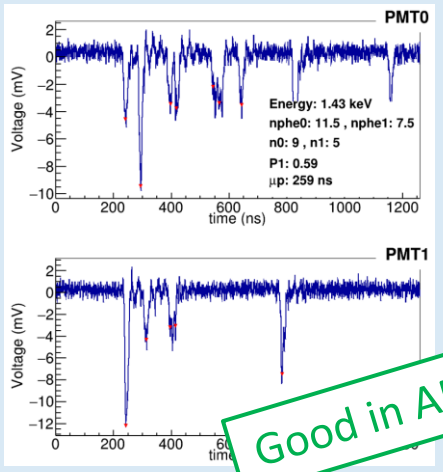
Scintillation + asym. events <2 keV

ANAIS

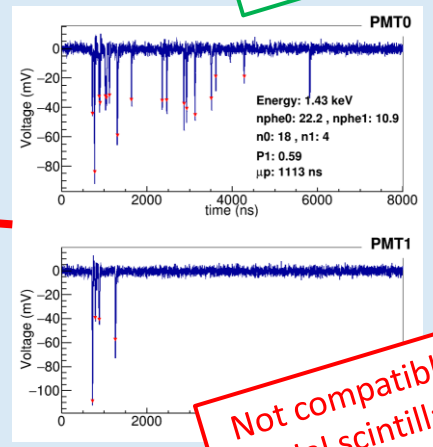


ANOD



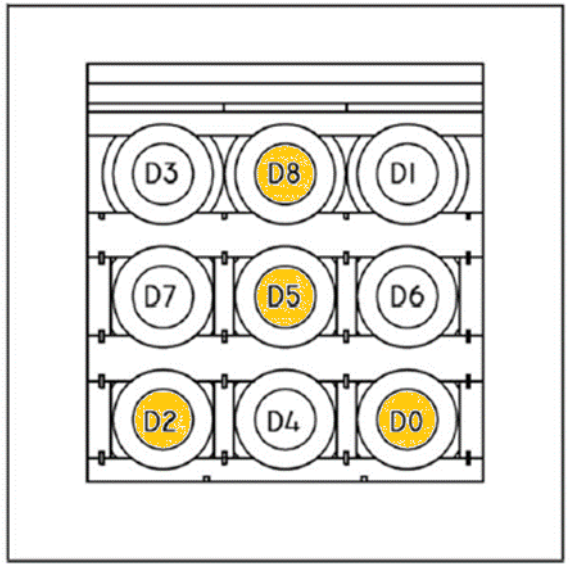


Good in ANAIS



Not compatible with NaI scintillation

New DAQ system in ANAIS–112



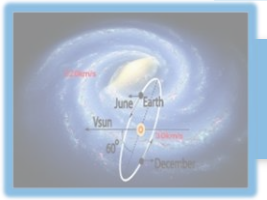
ANOD is working smoothly since winter 2023

By now, only 4 crystals (8 PMTs) are readout, but **very promising results**!

We have acquired a VX2730 CAEN card (32 channels, 14 bit, 500MS/s, memory 83 MS/ch) that will allow to digitize the 9 detectors + blank module (delivery expected in June 2024)

Our plan is to start taking data with 9 crystals + blank at the beginning of summer 2024

Outline



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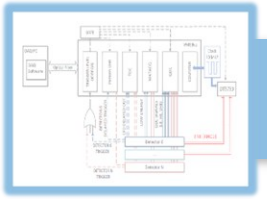
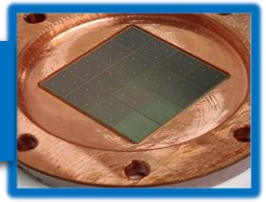


New DAQ system in ANAIS–112

Beyond ANAIS–112: ANAIS+

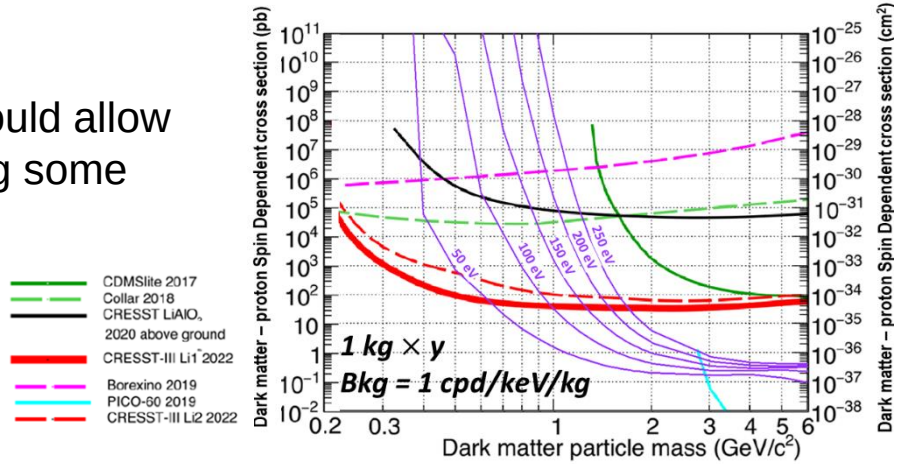


Beyond ANAIS–112: ANAIS+

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



ANAIS+ test setup

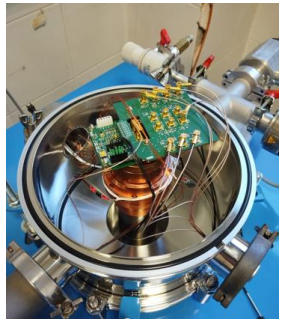
➔ A **prototype** has been built (NaI(Tl) 1'' cube + Hamamatsu SiPMs array + MUSIC readout + optical fiber) and first measurements show the expected behaviour of the SiPMs and NaI(Tl) scintillator with T

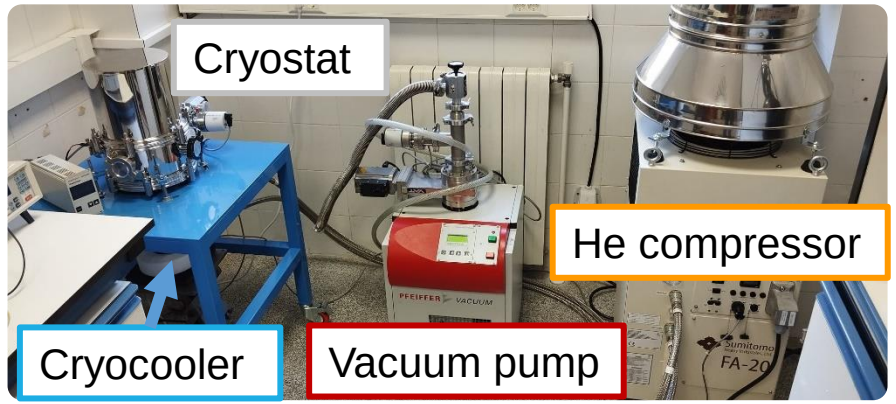
Low exposure, reasonable bkg feasible if combined with radiopure crystals built at the new LSC facility and using a LAr bath as active veto

Cryogenic installation at U. Zaragoza

➔ Capability to reach **T < 40 K**

➔ Already installed and tested





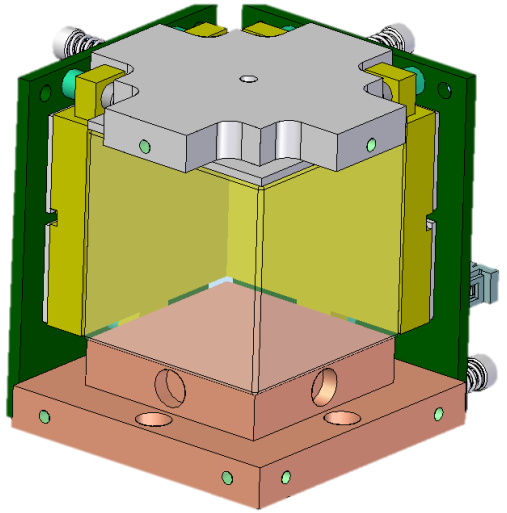
Plan de Recuperación, Transformación y Resiliencia

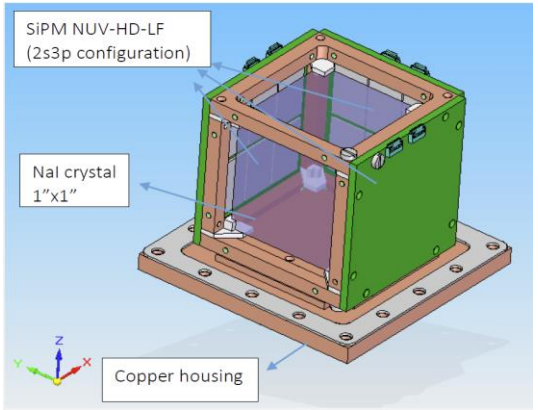
Beyond ANAIS–112: ANAIS+

First ANAIS+ prototype

Designed in collaboration with A. Razeto (LNGS)

- ➔ Four faces covered by SiPMs arrays (6 SiPM/side summed up)
- ➔ SiPMs have been designed and are being produced at LNGS
- ➔ Testing of the prototype (without NaI crystal, maybe other crystal) is foreseen for mid-June at LNGS
- ➔ The prototype will be sent to Zaragoza for integrating the NaI crystals and further testing at the Zaragoza facility
- ➔ Medium/long term: test in LAr at LSC





Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

INFN LNGS

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Summary and outlook

- Many efforts trying to provide an **independent test** of the DAMA/LIBRA signal with the same target
- ANAIS−112 is leading the international efforts of this test, working properly after 7 years of data-taking
- Sensitivity improved with machine-learning techniques. ANAIS−112 observes no modulation and discards DAMA/LIBRA DM interpretation with $\sim$ **3σ sensitivity** in [1-6] keV ([2-6] keV)
- 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-year modulation results** to be released soon. **5σ sensitivity in late 2025**
- ANAIS has carried out **QF measurements**. Understanding the response of NaI(Tl) crystals to nuclear recoils is crucial in the 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
- **ANAIS+ first prototype** this summer. Assessment of performance and achievable backgrounds testing a prototype in underground in the medium term

Acknowledgements

Thank you for your attention!

ANAIS research team

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