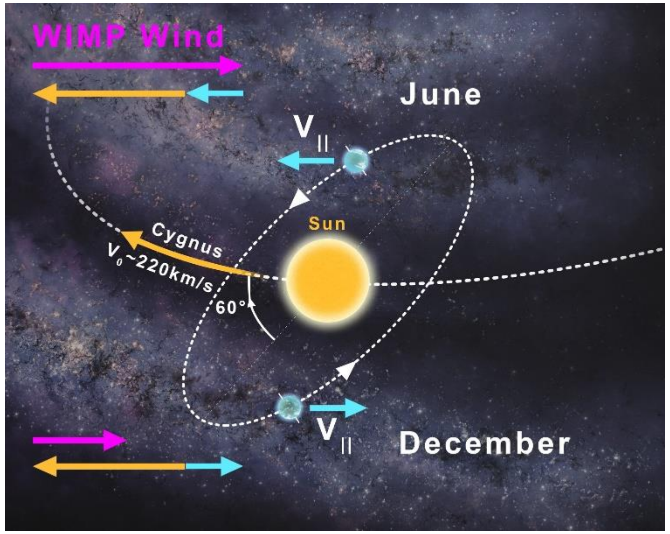
Improving ANAIS–112 sensitivity to the DAMA/LIBRA dark matter signal

Iván Coarasa on
behalf of the **ANAIS team**
icoarasa@unizar.es

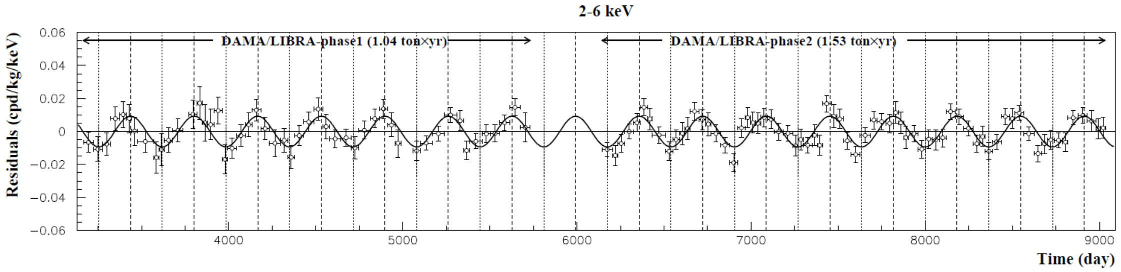
1ª Reunión Nacional Planes Complementarios de Astrofísica y Altas Energías
6 June 2024

ANAIS
CAPA 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

Dark matter annual modulation & DAMA/LIBRA positive signal



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



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

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

Only at low energy

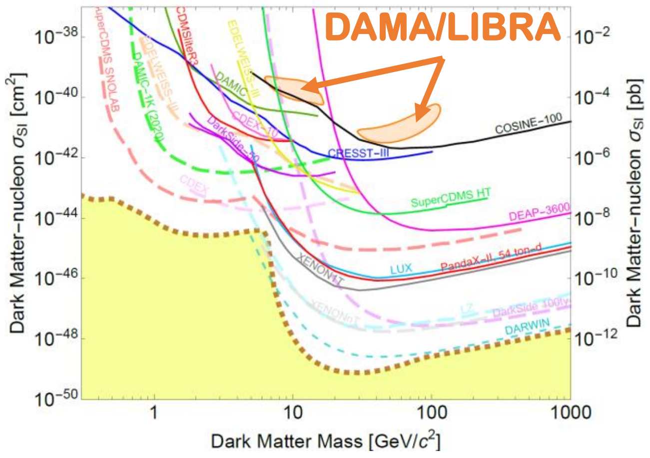
Single-hit events

$S_m/S_0 \lesssim 7\%$

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**

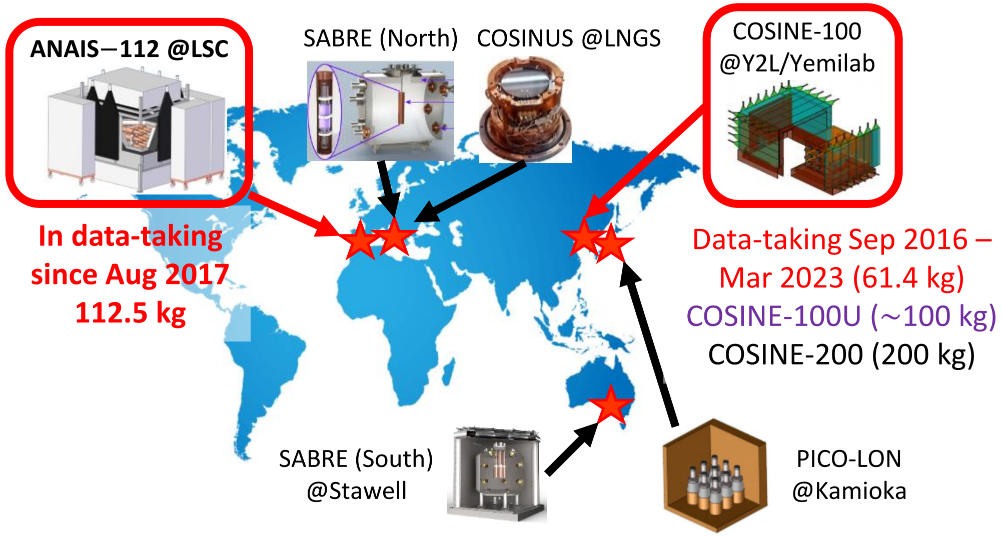
STRONG TENSION



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

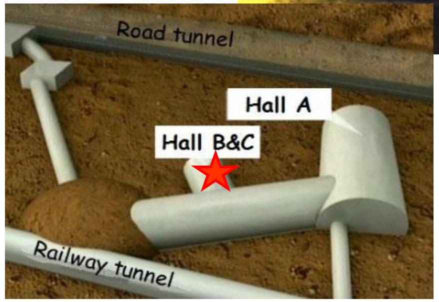


The ANAIS experiment

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

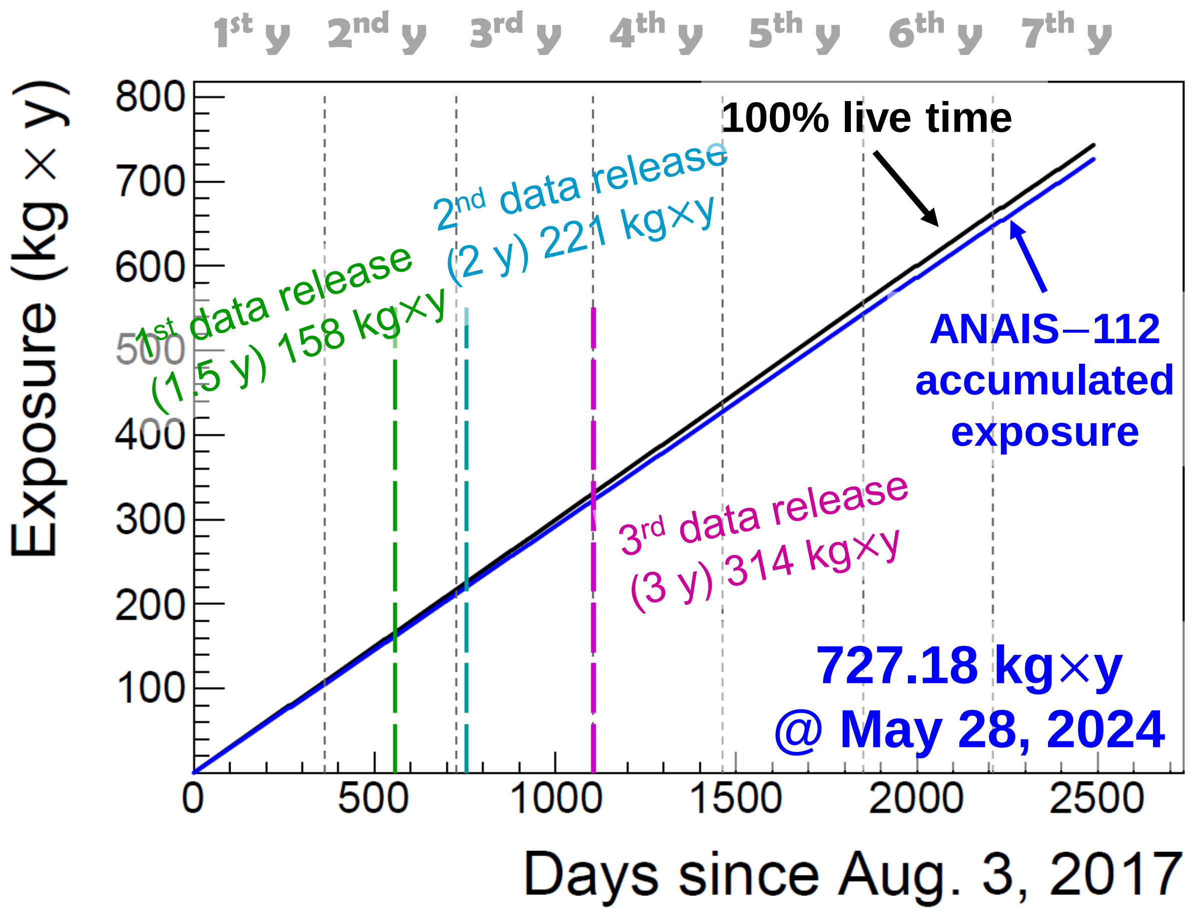


ANAIS–112 experimental set-up

- 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



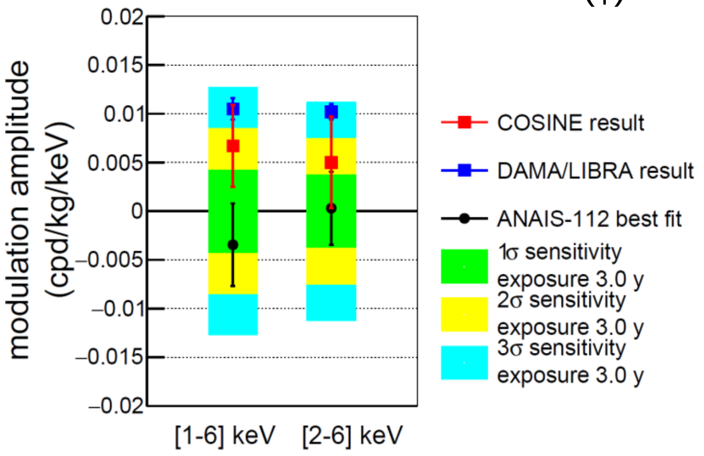
About 95% of live time

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: $\sim 2.5\sigma$ sensitivity

Improving ANAIS sensitivity

1. New filtering protocol based on machine learning (ML) techniques
2. Improving the background model (6 years analysis)
3. NR Quenching factor measurements
4. Participation in an underground crystal growing facility at LSC
5. New Data acquisition system (DAQ) in parallel with ANAIS–112 one
6. Towards ANAIS+

Improved filtering protocol with ML techniques

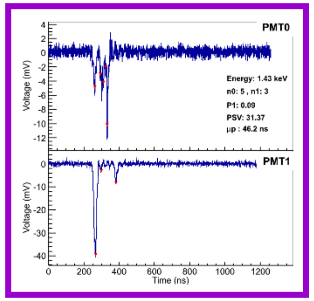
The region of interest (1-6 keV) is dominated by **non-bulk scintillation events**

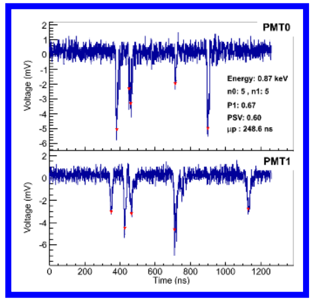
Improve the “bulk scintillation” event selection with ML techniques based on BDT

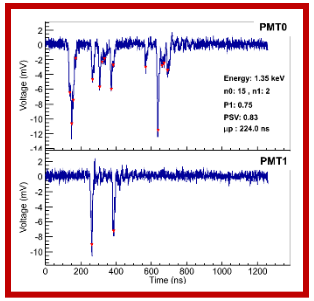
Training populations

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)

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

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

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

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

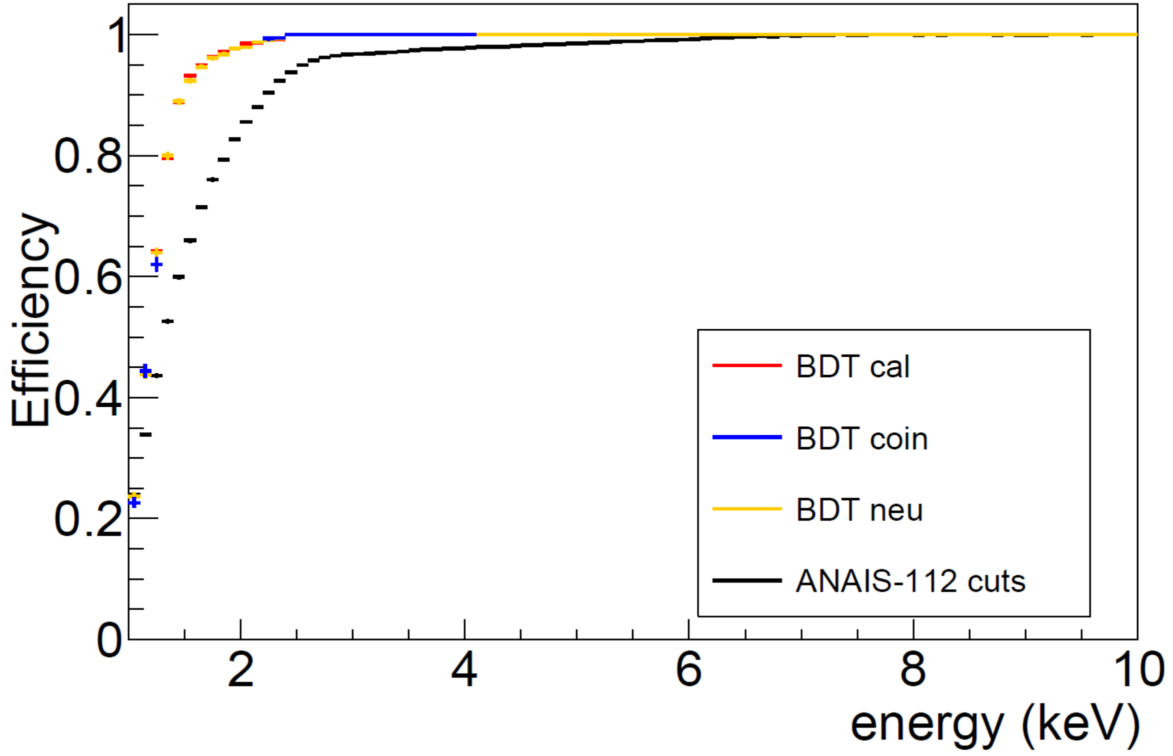
Performance of using ML for event selection in: *JCAP11(2022)048 and JCAP06(2023)E01*

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

Event selection with BDT

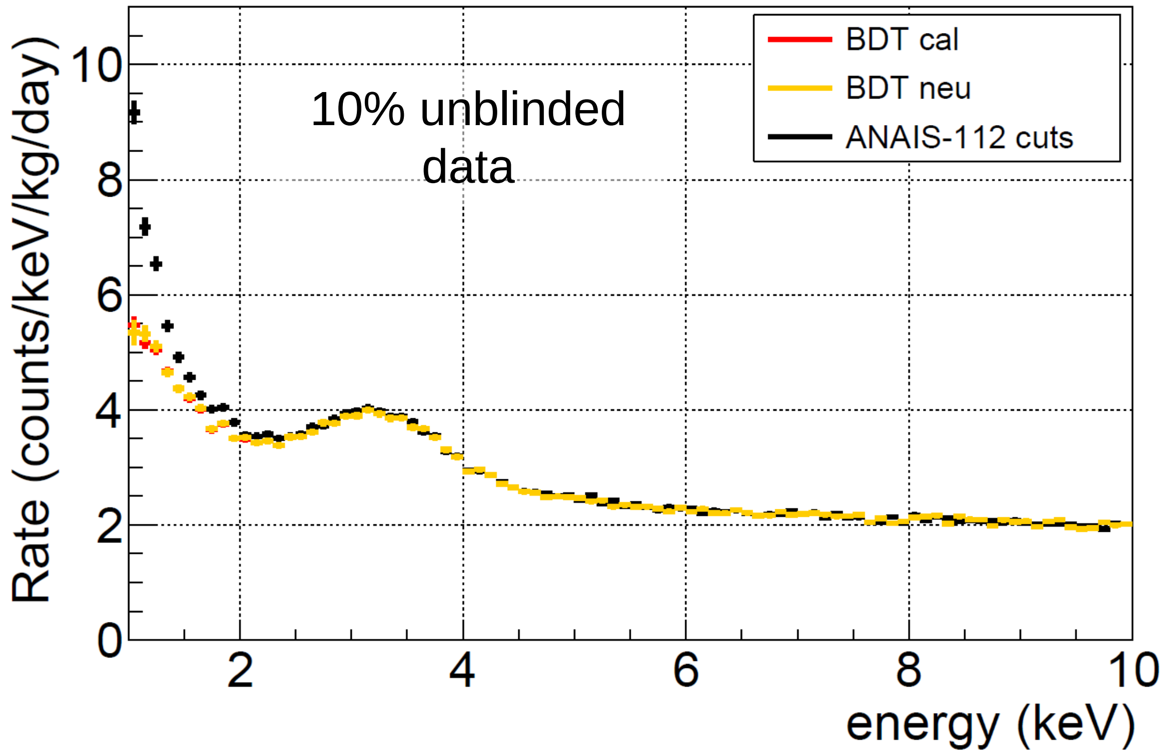
Following
JCAP11(2022)048

Acceptance efficiency



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

Efficiency-corrected background



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

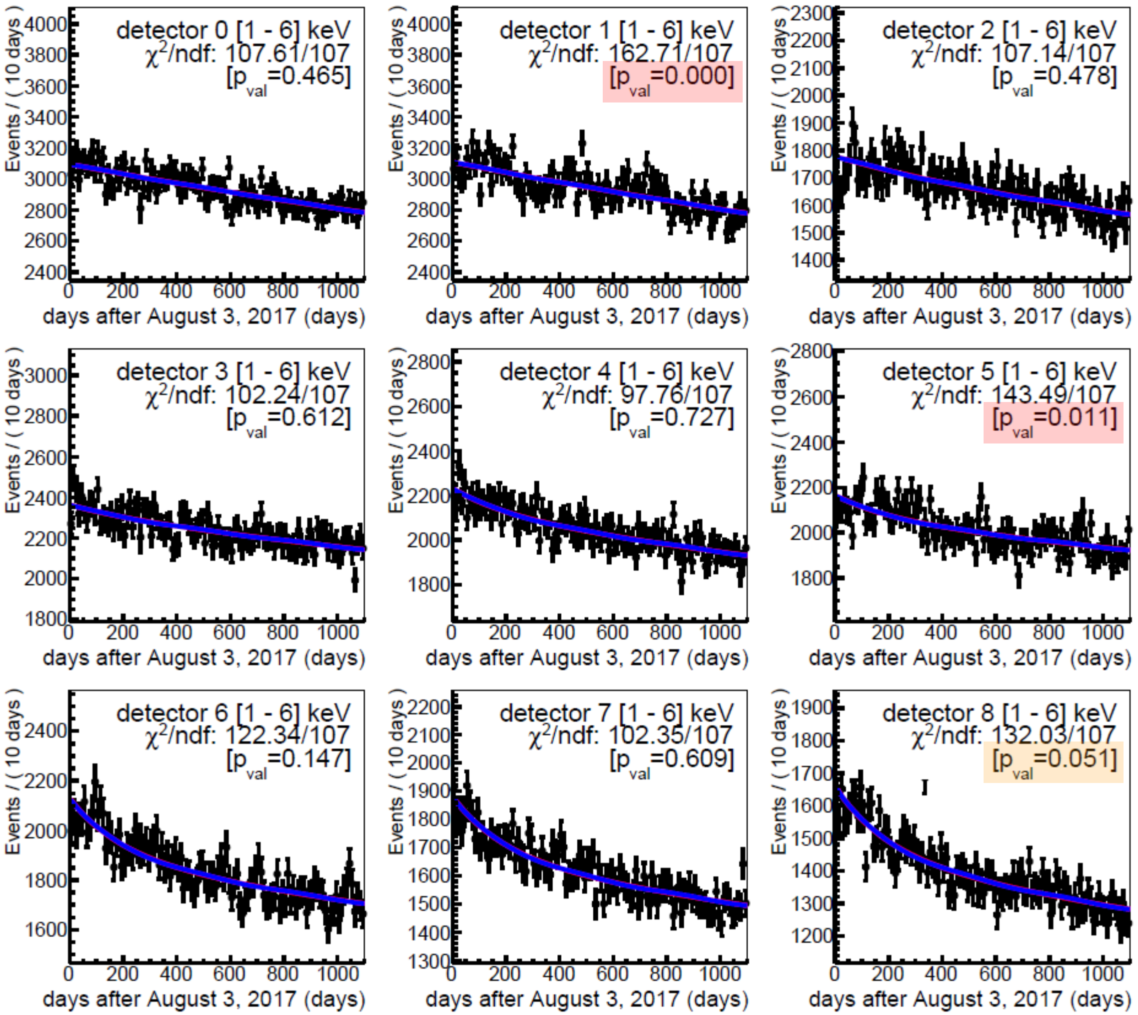
Improved 3-year results [1-6] keV

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)

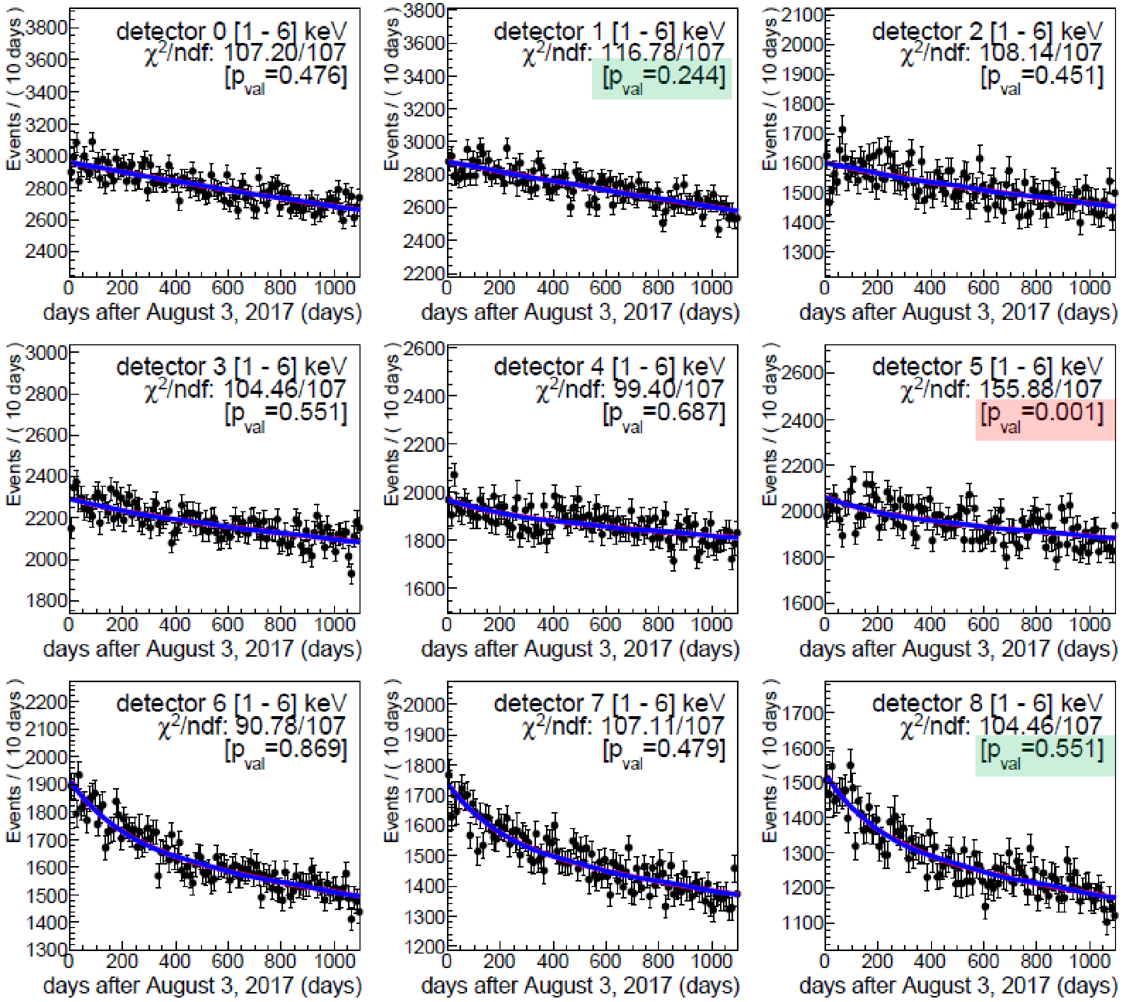


arXiv:2404.17348

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

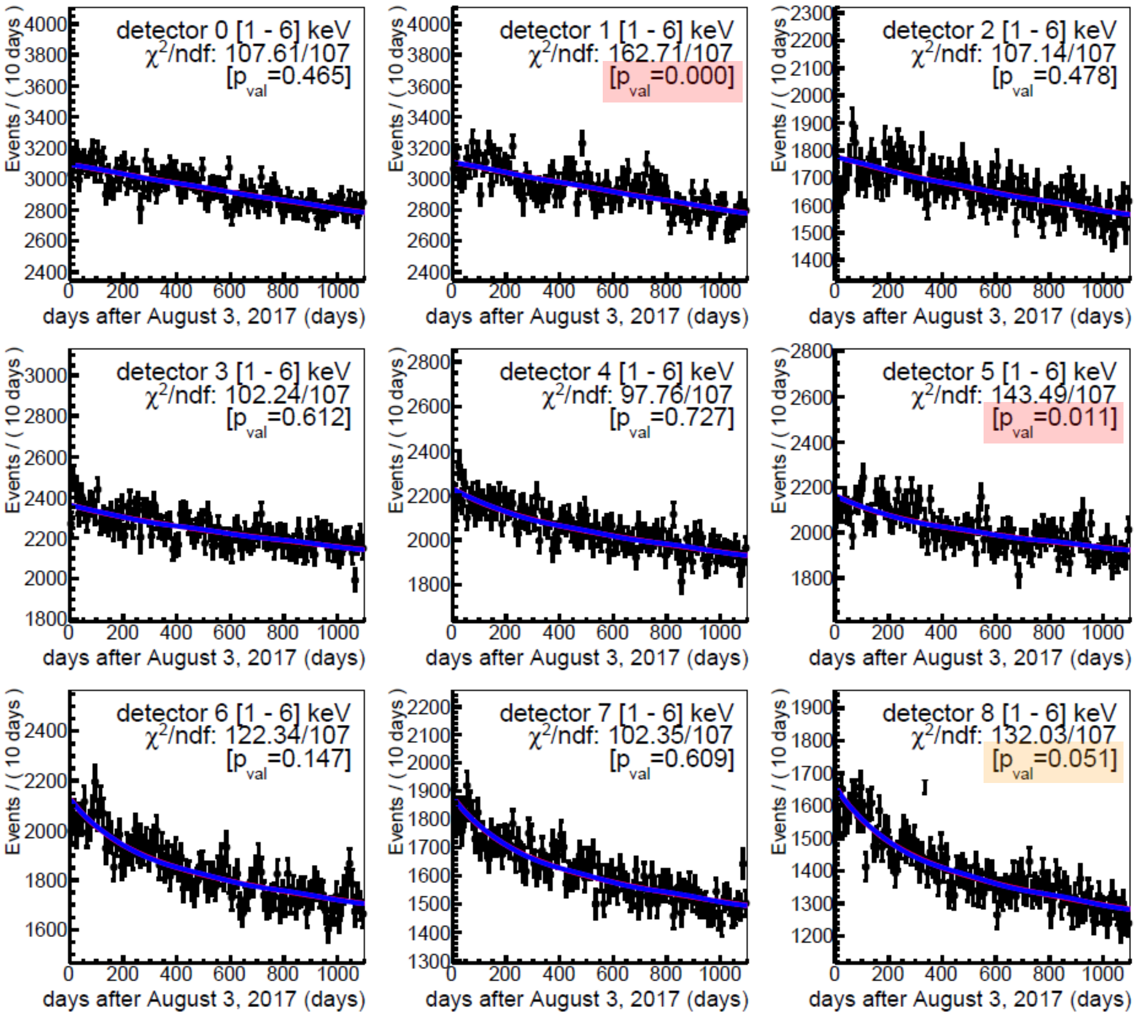
$2.5\sigma \rightarrow 2.8\sigma$

PRD103(2021)102005

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)

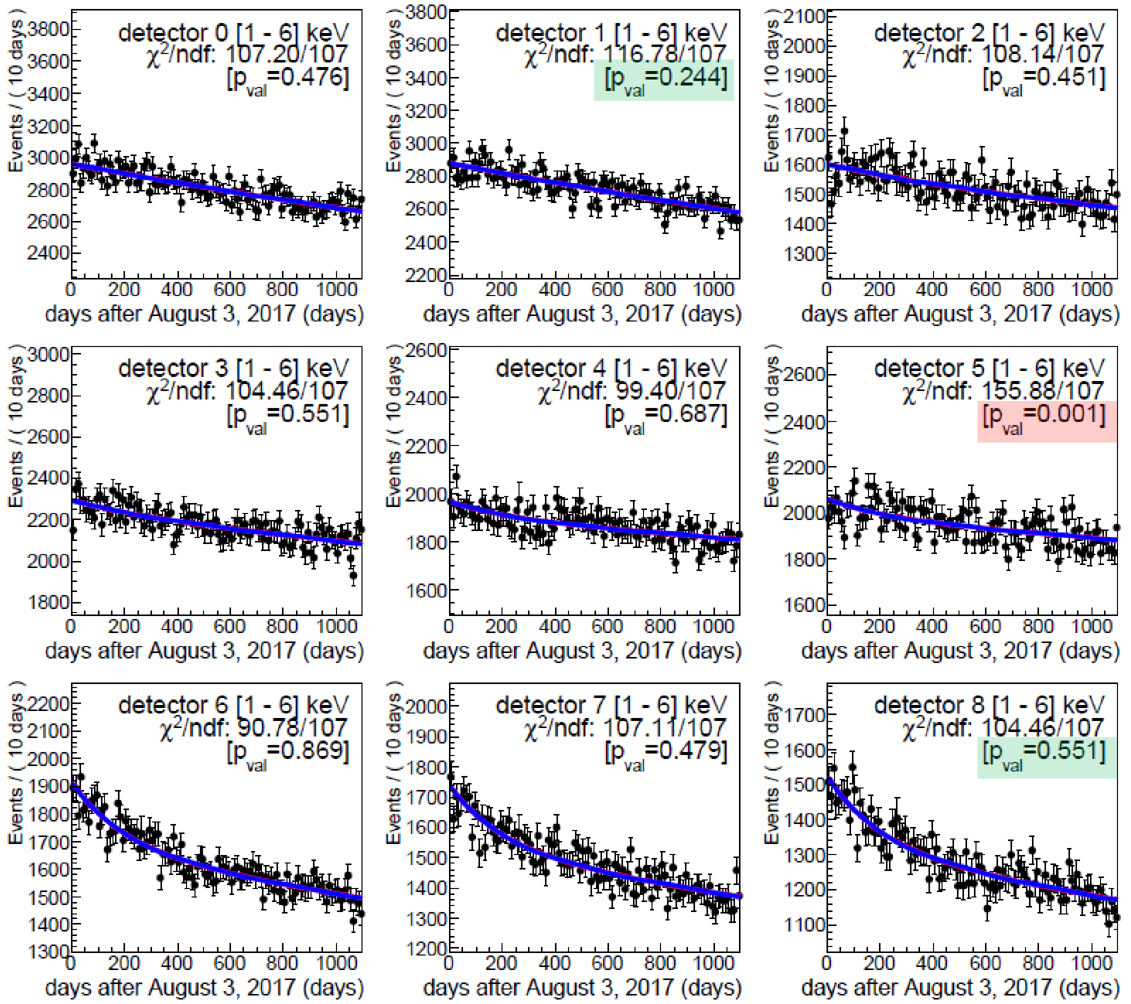


arXiv:2404.17348

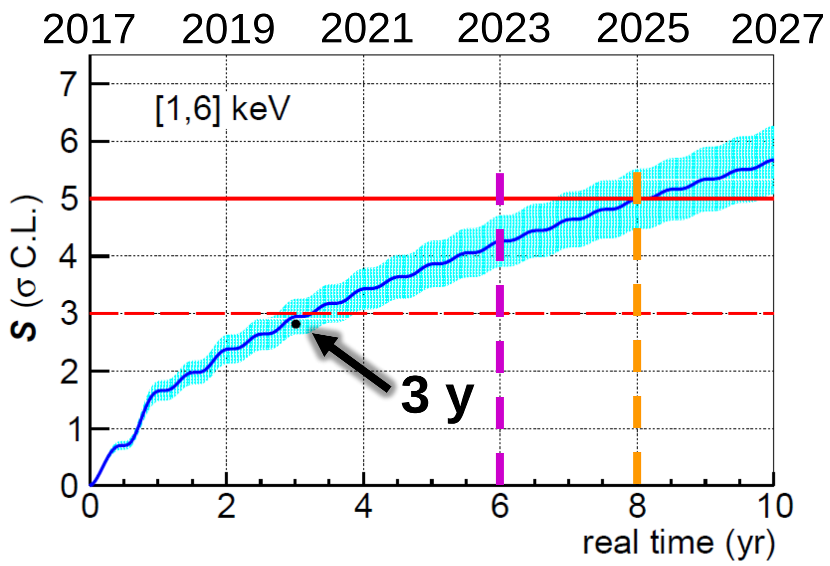
Null hyp χ^2/ndf: 993.38/972 [p_{val}=0.310]

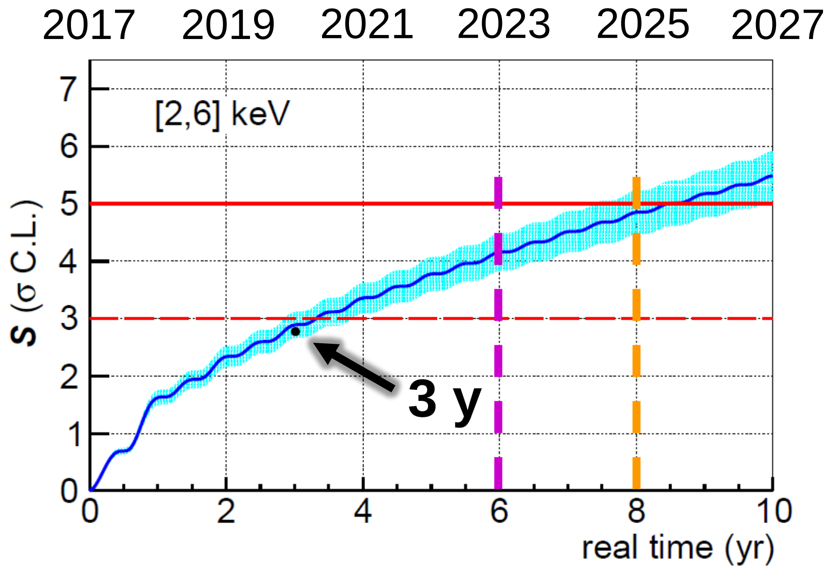
Mod hyp χ^2/ndf: 992.68/971 [p_{val}=0.307]

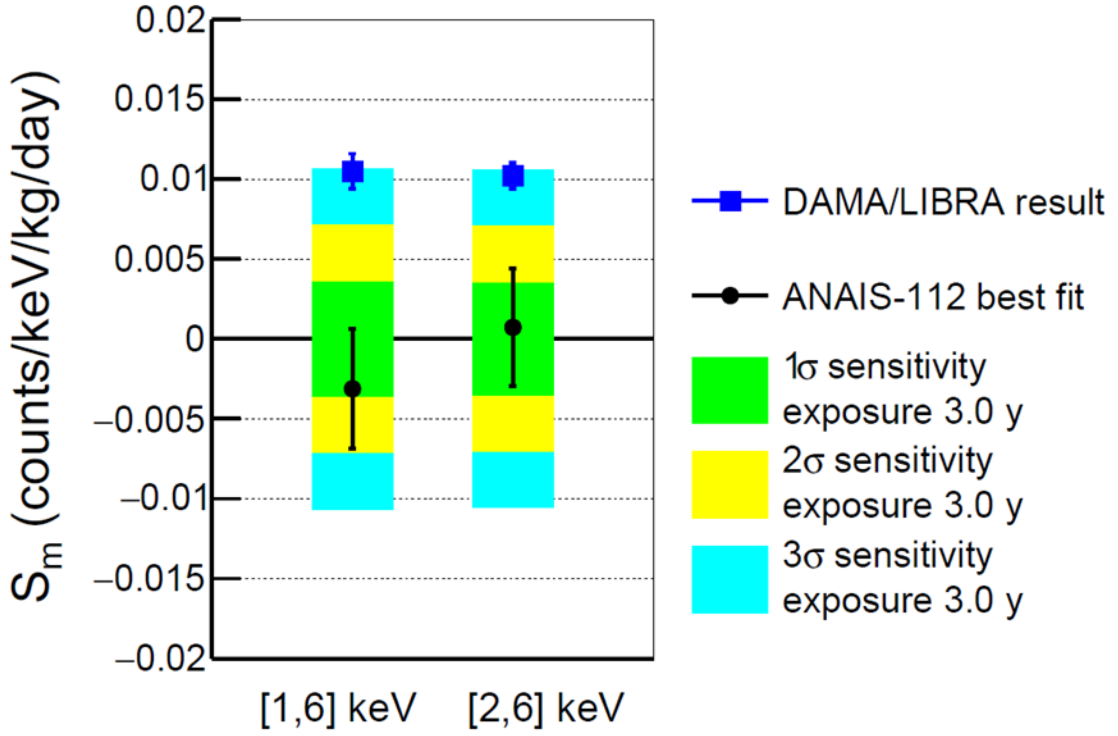
S_m = (-0.0031 ± 0.0037) (cpd/kg/keV)



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 (NOW)

5σ sensitivity in late 2025

Improving the background model

- 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

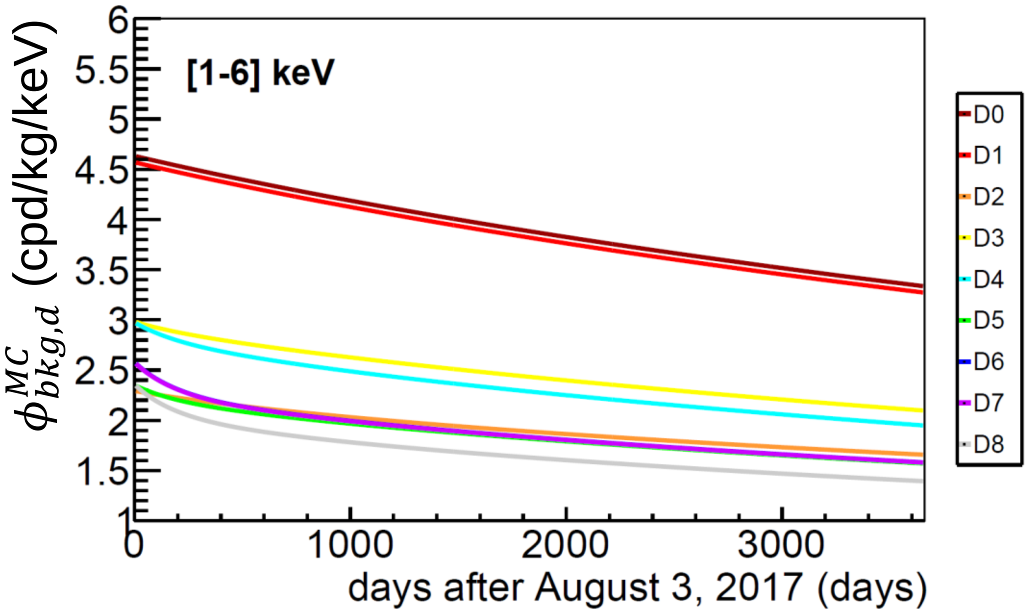
9 crystals (^{40}K, ^{210}Pb, ^{232}Th, ^{238}U, ^{235}U, ^{3}H, ^{22}Na, ^{109}Cd, ^{113}Sn, I's, Te's)

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

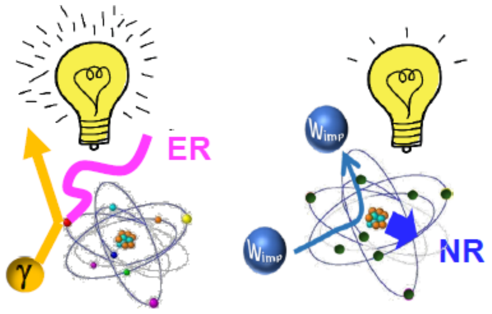
NR Quenching factor measurements

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

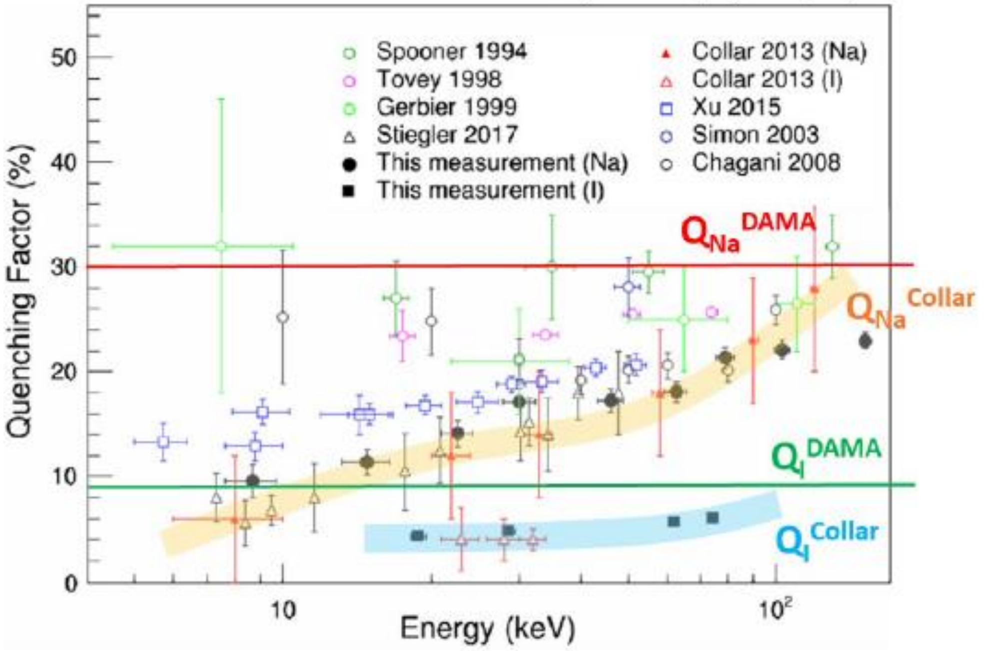
➔ Still too many uncertainties in the Q values and energy dependences



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

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

Joo, et al. Astrop. Phys. 108 (2019) 50



$$\boxed{\begin{aligned} Q_{Na}^{DAMA} &= 30\% \\ Q_{I}^{DAMA} &= 9\% \end{aligned}}$$

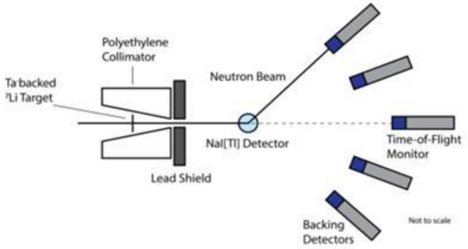
The response of different detectors to DM particles could differ if Q is different

NR Quenching factor measurements

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

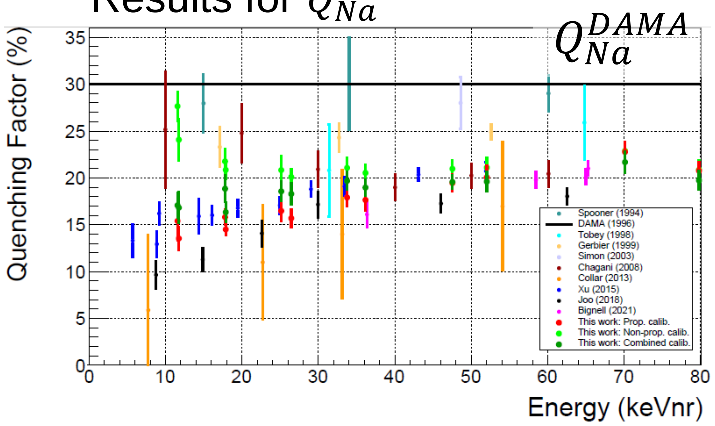
Monochromatic neutron source at TUNL (Duke Univ.)

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

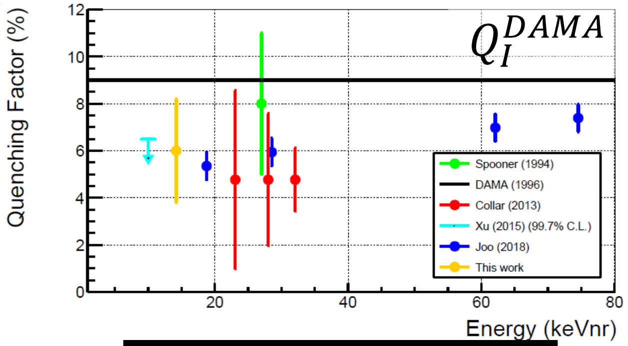


- ➔ **Compatible** values for the 5 crystals
- ➔ Noticeable differences for different energy calibrations (**NaI non-linearity**)
- ➔ **Lower QF** than **DAMA/LIBRA** measurement

Results for Q_{Na}



Results for Q_I



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

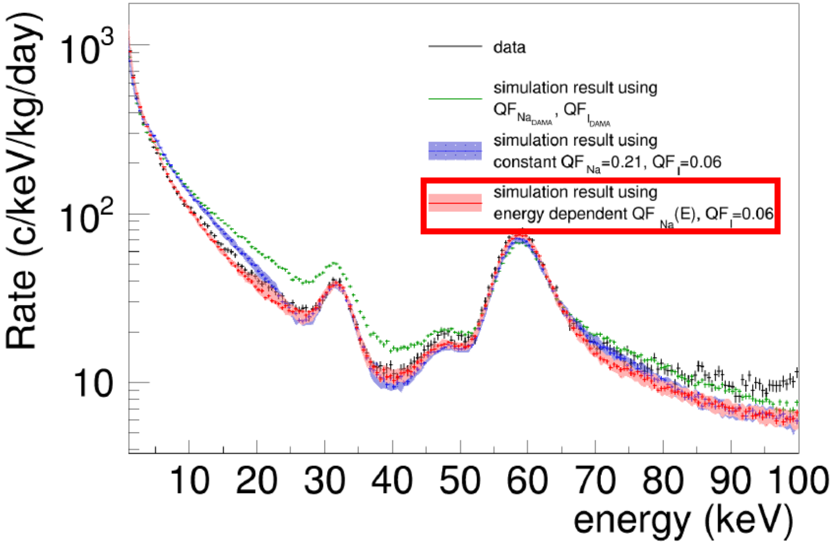
D. Cintas et al., arXiv:2402.12480 (Feb. 2024), Submitted to Phys. Rev. C

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]

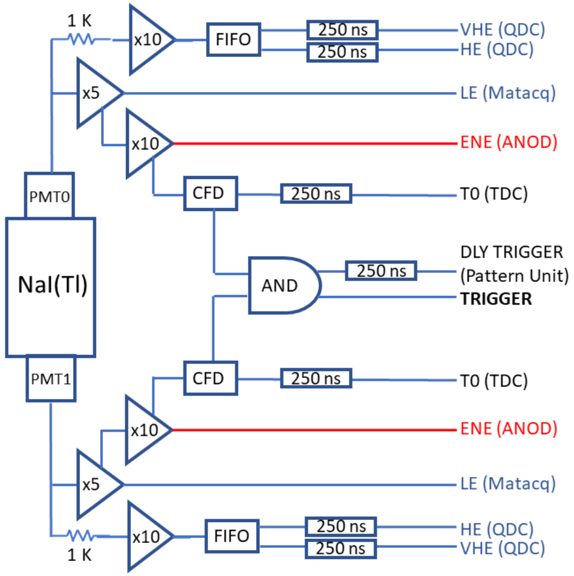
T. Pardo et al., PoS(TAUP2023)078

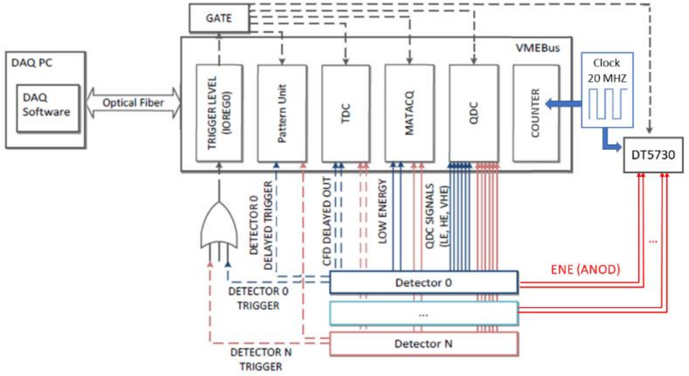
New DAQ system in ANAIS–112

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

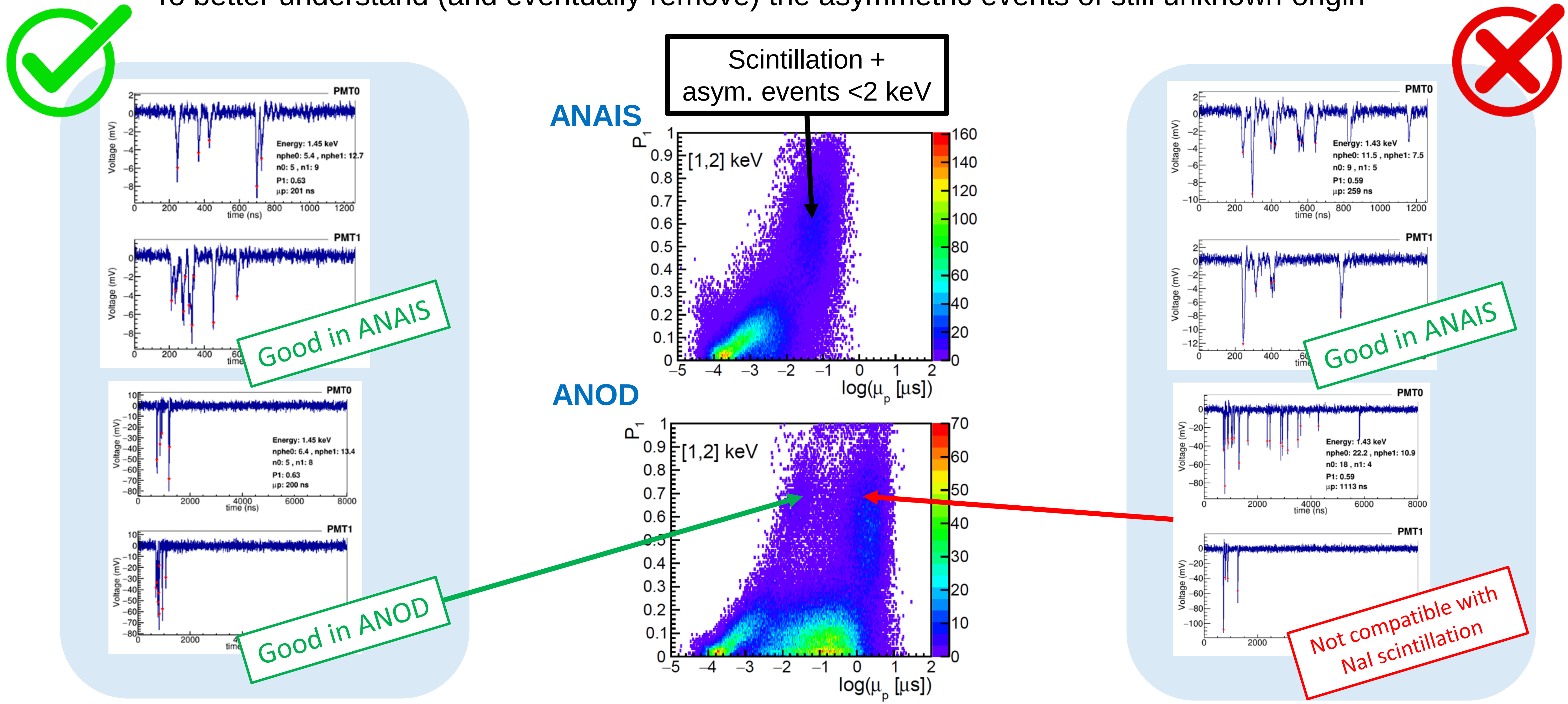
Plan de Recuperación, Transformación y Resiliencia

New DAQ system in parallel (ANOD, Anais NO Dead time)

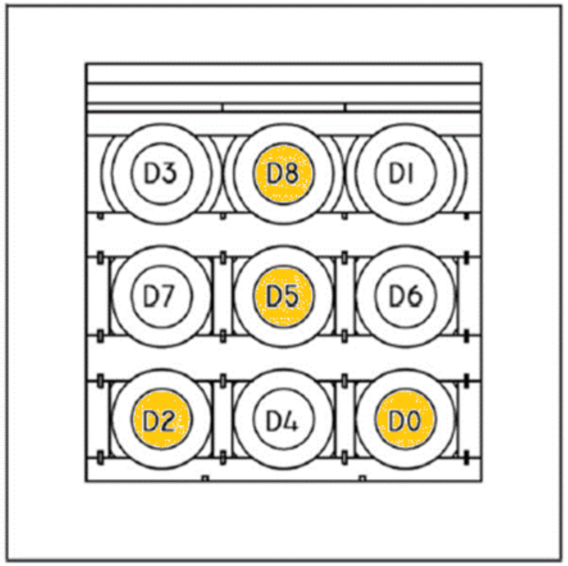
CAEN DT5730 **(8 channels)** → 4 modules
14 bits, 500 MS/s → 8 μs window
Internal buffer: 640 kS/ch
No dead time for rates <100 Hz

New DAQ system in ANAIS–112

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



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**!

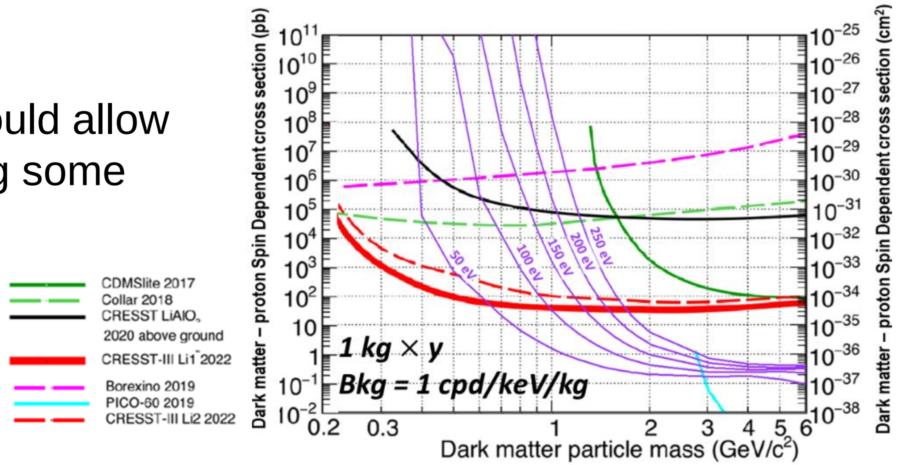
We have acquired a VX2730 CAEN card (32 channels, 14 bit, 500MS/s, memory 83 MS/ch) that will allow to digitize the 9 detectors + blank module (delivery expected in June 2024)

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

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



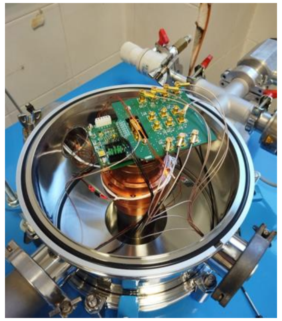
Low exposure, reasonable bkg feasible if combined with radiopure crystals built at the new LSC facility and using a LAr bath as active veto

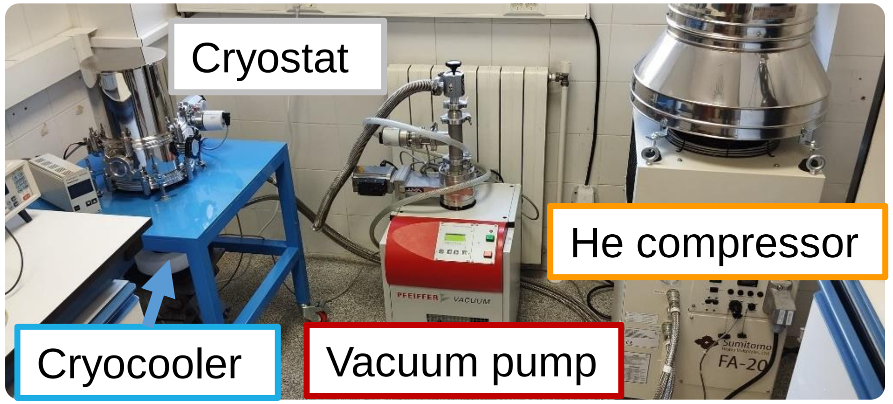
ANAIS+ test setup

- 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

Cryogenic installation at U. Zaragoza

- Capability to reach **T < 40 K**
- Already installed and tested





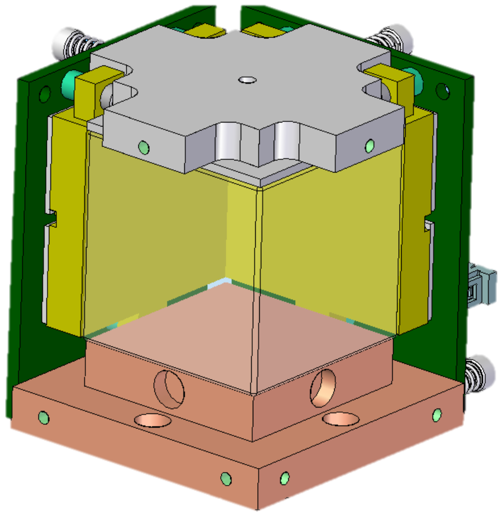
Plan de Recuperación, Transformación y Resiliencia

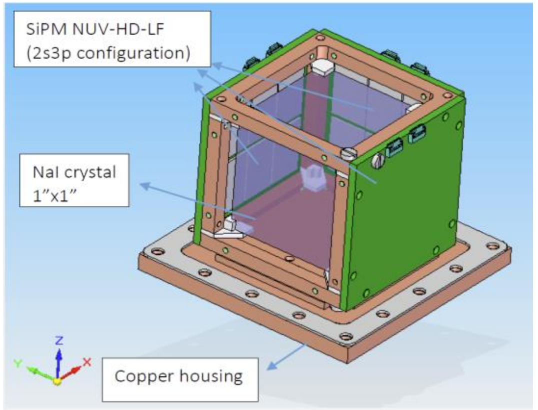
Beyond ANAIS—112: ANAIS+

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





CAPA 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 ~ $\boldsymbol{3\sigma}$ **sensitivity** in [1-6] keV ([2-6] keV)
- **6-year modulation results** to be released soon. $\boldsymbol{5\sigma}$ **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
- 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

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

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

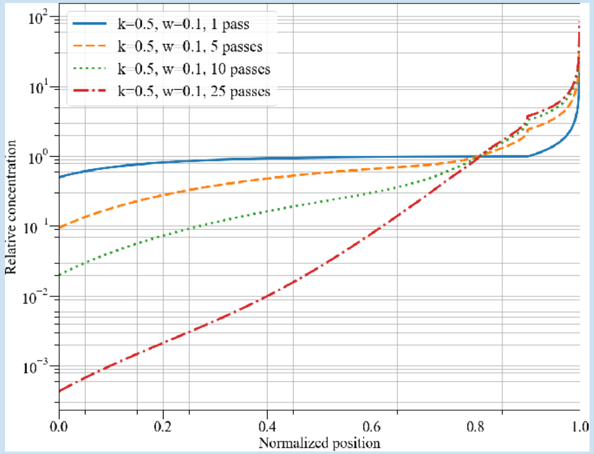
Backup

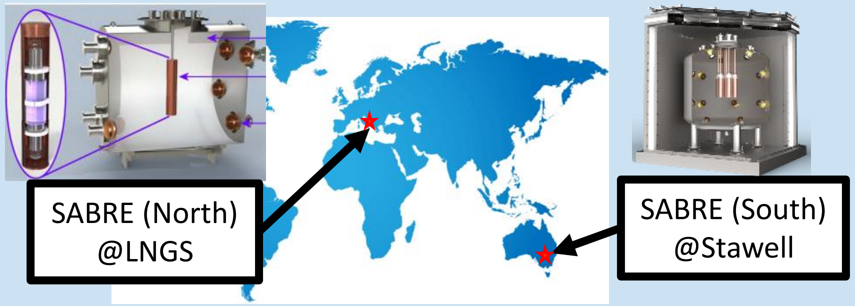
Underground crystal growing facility at LSC

Project supported by INFN-GSSI-LSC for the installation of a dedicated underground facility for purifying and growing radiopure NaI(Tl) and NaI crystals at LSC

Zone refining purification (approach currently being developed by the SABRE collaboration)

zone refiner suitable for ~100 kg crystal production





impurities are pushed to the end of the refining tube at different level and eliminated from the material selection before the growth

Our role: characterization of the samples (especially for ^{210}Pb and ^{40}K)

This facility should have been moved to LSC before the end of 2023
→ **Important delay foreseen for this activity**