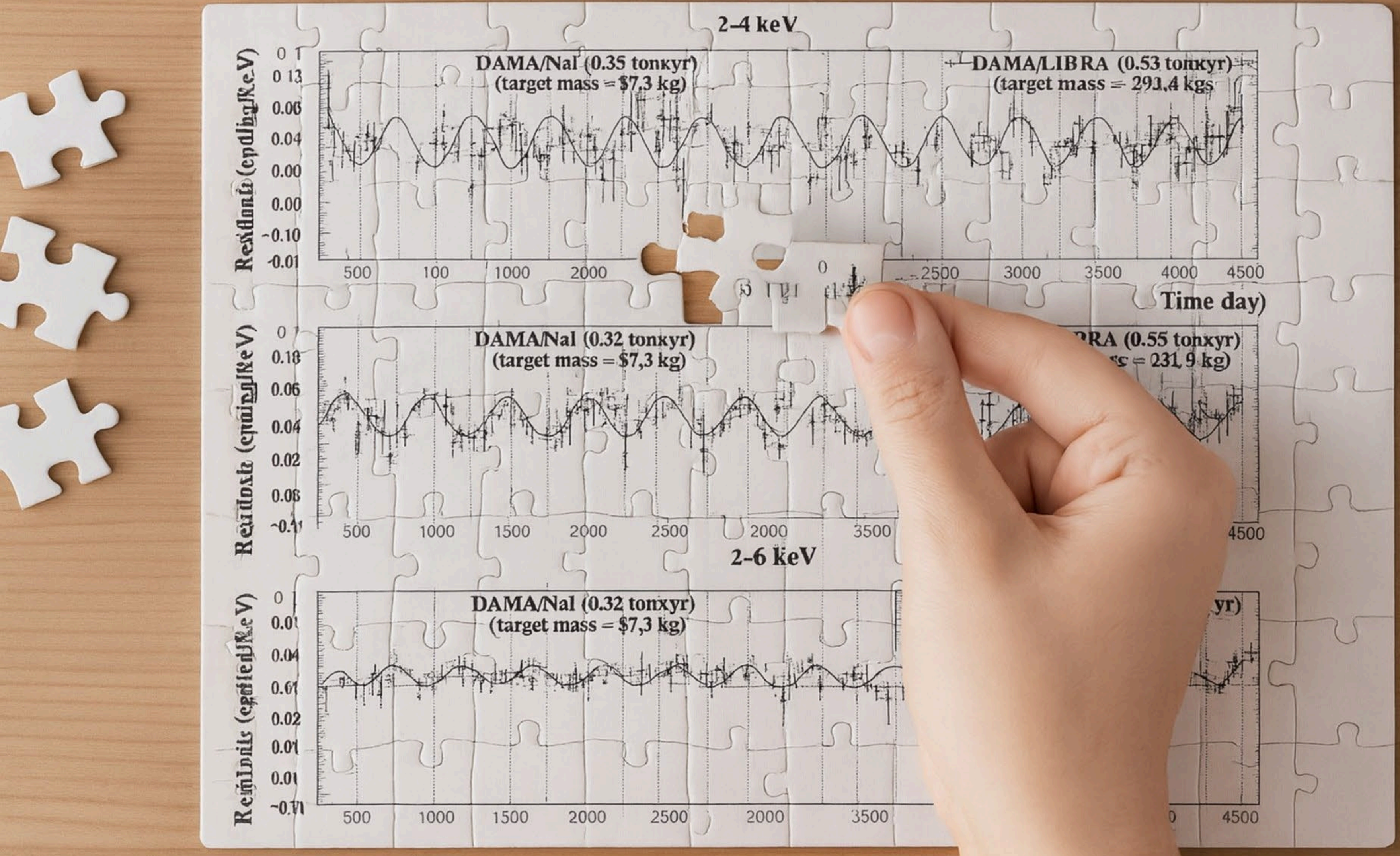
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
MultiDark Multimessenger Approach for Dark Matter Detection
GOBIERNO DE ARAGON
Plan de Recuperación, Transformación y Resiliencia
Financiado por la Unión Europea NextGenerationEU

Strong constraints on the DAMA/LIBRA modulation signal from ANAIS-112



TAUP XICHANG

Maria Martinez
CAPA, U. Zaragoza
on behalf of the ANAIS team

ANAIS-112

Annual Modulation with NaI Scintillators

https://gifna.unizar.es/anais/

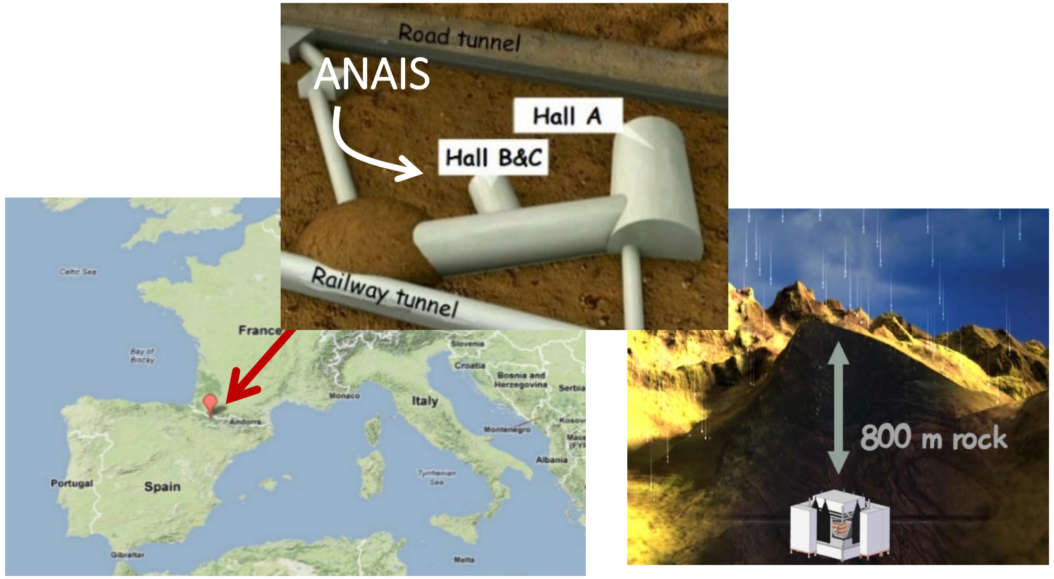
J. Amaré, J. Apilluelo, S. Cebrián, D. Cintas, I. Coarasa, E. García, M. Martínez, Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, M. L. Sarsa, C. Seoane

Universidad Zaragoza

GOAL: **Confirmation/refutation of DAMA-LIBRA modulation signal with the same target and technique** (but different experimental approach and environmental conditions)

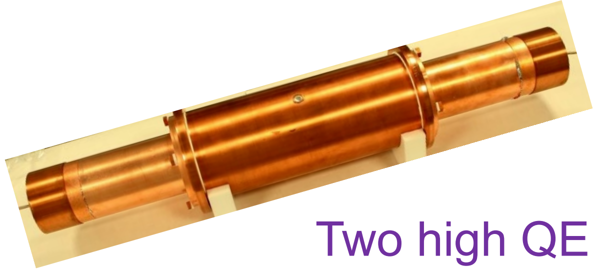
Projected sensitivity: 3σ in 5 years data-taking

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

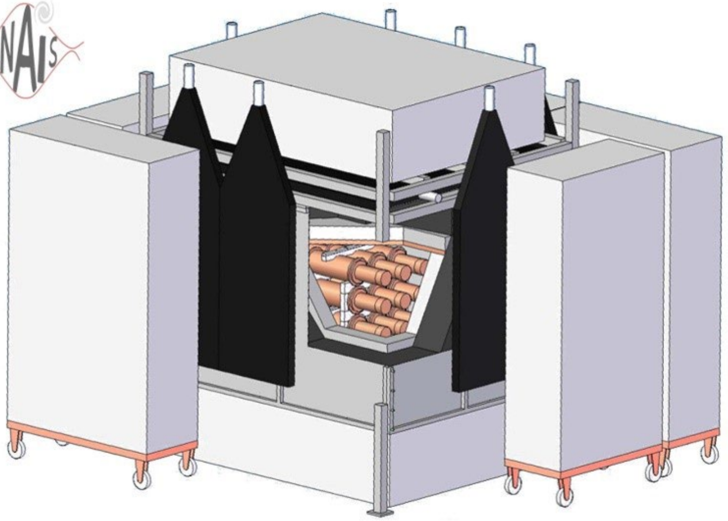


taking data since August 2017

THE DETECTOR:
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass

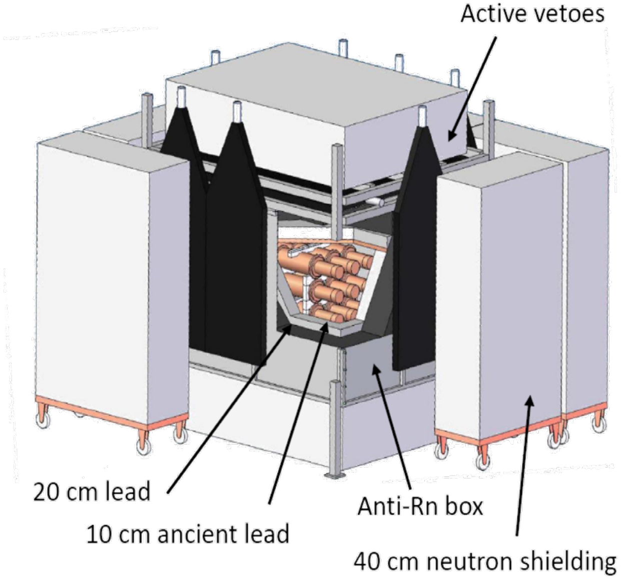


Two high QE PMTs per detector



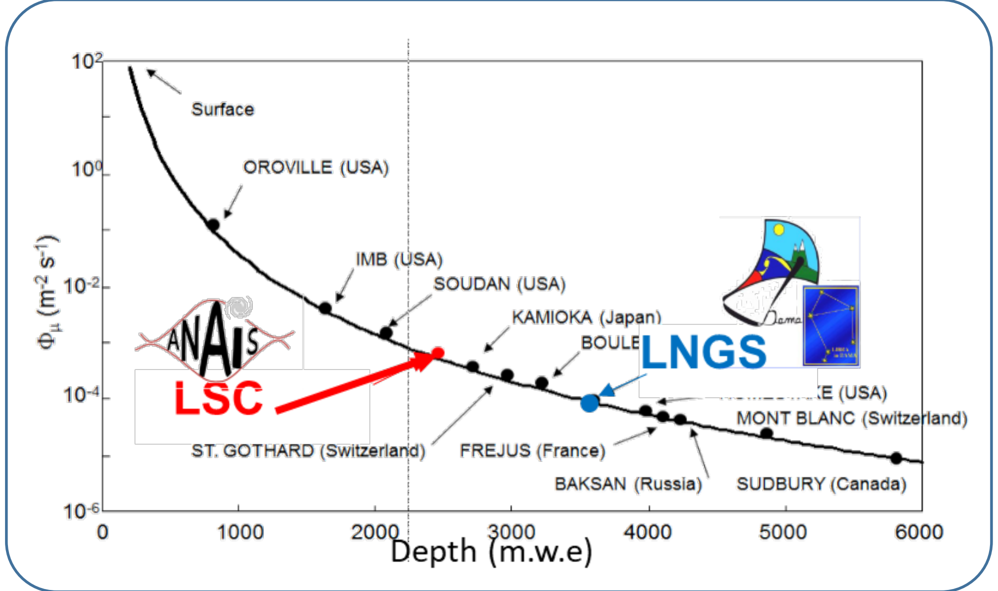
ANAIS-112 vs DAMA/LIBRA

9 NaI(Tl) scintillating crystals (Alpha Spectra, same as COSINE)
12 cm $\phi \times$30 cm, 12.5 kg each
TOTAL MASS: 112.5 kg

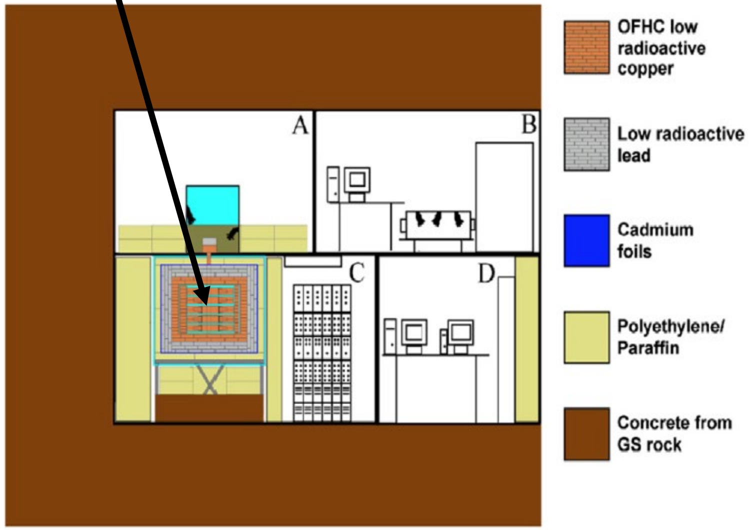


shielding:

- 10 cm of ancient Pb + 20 cm of Pb
- Anti-Rn metallic box flushed with N2 gas
- 40 cm Polyethylene/water tanks
- **Active muon vetoes**



25 NaI(Tl) scintillating crystals (Sain Gobain), 10.2×10.2×25.4 cm^3, 9.7 kg each
TOTAL MASS: 250 kg



shielding:

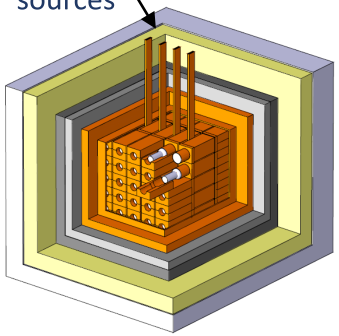
- >10 cm of OFHC Cu + 15 cm of Pb
- Anti-Rn: Plexiglas box flushed with N2 gas
- 10/40 cm Polyethylene/paraffin + Cd foils
- **No muon veto**

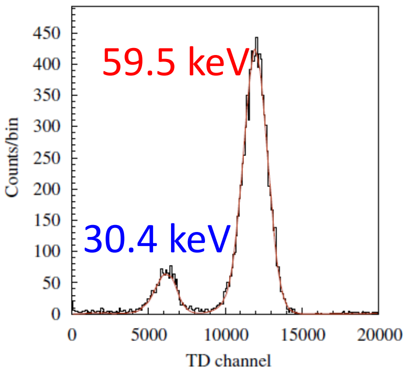
ANAIS-112 vs DAMA/LIBRA

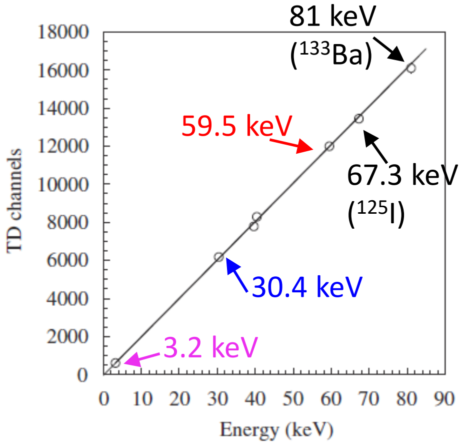
Low energy calibration – RoI [1-6 keV]

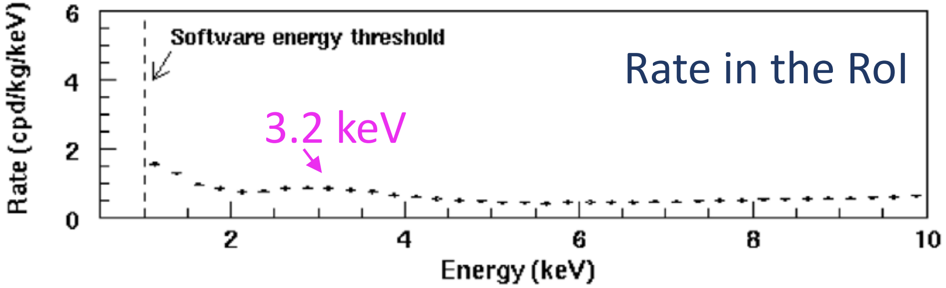
- Periodical calibrations every ~10 days with a ^{241}Am source (30.4 keV (composite), 59.5 keV). Linear calibration down to threshold
- Linearity check and corrected @ 3.2 keV with whole statistics

Guides for ^{241}Am sources

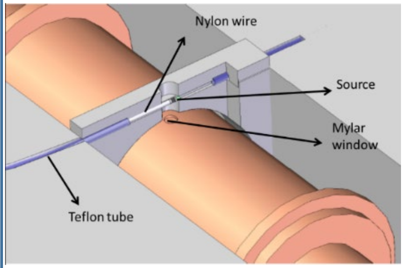


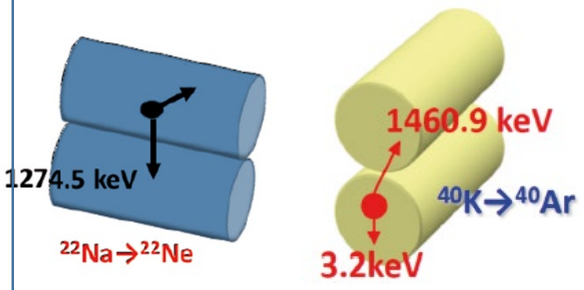


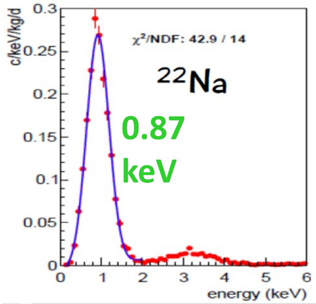


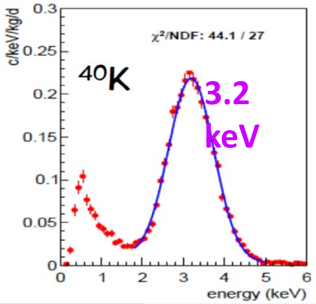


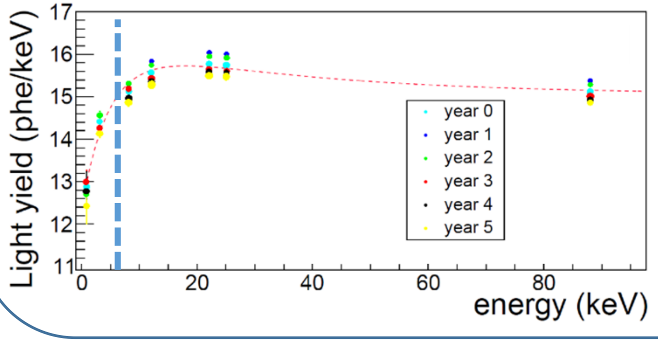
- Detectors equipped with a **Mylar window**
- Calibration with **^{109}Cd sources (**11.9 keV, 22.6 keV and 88.0 keV) every two weeks for gain correction
- Calibration in the ROI with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) (whole statistics)











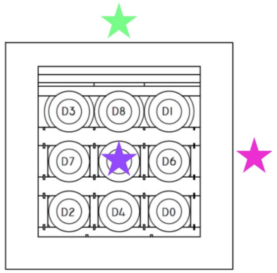
Non proportionality < 25 keV (20%)

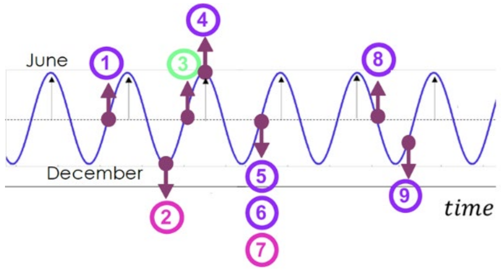
Linear calibration in 2 ranges:

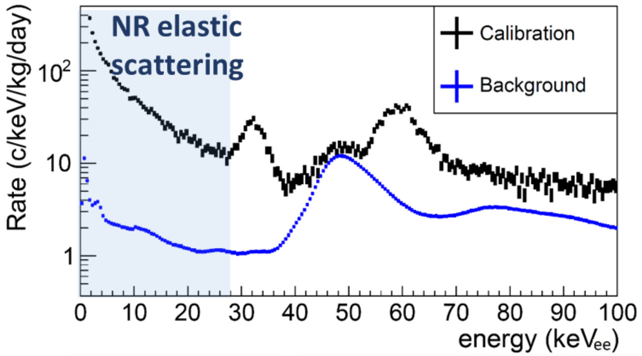
- 1-10 keV [ROI]
- 10-100 keV

ANAIS-112 neutron calibrations

SINCE APRIL 2021: periodic in-situ neutron calibrations with ^{252}Cf source







NR population in the ROI!! Used for:

- Training population for ML-event selection
- Efficiency calculation
- In-situ QF cross-check (via MC)

Neutron calibration for event selection

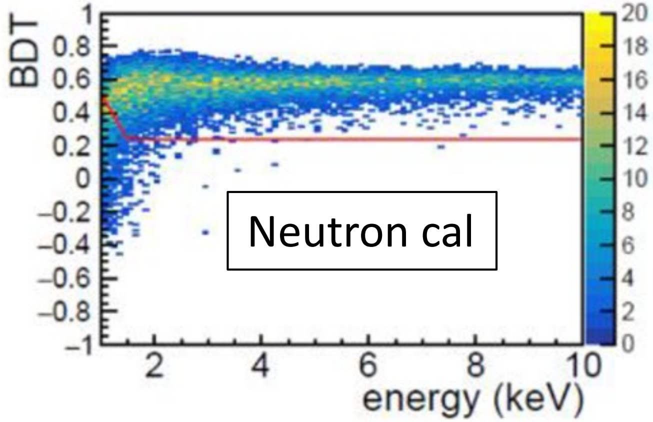
Blank module

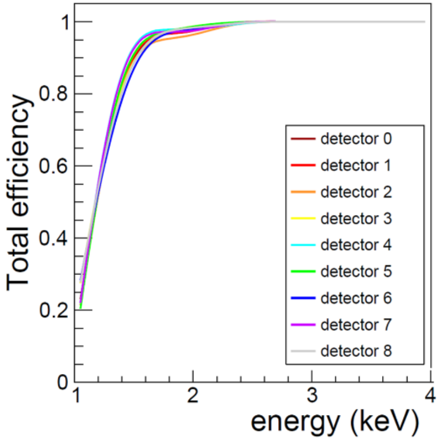
BDT (15 parameters) trained with:

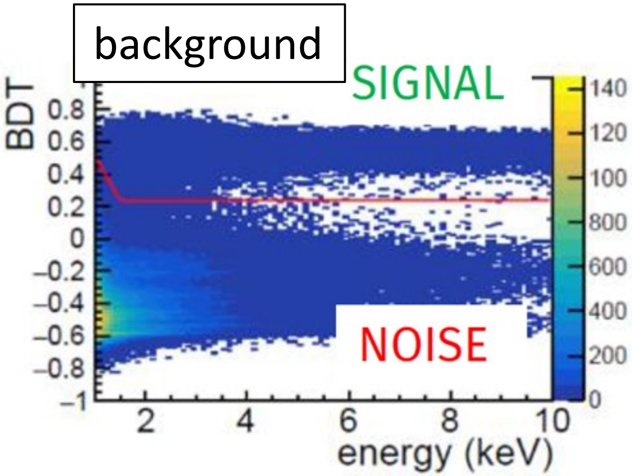
Signal events: on-site neutron calibrations. Events in [1-2] keV range

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

BDT cut defined for every detector and energy bin:

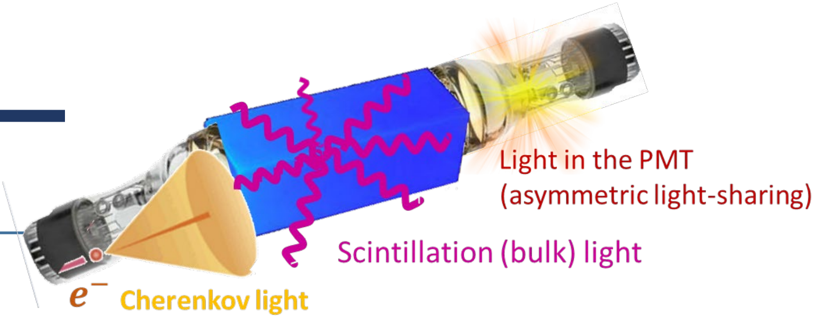






ANAIS-112 vs DAMA/LIBRA

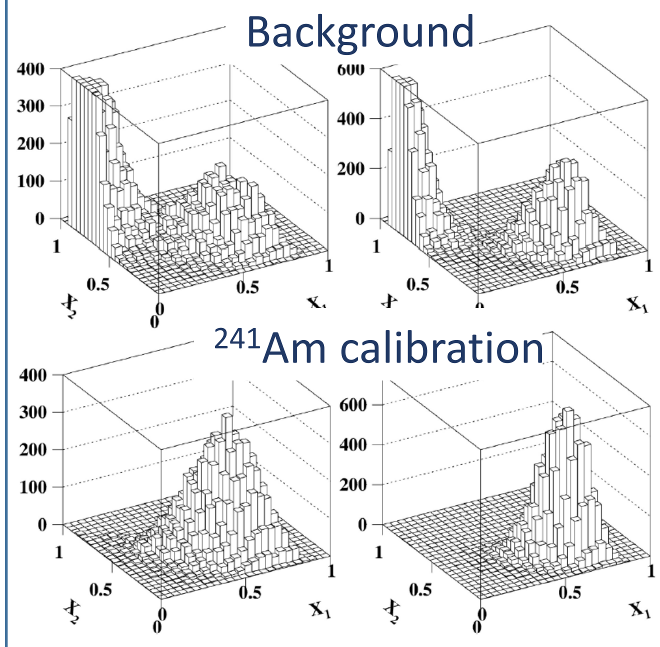
Event selection & efficiency

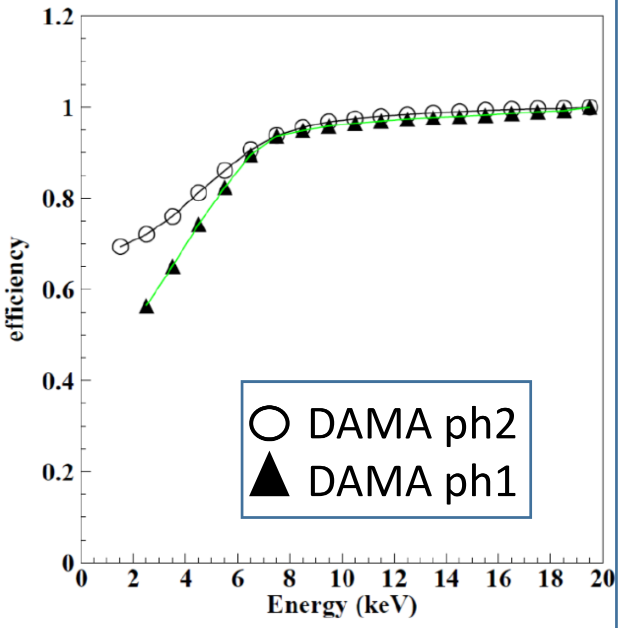


X_1 = Area(from 100 to 600 ns)=Area(from 0 to 600 ns)

X_2 = Area(from 0 to 50 ns)=Area(from 0 to 600 ns)

$$ES = \frac{1-(X_2-X_1)}{2} \qquad ES > 0.54\ (0.60) \text{ in } 1\text{–}3\ (3\text{–}6) \text{ keV}$$





JINST 7 P03009 (2012)

Standard analysis (4)

$$P_1 = \frac{\sum_{100\text{ ns}}^{600\text{ ns}} A(t)}{\sum_{0\text{ ns}}^{600\text{ ns}} A(t)}$$

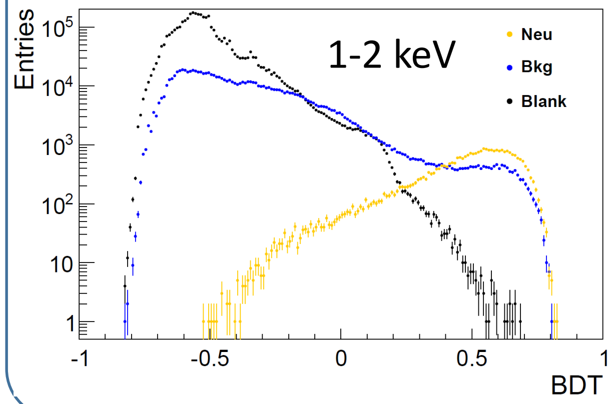
$$\mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i} \qquad n_0, n_1$$

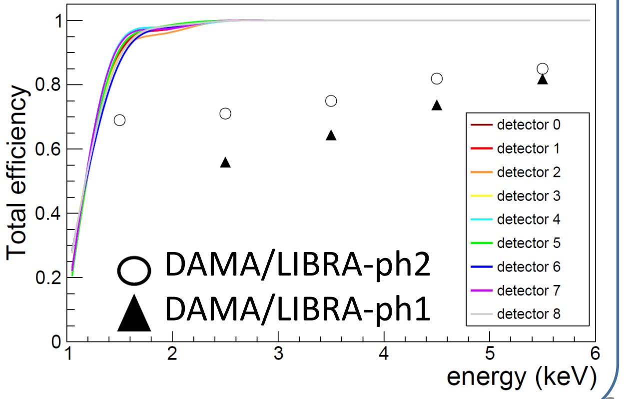
New parameters (11)

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

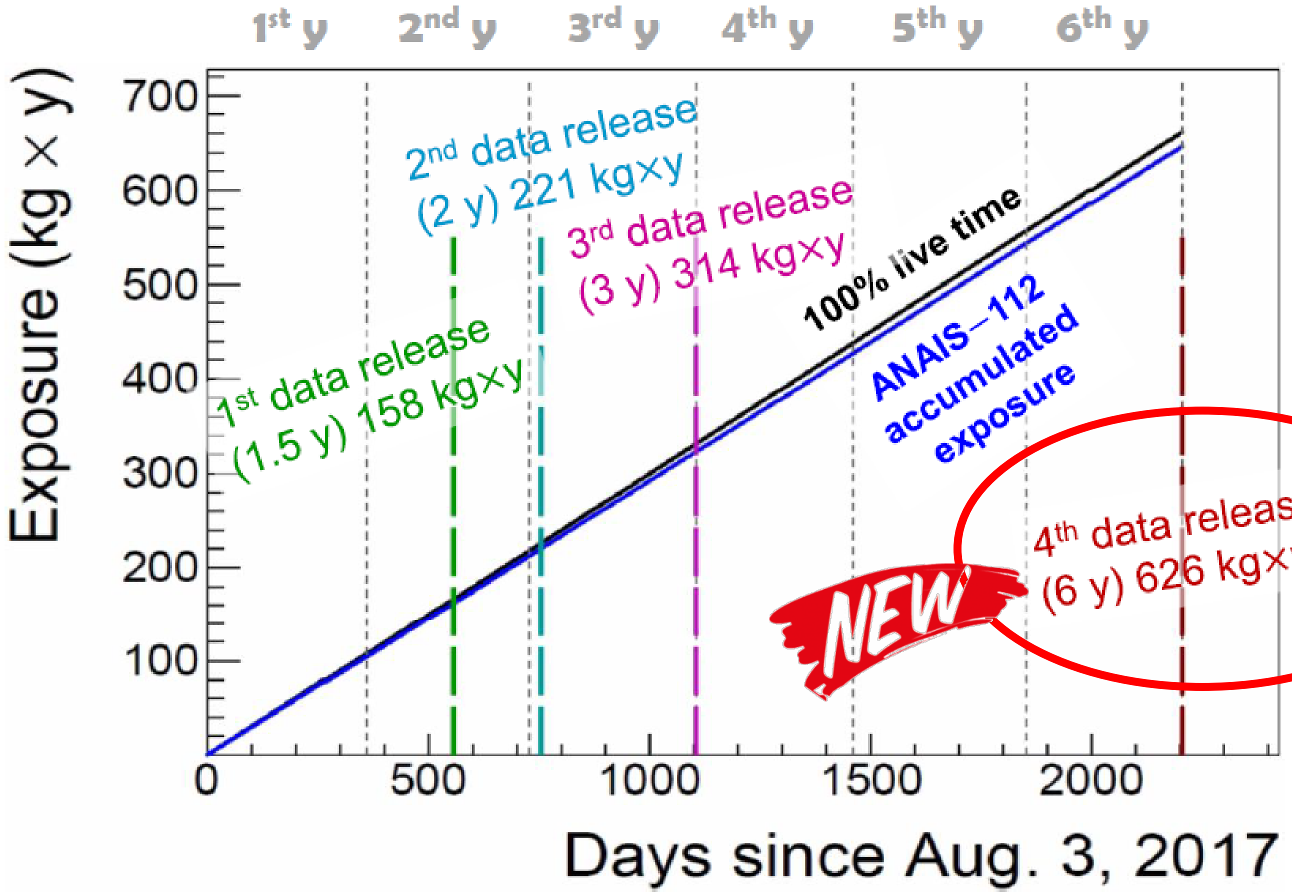
$$CAP_x = \frac{\sum_{0\text{ ns}}^{x\text{ ns}} A(t)}{\sum_{0\text{ ns}}^{t_{max}} A(t)} \qquad x = 50, 100, 200, 300, 400, 500, 600, 700, 800 \text{ ns}$$

Boosted Decision Tree (BDT)

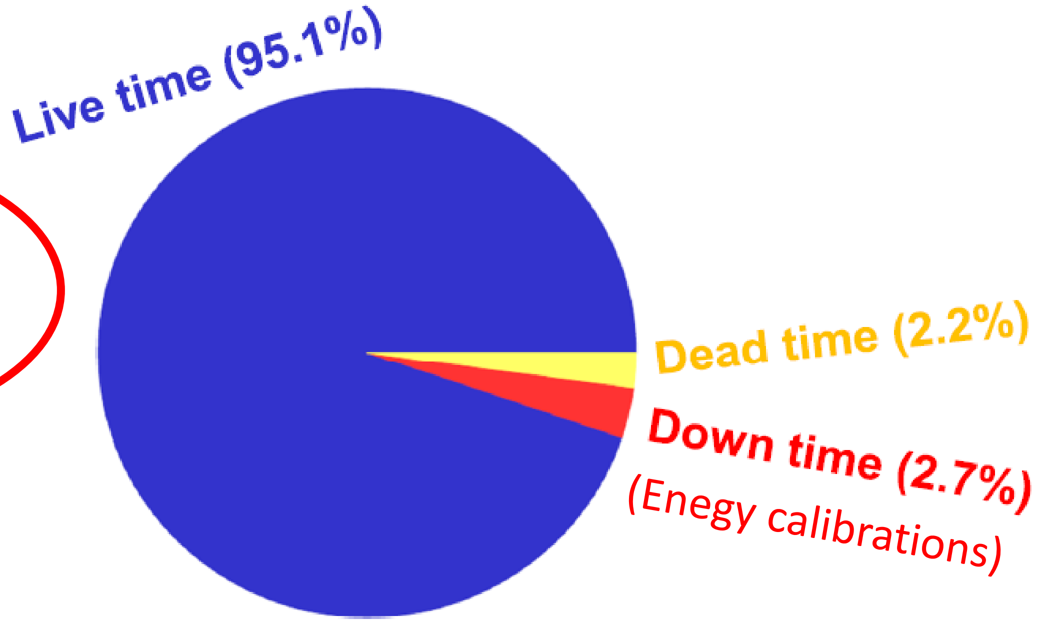




ANAIS-112 Data-taking overview



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



- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: Phys. Rev. D 103, 102005 (2021
- 3y + ML: Comm. Phys. 7, 345 (2024)

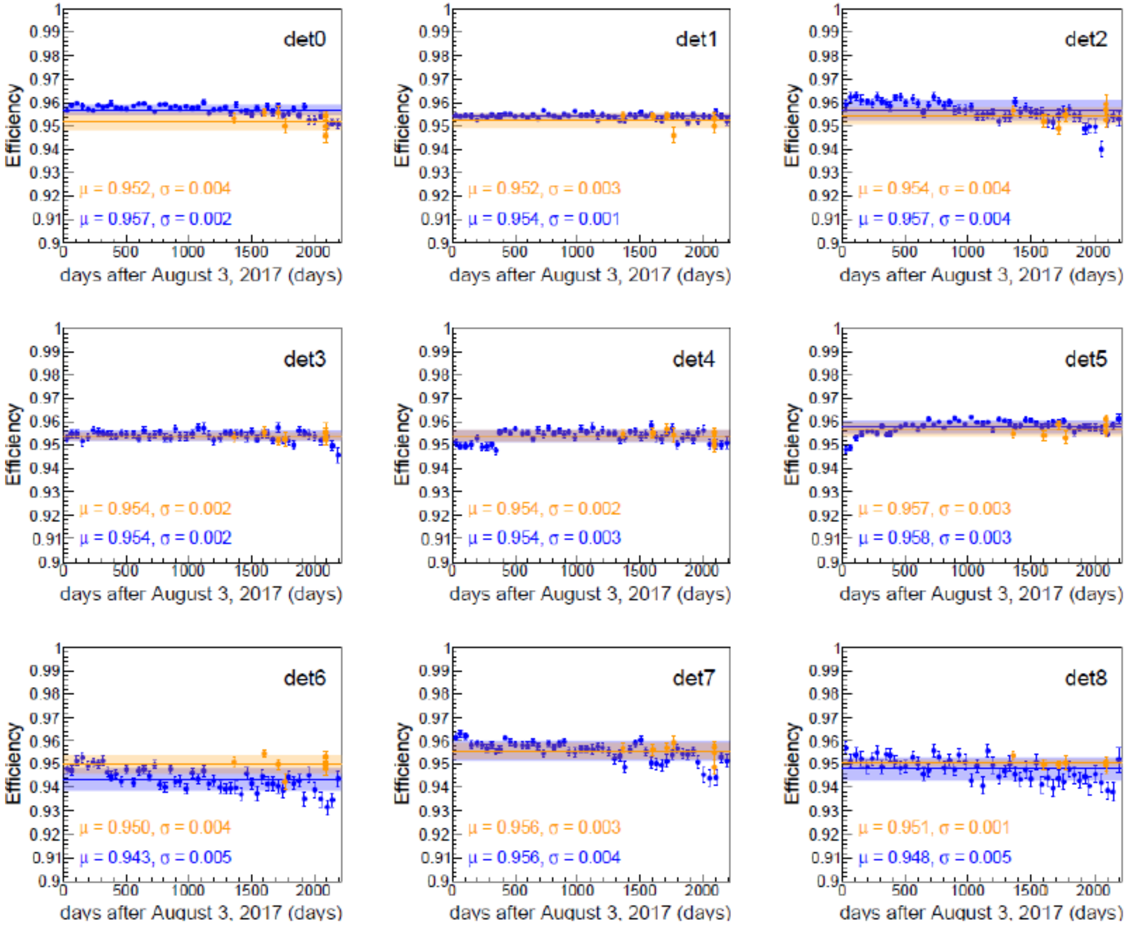
(*) PRL 135, 051001 (2025), arxiv: 2502.01542

Stability checks

PRL 135, 051001 (2025)

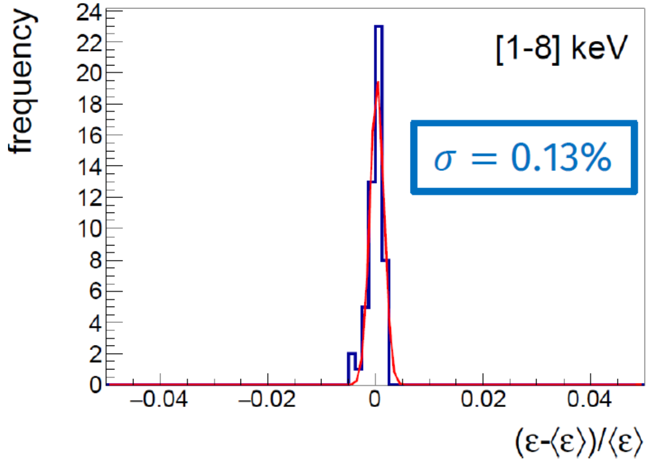
Event selection efficiency stability

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

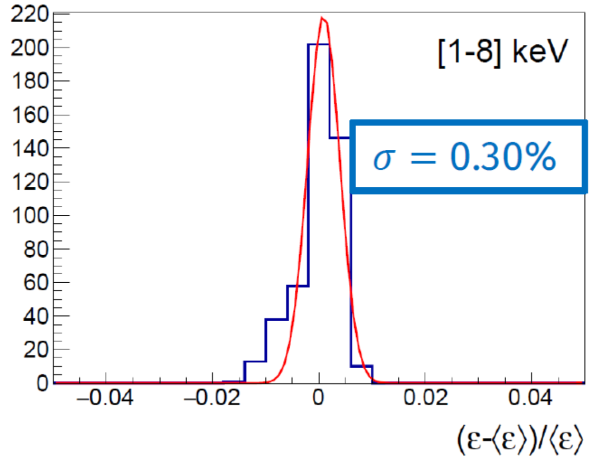


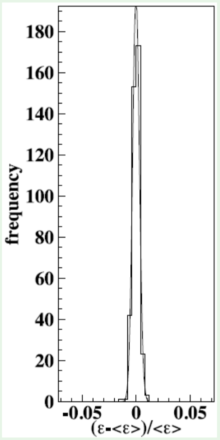
det4 & det 5: change in HV after 1 year
det 0: change in gain PMT0 after 5 year

Averaging all detectors



Considering independently





DAMA/LIBRA-phase2 reports a similar spread σ = **0.30%** in [1-8] keV

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

Annual modulation analysis strategy

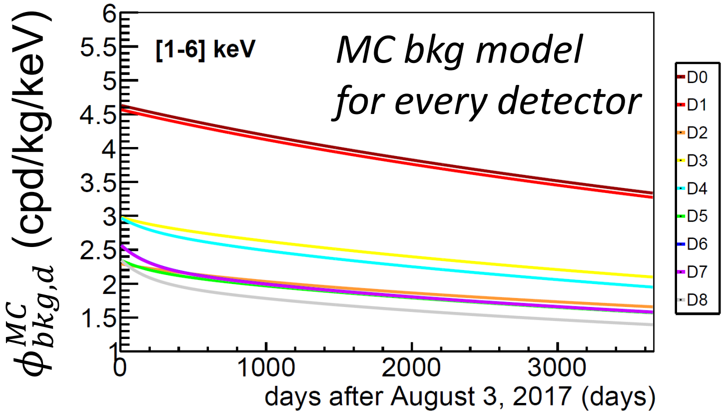
PRL 135, 051001 (2025)

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:

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

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

PRL 135, 051001 (2025)

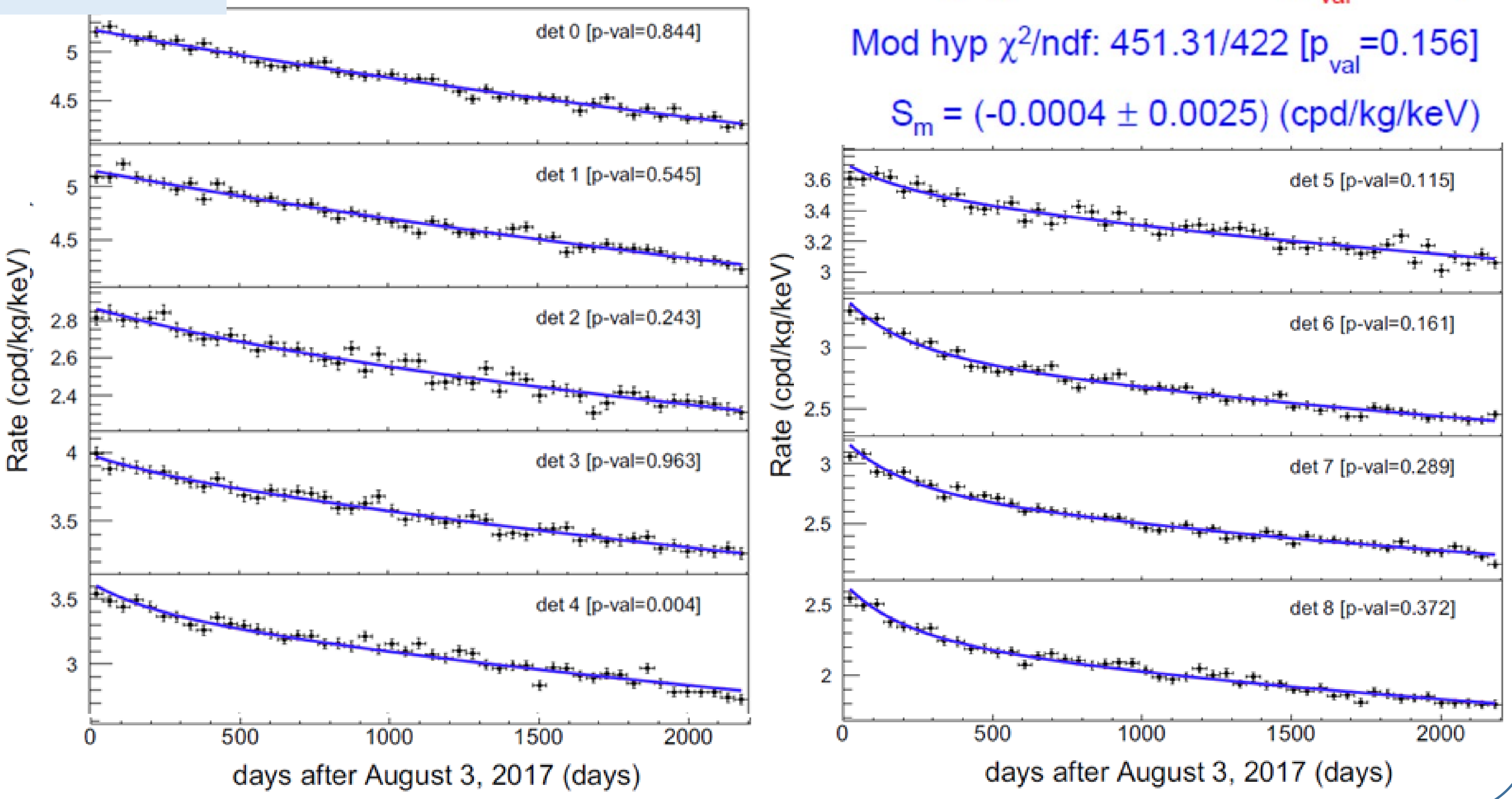
ANAIS-112 rejects the DM origin of the DAMA/LIBRA modulation signal at $\sim 4\sigma$ C.L.

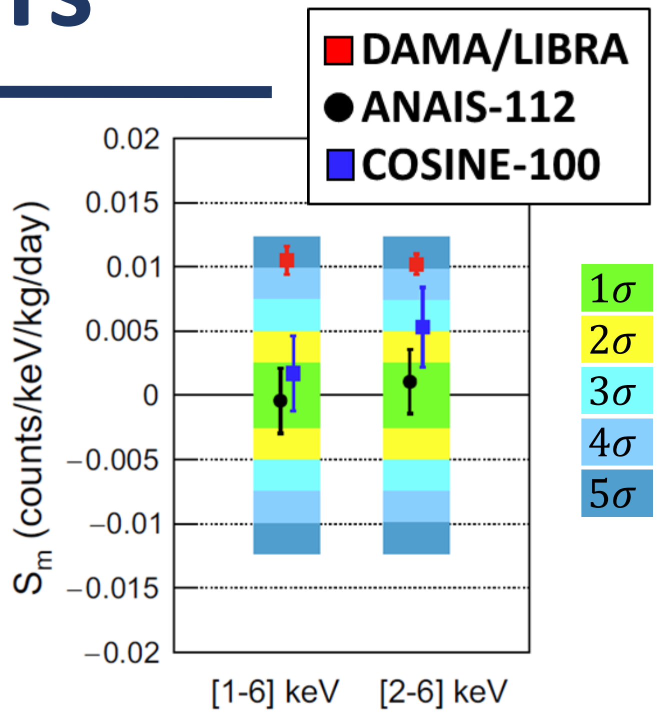
[1-6] keV

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

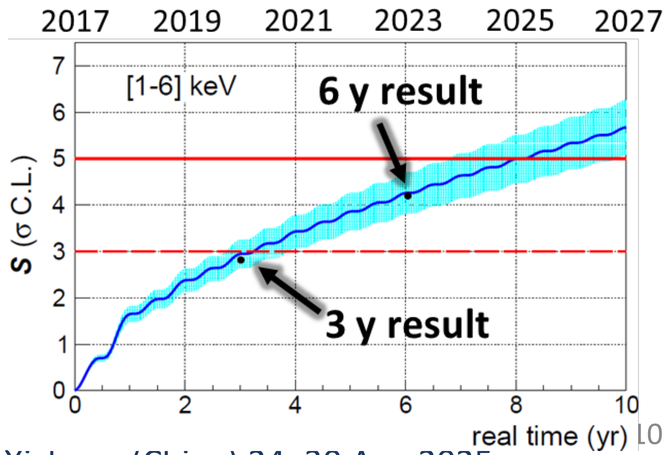
Mod hyp χ^2/ndf: 451.31/422 [p_{val}=0.156]

S_m = (-0.0004 ± 0.0025) (cpd/kg/keV)



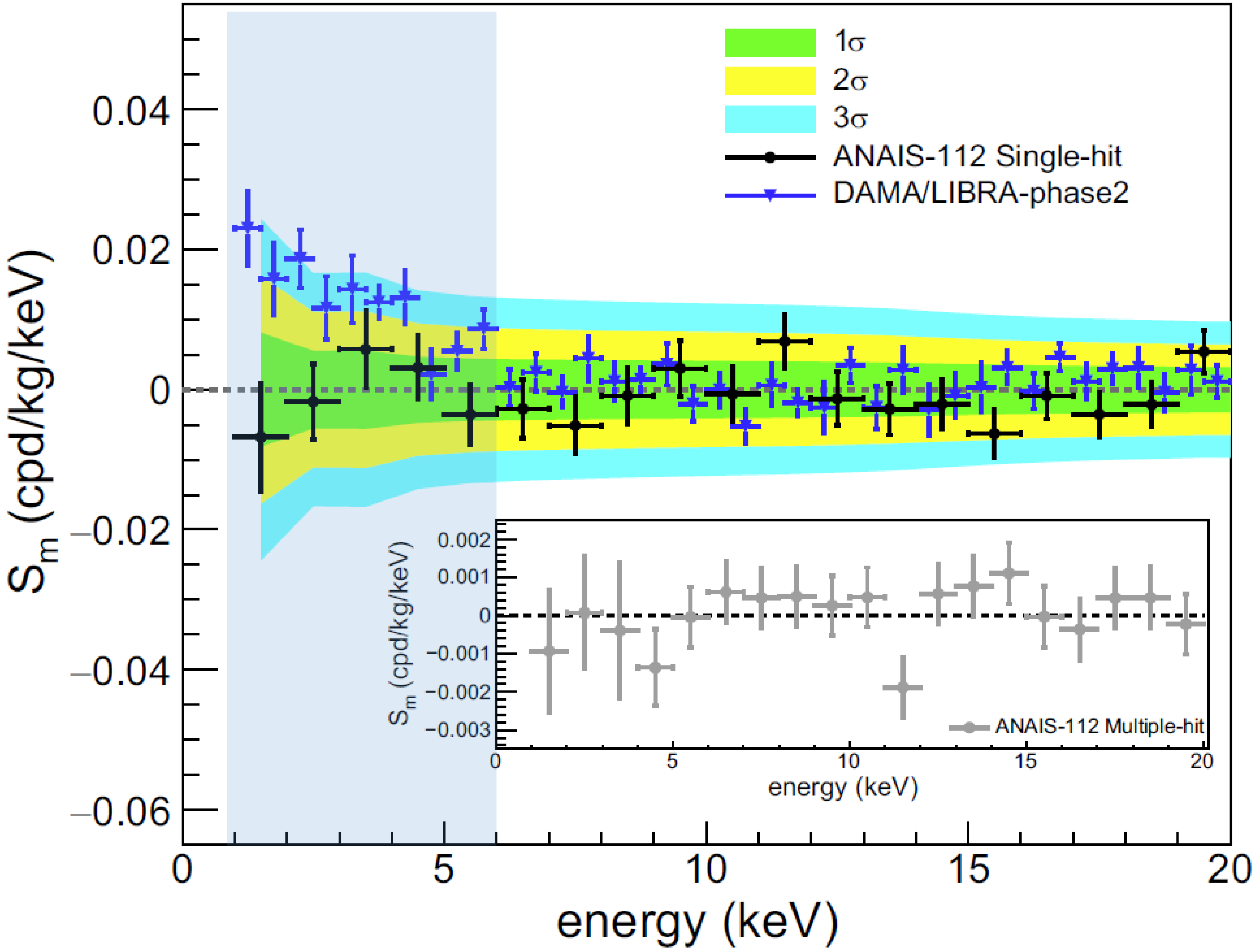


Results well in agreement with projections:



Modulation amplitude vs energy

PRL 135, 051001 (2025)



toyMC study of systematics

PRL 135, 051001 (2025)

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

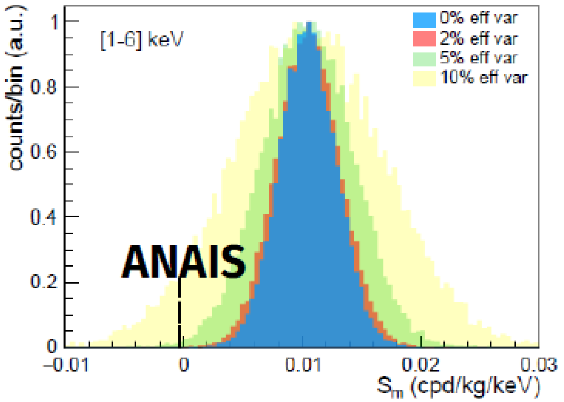
Fit bias study

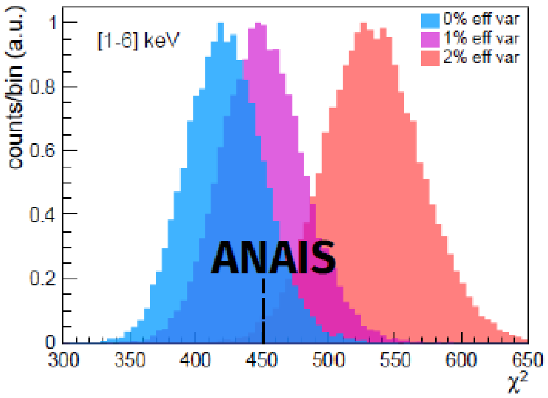
No bias is observed and similar standard deviations than found in the ANAIS–112 6-year results

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

ANAIS-112 Open data

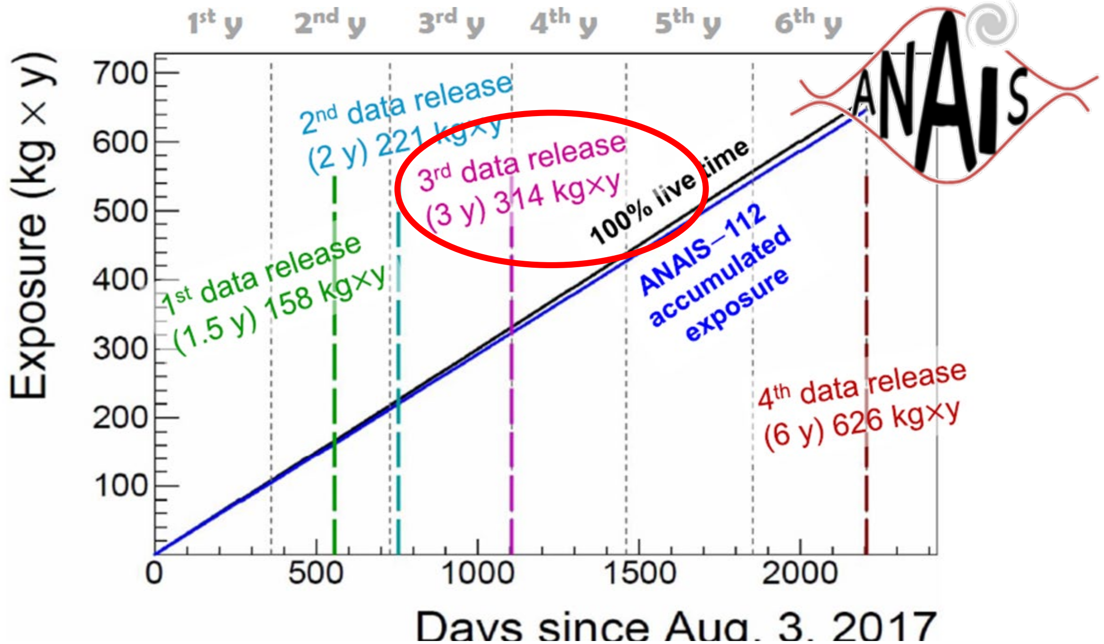
ORIGINS Excellence Cluster THE DARK MATTER DATA CENTER

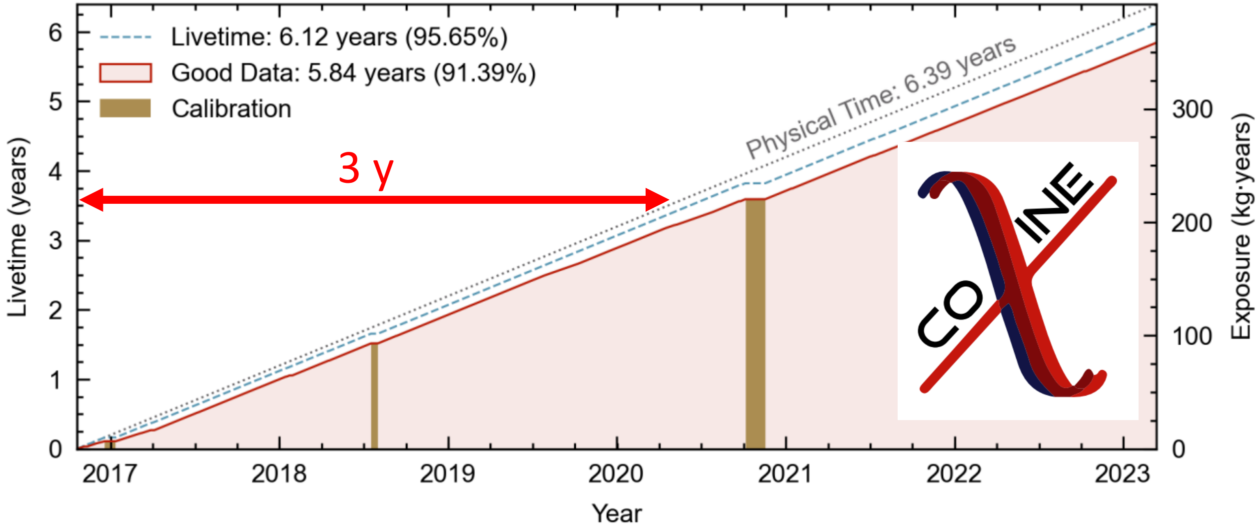
https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais

ANAIS112-6years Available Resources

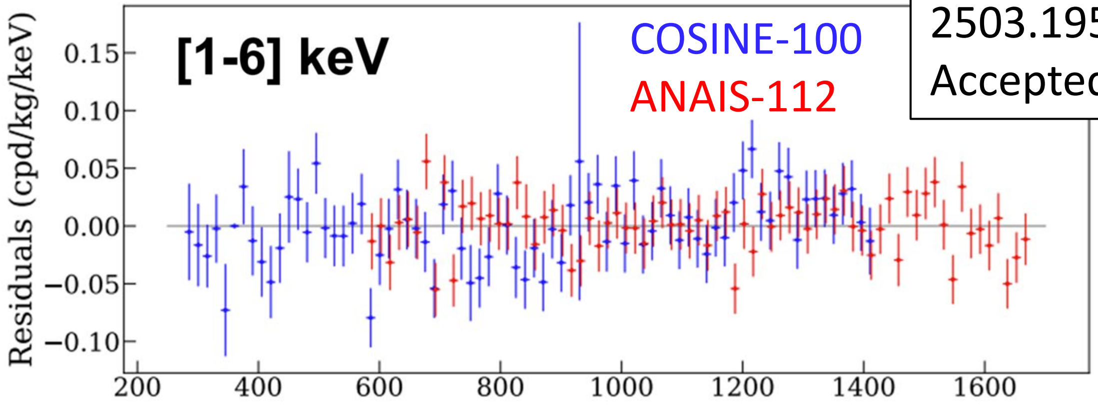
Resource	Description
Event Data	Experimental event data in counts/keV/kg/day (corrected by efficiency and live time) in 45 days bins. One CSV file for each detector D0-D8 for for [1-6] keV energy region, another for [2-6] keV energy region and one more for [1.3-4]keV. Format: bin_center(days) , events(counts/keV/kg/d) , error(counts/keV/kg/d)
Simulated Background	MC simulated background in counts/kg/day for every detector D[0-8] in energy regions [1-6] keV, [2-6] keV and [1.3-4] keV in 15 days bins. Format: bin_center(days) , events(counts/kg/d).
Efficiency	Efficiency vs energy for every detector(0-8) from 1-6 keV. Format: bin_center(keV) , efficiency , error.
Live Time	Live time in days for every 45-days bin
Chi2 Minimization (RooFit)	Fitting Root macro (RooFit). ROOT Version v6-20-00-rc1 Perform the chi2 minimization according to arXiv:2502.01542 equation (2). output: figures (5), (6) and (7) of the supplemental material Usage: a112modFit(int enel, bool useMC=1) Input parameters: , **enel, eneE: initial and end energies. Possible values:** (1, 6) -> fit [1-6] keV (figure 5, supplemental material). (2, 6) -> fit [2-6] keV (figure 6, supplemental material). (1.3, 4) -> fit [1.3-4] keV (figure 7, supplemental material) **useMC: background model** 1 (default) -> use MC background model (equation 2) 0 -> use single exponential approximation for background (this result is not included in arXiv:2502.01542)

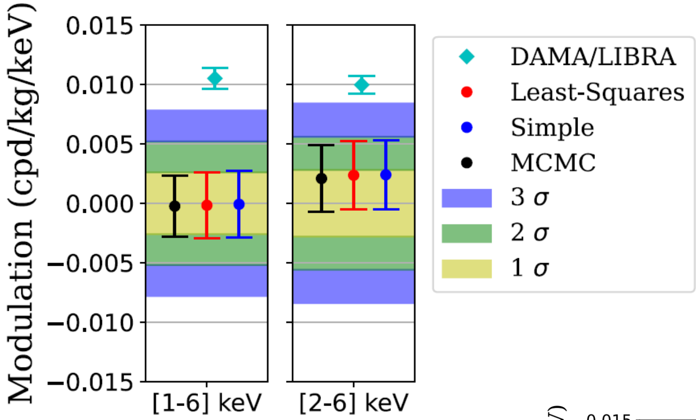
Combined analysis ANAIS-112 & COSINE-100 (3y)





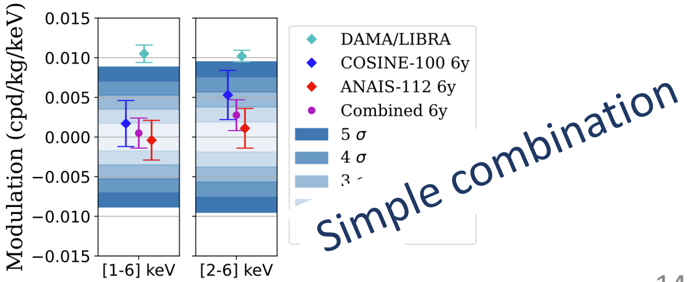
2503.19559, Accepted in PRL





COMBINED 3 years DATA is incompatible with DAMA/LIBRA's DM interpretation of annual modulation at **3.7σ ([1-6] keV) and 2.6σ ([2-6] keV)**

Work in progress to combine data for total statistics + systematic analysis

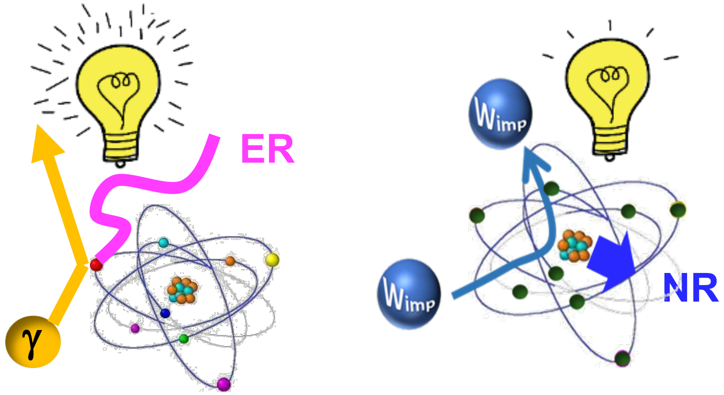


Impact of the hypothesis of different quenching factors

ANAIS-112 rejects the DM origin of the DAMA/LIBRA modulation signal at $\sim 4\sigma$ C.L.

But this is true for a direct comparison in electron-equivalent energy

For candidates interacting with the nuclei (i.e., standard WIMPs) the light produced by the nuclear recoil is quenched, and the quenching factor (QF) may be different in ANAIS and DAMA → **DIFFERENT ENERGY SCALE**



$$\boldsymbol{QF}(E) = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$

Up to date there is not a theoretical model to describe the QF and the energy dependence.

The QF has to be measured experimentally to correct the energy scale

QF measurement ANAIS-112 vs DAMA/LIBRA

^{252}Cf calibration

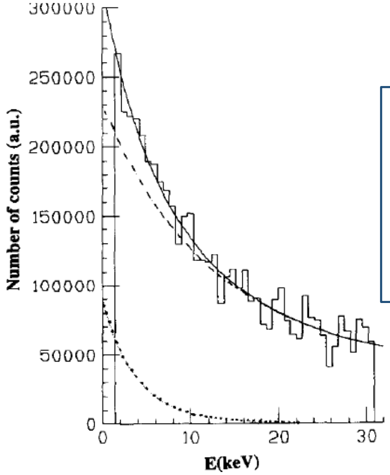
$$E_R = E_{det}/QF$$

Hypothesis: constant QF

Spectrum fitted to:

$$Y(E_{det}) = \alpha_{Na} G_{Na}\left(\frac{E_{det}}{q_{Na}}\right) + \alpha_I G_I\left(\frac{E_{det}}{q_I}\right)$$

$$G_X(E_R) = \exp(a_{1,X}E_R^3 + a_{2,X}E_R^2 + a_{3,X}E_R$$



Result:

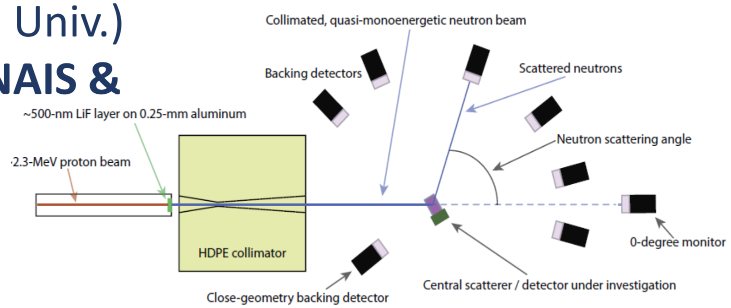
$QF_{Na} = 30\%$

$QF_I = 9\%$

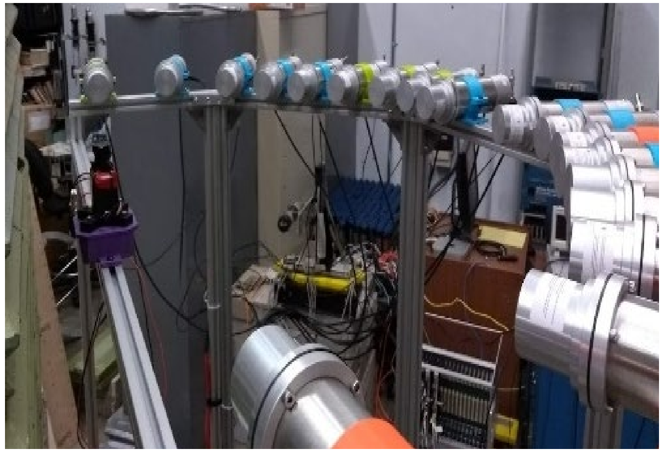
Phys. Lett. B 389 (1996) 757-766

Measurements @ TUNL (Duke Univ.)

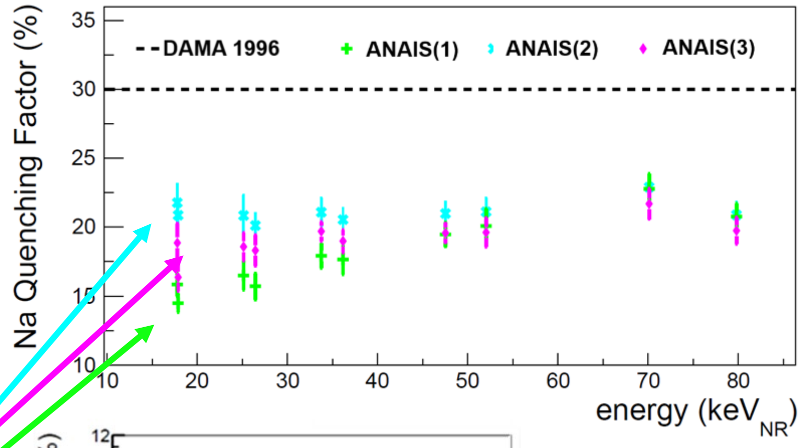
5 different NaI(Tl) crystals (ANAIS & COSINE) in the same setup

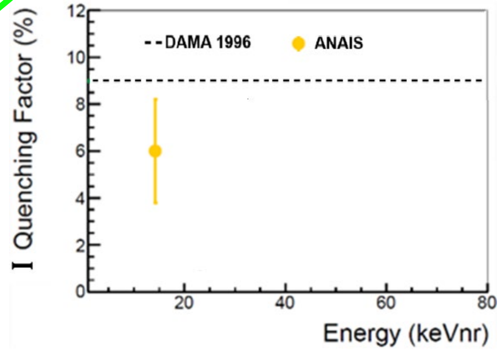


Phys. Rev. C 110 (2024) 014613



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





PRL 135, 051001 (2025)

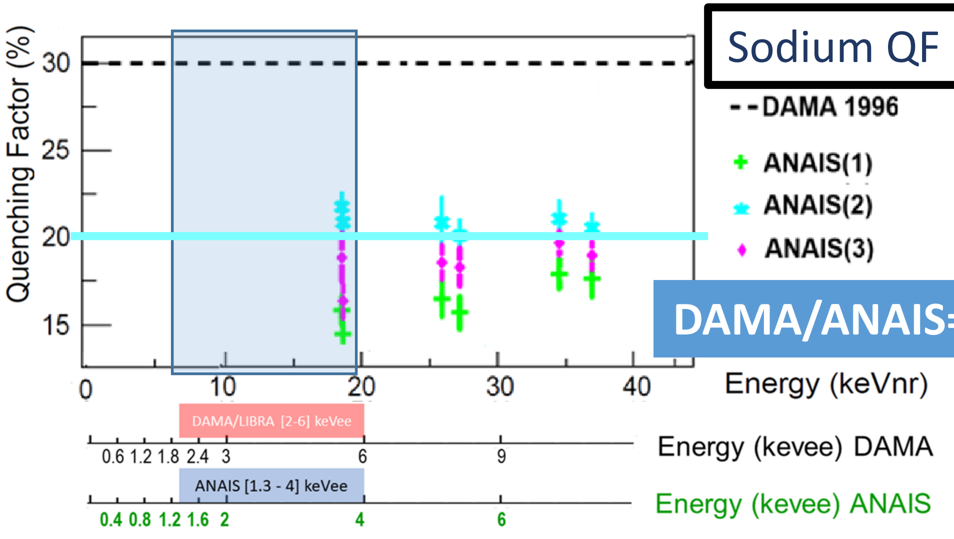
ANAIS-112 constant QF hypothesis

DAMA [2-6] keV

ANAIS [1.3 - 4] keV

6.7 – 20 keVnr

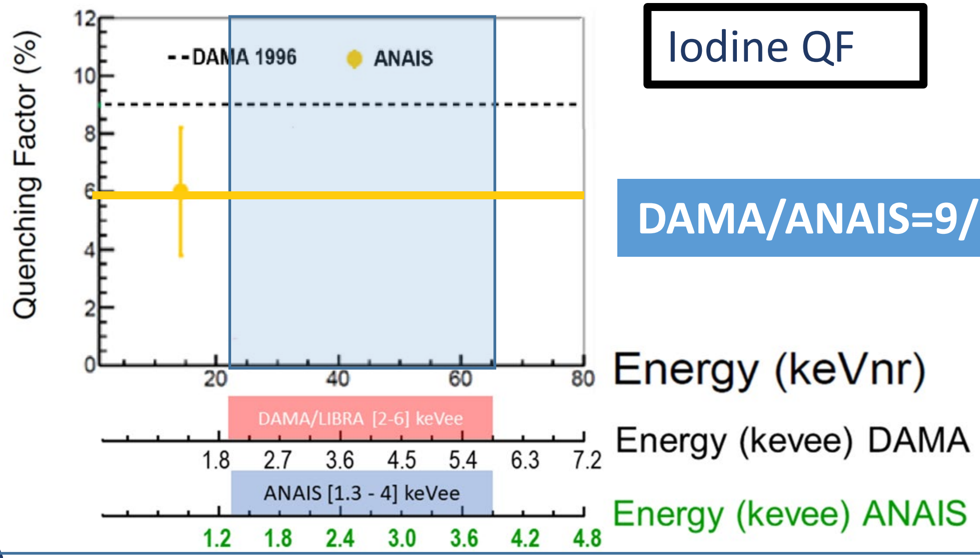
Sodium QF



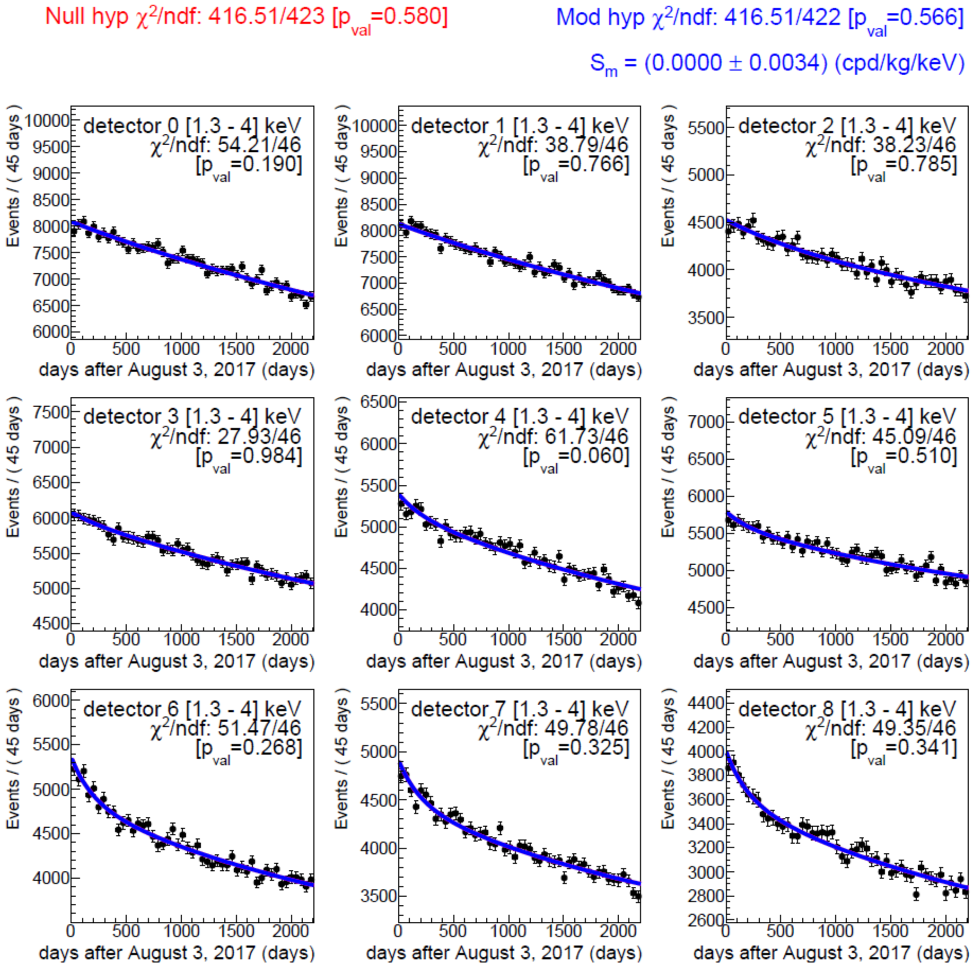
DAMA/ANAIS=30/20=3/2

22.2 – 66.7 keVnr

Iodine QF



DAMA/ANAIS=9/6=3/2

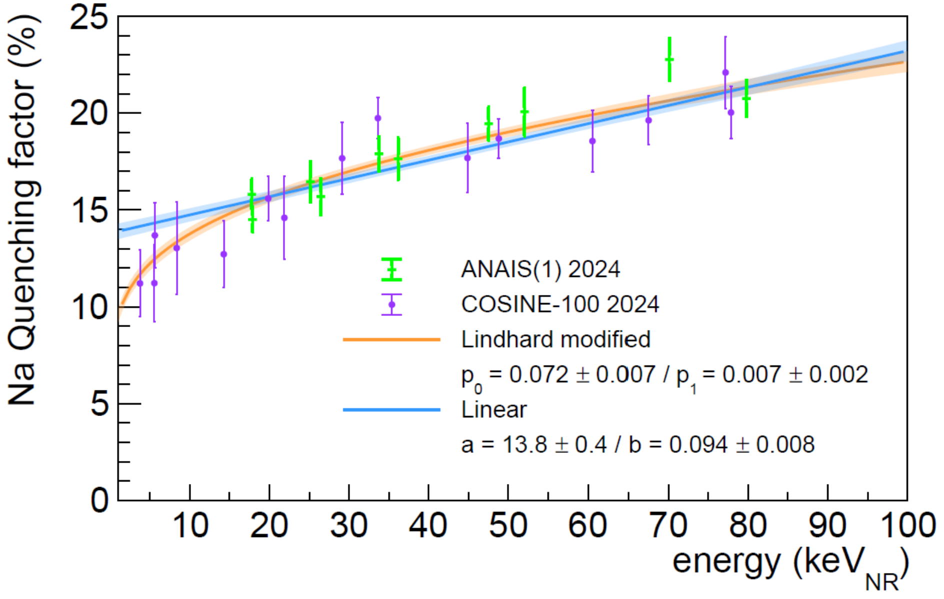


No modulation observed, sensitivity 4.4σ

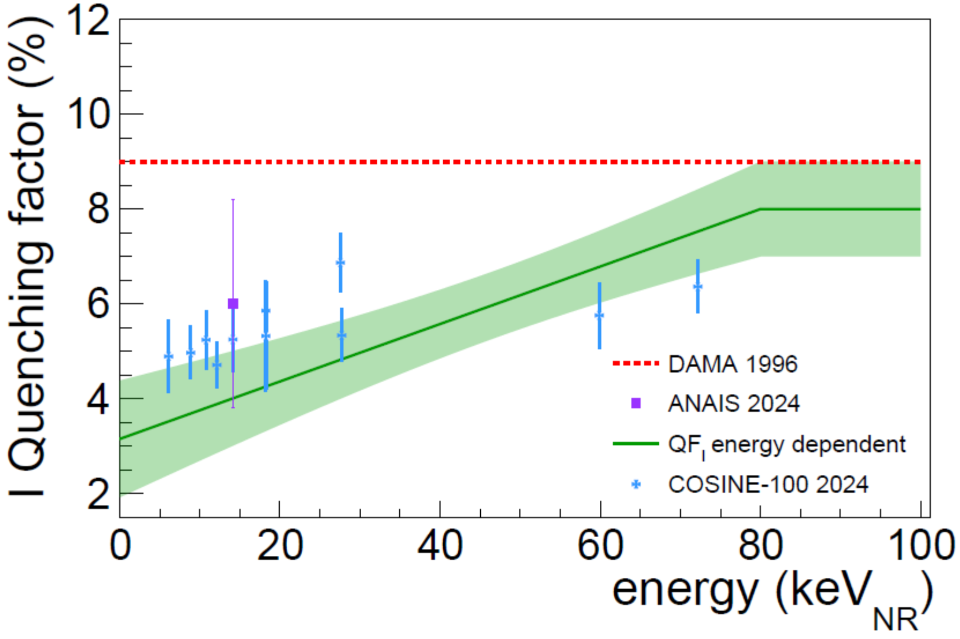
ANAIS-112 energy-variable QF hypothesis

T. Pardo PhD thesis

- Sodium data: (ANAIS(1)+COSINE-100) well fitted to a Modified Lindhard model with two free parameters (p_0, p_1)



- Iodine data: Linear hypothesis

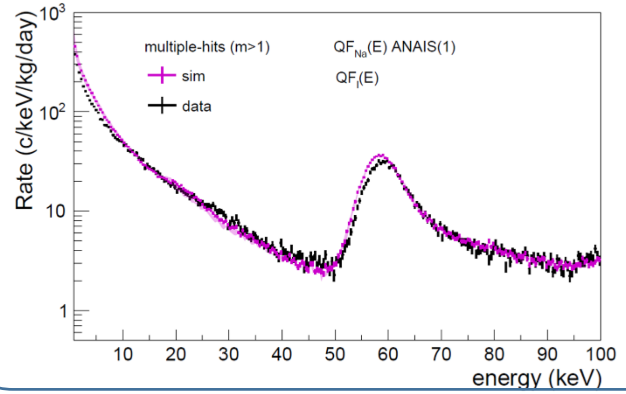


Modified Lindhard model:

$$QF(E_{NR}) = \frac{p_0 g(\epsilon)}{1 + p_0 g(\epsilon)} \qquad g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = p_1 E_{NR}$$

$$p_0 = 0.072 \pm 0.007 \qquad p_1 = 0.007 \pm 0.002$$

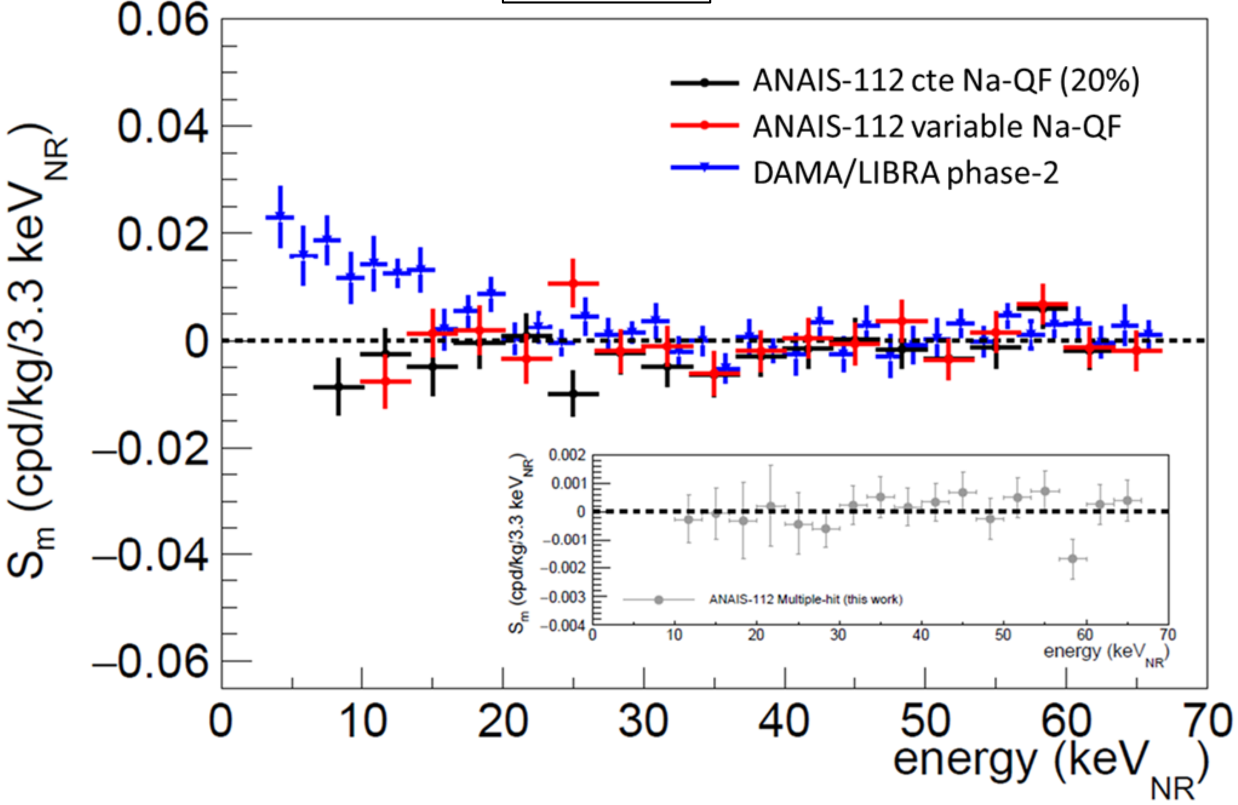


Geant4 simulation of on-site neutron calibration in good agreement with these QF!

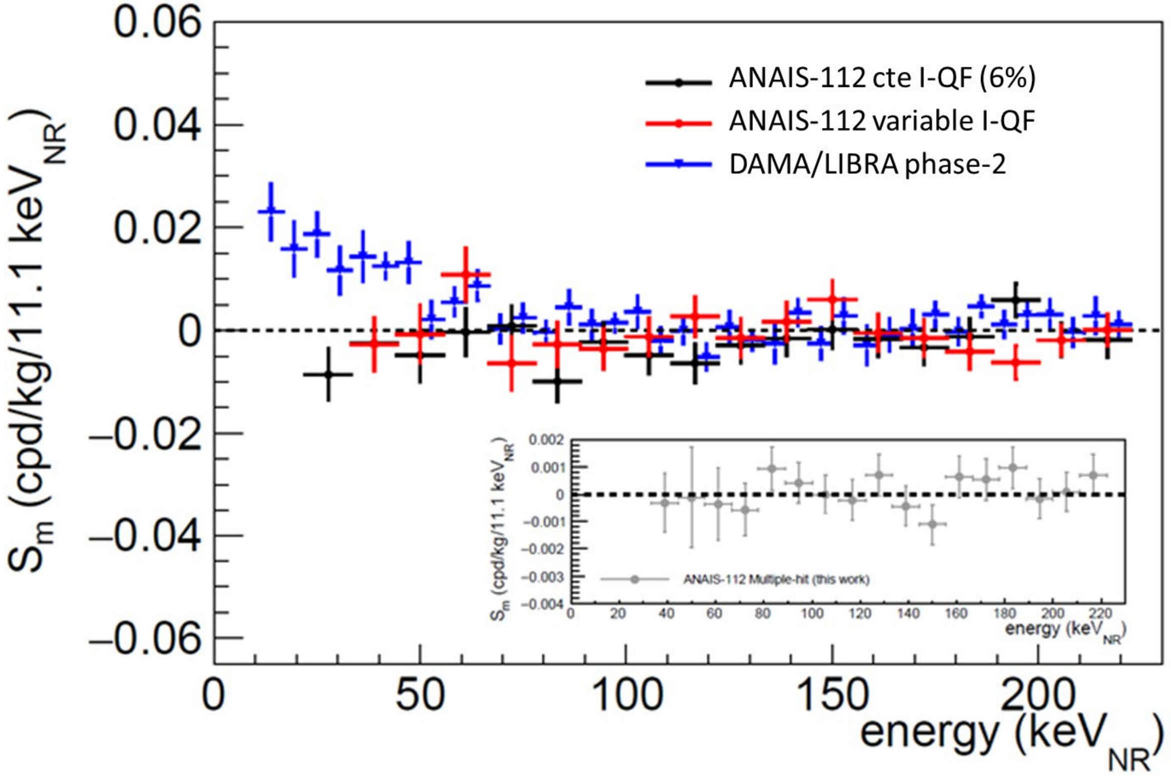
ANAIS-112 energy-variable QF hypothesis

T. Pardo PhD thesis

SODIUM



IODINE



ANAIS-112 variable Na-QF in [10–20] keV$_{NR}$:

Null hypothesis: χ^2/NDF = 2.95/3 (p-value = 0.4)

Modulation hypothesis: χ^2/NDF = 14.9/3 (p-value = 1.9×10^{-3})

ANAIS-112 variable I-QF in [33.3–66.7] keV$_{NR}$:

Null hypothesis: χ^2/NDF = 4.82/3 (p-value = 0.18)

Modulation hypothesis: χ^2/NDF = 8.66/3 (p-value = 0.03)

Outlook

- **ANAIS-112 rejects DM as an explanation of the DAMA/LIBRA modulation signal at $\sim 4\sigma$ C.L. for DM interacting with electrons**

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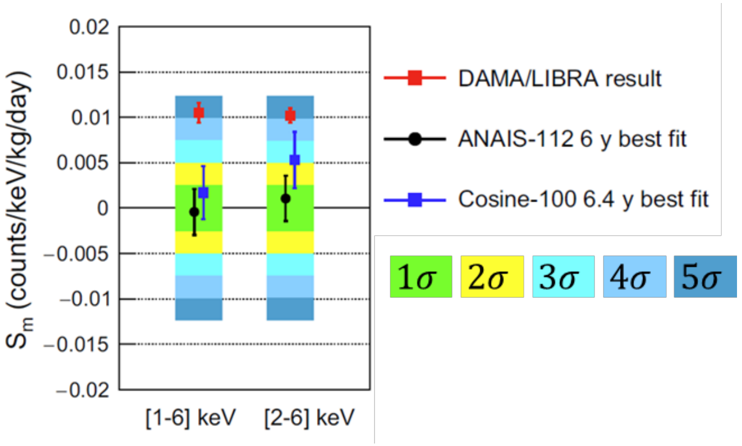
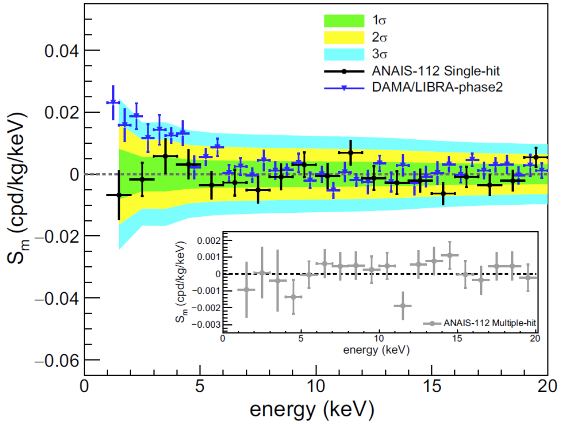
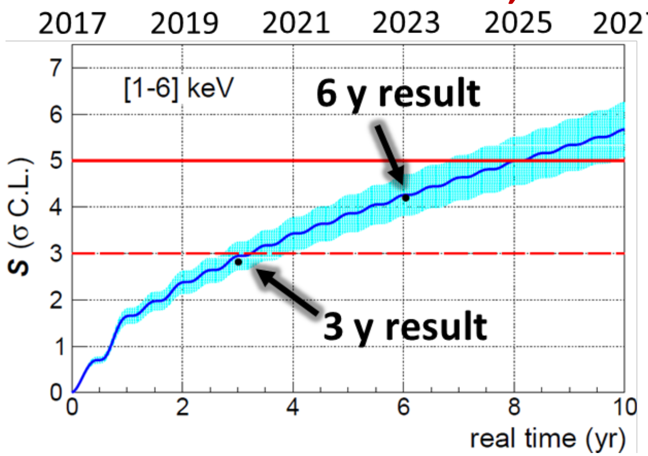
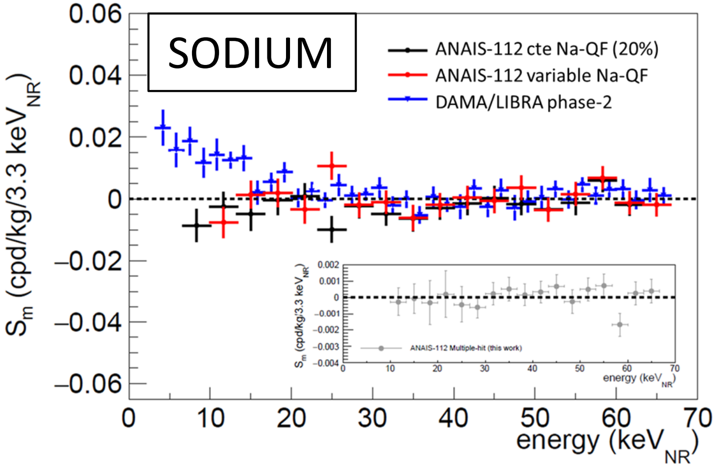




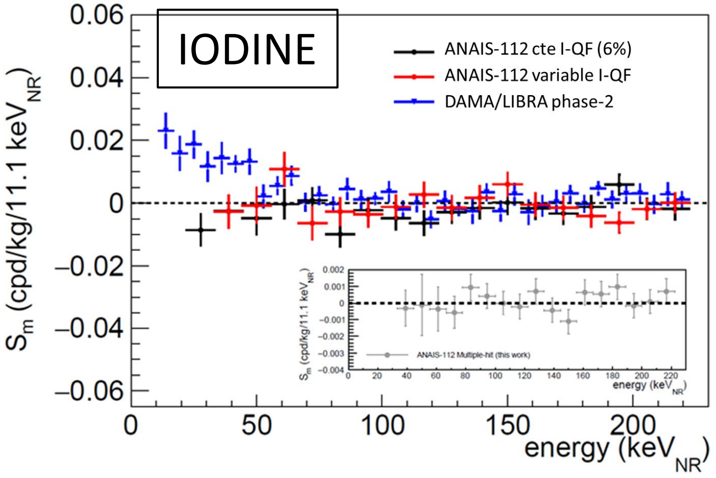


- **ANAIS-112 strongly challenges DM as an explanation for the DAMA/LIBRA modulation signal for DM interacting with nuclei, even taking into account possible QF effects**



Null hypothesis:
χ^2/NDF = 2.95/3
(p-value = 0.4)

Modulation hypothesis:
χ^2/NDF = 14.9/3
(p-value = 1.9×10^{-3})



Null hypothesis:
χ^2/NDF = 4.82/3
(p-value = 0.18)

Modulation hypothesis:
χ^2/NDF = 8.66/3
(p-value = 0.03)

Outlook

- **ANAIS-112 rejects DM as an explanation of the DAMA/LIBRA modulation signal at $\sim 4\sigma$ C.L. for DM interacting with electrons**
- **ANAIS-112 strongly challenges DM as an explanation for the DAMA/LIBRA modulation signal for DM interacting with nuclei, even taking into account possible QF effects**

Upcoming NaI experiments will enhance the exclusion of the DAMA signal as DM. new ANAIS+ project (NaI+SiPM to reduce threshold). Combined ANAIS+COSINE total exposure results in progress.

Understanding the DAMA/LIBRA signal could be beyond our possibilities without direct access to their data and analysis procedures, BUT:

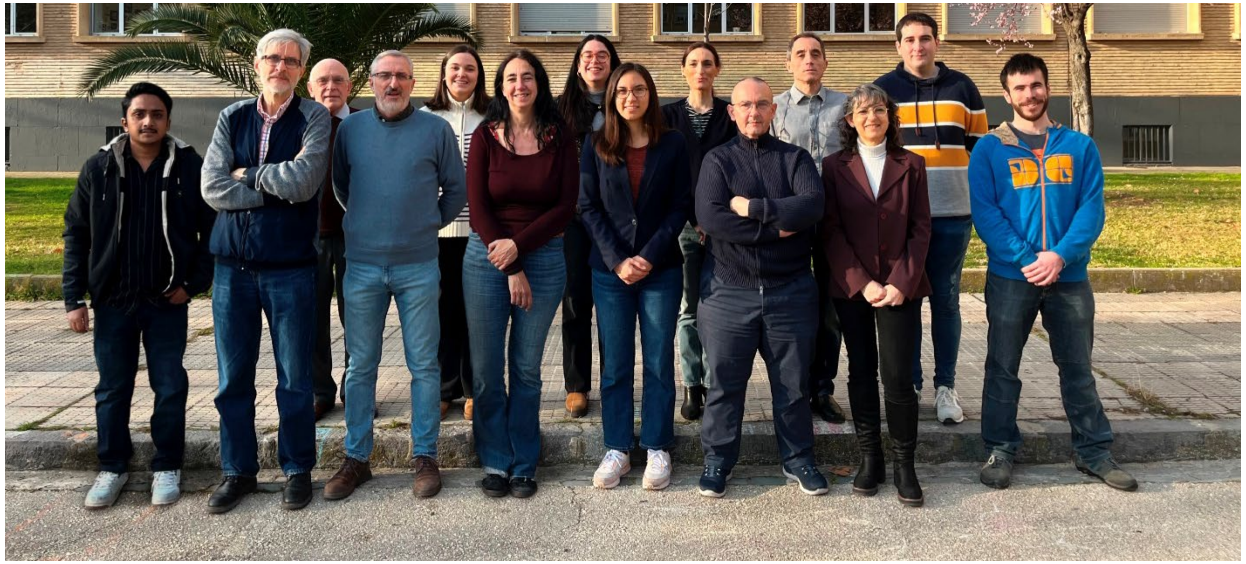
expression of intent to INFN-LNGS to merge know-how, experience, and equipment among ANAIS, COSINE, and SABRE collaborations for operating DAMA/LIBRA detectors:

- Direct search for modulation in same/different setup
- Independent measurement of DAMA/LIBRA NR quenching factors

OPEN SCIENCE IS A MUST

ANAIS-112 & COSINE-100 data freely available for downloading:
https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais (3+6 years data with scripts)
https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/cosine (3 years data)

Thank you for your attention!



ANAIS
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

ANAIS research team: J. Amaré, J. Apilluelo, S. Bharat, S. Cebrián, D. Cintas, I. Coarasa, E. García, S. Hollick, M. Martínez(*), Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, M. L. Sarsa, C. Seoane
(*) mariam@unizar.es

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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