ANAIS–112: updated results on annual modulation with three-year exposure

Iván Coarasa on behalf of the **ANAIS team**

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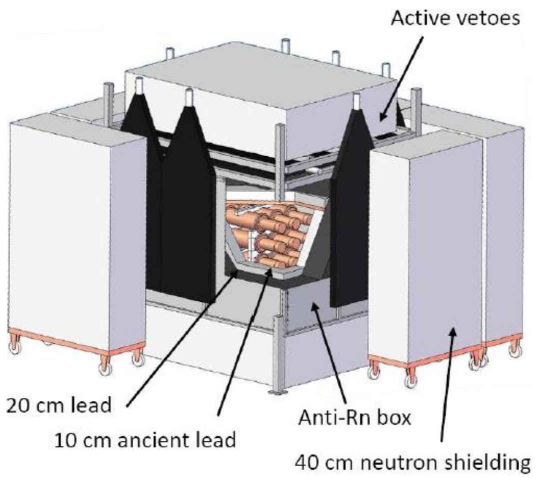
MultiDark Multimessenger Approach for Dark Matter Detection

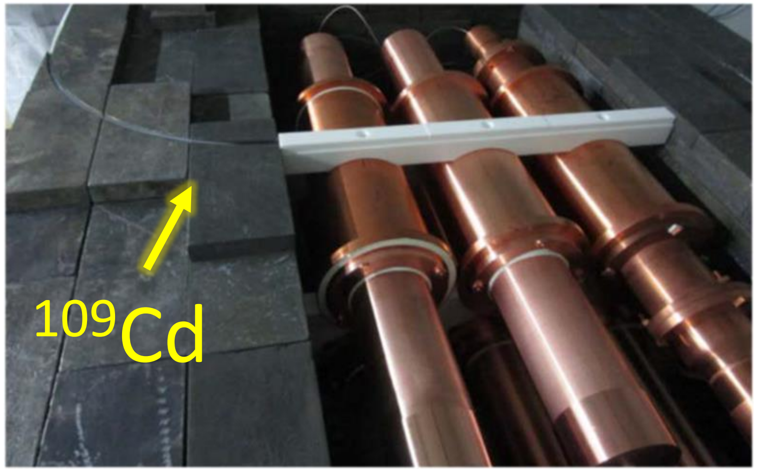
The ANAIS-112 experiment



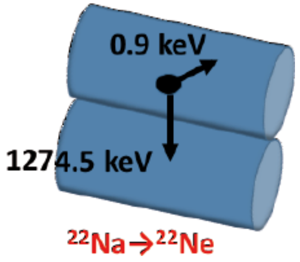
Goal

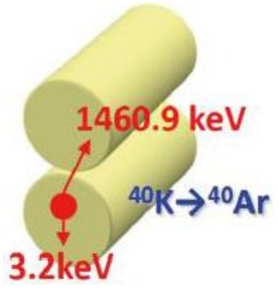
ANAIS (*<u>A</u>nnual modulation with <u>NaI</u>(Tl) <u>s</u>cintillators*) intends to provide a **model independent** test of the signal reported by DAMA/LIBRA, using the **same target and technique** at the **Canfranc Underground Laboratory** (Spain)

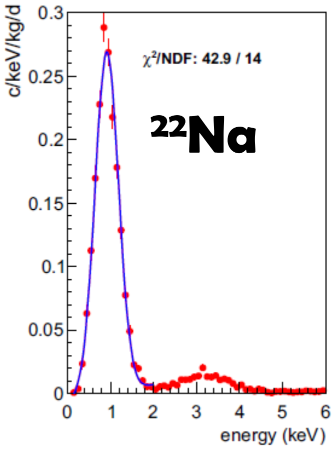
Low energy calibration

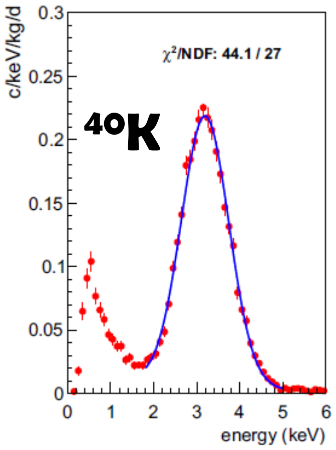


- ➔ 9 NaI(Tl) crystals (112.5 kg) equipped with a **Mylar window**
- ➔ Calibration with external **^{109}Cd sources** (11.9, 22.6 and 88.0 keV) every two weeks for gain correction
- ➔ Calibration in the **ROI [1-6] keV** with internal bulk contaminants **^{22}Na (0.9 keV)** and **^{40}K (3.2 keV)** using whole statistics



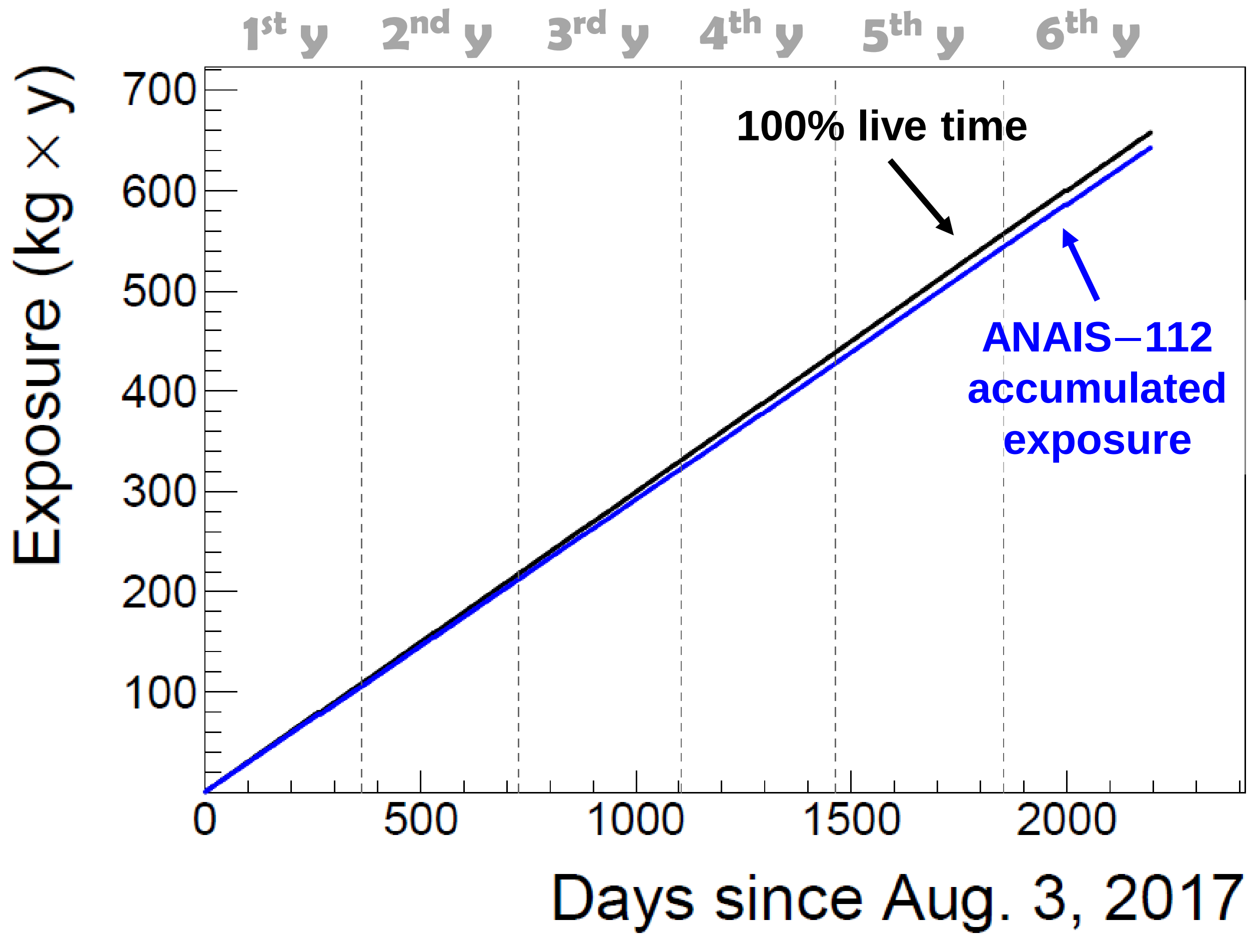






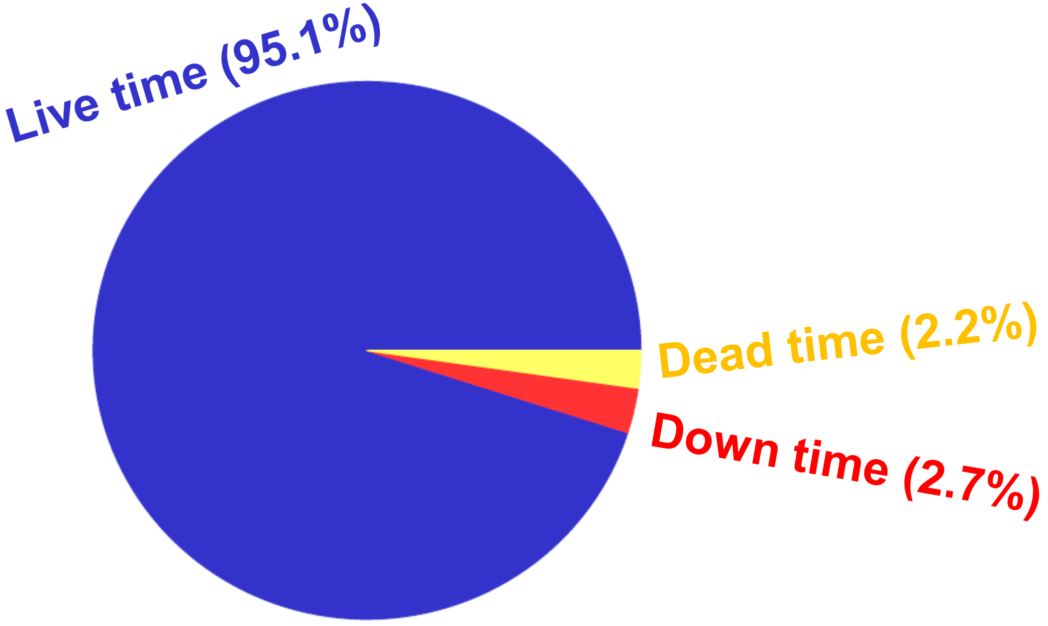
Data-taking overview

➔ The ANAIS−112 dark matter run started on **August 3, 2017**



ANAIS−112 accumulated exposure

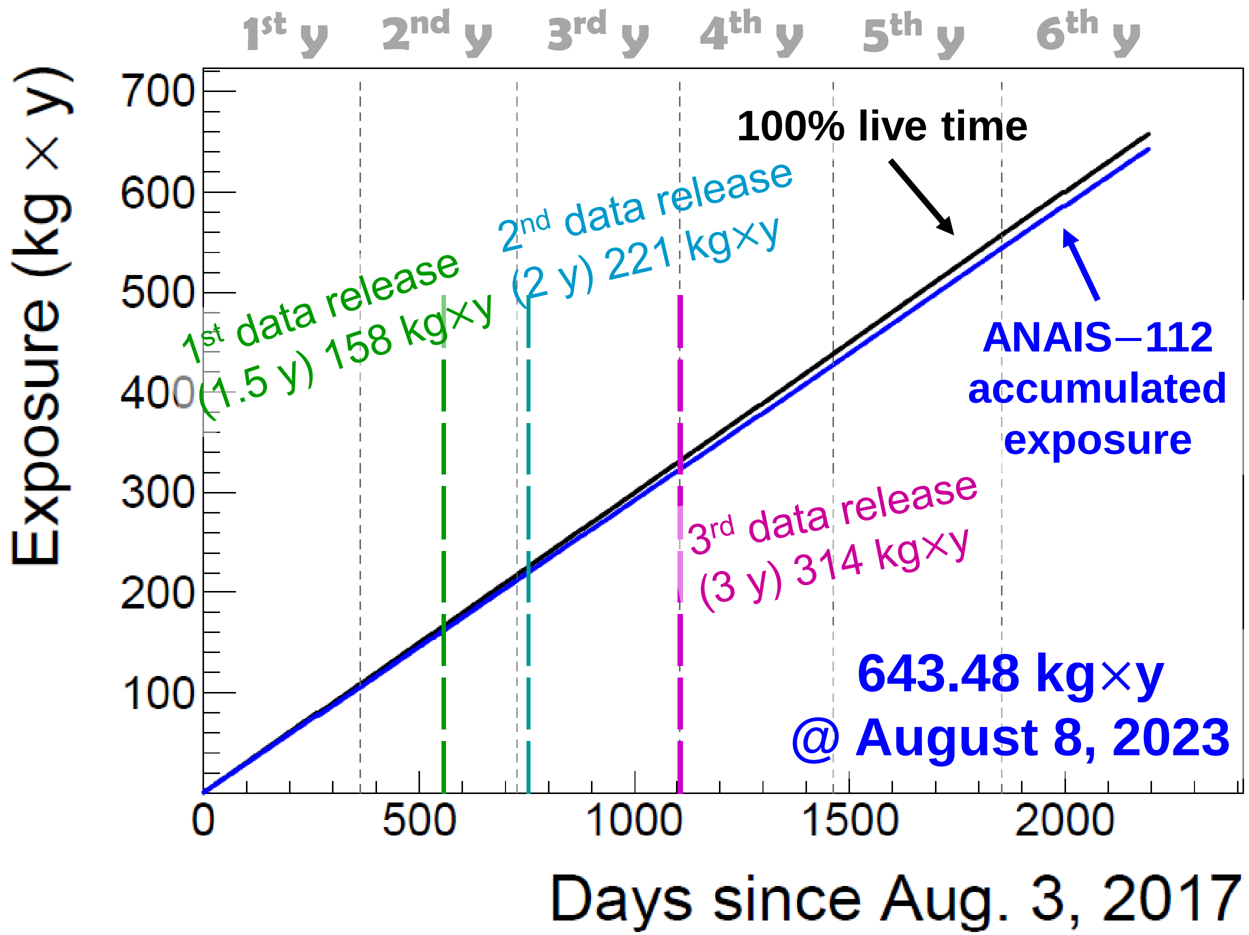
643.48 kg×y
@ August 8, 2023



➔ Six-year exposure has already been completed this August with about 95% of live time

Modulation results

➔ The ANAIS−112 dark matter run started on **August 3, 2017**



➔ Six-year exposure has already been completed this August with about 95% of live time

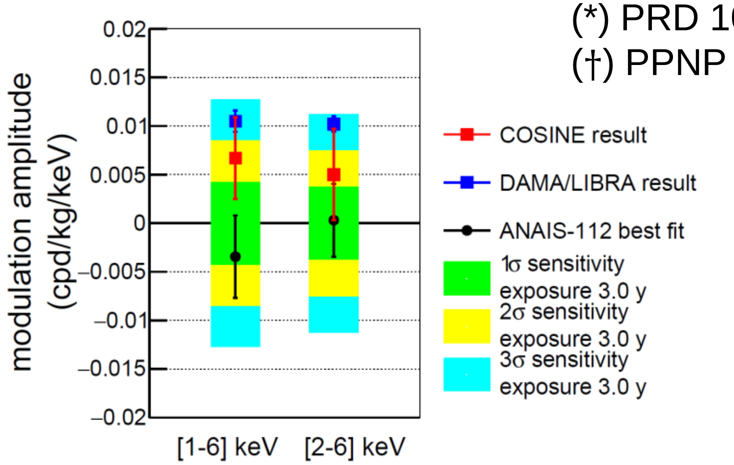
ANAIS−112 modulation results:

- 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)

LATEST RESULTS (3 y)

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)

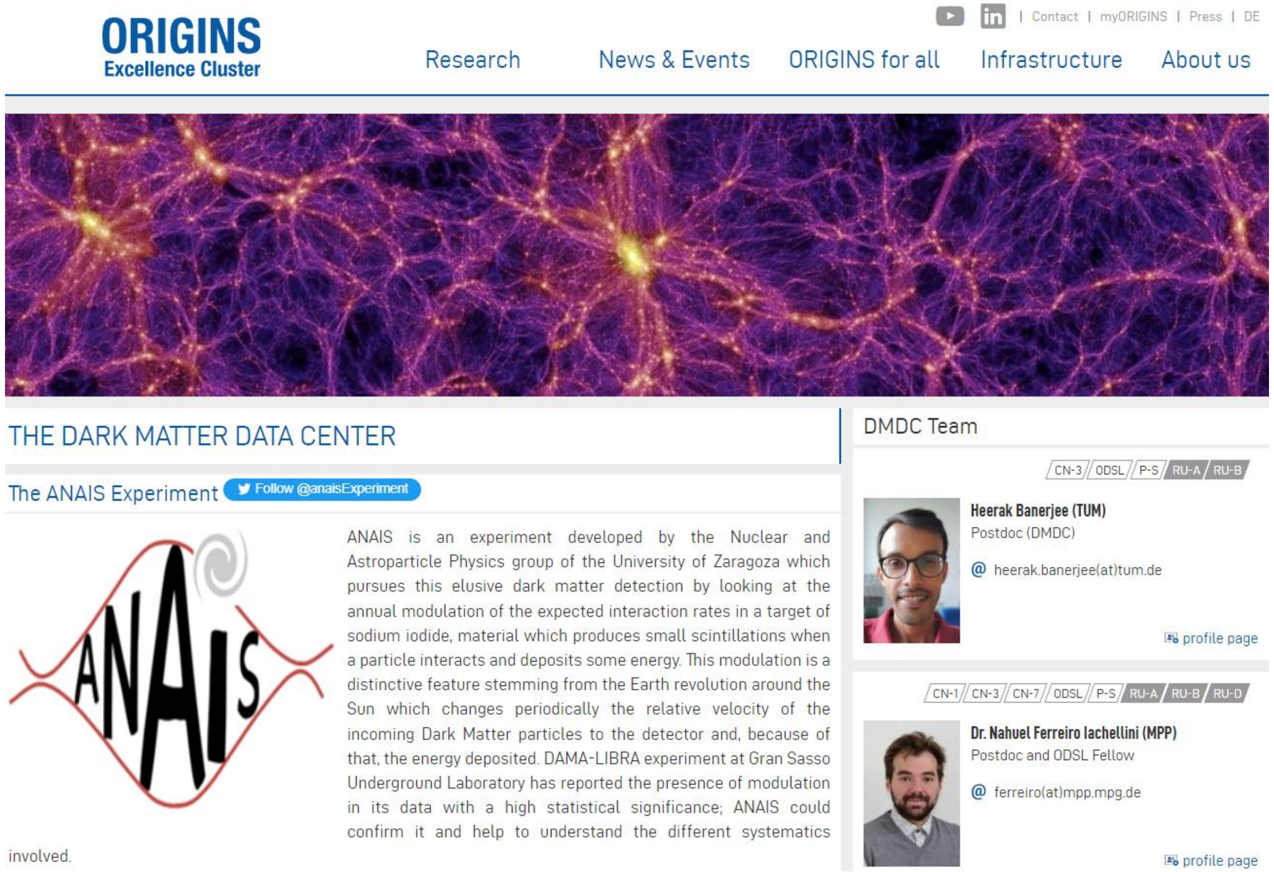


ANAIS: ~ 2.5σ sensitivity

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 data are freely available for downloading

https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais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THE DARK MATTER DATA CENTER

The ANAIS Experiment — Follow @anaisExperiment

ANAIS is an experiment developed by the Nuclear and Astroparticle Physics group of the University of Zaragoza which pursues this elusive dark matter detection by looking at the annual modulation of the expected interaction rates in a target of sodium iodide, material which produces small scintillations when a particle interacts and deposits some energy. This modulation is a distinctive feature stemming from the Earth revolution around the Sun which changes periodically the relative velocity of the incoming Dark Matter particles to the detector and, because of that, the energy deposited. DAMA-LIBRA experiment at Gran Sasso Underground Laboratory has reported the presence of modulation in its data with a high statistical significance; ANAIS could confirm it and help to understand the different systematics involved.

DMDC Team

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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]

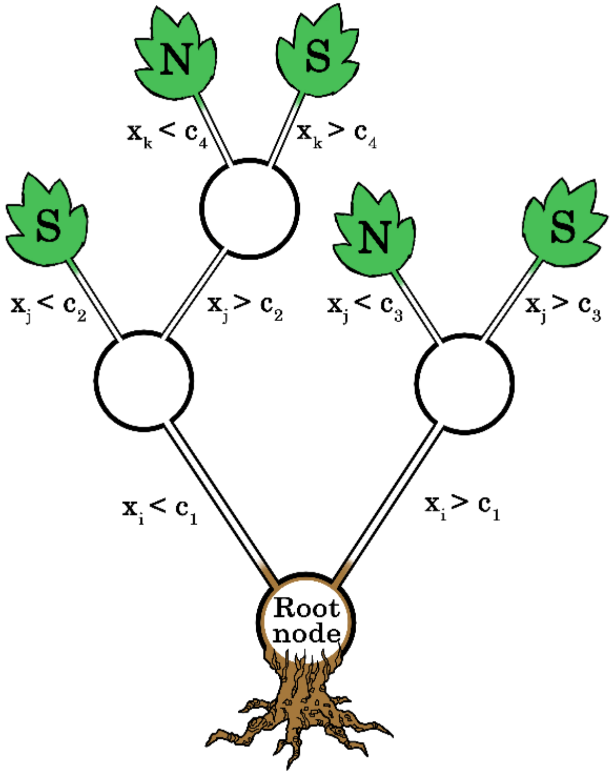
Resources | Visualize

Machine-learning techniques for event selection

Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques, I. Coarasa et al, JCAP11(2022)048
JCAP06(2023)E01

Boosted Decision Tree (BDT)

- Multivariate analysis
- Combination of several weak discriminating variables into a single powerful discriminator
- Two classes: signal-like and noise-like events
- BDT response: from -1 (noise-like) to +1 (signal-like)



$$BDT(\vec{x}_i) = \frac{1}{n_{Trees}} \sum_{j=1}^{n_{Trees}} \ln(\alpha_j) \cdot T_j(\vec{x}_i)$$

AdaBoost

n_{Trees}: number of trees

$\alpha_j = \frac{1-f_j}{f_j}$: boost weight

f_j: fraction of misclassified events of the previous tree

$T_j(\vec{x}_i)$: result of an individual classifier (-1 or +1)

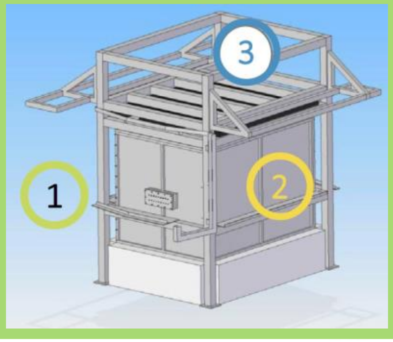
Training populations

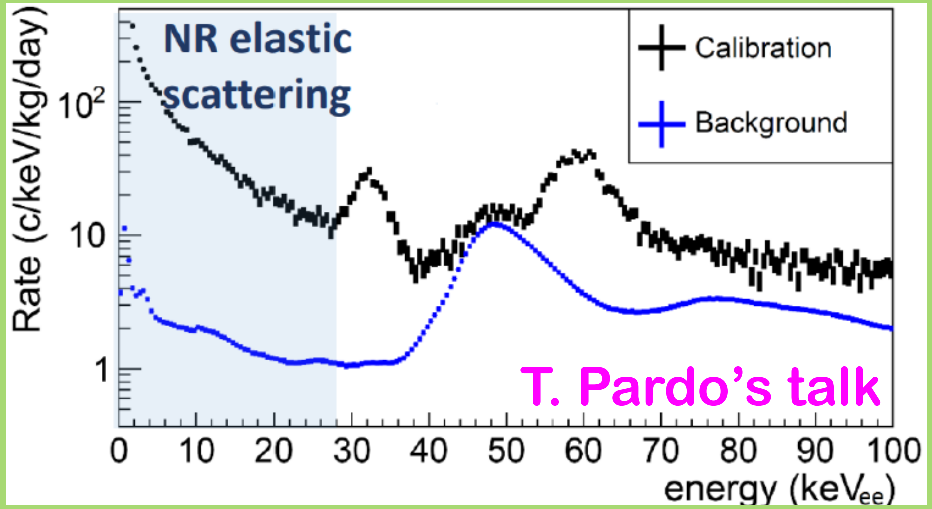
JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations

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

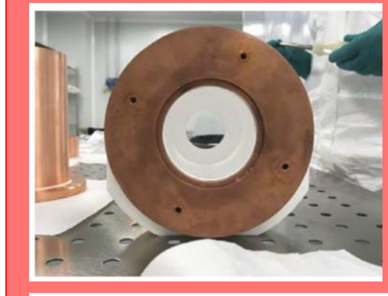
^{252}Cf

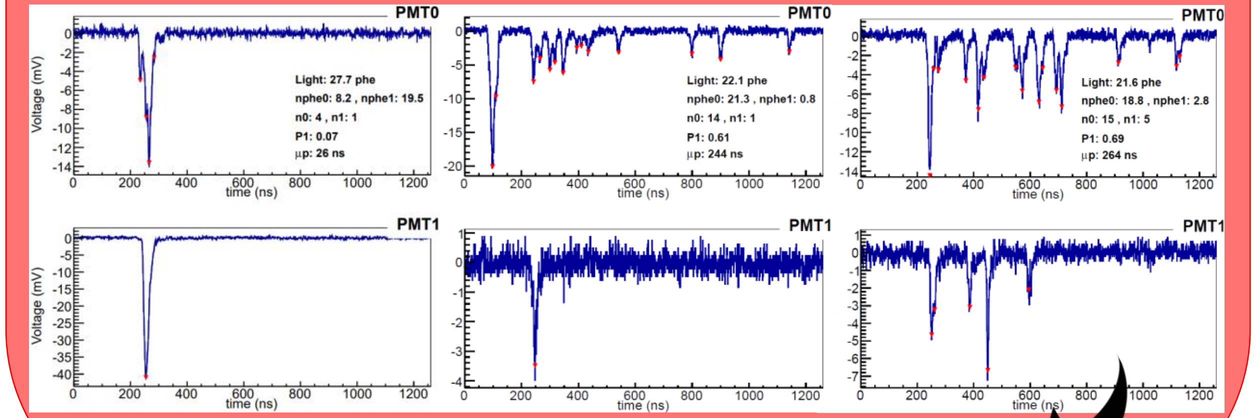




NOISE EVENTS: "Blank" module (No NaI(Tl))

Since 2018 a Blank module (similar to ANAIS−112 modules, but without NaI(Tl) crystal) is taking data with the same DAQ, but in an independent shielding close to ANAIS−112





Not rejected by ANAIS−112 standard cuts

Training parameters

JCAP11(2022)048

15 discrimination parameters combined in a boosted decision tree

instead of the **4** parameters used in the standard analysis

BDT

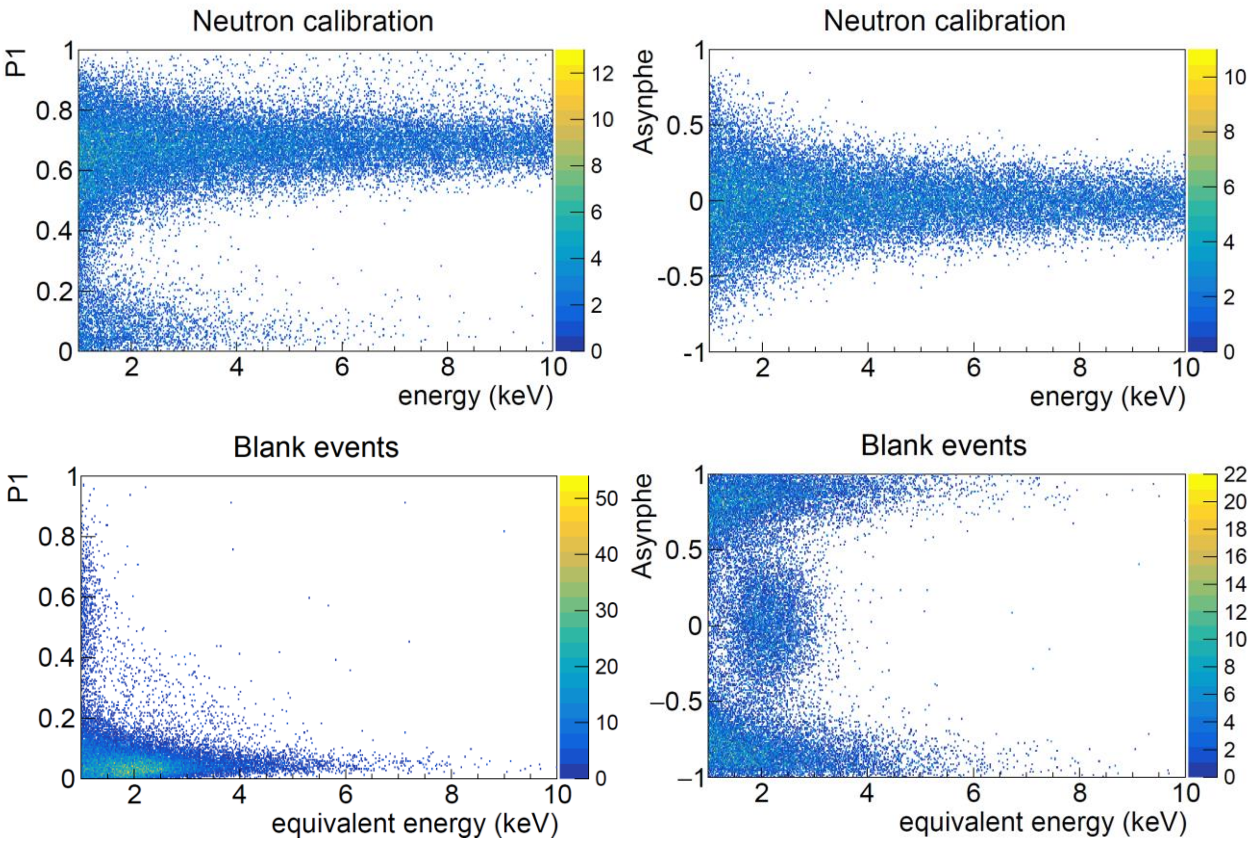
Standard analysis

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

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

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

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

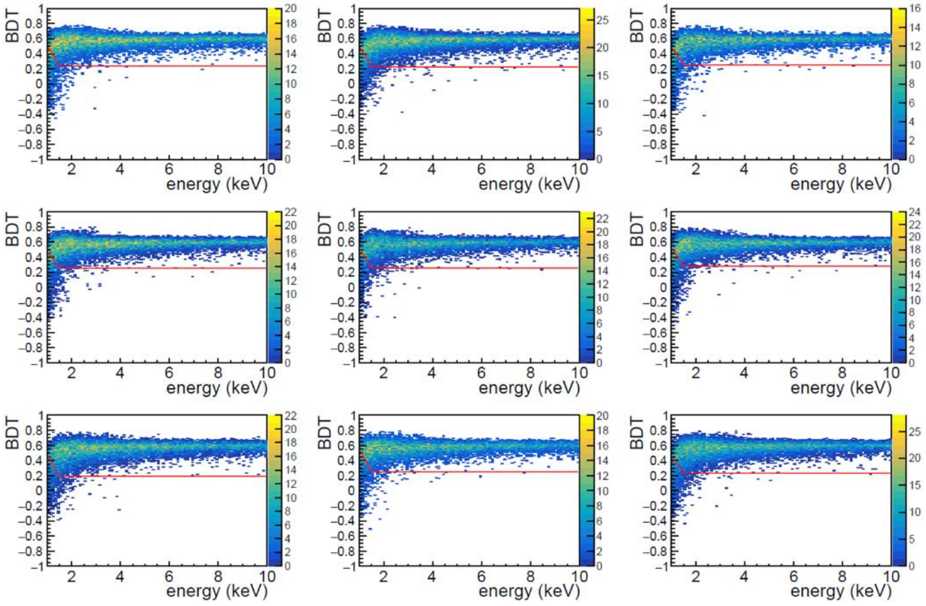


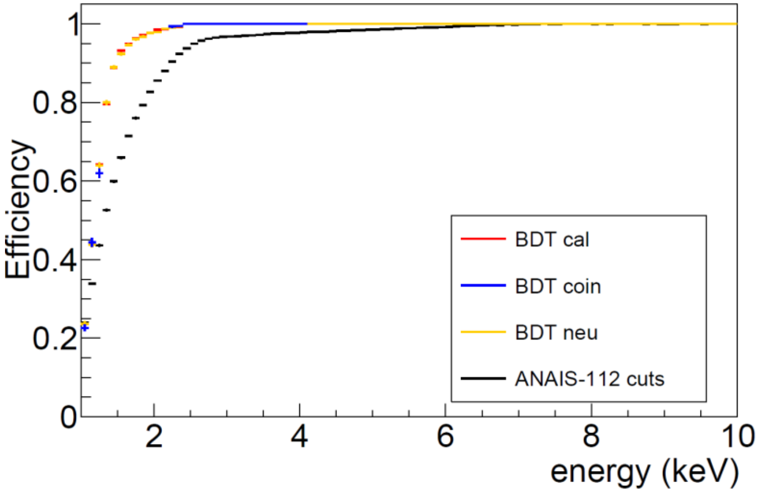
Equivalent energy from $LC = 14.5\ \mathrm{phe/keV}$

Event selection with BDT

Following JCAP11(2022)048

Neutron calibration

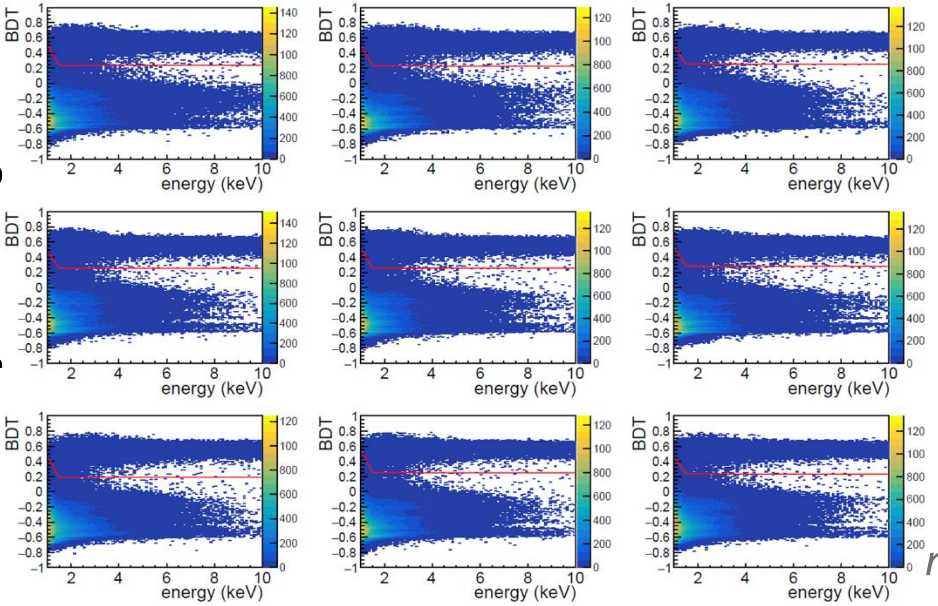


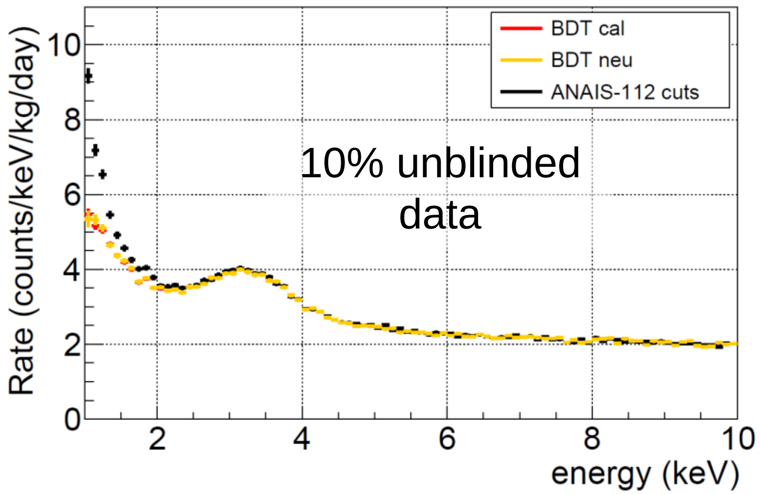


~30% improvement in efficiency

CUT on BDT parameter applied to background

10% 3 years bkg events





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

Event selection with BDT

Following JCAP11(2022)048

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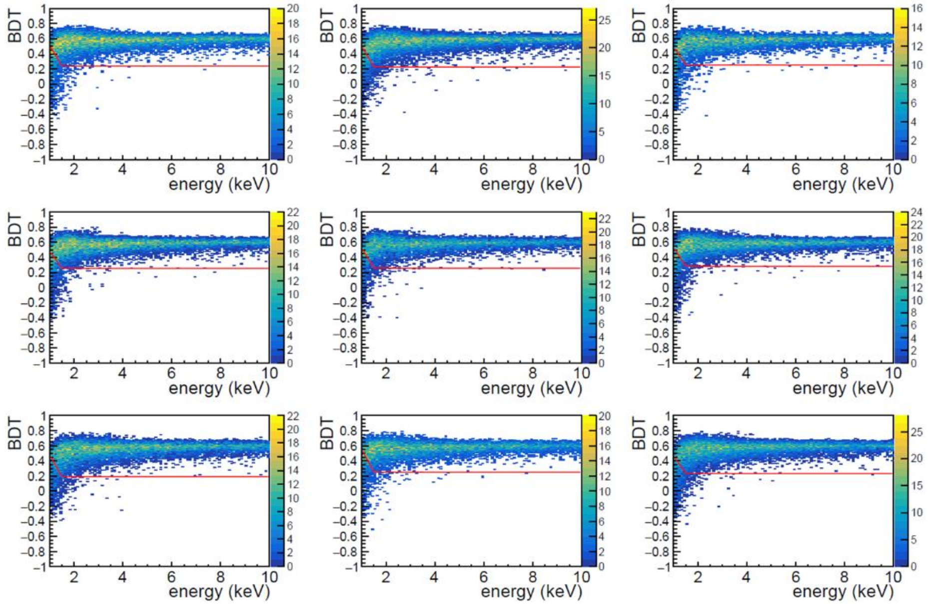
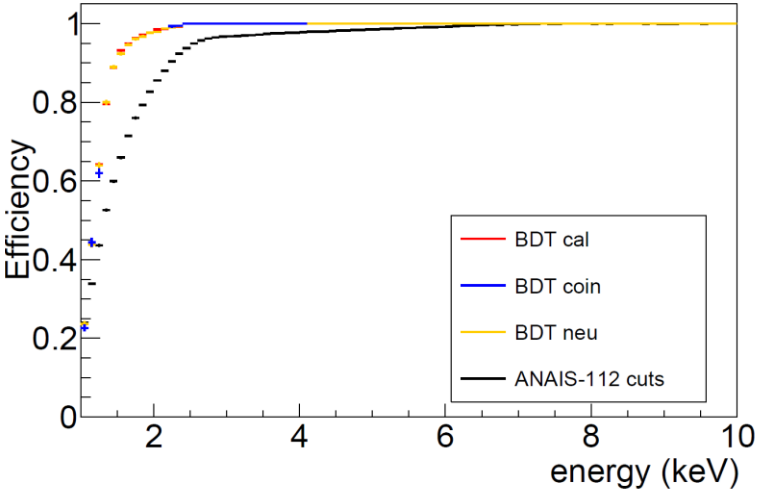
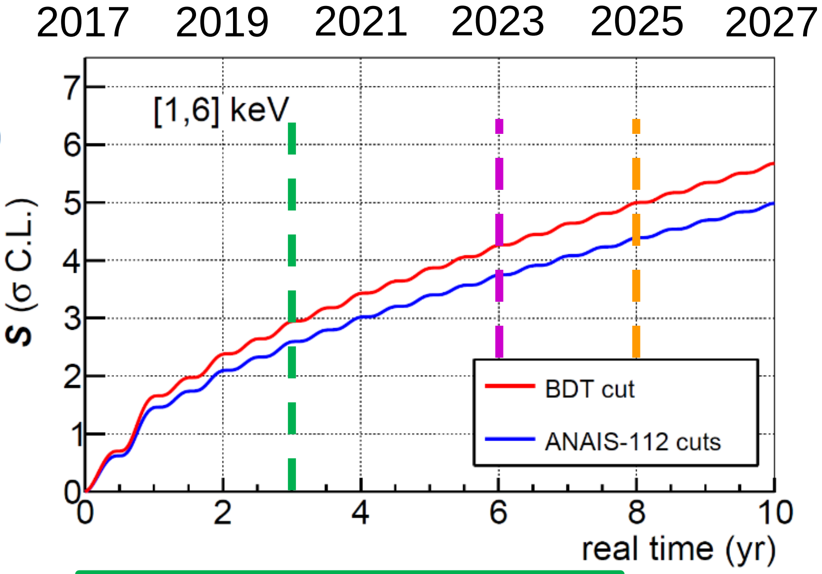




$$S = \frac{S_m^{DAMA}}{\sigma(\hat{S}_m)} \propto \sqrt{\frac{M\ T\ \varepsilon}{B}}$$



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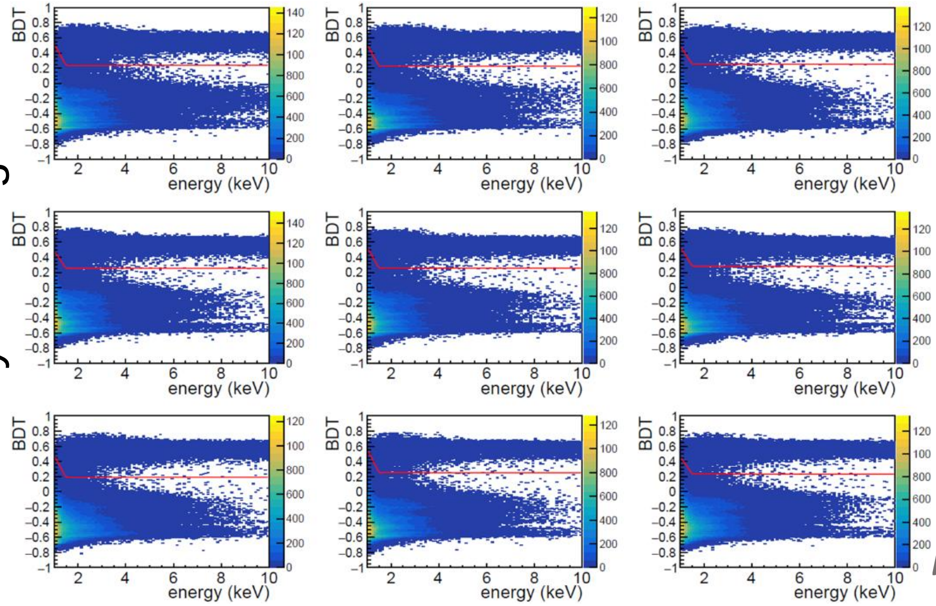

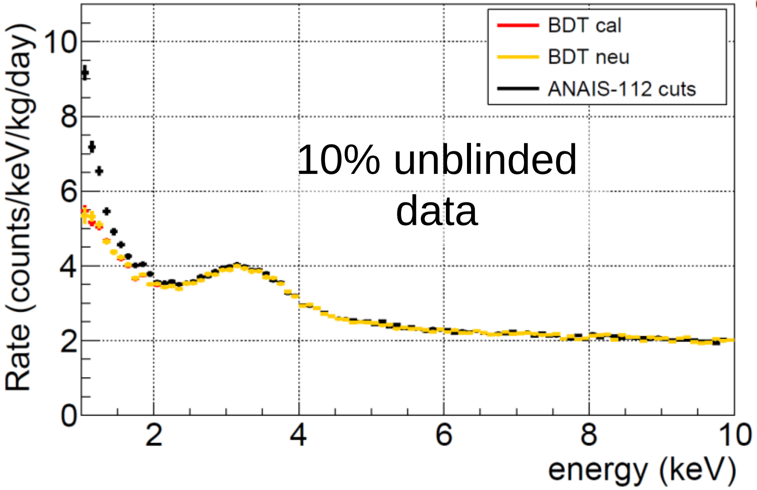

3σ sensitivity with 3 y

$>4\sigma$ sensitivity with 6 y (NOW)

5σ sensitivity in late 2025

Annual modulation with new analysis

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 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i - \mu_i)^2/\sigma_i^2$, where the expected number of events μ_i for detector d in time bin i is given by:

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

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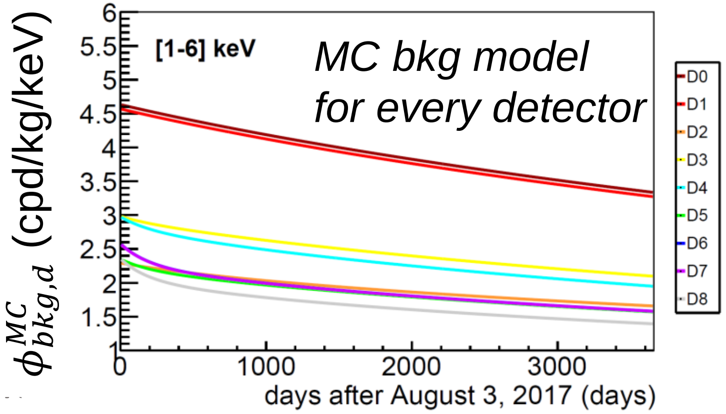
Constant background (long-lived isotopes and residual noise)

Decaying background, modeled by MC

Modulation signal (fixed period and phase)



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

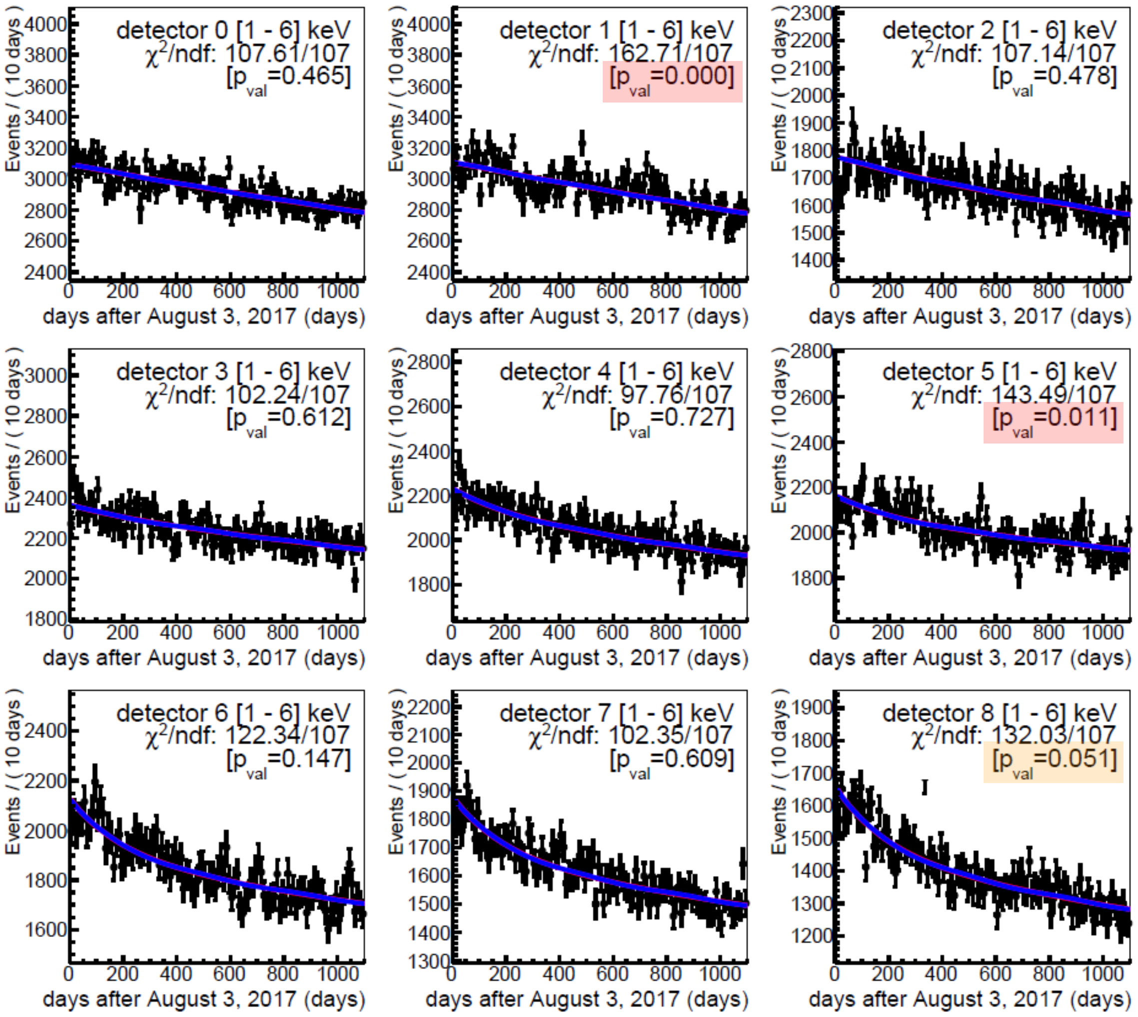
Improved 3-year results [1-6] keV

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)



PRELIMINARY

Null hyp χ^2/ndf: 993.78/972 [p_{val}=0.307]

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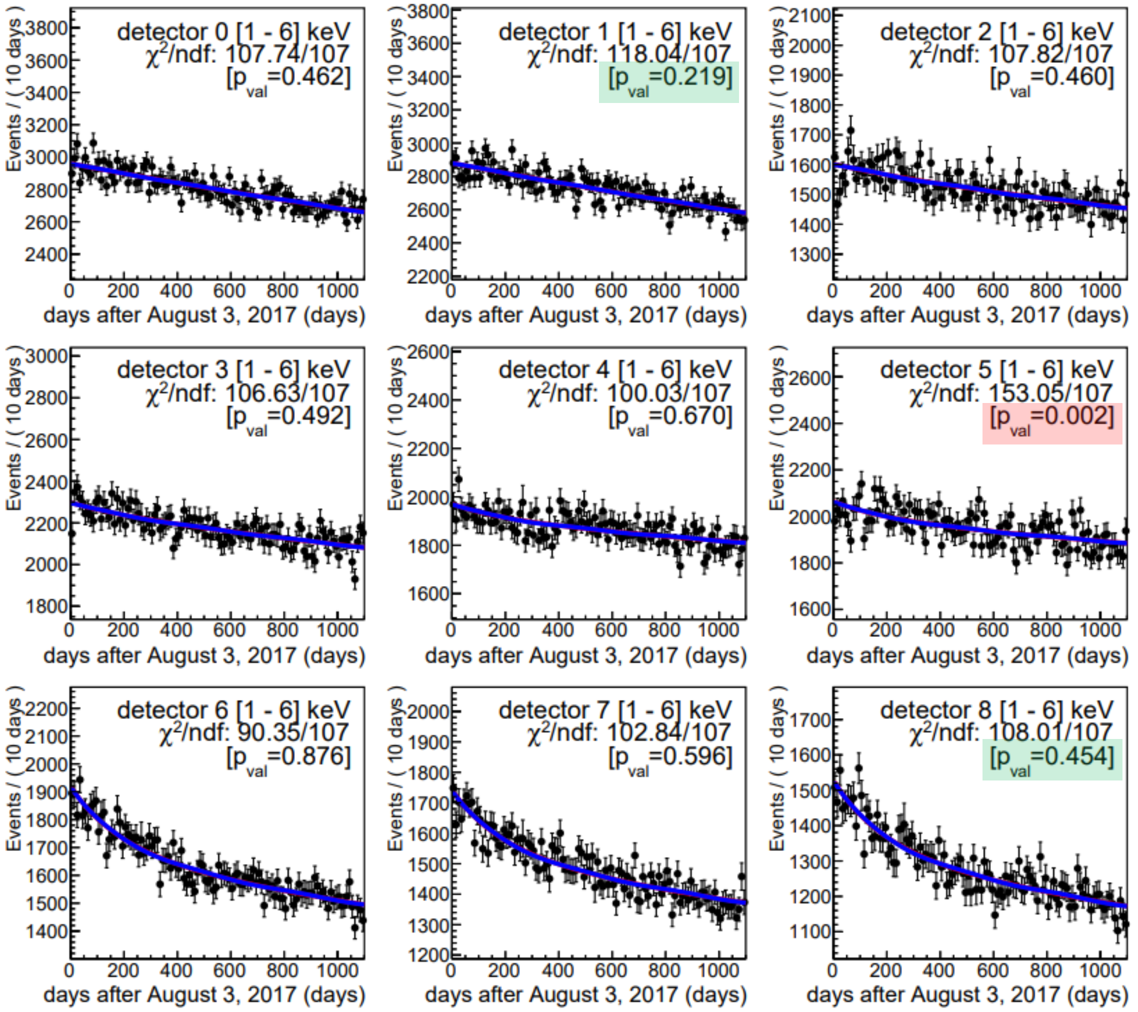

Improved 3-year results [1-6] keV

$2.5\sigma \rightarrow 2.9\sigma$

PRD103(2021)102005

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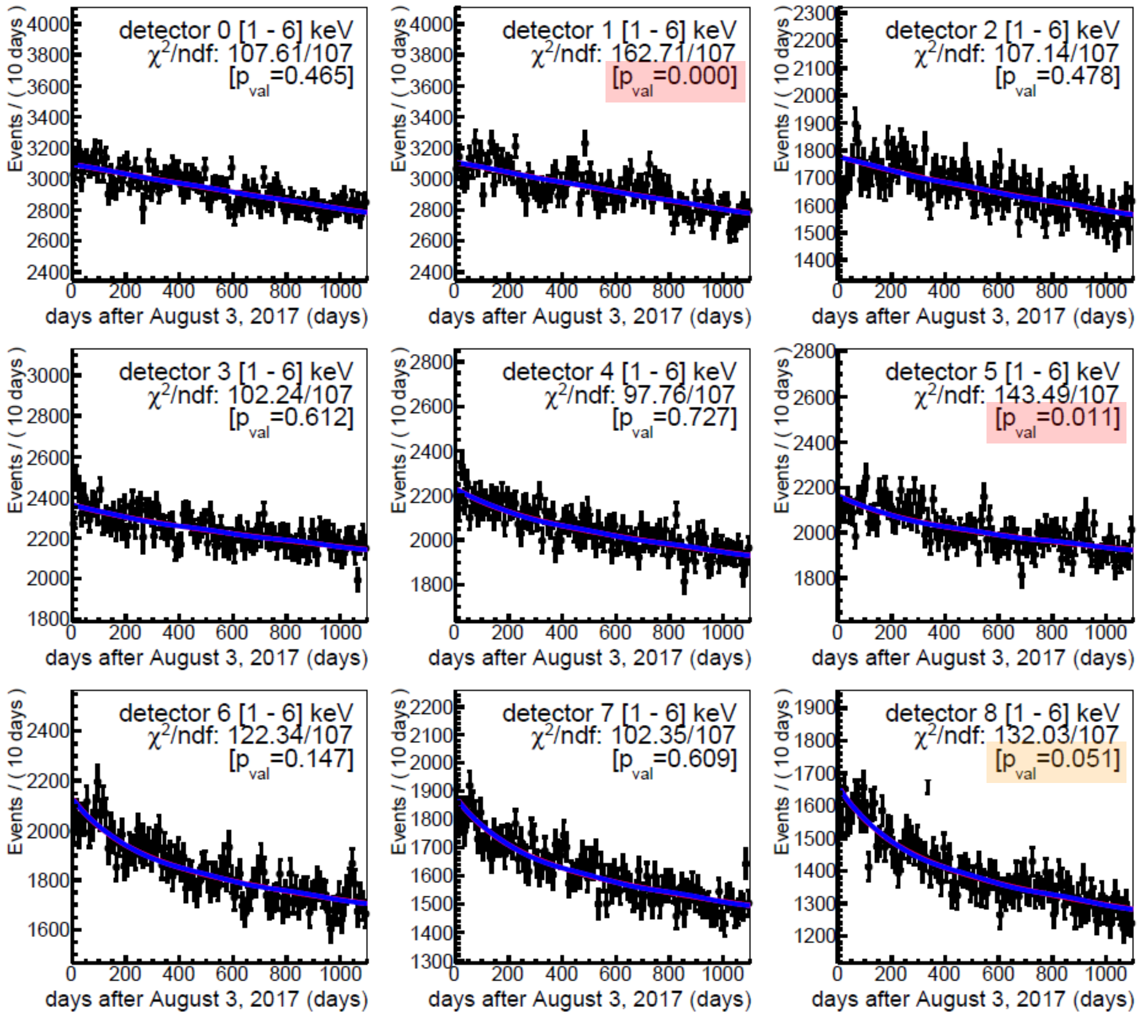

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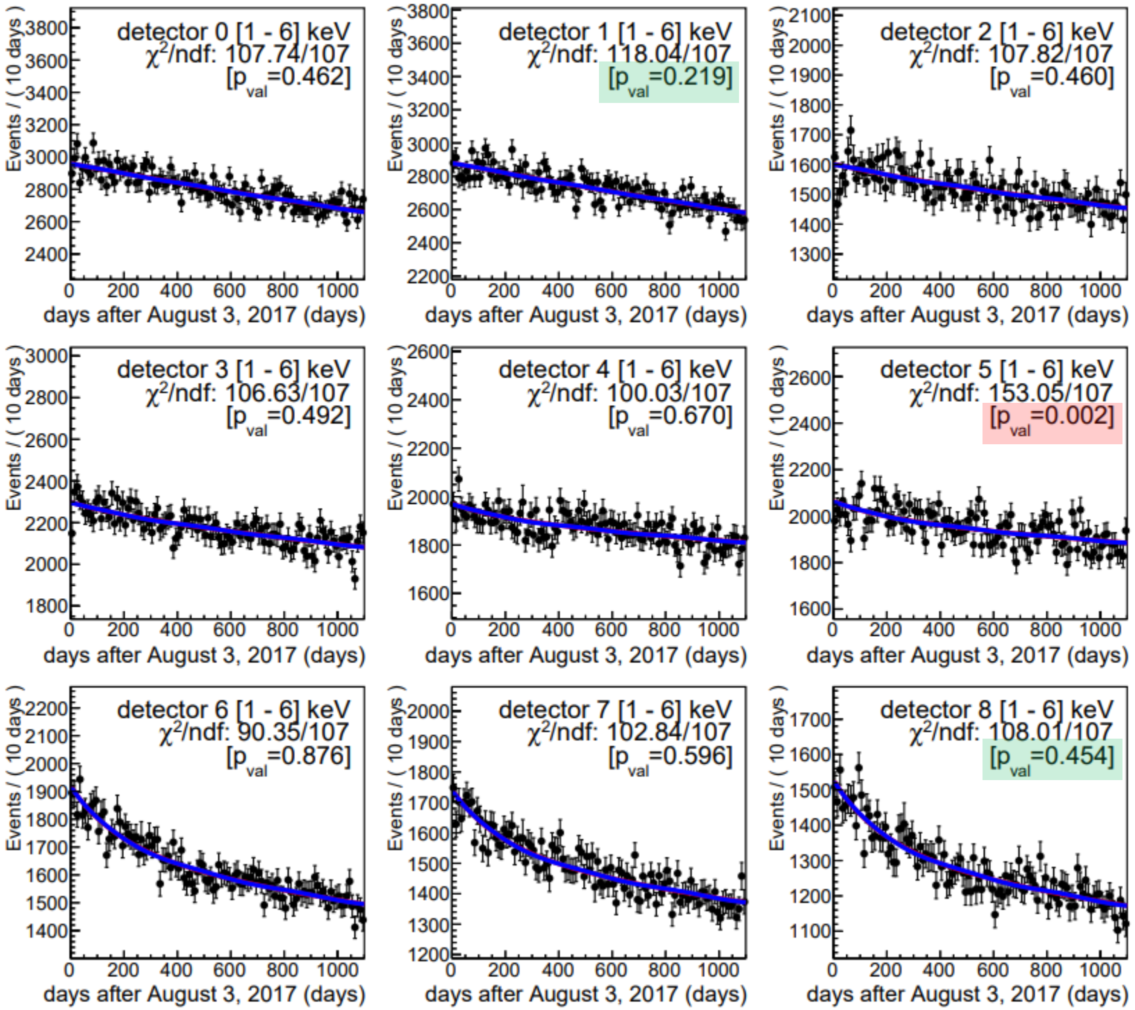
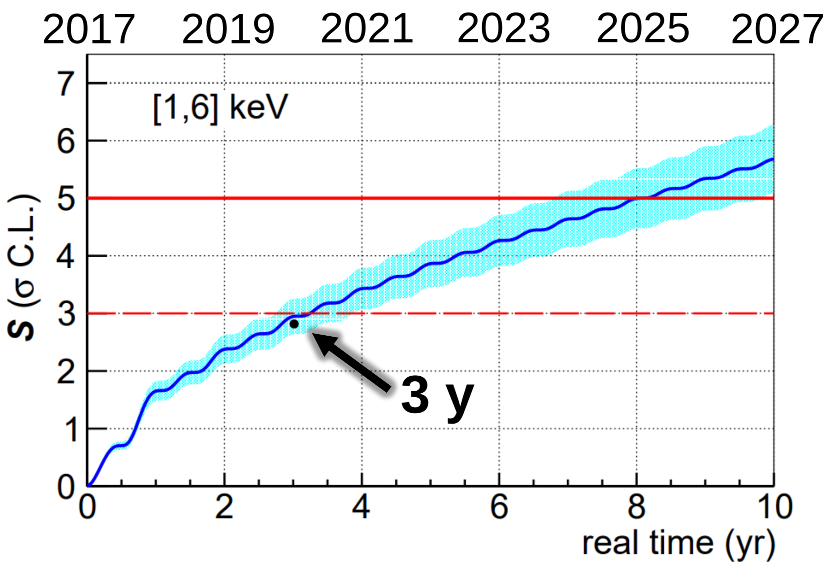
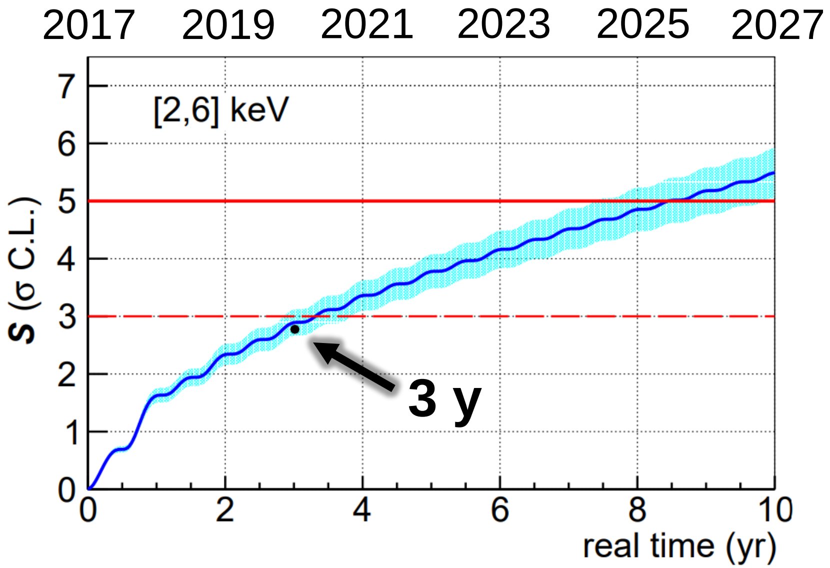
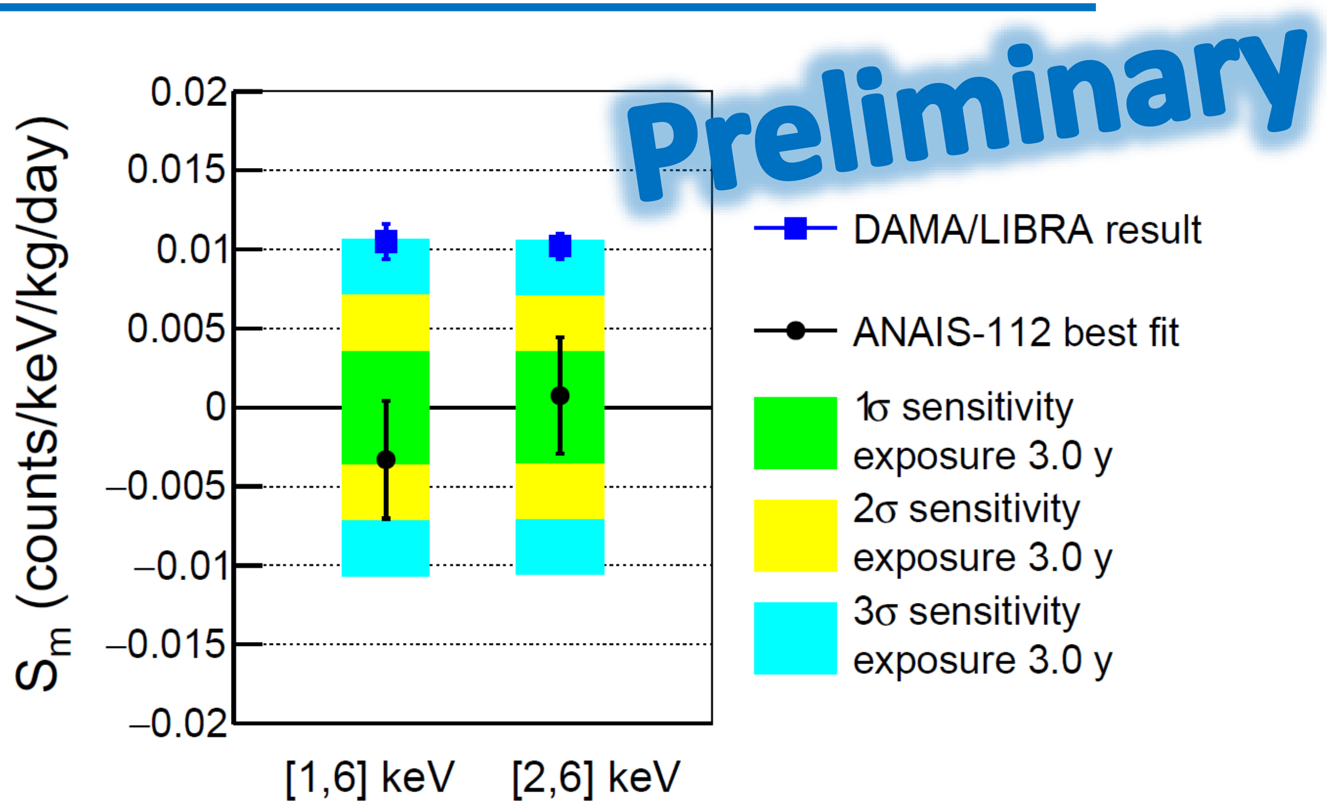


3-year annual modulation with BDT cut







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

Best fit **incompatible with DAMA/LIBRA** at 3.9 (2.8) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.9σ for [1-6] and [2-6] keV

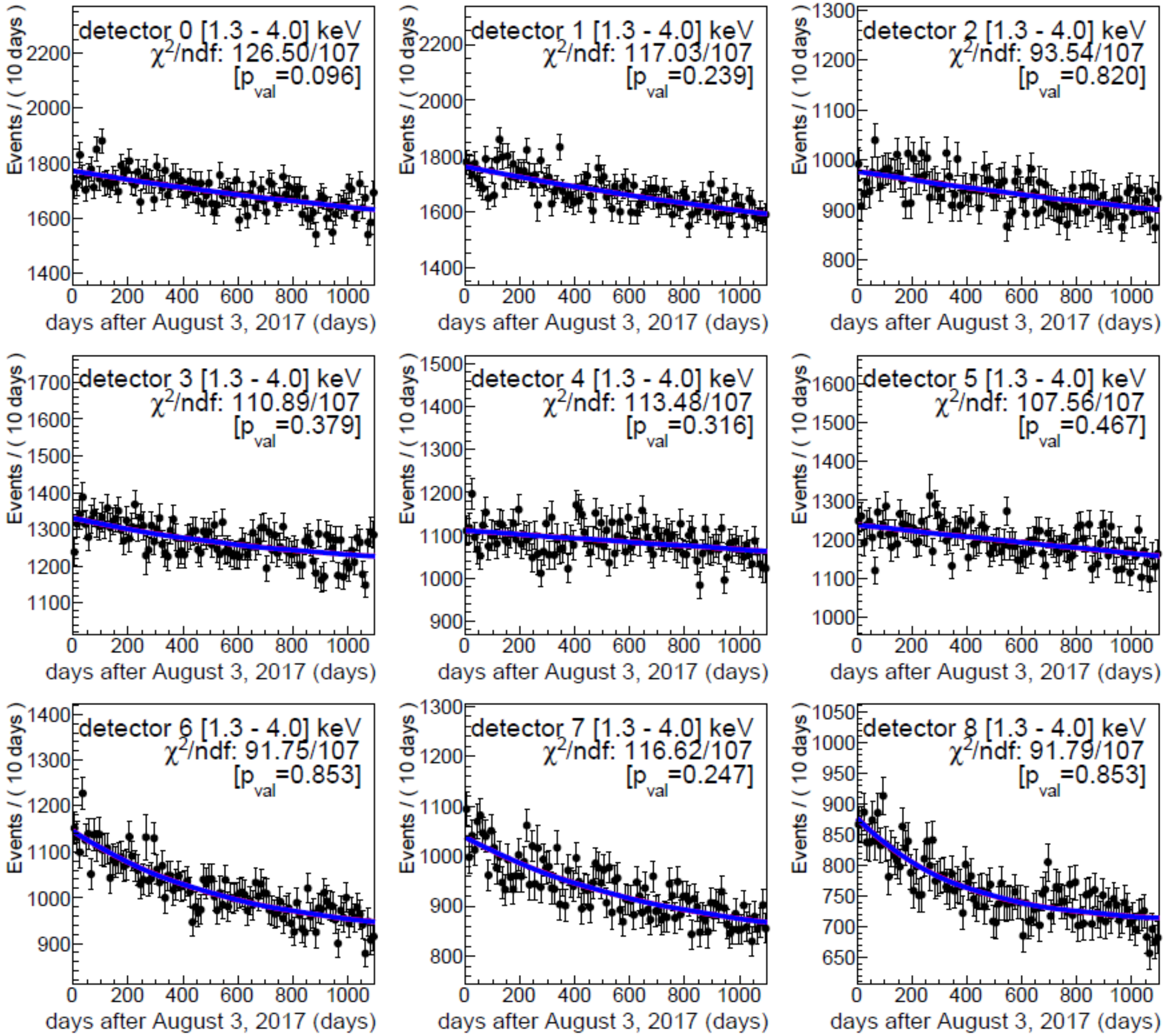
5σ sensitivity at reach in late 2025

3-year annual modulation analysis in 1.3 – 4 keV

Null hyp χ^2/ndf: 968.31/963 [p_{val}=0.446]

Mod hyp χ^2/ndf: 968.16/962 [p_{val}=0.438]

S_m = (-0.0019 ± 0.0050) (cpd/kg/keV)



Preliminary

Supposing:

➔ $Q_{Na} = 0.30$ in DAMA/LIBRA

➔ $Q_{Na} = 0.20$ in ANAIS−112 **T. Pardo's talk**

DAMA [2 – 6] keV ⟶ ANAIS [1.3 – 4] keV

Best fit modulation amplitude $S_m = (-0.0019 \pm 0.0050)$ counts/keV/kg/day **compatible with zero** at 1σ

Best fit **incompatible with DAMA/LIBRA** at 2.4σ

Sensitivity with 3 years data: 2σ

Summary and outlook

- Currently, many efforts trying to provide an **independent confirmation** of DAMA/LIBRA signal with the same target. ANAIS−112 and COSINE−100 in data-taking.
- ANAIS – 112 is taking data in stable condition at LSC since 3rd August 2017 with excellent performances. Up to now it has accumulated more than **600 kg×y exposure**.
- 3-year annual modulation analysis (PRD 103, 102005 (2021)) **public for downloading** at https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais
- Sensitivity improved with machine-learning techniques. **ANAIS−112 observes no modulation and discards DAMA/LIBRA DM interpretation with** $\sim 3\sigma$ **sensitivity** in [1-6] keV ([2-6] keV).
- **For the first time, a direct test (i.e. model independent) of DAMA is at reach with >**3σ **sensitivity.** 5σ **sensitivity in late 2025.**
- Analysis including possible **quenching factor difference on NaI crystals** ongoing. Results soon.
- Plan to **improve our background model** with the accumulated exposure and **analyze the 5 years** of data while the experiment continues taking data at the LSC until the end of 2025.

Acknowledgements

Thank you for your attention!

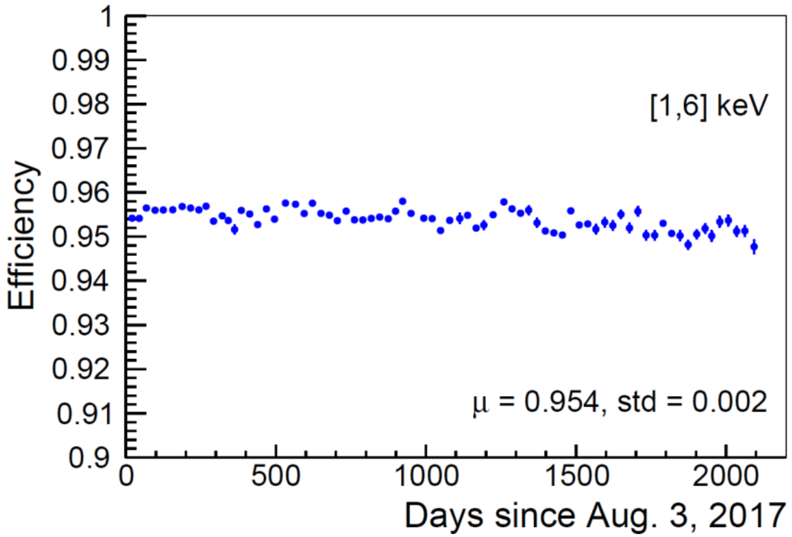
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

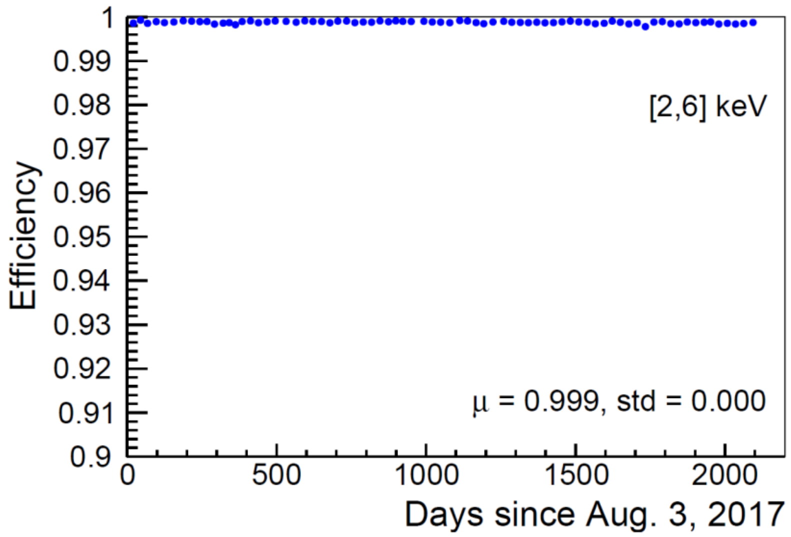
MultiDark
Multimessenger Approach for Dark Matter Detection

Backup

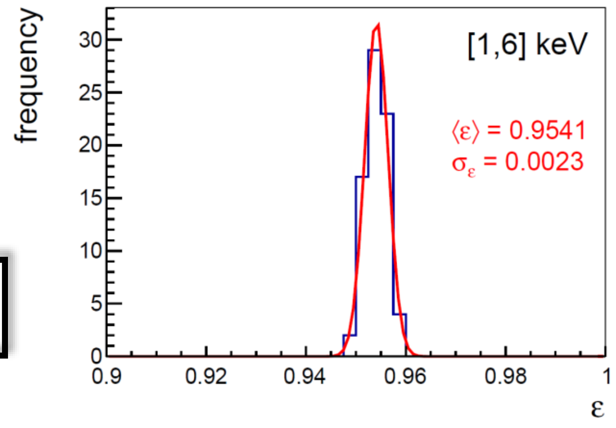
Efficiency stability and associated systematic uncertainty

➔ We are working on determining the possible variation in time of the BDT's efficiencies using ^{109}Cd data for the first three years with all detectors averaged

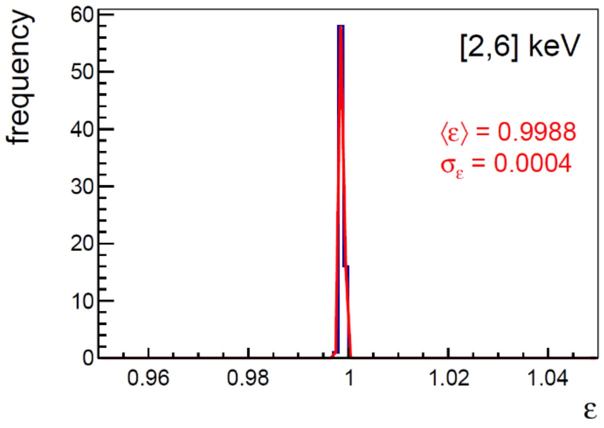




Systematic uncertainty is taken as half the difference between maximum and minimum values



0.28%



0.05%

DAMA/LIBRA-phase2 reports **0.30%** in **[1-8] keV**