ANAIS-112: updated results on annual modulation with three-year exposure and future prospects

M. Martinez (Univertisty of Zaragoza)

PPC23, Daejeon (Korea) 12-16 June 2023

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, M.A. Oliván, Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, M.L. Sarsa

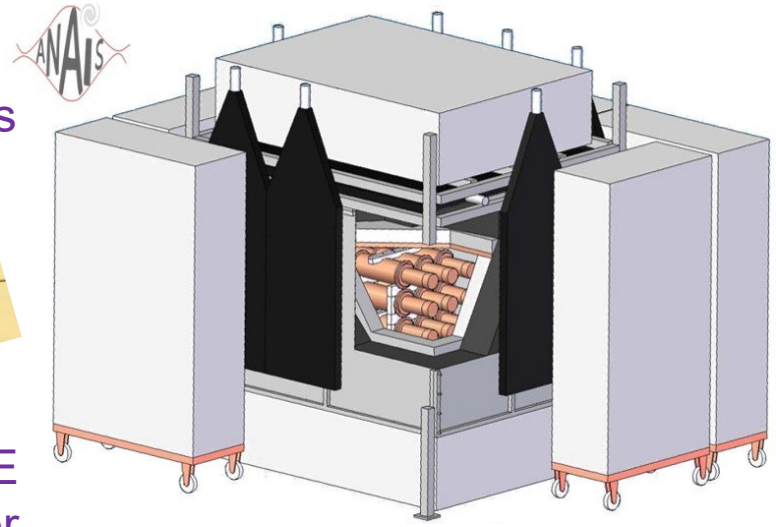
GOAL: **Confirmation/refutation of DAMA-LIBRA modulation signal with the same target and technique** (but different experimental approach and environmental conditions)

Projected sensitivity: 3σ in 5 years data-taking

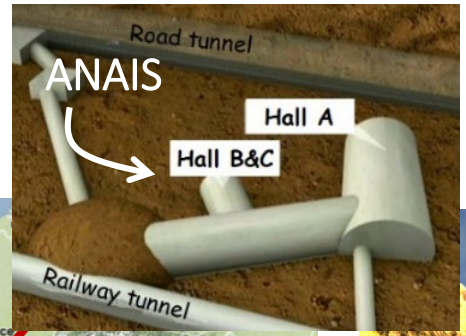
THE DETECTOR:

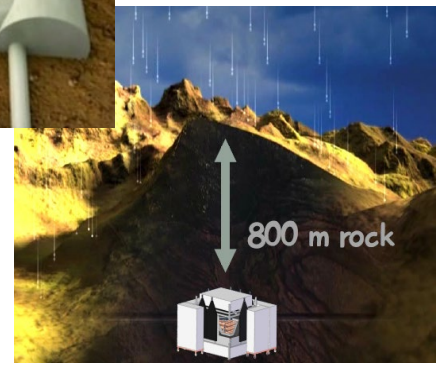
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass

Two high QE PMTs per detector



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

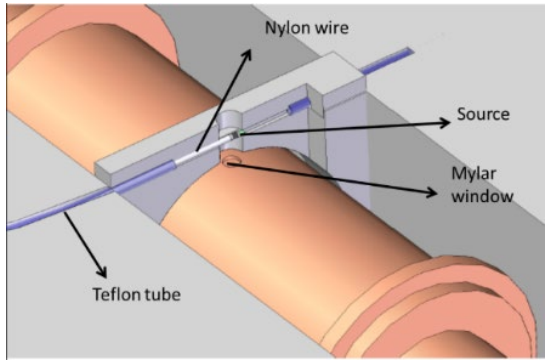


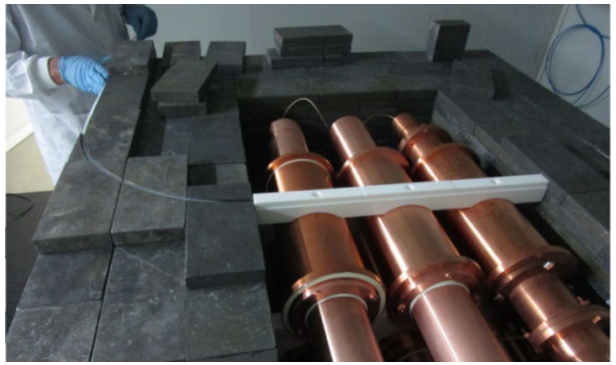


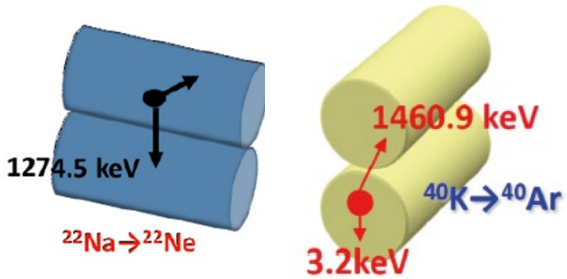
taking data since August 2017

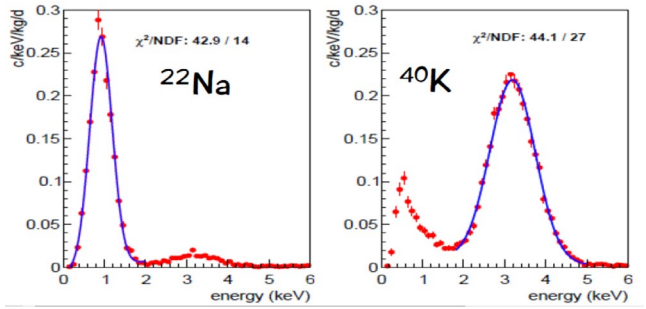
Light yield & low energy calibration

- 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 [1-6 keV] with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) (whole statistics)



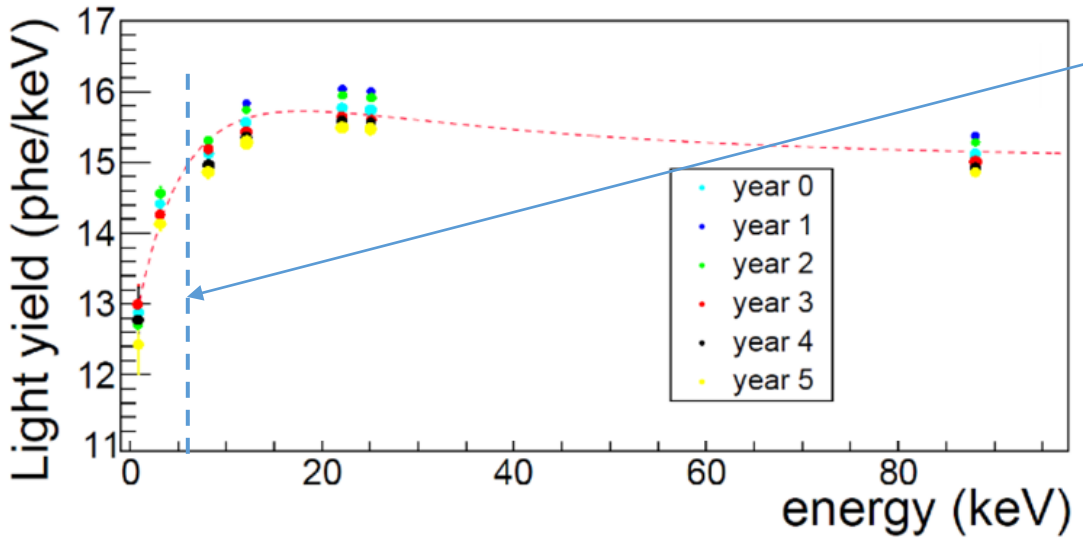


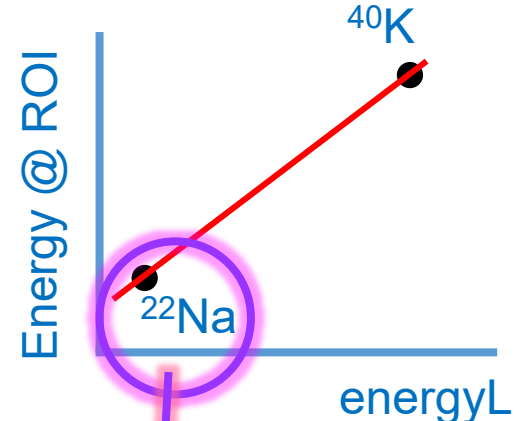


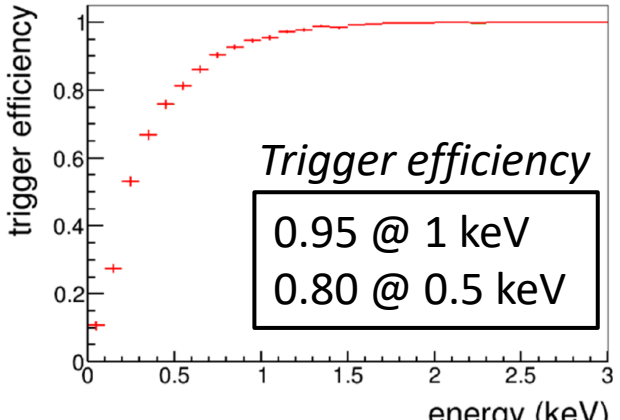


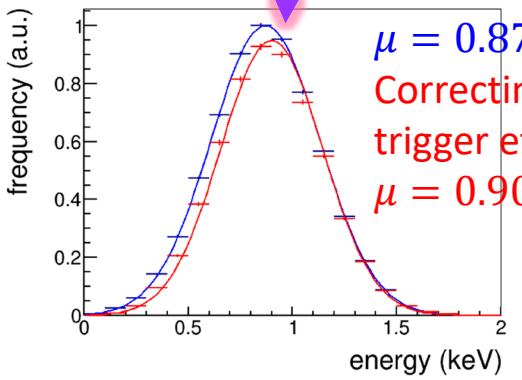
Non proportionality < 25 keV (20%)

Linear calibration in 2 ranges:
- 1-10 keV [ROI]
- 10-100 keV









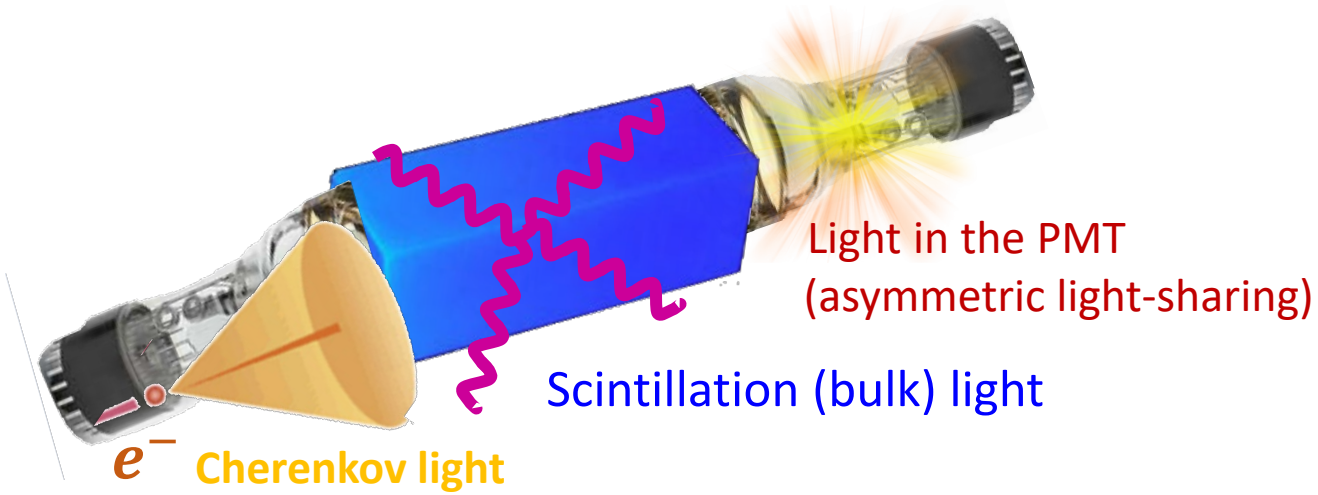
$\mu = 0.87\ keV$

Correcting with trigger efficiency:

$\mu = 0.90\ keV$

EPJC (2019) 79:228

Event selection, background and efficiency

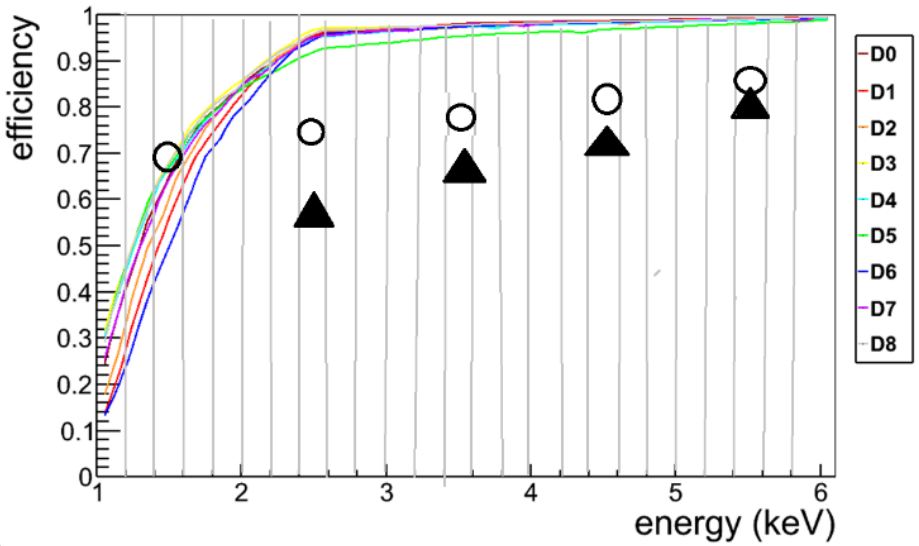


Pulse shape cut to select pulses with NaI(Tl) scintillation constant (biparametric)

$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$

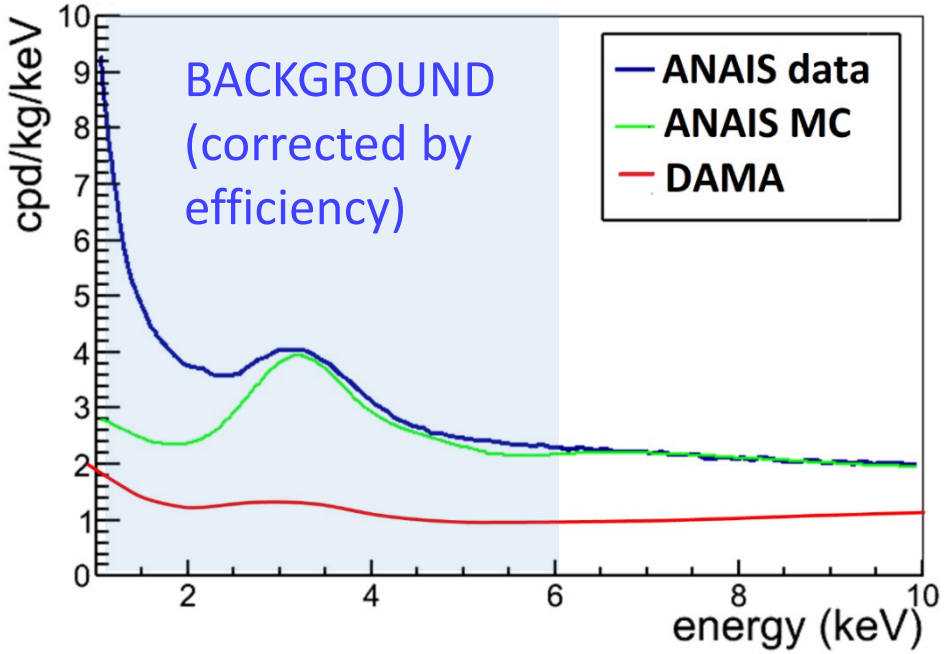
We remove asymmetric low-energy events (<2 keVee) with origin in the PMT (n1> 4, n2>4)

EVENT SELECTION EFFICIENCY

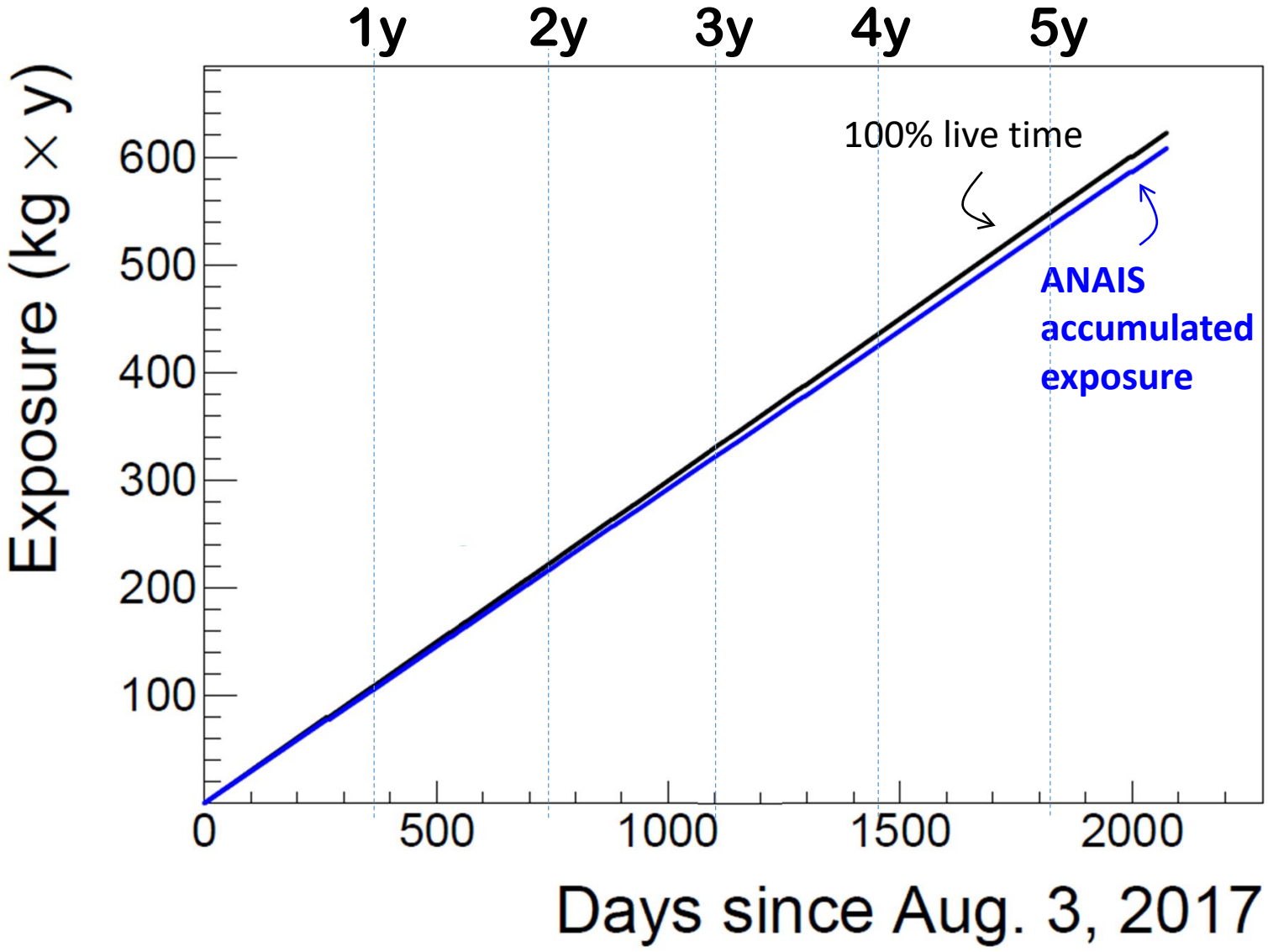


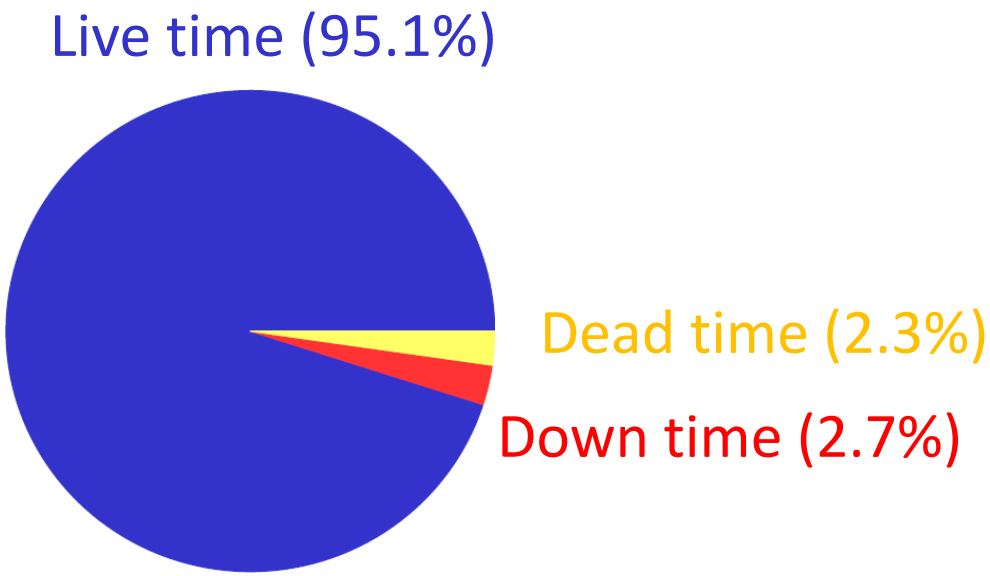
Continuos lines: ANAIS eff, from ^{109}Cd and ^{22}Na/^{40}K

○ DAMA ph2
▲ DAMA ph1



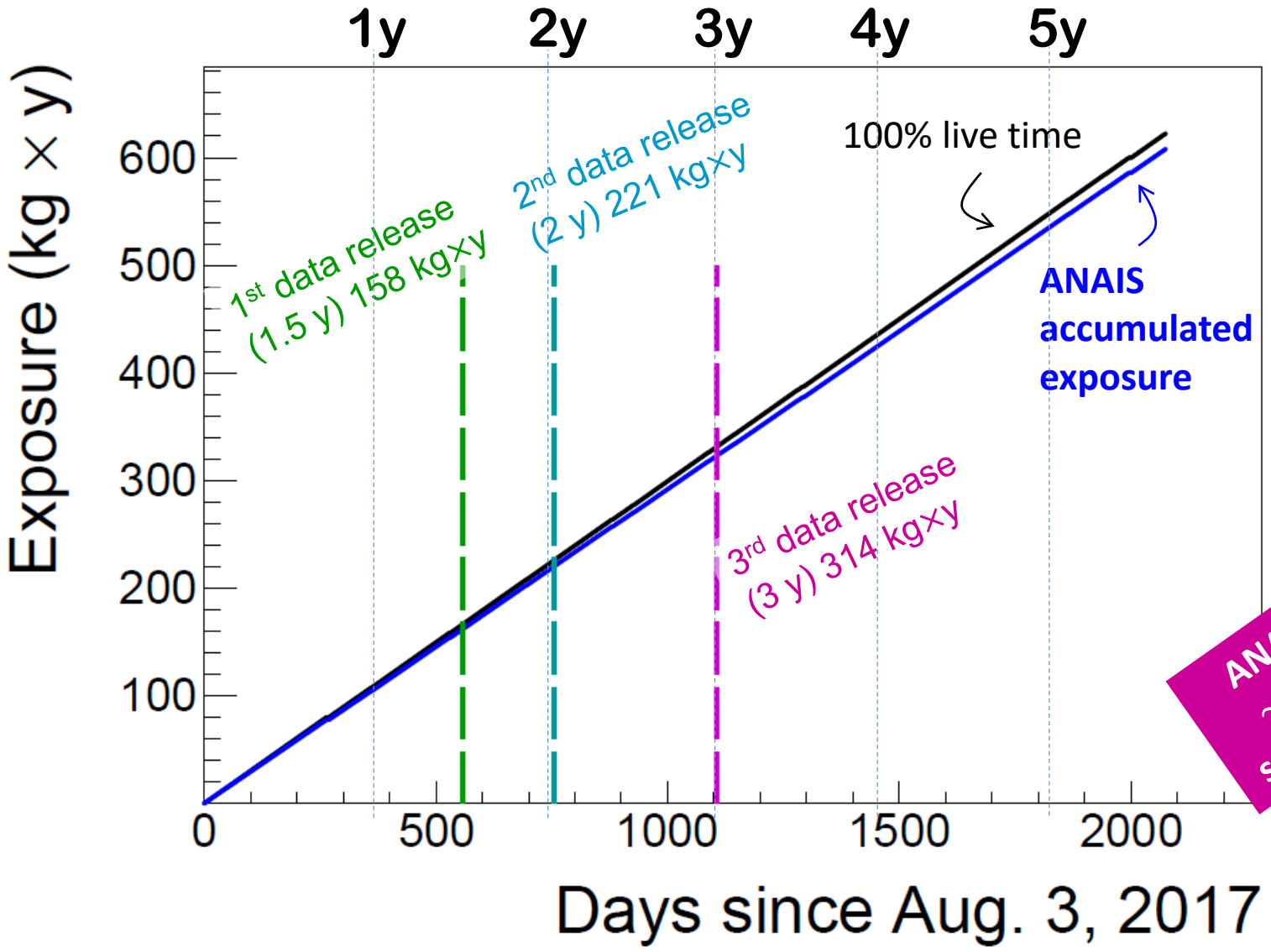
Data-taking overview





Up to date, more than 600 kg x y exposure

Modulation results



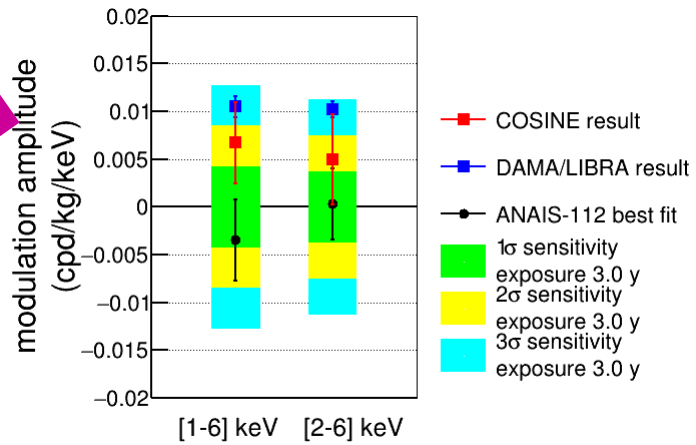
ANAIS-112 modulation results:

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

LATEST RESULTS (ANAIS, COSINE, 3y):

	S_m (counts/keV/kg/day)		
E/keV	**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

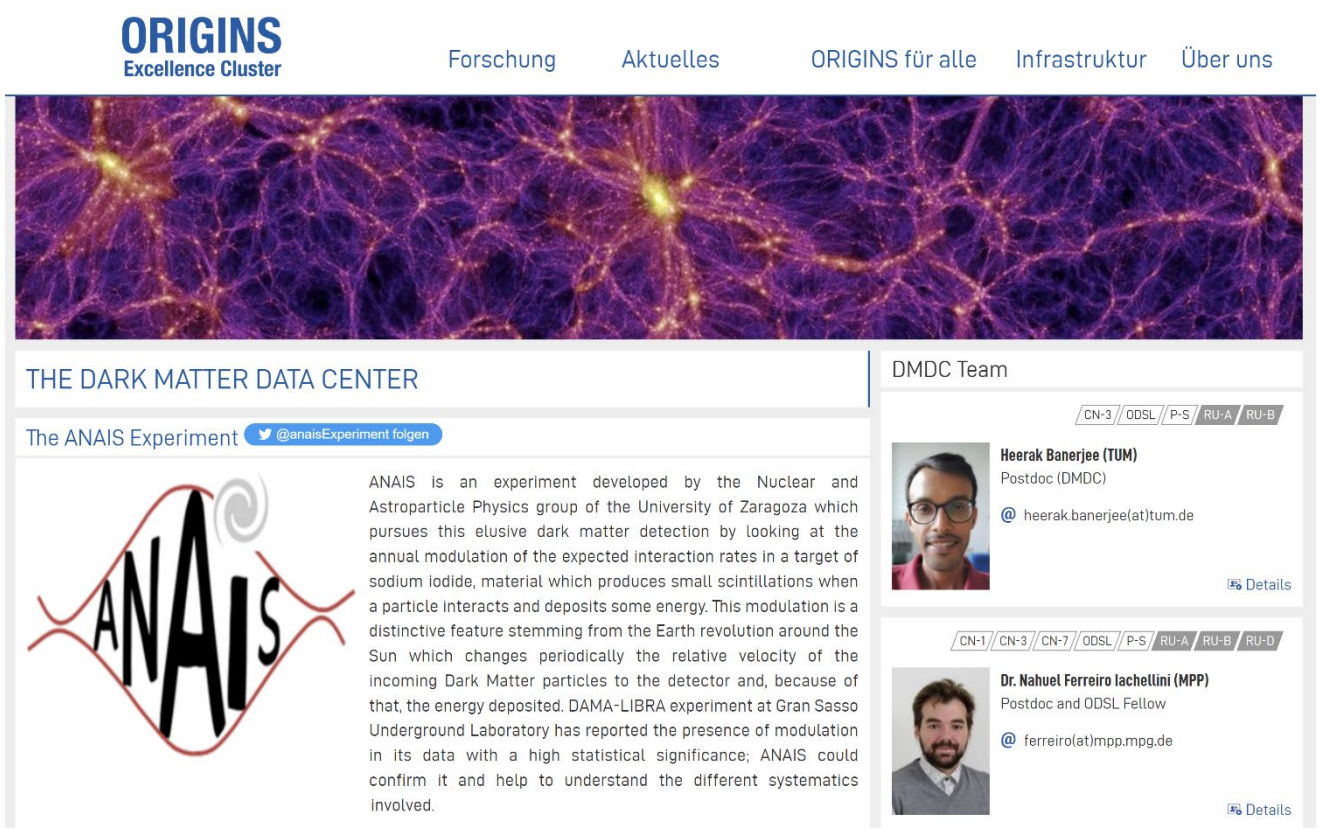
ANAIS: ~2.5σ sensitivity



ANAIS-112 3-years data public

Thanks to the support of the Dark Matter Data Center, funded by the ORIGINS excellence cluster, ANAIS-112 3-years data is freely available for downloading

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



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

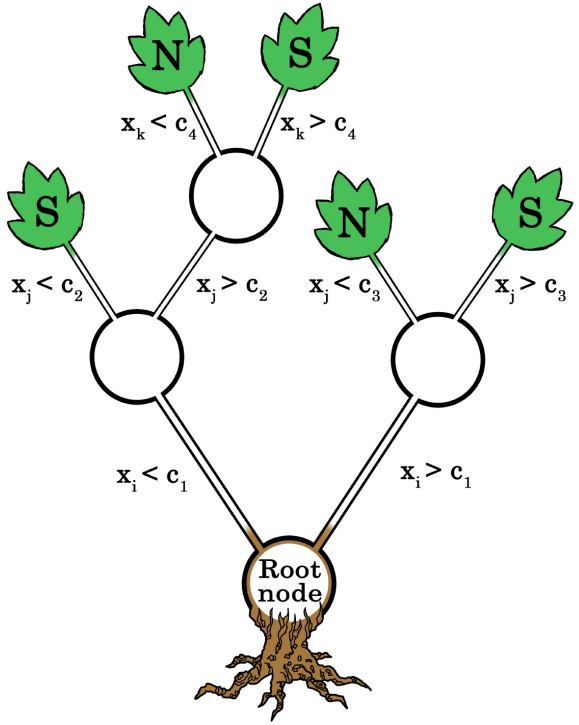
Download full repository as tar.gz: GitLab

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

Improving ANAIS-112 sensitivity

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

Improve the "bulk scintillation" event selection with machine learning techniques



15 discrimination parameters combined in a boosted decision tree (instead of the 4 parameters used in the standard analysis)

Std analysis

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

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

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

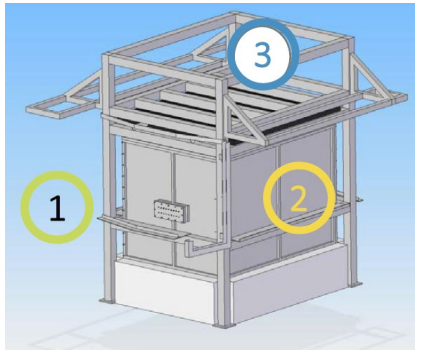
$$x = 50,\ 100,\ 200,\ 300,\ 400,\ 500,\ 600,\ 700 \text{ and } 800 \text{ ns}$$

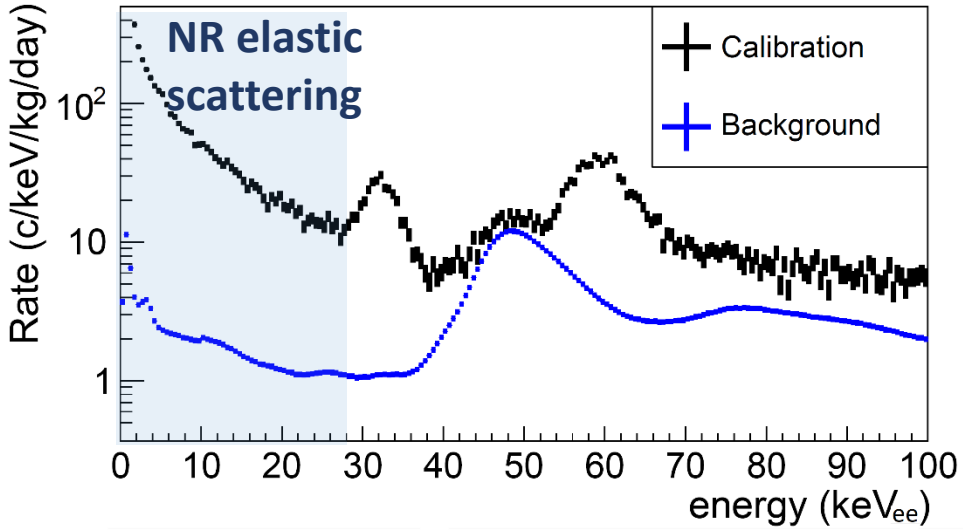
Training populations

JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations

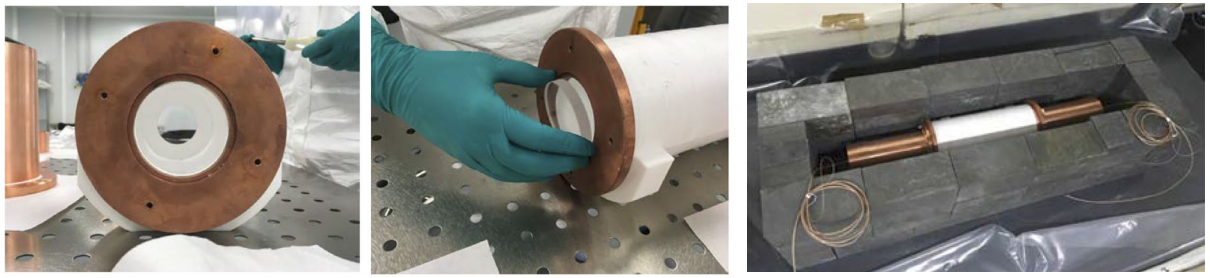
Six calibration runs since April 2021 using ^{252}Cf neutron source at different positions in the ANAIS-112 set-up

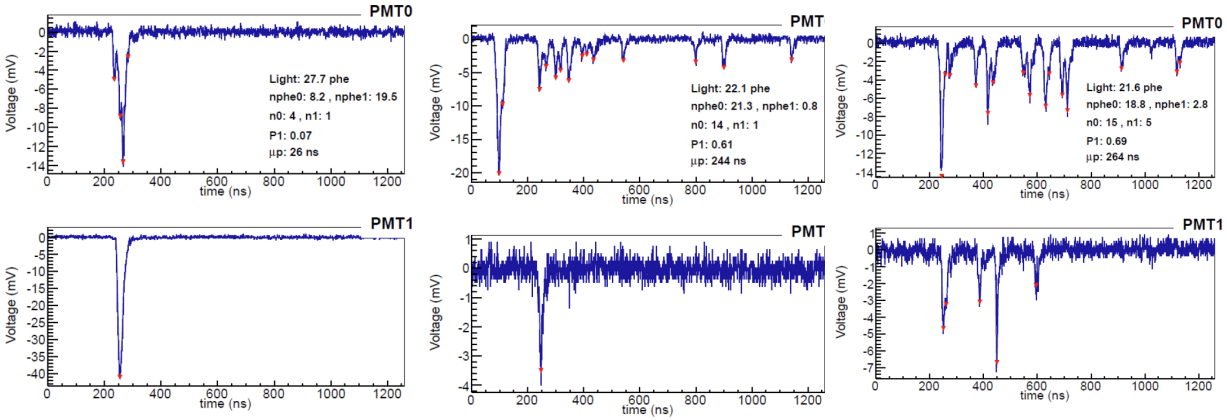




NOISE EVENTS: "Blank" module (No NaI(Tl))

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

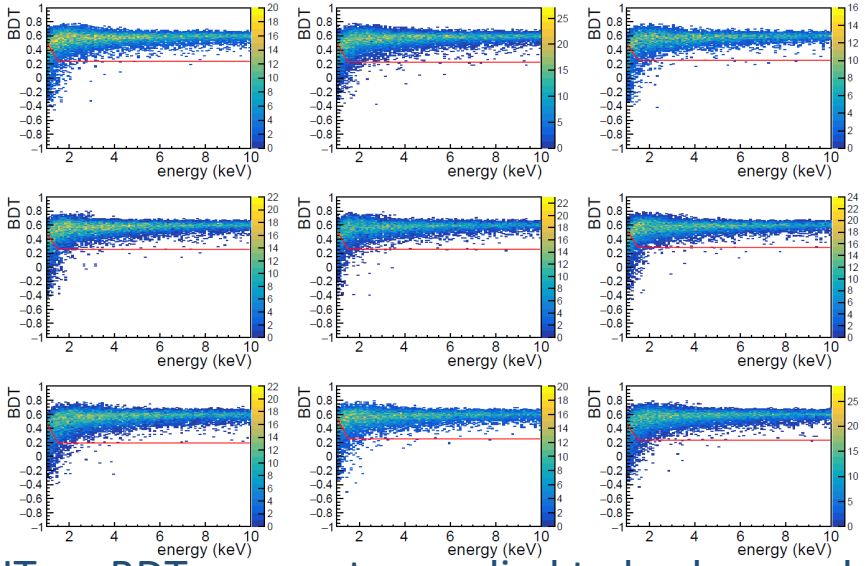


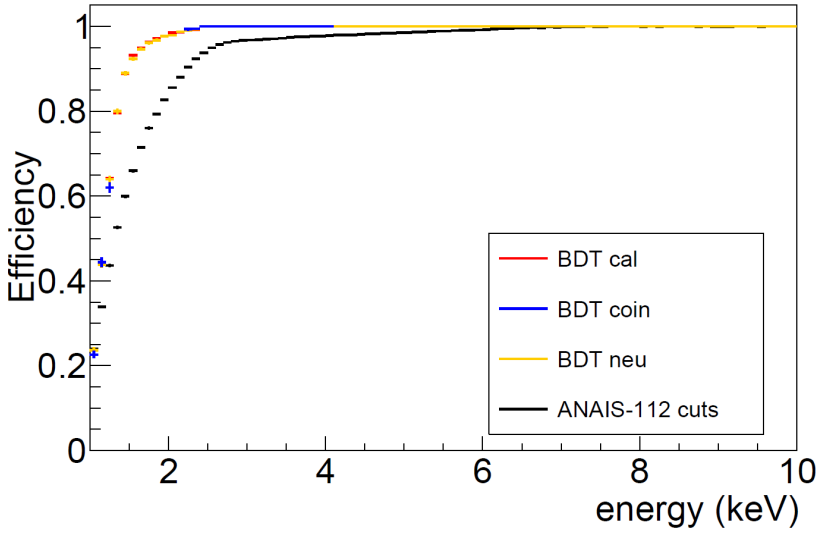


Event selection with BDT

JCAP11(2022)048

Neutron calibration

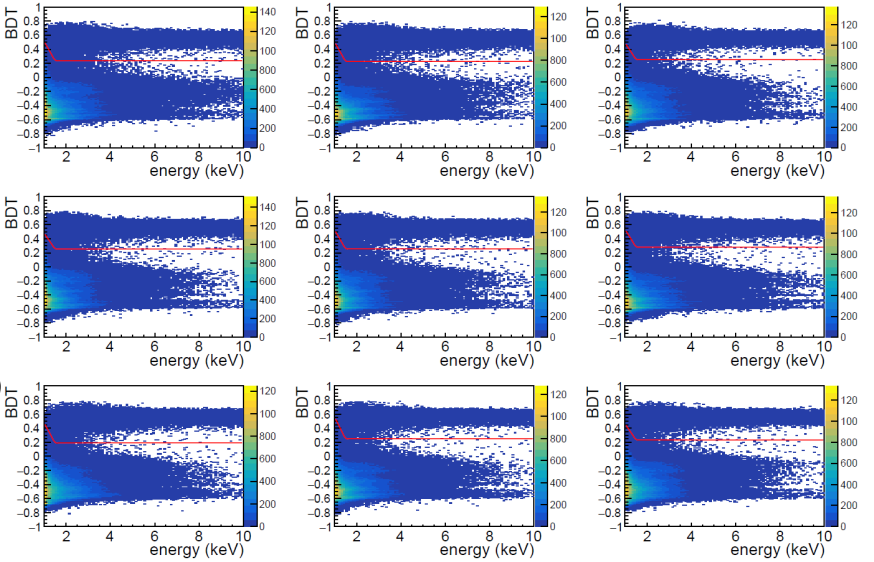


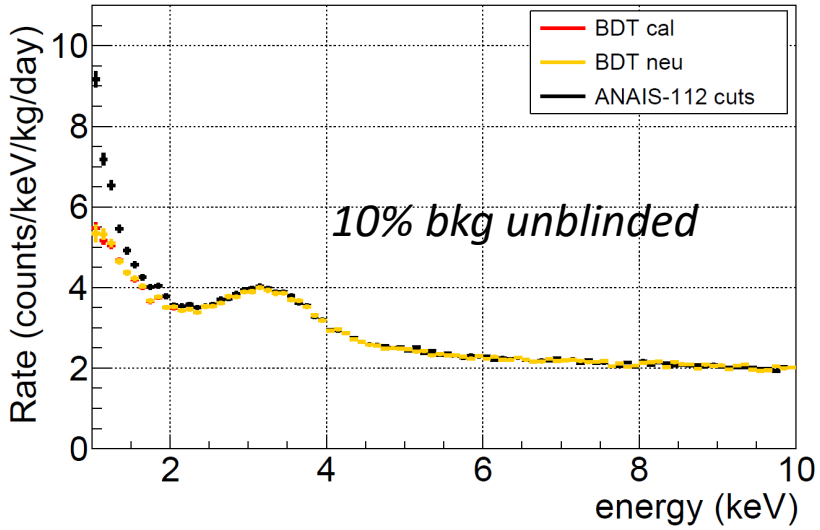


~30% improvement in efficiency

CUT on BDT parameter applied to background

(10% bkg unblinded events)



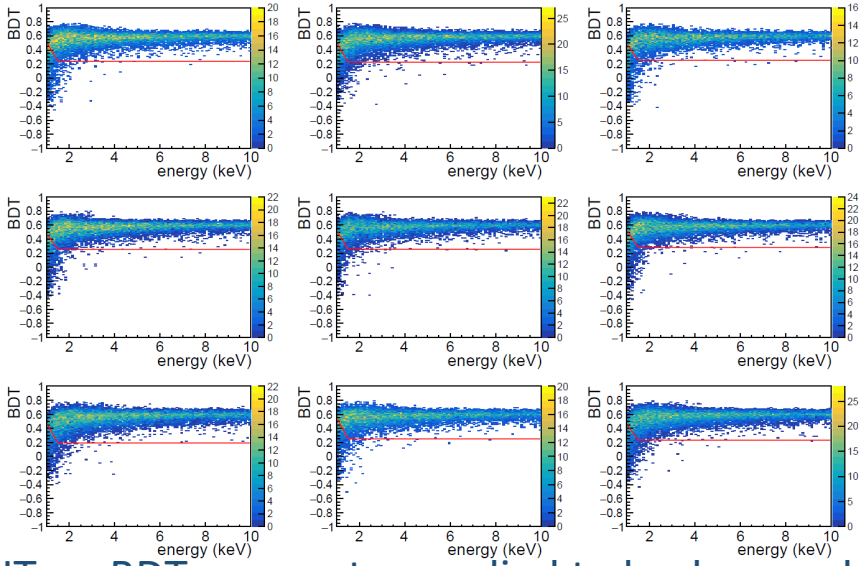


~18% bkg reduction in [1-2] keV

Event selection with BDT

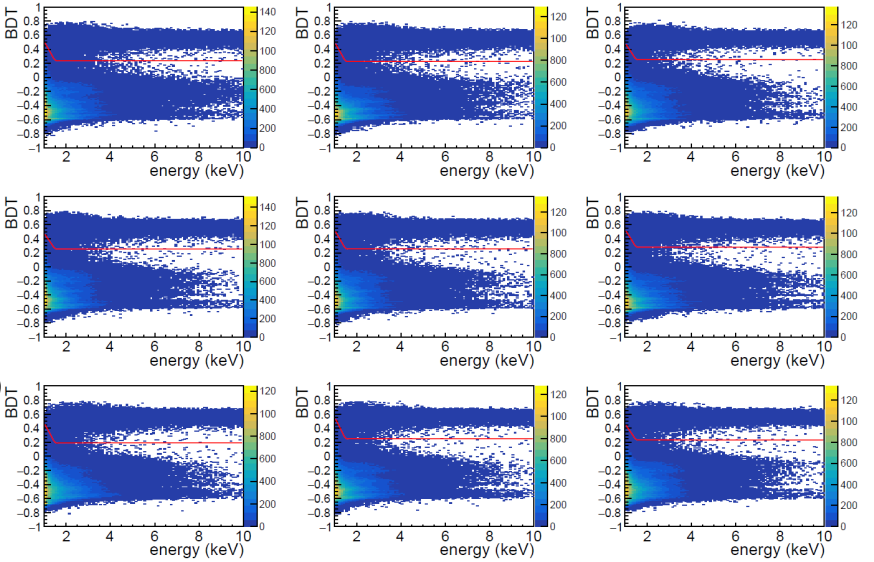
JCAP11(2022)048

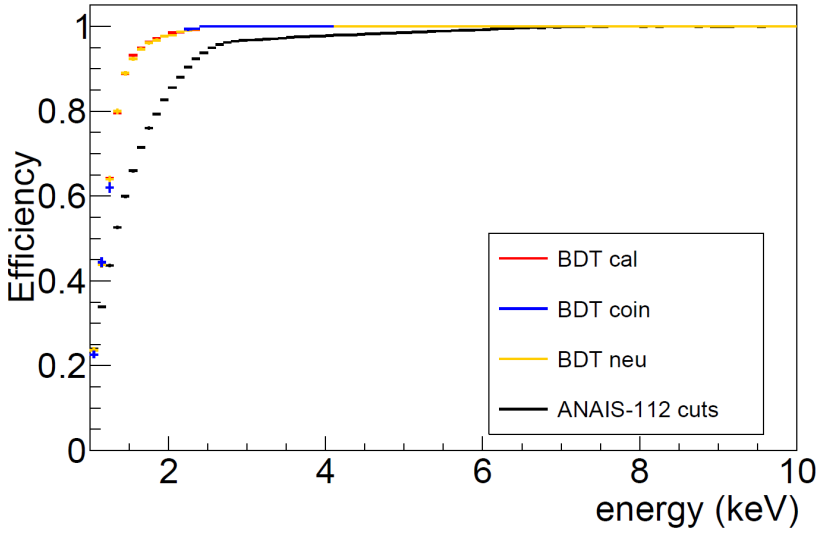
Neutron calibration

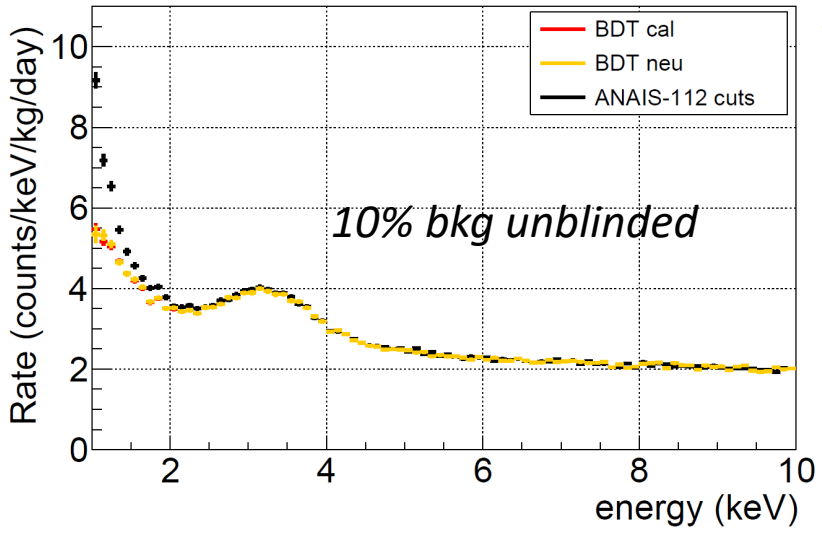


CUT on BDT parameter applied to background

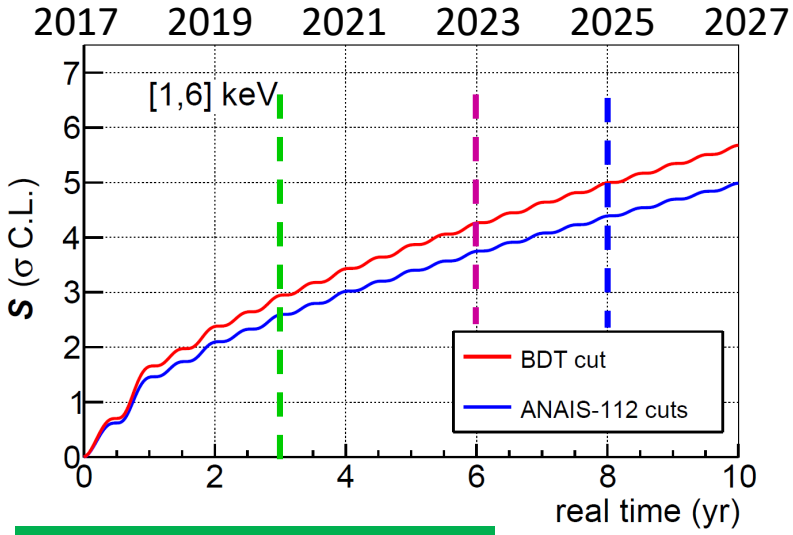
(10% bkg unblinded events)







DM Sensitivity $\propto \sqrt{\frac{MT\epsilon}{B}}$



3σ sensitivity with 3y

>4σ sensitivity with 6y (this summer)

5σ sensitivity in late 2025

Annual modulation with new analysis

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. 10 days bins. ChiSquare minimization: $\chi^2 = \sum (n_i - \mu_i)^2 / \sigma_i^2$

where the expected number of events μ_i for detector d in time bin i is given by:

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

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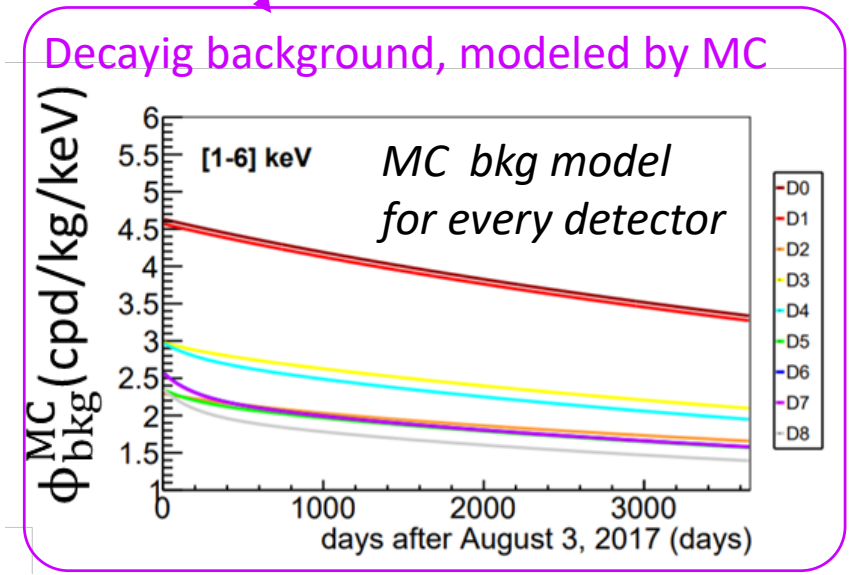
Constant background (long-lived isotopes and residual noise)

Decayig background, modeled by MC



Modulation signal (fixed period and phase)

19 Free parameters: $R_{o,d}$, f_d, S_m

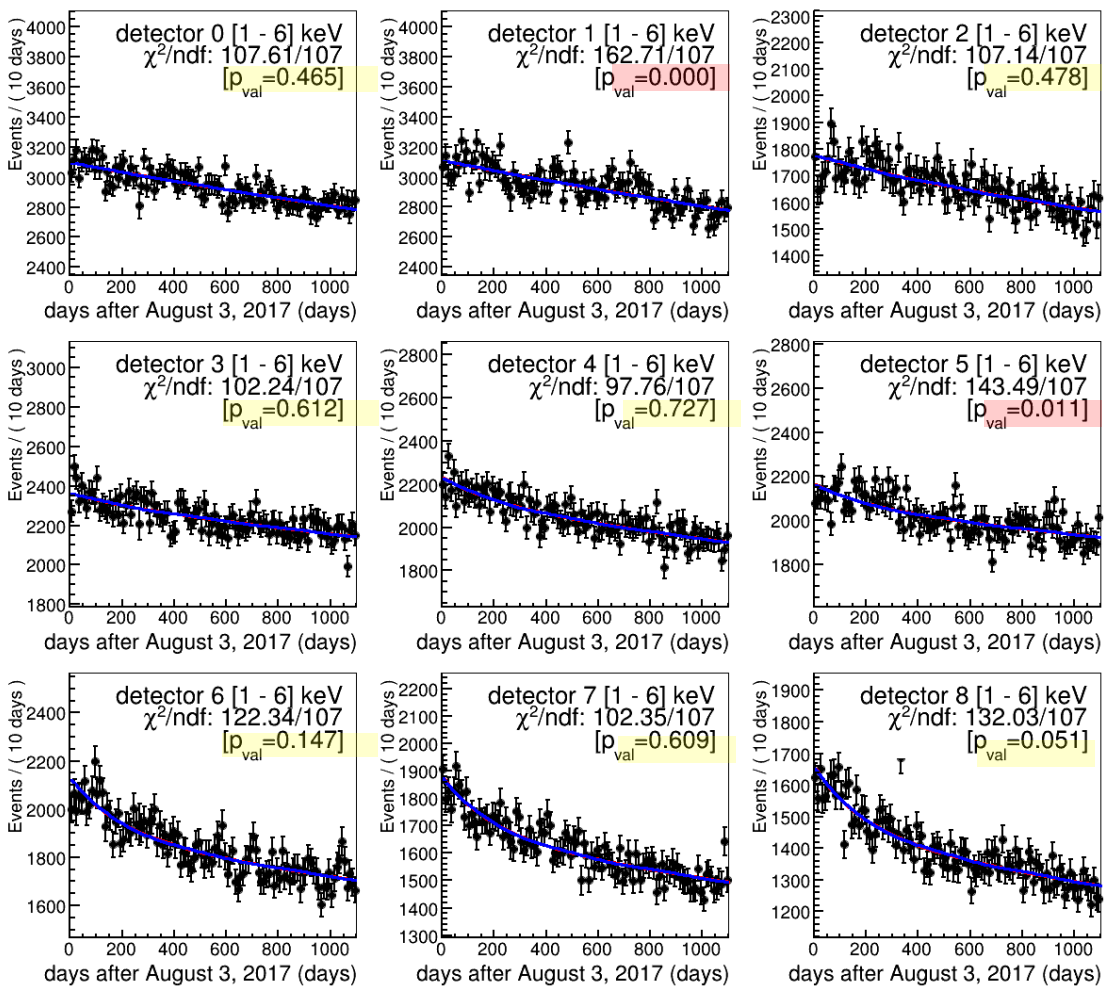
Improved 3-years results [1-6] keV

PRD 103, 102005 (2021)

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)



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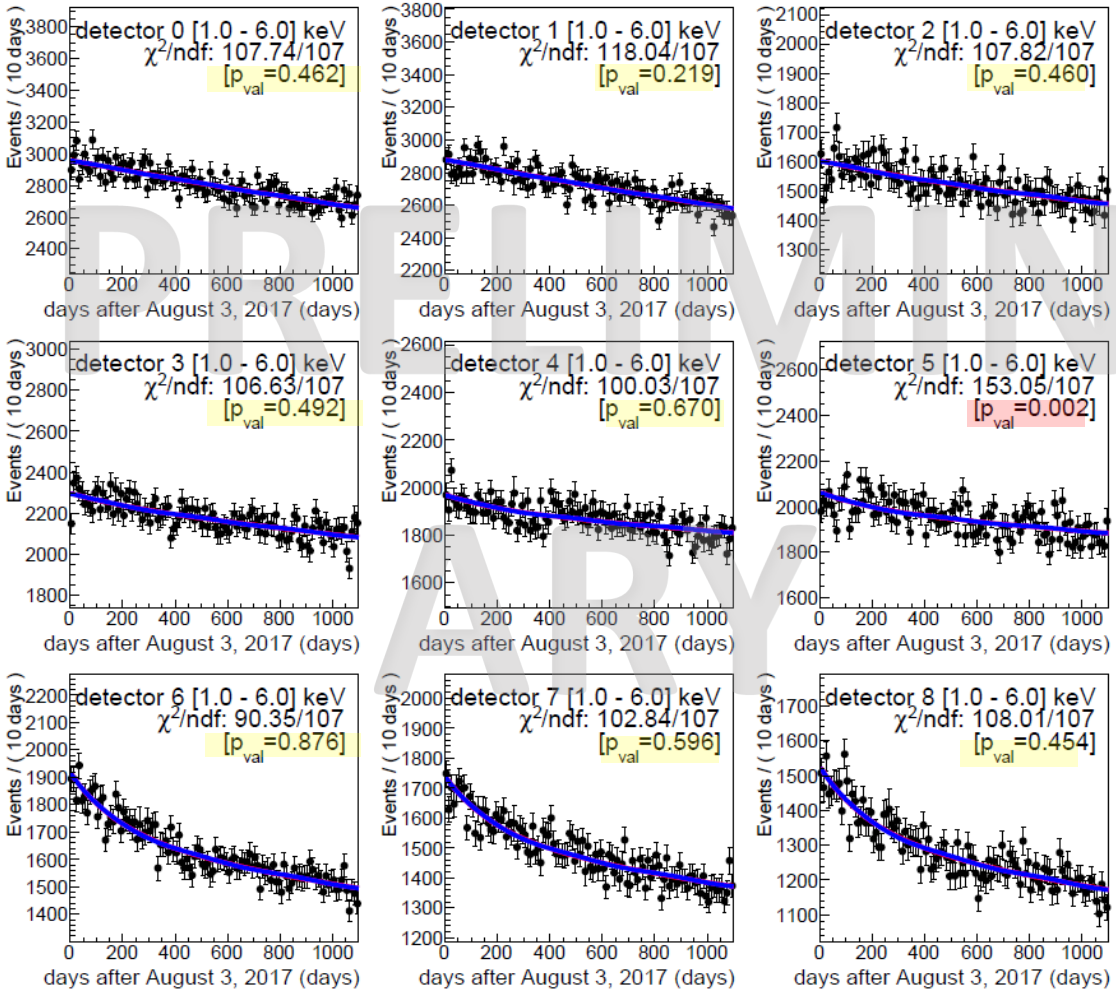

Improved 3-years results [1-6] keV

2.5σ → 2.9σ

NEW

PRD 103, 102005 (2021)

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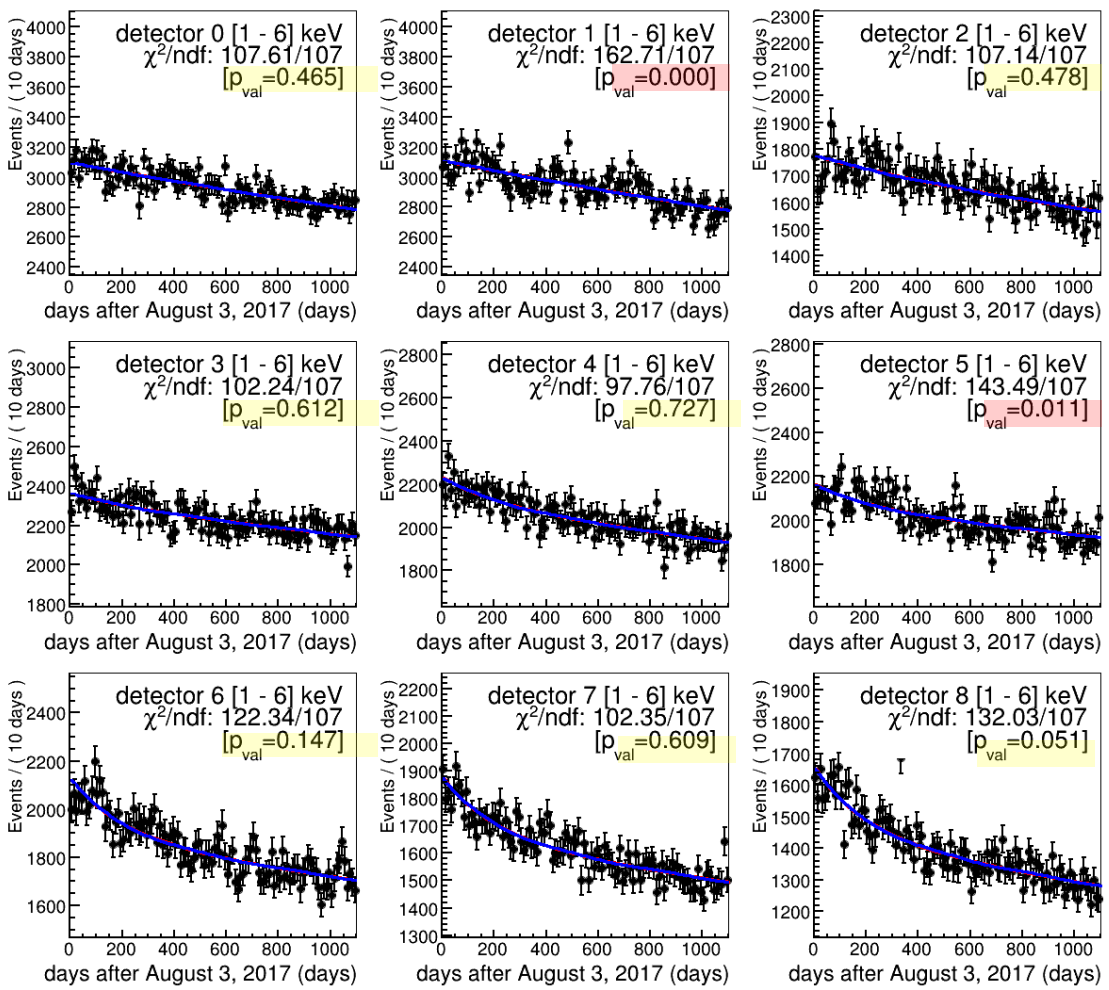

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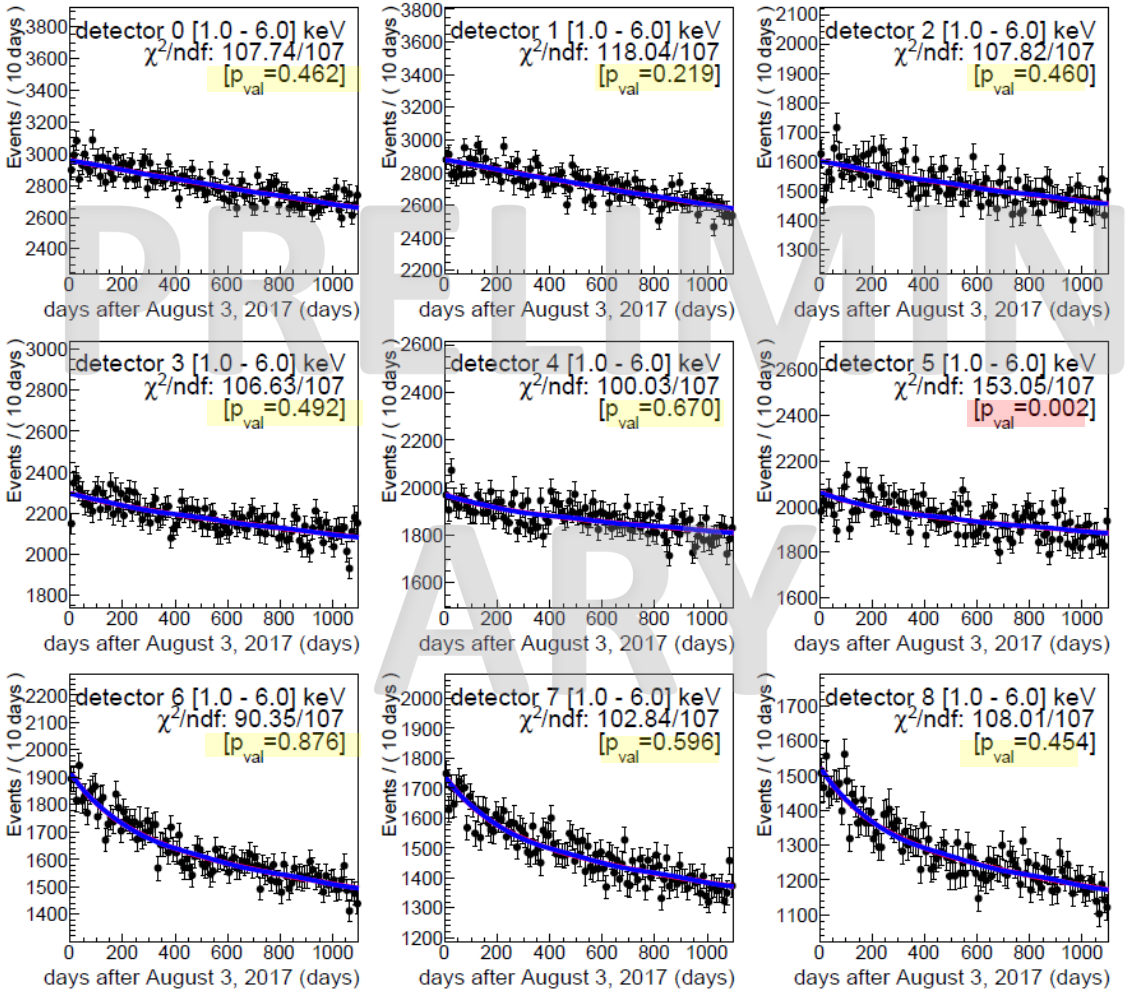
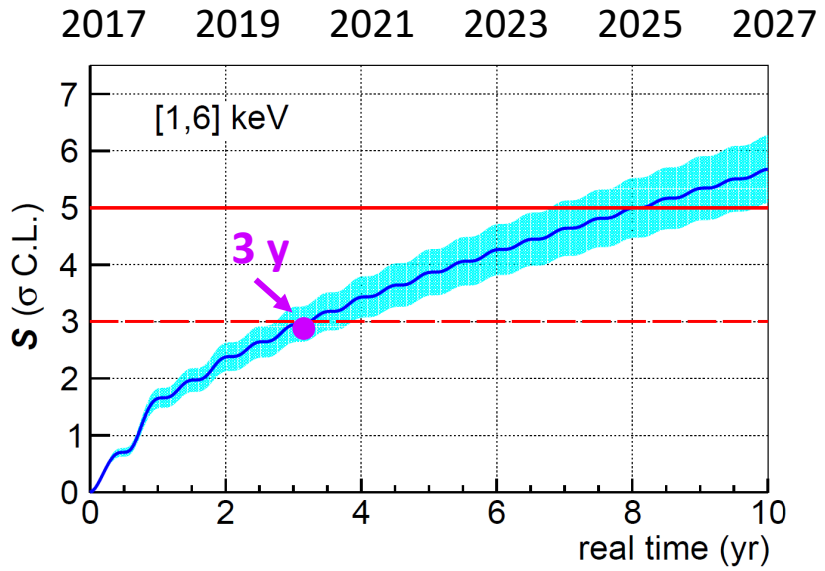
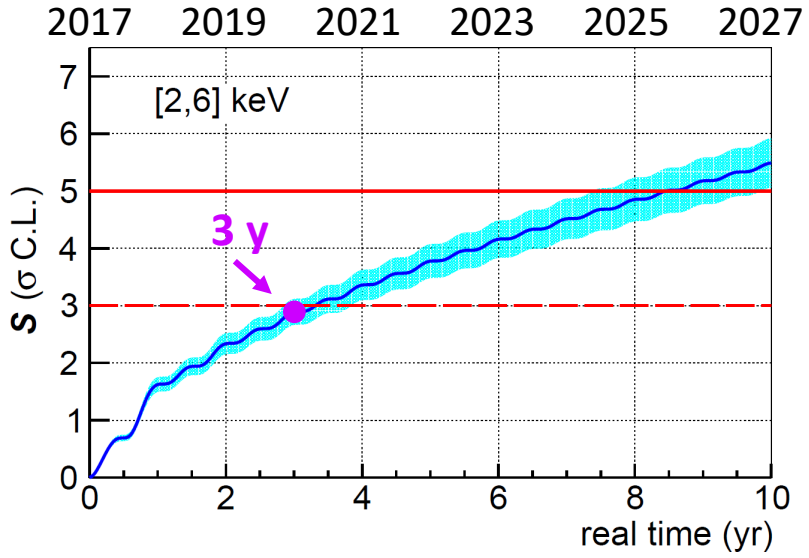
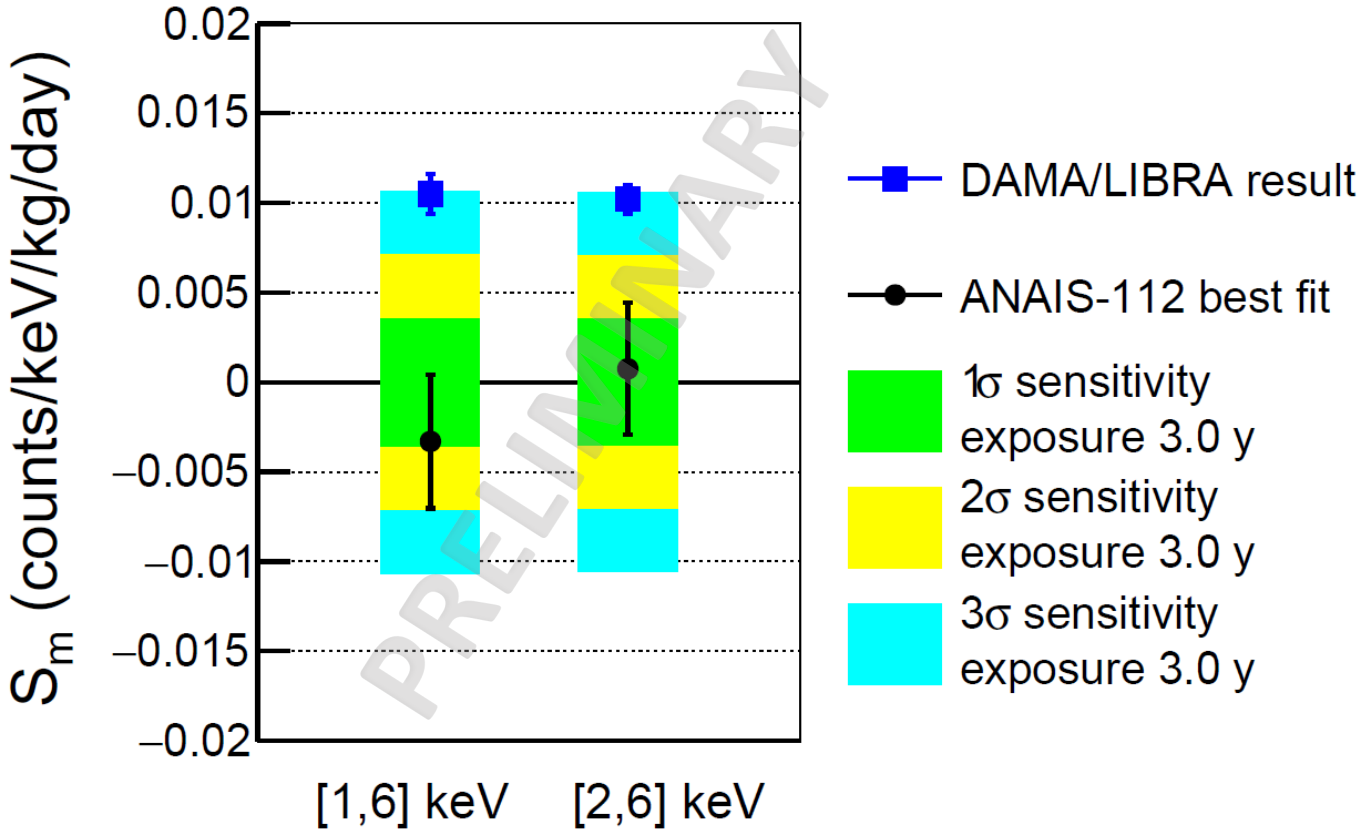


3-years annual modulation with BDT cut







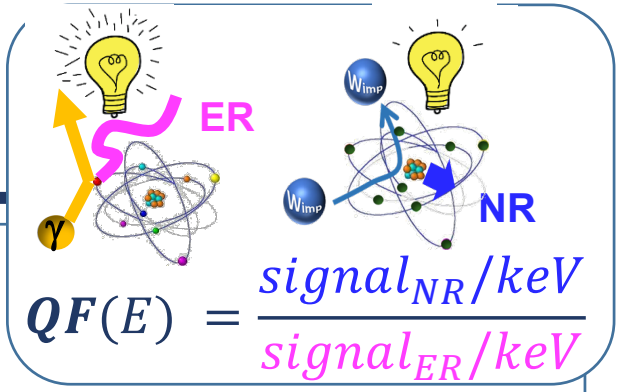
best fit modulation amplitudes compatible with zero at ~1σ

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] & [2-6] keV

5σ sensitivity at reach in late 2025

NR Quenching factor ANAIS vs DAMA



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

DAMA/LIBRA

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

^{252}Cf calibration

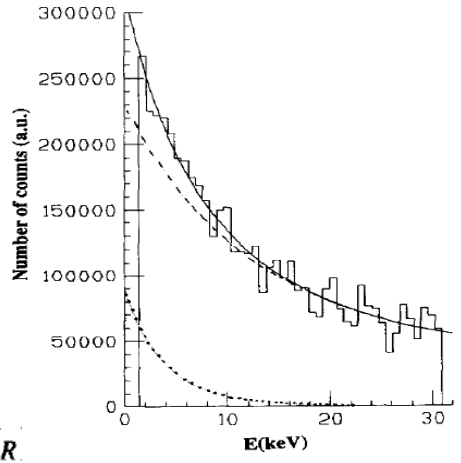
$$E_R = E_{det}/QF$$

Hypothesis: constant QF

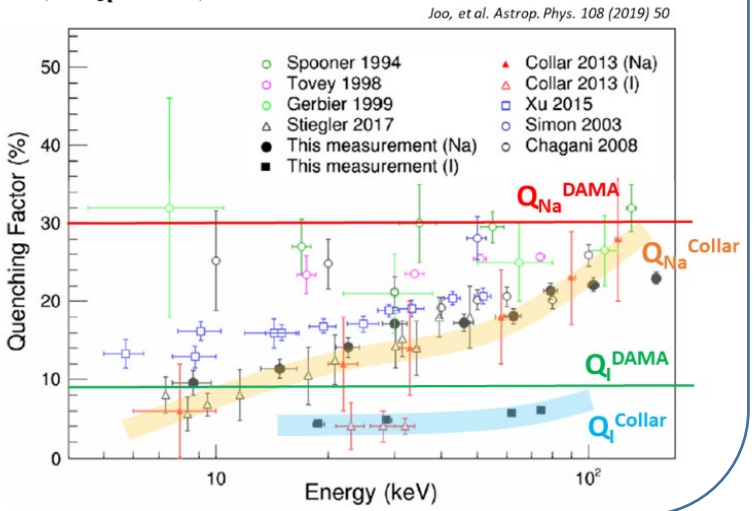
Spectrum fitted to:

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

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



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



Result:

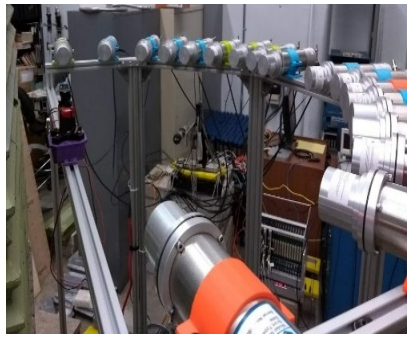
$QF_{Na} = 30\%$

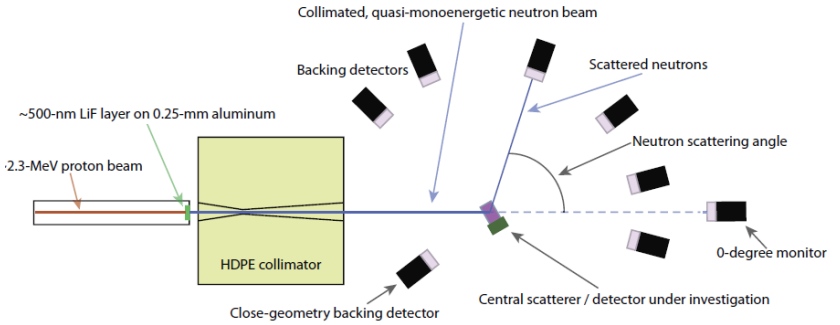
$QF_I = 9\%$

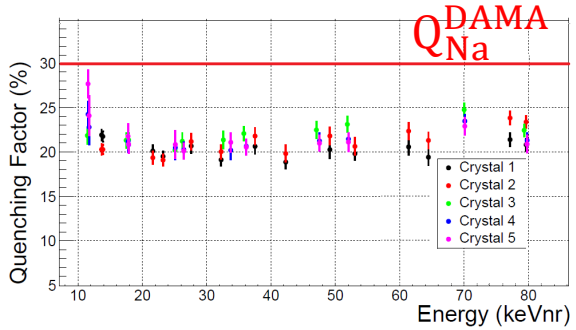
ANAIS

Measurements @ TUNL (Duke Univ.)

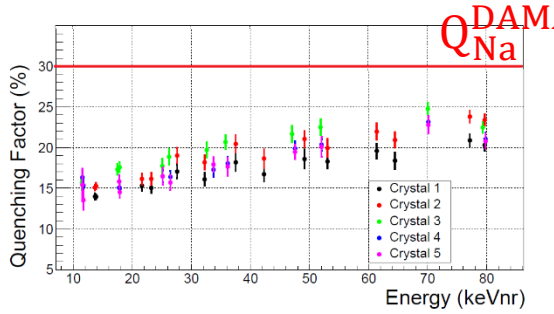
5 different NaI(Tl) crystals (ANAIS & Yale group of COSINE) in the same setup







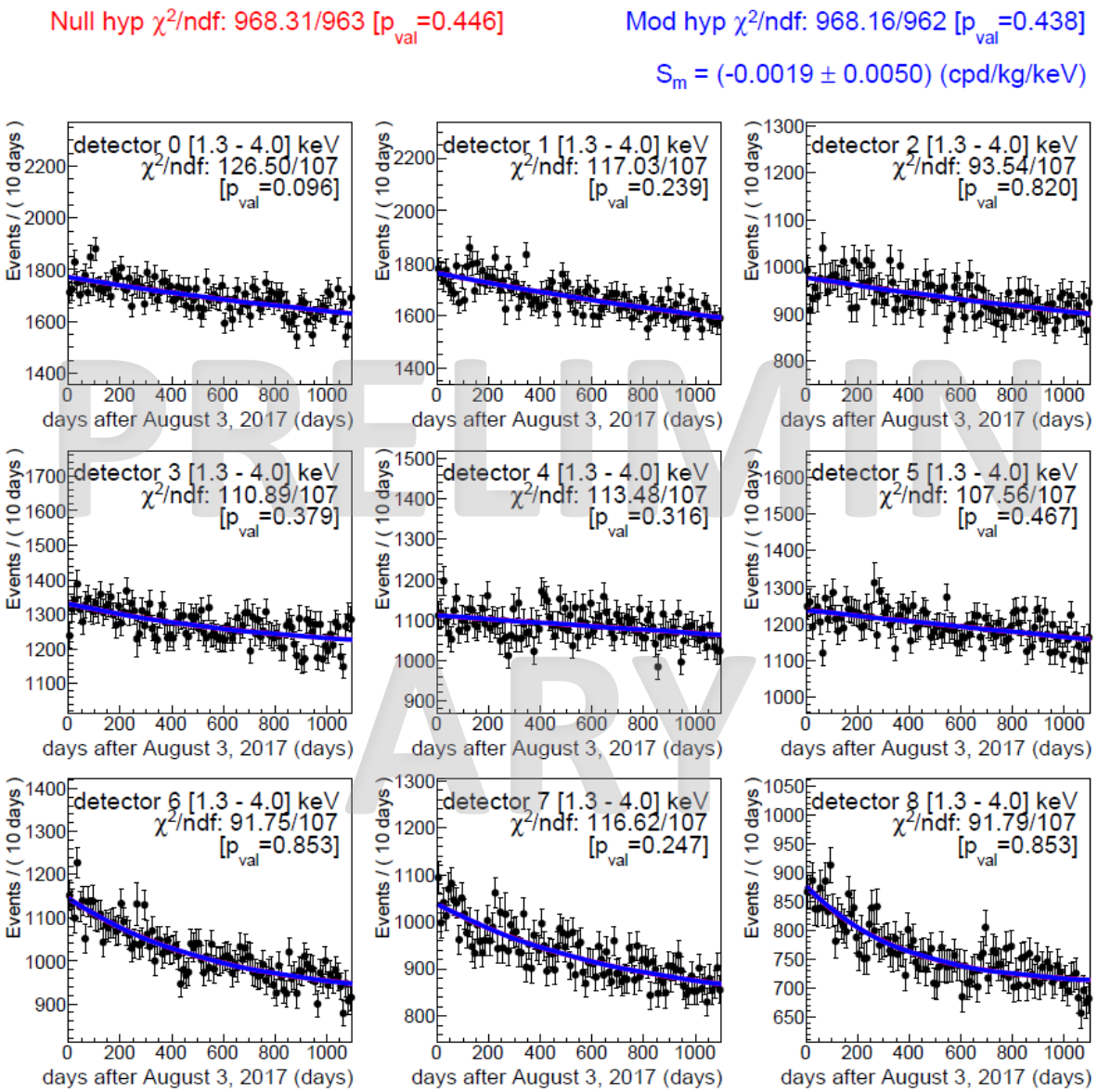
Calibration lines in the RoI (6.6, 30.8, 35.1 keV)



Calibration line: 57 keV (assuming proportional response)

NaI non-linearity could explain QF measurements disagreement

3 y modulation analysis in 1.3 – 4 keV



Supposing

- DAMA/LIBRA Q_{Na} = 30%
- ANAIS Q_{Na}= 20%

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

ANAIS 3 years annual modulation fit:

$$S_m = -0.0019 \pm 0.0050$$

Considering Na Quenching difference:

- ANAIS compatible with no modulation
- ANAIS best fit incompatible with DAMA @ 2.4σ (sensitivity = 2σ)

Outlook & summary

- Currently, many efforts trying to provide an independent confirmation of DAMA/LIBRA signal with the same target.
- ANAIS-112: is taking data in stable condition @ LSC **since 3rd August 2017** with excellent performances. Up to now it has accumulated more than 600 kg×y exposure.
- 3-years 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.**
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Thanks!!

gifna.unizar.es/anais/

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