ANAIS-112: testing DAMA/LIBRA signal beyond three sigma

María Martínez, CAPA (U. Zaragoza) on behalf of the ANAIS team

UCLA DM 2023, Los Angeles, March 29- April 1 2023

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

MultiDark
Multimessenger Approach for Dark Matter Detection

LSC
Laboratorio Subterráneo de Canfranc

ANAIS-112

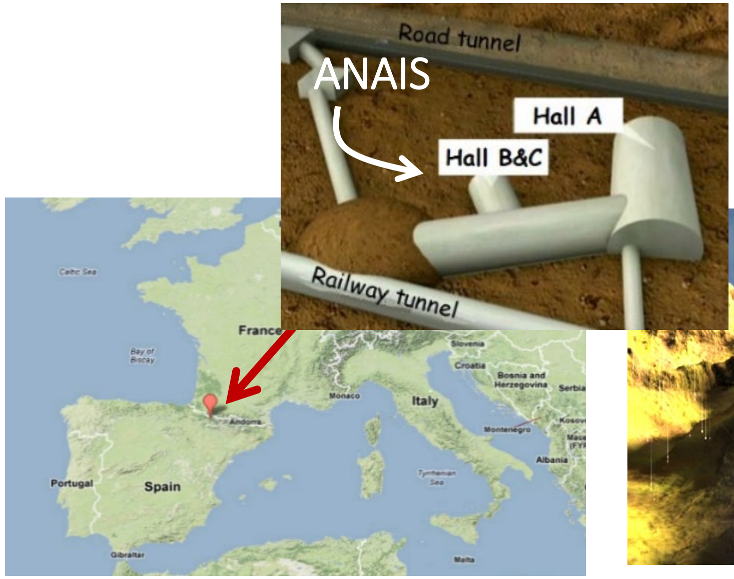
Annual Modulation with NaI Scintillators https://gifna.unizar.es/anais/

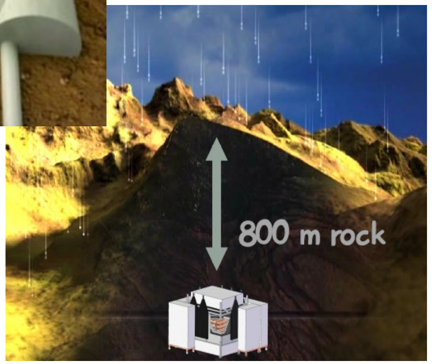
J. Amaré, J. Apilluelo, S. Cebrián, D. Cintas, I. Coarasa, E. García, M. Martínez, M.A. Oliván,
Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, A. Salinas, M.L. Sarsa, P. Villar

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.**)



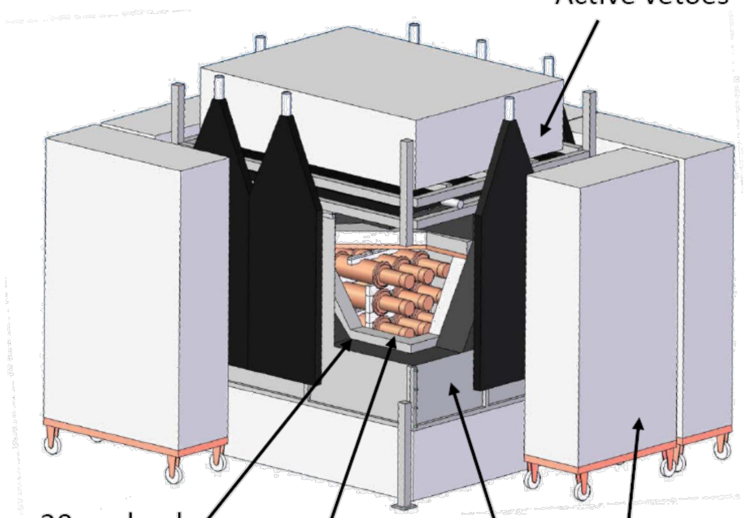


taking data since August 2017

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

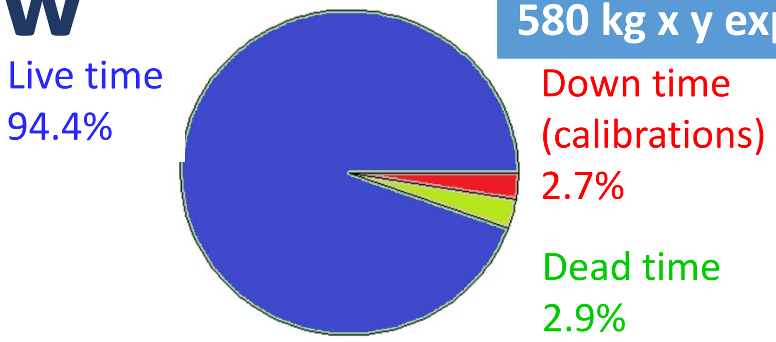
Mylar window for lowE calibration

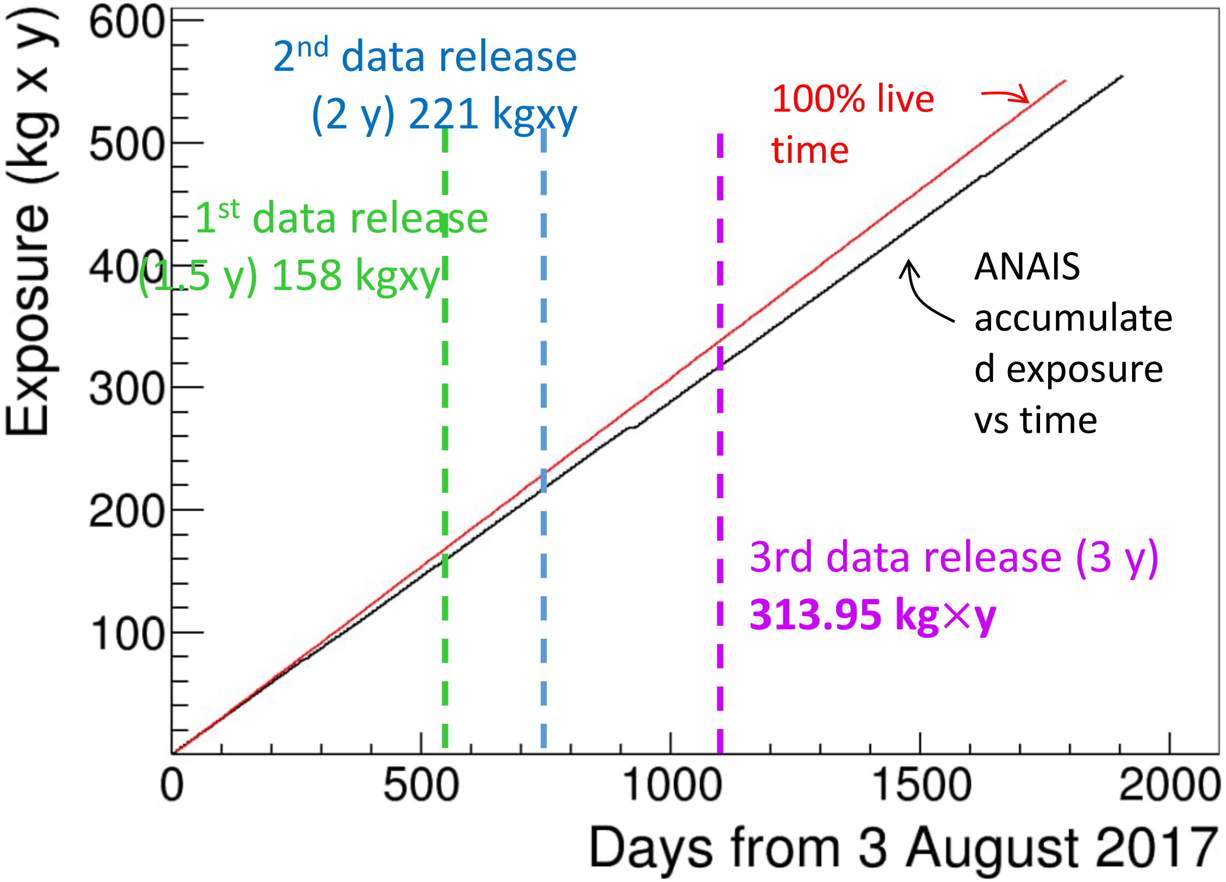
Two high QE PMTs per detector



ANAIS-112 data-taking overview

Up to date, more than 580 kg x y exposure

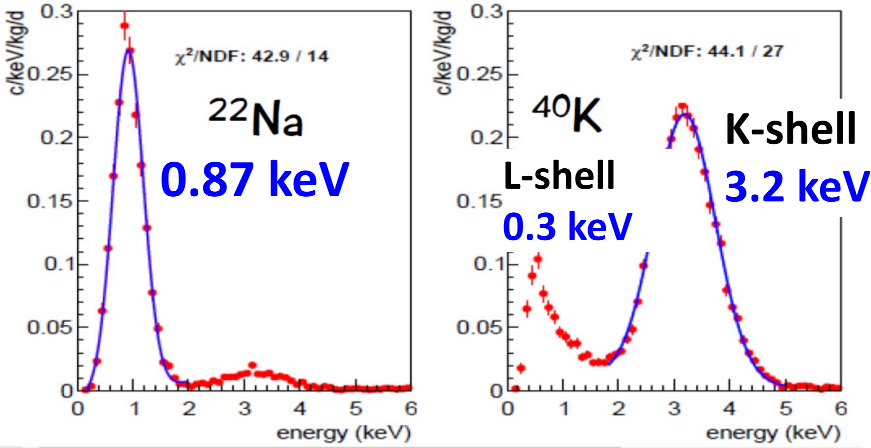


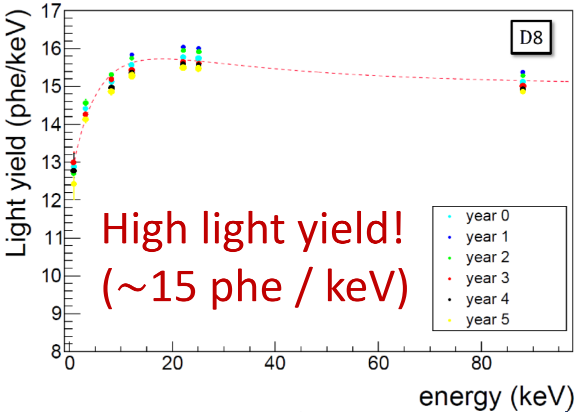


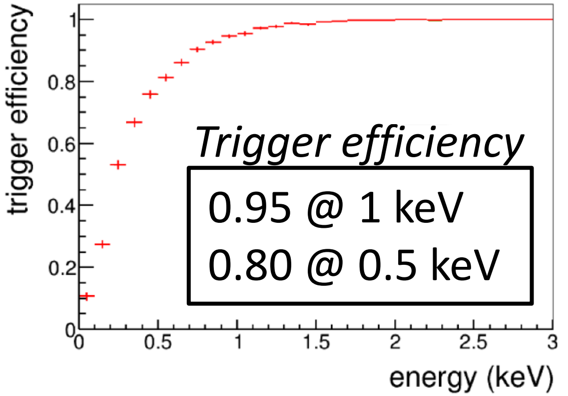
Accurate calibration in the RoI

periodical external calibration using ^{109}Cd (**88.0, 22.6 and 11.9 keV**) every two weeks

+ internal ^{22}Na & ^{40}K







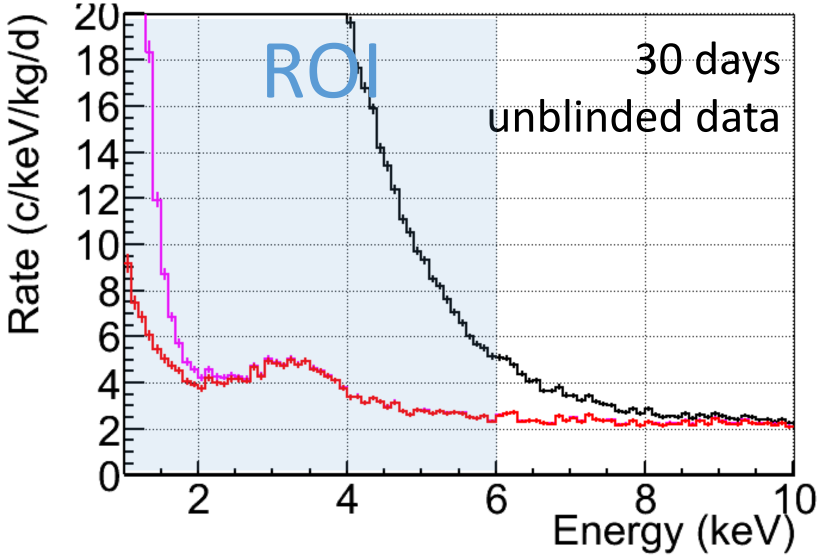
ANAIS-112 modulation results:

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

EPJC (2019) 79:228

Event selection

Blind analysis



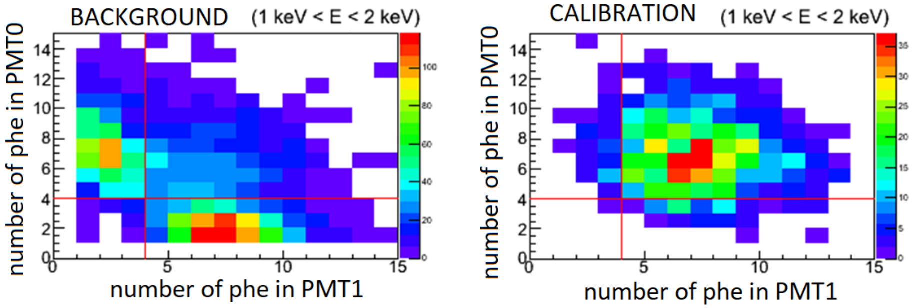
1. Pulse shape cut to select pulses with NaI(Tl) scintillation constant (biparametric)

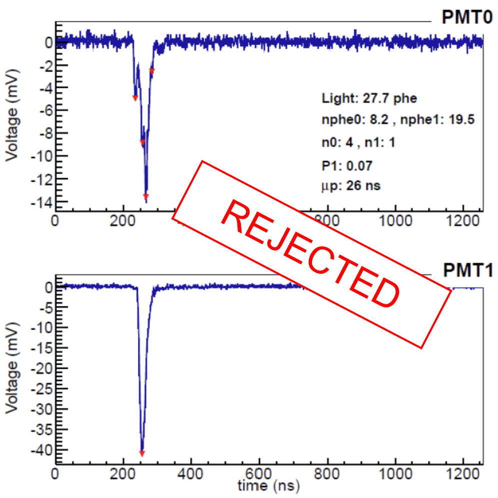
$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_0^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$

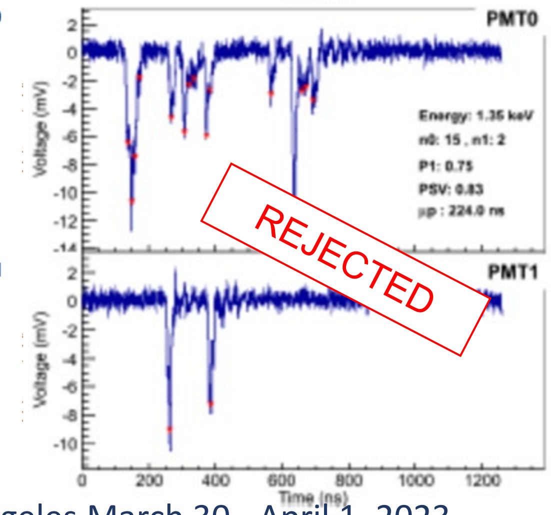
Rejects fast "Cherenkov-like" events

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

1 keVee threshold



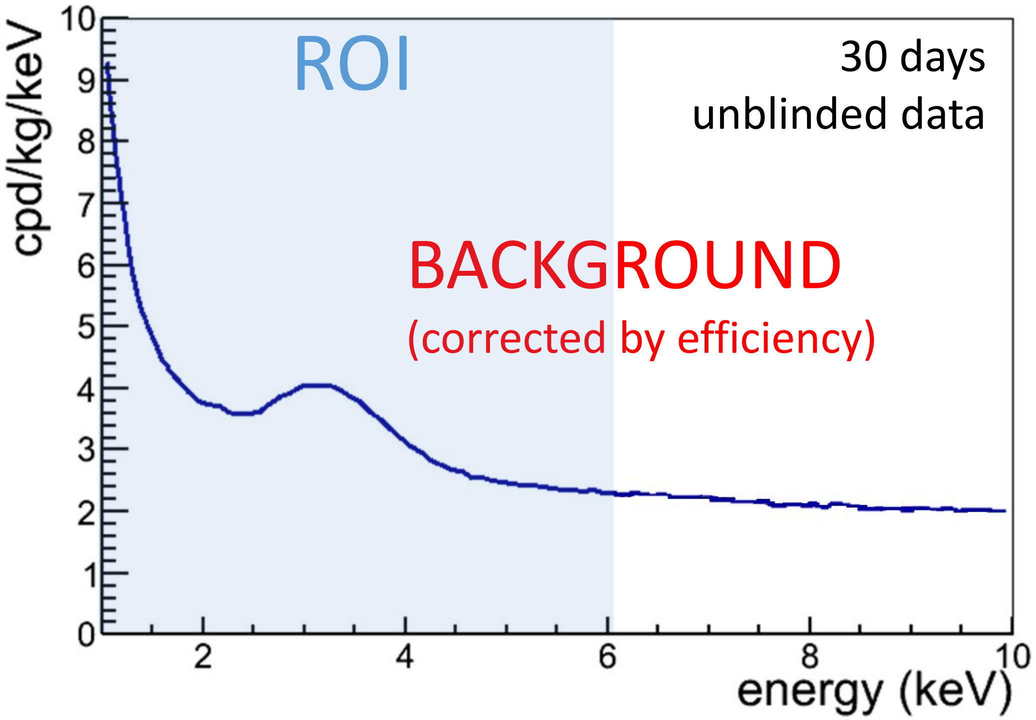


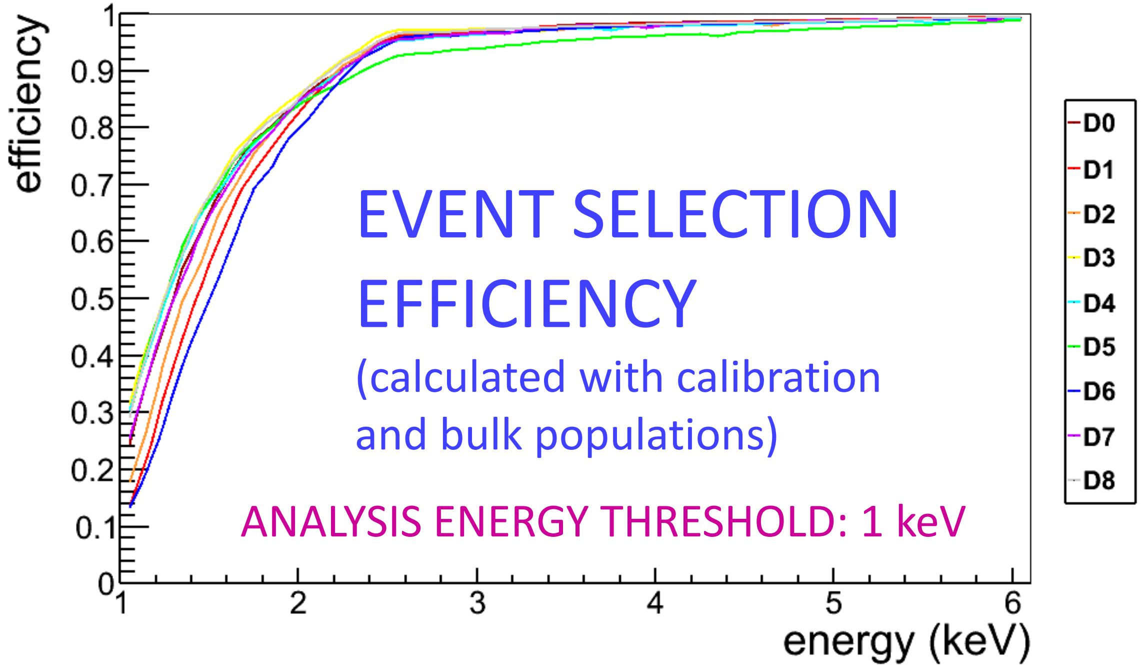


Background @ ROI and event selection efficiency

EPJC (2019) 79:228

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

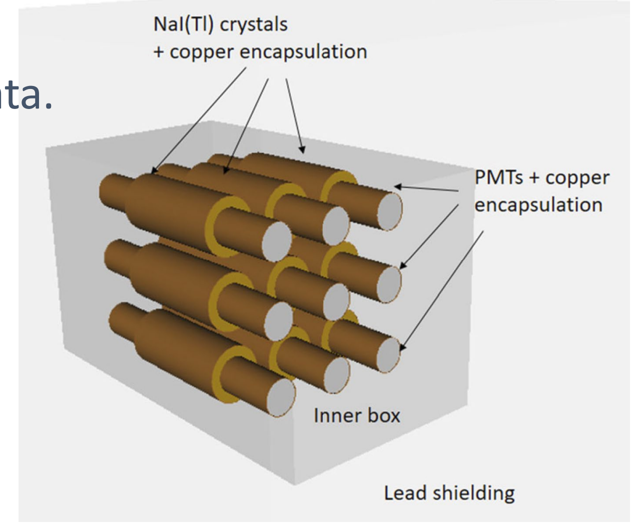




Data vs background model

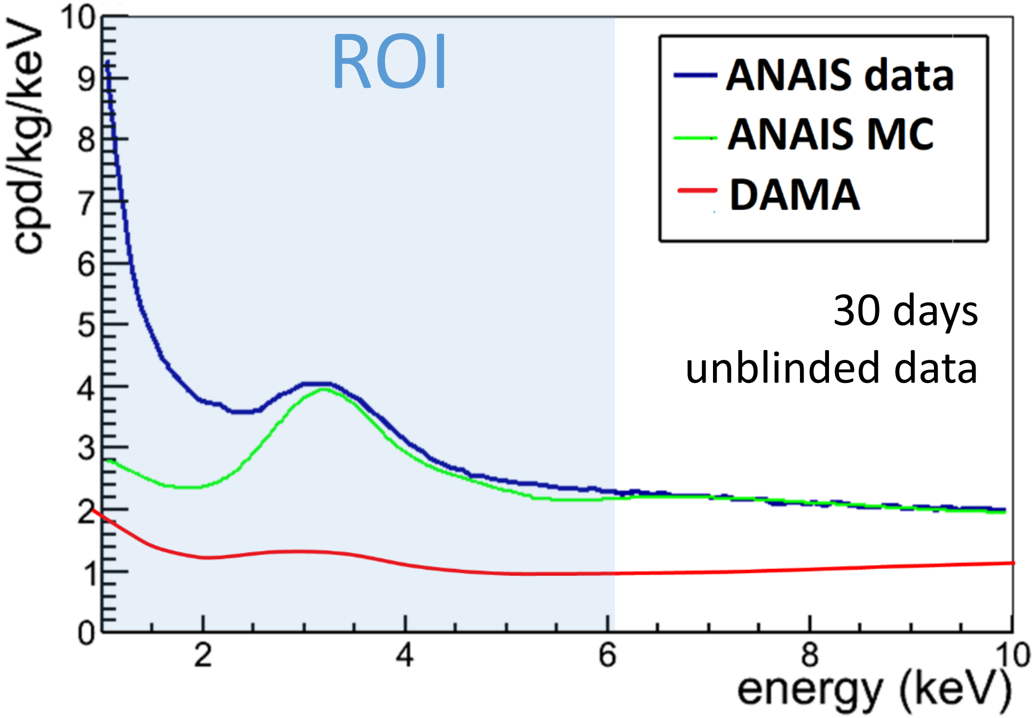
EPJC (2019) 79:228

Geant4 MC simulation including:
- activity from external components measured with HPGe
- internal and cosmogenic activity directly assessed from data.



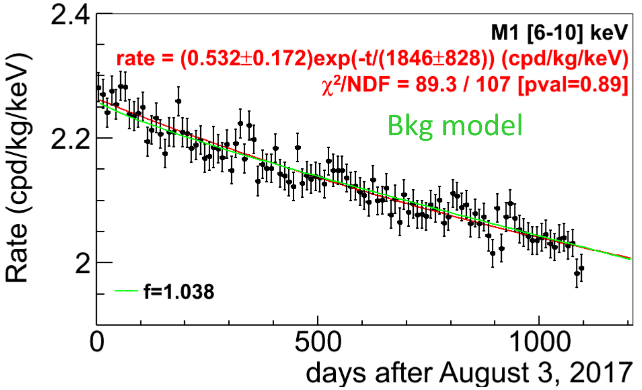
At very low energy (<20 keV), main contribution to background from internal contamination:

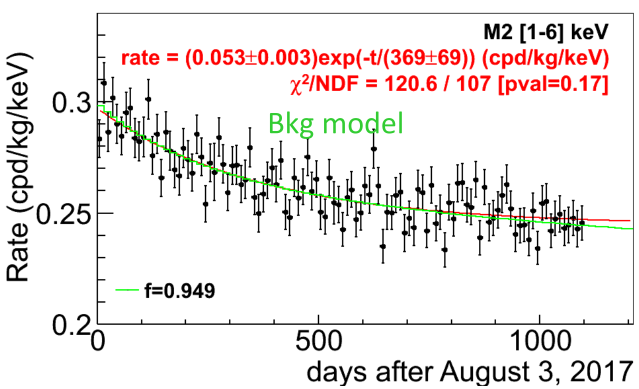
- **^{40}K** and **^{22}Na** ($T_{1/2}$ = 2.6 y) peaks
- **^{210}Pb** (bulk+surface) ($T_{1/2}$ = 22.3 y)
- **^{3}H** ($T_{1/2}$ = 12.3 y)



Cosmogenic isotopes (^{3}H, ^{22}Na, …) and ^{210}Pb are decaying

→ **Our MC model reproduce satisfactorily the time evolution for non-blinded populations**





Annual modulation analysis

PRD 103, 102005 (2021)

Blind 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:

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

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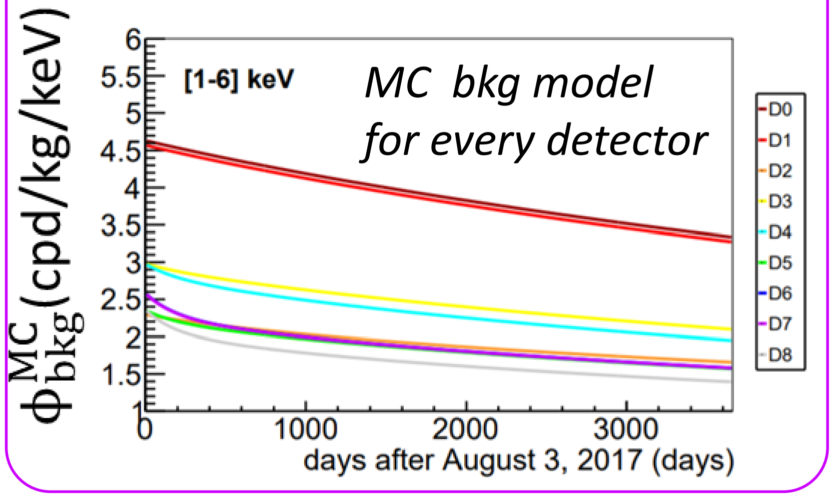
Constant background (long-lived isotopes and residual noise)

Decayig background, modeled by MC



Modulation signal (fixed period and phase)

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

3-years results (313.95 kg x y)

PRD 103, 102005 (2021)

[1-6] keV

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

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

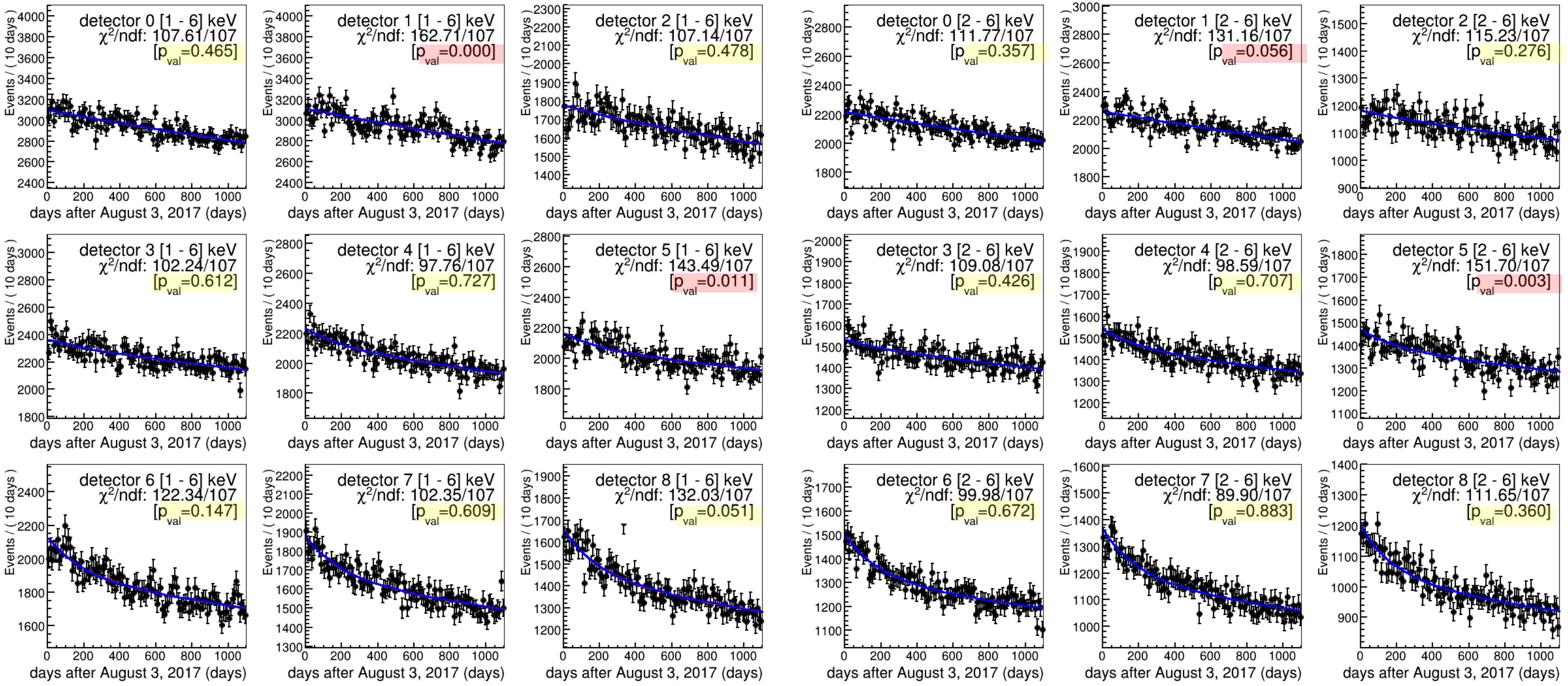
S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)

[2-6] keV

Null hyp χ^2/ndf: 1018.19/972 [p_{val}=0.148]

Mod hyp χ^2/ndf: 1018.18/971 [p_{val}=0.143]

S_m = (0.0003 ± 0.0037) (cpd/kg/keV)



3-years results (313.95 kg x y)

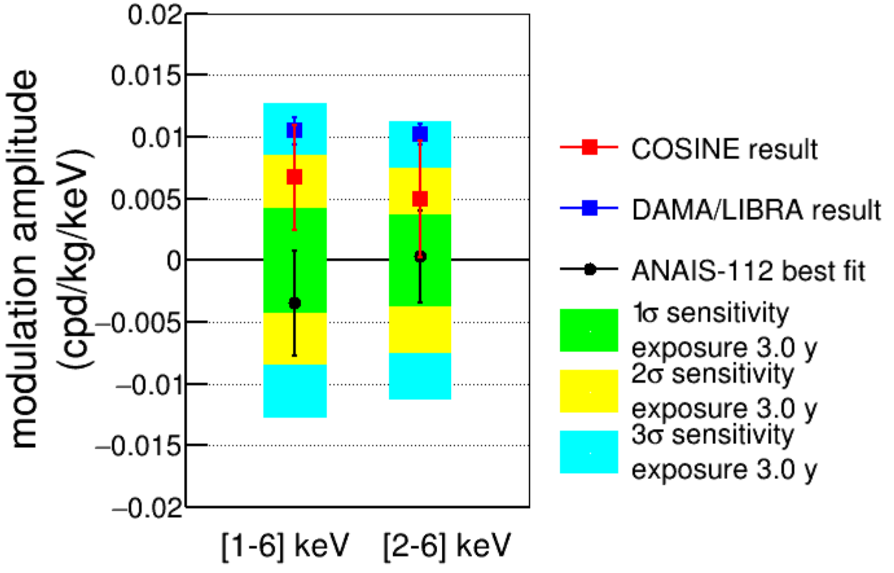
PRD 103, 102005 (2021)

Energy region	χ^2/NDF null hyp	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	1076 / 972	-0.0034±0.0042	0.011	0.011
[2-6] keV	1018 / 972	0.0003±0.0037	0.14	0.15

DAMA modulation. Prog. Part. Nucl. Phys. 114 (2020) 103810

		A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/LIBRA-phase2	1–6 keV	(0.0105 ± 0.0011)	1.0	152.5	9.5 σ
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2	2–6 keV	(0.0102 ± 0.0008)	1.0	152.5	12.8 σ

- Compatible results for 3 different background descriptions / fit approaches
- **Data supports the null hypothesis** (lower p-value for [1-6] keV mainly due to detectors 1 and 5)
- For the modulation hypothesis, we obtain in all **cases best fit modulation amplitudes compatible with zero at 1σ. Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ.**



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

(*) PRD 106, 052005 (2022)

ANAIS-112 SENSITIVITY

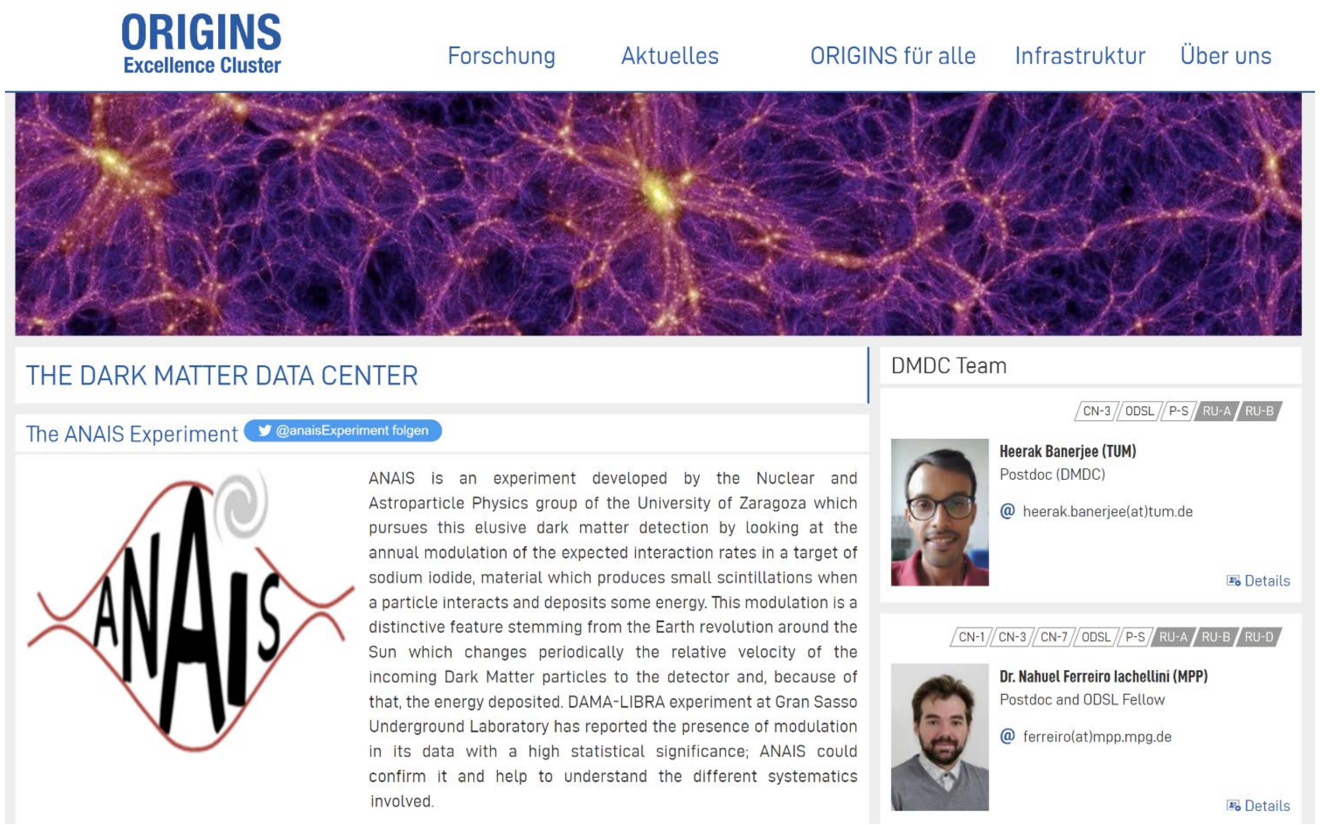
2.5σ [1–6] keV

2.7σ [2–6] keV

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	$\sigma = (-0.008 \pm 0.001) + (0.378 \pm 0.002) \times \sqrt{E(keV)}$

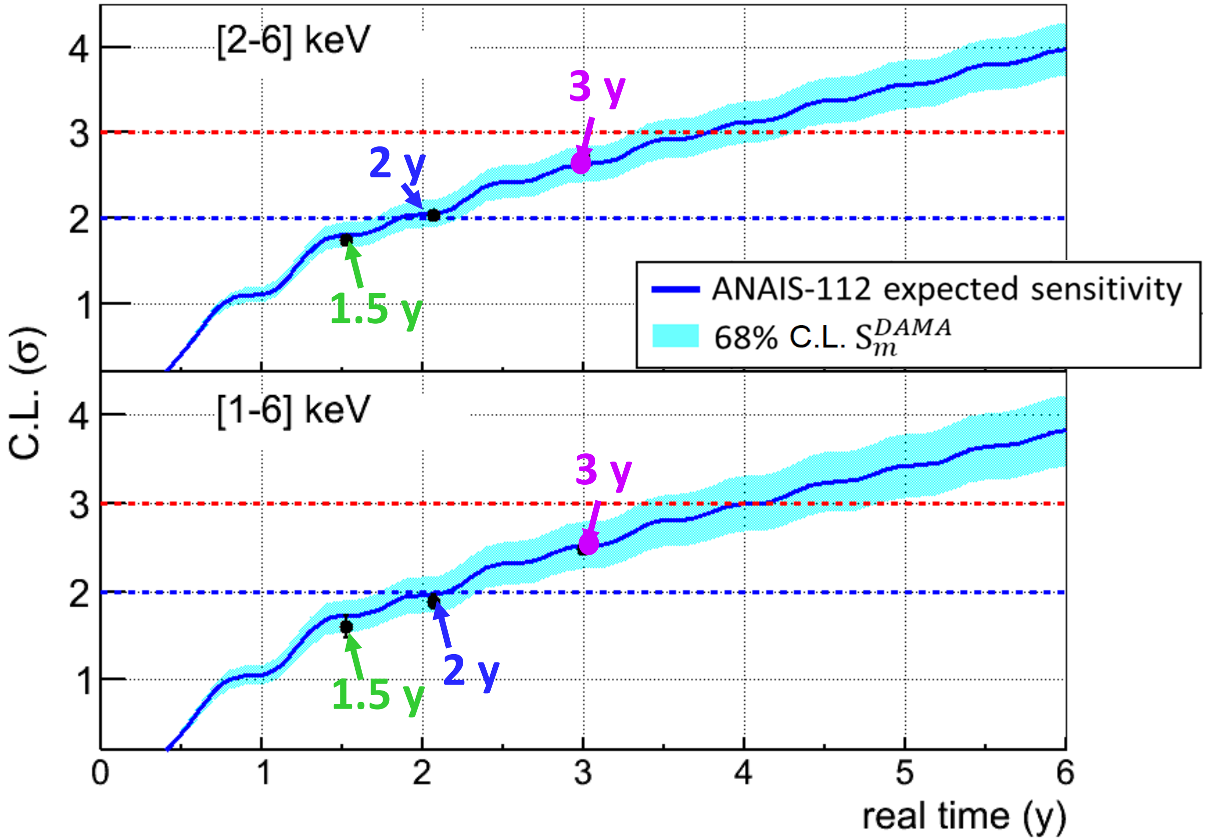
ANAIS provides a JuPyter Notebook with examples of how to plot the data in these datasets and to run the RooFit macro for fitting the data.
Launch a Binder session with the notebook preloaded: launch binder

Download full repository as tar.gz: GitLab

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

Expected sensitivity

We quote our sensitivity to DAMA/LIBRA as the ratio $S_m^{DAMA}/\sigma(S_m)$



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

Sensitivity projection based on bkg and efficiency
Eur. Phys. J. C (2019) 79:233, 1812.02000

3 data releases ANAIS-112:

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

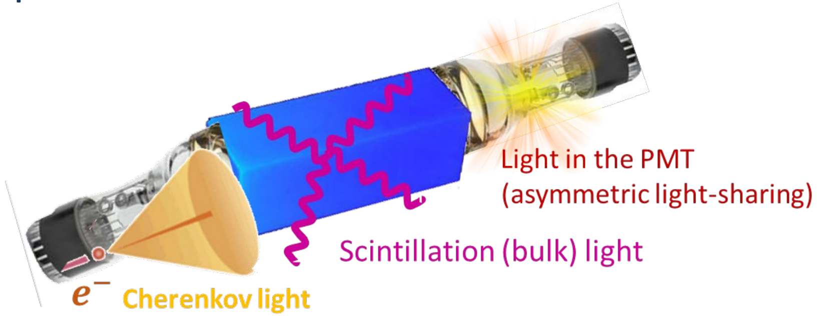
data confirm our sensitivity projection

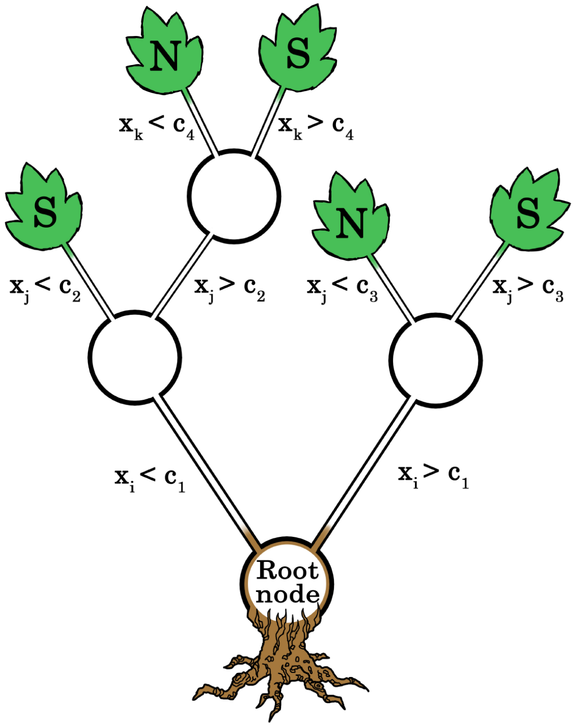
sensitivity @ 3 years:
2.5σ (2.7σ) in [1-6] ([2-6]) keV

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 (BDT)** (instead of the 4 parameters used in the standard analysis)

Std analysis

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

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

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

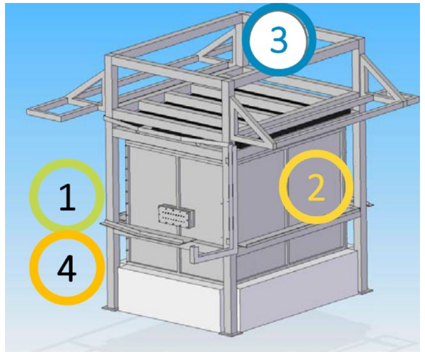
$$x = 50,\ 100,\ 200,\ 300,\ 400,\ 500,\ 600,\ 700 \text{ and } 800\ \mathrm{ns}$$

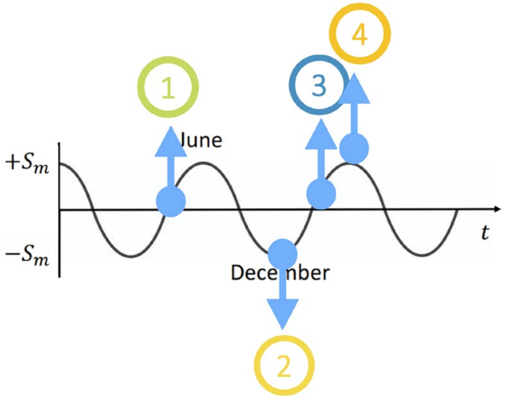
Training populations

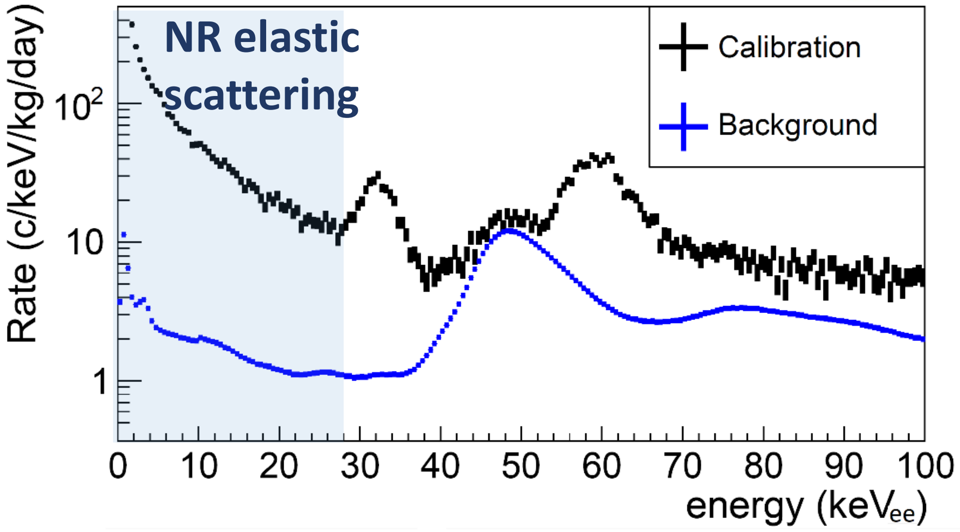
JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations

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

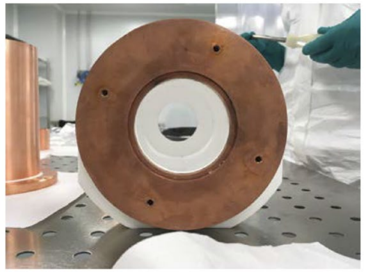


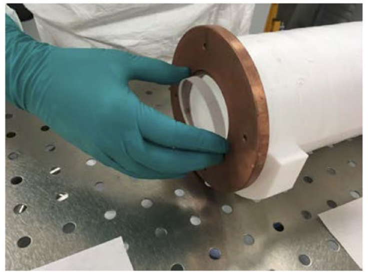


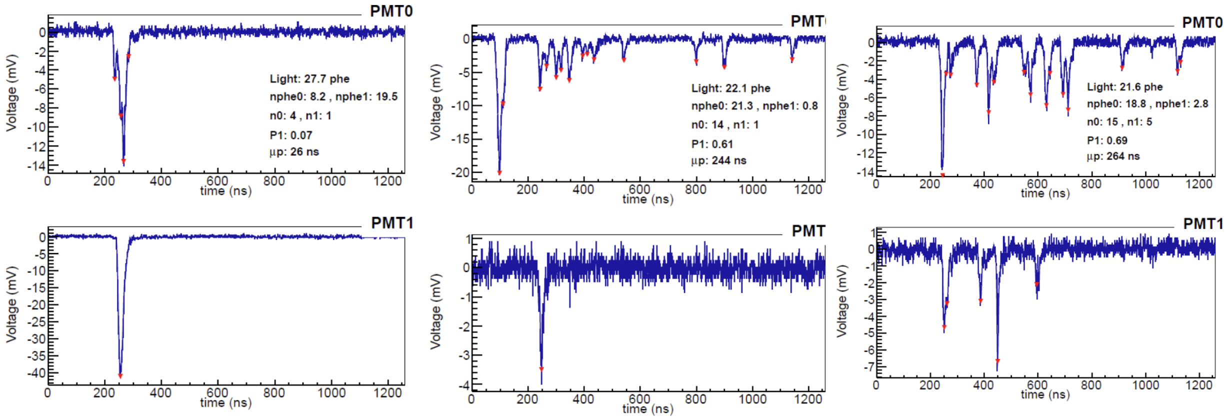


NOISE EVENTS: "Blank" module (No NaI(Tl))

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



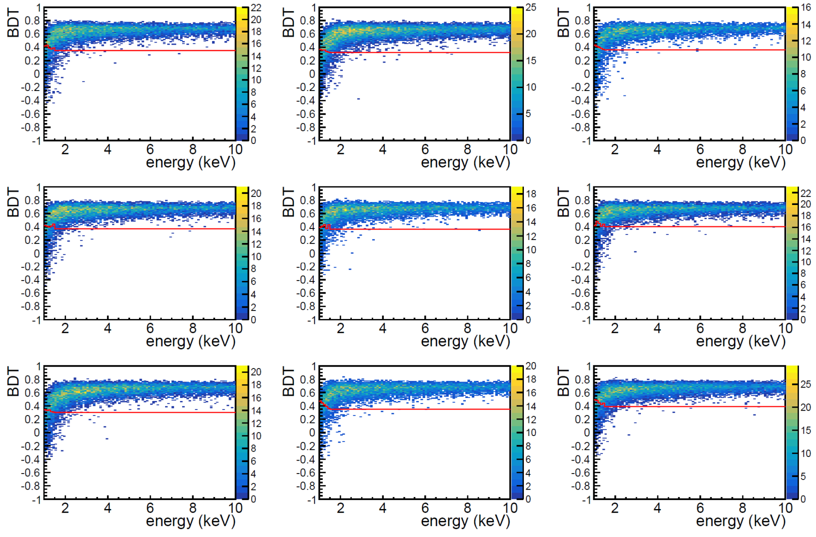


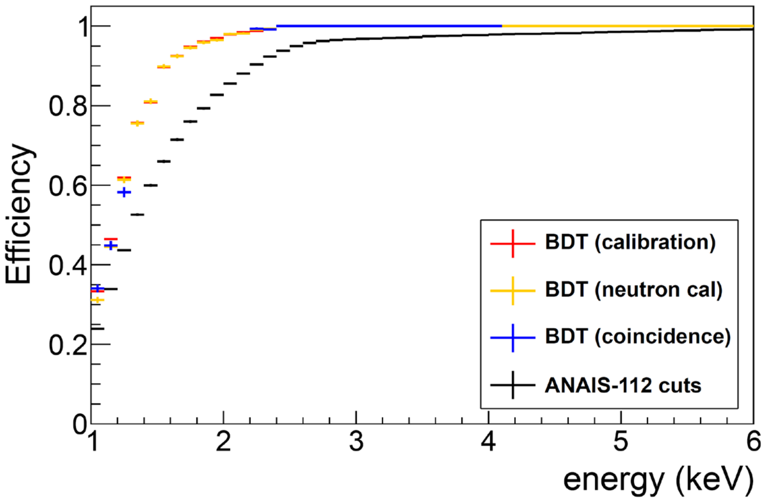


Event selection with BDT

JCAP11(2022)048

Neutron calibration

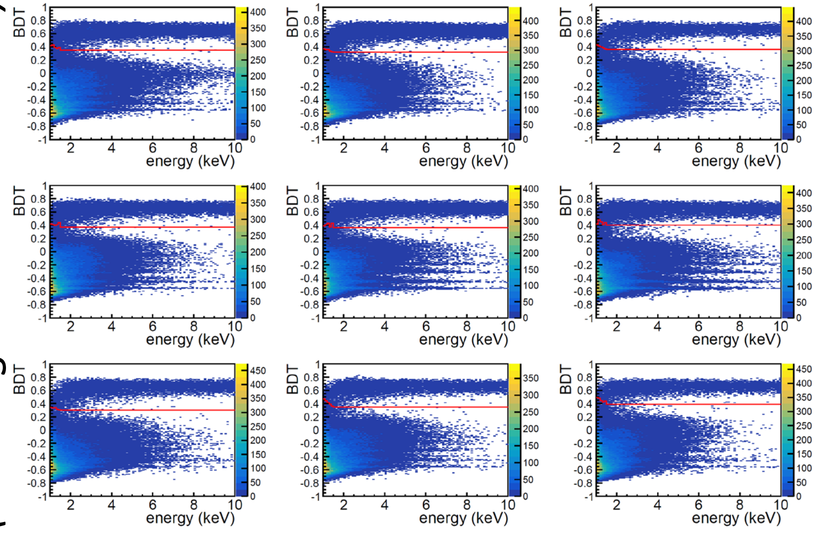


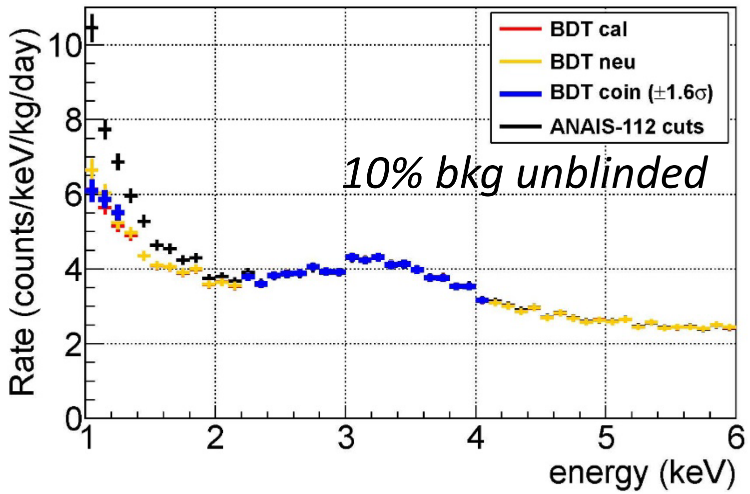


~30% improvement in efficiency

CUT on BDT parameter applied to background

(10% bkg unblinded events)



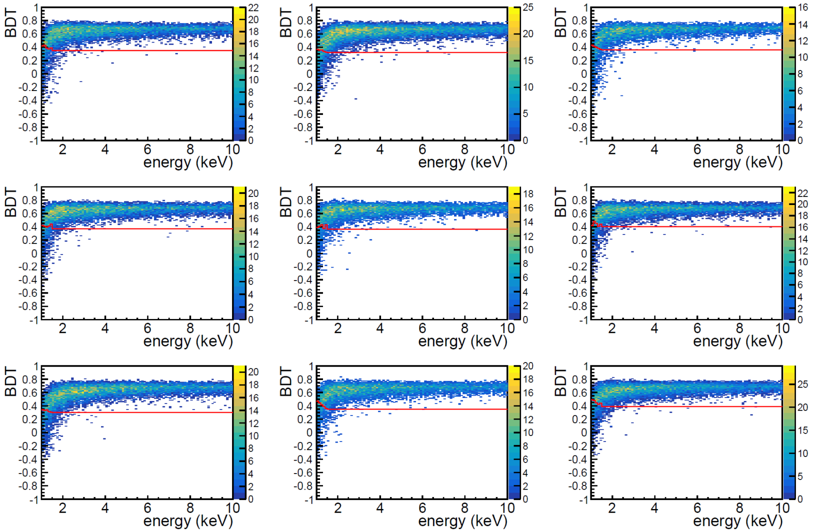


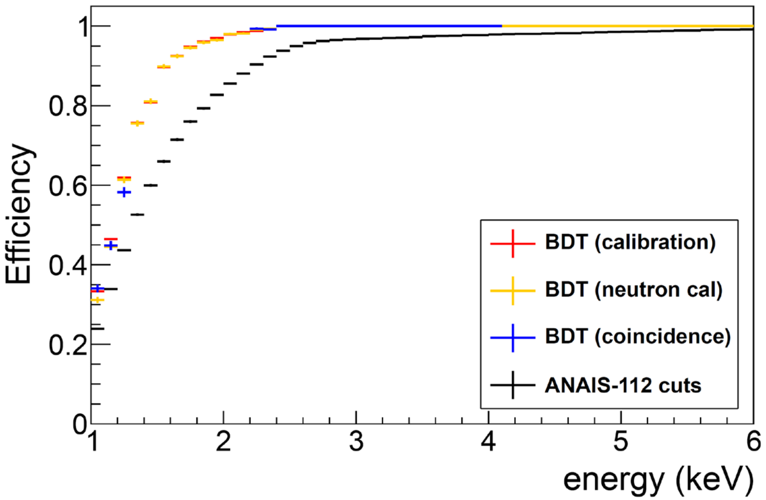
~19% bkg reduction in [1-2] keV

ANAIS-112 projected sensitivity with BDT

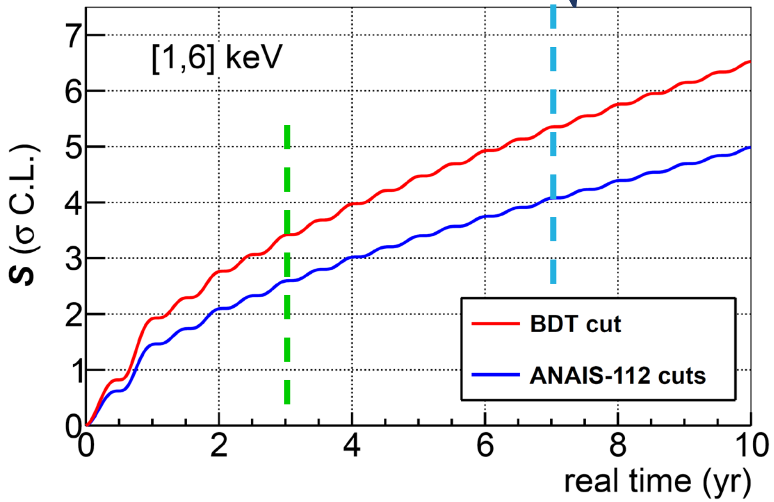
JCAP11(2022)048

Neutron calibration



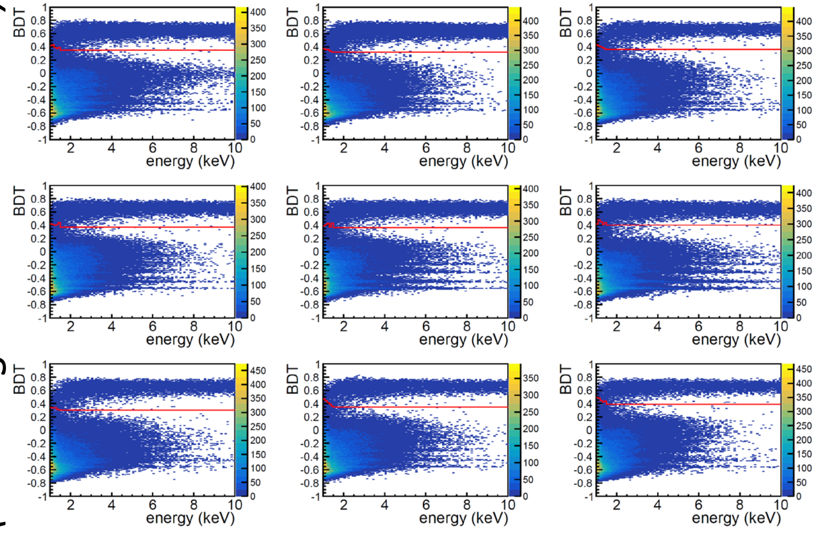


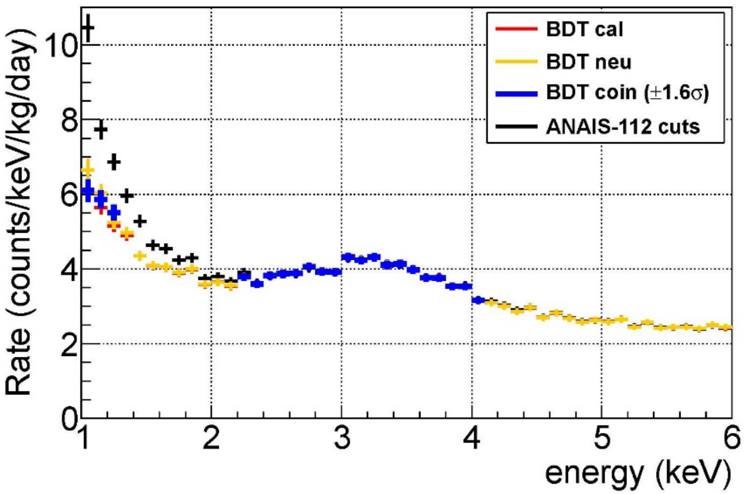
DM Sensitivity $\propto \sqrt{\frac{MT\epsilon}{B}}$

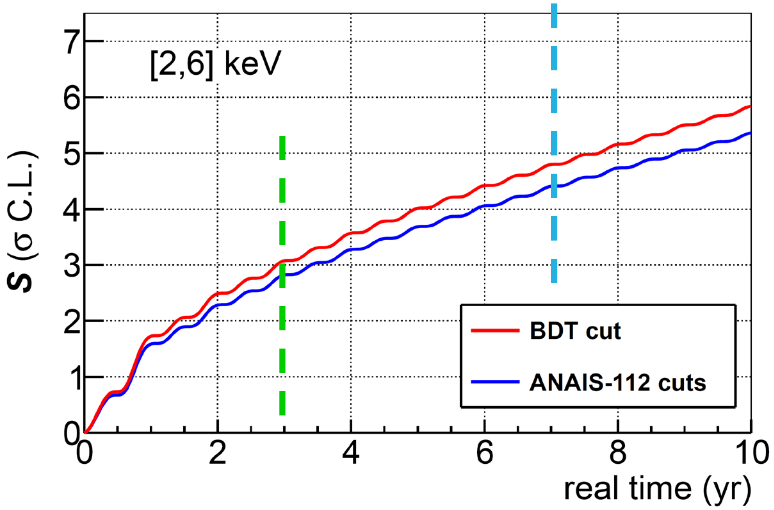


CUT on BDT parameter applied to background

(10% bkg unblinded events)





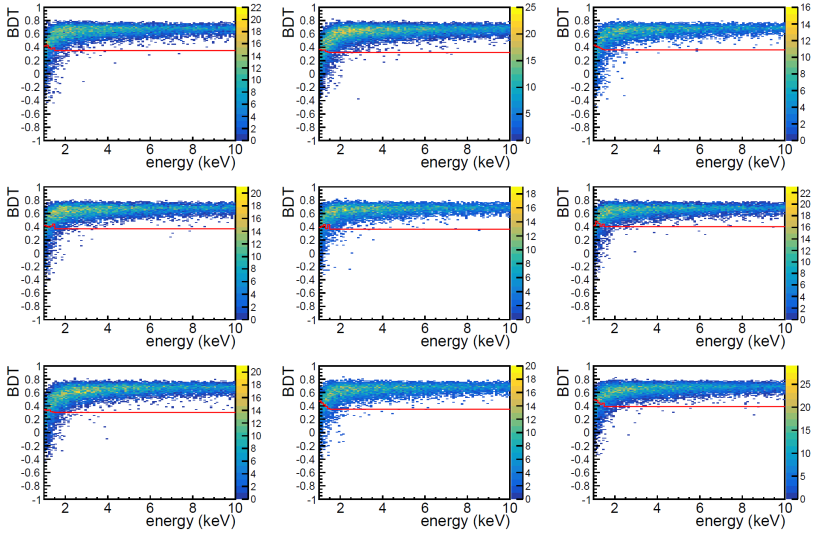


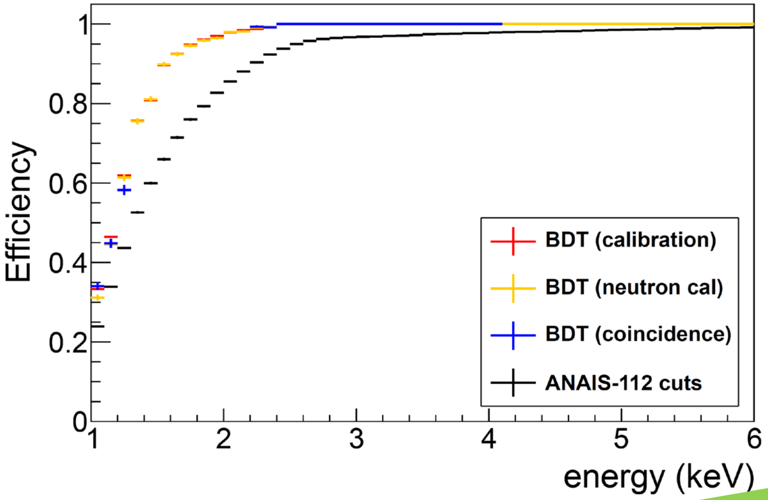
ANAIS-112 projected sensitivity with BDT

JCAP11(2022)048

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

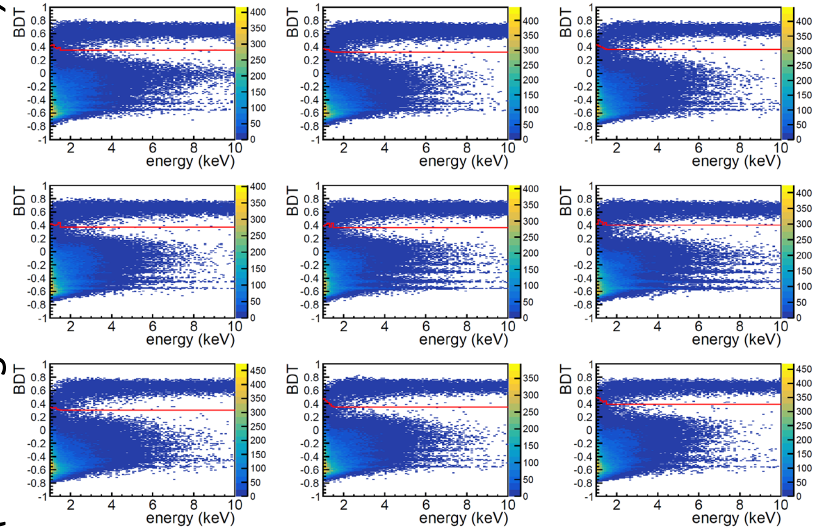
Neutron calibration

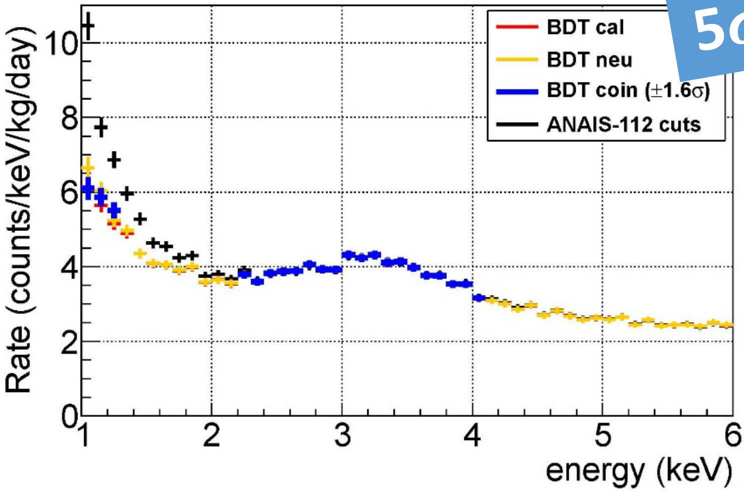


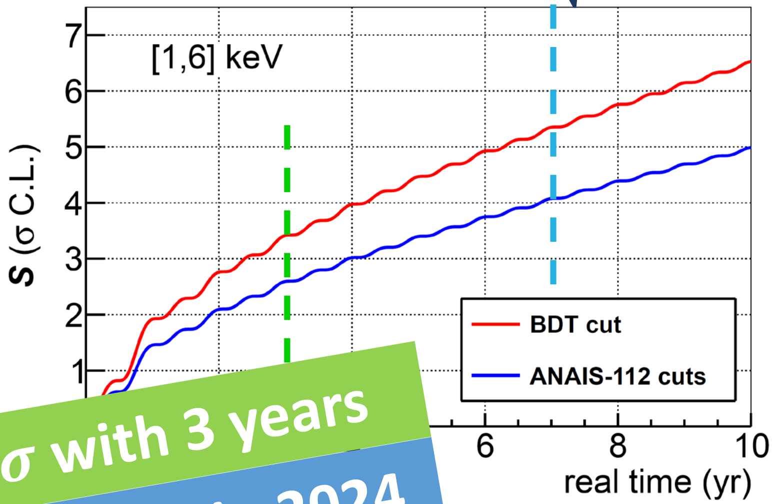


CUT on BDT parameter applied to background

(10% bkg unblinded events)

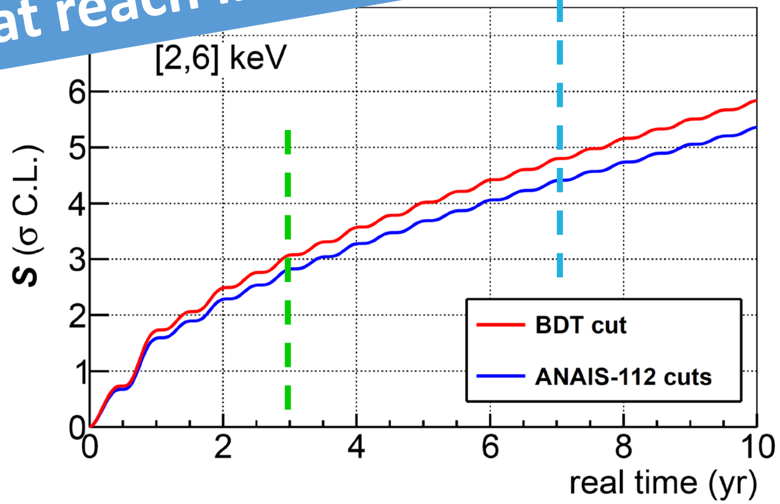






> 3σ with 3 years

5σ at reach in 2024



3-years annual modulation with BDT cut

[1-6] keV

Null hyp χ^2/ndf: 1019.37/972 [p_{val}=0.142]

Mod hyp χ^2/ndf: 1019.14/971 [p_{val}=0.138]

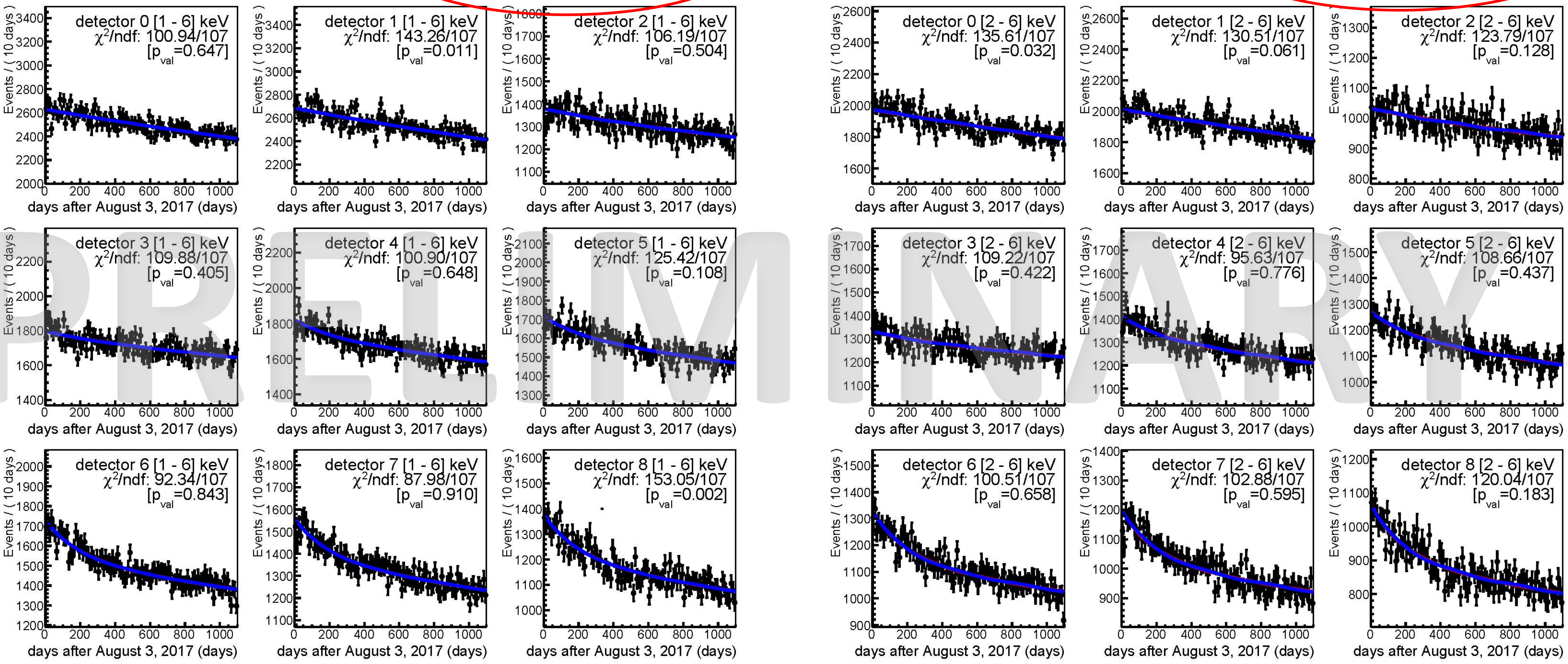
S_m = (-0.0015 ± 0.0032) (cpd/kg/keV)

[2-6] keV

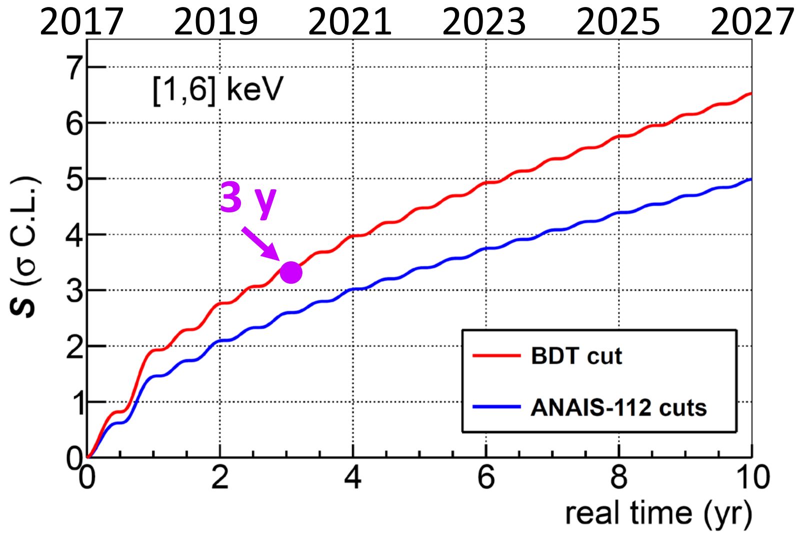
Null hyp χ^2/ndf: 1027.24/972 [p_{val}=0.107]

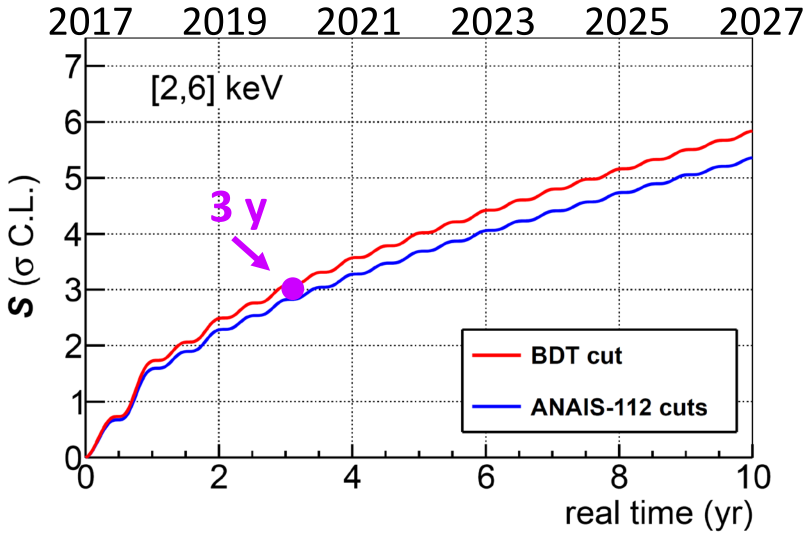
Mod hyp χ^2/ndf: 1025.81/971 [p_{val}=0.108]

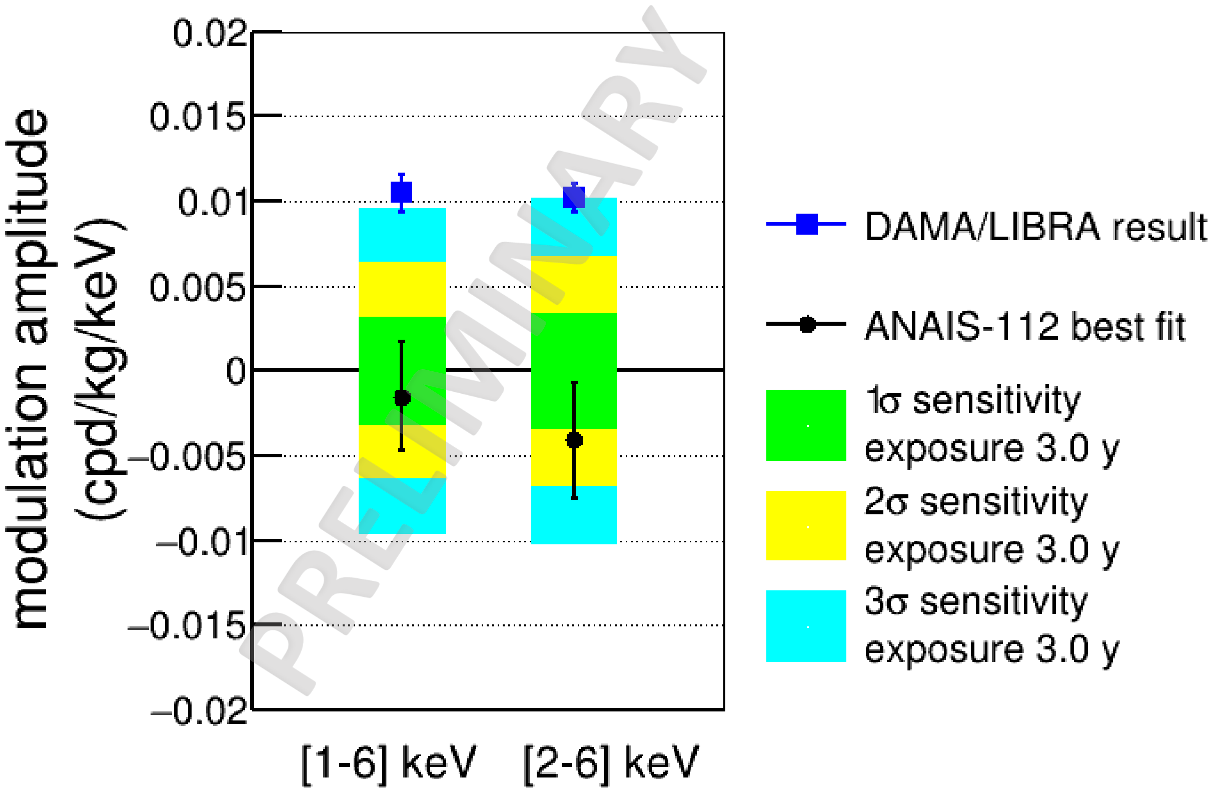
S_m = (-0.0041± 0.0034) (cpd/kg/keV)



3-years annual modulation with BDT cut







best fit modulation amplitudes compatible with zero at ~1σ
Best fit incompatible with DAMA/LIBRA at 3.75 (4.2) σ for [1-6] ([2-6]) keV
Sensitivity with 3 years data: 3.3 (3.0) σ for [1-6] ([2-6]) keV

Summary

- 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 @ LSC **since 3rd August 2017** with excellent performances. Up to now it has accumulated more than 580 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 is incompatible with DAMA/LIBRA DM interpretation with 3 sigma sensitivity. 5 sigma at reach in 2024.**
- We are **analyzing quenching factor on NaI crystals** to discard systematic uncertainties in the comparison. **Preliminary results have been presented and results will be released soon.**

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Thanks!!

gifna.unizar.es/anais/

ANAIS

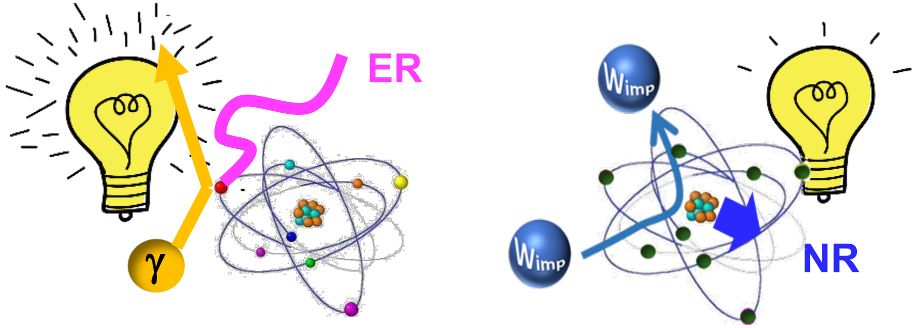
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

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, A. Salinas, M.L. Sarsa, P. Villar

Backup

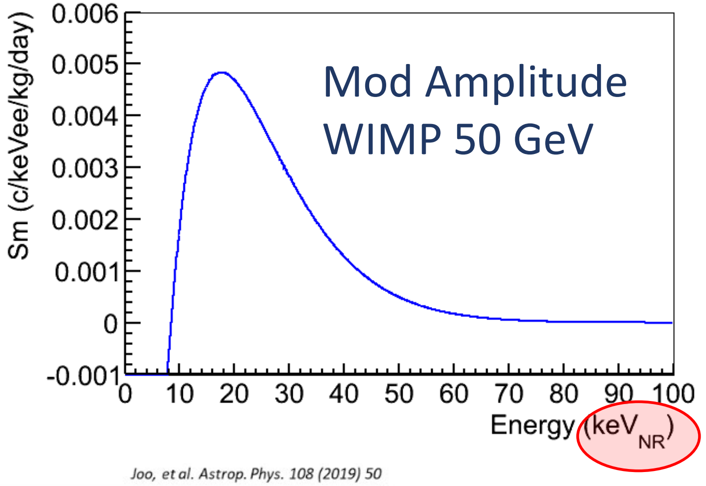
Testing DAMA/LIBRA with NaI(Tl) scintillators

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

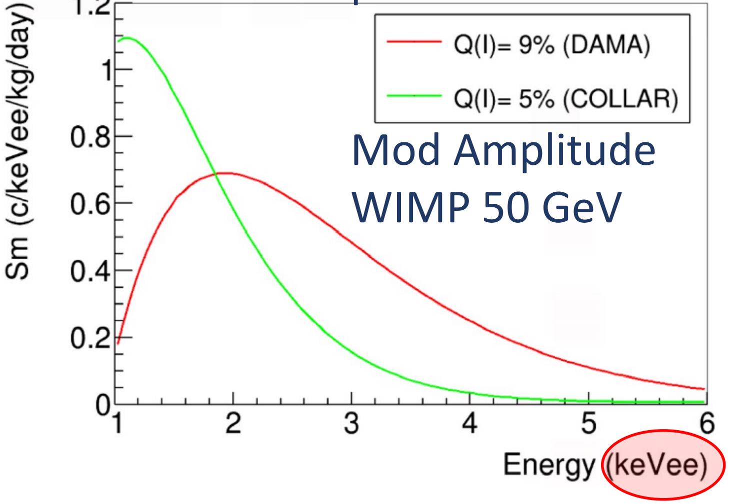


$$Q = \frac{light_{NR}/keV}{light_{ER}/keV}$$

The “true” NR energy is:

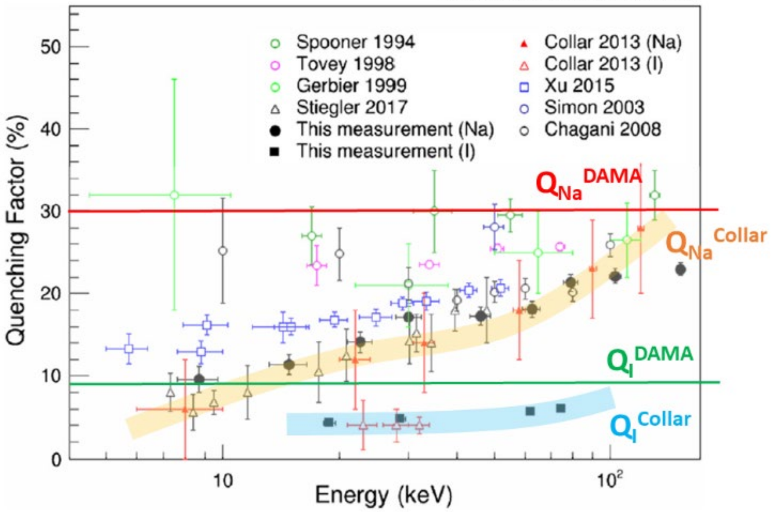


What the experiments “see”:



Experimental Q(Na) & Q(I) measurements:

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



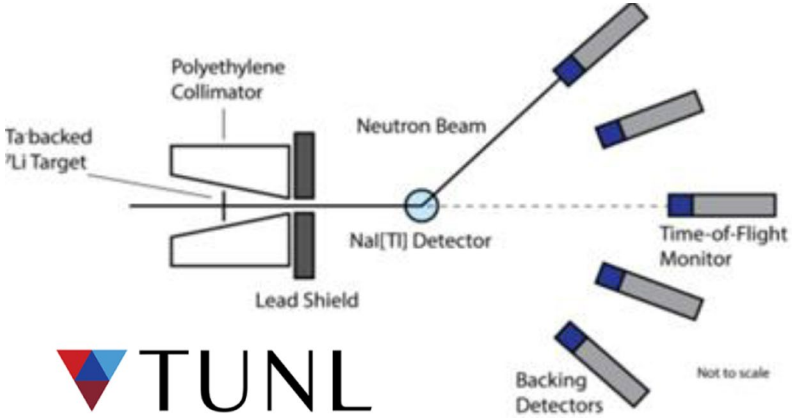
Systematics in the measurements or crystal dependency?

NaI(Tl) quenching factor measurement @ TUNL

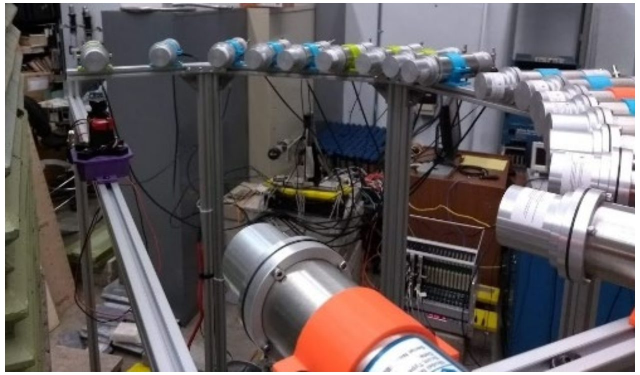
Collaboration between Yale, Duke and ANAIS

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

J. Physics (Conference series) **2156** (2022) 012065

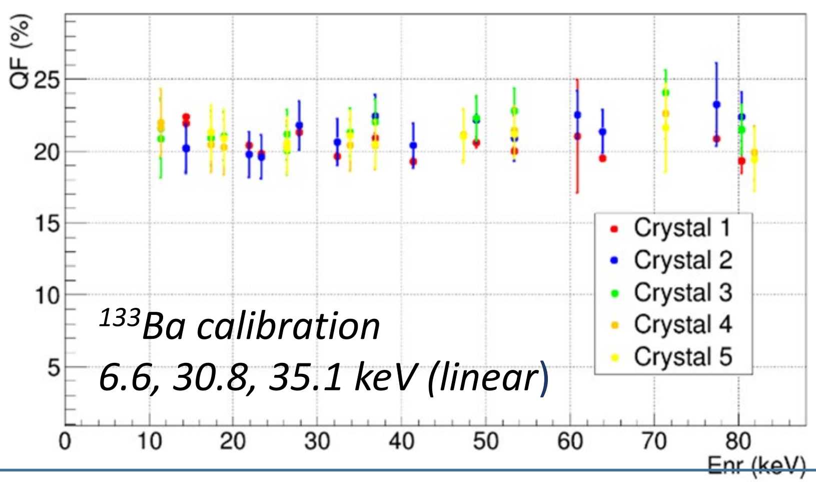


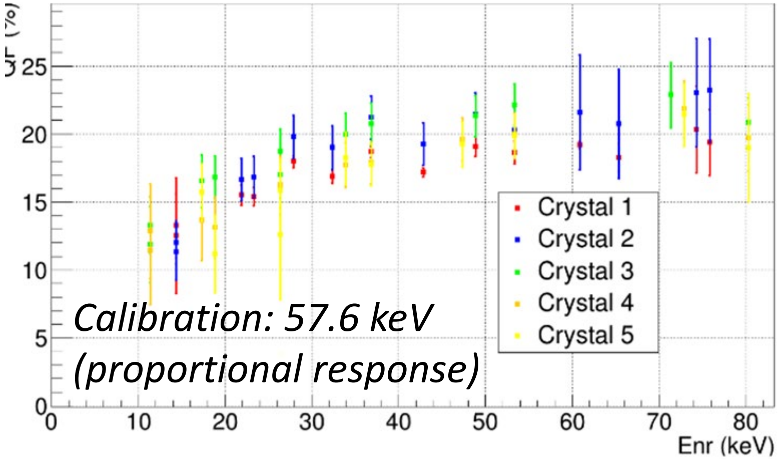
TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY



Results for Na:

- No differences among different crystals
- QF_{Na}~20% @ 30 keVNR, but energy calibration method changes the energy dependence (non-linearity!)





Results for I:

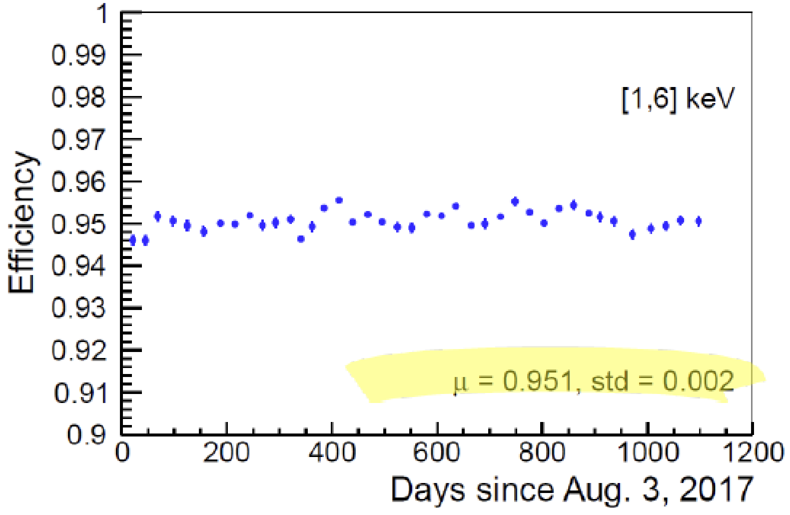
- Lower energy threshold needed for this measurement
- Only upper limits for two of the crystals

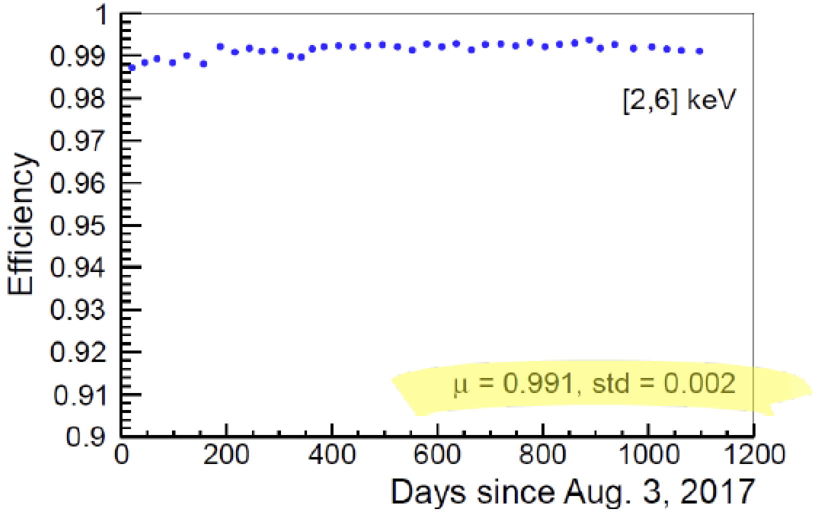
QF_I < 9.4 % @ 11.5 keV
QF_I < 8.2 % @ 13.6 keV

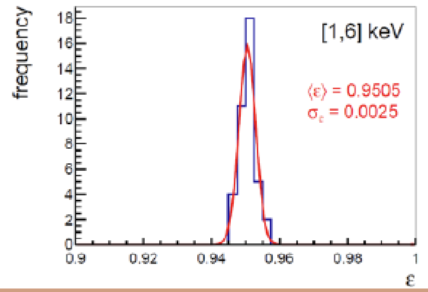
Efficiency stability

Efficiency stability and associated systematic uncertainty

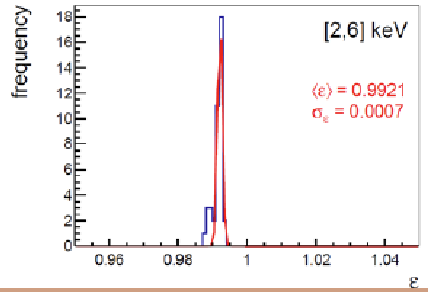
We are working on determining the possible variation in time of the BDT's efficiencies
Using ^{109}Cd data for the first three years with all detectors averaged







0.5%



0.33%

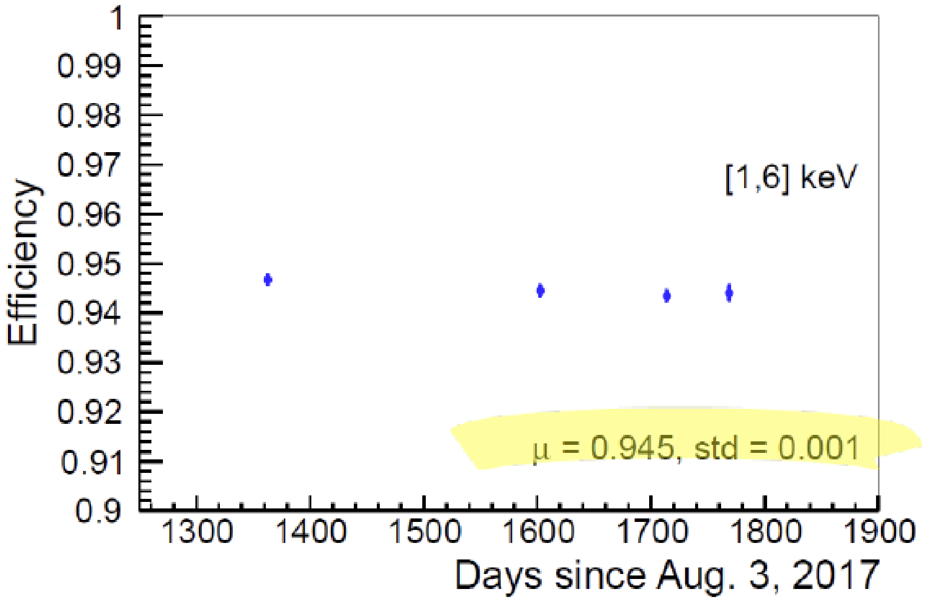
Systematic uncertainty is taken as half the difference between maximum and minimum values

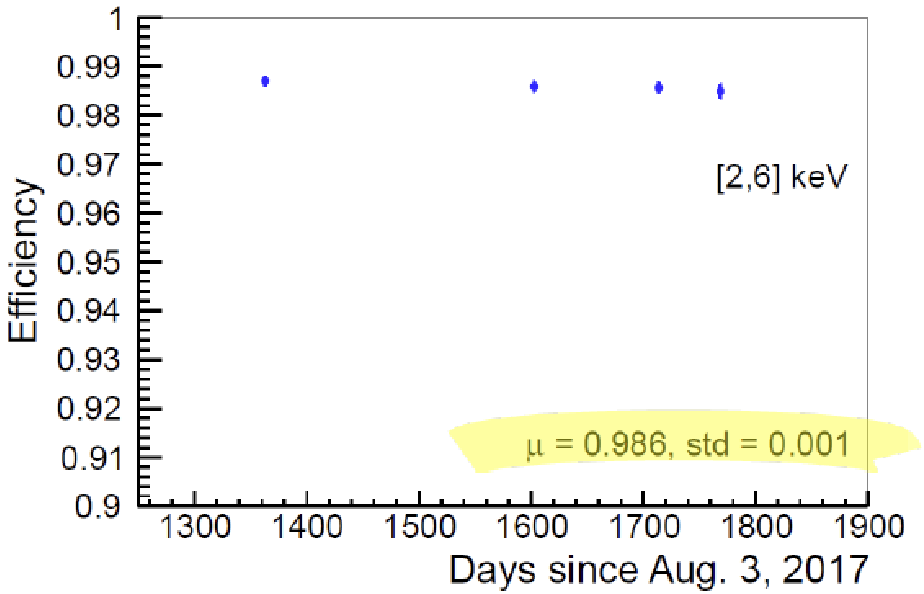
Efficiency stability

Efficiency stability and associated systematic uncertainty

We are working on determining the possible variation in time of the BDT's efficiencies

Using neutron data (4^{th}-5^{th} years)





NaI(Tl) radiopurity

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

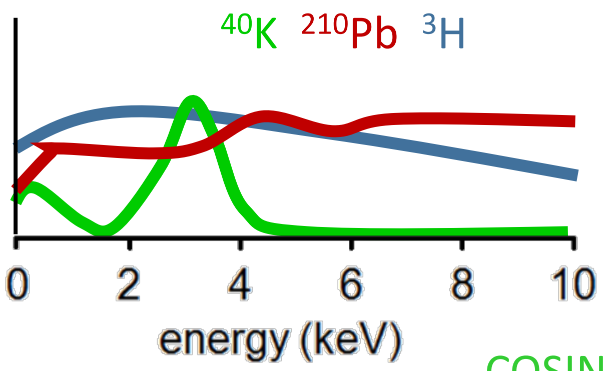
Large mass

Stable conditions over years

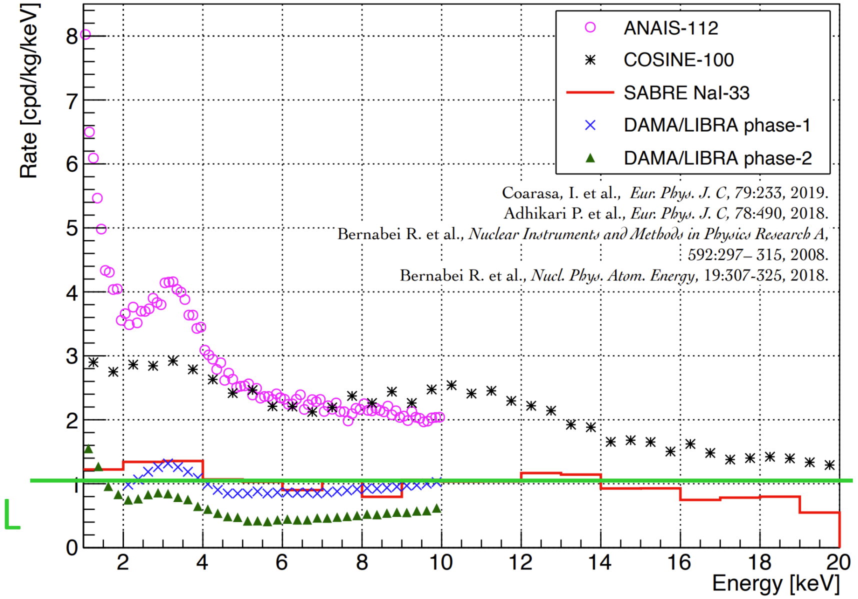
Very low radioactive background

High efficiency at very low energy

- **Main bkg contribution comes from the crystal itself**
- Long effort of ANAIS team looking for ultra pure NaI(Tl), **R&D with Alpha Spectra → crystals now used by ANAIS-112 and COSINE-100**
- **only very recently the quality of the DAMA crystals is at reach!**



COSINE-200 & PICOLON GOAL



	DAMA	ANAIS-112/ COSINE-100	SABRE(*)	PICOLON(*)	COSINE-200(*)	COSINUS
K (ppb)	13	18-40	2.2	<20	<42	Can discriminate NR / ER
^{210}Pb (μBq/kg)	10-30	700-3000	410	<5	$\sim$ 10	

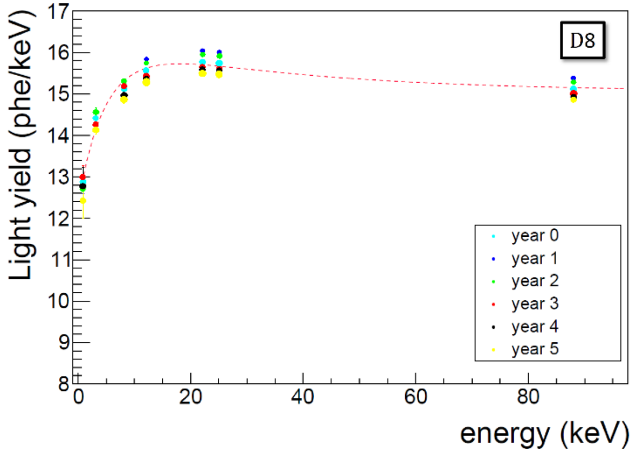
(*) contamination levels achieved in prototypes

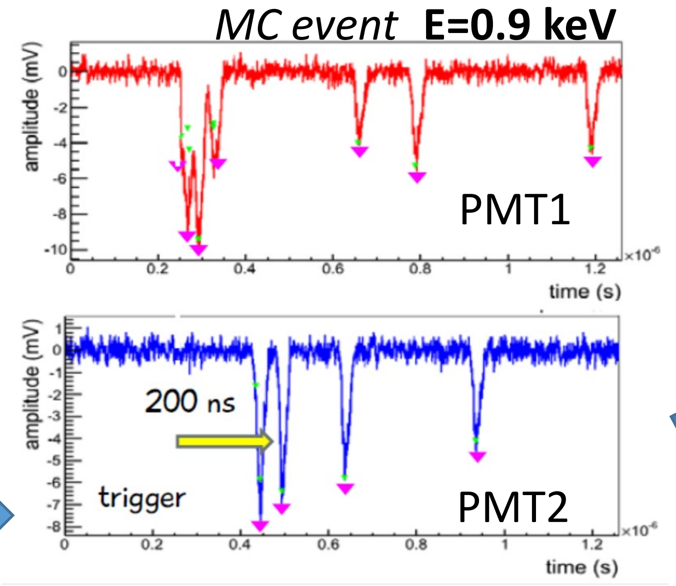
Trigger efficiency

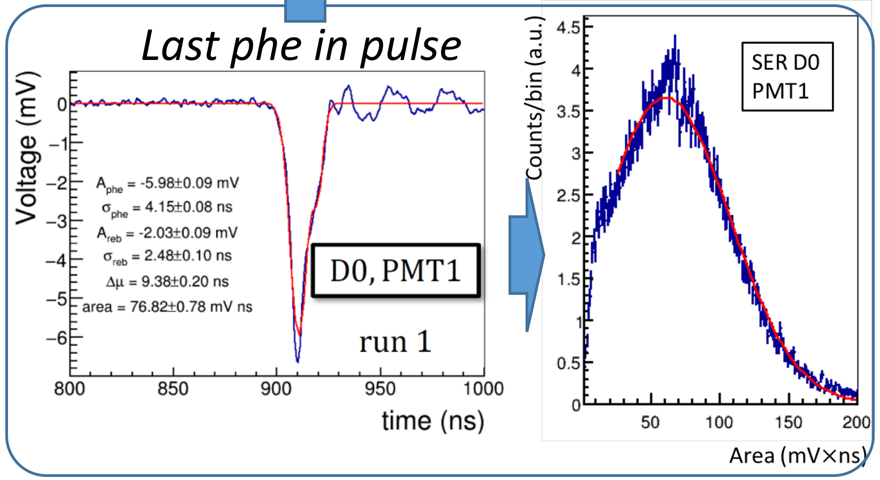
Trigger condition: PMT1 AND PMT2 in 200 ns coincidence window

Trigger efficiency vs energy evaluated by a MC “scintillation” simulation. Inputs:

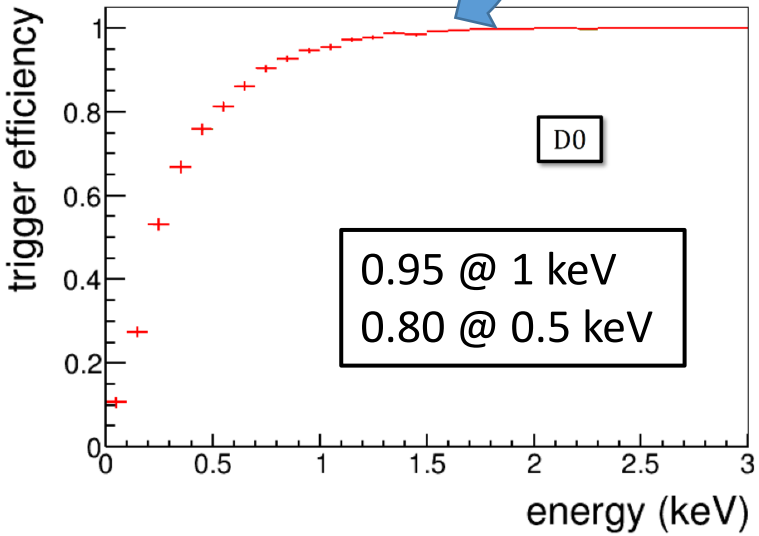
- Baseline DC & RMS
- NaI(Tl) scintillation constant (230 ns)
- SER (phe amplitude, rms, σ)
- Light yield (energy dependent)







For every energy, count number of MC events that trigger in a 200 ns coincidence window

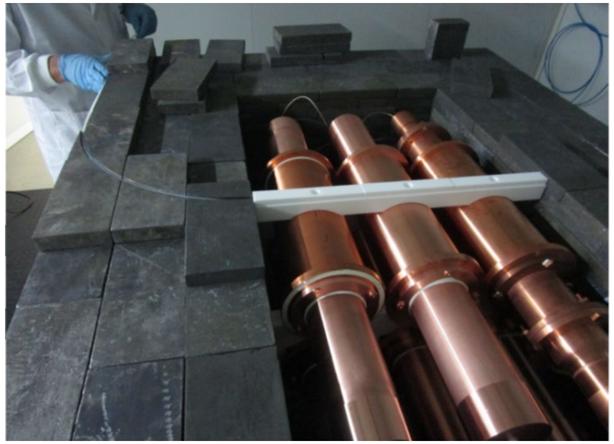


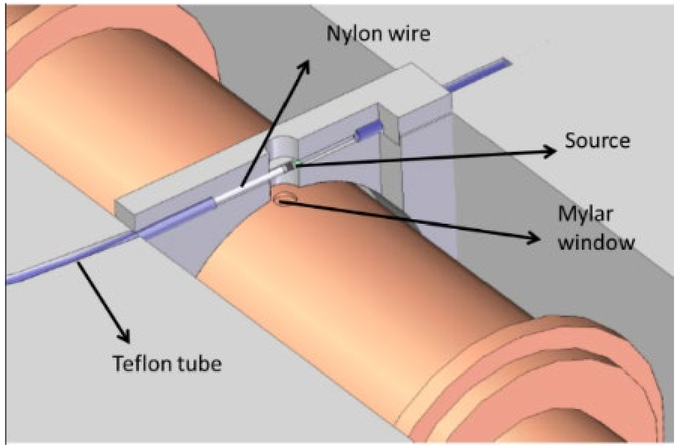
Low energy calibration

Detectors equipped with a **Mylar window**!

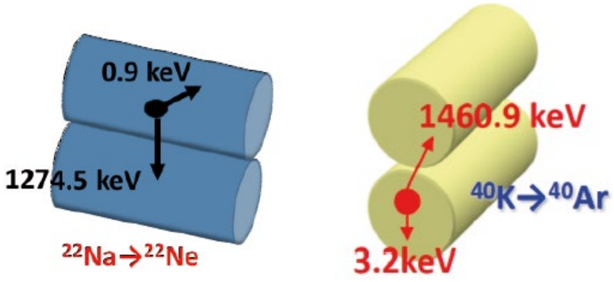
Radon-free system for low energy calibration:

- ^{109}**Cd sources** on flexible wires (radon-free)
- Energies: 11.9, 22.6 and 88.0 keV
- Simultaneous calibration of the nine modules
- Performed every two weeks





- In addition to the ^{109}Cd lines (**22.6**, **11.9 keV**), for calibration & filtering protocols we use also internal bulk contaminants ^{22}Na and ^{40}K summed up every 1.5 months



identified by coincidences with high energy gammas