Updated background studies for the ANAIS dark matter experiment

- ANAIS-112: goal, set-up, performance, results
- Background studies: first model, updates
- ANAIS+: prospects

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

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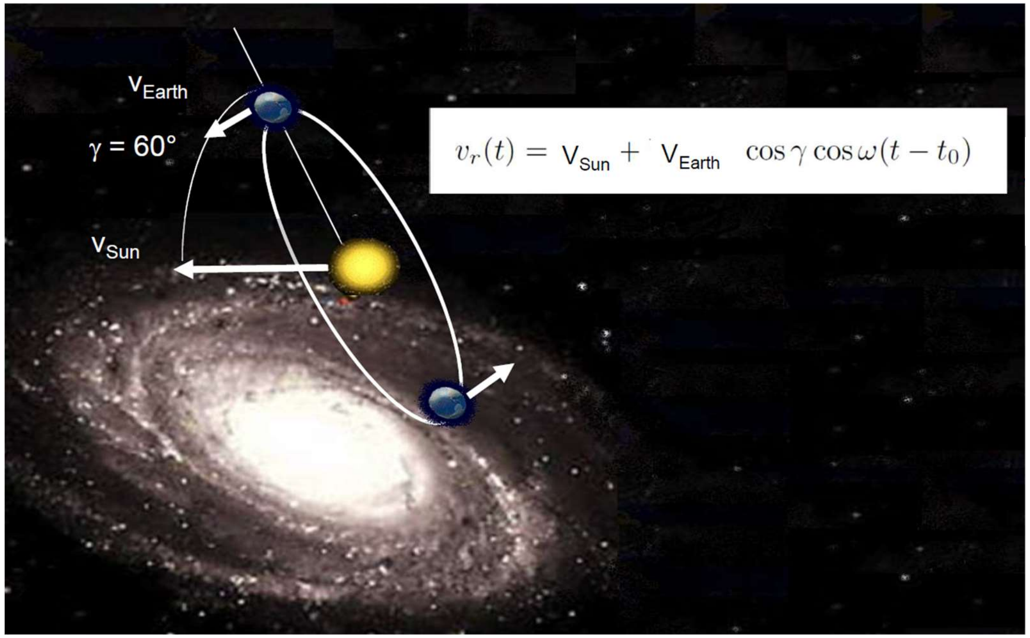
Goal: Dark Matter annual modulation



Interaction rate of WIMPs

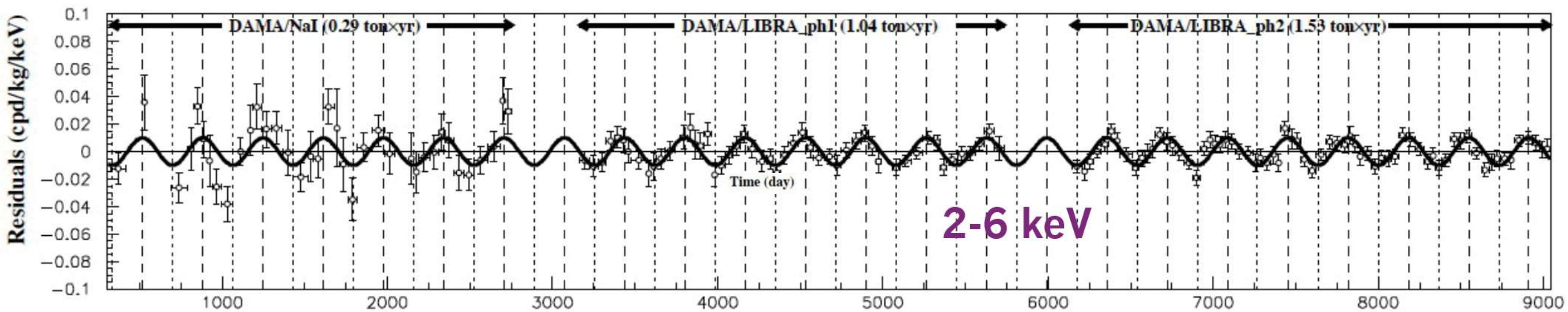
$$S_k(t) = S_{0,k} + S_{m,k} \cos\omega(t - t_0)$$

k: energy bin

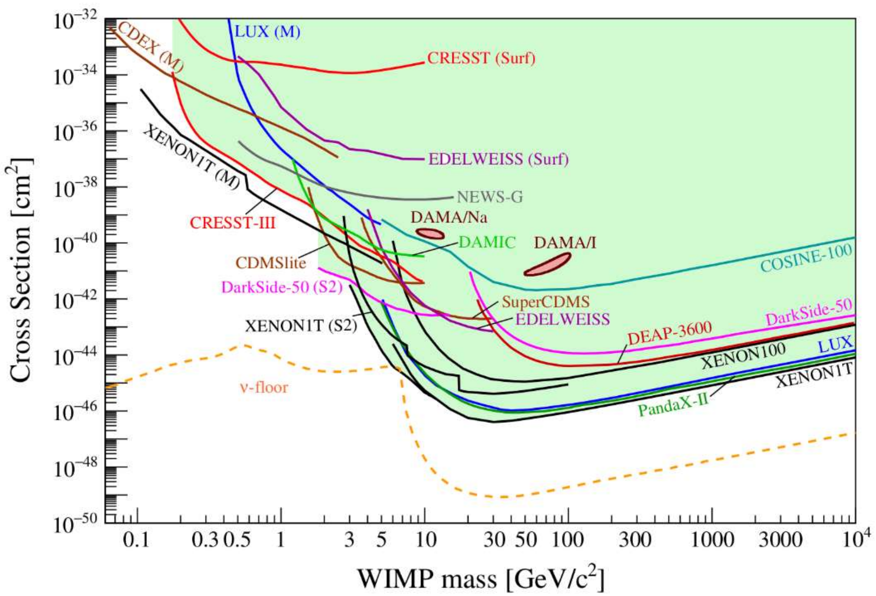
- ✓ 1 year period (for SHM)
- ✓ Maximum around June 2nd
- ✓ Weak effect (1-10%)
- ✓ Only noticeable at low energy

Observed annual modulation signal by **DAMA/LIBRA experiment** (at LNGS, Italy) over 22 y compatible with DM (2.86 t x y) at 13.7σ CL

S_m = (0.01014 ± 0.00074) cpd/kg/keV



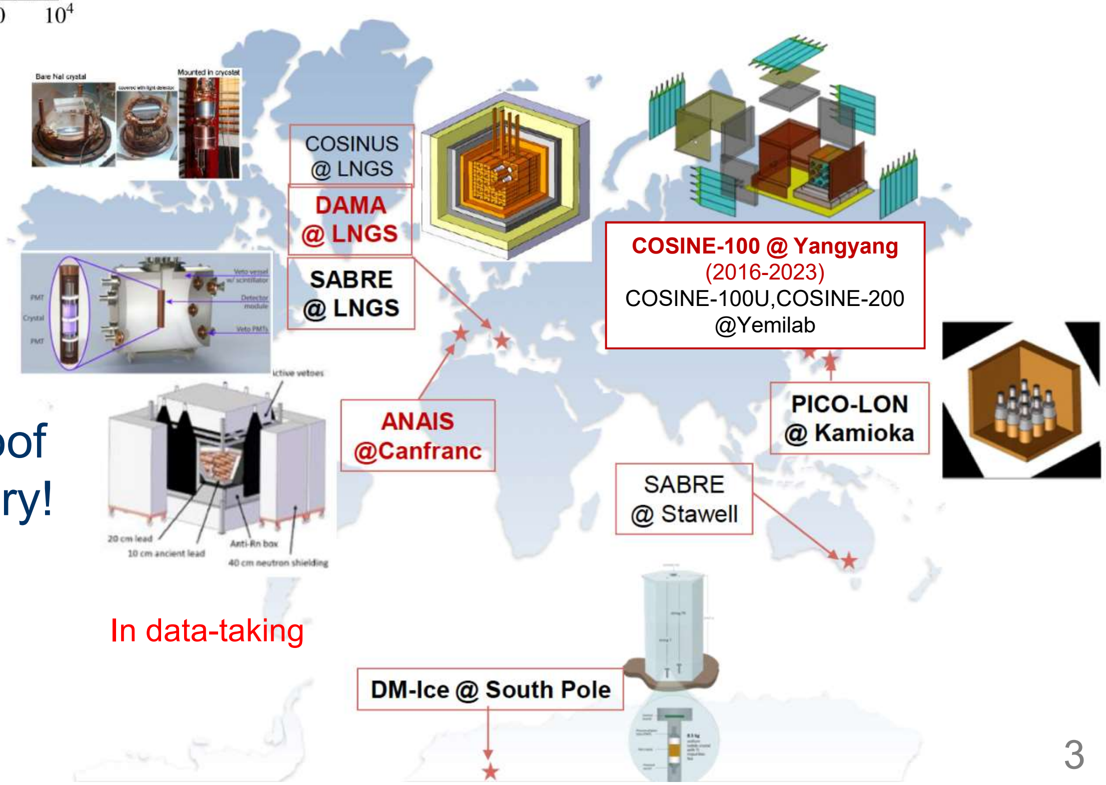
Goal: Dark Matter annual modulation



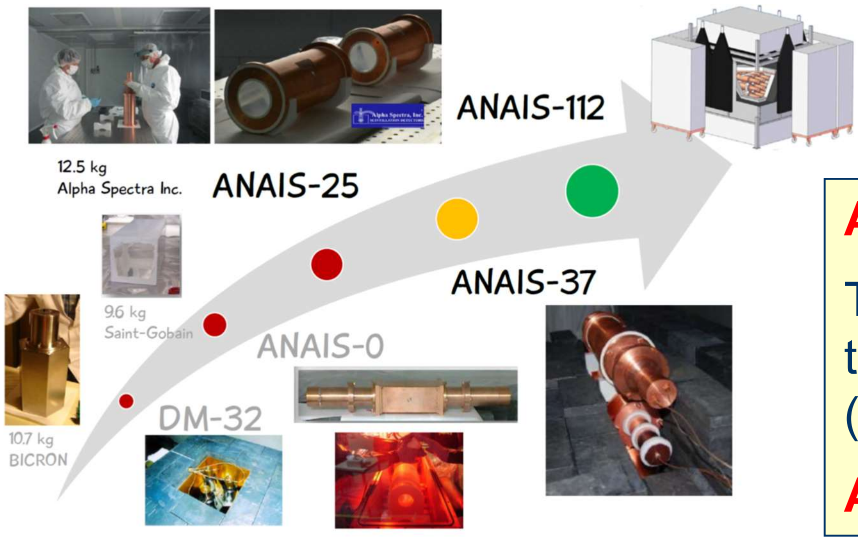
APPEC Committee Report, Rep. Prog. Phys. 85 (2022) 056201

Strong tension when interpreting DAMA/LIBRA annual modulation signal as due to DM, even assuming more general halo / interaction models

A model-independent proof / disproof with **the same NaI target** mandatory!



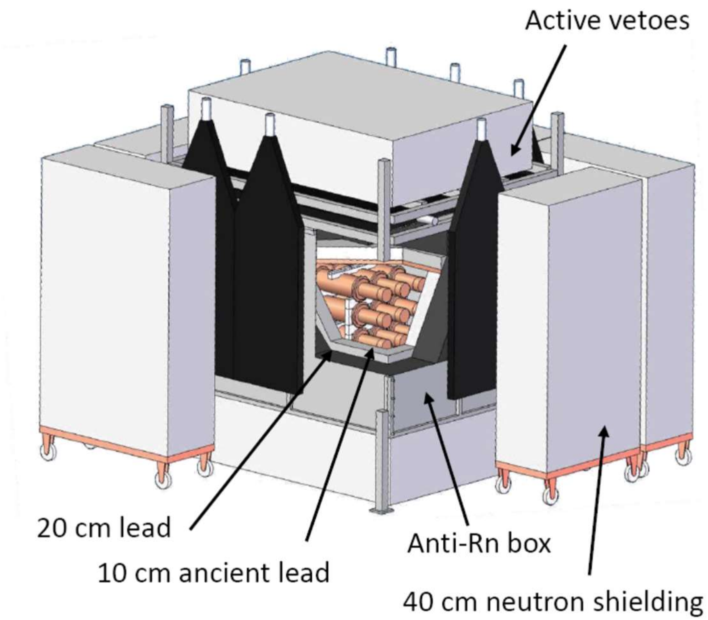
ANAIS: goal and set-up



ANAIS (*Annual modulation with NAI Scintillators*)

To confirm or refute DAMA/LIBRA result using the same technique at a different location (**Canfranc Underground Laboratory)**

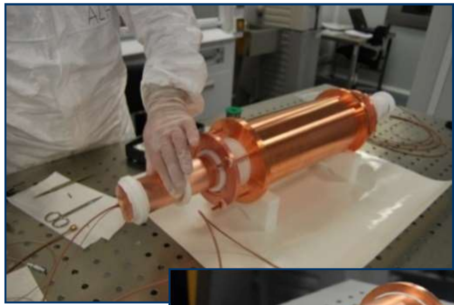
ANAIS-112: 9 detectors, 112.5 kg NaI(Tl)



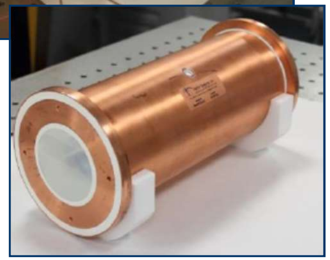
ANAIS-112: performance

− 9 ultrapure NaI(Tl) crystals from Alpha Spectra Company

Detector	*Quality powder*	*Received at Canfranc in*
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017



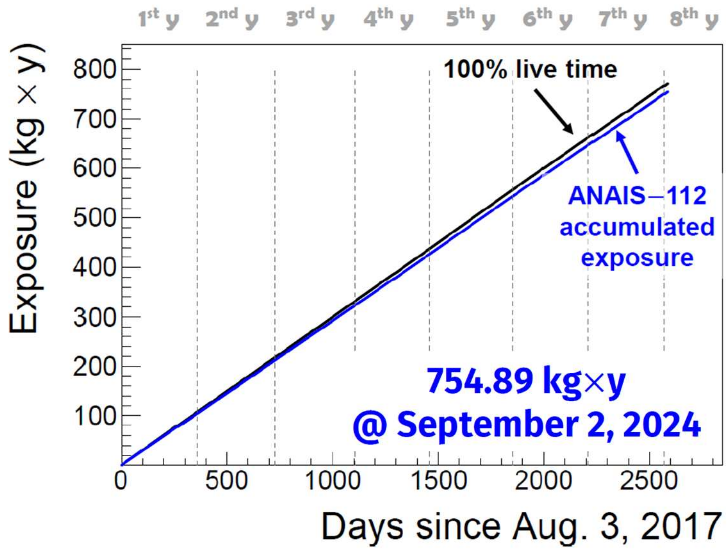
12.5 kg each
4.75" diameter
11.75" length



− Cylindrical modules coupled to 2 PMTs (Hamamatsu R12669SEL2) with high QE (~40%)
− Mylar window in copper vessel for external calibration

J. Amaré et al, Eur. Phys. J. C 79 (2019) 228

− Data taking ongoing **since August 2017**, with ~95% live time
− Excellent **light collection** and **energy threshold** in all modules: **~15 phe/keV, 1 keV_{ee}**
− New electronics running in parallel to improve noise rejection

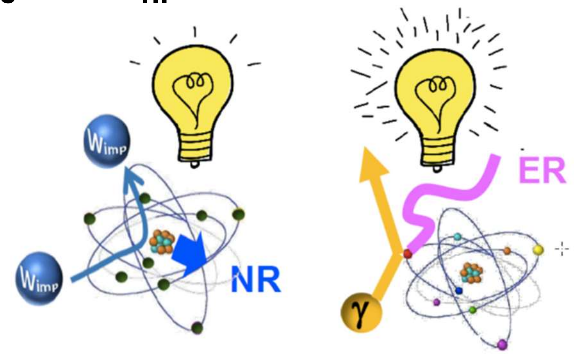


ANAIS-112: quenching factor determination

Relative efficiency factor for nuclear recoil scintillation $E_{ee} = Q\, E_{nr}$

Large dispersion between the many available measurements of Q for different **NaI detectors**

$Q_{Na}^{DAMA} = 30\ \%$
$Q_{I}^{DAMA} = 9\ \%$

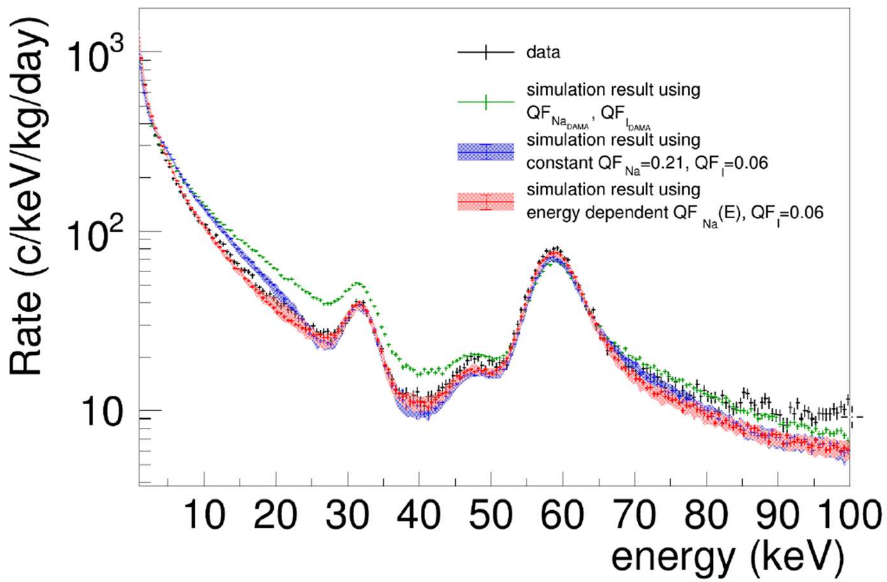


In a scintillator, an **ER** produces much more light than a **NR** of the same energy!

➡ ***Q* determination for ANAIS−112** crystals ongoing following two approaches

1) **Comparing neutron calibration** data with ^{252}Cf source **with MC simulation**, assuming a certain Q
   - Constant Q_{DAMA} not compatible with ANAIS data
   - Energy-dependent Q (at least for Na) favoured

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



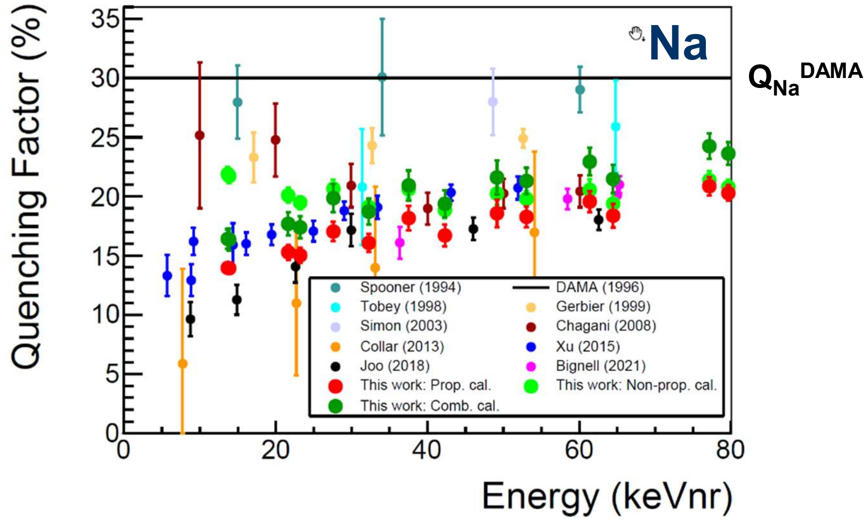
ANAIS-112: quenching factor determination

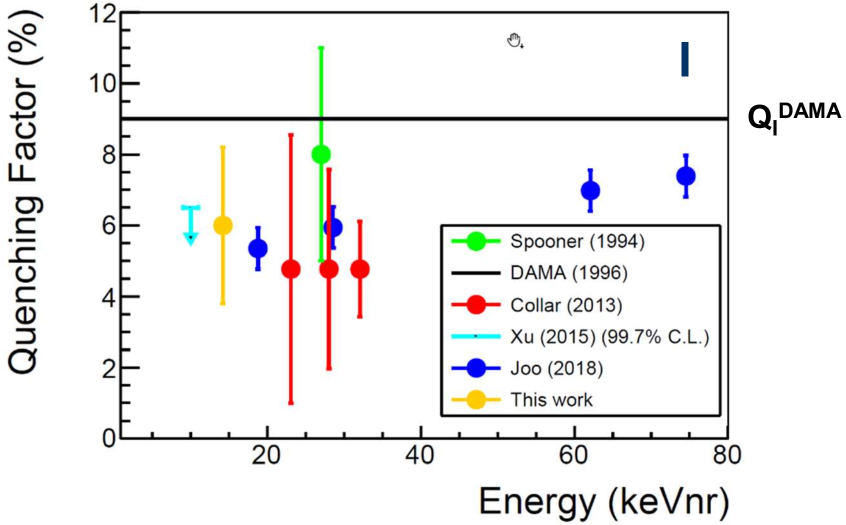
2) Measurements at TUNL (Duke University, US) in collaboration with COSINE using a **neutron beam**

Five small crystals from ANAIS supplier with different powder quality

- Noticeable differences for different energy calibrations (NaI non-linearity)
- Lower Q than DAMA/LIBRA measurement

D. Cintas et al, Phys. Rev. C 110 (2024) 014613





ANAIS-112: annual modulation results

- Published annual modulation analysis of 3 y data

- Least square fit of the counting rate

$$\chi^2 = \sum_i \frac{(n_i - \mu_i)^2}{\sigma_i^2}$$

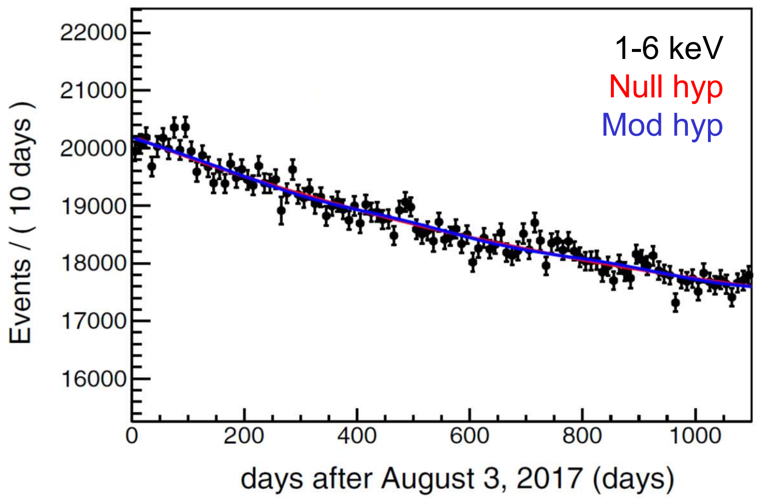
$$\mu_{i,d} = \left[R_{0,d}\left(1 + f_d \phi^{MC}_{bkg,d}(t_i)\right) + S_m \cos(\omega(t_i - t_0))\right] M_d \Delta E \Delta t$$

detector d, time bin i

- Null hypothesis well supported
- Best fits for amplitude **incompatible with DAMA/LIBRA at 3.3 (2.7)σ** for 1-6 (2-6) keV_{ee}

S_m= (-0.0034 ± 0.0042) cpd/kg/keV (1-6 keV)
S_m= (0.0003 ± 0.0037) cpd/kg/keV (2-6 keV)

Phys. Rev. D 103 (2021) 102005



- Reanalysis of 3 y data after applying **machine learning techniques** to improve sensitivity: region of interest dominated by **non-bulk scintillation events**

I. Coarasa et al, JCAP11(2022)048; arXiv:2404.17348, accepted in Comm. Phys.

- Analysis of 6 y data preliminary results

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First background model: inputs

Detailed **background model** for each detector of **ANAIS-112**, based on Geant4 Monte Carlo **simulations** and accurate quantification of **background sources**

J. Amaré et al, Eur. Phys. J. C 76 (2016) 429, Eur. Phys. J. C 79 (2019) 412

– **Activity from external components** measured with HPGe detectors at Canfranc

Component	Unit	^{40}K	^{232}Th	^{238}U	^{226}Ra	Others
PMTs (R12669SEL2)	mBq/PMT	97±19	20±2	128±38	84±3	
		133±13	20±2	150±34	88±3	
		108±29	21±3	161±58	79±56	
		95±24	22±2	145±29	88±4	
		136±26	18±2	187±58	59±3	
		155±36	20±3	144±33	89±5	
mean activity all units	mBq/PMT	111±5	20.7±0.5	157±8	82.5±0.8	
Copper encapsulation	mBq/kg	<4.9	<1.8	<62	<0.9	^{60}Co: <0.4
Quartz windows	mBq/kg	<12	<2.2	<100	<1.9	
Silicone pads	mBq/kg	<181	<34		51±7	
Archaelogical lead	mBq/kg		<0.3	<0.2		^{210}Pb: <20
Inner volume air	Bq/m^3					^{222}Rn: 0.6

Upper limits at 95% C.L.

First background model: inputs

Detailed **background model** for each detector of **ANAIS-112**, based on Geant4 Monte Carlo **simulations** and accurate quantification of **background sources**

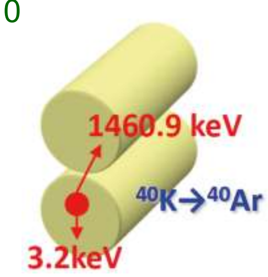
J. Amaré et al, Eur. Phys. J. C 76 (2016) 429, Eur. Phys. J. C 79 (2019) 412

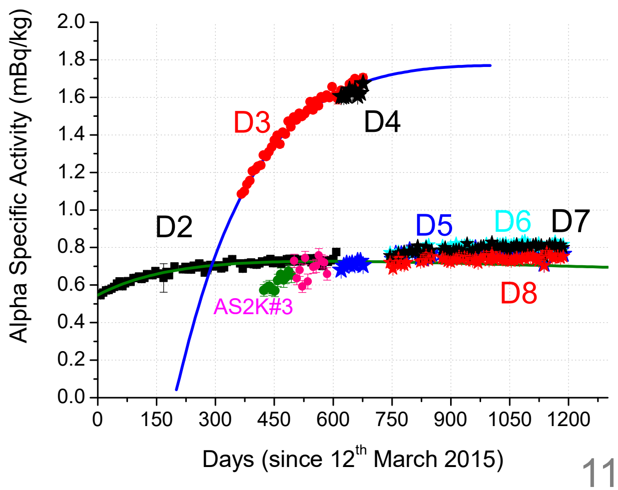
– **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb

Detector	^{40}K (mBq/kg)	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.33±0.04	(4±1) 10^{-3}	(10±2) 10^{-3}	3.15±0.10
D1	1.21±0.04			3.15±0.10
D2	1.07±0.03	(0.7±0.1) 10^{-3}	(2.7±0.2) 10^{-3}	0.7±0.1
D3	0.70±0.03			1.8±0.1
D4	0.54±0.04			1.8±0.1
D5	1.11±0.02			0.78±0.01
D6	0.95±0.03	(1.3±0.1) 10^{-3}		0.81±0.01
D7	0.96±0.03	(1.0±0.1) 10^{-3}		0.80±0.01
D8	0.76±0.02	(0.4±0.1) 10^{-3}		0.74±0.01

^{40}K: by identifying coincidences

C. Cuesta et al., Int. J. Mod. Phys. A. 29 (2014) 1443010





^{232}Th, ^{238}U: determined by alpha rate following PSA and analysis of BiPo sequences at a level of a few μBq/kg, but **^{210}Pb out of equilibrium**

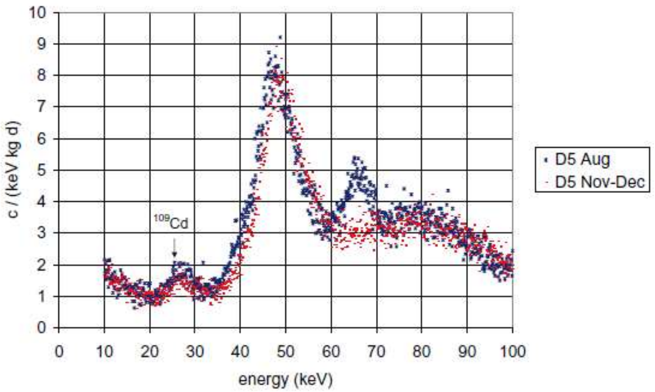
First background model: inputs

Detailed **background model** for each detector of **ANAIS-112**, based on Geant4 Monte Carlo **simulations** and accurate quantification of **background sources**

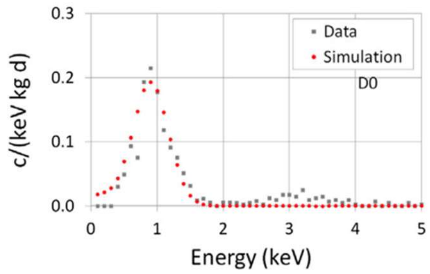
– **Cosmogenic activity** in crystals: short-lived Te, I isotopes, ^{3}H, ^{22}Na, ^{109}Cd, ^{113}Sn

J. Amaré et al, JCAP 02 (2015) 046; Astropart. Phys.97 (2018) 96; P. Villar et al, Int. J. Mod. Phys. A 33 (2018) 1843006

^{109}Cd, ^{113}Sn: from peaks at binding energies of K-shell electrons (after EC)

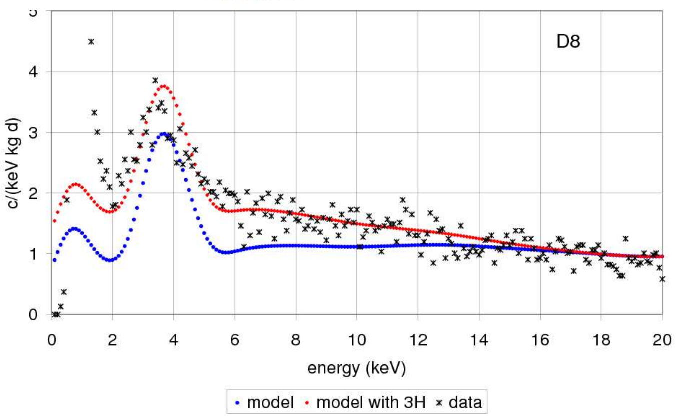


^{22}Na: from analysis of coincidences in different set-ups, validated comparing with measured rate at 0.9 keV peak



Detector	ANAIS-25 [41]	ANAIS-37 [42]	A37D3	ANAIS-112
D0	159.7 ± 4.9	158.4 ± 7.9	164 ± 17	155 ± 11
D1	159.7 ± 4.9			168 ± 11
D2		70.2 ± 3.9	57.6 ± 8.1	43.9 ± 6.0
D3			69.9 ± 3.6	68.6 ± 4.6
D4				61.8 ± 3.1
D5				43.7 ± 2.3
D6				53.8 ± 2.7
D7				55.6 ± 2.7
D8				56.4 ± 2.8

A_0 (kg^{-1} d^{-1})



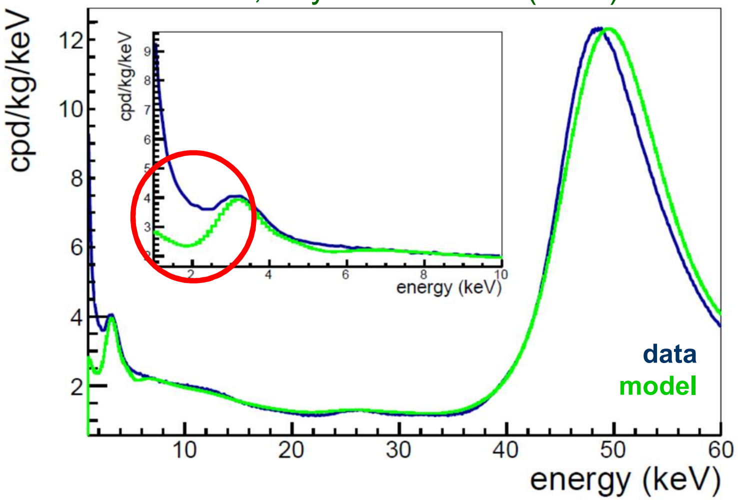
^{3}H: additional background source only in the very LE region

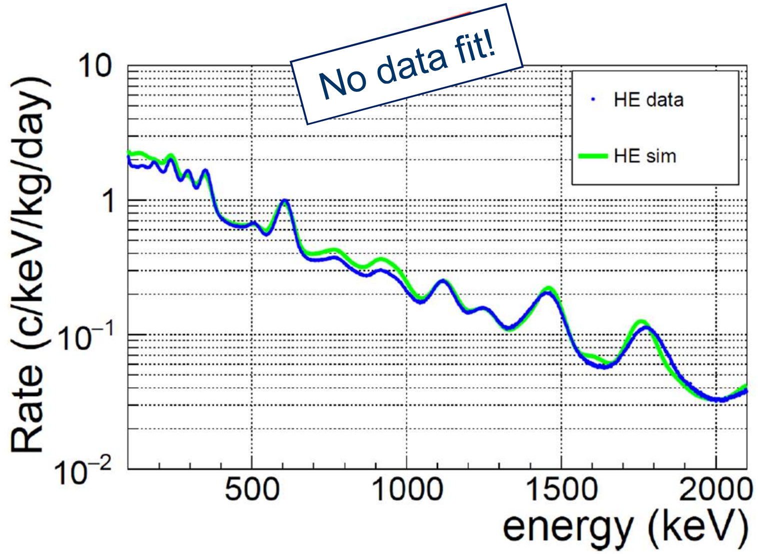
D0-D1: 0.20 mBq/kg, D2-D8: 0.09 mBq/kg

First background model: results

- Comparison with **ANAIS-112 spectra** (3y) at **low and high energy**

J. Amaré et al, Phys. Rev. D 103 (2021) 102005



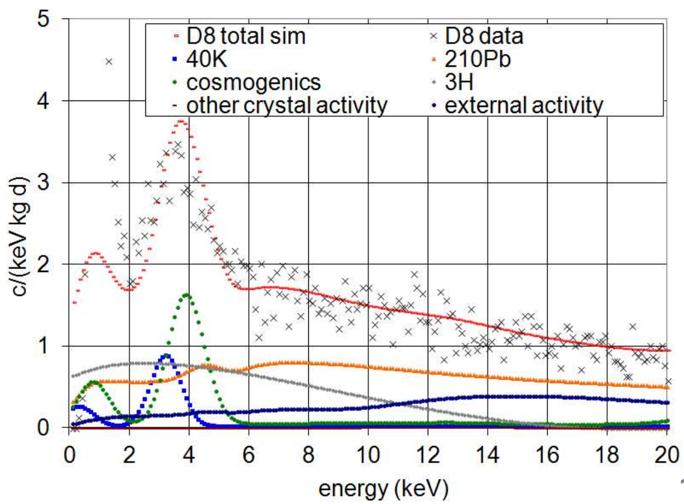


Unexplained events <3 keV could be due to:
- some unknown background source not considered in the model
- non-bulk scintillation events leaking in RoI

- **Individual contributions** in ANAIS-112

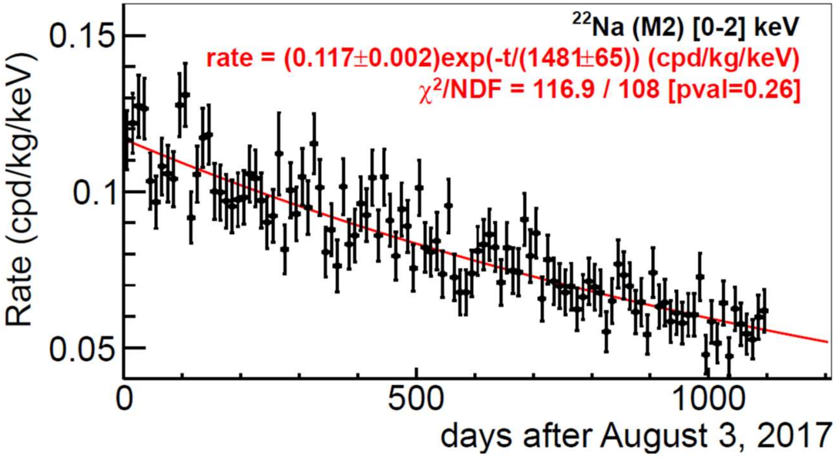
^{40}**K** and ^{22}**Na** peaks and ^{210}**Pb** (bulk+surface) and ^{3}**H** continua are main contributors in RoI

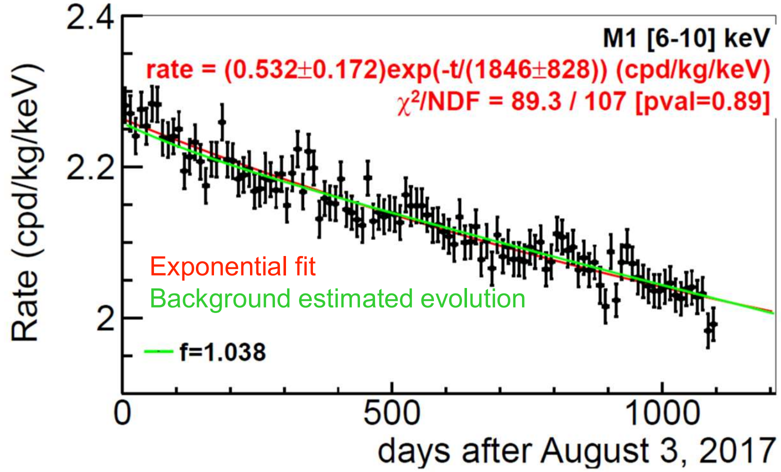
^{210}Pb:	32.5%	^{3}H:	26.5%
^{40}K:	12%	^{22}Na:	2.0%



First background model: results

- **Time evolution:**

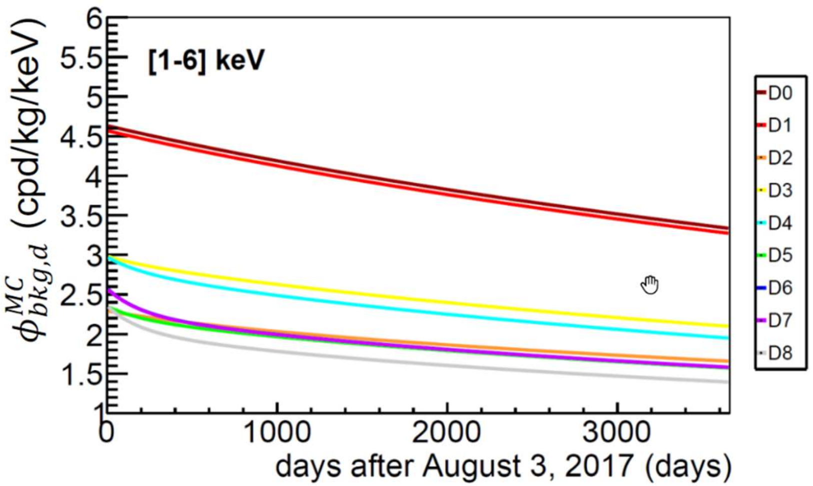




Measured rate of ^{40}**K** and ^{22}**Na** events (identified by coincidences with HE gamma) has proper decay

Model reproduces the rate decay inside and outside the RoI

Prediction from decaying **cosmogenics** and ^{210}**Pb** used in annual modulation analysis



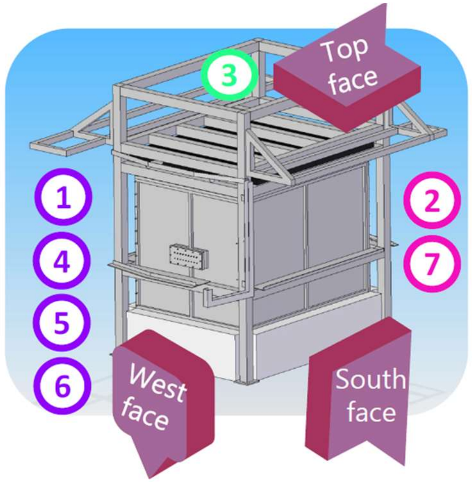
Machine-learning techniques: method

A **Boosted Decision Tree (BDT)** developed to improve the rejection of PMT-related noise: multivariate analysis combining several variables into one parameter

I. Coarasa et al, JCAP11(2022)048

- Training populations independent from background data:

- ***Signal***: in situ neutron calibrations with ^{252}Cf



- ***Noise:*** blank module

BDT

Standard analysis

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

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

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

$x = 50, 100, 200, 300, 400, 500, 600, 700, 800$ ns

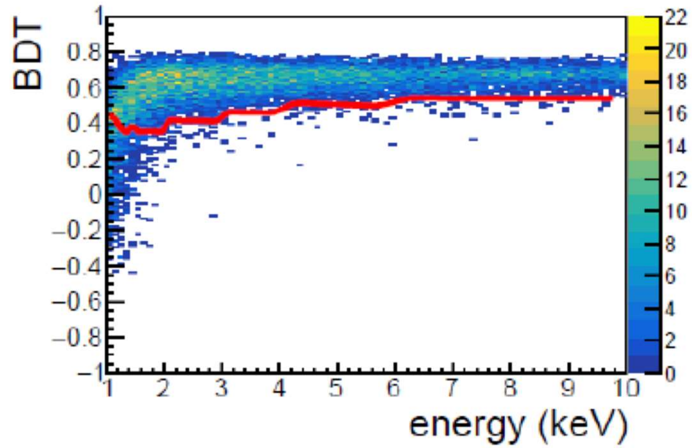
Machine-learning techniques: method

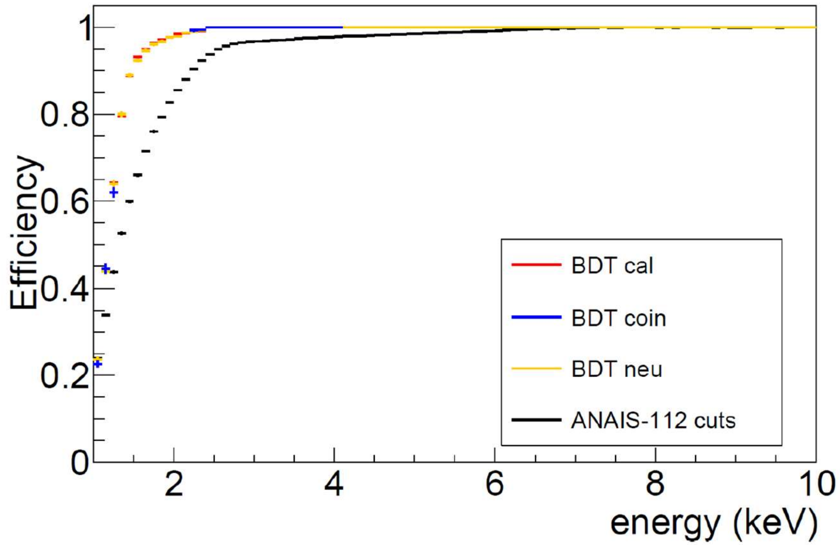
A **Boosted Decision Tree (BDT)** developed to improve the rejection of PMT-related noise: multivariate analysis combining several variables into one parameter

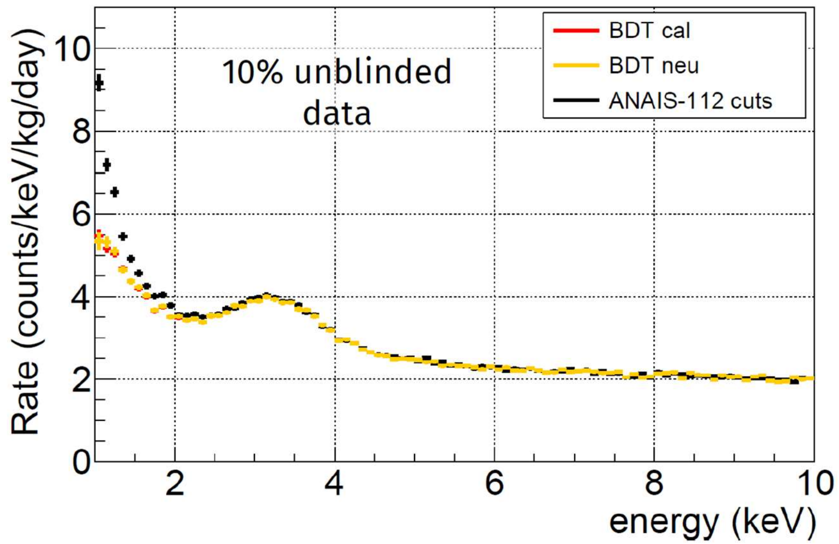
I. Coarasa et al, JCAP11(2022)048

- **Cuts** on BDT (-1 noise, +1 signal) defined for each energy bin and detector

- Much improved **acceptance efficiency** by **30%** and **background reduction** by **~18%** in1-2 keV, although with still some excess over background model





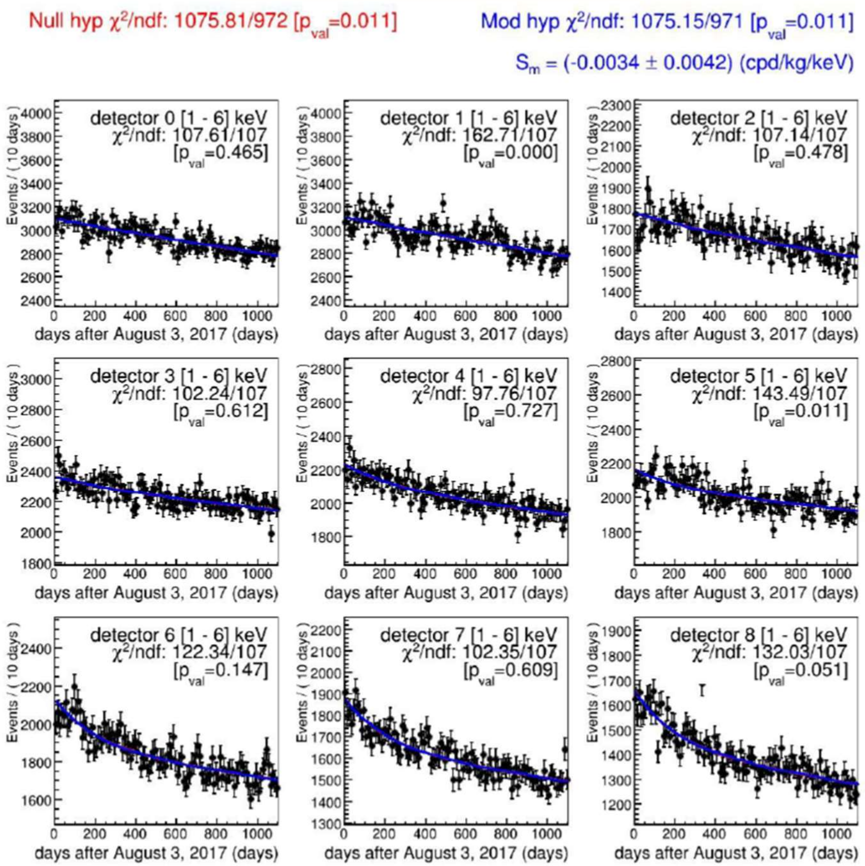


Machine-learning techniques:results for annual modulation

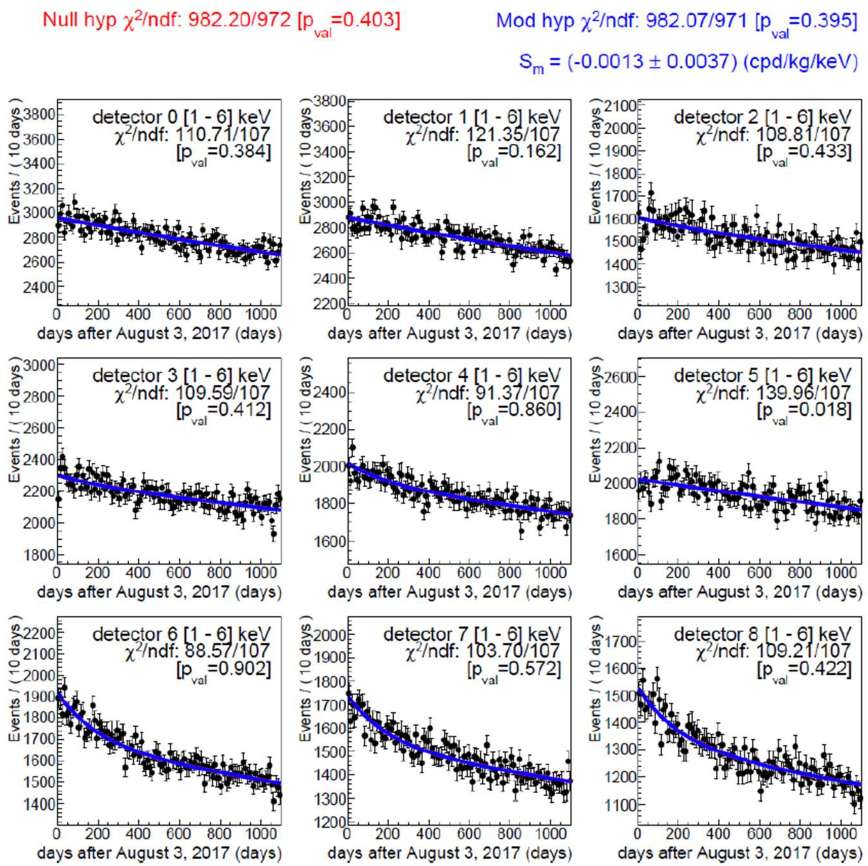
Improved annual modulation results with **3 y data** **2.5σ → 2.8σ**

I. Coarasa et al, arXiv:2404.17348, accepted in Comm. Phys.

PRD103(2021)102005



arXiv:2404.17348



Incompatible with DAMA/LIBRA at **3.2σ (1.9σ)**, with a present sensitivity of 2.8σ

Machine-learning techniques:results for annual modulation

Preliminary annual modulation results with **6 y data**

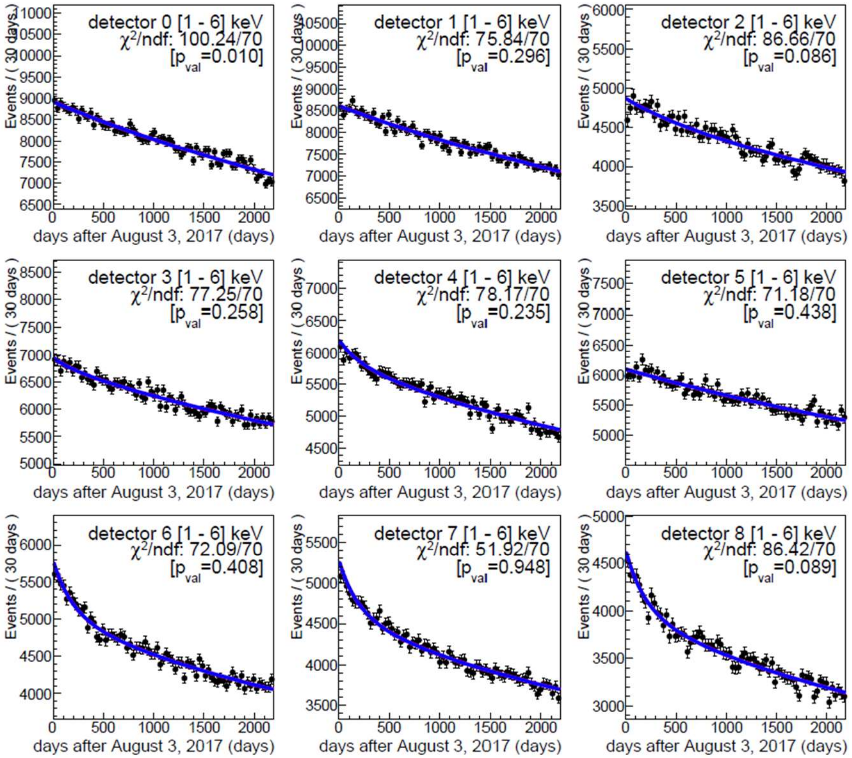
642.05 kg × y

[1-6] keV: **4.2σ**

Null hyp χ^2/ndf: 699.60/639 [p_{val}=0.048]

Mod hyp χ^2/ndf: 699.53/638 [p_{val}=0.046]

S_m = (0.0007 ± 0.0025) (cpd/kg/keV)

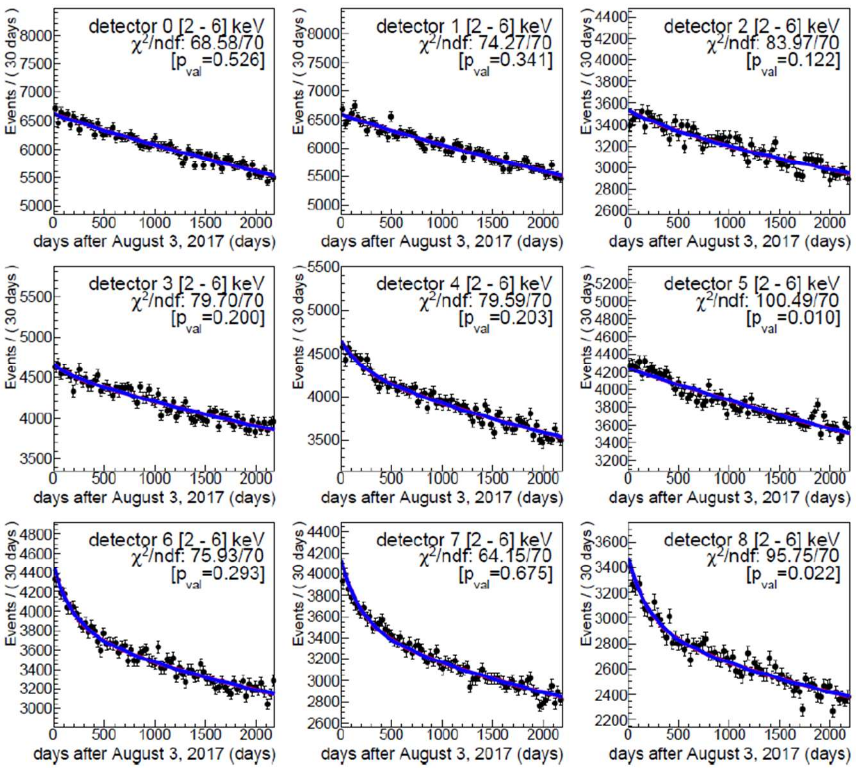


[2-6] keV: **4.1σ**

Null hyp χ^2/ndf: 723.68/639 [p_{val}=0.011]

Mod hyp χ^2/ndf: 722.17/638 [p_{val}=0.011]

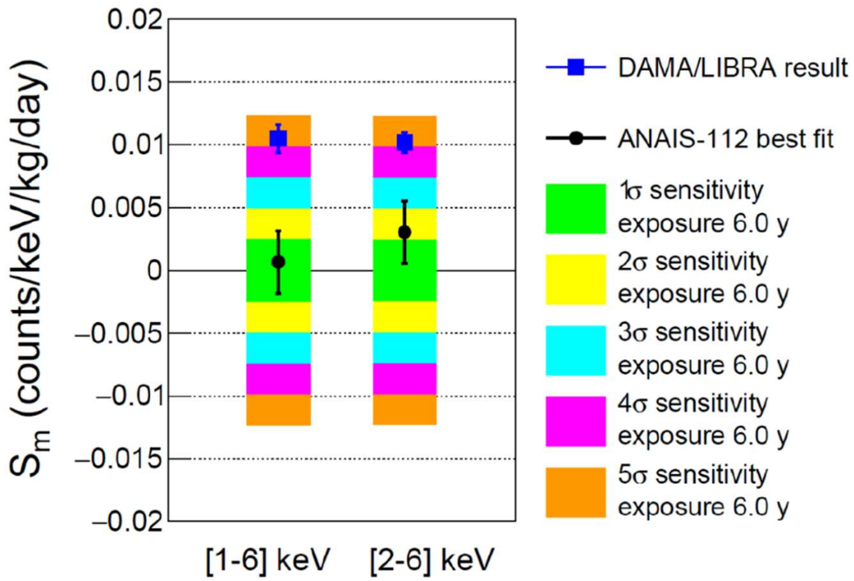
S_m = (0.0030 ± 0.0025) (cpd/kg/keV)



PRELIMINARY

Incompatible with DAMA/LIBRA at **3.9σ (2.9σ)** at [1-6] ([2-6]) keV

Machine-learning techniques:results for annual modulation



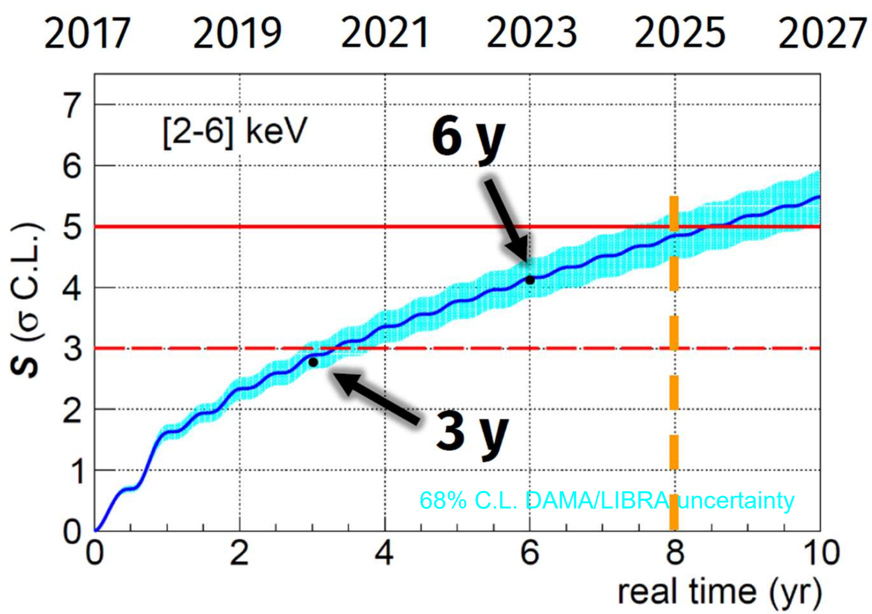
PRELIMINARY

Open data available for independent analysis at Dark Matter Data Center:
https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais

Sensitivity to DAMA/LIBRA result

$S = S_m^{DAMA} / \sigma(S_m)$

Considering obtained background from machine-learning techiques: **5σ in 8 y**



Updated background model

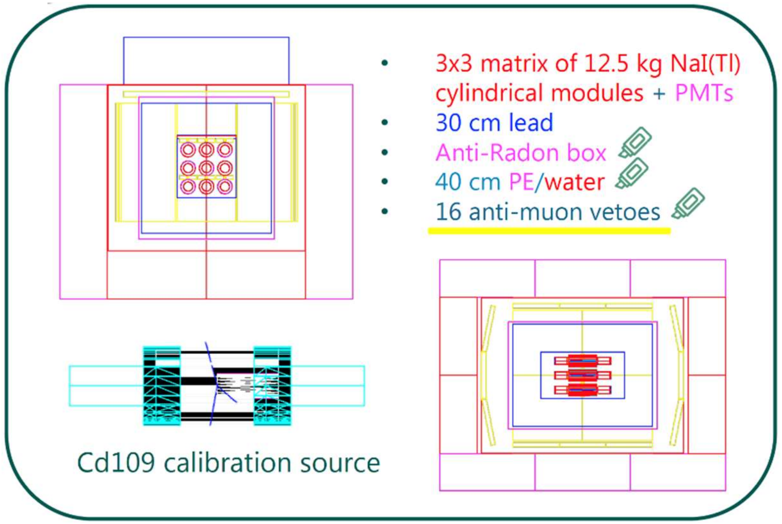
Motivation: activity of ^{3}H and ^{210}Pb **on crystal surface** not independently measured, but both are very relevant in LE counting rate and time evolution
→ Improved description is being attempted by **fitting** simulations to data

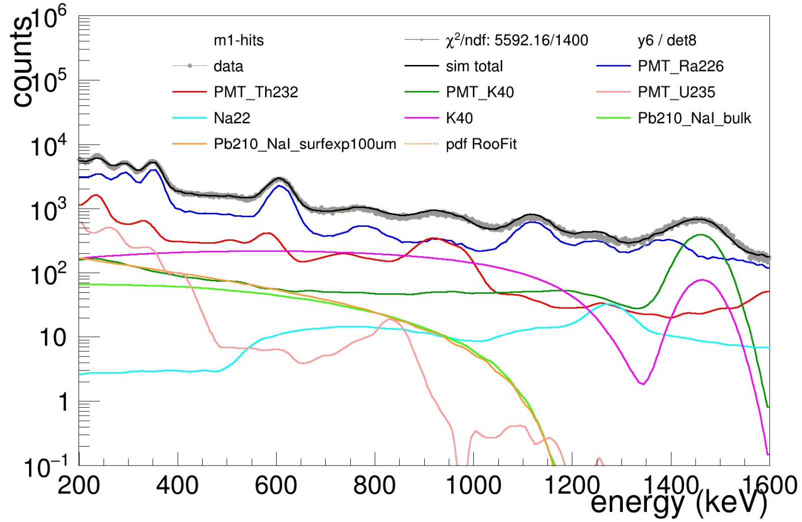
- **Experimental input:** 7-year data in HE and LE regions (excluding RoI), anticoincidence and coincidence events
- Geant4 version: v10.7 vs v9.4.1
- Extended **geometry,** improved description of PMTs
- **Multiparametric fit** using RooFit considering different simulated contributions from all sources to get pdfs

9 crystals (K40, Pb210, Th232, U238, U235, H3, Na22, Cd109, Sn113, I's,Te's)

18 PMTs (K40,Ra226,Th232,U238,U235)

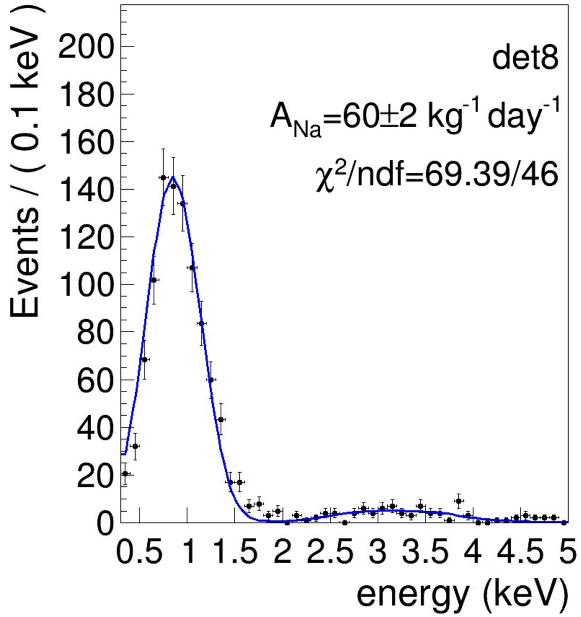
Others: 9 Cu housing, 18 SiPads, 18 Quartz windows (K40, Ra226, Th232, U238)

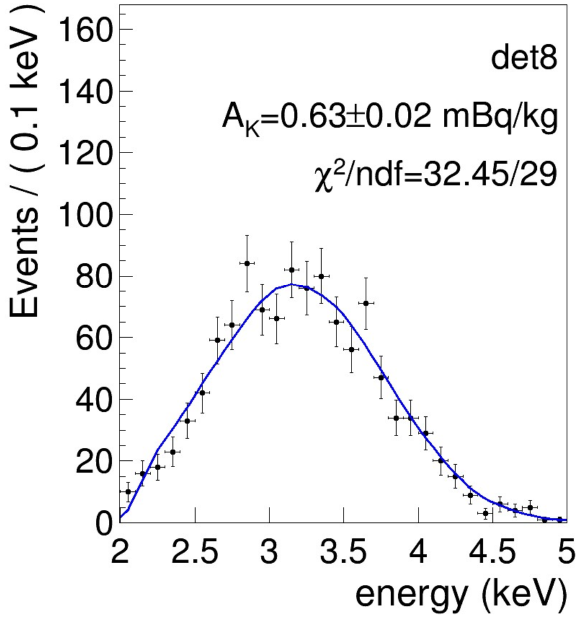




Updated background model

Main activities well reproduced from the fit



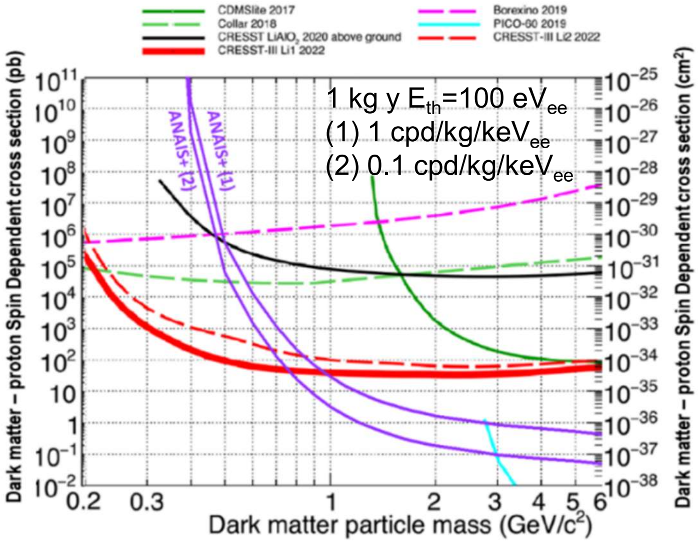


- **Optical simulation** of light signals ongoing to understand the response to specific components of background

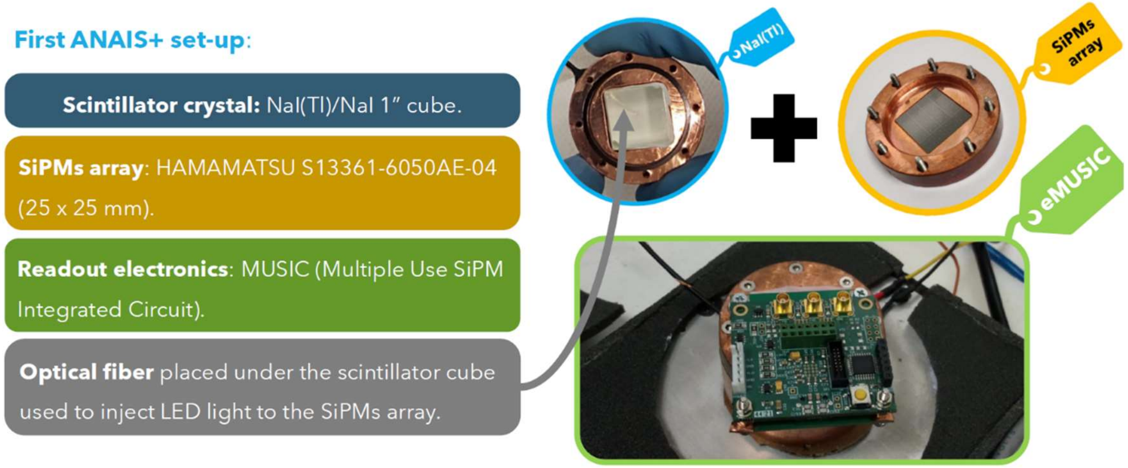
Prospects: ANAIS+

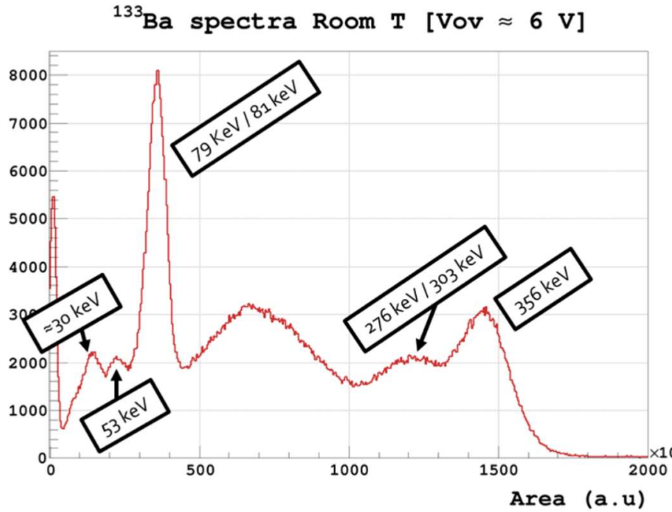
Motivation: replacing PMTs by **SiPMs** (at 100 K) could allow a **reduction in energy threshold <0.5 keV$_{ee}$**

- Better sensitivity, specially to light WIMPs and SD interaction



Test set-up at Zaragoza



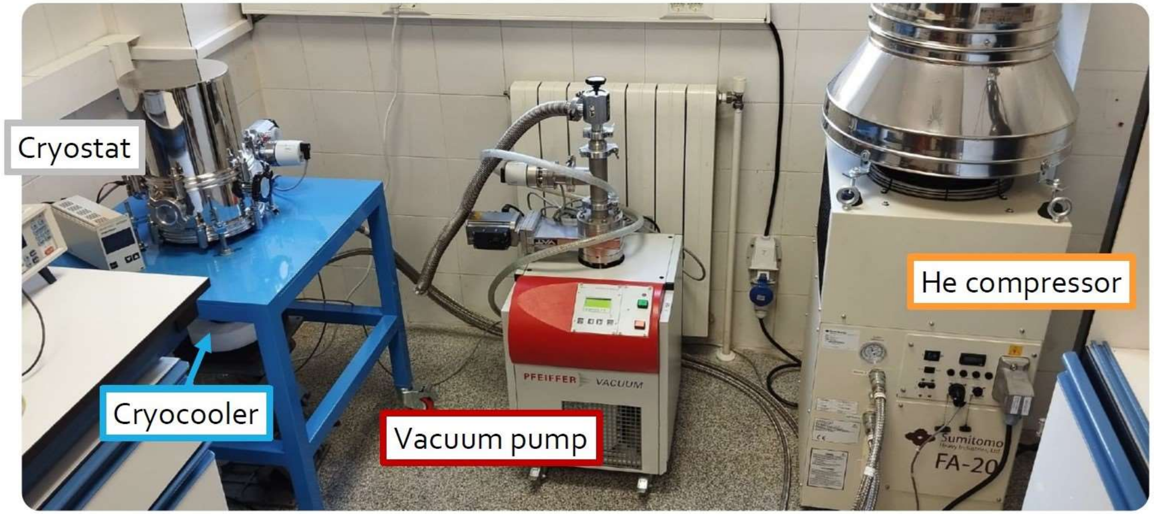


SiPMs characterization and study of light collection from room temperature to ≈30 K

Prospects: ANAIS+

Test set-up at Zaragoza

Cryogenic facility ready

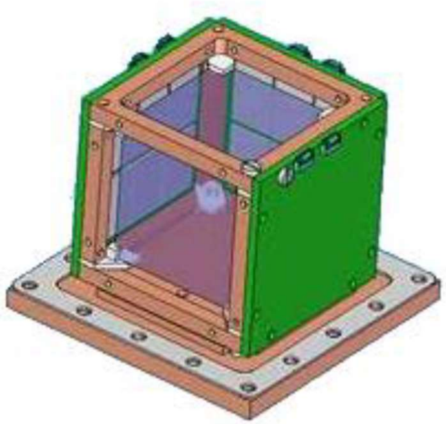


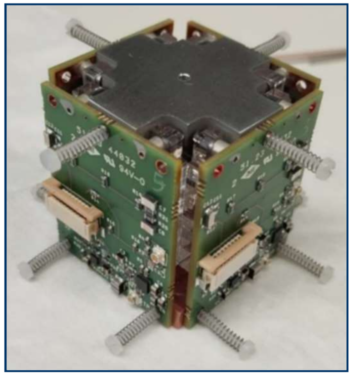
ANAIS+ prototype prepared and tested at **LNGS**

Four faces covered by SiPMs

Further tests at Zaragoza

Medium / long term: test in **LAr** (thermal bath+veto) at Canfranc in collaboration with **CIEMAT**





Summary

- **ANAIS-112** is taking data smoothly **for 7 years** to have a definitive, independent test of the **DAMA/LIBRA annual modulation result**

No modulation is observed; preliminary results are **incompatible with DAMA/LIBRA signal** at **3.9σ (2.9σ) at [1-6] ([2-6]) keV** from **6-year data**

  – **5σ sensitivity** is expected for late 2025

- Thorough **background study** underway since the beginning of the project
  – **First background model** based on quantified activities from different techniques
    - Helped to identify main background sources
    - Described well time evolution and measured spectra except at very low energy
  – **Machine-learning techniques** have allowed to partly reduce observed excess, improving significantly the sensitivity
  – **Updated background model** in development by fitting data to better describe some components

- **ANAIS+** project with SiPMs underway, with first prototypes in development

Acknowledgements

Thank you for your attention!

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