Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

MultiDark
Multimessenger Approach for Dark Matter Detection

LSC
Laboratorio Subterráneo de Canfranc

ANAIS

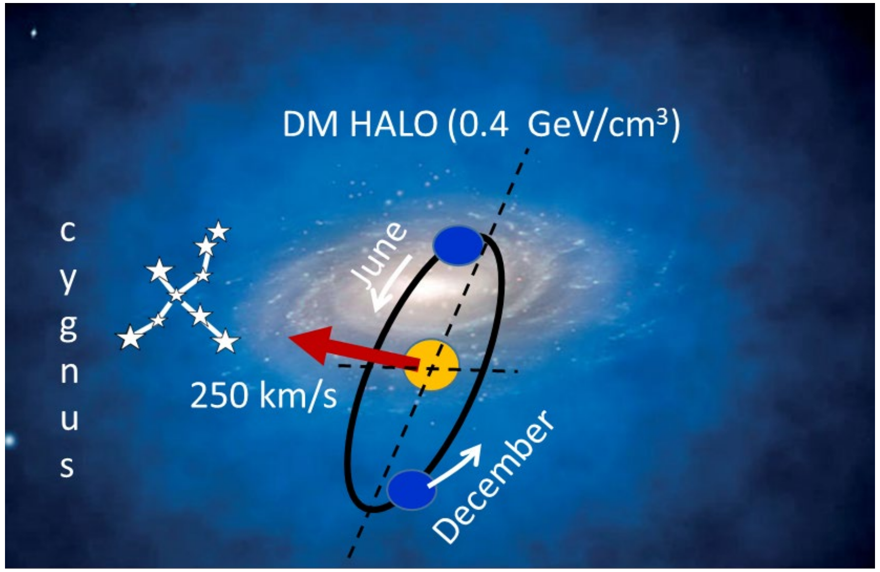
ANAIS-112

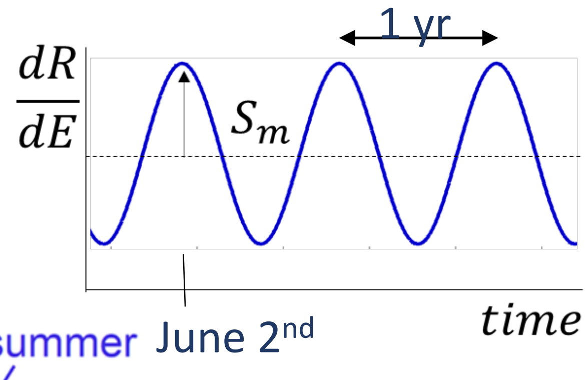
updated results on dark matter annual modulation

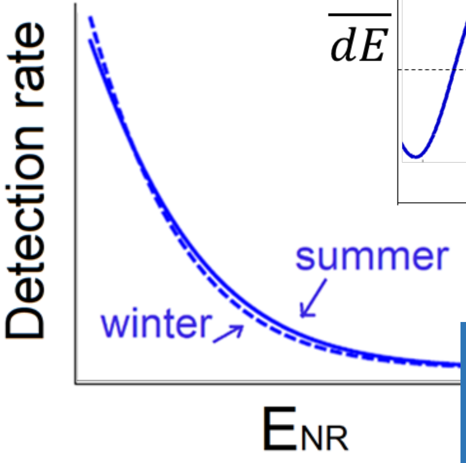
M. Martinez
CAPA, U. Zaragoza
On behalf of the ANAIS team

42nd ICHEP, Prague, 18–24 July 2024

DM annual modulation & DAMA/LIBRA positive signal

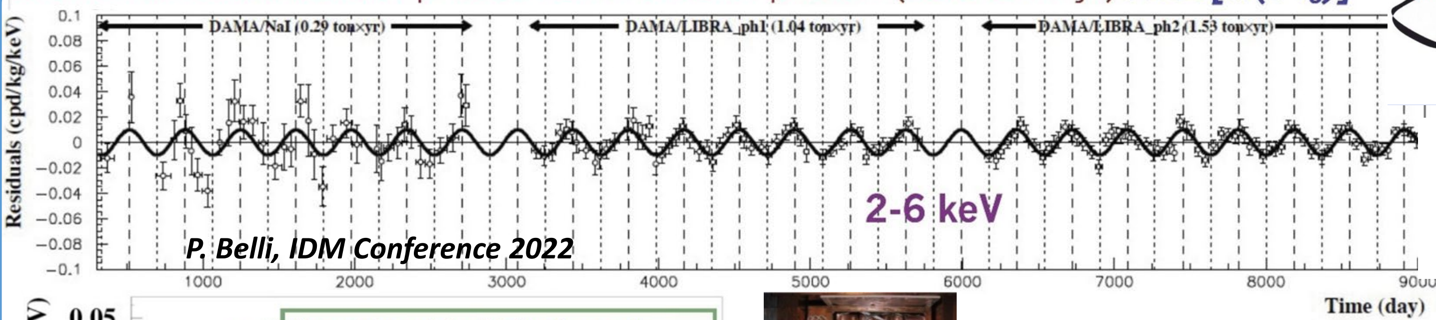


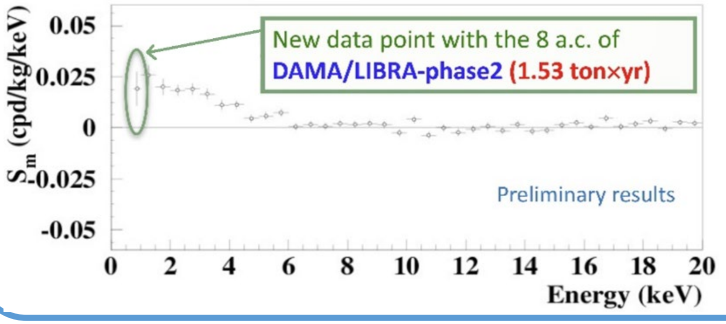




Clear DM signature!! (but small amplitude ~7%)

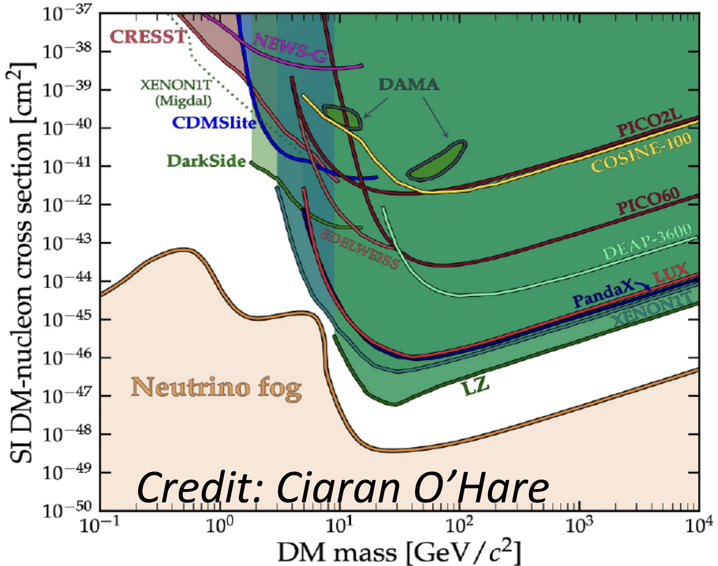
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr) ***Acos[ω(t-t₀)]***





- 1995-2002: DAMA/NaI: 100 kg NaI(Tl)
- 2003-today: DAMA/LIBRA: 250 kg NaI(Tl)

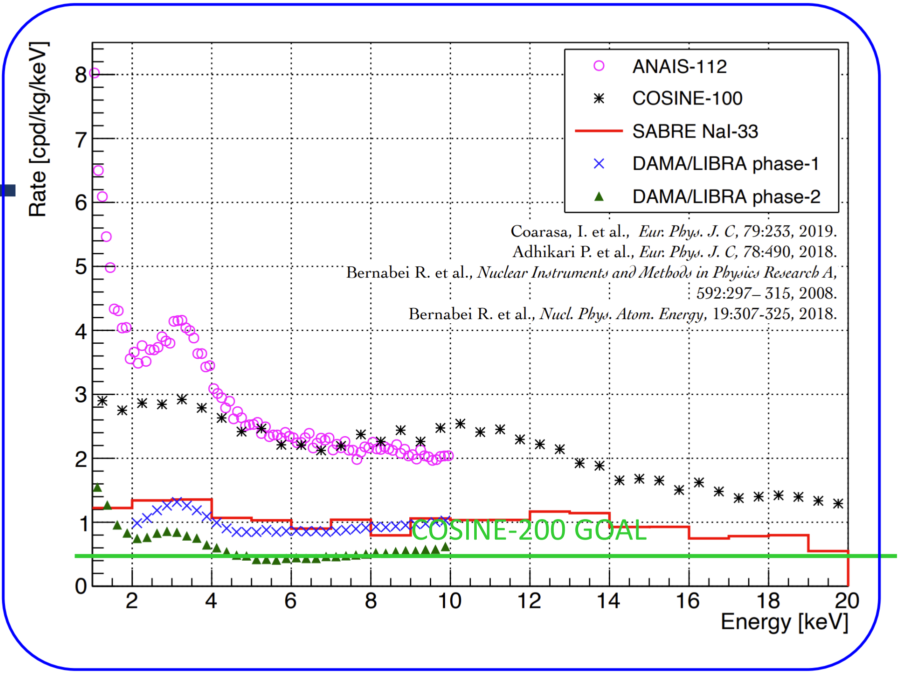
DAMA sees an annual modulation compatible with DM at 13.7 σ



Other direct detection experiments do not see the signal, **but the comparison is model dependent**

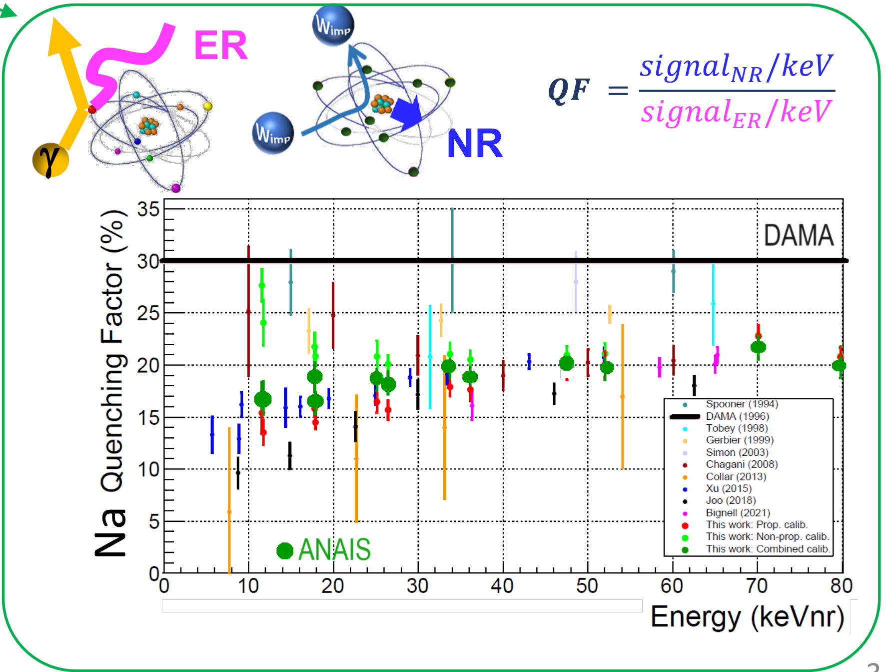
A model independent confirmation is needed using the same target → NaI(Tl)

Testing the DAMA/LIBRA signal

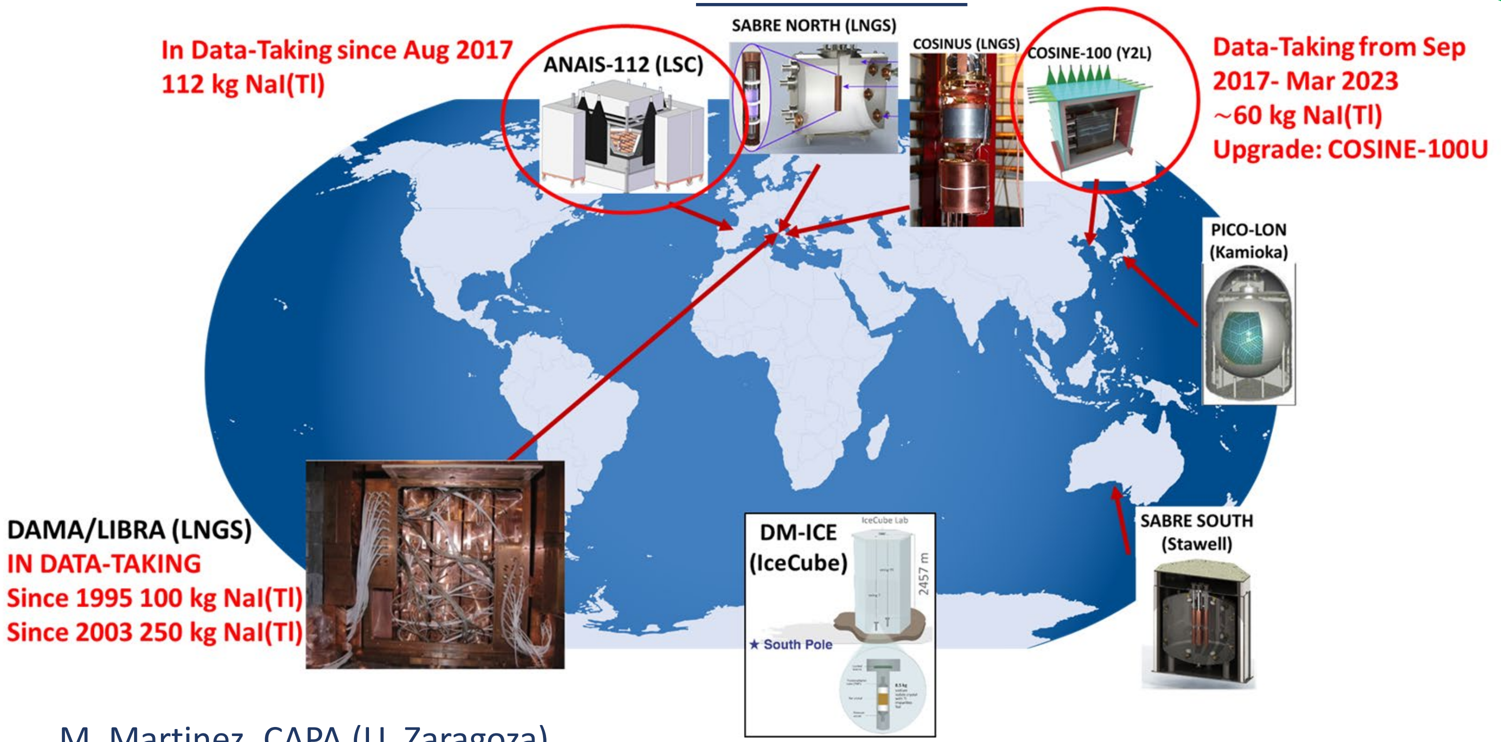


Experimental requirements

- **Target: NaI / NaI(Tl)**
- Large exposure
- Very stable operation conditions
- Energy threshold: 1 keVee
- Background level as low as possible (DAMA: 1 cpd/kg/keV @ 2 keVee)
- Good knowledge of the detector response to nuclear recoils



A world effort



ANAIS-112

Annual Modulation with NaI Scintillators

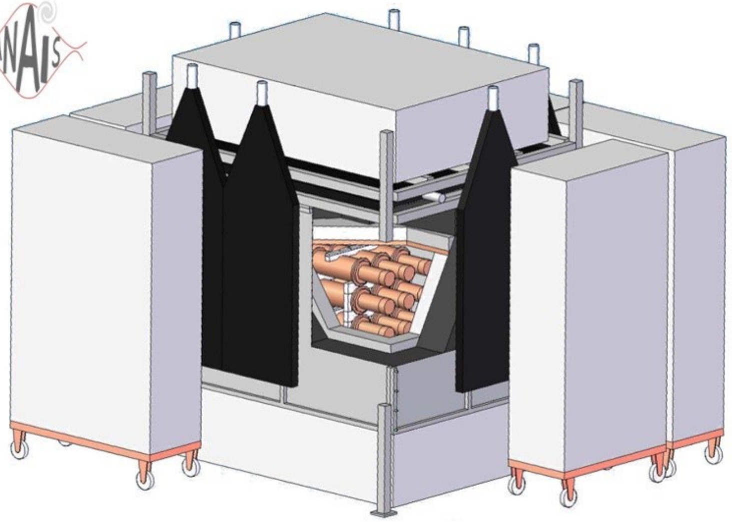
https://gifna.unizar.es/anais/

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

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

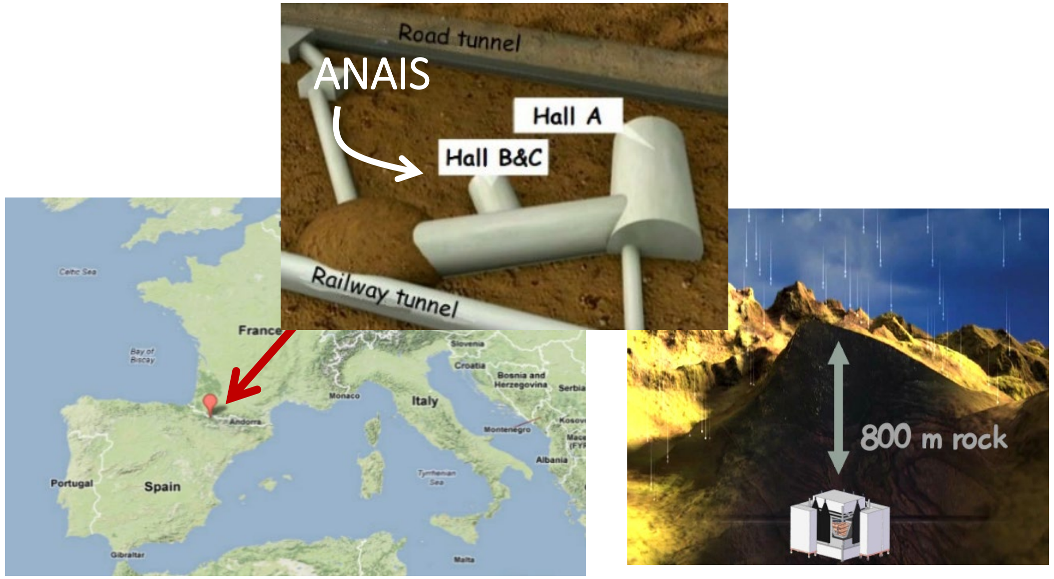
Projected sensitivity: 3σ in 5 years data-taking

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.**)

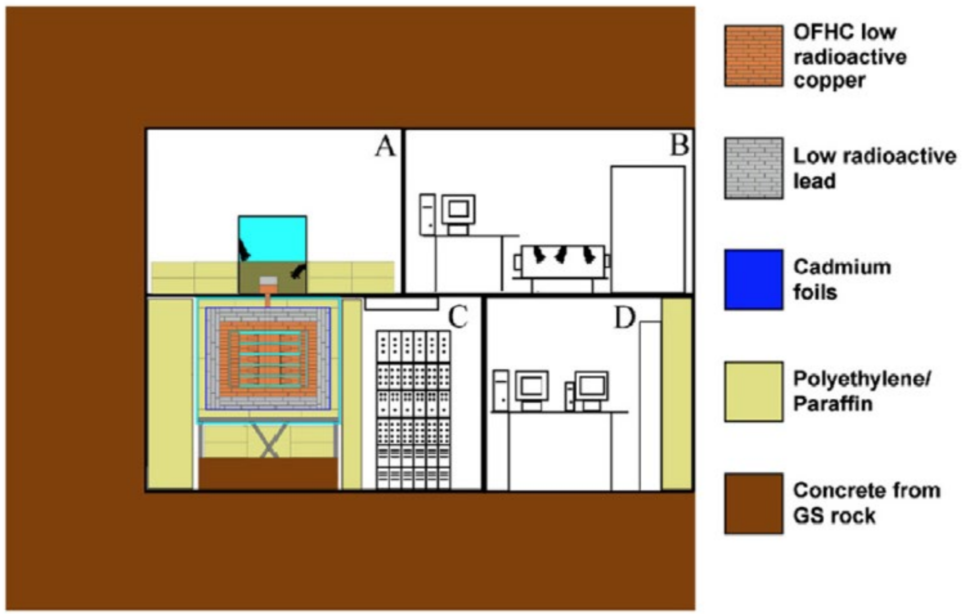


taking data since August 2017

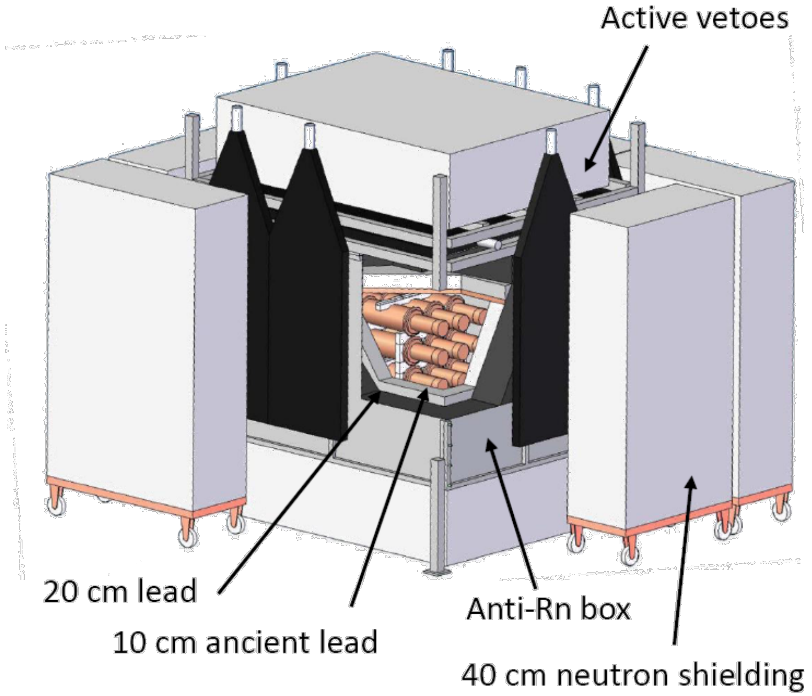
ANAIS-112 vs DAMA/LIBRA

Shielding

- Gamma shielding:
  >10 cm of OFHC Cu + 15 cm of Pb
- Anti-Rn: Plexiglas box flushed with N2 gas
- Neutron shielding:
  10/40 cm Polyethylene/paraffin + Cd foils



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

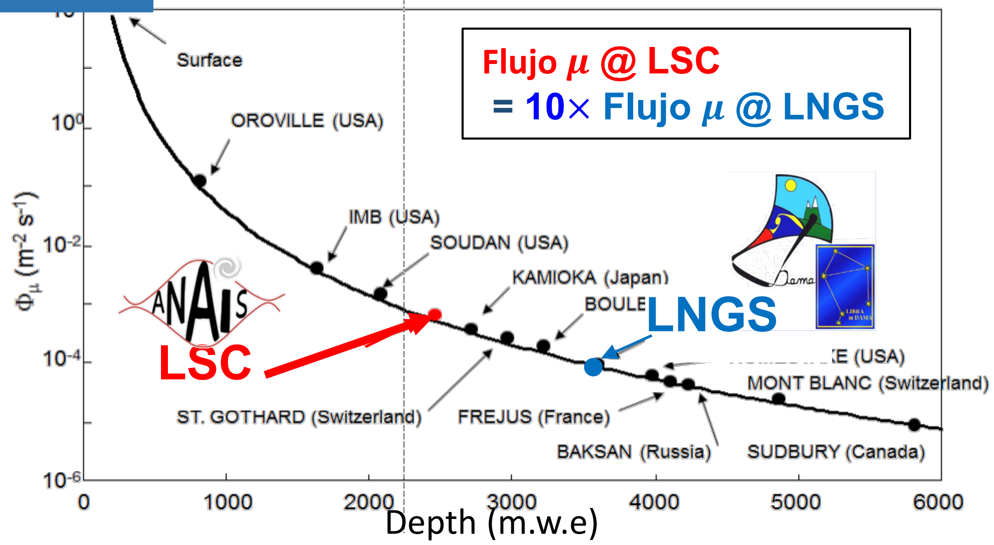


ANAIS-112 vs DAMA/LIBRA

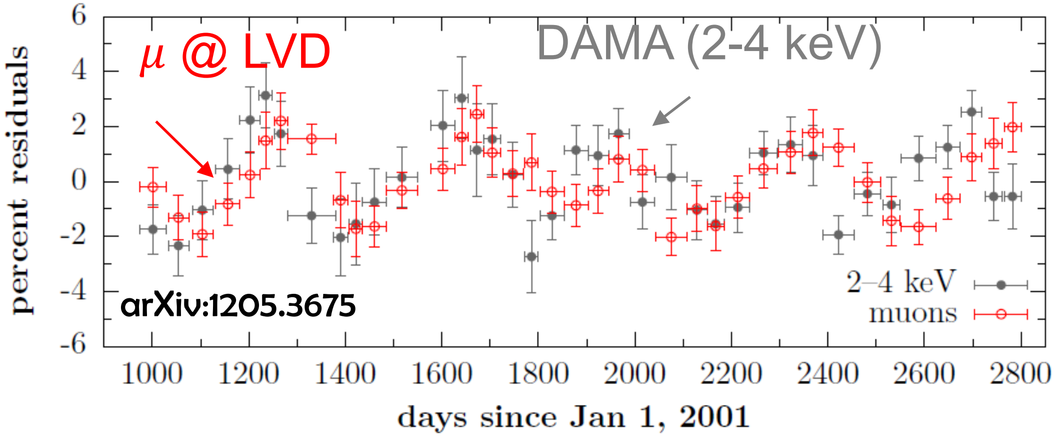
Muon veto

In ANAIS we flag every muon that cross the shielding
We set a (configurable) dead-time after every passage

DAMA/LIBRA has no muon veto



The underground muon flux is annual-modulated!



Can muons explain DAMA signal?

- Modulation phase inconsistency
- Muons interacting directly in the detectors do not fulfill the DM requisites
- Not enough muon-induced fast neutrons to account for the signal

But still some open questions:

- (delayed) effect of muons in PMTs?
- slow phosphorescence in NaI?

ANAIS-112 vs DAMA/LIBRA

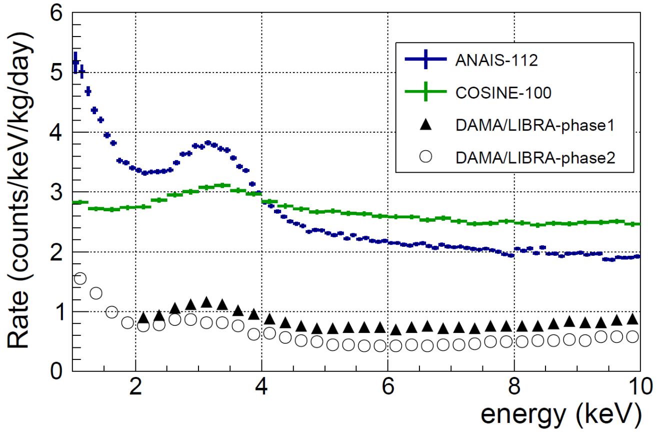
NaI(Tl) scintillating detectors

- 25 crystals, 10.2×10.2×25.4 cm^3, 9.7 kg each
- Sain Gobain, Kyropoulos method with a platinum crucible
- PMTs phase-1: ETL 9265–B53/FL and 9302–A/FL (QE~30%)
- PMTs phase-2: Hamamatsu R6233MOD (QE ~38%)
- Light guides: 10 cm Suprasil B

- 9 cylindrical crystals, 12 cm ϕ ×30 cm, 12.5 kg each
- Alpha Spectra (same as COSINE)
- PMTS: Hamamatsu R12669SEL2 (QE ~40%)
- Quartz window (no light guides)

Superior radiopurity of DAMA/LIBRA crystals wrt ANAIS/COSINE

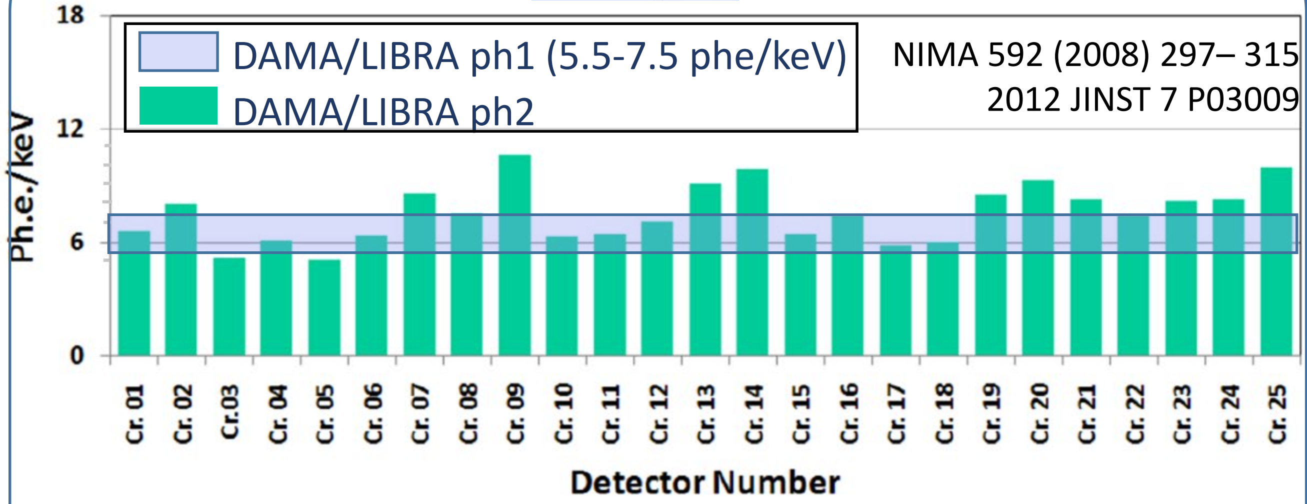
	K (ppb)	^{210}Pb (mBq/kg)
DAMA (Saint Gobain)	13	0.01-0.03
ANAIS/COSINE (Alpha Spectra)	18-44	0.7-3



ANAIS: 6 y 10% unblinded
COSINE: Sci. Adv. 7 (2021) eabk2699
DAMA-ph1: NIMA 592 (2008) 297– 315
DAMA-ph2: Nucl. Phys. At. Energy, 19:307-325, 2018

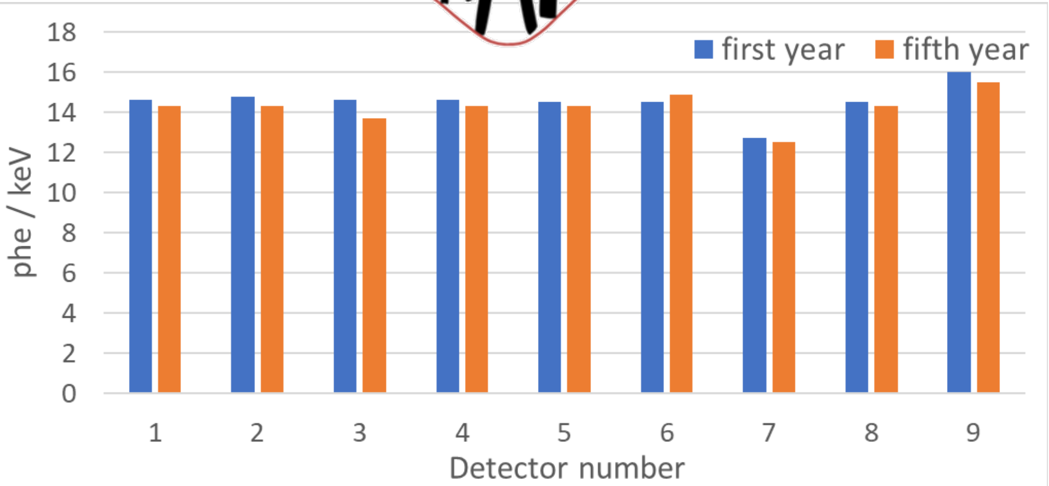
ANAIS-112 vs DAMA/LIBRA

Light collection

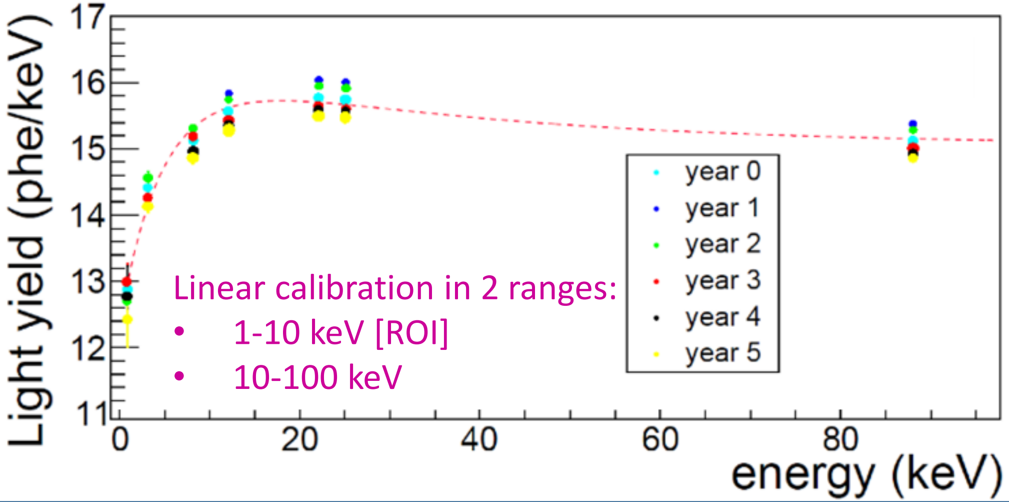


- DAMA/LIBRA-phase1 showed a very good linearity between the calibration with the 59.5 keV line of ^{241}Am and the tagged 3.2 keV line of ^{40}K
- in DAMA/LIBRA-phase2 a slight nonlinearity is observed(it gives a shift of about 0.2 keV at the software energy threshold and vanishes above 15 keV).

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



In ANAIS non proportionality is observed < 25 keV (20%)

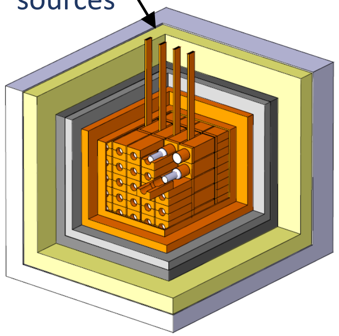


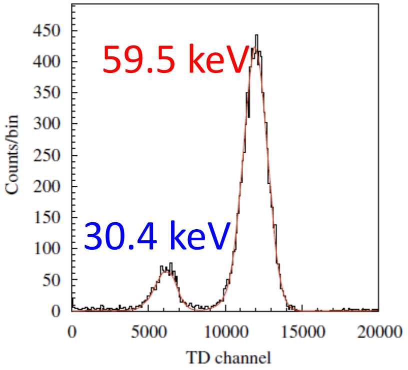
ANAIS-112 vs DAMA/LIBRA

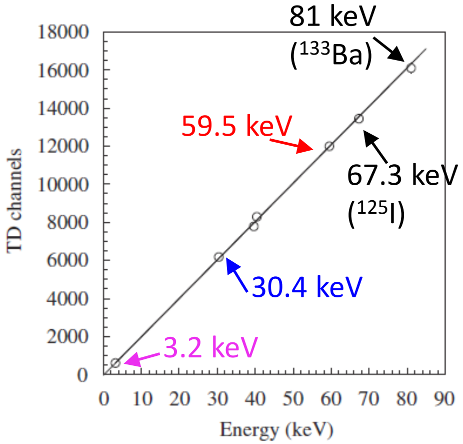
Low energy calibration – RoI [1-6 keV]

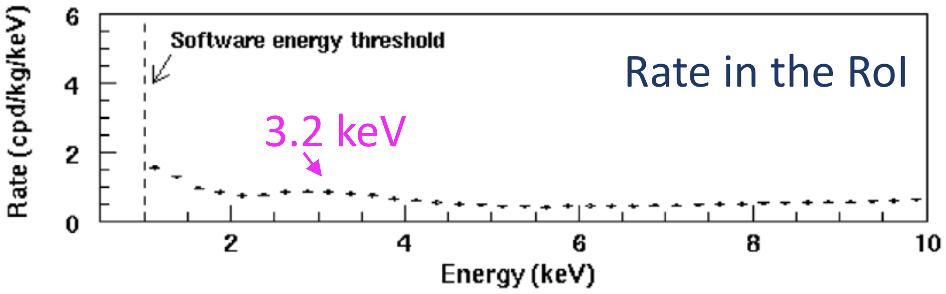
- Periodical calibrations every ~10 days with a ^{241}Am source (30.4 keV (composite), 59.5 keV). Linear calibration down to threshold
- Linearity check and corrected @ 3.2 keV with whole statistics

Guides for ^{241}Am sources

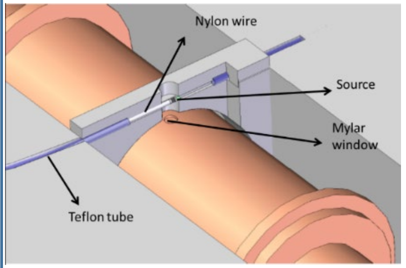


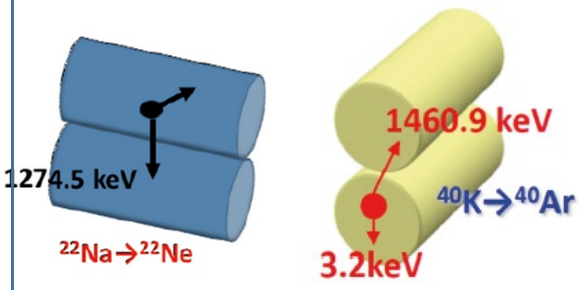


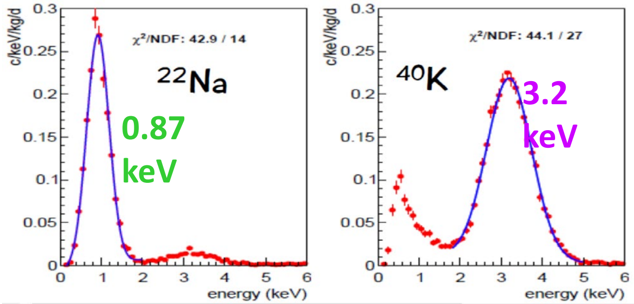


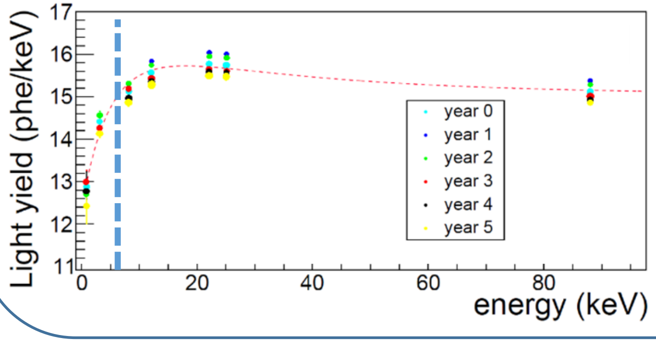


- Detectors equipped with a **Mylar window**
- Calibration with **^{109}Cd sources** (11.9 keV, 22.6 keV and 88.0 keV) every two weeks for gain correction
- Calibration in the ROI with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) (whole statistics)









Non proportionality < 25 keV (20%)

Linear calibration in 2 ranges:

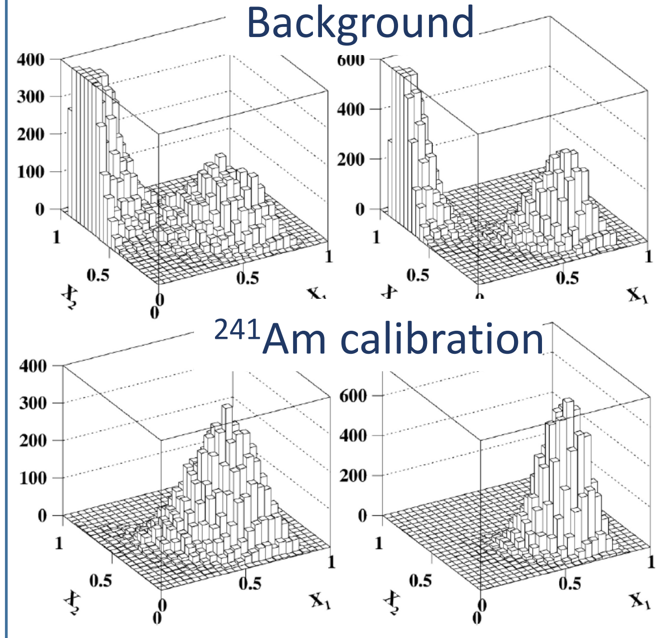
- 1-10 keV [ROI]
- 10-100 keV

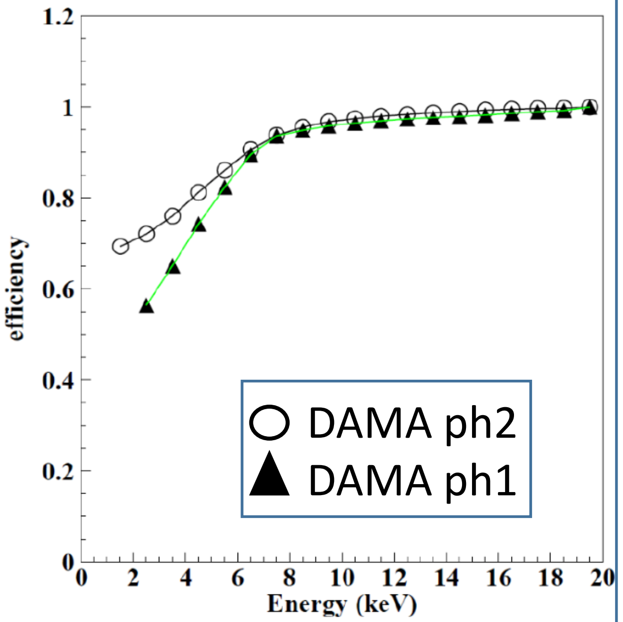
ANAIS-112 vs DAMA/LIBRA

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)

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





Standard analysis (4)

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

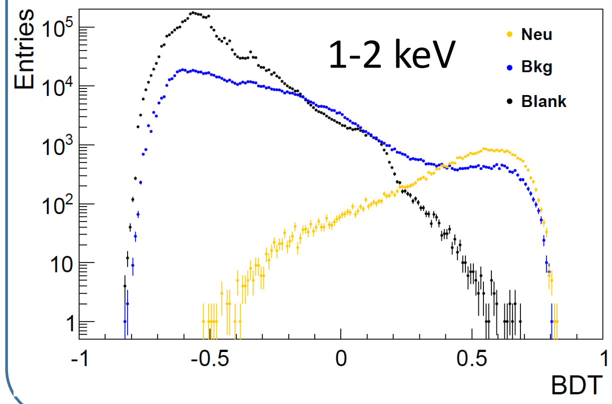
$$\mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i} \qquad n_0, n_1$$

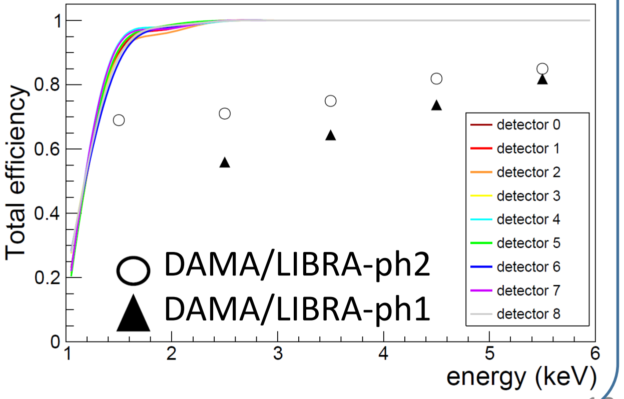
New parameters (11)

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

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

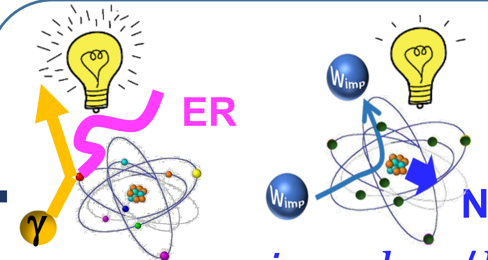
Boosted Decision Tree (BDT)





JINST 7 P03009 (2012)

ANAIS-112 vs DAMA/LIBRA



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

NR Quenching factors
Required for the WIMP interpretation

^{252}Cf calibration

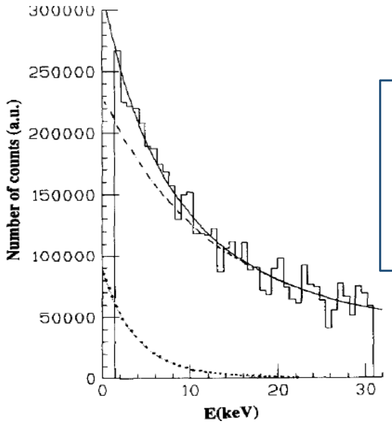
$$E_R = E_{det}/QF$$

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:

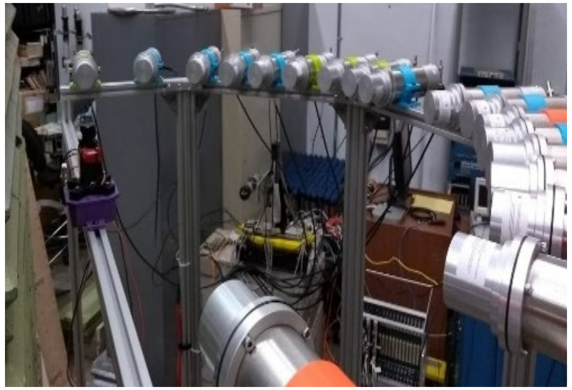
$QF_{Na} = 30\%$

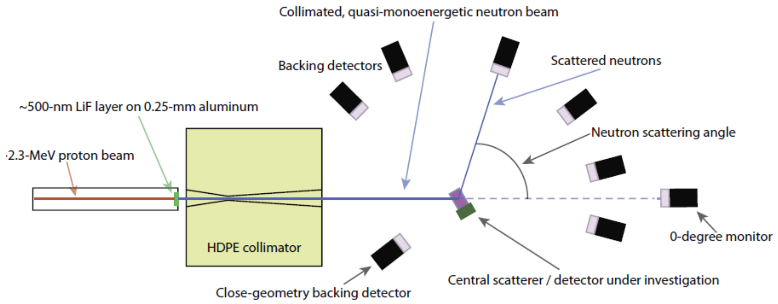
$QF_I = 9\%$

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

Measurements @ TUNL (Duke Univ.)

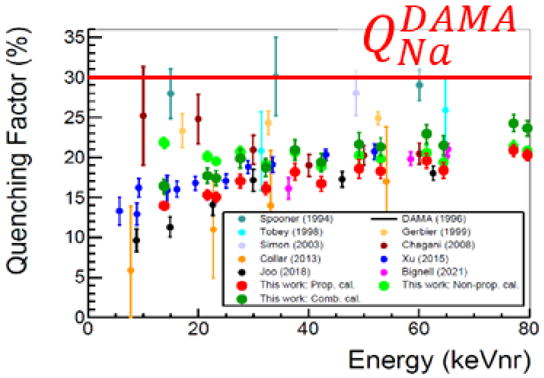
5 different NaI(Tl) crystals (ANAIS & Yale group of COSINE) in the same setup

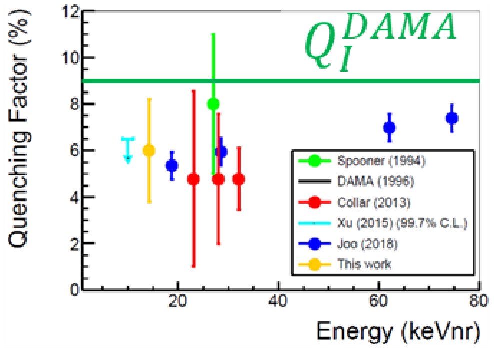




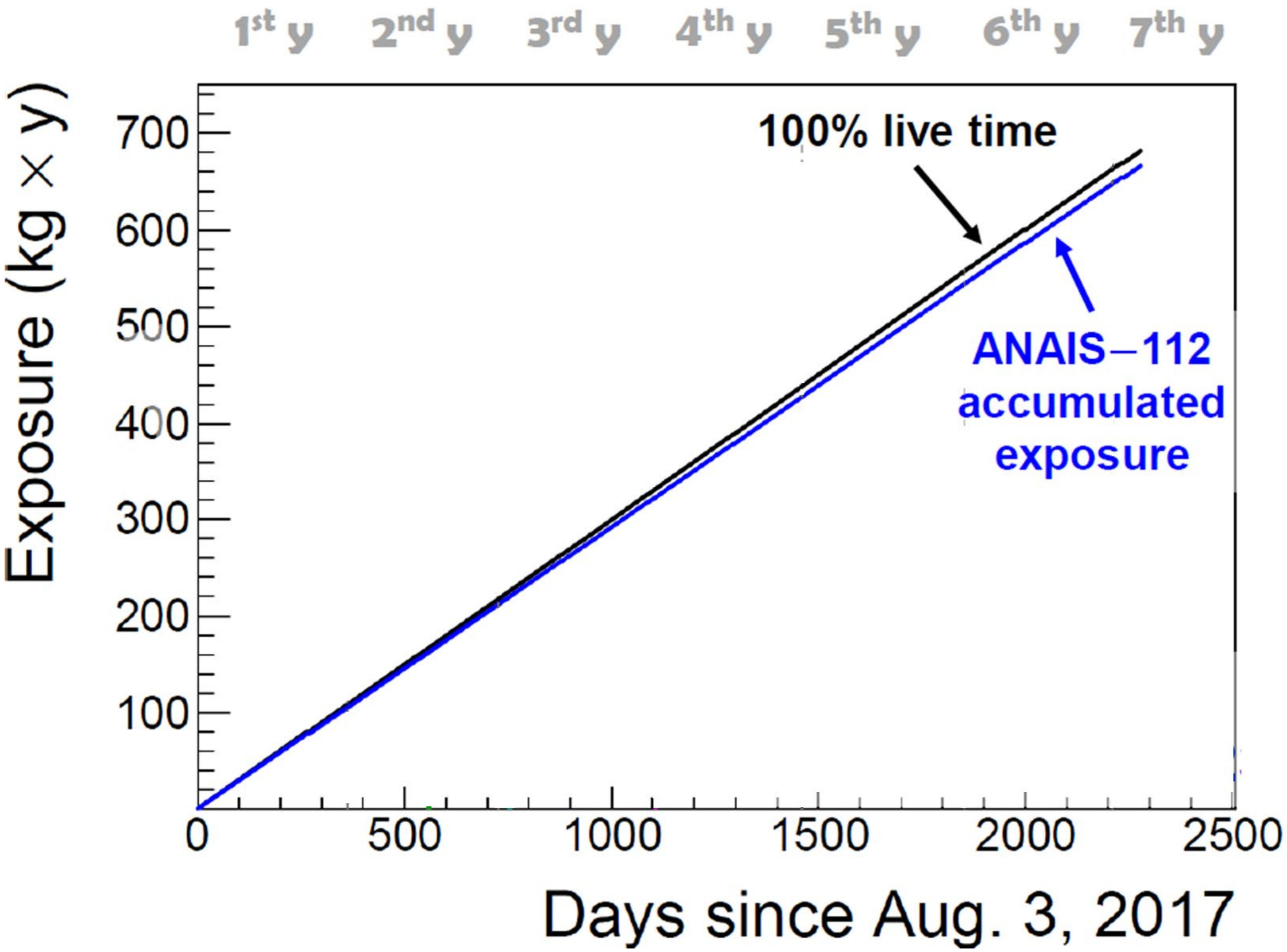
Phys. Rev. C 110 (2024) 014613

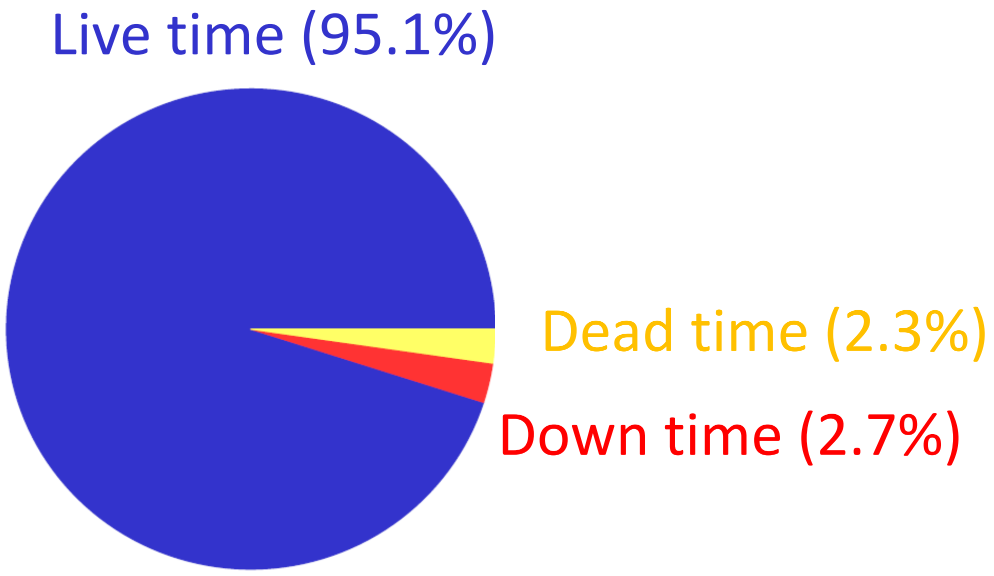
- **Compatible** values for the 5 crystals
- Noticeable differences for different energy calibrations (NaI non-linearity)
- **Lower QF** than DAMA/LIBRA measurement





Data-taking overview





Annual modulation analysis strategy

Following PRD103(2021)102005

Focus on **model independent** analysis searching for modulation

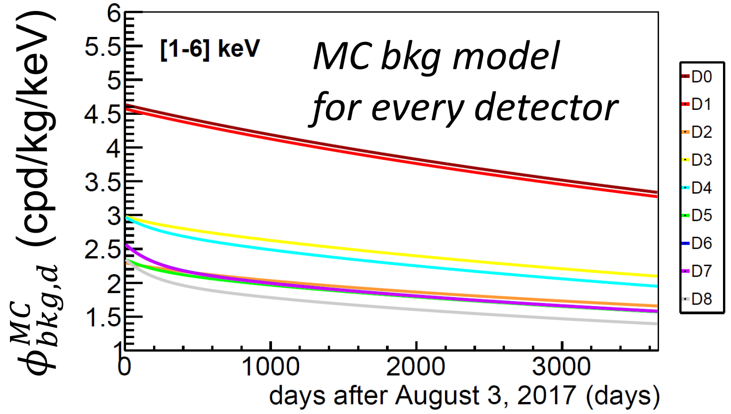
- In order to better compare with DAMA/LIBRA results
  - use the same energy regions ([1-6] keV, [2-6] keV)
  - Fix period 1 year and phase to June 2nd
- Simultaneous fit of the 9 detectors in 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i - \mu_i)^2/\sigma_i^2$, where the expected number of events μ_i for detector d in time bin i is given by:

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

Constant background (long-lived isotopes and residual noise)

Decaying background, modeled by MC

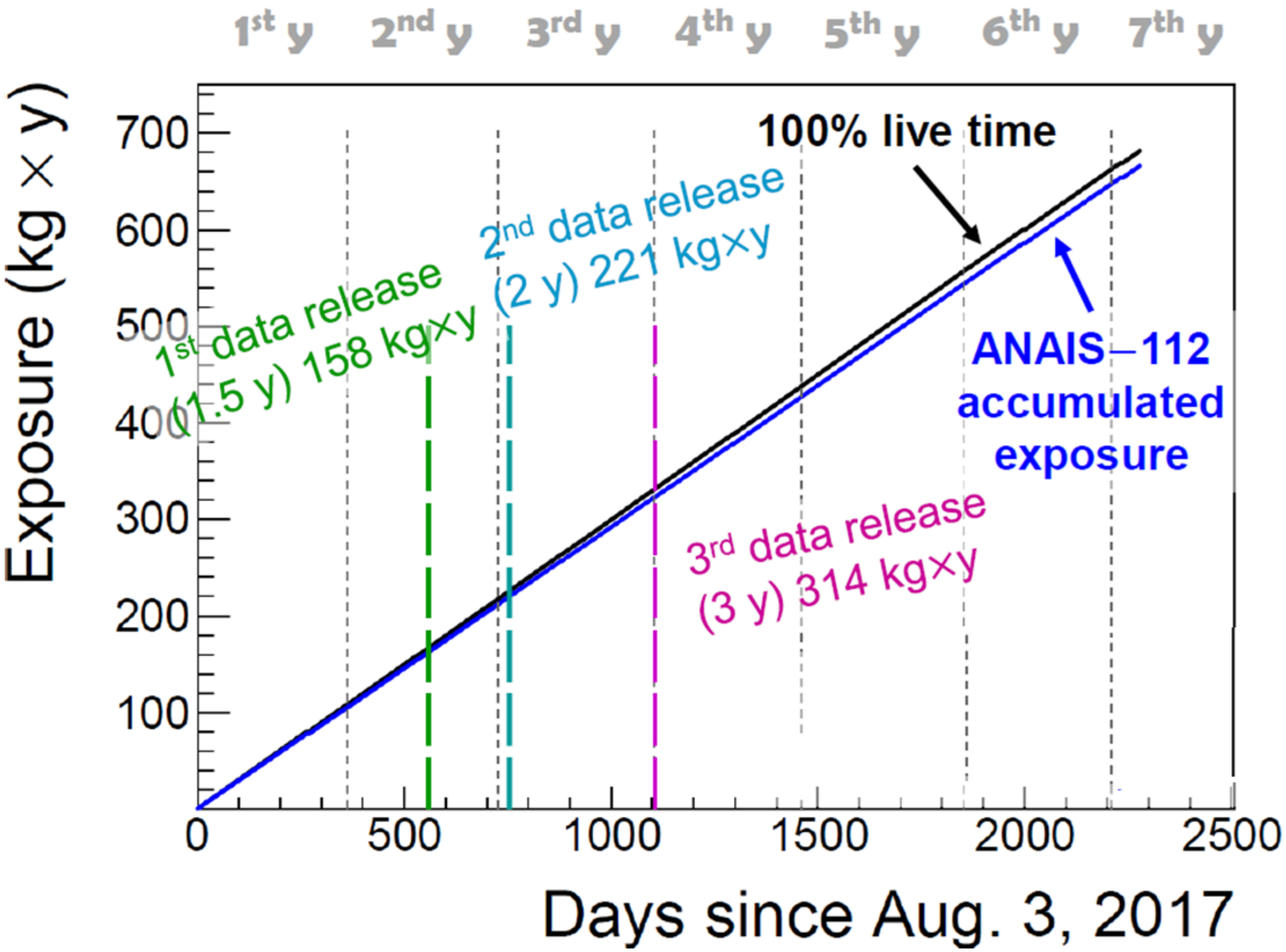
Modulation signal (fixed period and phase)



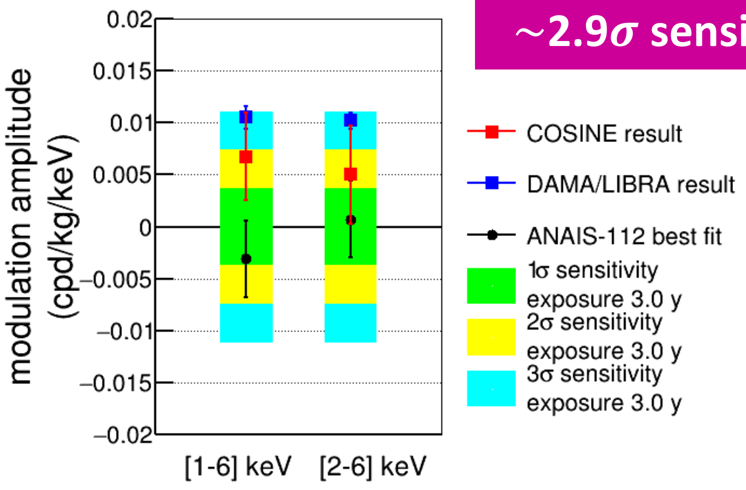
19 free parameters: $R_{0,d}, f_d, S_m$

ANAIS-112 data releases

- 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: 2404.17348**



ANAIS-112 3y: ~2.9σ sensitivity



	S_m (cpd/keV/ton)		
E (keV)	ANAIS-112	COSINE-100	DAMA/LIBRA
[1-6]	-3.1±3.7	6.7±4.2	10.5±1.1
[2-6]	0.7±3.7	5.0±4.7	10.2±0.8

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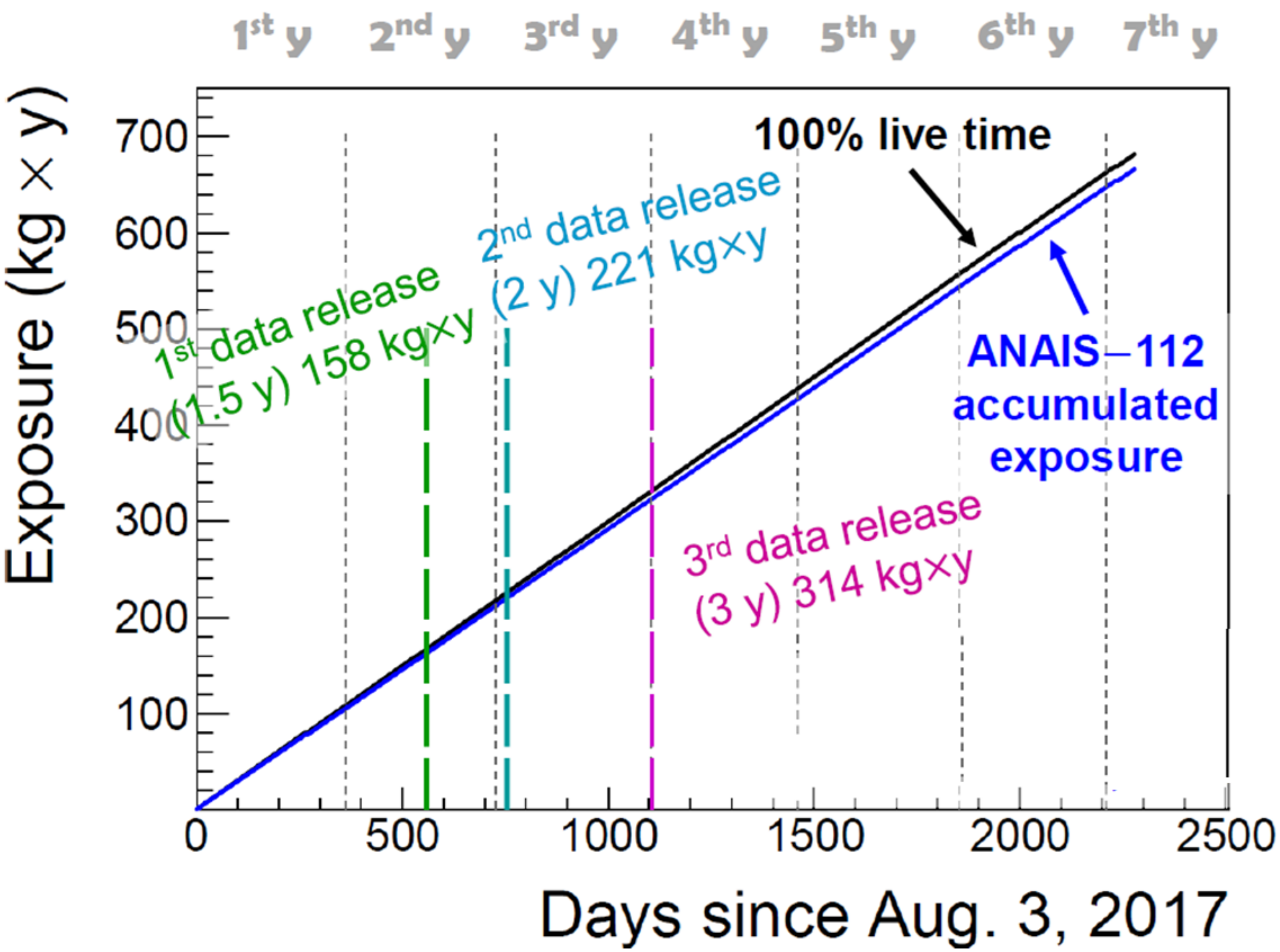

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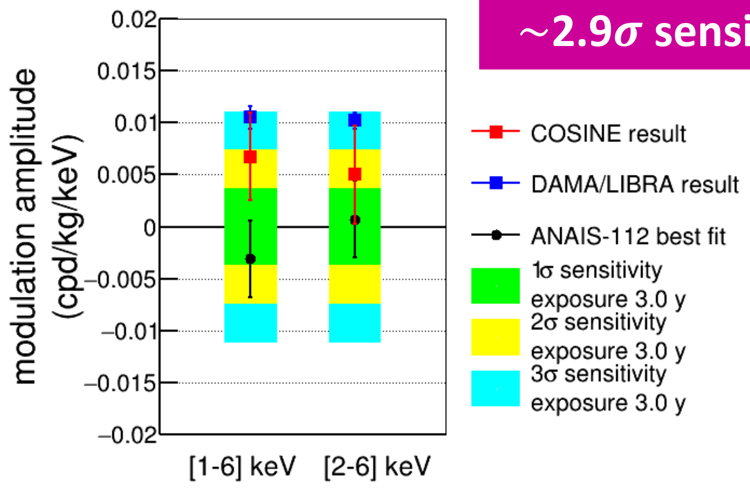

	S_m(cpd/keV/ton)		
E (keV)	ANAIS-112	COSINE-100	DAMA/LIBRA
[1-6]	-3.7±3.7	6.7±4.2	10.5±1.1
[2-6]	0.7±3.7	5.0±4.7	10.2±0.8

E(keV)	COMBINED ANAIS+COSINE	DAMA excl.
[1-6]	-0.3±2.8	3.6σ
[2-6]	2.3±2.9	2.6σ

PRELIMINARY

S. Hollick, IDM24

ANAIS-112 data releases

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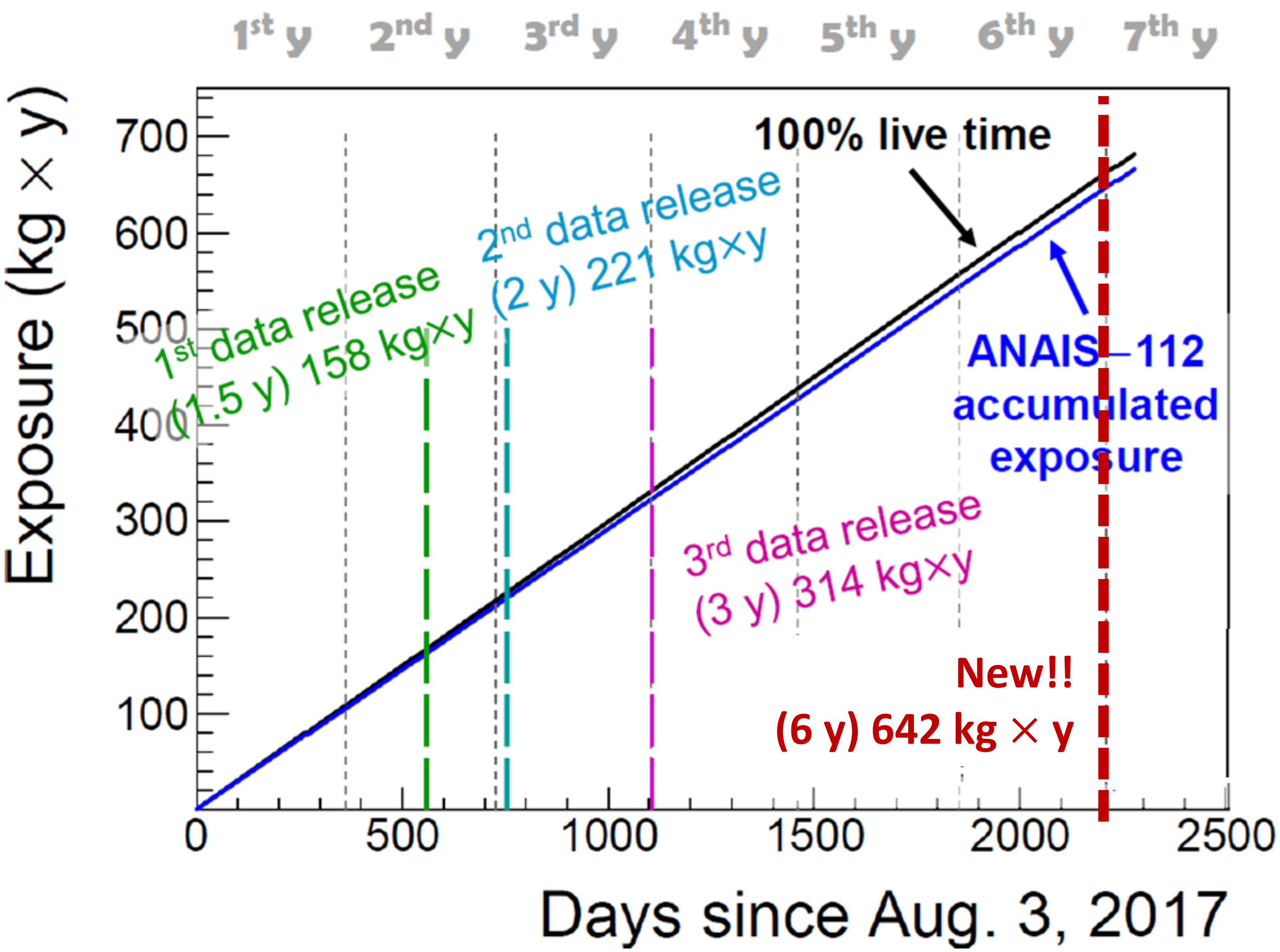
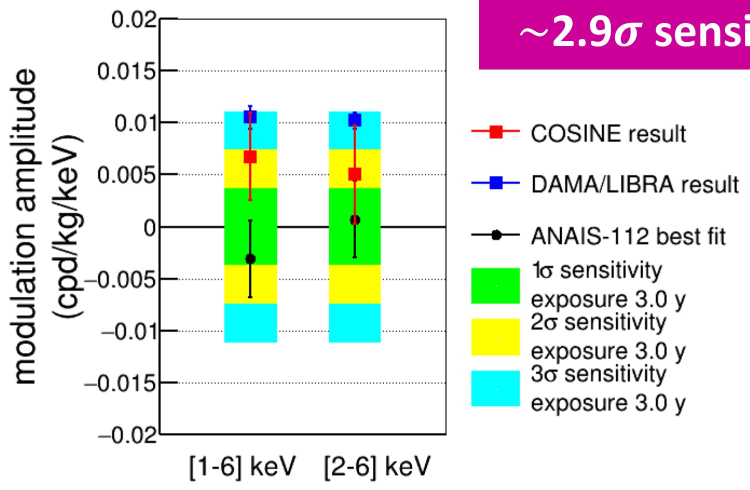


ANAIS-112 3y: ~2.9σ sensitivity



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E (keV)	**ANAIS-112**	**COSINE-100**	**DAMA/LIBRA**
[1-6]	-3.7±3.7	6.7±4.2	10.5±1.1
[2-6]	0.7±3.7	5.0±4.7	10.2±0.8

E(keV)	COMBINED ANAIS+COSINE	DAMA excl.
[1-6]	-0.3±2.8	3.6σ
[2-6]	2.3±2.9	2.6σ

PRELIMINARY

S. Hollick, IDM24

Annual modulation results with 6 years

NEW

642.05 kg × y

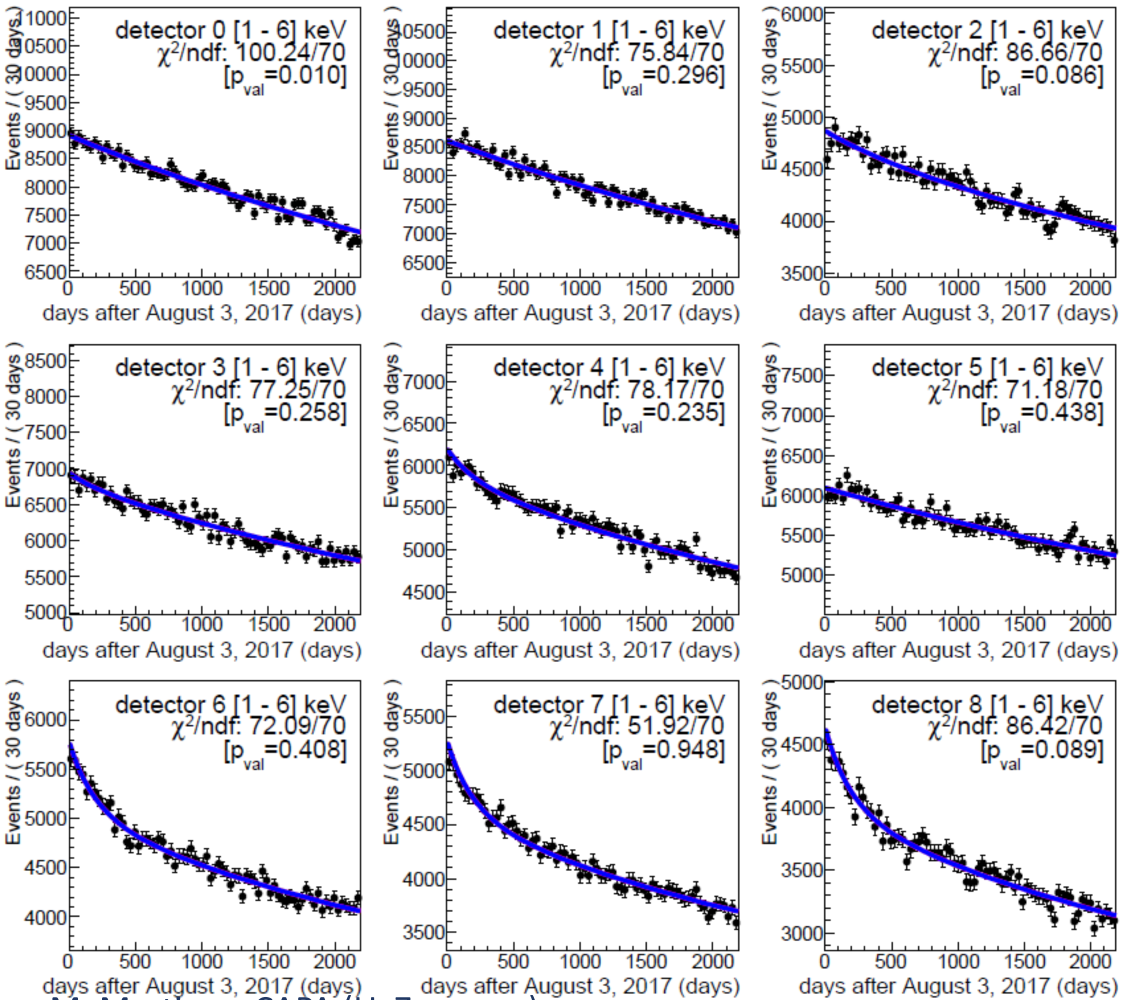
[1-6] keV: **4.2σ**

[2-6] keV: **4.1σ**

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

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

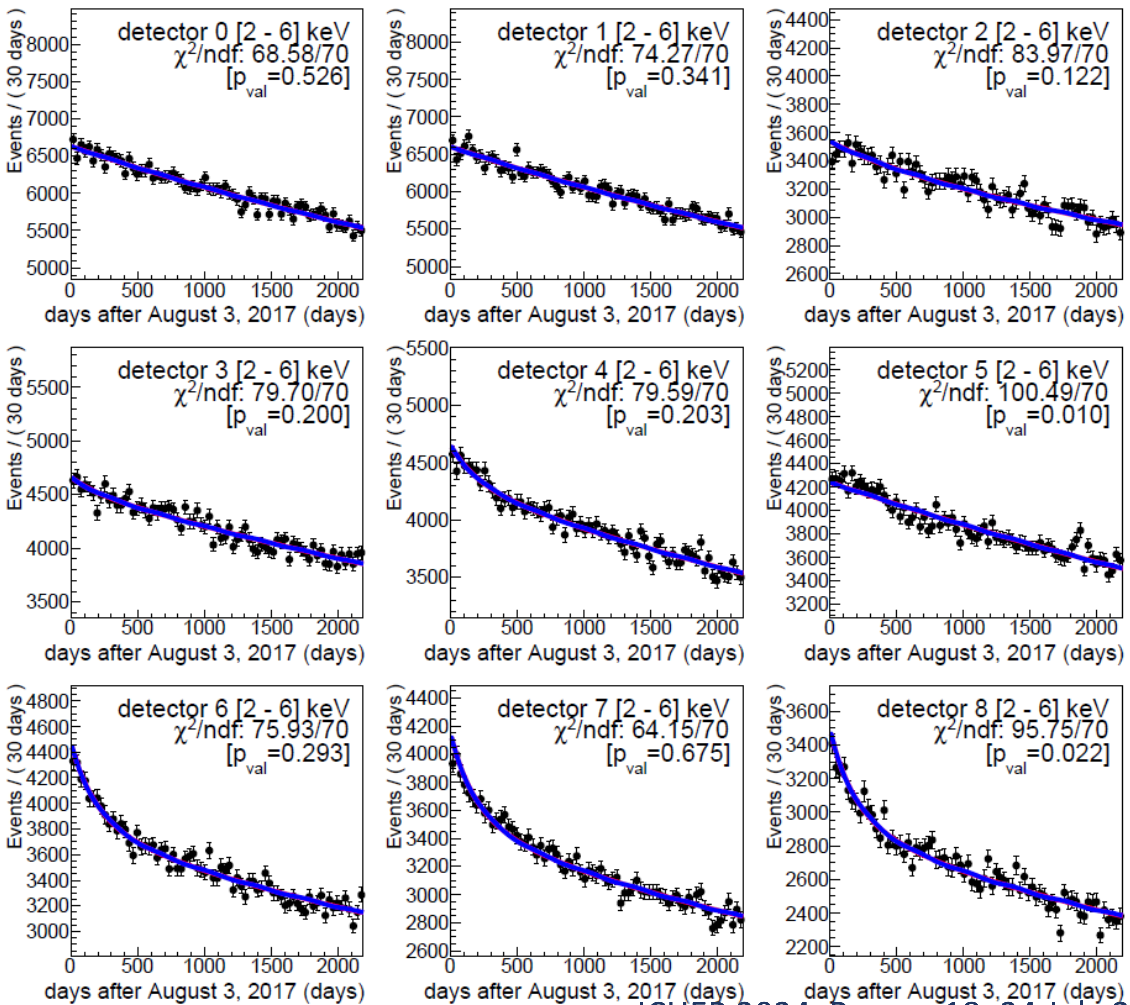
S_m = (0.0007 ± 0.0025) (cpd/kg/keV)



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

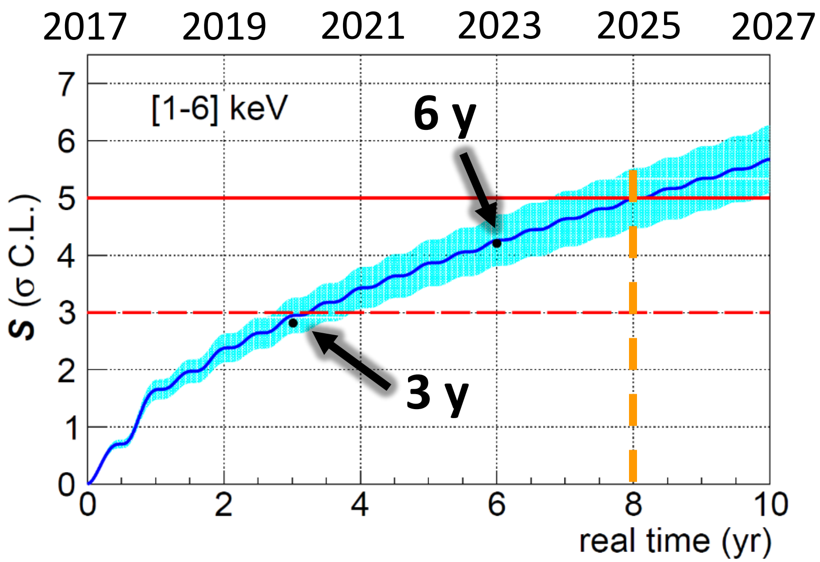
Mod hyp χ^2/ndf: 722.17/638 [p_{val}=0.011]

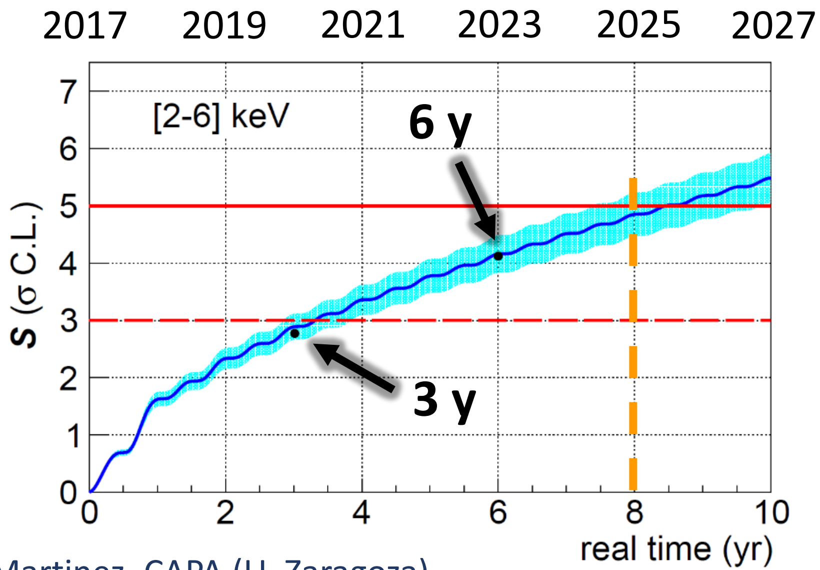
S_m = (0.0030 ± 0.0025) (cpd/kg/keV)

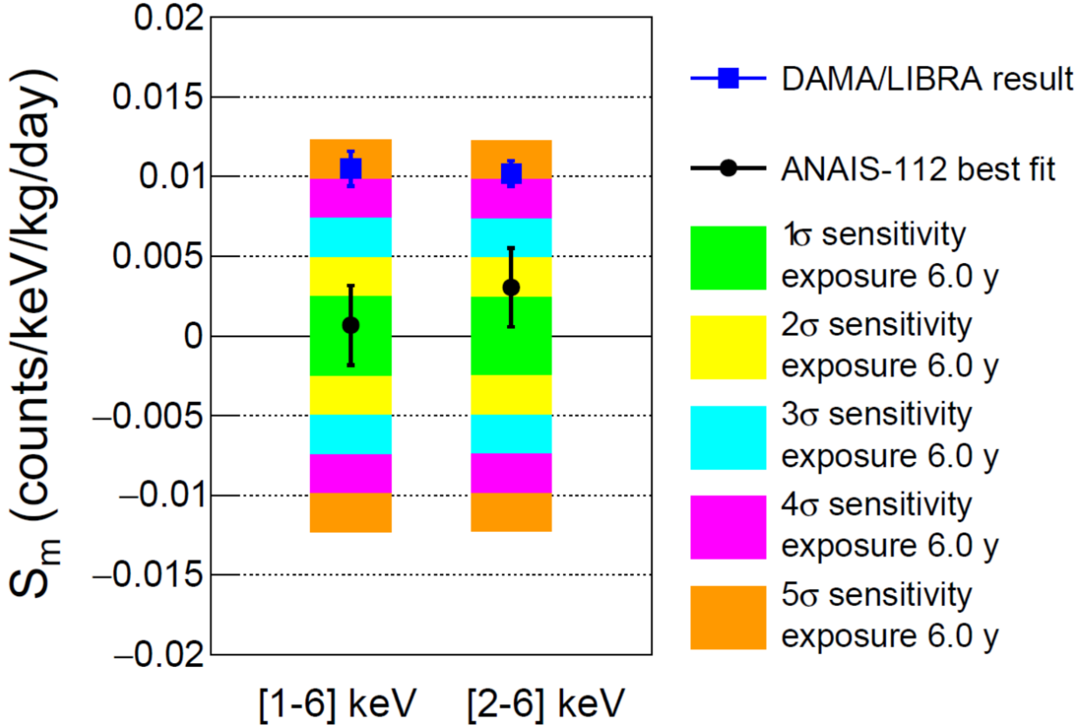


PRELIMINARY

Annual modulation results with 6 years







PRELIMINARY

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

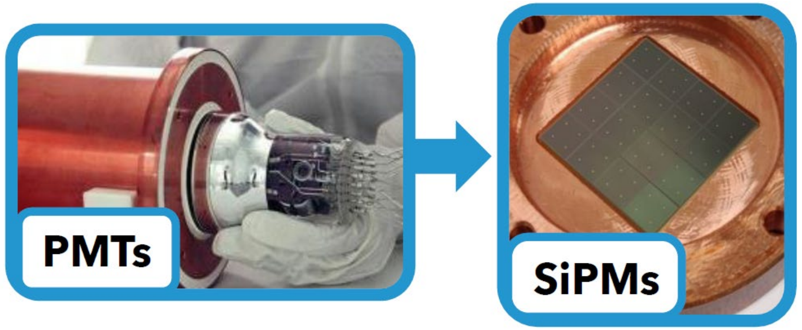
Best fit **incompatible with DAMA/LIBRA** at 3.9 (2.9) σ for [1-6] ([2-6]) keV

Sensitivity with 6 years data: 4.2 (4.1) σ for [1-6] ([2-6]) keV

5σ sensitivity in late 2025

ANAIS+

Goal: Lower the energy threshold Eth <0.5 keV.



Replace PMTs for SiPM at low T (~100 K)

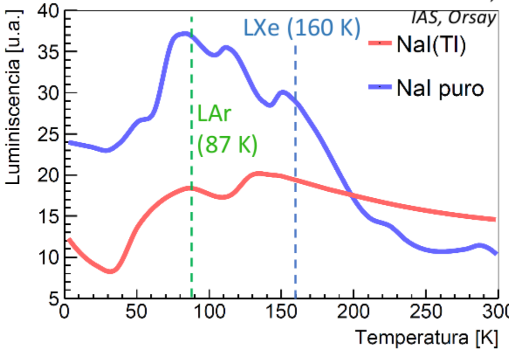
ADVANTAGES

- High QE.
- High radiopurity.
- Low operating voltage.
- No Cherenkov emission.
- Reduction of spurious light emission

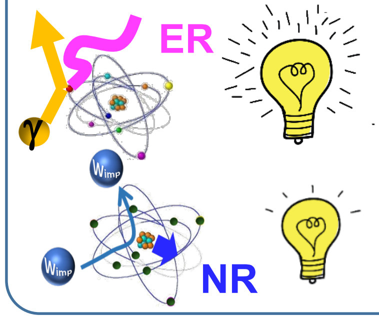
MAIN DRAWBACK: High dark current rate
-> Overcome by working at low T

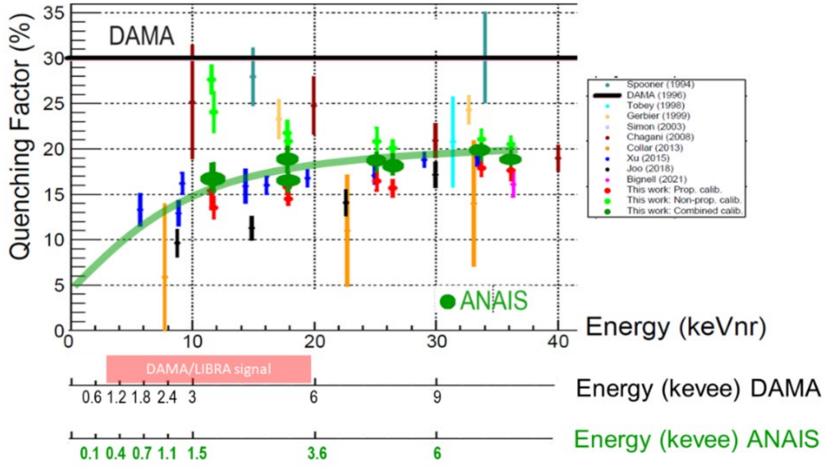
BONUS: NaI pure is a very good scintillator at 100 K

Measurement in collaboration with N. Coron, IAS, Orsay

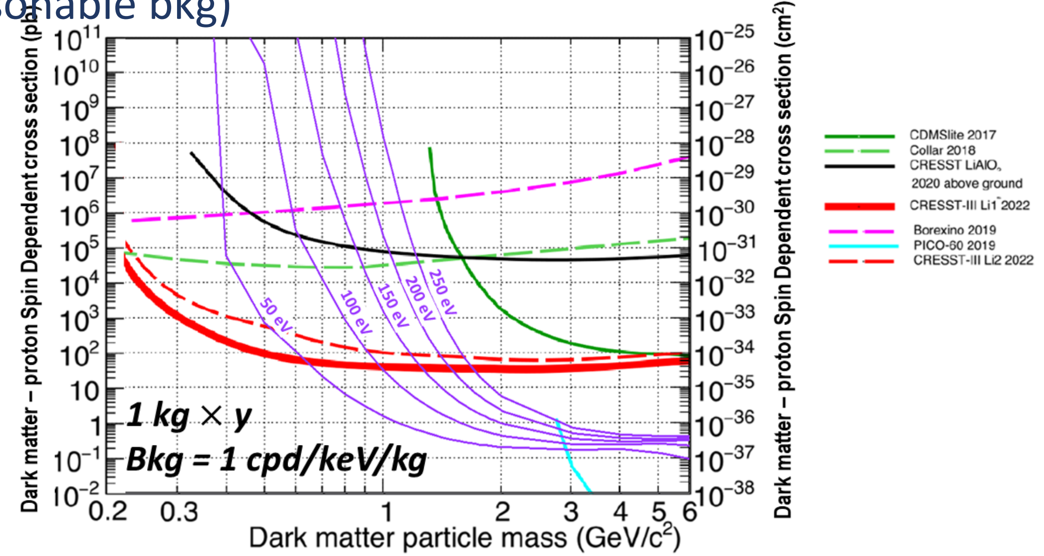


rule out any effect related to QF differences





Very sensitive to light WIMPs (SI, SD) (low exposure, reasonable bkg)



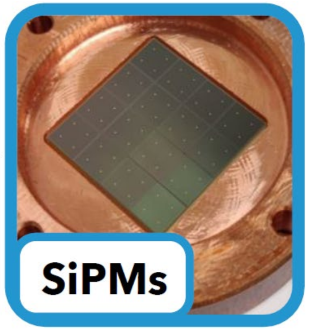
ANAIS+

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

INFN LNGS

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Goal: Lower the energy threshold Eth <0.5 keV.



Replace PMTs for SiPM at low T (~100 K)

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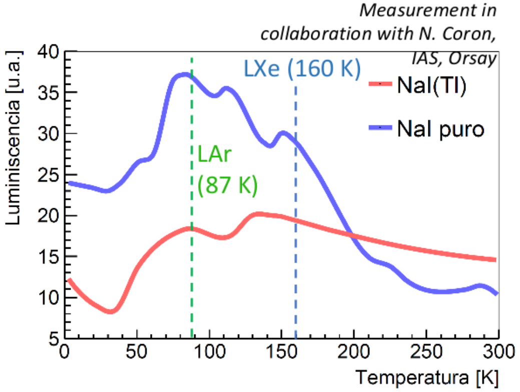
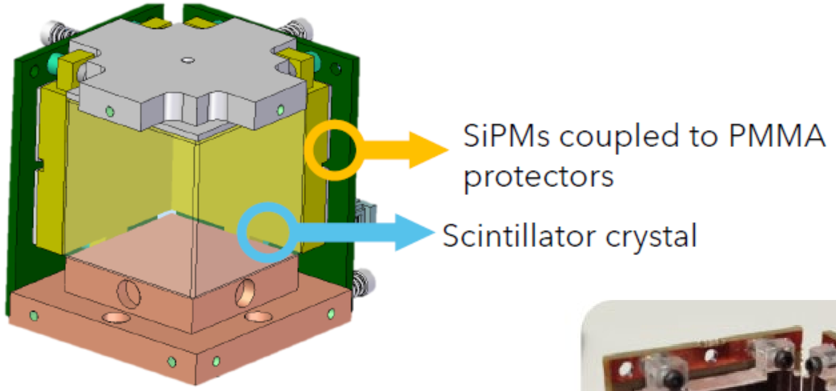
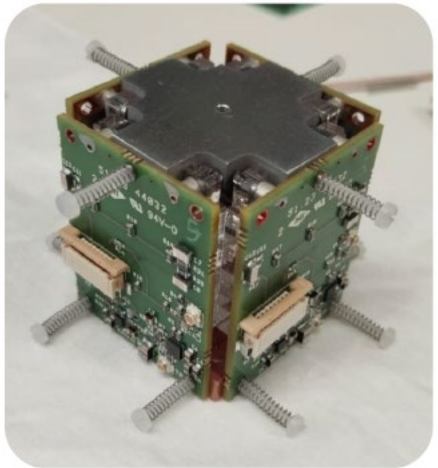
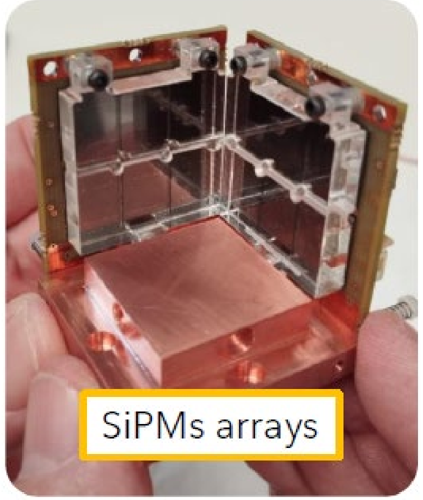


First prototype: the SiPMs designed in LNGS have been tested and the complete first ANAIS+ prototype will be soon assembled in Zaragoza







Outlook & summary

- **ANAIS–112 is leading the international efforts in the independent test of the DAMA/LIBRA** signal. It is taking data in stable condition @ LSC since 3rd August 2017 with excellent performances (>700 kg×y exposure).
- Low-energy event selection and sensitivity have been improved with machine-learning techniques
- **Preliminary results for 6 years: ANAIS−112 is compatible with the absence of modulation and incompatible with the DAMA/LIBRA signal at 4σ (3σ) in [1-6] keV ([2-6] keV), for a sensitivity of 4.2σ (4.1σ) at [1-6] keV ([2-6] keV)**
- **For the first time, a direct test (i.e. model independent) of DAMA is performed with >4σ sensitivity. 5σ sensitivity in late 2025**
- Working on the combination of results with COSINE-100. Preliminary 3y results presented at IDM2024
- ANAIS has carried out QF measurements, pointing to values lower than those of DAMA. Disagreement still to be understood. Understanding the response of NaI(Tl) crystals to nuclear recoils is crucial in the model independent comparison with DAMA/LIBRA
- ANAIS+ (1 kg NaI+SiPM @ 100 K) can improve current SD-proton sensitivity for low-mass WIMPs and discard QF differences as explanation for DAMA/LIBRA signal

Open Data Policy: ANAIS−112 3-year annual modulation analysis and the reanalysis can be downloaded at https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais. 6 years in the near future

Thank you for your attention!

ANAIS research team
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E. García, M. Martínez(*), Y. Ortigoza, A. Ortiz de Solórzano,
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Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

GOBIERNO DE ARAGON

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea
NextGenerationEU

MultiDark
Multimessenger Approach for Dark Matter Detection

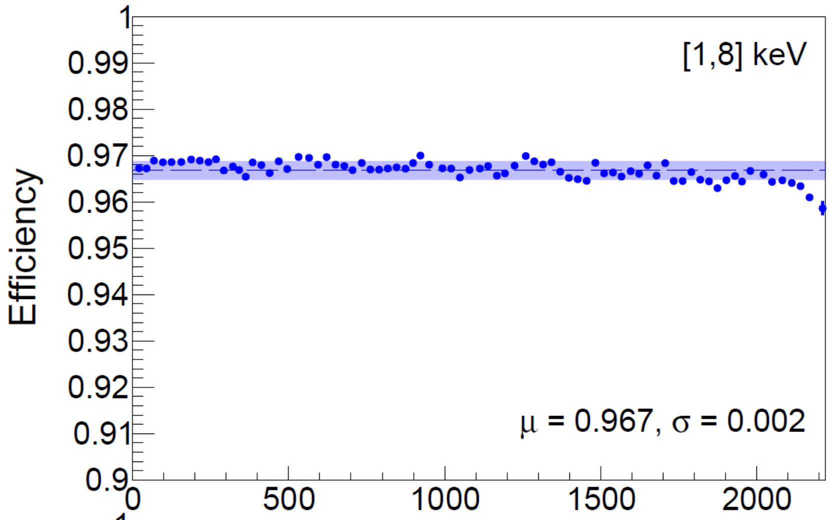
ANAIS experiment operation is presently financially supported by MICIU/AEI/10.13039/501100011033 (Grants No. PID2022-138357NB-C21 and PID2019-104374GB-I00), and Unión Europea NextGenerationEU/PRTR (AstroHEP) and the Gobierno de Aragón. Funding from Grant FPA2017-83133-P, Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, the Gobierno de Aragón and the LSC Consortium made possible the setting-up of the detectors. The technical support from LSC and GIFNA staff as well as from Servicios de Apoyo a la Investigación de la Universidad de Zaragoza (SAIs) is warmly acknowledged.

Backup

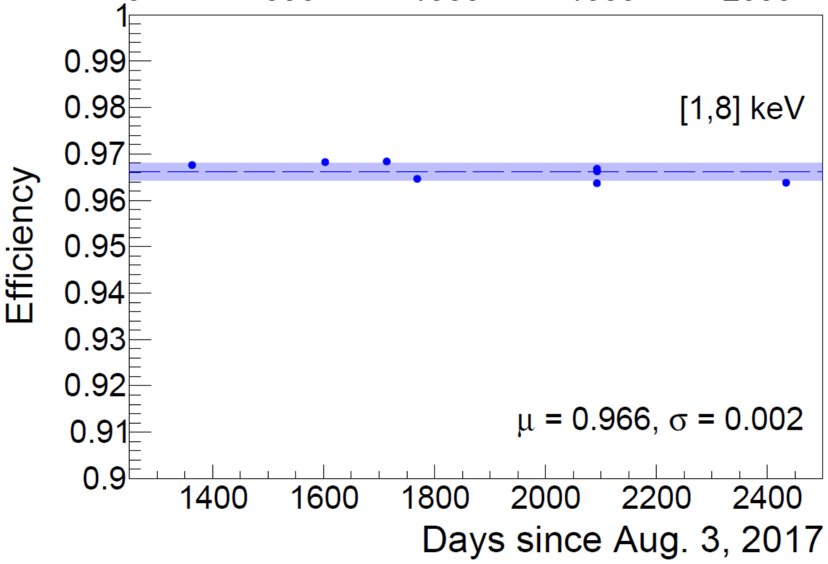
Stability checks before 6-year unblinding

Event selection efficiency stability

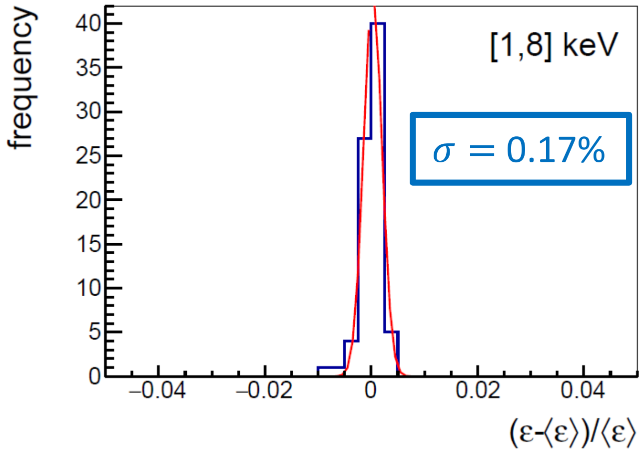
Efficiency calculated from ^{109}Cd calibrations



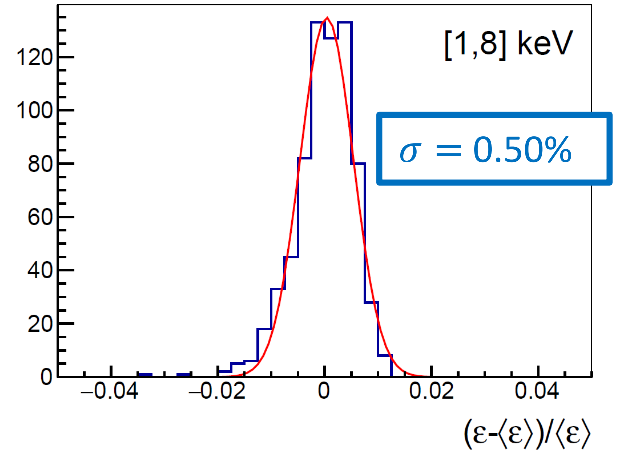
Efficiency calculated from neutron calibrations

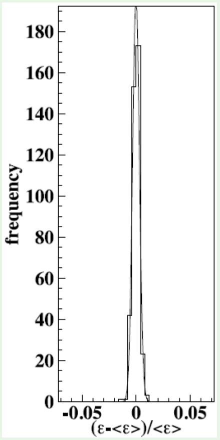


Averaging all detectors



Considering independently





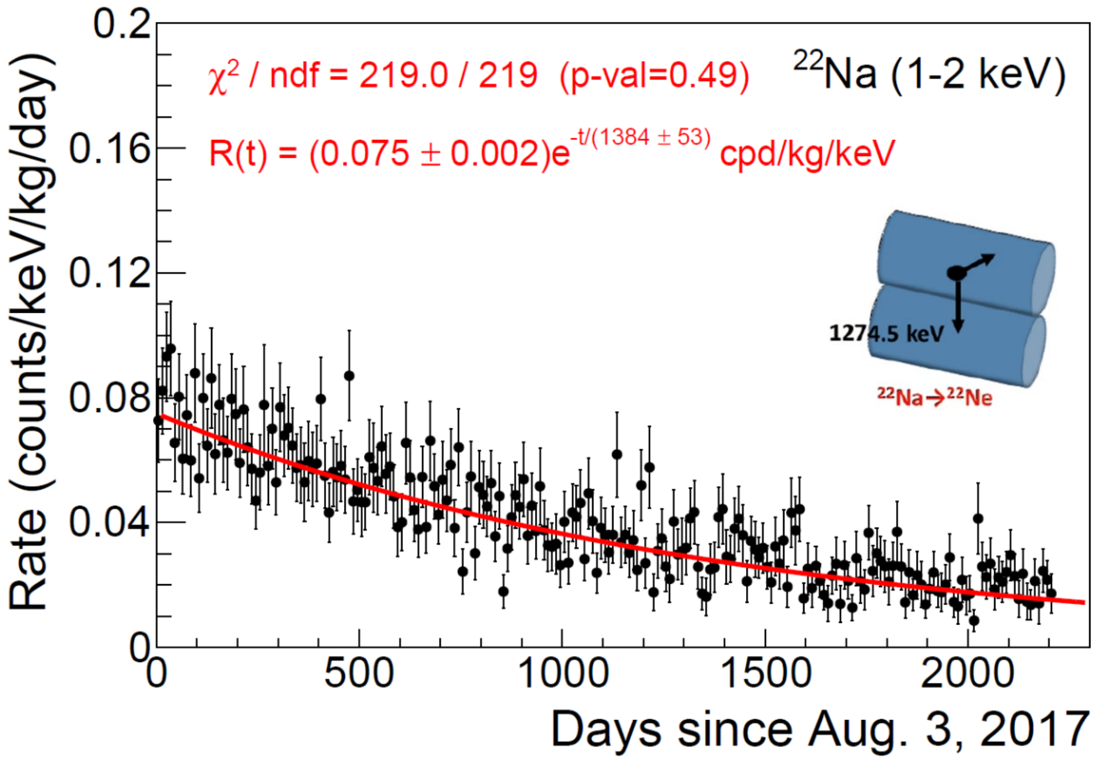
DAMA/LIBRA-phase2 reports a similar spread $\boldsymbol{\sigma} = \mathbf{0.30\%}$ in [1-8] keV

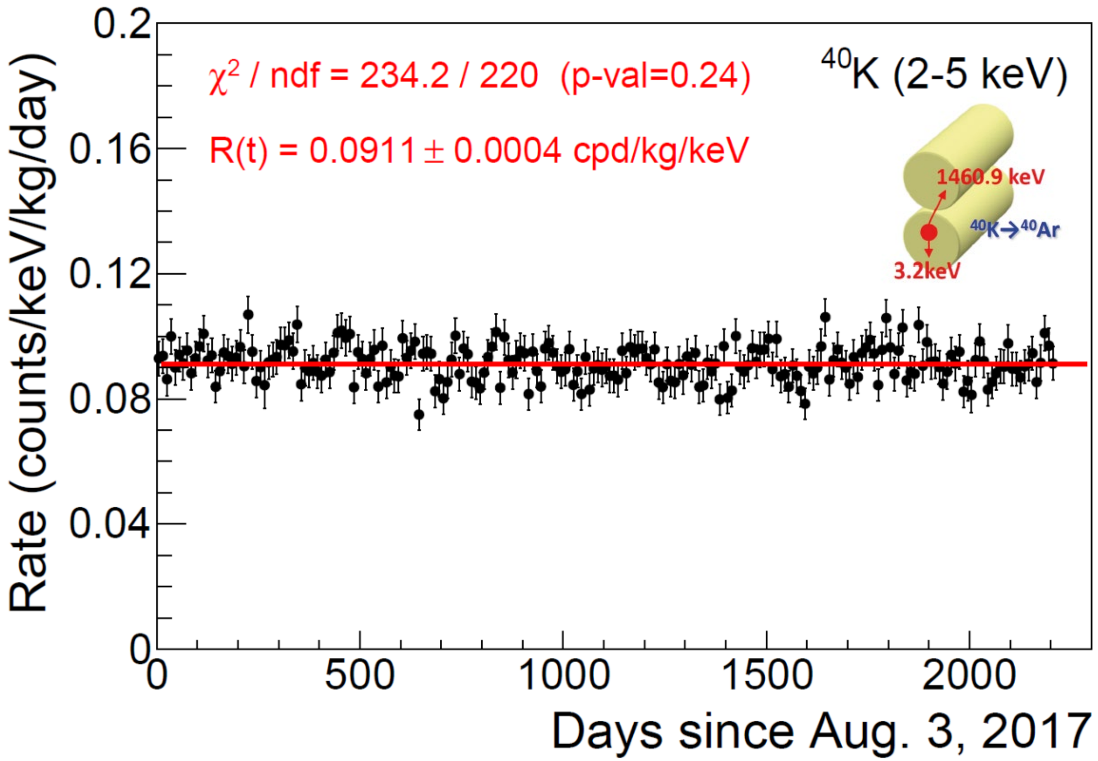
R. Bernabei et al., Prog. Part. Nucl. Phys. 114 (2020) 103810

Stability checks before 6-year unblinding

Evolution of control populations

0.9 keV (^{22}Na) and 3.2 keV (^{40}K) selected by coincidence. BDT cut and efficiency corrected (trigger+BDT)





$\tau_{fit} = 1384 \pm 53$ days

$\boldsymbol{\tau_{22Na} = 1369}$ **days**

Annual modulation results with 5 years

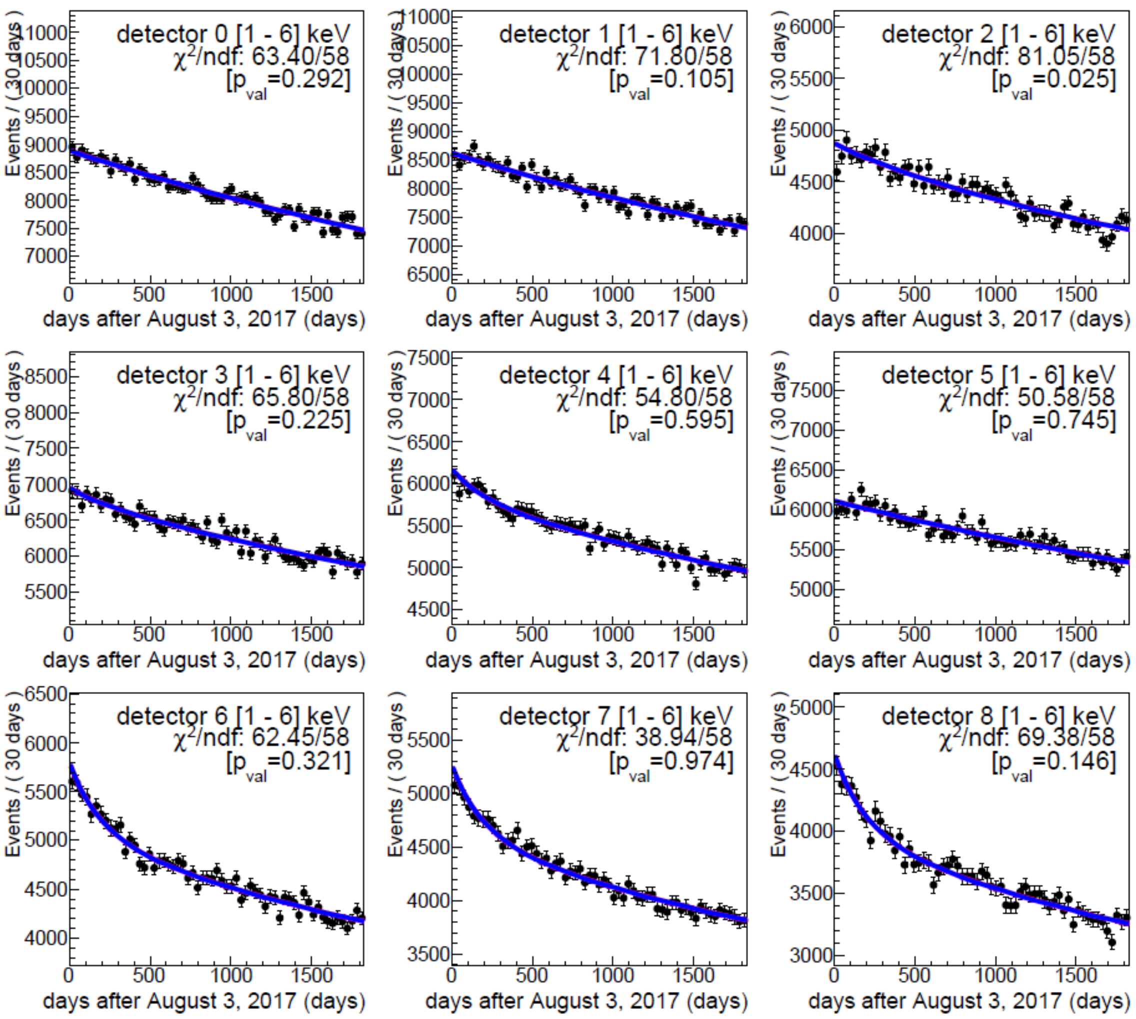
537.44 kg × y

[1-6] keV: **3.8σ**

Null hyp χ^2/ndf: 558.21/531 [p_{val}=0.200]

Mod hyp χ^2/ndf: 557.96/530 [p_{val}=0.194]

S_m = (0.0014 ± 0.0028) (cpd/kg/keV)

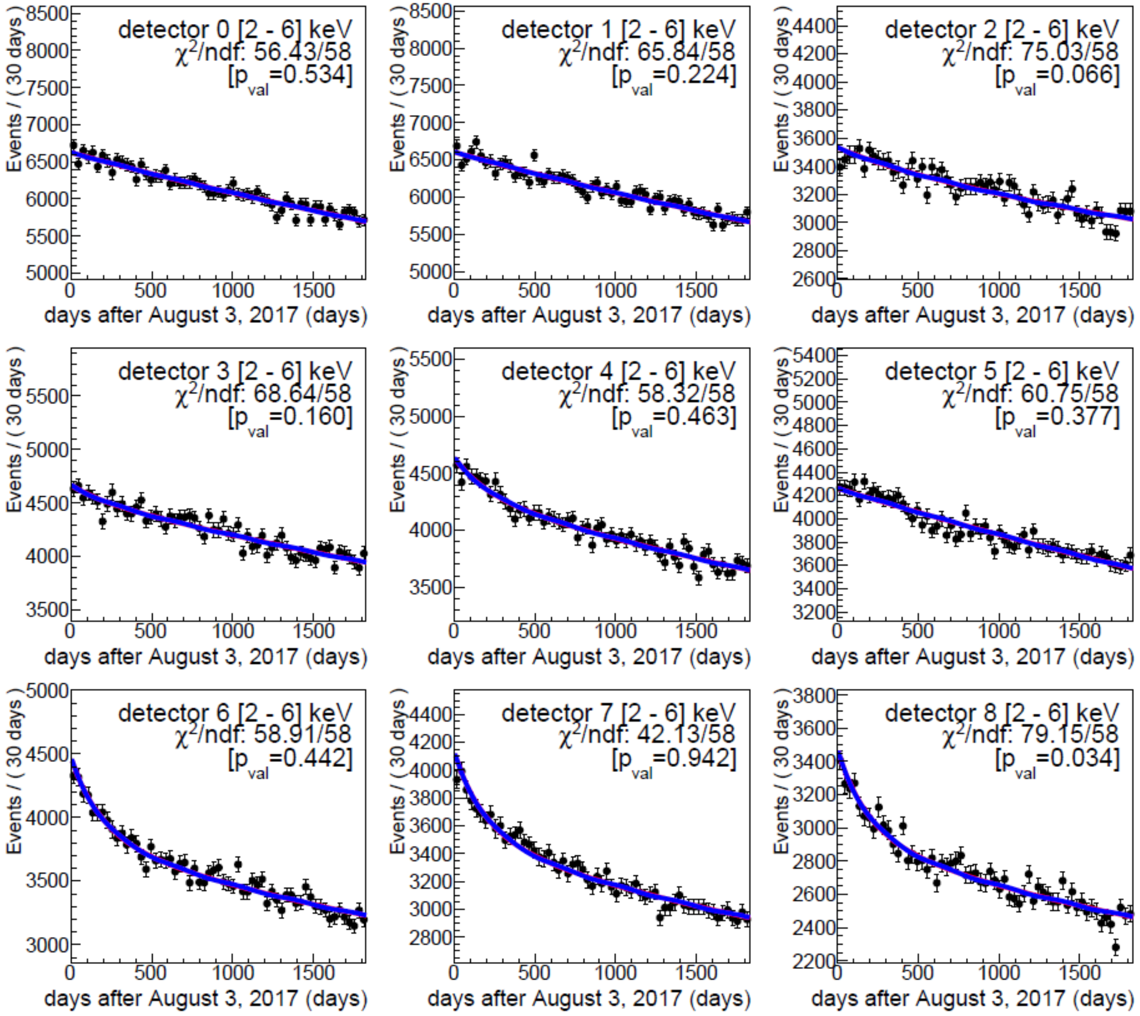


[2-6] keV: **3.7σ**

Null hyp χ^2/ndf: 566.38/531 [p_{val}=0.139]

Mod hyp χ^2/ndf: 565.00/530 [p_{val}=0.142]

S_m = (0.0032 ± 0.0027) (cpd/kg/keV)

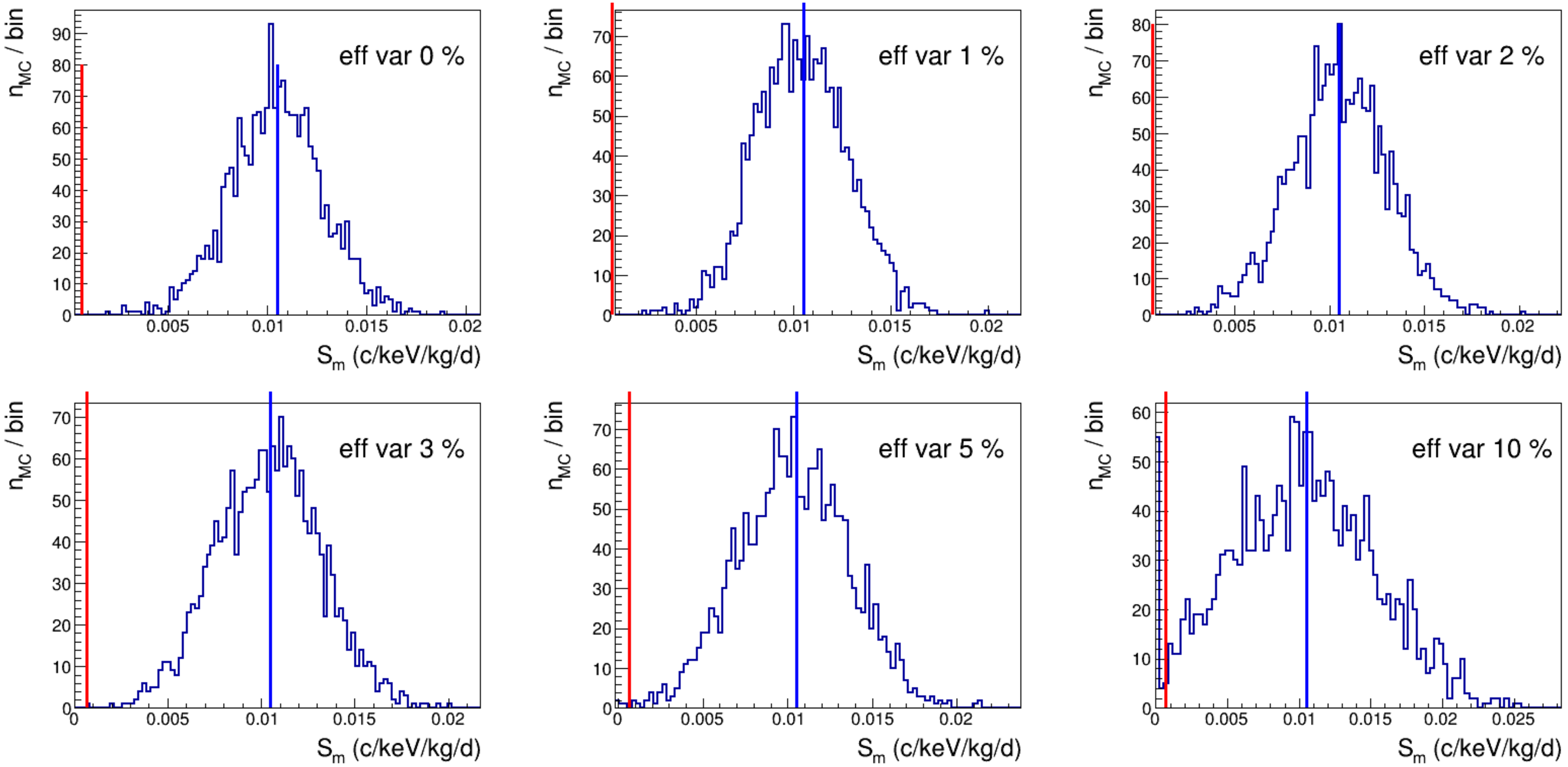


PRELIMINARY

Toy MC for efficiency analysis

- 2000 Toy MC carried out with ANAIS background + DAMA/LIBRA modulation
- Updated to include variations in the efficiency around the mean value of different size
- We recover in all cases the right modulation amplitude enlarging the standard deviation

[1-6] keV



ANAIS result in red

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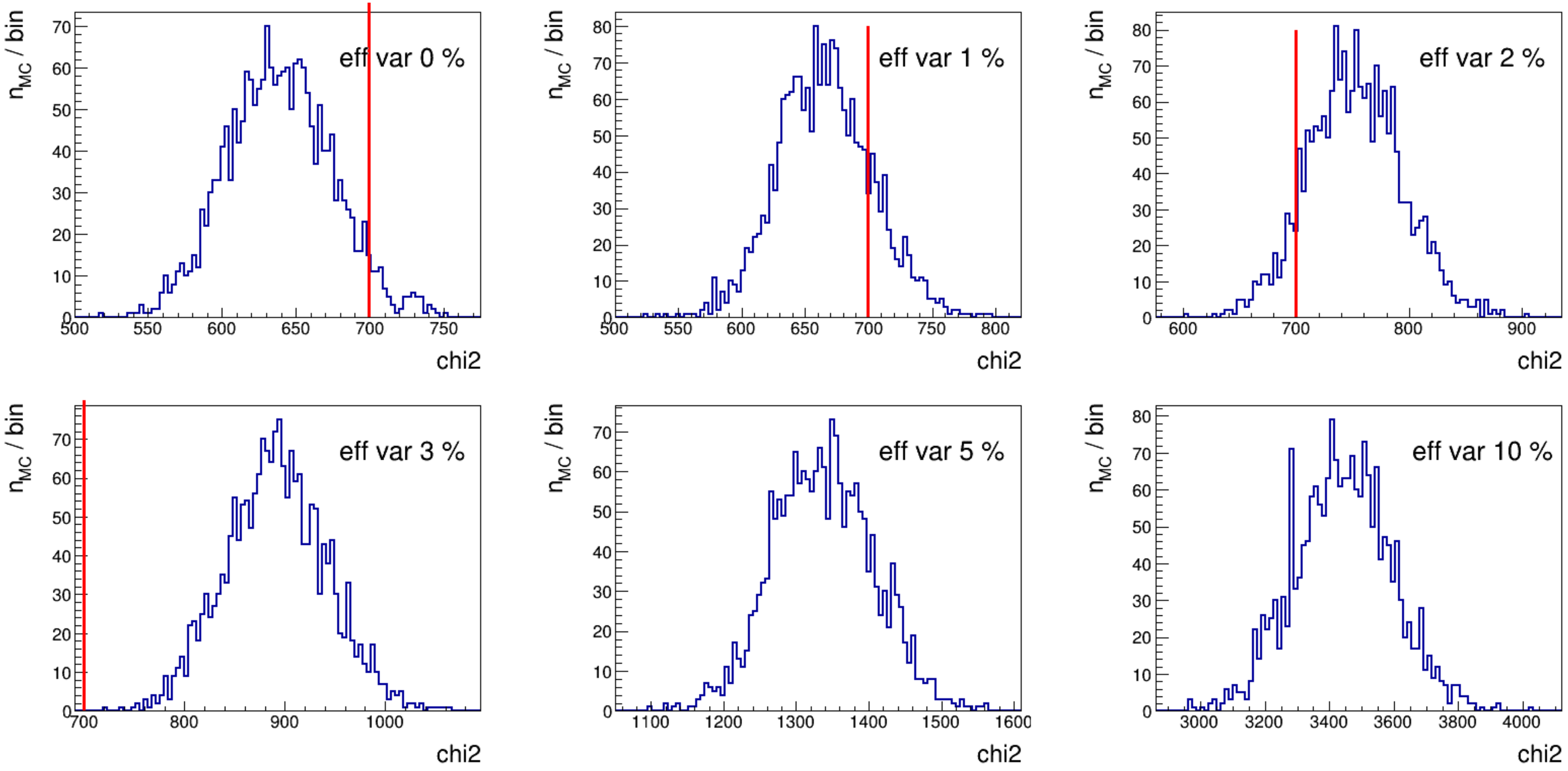
Toy MC for efficiency analysis

- 2000 Toy MC carried out with ANAIS background + DAMA/LIBRA modulation
- Updated to include variations in the efficiency around the mean value of different size
- We recover in all cases the right modulation amplitude enlarging the standard deviation
- The Chi2 value is strongly sensitive to this efficiency "variation". **Our analysis suggests is <3% [1-6] keV**

[1-6] keV



ANAIS result in red

PRELIMINARY