Dark matter annual modulation with ANAIS-112: three years results

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On behalf of the ANAIS team
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ANAIS
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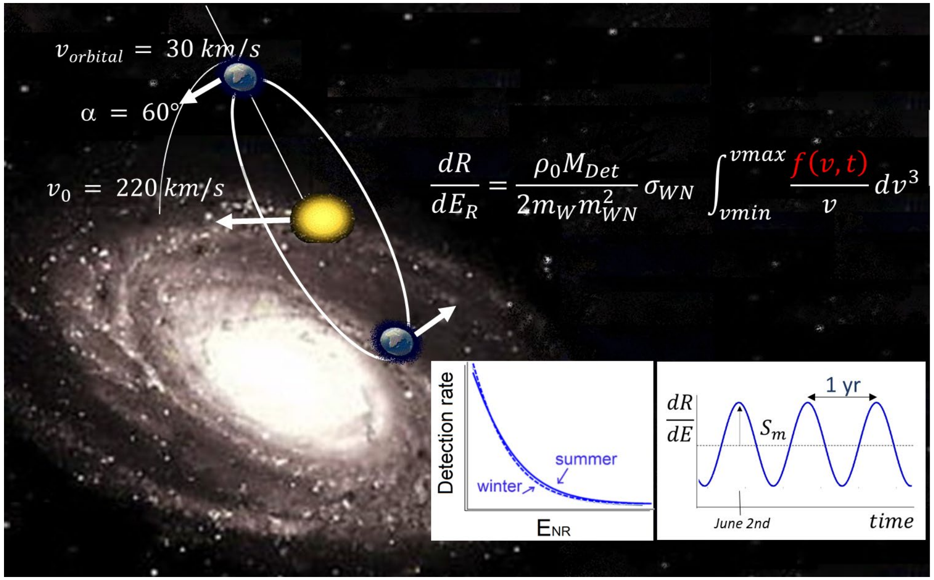
Universidad Zaragoza
LSC Laboratorio Subterráneo de Canfranc
araid Fundación Agencia Aragonesa para la Investigación y el Desarrollo
MultiDark Multimessenger Approach for Dark Matter Detection

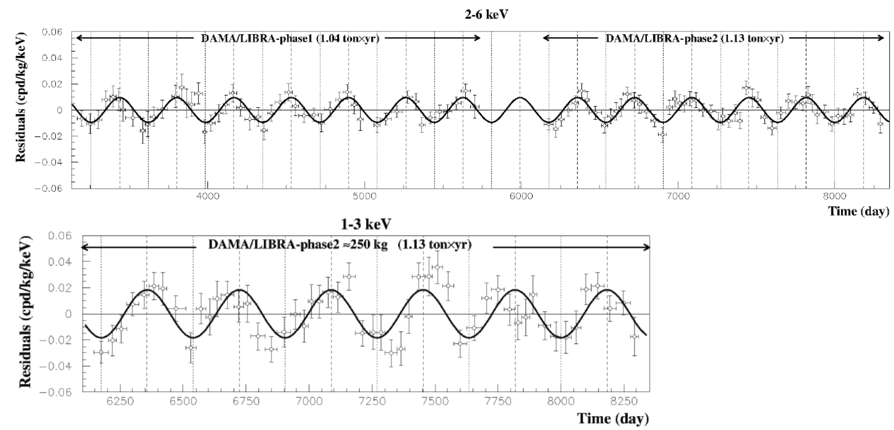
OUTLINE

- Intro
- ANAIS-112 set-up
- Detector performance
- 3 years results on annual modualation
- Projected sensitivity
- Conclusions

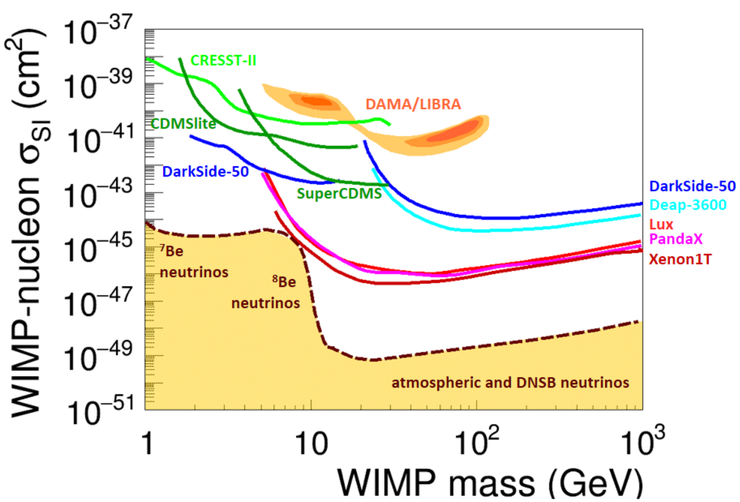
DM annual modulation & DAMA/LIBRA positive signal



DAMA/NaI & DAMA/LIBRA (LNGS) [since 1995]



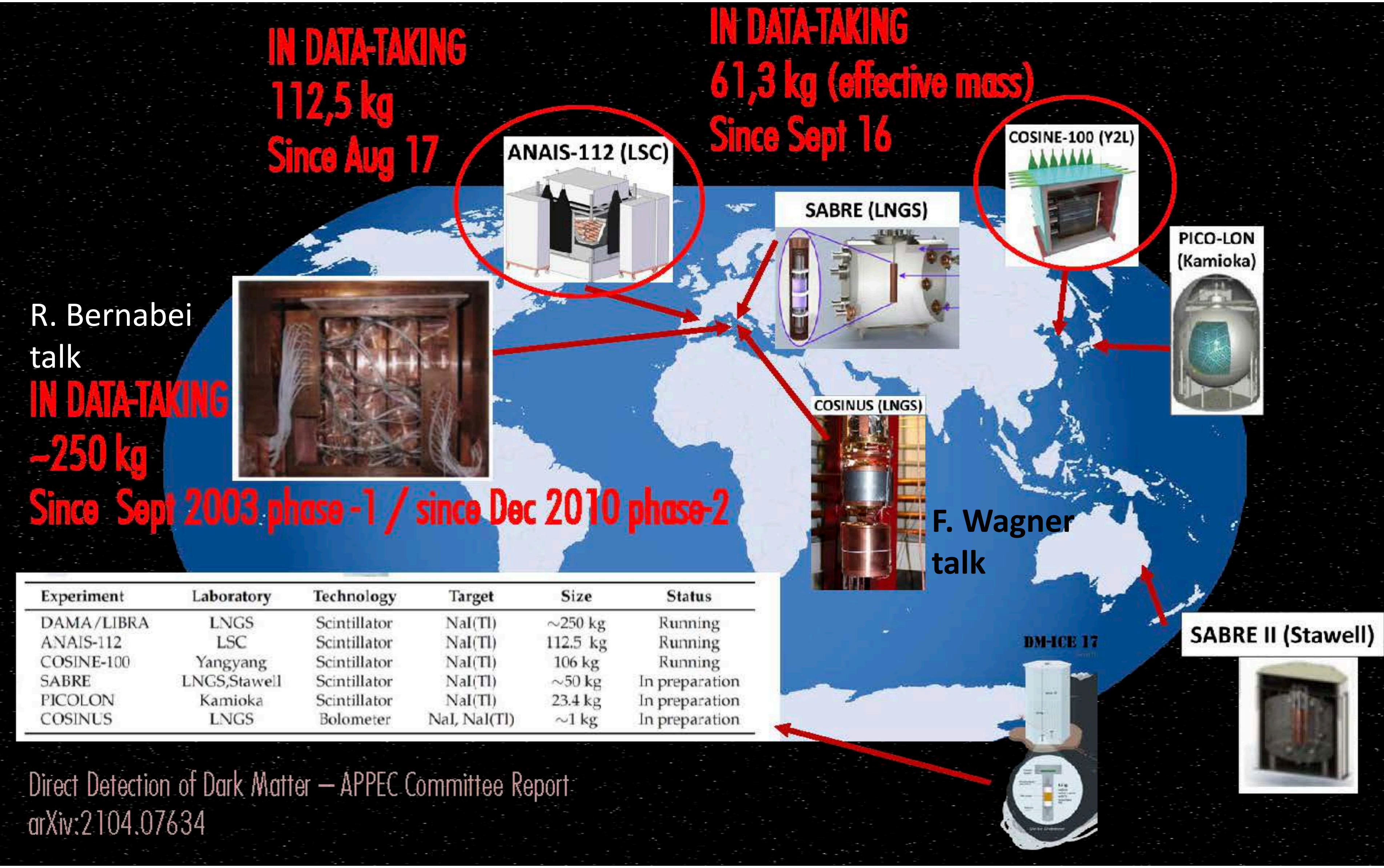
DAMA clearly sees an annual modulation compatible with DM at more than 12σ



other very sensitive experiments do not see the signal, **but the comparison is model dependent**

-> a model independet confirmation is needed using the same target

Experimental situation



Experiment	Laboratory	Technology	Target	Size	Status
DAMA/LIBRA	LNGS	Scintillator	NaI(Tl)	~250 kg	Running
ANAIS-112	LSC	Scintillator	NaI(Tl)	112.5 kg	Running
COSINE-100	Yangyang	Scintillator	NaI(Tl)	106 kg	Running
SABRE	LNGS,Stawell	Scintillator	NaI(Tl)	~50 kg	In preparation
PICOLON	Kamioka	Scintillator	NaI(Tl)	23.4 kg	In preparation
COSINUS	LNGS	Bolometer	NaI, NaI(Tl)	~1 kg	In preparation

ANAIS-112 experiment

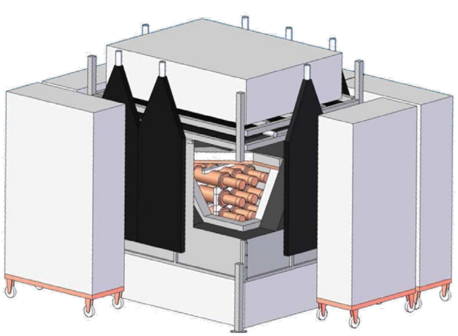
ANAIS-112

Annual Modulation with NaI Scintillators

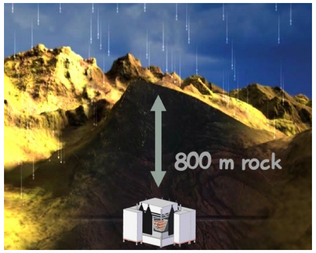
J. Amaré, I. Coarasa, S. Cebrián, D. Cintas, E. García, M. Martínez, M.A. Oliván,
Y. Ortigoza, A. Ortiz de Solórzano, J. Puimedón, A. Salinas, M.L. Sarsa

GOAL:
Independent confirmation of DAMA/LIBRA modulation signal with the same target and technique
(but different experimental approach and environmental conditions)

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

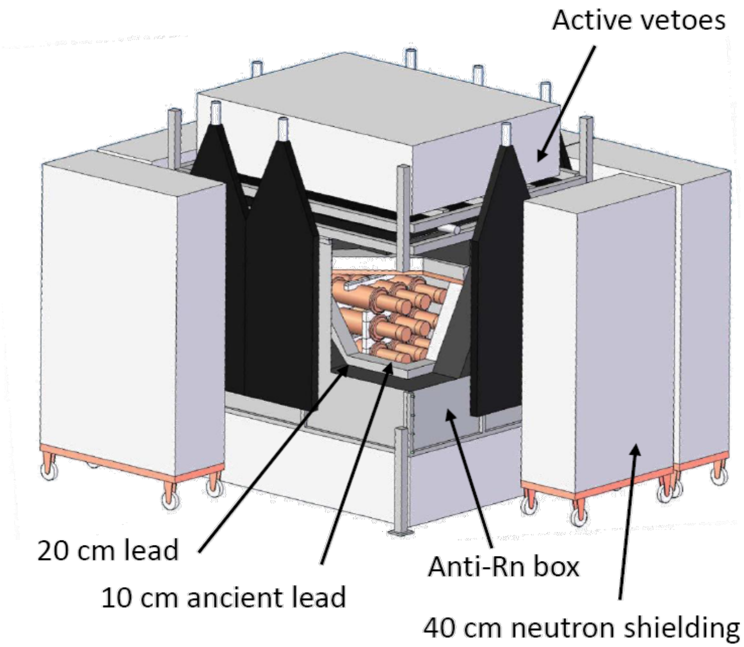


WHERE:
At Canfranc Underground Laboratory,
@ **SPAIN** (under **2450 m.w.e.**)

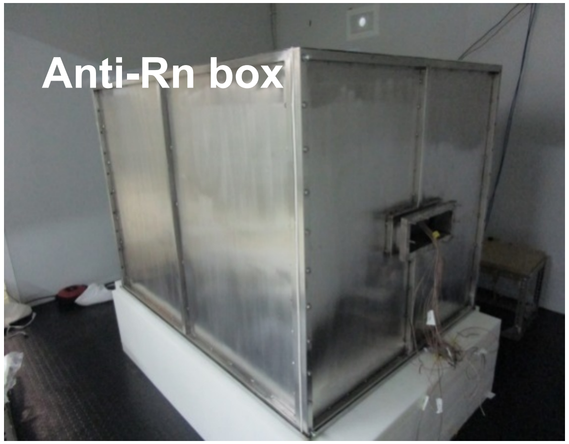


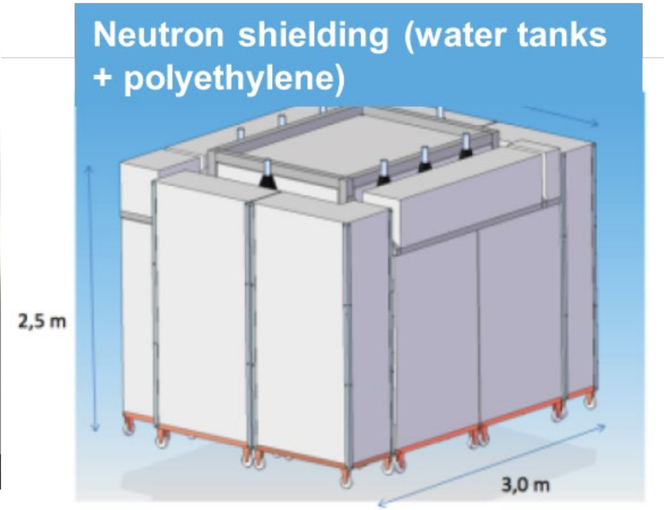
taking data since August 2017

ANAIS-112: experimental setup



- 9 NaI(Tl) cylindrical crystals (12.5 kg each) in 3x3 matrix
- Ultrapure NaI powder (Alpha Spectra Inc)
- Each coupled to two Hamamatsu R12669SEL2 PMT (QE ~40%)



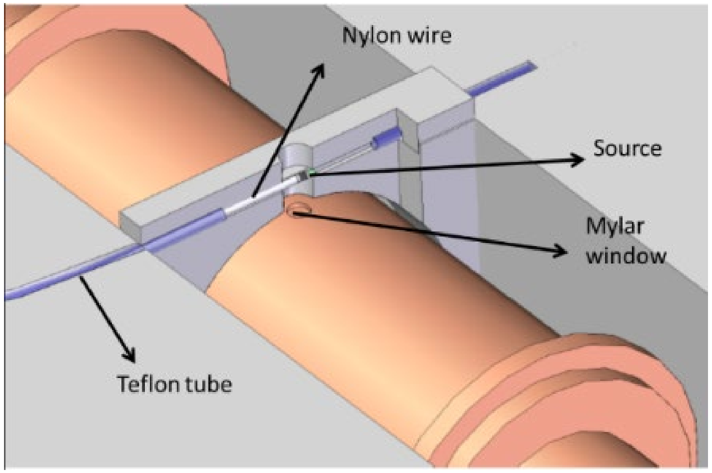


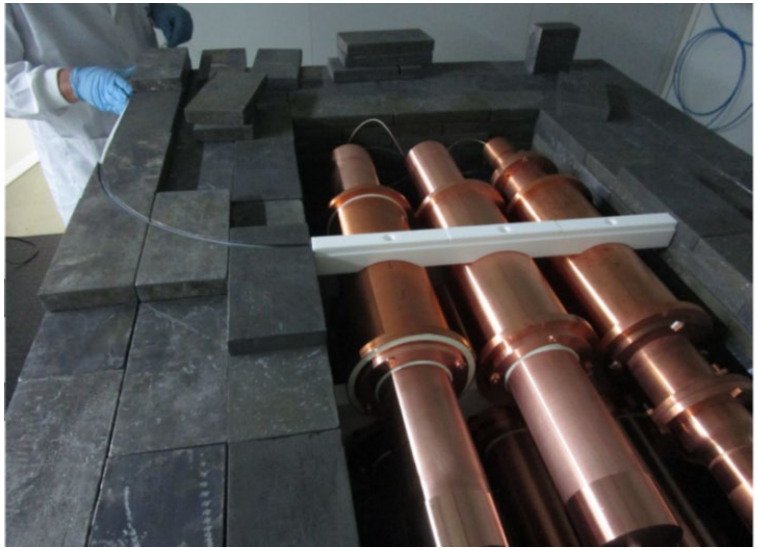
ANAIS-112: Low energy calibration

Detectors equipped with a **Mylar window**!

Radon-free system for low energy calibration:

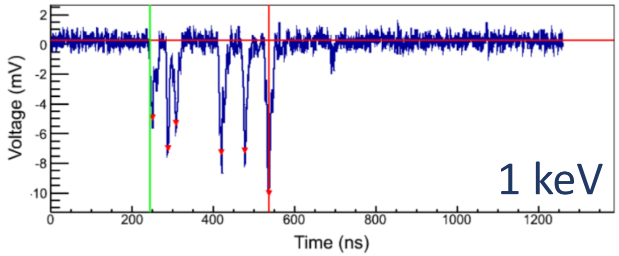
- **^{109}Cd sources** on flexible wires (radon-free)
- Energies: 11.9, 22.6 and 88.0 keV
- Simultaneous calibration of the nine modules
- Performed every two weeks

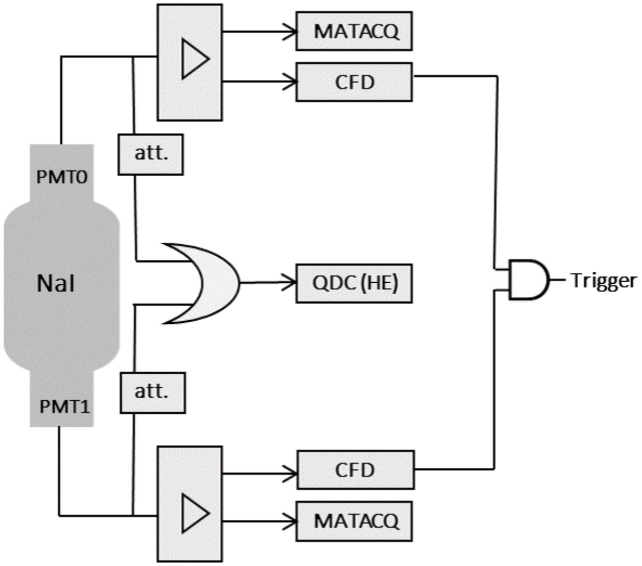


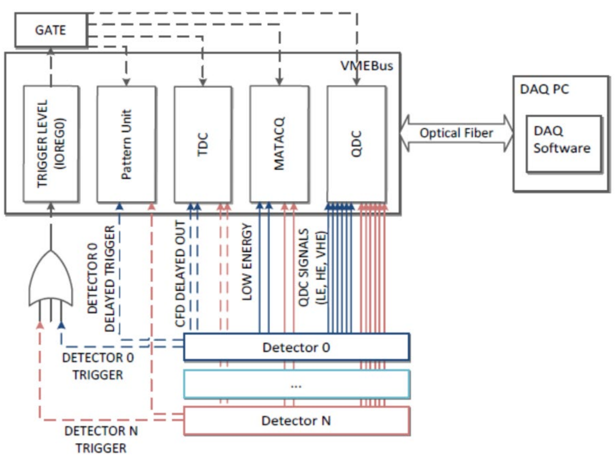


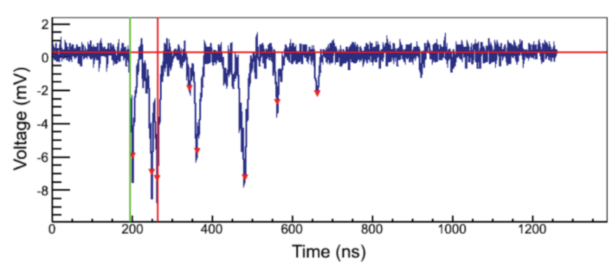
ANAIS-112: Data acquisition system

- Individual PMT signals **digitized** and fully processed **(14 bits, 2 GS/s)**
- Trigger at phe level for each PMT signal
- AND coincidence in 200 ns window
- Redundant energy conversion by QDC
- Trigger in OR mode among modules
- Electronics at air-conditioned-room to decouple from temperature fluctuations
- Muon detection system: tag every muon event to offline processing



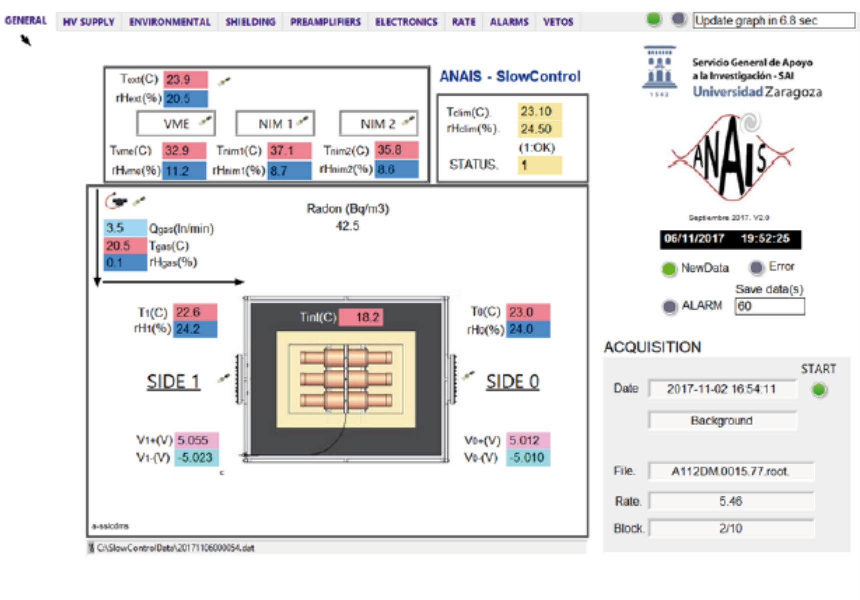


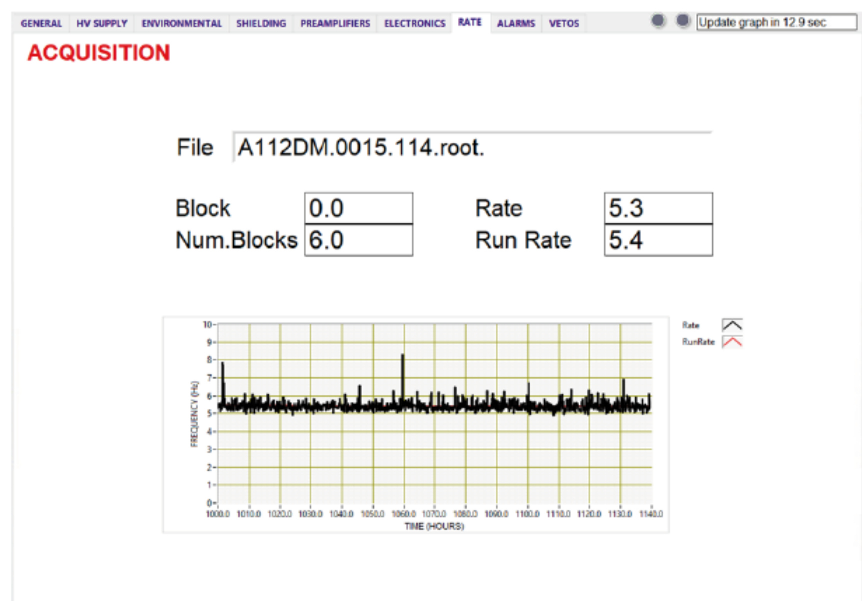




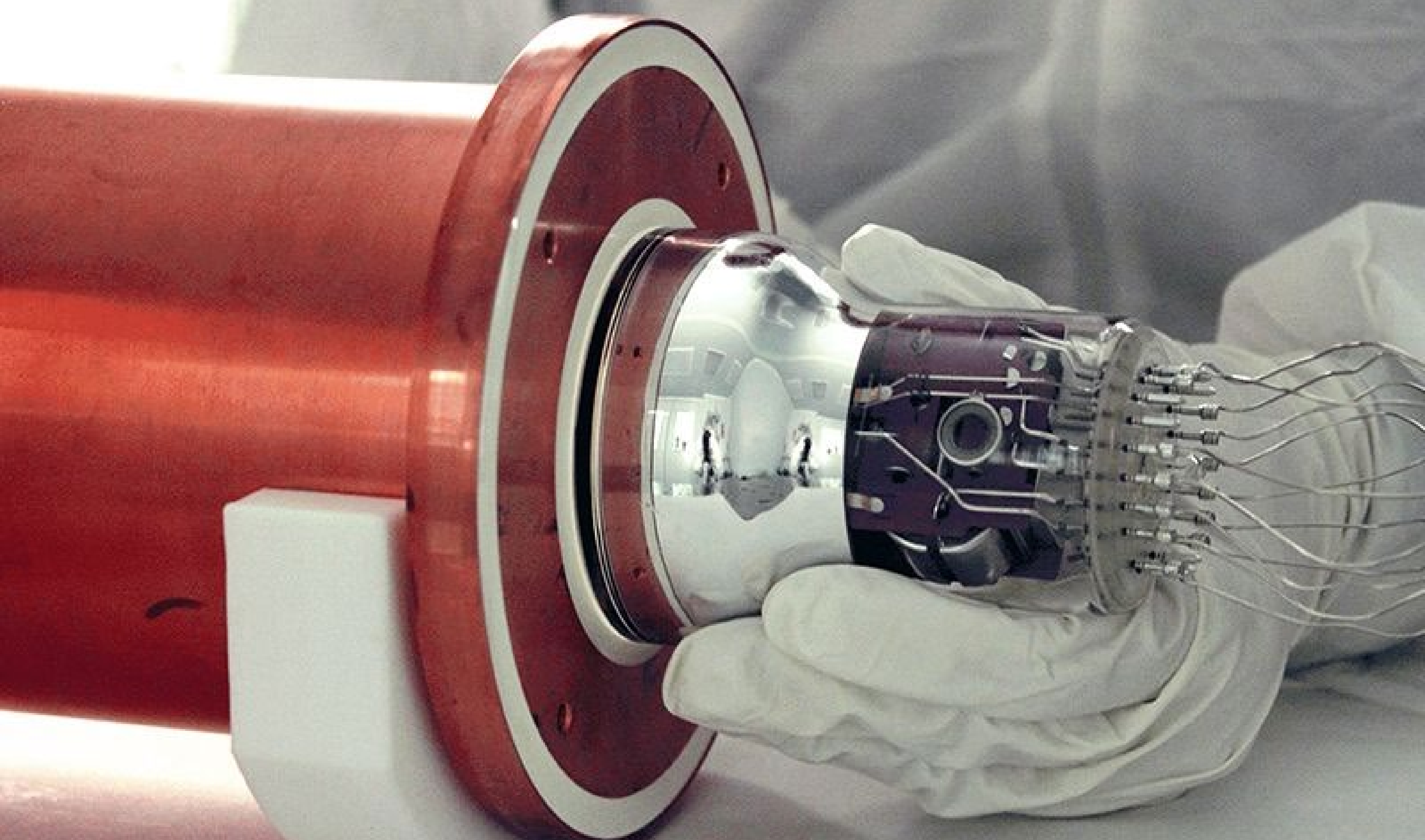
ANAIS-112: Slow control

- Monitoring **environmental parameters** since the start of DM run
  - Monitoring:
    Rn content, humidity, pressure, different temperatures, N_2 flux, PMT HV, muon rate, …
    Data saved every few minutes and alarm messages implemented
  - Stability checks:
    gain, trigger rate, …





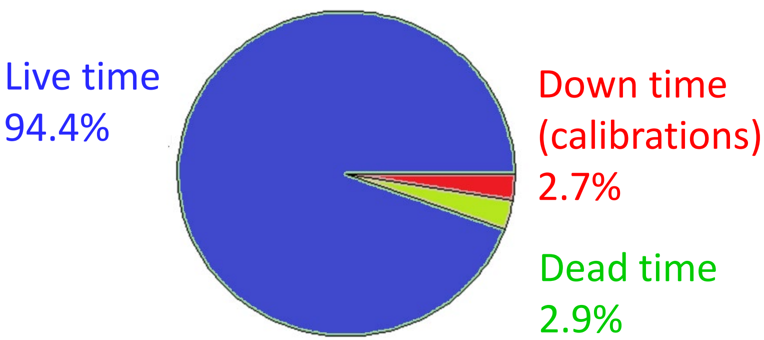
DETECTOR PERFORMANCE

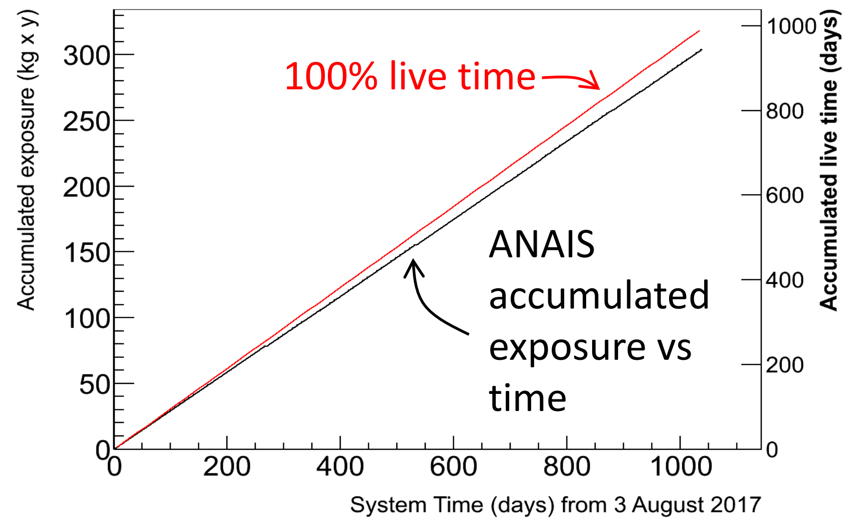


Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

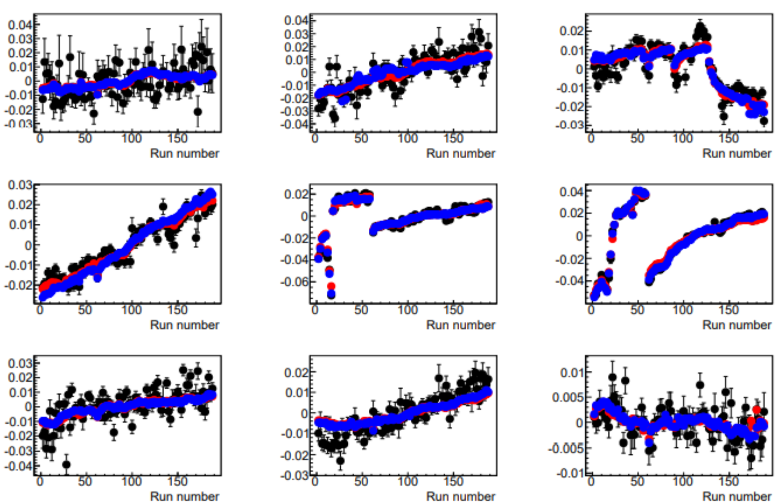
Detector Response: duty cycle & stability

- Excellent **duty cycle**





- Good **total rate and gain stability**



Evolution of ^{109}**Cd lines from calibrations** along the whole data-taking (~ 3 year) show good stability except for D4 & D5 (HV changed after first year)

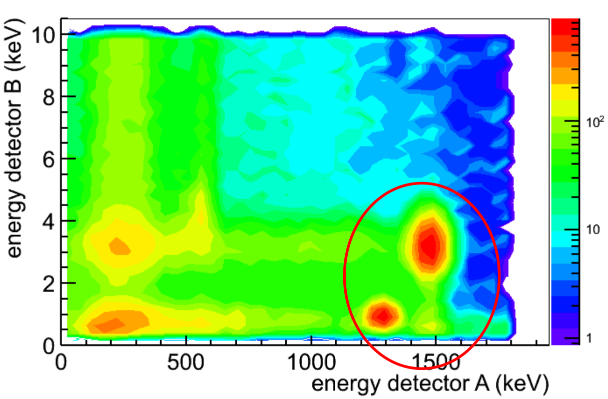
Thanks to the periodic calibration **we can correct** the small (few percent) gain variations

Detector response: light yield & threshold

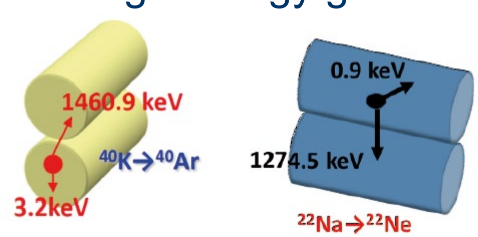
- **Excellent light collection ~ 15 photoelectrons / keV** (2x DAMA ph1)

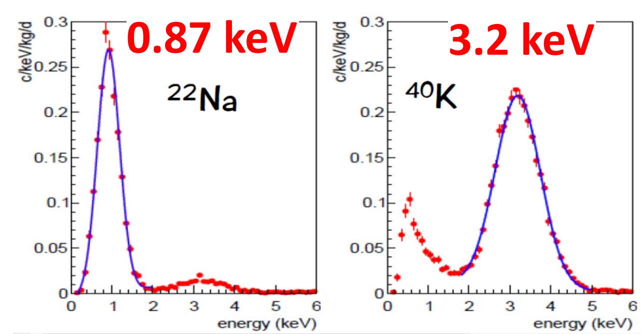
Module	Q.E. PMT0/PMT1 (%)	Total light collection (p.e./keV) 2017 results [33]	3 years results average	3 years results std. deviation	Energy resolution FWHM @ 3.2 keV (keV)
D0	38.2/37.2	14.6 ± 0.1	14.49	0.11	1.26 ± 0.03
D1	39.7/39.7	14.8 ± 0.1	14.64	0.15	1.30 ± 0.04
D2	39.2/42.6	14.6 ± 0.1	14.21	0.30	1.25 ± 0.03
D3	37.3/39.4	14.5 ± 0.1	14.33	0.12	1.14 ± 0.05
D4	40.1/41.8	14.5 ± 0.1	14.33	0.13	1.34 ± 0.06
D5	43.6/43.9	14.5 ± 0.1	14.82	0.23	1.22 ± 0.02
D6	40.4/38.9	12.7 ± 0.1	12.74	0.12	1.35 ± 0.04
D7	41.9/42.5	14.8 ± 0.1	14.55	0.18	1.38 ± 0.04
D8	41.6/43.4	16.0 ± 0.1	15.81	0.21	1.30 ± 0.05

- Effectively **triggering below 1 keV_{ee}** checked with internal contaminants ^{22}Na, ^{40}K



bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas

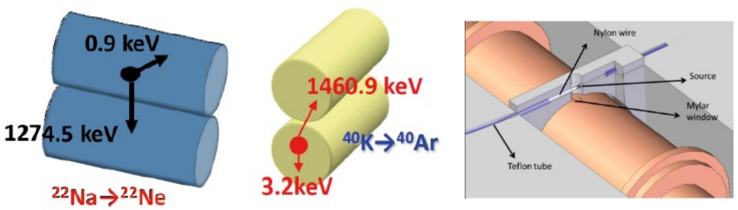




Blinded analysis

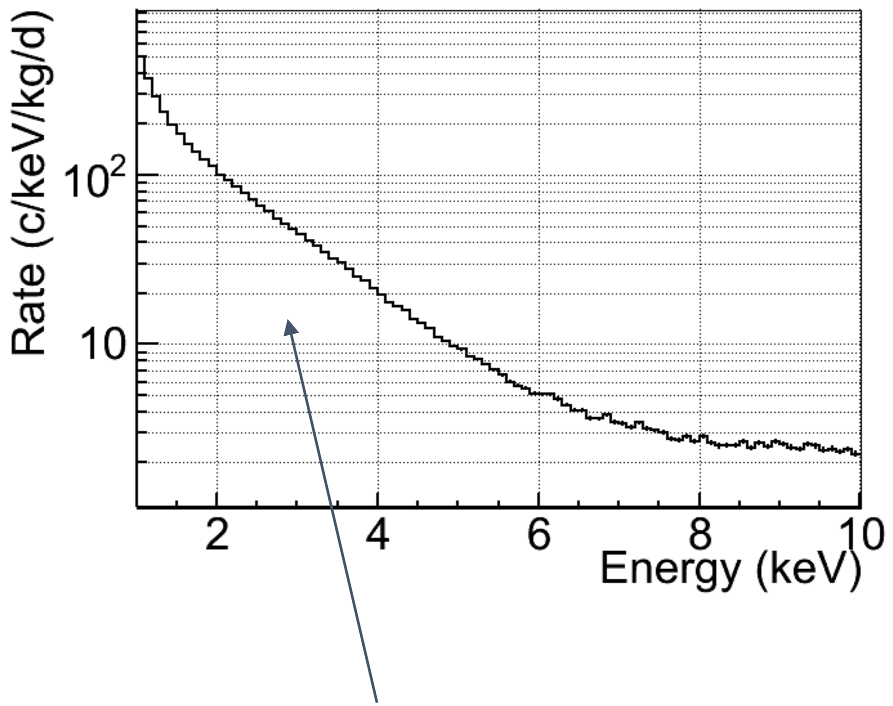
ANALYSIS STRATEGY

- Multiplicity-1 events in the RoI (1-6 keV) **blinded**
- We use **multiplicity-2 events** in the RoI and **calibration events** to tune the **filtering** algorithms and calculate the **cut efficiencies**



- We unblind ~30 days randomly distributed along the first year for background assessment

unblinded data (30 days)



Bkg in the ROI dominated by non-bulk scintillation events!

Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

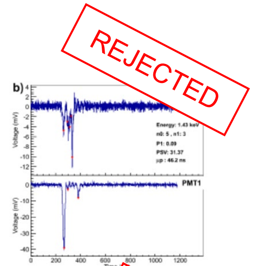
Event selection & efficiency

Procedure fixed before unblinding

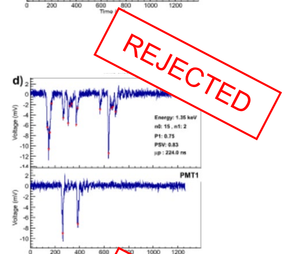
CUTS

1. Pulse shape cut to remove pulses not compatible with NaI(Tl) scintillation constant

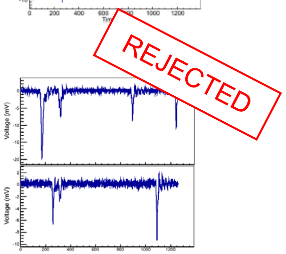
$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$



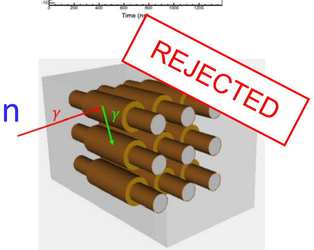
2. We remove asymmetric events (<2 keVee) with origin in the PMT



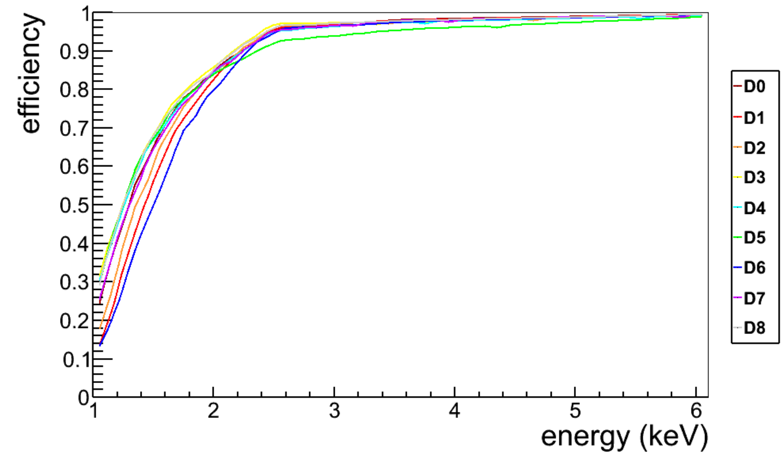
3. Remove 1 s after a muon passage



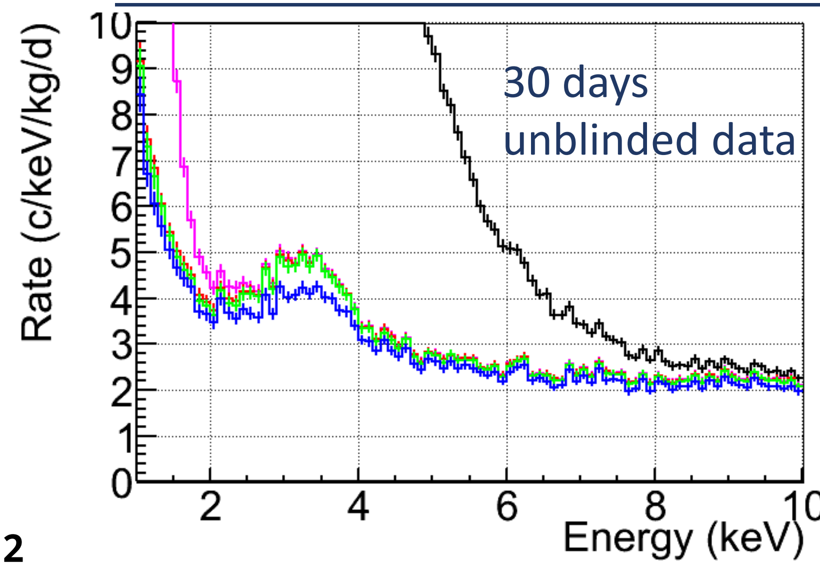
4. Multiplicity > 1 (Reject events that deposit energy simultaneously in more than one crystal)



TOTAL EFFICIENCY

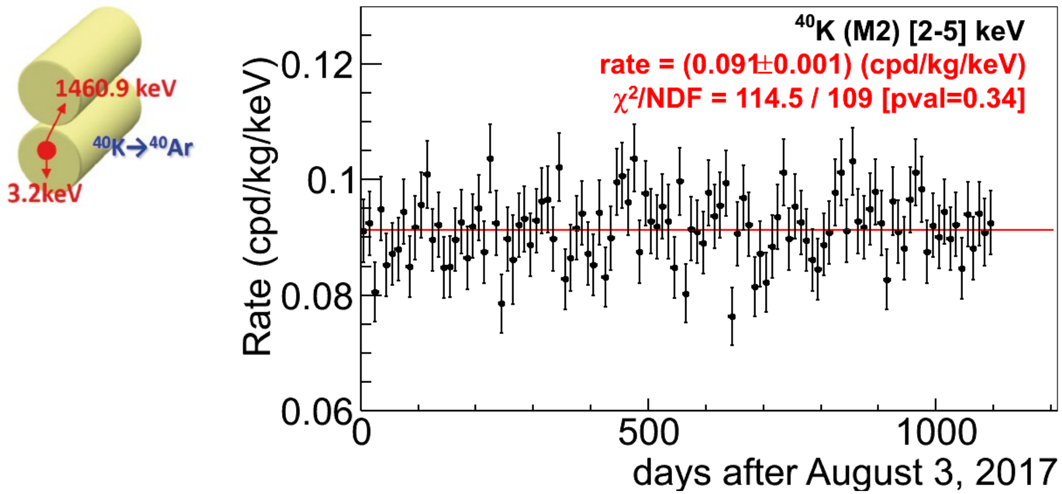


EFFICIENCY-CORRECTED BACKGROUND



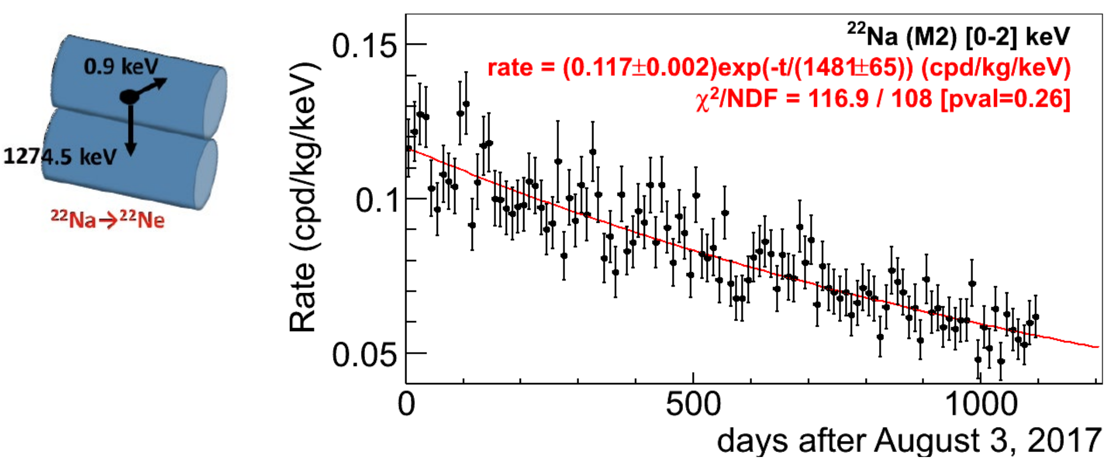
Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

Stability check with control populations



^{40}K ($T_{1/2} = 1.28 \times 10^9 y$)

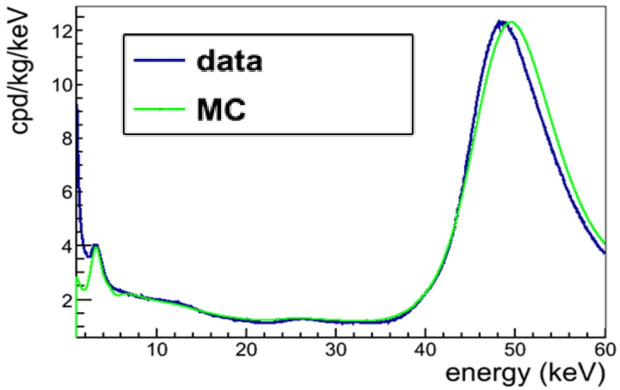
[2-5] keV rate in coincidence with HE gamma compatible with constant



^{22}Na ($T_{1/2} = 2.6\ y$)

[0-2] keV rate in coincidence with HE gamma compatible with ^{22}Na decay (exponential decay with $\tau = 1481 \pm 65$ d)

Background model



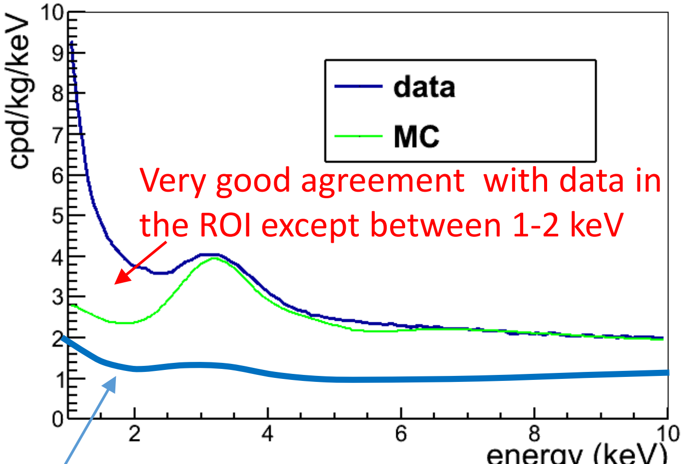
Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

Geat4 MC simulation including:

- activity from external components measured wiht 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)

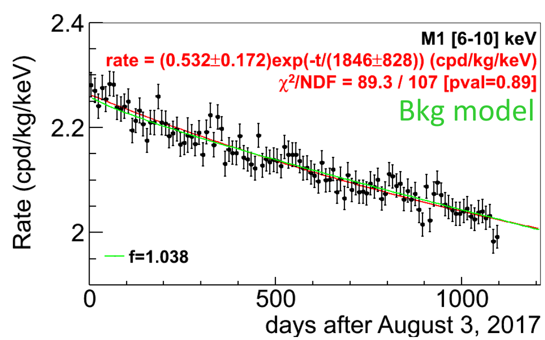


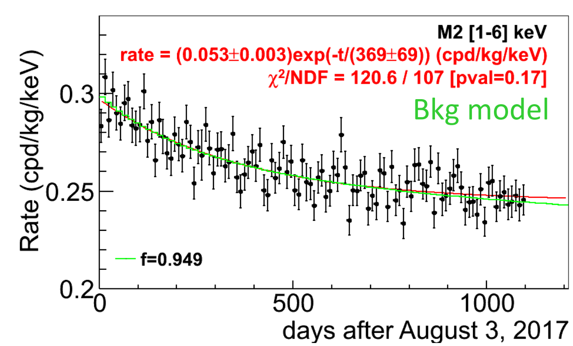
DAMA/LIBRA

`Universe 4, 116 (2018), 1805.10486`

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

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





RESULTS ON ANNUAL MODULATION

Analysis strategy

Phys. Rev. D 103, 102005 (2021)

Focus on model independent analysis searching from 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**
- ChiSquare minimization: $\chi^2 = \sum(n_i - \mu_i)^2/\sigma_i^2$

  where the expected number of events depends on the **bkg model** ($\phi_{bkg}(t_i)$):

$$\mu_i = \left[R_0 \boldsymbol{\phi_{bkg}}(\boldsymbol{t_i}) + \boldsymbol{S_m} \cos\left(\omega(t_i - t_0)\right)\right] M \Delta E \Delta t$$

We need a model for the decreasing bkg!

Analysis strategy

Phys. Rev. D 103, 102005 (2021)

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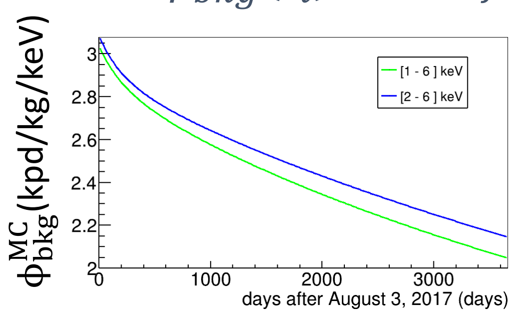
MODEL 1: assume exponential decay

$$\phi_{bkg}(t_i) = 1 + f exp\left(-\frac{t_i}{\tau}\right)$$

Free parameters: $R_o, f, \tau \; + S_m$

MODEL 2: Use MC simulation

$$\phi_{bkg}(t_i) = 1 + f\phi_{bkg}^{MC}(t_i)$$

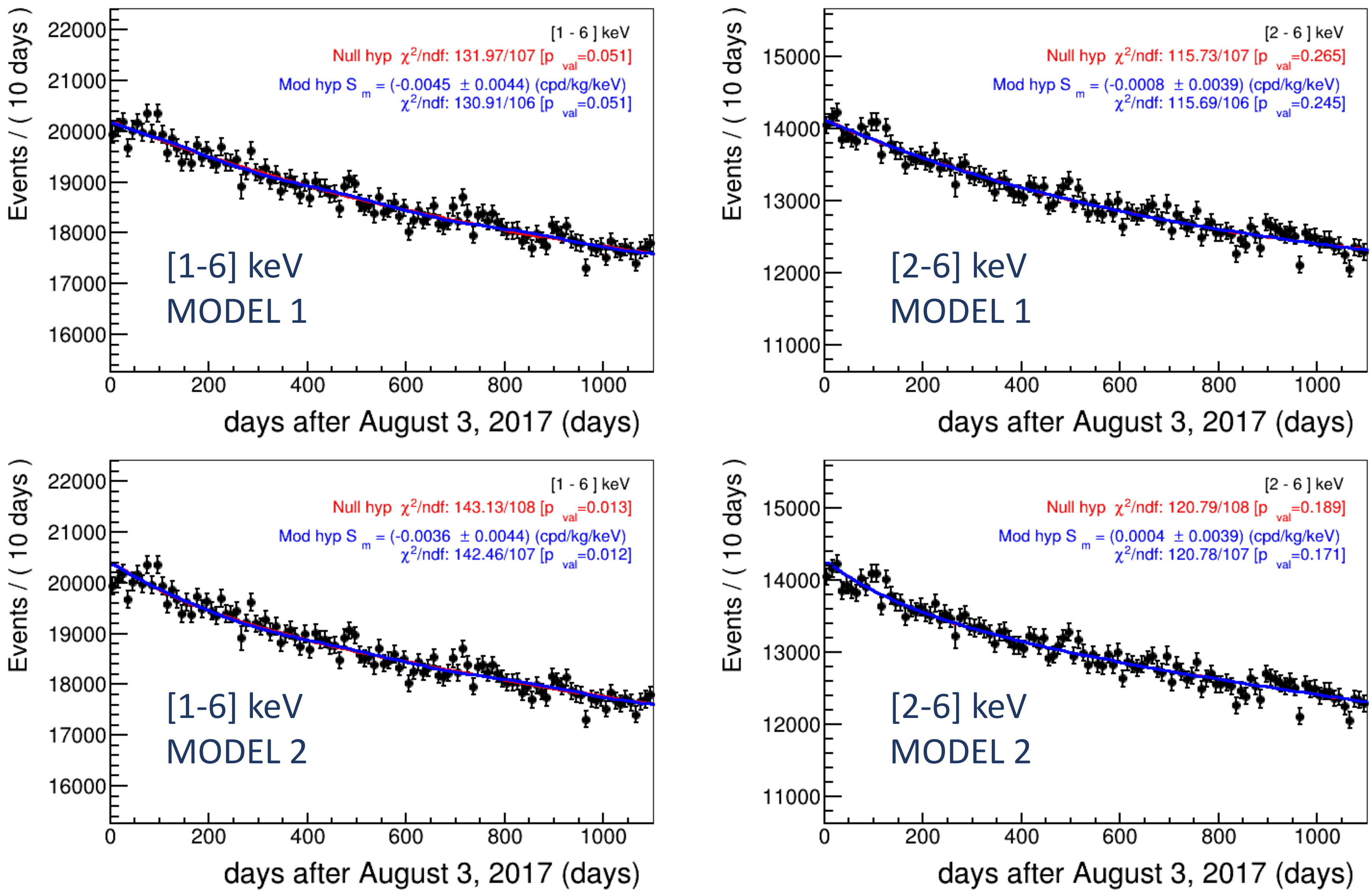


Free parameters: $R_o, f + S_m$

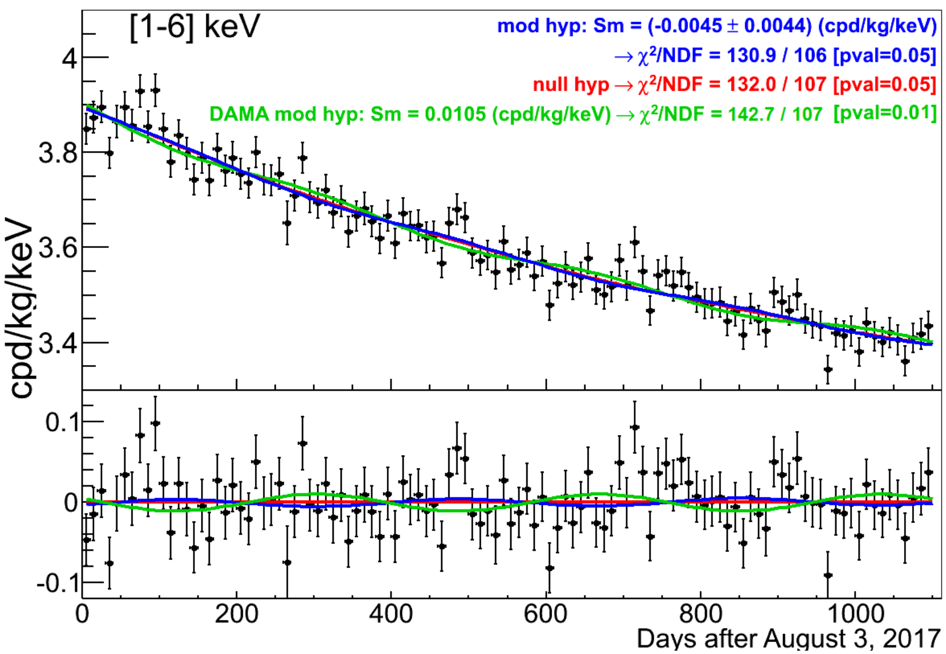
NOTE: the constant term in both equations represent any nonvarying rate, including the unmodulated term of an hypothetical WIMP component.

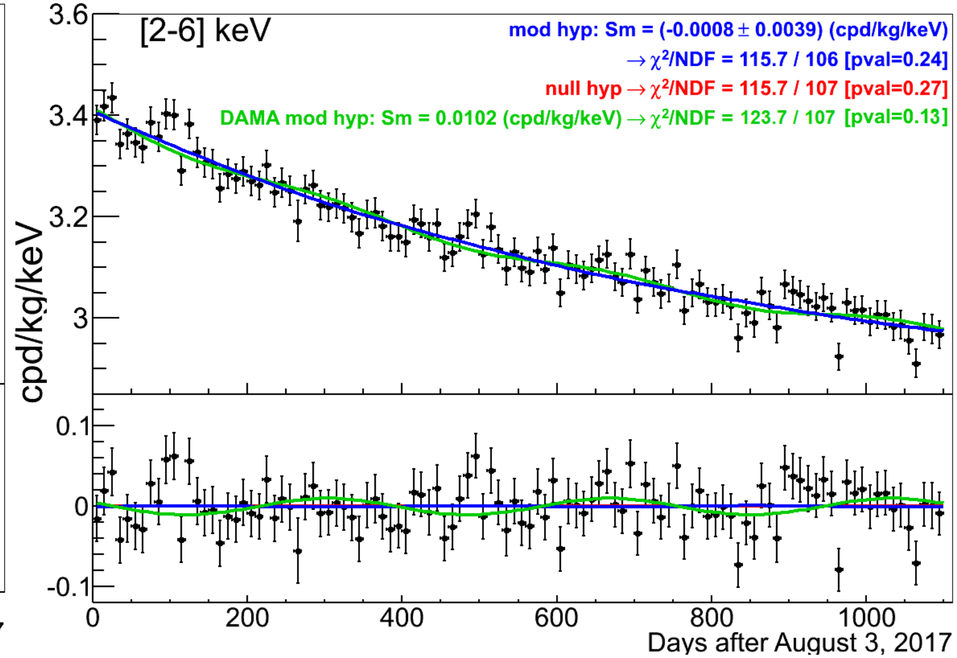
3 years results (313.95 kgxy)

Phys. Rev. D 103, 102005 (2021)



ANAIS-112 vs DAMA/LIBRA



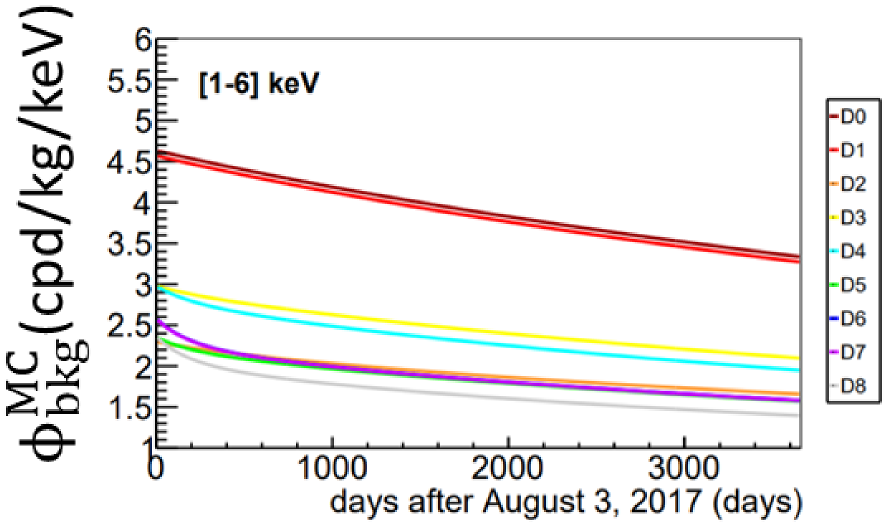


Improving data description

Phys. Rev. D 103, 102005 (2021)

MODEL 3: Simultaneous fit using data and bkg model separately for every detector

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



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

3 years results (313.95 kgxy)

Phys. Rev. D 103, 102005 (2021)

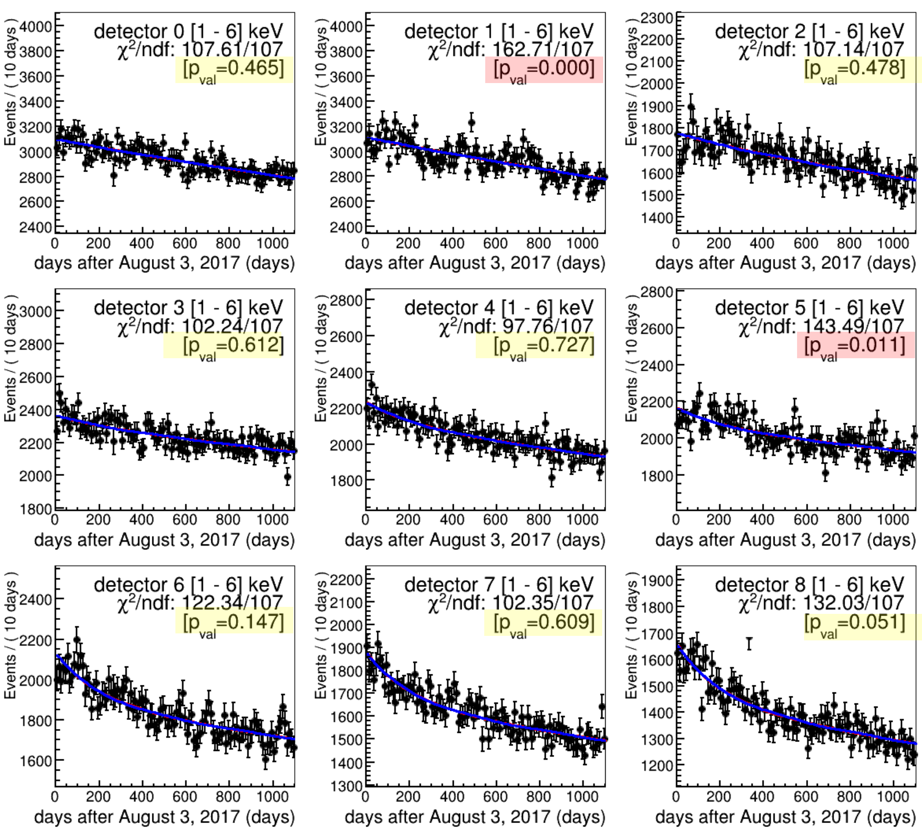
MODEL 3: Simultaneous fit using data and bkg model separately for every detector

[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)

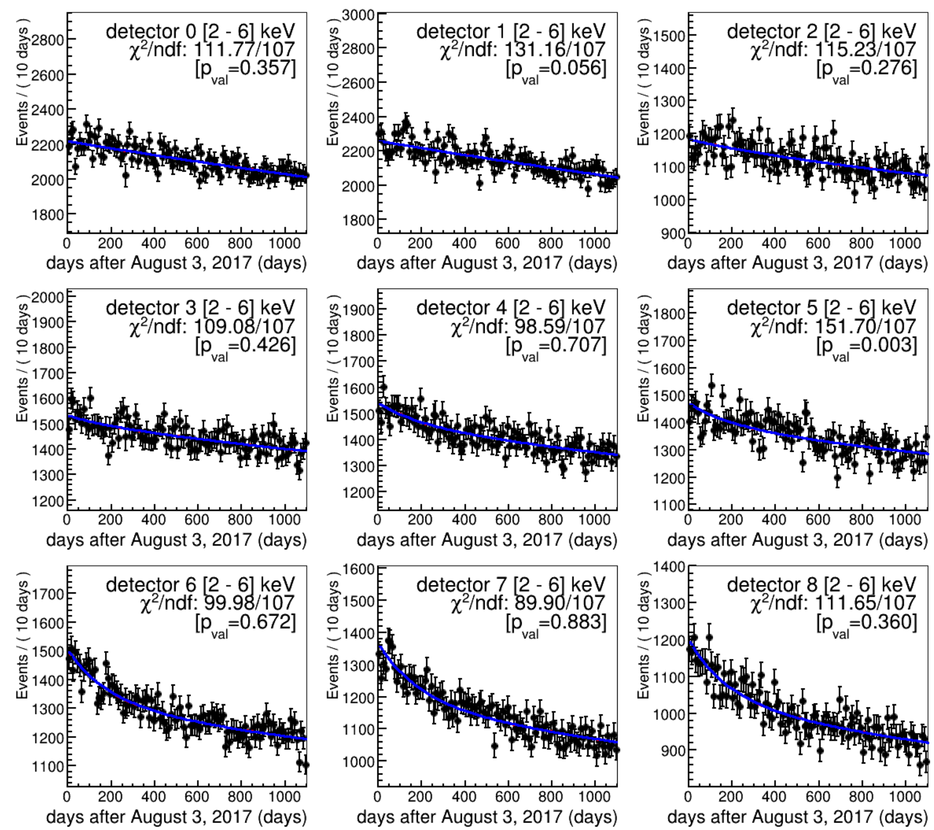


[2-6] keV

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)



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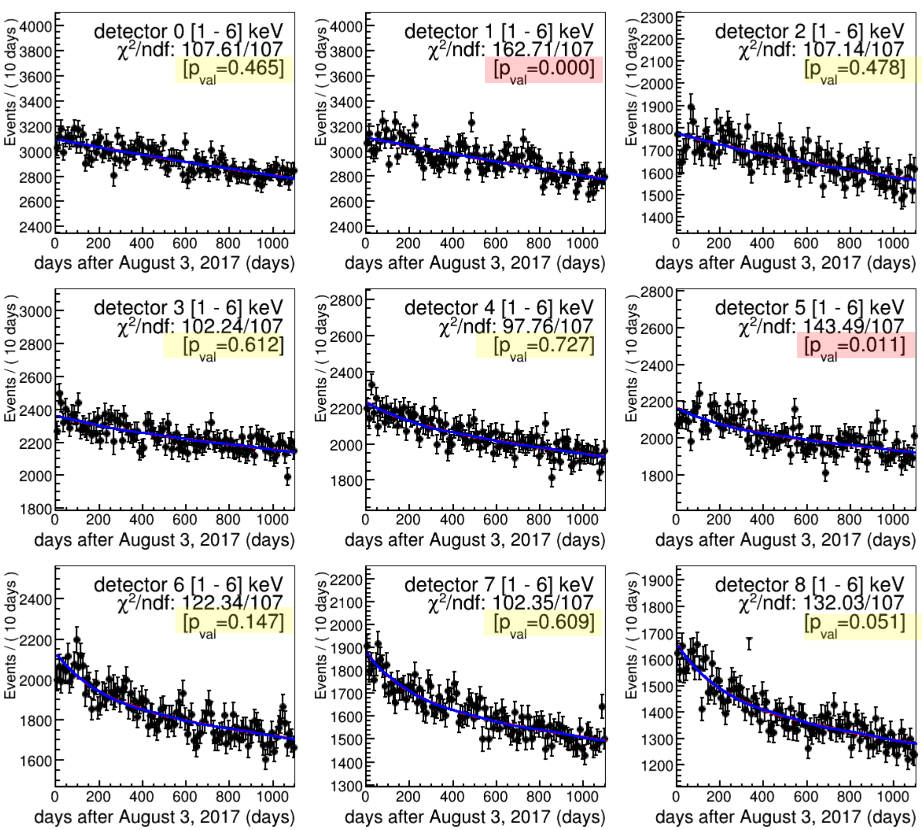
Null hyp χ^2/ndf: 1075.81/972 [p_{val}=0.011]   Mod hyp χ^2/ndf: 1075.15/971 [p_{val}=0.011]

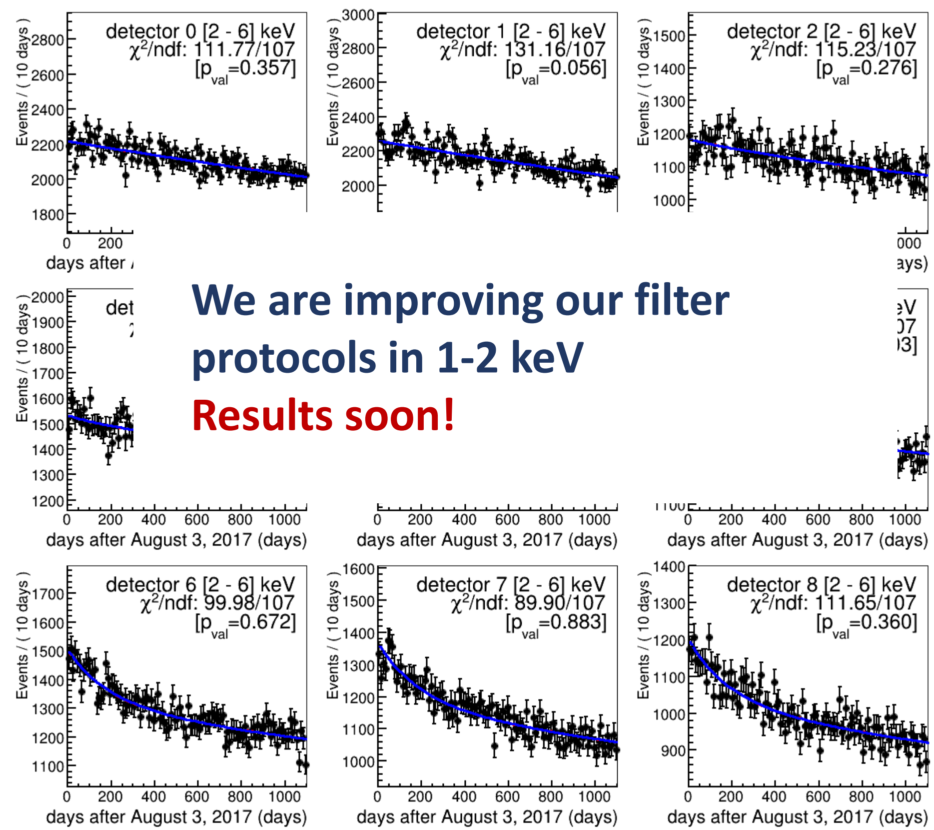
S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)



[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)



We are improving our filter protocols in 1-2 keV

Results soon!

3 years results (313.95 kgxy)

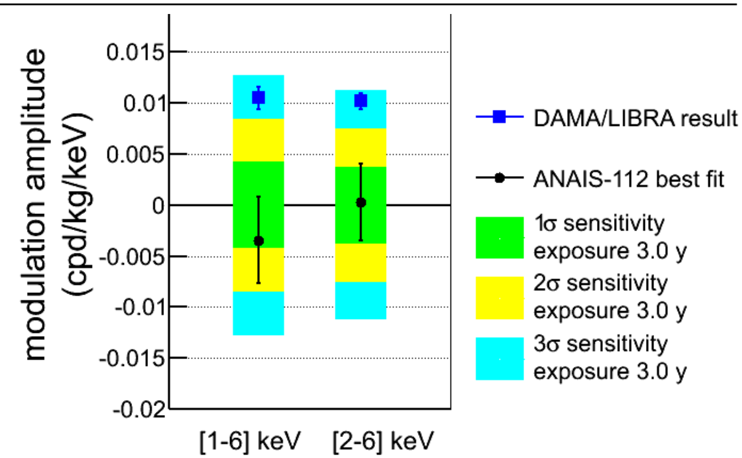
Phys. Rev. D 103, 102005 (2021)

ANAIS-112 results:

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	1	132 / 107	3	-0.0045±0.0044	0.051	0.051
	2	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	3	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	1	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	2	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	3	1018 / 972	18	0.0003±0.0037	0.14	0.15

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.**
- As expected (Eur. Phys. J. C (2019) 79:233), Model 3 gives slightly slower $\sigma(S_m)$ and is taken to quote final result

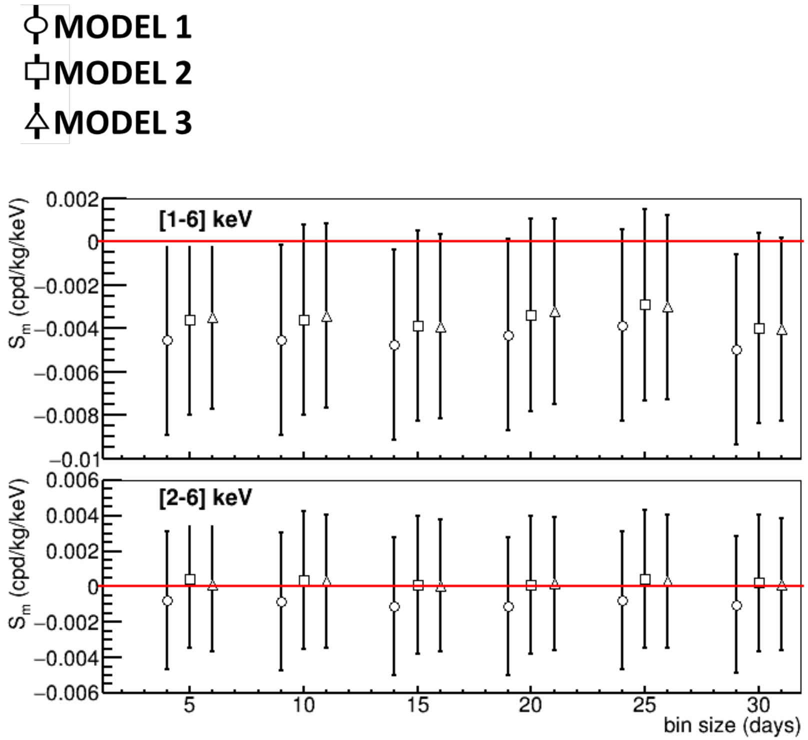


Current sensitivity: 2.5σ [1−6] keV
2.7σ [2−6] keV

Consistency checks

Phys. Rev. D 103, 102005 (2021)

- Time binning: negligible effect on results



- Toy MC to check fit unbiasedness

Fit unbiased!

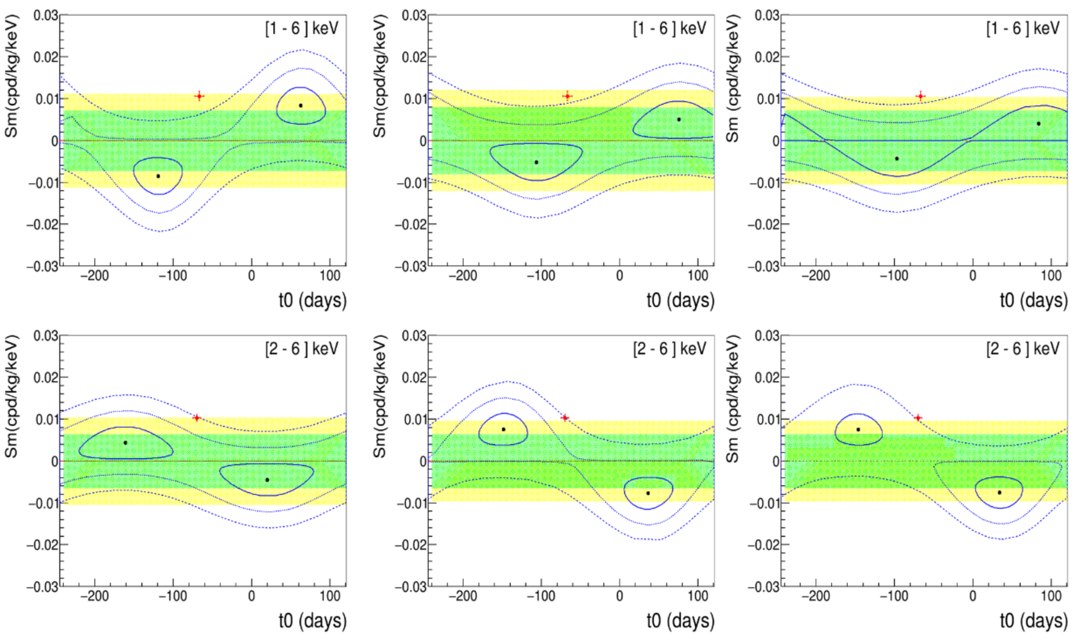
Energy region	Model	bias[null hypothess] cpd/kg/keV	bias[DAMA Sm] cpd/kg/keV
[1-6] keV	1	$(-3\pm6)\times10^{-5}$	$(-1\pm6)\times10^{-5}$
	2	$(-7\pm6)\times10^{-5}$	$(3\pm6)\times10^{-5}$
	3	$(-26\pm6)\times10^{-5}$	$(31\pm6)\times10^{-5}$
[2-6] keV	1	$(3\pm5)\times10^{-5}$	$(-10\pm5)\times10^{-5}$
	2	$(8\pm6)\times10^{-5}$	$(-10\pm6)\times10^{-5}$
	3	$(-28\pm5)\times10^{-5}$	$(29\pm5)\times10^{-5}$

Phase free analysis

Phys. Rev. D 103, 102005 (2021)

DAMA
• ANAIS

MODEL 1 MODEL 2 MODEL 3



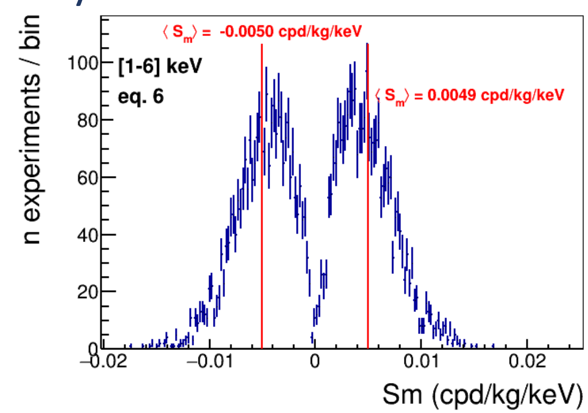
Fit is non linear in the parameters

$$\mu_i = A\left[\boldsymbol{R_0}\left(1 + \boldsymbol{f}\phi_{bkg}^{MC}(t_i)\right) + \boldsymbol{S_m}\cos\left(\omega(t_i - \boldsymbol{t_0})\right)\right]$$

The fit with phase free is biased!!

$$\boldsymbol{E(S_m) = \sqrt{\frac{\pi}{2}}\sigma}$$

Toy MC:



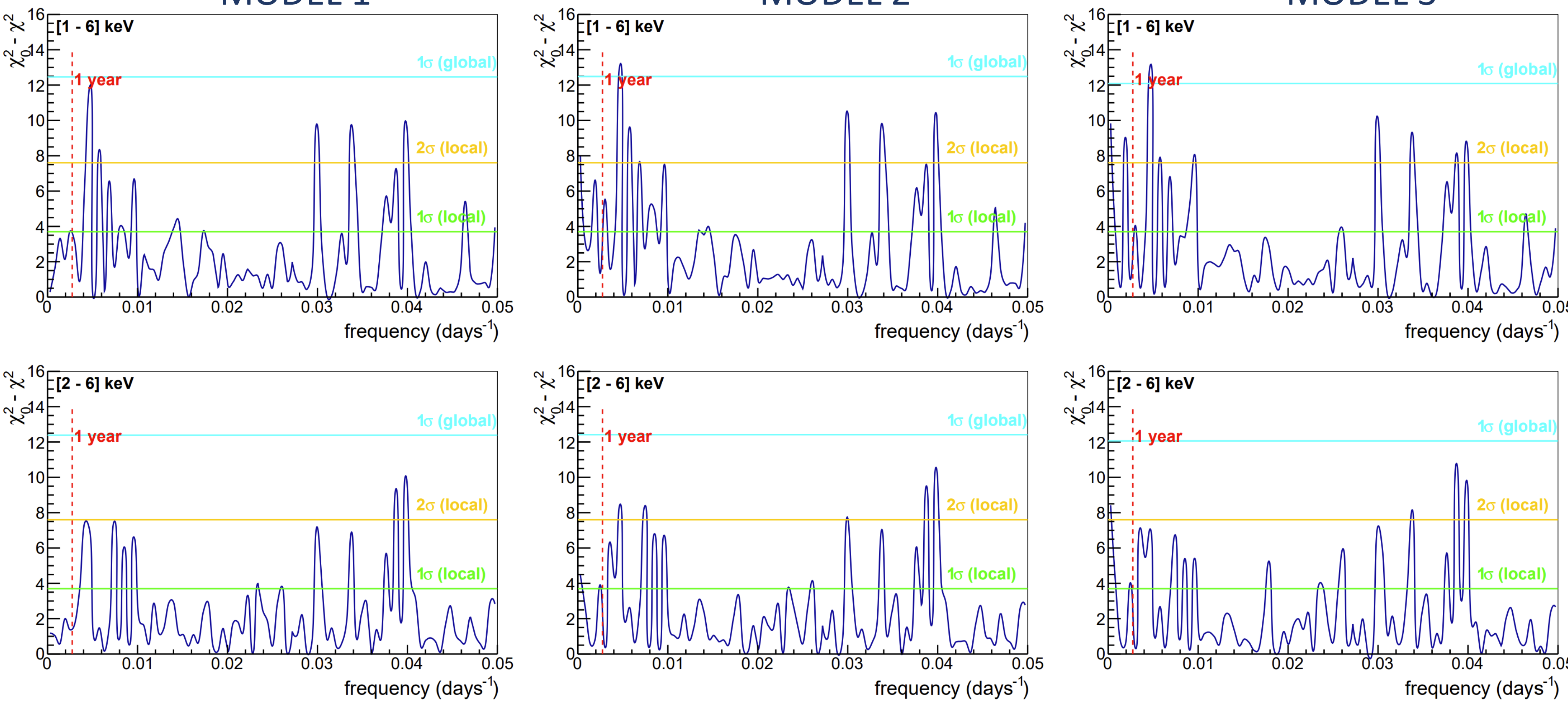
- Best fit ANAIS 3σ away from DAMA result
- **Considering bias, in most cases compatible at 1σ with absence of modulation**

Frequency analysis

Phys. Rev. D 103, 102005 (2021)

Least-squared periodogram:
for every frequency, fit to null and modulation hypothesis and compute $\chi_0^2 - \chi^2$

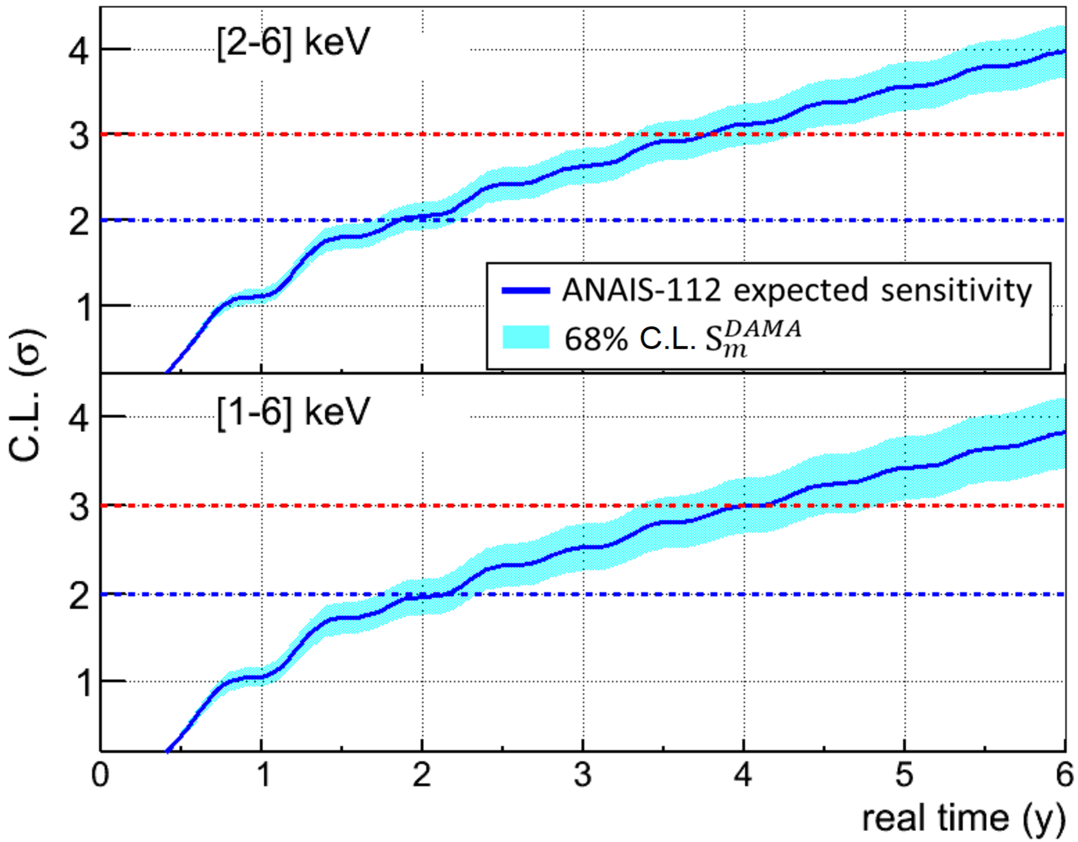
MODEL 1 MODEL 2 MODEL 3



→ **No statistically significant modulation at any frequency**

Expected sensitivity

See details in **Coarasa et al., Eur. Phys. J. C (2019) 79:233, 1812.02000**



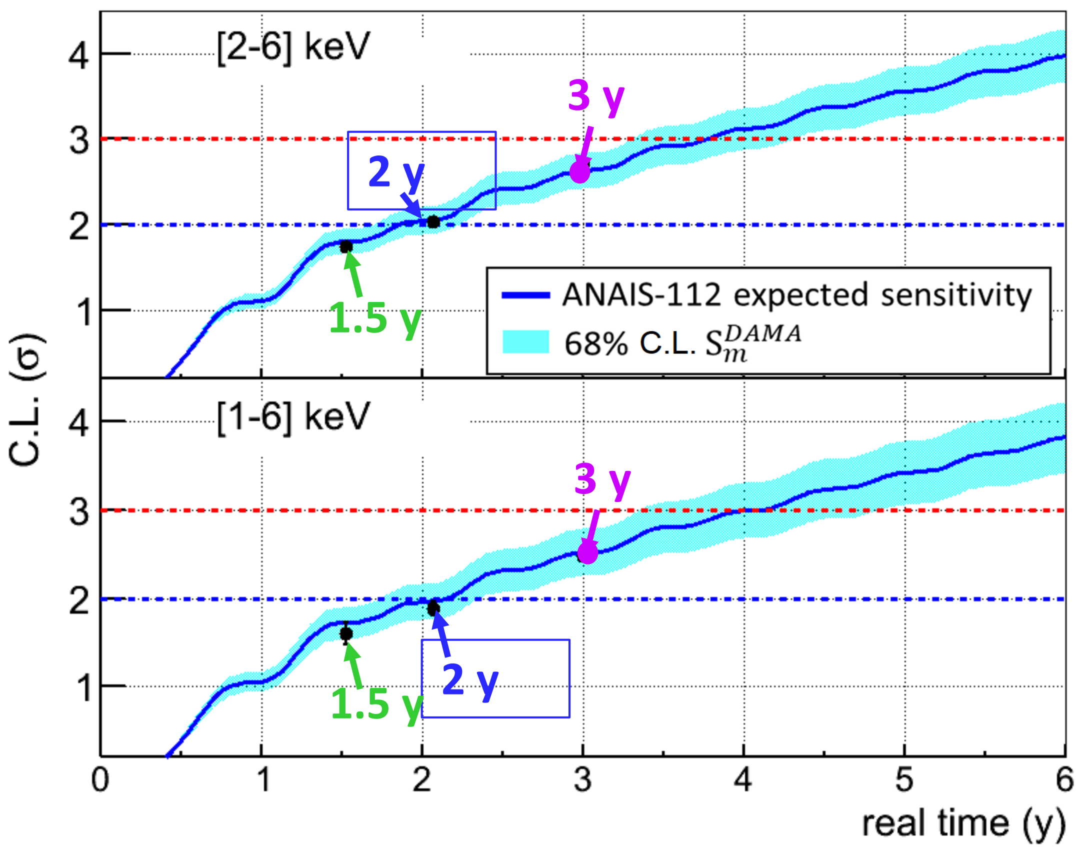
The experimental sensitivity is given by the standard deviation of the modulation amplitude $\boldsymbol{\sigma(S_m)}$, that can be calculated analytically from :

- Updated background
- Efficiency estimate and its error
- Live time distribution

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

Experimental sensitivity

See details in **Coarasa et al., 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

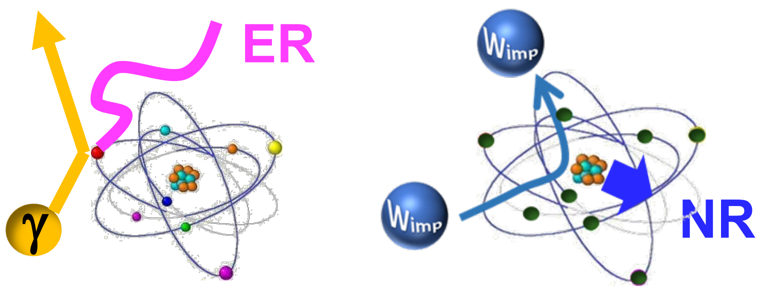
3σ sensitivity at reach in about 1 year from now

Corollary

Is this a model independent test of the DAMA/LIBRA result?

Using same target material -> **direct comparison in electron recoil energy**

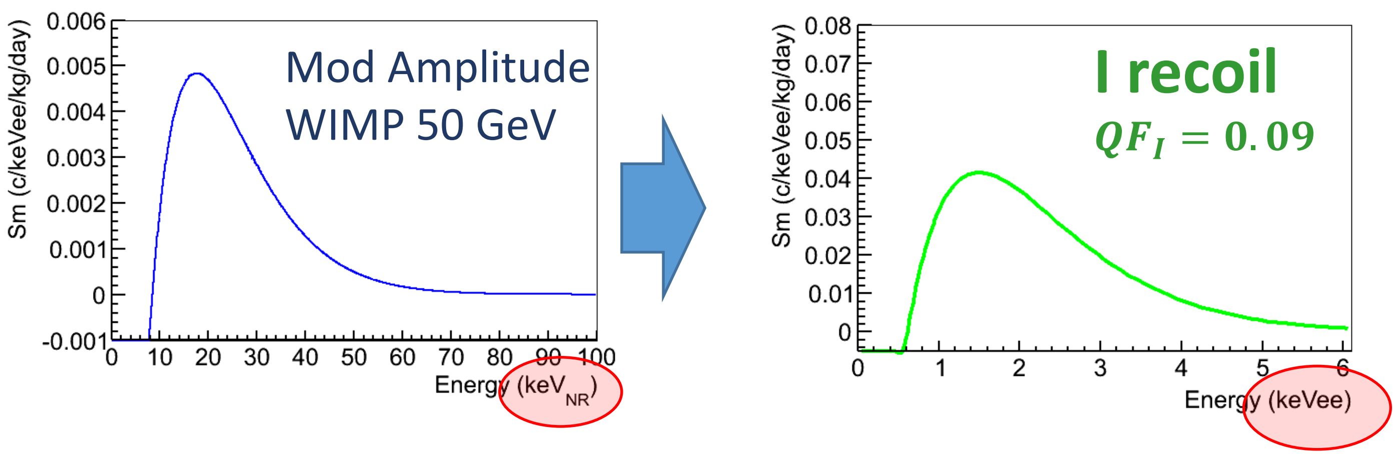
In a scintillator, an **ER** produces much more light than a **NR** of the same energy!



The spectra are calibrated with X/γ sources, so are given in keVee(*). In order to be interpreted as NR, QF **has to be measured** to correct the energy scale:

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

(*) keVee: electron-equivalent keV



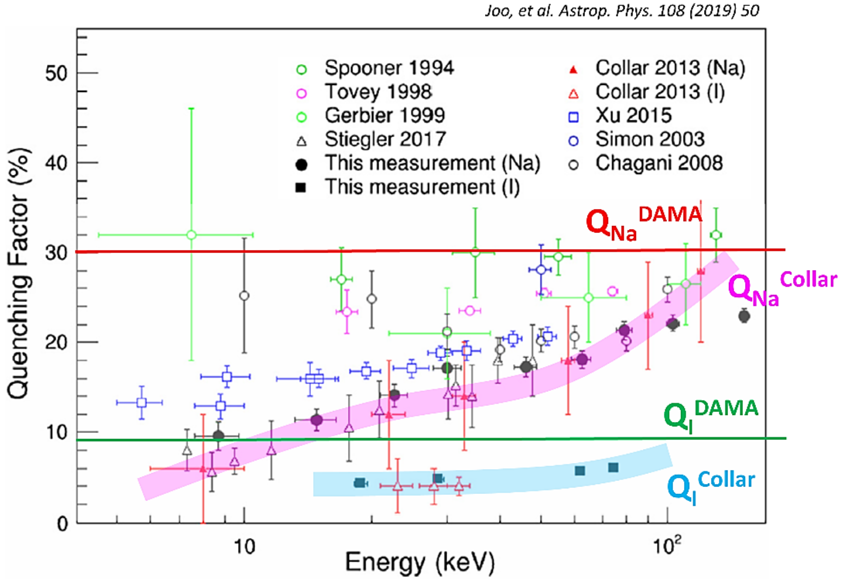
the response of different detectors to DM particles could differ if QF is different

Corollary

Is this a model independent test of the DAMA/LIBRA result?

-> Need to improve our knowledge on NR response function

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



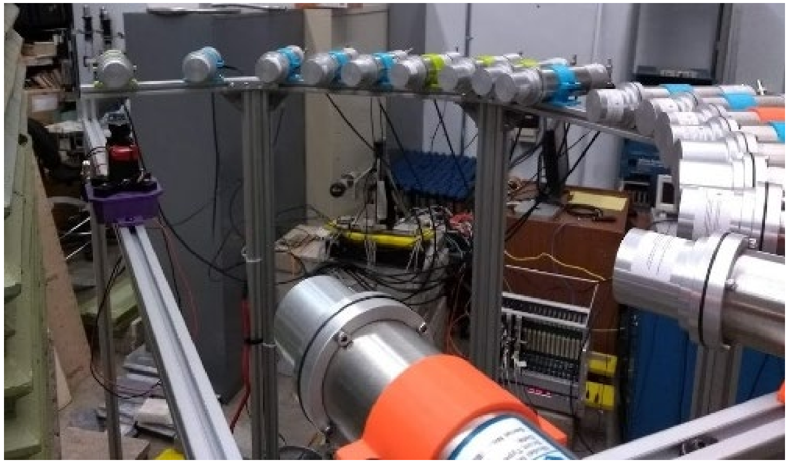
Does the QF depend on the crystal?

- Impurities
- Tl level
- Crystal quality
- …

Or the spread in QF measurements is due to systematics?

To answer this question,
Anais + Yale QF measurements @ TUNL (Duke Univ.) different NaI(Tl) crystals (ANAIS & COSINE) in the same setup

Results soon!



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 300 kg$\times$y exposure.
- **ANAIS-112 results up to now are compatible with absence of modulation and incompatible with DAMA/LIBRA at 3.3(2.6)σ. Present sensitivity : 2.7σ (2.5σ) in [1-6] ([2-6]) keV after 3 years of data-taking. 3σ sensitivity at reach in about 1 year from now.**
- Work ongoing on improving filter protocols with machine learning techiniques
- We are analyzing quenching factor on NaI crystals to discard systematic uncertainties in the comparison.
- Plan to make ANAIS data public after use to allow independent analysis .