Dark matter annual modulation results from the ANAIS-112 experiment

- Motivation and goals
- Detector set-up
- Performance and analysis
- Background model
- Annual modulation results and sensitivity

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14th June 2021

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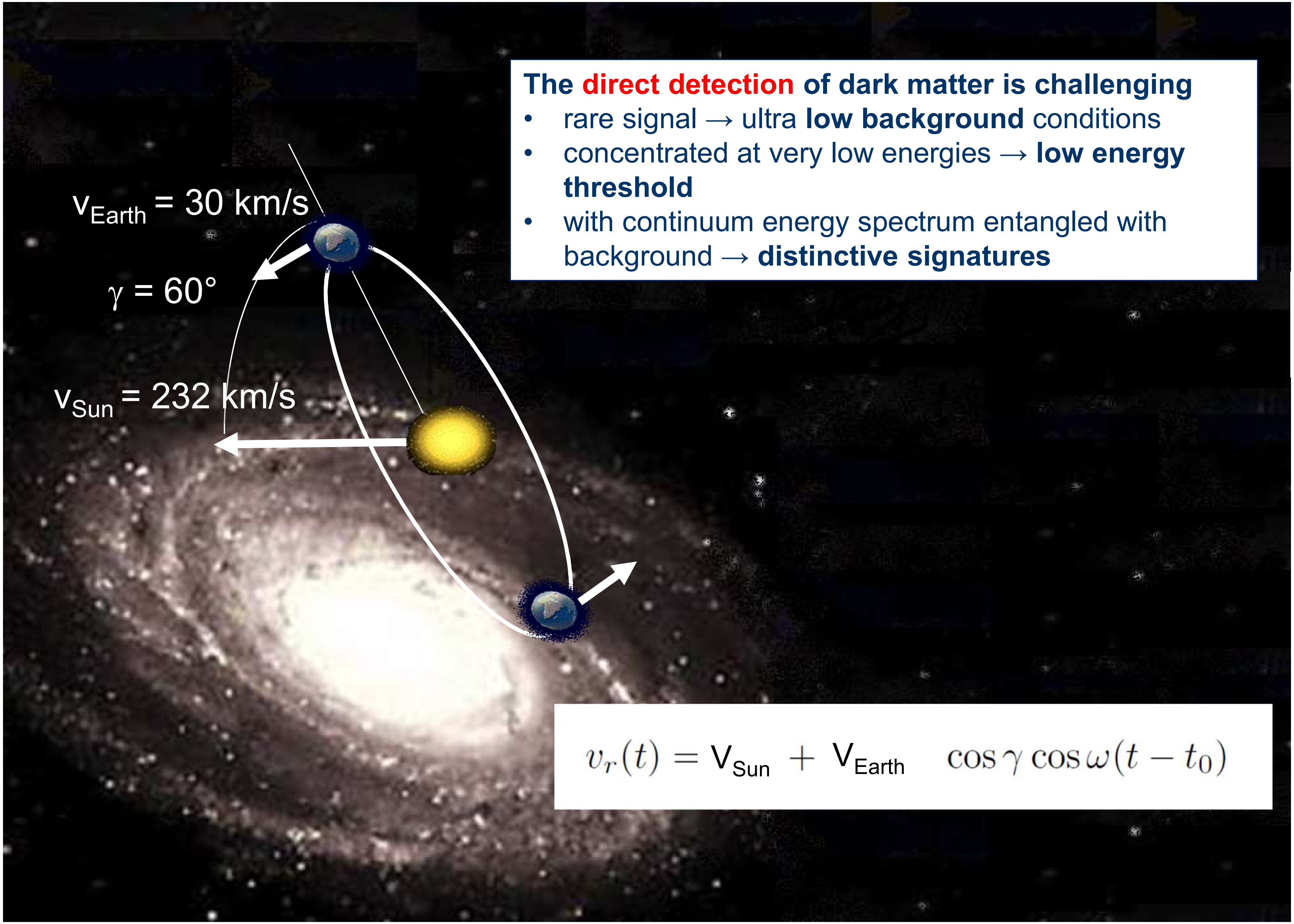


The direct detection of dark matter is challenging

- rare signal → ultra **low background** conditions
- concentrated at very low energies → **low energy threshold**
- with continuum energy spectrum entangled with background → **distinctive signatures**

$$v_r(t) = V_{Sun} + V_{Earth} \cos\gamma \cos\omega(t - t_0)$$

Motivation

Distinctive signal in interaction rate of WIMPs

A. K. Drukier et al, Phys. Rev. D 33 (1986) 3495
K. Freese et al, Phys. Rev. D 37 (1988) 3388
K. Freese et al, Rev. Mod. Phys. 85 (2013) 1561

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

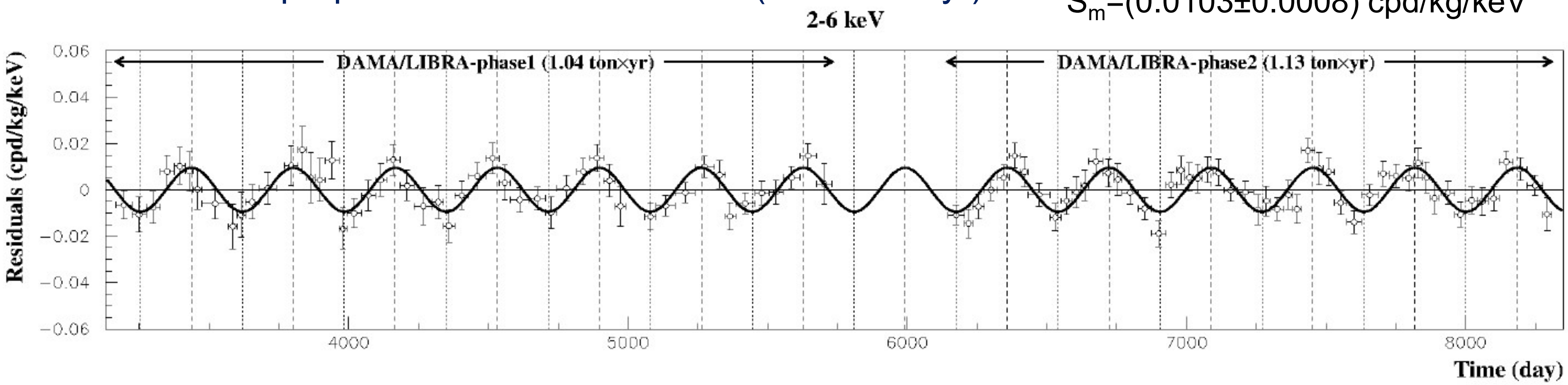
k: energy bin

- ✓ Cosine behaviour
- ✓ 1 year period
- ✓ Maximum around June 2nd
- ✓ Weak effect (1-10%)
- ✓ Only noticeable at low energy
- ✓ Should have a phase reversal at low energies

No background known to mimic the effect

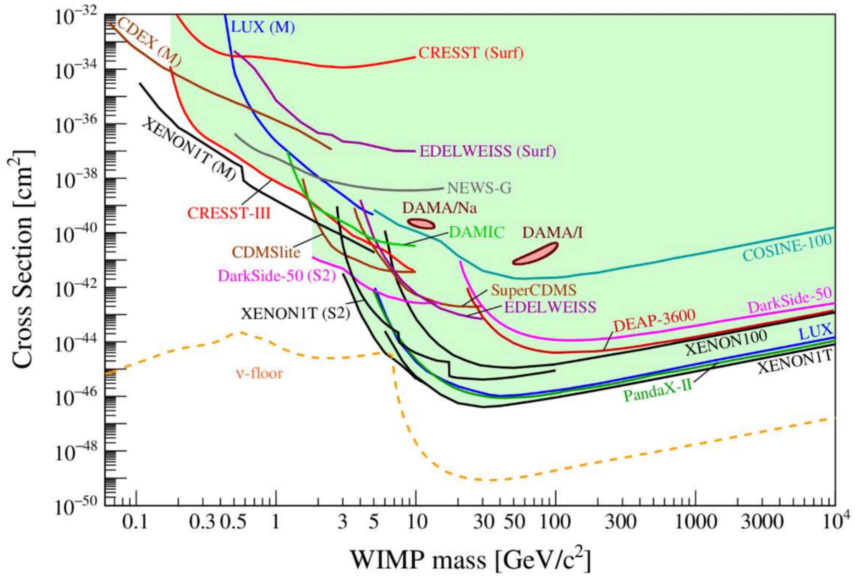
DAMA/LIBRA (250 kg NaI, LNGS): phase1+phase2 results favor the presence of a modulation with proper features at **12.9σ CL** (2.46 ton × yr)

S_m=(0.0103±0.0008) cpd/kg/keV



R. Bernabei et al, Nucl. Phys. At. Energy 19, 307 (2018)
Prog. Part. Nucl. Phys. 114 (2020) 103810

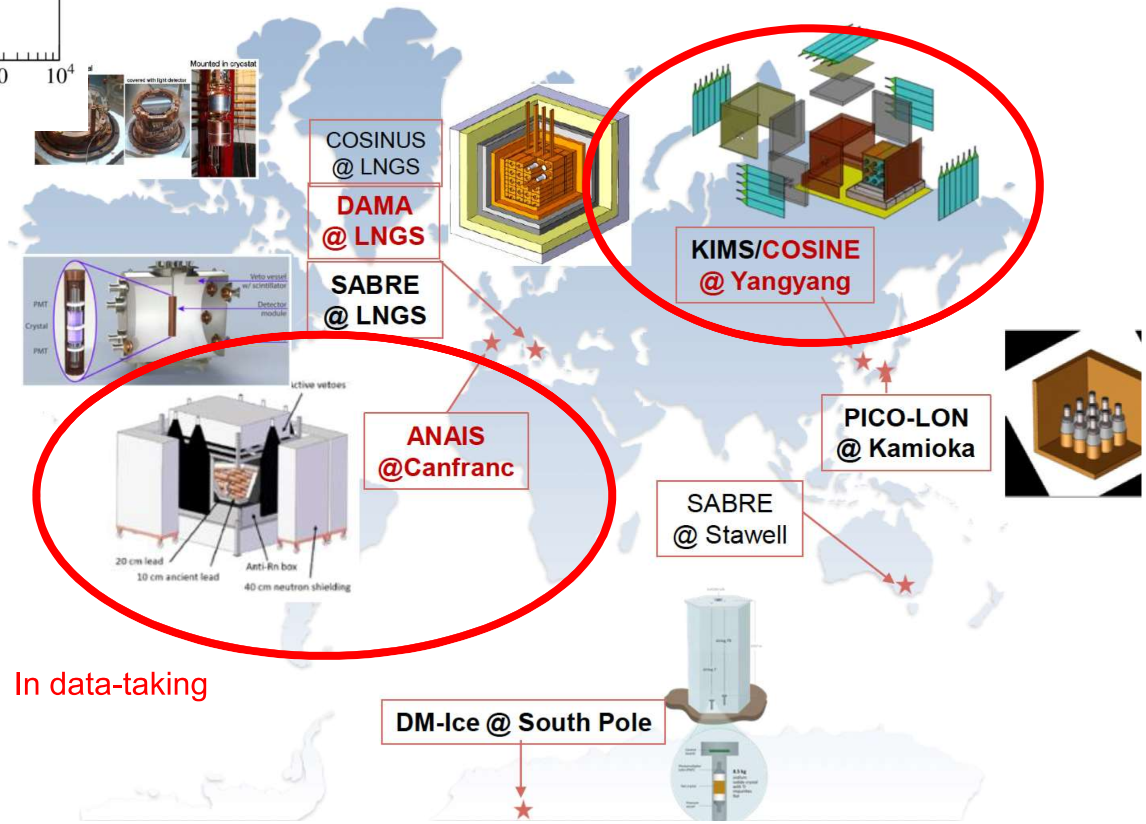
Motivation



Direct Detection of Dark Matter – APPEC Committee Report, arXiv:2104.07634 [hep-ex]

Strong **tension** when interpreting DAMA/LIBRA annual modulation signal as Dark Matter, even assuming more general halo/interaction models

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



In data-taking

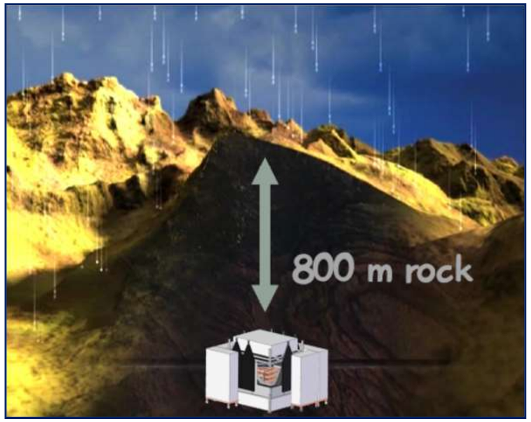
Goals

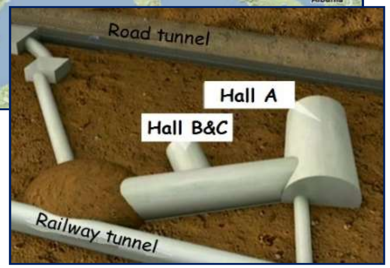
ANAIS (*Annual modulation with NAI Scintillators*) intends

to confirm the **DAMA/LIBRA** modulation signal

using the **same target and technique**

in a different environment at the **Canfranc Underground Laboratory** (Spain)



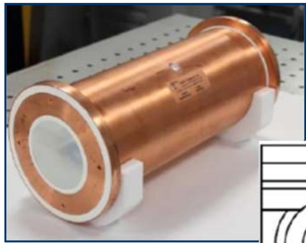


ANAIS-112:
- Commissioning in March-April 2017 (3x3 detectors, 112.5 kg)
- Calibration and general assessment from April to July 2017
- **Dark matter run** is underway since **3rd, August 2017**
- First **3 years** of data analyzed, data taking ongoing smoothly

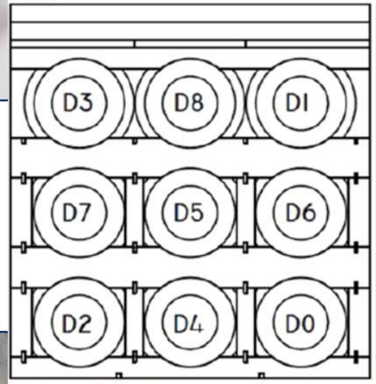
Detector set-up: NaI modules

Nine modules produced by Alpha Spectra Inc (US) following low radioactivity protocols

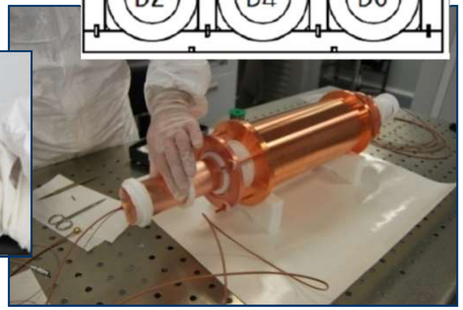
Detector	*Quality powder*	*Received at Canfranc in*
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017



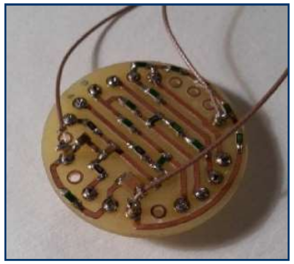
12.5 kg each
4.75'' diameter
11.75'' length



- **NaI(Tl) crystals** grown from selected ultrapure NaI powder and housed in OFE copper
- Mylar **window** allowing low energy calibration



- Two Hamamatsu R12669SEL2 **photomultipliers** coupled to each crystal at Canfranc clean room
  - Low background and high Quantum Efficiency
  - Radioactivity screening at Canfranc

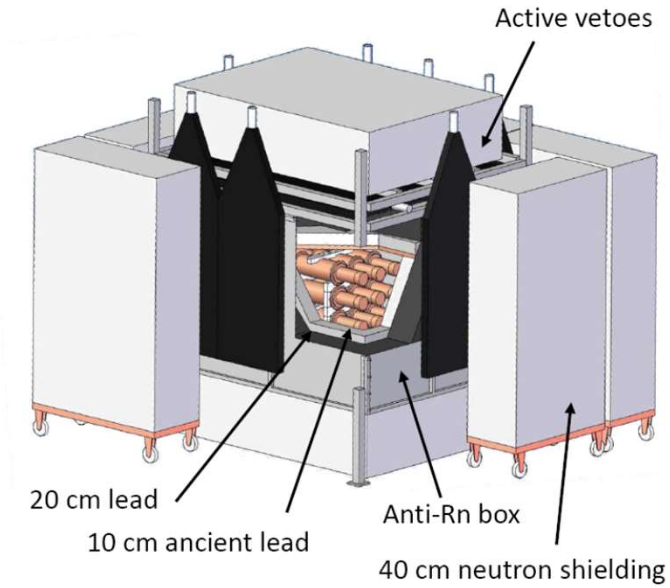


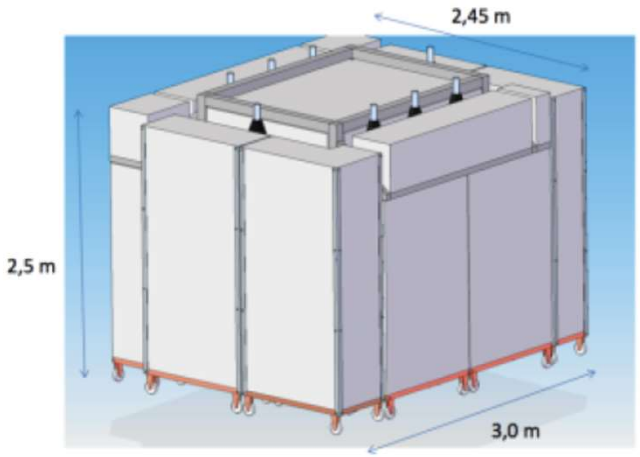
Voltage dividers in cuflon PCB

Housing made at LSC of electroformed copper

Detector set-up: shielding

ANAIS-112 is located inside a hut in hall B at Canfranc laboratory

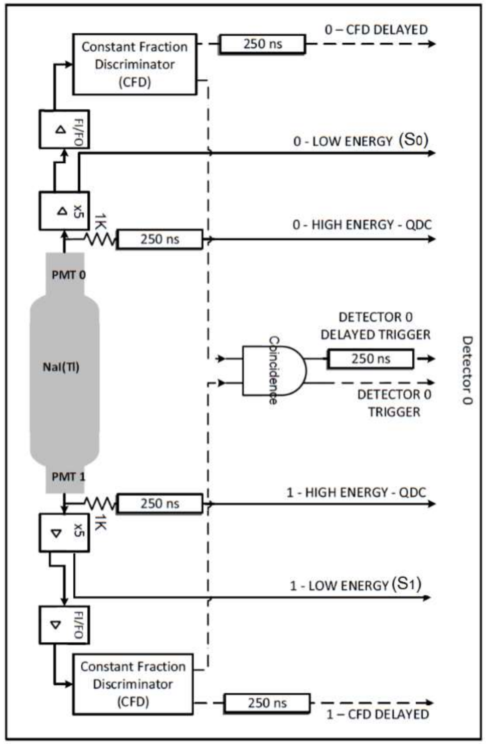


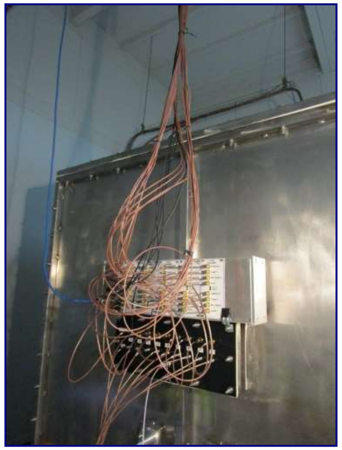


- Radon-free **system** to allow simultaneous calibration at low energy with ^{109}**Cd sources** on flexible wires, performed every two weeks

Detector set-up: data acquisition

- **DAQ hardware and software** designed and tested in previous ANAIS set-ups
  - – Individual PMT signals digitized and fully processed (2 Gs/s, 14 bits)
  - – 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



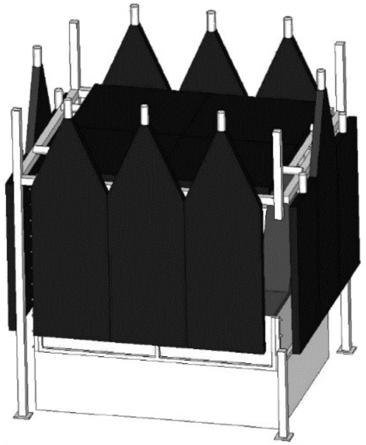


- **Muon detection system** implemented to:
  - – tag muon related events
  - – monitor onsite muon flux

- Monitoring of **environmental parameters** ongoing since the start of dark matter run:

  Rn content, humidity, pressure, different temperatures, N_2 flux, PMT HV, muon rate, …

Data saved every few minutes and alarm messages implemented



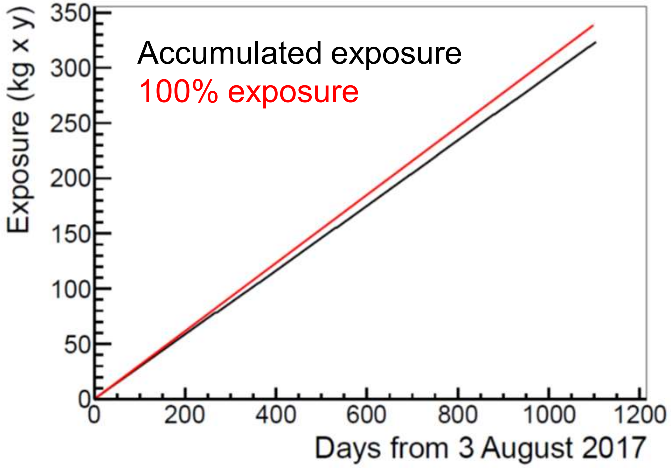
Detector performance

Performance of ANAIS-112 experiment after the first year of data taking 341.72 days, 105.32 kg y
J. Amaré et al, Eur. Phys. J. C (2019) 79:228

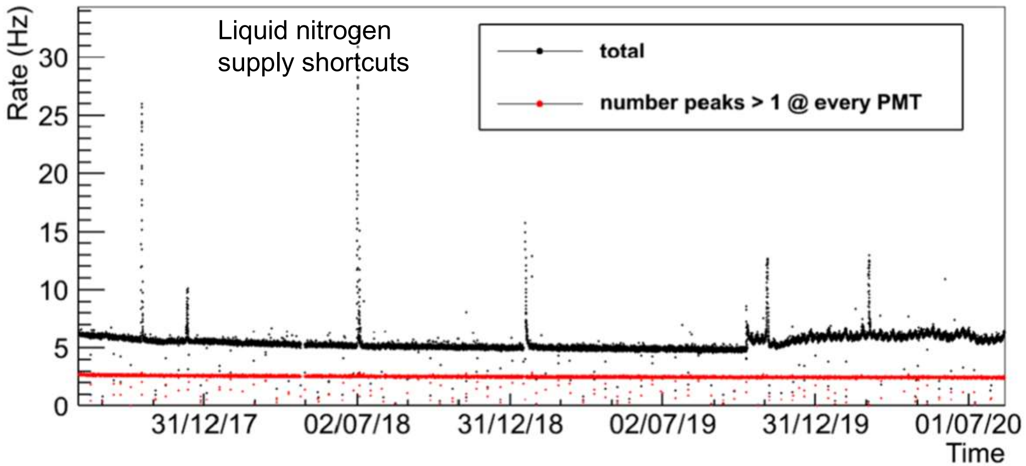
Now 3 years analyzed: 1018.6 days, 313.95 kg y

Time period	Live time (days)	Live time (%)	Down time (%)	Dead time (%)
08/03/2017 – 07/31/2018	341.722	94.40	2.84	2.76
08/01/2018 – 08/28/2019	374.302	95.48	2.44	2.07
08/29/2019 – 08/13/2020	333.791	95.10	2.62	2.28

- Excellent **duty cycle:** ~95% live time



- Good **stability** Total trigger rate

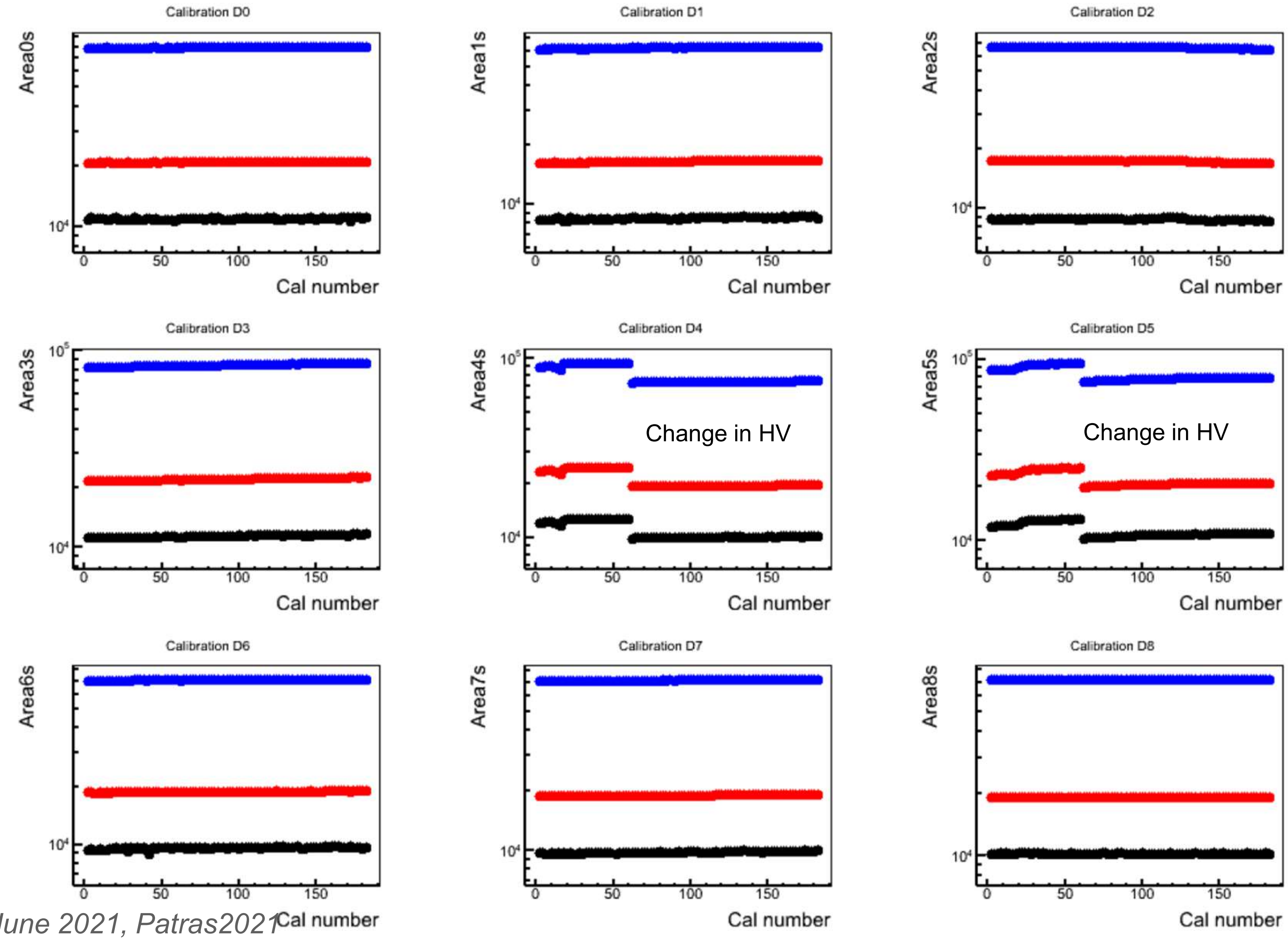


Detector performance

- Good **stability**

Evolution of positions of ^{109}Cd lines from calibrations

→ monitoring (and correction if necessary) of possible gain drifts



Detector performance

- Outstanding **light collection** of **~15 phe/keV** measured in:
  - all modules
  - at different set-ups
  - checked to be stable over time

M.A. Oliván et al, Astropart. Phys. 93 (2017) 86

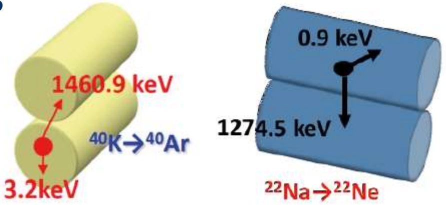
	phe/keV
D0	14.6 ± 0.1
D1	14.8 ± 0.1
D2	14.6 ± 0.1
D3	14.5 ± 0.1
D4	14.5 ± 0.1
D5	14.5 ± 0.1
D6	12.7 ± 0.1
D7	14.8 ± 0.1
D8	16.0 ± 0.1

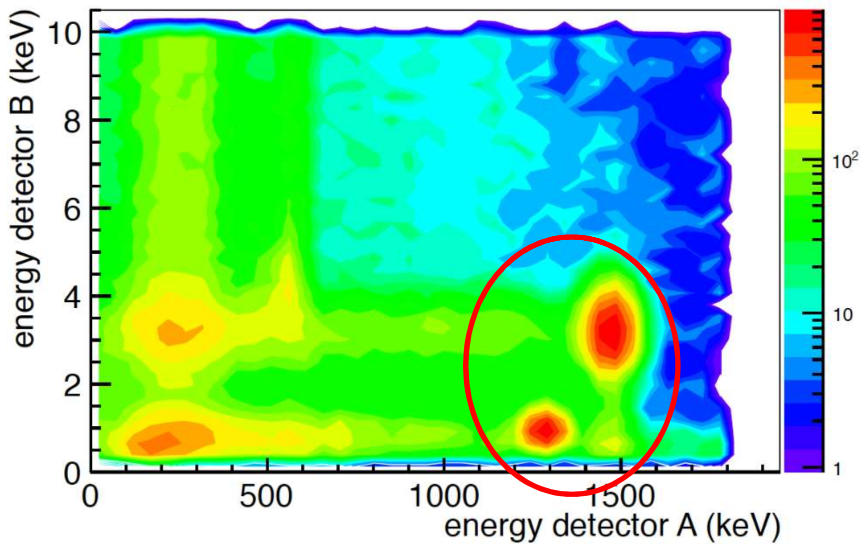
Larger and more homogeneous than the reported light collection for DAMA/LIBRA detectors:
Phase 1: **5.5-7.5 phe/keV**
Phase 2: **6-10 phe/keV**

Detector performance

- Effective **filtering** protocols to reject PMT noise events, which limit energy threshold

- **Triggering** below 1 keV_{ee}: bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas





- Based **on ^{109}Cd calibrations and data from ^{22}Na and ^{40}K** coincidence populations

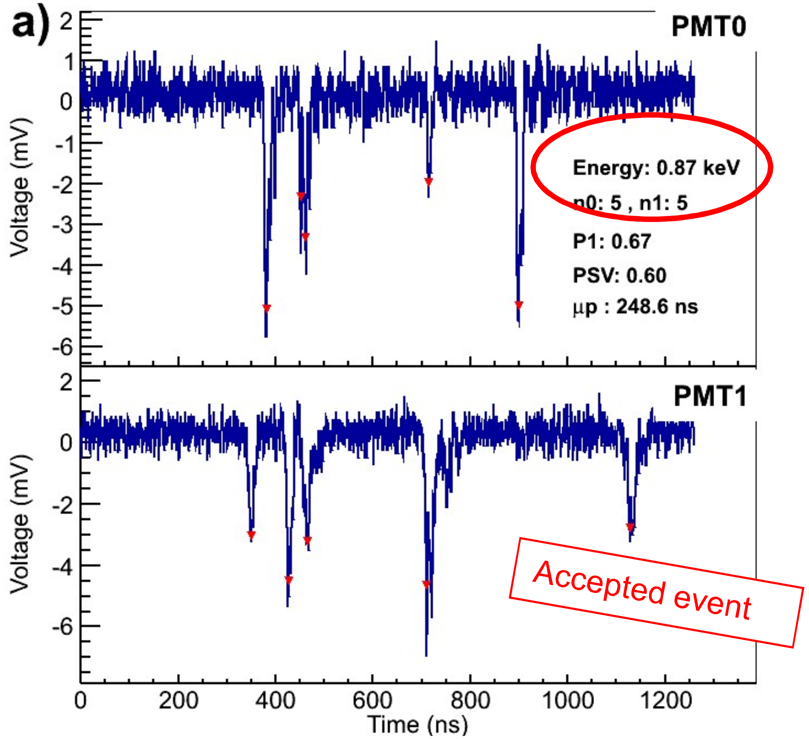
- **Multiparametric cuts** to select events

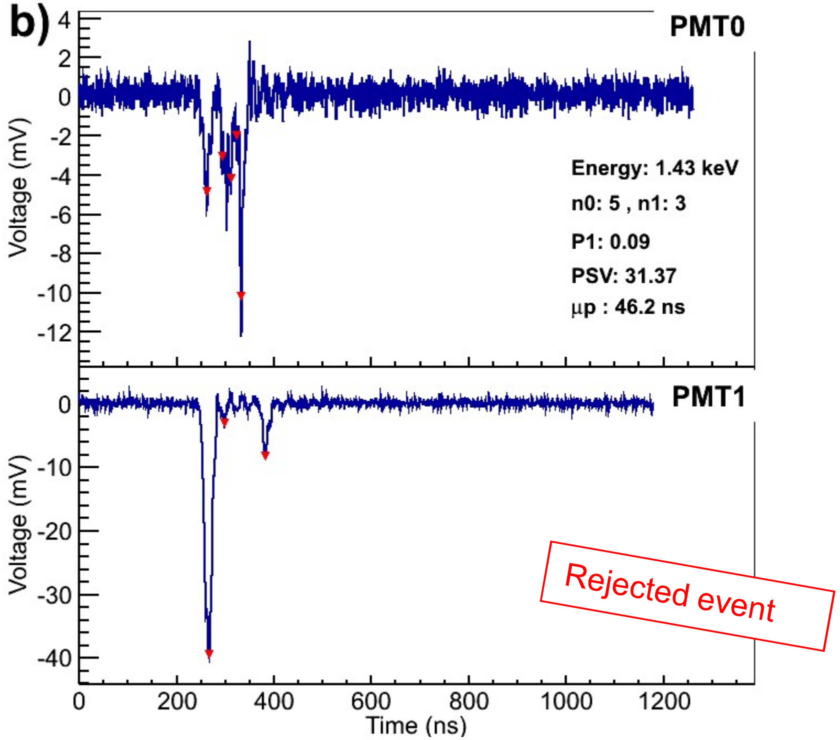
$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$

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

Detector performance

• Effective **filtering** protocols to reject PMT noise events, which limit energy threshold





Fast event: Cherenkov light emission in one PMT, seen in the opposite PMT

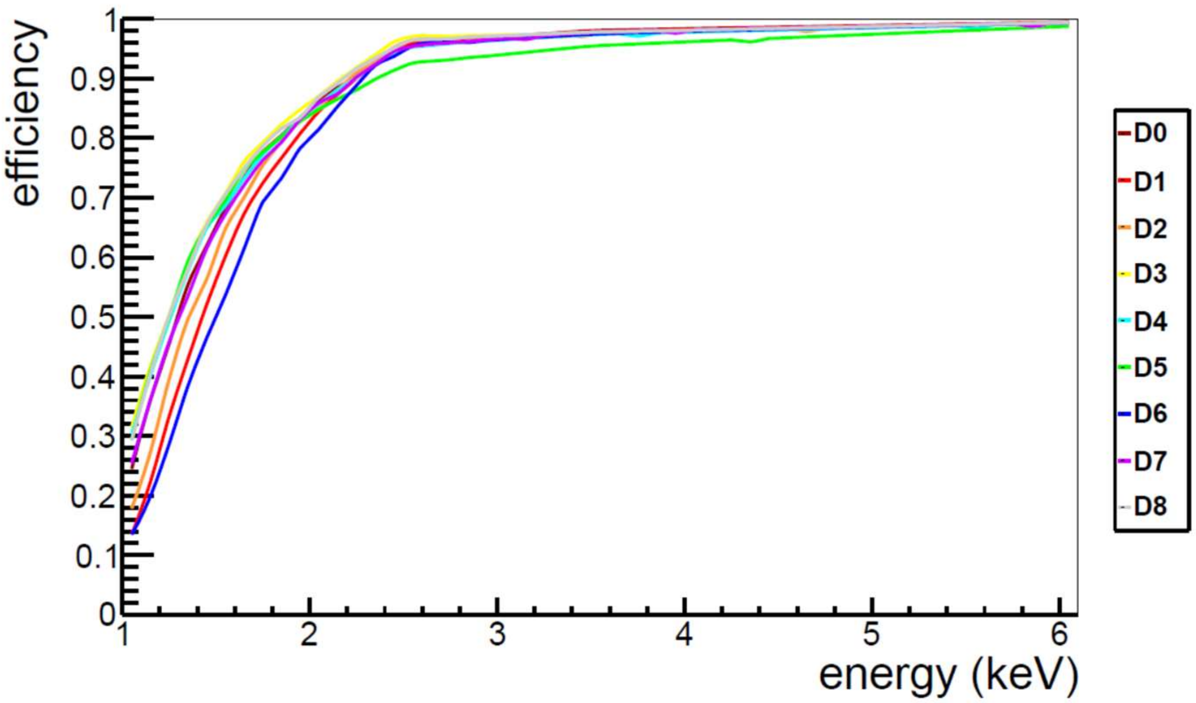
A **blank module** set-up to monitor non NaI(Tl) scintillation events along the second year of operation

Detector performance

- Effective **filtering** protocols to reject PMT noise events, which limit energy threshold

  - **Acceptance efficiency curves** after all cuts for each detector
    - Trigger efficiency: from the measured light collected by a Monte Carlo technique
    - Pulse shape cut: from ^{22}Na and ^{40}K populations
    - Asymmetry cut: from calibration runs

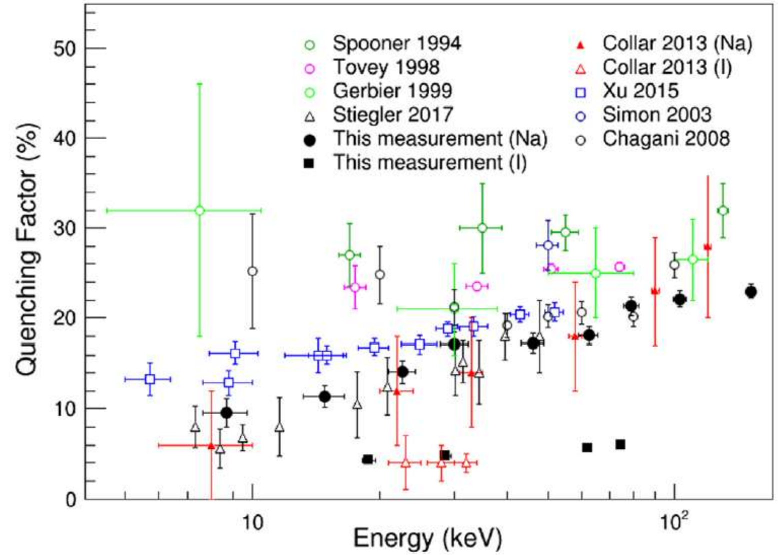
$$\varepsilon(E,d) = \varepsilon_{trg}(E,d) \times \varepsilon_{PSA}(E,d) \times \varepsilon_{asy}(E,d)$$



Detector performance

- **Quenching factor** determination $E_{ee} = QF\ E_{nr}$

  Relative efficiency factor for nuclear recoil scintillation



H.W. Joo, H.S. Park and J.H. Kim et al./Astroparticle Physics 108 (2019) 50–56

- Measurements carried out in October 2018 in the Triangle Universities Nuclear Laboratory (Duke University, US) with a neutron beam, in coordination with Duke and Yale groups
- Two small crystals from Alpha Spectra company with different powder quality
- Results coming soon

Background model

Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

Assessment of backgrounds of the ANAIS experiment for dark matter direct detection, J. Amaré et al, Eur. Phys. J. C 76 (2016) 429

Analysis of backgrounds for the ANAIS-112 dark matter experiment, 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.

Background model

Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

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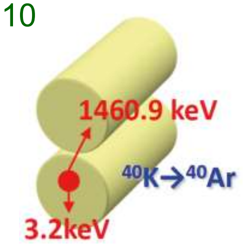
Analysis of backgrounds for the ANAIS-112 dark matter experiment, Eur. Phys. J. C 79 (2019) 412

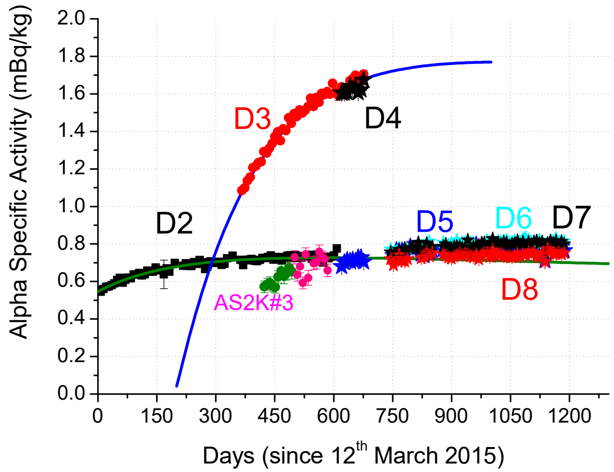
- **Activity from external components** measured with HPGe detectors at Canfranc
- **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb

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**

Background model

Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

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

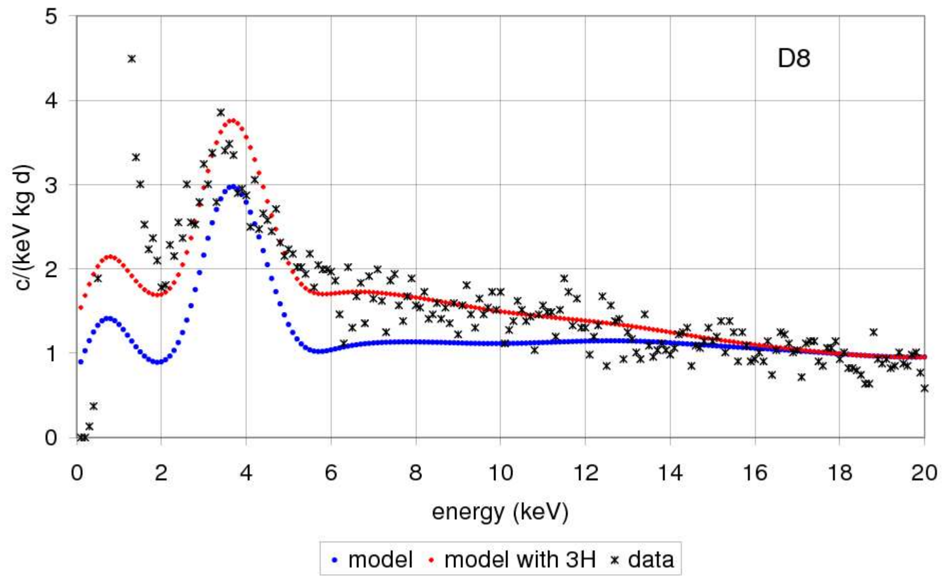
^{22}Na: from analysis of coincidences

J. Amaré et al, JCAP 02 (2015) 046
J. Amare et al, 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)

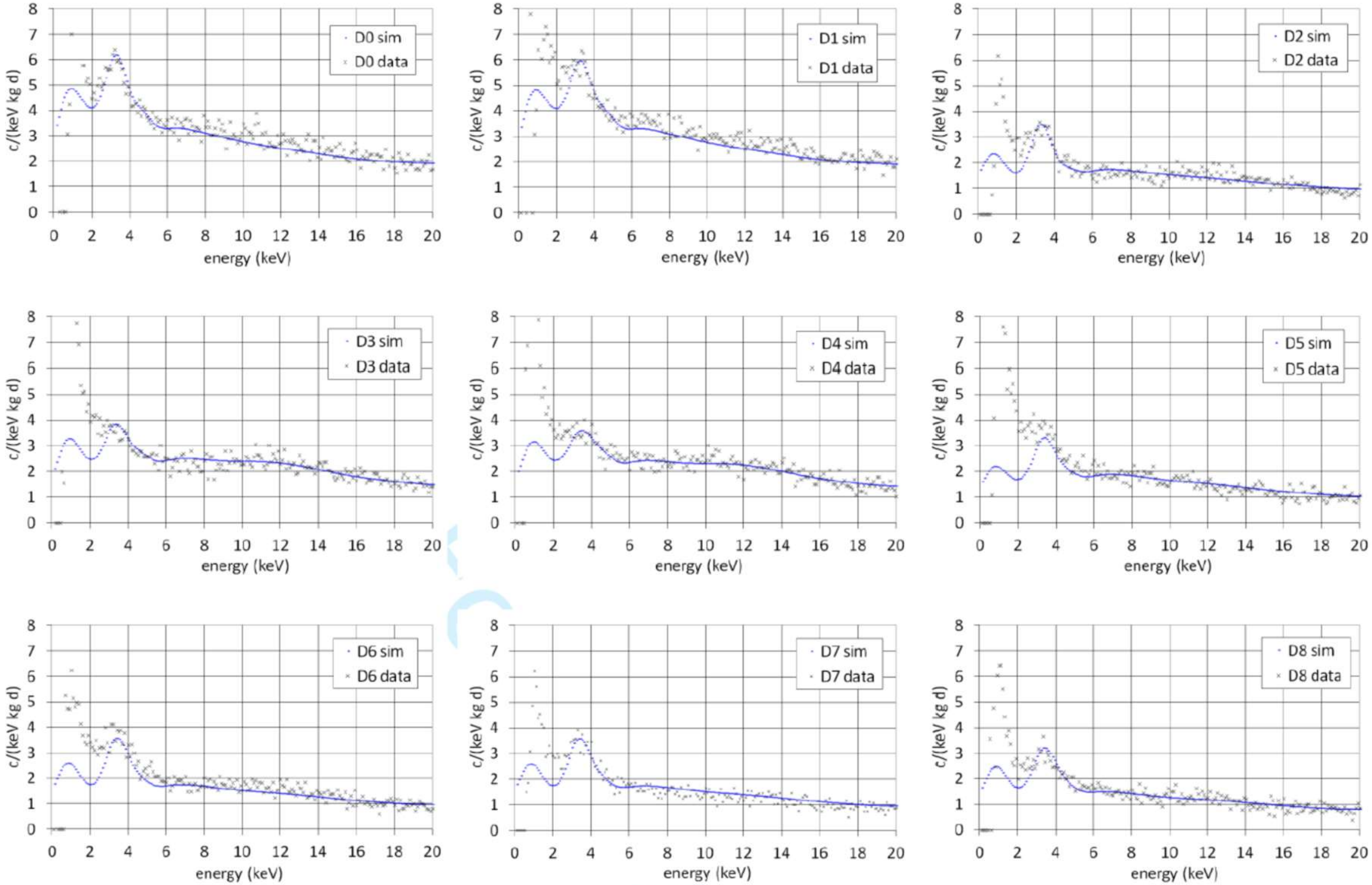
^{3}H: additional background source contributing only in the very low energy region required, which could be tritium

D0-D1: 0.20 mBq/kg
D2-D8: 0.09 mBq/kg (upper limit set by DAMA/LIBRA)



Background model

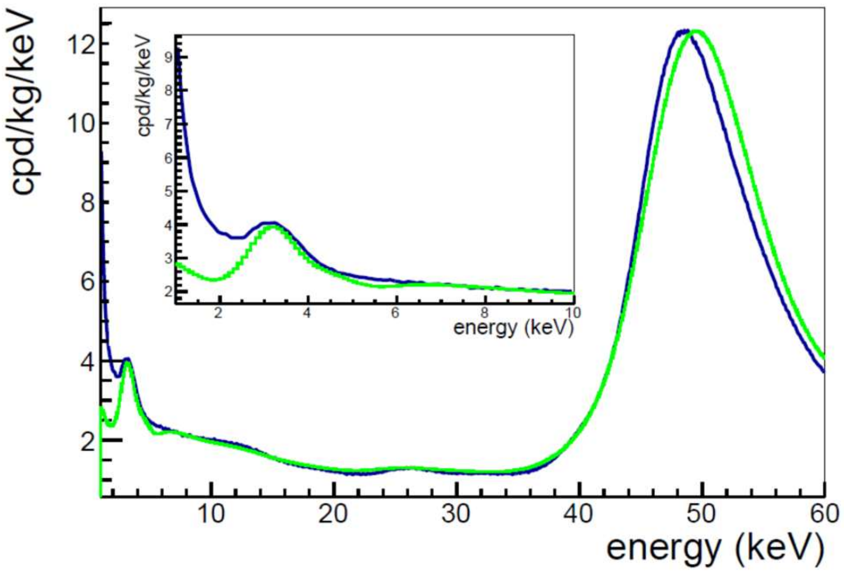
Comparison with first year of ANAIS-112 data at **very low energy**

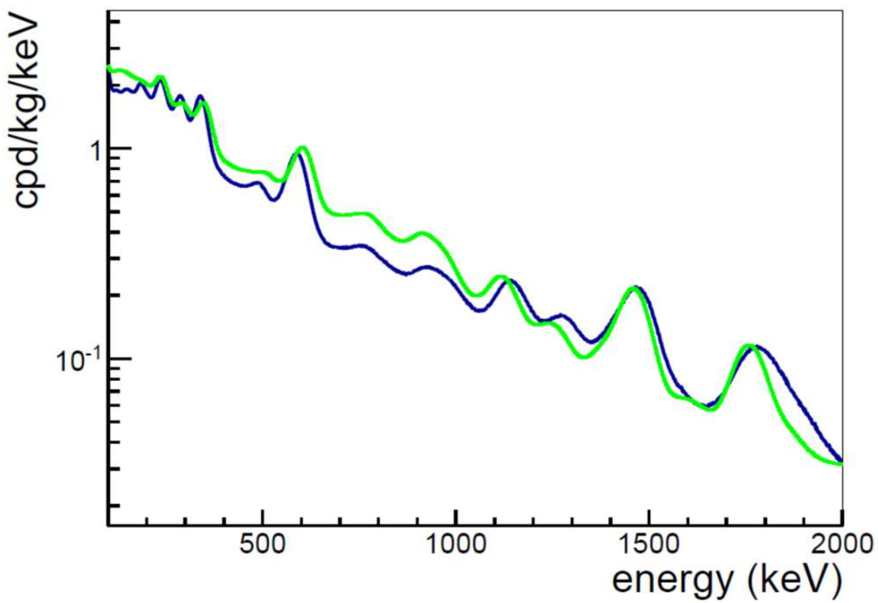


Unexplained events <3 keV: non-bulk scintillation events leaking in the RoI or some unknown background source not considered in the model

Background model

Comparison with ANAIS-112 full exposure background at **low and high energy**

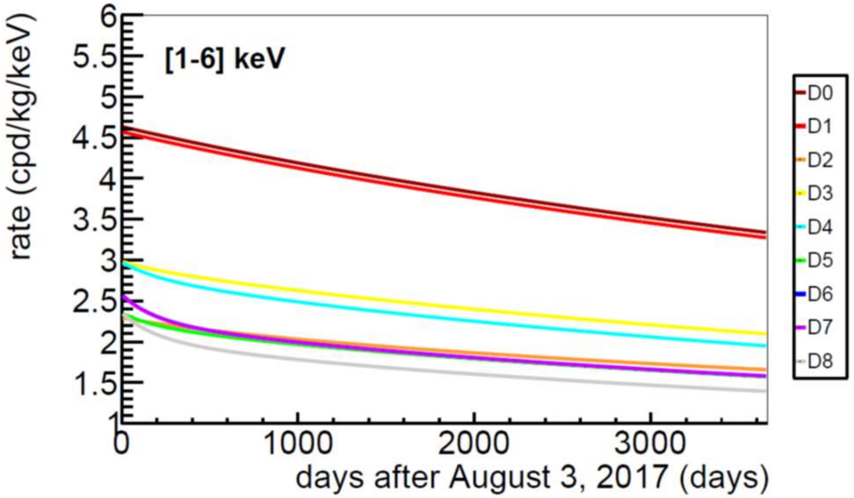




M1 events (after filtering and efficiency correction)
model

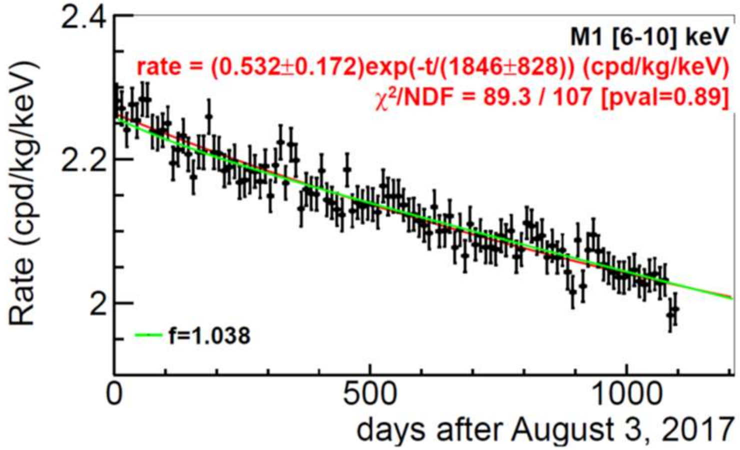
Background model

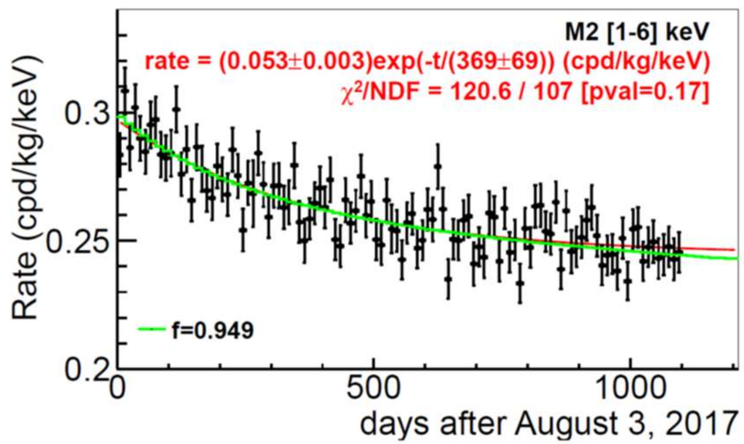
- **Time evolution:** predicted from decaying cosmogenics and ^{210}Pb



- **Time evolution:** measured and predicted rates of **M1** and **M2** events

Exponential fit
Background estimated evolution





Annual modulation results

PHYSICAL REVIEW LETTERS **123**, 031301 (2019)

First Results on Dark Matter Annual Modulation from the ANAIS-112 Experiment

J. Amaré,[1,2] S. Cebrián,[1,2] I. Coarasa,[1,2] C. Cuesta,[1,‡] E. García,[1,2] M. Martínez,[1,2,3] M. A. Oliván,[1,§] Y. Ortigoza,[1,2] A. Ortiz de Solórzano,[1,2] J. Puimedón,[1,2] A. Salinas,[1,2] M. L. Sarsa,[1,2,†] P. Villar,[1,2] and J. A. Villar[1,2,*]

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(Received 12 March 2019; published 16 July 2019)

ANAIS is a direct detection dark matter experiment aiming at the testing of the DAMA/LIBRA annual modulation result, which, for about two decades, has neither been confirmed nor ruled out by any other experiment in a model independent way. ANAIS – 112, consisting of 112.5 kg of sodium iodide crystals, has been taking data at the Canfranc Underground Laboratory, Spain, since August 2017. This Letter presents the annual modulation analysis of 1.5 years of data, amounting to 157.55 kg yr. We focus on the model independent analysis searching for modulation and the validation of our sensitivity prospects. ANAIS – 112 data are consistent with the null hypothesis (p values of 0.67 and 0.18 for [2–6] and [1–6] keV energy regions, respectively). The best fits for the modulation hypothesis are consistent with the absence of modulation ($S_m = -0.0044 \pm 0.0058$ cpd/kg/keV and -0.0015 ± 0.0063 cpd/kg/keV, respectively). They are in agreement with our estimated sensitivity for the accumulated exposure, which supports our projected goal of reaching a 3σ sensitivity to the DAMA/LIBRA result in five years of data taking.

Data from 3rd August 2017 to 12th February 2019
1.5 y, 157.55 kg x y

J. Phys (Conference Series) 1468 (2020) 012014

ANAIS-112 status: two years results on annual modulation

J. Amaré[1,2], S. Cebrián[1,2], D. Cintas[1,2], I. Coarasa[1,2], E. García[1,2], M. Martínez[1,2,3], M.A. Oliván[1,2,4], Y. Ortigoza[1,2], A. Ortiz de Solórzano[1,2], J. Puimedón[1,2], A. Salinas[1,2], M.L. Sarsa[1,2] and P. Villar[1,2]

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Same analysis for **2 y**, 220.69 kg x y
Presented at TAUP2019 conference

[2-6] keV → $S_m = -0.0029 \pm 0.0050$ c/keV/kg/d

[1-6] keV → $S_m = -0.0036 \pm 0.0054$ c/keV/kg/d

Annual modulation results

Annual Modulation Results from Three Years Exposure of ANAIS-112

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Data for **3 y**, 313.95 kg x y

ANAIS (Annual modulation with NaI Scintillators) is a dark matter direct detection experiment consisting of 112.5 kg of NaI(Tl) detectors in operation at the Canfranc Underground Laboratory (LSC), in Spain, since August 2017. ANAIS' goal is to confirm or refute in a model independent way the DAMA/LIBRA positive result: an annual modulation in the low-energy detection rate having all the features expected for the signal induced by dark matter particles in a standard galactic halo. This modulation, observed for about 20 years, is in strong tension with the negative results of other very sensitive experiments, but a model-independent comparison is still lacking. By using the same target material, NaI(Tl), such comparison is more direct and almost independent on dark matter particle and halo models. Here, we present the annual modulation analysis corresponding to three years of ANAIS data (for an effective exposure of 313.95 kg$\times$y), applying a blind procedure, which updates the one developed for the 1.5 years analysis, and later applied to 2 years. The analysis also improves the background modelling in the fitting of the ROI rates. We obtain for the best fit in the [1–6] keV ([2–6] keV) energy region a modulation amplitude of –0.0034±0.0042 cpd/kg/keV (0.0003±0.0037 cpd/kg/keV), supporting the absence of modulation in our data, and incompatible with DAMA/LIBRA result at 3.3 (2.6) σ, for a sensitivity of 2.5 (2.7) σ. Moreover, we include two complementary analyses: a phase-free annual modulation search and the exploration of the possible presence of a periodic signal at other frequencies. Finally, we carry out several consistency checks of our result, and we update the ANAIS-112 projected sensitivity for the scheduled 5 years of operation.

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

Annual modulation results

Least-squares fits of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV

Minimizing $$\chi^2 = \sum_i \frac{(n_i - \mu_i)^2}{\sigma_i^2} \qquad \mu_i = [R_0 \phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))] M \Delta E \Delta t$$

n_i, σ_i	number of events and Poisson uncertainty at time bin *i* (corrected by livetime and efficiency)
μ_i	expected number of events
R_0	free parameter for unmodulated rate
ϕ_{bkg}	probability distribution function (PDF) of any unmodulated component
ω	fixed corresponding to 1 year period
t_0	fixed to have the cosine maximum in June, 2nd
M	total detector mass
ΔE	energy interval width
Δt	time bin width (10 days)
S_m	fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

Annual modulation results

Least-squares fits of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV

Three different **background modelling procedures**: including a constant term and

- Exponentially decaying background:

$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

R_0, τ, f free parameters

- Probability distribution function (PDF) derived from background model:

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

R_0, f free parameters

- Probability distribution function for every detector individually:

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

(to account for possible systematic effects related to different backgrounds and efficiencies in different modules)

$R_{0,d}$, f_d free parameters (18 nuisance parameters)

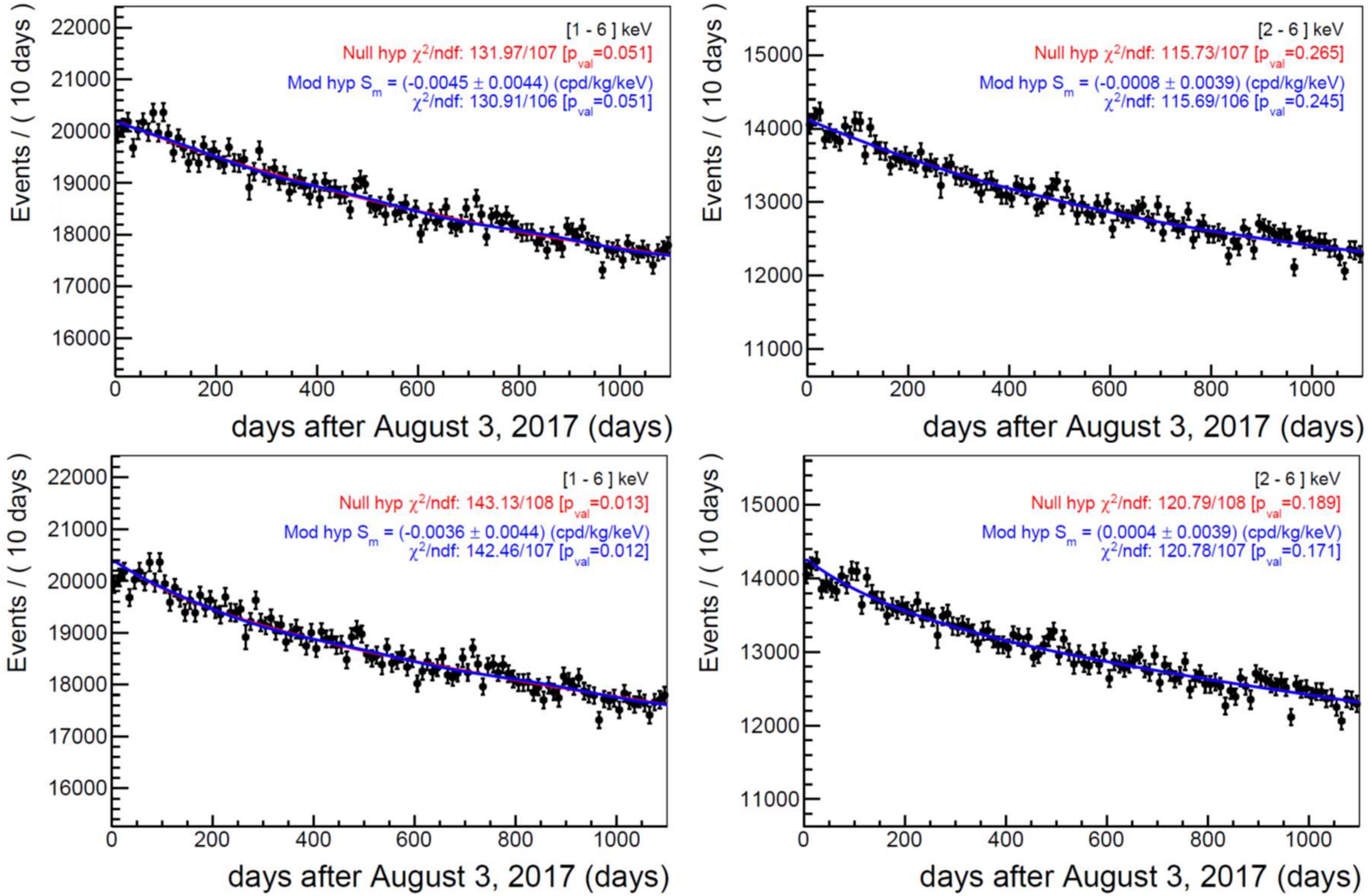
Annual modulation results

Least-squares fits of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV

Null hypothesis well supported by the χ^2 test, Modulation hypothesis best fits

Decaying background

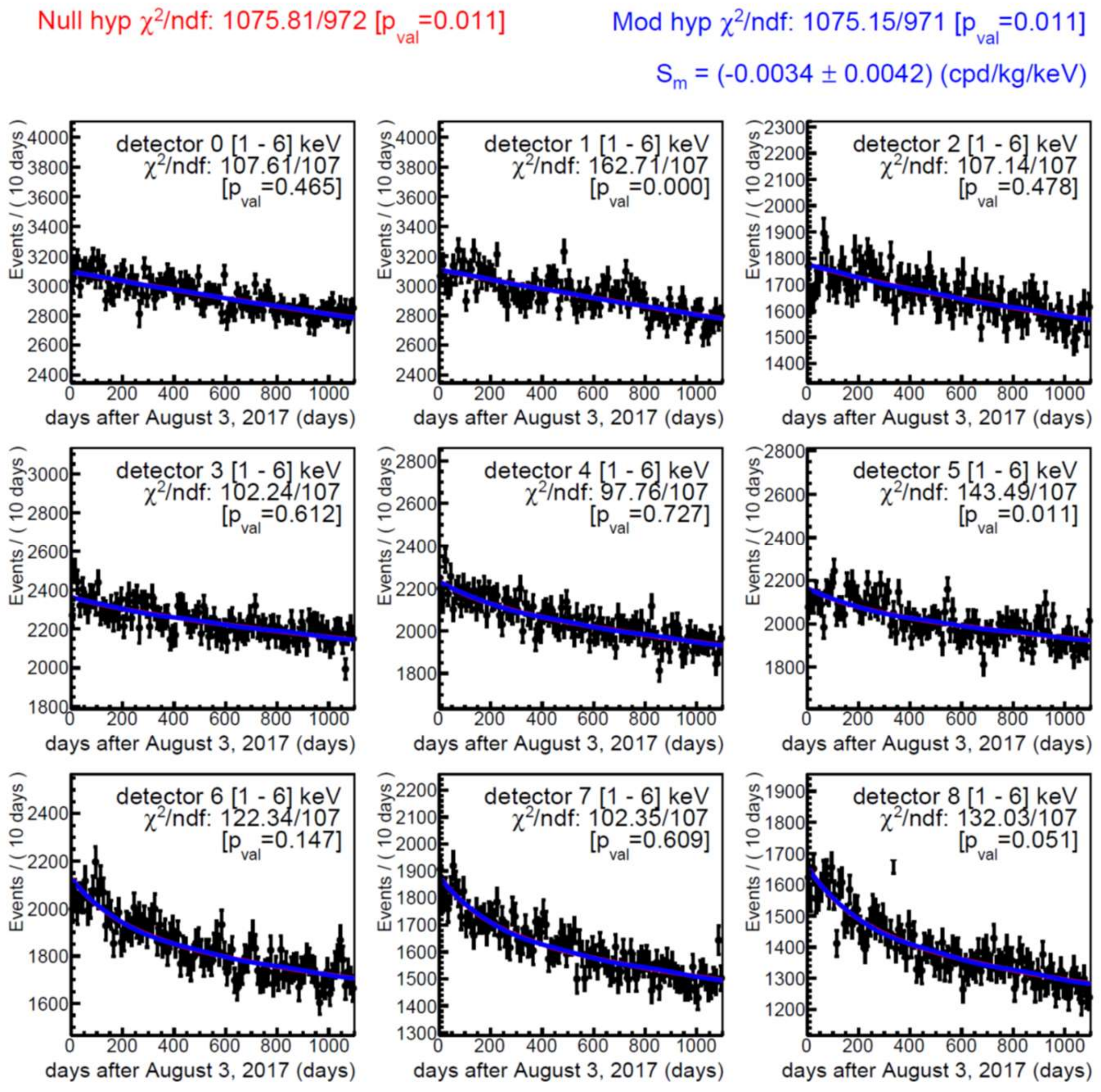
PDF from MC



Annual modulation results

Least-squares fits of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV

PDF from MC for every detector

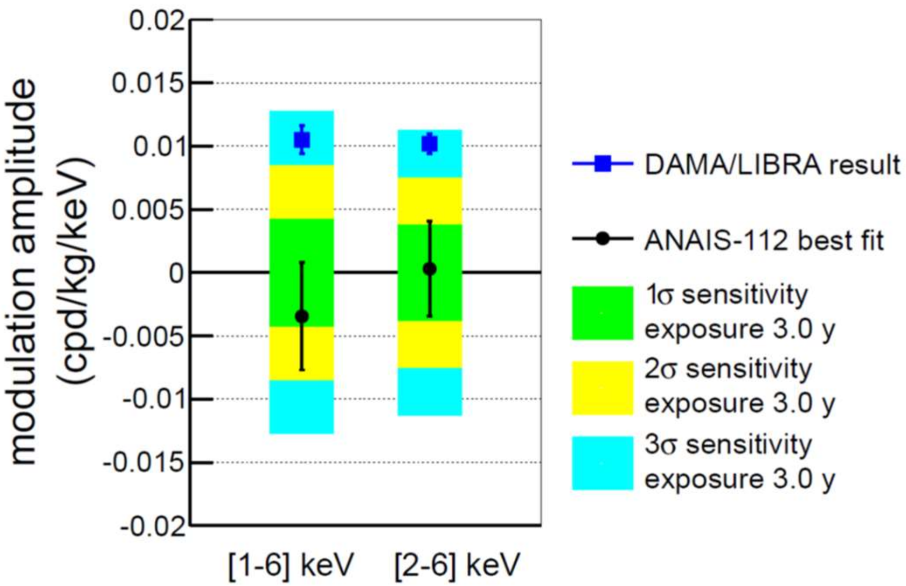


Annual modulation results

Least-squares fits of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV

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

Data support absence of modulation in both energy regions and three background models



Best fits are incompatible with DAMA/LIBRA result at:

3.3σ in [1-6] keV

2.6σ in [2-6] keV

Sensitivity for 3 y is at 2.5 and 2.7σ in [1-6] and [2-6] keV energy regions

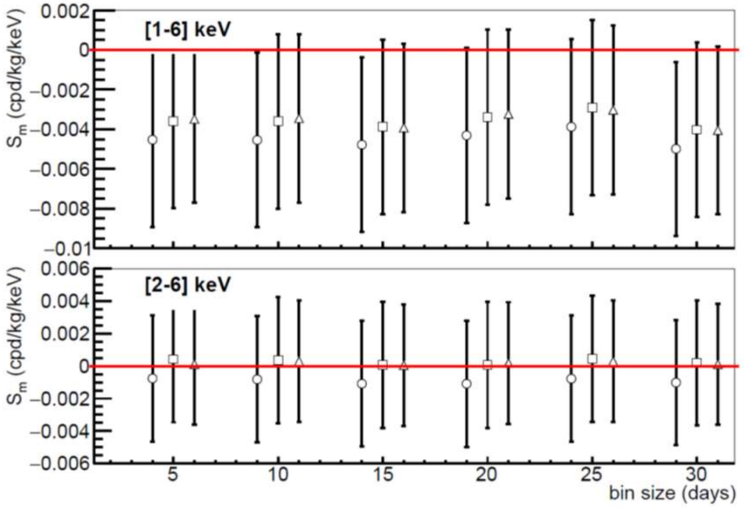
Annual modulation results

Consistency checks

- Fit results with fixed phase in the last 2 y for different background modelling

Energy region	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	81.23 / 70	3	-0.0056±0.0055	0.17	0.17
	81.37 / 71	2	-0.0057±0.0055	0.19	0.19
	621.7 / 639	18	-0.0100±0.0051	0.71	0.68
[2-6] keV	81.65 / 70	3	0.0032±0.0049	0.15	0.16
	81.82 / 71	2	0.0034±0.0049	0.17	0.18
	604.1 / 639	18	0.0013±0.0046	0.83	0.84

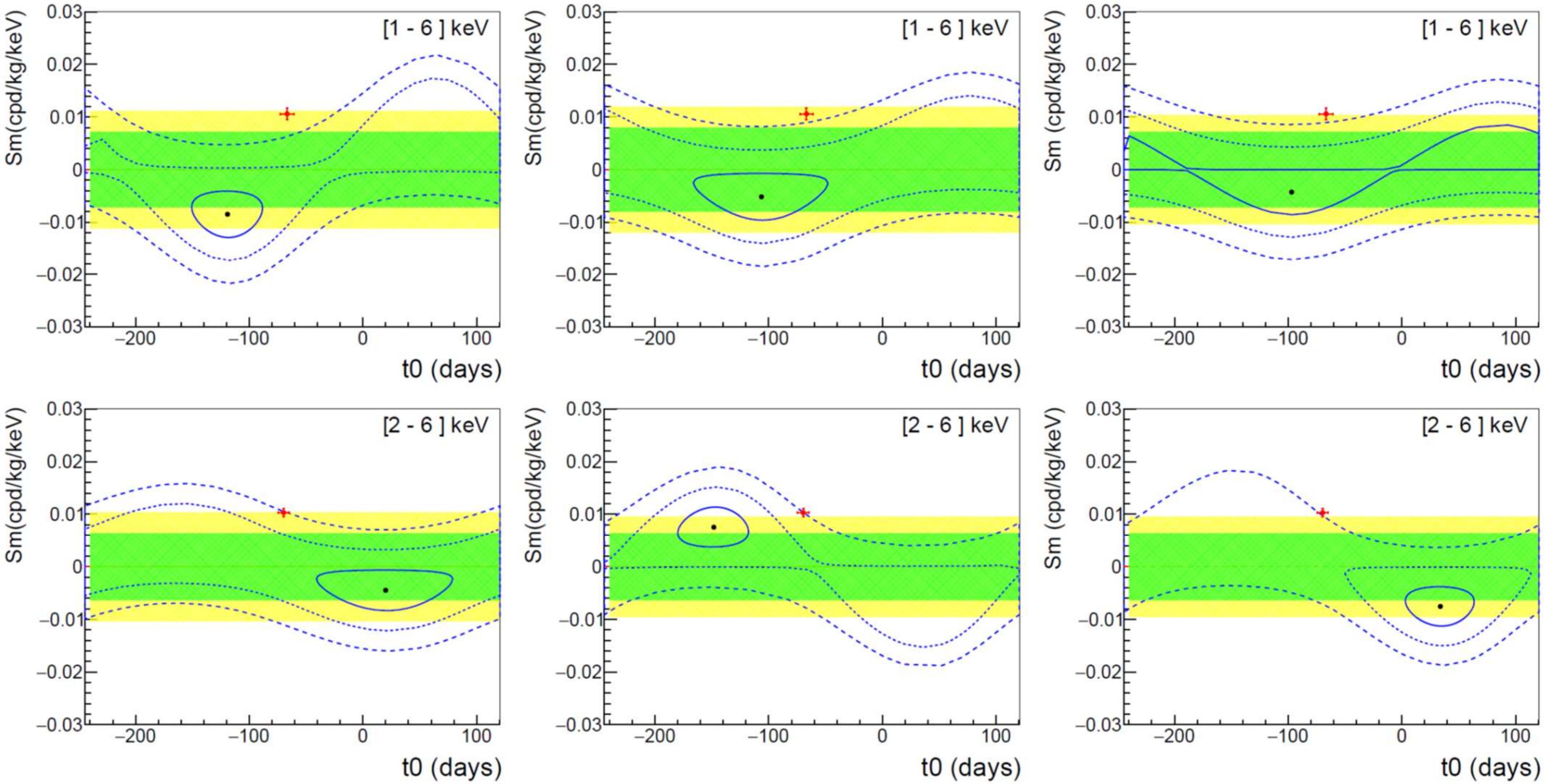
- Best fit values for different choices of the time binning (for different background modelling: circles, squares and triangles)



- **Compatible results** obtained in all checks
- **Fits** checked to be **unbiased** by MC simulation of pseudo-experiments with S_m=0 and S_m of DAMA/LIBRA

Annual modulation results

Phase-free modulation analysis t_0 as free parameter



ANAIS-112 result, exclusion contours at 1, 2, 3σ
DAMA/LIBRA result
Green and yellow bands show 1, 2σ biased contours from MC simulation for each fit

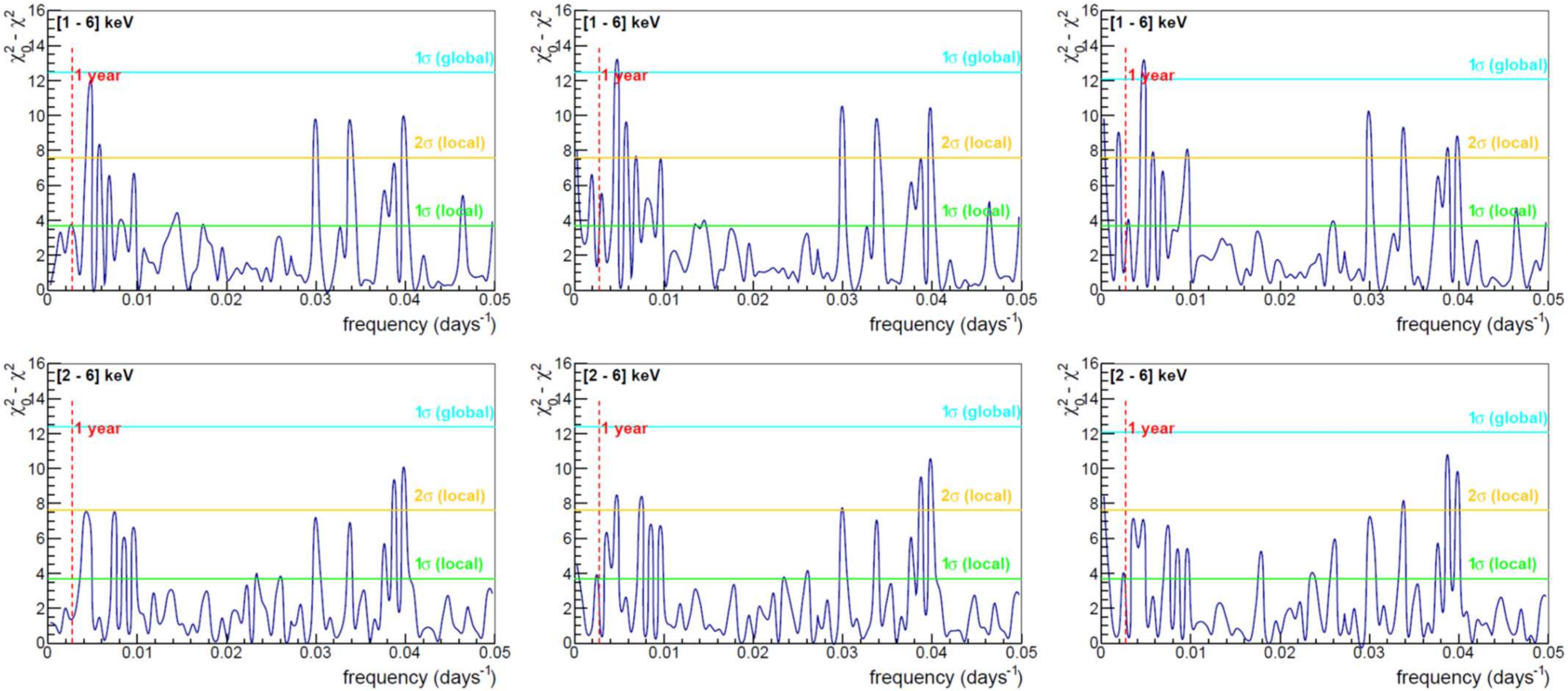
- In all cases: best fits 3σ away from DAMA/LIBRA result
- **Fit biased** due to non-linearity in model.

Best fits compatible with no modulation after correction with calculated bias

Annual modulation results

Frecuency analysis search for the presence of a periodic signal in the data

Periodograms using as test statistics the difference in χ^2 between the null and the modulation hypothesis when fitting data for each frequency considered



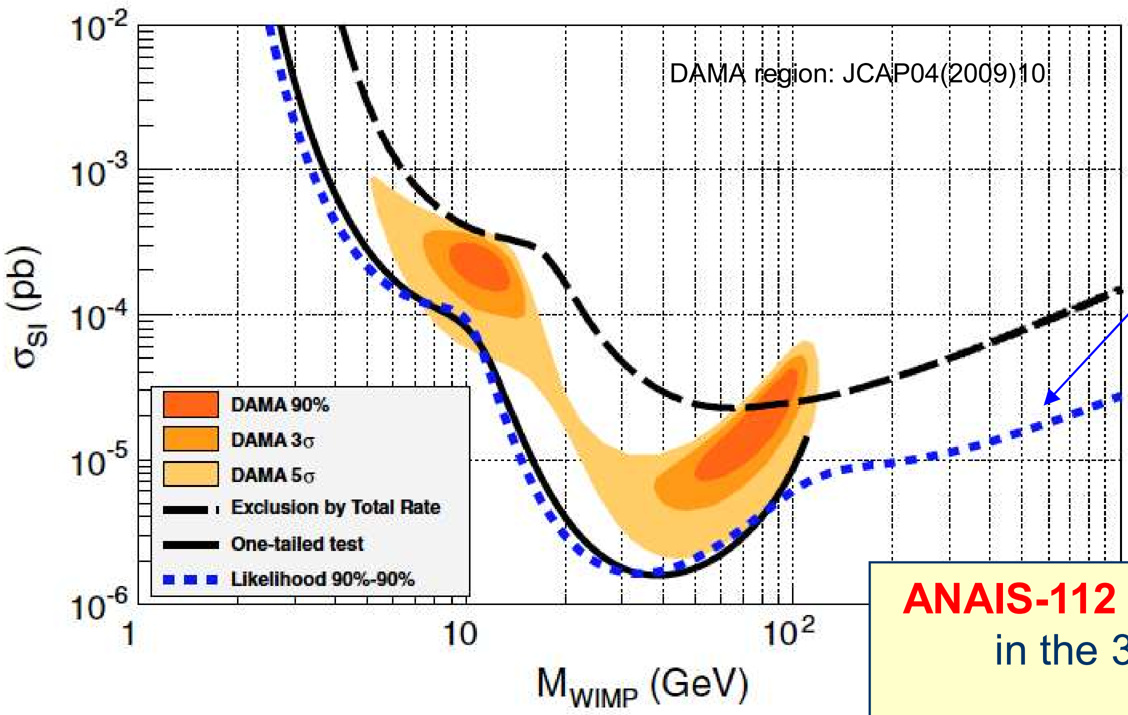
No statistically significant modulation found in the frequency range analyzed in the ANAIS-112 data

Annual modulation sensitivity

I.Coarasa et al, ANAIS-112 sensitivity in the search for dark matter annual modulation, Eur. Phys. J. C79 (2019) 233

- **Background** from measured, efficiency corrected levels (10% unblinded data)
- 1-6 keV_{ee} region
- 5 years

Model-dependent annual modulation: dark matter SI interaction

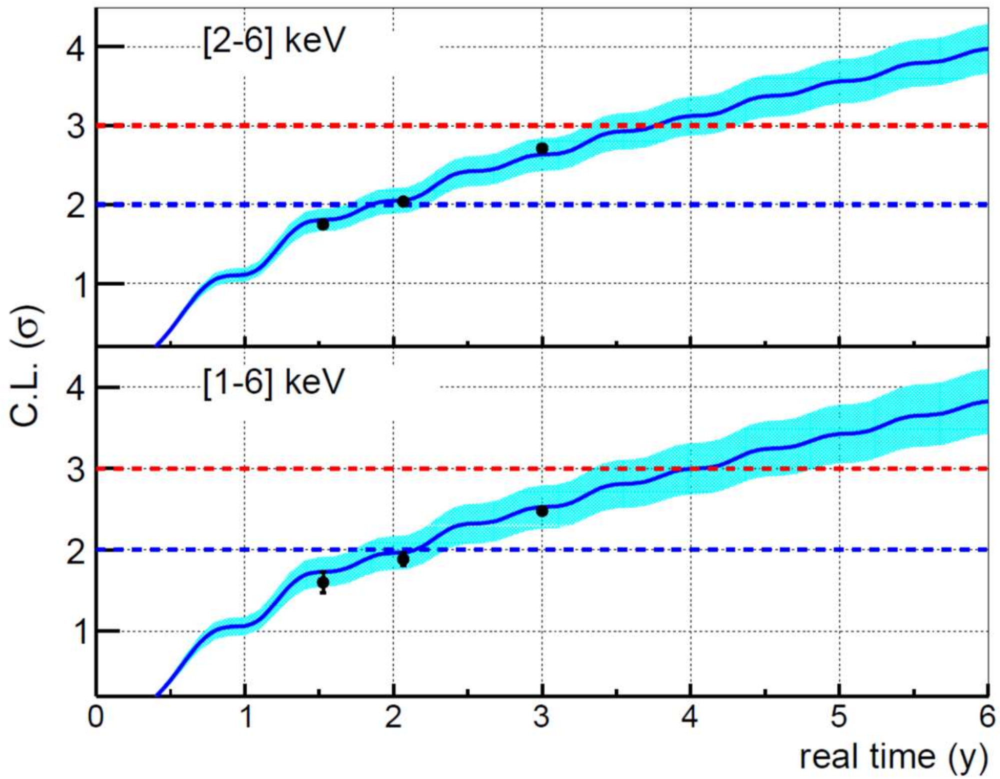


90% probability of detecting an annual modulation signal at 90% C.L.

ANAIS-112 can detect the annual modulation in the 3σ region compatible with the DAMA/LIBRA result

Annual modulation sensitivity

Sensitivity to DAMA/LIBRA result as $S_m^{DAMA} / \sigma(S_m)$



predicted sensitivity
3σ sensitivity
measured sensitivity $\sigma(S_m)$
68% C.L. DAMA/LIBRA uncertainty

Model-independent annual modulation

Standard deviation of the modulation amplitude analitically estimated from:

- updated background
- efficiency estimates
- live time distribution

Sensitivity projection to DAMA/LIBRA result fully confirmed by data

3σ sensitivity at reach in less than 1 y from now!

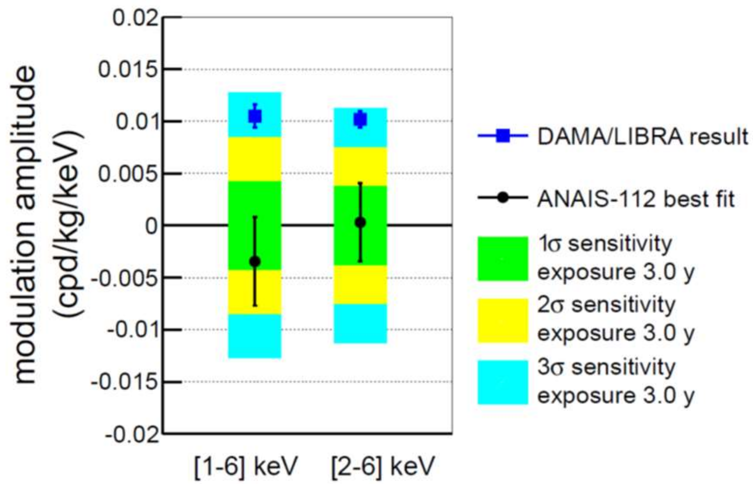
Summary and outlook

✓ **ANAIS-112:** data taking using **112.5 kg** of **NaI(Tl)** running smoothly for >3 y

- Excellent **light collection** of **~15 phe/keV** and **threshold** at **1 keV$_{ee}$** in all modules
- Robust **filtering** of PMT events and good **background understanding**, dominated by crystal activity

Analysis for model-independent **annual modulation** of **3 y** of data taking:

- Best fits for modulation amplitude **incompatible with DAMA/LIBRA result at 3.3 (2.7)** σ for 1-6 (2-6) keV region
- Present sensitivity at 2.5 (2.7) σ for 1-6 (2-6) keV region
- Confirmed sensitivity of 3σ for 5 y of data



✓ **Next future and longer term:**

- Data taking will continue in same conditions up to complete scheduled **5 y**
- Determination of scintillation **Quenching Factor** for nuclear recoils ongoing, investigating possible dependence on crystal quality
- Plan to make ANAIS **data public** after use to allow independent analysis
- ANAIS-112 **extension** under consideration
  - Reduce threshold working with SiPM at low temperature
  - Reduce background by growing ultrapure crystals underground

Dark matter annual modulation results from the ANAIS-112 experiment

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