Annual modulation results from three-year exposure of ANAIS-112

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

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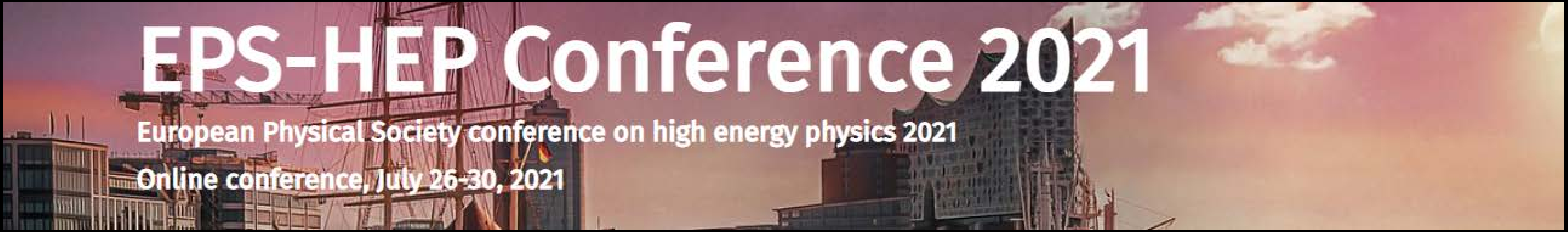


OUTLINE

-ANNUAL MODULATION in direct dark matter searches

-ANAIS-112 EXPERIMENT

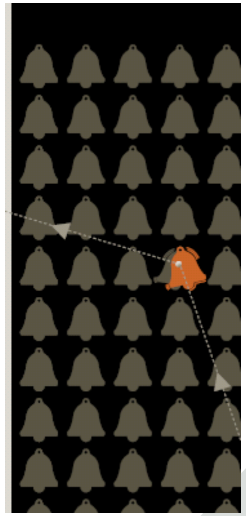
-ANAIS-112 UPDATED ANNUAL MODULATION RESULTS FOR THREE YEARS

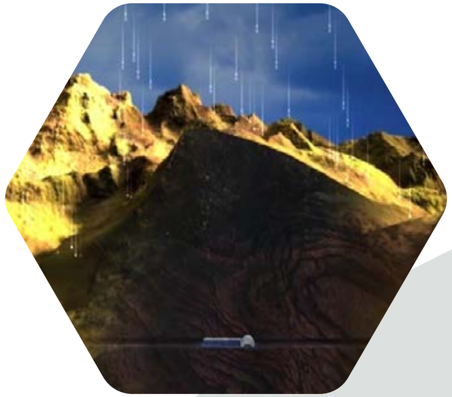
- -SYSTEMATICS
- -SENSITIVITY PROSPECTS

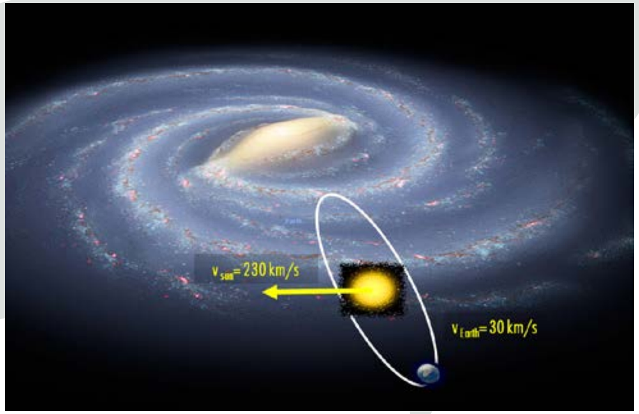
J. Amaré et al., arXiv: 2103.01175
Phys. Rev. D103 (2021) 102005

DM Direct Detection Approach

Analysis of signatures of DM particle interactions are key for a positive result

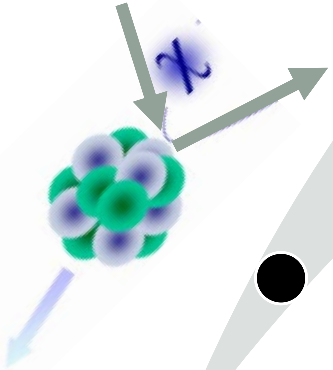






Experiments have to be shielded against all possible backgrounds and profit from active bckg rejection techniques

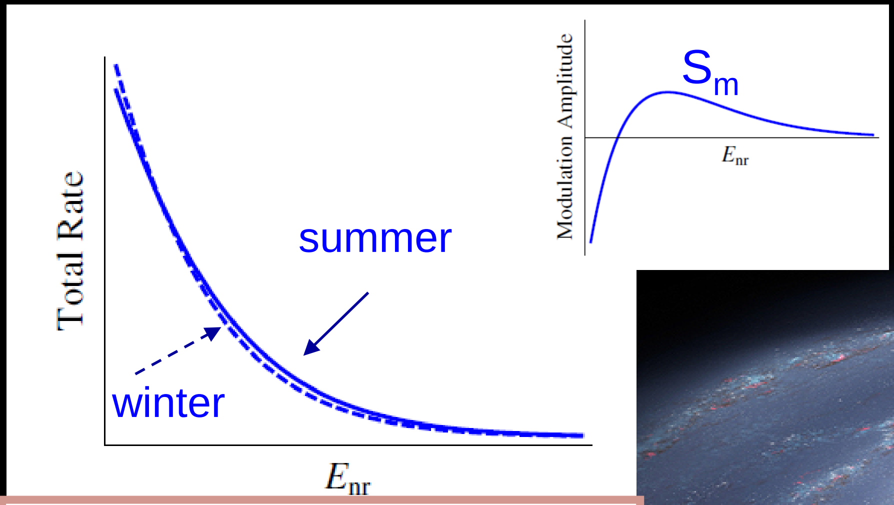
Requirement of very sensitive & radiopure particle detectors



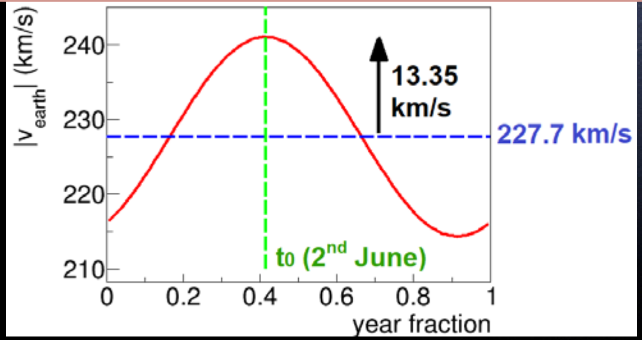
DM particles interact (although weakly) with ordinary matter with unknown coupling

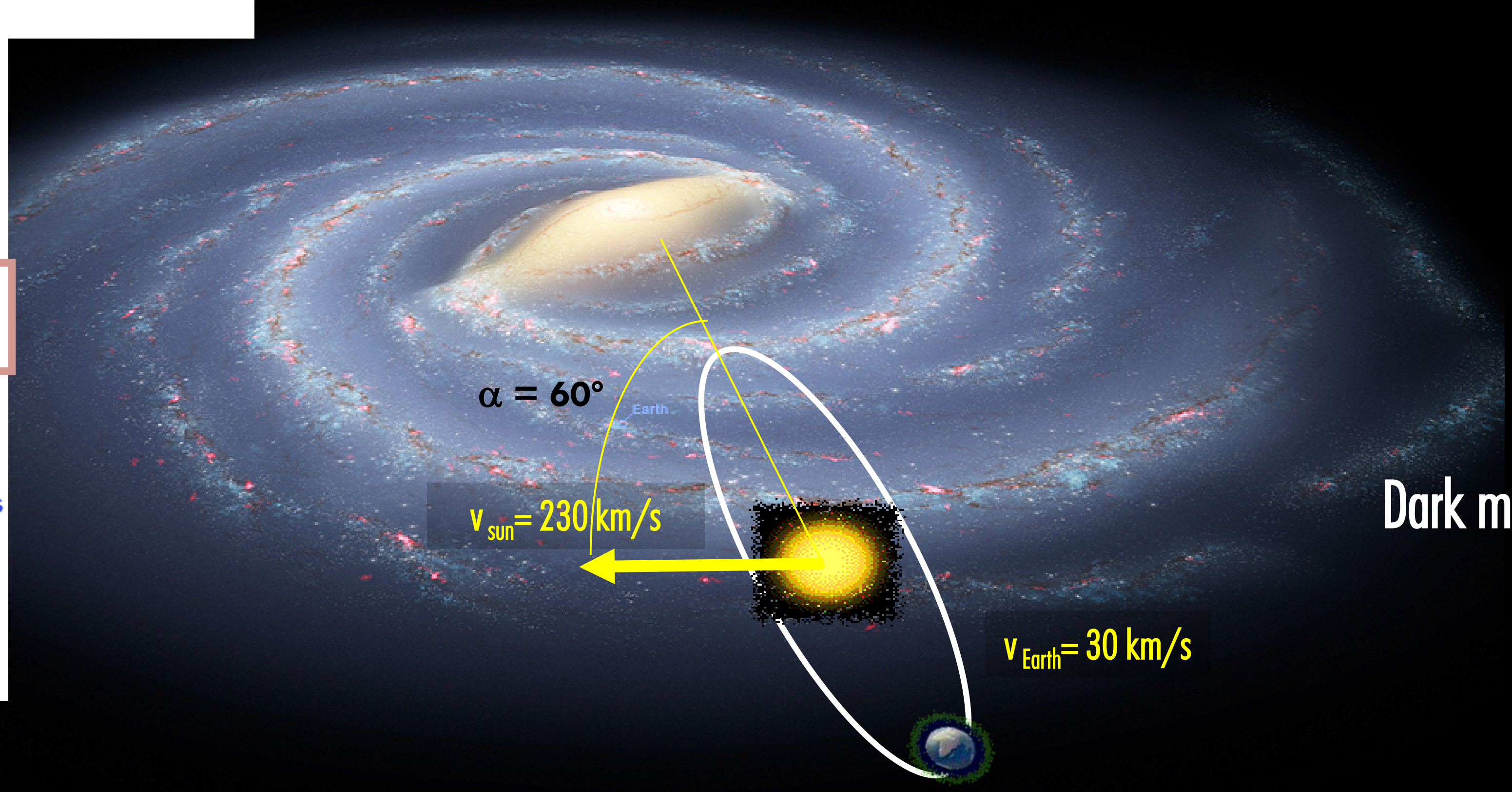
$$S(E_R,t) = \frac{dR}{dE_R} = \frac{\rho\, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

Annual modulation in dark matter interaction rate



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





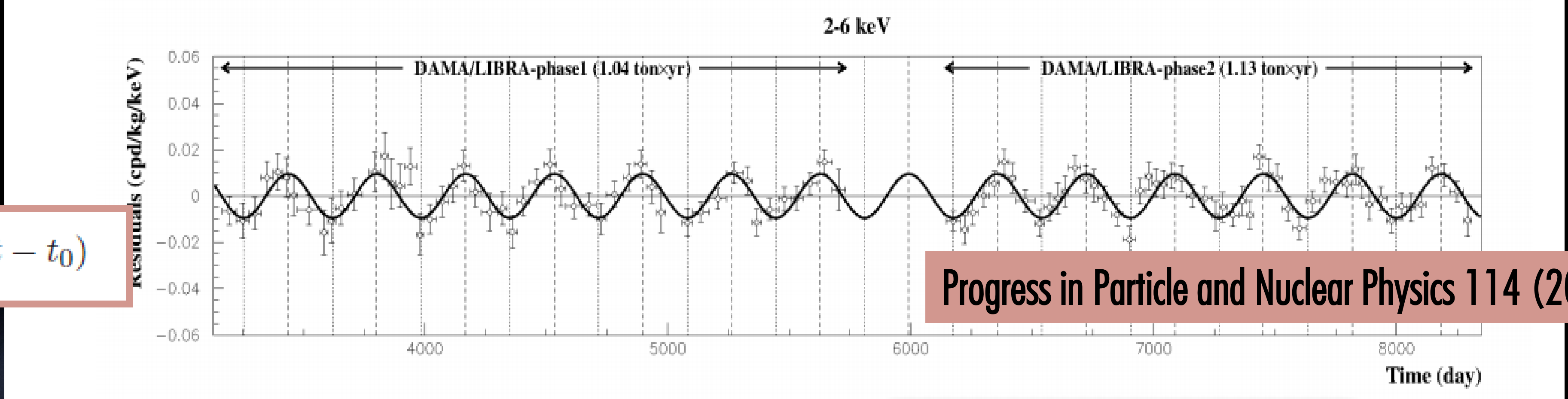
Dark matter halo

Relative velocity Earth –halo changes along the year

$$S(E_R, t) = \frac{dR}{dE_R} = \frac{\rho\, M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

Annual modulation in dark matter interaction rate

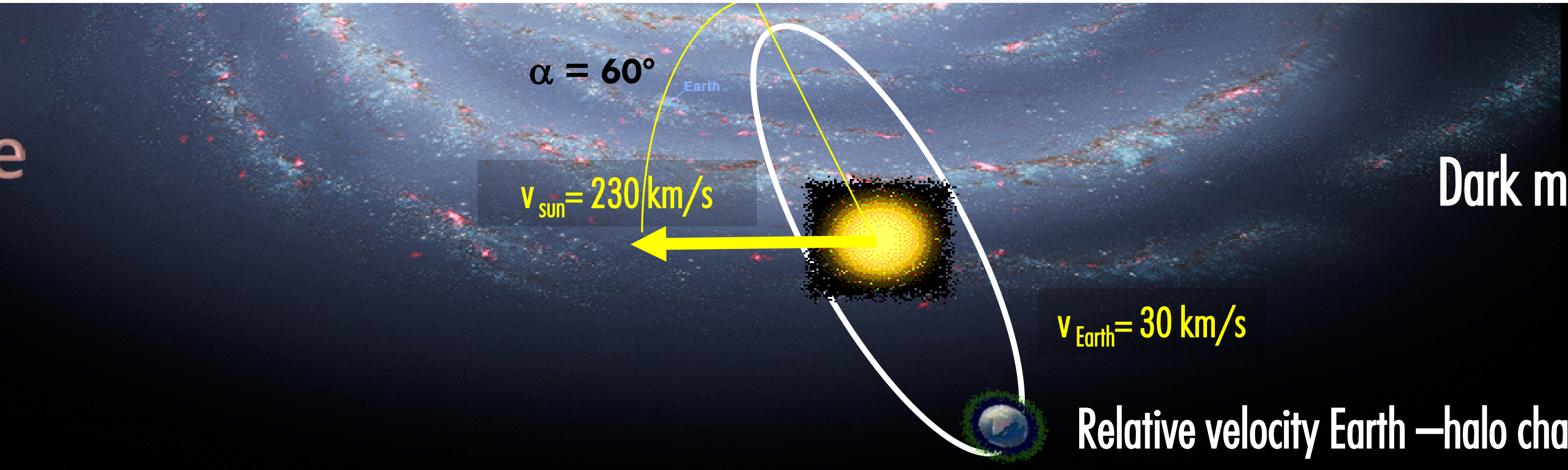
MILKYWAY GALAXY (2008 CONCEPT)



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

Progress in Particle and Nuclear Physics 114 (2020)

P. Belli's talk this conference



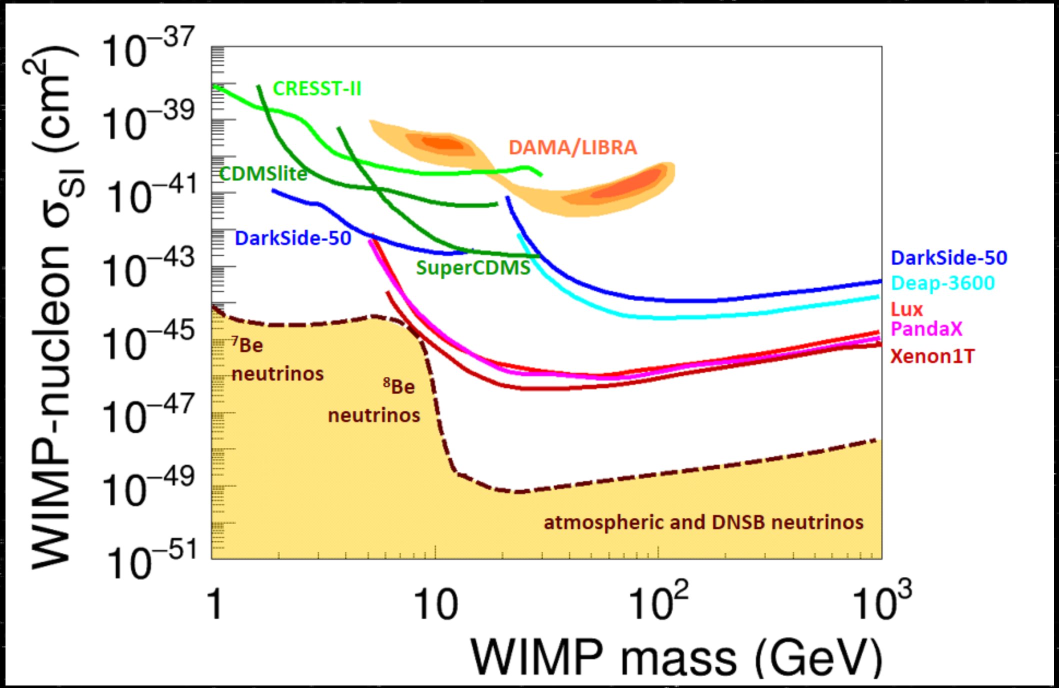
Dark matter halo

Relative velocity Earth –halo changes along the year

$$S(E_R, t) = \frac{dR}{dE_R} = \frac{\rho\, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

DAMA/LIBRA observes a model independent annual modulation compatible with DM in standard halo

Other very sensitive experiments do not see any hint -> Strong tension even assuming more general halo/interaction models, BUT MODEL – DEPENDENT



MODEL INDEPENDENT confirmation or refutation is mandatory → using same target

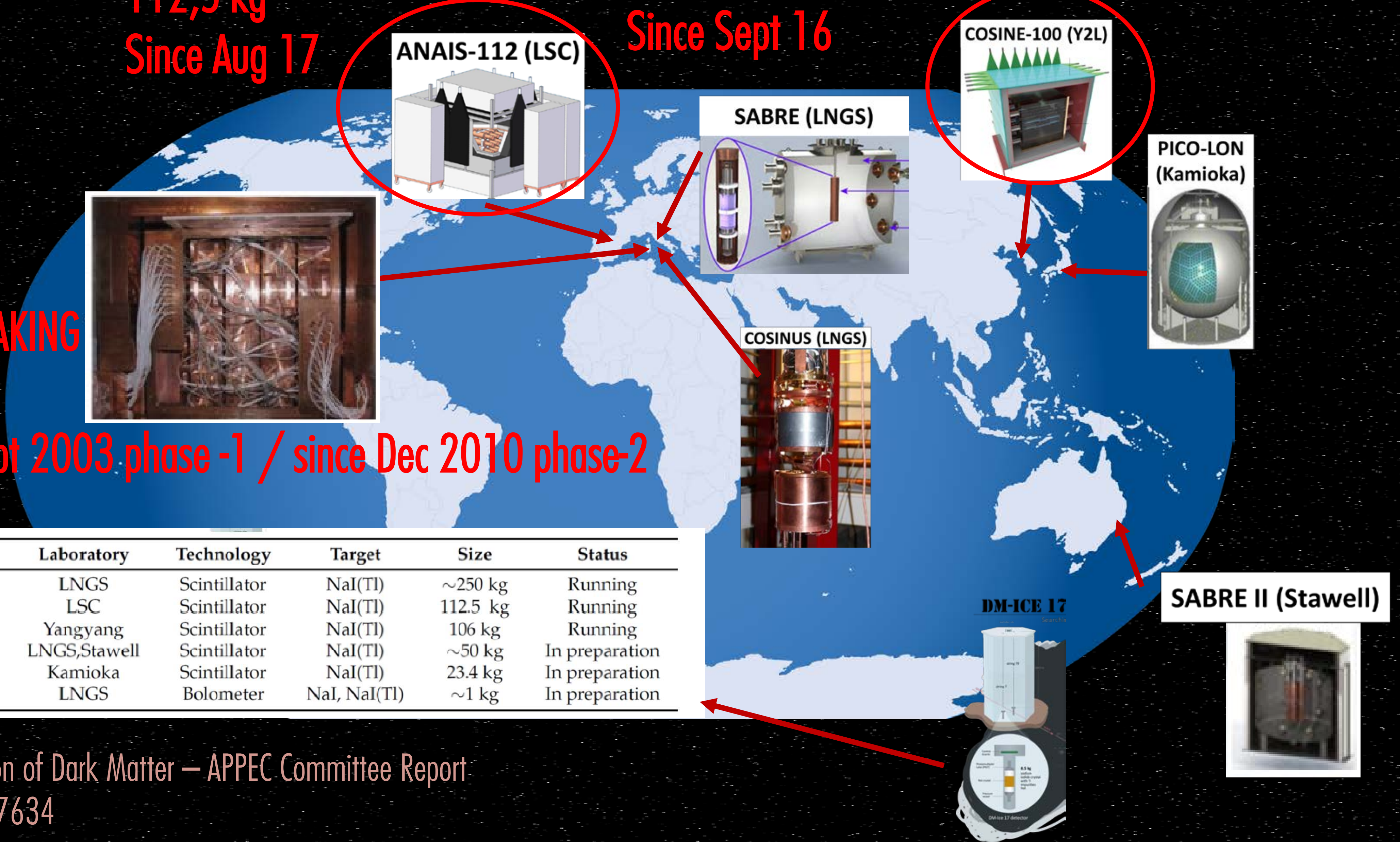
Experimental Situation

Experimental Situation

IN DATA-TAKING
112,5 kg
Since Aug 17

IN DATA-TAKING
61,3 kg (effective mass)
Since Sept 16

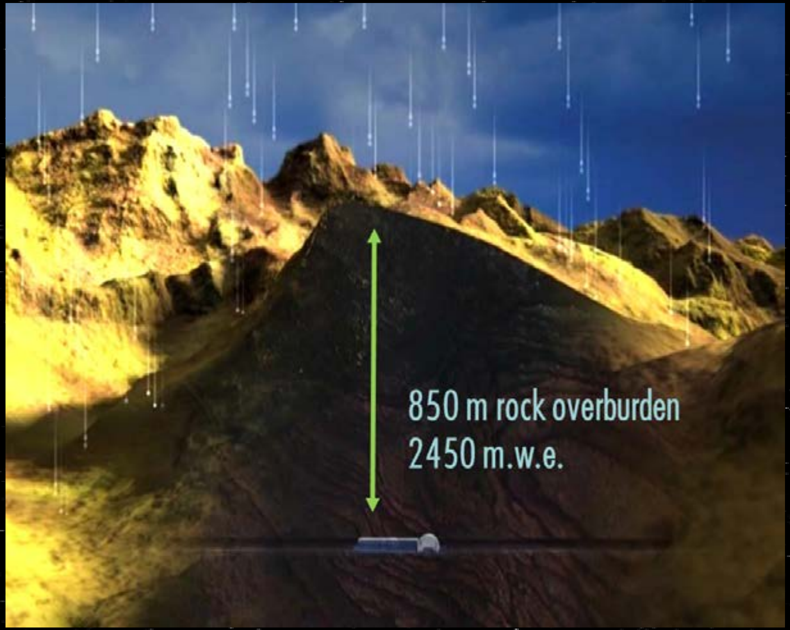
IN DATA-TAKING
~250 kg
Since Sept 2003 phase -1 / since Dec 2010 phase-2

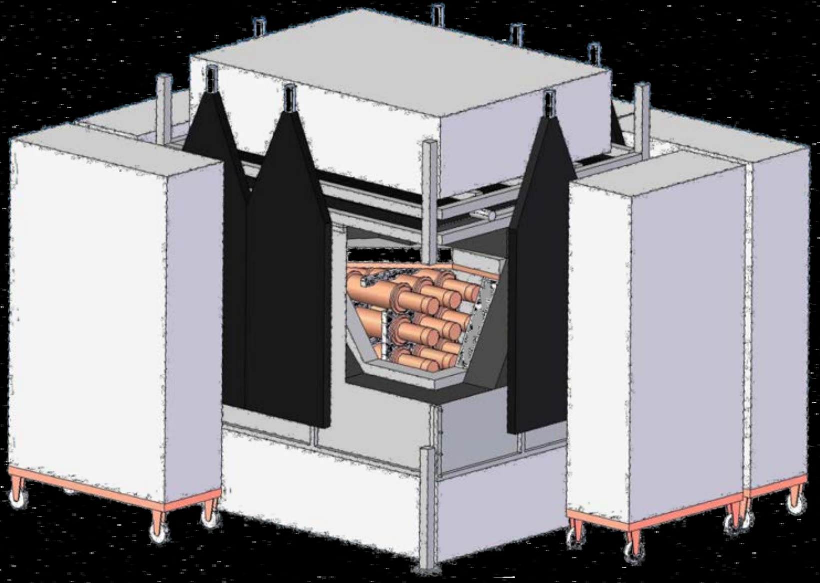


Experiment	Laboratory	Technology	Target	Size	Status
DAMA/LIBRA	LNGS	Scintillator	NaI(Tl)	~250 kg	Running
ANAIS-112	LSC	Scintillator	NaI(Tl)	112.5 kg	Running
COSINE-100	Yangyang	Scintillator	NaI(Tl)	106 kg	Running
SABRE	LNGS,Stawell	Scintillator	NaI(Tl)	~50 kg	In preparation
PICOLON	Kamioka	Scintillator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

Direct Detection of Dark Matter – APPEC Committee Report
arXiv:2104.07634

Annual modulation with NaI Scintillators





- Confirmation of DAMA-LIBRA modulation signal -> **same target and technique** / **different** experimental approach / **different** environmental conditions affecting **systematics**
- At Canfranc Underground Laboratory, @ SPAIN (under 2450 m.w.e.) taking data since August 2017
- 3x3 matrix of 12.5 kg cylindrical modules = 112.5 kg of active mass grown @ Alpha Spectra, Inc.
- HE PMTs coupled at LSC clean room
- DATA ANALYSIS: ROI BLINDED

Relevant experimental features

- **Mylar windows built-in, allowing for low energy calibration**
- **^{109}Cd sources on flexibles wires** in Radon-free calibration system for simultaneous calibration of the nine modules

- **Excellent light collection in all the nine modules ~ 15 p.e./keV**
  (12.7-15.8 p.e./keV) $\rightarrow$ 7/9 modules between 14.0 and 15.0 p.e./keV
  Larger and more homogeneous than that of DAMA/LIBRA modules
  Under continuous monitoring along data taking

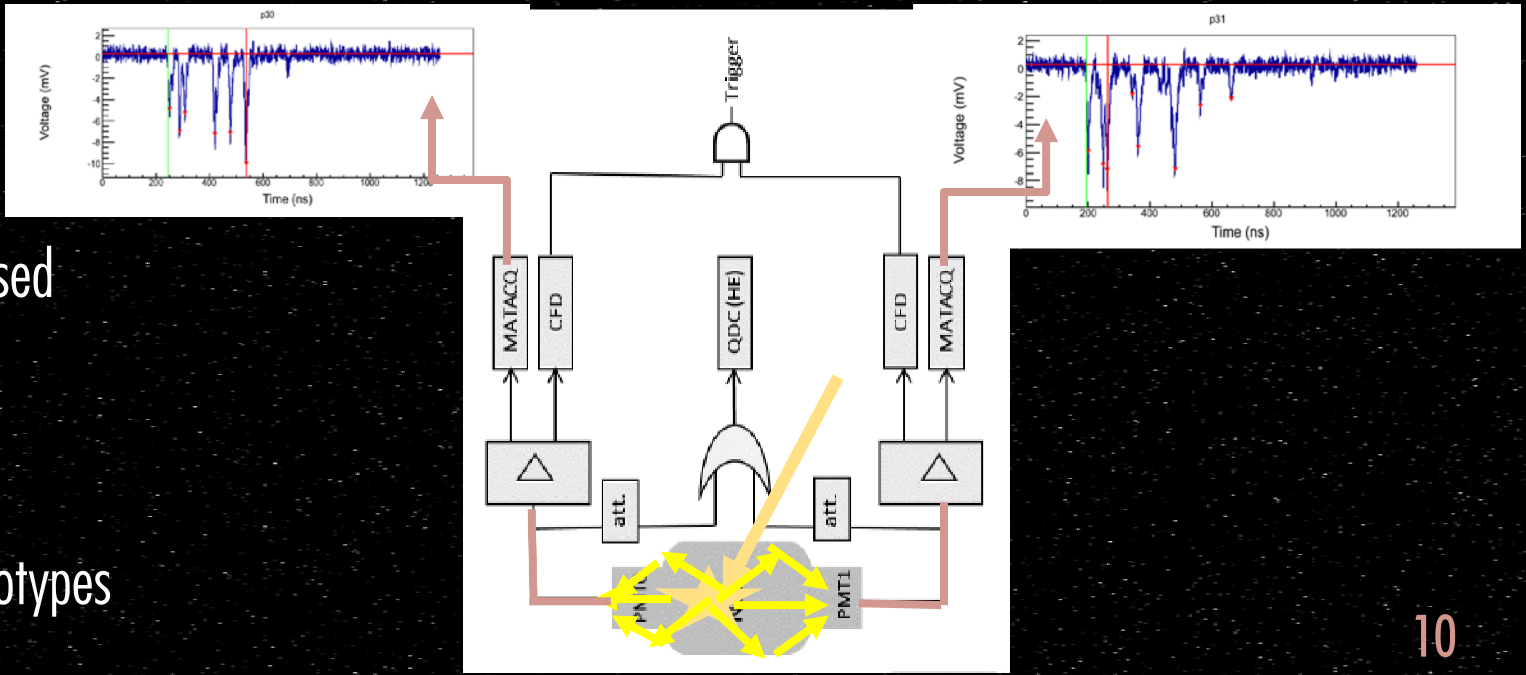
Relevant experimental features

ANAIS-112 set-up

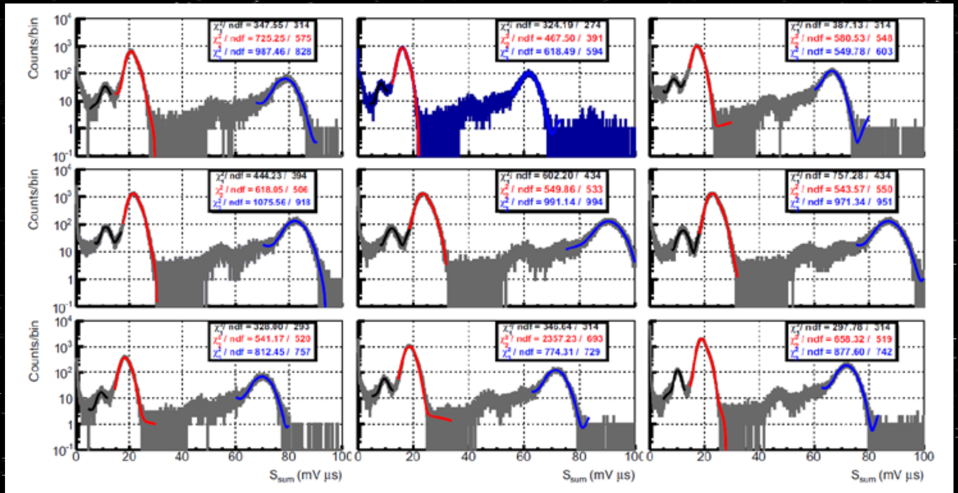
- 10 cm archaeological lead
- 20 cm low activity lead
- Tight box preventing Radon entrance
- 16 plastic scintillators acting as muon veto system
- 40 cm polyethylene / water

ANAIS-112 DAQ

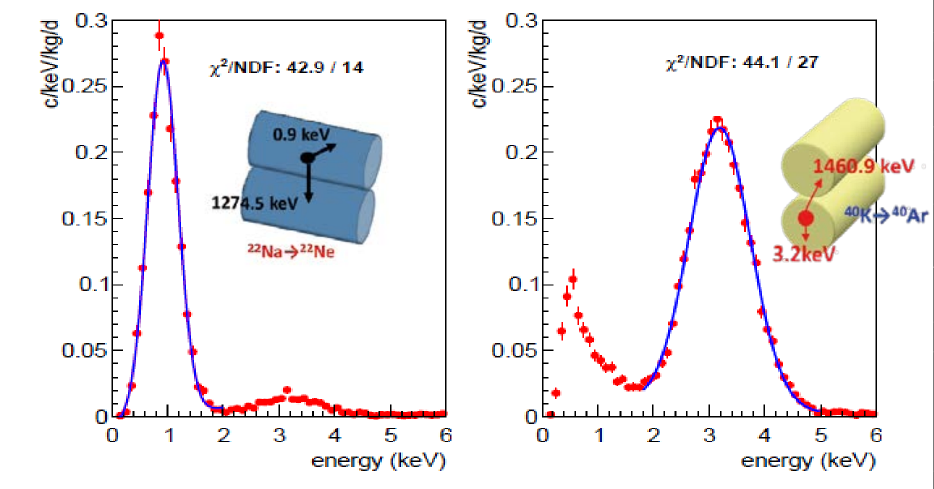
- Individual PMT signals digitized and fully processed (14 bits / 2 GS/s)
- Trigger at p.e. level for each PMT + Logical AND coincidence in 200ns window
- Robust / Low noise / tested with previous prototypes

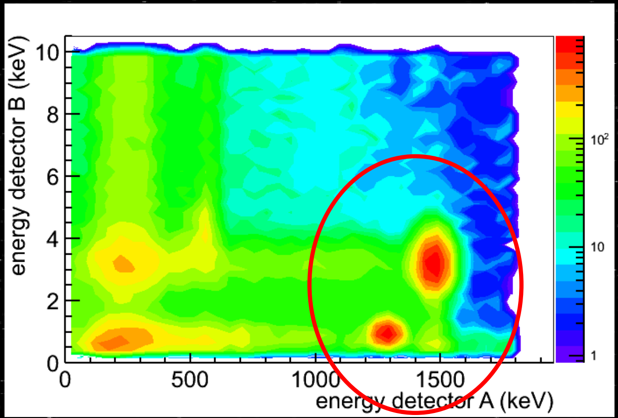


Calibrating the ROI with high accuracy



- Combination of periodical external calibration using ^{109}Cd (88.0, 22.6 and 11.9 keV) every two weeks and ^{40}K and ^{22}Na internal contamination background lines (3.2 and 0.9 keV) every 1.5 months
- ROI calibrated with 22.6, 11.9, 3.2 and 0.9 keV





Events @ROI from ^{40}K and ^{22}Na selected by the coincidence with a HE gamma in a second module

Demonstration of triggering below 1 keV

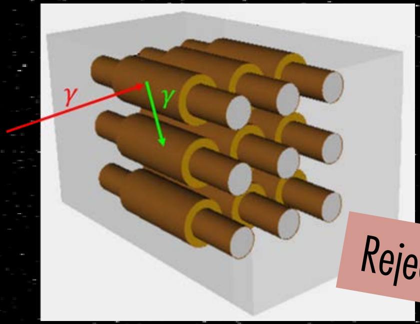
Blind analysis strategy

- M1 (single hit) events in the ROI (1-6 keV) BLINDED from beginning
- M2 in the ROI and Cd - calibration events used for fine-tuning analysis and determination of efficiencies along the first year
- Unblinding 10% (30 days randomly chosen) of the first year for background assessment

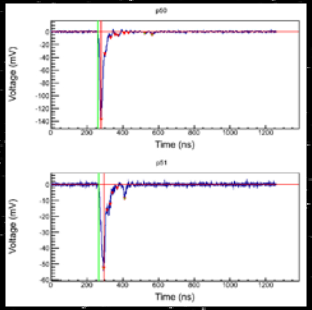
ANAIS general performance:
J. Amaré et al., EPJC79 (2019) 228

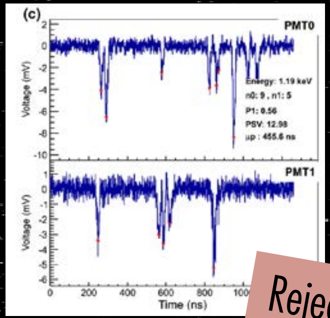
EVENTS SELECTION CRITERIA from the first year analysis are kept for subsequent analysis UPDATING EFFICIENCIES

Events selection procedure developed before unblinding

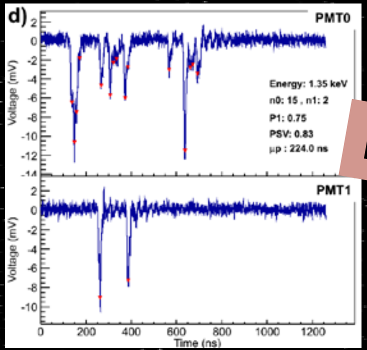


Rejected event





Rejected events



Rejected event

- Single hit events
- Events arriving more than 1 second after a muon interacting in the veto system

Our trigger rate is dominated by events non-compatible with bulk scintillation

- Time behavior compatible with NaI scintillation constant: biparametric cut

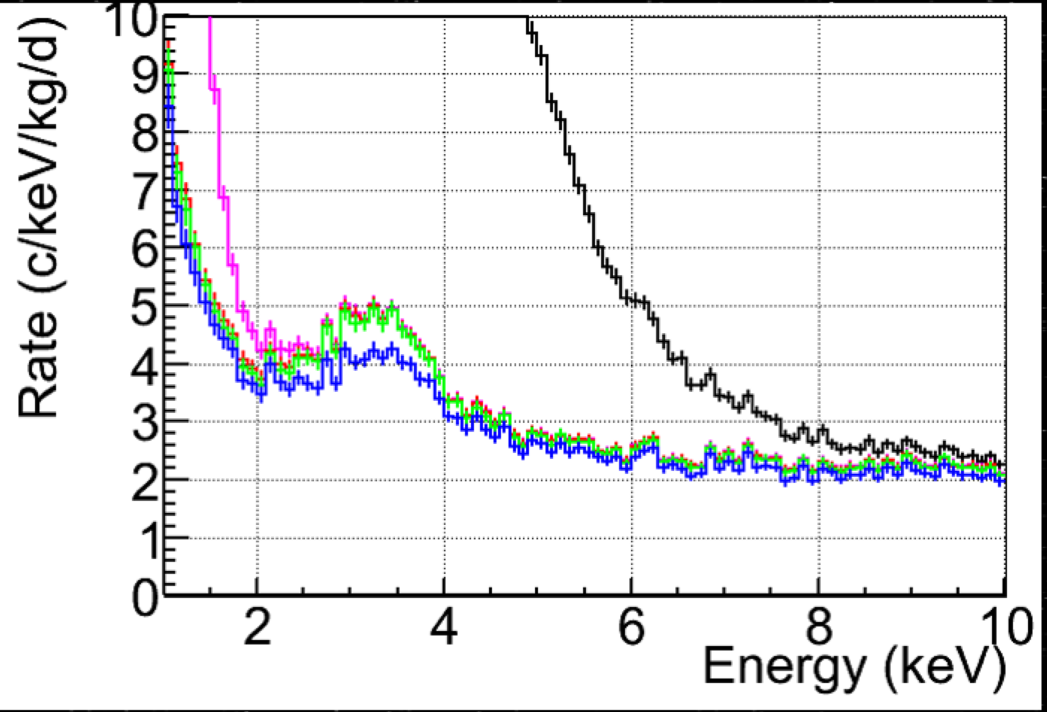
$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$

- Light sharing between the 2 PMTs compatible with bulk scintillation, number of p.e. >4 at each PMT

Events selection procedure developed before unblinding

General performance:
J. Amaré et al., EPJC79 (2019) 228

- Robust estimate of the efficiencies using ^{109}Cd / ^{22}Na and ^{40}K events BEFORE UNBLINDING / updated for the three years analysis

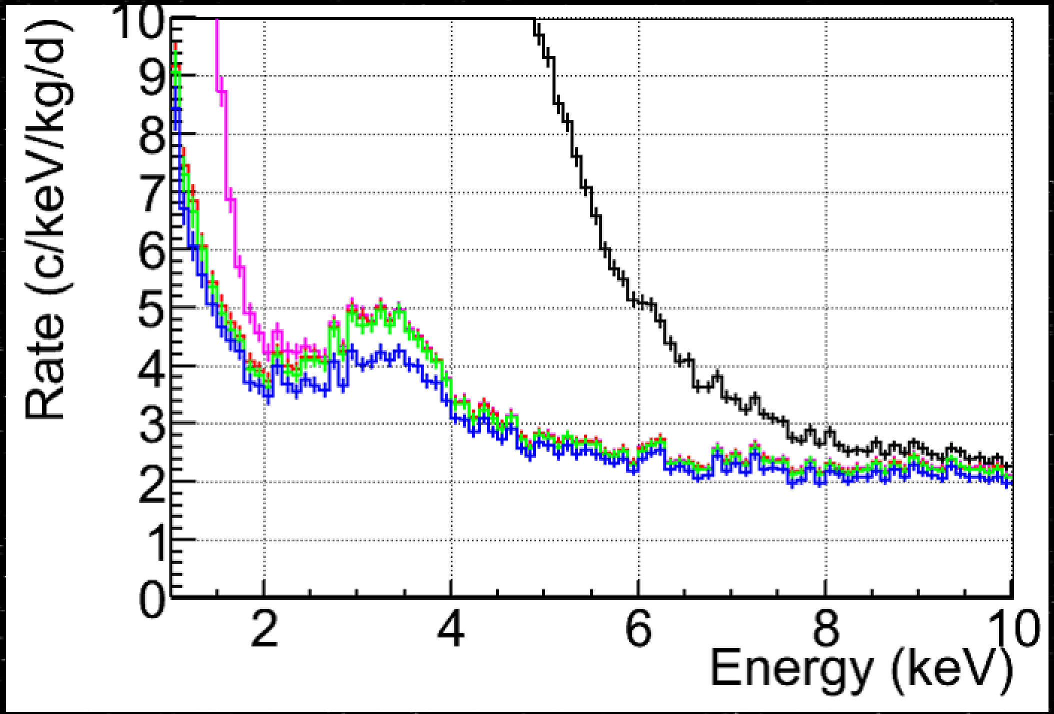


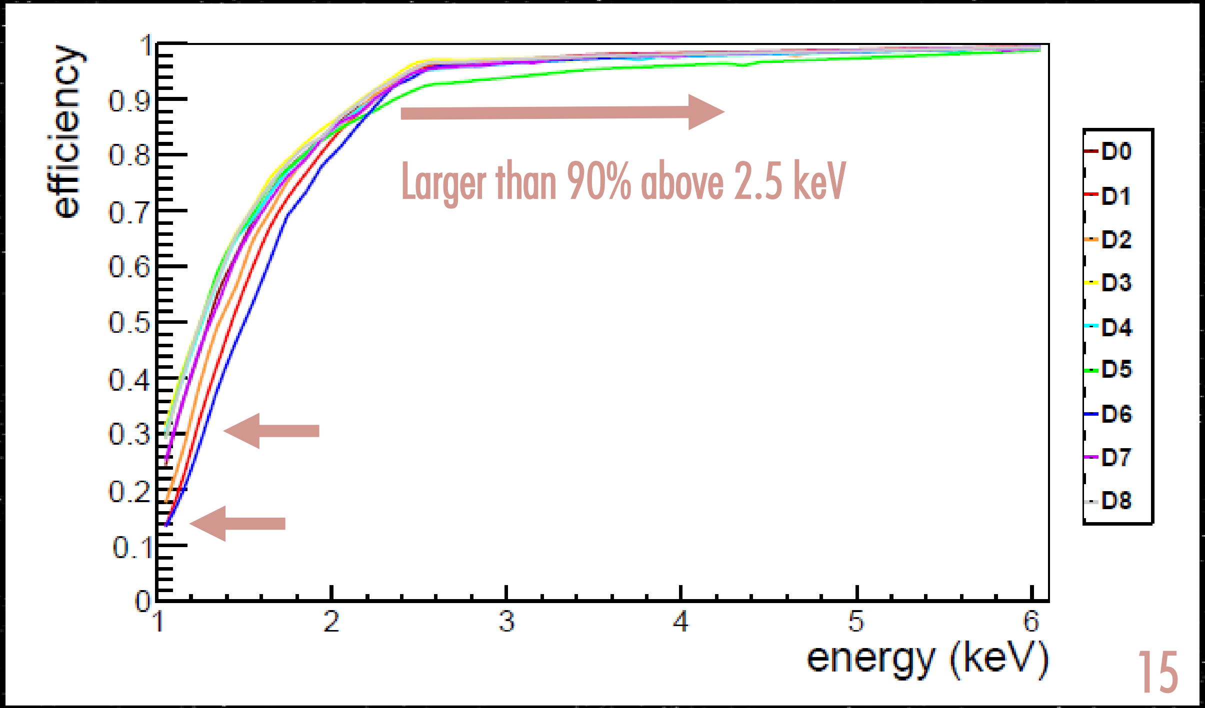
Raw data
NaI scintillation time behaviour/biparametric cut
Npeaks >4 at both PMTs
More than 1 s after a muon
Single Hits

Events selection procedure developed before unblinding

General performance:
J. Amaré et al., EPJC79 (2019) 228

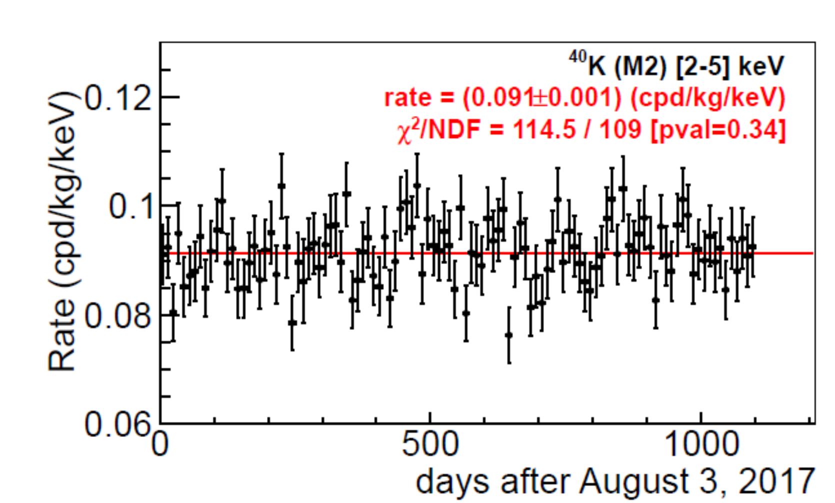
- Robust estimate of the efficiencies using ^{109}Cd / ^{22}Na and ^{40}K events BEFORE UNBLINDING / updated for the three years analysis
- Choice of analysis threshold → 1 keV
- Working on machine learning techniques to improve rejection

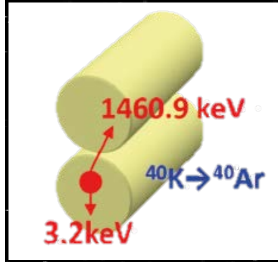




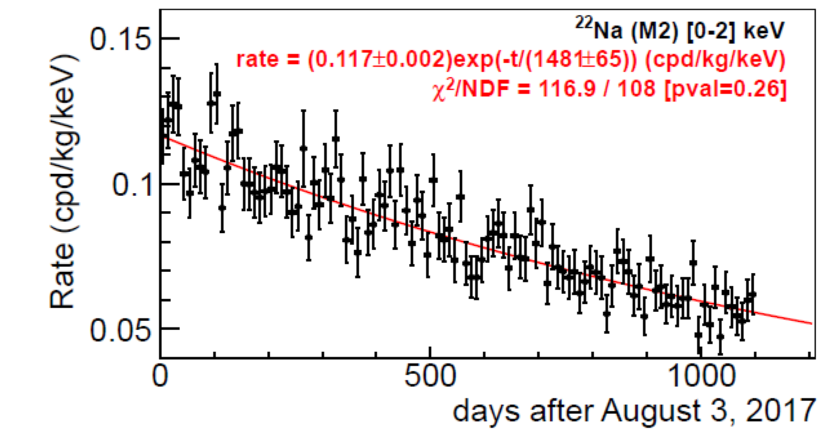
Events selection procedure developed before unblinding

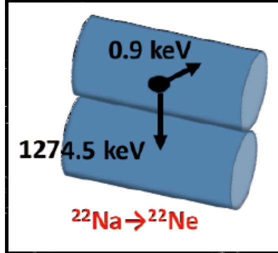
Efficiency and calibration stability checks using ^{40}K and ^{22}Na populations





- Constant for ^{40}K

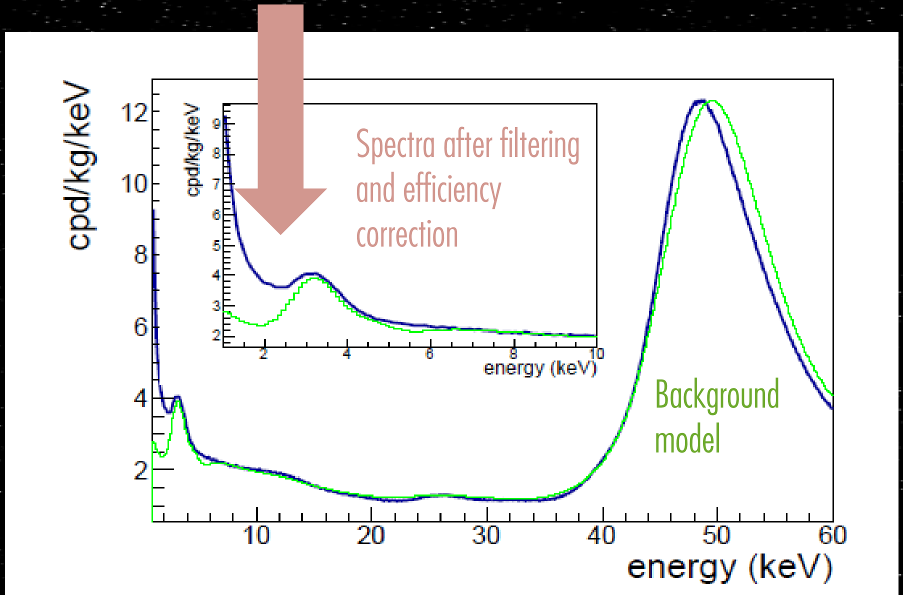




- Exponential decay for ^{22}Na -> $\tau = 1481 \pm 65$ d (vs 1370 d)

Robust background model

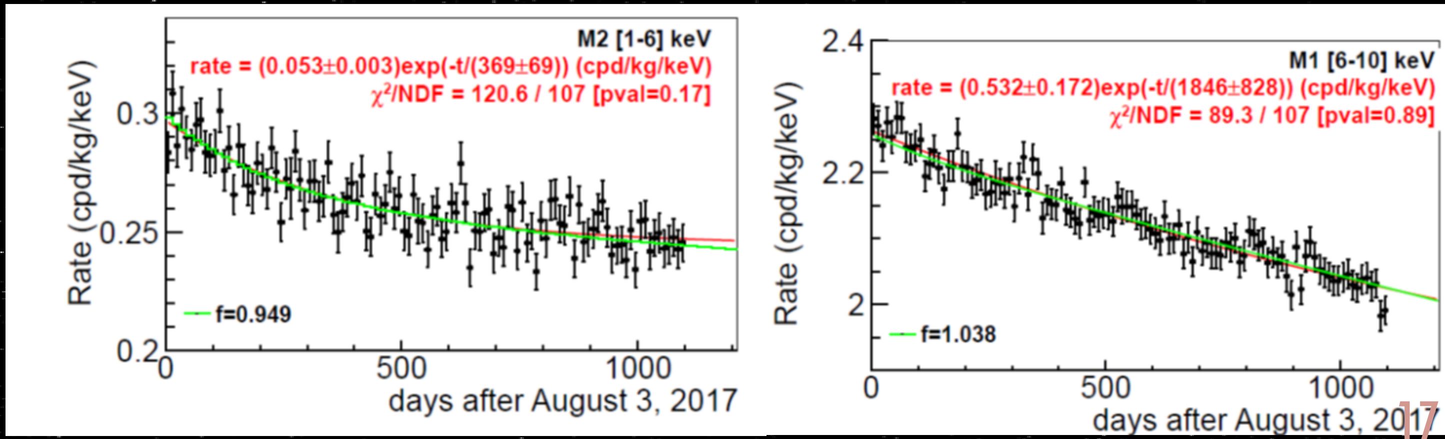
J. Amaré et al., EPJC79 (2019) 412



Comparison after unblinding three years data
Background model was established before unblinding

- ROI background dominated by ^{210}Pb, ^{40}K and cosmogenic isotopes, as ^{3}H -> higher than DAMA/LIBRA
- Good agreement in all energy regions, but underestimate in 1-2 keV energy region / Work in progress

- Our model predicts time evolution of the background detector by detector and reproduce satisfactorily the time evolution outside the ROI



ANAIS-112 three year results – annual modulation analysis

PHYSICAL REVIEW D **103,** 102005 (2021)

Editors' Suggestion | Featured in Physics

Annual modulation results from three-year exposure of ANAIS-112

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]

[1] *Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain*

[2] *Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s.n., 22880 Canfranc Estación, Huesca, Spain*

[3] *Fundación ARAID, Avenida de Ranillas 1D, 50018 Zaragoza, Spain*

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First results analysis was published in 2019: Phys. Rev. Lett. 123 (2019) 031301

https://link.aps.org/doi/10.1103/PhysRevD.103.102005

https://arxiv.org/abs/2103.01175

313.95 kg x y (95% live time for the first three years operation)

- Improved background modelling
- Checking of systematics and consistency of the results
    - Simulation of MC pseudo-experiments to analyze bias and checking sensitivity

MODEL INDEPENDENT ANALYSIS

Minimizing:

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

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

n_i, σ_i are number of events (and Poisson uncertainty) in 10d bins corrected by live time and efficiency

ANAIS-112 three year results – annual modulation analysis

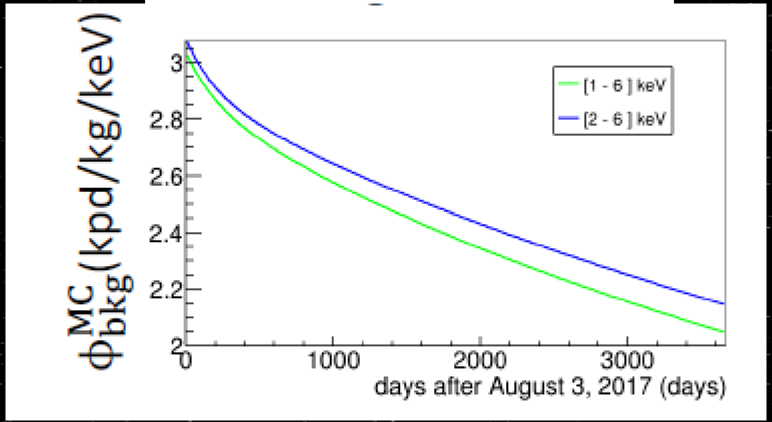
Three independent background modelling procedures

1. Exponentially decaying background -> τ, f, R_0 free param.

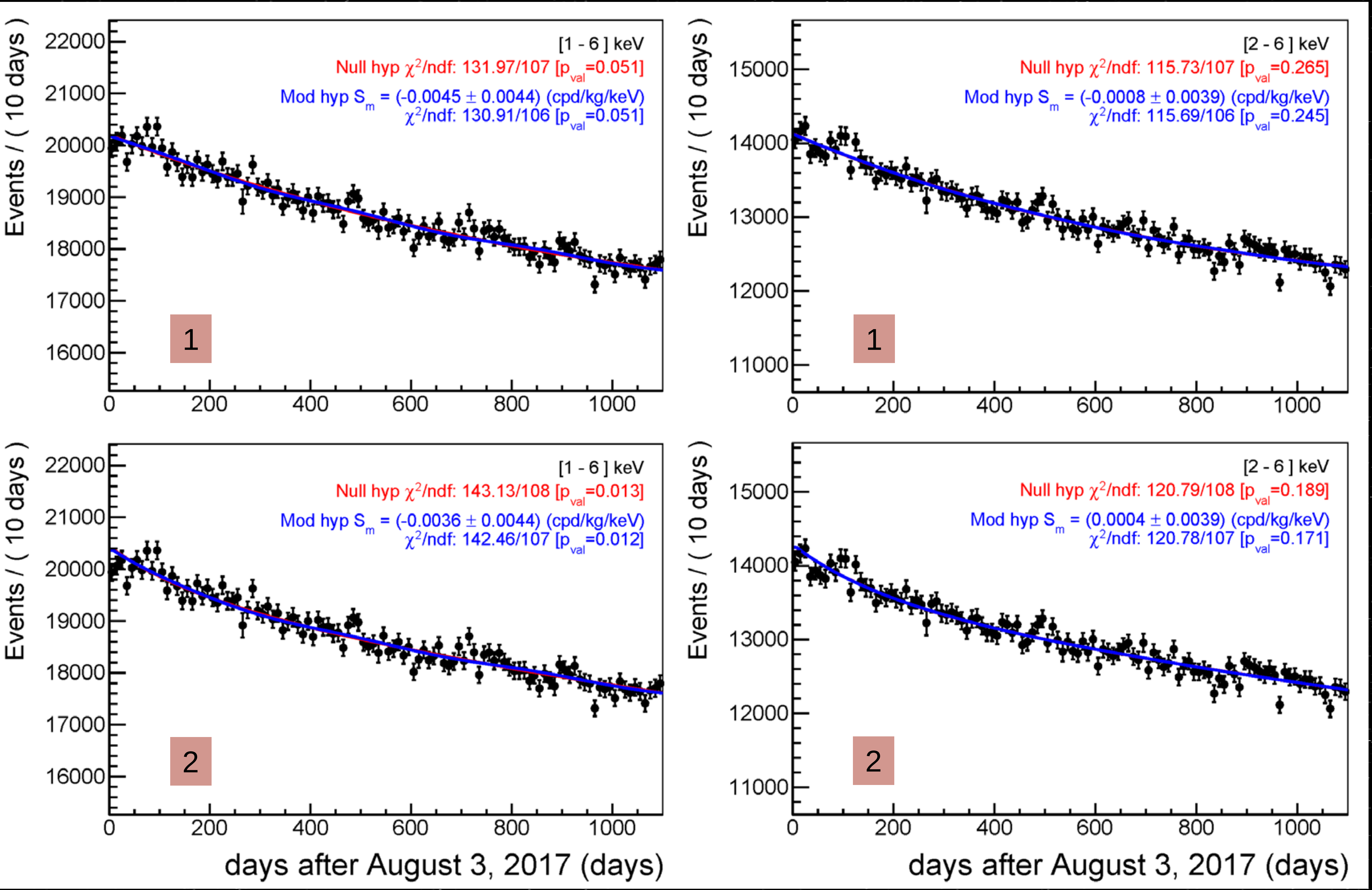
$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

2. Probability distribution function derived from background model corrected by a factor f and a constant term, R_0, both free

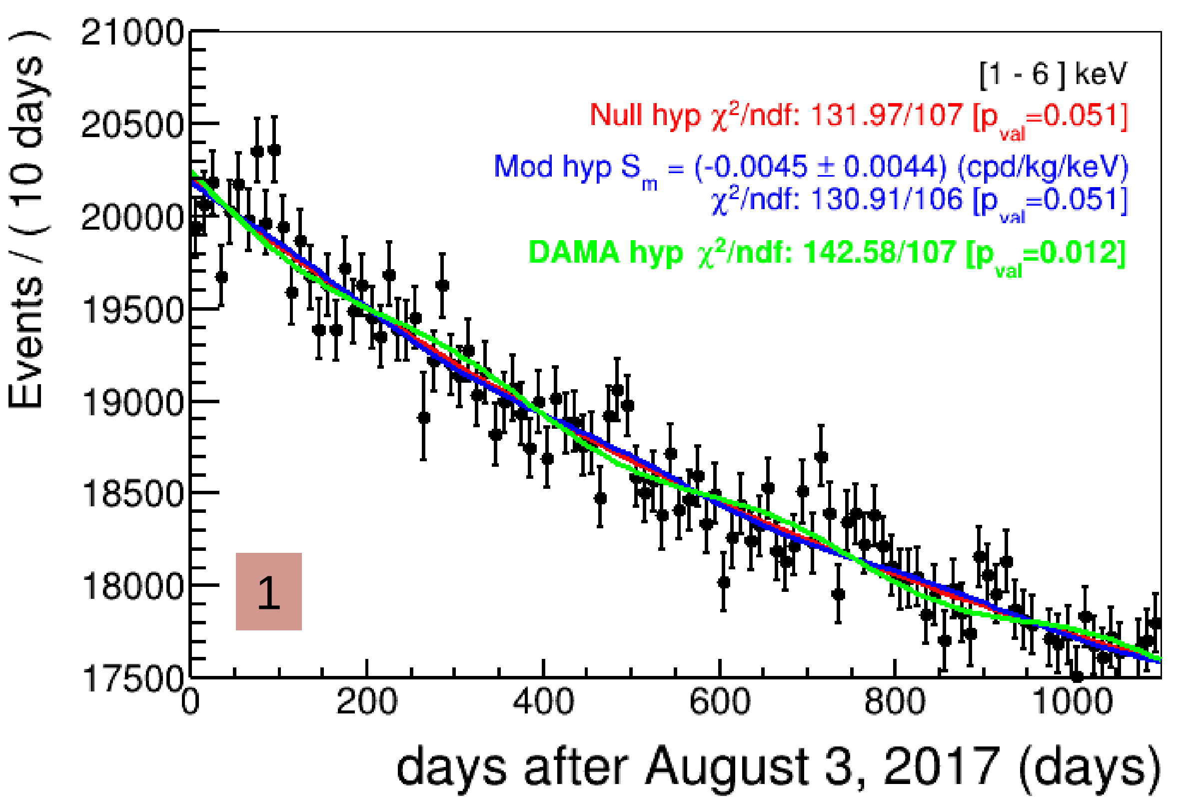
$$\phi_{bkg}(t_i) = 1 + f\phi_{bkg}^{MC}(t_i)$$

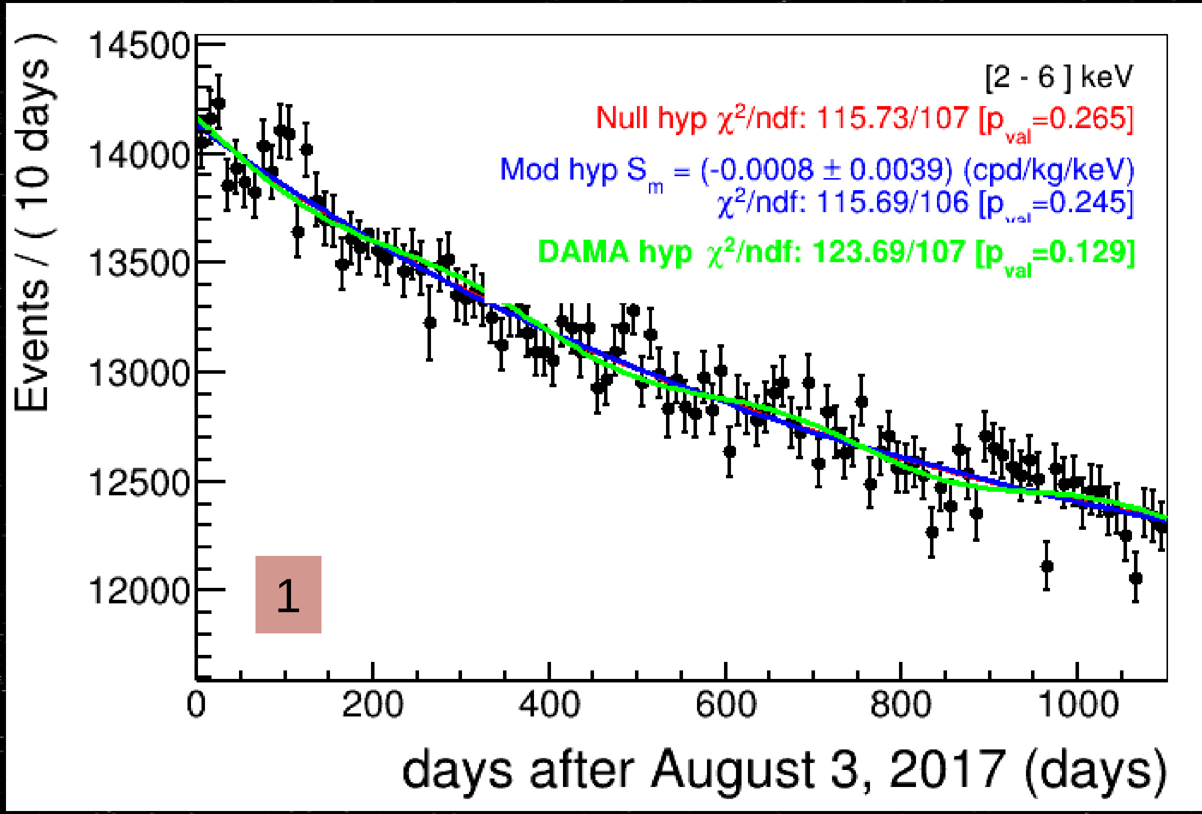


$$\mu_i = [R_0\phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))]M\Delta E\Delta t$$


[1 - 6] keV
Null hyp χ2/ndf: 131.97/107 [pval=0.051]
Mod hyp Sm = (-0.0045 ± 0.0044) (cpd/kg/keV)
χ2/ndf: 130.91/106 [pval=0.051]
1
[2 - 6] keV
Null hyp χ2/ndf: 115.73/107 [pval=0.265]
Mod hyp Sm = (-0.0008 ± 0.0039) (cpd/kg/keV)
χ2/ndf: 115.69/106 [pval=0.245]
1
[1 - 6] keV
Null hyp χ2/ndf: 143.13/108 [pval=0.013]
Mod hyp Sm = (-0.0036 ± 0.0044) (cpd/kg/keV)
χ2/ndf: 142.46/107 [pval=0.012]
2
[2 - 6] keV
Null hyp χ2/ndf: 120.79/108 [pval=0.189]
Mod hyp Sm = (0.0004 ± 0.0039) (cpd/kg/keV)
χ2/ndf: 120.78/107 [pval=0.171]
2
Events / (10 days)
days after August 3, 2017 (days)

ANAIS-112 vs DAMA/LIBRA





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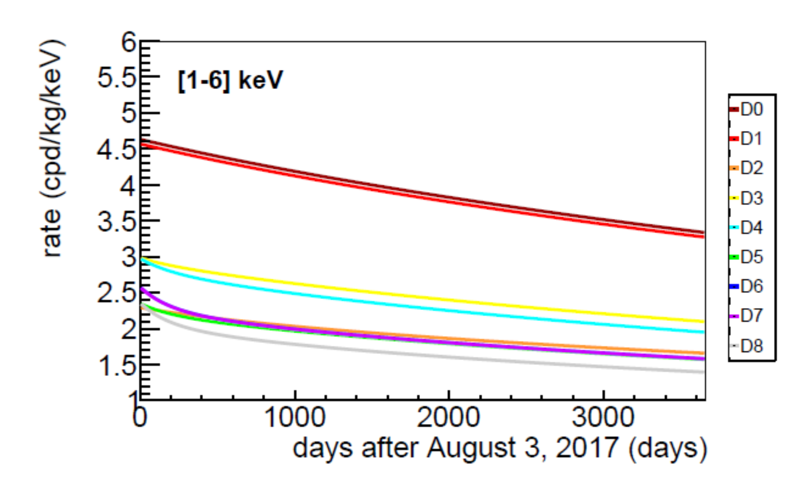
2. Probability distribution function derived from background model corrected by a factor f and a constant term, R_0, both free

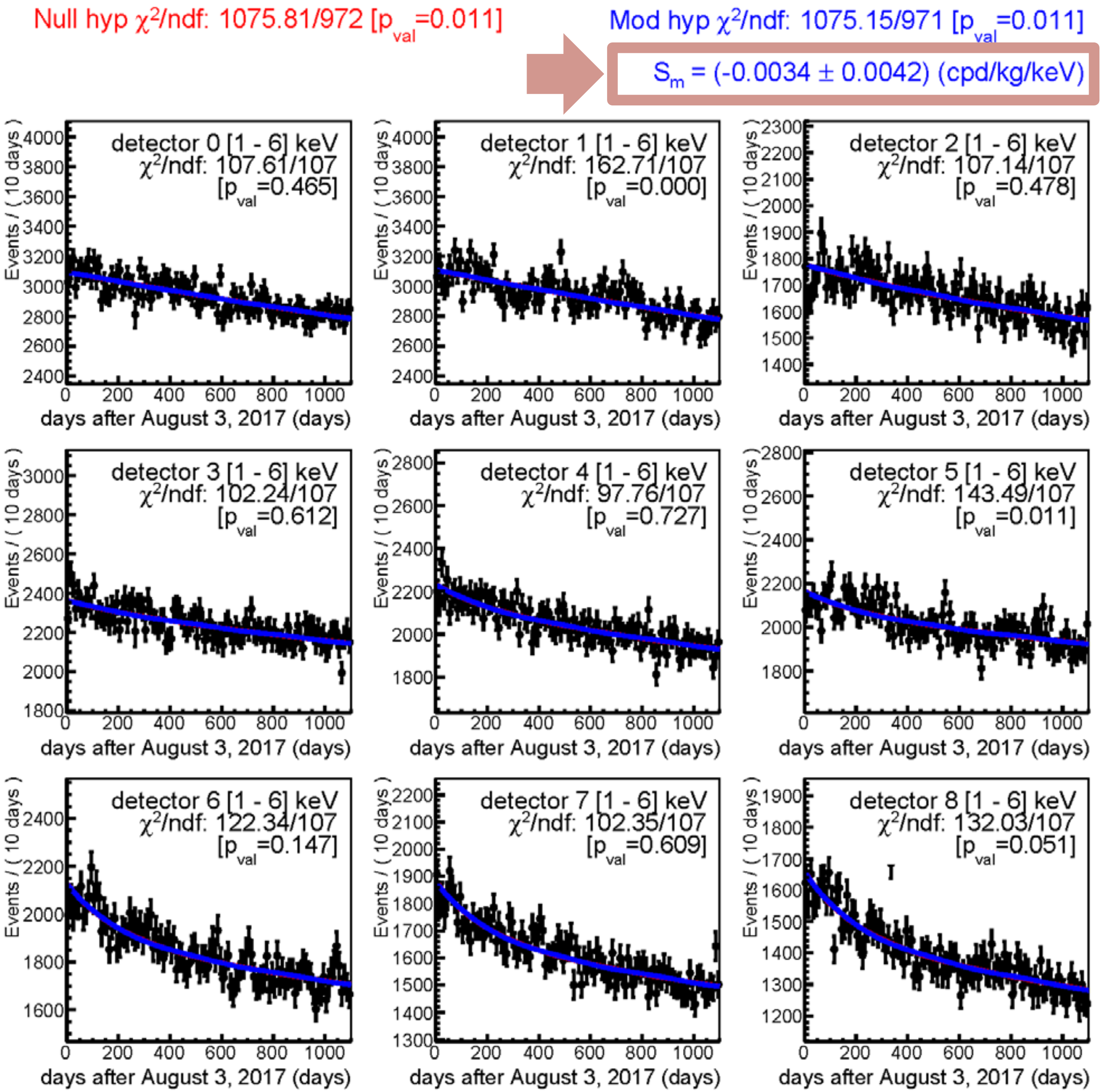
$$\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$$

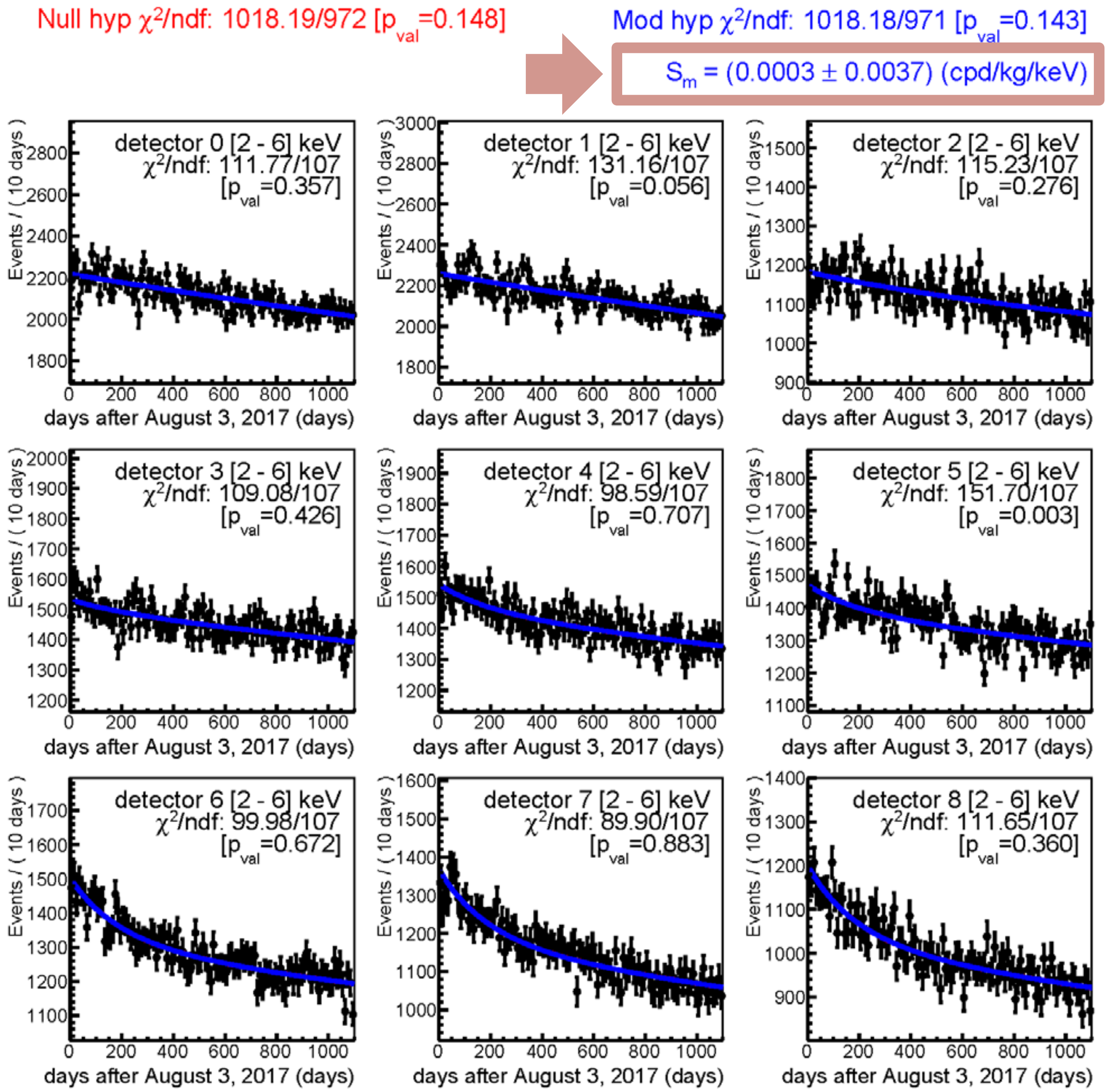
$$\mu_i = [R_0 \phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))] M \Delta E \Delta t$$

3. Probability distribution function for every detector to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules

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




Null hyp χ2/ndf: 1075.81/972 [pval=0.011]
Mod hyp χ2/ndf: 1075.15/971 [pval=0.011]
Sm = (-0.0034 ± 0.0042) (cpd/kg/keV)
detector 0 [1 - 6] keV χ2/ndf: 107.61/107 [pval=0.465]
detector 1 [1 - 6] keV χ2/ndf: 162.71/107 [pval=0.000]
detector 2 [1 - 6] keV χ2/ndf: 107.14/107 [pval=0.478]
detector 3 [1 - 6] keV χ2/ndf: 102.24/107 [pval=0.612]
detector 4 [1 - 6] keV χ2/ndf: 97.76/107 [pval=0.727]
detector 5 [1 - 6] keV χ2/ndf: 143.49/107 [pval=0.011]
detector 6 [1 - 6] keV χ2/ndf: 122.34/107 [pval=0.147]
detector 7 [1 - 6] keV χ2/ndf: 102.35/107 [pval=0.609]
detector 8 [1 - 6] keV χ2/ndf: 132.03/107 [pval=0.051]
Events / (10 days)
days after August 3, 2017 (days)


Null hyp χ2/ndf: 1018.19/972 [pval=0.148]
Mod hyp χ2/ndf: 1018.18/971 [pval=0.143]
Sm = (0.0003 ± 0.0037) (cpd/kg/keV)
detector 0 [2 - 6] keV χ2/ndf: 111.77/107 [pval=0.357]
detector 1 [2 - 6] keV χ2/ndf: 131.16/107 [pval=0.056]
detector 2 [2 - 6] keV χ2/ndf: 115.23/107 [pval=0.276]
detector 3 [2 - 6] keV χ2/ndf: 109.08/107 [pval=0.426]
detector 4 [2 - 6] keV χ2/ndf: 98.59/107 [pval=0.707]
detector 5 [2 - 6] keV χ2/ndf: 151.70/107 [pval=0.003]
detector 6 [2 - 6] keV χ2/ndf: 99.98/107 [pval=0.672]
detector 7 [2 - 6] keV χ2/ndf: 89.90/107 [pval=0.883]
detector 8 [2 - 6] keV χ2/ndf: 111.65/107 [pval=0.360]
Events / (10 days)
days after August 3, 2017 (days)

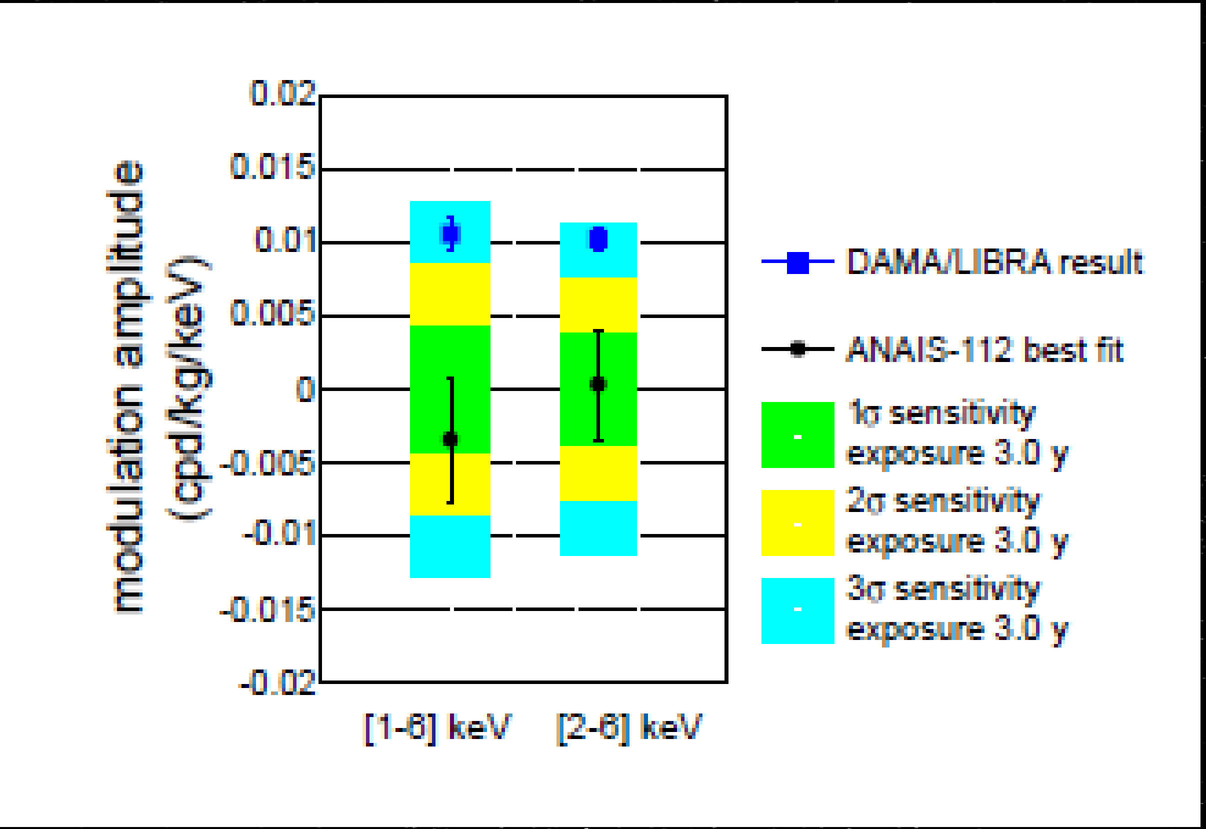
ANAIS-112 three year results – annual modulation analysis

- Data support the absence of modulation in both energy regions and three background models / All of them provide compatible 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

- Results of the third approach for bckg modelling show slightly lower σ(Sm), as expected, is taken for the comparison with DAMA/LIBRA

ANAIS-112 three year results – annual modulation analysis

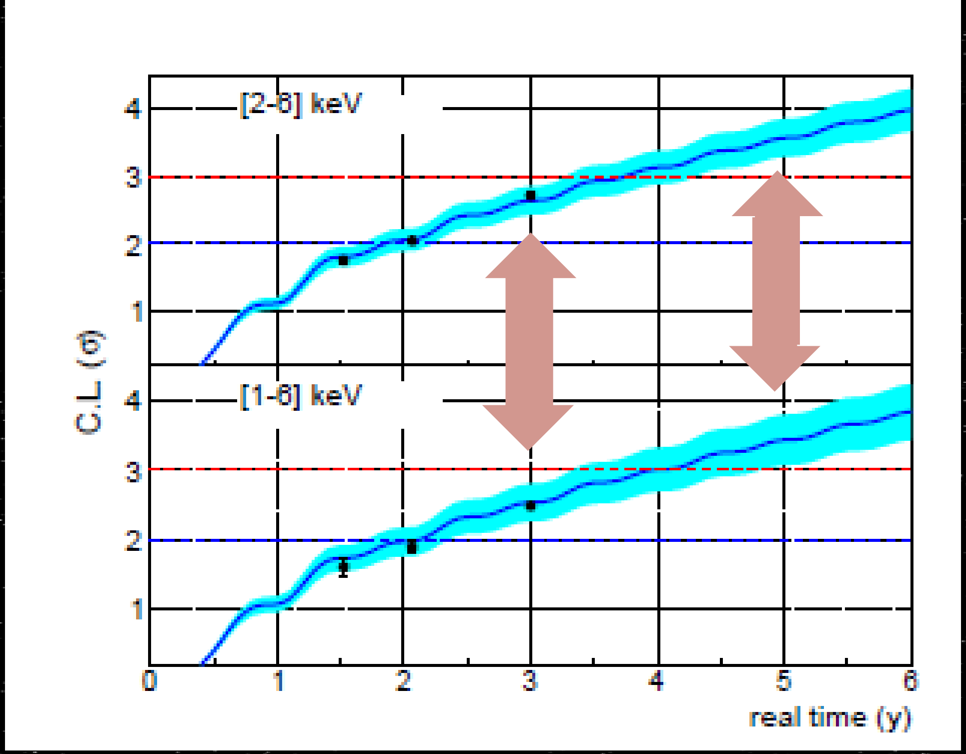


- Best fits are incompatible with DAMA/LIBRA result at 3.3 and 2.6 σ in [1-6] and [2-6] keV energy regions

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

ANAIS-112 three year results – annual modulation analysis

Sensitivity prospects:
I. Coarasa et al., EPJC79 (2019) 233



- **Full agreement with our "a priori" sensitivity estimates**
- **We should be well at 3σ from DAMA/LIBRA result within the scheduled 5 years of data taking**

Statistical significance of our result is determined by the standard deviation of the modulation amplitude distribution, σ(Sm)

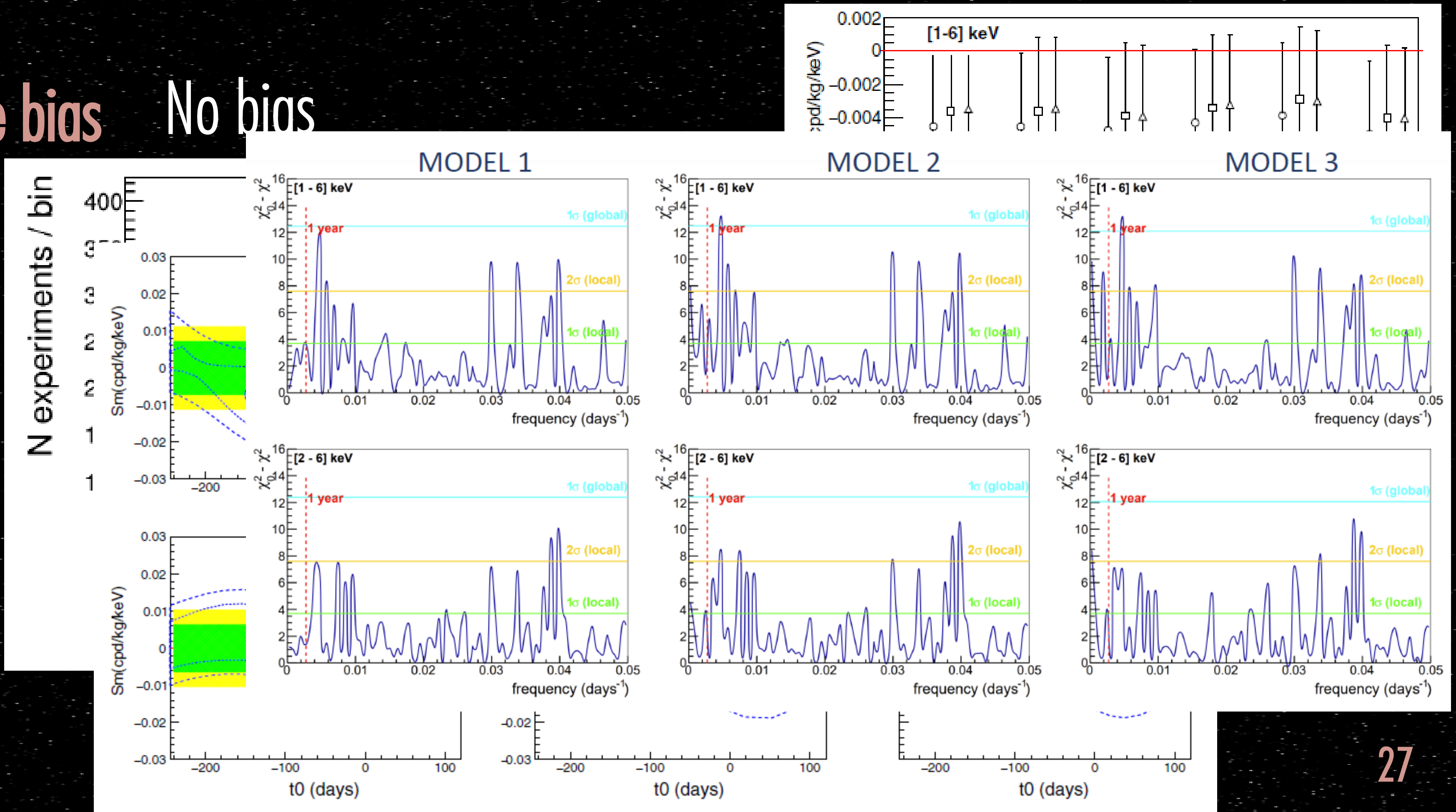
We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA} / \sigma(Sm)$

We project our sensitivity with our updated background, efficiency estimates and its errors and live time distribution

ANAIS-112 three year results – annual modulation analysis
Consistency Checks

- Time binning -> checked bin sizes from 5 to 30 days   Negligible effect
- Toy MC to check possible bias   No bias
- 1-2 years / 2-3 years

  Compatible results



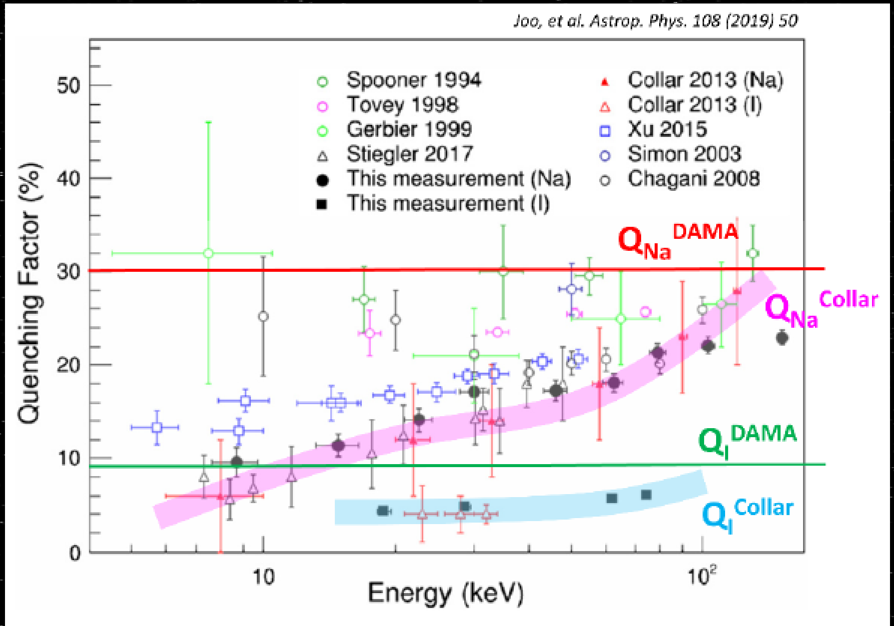
Phase-free analysis
Frequency analysis

Corollary

Is this a "MODEL INDEPENDENT" testing of DAMA/LIBRA result?

Using same target material the comparison between DAMA/LIBRA and ANAIS results is DIRECT

However, response of both detectors to the energy depositions from dark matter particles could be different -> improve knowledge on RESPONSE FUNCTION, specially for nuclear recoils



Scintillation produced by nuclear recoils is quenched with respect to electron recoils (used for calibration)

Today still too many uncertainties in the QF values and dependences for NaI

We have measured QF for different crystals in similar conditions, work is in progress, but results will appear soon

We are also working in direct calibrations with neutrons "onsite"

Summary and Outlook

- **ANAIS-112 is** taking data using **112.5 kg of sodium iodide at LSC** and is running smoothly
  - Careful **low energy calibration** (from external gamma sources and bulk emissions)
  - Excellent **light collection** of **~15 phe/keV** and **triggering** below **1 keV_{ee}** in all modules
  - **1 keV_{ee} analysis threshold**
  - Good **background understanding (but in 1-2 keV energy region)**, ROI bkg dominated by crystal activity (^{210}Pb, ^{40}K, ^{22}Na, ^{3}H)
- **3 years of data** blind - analysed **for model independent annual modulation**
  - We confirm our sensitivity projections to DAMA/LIBRA result -> 3σ at reach in 2022
  - Null hypothesis is well supported and best fits are incompatible at 3.3σ (1-6 keV energy region) and 2.7σ (2-6 keV energy region) with DAMA/LIBRA results → sensitivity: $2.5 – 2.7\sigma$
- We are analysing **quenching factor on NaI crystals** to discard systematic uncertainties in the comparison
- Plan to make ANAIS **data public** after use to allow independent analysis