Three years annual modulation results from ANAIS-112 experiment

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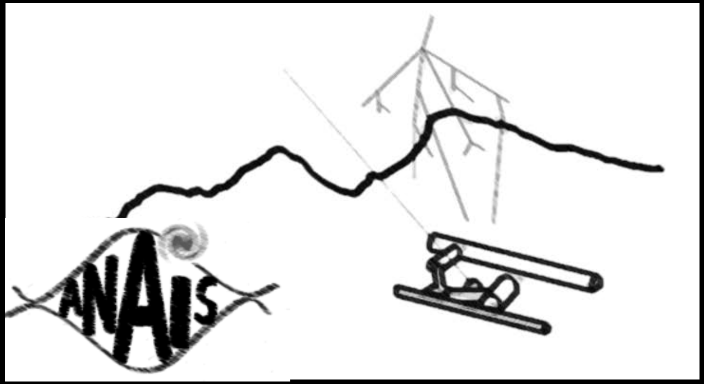
10 May 2021
EPAP Seminar



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OUTLINE

-ANNUAL MODULATION in direct dark matter searches

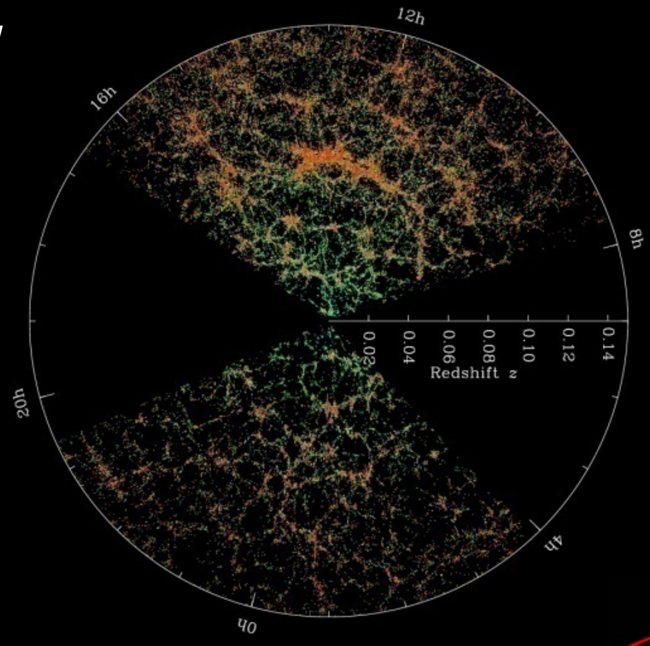
-DAMA/LIBRA POSITIVE SIGNAL AND STATUS OF TESTING

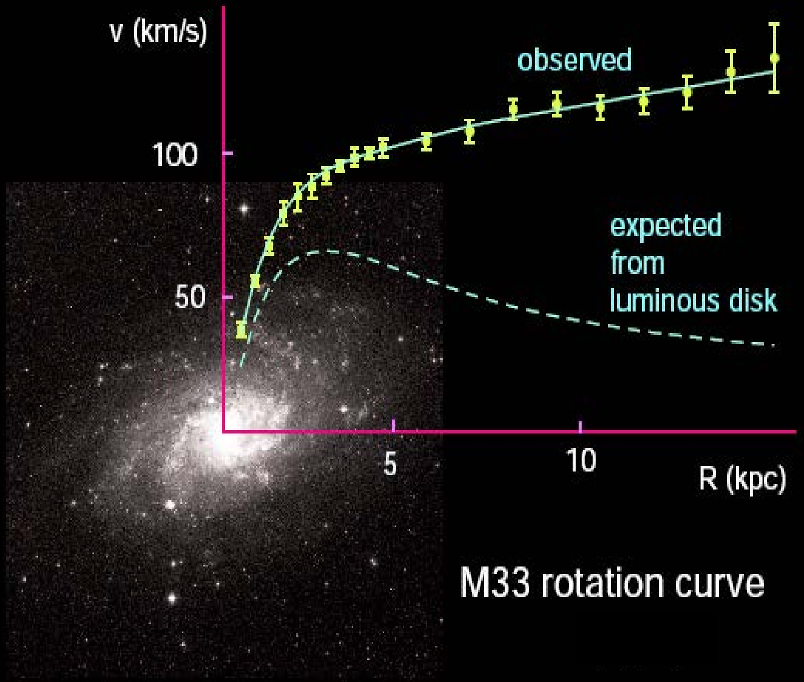
-ANAIS-112 EXPERIMENT

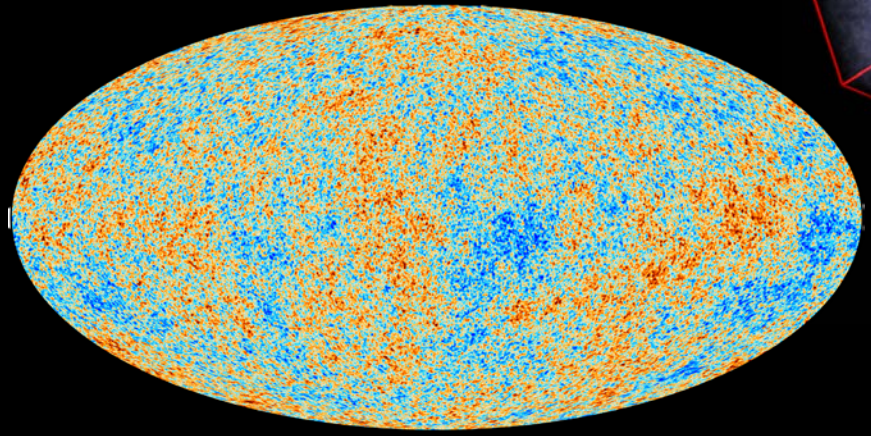
-ANAIS-112 UPDATED ANNUAL MODULATION RESULTS FOR THREE YEARS

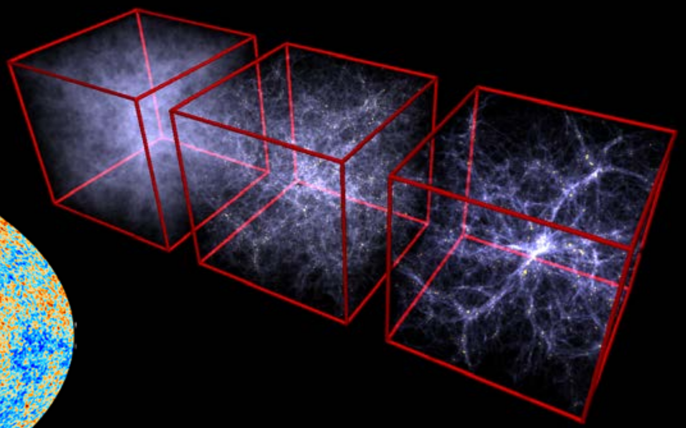
J. Amaré et al., arXiv: 2103.01175
Accepted for publication in Phys. Rev. D

Dark Matter evidences come from very different observational techniques at different scales and times of the Universe history

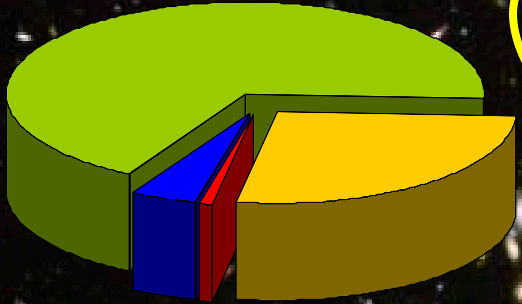


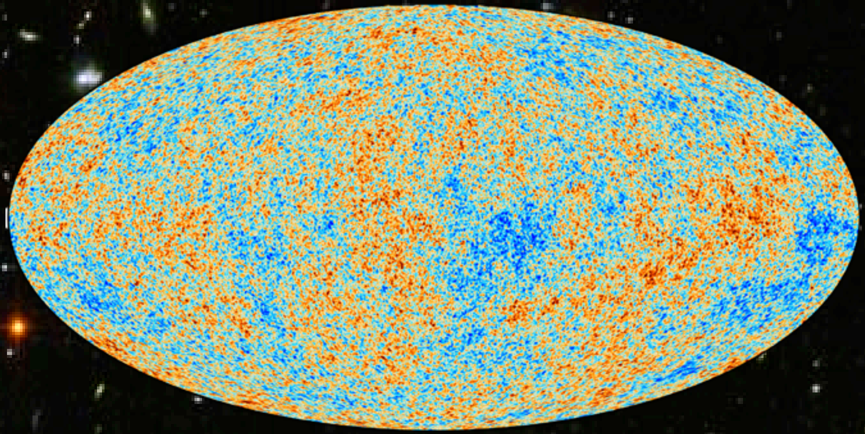






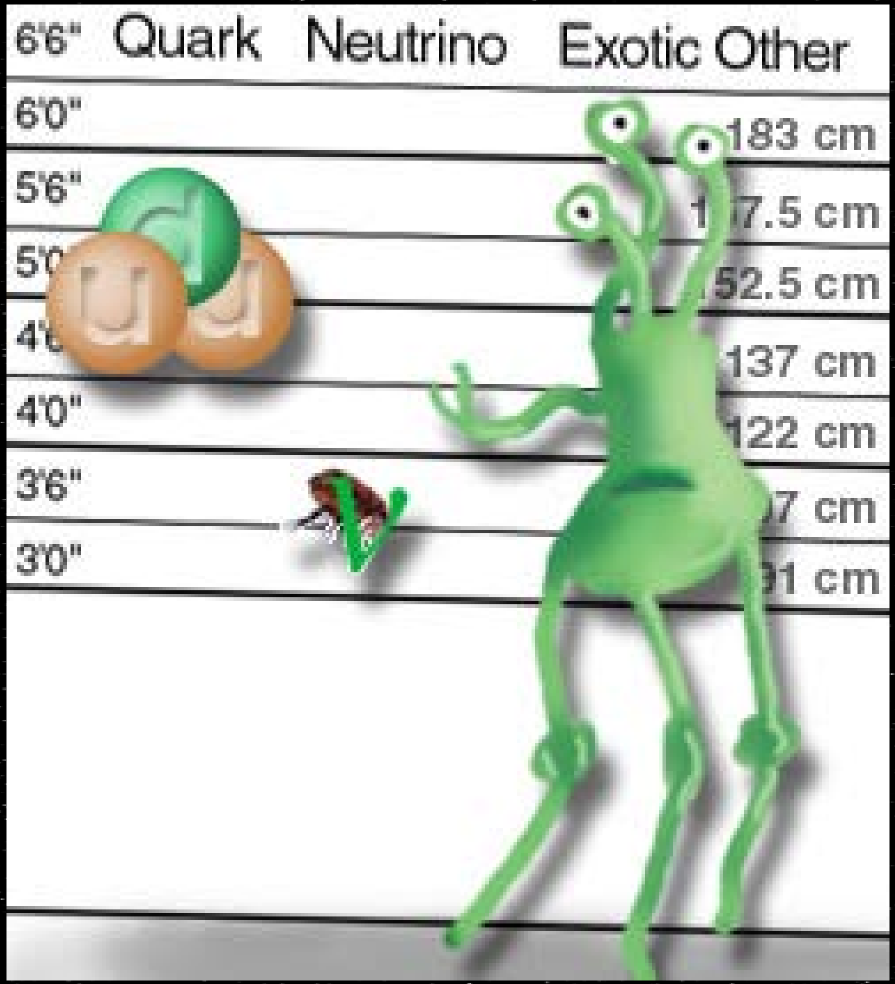
$\Omega \sim 1$





ΛCDM cosmology has been impressively succesful explaining the observations …

Unambiguous proof of the particle nature of dark matter is still lacking
Particle Dark Matter arises because of the limited baryon budget: light nuclei abundances, CMB isotropy, Large Scale Structure formation, …

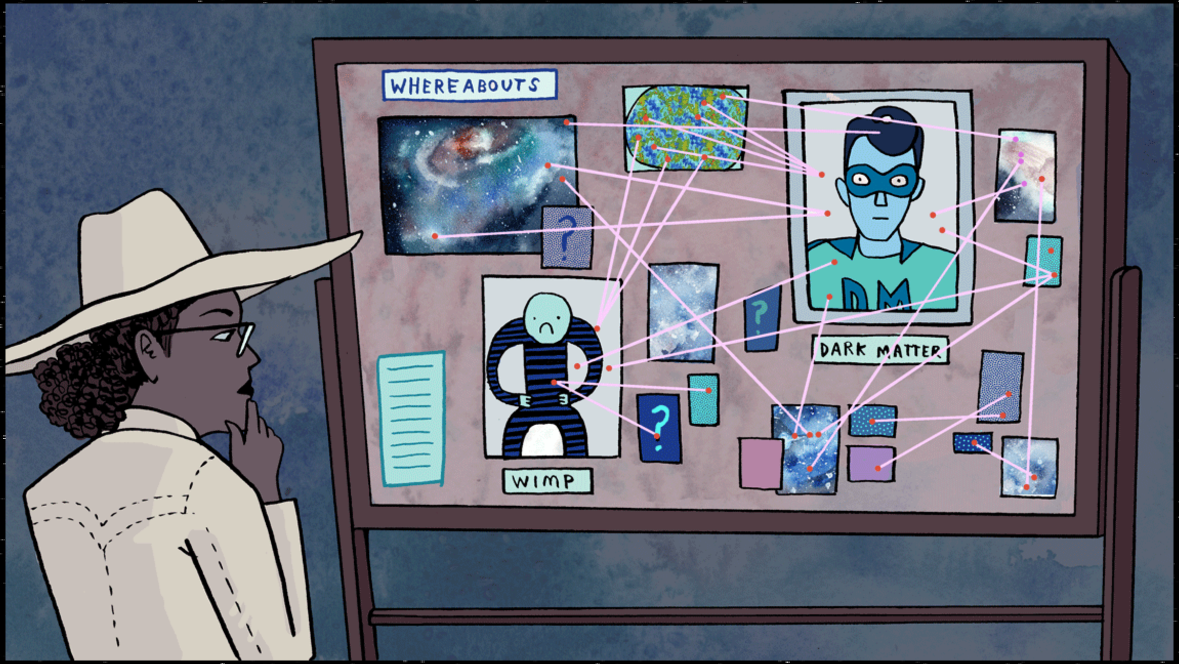


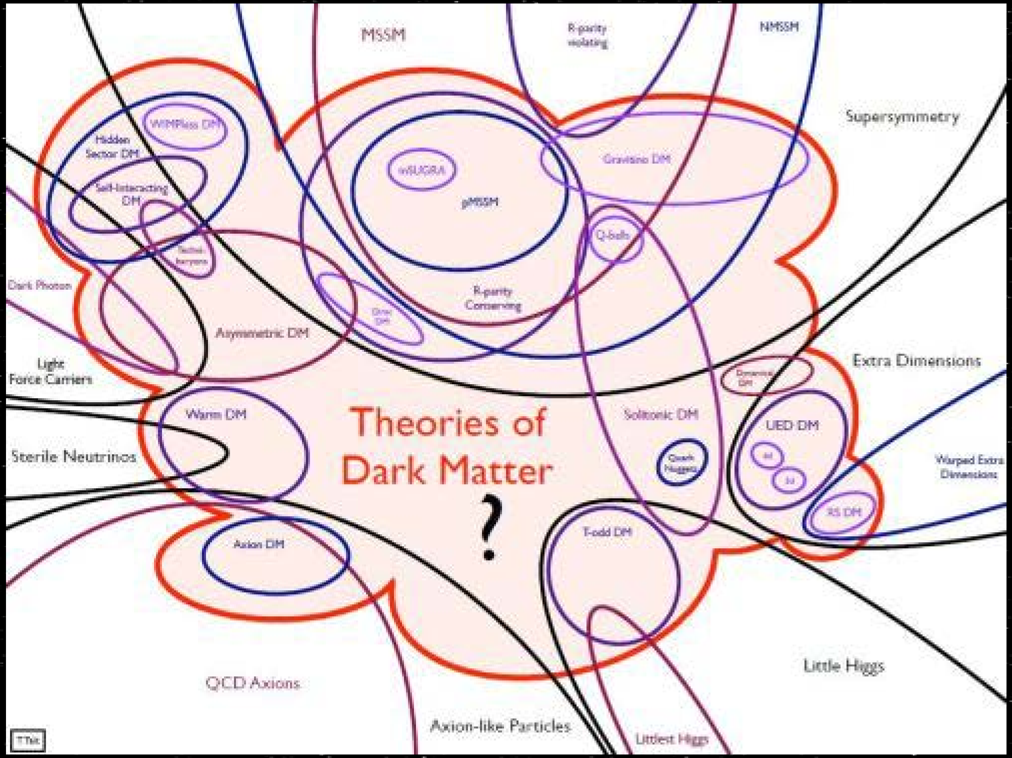
- massive
- non-baryonic
- neutral / millicharged
- stable or very long lived
- non relativistic when structures formed (cold / warm dark matter)

Beyond the Standard Model of Particle Physics

Many DM candidates are on scene

Covering many orders of magnitude in mass and cross section



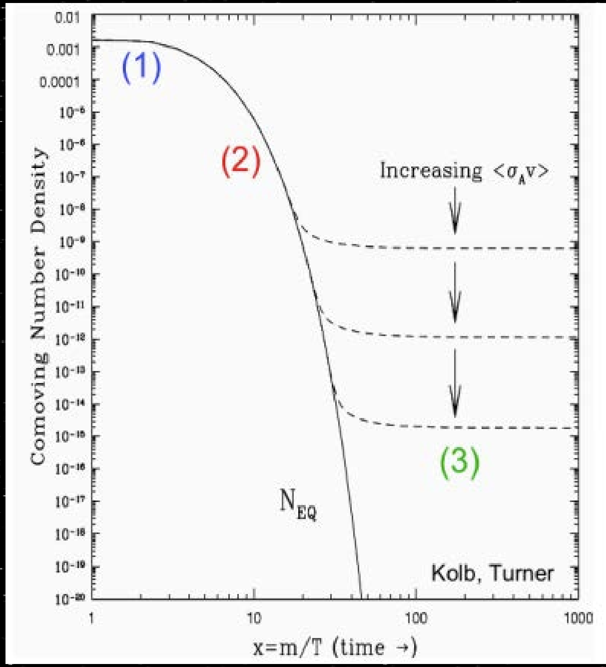


Best motivated candidates arise to solve other problems …

WIMPs are convenient DM candidates:

Weakly Interacting Massive Particles

If DM particle was in thermal equilibrium in the early Universe, at freeze-out the annihilation cross-section determined the relic abundance, Ω_m

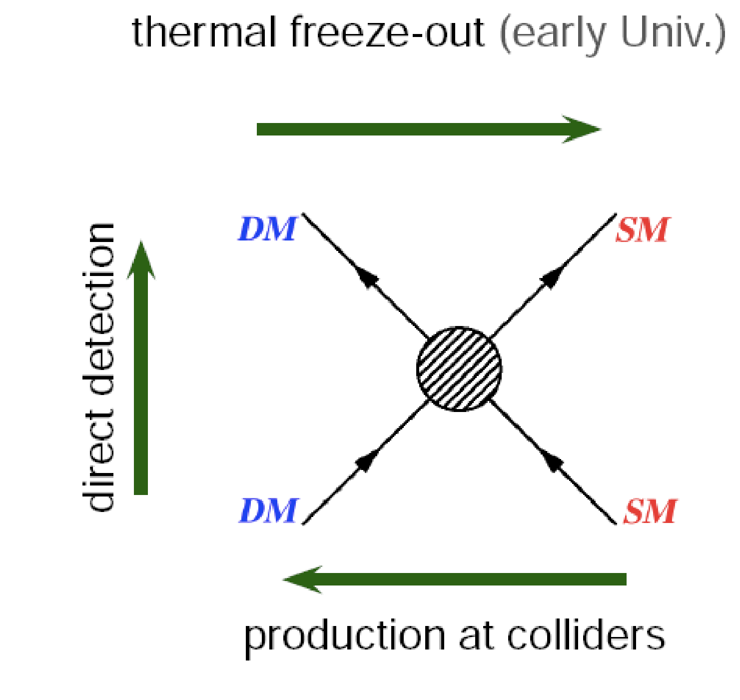


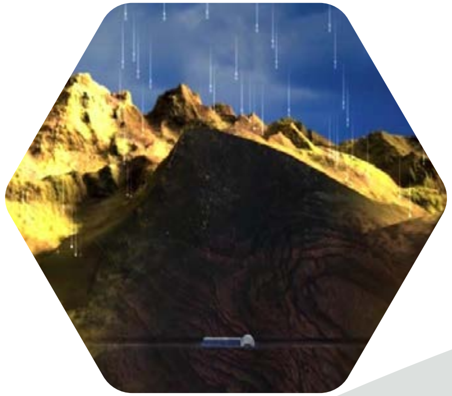
WIMP MIRACLE

Electroweak scale cross-sections for a GeV particle reproduce reasonably the measured relic Ω_m

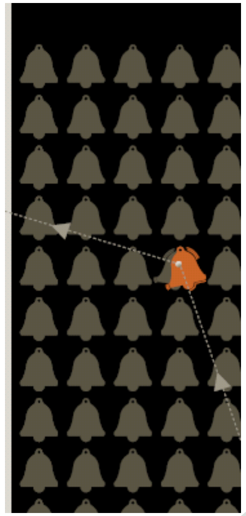
WIMP DETECTION

WIMP detection can be envisaged —> Direct and Indirect Detection Approach



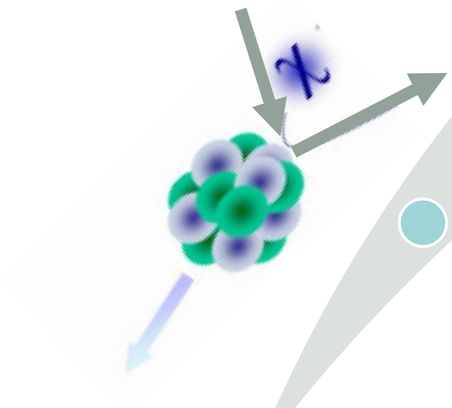


Analysis of signatures of DM particle interactions are key for a positive result



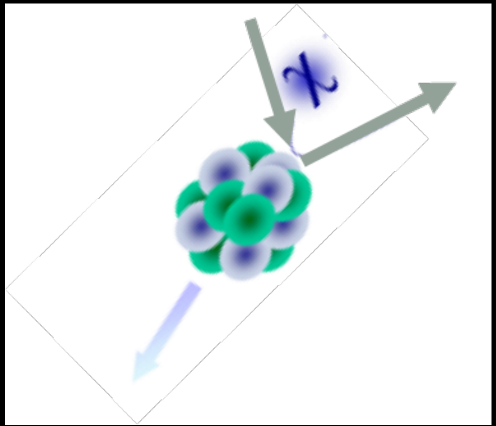
Experiments have to be shielded against all possible backgrounds and profit from active bckg rejection techniques

Availability of very sensitive & radiopure particle detectors



DM particles interact (although weakly) with ordinary matter

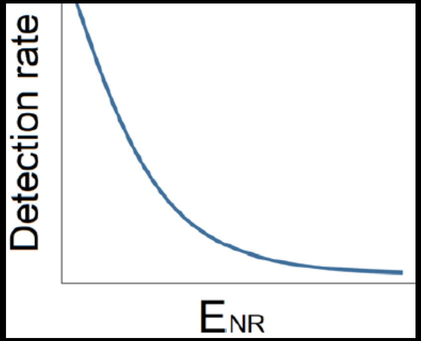
WIMP interaction rate



WIMPs interact weakly with ordinary matter

Small transfer of energy in form of nuclear recoil energy is expected as result by elastic (or inelastic) scattering

Interaction rate depends on the specific WIMP (m_W and σ_{WN}) and halo model (dark halo mass density, WIMP velocity distribution at the Solar System position)



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

Which could be the interaction mechanism?

WIMP interaction rate

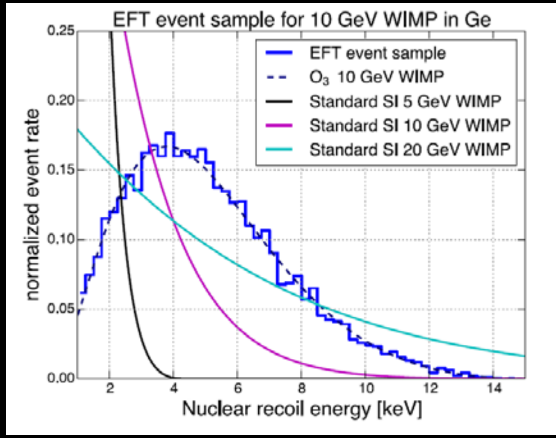
The most general case can be described by means of an Effective Field Theory

$$\mathcal{L}_{\text{int}} = \sum_{i=1,15} c_i \chi^* \mathcal{O}_\chi \chi \Psi_N^* \mathcal{O}_i \Psi_N$$

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

The scattering cross section is unknown and contains details from DM particle model and target nuclear structure

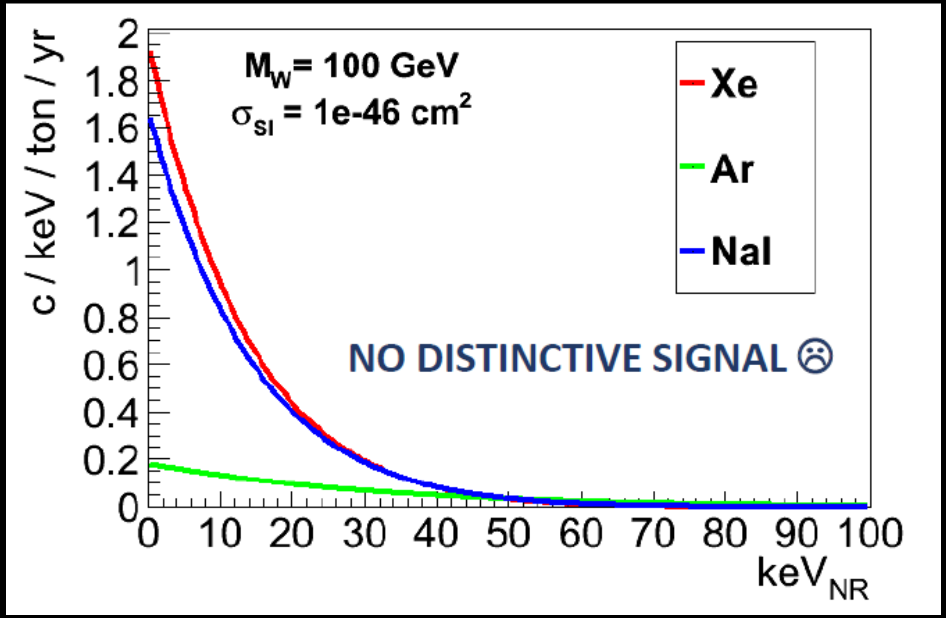
Interaction rate depends on the specific WIMP (m_W and σ_{WN}) and halo model (dark halo mass density, WIMP velocity distribution at the Solar System position)



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

WIMP interaction rate

For SI interacting WIMPs -> rate scale with target nucleus mass, but no distinctive energy spectrum is expected -> difficult to disentangle from backgrounds

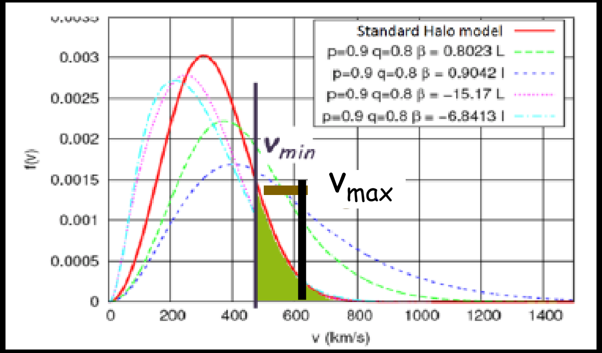


Easy to scale

$$\sigma_{SI} \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 F^2 \sigma^0_{SI-nucleon}$$

Easy to apply to compare exp.

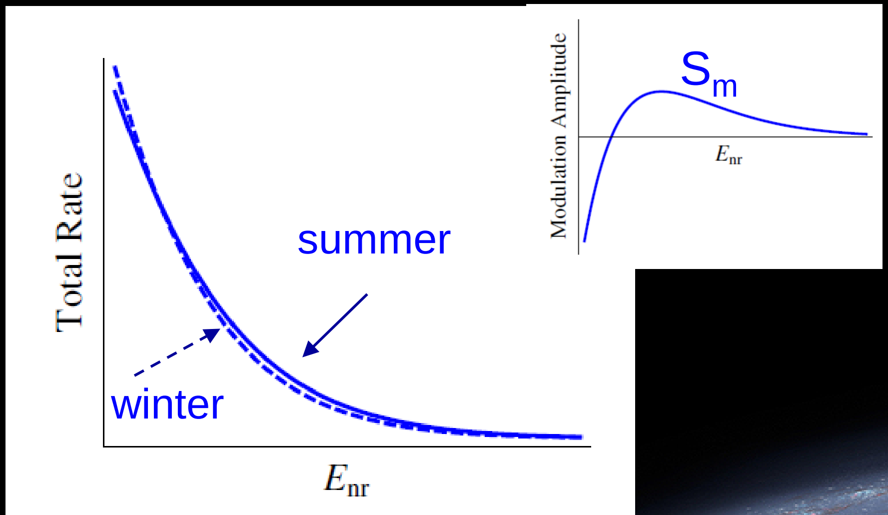
Same arguments for the halo model:
Standard halo model (maxwellian distr.) easy to compare



$$v_{min} = \sqrt{\frac{m_N E_{th}}{2M_{WN}^2}}$$

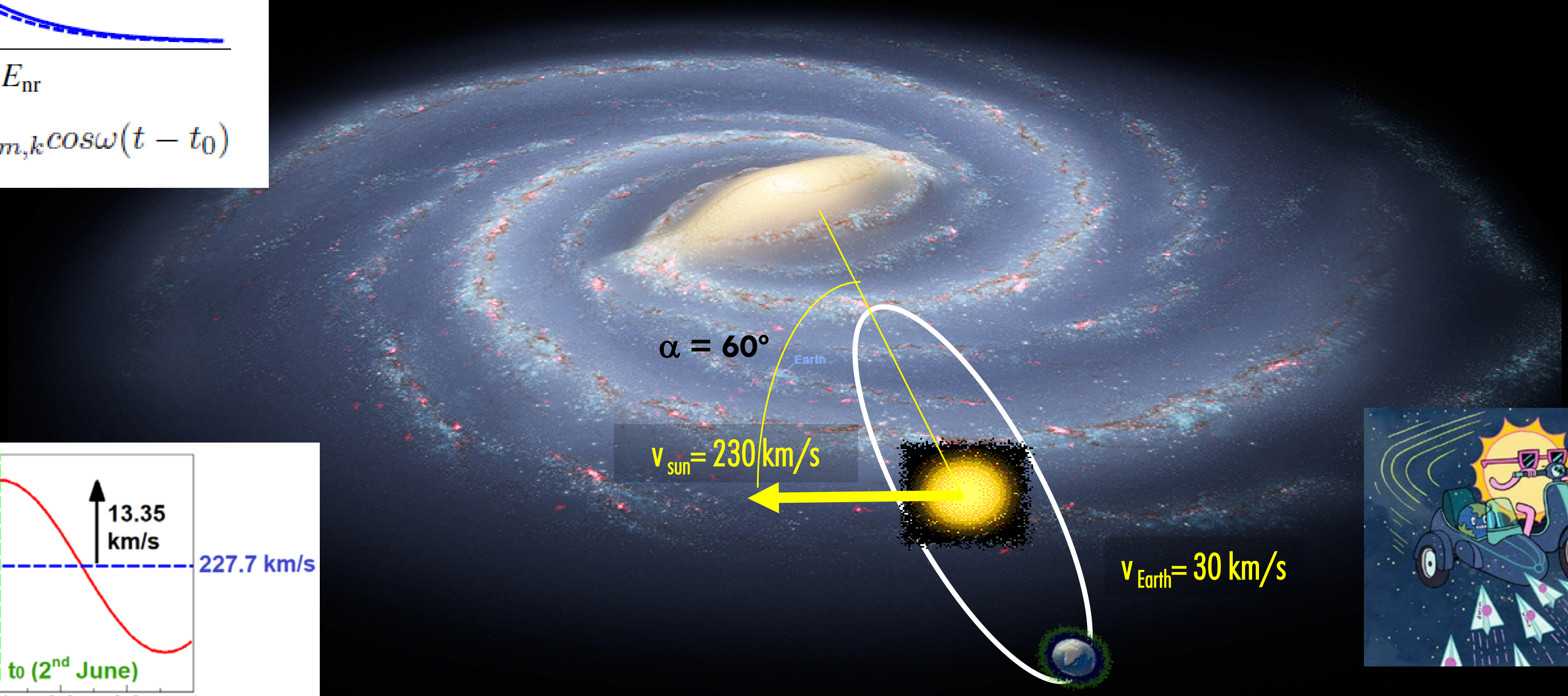
$$S(E_{NR}) = \frac{dR}{dE_{NR}} = \frac{\rho\, M_{det}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v}\, \sigma_{WN}\, dv^3$$

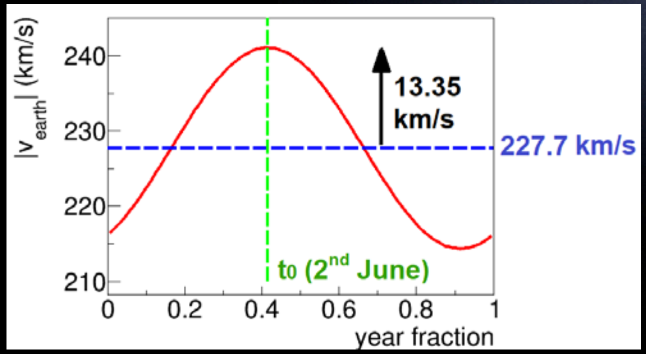
Annual modulation in dark matter interaction rate



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

Dark matter halo





Relative velocity Earth – halo changes along the year

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

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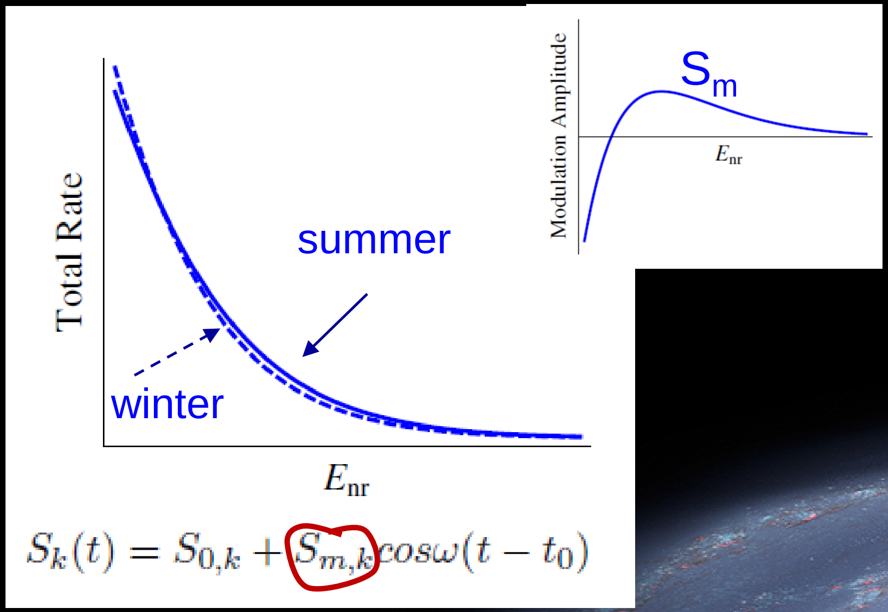
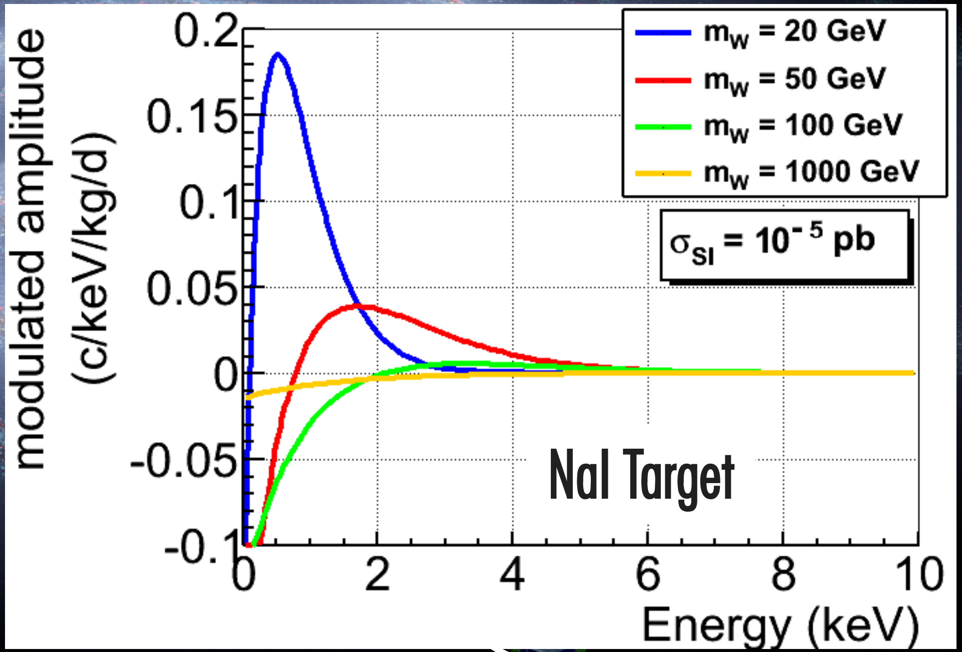


Dark matter halo

Small effect (<~7% of S_0)

Inverse modulation at very low energies

It depends strongly on the halo model

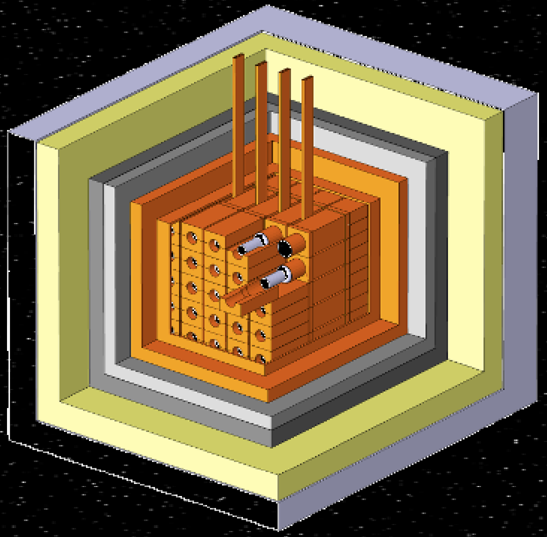


Relative velocity Earth – halo changes along the year

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

DAMA/LIBRA experiment

@ LNGS, Laboratori Nazionali del Gran Sasso, Italy



DAMA / NaI (1995-2002)

- 9 × 9.7 kg NaI(Tl) (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y

DAMA / LIBRA (2003-2010)

- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure : 1.04 ton × y

DAMA / LIBRA – phase2 (2011-2018)

- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure : 1.13 ton × y

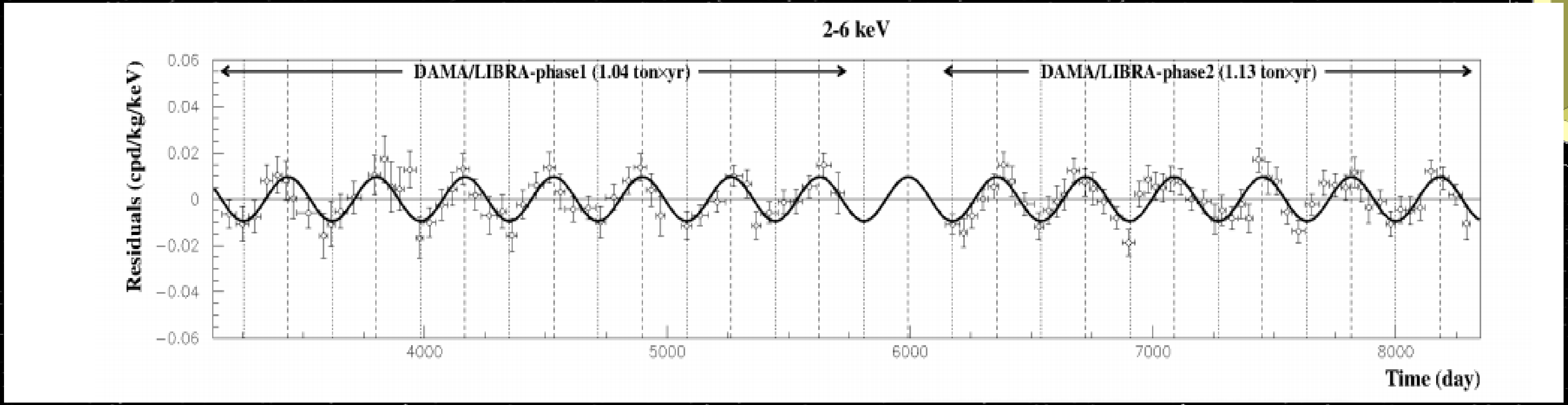
All PMTs replaced with new ones of higher Q.E.

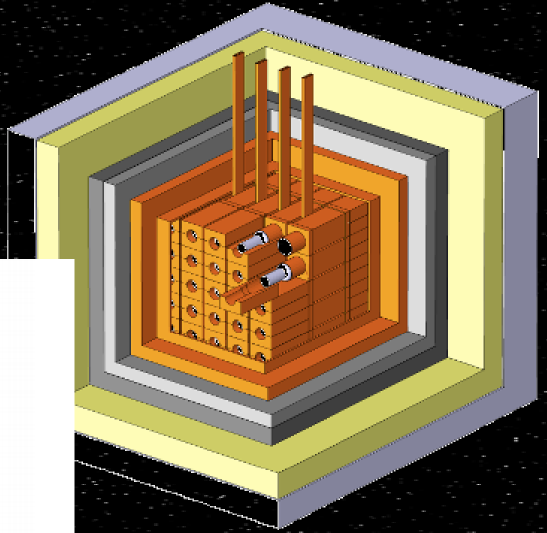
Last results release in March 2018

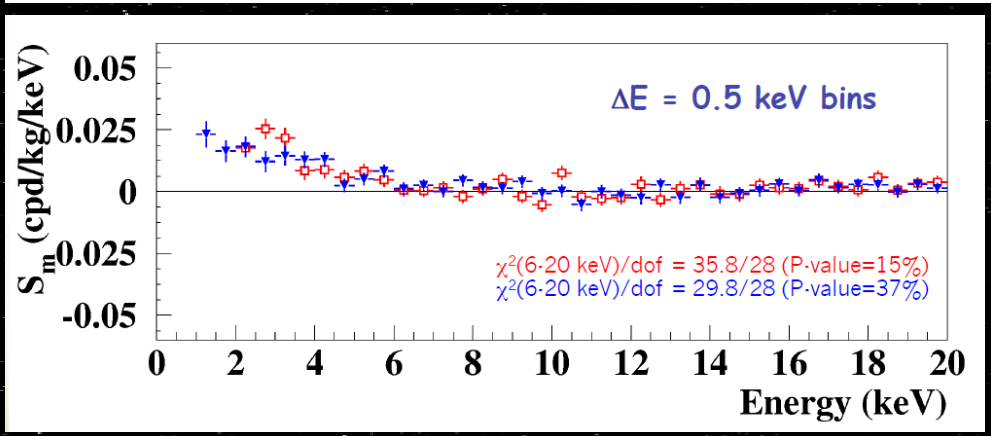
Universe 4, 116 (2018), 1805.10486

DAMA/LIBRA experiment

@ LNGS, Laboratori Nazionali del Gran Sasso, Italy







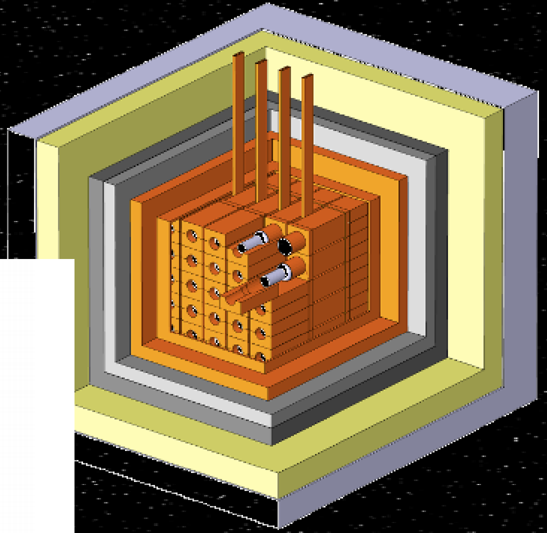
Universe 4, 116 (2018), 1805.10486

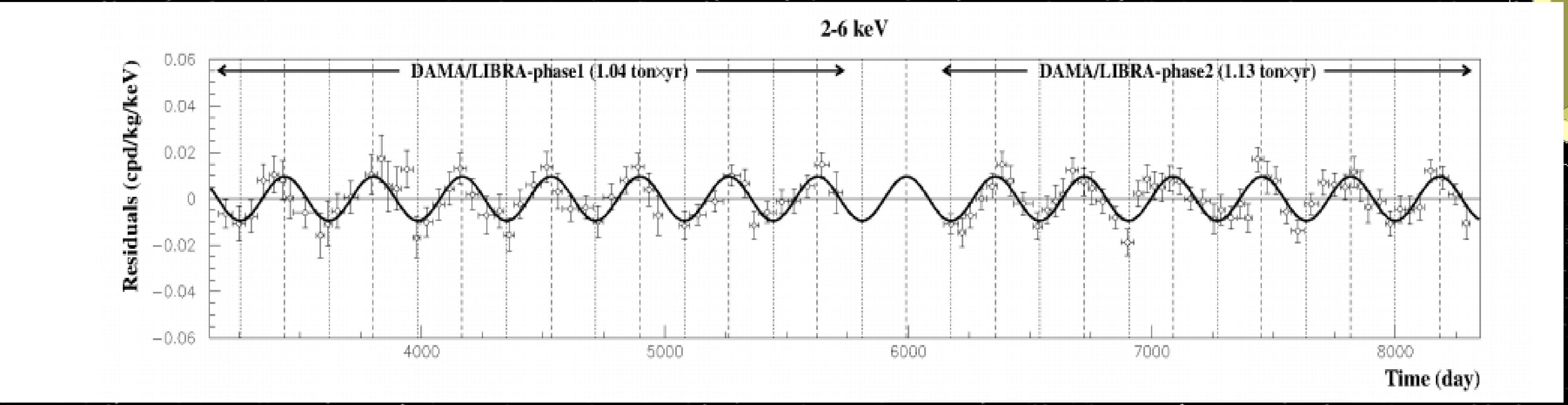
Progress in Particle and Nuclear Physics 114 (2020)

The data of DAMA/LIBRA favor the presence of a modulation with proper features at 12.9σ CL (2.46 ton × yr) in the 2-6 keV energy region

DAMA/LIBRA experiment

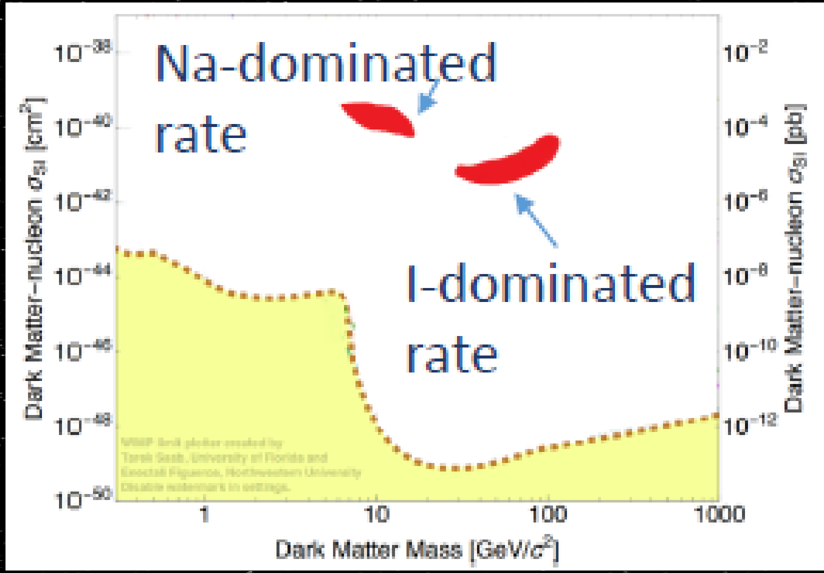
@ LNGS, Laboratori Nazionali del Gran Sasso, Italy





This signal can be interpreted as produced by WIMPs

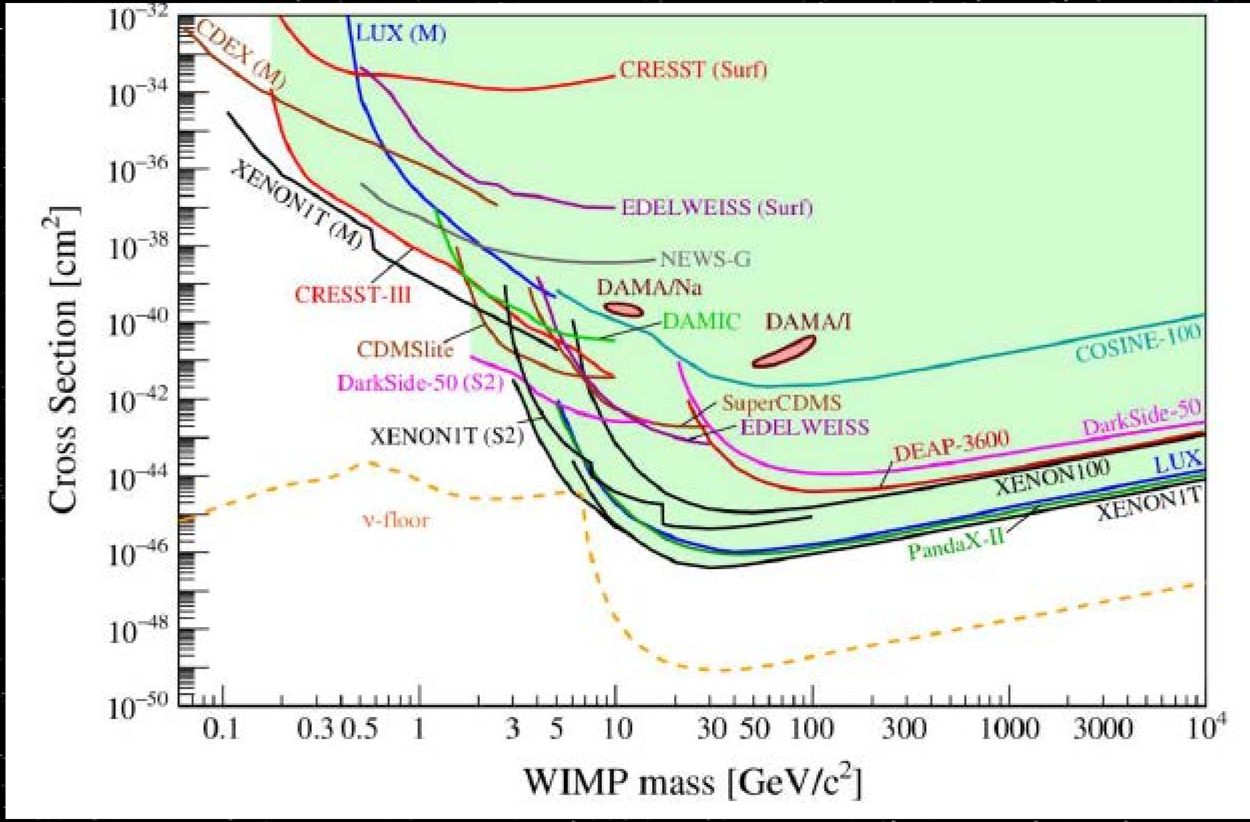
But …Model-dependent interpretation !



Only for the [2-6] keV data
SI - isospin conserving interacting WIMPs and standard halo
do not provide a solution compatible with [1-6] keV data

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

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



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

Experimental Situation

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

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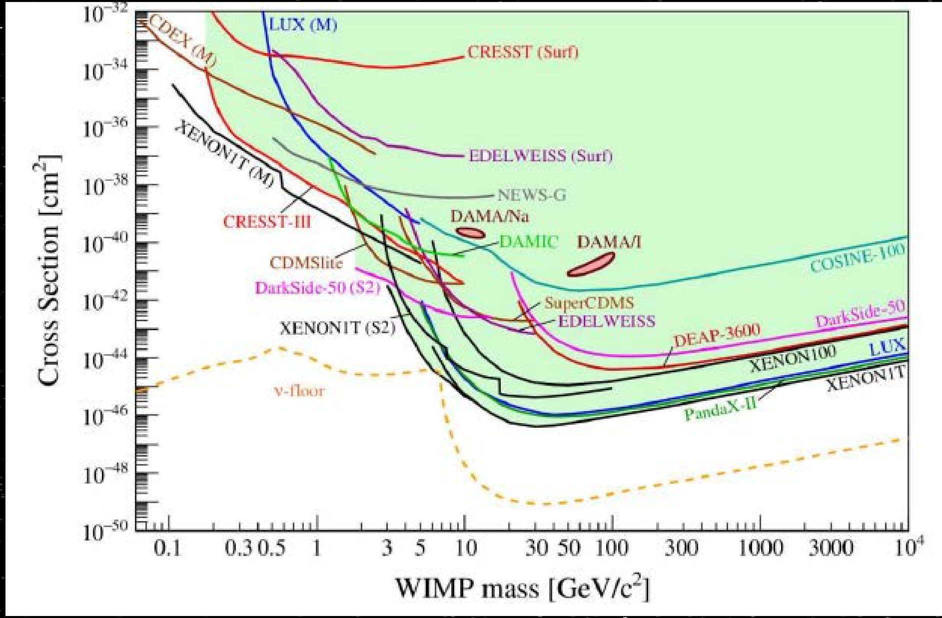


MODEL INDEPENDENT confirmation or refutation is mandatory → using same target

Can DAMA/LIBRA result be a door into new Physics or just systematics?

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

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

Model dependences are strongly reduced
BUT…
Good knowledge of detector response is mandatory

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

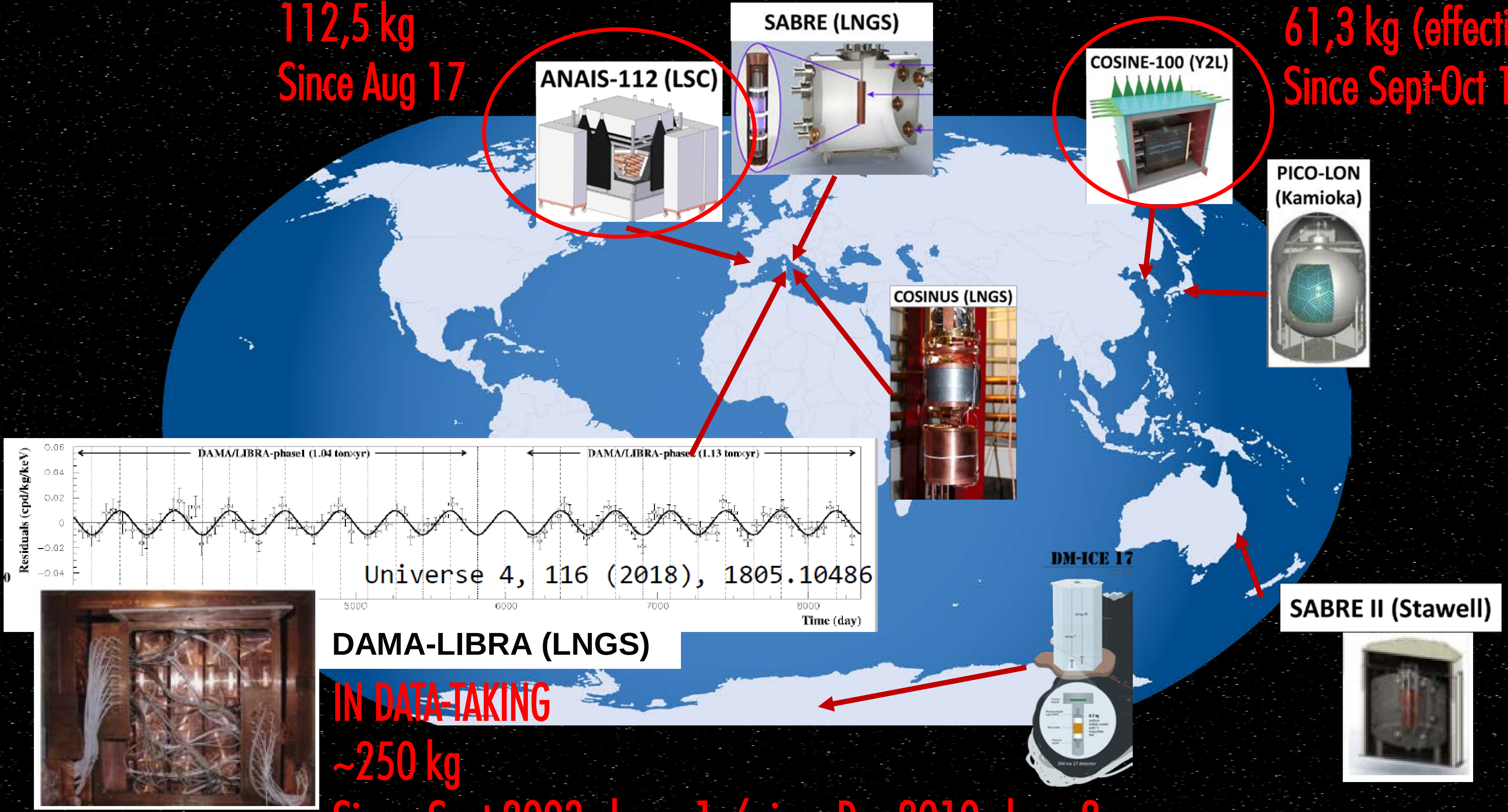
Experiment	Laboratory	Technology	Target	Size	Status
DAMA/LIBRA	LNGS	Scintillator	NaI(Tl)	~250 kg	Running
ANAIS-112	LSC	Scintillator	NaI(Tl)	112.5 kg	Running
COSINE-100	Yangyang	Scintillator	NaI(Tl)	106 kg	Running
SABRE	LNGS,Stawell	Scintillator	NaI(Tl)	~50 kg	In preparation
PICOLON	Kamioka	Scintillator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

MODEL INDEPENDENT confirmation or refutation is mandatory → using same target
Can DAMA/LIBRA result be a door into new Physics or just systematics?

Experimental Situation

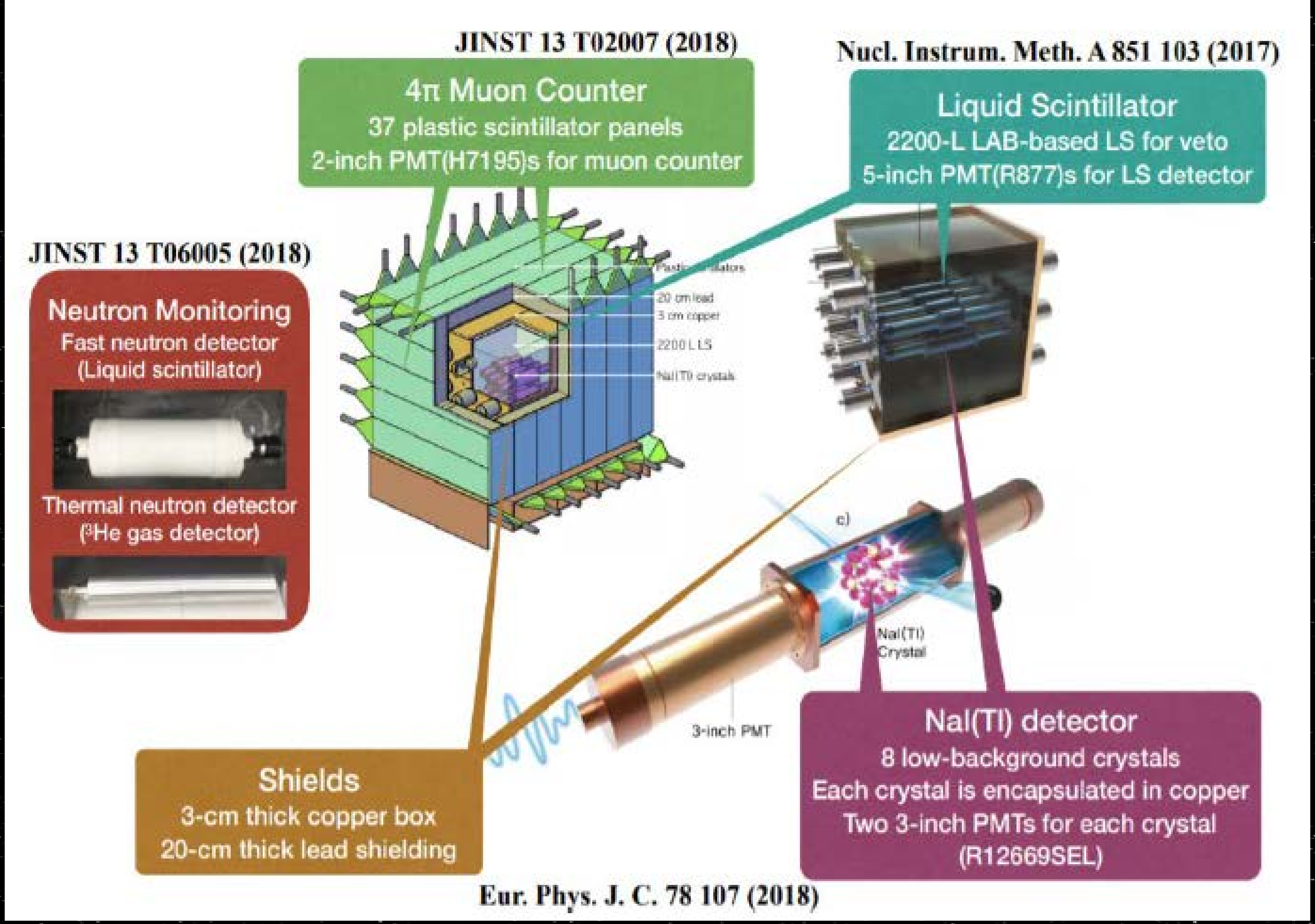
IN DATA-TAKING
112,5 kg
Since Aug 17

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



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

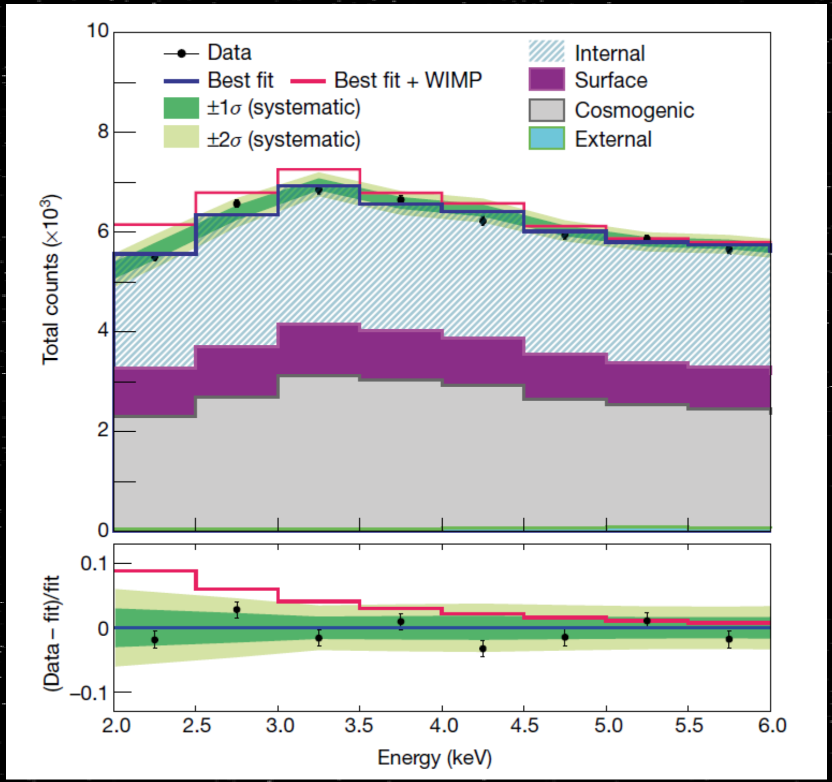
COSINE-100



- From Y.J. Ko @ TAUP2019
- Data taking @YangYang Lab (South Korea) since Sep-Oct 2016
- 106kg NaI(Tl) in the set-up but only about 60kg used for DM searches
- Crystals produced by Alpha Spectra → similar radiopurity than ANAIS crystals
- Liquid scintillator tank allows a higher coincidental background rejection factor

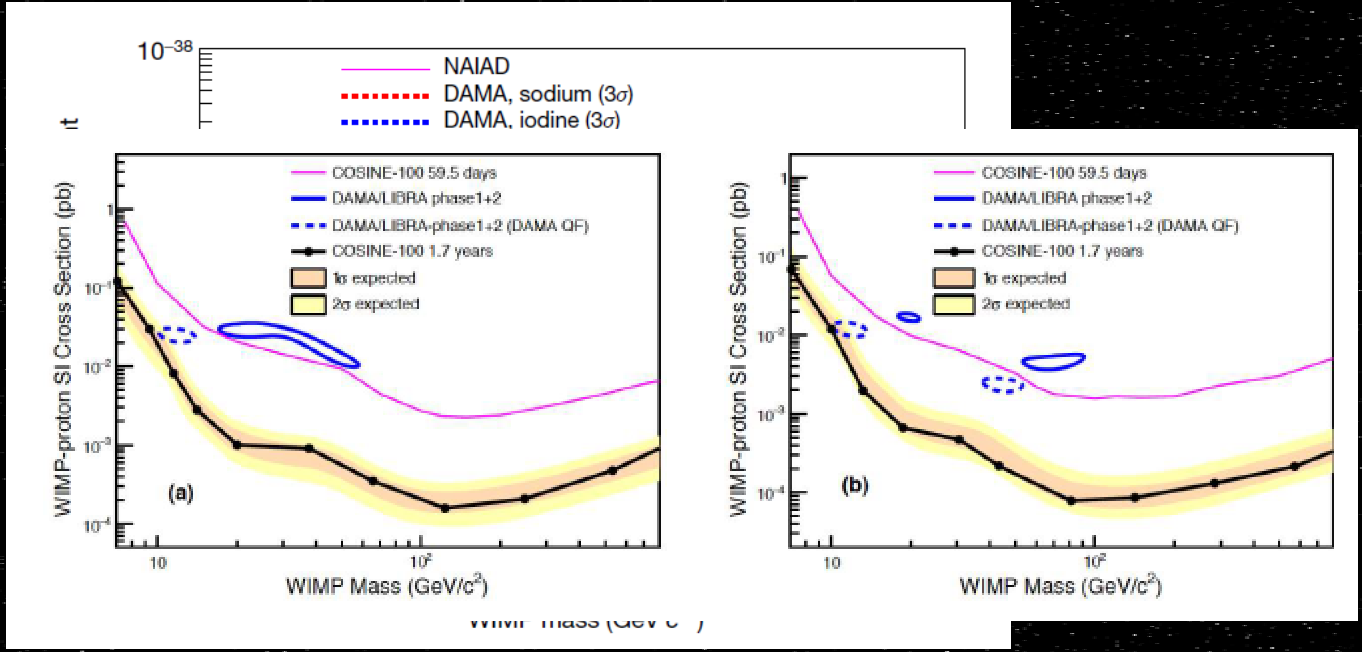
Progressing towards COSINE-200 with better radiopurity crystals

COSINE-100



Nature 564 (2018) 83

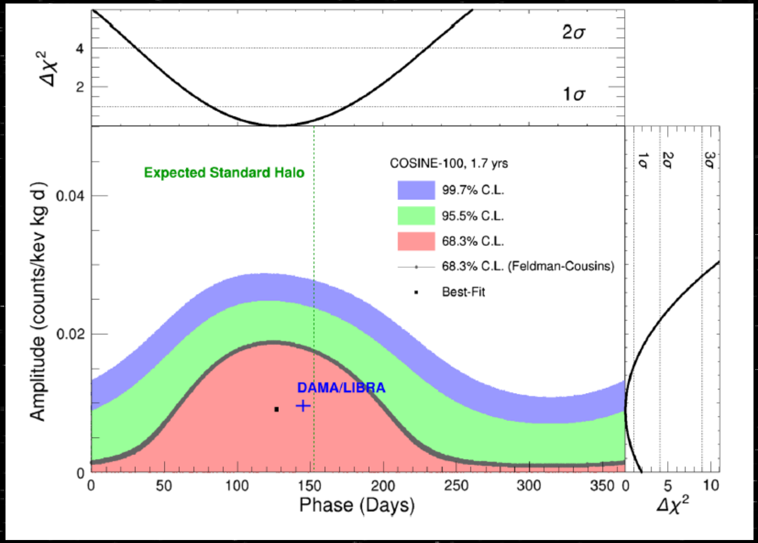
- 2 keVee energy threshold
- 59.5 days
- Fitting of the background + WIMP signal to data
- MODEL DEPENDENT ANALYSIS excluding DAMA/LIBRA phase 1 SI interpretation



Recently updated to 1.7 y with 1 keVee threshold: arXiv:2104.03537

COSINE-100

Phys. Rev. Lett. 123 (2019) 031302

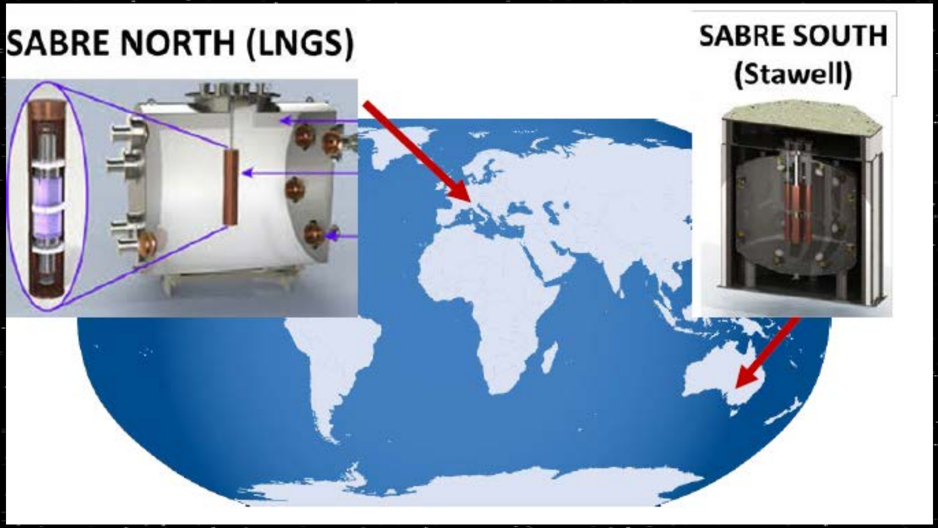


- 2 keVee energy threshold
- 1,7 years
- Results compatible with absence of modulation and with DAMA/LIBRA result
- More data are under analysis, improved threshold at 1 keVee

TABLE I. Summary of fit results for the modulation and null hypotheses for the 2–6 keV energy region in COSINE-100. Detector rates were fit to Eq. (1), with the period fixed at 365.25 d. Results with phase floated and fixed at 152.5 d are listed. The result without using the LS veto is presented as a crosscheck. DAMA/LIBRA results [12] and the ANAIS-112 2019 result [27] are also shown.

Configuration	χ^2	DOF	p value	Amplitude [cpd/kg/keV]	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092 ± 0.0067	127.2 ± 45.9
DAMA/LIBRA (Phase1 + Phase2)	...	...	...	0.0096 ± 0.0008	145 ± 5
COSINE-100	175.6	175	0.473	0.0083 ± 0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.147	0.0024 ± 0.0071	152.5 (fixed)
ANAIS-112	48.0	53	0.67	-0.0044 ± 0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1 + Phase2)	71.8	101	0.988	0.0095 ± 0.0008	152.5 (fixed)

SABRE



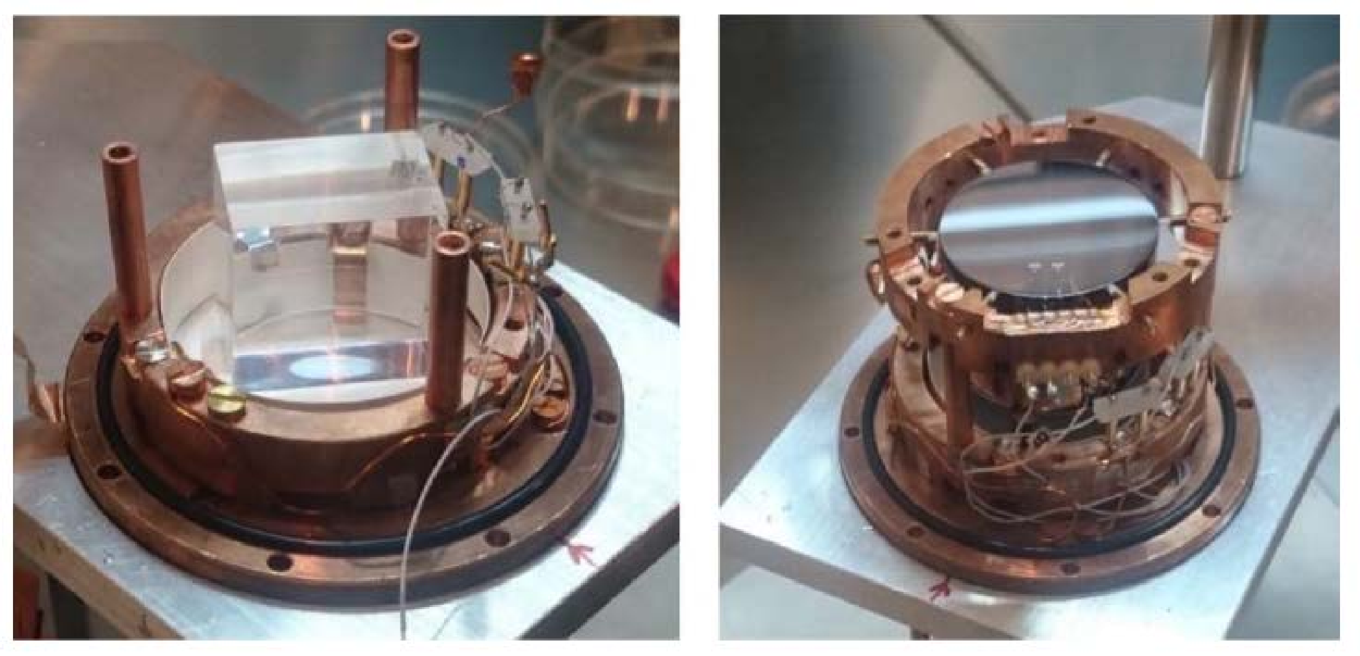
- Two Sites (North and South hemispheres)
- Ultra-radiopure NaI(Tl) grown at Princeton

	K (ppb)	^{210}Pb (mBq/kg)
SABRE	4	0.4
DAMA	13	0.01-0.03
ANAIS	18-44	0.7-3

- Proof of Principle:
  3.5 kg NaI crystal in LS vessel at LNGS

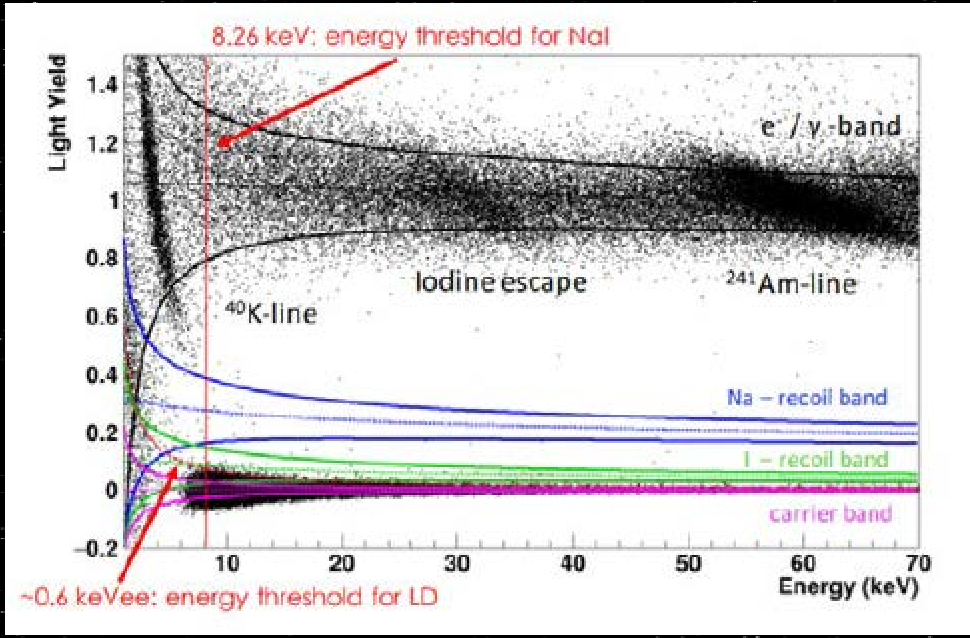
Eur. Phys. J. C79 (2019) 363
Eur. Phys. J. C81 (2021) 299

COSINUS



- First NaI detector with particle discrimination ability by simultaneously measuring HEAT & LIGHT

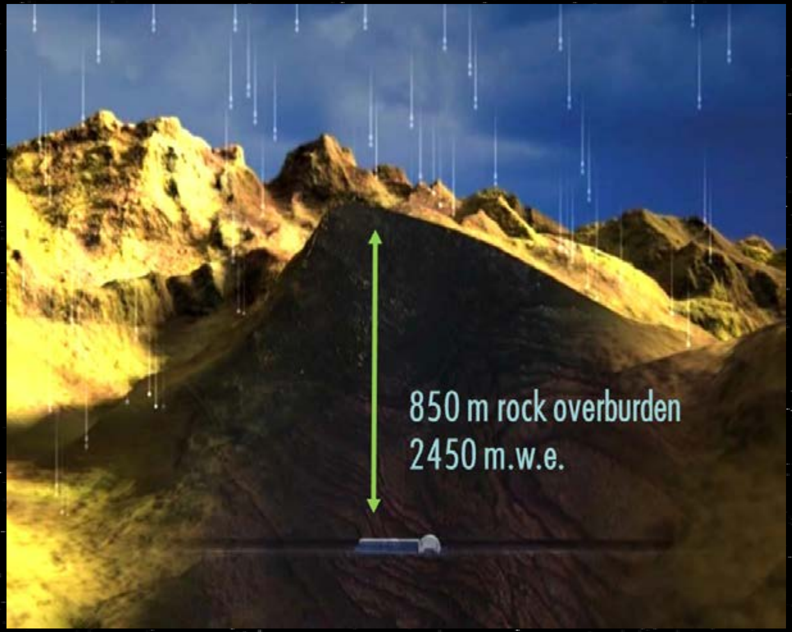
J. Low Temp. Phys. 193 (2018) 1174
JINST 12 (2017) P11007



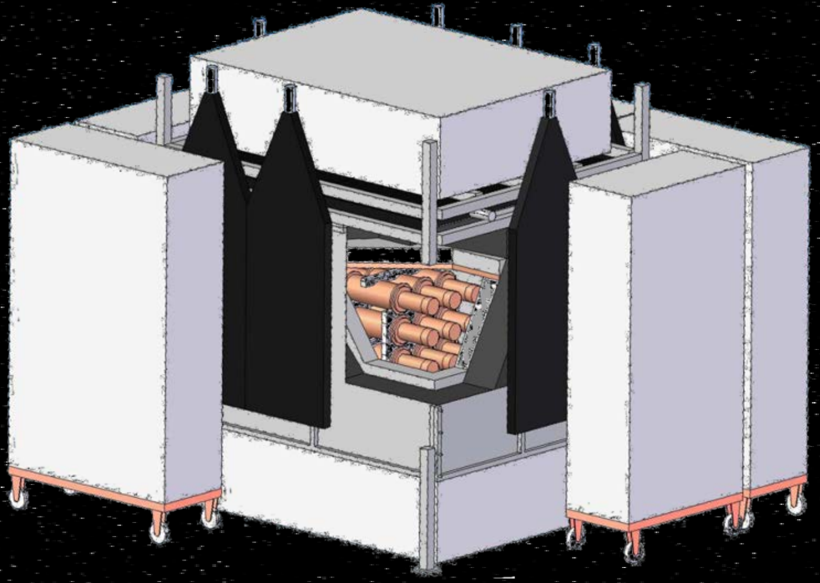
- Distinguishing Na from I nuclear recoils and rejection of gamma background -> testing nuclear recoil origin of DAMA/LIBRA claim

- GOAL -> 1 keV_{NR} threshold

Annual modulation with NaI Scintillators



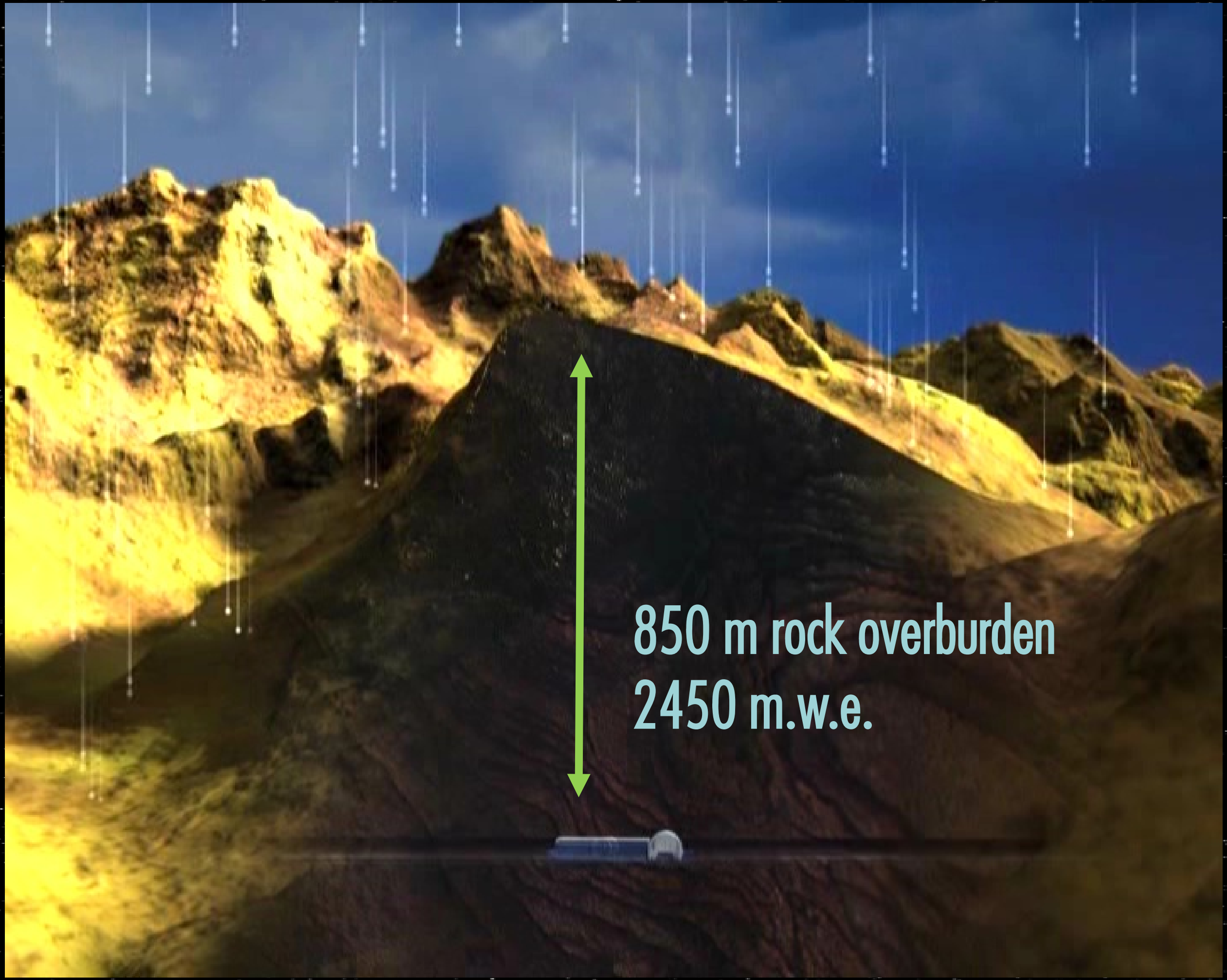
- Confirmation of DAMA-LIBRA modulation signal -> **same target and technique** / **different** experimental approach / **different** environmental conditions affecting **systematics**
- At Canfranc Underground Laboratory, @ SPAIN (under 2450 m.w.e.) taking data since August 2017
- 3x3 matrix of 12.5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



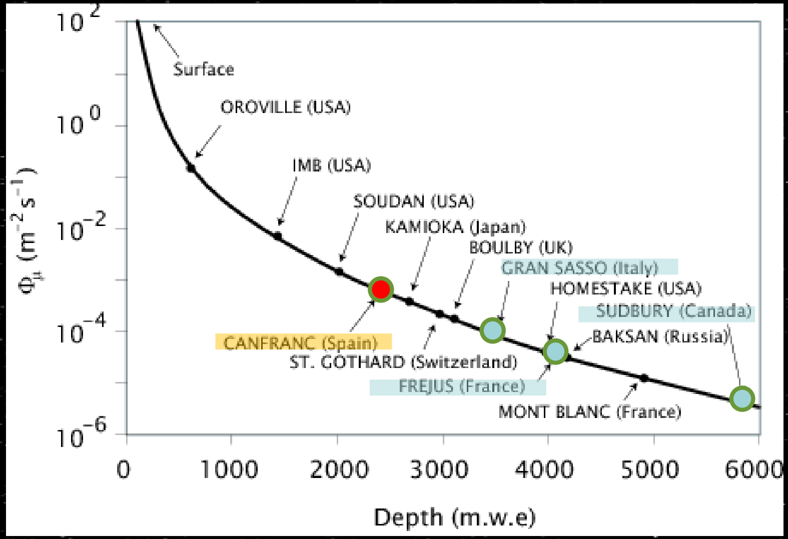
Canfranc Underground Laboratory (SPAIN)

under the Pyrenees, at the Somport tunnel connecting France and Spain

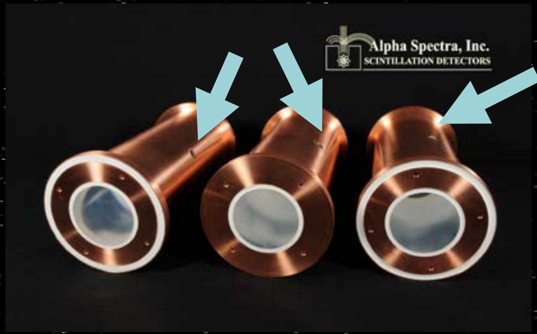
Laboratorio Subterráneo de Canfranc



Reduces muon flux in a factor 10^5 with respect to surface



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) → 7/9 modules between 14.0 and 15.0 p.e./keV
- Larger and more homogeneous than that of DAMA/LIBRA modules

JINST 7 (2012) 03009

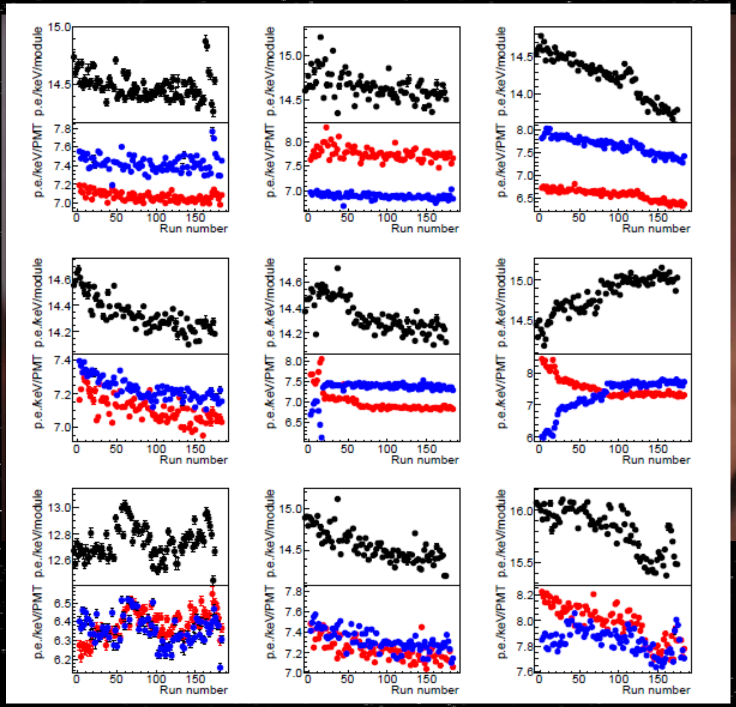
Phase 1: 5.5-7.5 p.e./keV
Phase 2: 6-10 p.e./keV

- Under continuous monitoring along data taking

arXiv:2103.01175

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) → 7/9 modules between 14.0 and 15.0 p.e./keV

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

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

Setting-up ANAIS-112 at LSC
Commissioning March-June 2017

Data Taking started 3 August 2017

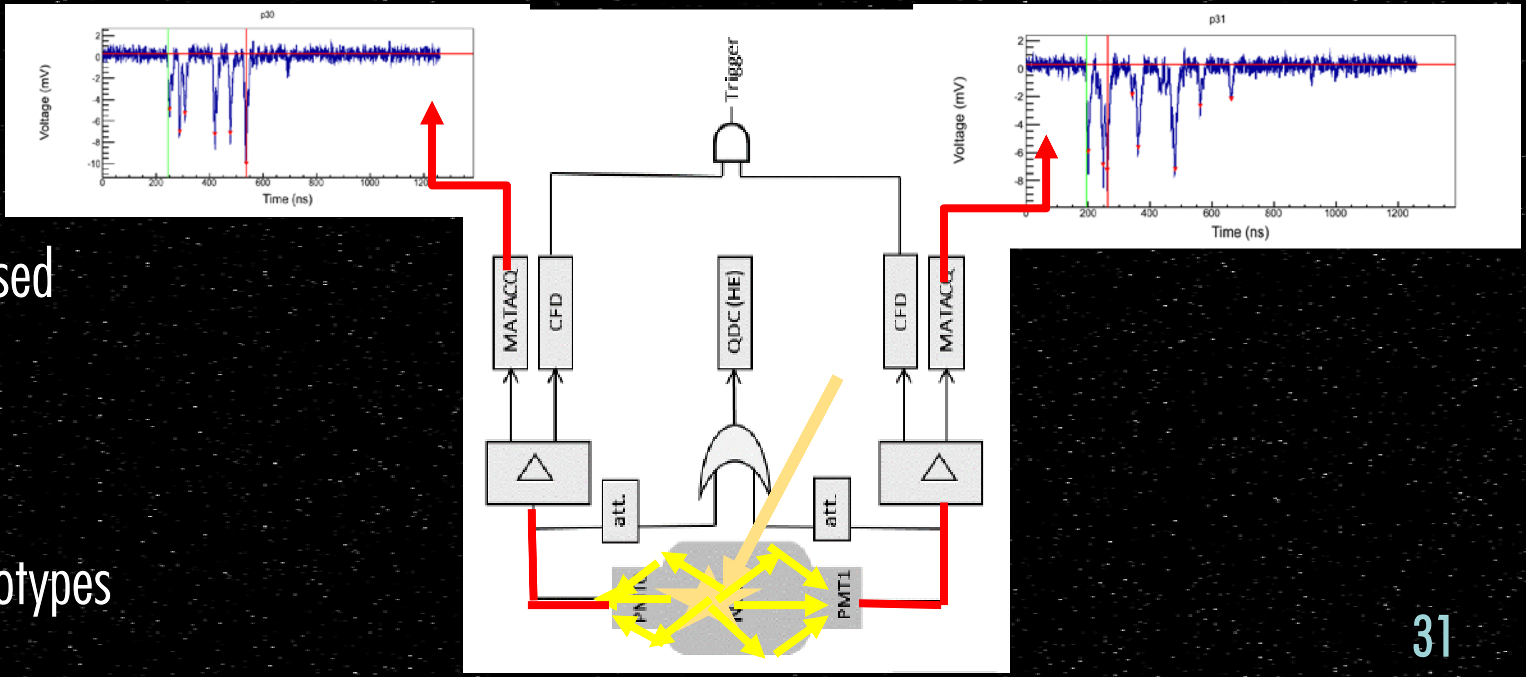
Relevant experimental features

ANAIS-112 set-up

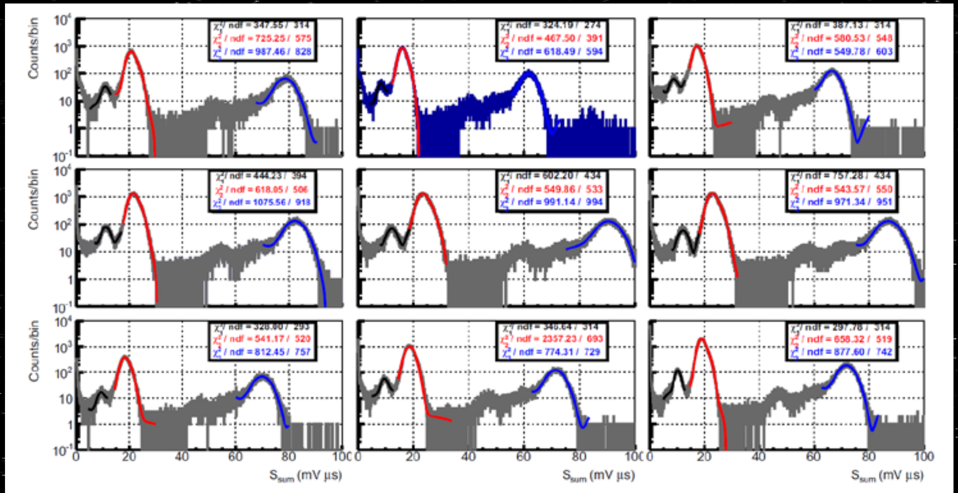
- 10 cm archaeological lead
- 20 cm low activity lead
- Tight box preventing Radon entrance
- 16 plastic scintillators acting as muon veto system
- 40 cm polyethylene / water

ANAIS-112 DAQ

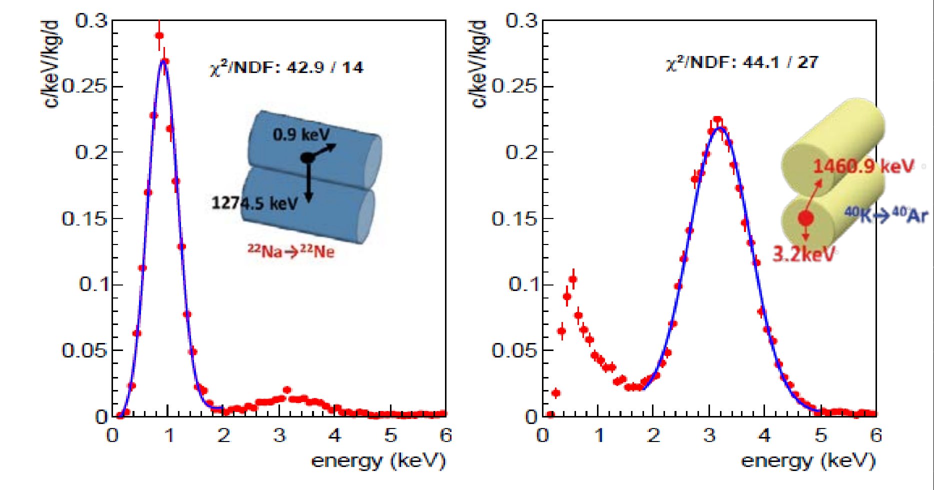
- Individual PMT signals digitized and fully processed (14 bits / 2 GS/s)
- Trigger at p.e. level for each PMT + Logical AND coincidence in 200ns window
- Robust / Low noise / tested with previous prototypes

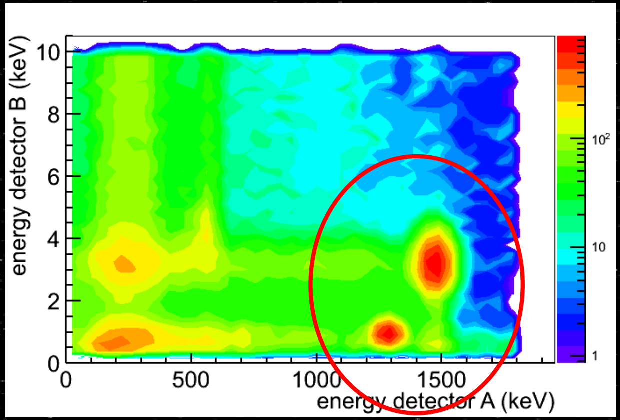


Calibrating the ROI with high accuracy



- 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

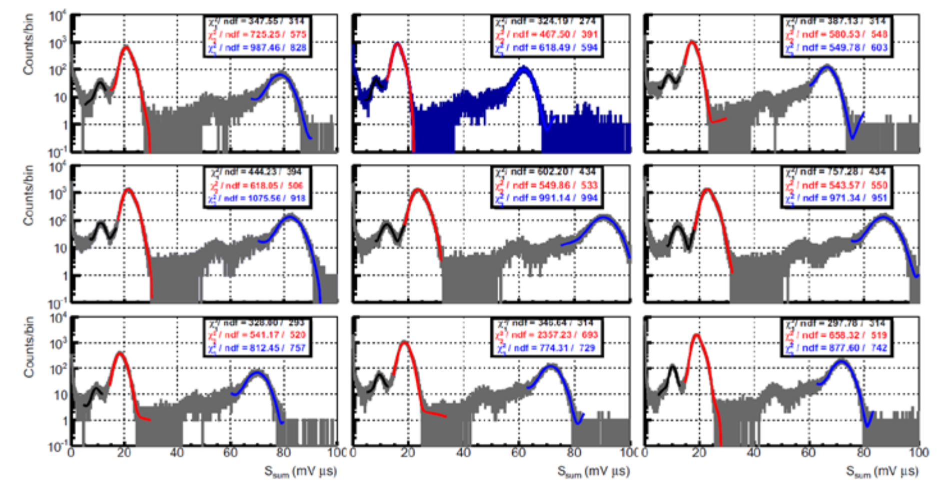


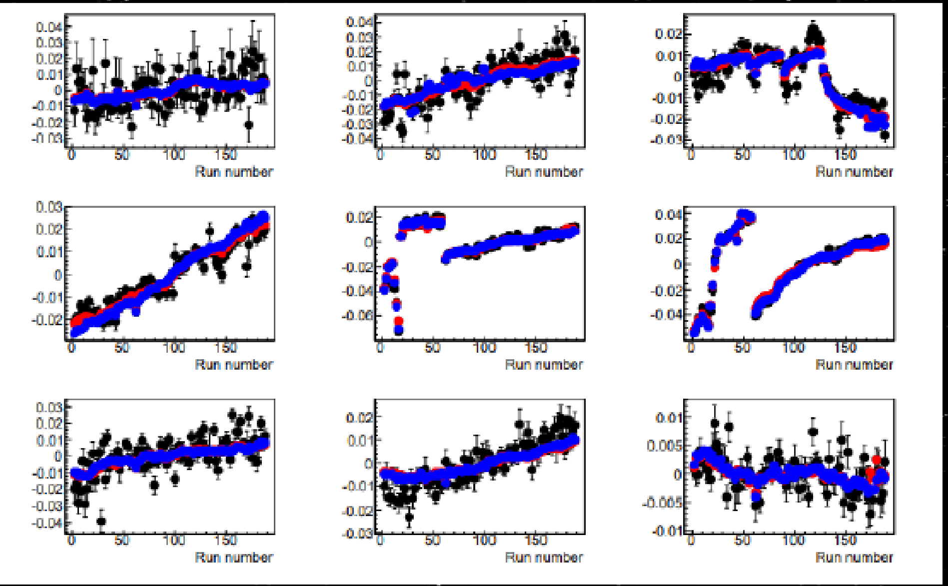


Events @ROI from ^{40}K and ^{22}Na selected by the coincidence with a HE gamma in a second module

Demonstration of triggering below 1 keV

Calibrating the ROI with high accuracy





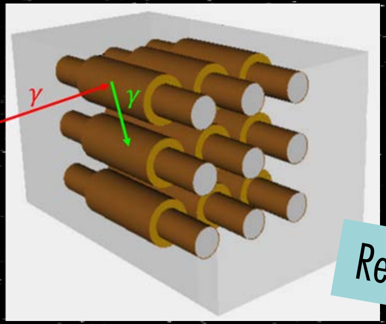
- Combination of periodical external calibration using ^{109}Cd (88.0, 22.6 and 11.9 keV) every two weeks and ^{40}K and ^{22}Na internal contamination background lines (3.2 and 0.9 keV) every 1.5 months
- ROI calibrated with 22.6, 11.9, 3.2 and 0.9 keV
- Evolution of Cd-lines from calibrations along 3 years show good stability (at a few percent level) but in D4/D5 (HV was modified after the first year)
- But, we correct this gain drift

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

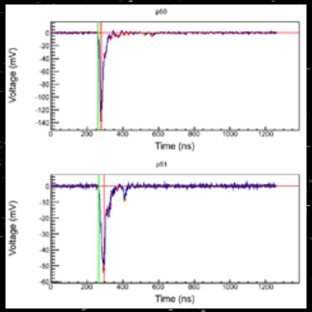
Events selection procedure developed before unblinding

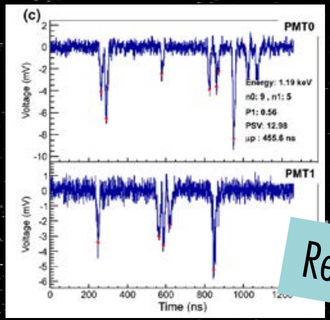


Rejected event

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

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

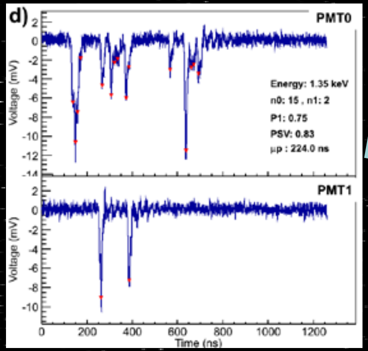




Rejected events

- Time behavior compatible with NaI scintillation constant: biparametric cut

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



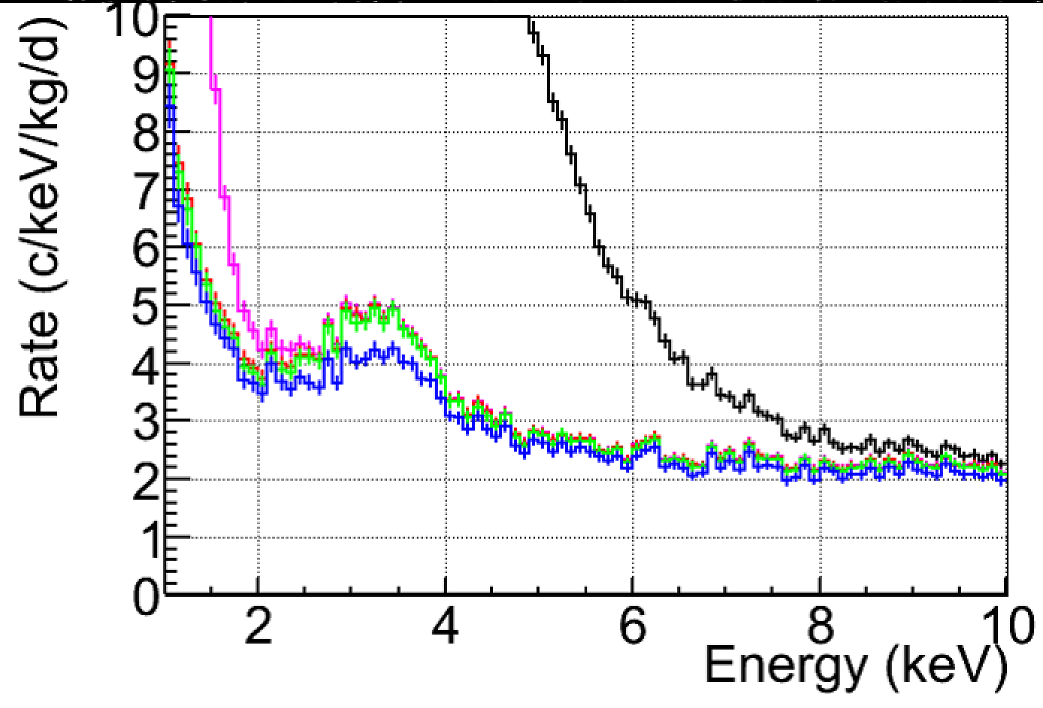
Rejected event

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

Events selection procedure developed before unblinding

ANAIS 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

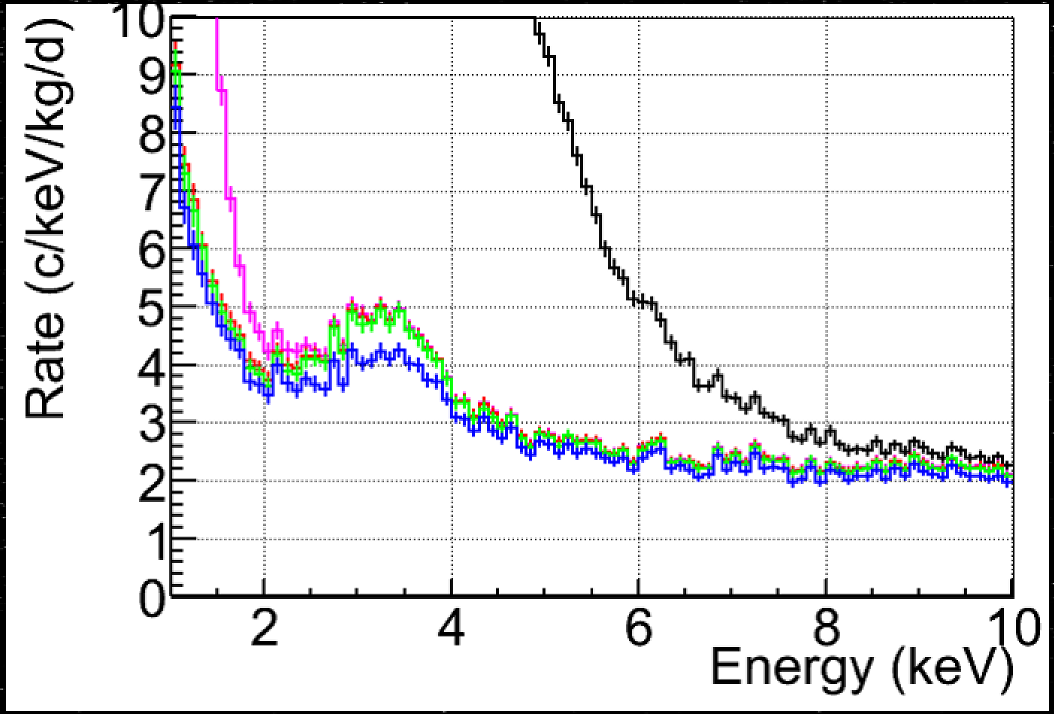


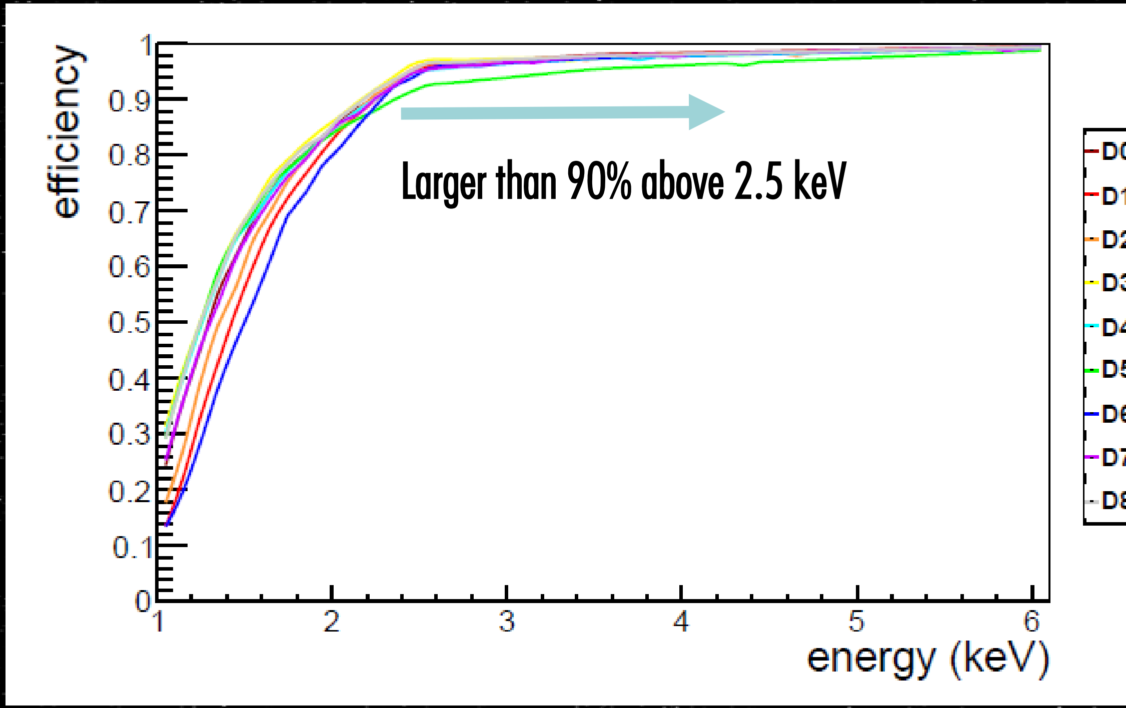
Raw data
NaI scintillation time behaviour/biparametric cut
Npeaks >4 at both PMTs
More than 1 s after a muon
Single Hits

Events selection procedure developed before unblinding

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

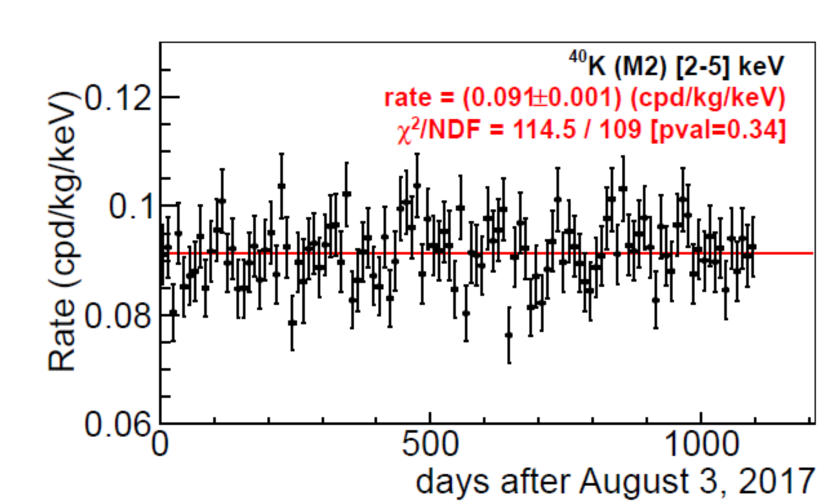
- Robust estimate of the efficiencies using ^{109}Cd / ^{22}Na and ^{40}K events BEFORE UNBLINDING / updated for the three years analysis
- Choice of analysis threshold → 1 keV

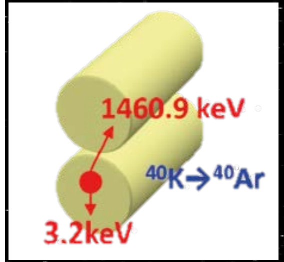




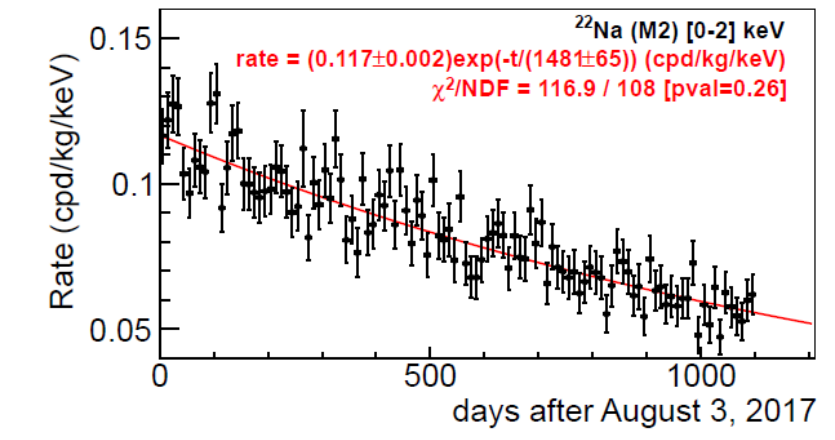
Events selection procedure developed before unblinding

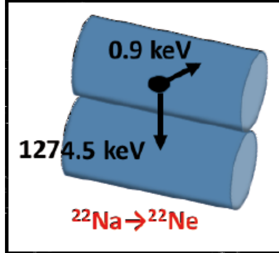
Efficiency and calibration stability checks using ^{40}K and ^{22}Na populations (M2 with a HE gamma of the right enegy in a second module)





- Constant for ^{40}K (vs $\tau = 1.8\ 10^9$ y)





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

Background in the ROI

Long effort of ANAIS team looking for ultrapure NaI(Tl) -> know-how lost since DAMA/LIBRA crystal growing and detector building + confidentiality agreement between Saint Gobain and DAMA/LIBRA collaboration

Up to date, background budget in the ROI is dominated by crystal radioactivity
Quality of DAMA crystals still not reached

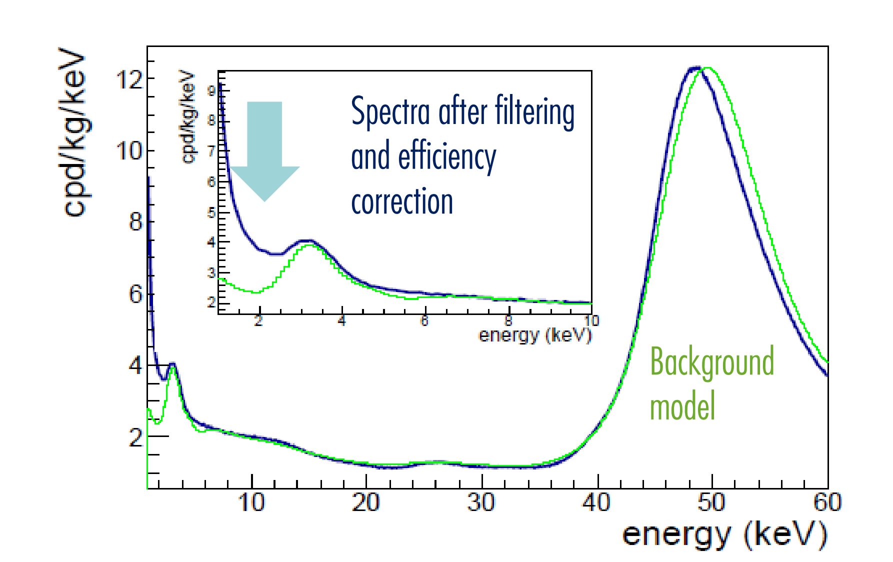
- ^{40}**K** and ^{22}**Na** ($T_{1/2}$ = 2.6 y) peaks
- ^{210}**Pb** (bulk+surface) ($T_{1/2}$ = 22.3 y)
- ^{3}**H** ($T_{1/2}$ = 12.3 y)

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

	K (ppb)	^{210}Pb (mBq/kg)
SABRE	4	0.4
DAMA	13	0.01-0.03
ANAIS	18-44	0.7-3

Robust background model

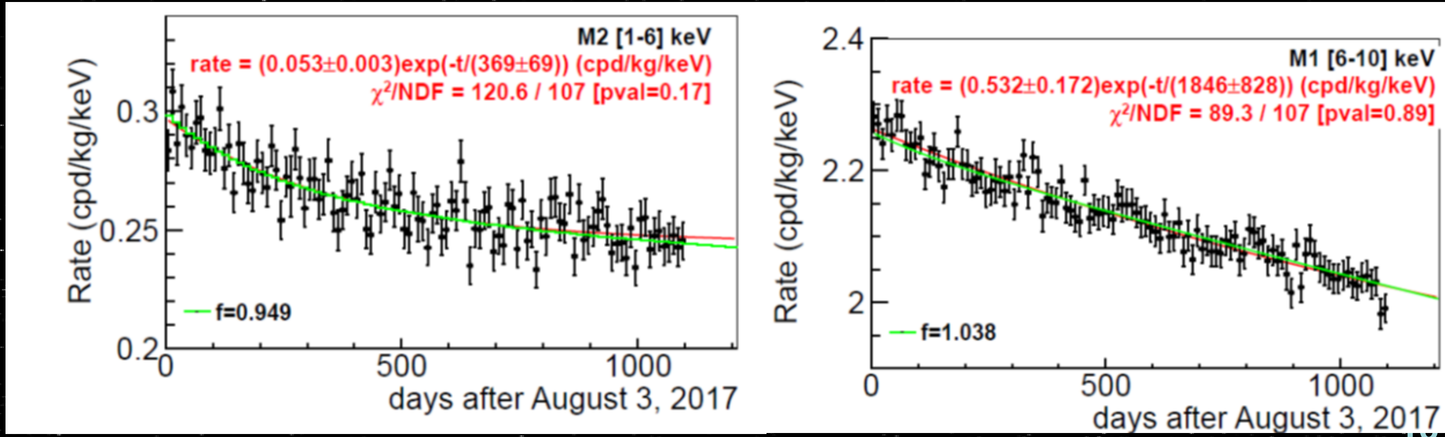
J. Amaré et al., EPJC79 (2019) 412



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
- Remark: constant backgrounds should not affect the annual modulation analysis

- 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

arXiv: 2103.01175 Accepted for publication in PRD

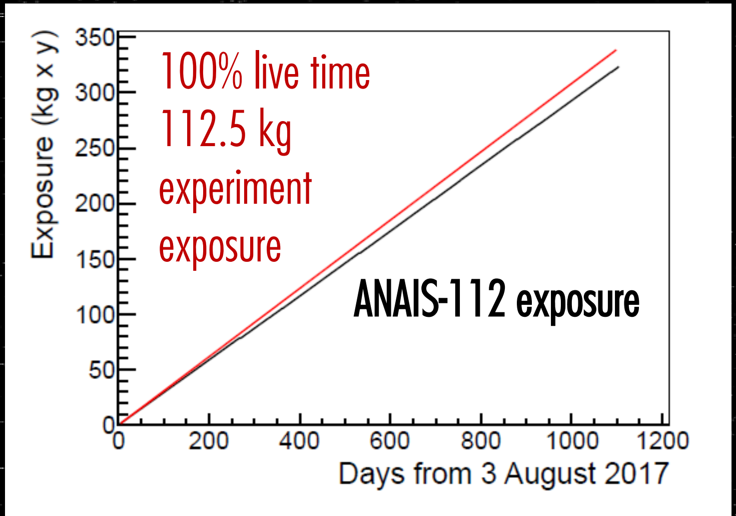
Annual Modulation Results from Three Years Exposure of ANAIS-112

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, Av. de Ranillas 1D, 50018 Zaragoza, Spain*
[4]*Fundación CIRCE, Av. de Ranillas 3D, 50018 Zaragoza, Spain*

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

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



- Excellent duty cycle, 95% live time
- Down time (2.6%) mostly due to periodical calibration (every two weeks)
- Dead time (2.4%)
- Three year results: 1049.8 days live time raw / 1018.6 days after removing muon-tagged events

ANAIS-112 three year results – annual modulation analysis

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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

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

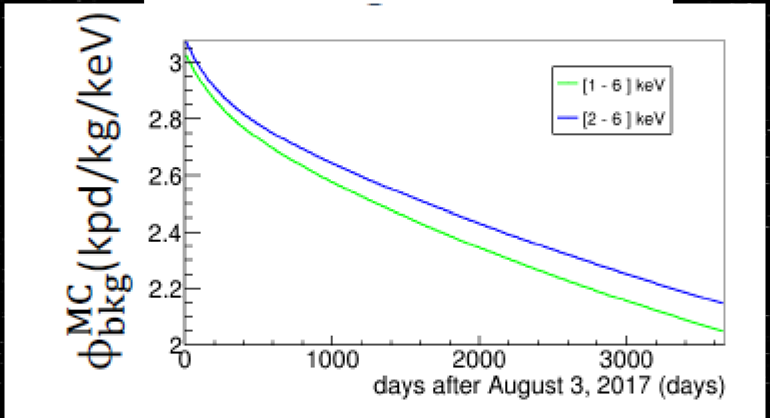
Three independent background modelling procedures

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

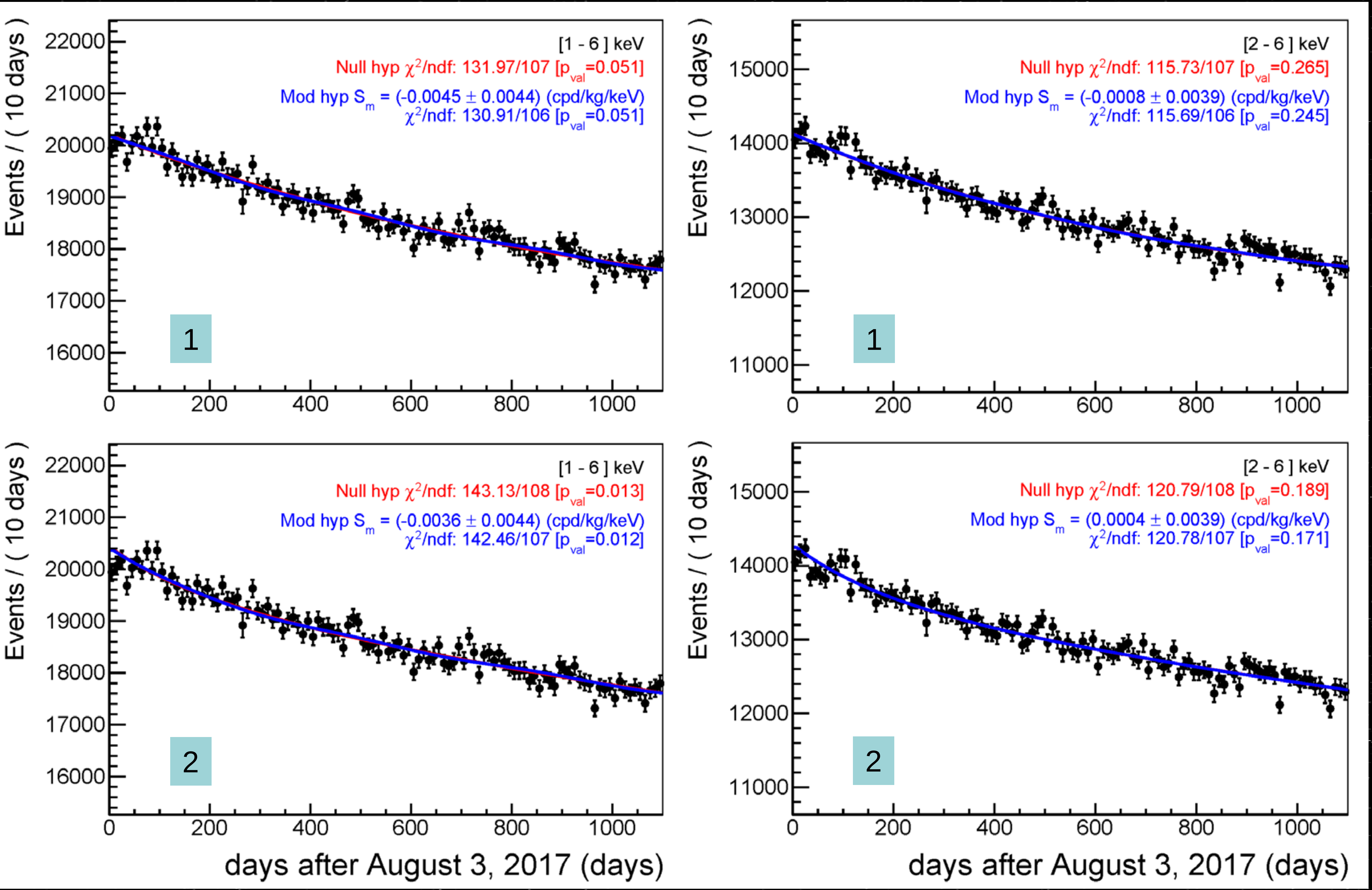
$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

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

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

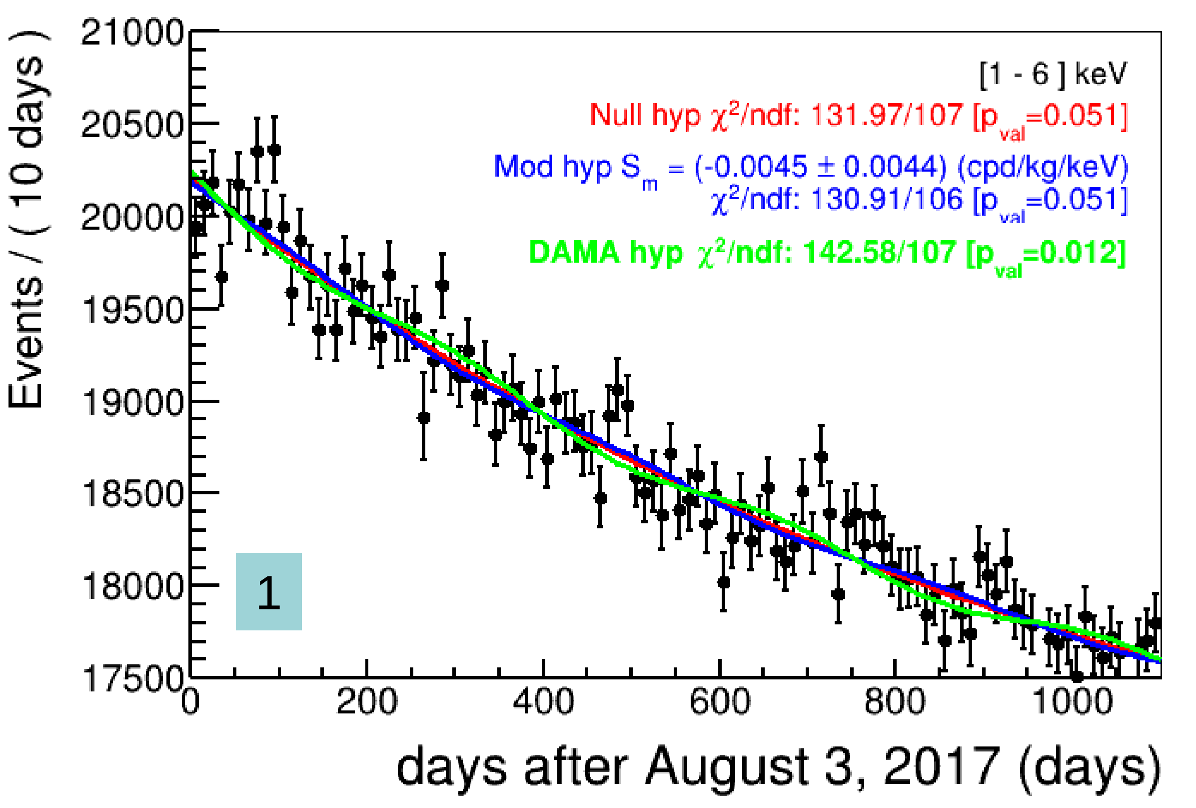


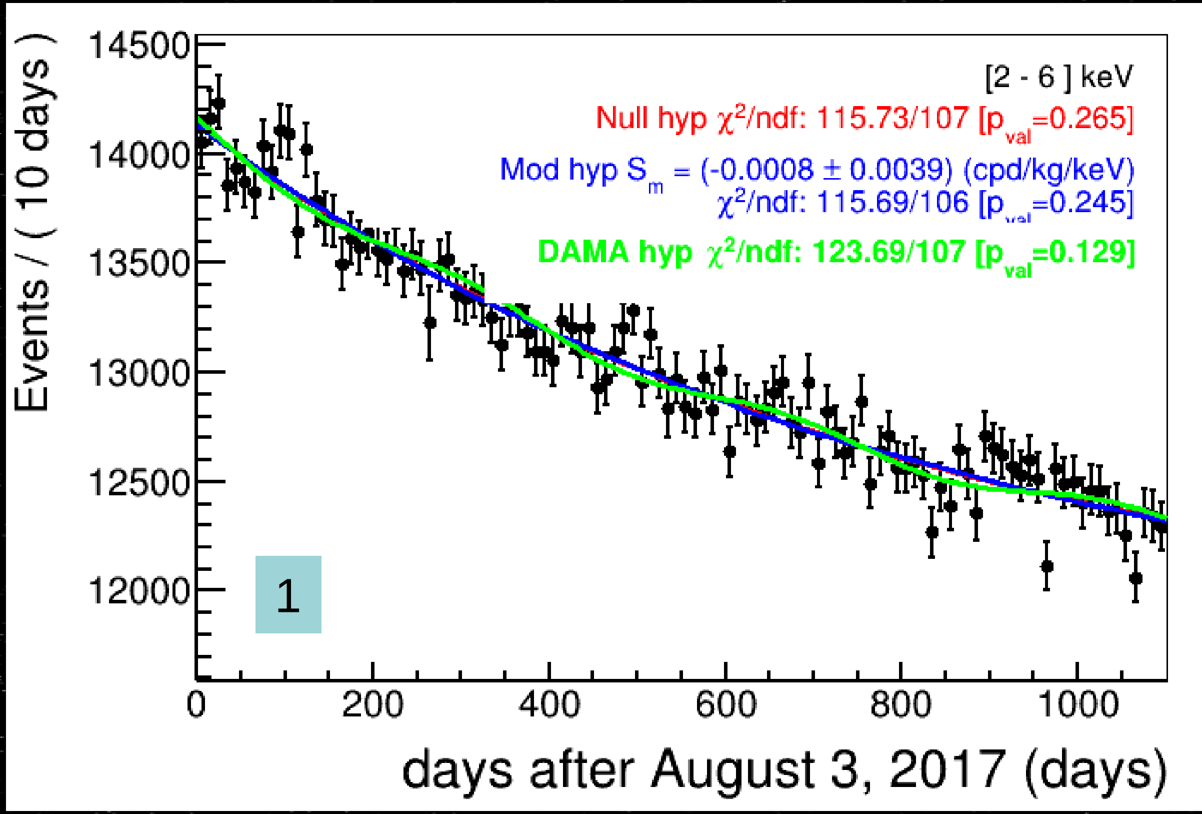
$$\mu_i = [R_0 \phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))] M \Delta E \Delta t$$



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

ANAIS-112 vs DAMA/LIBRA





ANAIS-112 three year results – annual modulation analysis

Three independent background modelling procedures

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

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

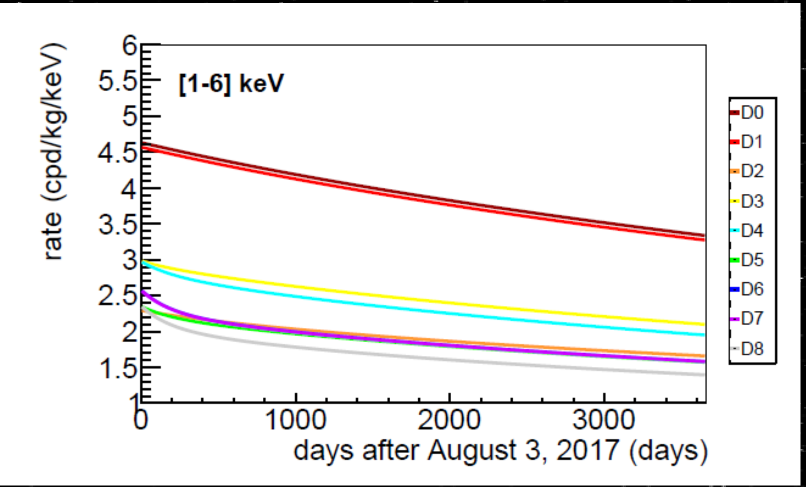
2. Probability distribution function derived from background model corrected by a factor f, and R_0 both free

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

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

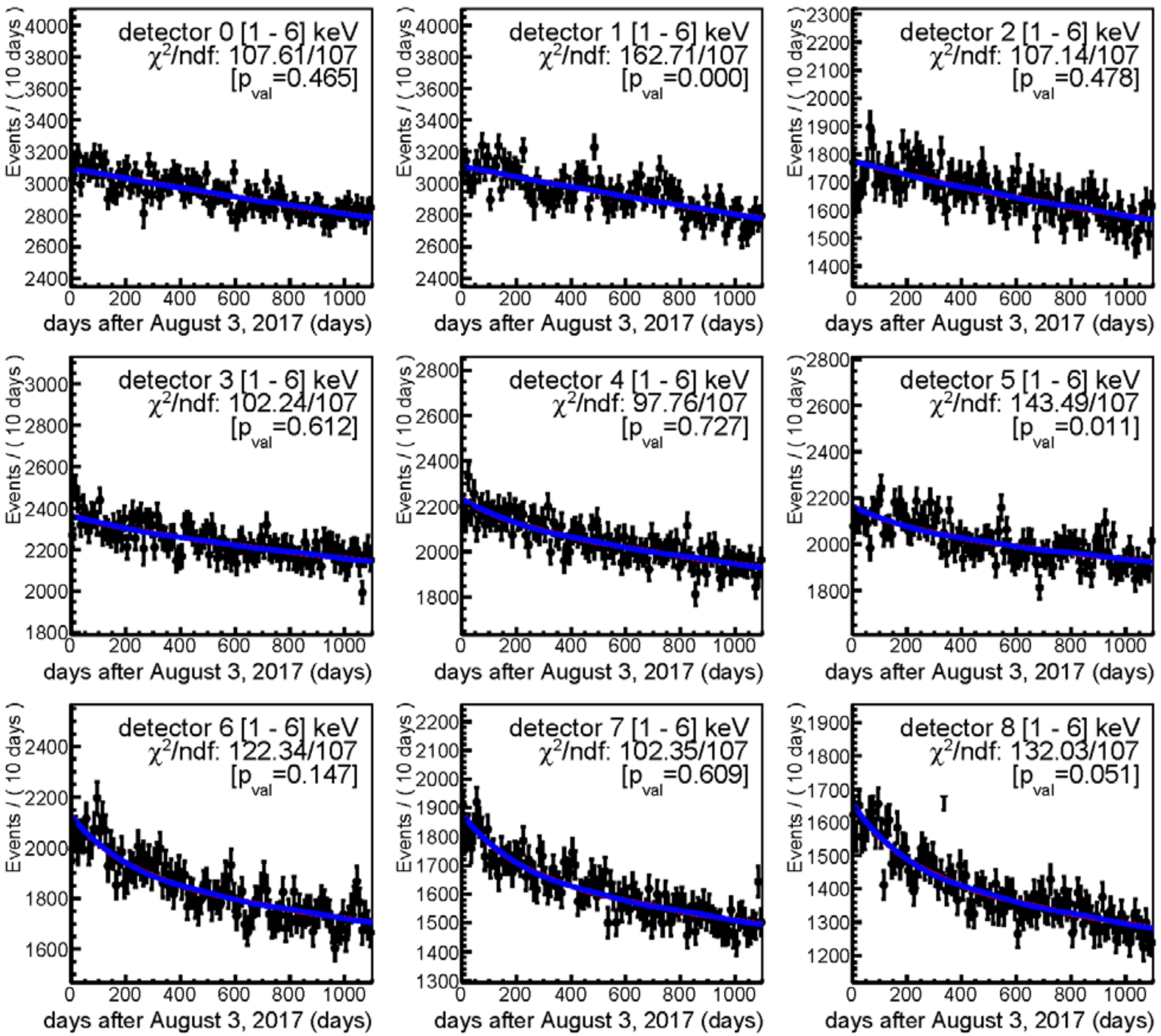
3. Probability distribution function for every detector individually to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules

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



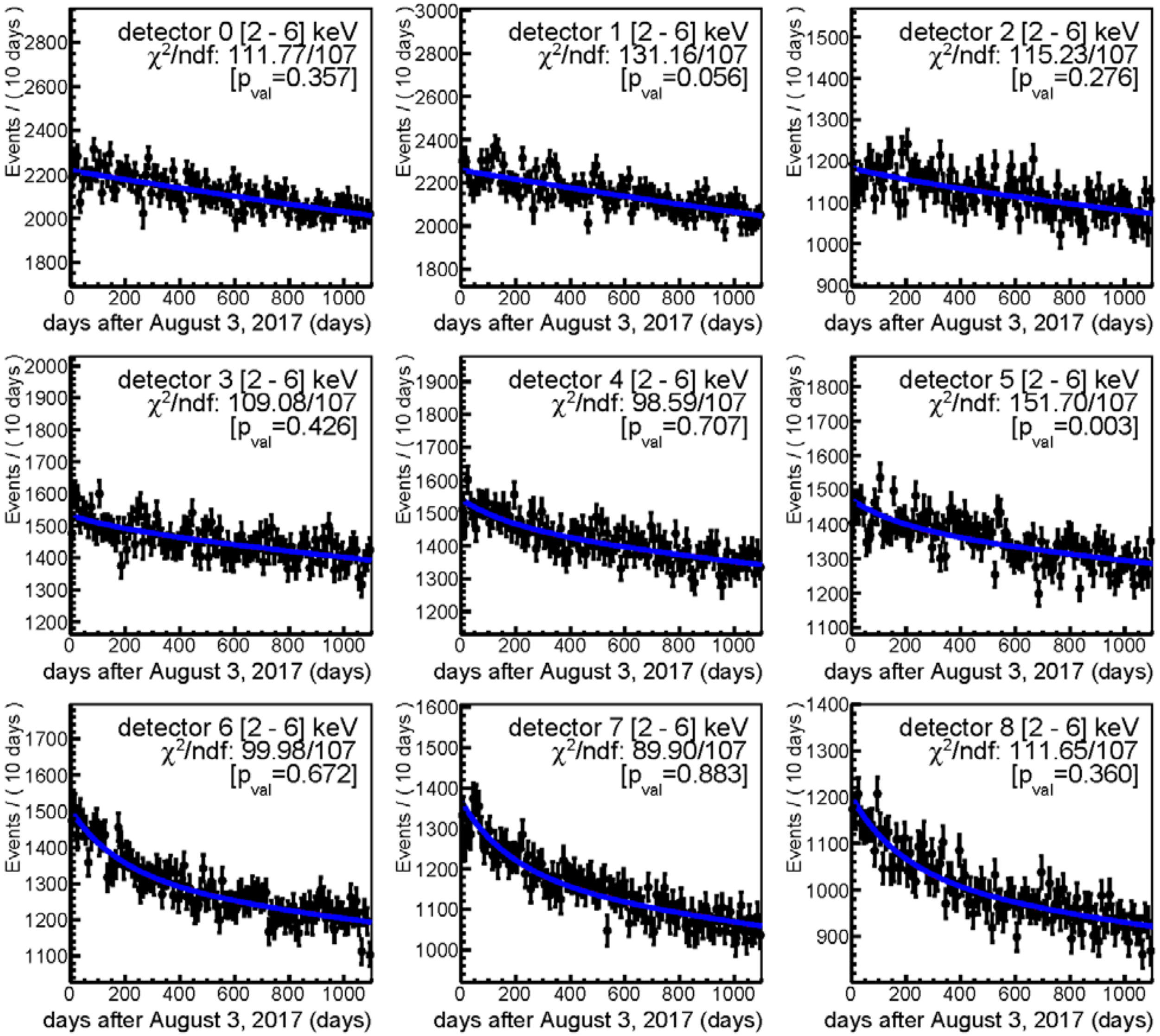
Null hyp χ^2/ndf: 1075.81/972 [p_{val}=0.011] Mod hyp χ^2/ndf: 1075.15/971 [p_{val}=0.011]

S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)



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)



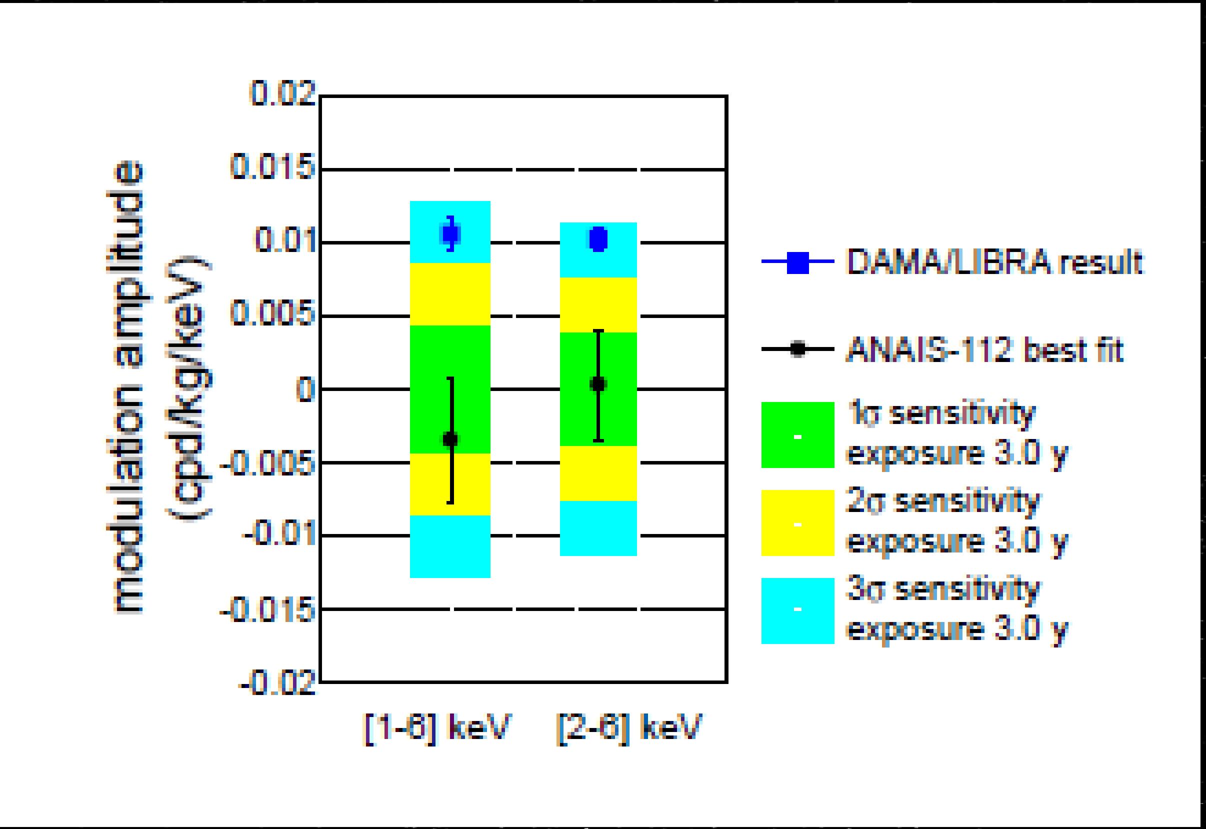
ANAIS-112 three year results – annual modulation analysis

- 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	eq. 4	132 / 107	3	-0.0045±0.0044	0.051	0.051
	eq. 5	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	eq. 6	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	eq. 4	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	eq. 5	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	eq. 6	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, and is taken for the comparison with DAMA/LIBRA

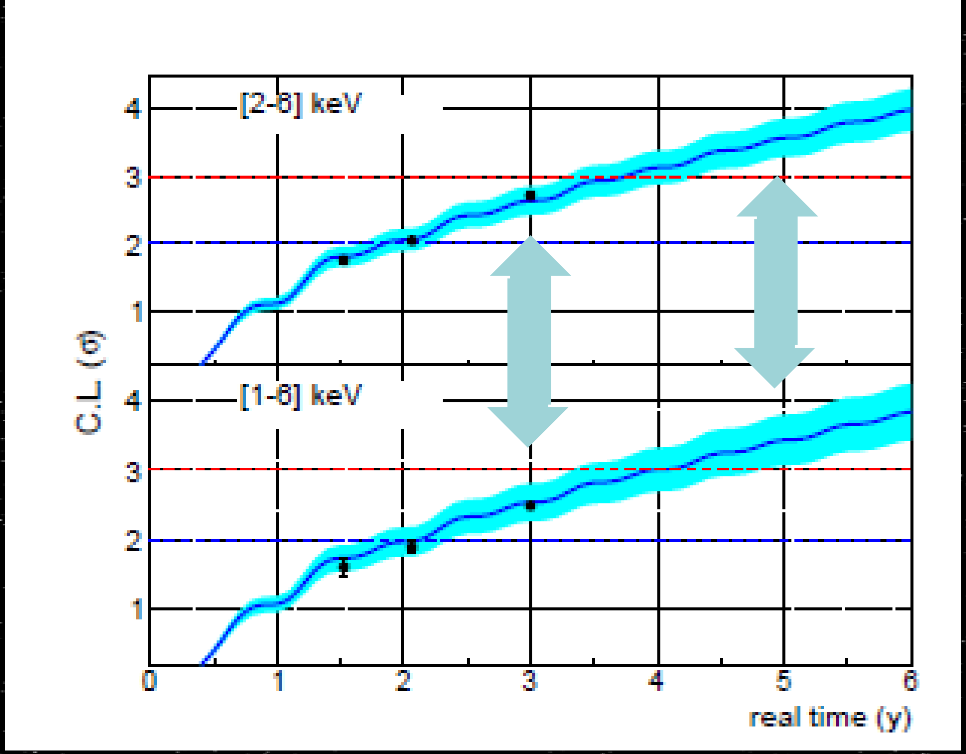
ANAIS-112 three year results – annual modulation analysis



- 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)

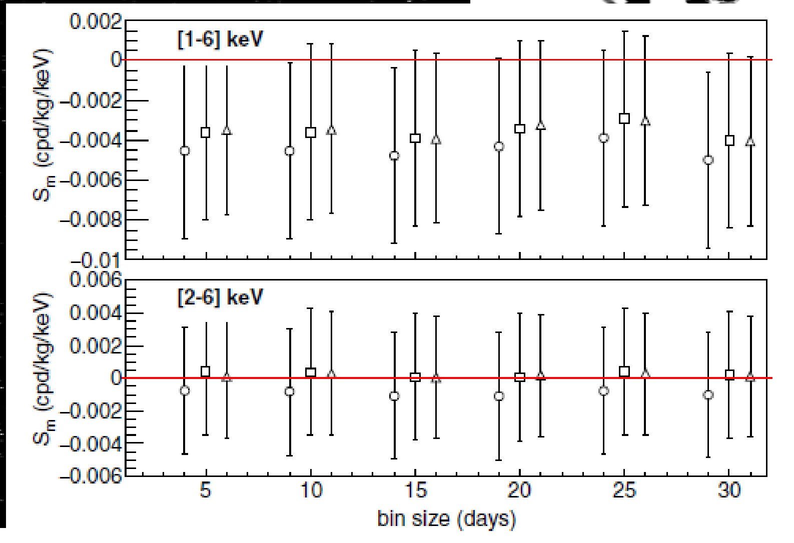
We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA} / \sigma(Sm)$

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

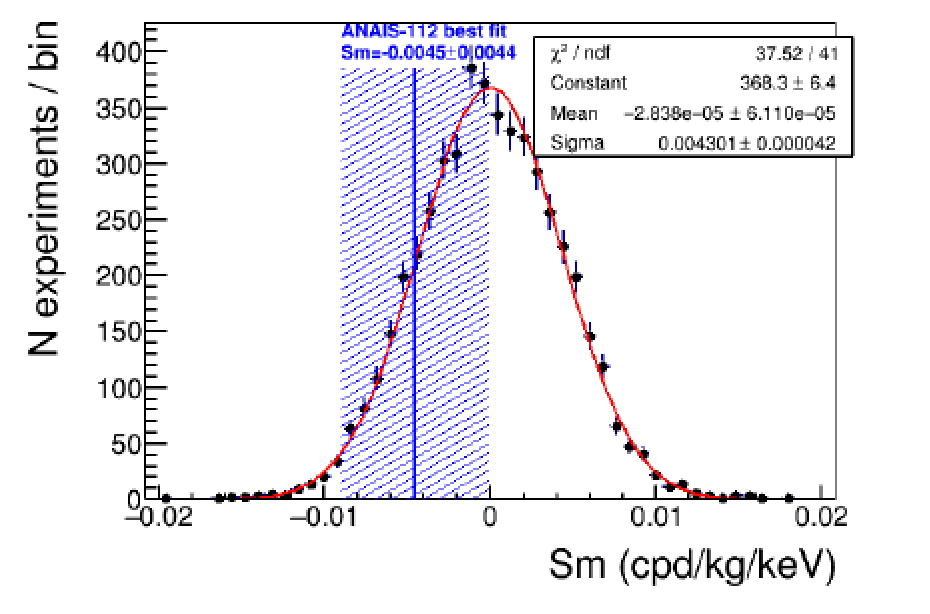
- Consistency checks of our analysis
  - Time binning -> changed from 5 t 30 days

Negligible effect



  - Toy MC to check possible bias

No bias

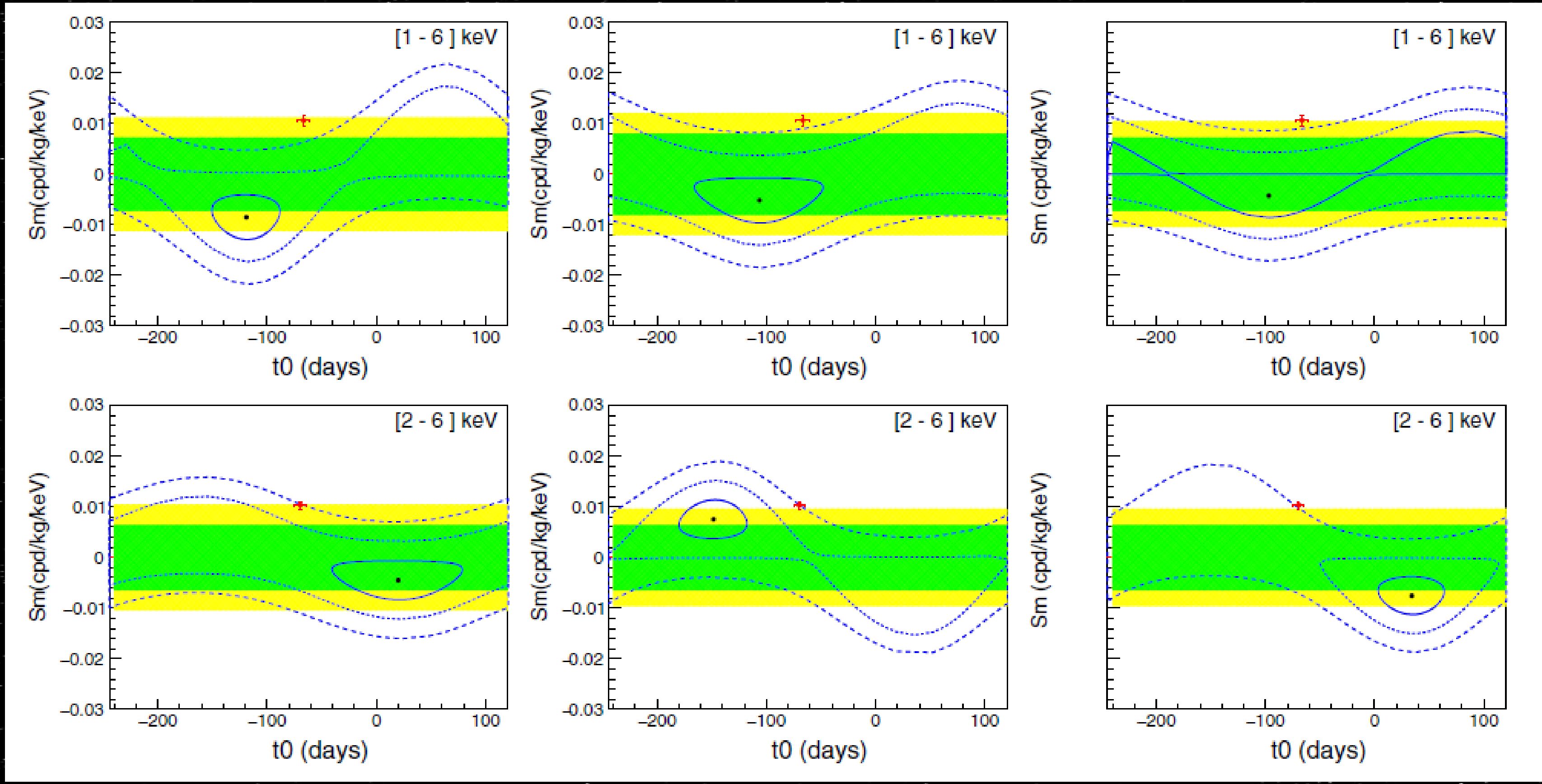


  - 1-2 years / 2-3 years

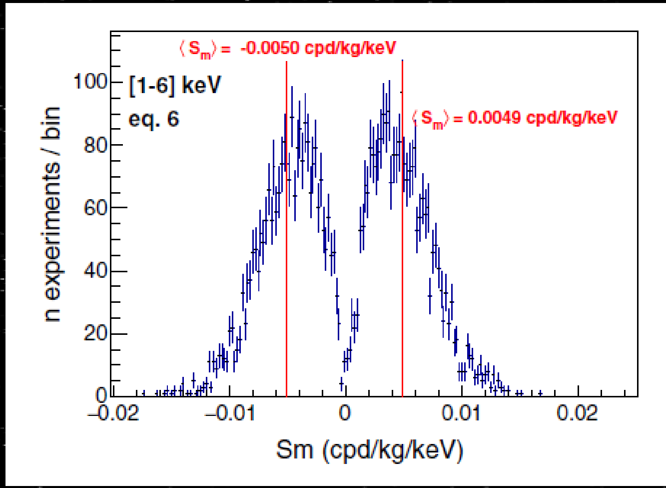
Compatible results

ANAIS-112 three year results – annual modulation analysis

- Phase free analysis



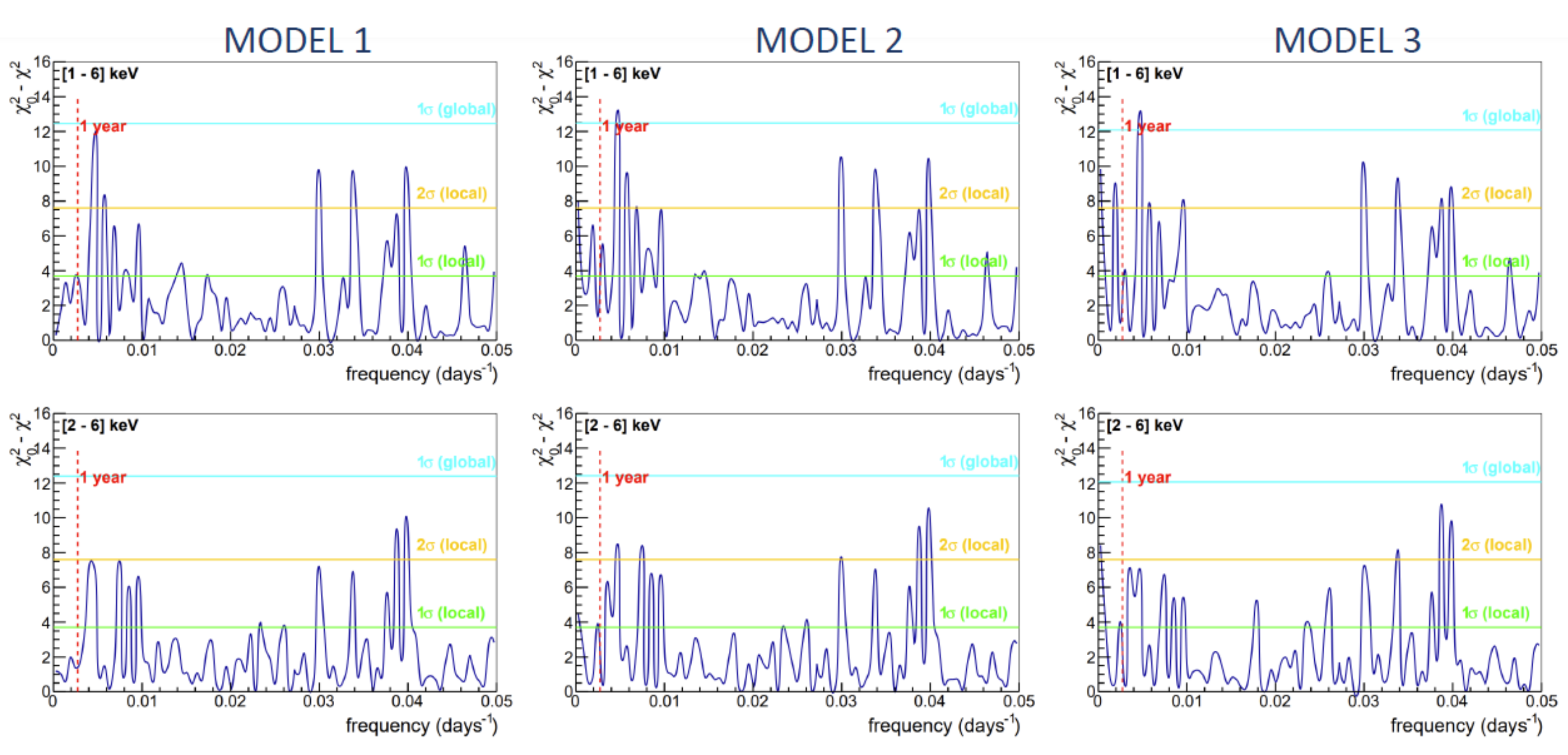
Biased fit …



Considering the bias, compatibility at 1 σ with absence of modulation

ANAIS-112 three year results – annual modulation analysis

- Frequency analysis



No statistically significant modulation at any frequency

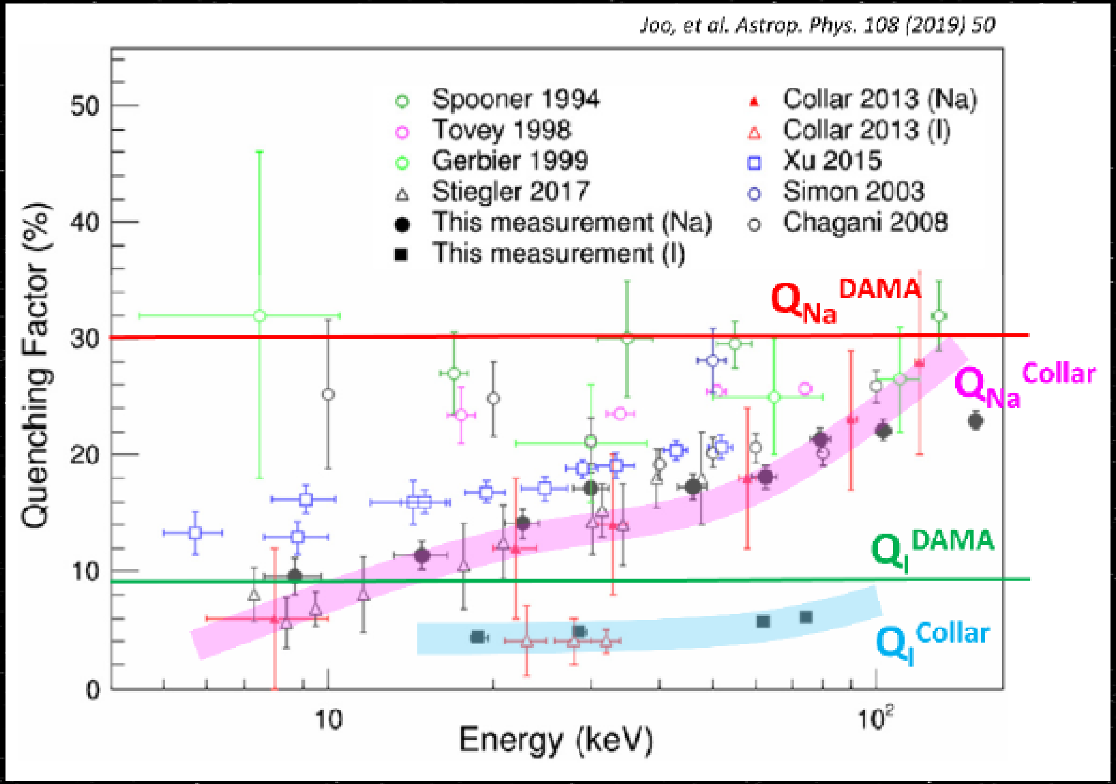
Summary and Outlook

- **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** used **for model independent annual modulation blind-analysis**
  - We confirm our sensitivity projections to DAMA/LIBRA result -> 3σ at reach in 2022 (5 years of measurement)
  - 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 – 2.7σ

Corollary

How to explain DAMA/LIBRA positive result ?
If experiments using the same target do not find any modulation ….

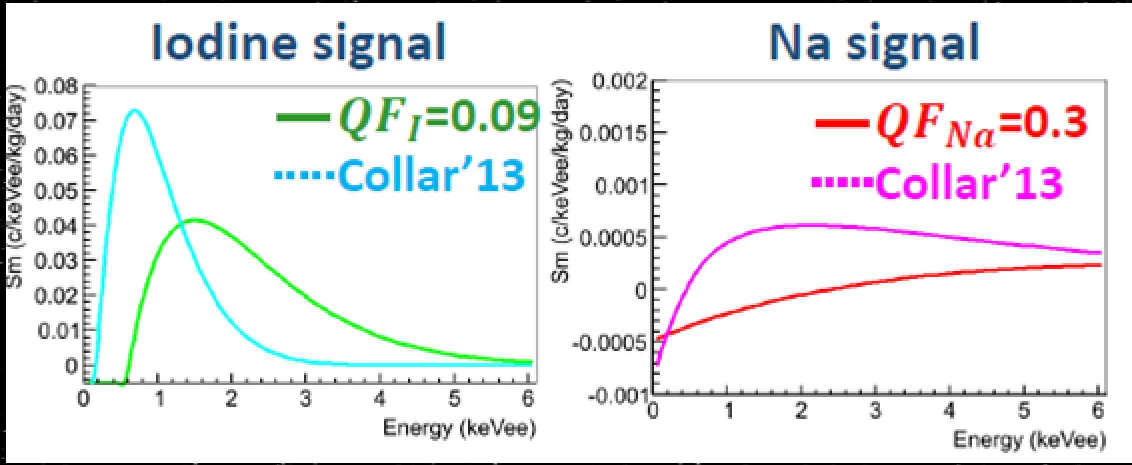
- Possible different response of detectors to nuclear recoils ?



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

Still too many uncertainties in the QF values and dependences for NaI

We have measured QF for different quality crystals, results soon



How to explain DAMA/LIBRA positive result ?
If experiments using the same target do not find any modulation ….

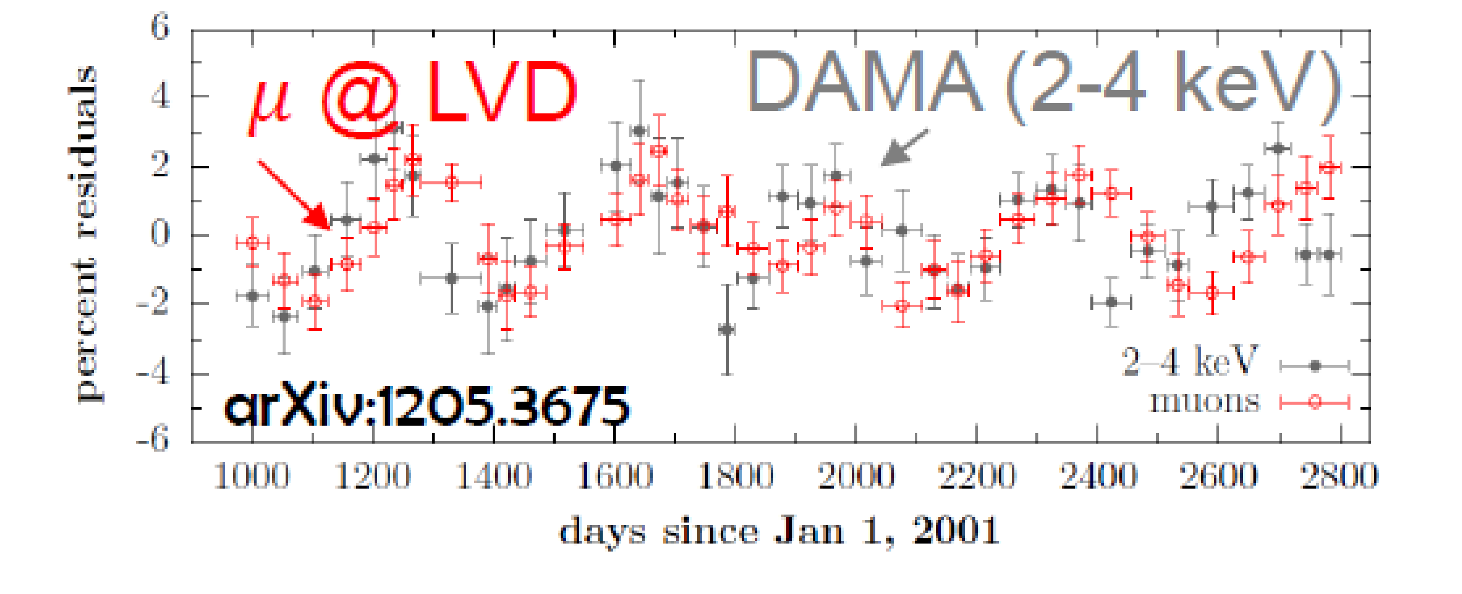
- **Muon related events ?**

DAMA reply:

-Phase of the modulation inconsistent

-Muon interactions do not fulfill DM requisites

-Muon induced fast neutrons are not enough



But …

We remove from our data muon related events, tagged by our Veto System

Additional analysis on these events is ongoing

Corollary

Can DAMA/LIBRA result be tested with experiments having smaller detection mass, smaller exposure and worse background in the Region Of Interest?

$$Sensitivity \propto \sqrt{\frac{MT\epsilon}{B}}$$

The modulation amplitude of DAMA/LIBRA is really large and then, our sensitivity is enough to do this test, however we cannot reach 5 σ in a reasonable time frame, lowering background is a must

Summary and Outlook

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  - Null hypothesis is well supported and best fits are incompatible at 3.3σ (1-6 keV energy energy region) with DAMA/LIBRA results → sensitivity: 2.5 – 2.7σ
- We are analysing **quenching factor on NaI crystals** to discard systemati parison
- Plan to make ANAIS **data public** after use to allow independent analysis

Sharing DATA and PROCEDURES
is the way to solve DAMA/LIBRA
puzzle