# Testing DAMA/LIBRA result with ANAIS-112 experiment at the Canfranc Underground Laboratory in Spain

- Annual modulation in direct detection of WIMPs
- DAMA/LIBRA result
- ANAIS experiment

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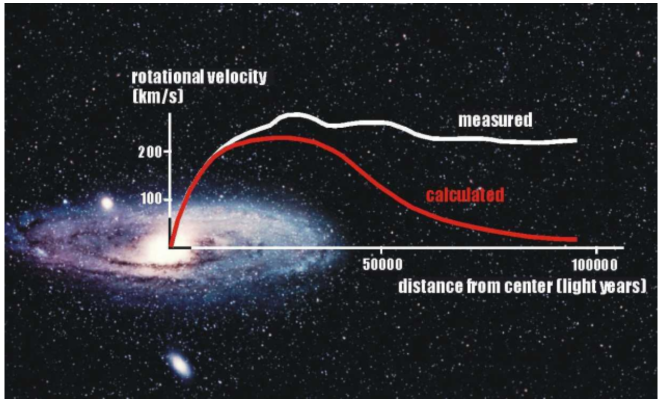
**Cosmology Seminars, Helsinki,** 4th December 2019

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Universidad Zaragoza
LSC Laboratorio Subterráneo de Canfranc

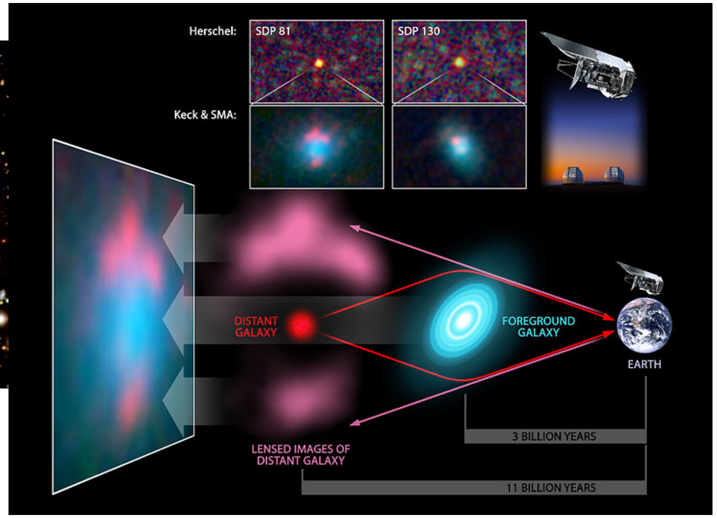
# Annual modulation

Overwhelming **evidence** of the existence of dark matter from observations

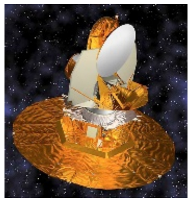
- **Galaxies:** flat rotation curves of spiral galaxies
- **Galaxy clusters:** gravitational lensing

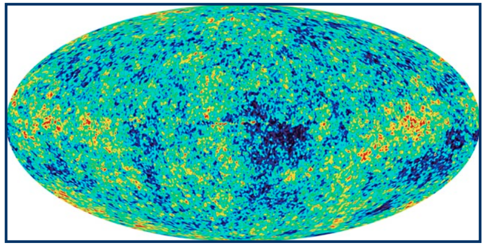


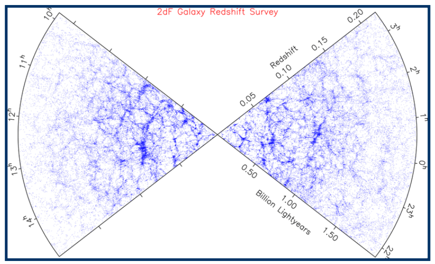


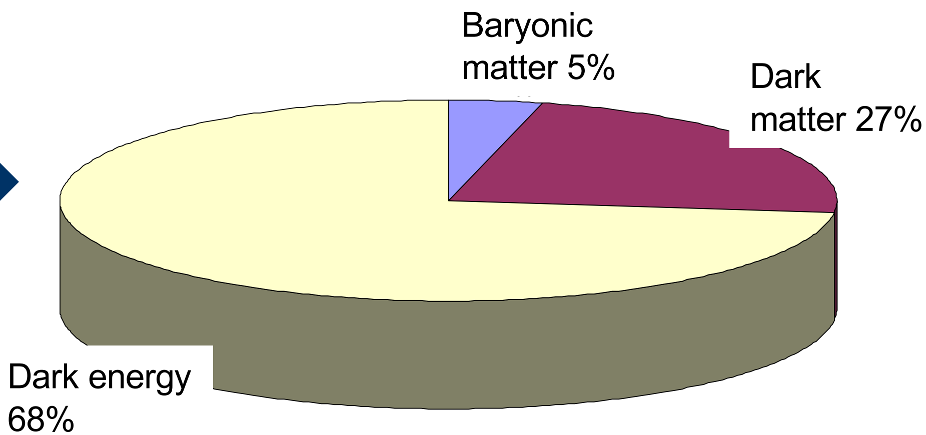



- **Universe:** supernovae Ia, Cosmic Microwave Background, galaxy maps





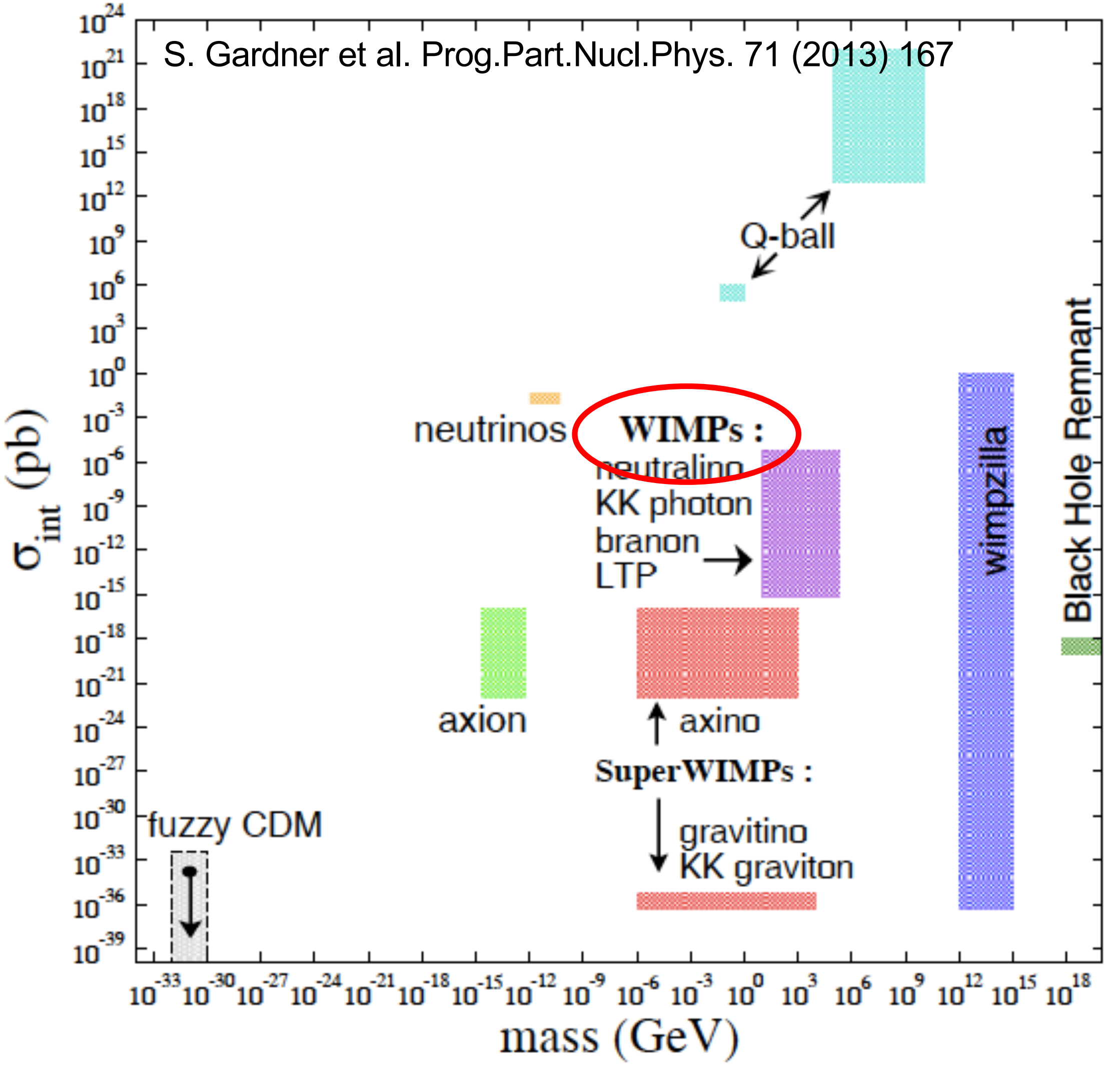



Supporting that a large fraction of the Universe budget is not explained within the Standard Model

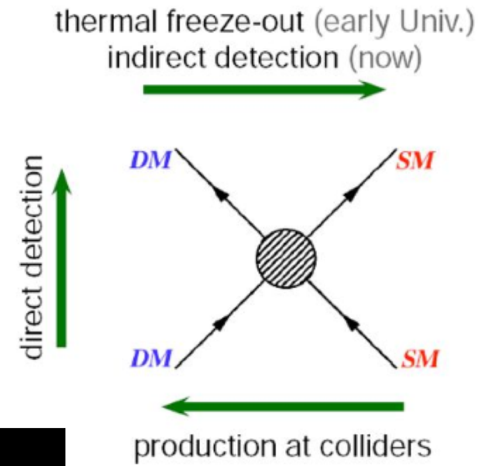
# Annual modulation

Plethora of dark matter **candidates:** non-zero-mass particles having a very low interaction probability with baryonic matter.



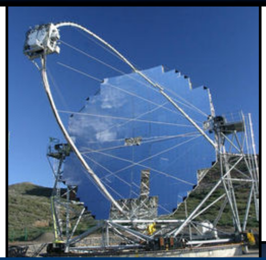
# Annual modulation

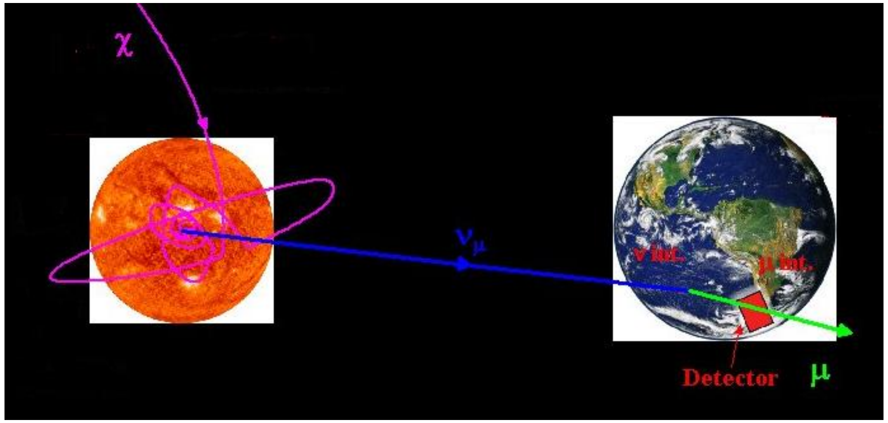
Different complementary strategies for **detection**




**Indirect detection:**

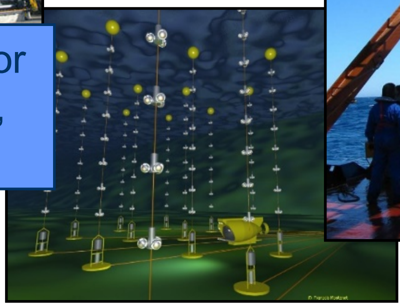
Annihilation → standard particles: $\gamma$, $\nu$, $e^+$, antiprotons



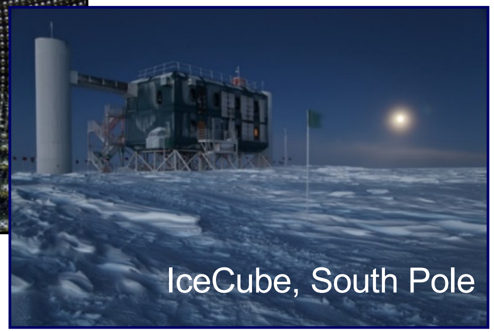



Detectors for antimatter: AMS

Observatories for $\gamma$ rays: MAGIC, FERMI



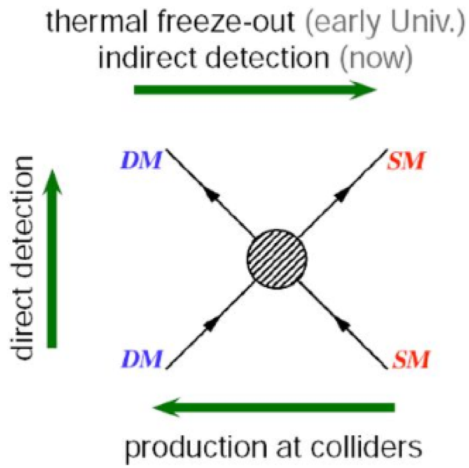




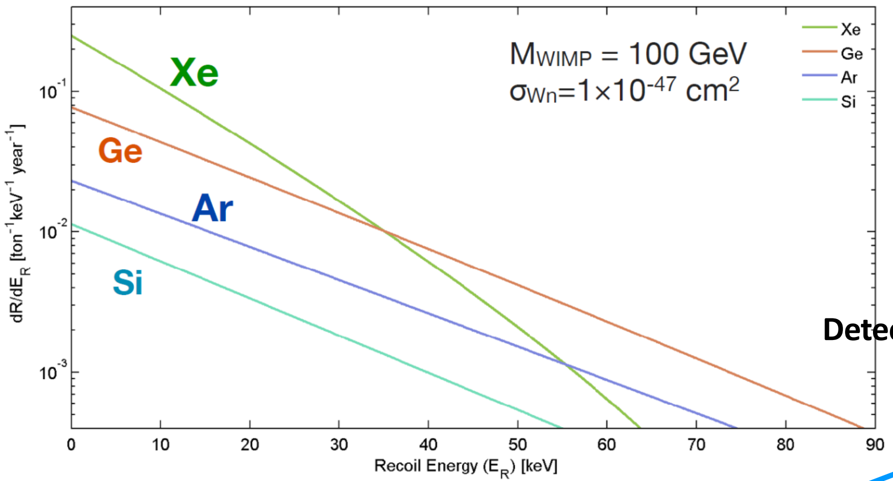

Telescopes for $\nu$: ANTARES, SuperKamiokande, IceCUBE

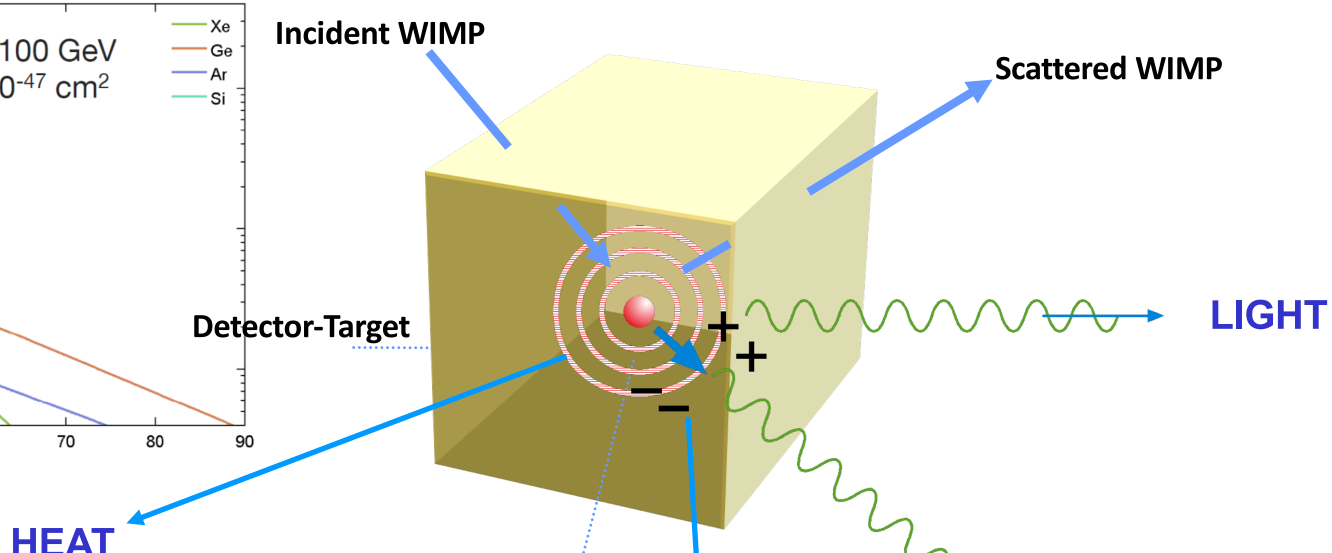
# Annual modulation

Different complementary strategies for **detection**



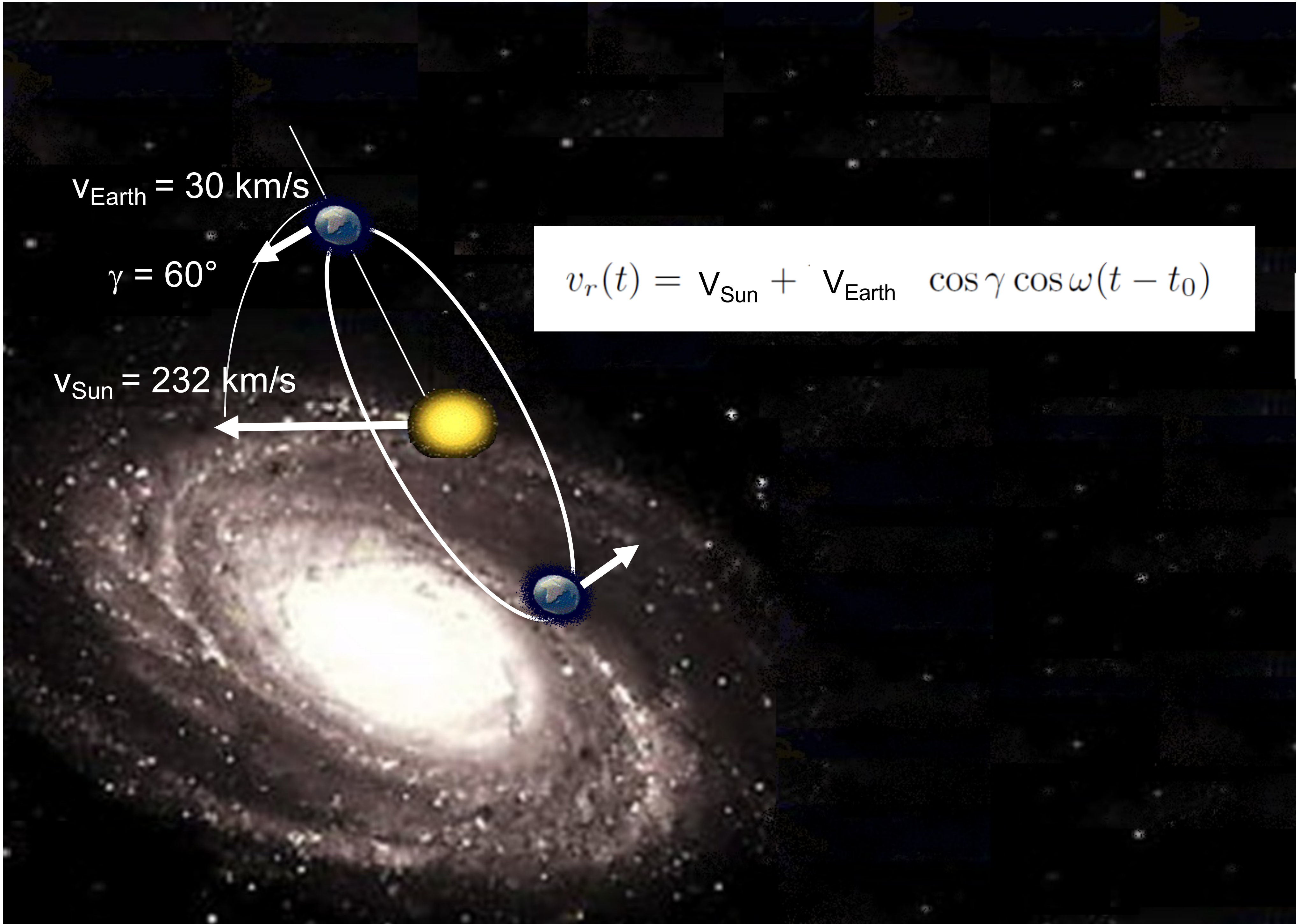

**Direct detection:** elastic scattering off target nuclei




$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

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




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

# Annual modulation

**Distinctive signal** in the interaction rate of WIMPs

$$S_k(y) = S_{0,k} + \left(\frac{\partial S_k}{\partial y}\right)_{y_0} \Delta y \cos\omega(t - t_0) = S_{0,k} + S_{m,k} \cos\omega(t - t_0)$$

$$y = \sqrt{\frac{3}{2}} \frac{v_r}{v_{rms}}$$

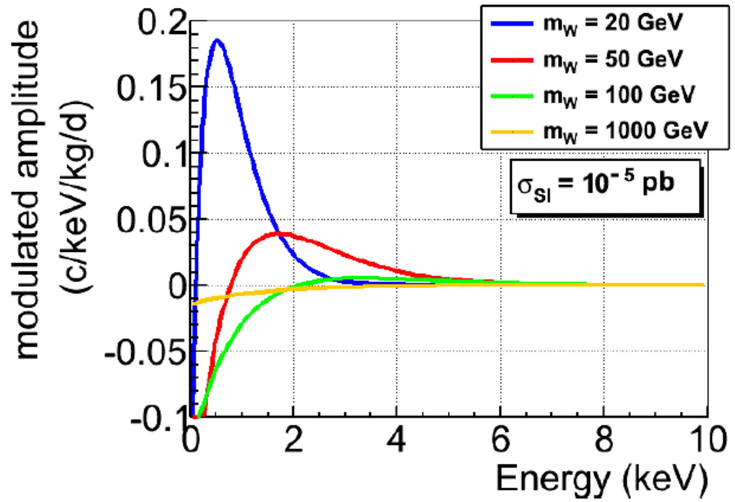
*k:* bin energy

- ✓ 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

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

No background known to mimic the effect

**Challenge:** several years of measurement in very stable conditions



# Testing DAMA/LIBRA result with ANAIS-112 experiment at the Canfranc Underground Laboratory in Spain

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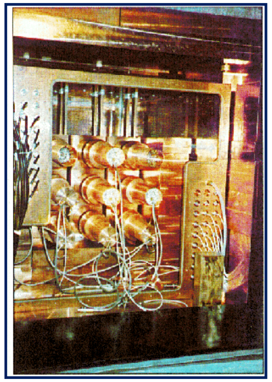
# DAMA / LIBRA: experiment and results

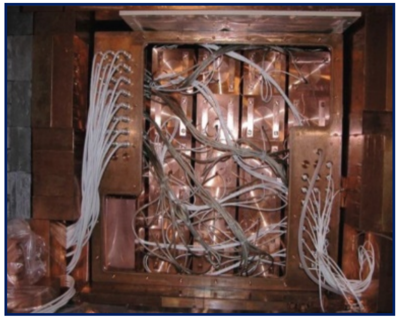

**DAMA/NaI & DAMA/LIBRA (phase 1)**
Laboratori Nazionali del Gran Sasso, Italy

## DAMA / NaI (1995-2002)

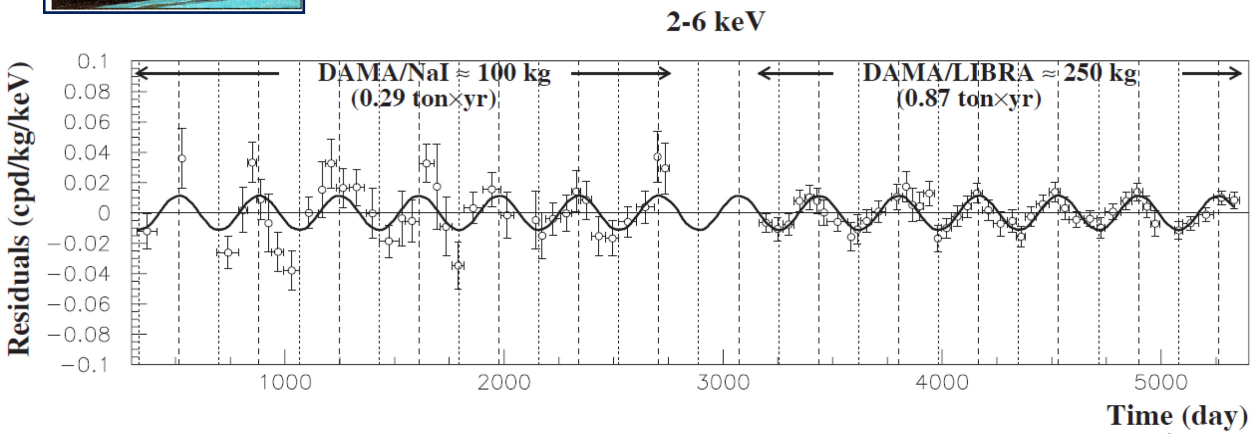


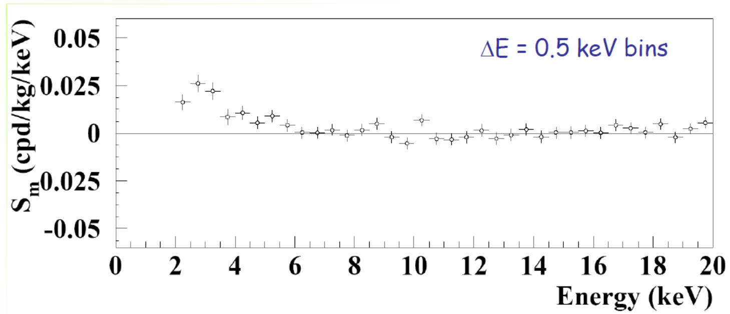
- 9 × 9.7 kg NaI(Tl) (3x3 detector matrix)
- 7 annual cycles
- Exposure: 0.29 ton × y

## DAMA / LIBRA (2003-2010)



- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure: 1.17 ton × y



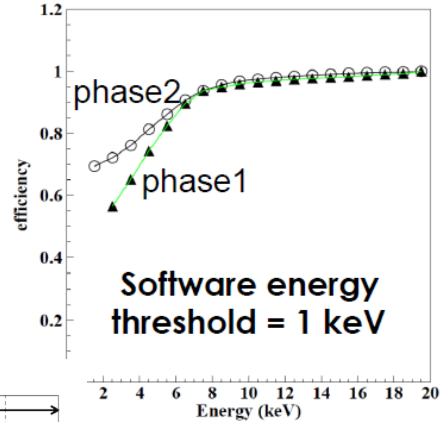

Solid line: $Cos\omega(t - t_0)$, with period 1 year and phase on June 2nd

R. Bernabei et al, Eur. Phys. J. C 73 (2013) 2648

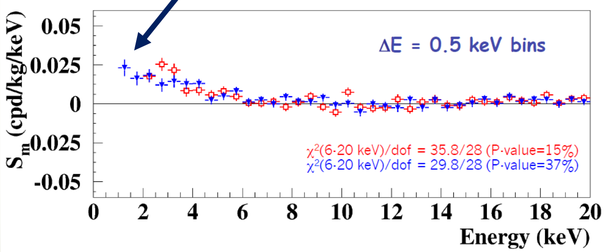
# DAMA / LIBRA: experiment and results

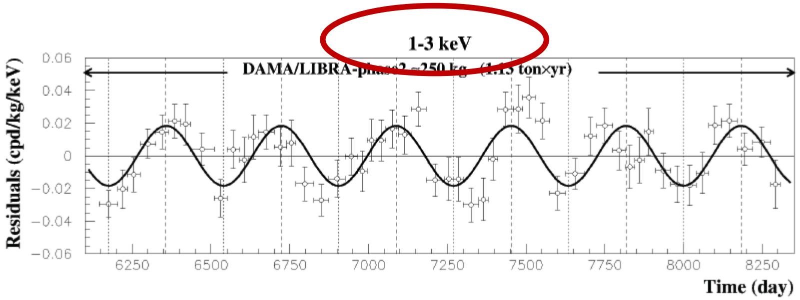
**DAMA/LIBRA phase2 (2011-2018)**

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

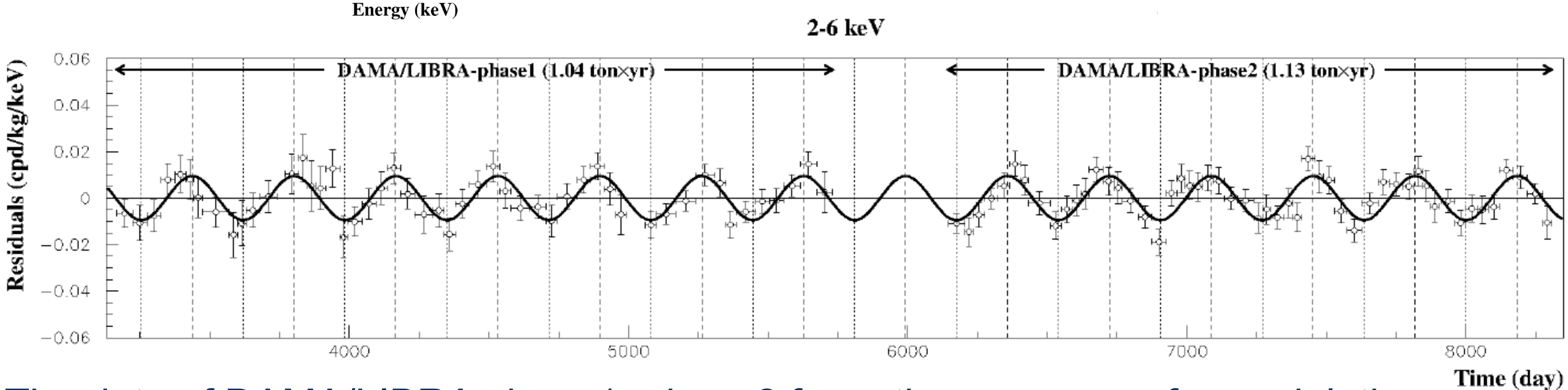



2 more points




- 6 annual cycles
- Exposure: 1.13 ton × y



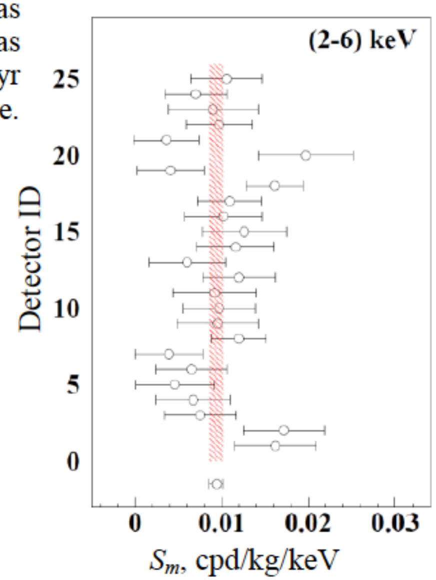

The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at **12.9σ CL** (2.46 ton × yr)

R. Bernabei et al, Nucl. Phys. At. Energy 19, 307 (2018)

# DAMA / LIBRA: experiment and results

| | | $A$, cpd/kg/keV | $T = 2\pi/\omega$, yr | $t_0$, d | C.L. |
|---|---|---|---|---|---|
| DAMA/LIBRA-phase2: | | | | | |
| | 1 - 3 keV | (0.0184 ± 0.0023) | 1.0 | 152.5 | 8.0 σ |
| | 1 - 6 keV | (0.0105 ± 0.0011) | 1.0 | 152.5 | 9.5 σ |
| | 2 - 6 keV | (0.0095 ± 0.0011) | 1.0 | 152.5 | 8.6 σ |
| | 1 - 3 keV | (0.0184 ± 0.0023) | (1.0000 ± 0.0010) | 153 ± 7 | 8.0 σ |
| | 1 - 6 keV | (0.0106 ± 0.0011) | (0.9993 ± 0.0008) | 148 ± 6 | 9.6 σ |
| | 2 - 6 keV | (0.0096 ± 0.0011) | (0.9989 ± 0.0010) | 145 ± 7 | 8.7 σ |
| DAMA/LIBRA-phase1 + phase2: | | | | | |
| | 2 - 6 keV | (0.0095 ± 0.0008) | 1.0 | 152.5 | 11.9 σ |
| | 2 - 6 keV | (0.0096 ± 0.0008) | (0.9987 ± 0.0008) | 145 ± 5 | 12.0 σ |
| DAMA/NaI + DAMA/LIBRA-phase1 + phase2: | | | | | |
| | 2 - 6 keV | (0.0102 ± 0.0008) | 1.0 | 152.5 | 12.8 σ |
| | 2 - 6 keV | (0.0103 ± 0.0008) | (0.9987 ± 0.0008) | 145 ± 5 | 12.9 σ |

N o t e. Modulation amplitudes, $A$, obtained by fitting the *single-hit* residual rate of DAMA/LIBRA-phase2, as reported in Fig. 2, and also including the residual rates of the former DAMA/NaI and DAMA/LIBRA-phase1. It was obtained by fitting the data with the formula: $A \cos \omega(t - t_0)$. The period $T = 2\pi/\omega$ and the phase $t_0$ are kept fixed at 1 yr and at 152.5 d (June 2nd), respectively, as expected by the DM annual modulation signature, and alternatively kept free. The results are well compatible with expectations for a signal in the DM annual modulation signature.




Modulation amplitudes deduced compatible for: different fitting procedures, periods of time, energy regions from 1 to 6 keV, detector units

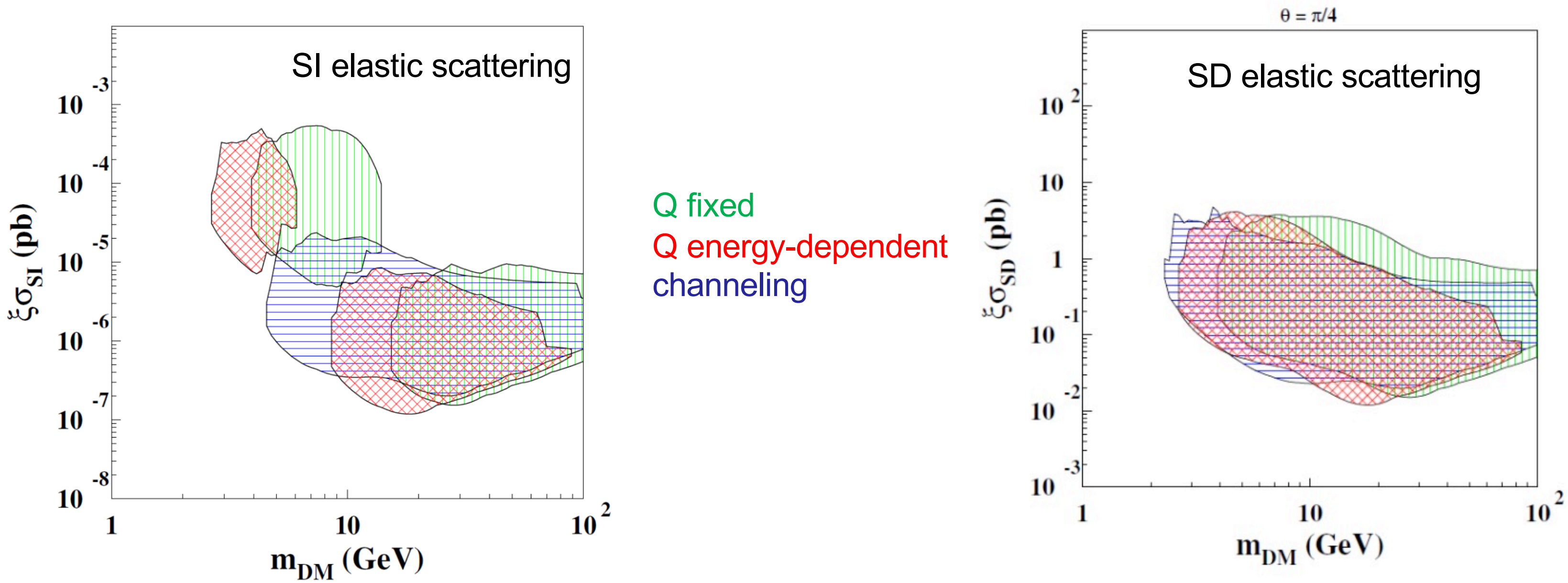


R. Bernabei et al, Nucl. Phys. At. Energy 19, 307 (2018)

# DAMA / LIBRA: experiment and results

Improved **model-dependent corollary analyses after DAMA/LIBRA-phase2**: maximum likelihood procedure to derive **allowed regions** in the parameters' space of each considered scenario by comparing the measured annual modulation amplitude with the theoretical expectation ($S_{m,k}$)

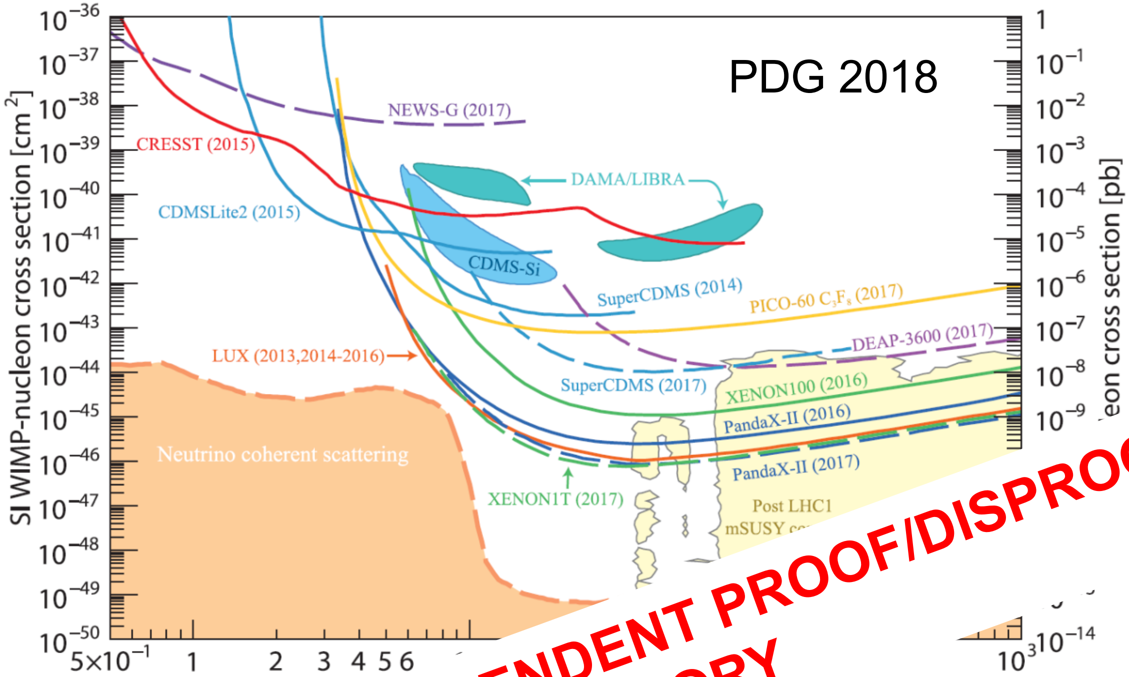
- Allowed intervals at 10$\sigma$ from the null signal hypothesis
- Accounting for uncertainties in halo models and parameters, quenching factor, channeling, Tl impurities effect…




Also scenarios with preferred electron interaction, preferred inelastic scattering, light DM, asymmetric and symmetric mirror DM

R. Bernabei et al, arXiv:1907.06405v1 [hep-ph])

# DAMA / LIBRA: other experiments




Strong **tension** when interpreting DAMA/L... A anual modul... ...s Dark ... ...general ...action models

**A MODEL-INDEPENDENT PROOF/DISPROOF WITH THE SAME NaI TARGET WAS MANDATORY**

No annua... ...n other experiments

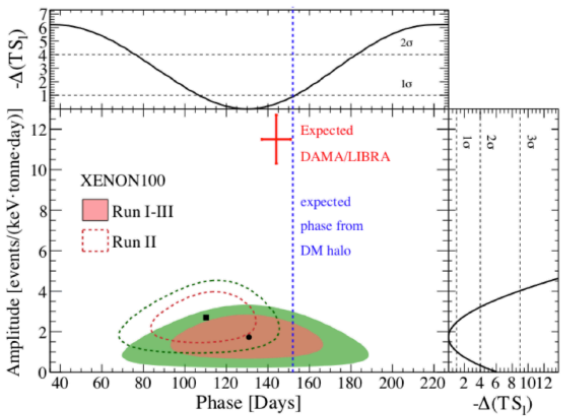
XE...
E. Ap... ...ev. Lett. 118, 101101 (2017)

XMA...
K. Abe et al, Phys. Rev. D 97, 102006 (2018)
M. Kobayashi et al, Phys. Lett. B 795 (2019) 308

LUX
D.S. Akerib et al, Phys. Rev. D 98, 062005 (2018)

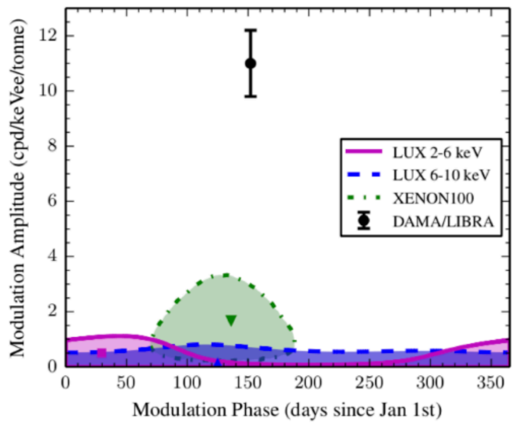
CDEX
L.T. Yang et al, Phys. Rev. Lett. 123 (2019) 221301

XENON100




>5σ tension with DAMA*

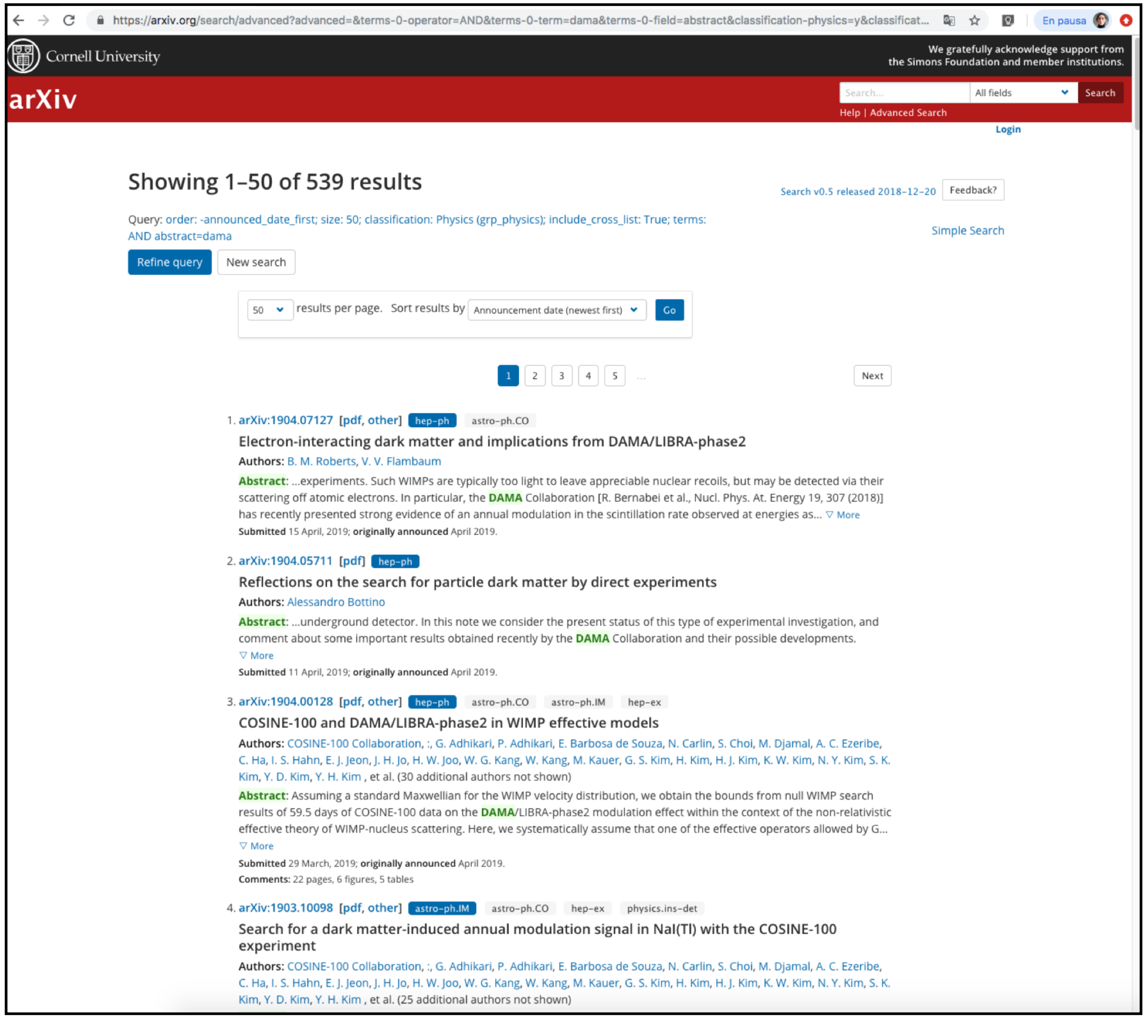
LUX




>9σ tension with DAMA*

# DAMA / LIBRA: other experiments

Hundreds of papers trying to understand the DAMA conundrum!


https://arxiv.org/search/advanced?advanced=&terms-0-operator=AND&terms-0-term=dama&terms-0-field=abstract&classification-physics=y&classificat...

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

arXiv

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Query: order: -announced_date_first; size: 50; classification: Physics (grp_physics); include_cross_list: True; terms: AND abstract=dama

Simple Search

Refine query New search

50 results per page. Sort results by Announcement date (newest first) Go

1 2 3 4 5 … Next

1. arXiv:1904.07127 [pdf, other] hep-ph astro-ph.CO

Electron-interacting dark matter and implications from DAMA/LIBRA-phase2

Authors: B. M. Roberts, V. V. Flambaum

Abstract: ...experiments. Such WIMPs are typically too light to leave appreciable nuclear recoils, but may be detected via their scattering off atomic electrons. In particular, the DAMA Collaboration [R. Bernabei et al., Nucl. Phys. At. Energy 19, 307 (2018)] has recently presented strong evidence of an annual modulation in the scintillation rate observed at energies as... ▽ More

Submitted 15 April, 2019; originally announced April 2019.

2. arXiv:1904.05711 [pdf] hep-ph

Reflections on the search for particle dark matter by direct experiments

Authors: Alessandro Bottino

Abstract: ...underground detector. In this note we consider the present status of this type of experimental investigation, and comment about some important results obtained recently by the DAMA Collaboration and their possible developments. ▽ More

Submitted 11 April, 2019; originally announced April 2019.

3. arXiv:1904.00128 [pdf, other] hep-ph astro-ph.CO astro-ph.IM hep-ex

COSINE-100 and DAMA/LIBRA-phase2 in WIMP effective models

Authors: COSINE-100 Collaboration, :, G. Adhikari, P. Adhikari, E. Barbosa de Souza, N. Carlin, S. Choi, M. Djamal, A. C. Ezeribe, C. Ha, I. S. Hahn, E. J. Jeon, J. H. Jo, H. W. Joo, W. G. Kang, W. Kang, M. Kauer, G. S. Kim, H. Kim, H. J. Kim, K. W. Kim, N. Y. Kim, S. K. Kim, Y. D. Kim, Y. H. Kim , et al. (30 additional authors not shown)

Abstract: Assuming a standard Maxwellian for the WIMP velocity distribution, we obtain the bounds from null WIMP search results of 59.5 days of COSINE-100 data on the DAMA/LIBRA-phase2 modulation effect within the context of the non-relativistic effective theory of WIMP-nucleus scattering. Here, we systematically assume that one of the effective operators allowed by G... ▽ More

Submitted 29 March, 2019; originally announced April 2019.

Comments: 22 pages, 6 figures, 5 tables

4. arXiv:1903.10098 [pdf, other] astro-ph.IM astro-ph.CO hep-ex physics.ins-det

Search for a dark matter-induced annual modulation signal in NaI(Tl) with the COSINE-100 experiment

Authors: COSINE-100 Collaboration, :, G. Adhikari, P. Adhikari, E. Barbosa de Souza, N. Carlin, S. Choi, M. Djamal, A. C. Ezeribe, C. Ha, I. S. Hahn, E. J. Jeon, J. H. Jo, H. W. Joo, W. G. Kang, W. Kang, M. Kauer, G. S. Kim, H. Kim, H. J. Kim, K. W. Kim, N. Y. Kim, S. K. Kim, Y. D. Kim, Y. H. Kim , et al. (25 additional authors not shown)

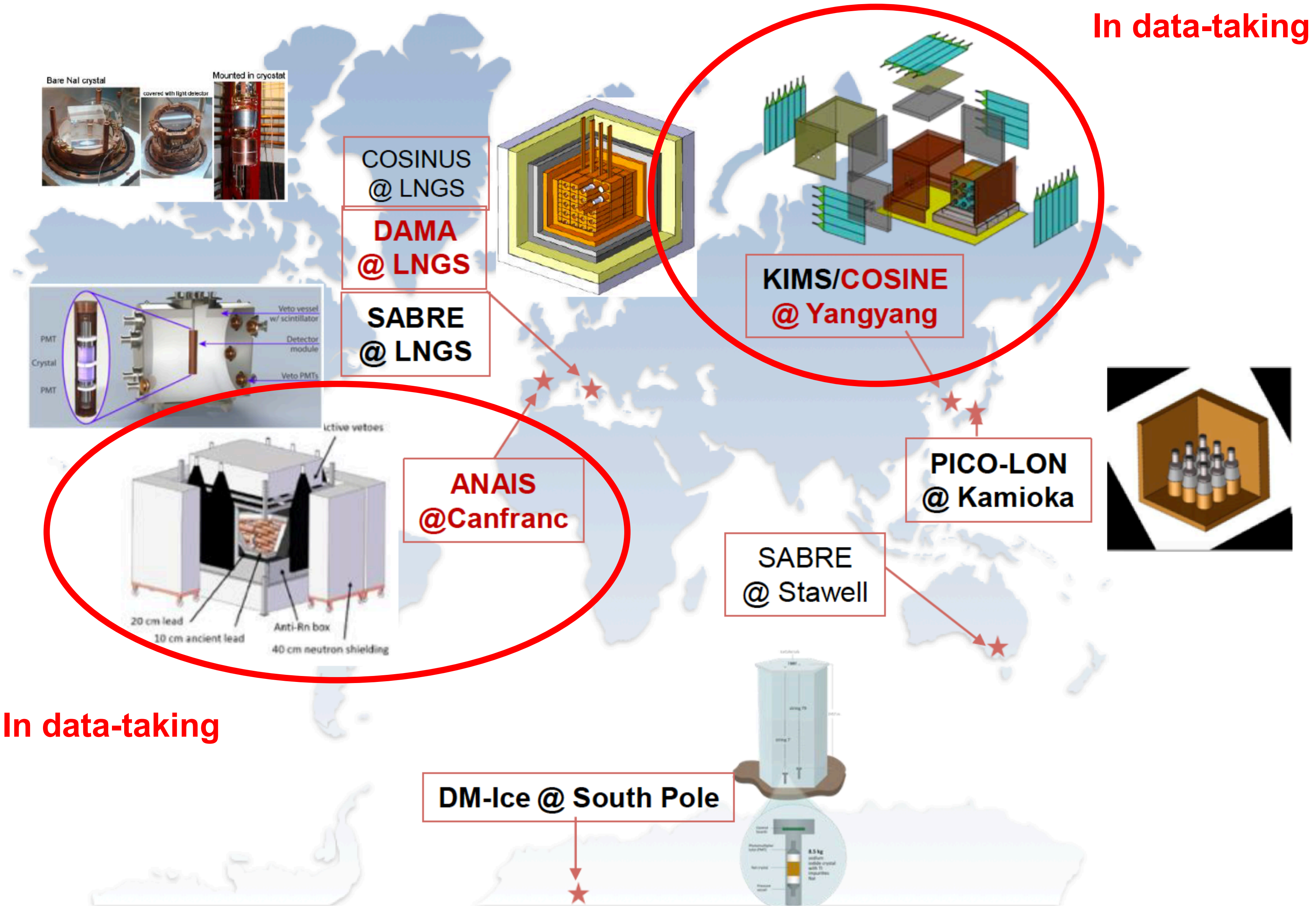
**Particles and Interactions:** mirror / scalar / pseudoscalar / inelastic / hidden sector / anapole / self-interacting / SIMP / leptophilic / xenonphobic / multi-component dark matter, …

**Astrophysical uncertainties:** halo, velocities ($v_{esc}$, $v_{Sun}$), dark matter density …

**Backgrounds:** muons, neutrons, solar neutrinos, He atoms …

**Detector effects:** quenching, channeling, …

# Other NaI experiments



# Other NaI experiments: COSINE-100

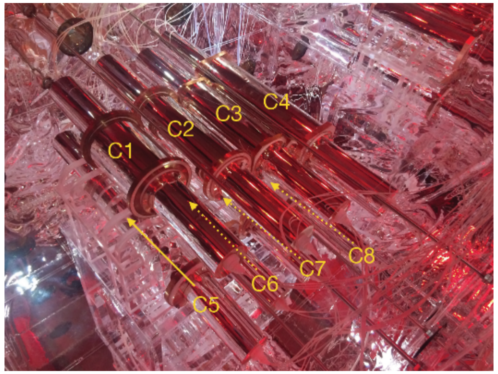
KIMS + DM-ICE

- At **Yangyang** underground Laboratory, South Korea
- 8 NaI(Tl) crystals from Alpha Spectra, **106 kg** in total
- Inmersed in 2200 l of liquid scintillator
- **Threshold at 2 keV$_{ee}$**
- Physics run started in September 2016

G. Adhikari et al
Eur. Phys. J. C (2018) 78:107

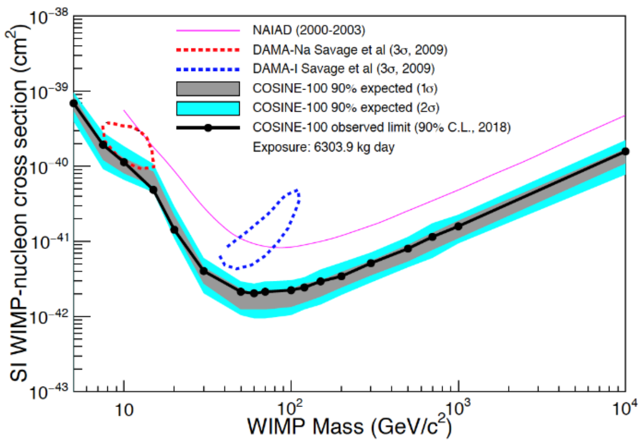
P. Adhikari et al
Eur. Phys. J. C (2018) 78:490

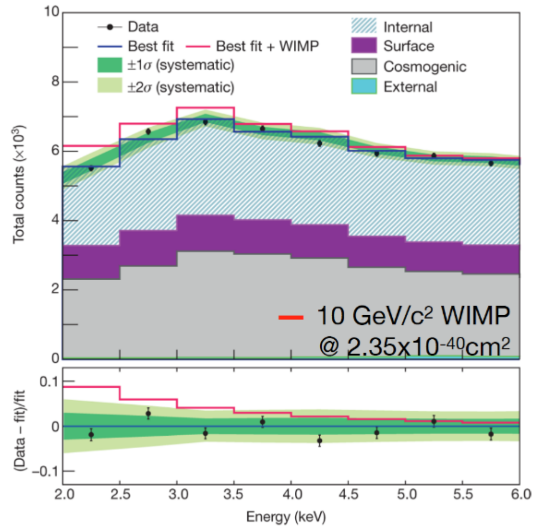
COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin-independent WIMP with Standard Halo Model in NaI(Tl)




## Spin-Independent WIMP Search

Nature **564** 83-86 (2018)




- First 6303.9 kg•da exposure (SET1, 59.5 days)
- Spectrum fit for 2-20 keV bgd + WIMP

# Other NaI exper

JCAP06(2019)048

**COSINE–100 and DAMA/LIBRA-phase2 in WIMP effective models**


The COSINE-100 Collaboration
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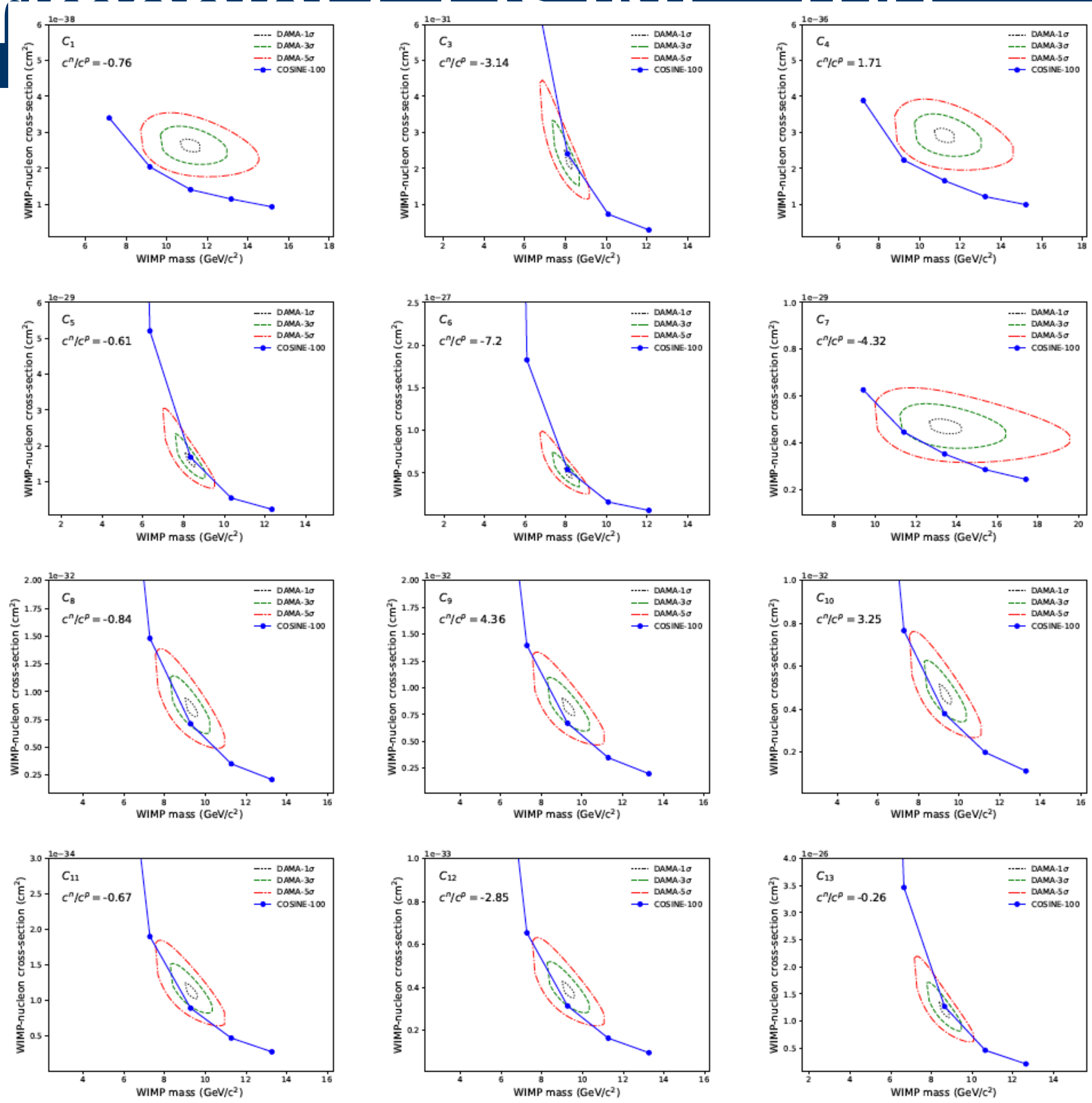
The Sogang Phenomenology Group
Sunghyun Kang[aa] Stefano Scopel[aa] Gaurav Tomar[aa] and Jong–Hyun Yoon[aa,bb]

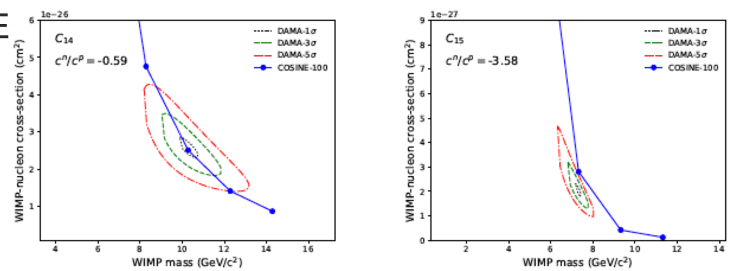


**Abstract.** Assuming a standard Maxwellian for the WIMP velocity distribution, we obtain the bounds from null WIMP search results of 59.5 days of COSINE–100 data on the DAMA/LIBRA–phase2 modulation effect within the context of the non–relativistic effective theory of WIMP–nucleus scattering. Here, we systematically assume that one of the effective operators allowed by Galilean invariance dominates in the effective Hamiltonian of a spin–1/2 dark matter (DM) particle. We find that, although DAMA/LIBRA and COSINE–100 use the same sodium–iodide target, the comparison of the two results still depends on the particle–physics model. This is mainly due to two reasons: i) the WIMP signal spectral shape used for background subtraction in COSINE–100; ii) the expected modulation fractions, when the upper bound on the time–averaged rate in COSINE–100 is converted into a constraint on the annual modulation component in DAMA/LIBRA. We find that the latter effect is the dominant one. For several effective operators the expected modulation fractions are larger than in the standard spin–independent or spin–dependent interaction cases. As a consequence, compatibility between the modulation effect observed in DAMA/LIBRA and the null result from COSINE–100 is still possible for several non–relativistic operators. At low WIMP masses such relatively high values of the modulation fractions arise because COSINE–100 is mainly sensitive to WIMP–sodium scattering events, due to the higher threshold compared to DAMA/LIBRA. A next COSINE analysis is expected to have a full sensitivity for the $5\,\sigma$ region of DAMA/LIBRA.


| | |
|---|---|
| $\mathcal{O}_1 = 1_\chi 1_N$ | $\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$ |
| $\mathcal{O}_2 = (v^\perp)^2$ | $\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$ |
| $\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$ | $\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$ |
| $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$ | $\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$ |
| $\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$ | $\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$ |
| $\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$ | $\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$ |
| $\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$ | $\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$ |
| $\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$ | |



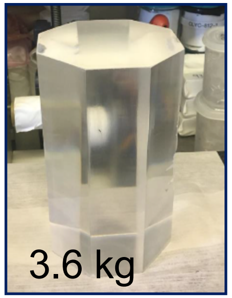

Exclusion plots from COSINE for each coupling of the Hamiltonian compared to the best fits to modulation amplitudes of DAMA/LIBRA

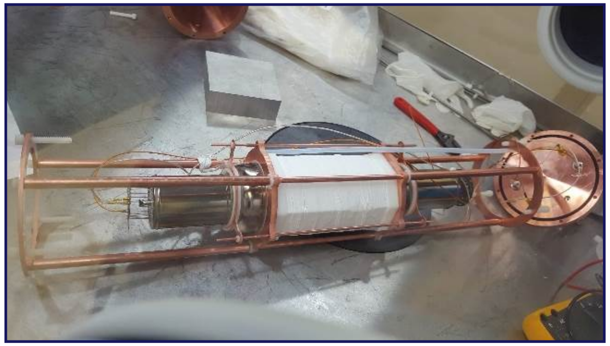


# Other NaI experiments: SABRE

## **S**odium-iodide with **A**ctive **B**ackground **RE**jection

In preparation at Laboratori Nazionali del Gran Sasso

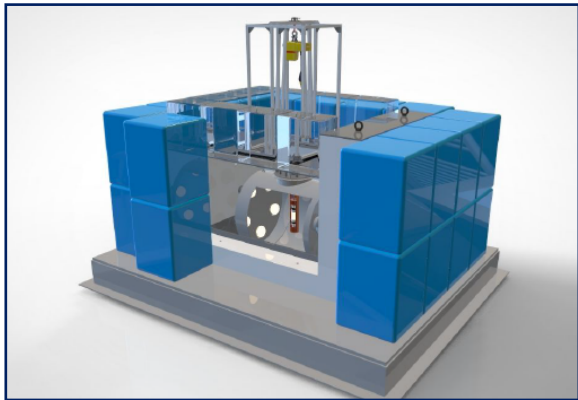


- New development of ultra-high purity NaI(Tl) crystals in US, up to **50 kg**
  ICPMS determination of **K**: 4 ppb at crystal

- Use of passive and **active (liquid scintillator veto)** shielding

- Tests with one detector (**SABRE Proof of Principle**, PoP): set-up ready at Hall C, crystal shipped to Gran Sasso

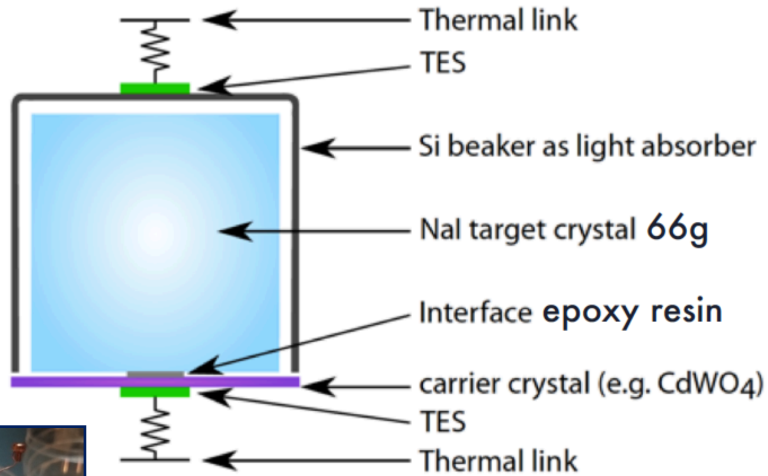


- **Two identical detectors in northern and southern hemispheres** (Gran Sasso and Stawell Laboratory in Australia)
  Seasonal backgrounds have opposite phase while dark matter signal the same

M. Antonello et al, Eur. Phys. J. C 79 (2019) 363

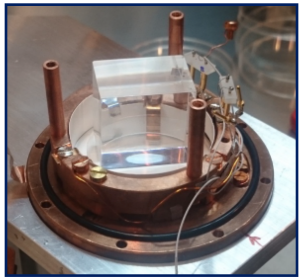
# Other NaI experiments: COSINUS

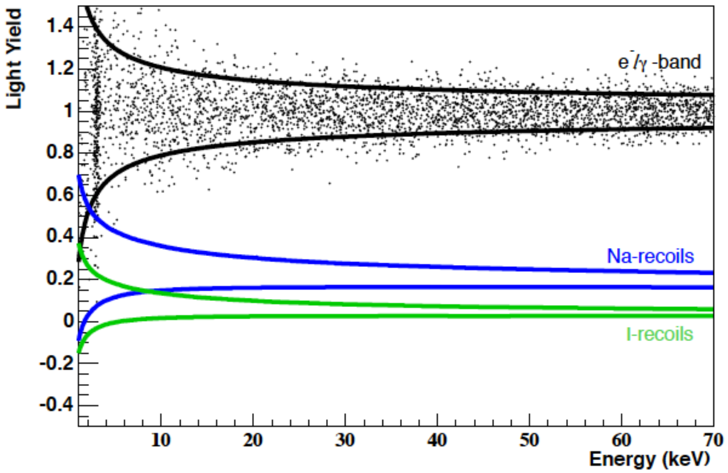
Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches




In preparation at Laboratori Nazionali del Gran Sasso

- Develoment of NaI **scintillating bolometers**: phonon signal independent of the particle type while scintillation light dependent
- Potential proved to **discriminate nuclear recoil events from β/γ background**
- Tests with small crystals, from SICCAS (China), set-up funded






G. Angloher et al., Eur. Phys. J. C 76 (2016) 441
F. Kahlhoefer et al, JCAP 05 (2018) 074

# Testing DAMA/LIBRA result with ANAIS-112 experiment at the Canfranc Underground Laboratory in Spain

- Annual modulation in direct detection of WIMPs
- DAMA/LIBRA result
- **ANAIS experiment**
  - Goals and history
  - Detector set-up
  - Performance and analysis
  - Background model
  - Annual modulation results and sensitivity

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**Cosmology Seminars, Helsinki,** 4th December 2019

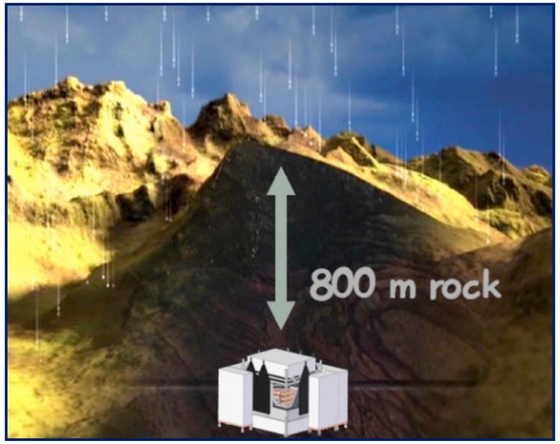
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Universidad Zaragoza

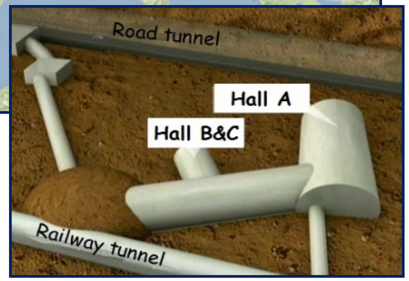
LSC
Laboratorio Subterráneo de Canfranc

# ANAIS: goals and history

**ANAIS** (*Annual modulation with NAI Scintillators*) intends to confirm the **DAMA/LIBRA** modulation signal using the **same target and technique** (3x3 detectors, 112.5 kg) in a different environment at the **Canfranc Underground Laboratory** (Spain)






**Experimental requirements:**

- Energy **threshold** at or below 1-2 $keV_{ee}$
- **Background** as low as possible below 10 $keV_{ee}$ (at or below a few cpd/keV/kg)
- Very stable operation conditions

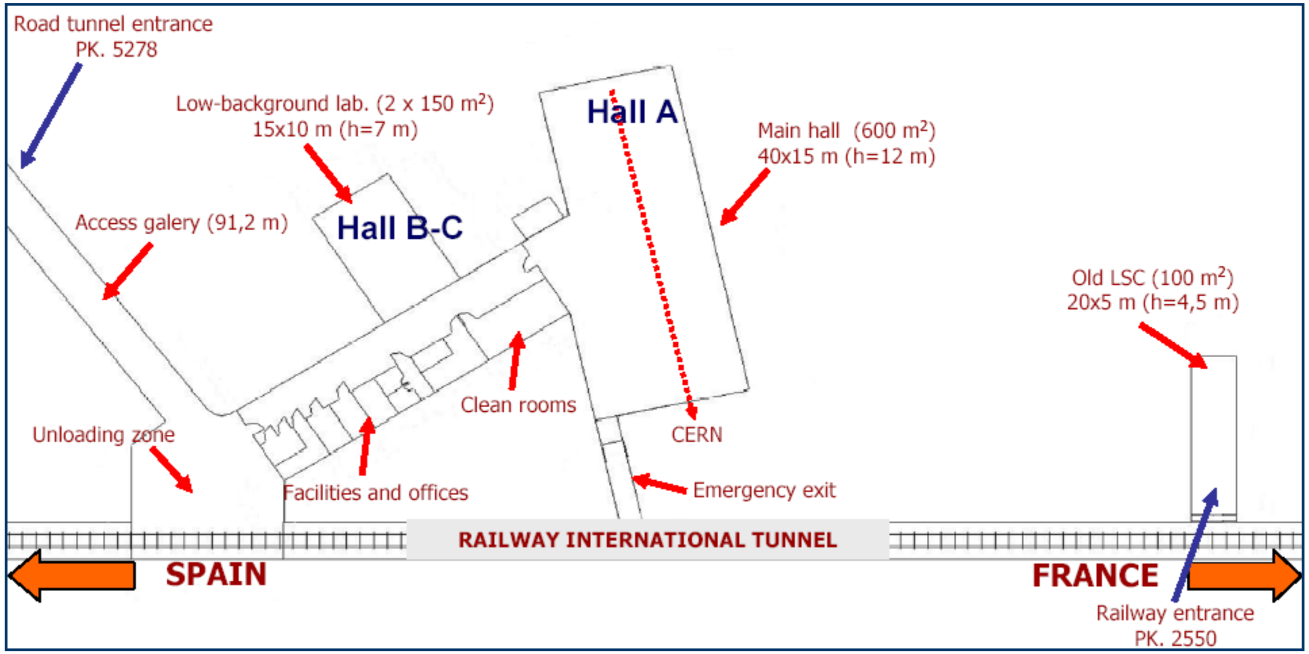
# ANAIS: Canfranc Underground Laboratory

- Since 1985, unique facility in Spain, officially opened up in 2006
- Under Tobazo mountain in the Spanish Pyrenees, at 2450 m.w.e.
- 1500 m$^2$ of underground facilities open to the international community + two external buildings

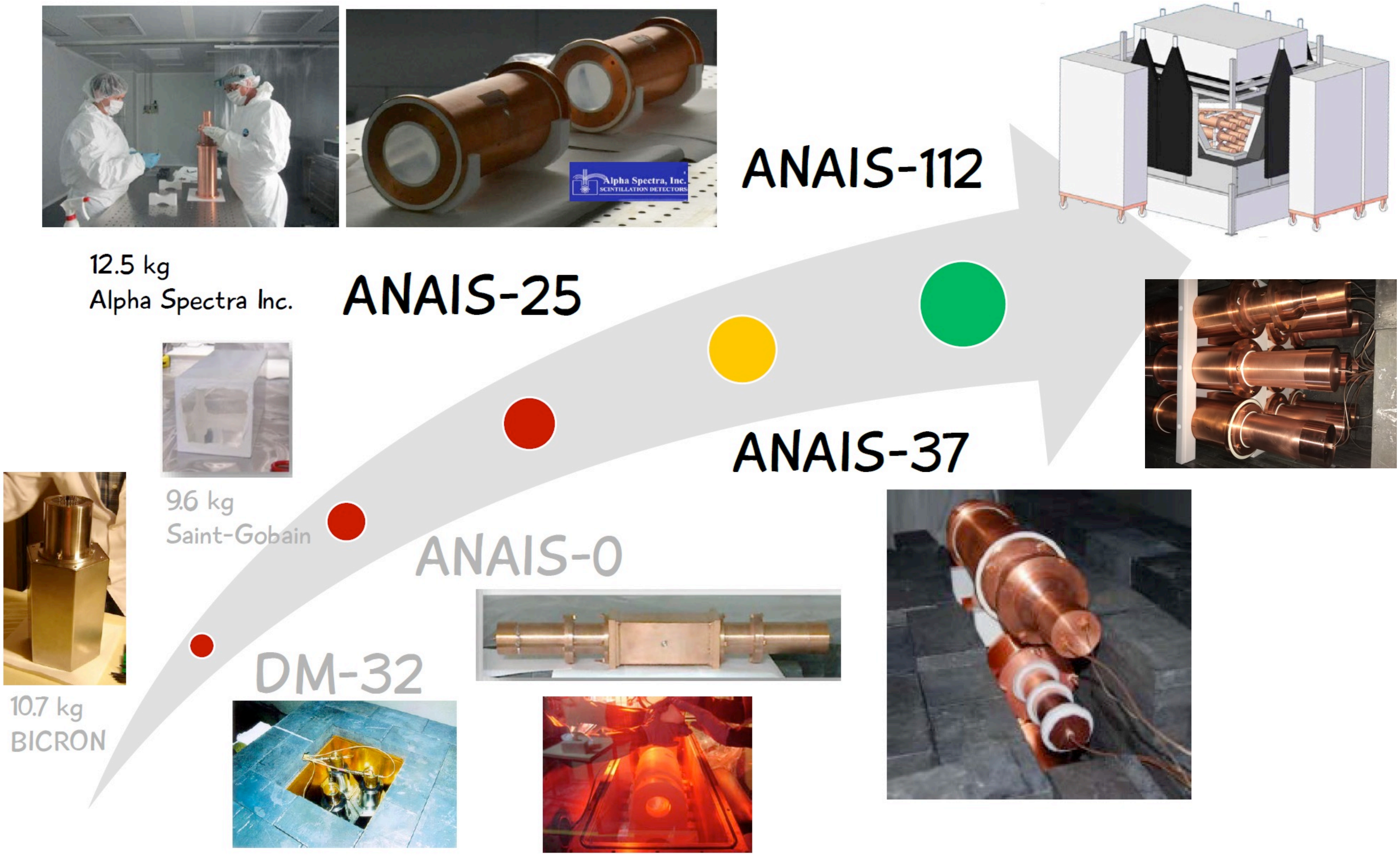
http://www.lsc-canfranc.es/

- Present experiments: **ArDM, TREX-DM** (dark matter); **NEXT, CROSS** (double beta decay)

https://www.facebook.com/LaboratorioSubterraneoDeCanfranc/videos/1390780341019803/



# ANAIS: goals and history



# ANAIS: goals and history

ELSEVIER

3 October 1996

Physics Letters B 386 (1996) 458–462

PHYSICS LETTERS B

## Searching for annual modulations of WIMPs with NaI scintillators

M.L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, J.A. Villar

*Laboratory of Nuclear and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain*

Received 18 June 1996
Editor: K. Winter

**Abstract**

A search for cold dark matter has been carried out at the Canfranc Undergr... sodium iodide scintillators during about two years of data taking. Boun... exposure of 4613.6 kg day are presented, both for spin-independe... predicted annual modulation of the signal has been also in... stronger than those derived from the conventional metho...

*PACS:* 95.35; 29.40.M; 14.60.S
*Keywords:* Scintillation counter; Dark matter; WIMPs; Underground...

PHYSICAL REVIEW D VOLUME 56, NUMBER 4 15 AUGUST 1997

## Results of a search for annual modulation of WIMP signals

M. L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, and J. A. Villar

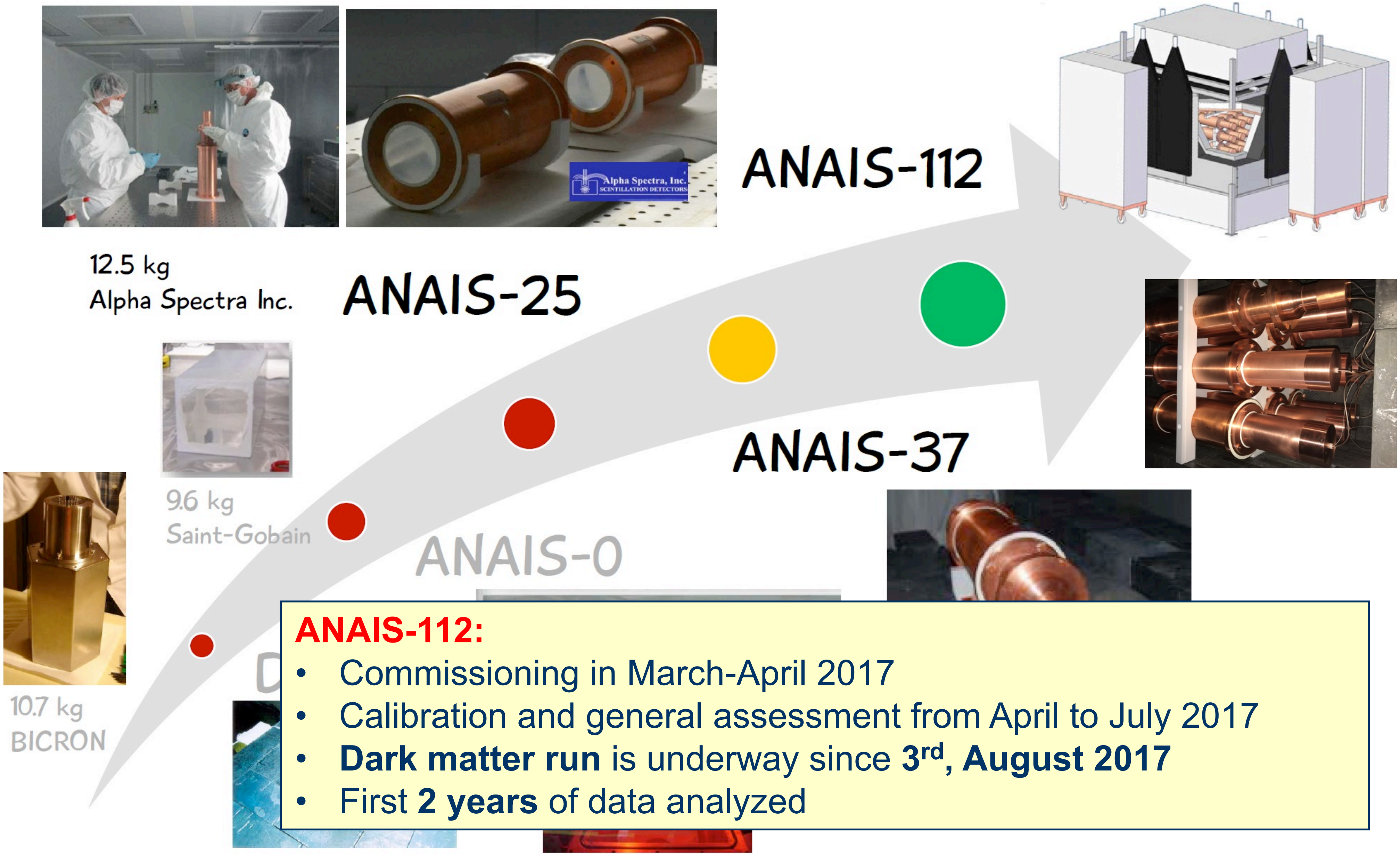
*Laboratory of Nuclear and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain*

(Received 20 January 1997)

A search for particle cold dark matter (CDM) has been carried out at the Canfranc Underground Laboratory (Spain) with a set of three sodium iodide scintillators of 10.7 kg each, during about 2 yr of data taking. The results, corresponding to an exposure of 4613.6 kg day are presented in the form of exclusion plots of the WIMP-target nuclei cross section versus WIMP mass (both for spin-independent and spin-dependent WIMP-matter interactions), obtained with the standard method of comparing the observed rate with the expected signal. A distinctive feature of the CDM signal, like its expected annual modulation, has also been looked for in 1342.8 kg day of data. The nonobservance of such a modulation has been used to draw more stringent exclusion plots than those derived from the standard method. [S0556-2821(97)02316-3]

PACS number(s): 95.35.+d, 14.60.St, 29.40.Mc

# ANAIS: goals and history



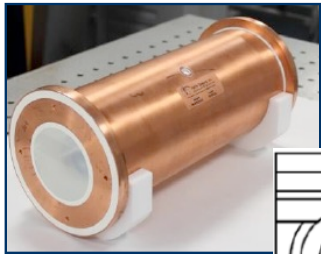

**ANAIS-112:**

- Commissioning in March-April 2017
- Calibration and general assessment from April to July 2017
- **Dark matter run** is underway since **3rd, August 2017**
- First **2 years** of data analyzed

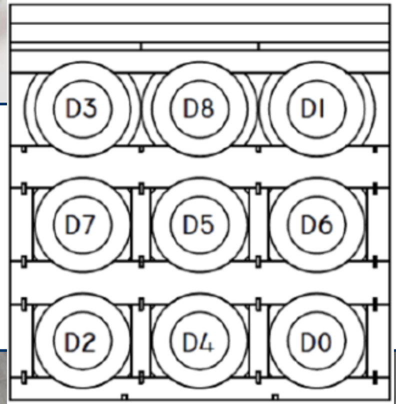
# Detector set-up: detectors

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

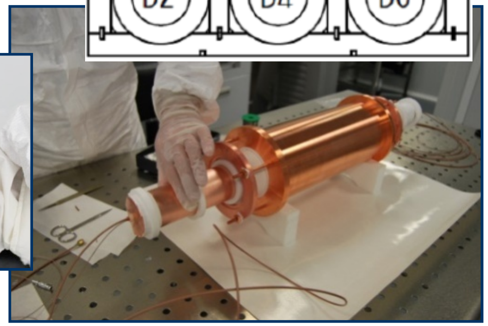
| *Detector* | *Quality powder* | *Received at Canfranc in* |
|---|---|---|
| **D0, D1** | <90 ppb K | December 2012 |
| **D2** | WIMPScint-II | March 2015 |
| **D3** | WIMPScint-III | March 2016 |
| **D4, D5** | WIMPScint-III | November 2016 |
| **D6, D7, D8** | WIMPScint-III | March 2017 |



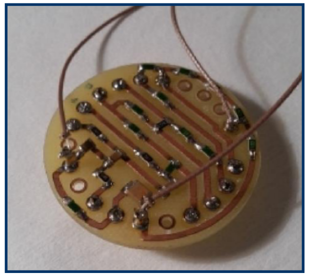
12.5 kg each
4.75'' diameter
11.75'' length




- **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

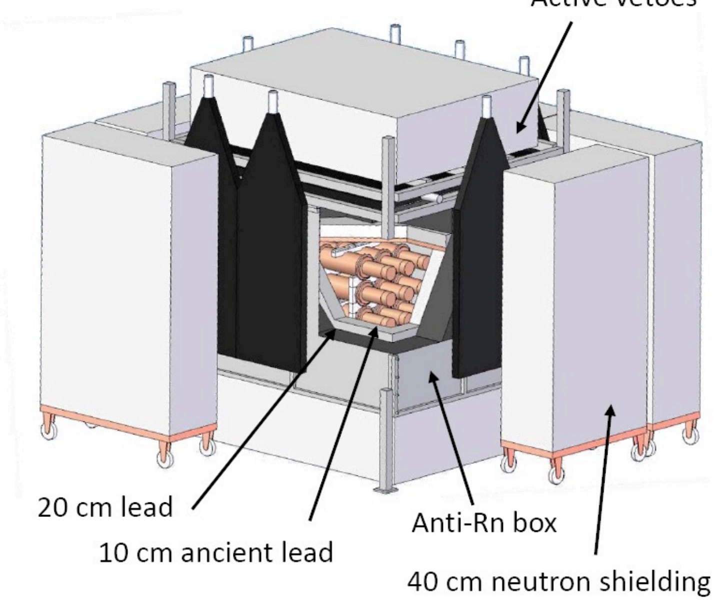


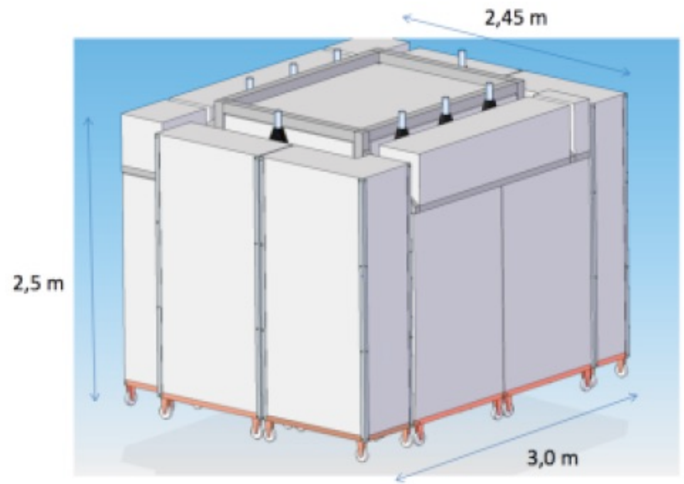
Voltage dividers in cuflon PCB

Housing made at LSC of electroformed copper

# Detector set-up: shielding

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



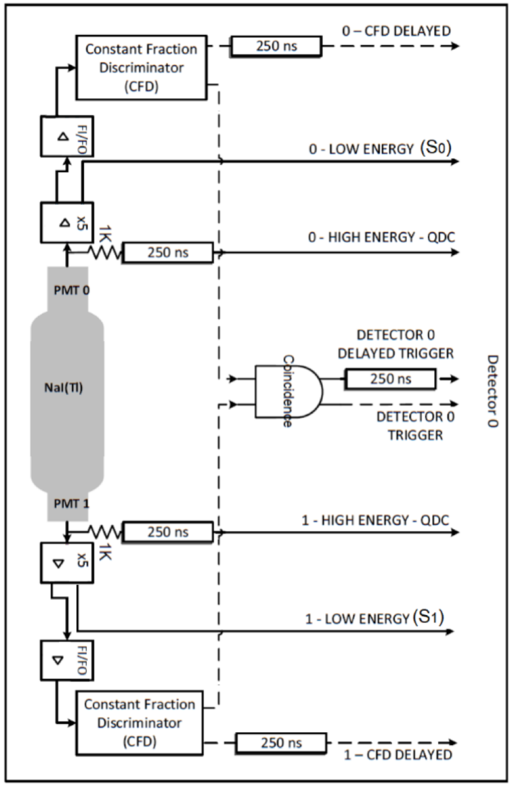



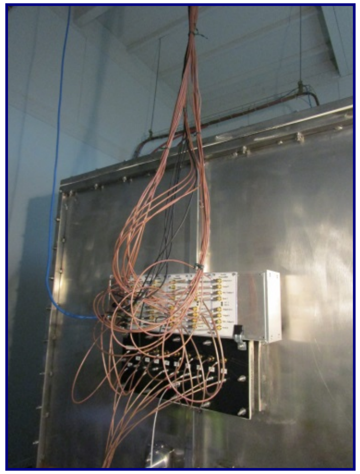


- Partial opening for periodic calibrations
- Radon-free **system** to allow calibration at low energy with **$^{109}$Cd sources** on flexible wires

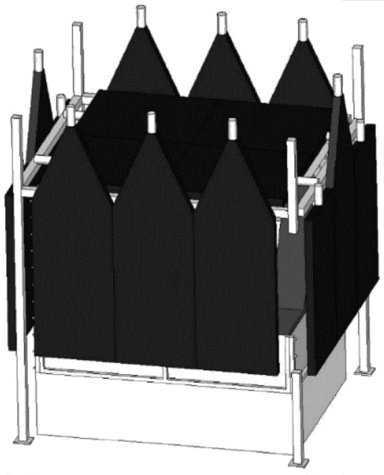
# Detector set-up: data acquisition

- **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



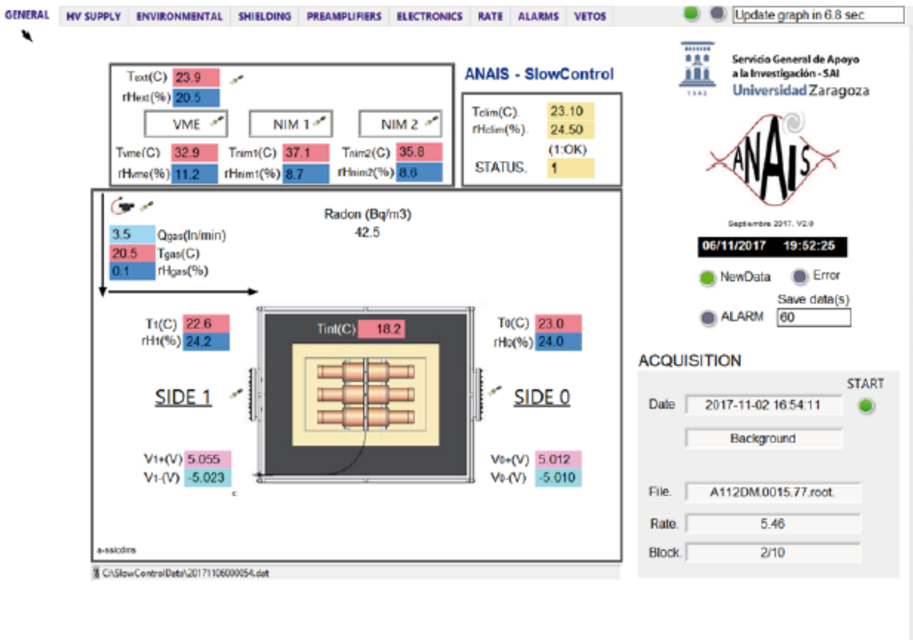



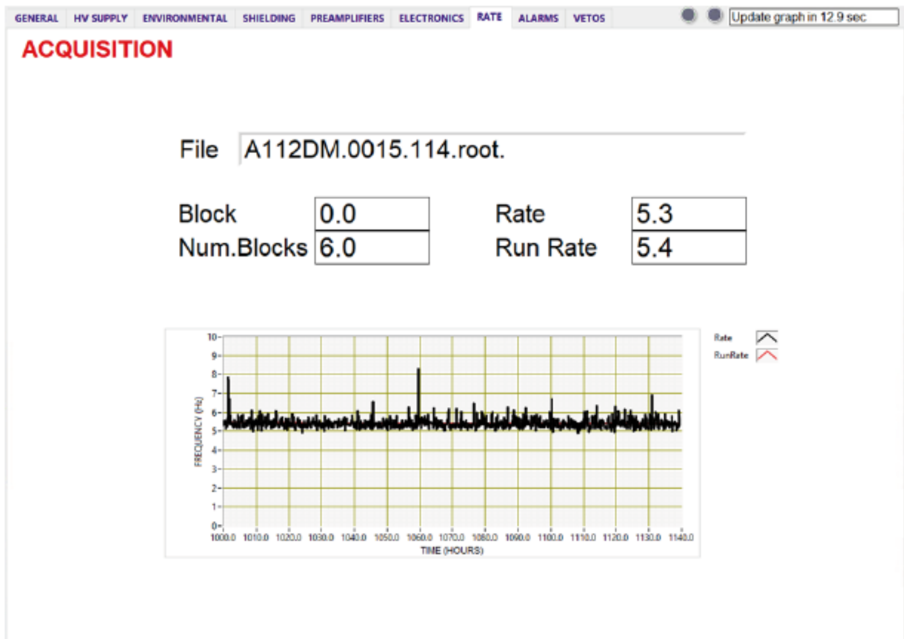
- **Muon detection system** implemented to:
  - tag muon related events
  - monitor onsite muon flux



# Detector set-up: slow control

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



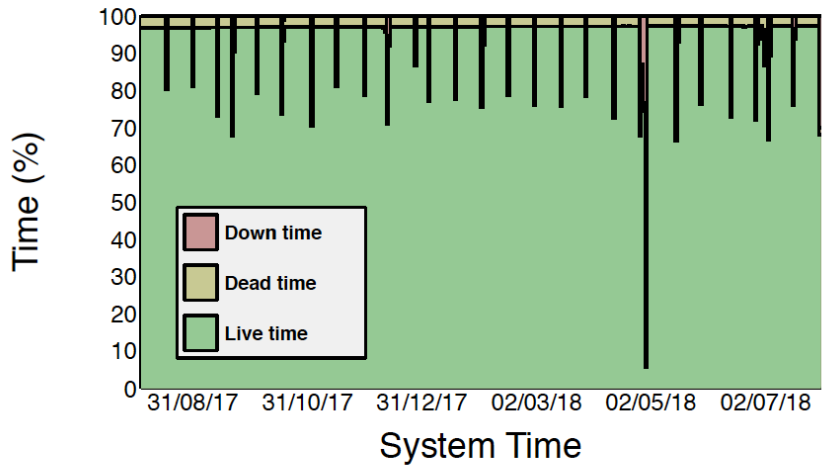
# Detector response

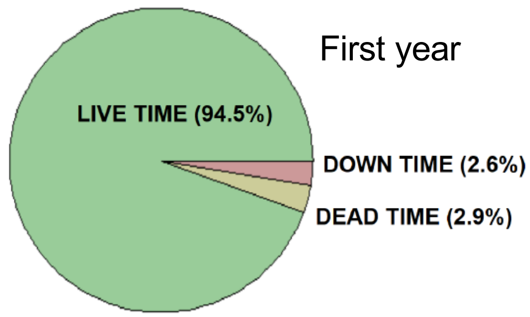
**Performance of ANAIS-112 experiment after the first year of data taking**
**J. Amaré et al, Eur. Phys. J. C (2019) 79:228**

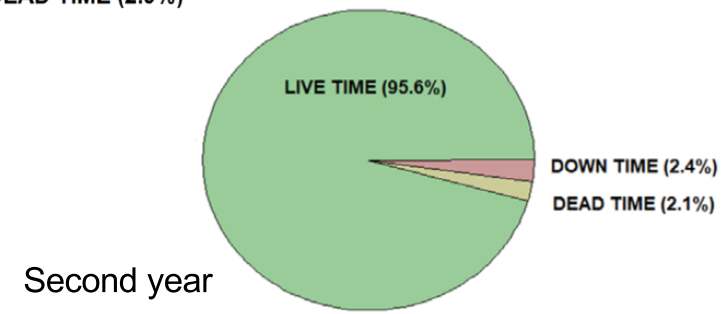
341.72 days, 105.32 kg y

Now 2 years analyzed: 716.02 days, 220.69 kg y

- Excellent **duty cycle**

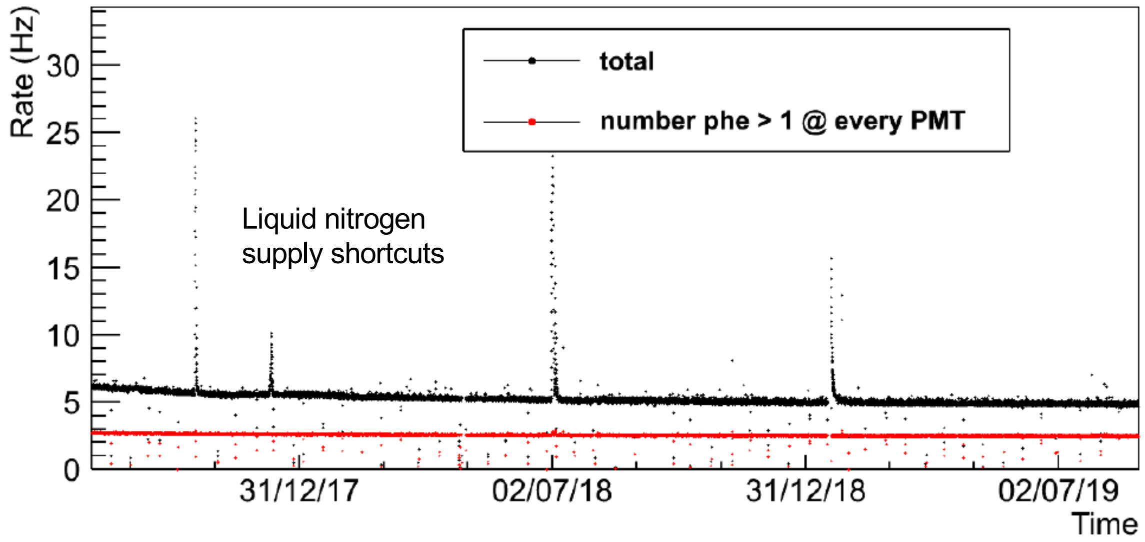



- Good **stability**

Total trigger rate

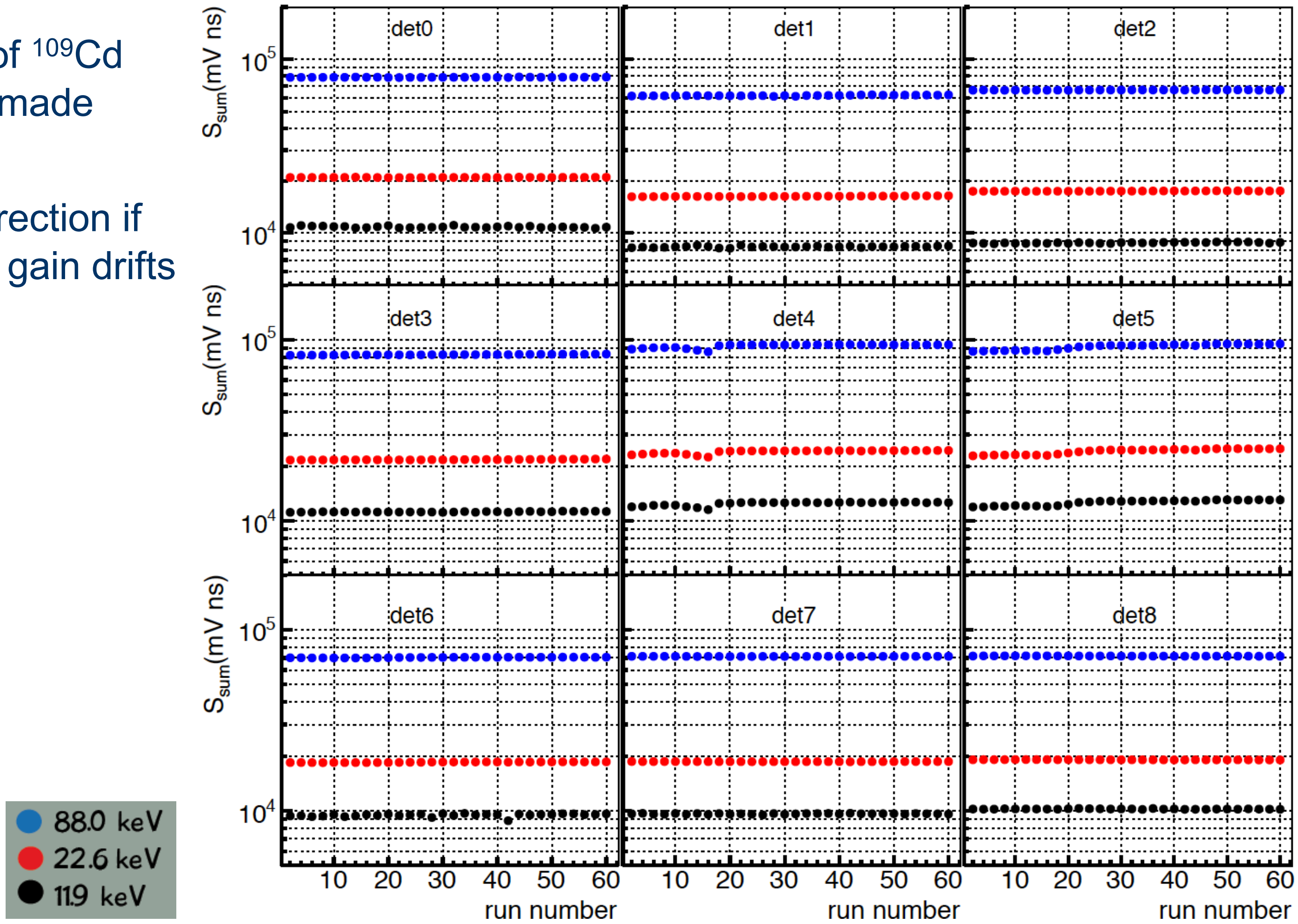


# Detector response

- Good **stability**

Evolution of positions of $^{109}$Cd lines from calibrations made every two weeks

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



# Detector response

- 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

| Detector | Average light collected (phe/keV) | Standard deviation |
|---|---|---|
| D0 | 14.532 | 0.102 |
| D1 | 14.745 | 0.169 |
| D2 | 14.506 | 0.104 |
| D3 | 14.453 | 0.109 |
| D4 | 14.483 | 0.090 |
| D5 | 14.572 | 0.158 |
| D6 | 12.707 | 0.104 |
| D7 | 14.743 | 0.137 |
| D8 | 15.994 | 0.076 |

Larger and more homogeneous than the reported light collection for DAMA/LIBRA detectors:

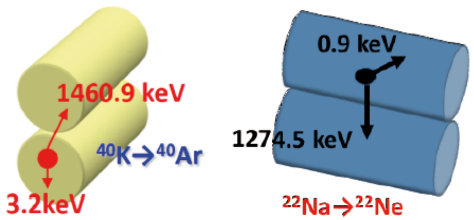
Phase 1: **5.5-7.5 phe/keV**

Phase 2: **6-10 phe/keV**

# Detector response

- 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

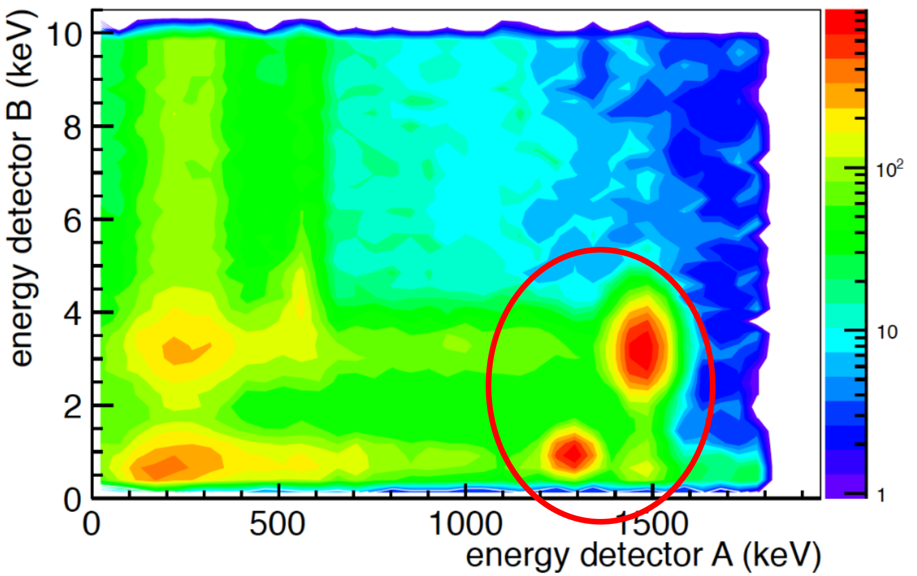


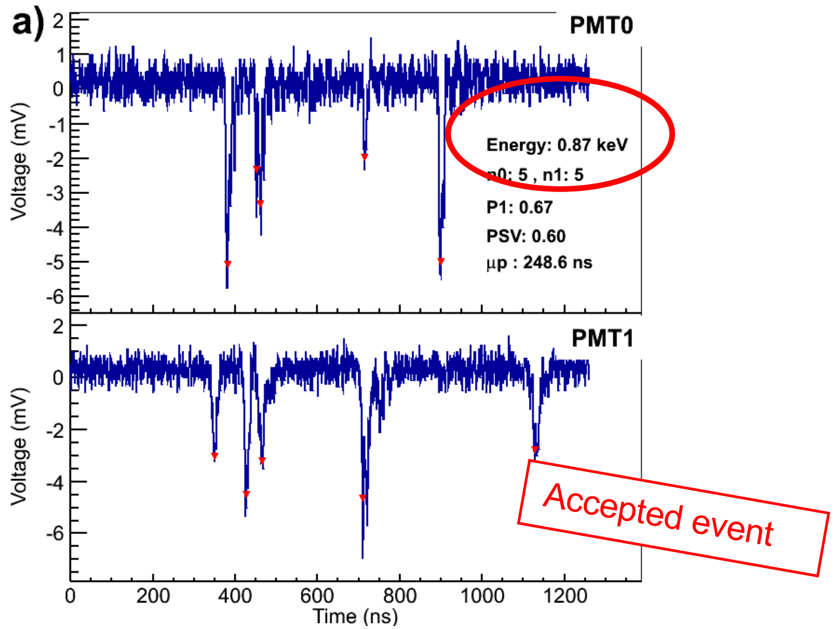

- Based **on $^{109}$Cd calibrations and data from $^{22}$Na and $^{40}$K** coincidence populations

  From non-blinded populations and 10% of unblinded data (32.9 days)

- **Multiparametric cuts** to properly select events with pulse shapes from NaI(Tl) scintillation

  Event selection procedures refined and tuned from previous ANAIS set-ups



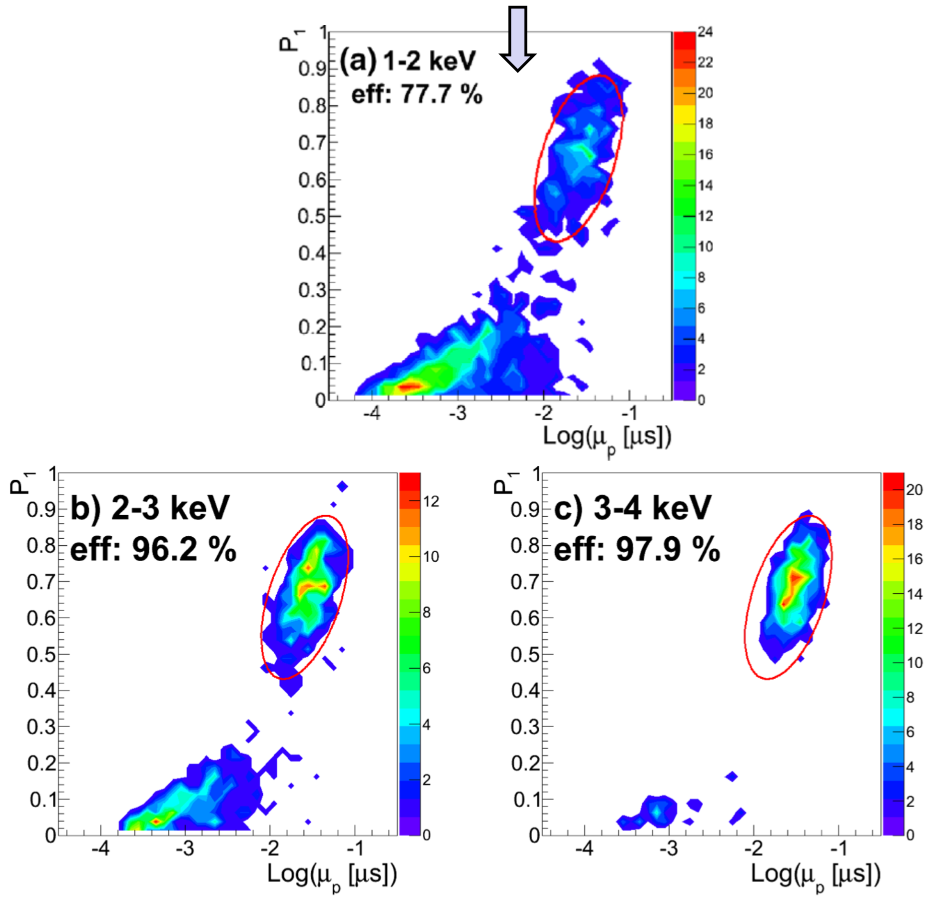



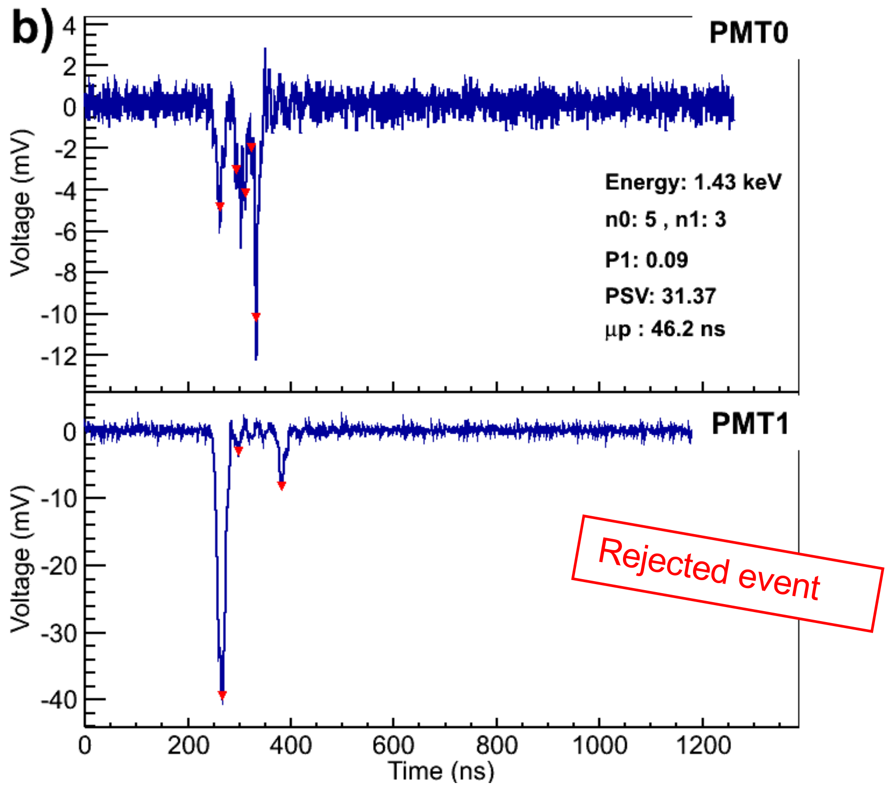
# Detector response

- Effective **filtering** protocols to reject PMT noise events, which limit energy threshold
  - **Multiparametric cuts** to properly select events with pulse shapes from NaI(Tl) scintillation
    - ○ Bidimensional cut based on temporal parameters of the pulse

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

region of 77.7% acceptance from $^{22}$Na and $^{40}$K populations



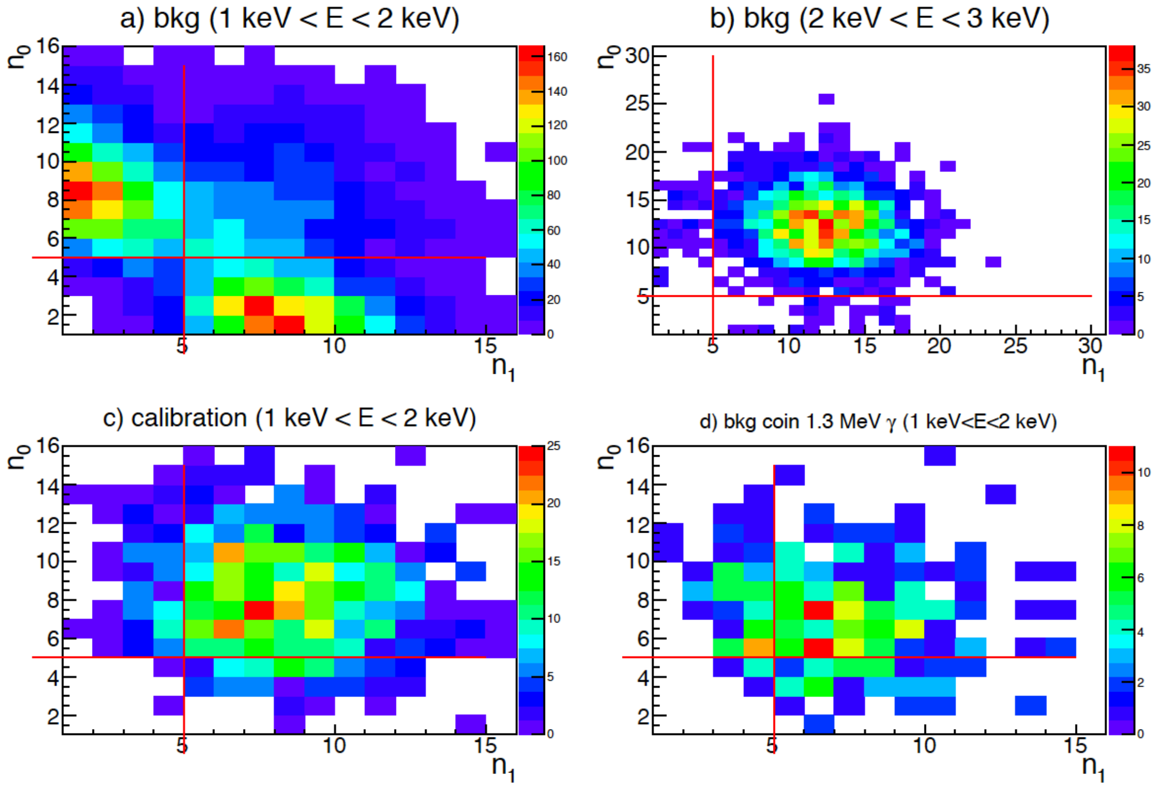



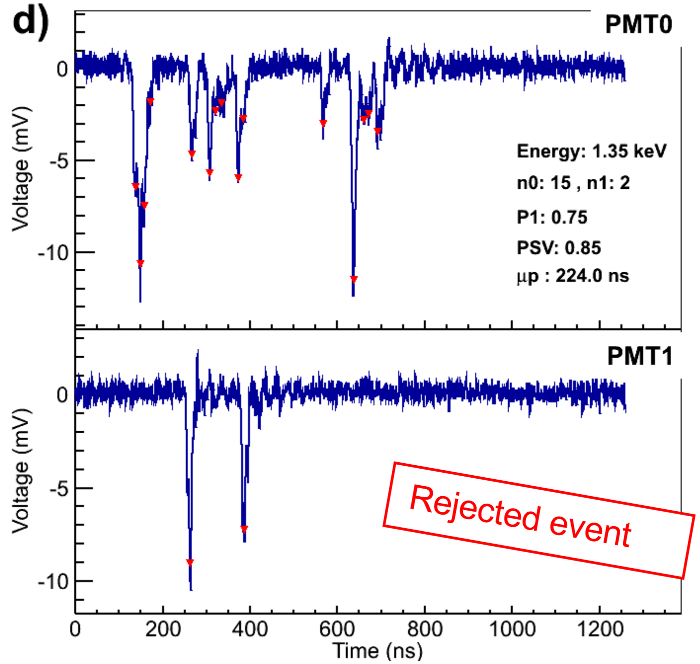

Fast event: Cherenkov light emission in one PMT, seen in the opposite PMT

# Detector response

- Effective **filtering** protocols to reject PMT noise events, which limit energy threshold
  - **Multiparametric cuts**
    - Asymmetric events (<2 $keV_{ee}$)

number_of_peaks > 4 for every PMT



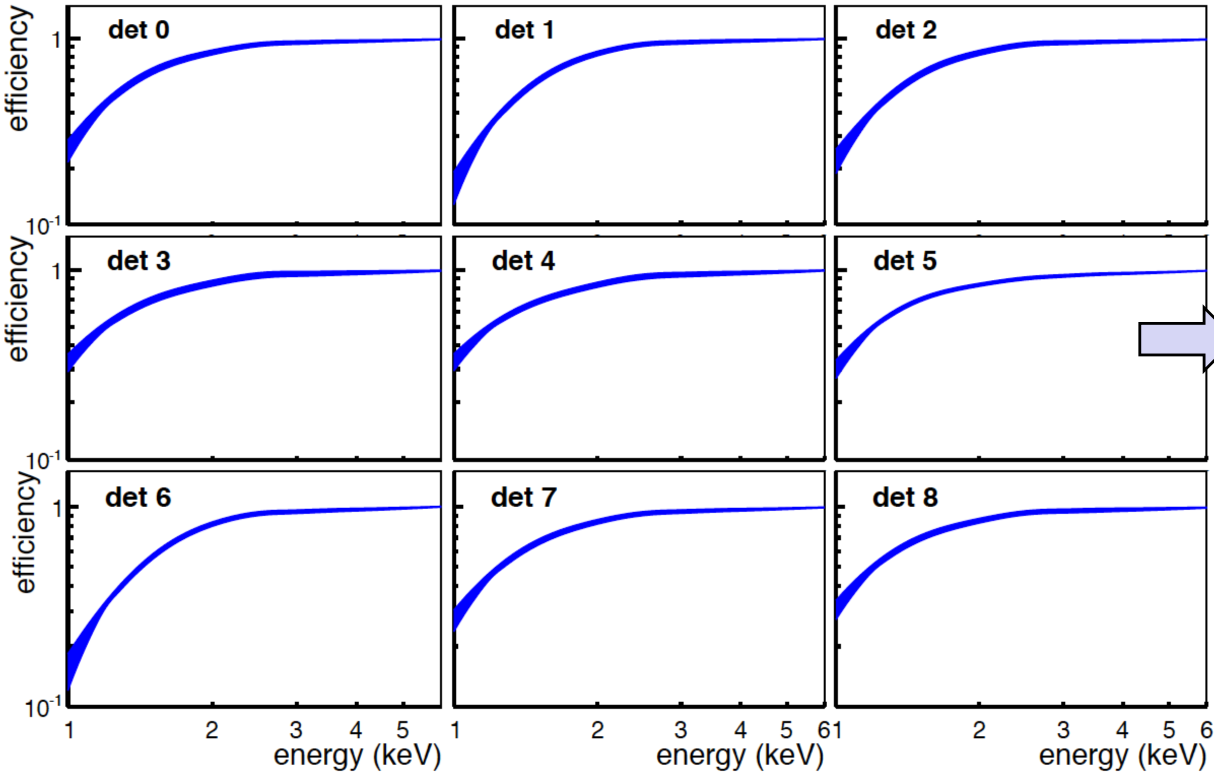



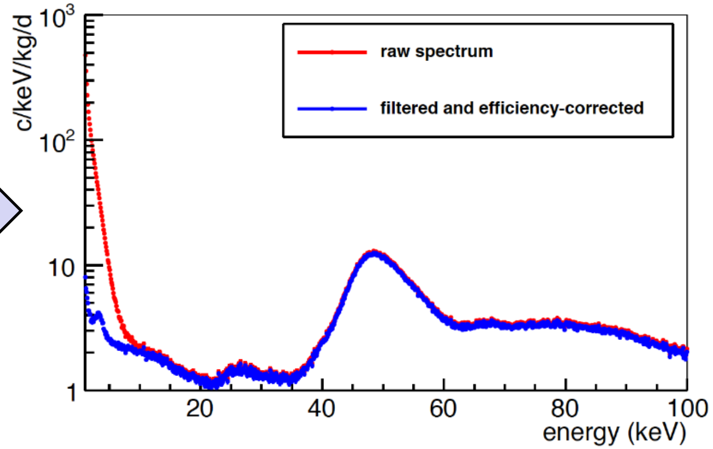

A **blank module** set-up to monitor non NaI(Tl) scintillation events along the second year of operation

# Detector response

- 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

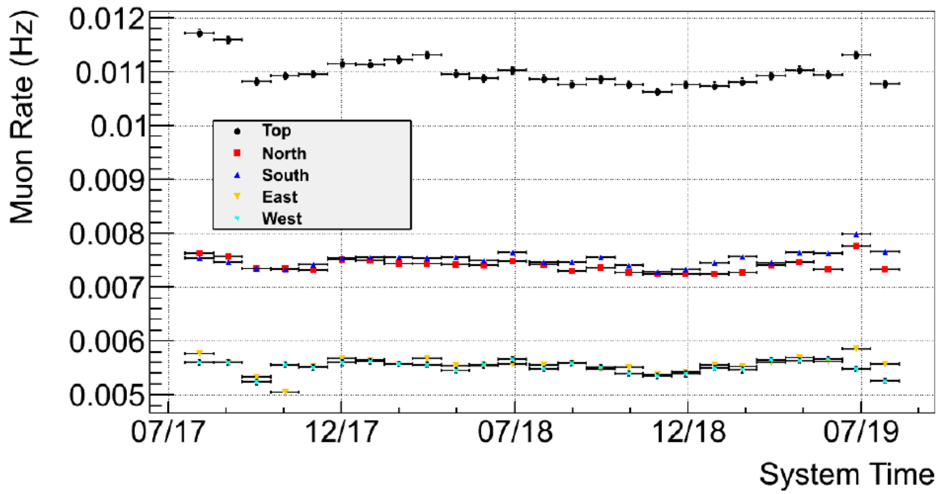
$$\varepsilon(E,d) = \varepsilon_{trg}(E,d) \times \varepsilon_{PSA}(E,d) \times \varepsilon_{asy}(E,d)$$

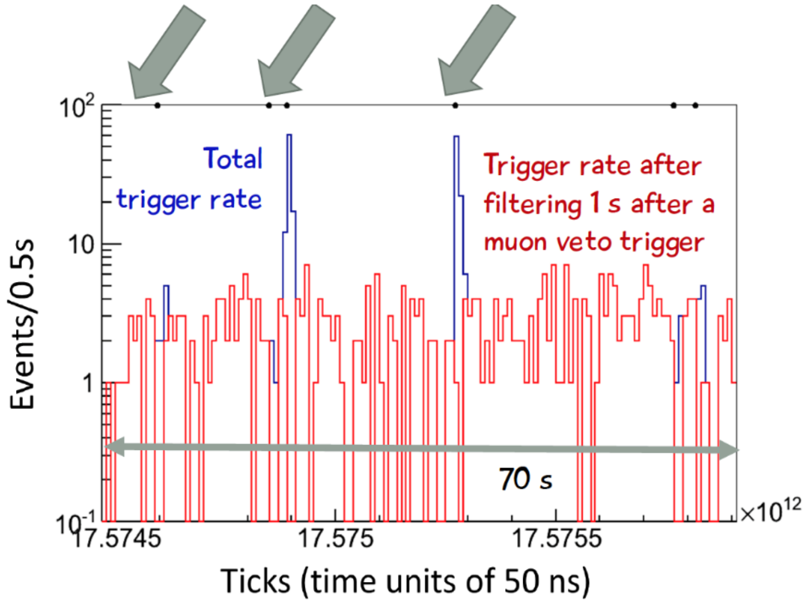


# Detector response

- **Time evolution** of relevant parameters



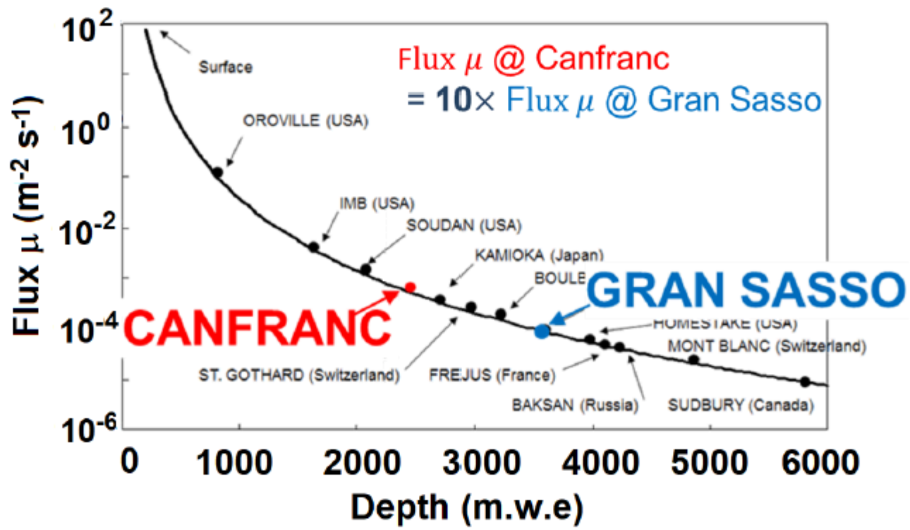

Muon-related events are triggering ANAIS DAQ

Underground muon flux is annually-modulated

- Delayed effect of muons in PMTs?
- Slow phosphorescence in NaI?

**DAMA reply:**

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

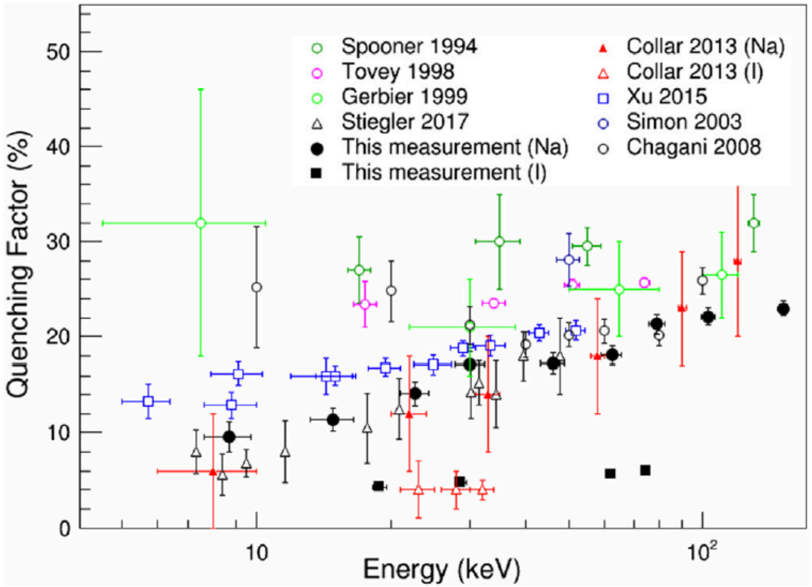



ANAIS can test these hypotheses

# Detector response

- **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), in coordination with Duke and Yale groups
- Two small crystals from Alpha Spectra company with different quality powder quality
- Analysis ongoing

# 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**

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**

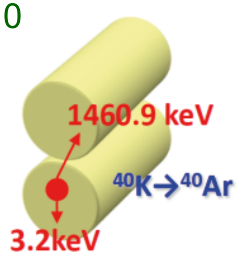
- **Activity from external components** measured with HPGe detectors at Canfranc
- **Internal activity** directly assessed: mainly $^{40}$K, $^{210}$Pb

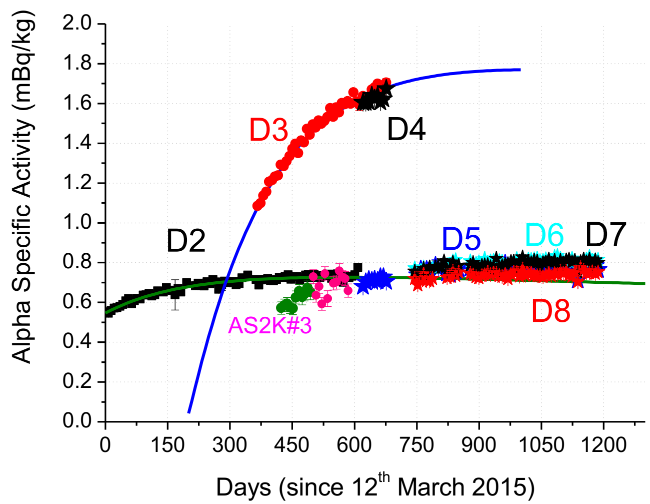
| Detector | $^{40}$K (mBq/kg) | $^{232}$Th (mBq/kg) | $^{238}$U (mBq/kg) | $^{210}$Pb (mBq/kg) |
|---|---|---|---|---|
| D0 | 1.33±0.04 | $(4\pm1)\ 10^{-3}$ | $(10\pm2)\ 10^{-3}$ | 3.15±0.10 |
| D1 | 1.21±0.04 | | | 3.15±0.10 |
| D2 | 1.07±0.03 | $(0.7\pm0.1)\ 10^{-3}$ | $(2.7\pm0.2)\ 10^{-3}$ | 0.7±0.1 |
| 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 | $(1.3\pm0.1)\ 10^{-3}$ | | 0.81±0.01 |
| D7 | 0.96±0.03 | $(1.0\pm0.1)\ 10^{-3}$ | | 0.80±0.01 |
| D8 | 0.76±0.02 | $(0.4\pm0.1)\ 10^{-3}$ | | 0.74±0.01 |

**$^{232}$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**

**$^{40}$K:** by identifying coincidences

C. Cuesta et al., Int. J. Mod. Phys. A. 29 (2014) 1443010



# Background model

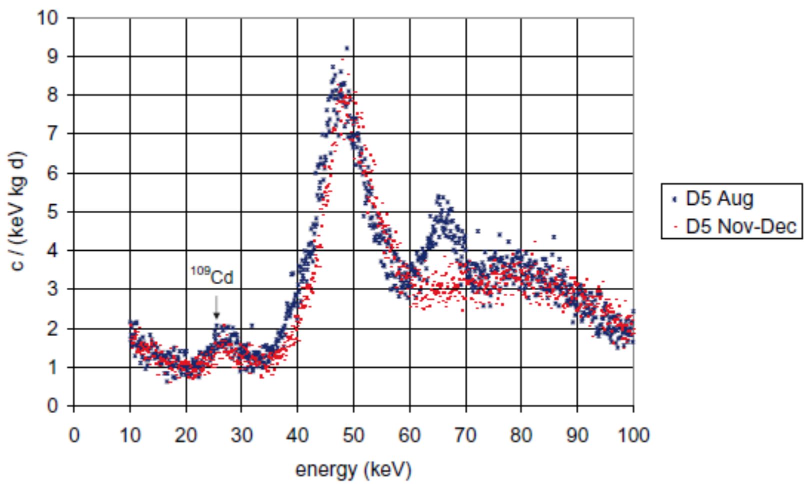
Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

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

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)

Estimate of production rates:

$^{109}Cd$ (2.38±0.20) $kg^{-1}d^{-1}$

$^{113}Sn$ (4.53±0.40) $kg^{-1}d^{-1}$

Table 7. Comparison of cosmogenically produced $^{22}Na$ initial activity, $A_0$, estimates (in $kg^{-1}$ $d^{-1}$) for ANAIS detectors in different set-ups (see text).

| Detector | ANAIS-25[33] | ANAIS-37[35] | A37D3 | ANAIS-112 |
|---|---|---|---|---|
| D0 | $159.7 \pm 4.9$ | $158.4 \pm 7.9$ | $164 \pm 17$ | $155 \pm 11$ |
| D1 | $159.7 \pm 4.9$ | | | $168 \pm 11$ |
| D2 | | $70.2 \pm 3.9$ | $57.6 \pm 8.1$ | $43.9 \pm 6.0$ |
| D3 | | | $69.9 \pm 3.6$ | $68.6 \pm 4.6$ |
| D4 | | | | $61.8 \pm 3.1$ |
| D5 | | | | $43.7 \pm 2.3$ |
| D6 | | | | $53.8 \pm 2.7$ |
| D7 | | | | $55.6 \pm 2.7$ |
| D8 | | | | $56.4 \pm 2.8$ |

**$^{22}Na$:** from analysis of coincidences

Same order of activity measured using HPGe by SABRE on AstroGrade powder

# Background model

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

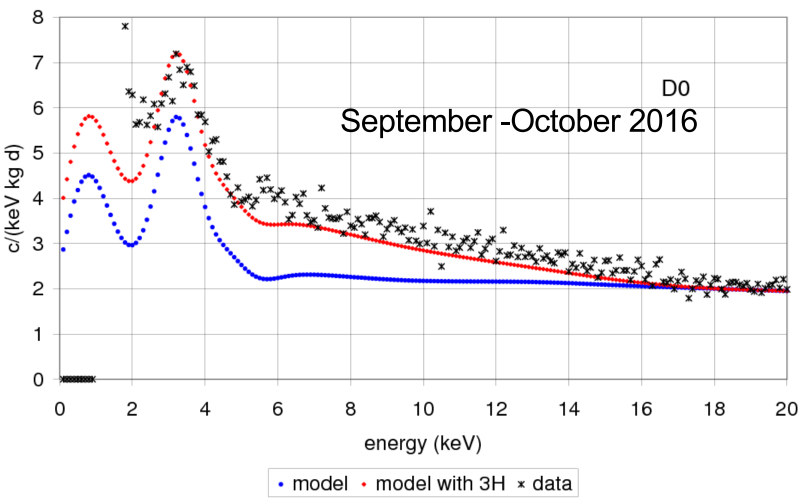
- **Cosmogenic activity** in crystals: short-lived Te and I isotopes, $^{3}H$, $^{22}Na$, $^{109}Cd$, $^{113}Sn$

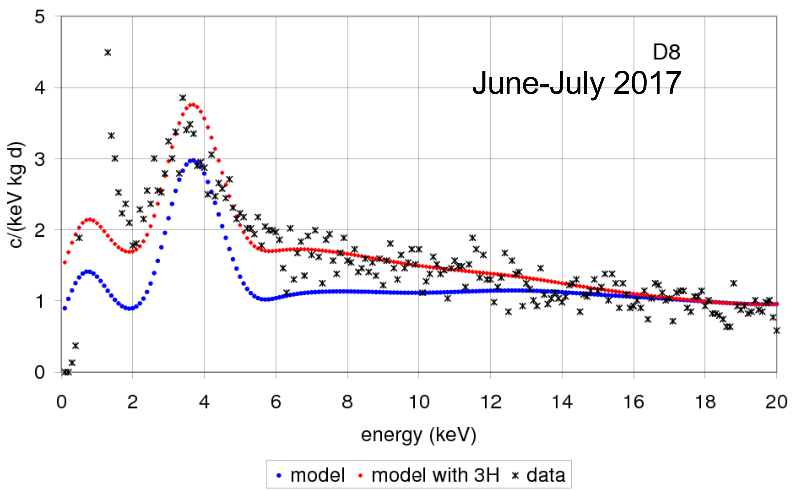
**$^{3}$H:** additional background source contributing only in the very low energy region required, which could be tritium

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

Same order of $^{3}$H activity fitted by COSINE-100
P. Adhikari et al, Eur. Phys. J. C (2018) 78:490

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

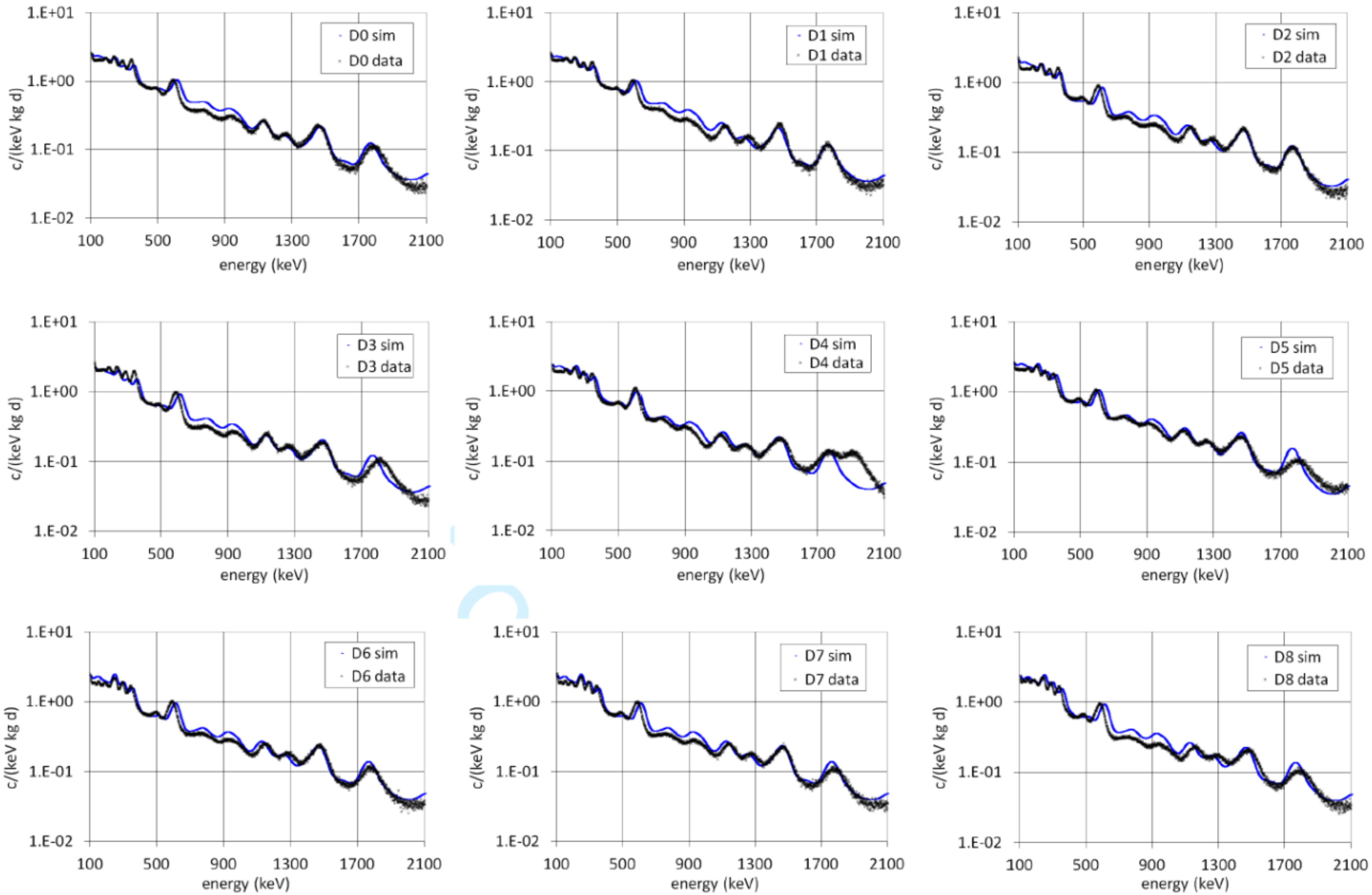


# Background model

Comparison with first year of ANAIS-112 data: **high energy** total spectra

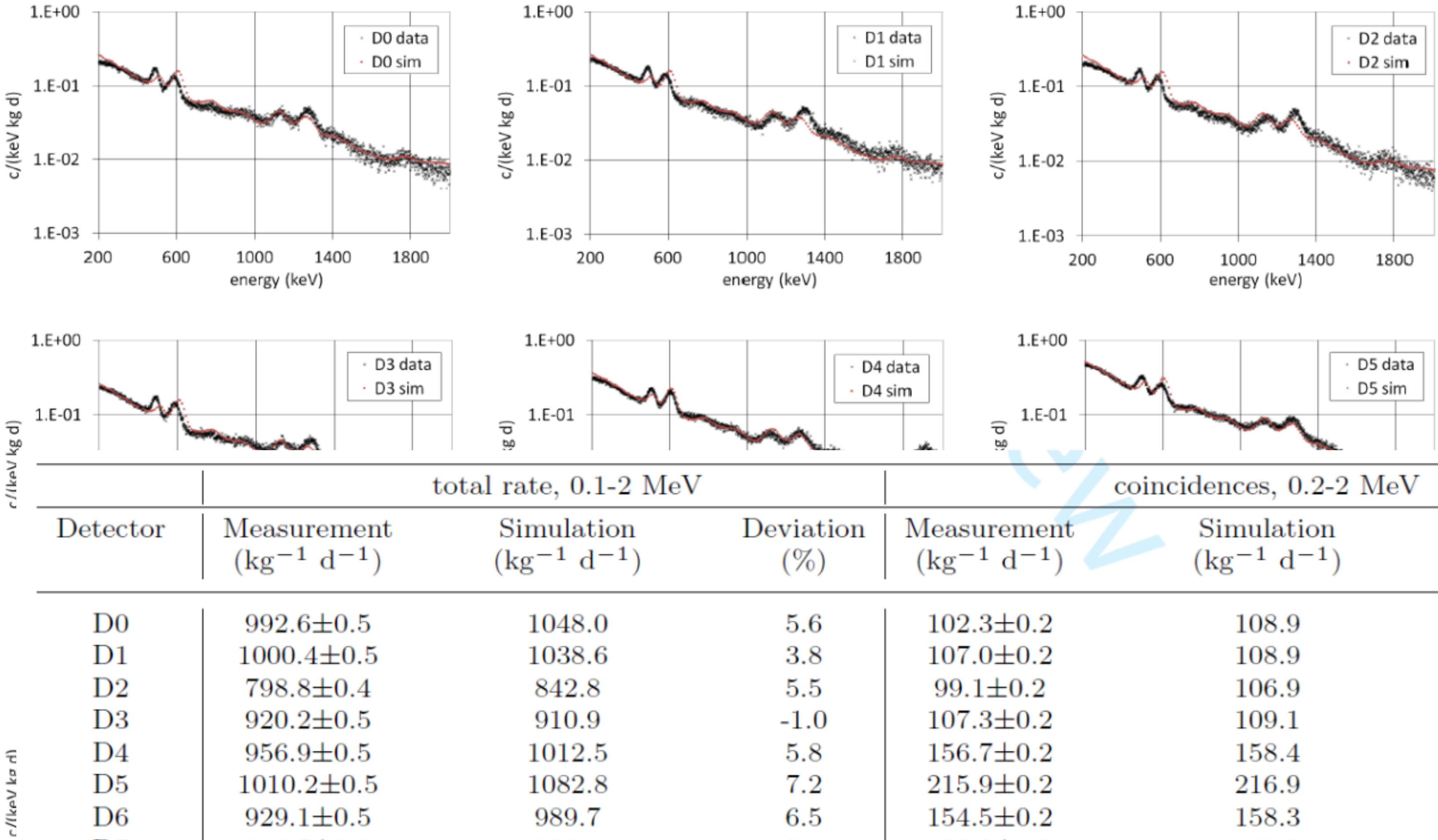
(3 August 2017 to 31 July 2018, 341.72 days)



# Background model

Comparison with first year of ANAIS-112 data: **high energy** coincidence spectra

(3 August 2017 to 31 July 2018, 341.72 days)

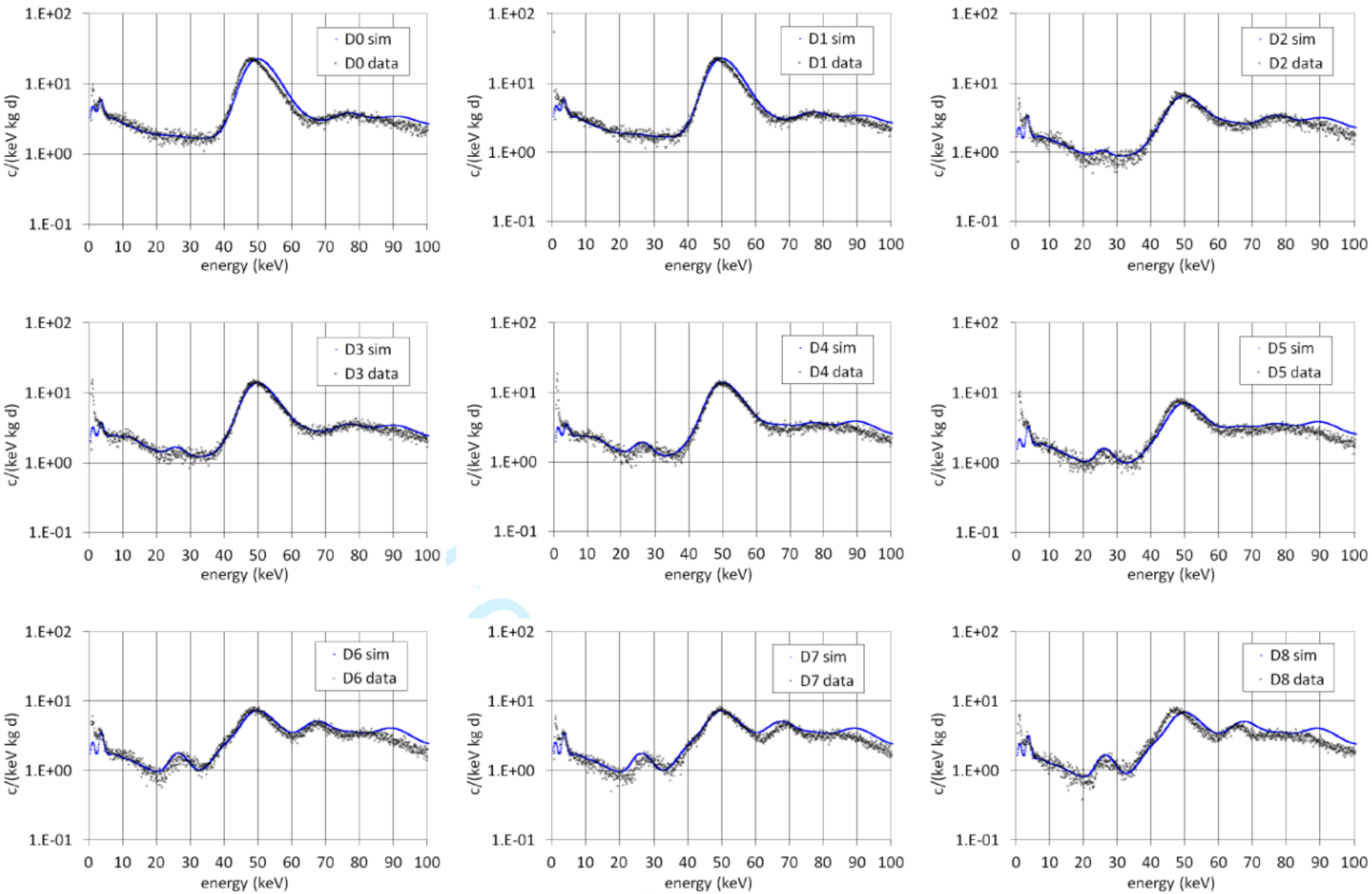



| Detector | total rate, 0.1-2 MeV Measurement ($kg^{-1}$ $d^{-1}$) | Simulation ($kg^{-1}$ $d^{-1}$) | Deviation (%) | coincidences, 0.2-2 MeV Measurement ($kg^{-1}$ $d^{-1}$) | Simulation ($kg^{-1}$ $d^{-1}$) | Deviation (%) |
|---|---|---|---|---|---|---|
| D0 | 992.6±0.5 | 1048.0 | 5.6 | 102.3±0.2 | 108.9 | 6.5 |
| D1 | 1000.4±0.5 | 1038.6 | 3.8 | 107.0±0.2 | 108.9 | 1.7 |
| D2 | 798.8±0.4 | 842.8 | 5.5 | 99.1±0.2 | 106.9 | 7.8 |
| D3 | 920.2±0.5 | 910.9 | -1.0 | 107.3±0.2 | 109.1 | 1.6 |
| D4 | 956.9±0.5 | 1012.5 | 5.8 | 156.7±0.2 | 158.4 | 1.1 |
| D5 | 1010.2±0.5 | 1082.8 | 7.2 | 215.9±0.2 | 216.9 | 0.5 |
| D6 | 929.1±0.5 | 989.7 | 6.5 | 154.5±0.2 | 158.3 | 2.4 |
| D7 | 909.7±0.5 | 990.8 | 8.9 | 152.2±0.2 | 159.0 | 4.5 |
| D8 | 904.8±0.5 | 976.8 | 8.0 | 159.3±0.2 | 158.9 | -0.3 |
| ANAIS-112 | 935.8±0.1 | 988.1 | 5.6 | 139.4±0.1 | 142.8 | 2.9 |

# Background model

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

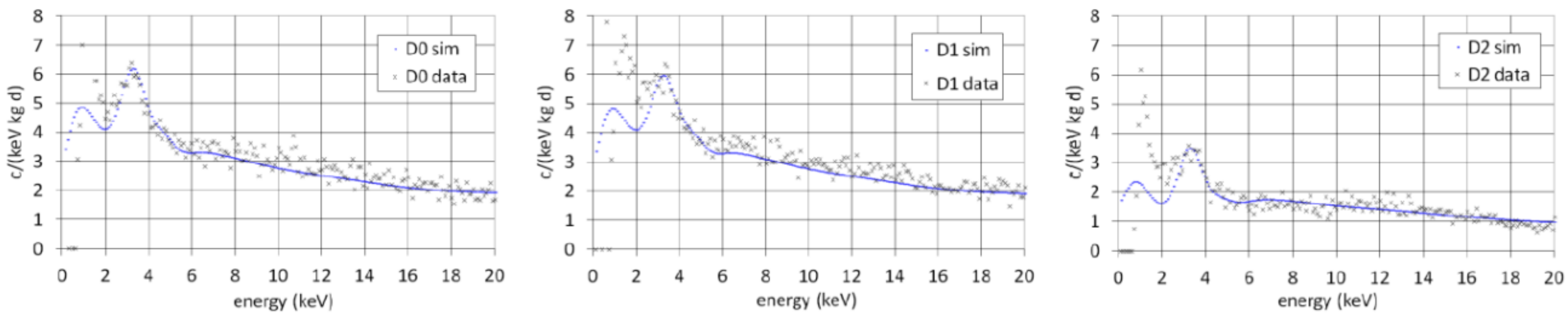
(3 August 2017 to to 31 July 2018, 341.72 d; 10% unblinded data 32.9 d)



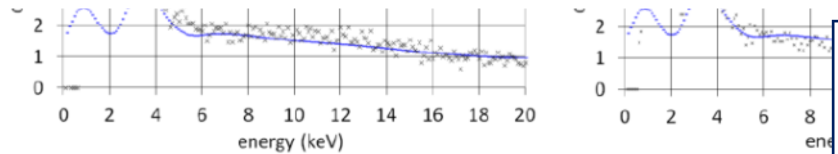
# Background model

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

(3 August 2017 to to 31 July 2018, 341.72 d; 10% unblinded data 32.9 d)

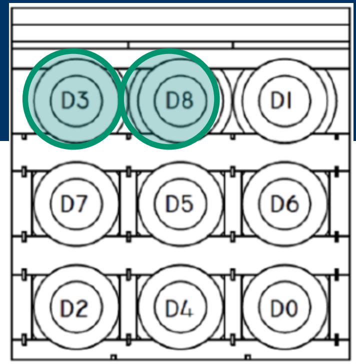



| | 1 to 2 keV | | | 2 to 6 keV | | |
|---|---|---|---|---|---|---|
| Detector | Measurement ($keV^{-1}$ $kg^{-1}$ $d^{-1}$) | Simulation ($keV^{-1}$ $kg^{-1}$ $d^{-1}$) | Deviation (%) | Measurement ($keV^{-1}$ $kg^{-1}$ $d^{-1}$) | Simulation ($keV^{-1}$ $kg^{-1}$ $d^{-1}$) | Deviation (%) |
| D0 | 6.62±0.18 | 4.37 | -34 | 4.58±0.05 | 4.53 | -1.0 |
| D1 | 6.55±0.20 | 4.36 | -33 | 4.66±0.05 | 4.46 | -4.4 |
| D2 | 3.62±0.14 | 1.84 | -49 | 2.44±0.04 | 2.27 | -7.0 |
| D3 | 6.40±0.17 | 2.77 | -57 | 3.16±0.04 | 2.97 | -6.2 |
| D4 | 5.54±0.16 | 2.73 | -51 | 3.12±0.04 | 2.88 | -7.6 |
| D5 | 5.84±0.16 | 1.84 | -68 | 2.96±0.04 | 2.34 | -20.9 |
| D6 | 4.16±0.16 | 2.04 | -51 | 2.90±0.04 | 2.42 | -16.3 |
| D7 | 3.78±0.13 | 2.03 | -46 | 2.61±0.04 | 2.42 | -7.4 |
| D8 | 3.74±0.13 | 1.94 | -48 | 2.29±0.04 | 2.18 | -5.1 |
| ANAIS-112 | 5.14±0.05 | 2.66 | -48 | 3.19±0.01 | 2.94 | -7.9 |



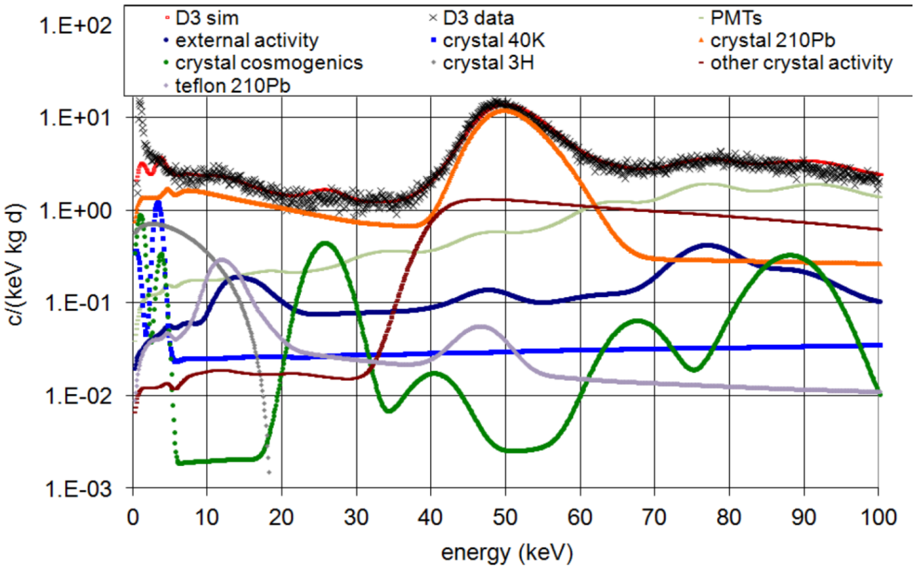

Unexplained events <2 keV could be due to non-bulk scintillation events leaking in the RoI or some unknown background source not considered in the model

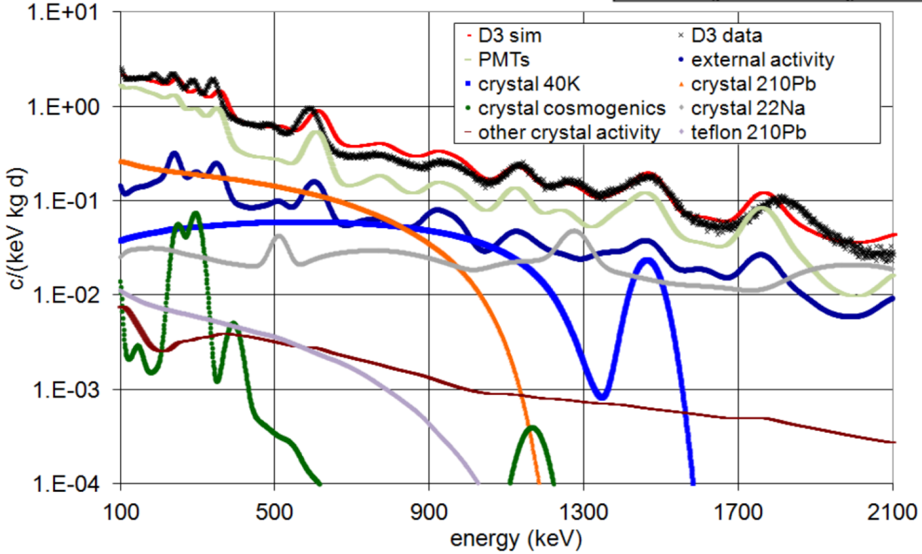
# Background model

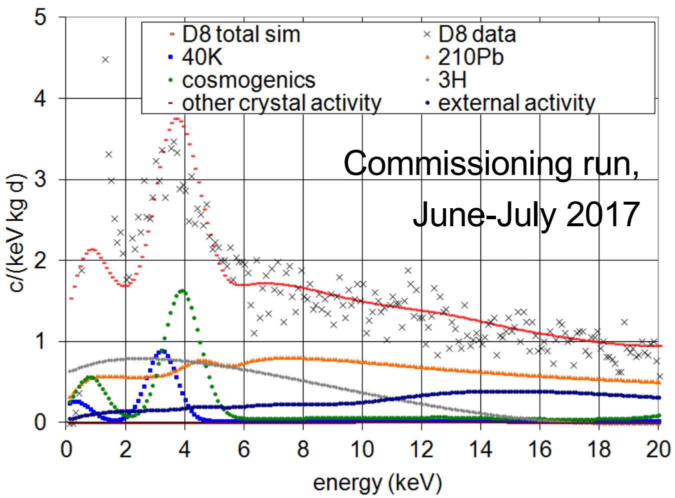



Individual contributions for first year of ANAIS-112 data

(3 August 2017 to 31 July 2018, 341.72 d)




**$^{40}K$ and $^{22}Na$ peaks and $^{210}Pb$** (bulk+surface) and **$^{3}H$** continua are the most significant contributions in the very low energy region

| | |
|---|---|
| $^{210}Pb$: | 32.5% |
| $^{3}H$: | 26.5% |
| $^{40}K$: | 12% |
| $^{22}Na$: | 2.0% |

# 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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[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*

(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 $-0.0015 \pm 0.0063$ cpd/kg/keV, respectively). They are in agreement with our estimated sensitivity for the accumulated exposure, which supports our projected goal of reaching a $3\sigma$ sensitivity to the DAMA/LIBRA result in five years of data taking.

- Data from 3rd August 2017 to 12th February 2019
- 527.08 days

arXiv:1910.13365v2 [astro-ph.IM] 30 Oct 2019

**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]

[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, 50018, Zaragoza, Spain

E-mail: mlsarsa@unizar.es

- Same analysis for two years
- Presented at TAUP2019 conference in Japan

# Annual modulation results

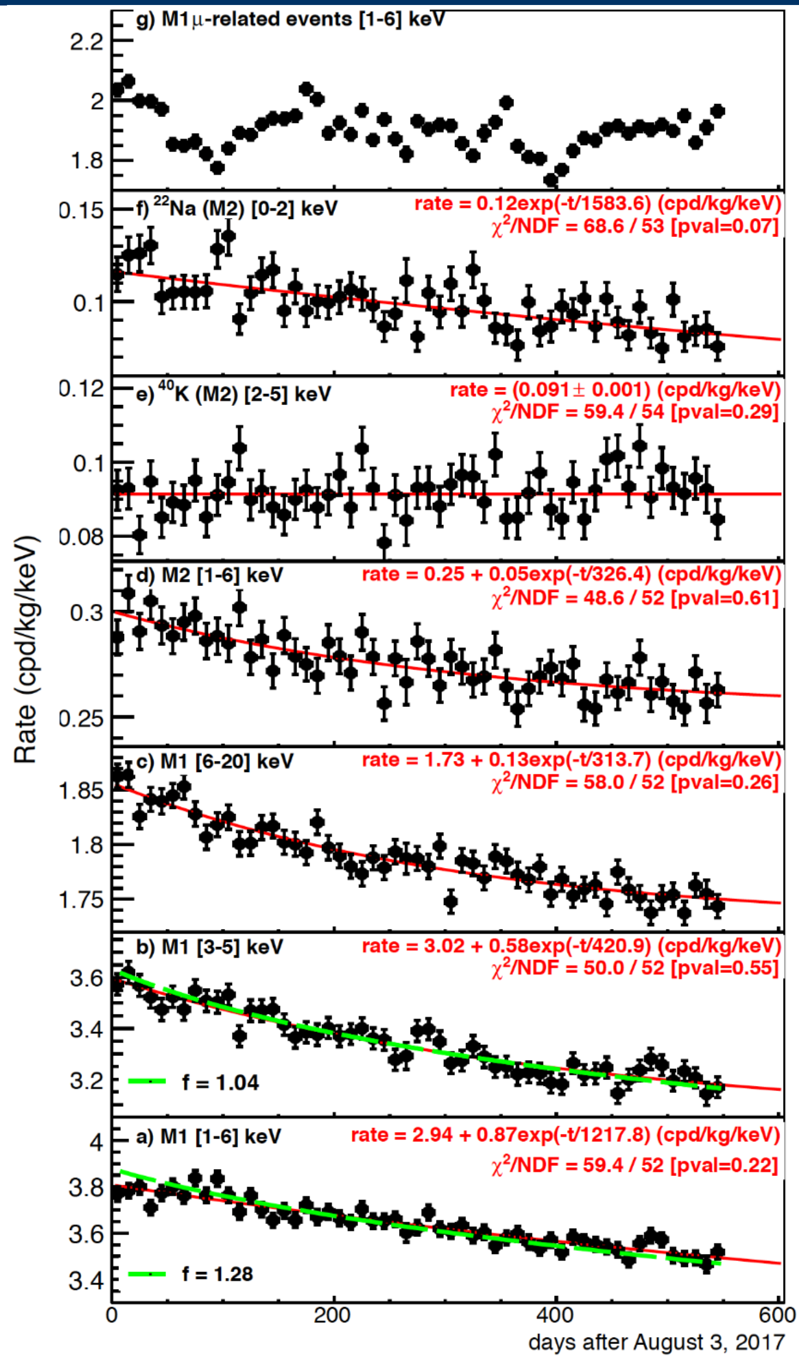
**Time evolution of the rate of different event populations** in 1.5 years of ANAIS-112 data

- g) single hit muon related events in 1-6 keV
- f) $^{22}$Na events (coincidence selected)
- e) $^{40}$K events (coincidence selected)
- d) multiple hit (M=2) events in 1-6 keV
- c) single hit events in 6-20 keV
- b) single hit events in 3-5 keV
- a) single hit events in 1-6 keV

Least-squares fits to a constant term + exponential function (a-d)

Background estimated evolution

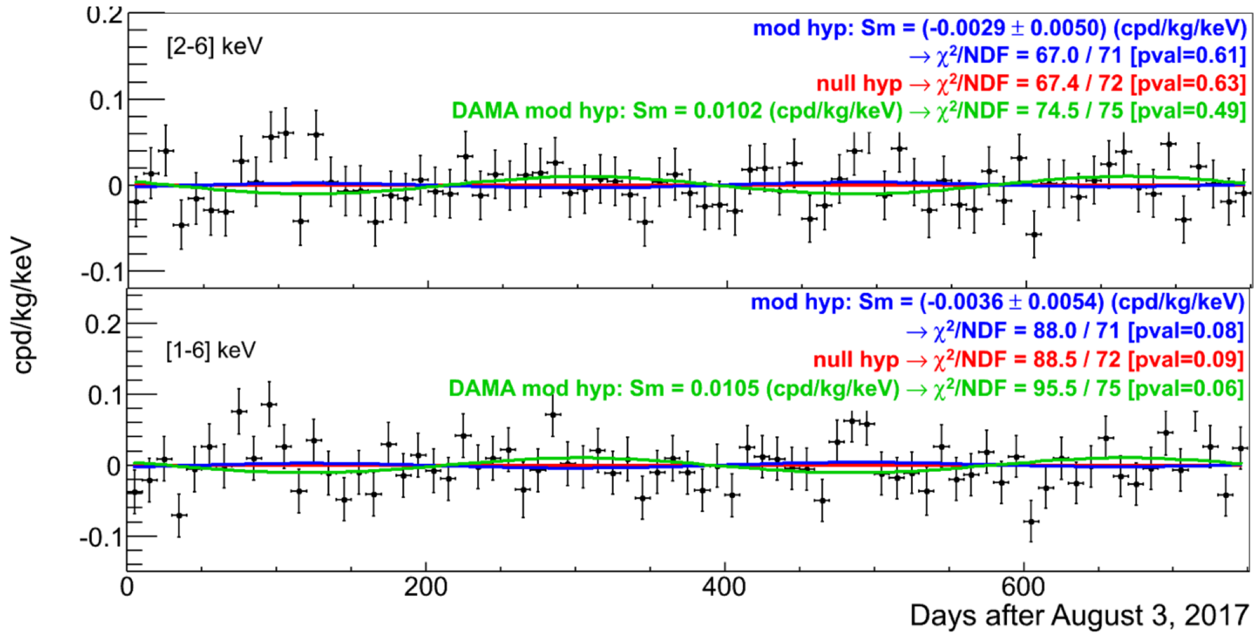
Exponential + constant fit



# Annual modulation results

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

$$R(t) = R_0 + R_1 \exp(-t/\tau) + \boldsymbol{S_m} \cos(\omega(t+\phi))$$




$\tau$ fixed from our background model

$\omega$ fixed corresponding to 1 year period

$\phi$ fixed to have the cosine maximum in June, 2nd

$S_m$ fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

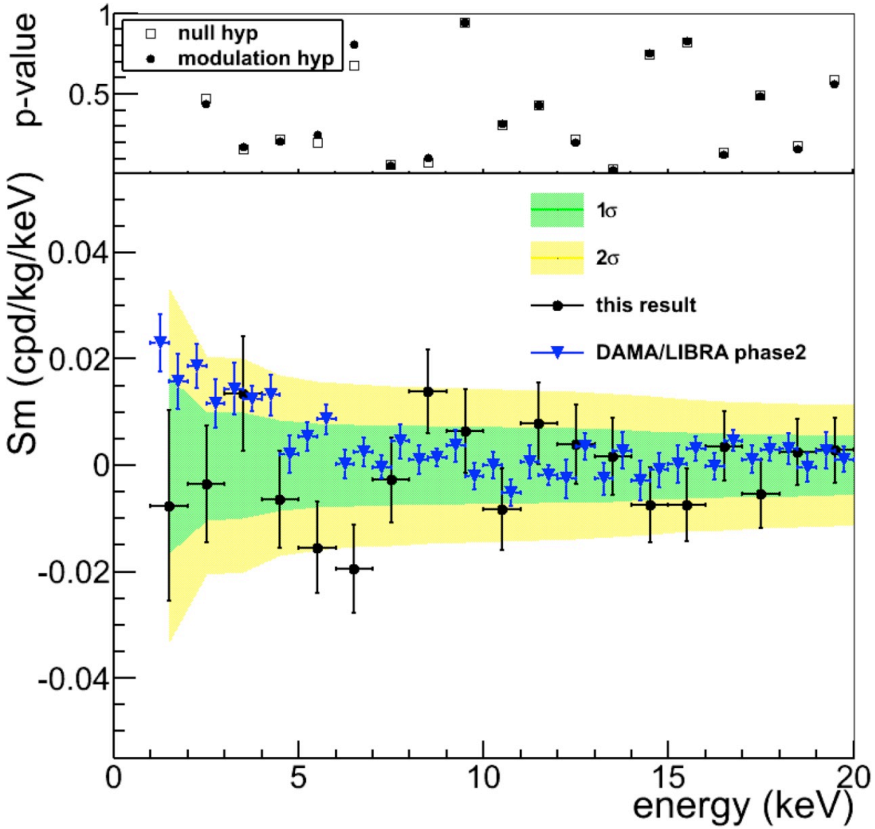
Null hypothesis well supported by the $\chi^2$ test
Modulation hypothesis best fits for 2-6 and 1-6 keV:
DAMA/LIBRA result with 1–free parameter also shown

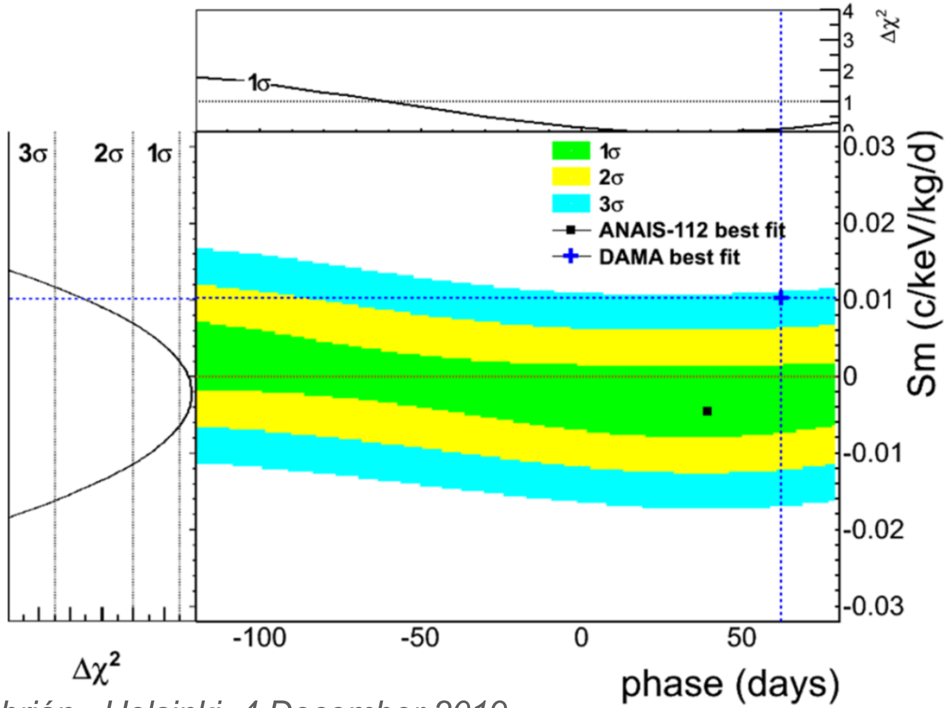
| |
|---|
| [2-6] keV → $Sm = -0.0029 \pm 0.0050$ c/keV/kg/d |
| [1-6] keV → $Sm = -0.0036 \pm 0.0054$ c/keV/kg/d |

# Annual modulation results

**Modulation amplitudes estimates in 1 keV bins from 1 to 20 keV (2 y)**

- All the amplitudes compatible with 0; in general p-values are larger for the null hyp. than for the modulation hyp.
- Green and yellow bands show our estimated sensitivity at 1σ and 2σ for the present ANAIS-112 exposure




**Modulation amplitude estimate in [2-6] keV (2 y)**

- Letting free phase $\phi$ and amplitude $S_m$
- ANAIS data compatible with the absence of modulation in all phases

# Annual modulation sensitivity

I. Coarasa et al, ANAIS-112 sensitivity in the search for dark matter anual modulation, Eur. Phys. J. C 79 (2019) 233

**Detection limit** at 90% C.L. for a critical limit at 90% C.L. for ANAIS-112

- **Background** from measured, efficiency corrected levels (10% unblinded data)
- 2-6, 1-6 $keV_{ee}$ region
- 5 years

Model-independent annual modulation

**Factor of Merit:** from the variance of the estimator of the modulated amplitude

$$FOM = \left(\frac{2 \cdot B}{\Delta E \cdot M \cdot T_M \cdot \varepsilon}\right)^{\frac{1}{2}}$$

**Detection Limit** for annual modulation amplitude: for ANAIS-112 parameters

$$L_D = (7.24 \pm 0.02) \cdot 10^{-3} \text{ cpd/kg/keV}_{ee} \quad (90\% \text{ C.L.})$$

$$L_D = (7.77 \pm 0.01) \cdot 10^{-3} \text{ cpd/kg/keV}_{ee} \quad (90\% \text{ C.L.})$$

0.0102 ± 0.0008 cpd/kg/$keV_{ee}$

0.0105 ± 0.0011 cpd/kg/$keV_{ee}$

**DAMA/LIBRA**

**ANAIS-112** has a detection limit for annual modulation lower than the measured amplitude by DAMA/LIBRA

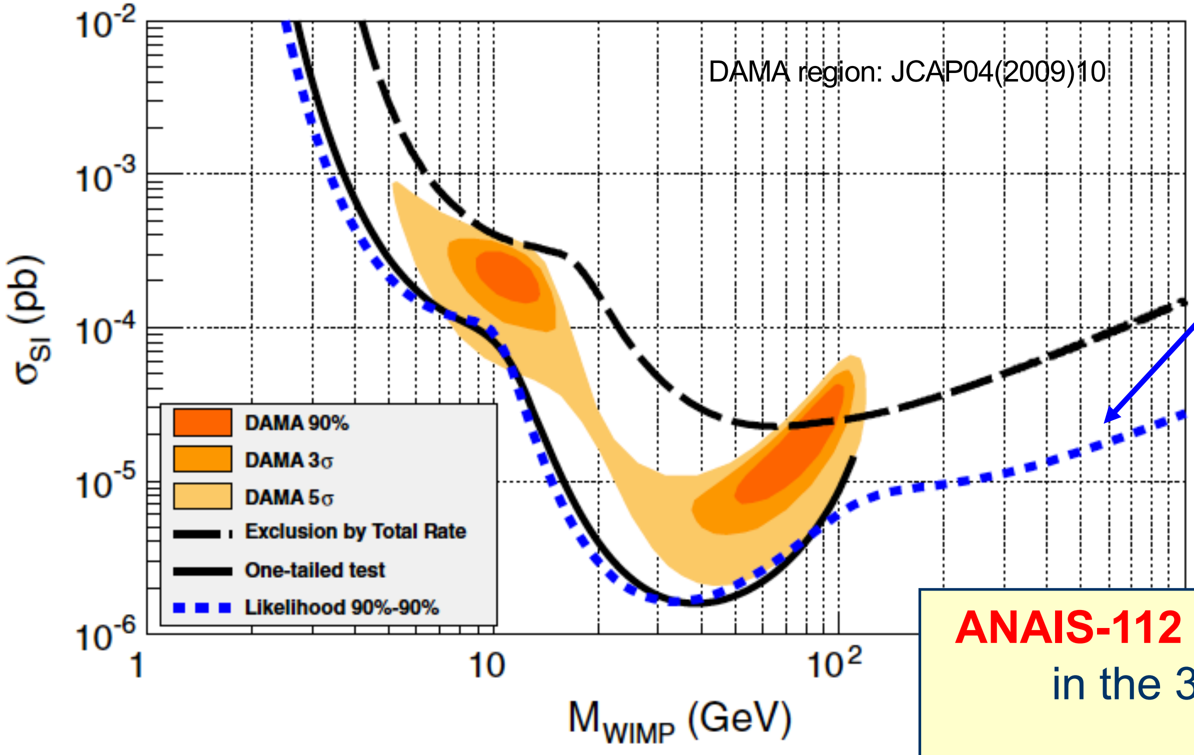
# Annual modulation sensitivity

I. Coarasa et al, ANAIS-112 sensitivity in the search for dark matter anual modulation, Eur. Phys. J. C 79 (2019) 233

**Detection limit** at 90% C.L. for a critical limit at 90% C.L. for ANAIS-112

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

Dark matter hypothesis (SI interaction)

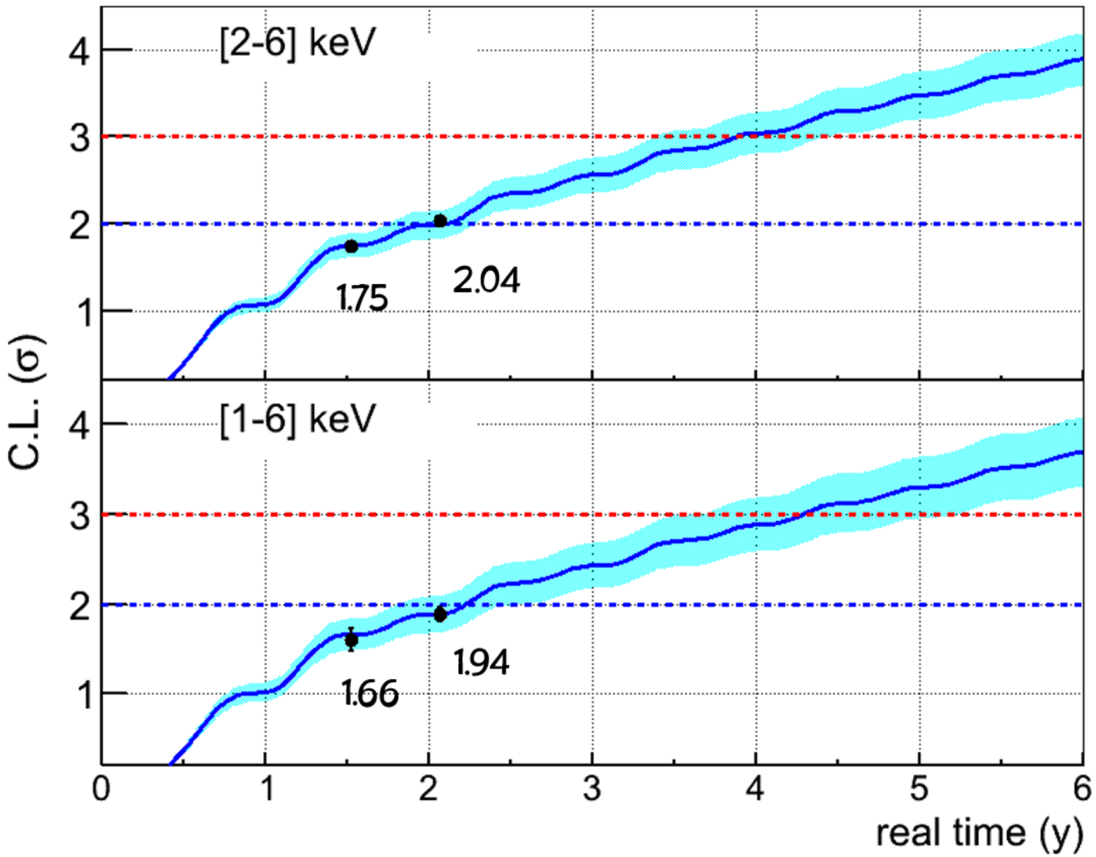



90% probability of detecting an annual modulation signal at 90% C.L.

**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 $S_m^{DAMA}$ / $\sigma(S_m)$**




Standard deviation of the modulation amplitude distribution:

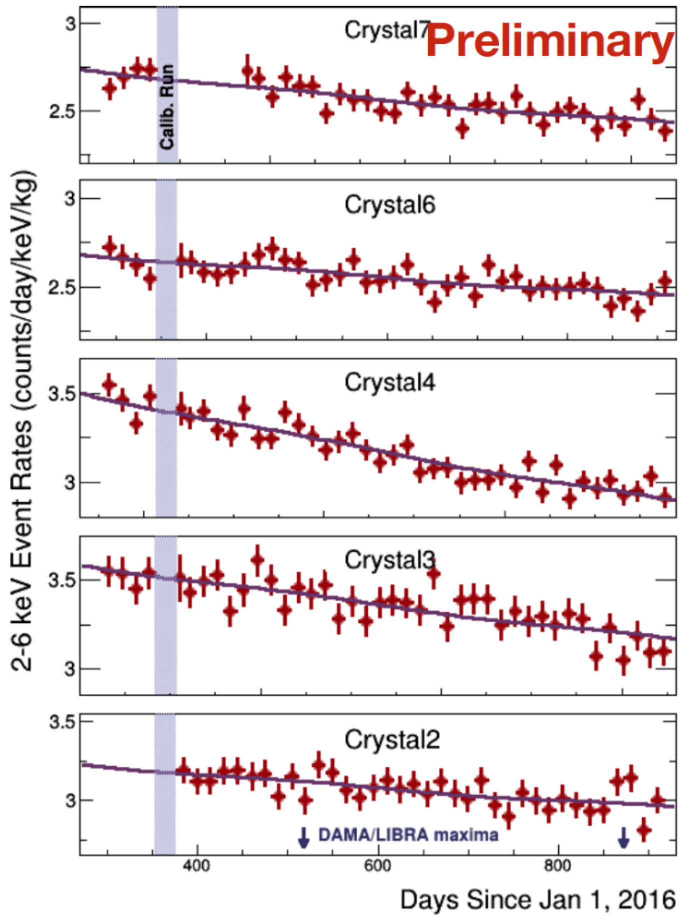
$$\sigma(S_m) = \sqrt{\frac{2}{\Delta E \; m \; T_m}} \left( \sum_{k=1}^{9} \frac{1}{\langle B/\epsilon \rangle^k} \right)^{-1/2}$$

(estimated from updated background, efficiency estimates and live time distribution)

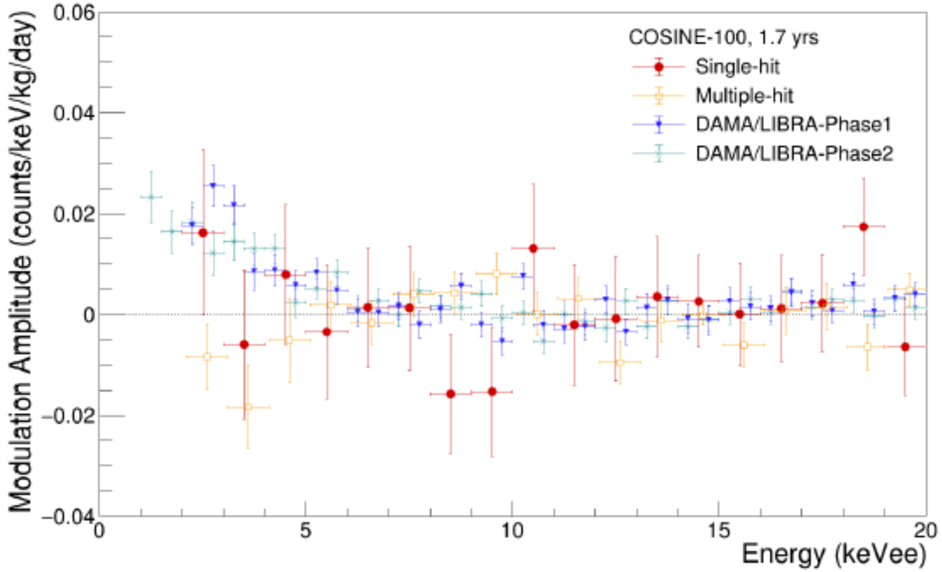
3σ sensitivity (model independent) at reach in 4-5 years (total) of data taking

# Annual modulation: COSINE-100 results

COSINE-100's first annual modulation analysis with 1.7 years of data (97.79 kg.year)




61.3 kg, 21 October 2016 to 18 July 2018

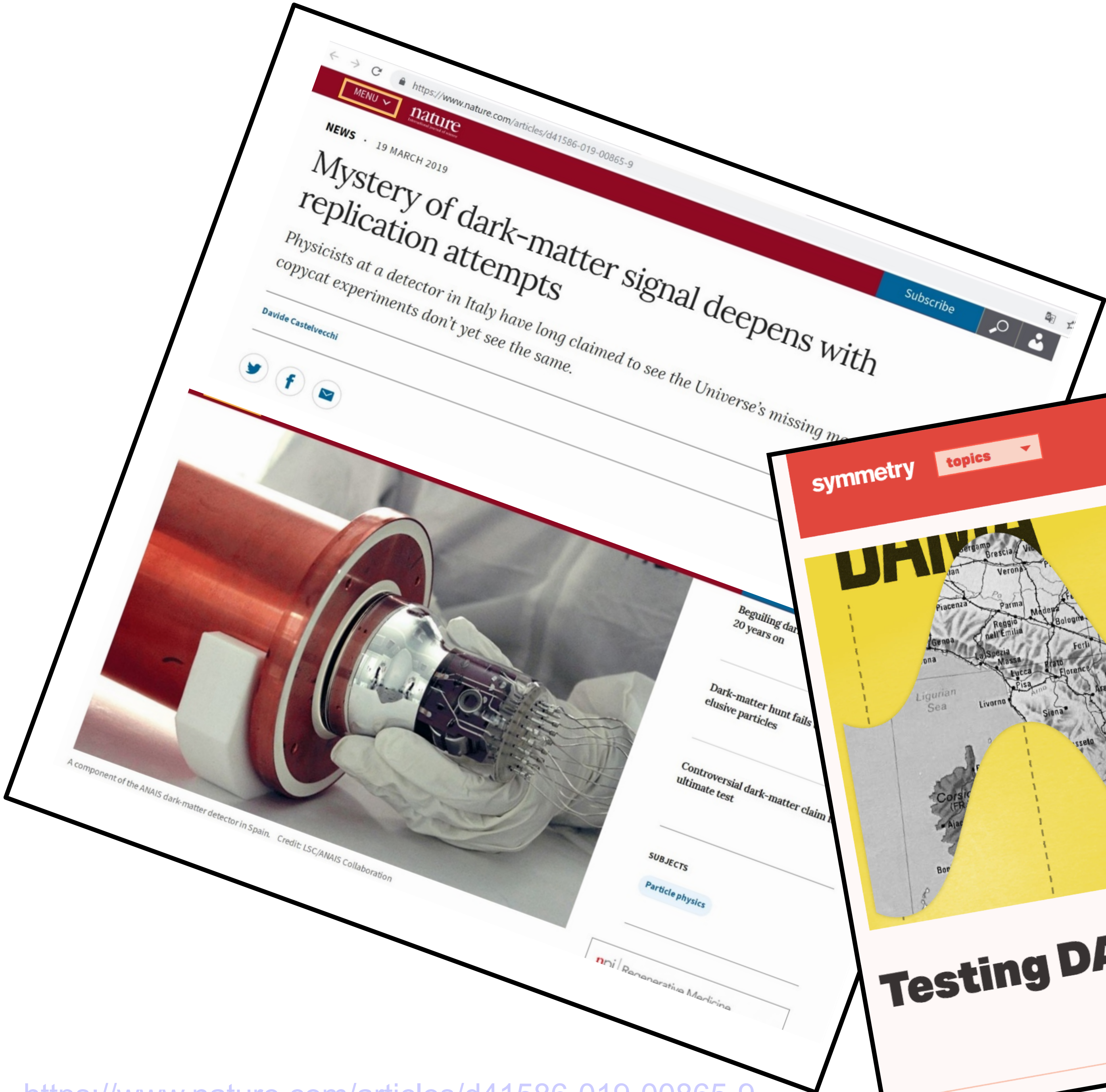


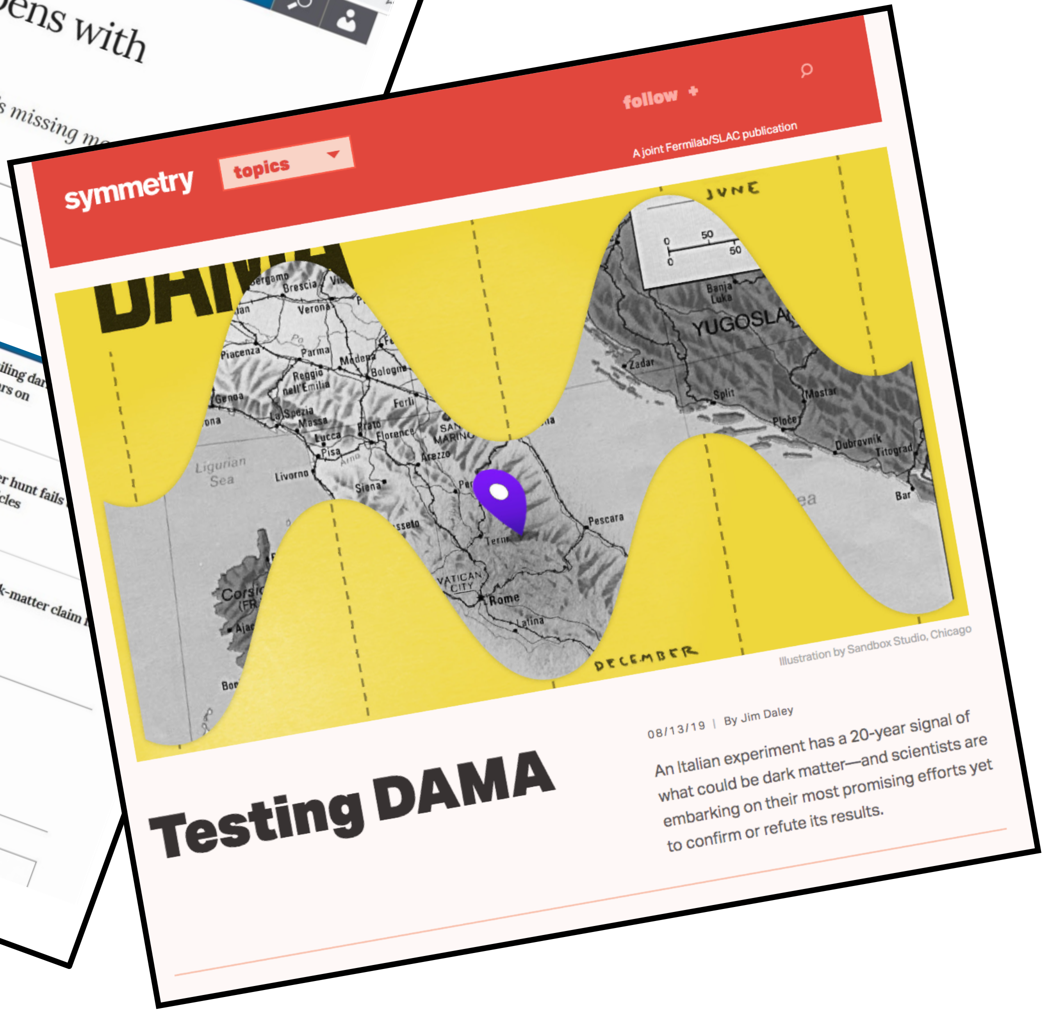

- Global fit using cosmogenic and sinusoidal components simultaneously for crystals
- Crystal 1, 5, and 8 excluded in this analysis due to low light yield and excessive PMT noise

Best fit amplitude for 2 – 6 keV:

- 0.0083 ± 0.0068 cpd/kg/keV
- phase fixed at 152.5 day


Search for a dark matter-induced annual modulation signal in NaI(Tl) with the COSINE-100 experiment
G. Adhikari et al,
Phys. Rev. Lett. 123 (2019) 032302




https://www.nature.com/articles/d41586-019-00865-9

https://www.symmetrymagazine.org/article/testing-dama

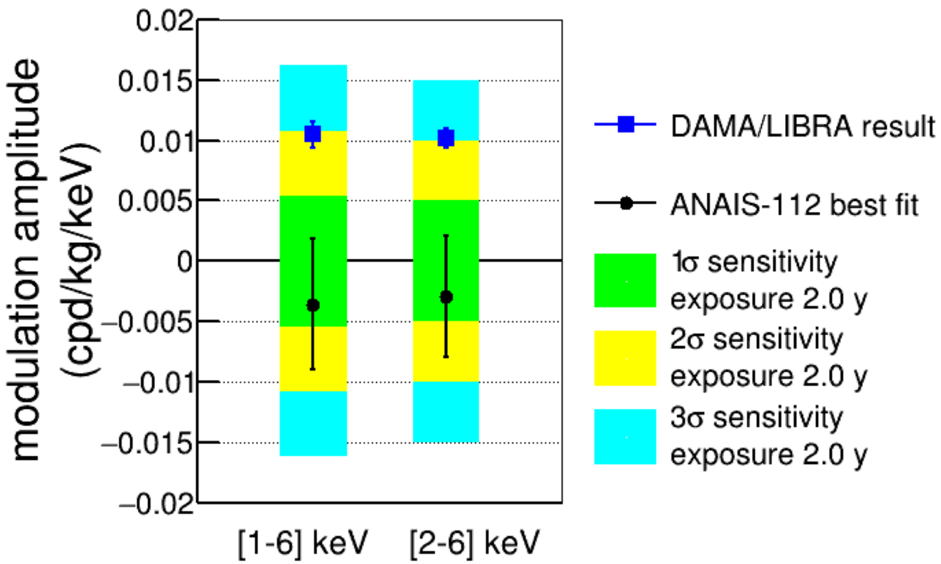
# Summary and outlook

✓ **ANAIS-112:** data taking using **112.5 kg** of **NaI(Tl)** running smoothly for >2 y

- Very high **duty cycle**
- Careful **low energy calibration** (from external gamma sources and bulk emissions)
- Excellent **light collection** of **~15 phe/keV** and **analysis threshold** at **1 keV$_{ee}$** in all modules
- Robust **filtering** of PMT events (dominating below 10 keV$_{ee}$)
- Good **background understanding**, dominated by crystal activity ($^{210}$Pb, $^{40}$K, $^{22}$Na, $^{3}$H)

**Analysis** for model independent **annual modulation** of 2 y of data taking up to July 2019:

- Best fits are incompatible at **2.6σ** with DAMA/LIBRA results
- Null hypothesis well supported
- Confirmed sensitivity of 3σ for 5 y of data



# Summary and outlook

✓ **Next future:**

- Data taking will continue in the same conditions for at least a third year, together with a **blank module** to monitor non-NaI(Tl) scintillation events
- Excess of **events in 1-2 keV** to be understood
- Measurement of scintillation **Quenching Factor** for nuclear recoils at TUNL laboratories (Duke University, US) underway, investigating possible dependence on crystal quality
- Combining data between **COSINE-100 and ANAIS-112** agreed to reach 3$\sigma$ sensitivity to DAMA/LIBRA sooner
- Plan to make ANAIS **data public** after use to allow independent analysis


- First results on dark matter annual modulation from ANAIS-112 experiment, J. Amaré et al, Phys. Rev. Lett. 123 (2019) 031301.
- ANAIS-112 status: two years results on annual modulation , J. Amaré et al, arXiv:1910.13365v2 [astro-ph.IM].
- Performance of ANAIS-112 experiment after the first year of data taking, J. Amaré et al, Eur. Phys. J. C (2019) 79:228.
- Analysis of backgrounds for the ANAIS-112 dark matter experiment, J. Amaré et al, Eur. Phys. J. C (2019) 79:412.
- ANAIS-112 sensitivity in the search for dark matter annual modulation, I. Coarasa et al, Eur. Phys. J. C (2019) 79:223.