Dark matter annual modulation results from the ANAIS-112 experiment

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

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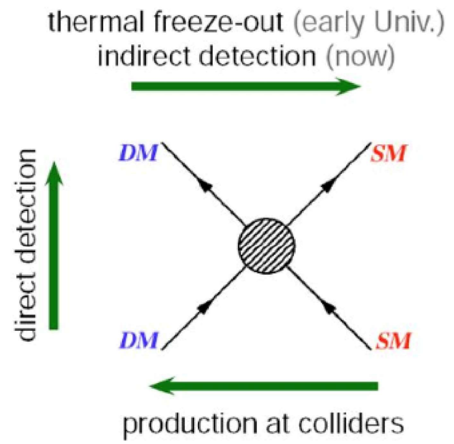
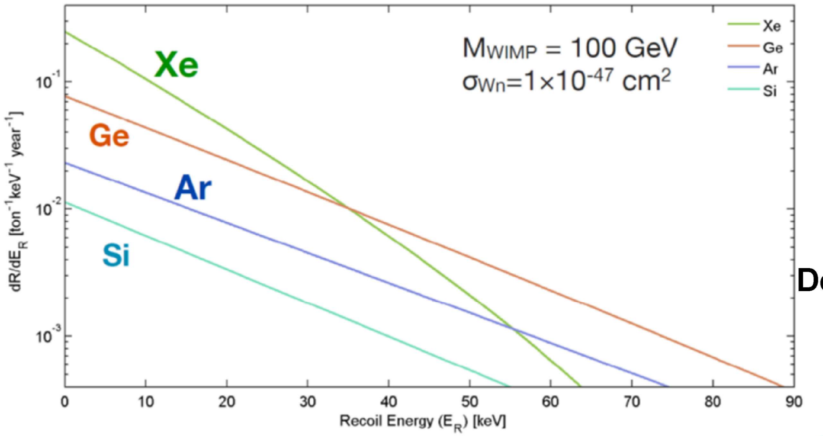
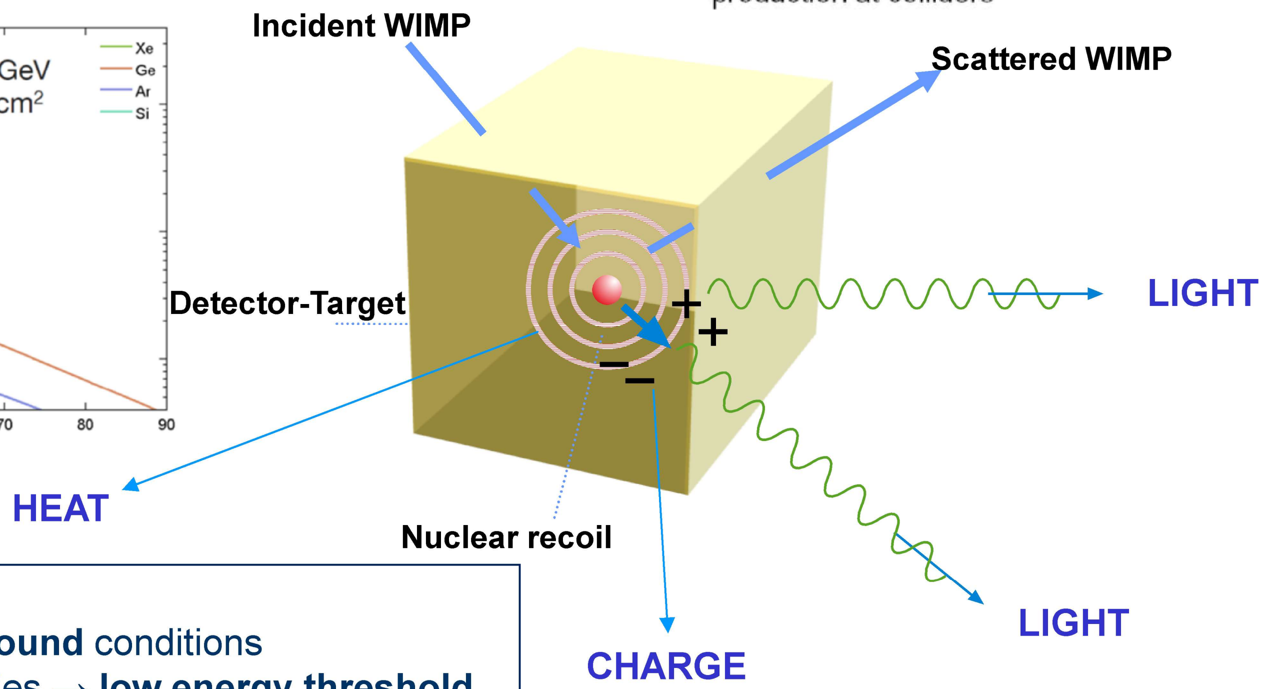
Direct detection of dark matter

- Different complementary strategies for **dark matter detection**



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

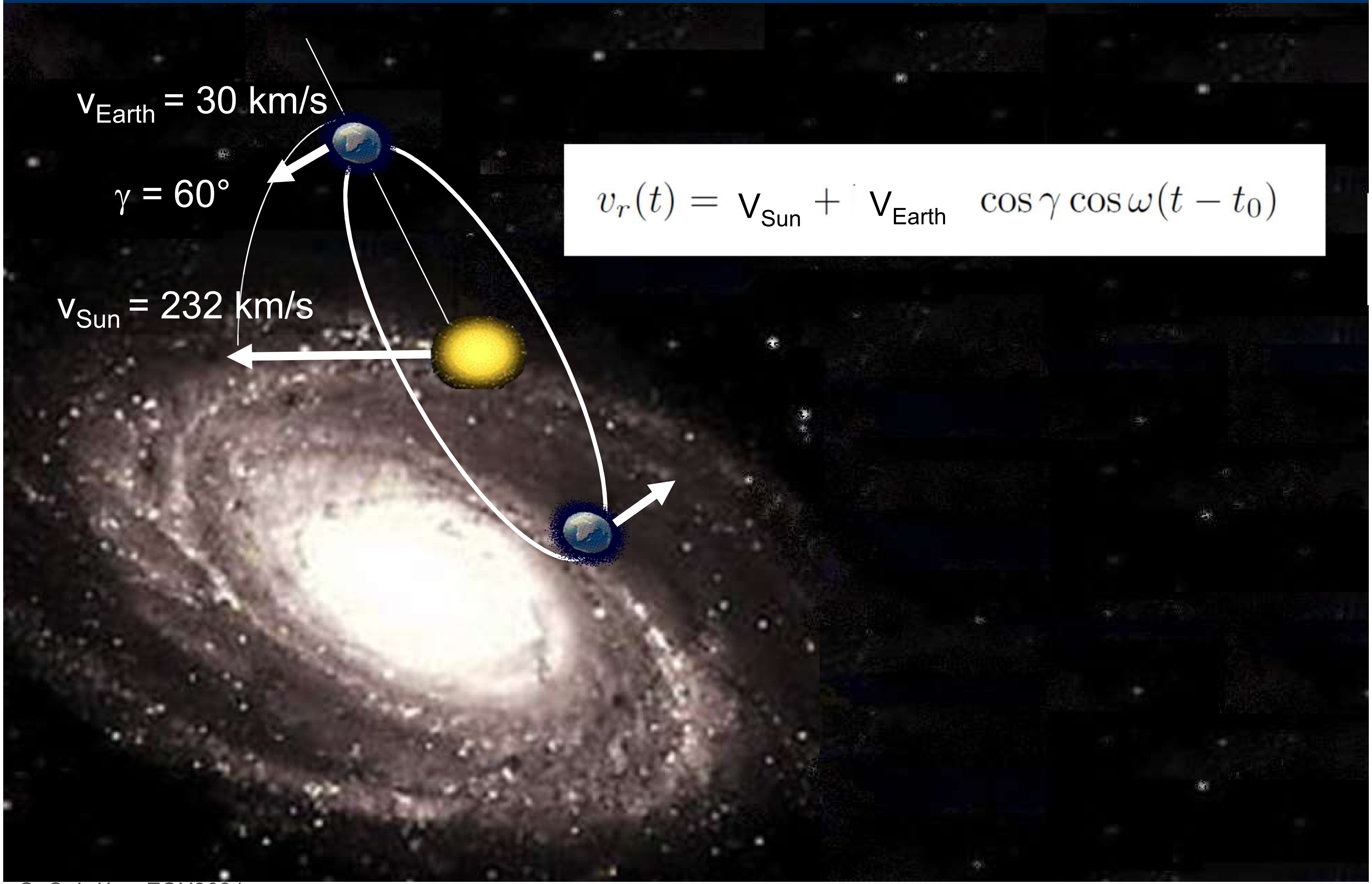




Challenge:
- rare signal → ultra **low background** conditions
- concentrated at very low energies → **low energy threshold**
- with continuum energy spectrum entangled with background → **distinctive signatures**

S. Cebrián, ECU2021

Direct detection: annual modulation



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

Direct detection: annual modulation

Distinctive signal in the interaction rate of WIMPs

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

k: bin energy

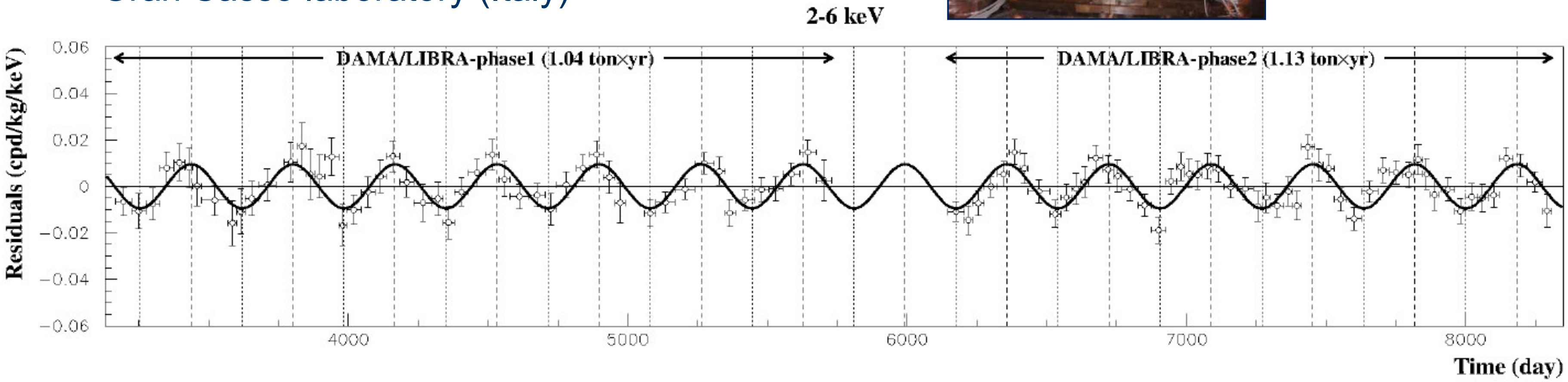
- ✓ Cosine behaviour
- ✓ 1 year period
- ✓ Maximum around June 2nd
- ✓ Weak effect (1-10%)
- ✓ Only noticeable at low energy
- ✓ Should have a phase reversal at low energies

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

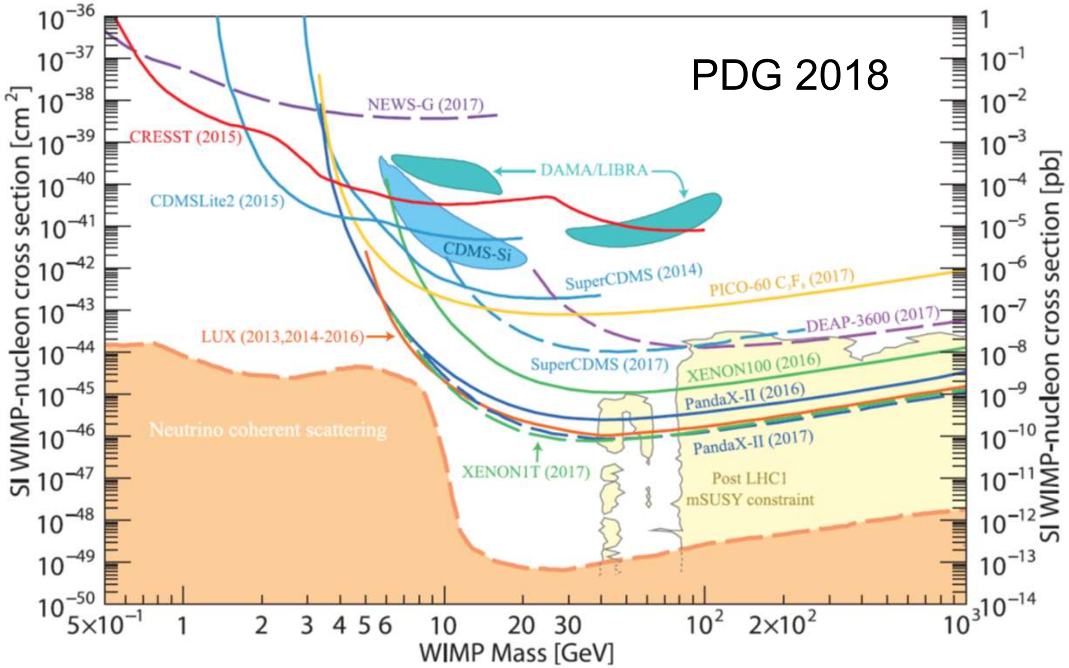
DAMA/LIBRA results: modulation with proper features at **12.9σ CL**

- 2.46 ton×y (over 20 y, 25x9.7 kg NaI(Tl))
- Gran Sasso laboratory (Italy)



R. Bernabei et al, Eur. Phys. J. C 73 (2013) 2648
R. Bernabei et al, Nucl. Phys. At. Energy 19, 307 (2018)

Direct detection: annual modulation



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

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

No annual modulation signal in other experiments

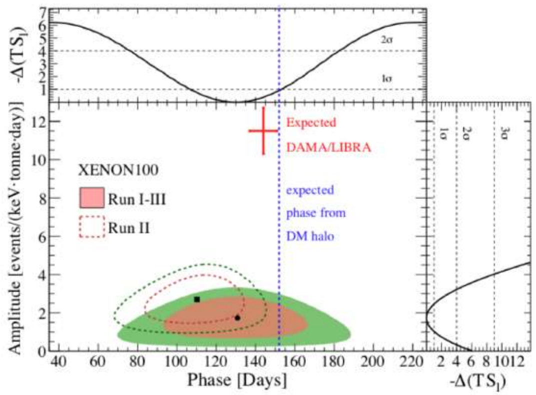
XENON100
E. Aprile et al, Phys. Rev. Lett. 118, 101101 (2017)

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

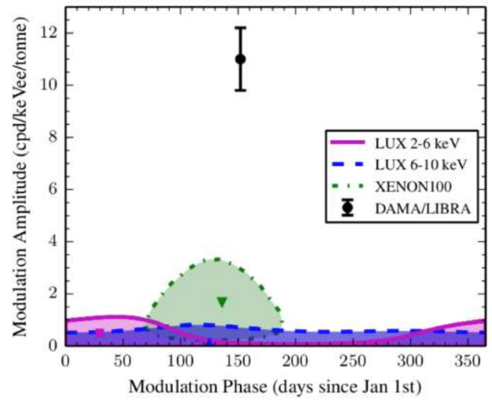
LUX
D.S. Akerib et al, Phys. Rev. D 98, 062005 (2018)

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

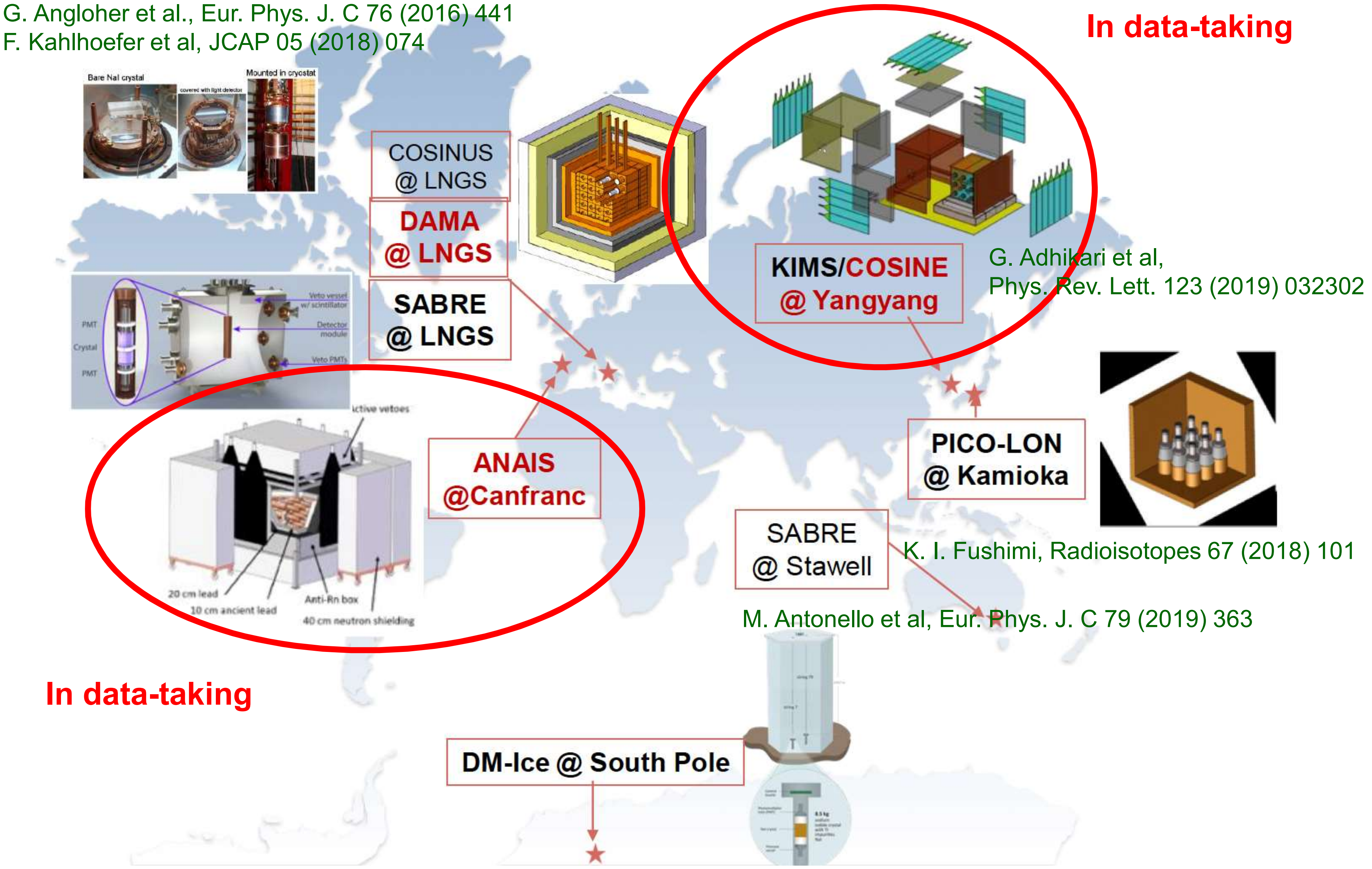
XENON100



LUX

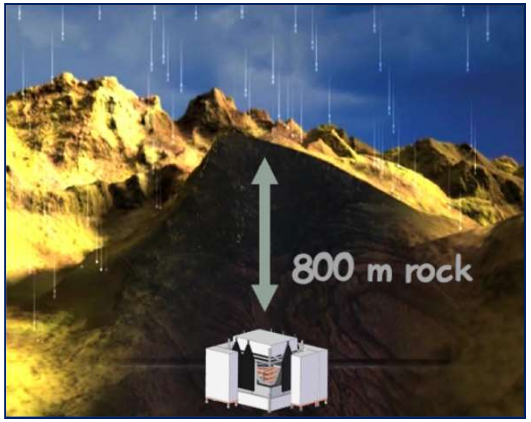


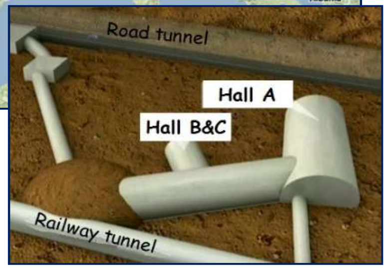
Direct detection: annual modulation



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)

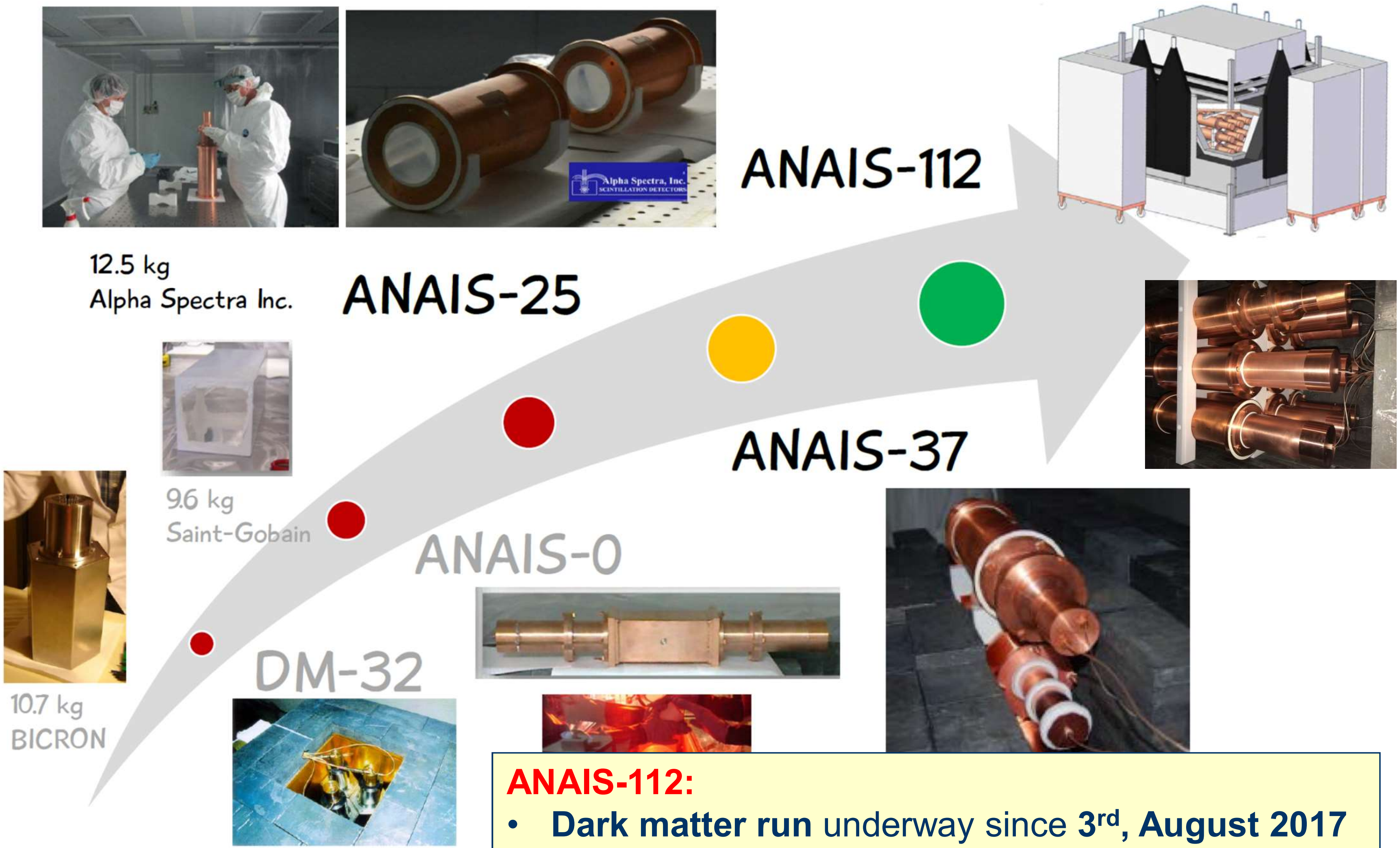




Experimental requirements:

- 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: goals and history

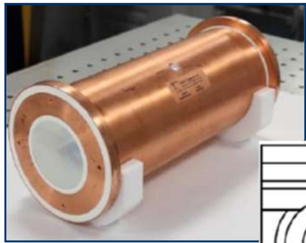


ANAIS-112:
- **Dark matter run** underway since **3rd, August 2017**
- First **3 years** of data analyzed

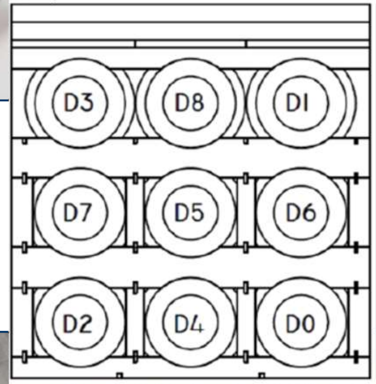
Detector set-up: detectors

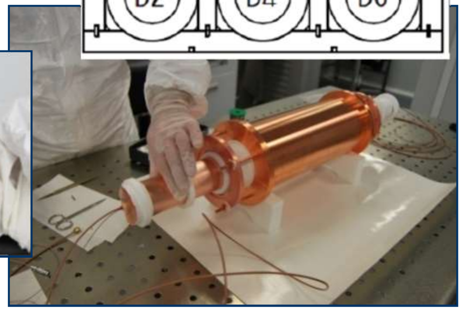
Nine modules produced by Alpha Spectra Inc (US) following low radioactivity protocols

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



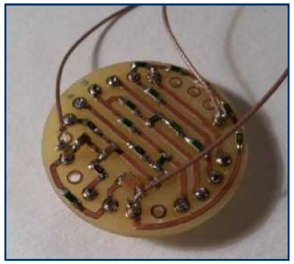
12.5 kg each
4.75'' diameter
11.75'' length





- **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

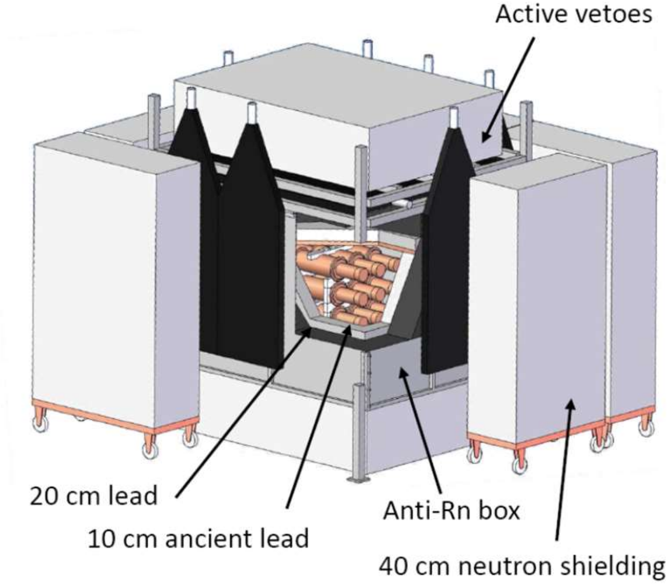


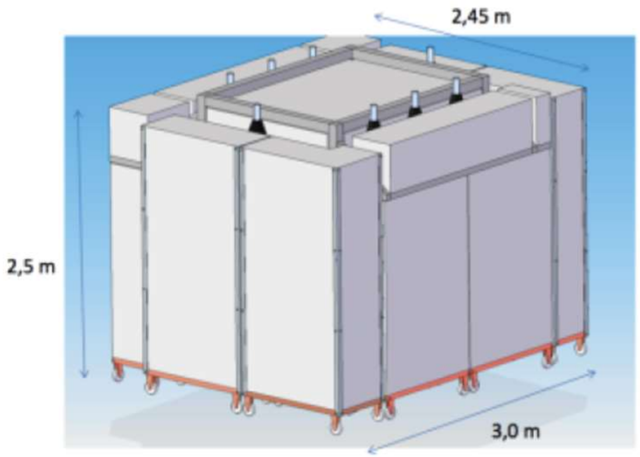
Voltage dividers in cuflon PCB

Housing made at LSC of electroformed copper

Detector set-up: shielding

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

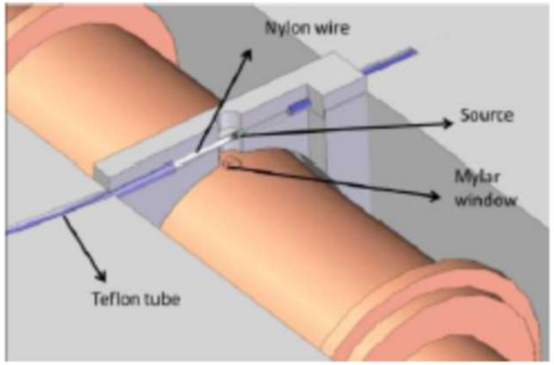




Detector set-up: calibration system

Radon-free **system** to allow calibration at low energy

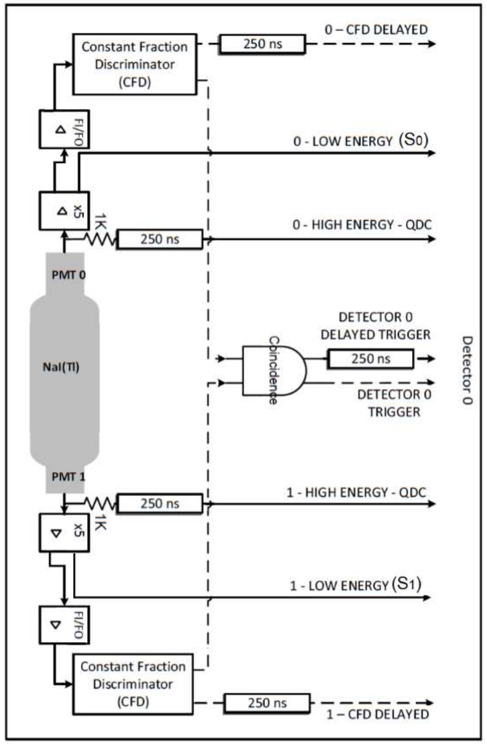
- Detectors equipped with a **mylar window**
- **^{109}Cd sources** on flexible wires
- Simultaneous calibration of the nine modules
- Energies 11.9 keV, 22.6 keV and 88.0 keV
- Performed every two weeks

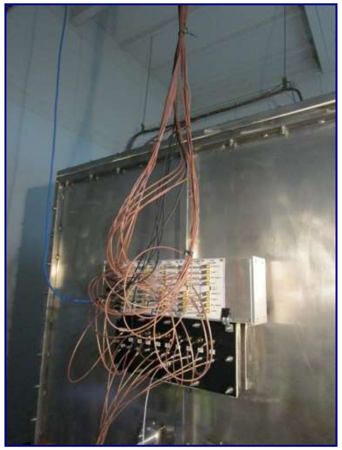


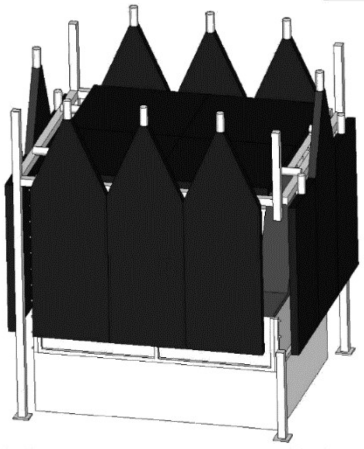
Detector set-up: data acquisition

- **DAQ hardware and software** designed and tested in previous ANAIS set-ups
  - Individual PMT signals digitized and fully processed (2 Gs/s, 14 bits)
  - Trigger at phe level for each PMT signal
  - AND coincidence in 200 ns window
  - Redundant energy conversion by QDC
  - Trigger in OR mode among modules

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







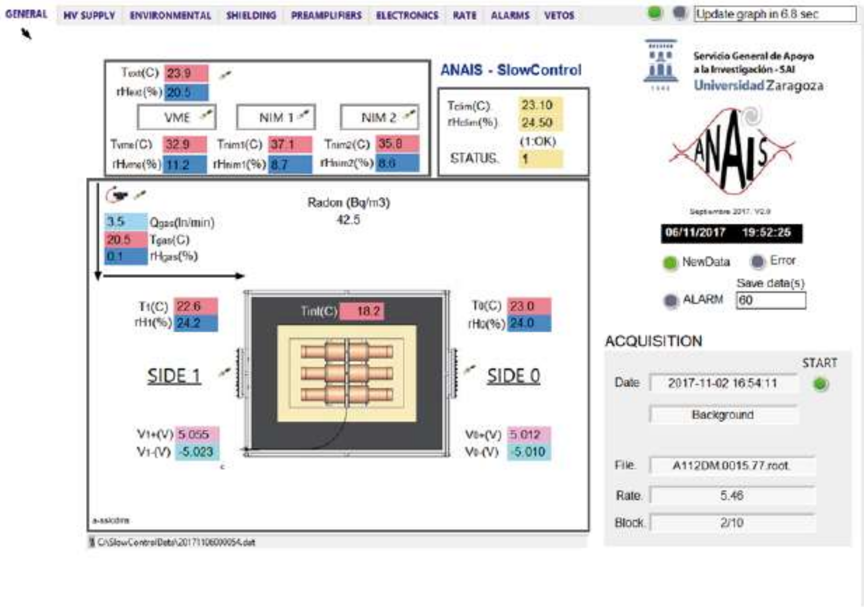
Detector set-up: slow control

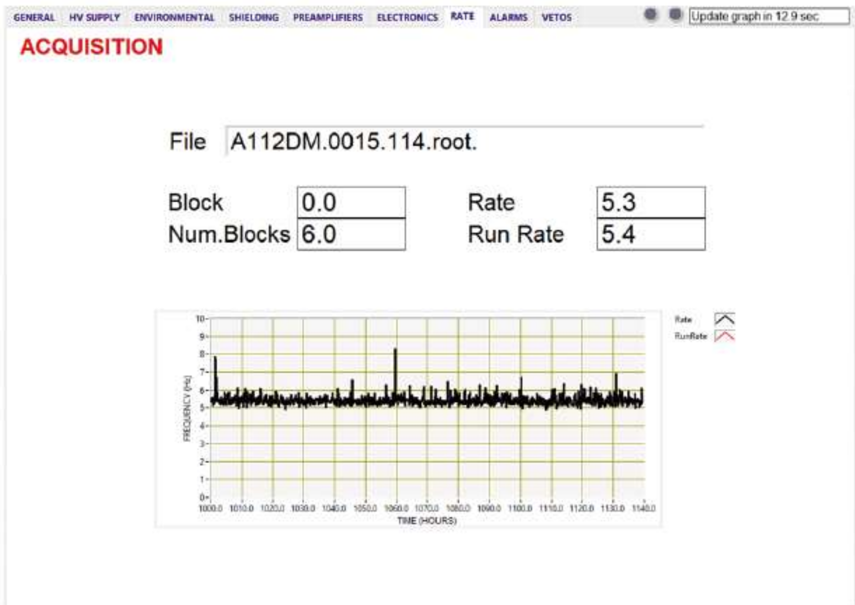
- Monitoring of **environmental parameters** ongoing since the start of dark matter run:
  - Monitoring:

    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 performance

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

Now 3 years analyzed: 1018.6 days, 313.95 kg y

- Excellent **duty cycle:** ~95% live time
- Outstanding **light collection** of **~15 phe/keV** measured in:
  - all modules
  - at different set-ups
  - checked to be stable over time

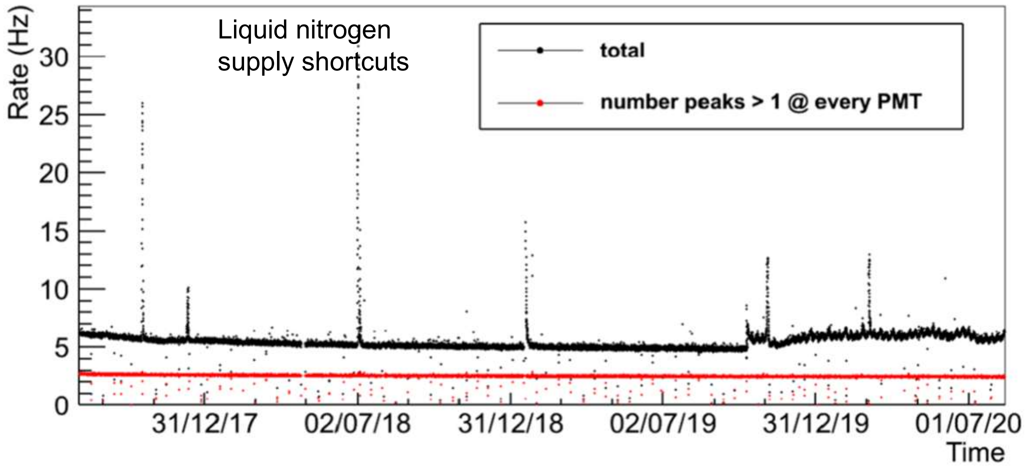
M.A. Oliván et al, Astropart. Phys. 93 (2017) 86

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

Larger than reported for DAMA/LIBRA detectors:
Phase 1: **5.5-7.5 phe/keV**
Phase 2: **6-10 phe/keV**

- Good **stability**

Total trigger rate

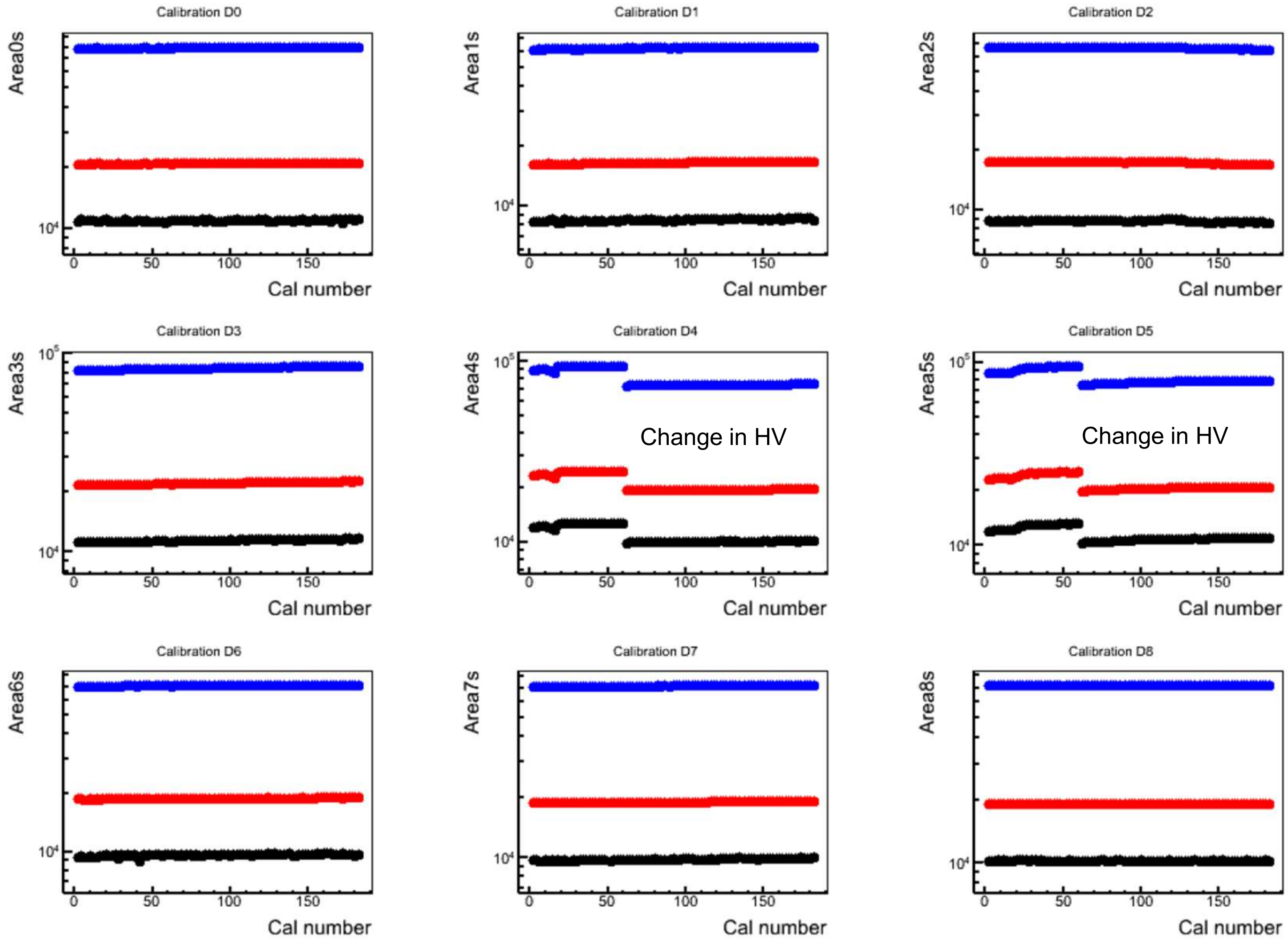


Detector performance

- Good **stability**

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

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

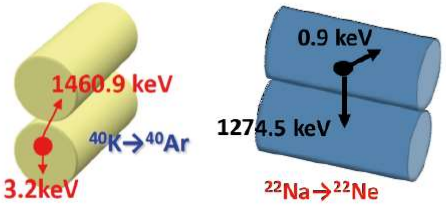


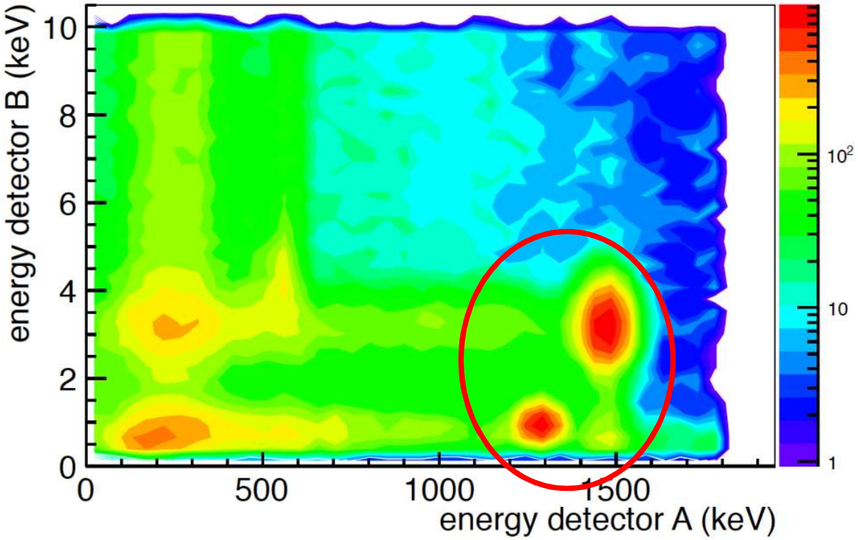
S. Cebrián, ECU2021

Detector performance

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

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

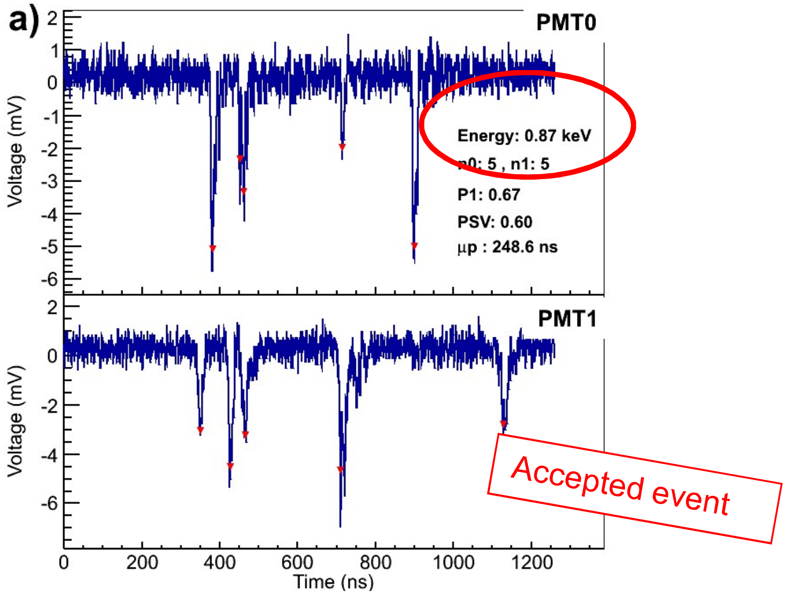




- Based **on ^{109}Cd calibrations and data from ^{22}Na and ^{40}K** coincidence populations

- **Multiparametric cuts** to select events

1. Pulse shape cut to select pulses with NaI(Tl) scintillation constant
2. We remove asymmetric events (<2 keVee) with origin in the PMT
3. Remove 1 s after a muon passage
4. Multiplicity = 1 (Reject events that deposit energy simultaneously in more than one crystal)



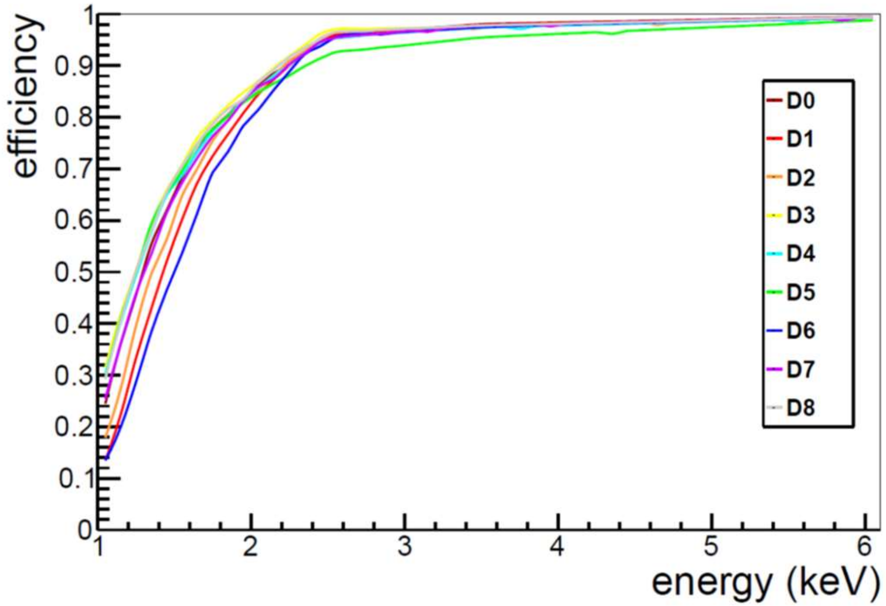
Detector performance

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

  - **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

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

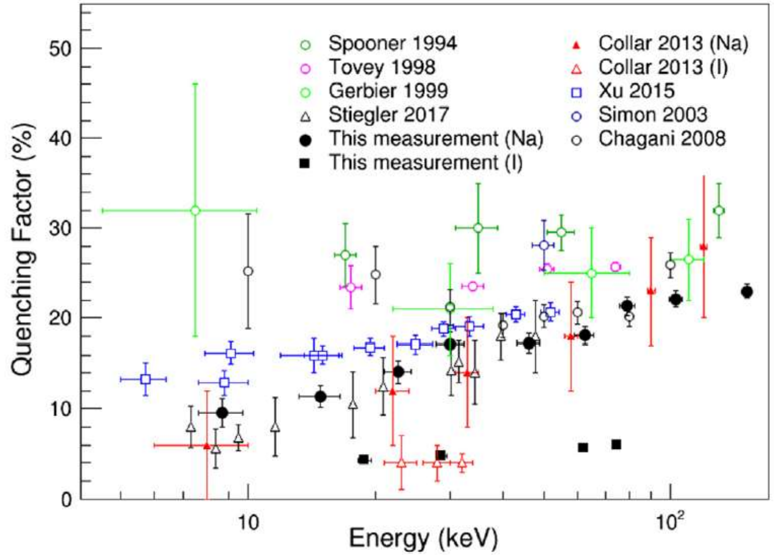
Updated to 3 years



Detector performance

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

  Relative efficiency factor for nuclear recoil scintillation



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

- Measurements carried out in October 2018 in the Triangle Universities Nuclear Laboratory (Duke University, US), in coordination with Duke and Yale groups from COSINE collaboration
- Several small crystals from Alpha Spectra company with different quality powder quality
- Analysis almost finished

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

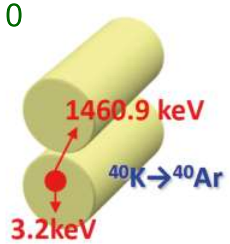
- **Activity from external components** measured with HPGe detectors at Canfranc
- **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb

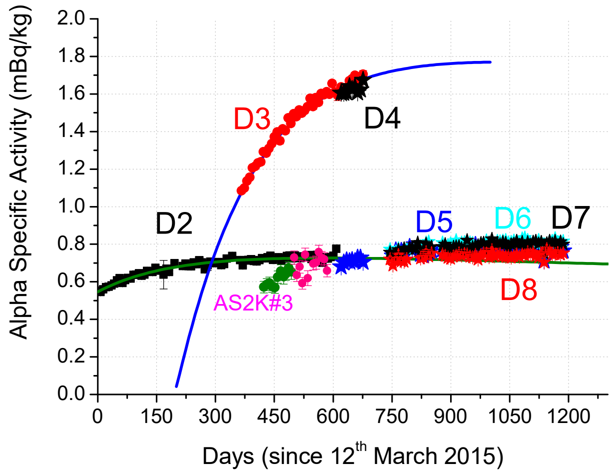
Detector	^{40}K (mBq/kg)	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.33±0.04	$(4\pm1)\ 10^{-3}$	$(10\pm2)\ 10^{-3}$	3.15±0.10
D1	1.21±0.04			3.15±0.10
D2	1.07±0.03	$(0.7\pm0.1)\ 10^{-3}$	$(2.7\pm0.2)\ 10^{-3}$	0.7±0.1
D3	0.70±0.03			1.8±0.1
D4	0.54±0.04			1.8±0.1
D5	1.11±0.02			0.78±0.01
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

^{22}Na: from analysis of coincidences

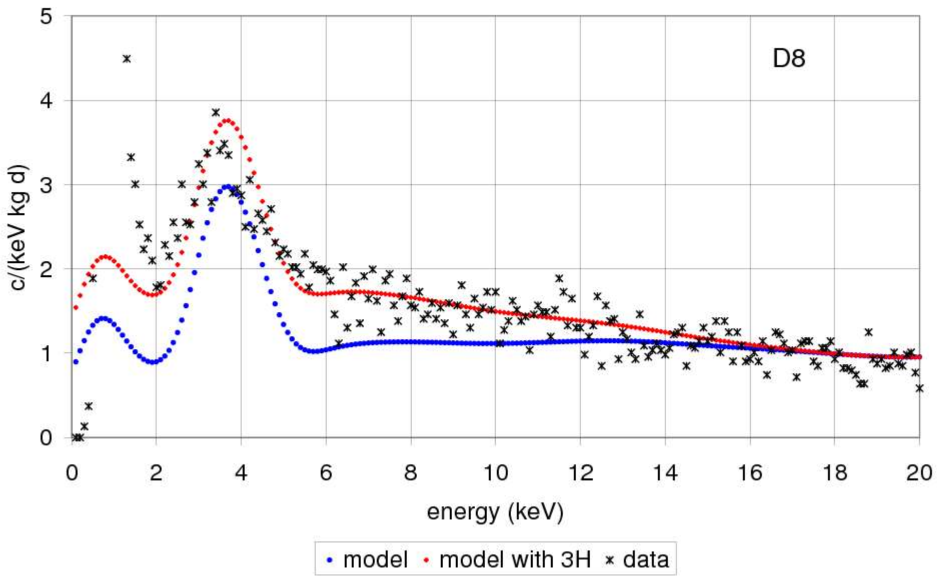
^{109}Cd, ^{113}Sn: from peaks at binding energies of K-shell electrons (after EC)

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

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

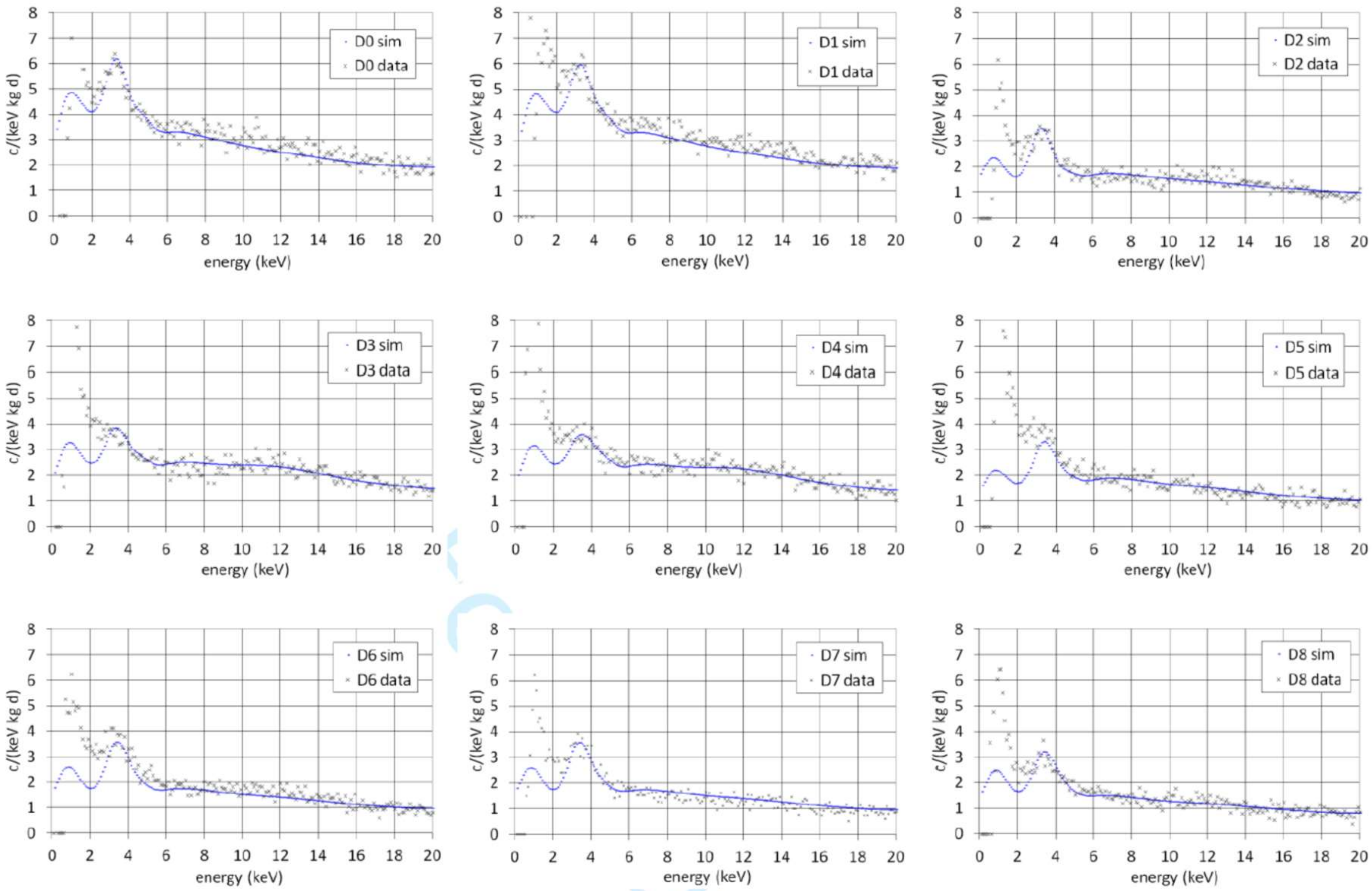
D0-D1: 0.20 mBq/kg

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



Background model

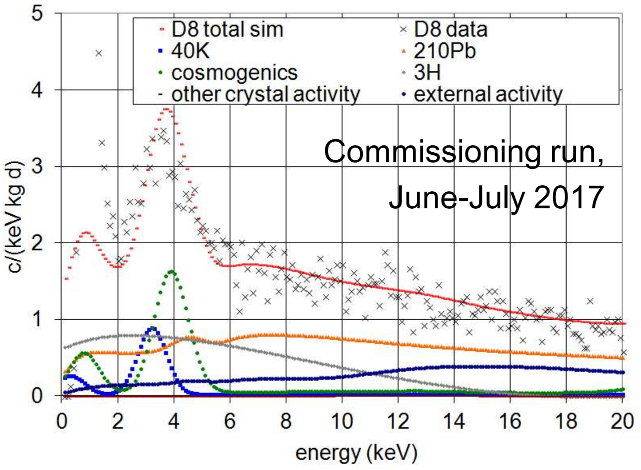
Comparison with first year of ANAIS-112 data at **very low energy**



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

Background model

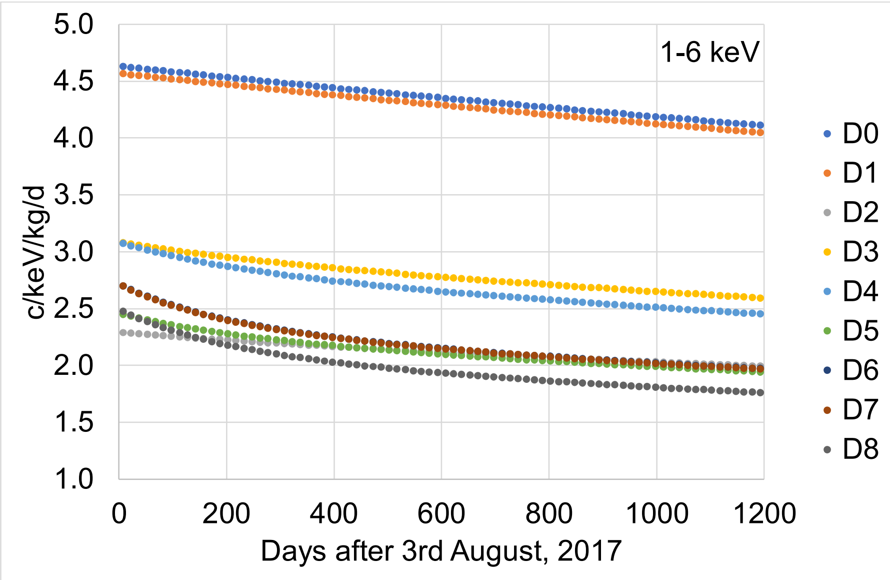
- **Individual contributions** in ANAIS-112 data



^{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%

- **Prediction of time evolution** (from decaying cosmogenics and ^{210}Pb)



Annual modulation results

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

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

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

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

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

ANAIS-112 status: two years results on annual modulation

J. Amaré[1,2], S. Cebrián[1,2], D. Cintas[1,2], I. Coarasa[1,2], E. García[1,2], M. Martínez[1,2,3], M.A. Oliván[1,2,4], Y. Ortigoza[1,2], A. Ortiz de Solórzano[1,2], J. Puimedón[1,2], A. Salinas[1,2], M.L. Sarsa[1,2] and P. Villar[1,2]
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Same analysis for **2 y**, 213.6 kg x y
Presented at TAUP2019

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

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

Annual modulation results

DAMA/LIBRA results:

[1-6] keV S_m^{DAMA} = 0.0105 cpd $\pm$ 0.0011/kg/keV

[2-6] KeV S_m^{DAMA} = 0.0102 $\pm$0.0008 cpd/kg/keV

Period fixed @ 1 year, phase fixed @ 2nd June

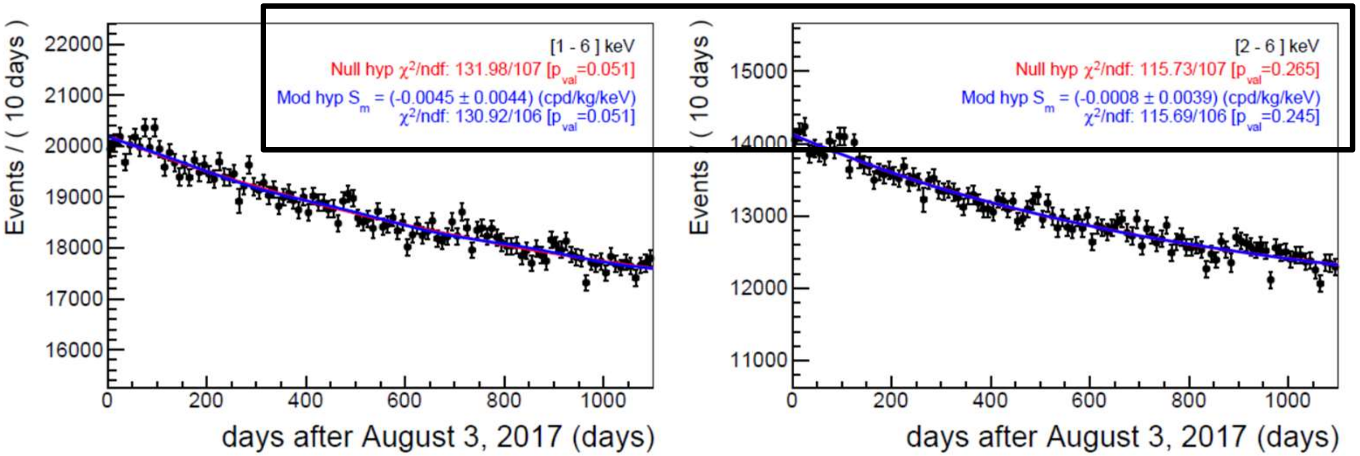
Preliminary analysis for **3 y**, 313.95 kg x y

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

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

- τ fixed from background model
- ω fixed corresponding to 1 year period
- ϕ fixed to have the cosine maximum in June, 2nd
- $\boldsymbol{S_m}$ fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

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



Different fit approaches ongoing. Results very soon in arXiv.

PRELIMINARY

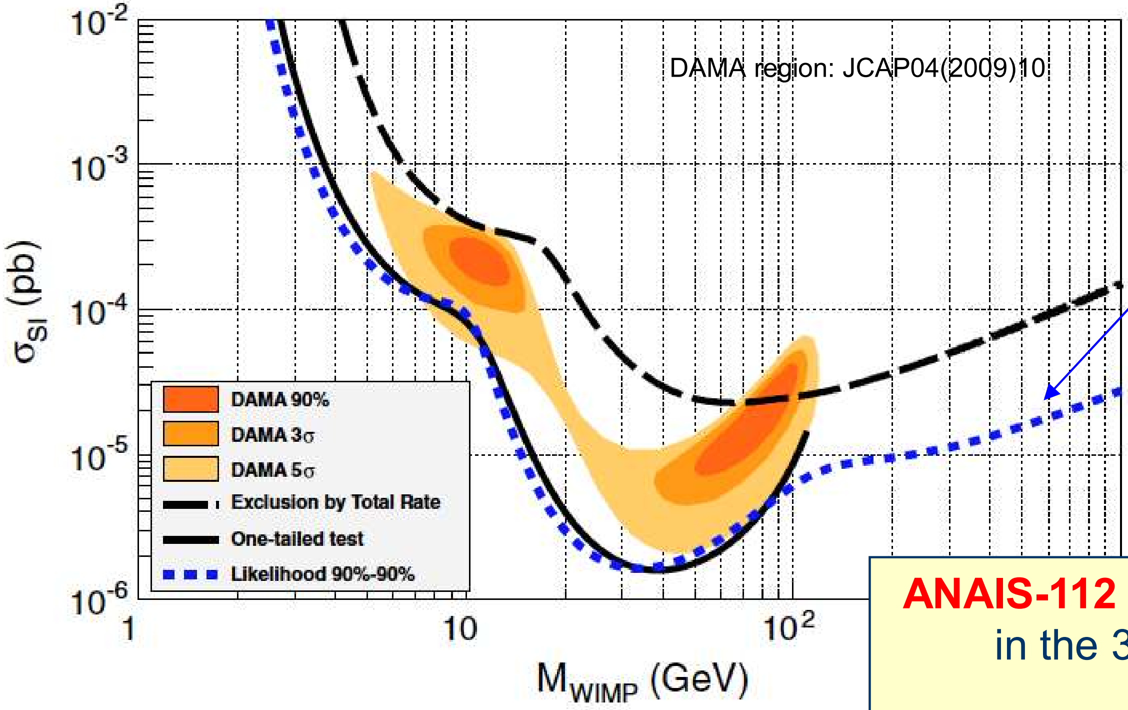
Annual modulation sensitivity

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)

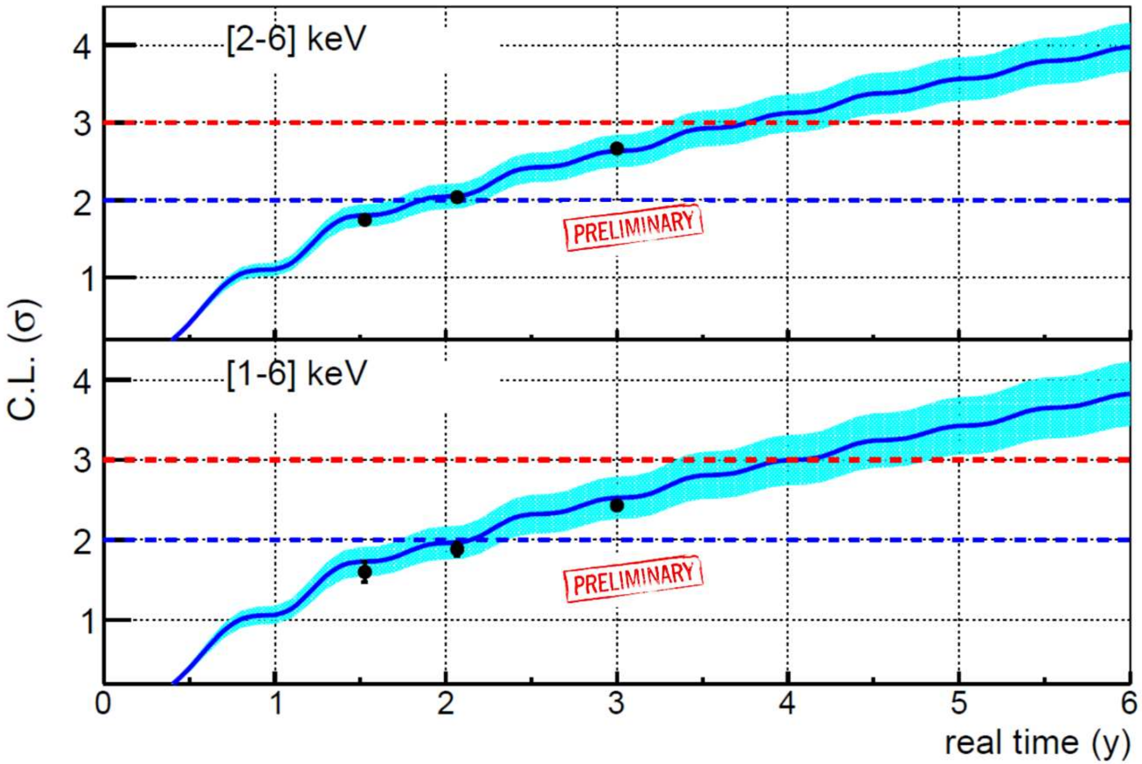


90% probability of detecting an annual modulation signal at 90% C.L.

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 analitically estimated from:

- updated background
- efficiency estimates
- live time distribution

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

Sensitivity projection to DAMA/LIBRA result fully confirmed by data

3σ sensitivity at reach in ~1 y from now!

Summary and outlook

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

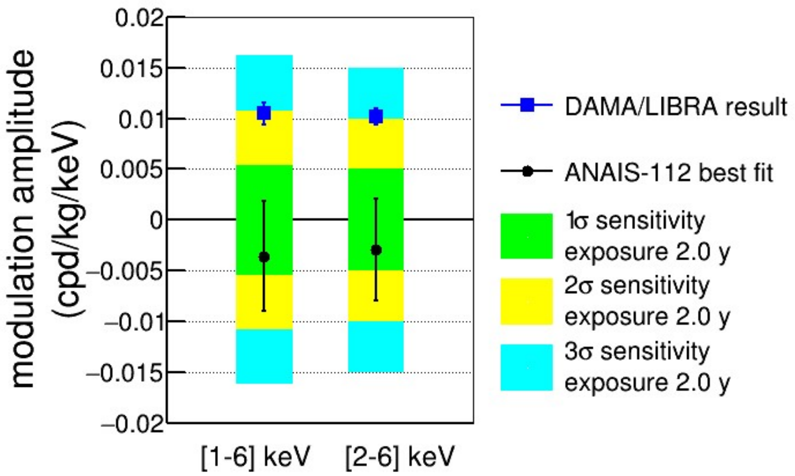
- Very high **duty cycle**
- Careful **low energy calibration** (from external gamma sources and bulk emissions)
- Excellent **light collection** of **~15 phe/keV** and **analysis threshold** at **1 keV$_{ee}$** in all modules
- Robust **filtering** of PMT events
- Good **background understanding**,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

Analysis for model-independent **annual modulation** of **2 y** of data taking:

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

Analysis for **3 y** of data up to August 2020 will be **released very soon**

- Expected sensitivity to DAMA/LIBRA result at 1-6 (2-6) keV of 2.3 (2.7) σ



Summary and outlook

✓ **Next future:**

- Data taking will continue in the same conditions up to at least 5 y
- Excess of **events in 1-2 keV** to be understood
- Determination of scintillation **Quenching Factor** for nuclear recoils at TUNL laboratories (Duke University, US) underway, investigating possible dependence on crystal quality

✓ **Longer term:**

- ANAIS-112 **extension** under consideration
  - Reduce threshold working with SiPM at low temperature
  - Reduce background by growing ultrapure crystals underground

- 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, J.Phys. (Conf. Ser.) 1468 (2020) 012014.
- 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.

Dark matter annual modulation results from the ANAIS-112 experiment

Julio Amaré [1,2], Susana Cebrián [1,2,*], David Cintas [1,2], Iván Coarasa [1,2], Eduardo García [1,2], María Martínez [1,2,3], Miguel Ángel Oliván [1,2,4], Ysrael Ortigoza [1,2], Alfonso Ortiz de Solórzano [1,2], Jorge Puimedón [1,2], Ana Salinas [1,2], María Luisa Sarsa [1,2] and Patricia Villar [1,2]

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