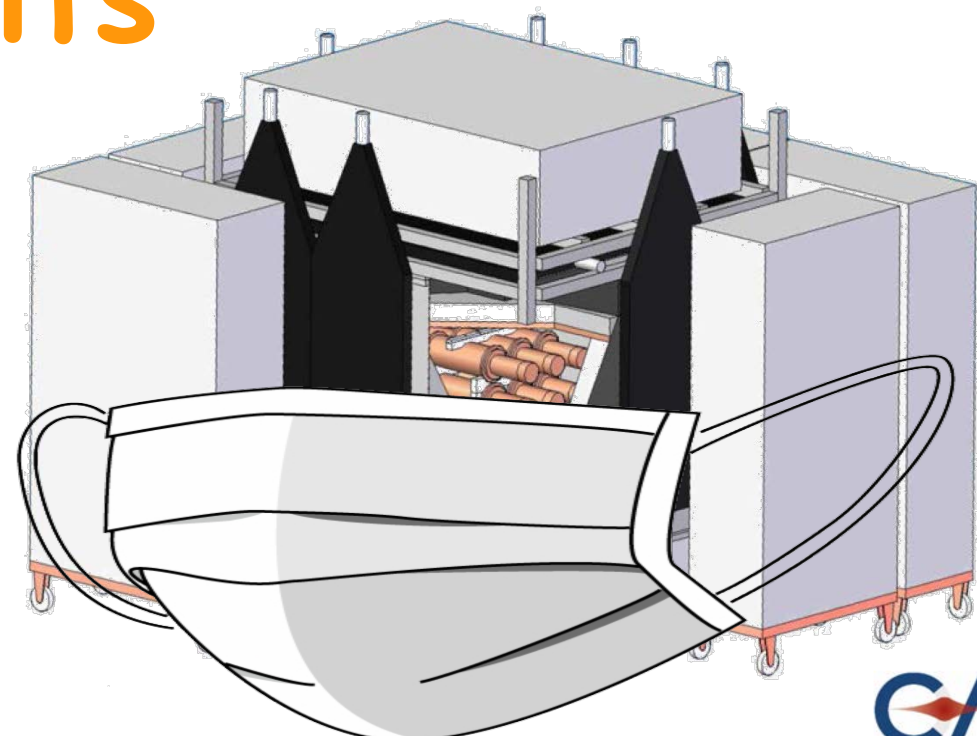
ANAIS-112 status and preliminary 3 years results



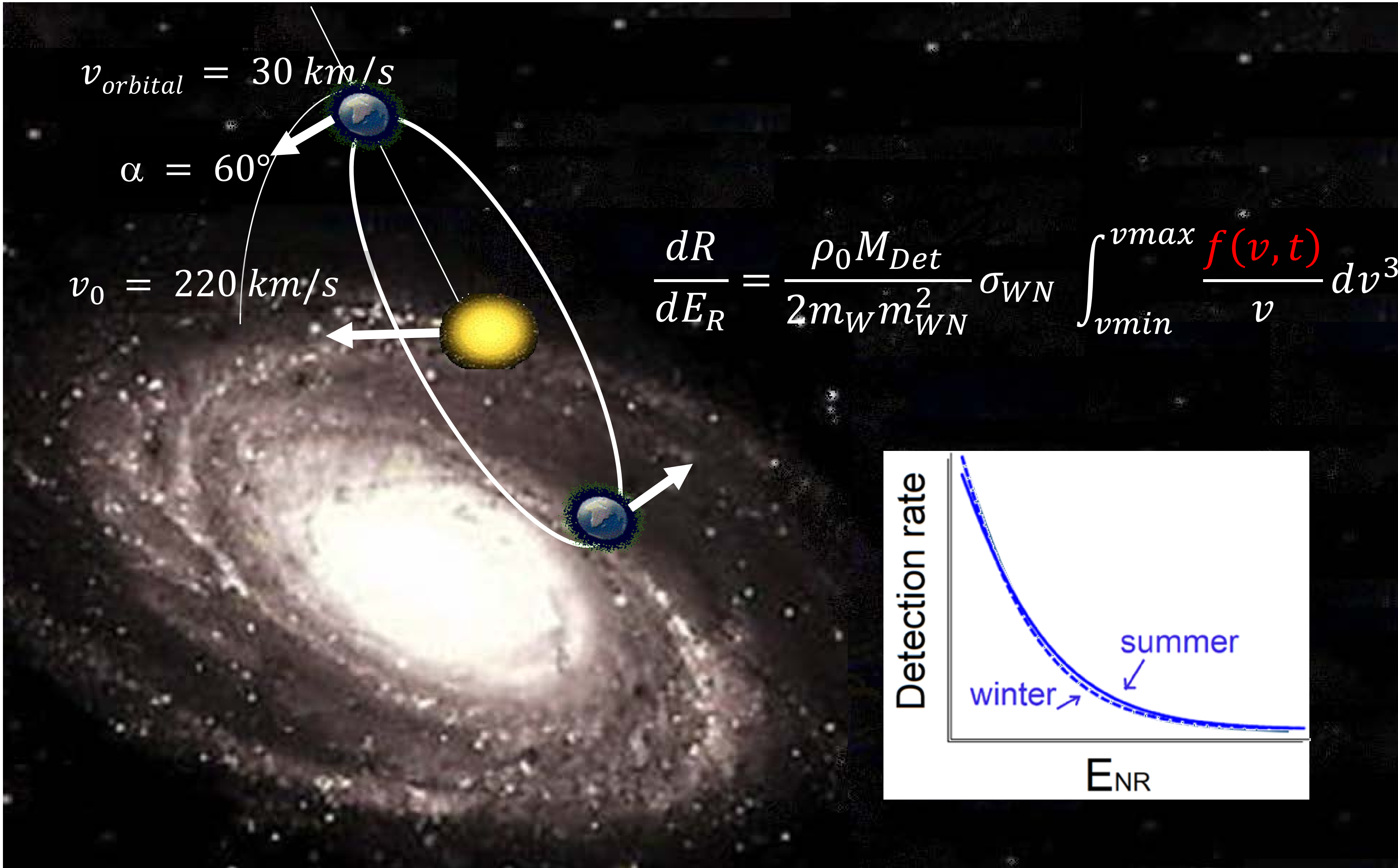
María Martínez, ARAID & CAPA
On behalf of ANAIS team
Multidark Online Meeting, January 26, 2021

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

OUTLINE

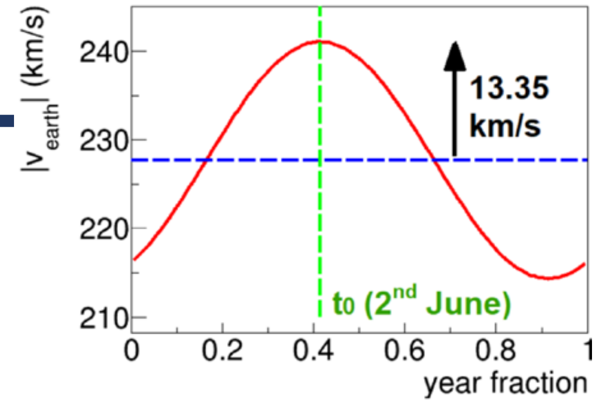
- Intro: DM annual modulation and DAMA/LIBRA positive signal
- ANAIS-112 status
  - Experimental set-up
  - Detector performance
- Results on annual modulation: 3 years update
- ANAIS-112 sensitivity
- Future plans and summary

DM Annual modulation



$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v,t)}{v} dv^3$$

DM Annual modulation

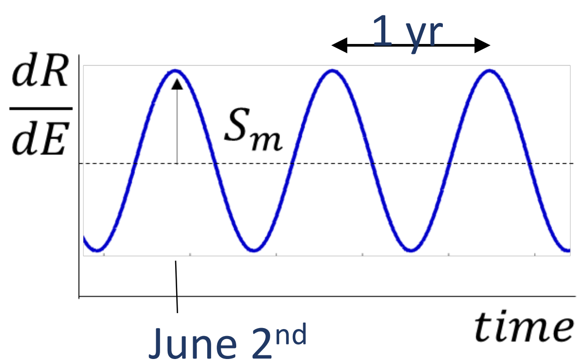


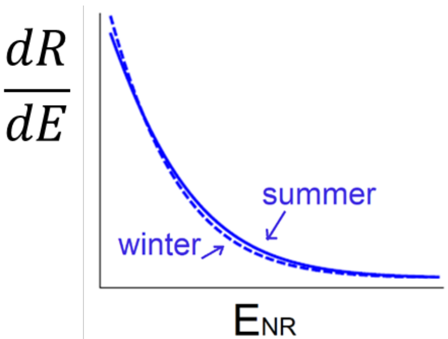
Due to the Earth revolution around the Sun, the relative speed Earth-halo is cosine-like with 1 year periodicity and small amplitude (~ 7%), and that implies **a modulation in the expected rate:**

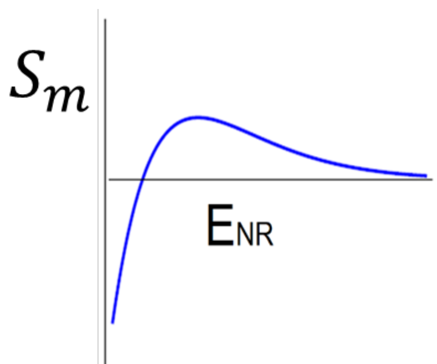
$$\boxed{\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t-t_0)}$$

Where

$$S_m(E) = \frac{1}{2}\left(\frac{dR}{dE}(E,t_0) - \frac{dR}{dE}(E,t_0+182)\right)$$





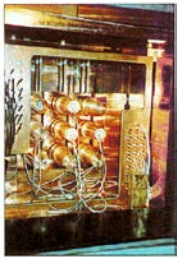


A distinctive signal hard to mimic by background

- ✓ **Cosine behaviour**
- ✓ **1 year period**
- ✓ **Maximum around June 2nd**
- ✓ **Weak effect $\left(\frac{S_m}{S_0} \sim 0.01 - 0.1\right)$**
- ✓ **Only noticeable at low energy**
- ✓ **Phase reversal at low E**

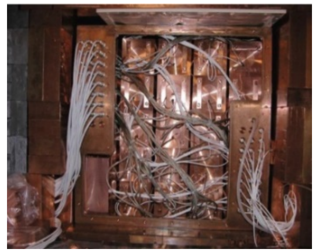
DAMA/LIBRA positive signal

DAMA / NaI (1995-2002)



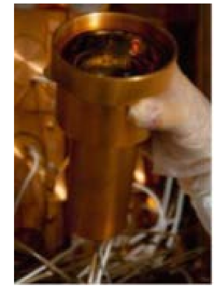
- 10 ×9.7 kg NaI(Tl)
- 7 annual cycles
- 0.29 ton×y

DAMA / LIBRA phase 1 (2003-2010)



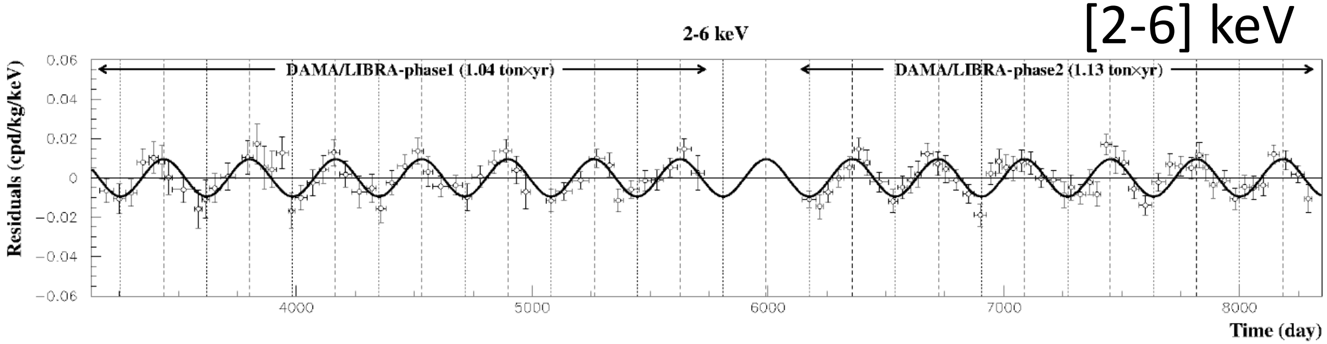
- 25×9.7 kg NaI(Tl)
- 7 annual cycles
- 1.17 ton×y

DAMA / LIBRA phase 2 (2011-2018)

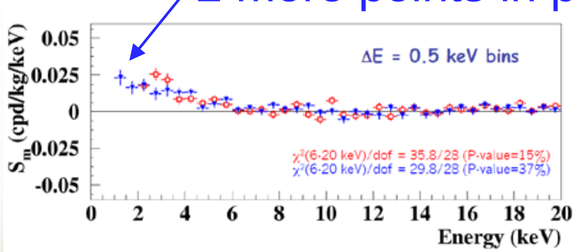


- 25×9.7 kg NaI(Tl)
- PMT with high QE
→threshold at 1 keV
- 6 annual cycles
- 1.13 ton×y

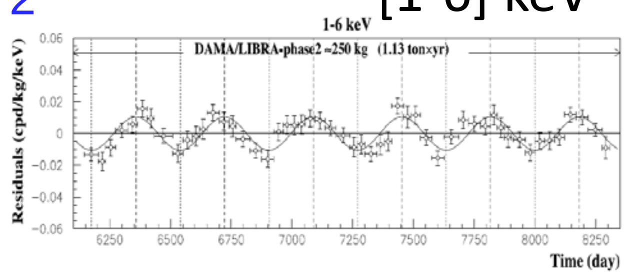
[2-6] keV



2 more points in phase 2



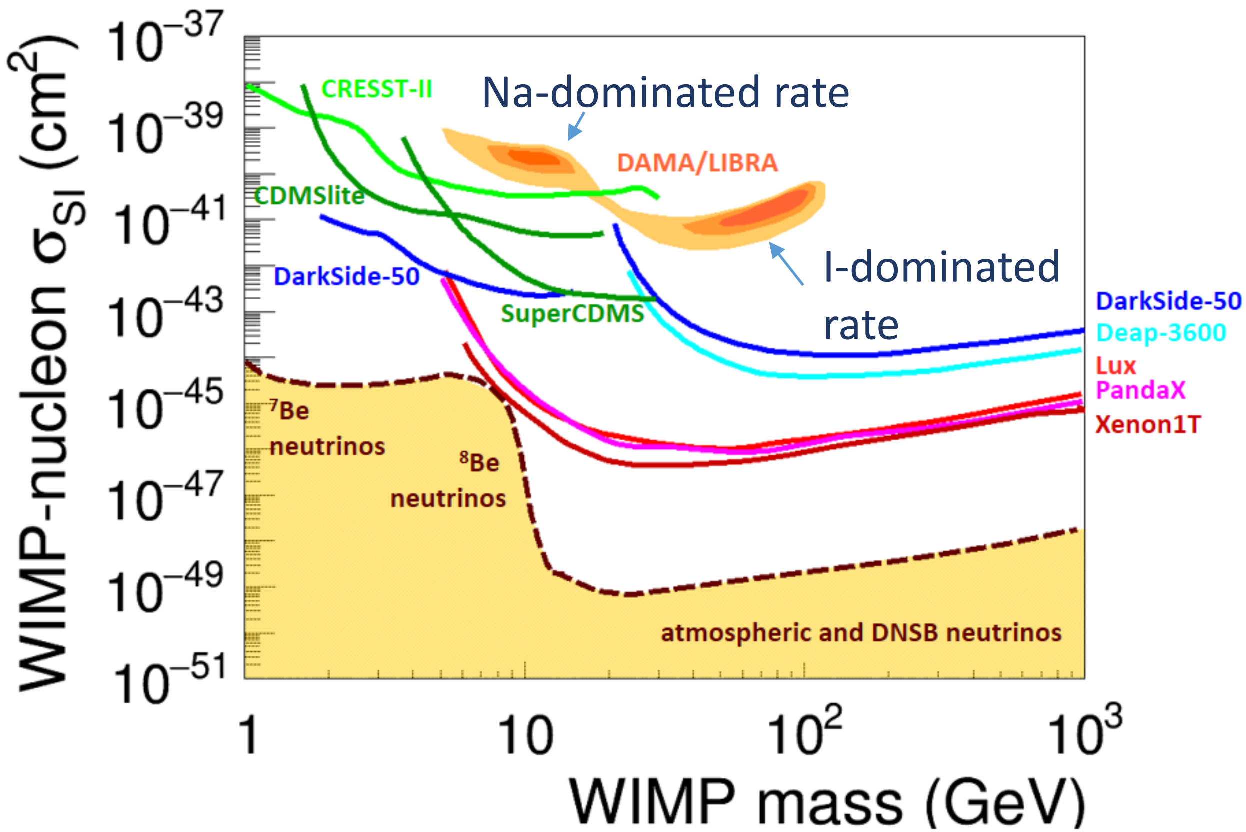
[1-6] keV



The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at **11.9σ CL** (2.17 ton × yr)

Interpreting DAMA/LIBRA ph1 as WIMPs

The signal satisfies all requirements for DM and **can be interpreted as a WIMP** but **the parameter's region singled out by DAMA/LIBRA is excluded by most sensitive experiments**



Dark matter or systematics?

TO AVOID ANY MODEL DEPENDENCE, WE NEED A PROOF/DISPROOF WITH THE SAME TARGET

Target dependence

Wimp model

TARGET DEPENDENT!

Expected rate @ Earth:

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v)}{v} dv^3$$

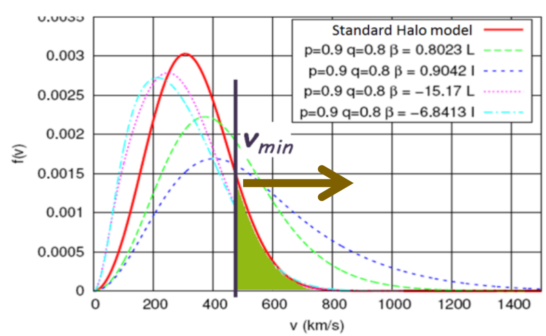
Halo model

In order to compare experiments using different targets I have to assume:

- Only SI or SD coupling
- For SI: - Isospin conserving (couplings are identical for protons and neutrons)
  - A scaling law for the cross section

$$\sigma_{SI} \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 \, F^2 \sigma_{SI}^{nucleon}$$

- A model for the WIMPs velocity distribution, usually the standard Halo Model (Maxwellian distribution)



$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu_{NW}^2}}$$

- A good knowledge of the NR quenching factor

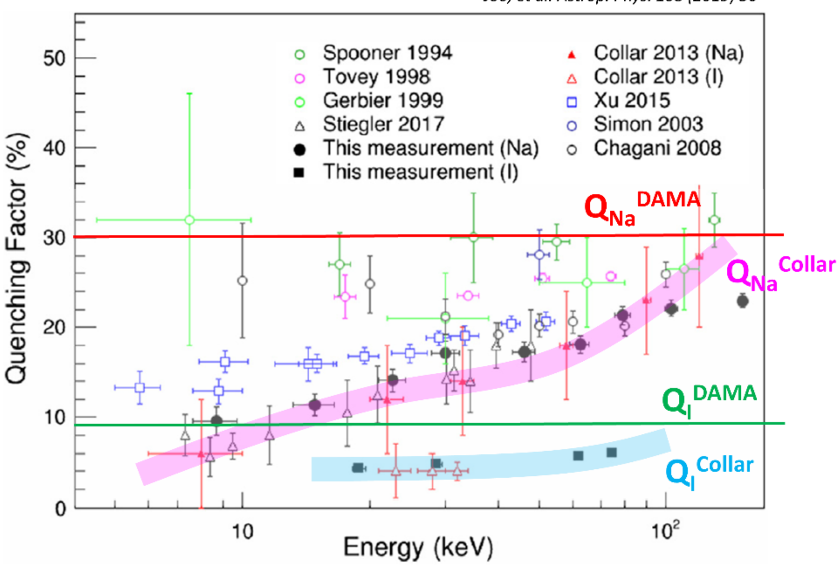
That is the only dependence that **<u>could</u>** remain when using the same target

NR quenching factor measurements

DAMA: $QF_{Na} = 0.3$ $QF_I = 0.09$

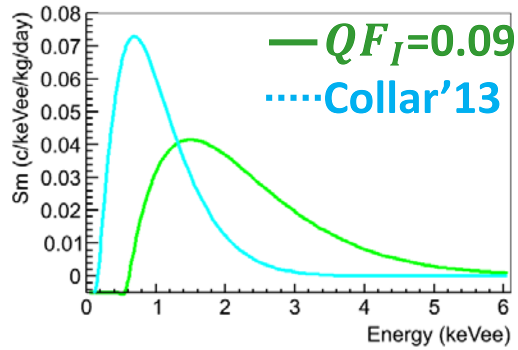
But recent measurements give lower values. Na quenching decreases when decreasing the energy.

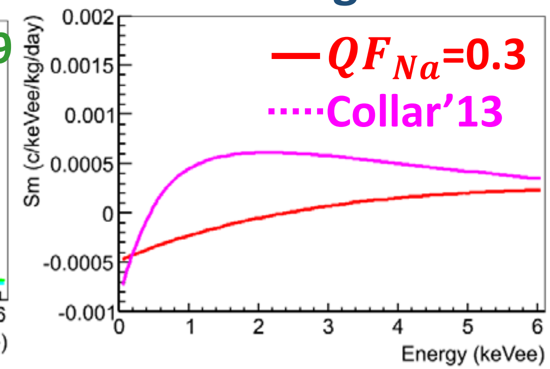
Joo, et al. Astrop. Phys. 108 (2019) 50

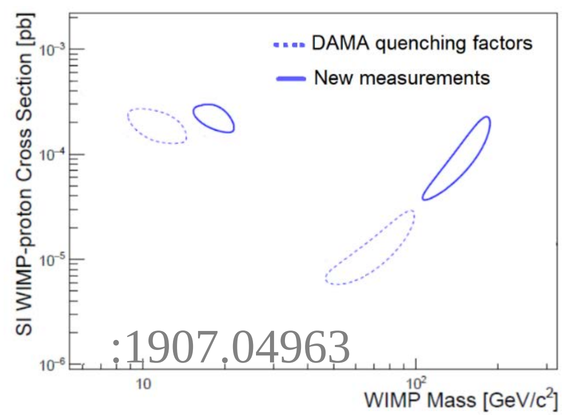


Mod Amplitude in keVee WIMP 50 GeV

Iodine signal **Na signal**







NR quenching factor measurements

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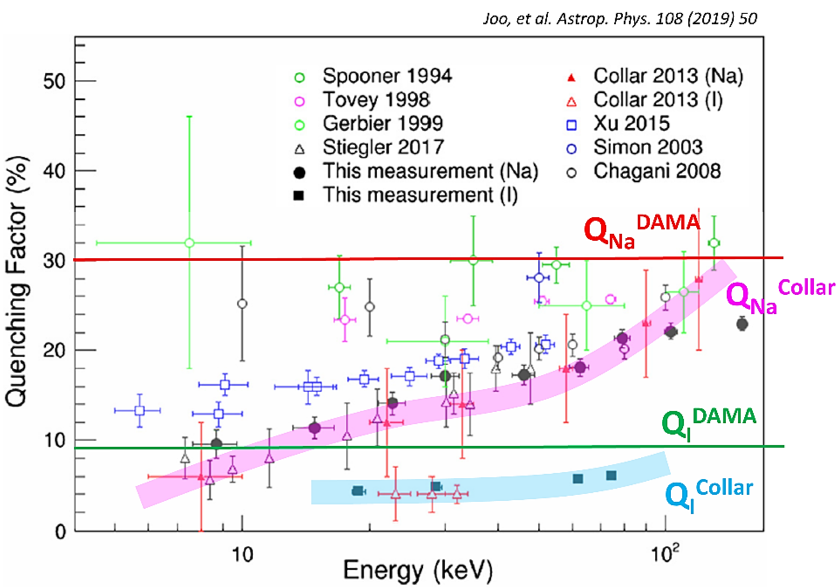


Does the QF depend on the crystal?

- Impurities
- Tl level
- Crystal quality
- …

To answer this question,

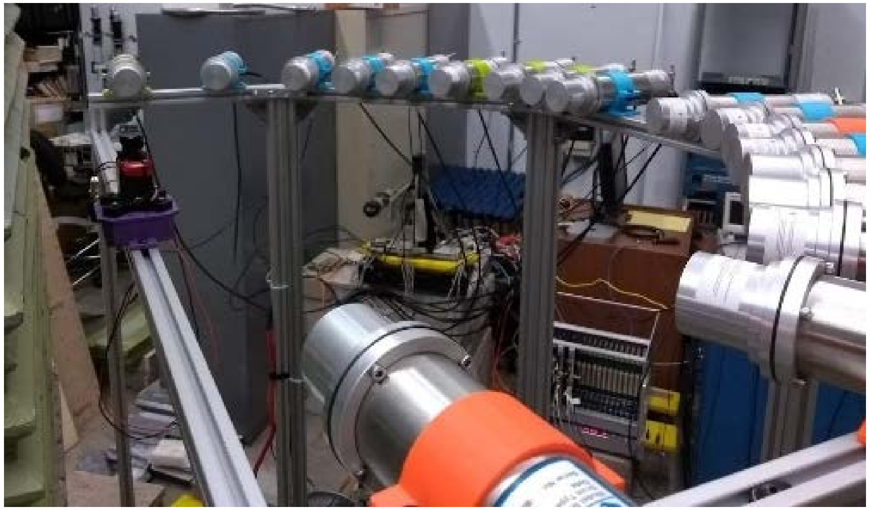
Anais + Yale

QF measurements @ TUNL (Duke Univ.)

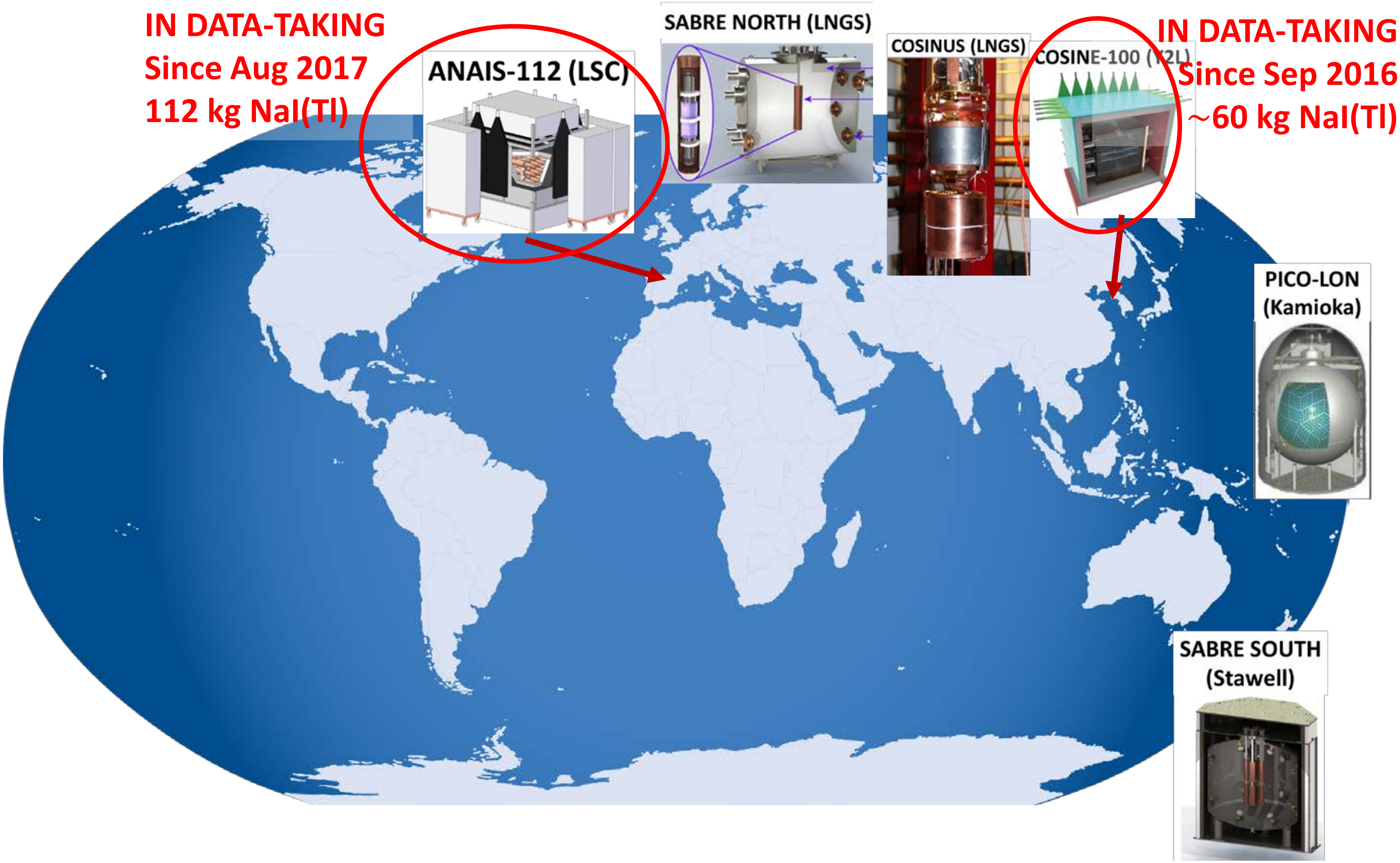
different NaI(Tl) crystals (ANAIS & COSINE)

in the same setup

Results soon!



NaI experiments around the World



ANAIS-112

Annual Modulation with NaI Scintillators

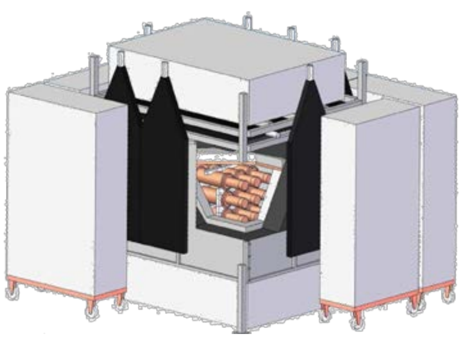
J. Amaré, I. Coarasa, S. Cebrián, D. Cintas, E. García, M. Martínez, M.A. Oliván,
Y. Ortigoza, A. Ortiz de Solórzano, J. Puimedón, A. Salinas, M.L. Sarsa

GOAL:

Confirmation of DAMA-LIBRA modulation signal with the same target and technique
(but different experimental approach and environmental conditions)

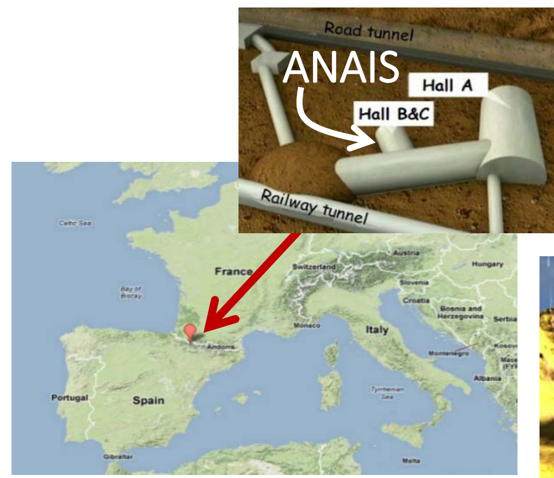
THE DETECTOR:

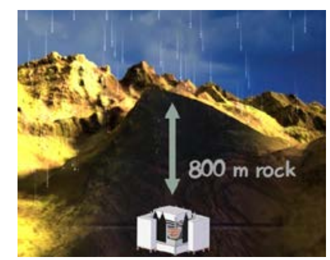
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass



WHERE:

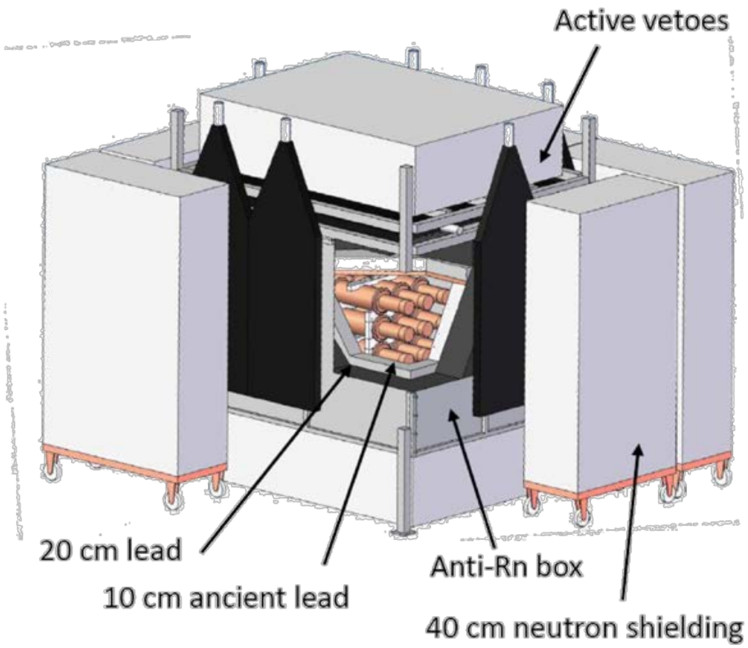
At Canfranc Underground Laboratory,
@ **SPAIN** (under **2450 m.w.e.**)



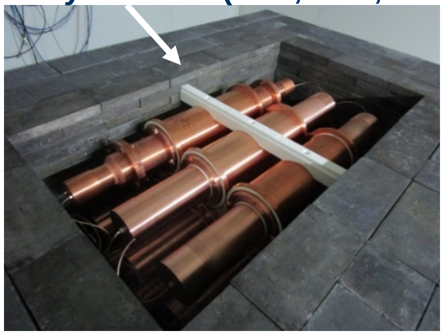


taking data since August 2017

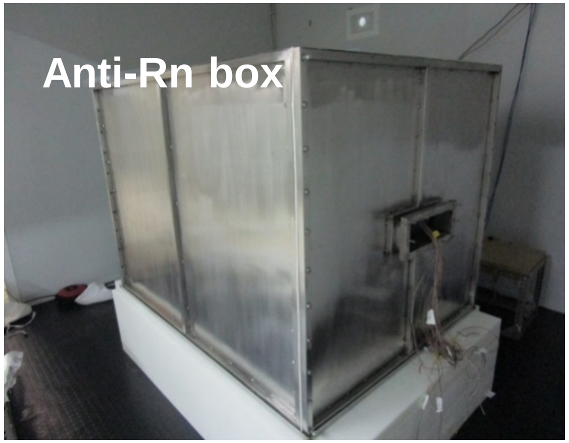
ANAIS-112: experimental setup

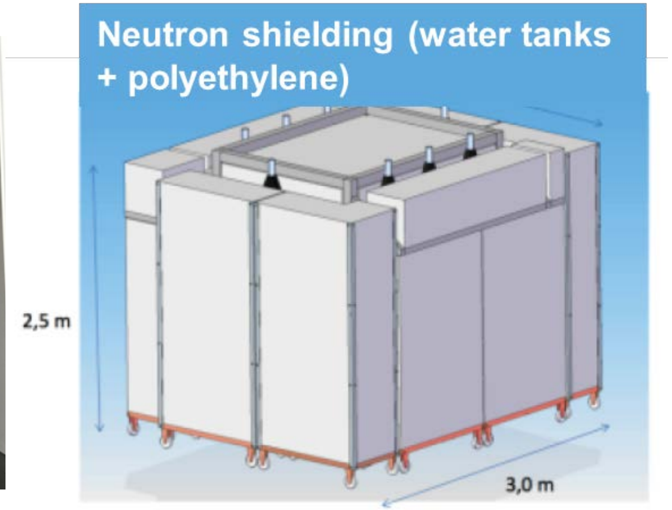


Periodic calibration with ^{109}Cd every 2 weeks (11.9, 22.6, 88 keV)

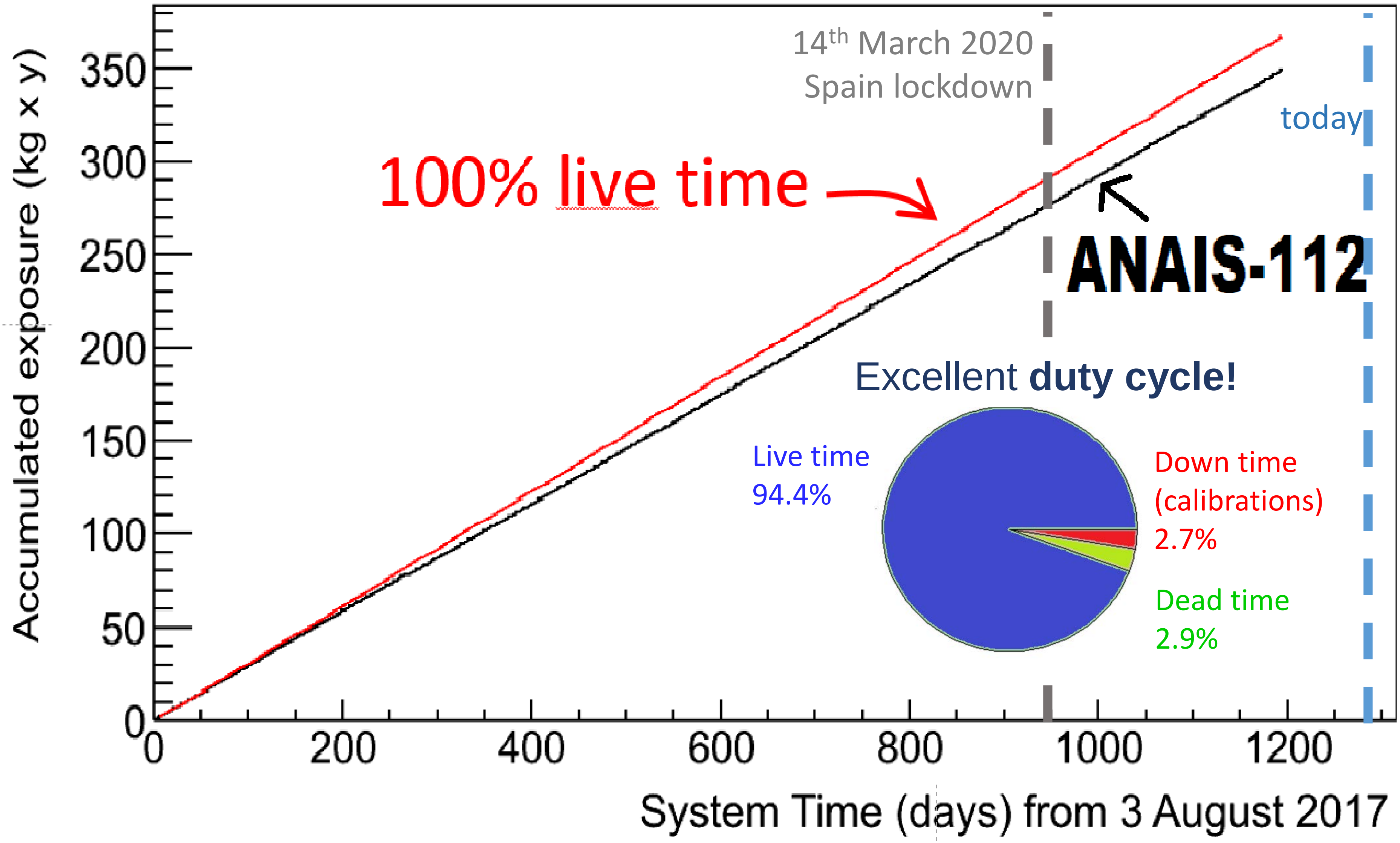


- 9 NaI(Tl) cylindrical crystals (12.5 kg each) in 3x3 matrix
- Ultrapure NaI powder (Alpha Spectra Inc)
- Each coupled to two Hamamatsu R12669SEL2 PMT (QE ~40%)





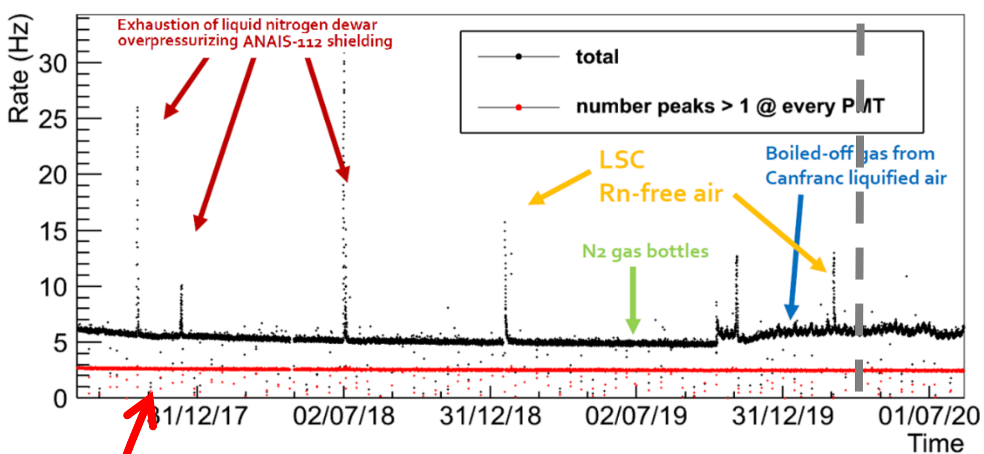
ANAIS-112 Accumulated exposure



Total rate and gain stability

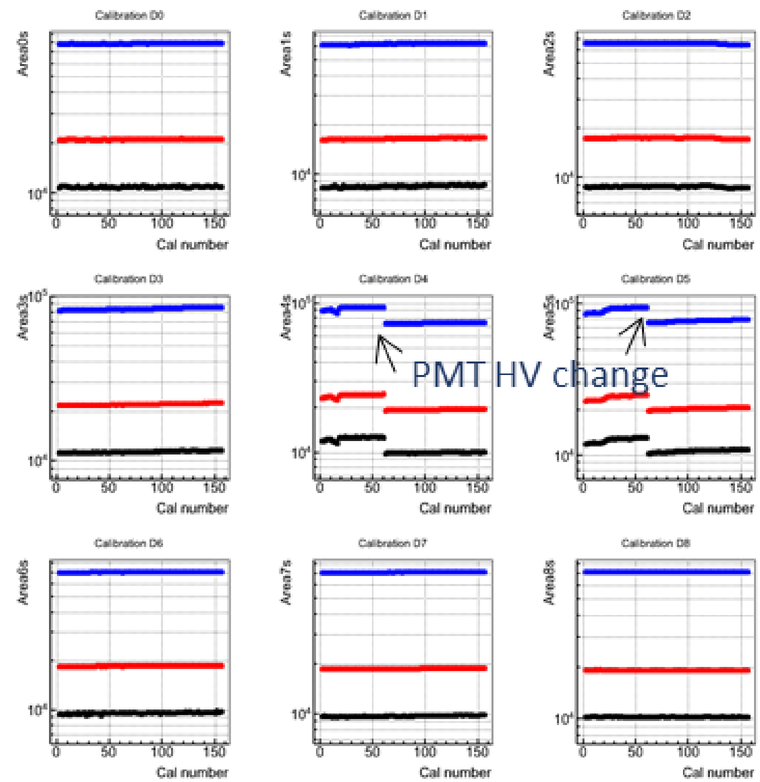
total rate

14th March 2020
Spain lockdown



Stable rate for events with more than 1 phe- / PMT (well below energy threshold)

gain



Evolution of ^{109}Cd lines from calibrations along the whole data-taking (~ 3 years)

Light collection and threshold

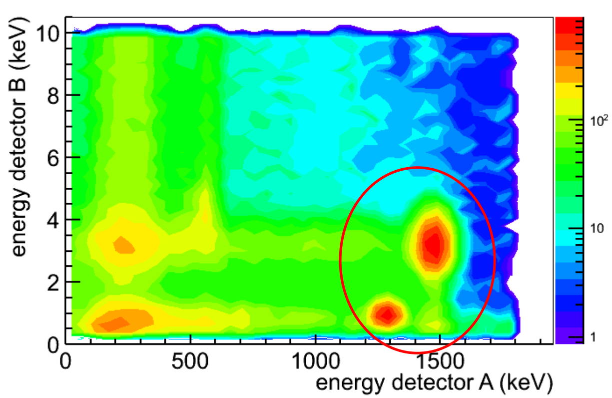
- Outstanding **light collection** of **~15 phe/keV**

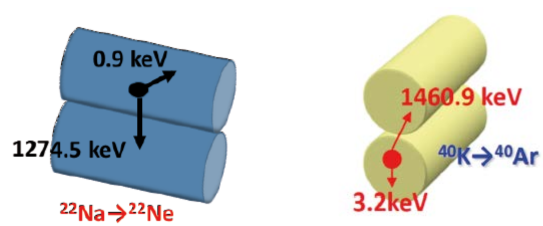
For comparison DAMA/LIBRA:
Phase 1: **5.5-7.5 phe/keV**
Phase 2: **6-10 phe/keV**
JINST 7 (2012)03009

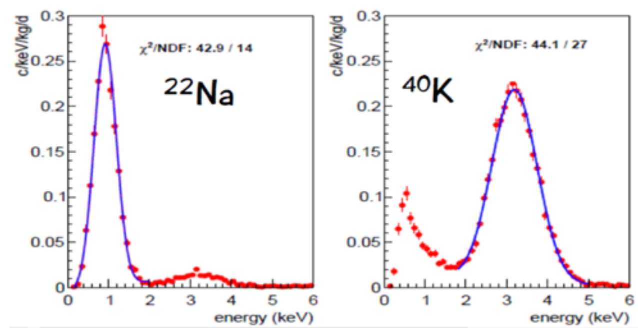
Detector	Total Light Collection (phe/keV)
D0	14.6± 0.1
D1	14.8 ± 0.1
D2	14.6 ± 0.1
D3	14.5 ± 0.1
D4	14.5 ± 0.1
D5	14.5 ± 0.1
D6	12.7 ± 0.1
D7	14.8 ± 0.1
D8	16.0 ± 0.1

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

- Effectively **triggering below 1 keV$_{ee}$**







bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas

- **Analysis threshold at 1 keV$_{ee}$** (determined by the event-selection efficiency)

Event selection & efficiency

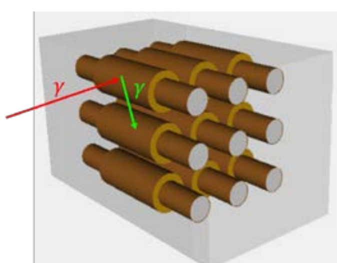
RoI (1-6 keV) **blinded!**

We use multiplicity-2 and calibration events to calculate the cut efficiencies

The **efficiency is calculated with the whole statistics (3 years)**

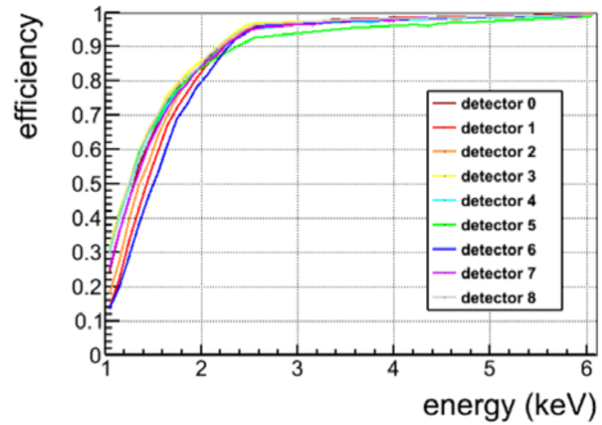
CUTS

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)

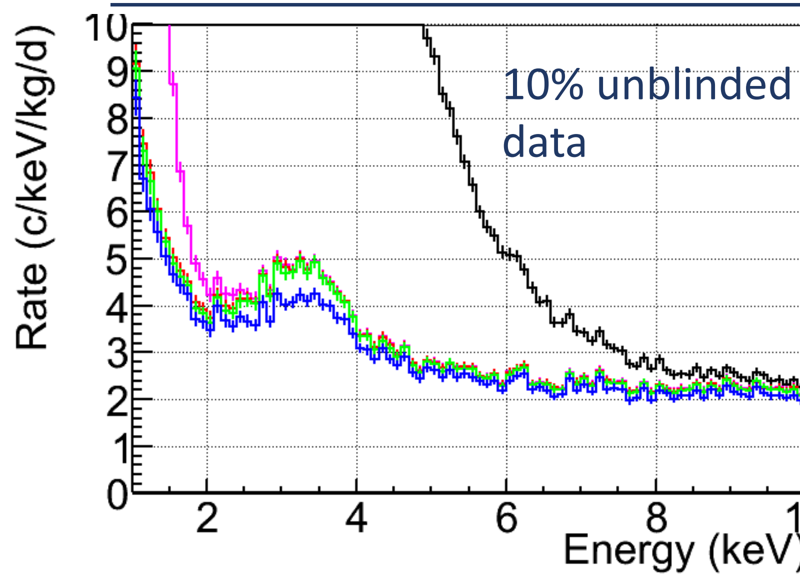


TOTAL EFFICIENCY

Updated 3 years



EFFICIENCY-CORRECTED BACKGROUND



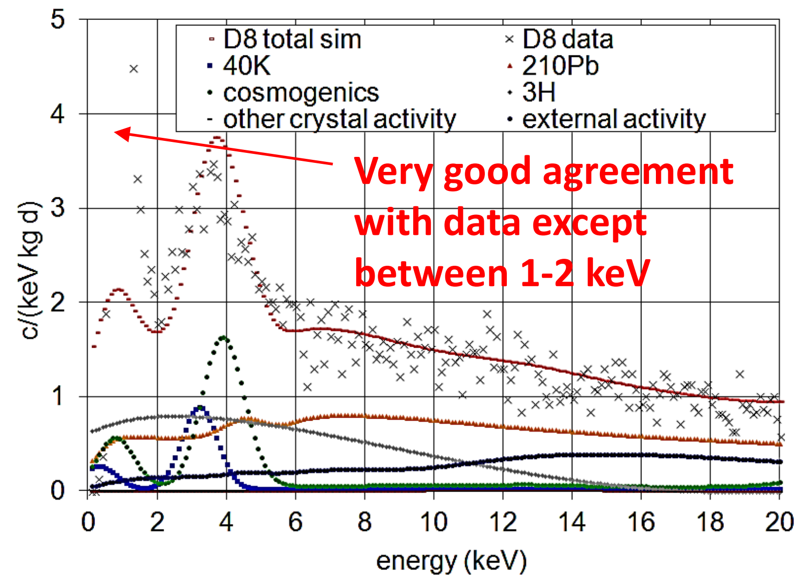
Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

Background model

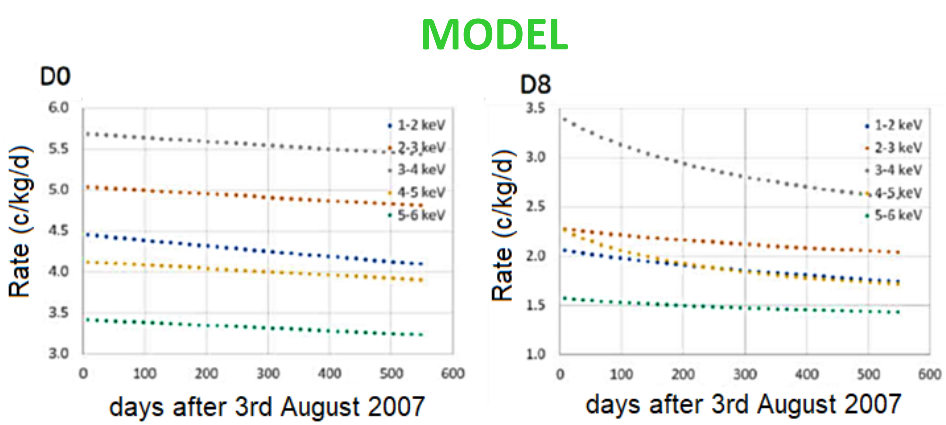
At very low energy (<20 keV), main contamination in the crystal itself

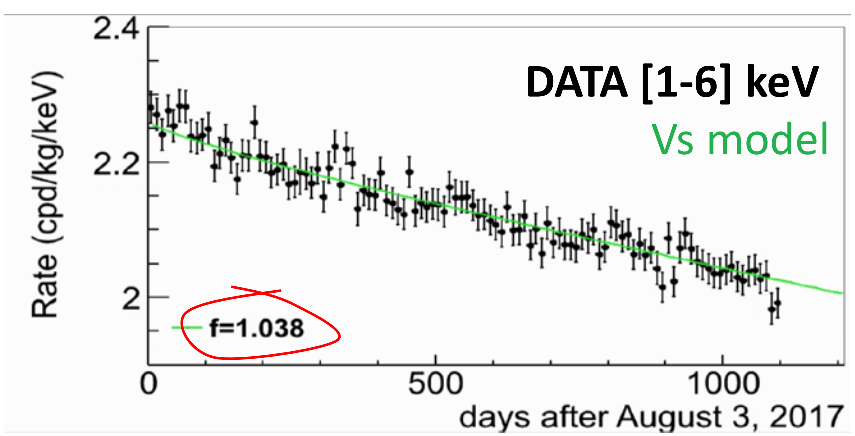
Amaré et al., Eur. Phys. J. C (2019) 79:412, 1812.01377

- **^{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)



Cosmogenic isotopes (^{3}H, ^{22}Na, …) and ^{210}Pb are decaying
→ **prediction of the time dependence of the rate in the RoI**





RESULTS ON ANNUAL MODULATION

Analysis strategy

MODEL INDEPENDENT ANALYSIS TO CHECK:

[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

ANALYSIS STRATEGY

- Focus on model independent analysis searching from modulation
- In order to better compare with DAMA/LIBRA results, we use the **same energy regions ([1-6] keV, [2-6] keV) and fit parameters**
- Least square fit to

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

Fixed parameters:

τ (background model)
ω (freq. corresponding to a period of 1 year)
ϕ (maximum in June, 2nd)

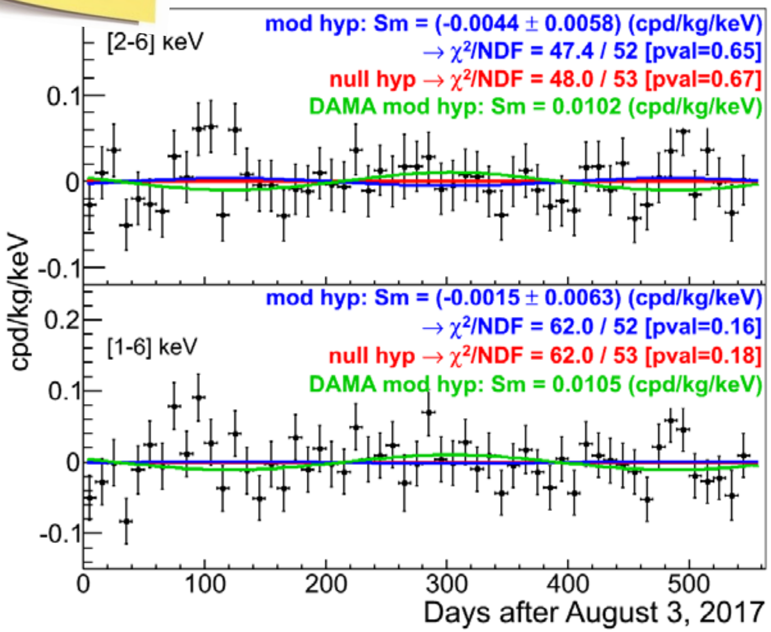
Previous annual modulation results

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

1.5 years

157.55 kg x yr

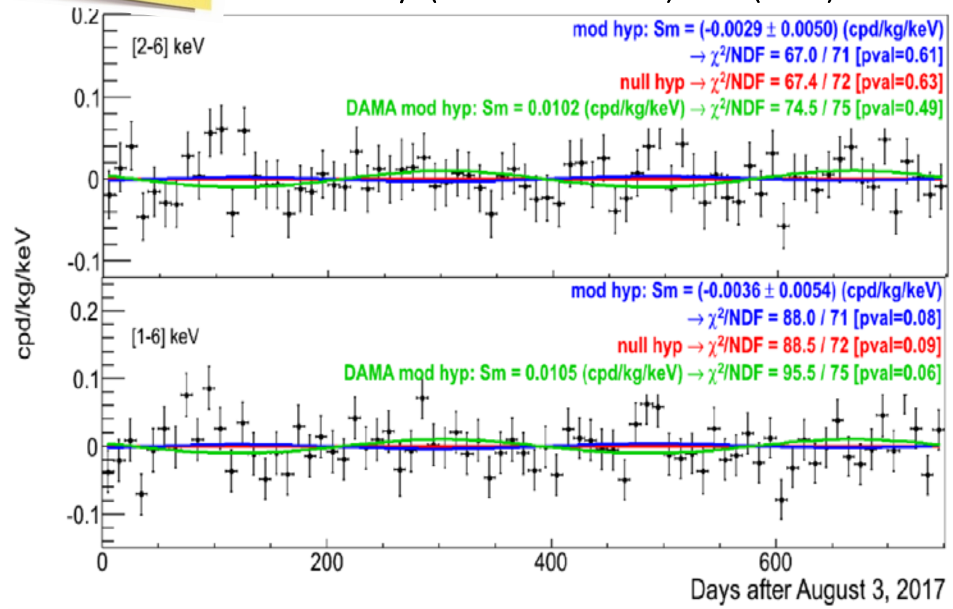
Phys. Rev. Lett., 123, 031301 (2019)



2 years

213.6 kg x yr

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



DAMA/LIBRA result with 1 –free parameter is shown for comparison

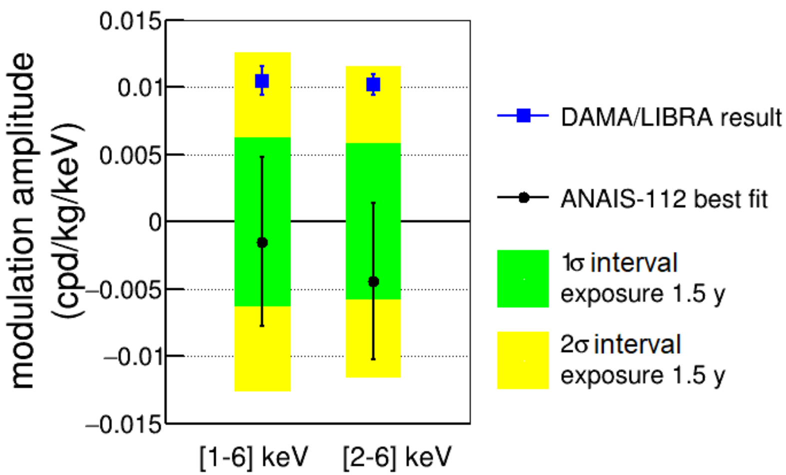
Previous annual modulation results

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

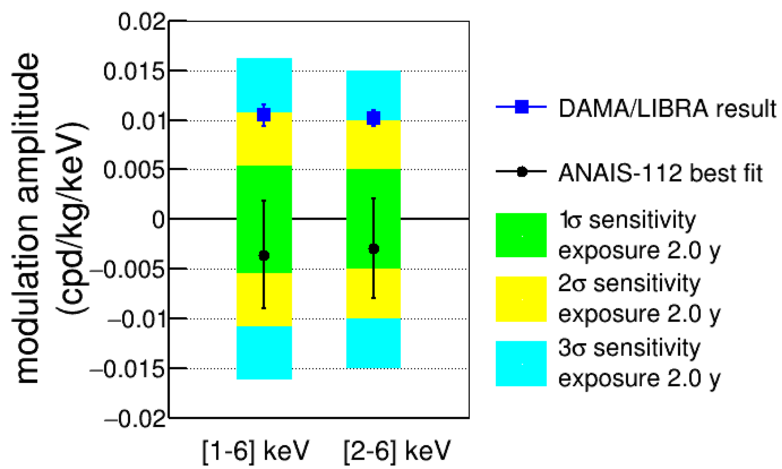
2 years
213.6 kg x yr

- Null hypothesis is well supported by the χ^2test (p-values=0.09, 0.63)
- Best fits for the mod. hypothesis p-values slightly lower than for the null hypothesis
- Best fits are compatible with no modulation and incompatible at 2.6σ with DAMA/LIBRA results. 2 years sensitivity: 2σ

1.5 years (PRL 123 (2019) 031301)



2 years (TAUP 2019)

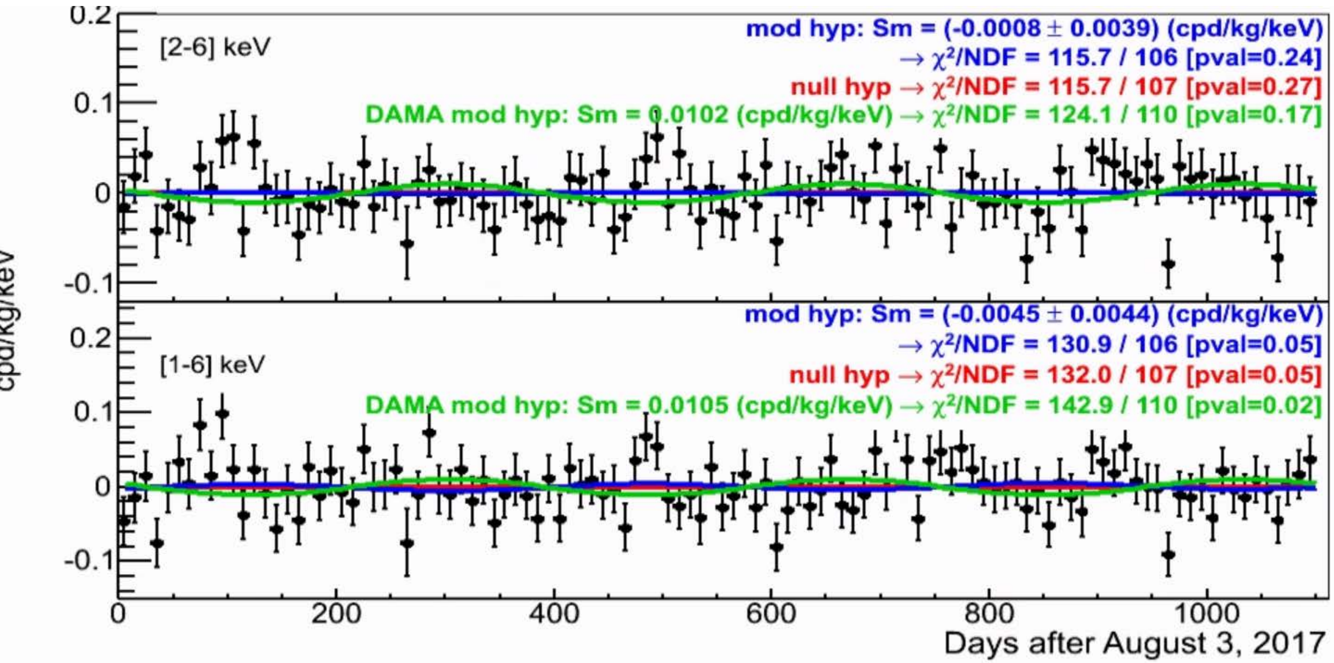


3 years results

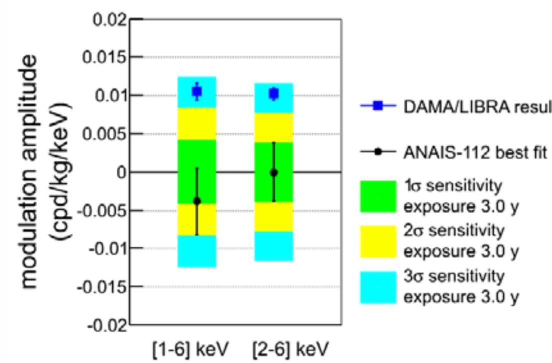
3 years
313.6
kg x yr

PRELIMINARY

NEW!



- **Preliminary sensitivity @ 3 years: 2.6σ**



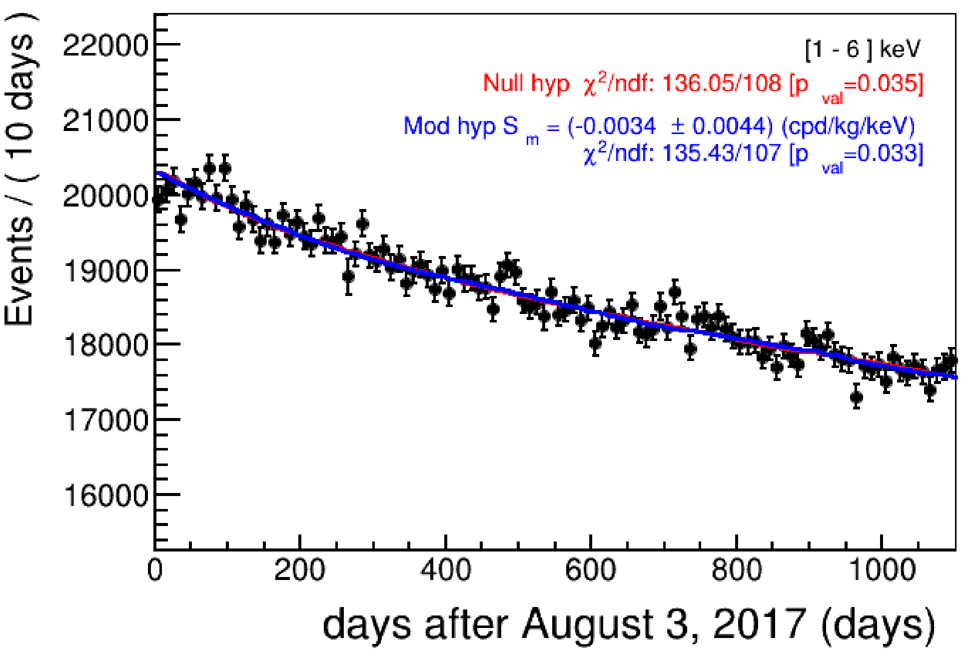
Work on progress: new fit approaches

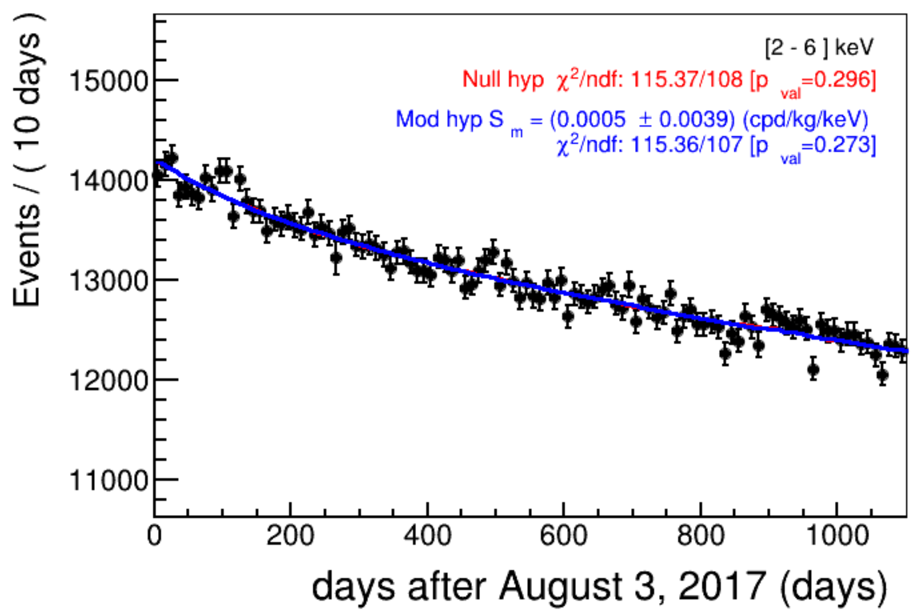
1. $R(t) = R_0 + R_1 \exp(-t/\tau) + \boldsymbol{S_m} \cos(\omega(t+\phi))$

2. Substitute the exponential term by the MC simulated background evolution in time converted into a probability distribution function (PDFbkg):

$$R(t) = R_0 + R_1 PDF_{bkg} + \boldsymbol{S_m} \cos(\omega(t+\phi))$$

- Improved background description
- 2 nuisance parameters instead of three





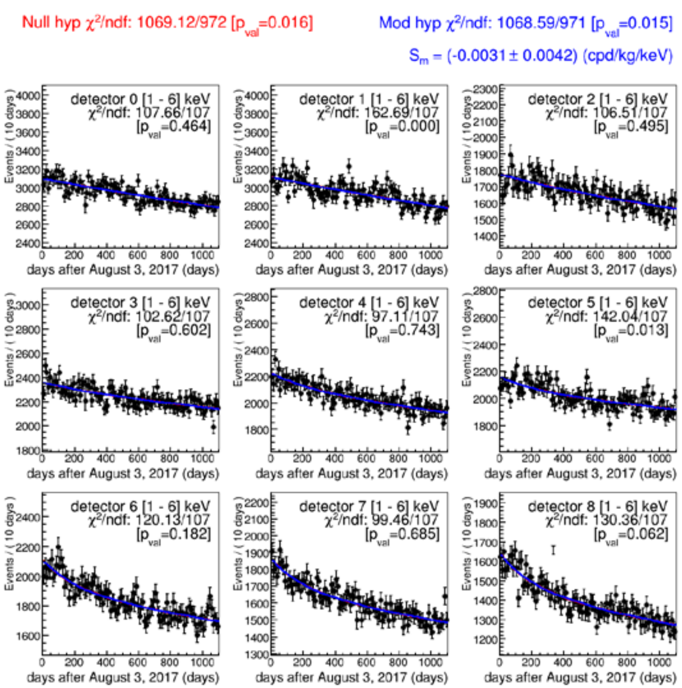
Work on progress: new fit approaches

PRELIMINARY

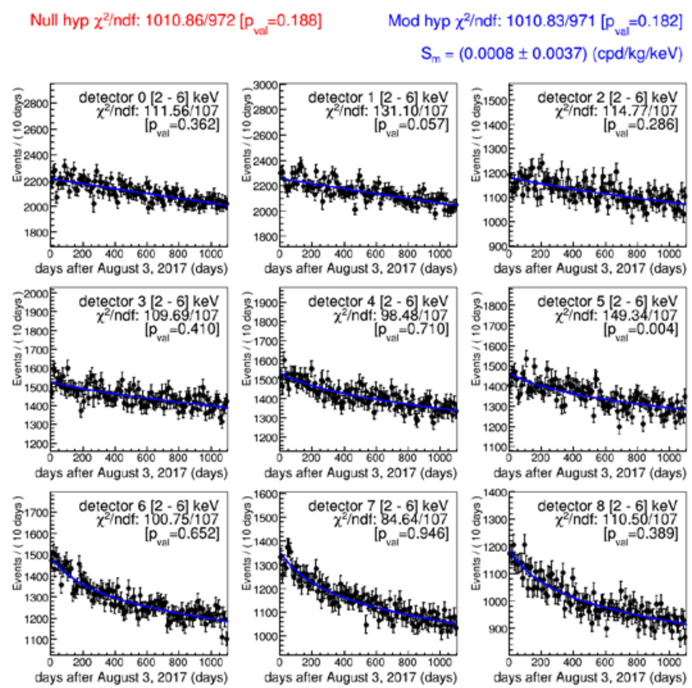
1. $R(t) = R_0 + R_1 \exp(-t/\tau) + \boldsymbol{S_m} \cos(\omega(t+\phi))$
2. $R(t) = R_0 + R_1 PDF_{bkg} + \boldsymbol{S_m} \cos(\omega(t+\phi))$
3. Fit simultaneously all detectors, every one with its own MC simulated background evolution and same modulation amplitude for all of them

$$R^i(t) = R_0^i + R_1^i PDF_{bkg}^i + \boldsymbol{S_m} \cos(\omega(t+\phi))$$

[1-6] keV



[2-6] keV



	P-values	
det	[1-6] keV	[2-6] keV
0	0.46	0.36
1	0.00	0.06
2	0.49	0.29
3	0.60	0.41
4	0.74	0.71
5	0.01	0.004
6	0.18	0.65
7	0.68	0.97
8	0.06	0.39
combined	0.015	0.182

Work on progress: new fit approaches

PRELIMINARY

1. $R(t) = R_0 + R_1 \exp(-t/\tau) + \boldsymbol{S_m} \cos(\omega(t+\phi))$ [3 nuisance par: R_0, R_1, τ]
2. $R(t) = R_0 + R_1 PDF_{bkg} + \boldsymbol{S_m} \cos(\omega(t+\phi))$ [2 nuisance par: R_0, R_1]
3. $R^i(t) = R_0^i + R_1^i PDF_{bkg}^i + \boldsymbol{S_m} \cos\big(\omega(t+\phi)\big)$ [18 nuisance par: R_0^i, R_1^i]

Energy region	Fit function	S_m events/keV/kg/d	P value mod	P value null
[1-6] keV	eq. 1	-0.0045 ± 0.0044	0.051	0.051
	eq. 2	-0.0034 ± 0.0044	0.033	0.035
	eq. 3	-0.0031 ± 0.0042	0.015	0.016
[2-6] keV	eq. 1	-0.0008 ± 0.0039	0.245	0.265
	eq. 2	0.0005 ± 0.0039	0.273	0.296
	eq. 3	-0.0007 ± 0.0037	0.182	0.188

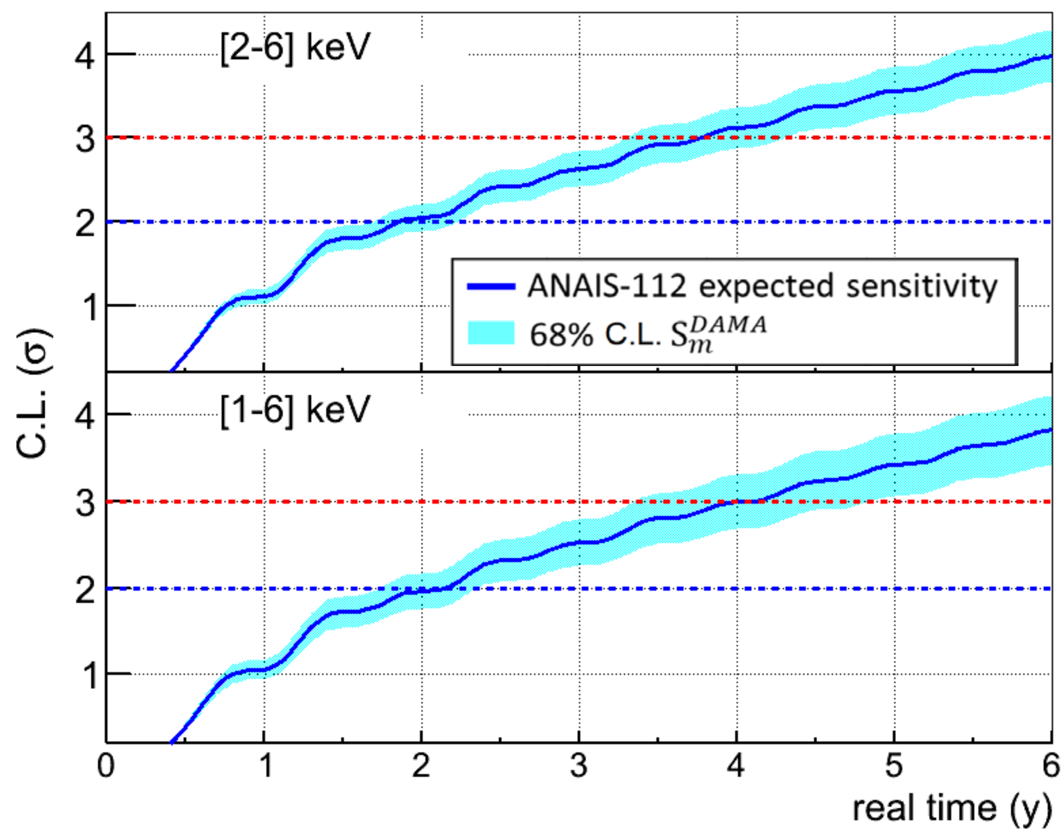
Results very similar (publication in preparation)

Expected sensitivity

The experimental sensitivity is given by the standard deviation of the modulation amplitude $\sigma(S_m)$, that can be calculated analytically from :

- Updated background
- Efficiency estimate and its error
- Live time distribution

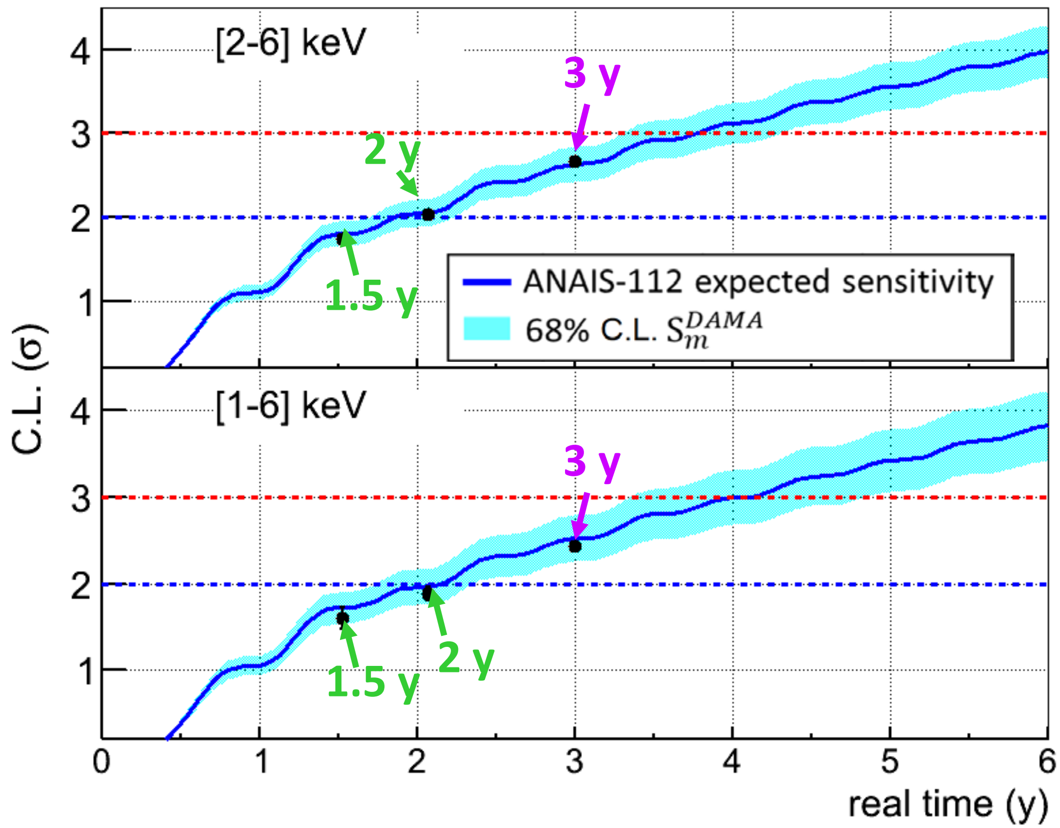
We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA}/\sigma(S_m)$



Expected sensitivity

- data confirm our sensitivity projection to DAMA/LIBRA result
- Sensitivity @ 2 years: 2σ
- Preliminary sensitivity @ 3 years: 2.6σ

3σ sensitivity at reach in about 1 year from now!



Future plans

Mid-term

- Complete analysis of the quenching factor measurement and interpretation in ANAIS-112 data
- Machine-learning techniques to improve efficiency in [1-2] keV
- Study of a possible modulation in muon-related events
- Neutron calibration in the ANAIS-112 setup to correct efficiencies for nuclear-recoil populations
- Precise determination of the neutron background at Hall B and its possible seasonal fluctuation, HENSA collaboration (UPC, IFIC, UCM,UZ)

Long-term

- work with NaI(Tl) coupled to SiPMs at low temperatures trying to increase the sensitivity (R+D experimental phase)
- We support the installation at LSC of a crystal growing infrastructure to produce ultrapure NaI(Tl) crystals underground (coll. SABRE)
- An extension of ANAIS-112 data taking period beyond the scheduled 5 years is under consideration

Summary

- Currently, many efforts trying to confirm / rule out DAMA/LIBRA signal with the same target. Only COSINE-100 and ANAIS-112 in data-taking.
- ANAIS-112 data-taking is progressing smoothly since 3rd August 2017 with excellent performances. Currently it is the best positioned experiment to solve the DAMA/LIBRA puzzle
- **ANAIS-112 results** are compatible with absence of modulation and **incompatible with DAMA/LIBRA at 2σ after 2 years of data-taking**. Preliminary results for 3 years reach 2.6 sensitivity in [2-6] keV. **3σ sensitivity in reach in about 1 year from now!**
- ANAIS-112 data-taking extension under consideration. Plans to increase sensitivity in the future:
    - Reduce threshold working with SiPM at low temperature
    - Reduce background by growing ultrapure crystals underground