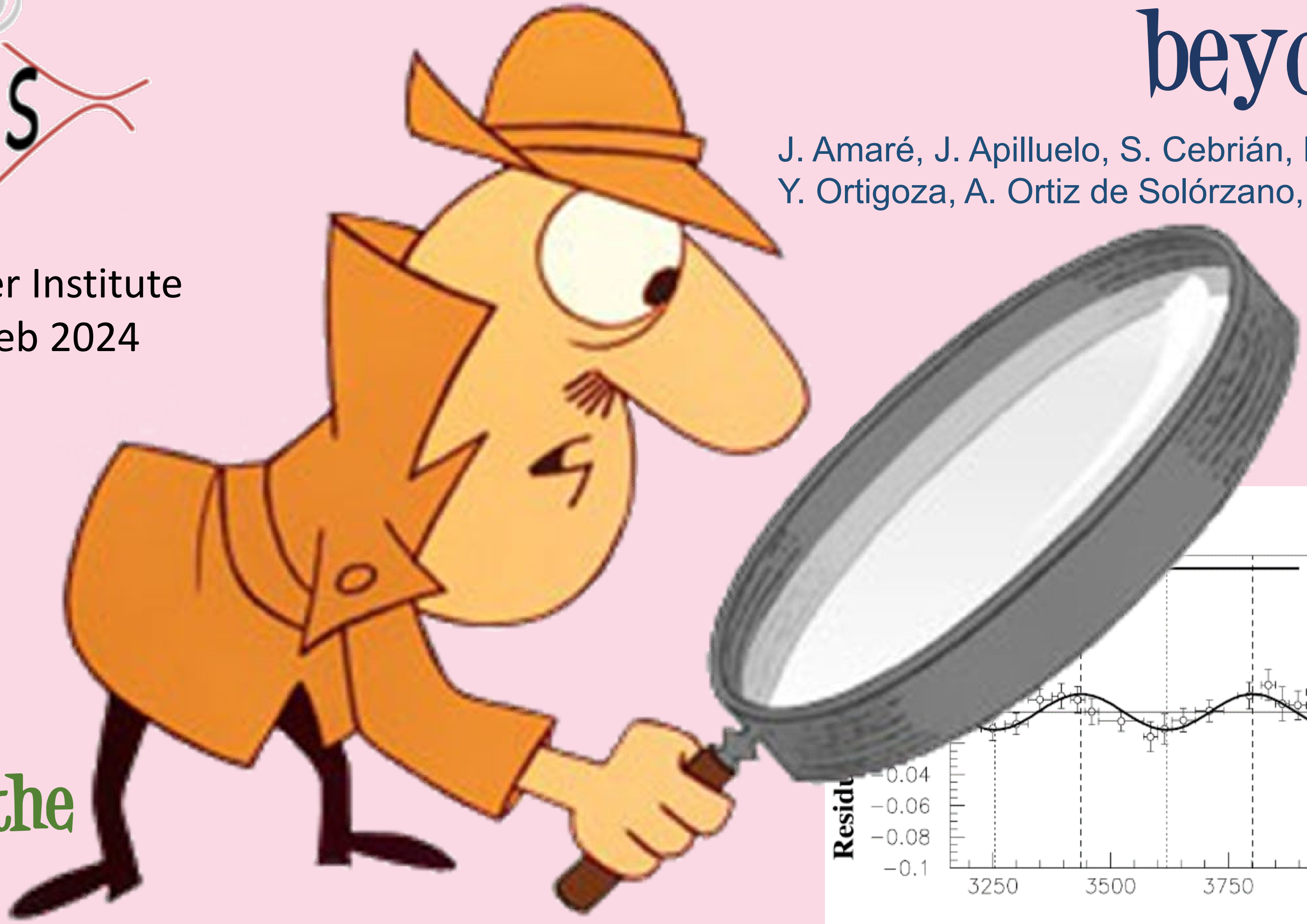
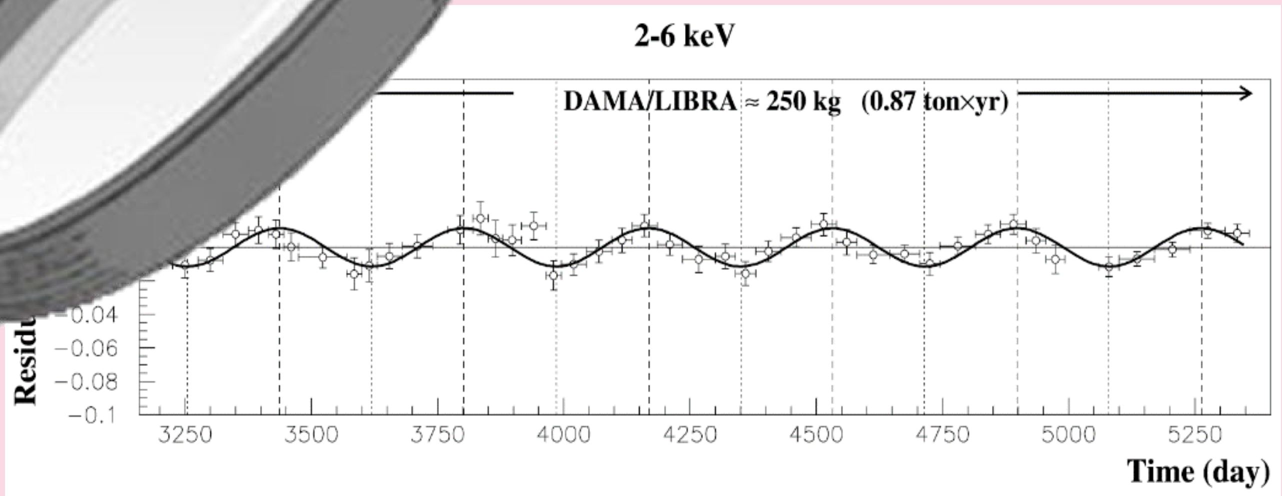
ANAIS-112

First direct test of DAMA/LIBRA beyond three sigma

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

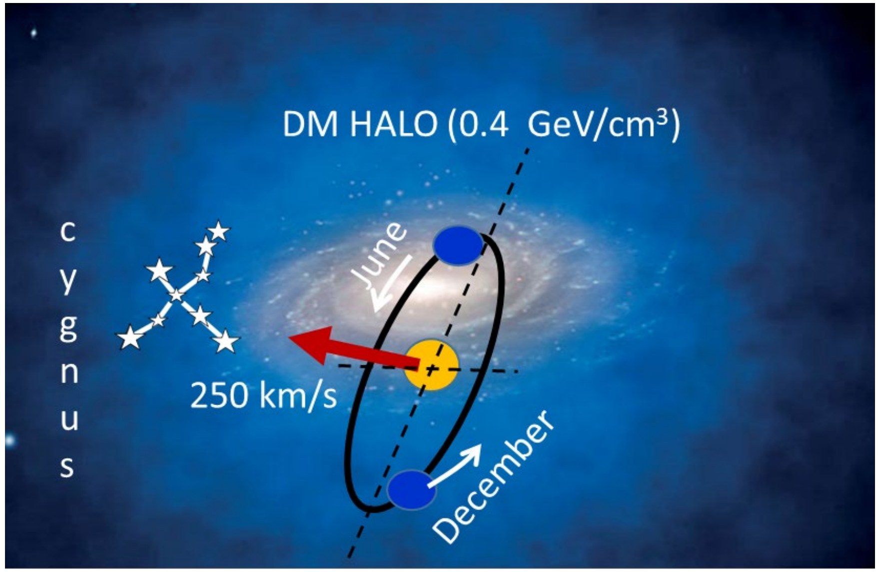
Lake Louise Winter Institute (Canada) 18–24 Feb 2024

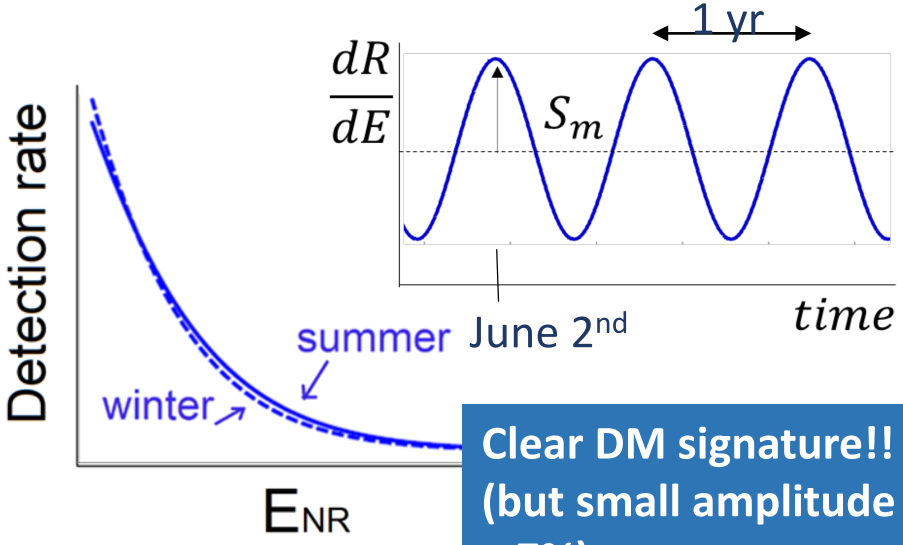




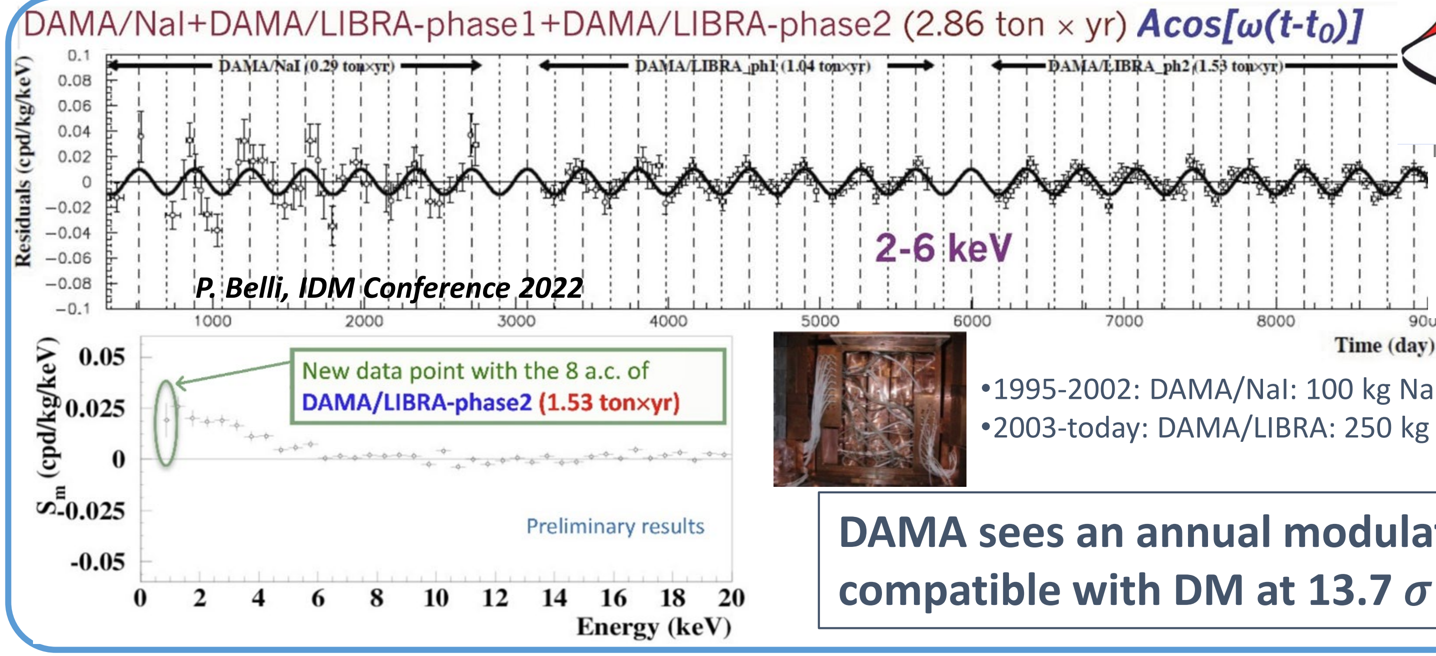
M. Martinez, On behalf of the ANAIS team

DM annual modulation & DAMA/LIBRA positive signal



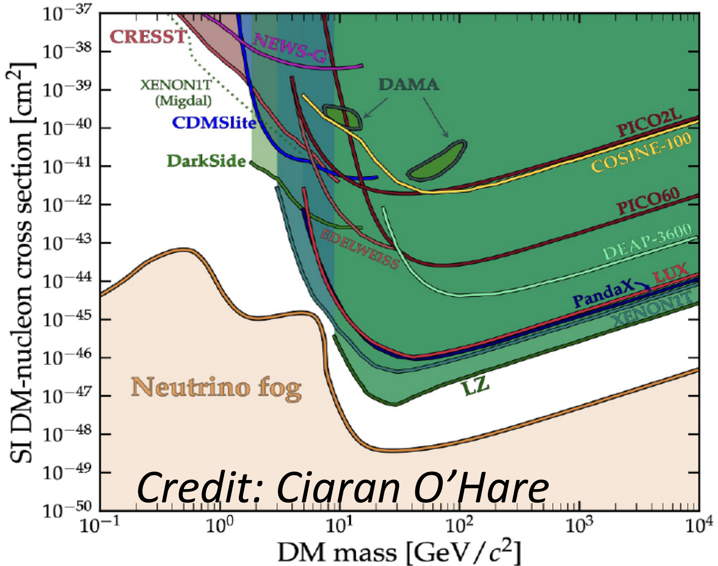


Clear DM signature!! (but small amplitude ~7%)



- 1995-2002: DAMA/NaI: 100 kg NaI(Tl)
- 2003-today: DAMA/LIBRA: 250 kg NaI(Tl)

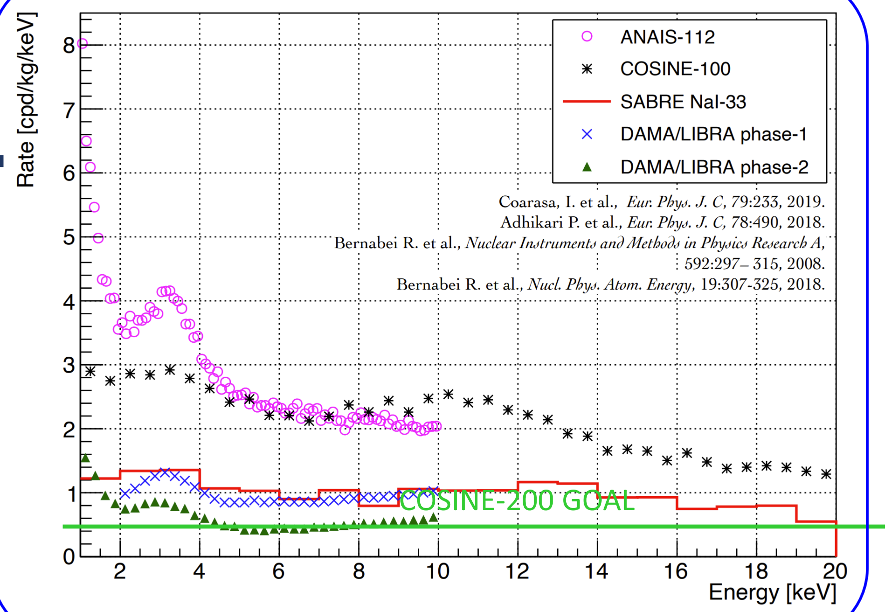
DAMA sees an annual modulation compatible with DM at 13.7 σ



Other direct detection experiments do not see the signal, **but the comparison is model dependent**

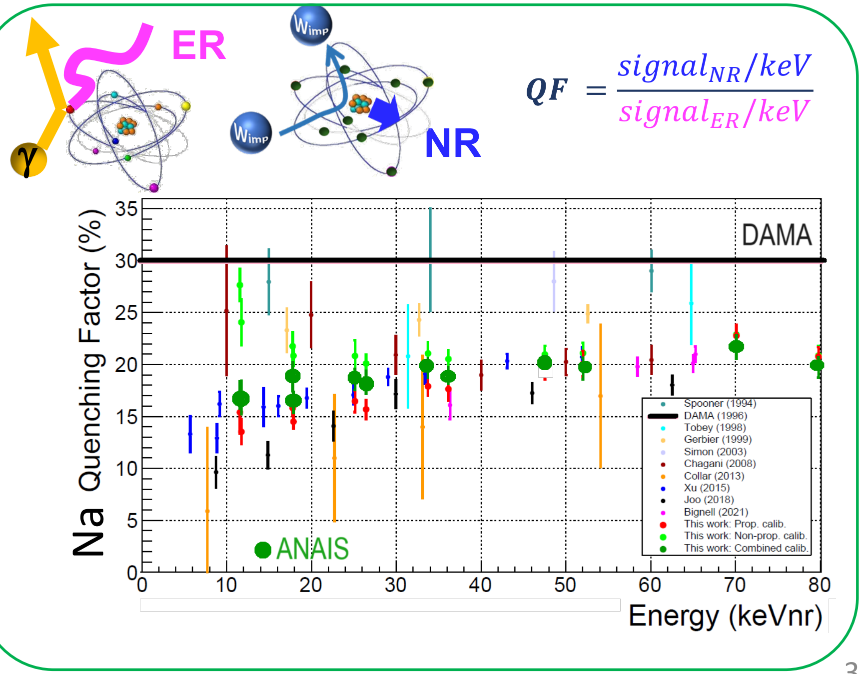
A model independent confirmation is needed using the same target → NaI(Tl)

Testing the DAMA/LIBRA signal



Experimental requirements

- **Target: NaI / NaI(Tl)**
- Large exposure
- Very stable operation conditions
- Energy threshold: 1 keVee
- Background level as low as possible (DAMA: 1 cpd/kg/keV @ 2 keVee)
- Good knowledge of the detector response to nuclear recoils



A world effort

ANAIS-112

Annual Modulation with NaI Scintillators https://gifna.unizar.es/anais/

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

Universidad Zaragoza

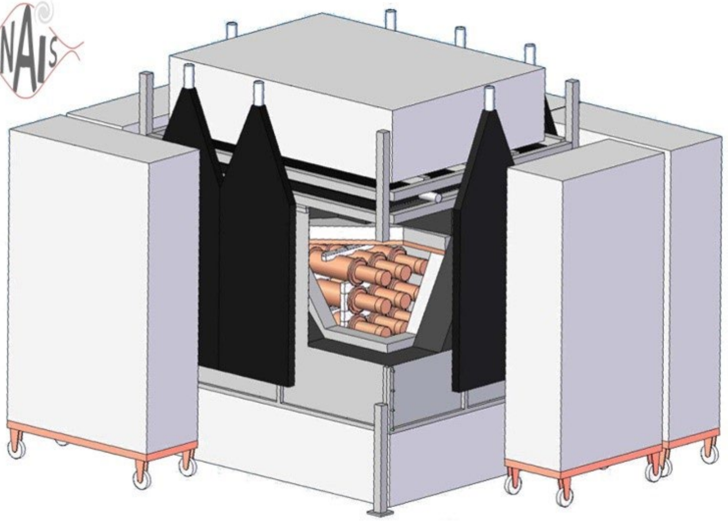
LSC Laboratorio Subterráneo de Canfranc

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

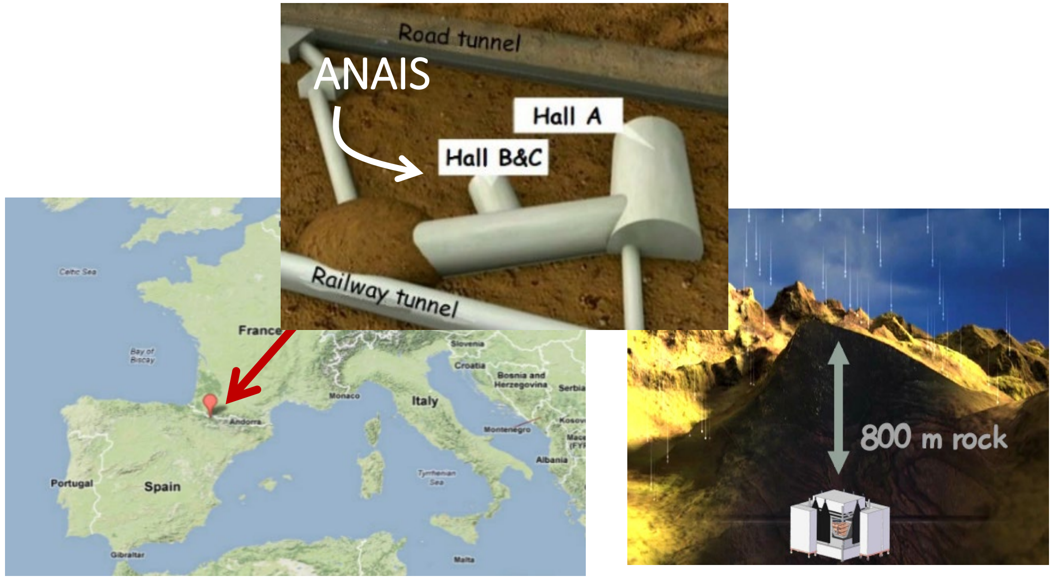
Projected sensitivity: 3σ in 5 years data-taking

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

Two high QE PMTs per detector



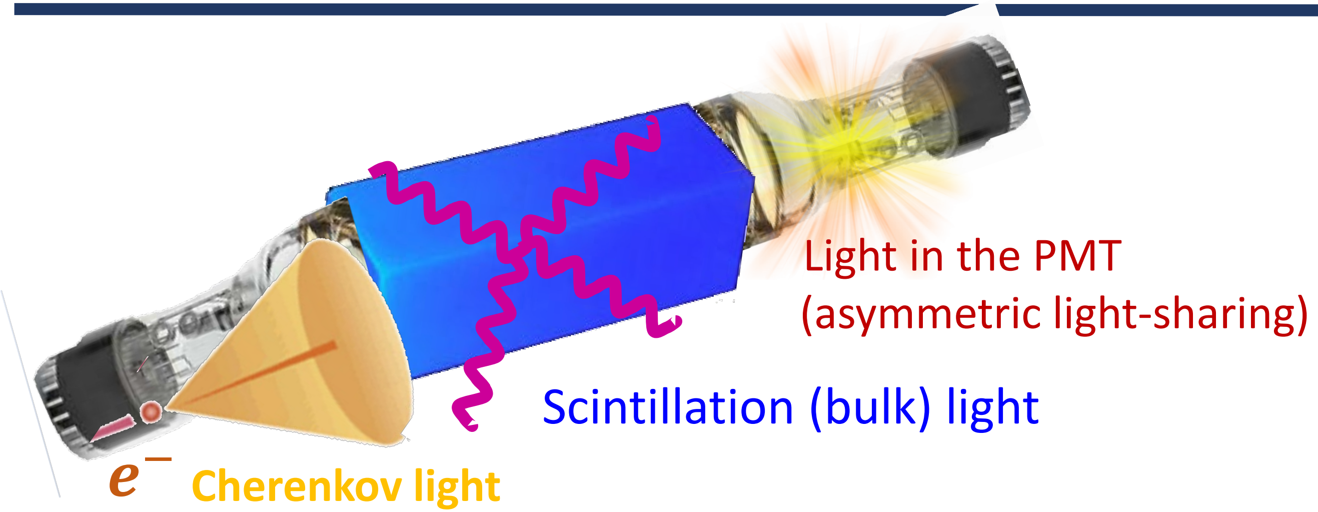
WHERE: At Canfranc Underground Laboratory, @ **SPAIN** (under **2450 m.w.e.**)



taking data since August 2017

EPJC (2019) 79:228

Event selection, background and efficiency

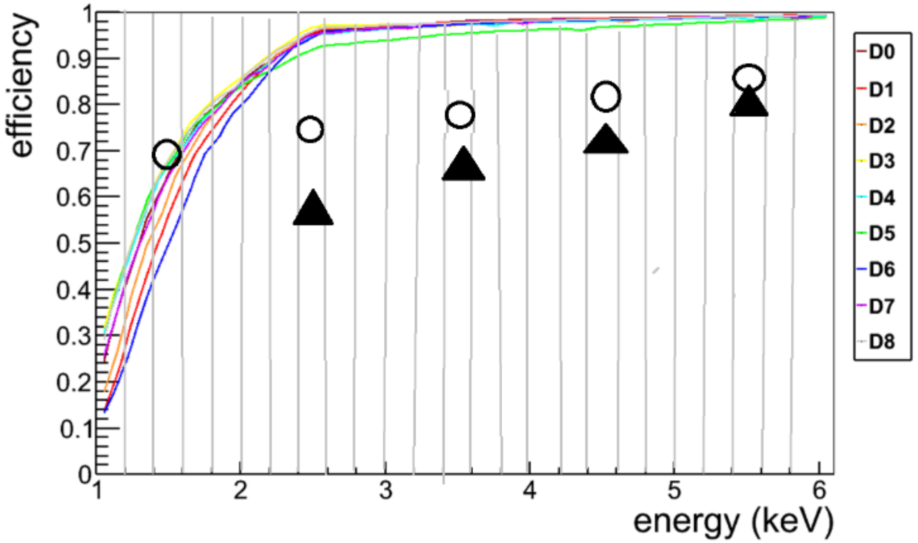


Pulse shape cut to select pulses with NaI(Tl) scintillation constant (biparametric)

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

We remove asymmetric low-energy events (<2 keVee) with origin in the PMT (n1> 4, n2>4)

EVENT SELECTION EFFICIENCY

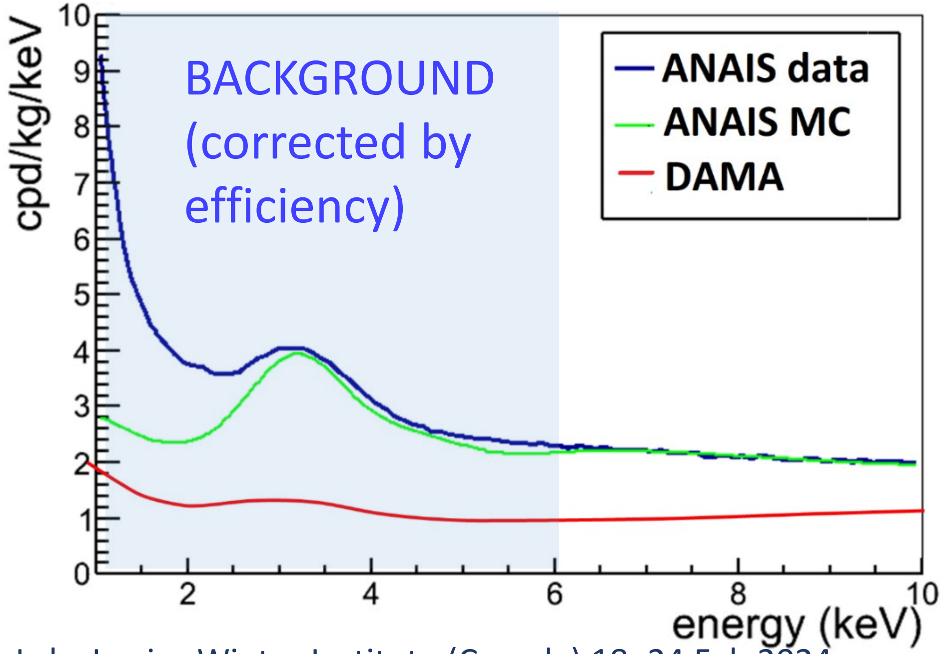


solid lines: ANAIS eff, from ^{109}Cd and ^{22}Na/^{40}K

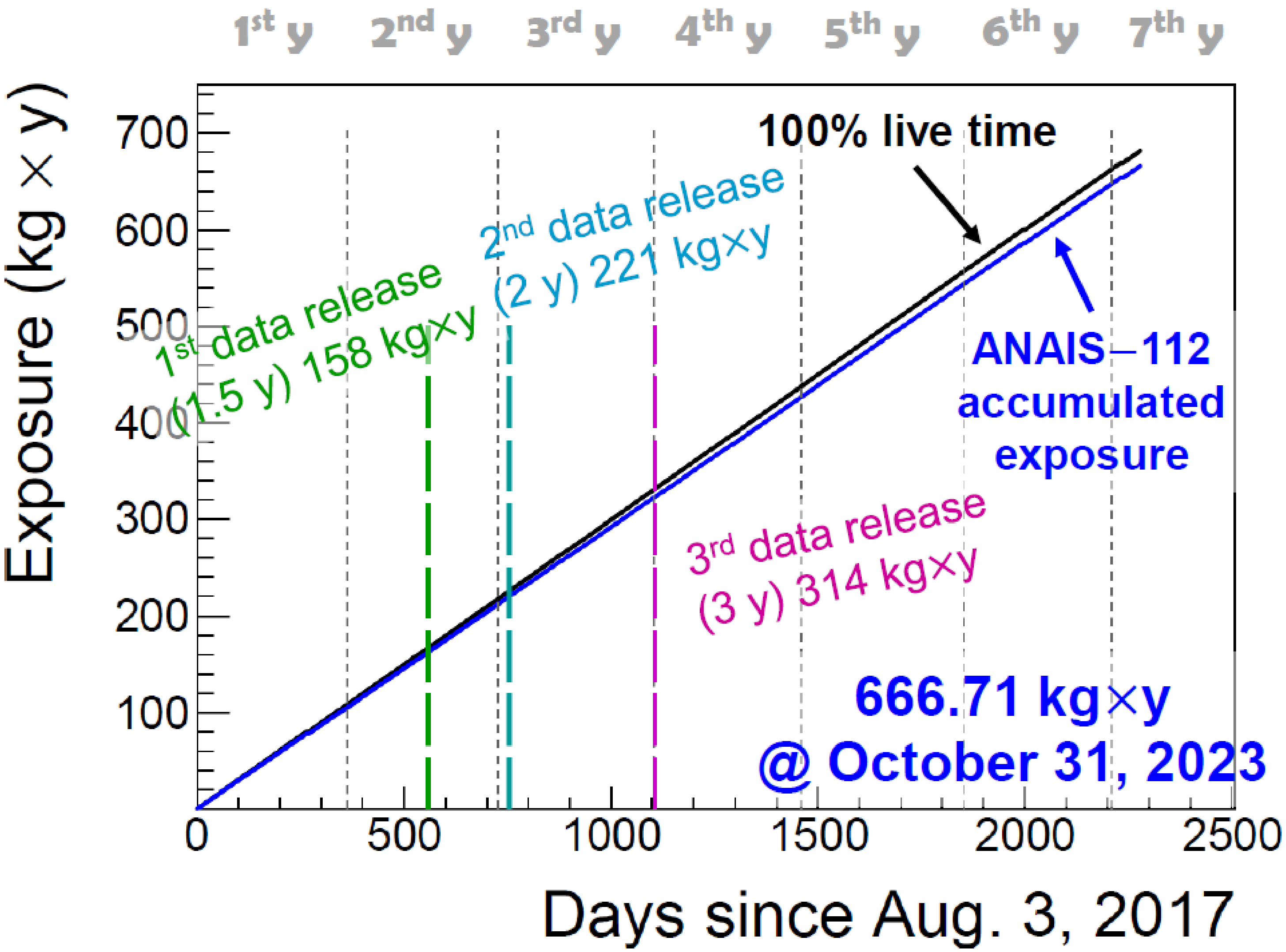
○ DAMA ph2

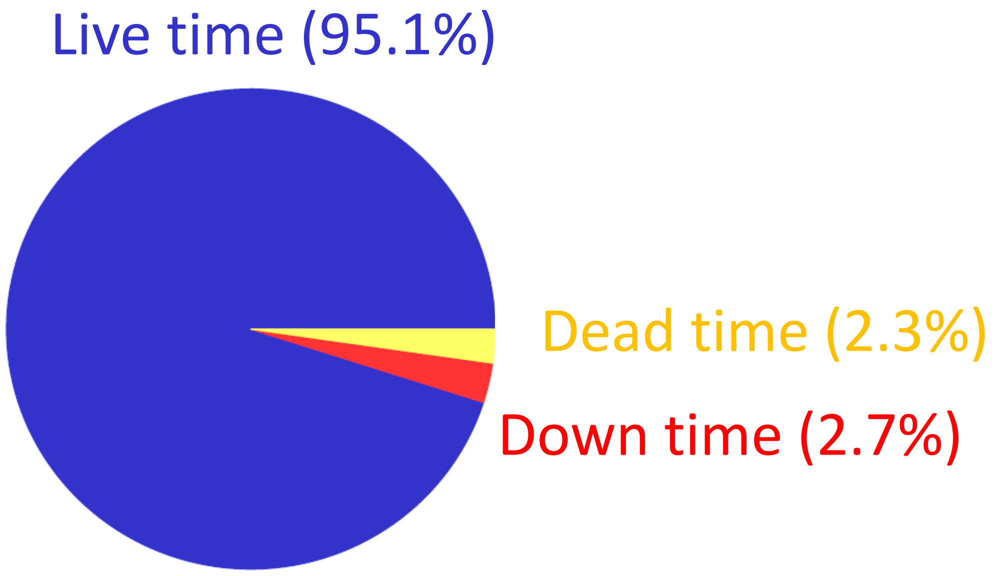
▲ DAMA ph1

JINST 7 P03009 (2012)



Data-taking overview





Annual modulation analysis

PRD 103, 102005 (2021)

Focus on model independent analysis searching for modulation

- In order to better compare with DAMA/LIBRA results
    - **use the same energy regions ([1-6] keV, [2-6] keV)**
    - **fix period 1 year and phase to June 2nd**
- Simultaneous fit of the 9 detectors. 10 days bins.

Fit each detector bkg to:

$$R_{0,d} + R_d \phi^{MC}_{bkg,d}(t_i) + \boldsymbol{S_m} \cos(\omega(t_i - t_0))$$

$\phi^{MC}_{bkg,d}$: Decaying background, modeled by MC

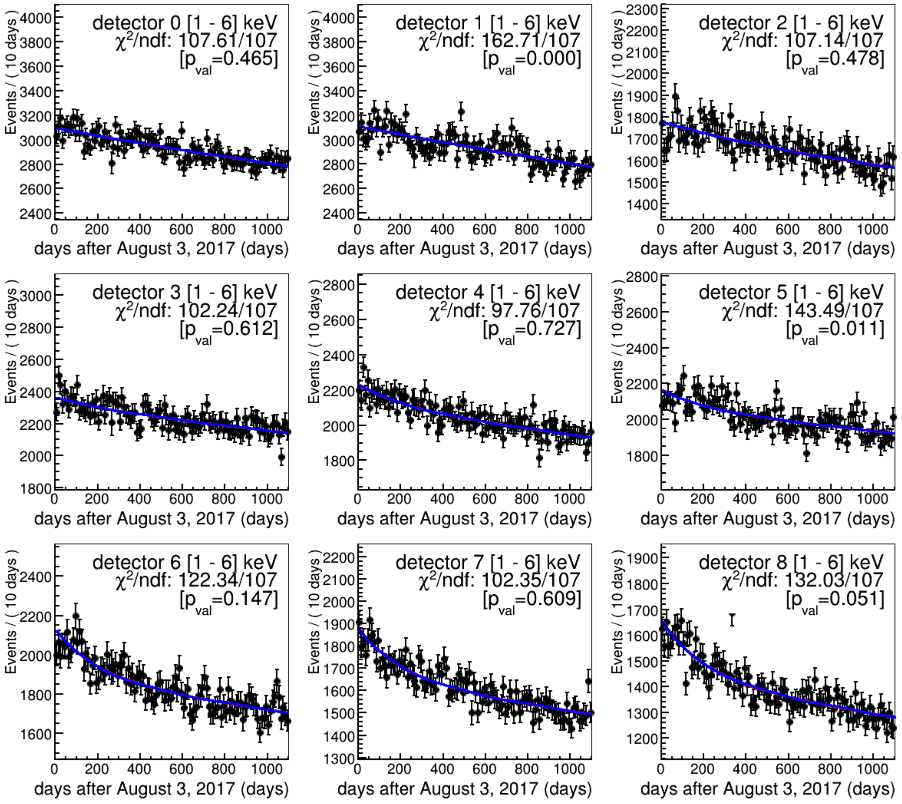
S_m: modulation amplitude

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

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

S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)

[1-6] keV

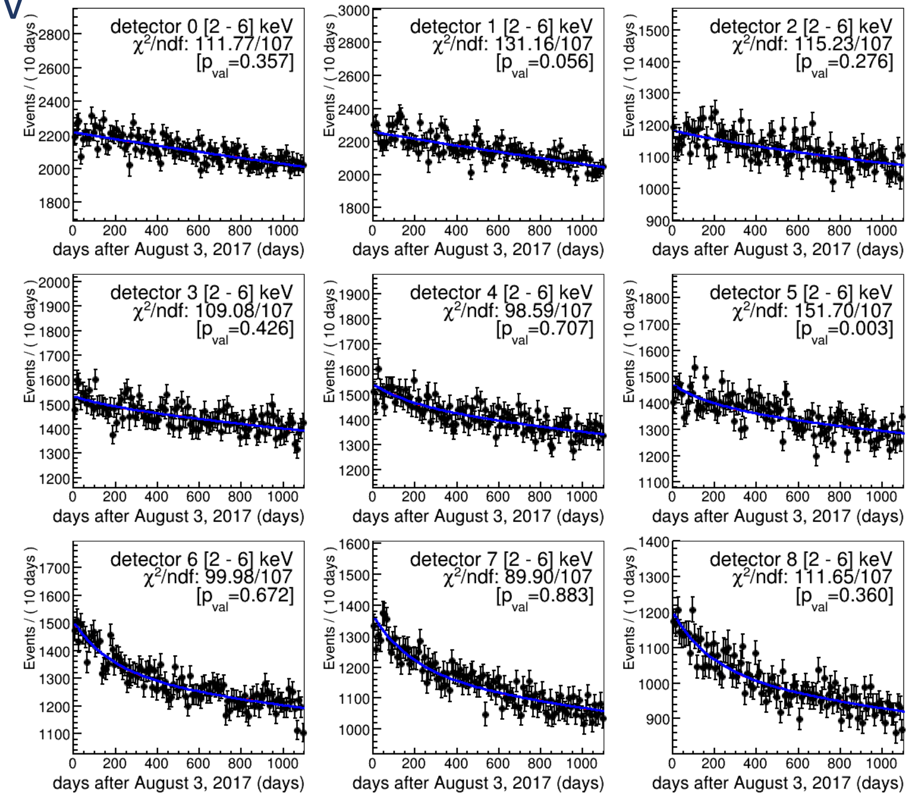


Null hyp χ^2/ndf: 1018.19/972 [p_{val}=0.148]

Mod hyp χ^2/ndf: 1018.18/971 [p_{val}=0.143]

S_m = (0.0003 ± 0.0037) (cpd/kg/keV)

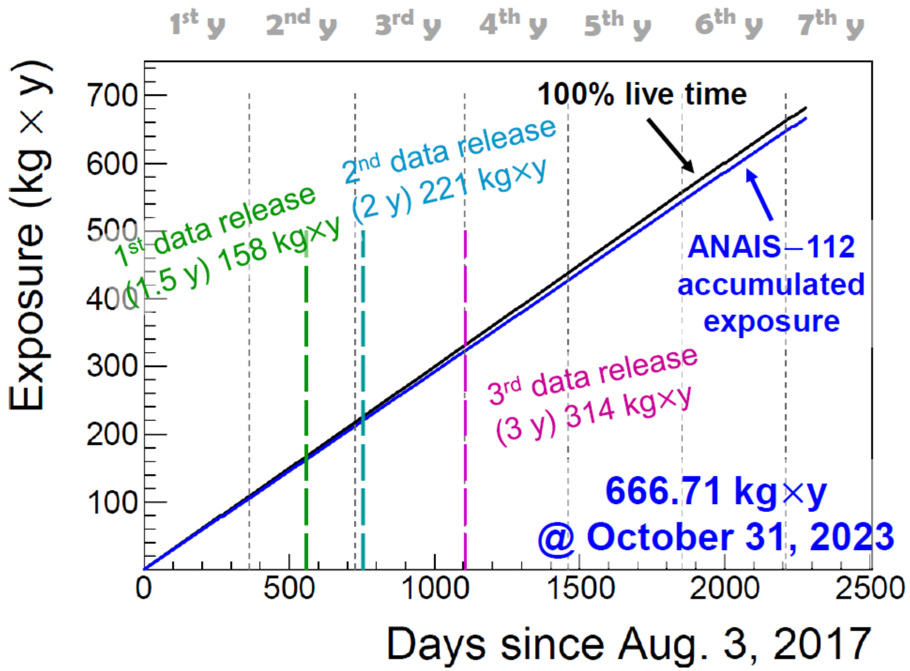
[2-6] keV



Annual modulation results

ANAIS-112 data releases:

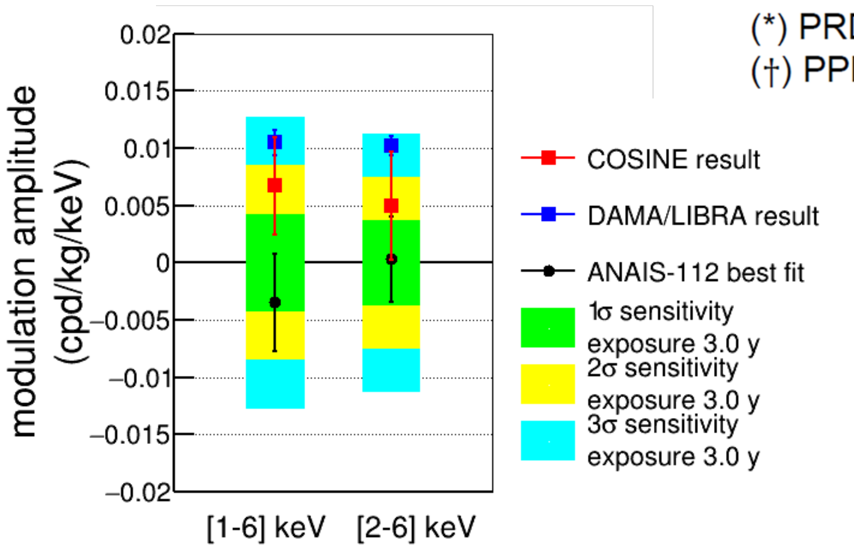
- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: Phys. Rev. D 103, 102005 (2021)



ANAIS-112 3y modulation results:

E (keV)	S_m (counts/keV/kg/day) ANAIS−112	COSINE−100 (*)	DAMA/LIBRA (†)
[1-6]	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011
[2-6]	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008

(*) PRD 106, 052005 (2022)
(†) PPNP 114, 103810 (2020)



ANAIS-112 3y: ~2.5σ sensitivity

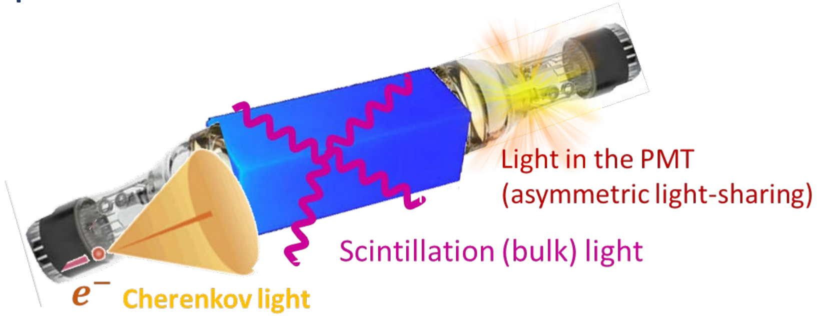
Thanks to the support of the Dark Matter Data Center, funded by the ORIGINS excellence cluster, **ANAIS-112 3-years data is freely available for downloading**

https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais

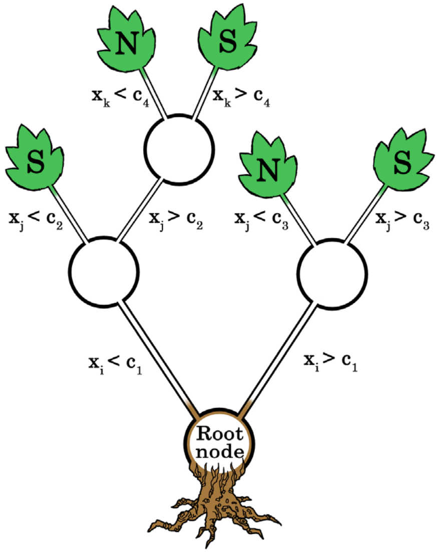
Improving ANAIS-112 sensitivity

"Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques", I. Coarasa et al, JCAP11(2022)048

Improve the "bulk scintillation" event selection with machine learning techniques



15 discrimination parameters combined in a boosted decision tree (instead of the 4 parameters used in the standard analysis)



Std analysis

$$P_1 = \frac{\sum_{100\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)} \qquad \mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i} \qquad n_0, n_1$$

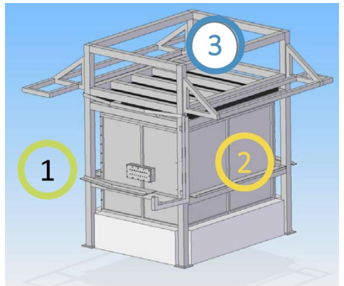
$$P_2 = \frac{\sum_{0\ \mathrm{ns}}^{50\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{600\ \mathrm{ns}} A(t)} \qquad Asynphe = \frac{nphe_0 - nphe_1}{nphe_0 + nphe_1}$$

$$\mathrm{CAP}_x = \frac{\sum_{0\ \mathrm{ns}}^{x\ \mathrm{ns}} A(t)}{\sum_{0\ \mathrm{ns}}^{t_{\max}} A(t)}$$

$$x = 50,\ 100,\ 200,\ 300,\ 400,\ 500,\ 600,\ 700 \text{ and } 800\ \mathrm{ns}$$

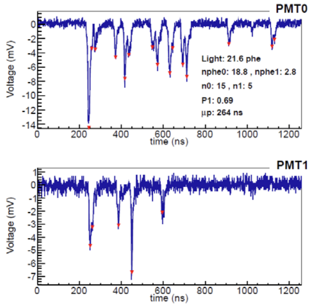
TRAINING POPULATIONS

SIGNAL EVENTS: Neutron calibrations



NOISE EVENTS: "Blank" module (No NaI(Tl))

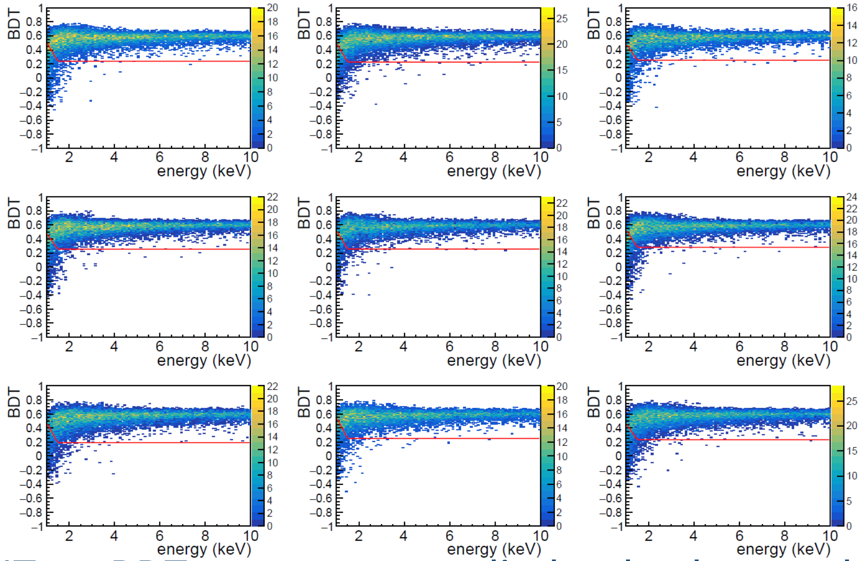
Since 2018 a BLANK module (without NaI(Tl) crystal) taking data with the same DAQ

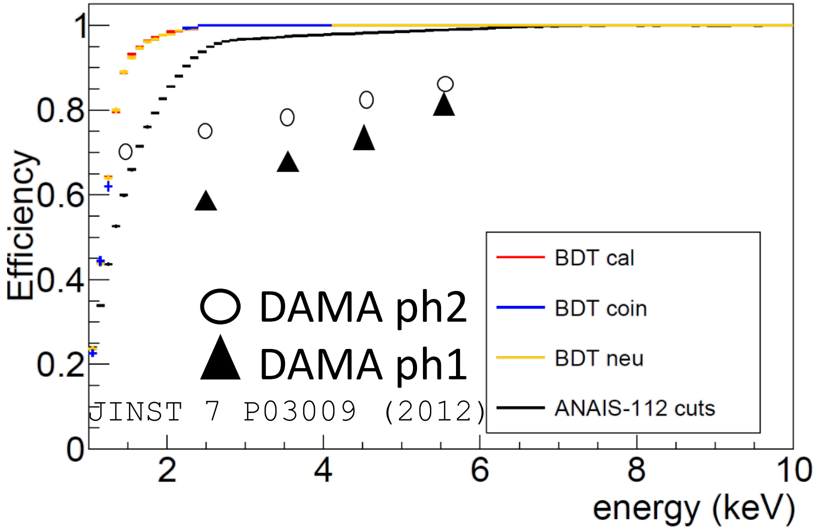


Event selection with BDT

JCAP11(2022)048

Neutron calibration

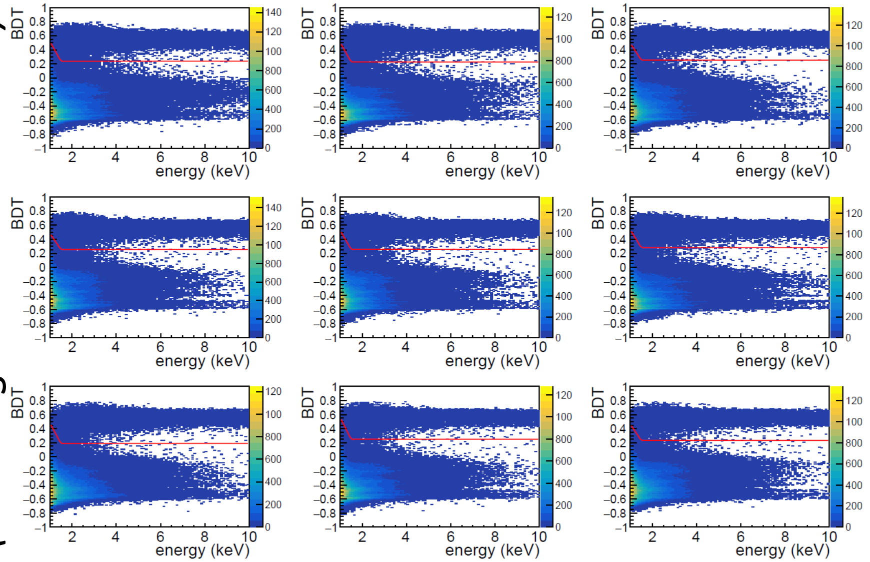


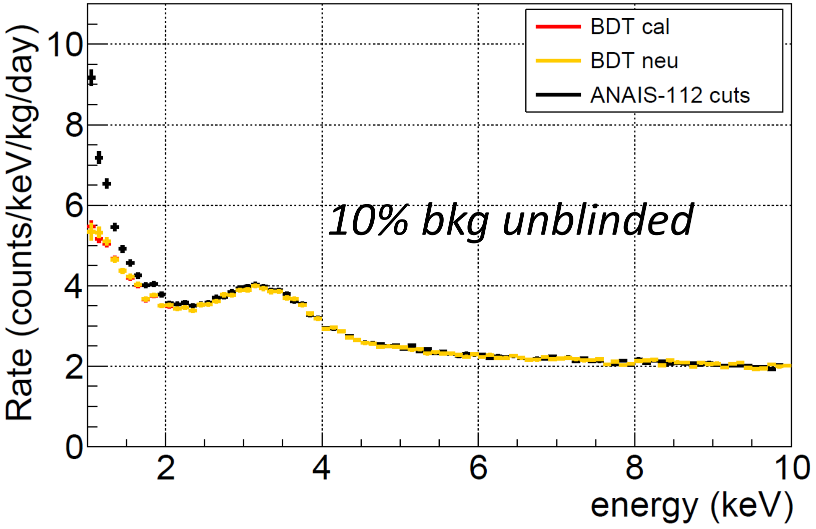


~30% improvement in efficiency

CUT on BDT parameter applied to background

(10% bkg unblinded events)



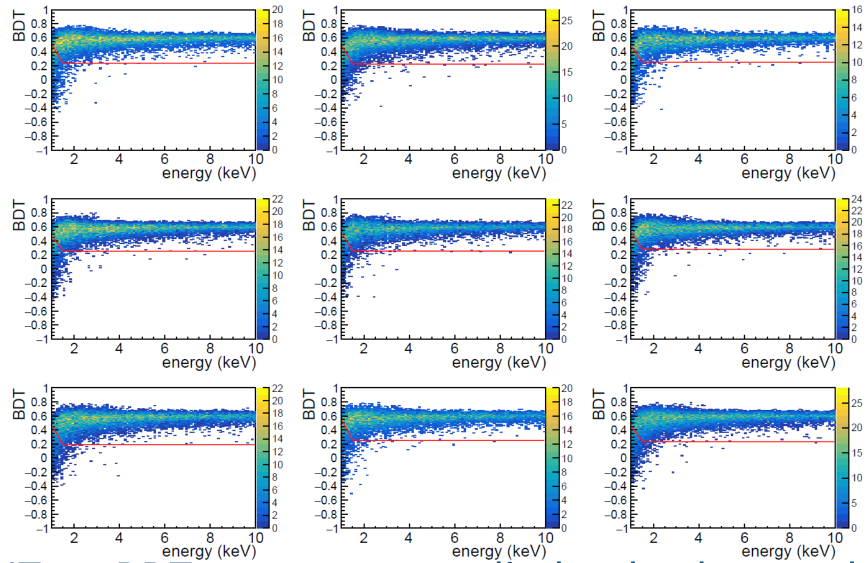


~18% bkg reduction in [1-2] keV

Event selection with BDT

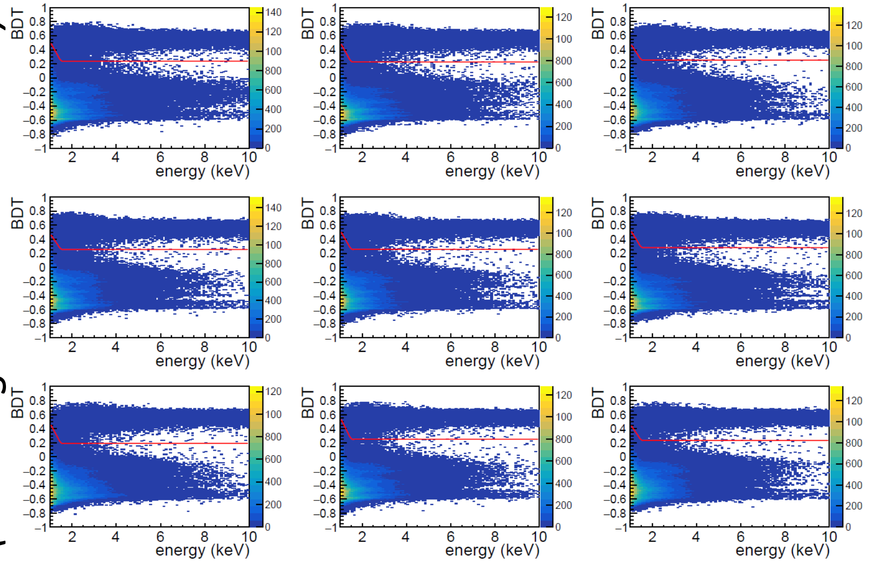
JCAP11(2022)048

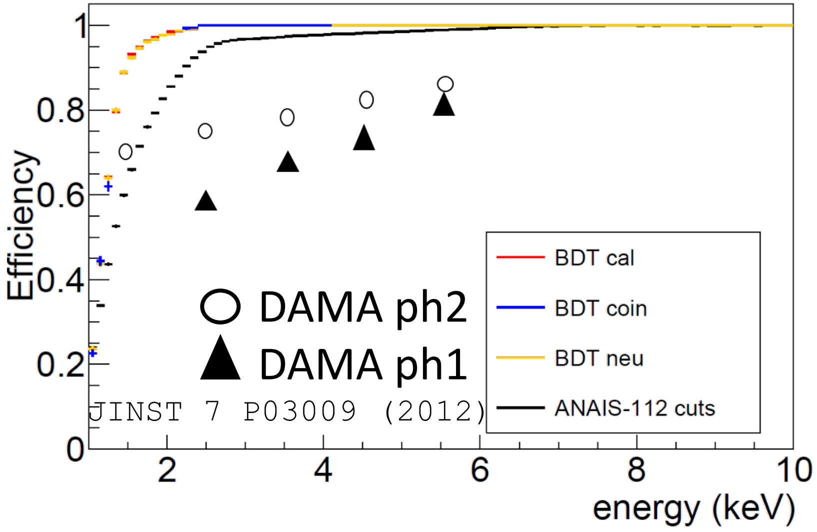
Neutron calibration

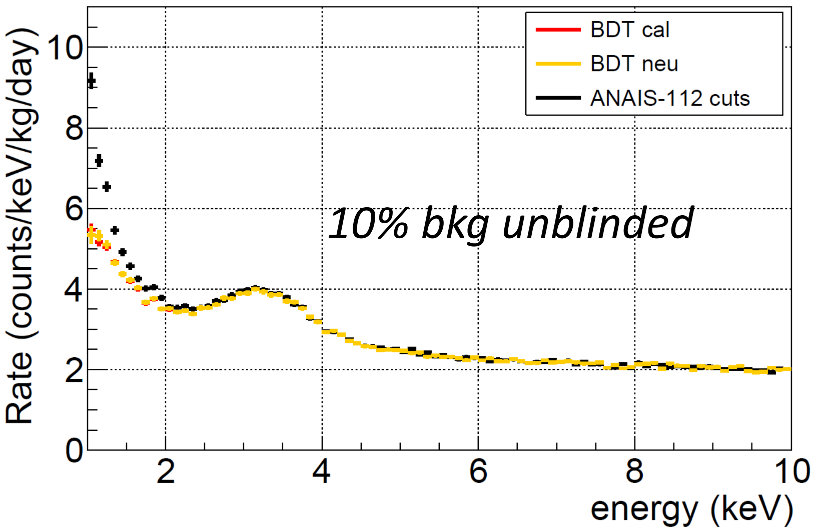


CUT on BDT parameter applied to background

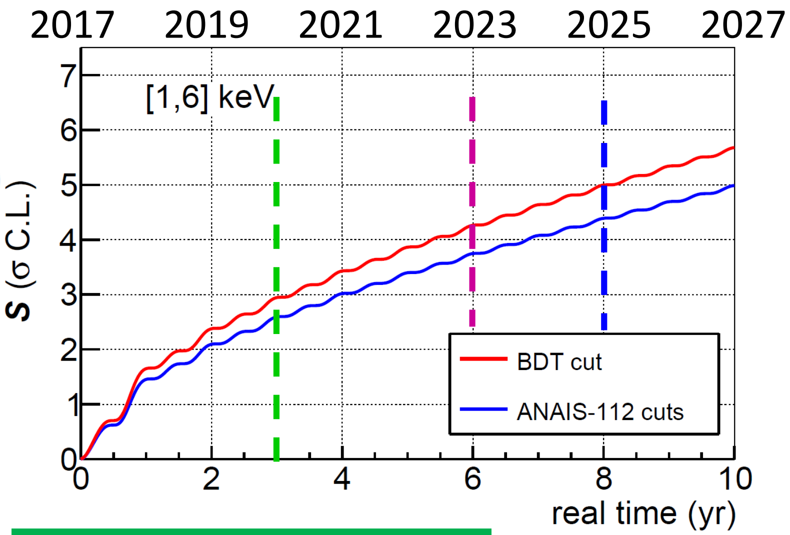
(10% bkg unblinded events)







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



3σ sensitivity with 3y

$>4\sigma$ sensitivity with 6y (last summer)

5σ sensitivity in late 2025

Improved 3-years results [1-6] keV

$2.5\sigma \rightarrow 2.9\sigma$

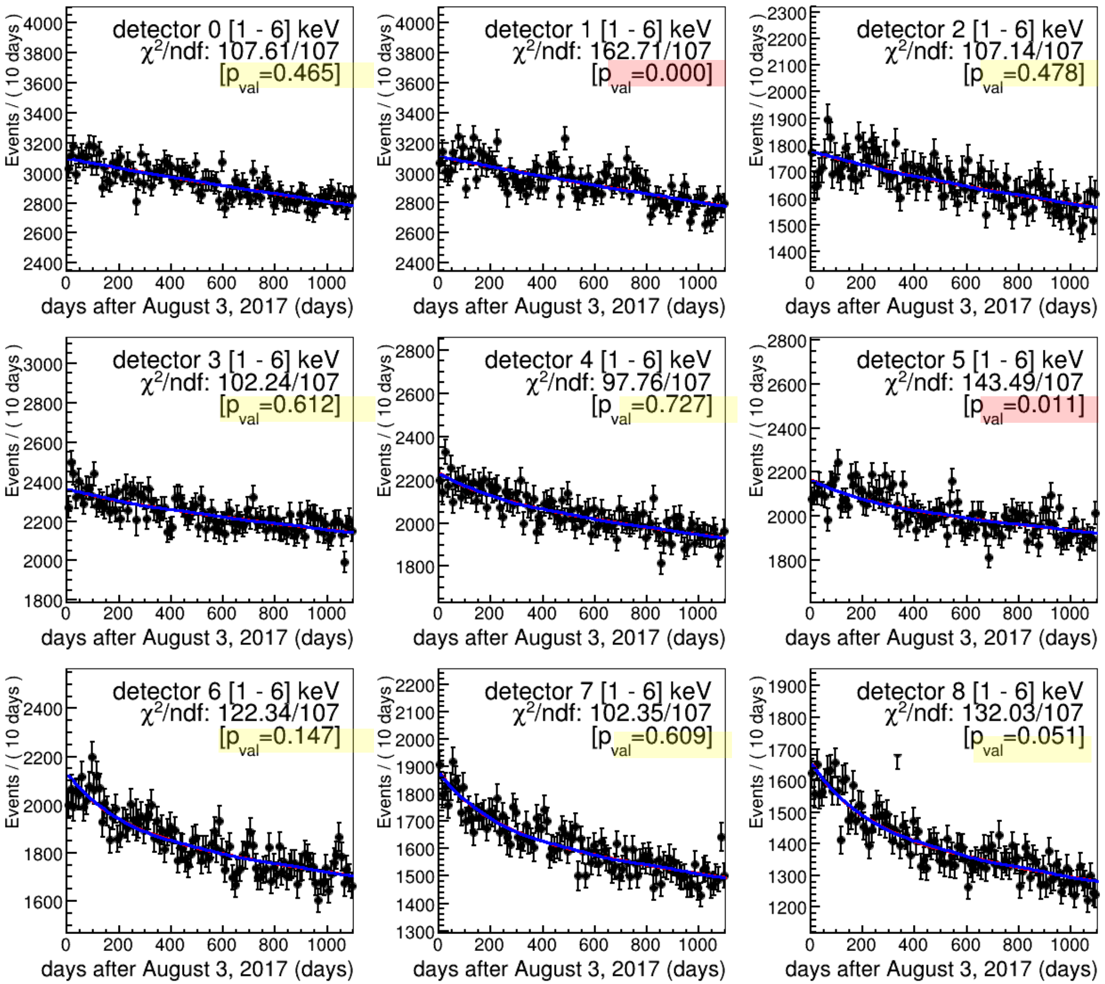
NEW

PRD 103, 102005 (2021)

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

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

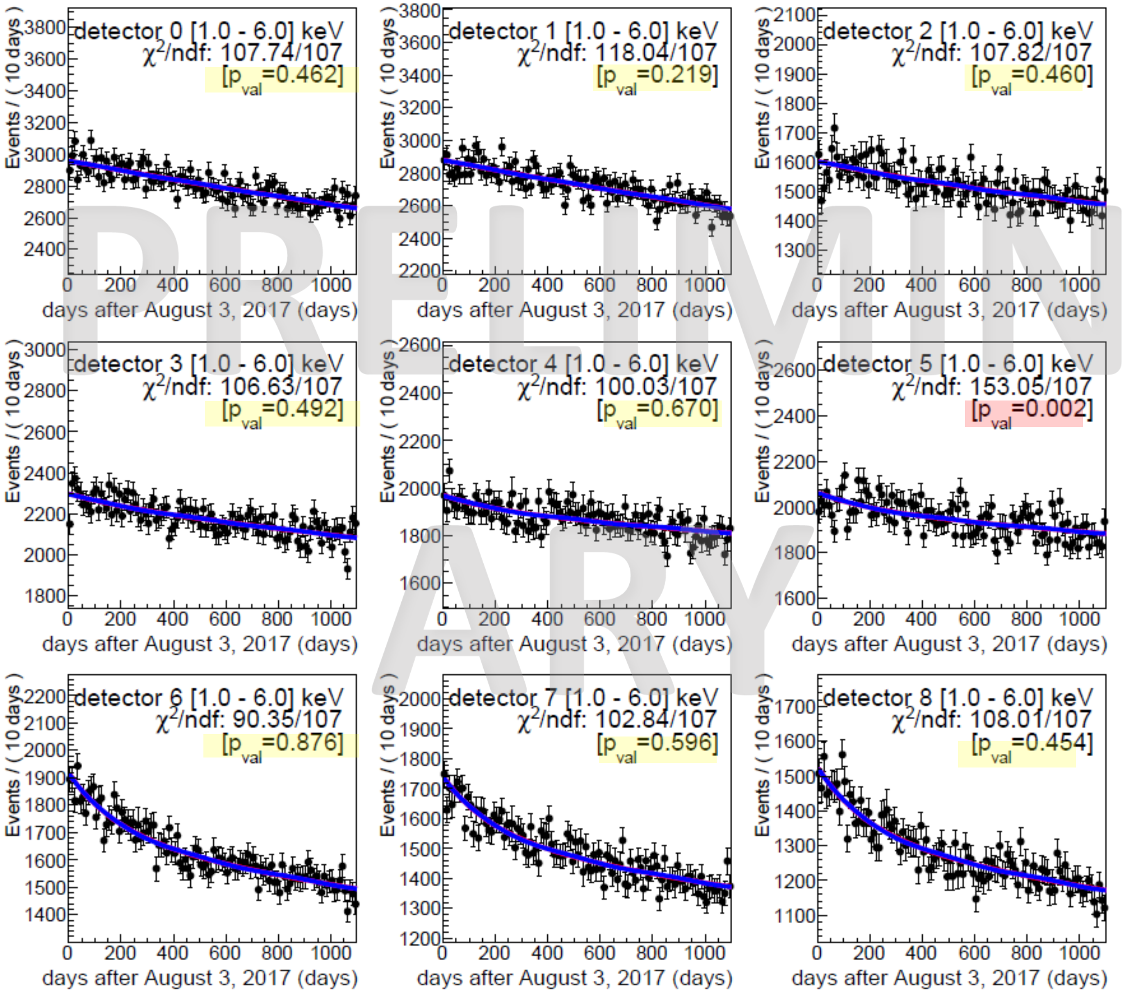
S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)



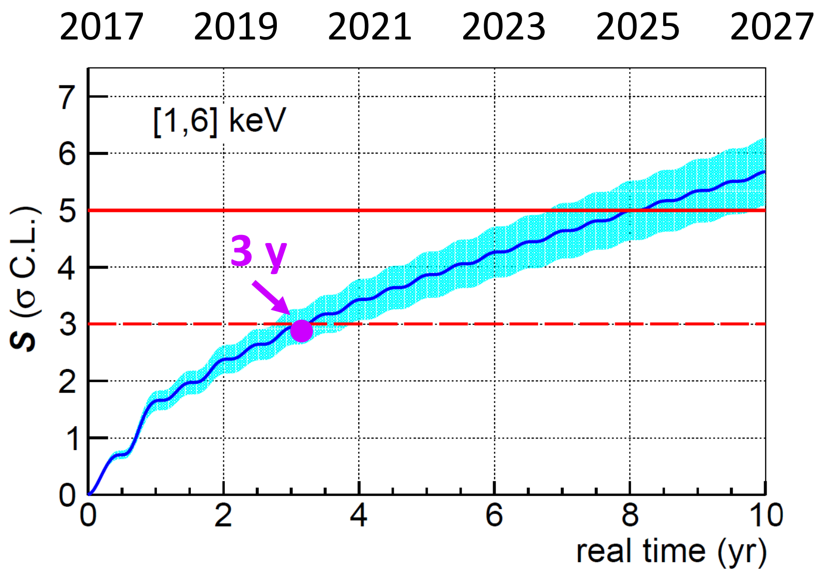
Null hyp χ^2/ndf: 993.78/972 [p_{val}=0.307]

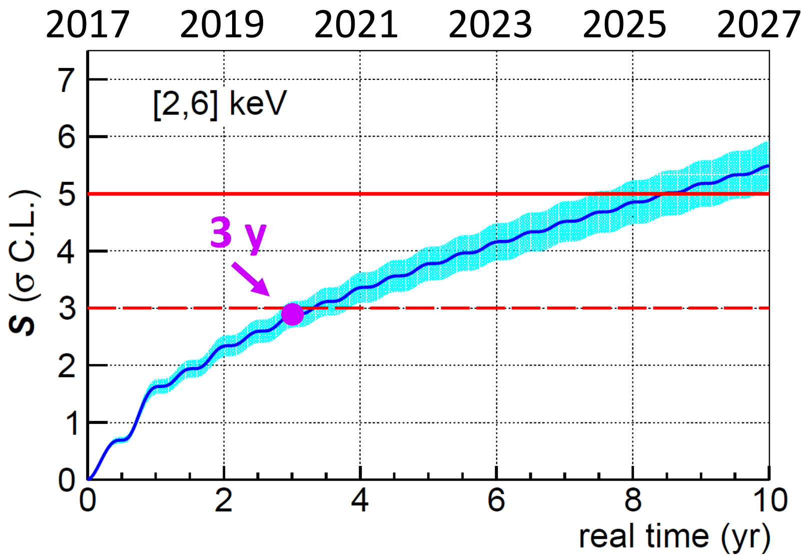
Mod hyp χ^2/ndf: 992.99/971 [p_{val}=0.305]

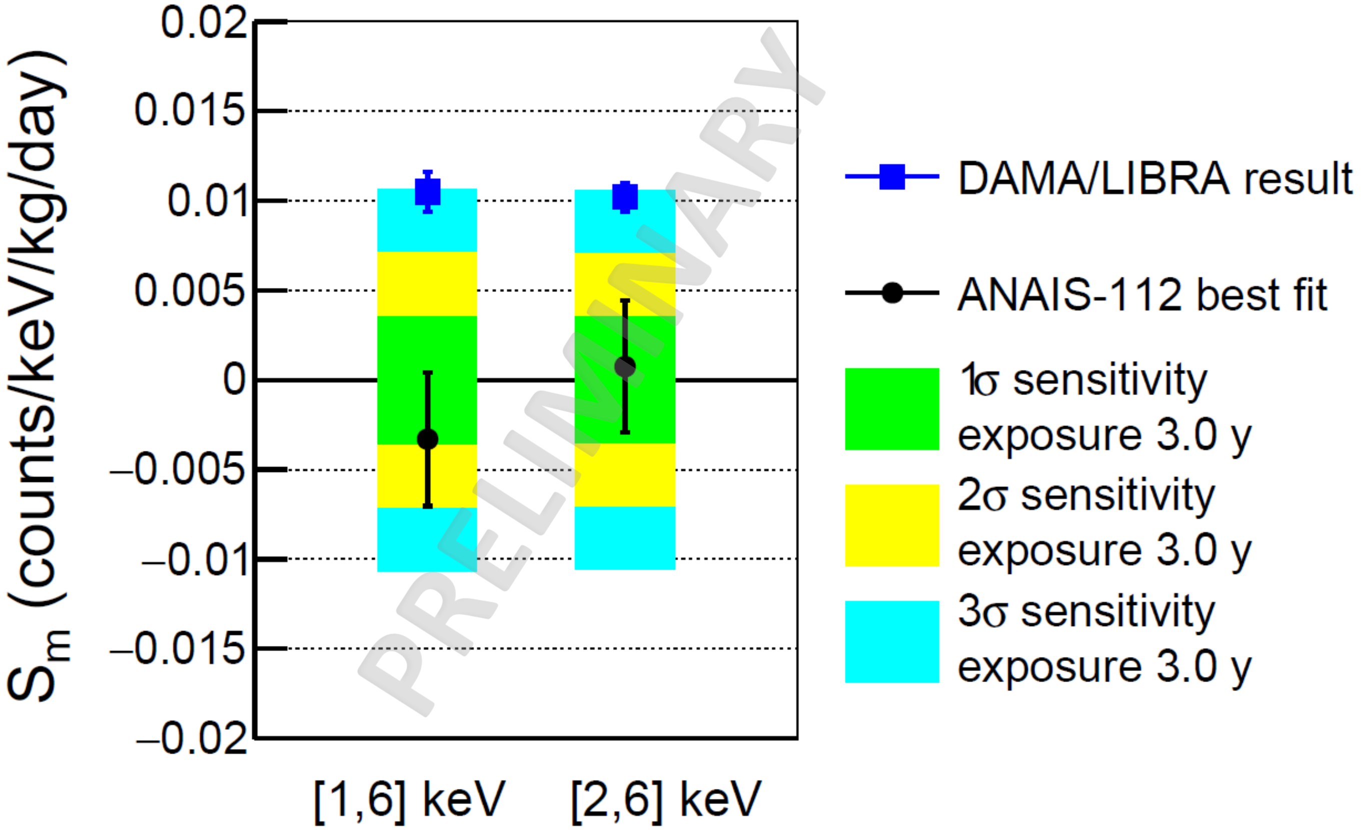
S_m = (-0.0033 ± 0.0037) (cpd/kg/keV)



3-years annual modulation with BDT cut







best fit modulation amplitudes compatible with zero at ~1σ

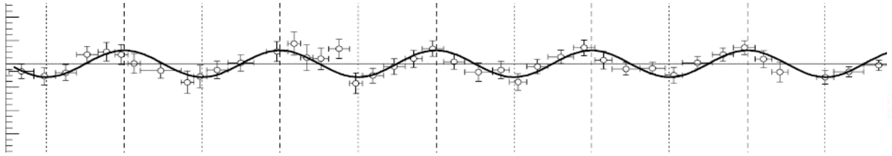
Best fit incompatible with DAMA/LIBRA at 3.9 (2.8) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.9σ for [1-6] & [2-6] keV

5σ sensitivity at reach in late 2025

Outlook & summary

- Currently, many efforts trying to provide an independent confirmation of DAMA/LIBRA signal with the same target.
- ANAIS-112: is taking data in stable condition @ LSC **since 3rd August 2017** with excellent performances. Up to now it has accumulated ~ 700 kg×y exposure.
- 3-years annual modulation analysis (PRD 103, 102005 (2021)) **public for downloading** at https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais
- Sensitivity improved with machine learning techniques**. ANAIS-112 observes no modulation and discards DAMA/LIBRA DM interpretation with $\sim 3\sigma$ sensitivity** in [1-6] keV ([2-6] keV).
- **For the first time, a direct test (i.e. model independent) of DAMA is at reach with >3σ sensitivity. 5σ sensitivity in late 2025.**
- Analysis including possible **quenching factor difference on NaI crystals** ongoing. Results soon.



Outlook & summary

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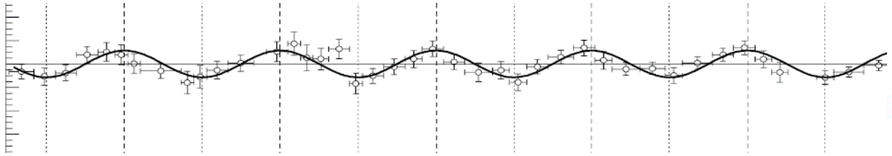
Thanks!!

gifna.unizar.es/anais/

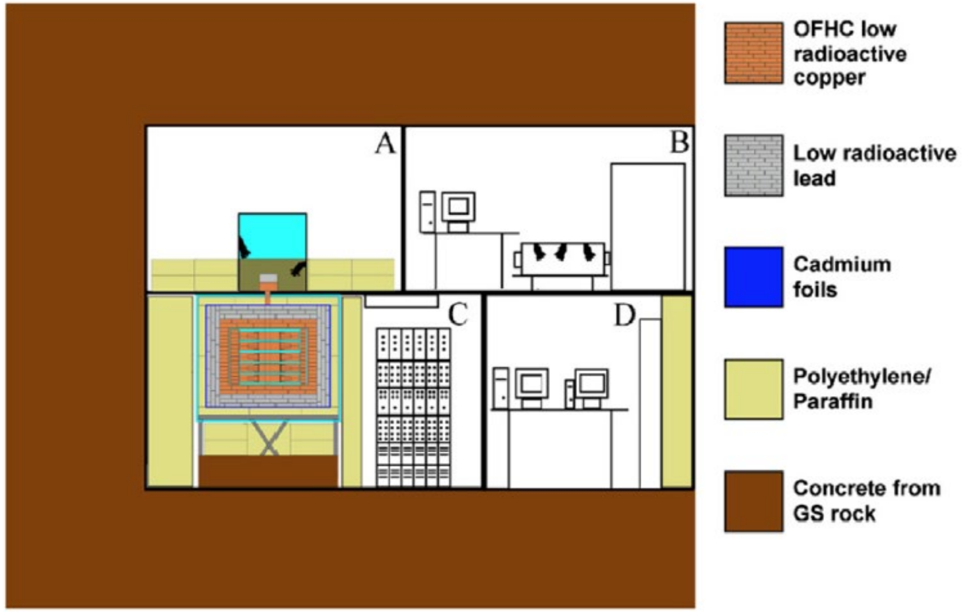


Backup

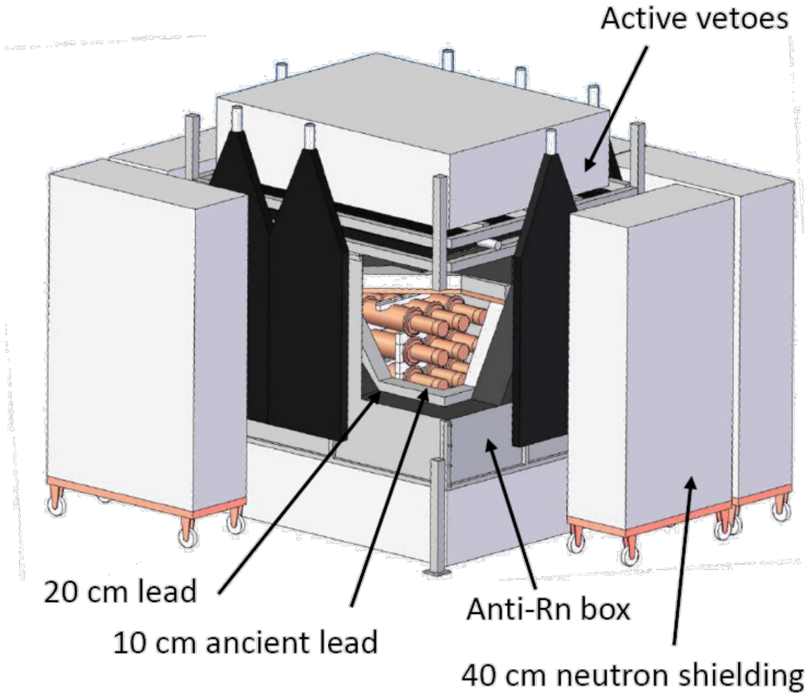
What is different wrt DAMA/LIBRA

Shielding

- Gamma shielding:
  >10 cm of OFHC Cu + 15 cm of Pb
- Anti-Rn: Plexiglas box fluxed with N2 gas
- Neutron shielding:
  10/40 cm Polyethylene/paraffin + Cd foils



- Gamma shielding:
  10 cm of ancient Pb + 20 cm of Pb
- Anti-Rn metallic box fluxed with N2 gas
- Active muon vetoes
- Neutron shielding:
  40 cm Polyethylene/water tanks

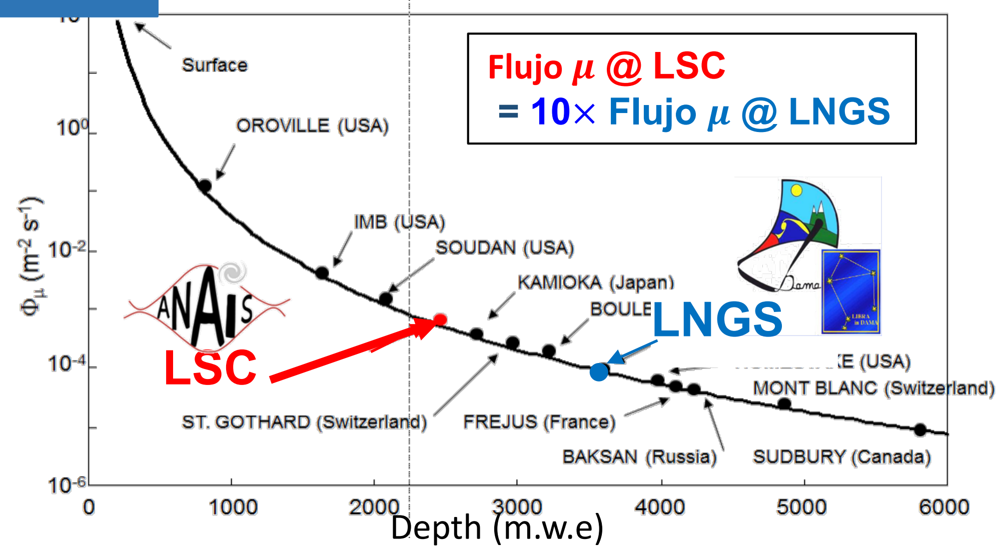


What is different wrt DAMA/LIBRA

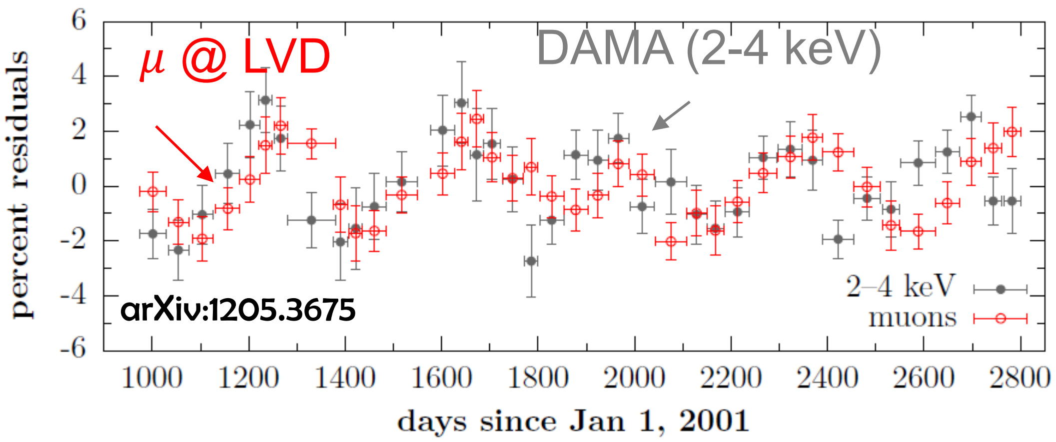
Muon veto

In ANAIS we flag every muon that cross the shielding
We set a (configurable) dead-time after every passage

DAMA/LIBRA has no muon veto



The underground muon flux is annual-modulated!



<u>Can muons explain DAMA signal?</u>

- 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

But still some open questions:

- (delayed) effect of muons in PMTs?
- slow phosphorescence in NaI?

What is different wrt DAMA/LIBRA

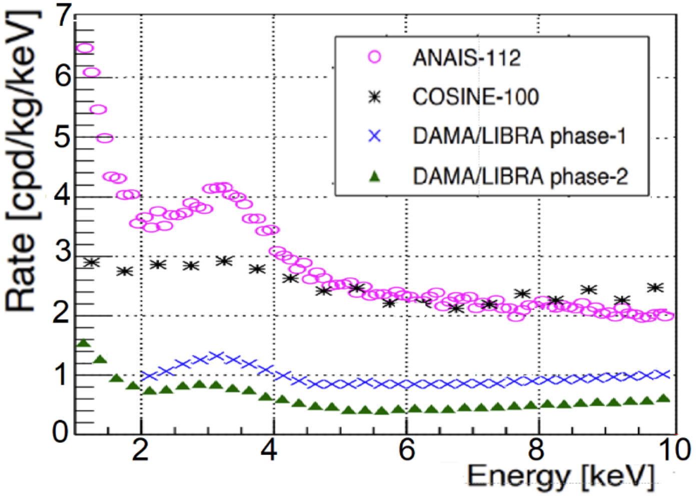
NaI(Tl) scintillating detectors

- 25 crystals, 10.2×10.2×25.4 cm^3, 9.7 kg each
- Sain Gobain, Kyropoulos method with a platinum crucible
- PMTs phase-1: ETL 9265–B53/FL and 9302–A/FL (QE~30%)
- PMTs phase-2: Hamamatsu R6233MOD (QE ~38%)
- Light guides: 10 cm Suprasil B

- 9 cylindrical crystals, 12 cm ϕ ×30 cm, 12.5 kg each
- Alpha Spectra (same as COSINE)
- PMTS: Hamamatsu R12669SEL2 (QE ~40%)
- Quartz window (no light guides)

Superior radiopurity of DAMA/LIBRA crystals wrt ANAIS/COSINE

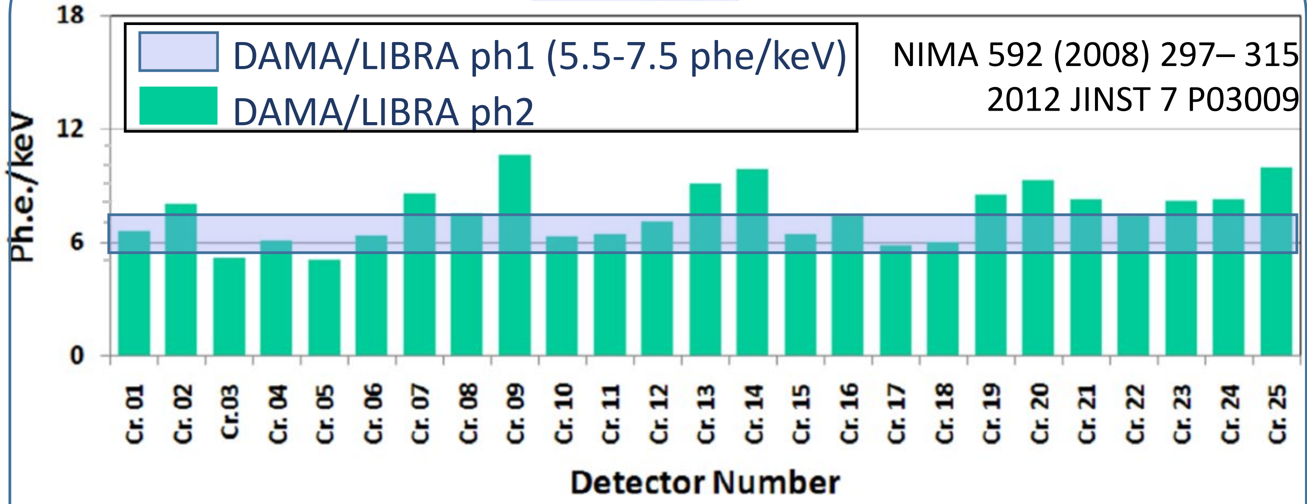
	K (ppb)	^{210}Pb (mBq/kg)
DAMA (Saint Gobain)	13	0.01-0.03
ANAIS/COSINE (Alpha Spectra)	18-44	0.7-3



ANAIS: EPJC 79:233, 2019
COSINE: EPJC 78:490, 2018
DAMA-ph1: NIMA 592 (2008) 297– 315
DAMA-ph2: Nucl. Phys. At. Energy, 19:307-325, 2018

What is different wrt DAMA/LIBRA

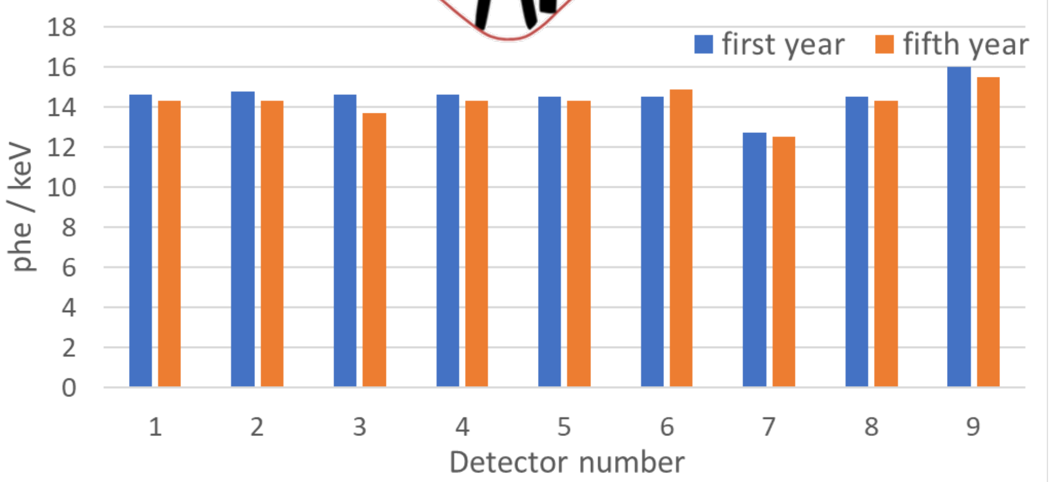
Light collection



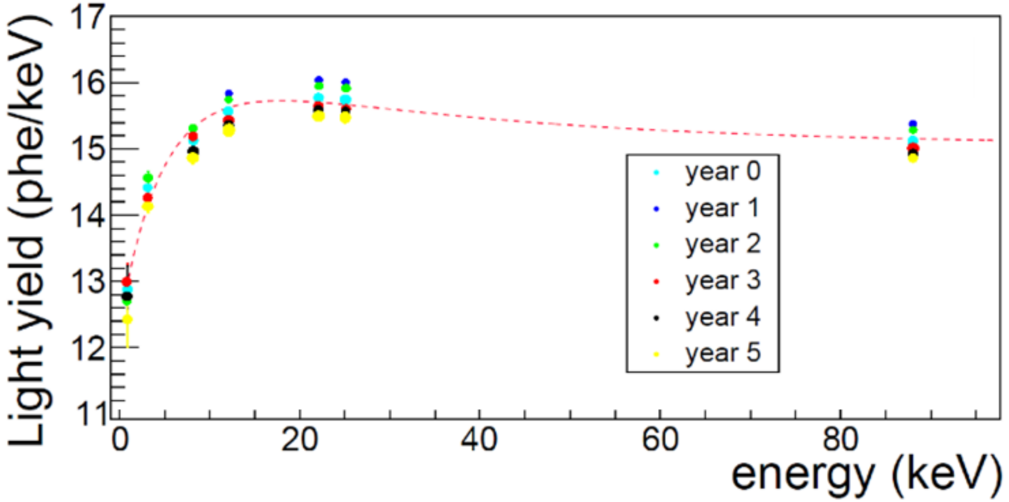
NIMA 592 (2008) 297– 315
2012 JINST 7 P03009

- DAMA/LIBRA-phase1 showed a very good linearity between the calibration with the 59.5 keV line of ^{241}Am and the tagged 3.2 keV line of ^{40}K
- in DAMA/LIBRA-phase2 a slight nonlinearity is observed(it gives a shift of about 0.2 keV at the software energy threshold and vanishes above 15 keV).

Prog. Part. Nucl. Phys. 114 (2020) 103810



In ANAIS non proportionality is observed < 25 keV (20%)

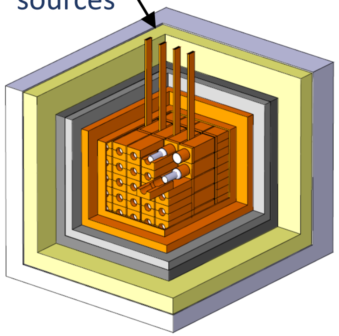


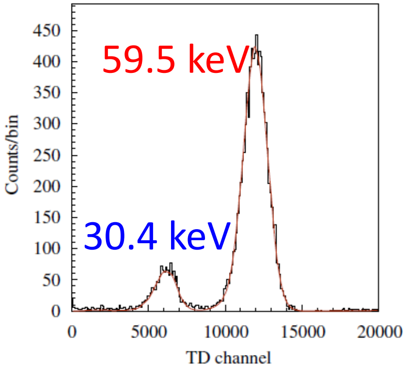
What is different wrt DAMA/LIBRA

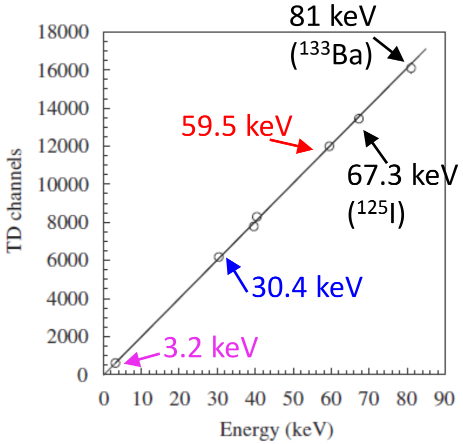
Low energy calibration – RoI [1-6 keV]

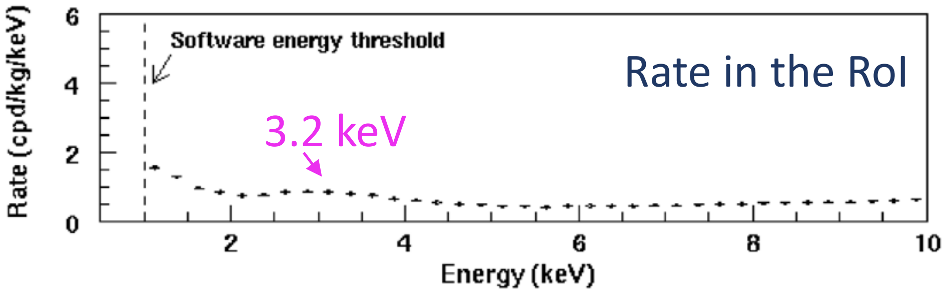
- Periodical calibrations every ~10 days with a ^{241}Am source (30.4 keV (composite), 59.5 keV). Linear calibration down to threshold
- Linearity check and corrected @ 3.2 keV with whole statistics

Guides for ^{241}Am sources

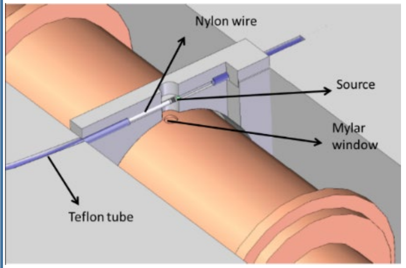


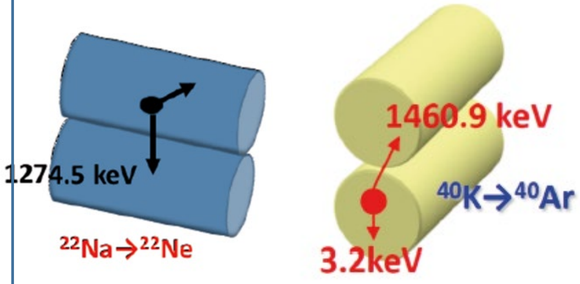


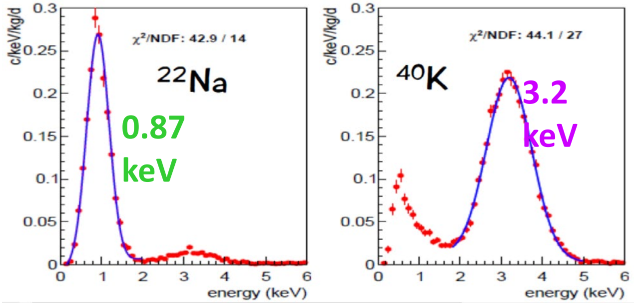


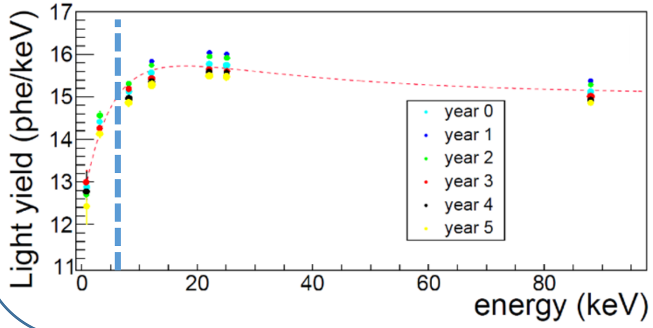


- Detectors equipped with a **Mylar window**
- Calibration with **^{109}Cd sources** (11.9 keV, 22.6 keV and 88.0 keV) every two weeks for gain correction
- Calibration in the ROI with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) (whole statistics)









Non proportionality < 25 keV (20%)

Linear calibration in 2 ranges:

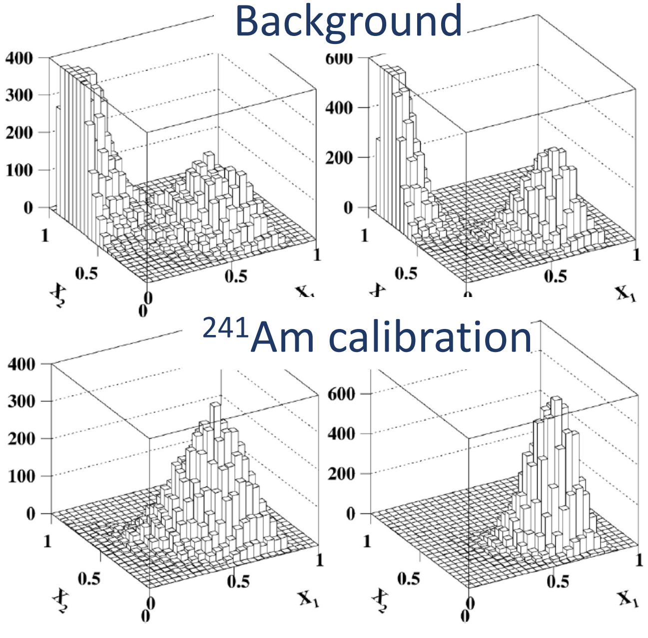
- 1-10 keV [ROI]
- 10-100 keV

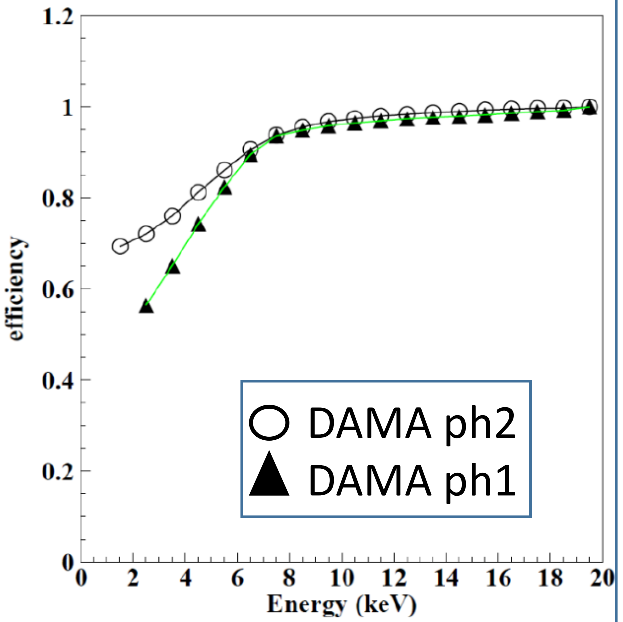
What is different wrt DAMA/LIBRA

Event selection & efficiency

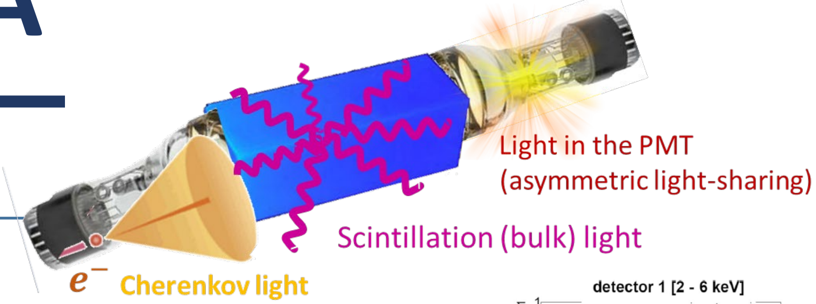
X_1 = Area(from 100 to 600 ns)=Area(from 0 to 600 ns)
X_2 = Area(from 0 to 50 ns)=Area(from 0 to 600 ns)

$$ES = \frac{1-(X_2-X_1)}{2} \qquad ES > 0.54\ (0.60) \text{ in } 1\text{–}3\ (3\text{–}6)\ \text{keV}$$

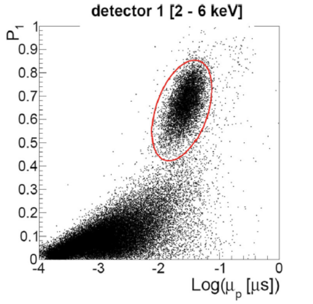




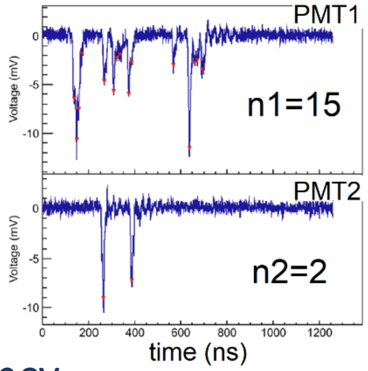
JINST 7 P03009 (2012)



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

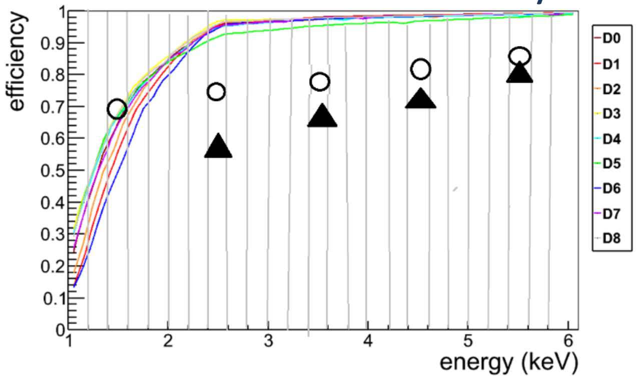


Between 1-2 keV, in ANAIS-112 there is a population of asymmetric events (more light in one PMT wrt the other)



Select events with n1>4 & n2>4

ANAIS vs DAMA efficiency



Continuos lines: ANAIS eff, from ^{109}Cd and ^{22}Na/^{40}K
○ DAMA ph2
▲ DAMA ph1

NR Quenching factor measurements

DAMA/LIBRA

^{252}Cf calibration

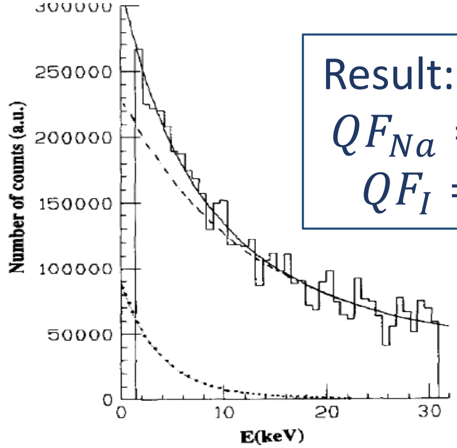
$E_R = E_{det}/QF$

Hypothesis: constant QF

Spectrum fitted to:

$$Y(E_{det}) = \alpha_{Na} G_{Na}\left(\frac{E_{det}}{q_{Na}}\right) + \alpha_I G_I\left(\frac{E_{det}}{q_I}\right)$$

$$G_X(E_R) = \exp(a_{1,X}E_R^3 + a_{2,X}E_R^2 + a_{3,X}E_R$$

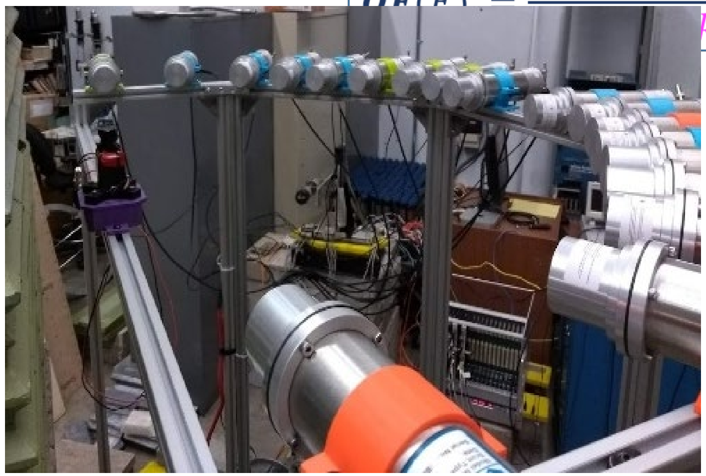


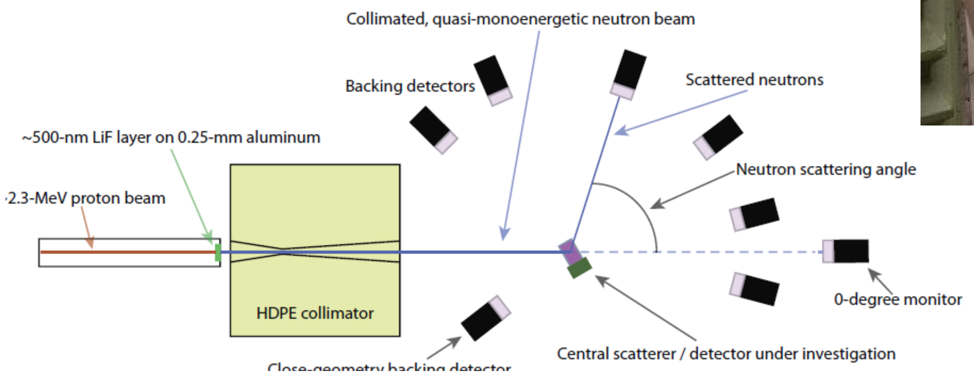
Result:
$QF_{Na} = 30\%$
$QF_I = 9\%$

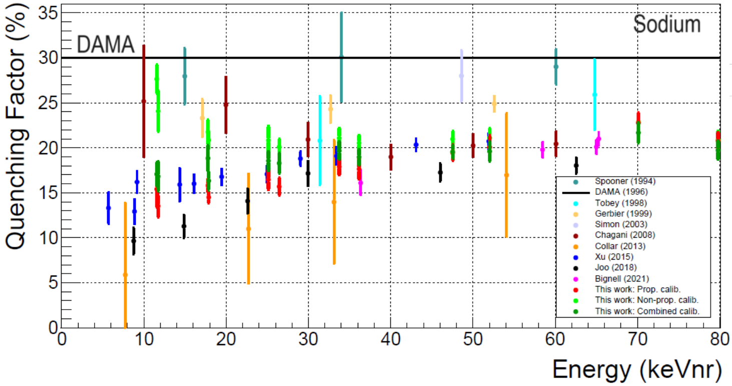
Phys. Lett. B 389 (1996) 757-766

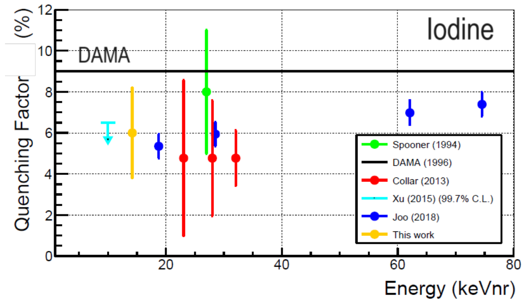
ANAIS method 1

Measurements @ TUNL (Duke Univ.)
5 different NaI(Tl) crystals (ANAIS & Yale group of COSINE) in the same setup









- Similar response for the 5 crystals
- Noticeable differences for different energy calibrations (NaI non-linearity)
- Lower QF than DAMA/LIBRA measurement

[paper ready to be send to Phys. Rev. C]

NR Quenching factor measurements

$$QF(E) = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$

DAMA/LIBRA

^{252}Cf calibration

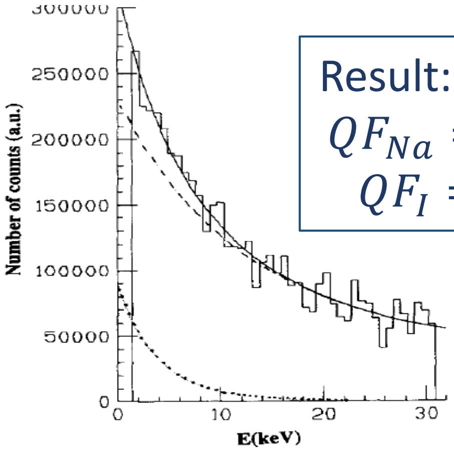
$E_R = E_{det}/QF$

Hypothesis: constant QF

Spectrum fitted to:

$$Y(E_{det}) = \alpha_{Na} G_{Na}\left(\frac{E_{det}}{q_{Na}}\right) + \alpha_I G_I\left(\frac{E_{det}}{q_I}\right)$$

$$G_X(E_R) = \exp(a_{1,X}E_R^3 + a_{2,X}E_R^2 + a_{3,X}E_R$$



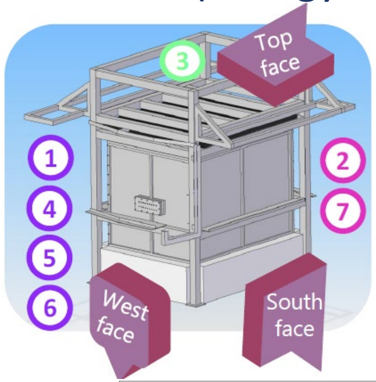
Result:
$QF_{Na} = 30\%$
$QF_I = 9\%$

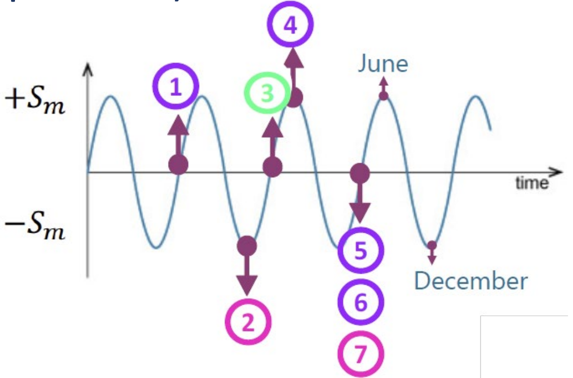
Phys. Lett. B 389 (1996) 757-766

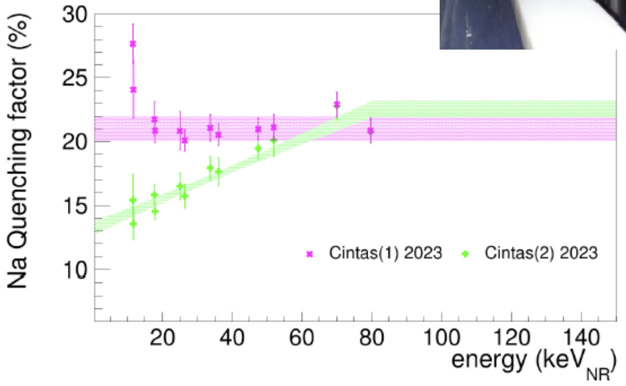
ANAIS method 2

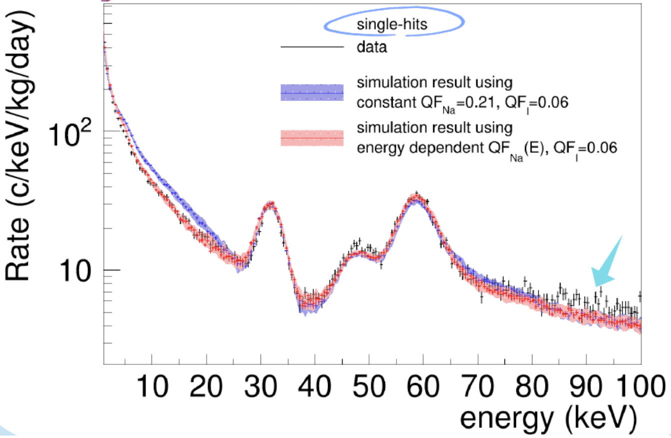
^{252}Cf onsite calibration

Method: Compare calibration data with MC simulation, assuming a certain QF (energy dependent)





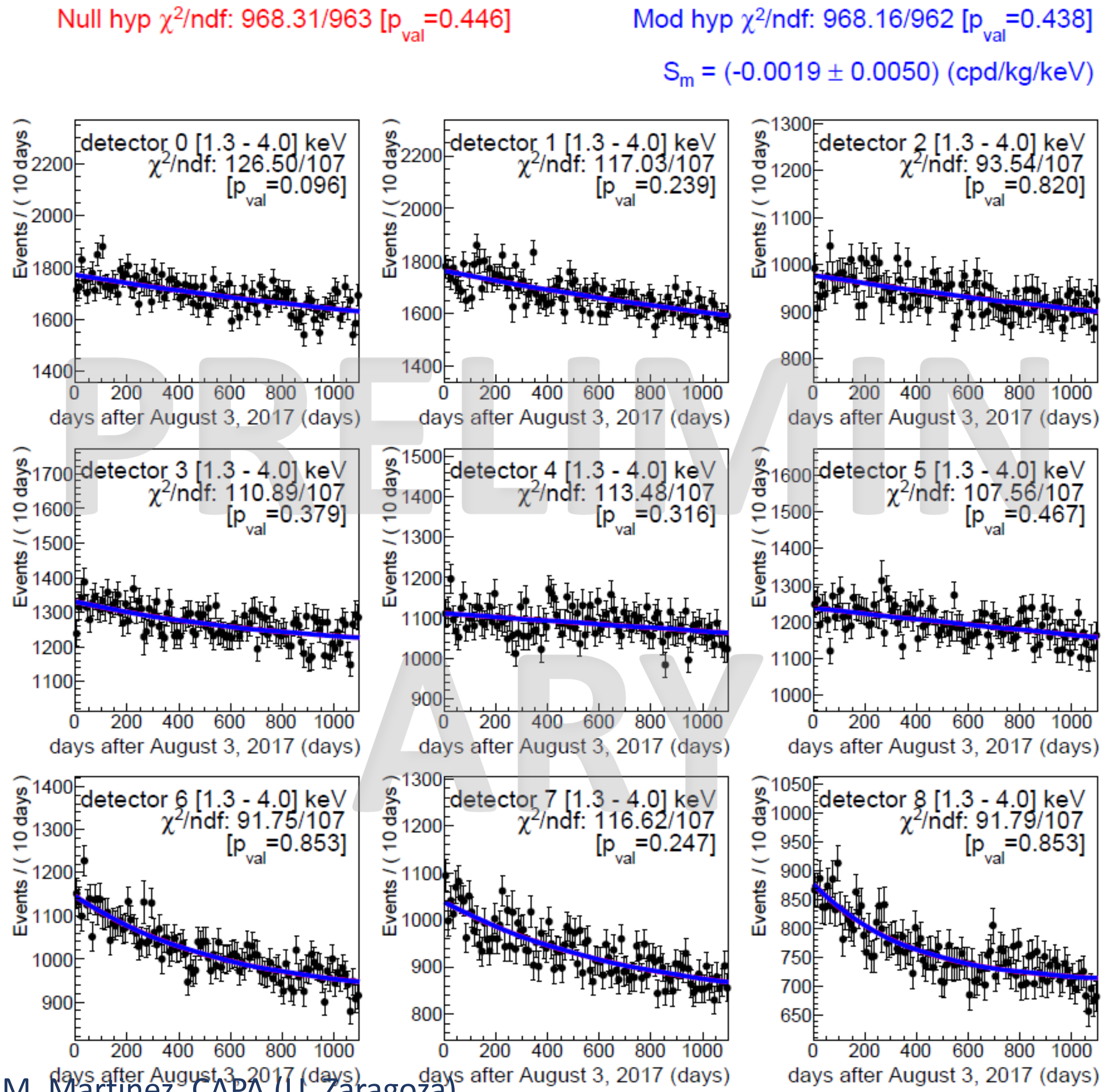




- Very sensitive to the QF
- DAMA/LIBRA QF not compatible with ANAIS data
- Robust agreement with Method 1 (QF variable with energy favored over constant QF)

[analysis almost finished. Paper soon]

3 y modulation analysis in 1.3 – 4 keV



Supposing

DAMA/LIBRA Q_{Na} = 30%

ANAIS Q_{Na}= 20%

DAMA [2 – 6] keV → ANAIS [1.3 – 4] keV

ANAIS 3 years annual modulation fit:

$$S_m = -0.0019 \pm 0.0050$$

Considering Na Quenching difference:

- ANAIS compatible with no modulation
- ANAIS best fit incompatible with DAMA @ 2.4σ (sensitivity = 2σ)