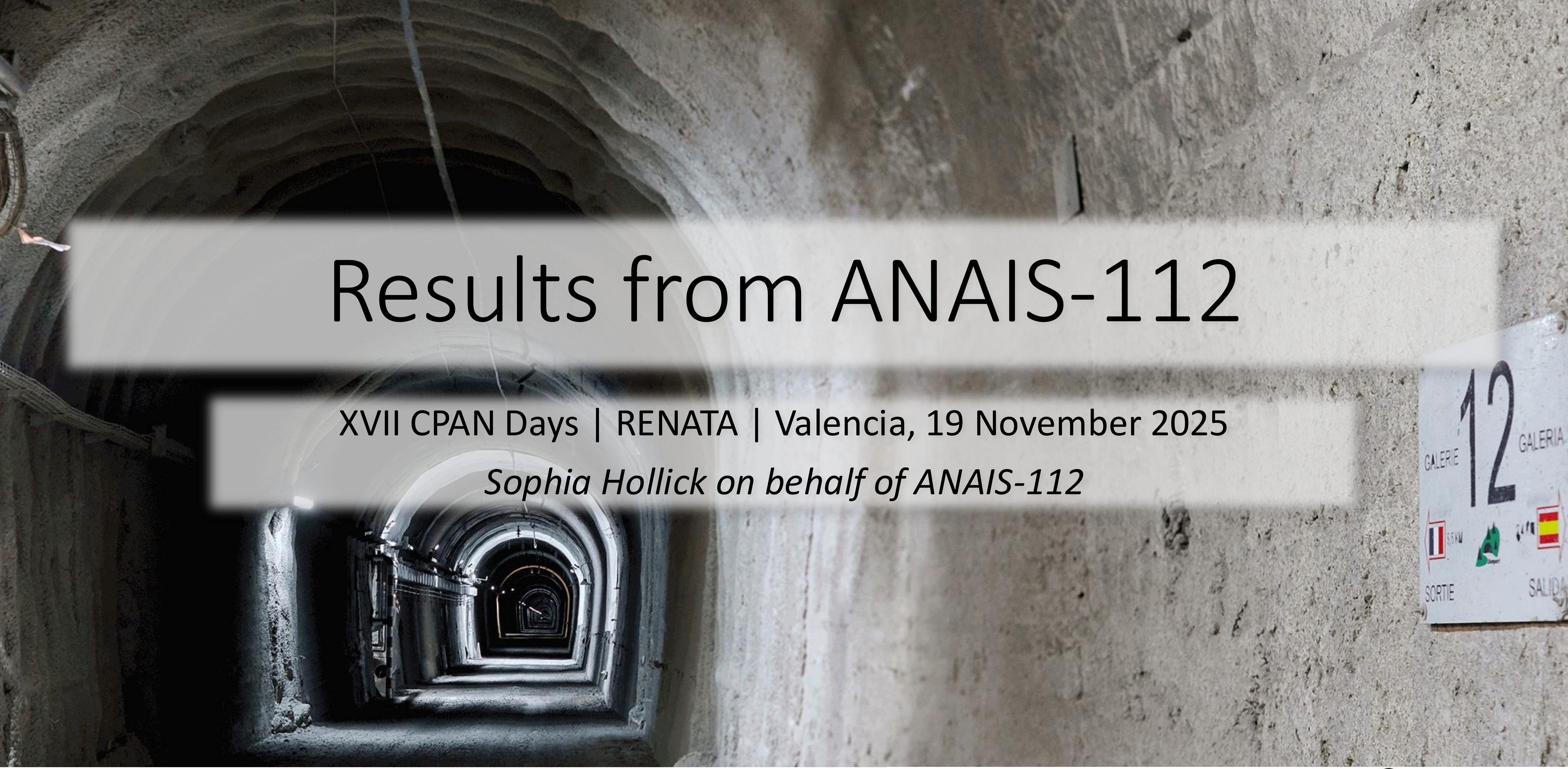


Results from ANAIS-112

XVII CPAN Days | RENATA | Valencia, 19 November 2025

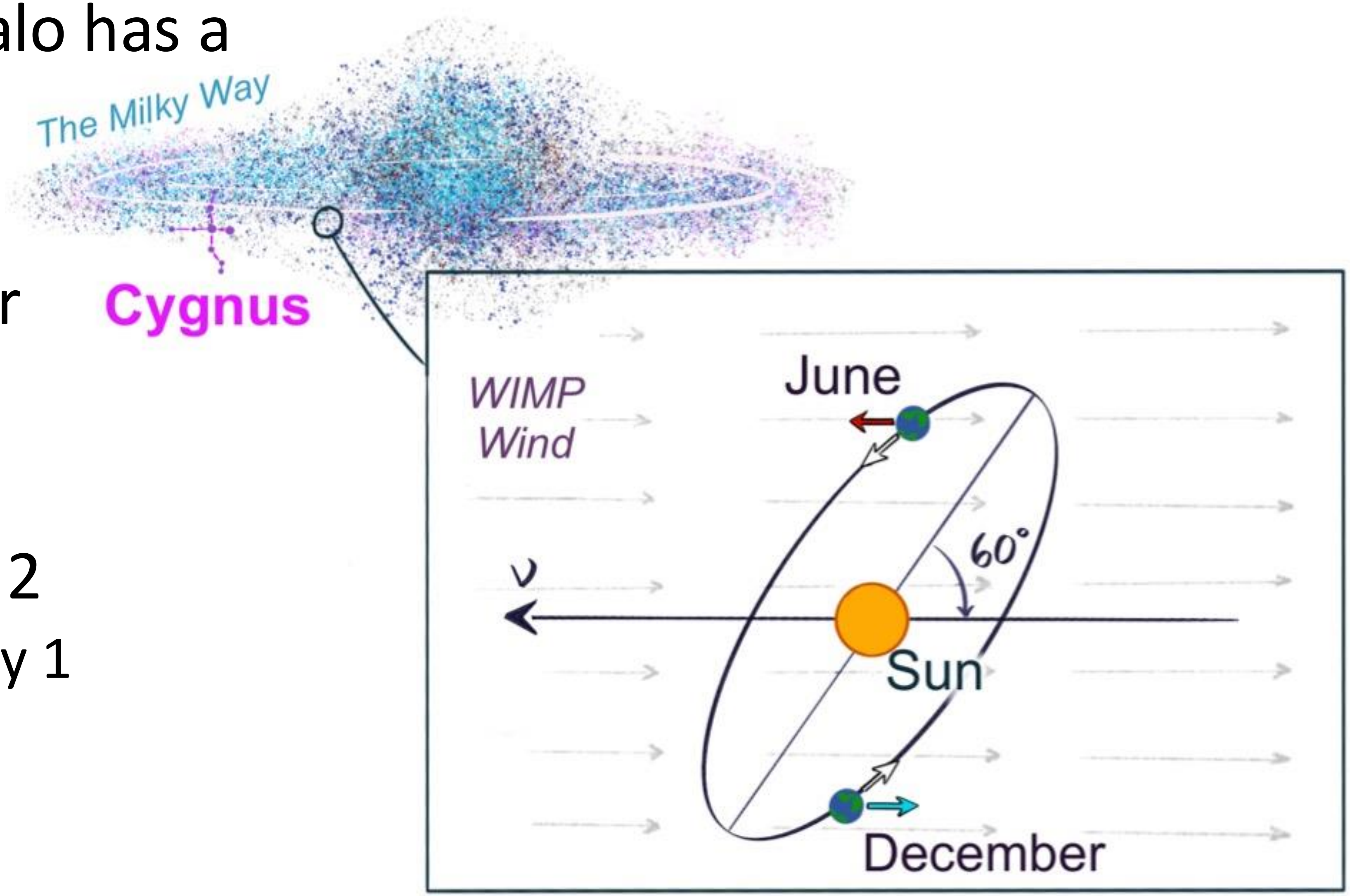
Sophia Hollick on behalf of ANAIS-112

Universidad Zaragoza 1542

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Annual Modulation Signature

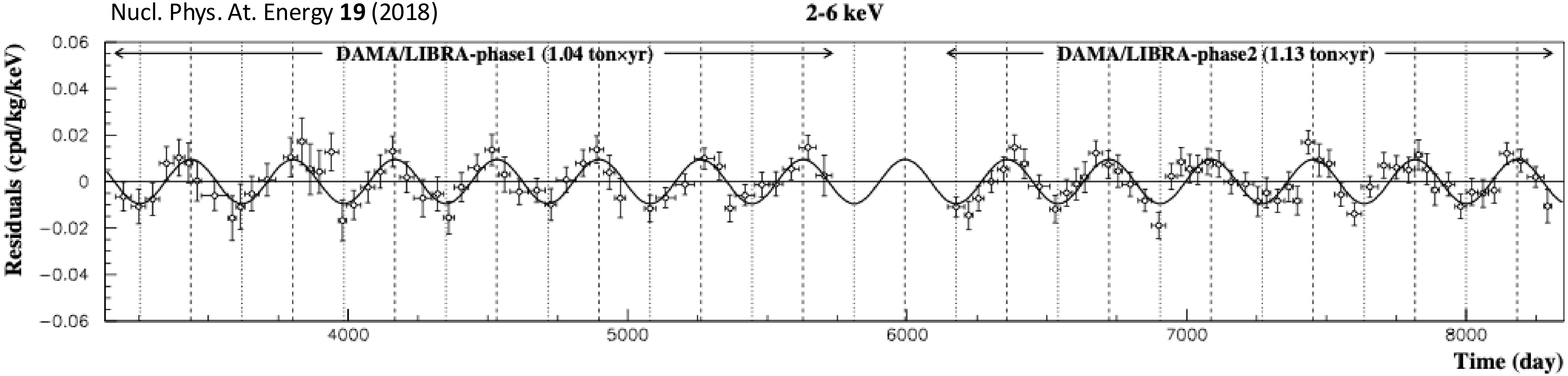
- Galaxy’s dark matter halo has a uniform distribution
- Sun orbits galaxy center
  - Earth orbits Sun
- Fastest "wind" on June 2
  - 152.5 days after January 1
  - Minimum on Dec. 2



K. Freese et.al.
PRD 33 (1986) 3495–3508.

DAMA/LIBRA and NaI(Tl)

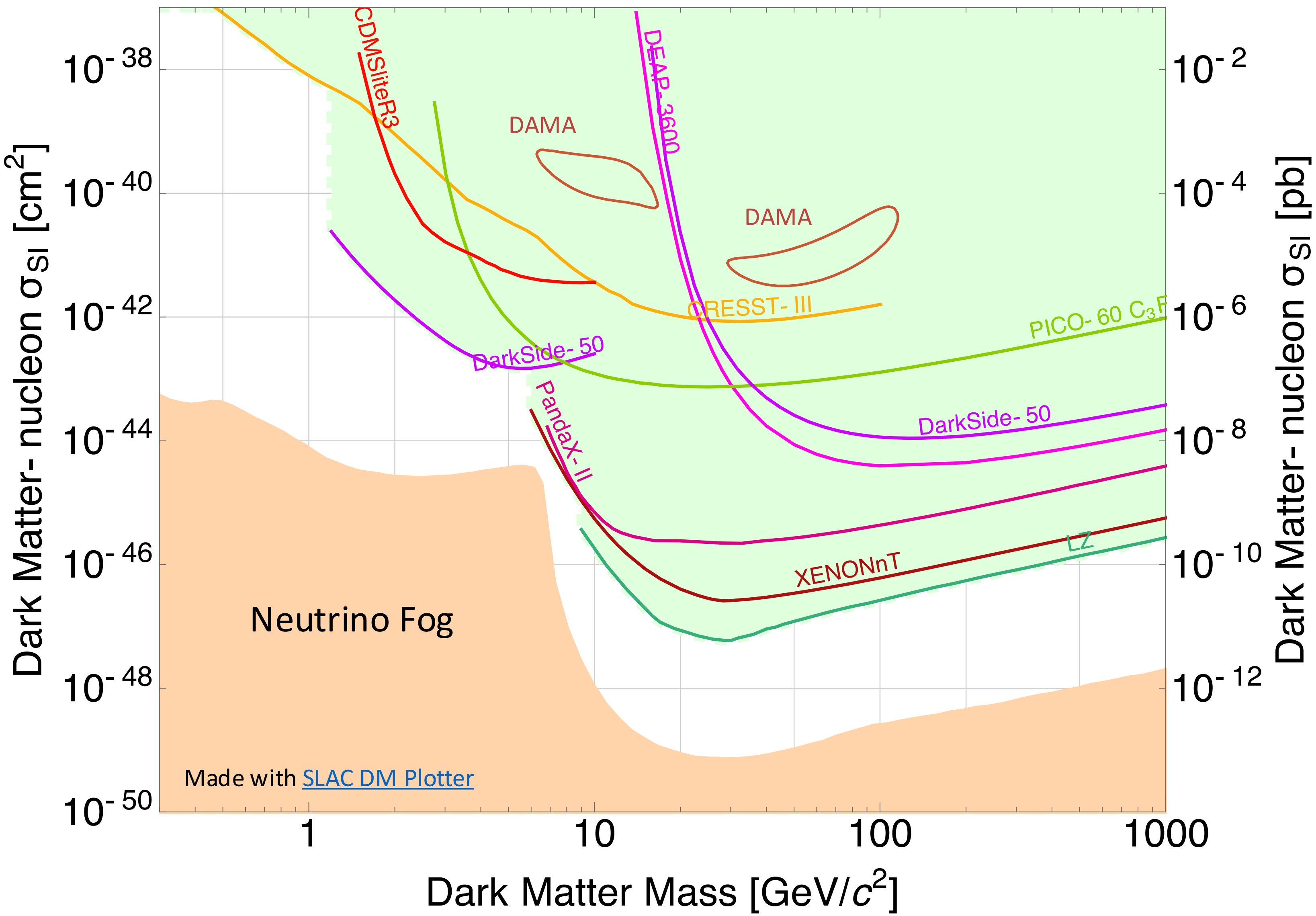
DAMA/LIBRA Collaboration
Nucl. Phys. At. Energy **19** (2018)

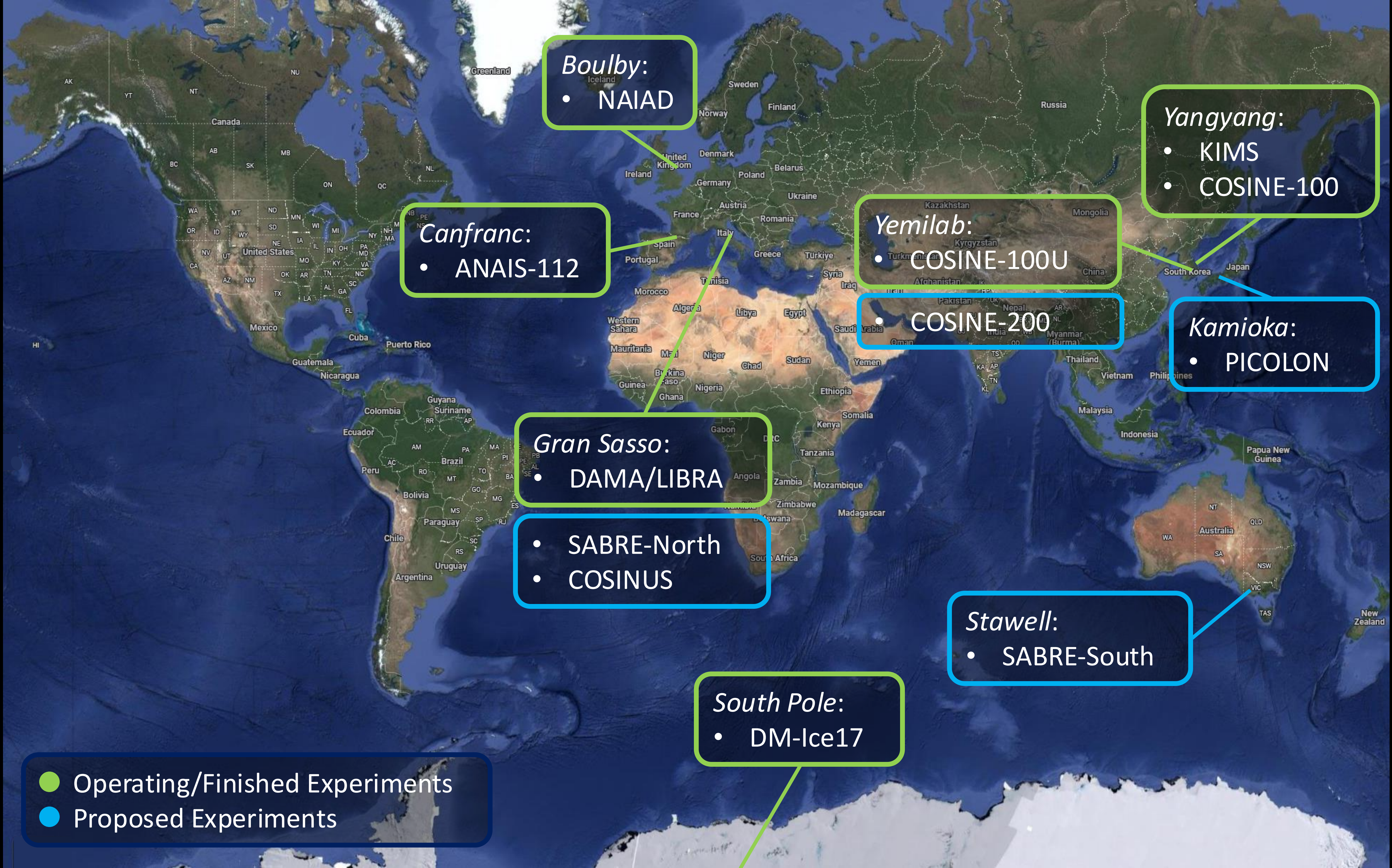


- DAMA/LIBRA: 250 kg of NaI(Tl) operated 2003-2025 at LNGS
  - Purest NaI(Tl) detectors in DM experiment (1 cpd/kg/keV)
- Observe modulation signal over 20 annual cycles
  - 13σ significance, 2.5 ton・yr exposure

Direct Detection Community

- Much of the WIMP phase space has been explored and excluded
- DAMA appears in the excluded region for many experiments
- Note: No other experiment in this plot uses NaI(Tl) target material

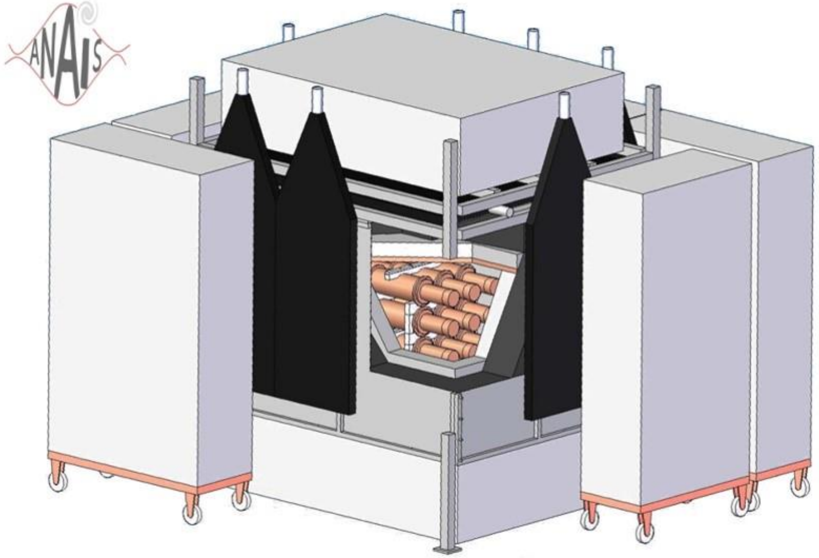




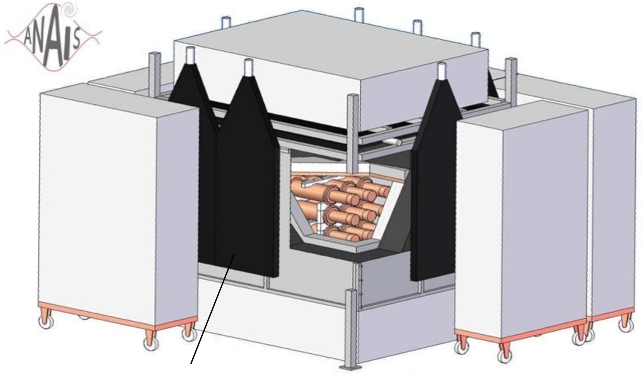
Boulby:
• NAIAD
Canfranc:
• ANAIS-112
Gran Sasso:
• DAMA/LIBRA
• SABRE-North
• COSINUS
Yemilab:
• COSINE-100U
• COSINE-200
Yangyang:
• KIMS
• COSINE-100
Kamioka:
• PICOLON
Stawell:
• SABRE-South
South Pole:
• DM-Ice17
Operating/Finished Experiments
Proposed Experiments

The ANAIS Collaboration

- ANAIS-112 is housed in Hall B of LSC, Canfranc
- 112.5 kg of NaI(Tl) across 9 detectors
- Data taking began Aug. 2017

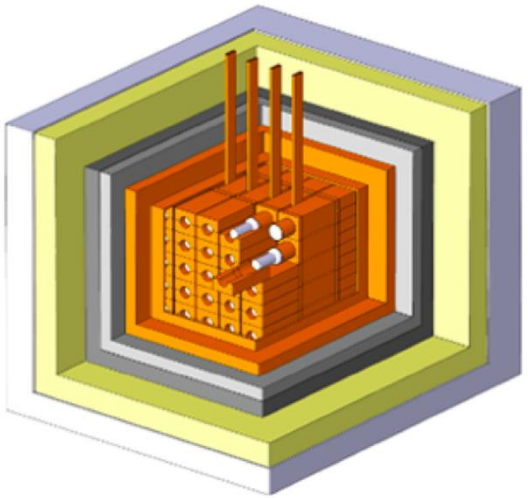


Main Differences with DAMA/LIBRA

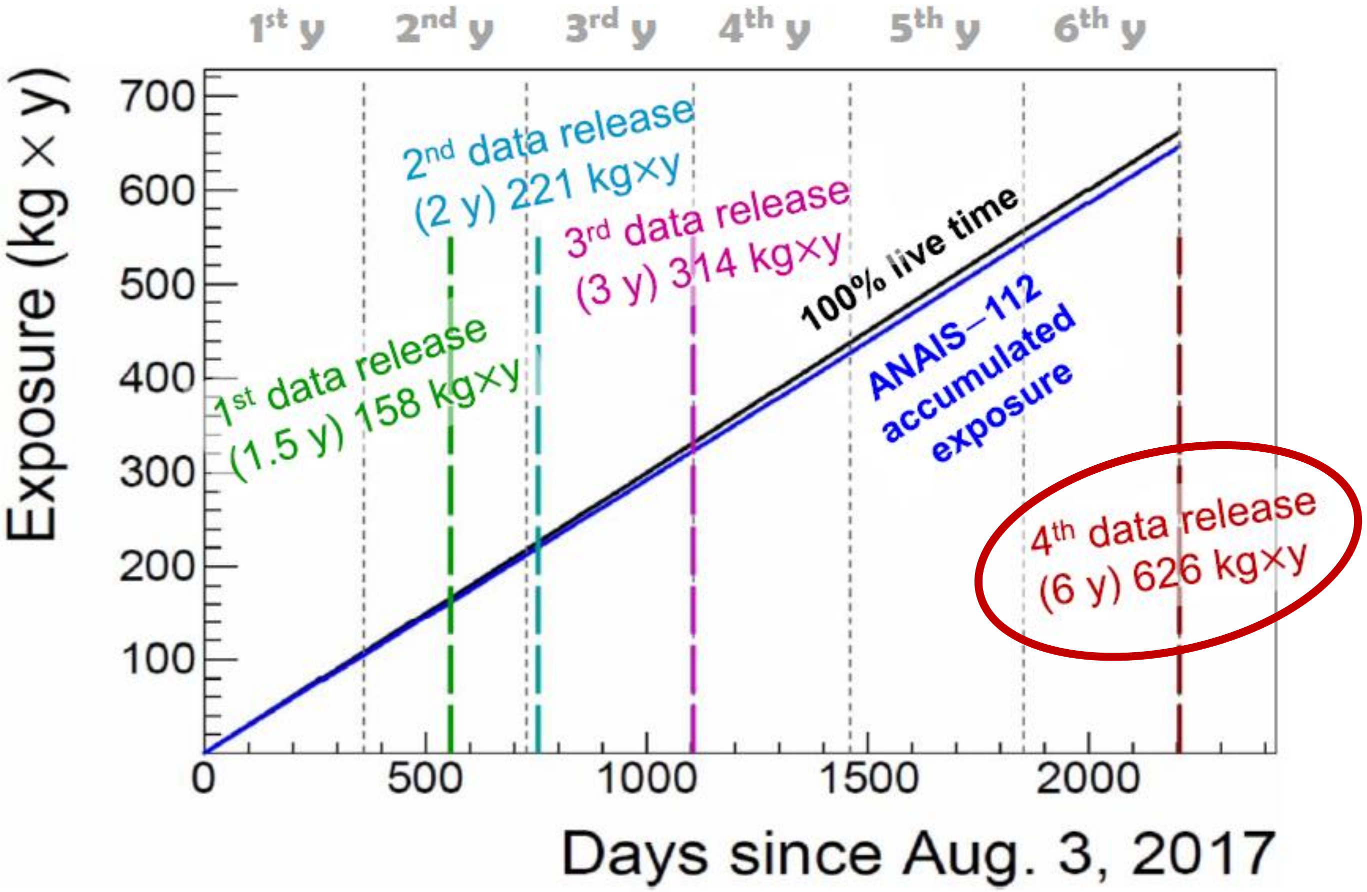


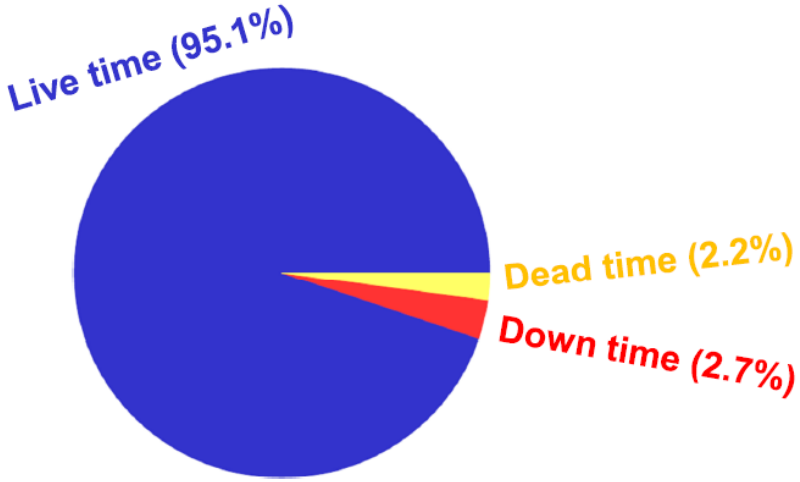
Plastic Scintillator Muon Veto

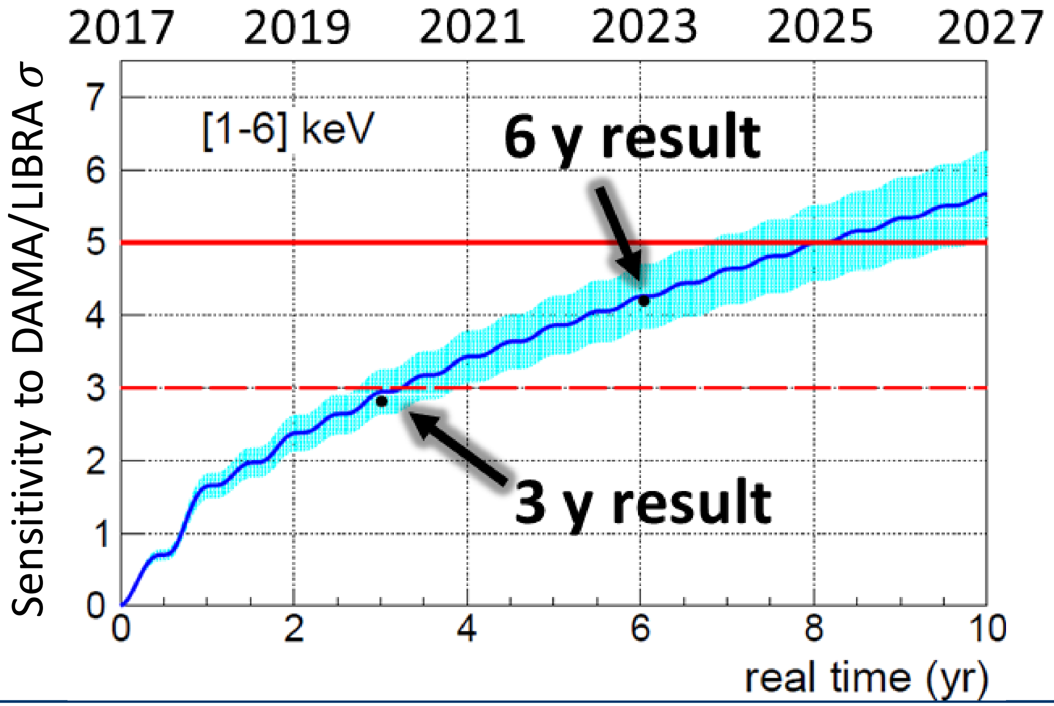
≈ 2 – 3 cpd/kg/keV	Background Rates	≈ 1 cpd/kg/keV
Time Dependent	Background Modeling	Time Independent
Muon Vetos	Veto Systems	No Vetos
Nonlinear QF	Quenching Factors	QF = 0.3



ANAIS-112 Exposure Aug 3, 2017 – Aug 17, 2023







1.5y: Phys. Rev. Lett. 123, 031301 (2019)

2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)

3y: Phys. Rev. D 103, 102005 (2021)

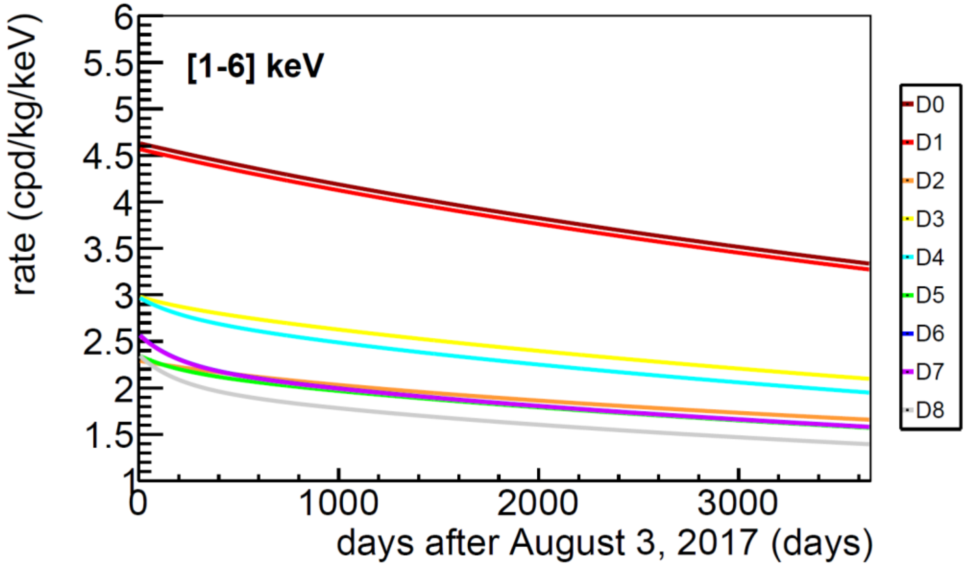
3y + ML: Comm. Phys. 7, 345 (2024)

6y PRL 135, 051001 (2025), arxiv: 2502.01542

Analysis Strategy

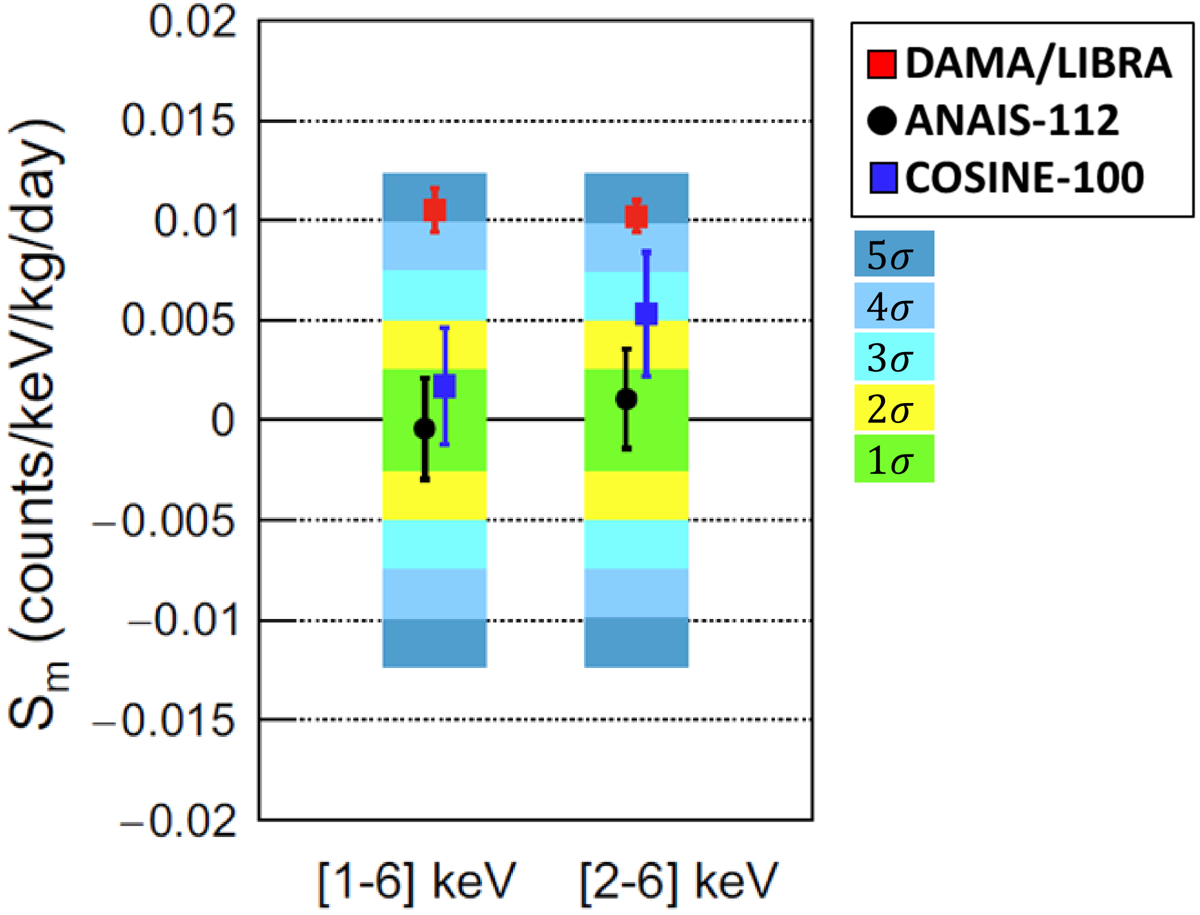
$$\mu_{i,d} = [R_{0,d}(f_d \boxed{\phi^{MC}_{bkg,d}(t_i)} + (1 - f_d)\boxed{\phi_{flat}(t_i)}) + \boxed{S_m \cos(\omega(t_i - t_0))}]M_d \Delta E \Delta t$$

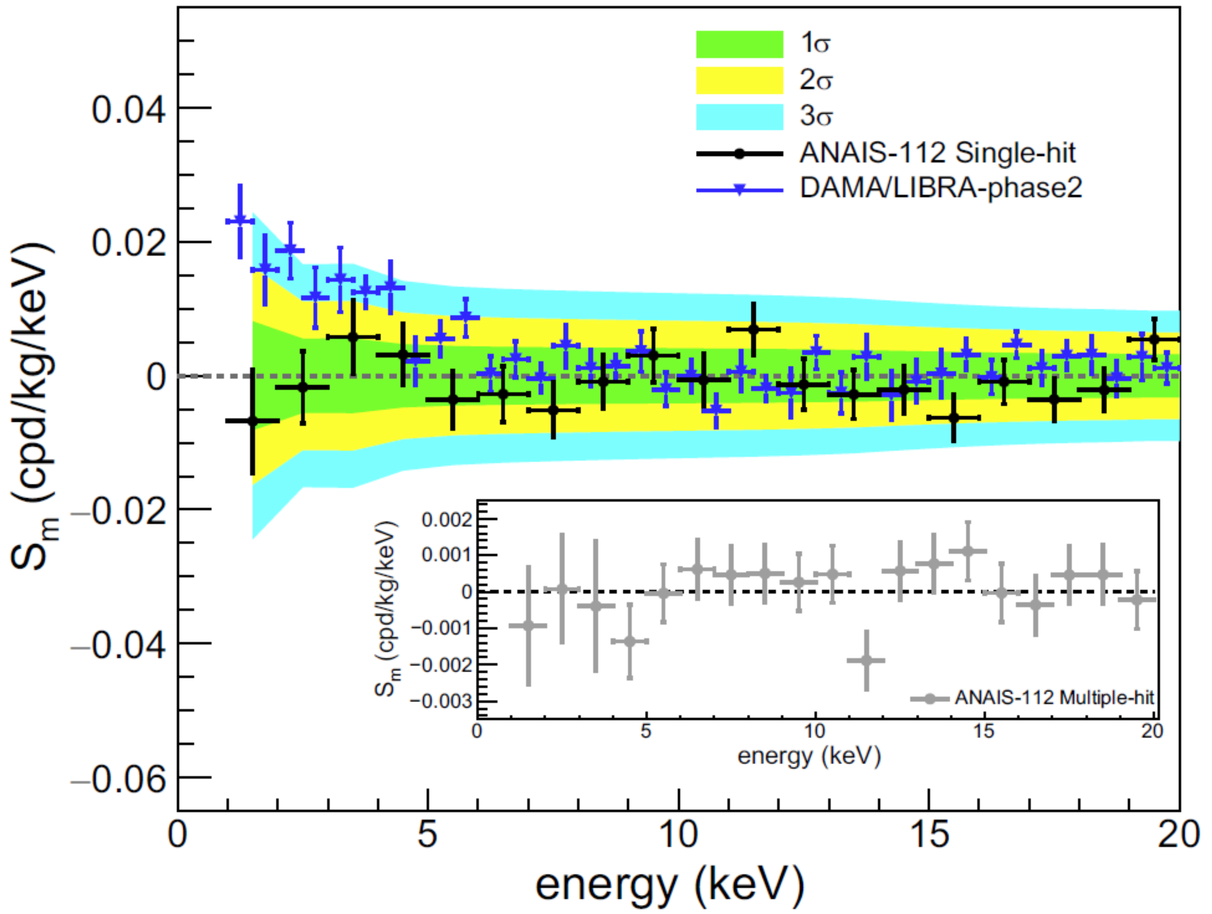
- Fit the 9 detectors simultaneously with 45-day bins
  - Amounts to 19 free parameters
- ANAIS-112 Background Model:
  - Constant noise term
  - Monte Carlo background model for each detector
- Expected Modulation Signal:
  - Fixed period of 1 year with peak phase of June 2nd
  - Use 1—6 and 2—6 keV energy regions to compare with DAMA/LIBRA signal region



Modulation Results (6-years)

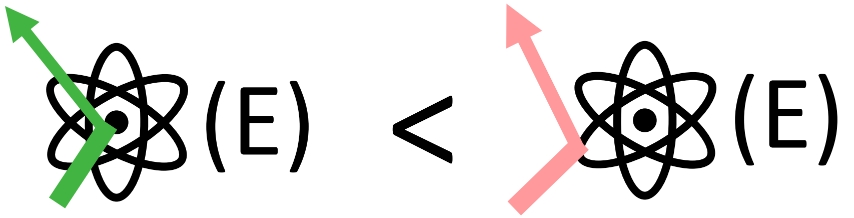
- Consistency with no modulation



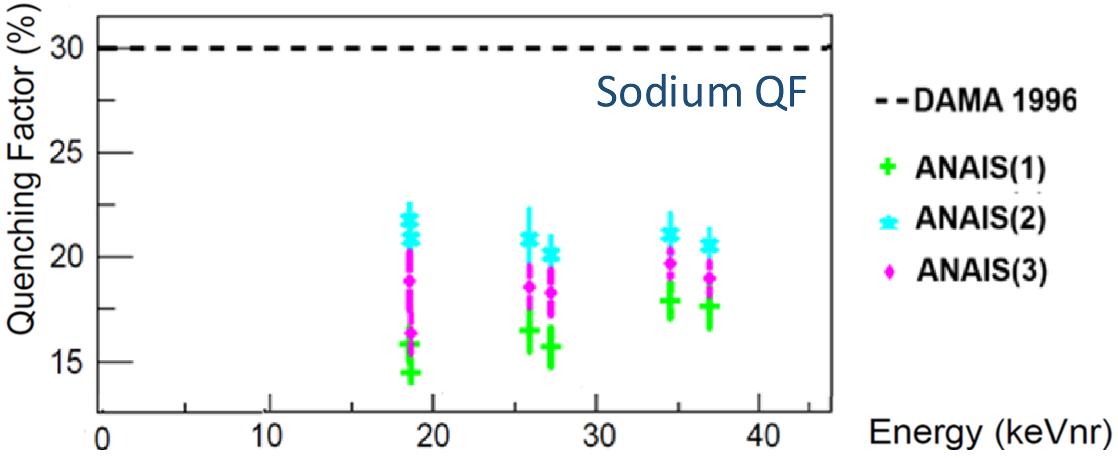


- Rejection of DAMA/LIBRA signal to 4.0σ and 3.5σ in 1—6 and 2—6 keV

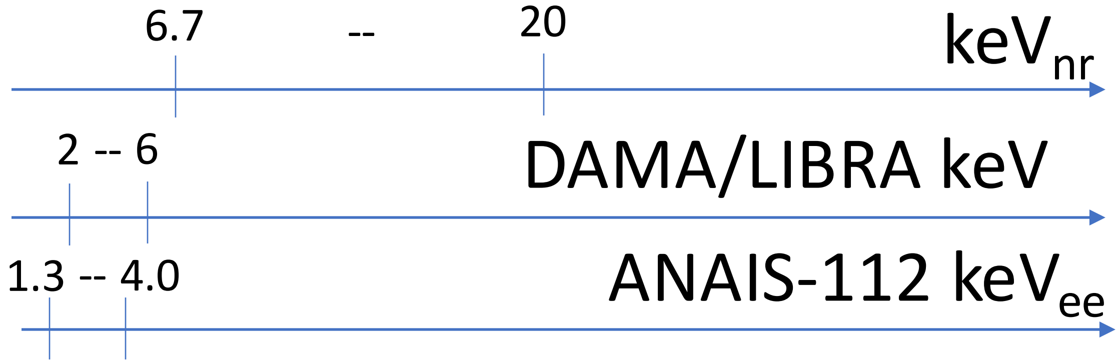
Accounting for Quenching Factors



∴ QF < 1



- QFs change the effective energy region

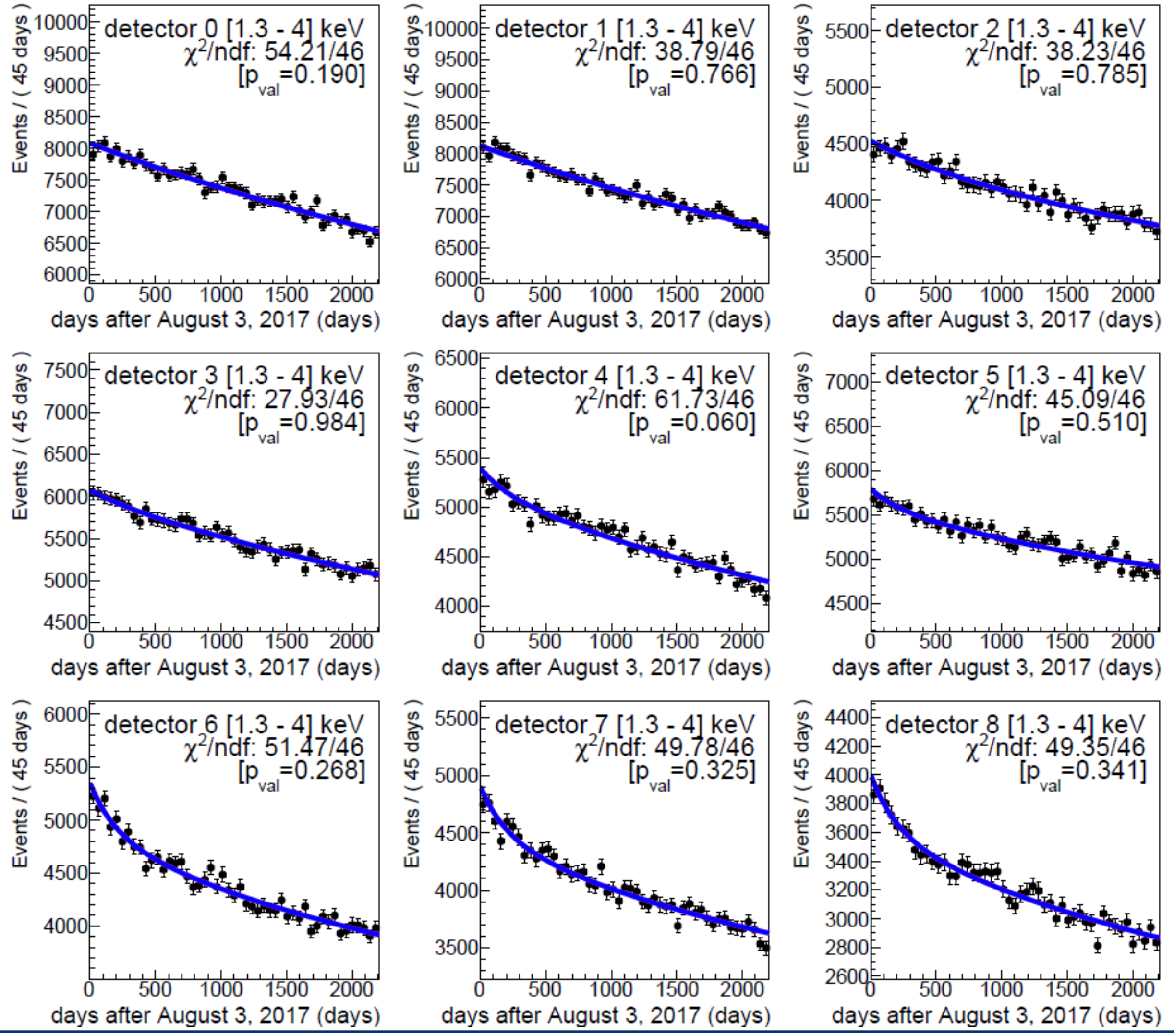


Null hyp χ^2/ndf: 416.51/423 [p_{val}=0.580]

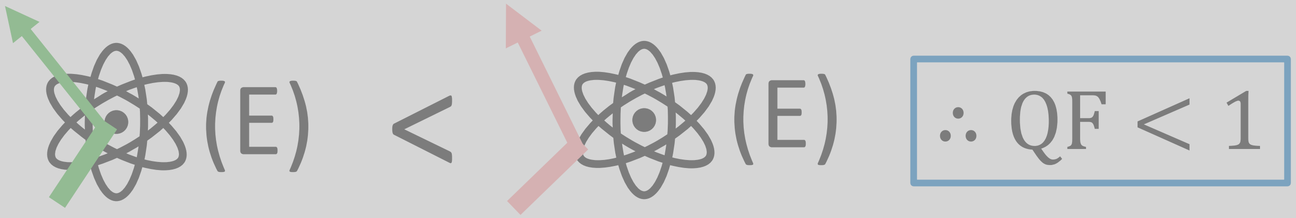
Mod hyp χ^2/ndf: 416.51/422 [p_{val}=0.566]

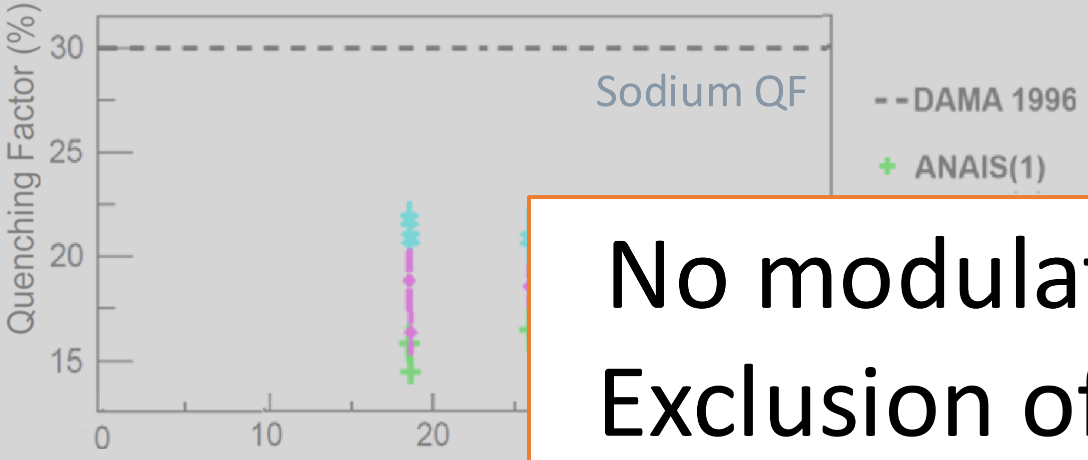
PRL 135, 051001 (**2025**)

S_m = (0.0000 ± 0.0034) (cpd/kg/keV)



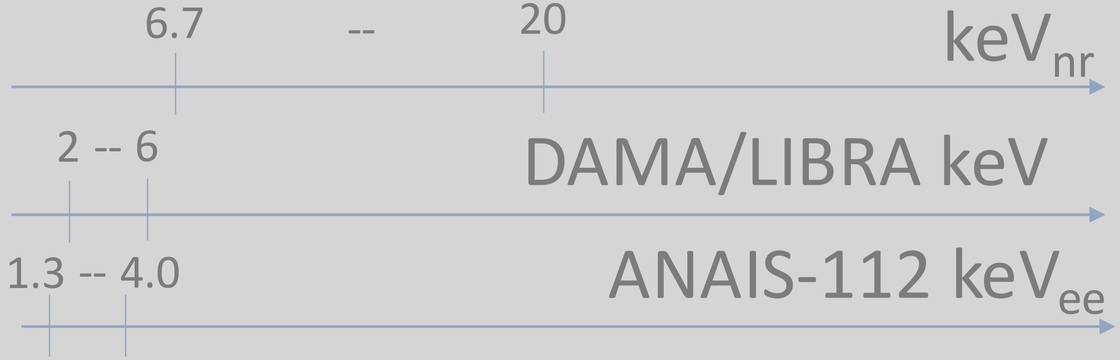
Accounting for Quenching Factors

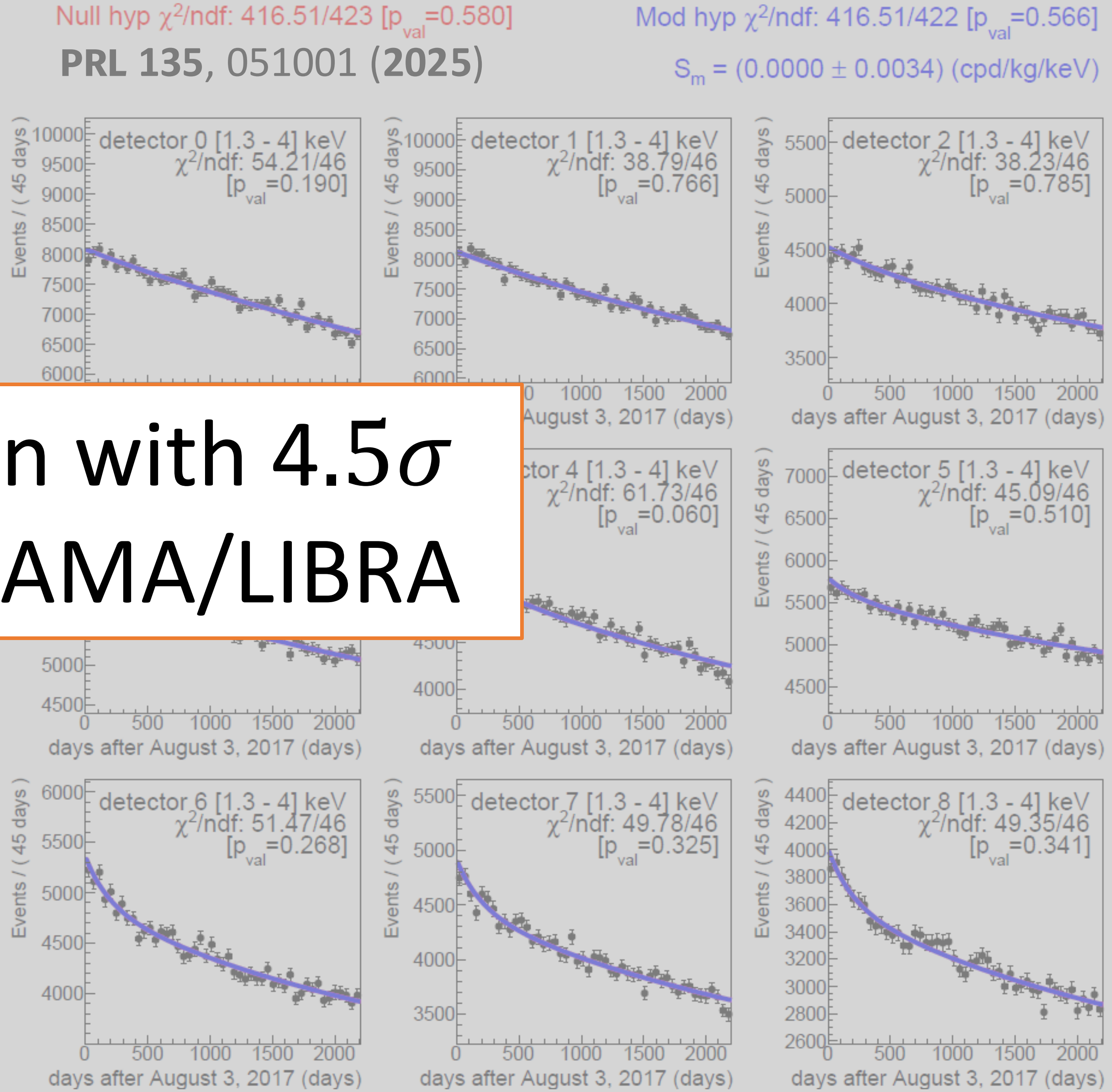




No modulation with 4.5σ
Exclusion of DAMA/LIBRA

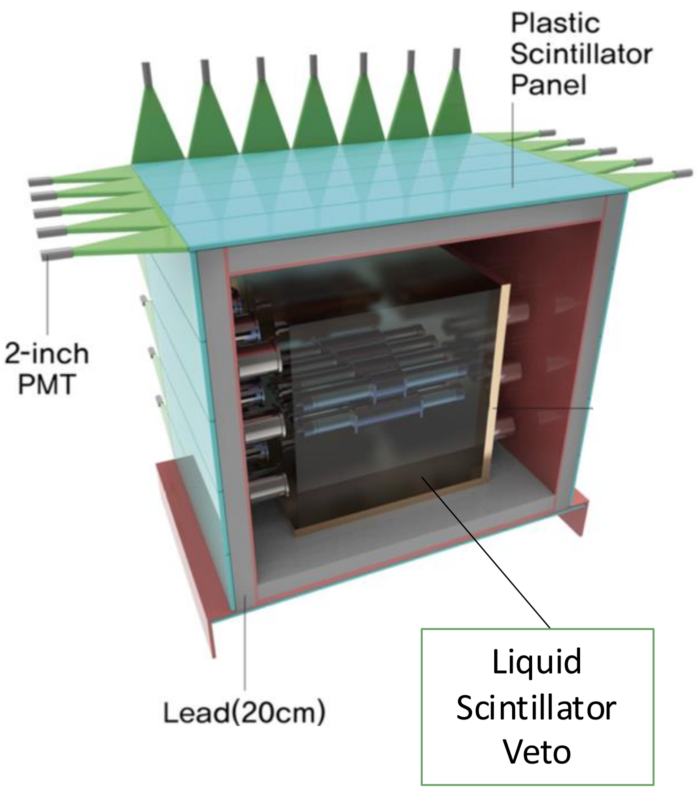
- QFs change the effective energy region





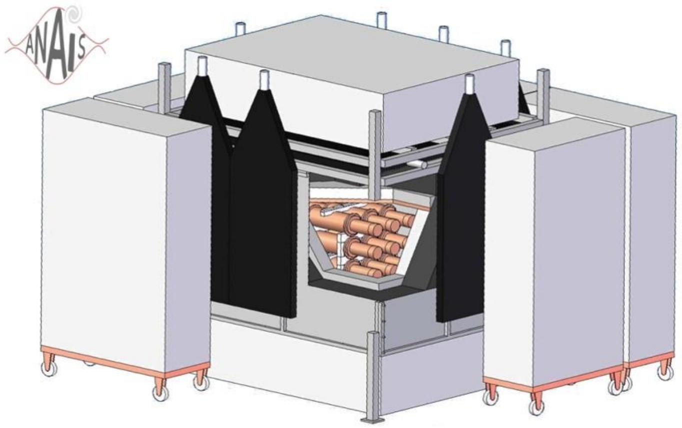
COSINE-100 and ANAIS-112 Collaborations

COSINE-100

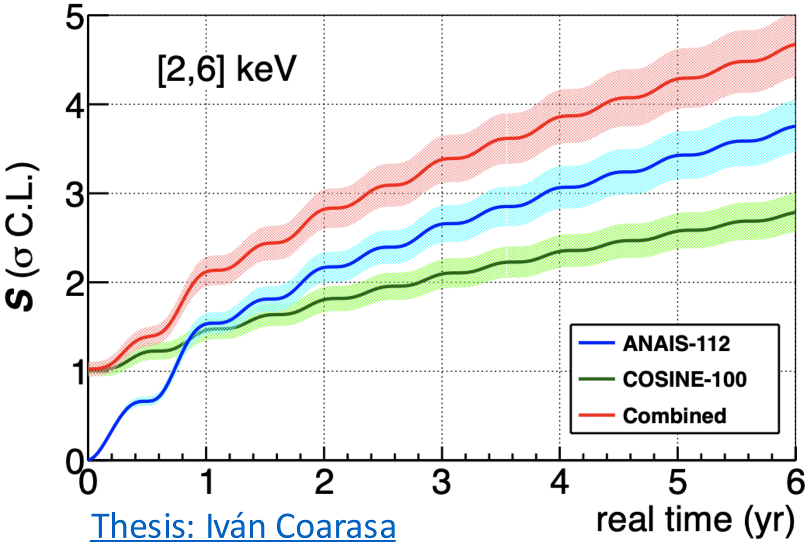


COSINE-100		ANAIS-112
Yangyang, South Korea	Location	Canfranc, Spain
September 2016	Comissioning	August 2017
61.3 kg 5 detectors	Active NaI(Tl) Mass	112.5 kg 9 detectors
~85%, 95% at 1.0, 1.5 keV	Efficiency	~25%, 80% at 1.0, 1.5 keV

ANAIS-112



Sensitivity Projections



Thesis: Iván Coarasa

ORIGINS Excellence Cluster

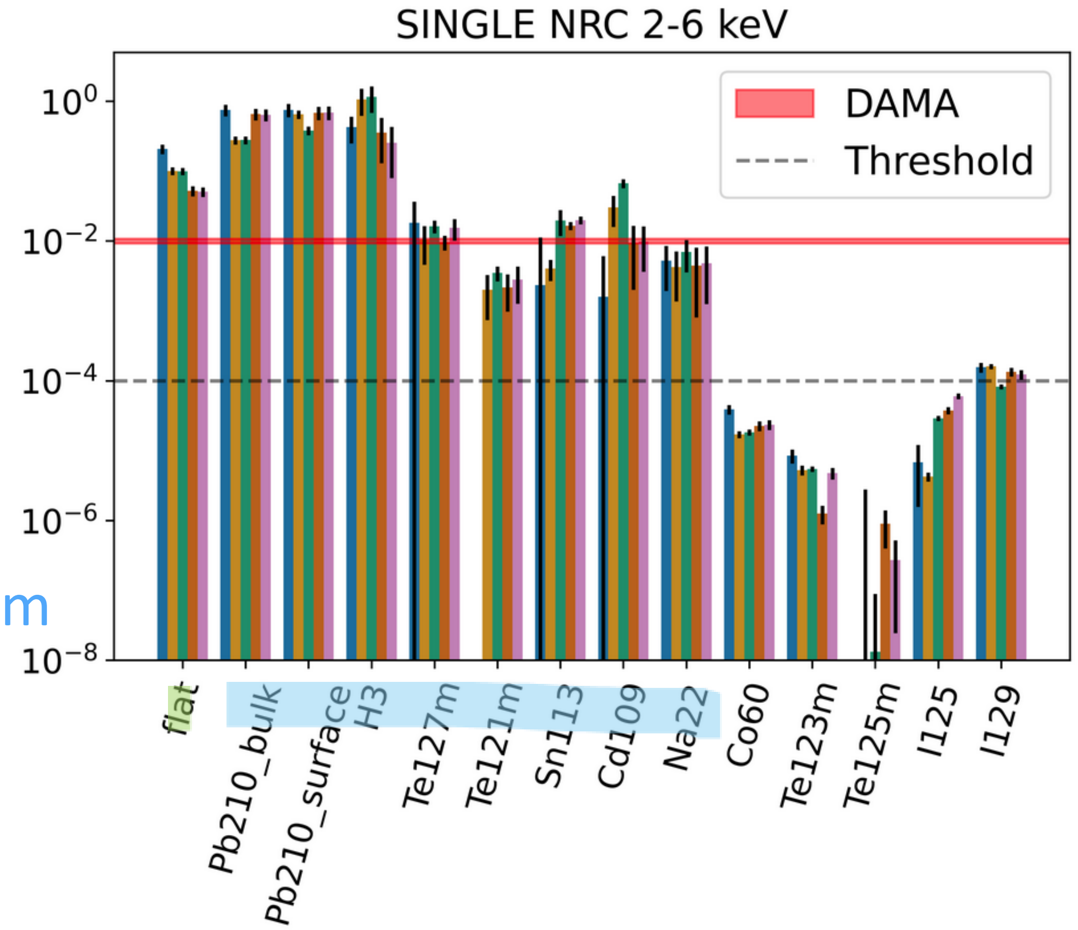
THE DARK MATTER DATA CENTER

*data found at

COSINE-100's Background Model

$$R(t) = \sum_i \left[\boxed{C^i} + \sum_{j=1}^{8} \boxed{A_j^i e^{-\lambda_j t}} \right]$$

- COSINE crystals fit with:
  - Constant term from long-lived backgrounds
  - Sum of exponential decays from short-lived radioisotopes



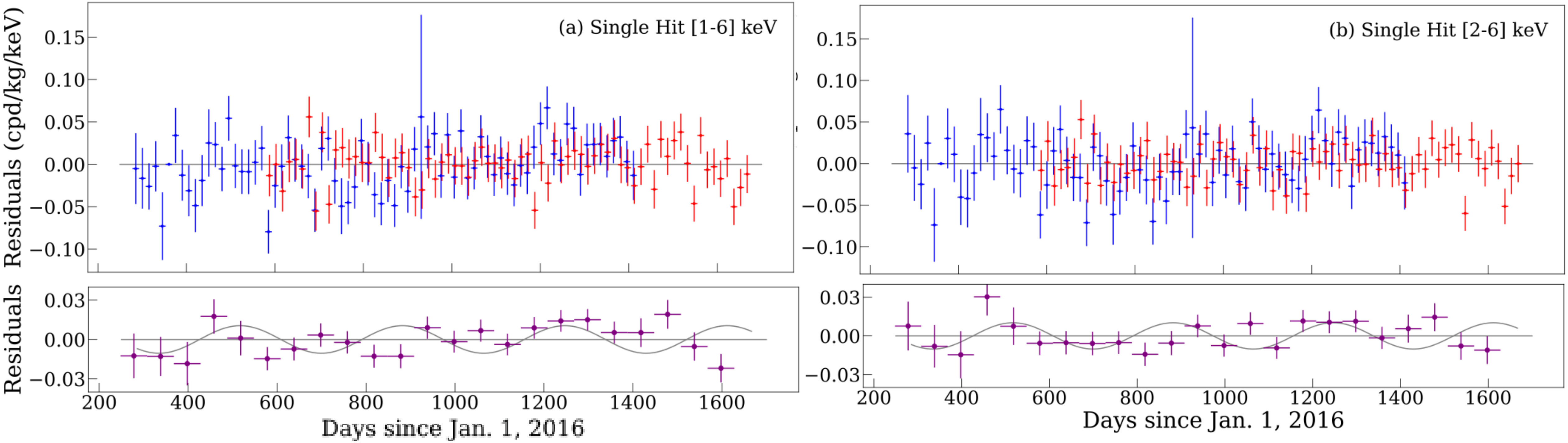
Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days

*surface Pb210 treated separately with effective half-life = 33.8 +/- 8 years from continuous Rn-222 contamination

COSINE-100 Background 2021

Combine Data and χ^2 Fit

- Proof of concept with 3-year datasets from both experiments

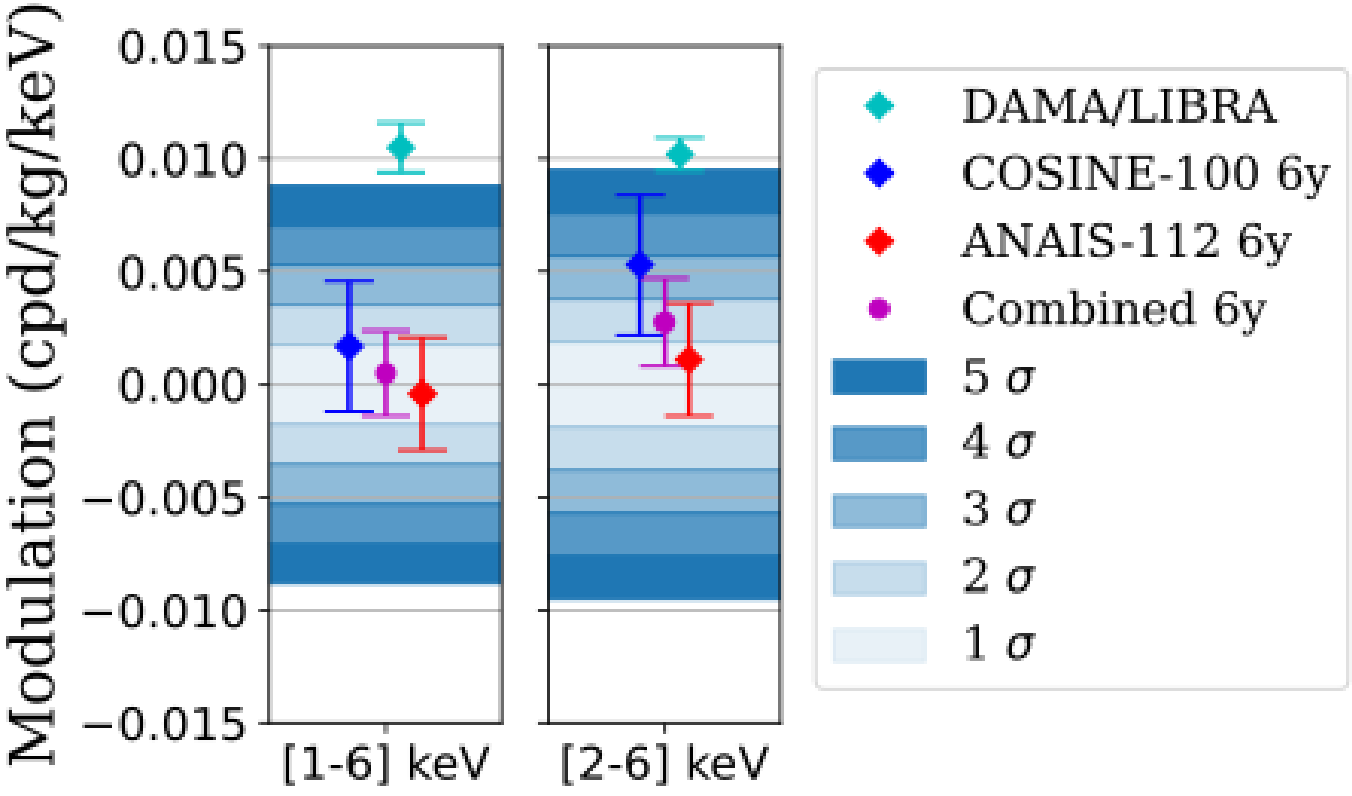


<u>Perform a modulation fit with</u>:
-Least-Squares Method with χ^2 Statistics
-MCMC Method with Bayesian Statistics

N. Carlin et.al **PRL** 2025
https://doi.org/10.1103/9j7w-qp1c

Plot with equal binning and timeline

6 years combined



- Expected results from 6 years datasets
- Exclude DAMA at 4.7σ in 1-6 keV and 3.5σ in 2-6 keV

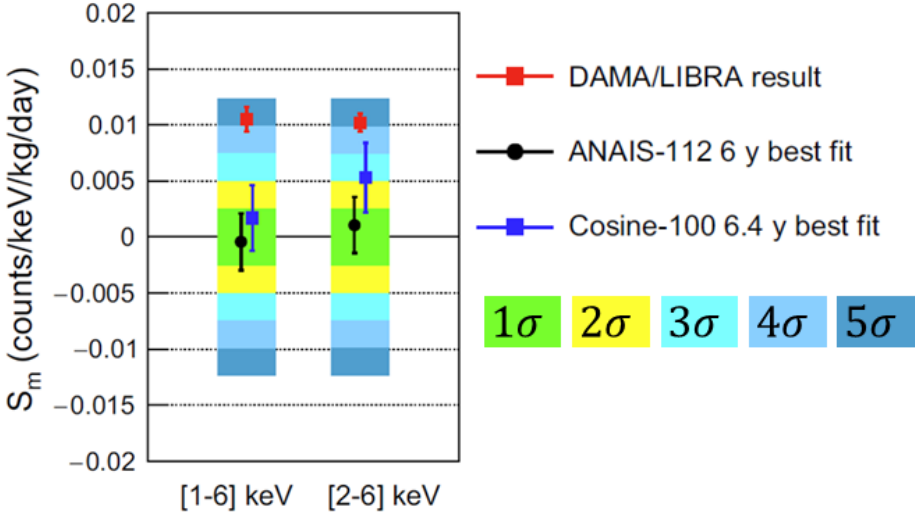
Energy ROI	COSINE 6-year	ANAIS 6-year	Combine Simple
1-6 keV	0.0017 ± 0.0029	-0.0004 ± 0.0025	0.0005 ± 0.0019
2-6 keV	0.0053 ± 0.0031	0.0011 ± 0.0025	0.0027 ± 0.0019

N. Carlin et.al **PRL** 2025
https://doi.org/10.1103/9j7w-qp1c

Conclusions

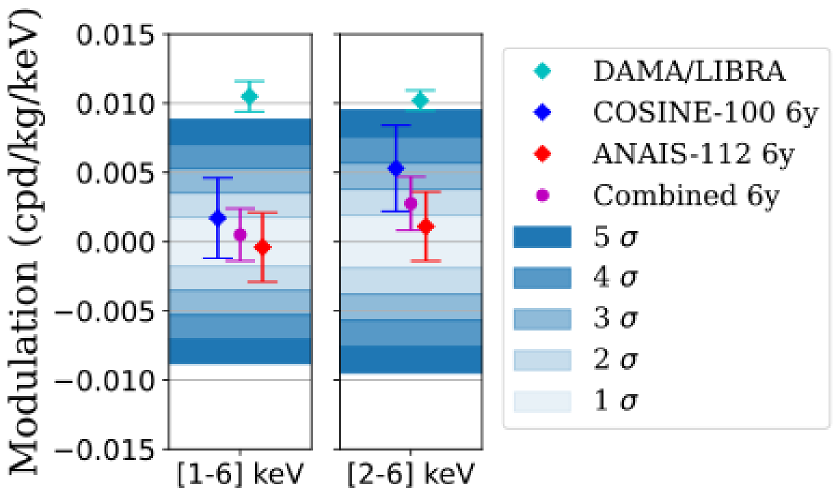
DAMA/LIBRA Excluded

		1—6 keV	2—6 keV	6.7—20 keV_{nr}
ANAIS-112 New Results	Compatible with no modulation	4.0 σ	3.5 σ	4.5 σ
ANAIS+COSINE	Compatible with no modulation	4.7 σ	3.5 σ	5.2 σ



PRL 135, 051001 **(2025)**

- ANAIS-112 strongly challenges dark matter as an explanation to the DAMA/LIBRA modulation signal



PRL 135, 121002 **(2025)**

Thank you for your attention!

ANAIS research team: J. Amaré, J. Apilluelo, S. Bharat, S. Cebrián, D. Cintas, I. Coarasa, E. García, S. Hollick, M. Martínez, Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, J. Puimedón, M. L. Sarsa, C. Seoane

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

GOBIERNO DE ARAGON

Plan de Recuperación, Transformación y Resiliencia

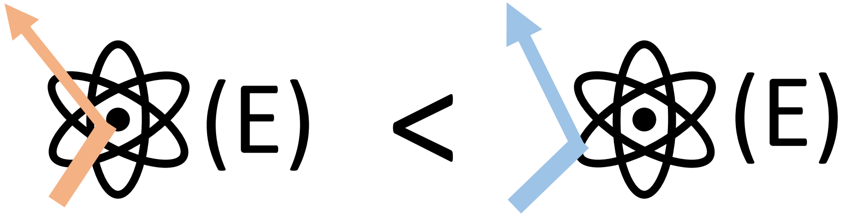
Financiado por la Unión Europea
NextGenerationEU

MultiDark
Multimessenger Approach for Dark Matter Detection

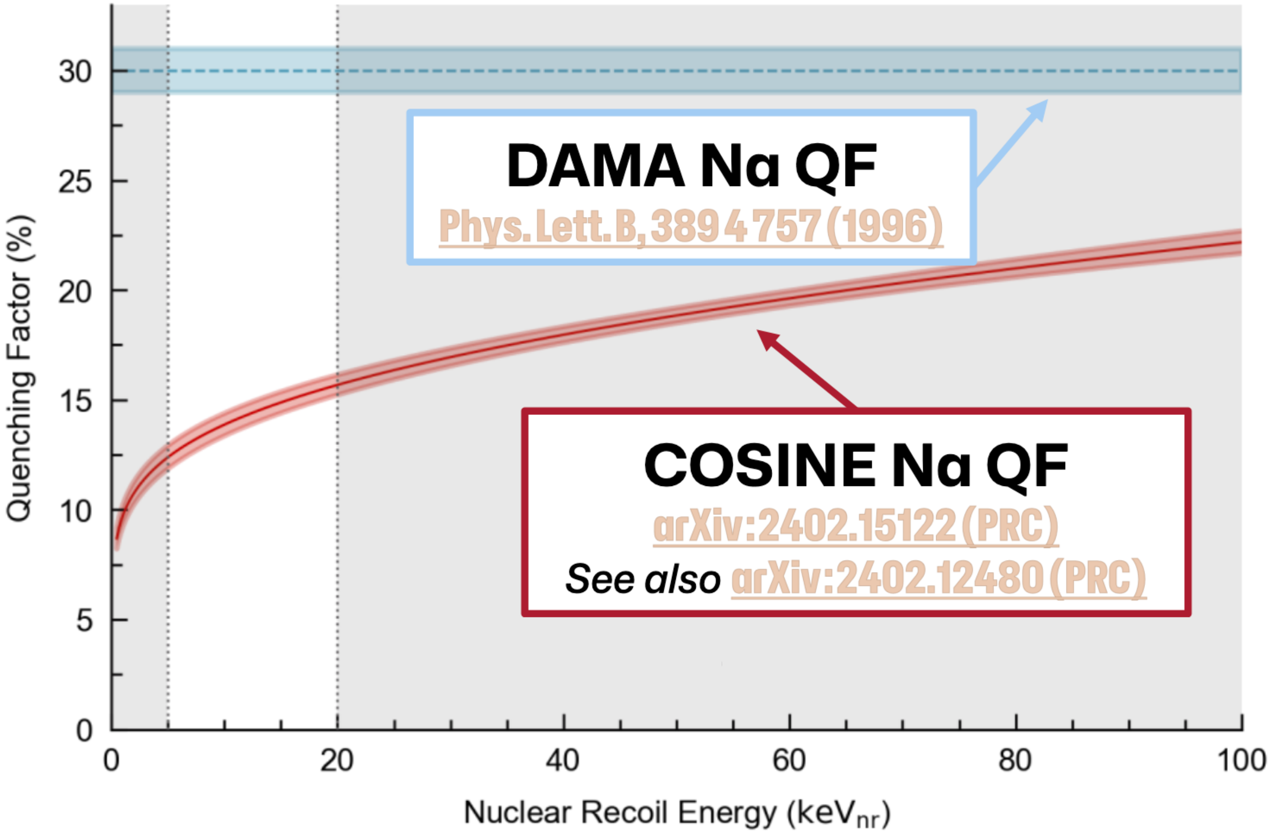
ANAIS experiment operation is presently financially supported by MICIU/AEI/10.13039/501100011033 (Grants No. PID2022-138357NB-C21 and PID2019-104374GB-I00), and Unión Europea NextGenerationEU/PRTR (AstroHEP) and the Gobierno de Aragón. Funding from Grant FPA2017-83133-P, Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, the Gobierno de Aragón and the LSC Consortium made possible the setting-up of the detectors. The technical support from LSC and GIFNA staff as well as from Servicios de Apoyo a la Investigación de la Universidad de Zaragoza (SAIs) is warmly acknowledged.

Backup

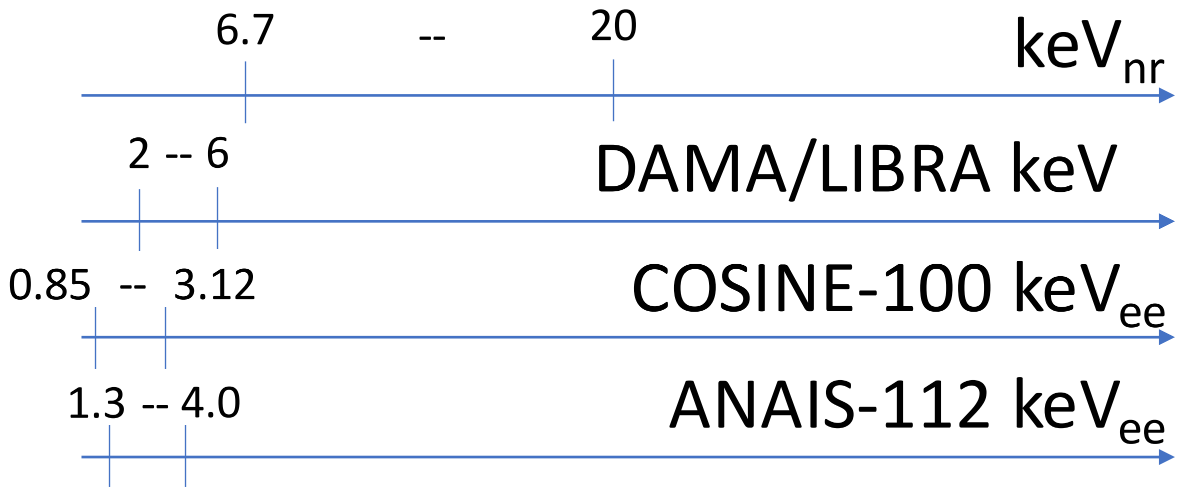
Accounting for Quenching Factors



$\therefore \text{QF} < 1$



- QFs change the effective energy region

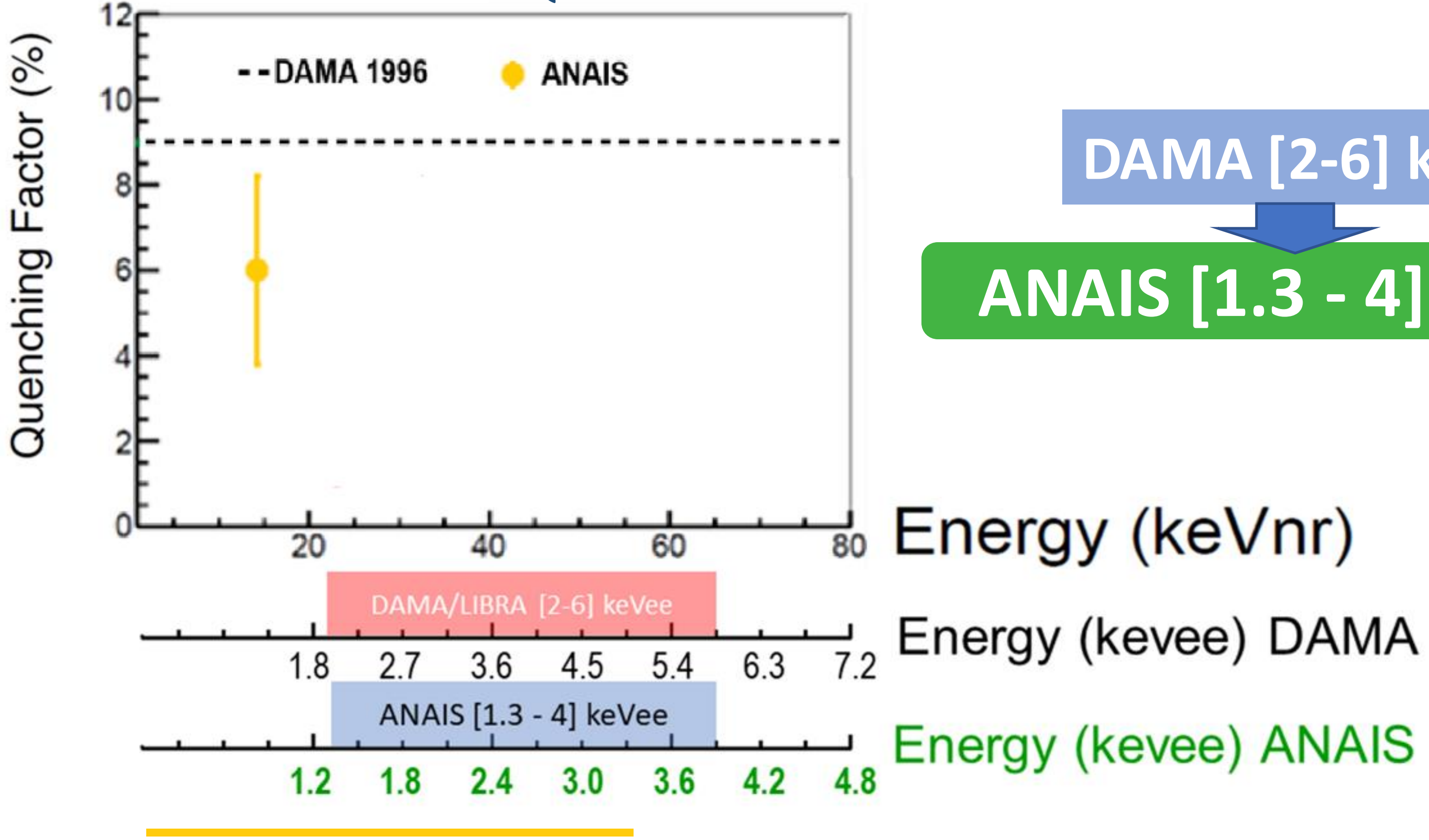


Configuration	6.7–20 keV$_{nr}$
COSINE-100 (2024)	0.0013 ± 0.0027
ANAIS-112 (2025)	0.0000 ± 0.0023
This Study 6-year	0.0005 ± 0.0017
DAMA/LIBRA-phase2	0.0102 ± 0.0008

5.2σ

ANAIS-112 constant QF hypothesis Iodine

Iodine QF



22.2 – 66.7 keVnr

DAMA [2-6] keV

ANAIS [1.3 - 4] keV

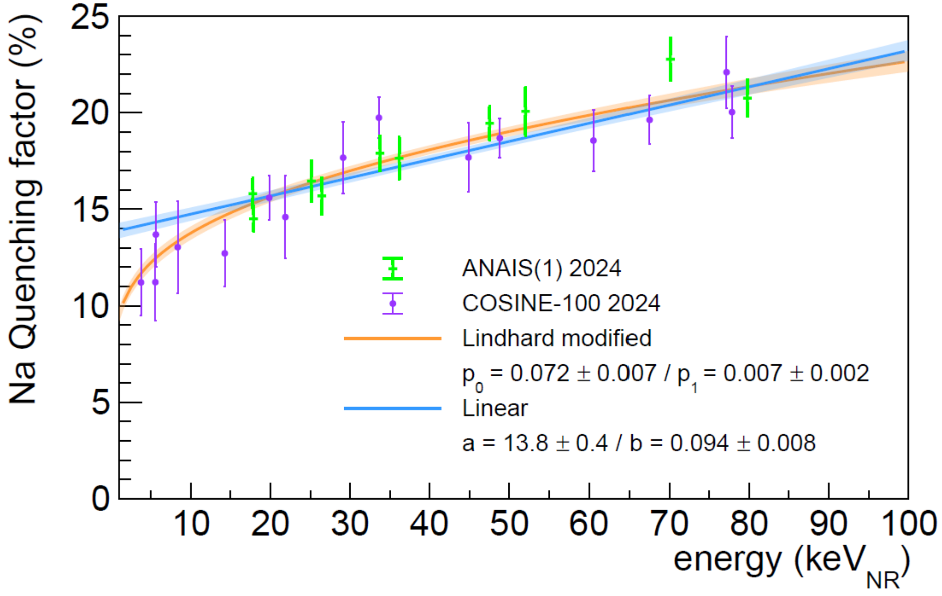
No modulation observed, sensitivity 4.4σ

PRL 135, 051001 (2025)

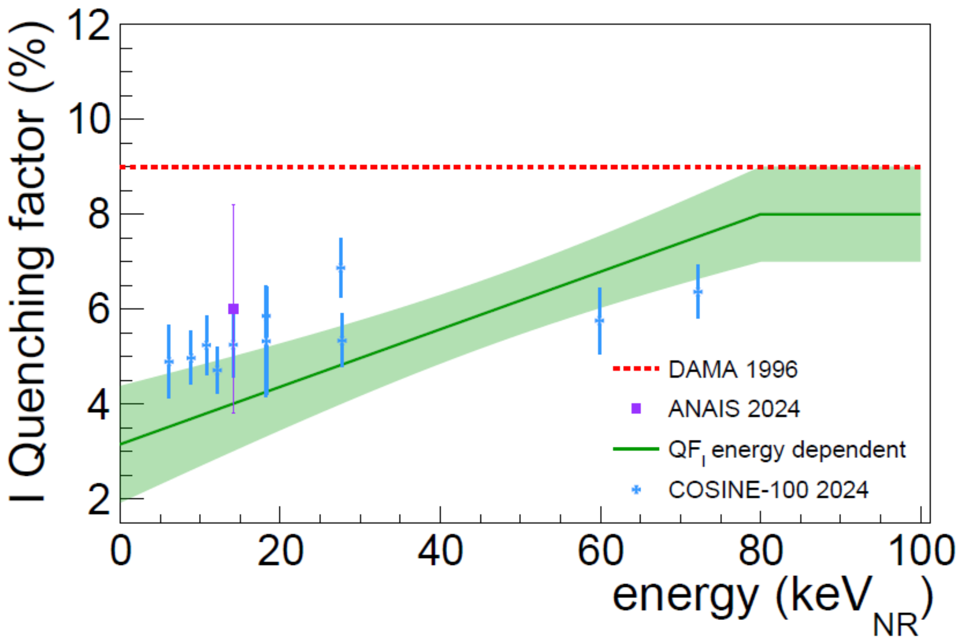
ANAIS-112 energy-variable QF hypothesis

T. Pardo PhD thesis

- Sodium data: (ANAIS(1)+COSINE-100) well fitted to a Modified Lindhard model with two free parameters (p_0, p_1)



- Iodine data: Linear hypothesis

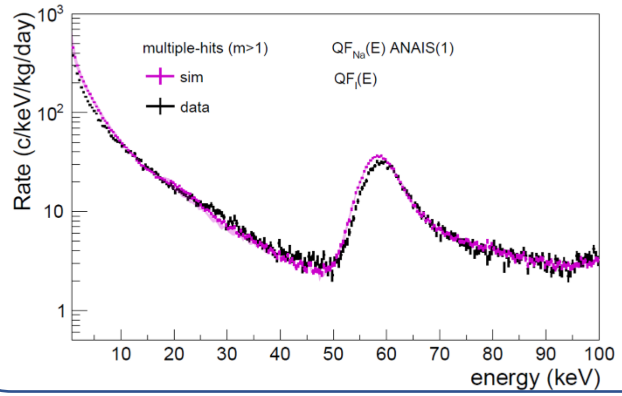


Modified Lindhard model:

$$\mathrm{QF(E_{NR})} = \frac{p_0 g(\epsilon)}{1 + p_0 g(\epsilon)} \qquad g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = p_1 E_{NR}$$

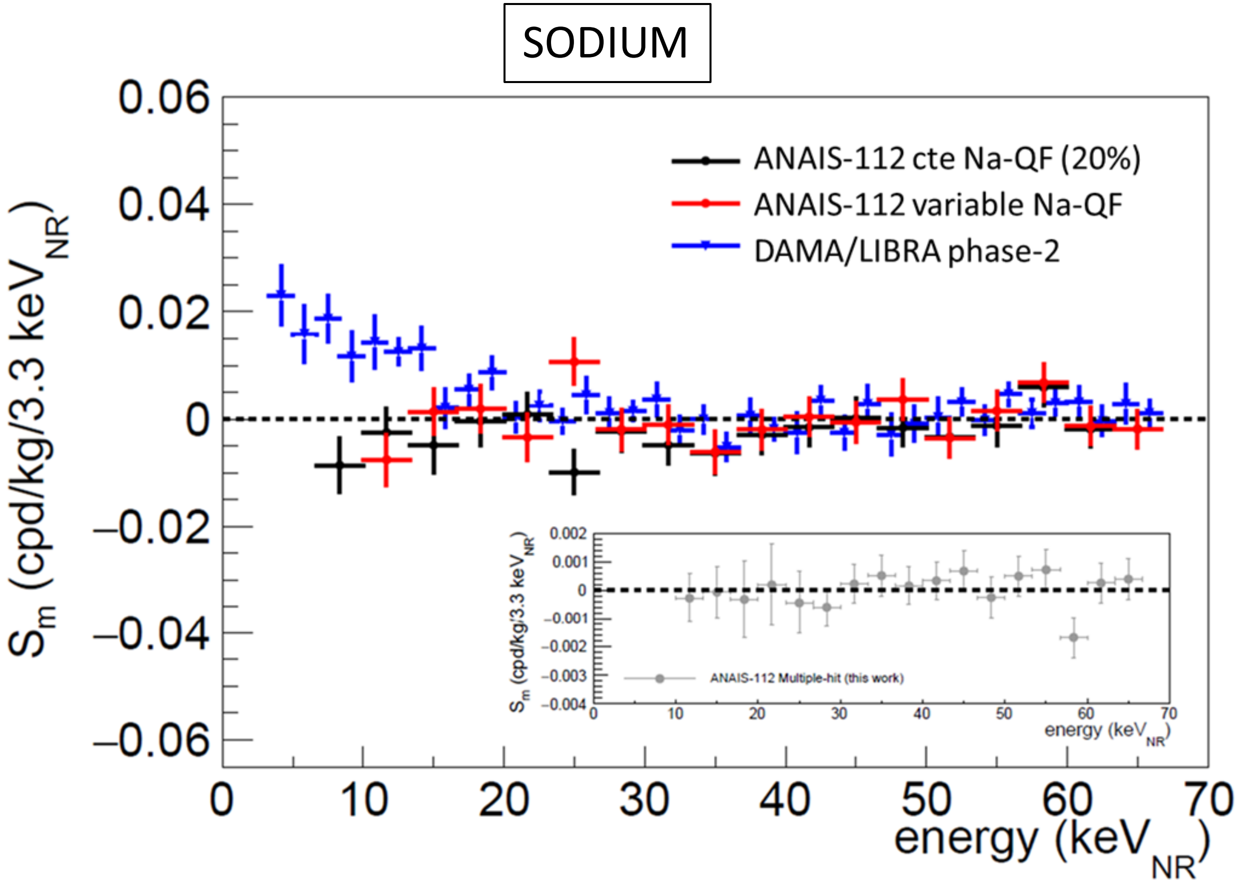
$$p_0 = 0.072 \pm 0.007 \qquad p_1 = 0.007 \pm 0.002$$

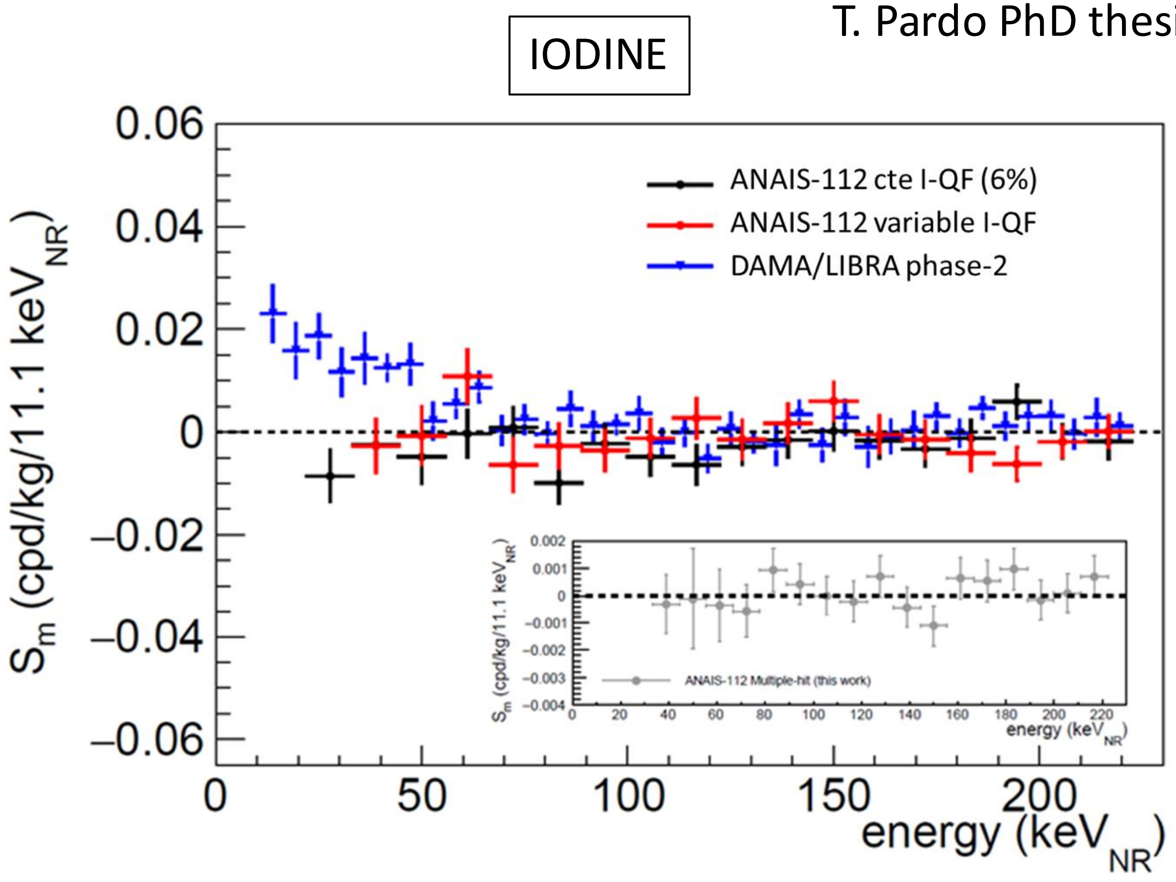


Geant4 simulation of on-site neutron calibration in good agreement with these QF!

ANAIS-112 energy-variable QF hypothesis

T. Pardo PhD thesis





ANAIS-112 variable Na-QF in [10–20] keV$_{NR}$:

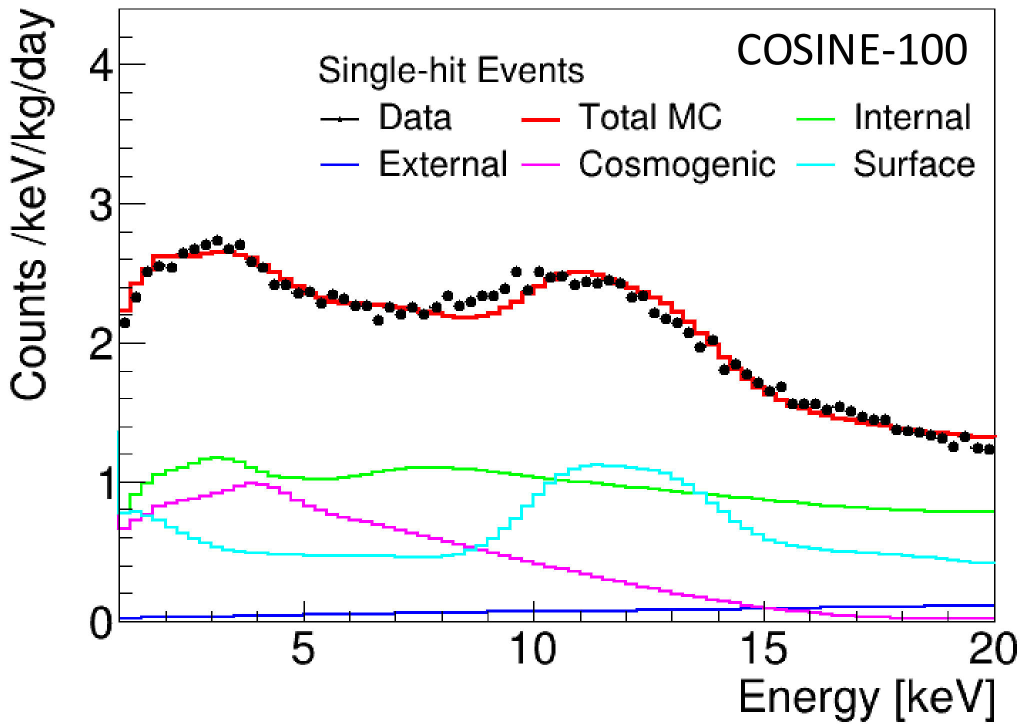
Null hypothesis: χ^2/NDF = 2.95/3 (p-value = 0.4)
Modulation hypothesis: χ^2/NDF = 14.9/3 (p-value = 1.9×10^{-3})

ANAIS-112 variable I-QF in [33.3–66.7] keV$_{NR}$:

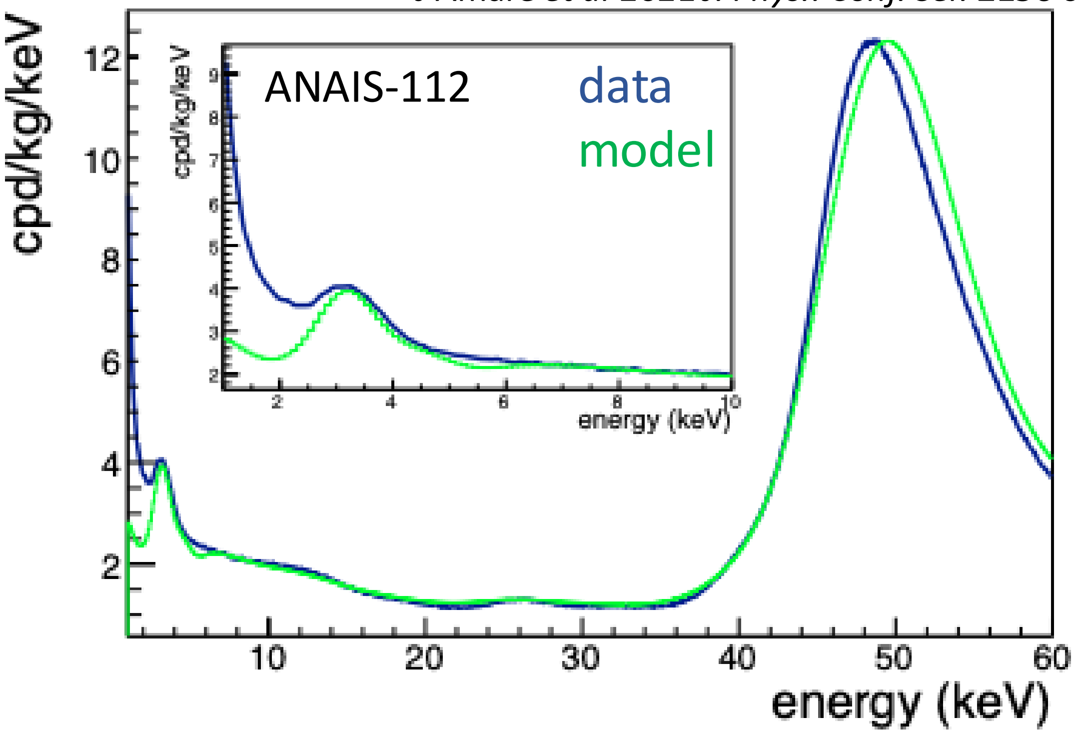
Null hypothesis: χ^2/NDF = 4.82/3 (p-value = 0.18)
Modulation hypothesis: χ^2/NDF = 8.66/3 (p-value = 0.03)

Backgrounds in NaI(Tl) Detectors

Adhikari, G. *et al.* *Eur. Phys. J. C* **81,** 837 (2021).

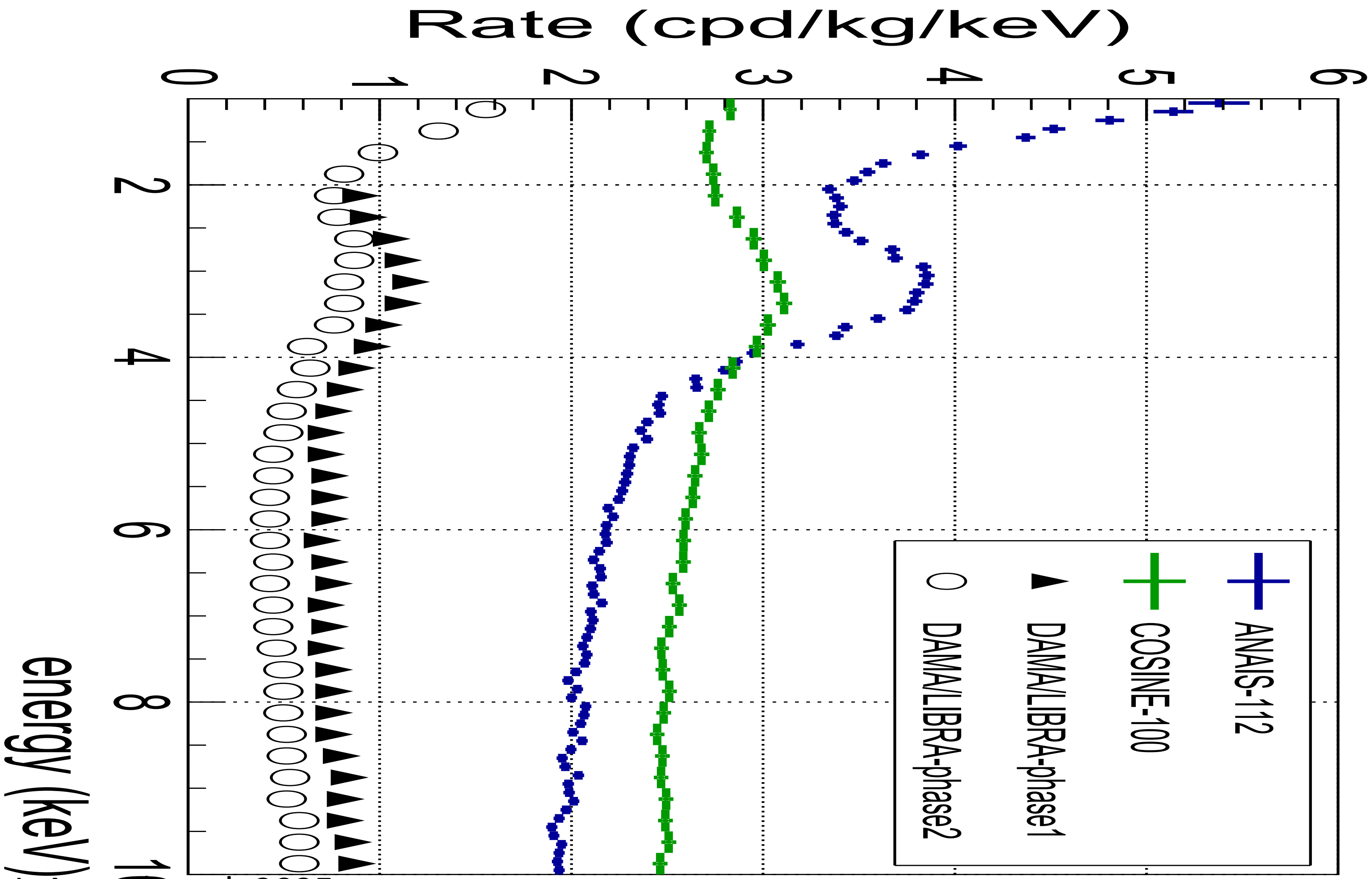


J Amaré *et al* 2021 *J. Phys.: Conf. Ser.* **2156** 012175



- ^{40}K and ^{210}Pb **internal** isotopes dominate the background
- ^{3}H, ^{22}Na, and others are **cosmogenic** radioisotopes activated by cosmic-rays
- ^{238}U, ^{232}Th, ^{40}K, and ^{210}Pb in **external** "dead" material also contaminate
- **Surface** ^{210}Pb is observed and replenished in COSINE-100 exposure to ^{222}Rn

Background Comparison



J. Amaré et al, 2025.
arxiv:2502.01542

- DAMA/LIBRA's background is reportedly lower than both COSINE-100 and ANAIS-112

Study of systematics with MC simulations

20000 MC pseudo-experiments with ANAIS parameters (background evolution and measured efficiencies), with and without adding the modulation observed by DAMA/LIBRA

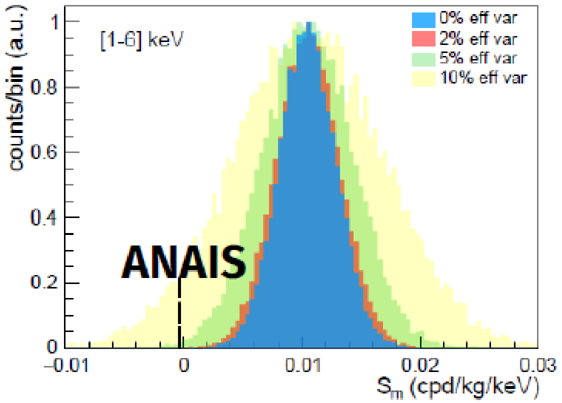
Fit bias study

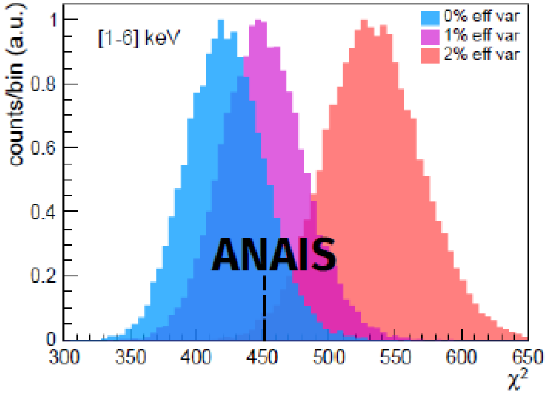
No bias is observed and similar standard deviations than found in the ANAIS–112 6-year results

Efficiency stability study

→ Including variations in efficiency around mean value

- We recover in all cases the right modulation amplitude enlarging the standard deviation
- The χ^2 distribution point at efficiency fluctuations **well below 2%**, which do not compromise the significance of our result





→ Introducing a linear dependence with time (decreasing or increasing)

→ Introducing an annual modulation or antimodulation

At the level of the variations observed in our efficiencies

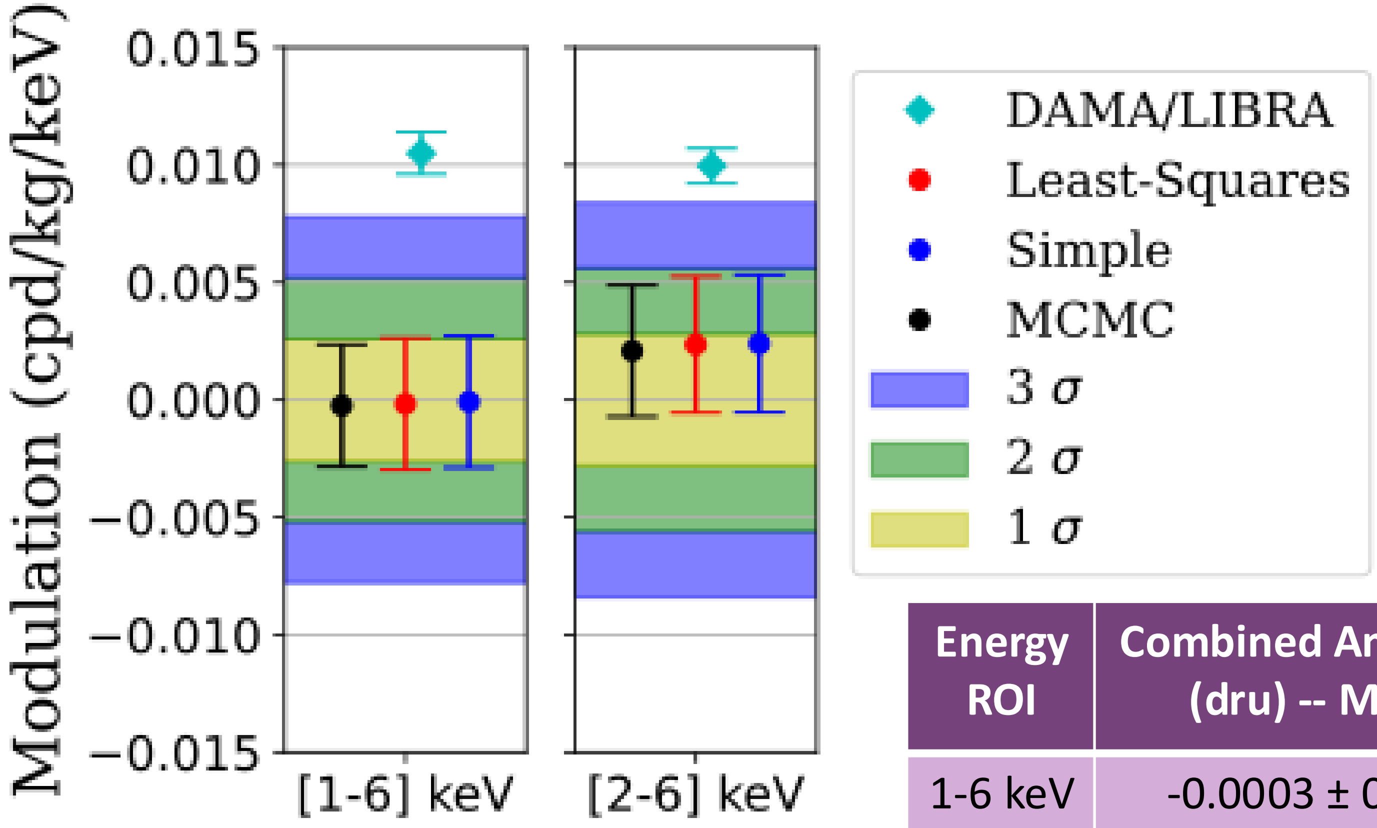
NEGLIGIBLE

PRL 135, 051001 (2025)

Results

- Since no systematics found for the two experiments, can combine

- Frequentist and Bayesian methods are compatible!

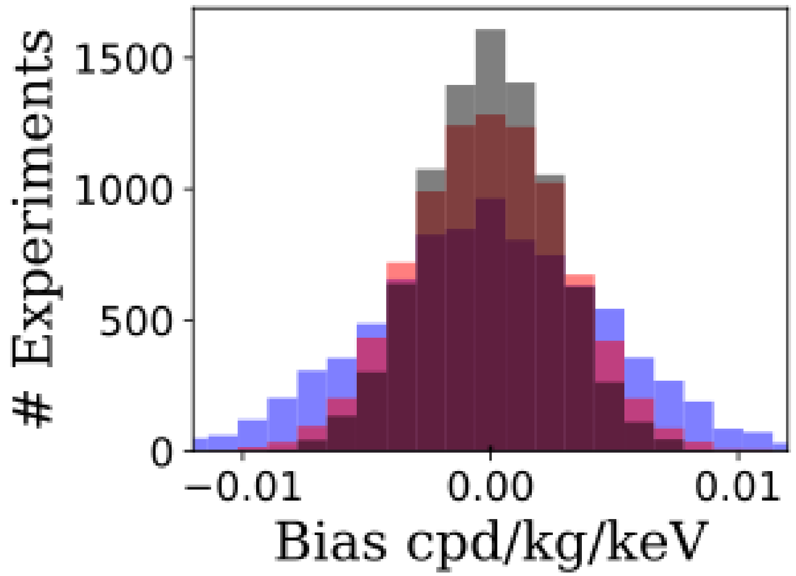


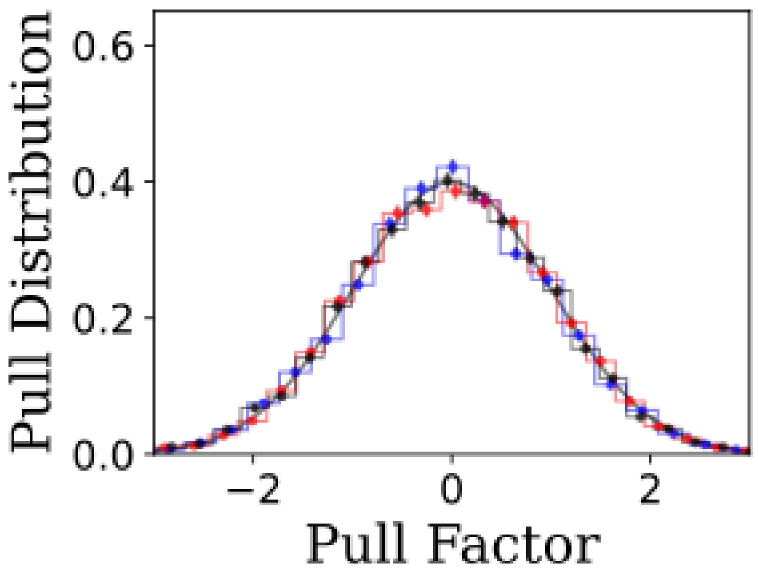
Energy ROI	Combined Amplitude (dru) -- MCMC	DAMA Exclusion
1-6 keV	-0.0003 ± 0.0028	3.6σ
2-6 keV	0.0023 ± 0.0029	2.6σ

N. Carlin et.al **PRL** 2025
https://doi.org/10.1103/9j7w-qp1c

Pseudo Study

- Ensembles of 9 modulations are generated from bkgd models + Poissonian
  - 0.0 ± 0.0025 ± 0.005 ± 0.0075 ± 0.0105





Model	Bias [0.0 dru] 10^{-4}	Bias [0.0105 dru] 10^{-4}	Standard Deviation 10^{-4}
COSINE SETZ Bkgd	0.2 +/- 1	-0.3 +/- 0.9	31
ANAIS Single Exp.	0.3 +/- 0.6	5 +/- 0.6	18
Combined Residuals	1 +/- 0.5	-4 +/- 0.5	15

- Bias = Fit – Injected Signal
- Bias Error = Standard Deviation / sqrt(# of entries)

~1000 Experiments

Alpha Spectra Crystals

- ANAIS

Detector	Powder Name	Date of arrival at Canfranc
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

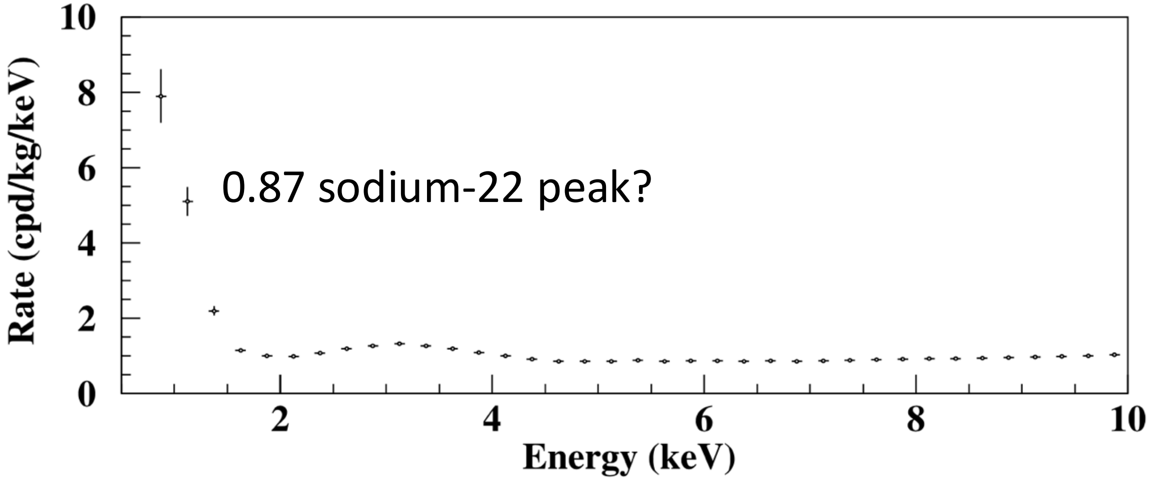
- COSINE

Crystal	Mass (kg)	Size (diameter×length) (inches)	Powder Type	Exposure Time (years)	Radioactivity cooling time at Y2L (years)
Crystal-1	8.3	5.0×7.0	AS-B	2.17	3
Crystal-2	9.2	4.2×11.0	AS-C	0.92	2.75
Crystal-3	9.2	4.2×11.0	AS-WSII	>0.92	1.2
Crystal-4	18.0	5.0×15.3	AS-WSII	1.83	0.5
Crystal-6	12.5	4.8×11.8	AS-WSIII	0.5	0.6
Crystal-7	12.5	4.8×11.8	AS-WSIII	0.5	0.6

Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days

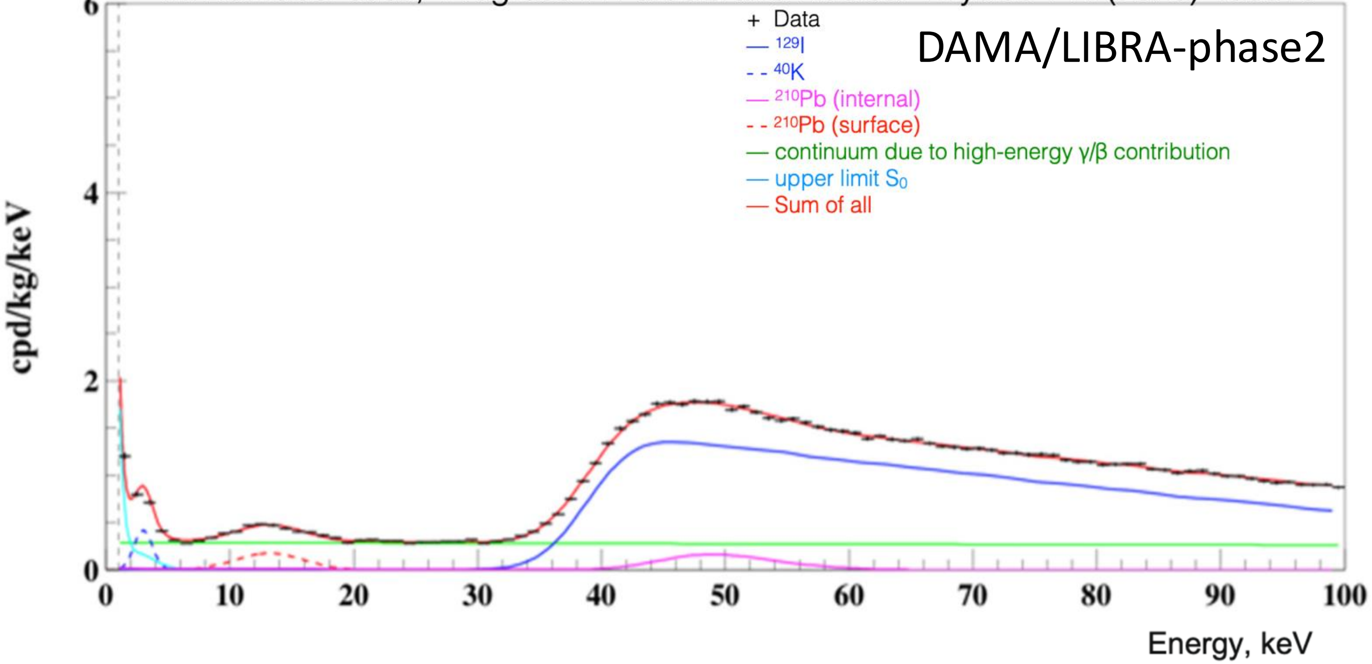
DAMA/LIBRA Background Data

DAMA/LIBRA-phase1

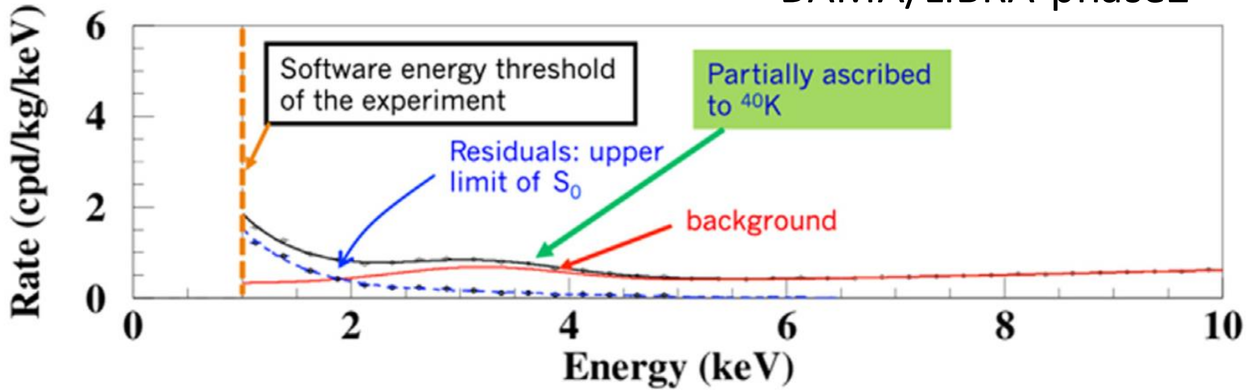


R. Bernabei et.all, Progress în Particle and Nuclear Physics 114 (2020) 103810

DAMA/LIBRA-phase2



DAMA/LIBRA-phase2



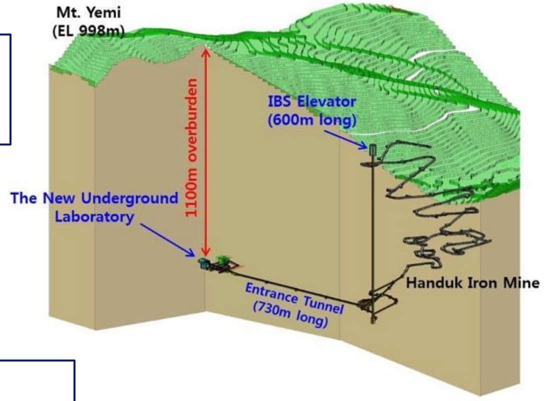
- Reproduce with simulation
- Simulate the DAMA/LIBRA detector in GEANT4 with known geometry

Optimize the Signal

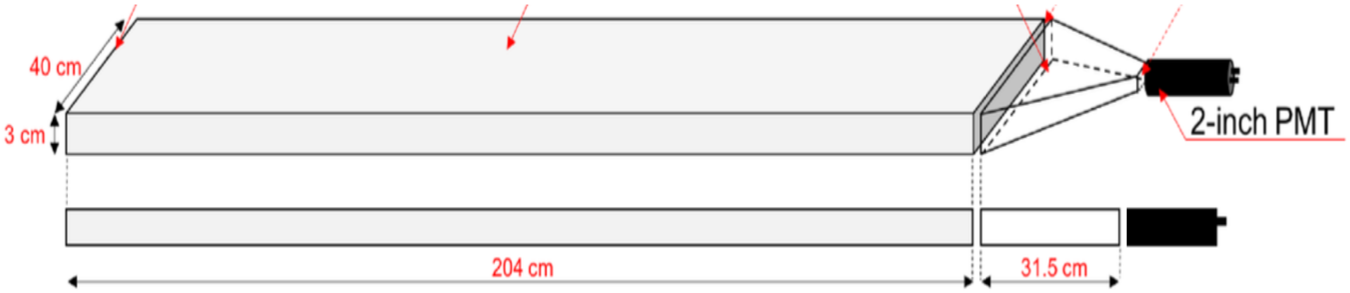
Go Underground

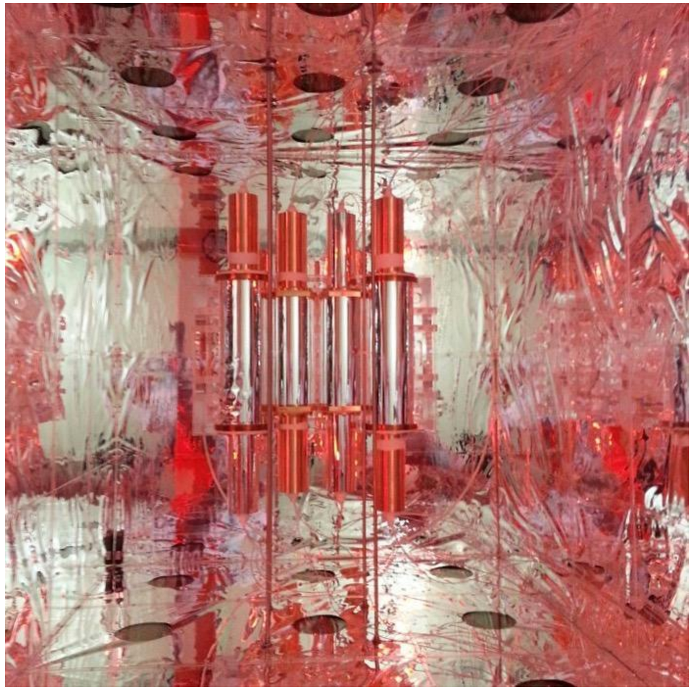
Use Shielding

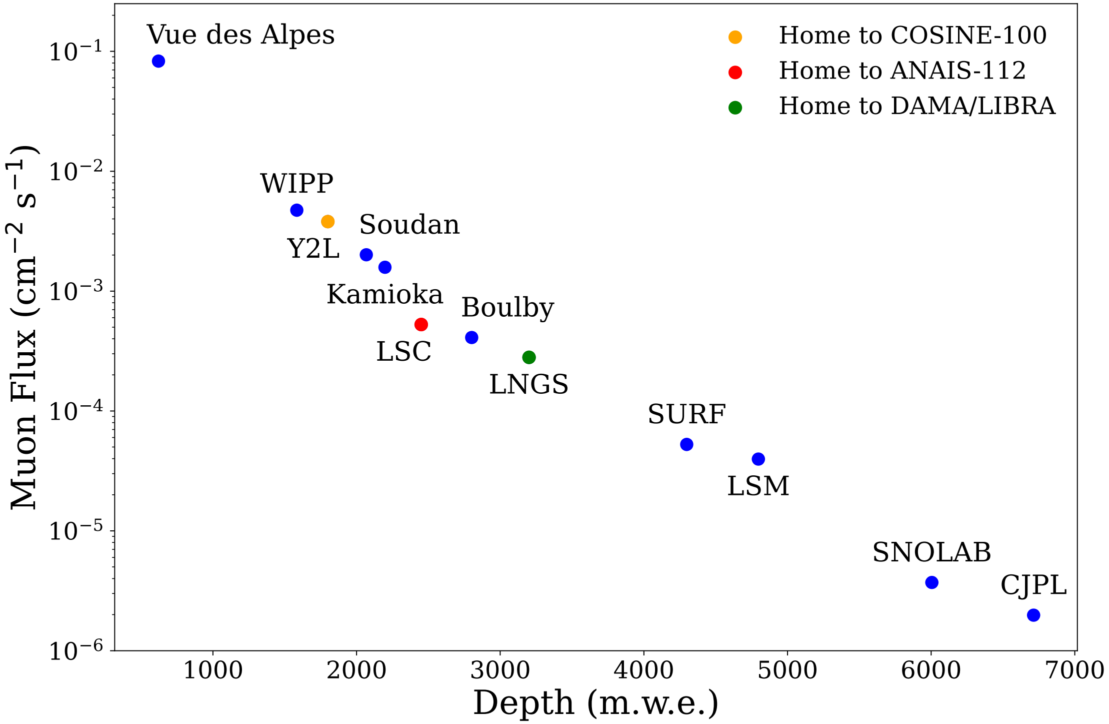
Use Pure Scintillators



Active







Passive