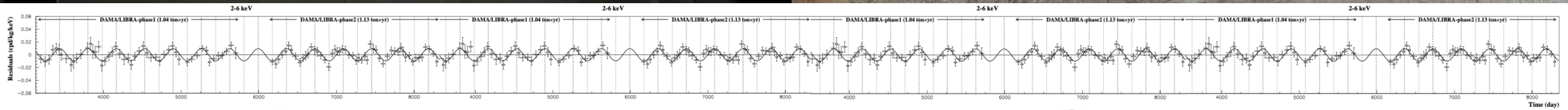
A combined search for dark matter with COSINE-100 and ANAIS-112

Sophia Hollick

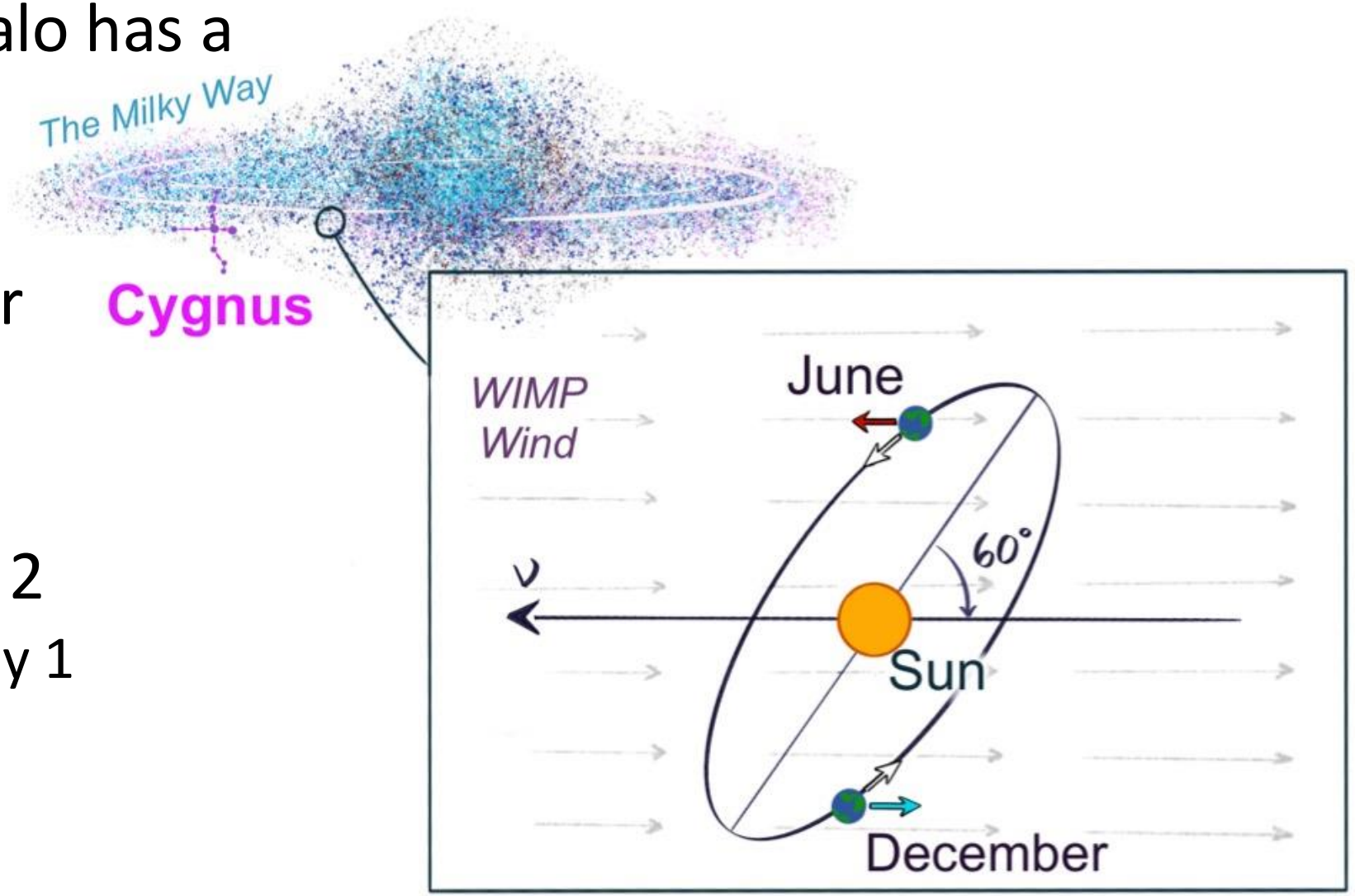
3rd Cost Action School, Annecy | 16 September 2025



Center for Underground Physics | ibs | Yale | Wright Laboratory | Centro de Astropartículas y Física de Altas Energías, Universidad Zaragoza | CAPA

Annual Modulation Signature

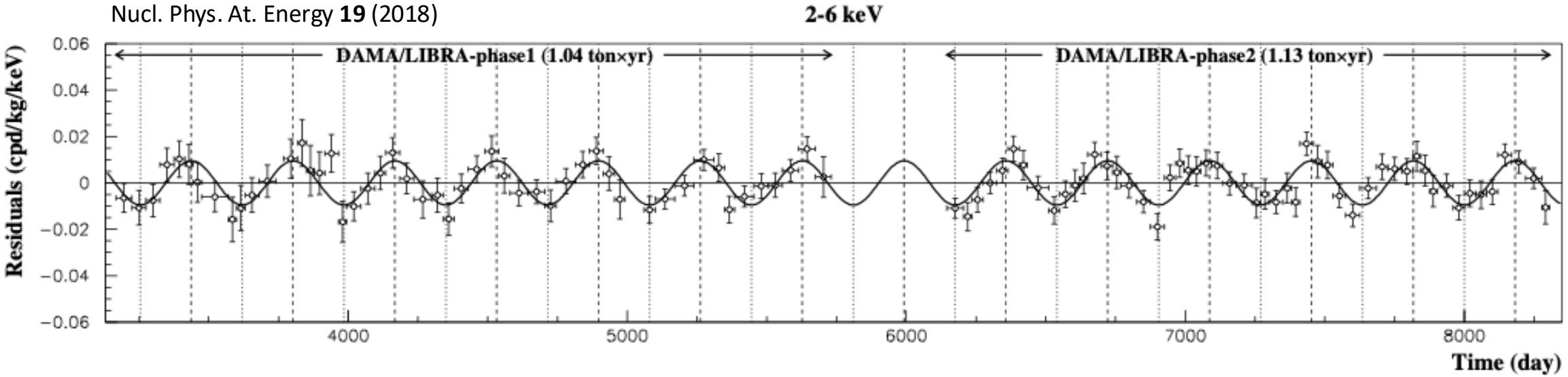
- Galaxy's dark matter halo has a uniform distribution
- Sun orbits galaxy center
  - Earth orbits Sun
- Fastest "wind" on June 2
  - 152.5 days after January 1
  - Minimum on Dec. 2



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

DAMA/LIBRA and NaI(Tl)

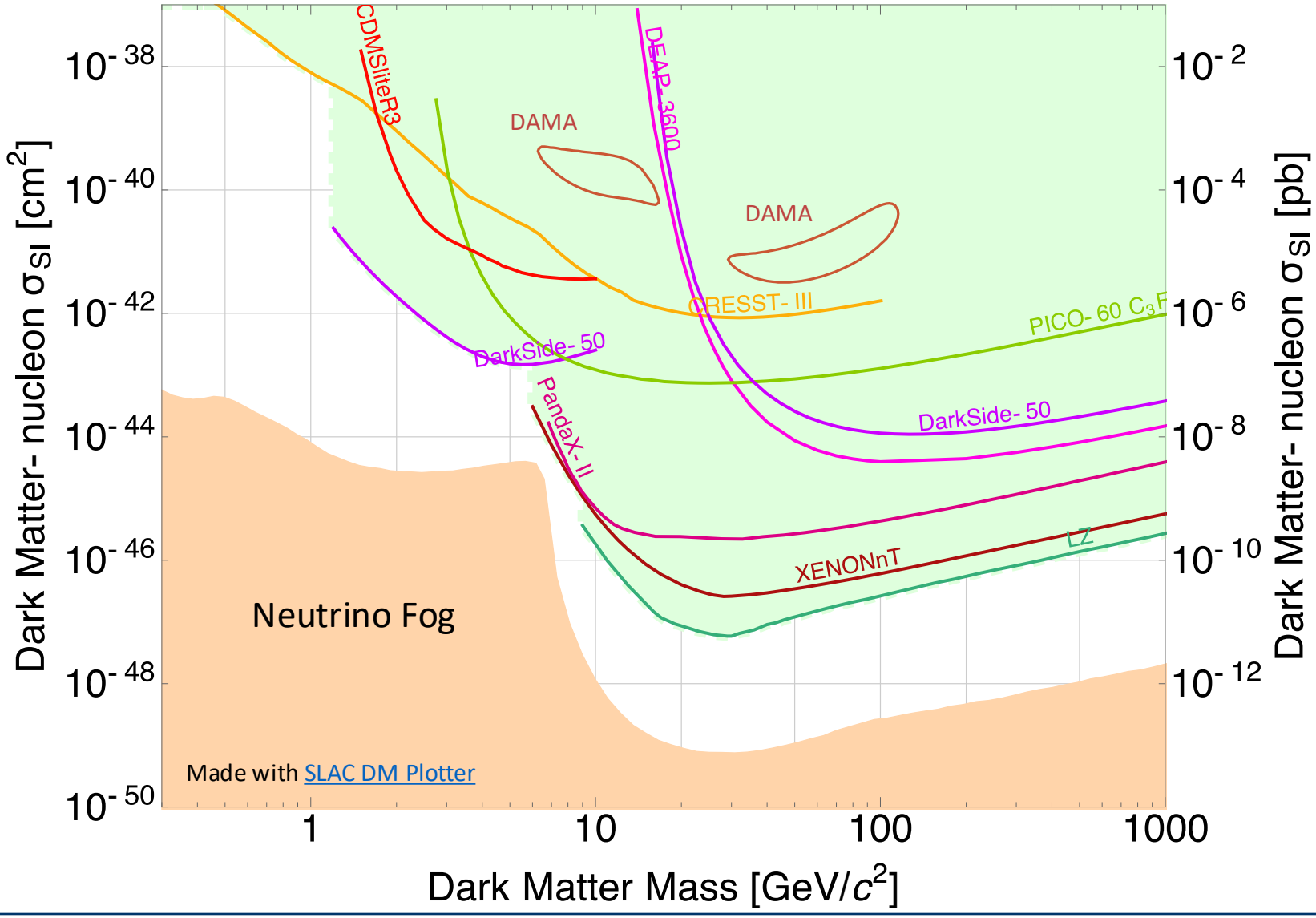
DAMA/LIBRA Collaboration
Nucl. Phys. At. Energy **19** (2018)



- 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

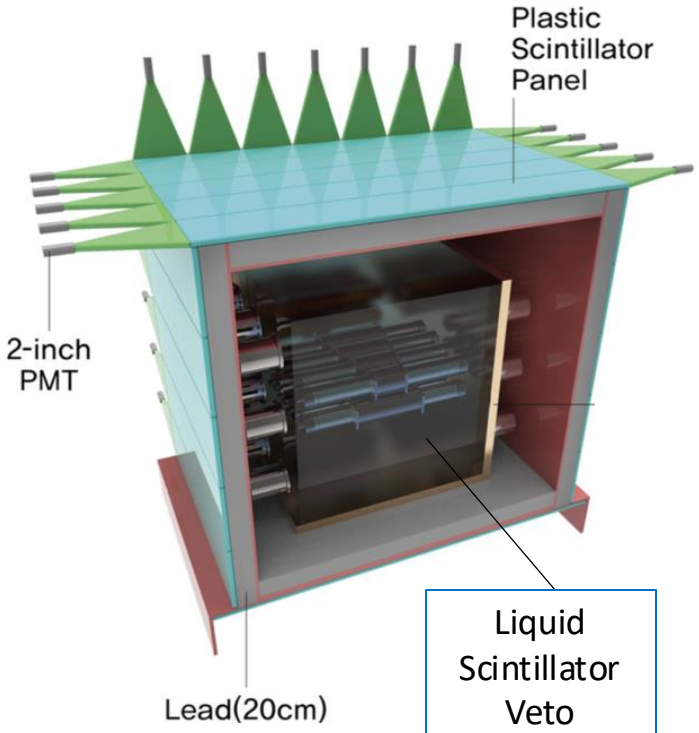
- Much of the WIMP phase space has been explored and excluded
- DAMA appears in the excluded region for many experiments
- Note: No other experiment in this plot uses NaI(Tl) target material




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

COSINE-100 and ANAIS-112 Collaborations

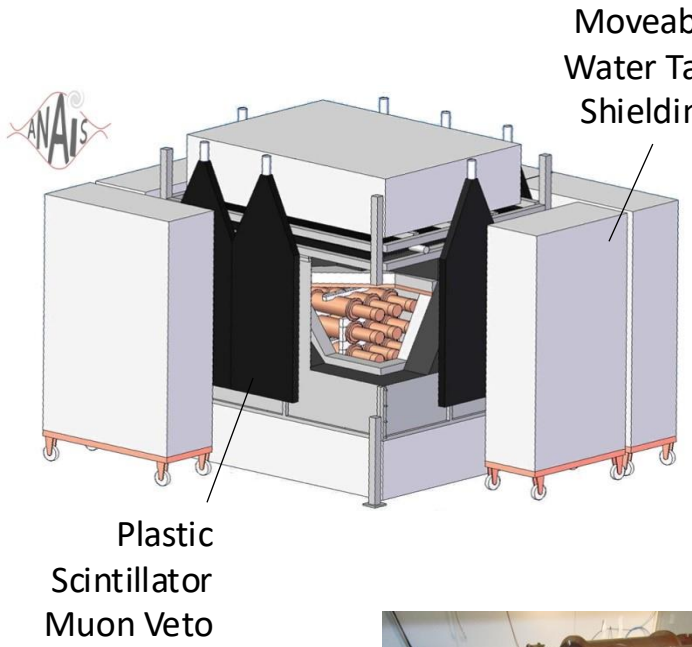
COSINE-100



KIMS + DM-ICE = COSINE

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



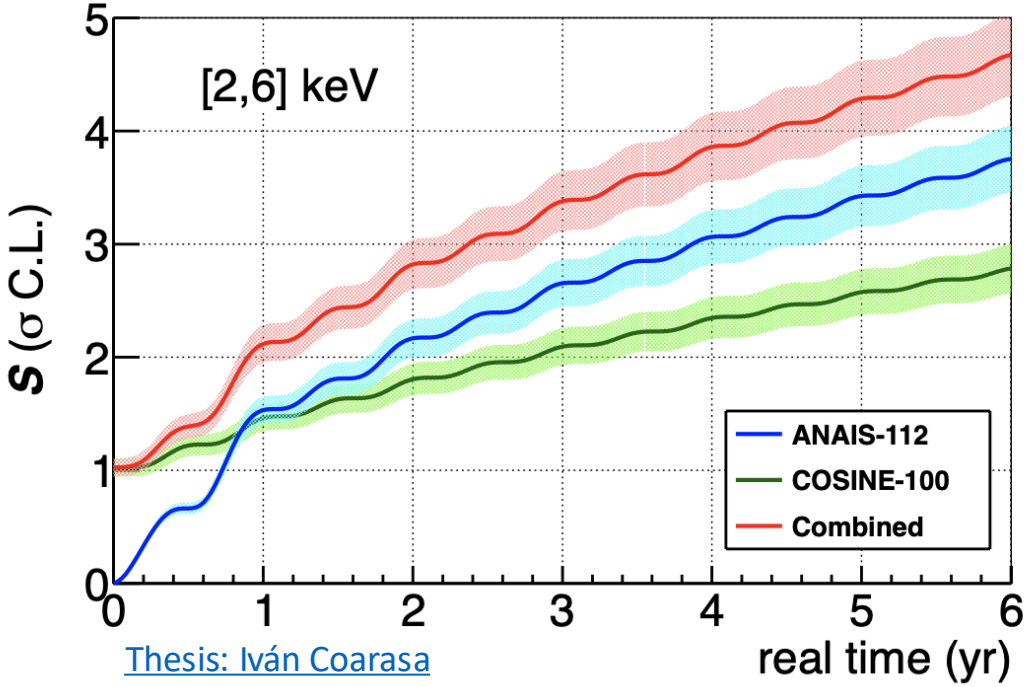
Motivation to Combine Data

- Using published 3-year data for both experiments, a 3σ significance can be achieved
  - ANAIS and COSINE provide open access to 3-year counting rates and background models at the Dark Matter Data Center (DMDC)

- Combining data directly allows for:
  - Validation of analysis methodologies
  - Confirmation for compatibility of results

- Promote the open access of data within the community :)

ANAIS 3y & COSINE 1.7y Sensitivity Projections



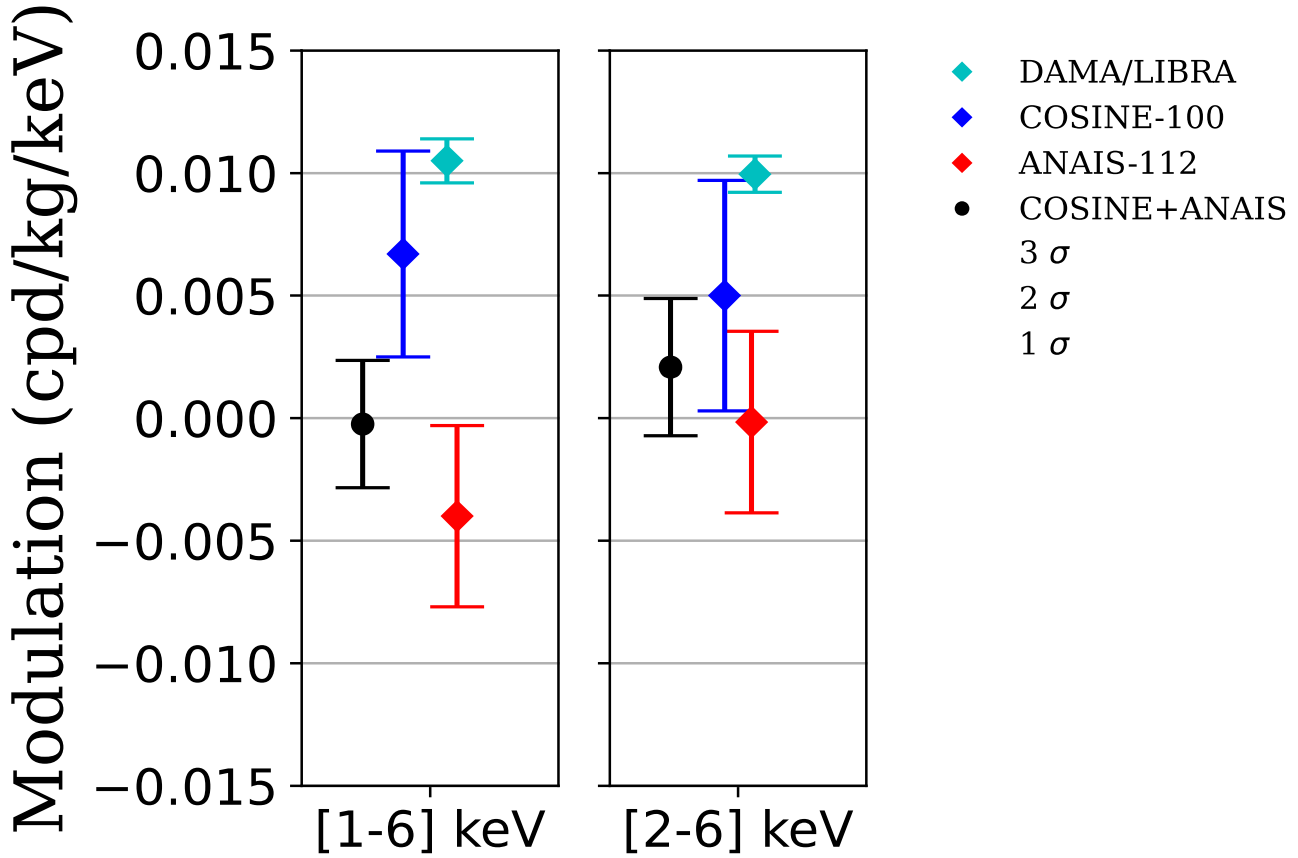
Thesis: Iván Coarasa

Simple Combination

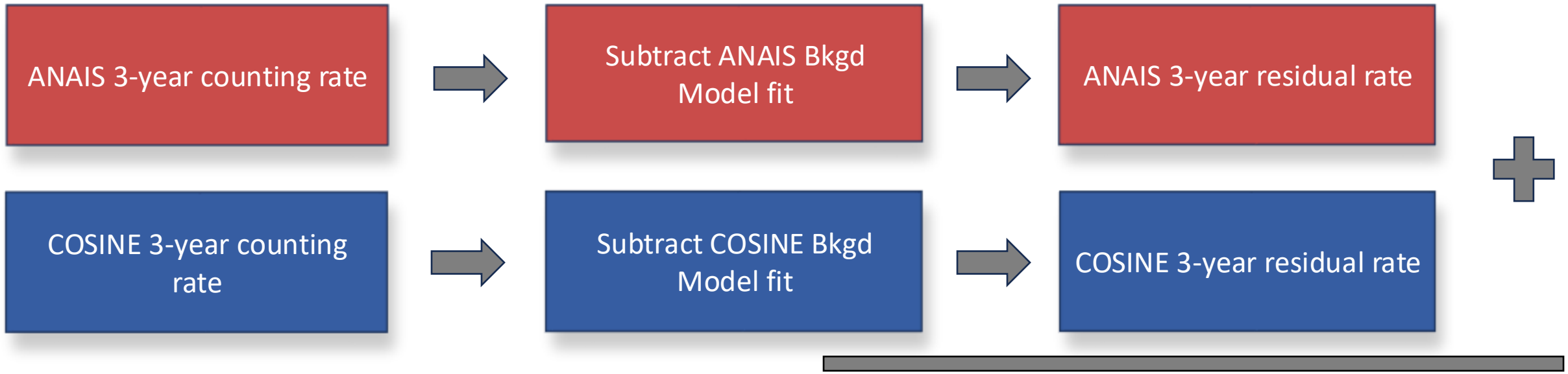
Perform χ^2 Minimization of Independent Experiment Results:

$$\frac{\frac{A}{\delta A^2}+\frac{B}{\delta B^2}}{\frac{1}{\delta A^2}+\frac{1}{\delta B^2}} \pm \sqrt{\frac{1}{\frac{1}{\delta A^2}+\frac{1}{\delta B^2}}}$$

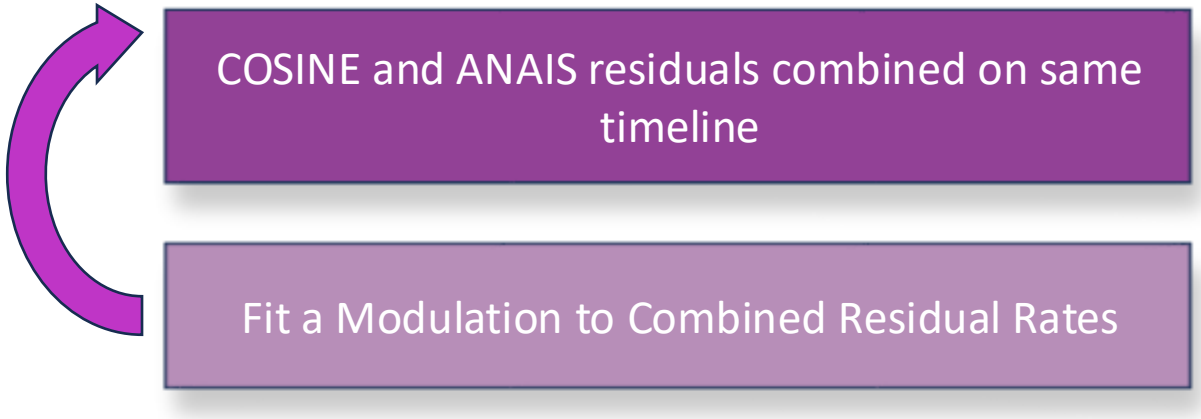
- Assumes
  - Uncertainties are well understood
  - Results are free from systematics
  - Experiments are compatible



Steps for Combination – Residuals Method



- Confirm individual experiment results
- Compare fitting methodologies
  - Frequentist vs Bayesian
- Confirm data compatibility



ANAIS-112's Background Model

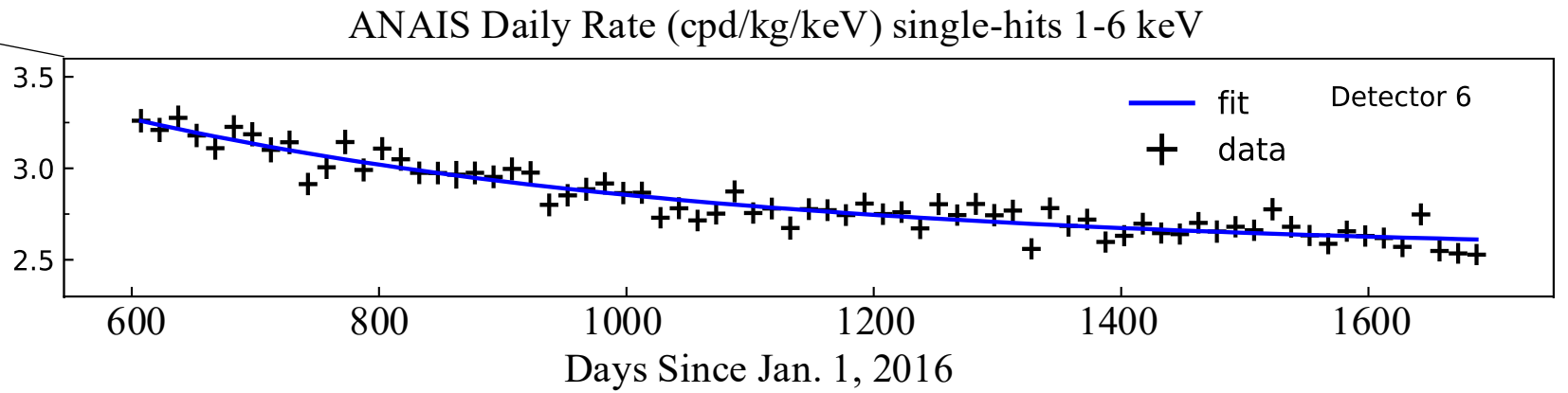
Single Exponential Decay

$$R_T(t_i) = R_0 \cdot (1 + f e^{-t_i/\tau})$$

MC-PDFs

$$\phi_{bkgd}(t_i) = 1 + f\phi^{MC}_{bkgd}(t_i)$$

$$f(t;\lambda) = \lambda e^{-\lambda t}$$



Energy ROI	χ^2 /ndf Single Exponential	χ^2/ndf Monte Carlo PDFs
1-6 keV	1.23	1.11
2-6 keV	1.08	1.05

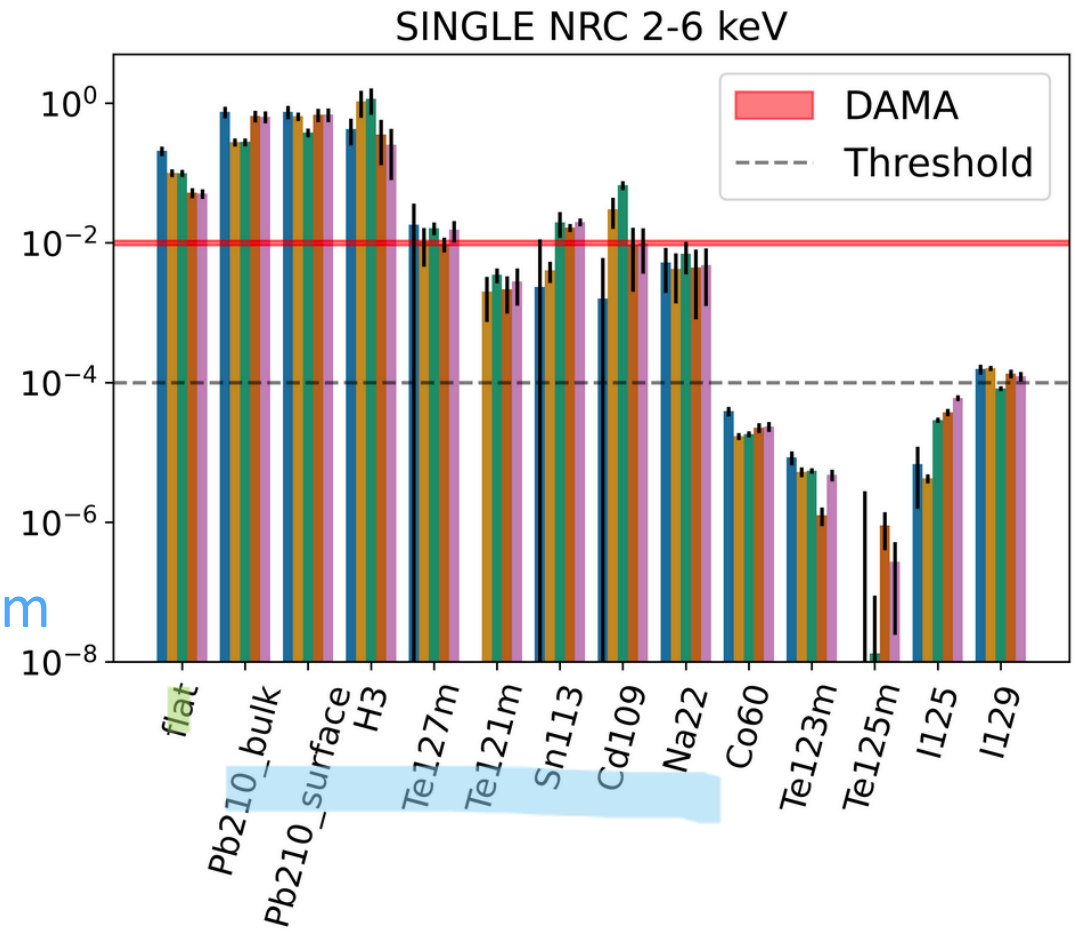
- Single exponential describes the ANAIS 3-year data well
- Allows for straightforward fitting of backgrounds

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

COSINE-100's Background Model

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

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

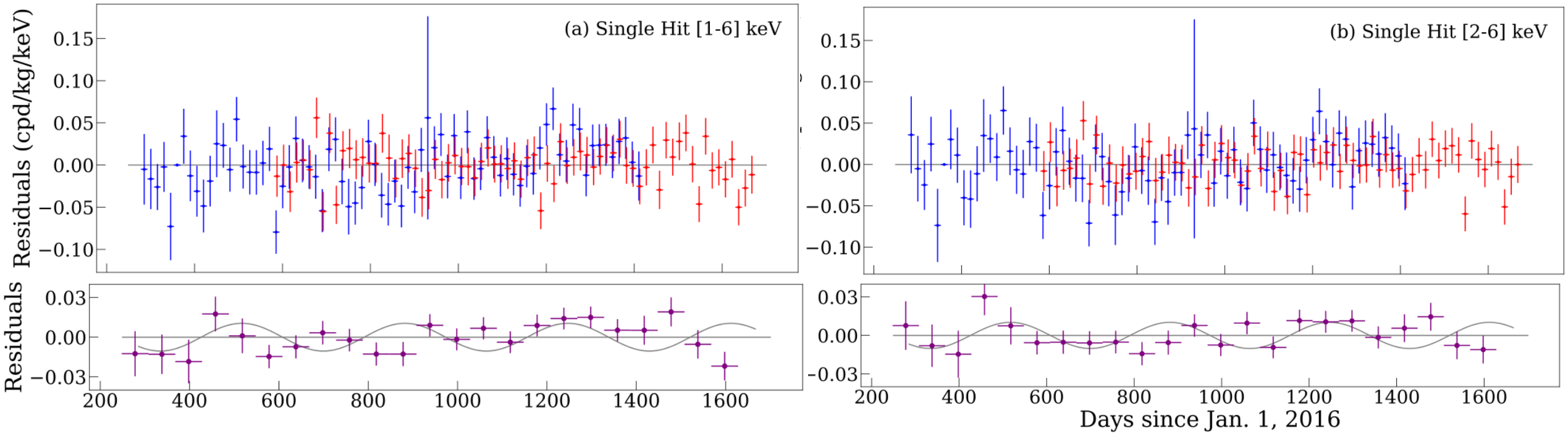


Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days

*surface Pb210 treated separately with effective half-life = 33.8 +/- 8 years from continuous Rn222 contamination

COSINE-100 Background 2021

Combine Data and χ^2 Fit



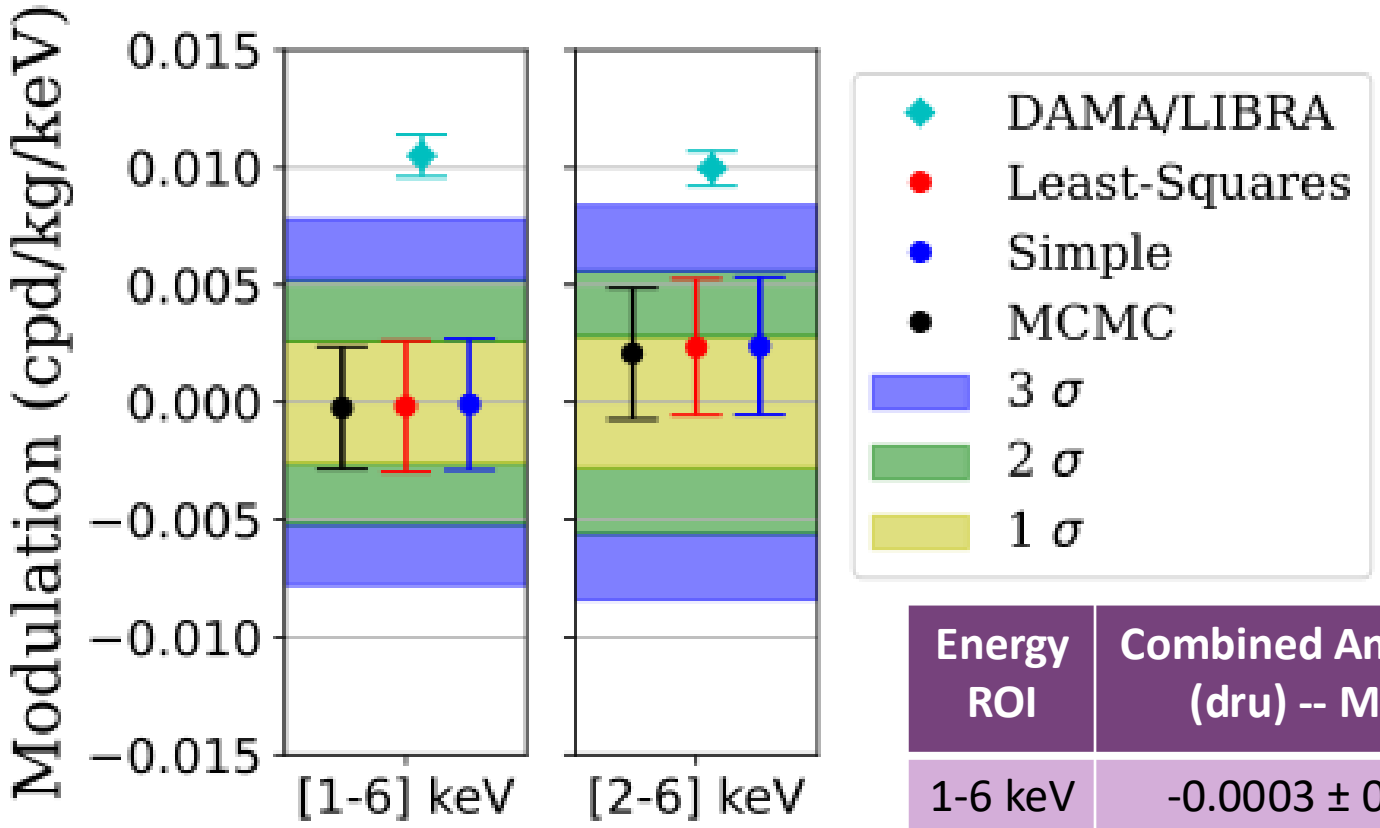
Perform a modulation fit with:
-Least-Squares Method with χ^2 Statistics
-MCMC Method with Bayesian Statistics

Plot with equal binning and timeline

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

Results

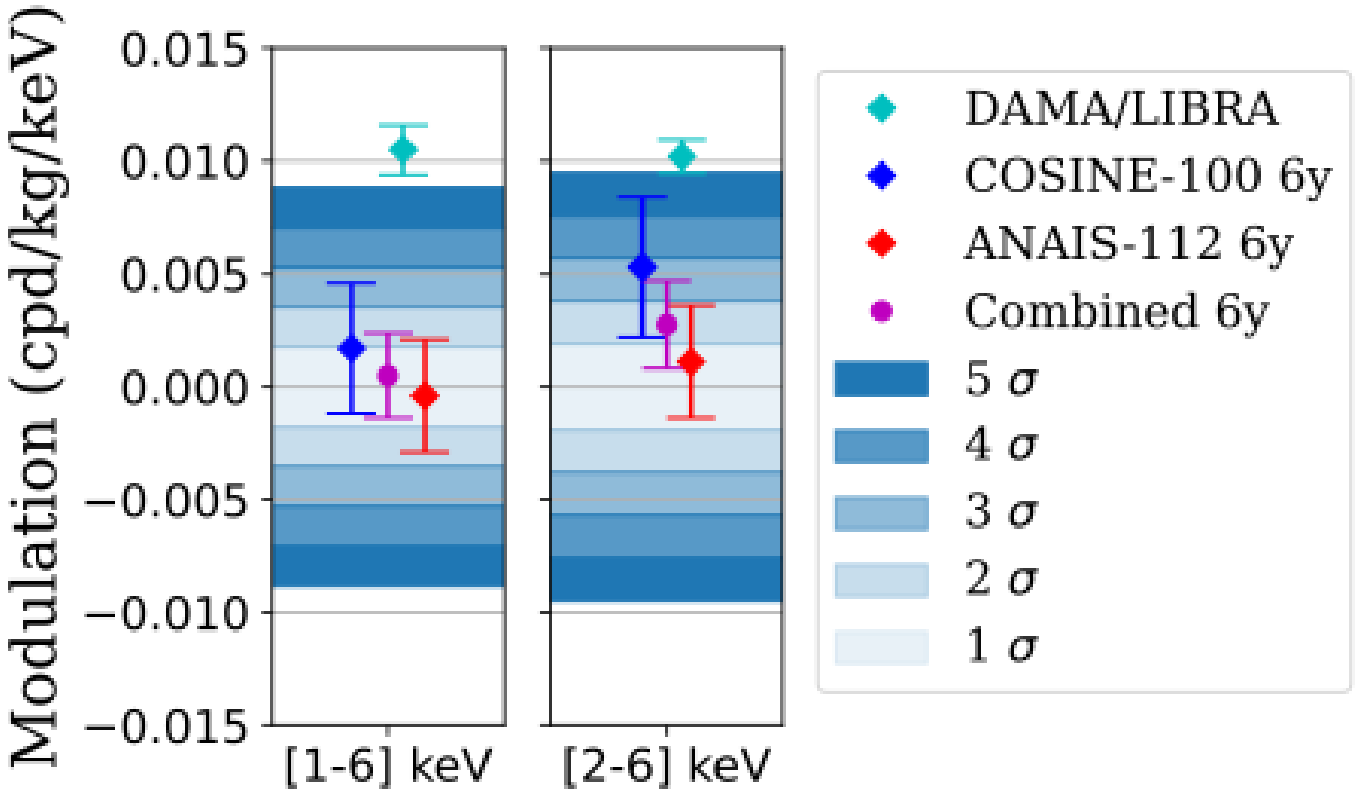
- Since no systematics found for the two experiments, can combine
- Frequentist and Bayesian methods are compatible!



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

6 years combined



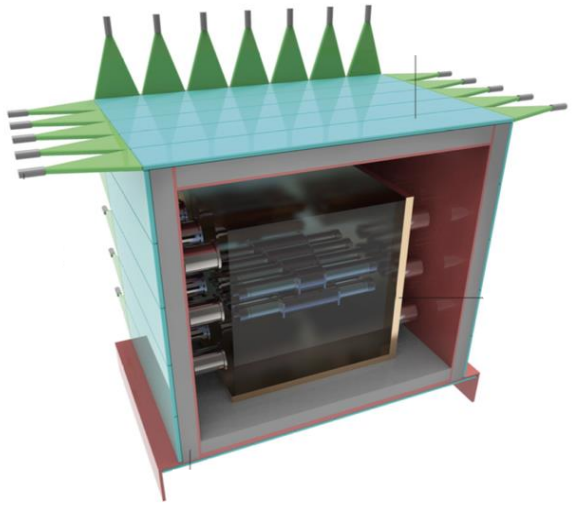
- Expected results from 6 years datasets
- Sensitive to DAMA at 5.3σ in 1-6 keV and 5.0σ in 2-6 keV

Energy ROI	*COSINE 6-year	*ANAIS 6-year	Combine Simple
1-6 keV	0.0017 ± 0.0029	0.0007 ± 0.0025	0.0011 ± 0.0019
2-6 keV	0.0053 ± 0.0031	0.0030 ± 0.0025	0.0039 ± 0.0019

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

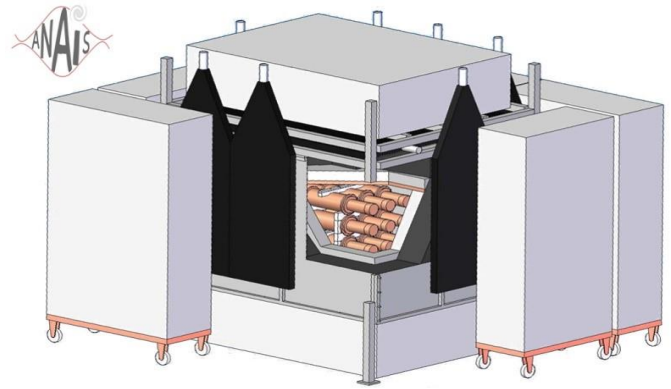
Summary

- COSINE-100 and ANAIS-112 are compatible NaI(Tl) experiments
  - Separate treatment of experiment backgrounds allows for direct combination of residuals
  - Combined annual modulation search provides 3σ exclusion of DAMA/LIBRA



- Combined 3-year analysis finds
  no modulation at 3.7σ in 1-6 keV
  and 2.6σ in 2-6 keV

- Expected 6-year combination to find
  no modulation at 4.7σ in 1-6 keV
  and 3.5σ in 2-6 keV



Thank you for your attention!

Acknowledgements

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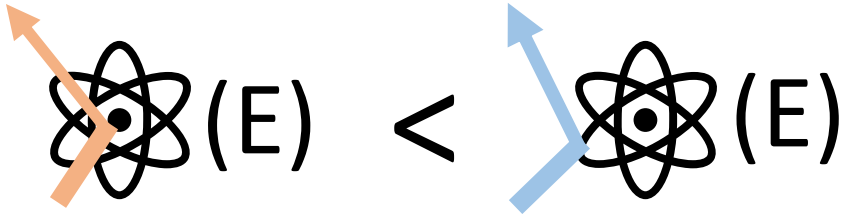
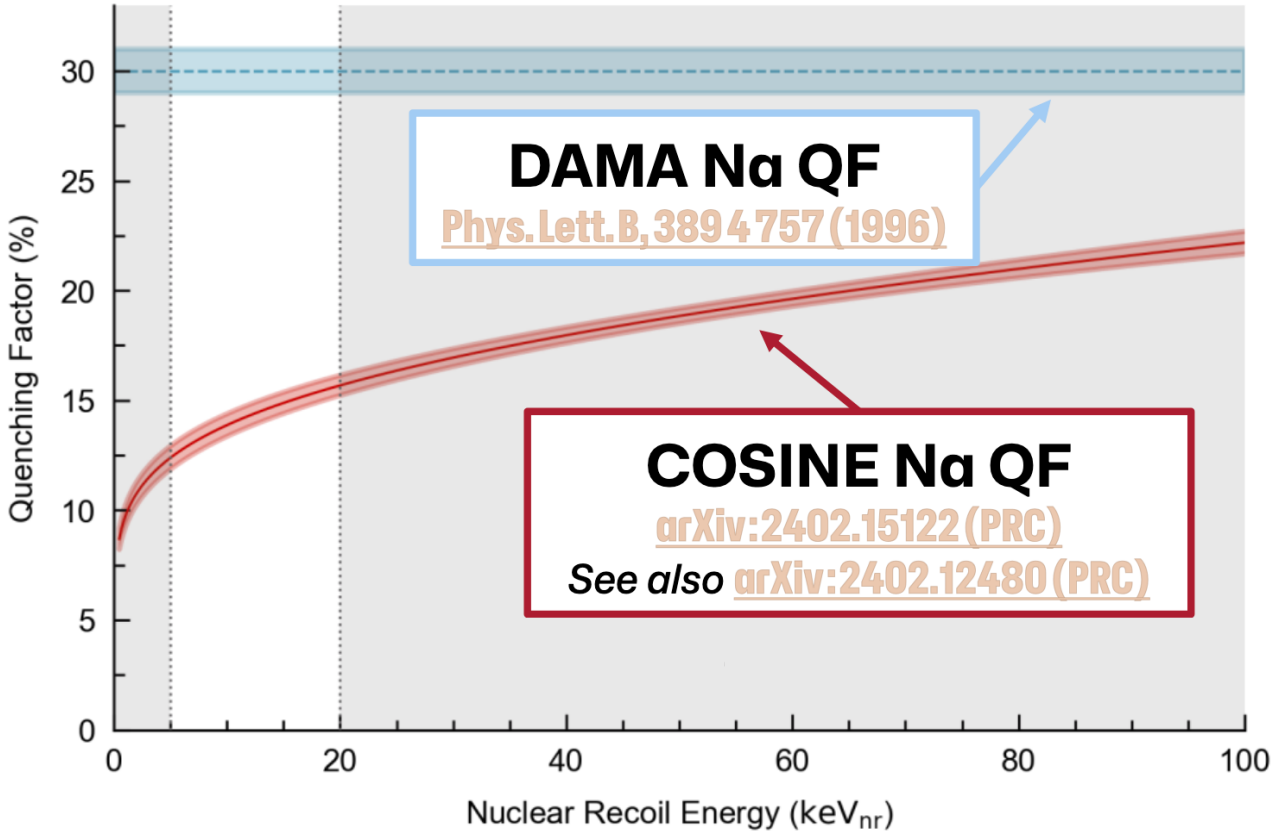
NSF Grants No. PHY-1913742, United States; STFC Grant ST/N000277/1 and ST/K001337/1, United Kingdom;
Grant No. 2021/06743-1, 2022/12002-7 and 2022/13293-5 FAPESP, CAPES Finance Code 001, CNPq 304658/2023-5, Brazil.
Additionally, this work has been financially supported by MCIN/AEI/10.13039/501100011033 under grant PID2022-138357NB-C21 and by the Gobierno of Aragón

Backup

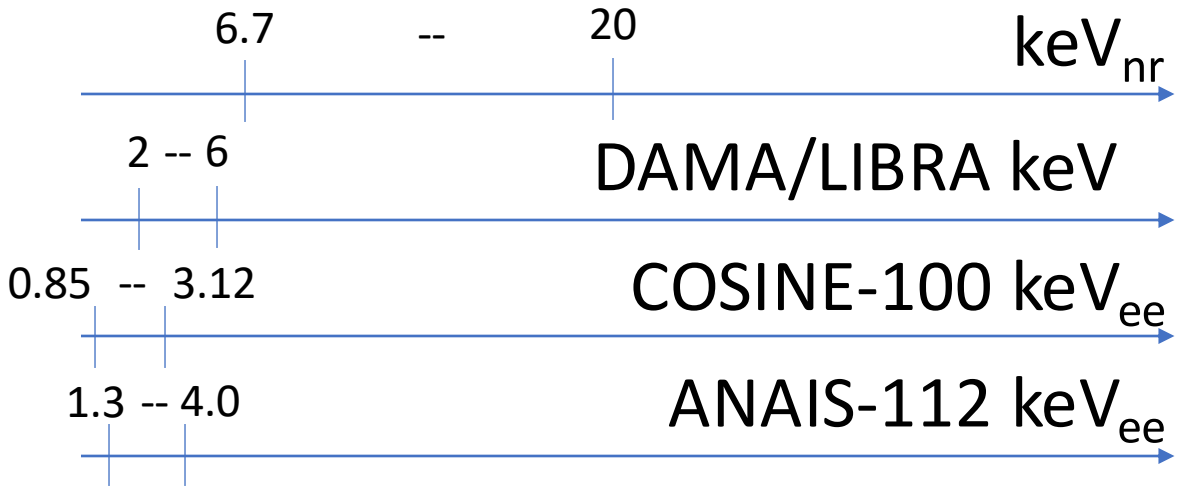
Accounting for Quenching Factors



$$\therefore QF < 1$$



- QFs change the effective energy region

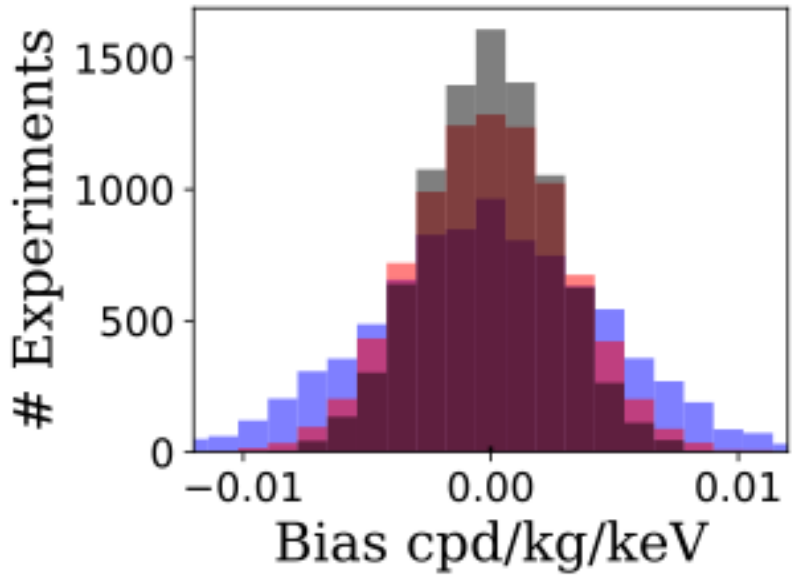


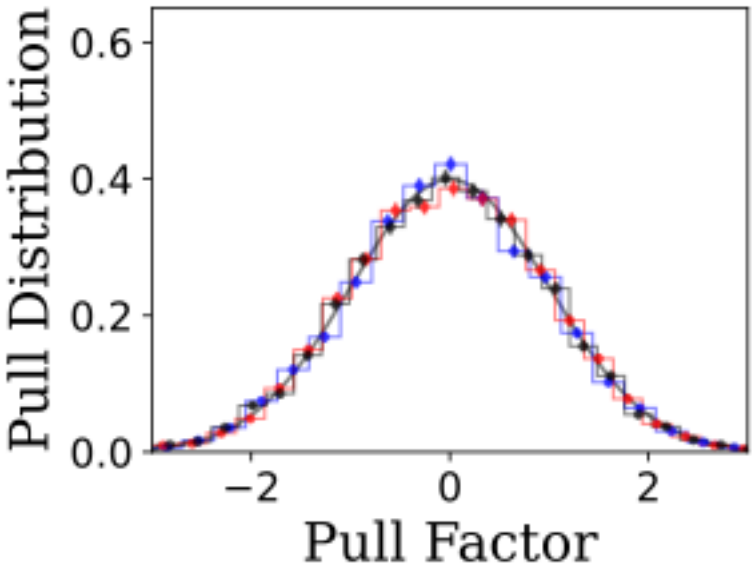
Configuration	6.7–20 keV$_{nr}$
COSINE-100 (2024)	0.0013 ± 0.0027
ANAIS-112 (2025)	0.0000 ± 0.0023
This Study 6-year	0.0005 ± 0.0017
DAMA/LIBRA-phase2	0.0102 ± 0.0008

5.2σ

Pseudo Study

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



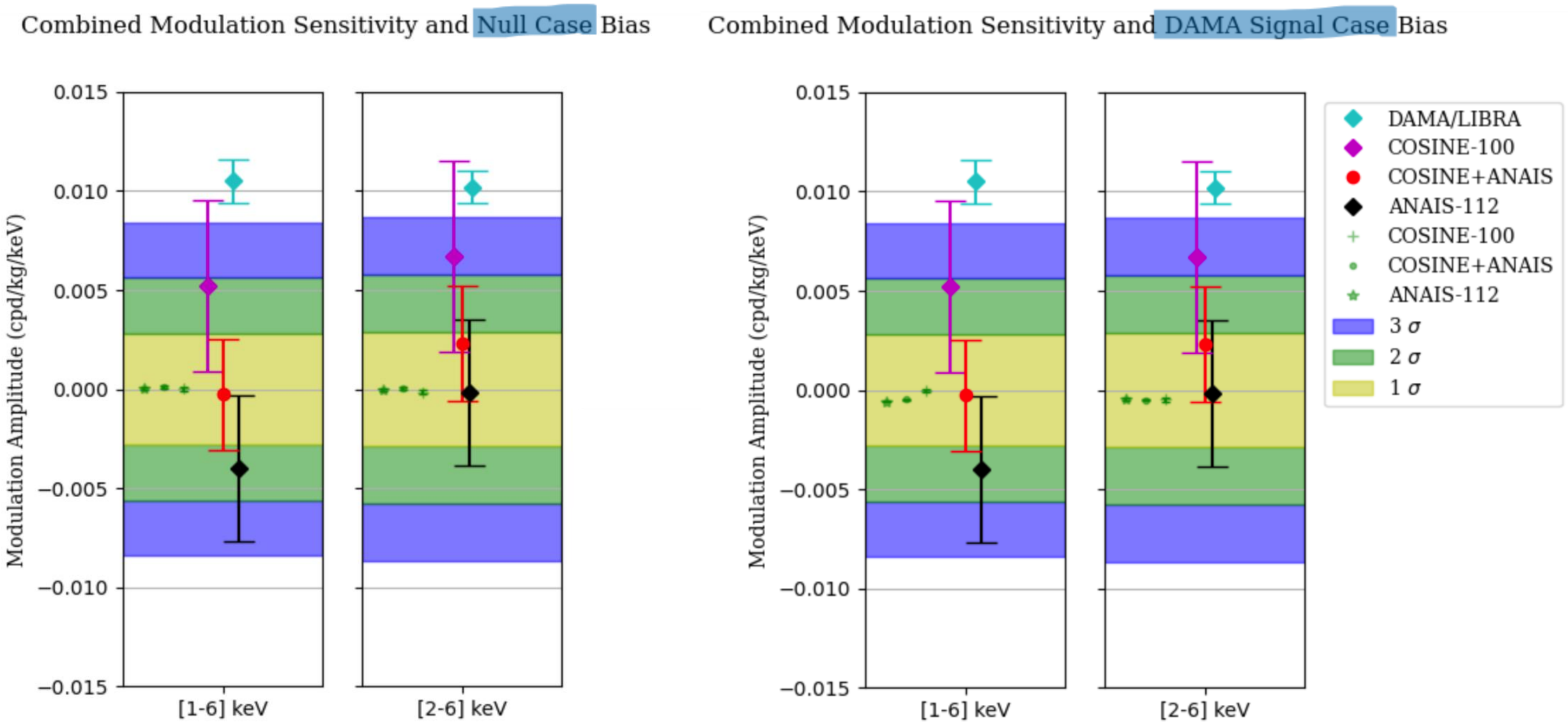


Model	Bias [0.0 dru] 10^{-4}	Bias [0.0105 dru] 10^{-4}	Standard Deviation 10^{-4}
COSINE SETZ Bkgd	0.2 +/- 1	-0.3 +/- 0.9	31
ANAIS Single Exp.	0.3 +/- 0.6	5 +/- 0.6	18
Combined Residuals	1 +/- 0.5	-4 +/- 0.5	15

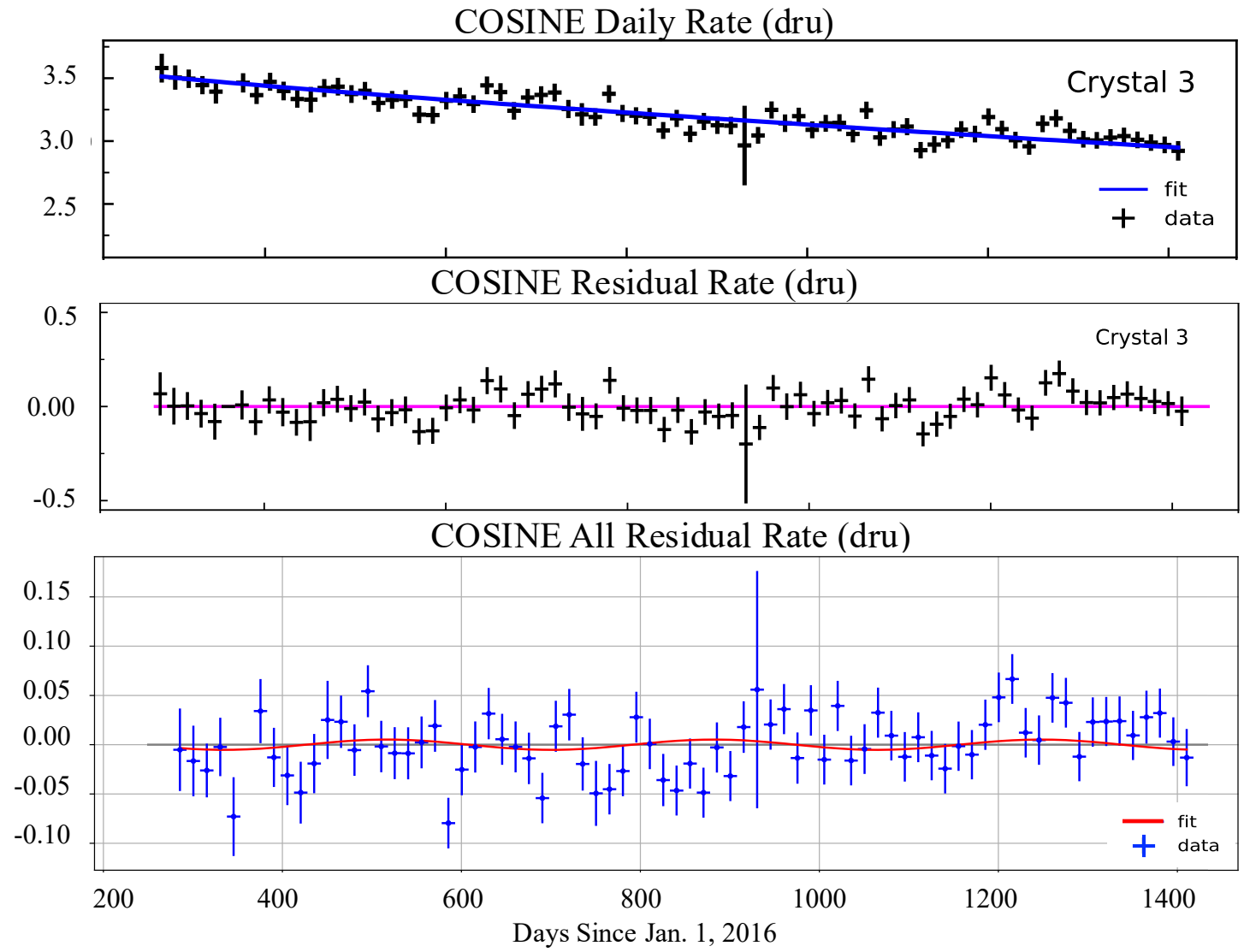
- Bias = Fit – Injected Signal
- Bias Error = Standard Deviation / sqrt(# of entries)

~1000 Experiments

Visual Respresentation of Bias Effect



COSINE data – Obtaining Residuals



Residuals Method – COSINE 1-6 keV

Sum of Exponentials Background Model

- Fit the daily rate with the chosen model

as in COSINE-100 *PRD* ***106***, *052005 2021*

Residuals

- Done for all crystals, though only crystal 3 shown here

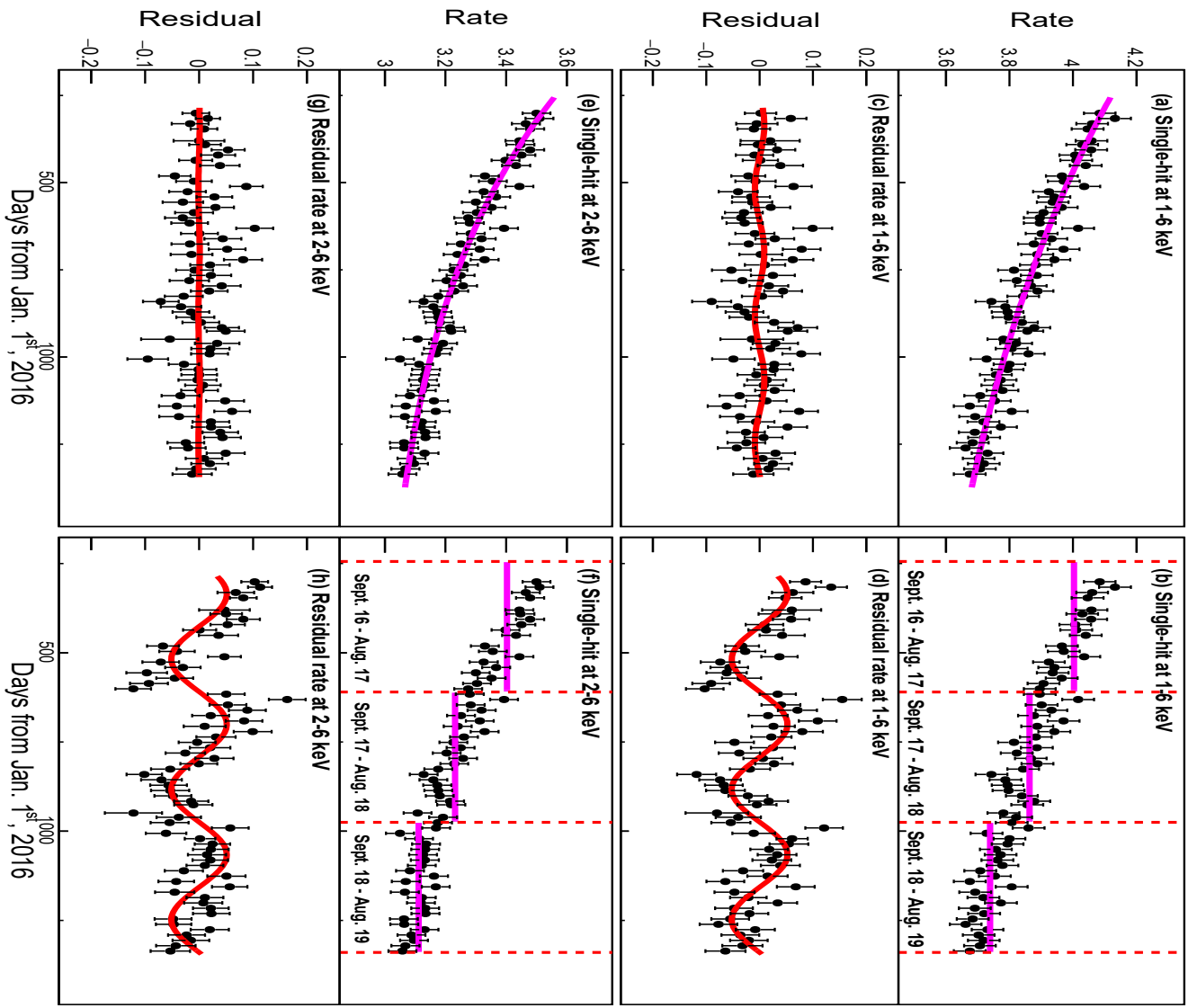
Modulation Fit

- Combine crystal residuals and fit a modulation

Energy ROI	This Study (dru)	COSINE (dru)
1-6 keV	0.0069 ± 0.0042	0.0067 ± 0.0042
2-6 keV	0.0048 ± 0.0047	0.0050 ± 0.0047

Time (In)dependent Background Subtraction Methods

- If a background decays exponentially over time, the subtracted background must account for this decay
- If a background does not decay over time (is flat), the subtracted background can be assumed to be the average annual rate



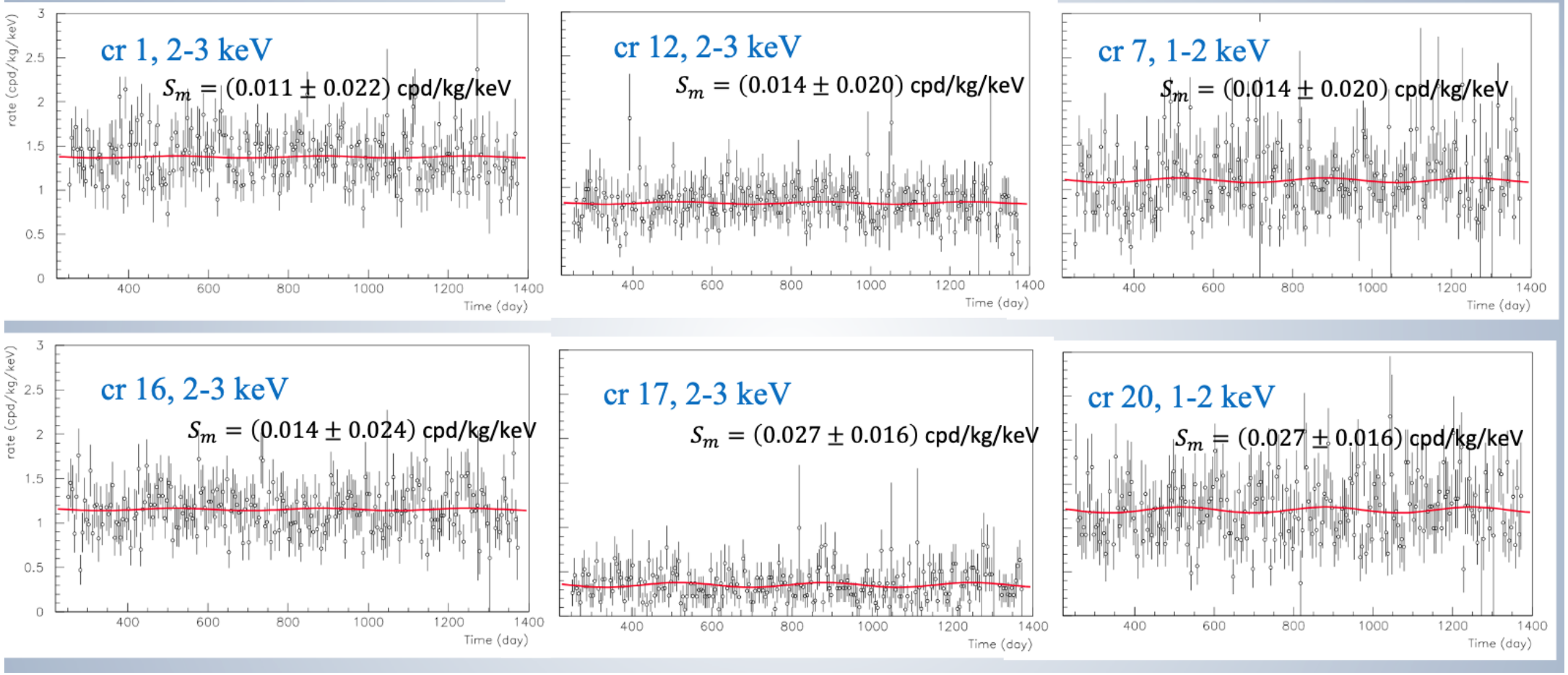
COSINE Collaboration *Sci Rep* **13**, 4676 (2023).

Response from DAMA

Investigation on the rate time dependence

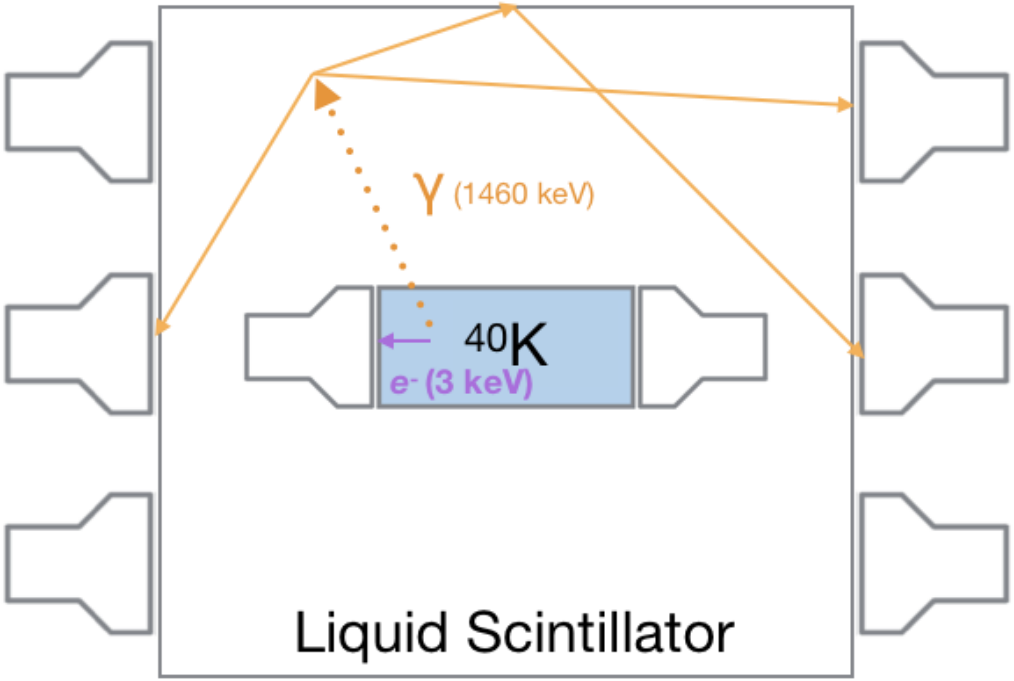
The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed **considering the same bckg**

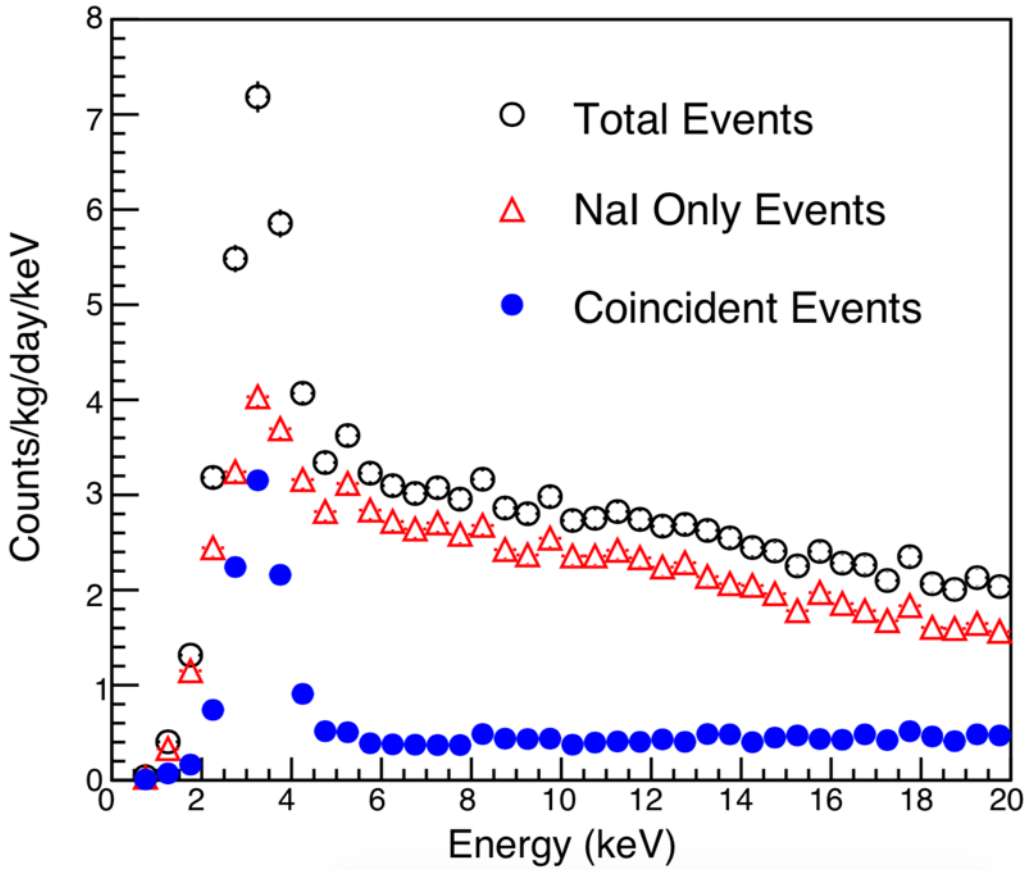
R. Cerulli ***IDM*** 2024



Liquid Scintillator Veto

- NaI(Tl) detectors immersed in 2200 L active LAB liquid scintillator veto
  - Scintillator contained in acrylic vessel lined with reflector
- LS veto ~80% efficient at rejecting ^{40}K events



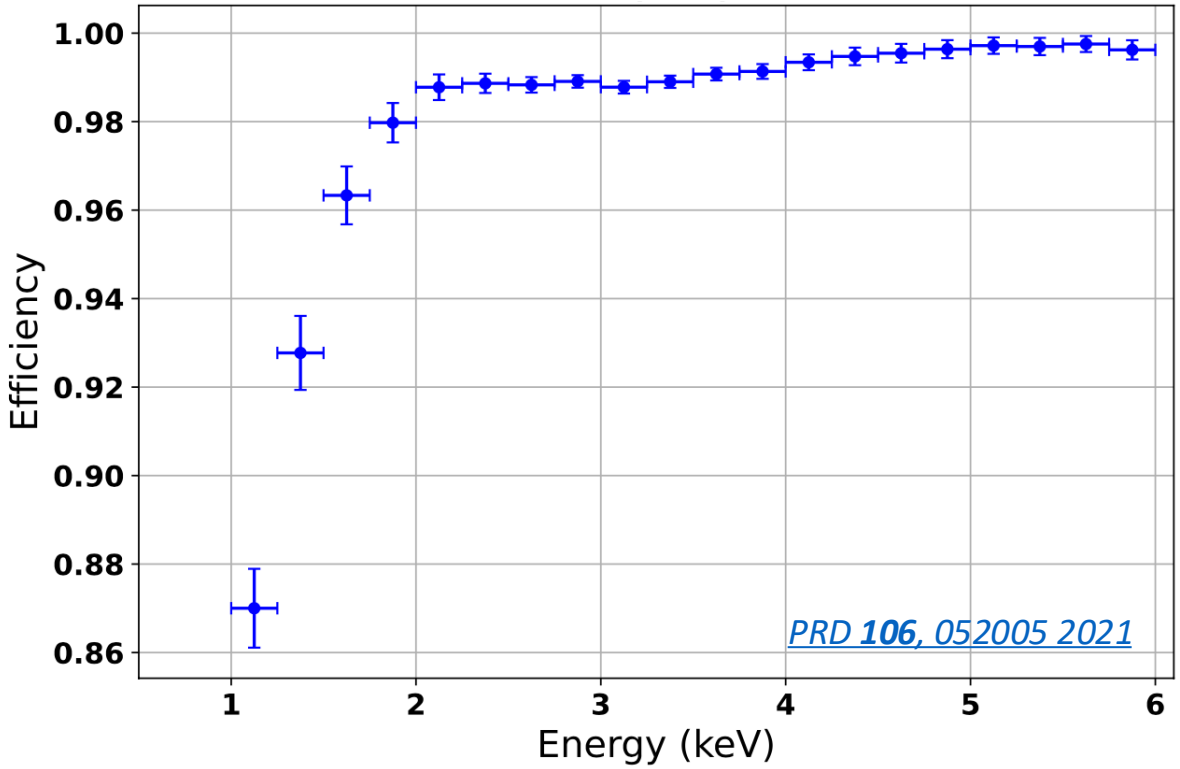


COSINE-100: Nuclear Instruments 1006:165431 (2021)

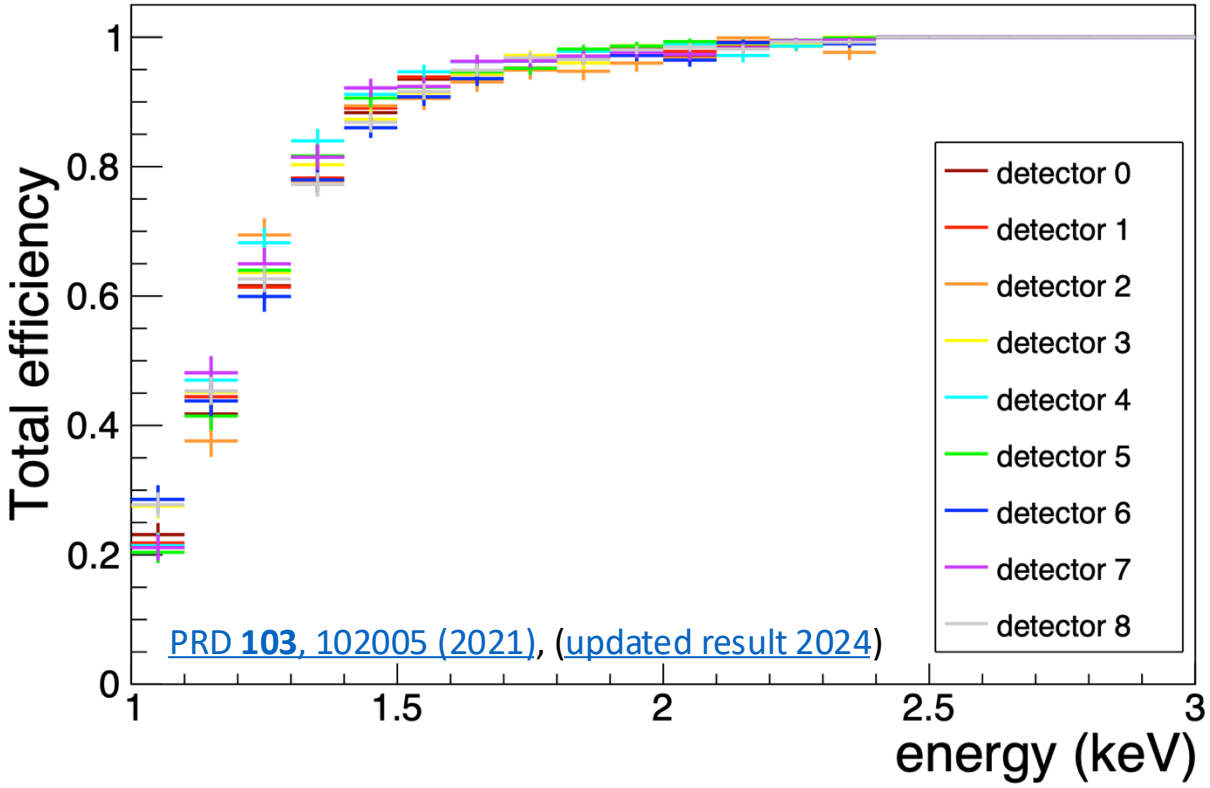
Efficiency Differences

- ANAIS-112 suffers a dramatic efficiency drop below 1.4 keV
- COSINE-100 is able to maintain efficiencies of ~85% down to 1 keV

COSINE-100



ANAIS-112



Alpha Spectra Crystals

- ANAIS

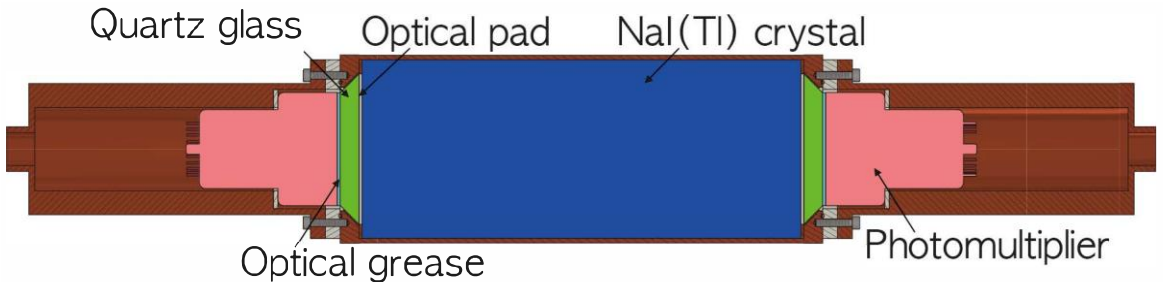
Detector	Powder Name	Date of arrival at Canfranc
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017

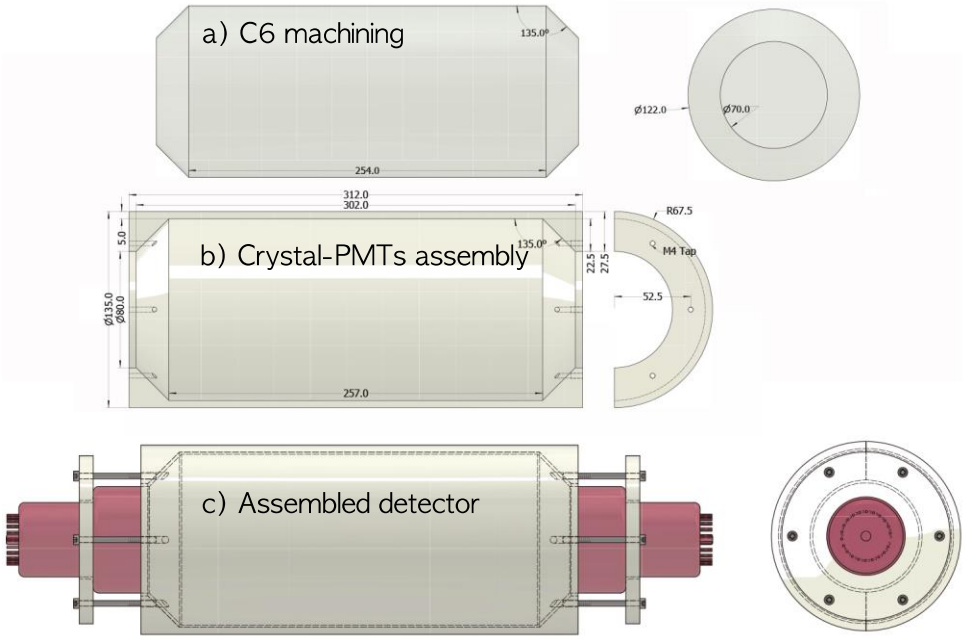
- COSINE

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

Refurbish Old Crystals for COSINE-100U





- Search for low-mass WIMPs