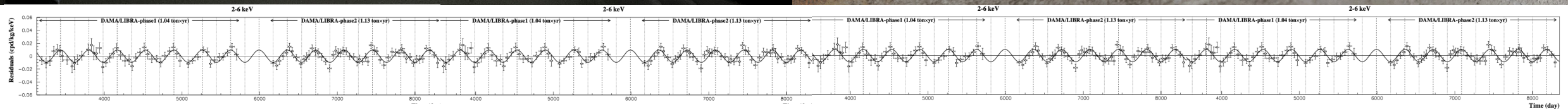
A combined search for dark matter with COSINE-100 and ANAIS-112

Sophia Hollick on behalf of the COSINE-100 and ANAIS-112

IDM | 9 July 2024

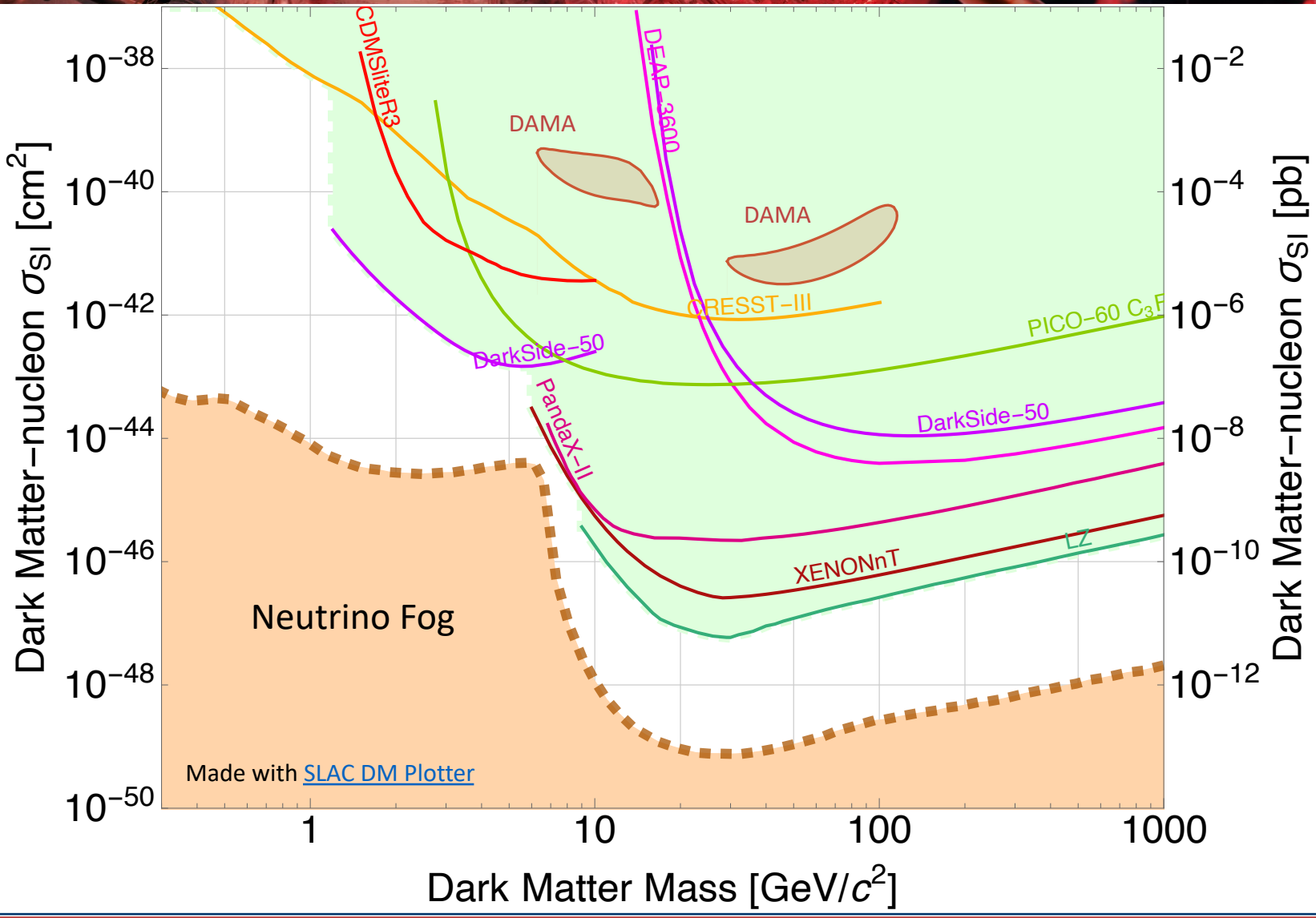
Foto: @j.l



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

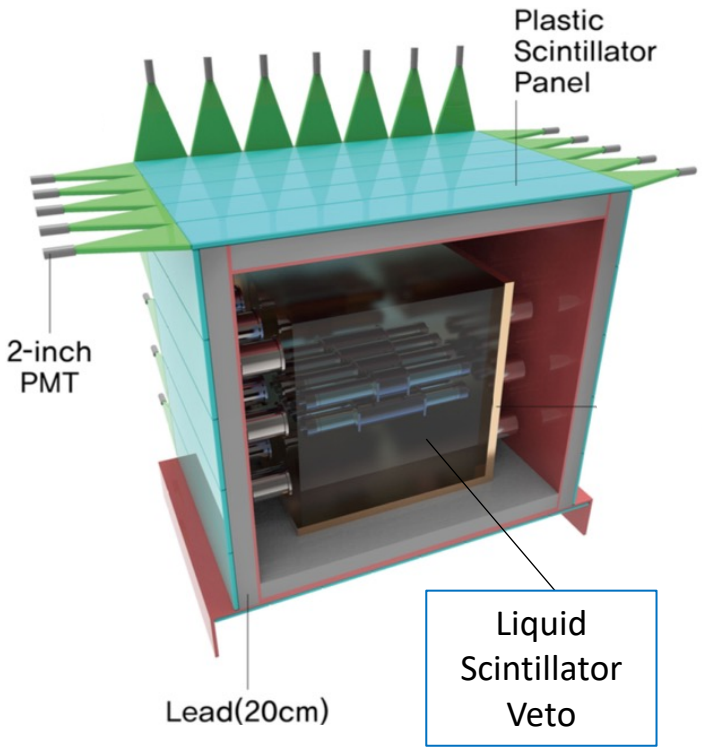
Direct Detection Community

- 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



COSINE-100 and ANAIS-112 Collaborations

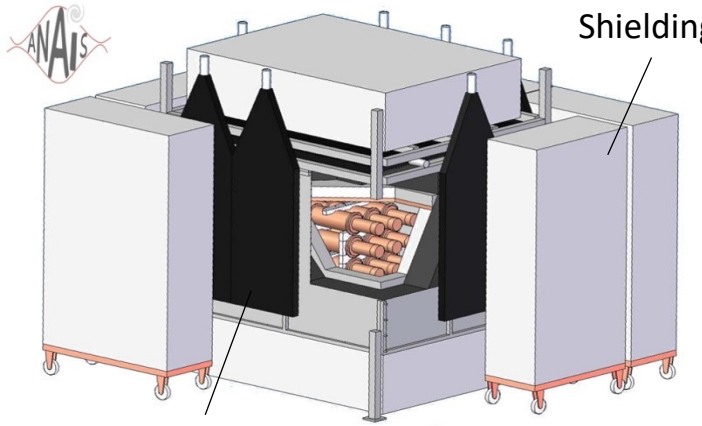
COSINE-100



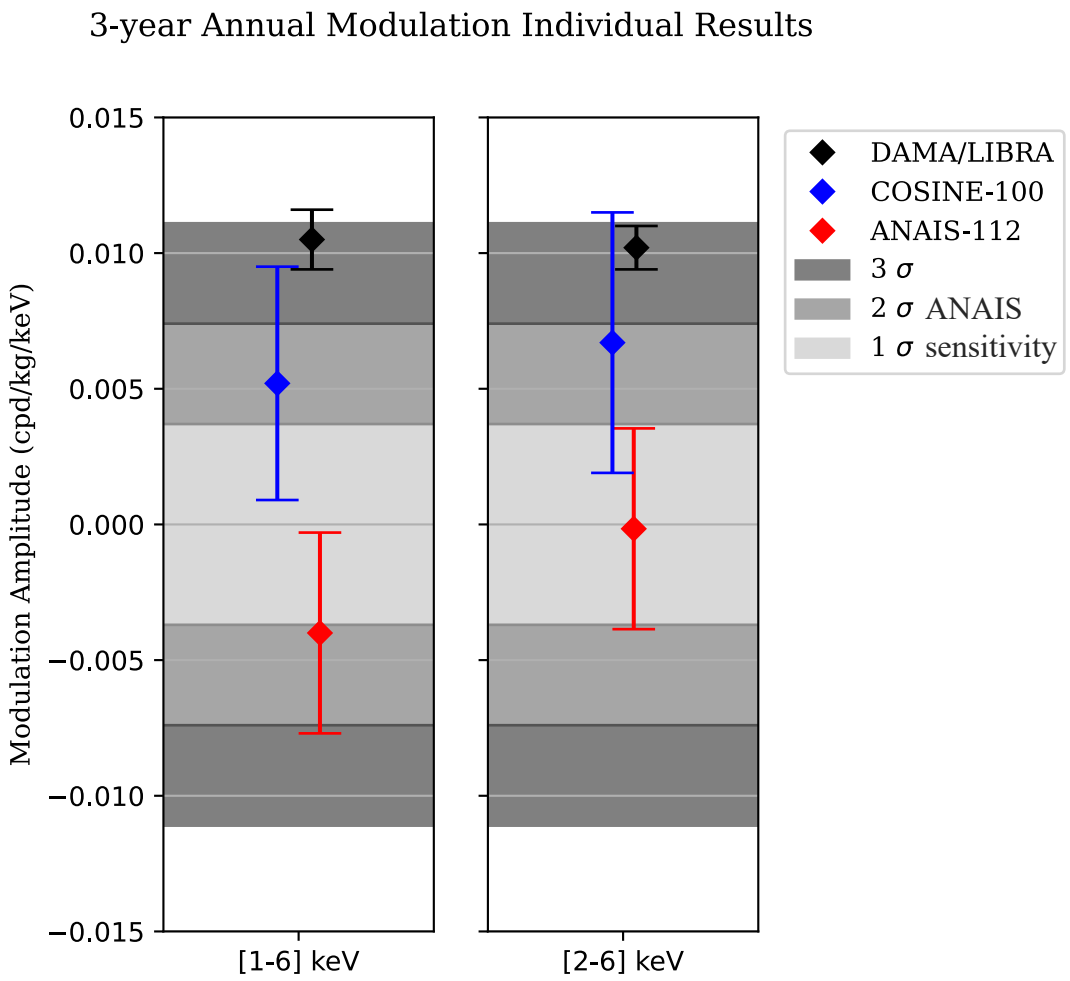
KIMS + DM-ICE = COSINE

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



COSINE-100 and ANAIS-112 3-year Results



- ANAIS-112 incompatible with DAMA at 2.6σ in [1-6] keV and 3.3σ in [2-6] keV
  - Recent updated 3-year results improve this

ANAIS-112: PRD **103**, 102005 (2021), (updated result 2024)

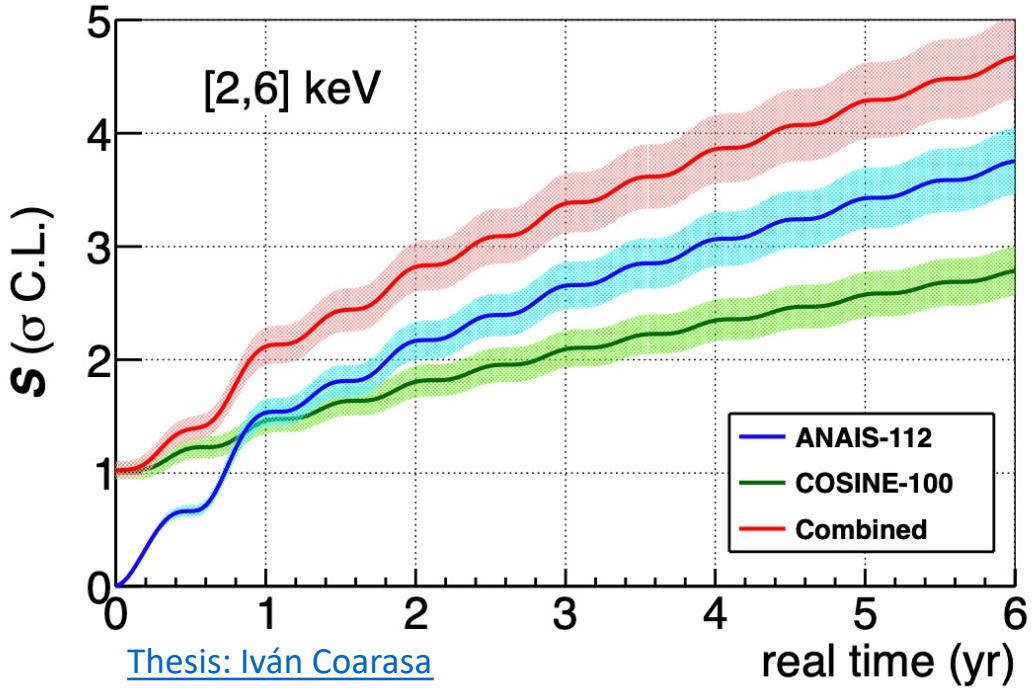
- COSINE-100 3-year dataset lacked statistics to exclude either case
  - Compatible with null and DAMA hypotheses

*COSINE-100: PRD **106**, 052005 2021*

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

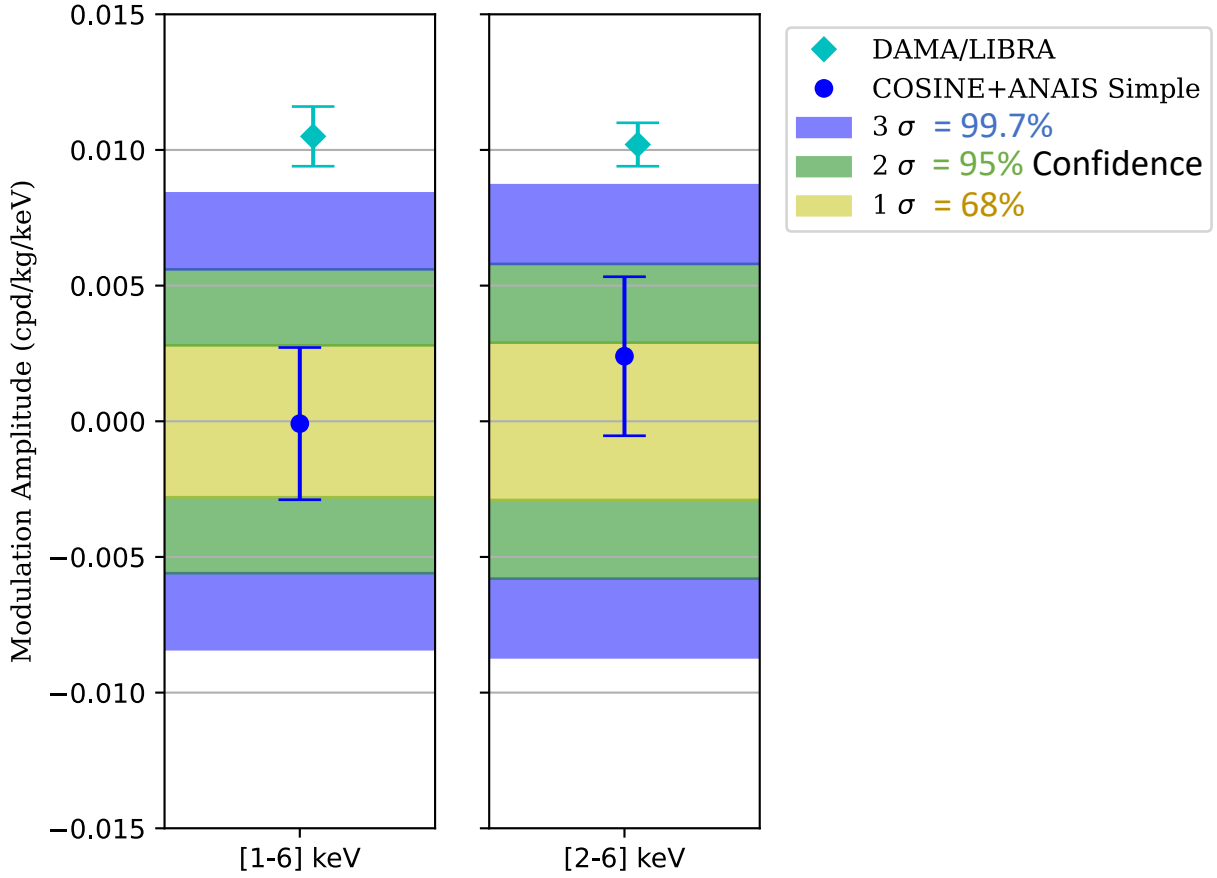
Simple Combination

Letting COSINE and ANAIS be, respectively, $A \pm \delta A$ and $B \pm \delta B$

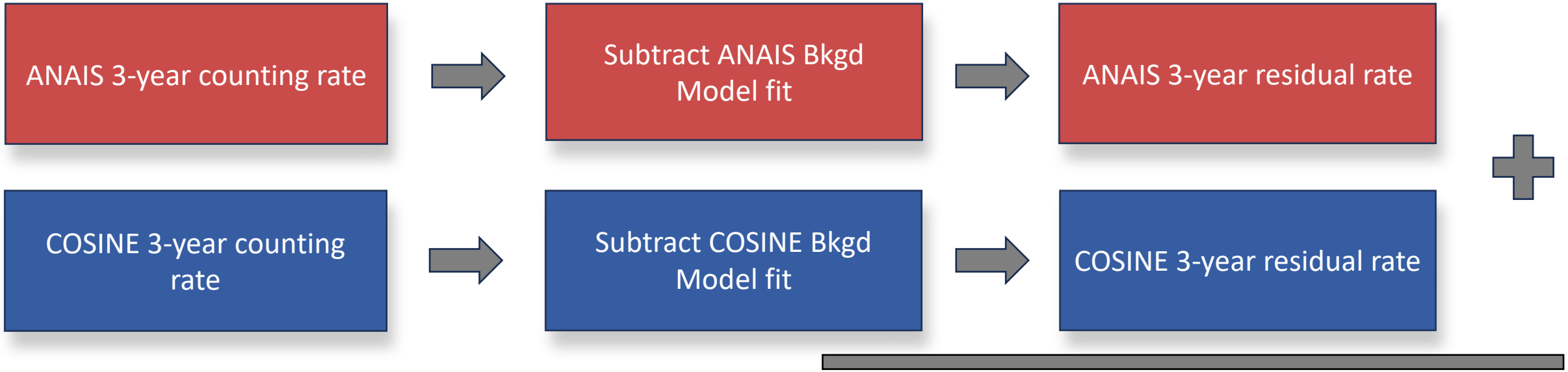
Perform χ^2 Minimization of Independent Experiment Results:

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

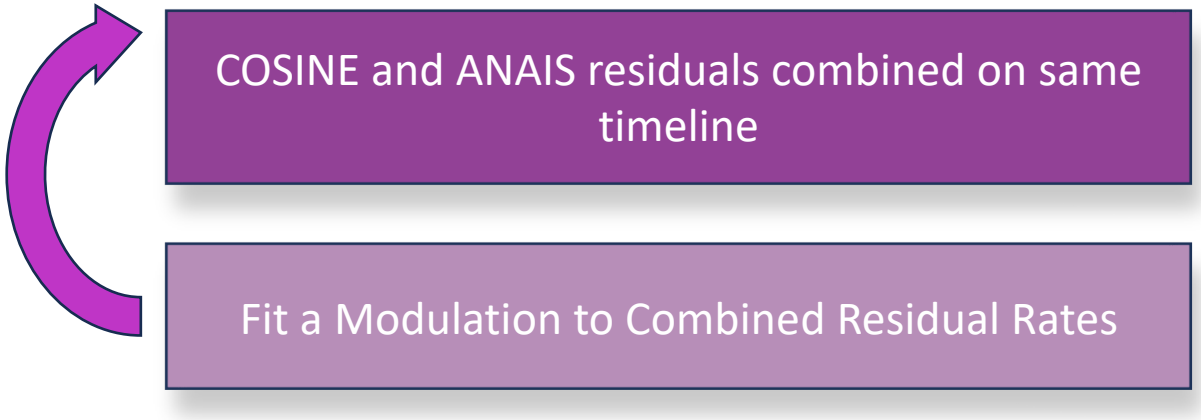
- Assumes
  - Uncertainties are well understood
  - Results are free from systematics
  - Experiments are compatible



Steps for Combination – Residuals Method



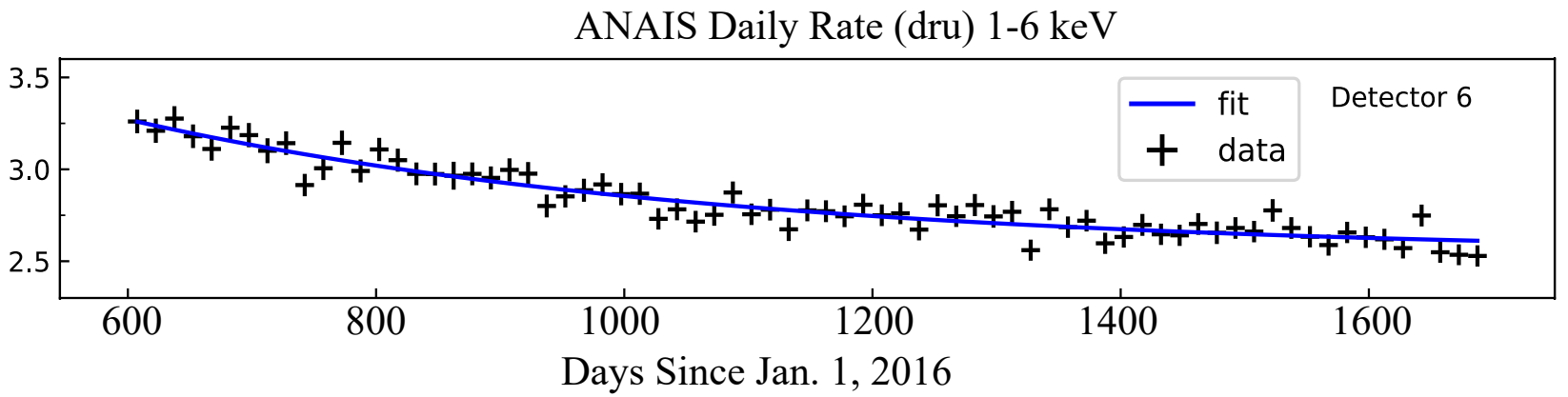
- Confirm individual experiment results
- Compare fitting methodologies
  - Frequentist vs Bayesian
- Confirm data compatibility



ANAIS-112's Background Model

Single Exponential Decay

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



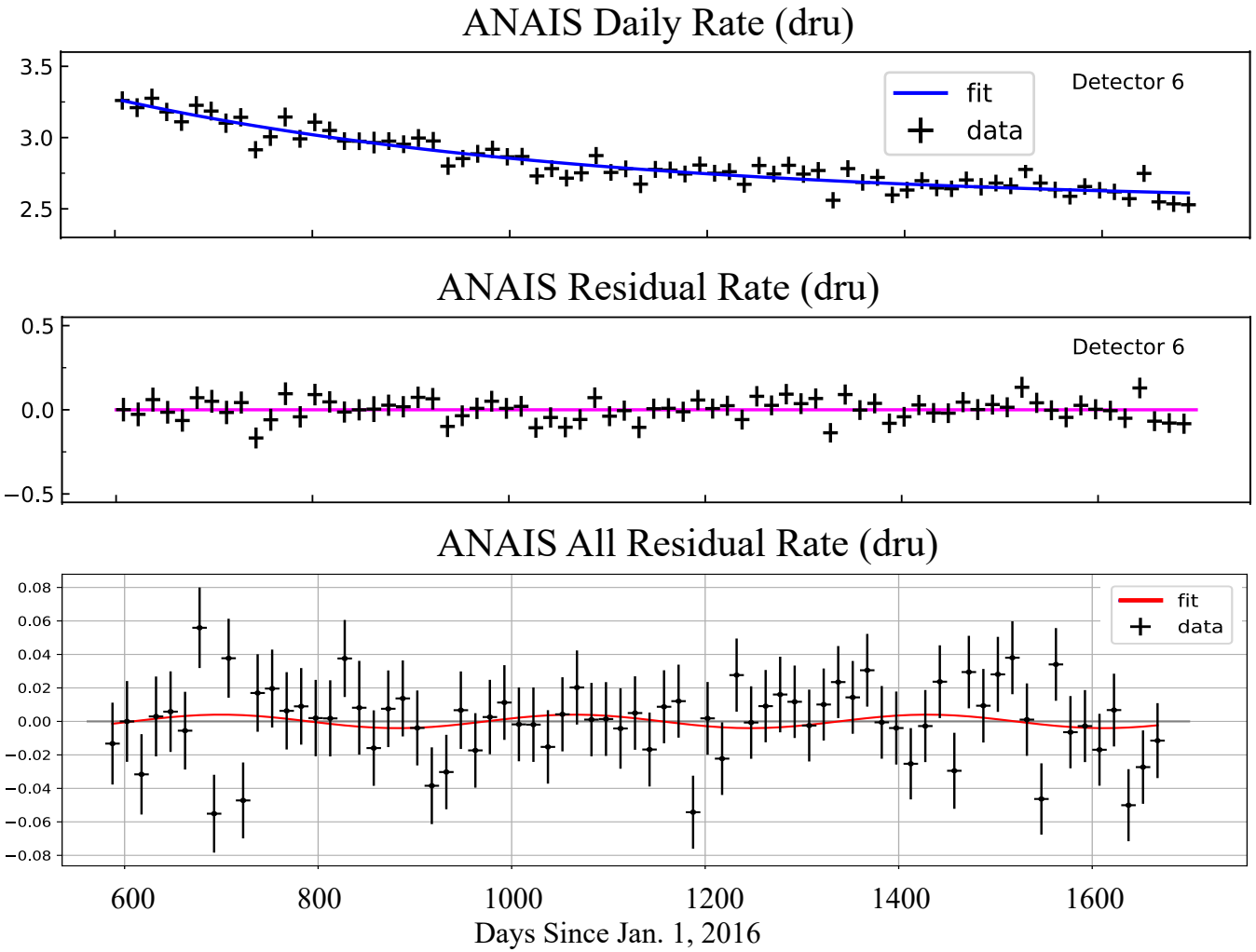
Energy ROI	χ^2 /ndf Single Exponential	χ^2/ndf Monte Carlo PDFs
1-6 keV	1.23	1.11
2-6 keV	1.08	1.05

- 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

ANAIS data – Obtaining Residuals

Residuals Method – ANAIS 1-6 keV



Single Exponential Background Model

- Fit the daily rate with the chosen model as in PRD **103**, 102005 (2021)

Residuals

- Done for all detectors, though only detector 6 shown here

Modulation Fit

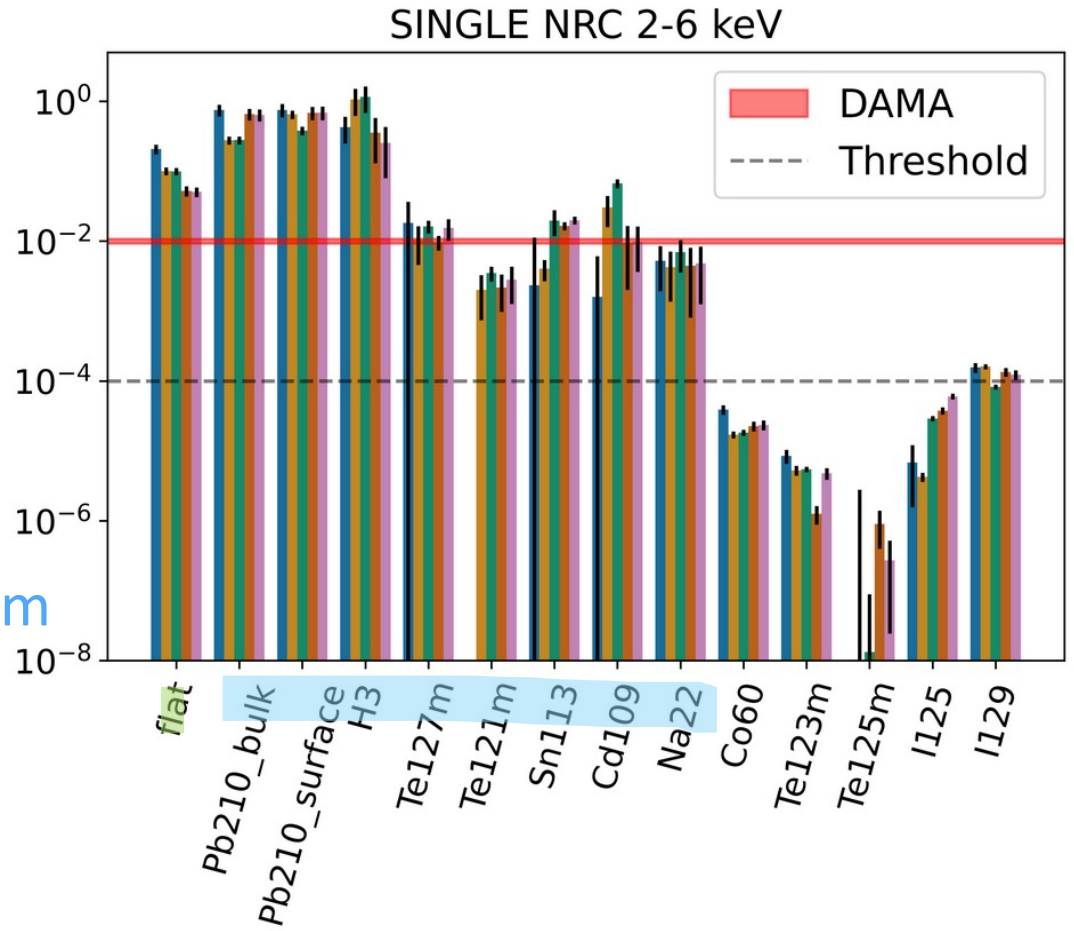
- Combine detector residuals and fit a modulation

Energy ROI	This Study (dru)	ANAIS (dru)
1-6 keV	-0.0040 ± 0.0037	-0.0039 ± 0.0037
2-6 keV	-0.00016 ± 0.0037	-0.0015 ± 0.0037

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

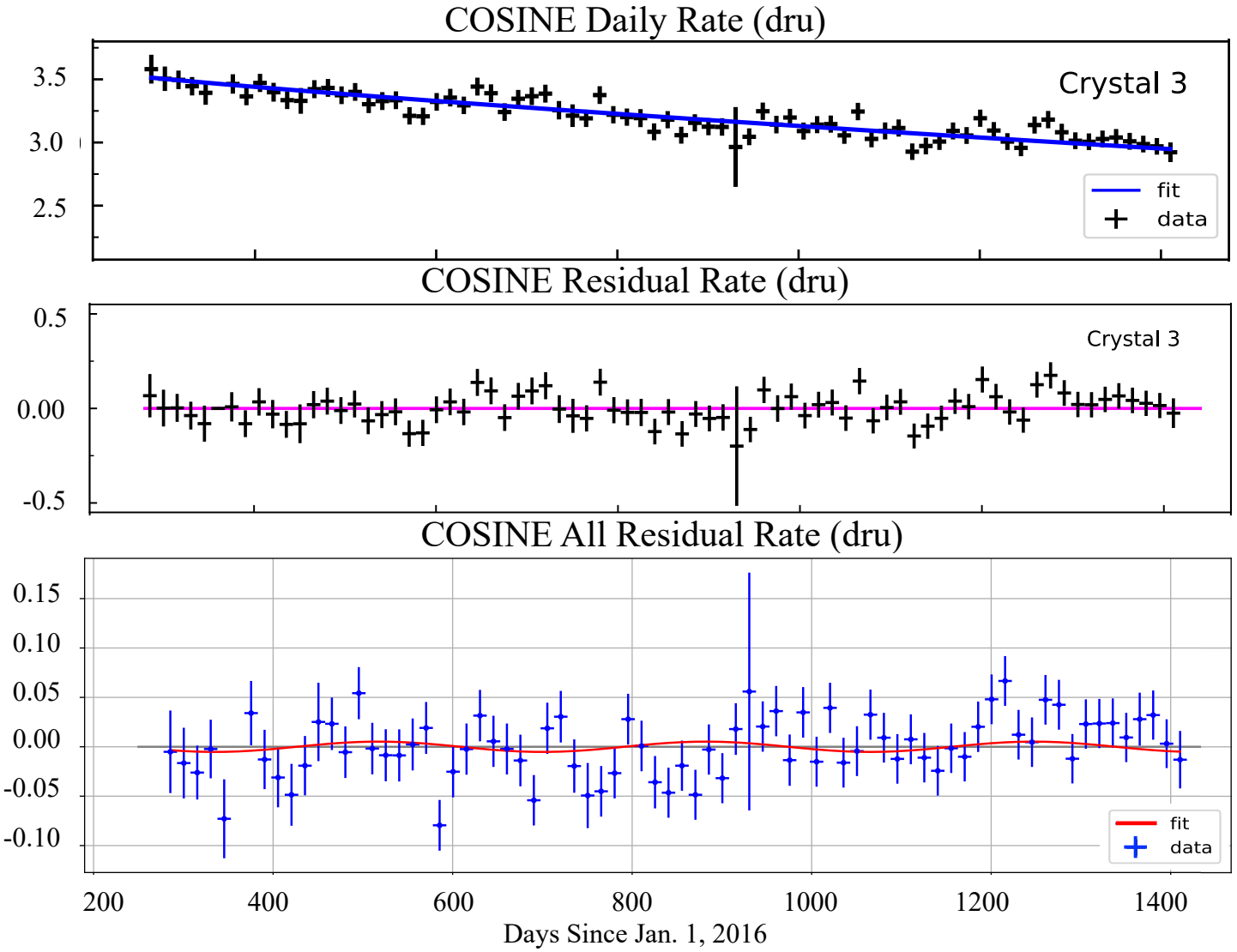


Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days

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

COSINE-100 Background 2021

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

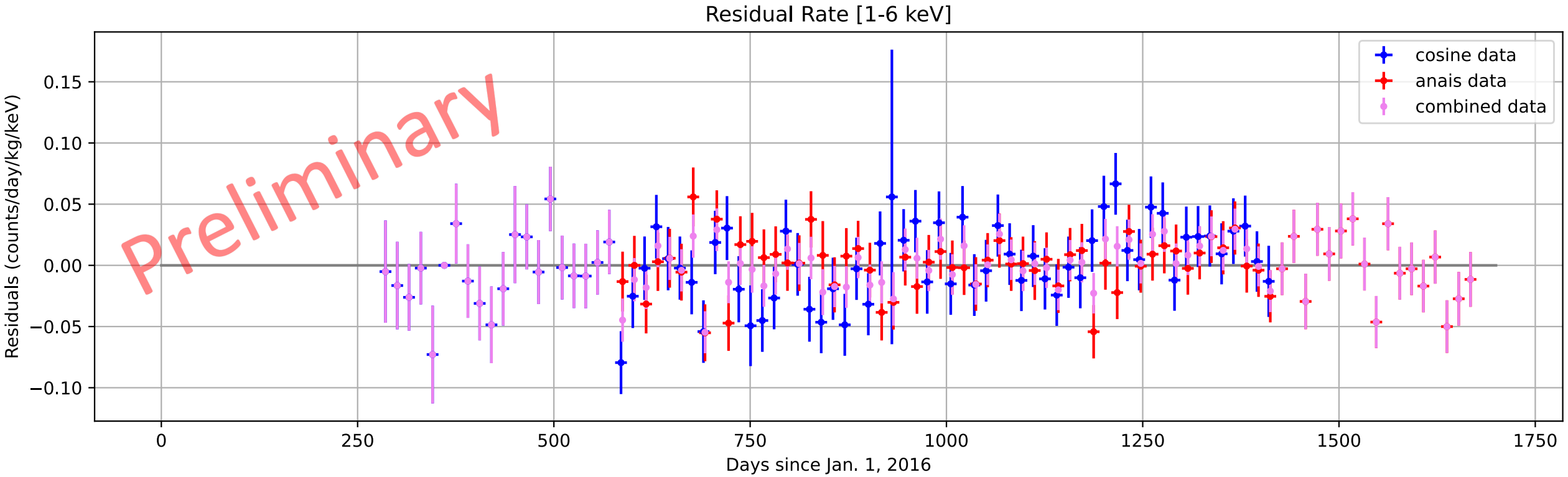
- Done for all crystals, though only crystal 3 shown here

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

Combine Data and χ^2 Fit

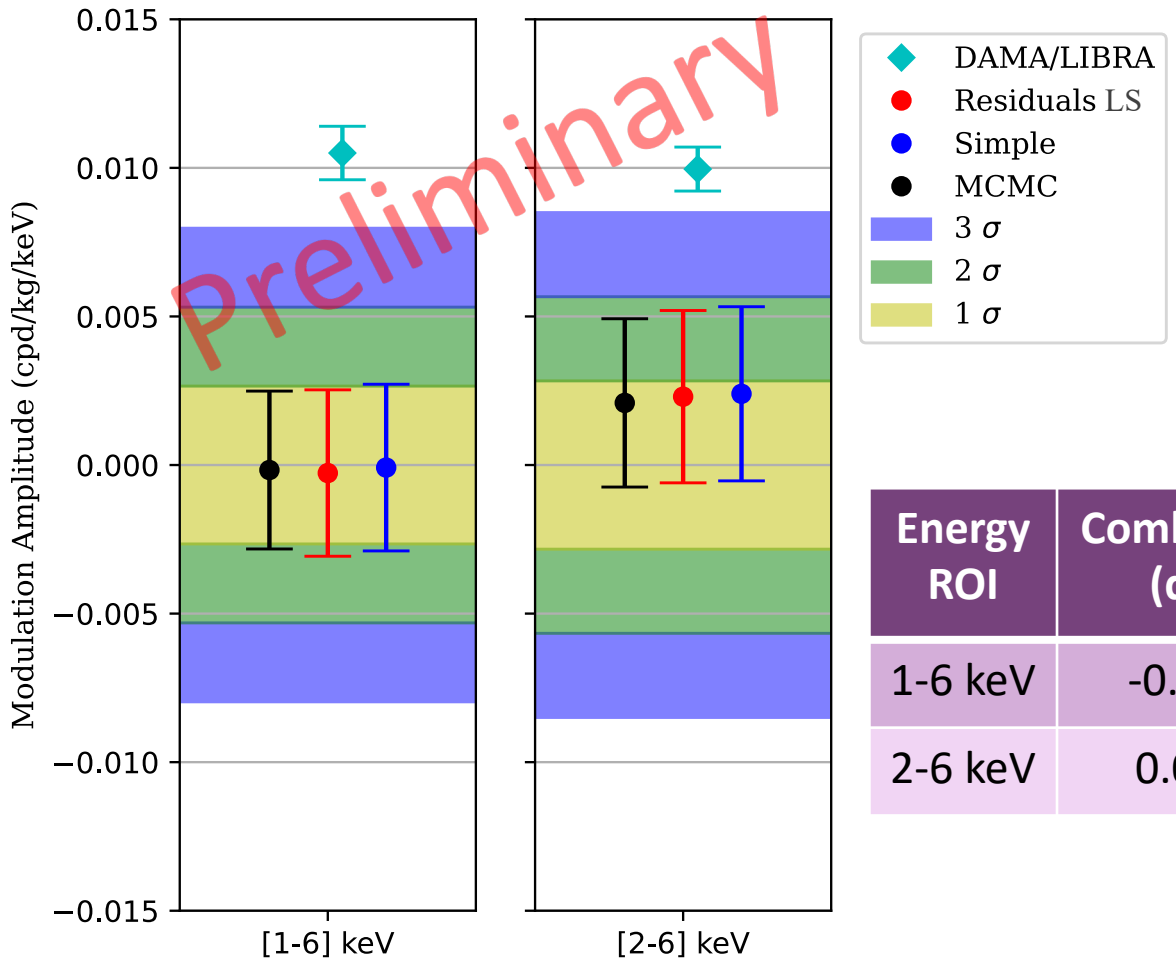


Perform a modulation fit with:
-Least-Squares Method with χ^2 Statistics
-MCMC Method with Bayesian Statistics

Plot with equal binning and timeline

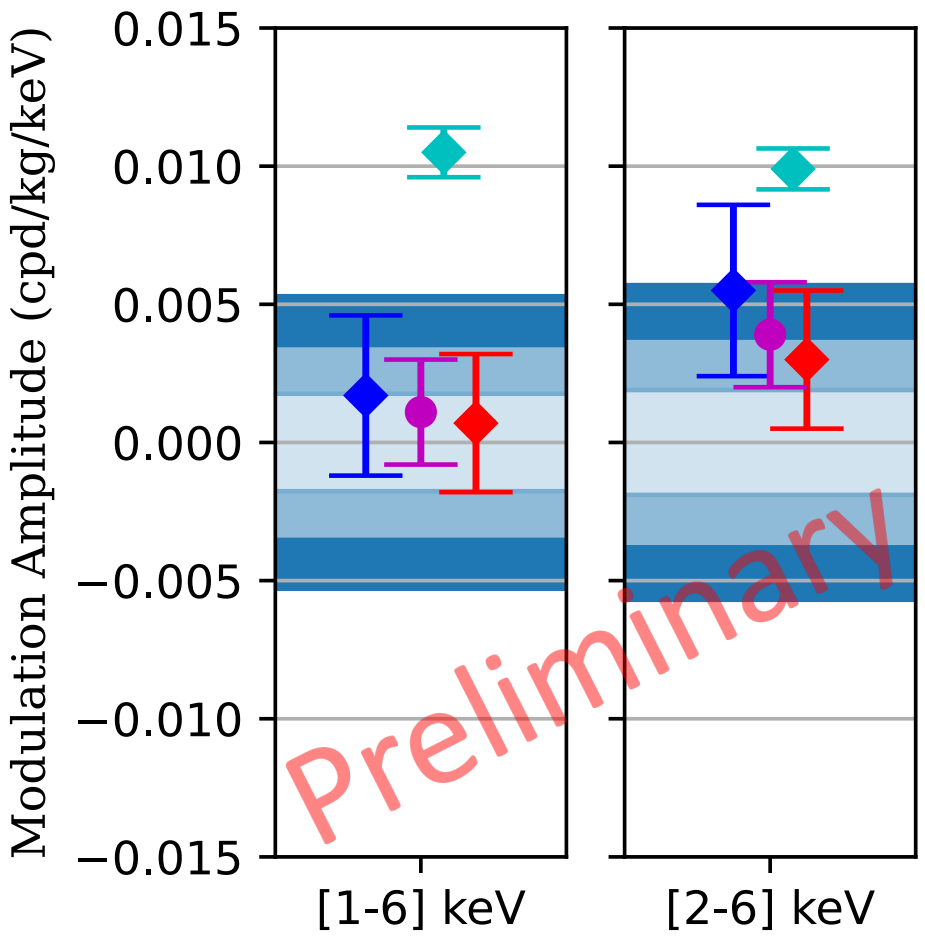
Preliminary Result

- 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

6 years combined sensitivity



*see previous two talks by Iván and SeungMok

- Expected sensitivity from 6 years of simulated data for the combined analysis
- Sensitive to DAMA at 5.3σ in 1-6 keV and 5.0σ in 2-6 keV

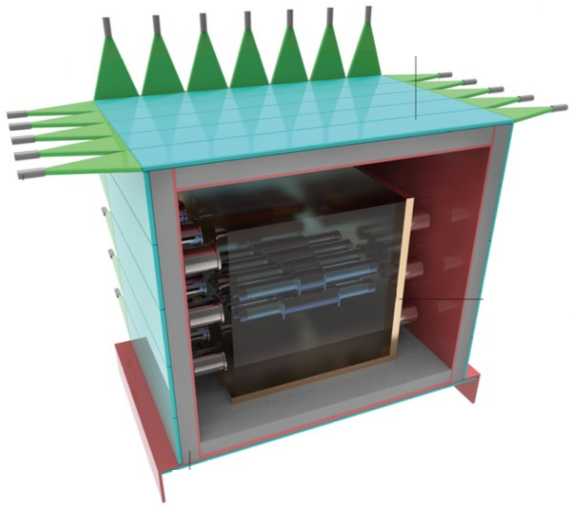
Energy ROI	*COSINE 6-year (dru)	*ANAIS 6-year (dru)	Combine Simple
1-6 keV	0.0017 ± 0.0029	0.0007 ± 0.0025	0.0011 ± 0.0019
2-6 keV	0.0053 ± 0.0031	0.0030 ± 0.0025	0.0039 ± 0.0019

ANAIS-112: the most sensitive experiment to test the DAMA/LIBRA signal in a model independent way
Iván Coarasa Casas

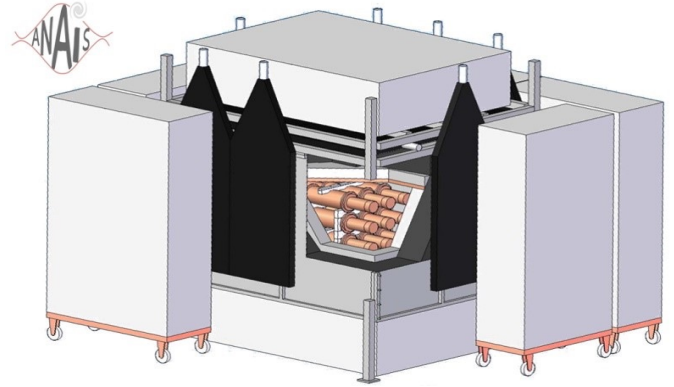
Dark Matter Annual Modulation Search in COSINE-100 Full Dataset and Beyond *SeungMok Lee*
Palazzo dell'Emiciclo, Sala Ipogea 15:00 - 15:20

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 sensitivity to DAMA for 3-years data



- Combined 3-year analysis finds
  no modulation at 3.6σ in 1-6 keV
  and 2.6σ in 2-6 keV



- Expected 6-year combination to find
  no modulation at 4.5σ in 1-6 keV
  and 2.8σ in 2-6 keV

Thank you for your attention!

Acknowledgements

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Center for Underground Physics

Universidad Zaragoza 1542

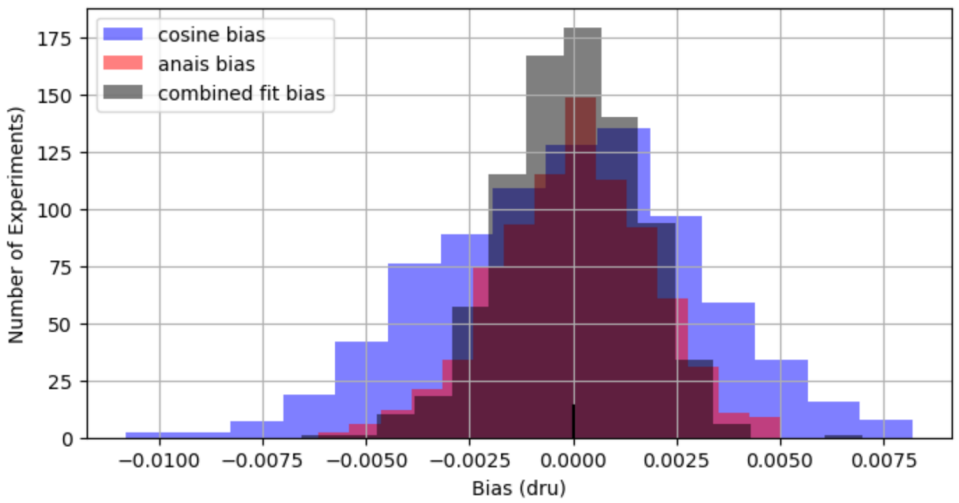
Wright Laboratory

Backup

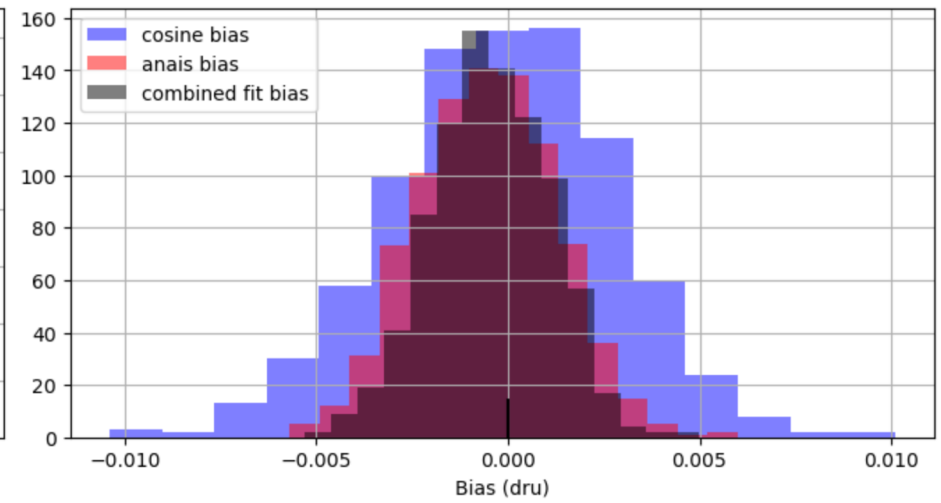
Pseudo Study

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

Null Hypothesis Case



DAMA Case

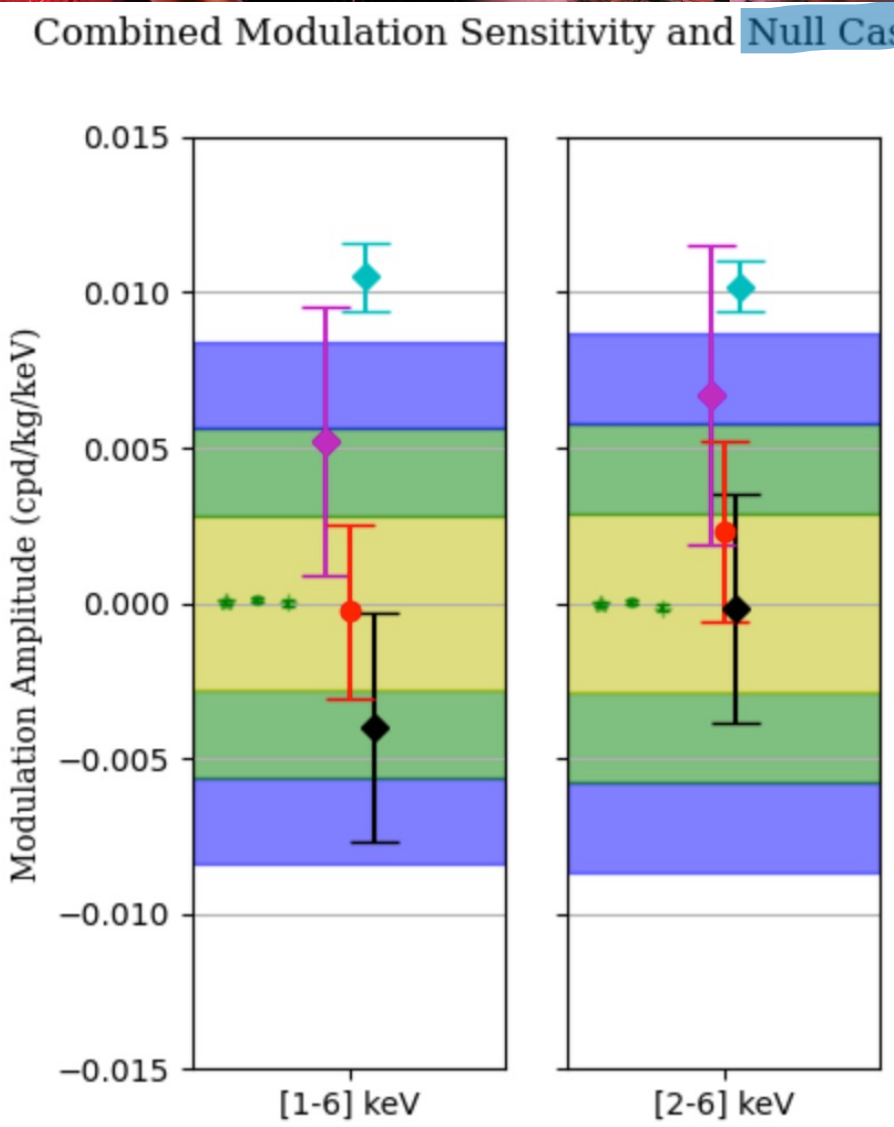


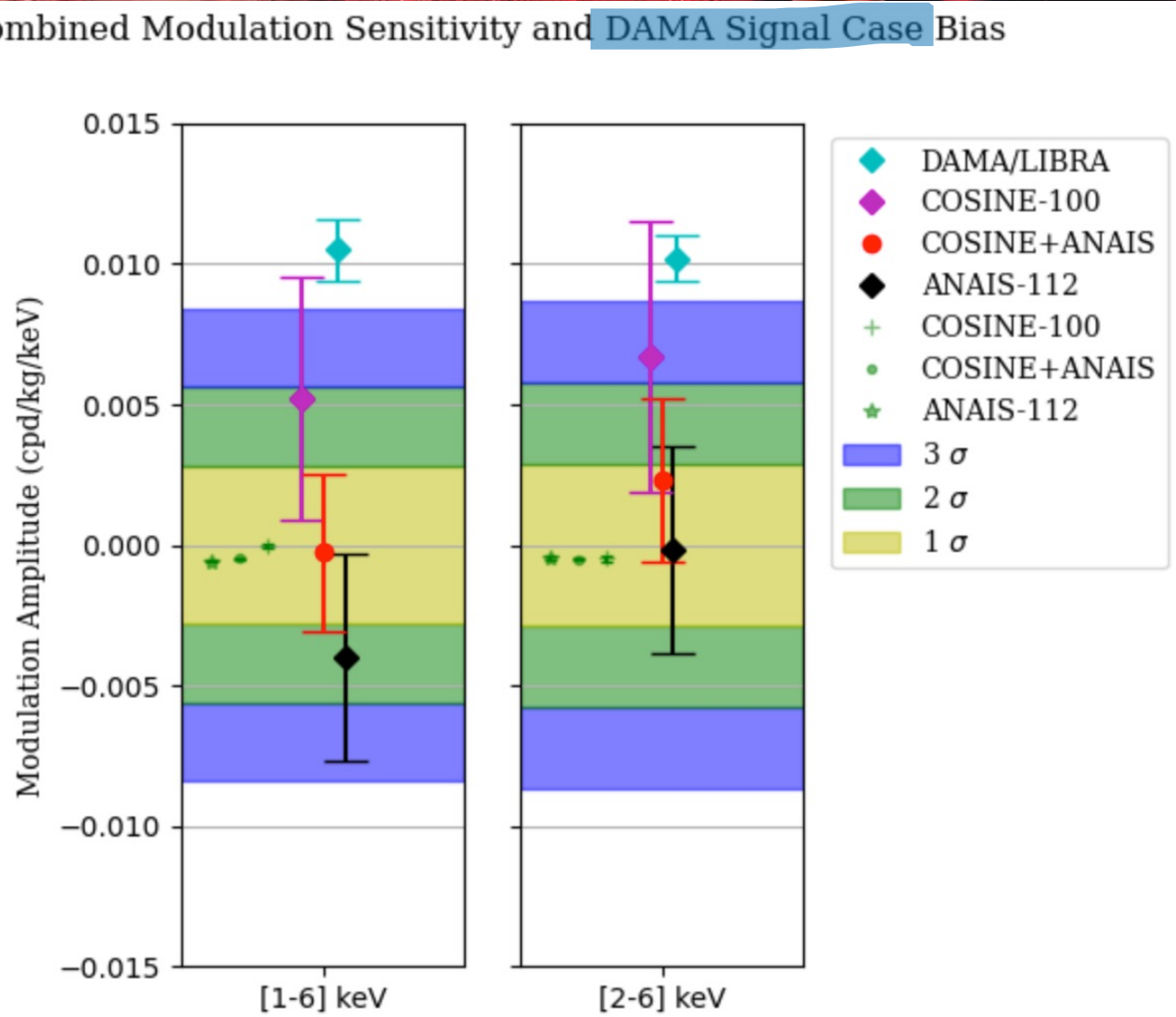
Model	Bias [0.0 dru] 10^{-4}	Bias [0.0105 dru] 10^{-4}	Standard Deviation 10^{-4}
COSINE SETZ Bkgd	0.2 +/- 1	-0.3 +/- 0.9	31
ANAIS Single Exp.	0.3 +/- 0.6	5 +/- 0.6	18
Combined Residuals	1 +/- 0.5	-4 +/- 0.5	15

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

~1000 Experiments

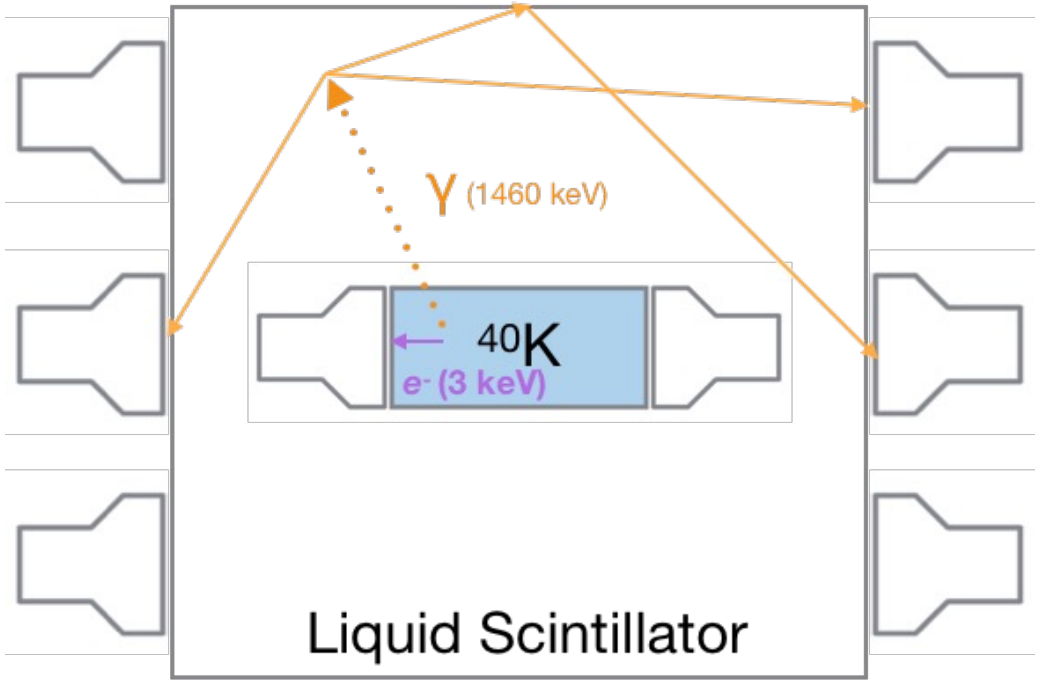
Visual Respresentation of Bias Effect

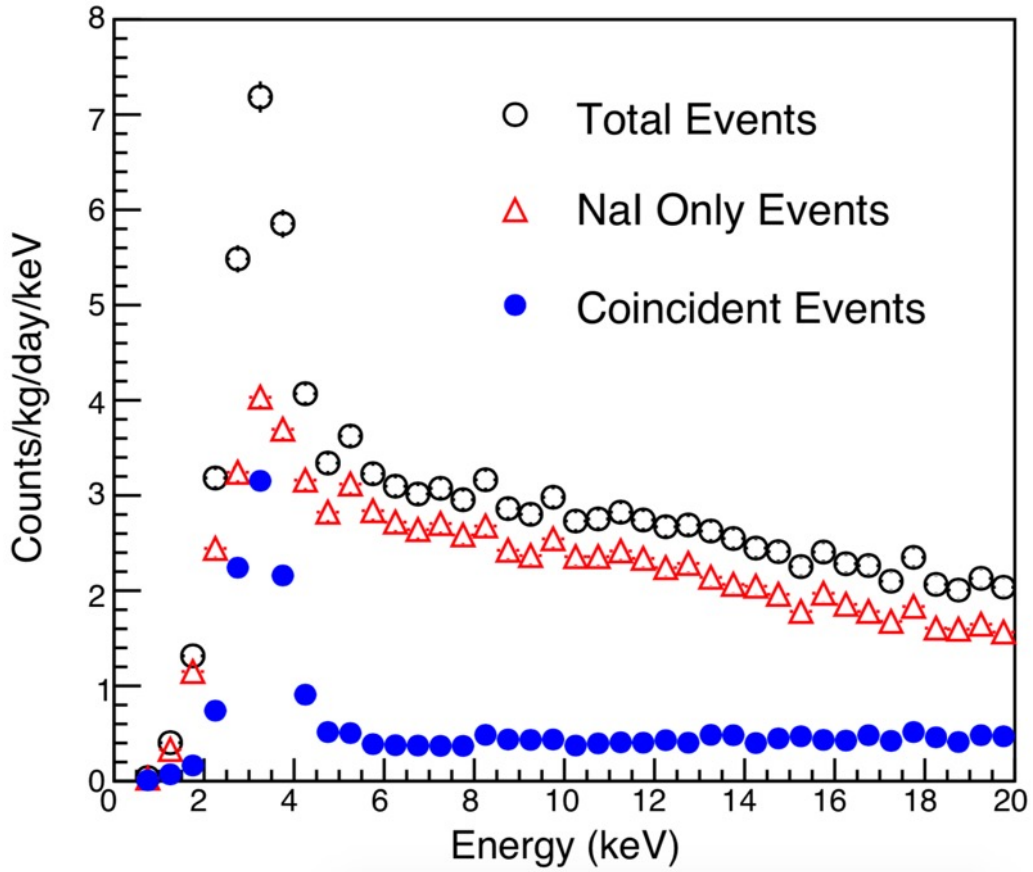




Liquid Scintillator Veto

- 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



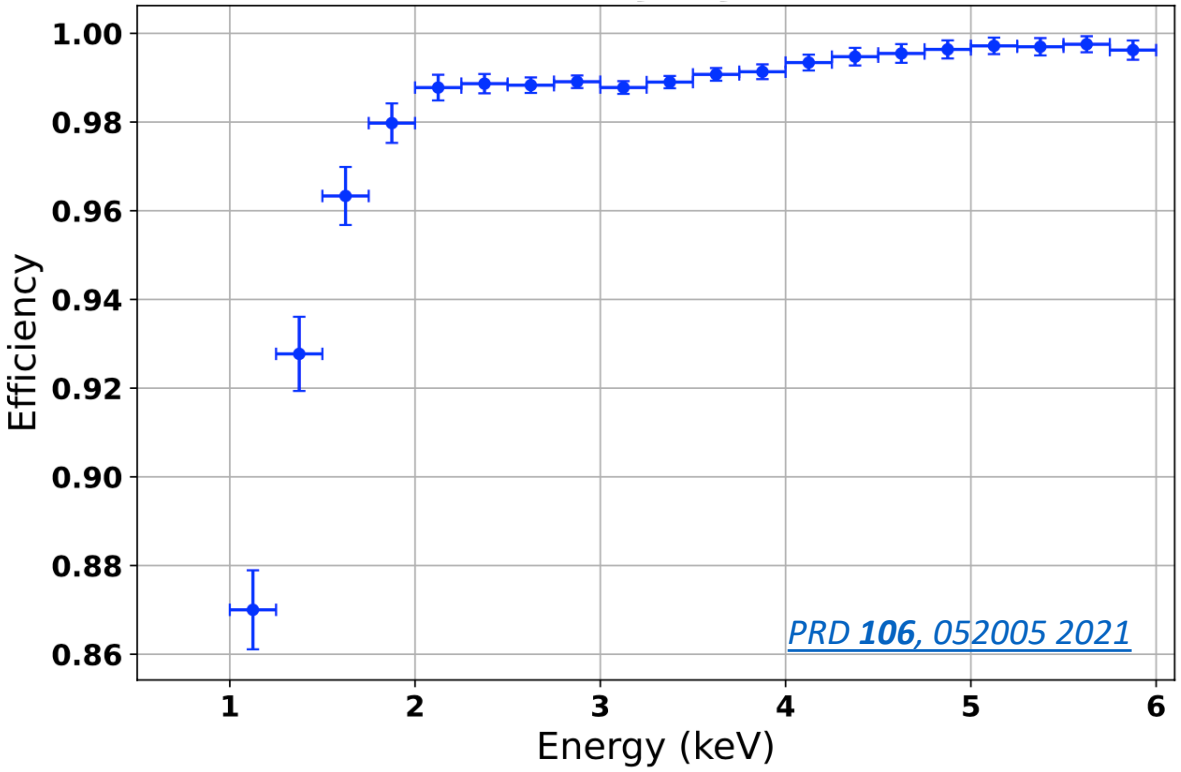


COSINE-100: Nuclear Instruments 1006:165431 (2021)

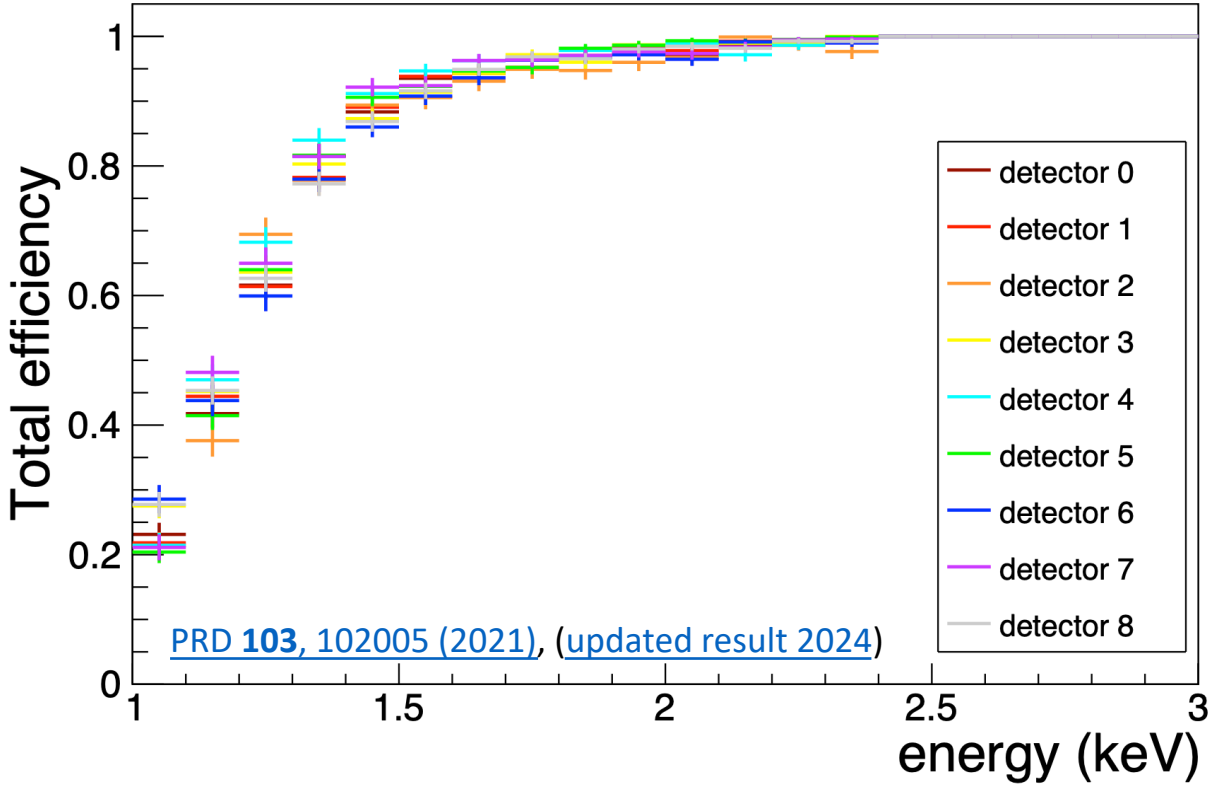
Efficiency Differences

- 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

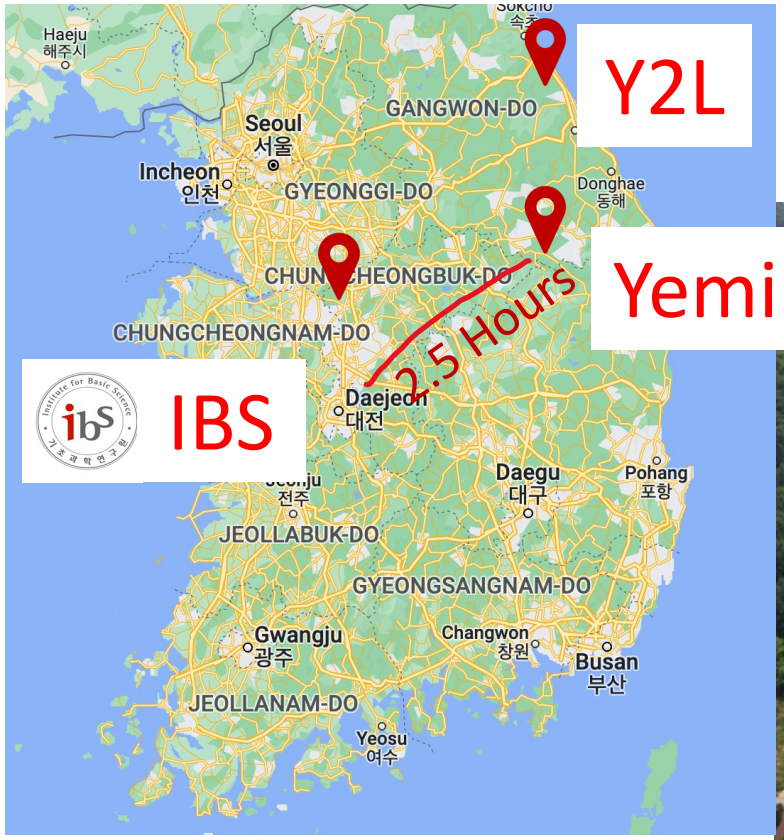
- COSINE

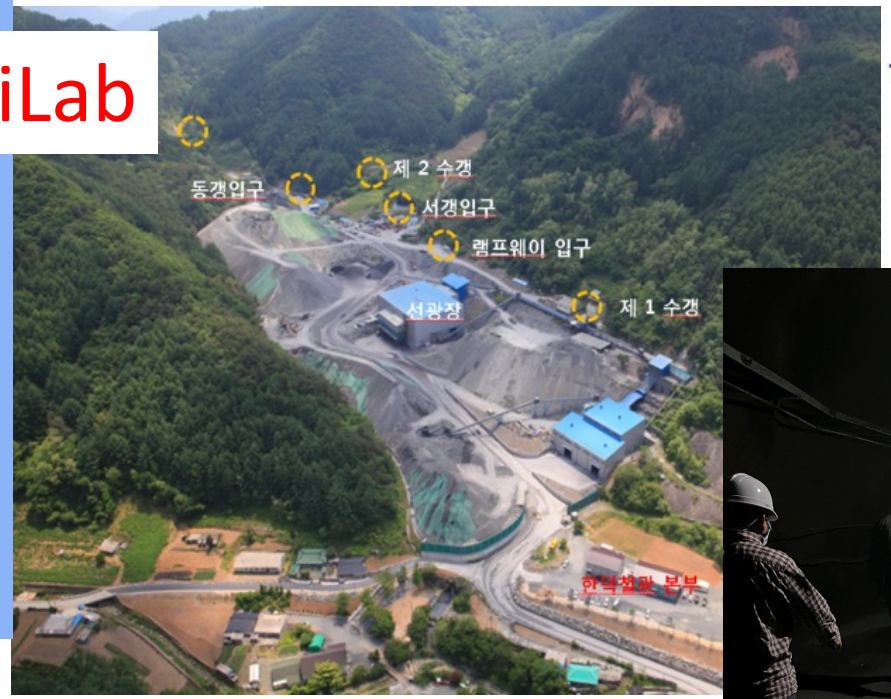
Crystal	Mass (kg)	Size (diameter×length) (inches)	Powder Type	Exposure Time (years)	Radioactivity cooling time at Y2L (years)
Crystal-1	8.3	5.0×7.0	AS-B	2.17	3
Crystal-2	9.2	4.2×11.0	AS-C	0.92	2.75
Crystal-3	9.2	4.2×11.0	AS-WSII	>0.92	1.2
Crystal-4	18.0	5.0×15.3	AS-WSII	1.83	0.5
Crystal-6	12.5	4.8×11.8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

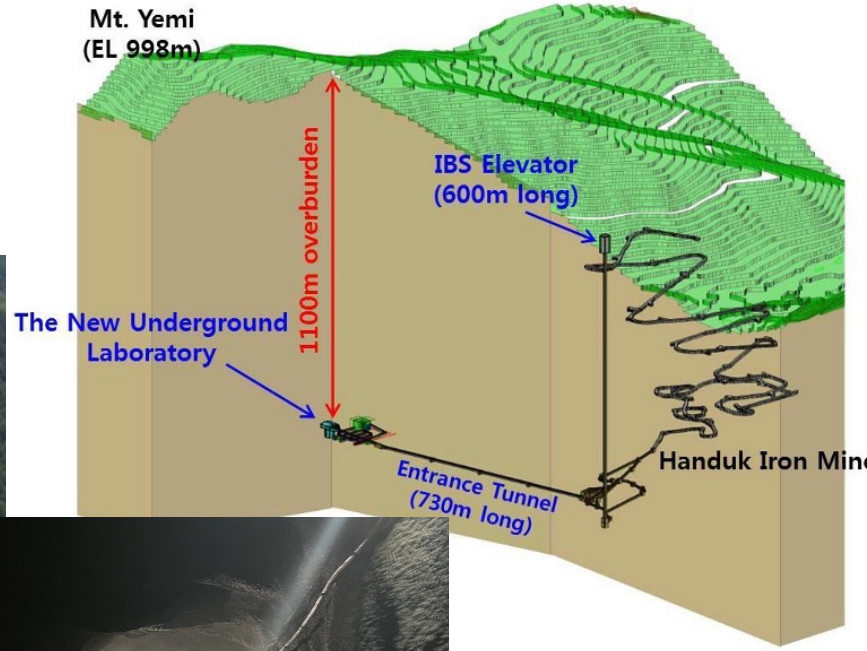
Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days

The COSINE-100U

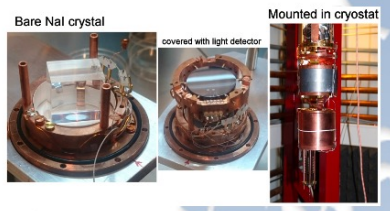
Y2L, Yangyang, South Korea → YemiLab, Jeongseon, South Korea







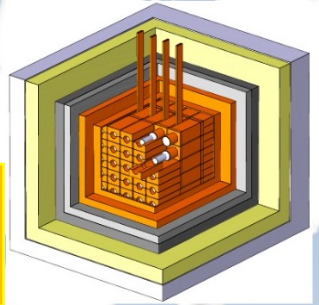
NaI(Tl) Experiments Around the World!

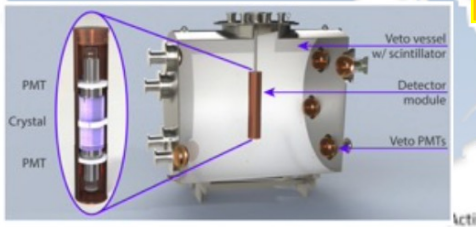


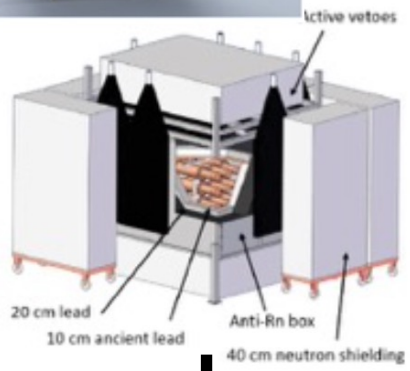
COSINUS @ LNGS

DAMA @ LNGS

SABRE @ LNGS



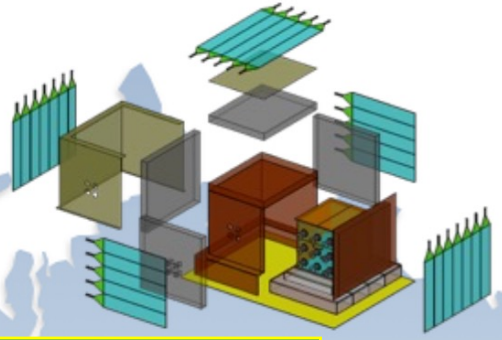




ANAIS @Canfranc

In Data-taking

PRD **103**, 102005 (2021)
(updated result 2024)



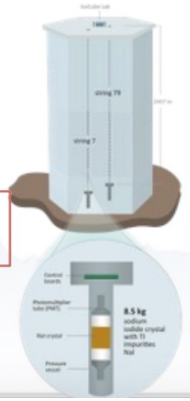
KIMS/COSINE @ Yangyang

PRD **103**, 102005 (2021)
Phys. Rev. D **106**, 052005 – 2022

COSINE-100U at YemiLab

PICO-LON @ Kamioka

SABRE @ Stawell



DM-Ice @ South Pole