Dark matter search via annual modulation

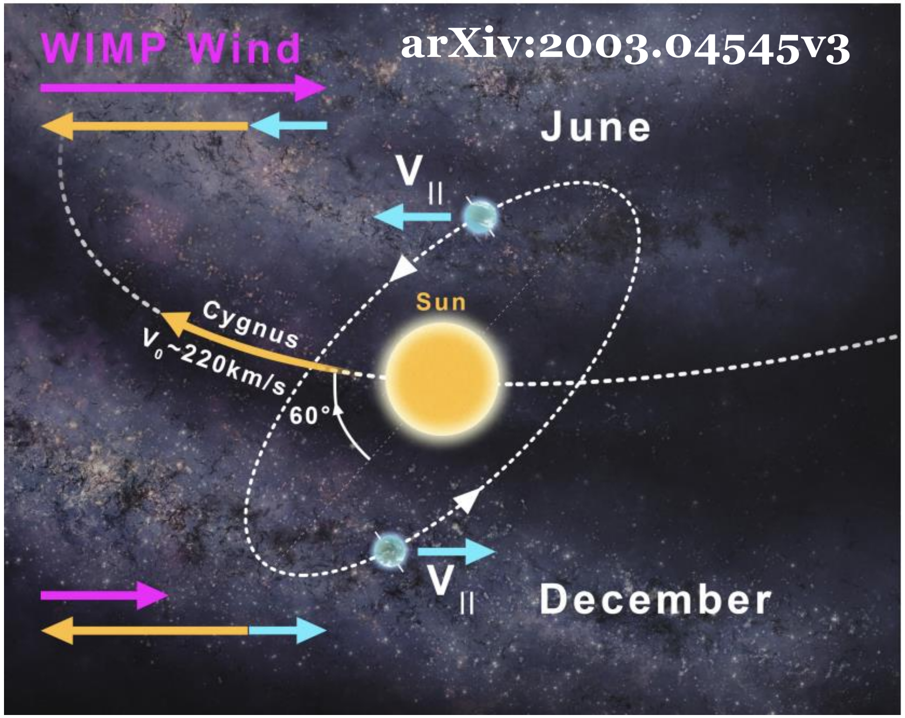
Institute for Basic Science

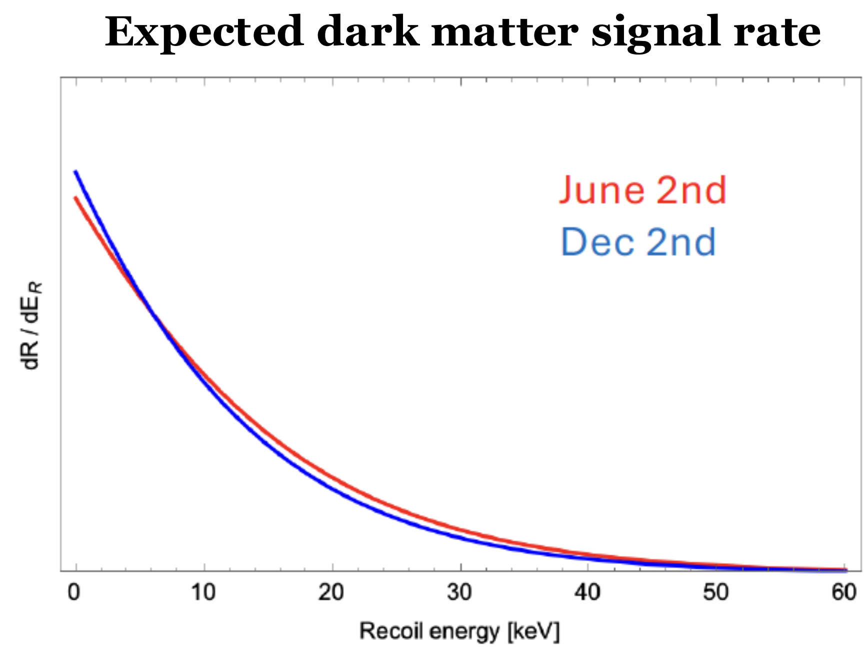
CENTER FOR UNDERGROUND PHYSICS

Hyunsu Lee
Institute for Basic Science
Center for Underground Physics

The 22nd Lomonosov conference
August 26th, 2025

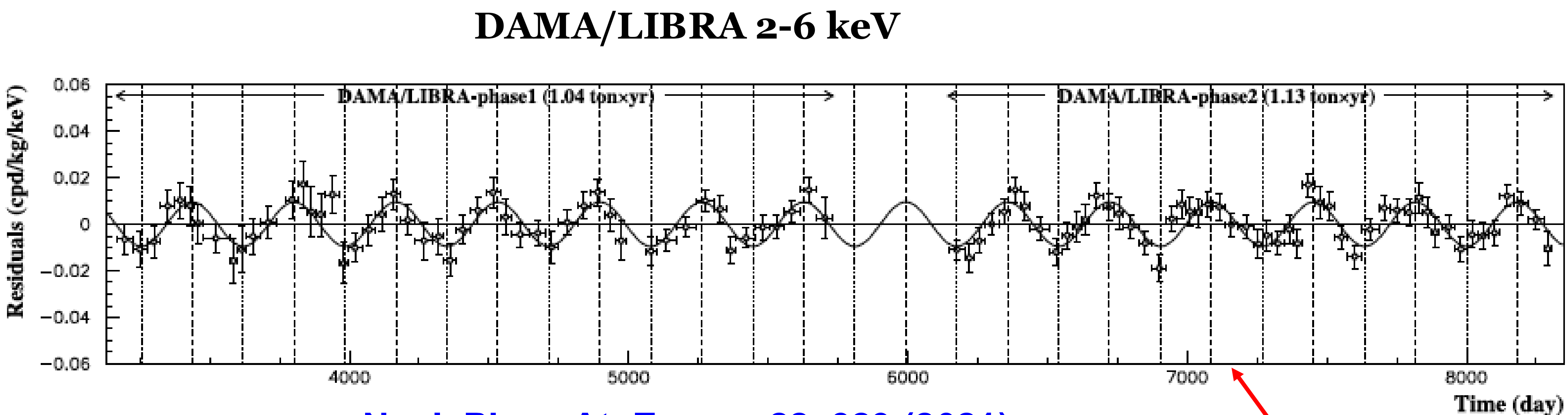
Dark matter annual modulation





- The Earth's orbit creates a seasonal "WIMP wind"
  - Maximum velocity expected between June 2nd and 3rd (~152.5 days)
- For a give energy bin : $R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}(t-\varphi)\right)$

A Persistent Signal : The DAMA/LIBRA Anomaly



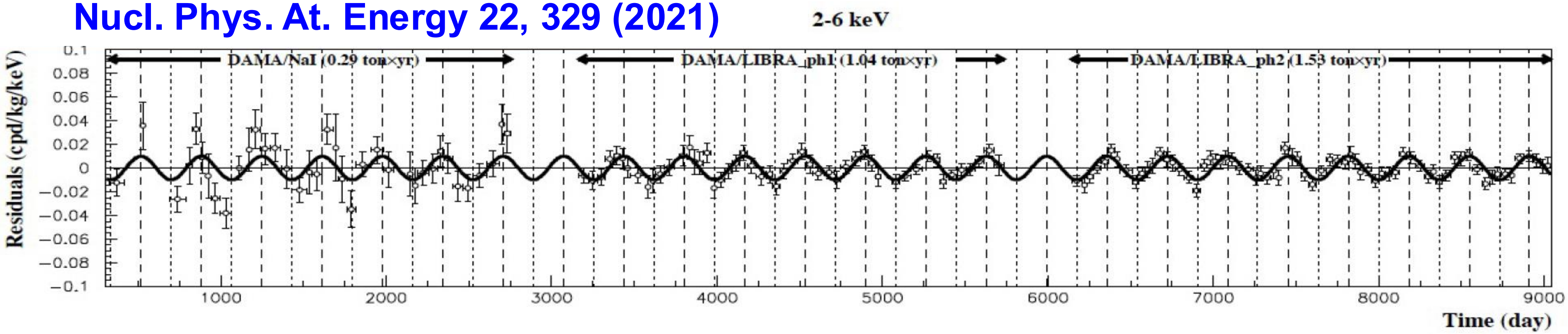
Nucl. Phys. At. Energy 22, 329 (2021)

$$R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}(t-\varphi)\right)$$

The DAMA/LIBRA Experiment & Claim

- 250 kg **NaI(Tl) crystal** array at Gransasso (Italy)
- Observed clear annual modulation for over 25 years
  - Claimed dark matter discovery

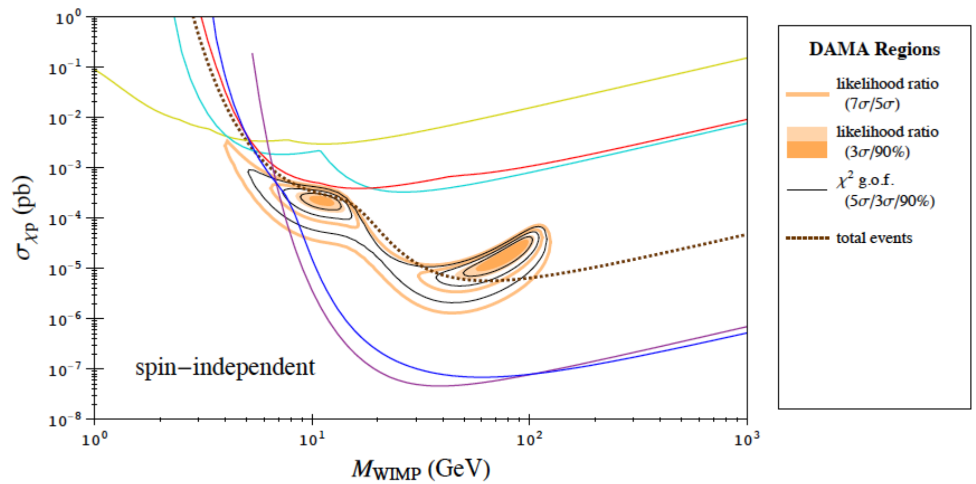
Nucl. Phys. At. Energy 22, 329 (2021)



The DAMA/LIBRA Experiment & Claim

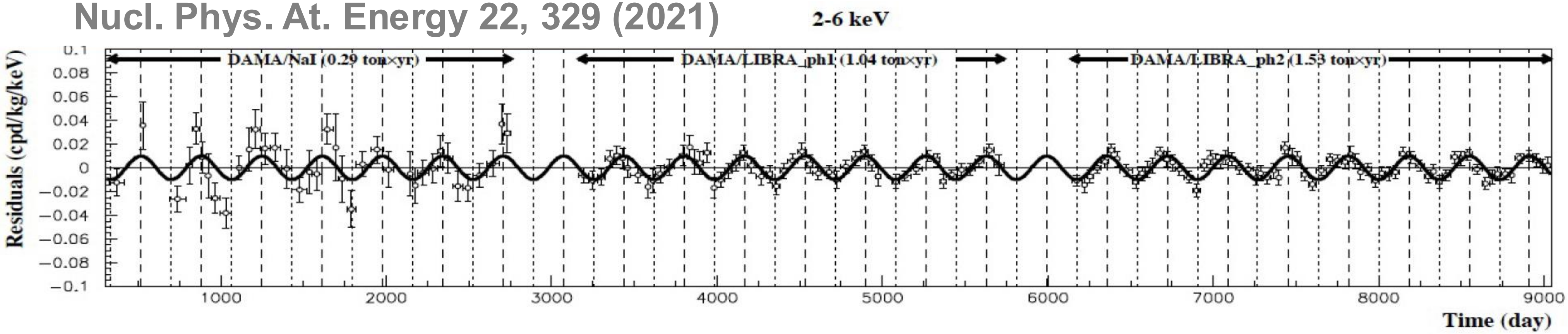
- 250 kg **NaI(Tl) crystal** array at Gransasso (Italy)
- Observed clear annual modulation for over 25 years
  - ❖ Claimed dark matter discovery

JCAP 04, 010 (2009)



Greatly matched with Standard-halo model of the dark matter distribution

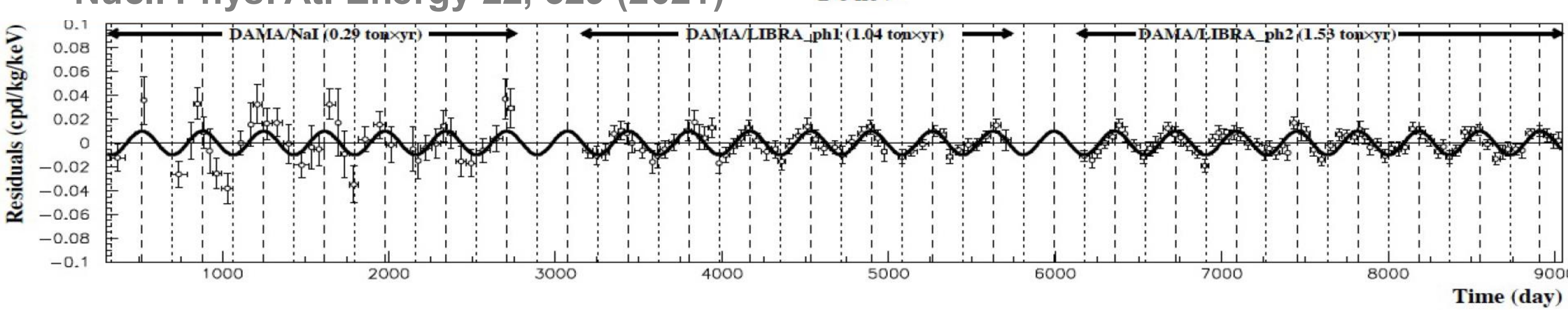
Nucl. Phys. At. Energy 22, 329 (2021)



The DAMA/LIBRA Experiment & Claim

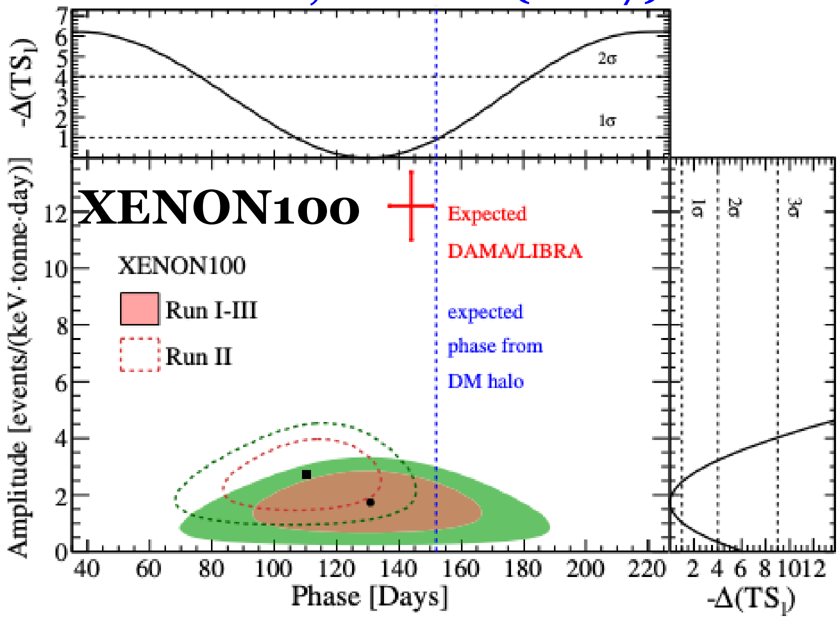
E (keV)	A (counts/day/kg/keV)	ϕ (day)	C.L.
$1 \sim 3$	0.0191 ± 0.0020	152.5 **(fixed)**	9.7σ
	0.0191 ± 0.0020	149.6 ± 5.9	9.6σ
$1 \sim 6$	0.01048 ± 0.00090	152.5 **(fixed)**	11.6σ
	0.01058 ± 0.00090	144.5 ± 5.1	11.8σ
$2 \sim 6$	0.00996 ± 0.00074	152.5 **(fixed)**	13.4σ
	0.01014 ± 0.00074	142.4 ± 4.2	13.7σ

Nucl. Phys. At. Energy 22, 329 (2021)

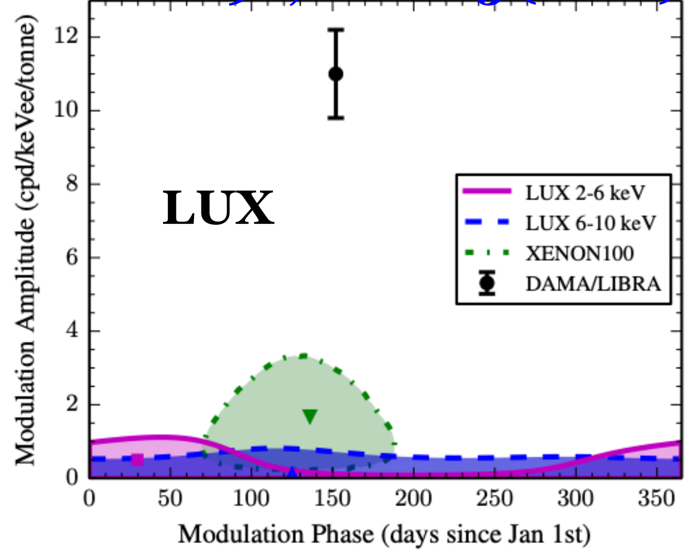


Annual modulation search with different target

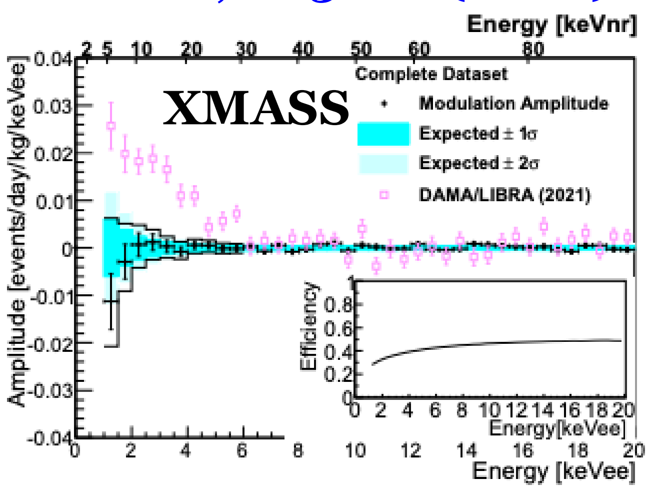
PRL 118, 101101 (2017)



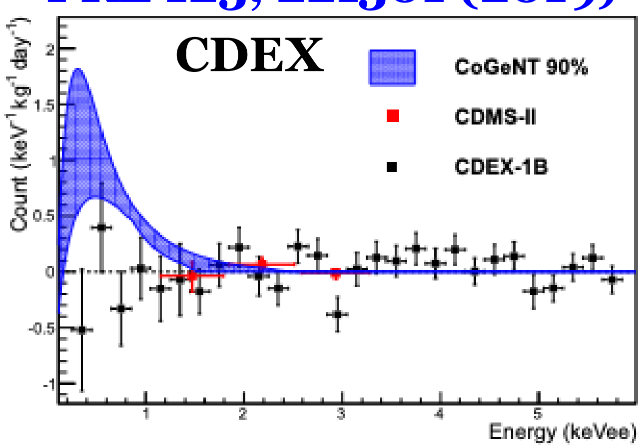
PRD 98, 062005 (2018)



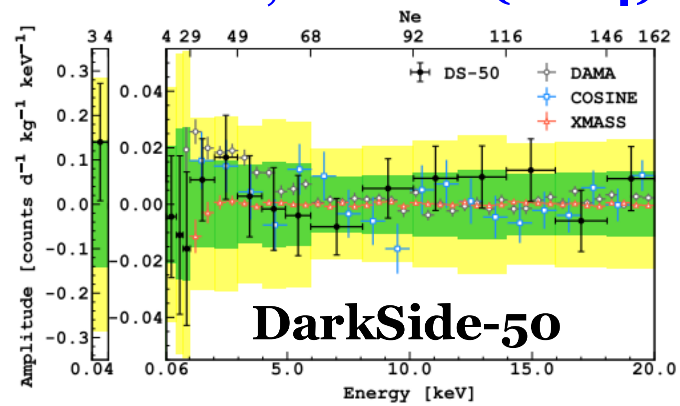
PRD 108, 083022 (2022)



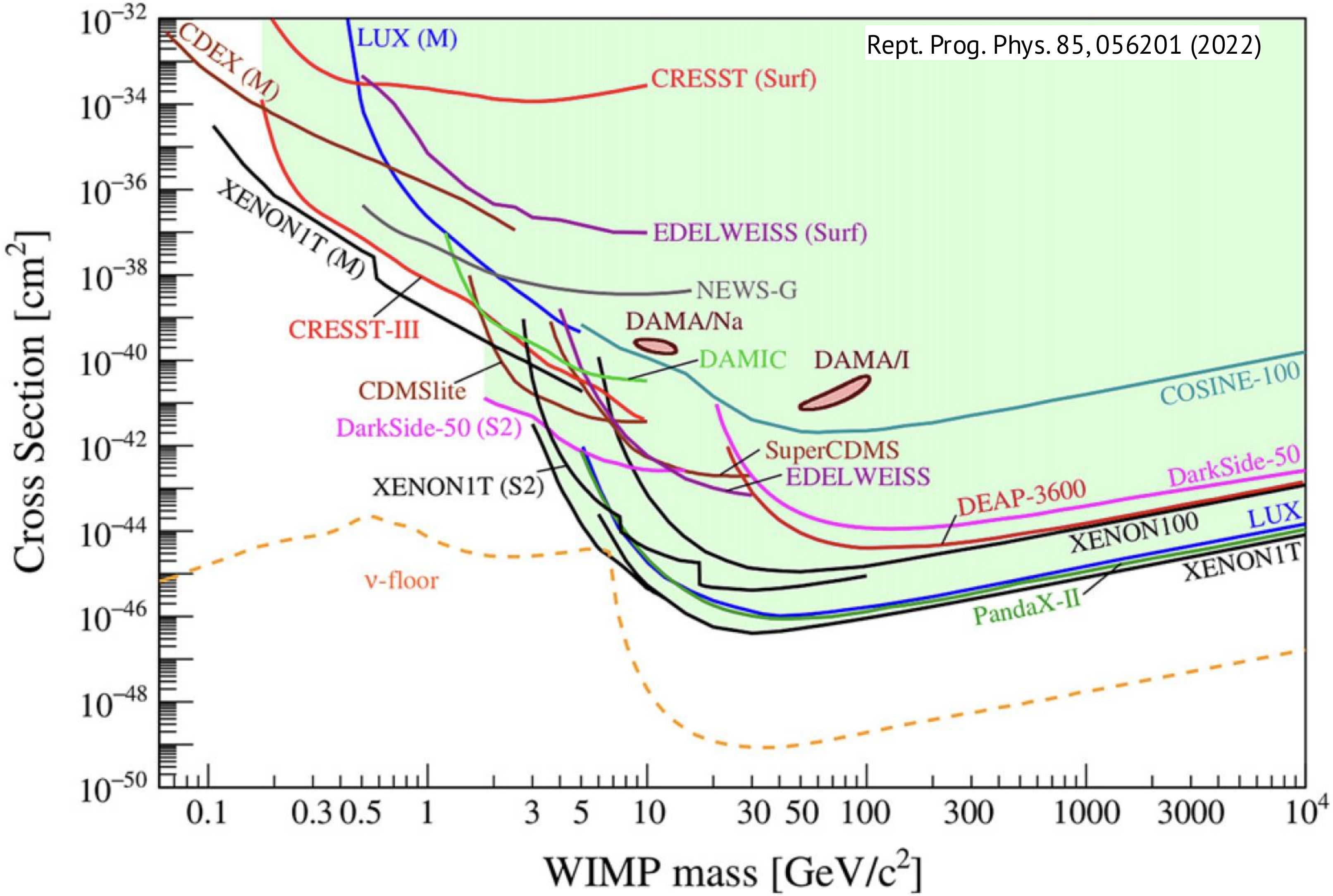
PRL 123, 221301 (2019)



PRD 110, 102006 (2024)

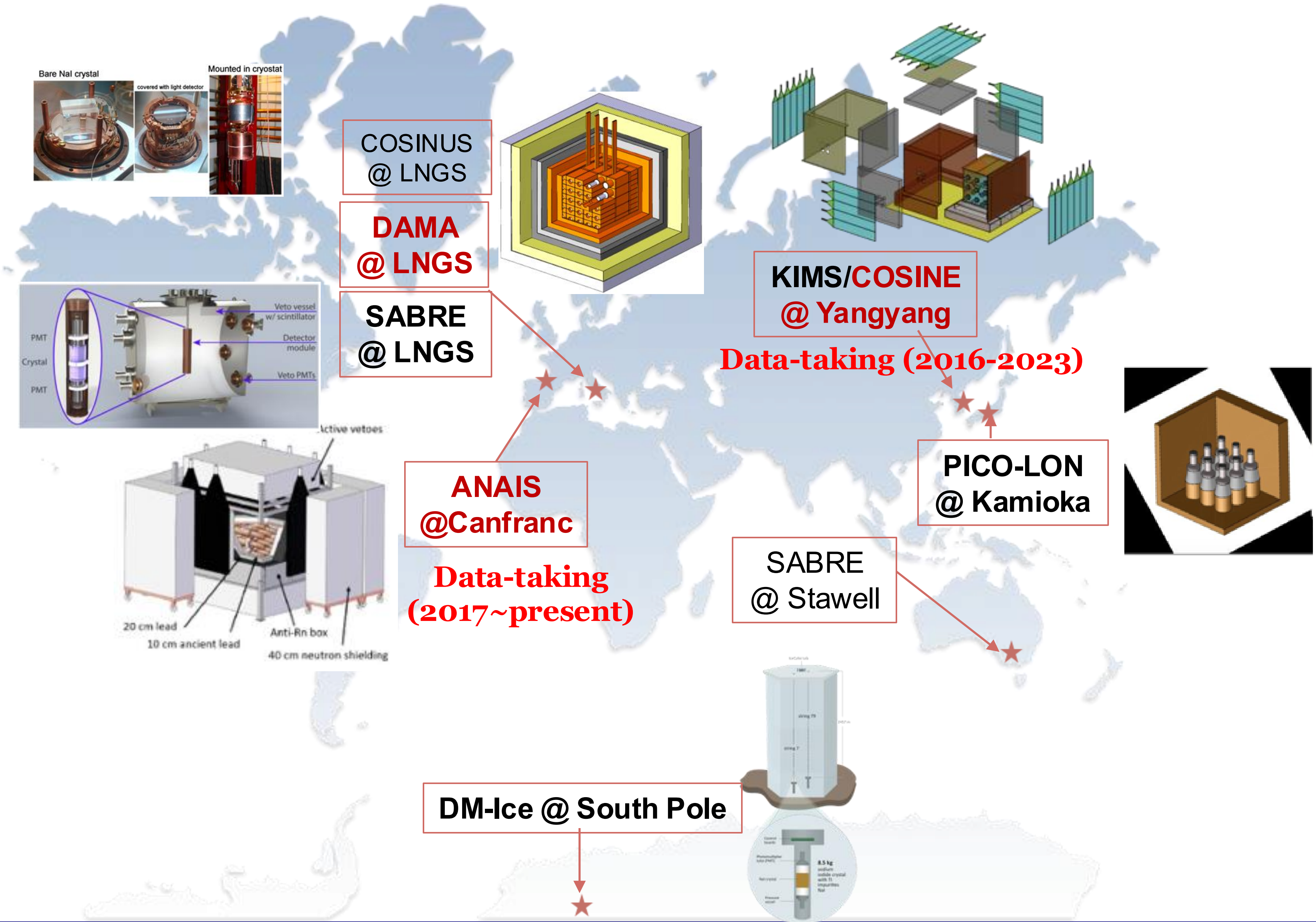


A Puzzling Discrepancy : DAMA vs other experiments



Requiring Model-independent test with same NaI(Tl) crystals

Apple-to-Apple Comparison with NaI(Tl) crystals



Annual modulation search practice

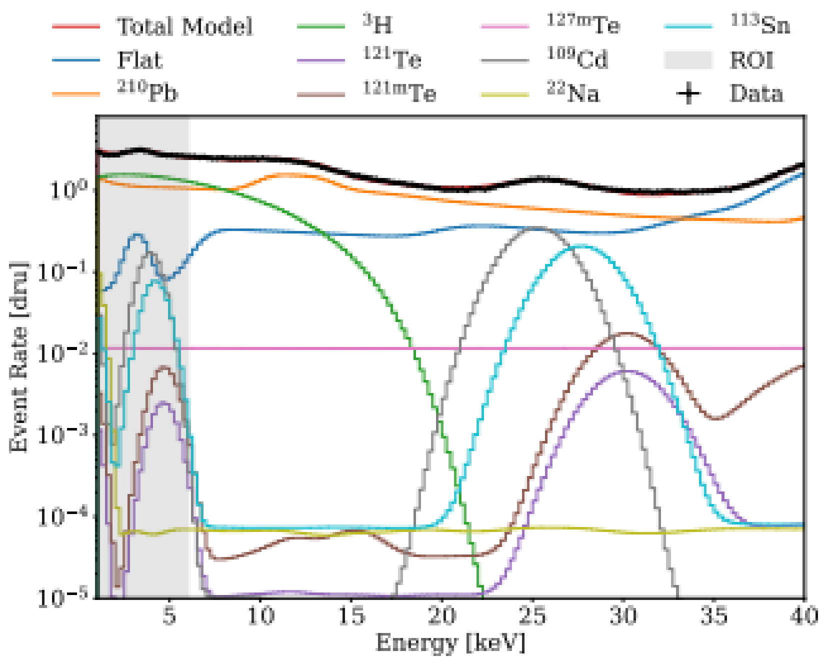
Measured event rate as a function of time $R(t)$

$$R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}(t-\varphi)\right)$$

$$R_0(t) = \sum_{j}^{N_{\mathrm{bkgd}}} C_{ij}\exp\left(-\lambda_{ij}\, t\right)$$

Time-dependent background components

COSINE-100



Phys. Rev. D 106, 052005 (2022)

1-3 keV

Component	Expected Initial Rate (counts/day/kg/keV$_{ee}$)	Fitted Initial Rate (counts/day/kg/keV$_{ee}$)	Half-life (years)
Total	3.67 ± 0.34	3.59 ± 0.15	
^{3}H	1.31 ± 0.32	1.33 ± 0.08	12.3
Surface ^{210}Pb	1.13 ± 0.10	1.05 ± 0.08	33.8±8.0
Internal ^{210}Pb	$(9.46 \pm 0.79) \times 10^{-1}$	$(9.13 \pm 0.72) \times 10^{-1}$	22.3
Flat	$(1.82 \pm 0.13) \times 10^{-1}$	$(1.83 \pm 0.56) \times 10^{-1}$	
^{109}Cd	$(4.48 \pm 0.65) \times 10^{-2}$	$(5.22 \pm 0.60) \times 10^{-2}$	1.26
^{127m}Te	$(2.65 \pm 0.61) \times 10^{-2}$	$(2.82 \pm 0.50) \times 10^{-2}$	0.29
^{113}Sn	$(2.04 \pm 0.39) \times 10^{-2}$	$(2.35 \pm 0.36) \times 10^{-2}$	0.31
^{22}Na	$(5.68 \pm 1.61) \times 10^{-3}$	$(6.28 \pm 1.46) \times 10^{-3}$	2.60
^{121m}Te	$(3.15 \pm 0.65) \times 10^{-3}$	$(3.24 \pm 0.61) \times 10^{-3}$	0.45
^{60}Co	$(4.38 \pm 0.28) \times 10^{-5}$	$(4.38 \pm 0.28) \times 10^{-5}$	5.27

arXiv:2409.13226

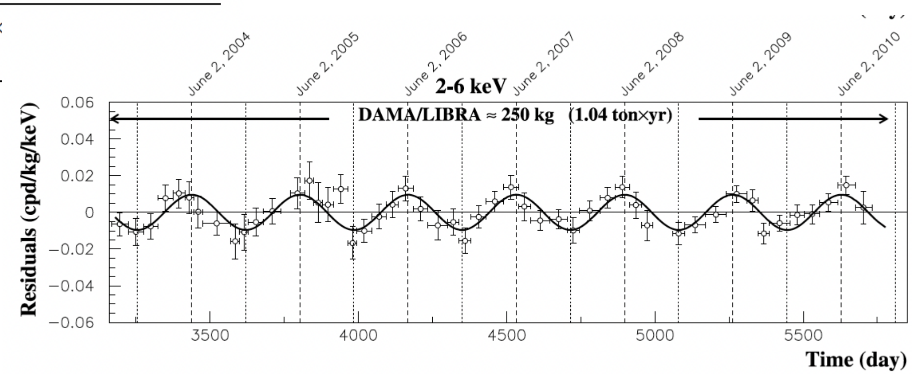
Precise background understanding is key factor

Modulation analysis adopted by DAMA/LIBRA

Eur. Phys. J. C 73, 2648 (2013)

	Period	Mass (kg)	Exposure (kg×day)	$(\alpha - \beta^2)$
DAMA/LIBRA-1	Sept. 9, 2003–July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004–Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005–July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006–July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007–Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008–Sept. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-7	Sep. 1, 2009–Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA–phase1	Sept. 9, 2003–Sept. 8, 2010		379795 ≃ 1.04 ton ×	
DAMA/NaI + DAMA/LIBRA–phase1:			1.33 ton × yr	

- Calculate residual rates of each yearly cycle (Sept.~Aug.)



Nucl. Phys. At. Energy 19, 307 (2018)

DAMA/LIBRA-phase2 annual cycle	Period	Mass, kg	Exposure, kg · d	$(\alpha - \beta^2)$
1	Dec. 23, 2010 - Sept. 9, 2011	Commissioning of phase2		
2	Nov. 2, 2011 - Sept. 11, 2012	242.5	62917	0.519
3	Oct. 8, 2012 - Sept. 2, 2013	242.5	60586	0.534
4	Sept. 8, 2013 - Sept. 1, 2014	242.5	73792	0.479
5	Sept. 1, 2014 - Sept. 9, 2015	242.5	71180	0.486
6	Sept. 10, 2015 - Aug. 24, 2016	242.5	67527	0.522
7	Sept. 7, 2016 - Sept. 25, 2017	242.5	75135	0.480
DAMA/LIBRA-phase2	Nov. 2, 2011 - Sept. 25, 2017	411137 ≃ 1.13 t · yr		0.502
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2: 2.46 t · yr				

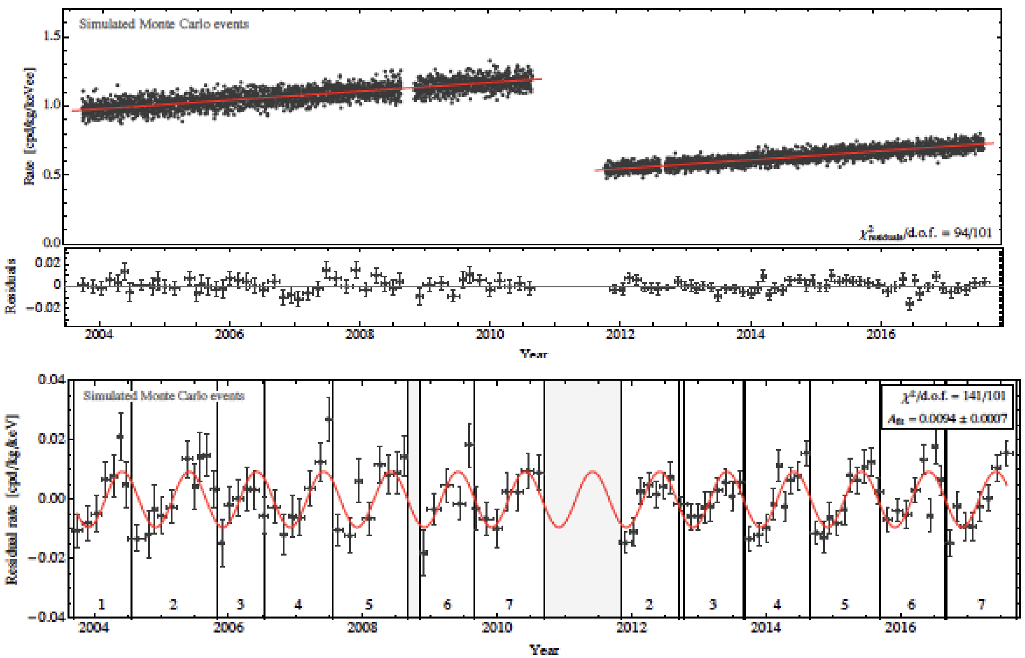
What if there is time-dependent background?

- Time-dependent background model of DAMA/LIBRA
  - ❖ Yearly average to obtain residual rate

$$R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}(t-\varphi)\right) \qquad \text{Assuming}: R_0(t) = C$$

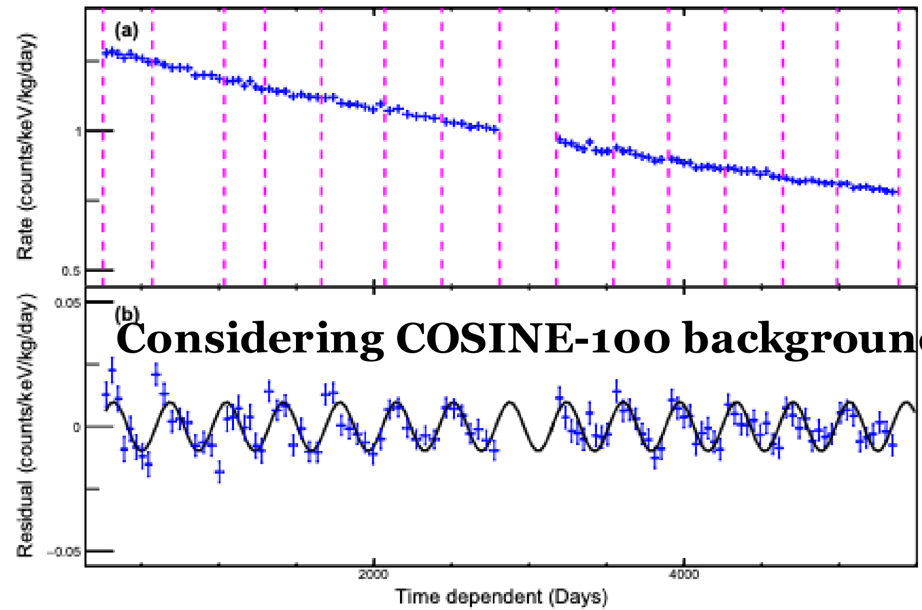
- However, if there is time-dependent background..

JHEP 04, 137 (2020)



Compatible modulation with DAMA/LIBRA

Sci. Rep. 13, 4676 (2023)



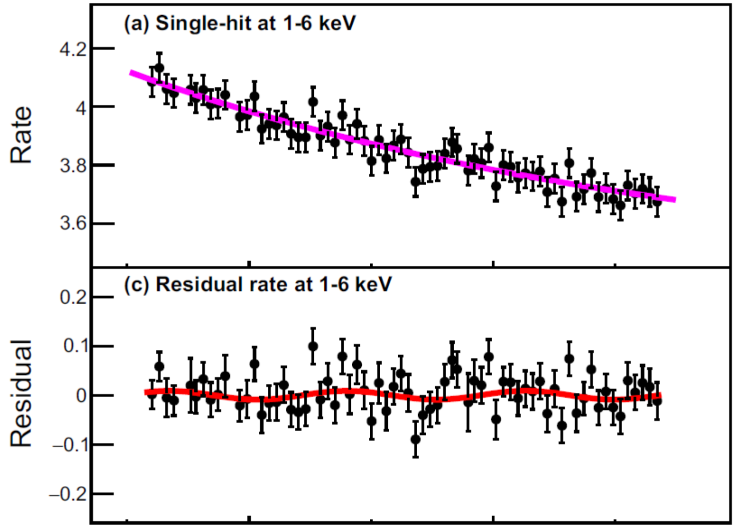
Considering COSINE-100 background

Consistent modulation amplitude but, Opposite phase

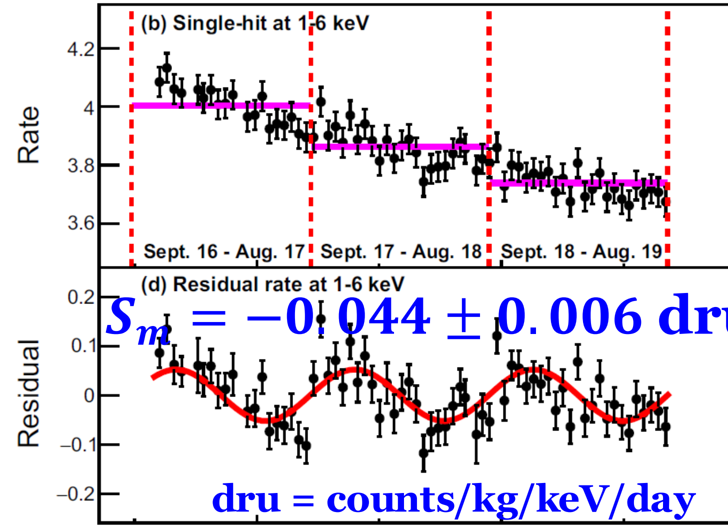
What if we use wrong background model?

Sci. Rep. 13, 4676 (2023)

Single exponential



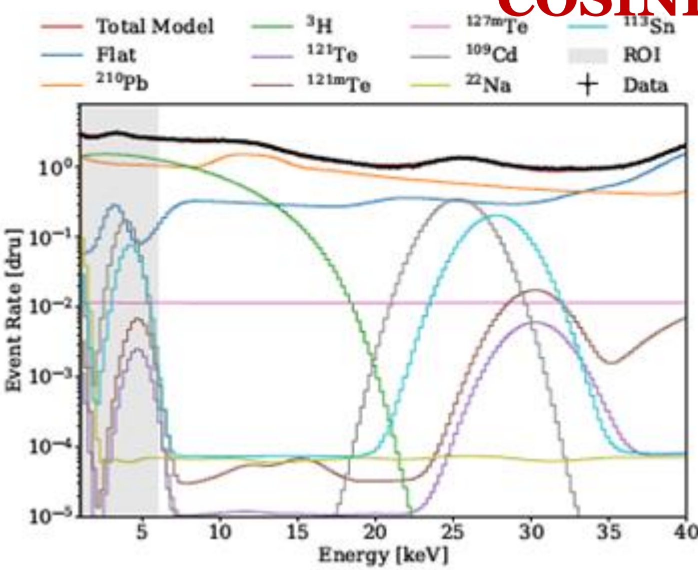
DAMA-like method



$S_m = -0.044 \pm 0.006$ **dru**

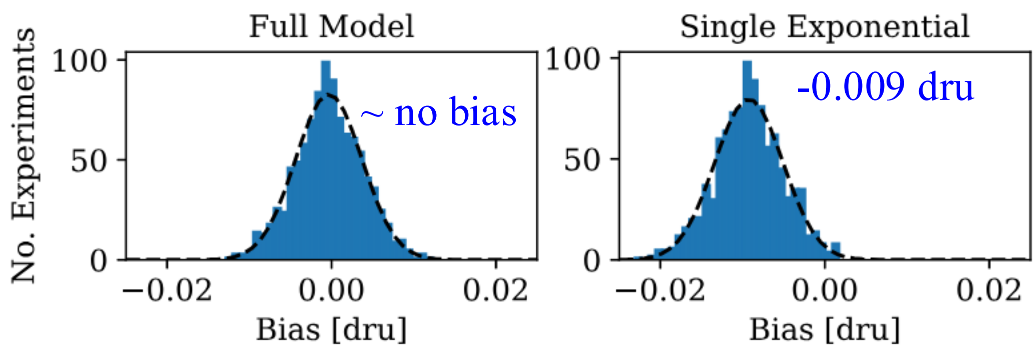
dru = counts/kg/keV/day

COSINE-100 3 years data



PRD 106, 052005 (2022)

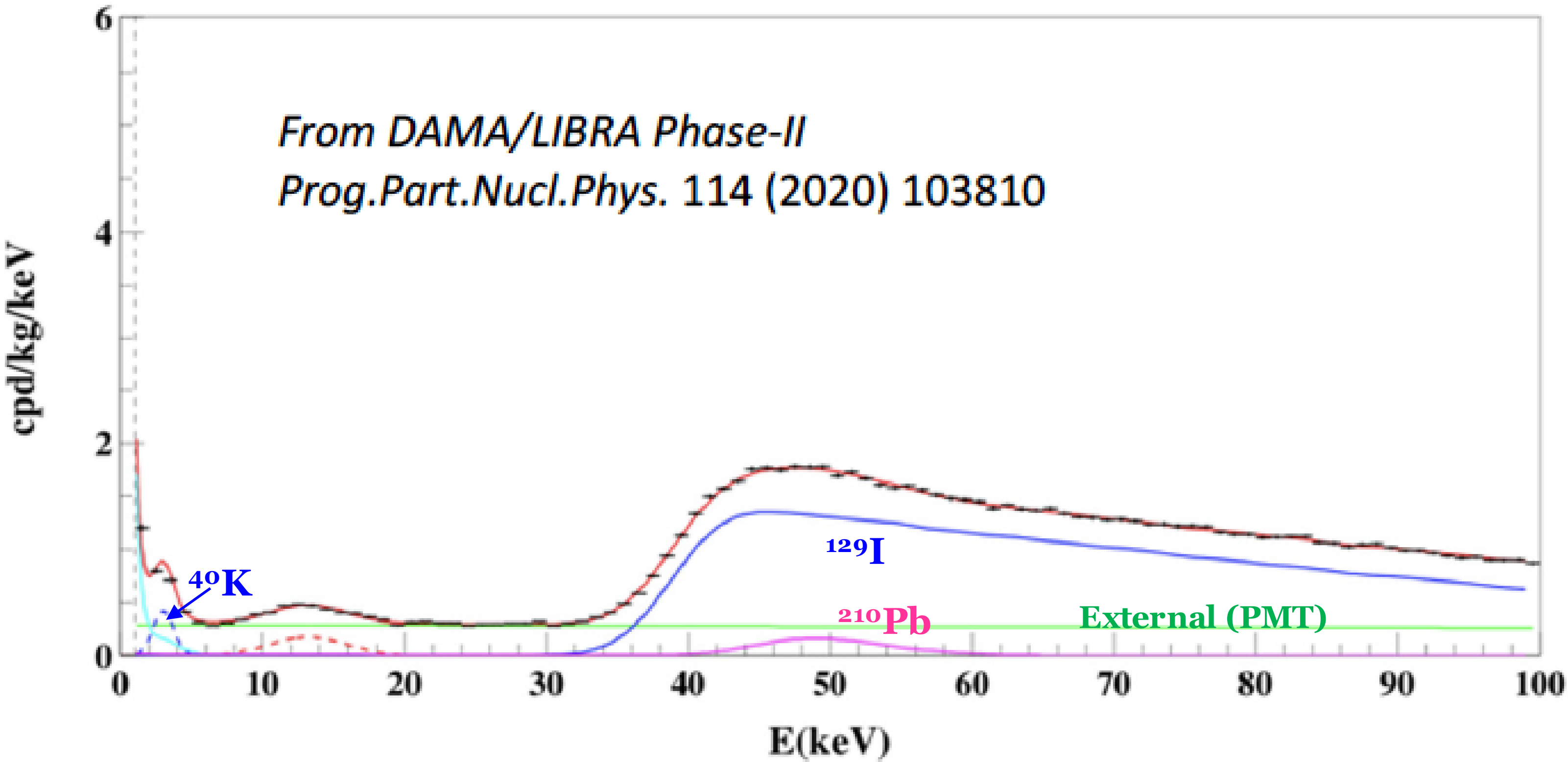
Full model : eight exponential components



DAMA/LIBRA : $\mathbf{0.010 \pm 0.001}$ dru

The background truly constant

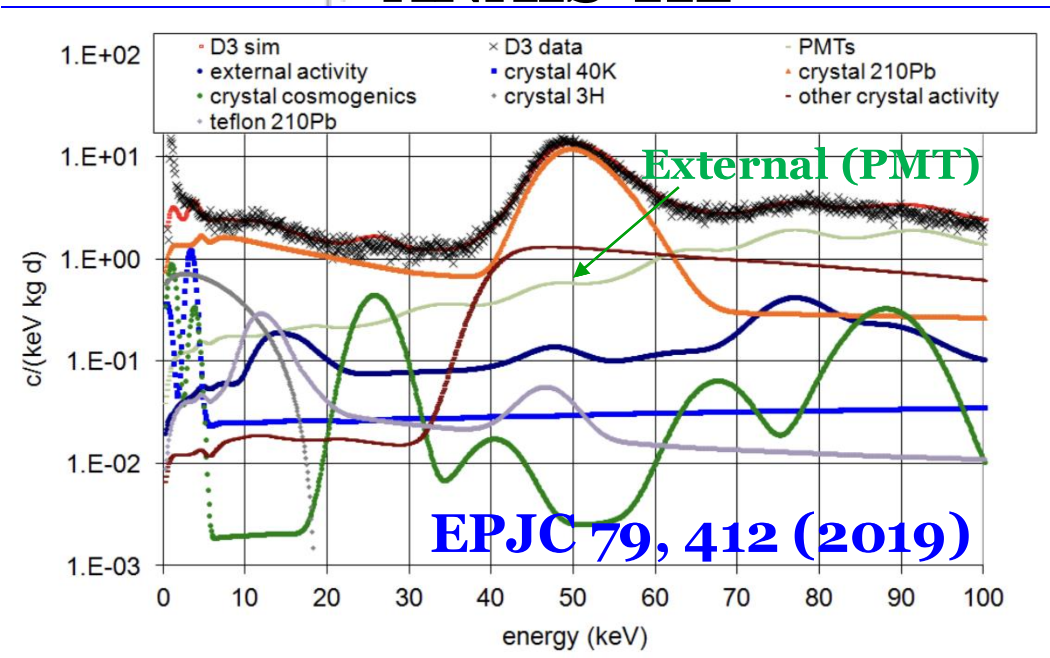
- The DAMA/LIBRA analysis assumes a constant, time-independent background
- However, experiments like COSINE-100 and ANAIS-112 have modeled time-dependent backgrounds



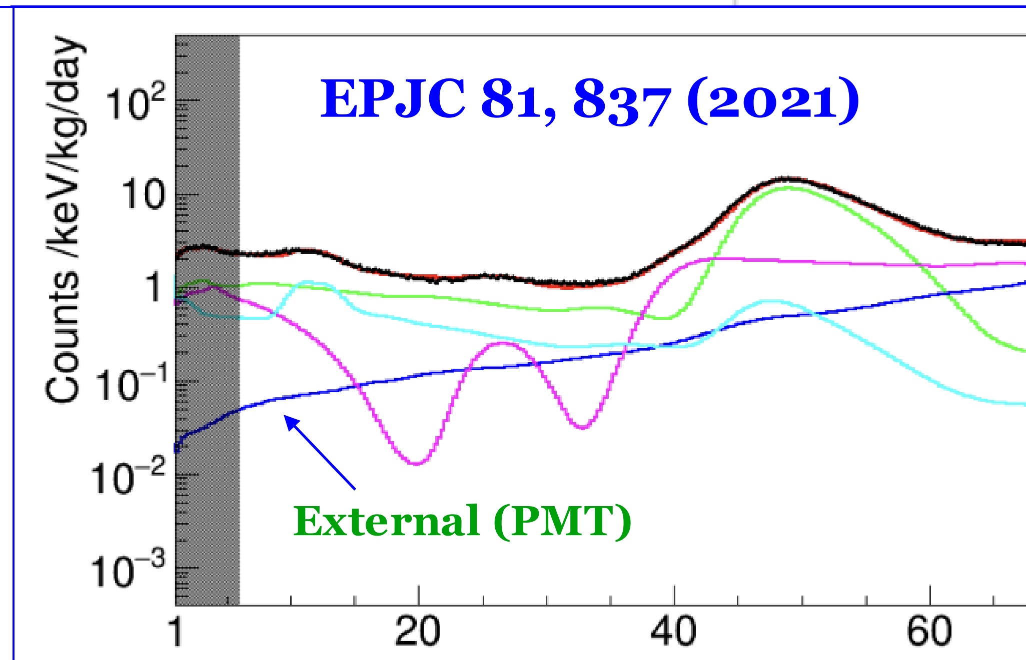
The background truly constant

- The DAMA/LIBRA analysis assumes a constant, time-independent background
- However, experiments like COSINE-100 and ANAIS-112 have modeled time-dependent backgrounds

ANAIS-112



COSINE-100

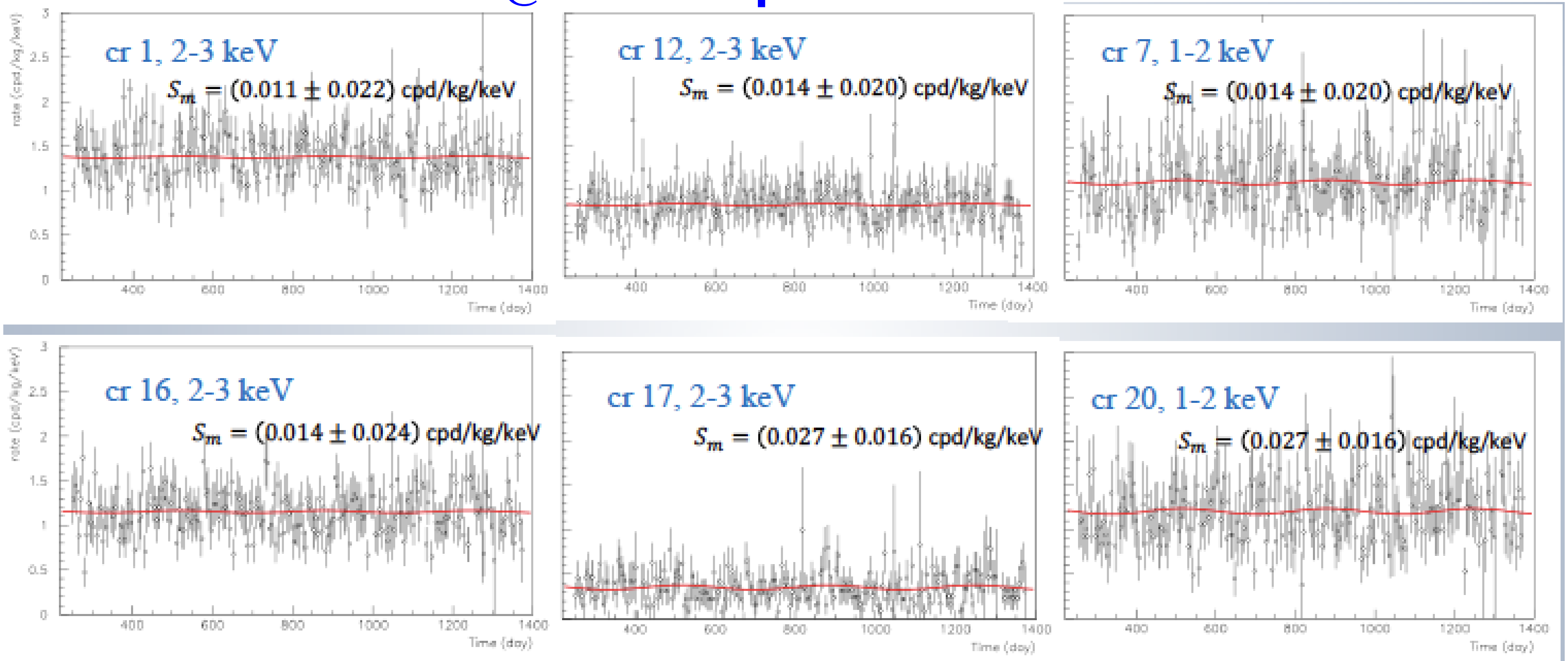


E(keV)

DAMA/LIBRA's latest 3 years data

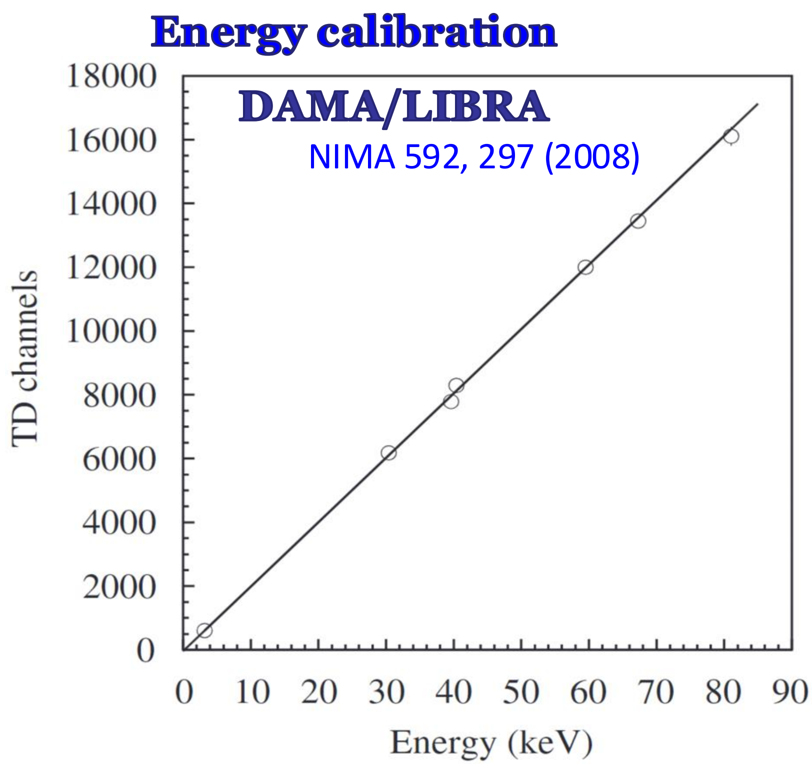
- The latest 3 years data of phase-2

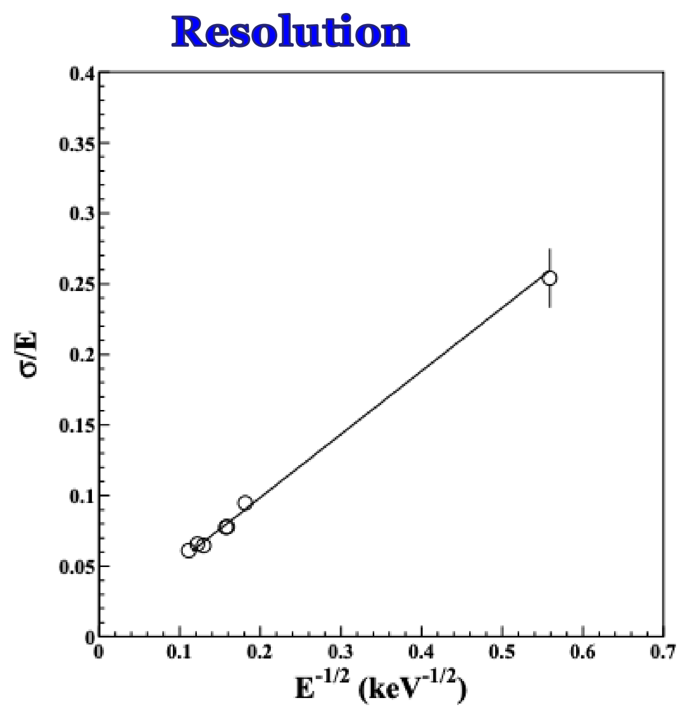
R. Cerulli @ IDM2024



- Desirable to show full data and to study detailed fit parameters and correlations

Energy calibration (electron recoil) of DAMA/LIBRA

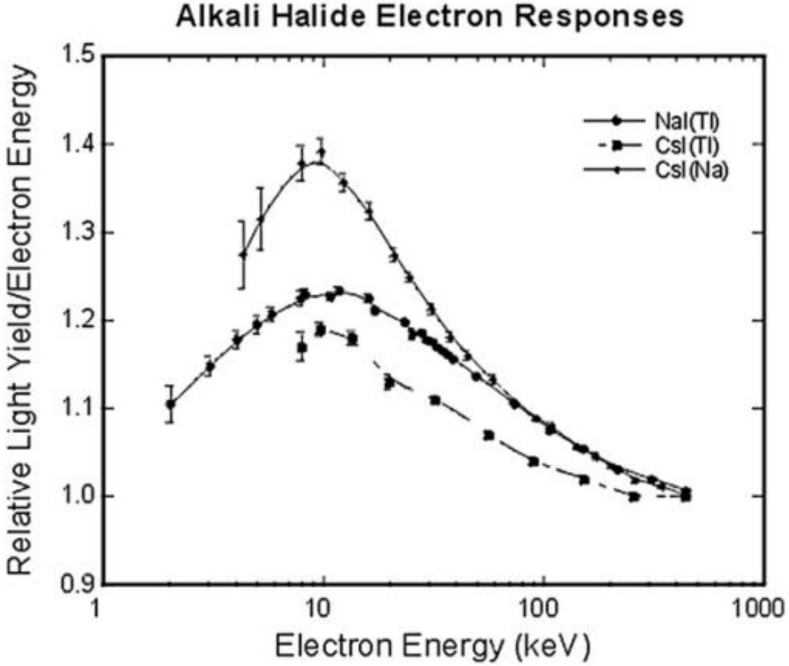




- Linear fit to various calibration points (internal x-ray, gamma-ray and external sources)

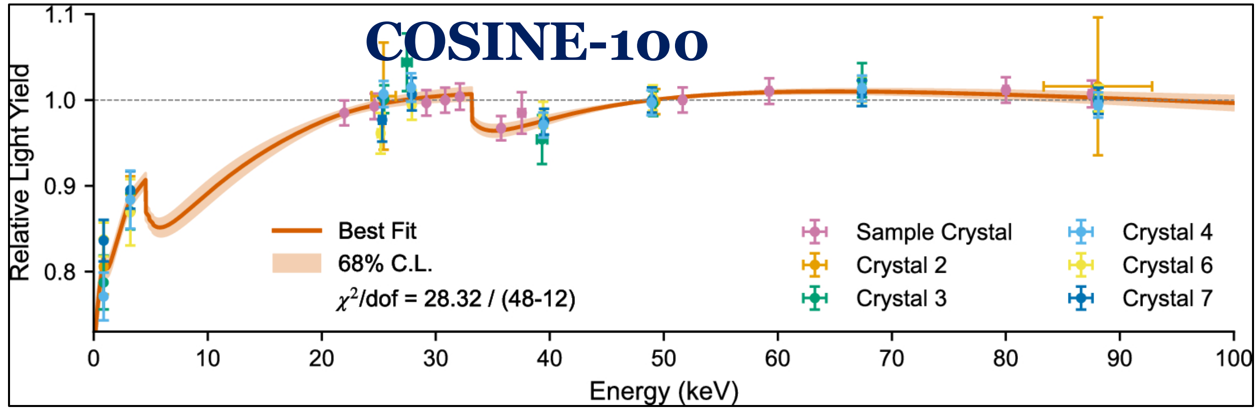
Energy calibration (electron recoil)

NIMA 45, 372 (2010)

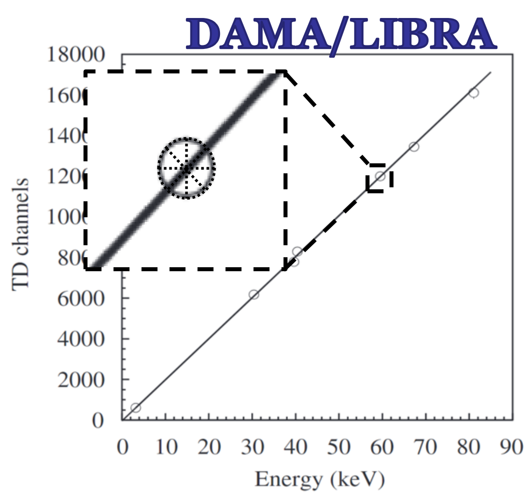


Electron response

EPJC 84, 484 (2024)



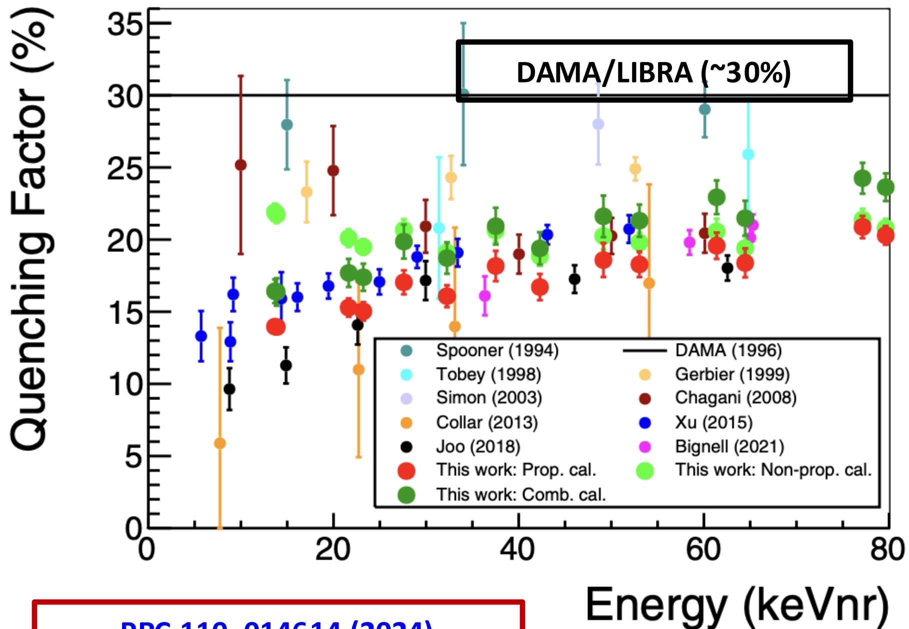
Gamma/x-ray response



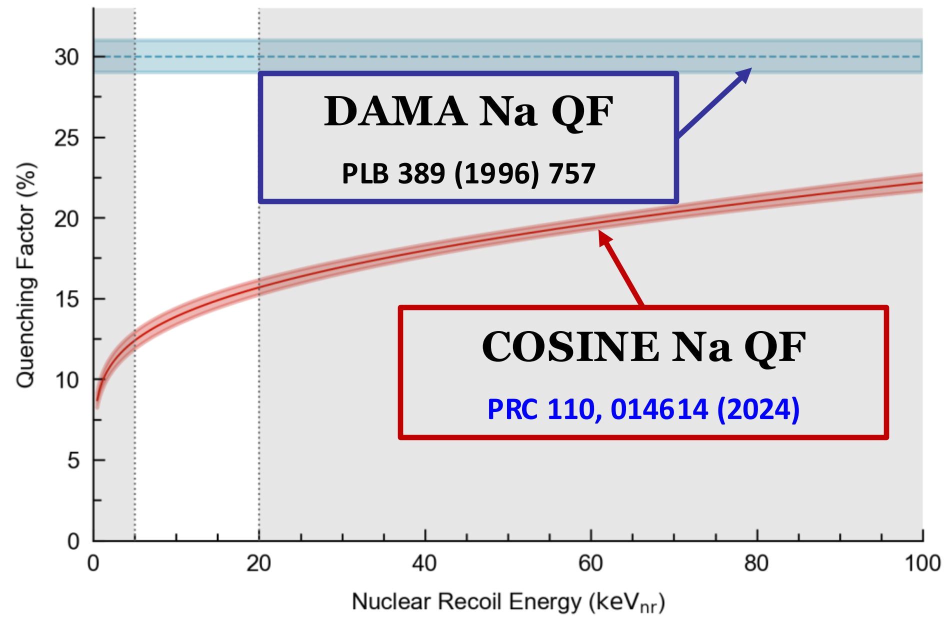
For the apple-to-apple comparison, we'd better to follow DAMA/LIBRA's method

Energy calibration (nuclear recoil)

Nuclear-recoil energy calibration (keV_{nr})



PRC 110, 014614 (2024)

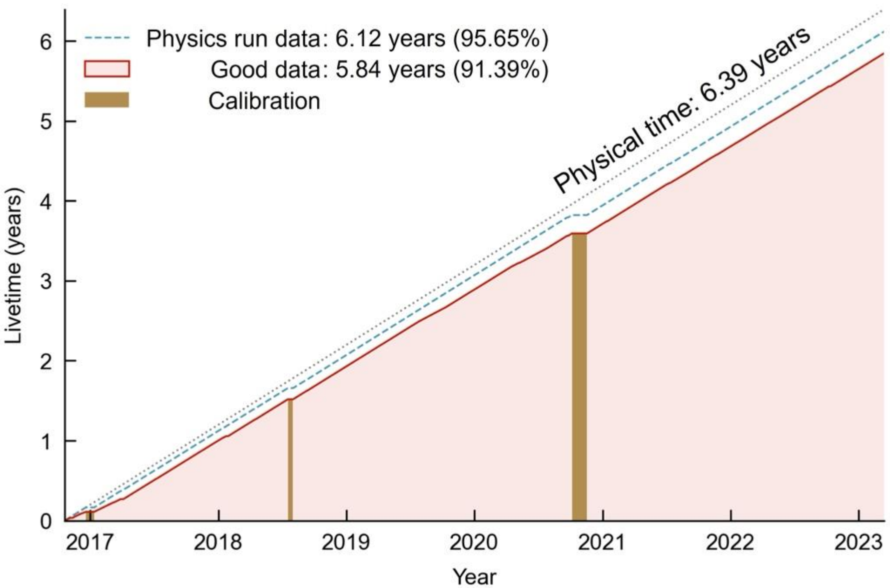


DAMA/LIBRA used ^{232}Cf neutron source and compared with simulated spectrum

Recent measurements used mono-energetic neutron beams with neutron tagging detectors

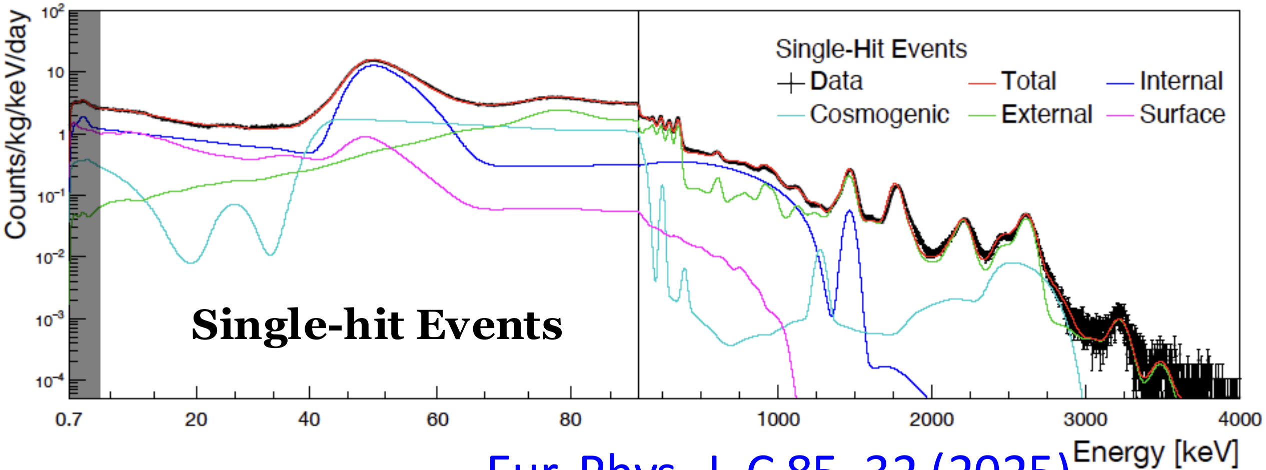
However, different QFs between DAMA/LIBRA's crystals and other experiments' crystals may be possible

COSINE-100 experiment (2016~2023)

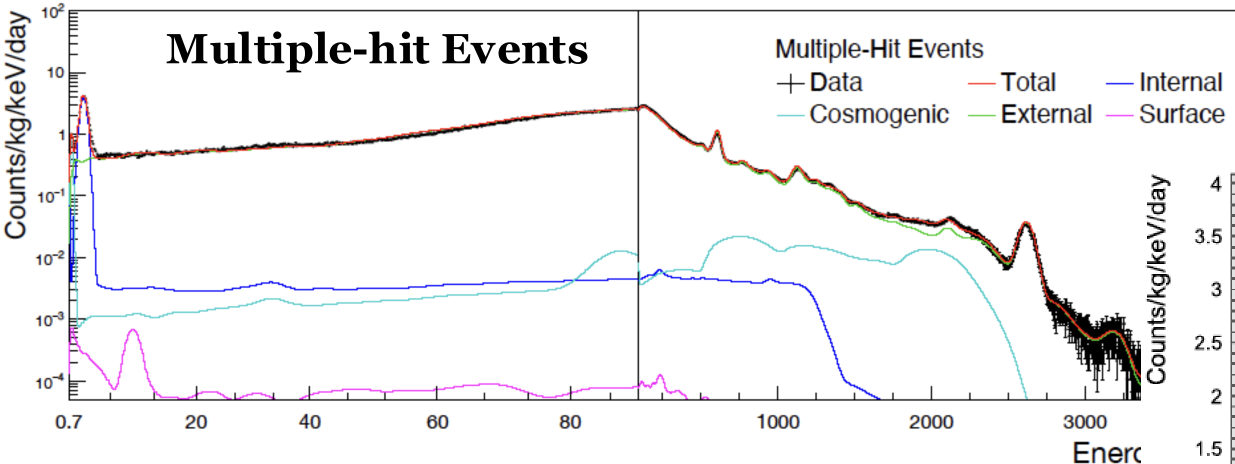


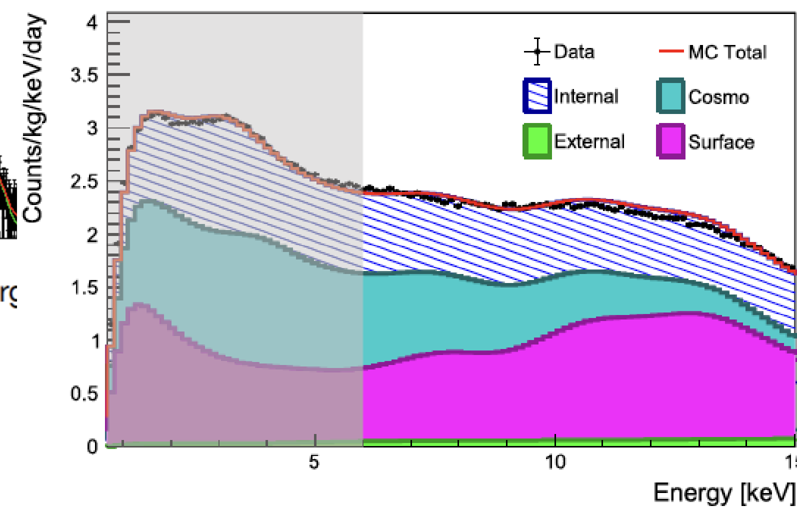
- YangYang underground laboratory
  - ❖ **October/2016 ~ March/2023**
- Decommissioning
  - ❖ Move to **Yemilab**
  - ❖ Upgrade of detector for **high light yield**

COSINE-100 Background understanding



Eur. Phys. J. C 85, 32 (2025)

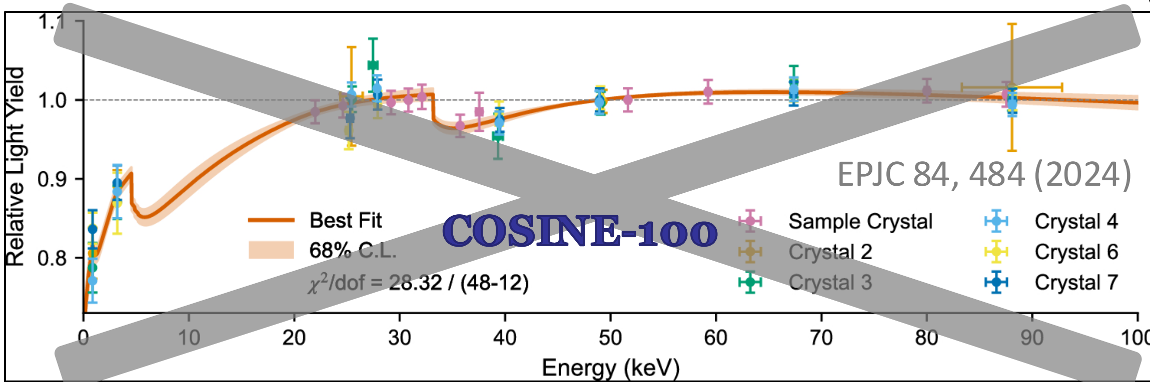


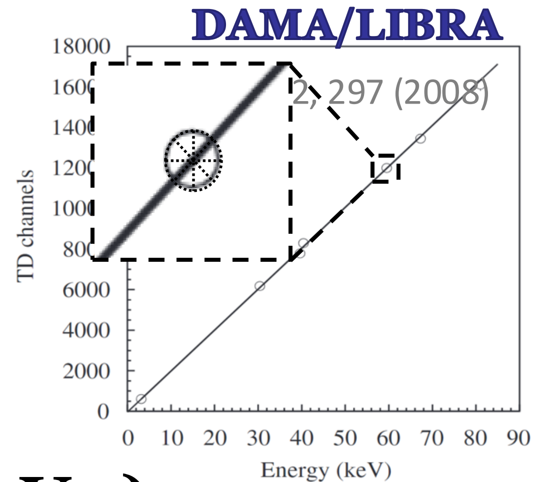


Good understanding of background contributions

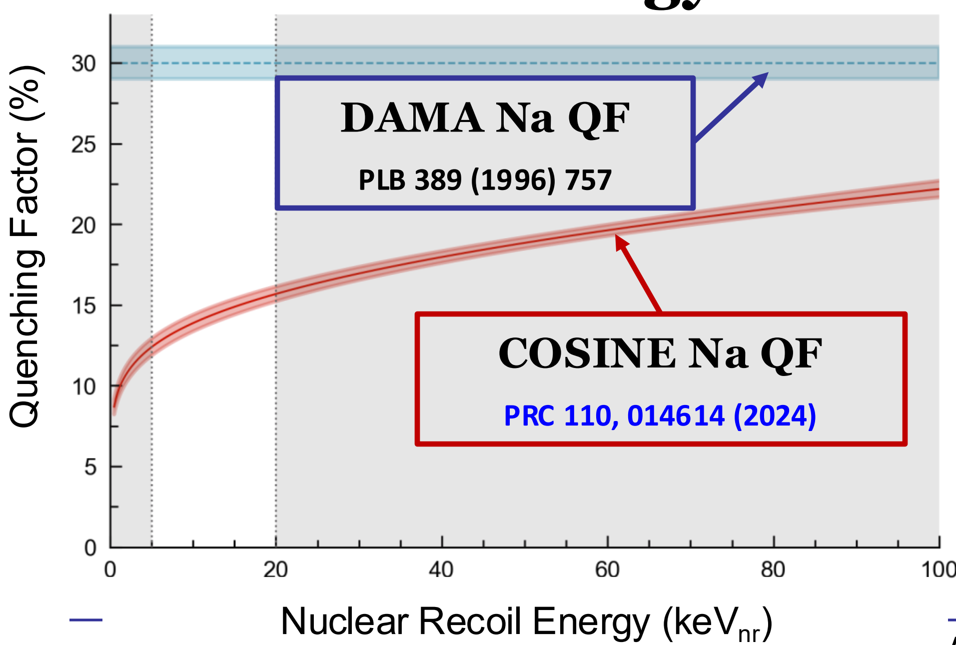
Comparison with DAMA : Energy calibration

Linear calibration to 59.54 keV : keV_{ee}





Nuclear-recoil energy calibration (keV_{nr})



Quenching factor (QF)

Measured electron-equivalent energy/True nuclear recoil energy

Signal region : 6.7-20 keV_{nr}

DAMA/LIBRA : 2-6 keV_{ee}

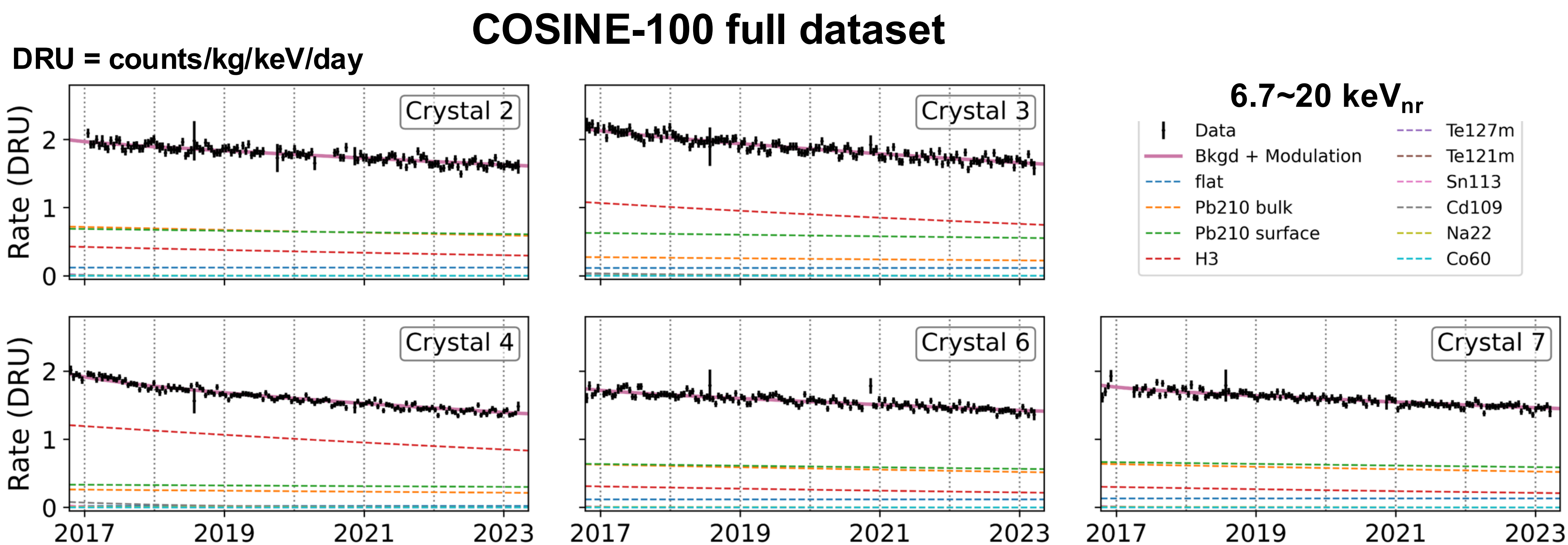
COSINE-100 : 0.85-3.12 keV_{ee}

Modulation fit of COSINE-100 full data

$$R_i(t) = A\cos\left(\frac{2\pi(t-\phi)}{T}\right) + \sum_j C_{ij} e^{-\lambda_{ij} t}.$$

Modulation signals

10 time-dependent components

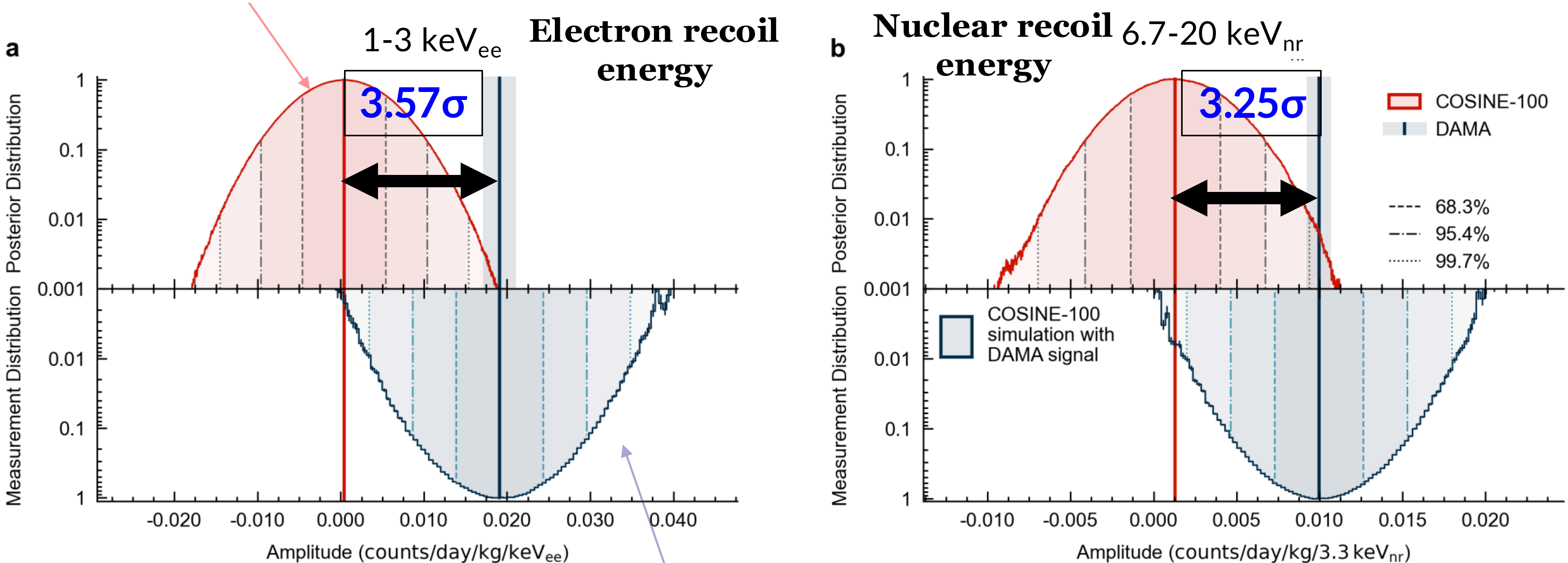


No modulation signal observed !!

COSINE-100 full dataset fits

Posterior of COSINE-100 full dataset

(2-6 keVee in DAMA/LIBRA)



Simulated experiments (300,000) assuming DAMA/LIBRA modulation signals

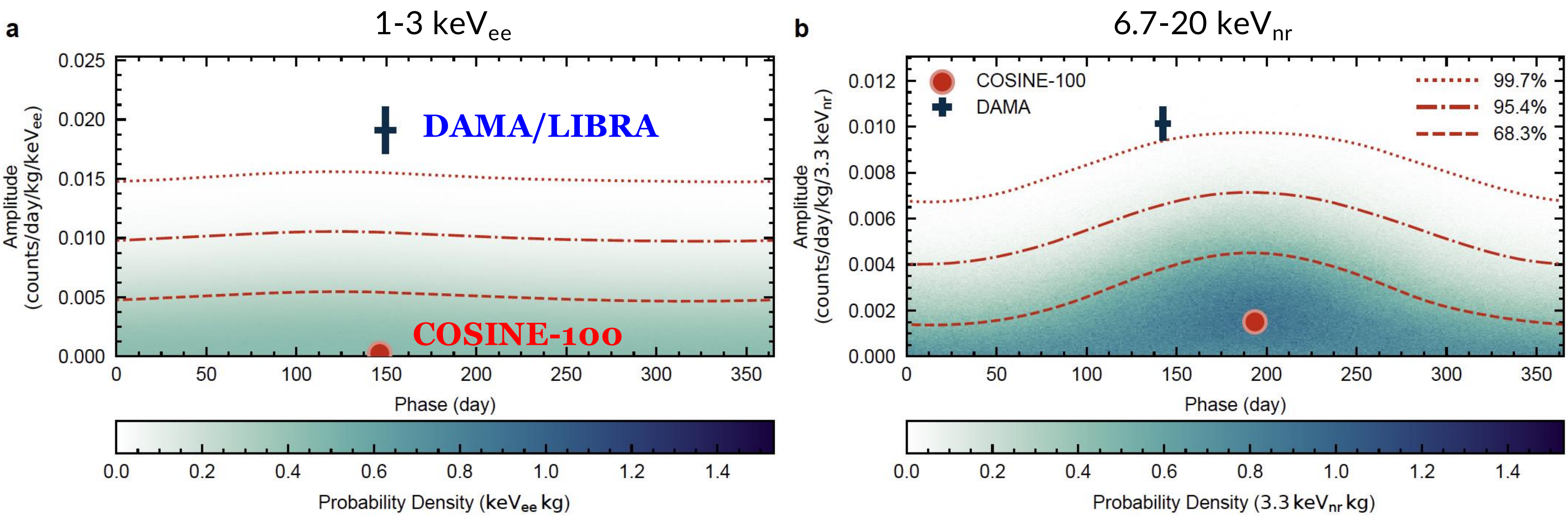
arXiv:2409.13226

Sci. Adv. (in press)

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

COSINE-100 full dataset fits

Phase floated 2-dimensional fit for COSINE-100 full dataset

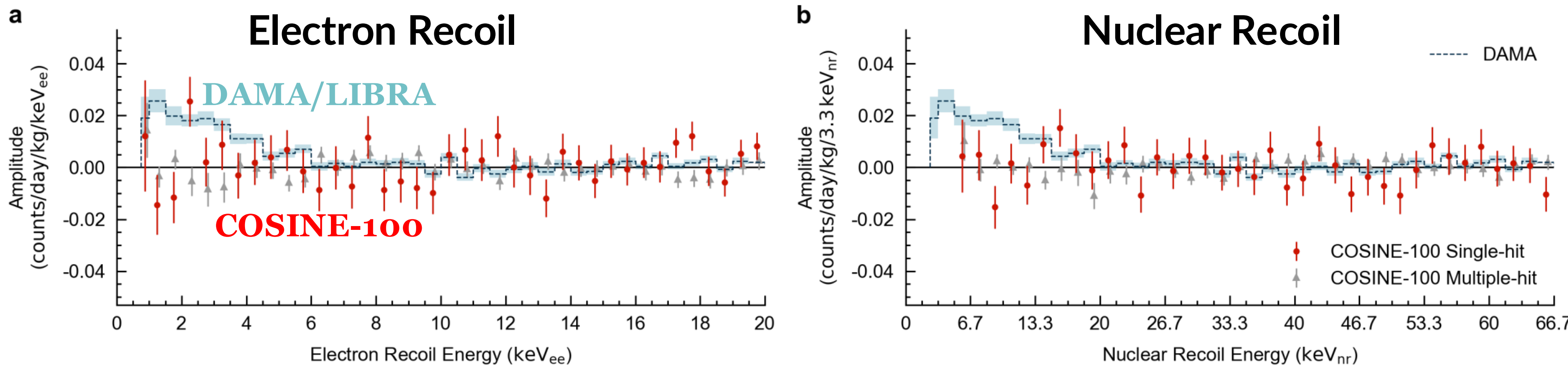


arXiv:2409.13226

Sci. Adv. (in press)

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

COSINE-100 full dataset fits



E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	**0.001 ± 0.005**	0.019 ± 0.002
1~6	**0.002 ± 0.003**	0.010 ± 0.001
2~6	**0.005 ± 0.003**	0.010 ± 0.001

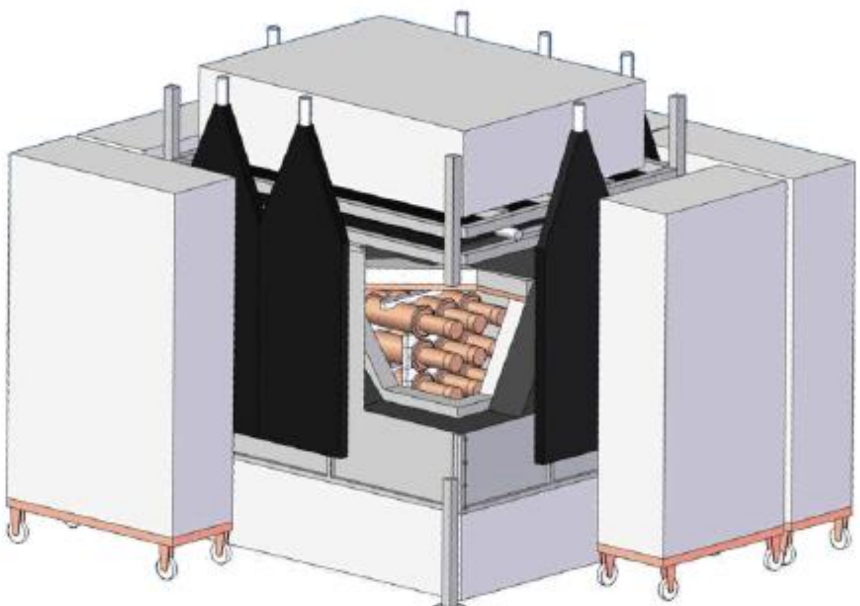
E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	**0.001 ± 0.003**	0.010 ± 0.001

arXiv:2409.13226

Sci. Adv. (in press)

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

ANAIS-112

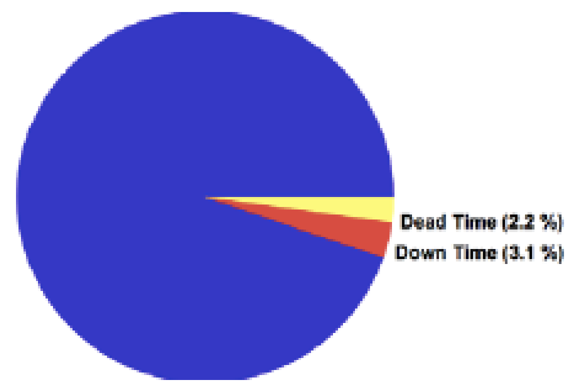


- 112.5 kg detector (nine modules)
- Physics run started from Aug. 2017 (currently running experiment)
- Canfranc Underground Laboratory (850 m rock overburden)

~15 photoelectrons/keV

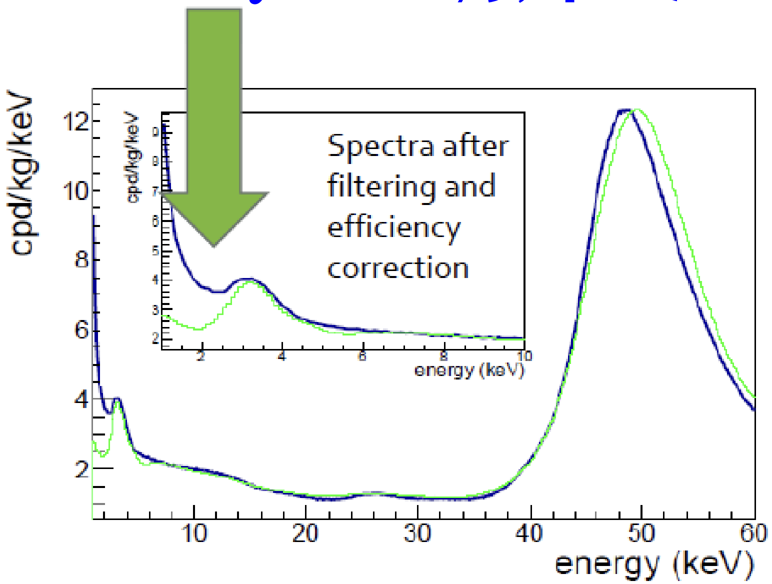
Similar with COSINE-100

~95% live time

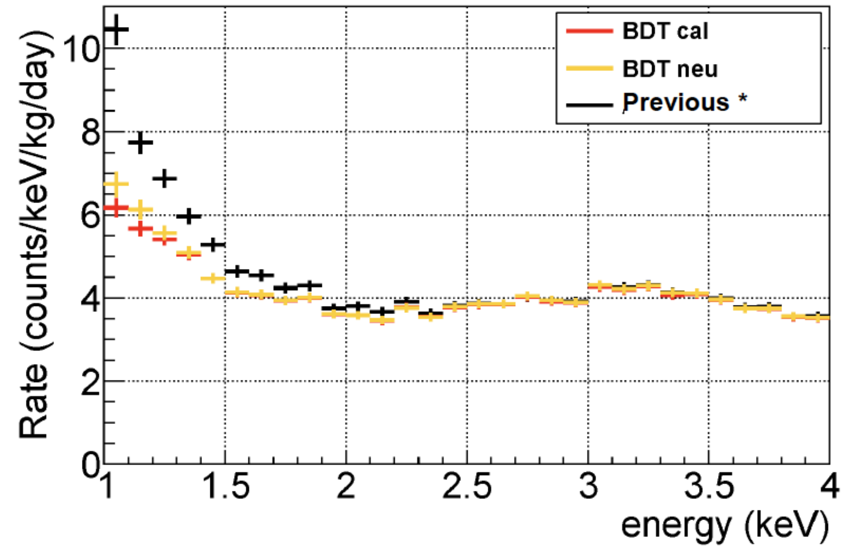


Background understanding of ANAIS-112

Eur. Phys. J. C 79, 412 (2019)



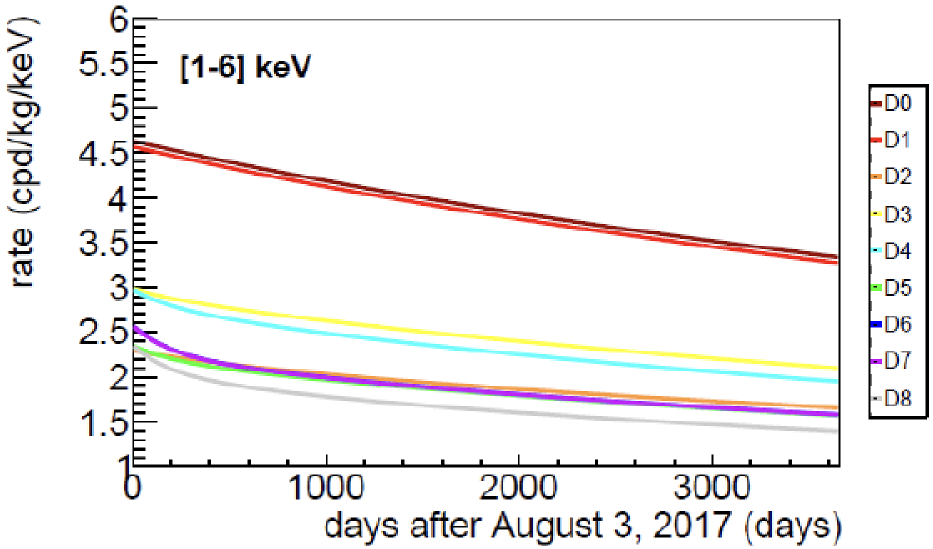
Phys. Rev. D 103, 102005 (2021)



- Time-dependent backgrounds are modeled
  - Simulation underestimates background events below 2 keV
- Various background hypothesis have been studied

Modulation analysis with 6 years data

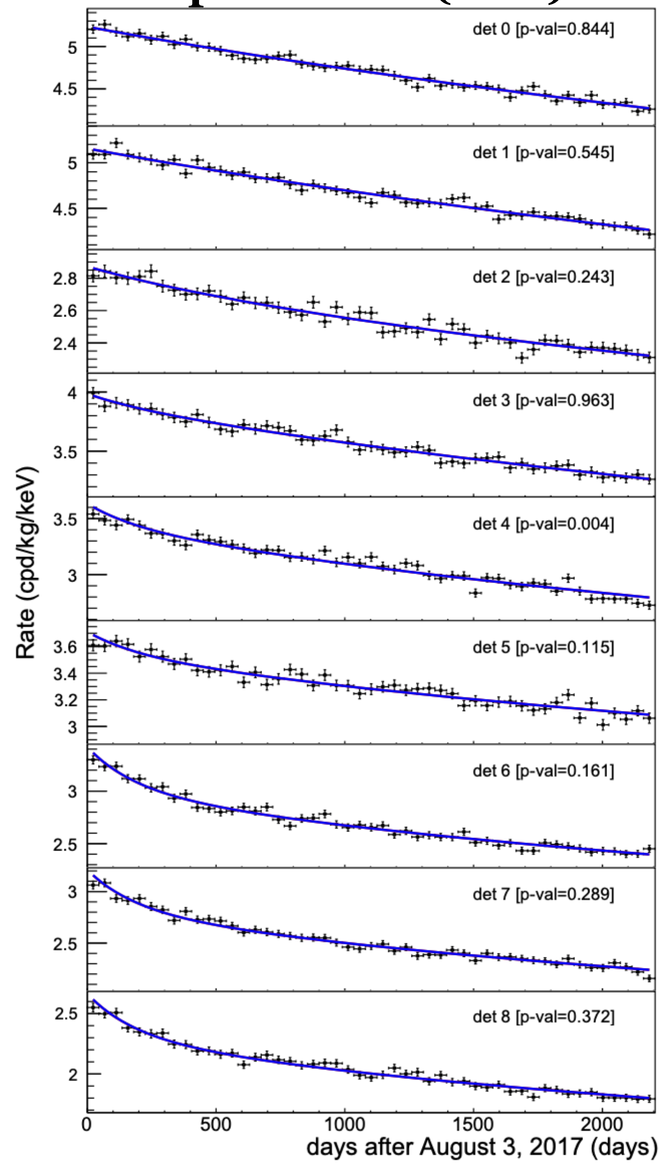
$$\mu_{i,d} = [R_{0,d}(1 + f_d \phi^{MC}_{bkg,d}(t_i)) + S_m cos(\omega(t_i - t_0))] M_d \Delta E \Delta t$$



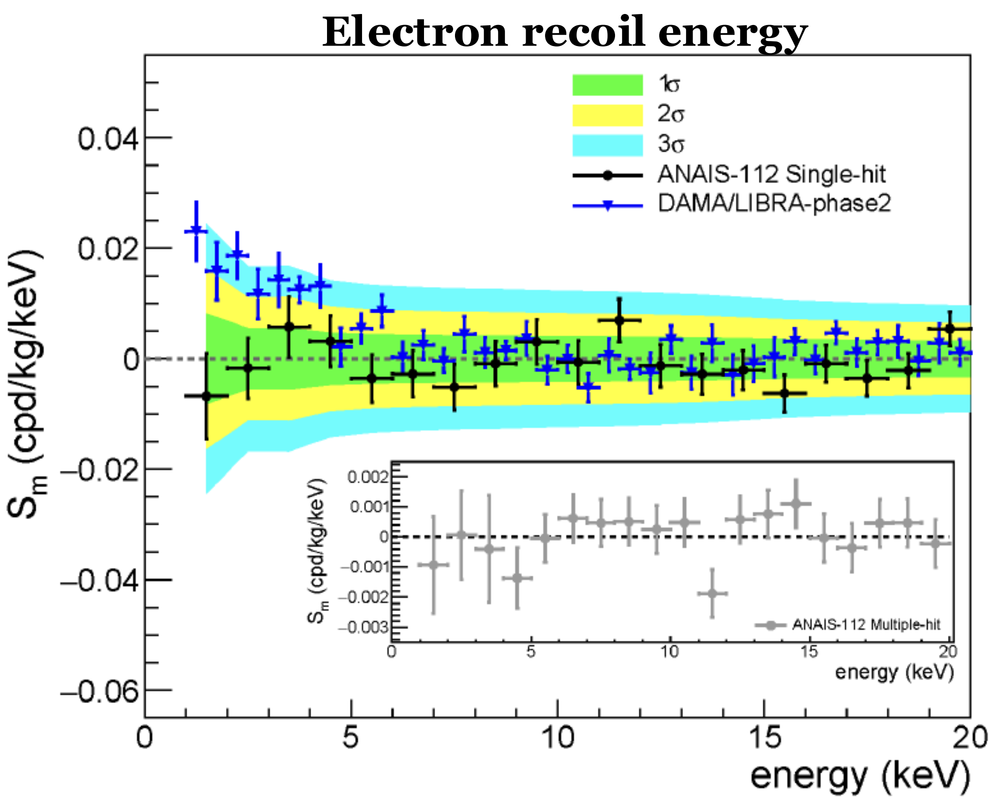
Minimizing:

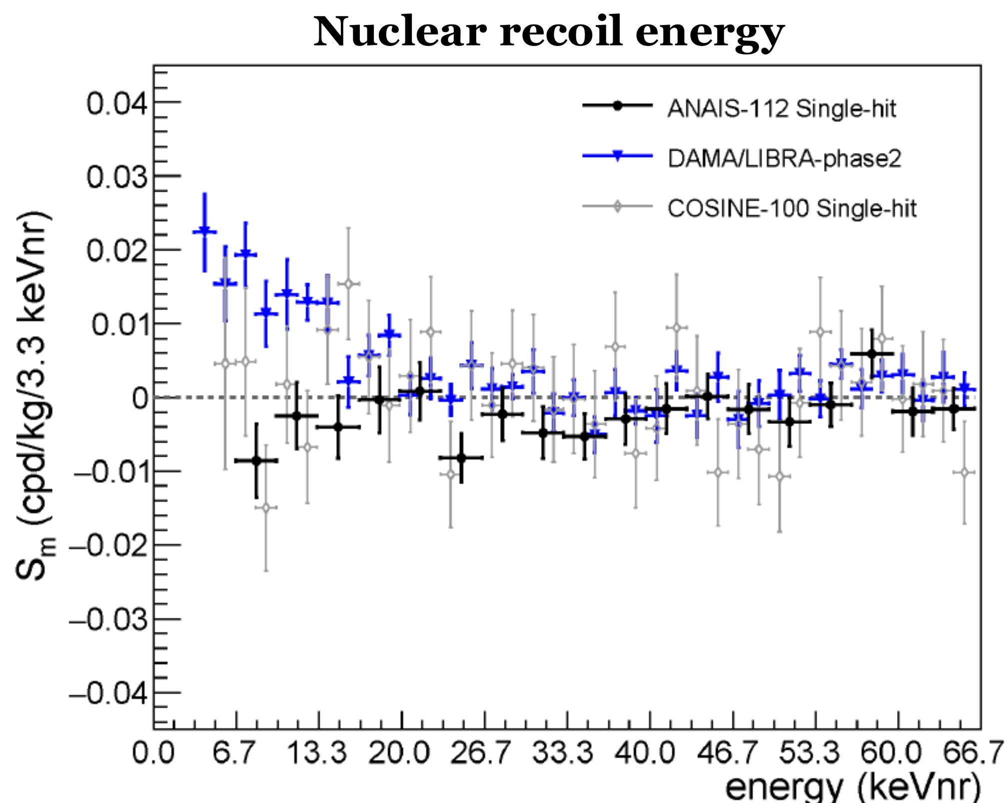
$$\chi^2 = \sum_{i,d} \frac{(n_{i,d} - \mu_{i,d})^2}{\sigma^2_{i,d}}$$

S_m = 0 hypothesis (red)
parameter (blue)



ANAIS-112 modulation results

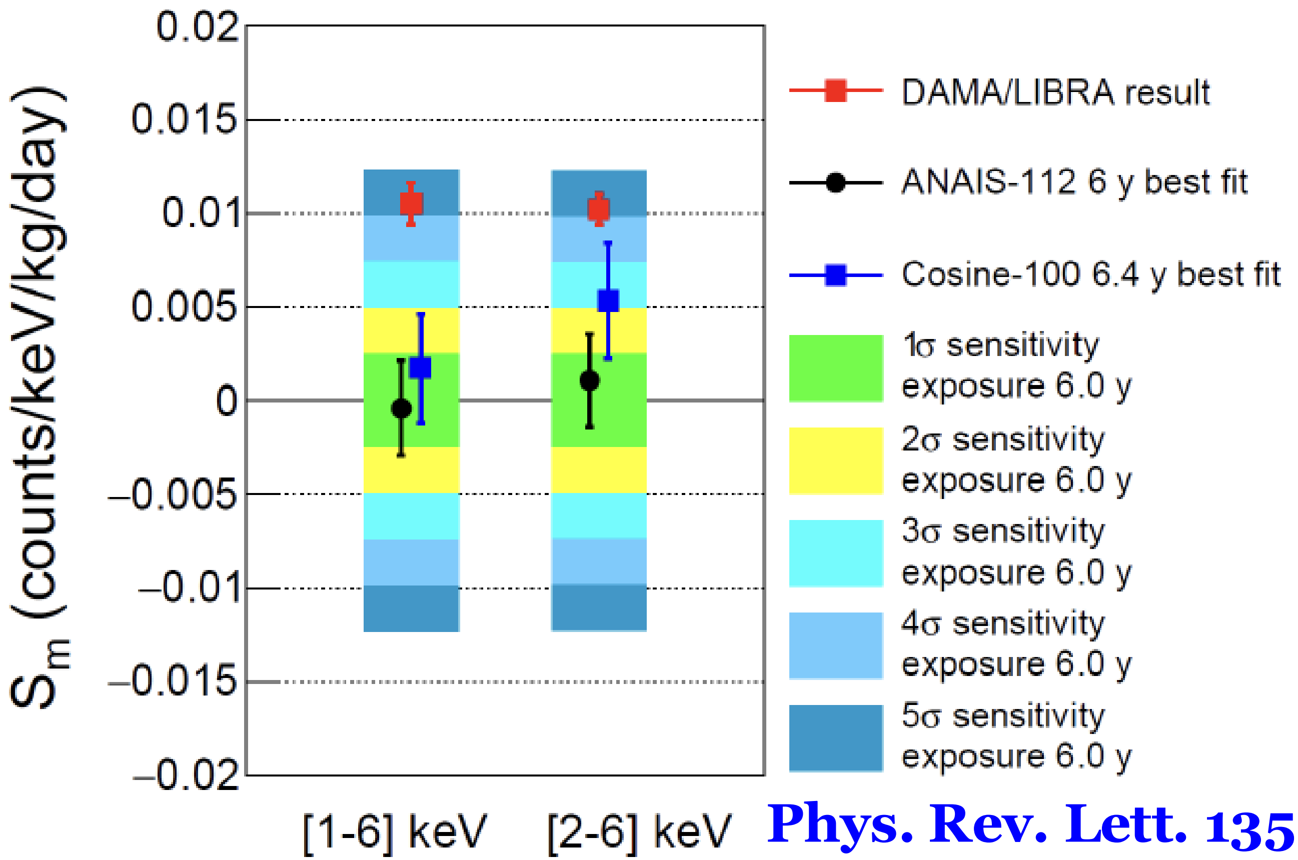




Phys. Rev. Lett. 135, 051001 (2025)

- ANAIS-112 results are incompatible with DAMA/LIBRA

ANAIS-112 modulation results



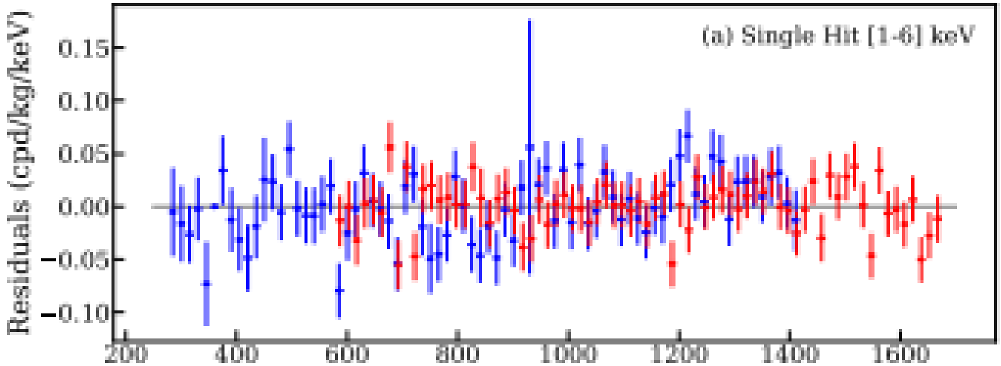
Phys. Rev. Lett. 135, 051001 (2025)

- Best fit are incompatible with DAMA/LIBRA results at 4.0σ and 3.5σ in 1-6 keV and 2-6 keV, respectively

Combined analysis between COSINE and ANAIS

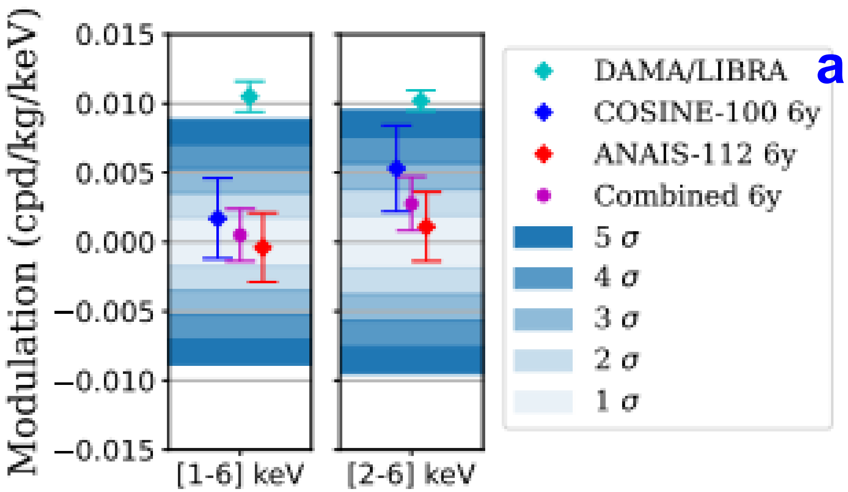
ANAIS-112: PRD 103, 102005 (2021)
COSINE-100: PRD 106, 052005 (2022)

Combining published data (~ 3 years)



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

Combining 6 years modulation result



arXiv:2503.19559, Phys. Rev. Lett. (in press)

Energy ROI	Combined result	DAMA Exclusion
1-6 keV	0.0005 ± 0.0019	4.68σ
2-6 keV	0.0027 ± 0.0019	3.53σ

What's next for DAMA/LIBRA?

- DAMA/LIBRA
  - ❖ End of data taking (2024)
  - ❖ All crystals were remained in the Gran Sasso (LNGS)
  - ❖ Desirable to study comprehensive time-dependent analysis
  - ❖ Sent "Letter of Intent" by Spokespersons of NaI(Tl) experiment to LNGS director to understand reason of the modulation signals
- Crystal development
  - ❖ ANAIS-112 and COSINE-100 detectors have ~2-3 times higher background
  - ❖ Better if we have lower background detectors (letter than DAMA/LIBRA)
    - ❑ SABRE, PICO-LON, COSINE-200 try to develop low-background NaI(Tl) crystals
    - ❑ COSINUS developed cryogenic detector to discriminate electron recoil background
- ANAIS-112 will take more data to reach 5 sigma level conclusion
- COSINE-100U will provide additional information for lower energy

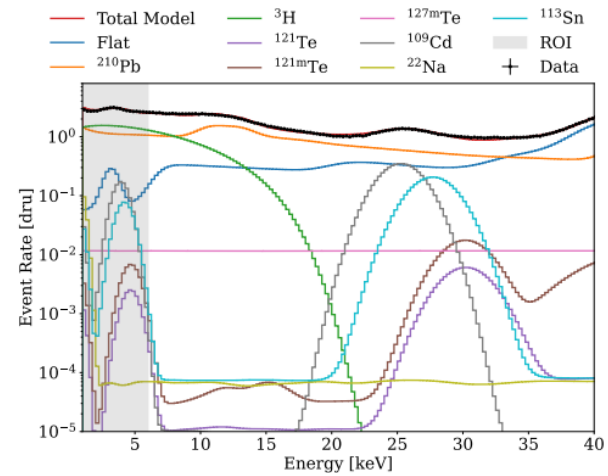
Summary

- Annual modulation is interesting channel to search dark matter interaction
- DAMA/LIBRA's modulation signals are disfavored with ANAIS-112 and COSINE-100 with significance more than 3 sigma
- Further efforts to understanding DAMA/LIBRA's signals are ongoing

Modulation fit

$$R_i(t) = A\cos\left(\frac{2\pi(t-\phi)}{T}\right) + \sum_j C_{ij} e^{-\lambda_{ij} t}.$$

Modulation signals — 10 time-dependent components



Simulated experiments

Measured signal

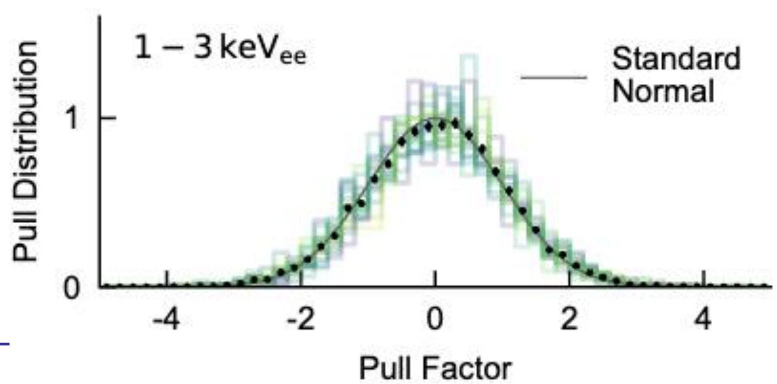
Pull Factor

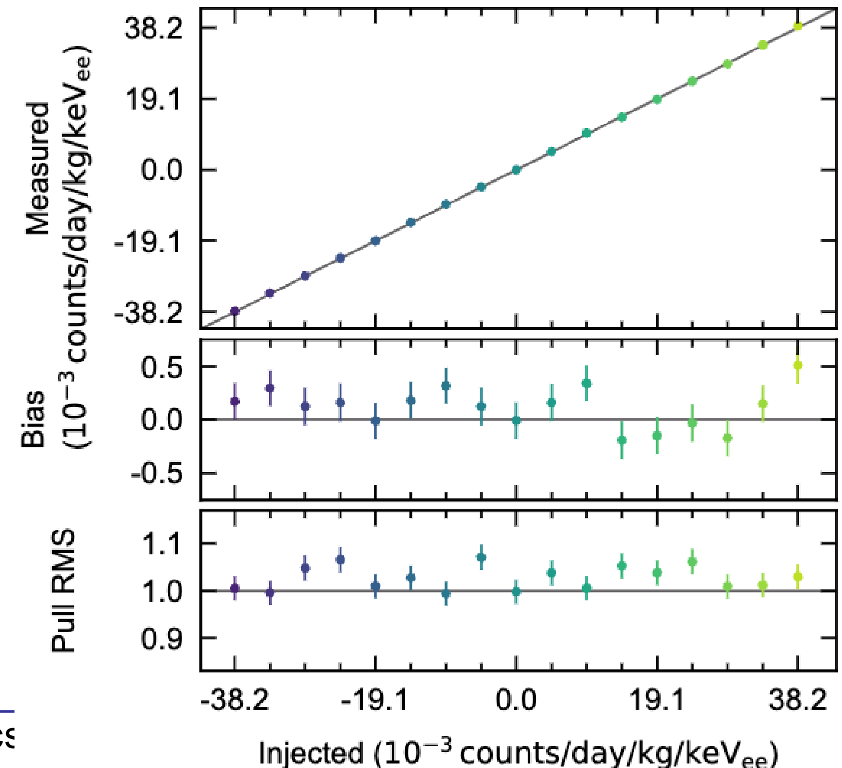
Input signal

$$z = \frac{m_A - I_A}{\sigma_A}$$

Measured uncertainty

No Bias





NaI-based experiments running or proposed

- Advantages of NaI(Tl)
  - Well known technology
  - Possible to grow ~10 kg crystals
  - High light output
  - Combination of low-mass (Na) and high-mass (I) element
  - Proton odd element
- Disadvantages of NaI(Tl)
  - Hygroscopic crystals
  - Less n/gamma separation (i.e. liquid xenon or photon-sensitive detectors)

Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	running
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Y2L	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North / South	LNGS + SUPL	NaI(Tl)	~50	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON	Kamioka	NaI(Tl)	~50	in preparation

- So far, NaIAD, DM-Ice, KIMS-NaI, DAMA/LIBRA, ANAIS-112 and COSINE-100 released DM search results with NaI(Tl) crystals