COSINE dark matter search

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Institute for Basic Science

Center for Underground Physics

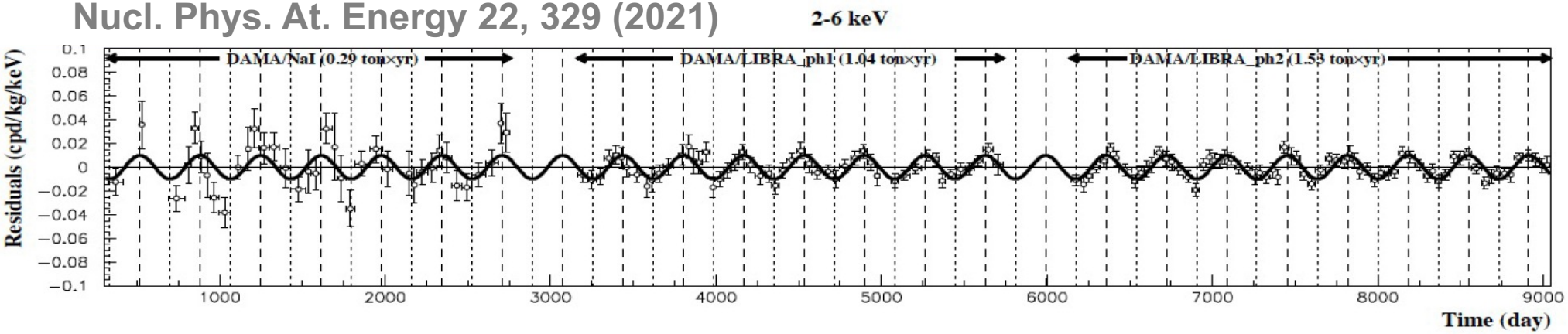
IBS-INFN Global Research Center Opening Meeting

October 31th, 2025

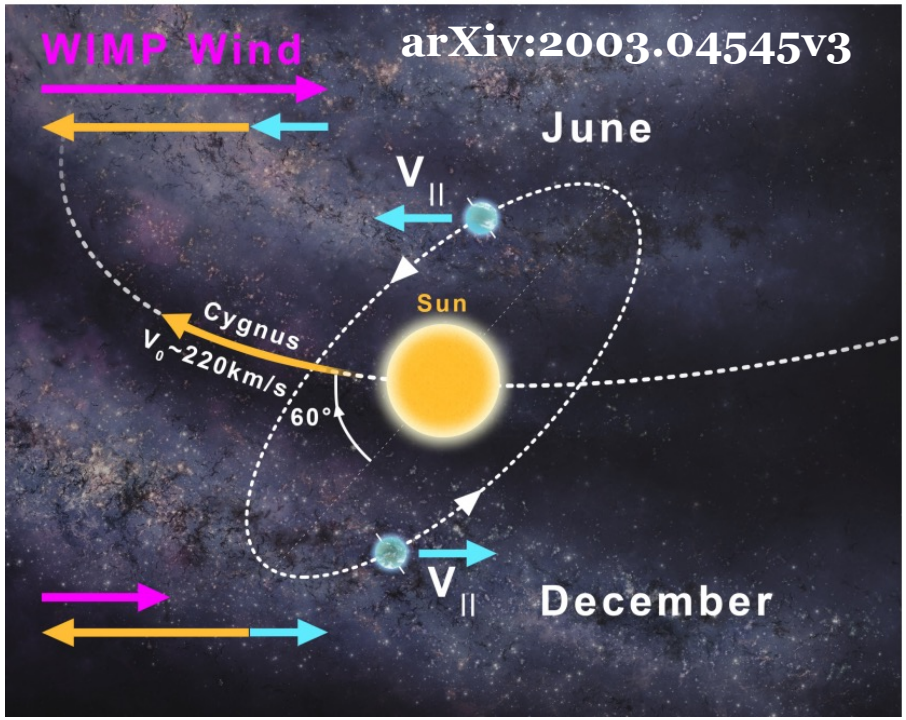
DAMA/LIBRA

- Dark matter discovery (more than 25 years old story)?
- Annual modulation signature of relic dark matter
- 250 kg **NaI(Tl) crystal** array at Gransasso (Italy)

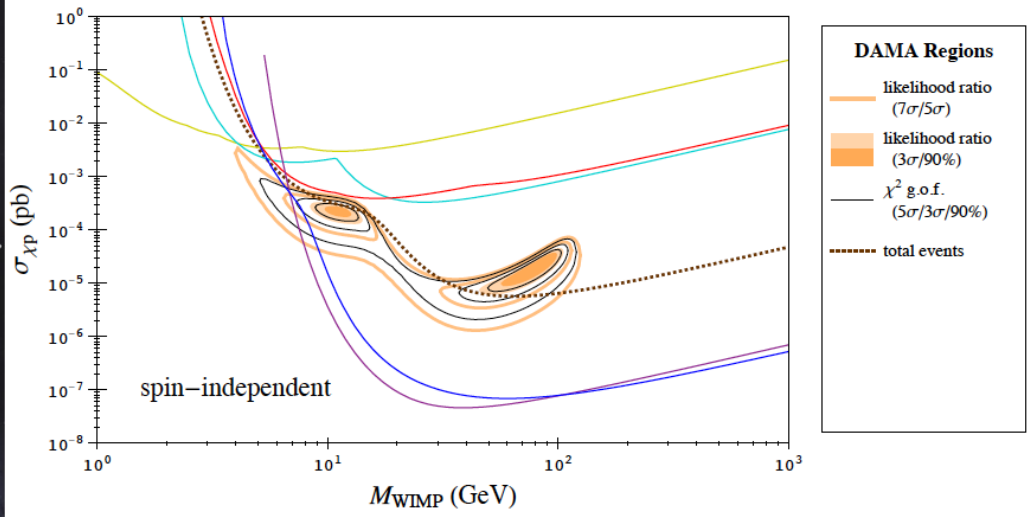
Nucl. Phys. At. Energy 22, 329 (2021)



DAMA/LIBRA

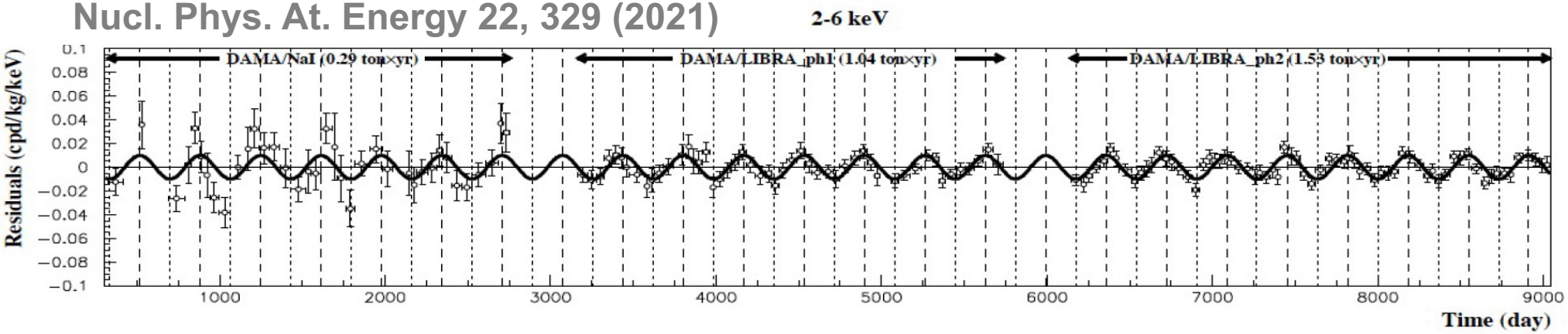


JCAP 04, 010 (2009)



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

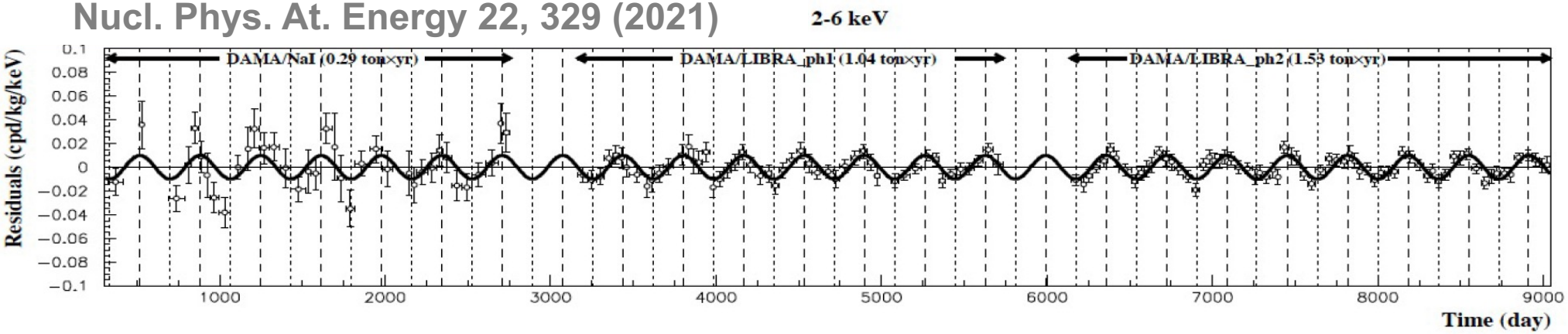
Nucl. Phys. At. Energy 22, 329 (2021)



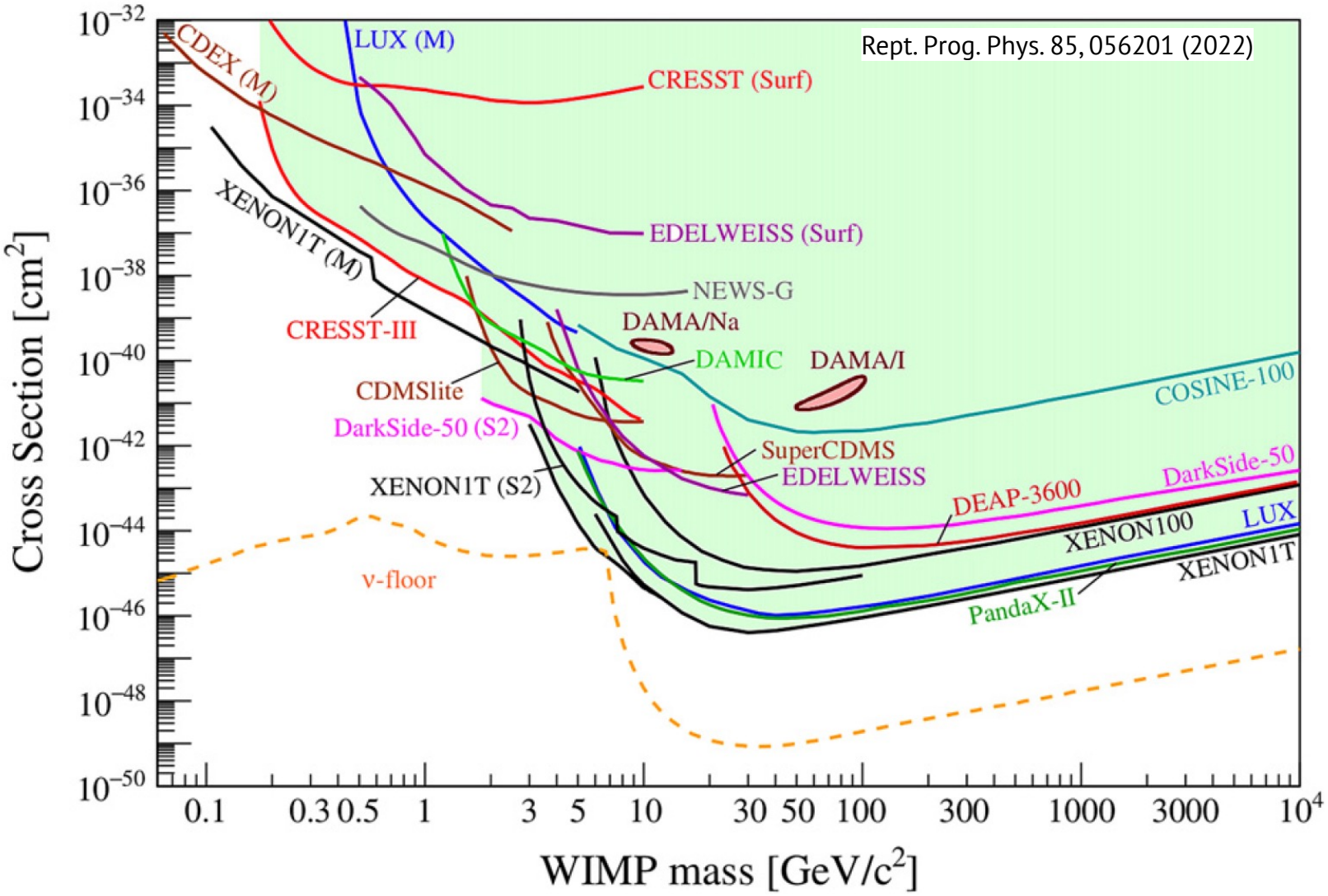
DAMA/LIBRA

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)

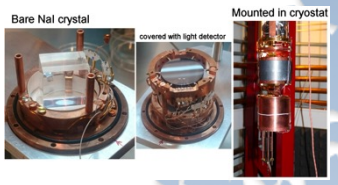


However…

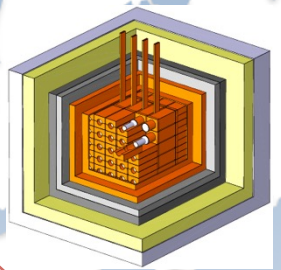


Requiring Model-independent test with same NaI(Tl) crystals

World-wide efforts on NaI(Tl)

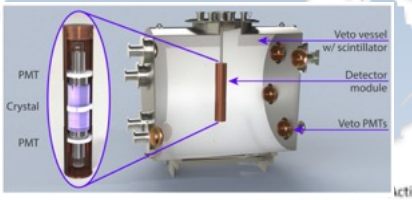


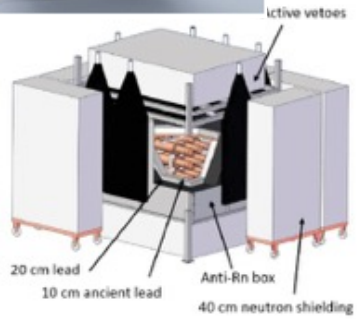
COSINUS
@ LNGS



DAMA
@ LNGS

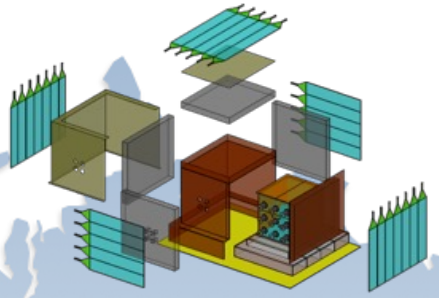
SABRE
@ LNGS





ANAIS
@Canfranc

Data-taking
(2017~present)

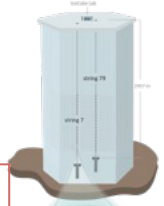


KIMS/COSINE
@ Yangyang

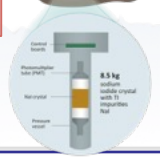
Data-taking (2016-2023)

PICO-LON
@ Kamioka

SABRE
@ Stawell



DM-Ice @ South Pole

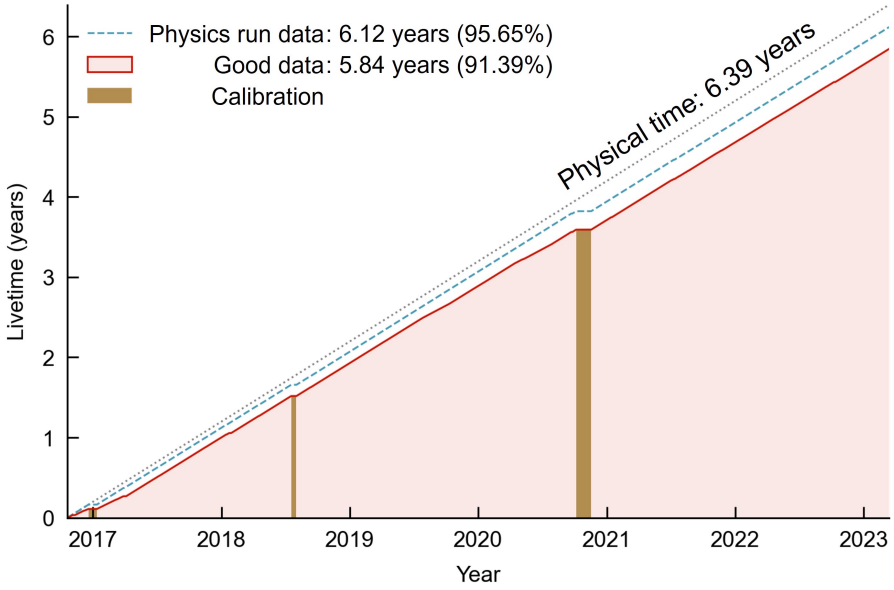


COSINE collaboration

15 institutes
~60 members

KIMS Korea Invisible Mass Search Experiment + DM-ICE = COSINE

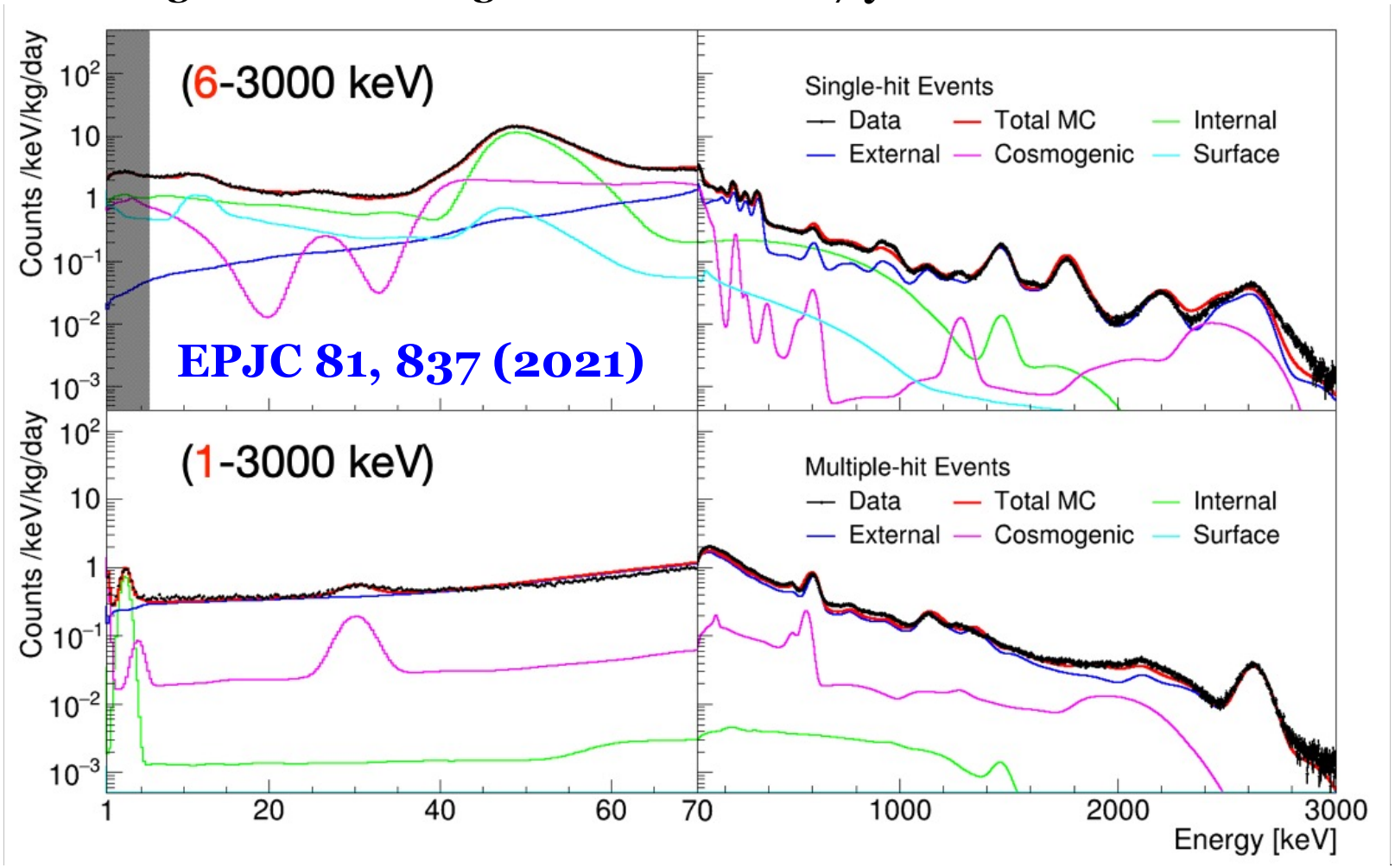
COSINE-100 experiment (2016~2023)



- YangYang underground laboratory
  - ❖ **October/2016 ~ March/2023**
- Decommissioning
  - ❖ Move to **Yemilab**
  - ❖ Upgrade of detector for **high light yield**
  - ❖ Restart run since **September 2025**

Background understanding (~ 2 years data)

Background modeling **1.7 years data**

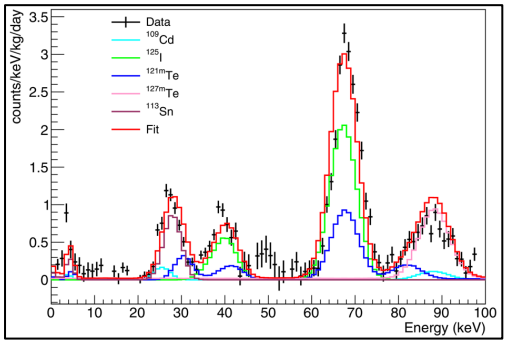


WIMP Extraction at 1-6 keV region Sci. Adv. 7, eabk2699 (2021)

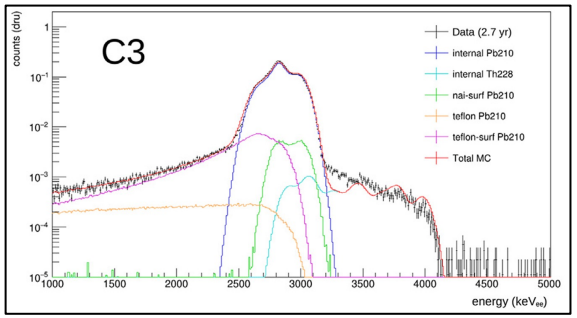
Annual Modulation Search PRD 106, 052005 (2022)

Improvement of NaI(Tl) detector understanding

ASP 115, 102390 (2020)



ASP 158, 102945 (2024)



Background components

Improvement of NaI(Tl) detector understanding

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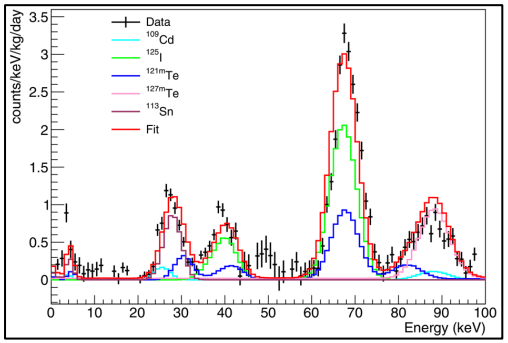
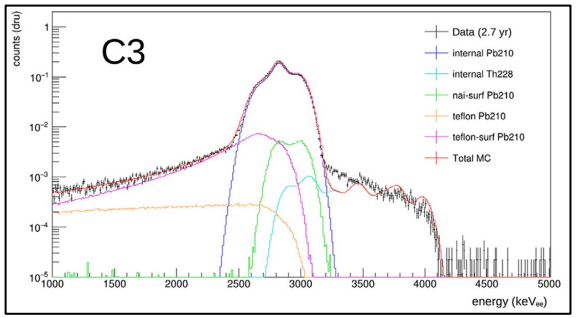
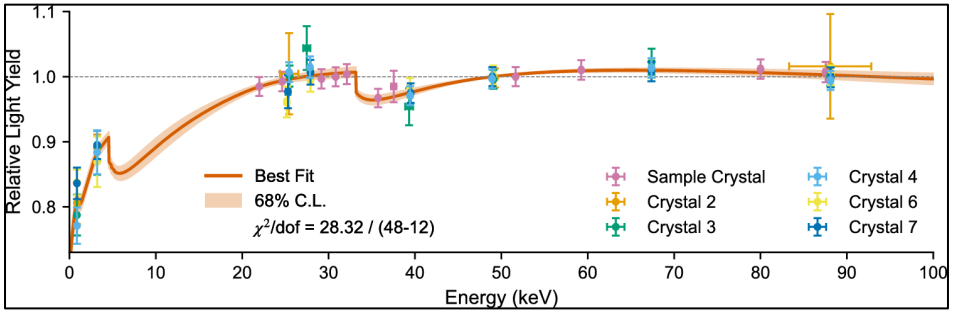


ASP 158, 102945 (2024)



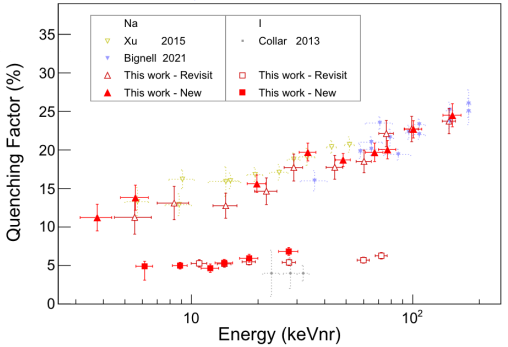
Background components

EPJC 84, 484 (2024)



Detector responses

PRC 110, 014614 (2024)



Improvement of NaI(Tl) detector understanding

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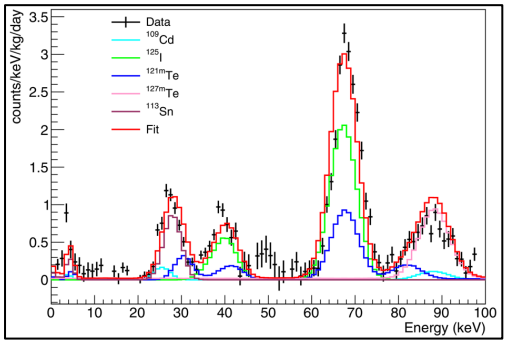

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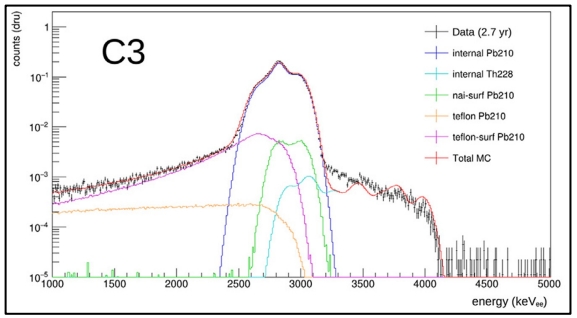
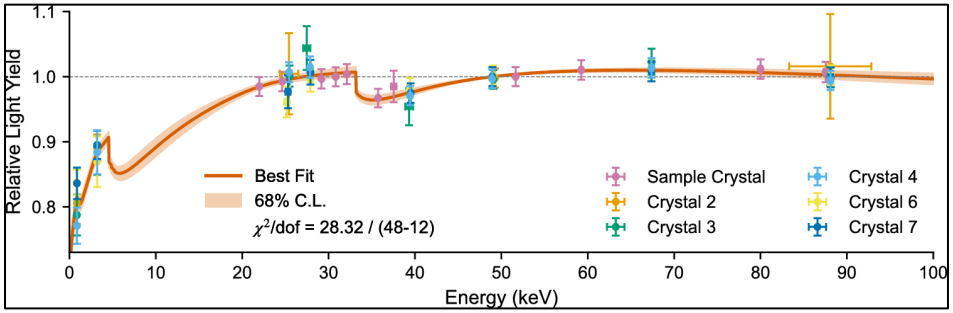


EPJC 84, 484 (2024)



Background components

Detector responses

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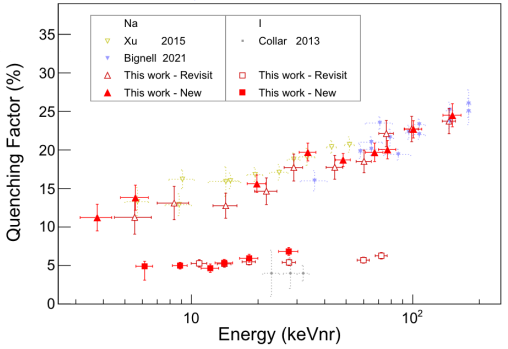
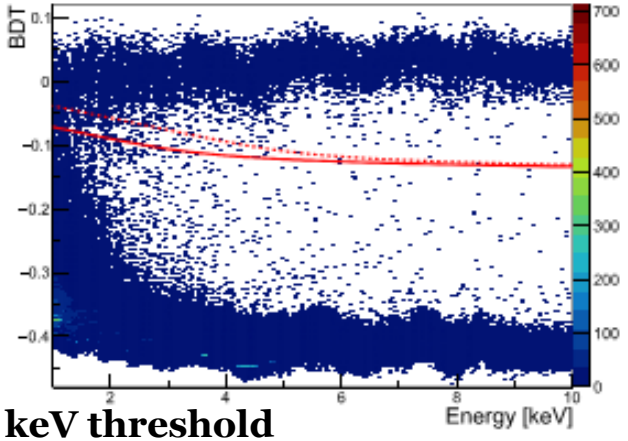


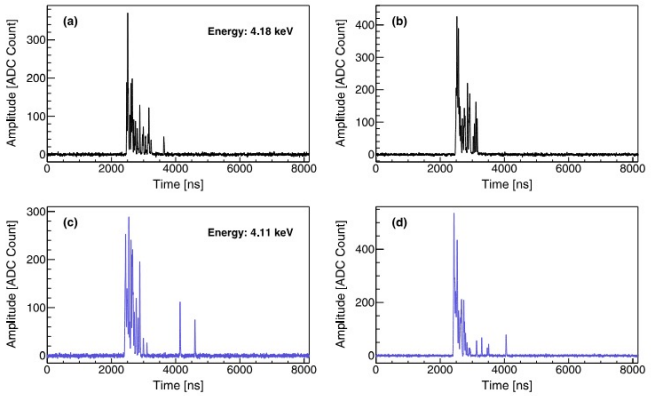
Low energy scintillation responses

ASP 130, 102581 (2021)

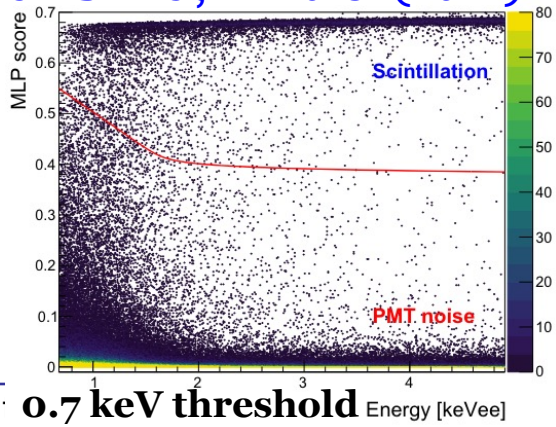


1 keV threshold

NIMA 1065, 169489 (2024)



JINST 19, P12013 (2024)



0.7 keV threshold

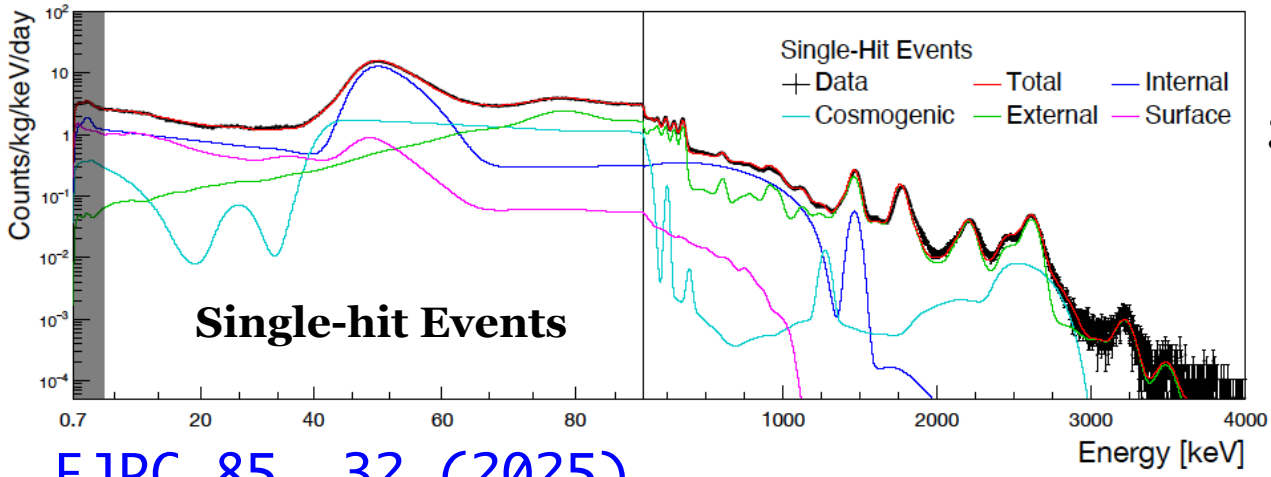
Improvement of NaI(Tl) detector understanding

Detector responses

Background components

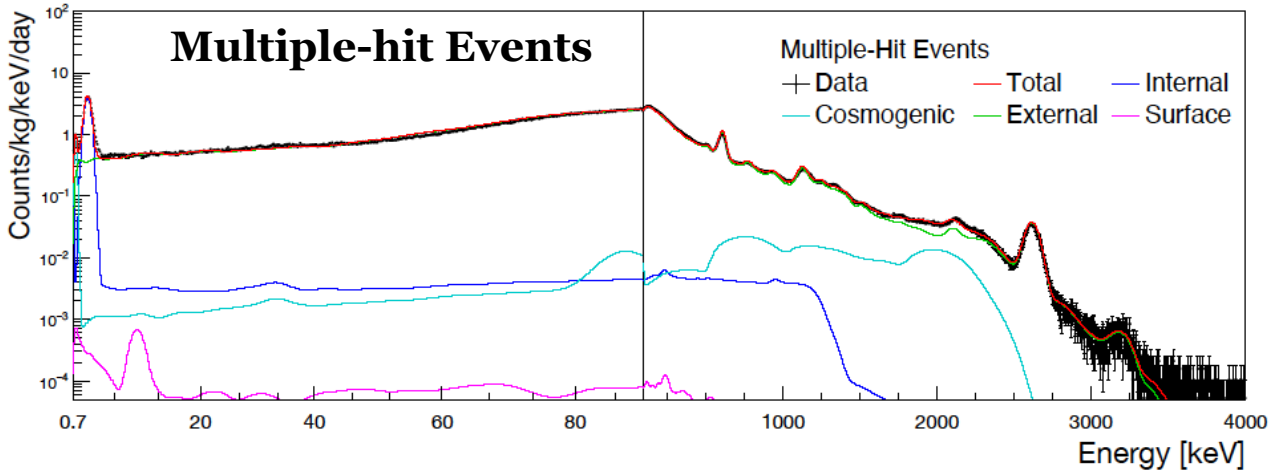
Low energy scintillation responses

Improved understanding of NaI(Tl) backgrounds in extended energy range 0.7 – 4000 keV



3 years data

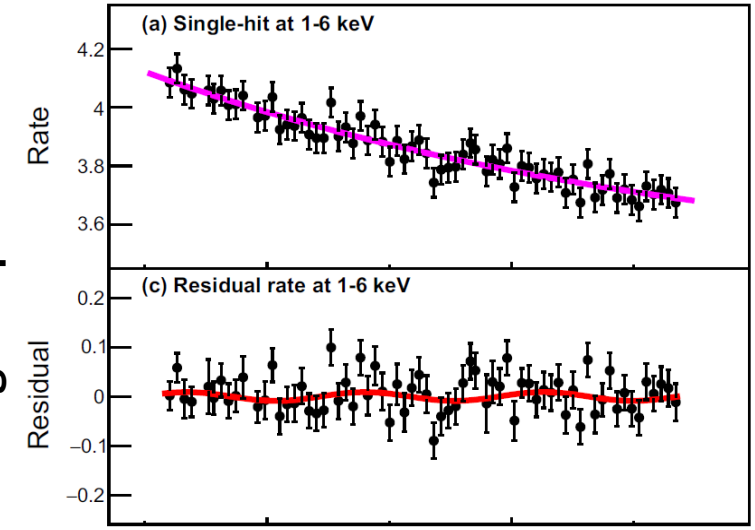
EJPC 85, 32 (2025)



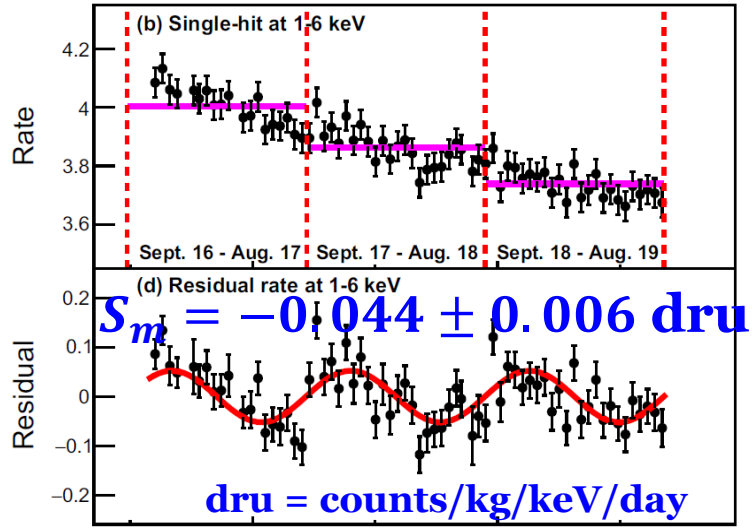
Time-dependent background models

Sci. Rep. 13, 4676 (2023)

Single exponential

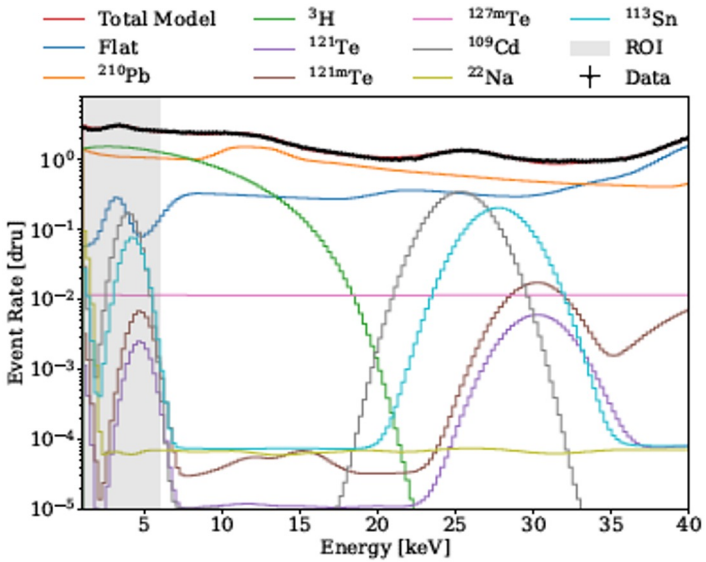


DAMA-like method



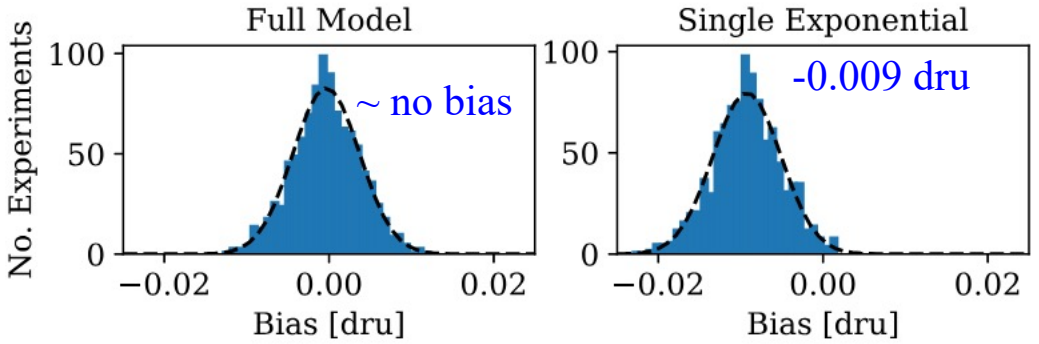
$S_m = -0.044 \pm 0.006$ dru

dru = counts/kg/keV/day



PRD 106, 052005 (2022) (3 years modulation search)

Full model : eight exponential components



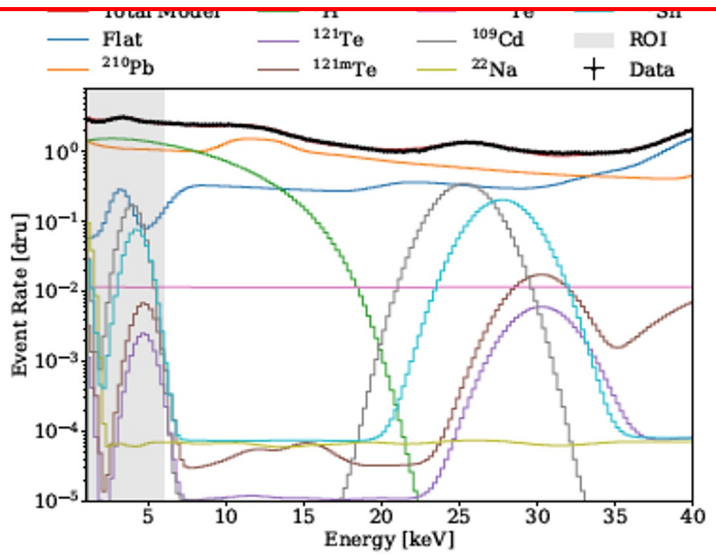
DAMA/LIBRA : 0.010 ± 0.001 dru

Time-dependent background models

Sci. Rep. 13, 4676 (2023)

Caveat : Understanding of time-dependent background is crucial for the annual modulation analysis

COSINE-100 is **a unique experiment** achieving precise background understanding of NaI(Tl) crystals



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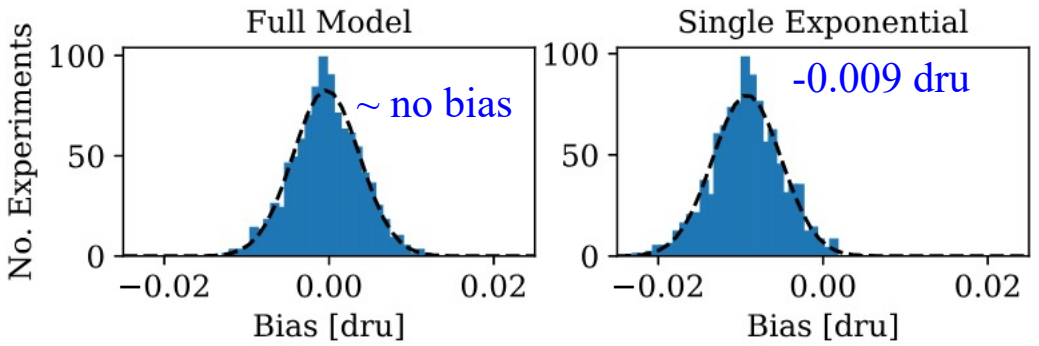
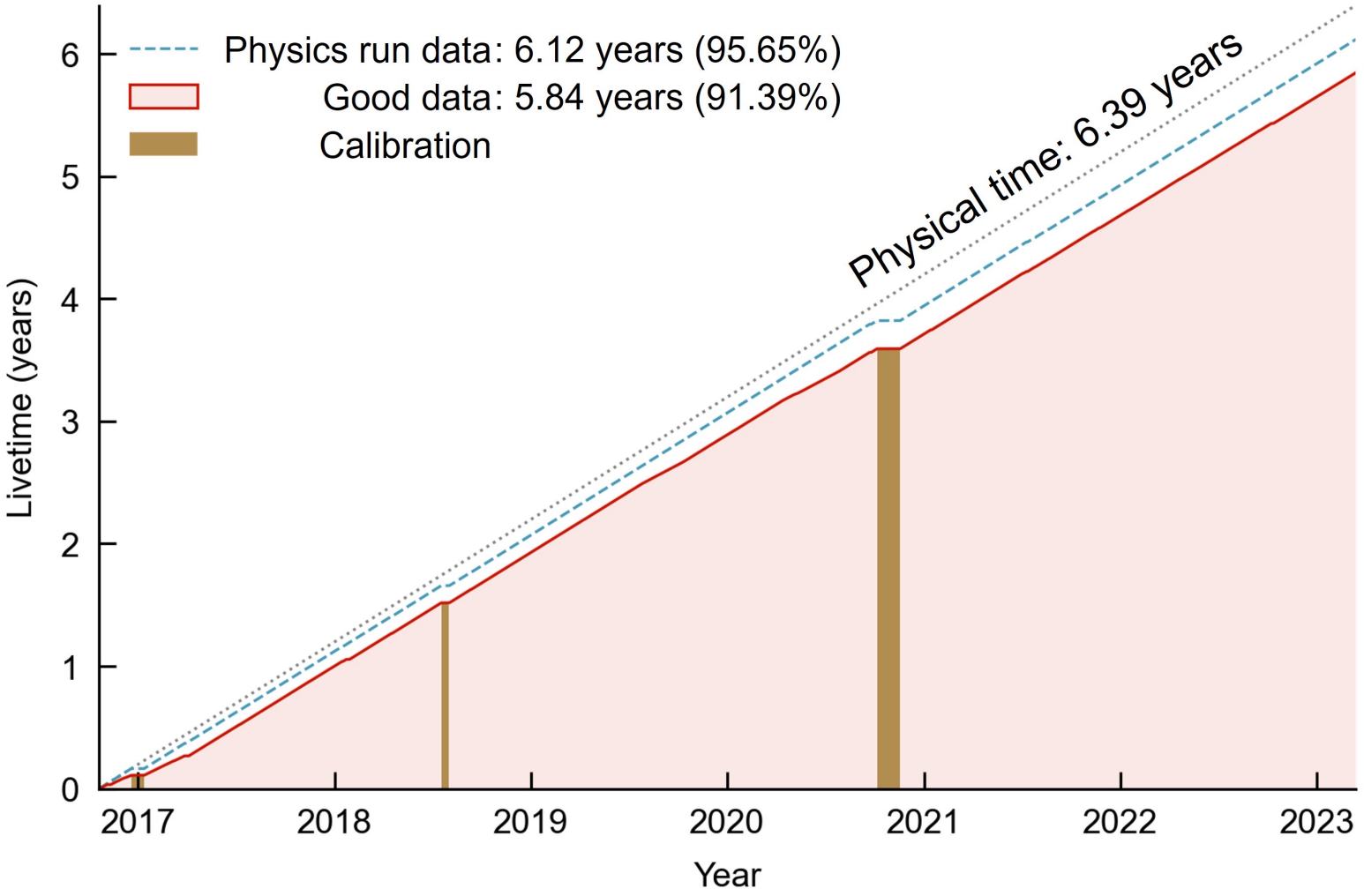


DAMA/LIBRA : 0.010 ± 0.001 dru

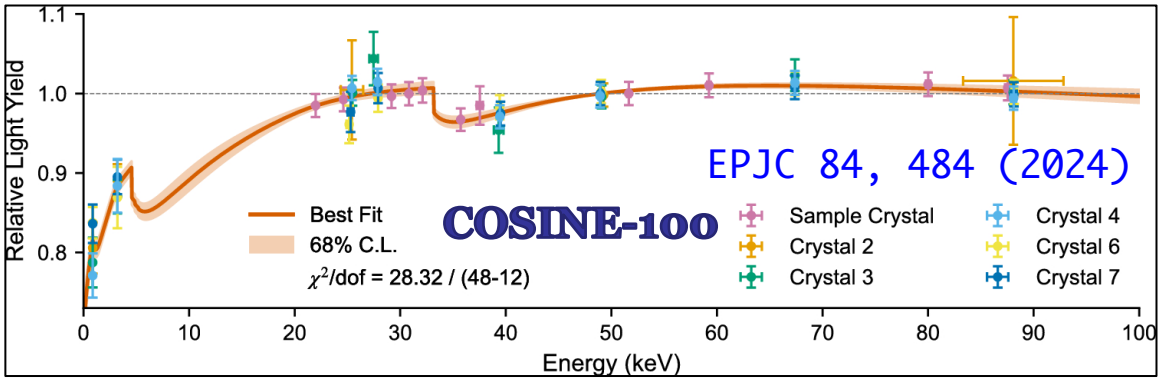
COSINE-100 full dataset

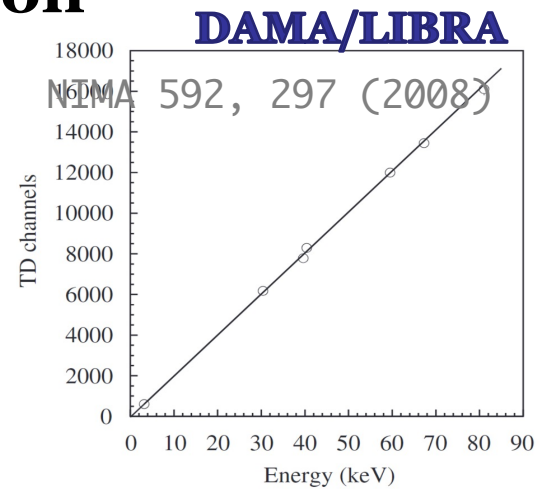


- Importance : Apple-to-apple comparison with **DAMA/LIBRA**

Comparison with DAMA : Energy calibration

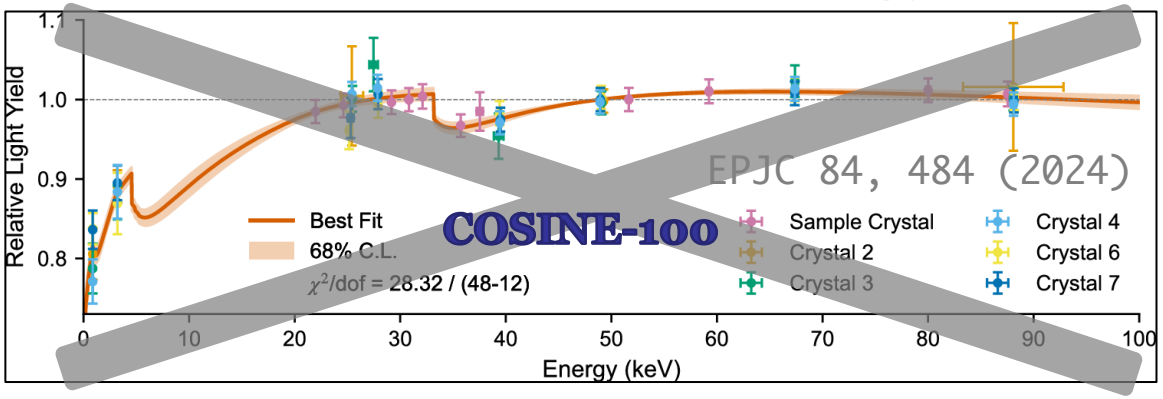
Electron-recoil energy calibration

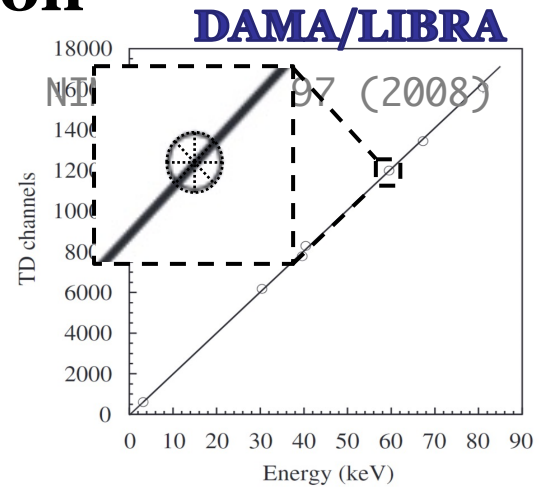




Comparison with DAMA : Energy calibration

Electron-recoil energy calibration

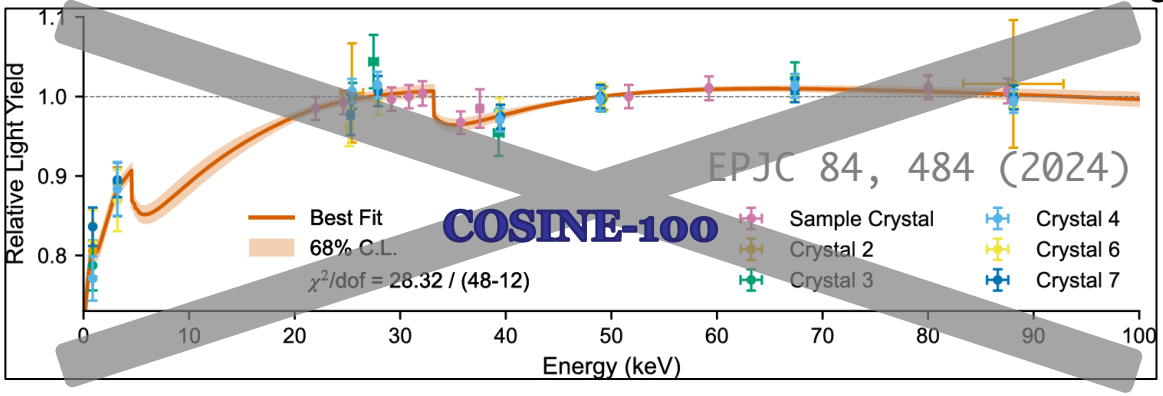


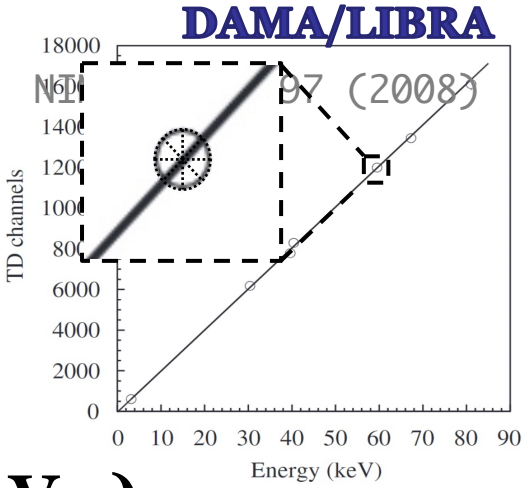


Linear calibration to 59.54 keV : keV_{ee}

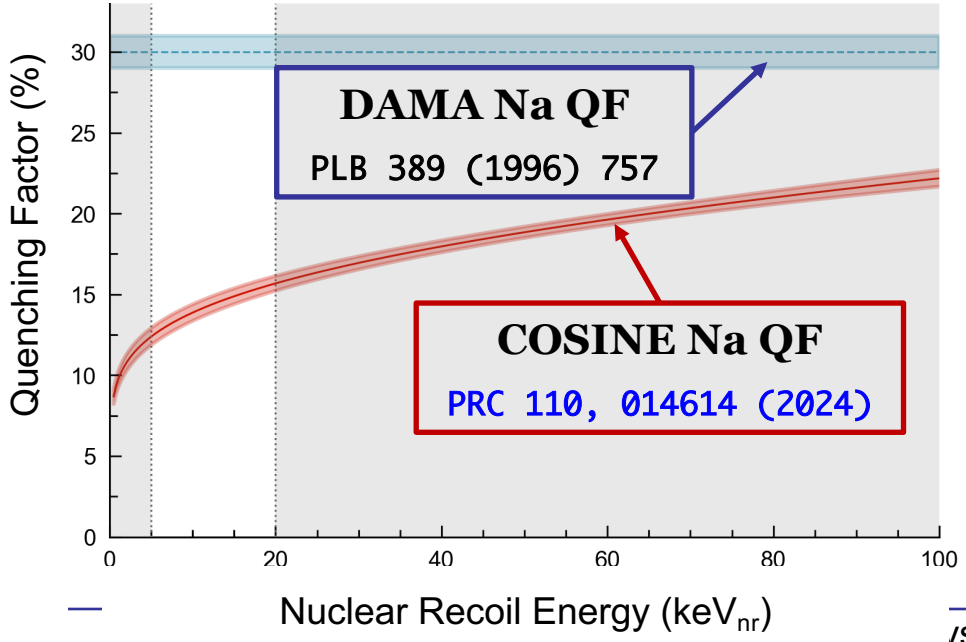
Comparison with DAMA : Energy calibration

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}

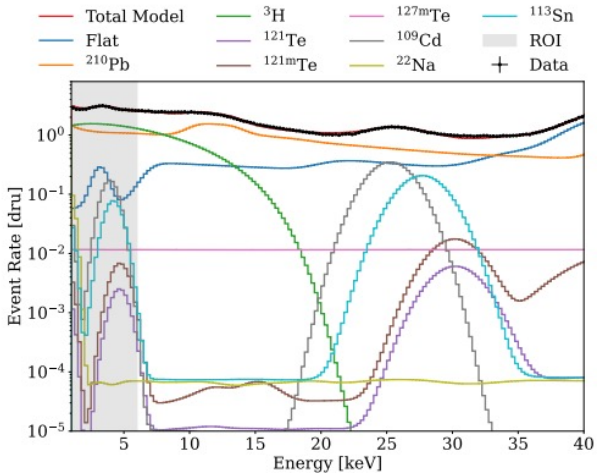
DAMA/LIBRA : 2-6 keV_{ee}

COSINE-100 : 0.85-3.12 keV_{ee}

Modulation fit

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

Modulation signals — 10 time-dependent components

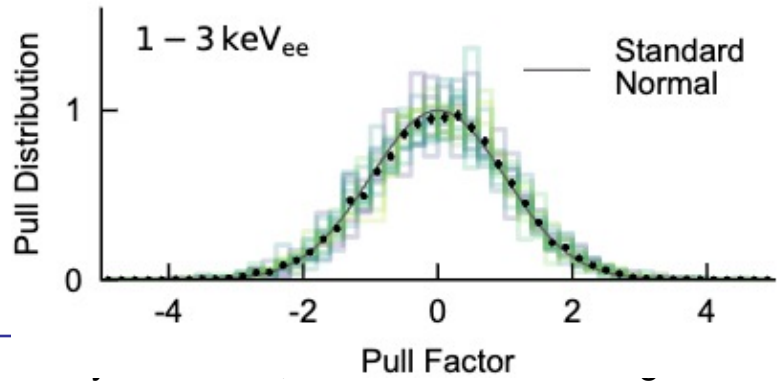


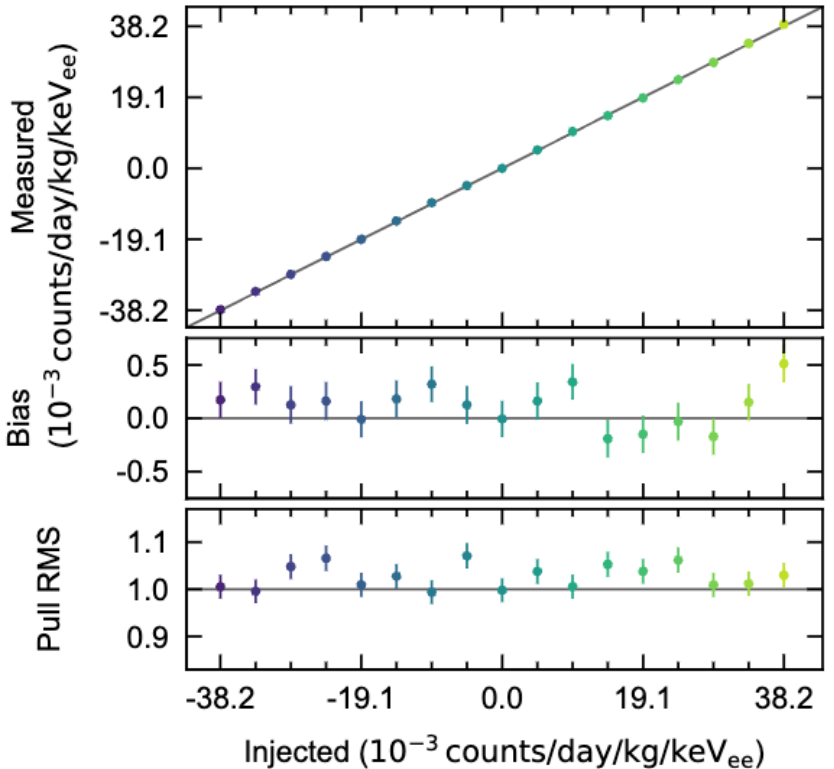
Simulated experiments

Pull Factor: $z = \frac{m_A - I_A}{\sigma_A}$

Measured signal; Input signal; Measured uncertainty

No Bias





Modulation fit

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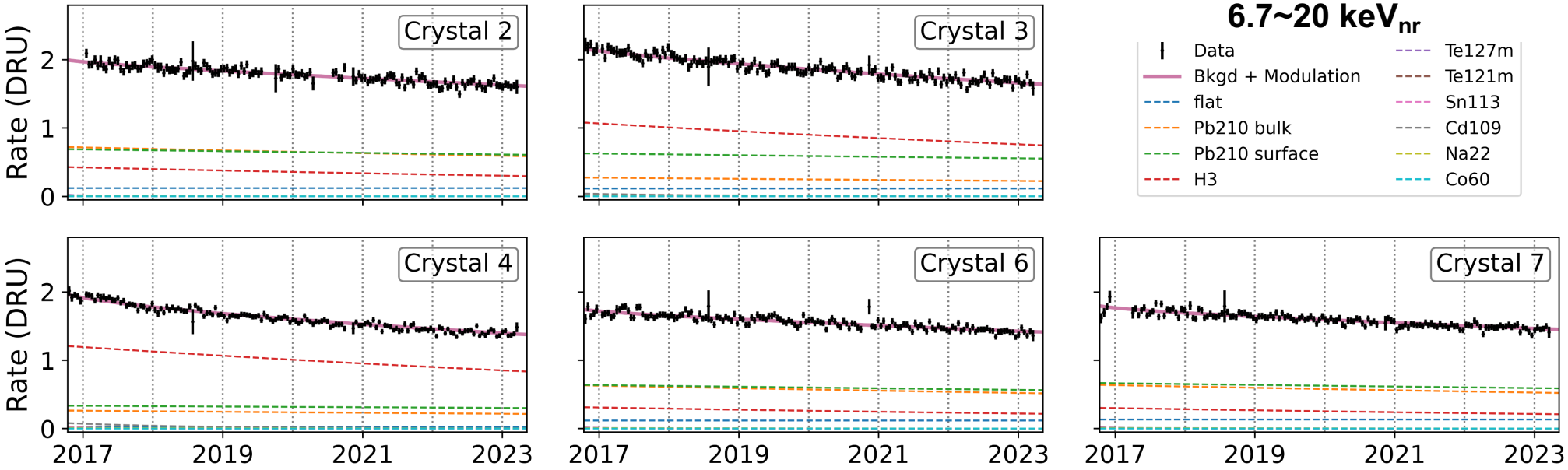
Modulation signals 10 time-dependent components

COSINE-100 full dataset

DRU = counts/kg/keV/day

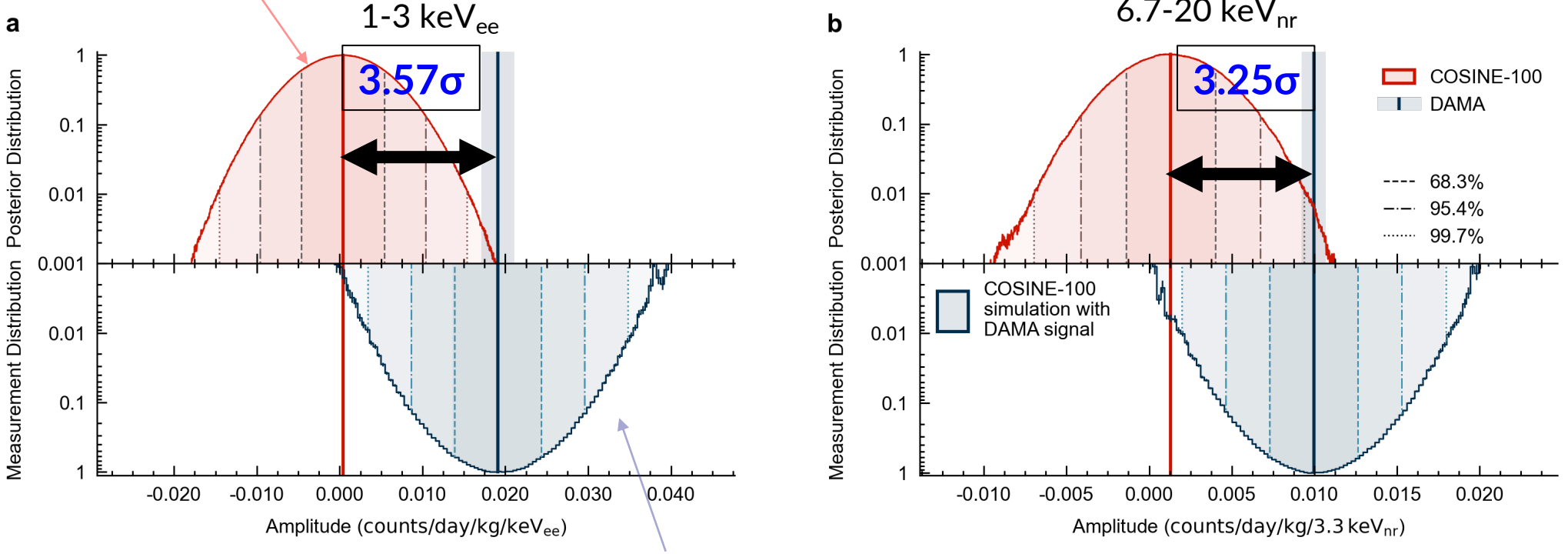


No modulation signal observed !!

COSINE-100 full dataset fits

Posterior of COSINE-100 full dataset

(2-6 keVee in DAMA/LIBRA)



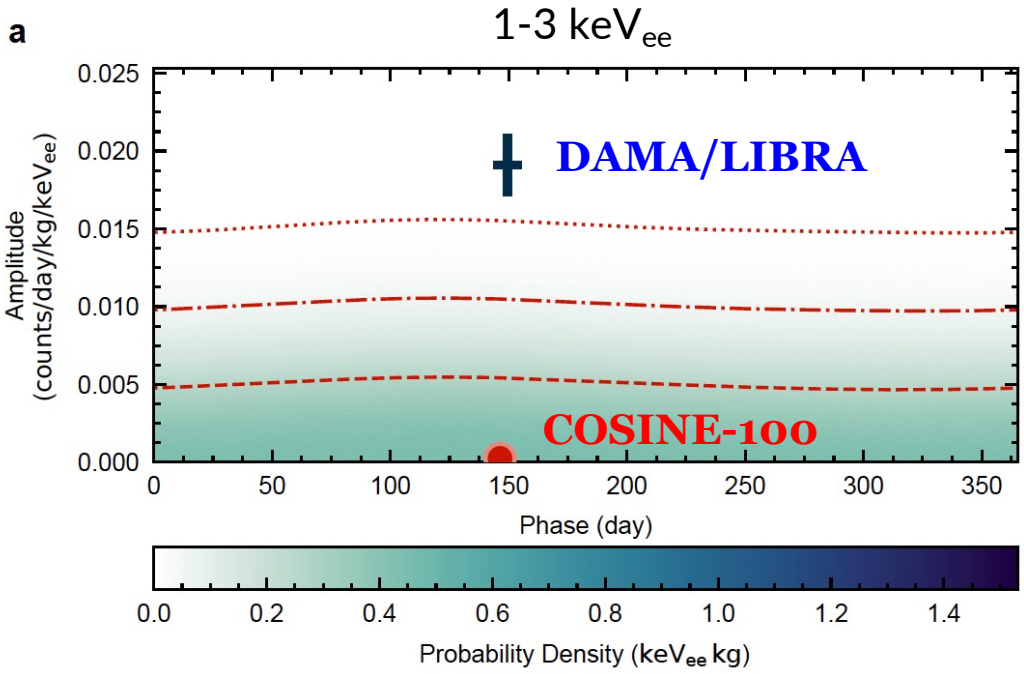
Simulated experiments (300,000) assuming DAMA/LIBRA modulation signals

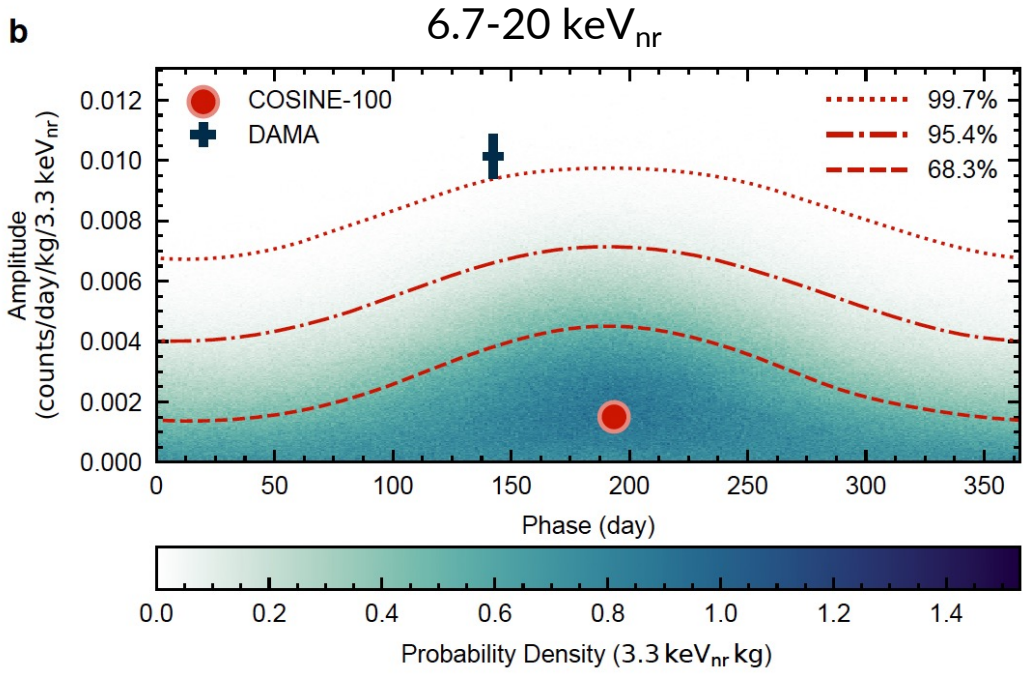
Sci. Adv. 11, eadv6503 (2025)

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

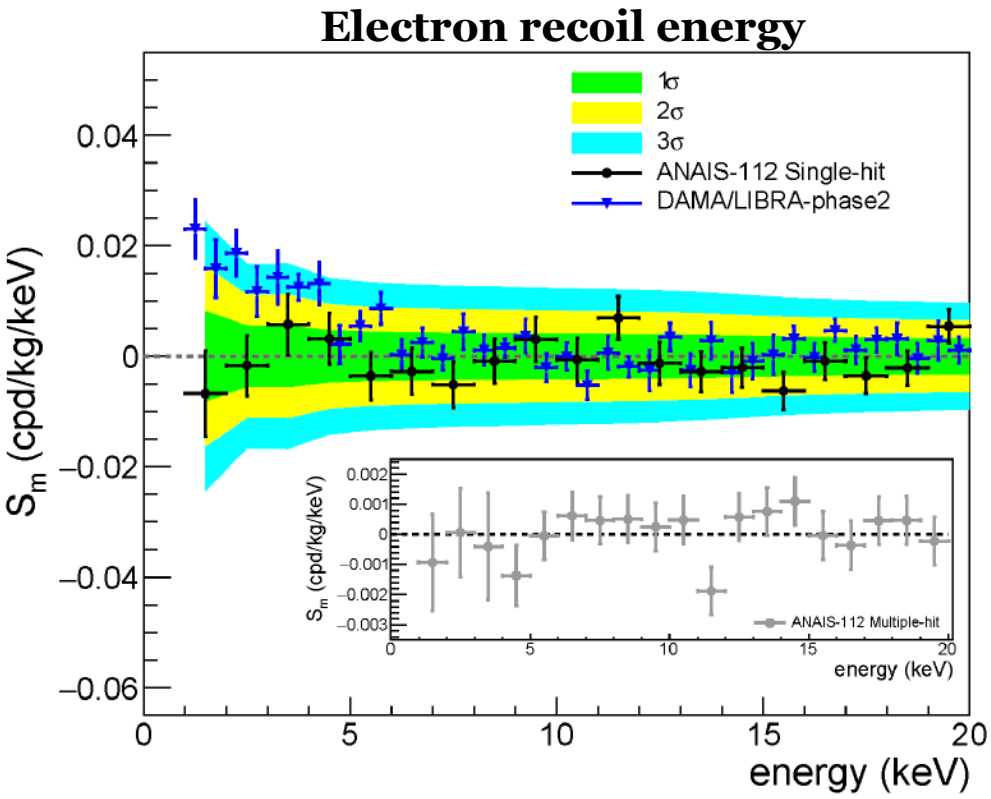


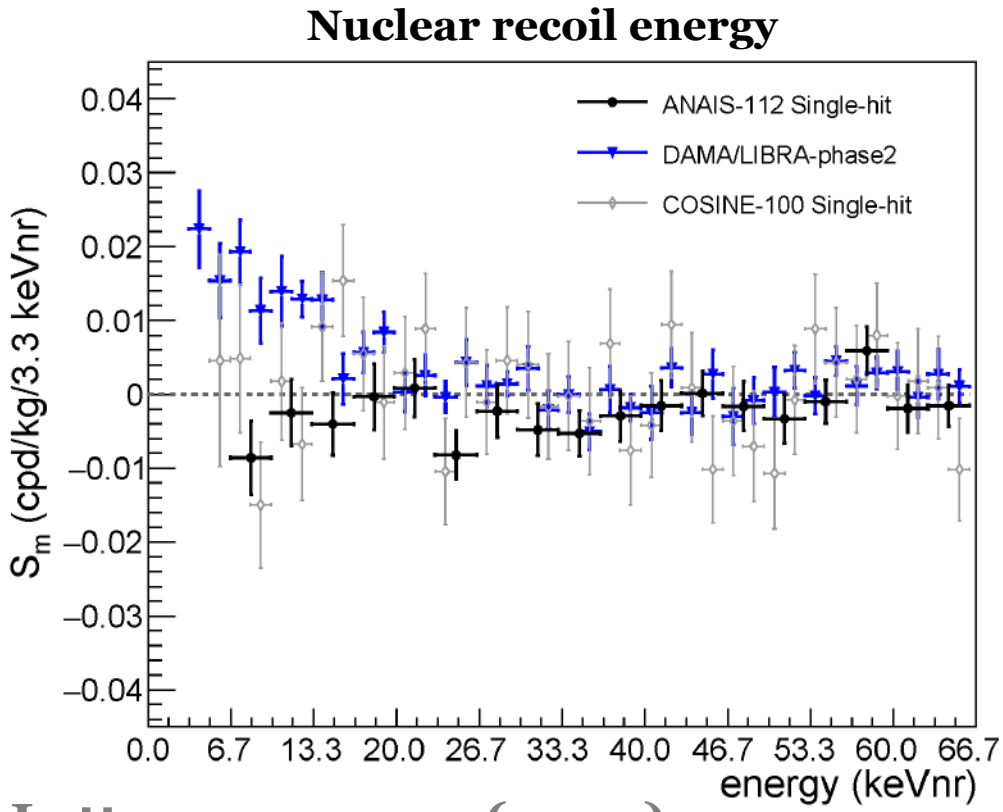


Sci. Adv. 11, eadv6503 (2025)

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

ANAIS-112 modulation results



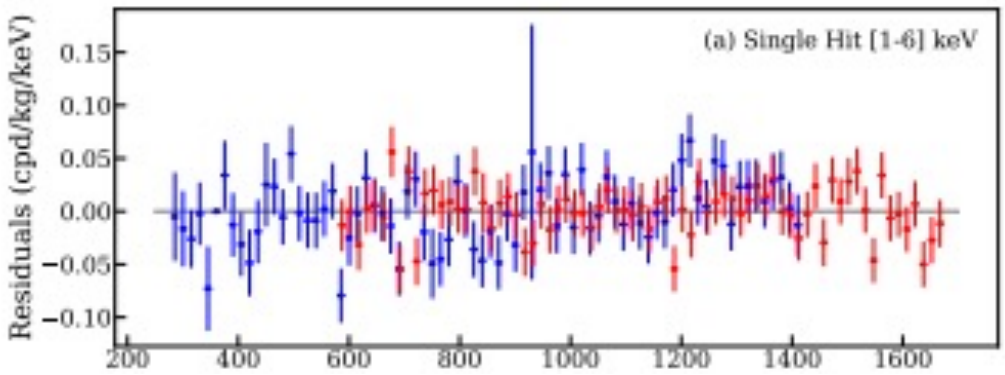


Phys. Rev. Lett. 135, 051001 (2025)

- ANAIS-112 results are incompatible with DAMA/LIBRA
- Best fit are incompatible with DAMA/LIBRA results at 4.0σ and 3.5σ in 1-6 keVee and 2-6 keVee, respectively

Combined analysis between COSINE and ANAIS

Combining published data (~ 3 years)

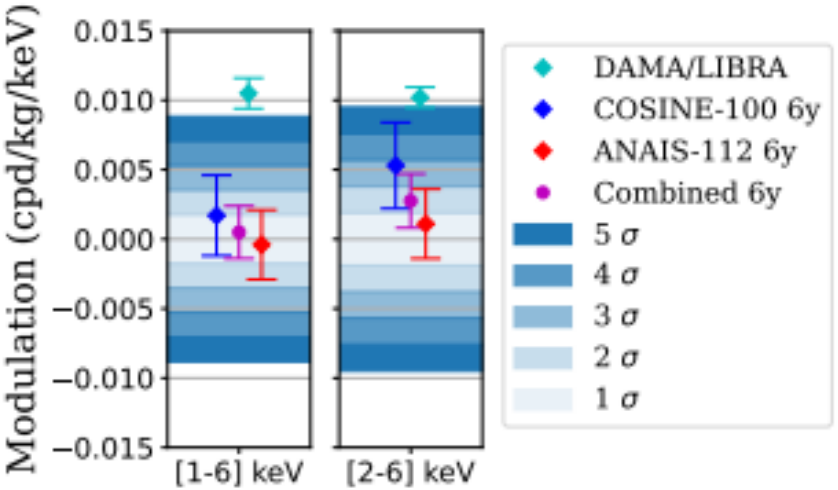


ANAIS-112: PRD 103, 102005 (2021)

COSINE-100: PRD 106, 052005 (2022)

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



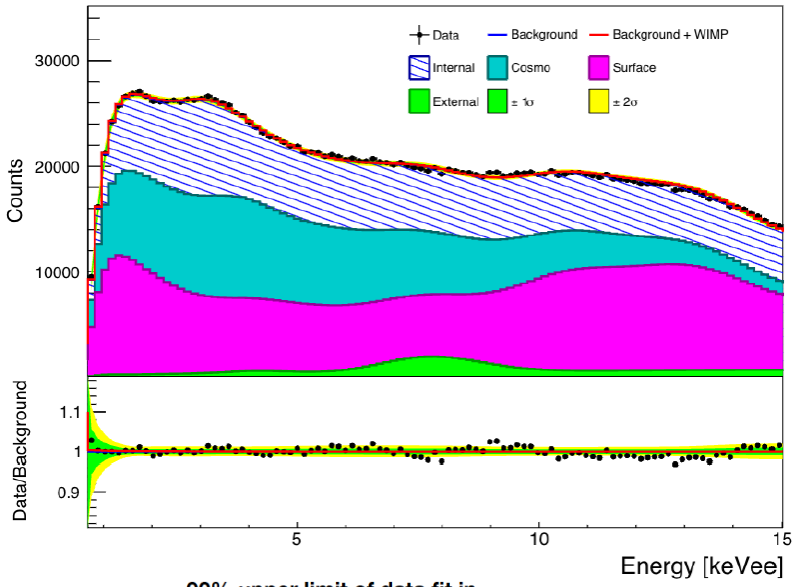
Phys. Rev. Lett. 135, 121002 (2025)

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

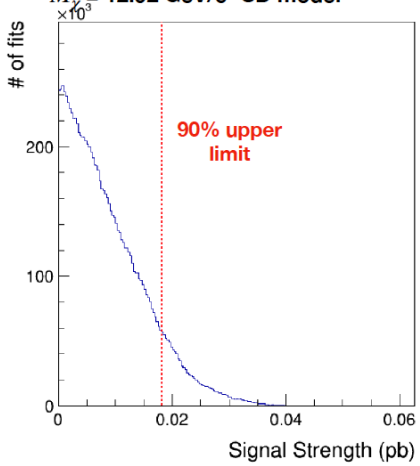
Model-dependent search

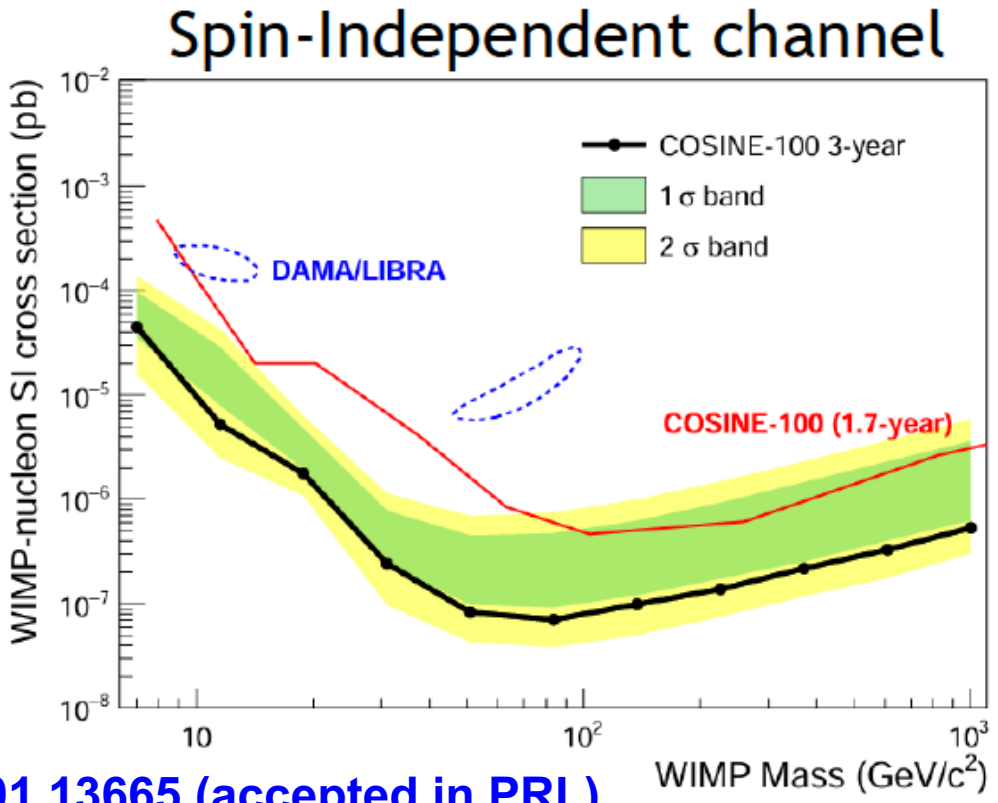
COSINE-100 3 years data

Example of WIMP presence test in M_χ = 12.92 GeV/c² SD model



90% upper limit of data fit in M_χ = 12.92 GeV/c² SD model





arXiv:2501.13665 (accepted in PRL)

COSINE-100 full dataset disfavors DAMA/LIBRA in model-dependent search

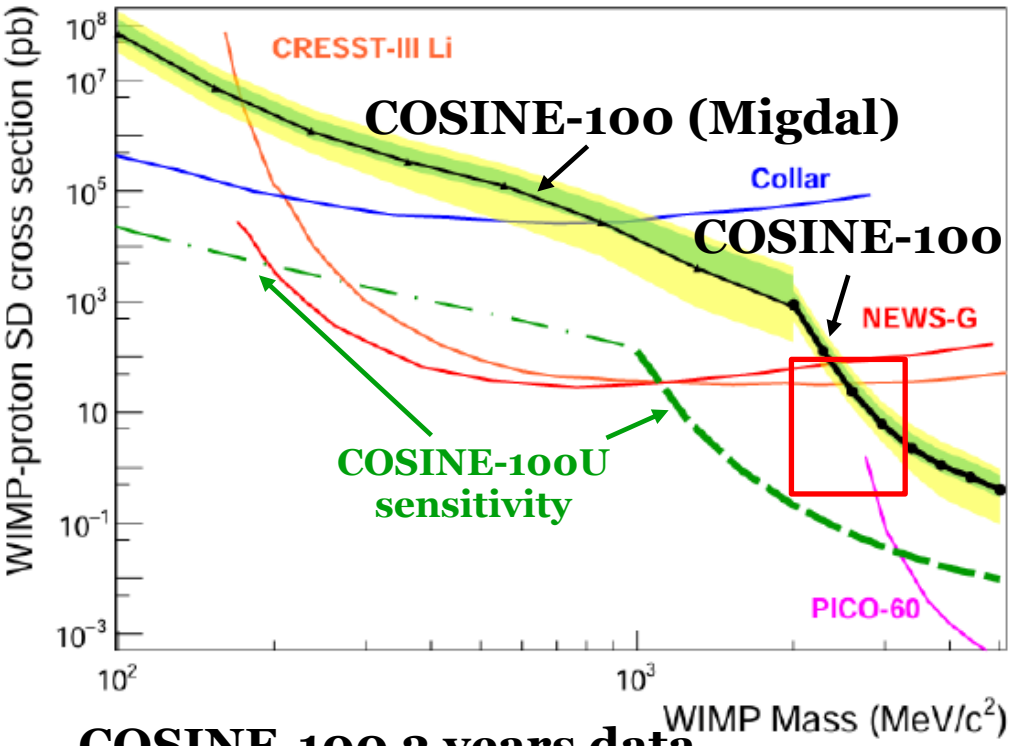
World best limit from COSINE-100

- Na (Z = 11) and I (Z=53)
  - ❖ Good for spin-dependent WIMP-proton interactions
  - ❖ Si (Z = 14), Ge (Z = 32), Ar (Z = 18), Xe (Z = 54)
  - ❖ Good for low-mass (sodium)

- Reduced threshold?
  - ❖ Current threshold : **8 NPE** (0.7 keV)
  - ❖ COSINE-100 goal : 5 NPE (0.5 keV)
    - ❑Waveform simulation
    - ❑Improving machine learning
    - ❑Employ deep learning

NPE = number of photoelectrons

WIMP-proton spin-dependent interaction



COSINE-100 3 years data

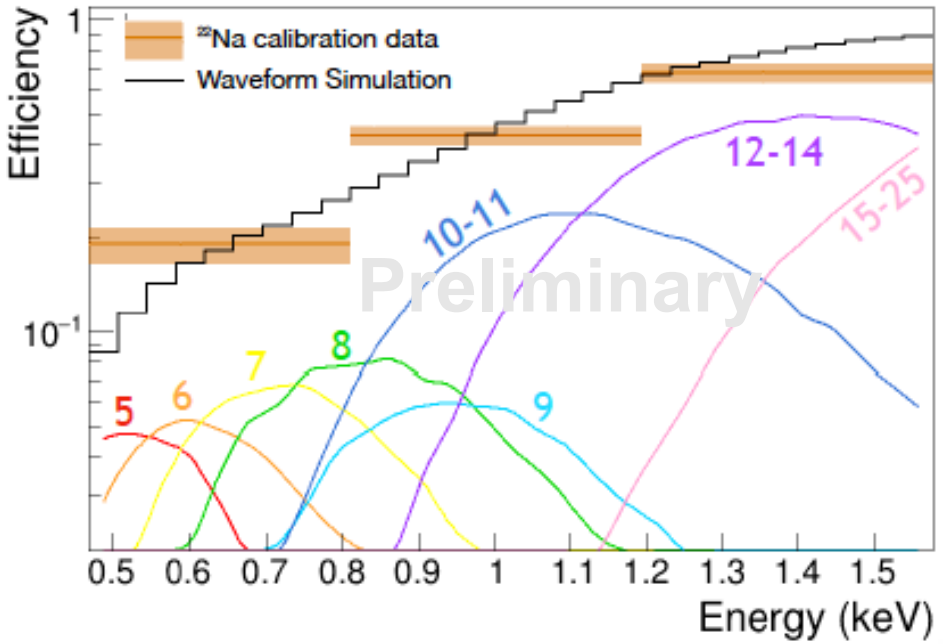
8 NPE threshold

arXiv:2501.13665 (accepted in PRL)

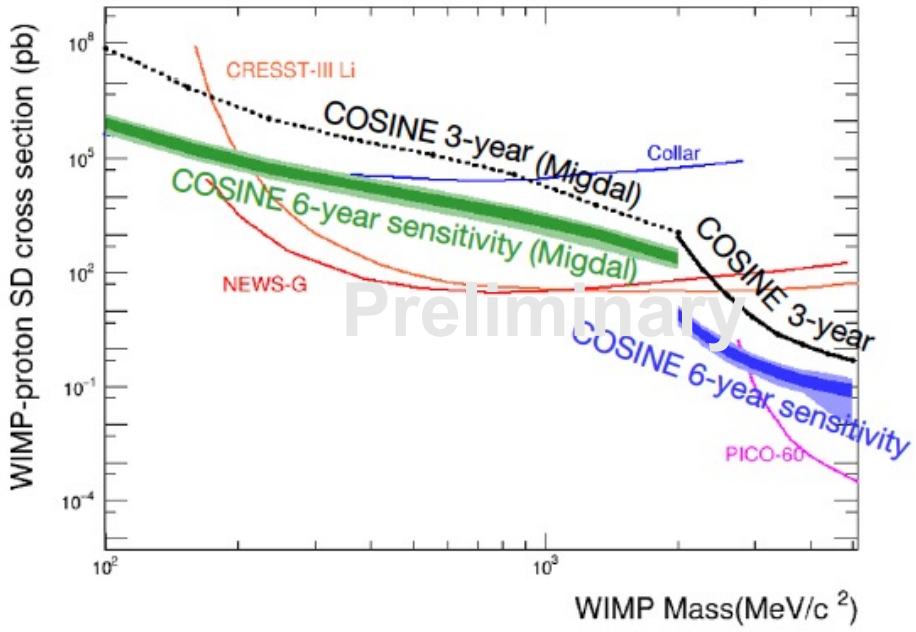
Lower energy threshold with full dataset

- Machine learning training with waveform simulation data
- Each reconstructed clusters (~ photoelectrons) trained separately
- Reduced threshold to ~ 0.5 keV (5 NPE) with ~ 10% efficiency
  - ❖ Consider deep learning with raw waveform

Selection Efficiency Curve

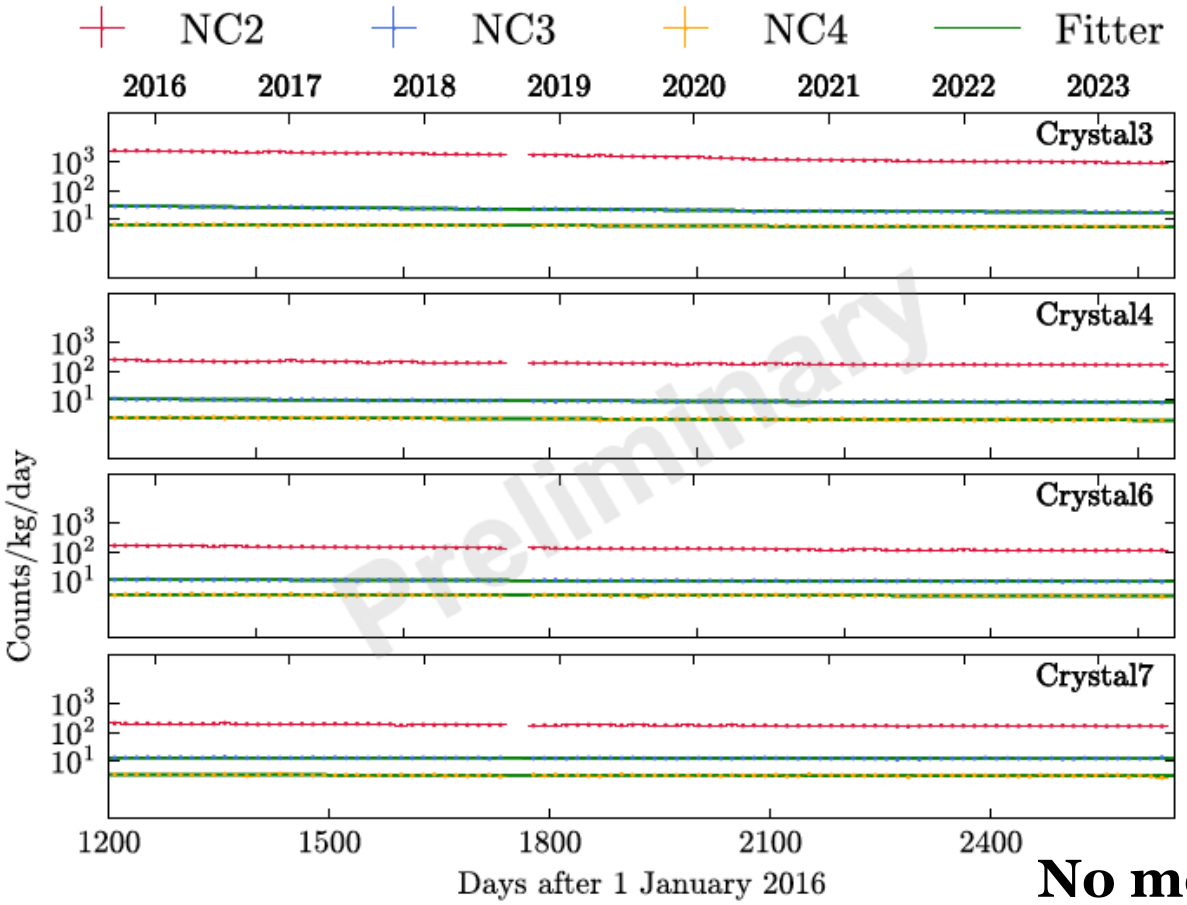


Sensitivity
with the new threshold



Modulation search with 2-4 NPE events

- We **could not remove all noise** contamination (ML selection)
- However, we can search annual modulation of event rate in this energy bin (**assuming** single exponential background)



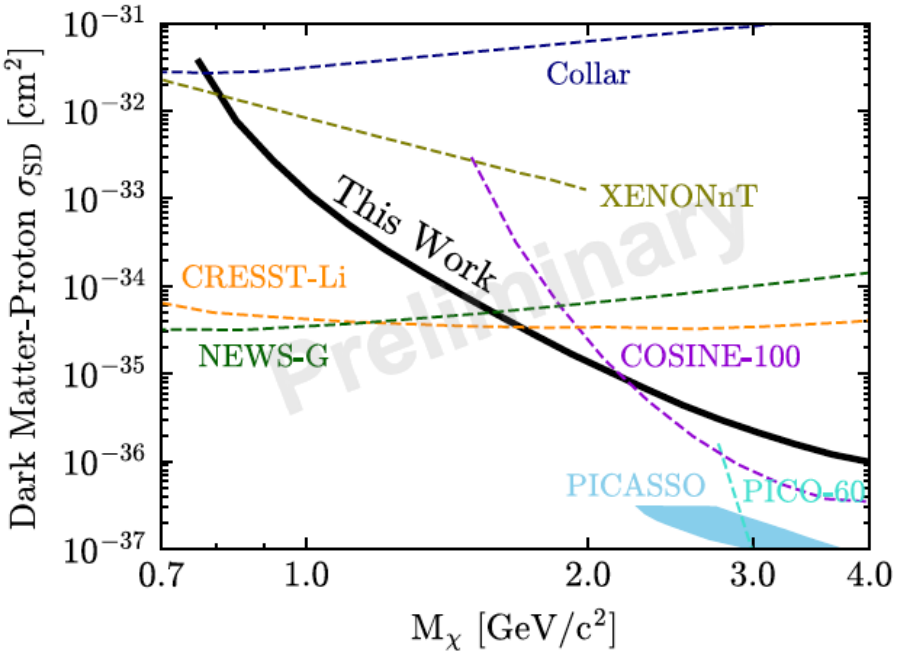
Trigger : 2 P.E.

No modulation

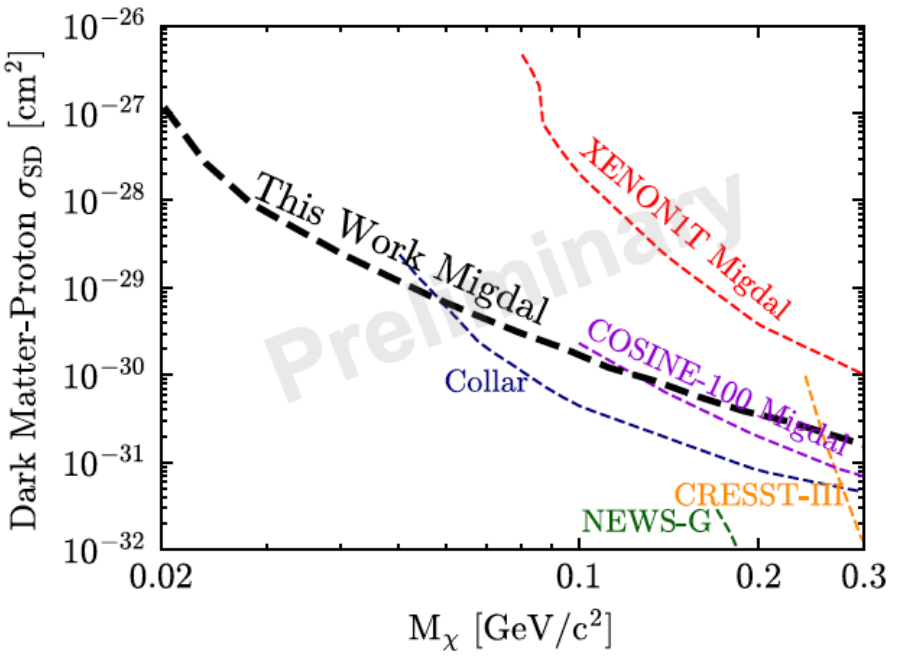
Modulation search with 2-4 NPE events

- We **could not remove all noise** contamination (ML selection)
- However, we can search annual modulation of event rate in this energy bin (**assuming** single exponential background)

➢ Spin-dependent only

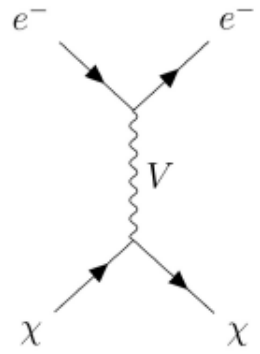


➢ Spin-dependent with Migdal effect



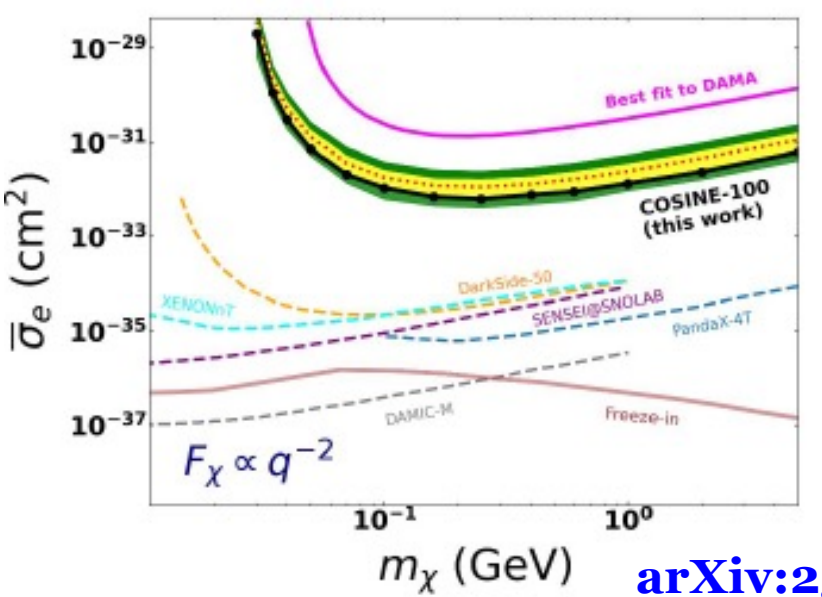
WIMP-electron scattering

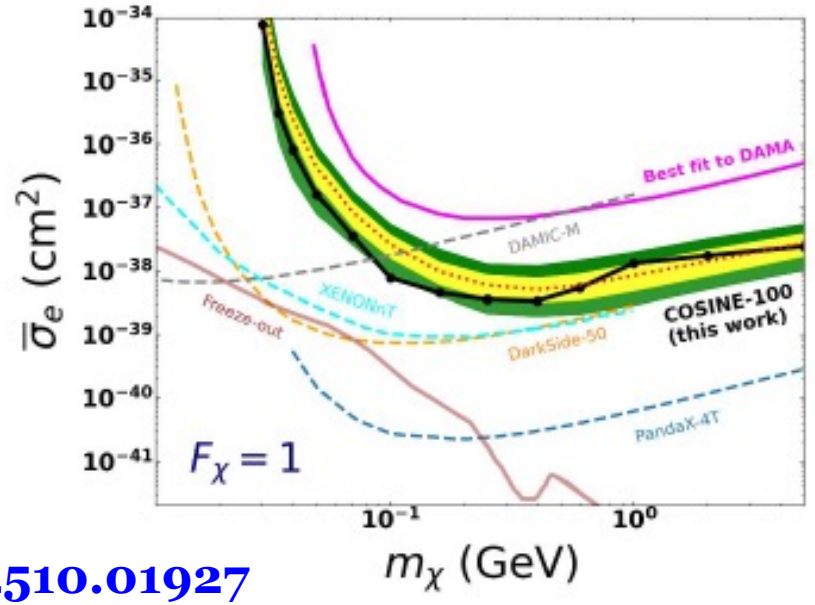
- Interpretation of DAMA/LIBRA signal, PRD 100, 063017 (2019)



Feynman diagram of the WIMP-electron scattering

COSINE-100 3 years data with 8 NPE threshold

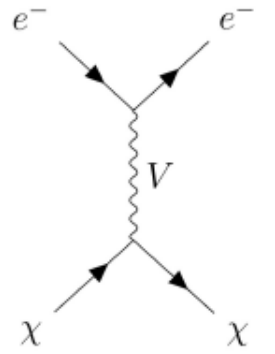




arXiv:2510.01927

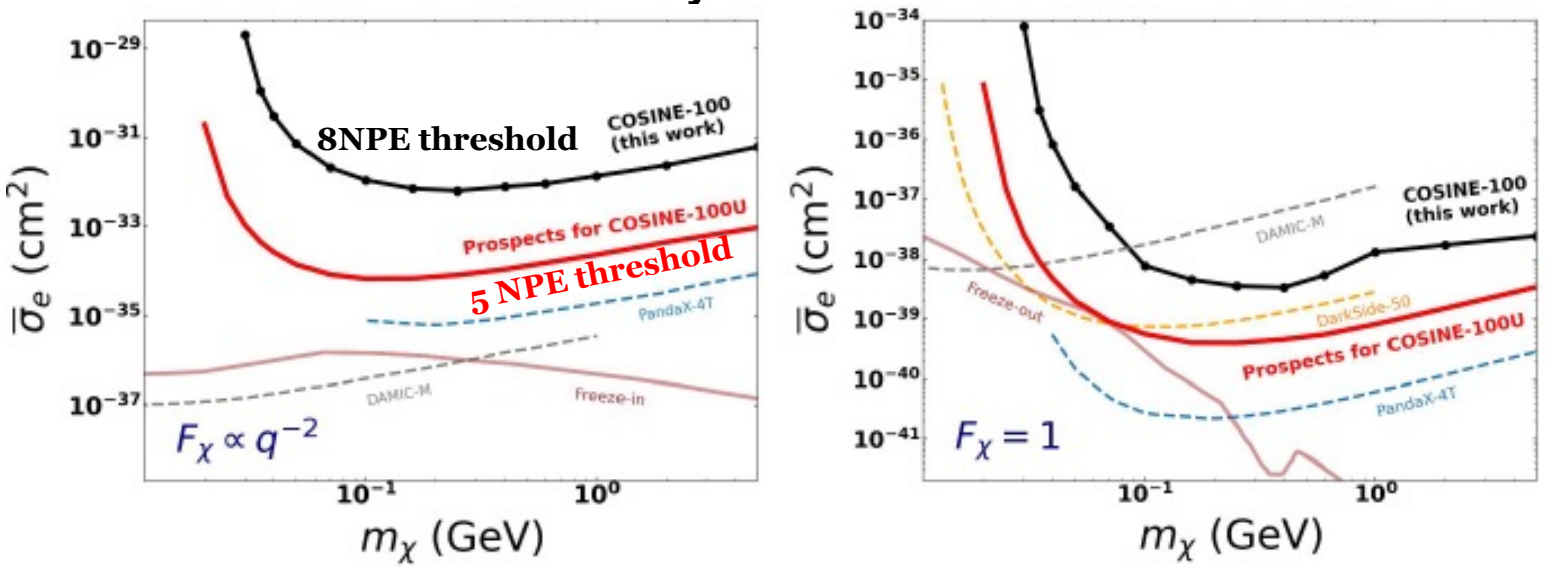
WIMP-electron scattering

- Interpretation of DAMA/LIBRA signal, PRD 100, 063017 (2019)



Feynman diagram of the WIMP-electron scattering

COSINE-100U 1 years data with 5 NPE threshold



arXiv:2510.01927

- Lower energy threshold analysis is available
  - 2-4 NPE with annual modulation

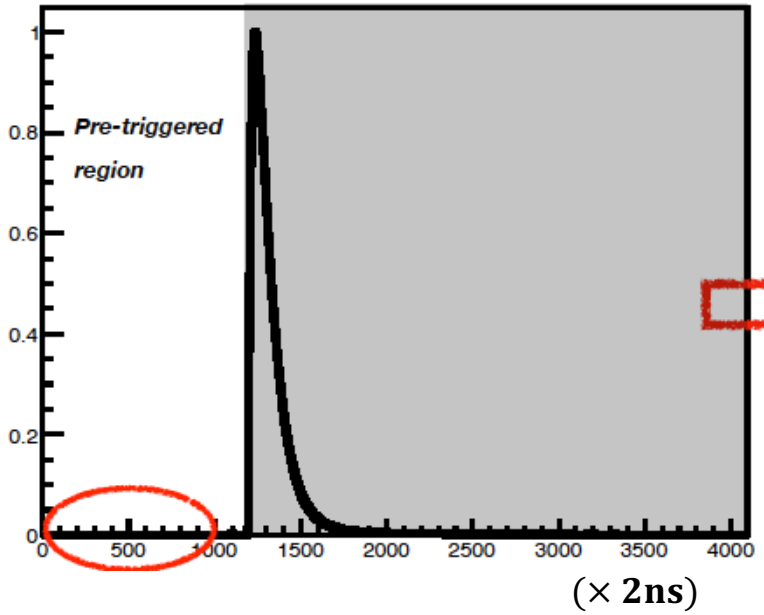
Crystal form factor

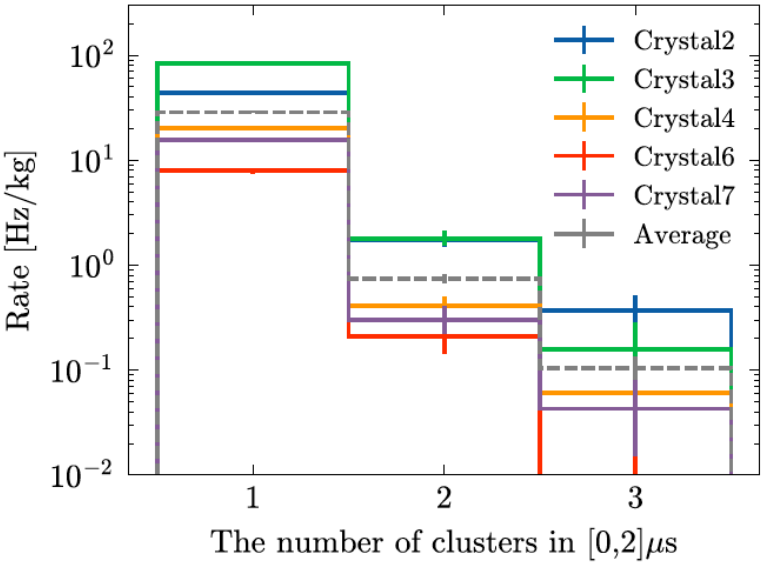
Band structure

$$\frac{dR}{d\ln E_e} = \bar{\sigma}_e \frac{\rho_\chi N_{\text{cell}} \alpha m_e^2}{m_\chi \mu_{\chi e}^2} \int d\ln q \left[\frac{E_e}{q}\eta(v_{\min})\right] \left|F_{\text{DM}}(q)\right|^2 \left|f_{\text{crystal}}(q, E_e)\right|^2$$

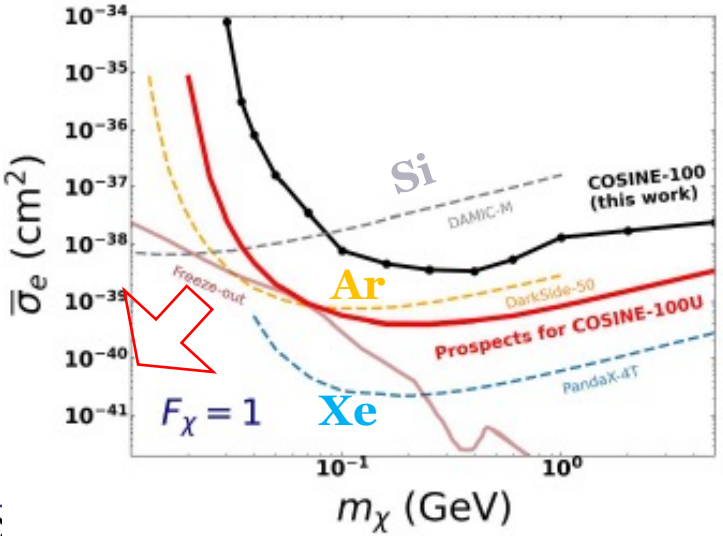
WIMP-electron scattering

- Single photoelectron threshold!!



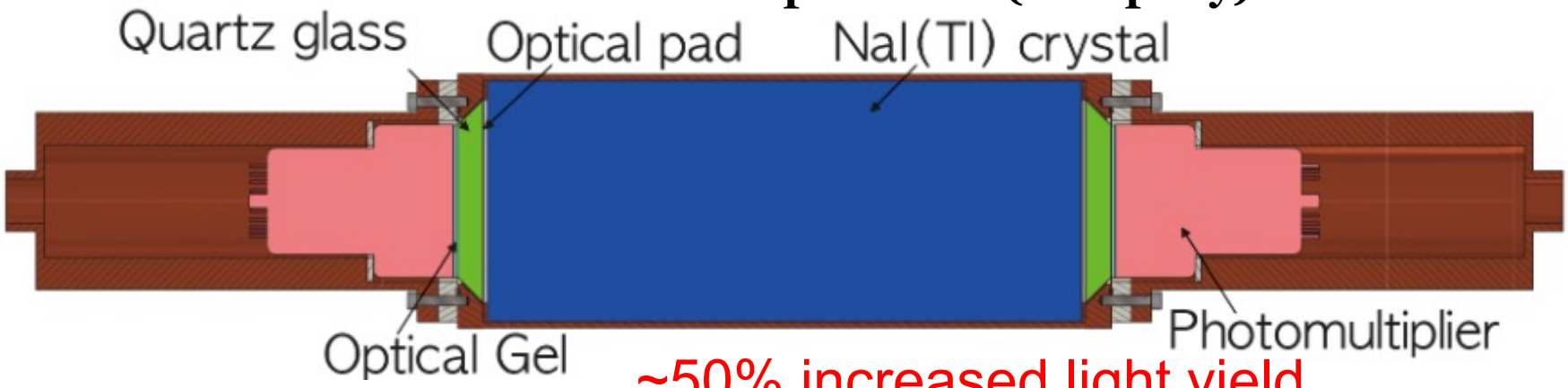


- Band gap
  - Si (1.12 eV)
  - NaI(4.8 eV)
  - Xe (9.2 eV)
  - Ar (14.3 eV)



Moving forward to COSINE-100Upgrade

COSINE-100 encapsulation (Company)

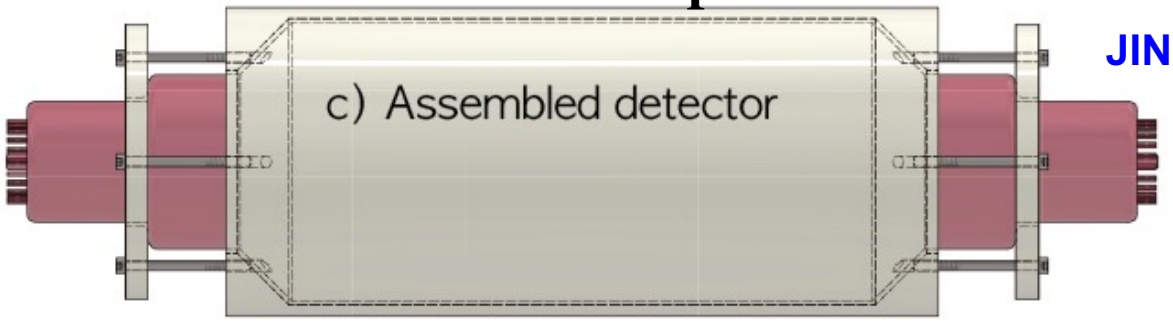


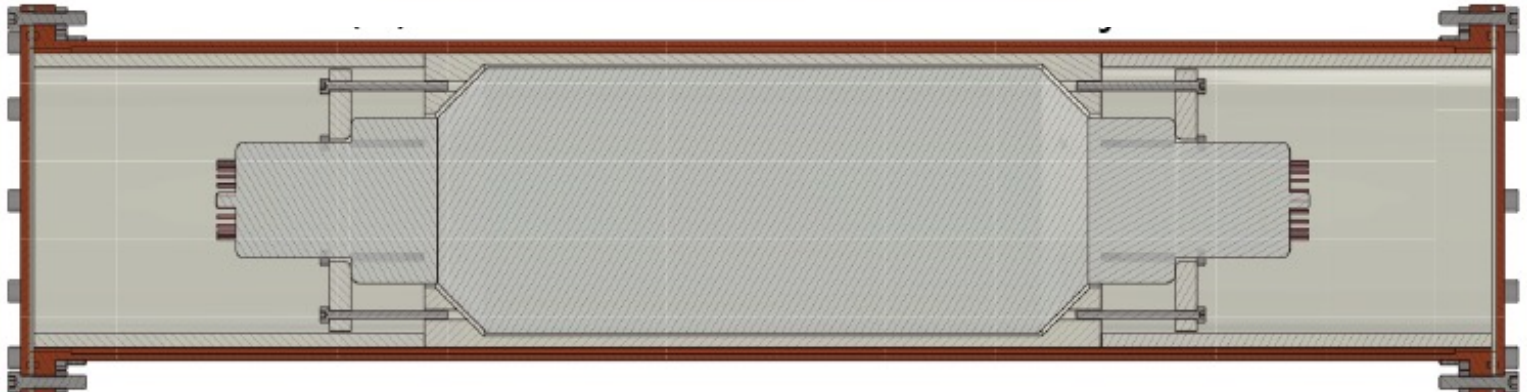
~50% increased light yield

COSINE-100U encapsulation

NIMA 981 (2020) 164556

JINST 19 (2024) P10020



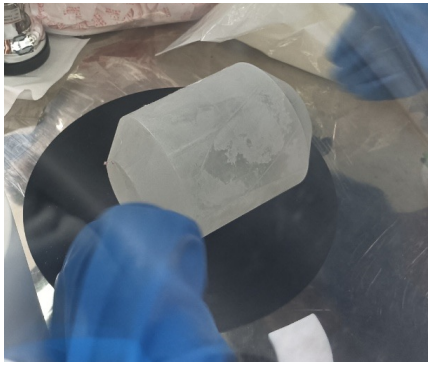


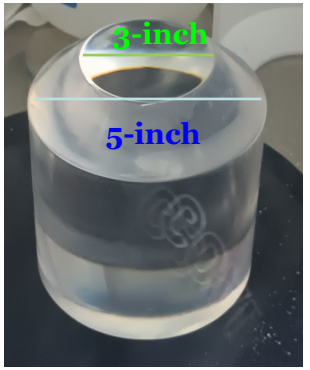
Moving forward to COSINE-100Upgrade

- Upgrade detector assembly for high light yield

Crystal machine

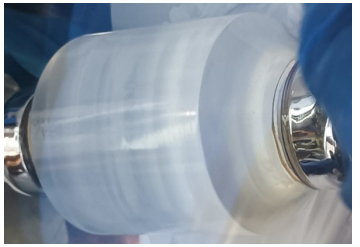
Deliver to glove box

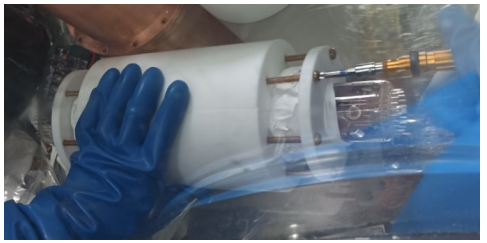


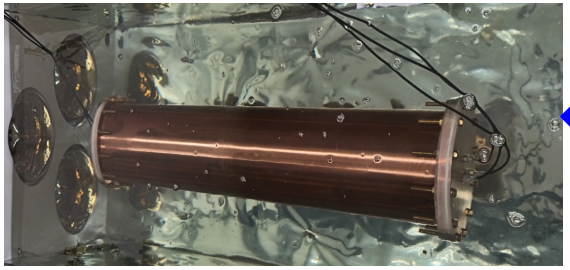


8.26 kg → 7.19 kg

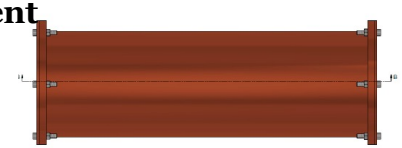
COSINE crystal-1

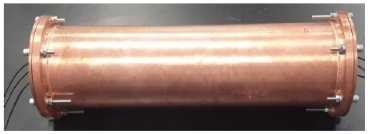




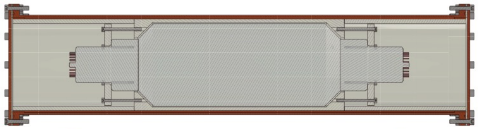


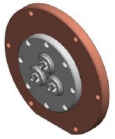
Above ground measurement





Cover design



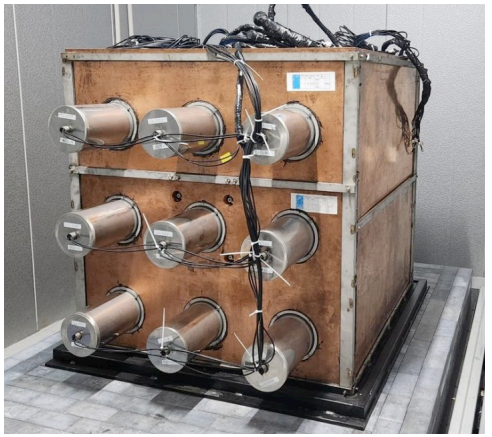


COSINE-100U : Yemilab installation

Freeze room for -30°C operation

Astropart. Phys. 141, 102709 (2022)

Liquid scintillator veto

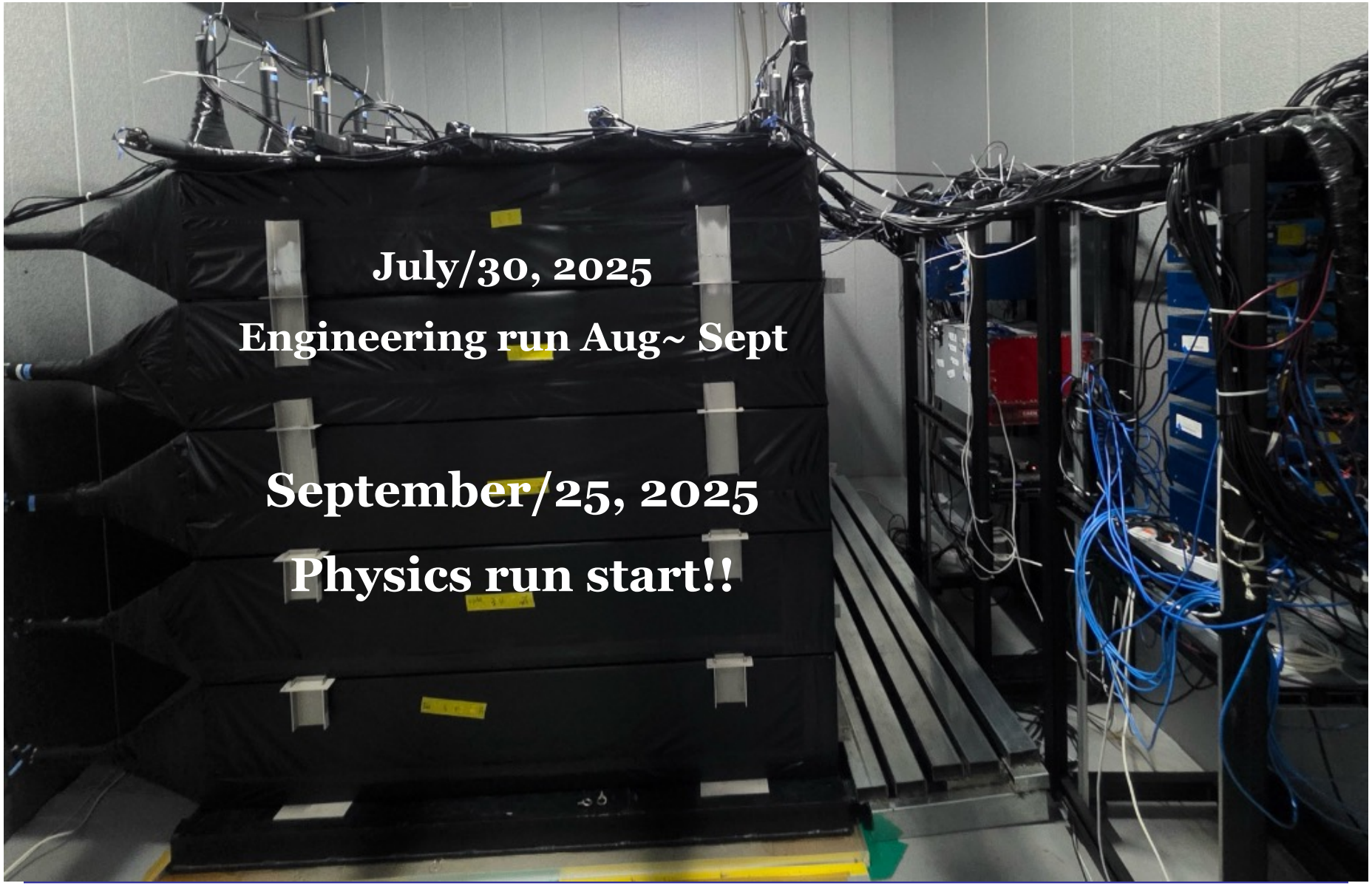


Lead shield

Crystal & LS install

- ~6 months **room temperature** operation, then move to -30°C

COSINE-100U : room temperature operation



COSINE-100U operation & monitoring

Environment monitoring in Grafana

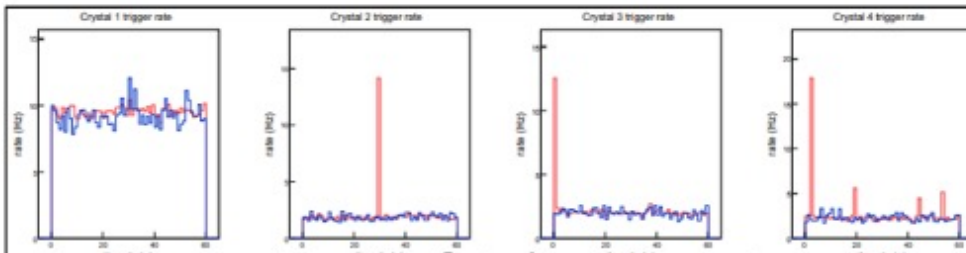
Run status & DAQ rate read from the log file.

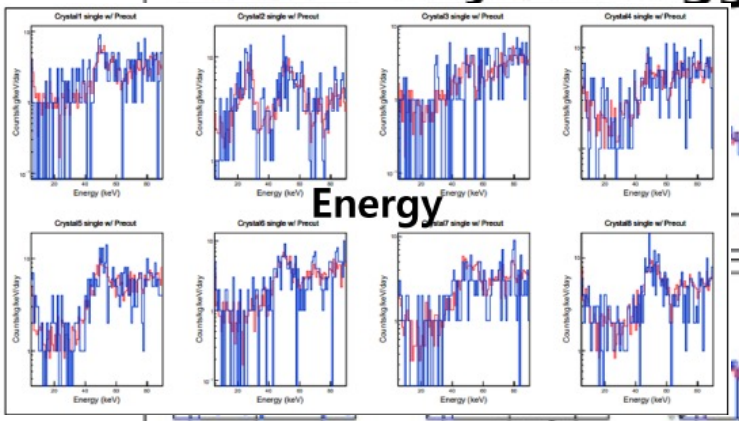
'Off' when latest DAQ information is over 5-min

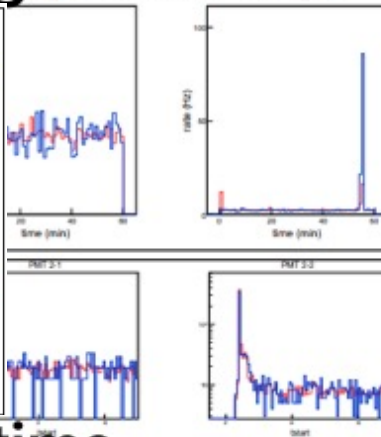
High Voltage, Dust level, Gas flow ....

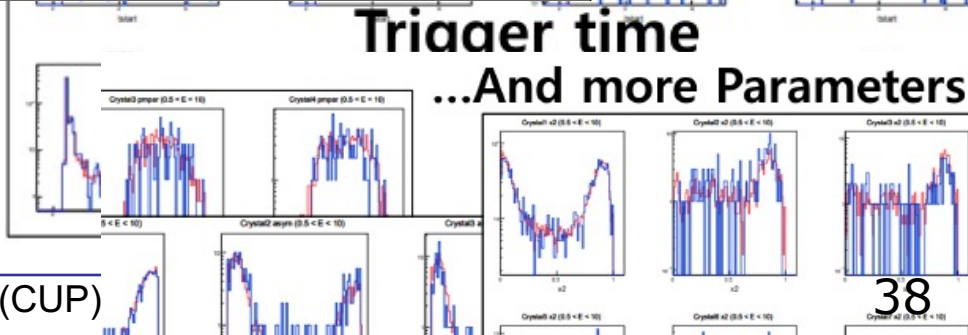
More than 200 parameters

Data monitoring in Wel

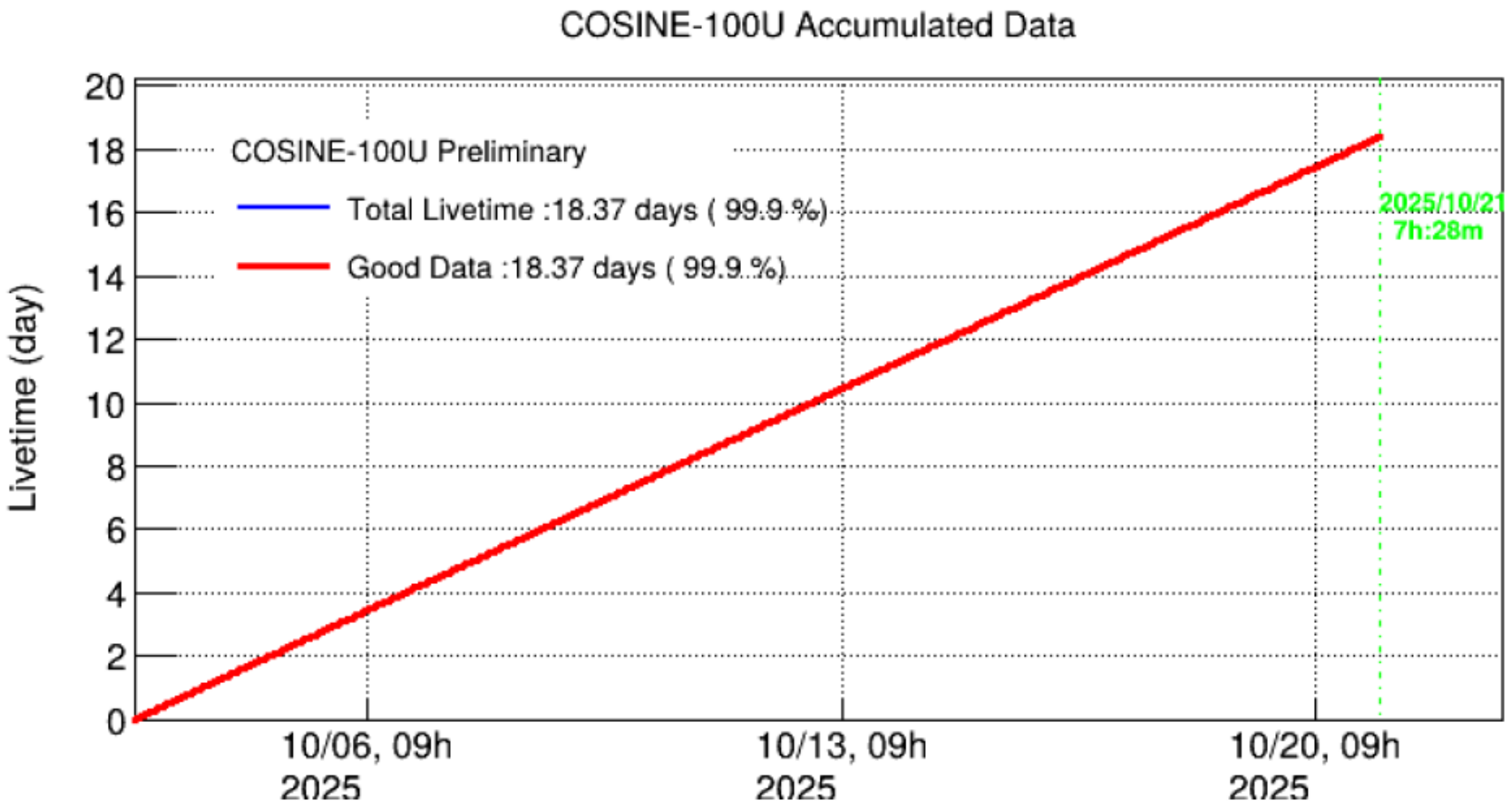








COSINE-100U operation

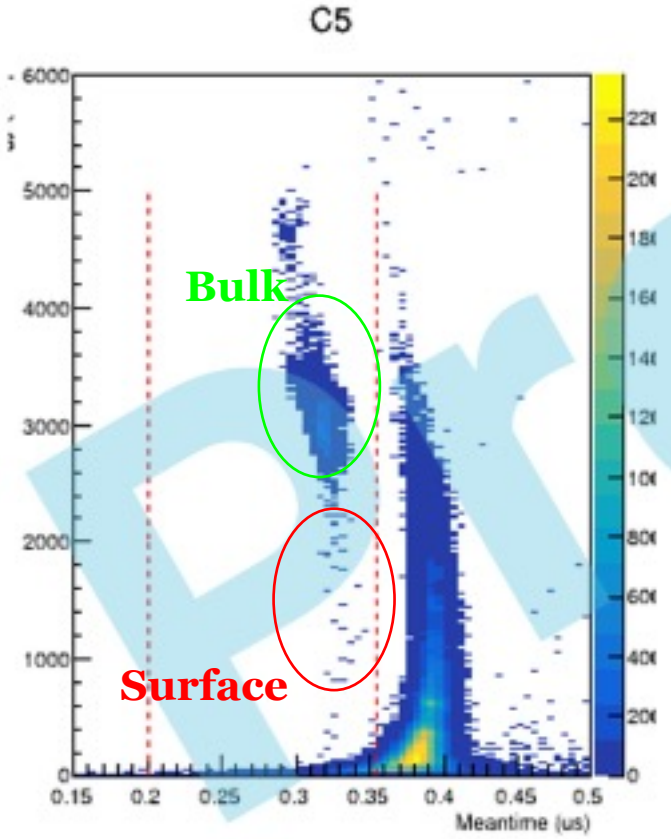


~ 100% DAQ efficiency

Initial data - Alpha background

- Bulk alpha (Po-210) – Consistent with COSINE-100
- Surface alpha (1 – 2 MeV) – Reduced by our own encapsulation

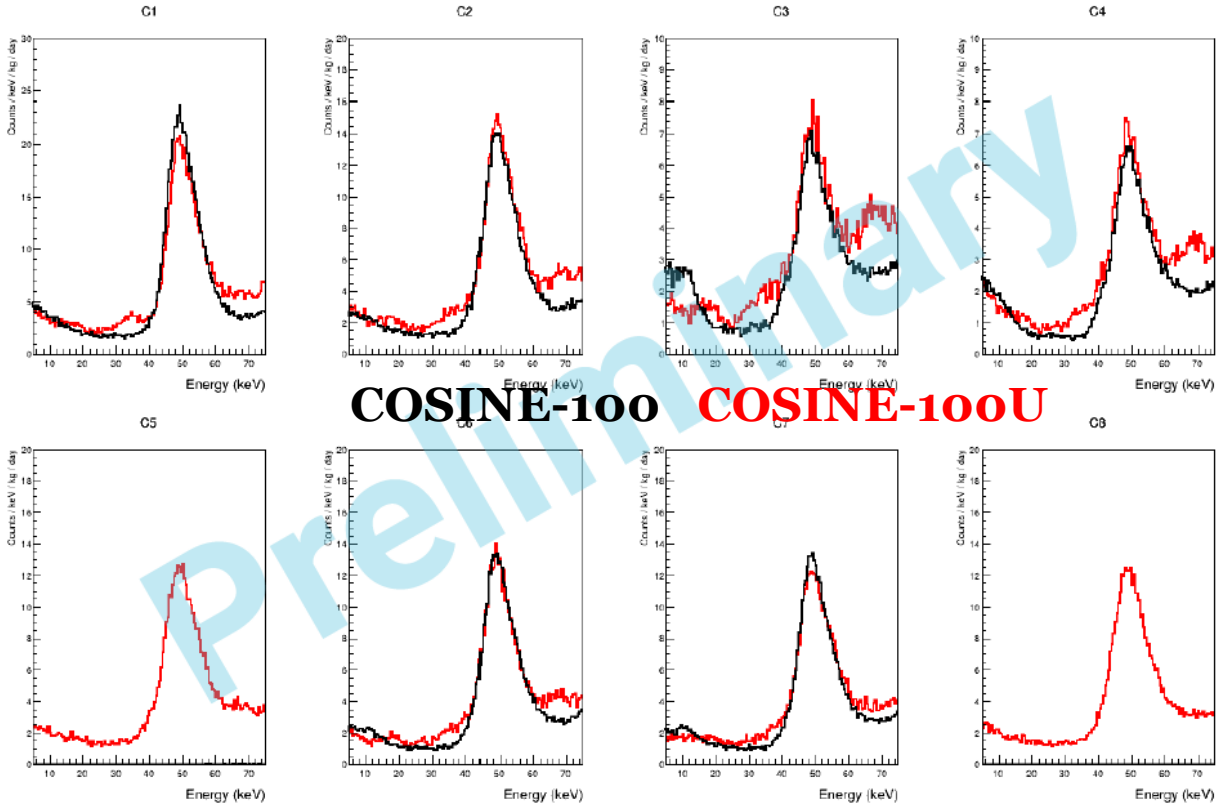
Crystal #	Bulk Alpha (mBq/kg)		LowE Alpha (nBq/cm²)	
1	2.59 ± 0.01	2.38 ± 0.02	33.07 ± 3.70	38.31 ± 5.98
2	1.69 ± 0.01	1.58 ± 0.01	39.61 ± 3.76	20.07 ± 4.10
3	0.63 ± 0.01	0.56 ± 0.01	71.73 ± 5.06	20.91 ± 4.18
4	0.64 ± 0.01	0.58 ± 0.01	24.27 ± 2.31	14.95 ± 2.78
5	–	1.58 ± 0.01	–	10.71 ± 2.34
6	1.52 ± 0.01	1.38 ± 0.01	120.9 ± 5.90	14.05 ± 3.07
7	1.51 ± 0.01	1.39 ± 0.01	95.35 ± 5.24	19.41 ± 3.60
8	–	1.57 ± 0.01	–	16.32 ± 2.89



COSINE-100 : ~90 nBq/cm² ➡ COSINE-100U : ~20 nBq/cm²

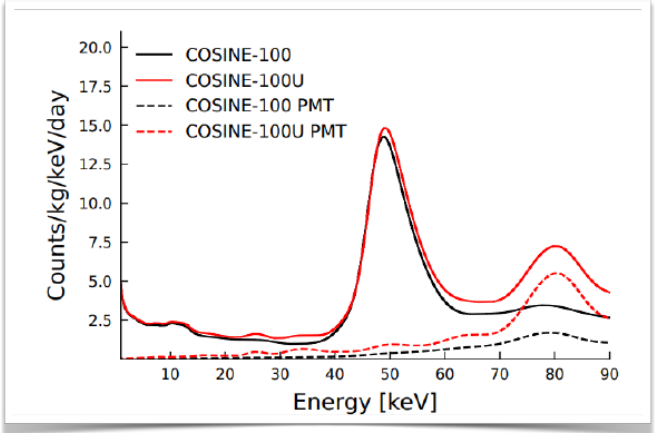
Initial data – Low energy spectra

- Low-energy single-hit energy spectra

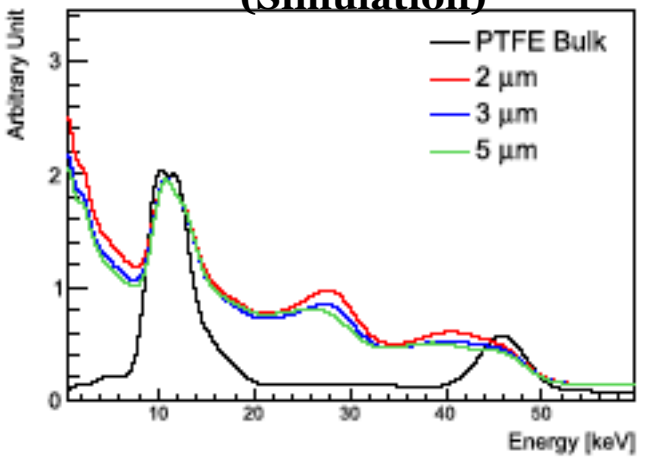


Expectation in Simulation

Commun. Phys. ***8****, 135 (2025)*



Surface Pb-210 contamination (Simulation)



EJPC 85, 32 (2025)

- Reduced surface contamination
  - ❖ Lower background @ ROI expected

Light yield improvement

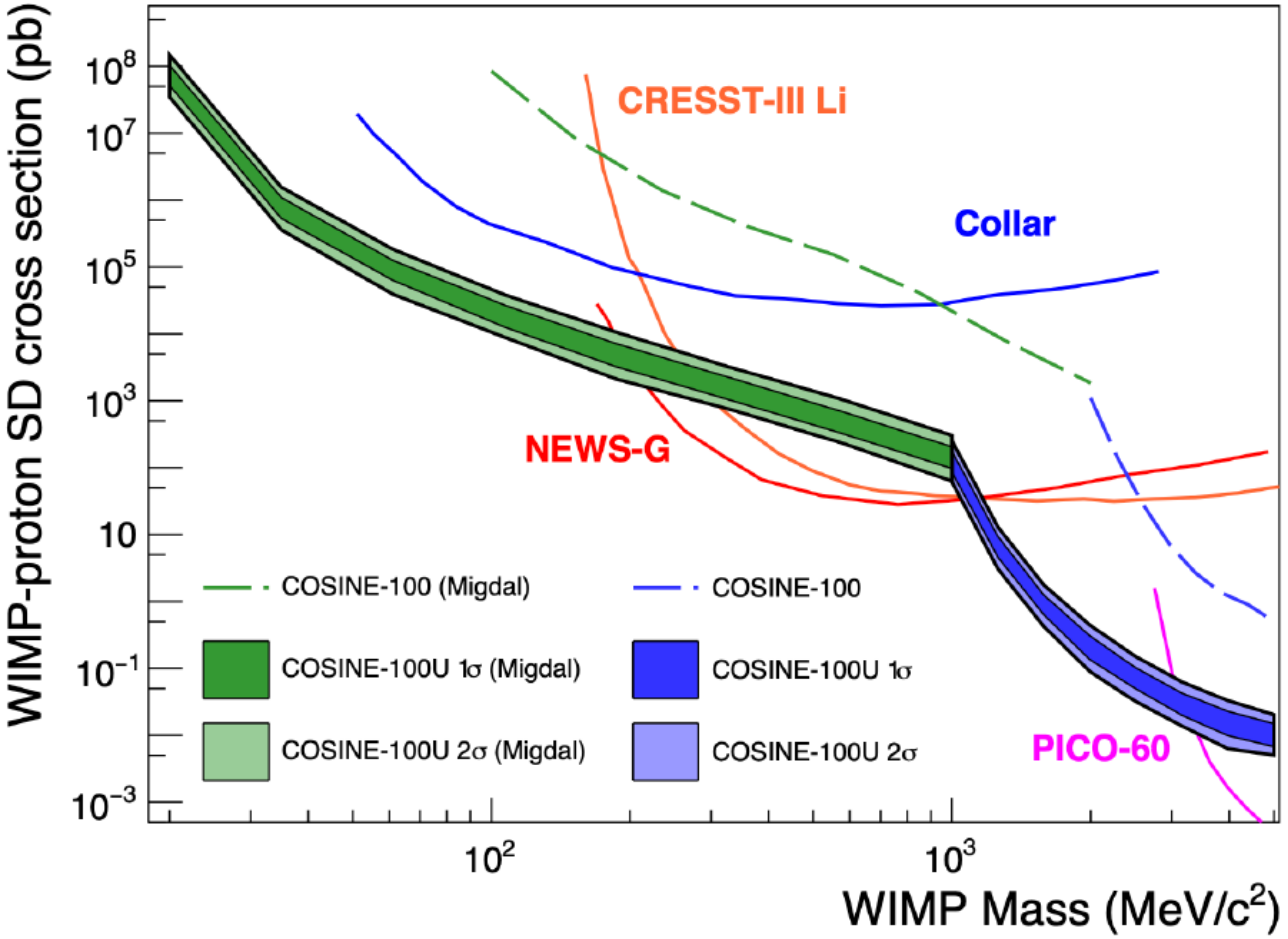
- 40~60% increased light yield !!

Crystal #	Size (inches)	Light Yield (p.e./keV)	
1	5.0 × 7.0	14.9 ± 1.5	24.5 ± 0.9
2	4.2 × 11.0	14.6 ± 1.5	24.9 ± 0.5
3	4.2 × 11.0	15.5 ± 1.6	27.7 ± 0.5
4	5.0 × 15.3	14.9 ± 1.5	22.6 ± 1.5
5	5.0 × 15.2	7.3 ± 0.7	17.8 ± 0.5
6	4.8 × 11.8	14.6 ± 1.5	20.9 ± 0.6
7	4.8 × 11.8	14.0 ± 1.4	22.5 ± 0.6
8	5.0 × 15.5	3.5 ± 0.3	15.8 ± 0.3

COSINE-100 ~ 15 p.e./keV ~ 23 p.e./keV (COSINE-100U)

Sensitivity of COSINE-100U

WIMP-Proton spin-dependent interaction



- Increased light yield
- 8 Crystals, total 99.0 kg
- 1-year exposure
- 5 NPE threshold (~ 0.25 keV)
- Expected Bkg. lvl.

Commun. Phys. 8, 135 (2025)

Next of COSINE-100U (Lower background crystal)

Powder purification performance

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

K.A. Shin et al., JINST 15, C07031 (2020)

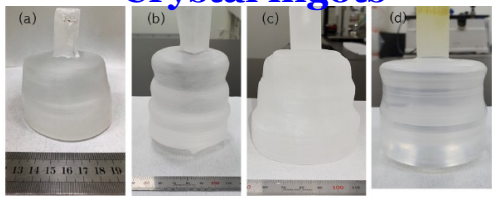
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

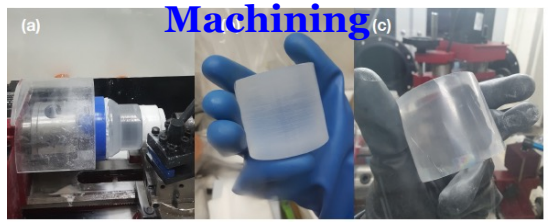
We produced ~ 400 kg low-background NaI powder

(Maximum production rate ~ 70 kg/month)

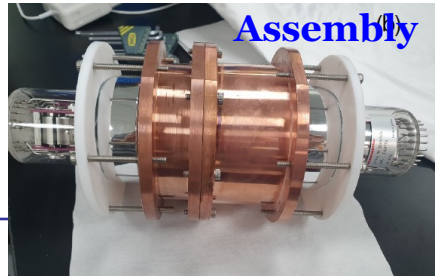
Crystal ingots

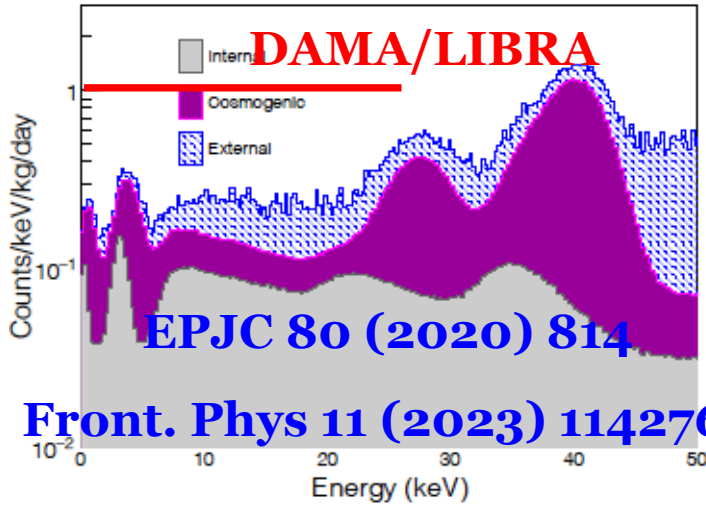


Machining



Assembly





A proof of principle for low background NaI

Large crystal growing is going on

Bridgman crystal grower @ KNU

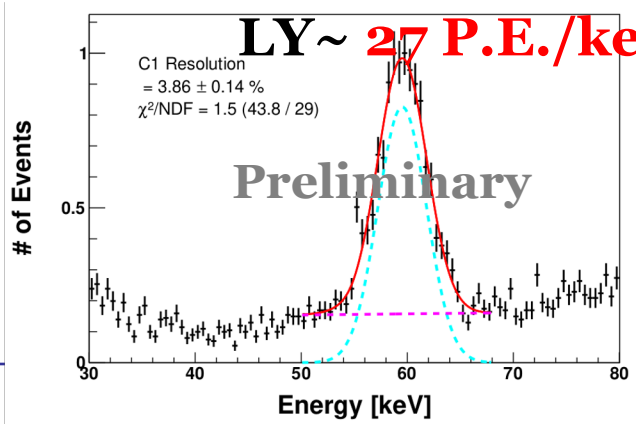
3-inch Grower

~ 3 years R&D

Resolving sticking issue between NaI and quartz ampoule

HF clean + NH4I treatment + Vacuum + anneal the ampoule At 900°C + Rotating

Successful growing 1 kg size (3-inch x 3-inch) crystal



Ongoing works

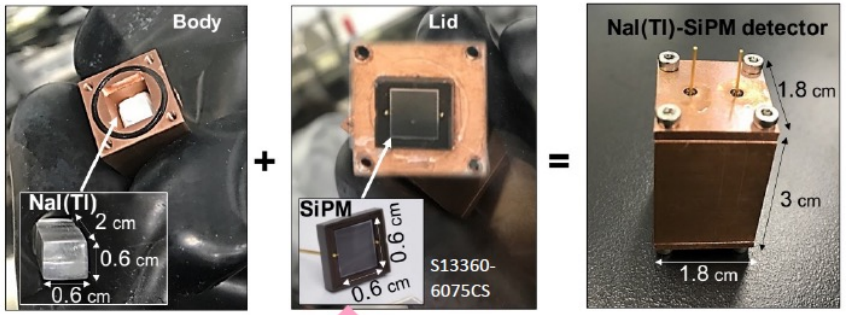
Background measurement

6-inch long crystal growing

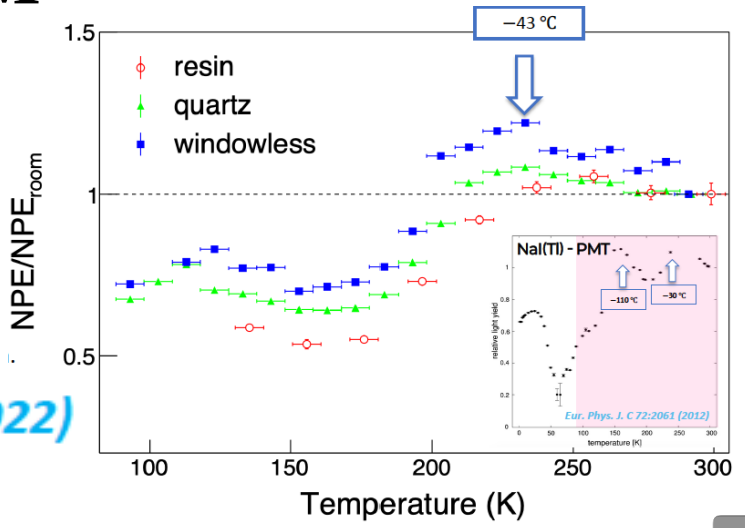
Manufacturing 4.5-inch grower

Ongoing R&D : Undoped NaI with SiPM or PMT

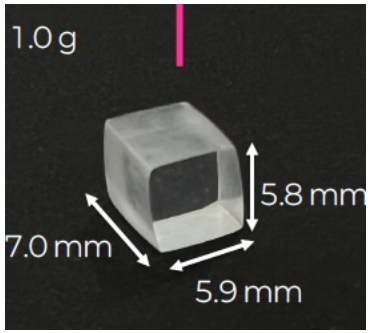
NaI(Tl) + SiPM

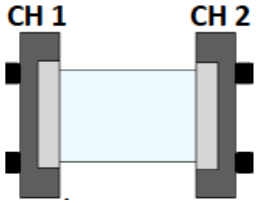


JINST 17 P02027 (2022)

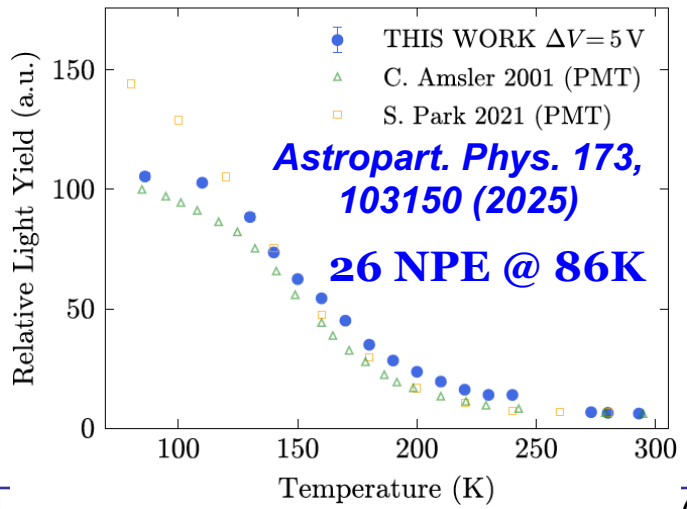


Undoped CsI +SiPM





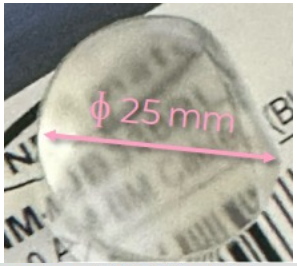
➢ Light Yield of pure CsI

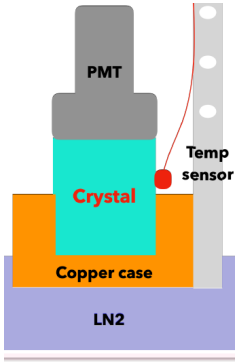


Astropart. Phys. 173, 103150 (2025)

26 NPE @ 86K

1-inch undoped CsI (and NaI) from KNU





1-inch PMT (30% QE @ 300nm)

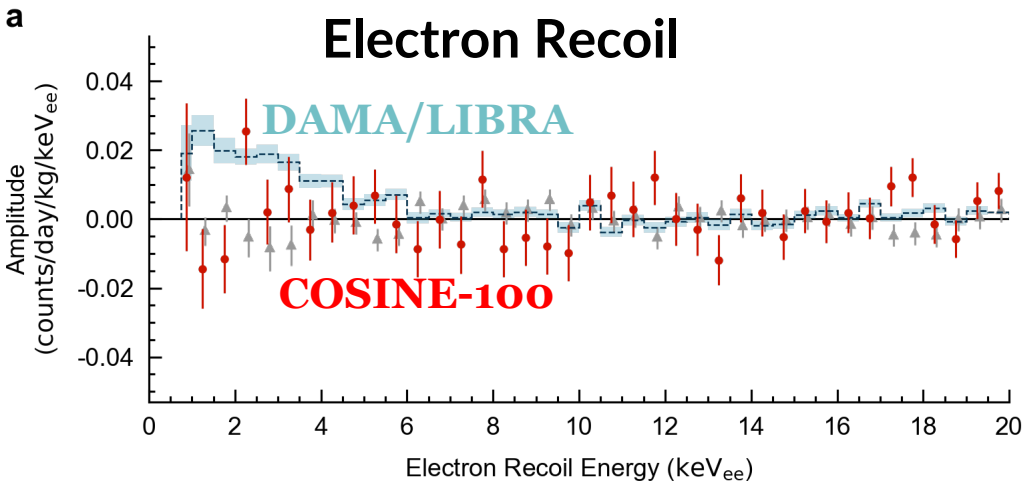
SiPM array

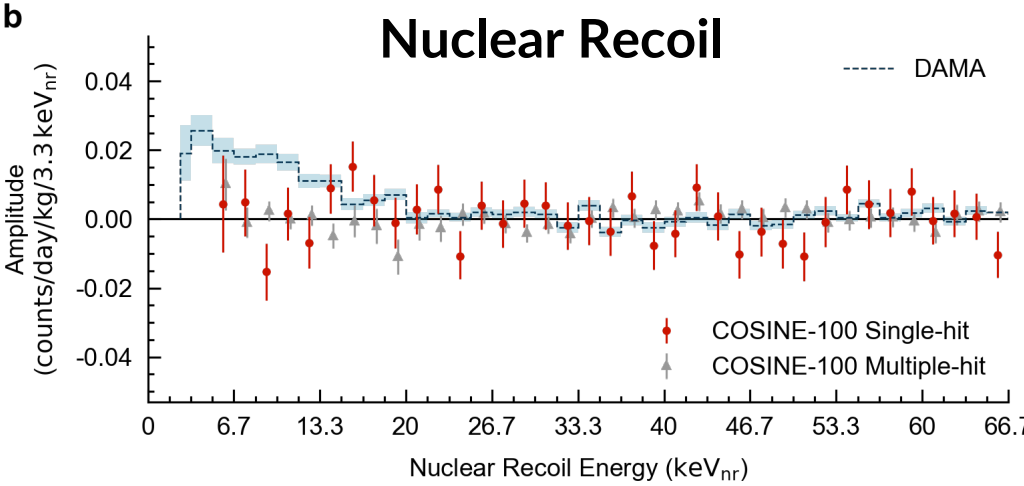
Summary

- COSINE-100 ruled out DAMA/LIBRA with significance above 3 sigma in model-independent analysis
  - ANAIS-112 and combined analysis between COSINE-100 and ANAIS-112 consistently disfavored with DAMA/LIBRA (significance as high as 4.68 sigma)
- COSINE-100 present world competitive sensitivities for low-mass dark matter
  - This will be enhanced with COSINE-100U experiment
- COSINE-100U just start physics operation @ room temperature
- COSINE-200 crystal R&D are extensively performed

Thank you for your attention

COSINE-100 full dataset fits





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

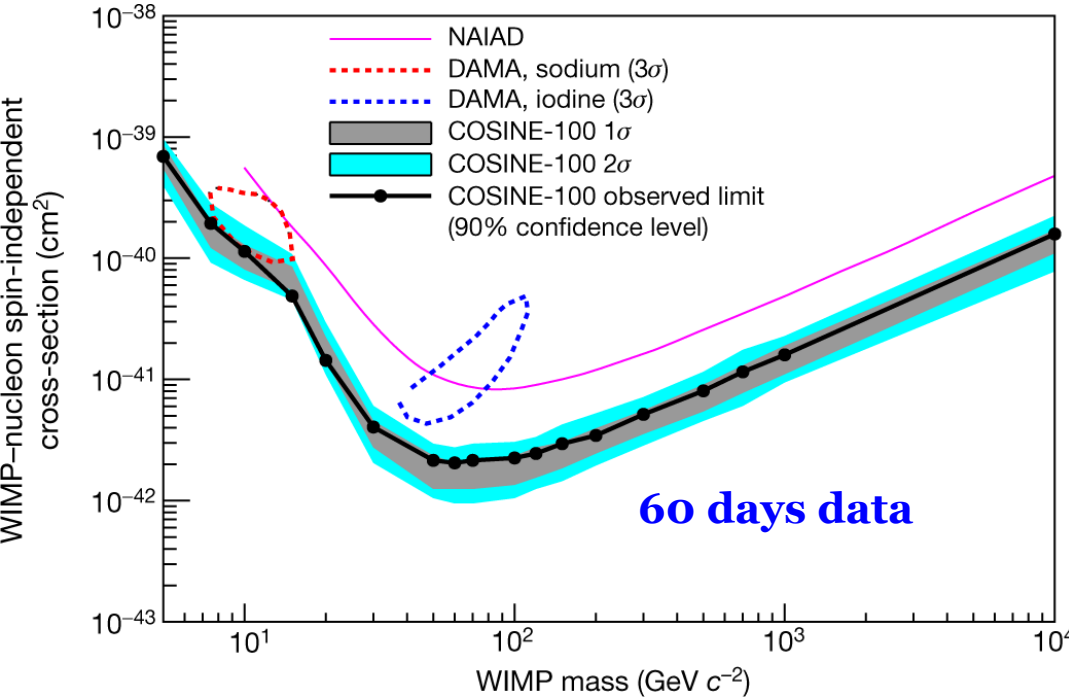
E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	$\mathbf{0.001 \pm 0.003}$	0.010 ± 0.001

Sci. Adv. 11, eadv6503 (2025)

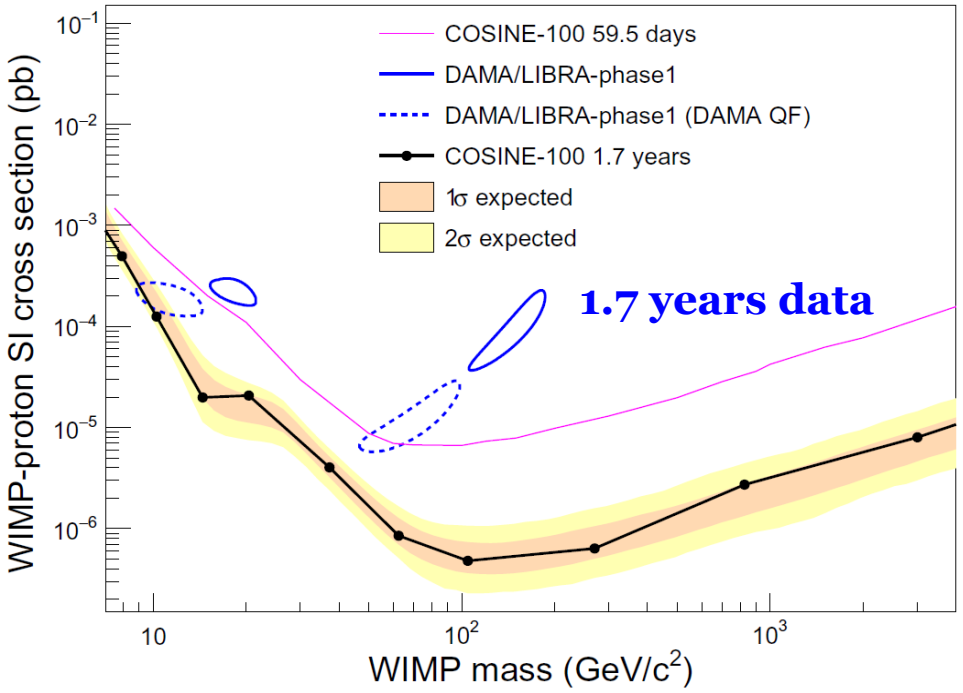
COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

Ruled out DAMA/LIBRA by COSINE-100

Model-dependent comparison



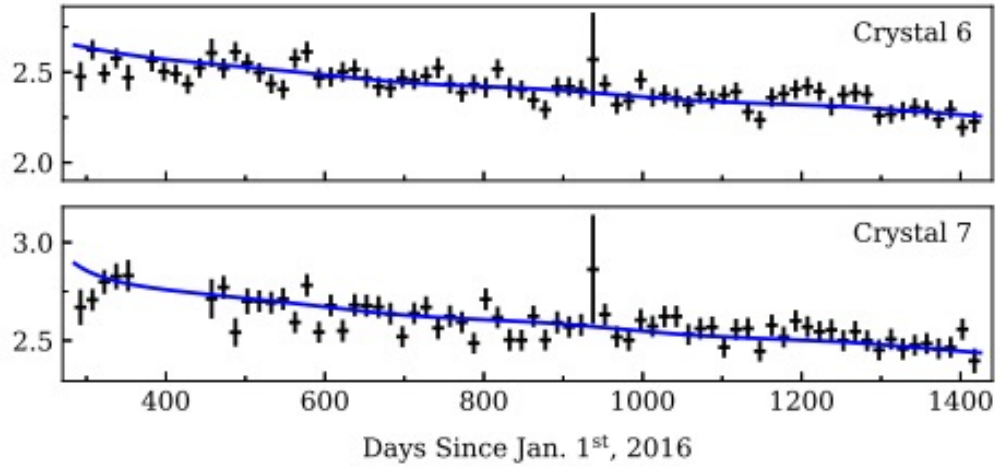
Nature 564, 83-86 (2018)



Sci. Adv. 7, eabk2699 (2021)

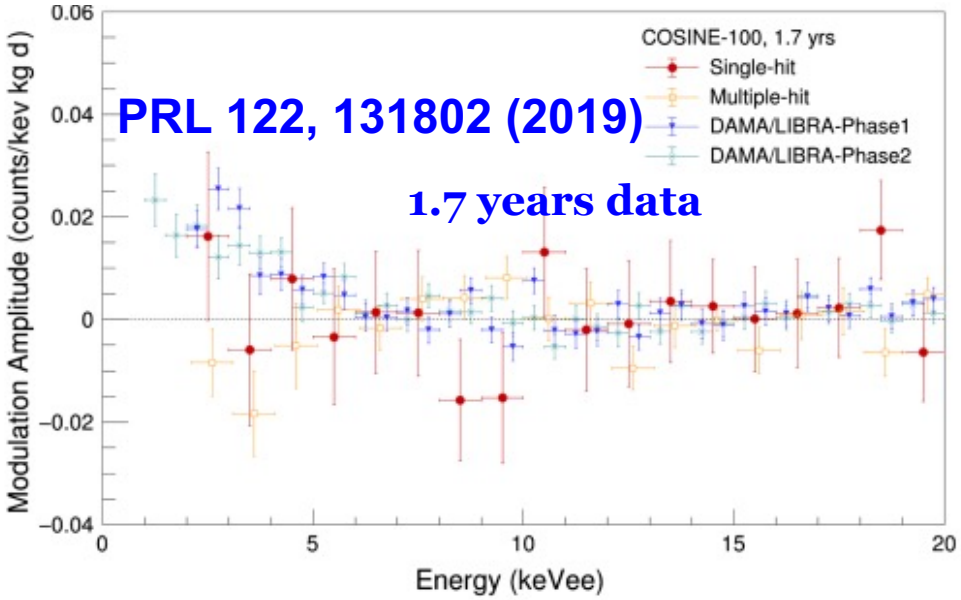
COSINE-100 data ruled out DAMA/LIBRA's 3 sigma contours for the canonical WIMP dark matter model

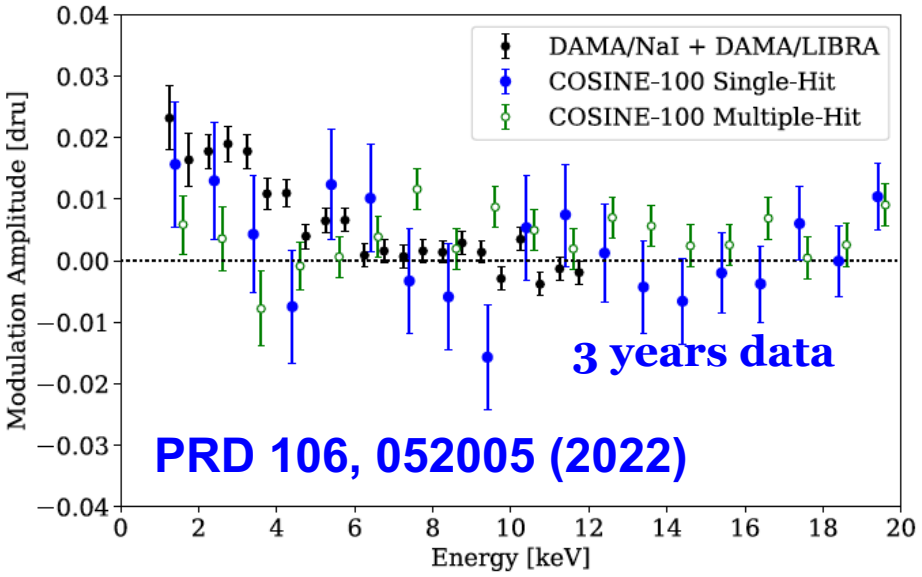
Annual modulation searches



1-6 keV modulation amplitude

COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042





Not enough statistics but, we have full 6.4 years data

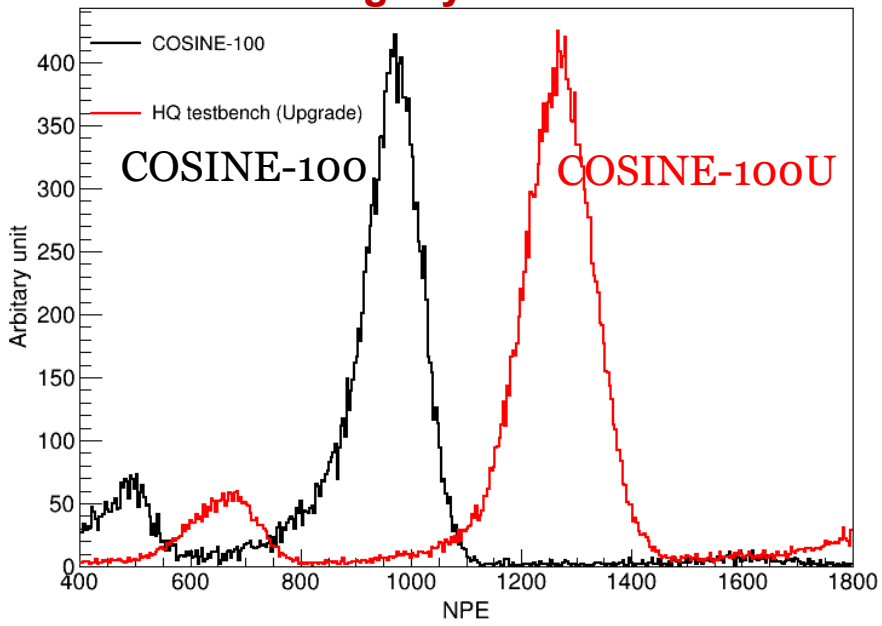
COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

arXiv:2409.15748

^{241}Am 59.54 keV

~40% light yield increase!!!

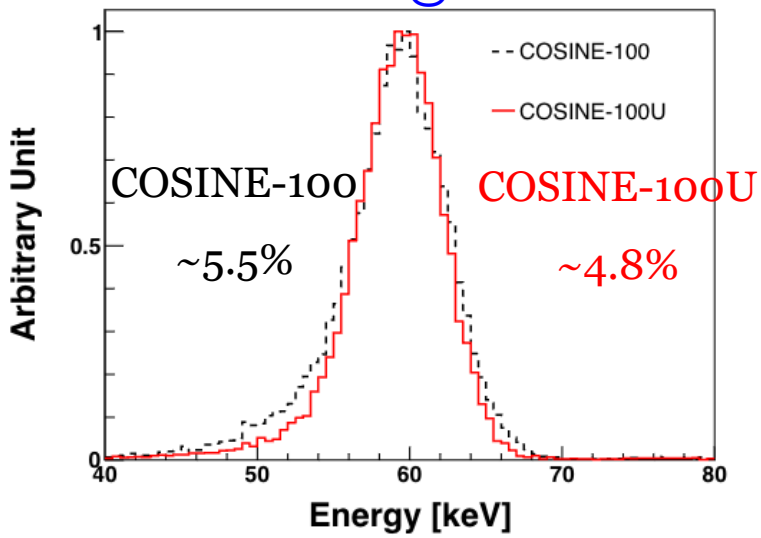


NPE = Number of photoelectrons

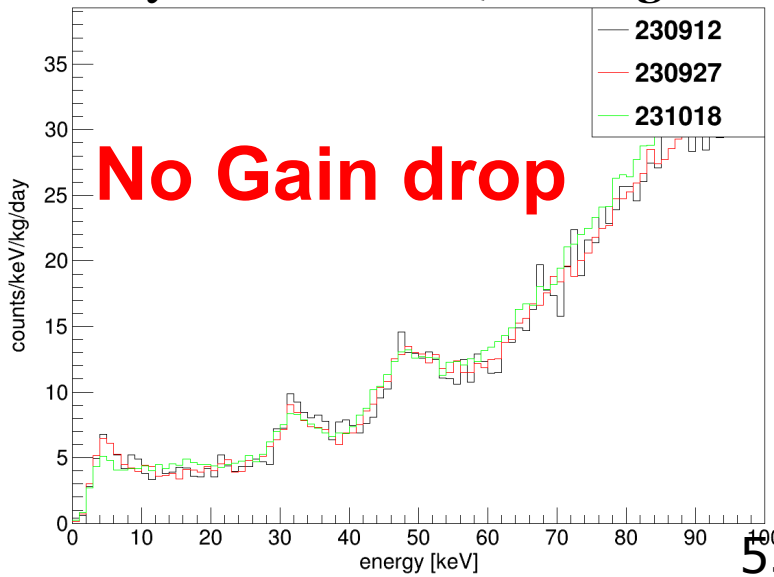
14.9 ± 1.5 ⟶ **21.5 ± 0.6 NPE/keV**

COSINE-100 C2 COSINE-100U C2

RMS resolution @ 59.54 keV for C3

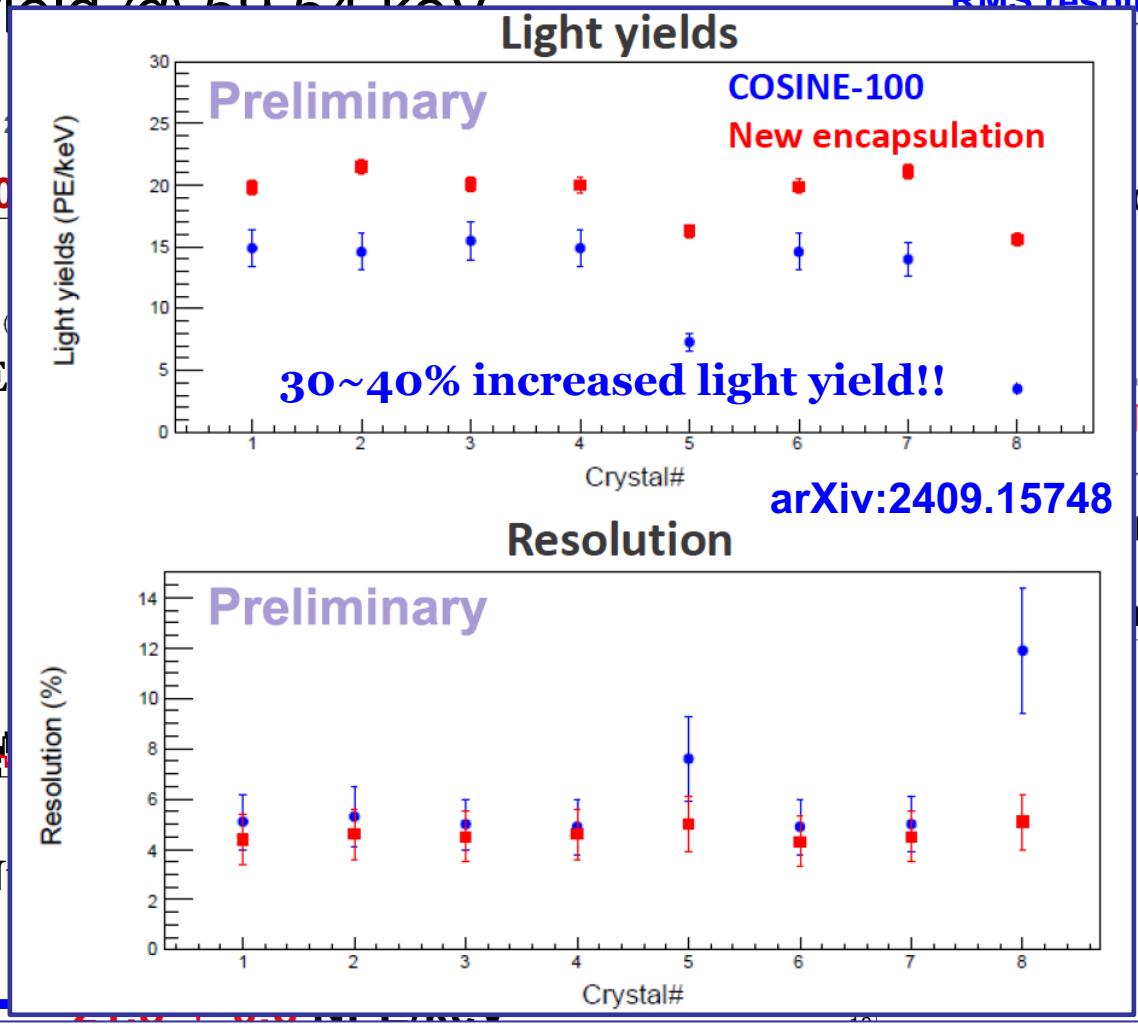


Stability of ~ 1 month (Above-ground)

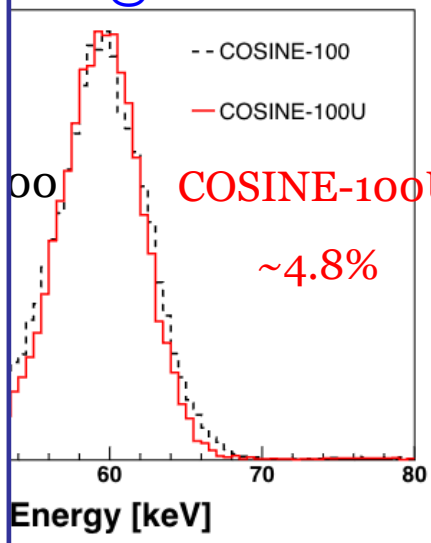


COSINE-100U : Detector upgrade

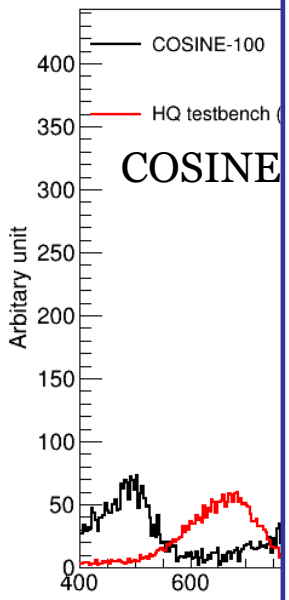
- Light yield @ 59.54 keV



RMS resolution @ 59.54 keV for C3



~40



COSINE

NPE = N

onth (Above-ground)

n drop

14.9 ± 1.5

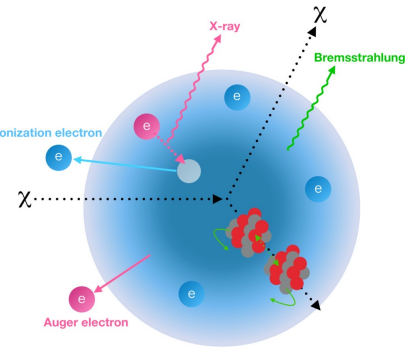
COSINE-10

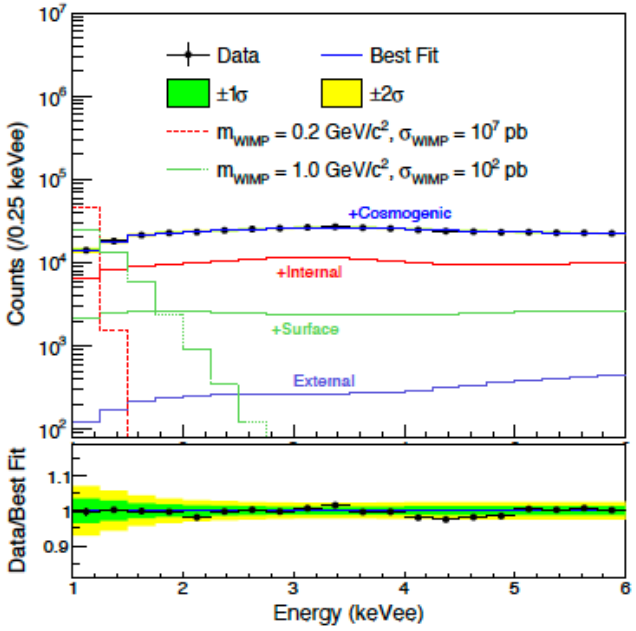
All crystals were assembled!!

Installation at Yemilab will soon be done

Dark matter search with spectral shape fit

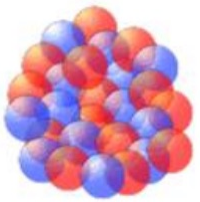
Migdal effect





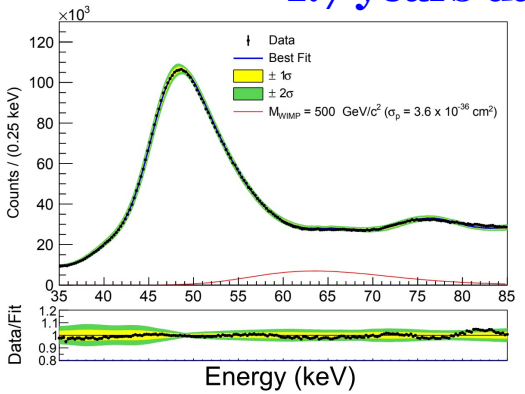
1.7 years data

^{127}I inelastic scattering



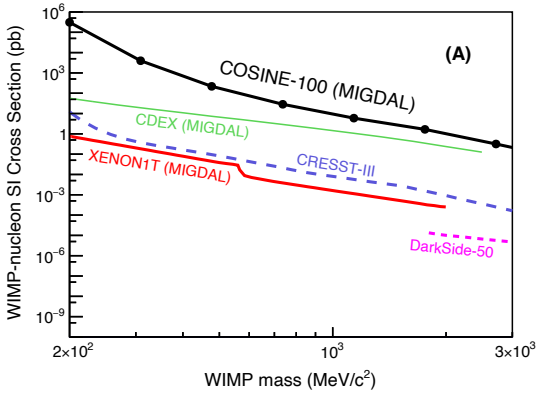
^{127}I

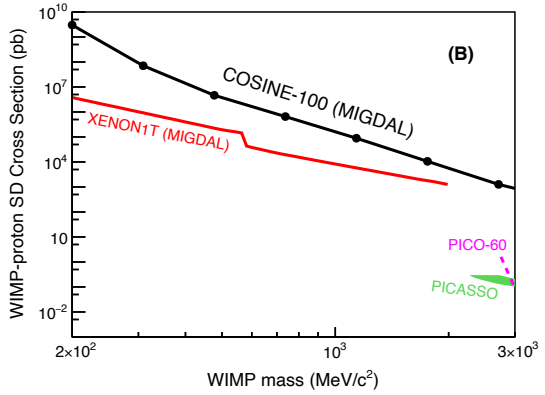
1.7 years data

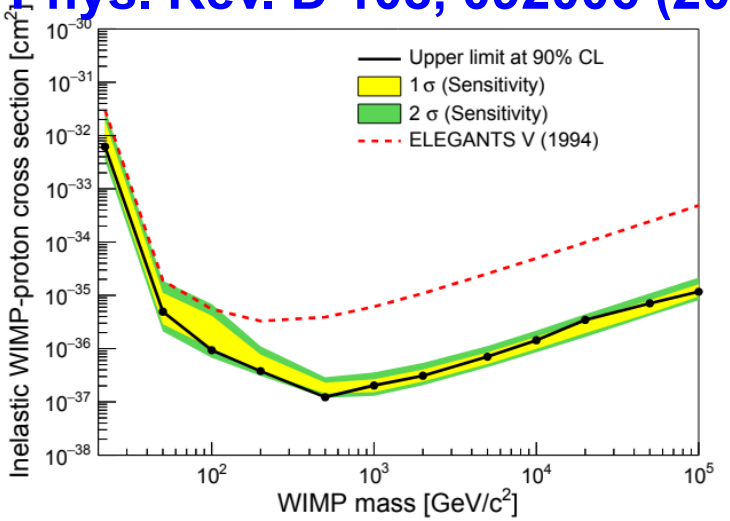


Phys. Rev. D 108, 092006 (2023)

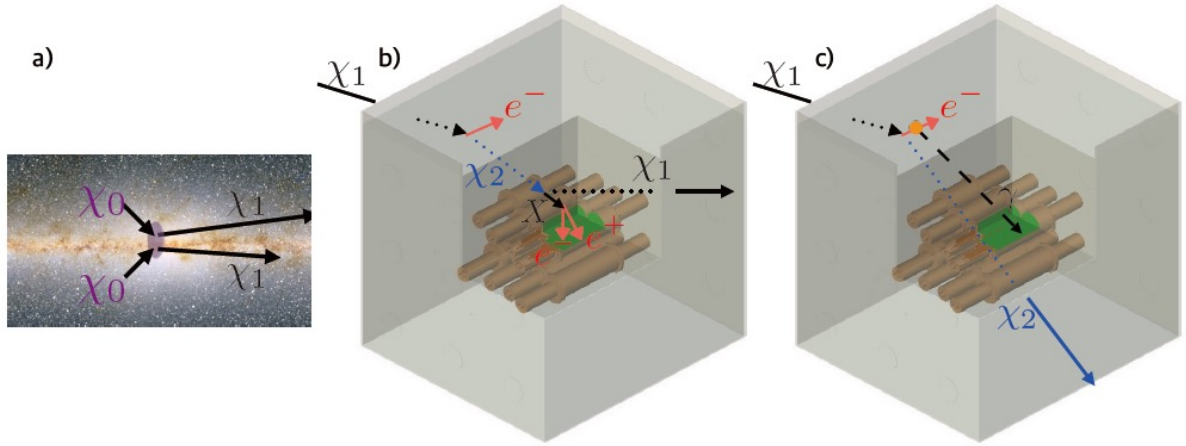
PRD 105, 042006 (2022)



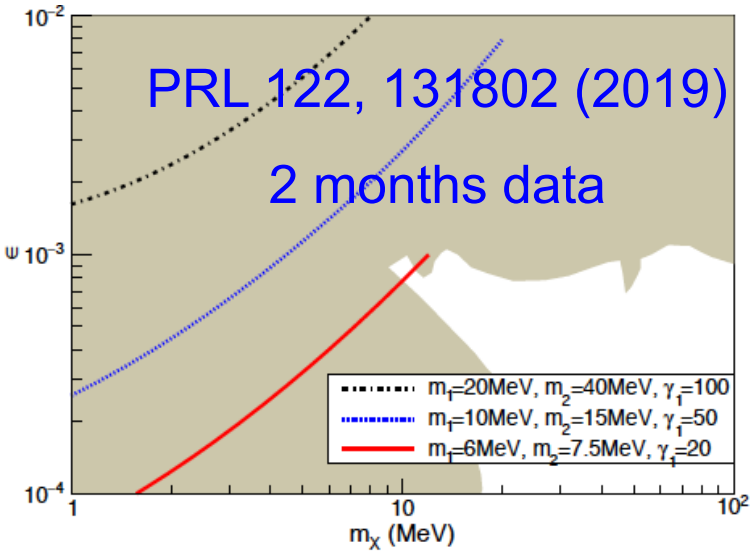




Boosted dark matter

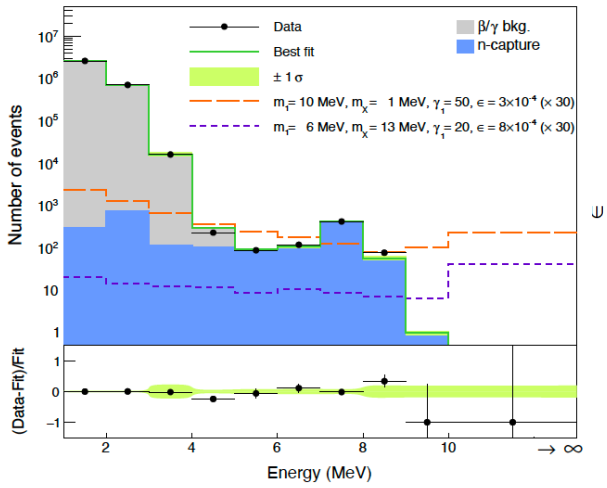


Inelastic interaction

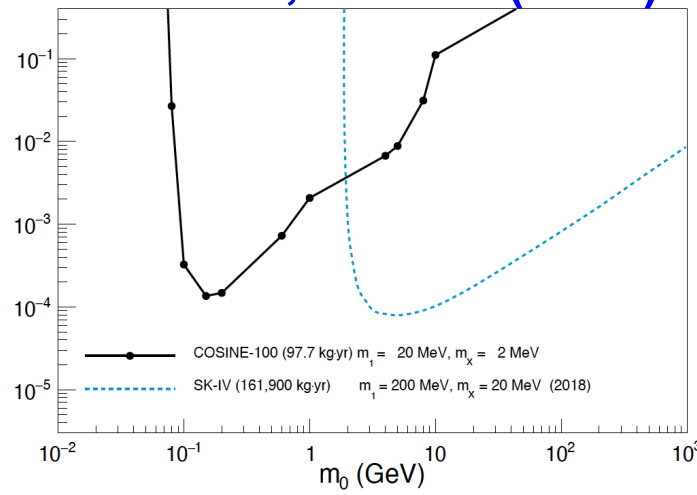


Elastic interaction

1.7 years data



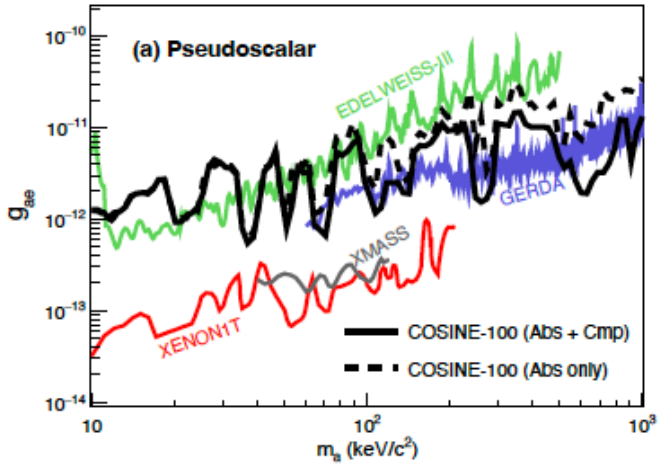
PRL 131, 201802 (2023)

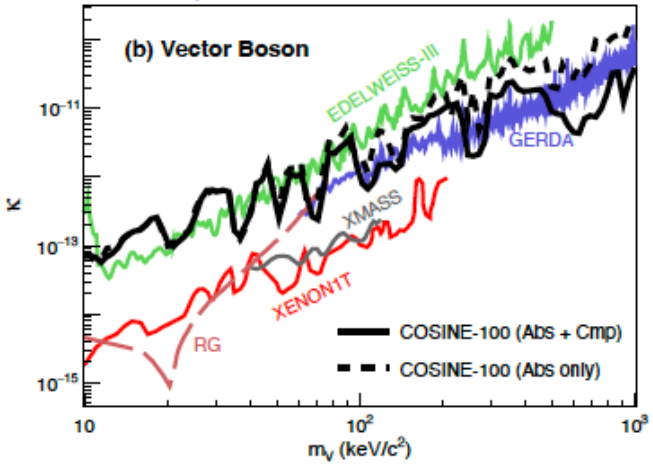


Bosonic superWIMP, solar dark bosonic particles..

Bosonic superWIMP

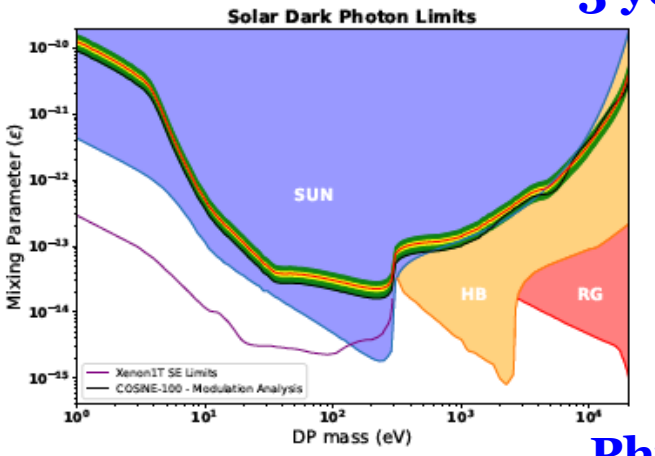
Phys. Rev. D 108,L041301 (2023)

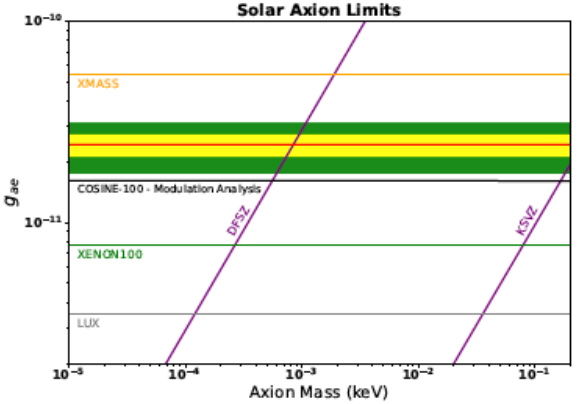


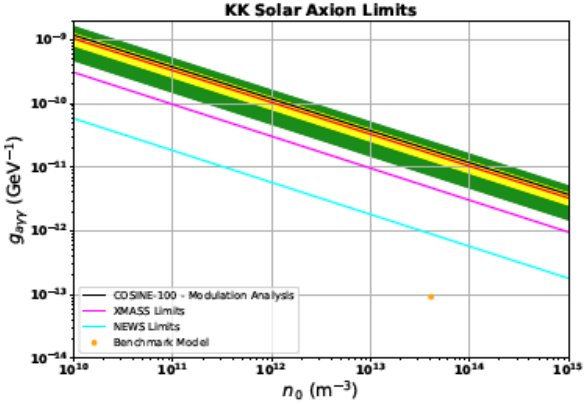


1.7 years data

3 years data for the modulation search



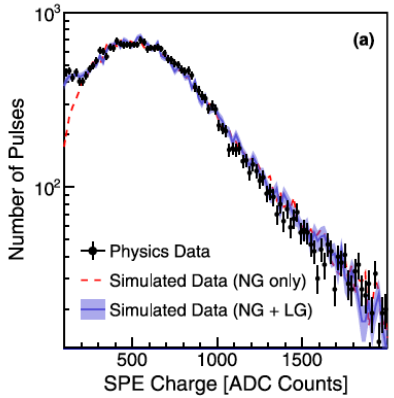


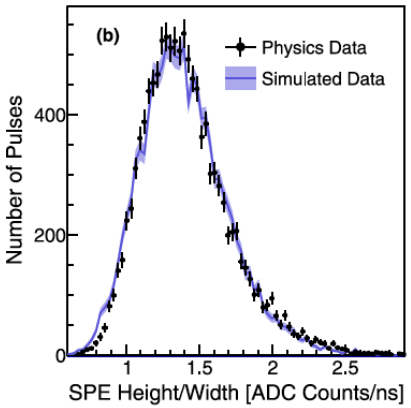


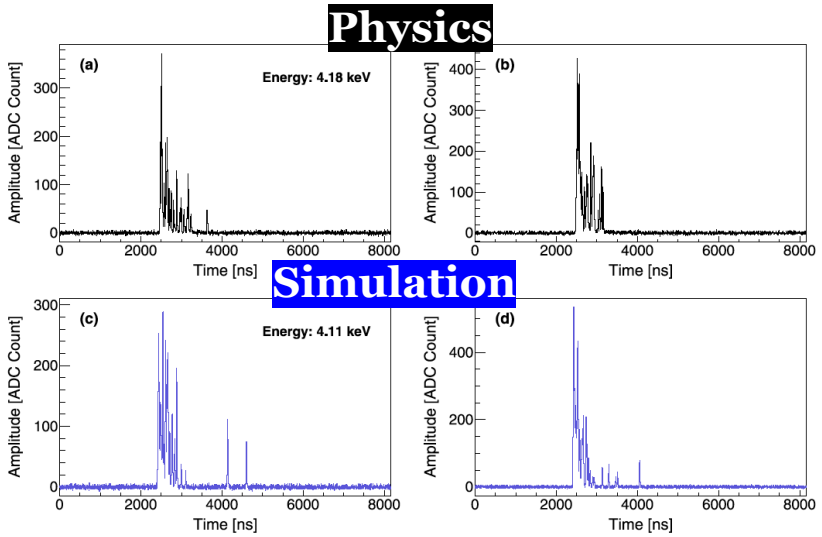
Phys. Rev. D 107, 122004 (2023)

Waveform simulation

Single photoelectron tuning

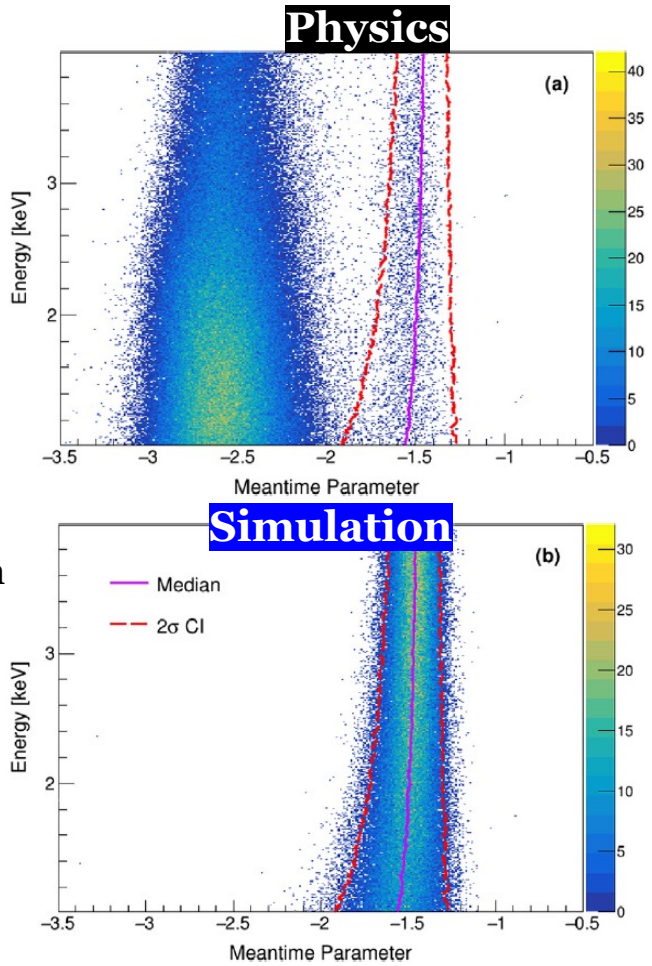






Scintillation waveform is generated with simulation

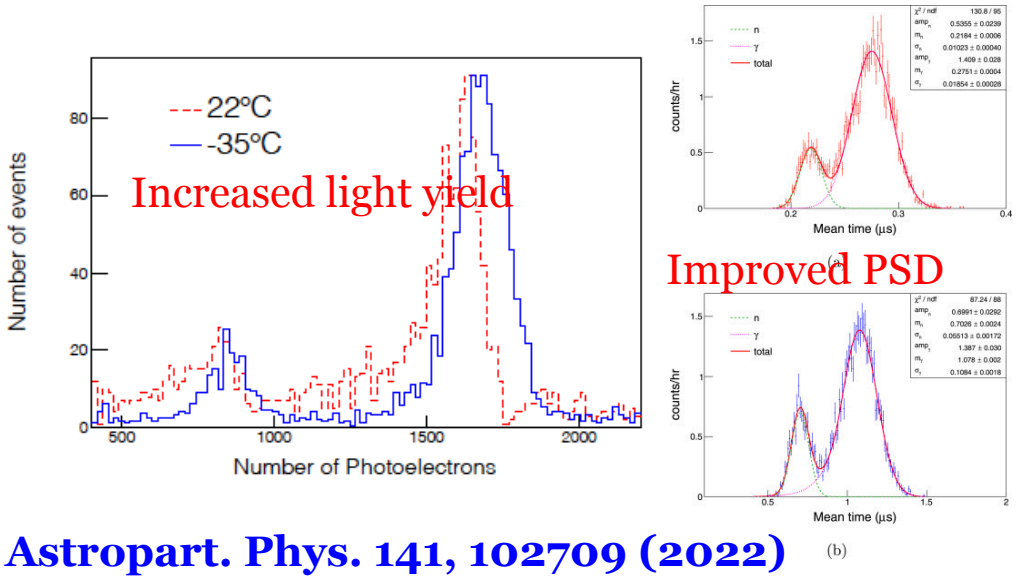
Nucl. Instrum. Meth. A
1065 (2024) 169489



- **Waveform simulation** is developed to **describe** low-energy events (**sub-keV**)
- Simulation describe the data reasonably well
- Currently, the waveform simulation cross checked the trigger/selection efficiencies
- The waveform simulation will be used as signal sample of the multivariable analysis

COSINE-100U @ Yemilab

-35°C operation



Astropart. Phys. 141, 102709 (2022)

- 5% gamma light yield increase
- 10% alpha quenching increase
  - ❖ Will measure nuclear recoil quenching
- Pulse shape discrimination is significantly improved

Warehouse freezer at Yemilab

Shielding base for muon detector