COSINE dark matter search

Resolving DAMA/LIBRA

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Institute for Basic Science

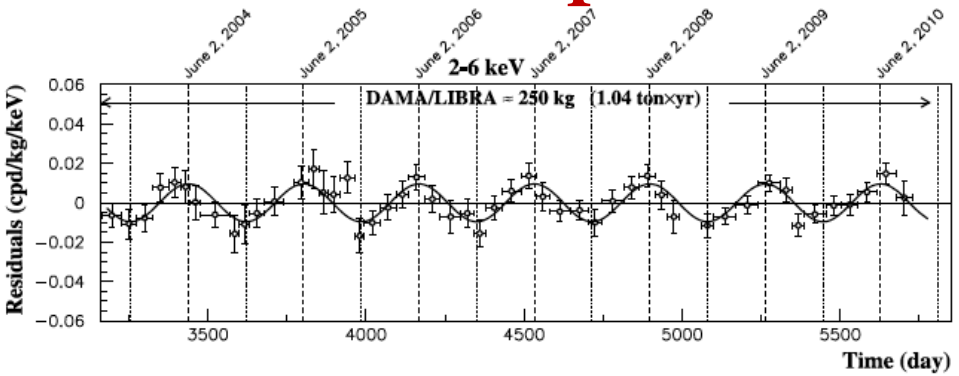
Center for Underground Physics

Light Dark World 2024

KAIST, August 13, 2024

Annual modulation signal from DAMA/LIBRA

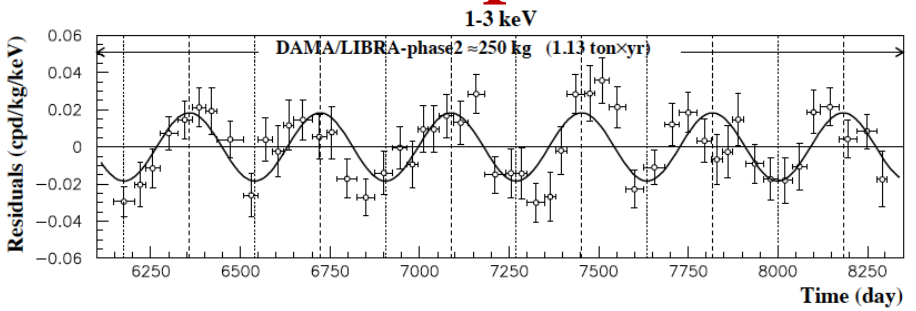
Phase1 experiment



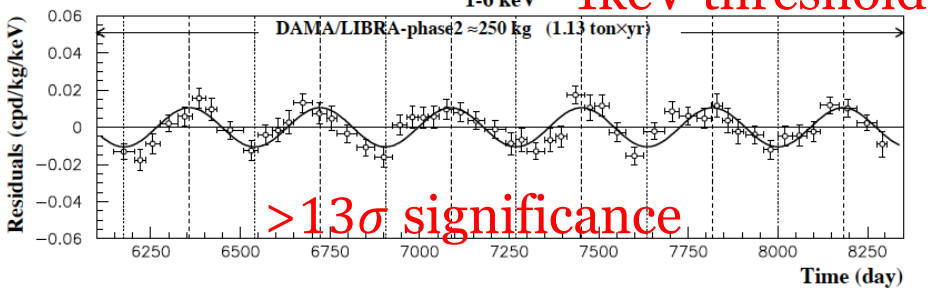
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



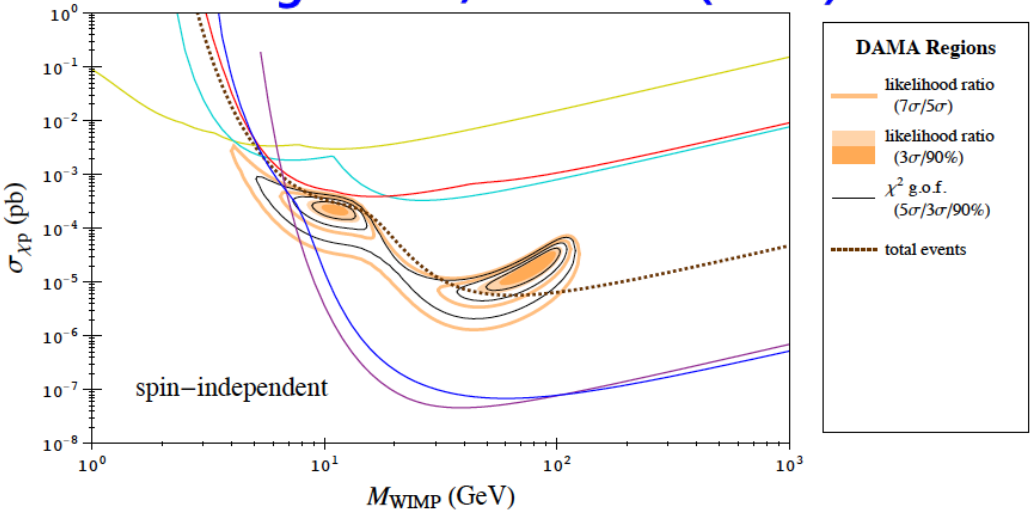
Nucl. Phys. At. Energy 19, 307 (2018)



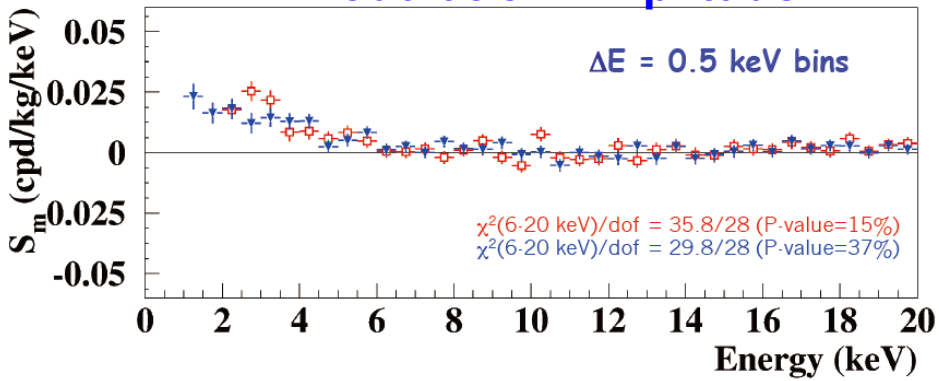
1keV threshold

>13σ significance

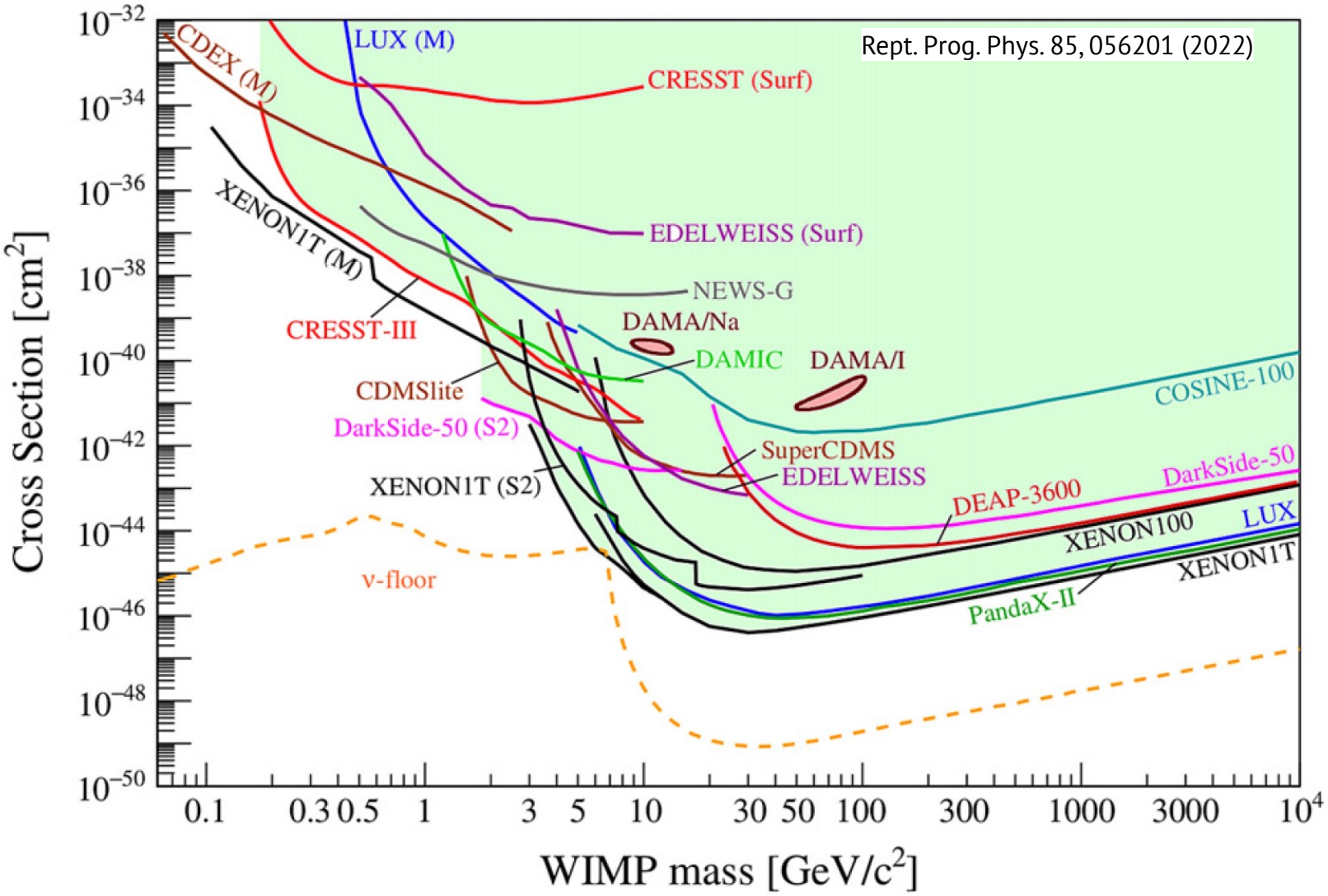
C. Savage *et al.*, JCAP 04 (2009) 010



Modulation Amplitude

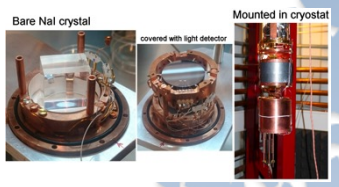


However…

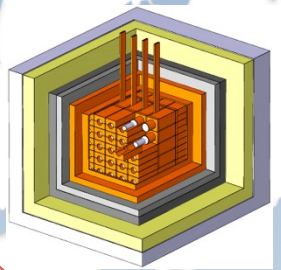


Requiring Model-independent test with same NaI(Tl) crystals

World-wide efforts on NaI(Tl)

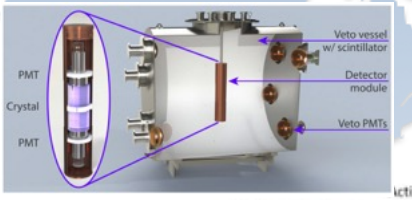


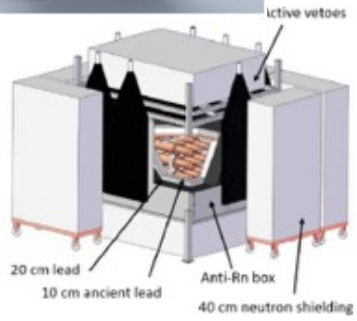
COSINUS @ LNGS



DAMA @ LNGS

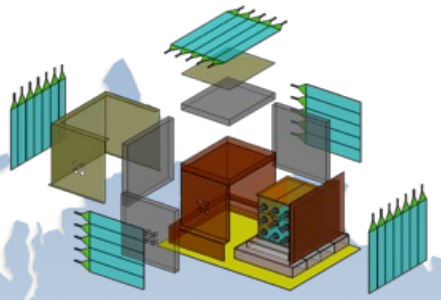
SABRE @ LNGS





ANAIS @Canfranc

In Data-taking

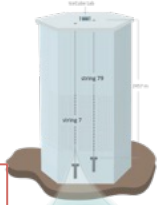


KIMS/COSINE @ Yangyang

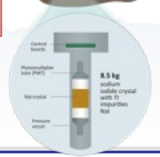
In Data-taking

PICO-LON @ Kamioka

SABRE @ Stawell



DM-Ice @ South Pole

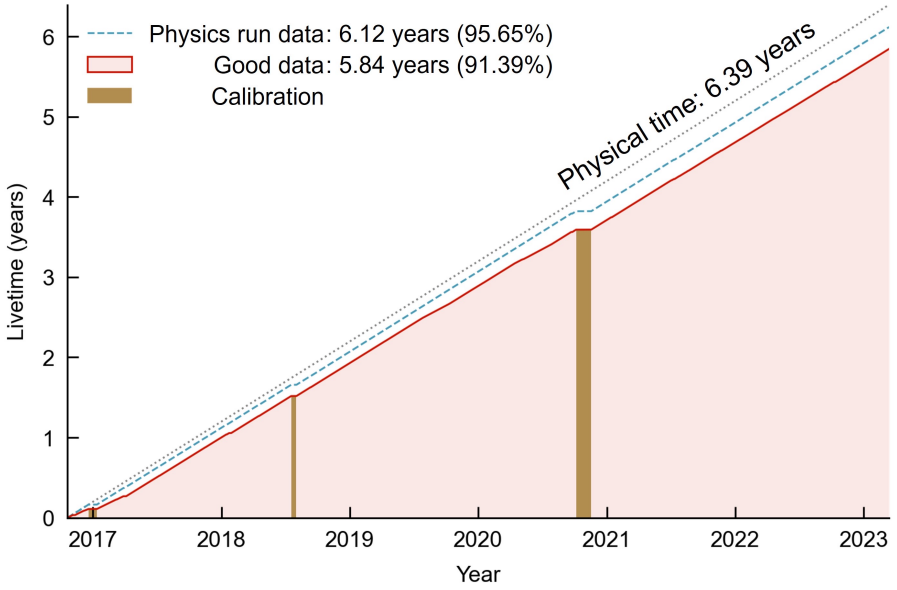


COSINE collaboration

15 institutes
~60 members

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

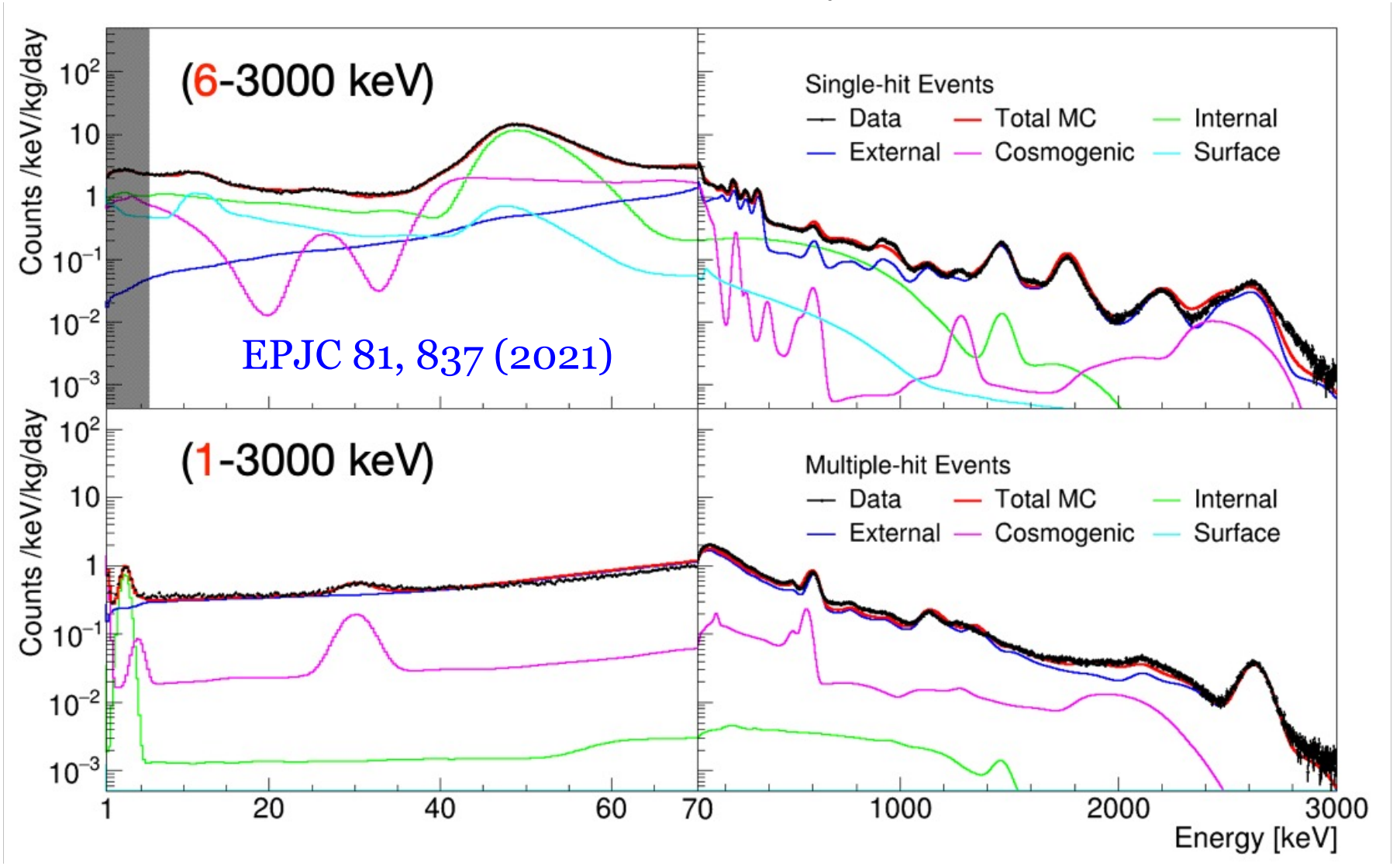
COSINE-100 experiment (2016~2023)



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

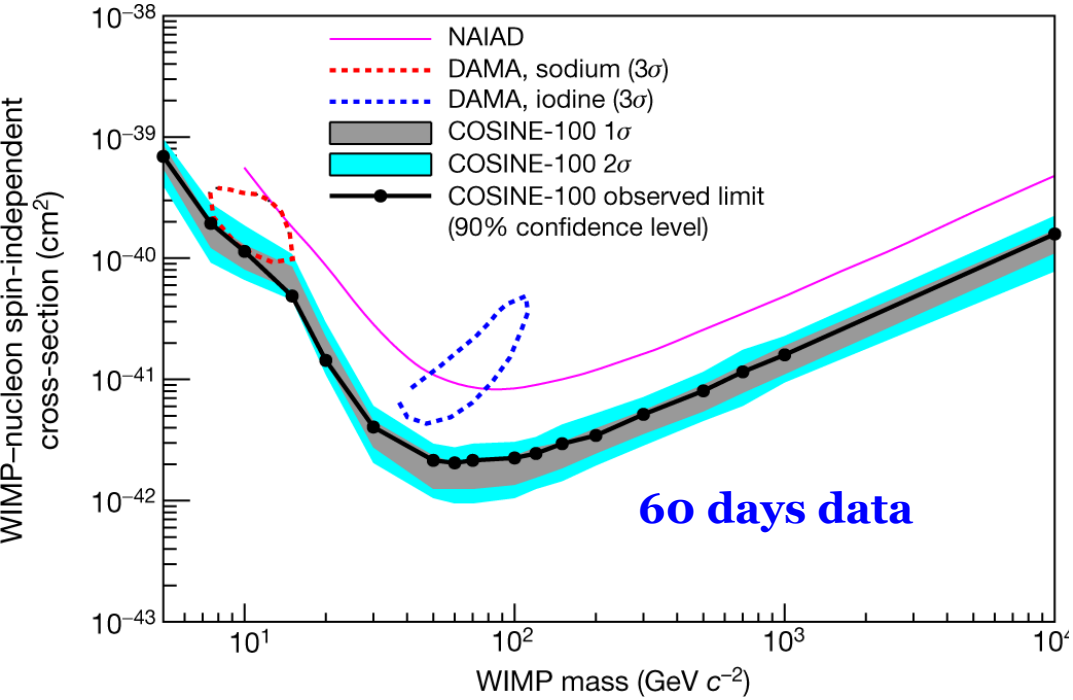
Background understanding

Background modeling **1.7 years data**

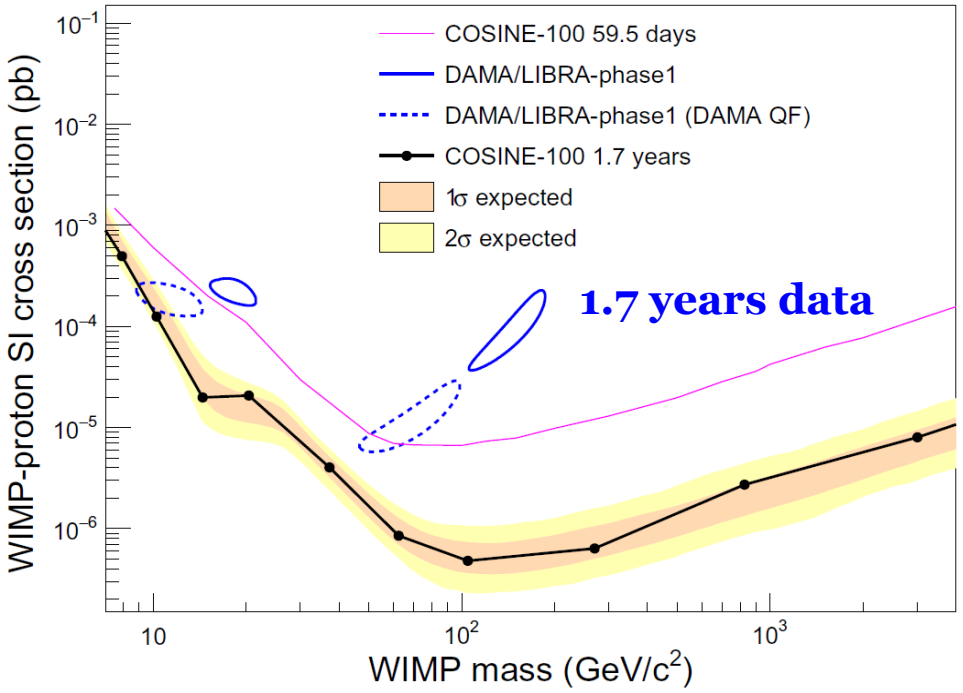


Rule out DAMA/LIBRA by COSINE-100

Model-dependent comparison



Nature 564, 83-86 (2018)



Sci. Adv. 7, eabk2699 (2021)

Model independent annual modulation searches could not resolve DAMA/LIBRA yet

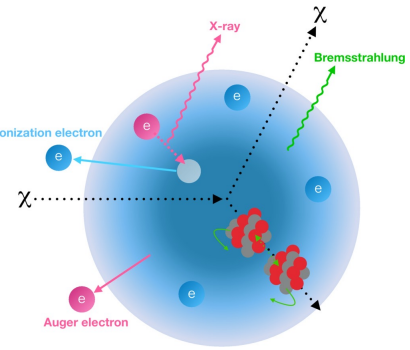
1.7 years data analysis Phys. Rev. Lett. 123, 031302 (2019)

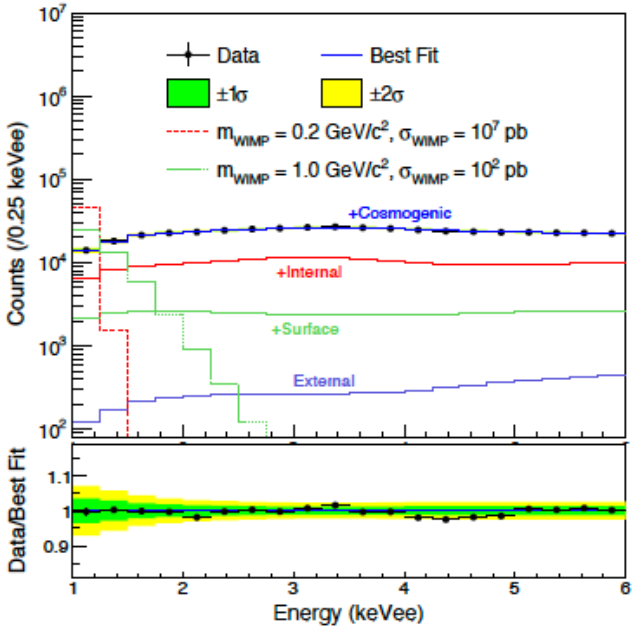
3 years data analysis Phys. Rev. D 106, 052005 (2022)

Full 6.4 years data are available

Dark matter search with spectral shape fit

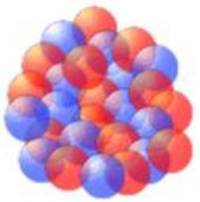
Migdal effect



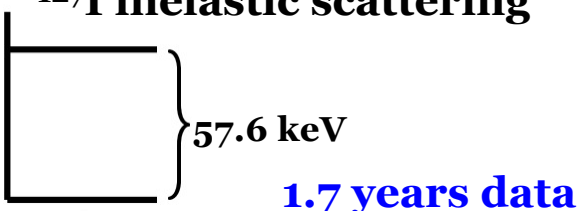


1.7 years data

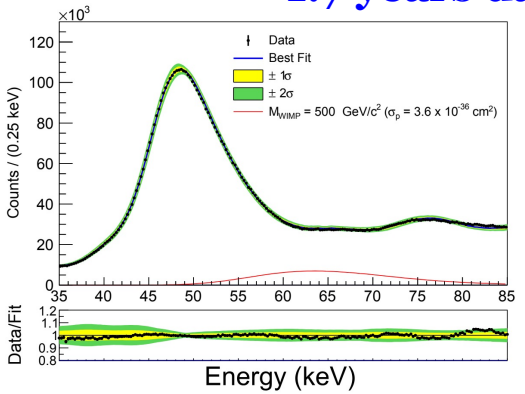
^{127}I inelastic scattering



^{127}I

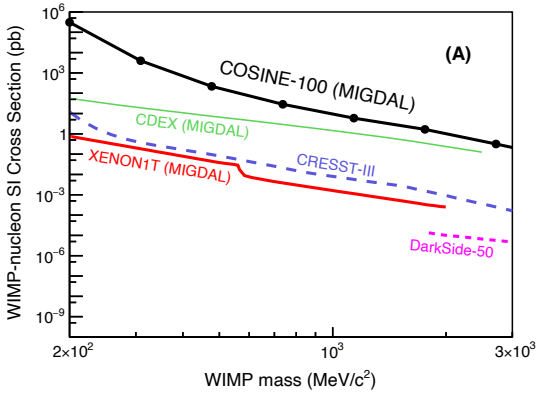


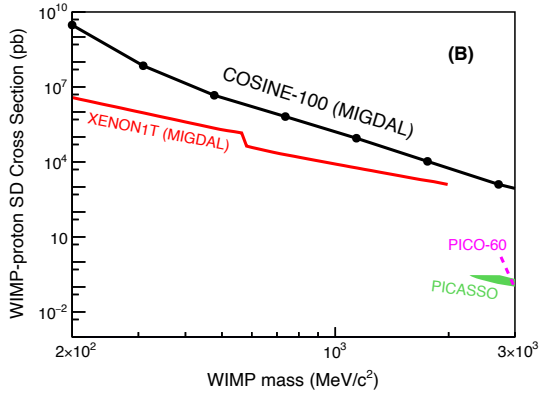
1.7 years data

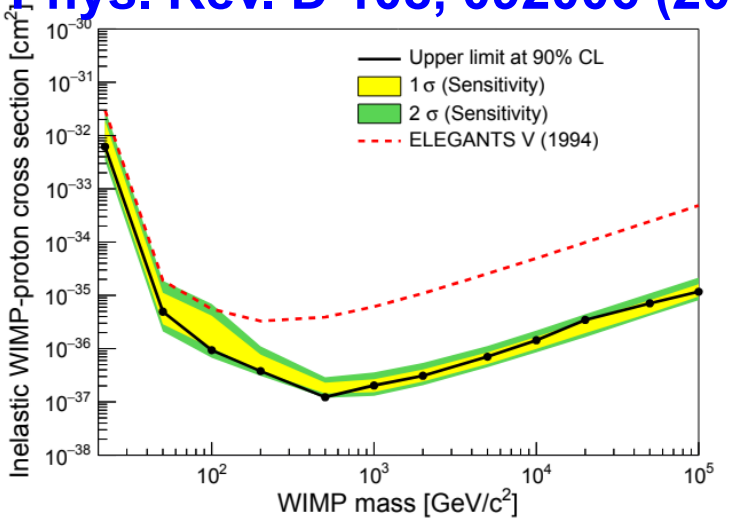


Phys. Rev. D 108, 092006 (2023)

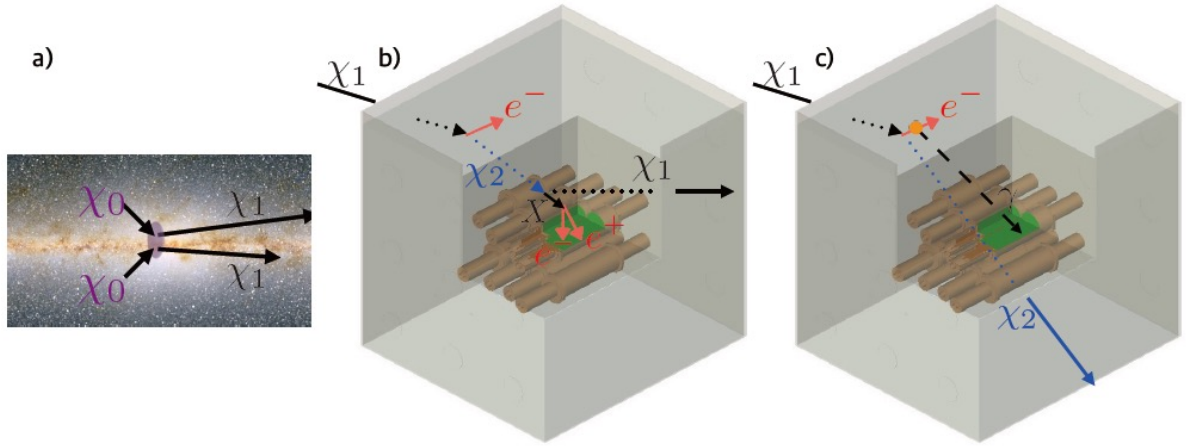
PRD 105, 042006 (2022)



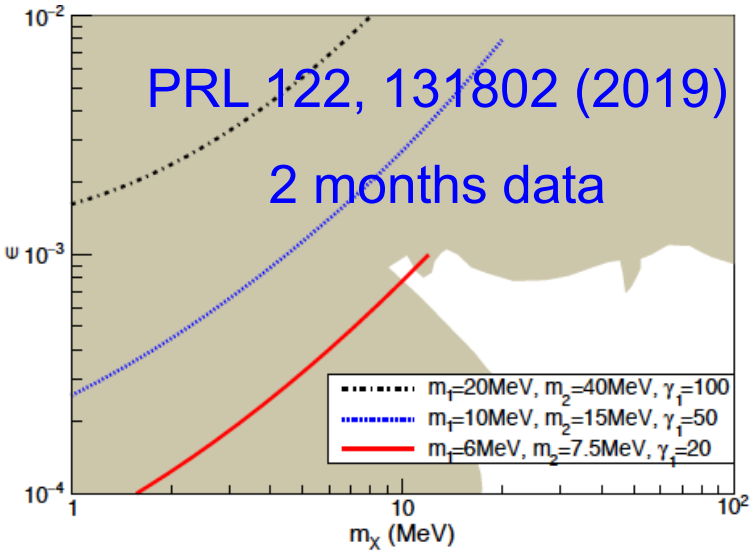




Boosted dark matter

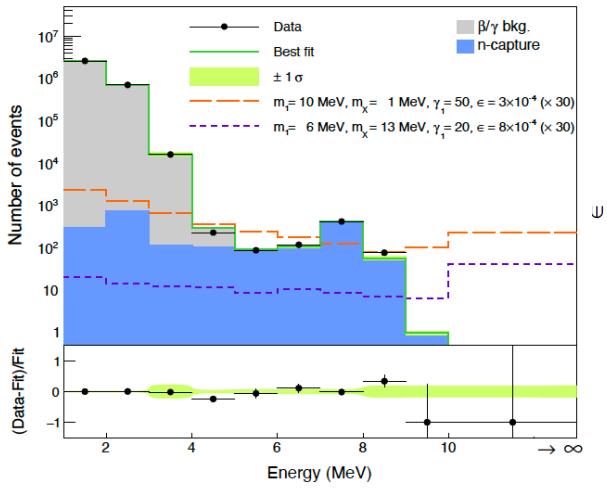


Inelastic interaction

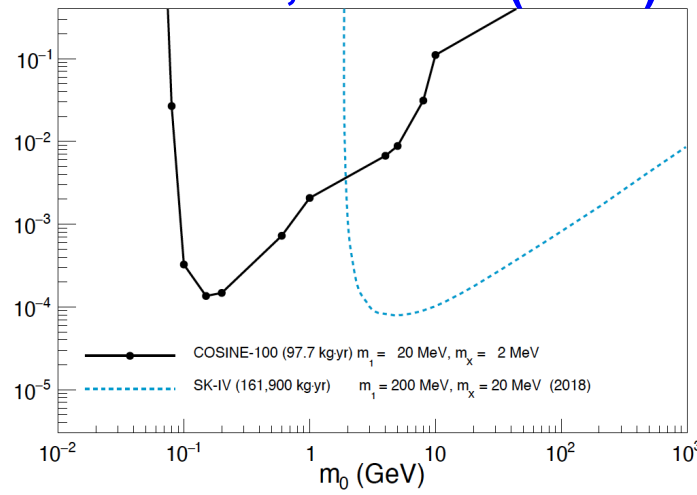


Elastic interaction

1.7 years data



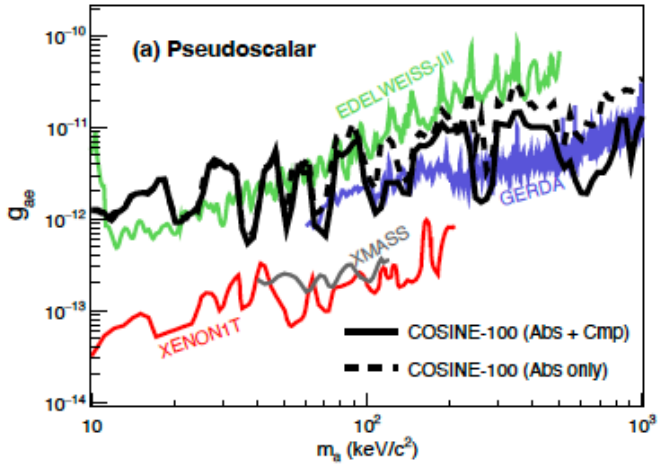
PRL 131, 201802 (2023)

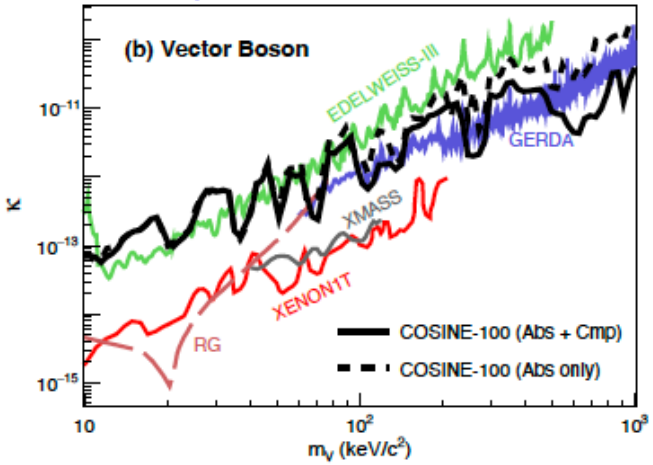


Bosonic superWIMP, solar dark bosonic particles..

Bosonic superWIMP

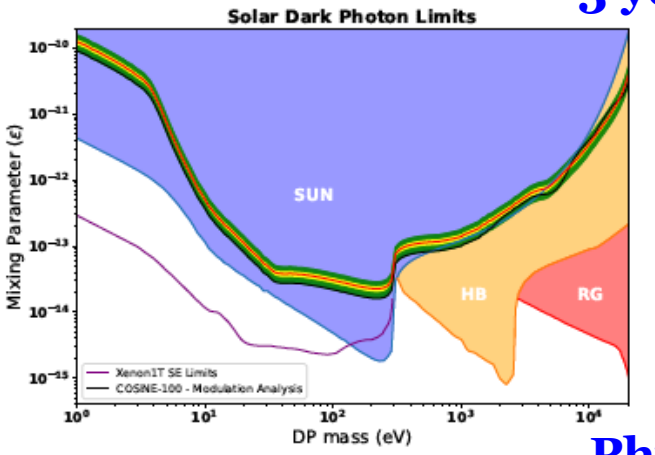
Phys. Rev. D 108,L041301 (2023)

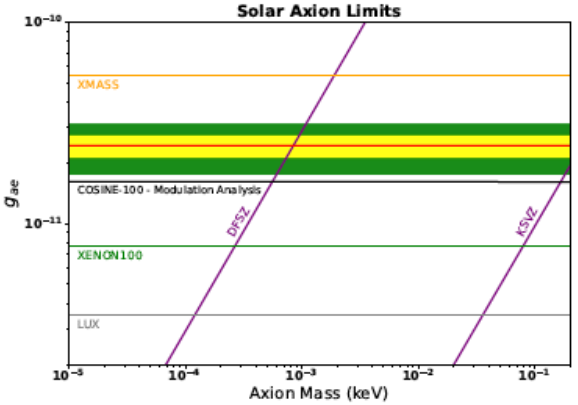


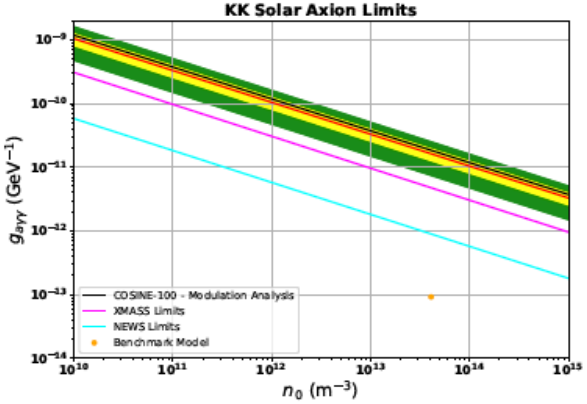


1.7 years data

3 years data for the modulation search



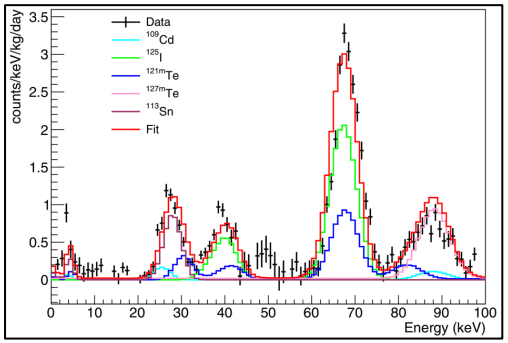




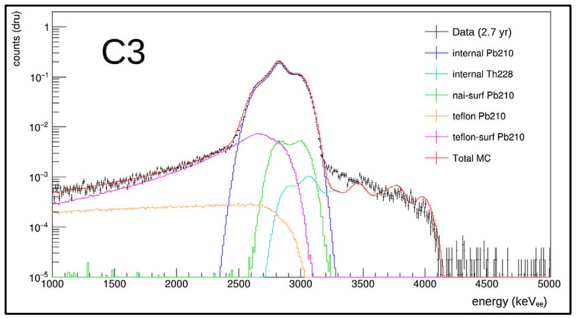
Phys. Rev. D 107, 122004 (2023)

Improvement of NaI(Tl) detector understanding

ASP 115, 102390 (2020)



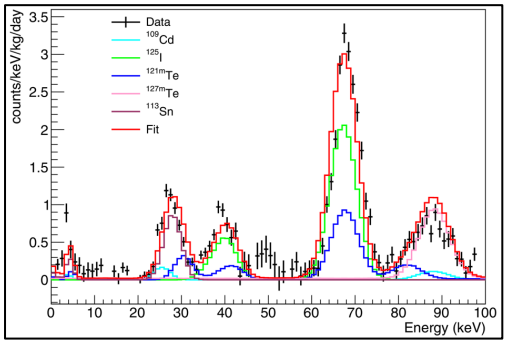
ASP 158, 102945 (2024)



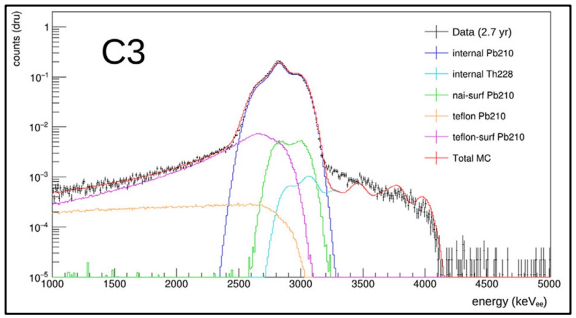
Background components

Improvement of NaI(Tl) detector understanding

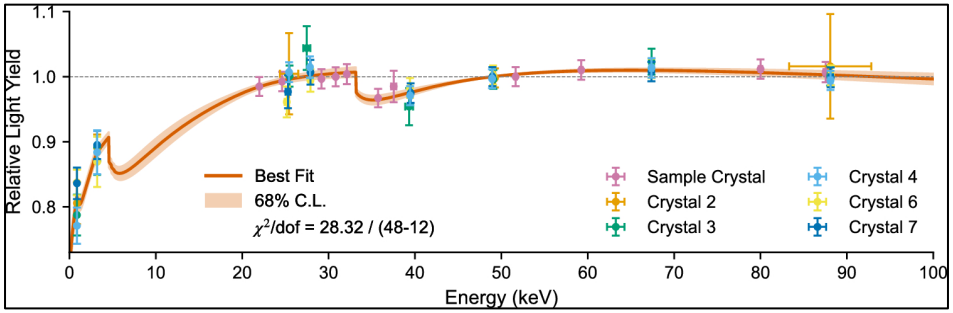
ASP 115, 102390 (2020)



ASP 158, 102945 (2024)



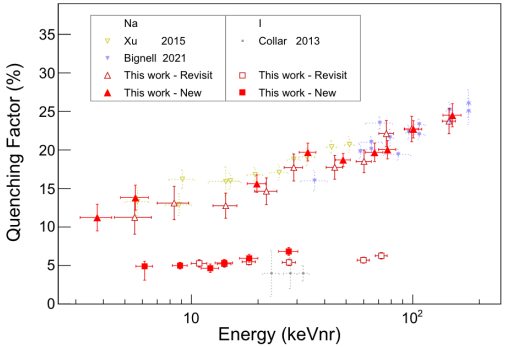
EPJC 84, 484 (2024)



Background components

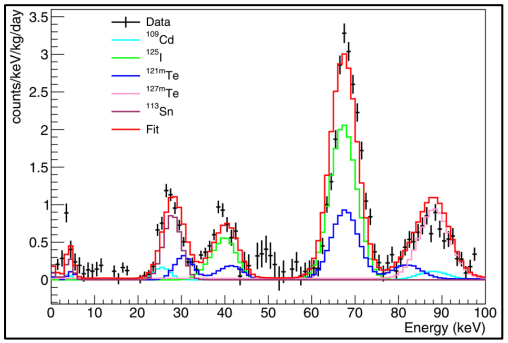
Detector responses

PRC 110, 014614 (2024)

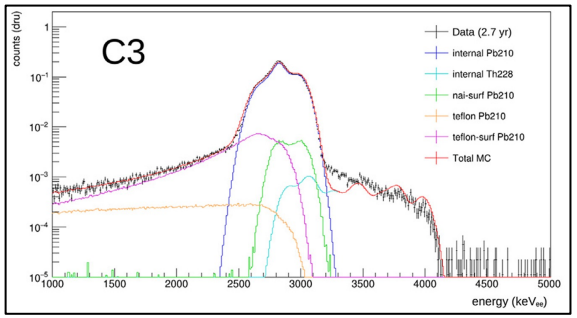


Improvement of NaI(Tl) detector understanding

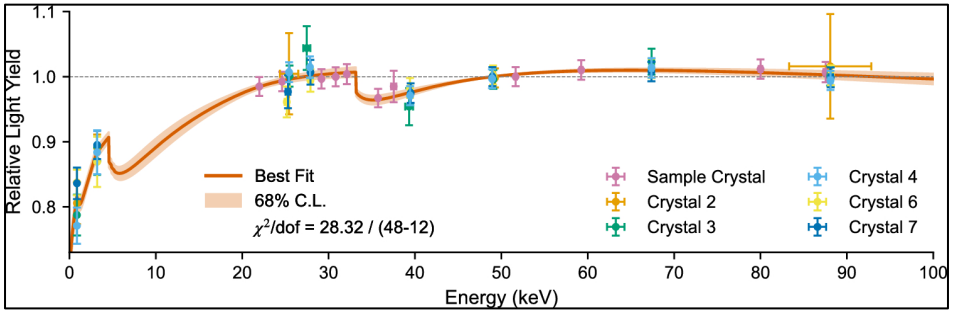
ASP 115, 102390 (2020)



ASP 158, 102945 (2024)



EPJC 84, 484 (2024)



Background components

Detector responses

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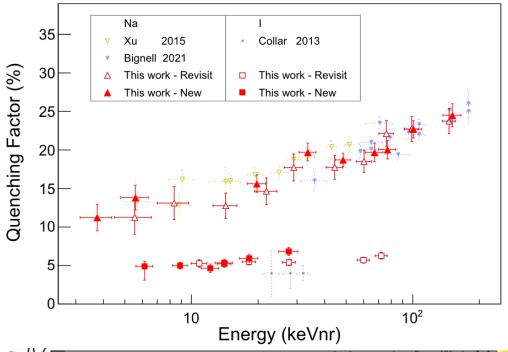
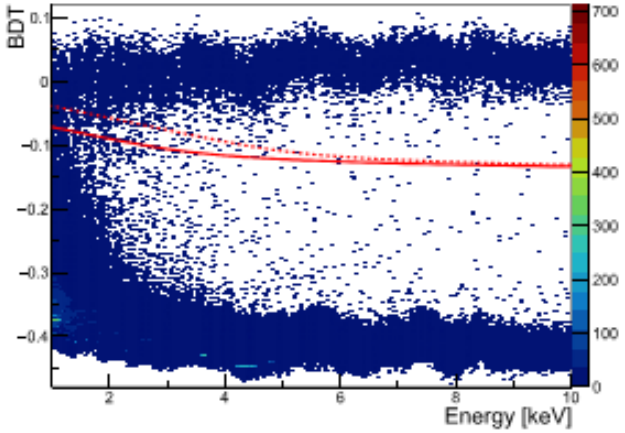
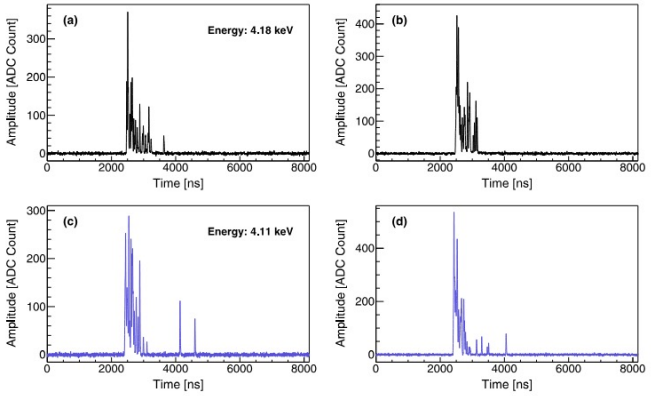


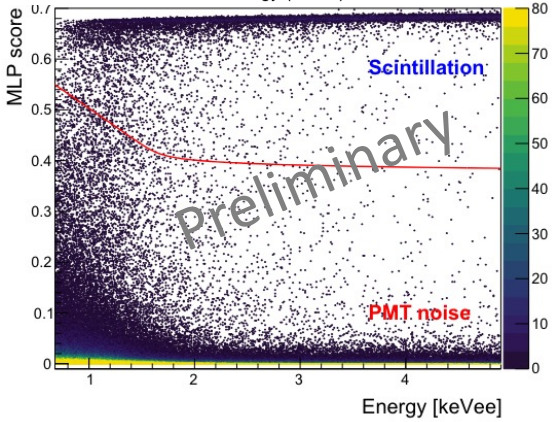
Low energy scintillation responses

ASP 130, 102581 (2021)



NIMA 1065, 169489 (2024)





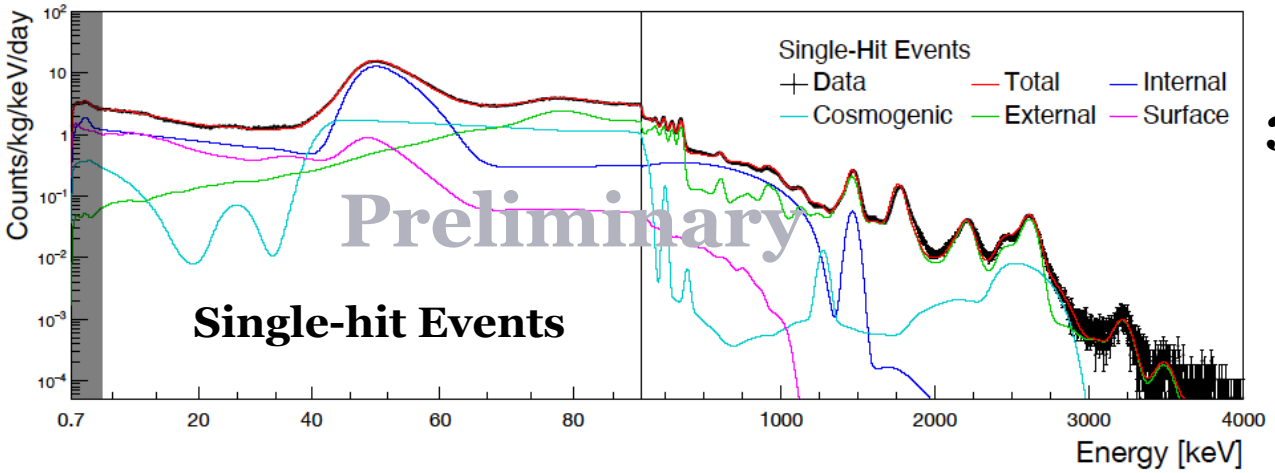
Improvement of NaI(Tl) detector understanding

Detector responses

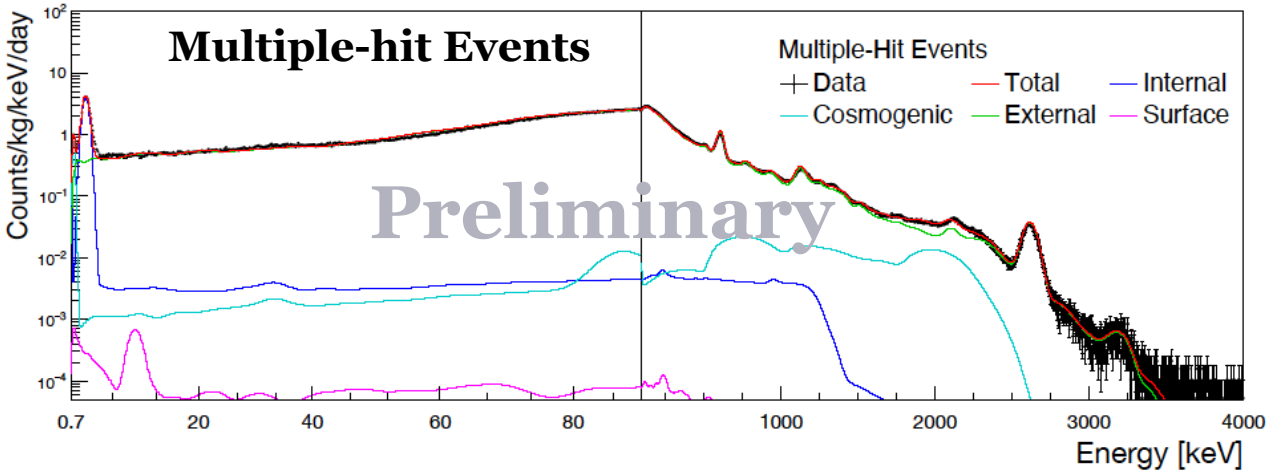
Background components

Low energy scintillation responses

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



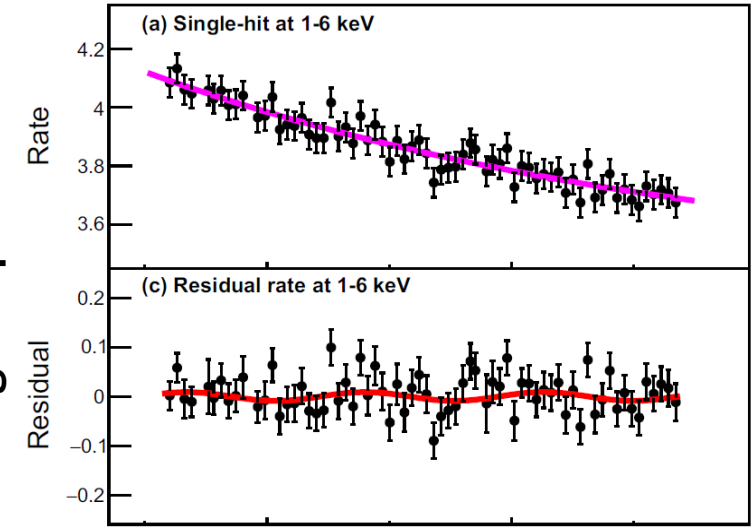
3 years data



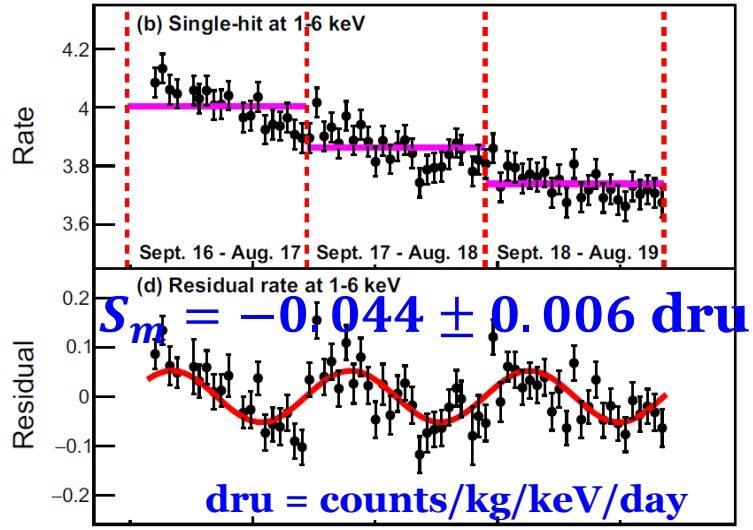
Time-dependent background models

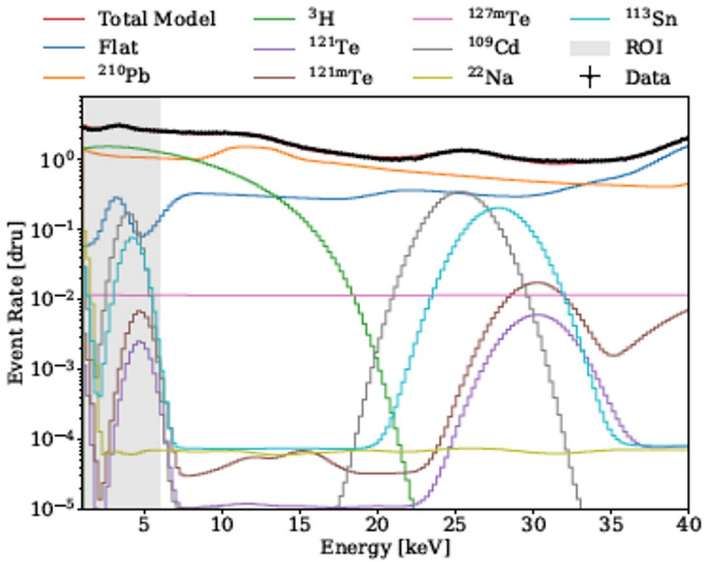
Sci. Rep. 13, 4676 (2023)

Single exponential



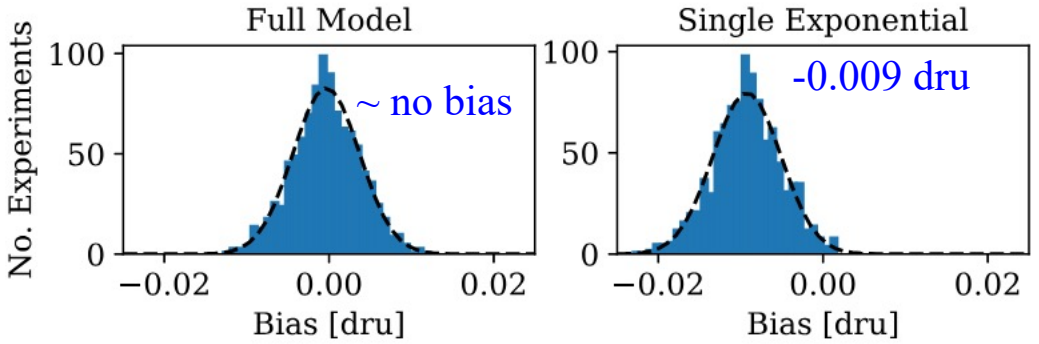
DAMA-like method





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

Full model : eight exponential components



DAMA/LIBRA : 0.010 ± 0.001 dru

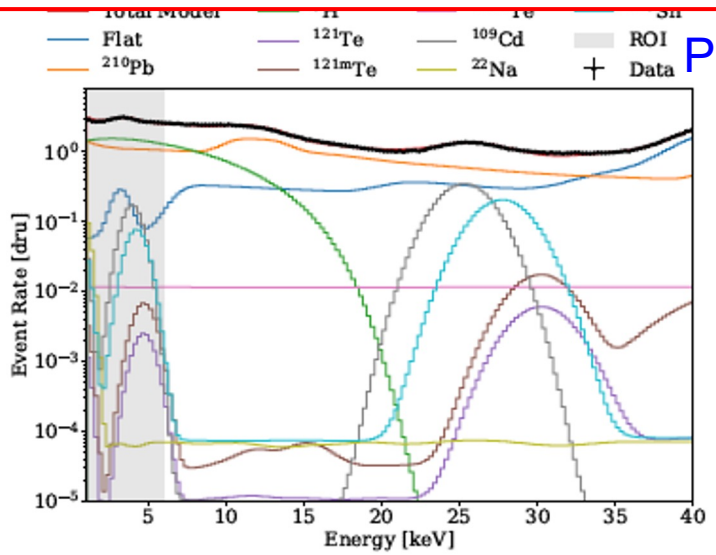
Time-dependent background models

Sci. Rep. 13, 4676 (2023)

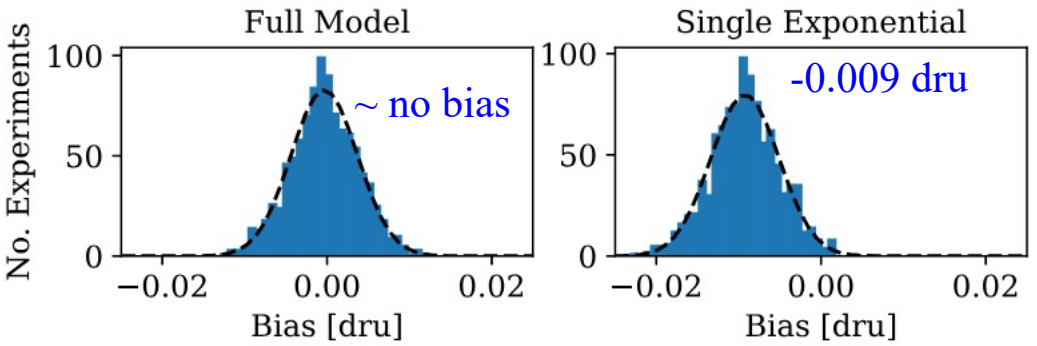
Caveat : Understanding of time-dependent background is crucial for the annual modulation analysis

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

PRD 106, 052005 (2022)

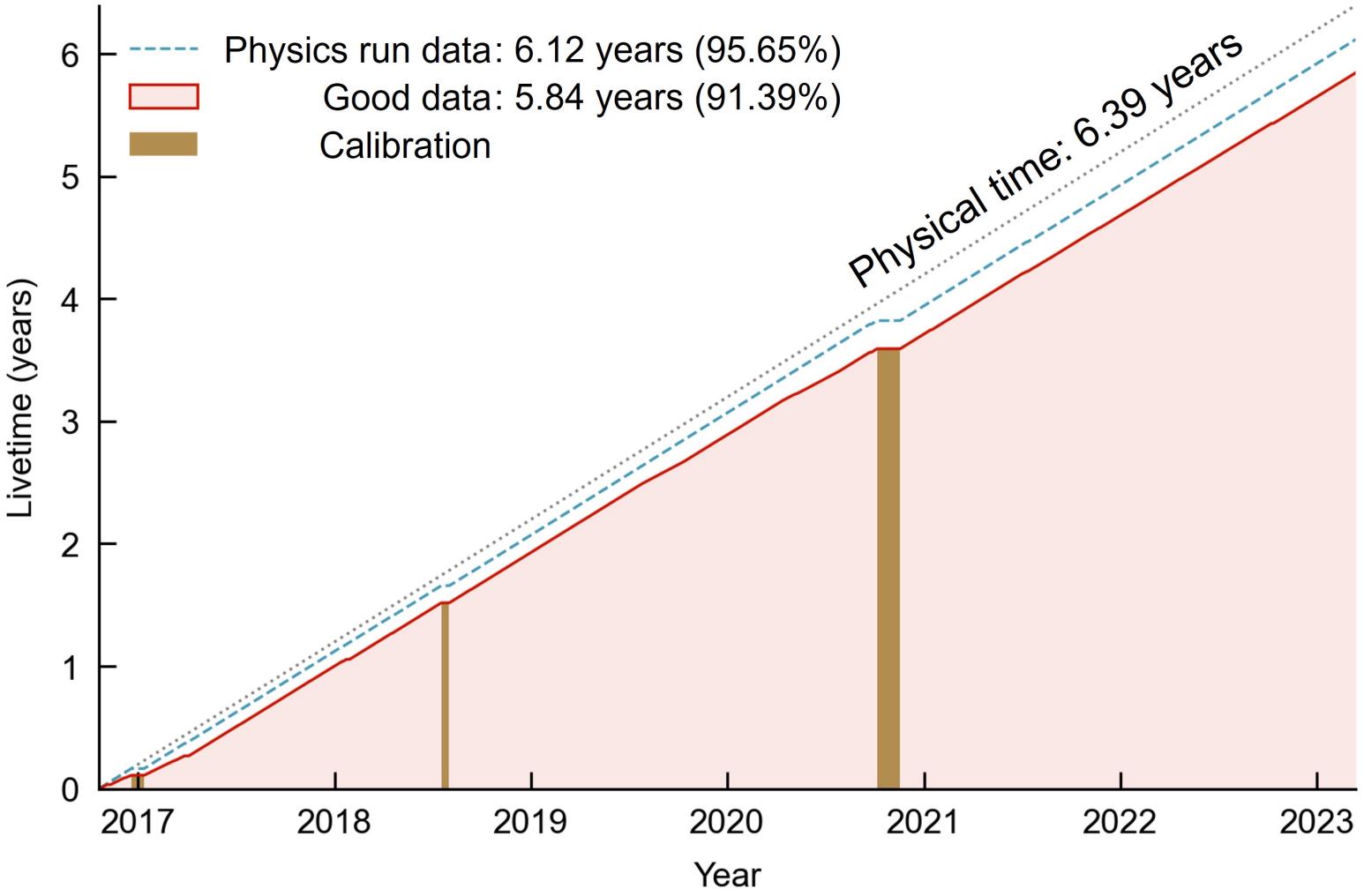


Full model : eight exponential components



DAMA/LIBRA : 0.010 ± 0.001 dru

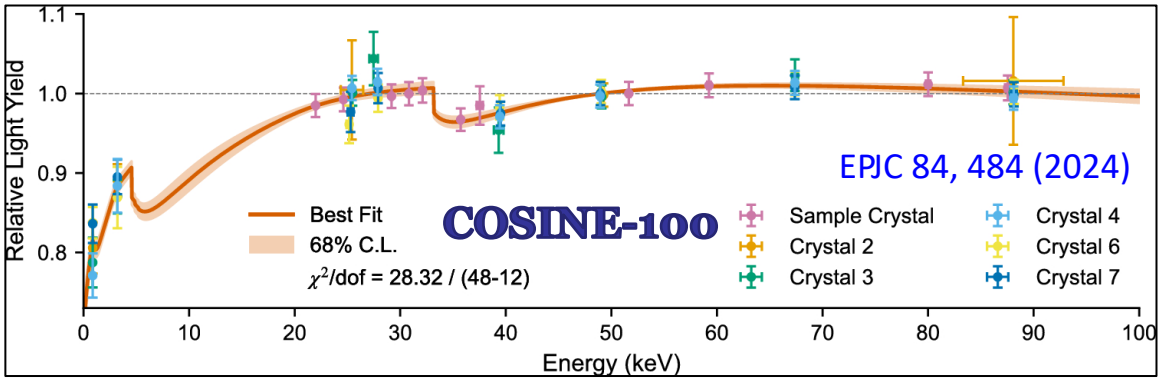
COSINE-100 full dataset

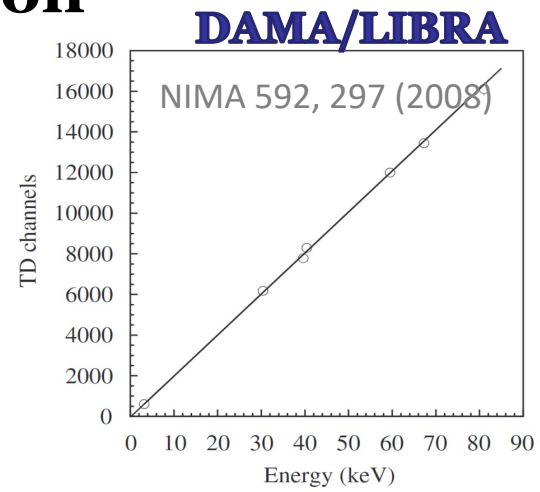


- Importance : Apple-to-apple comparison with **DAMA/LIBRA**

Comparison with DAMA : Energy calibration

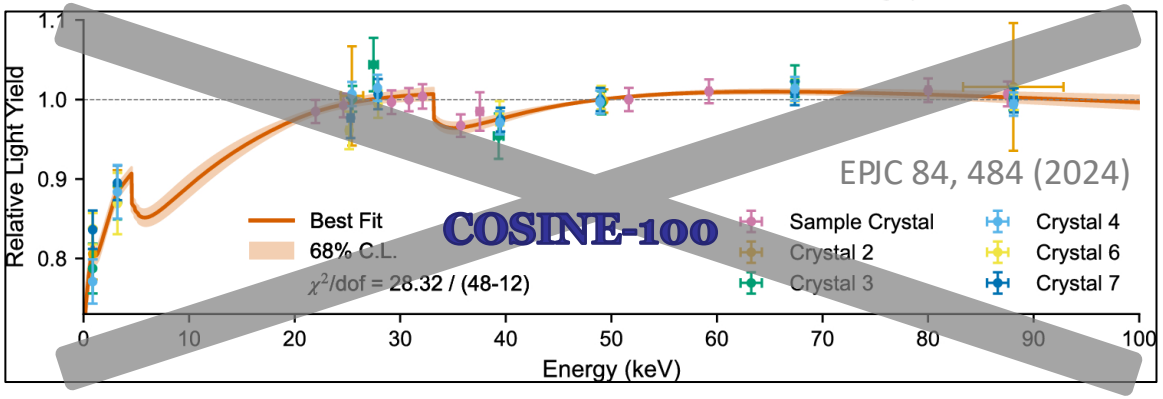
Electron-recoil energy calibration

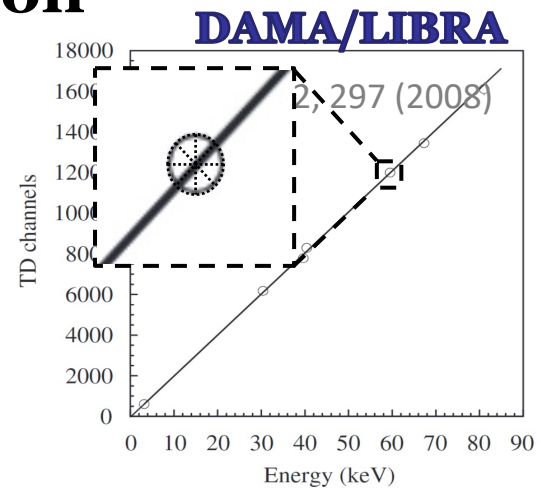




Comparison with DAMA : Energy calibration

Electron-recoil energy calibration

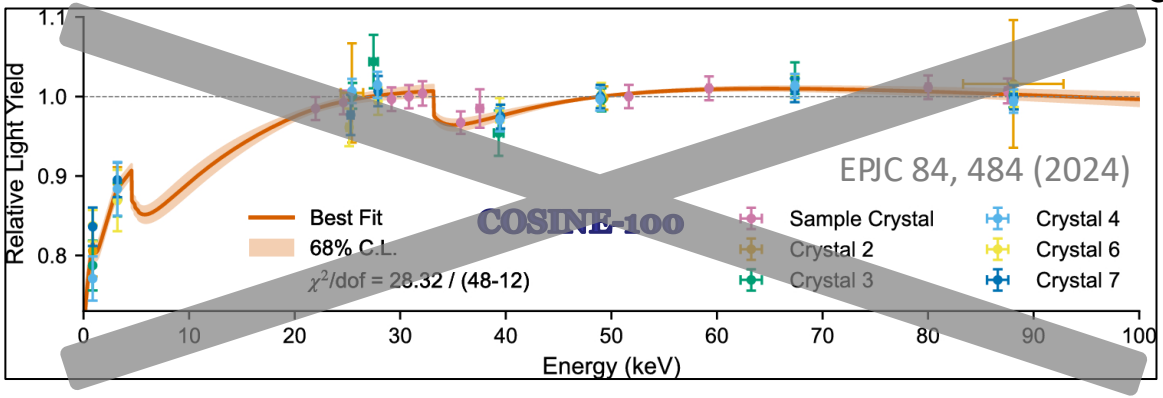


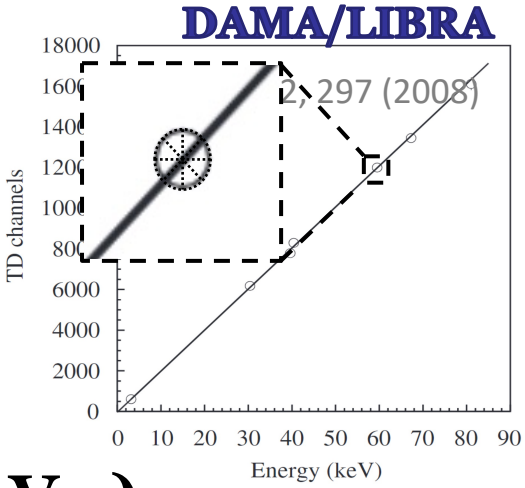


Linear calibration to 59.54 keV : keV_{ee}

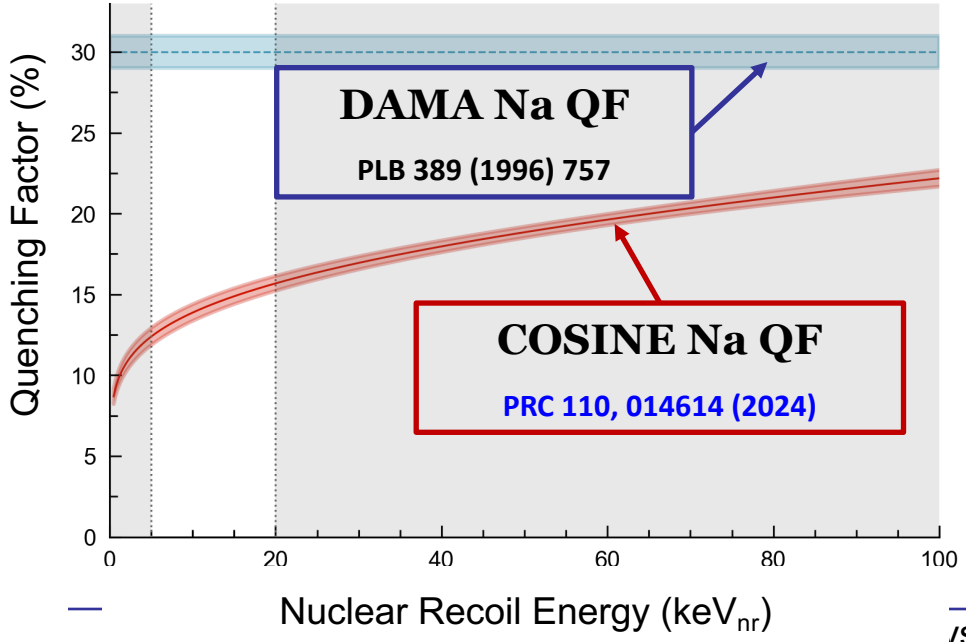
Comparison with DAMA : Energy calibration

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}

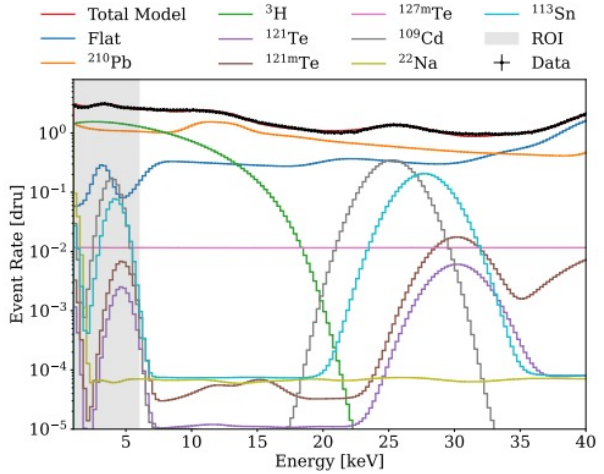
DAMA/LIBRA : 2-6 keV_{ee}

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

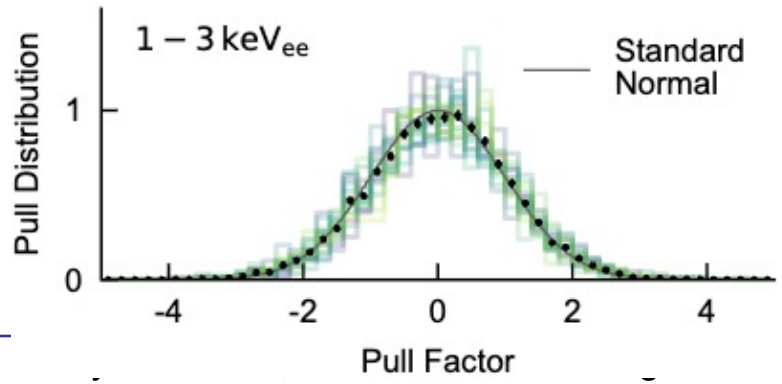


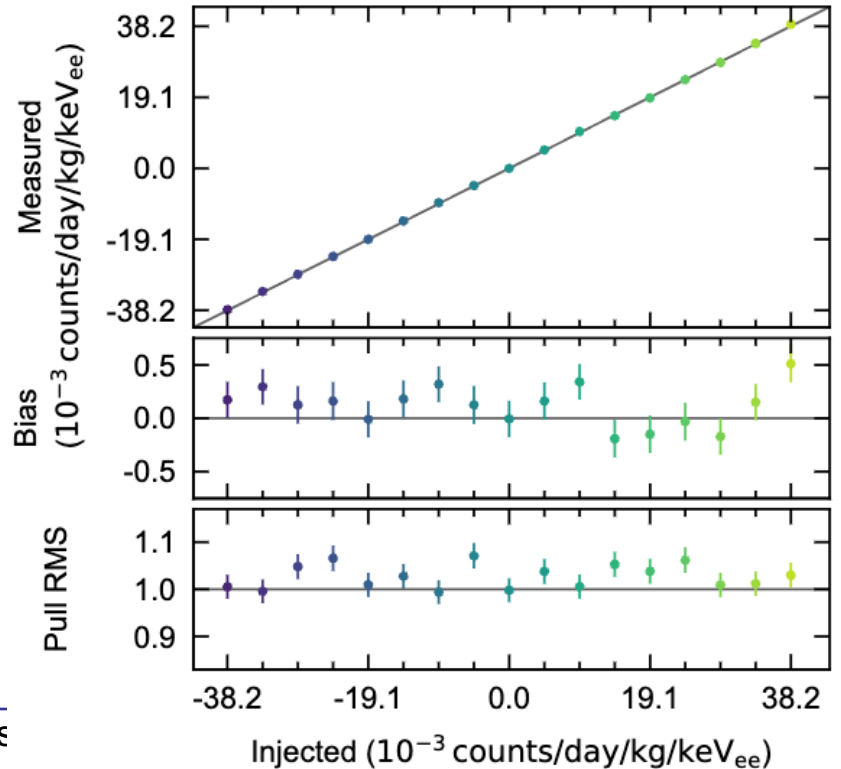
Simulated experiments

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

Measured signal; Input signal; Measured uncertainty

No Bias





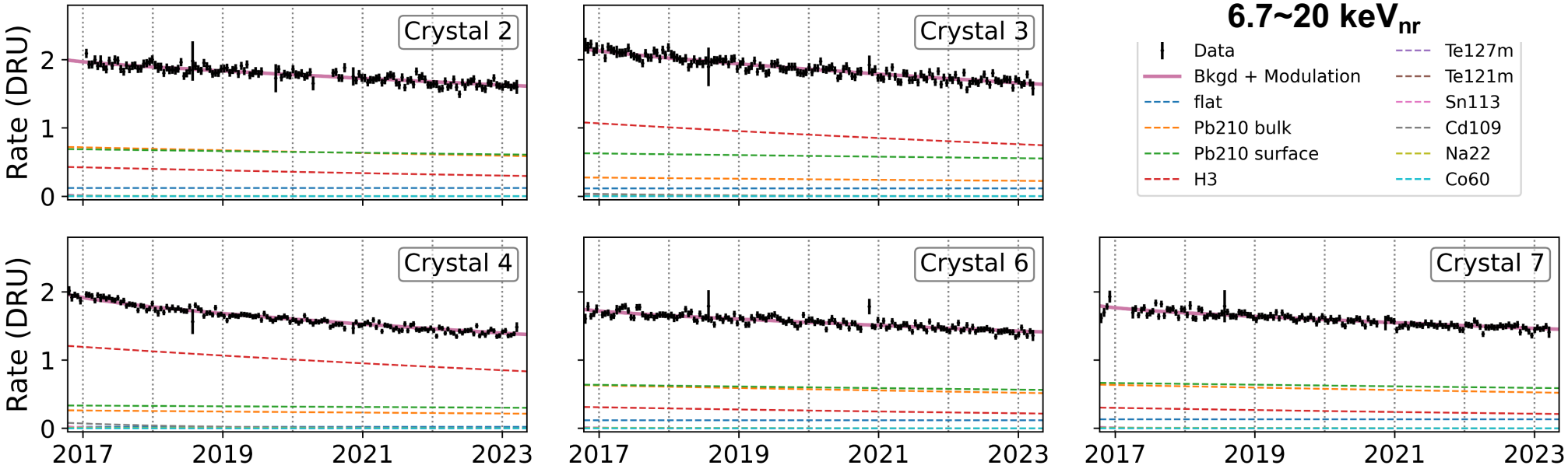
Modulation fit

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

Modulation signals 10 time-dependent components

COSINE-100 full dataset

DRU = counts/kg/keV/day

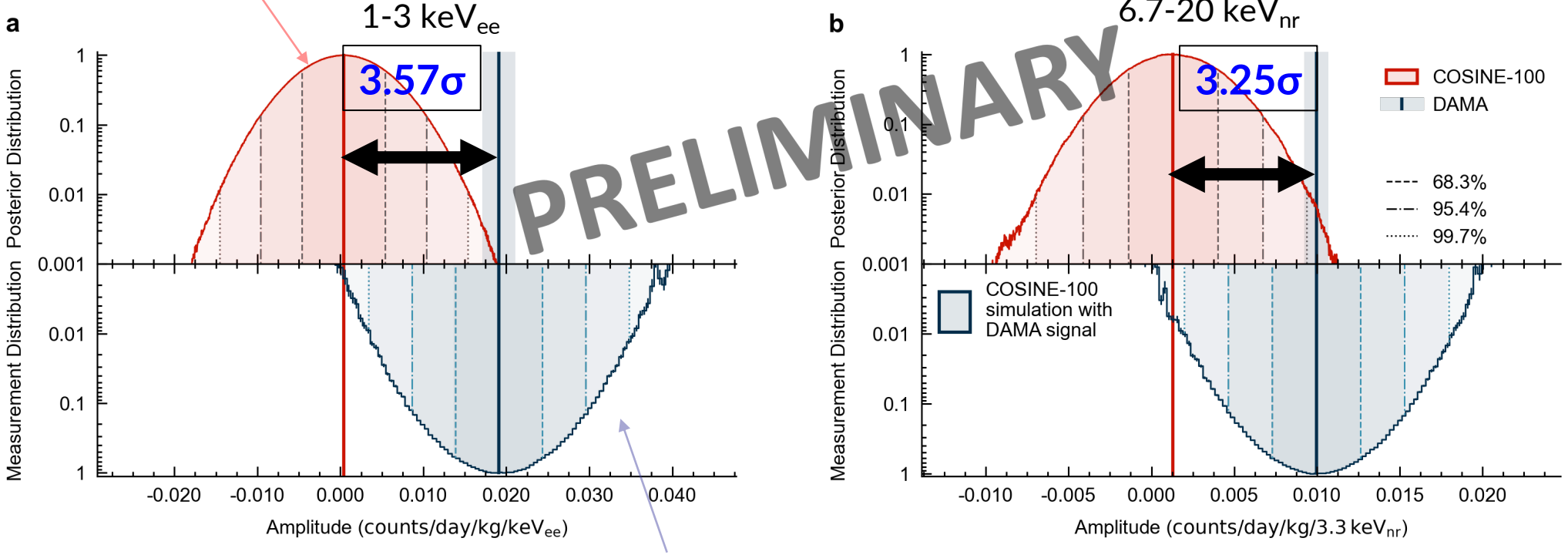


No modulation signal observed !!

COSINE-100 full dataset fits

Posterior of COSINE-100 full dataset

(2-6 keVee in DAMA/LIBRA)

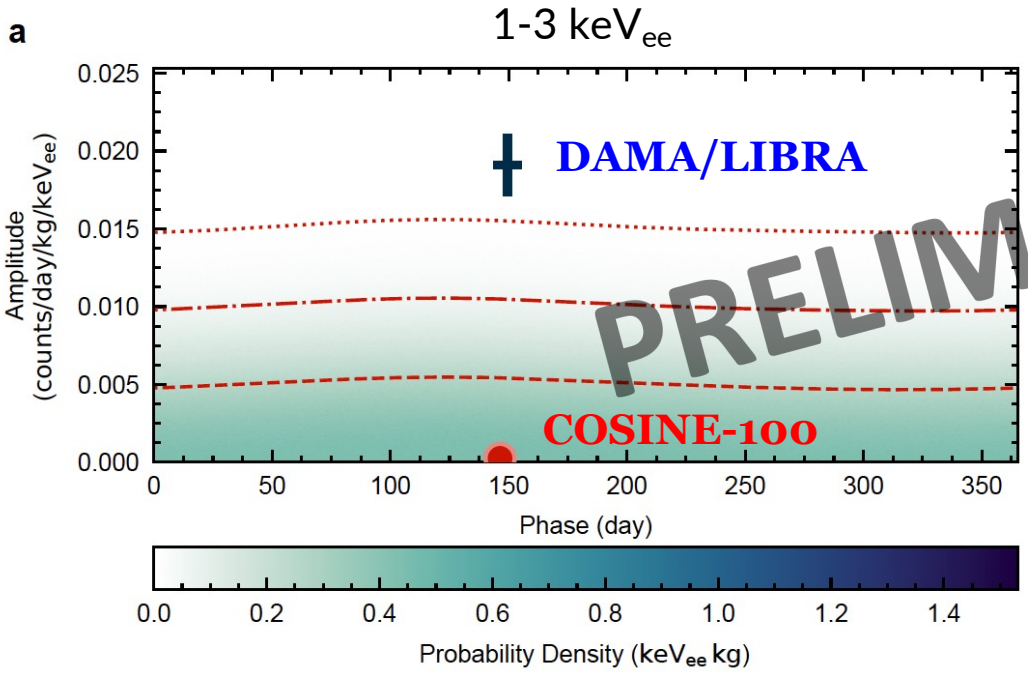


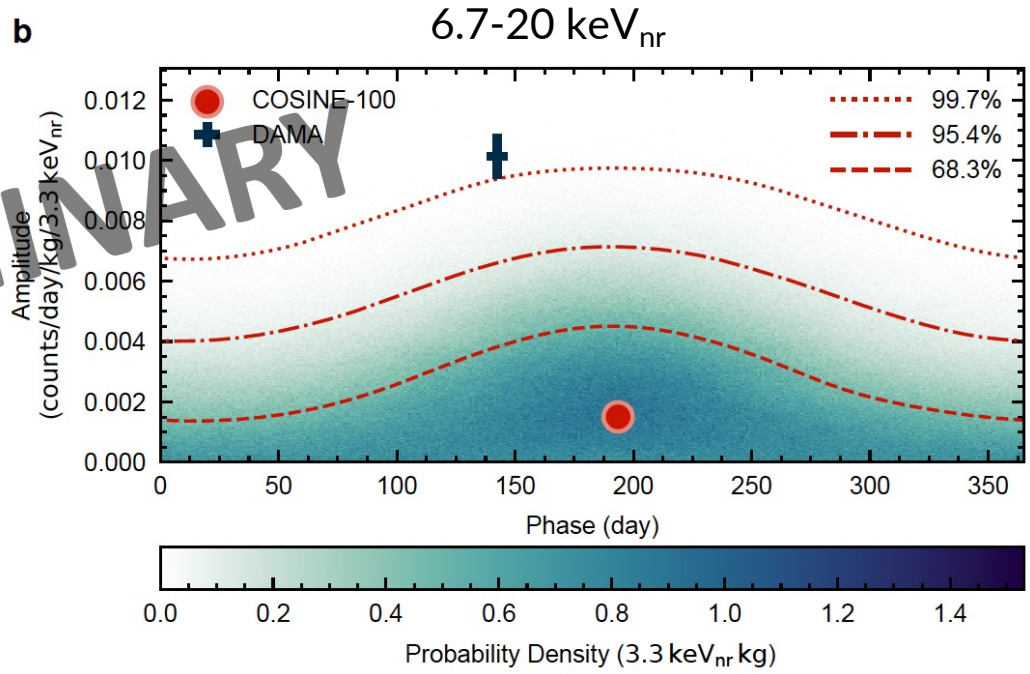
Simulated experiments (25,000) assuming DAMA/LIBRA modulation signals

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

COSINE-100 full dataset fits

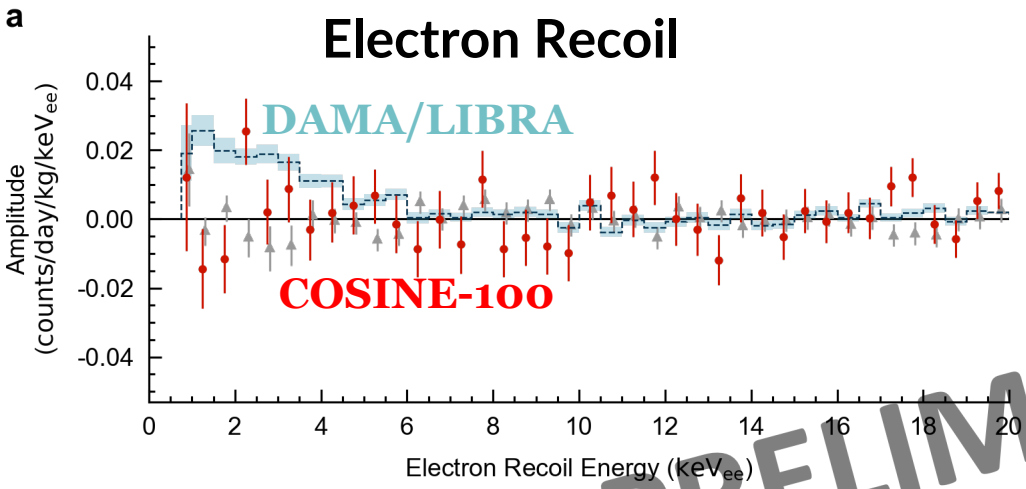
Phase floated 2-dimensional fit for COSINE-100 full dataset

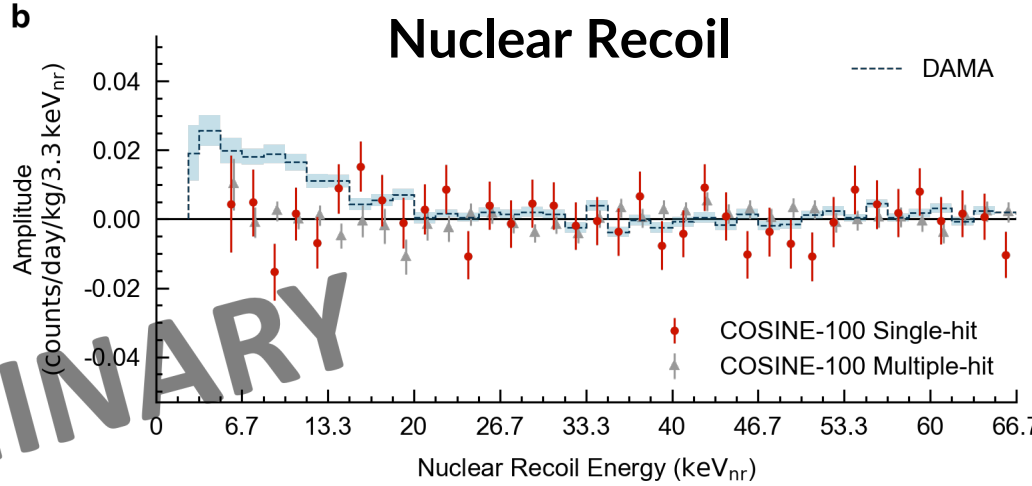




COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

COSINE-100 full dataset fits





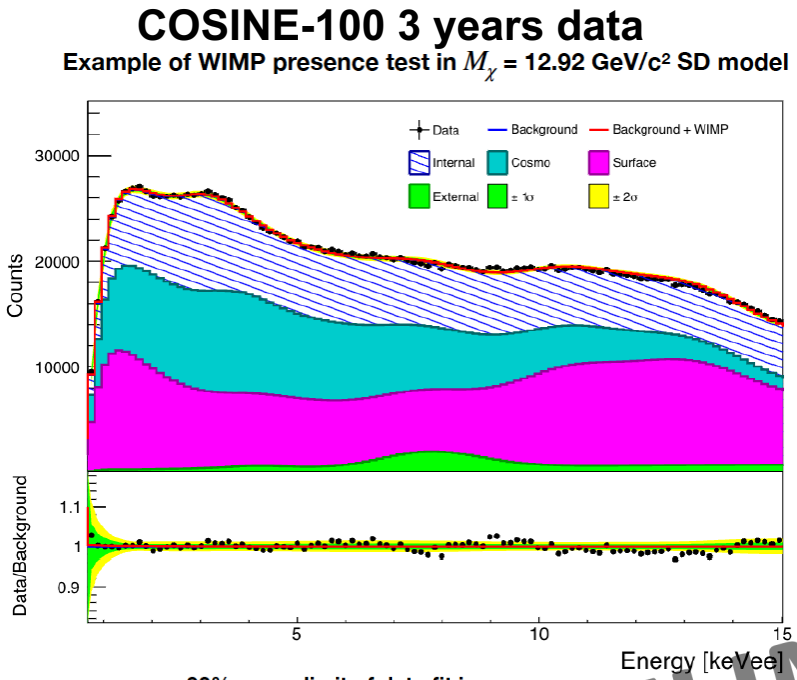
PRELIMINARY

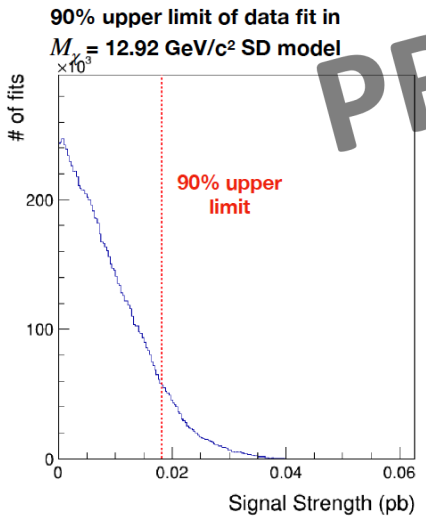
E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	$\mathbf{0.001 \pm 0.005}$	0.019 ± 0.002
1~6	$\mathbf{0.002 \pm 0.003}$	0.010 ± 0.001
2~6	$\mathbf{0.005 \pm 0.003}$	0.010 ± 0.001

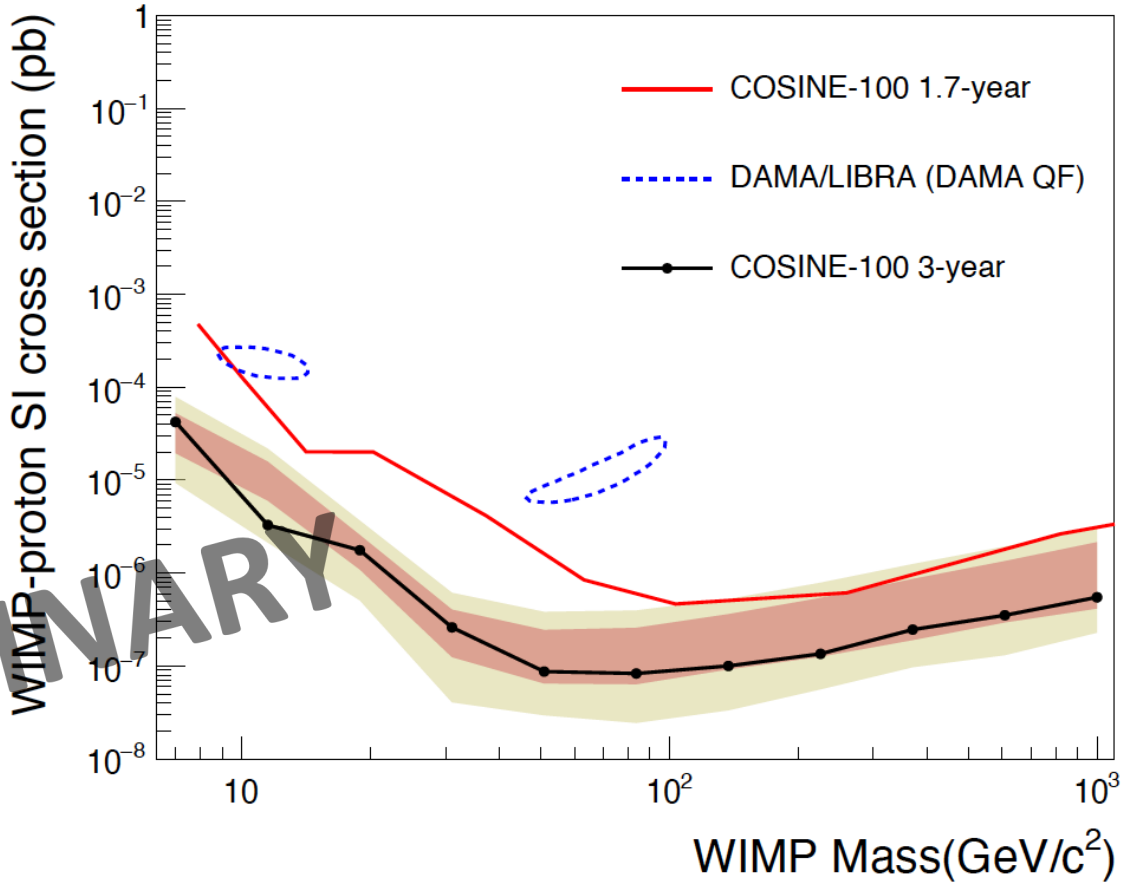
E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	$\mathbf{0.001 \pm 0.003}$	0.010 ± 0.001

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

Model-dependent searches







PRELIMINARY

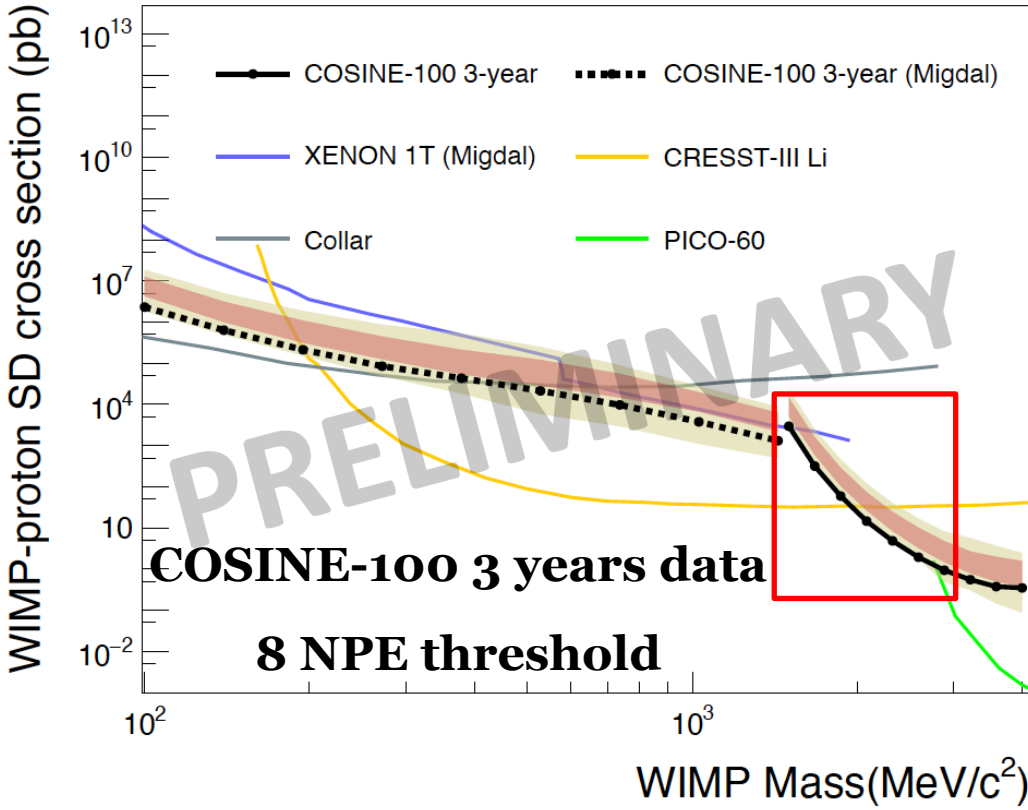
COSINE-100 full dataset disfavors DAMA/LIBRA in model-dependent search

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

WIMP-proton spin-dependent interaction

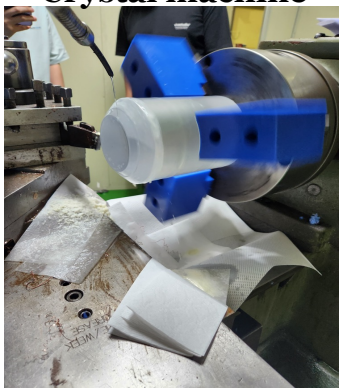


NPE = number of photoelectrons

Moving forward to COSINE-100Ugrade

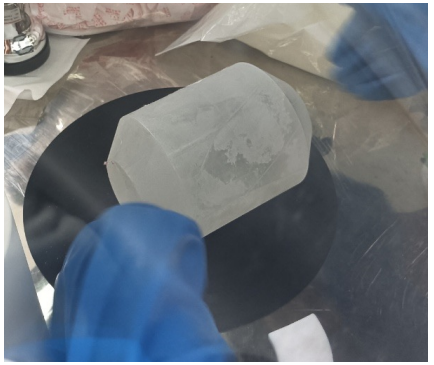
- Upgrade detector assembly for high light yield

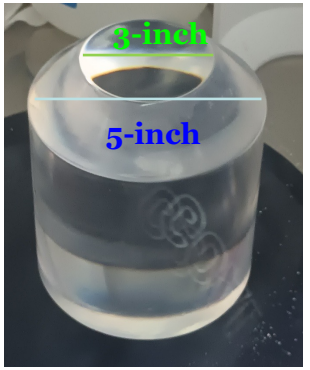
Crystal machine



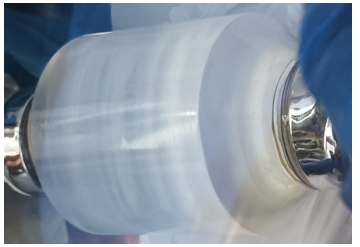
8.26 kg → 7.19 kg

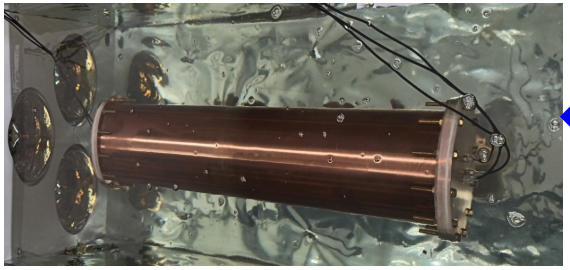
Deliver to glove box



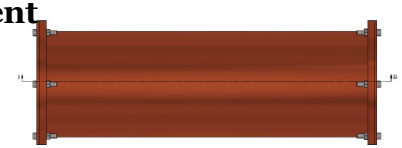


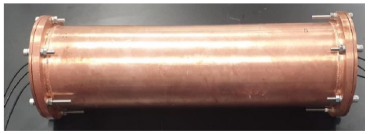
COSINE crystal-1



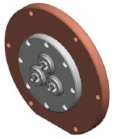


Above ground measurement





Cover design



NIMA 981 (2020) 164556

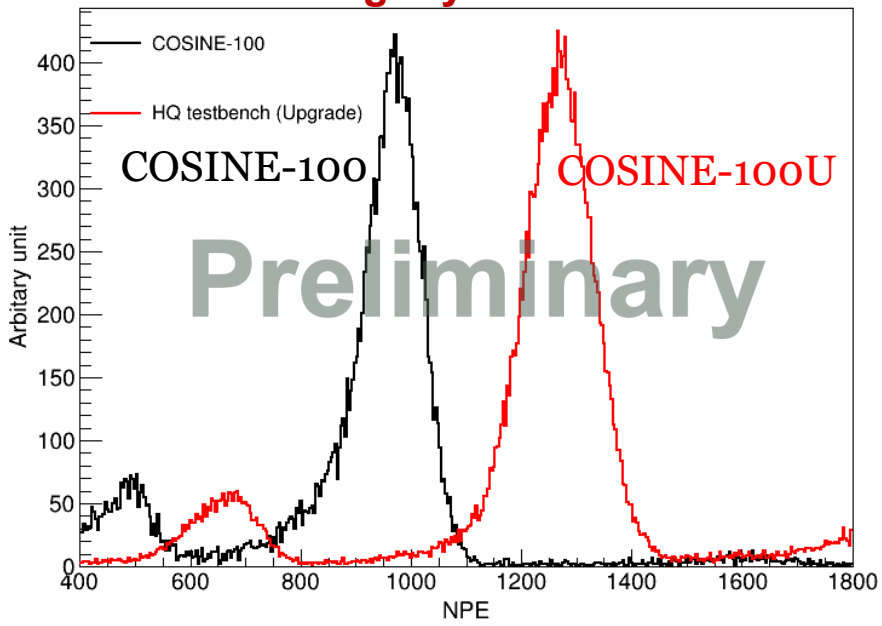
arXiv:2404.03691

COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

^{241}Am 59.54 keV

~40% light yield increase!!!

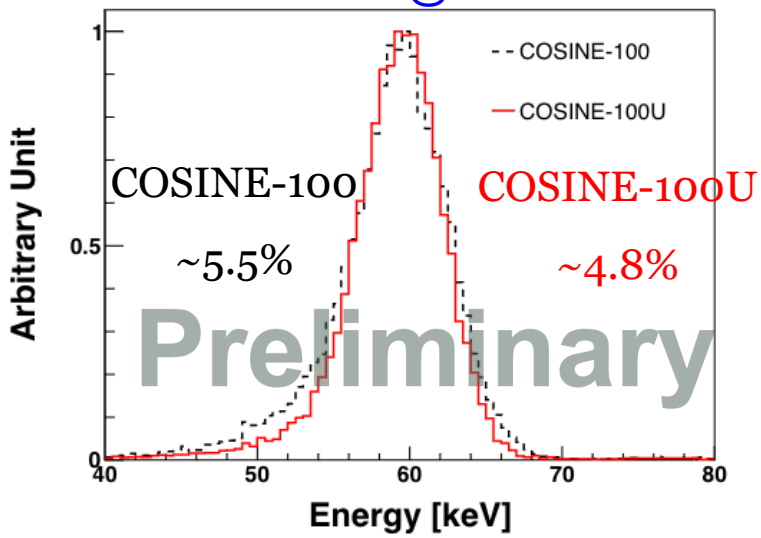


NPE = Number of photoelectrons

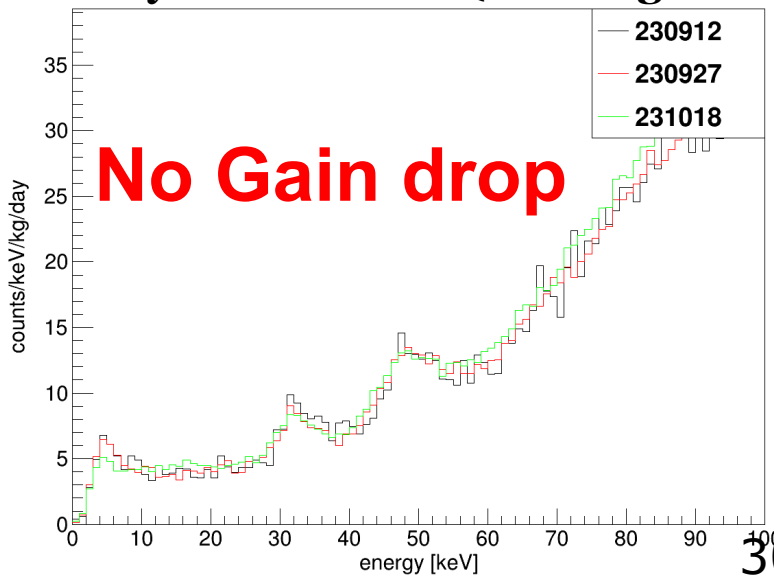
14.9 ± 1.5 ⟶ **21.5 ± 0.6 NPE/keV**

COSINE-100 C2 COSINE-100U C2

RMS resolution @ 59.54 keV for C3

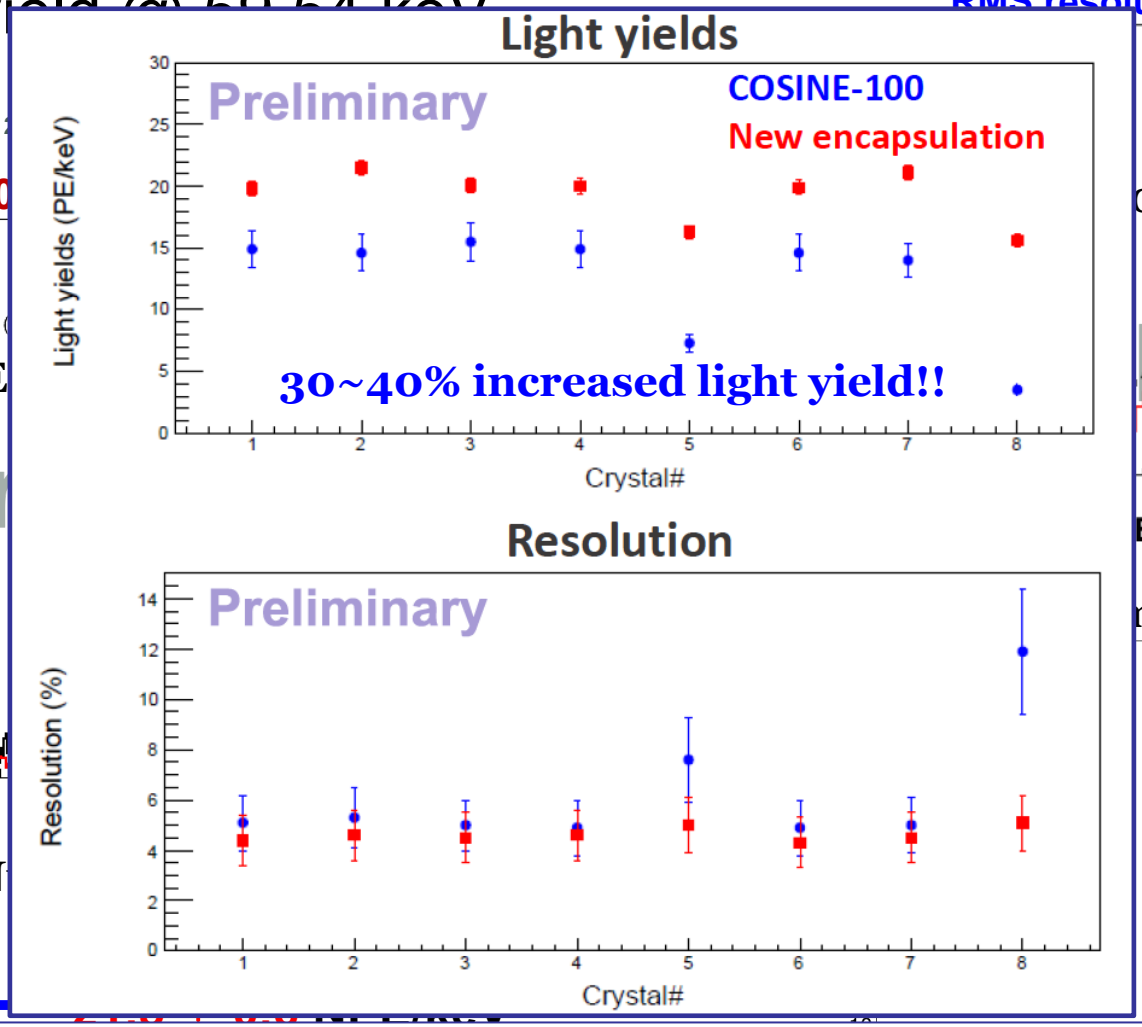


Stability of ~ 1 month (Above-ground)

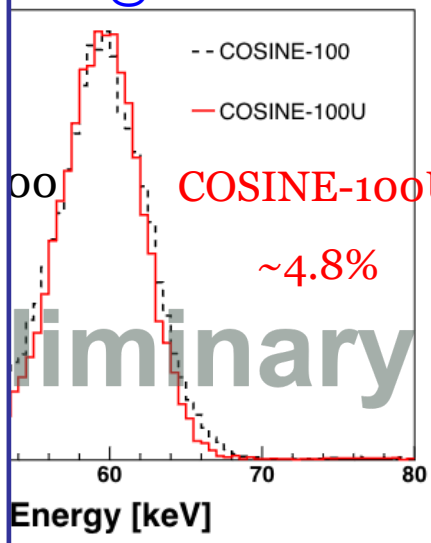


COSINE-100U : Detector upgrade

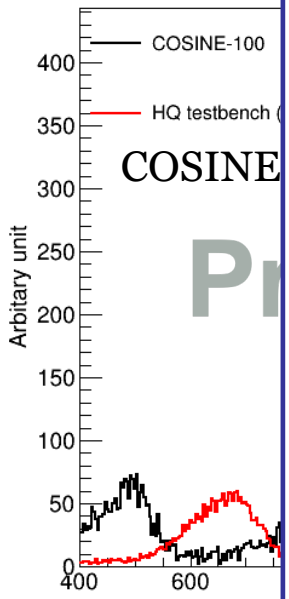
- Light yield @ 59.54 keV



RMS resolution @ 59.54 keV for C3



~40



COSINE

Pr

NPE = N

nonth (Above-ground)

n drop

14.9 ± 1.5

COSINE-10

All crystals were assembled!!

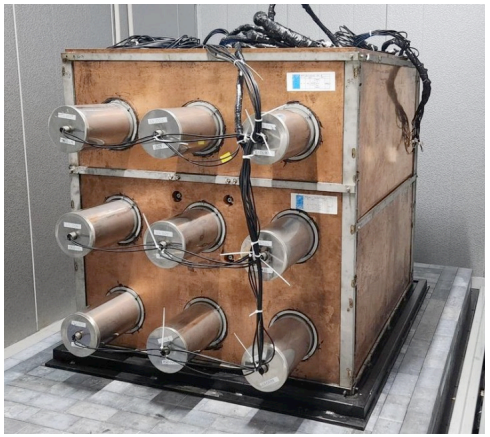
Installation at Yemilab is ongoing

COSINE-100U : Yemilab installation

Freeze room for -30°C operation

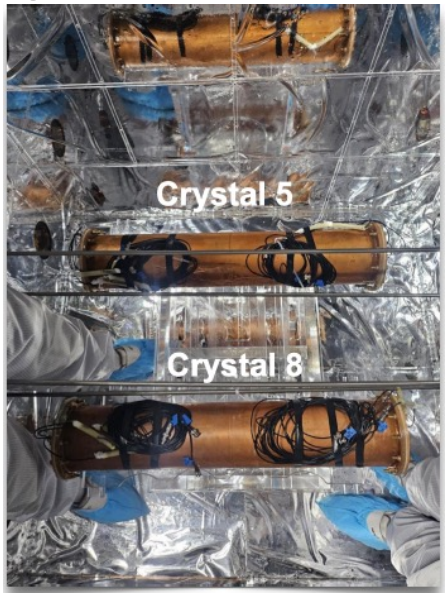
Astropart. Phys. 141, 102709 (2022)

Liquid scintillator veto

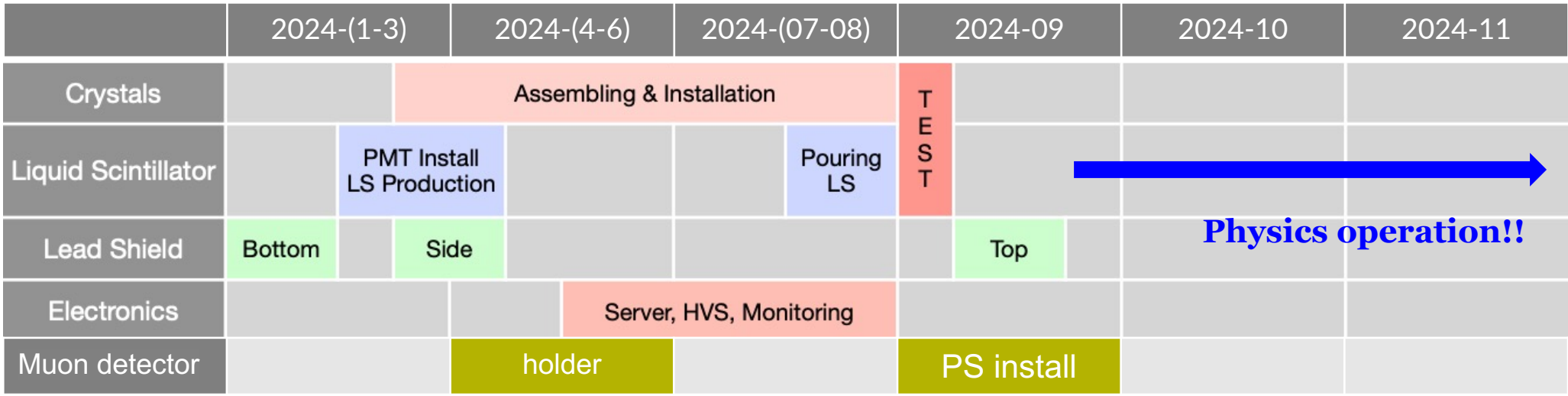


Lead shield

Crystal installation

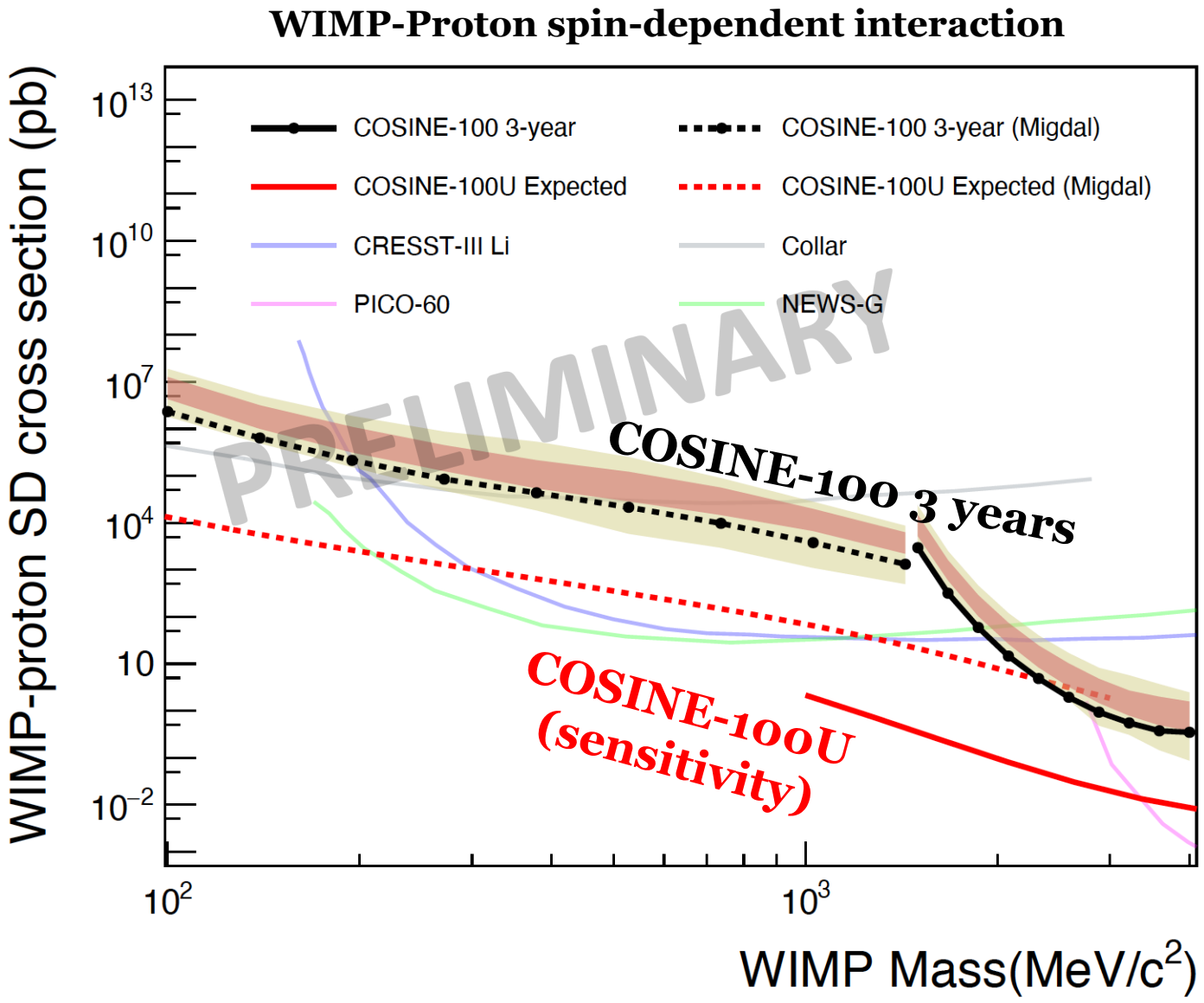


COSINE-100U schedule



- All crystals were encapsulated already
- We plan to start COSINE-100U in September/2024

Sensitivity of COSINE-100U



COSINE-200 crystal development

Powder purification performance

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

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

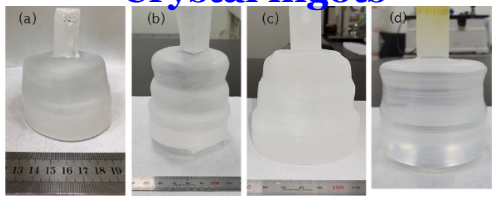
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

	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

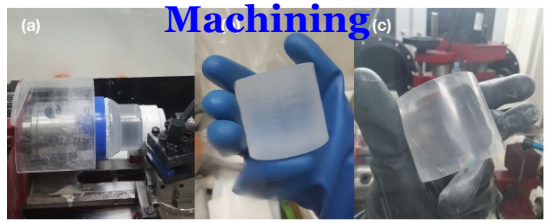
We produced ~ 400 kg low-background NaI powder

(Maximum production rate ~ 100 kg/month)

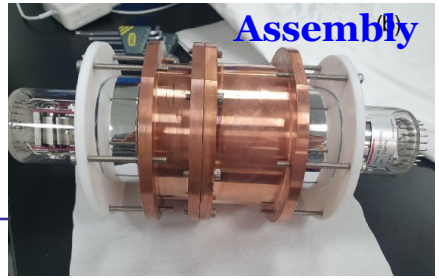
Crystal ingots

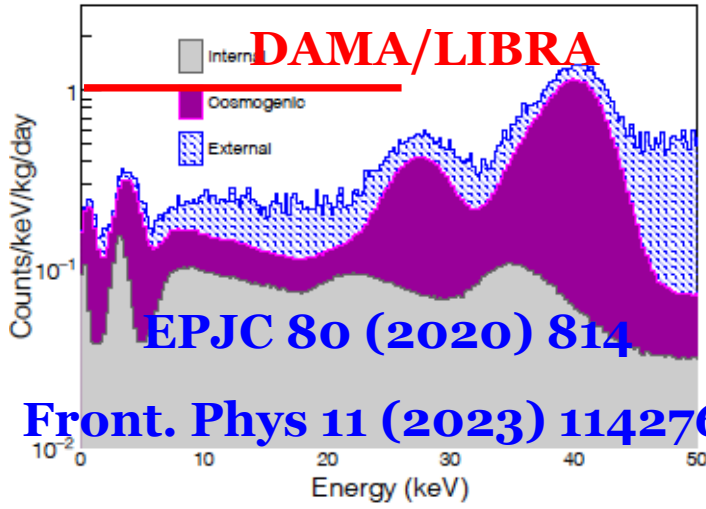


Machining



Assembly





A proof of principle for low background NaI

Large crystal growing is going on

Summary

- COSINE-100 ruled out DAMA/LIBRA with significance above 3 sigma in model-independent analysis

- COSINE-100 searched various dark matter candidates in wide energy ranges

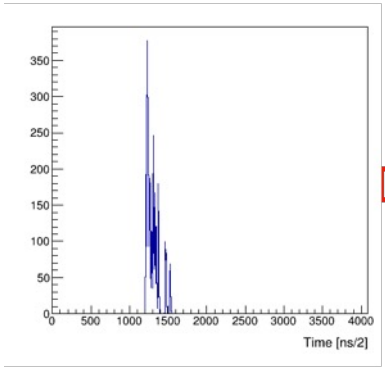
- COSINE-100U will have world competitive sensitivities for low-mass dark matter searches

Backup

Ongoing works : Event selection update

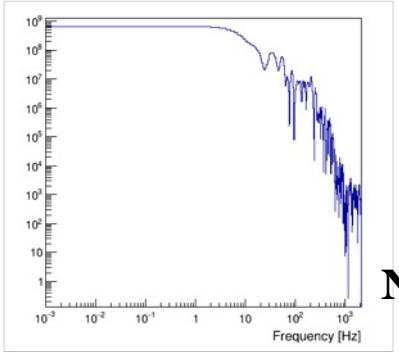
- Multivariable machine learning training

New parameter development example



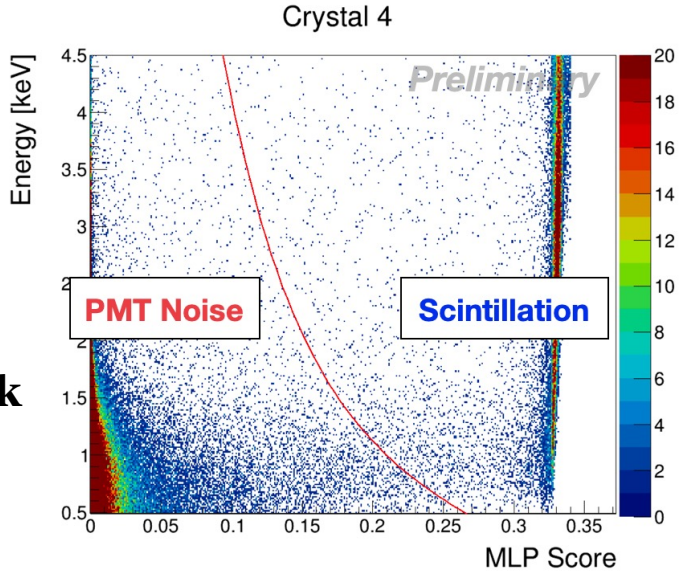
Waveform example of COSINE-100 data

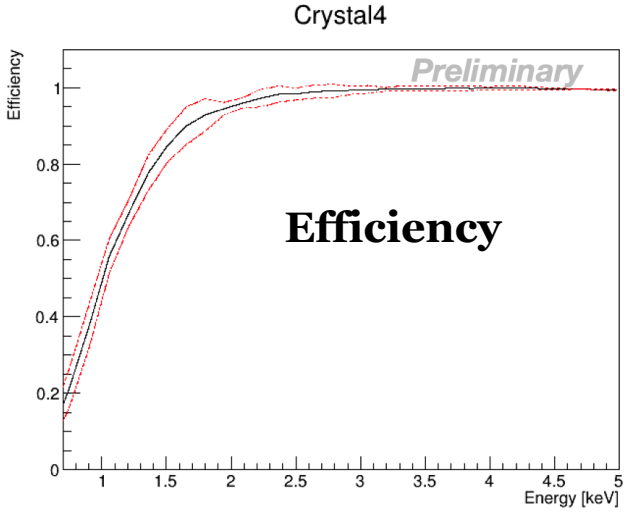
FFT

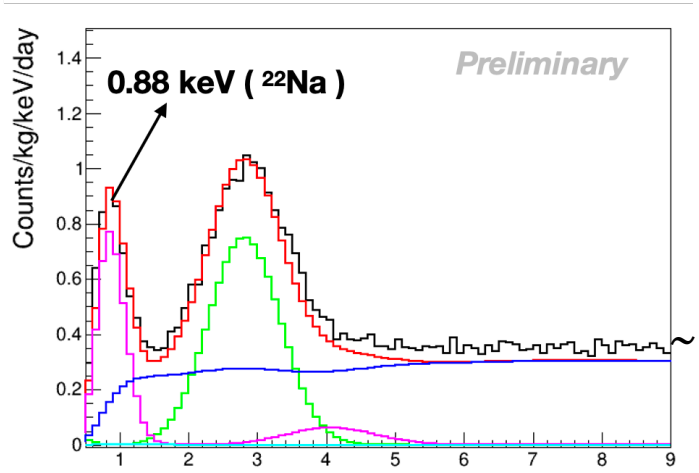


Fourier transformed waveform

Neutral network training







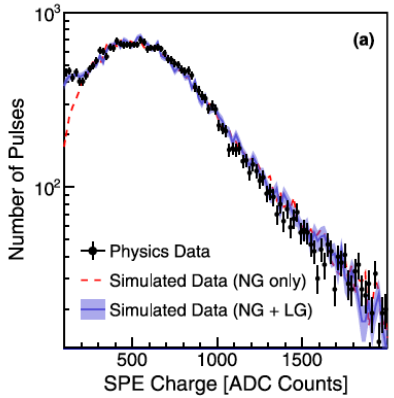
8 NPE threshold

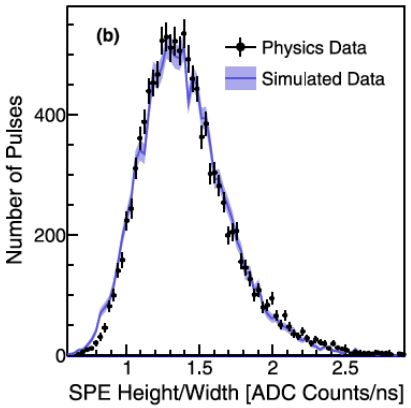
NPE (number of photoelectrons)

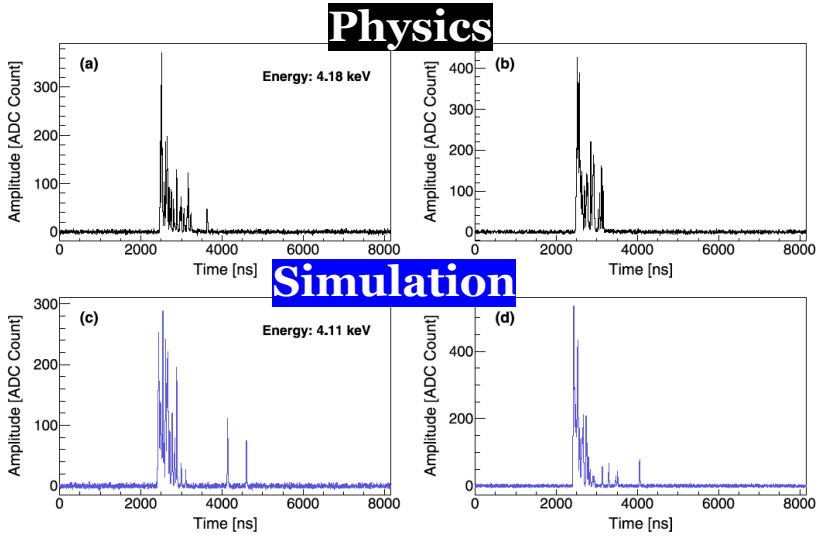
~ 15 NPE/keV light yield @ 59.54 keV

Ongoing works : Waveform simulation

Single photoelectron tuning







Scintillation waveform is generated with simulation

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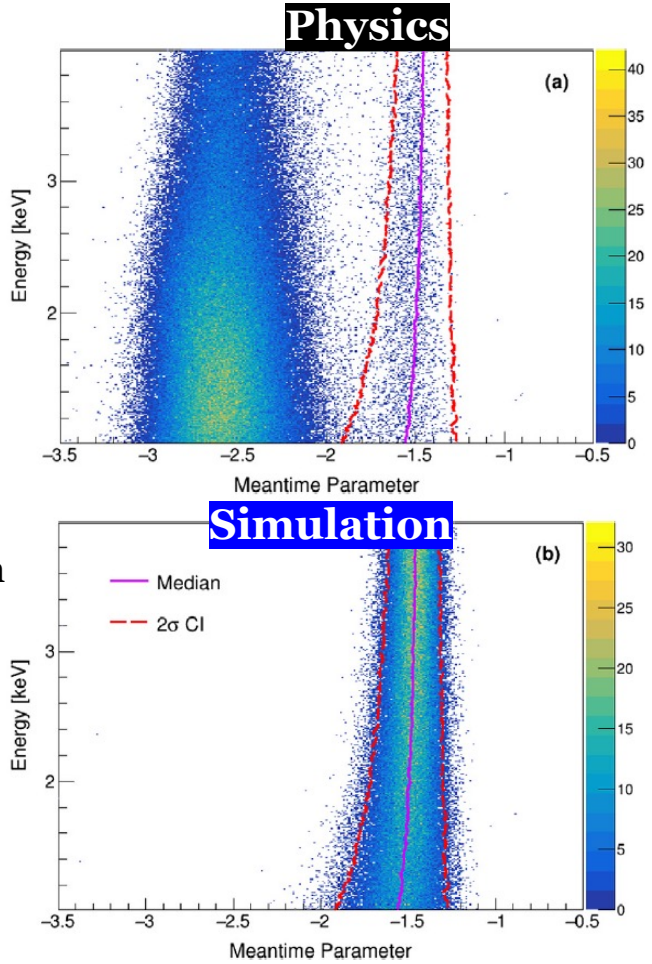
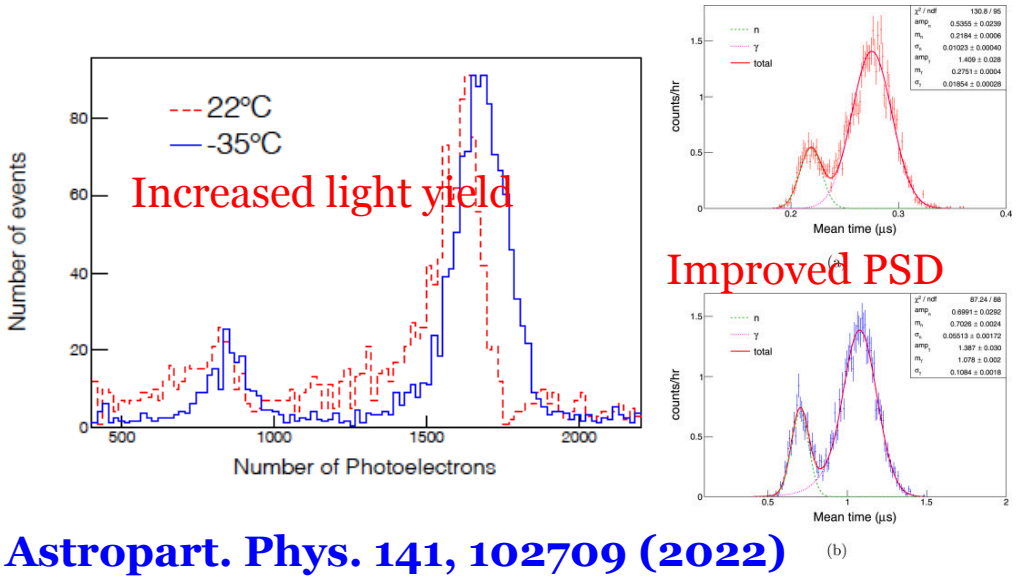


- **Waveform simulation** is developed to **describe** low-energy events (**sub-keV**)
- Simulation describe the data reasonably well
- Currently, the waveform simulation cross checked the trigger/selection efficiencies
- The waveform simulation will be used as signal sample of the multivariable analysis

COSINE-100U @ Yemilab

-35°C operation



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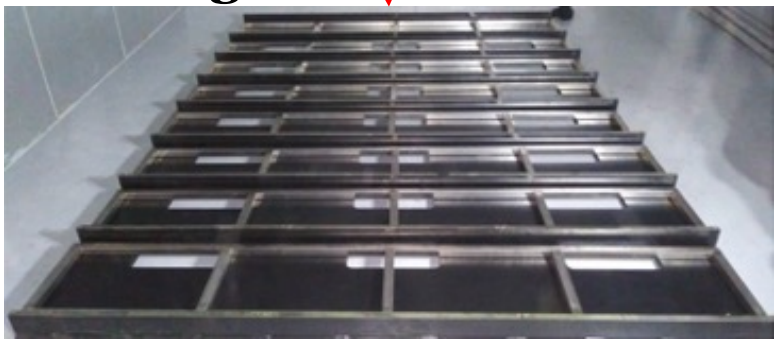
- 5% gamma light yield increase
- 10% alpha quenching increase
  - ❖ Will measure nuclear recoil quenching
- Pulse shape discrimination is significantly improved

Warehouse freezer at Yemilab

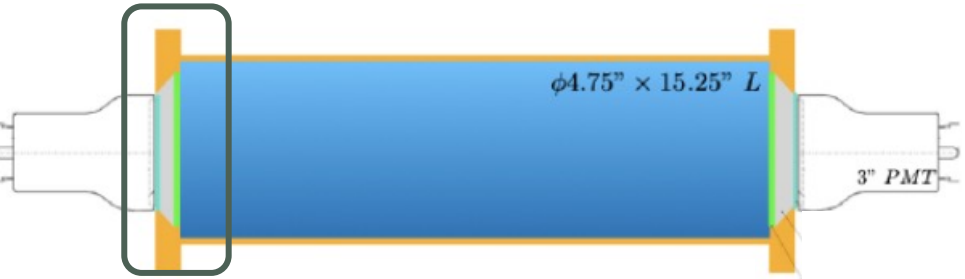
Shielding base for muon detector

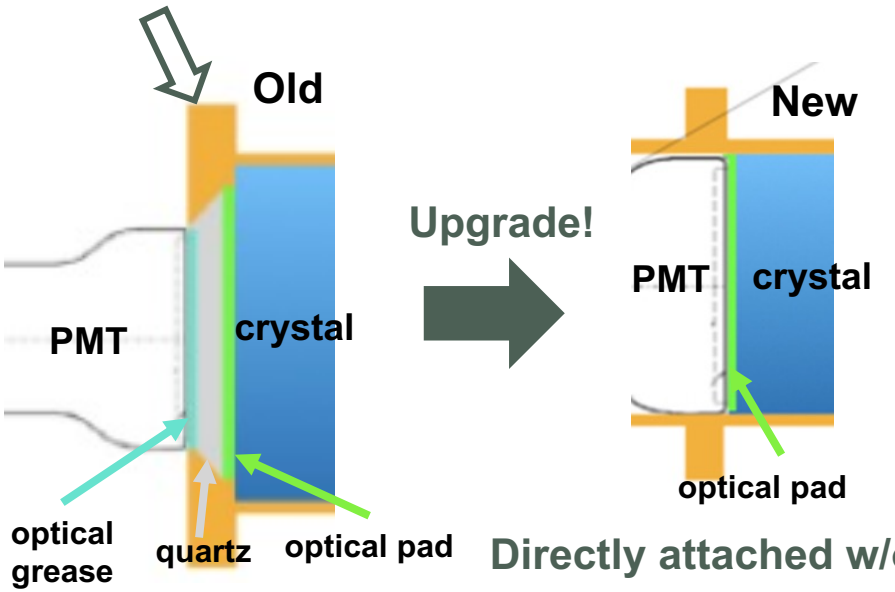


To start COSINE-100U at Yemilab September/2024

COSINE-100 Upgrade : New encapsulation

COSINE -100





Directly attached w/o quartz!

We achieved ~ 50% increased light yield

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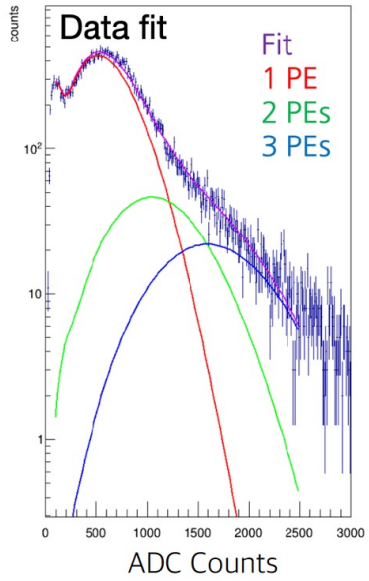

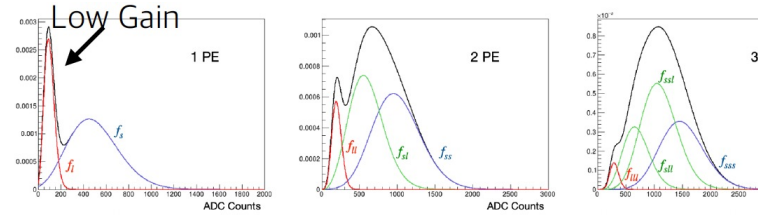

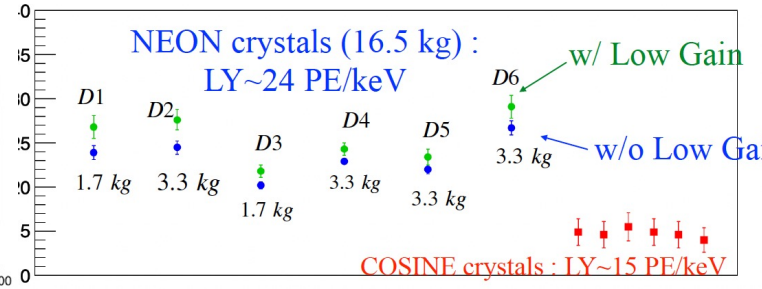

High light yield (24 NPE/keV) and long-term stability has been proved by NEON experiment

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