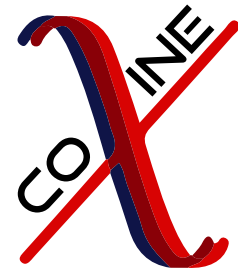


The COSINE dark matter search experiment

Current status and future prospects



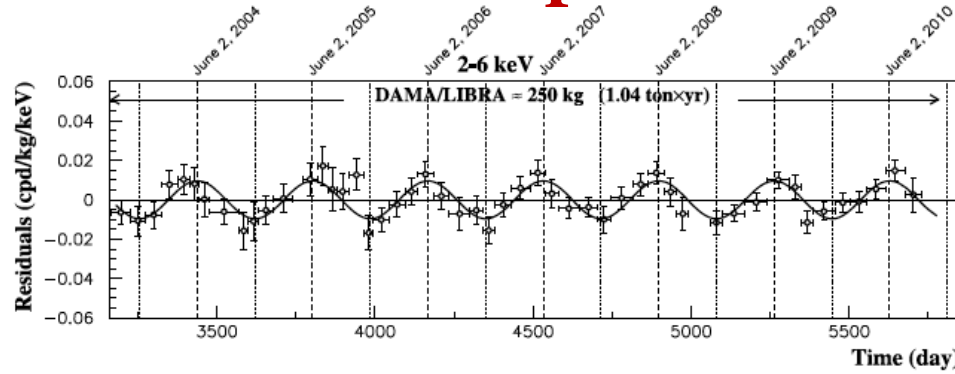
Hyunsu Lee
Institute for Basic Science
Center for Underground Physics



DBD23 @ Hawaii, December 1 2023

Annual modulation signal from DAMA/LIBRA

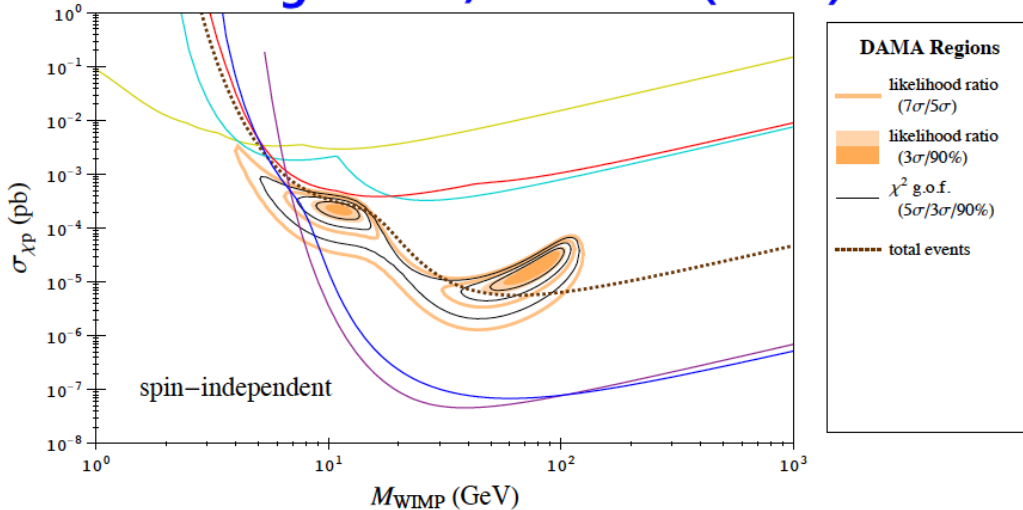
Phase1 experiment



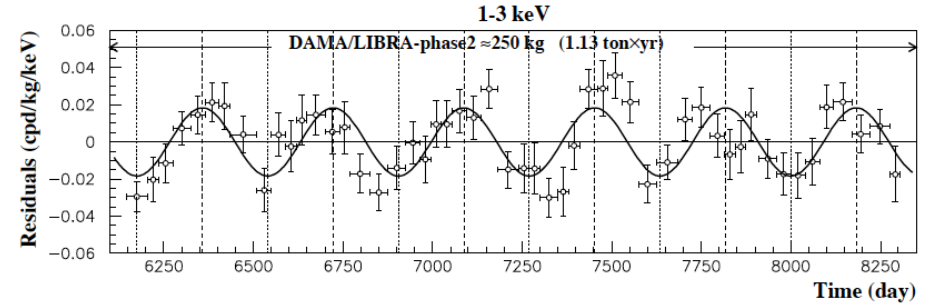
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

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

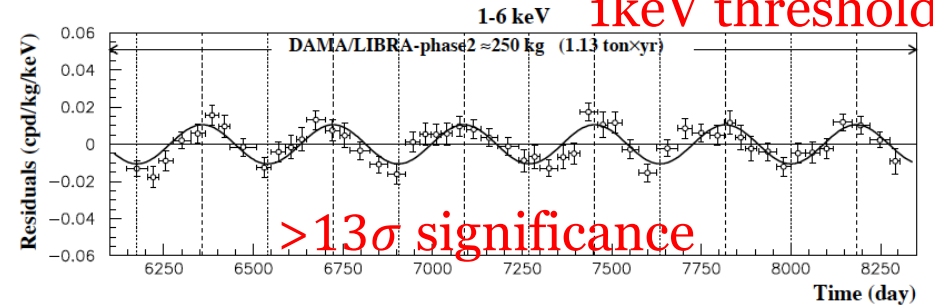


Phase2 experiment



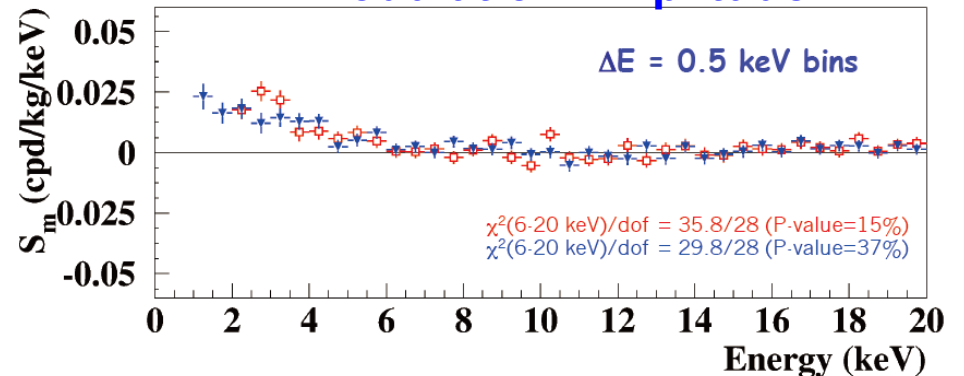
Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold



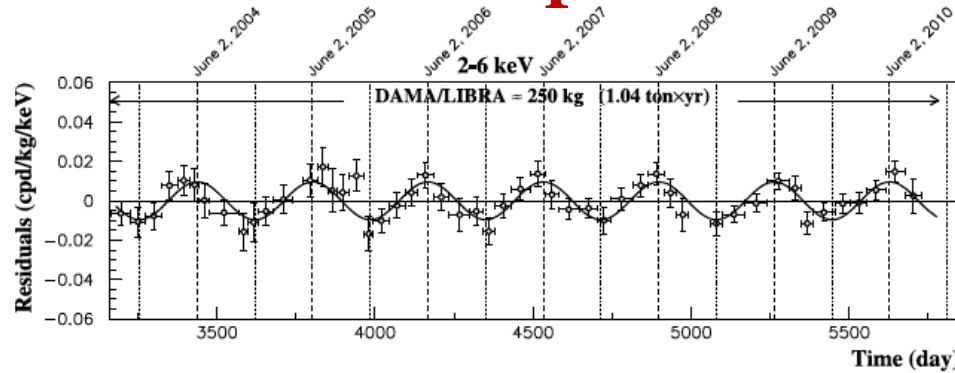
>13 σ significance

Modulation Amplitude



Annual modulation signal from DAMA/LIBRA

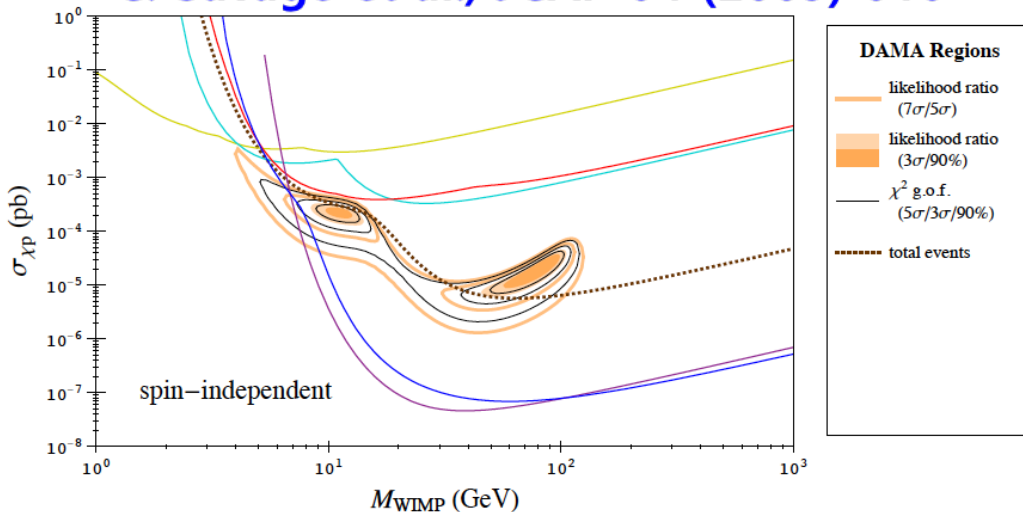
Phase1 experiment



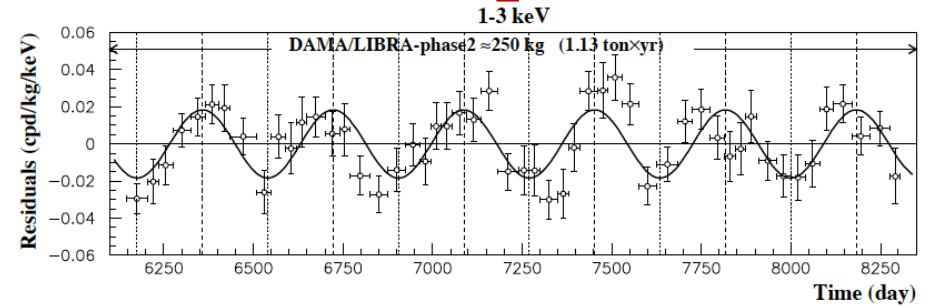
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

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

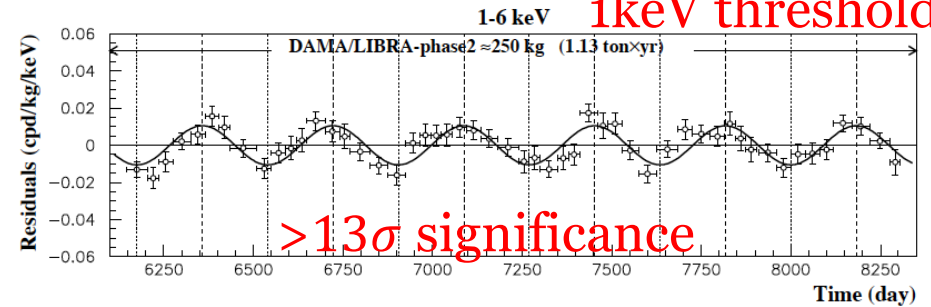


Phase2 experiment



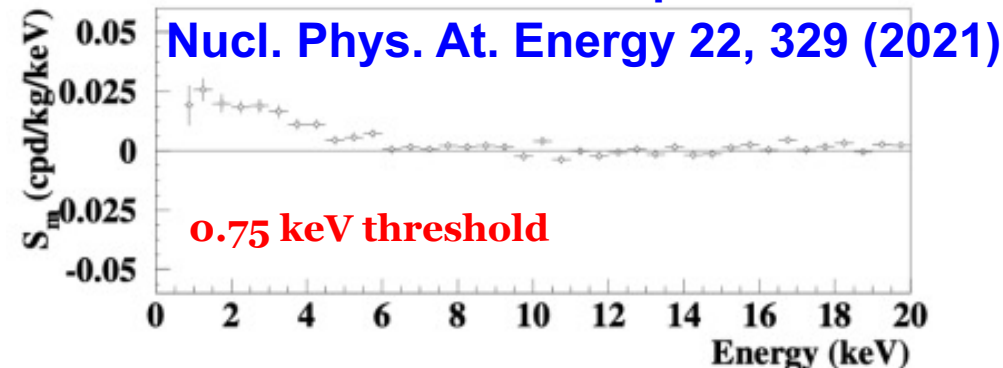
Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold



>13 σ significance

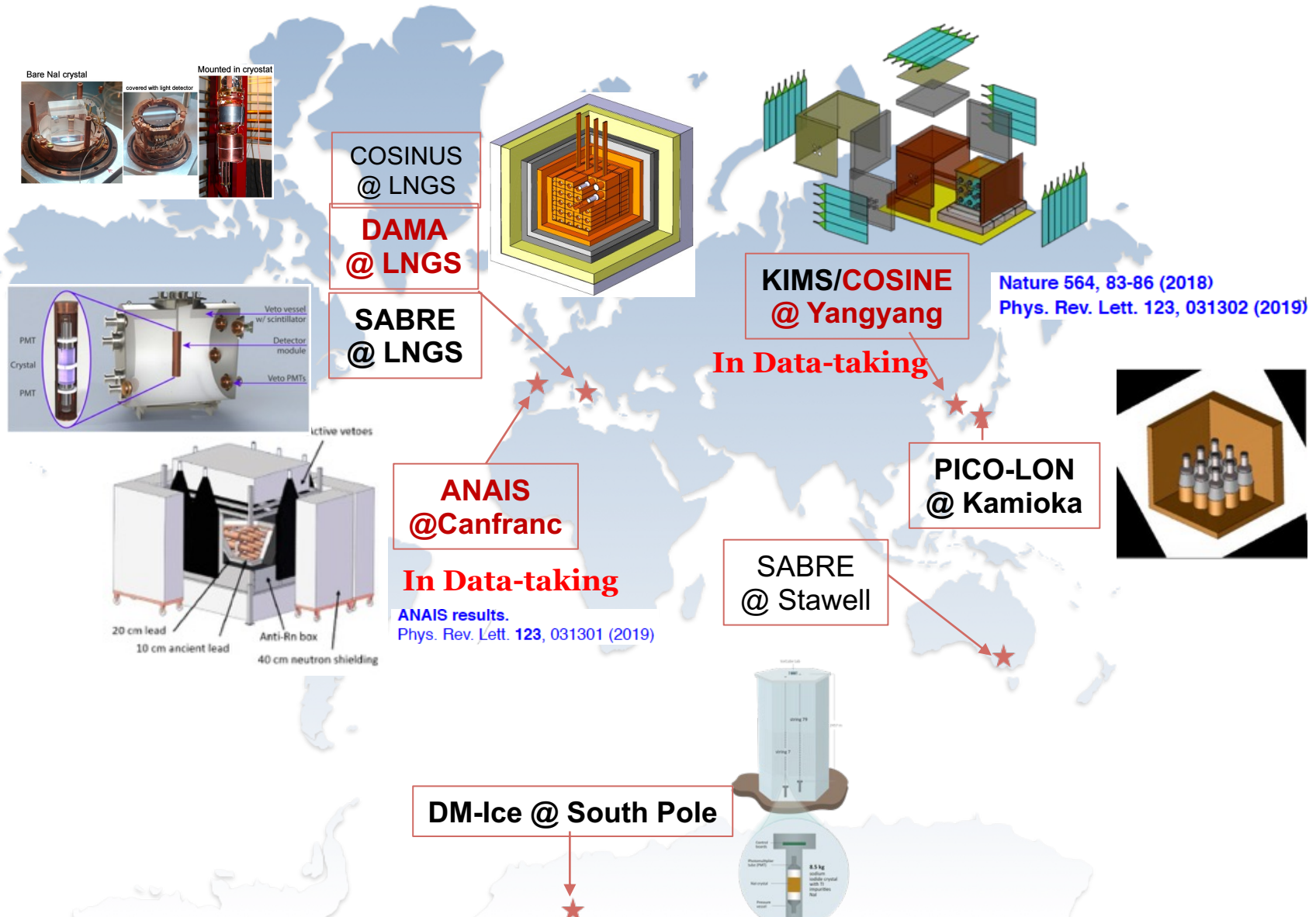
Modulation Amplitude



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

0.75 keV threshold

Global NaI(Tl) efforts



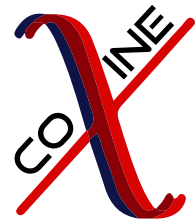
COSINE collaboration



15 institutes
~60 members



+ DM-ICE =



Hyun Su Lee,

Center for Underground Physics (CUP),

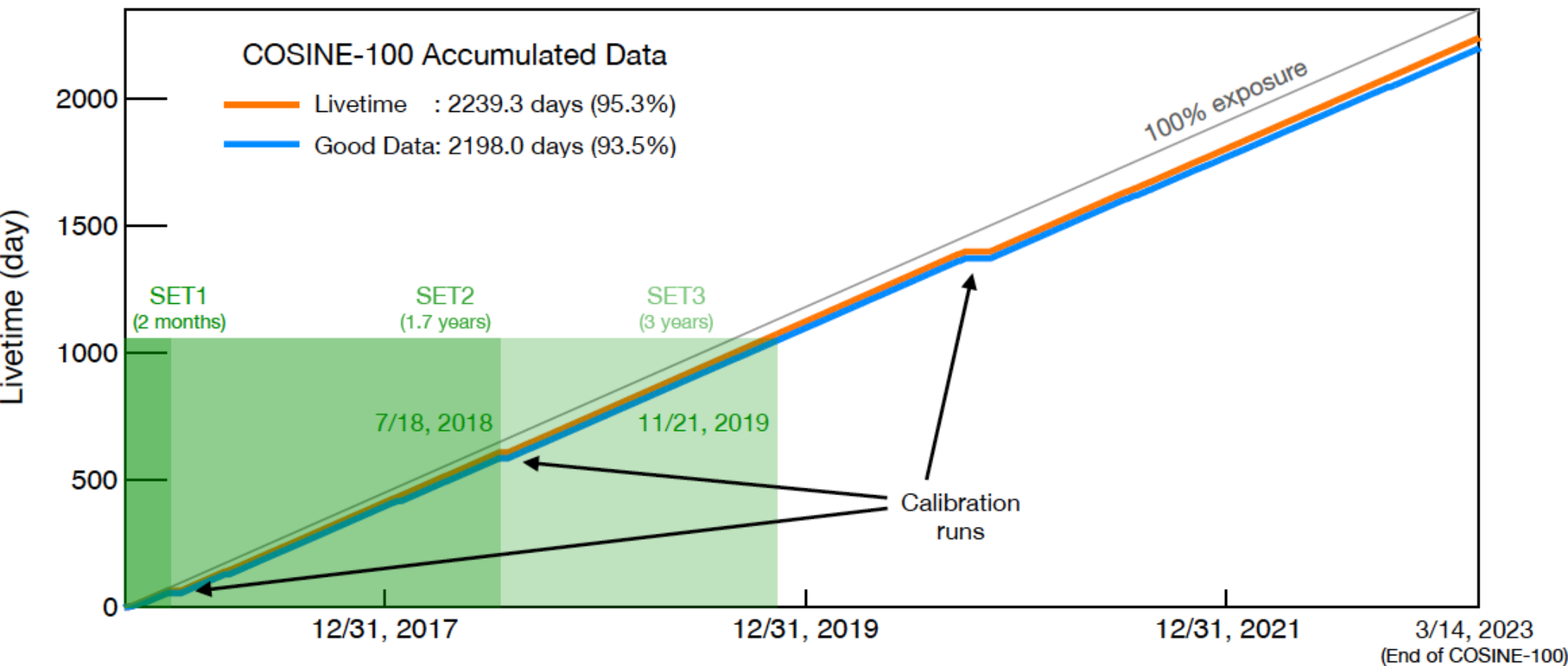
Institute for Basic Science (IBS)

COSINE-100 experiment (2016~2023)



- YangYang underground laboratory (Y2L)
- **Started** physics operation since **September/2016**
- **Ended** physics run **March/2023**
- Decommissioning for upgrade and moving to **Yemilab**
 - ❖ Plan to **restart COSINE-100 upgrade** by **early 2024** at Yemilab

COSINE-100 data exposure

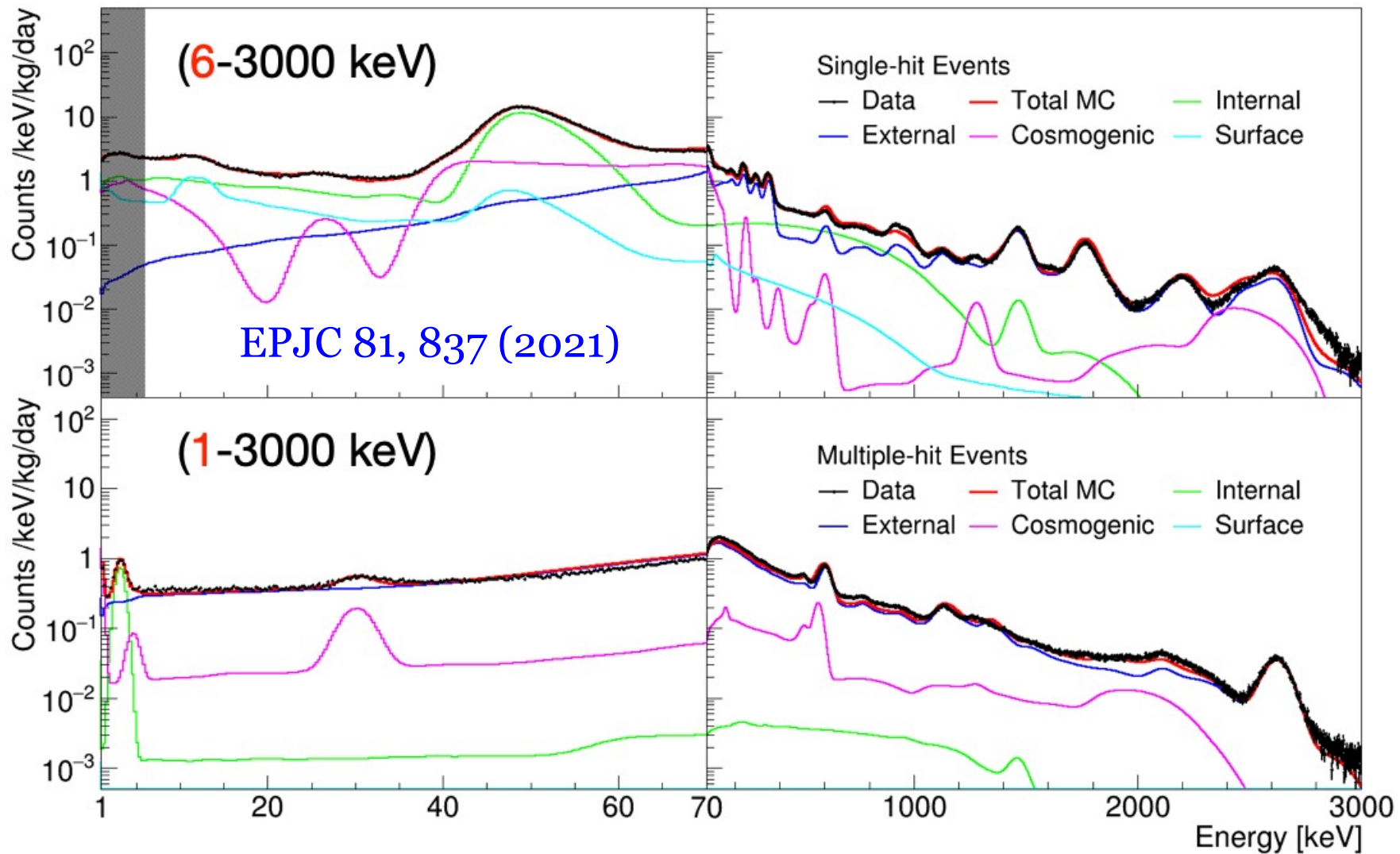


- **Stable operation Since Sep. 2016 for about 6.4 years**
 - ~95 % physics data
 - ~94 % good quality data (6.0 years data)

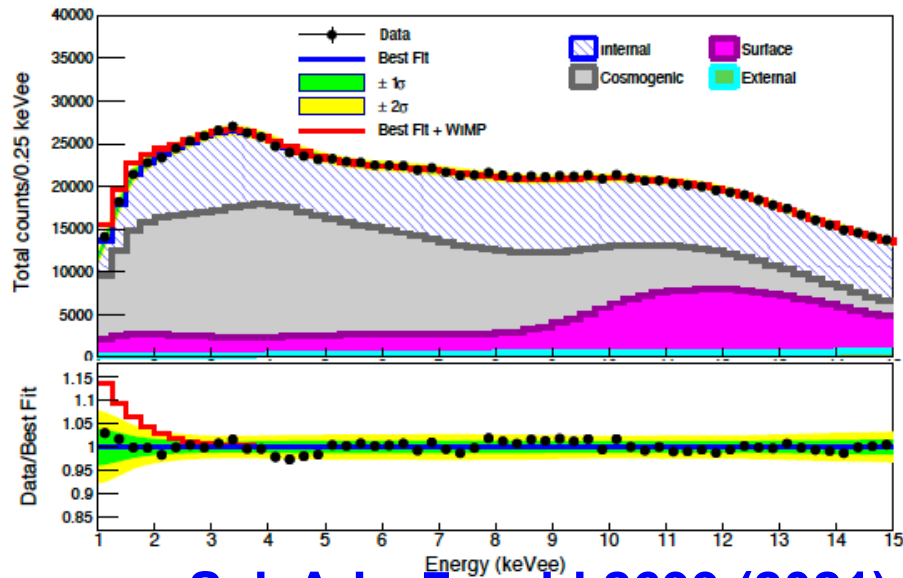
Detector background understanding

Background modeling

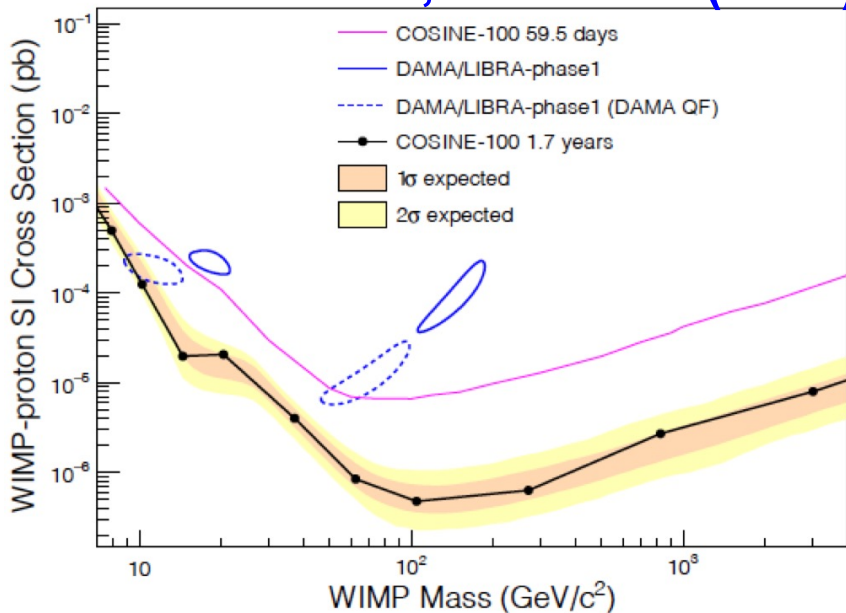
1.7 years data



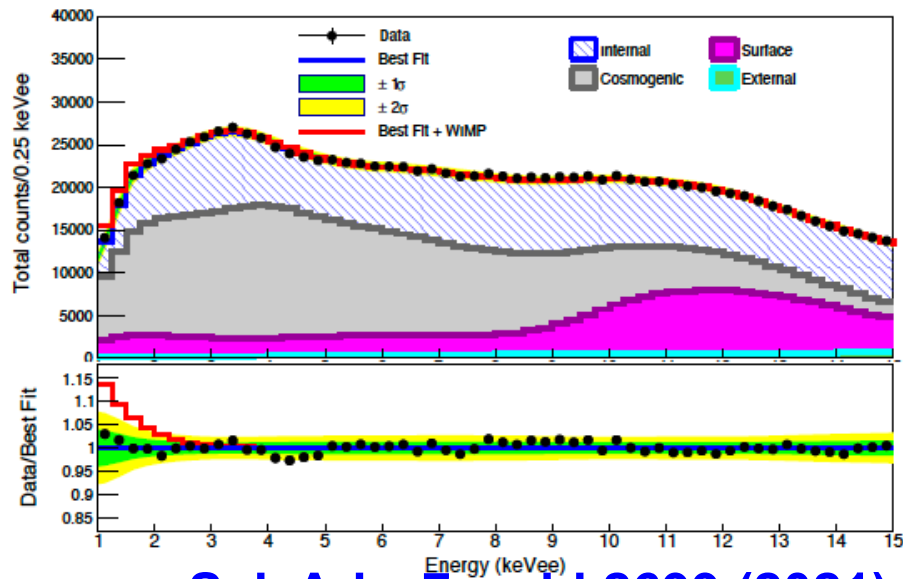
Dark matter search with spectral shape fit



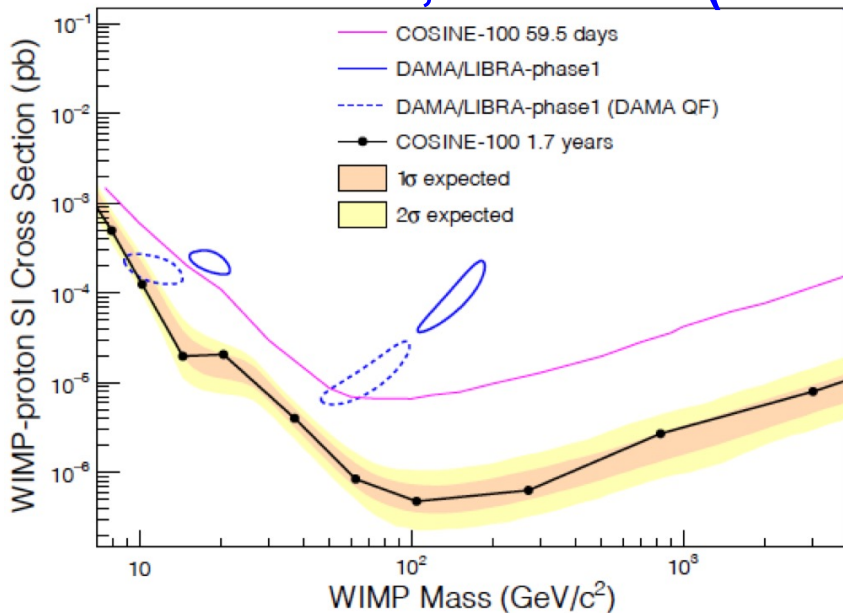
Sci. Adv. 7, eabk2699 (2021)



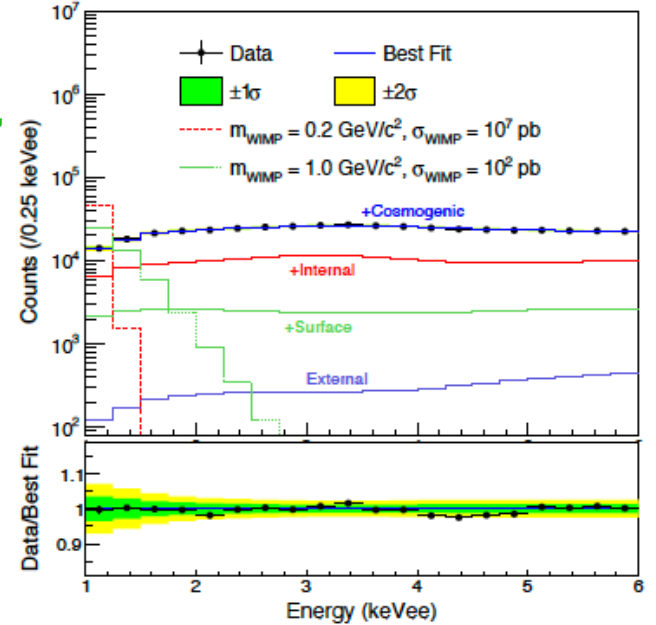
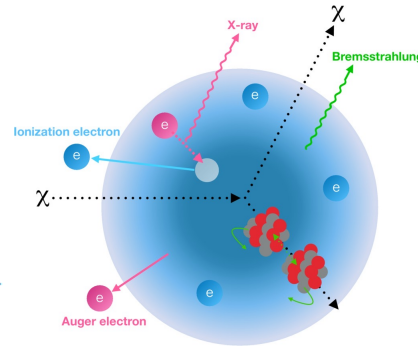
Dark matter search with spectral shape fit



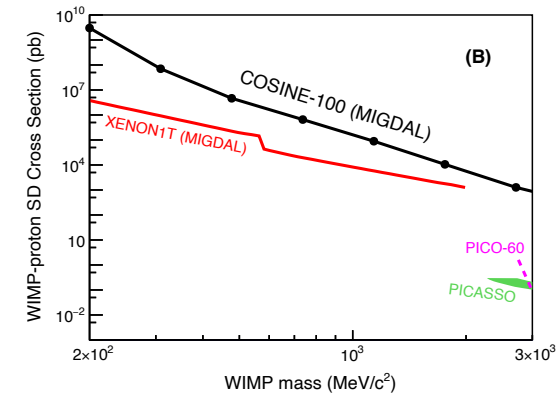
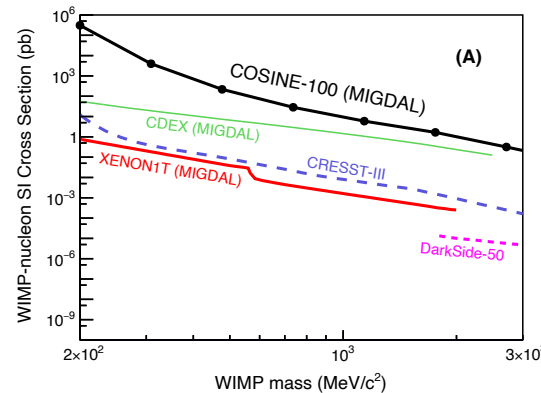
Sci. Adv. 7, eabk2699 (2021)



Migdal effect

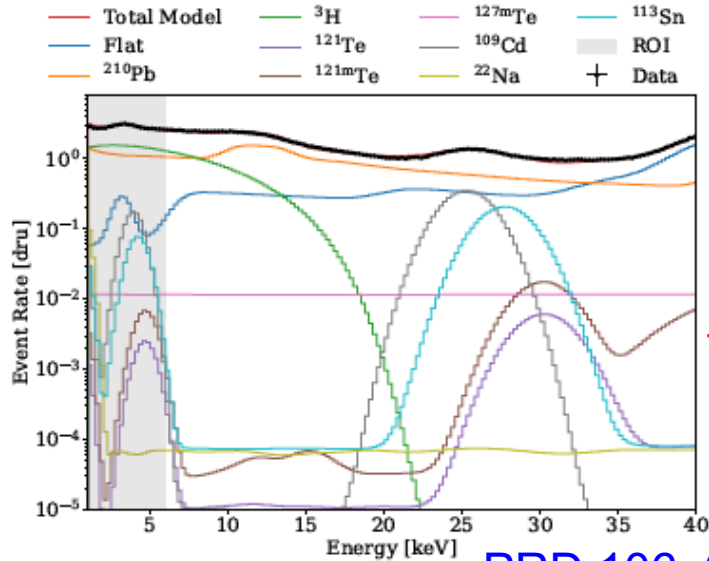


PRD 105, 042006 (2022)



Model-independent annual modulation search

Time dependent background modeling



PRD 106, 052005 (2022)

Component	Half life	Average activity (dru)
Total		$(2.74 \pm 0.23) \times 10^0$
^3H	12.3 year	$(1.41 \pm 0.18) \times 10^0$
^{210}Pb	22.3 year	$(1.12 \pm 0.15) \times 10^0$
Flat		$(1.35 \pm 0.08) \times 10^{-1}$
^{109}Cd	461.4 days	$(4.13 \pm 0.39) \times 10^{-2}$
^{113}Sn	115.1 days	$(1.55 \pm 0.16) \times 10^{-2}$
^{127}Te	109 day	$(6.59 \pm 0.52) \times 10^{-3}$
^{22}Na	2.6 year	$(5.88 \pm 1.34) \times 10^{-3}$
^{121m}Te	154 day	$(1.50 \pm 0.16) \times 10^{-3}$
^{121}Te	16.8 day	$(5.07 \pm 1.23) \times 10^{-4}$

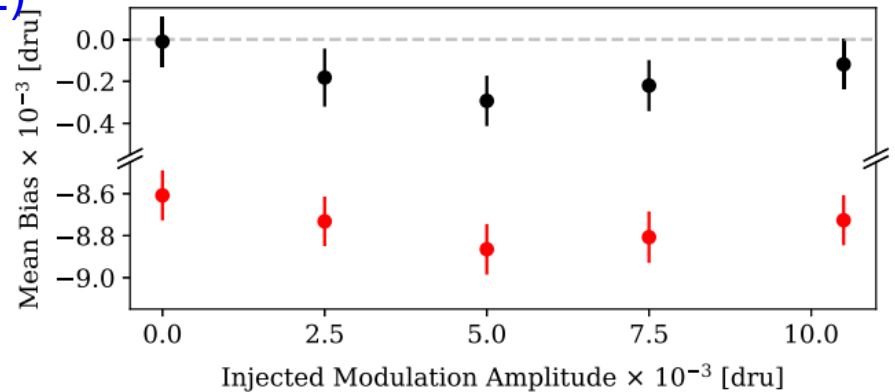
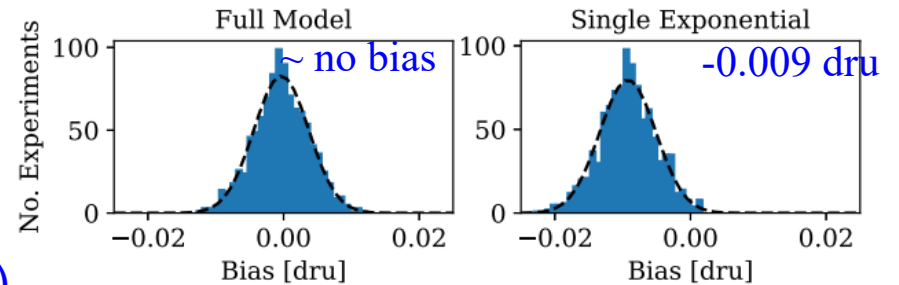
Single exponential

$$R(t) = P_0 + P_1 e^{-t/P_2} + S \cos\left(\frac{2\pi(t - t_0)}{T}\right)$$

Full model (8 exponential)

$$R(t) = P_0 + \sum_{i=1}^8 P_i e^{-t/\tau_i} + S \cos\left(\frac{2\pi(t - t_0)}{T}\right)$$

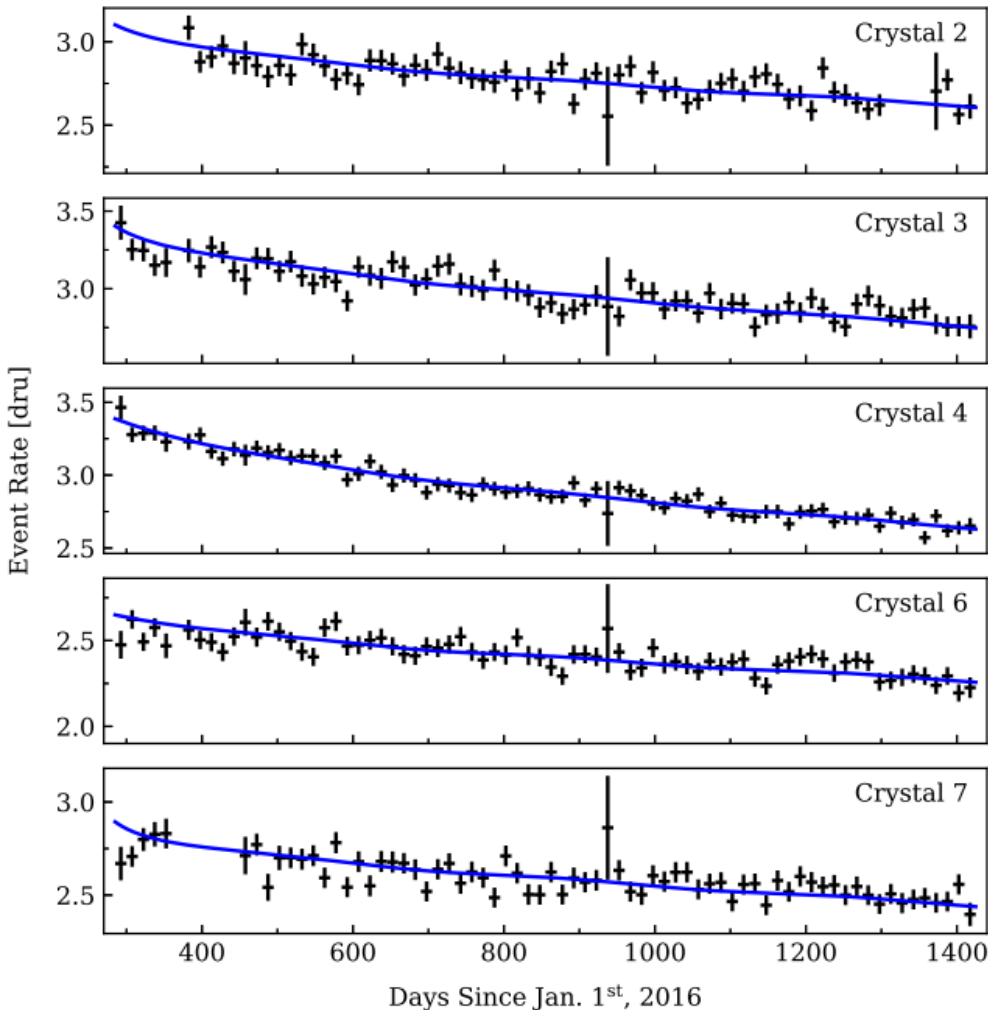
Bias test (1-6 keV)



Understanding time-dependent background is crucial for the annual modulation search

Model-independent annual modulation search

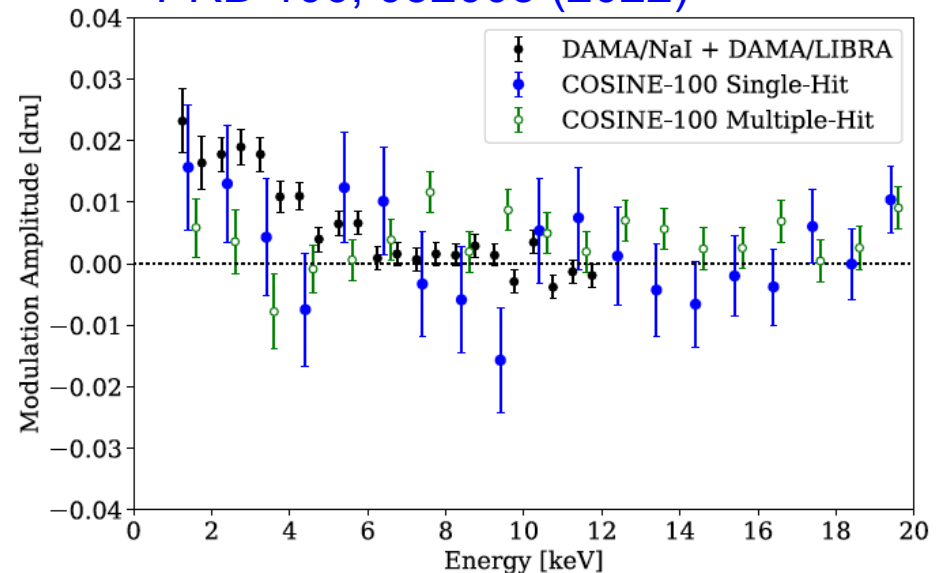
Data Fit (1-6 keV)



1-6 keV modulation amplitude

COSINE-100	0.0067 ± 0.0042
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

PRD 106, 052005 (2022)

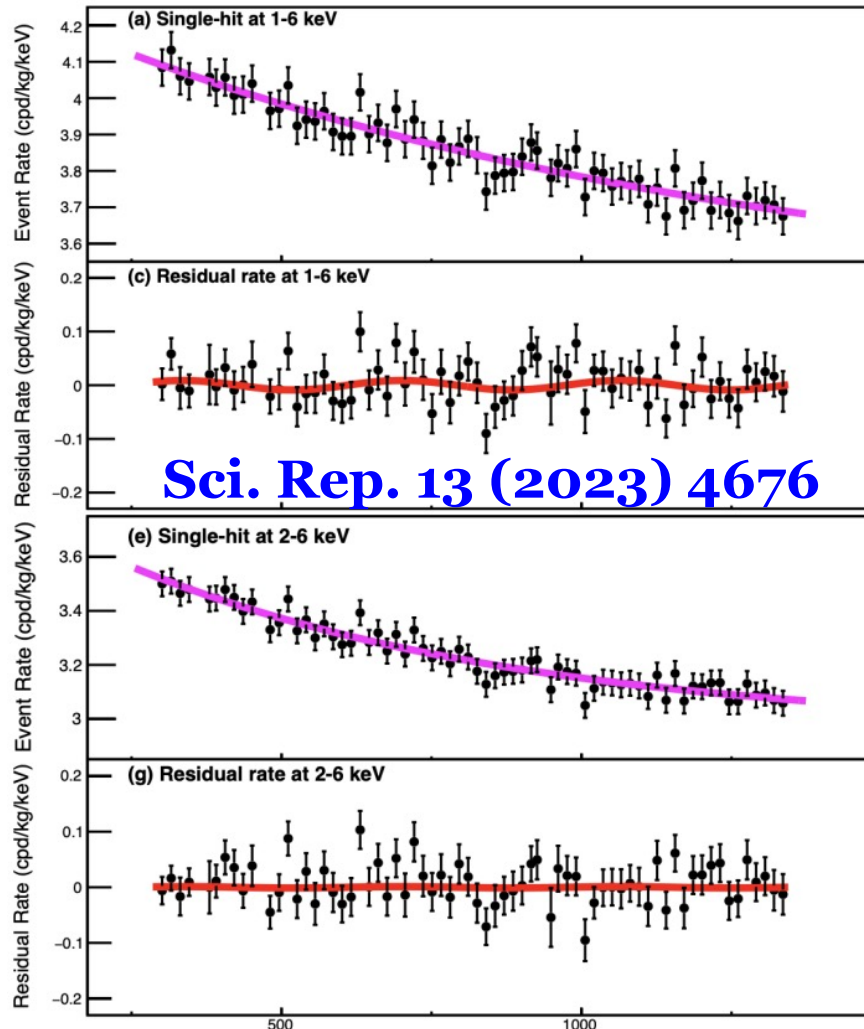


We need more data and/or better quality detector

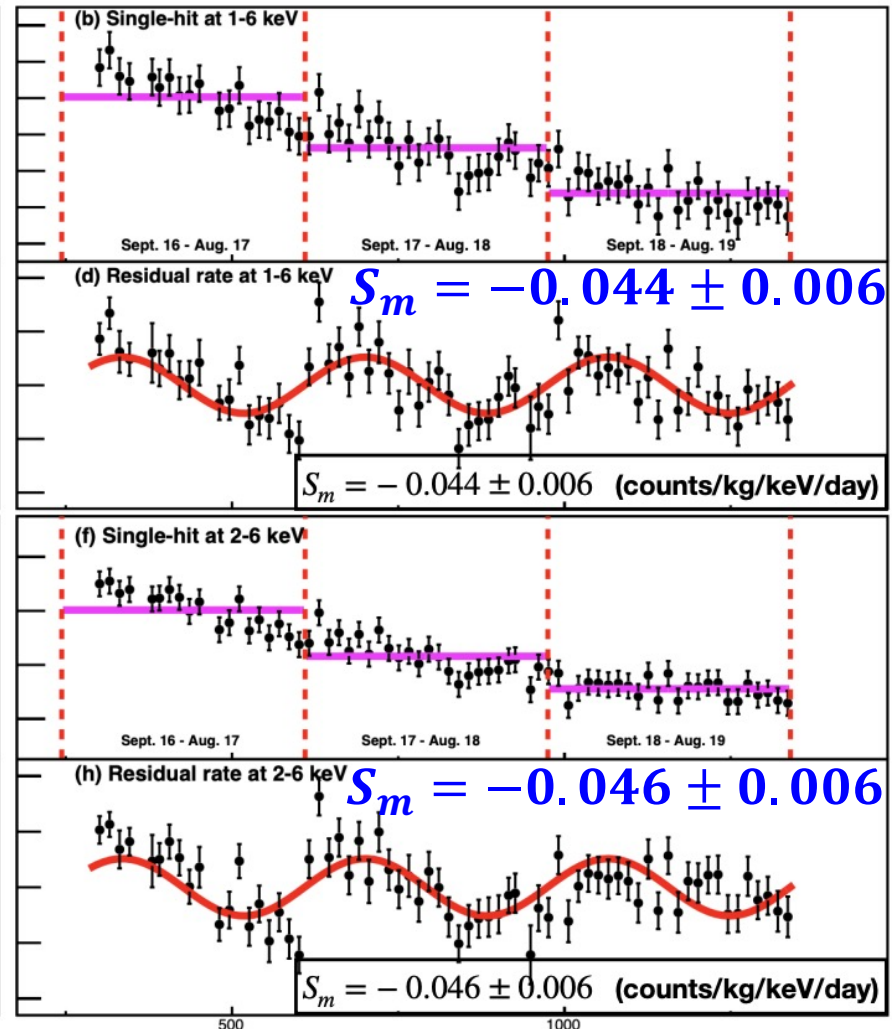
- Full data (~2.5 times larger dataset) open soon
- COSINE-200

DAMA/LIBRA's method (induced modulation)

Single exponential model (reference)

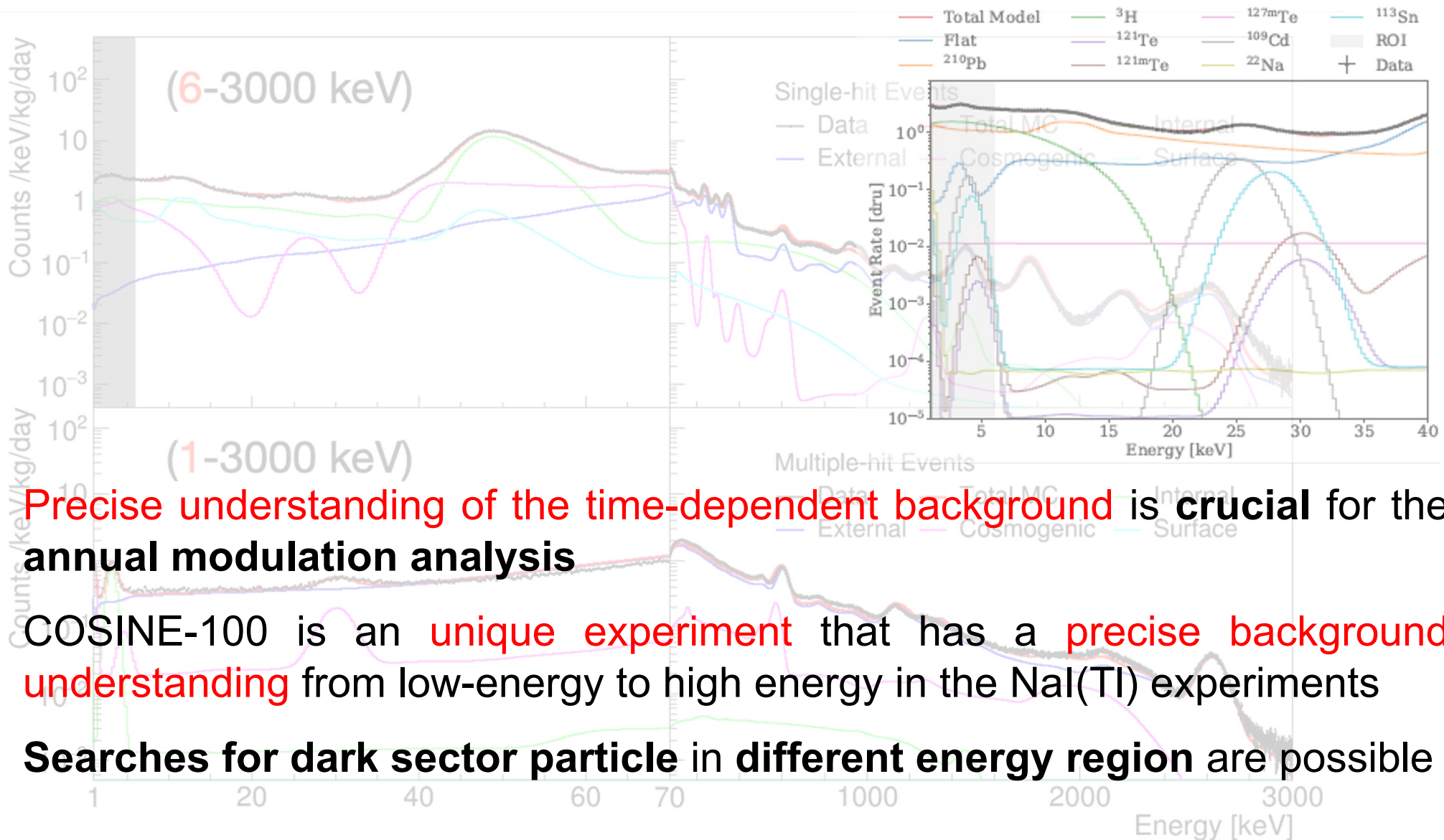


DAMA/LIBRA's method



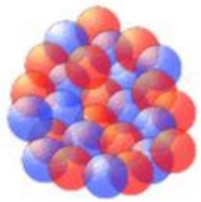
Very strong ($\sim 7\sigma$) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

Importance of background understanding

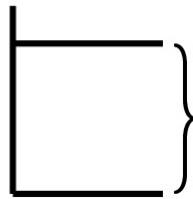


- Precise understanding of the time-dependent background is crucial for the annual modulation analysis
- COSINE-100 is an unique experiment that has a precise background understanding from low-energy to high energy in the NaI(Tl) experiments
- Searches for dark sector particle in different energy region are possible

WIMP- ^{127}I inelastic interaction

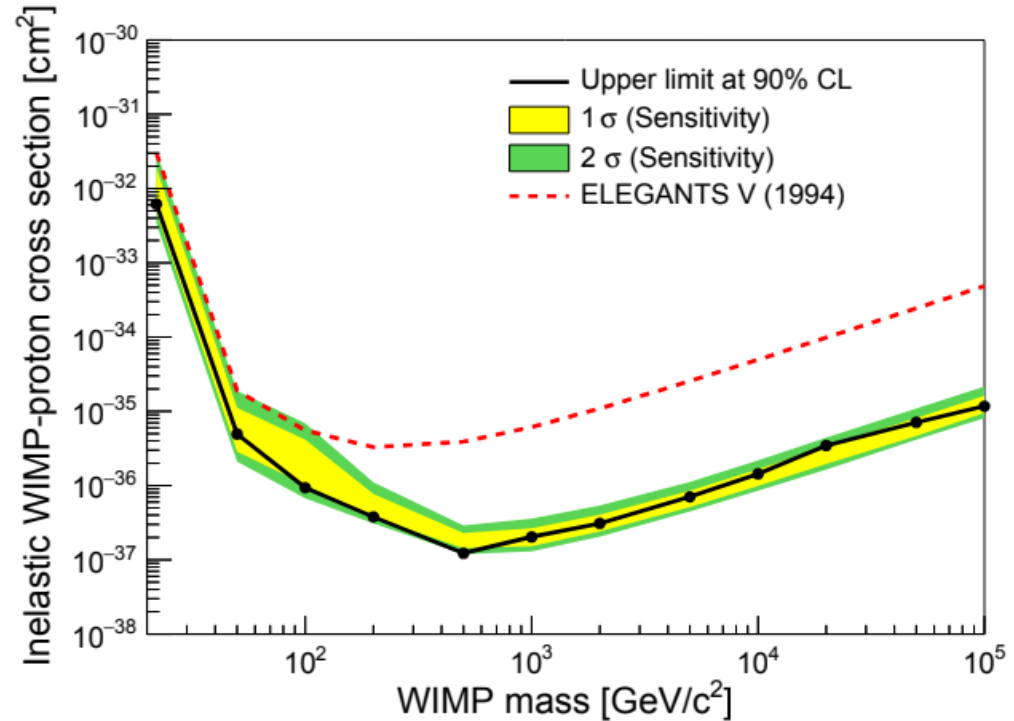
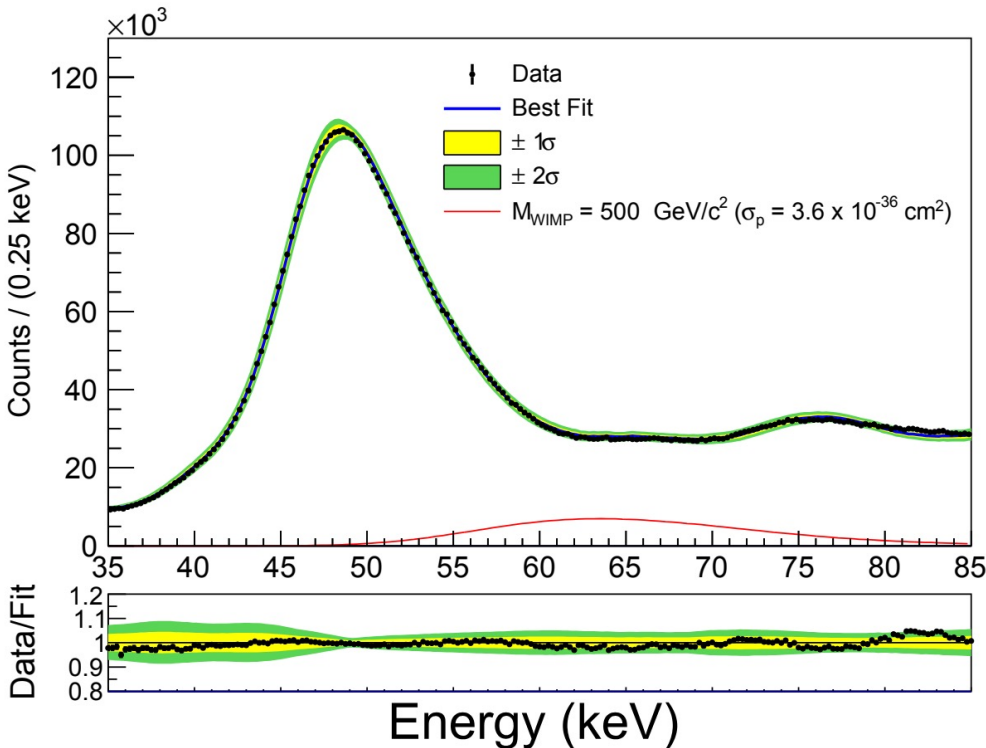


^{127}I



57.6 keV

- Signal : 57.6 keV gamma + nuclear recoil
- 1.7 years data
- Search for energy 35 keV – 85 keV

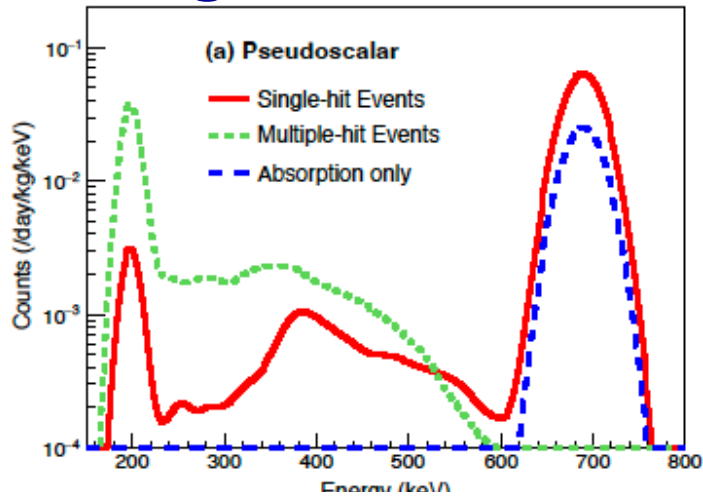


Phys. Rev. D 108, 092006 (2023)

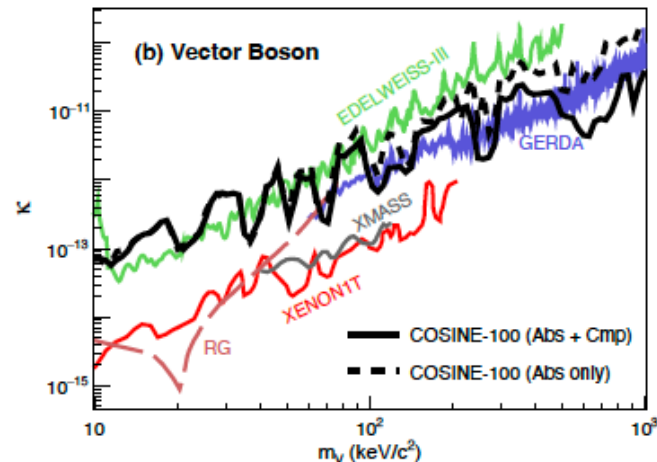
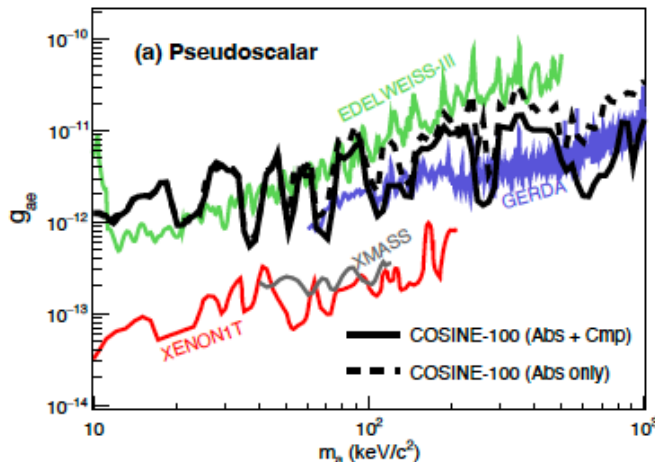
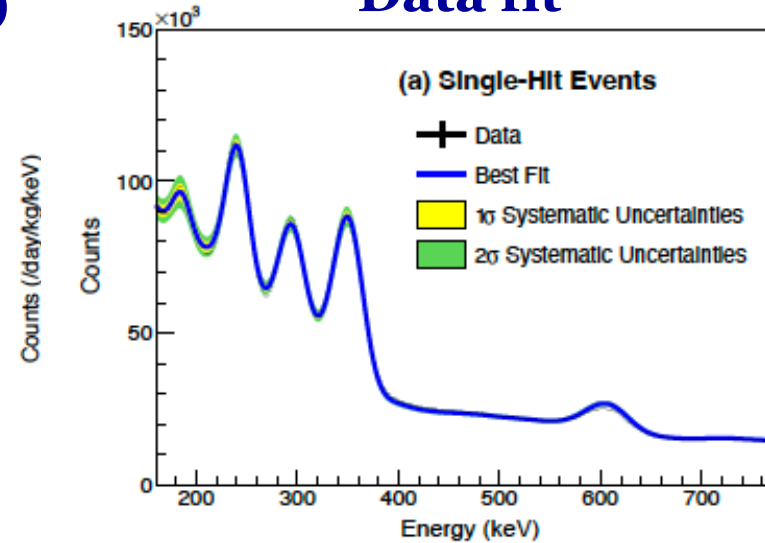
Bosonic super-WIMP (BSW)

- Bosonic dark matter with mass $10 \text{ keV} - 1 \text{ MeV}$

Expected Signal (690 keV BSW)

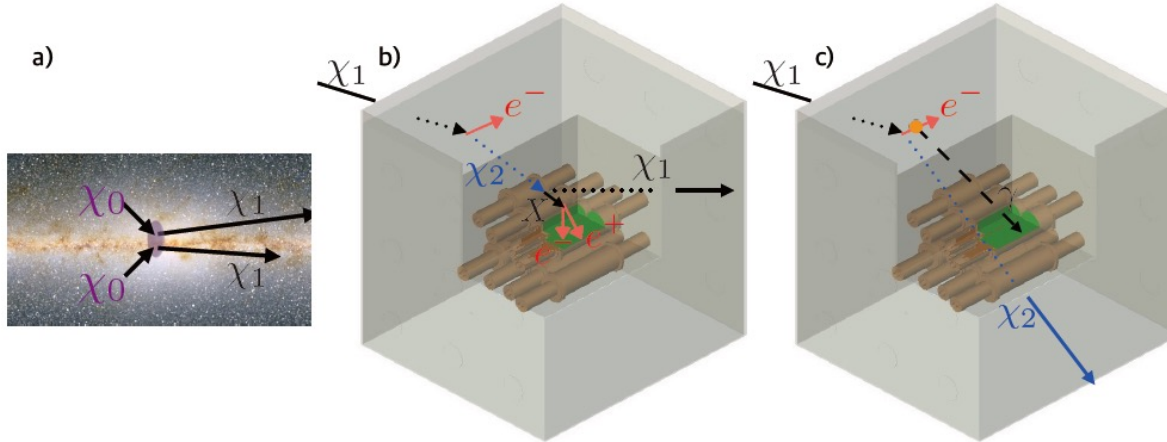


Data fit

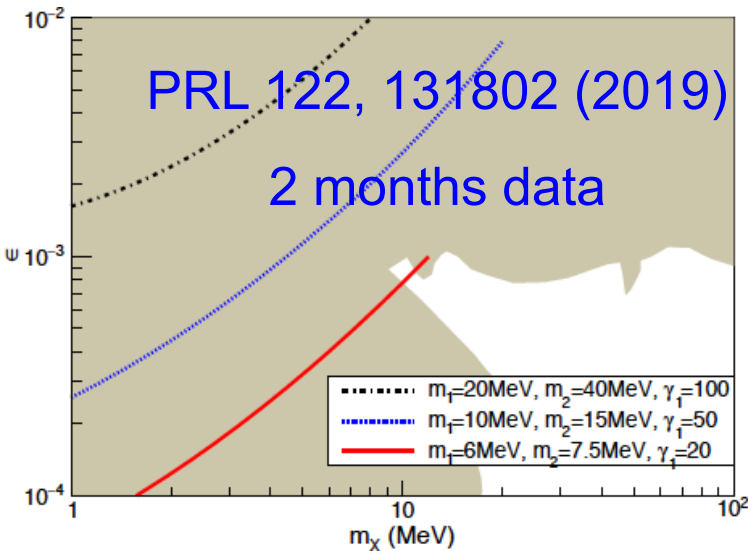


Phys. Rev. D 108,L041301 (2023)

Boosted dark matter with extended energy (~ 10 MeV)

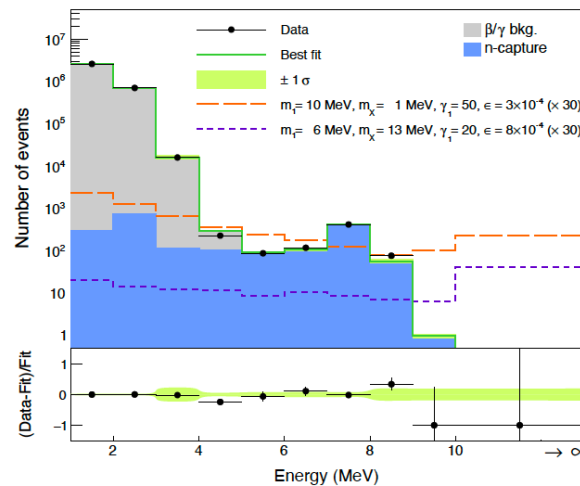


Inelastic interaction

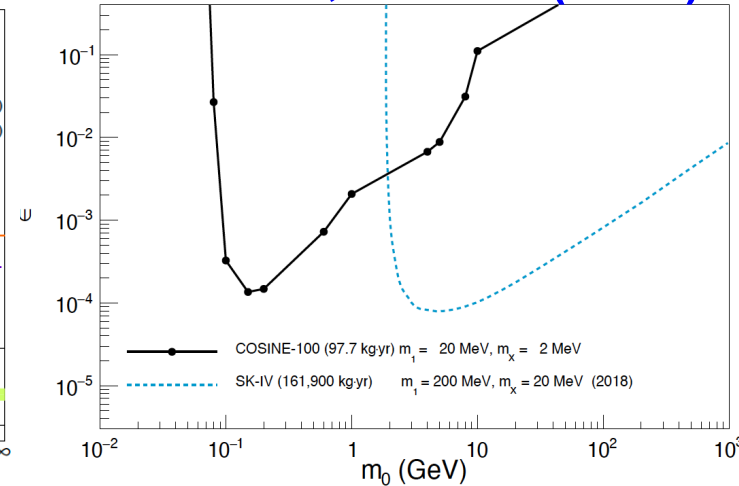


Elastic interaction

1.7 years data



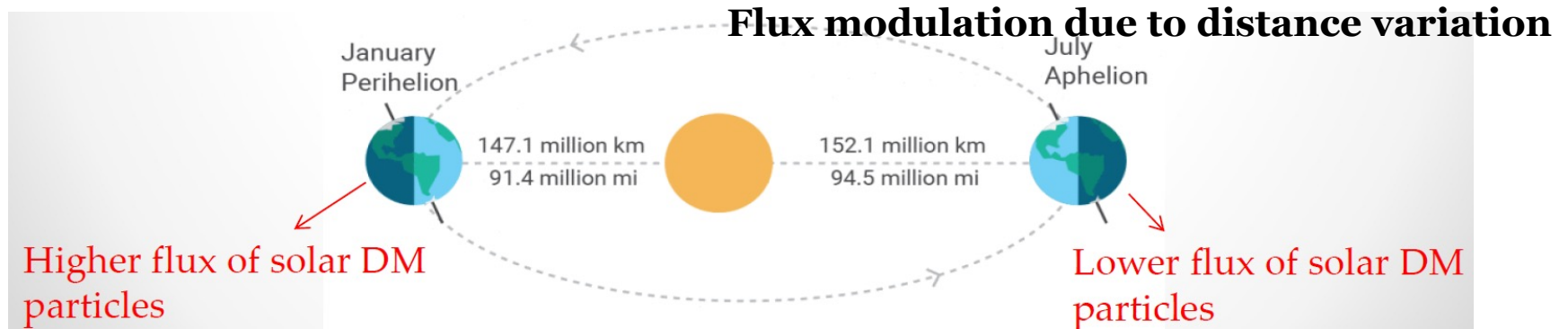
PRL 131, 201802 (2023)



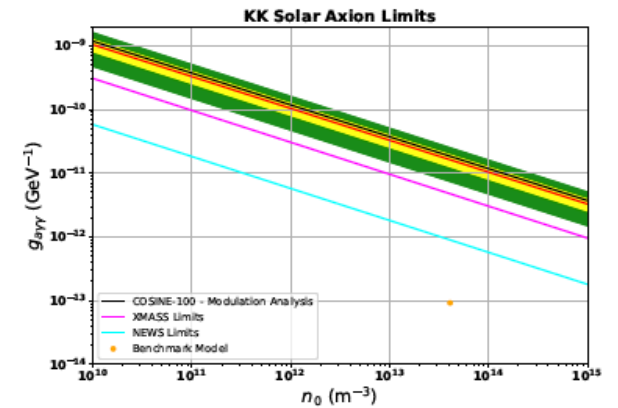
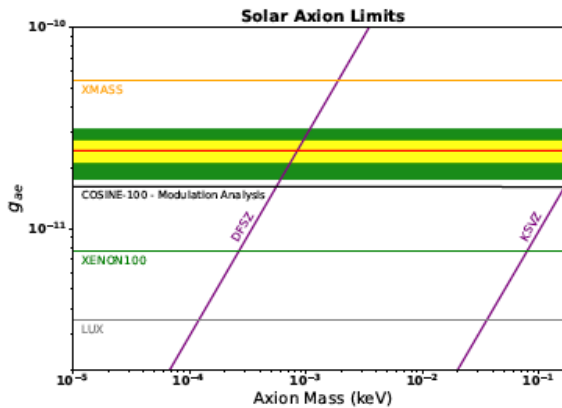
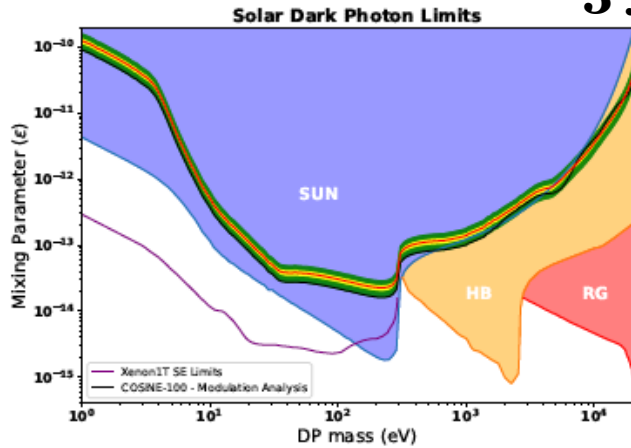
- Search for energy 1 MeV – 10 MeV

Solar bosonic dark matter annual modulation

- Sun is the strong source of gamma
 - ❖ Conversion to dark sector bosonic particle is possible



3 years data for the modulation search

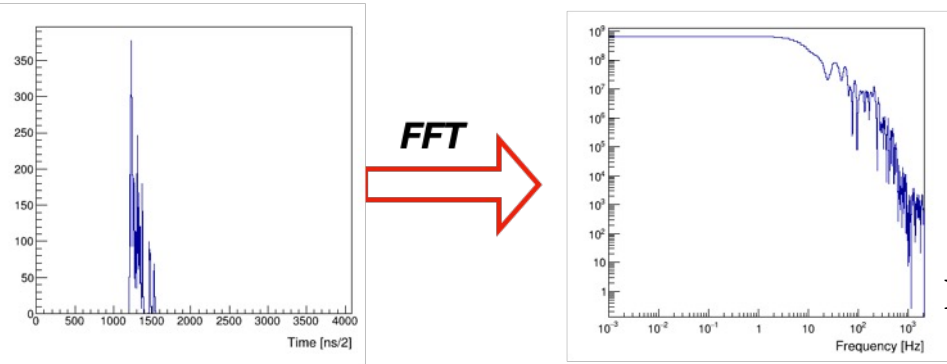


Phys. Rev. D 107, 122004 (2023)

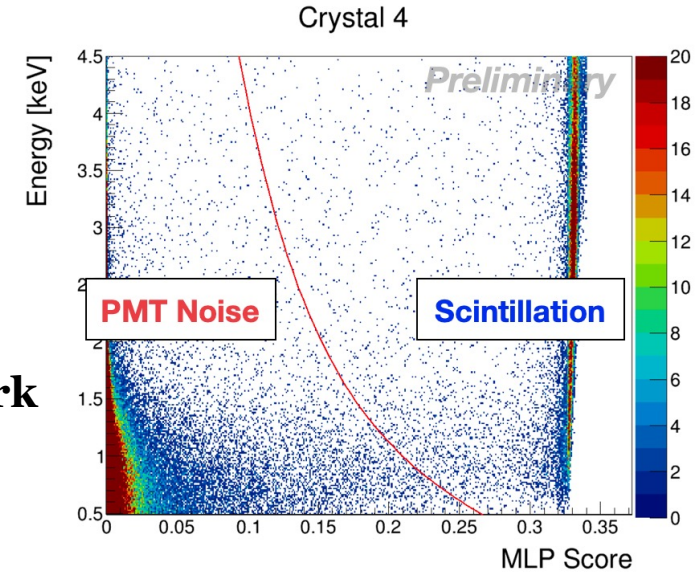
Ongoing works : Event selection update

- Multivariable machine learning training

New parameter development example

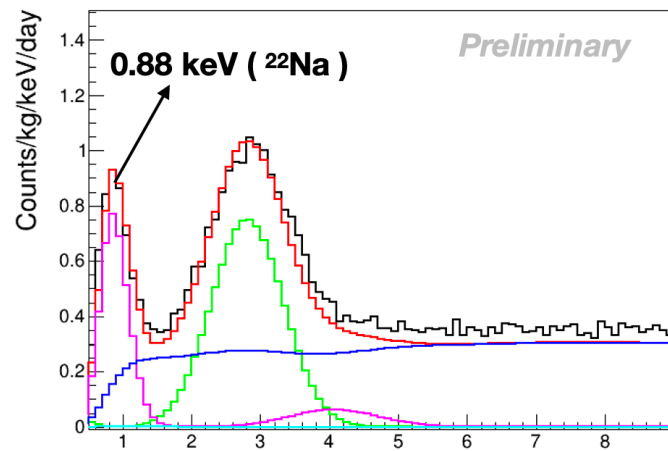
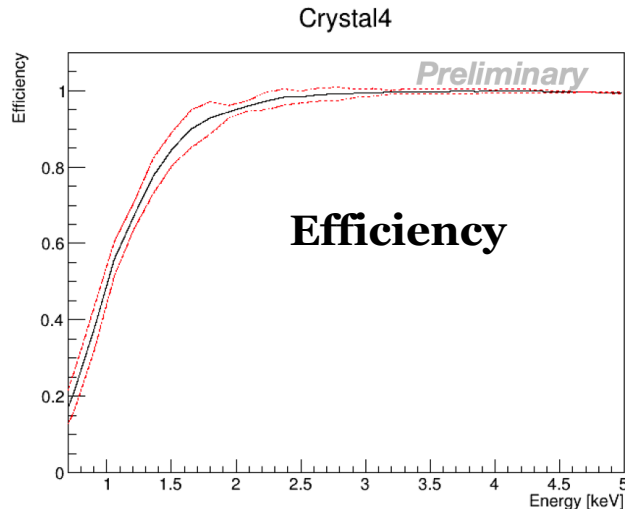


Neutral network training



Waveform example of COSINE-100 data

Fourier transformed waveform



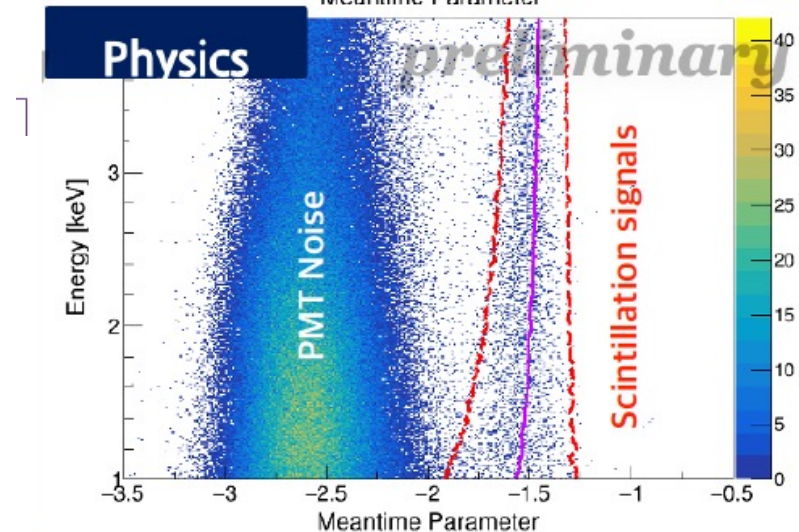
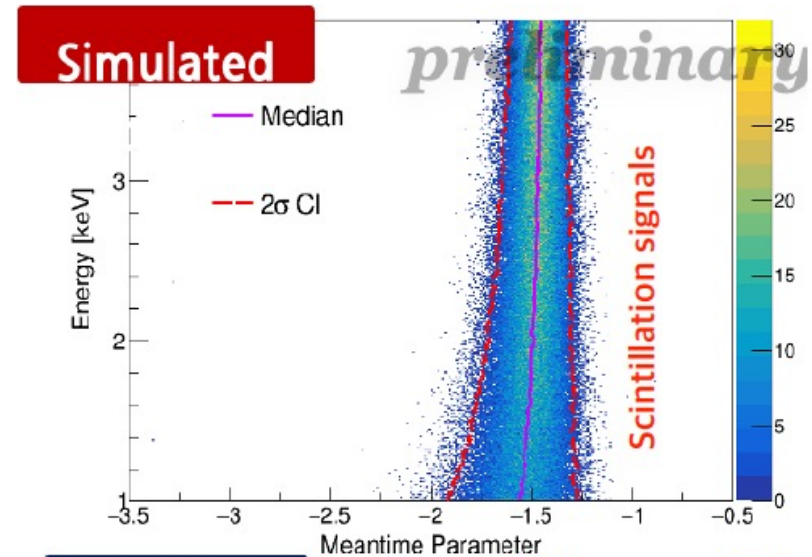
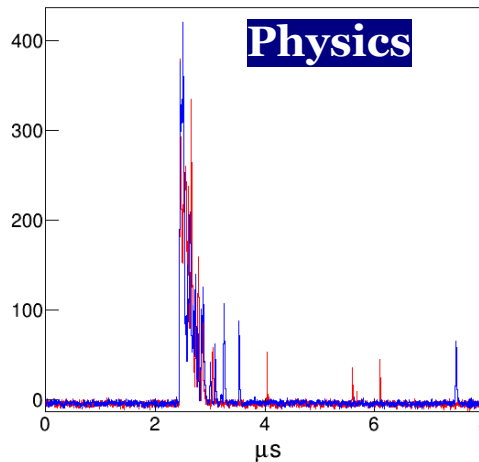
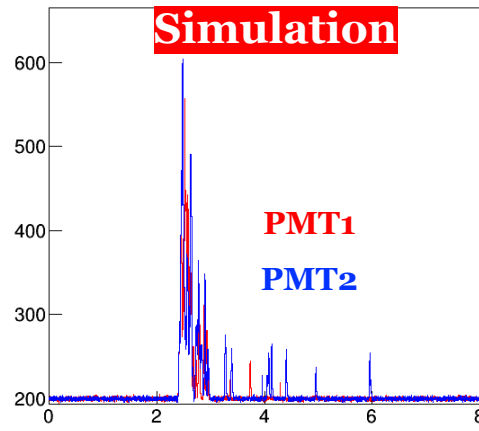
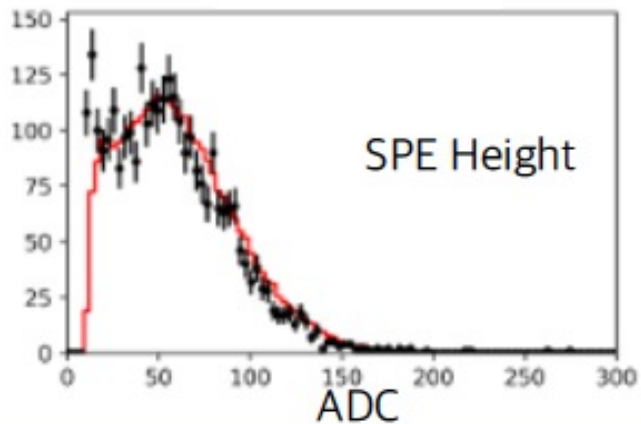
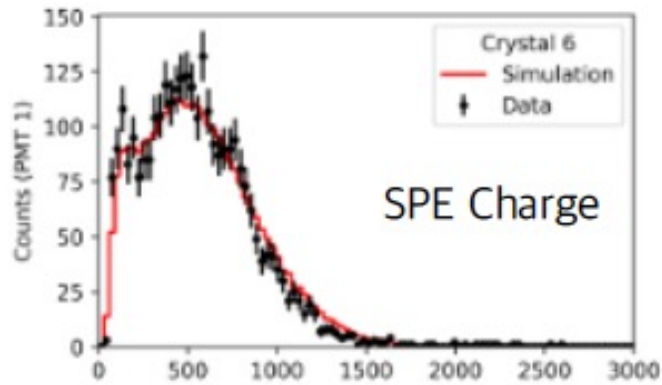
8 NPE threshold

NPE (number of photoelectrons)

~ 15 NPE/keV light yield @ 59.54 keV

Ongoing works : Waveform simulation

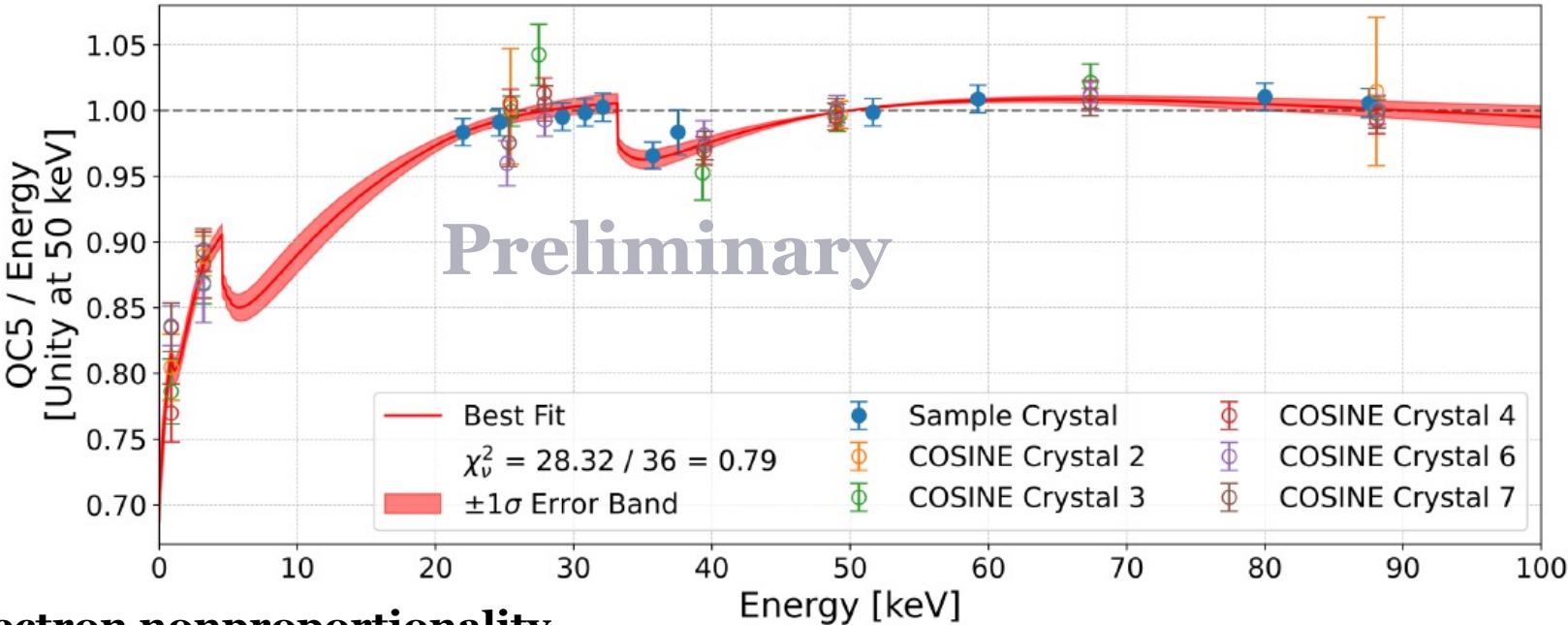
Single photoelectron tuning



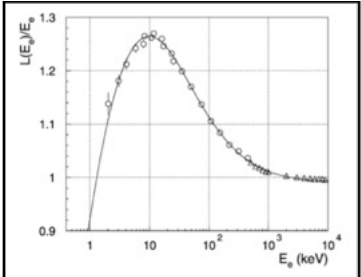
- **Waveform simulation** is developed to **describe** low-energy events (**sub-keV**)
- Simulation describe the data reasonably well
- Currently, the waveform simulation cross **checked the trigger/selection efficiencies**
- The waveform simulation will be used as **signal sample of the multivariable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

Ongoing works : Nonproportionality of NaI(Tl) crystals

- Internal background of COSINE-100 + external sources
- Nonproportionality of gamma & x-rays**



Electron nonproportionality



Nuclear Instruments and Methods in Physics Research Section A, 430, 2-3, (1999)

- Gamma & x-rays calibration** updated
- Electron can have different nonproportionality in low energy
- High energy nonproportionality

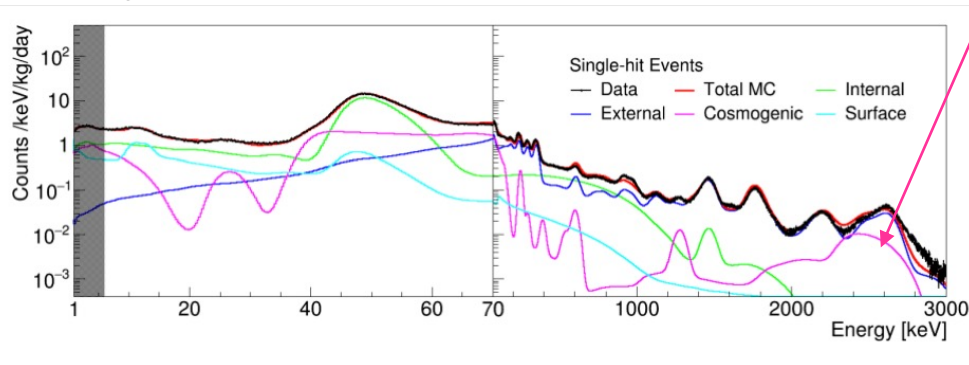
Ongoing works : Nonproportionality of NaI(Tl) crystals

^{22}Na : Two 511 keV gamma + 1274 keV gamma + e^+ (Q~545 keV)

2296 keV + e^+ (kinetic energy, end point 545 keV)

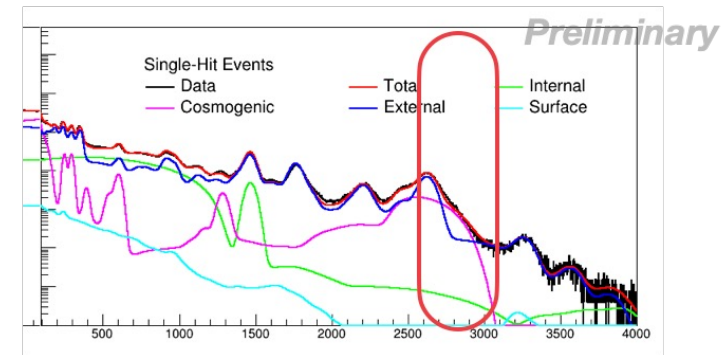
Non-Proportionality update in High energy

Eur. Phys. J. C. 81 837 (2021)

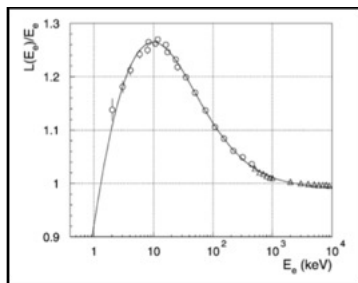


Non-Proportionality correction

Background modeling in 3 years data



Electron nonproportionality

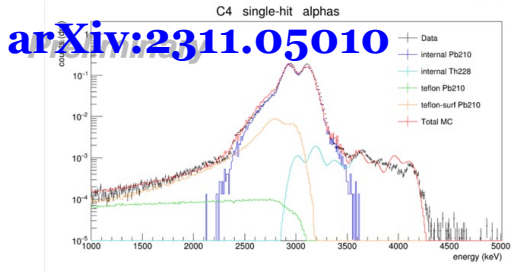


Nuclear Instruments and Methods in Physics Research Section A ,430, 2-3,(1999)

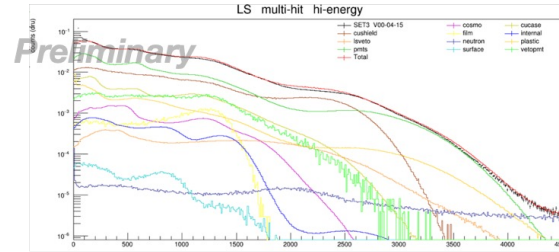
- Gamma & x-rays calibration updated
- Electron can have different nonproportionality in low energy
- **High energy nonproportionality**

Ongoing works : Background modeling update

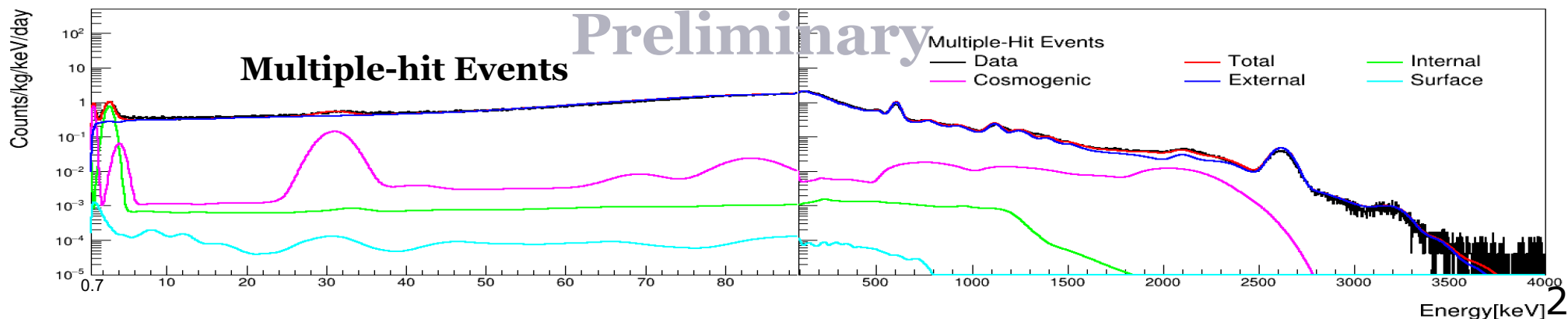
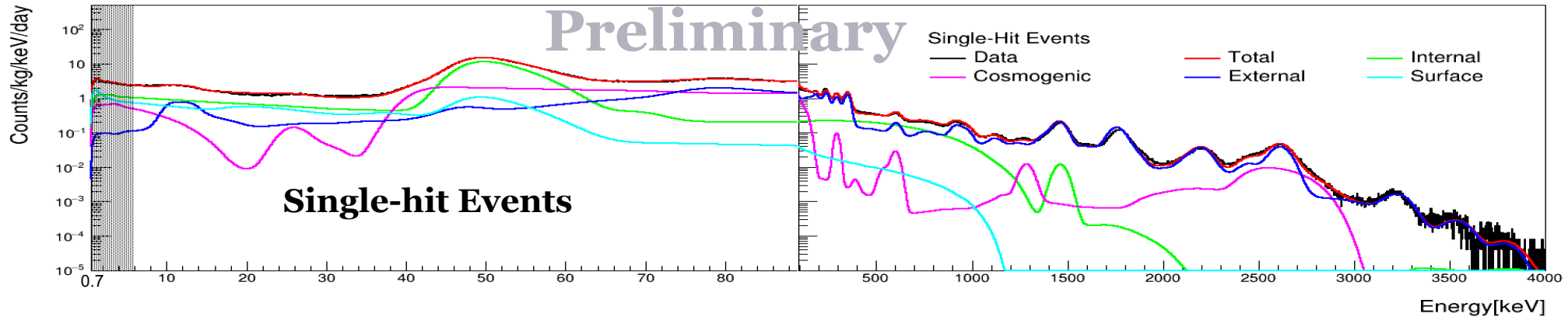
Alpha spectrum modeling



LS spectrum modeling



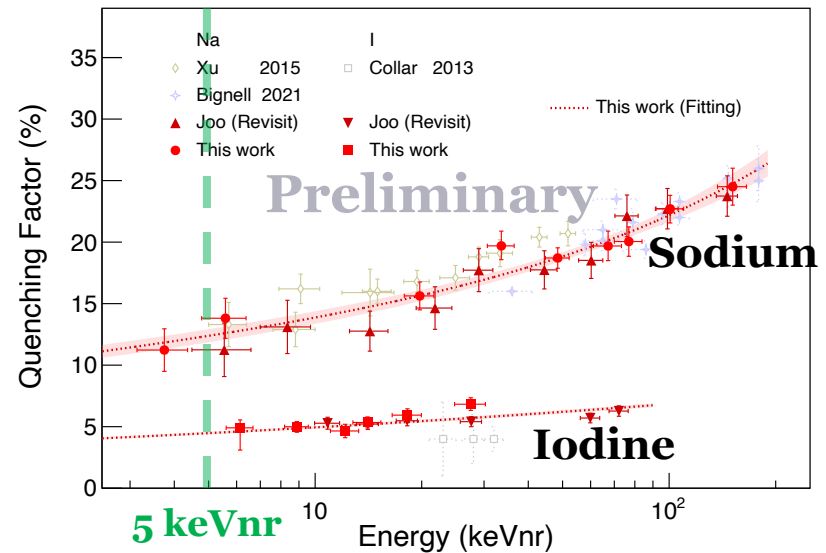
- **Detector calibration** (nonproportionality)
- Better understanding of internal (alpha) & external (LS) backgrounds
- **Extended energy** modeling between **0.7 – 4000 keVee** (considering nonproportionality)



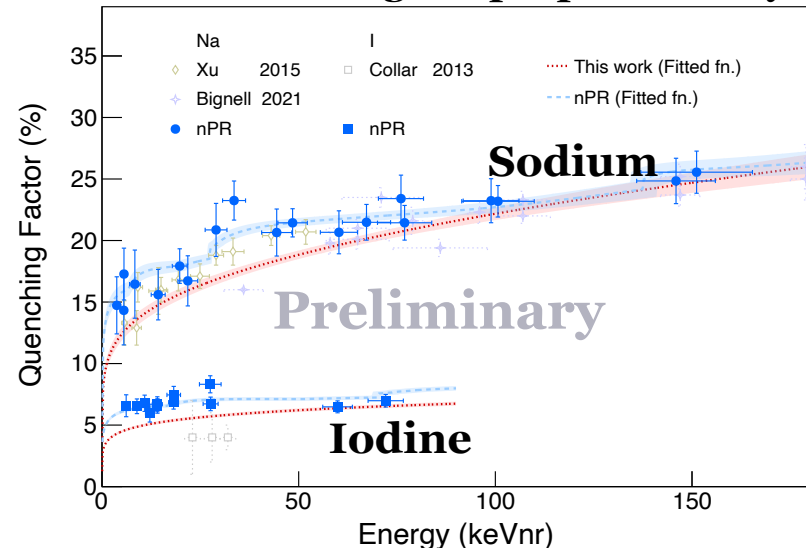
Ongoing works : Calibration of the nuclear recoils

- Update previous measurement with improved understanding of incident neutron energy and low-energy event selection
 - ❖ Consistent with other group's measurements
- New measurement including the **lowest energy point (3.8 keVnr)**
 - ❖ Modified Lindhard model describe the measured data well
- **Complete feature** including detector's **nonproportionality**

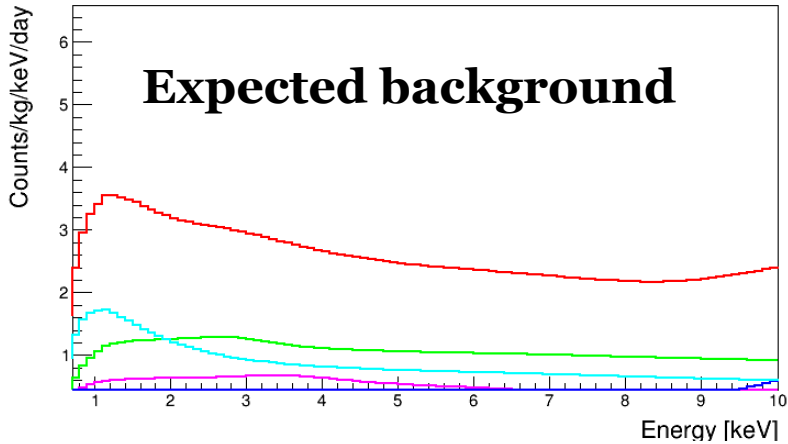
Linear calibration with 59.54 keV



Considering nonproportionality



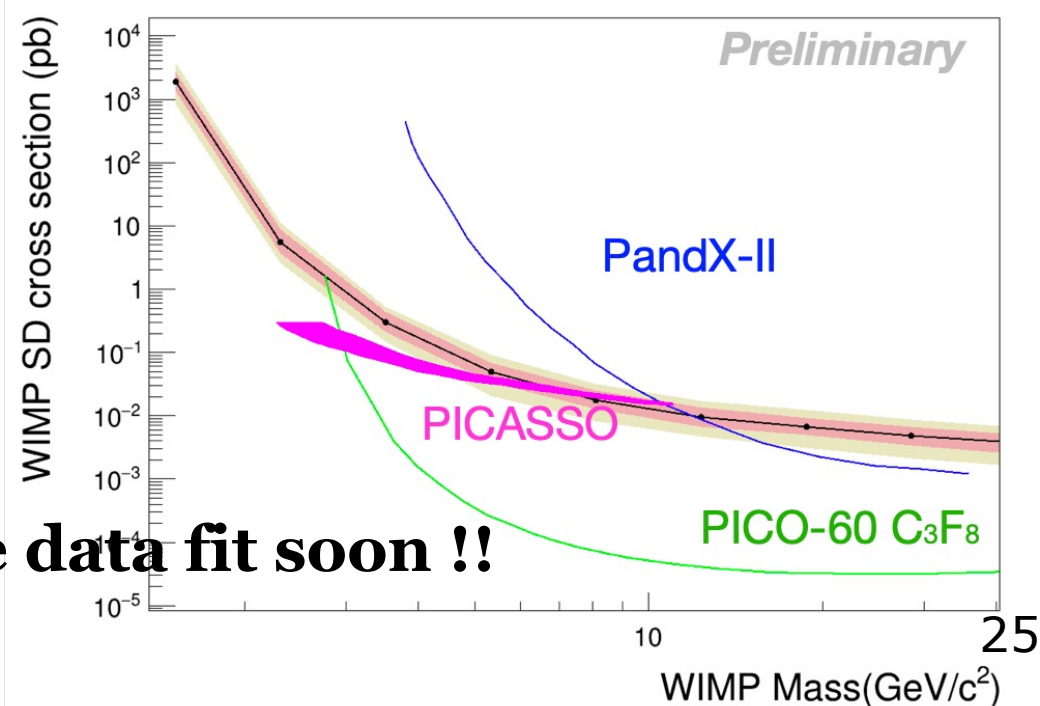
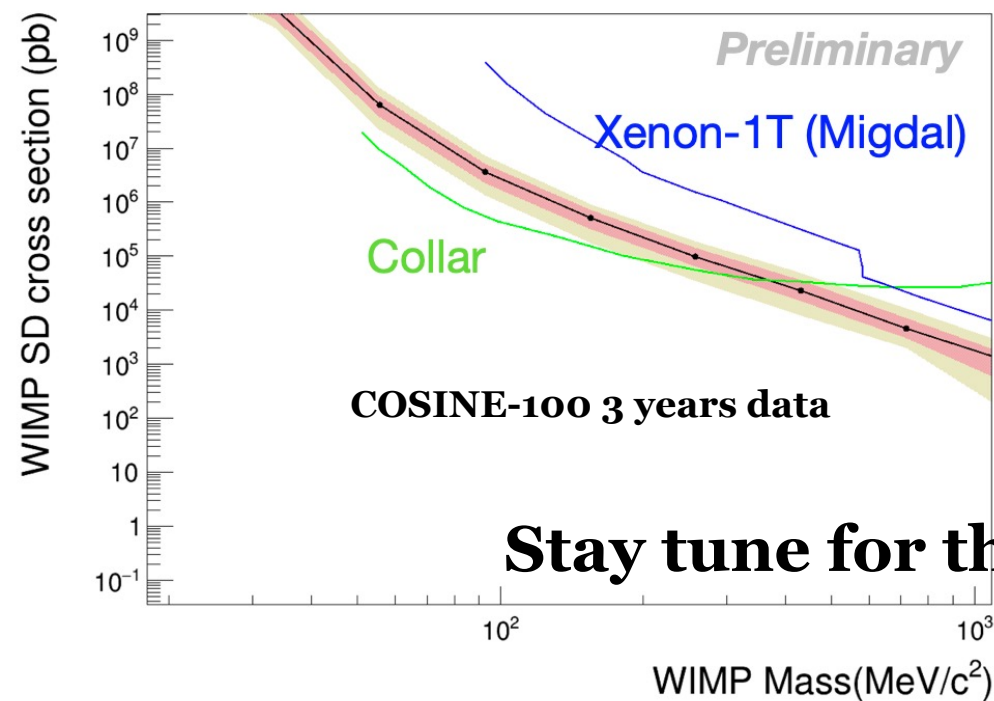
Ongoing works : Dark matter sensitivities



- In addition to cover the DAMA/LIBRA allowed region, we can do the **world best search** for the **low-mass** dark matter in the **spin-dependent WIMP-proton** interaction

W/ Migdal Effect (No systematics)

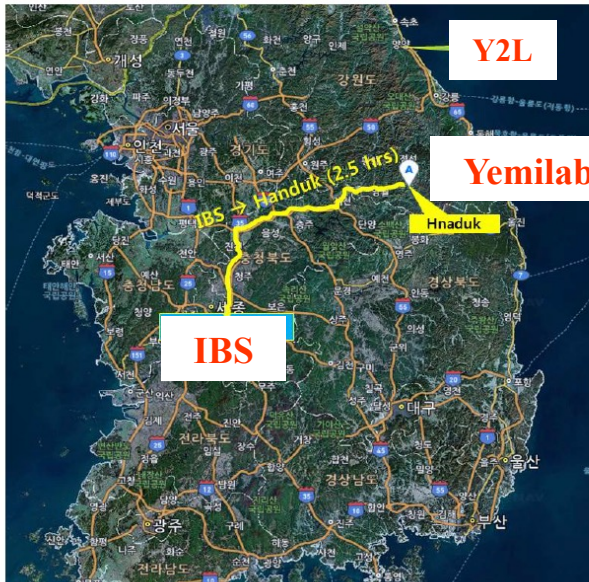
W/O Migdal Effect (No systematics)



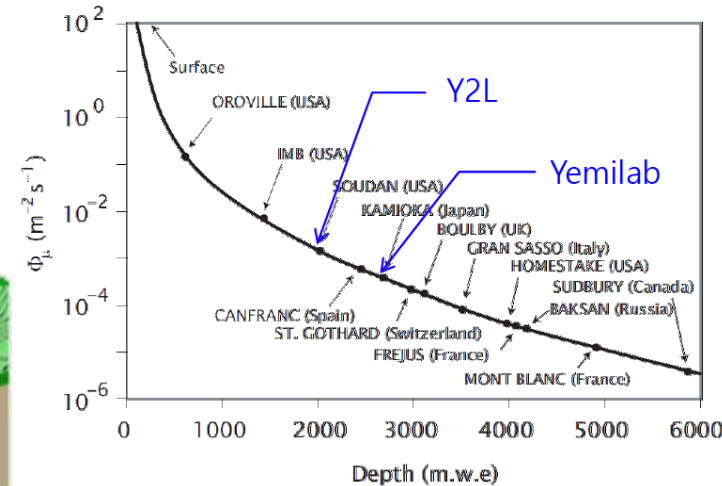
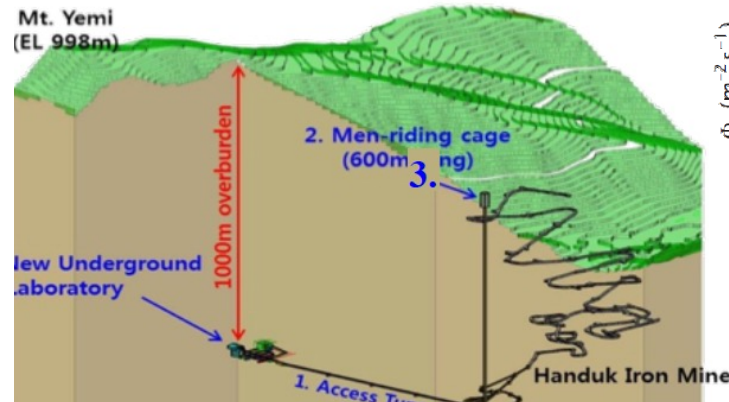
Yemilab for new discoveries

- **New underground laboratory** in Korea is one of the most **important milestone** of the **CUP/IBS** – 10 years journey

Handeok iron mine, Jeongseon, Gangwon, Korea

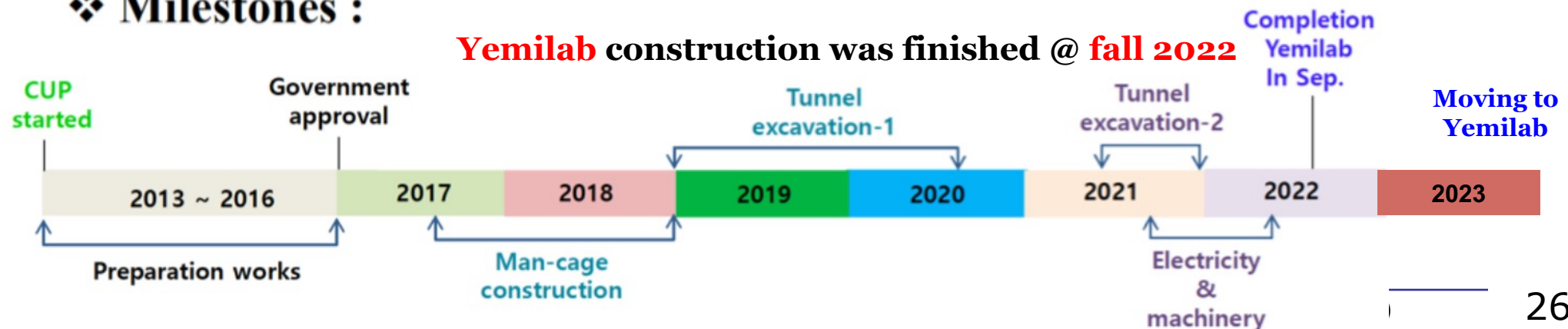


- **1000 meter underground.**
- **Construction cost ~30 M\$**
- **2018-2022**



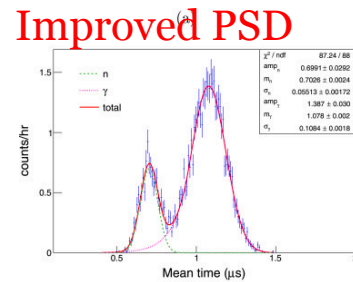
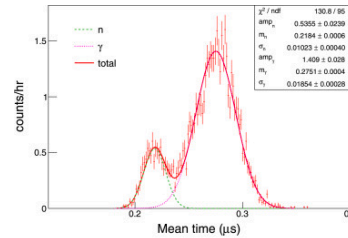
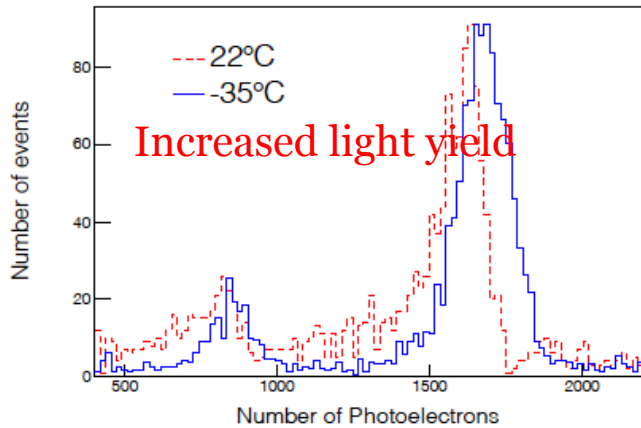
❖ Milestones :

Yemilab construction was finished @ **fall 2022**



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



To start COSINE-100U at Yemilab February/2024

Disassembly of the COSINE-100 detector @ Y2L

Sept/25



Sept/27



Oct/5



Oct/6



Oct/10



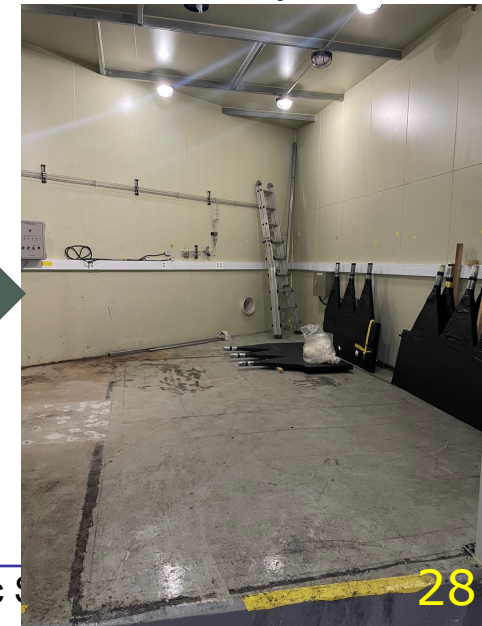
Oct/12



Oct/16



Oct/30



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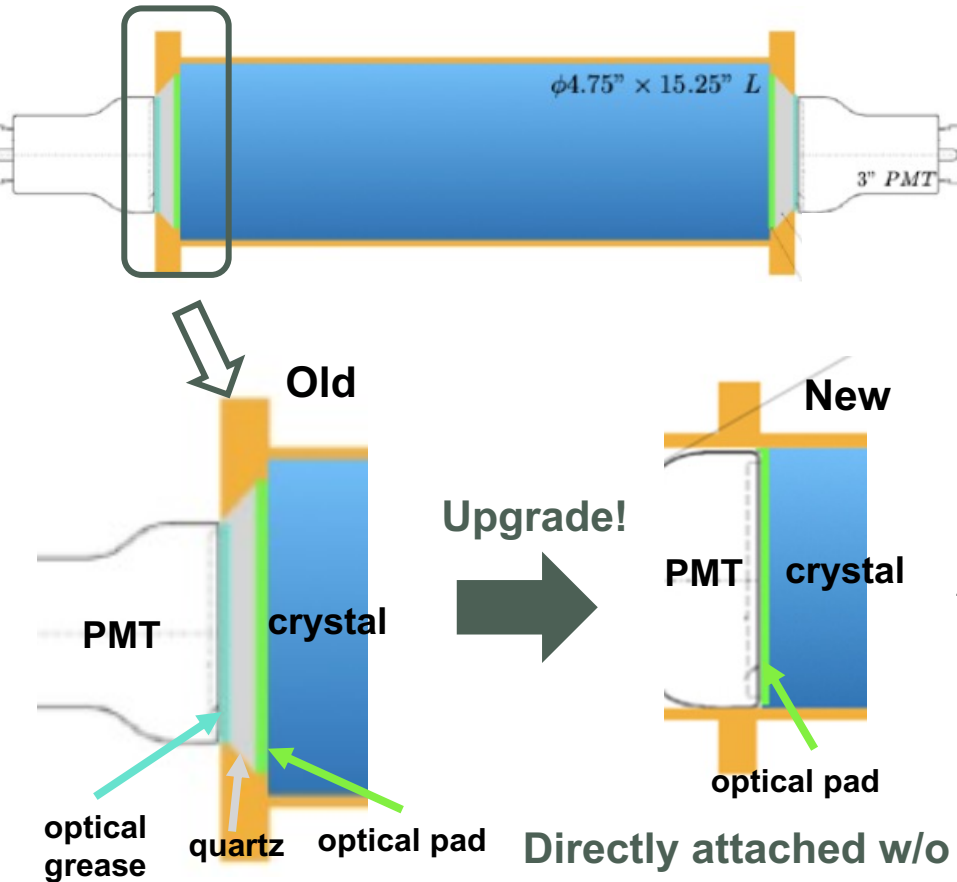
Y2L to Yemilab



- All COSINE-100 materials were delivered to Yemilab
- Installation will start soon

COSINE-100 Upgrade : New encapsulation

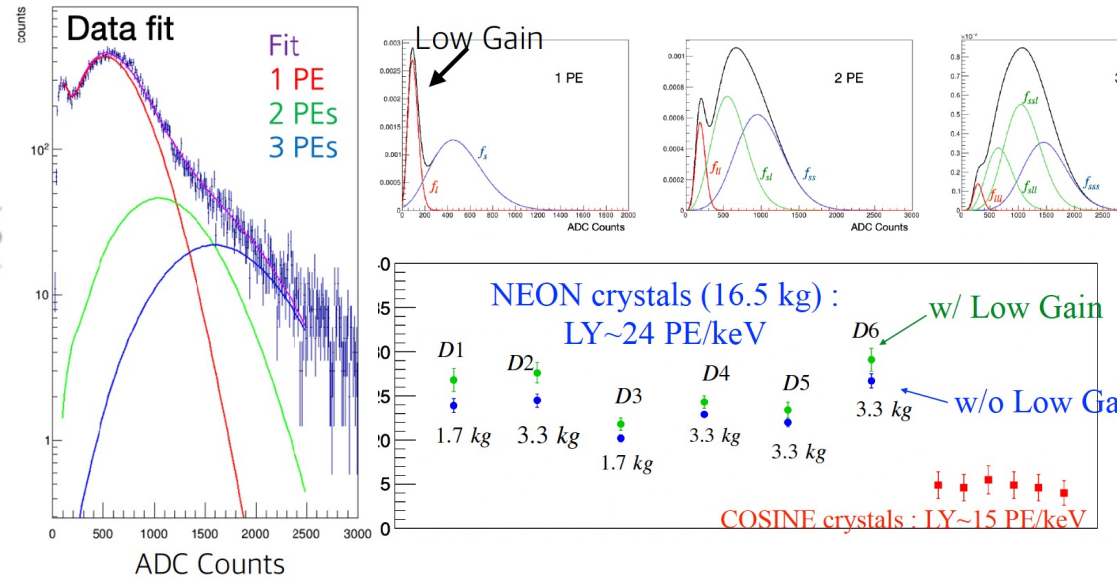
COSINE -100



Directly attached w/o quartz!

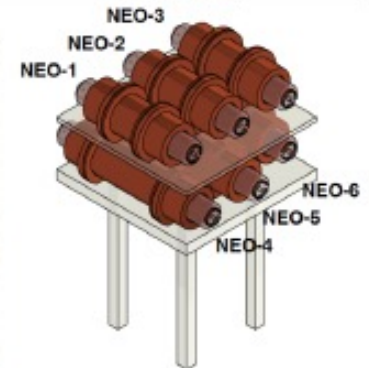
We achieved ~ 50% increased light yield

Nucl. Instrum. Meth. A 981 (2020) 164556



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

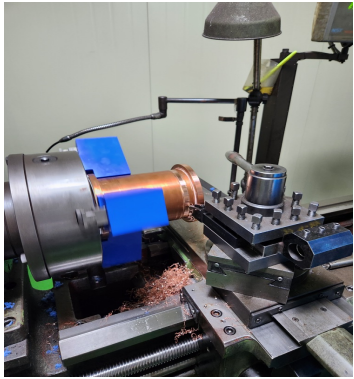
Eur. Phys. J. C 83, 226 (2023)



COSINE-100U : Detector upgrade

COSINE-100U for **high light yield**

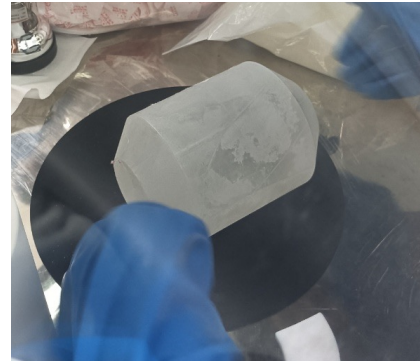
Remove the copper case



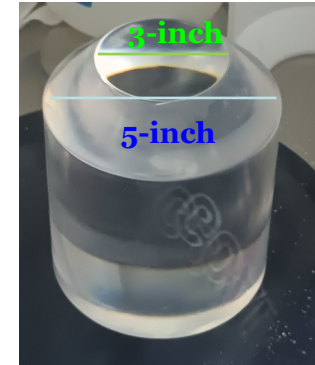
Crystal machine



Deliver to glove box

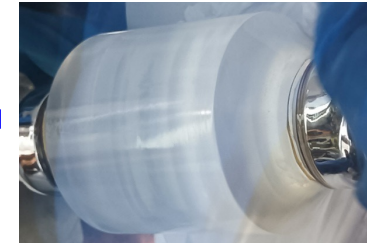
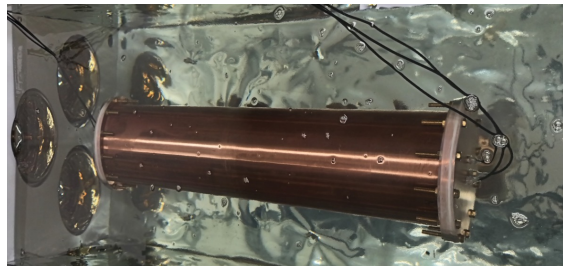


Polishing

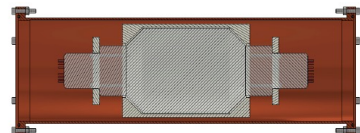
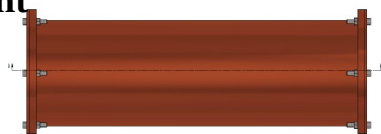


Mass : **8.26 kg** → **7.19 kg**

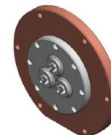
COSINE crystal-1



Above ground measurement

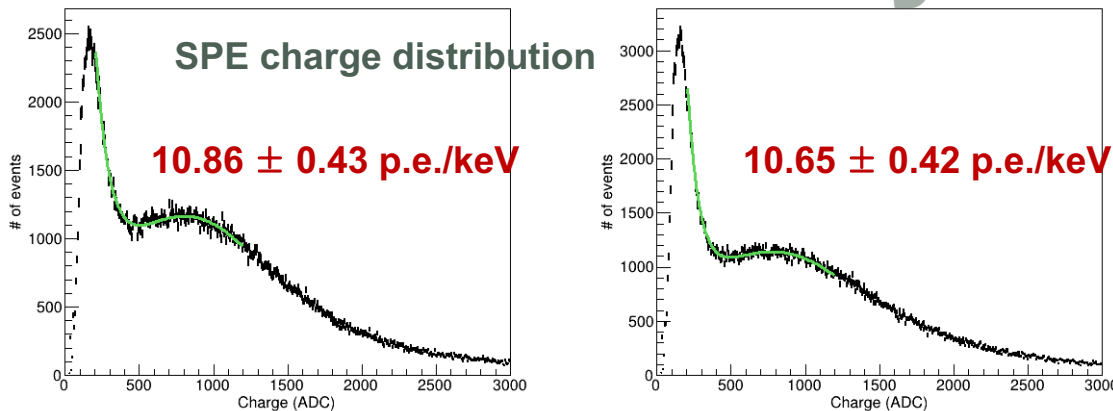
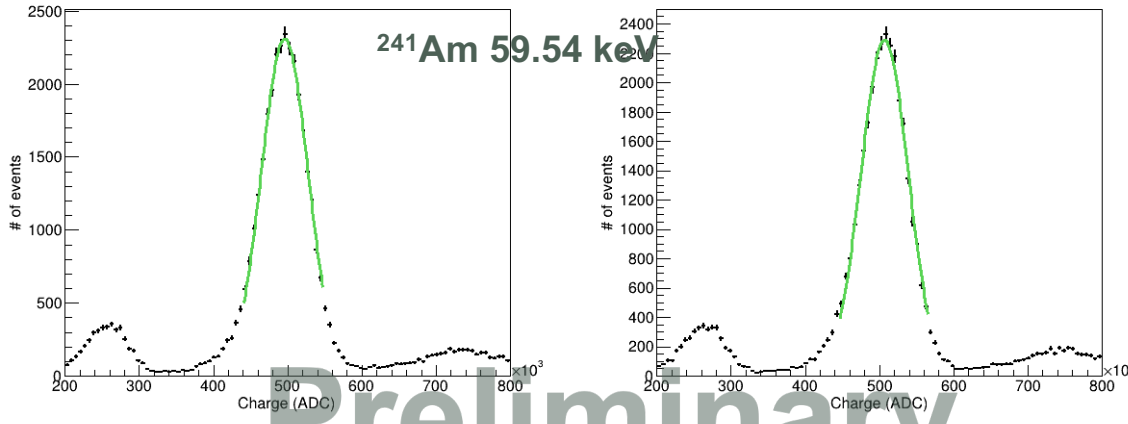


Cover design

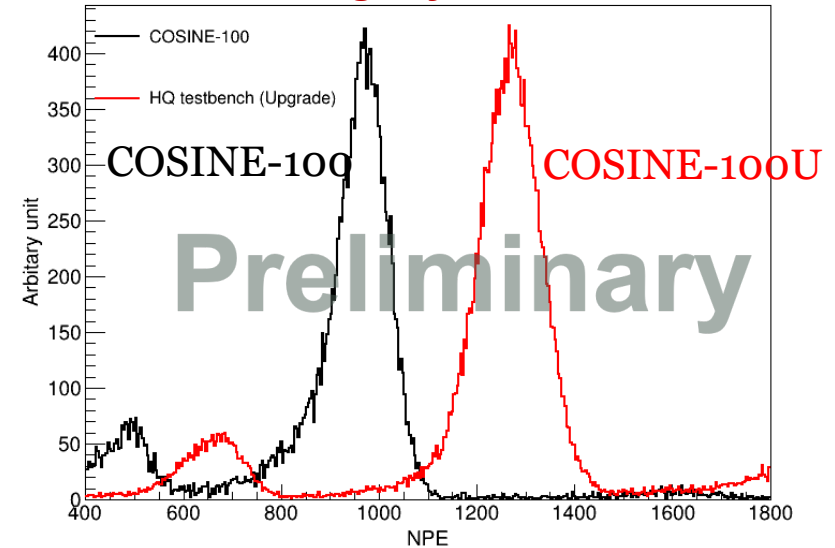


COSINE-100U : Detector upgrade

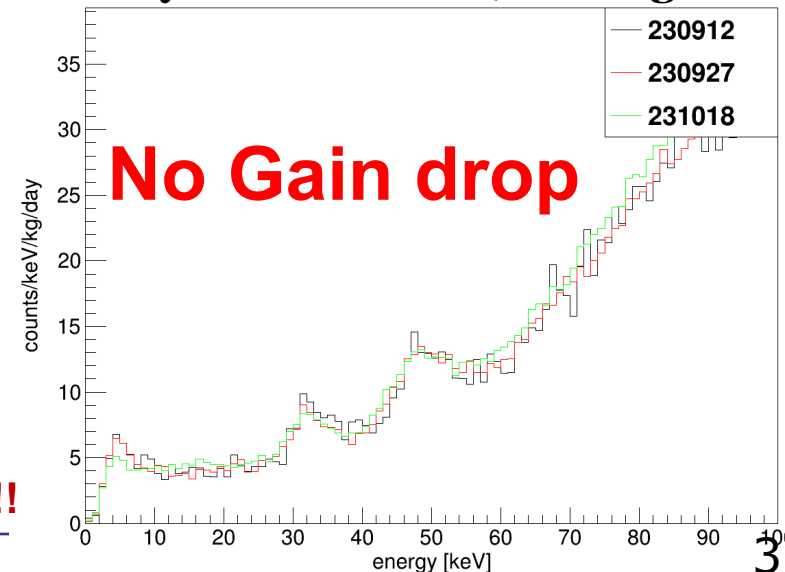
- Light yield @ 59.54 keV



~45% light yield increase!!!



Stability of ~ 1 month (Above-ground)



14.9 ± 1.5 → 21.5 ± 0.6 NPE/keV

COSINE-100 C1 COSINE-100U C1

C2 and C3 were assembled with similar improvement!!

COSINE-100U schedule

	2023-09	2023-10	2023-11	2023-12	2024-1	2024-2
Assembling			C2,C3	C4 ~ C8		
Case production		C2,C3		C4 ~ C8		
Machining	C2,C3		C4 ~ C8			
Movement	Y2L → Yemilab		Shielding installation			
Install					Crystal installation	Data taking!

- We already prove the **high light yield crystal** (C1,C2,C3 assembled)
- Production for other crystals are on the way
- Moving from Y2L to Yemilab was done and start to shield installation
- We plan to start **COSINE-100U** in **March/2024**

COSINE-200 crystal development



Powder purification performance

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

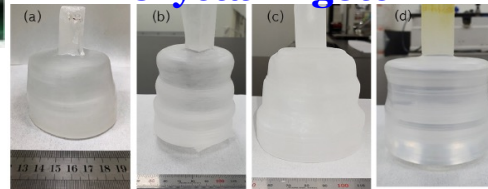
K.A. Shin et al., JINST 15, C07031 (2020)

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)

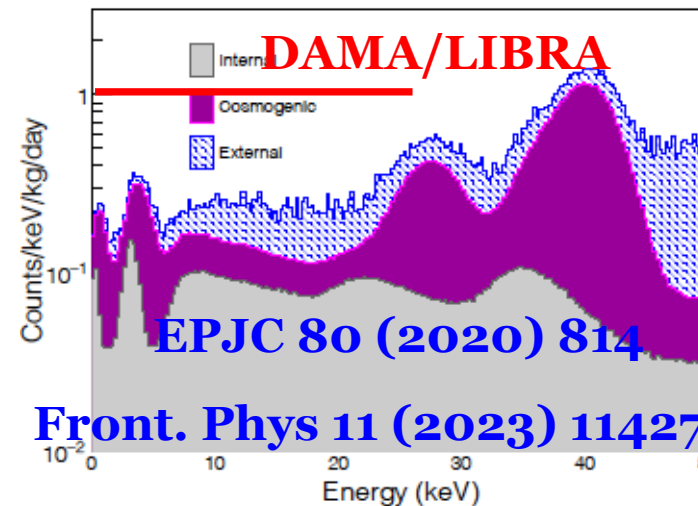
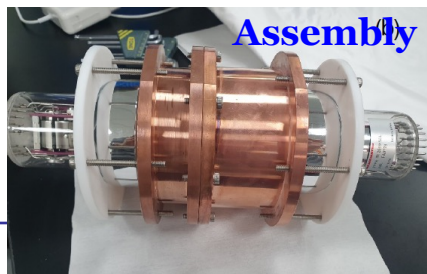
Crystal ingots



Machining



Assembly

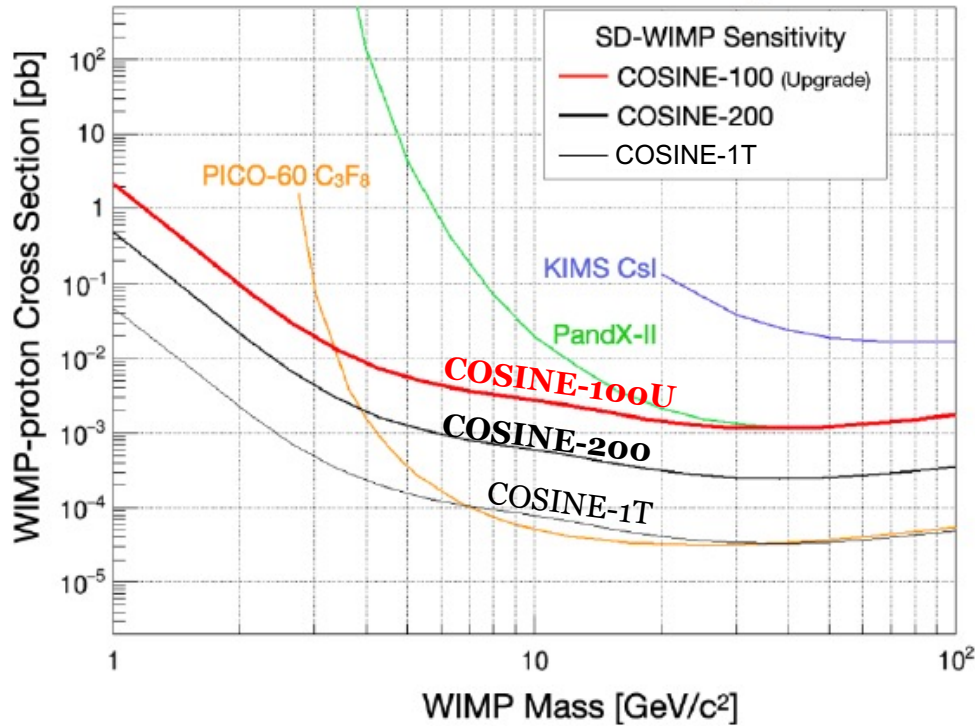


A proof of principle for low background NaI

Large crystal growing is going on 34

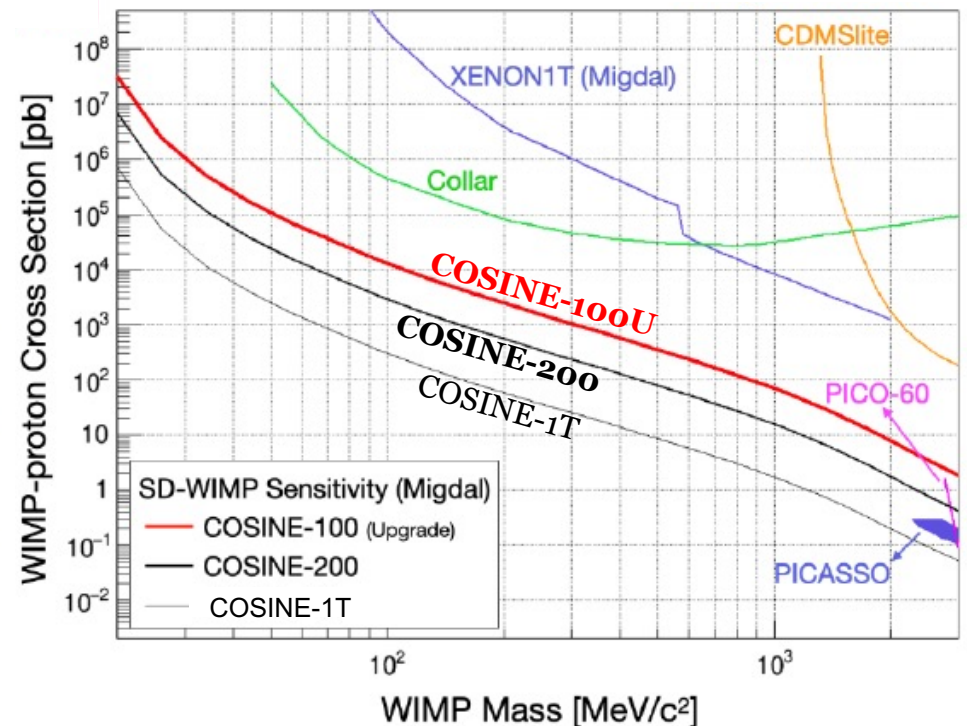
Low-mass sensitivities for spin-dependent limit

WIMP-proton spin-dependent



22 NPE/keV, 1 year operation (100% efficiency), 5 NPE threshold

Low mass search with Migdal



- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test for the COSINE-200 & 1T experiments

Summary

- World-wide efforts to understand DAMA/LIBRA's signature are actively ongoing
- COSINE-100 results are generally inconsistent with DAMA/LIBRA assuming WIMP dark matter with the standard halo model
- COSINE-100 searched various dark matter candidates in wide energy ranges
- COSINE-100U and COSINE-200 have world competitive sensitivities for low-mass dark matter searches