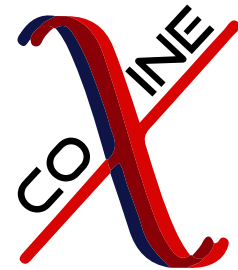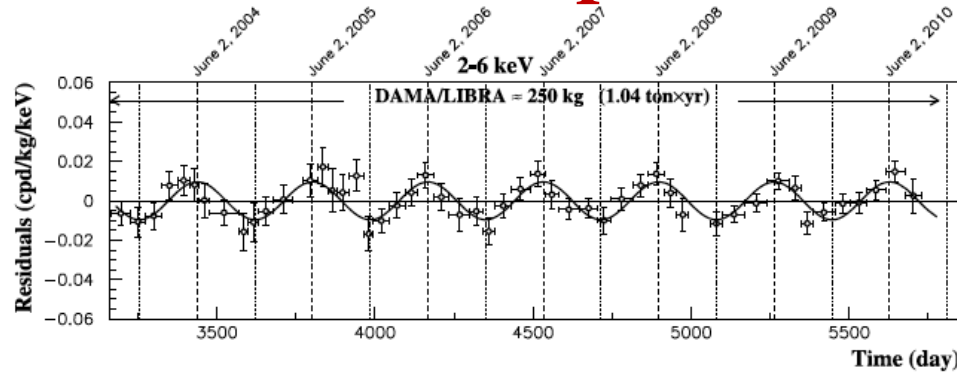# Status of COSINE-100 experiment

Hyunsu Lee

Institute for Basic Science

Center for Underground Physics

TAUP2023, August 31th 2023

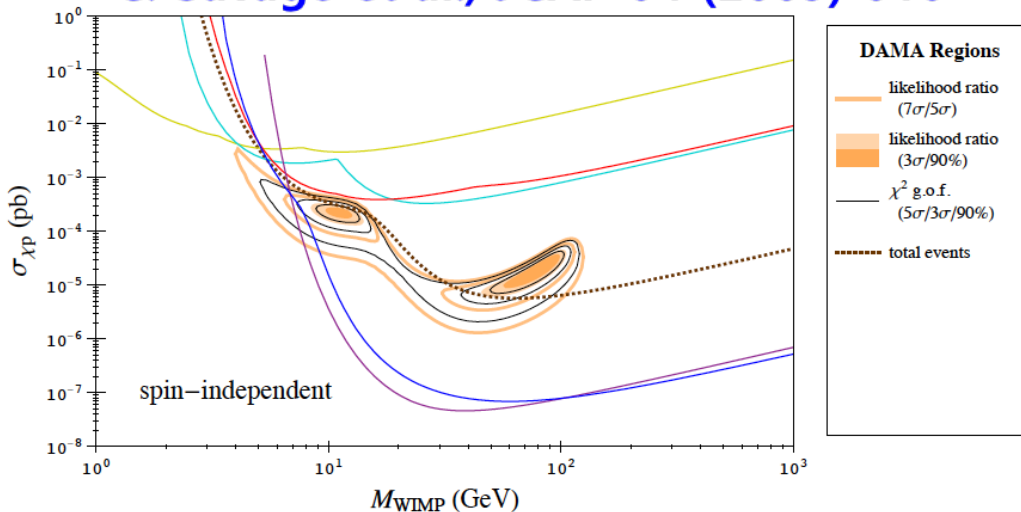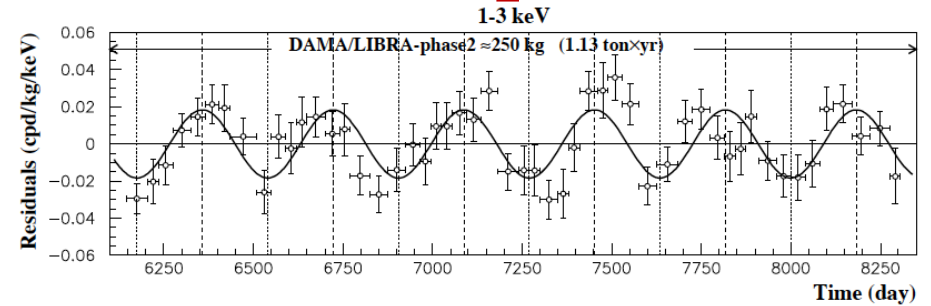# Annual modulation signal from DAMA/LIBRA

Phase1 experiment

Eur. Phys. J. C 73:2648 (2013)
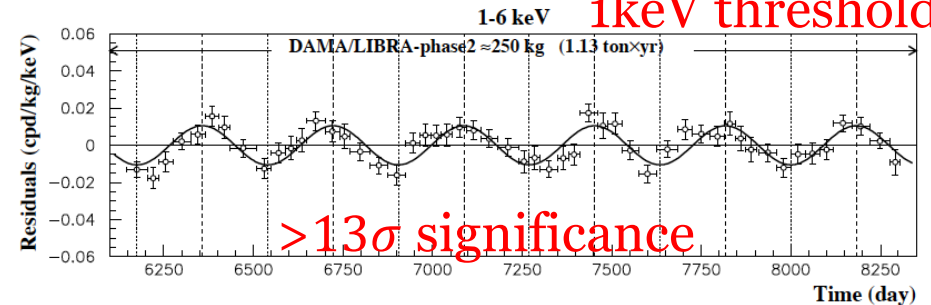
2keV threshold

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

DAMA Regions

likelihood ratio ($7\sigma/5\sigma$)

likelihood ratio ($3\sigma/90\%$)

χ^2 g.o.f. ($5\sigma/3\sigma/90\%$)

total events

Phase2 experiment

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

1keV threshold

>13σ significance

Modulation Amplitude

$\Delta E = 0.5$ keV bins

χ^2(6-20 keV)/dof = 35.8/28 (P-value=15%)
χ^2(6-20 keV)/dof = 29.8/28 (P-value=37%)

Global NaI(Tl) efforts

Bare NaI crystal
covered with light detector
Mounted in cryostat

Veto vessel w/ scintillator
Detector module
Crystal
PMT
PMT
Veto PMTs

COSINUS @ LNGS

DAMA @ LNGS

SABRE @ LNGS

KIMS/COSINE @ Yangyang

In Data-taking

Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

PICO-LON @ Kamioka

ANAIS @Canfranc

In Data-taking

ANAIS results.
Phys. Rev. Lett. **123**, 031301 (2019)

SABRE @ Stawell

20 cm lead
10 cm ancient lead
Anti-Rn box
40 cm neutron shielding
Active vetoes

DM-Ice @ South Pole

COSINE collaboration

15 institutes
~60 members

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

COSINE-100 experiment (2016~2023)

106 kg NaI(Tl) crystals

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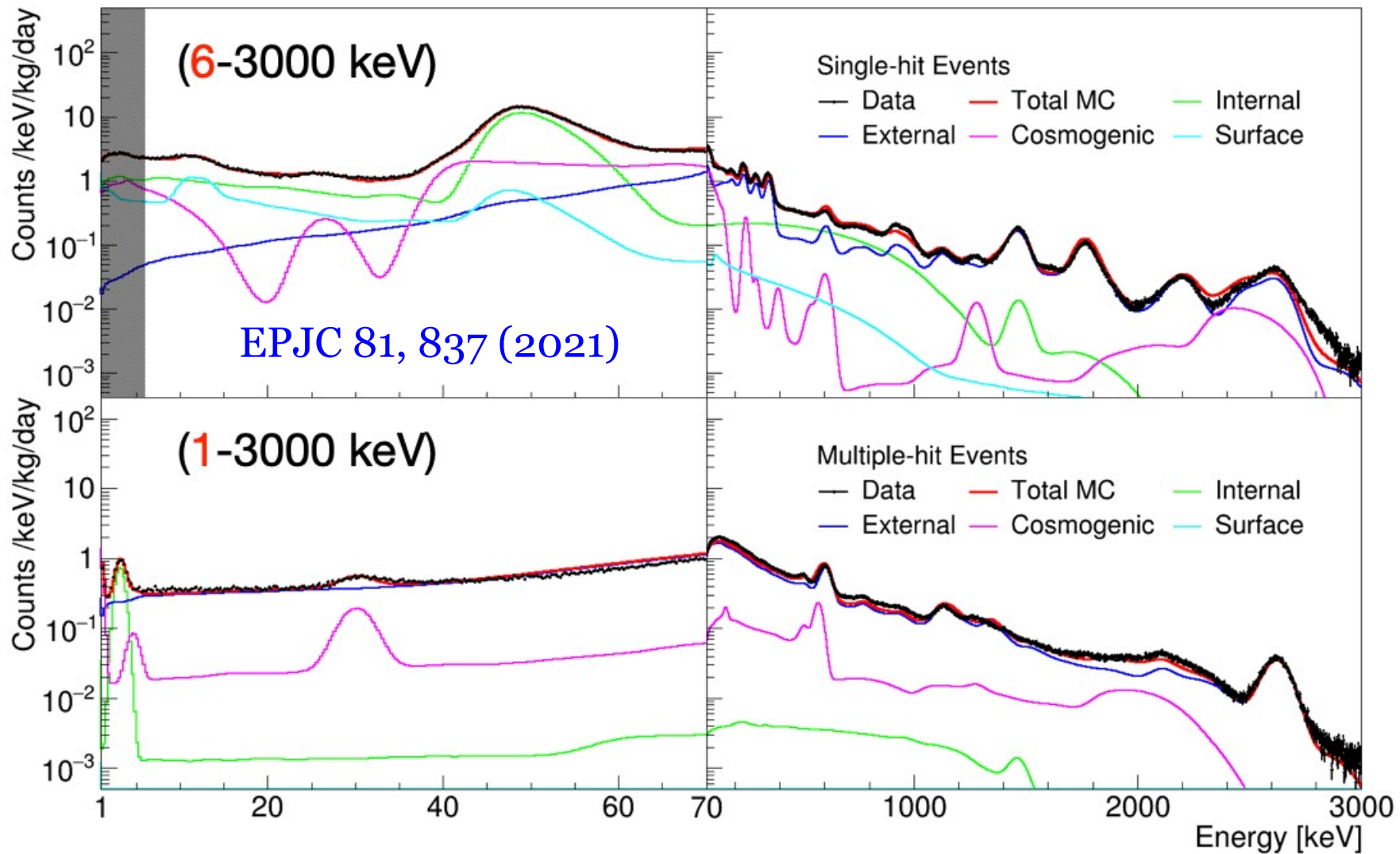   - ❖ Plan to restart COSINE-100 upgrade by end of 2023 at Yemilab

COSINE-100 data exposure
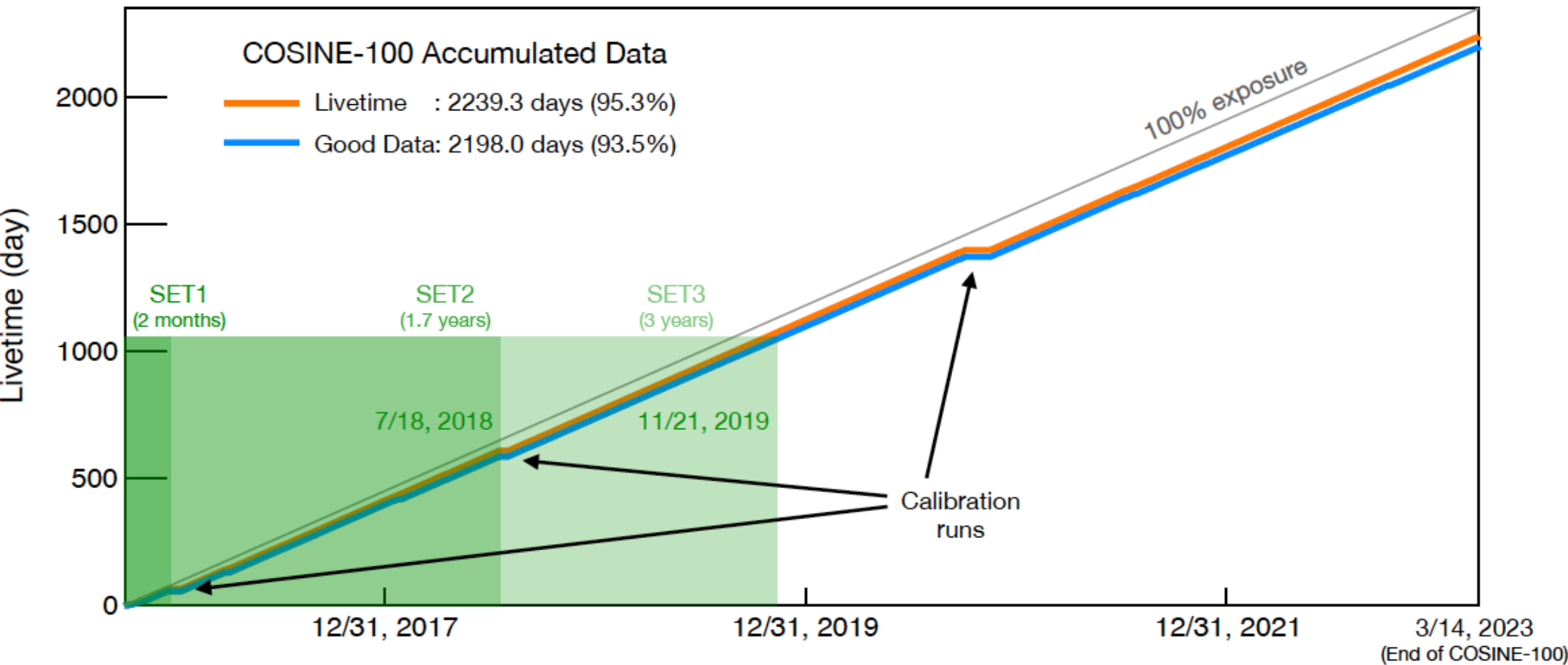
- **Stable operation Since Sep. 2016 for about 6.4 years**
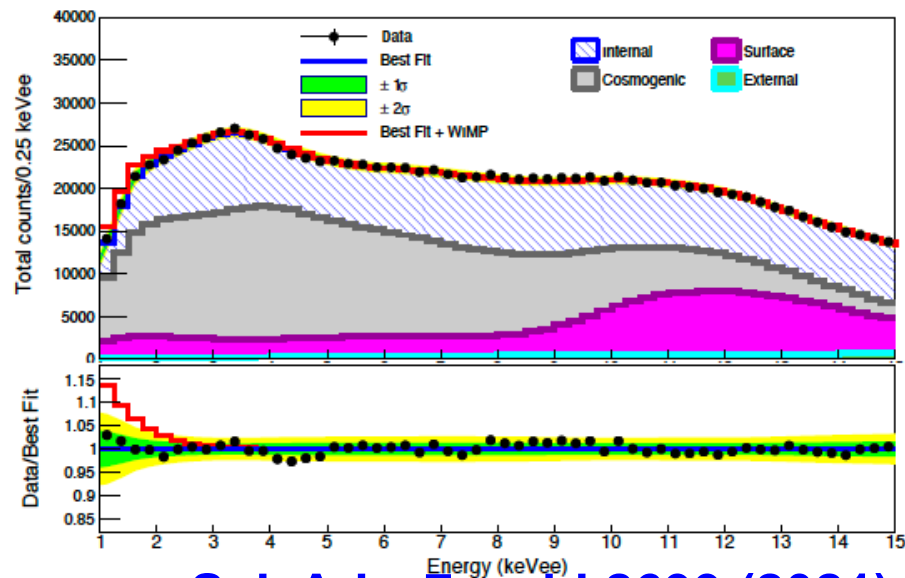 - **~95 % physics data**
  - **~94 % good quality data (6.0 years data)**

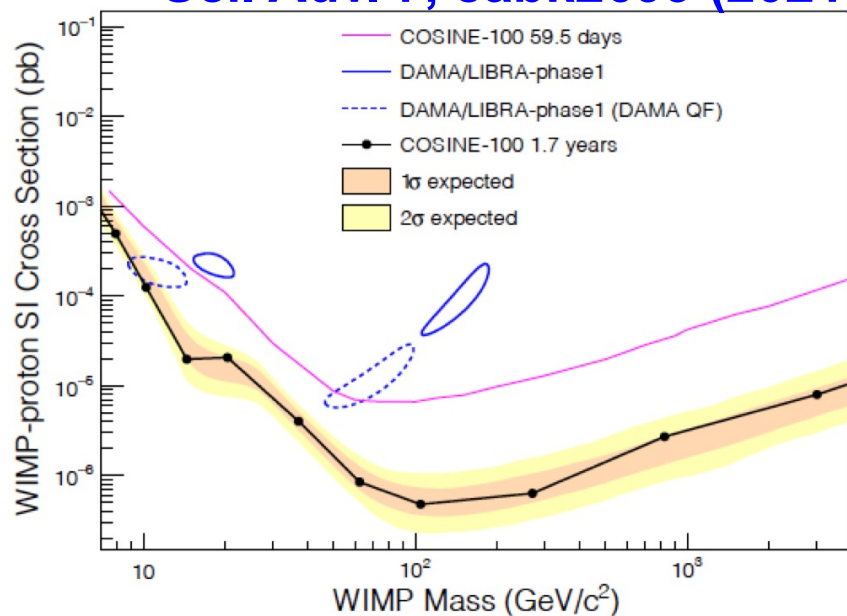# Detector background understanding

Background modeling

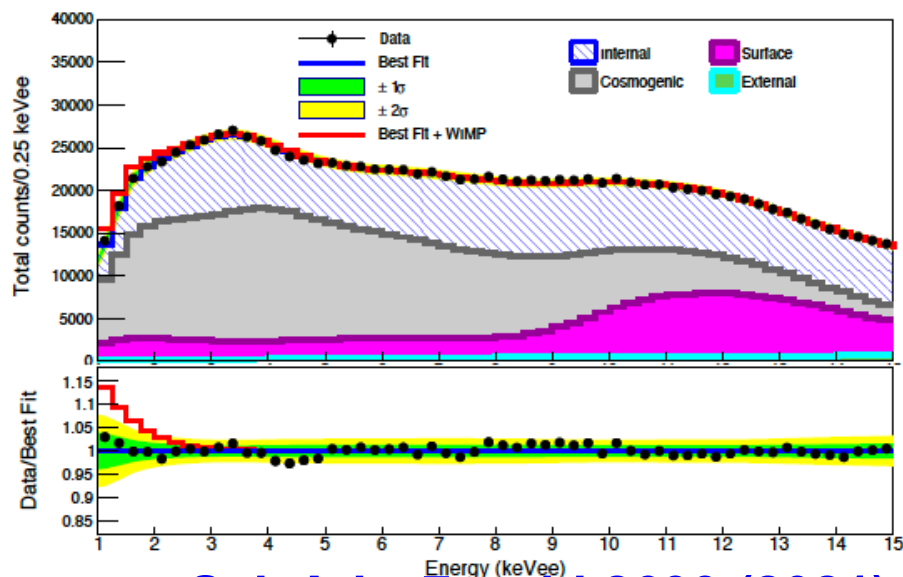**1.7 years data**

EPJC 81, 837 (2021)
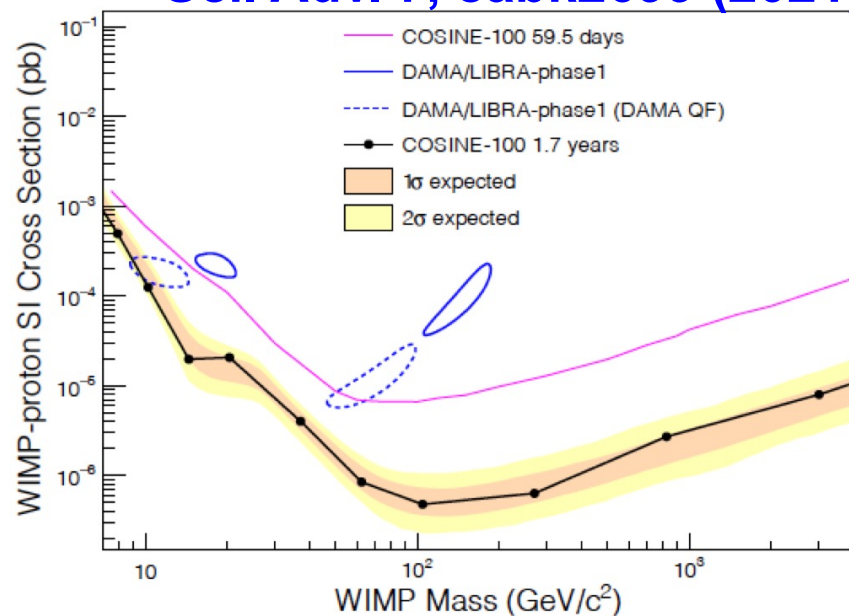
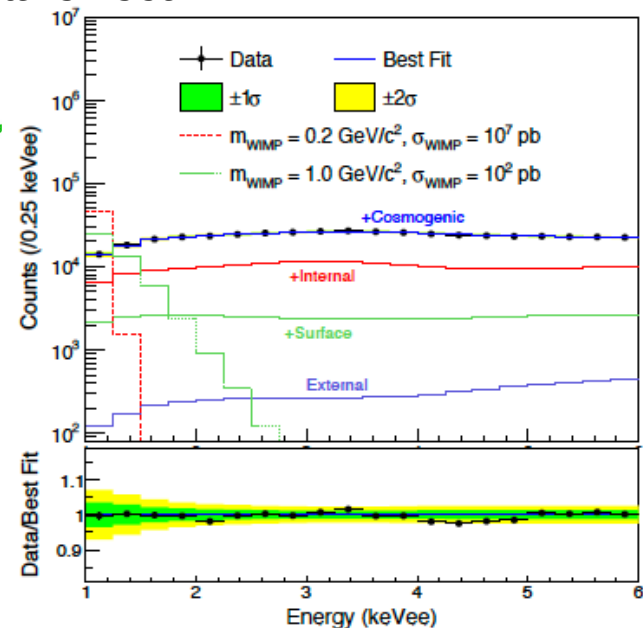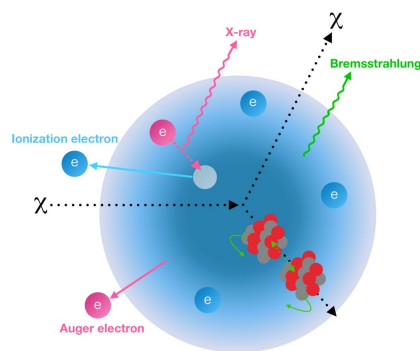# Dark matter search with spectral shape fit

Sci. Adv. 7, eabk2699 (2021)
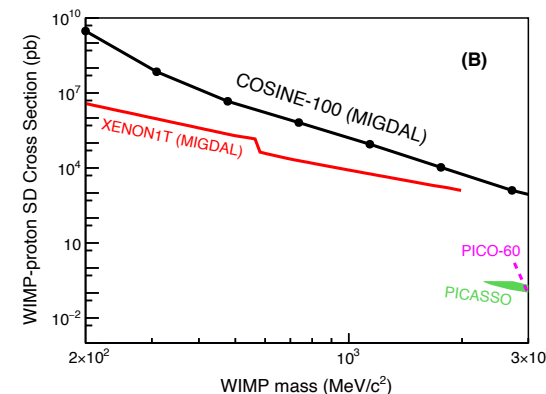
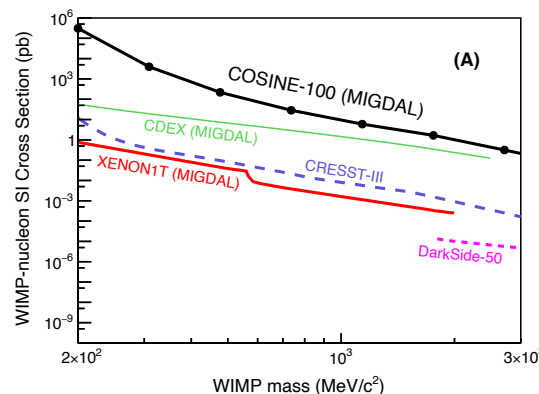# Dark matter search with spectral shape fit

Migdal effect

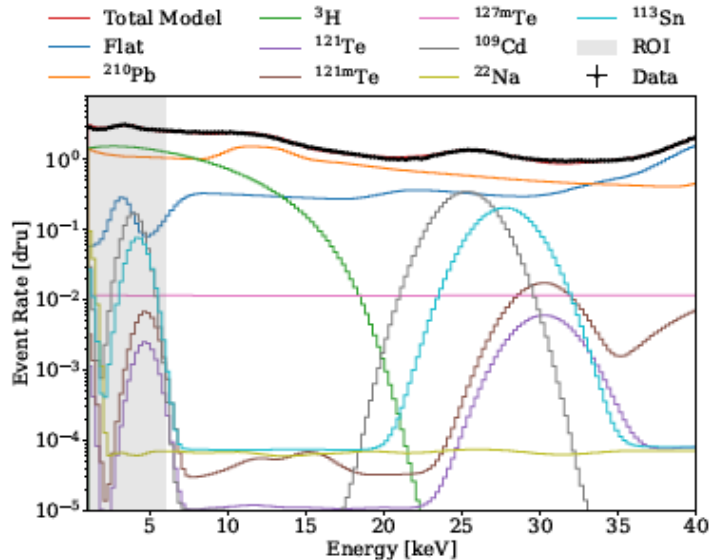**Sci. Adv. 7, eabk2699 (2021)**
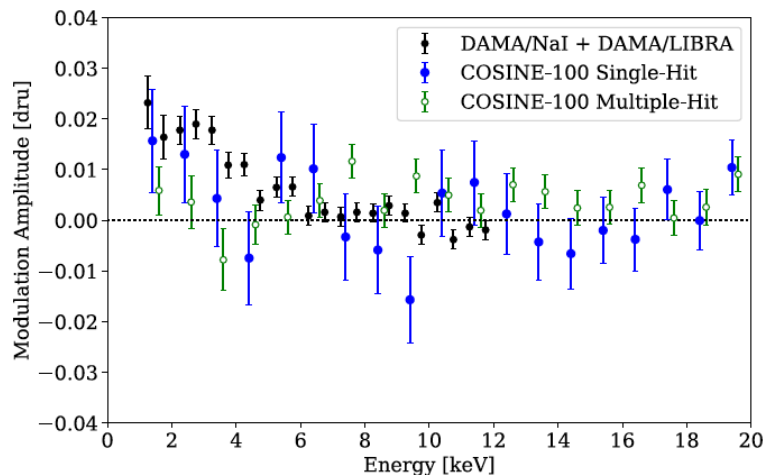

PRD 105, 042006 (2022)

Model-independent annual modulation search

Time dependent background modeling

PRD 106, 052005 (2022)

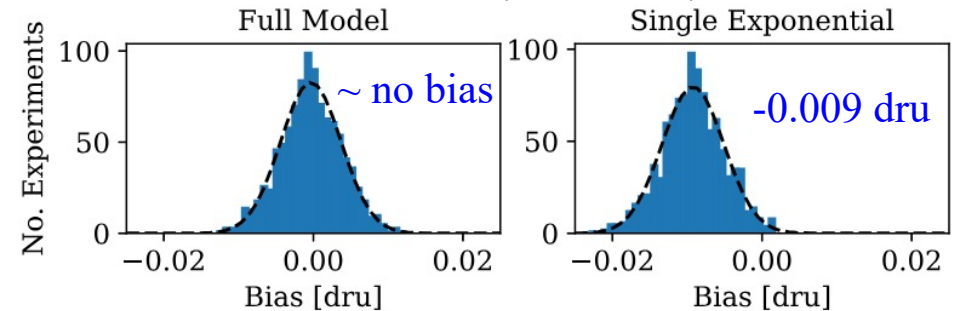

Single exponential

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

Full model (8 exponential)

$$R(t) = P_0 + \sum_{i=1}^{8} P_i e^{-t/\tau_i} + S \cos\left(\frac{2\pi(t - t_0)}{T}\right)$$
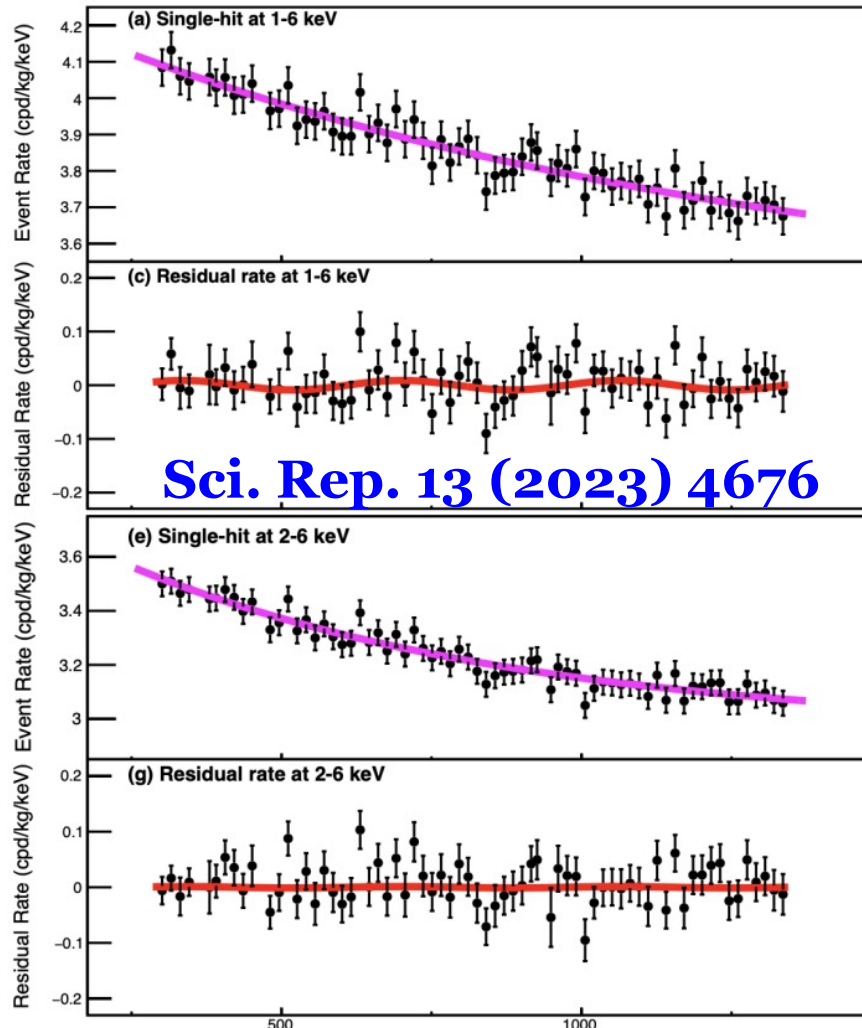
Bias test (1-6 keV)

Understanding time-dependent background is crucial for the annual modulation search
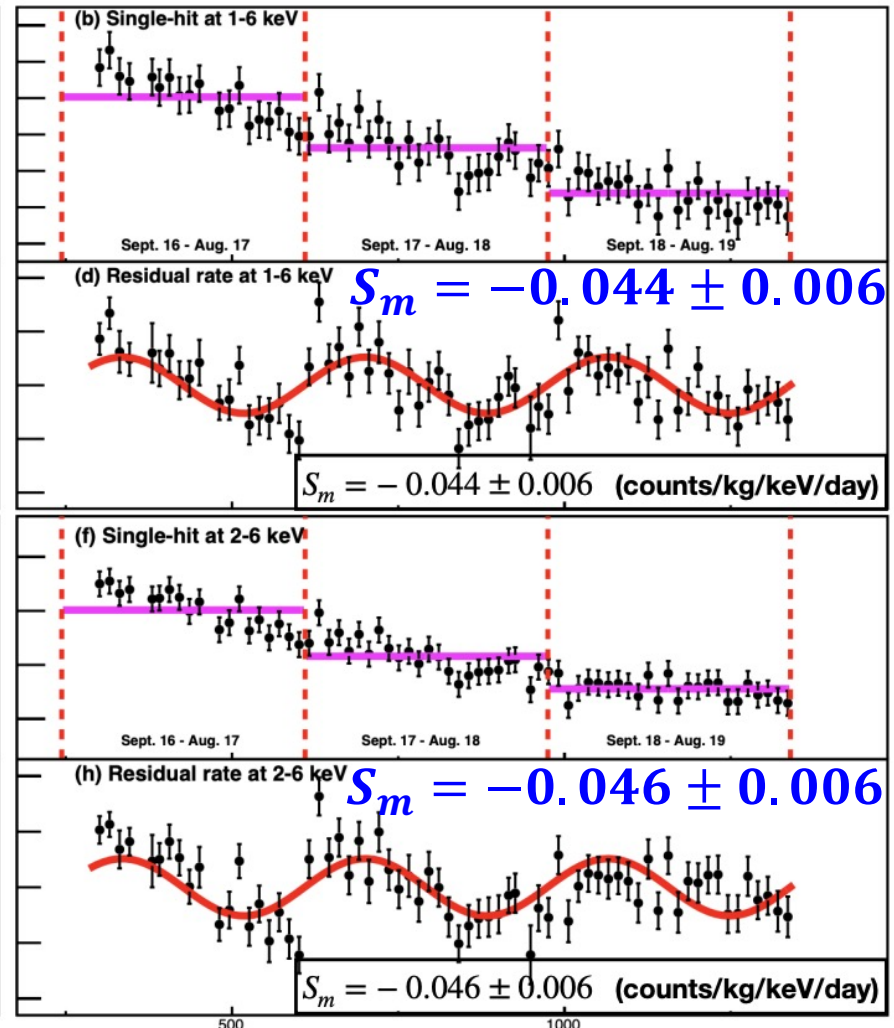
1-6 keV modulation amplitude

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

DAMA/LIBRA's method (induced modulation)

Single exponential model (reference)

DAMA/LIBRA's method

$$S_m = -0.044 \pm 0.006$$

Sci. Rep. 13 (2023) 4676

$S_m = -0.044 \pm 0.006$ (counts/kg/keV/day)

$$S_m = -0.046 \pm 0.006$$

$S_m = -0.046 \pm 0.006$ (counts/kg/keV/day)

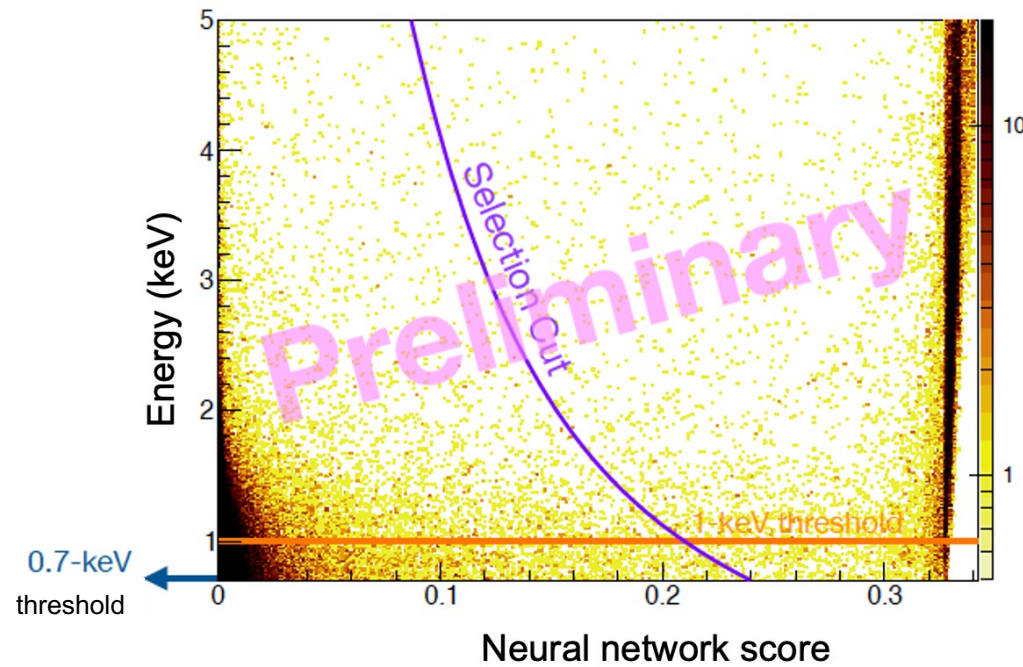**Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method**
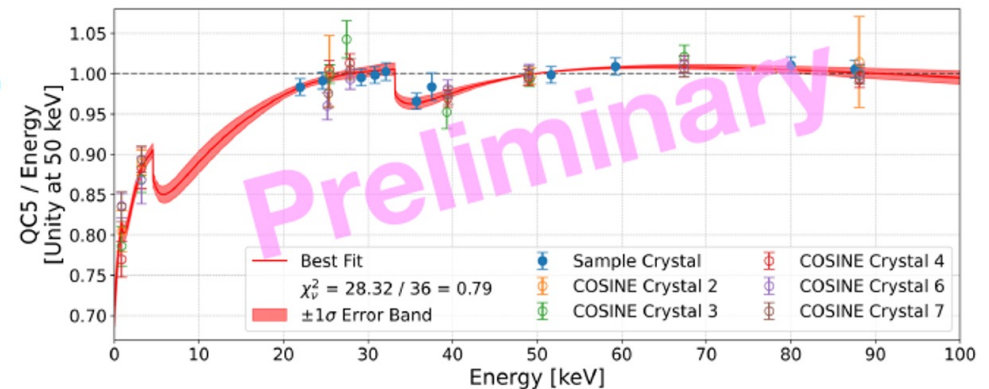
On going efforts : low energy detector responses

Neural network score

0.7-keV threshold

Nonproportionality of NaI(Tl) for γ or x-ray

Nuclear recoil quenching factor (not consider nonproportionality)

3.75 keVnr

See details in Kyungwon Kim's talk (WED)

- Improving low-energy selection using neutral network and reduce the analysis threshold to ~0.7 keVee (~8 NPE)
  - ❖ 5 NPE threshold with deep learning & waveform simulation **See also NEON talk (C. Ha TUE)**
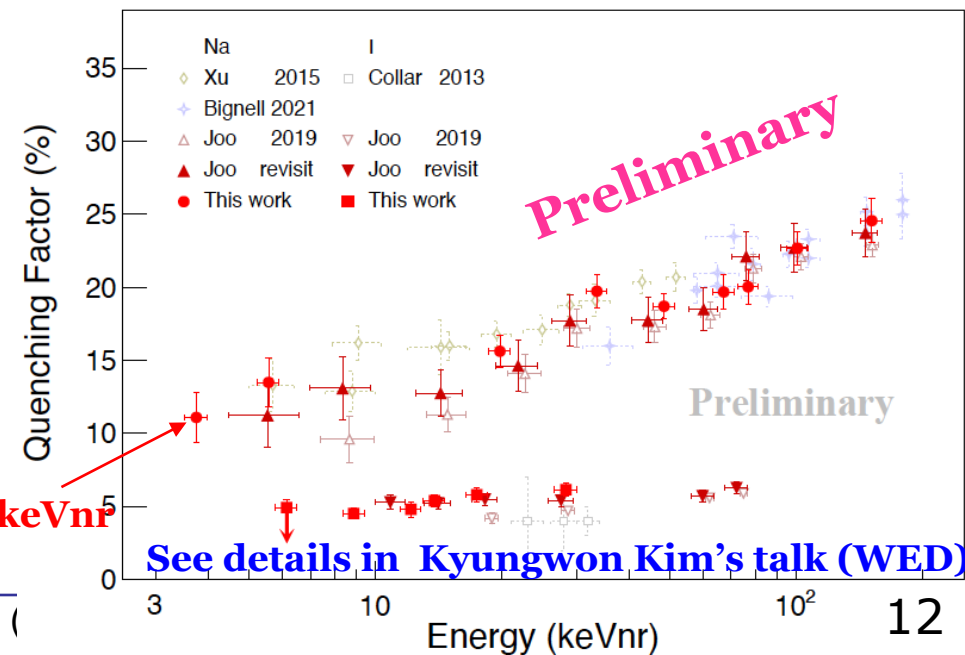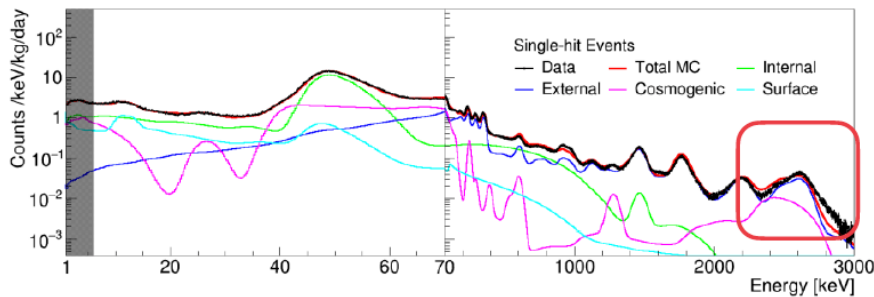- Low-energy calibration for the electron recoil (keVee) and the nuclear recoil (keVnr)
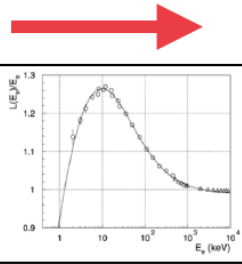 - ❖ Make ready for low-mass DM search

Ongoing efforts : modeling update

Non-Proportionality update example
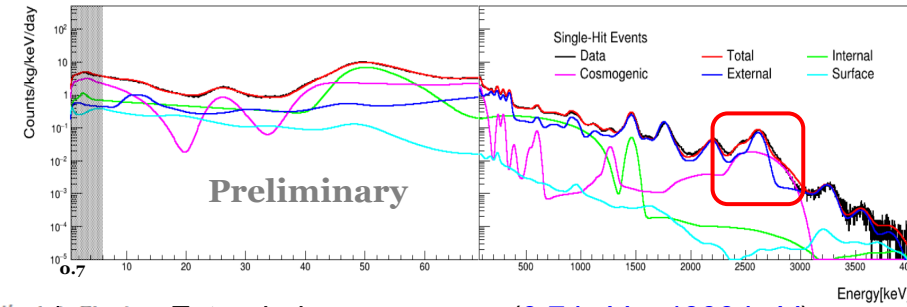
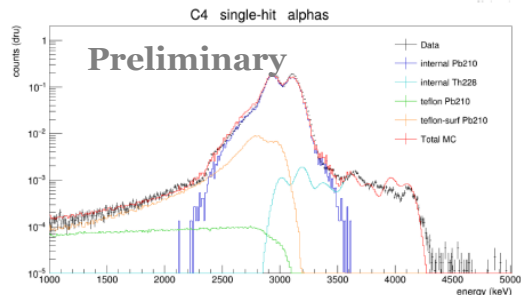*Eur. Phys. J. C. 81 837 (2021)*

Non-Proportionality correction

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

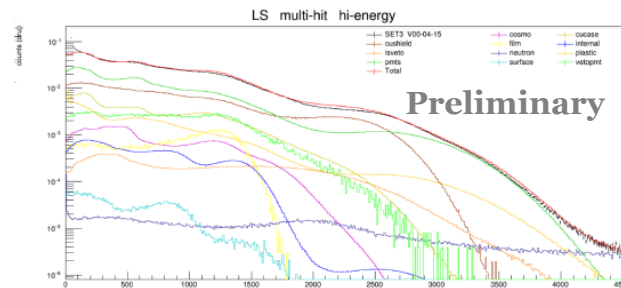## Background modeling in 3 years data

Preliminary

Extended energy range (0.7 keV – 4000 keV)

Alpha spectrum modeling

Preliminary

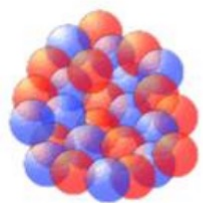## LS spectrum modeling

Preliminary

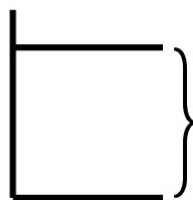**Dark sector signals from 0.7 keV – 4000 keV can be studied !!**

Background modeling updates

• Precise calibration considering non-proportional detector response

• Alpha / LS spectrum modeling for better background understanding
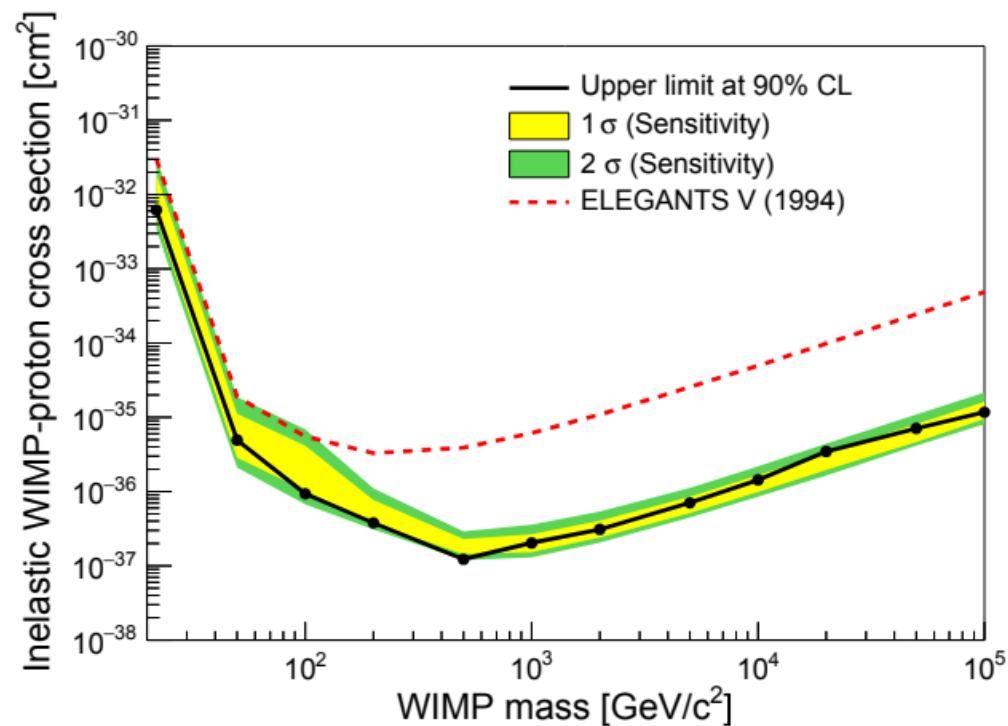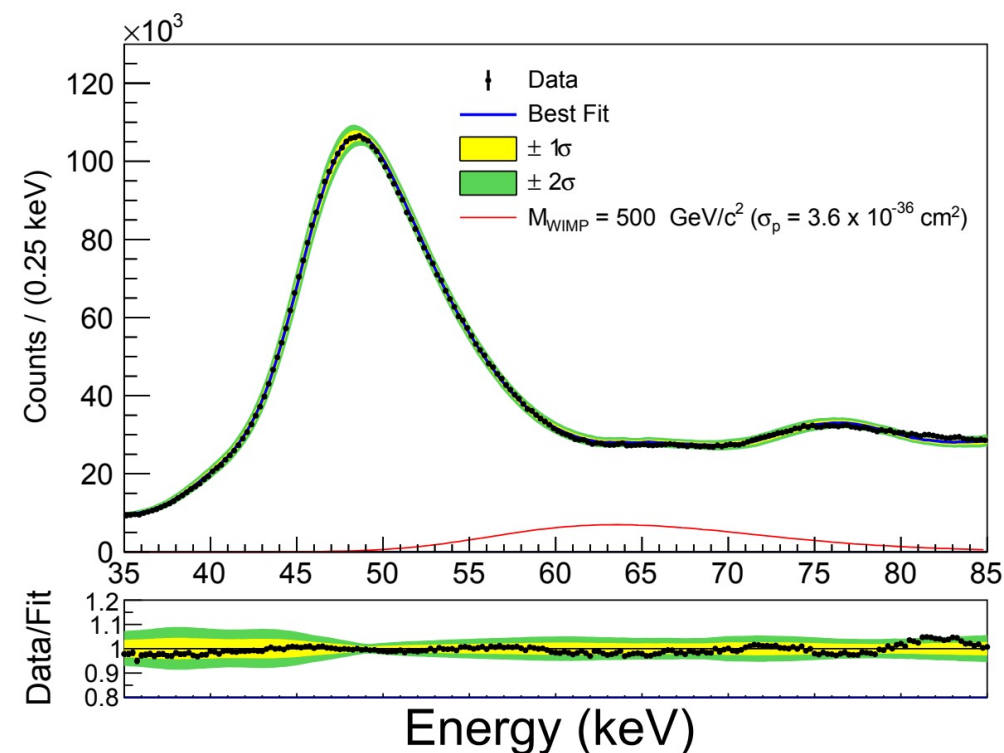
WIMP-^{127}I inelastic interaction

^{127}I

$\}$ 57.6 keV

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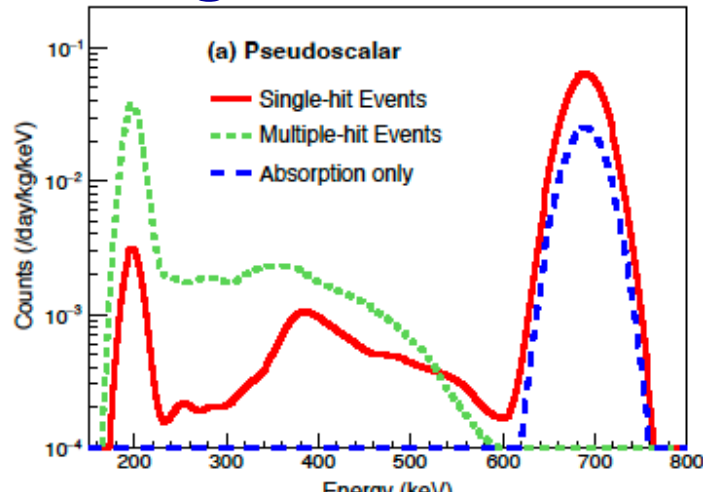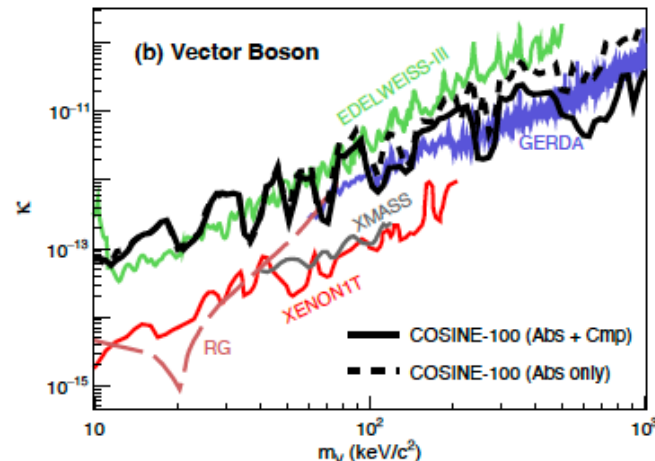- 1.7 years data
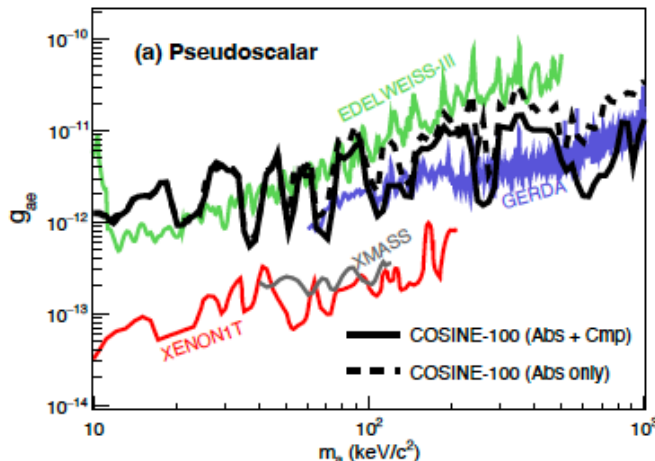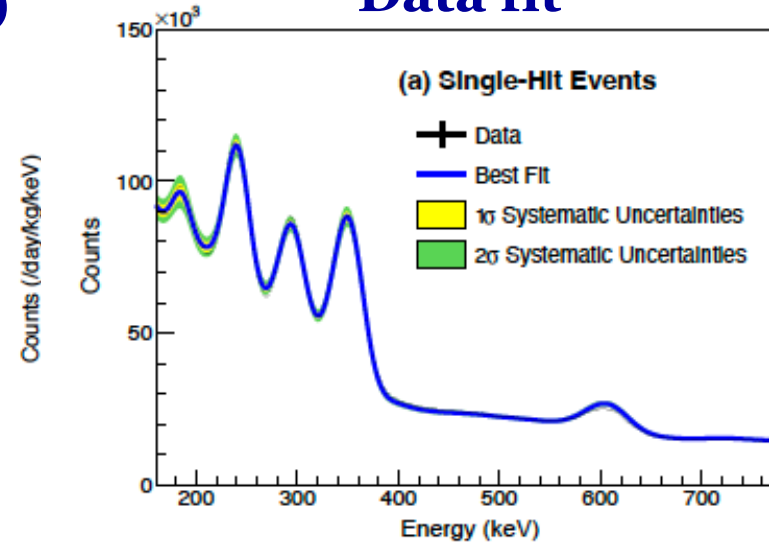- Search for energy 35 keV – 85 keV

arXiv:2037.09814

Bosonic super-WIMP (BSW)

- Bosonic dark matter with mass 10 keV – 1 MeV
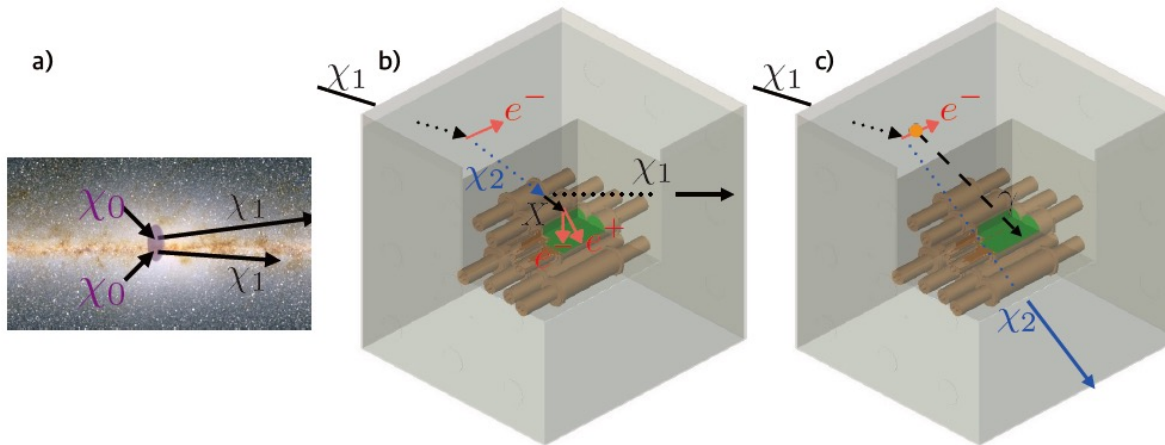
Expected Signal (690 keV BSW)

Data fit

arXiv:2304.01460 (Phys. Rev. D in press)
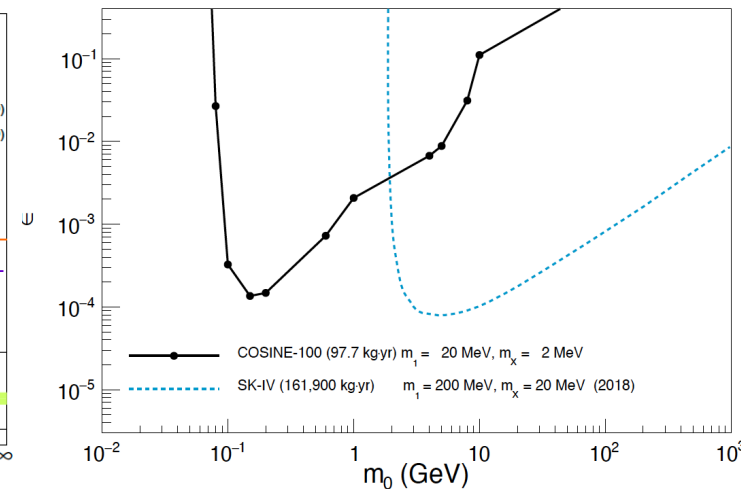
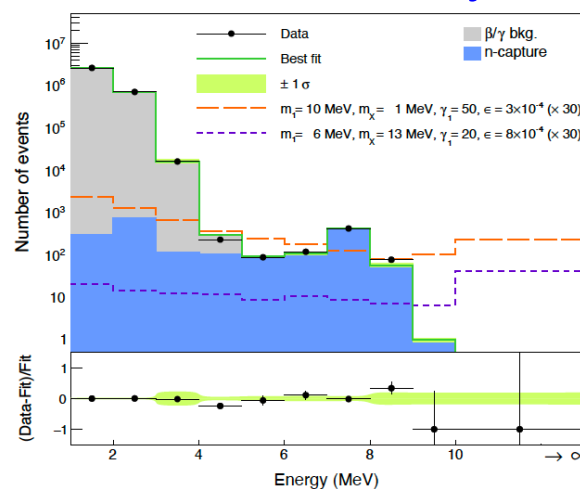# Boosted dark matter with extended energy (~10 MeV)

Inelastic interaction

PRL 122, 131802 (2019)

2 months data

- m_1=20MeV, m_2=40MeV, γ_1=100
- m_1=10MeV, m_2=15MeV, γ_1=50
- m_1=6MeV, m_2=7.5MeV, γ_1=20
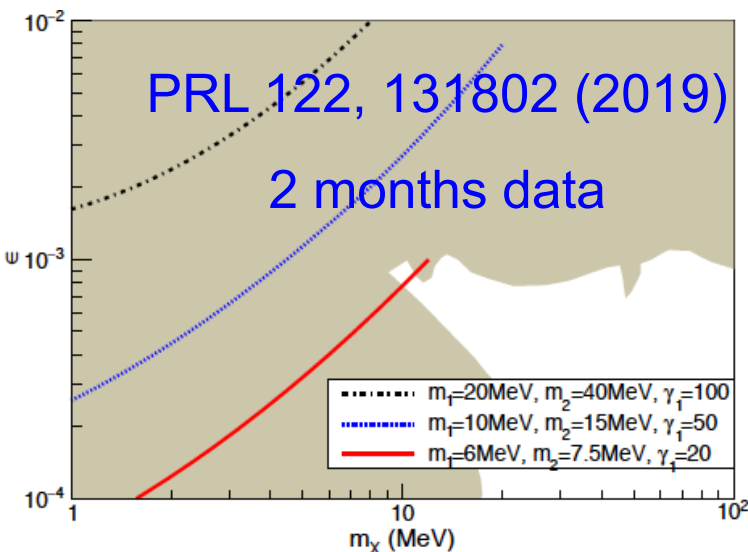
Elastic interaction

1.7 years data

arXiv:2306.00322

- Data
- Best fit
- ± 1σ
- m_1 = 10 MeV, m_X = 1 MeV, γ_1 = 50, ϵ = 3×10⁻⁴ (× 30)
- m_1 = 6 MeV, m_X = 13 MeV, γ_1 = 20, ϵ = 8×10⁻⁴ (× 30)
- β/γ bkg.
- n-capture

- COSINE-100 (97.7 kg·yr) m_1 = 20 MeV, m_X = 2 MeV
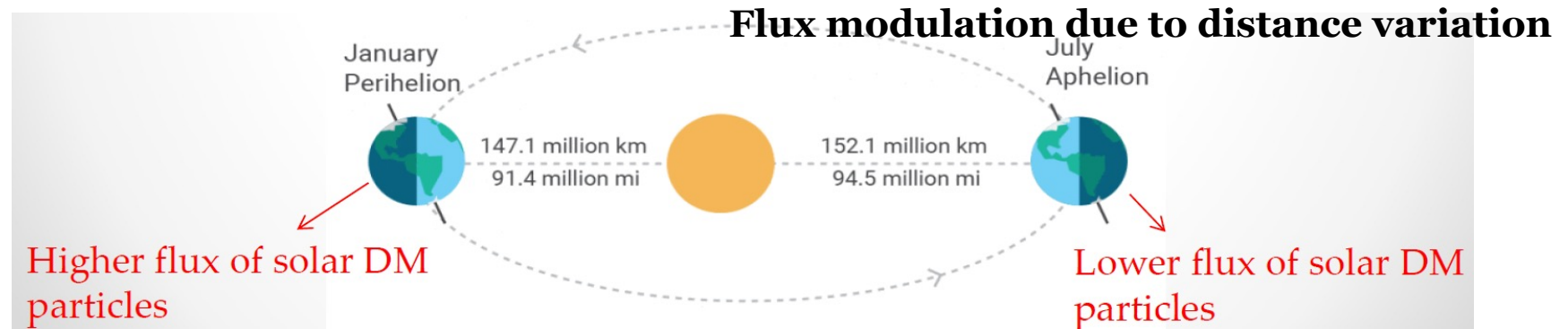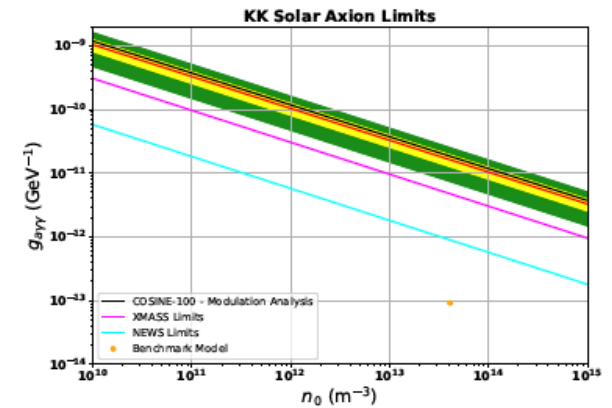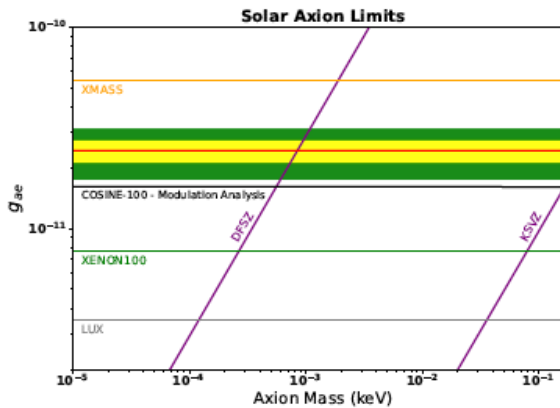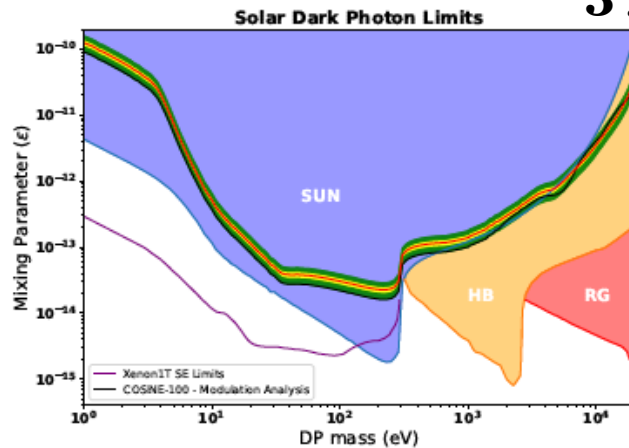- SK-IV (161,900 kg·yr) m_1 = 200 MeV, m_X = 20 MeV (2018)

- 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

Flux modulation due to distance variation

January Perihelion | 147.1 million km / 91.4 million mi | 152.1 million km / 94.5 million mi | July Aphelion

Higher flux of solar DM particles

Lower flux of solar DM particles

3 years data for the modulation search

Phys. Rev. D 107, 122004 (2023)

COSINE room at Yemilab is under preparation

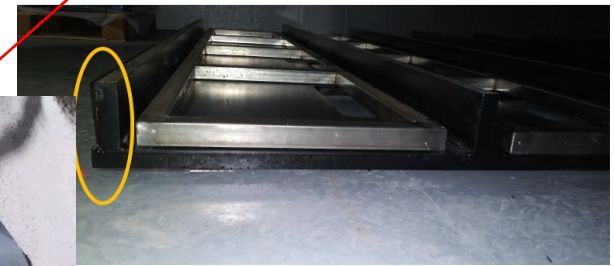- Detector room is ready as of May/2023 at Yemilab
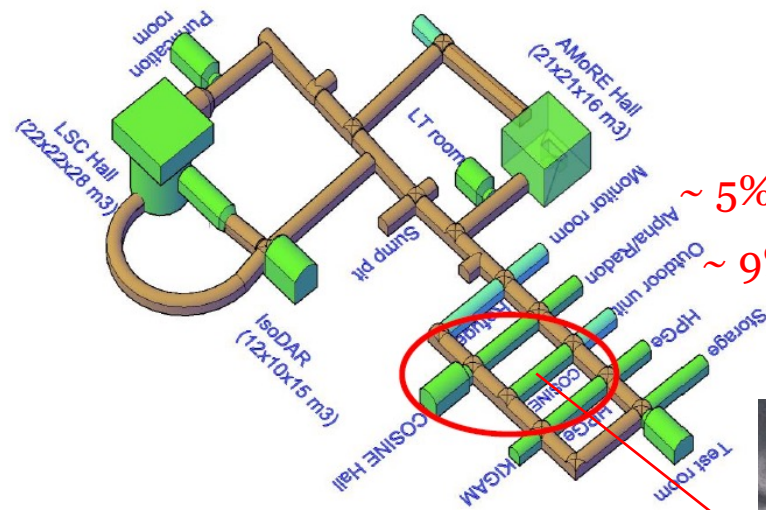
Yemilab map

−35ºC operation

~ 5% increased light yield for gamma

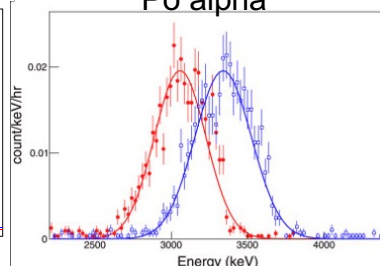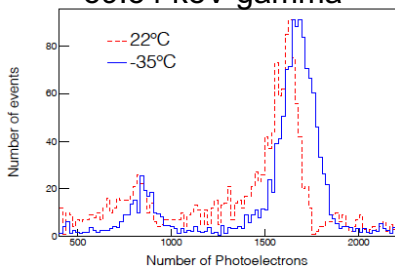~ 9% increased alpha in addition

Improved PSD

Astropart. Phys. 141, 102709 (2022)

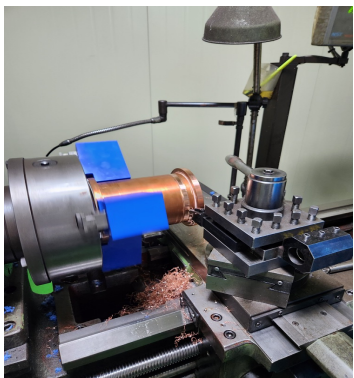59.54 keV gamma

^{210}Po alpha

See also Yemilab talk by

Jungho So (TUE)

- Moving from Yangyang to Yemilab is ongoing now
- Plan to start COSINE-100U by end of 2023

COSINE-100U : Detector upgrade
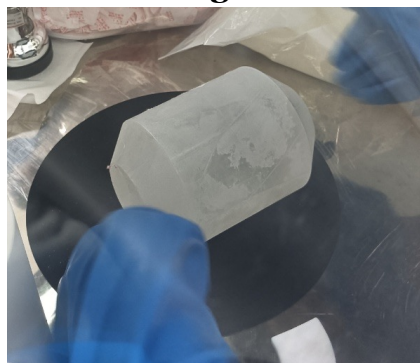
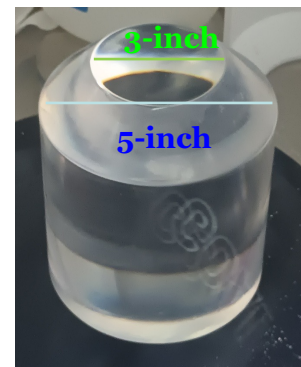## COSINE-100 upgrade for high light yield

Remove the copper case

Mass : 8.26 kg → **7.19 kg**

Crystal machine

Deliver to glove box

COSINE crystal-1

Polishing

3-inch

5-inch
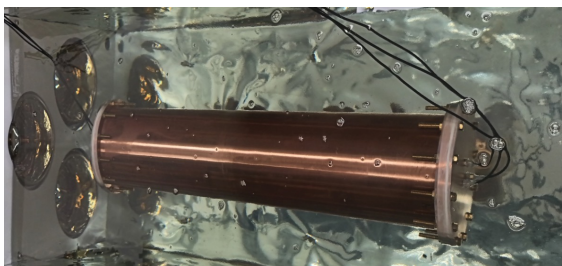
Above ground measurement

Cover design

Cable gland type   Vacuum feed-through type

Direct attachment of 3" PMT

NIMA 981 (2020) 164556

~50% increase light output with similar method

COSINE-100U

- ## Light yield with 59.54 keV gamma

Charge distribution of Am-241

PMT1

PMT2
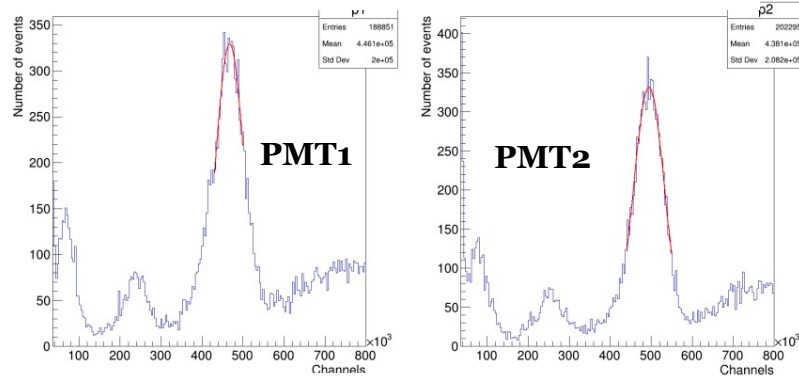
Charge of single photoelectron

PMT1

LY : 10.86 +/- 0.43

PMT2

LY : 10.75 +/- 0.42

Preliminary
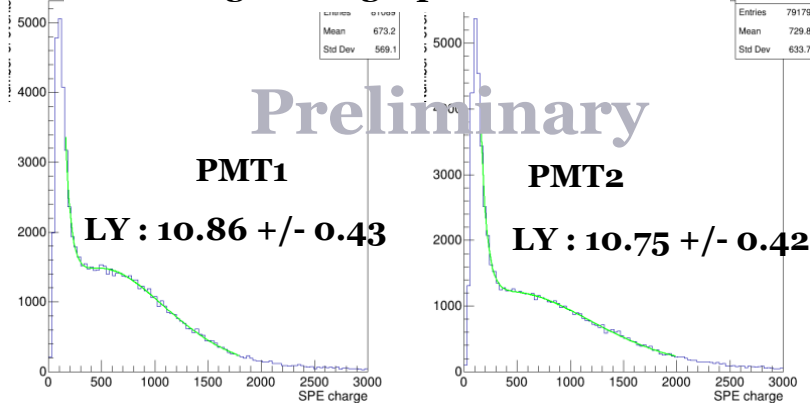
Stability of ~ 1 month (Above-ground)

- First day
- Middle day
- Last day

Preliminary

No gain drop
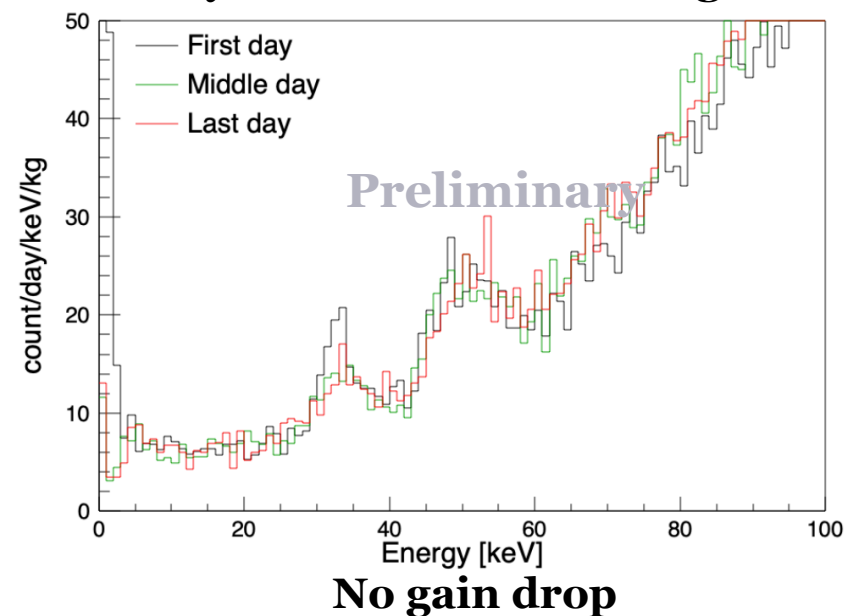
COSINE-100   **COSINE-100U**

14.9 +/- 0.5 NPE/keV ➡ 21.6 +/- 0.6 NPE/keV

45% increased light yield !!!

COSINE-200 crystal development

Purification factory ~ 70 kg powder load

Test grower ~ 1kg ingot

	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

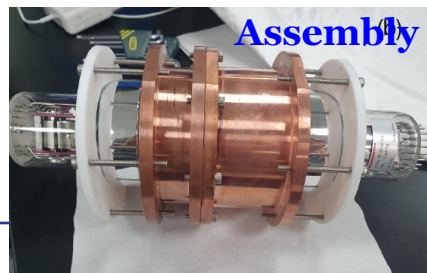**(Maximum production rate ~ 100 kg/month)**
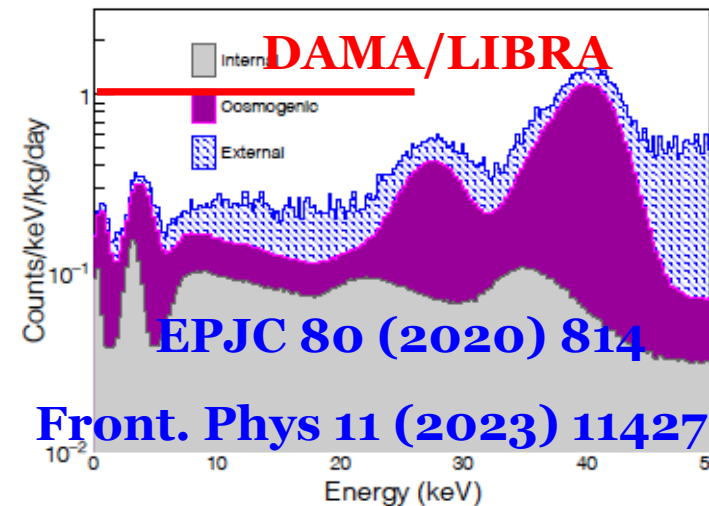
Crystal ingots
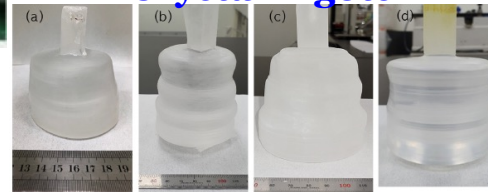
Machining

Assembly

DAMA/LIBRA

EPJC 80 (2020) 814

Front. Phys 11 (2023) 1142765

A proof of principle for **low background NaI**
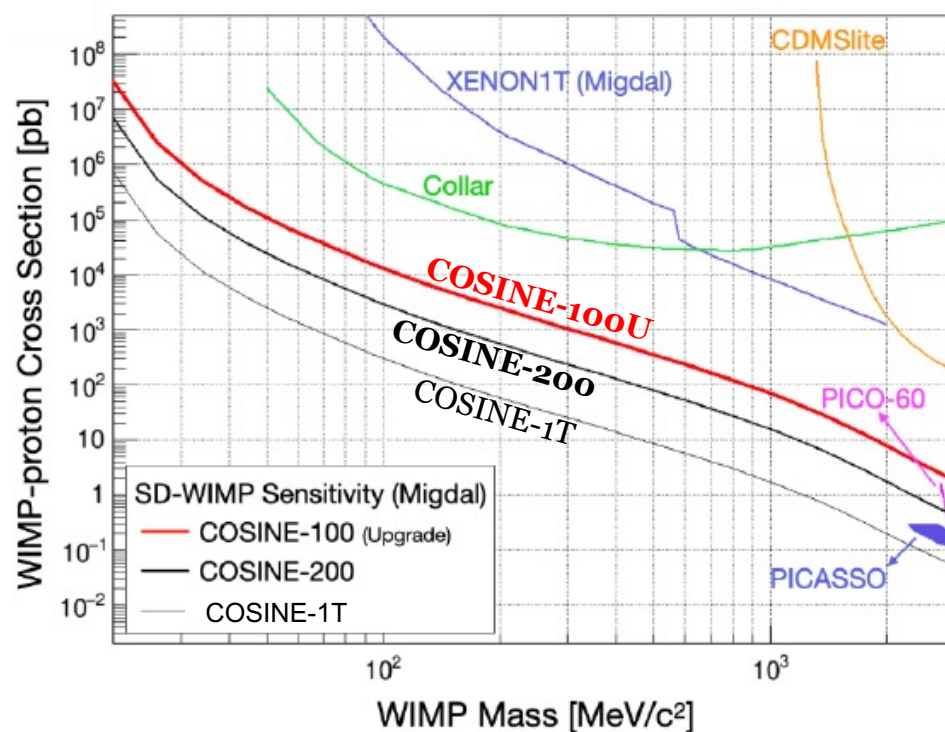
Large crystal growing is going on

Hyun Su Lee,

21

Low-mass sensitivities for spin-dependent limit

WIMP-proton spin-dependent   **Low mass search with Migdal**
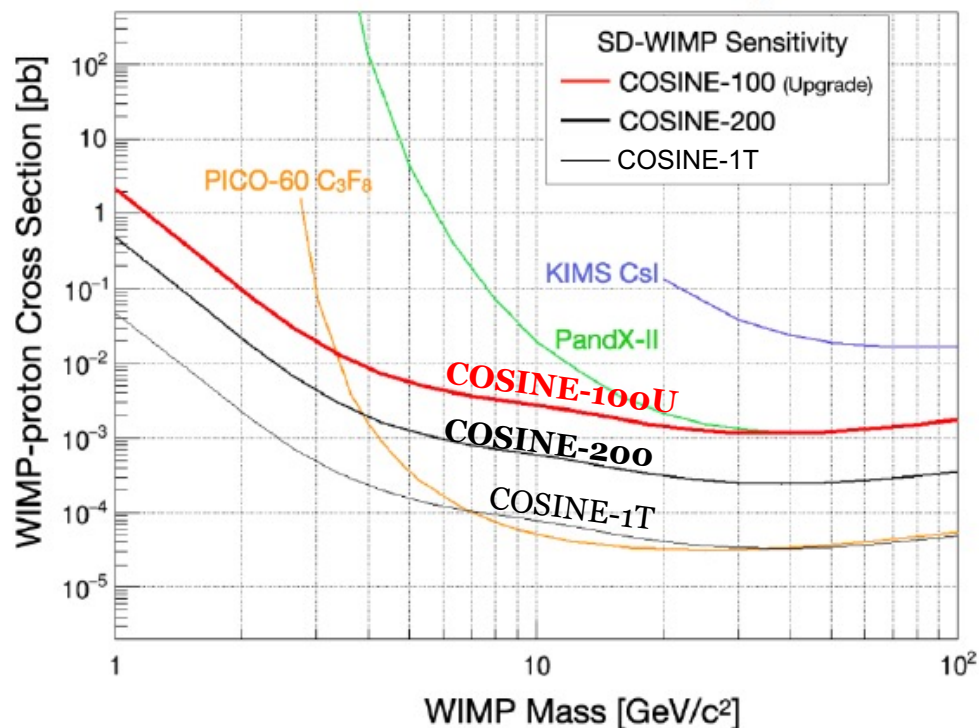
22 NPE/keV, 1 year operation (100% efficiency), 5 NPE threshold

- **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