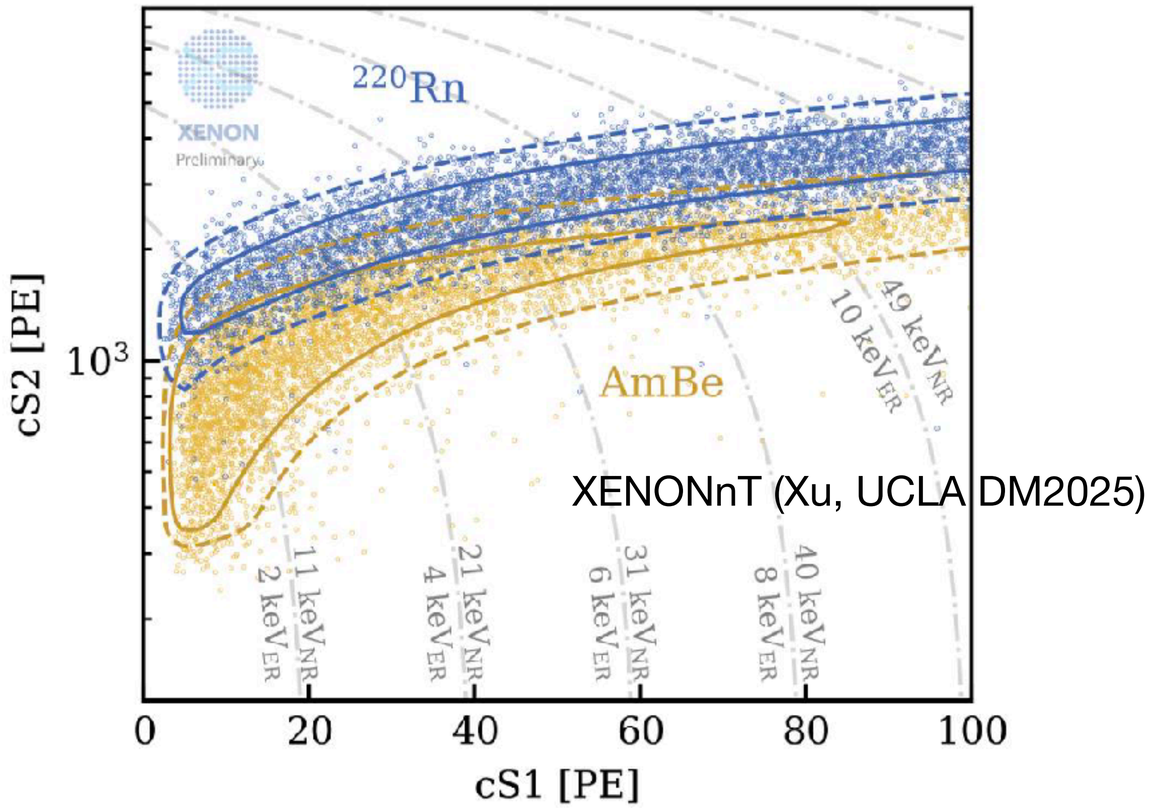
22nd Lomonosov Conference, August 26, 2025

Updates from the COSINE experiment

Chang Hyon Ha for the COSINE collaboration
Chung-Ang University
Seoul, Korea

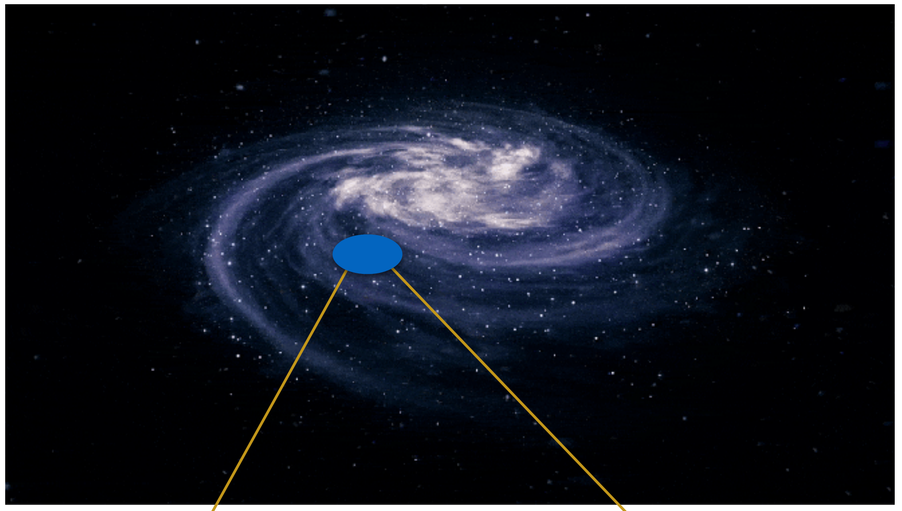
WIMP Signals & Backgrounds

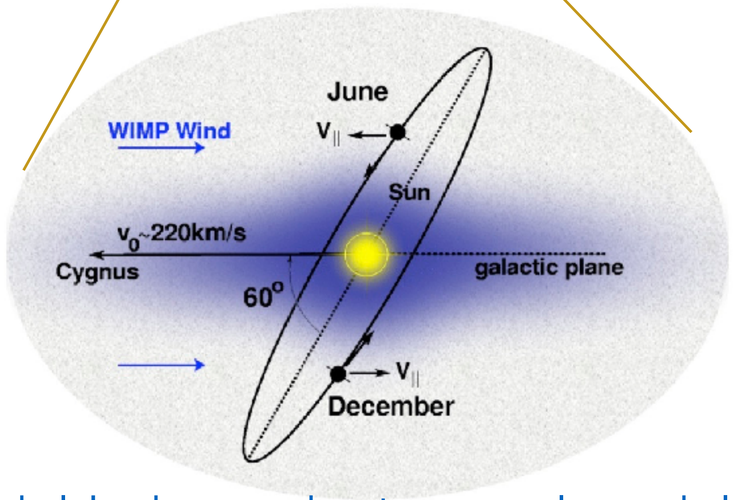
Discrimination of nuclear recoils (Signal) from electron/gamma recoils(Background)



XENONnT (Xu, UCLA DM2025)

Model-dependent searches (this talk)





Model-independent annual modulations (See H. Lee's talk)

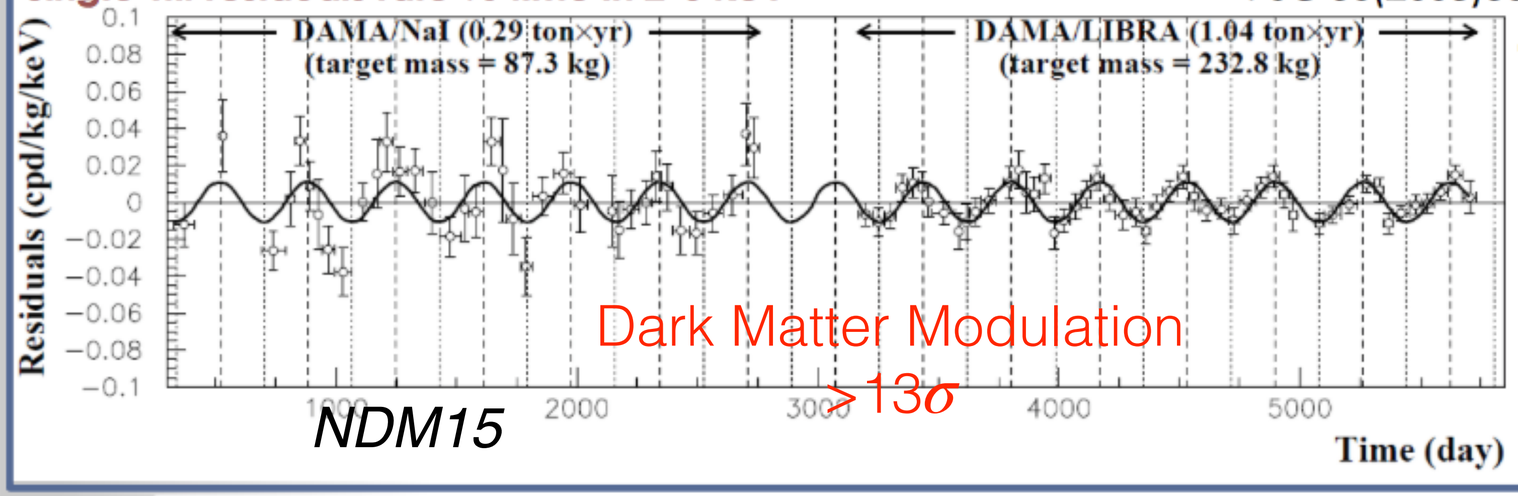
The DAMA signal,

to be confirmed with independent measurements by the same NaI(Tl) target material

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate *vs* time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 9.2 σ C.L.

Absence of modulation? No

χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:

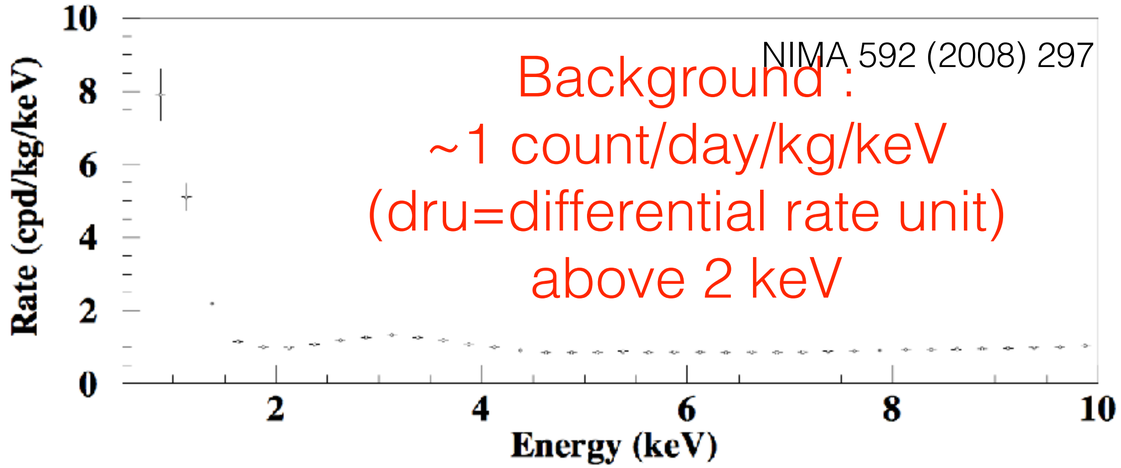
A = (0.0112 ± 0.0012) cpd/kg/keV

t_0 = (144±7) d - T = (0.998±0.002) y

Dark Matter Modulation

>13σ

NDM15



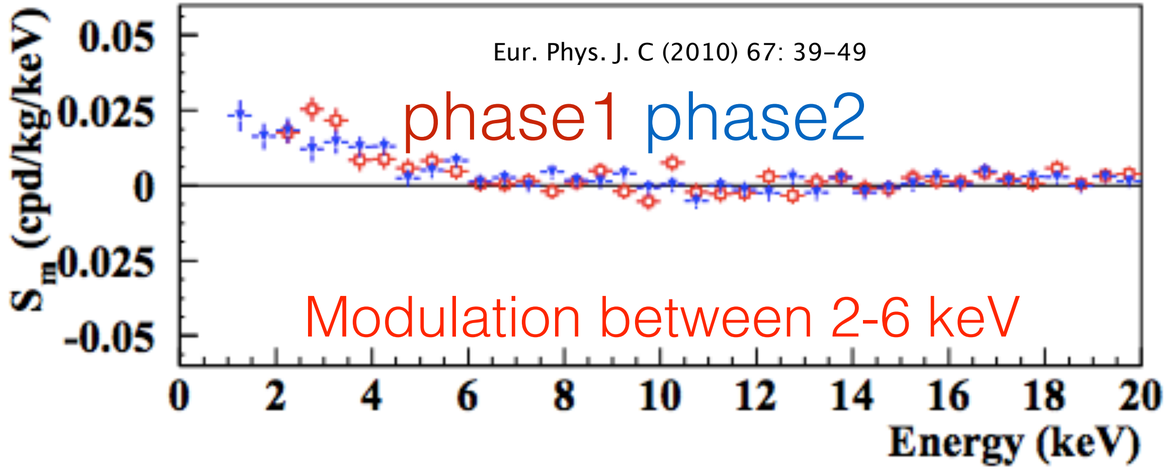
NIMA 592 (2008) 297

Background :

~1 count/day/kg/keV

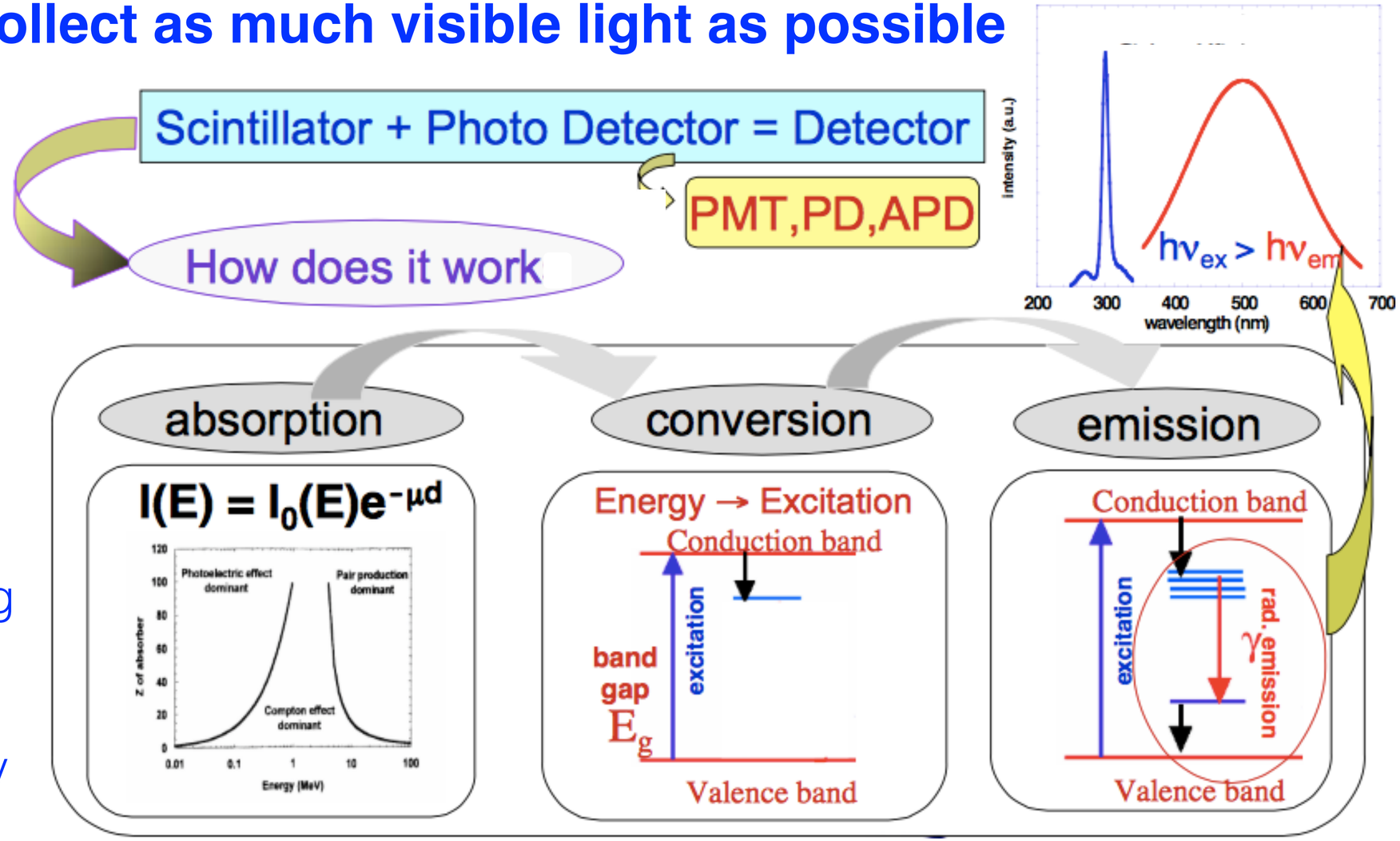
(dru=differential rate unit)

above 2 keV



Crystal Scintillator Technology

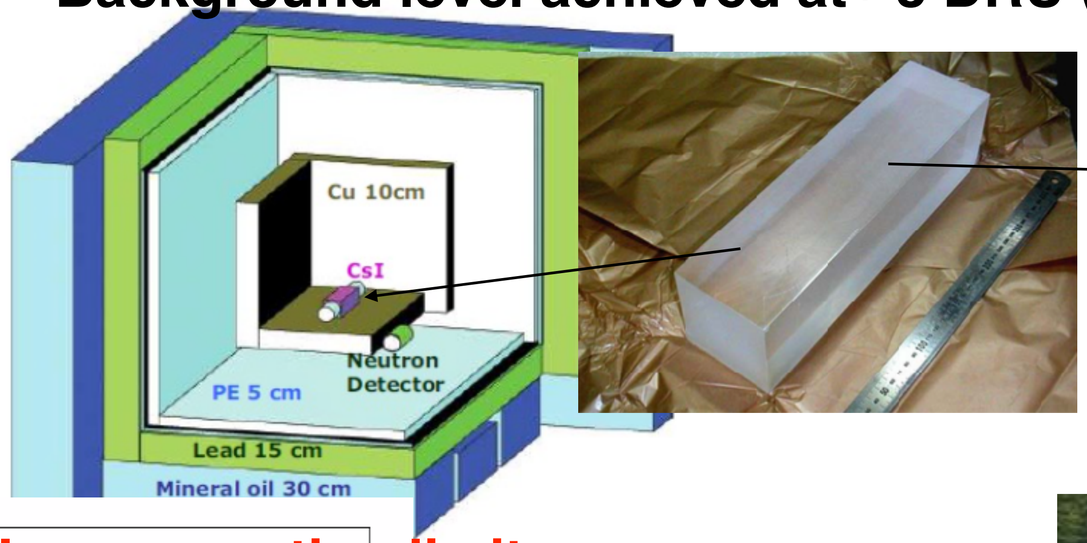
Goal : Collect as much visible light as possible



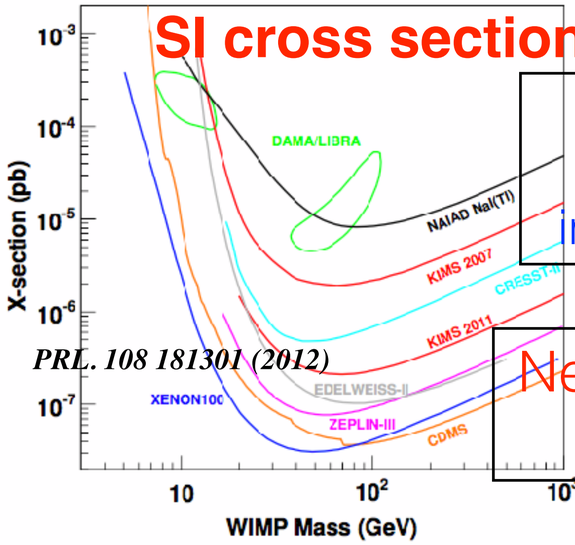
Good Resolution, Good Stopping power, Hygroscopic, Low scalability

Korea Invisible Matter Search : the KIMS experiment

12 CsI(Tl) 8.7 kg crystals (103 kg total)
Background level achieved at ~3 DRU (counts/keV/kg/day) at 3 keV



SI cross section limit

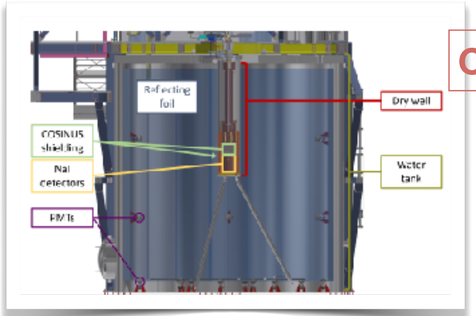


PRL. 108 181301 (2012)

KIMS-CsI results
rejects DAMA signal
in WIMP-Iodine interactions

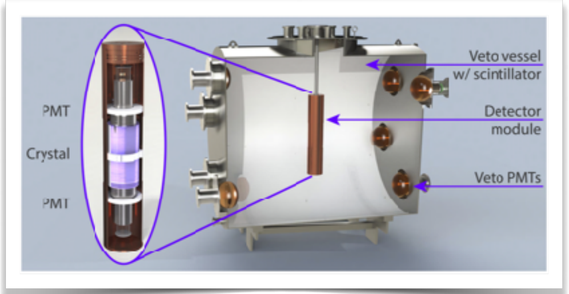
Need to investigate WIMP-Sodium interactions

Global NaI(Tl) efforts



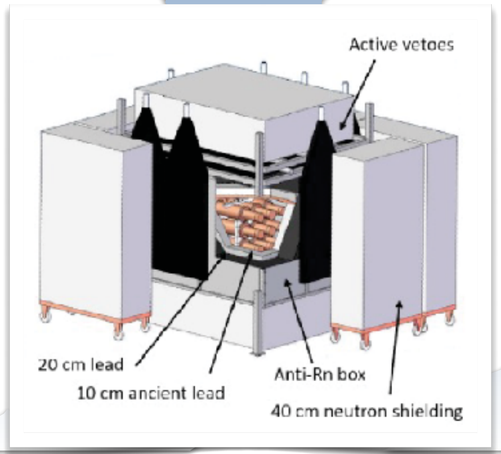
COSINUS @ LNGS

DAMA/LIBRA @ LNGS

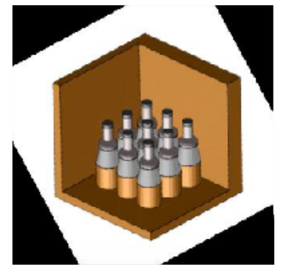


SABRE @ LNGS

ANAIS @ Canfranc

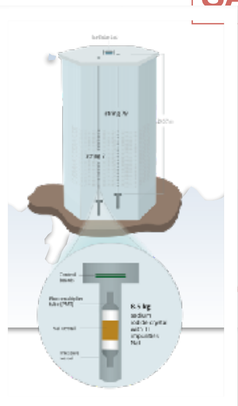


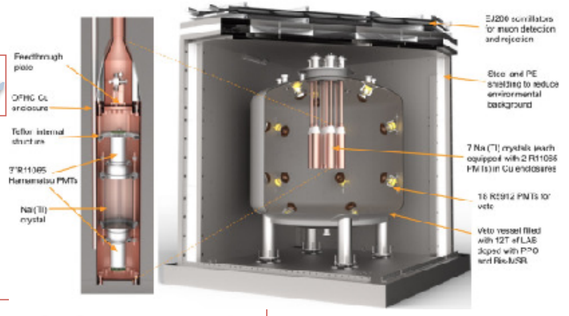
COSINE @ Y2L & Yemilab



PICO-LON @ Kamioka

SABRE @ Stawell



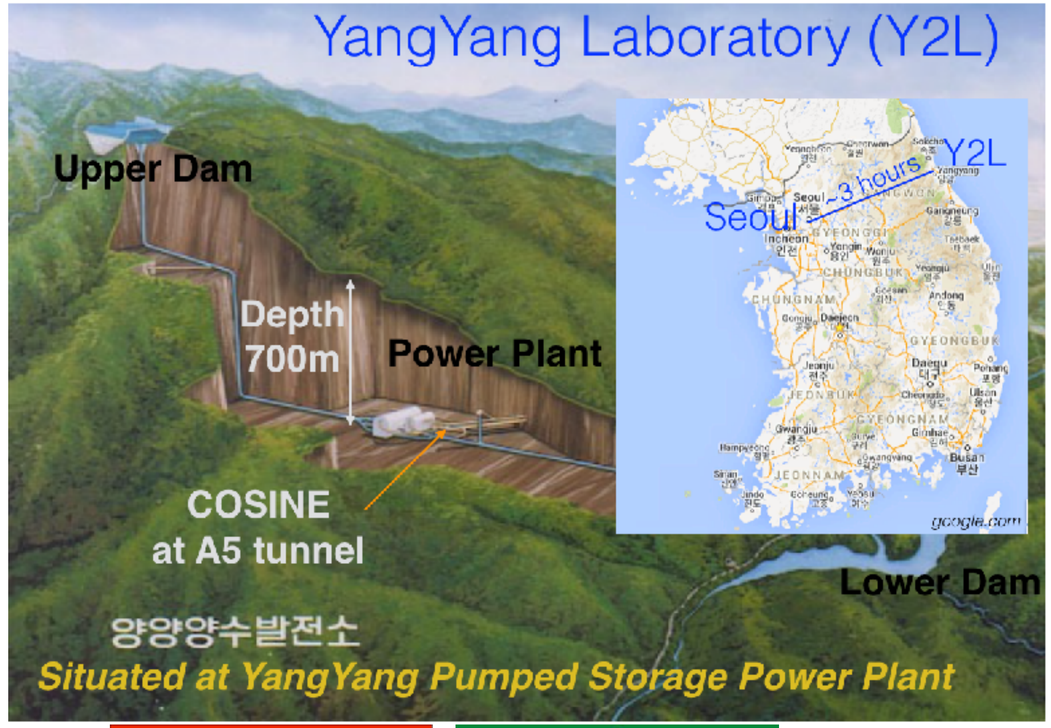


DM-Ice17 @ South Pole

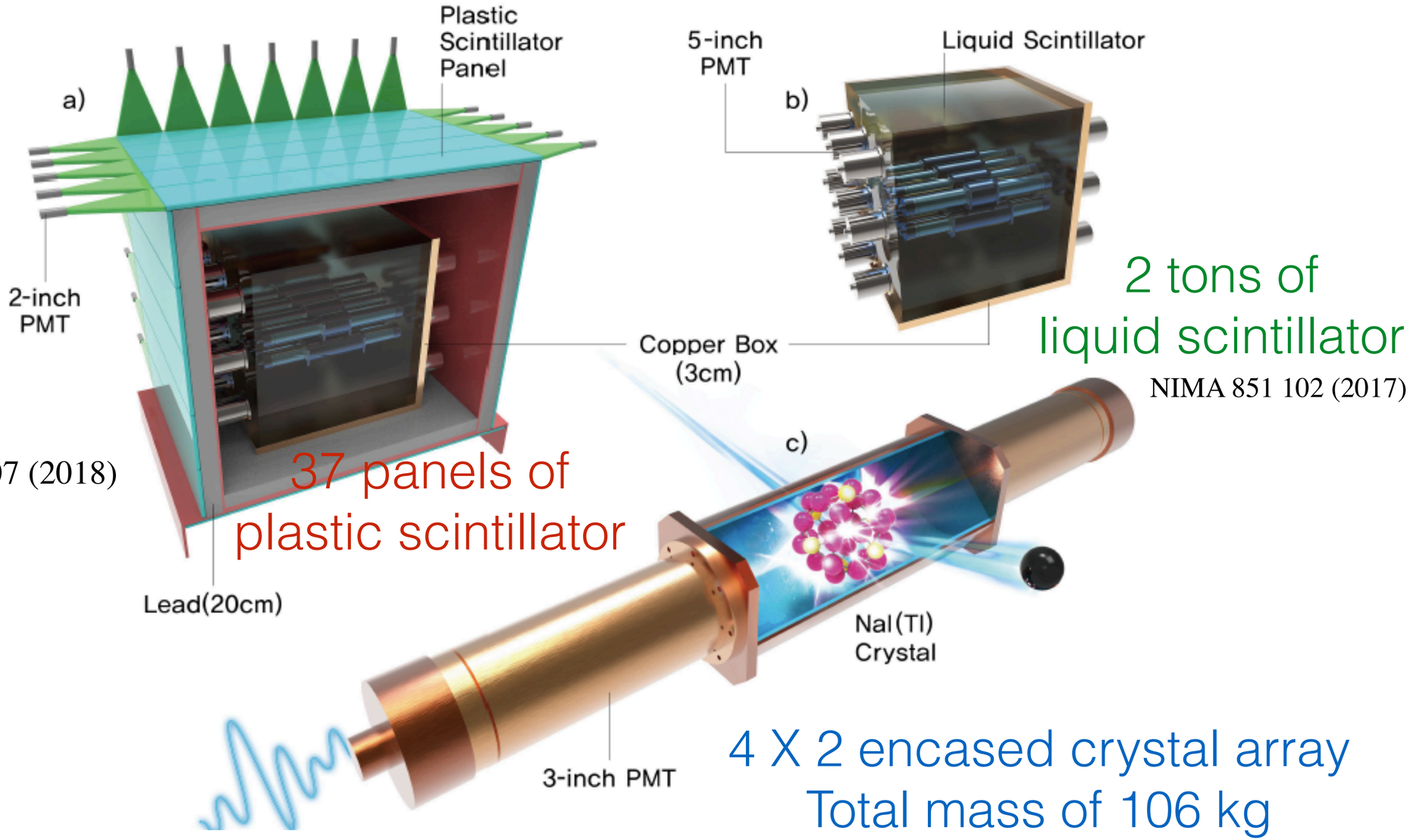
The COSINE-100 Experiment

5 countries,
18 institutes
60 scientists

Joint collaboration between KIMS and DM-Ice to search for dark matter interactions in NaI(Tl) scintillating crystals.



The COSINE-100 detector components



JINST13 T02007 (2018)

37 panels of
plastic scintillator

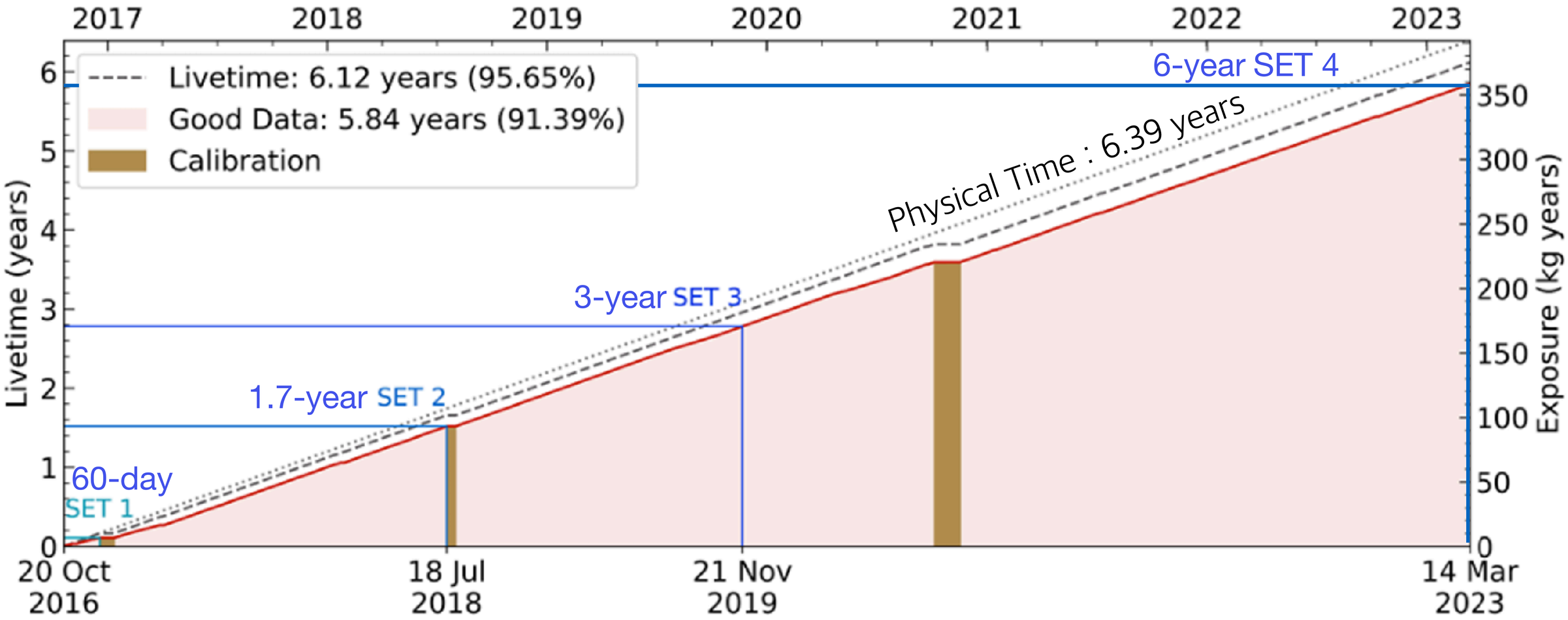
2 tons of
liquid scintillator

NIMA 851 102 (2017)

4 X 2 encased crystal array
Total mass of 106 kg

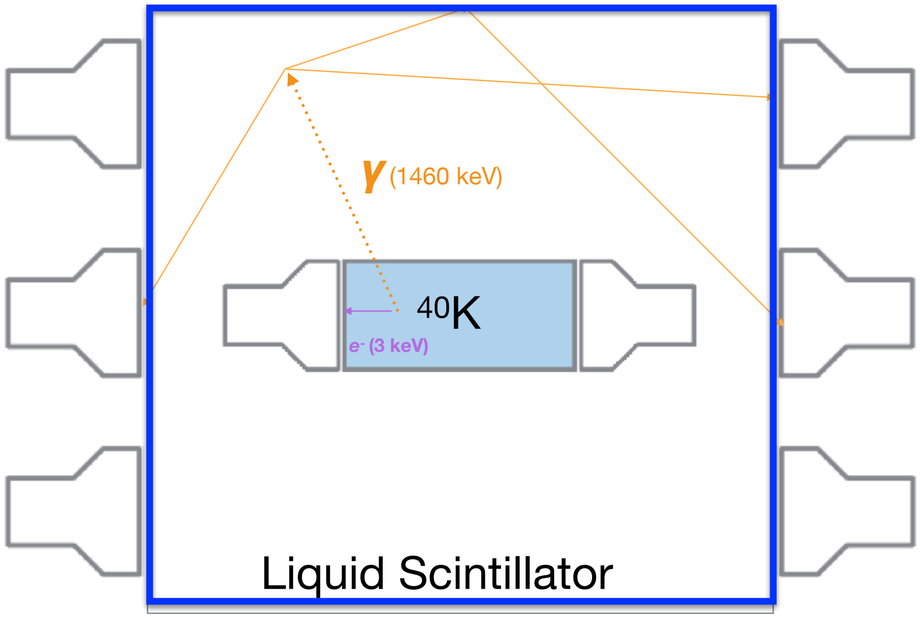
EPJC 78 107 (2018)

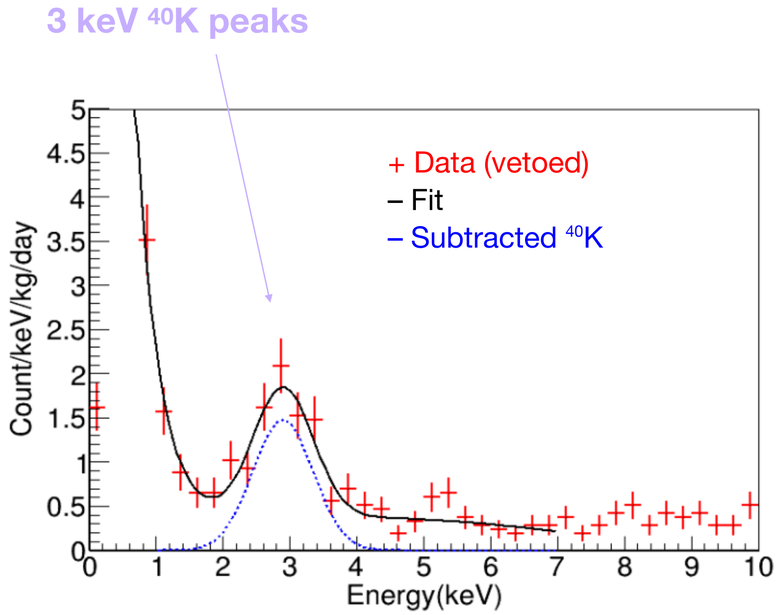
COSINE-100 Total Exposure
(Total 360 kg · years)

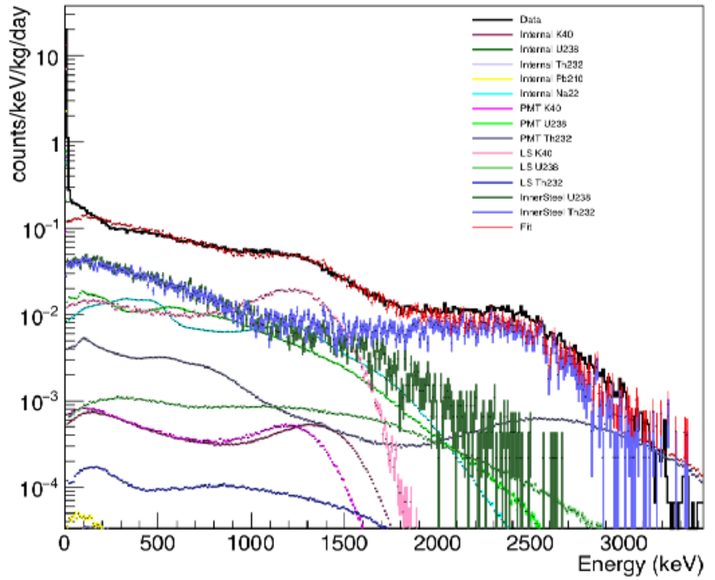


Stable running of the detector for 6.39 years. Good runs are more than 91%

Crystal-LS coincidence





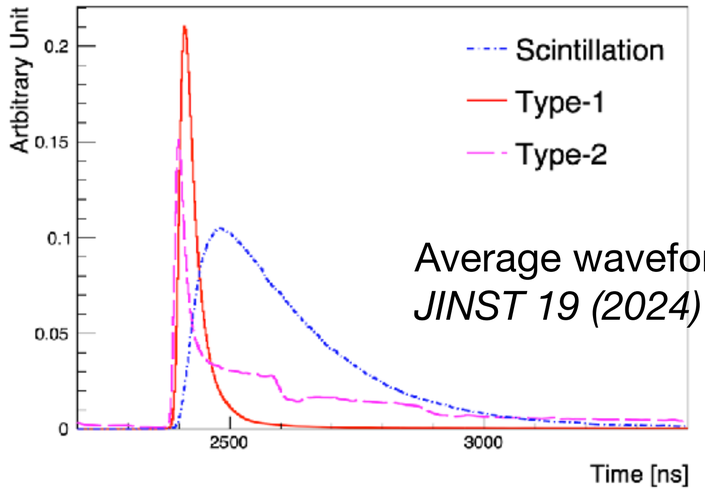


Nucl. Instrum. Methods A 1006, 165431 (2021)

- Liquid scintillator light is passively read out when there is a trigger in a crystal.
- A crystal trigger with LS energy deposit larger than 80 keV is defined as multiple hit events.
- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events (70-80%)**
- Liquid scintillator internal contamination well modeled with simulation

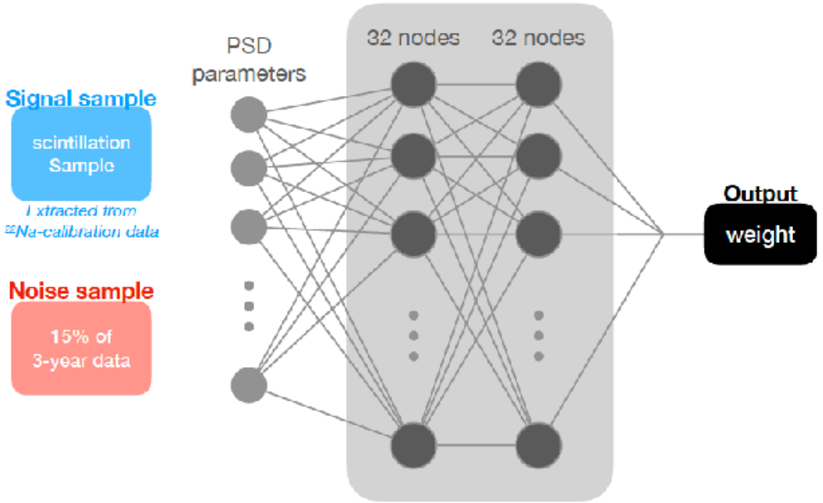
PMT noise reduction

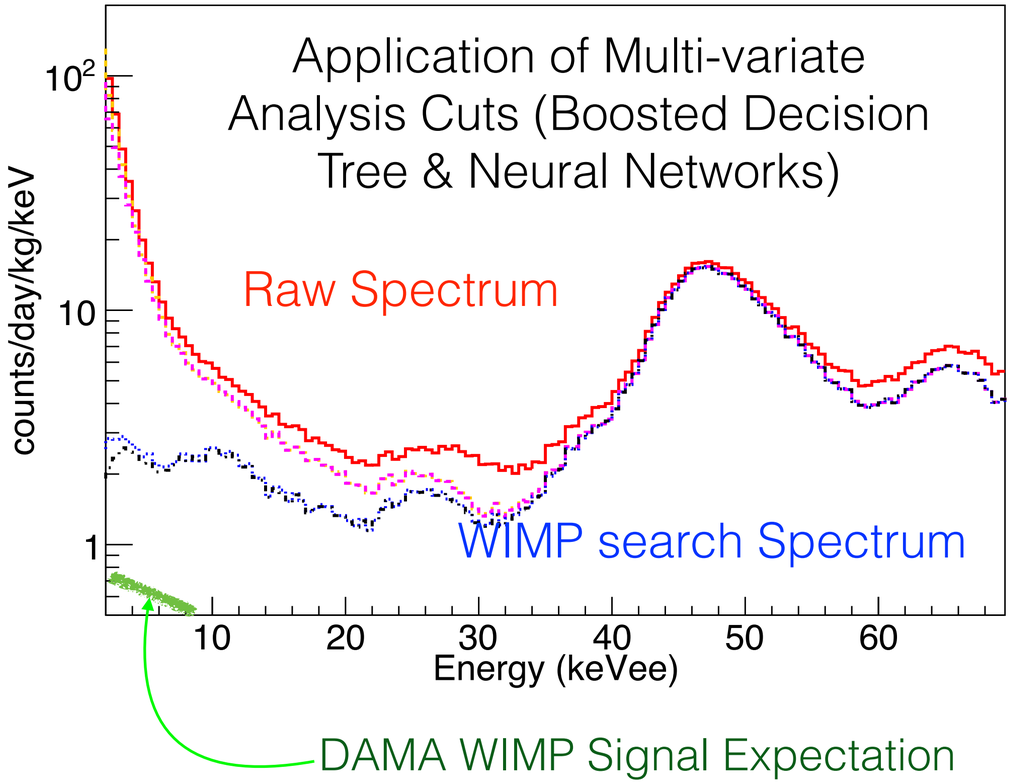
Experiment has noise and WIMP search=Noise Reduction



Average waveform (2-6 keV)
JINST 19 (2024) 12, P12013

Multi-layer perceptron (MLP)





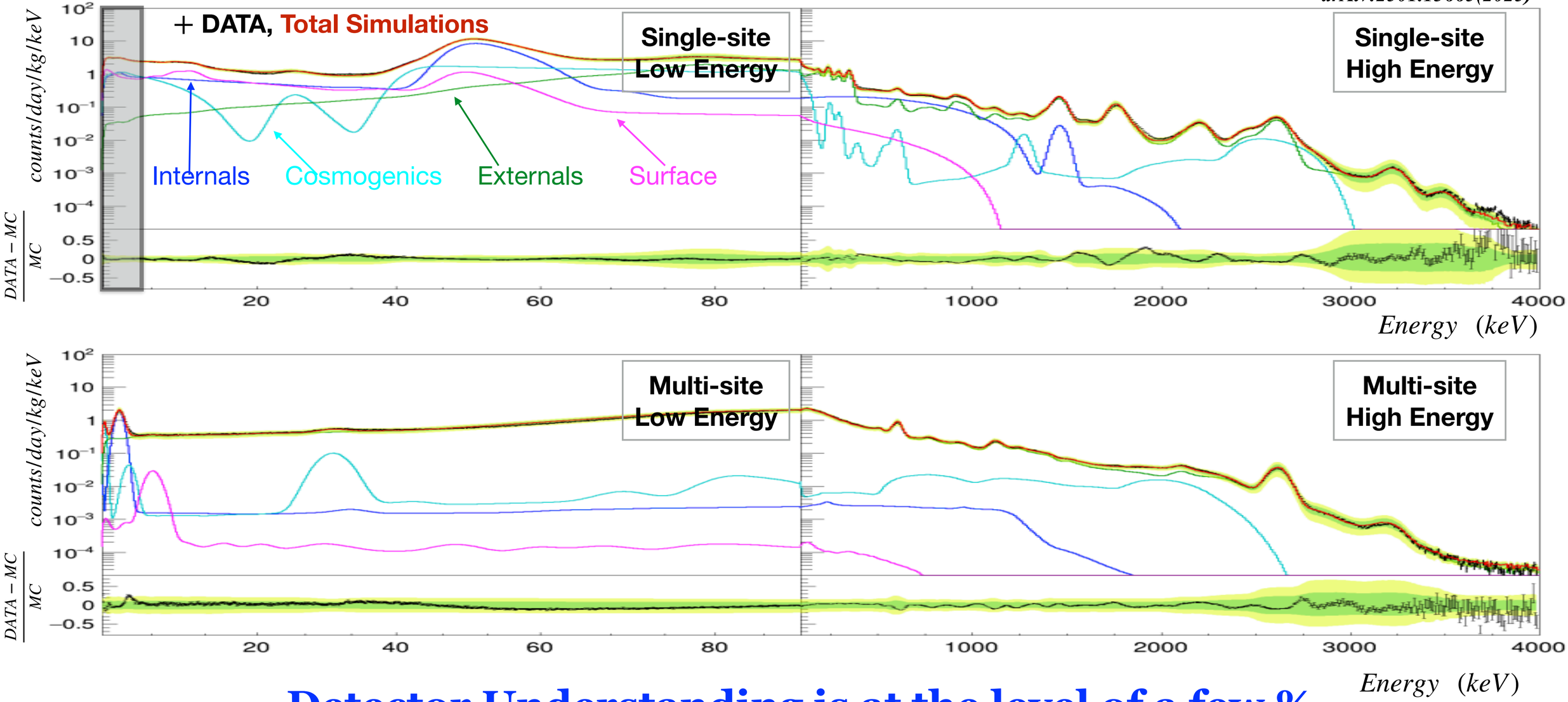
COSINE-100 model-dependent WIMP search strategies.

1. **Background-limited WIMP extraction**
2. **Pulse shape discrimination of nuclear recoils among background β/γ**

Background Spectra & Simulations

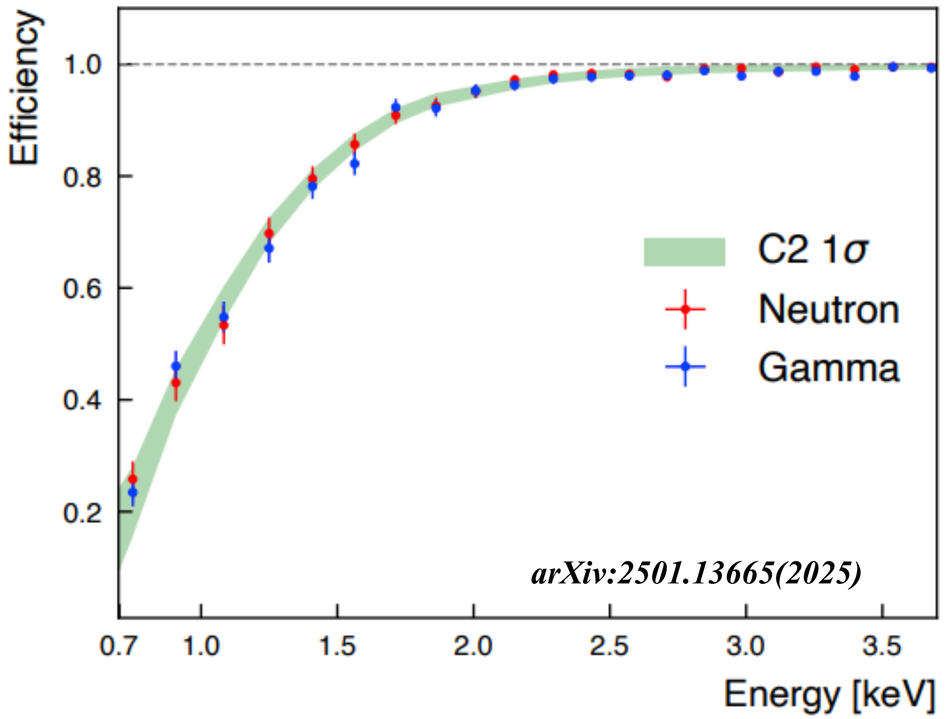
Eur. Phys. J. C (2025) 85: 32
arXiv:2501.13665(2025)

ROI

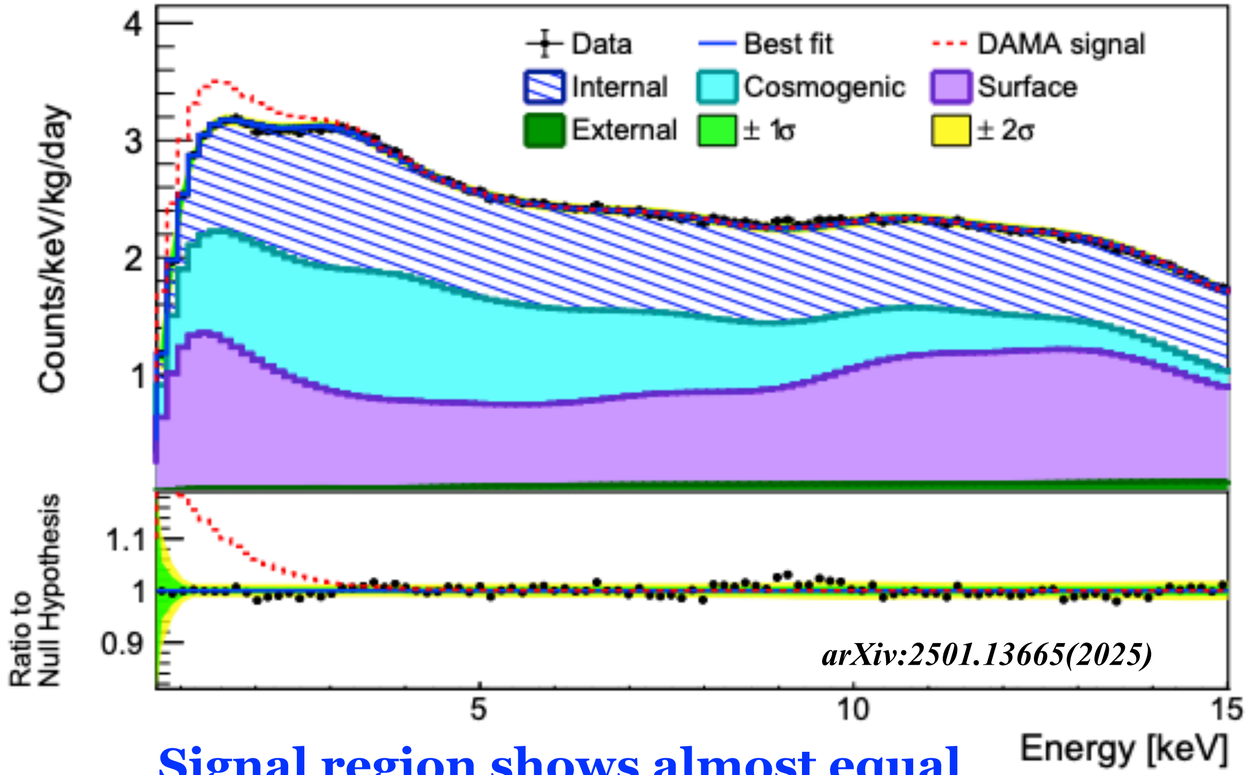


Detector Understanding is at the level of a few %

(Background-limited) Model-dependent WIMP search with 0.7-keV threshold (SET3, 3 yr)

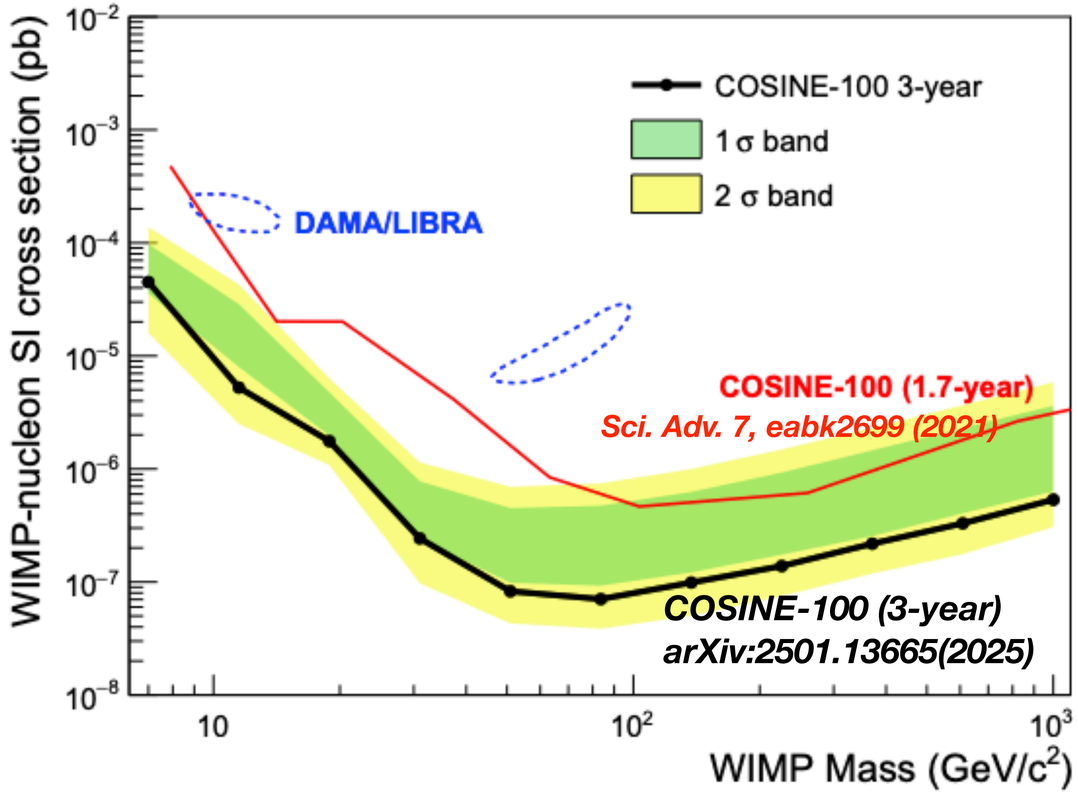


Efficiency near the threshold is mostly driven by Event selection (PMT noise) and Light Yields.



Signal region shows almost equal contributions of Internal (crystal growth), Cosmogenic (cosmic-ray activations), and Surface (detector encapsulation) components.

(Background-limited) Model-dependent WIMP search with 0.7-keV threshold (SET3, 3 yr)

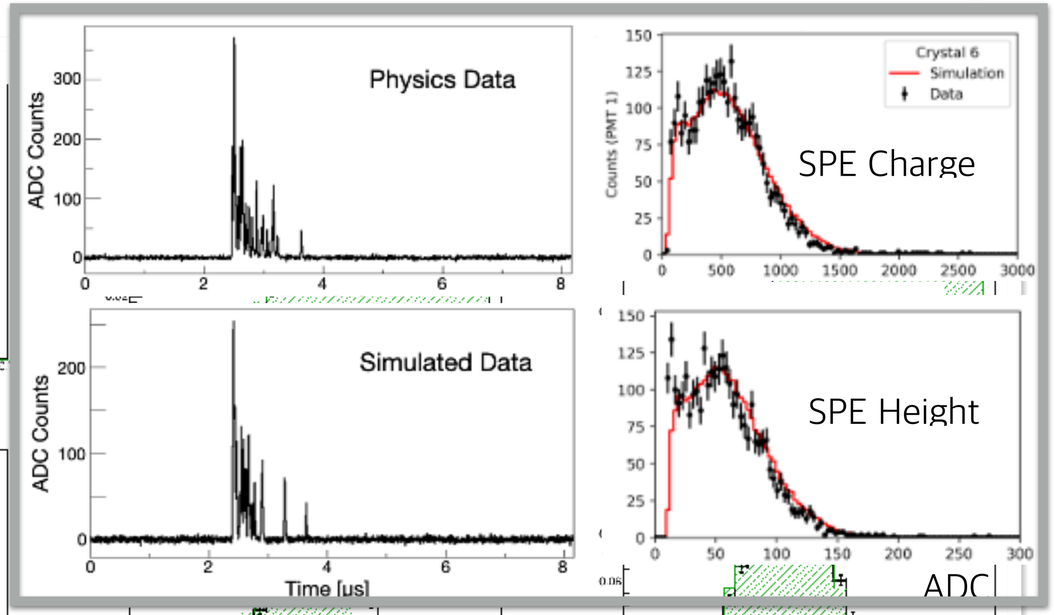


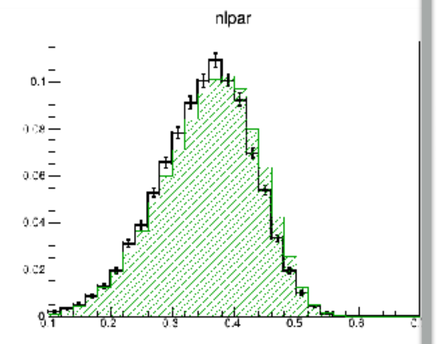
A factor of 10 improved result compared to the previous result

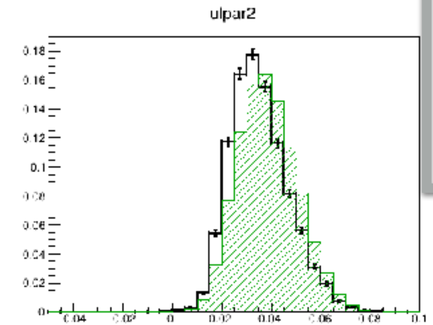
(Lowered threshold by better noise rejection, better background understanding)

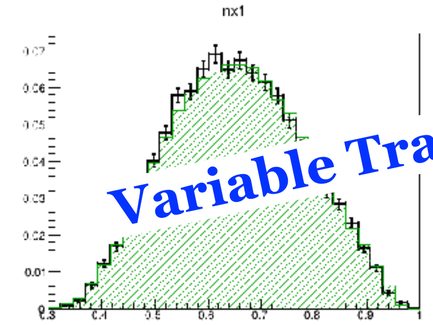
Model-dependent search for SET4, 6 year Full data with 0.5 keV threshold

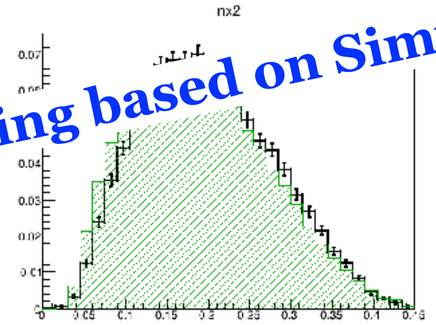
Generate Waveforms for training

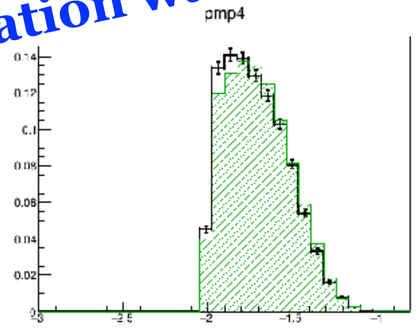




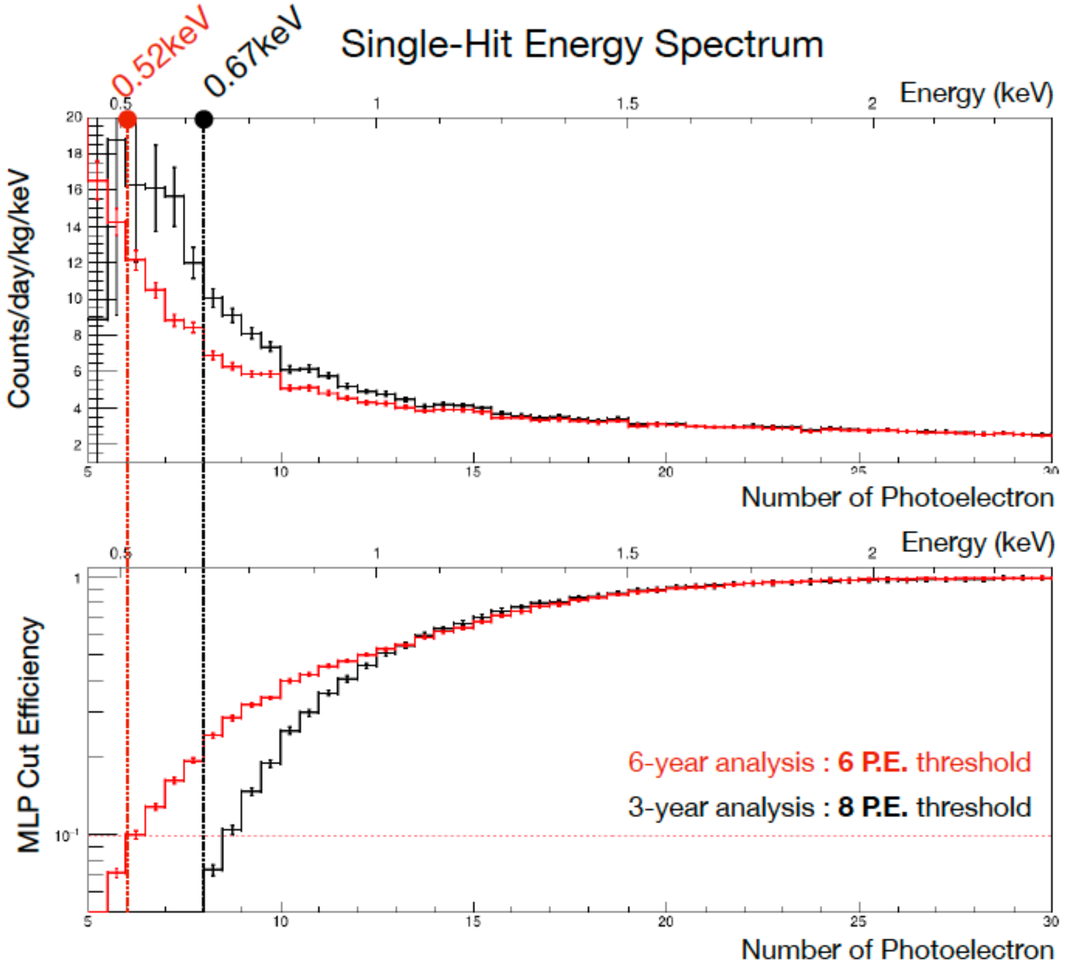








Variable Training based on Simulation waveforms

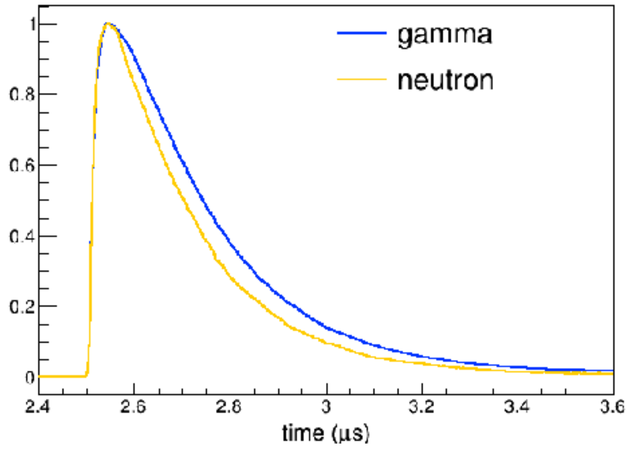


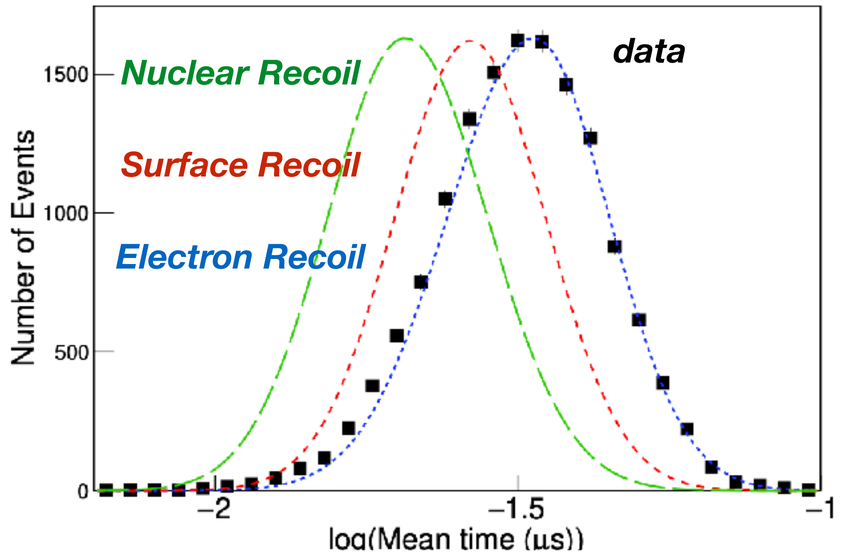
- **Analysis Threshold down to 0.5 keV**
- **Data size doubles**
- **Final results expected later this year**

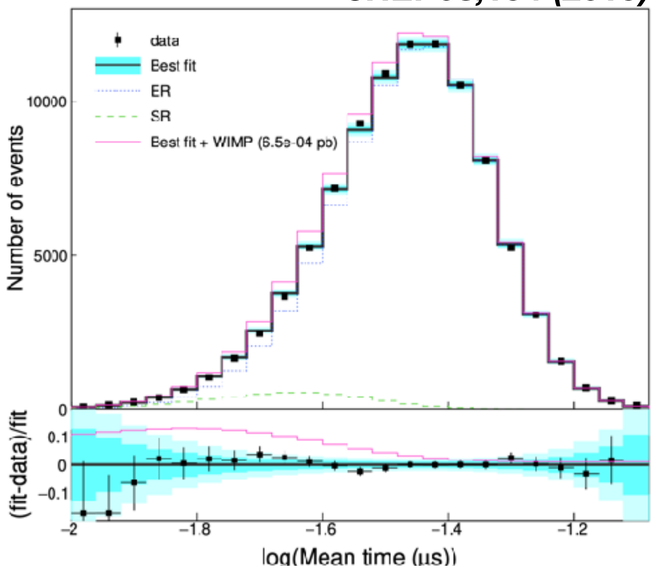
Pulse Shape Discrimination Analysis (ongoing)

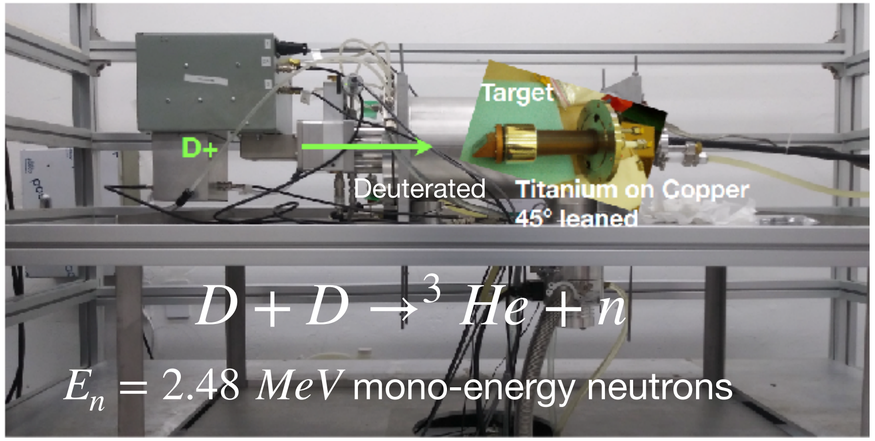
JHEP03,194 (2019)

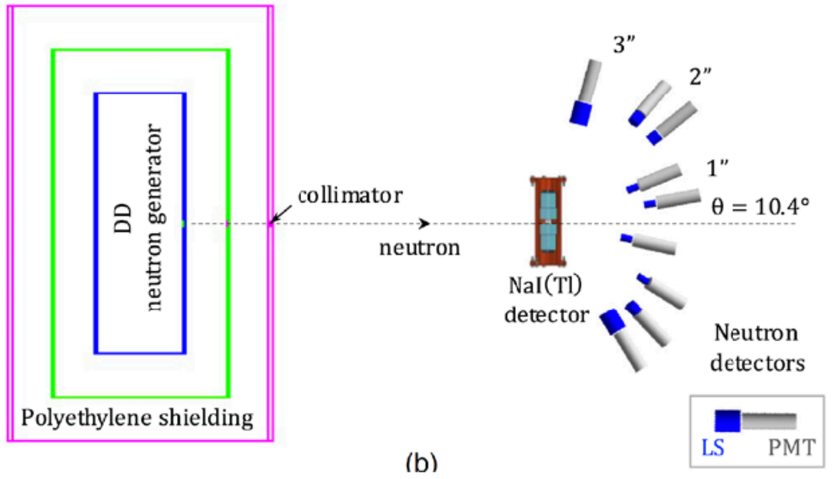
Pulse shape in NaI(Tl) crystal

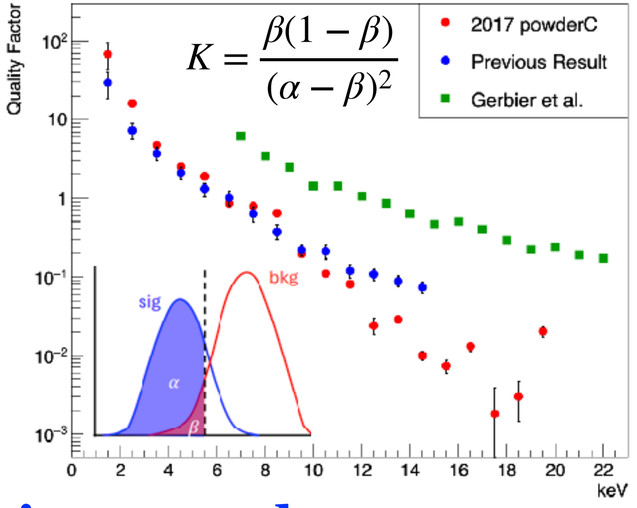










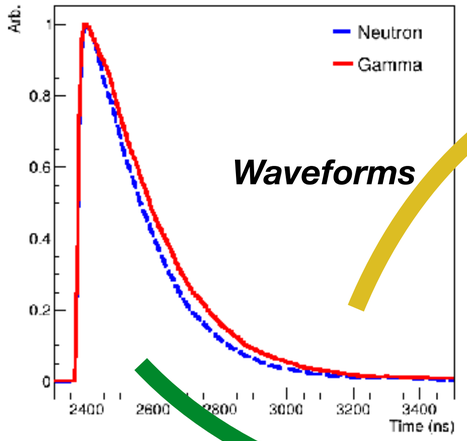


Addition of PSD analysis to the WIMP extraction will significantly improve the nuclear recoil sensitivity of NaI(Tl) crystal

Pulse Shape Discrimination Analysis (ongoing)

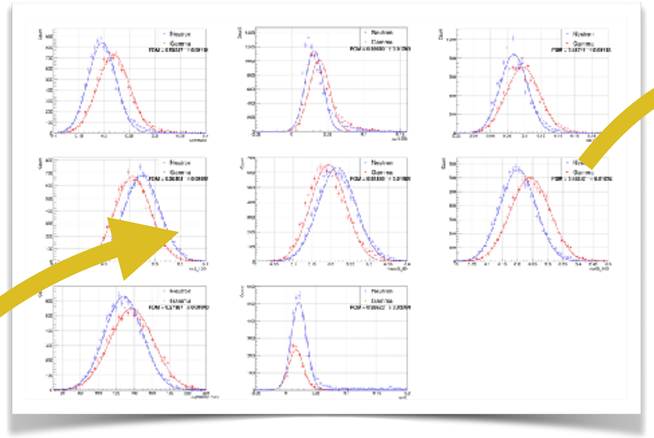
2-6 keV

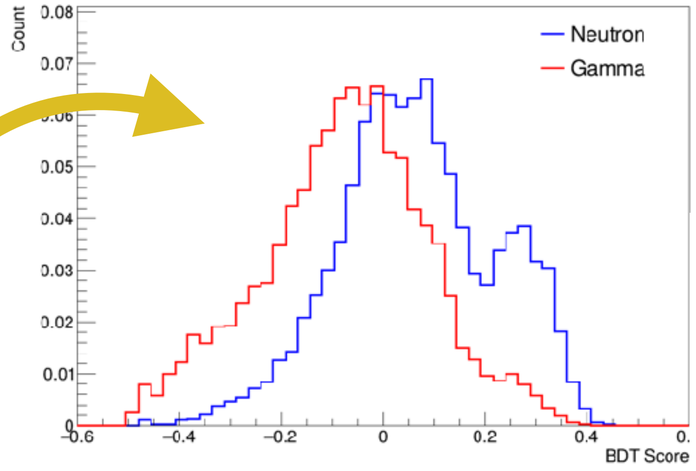
Pulse shape in NaI(Tl) crystal

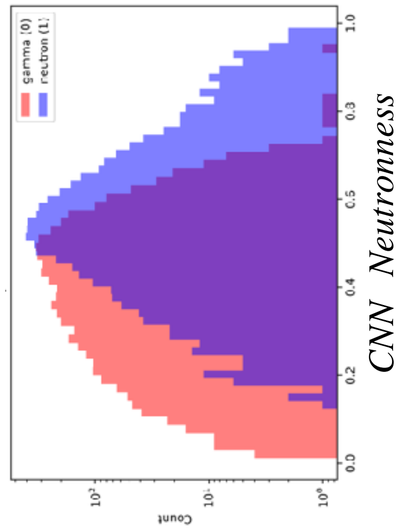


raw data training

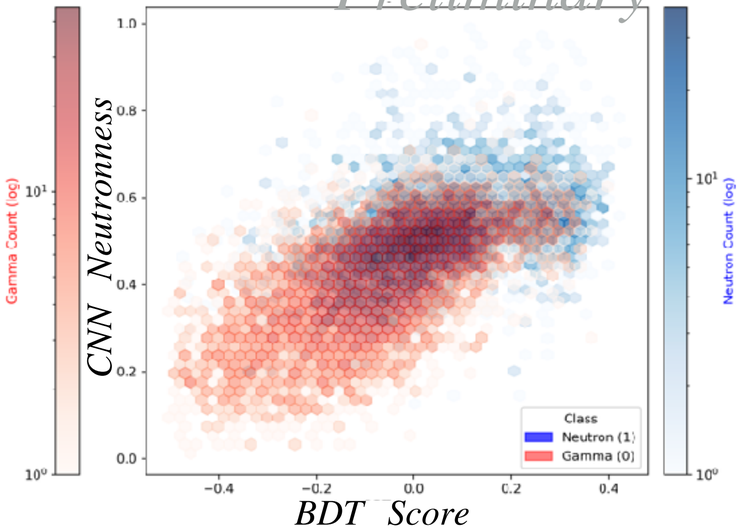
Event-wise parameters



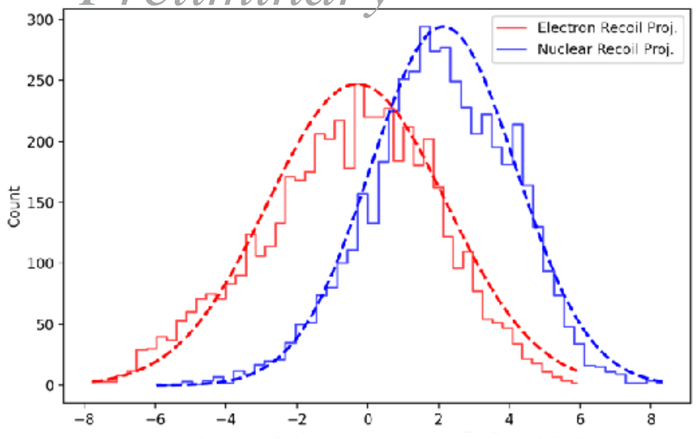




Preliminary



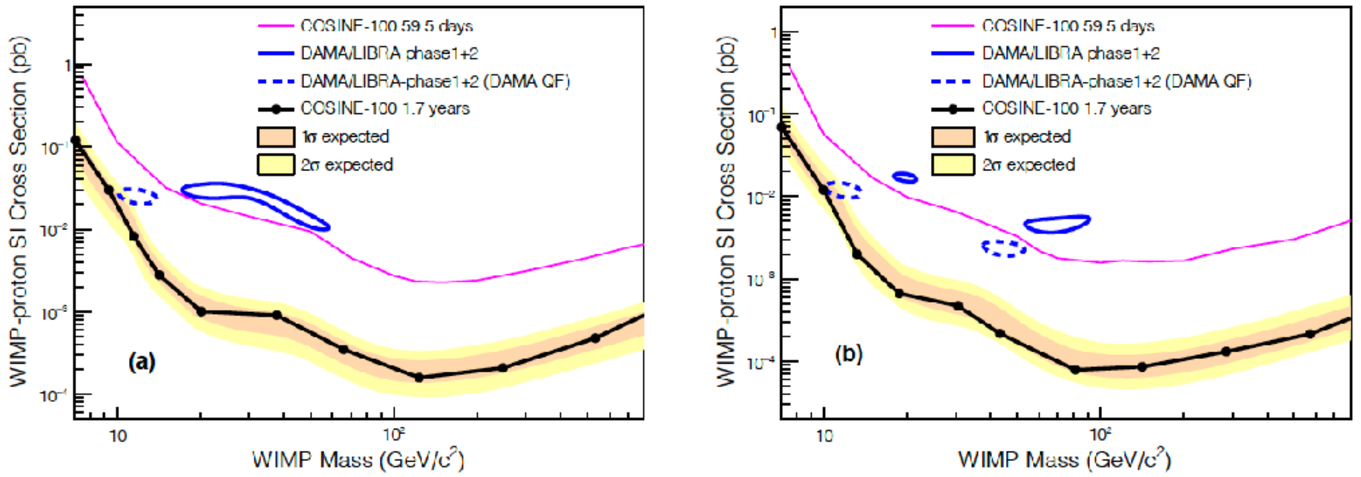
Preliminary



BDT-CNN combined PSD

Addition of PSD analysis to the WIMP extraction will significantly improve the nuclear recoil sensitivity of NaI(Tl) crystal

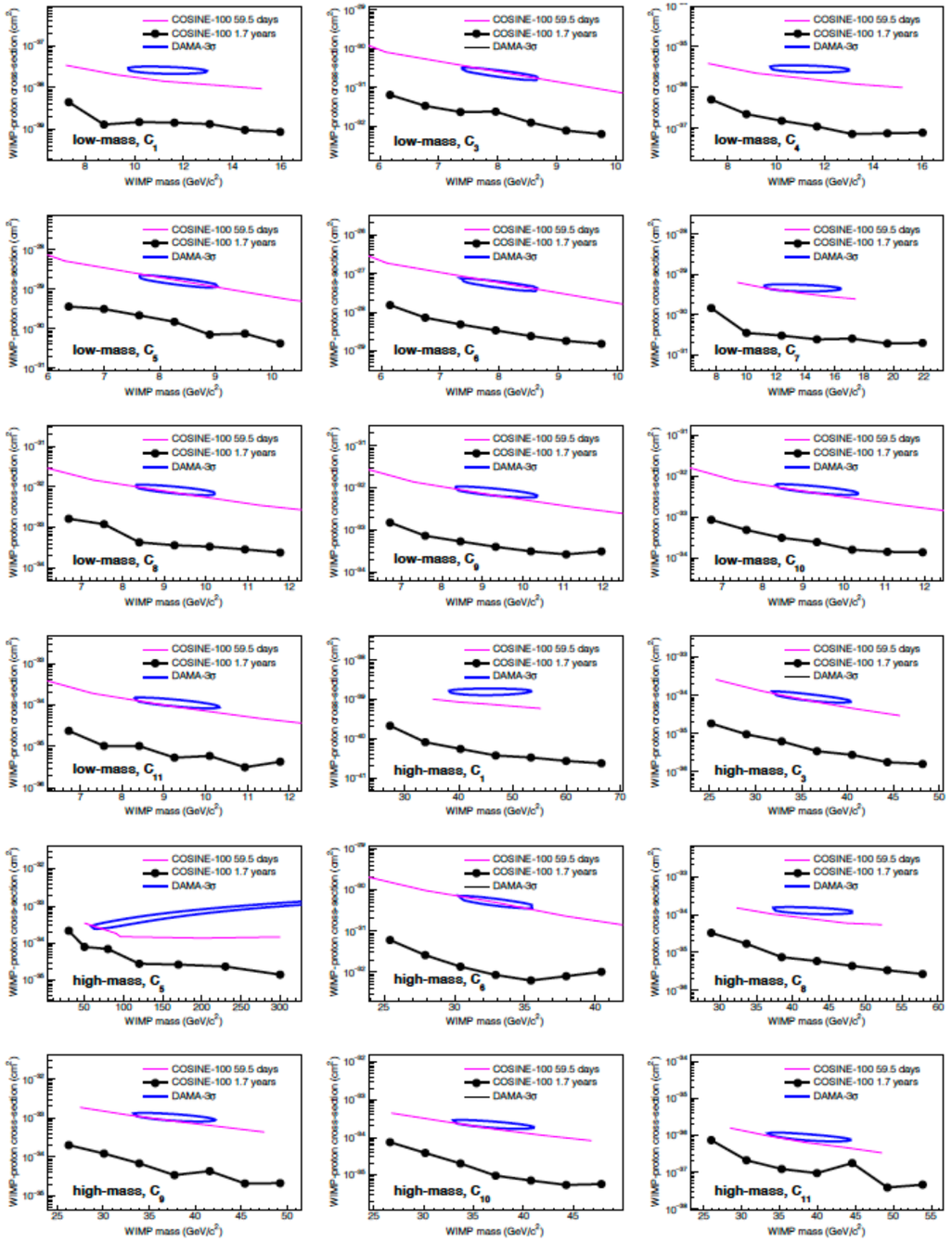
Other Model dependent Analysis with 1-keV threshold (1.7 yr)



Sci. Adv. 7, eabk2699 (2021)

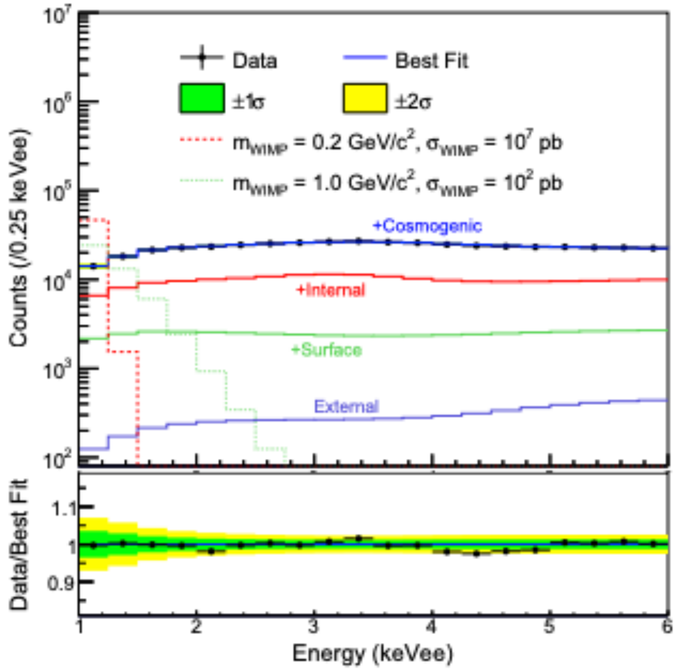
Additionally, we checked alternative hypotheses for isospin-violating cases and EFT operators with the same threshold and the updated quenching factors as DAMA/LIBRA.

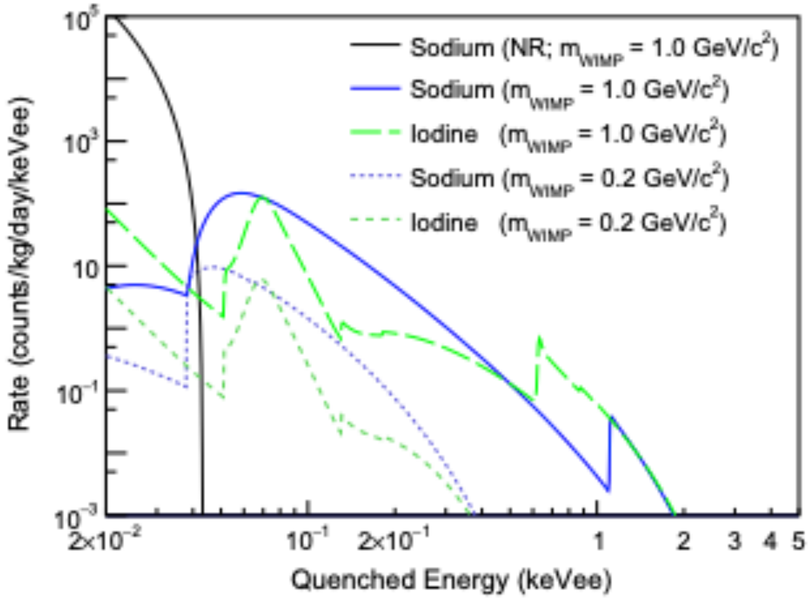
We find, in general, those are incompatible with COSINE-100 data. There is no excess of events over the expected background, that can be interpreted as DAMA's annual modulation signal under the assumption of dark matter interactions based on the Standard Halo Model.



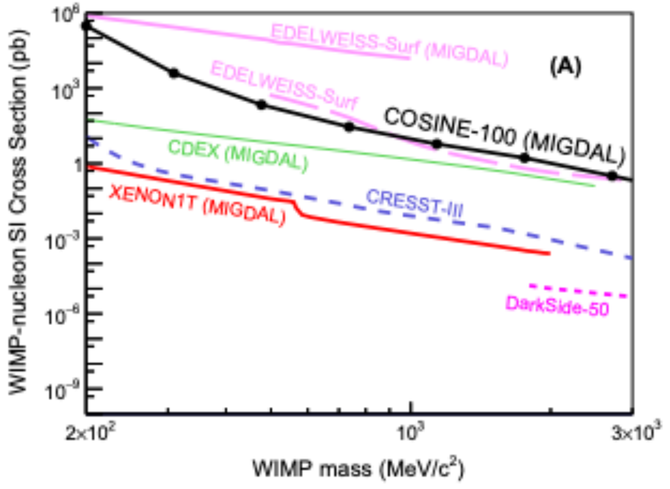
Search for the Migdal Effect (Look for ~GeV nuclear recoils)

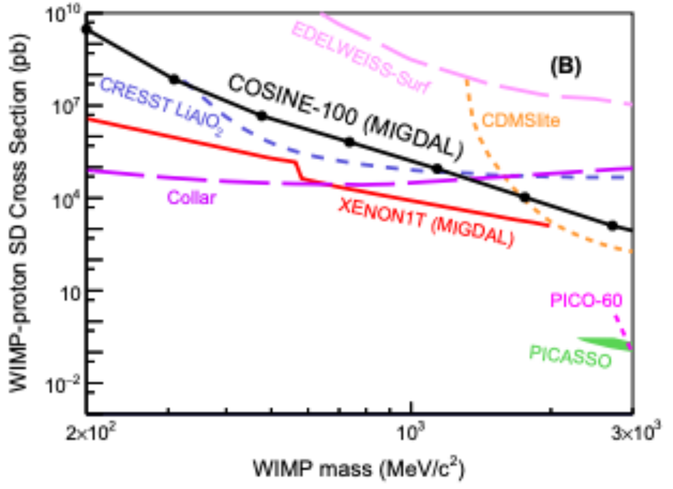
When a Nuclear Recoil by a Low Energy WIMP is small (a few keV), the recoil signal is not easy to detect directly. However, after the recoil, due to the lagging (excitations) of surrounding electrons, some energies come out as e/γ





Phys. Rev. D 105, 042006 (2022)

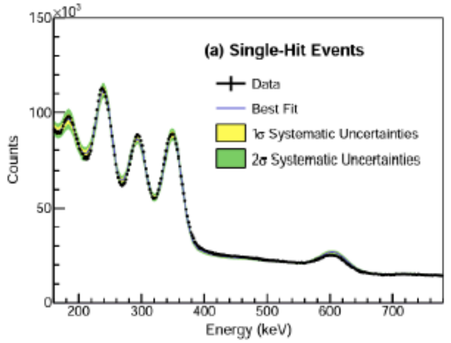


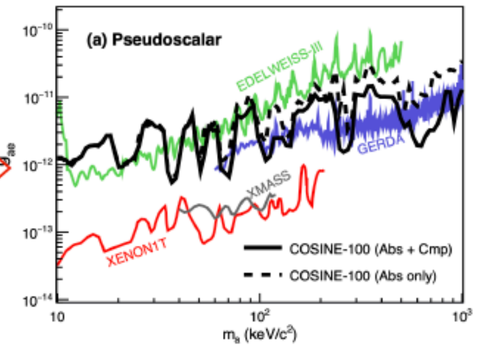


Other BSM searches in COSINE-100

1. Bosonic super WIMP *Phys. Rev. D **108** (2023) L041301*

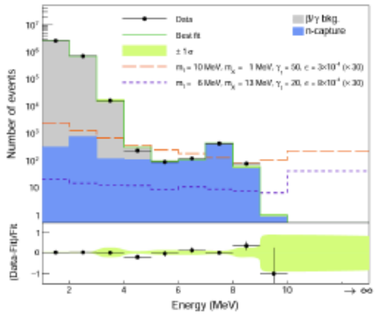
• Search region : COSINE-100 energy $\mathcal{O}$(100 keV)

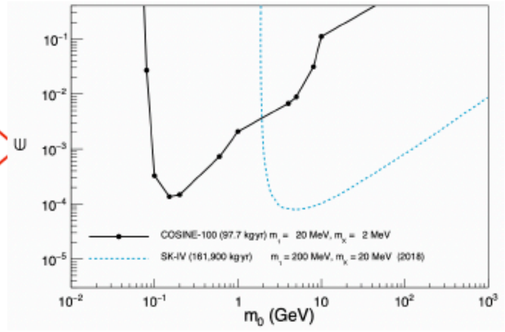




2. Boosted dark matter *Phys. Rev. Lett. **131**, 201802*

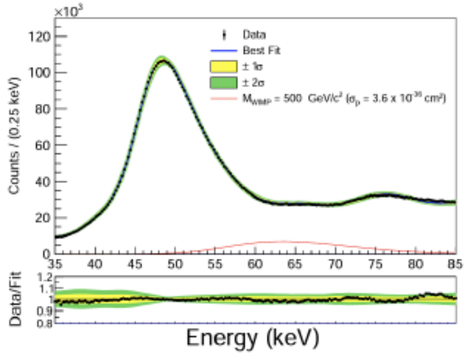
• Search region : COSINE-100 energy $\mathcal{O}$(MeV)

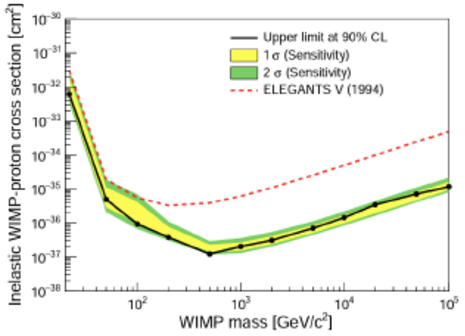




3. Inelastic ^{127}I - DM scattering *Phys. Rev. D **108**, 092006*

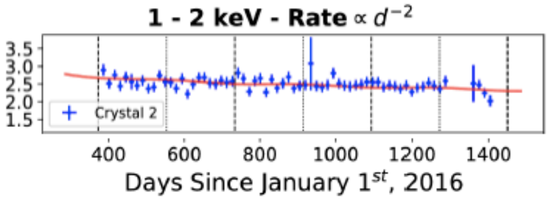
• Search region : COSINE-100 energy $\mathcal{O}$(10 keV)

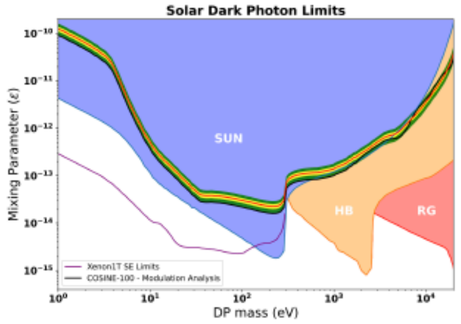




4. Solar bosonic dark matter modulation search

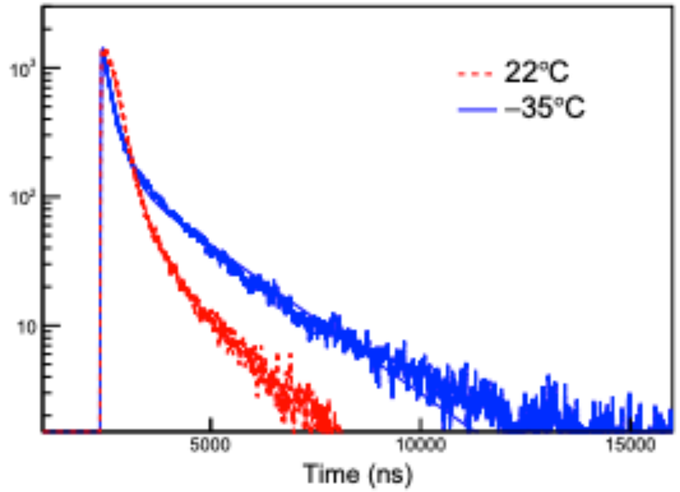
• Modulation search period : 3 years *Phys. Rev. D **107**, 122004*



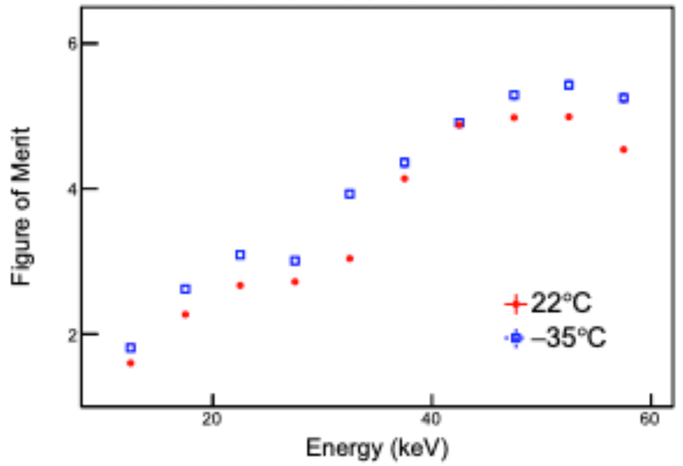


NaI(Tl) crystal at $-35^{\circ}C$

waveforms

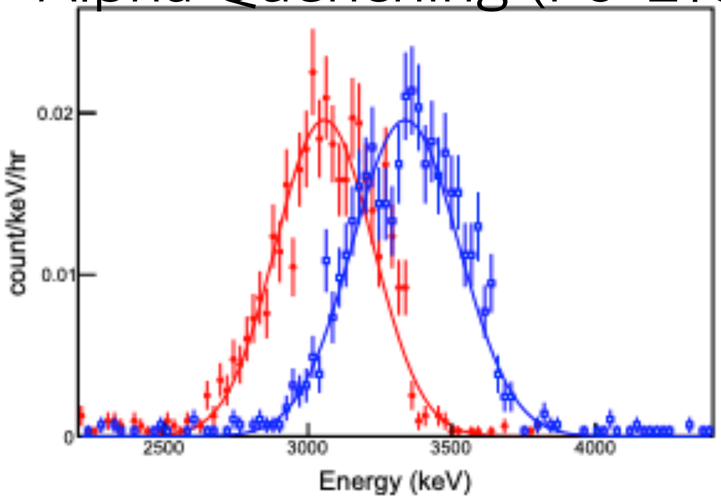


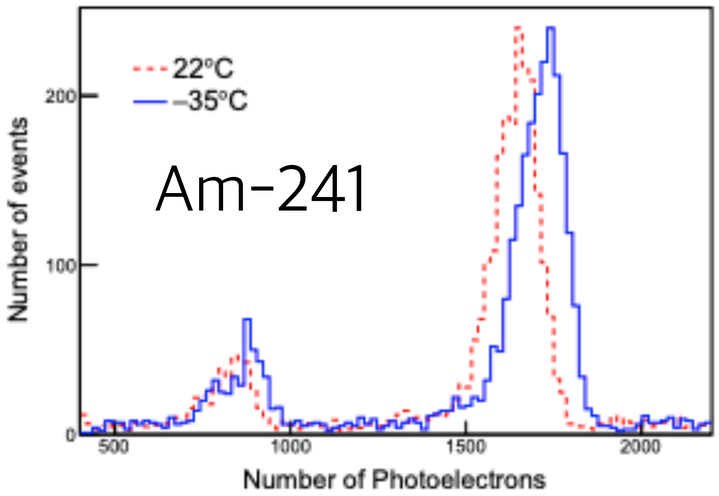
Neutron Source

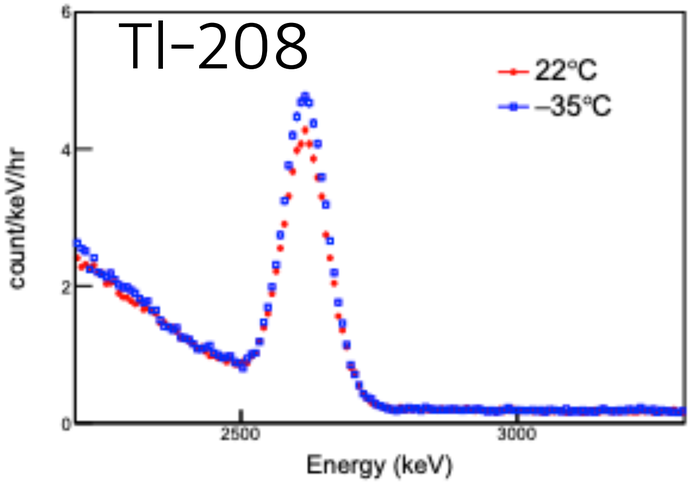


Astropart. Phys. **141** (2022) 102709

Alpha Quenching (Po-210)





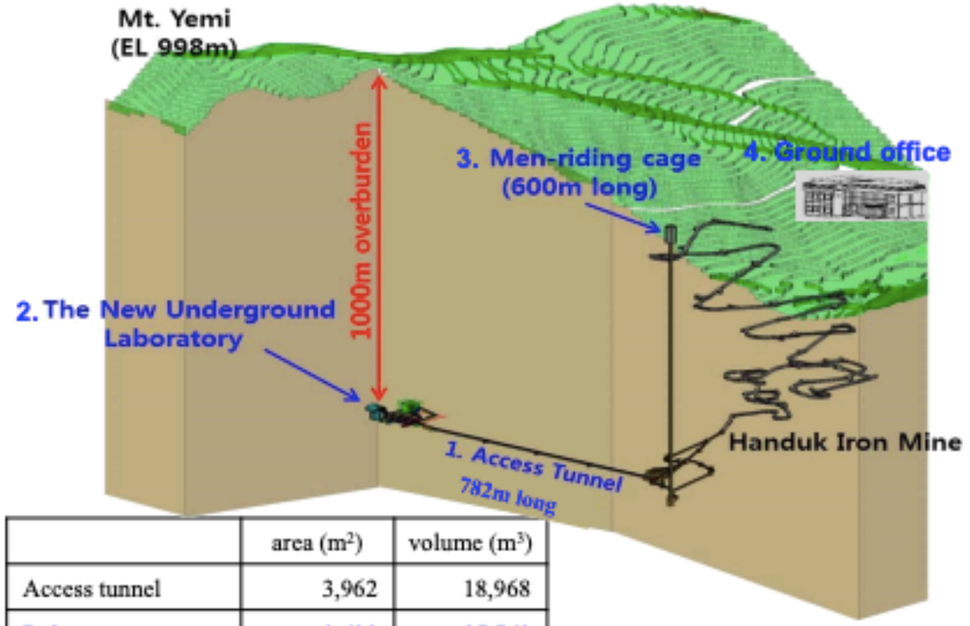


Temp. (°C)	LY (PEs/keV)	σ/mean (%)
22	27.6 ± 0.3	3.8 ± 0.1
−35	28.9 ± 0.2	3.7 ± 0.1

NaI(Tl) crystal produces more light as temperature decreases.

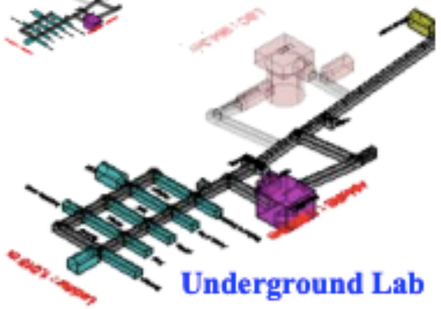
New COSINE home (starting 2023 @ Yemilab)

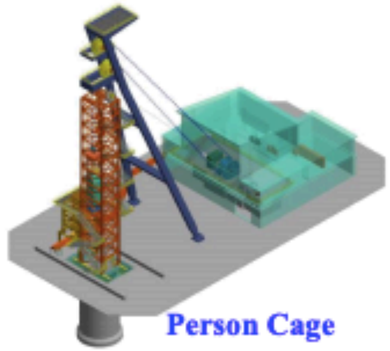
1. **Access Tunnel**, 782 m long with 12% down slope
2. **Underground Lab.** with 2600 m^2
3. **Person Cage**, running vertical 587 m
4. **Ground Office** with 2500 m^2



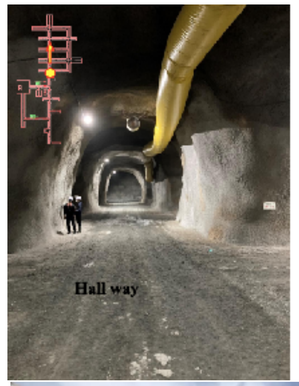
	area (m^2)	volume (m^3)
Access tunnel	3,962	18,968
Lab space	**2,600**	**25,562**
Connecting tunnel	4,847	14,161
amount	**11,525**	**58,691**

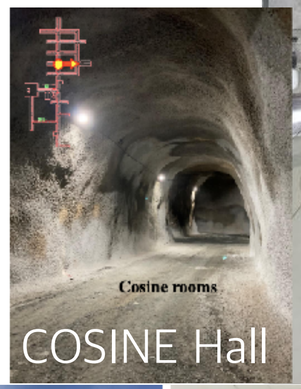

Access Tunnel


Underground Lab


Person Cage


Ground office





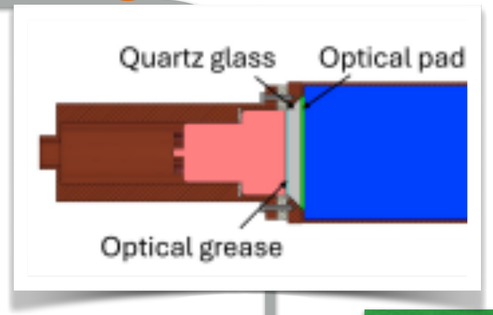

The ground office exterior

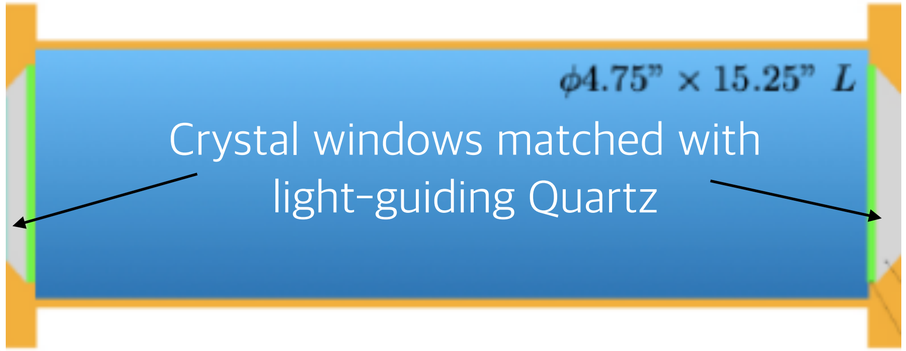

The reinforcement

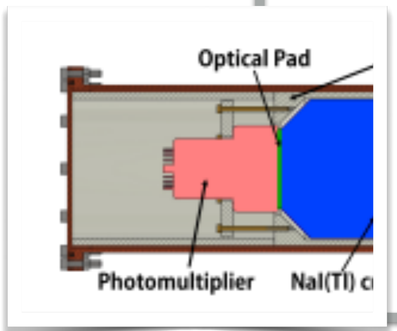
COSINE-100 Upgrade

In-house crystal machining, polishing, and encapsulation

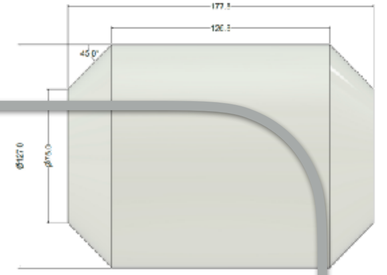
COSINE-100 Detector Design

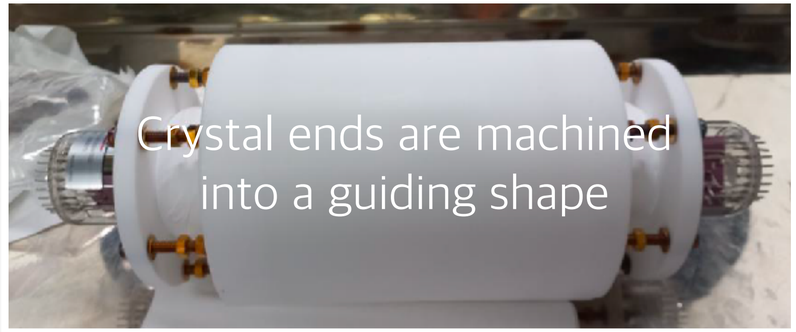






Upgrade Design





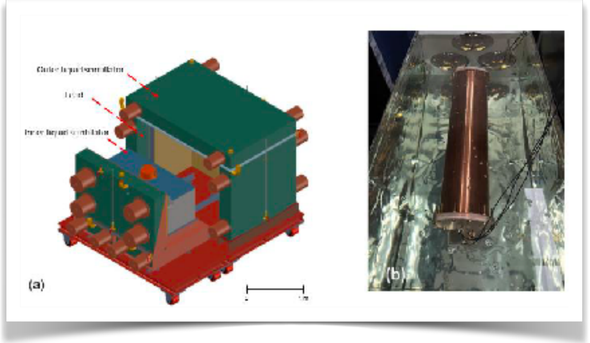
Commun. Phys. 8, 135 (2025)

Crystals are better light coupled with PMT photocathodes.

Crystal total mass reduced by 7% ($106\ kg \rightarrow 99\ kg$)

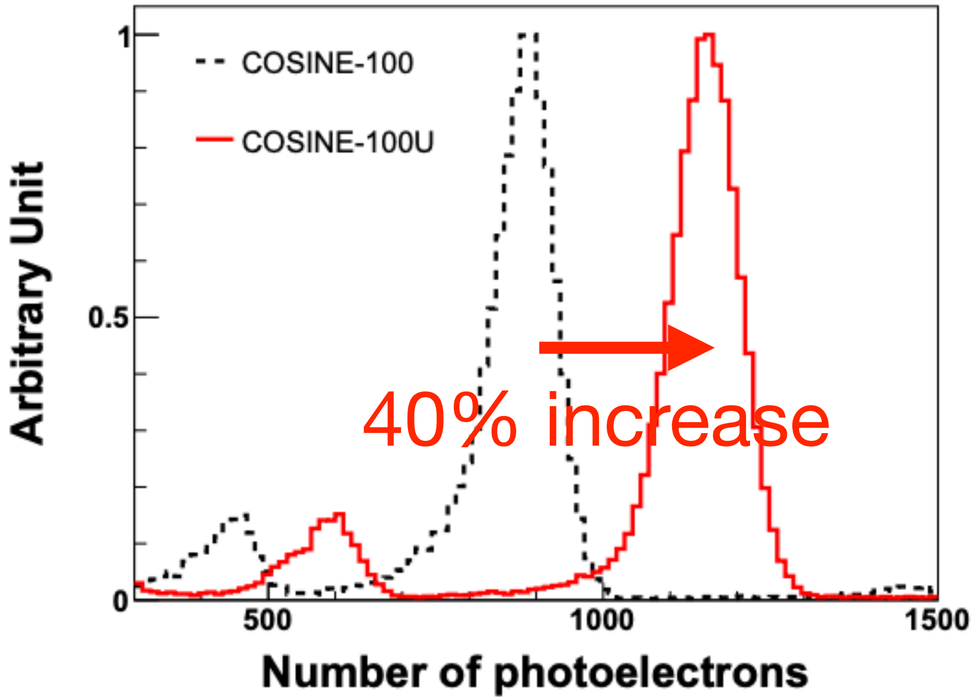
New Encapsulation Tests

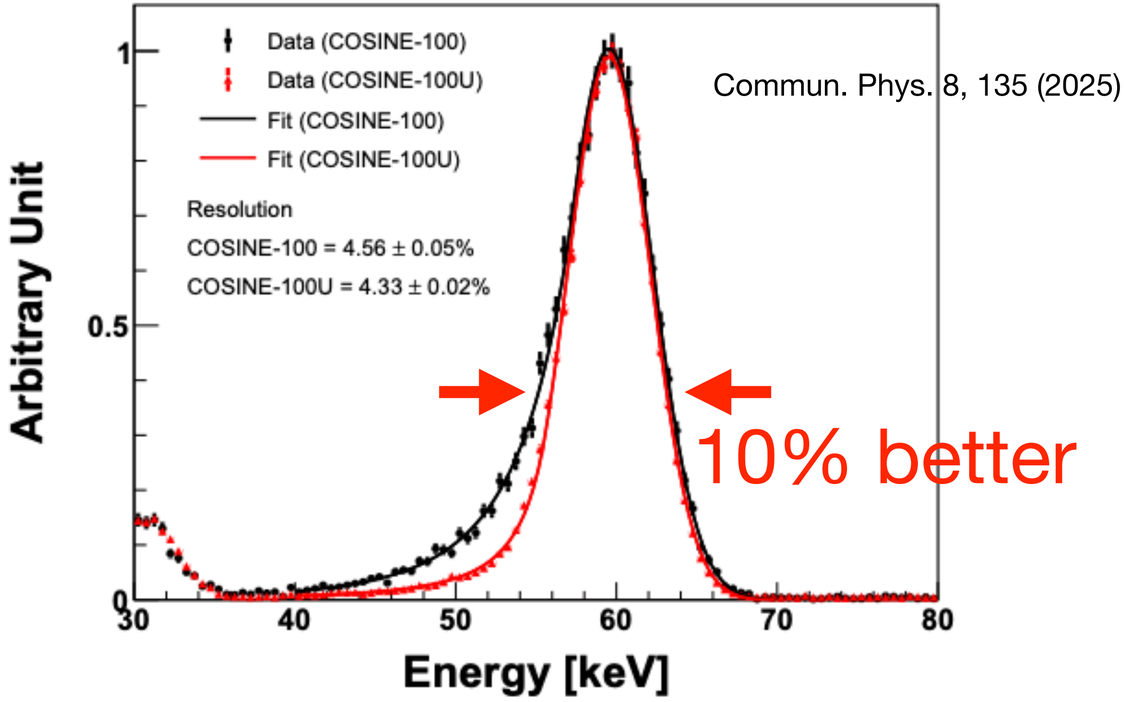
Test facility at the ground lab



Crystal 7

$^{241}Am\ (E_\gamma = 59.4keV)$





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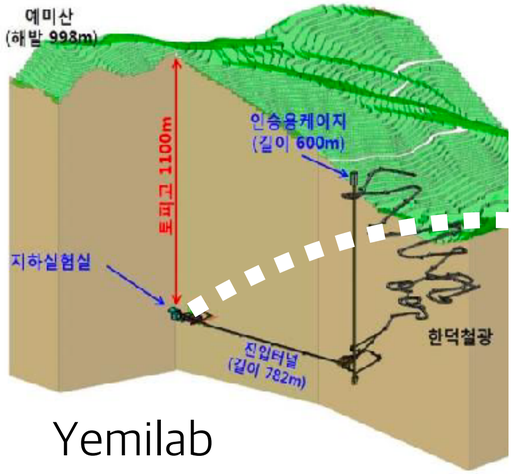
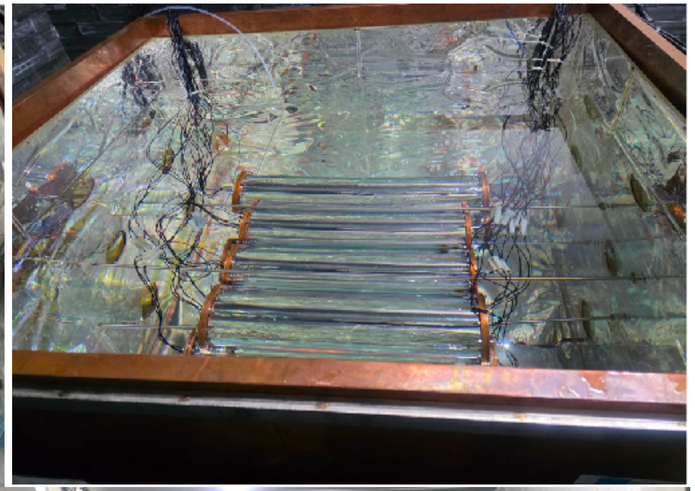
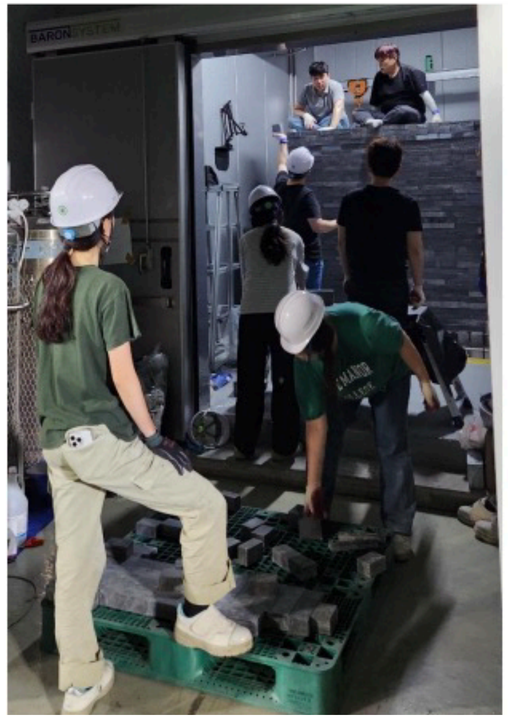
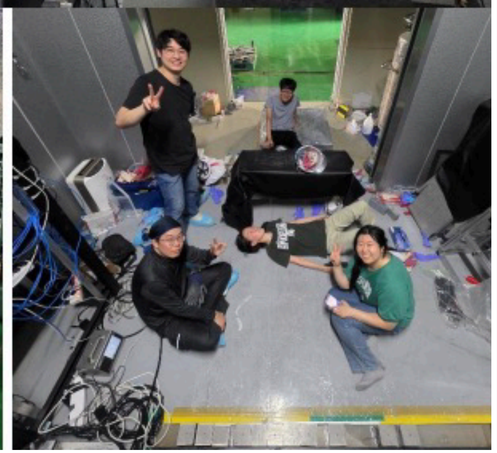
COSINE-100 Upgrade installation



Yemilab

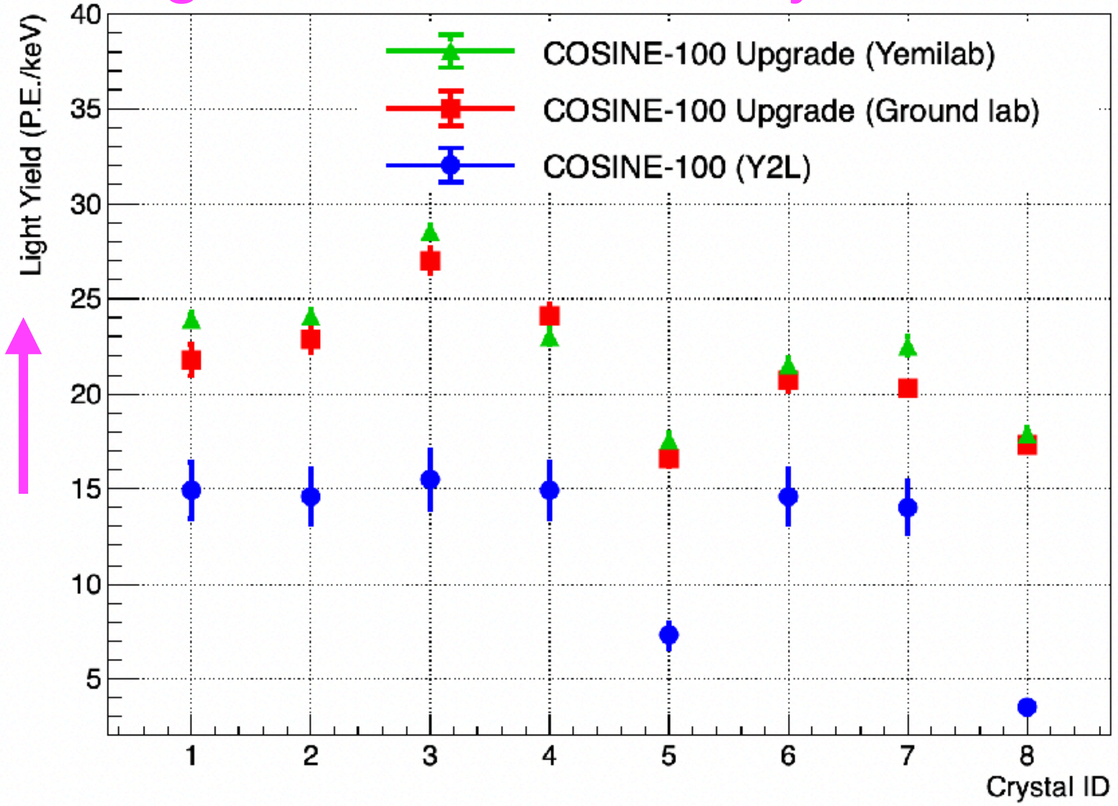




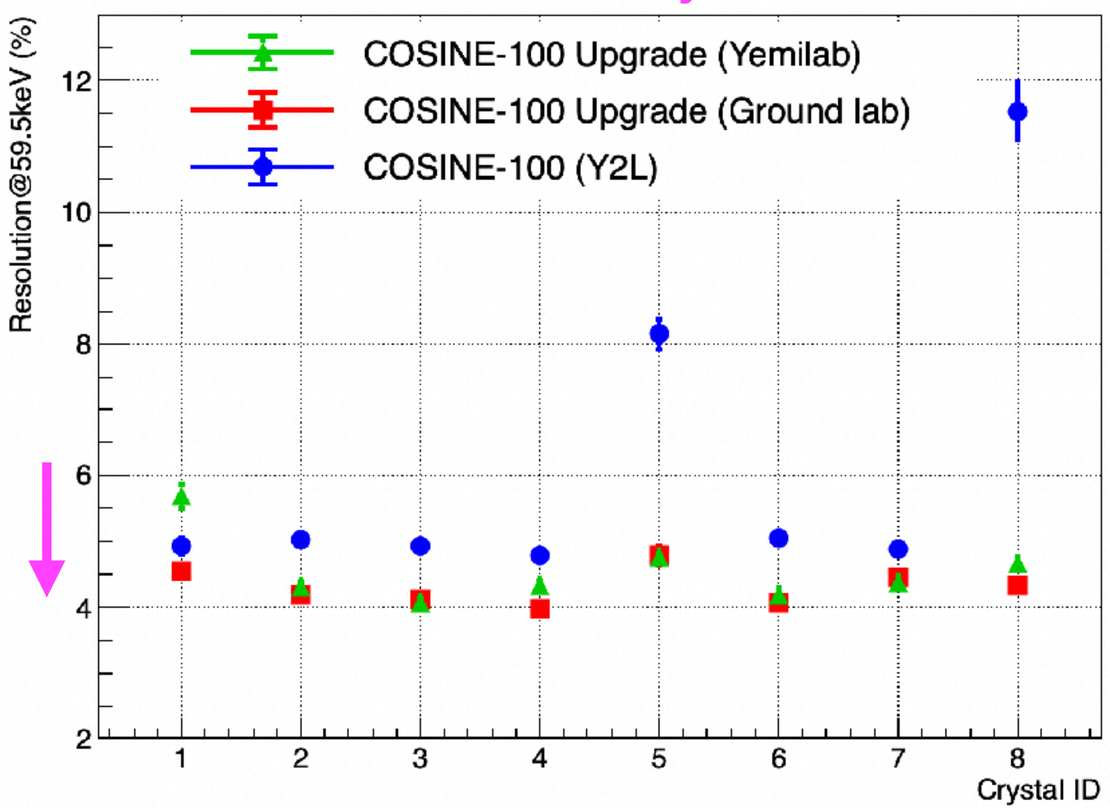


Upgrade Crystal Characterization at Yemilab

Light Yield increases by 50%

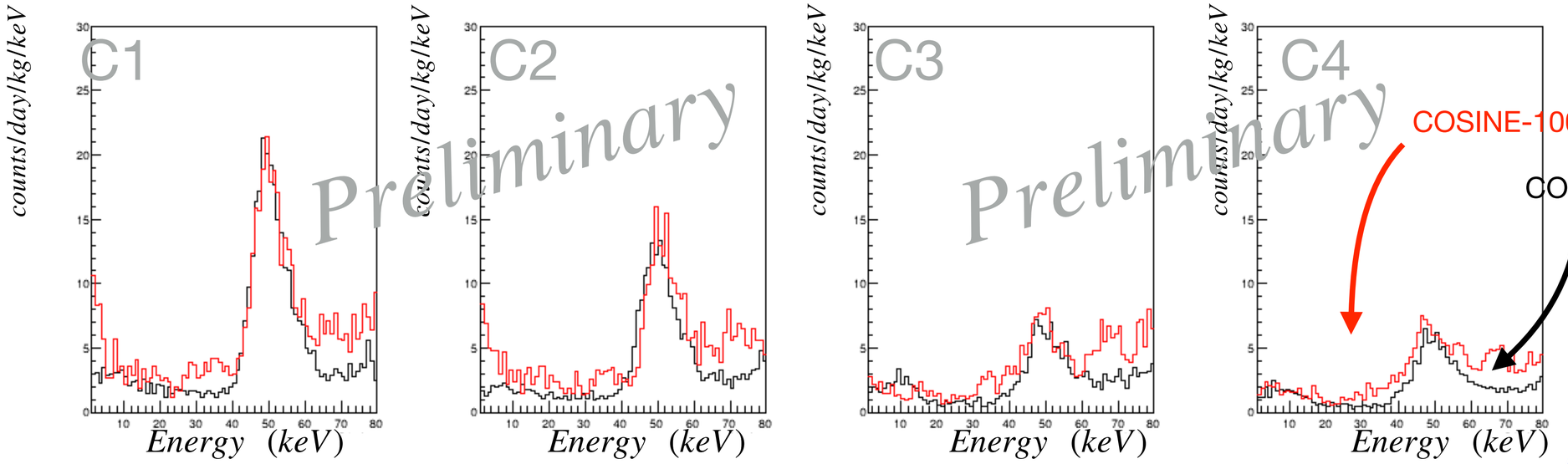


Resolution better by 10%

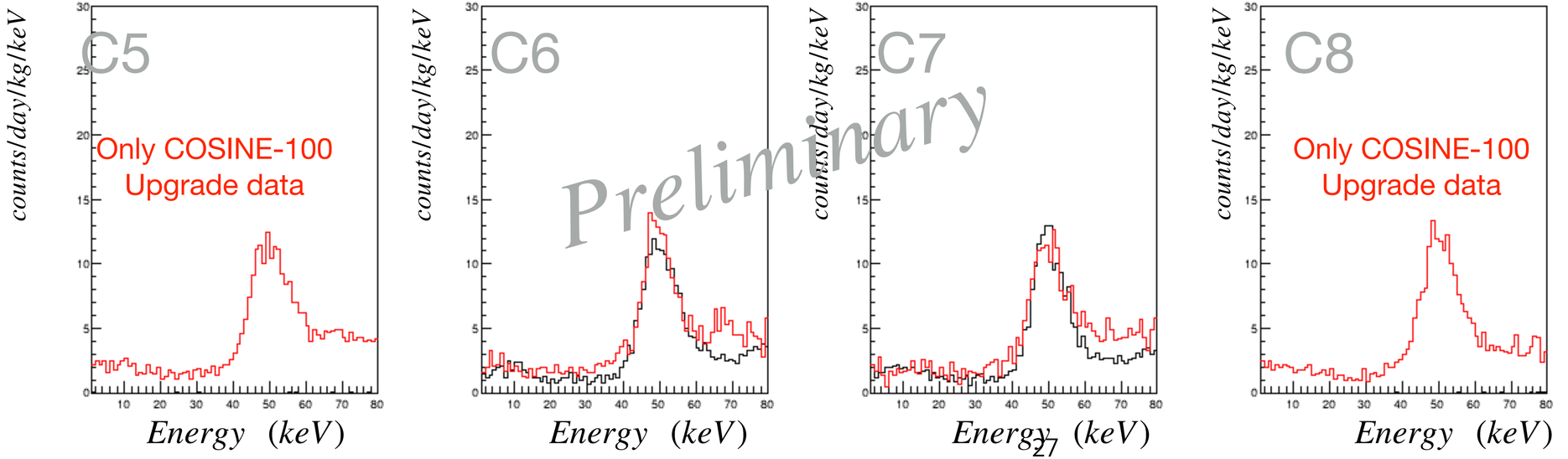


Crystal Re-encapsulation shows better light quality, 50% and 10% better in yields and resolutions, respectively

COSINE-100 Upgrade Initial Data

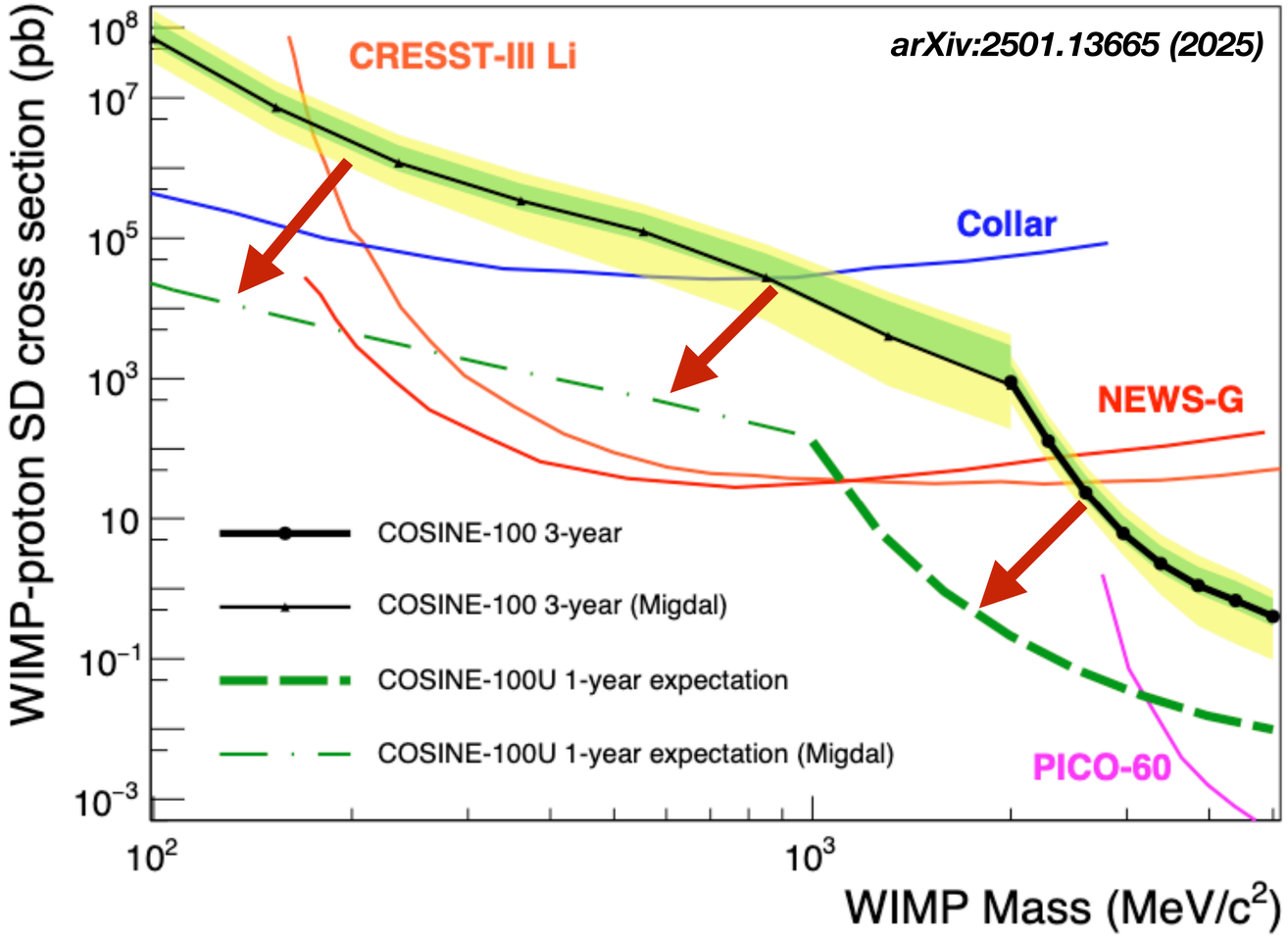


Initial Upgrade data show comparable background level at ~3 DRUs (counts/day/kg/keV) below 10 keV with COSINE-100.



In addition, we have successfully recovered two large detectors C5 and C8 (Previously, no data in COSINE-100)

COSINE-100 Upgrade Expected Sensitivity



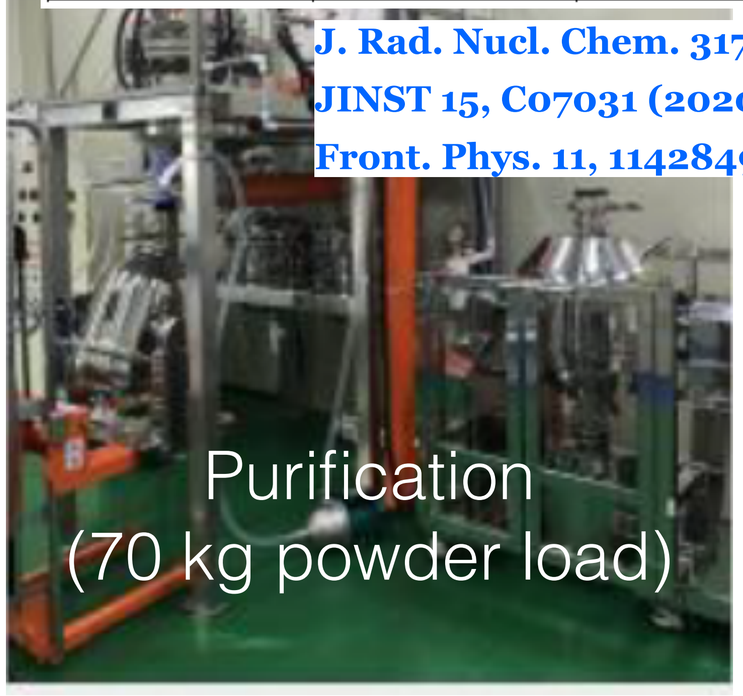
With Upgrade, we expect a significant improvement in Spin-Dependent WIMP search.

Preparation for Large crystal growth

Powder Purification

	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

J. Rad. Nucl. Chem. 317, 1329 (2018)
JINST 15, C07031 (2020)
Front. Phys. 11, 1142849 (2023)



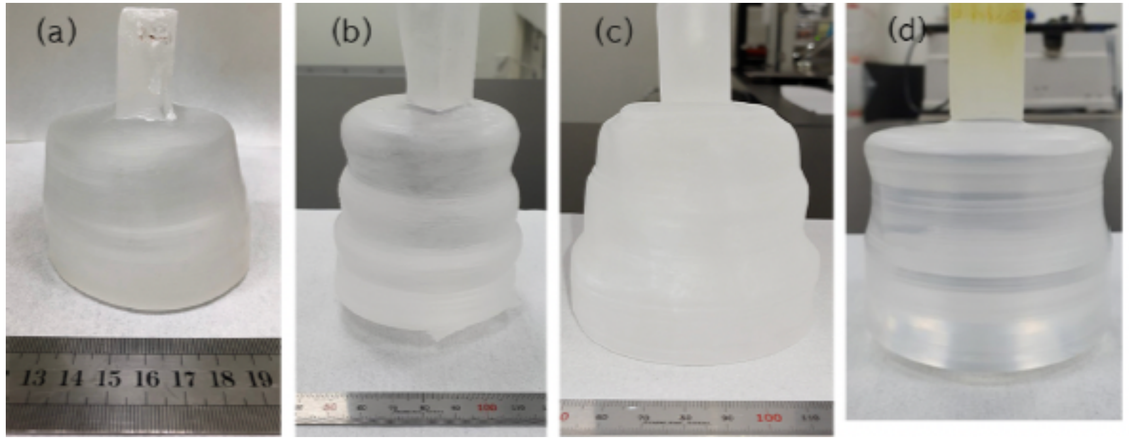
Purification
(70 kg powder load)

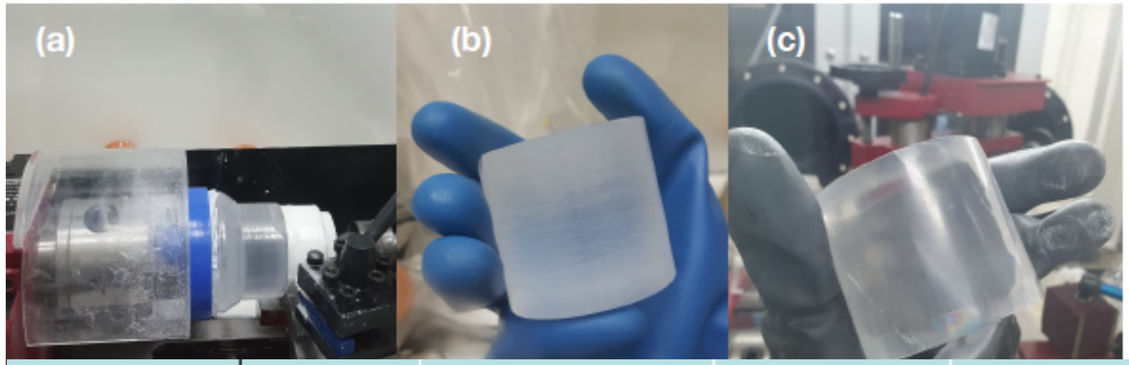
Small Grower
(1 kg crystal ingot)

Full-sized Grower
(100 kg crystal ingot)

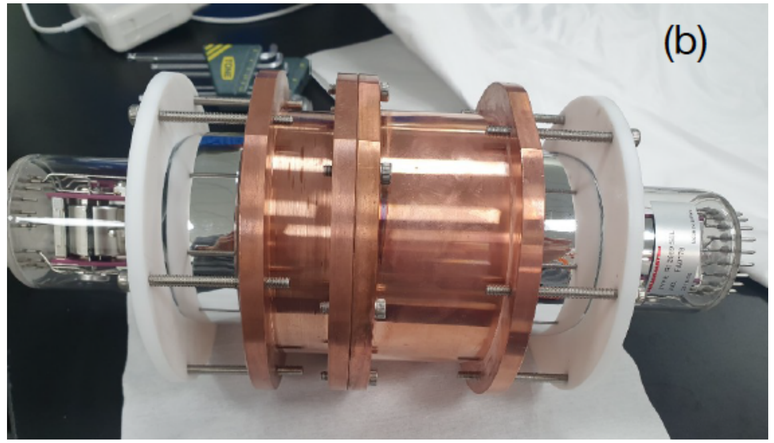
Background rate should be less than 1 DRU (less than DAMA)

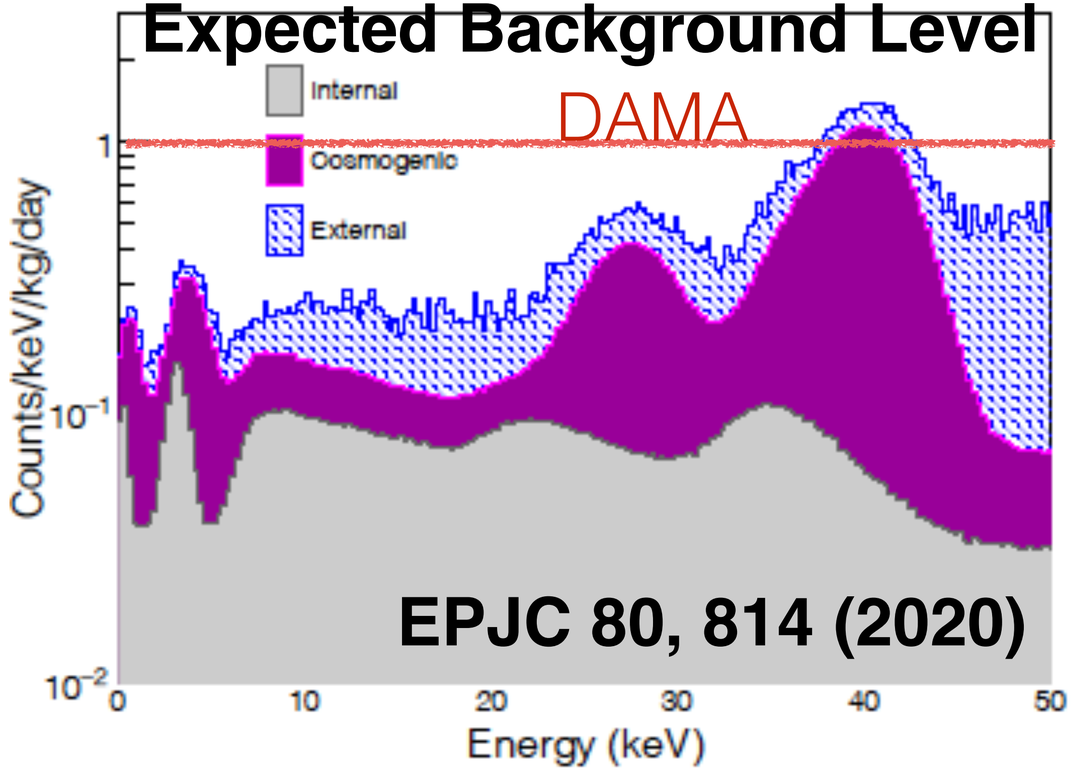
In-house NaI(Tl) crystal detector





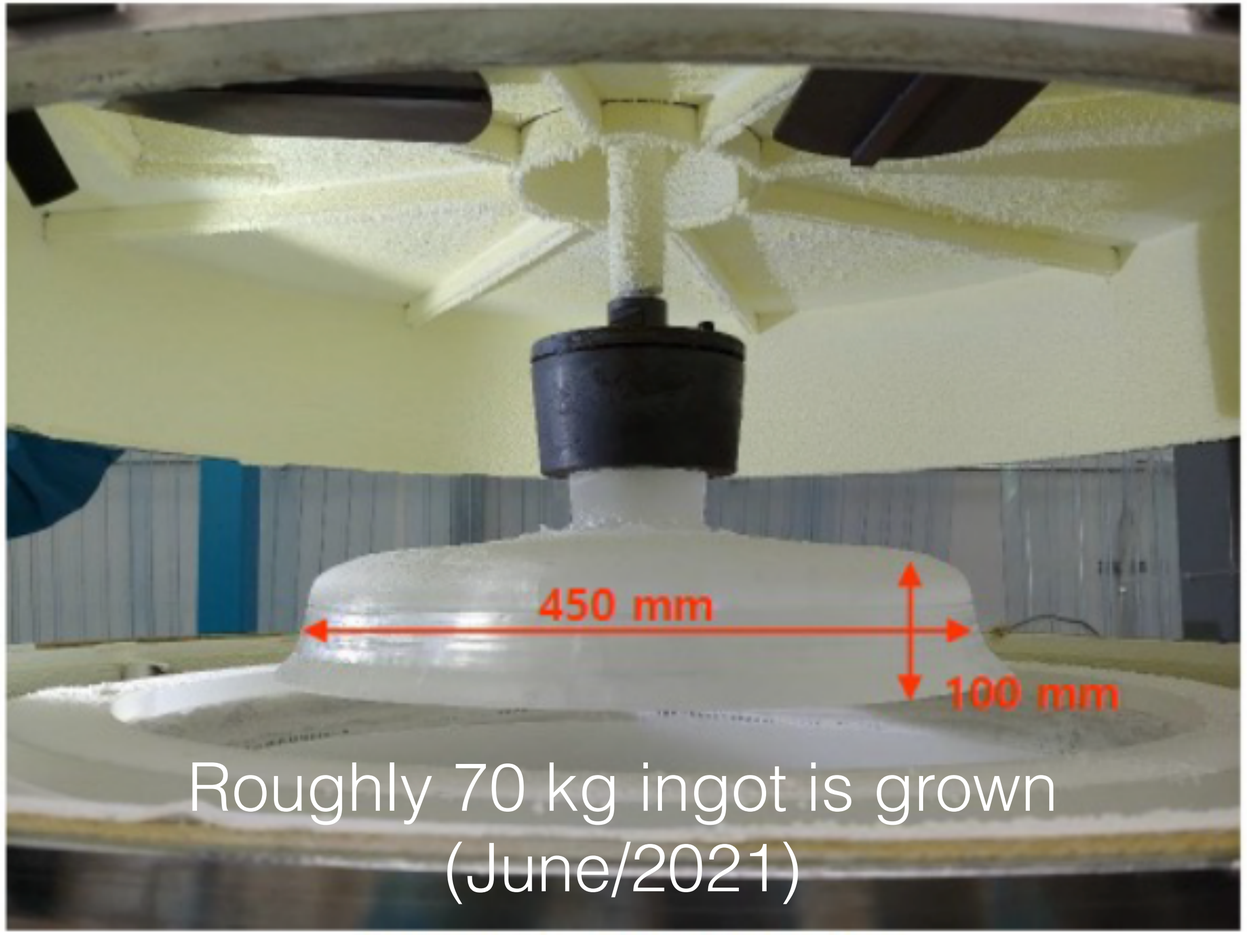
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31





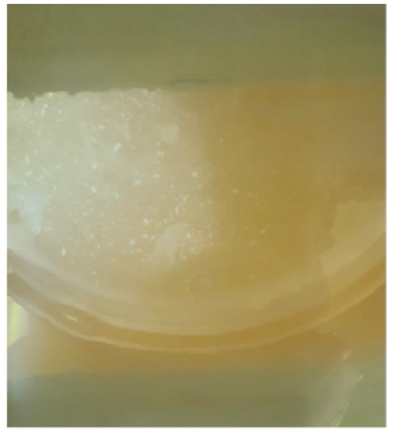
Large Size NaI(Tl) crystal growth

Test growing without Thallium doping



Roughly 70 kg ingot is grown (June/2021)

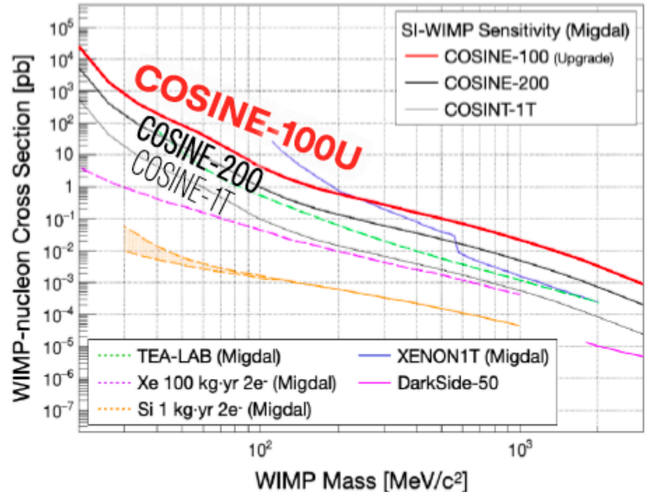
195 kg NaI Merck Powder loaded

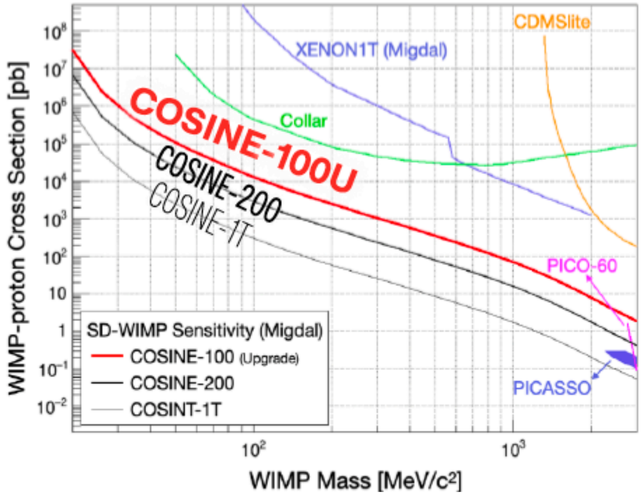


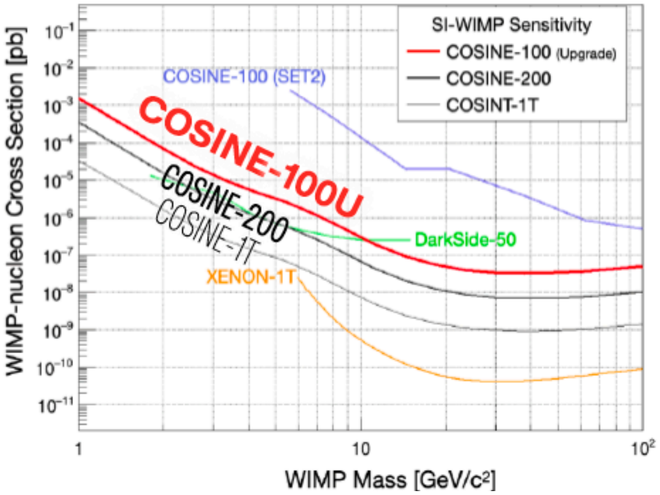
Sequence of crystallization

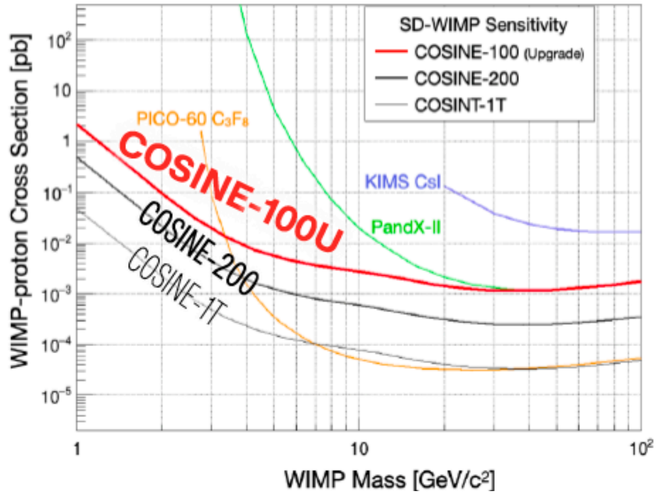
In-house Crystal growing starts working. Large-size Tl-doped and low-bkg crystal growth is the next step.

What's next for COSINE?









With mass production of low background crystals, we have an edge in low-mass spin-dependent WIMP interactions.

Summary and Outlook

- COSINE aims direct detection of dark matter via nuclear recoils from WIMPs.
- There is one claimed detection of WIMP from the DAMA experiment.
- Use crystal scintillators (same material as DAMA) → enables direct reproduction of their result.
- **Multiple model-dependent analyses exclude the DAMA signal as standard WIMP dark matter under the Standard Halo Model.**
- The source of the DAMA signal remains unresolved.
- We also search for other dark matter candidates such as Low-mass WIMPs with Migdal effect, and iBDM, and other interaction signatures.
- In-house detector encapsulation achieved high light yield.
- **COSINE-100 Upgrade** completed and ready. Operation to start soon at **Yemilab**.