Status on COSINE-100 experiment

In-Soo Lee

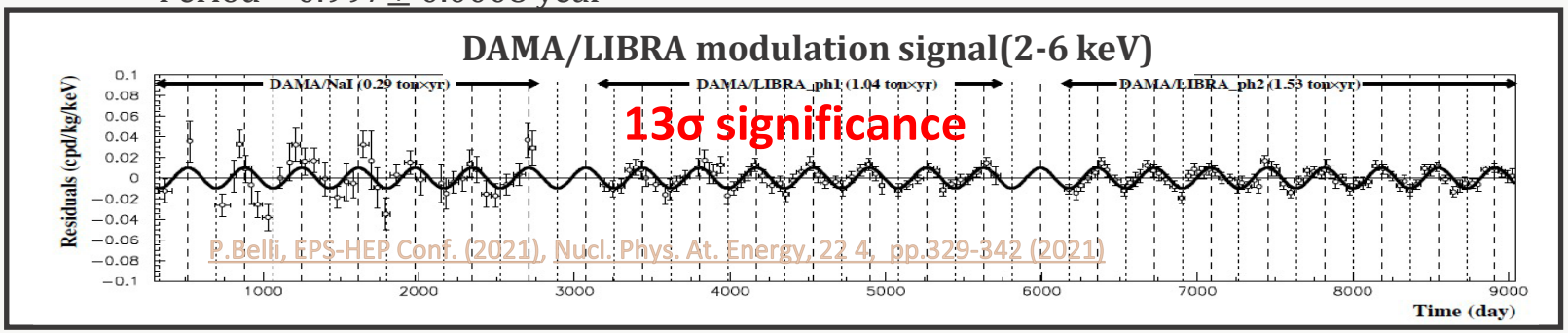
Center for Underground Physics (IBS)

On behalf of the COSINE-100 collaboration

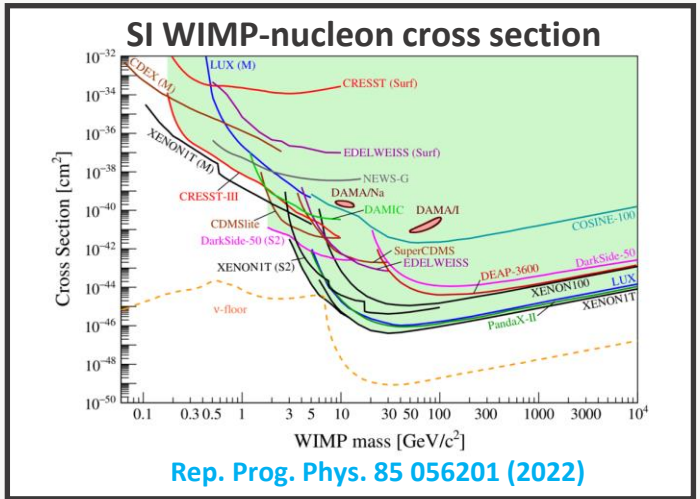
July 18th, 2024

Motivation-DAMA/LIBRA

- **DAMA/LIBRA experiment**
  - Search for **Dark matter (DM)** annual modulation signature
  - Using 25 × 9.7 kg **NaI(Tl)** detectors
  - **Claim an observation** of the DM (WIMP modulation signal) at **13σ C.L.** (2-6 keV)
  - **Amplitude** : 0.00996 ± 0.0007 counts/day/kg/keV
    - Phase = 145±5 days
    - Period = 0.997± 0.0008 year



- **No other experiment** has succeeded direct detection of DM except for **DAMA/LIBRA.**
  - **Is NaI(Tl) special** for DM interaction?



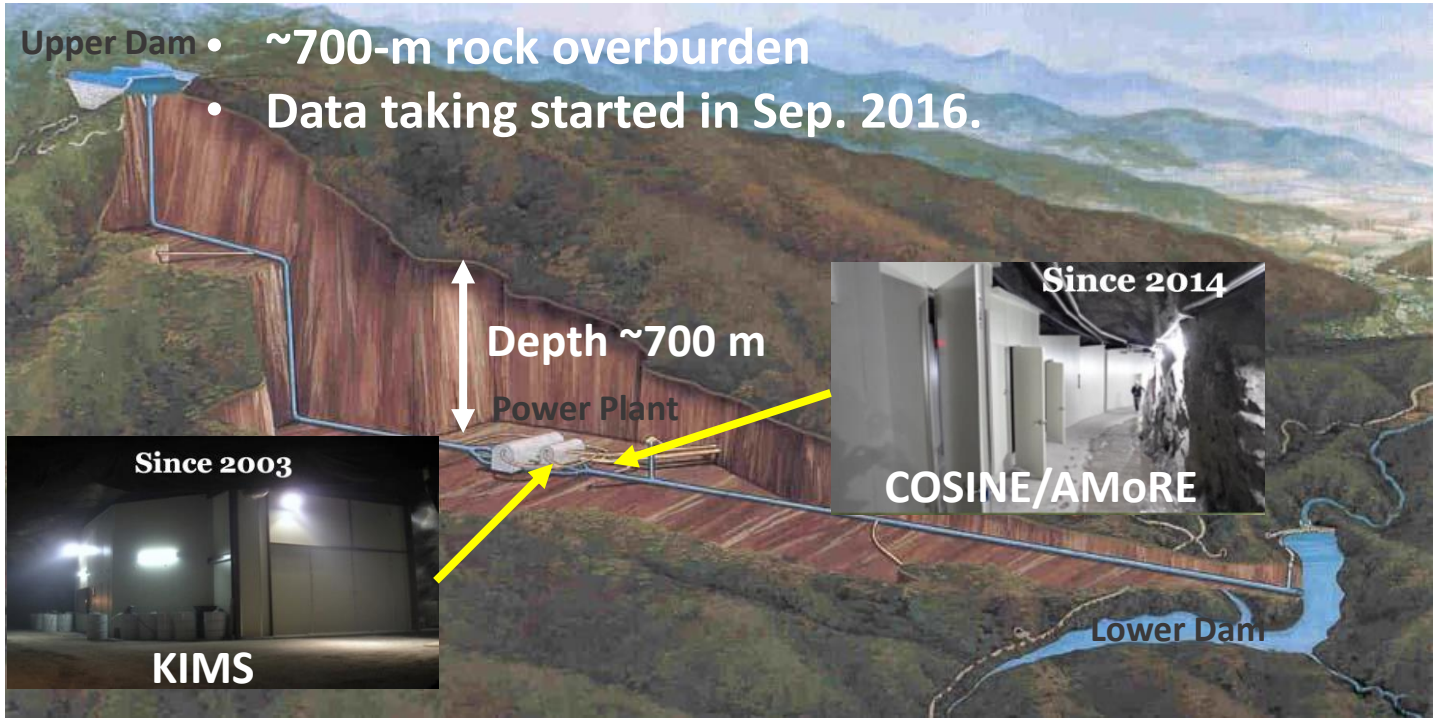
COSINE-100 experiment

DM-ICE + KIMS = COSINE

KRISS · UST · The University Of Sheffield. · WISCONSIN · Yale

- Joint collaboration of **DM-ICE** & **KIMS**
- **~50 collaborators** in **18 institutes**
- To confirm **DAMA/LIBRA's claim** using same target material, **NaI(Tl)**

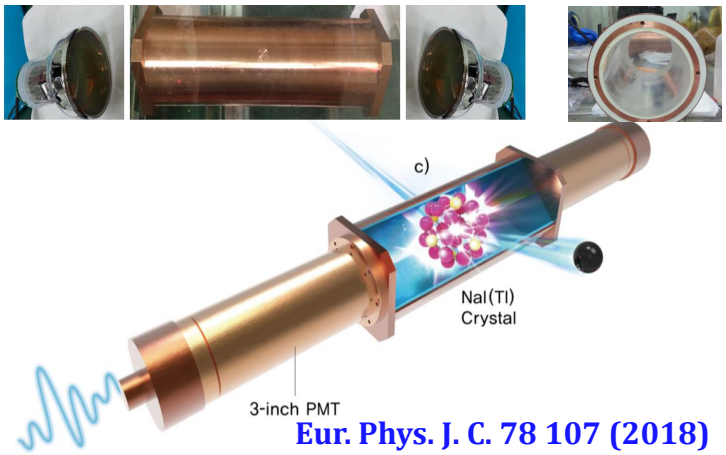
Yangyang underground laboratory (Y2L), Korea



COSINE-100 experiment

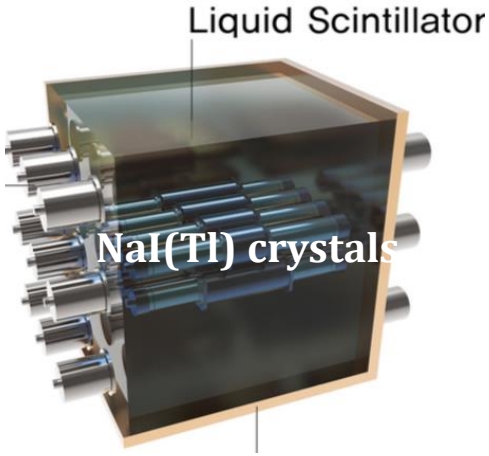
- 8 NaI(Tl) Crystals (106 kg)
  - Higher light yield (15 PE/keV) than DAMA/LIBRA (5-10 PE/keV)
- Shielding structure
  - 2200-L LAB-based Liquid scintillator(LS)
  - 4π plastic scintllator
  - 3-cm thick copper box
  - 20-cm thick lead castle

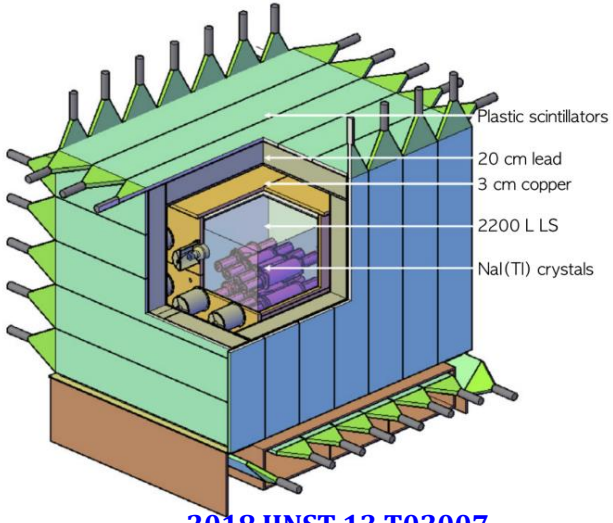
NaI(Tl) crystal



Eur. Phys. J. C. 78 107 (2018)
Eur. Phys. J. C. 78 490 (2018)

Shielding structure

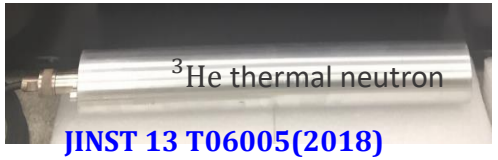




Nucl. Instrum. Meth. A 106, 165431 (2021)
Nucl. Instrum. Meth. A 851 103 (2017)

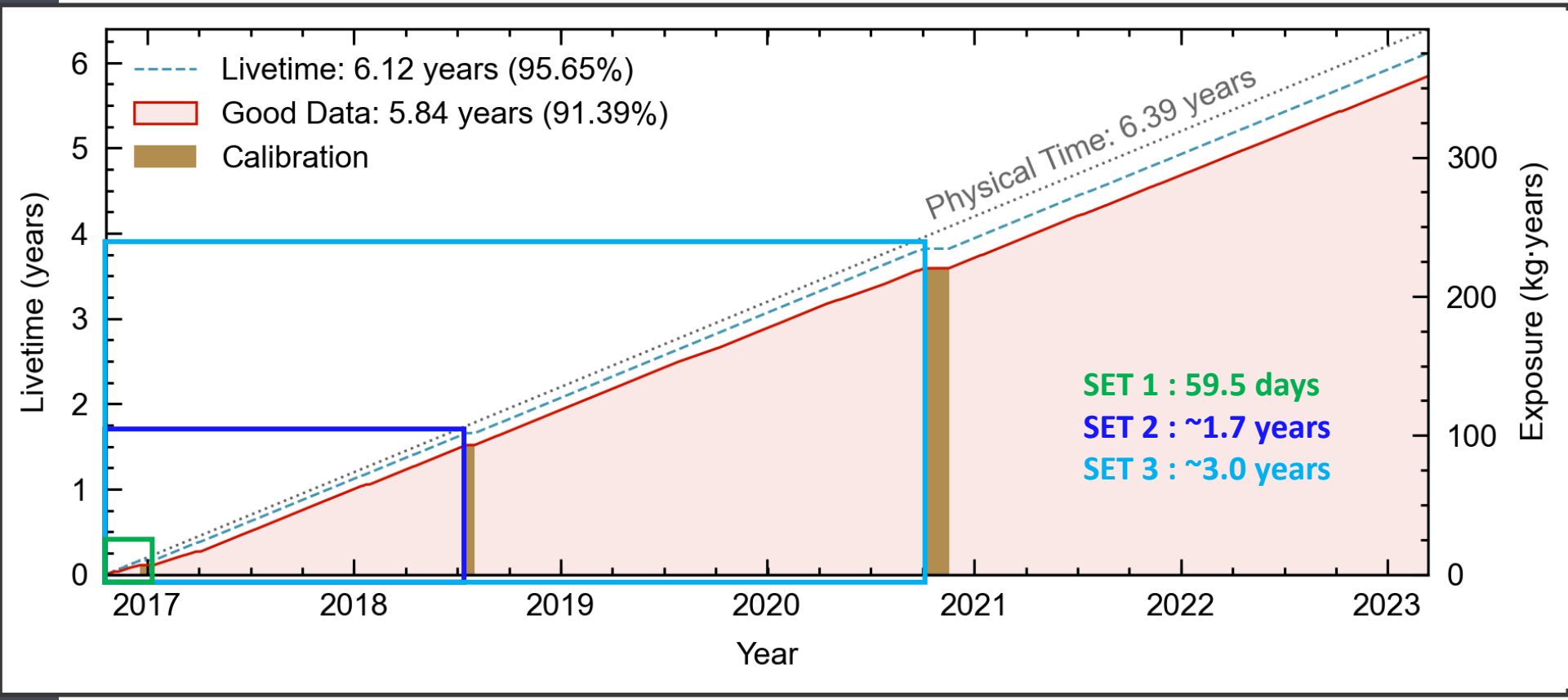
2018 JINST 13 T02007
Eur. Phys. J. C 78, 107 (2018)

Neutron monitoring



JINST 13 T06005(2018)

Data exposure



- **Operation from Sep. 2016 to Mar. 2023**
  - **Physics run : 6.12 years**
  - **Good data : 5.84 years**

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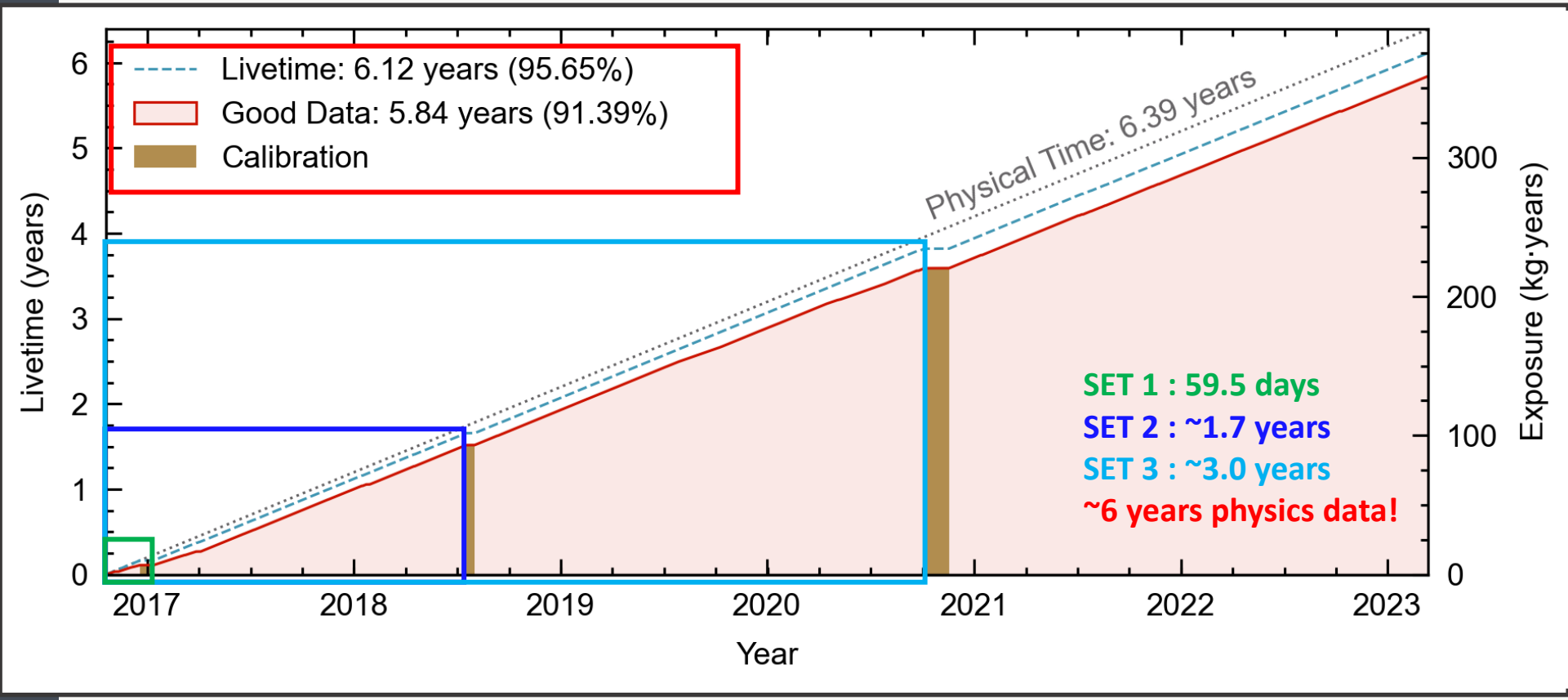

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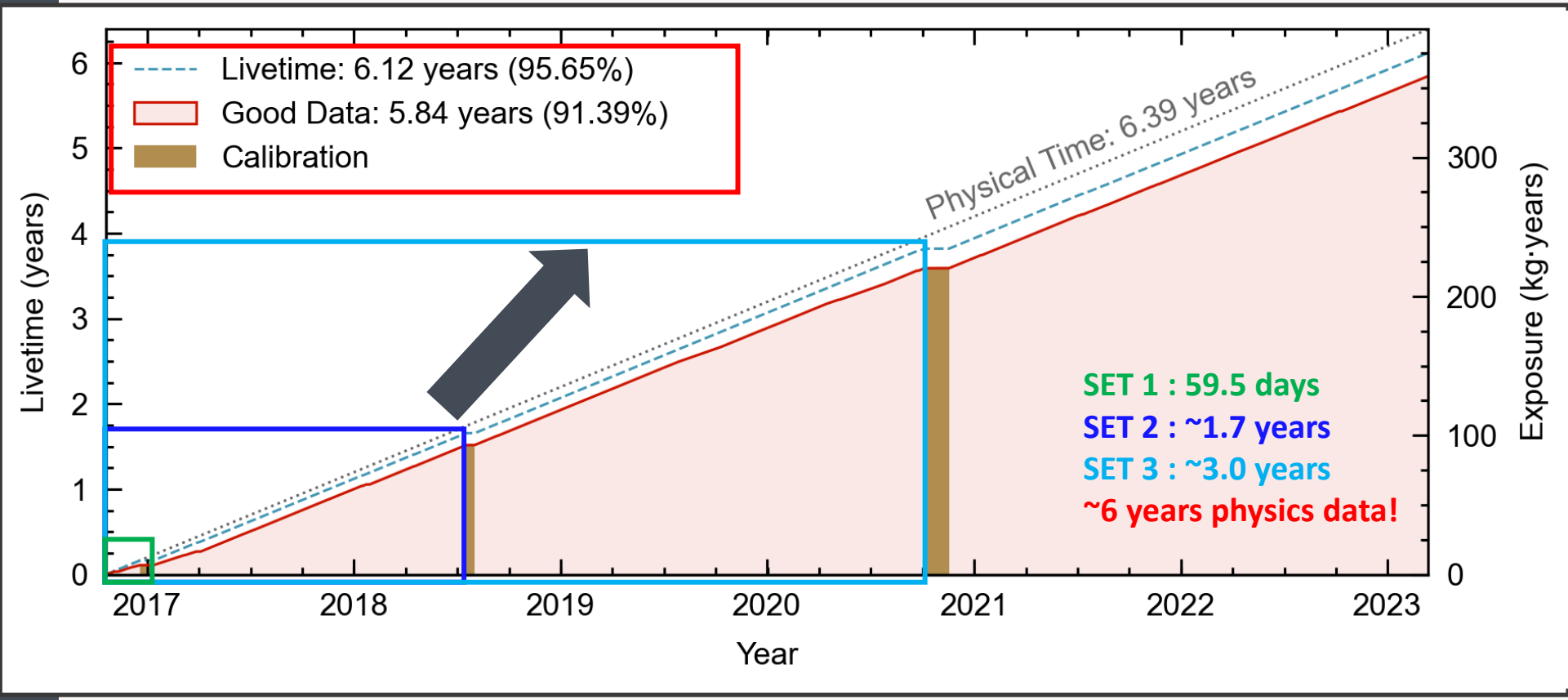


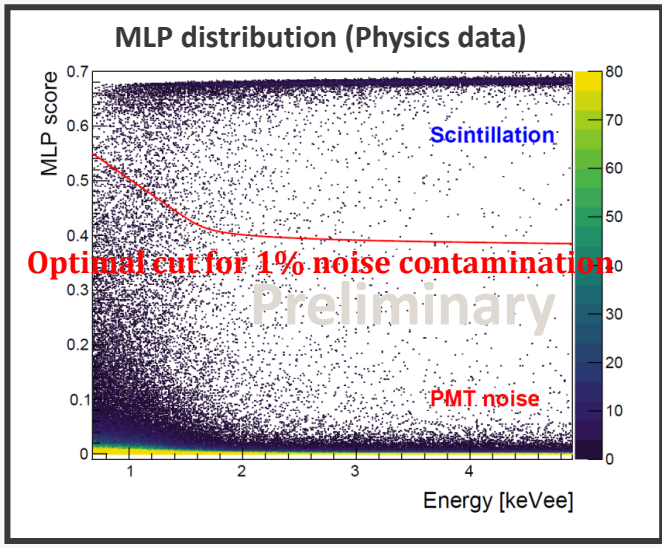
- **Main analysis is being performed with SET3**

Detector understanding update with SET3 data

- **Event selection**
  - **Multivariable analysis** with **pulse-shape parameters**
    - Meantime, likelihood parameters (SET2)

    $$F_{\mathcal{L}}^{N1} = \frac{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} - \ln \mathcal{L}_{\mathrm{FFT}}^{S}}{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} + \ln \mathcal{L}_{\mathrm{FFT}}^{S}}$$

    + **Fast Fourier Transformation** parameter(for **SET3**)
  - 1 keV → **0.7 keV**



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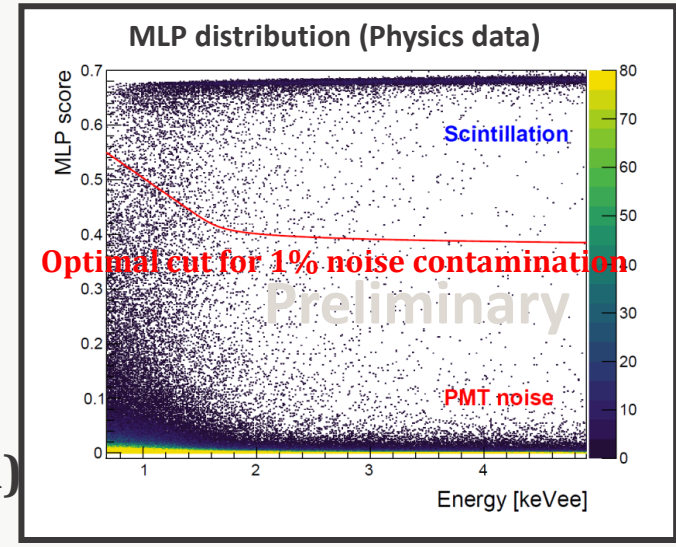
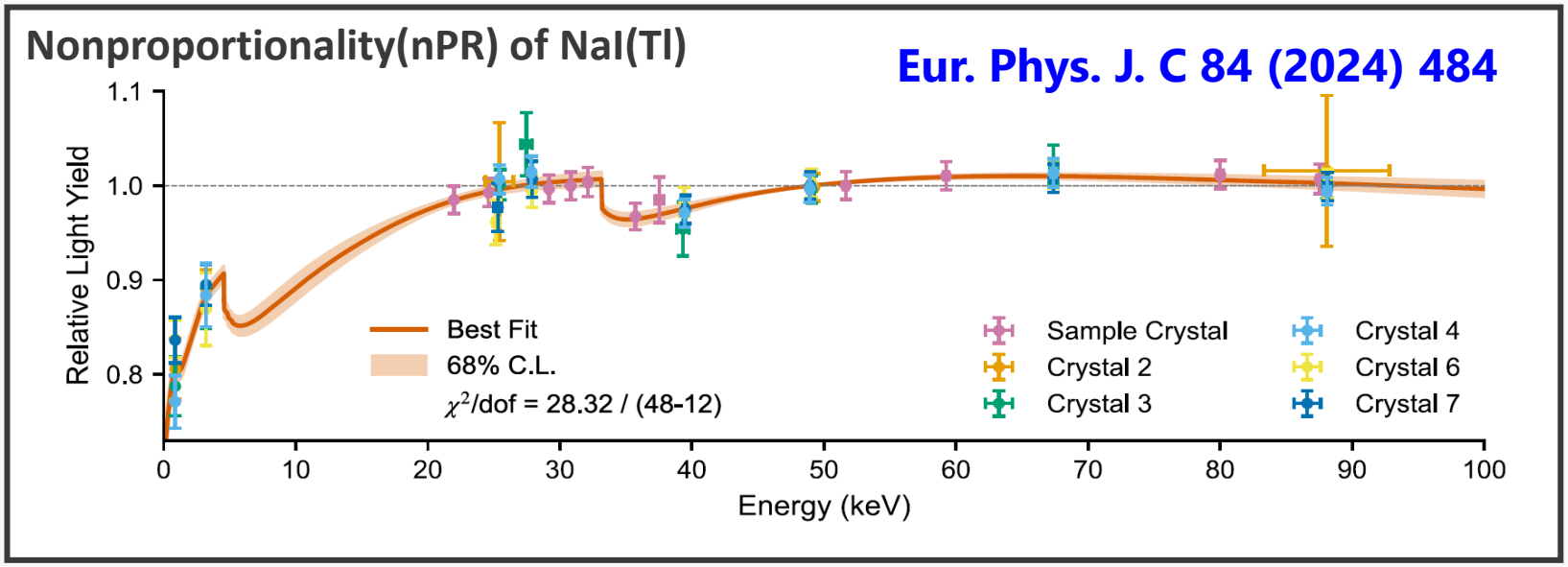
- **Background modeling**
  - Considers updated **nonproportionality of NaI(Tl)**





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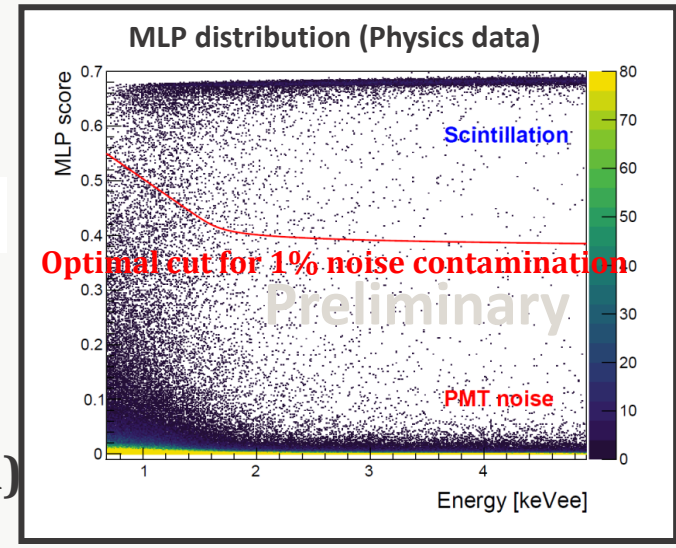

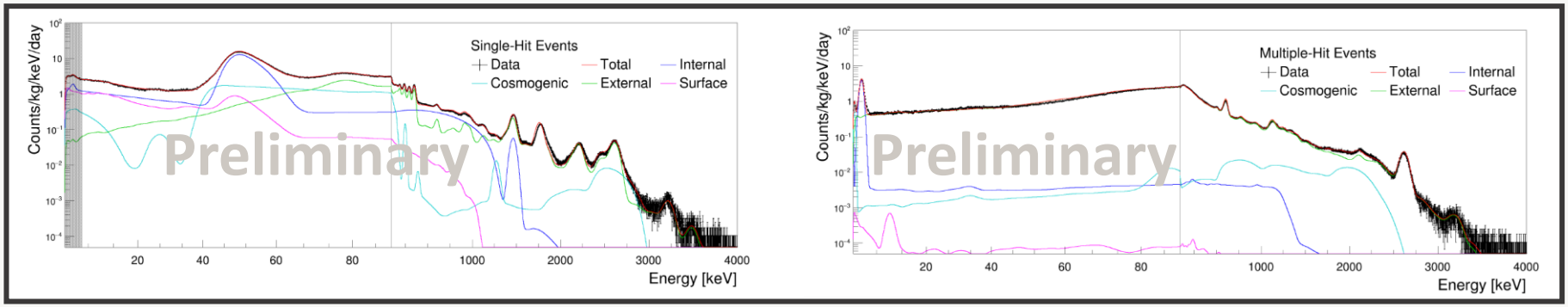

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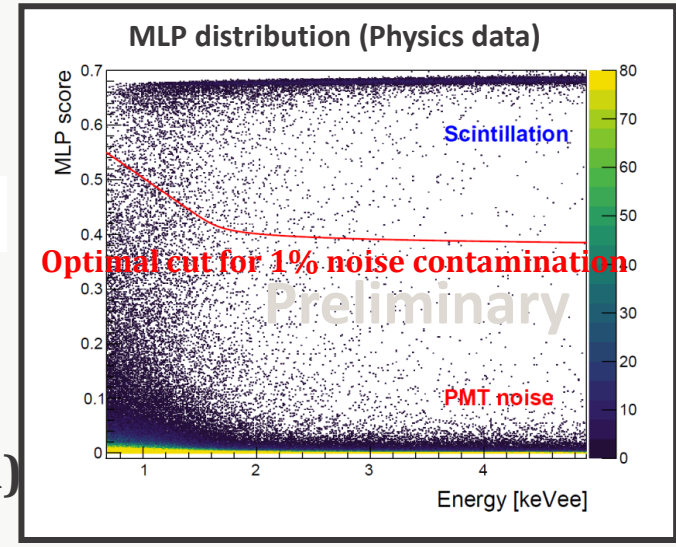
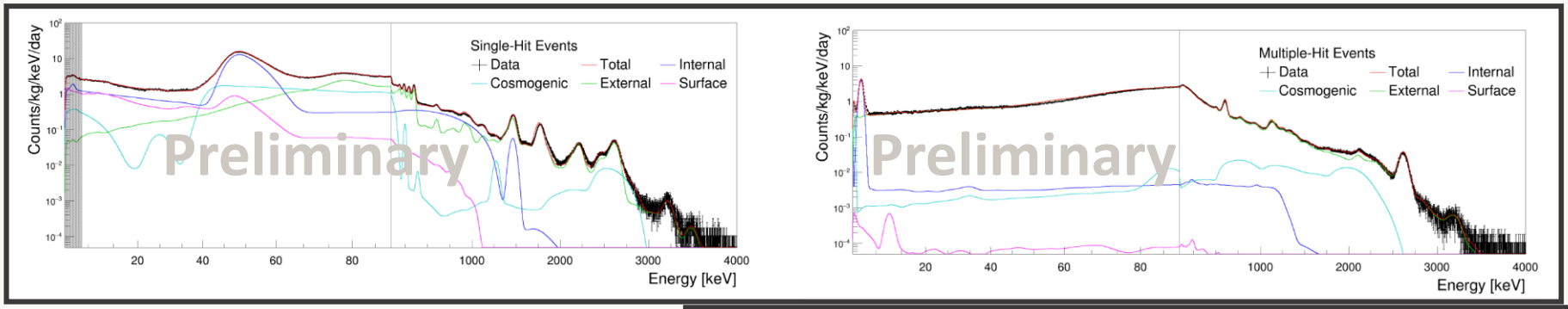
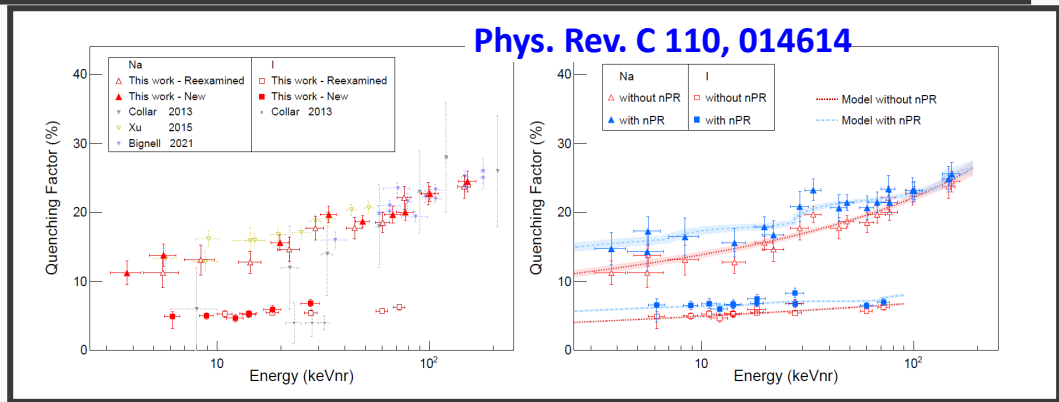


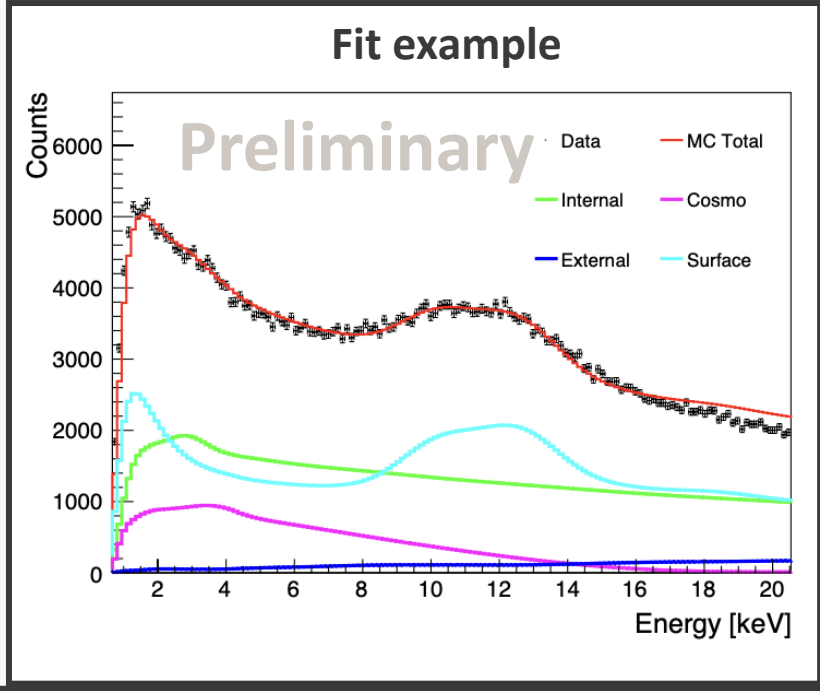


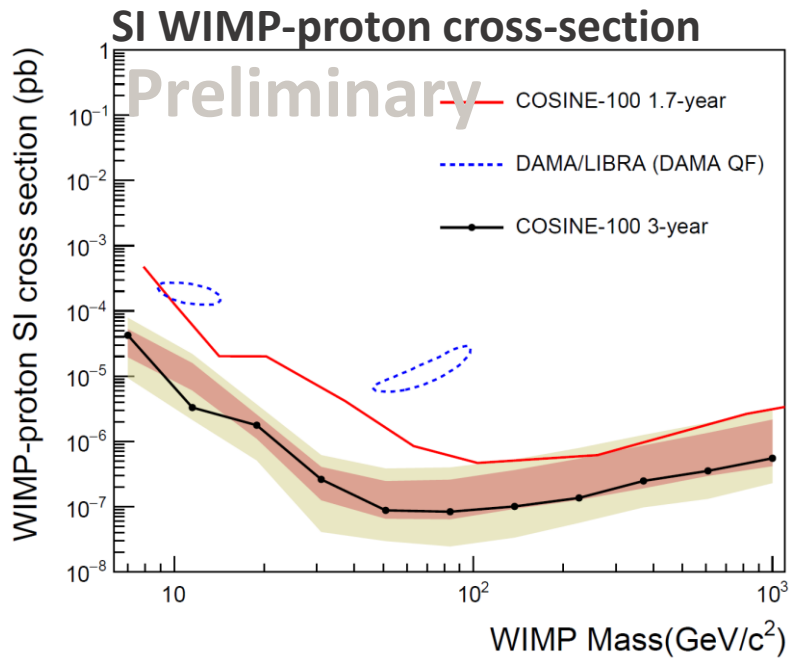
- **Quenching factor of NaI(Tl)**
  - **Update low energy region**

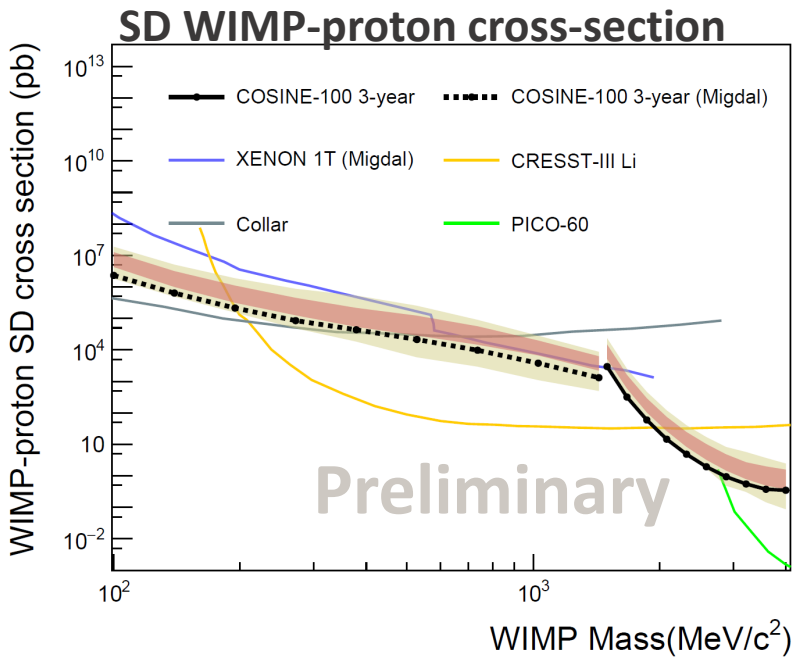


WIMP Extraction

- Analyze the **SET3 data** with **new event selection** and **new background modeling**
- **O(10) improvement** of SI WIMP-proton cross-section **limit** from **previous result**

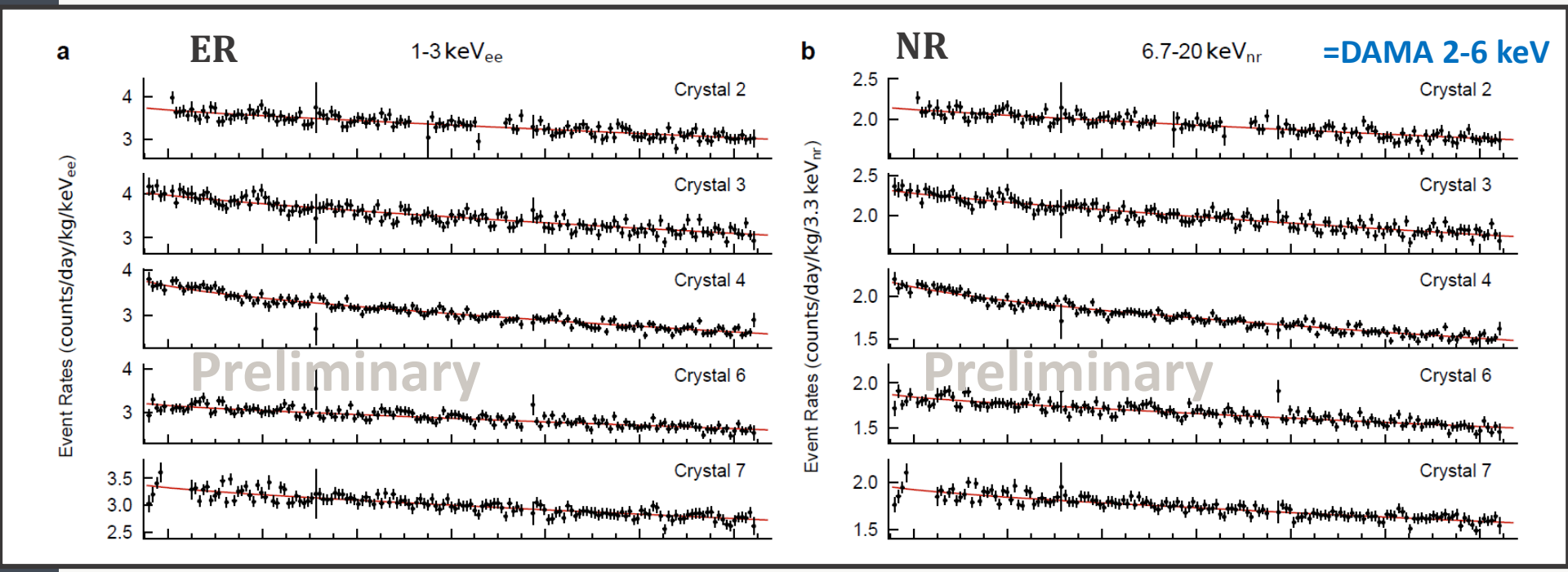






Annual modulation analysis

- **Using full COSINE-100 data (~6 years)**
  - Using **SET 3 event selection** and **modeling**
  - **Calibration method to test DAMA's claim**
    - Calibration for **Electron Recoil** (**ER**)
    - Calibration for **Nuclear Recoil** with **new quenching factor** (**NR**)



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  - Applying **full model** of **time dependent background** component

$$R^i(t|S_m,\alpha^i,\beta_k^i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t-t_0))$$

Constant from long-lived backgrounds
Exponential decays from short-lived
Modulation signal

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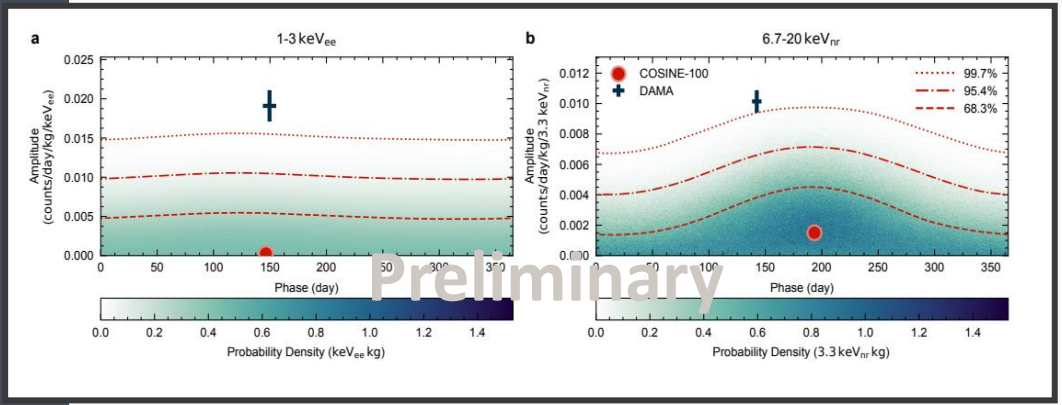
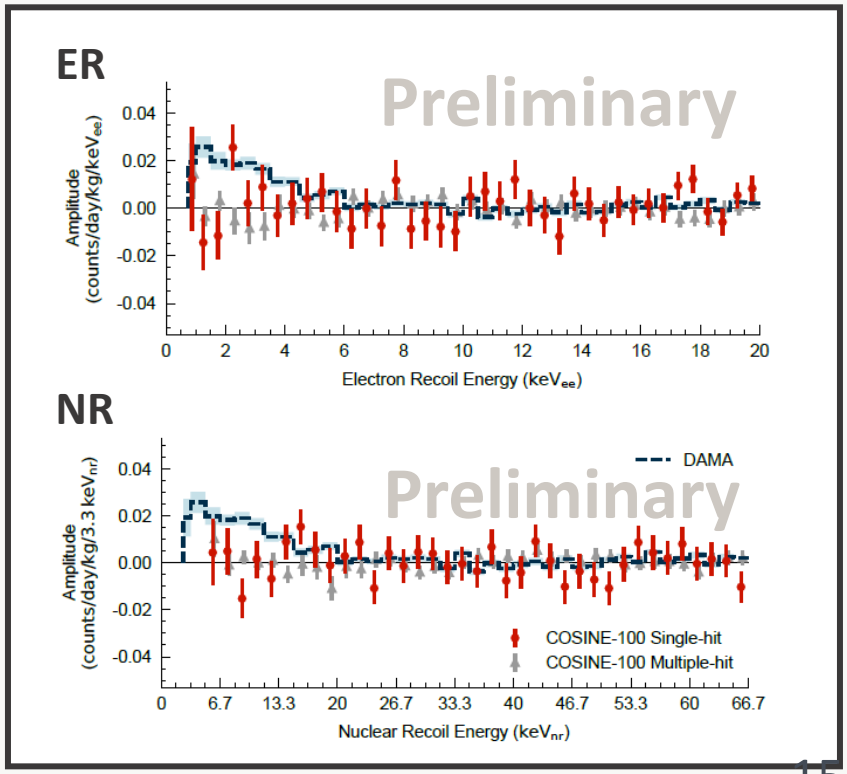
Energy (keV)		A_{COSINE} $(10^{-3}$ DRU$)$	A_{DAMA} $(10^{-3}$ DRU$)$	Exclusion C.L. (σ)
ERC	1-3	0.4 ± 5.0	19.1 ± 2.0	3.57
NRC	6.7-20	1.3 ± 2.7	10.0 ± 0.7	3.23





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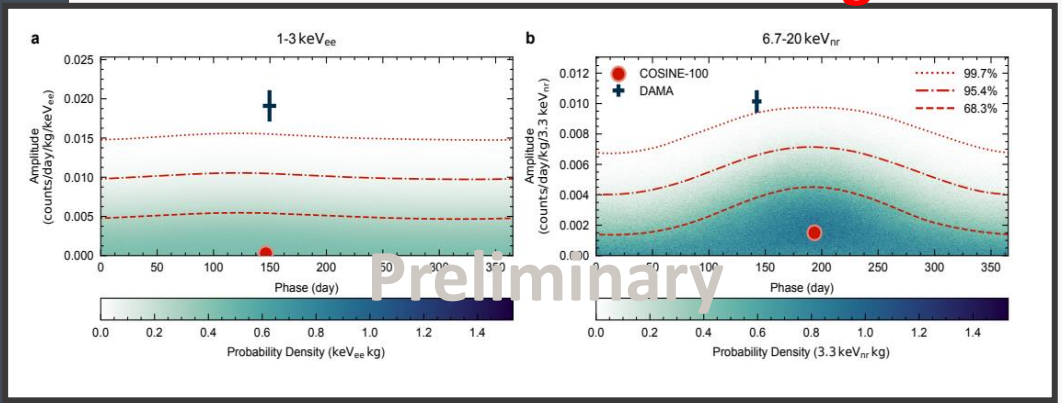
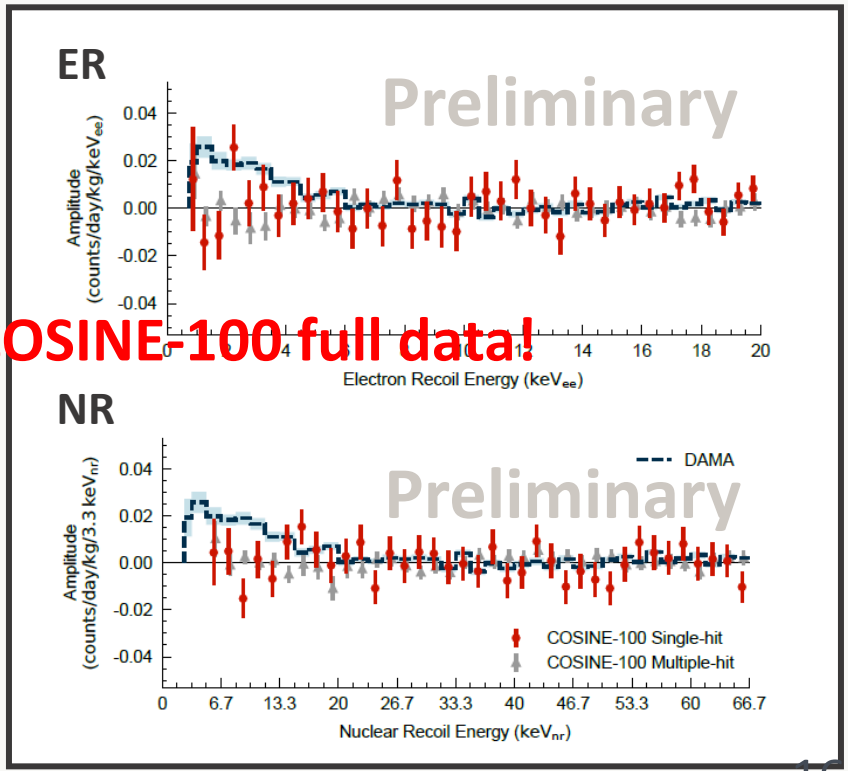


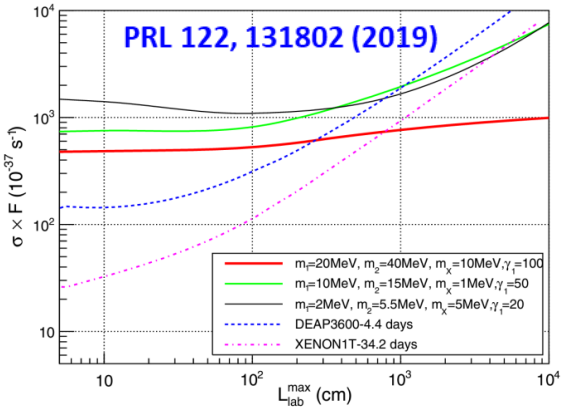
No DAMA like signal in COSINE-100 full data!

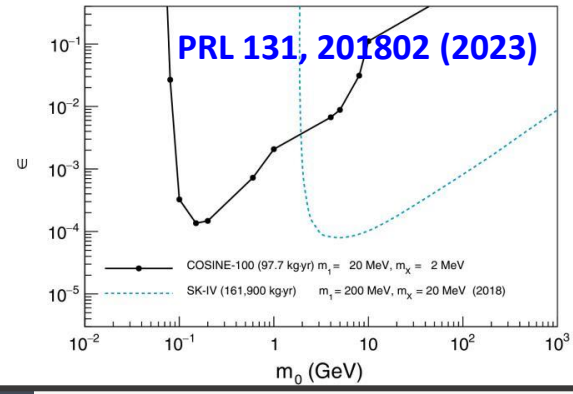


Other DM scenarios

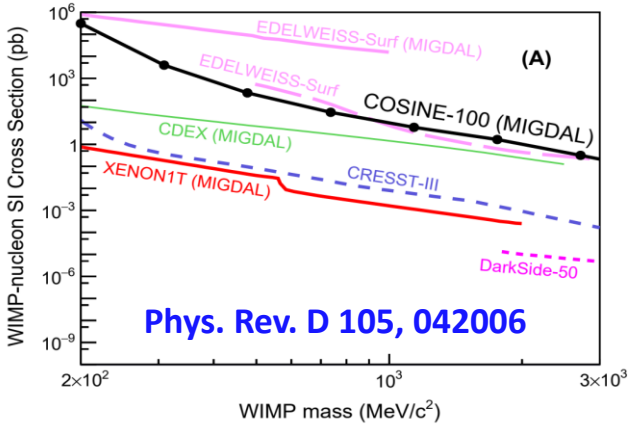
- Performed with SET2 data
- No dark matter signal

Boosted DM

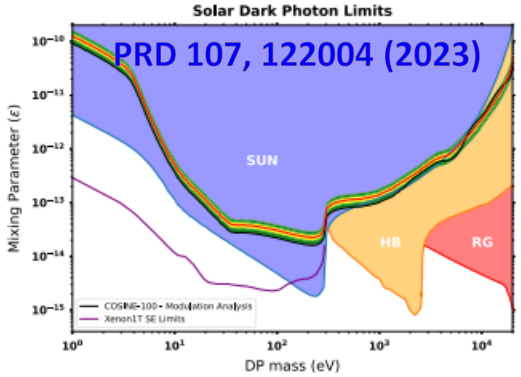




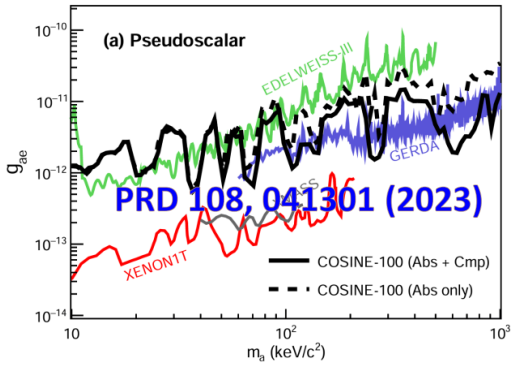
Migdal effect



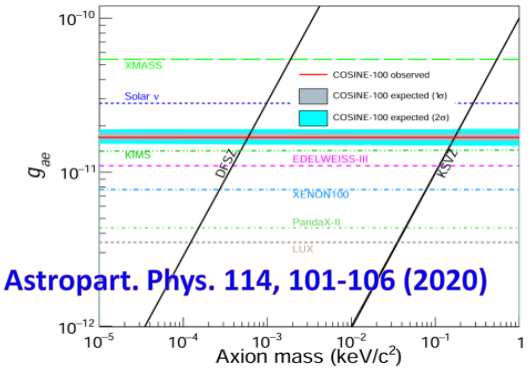
Solar Bosonic Particles



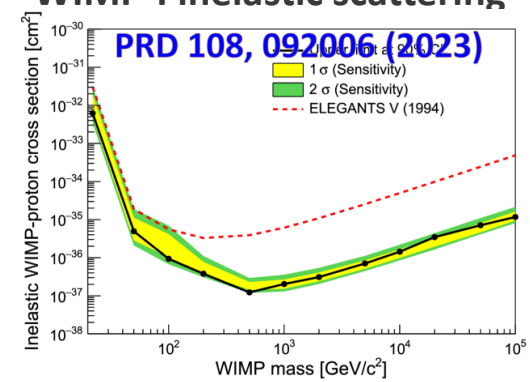
Bosonic Super WIMP



Solar Axion

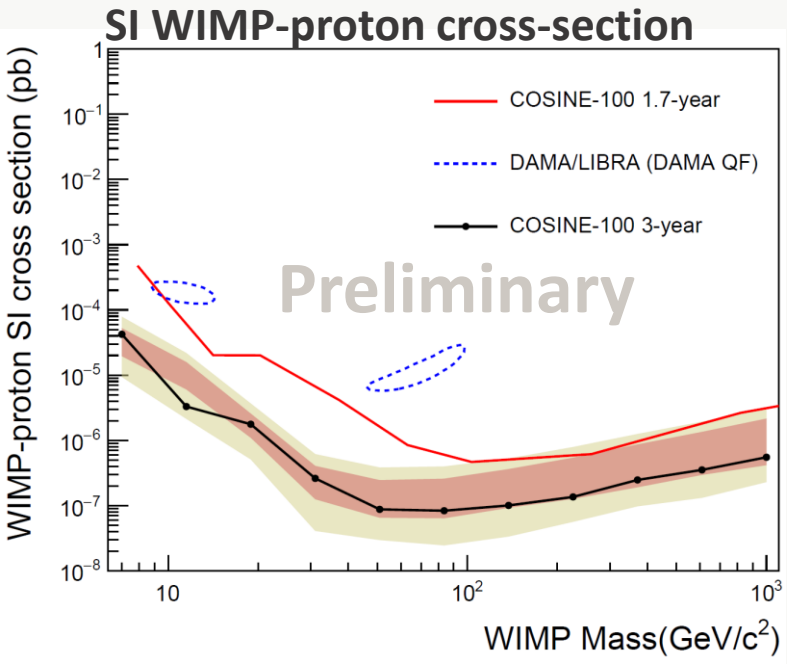


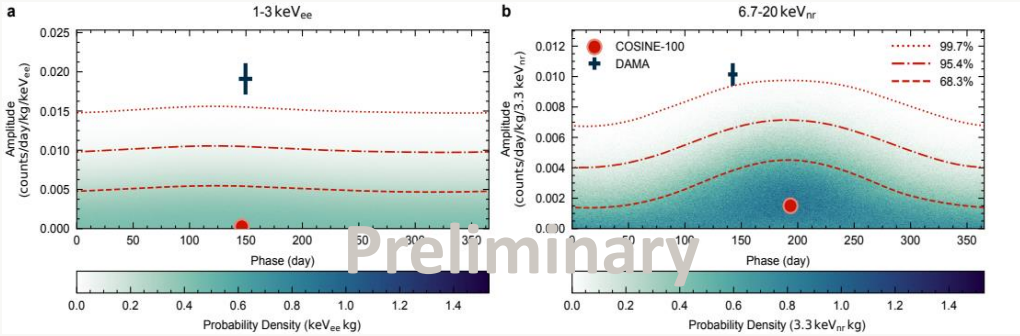
WIMP-I inelastic scattering



What is next for COSINE-100?

- Spectral Analysis
- Modulation analysis





- **No DAMA-like signal** in same target NaI(Tl) with COSINE-100 data

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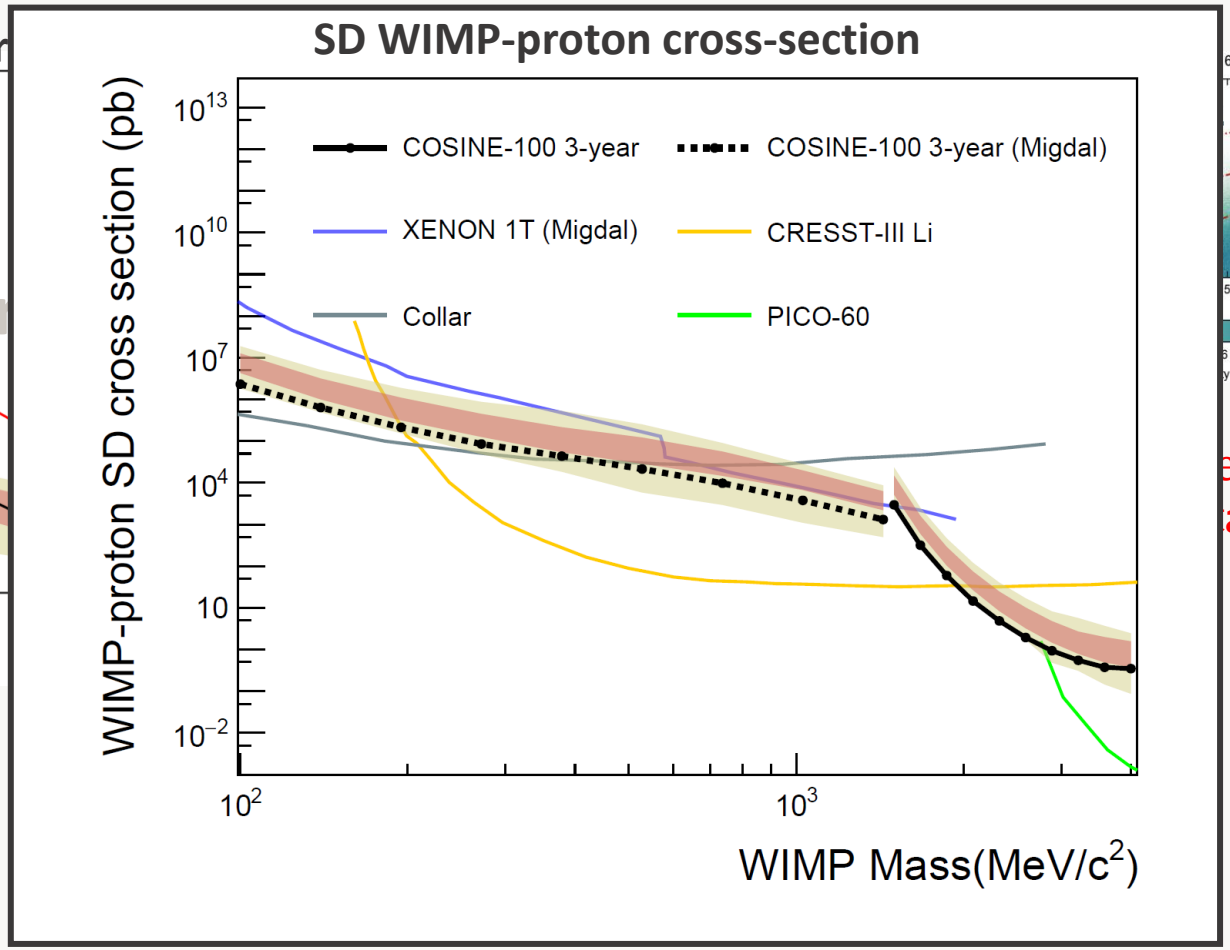
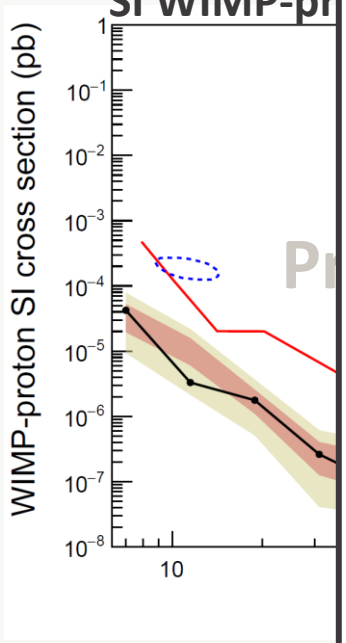
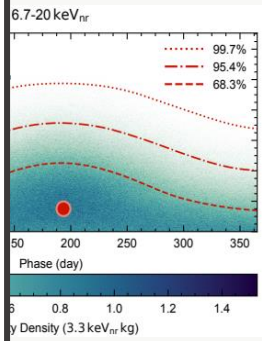






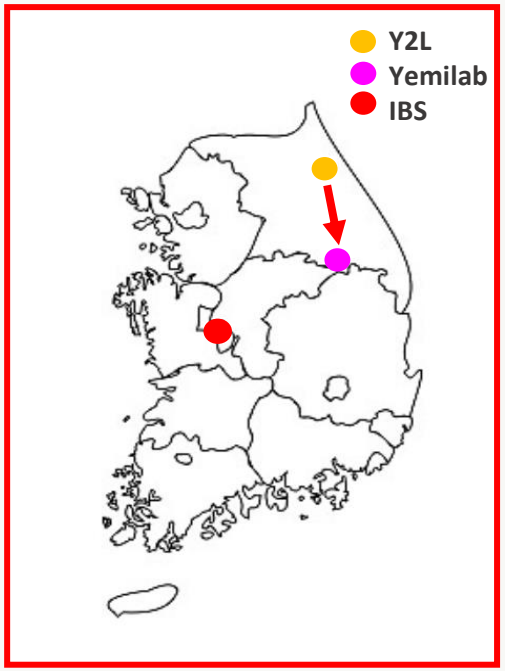
- Explore **low mass WIMP** with **lower threshold**!

→ Need **higher light yield** !

COSINE-100Upgrade

For lower threshold!

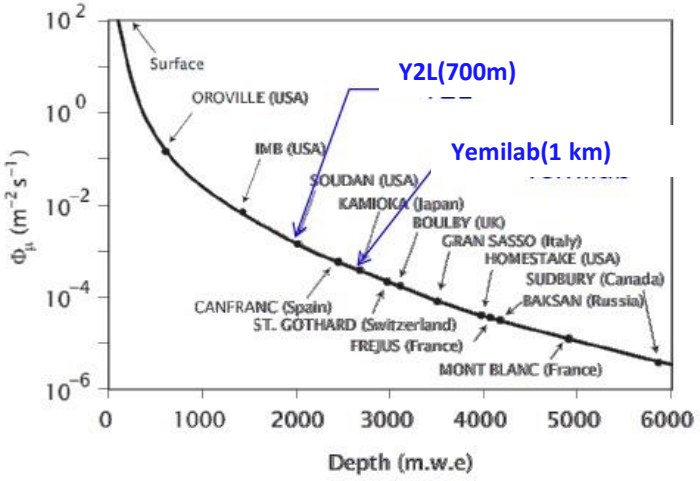
- **Enhance light yield** of **COSINE-100 crystals**
  - Operate at **-35°C environment**
  - **Upgrade encapsulation design**
- **Relocate COSINE-100 setup @ Yemilab**
  - Newly constructed **underground laboratory** in Korea
  - **Y2L→ Yemilab from 2023 to 2024** Front. Phys. 02 April 2024
  - **700 m → 1000 m overburden**
- **Same shielding** structure



COSINE-100 NaI(Tl) crystals

Crystal #	Size (diameter x length)	Light yield(PEs/keV)
1	5.0” x 7.0”	14.9 ±1.5
2	4.2” x 11.0”	14.6 ±1.5
3	4.2” x 11.0”	15.5 ±1.5
4	5.0” x 15.3”	14.9 ±1.5
5	5.0” x 15.5”	7.3 ±0.7
6	4.8” x 11.8”	14.6 ±1.5
7	4.8” x 11.8”	14.0 ±1.4
8	5.0” x 15.5”	3.5 ±0.3

Underground laboratories

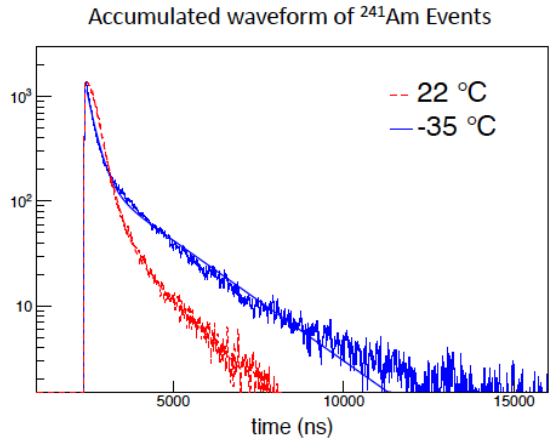


NaI(Tl) at -35°C

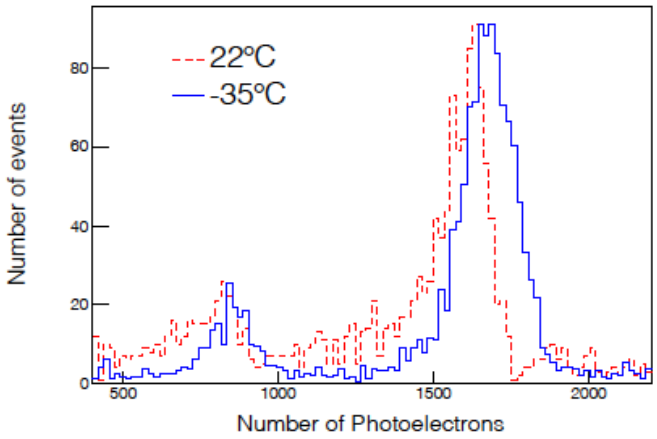
[Astroparticle Physics 141 (2022) 102709]

- **Low temperature** operation (**at -35°C**)
  - **~5%** increased **Light yields**
  - **~9%** increased **alpha quenching**

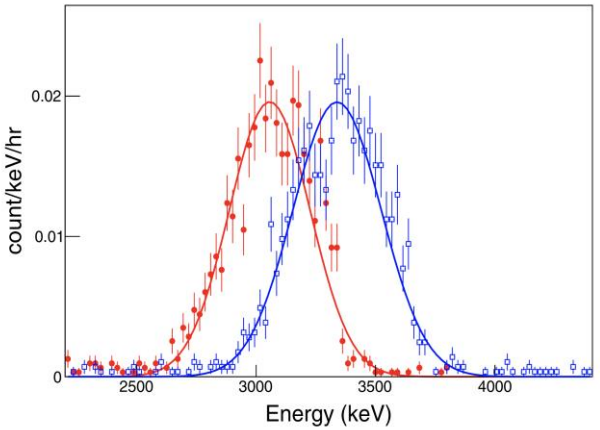
Accumulated waveform



NPE Measurement



Alpha response using ^{210}Po

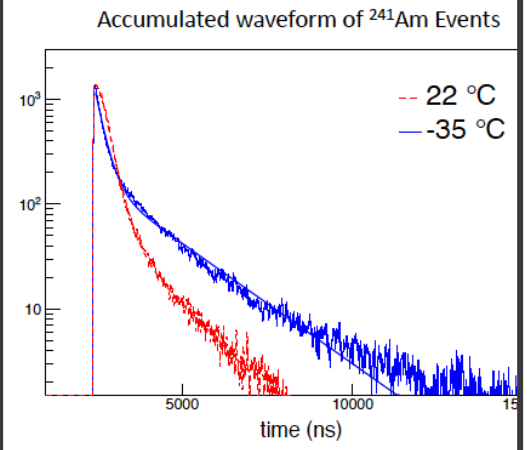


NaI(Tl) at -35°C

[Astroparticle Physics 141 (2022) 102709]

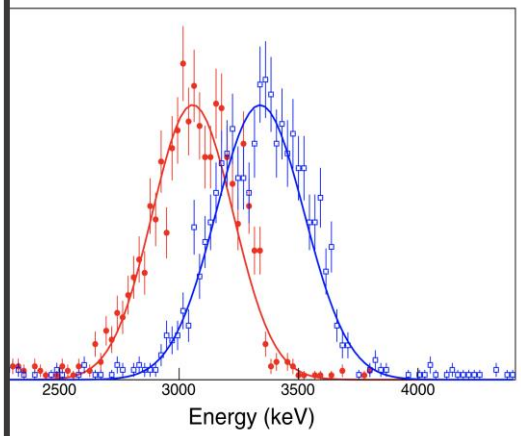
- **Low temperature** operation (**at -35°C**)
  - **~5%** increased **Light yields**
  - **~9%** increased **alpha quenching**

Accumulated wavefor



COSINE detector fridge room @Yemilab

pha response using ^{210}Po



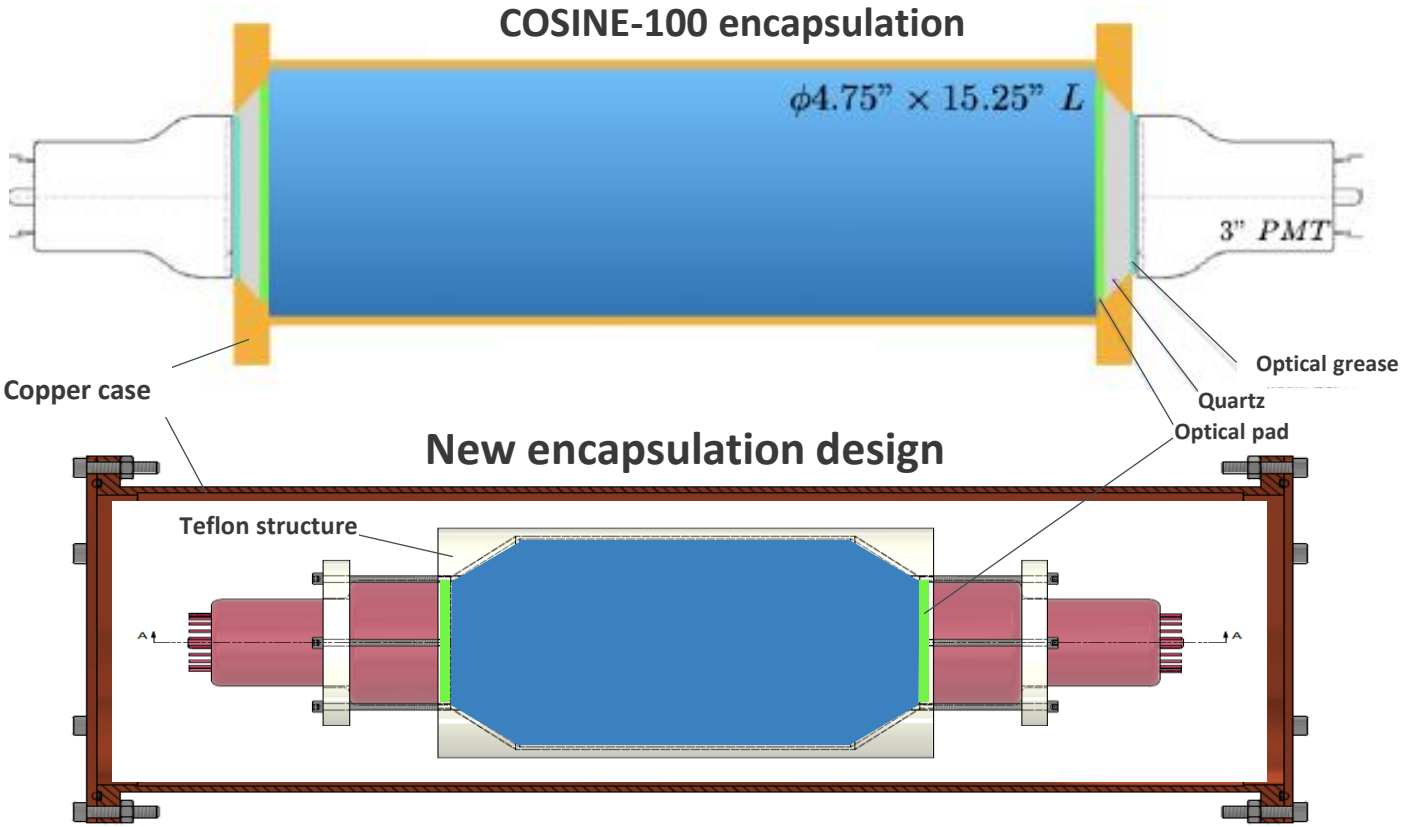
- **The detector fridge room** was prepared for COSINE-100U!

New encapsulation design

- **Minimize optical coupling layer** between **PMT** and **crystal**
  - **3 layers → 1-layer optical pad**
- **Teflon structure** for **stable optical contact**
- **Copper case** for protection from outside
- **Expect ~50% increase in light yield**
  - **15 P.E. → >20 P.E.**

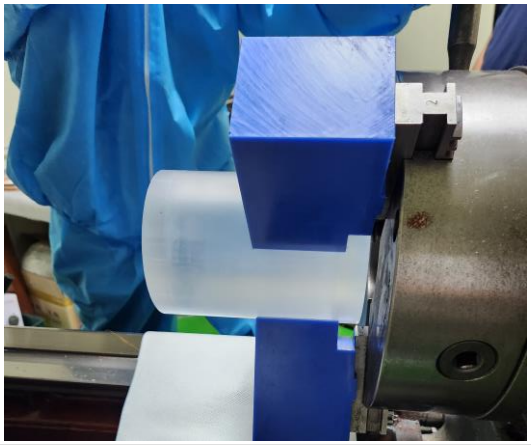
- **Machining** crystal edge with **light guide-like shape**
  - **7 cm diameter = PMT photocathode size**
  - **Maximize light collecting**

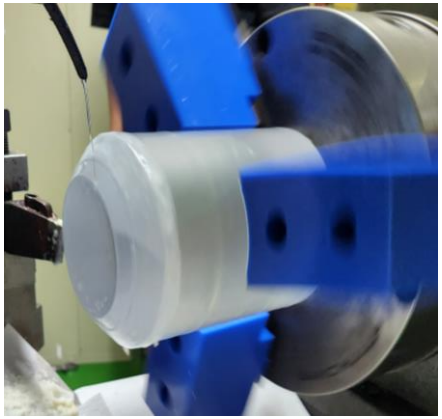
Nucl. Instrum. Meth. A 981, 164556 (2020)
arXiv:2404.03691



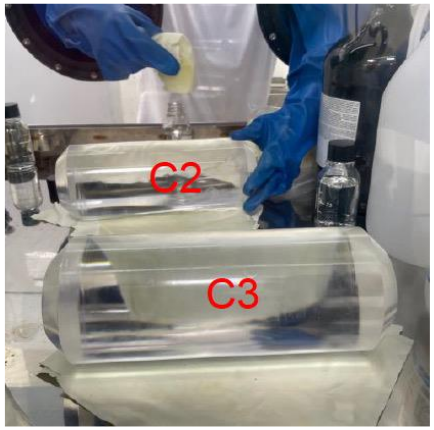
New encapsulation assembling

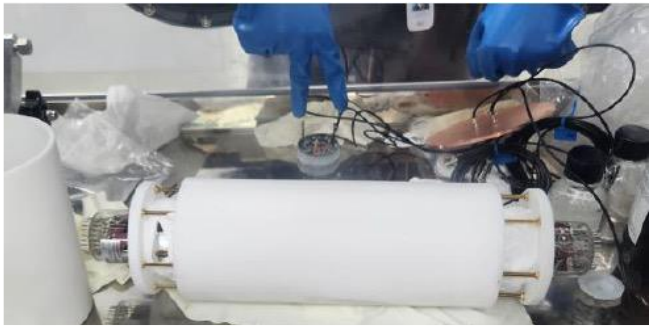
Machining crystal edge





Assembling @glovebox (H_2O< 10 ppm)

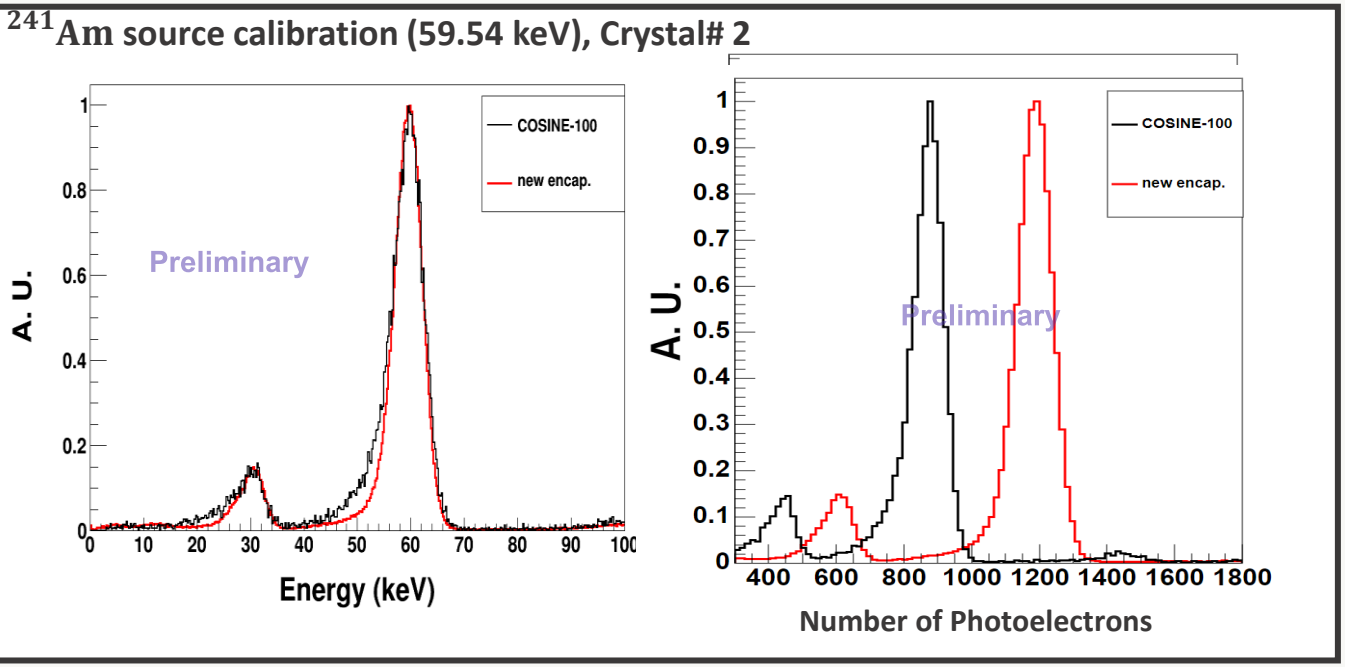


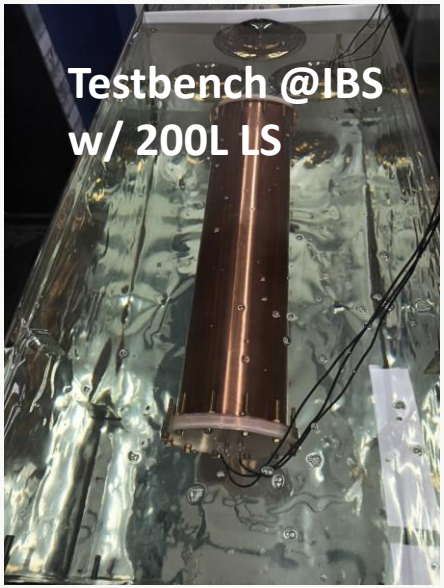


New encapsulation performance

Light yields

- Test performance in HQ testbench (On ground w/200 L LS)

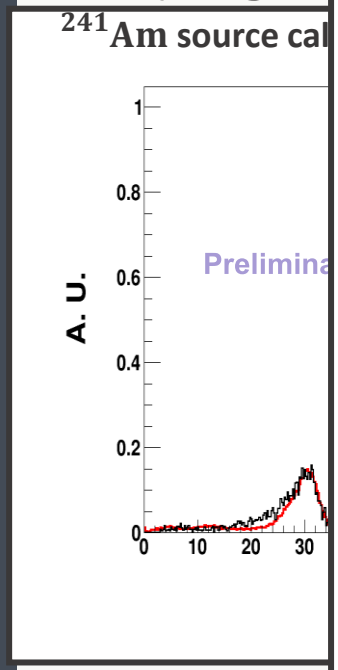


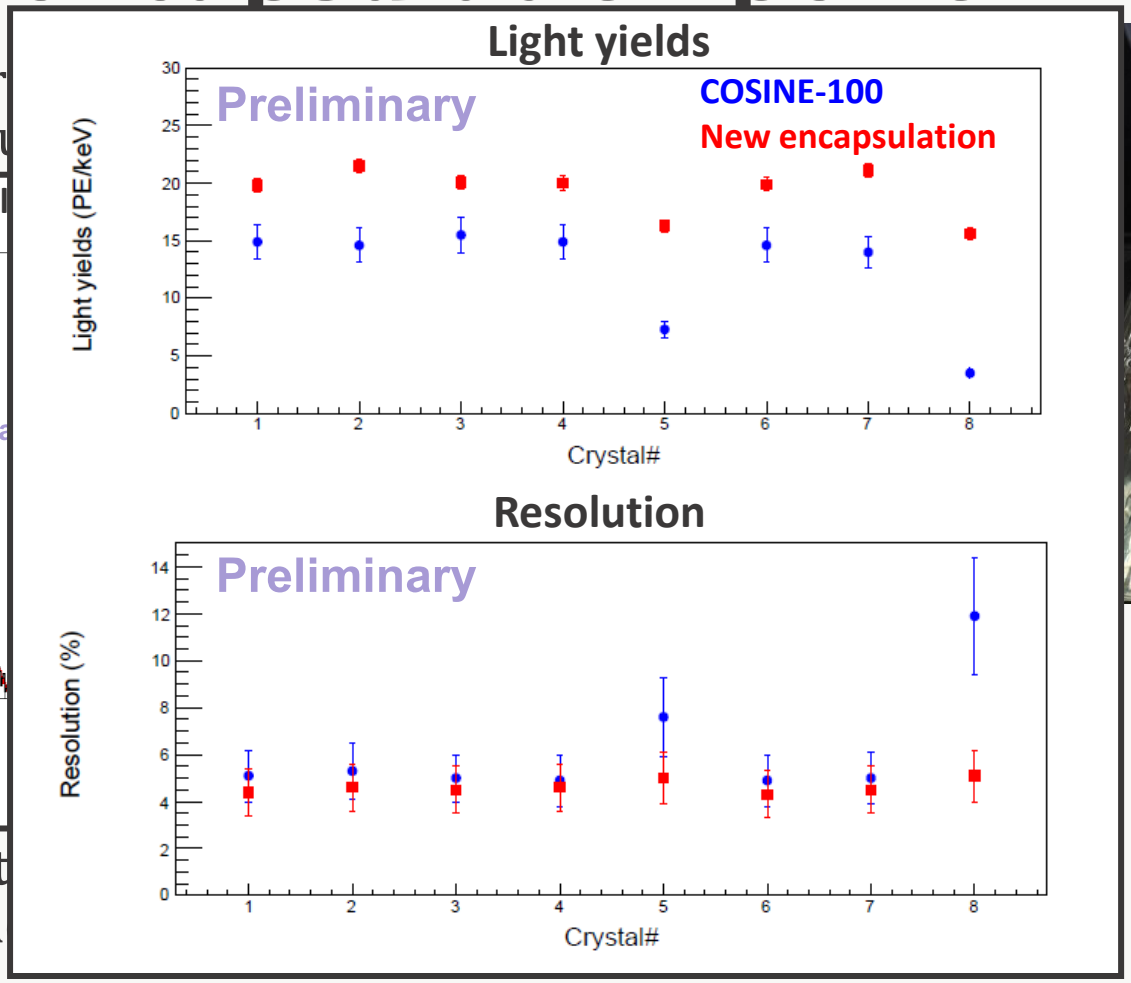


- **Resolution** : 5.3 ±1.2%→ 4.6 ±1.0%
  Light yield : 14.6 ± 1.5→21.0 ± 0.6 PE/keV

New encapsulation performance

- Test per
  (On grou





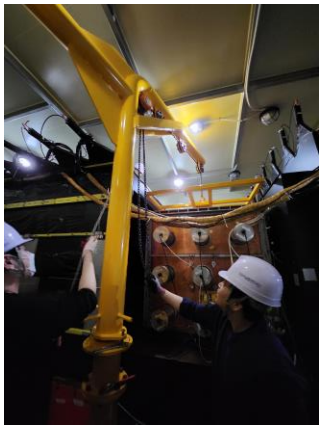
- **Resolut**
  Light yi

- **Assembling** for all crystals was **finished**!
  - Up to **45% light yield** improvement
  - **Resolution improved** by **~10%** @ 59.57keV

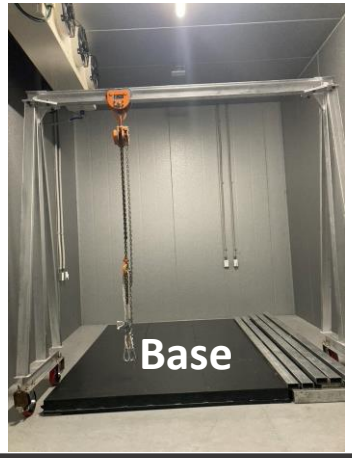
Status on COSINE-100U

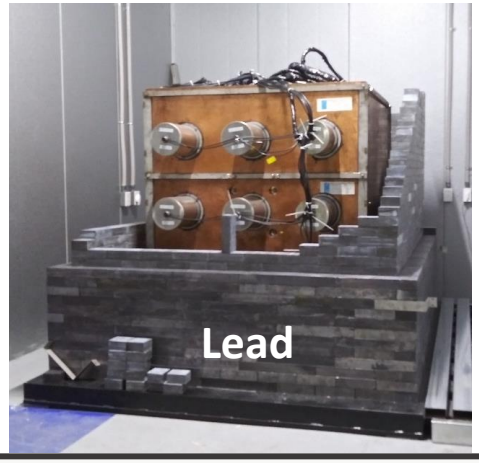
- Y2L → Yemilab (From Sep. 2023)

COSINE-100 decommissioning @Y2L



Shield installation in fridge room @ Yemilab

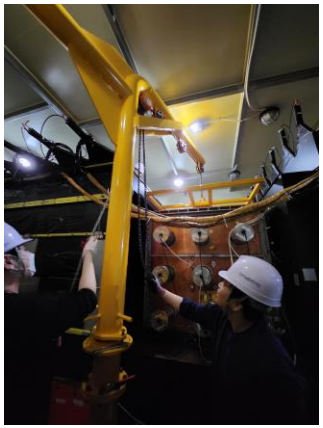




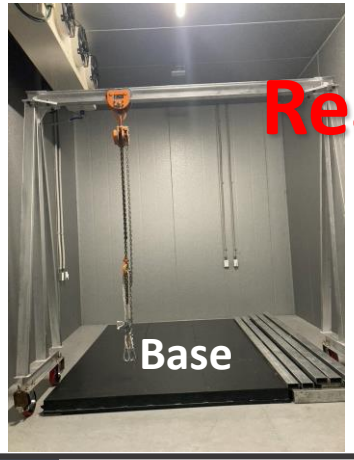
Status on COSINE-100U

- Y2L → Yemilab (From Sep. 2023)

COSINE-100 decommissioning @Y2L

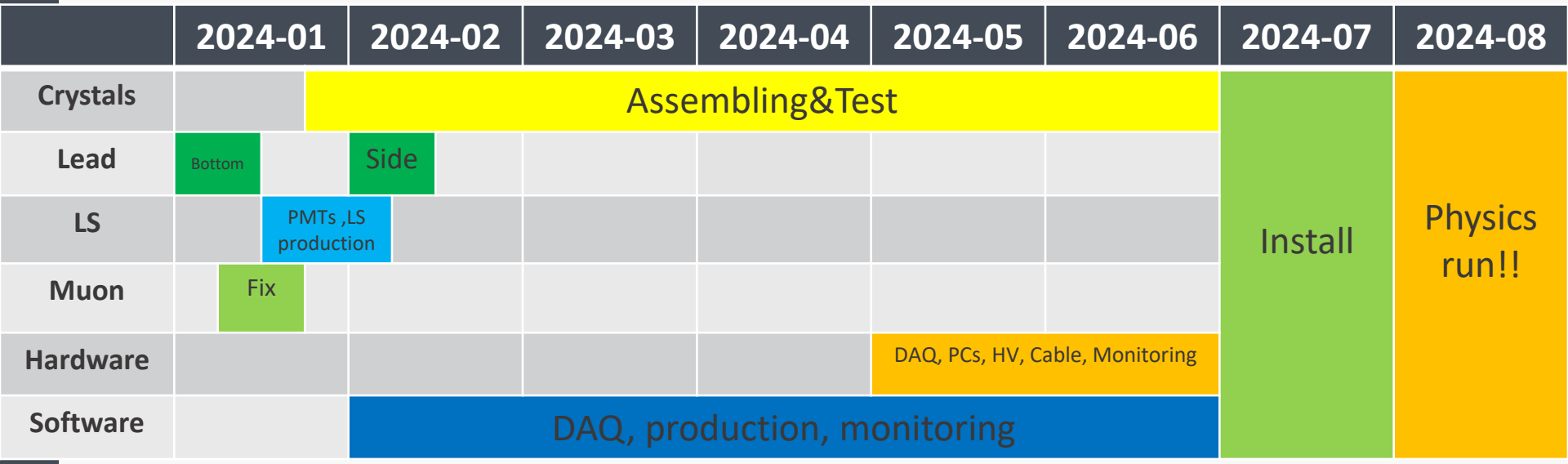


Shield installation in fridge room @ Yemilab



Ready to install COSINE-100U detectors!

Plan for COSINE-100U

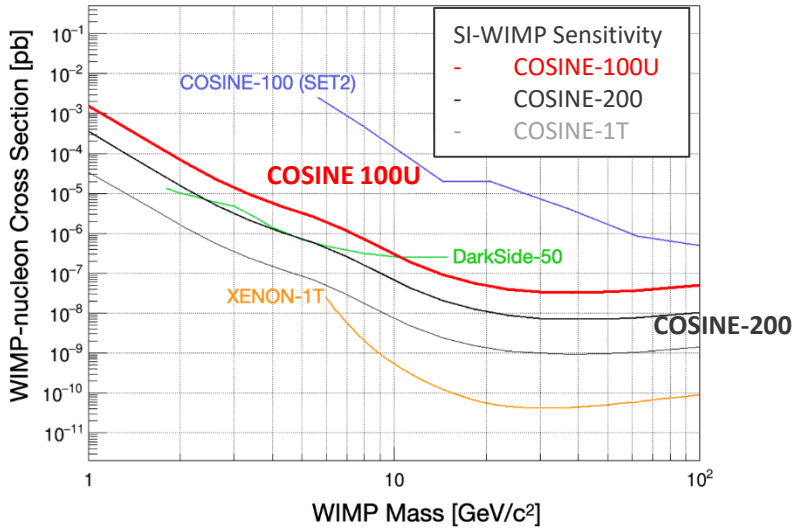


- Under preparation to start **physics run** in **August!**

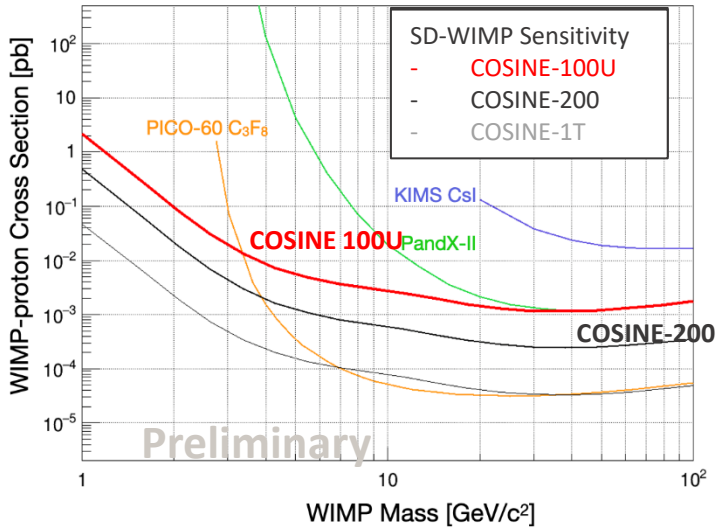
Sensitivity estimation

- **Condition for upgrade COSINE-100 (COSINE-200)**
  - **1 year**
  - Light yields **22 P.E./keV**
  - COSINE-100 (R&D crystal) background
  - No systematics

SI WIMP interaction

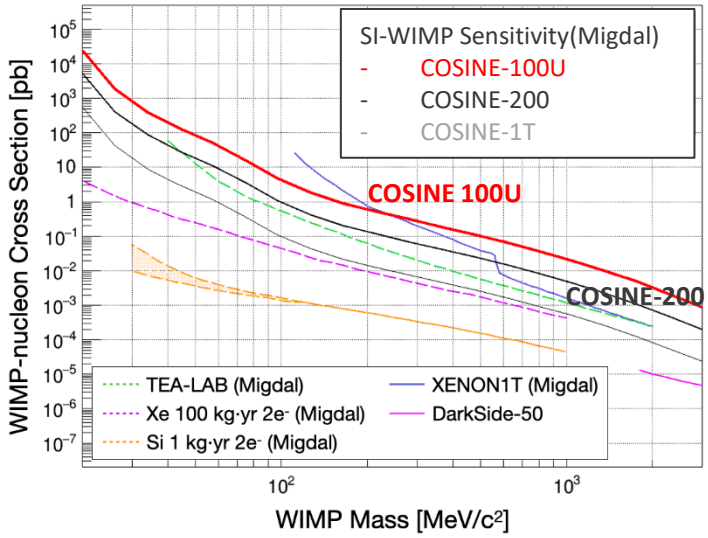


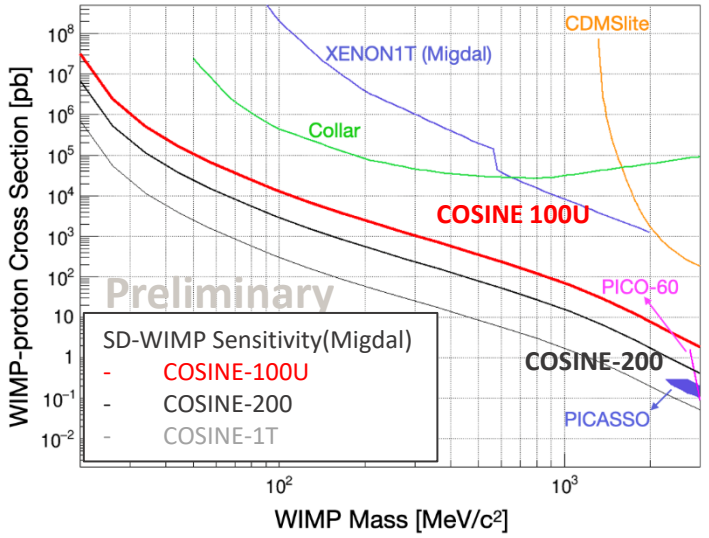
SD WIMP interaction



With Migdal effect

No systematics



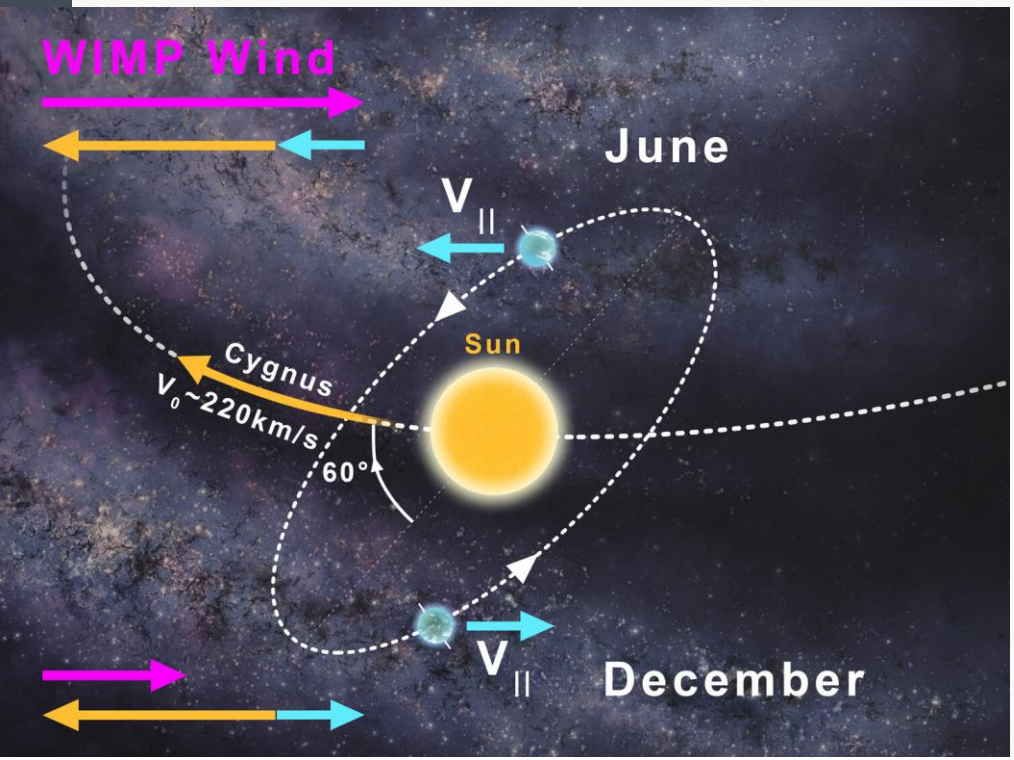


Summary

- COSINE-100 was designed to **test the DAMA/LIBRA signal** via the **same target material, NaI(Tl)** from Sep. 2016 to Mar. 2023
- Spectral Analysis
  - **Improved WIMP-nucleon cross section using 3-years data**
  - Investigation of various DM scenarios
- Modulation analysis
  - **No DAMA like modulation** with more than **3σ significance** using full COSINE-100 data
- **COISNE-100U** experiment is being prepared using detectors with **enhanced light yields** detectors in newly constructed underground laboratory.
  - **40% light yield improvement** with new encapsulation technique.
  - Detector fridge room for **-35°C operation** is ready
- **COSINE-100U** operation will start in **August 2024** for searching low mass WIMP!

Back up

Annual modulation signal



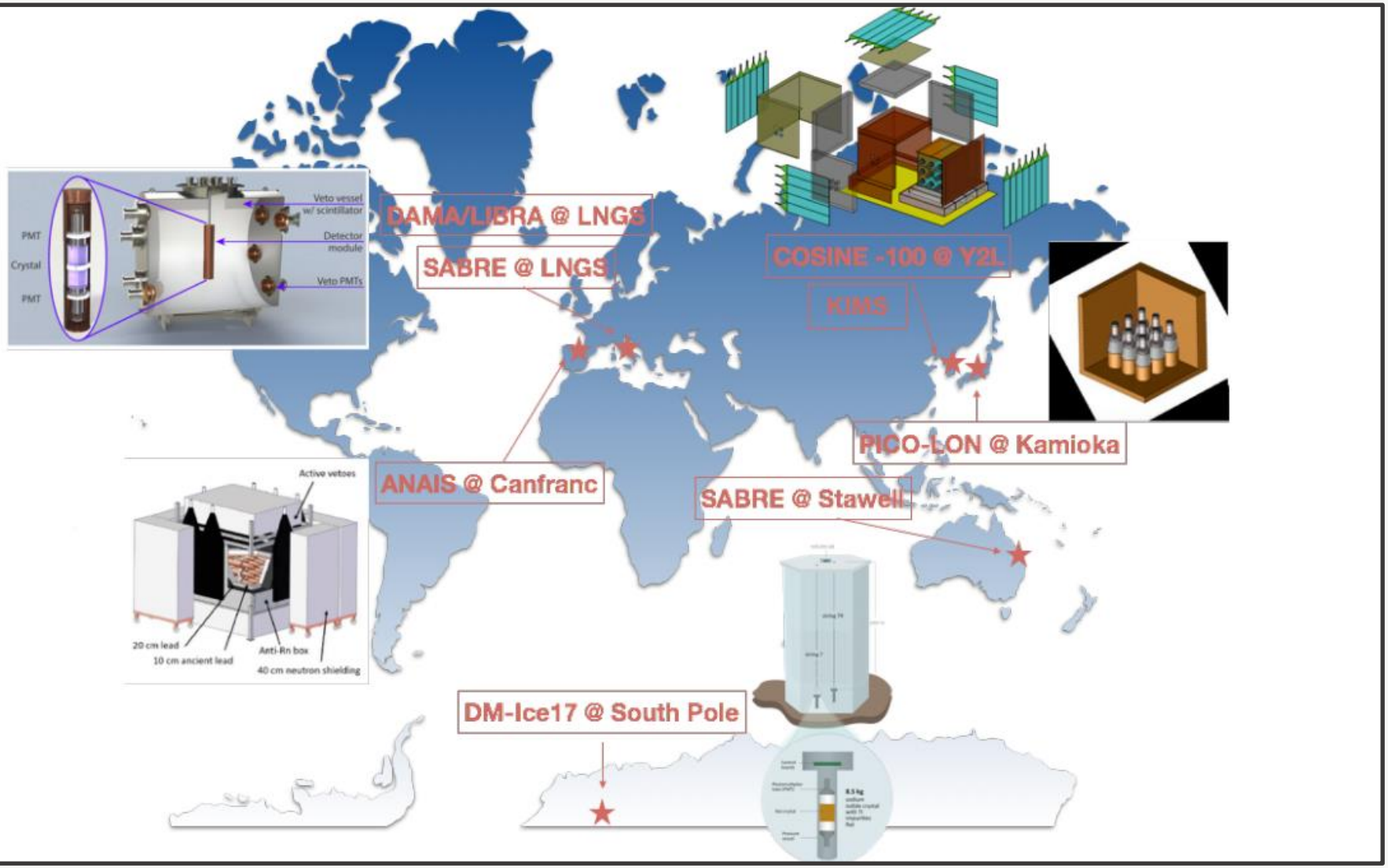
- Spherical halo of dark matter in our galaxy is expected to make dark matter flux to Solar system (WIMP Wind)
- Speed of WIMP wind changes according to seasonal rotation of the Earth.
- Changing WIMP speed induces changing interaction rate.

Rate of WIMP elastic scattering

$$R \propto N_T \cdot \sigma_{\chi^N} \cdot \frac{\rho_\chi}{m_\chi} \int_{v_{min}} \frac{f(v)}{v} dv$$

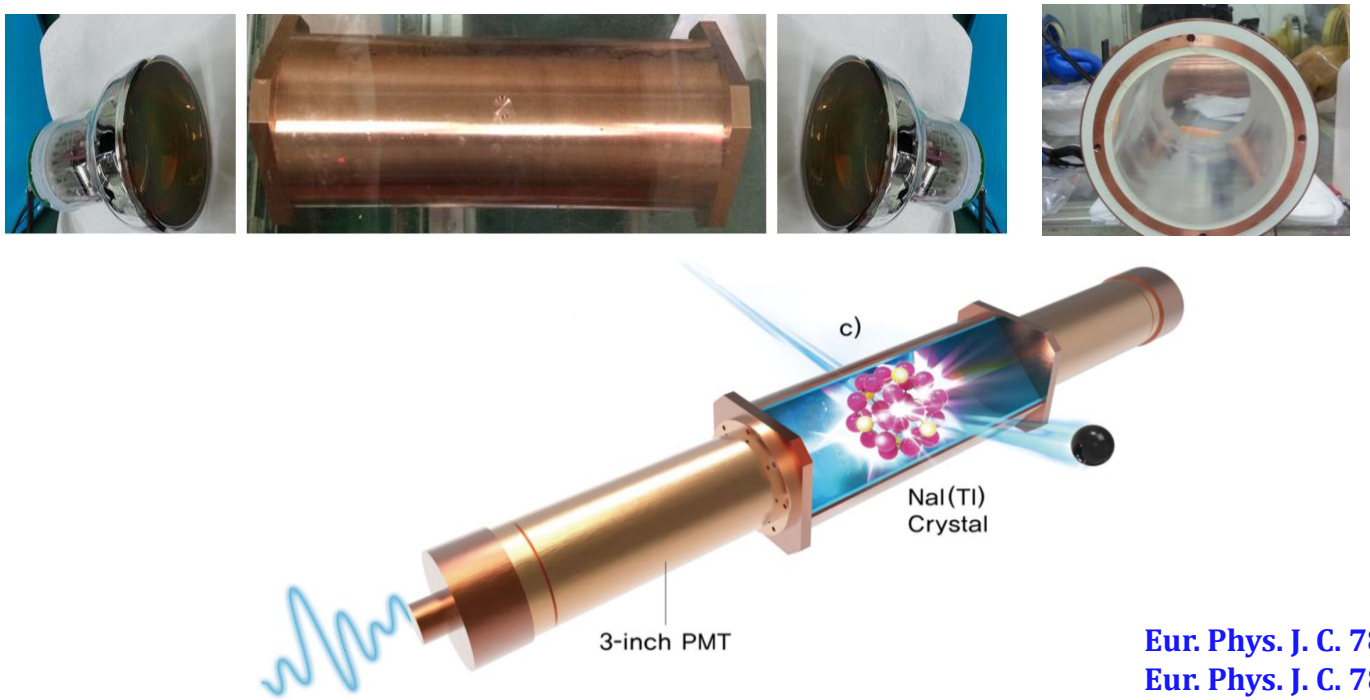
$f(v)$: WIMP velocity distribution
v_{min} : minimum velocity for interaction
ρ_χ : local WIMP density
m_χ : WIMP mass

NaI(Tl) Dark matter search



COSINE-100 experiment-NaI(Tl)

- **8 low-background NaI(Tl) crystals** with **106 kg** in total
  - **U/Th/K level** is less than DAMA, but total alphas (**^{210}Pb**) are higher than DAMA.
  - Total **background** level is **2-3 times that of DAMA/LIBRA.**
  - **Higher light yield (15 P.E./keV)** than **DAMA/LIBRA** (**5-10 P.E./keV**)
    - Can make the threshold lower easily
  - Each crystal is **encapsulated** in **copper and quartz windows**.
  - Two 3-inch PMTs (R12669SEL) are attached to each crystal.
    - Quantum efficiency: 35% @ 420 nm

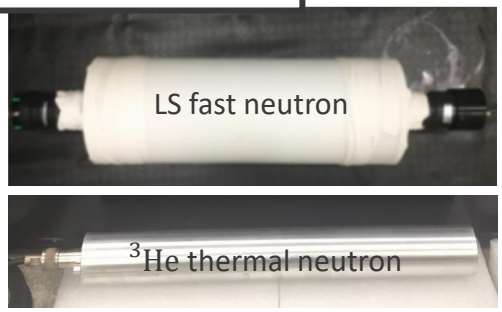


Eur. Phys. J. C. 78 107 (2018)
Eur. Phys. J. C. 78 490 (2018)

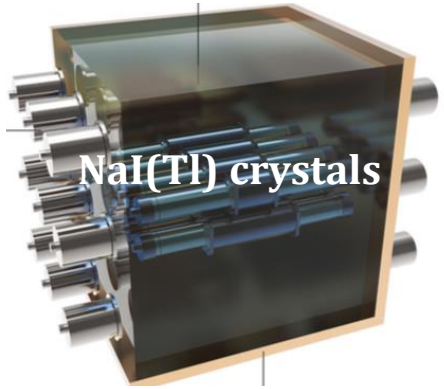
COSINE-100 experiment-Shielding

- **Active veto**
  - **Liquid scintillator (LS)**
    - **2200-L LAB-based** LS
    - **5-inch PMT(R877)** for LS detector
  - **4π Muon counter**
    - **37 plastic scintillator** panels
    - **2-inch PMT(H7195)** for muon counter
- **Passive veto**
  - **3-cm** thick **copper box**
  - **20-cm** thick **lead castle**
- **Neutron monitoring**
  - **Fast neutron** detector (**Liquid Scintillator**)
  - **Thermal neutron** detector (**^{3}He gas** detector)

Neutron monitoring — **JINST 13 T06005(2018)**

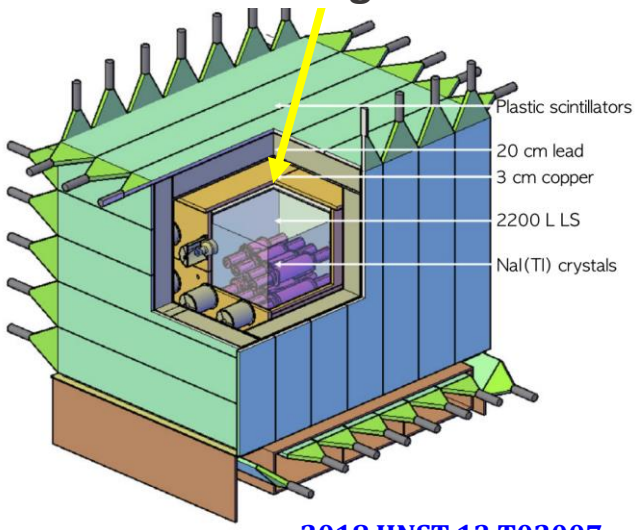


Liquid scintillator



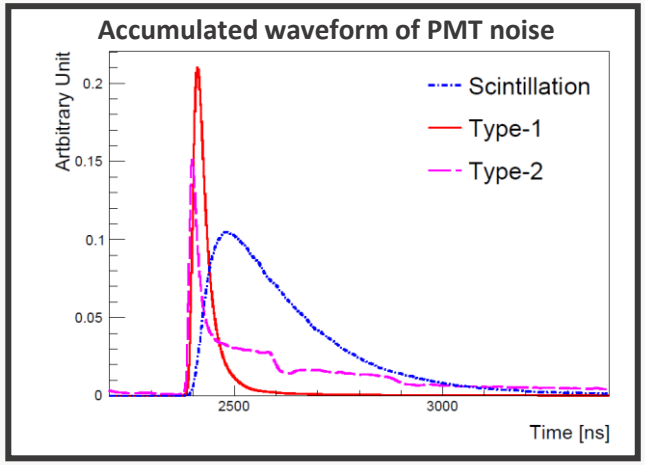
Nucl. Instrum. Meth. A 106, 165431 (2021)
Nucl. Instrum. Meth. A 851 103 (2017)

COSINE shielding structure



2018 JINST 13 T02007
Eur. Phys. J. C 78, 107 (2018)

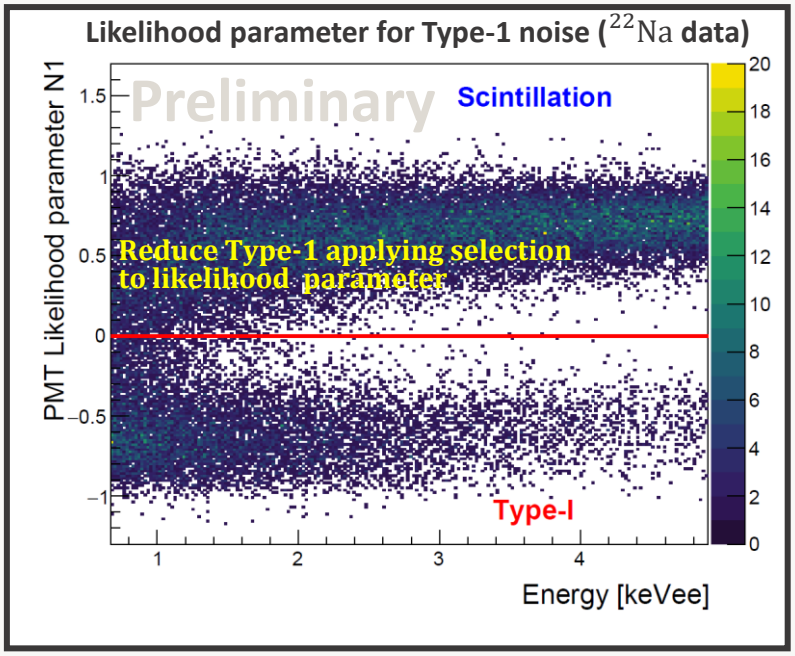
Event Selection (SET2)

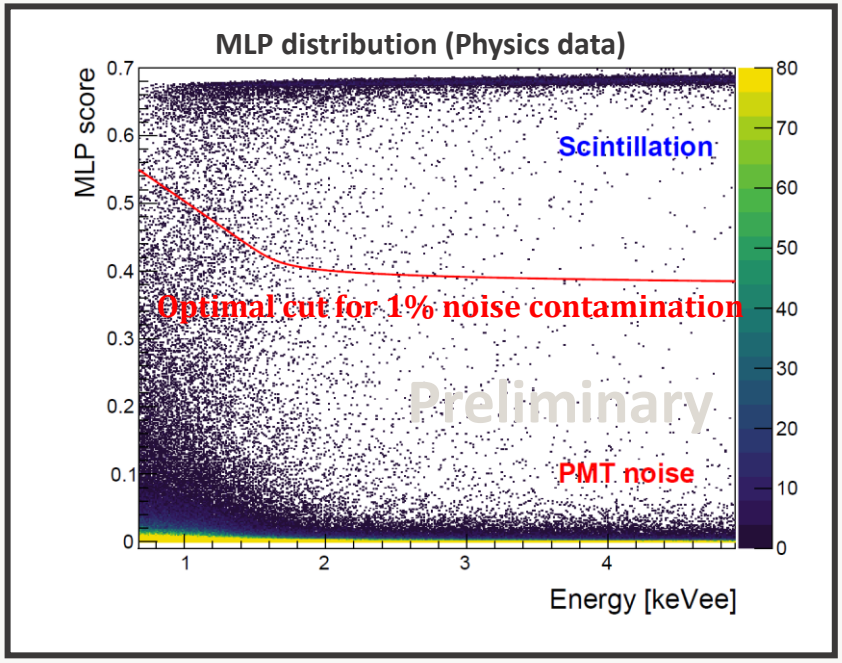


- **Event selection** updated since **Astropart. Phys 130, 102581 (2021)**
- To select **scintillation event** from **PMT-induced noise**
  - Use **pulse-shape parameters**
    - Meantime, likelihood parameters

    + **Fast Fourier Transformation** paramete r(for Set3)
- Multivariable analysis
  - BDT(SET2) → **MLP(SET3)**
    Boosted Decision Tree Multilayer perceptron
  - 1 keV → **0.75 keV**

$$F_{\mathcal{L}}^{N1} = \frac{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} - \ln \mathcal{L}_{\mathrm{FFT}}^{S}}{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} + \ln \mathcal{L}_{\mathrm{FFT}}^{S}}$$

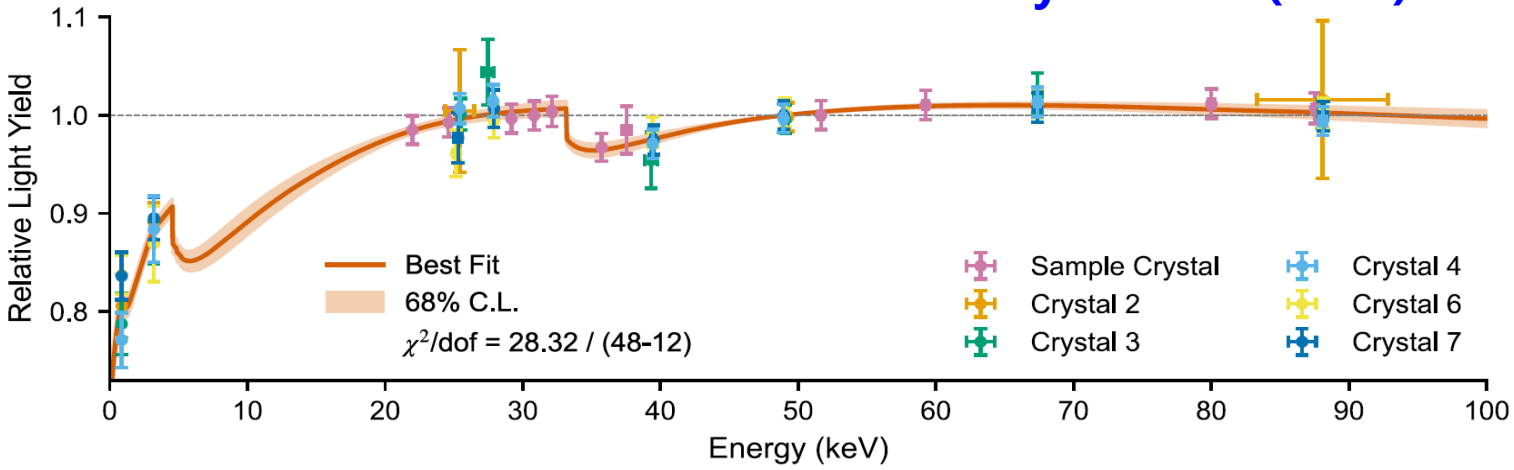




Update Nonproportionality and Quenching factor of NaI(Tl)

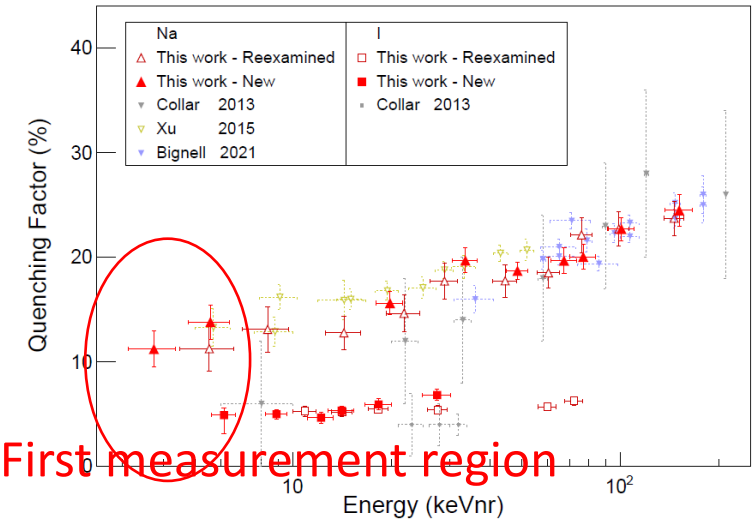
Nonproportionality(nPR) of NaI(Tl)

Eur. Phys. J. C 84 (2024) 484

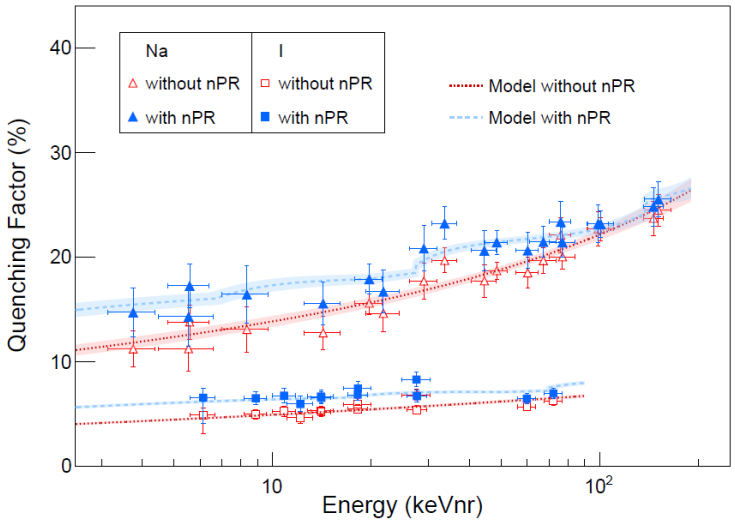


Quenching factor of NaI(Tl)

Phys. Rev. C 110, 014614



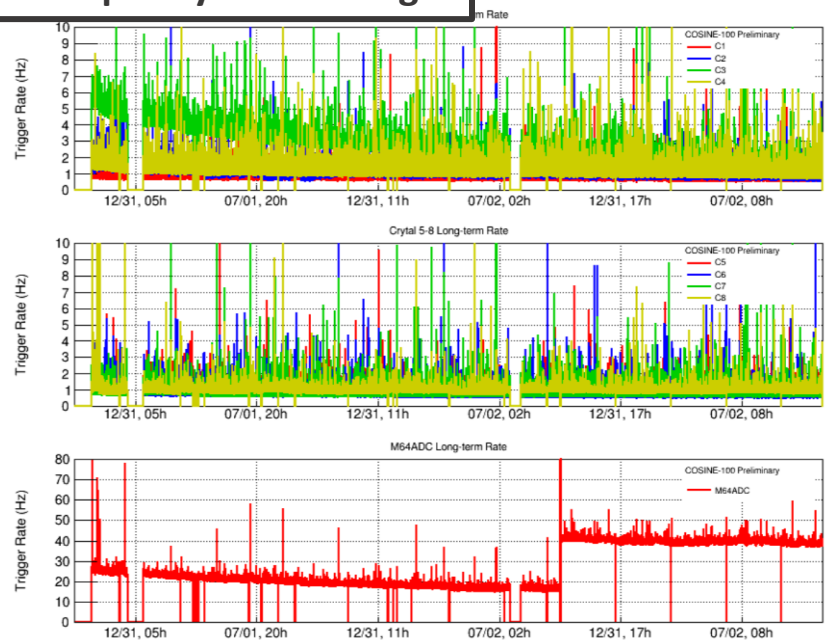
First measurement region



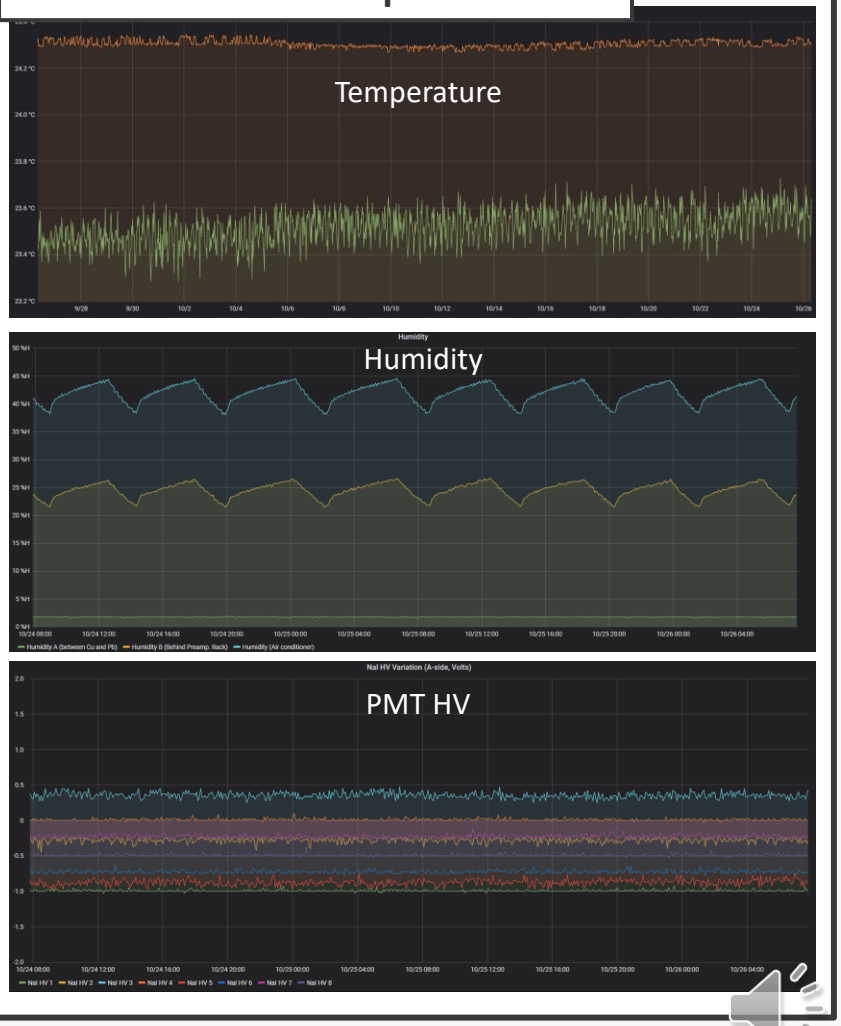
COSINE-100 operation cont'd

- Slow monitoring system

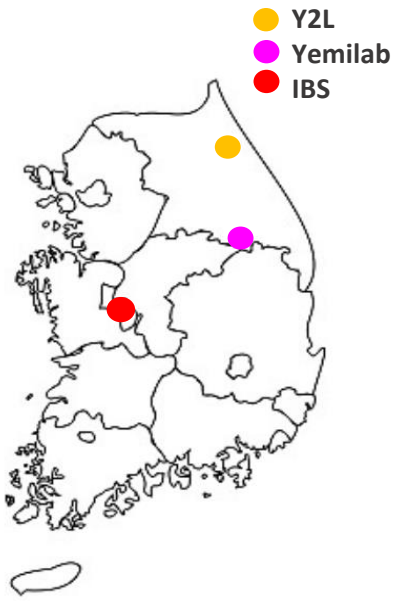
Data quality monitoring

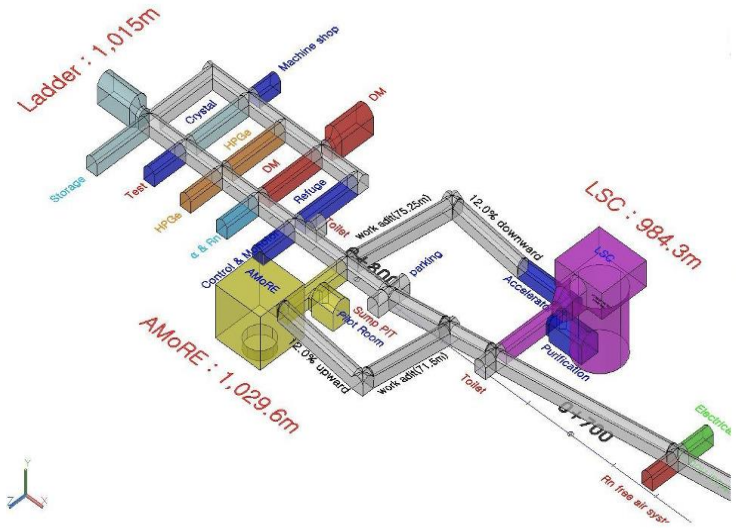


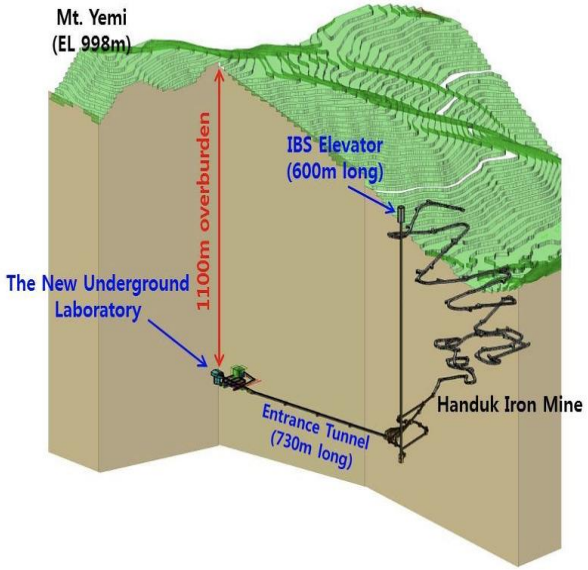
>200 Environmental parameters



Yemilab @ Jeongseon

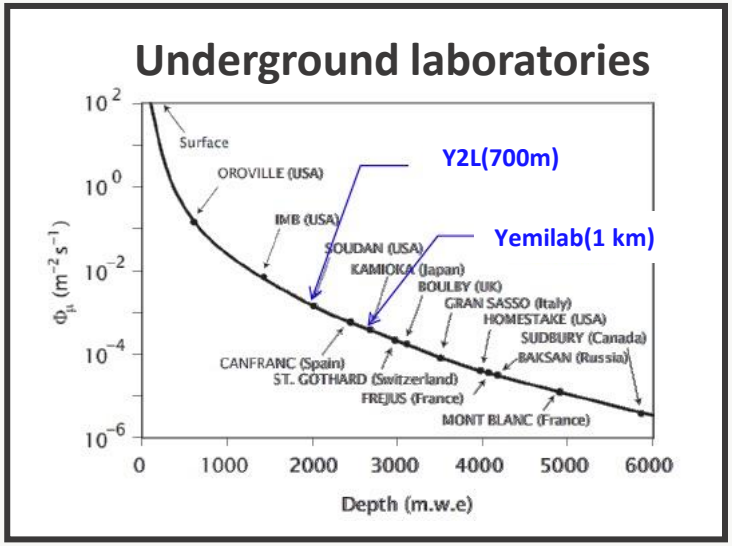






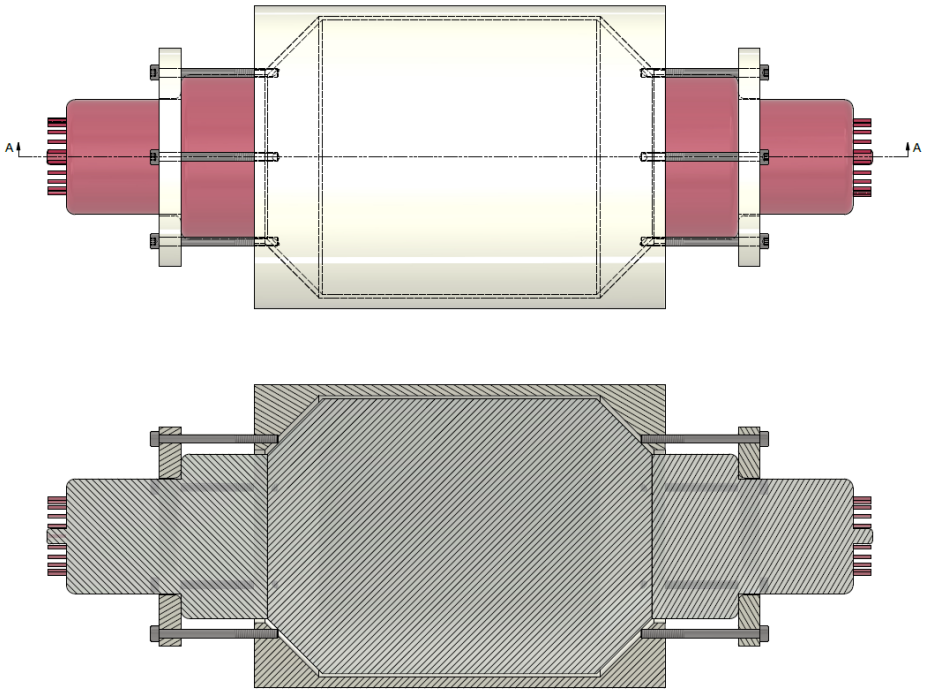
- **Newly** constructed **underground laboratory** at **Jeongseon in 2022**
  - **1000 m** rock **overburden**
  - **3000 m^3 experimental area**

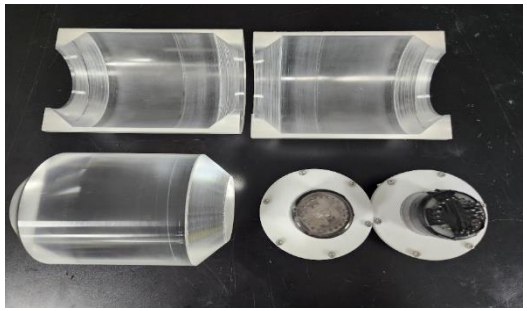
[Front. Phys., 02 April 2024]



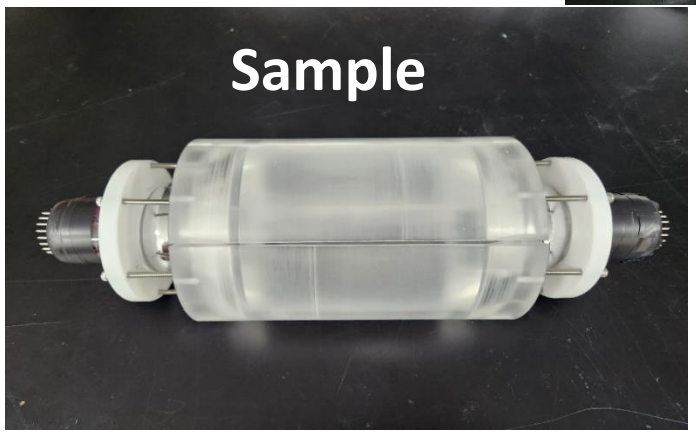
Encapsulation

- **Inner** structure for PMT-crystal connection
  - Direct contact PMT and crystal with optical pad
  - **PTFE** body, **Brass** bolt
  - PMT base shield (PTFE)



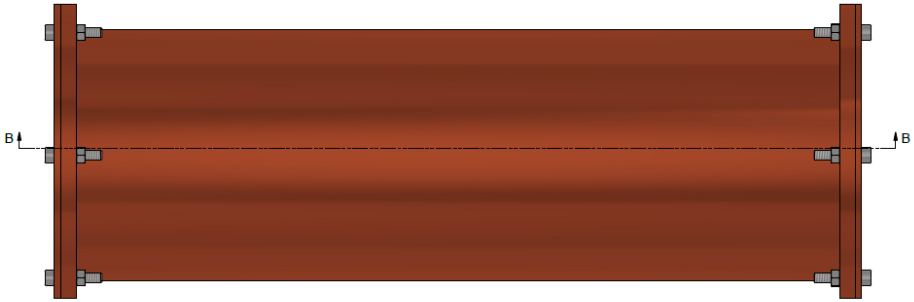


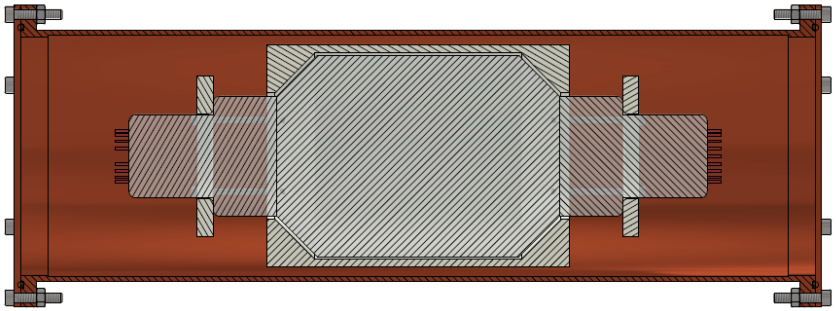
PMT base shield

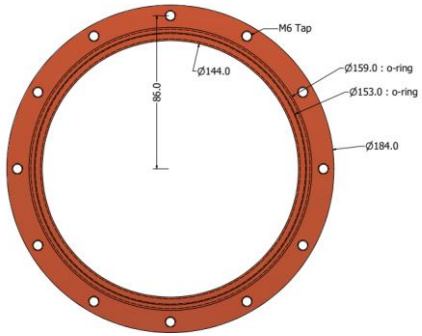


Encapsulation cont'd

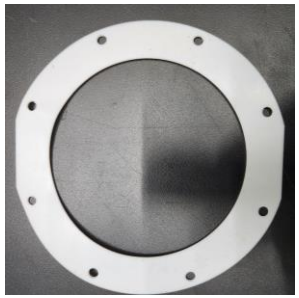
- **Copper case**
  - Same as **NEON** experiment
  - To prevent LS & air leak
    - **PTFE** Gasket
    - Cable gland







PTFE gasket



cable gland