# Yemilab Status (AMoRE + COSINE)

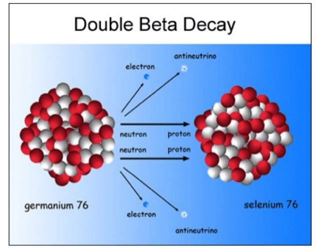
**Hyunsu Lee**
Center for Underground Physics (CUP)
Institute for Basic Science (IBS)

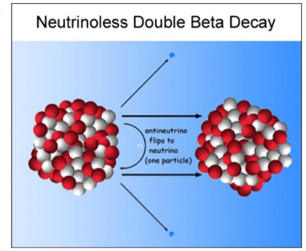
*KSHEP Fall Meeting Nov 28-30, 2024 @ UNIST*

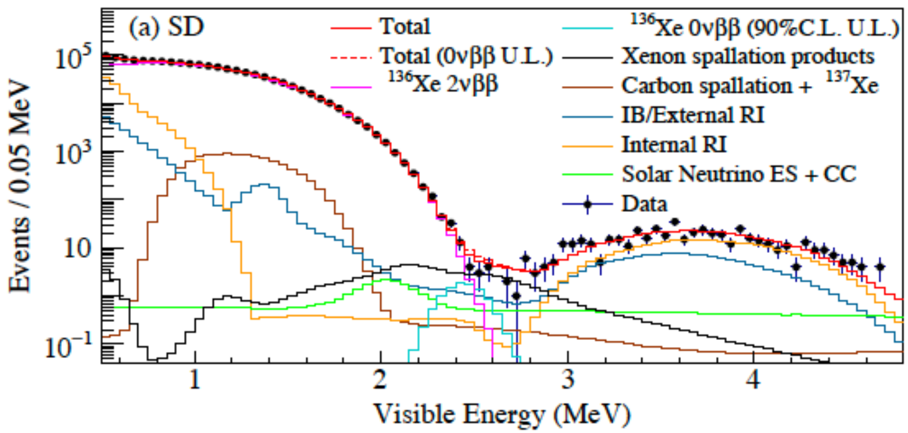
# What are we looking for?

- Neutrinoless double beta decay ($0\nu\beta\beta$)

- Kamland-ZEN




$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\ \text{yr} \quad (90\%\ \text{C.L.})$$

arXiv:2406.11438

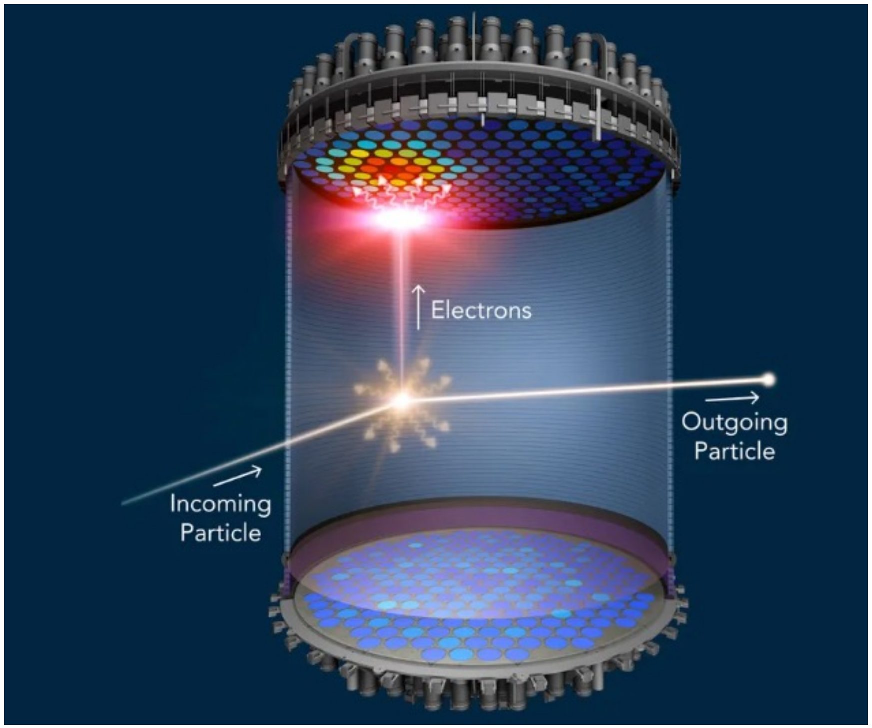
**2.097 ton yr of $^{136}$Xe**

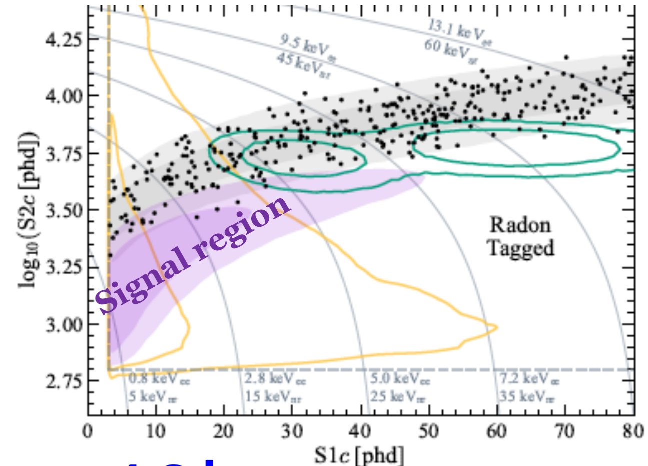
i.e. ) 136 kg of $^{136}$Xe = 1000 mol × $6.02\times10^{23}$ atom/mol = $6.02\times10^{26}$ atom

**Challenge : We need to observe 1 event signal from 100 kg detector of 1 year operation**

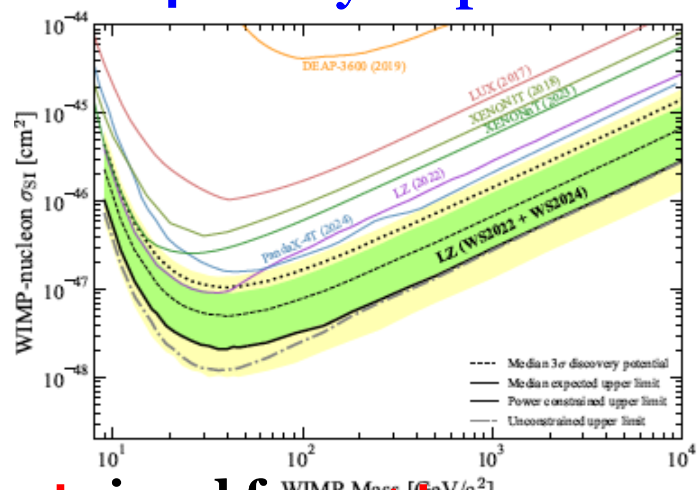
# What are we looking for?

- Dark matter direct detection
  - ❖ LZ    arXiv:2410.17036




**4.2 ton yr exposure**

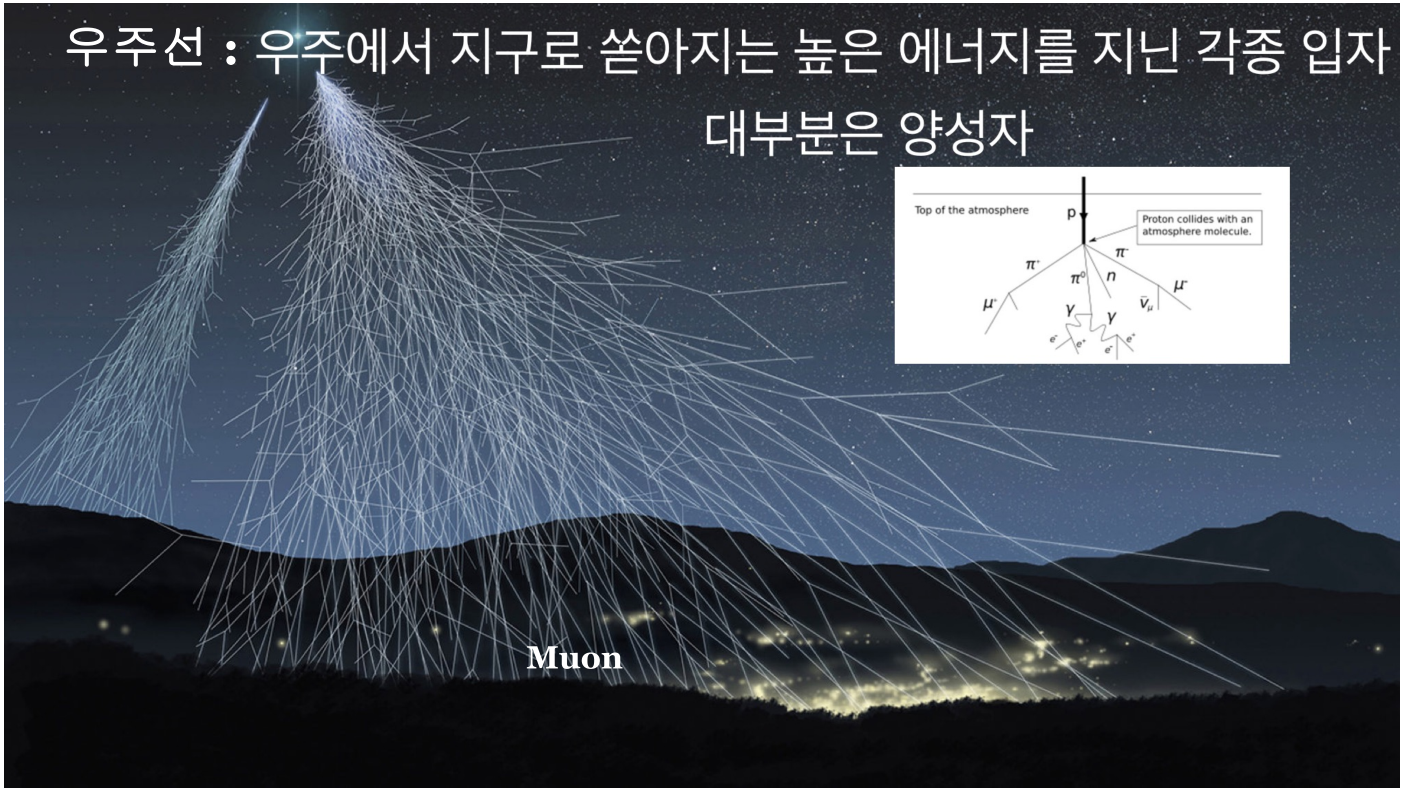


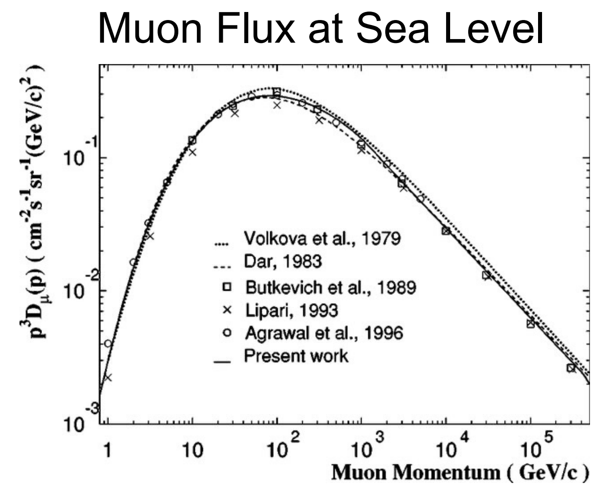

**Challenge : We need to observe 1 event signal from 1 ton detector of 1 year operation**

**Extremely Rare events!!**

# Background control is key

## Comic muon



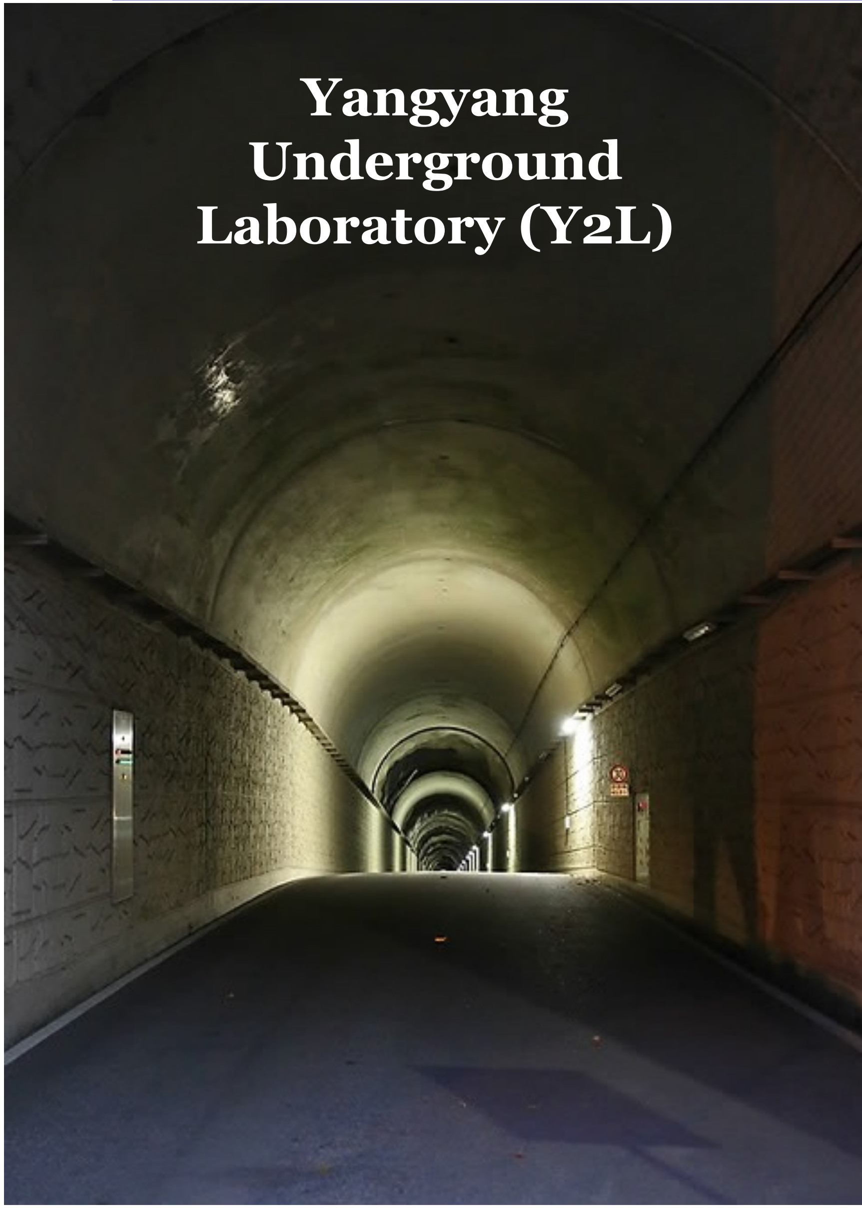



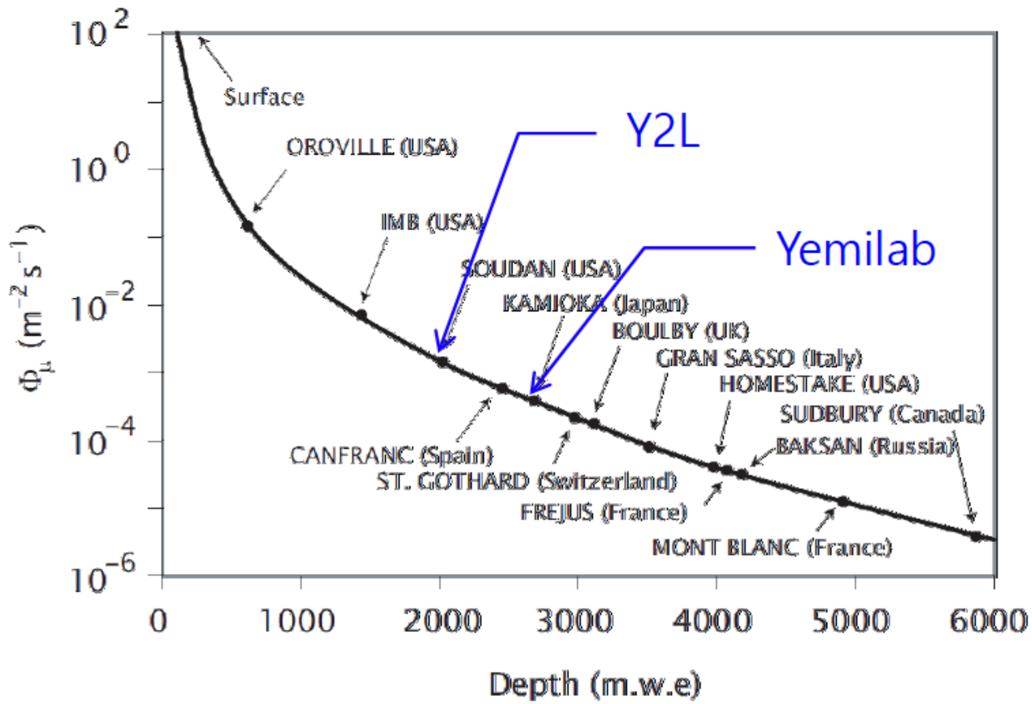

**Rate ~ 200 muon/m²/s ~ $6\times10^9$/year**

**Energy ~ 100 GeV**

**To stop 100 GeV muon, we need ~ 100 m length lead**

# Go to the underground laboratory




Sea level : 200 muon/m$^2$/s ~ $6\times10^9$/year

Y2L : 0.004 muon/m$^2$/s ~ $1\times10^5$/year

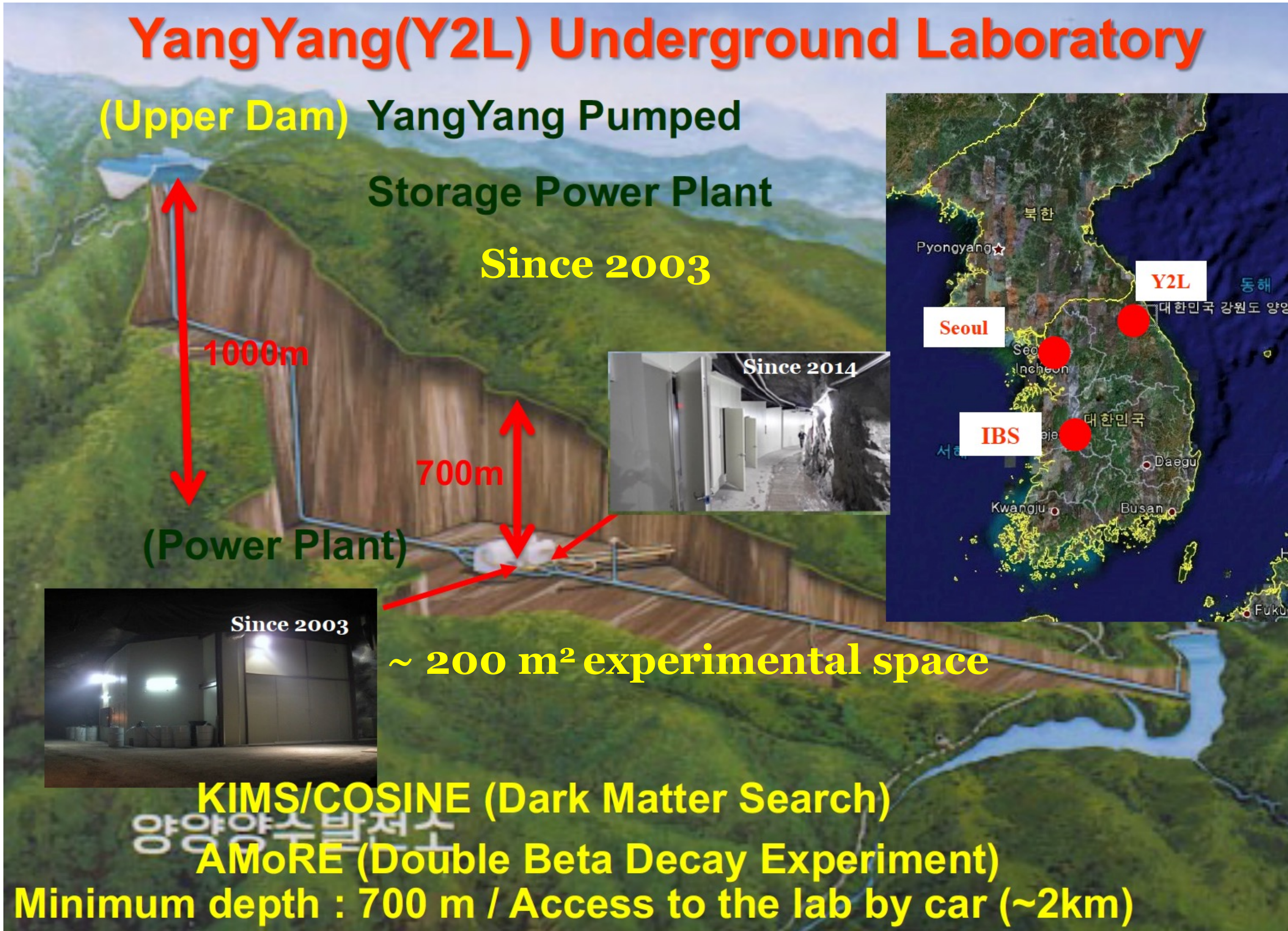
Yemilab : 0.001 muon/m$^2$/s ~ $2.5\times10^4$/year

**JCAP 02 (2021) 013**

**Front. Phys. 12 (2024) 1323991**

# Yangyang Underground Laboratory (Y2L)

- Korea has Yangyang underground laboratory (Y2L) with about 200m$^2$ space since 2003.




KIMS (2003-2012)

COSINE-100 (2015-2023)

AMoRE-pilot, I (2015-2023)

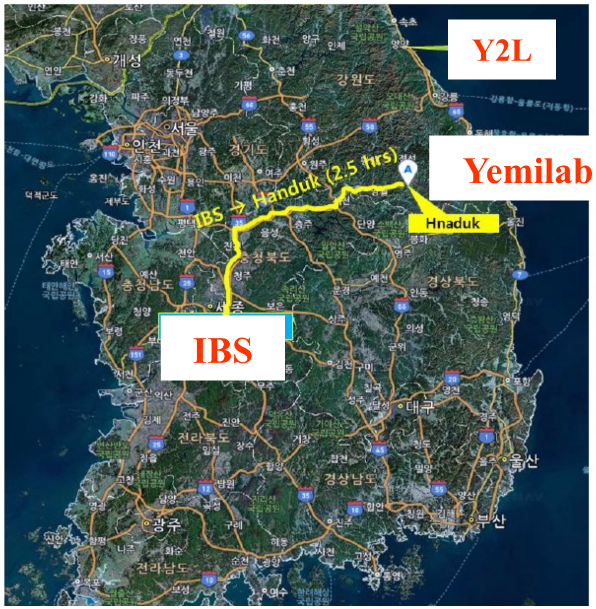
**Shallow depth**

**No expendable**

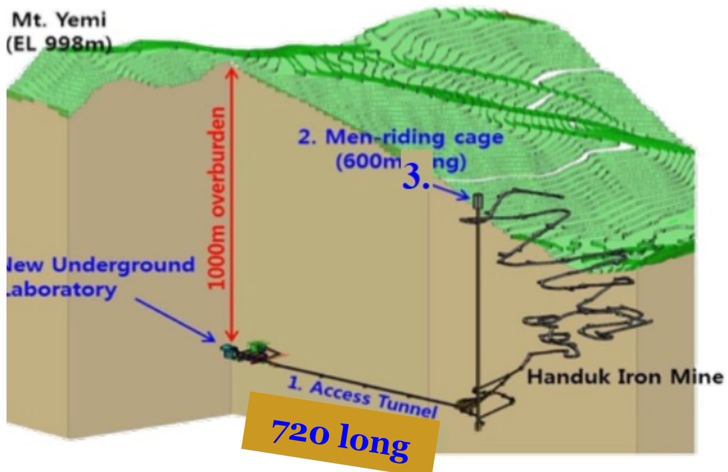
# Yemilab for new discoveries

- 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




**Construction completion ceremony (2022)**


❖ **Milestones :**

**Front. Phys. 12 (2024) 1323991**

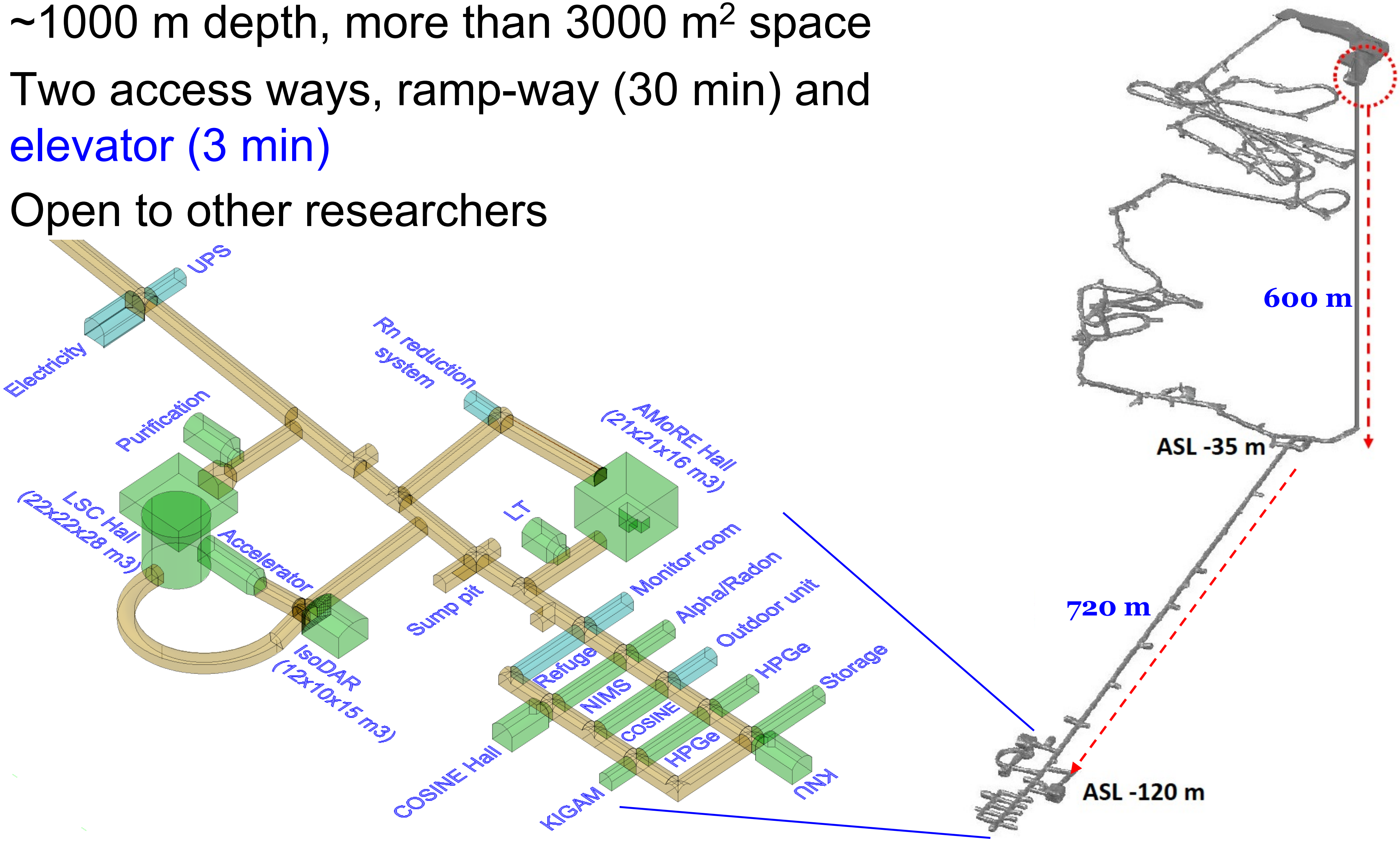
**AAPPS Bull. 34 (2024) 25**

- CUP started
- Government approval
- 2013 ~ 2016: Preparation works
- 2017 – 2018: Man-cage construction
- 2019 – 2020: Tunnel excavation-1
- 2021: Tunnel excavation-2; Electricity & machinery
- 2022: Completion Yemilab In Sep.
- 2023 – 2024: Moving to Yemilab; Installation of supporting infra

(IBS)

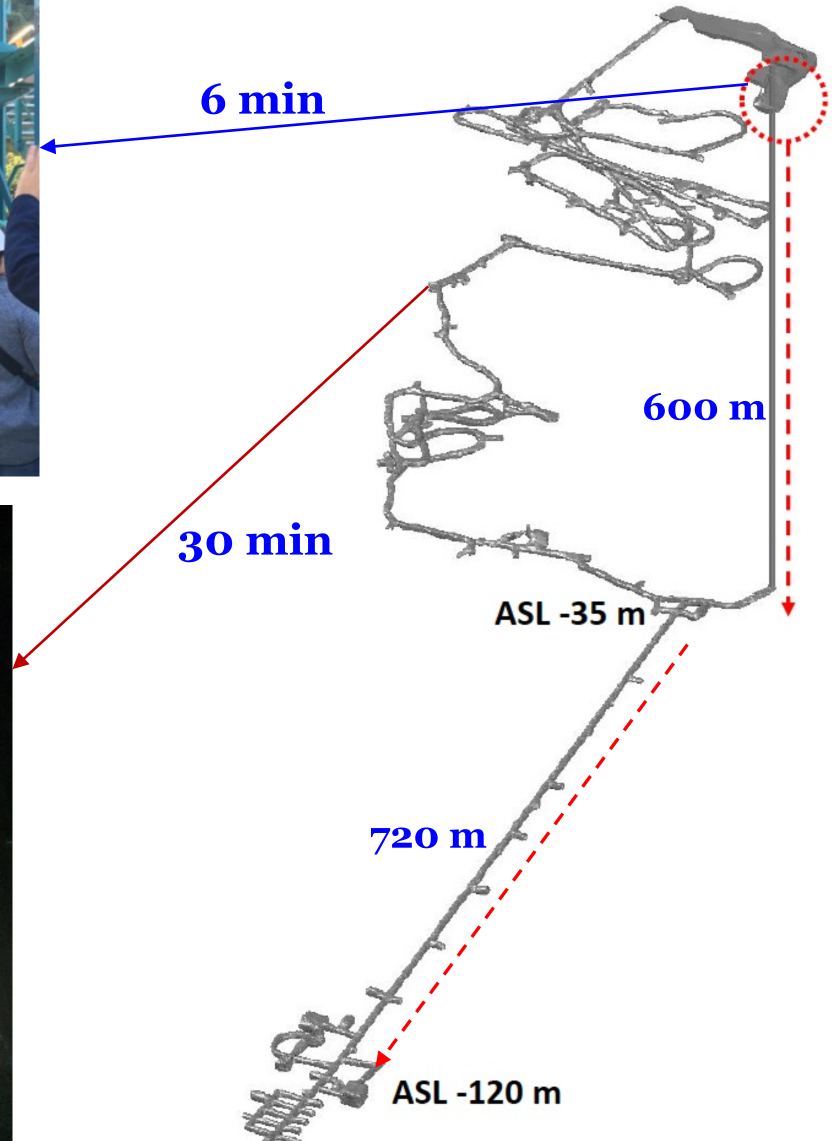
# Yemilab

- ~1000 m depth, more than 3000 $m^2$ space
- Two access ways, ramp-way (30 min) and elevator (3 min)
- Open to other researchers



# Yemilab aceess

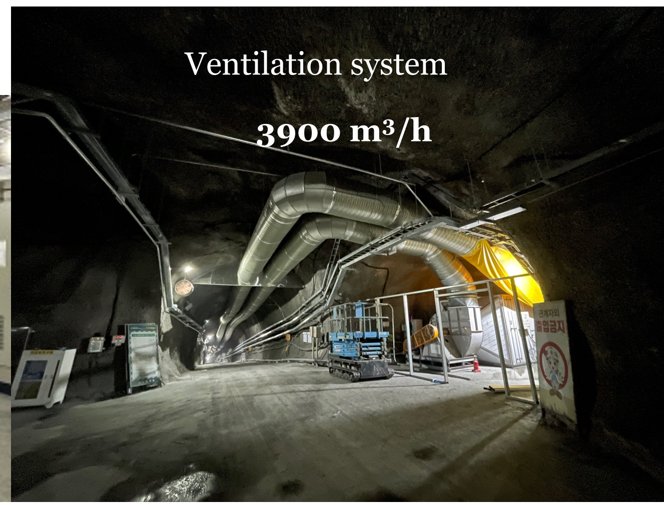




# Underground facilities







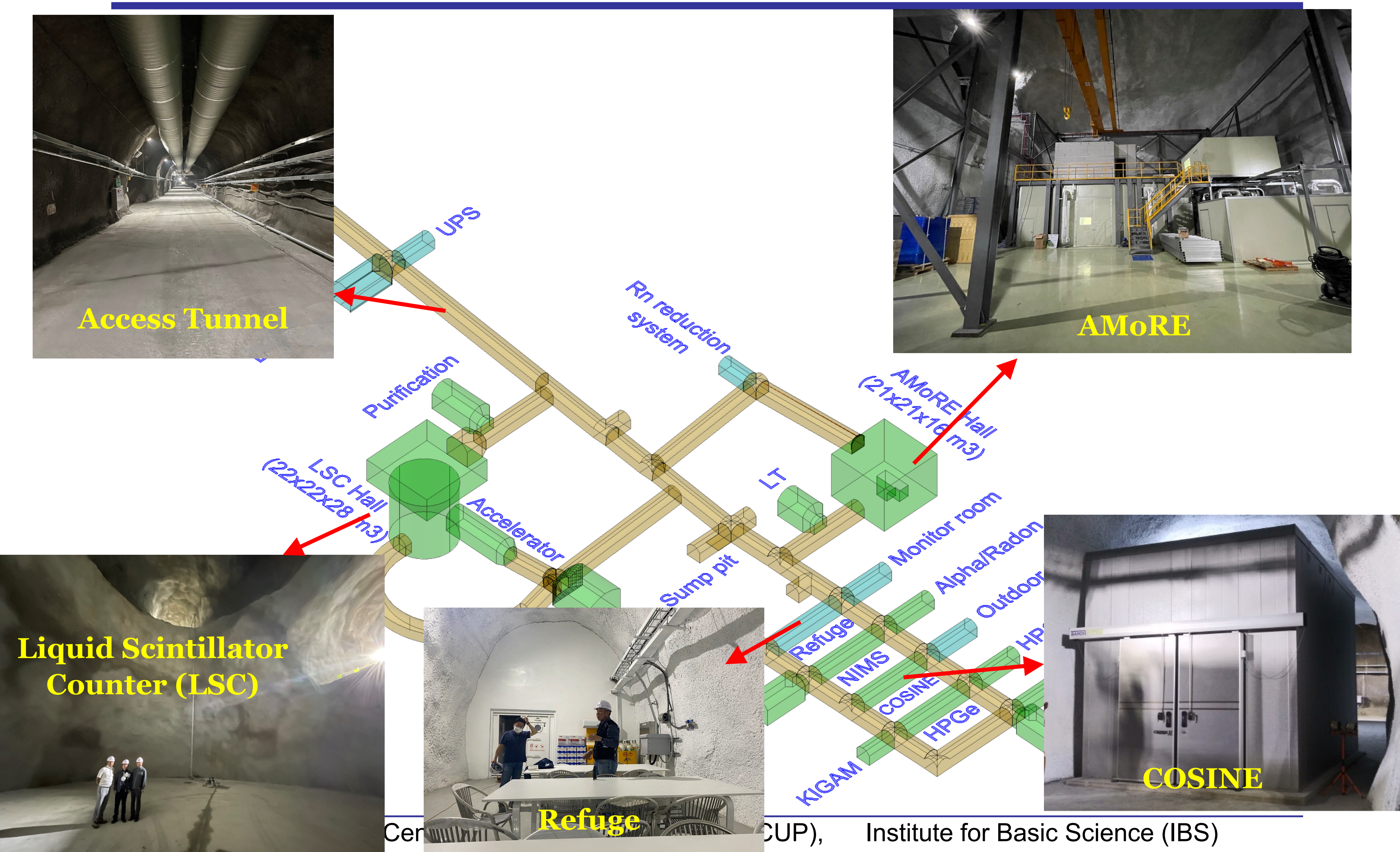


**Emergency power generator (360 kW)**

**Full mobile communication (LTE)**

**1 GB optical network to ground office**

# Yemilab

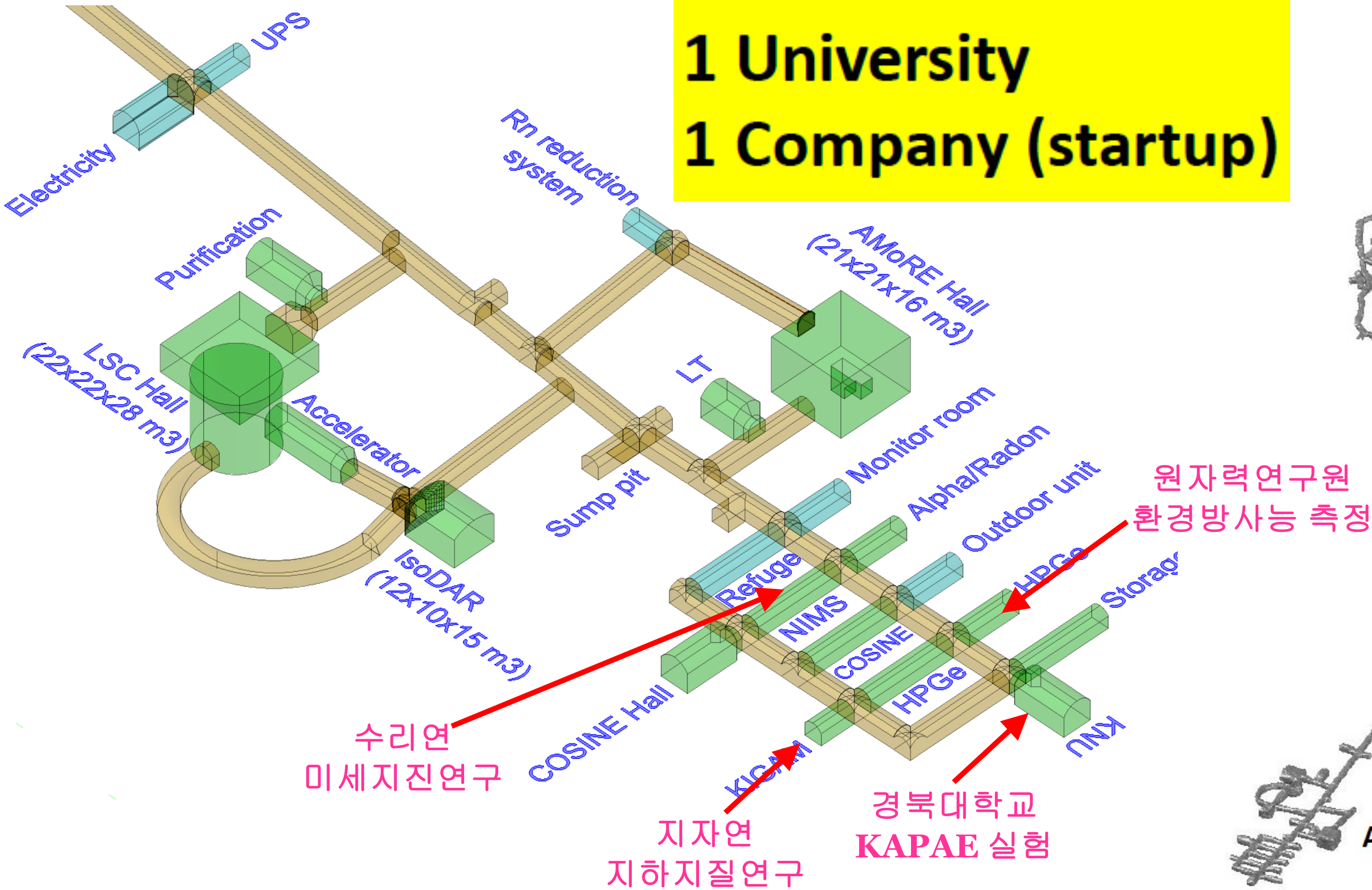


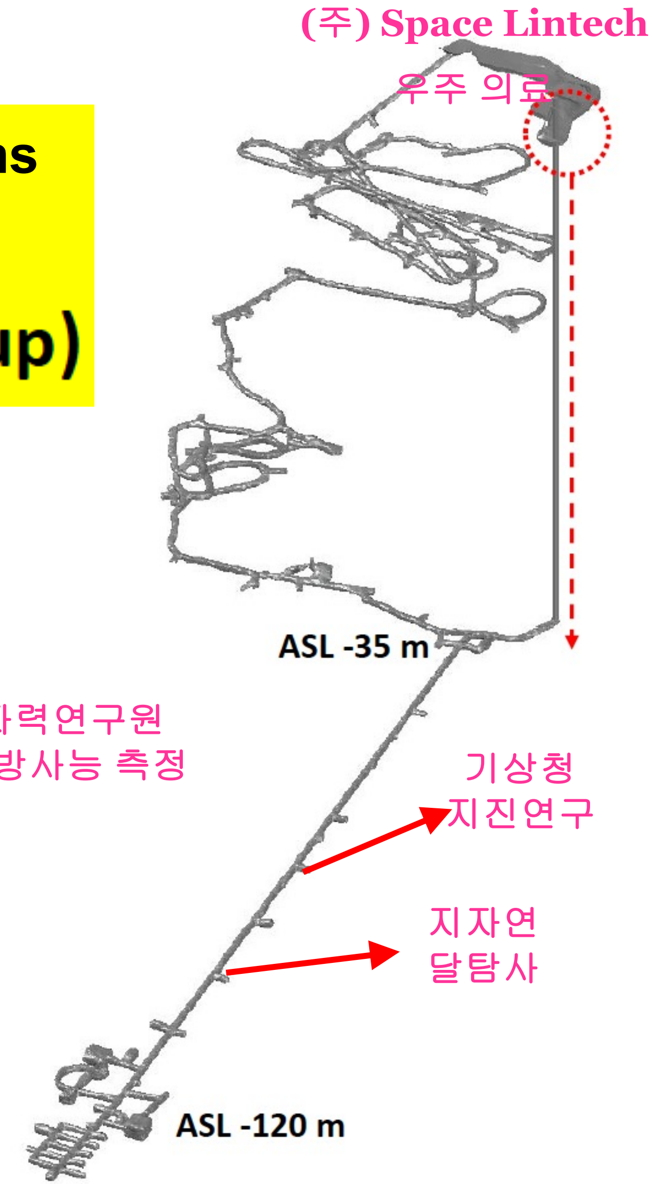
Access Tunnel
UPS
Rn reduction system
AMoRE Hall (21x21x16 m3)
AMoRE
Purification
LSC Hall (22x22x28 m3)
Accelerator
LT
Monitor room
Alpha/Radon
Sump pit
Refuge
NIMS
COSINE
HPGe
KIGAM
Liquid Scintillator Counter (LSC)
Refuge
COSINE

# Yemilab

**Yemilab is open for external users!!**

**4 Institutes 5 Teams**
**1 University**
**1 Company (startup)**

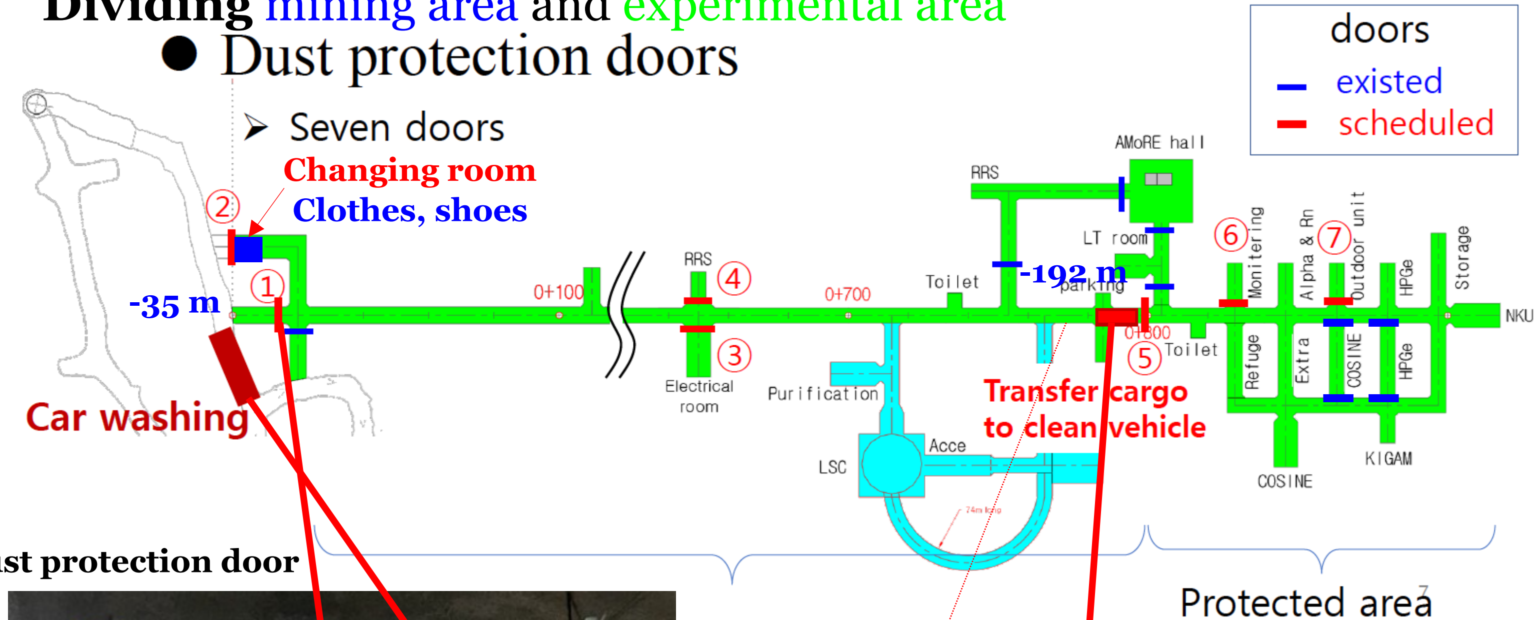


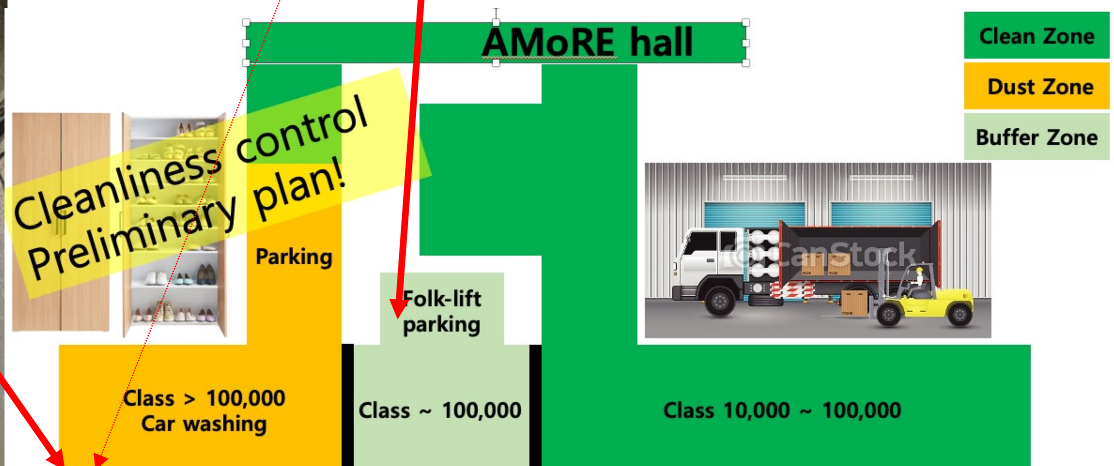
# Clean environment at Yemilab

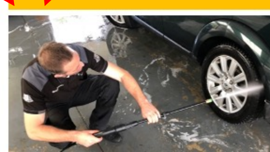
**Dividing** mining area and experimental area

- Dust protection doors
  - Seven doors




**Dust protection door**

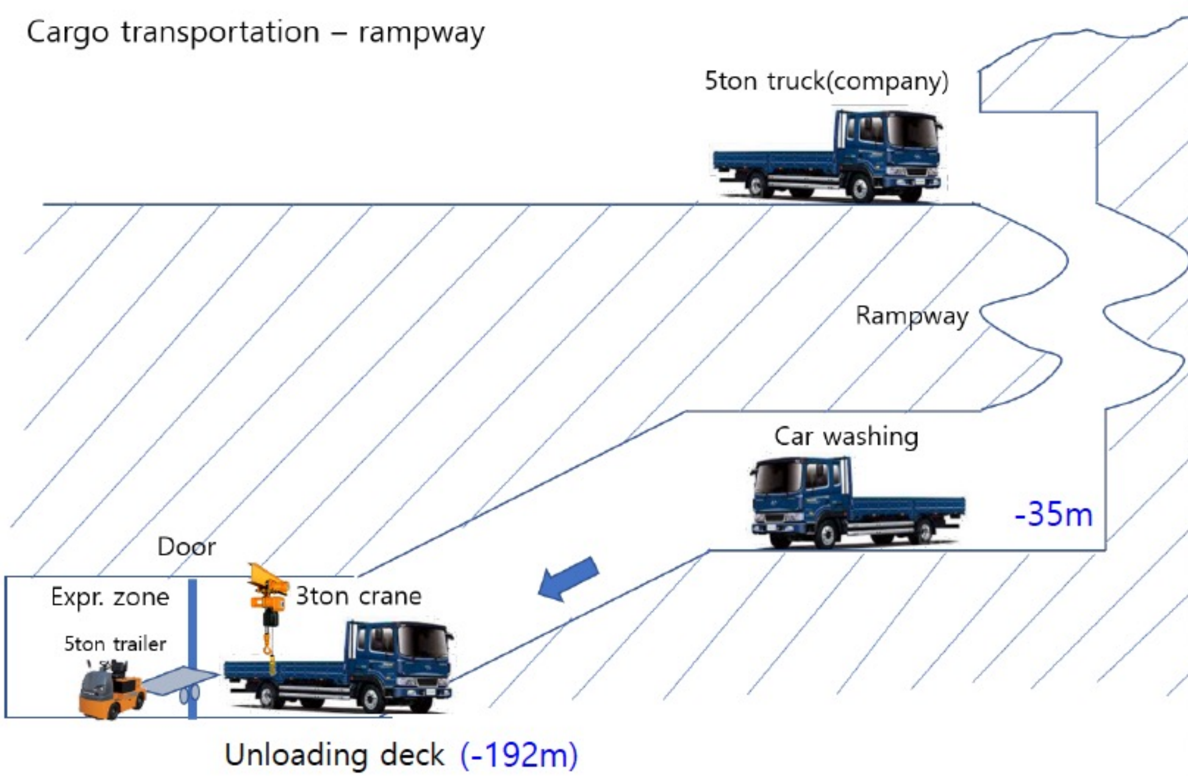


1. **Safety clothing** change to **lab clothing**
   - **Safety clothing : helmet, safety shoes, long jacket and pants**
   - **Lab clothing : free helmet, lab shoes**
2. **Cargo transferring** by trailer from clean zone

# Clean environment at Yemilab

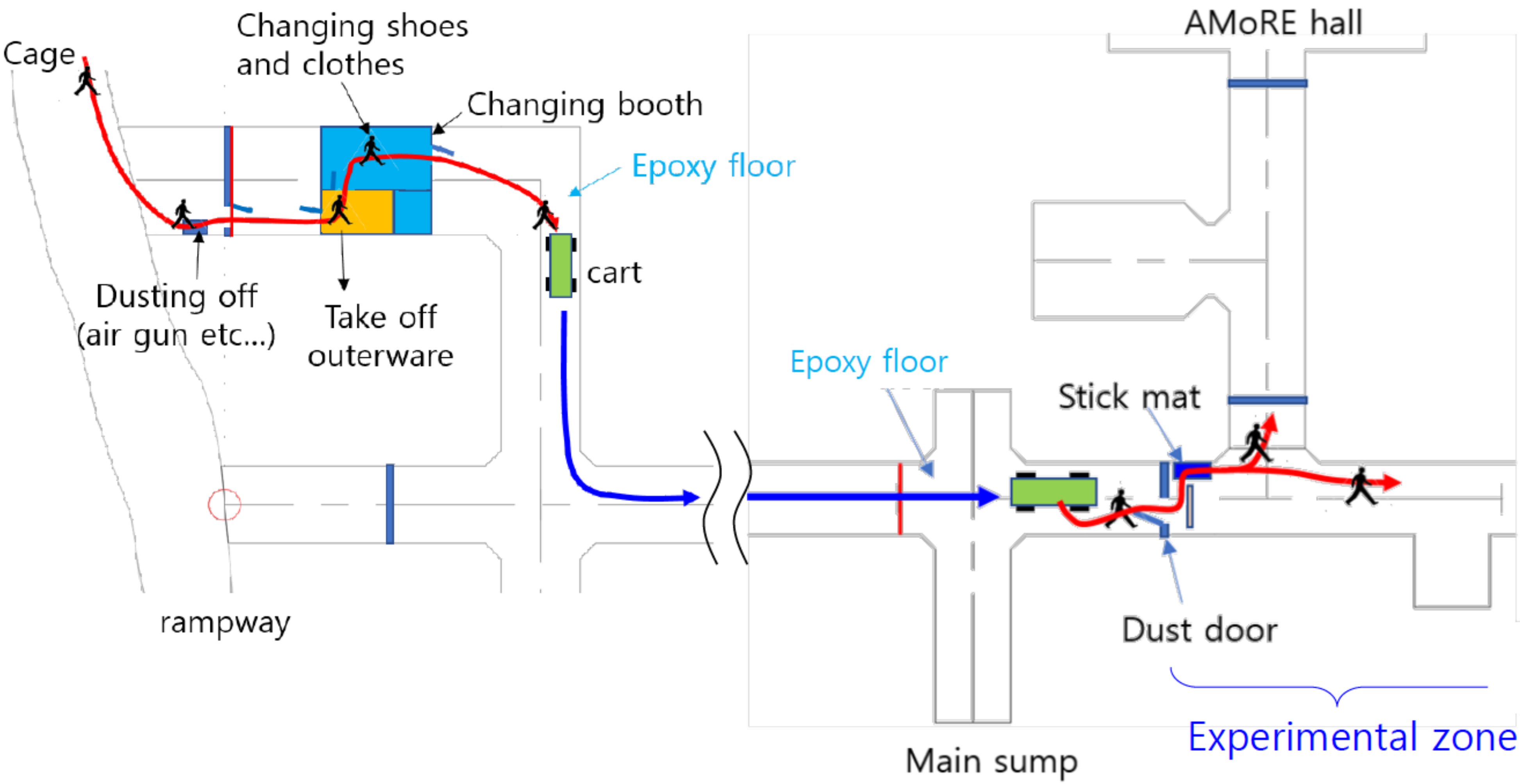
## ❖ Transportation (rampway)




Car washing system (-35m)

# Clean environment at Yemilab

- Human path



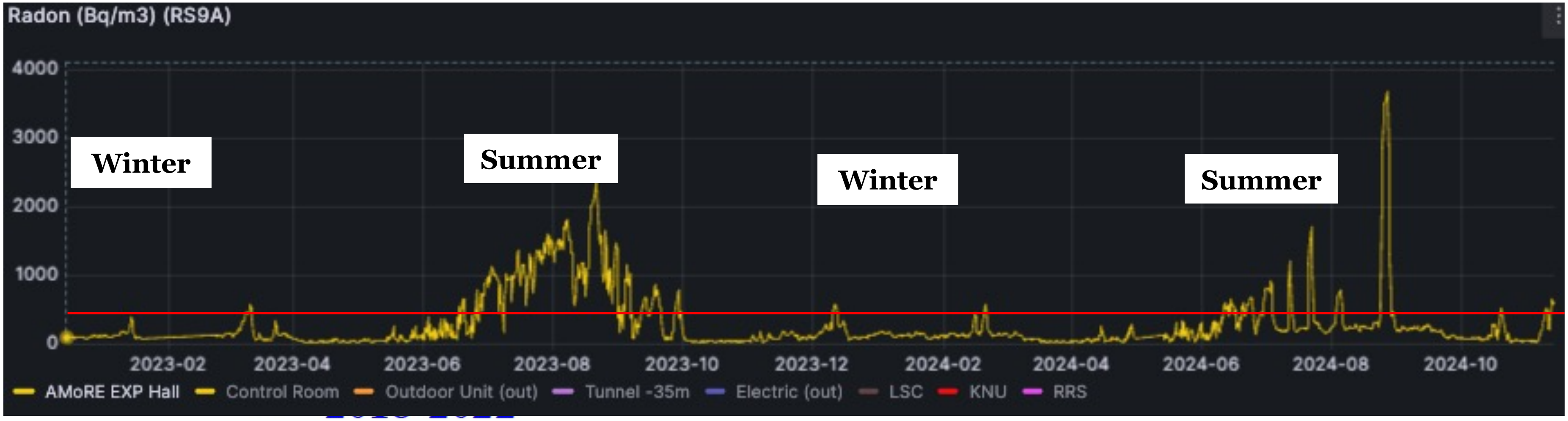
# Clean environment at Yemilab

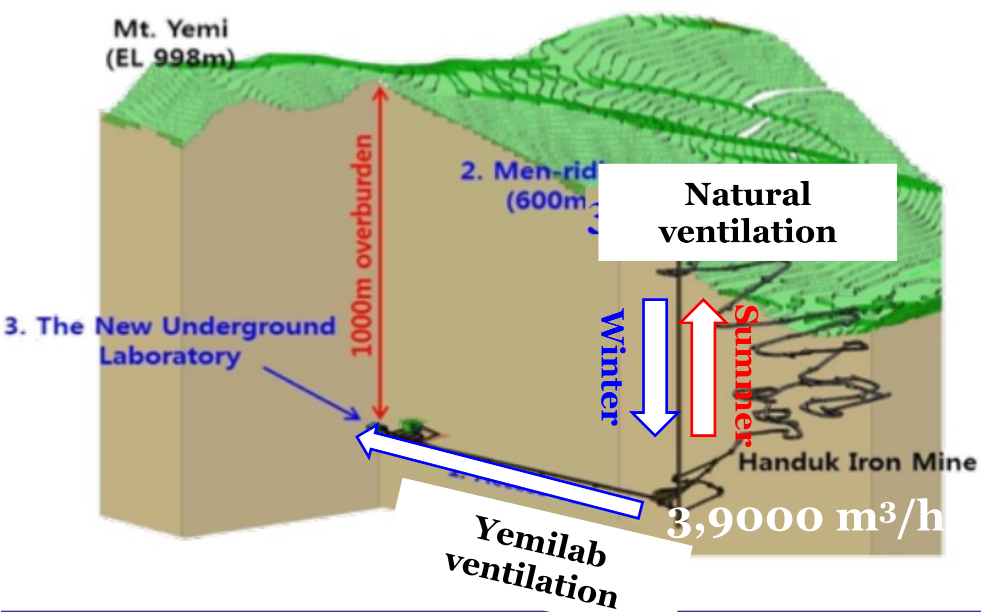

Experimental area

Access tunnel

- Started dust protection procedure since March 2024

# Radon level problem



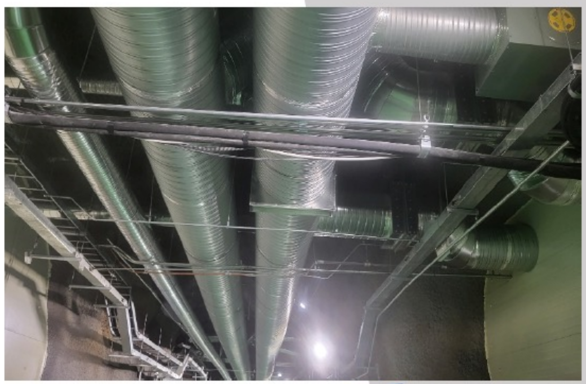

Radon level is extremely high at Summer season

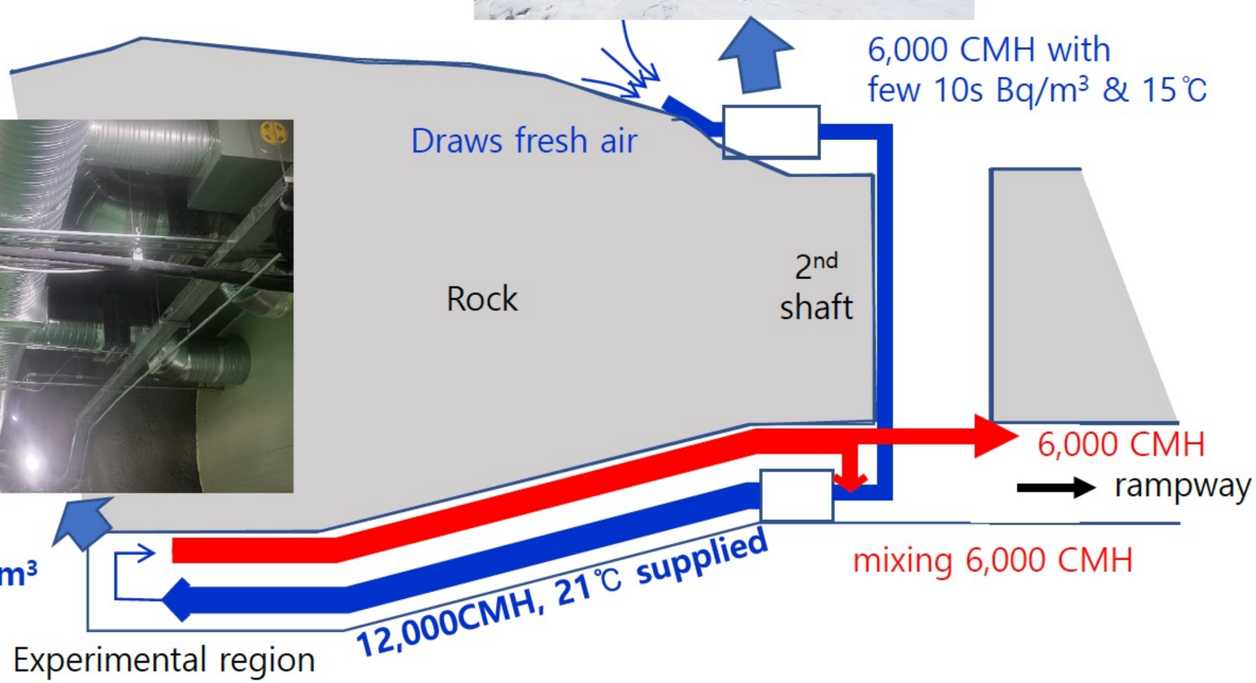
- 2000 Bq/m³
- Safety requirement < 200 Bq/m³

# Radon-less air supply system

- The construction was mostly done in Dec., just test remained
- The goal is keeping the Rn concentration always under 150 Bq/m$^3$
- The benefit of this system can be had from this summer

**This system worked well during summer 2024**






**Goal :**
- **Under 150Bq/m$^3$**
- **& 25℃**

# Monitoring of environment, infra, safety

## Online monitoring

### Monitoring device

Temperature & Humidity


Radon


Dust level


CO, $CO_2$, and $O_2$


- Initiating the monitoring of various environmental parameters
  - ❖ Support both experimental operations and safety measure
- To do lists
  - ❖ Implement access control and monitoring systems
  - ❖ Install and operation CCTV surveillance
  - ❖ Additional measures as needed
  - ❖ …… (contingent upon budget availability)

# Y2L relocation to Yemilab

## Y2L side, after moving

- HPGe array and PCW remained only

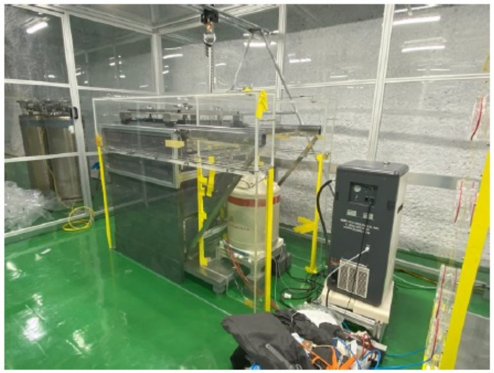
**Plan to move all remaining items by end of 2025**




# Y2L relocation to Yemilab

Most of detector and infrastructure were relocated to Yemilab without HPGe array

HPGe



CC1

CC2

Alpha counter

COSINE

COSINE-100U

COSINE test bench

COSINE-100 shield frame

# Outreach of Yemilab

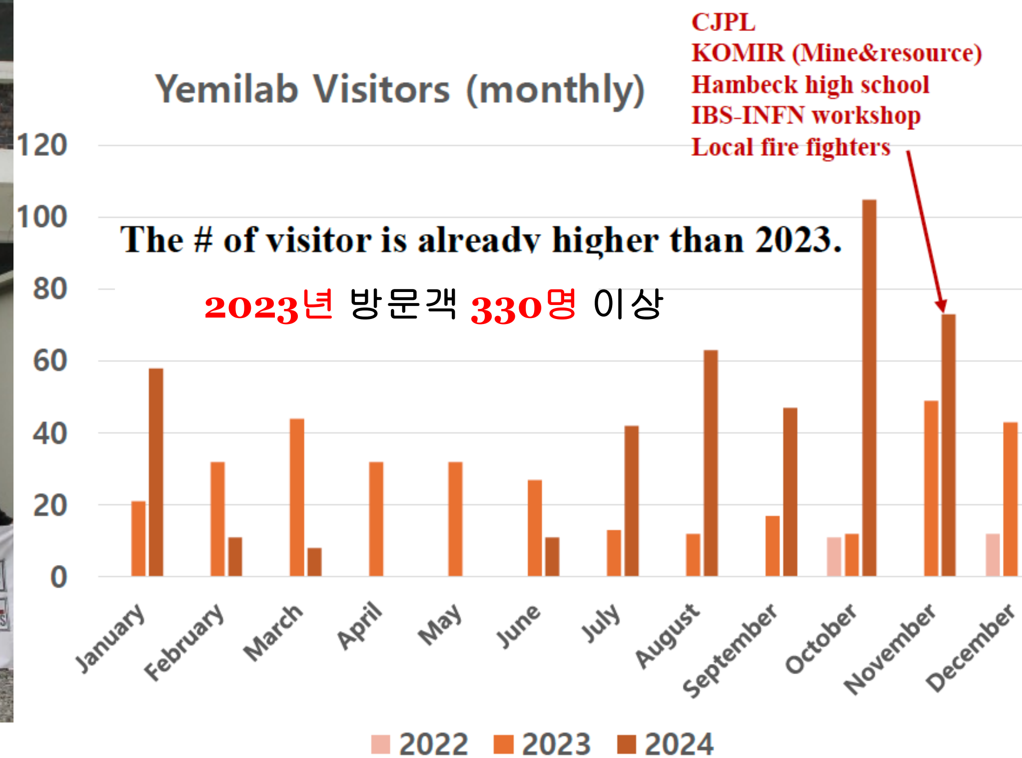

단편 영화 촬영 : 모든 점 (Every single dot)

2024년 부산국제영화제

https://www.youtube.com/watch?v=iYOmXgiumZU

오케스트라 (음악회) - 강원과학기술문화포럼

https://www.youtube.com/watch?v=E38cKTvICwo




신동 과학그림그리기 (2023,2024)


동아사이언스 "강원 정선 주민들과 중성미자 주제로 수다 떨어요"

"강원 정선 주민들과 중성미자 주제로 수다 떨어요"

0

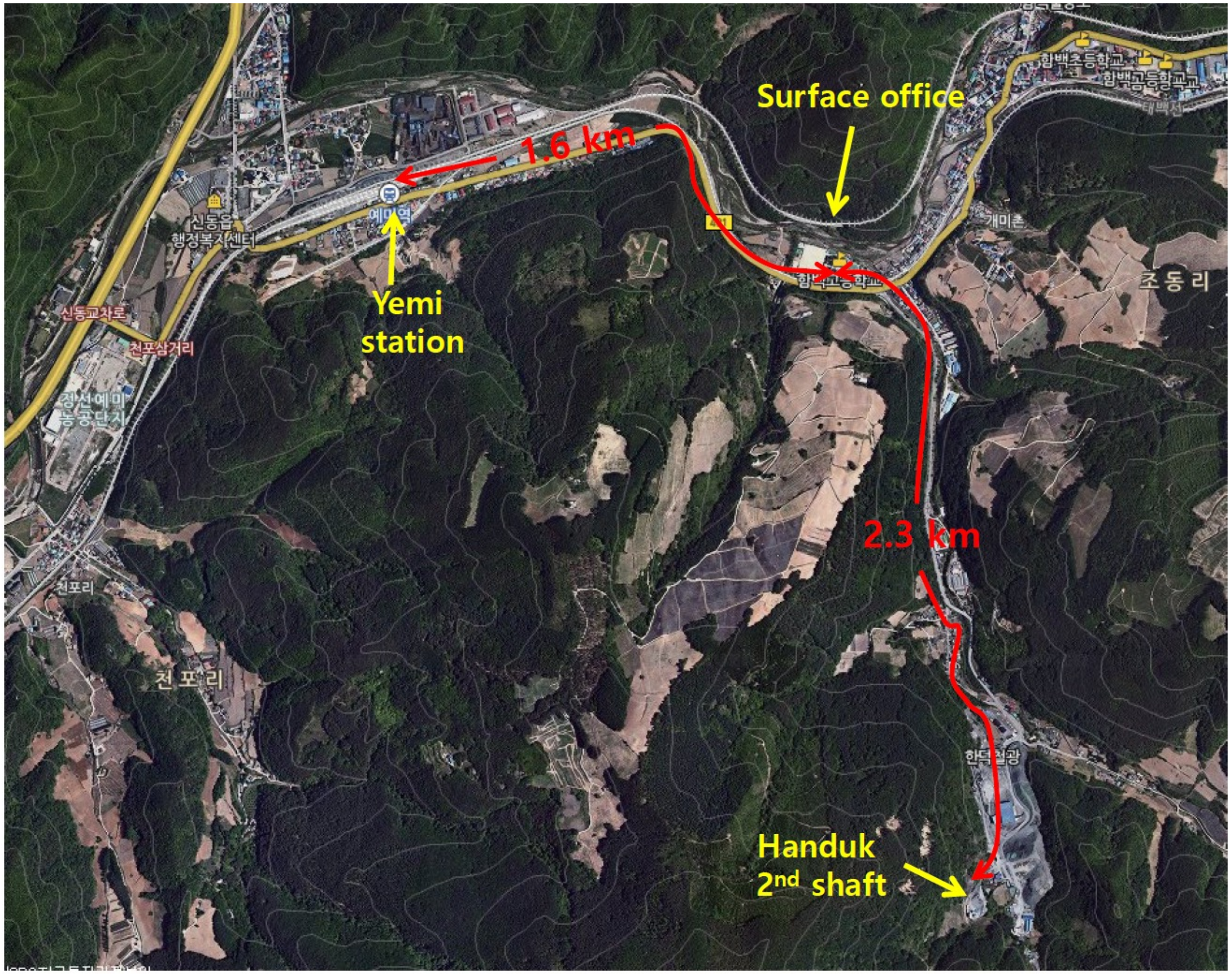
2023.11.13 07:00

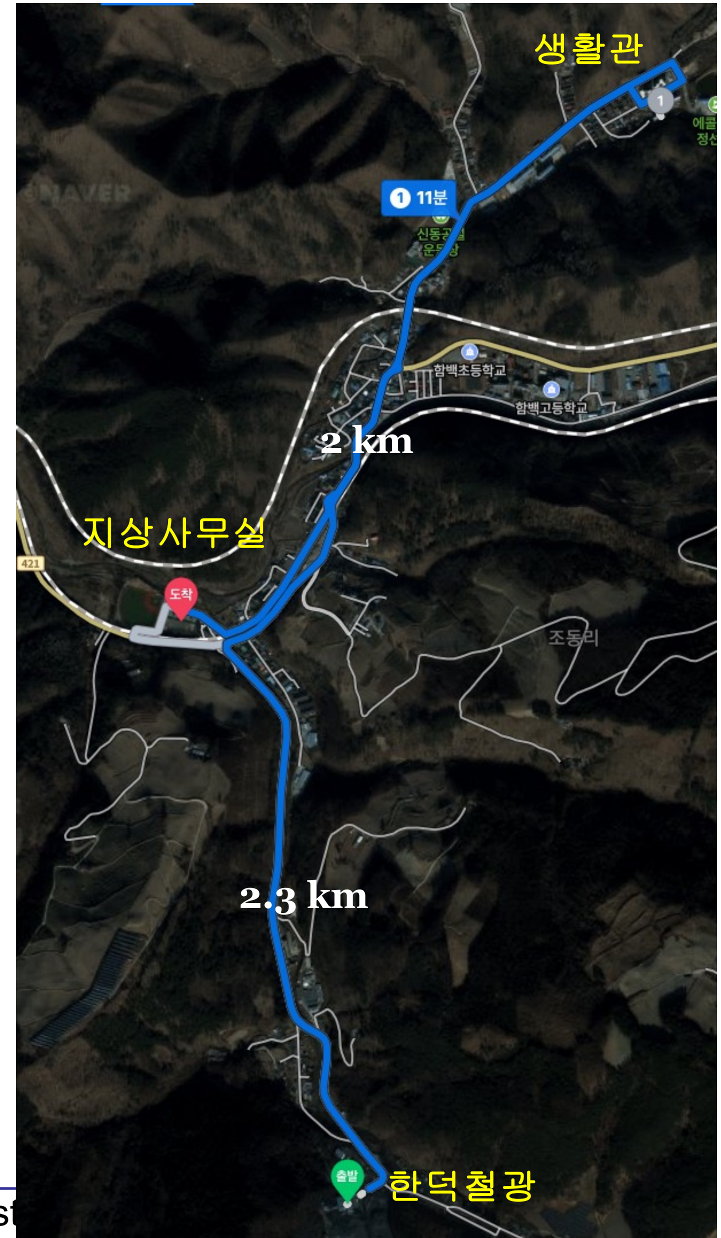
찜

| 지하 1000m 예미랩, 과학문화마을 거점으로

# Yemilab ground

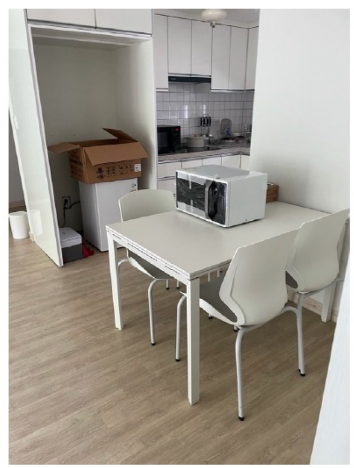
# Yemilab ground

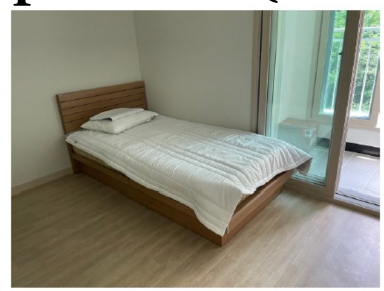


# Yemilab ground


**Jeonseon-gun (local city) provide 12 houses apartment (생활관)**



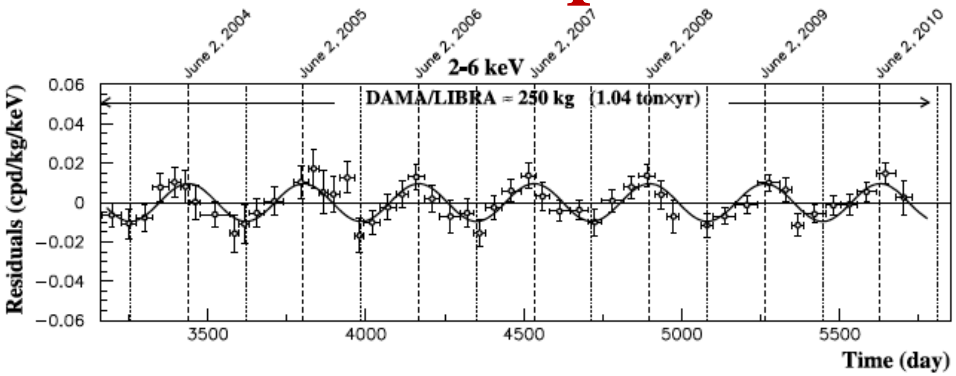


# Physics program at Yemilab

COSINE

# Annual modulation signal from DAMA/LIBRA

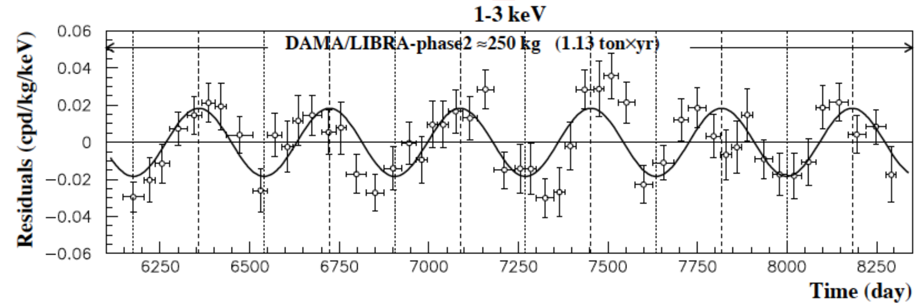
## Phase1 experiment




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

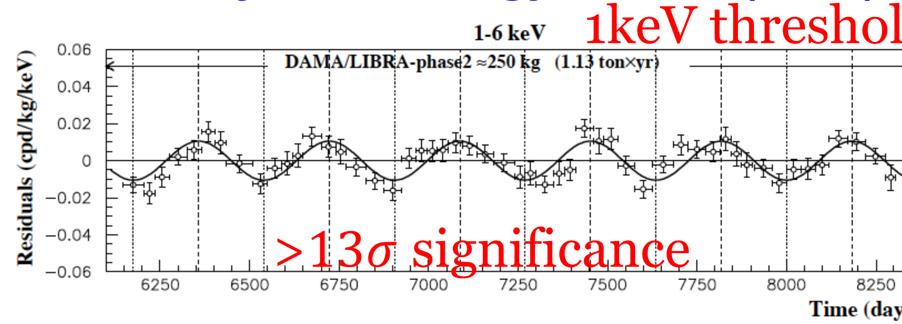
2keV threshold

## Phase2 experiment



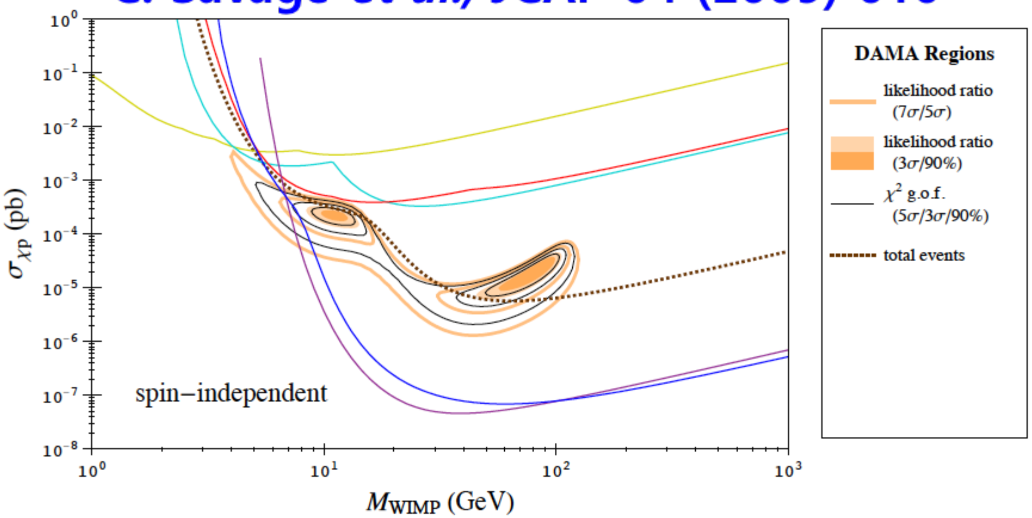

Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold

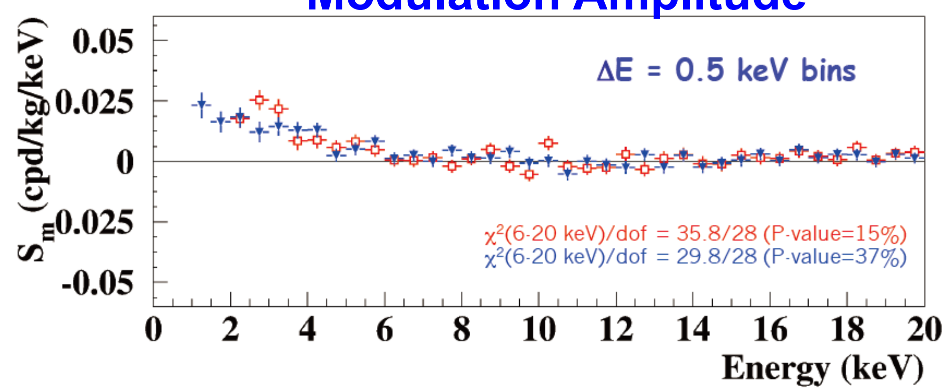



$>13\sigma$ significance

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




## Modulation Amplitude



# Back to 1998.. Before CUP.. KIMS

**Test of CsI(Tℓ) crystals for the Dark Matter Search**

**ICHEP1998 Proceeding**

H.J.Kim, [1,2] H.J.Ahn, S.K.Kim, E.Won, [3] T.Y.Kim

*Department of Physics, Seoul National University, Seoul 151-742, Korea*

Y.D.Kim

*Department of Physics, Sejong University, Seoul 143-747, Korea*

M.H.Lee

*KEK, Tsukuba, Ibaraki 305-0801, Japan*

NH ELSEVIER

2 April 1998

PHYSICS LETTERS B

Physics Letters B 424 (1998) 195–201

**DAMA**

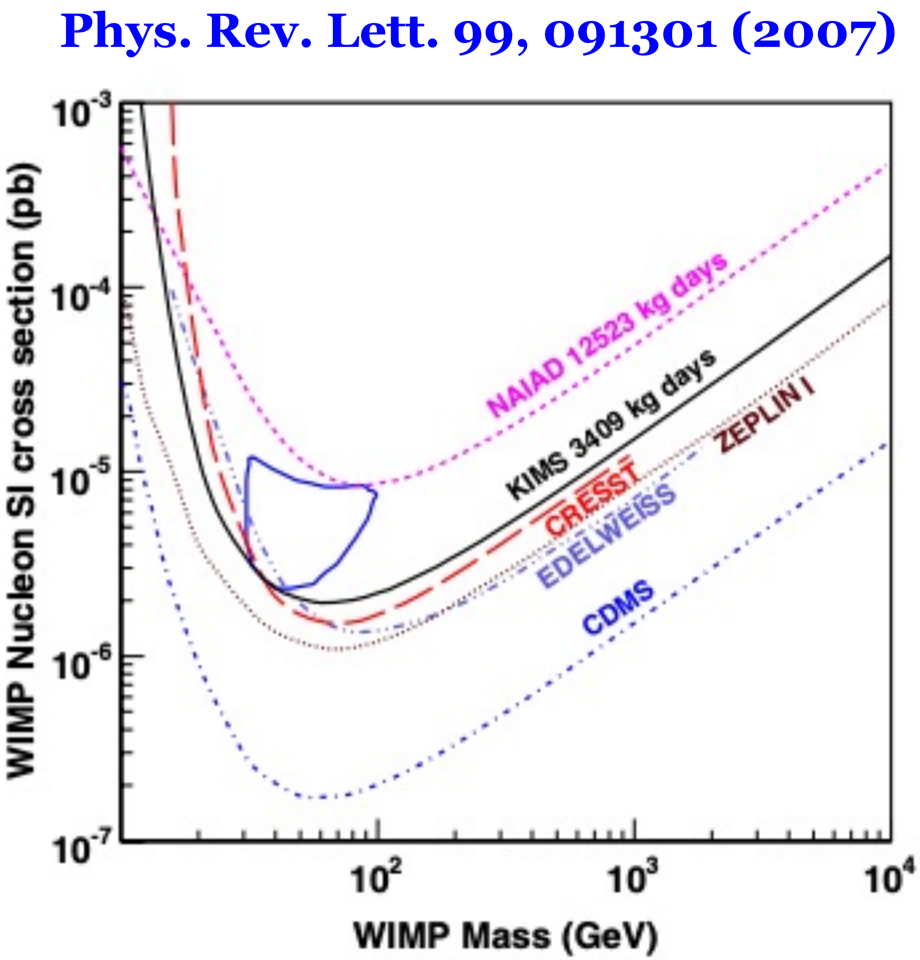
**First modulation result at 1998**

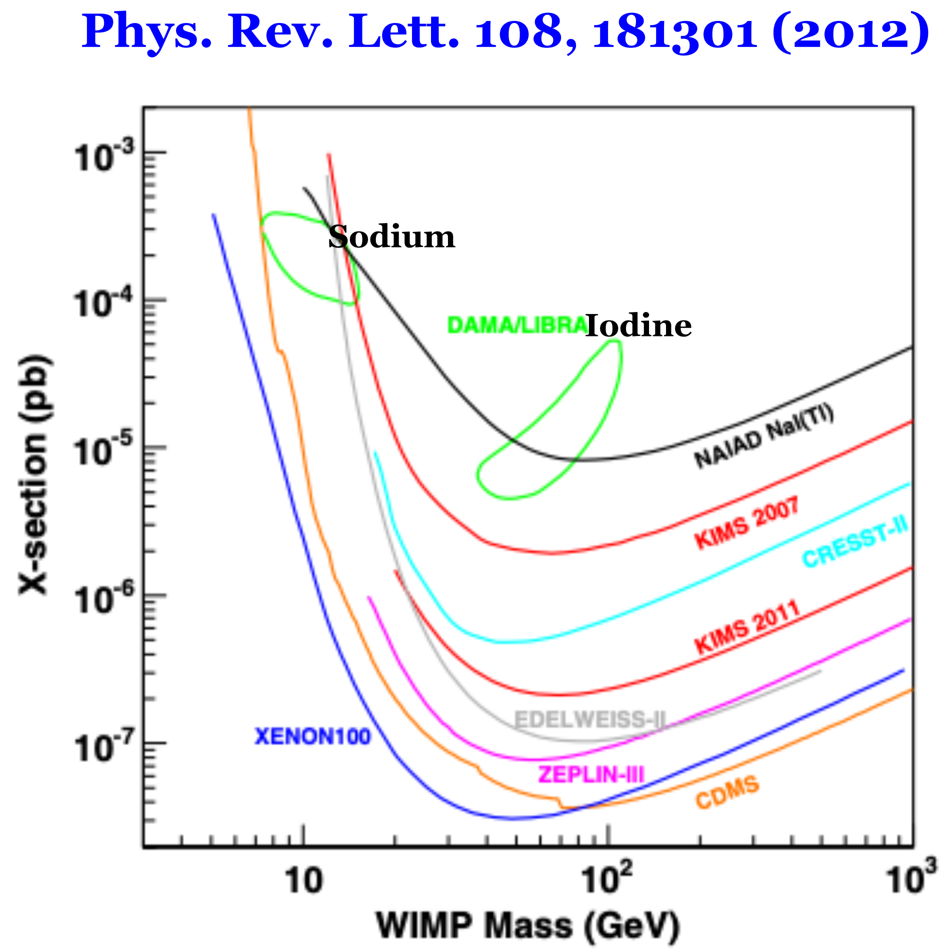
Searching for WIMPs by the annual modulation signature

R. Bernabei [a], P. Belli [a], F. Montecchia [a], W. Di Nicolantonio [b], A. Incicchitti [b],
D. Prosperi [b], C. Bacci [c], C.J. Dai [d], L.K. Ding [d], H.H. Kuang [d], J.M. Ma [d]

Recently, positive signal of annual modulation has been reported by DAMA group [6]. Looking at the similar sensitivity region with other experiments which involves different systematics is absolutely necessary to confirm their results. It has been noted by several authors that CsI(Tℓ) crystal may give better performance for the separation between recoiling events and the ionizing events by background $\gamma$ [7]. Although the light yield of CsI(Tℓ) crystal is slightly lower than NaI(Tl) crystal, better particle separation can be more advantageous for WIMP search. Also CsI(Tℓ) has much less hygroscopicity

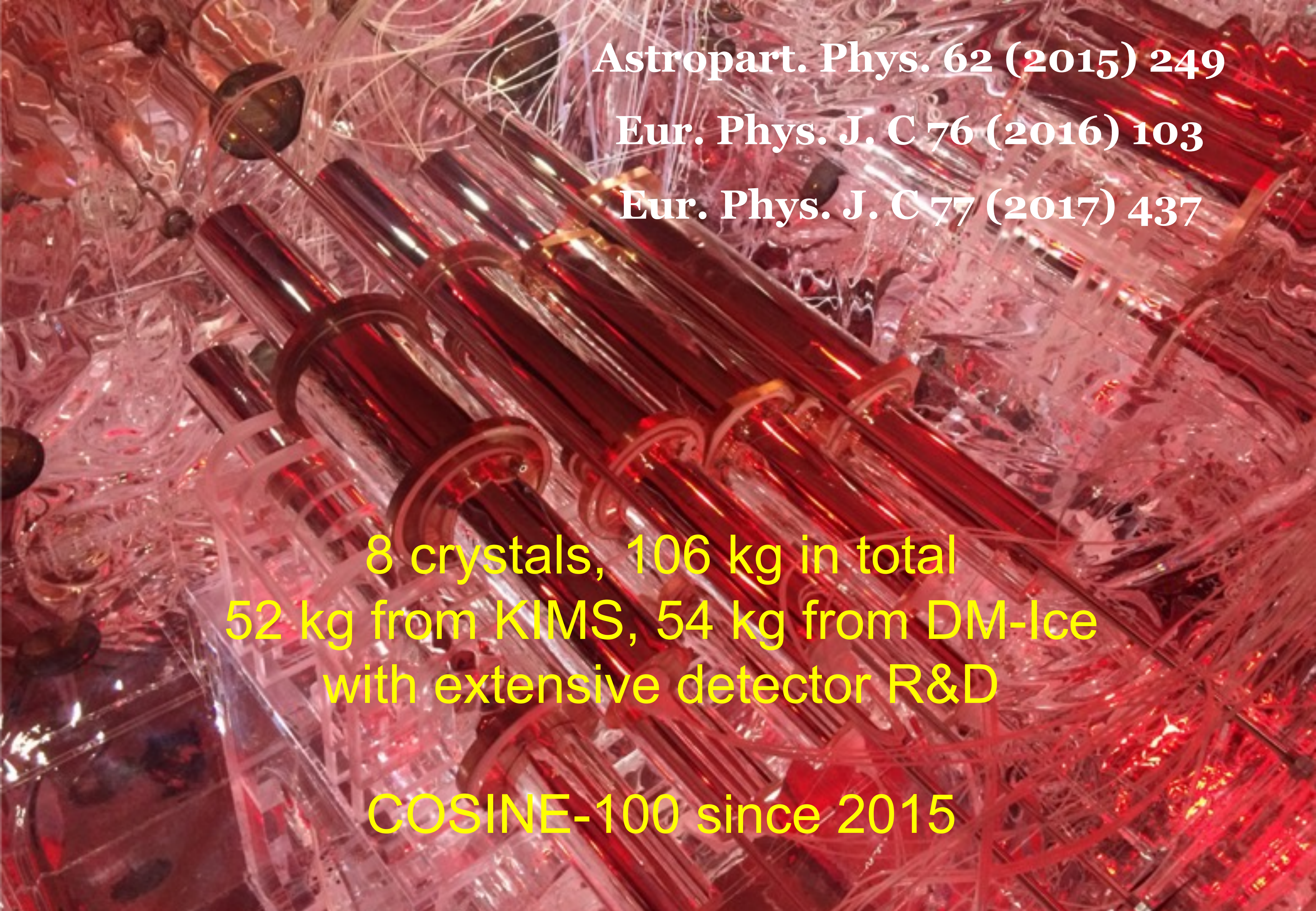
# KIMS Experiments




**Exclude dark matter-iodine interaction as the source of DAMA modulation signal**

**We need to check dark matter-sodium interaction!! Require NaI(Tl) experiment**



Astropart. Phys. 62 (2015) 249
Eur. Phys. J. C 76 (2016) 103
Eur. Phys. J. C 77 (2017) 437
8 crystals, 106 kg in total
52 kg from KIMS, 54 kg from DM-Ice
with extensive detector R&D
COSINE-100 since 2015

# COSINE-100 detectors

<u>Eur. Phys. J. C 78 (2018) 107</u>

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

JINST 13 (2018) P09006

JINST 13 (2018) T02007

JINST 13 (2018) T06005

NIMA 981 (2020) 164556

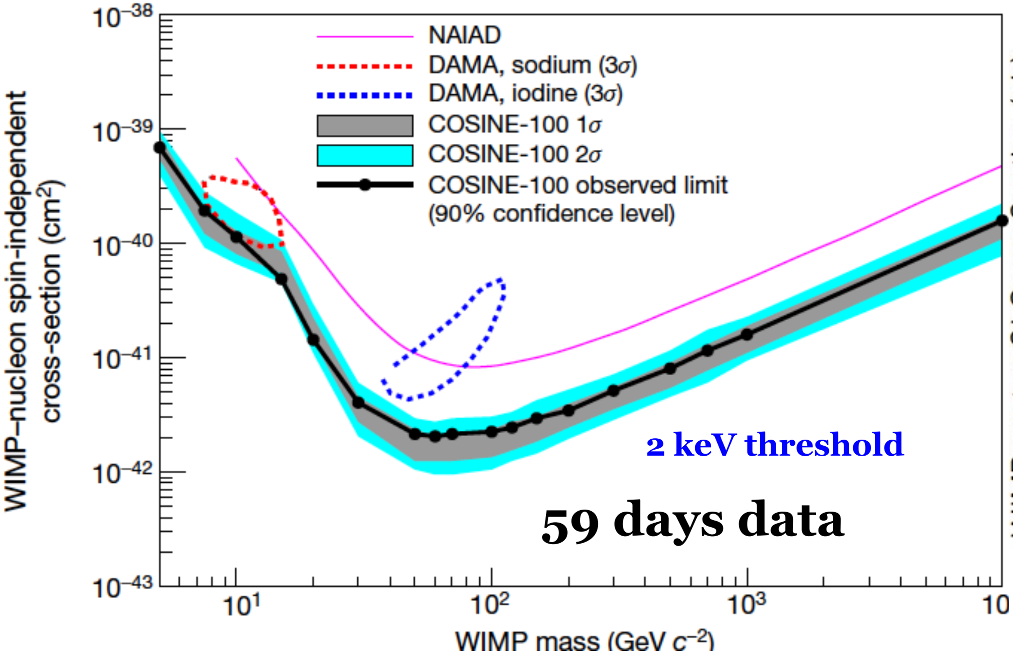
JINST 17 (2022) T01001

**Physics run October/2016 – April/2023**

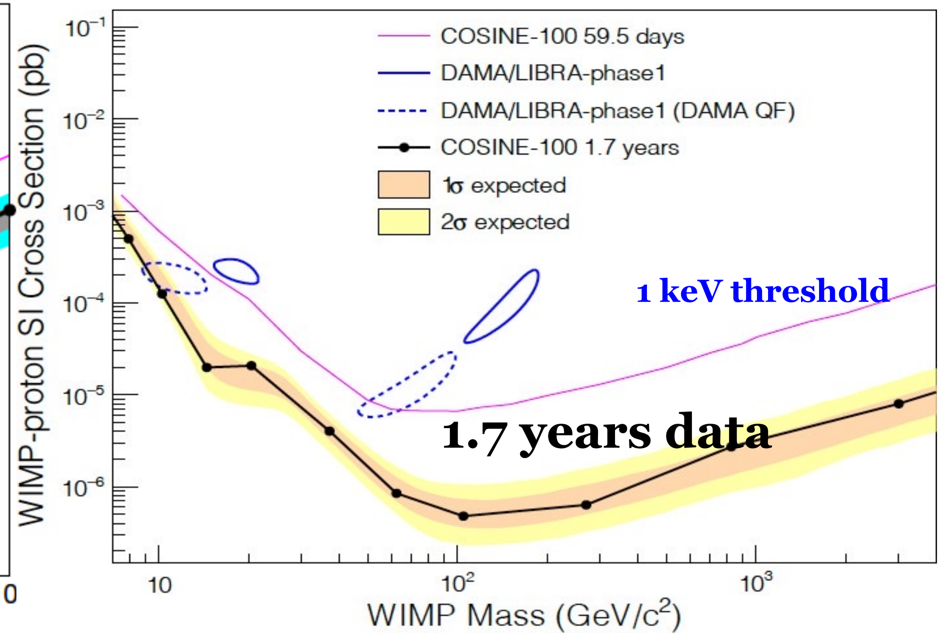
**Yangyang underground laboratory**

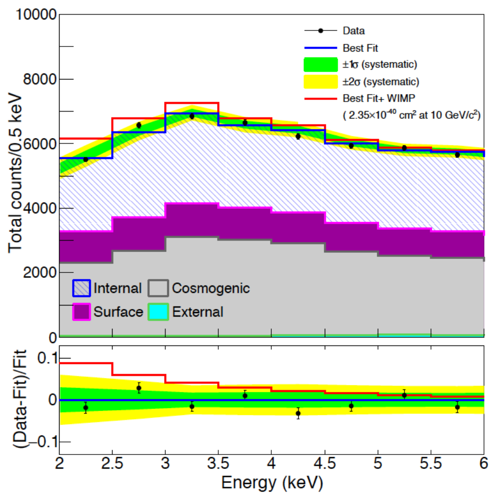
# COSINE-100 tested DAMA/LIBRA

Nature **564**, 83 (2018)



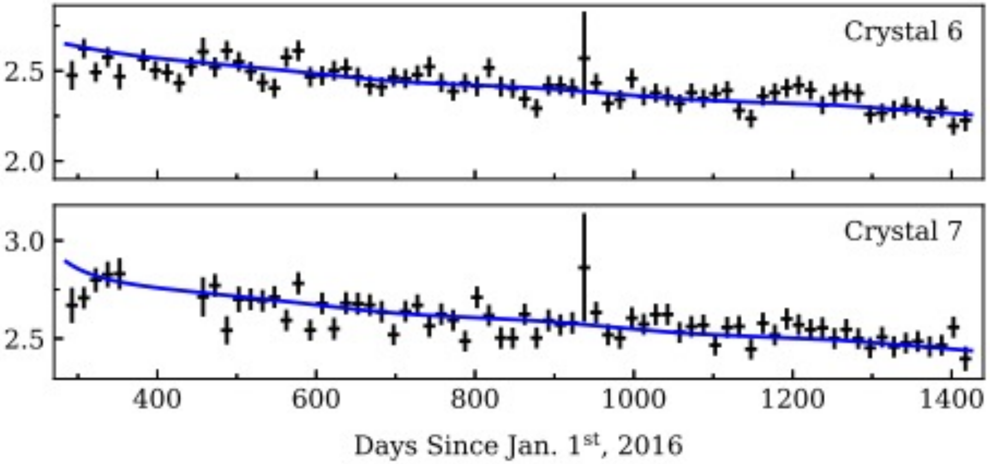

Sci. Adv. 7, eabk2699 (2021)



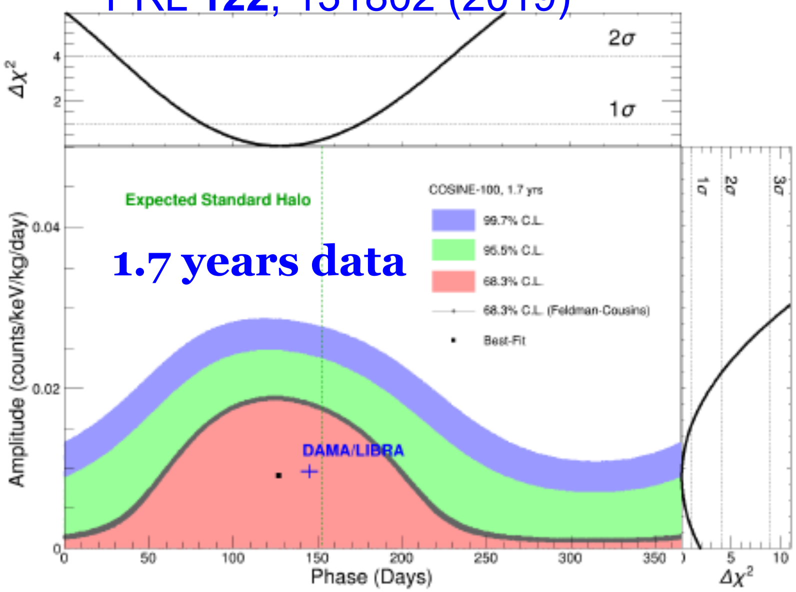




- Model-dependent test ruled out DAMA/LIBRA with same NaI(Tl)

# Annual modulation searches




PRL **122**, 131802 (2019)

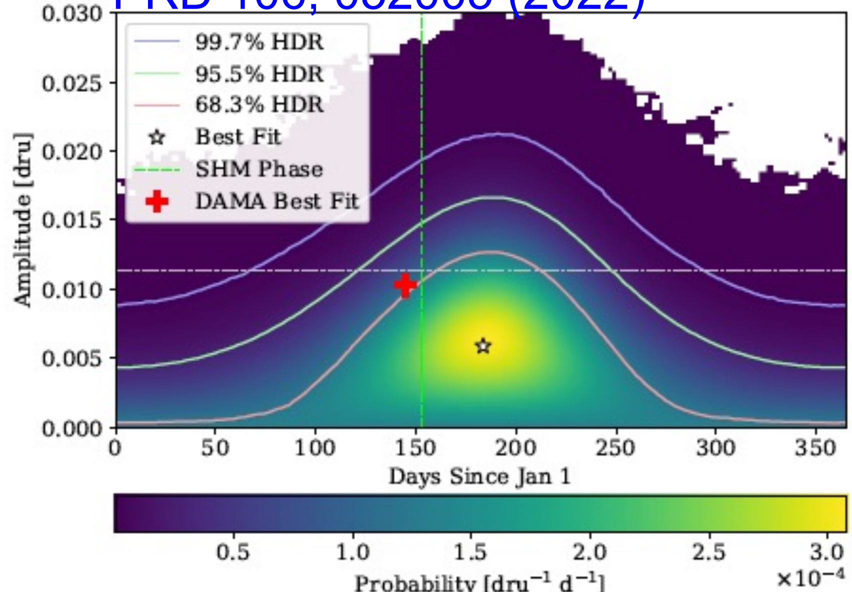



**1.7 years data**

**1-6 keV modulation amplitude**

| | |
|---|---|
| **COSINE-100** | $\mathbf{0.0067 \pm 0.0042}$ |
| DAMA/LIBRA | $0.0105 \pm 0.0011$ |
| ANAIS-112 | $-0.0034 \pm 0.0042$ |

PRD 106, 052005 (2022)

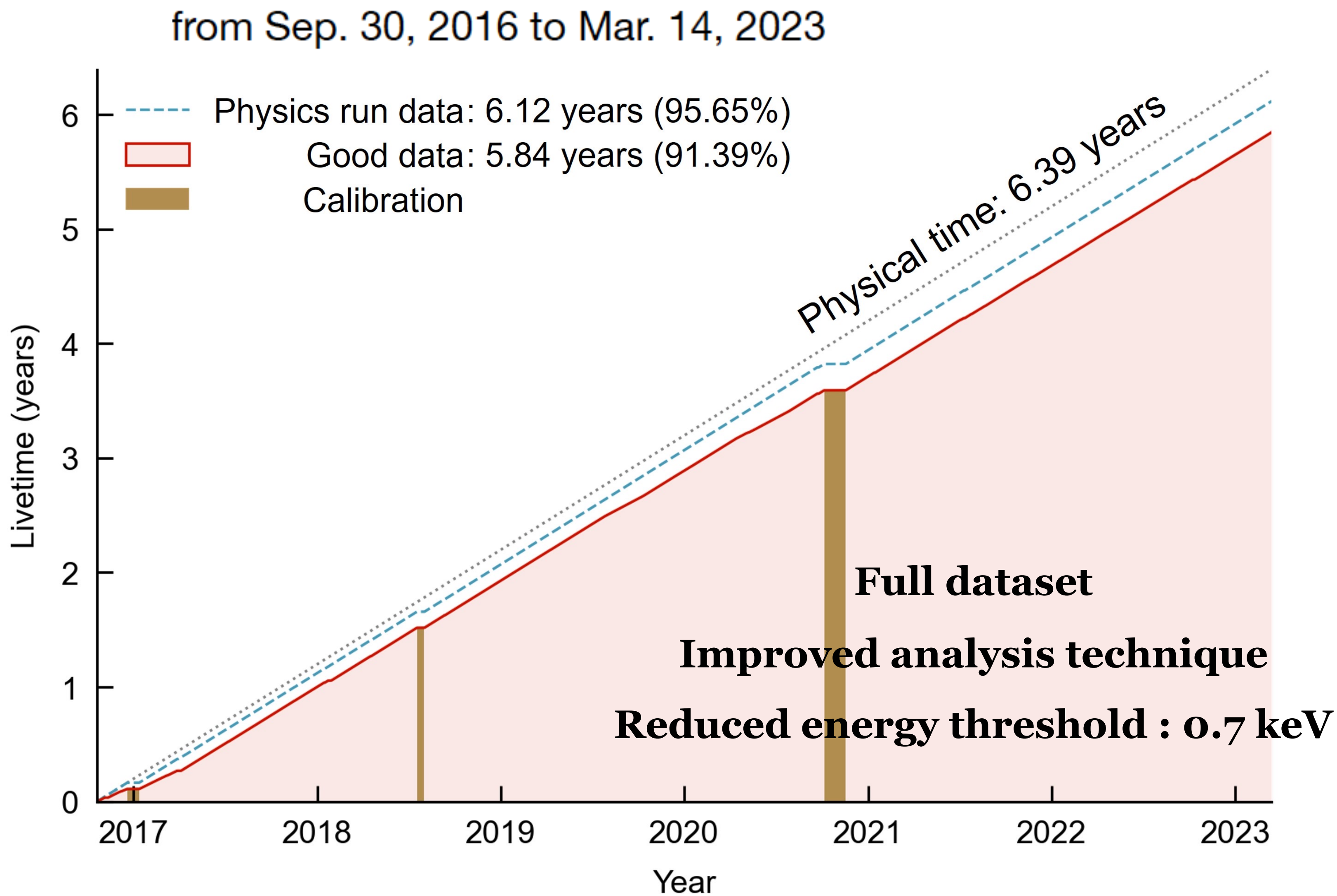



**3 years data**

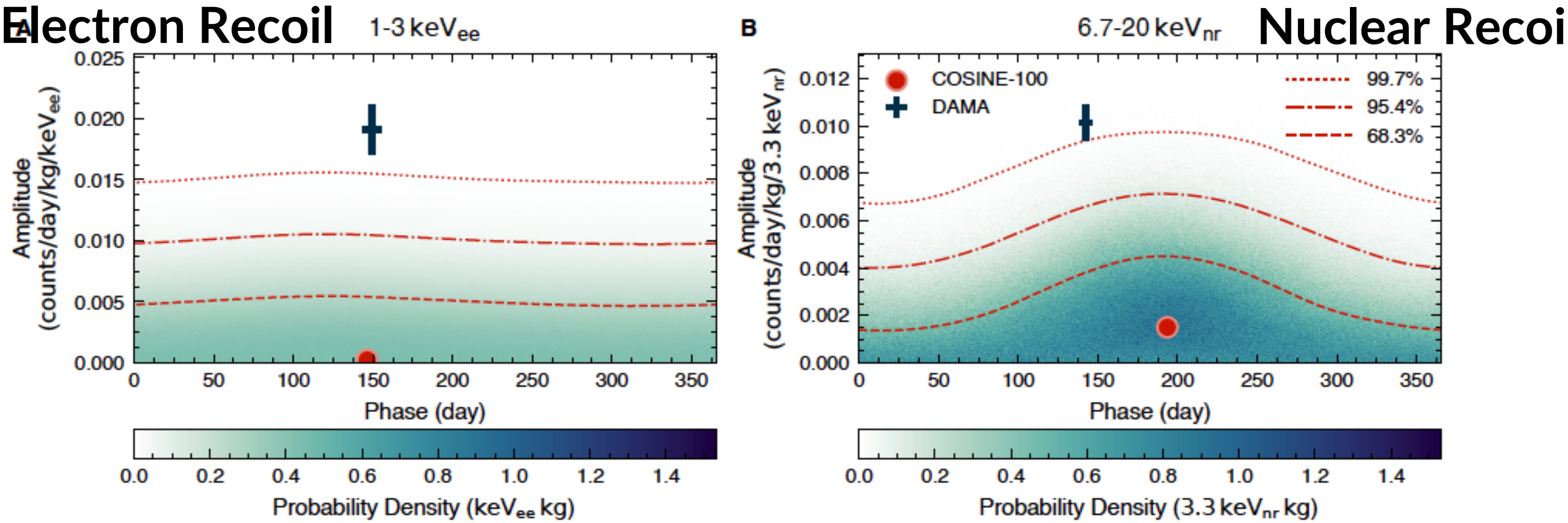
**Not enough statistics but, we have full 6.4 years data**

# COSINE-100 (2016-2023) @ Y2L

COSINE-100 operation was paused for moving to Yemilab and detector upgrades



# Full dataset annual modulation




| ***E*** **(keV$_{ee}$)** | ***A*** **(counts/day/kg/keV$_{ee}$)** | |
|---|---|---|
| | COSINE-100 | DAMA/LIBRA |
| $1\sim3$ | $\mathbf{0.001 \pm 0.005}$ | $0.019 \pm 0.002$ |
| $1\sim6$ | $\mathbf{0.002 \pm 0.003}$ | $0.010 \pm 0.001$ |
| $2\sim6$ | $\mathbf{0.005 \pm 0.003}$ | $0.010 \pm 0.001$ |

**arXiv:2409.13226**

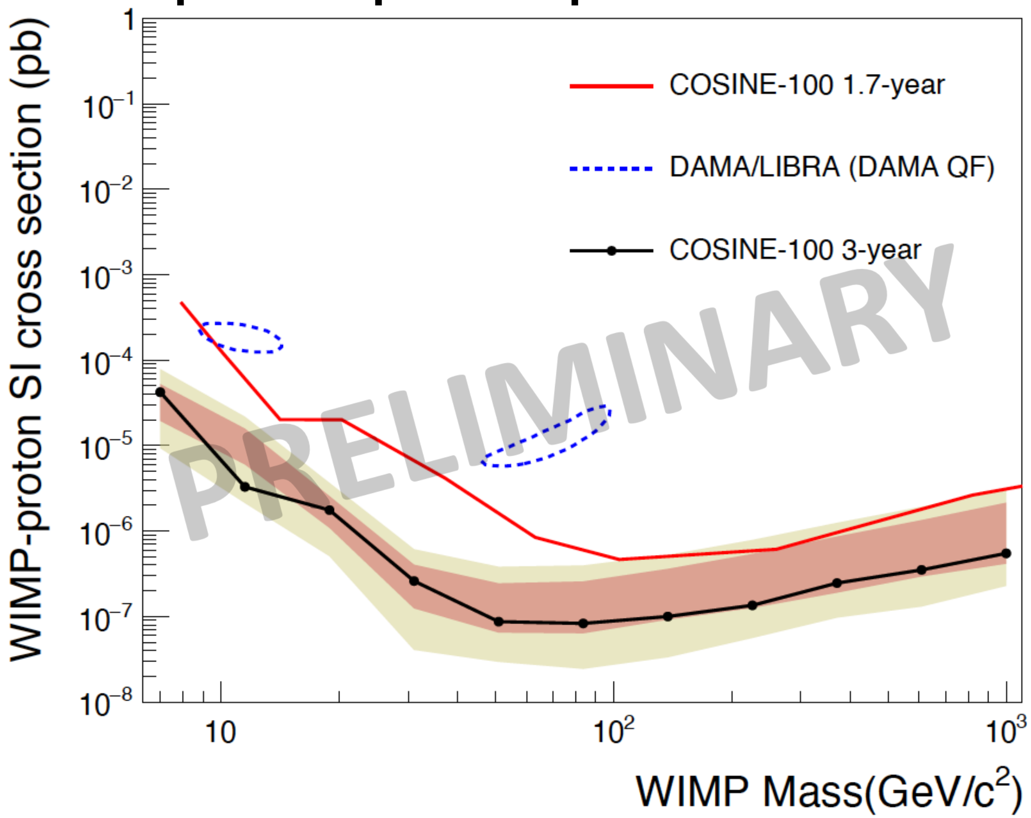
| ***E*** **(keV$_{nr}$)** | ***A*** **(counts/day/kg/3.3 keV$_{nr}$)** | |
|---|---|---|
| | COSINE-100 | DAMA/LIBRA |
| $6.7\sim20$ | $\mathbf{0.001 \pm 0.003}$ | $0.010 \pm 0.001$ |

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil $(> 3\sigma\ CL)$ **Closing DAMA/LIBRA**!!

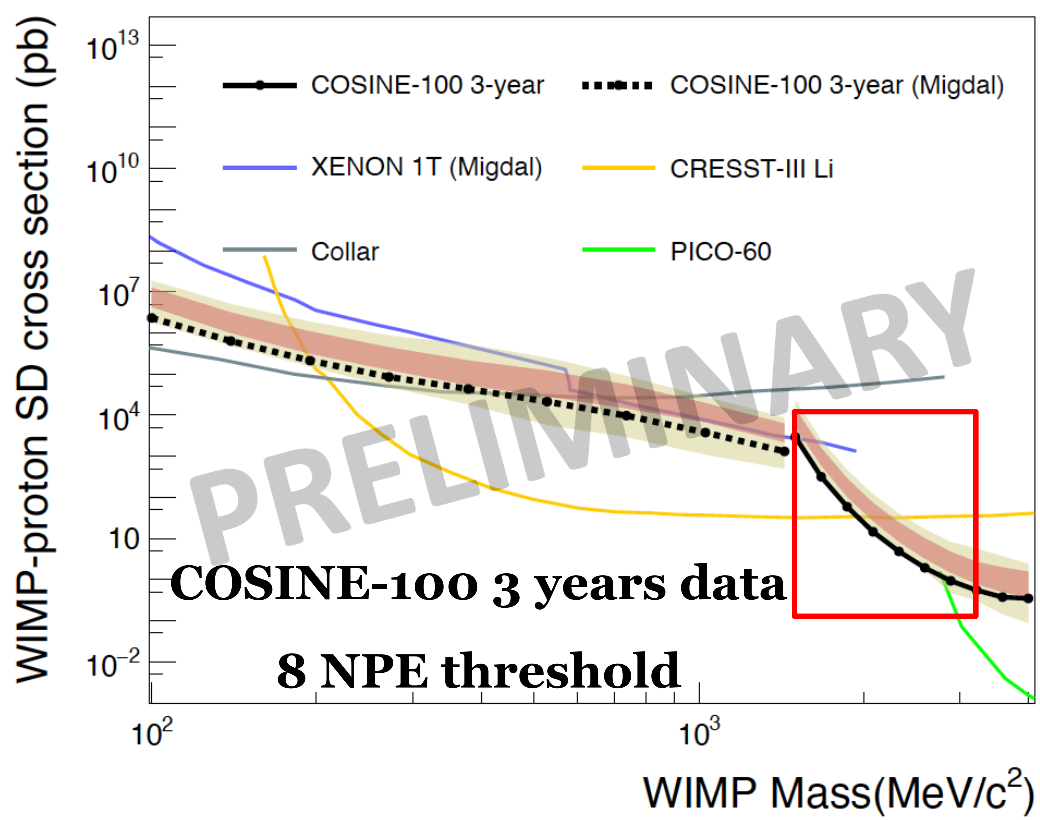
# Low-mass dark matter search with NaI(Tl)

- 3 years data (0.7 keV energy threshold, 8 number of photoelectrons)

**WIMP-proton spin-independent interaction**

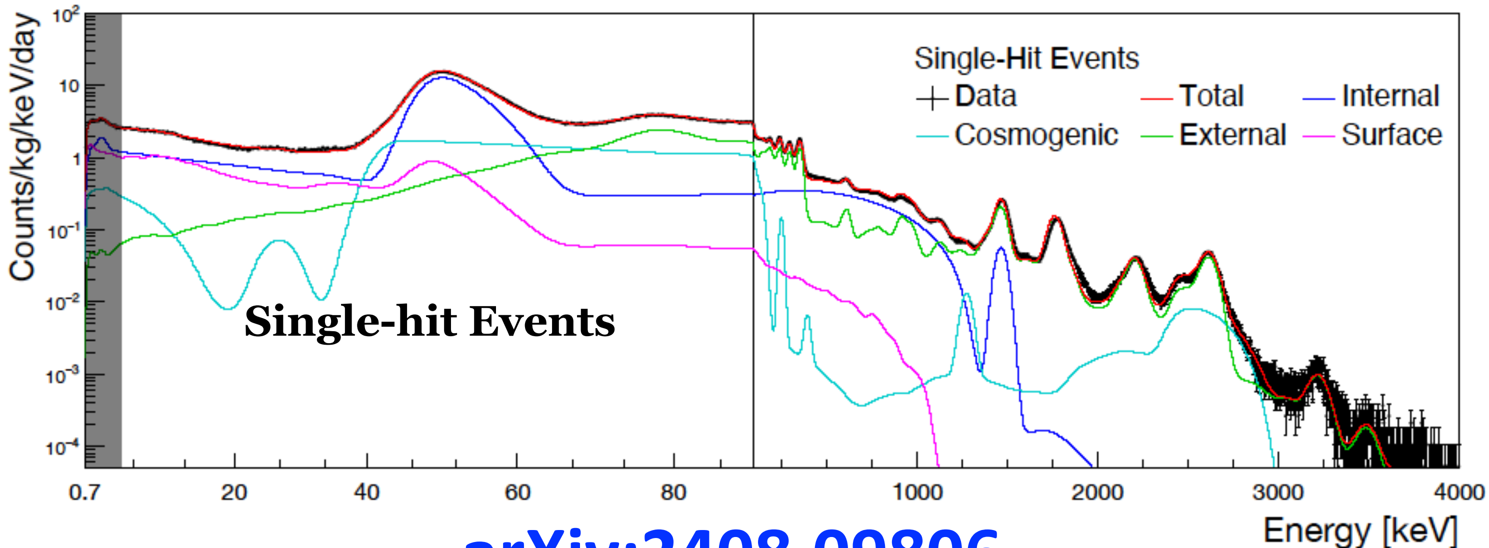



**WIMP-proton spin-dependent interaction**

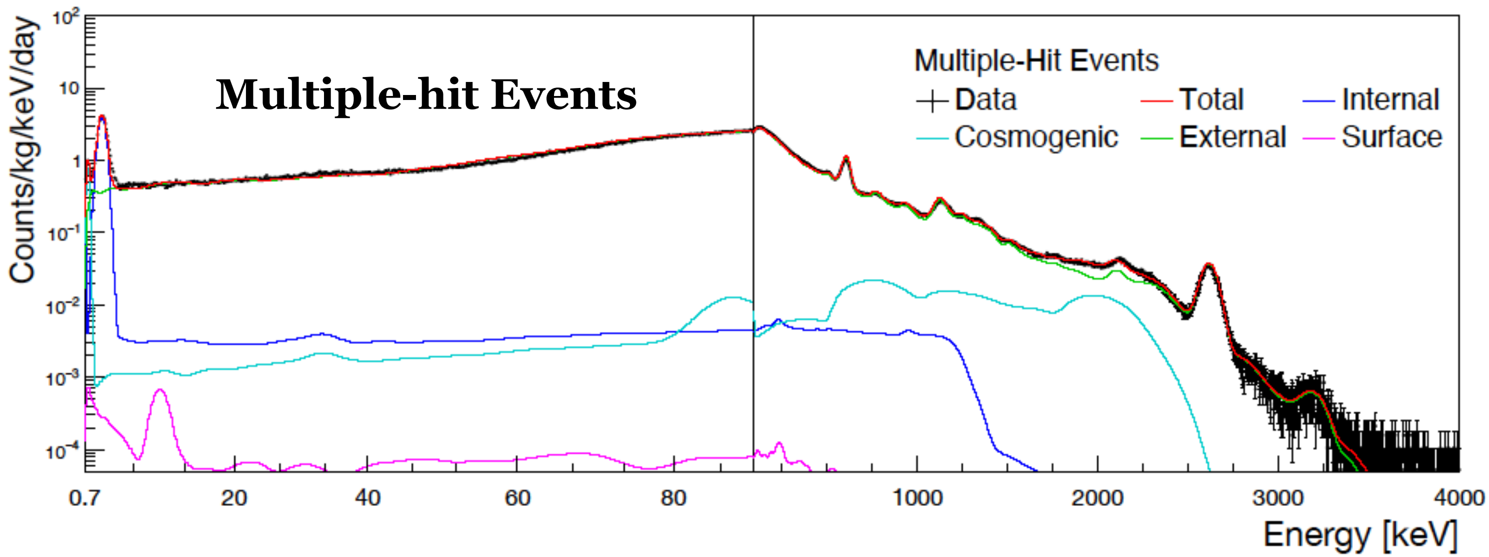



- This can be enhanced by reduced energy threshold!!
  - ❖ Can reach to 5 number of photoelectrons

# Detector understanding



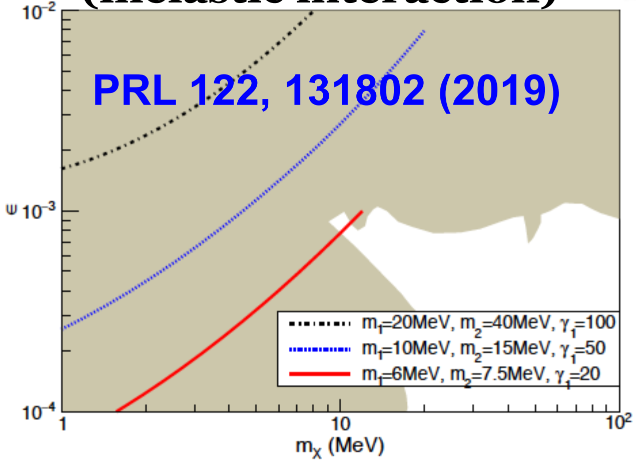

arXiv:2408.09806



# Search for dark-sector particles with COSINE-100

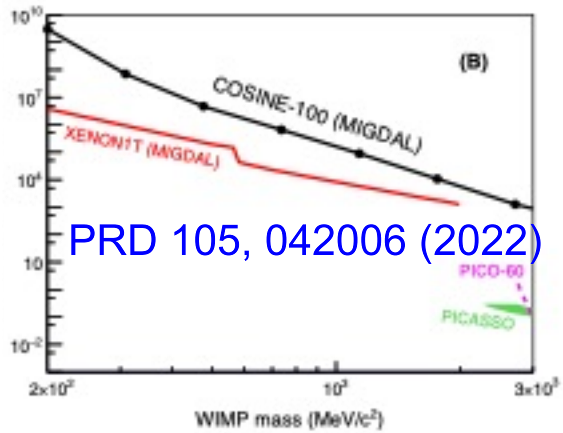
## Boosted dark matter (inelastic interaction)

PRL 122, 131802 (2019)



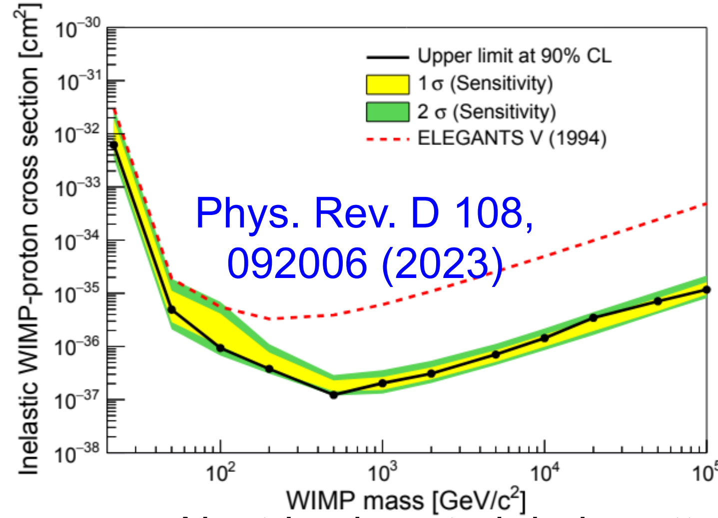

## Migdal effect

PRD 105, 042006 (2022)



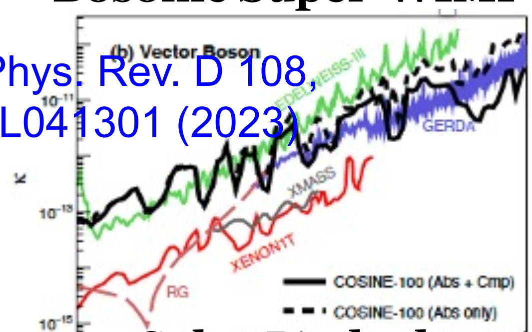

## WIMP-127I inelastic interaction

Phys. Rev. D 108, 092006 (2023)

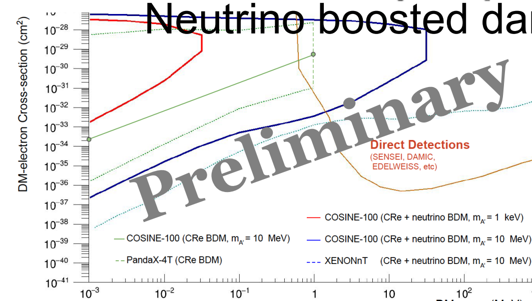



## Bosonic Super-WIMP

Phys. Rev. D 108, L041301 (2023)

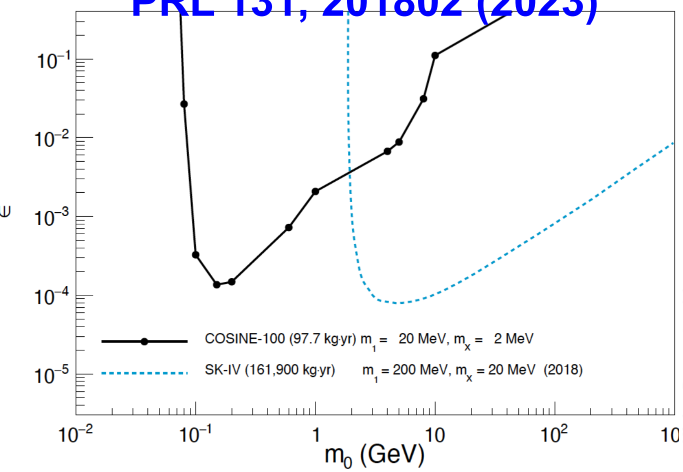



## Neutrino boosted dark matter



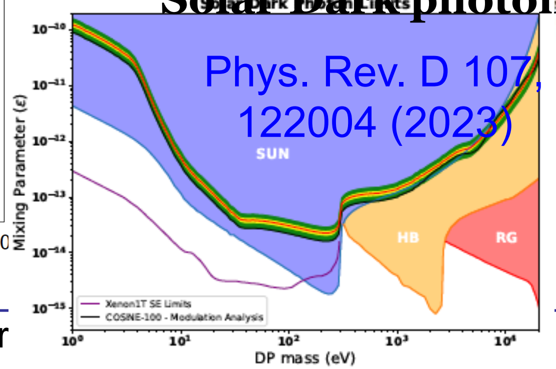

## Boosted dark matter (elastic interaction)

PRL 131, 201802 (2023)

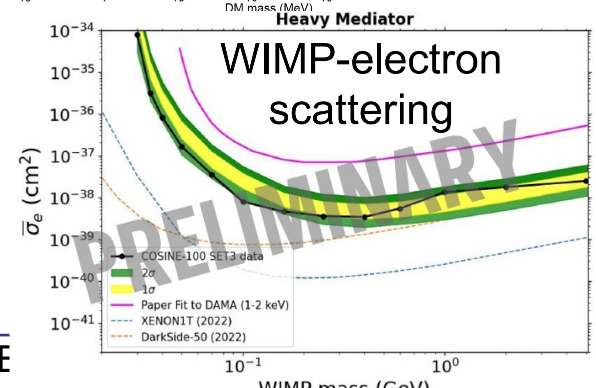



## Solar Dark photon

Phys. Rev. D 107, 122004 (2023)

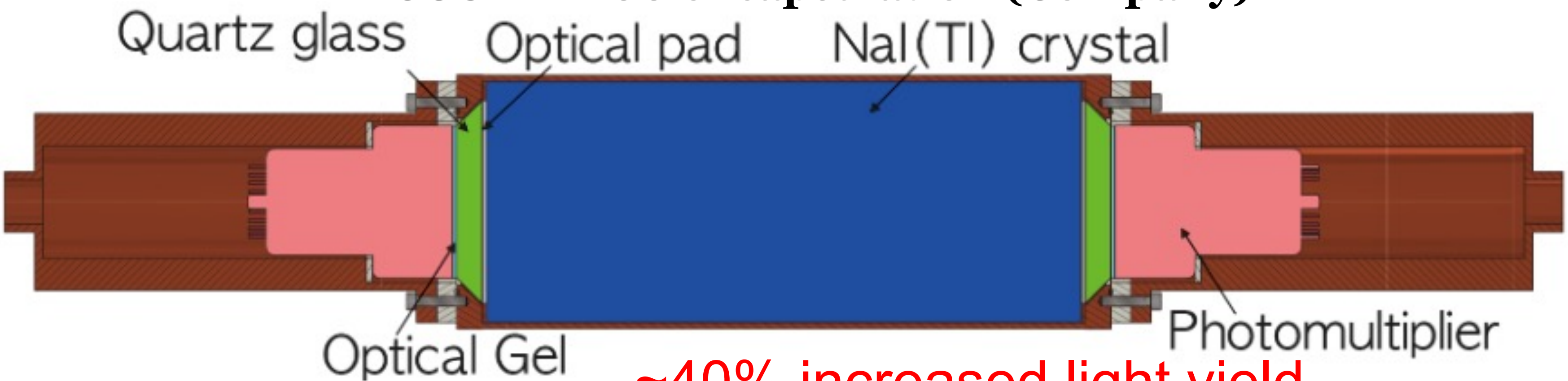



## WIMP-electron scattering



# Moving forward to COSINE-100Upgrade

**COSINE-100 encapsulation (Company)**

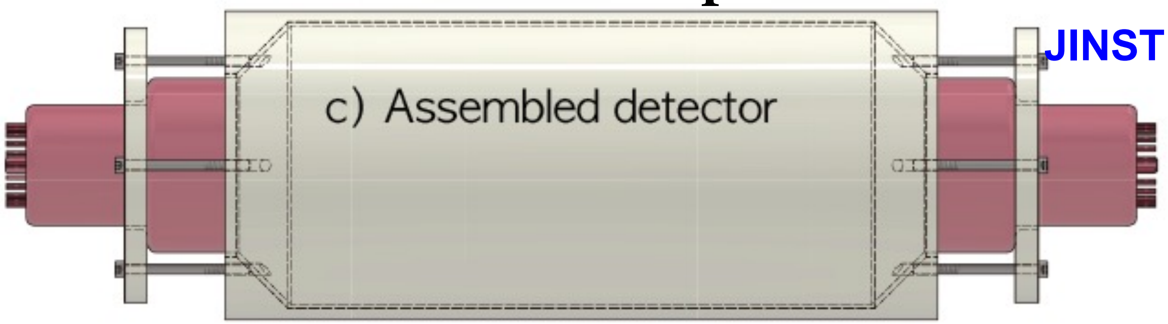


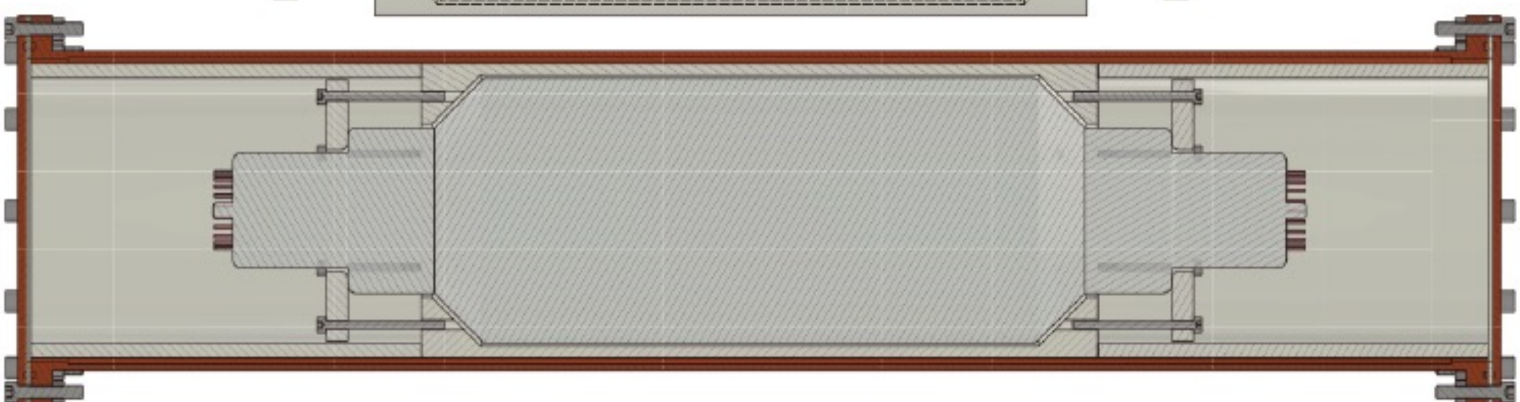

~40% increased light yield

**COSINE-100U encapsulation**

NIMA 981 (2020) 164556

JINST 19 (2024) P10020

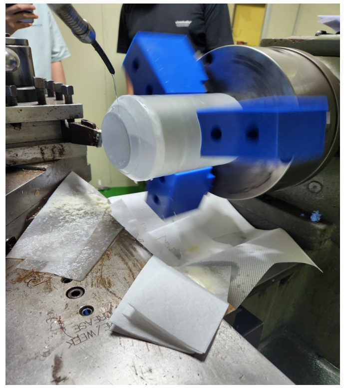


# Moving forward to COSINE-100Upgrade

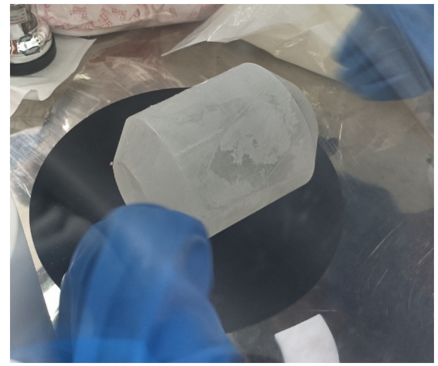
- Upgrade detector assembly for high light yield

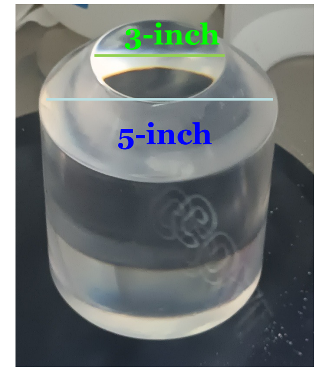
**Crystal machine @ company**



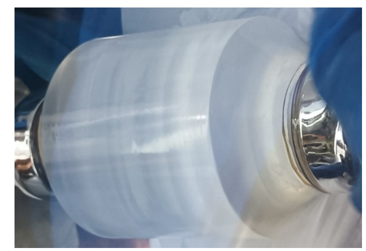
**8.26 kg → 7.19 kg**

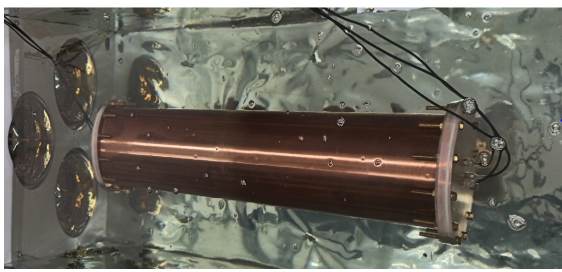
**Deliver to glove box**



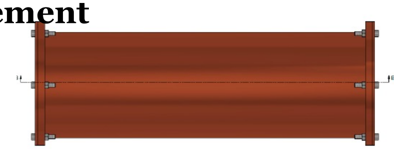


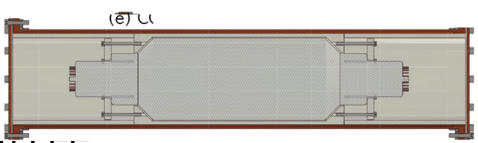

**COSINE crystal-1**



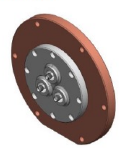


**Above ground measurement**





Cover design



**14.9 ± 1.5 → 21.5 ± 0.6 NPE/keV**

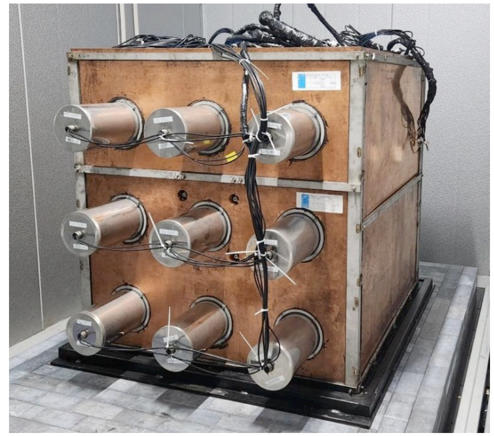
COSINE-100 C2 → COSINE-100U C2

# COSINE-100U : Yemilab installation

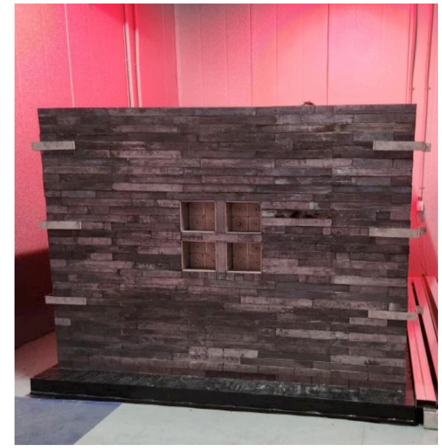
**Freeze room for -30°C operation**

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

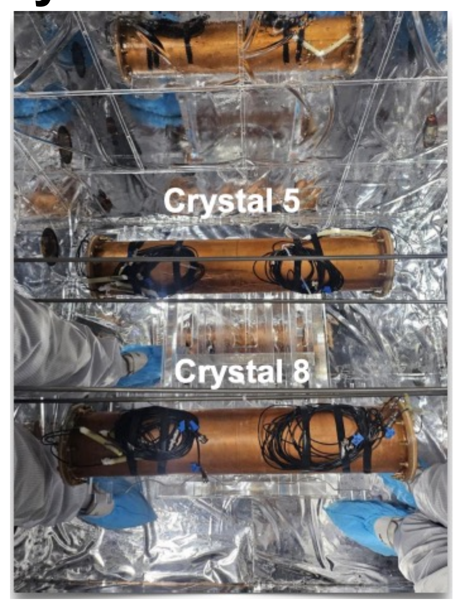
**Liquid scintillator veto**



**Lead shield**

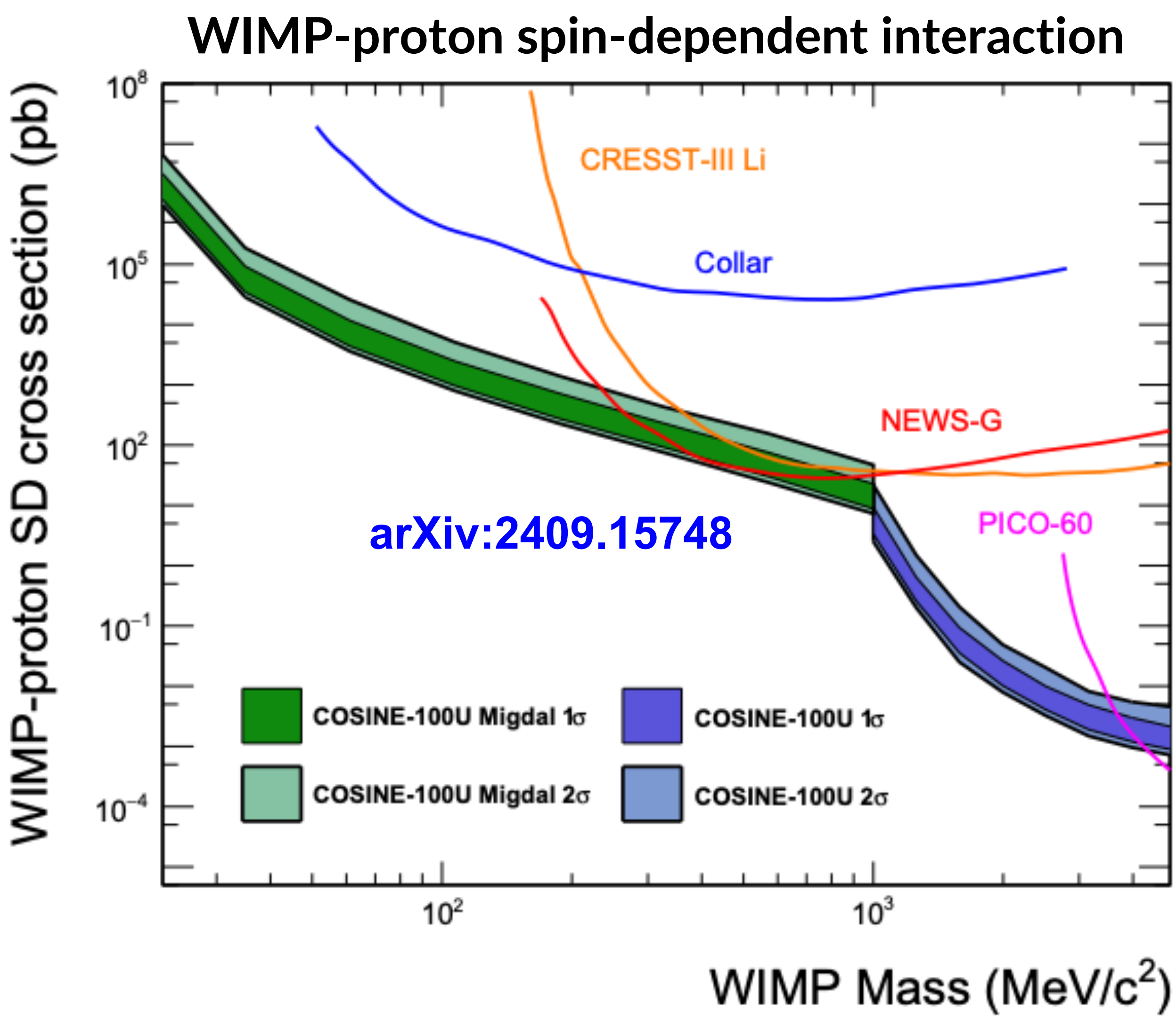


**Crystal installation**




- We plan to start COSINE-100U early 2025

# COSINE-100U sensitivity



# 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)

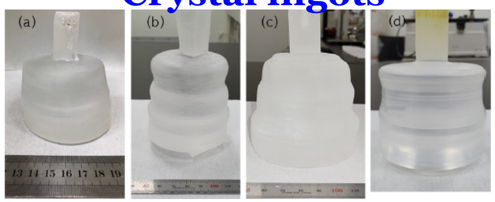
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

| | 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 |

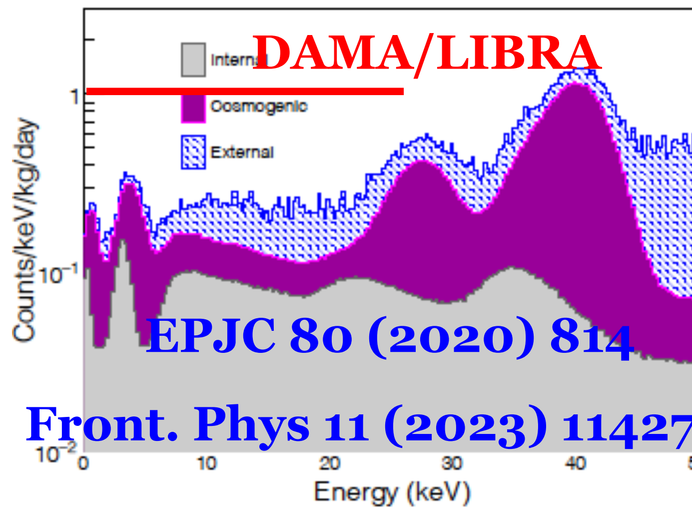
**We produced ~ 400 kg low-background NaI powder**

**(Maximum production rate ~ 100 kg/month)**


**Crystal ingots**





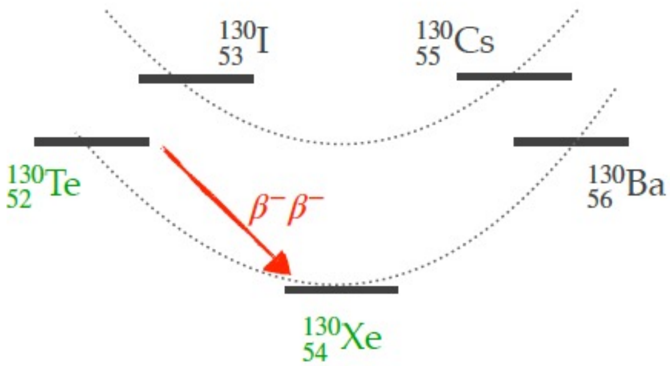

**A proof of principle for low background NaI**

**Large crystal growing is going on**

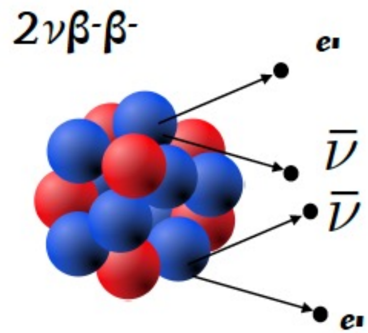
# Physics program at Yemilab

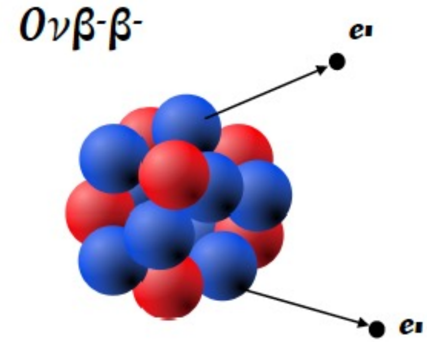
## AMoRE

# Neutrinoless double beta decay



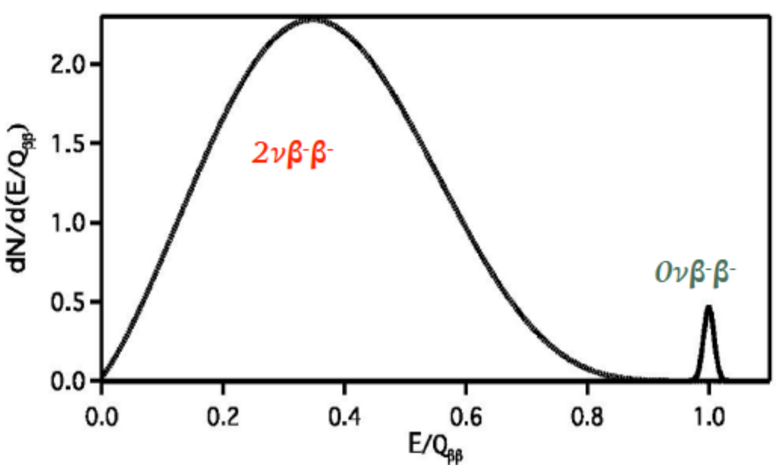

**Beta decay is forbidden**




**~ 35 candidate**

- If neutrinos are Majorana
- Lepton number violation
- Q > 2 MeV (Only 11 candidates)




- Measure absolute neutrino mass

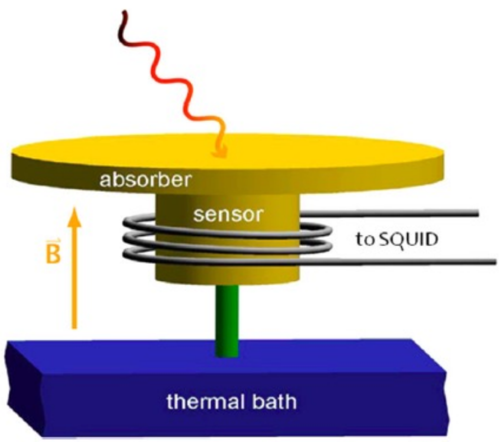
$$\Gamma^{0\nu}_{\beta\beta} = \frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

**Good Energy resolution** & low-background are required

# Detection Principle

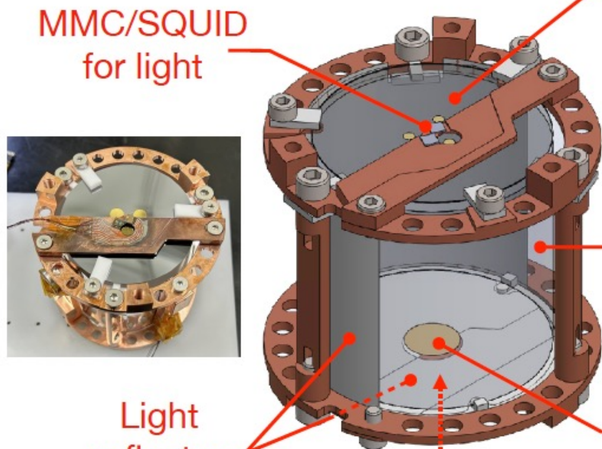
## Heat and light signals at low temperature

- Mo-100 based scintillation crystal (XMO) as source and target at 10–20 mK.

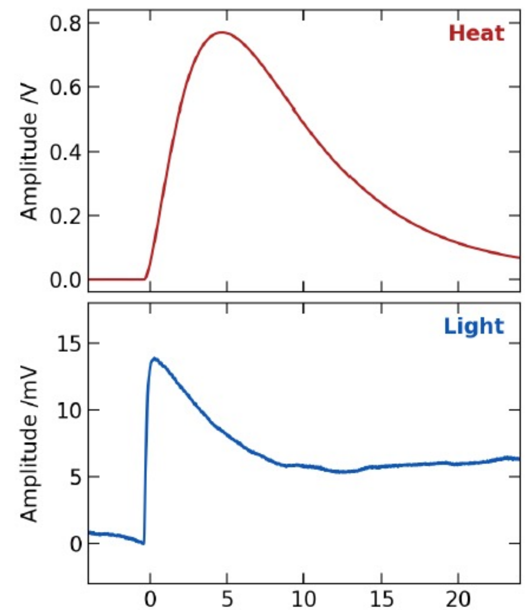



Metallic Magnetic Calorimeter (MMC)
Figure courtesy of D. Hengstler et al (2015)

AMoRE-II detector module
arXiv:2407.12227, EPJC accepted




Averaged 2.6 MeV-γ signals of an LMO detector in AMoRE-I



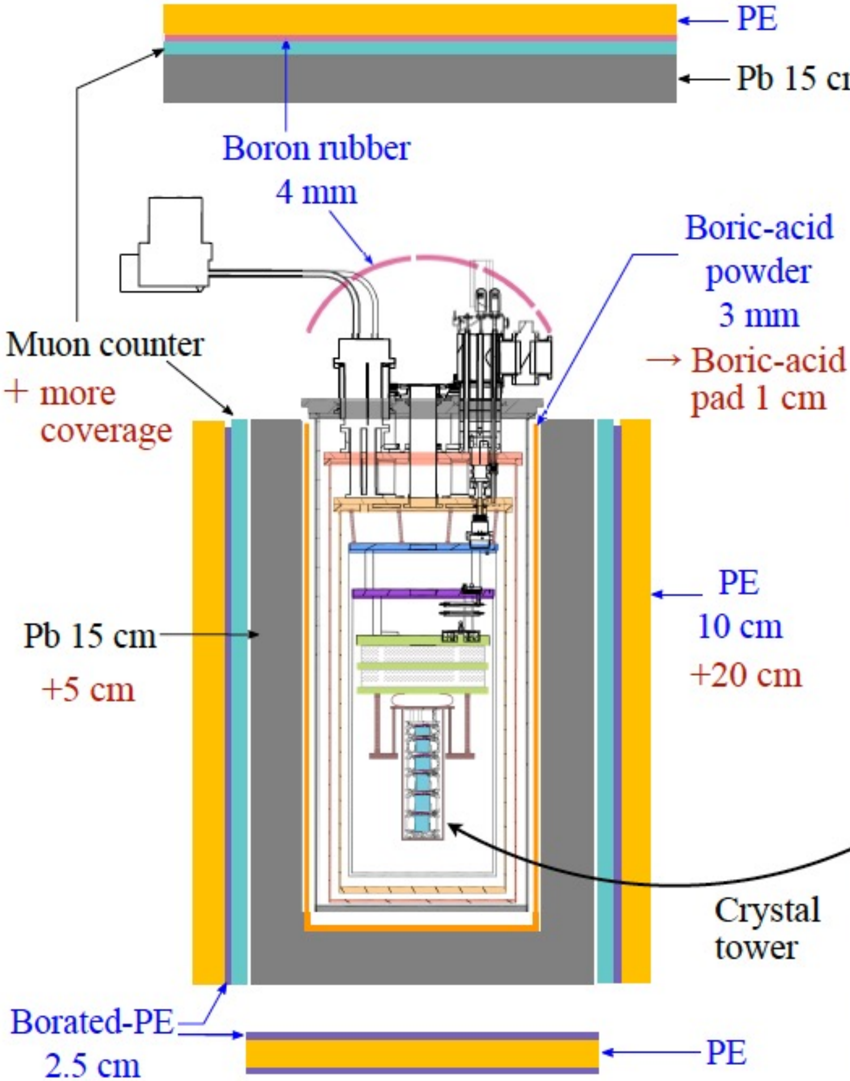

**arXiv:2407.12227**

**Mo-100**

Q-value : 3.034 MeV

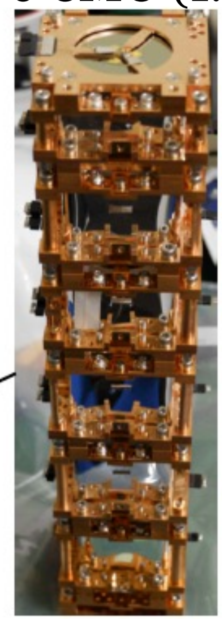
$T_{1/2}^{0\nu}$ >1.8×10$^{24}$ yr at 90% CL by CUPID-Mo

# AMoRE-pilot (2015-18) and AMoRE-I (2020-23)



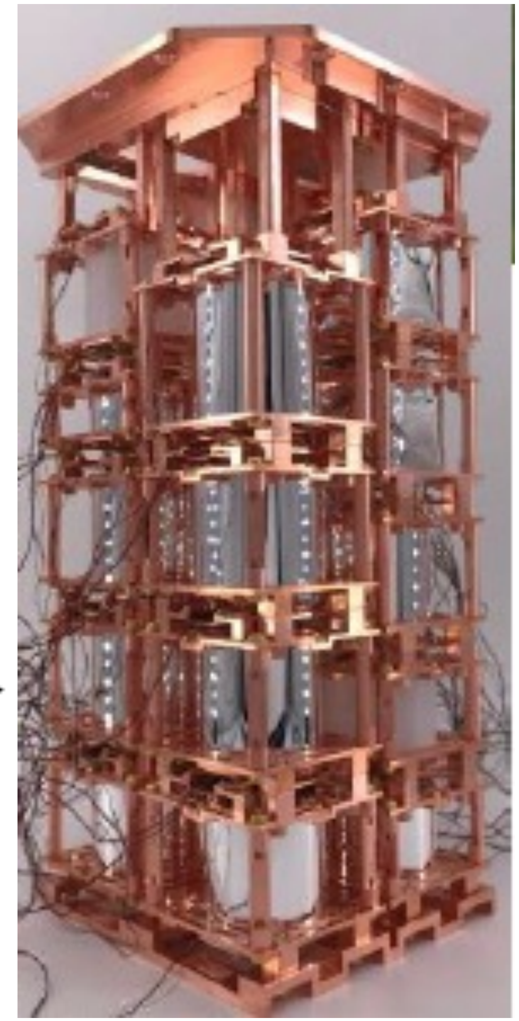

**AMoRE-pilot**

6 CMO (1.9 kg)

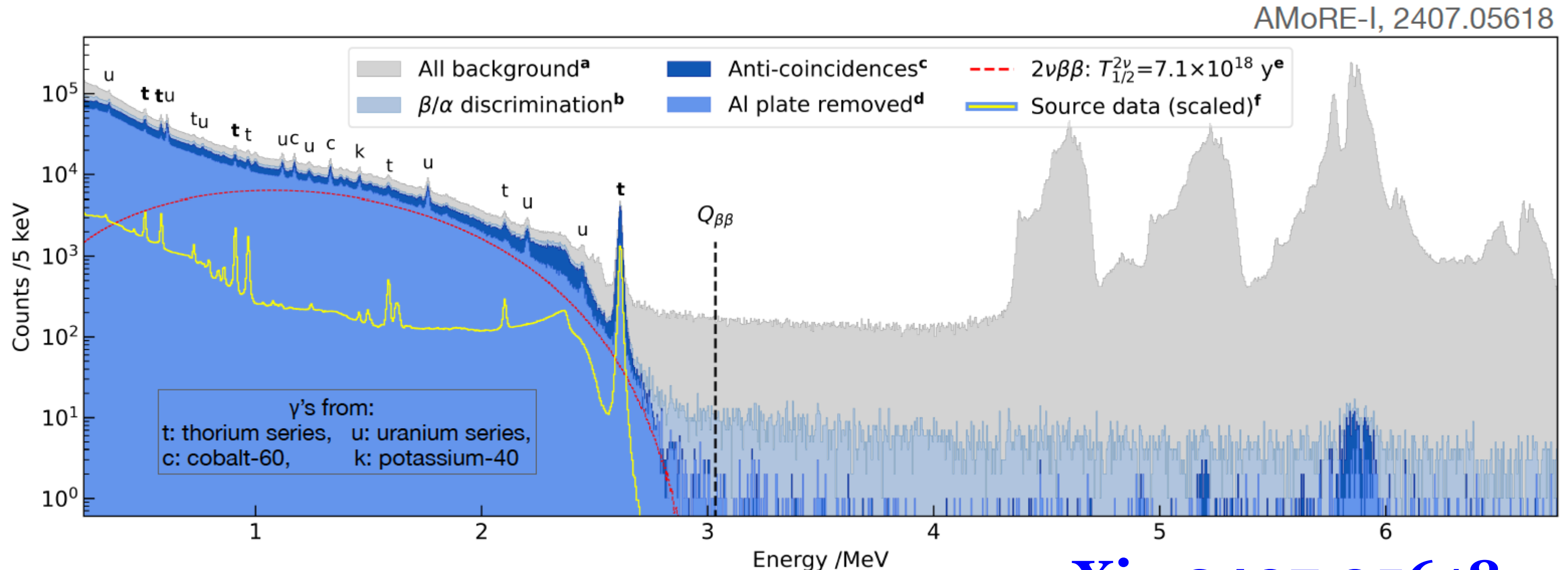


**AMoRE-I**

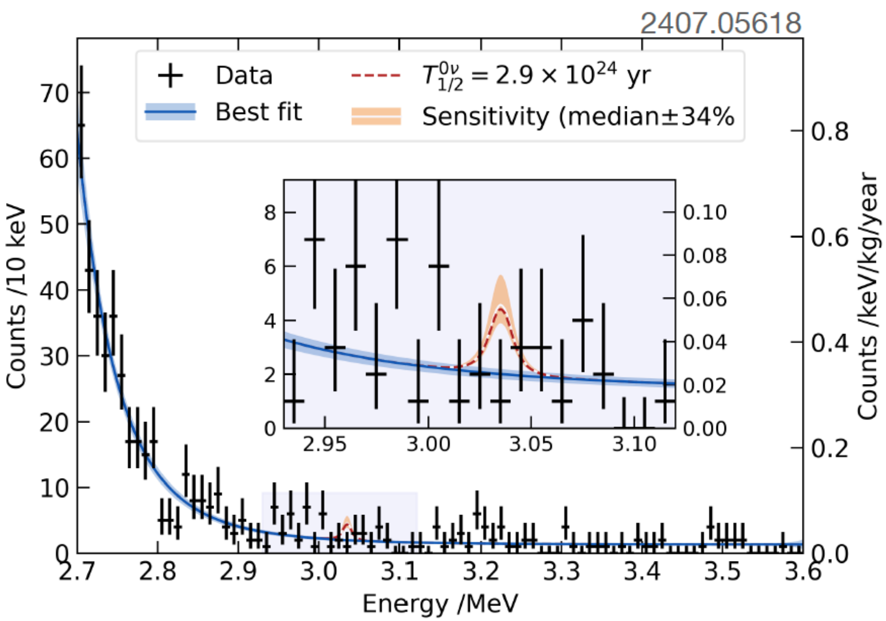
13 CMO, 5 LMO (6kg)



# AMoRE-I results




**arXiv:2407.05618**

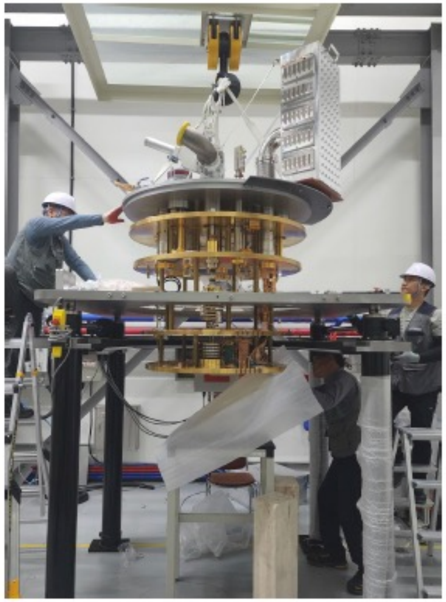



- Exposure : 4 kg $_{\text{Mo-100}}$ year
- Background : 0.025 counts/keV/kg/yr
- Reduction from pilot (1/12)

$$T^{0\nu}_{1/2} > 2.9\times10^{24} \text{ yr at 90\% CL}$$

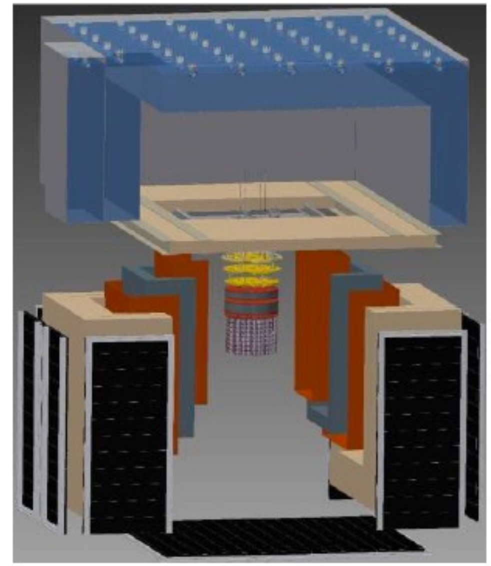
**The best half life limit for $^{100}$Mo**

# AMoRE-II is under preparation @ Yemilab

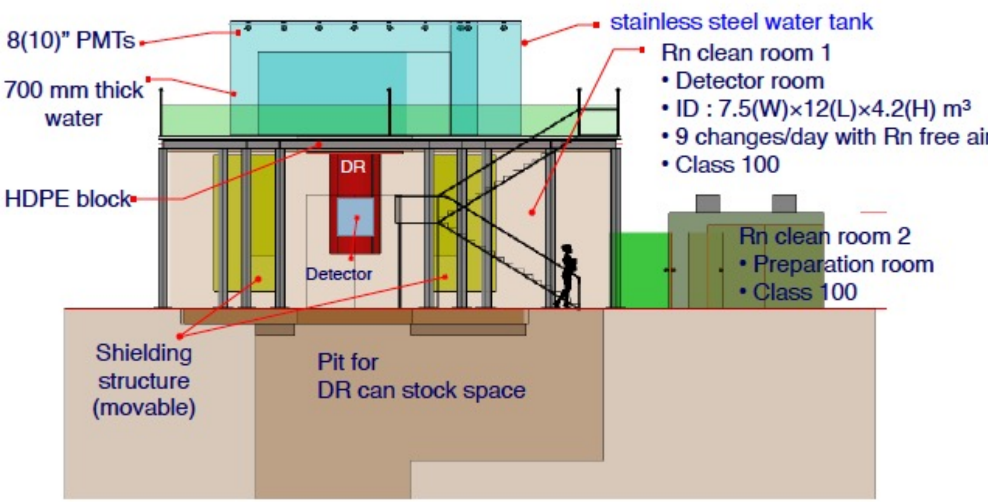


DR started moving
from the surface lab

DR installed in Yemilab



Detector/shielding scheme




AMoRE Hall in Yemilab

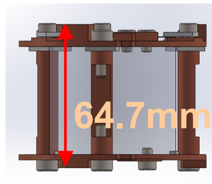
# AMoRE-II is under preparation @ Yemilab

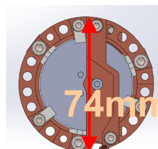
**Muon Counter**

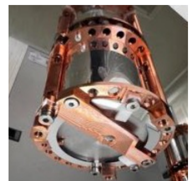


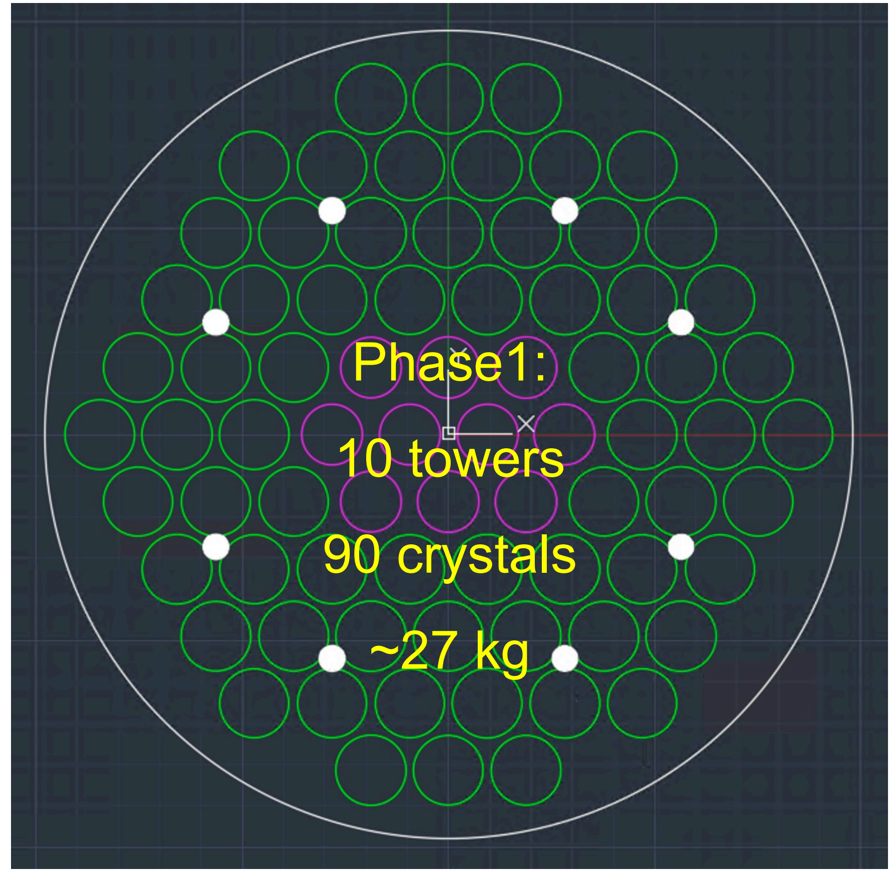
NIMA 1039 (2022) 167123

**Module design**




**Phase1 start around early 2025**

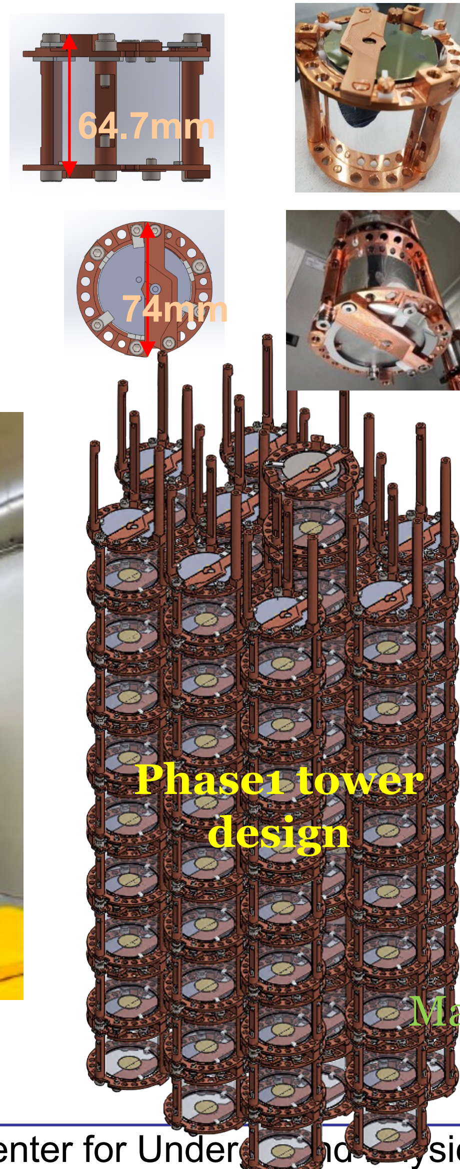
# AMoRE-II is under preparation @ Yemilab

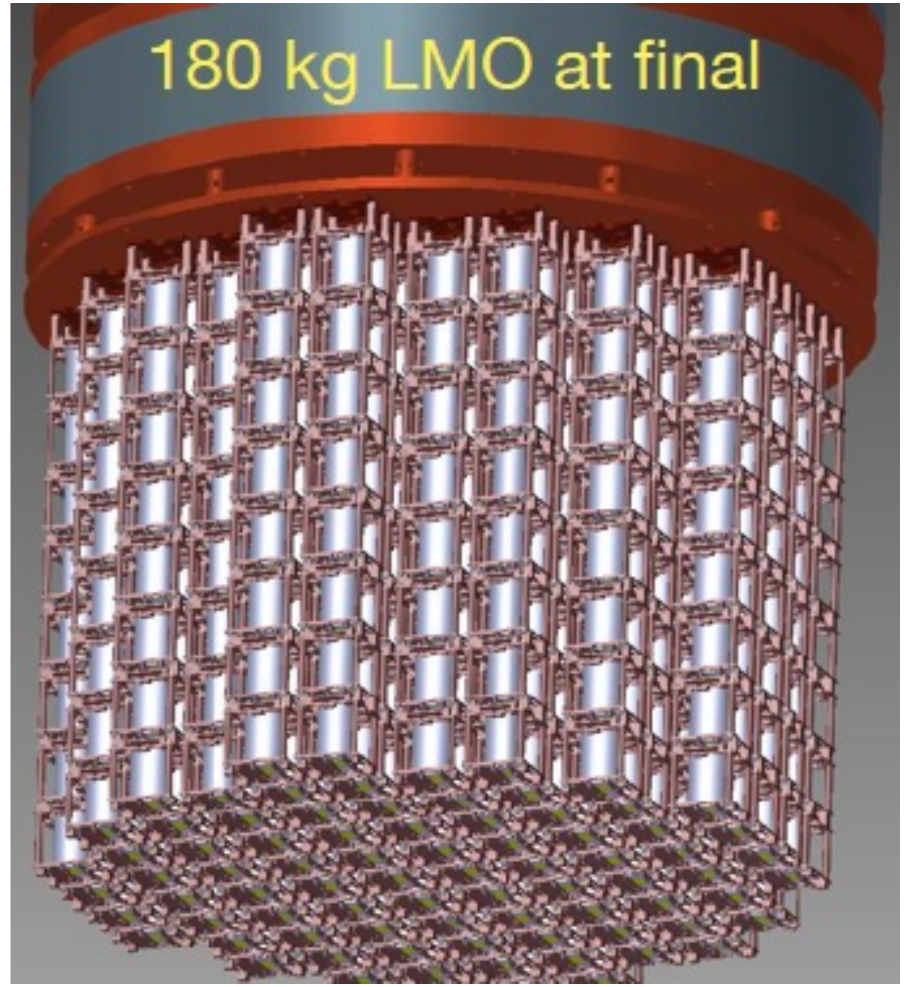
**Muon Counter**



**NIMA 1039 (2022) 167123**

**Module design**




Phase2: 10 +35 towers = 50 towers (450 crystals)

Maximum: 50+26 towers·12 crystal/tower ~ 912 crystals

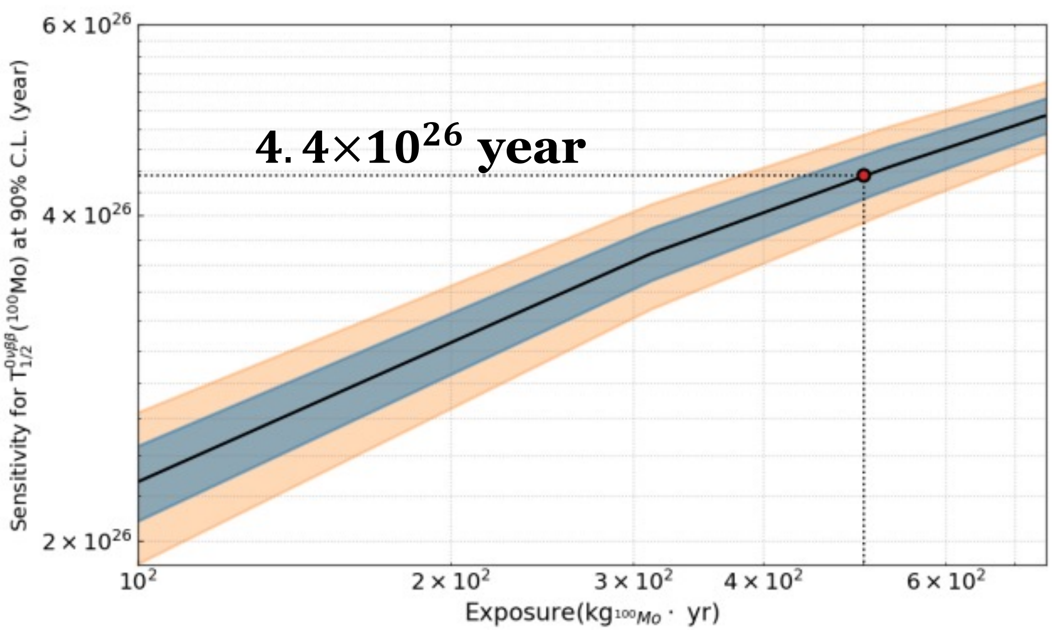
**Phase2 start around 2026~2027**

# AMoRE-II sensitivity

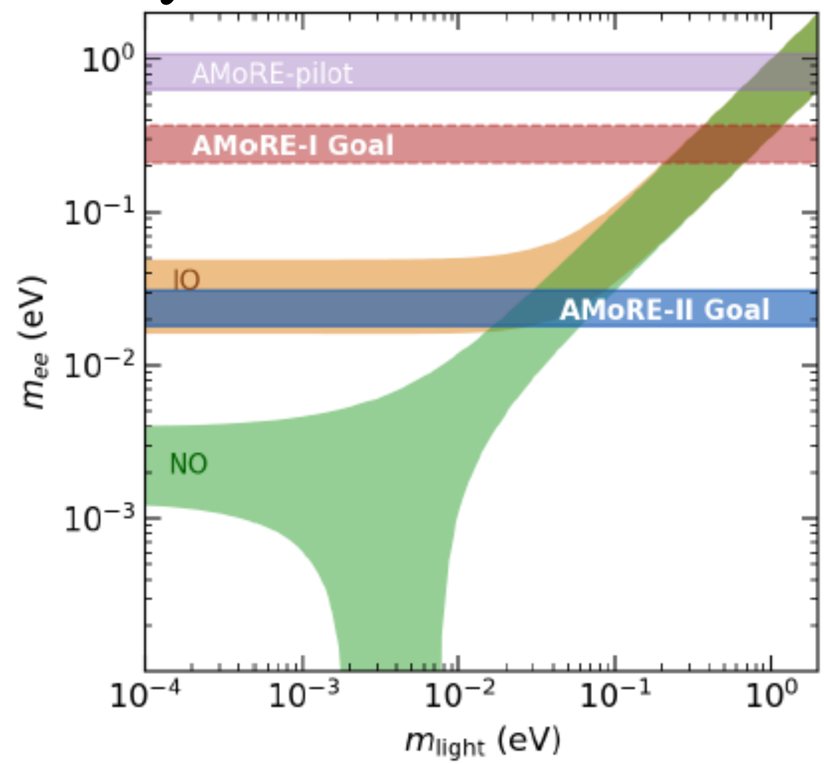
- Background assumption : $2\times10^{-4}$ counts/keV/kg/yr,
- FWHM energy resolution ~10 keV at ROI
- ~5 year operation can cover inverted mass ordering

**arXiv:2406.09698**

**Sensitivity for half-life**




**Sensitivity for effective neutrino mass**



# Summary

- **Yemilab** has been **opened and upgraded** to support cutting-edge experiments
  - Transitioned from Y2L, providing enhanced infrastructure and capabilities
  - AMoRE-II and COSINE-100U will start physics operation soon
  - Yemilab welcomes **external users** for collaborations

- COSINE-100 full dataset disfavor DAMA/LIBRA's annual modulation claims
- COSINE-100U will expand searches for **low-mass dark matter**

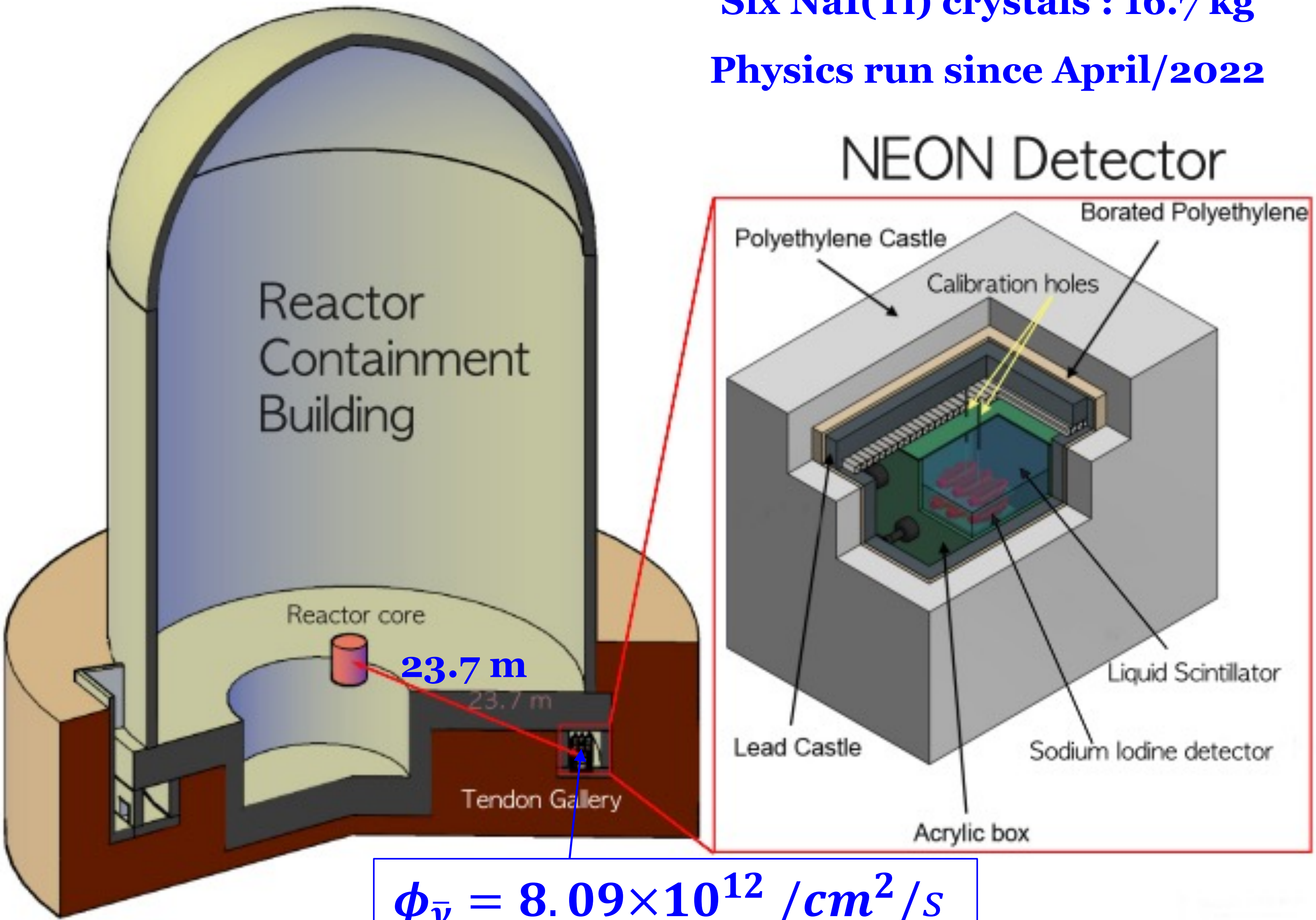
- AMoRE-I established the **best half life limit** for $^{100}$Mo
- AMoRE-II aiming to reach the **inverted ordering** regime

Thank you

# NEON Experiment

**Six NaI(Tl) crystals : 16.7 kg**

**Physics run since April/2022**

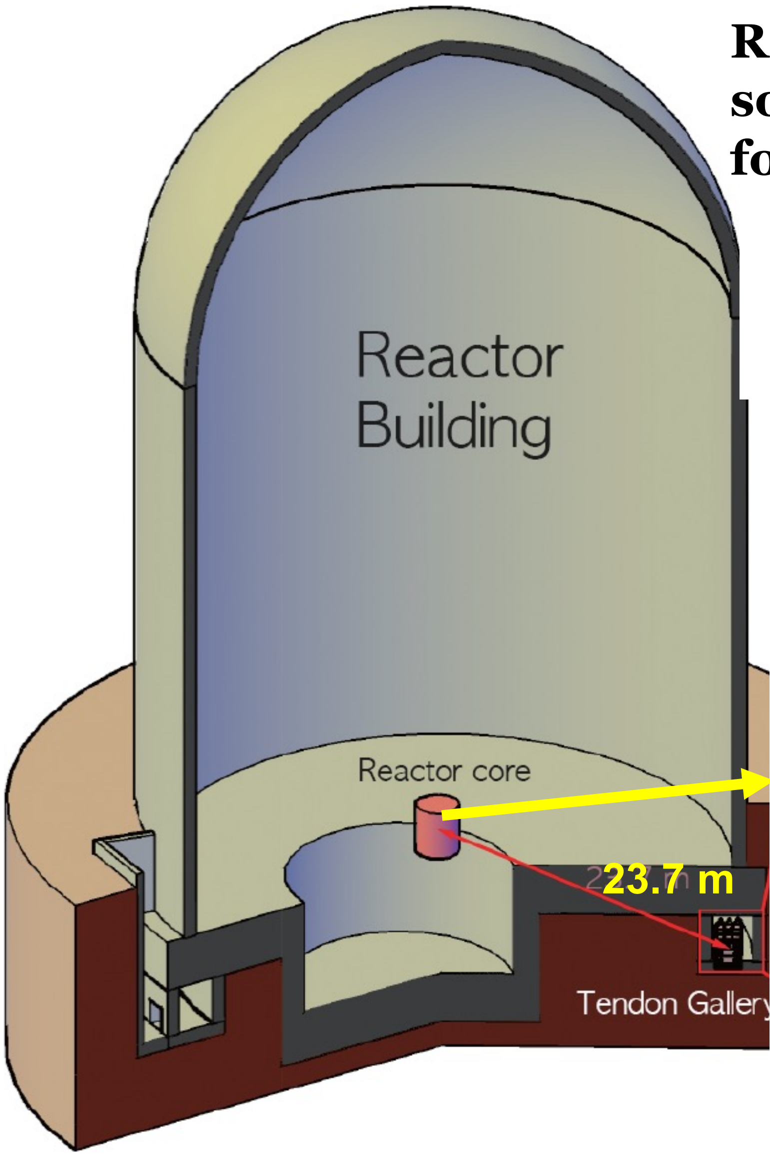


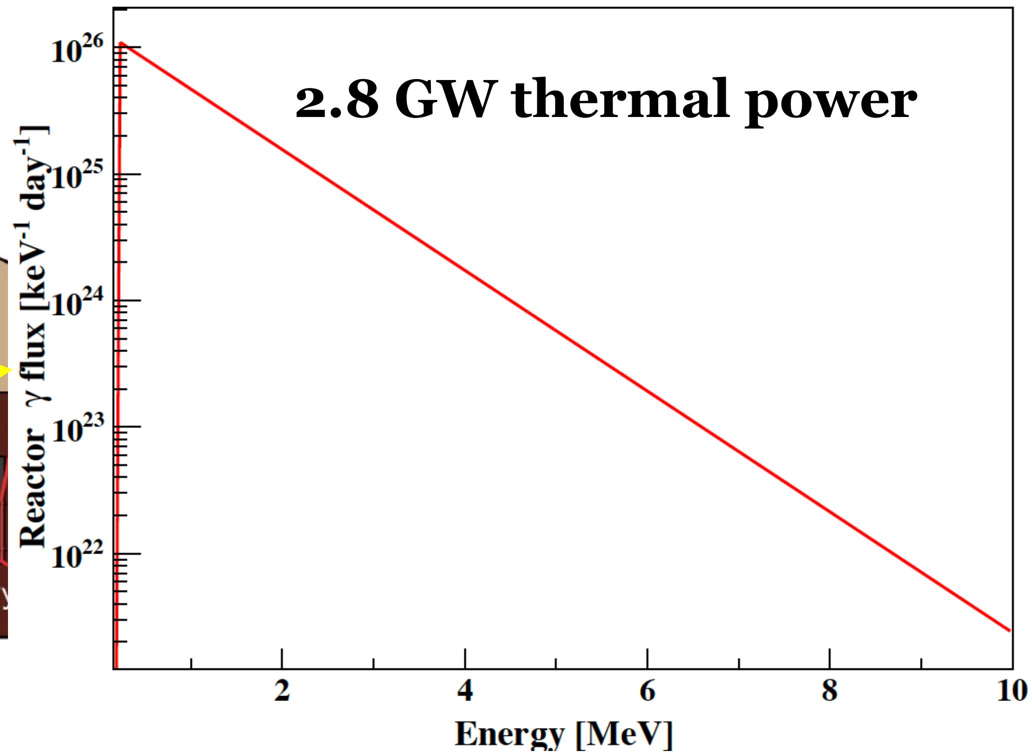

$$\phi_{\bar{\nu}} = 8.09 \times 10^{12}\ /cm^2/s$$

# Reactor photons

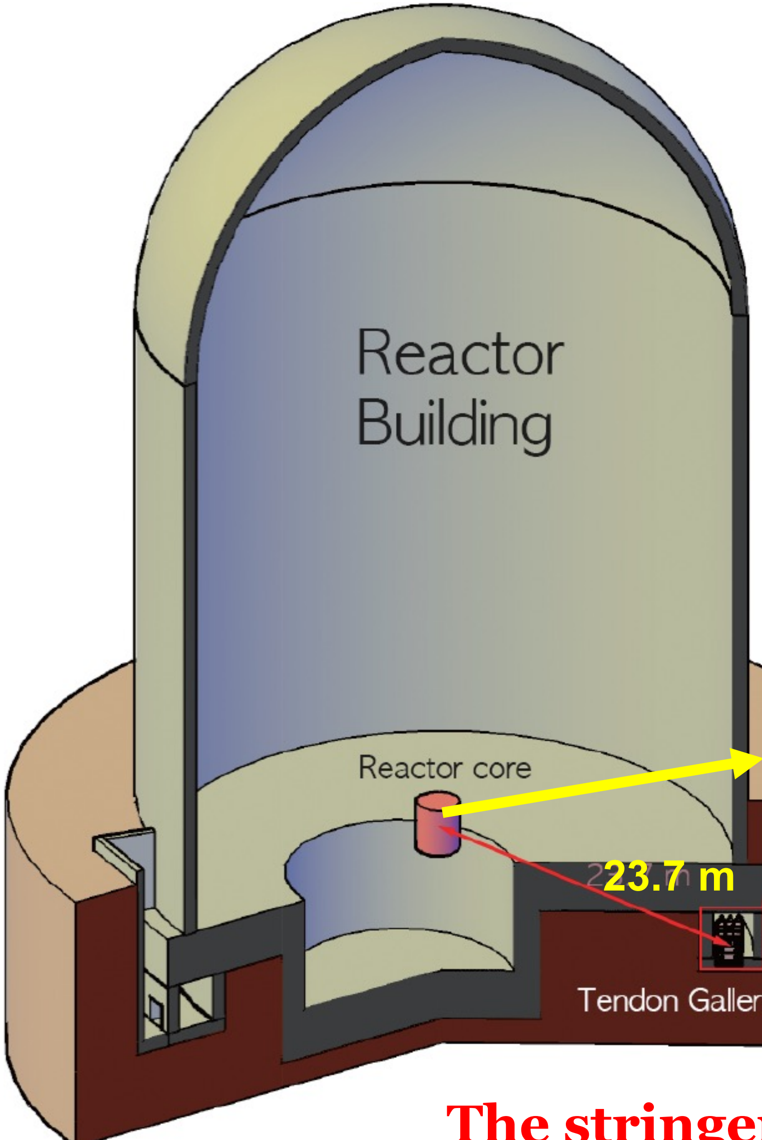
**Reactor is not only the stringent neutrino source but also the stringent gamma source for O(MeV) energy**

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{5.8\times 10^{17}}{[\mathrm{MeV}]\cdot[\mathrm{sec}]}\left(\frac{P}{[\mathrm{MW}]}\right) e^{-1.1E_\gamma/[\mathrm{MeV}]}$$

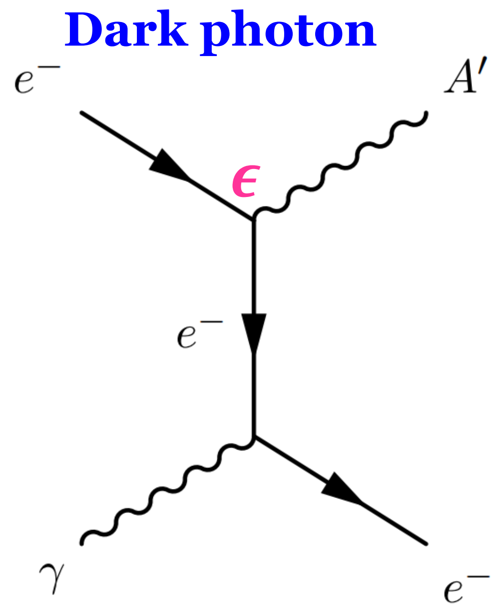


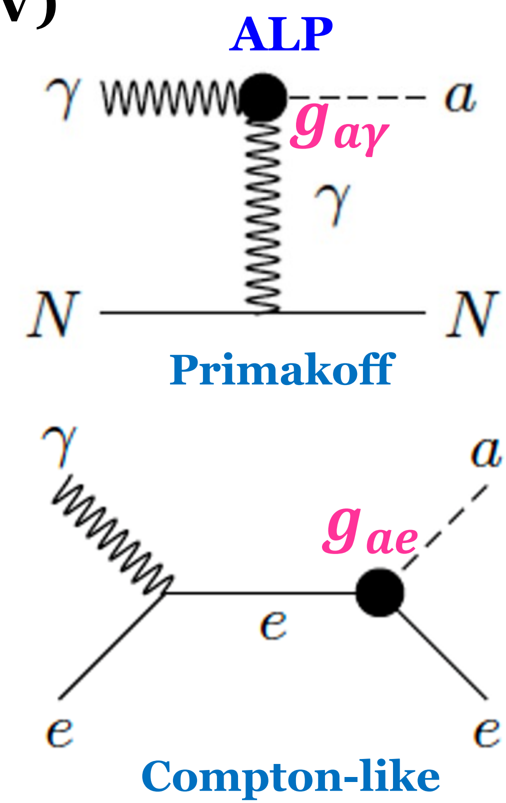



# Reactor dark sector bosonic particles




**Photons can couple to dark sector bosonic particles such dark photon and axion like particle (ALP) with their mass up to O(MeV)**



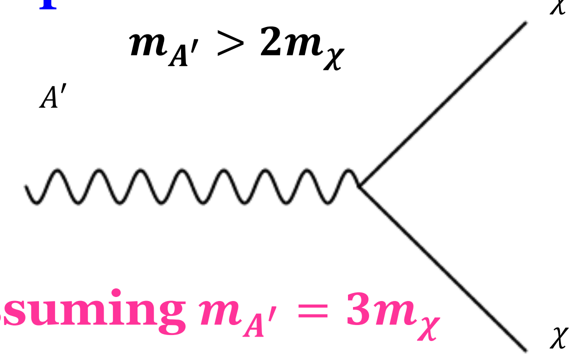

**The stringent source of dark photon & ALP**

# Light Dark Matter Search

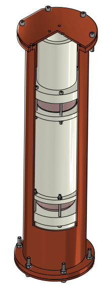
- Through light dark matter (LDM) production

**Dark photon**

$m_{A'} > 2m_\chi$

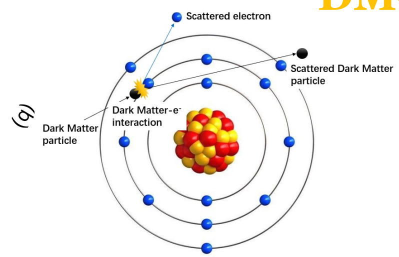


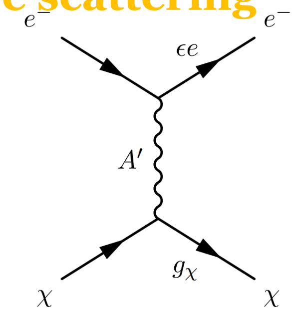

**Assuming $m_{A'} = 3m_\chi$**



**Detector**

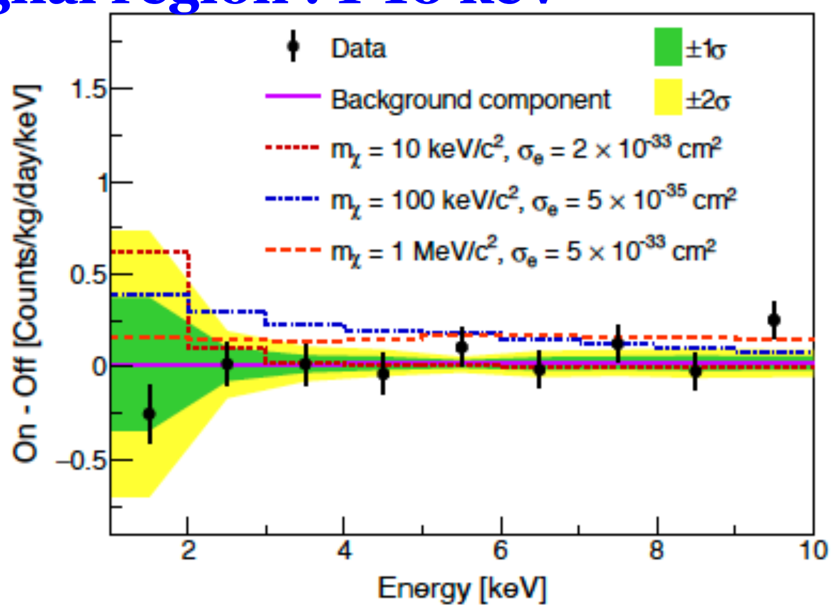
**DM-e scattering**

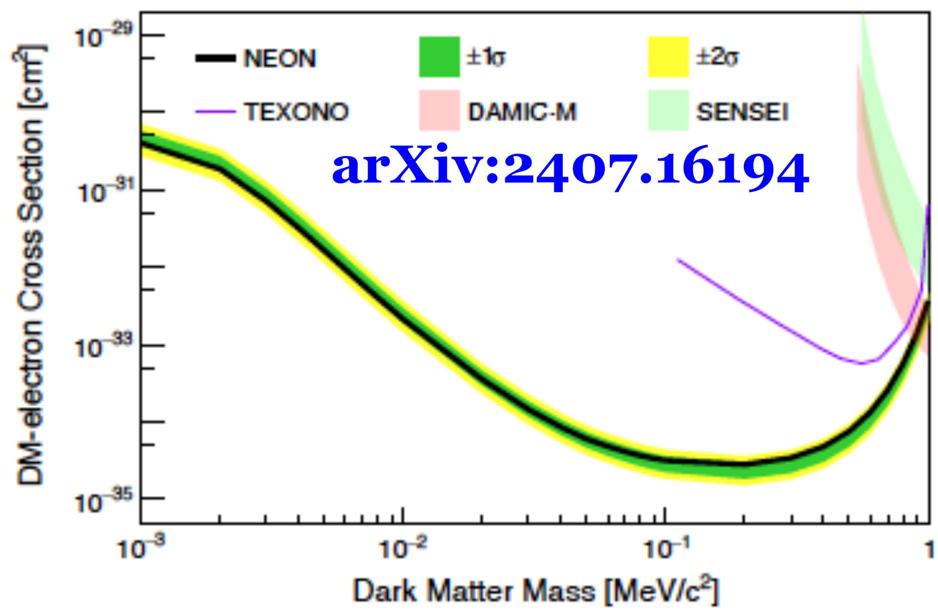



**Signal region : 1-10 keV**

COHERENT LDM-nucleon scattering : PRL 130, 051803 (2023)

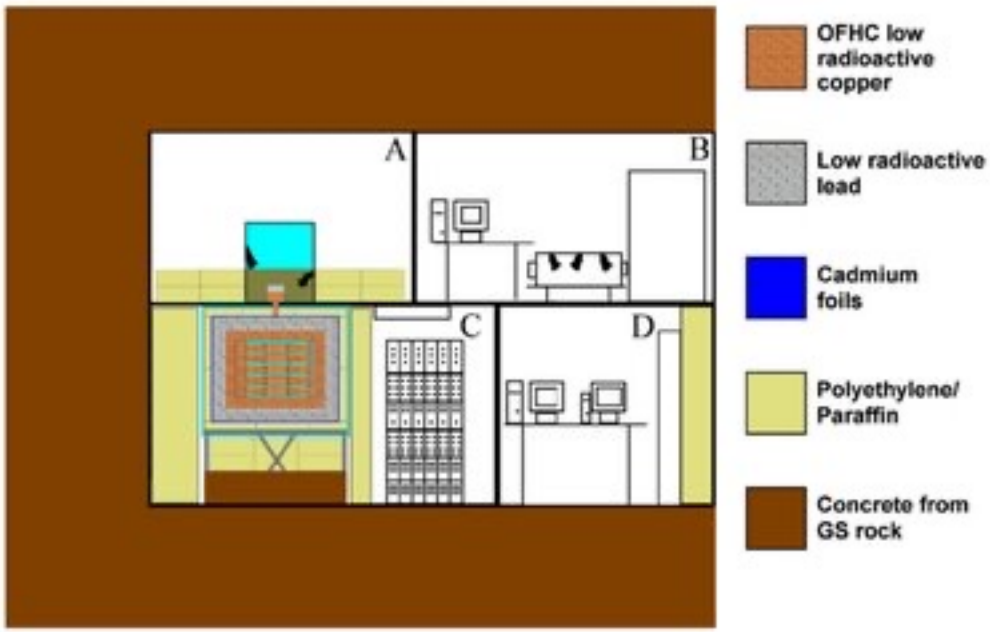


# Radon protection for rare event search

- Normal level of Rn (~40 Bq/$m^3$) provide huge background

**DAMA/LIBRA**



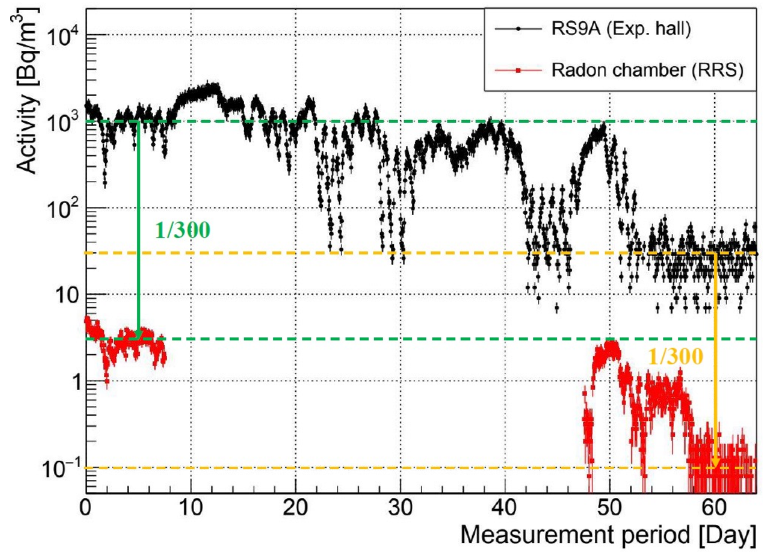

**Flushing N2 gas inside detector room**

# Radon-free air supply for experiment

- Y2L (ATEKO, Czech) : 150 $m^3/h$, 5 $mBq/m^3$
- Duty cycle <70%, Difficult to maintain

# Radon-free air supply for experiment

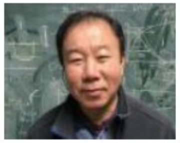
- Yemilab (Korean Company) : 50 $m^3$/h, 20 mBq/$m^3$
- Duty cycle >95%


- It has been successfully domestically developed
- Plan to create a larger system for a 200 $m^3$/h supply, contingent upon budget availability

# ❖ Yemilab operation team

- **Currently 8 members**

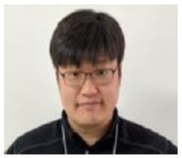


Kangsoon Park

- System development
- Construction
- Shield structure design

Ki Mun Bang

- System development
- Construction
- Tunnel safety



Jung Ho So

- Experimental equipment
- Background measurement
- Management external users

Seon Beom Kim

- System development
- Construction
- Tunnel safety

New

Sung Hyun Kim

- Underground communication
- Networking
- Tunnel monitor system

Ji Hoon Kim

- Electrical equipment
- Electrical Safety
- Visitor guide

Ji Hoo Jang

- Purchase
- Budget execution
- Visitor guide

Hyun chul Kim

- Electrical equipment
- Electrical Safety

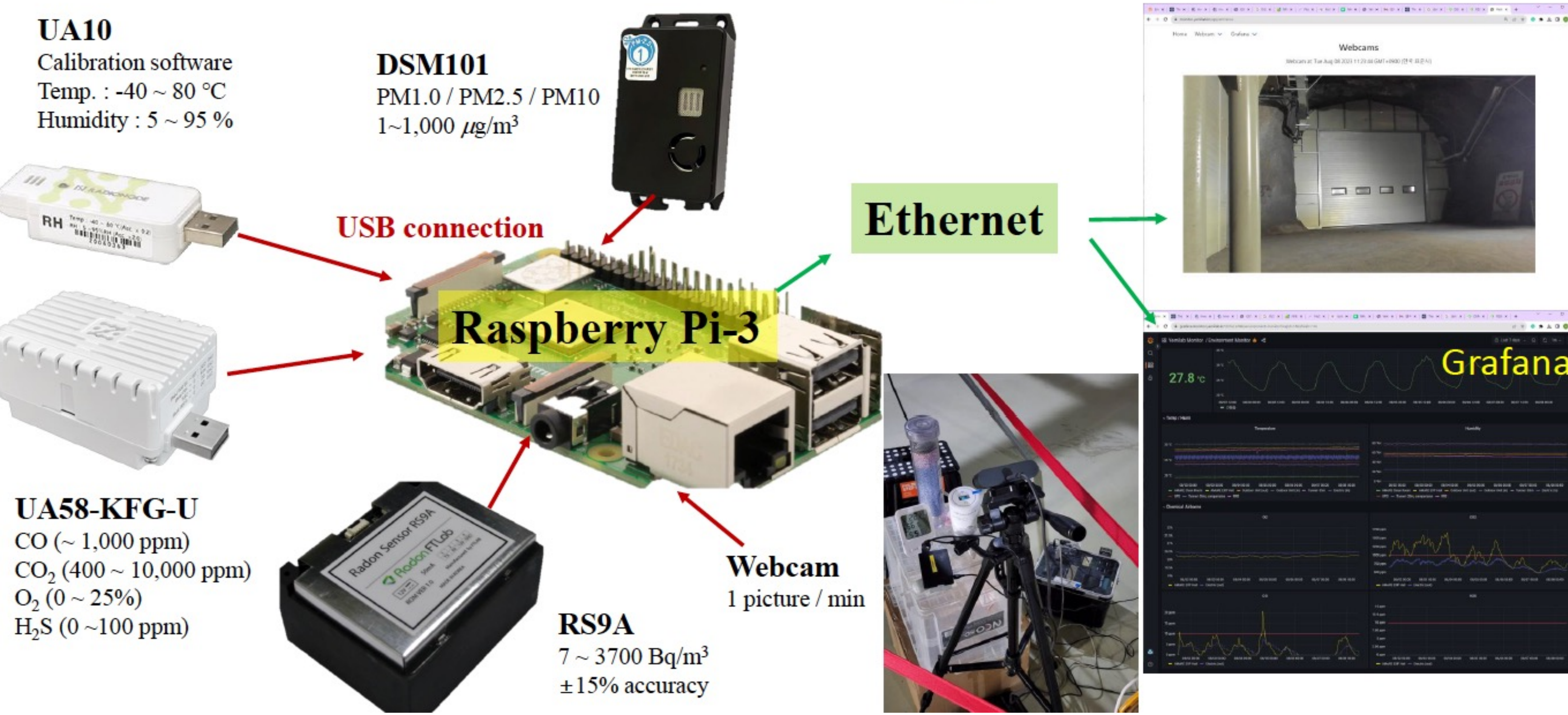
New

Sang Chul Yoon

Woon Gu Kang

Si Won Yoo

# Environmental monitoring



# COSINE collaboration


**Since 2015**

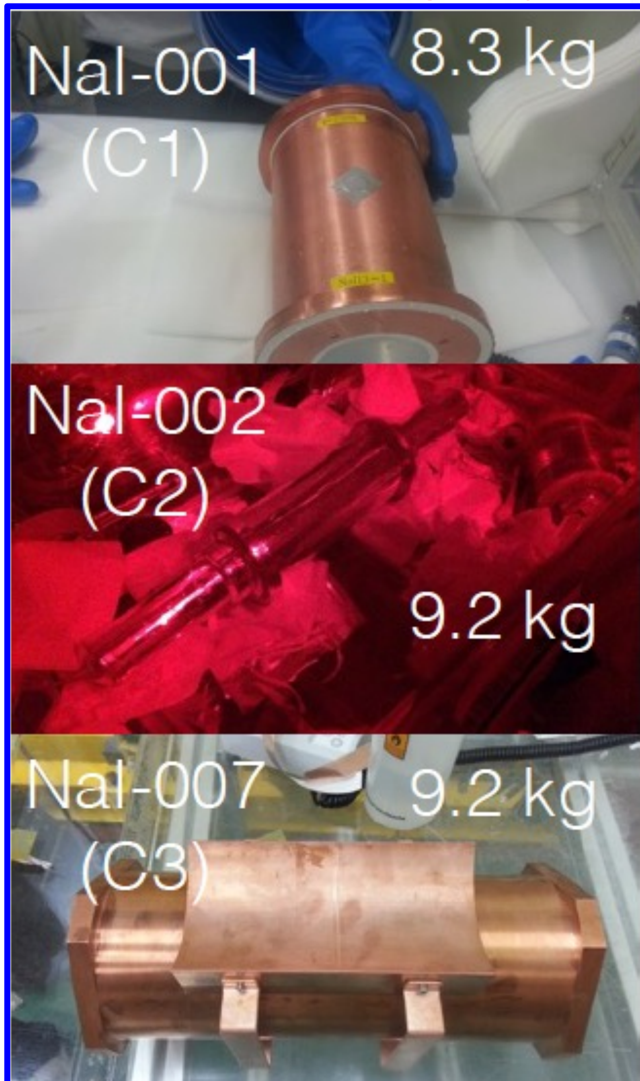
**15 institutes**
**~60 members**

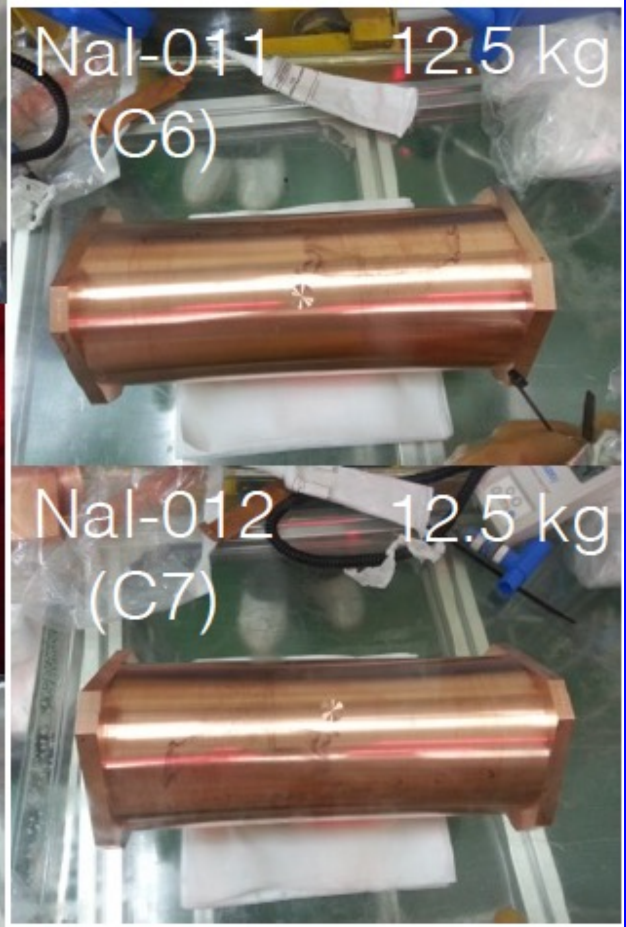
KIMS + DM-ICE = COSINE

# COSINE-100 detectors

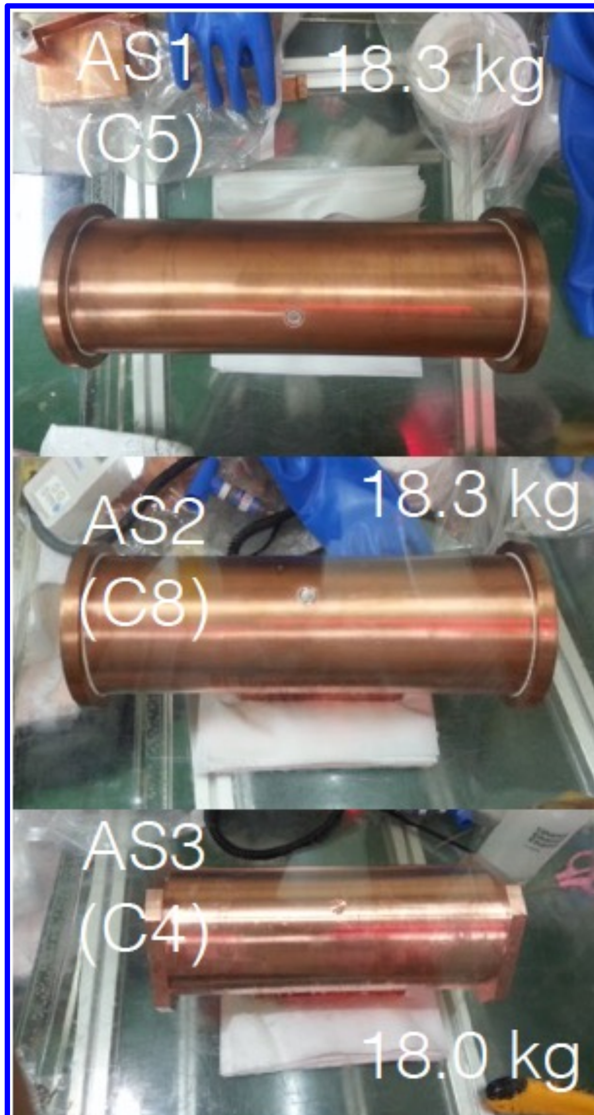
- ~106 kg crystals running since Sept/2016

**From DM-ICE**



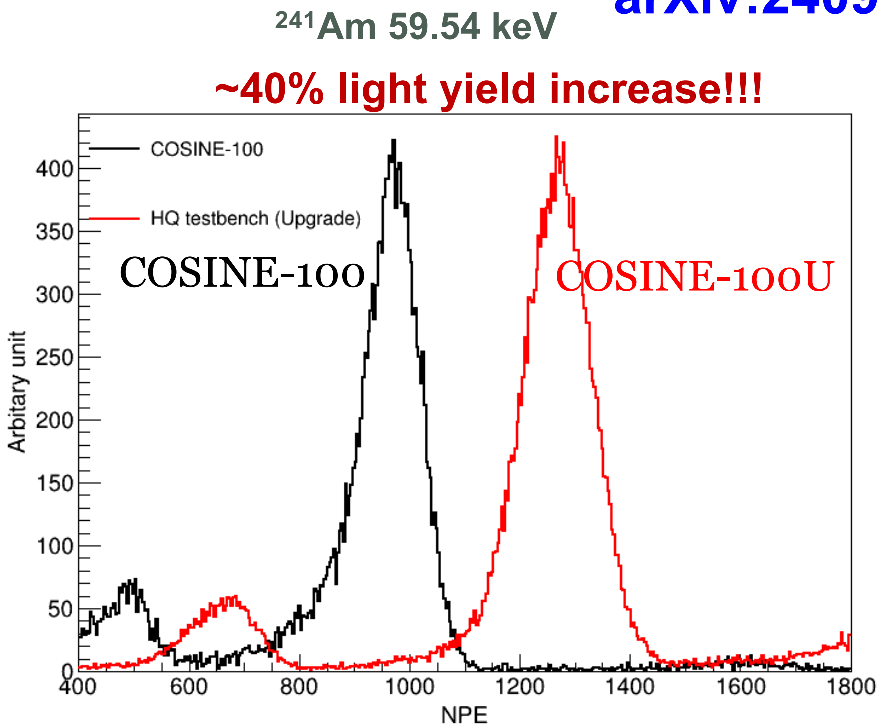

**From KIMS**



# COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

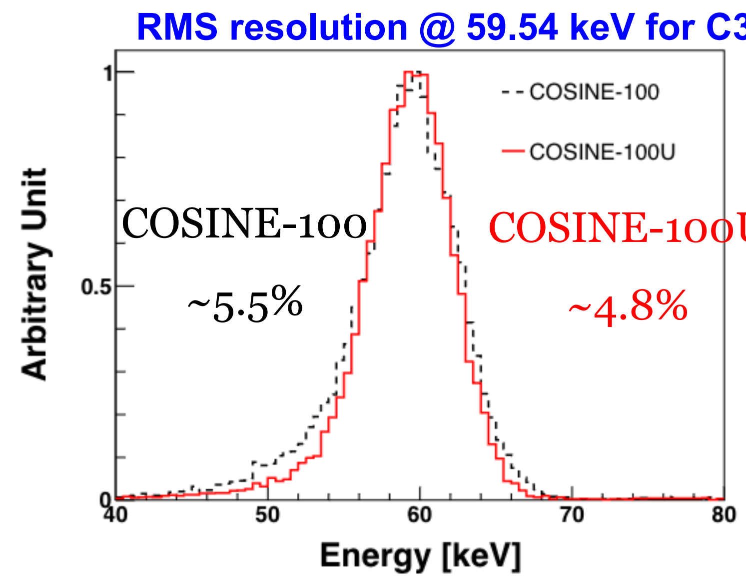
**arXiv:2409.15748**



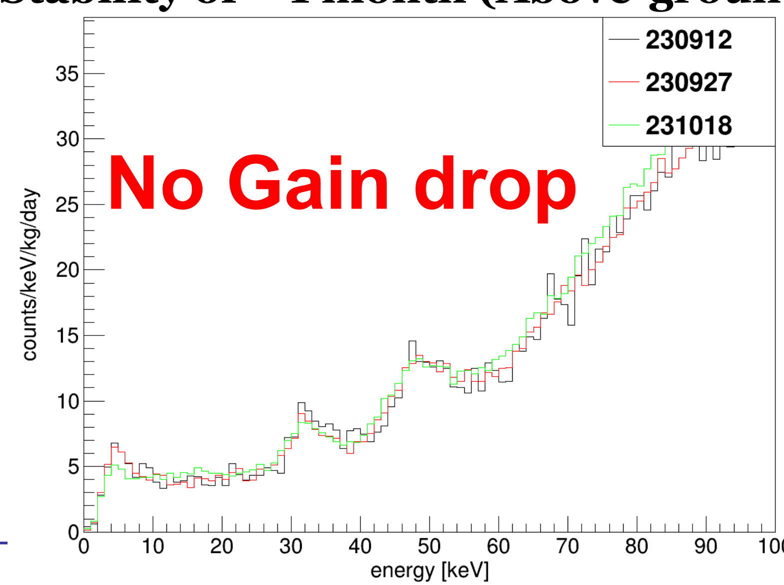

**NPE = Number of photoelectrons**

**14.9 ± 1.5 ⟶ 21.5 ± 0.6 NPE/keV**

COSINE-100 C2 → COSINE-100U C2




**Stability of ~ 1 month (Above-ground)**



# 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)

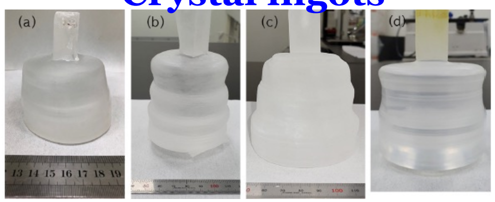
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

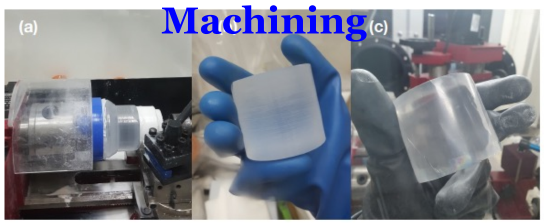
| | K (ppb) | Pb (ppb) | U (ppb) | Th (ppb) |
|---|---|---|---|---|
| Initial NaI | 248 | 19.0 | <0.01 | <0.01 |
| Purified NaI | <16 | 0.4 | <0.01 | <0.01 |

**We produced ~ 400 kg low-background NaI powder**

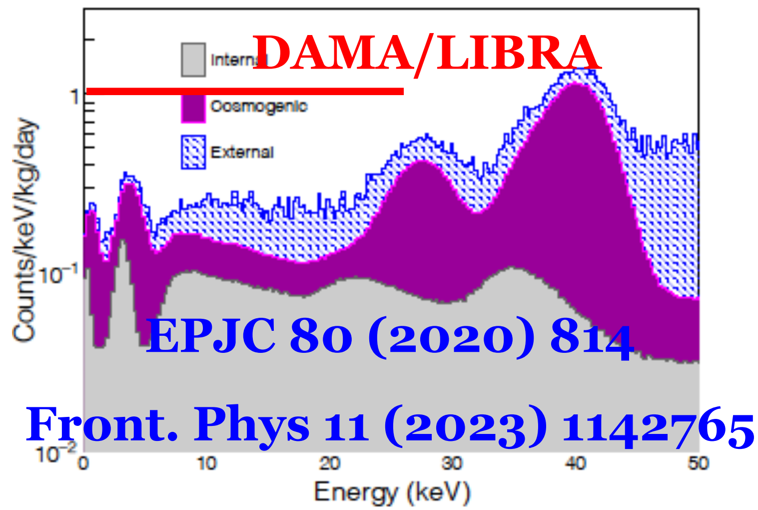
**(Maximum production rate ~ 100 kg/month)**

**Crystal ingots**





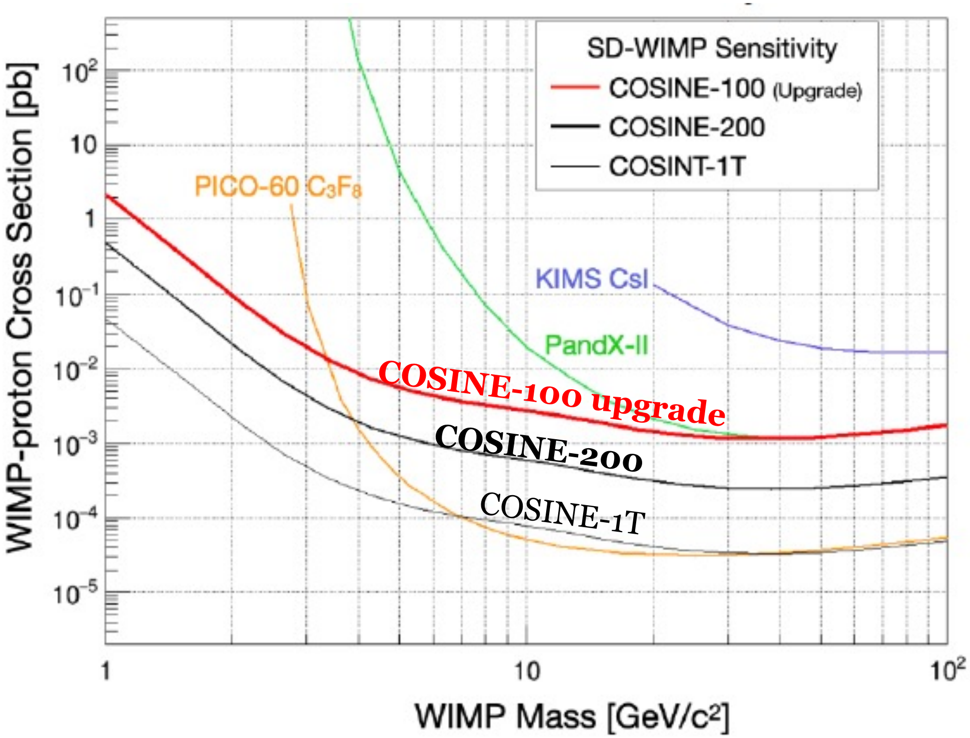




**A proof of principle for low background NaI**

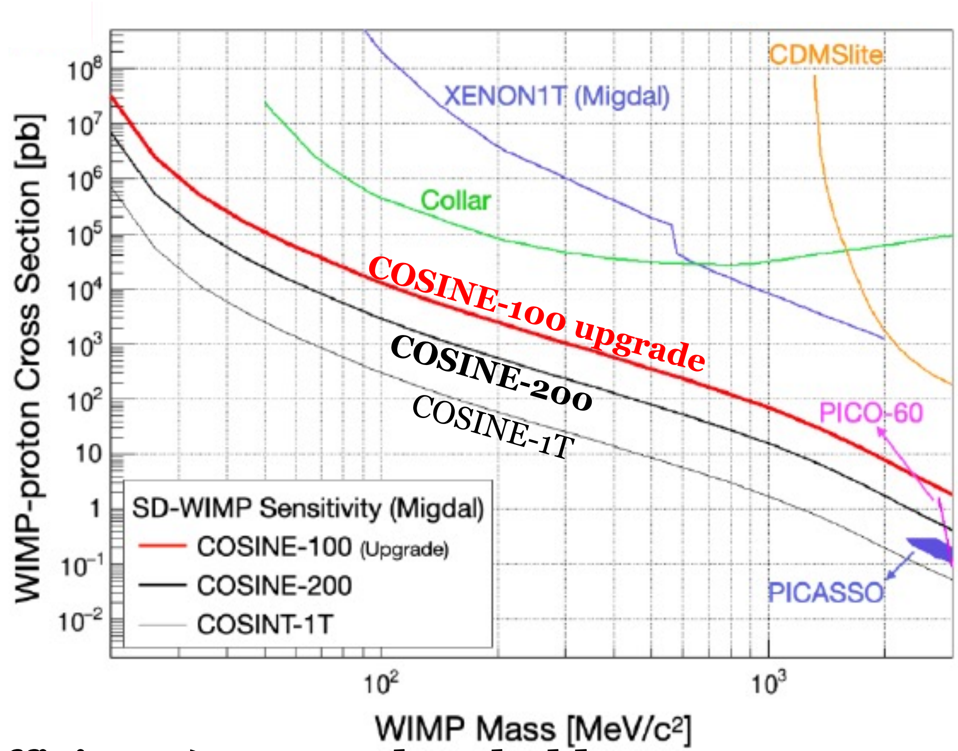
**Large crystal growing is going on**

# COSINE-100U sensitivities

## 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

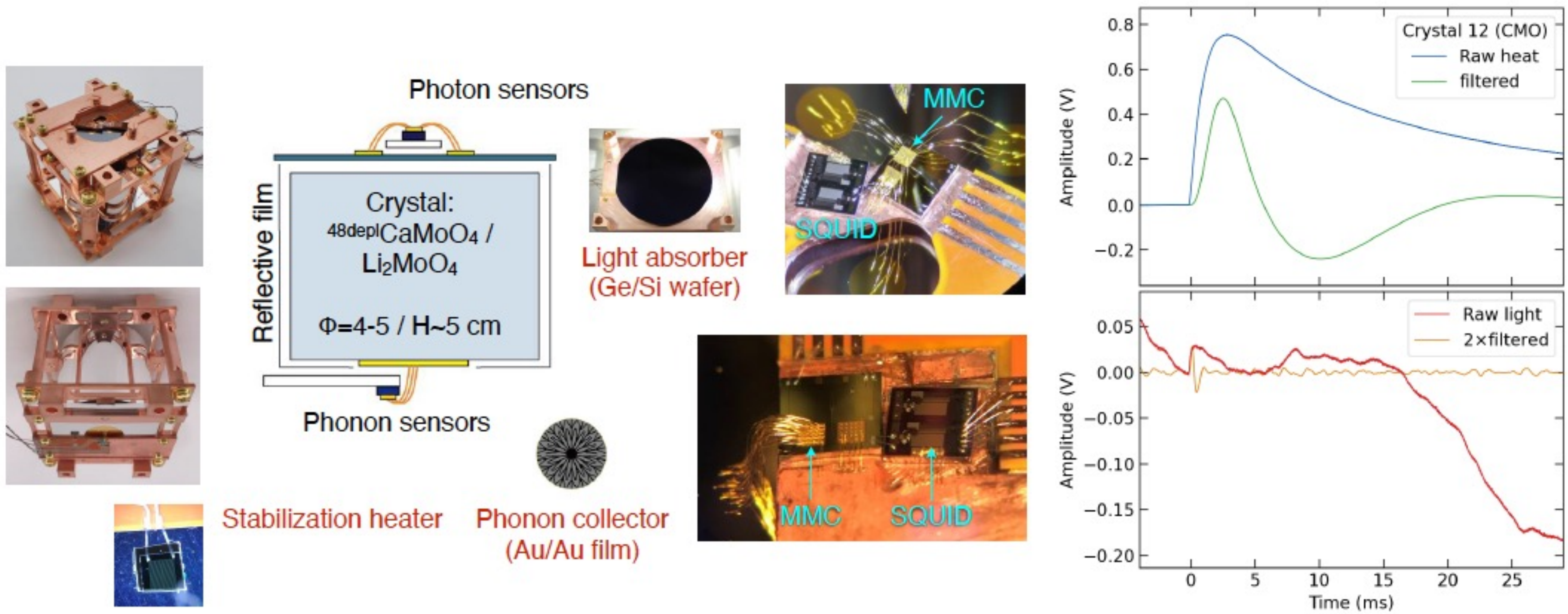
# AMoRE experiment

## Simultaneous detection of heat/light signals

To observed the neutrinoless double beta decay of $^{100}Mo$

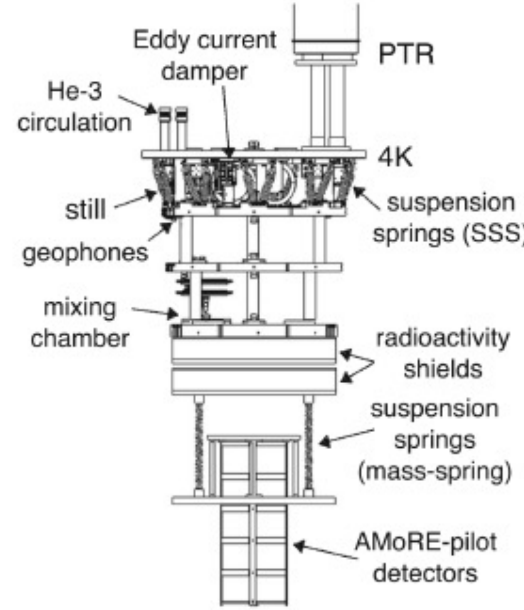
Yoomin's talk (Monday)

- Metallic magnetic calorimeter (MMC) and SQUID:
  - Fast signal response ➔ less random coincidence (pile-up) bkg.
  - Energy resolution ~ 10 keV FWHM at 2.6 MeV.
- Operation at 10-20 mK temperature for AMoRE.



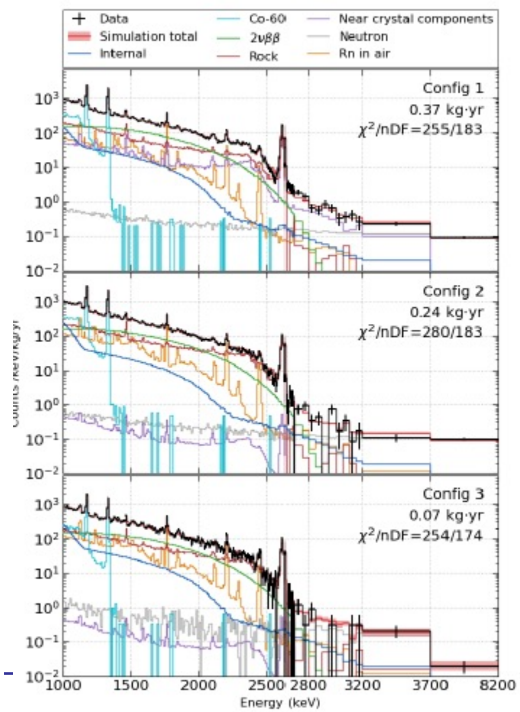
# AMoRE-pilot @ Y2L

- 6 $Ca^{100}MoO_4$ crystals (1.9 kg)
- Operated 2015-2018
- Understand vibration noise
- Understand radioactive backgrounds
  0.5 ckky(counts/kg/keV/year) @ ROI
- $T_{1/2} > 3.2\times10^{23}$ years

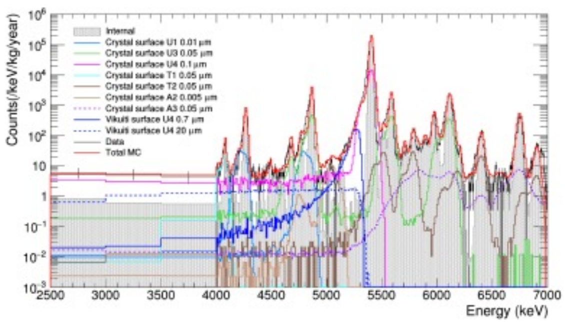



JLTP 193 (2018) 786-792

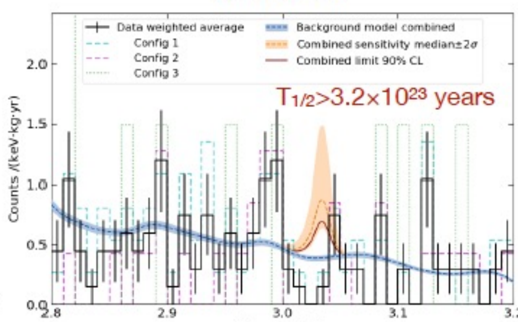
$\beta/\gamma$ background modeling

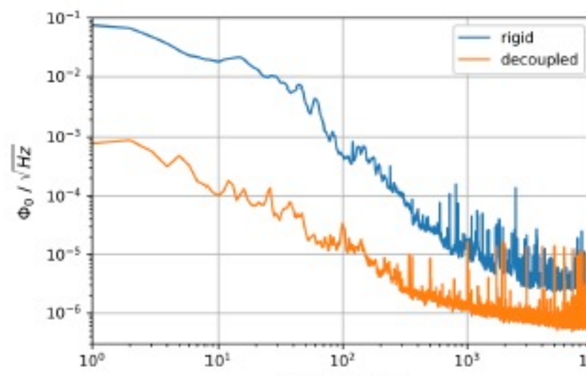



$\alpha$-spectrum of crystal 2 [EPJC 82 (2022) 1140]



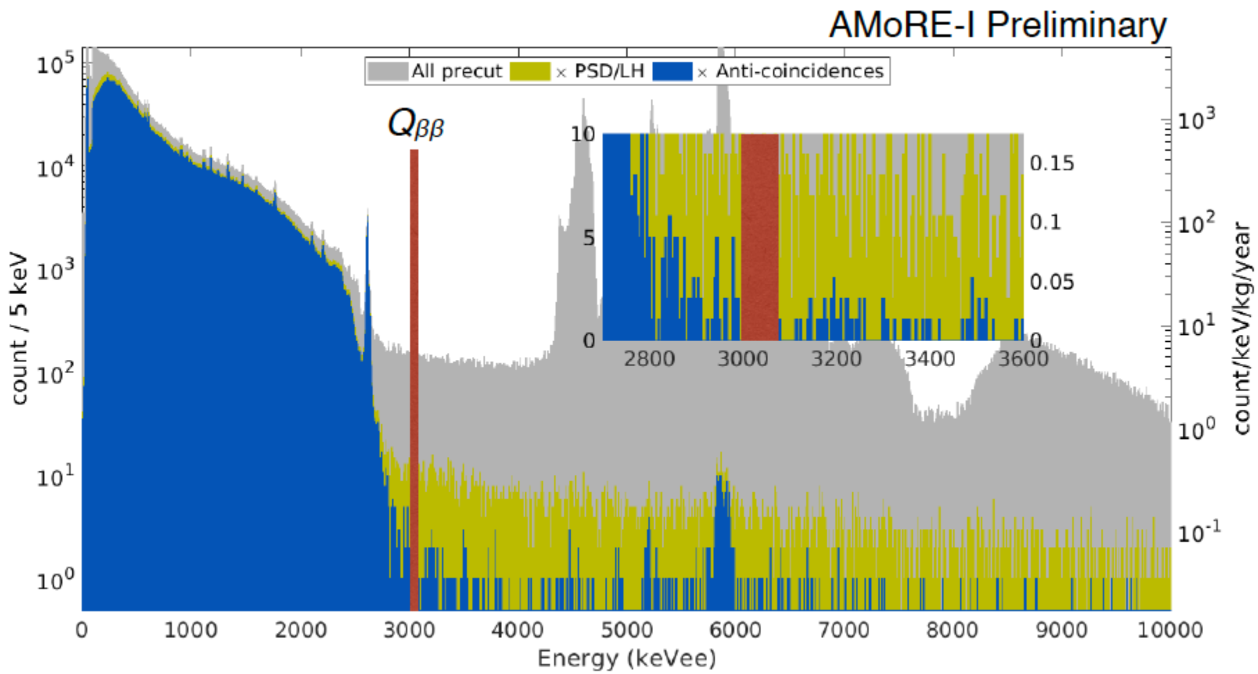

Around ROI

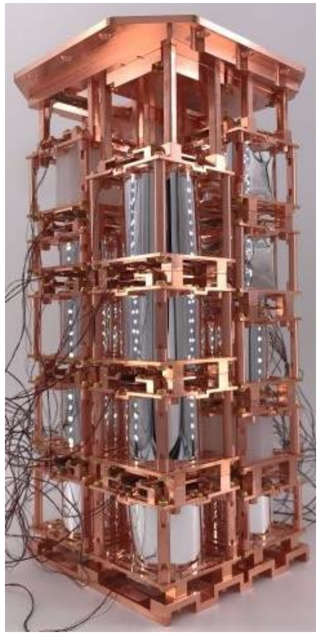


# AMoRE-I progress

- **AMoRE-I began Aug. 2020 @ Y2L and runs stably until May/2023**
- 13 $Ca^{100}MoO_4$ crystals and 5 $Li_2{}^{100}MoO_4$ crystals, ~6 kg (3 kg of $^{100}Mo$)



**Full data set**

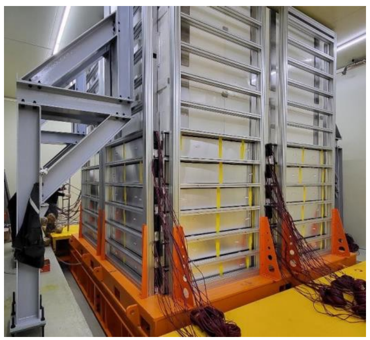
~10 kg years crystal exposure

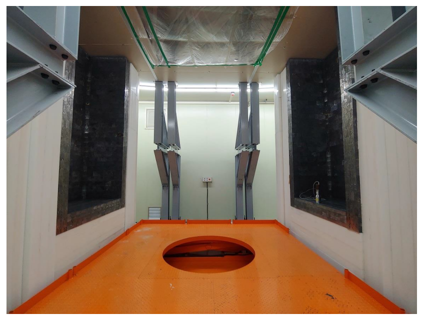
~5 kg years $^{100}Mo$ exposure

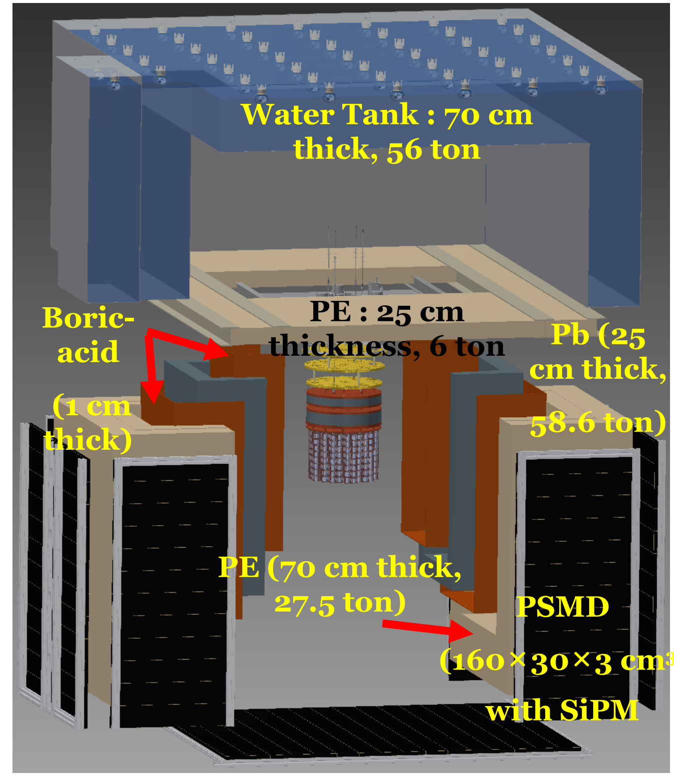
- Background around ROI ~ 0.03 count/kg/keV/year (ckky)
  - Finalizing result using full dataset : soon will be released!!
- AMoRE-I stopped physics operation May/2023 and AMoRE-II @ Yemilab is under preparation to start phase1 at early 2014

# AMoRE-II @ Yemilab

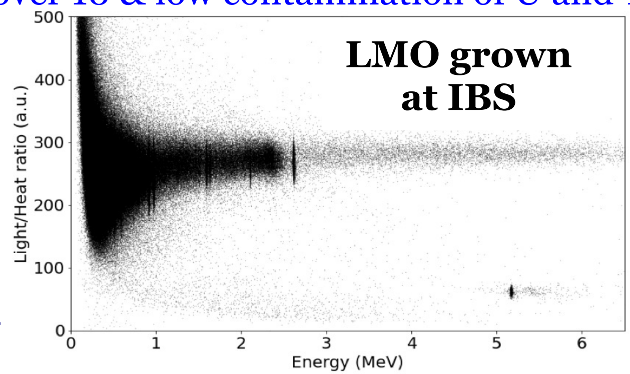
- 100 kg of $^{100}Mo$ @ Yemilab for 5 years
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 400 crystals)
- DR inside heavy shielding with Pb, PE, and water.
- Muon detectors installed.
  - 132 Plastic Scintillator Muon Detectors (PSMD)
  - Water Cherenkov Muon Detector(WCMD) with 48 PMTs, 70 cm thick water.

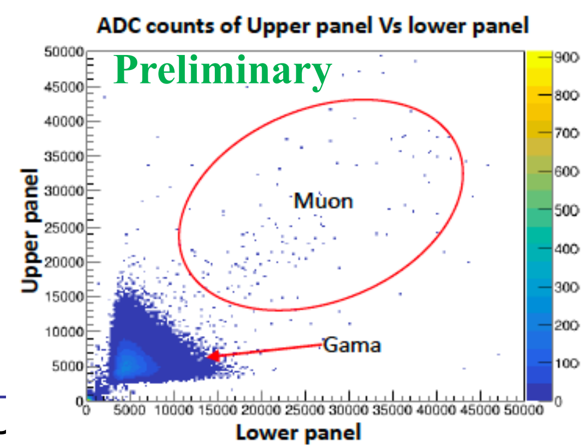




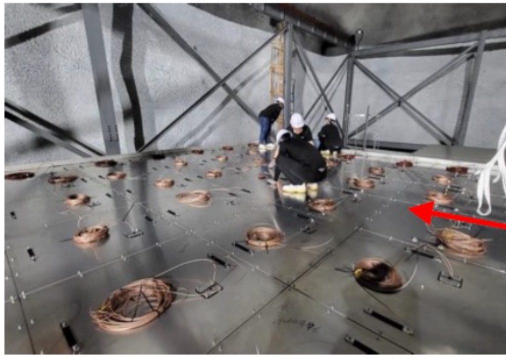


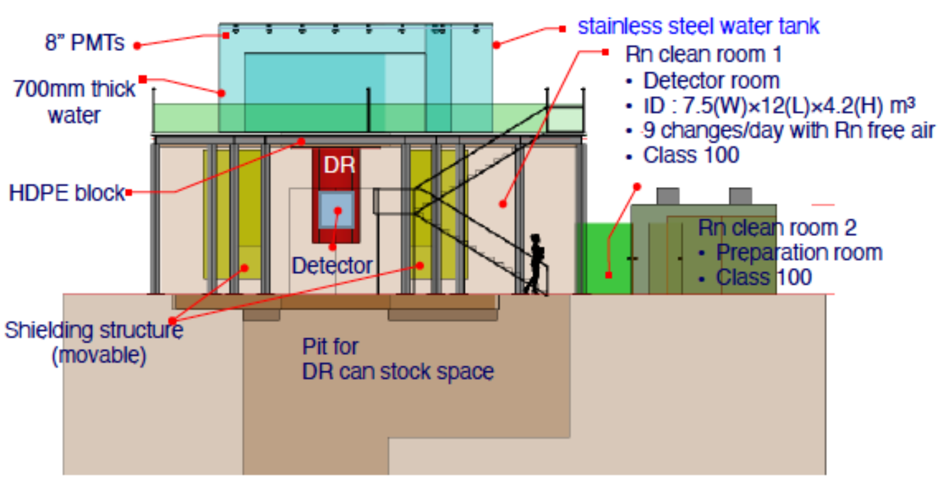

For the first time, $Li_2{}^{100}MoO_4$ enriched crystal grown at IBS(Daejeon) shows satisfactory performance. Alpha rejection power is over 10 & low contamination of U and Th



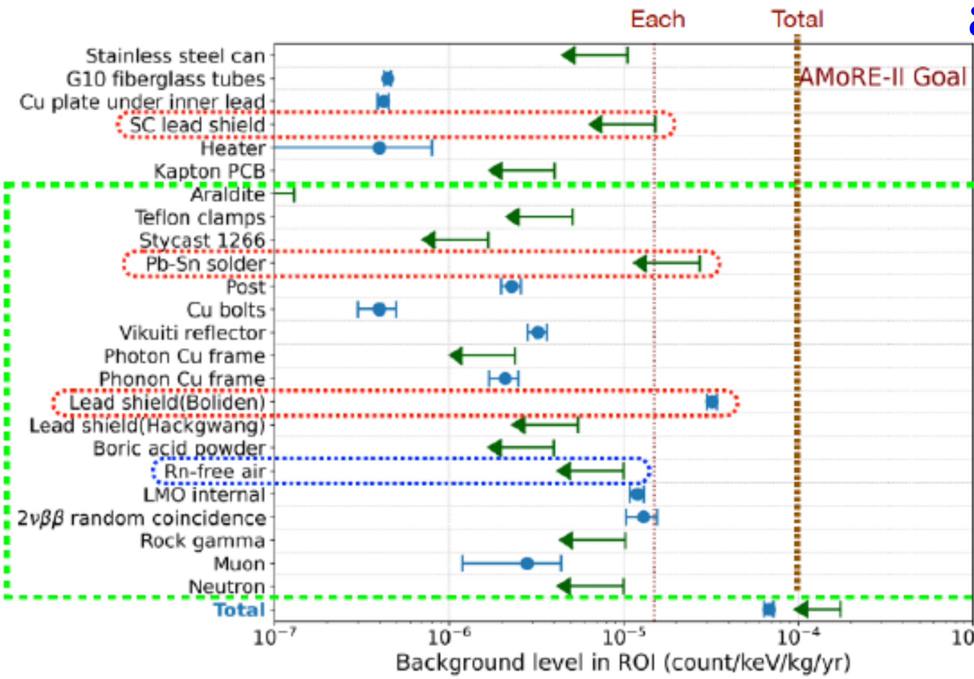
# AMoRE-II preparation @ Yemilab

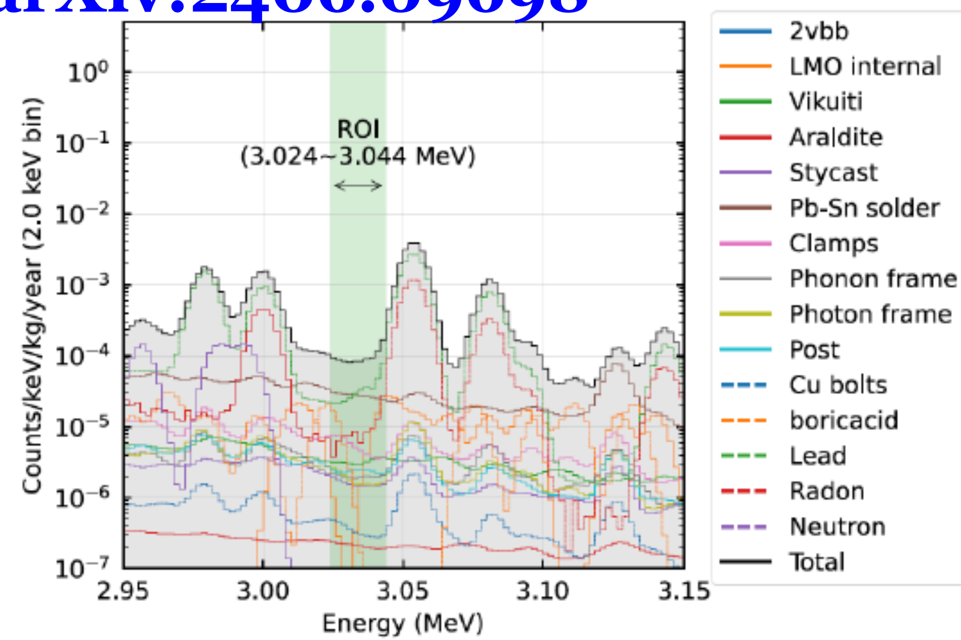




# AMoRE-II background

**arXiv:2406.09698**

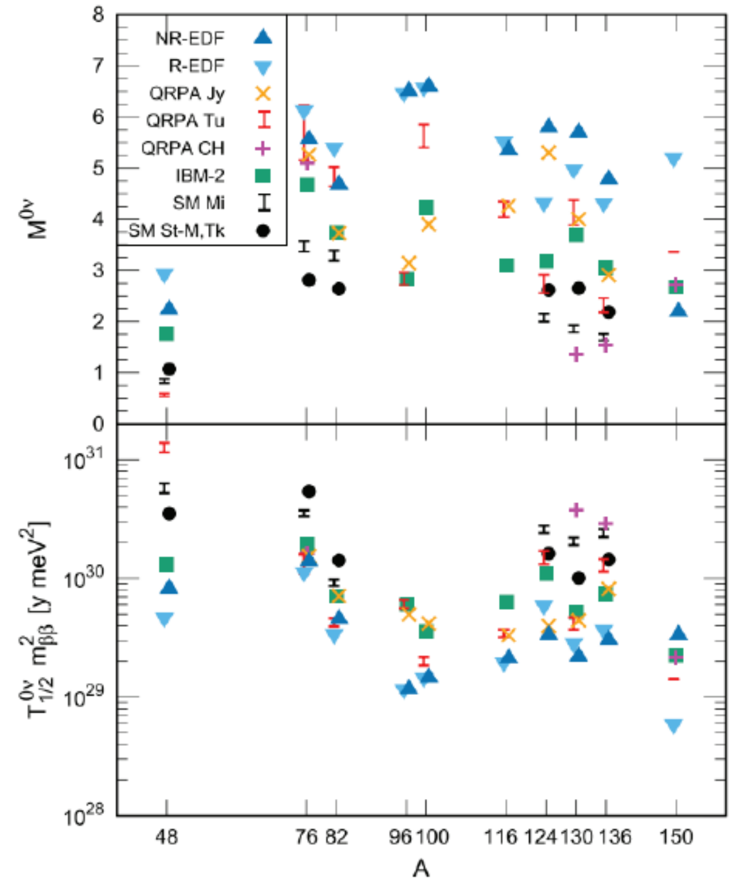



- Background understanding from AMoRE-pilot & I
- Various measurements of detectors & detector components
- ~$10^{-4}$ ckky at ROI is achievable

# Matrix Element Calculation

- Extremely hard problem to solve
- Both microscopic and macroscopic nuclear models are used to calculate NMEs, each with its own strengths and limitations
- Different successful approaches (e.g., IBM, QRPA, EDF) disagree by a factor of 2-3
- Difficult to quantify errors in a reliable way
- Ab-initio methods but not yet applicable to heavy nuclei
- Various experimental probes, including charge exchange reactions, nucleon exchange, muon capture, double gamma decay, etc are used to test and constrain NME calculations




an Engel and Javier Menéndez 2017 Rep. Prog. Phys. 80 046301

nuclear matrix element

$$[T^{0\nu}_{\frac{1}{2}}]^{-1} = G^{0\nu}(Z,Q)\cdot(g_A)^4\cdot\left|M^{0\nu}\right|^2\cdot\frac{m_{\beta\beta}^2}{m_e^2}$$

Effective Majorana mass

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

Axial vector coupling (factored out of NME)