Underground Experiments at Yemilab(예미, 禮美)

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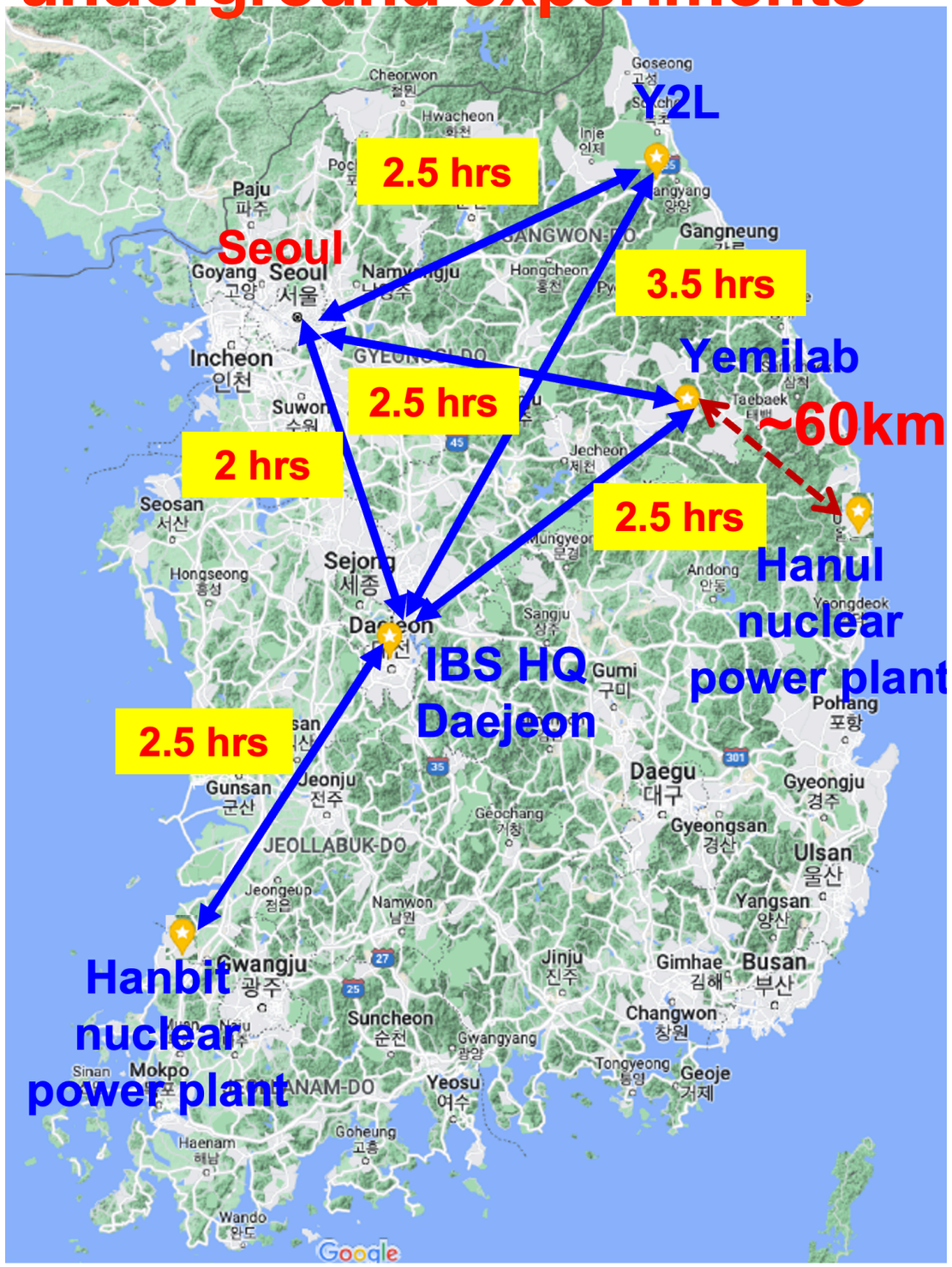
Underground Labs in Korea:

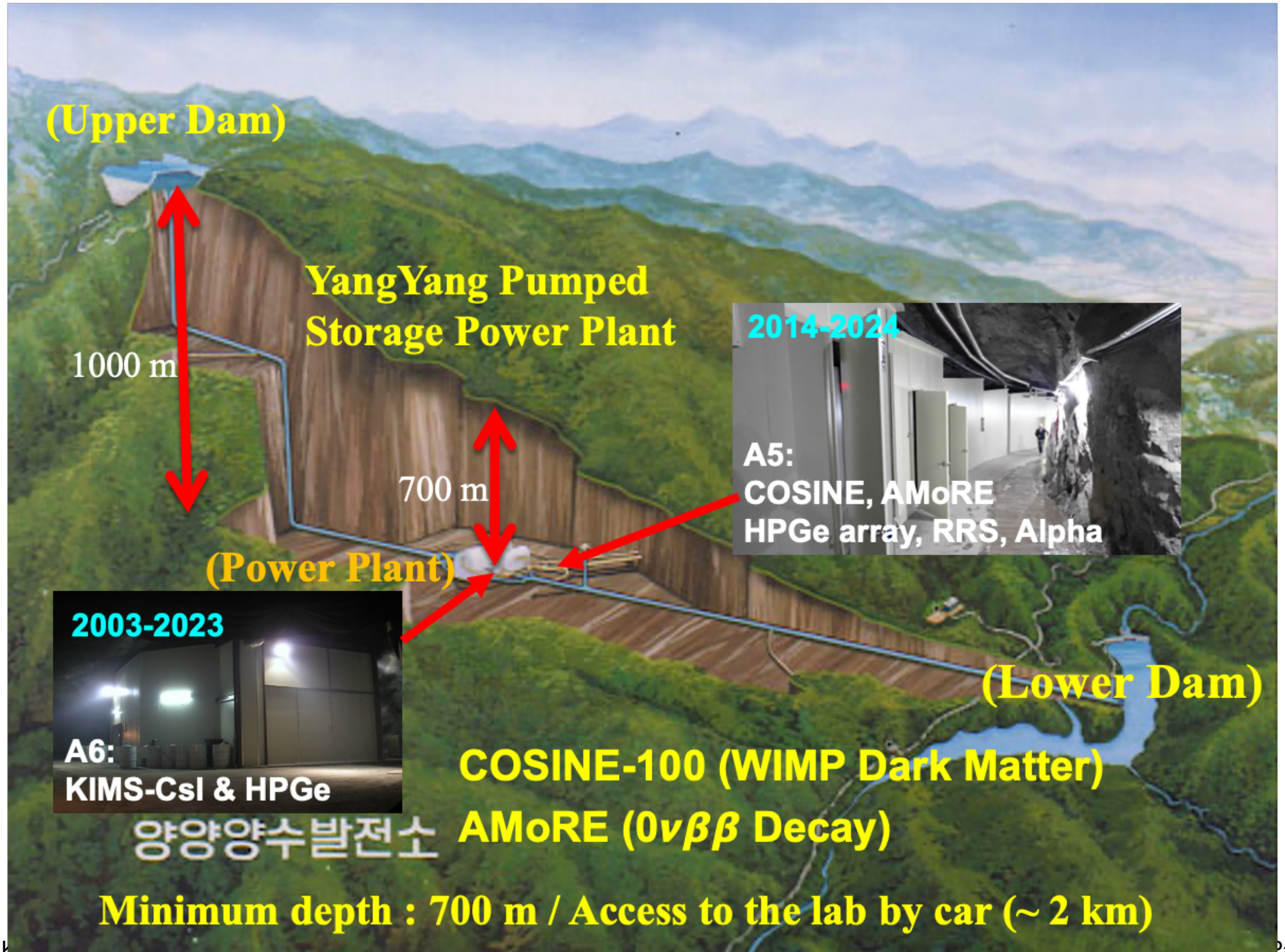
- **KU is one of core universities for underground experiments**

	Y2L (2003 ~ 2023)	Yemilab (2022 ~)
Location	Yangyang	Yemi, Jeongseon
Depth (m)	700	1000
Area (m^2)	350	~3000
Rock Radioactivity (ppm)	U: 3.9(14) Th: 10.5(65) K: 40000	U: 0.8(3) Th: 3.3(4) K: 11800
Experiments	KIMS (WIMP) AMoRE-I ($0\nu\beta\beta$) COSINE-100 (WIMP)	AMoRE-II COSINE-100 upgrade COSINE-200 + …

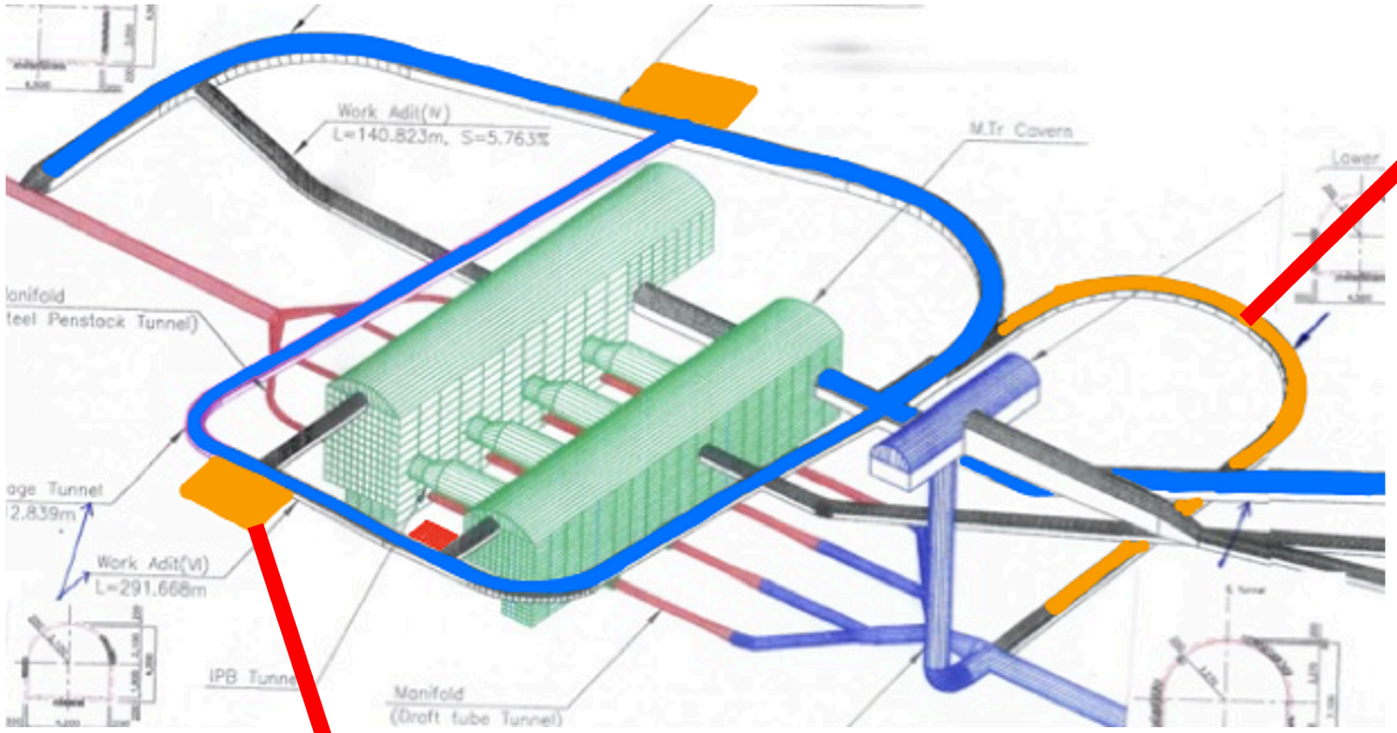


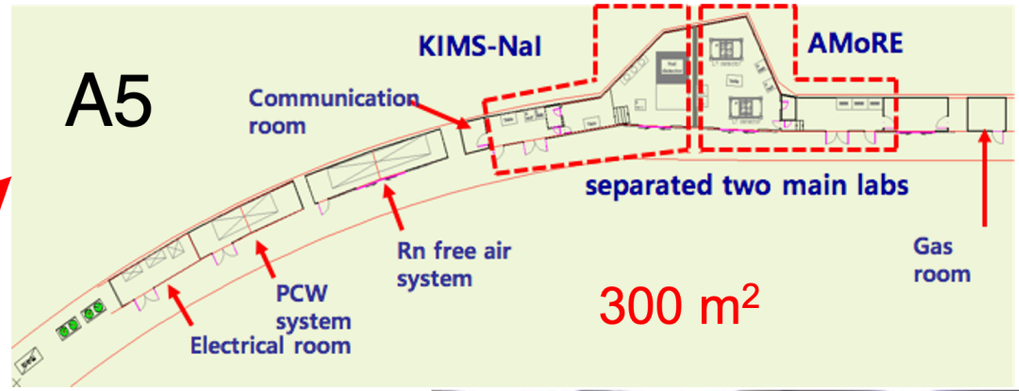
- **Reactor neutrino experiments at Hanbit power plant: RENO & NEOS**

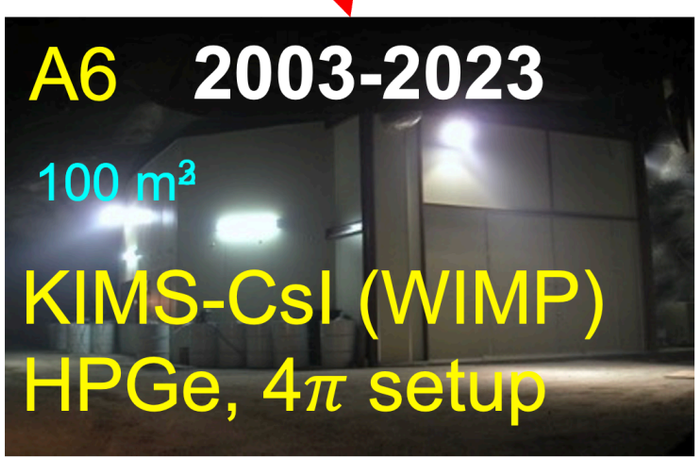
Yangyang Underground Laboratory (Y2L)

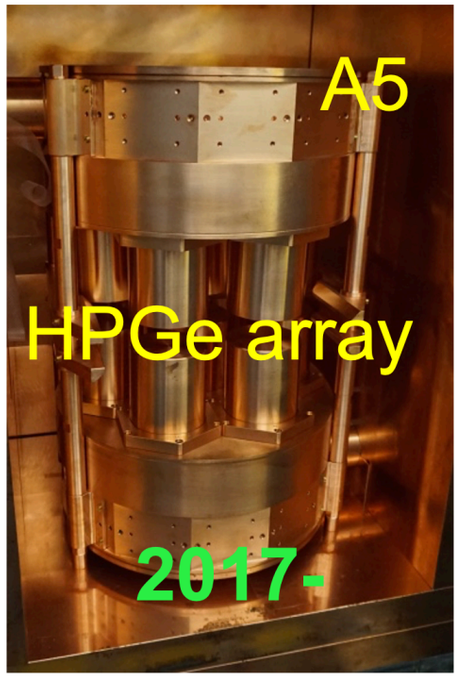


Experiments at Y2L

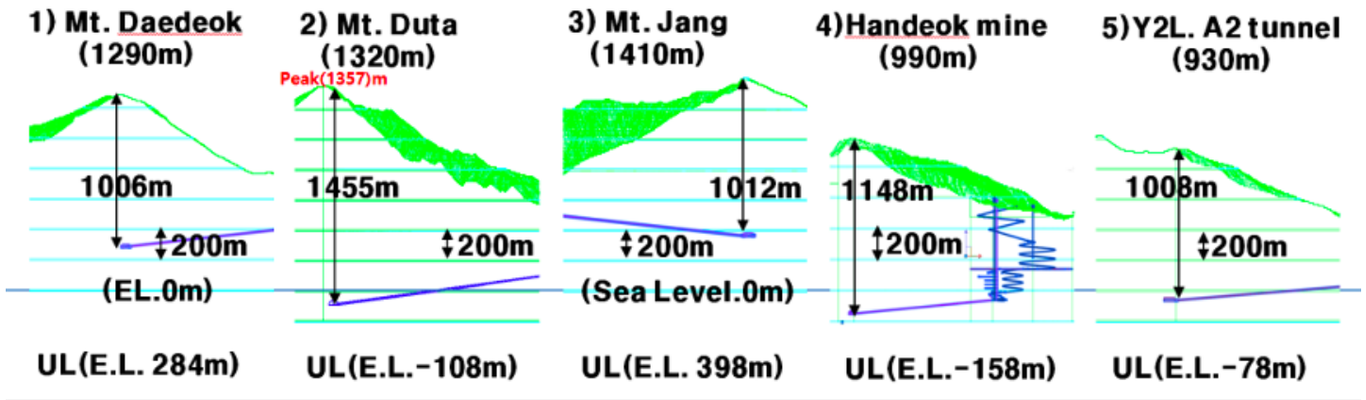


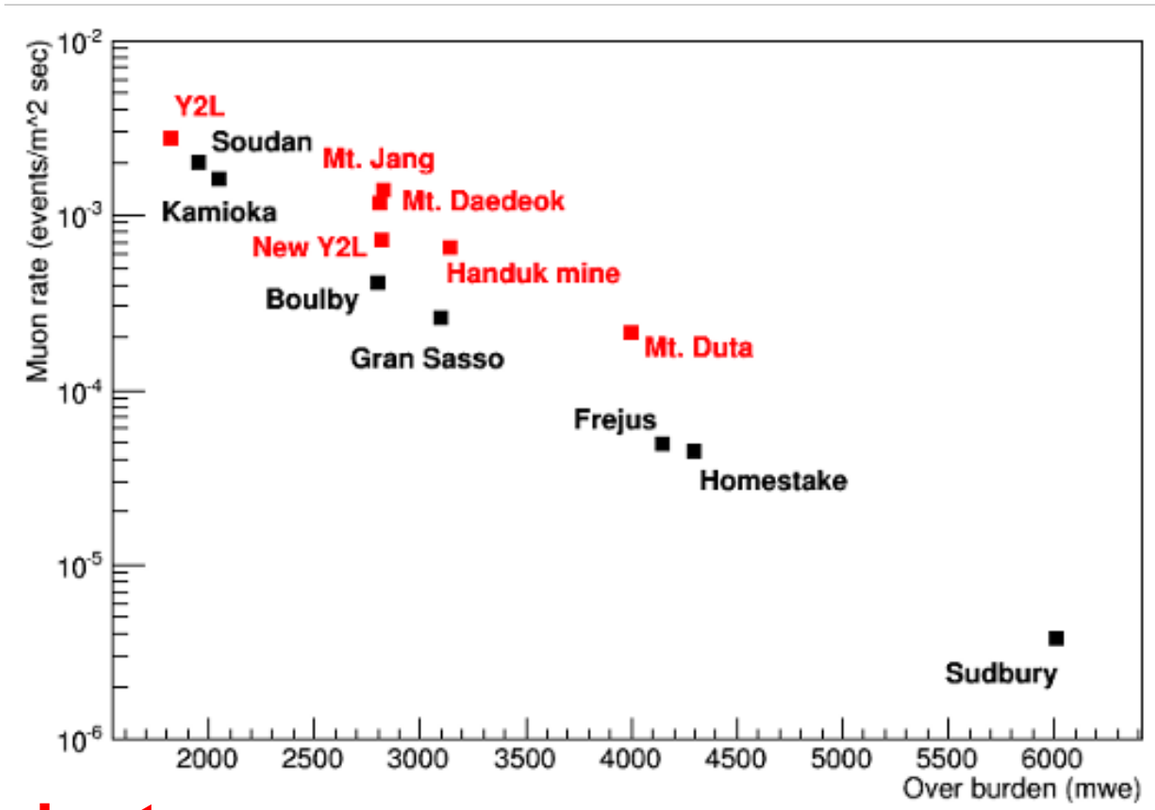






Investigation of new underground facility candidates





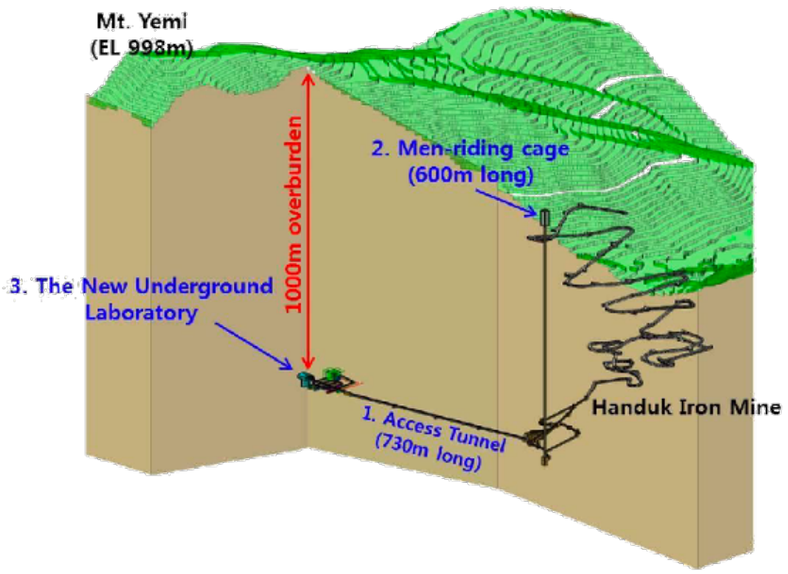
- **Considering depth, space, time, and budget.**

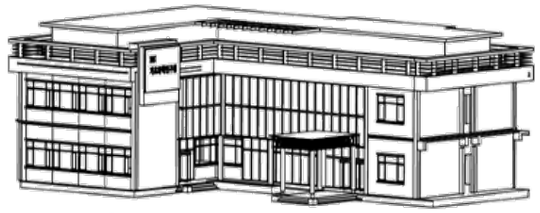
Candidates		H. of Peak (m)	EL. of Entrance (m)	Tunnel Length (m)	Depth of 8% (m)	Overburden (m)	EL. of UL (m)	Muon rate Event
1	Mt. Daedeok	1290	460	2200	176	1006	284	857
2	Mt. Duta	1350	180	3570	285.6	1455.6	-105.6	180
3	Mt. Jang	1410	550	1900	152	1012	398	877
4	Handeok mine	990	-70	1100	88	1148	-158	403
5	Y2L A2 tunnel	930	90	2100	168	1008	-78	547

Yemi

Yemilab: overview and construction

- **The only operating iron ore mine in Jeongseon, Korea.**
- **Access the underground lab. :**
  - **600 m long 2nd shaft with a man-riding cage (~4 min.)**
  - **5 km rampway (~30 min. driving) for underground access.**





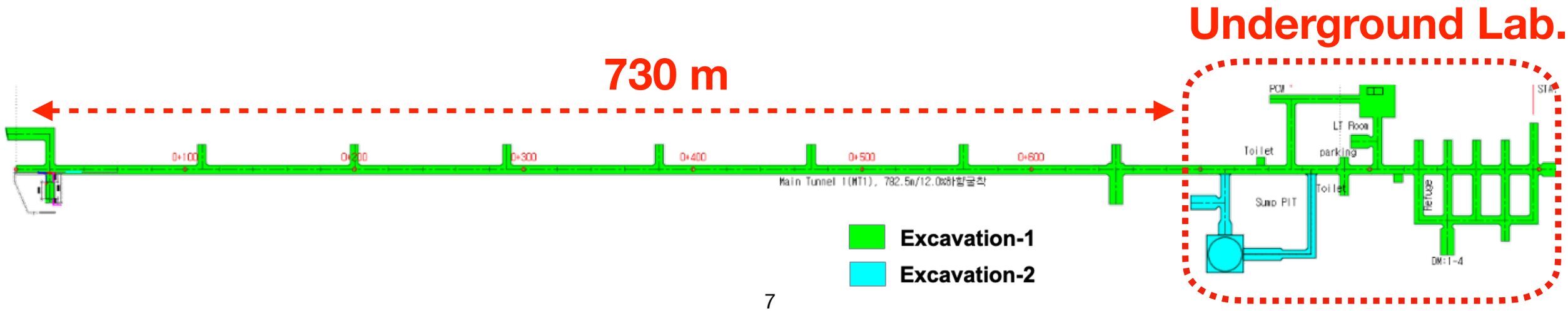
Ground office

The 1st phase of construction

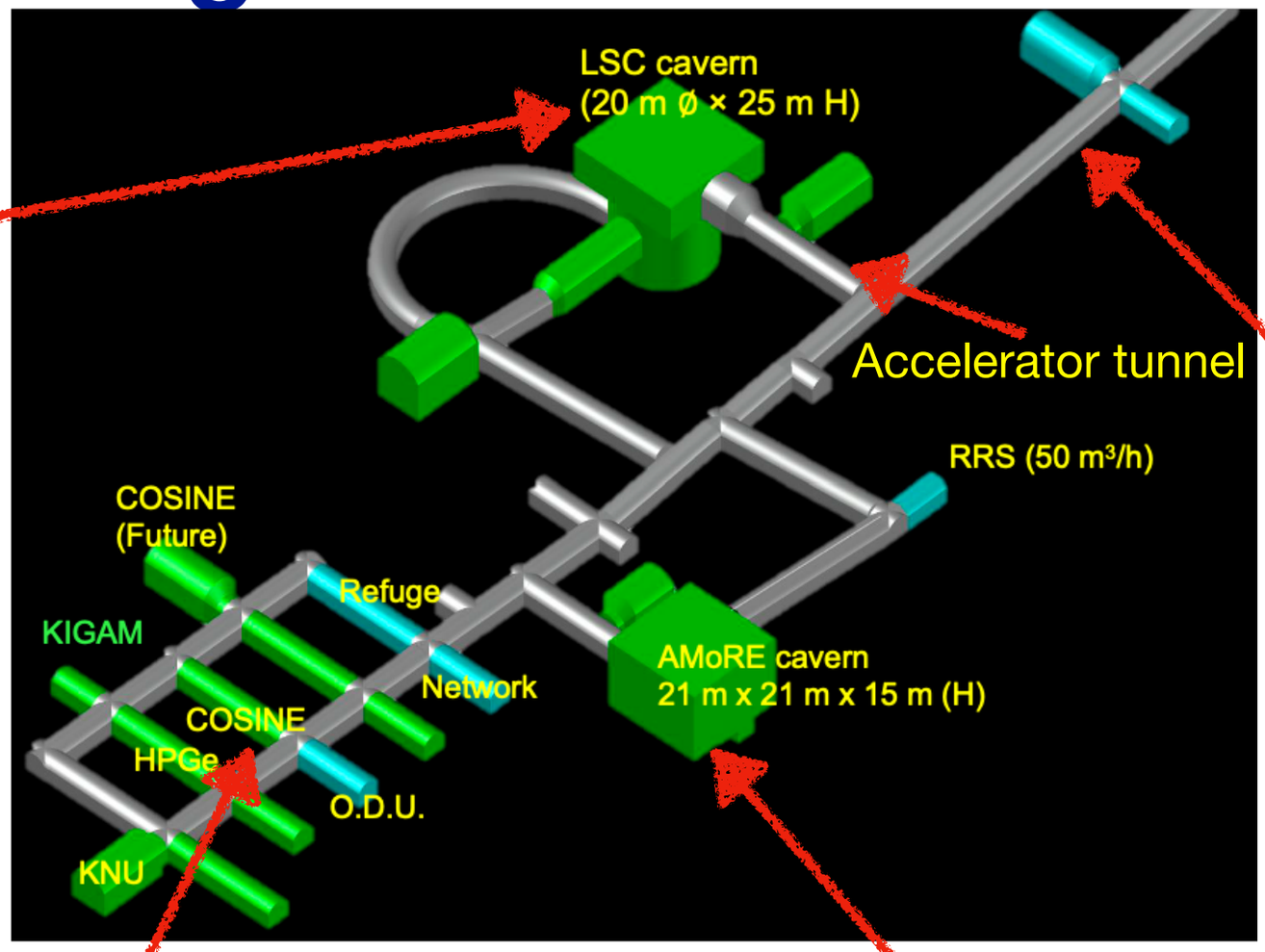
- Period: July 2017 ~ August 2020
- Man-riding cage installation in the shaft
- Excavation: 2000 m^2 (lab. area)

The 2nd phase of construction

- Period: May 2021 – July 2022
- Excavation: 1000 m^2
- Electricity and machinery
- Ground office renovation

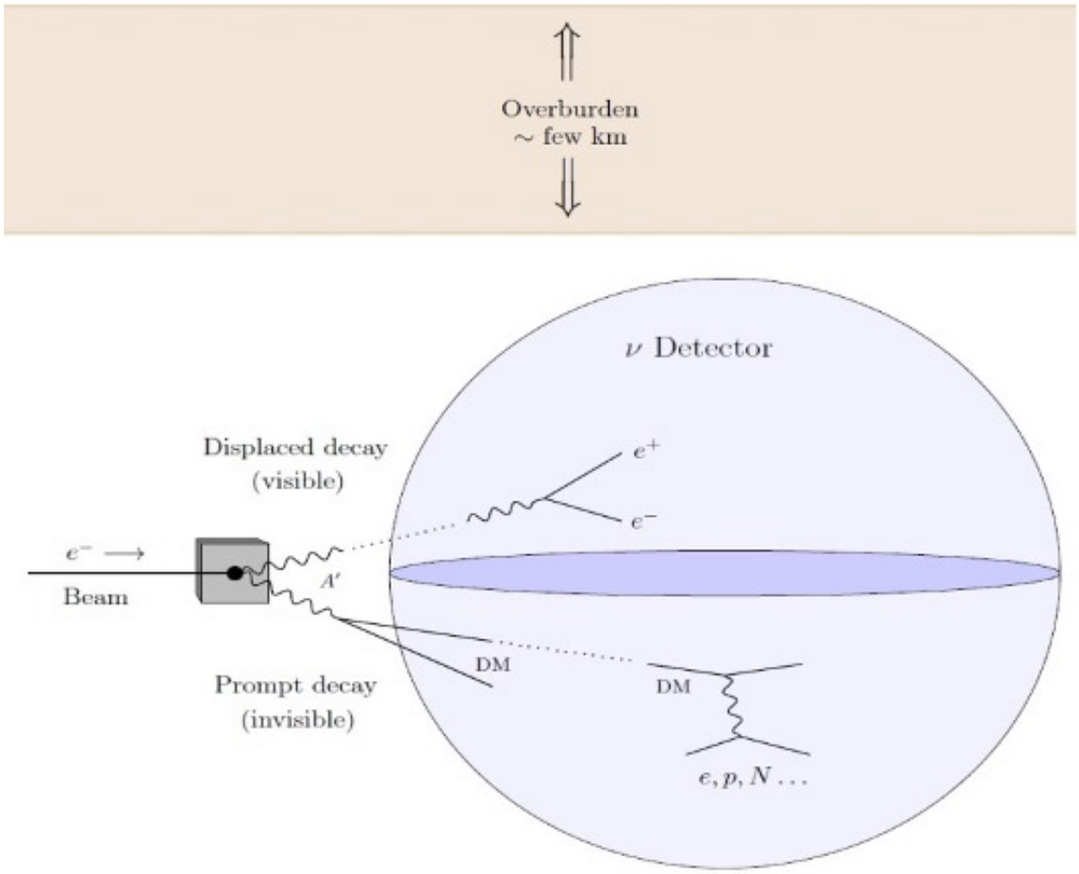


Yemilab underground tunnels and caverns

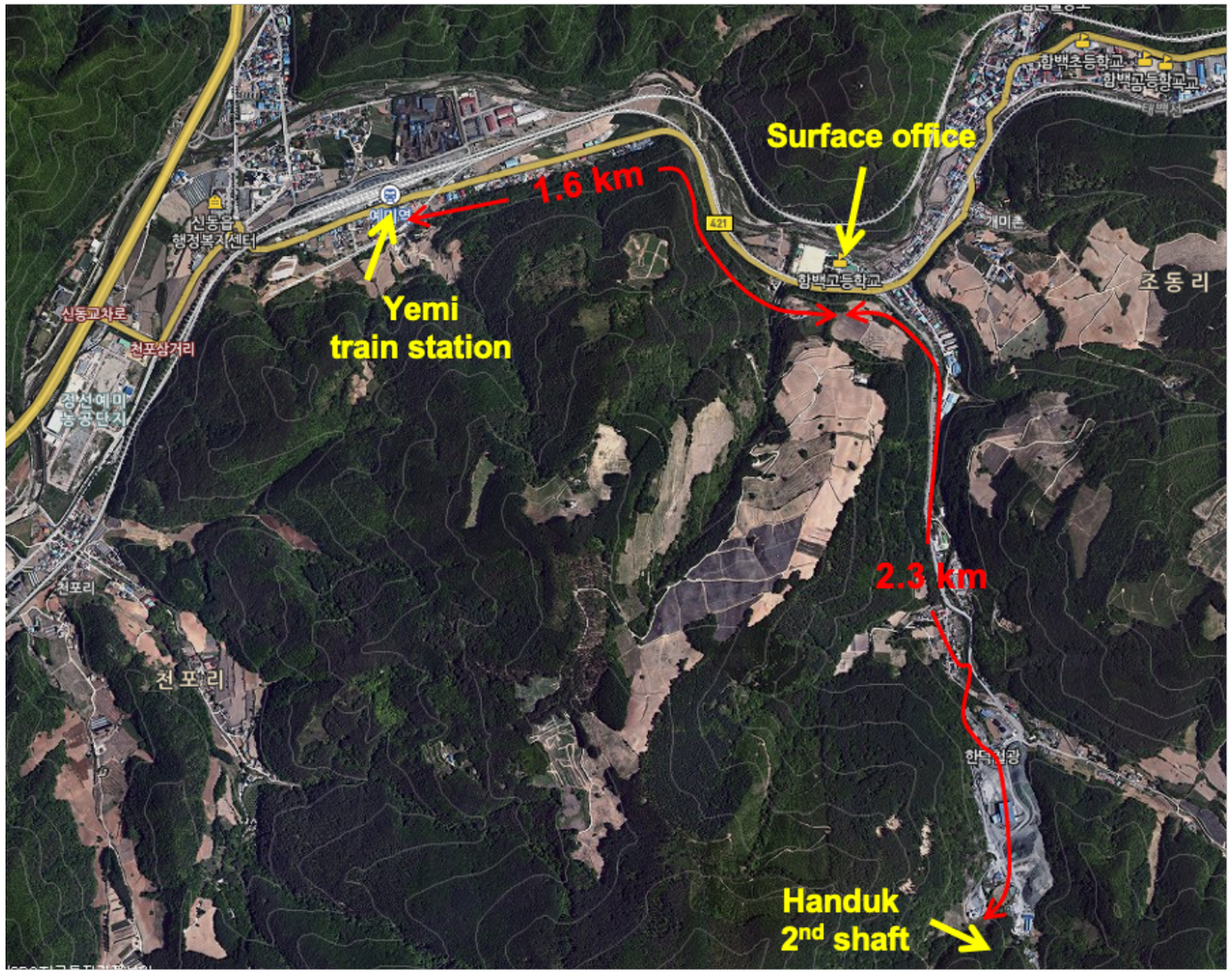


KU Proposal for LSC (Liquid Scintillator) cavern:

- **A large detector is located at a deep underground lab.**
  - ~2 kton of LS with ~ 200 keV threshold
  - Good detection efficiencies for e and γ events
- **Electron accelerator near by the detector**
  - ~100 kW power
  - e-beam energy: 20 MeV -> 100 MeV upgrdable.



Surface office at Yemilab



- One three-story building
- 12 m (W) × 80 m (L) ×12 m (H)
- Two Experimental rooms (1F):
  8 m (W) × 3.2 m (L) ×16 m (H)
- Six office rooms and 2 meeting rooms
  (2F: 20 peoples, 3F: 40 peoples)
- One lounge area

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Construction of Yemilab

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The Center for Underground Physics of the Institute for Basic Science (IBS) in Korea has been planning the construction of a deep underground laboratory since 2013 to search for extremely rare interactions such as dark matter and neutrinos. In September 2022, a new underground laboratory, Yemilab, was finally completed in Jeongseon, Gangwon Province, with a depth of 1,000 m and an exclusive experimental area spanning 3,000 m^3. The tunnel is encased in limestone and accommodates 17 independent experimental spaces. Over 2 years, from 2023 to 2024, the Yangyang Underground Laboratory facilities will be relocated to Yemilab. Preparations are underway for the AMoRE-II, a neutrinoless double beta decay experiment, scheduled to begin in Q2 2024 at Yemilab. Additionally, Yemilab includes a cylindrical pit with a volume of approximately 6,300 m^3, designed as a multipurpose laboratory for next-generation experiments involving neutrinos, dark matter, and related research. This article provides a focused overview of the construction and structure of Yemilab.

KEYWORDS

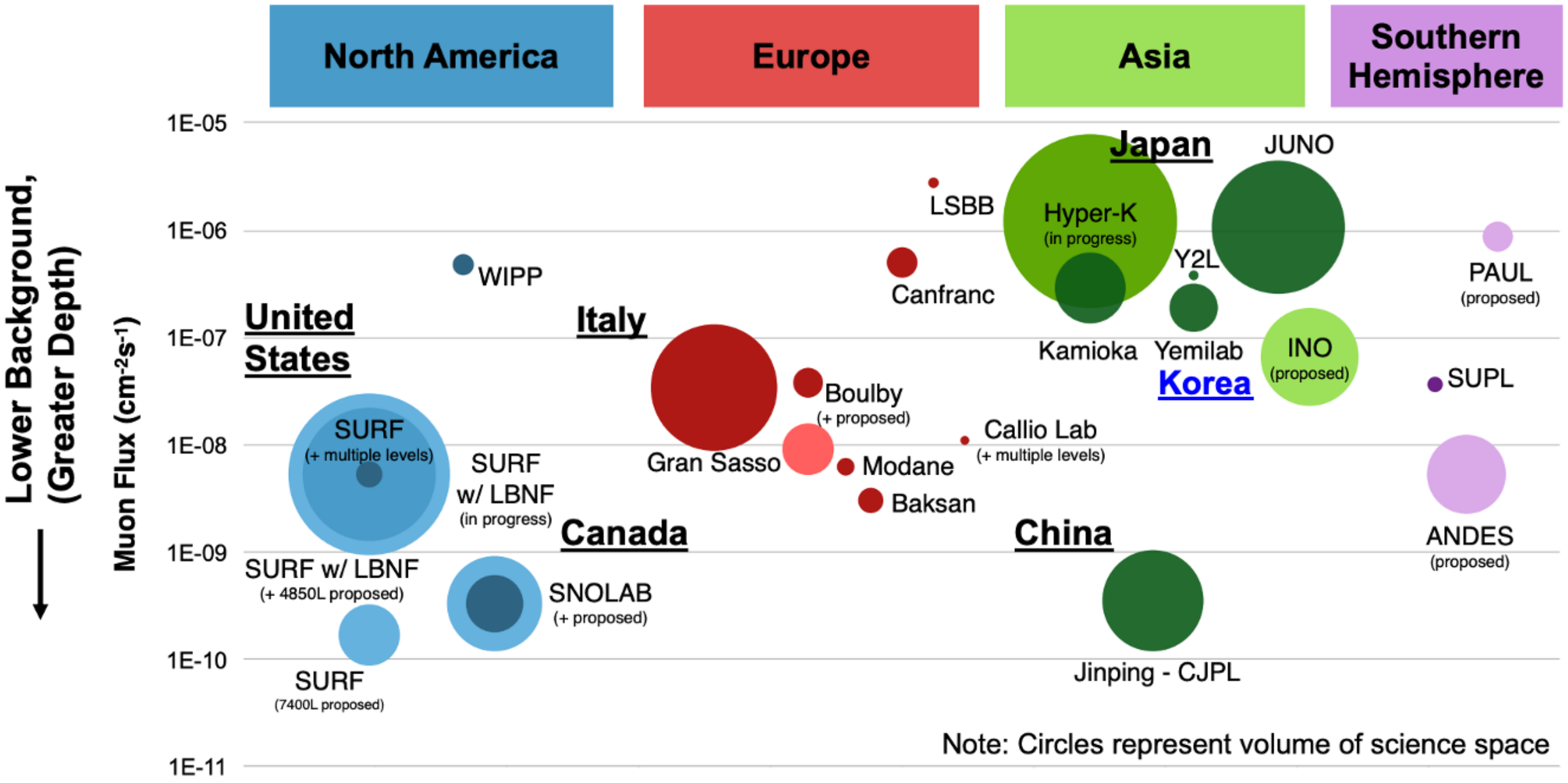
UL, underground Facility, Yemilab, Korea UL, underground laboratory, Asian underground laboratory

1 Introduction

The Institute for Basic Science (IBS) is a Korean national research institute established in 2011 to conduct basic scientific research. As of 2023, IBS includes 31 independent centers, each focusing on different research themes. The Center for Underground Physics (CUP) is one of the centers and, as indicated by its name, is a research center dedicated to astroparticle physics, conducting primary experiments underground. CUP started in 2013, and approximately 70 researchers are engaged in research activities to measure extremely rare interactions, such as dark matter and neutrinos. Since its inception, CUP planned to construct a new underground laboratory to expand the existing Yangyang Underground Laboratory (Y2L), which has a limited experimental space of ~200 m^2 at a depth of ~700 m. In September 2022, a new underground experimental facility with a depth of 1,000 m (2,500 m w. e.) and an exclusive experimental area of ~3,000 m^2 was finally completed in Jeongseon-gun, Gangwon province, named the Yemilab. All tunnels in the

Yemilab in the worldwide underground facilities

From Jaret Heise (SURF) slide



AMoRE

(Advanced Mo-based Rare process Experiment)

Main goal: Search for Neutrinoless Double Beta Decay in ^{100}Mo

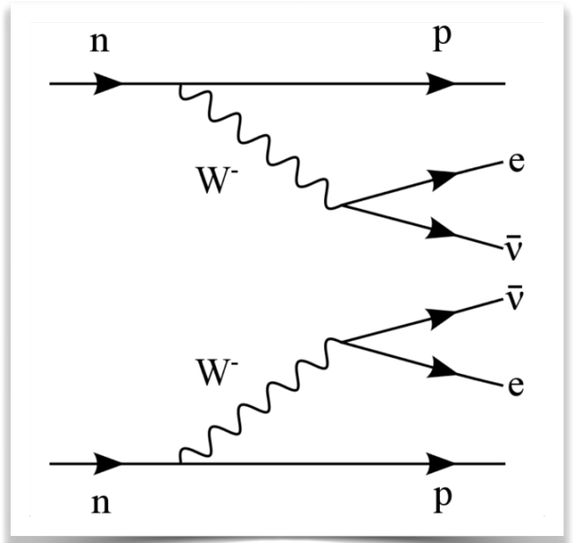
AMoRE Collaboration

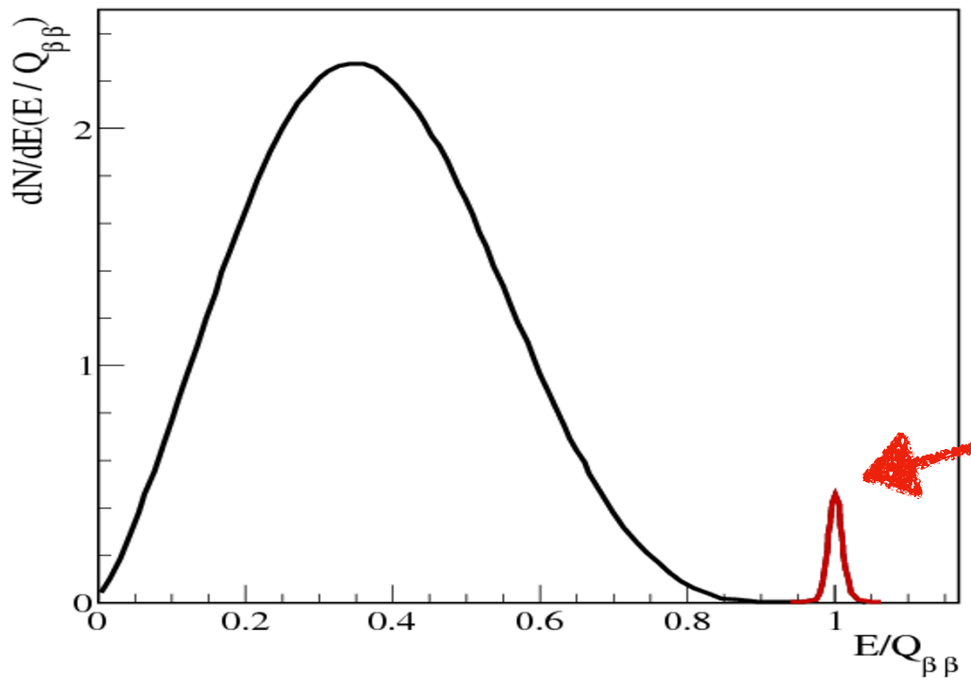
Total 107 members, from 24 institutes, at 10 countries including Prof. Qian Yue at Tsinghua University, China.

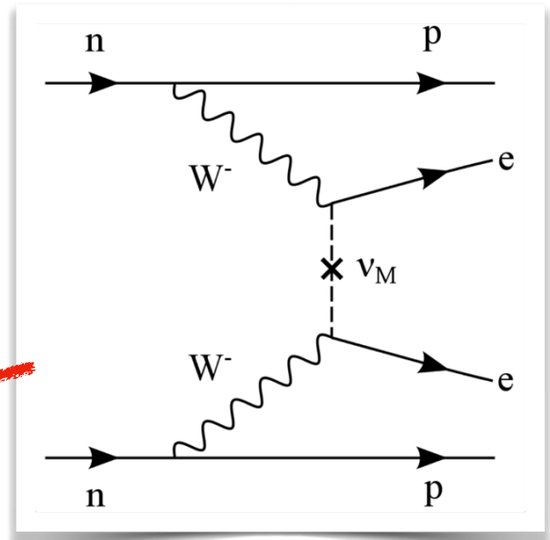
Neutrinoless double beta decays (0$\nu\beta\beta$)

- **2$\nu\beta\beta$ decays:**
  - 2nd order beta decays
  - Rare nuclear decay
  - 7x10^{18} years of half life for ^{100}Mo

- **Discovery of 0$\nu\beta\beta$:**
  - Proves neutrinos are Majorana fermions.
  - Lepton number violation
  - Beyond the Standard Model
  - Strengthen seesaw mechanism and leptogenesis.
  - (>10^{25} years of half life)



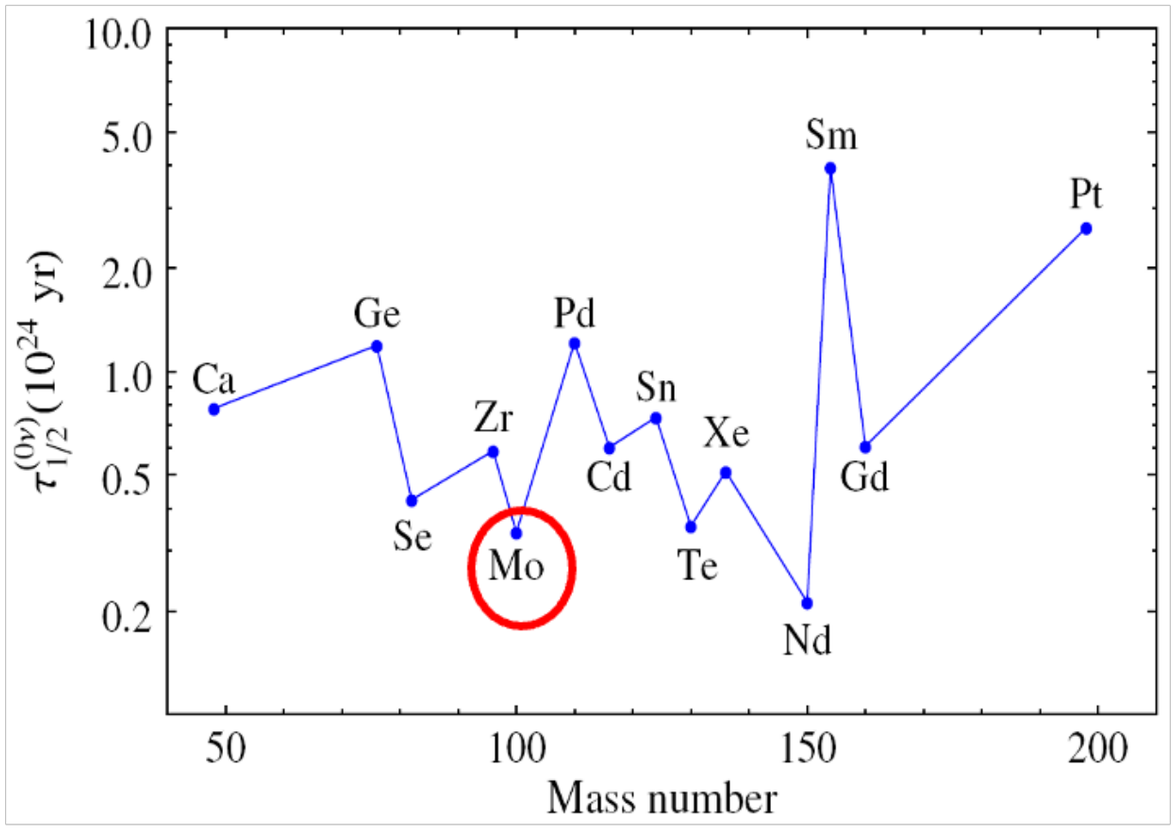




$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\text{anti-}\nu_e \quad (\Delta L = 0, \text{conserved})$$
$$(Z, A) \rightarrow (Z+2, A) + 2e^- \quad (\Delta L = 2, \text{violated})$$

Why we use ^{100}Mo for 0$\nu\beta\beta$ search ?

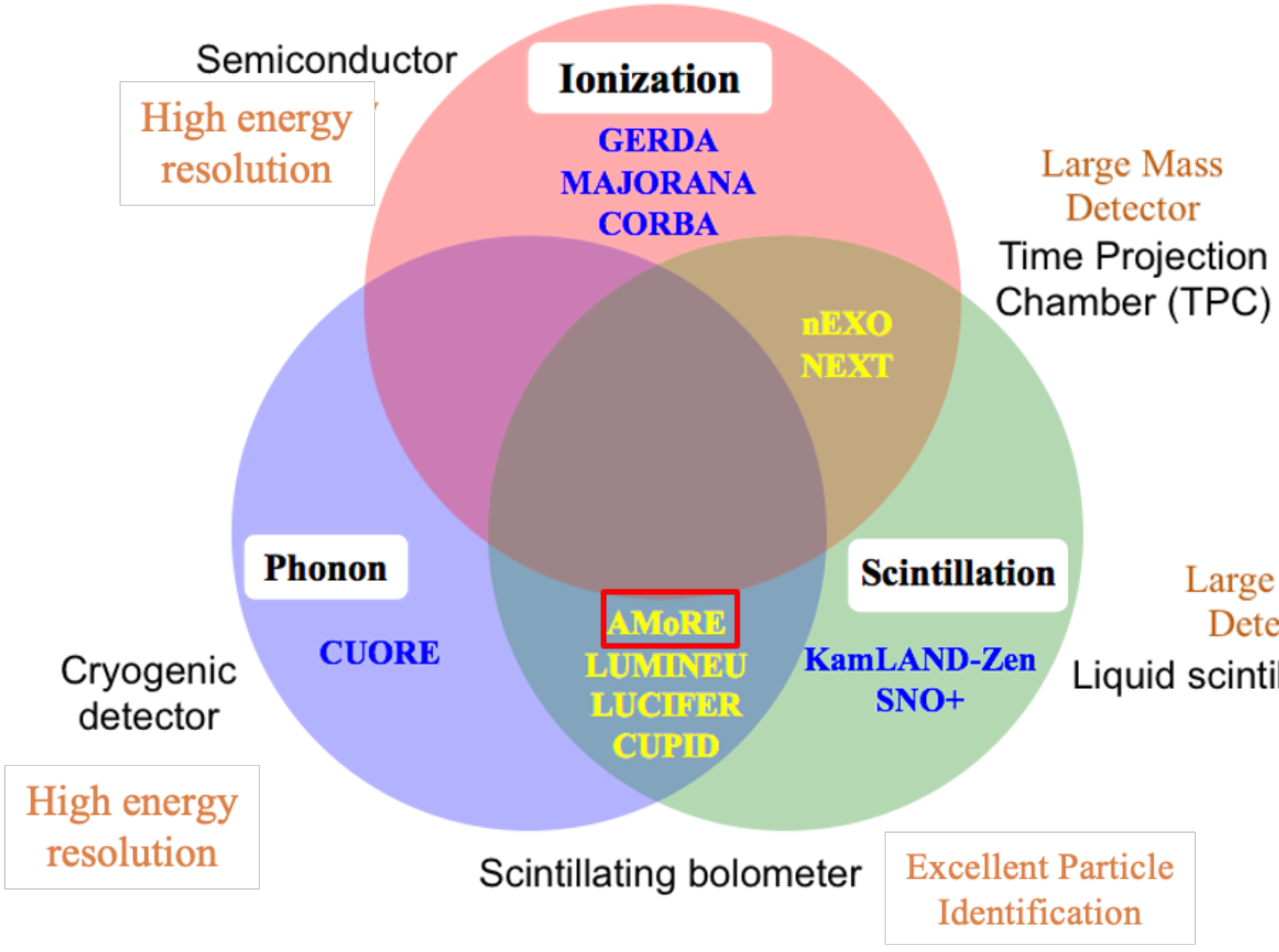
- **High Q-value ($\beta\beta$) of 3034.40 (12) keV.**
- **High natural abundance of 9.7%.**
- **Relatively short half life (0$\nu\beta\beta$) expected from theoretical calculation.**



Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

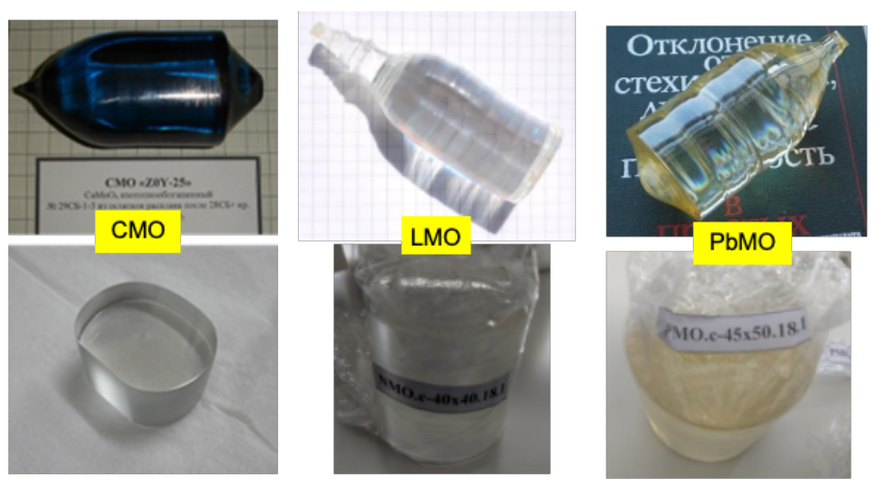
Candidate	Q (MeV)	Abund. (%)
^{48}Ca	4.271	0.19
^{76}Ge	2.040	7.8
^{82}Se	2.995	8.7
^{100}Mo	3.034	9.7
^{116}Cd	2.802	7.5
^{124}Sn	2.228	5.8
^{130}Te	2.533	34.1
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

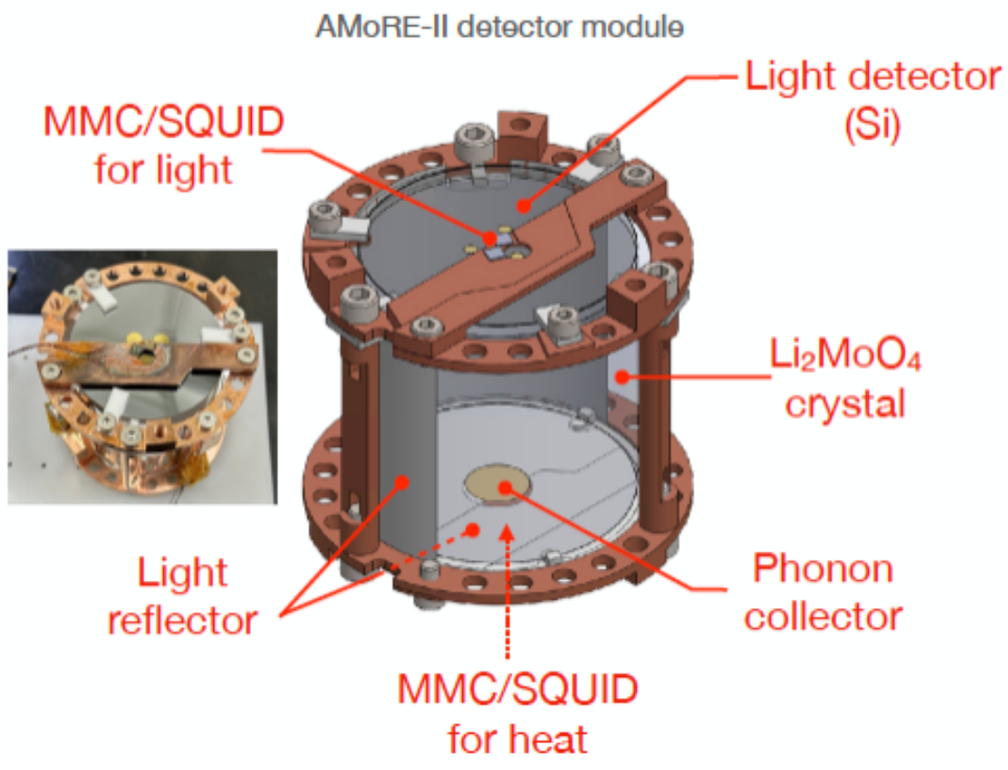
Detection Techniques of 0νββ

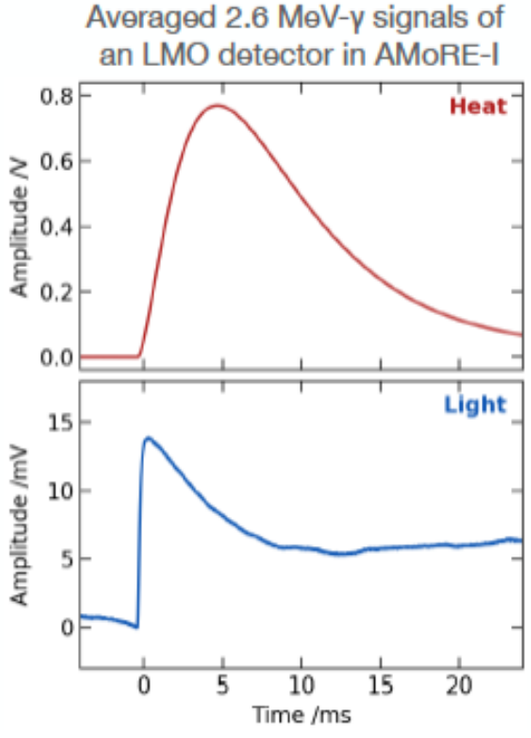


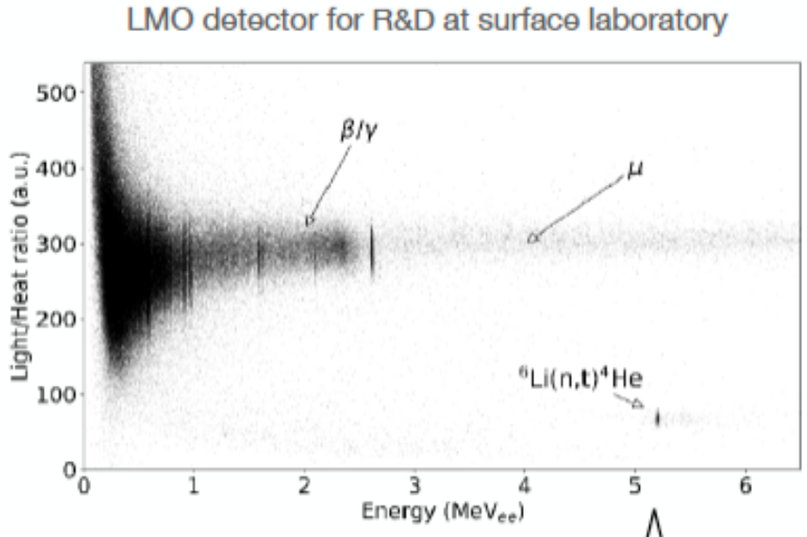
Overview of AMoRE detector module

- Use scintillating bolometer with $^{40}Ca^{100}MoO_4$(CMO) and $Li_2{}^{100}MoO_4$(LMO) crystals
- ^{100}Mo enriched: > 95 %
- Low-temperature (LT) detector: @10 – 30 mK
- Energy resolution: ~ 5 keV @ 3 MeV (goal)
- Excellent PID for α vs. e/γ





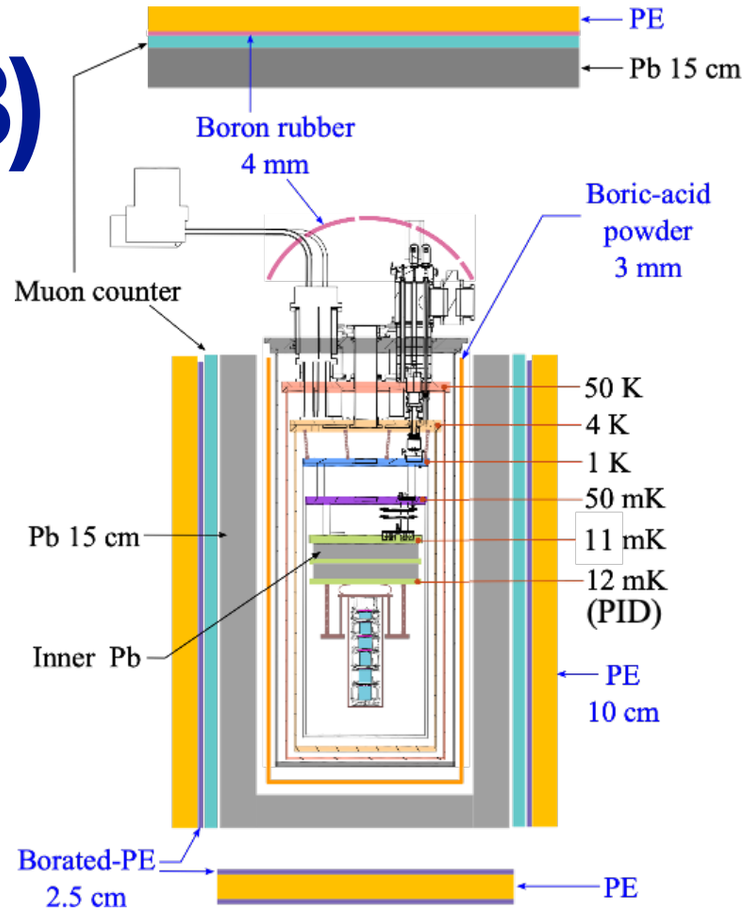


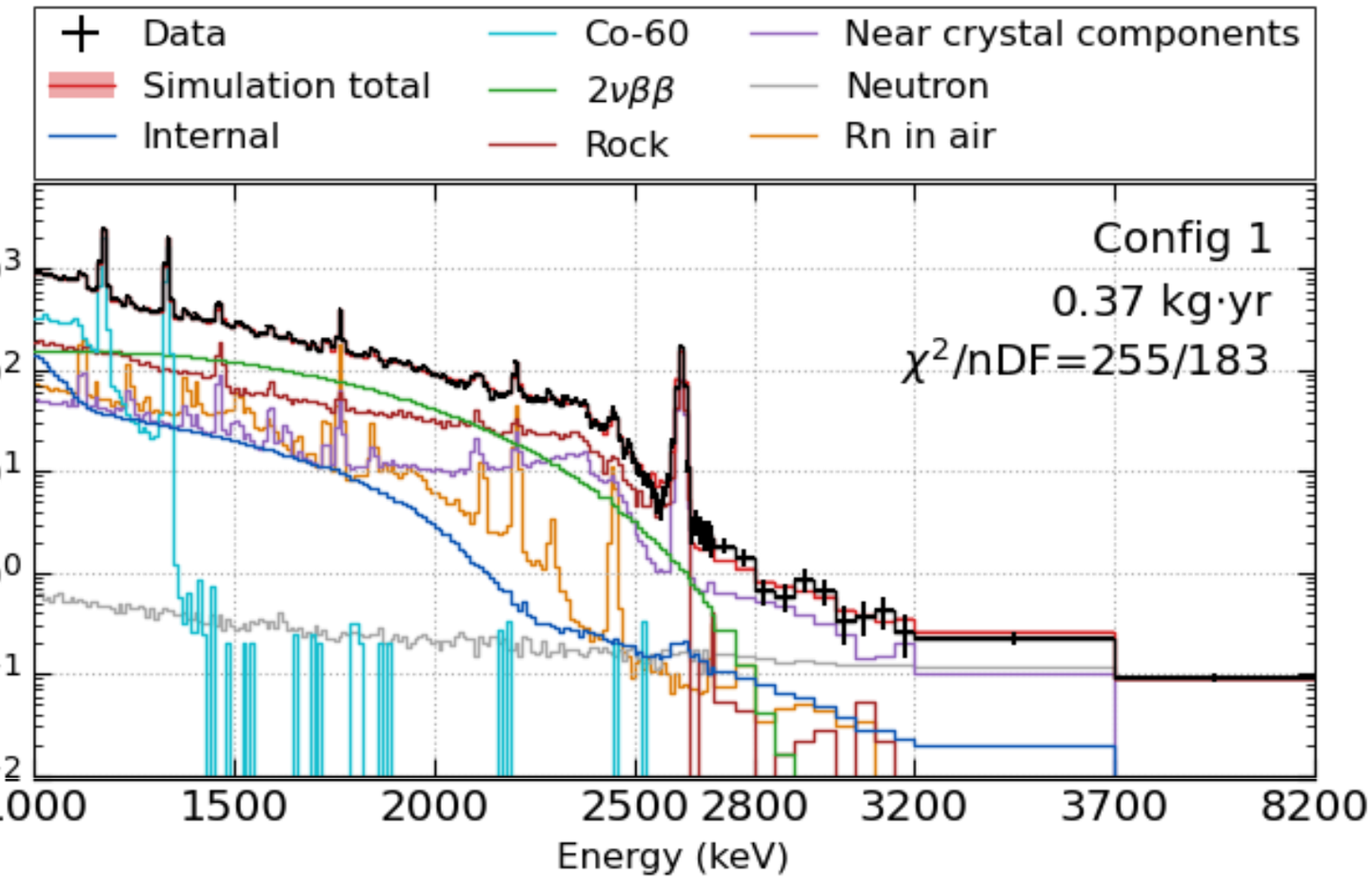


$$DP = \frac{|\mu_{\beta\gamma} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta\gamma} + \sigma^2_\alpha}} > 10$$

AMoRE-pilot @ Y2L (2015~2018)

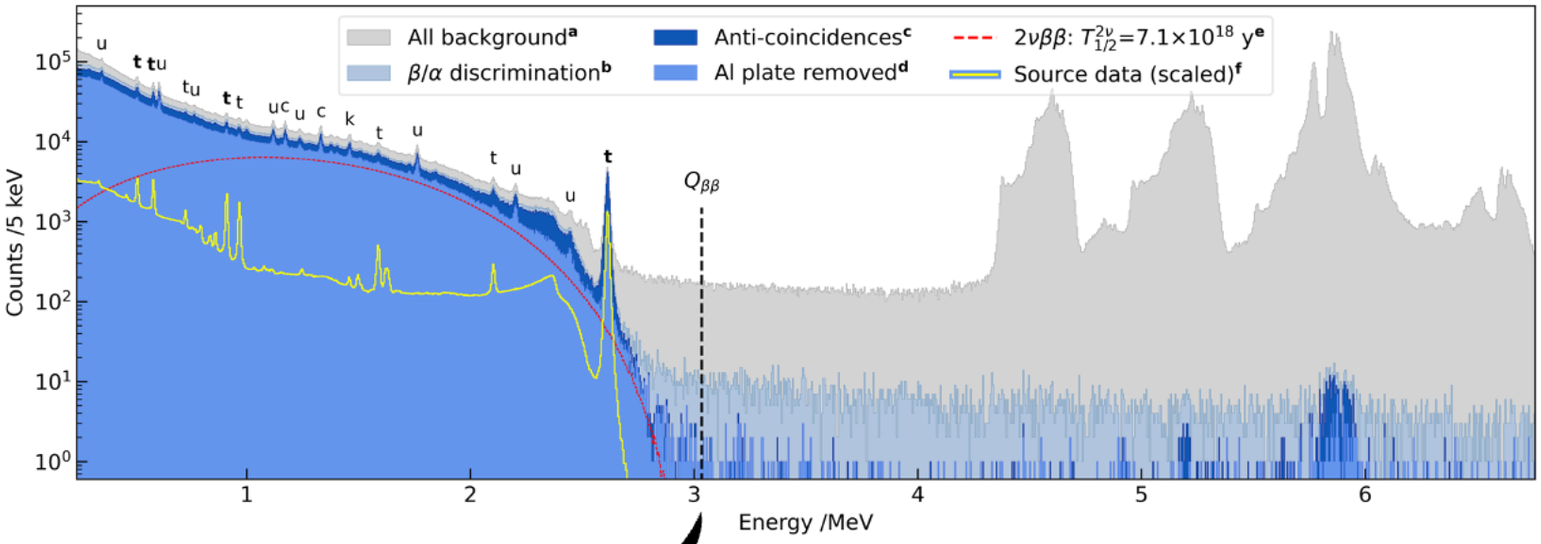
- 6 CMO crystals
- Operating at 10 mK with1.2 μW cooling power.
- Live exposure ~ 0.32 $kg_{Mo\text{-}100}$·yr.
- Background at ROI~0.5 ckky (count/keV/kg/yr).
- $T_{1/2}^{0\nu} > 3.2 \times 10^{23}$ years at 90% CL.

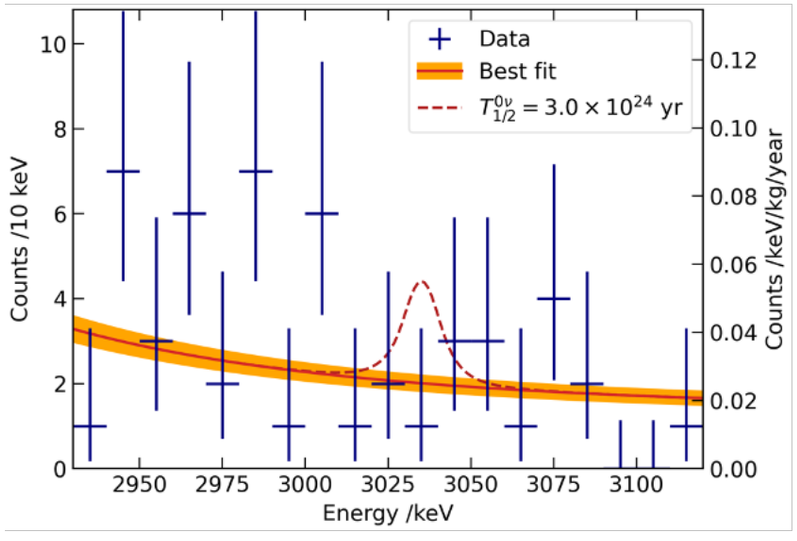




AMoRE-I @ Y2L : (2020.12-2023.5, ~ 900 days)

- 13 CMO crystals (4.6 kg) and 5 LMO (1.6 kg) crystals
- 20cm Pb shielding + neutron shields (boric acid+PE+b.PE)
- Confirmed stable operation of MMC+SQUID system @12 mK





Total exposure:
8.02kg•year (3.89 $kg_{^{100}Mo}$ • year)

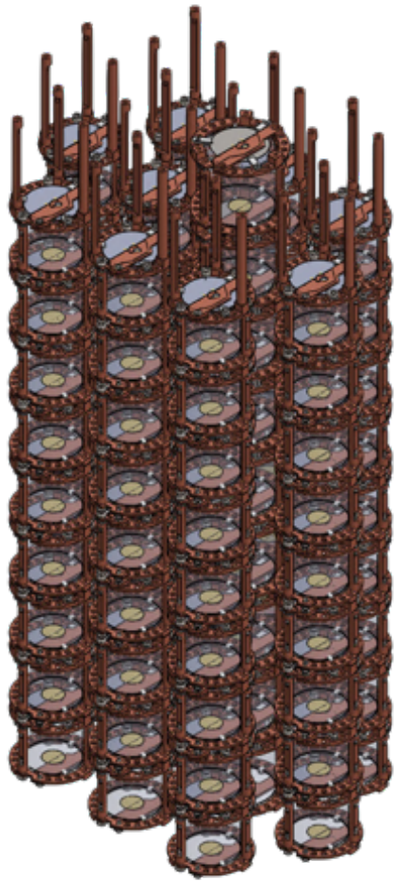
- Backgrounds : 0.025(2) ckky
  - CMO: 0.026(3) ckky
  - LMO: 0.021(5) ckky
- $T^{0\nu}_{1/2} > 3.0 \times 10^{24}$ years
- Cf. $T^{0\nu}_{1/2} > 1.8 \times 10^{24}$ years by CUPID-Mo
- Agrawal et al., arXiv:2407.05618, submitted to PRL

AMoRE-II @ Yemilab (2024~)

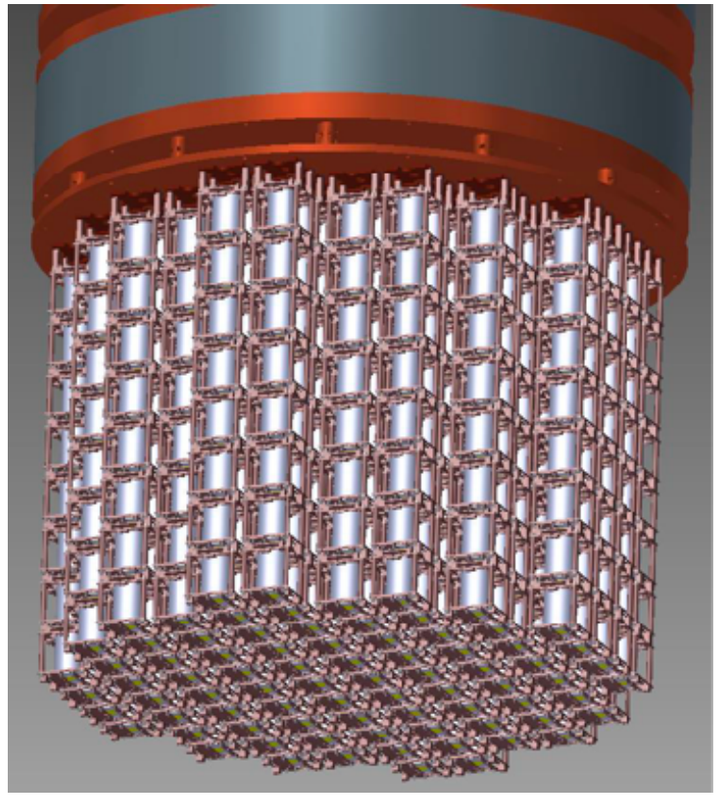
Overview

- Installed at Yemilab, 1000 meter deep
- 360 crystals (LMO+13CMO)
  - MMC+SQUID for both heat & light signals.
  - Si wafer for light detector
- Cryostat from Leiden.
- Shielding with Pb and PE, Water
  - Lower part : Pb (25cm) + PE(70cm) + PSMD
  - Upper part : Inner Pb (25cm) + WCMD (70cm)
- Backgrounds
  - Goal < 10^{-4} ckky
  - Main backgrounds are Outer Pb, Pileup
- Sensitivity : 4×10^{26} years, 90% CL
- Schedule
  - Stage 1: 90 crystals : 2024-2025
  - Stage 2: 360 crystals : 2026-2030

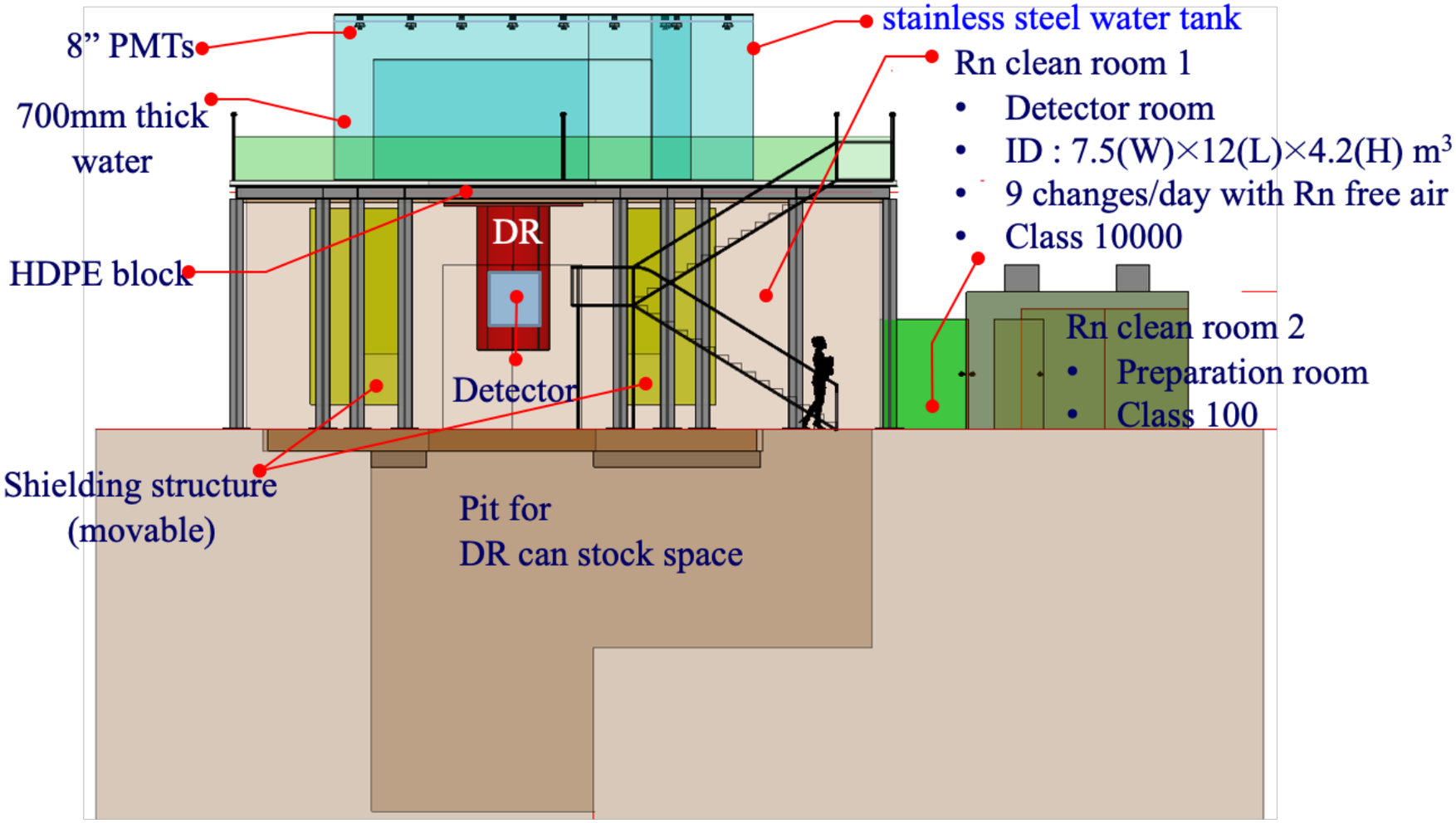
Stage 1:
90 LMOs
(27 kg)



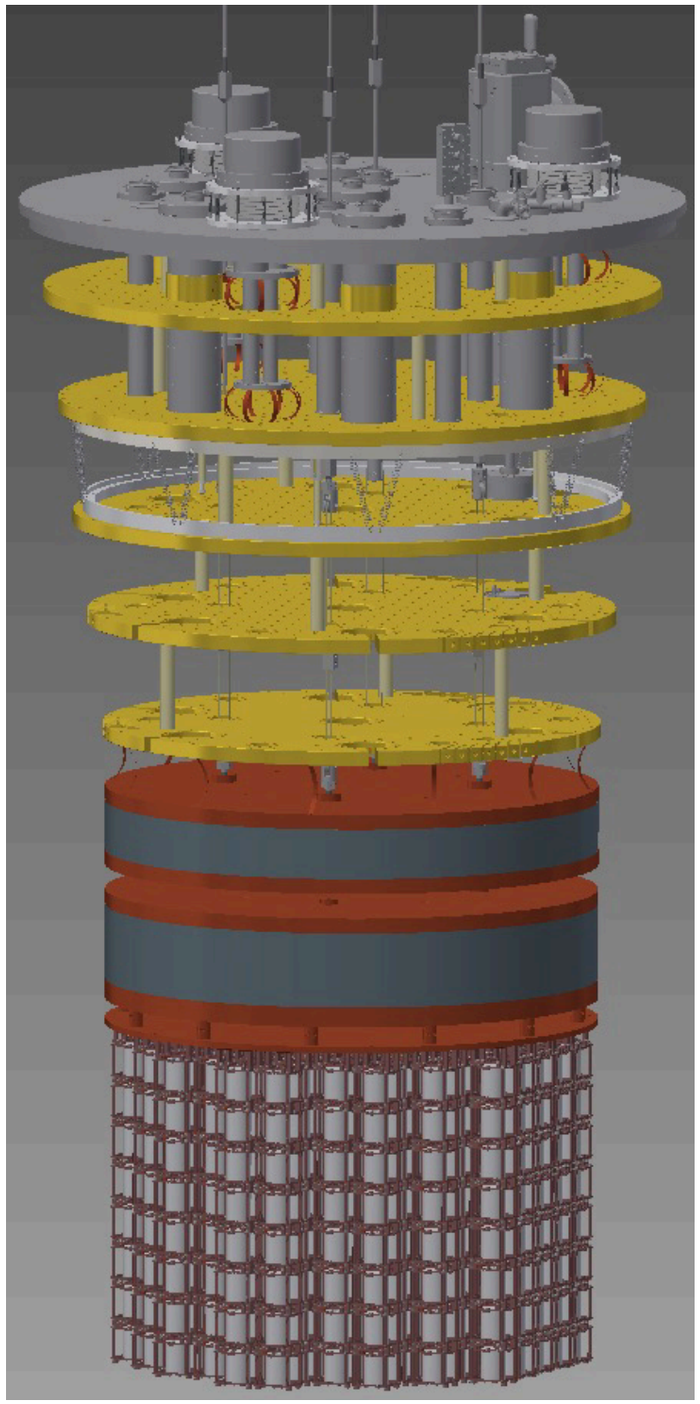
Stage 2:
360 crystals (157 kg)



Detector Structure for AMoRE-II



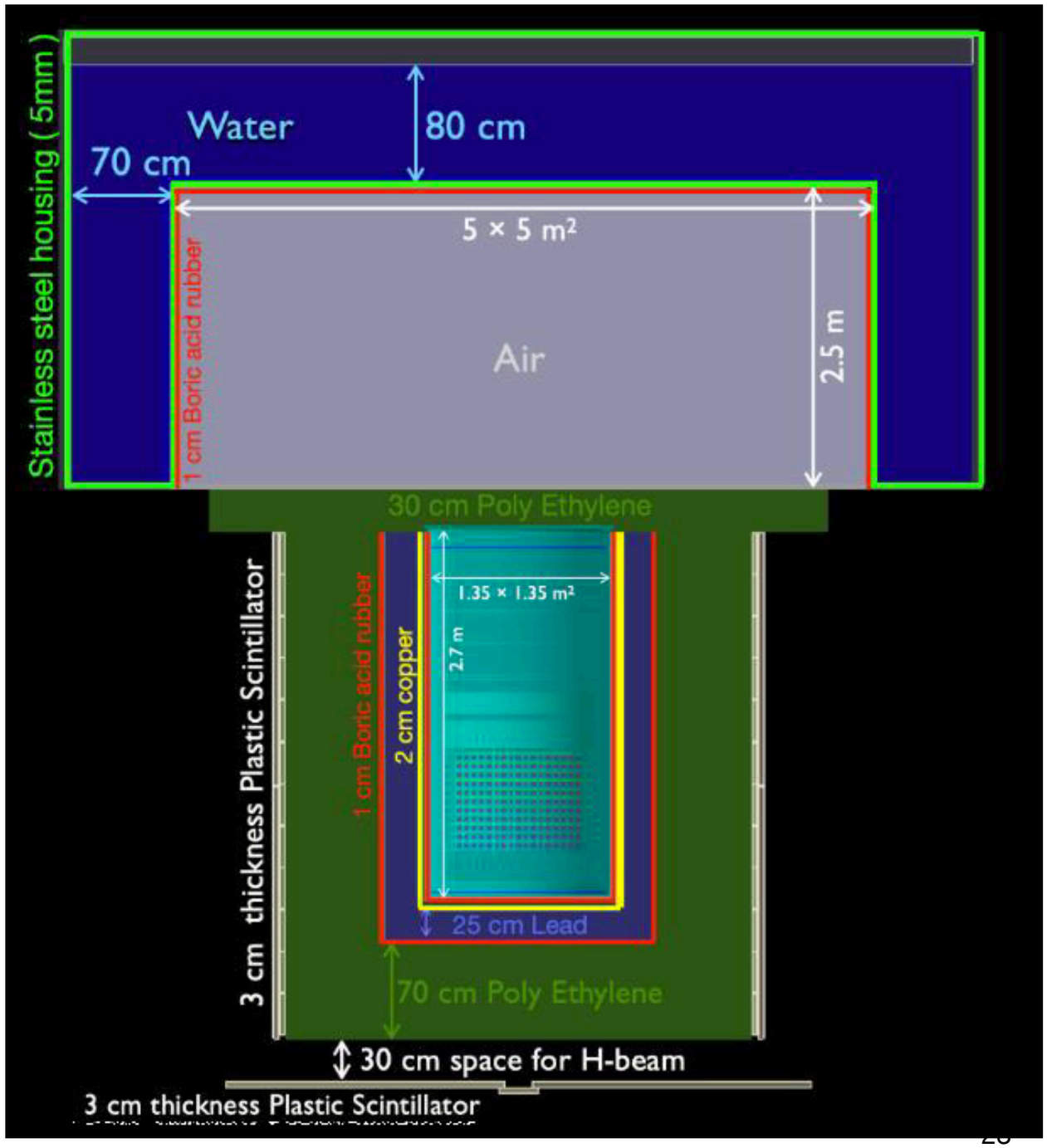
Dilution Refrigerator



- Dilution Refrigerator (Cryostat)
  - Three pulse tubes
  - Cooling power (normal opt):
    1 mW @ 100 mK,
    7 μW @ 10 mK.
  - Base temperature < 10 mK

Shielding for AMoRE-II

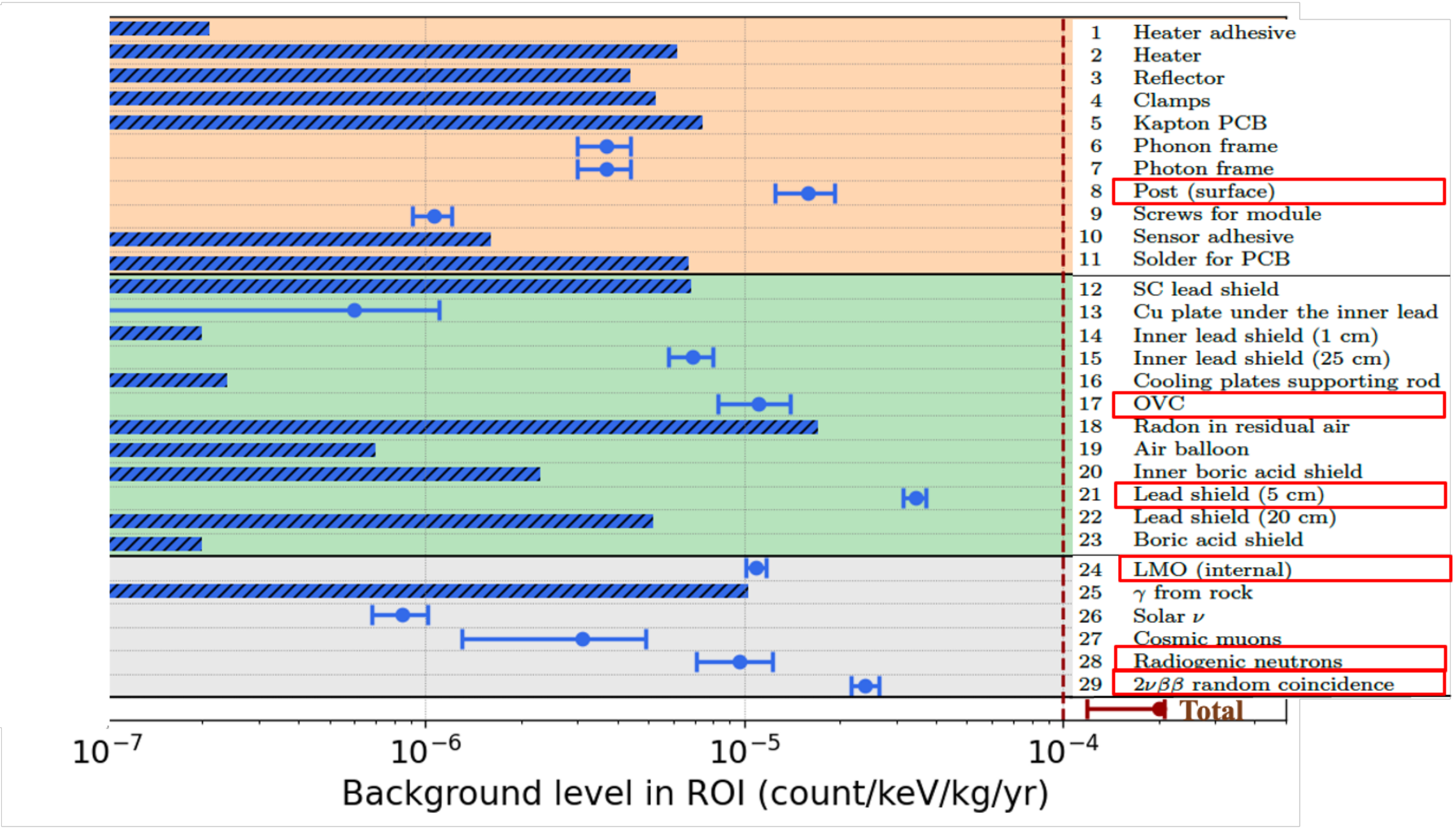
At 1,000 meter underground at Yemilab in Jeongseon, Korea



- Pb 26 cm over the crystal towers, below the mixing chamber plate in IVC.
- Bottom: boric acid rubber 1 cm < Cu 2 cm < Pb 25 cm < boric acid rubber 1 cm < polyethylene 70 cm < Plastic scint. μ-counter
- Top: boric acide rubber 1 cm < water cherenkov μ-counter 70-80 cm.
- Muon rate $\simeq 10^{-7}$ cm^{-2} s^{-1}.
- Radon-free air supply.

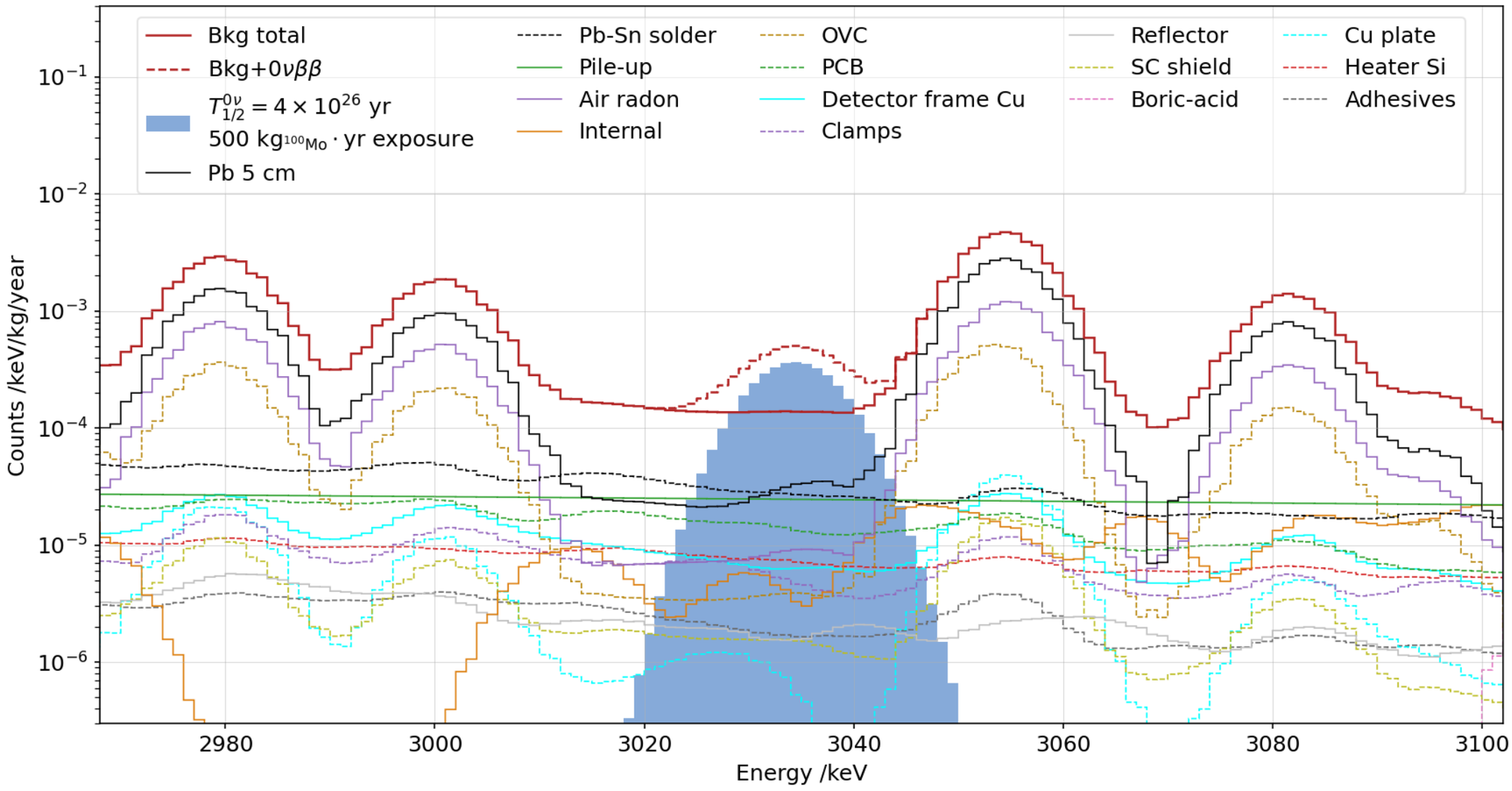
Background estimation (I)

Radioassay and simulation



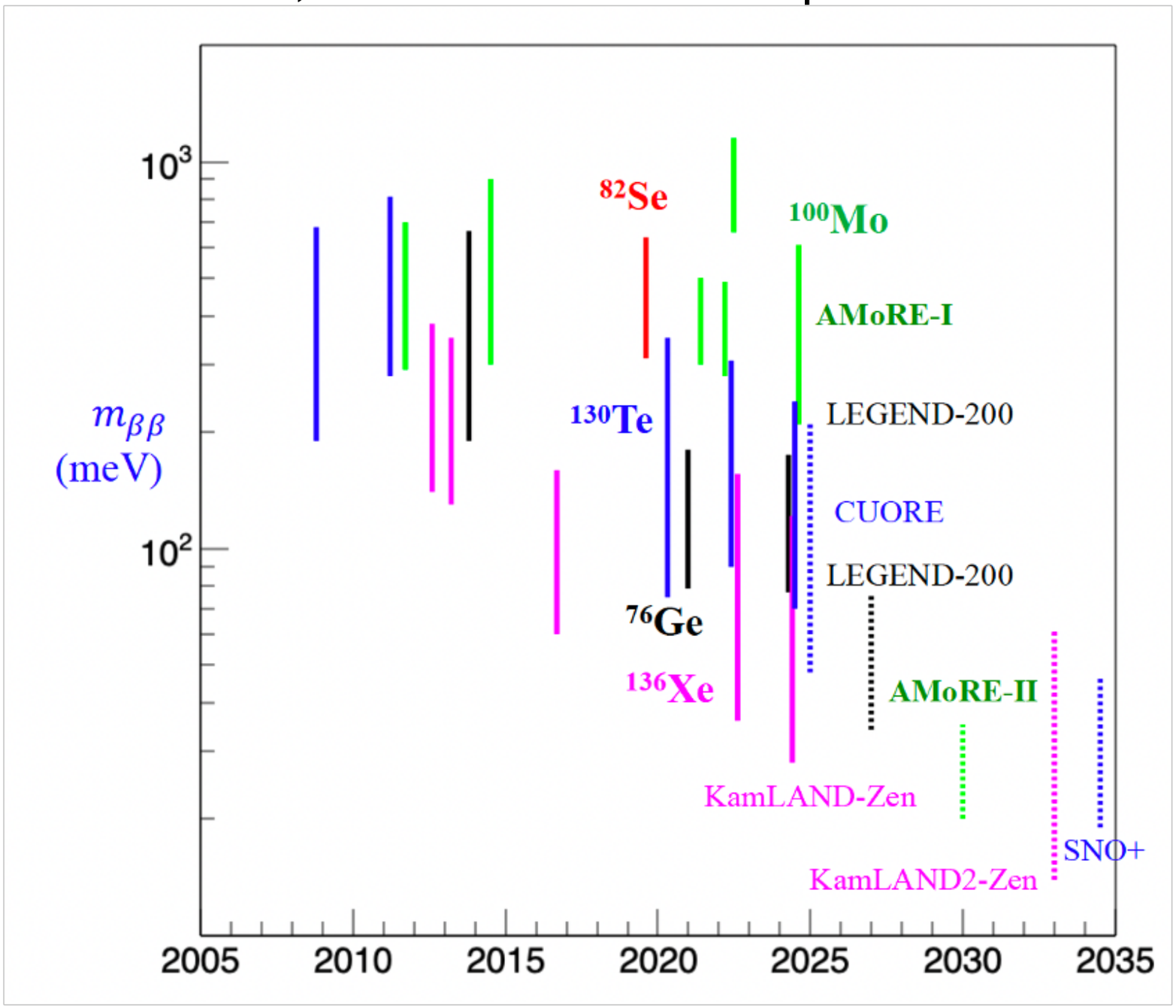
Background estimation (II)

b~10^{-4} ckky, ΔE=10 keV FWHM



0$\nu\beta\beta$ search prospectives

- New data from KamLAND-Zen (^{136}Xe) and LEGEND-200 (^{76}Ge) were released
- For the next decades, multi-tonne scale experiments will be constructed.

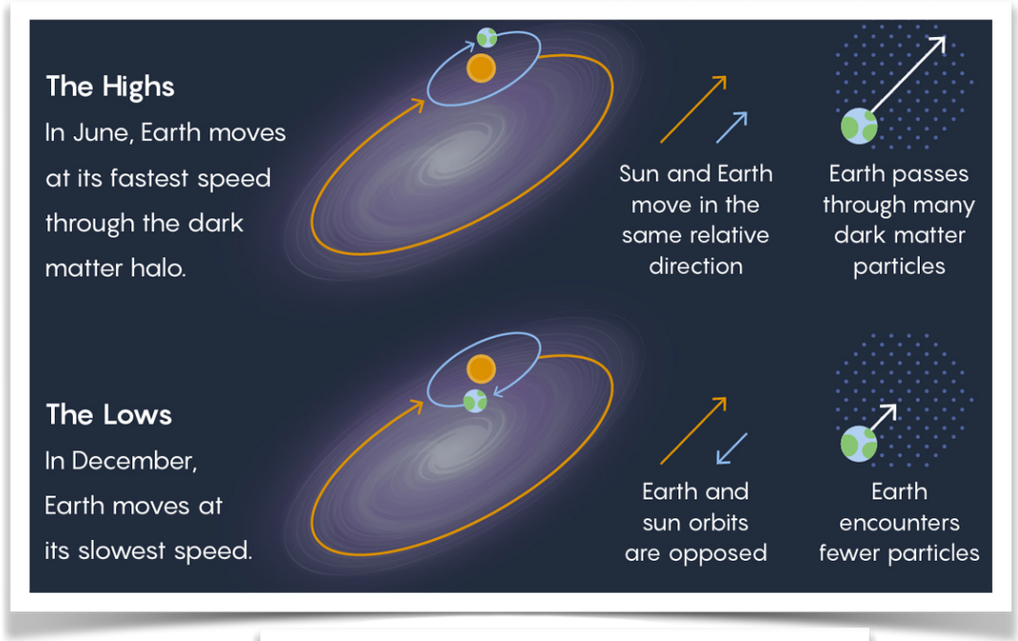


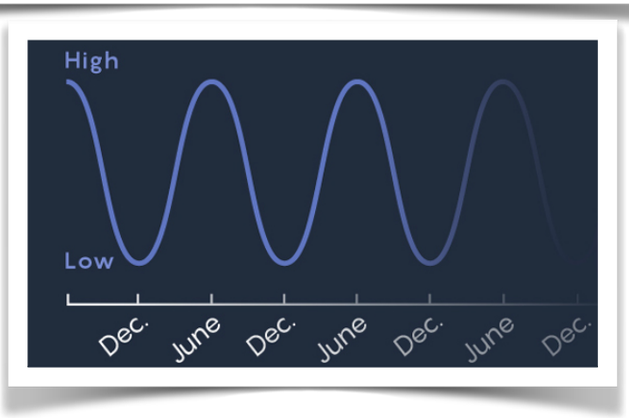
Dark Matter Search:

COSINE-100 Experiment

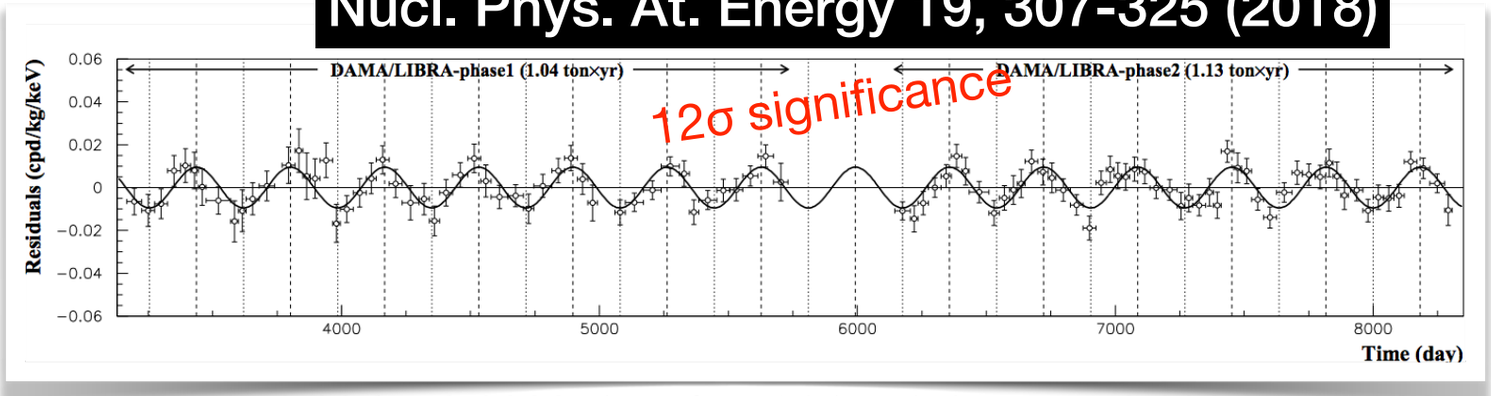
DAMA Signal
Discovery of Dark Matter ?

- Annual modulation signature by dark matter (DM)
  - Due to Earth's varying velocity
  - DAMA experiment
    - NaI(Tl) crystal detector
    - 1-keV (2-keV) threshold for phase1 (phase2)
    - 1-counts/kg/keV (dru) background level
- Observation of modulation signature
  - Phase & period are compatible w/ the nature of DM candidates
  - Claim observation of DM at 12σ CL





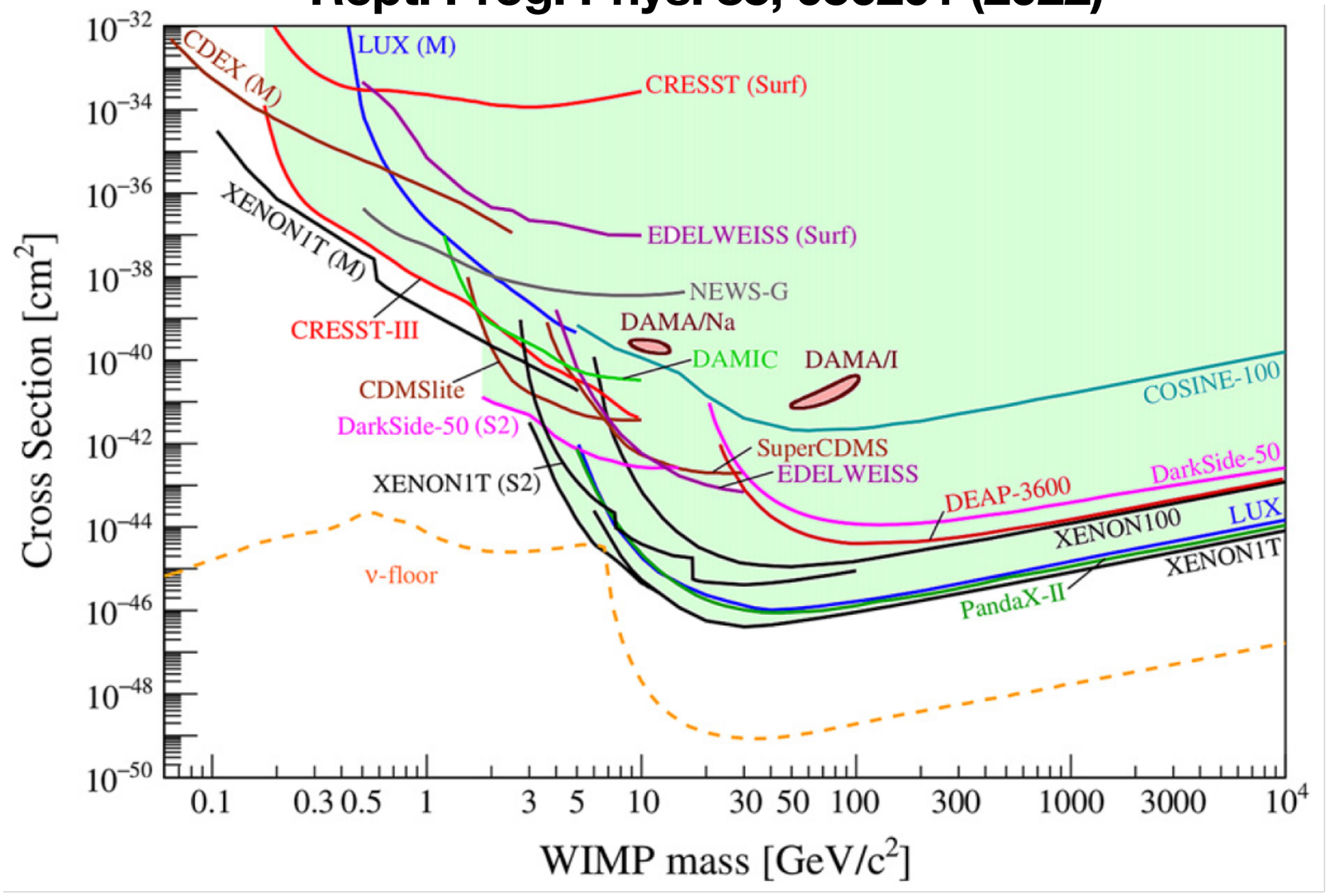
Nucl. Phys. At. Energy 19, 307-325 (2018)



$$S_m = 0.096 \pm 0.0008 \text{ dru}, \phi = 145 \pm 5 \text{ day}, T = 0.9987 \pm 0.0008 \text{ yr}$$

However…

Rept. Prog. Phys. 85, 056201 (2022)

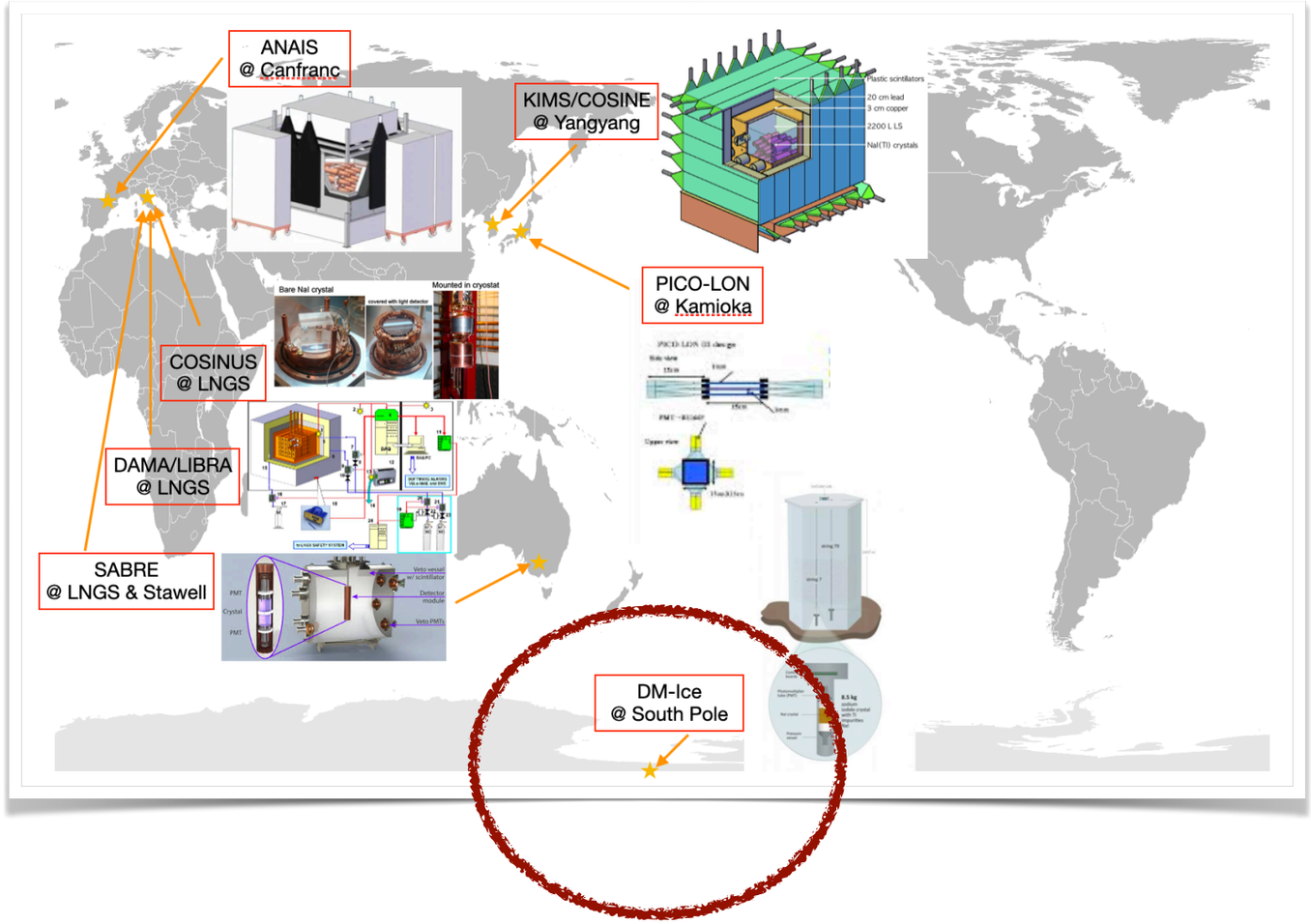


Requiring Model-independent test with same NaI(Tl) crystals

COSINE-100

An Effort to Verify DAMA Signal

- DM-Ice and KIMS joint effort to search for dark matter interactions
  - ~50 collaborators in 17 institutes
  - To test the DAMA claim via the same target material



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

COSINE-100

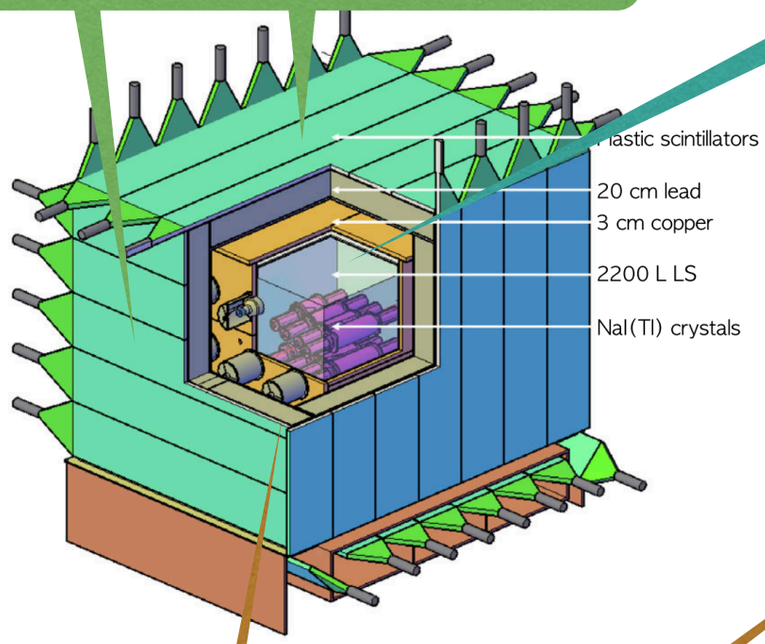
Detector Configuration

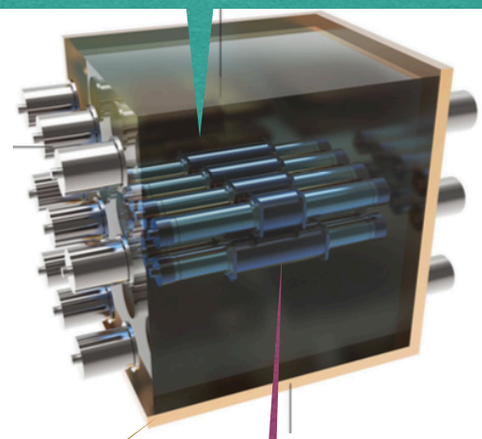
*JCAP **02**, 013 (2021) & JINST **13**, T02007 (2018)*

4π Muon Counter
37 plastic scintillator panels
2" PMTs (H7195) for muon counter

*Nucl. Instrum. Meth. A **851**, 103 (2017)*
*Nucl. Instrum. Meth. A **1006**, 165431 (2021)*

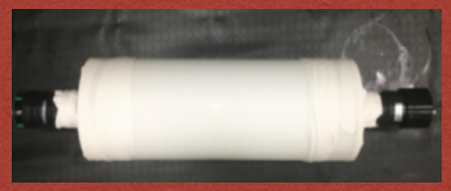
Liquid Scintillator
2200-L LAB-based LS for veto
5" PMTs for LS detector



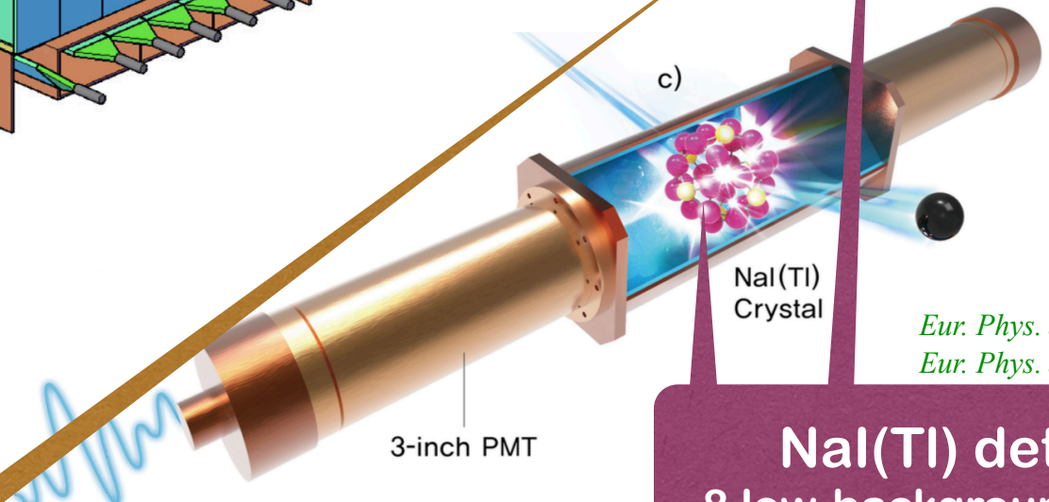


*JINST **13**, T06005 (2018)*

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)



Thermal neutron detector
(^{3}He gas detector)



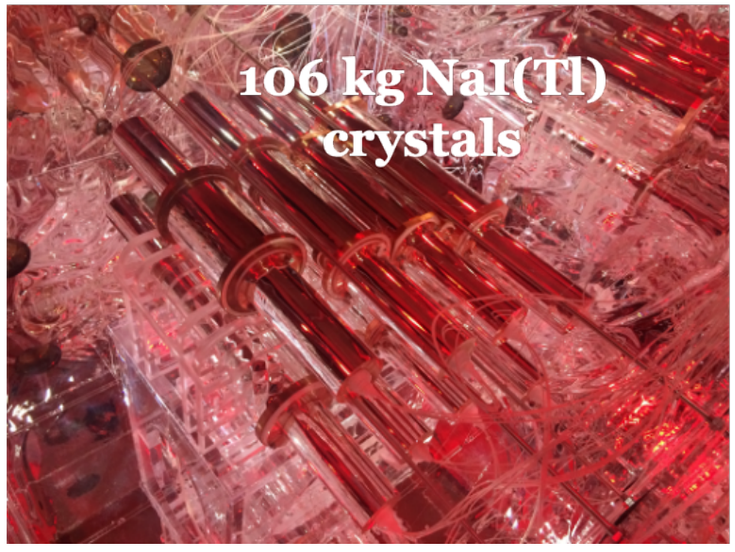
*Eur. Phys. J. C. **78**, 107 (2018)*
*Eur. Phys. J. C. **78**, 490 (2018)*

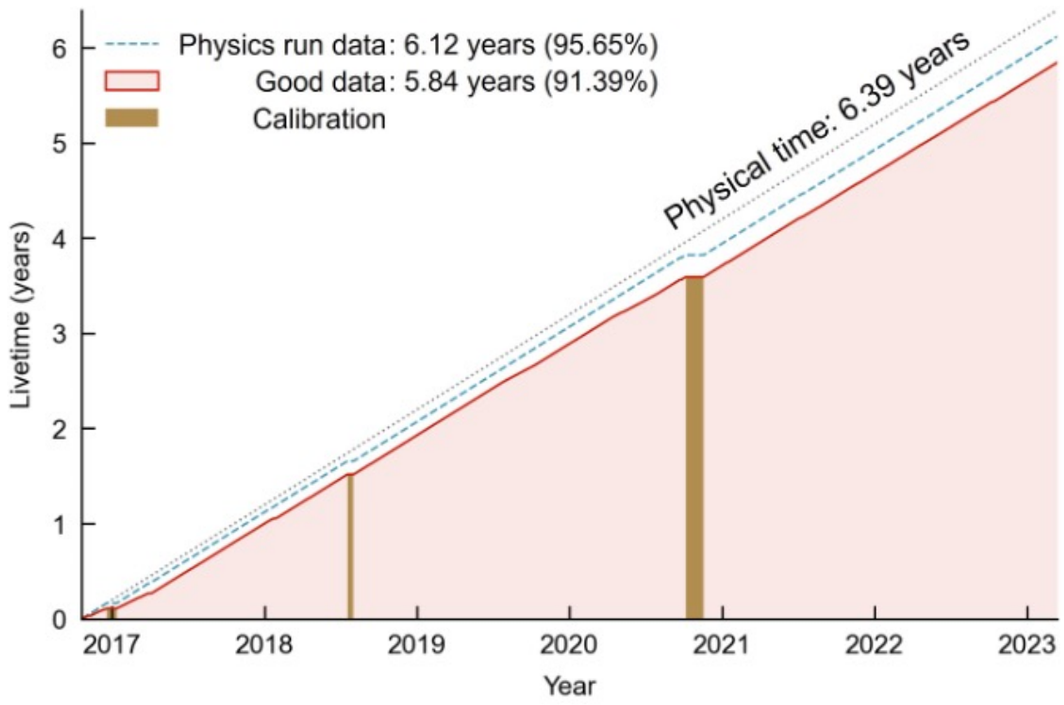
NaI(TI) detector
8 low-background crystals
Copper encapsulation
Two 3" PMTs

*Eur. Phys. J. C. **78**, 107 (2018)*

Passive Shields
3-cm thick copper box
20-cm thick lead shielding

COSINE-100 experiment (2016~2023)

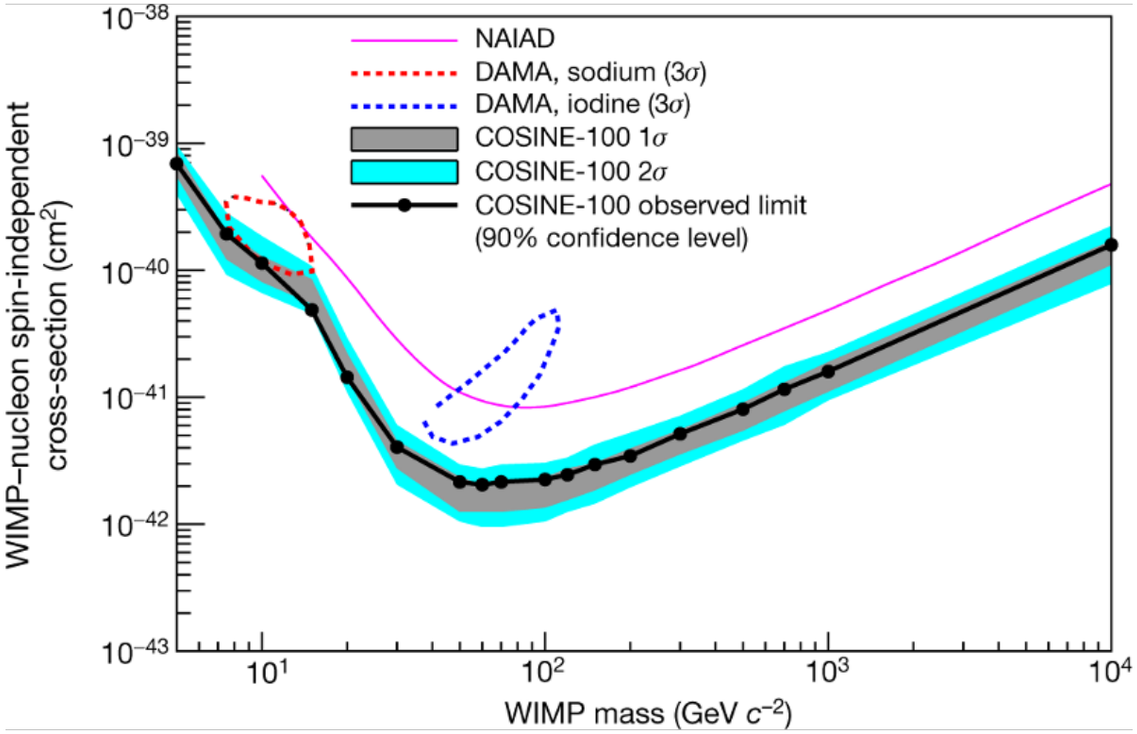




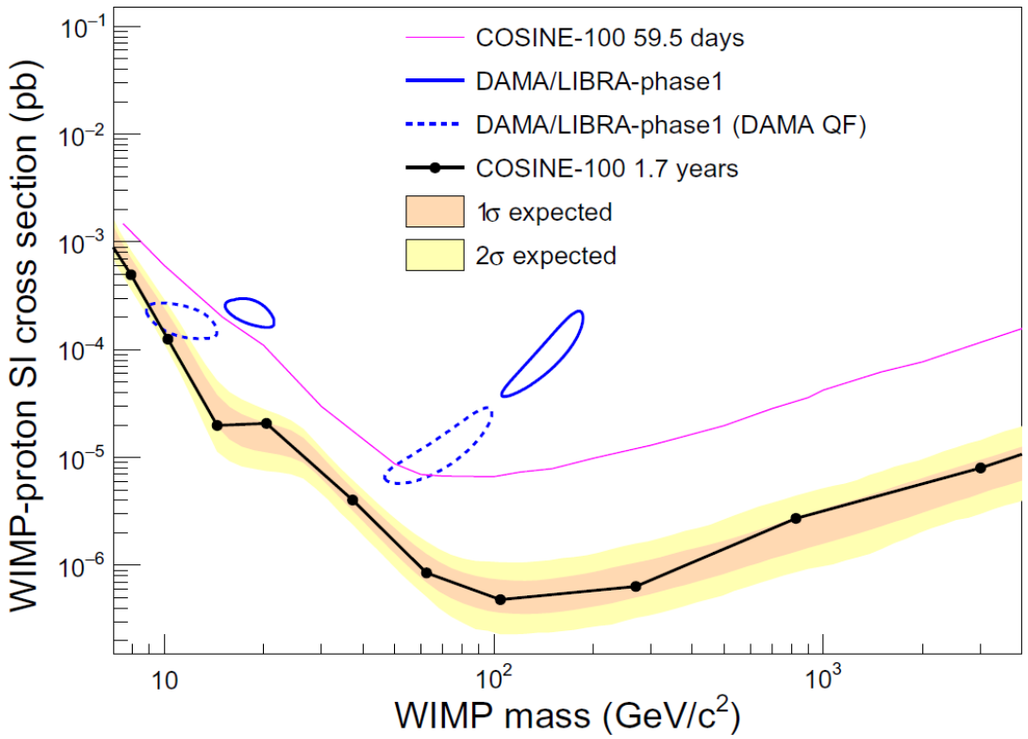
- YangYang underground laboratory
  - **October/2016 ~ March/2023**
- Decommissioning
  - Move to **Yemilab**
  - Upgrade of detector for **high light yield**

Rule out DAMA/LIBRA by COSINE-100

Model-dependent comparison



Nature 564, 83-86 (2018)



Sci. Adv. 7, eabk2699 (2021)

COSINE-100 data ruled out DAMA/LIBRA's 3 sigma contours for the canonical WIMP dark matter model

Bosonic superWIMP

- **KU group proposed a new mechanism to search for Bosonic superWIMP**

PHYSICAL REVIEW D **104,** 083030 (2021)

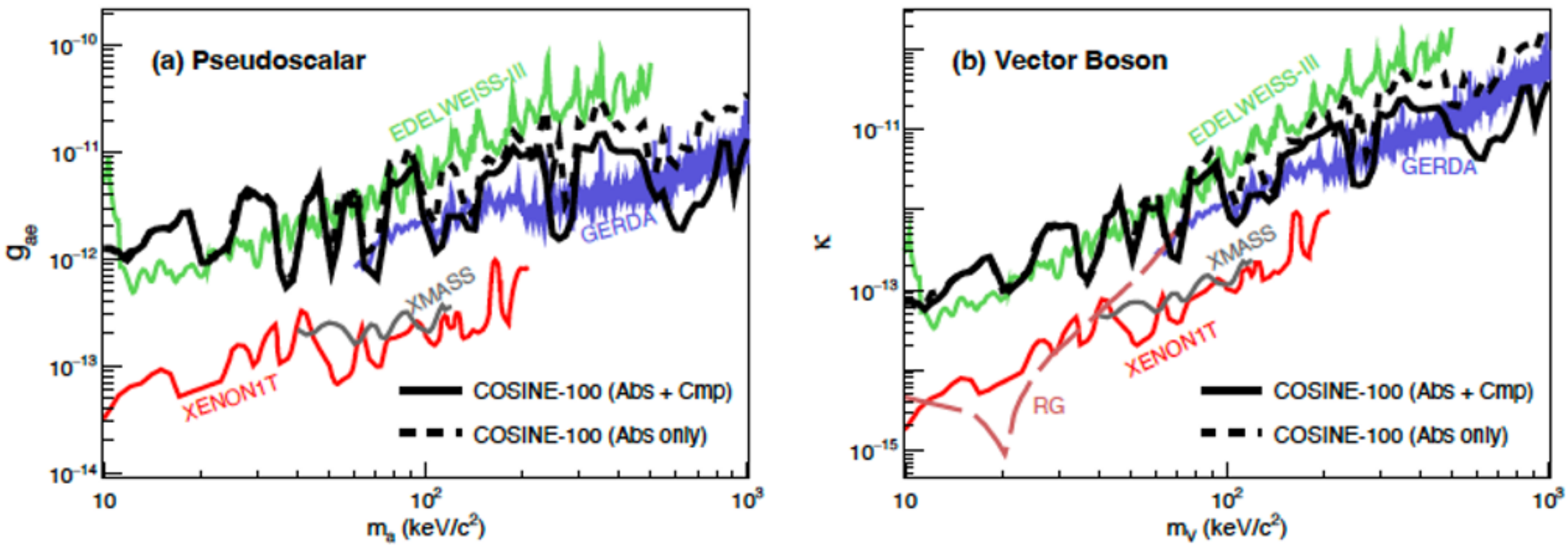
Remarks on bosonic super-WIMP search experiments

Young Ju Ko[1,*] and HyangKyu Park[2,†]
[1]*Center for Underground Physics, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea*
[2]*Department of Accelerator Science, Korea University, Sejong 30019, Republic of Korea*

(Received 4 June 2021; accepted 3 October 2021; published 26 October 2021)

Bosonic super–weakly interacting massive particles (WIMPs), including pseudoscalar and vector particles, are dark-matter candidates. To date, many underground experiments searches for super-WIMPs have been performed in the mass range of a few keV/c^2 to 1 MeV/c^2. All these searches utilize the

- **Search for Bosonic superWIMP with COSINE data**

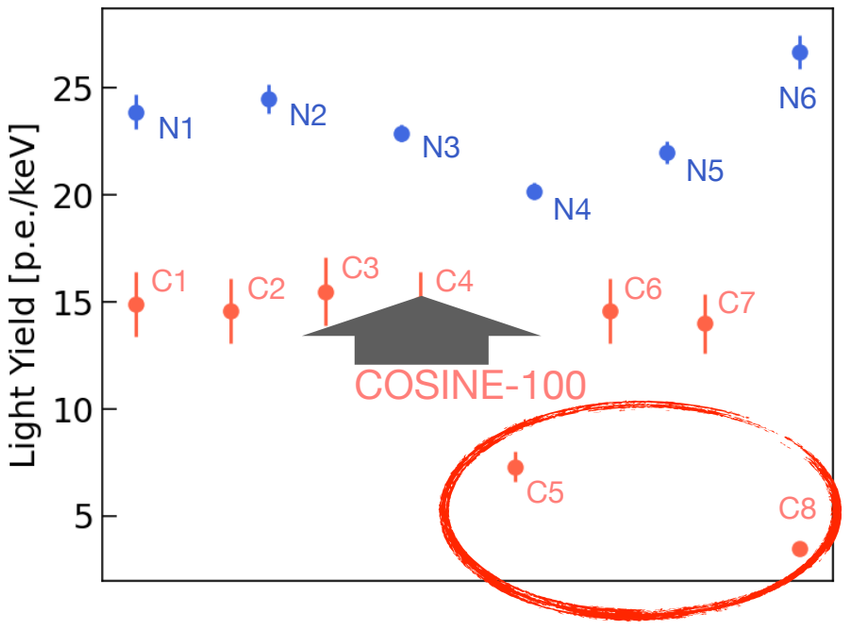


Phys. Rev. D 108,L041301 (2023)

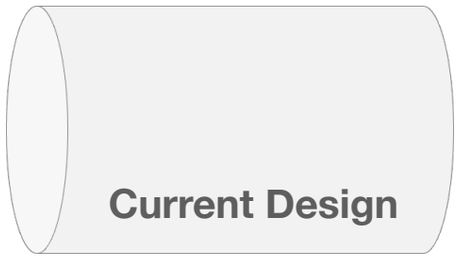
Moving forward to COSINE-100U (Upgrade)

Machining & Encapsulation

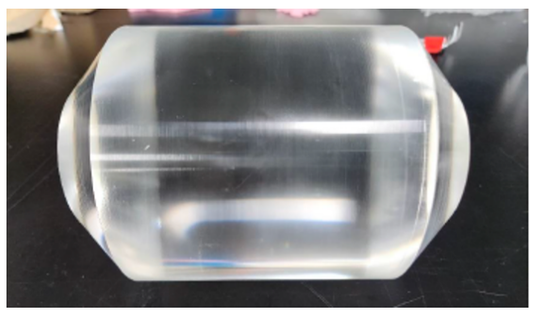
- Novel technique of crystal encapsulation
  - Direct attachment of crystals to PMTs
  - ~50% increased light yield
- COSINE-100 upgrade
  - Machining for design w/o light guide
  - Direct attachment



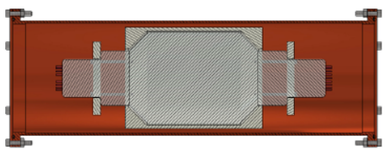
Expect to improve light yield



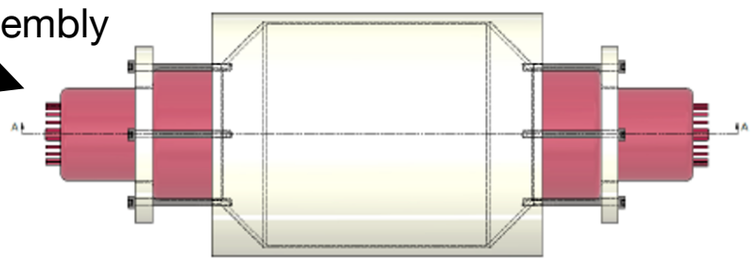
Machining crystal



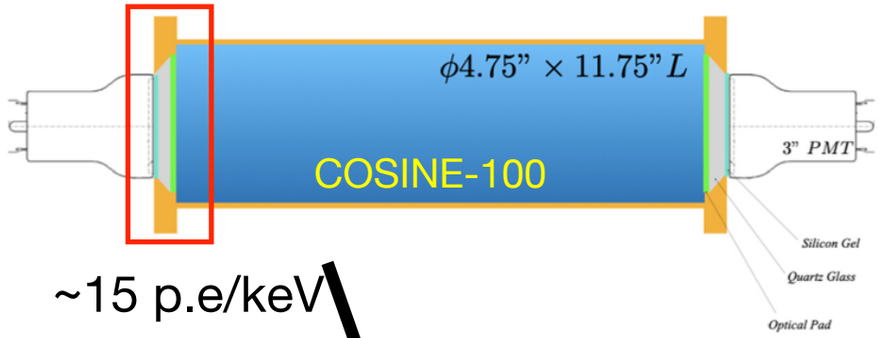
New Design



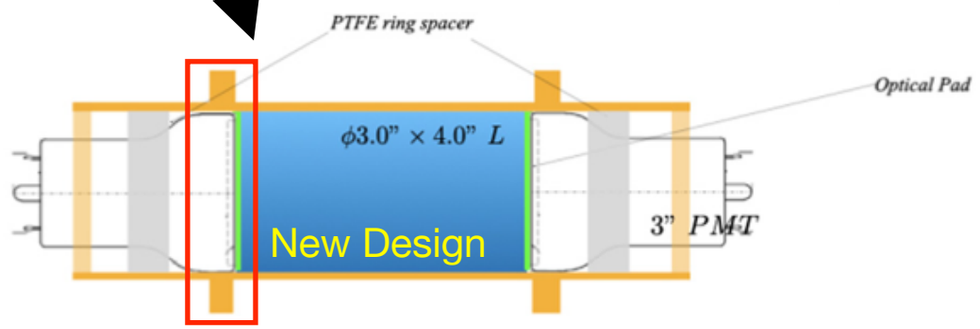
Assembly



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



~15 p.e/keV



~20 p.e/keV

KU Contribution: Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has 2-3 times higher background than DAMA/LIBRA
  - In-house development for the entire process
    - **NaI powder purification**

J. Rad. Nucl. Chem. 317, 1329 (2018)
JINST 15, C07031 (2020)

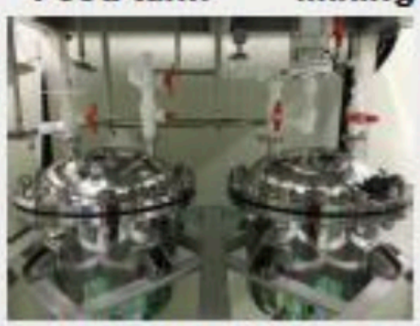
	K [ppb]	Pb [ppb]	U [ppb]	Th [ppb]
Initial	248	19.0	< 0.01	< 0.01
Purified	**< 16**	**0.4**	< 0.01	< 0.01

KU designed this system


Feed tank


Mixing tank


Filter unit

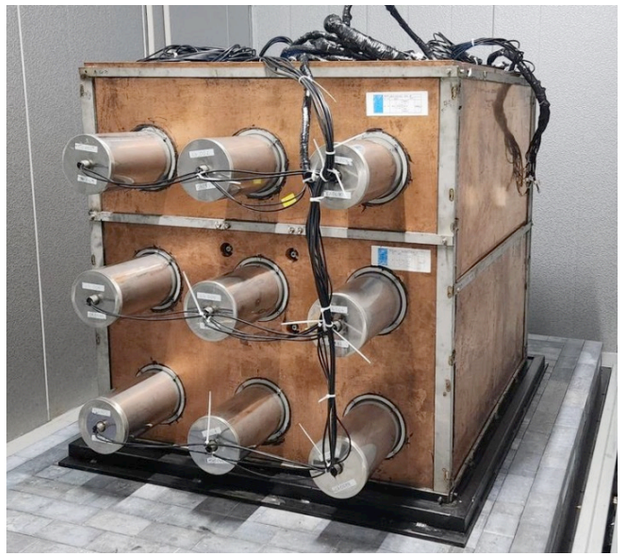

Receiver tank 1, 2


Conical dryer

COSINE-100U : Yemilab installation

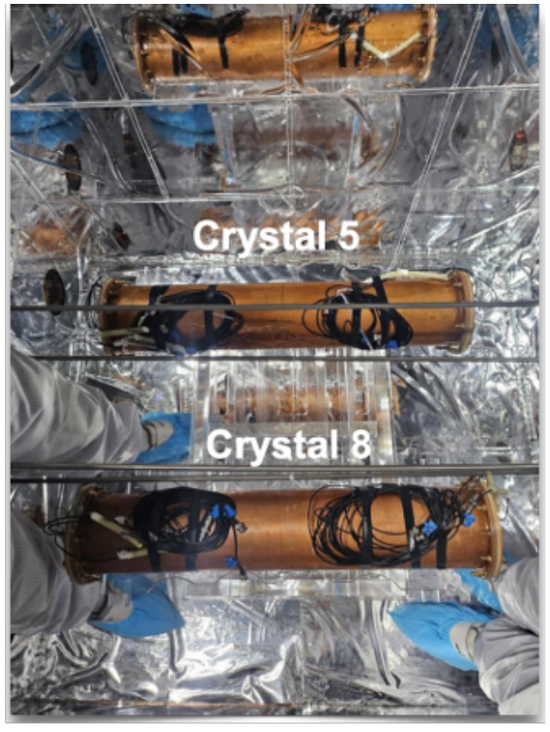
Freeze room for -30°C operation

Liquid scintillator veto



Lead shield

Crystal installation

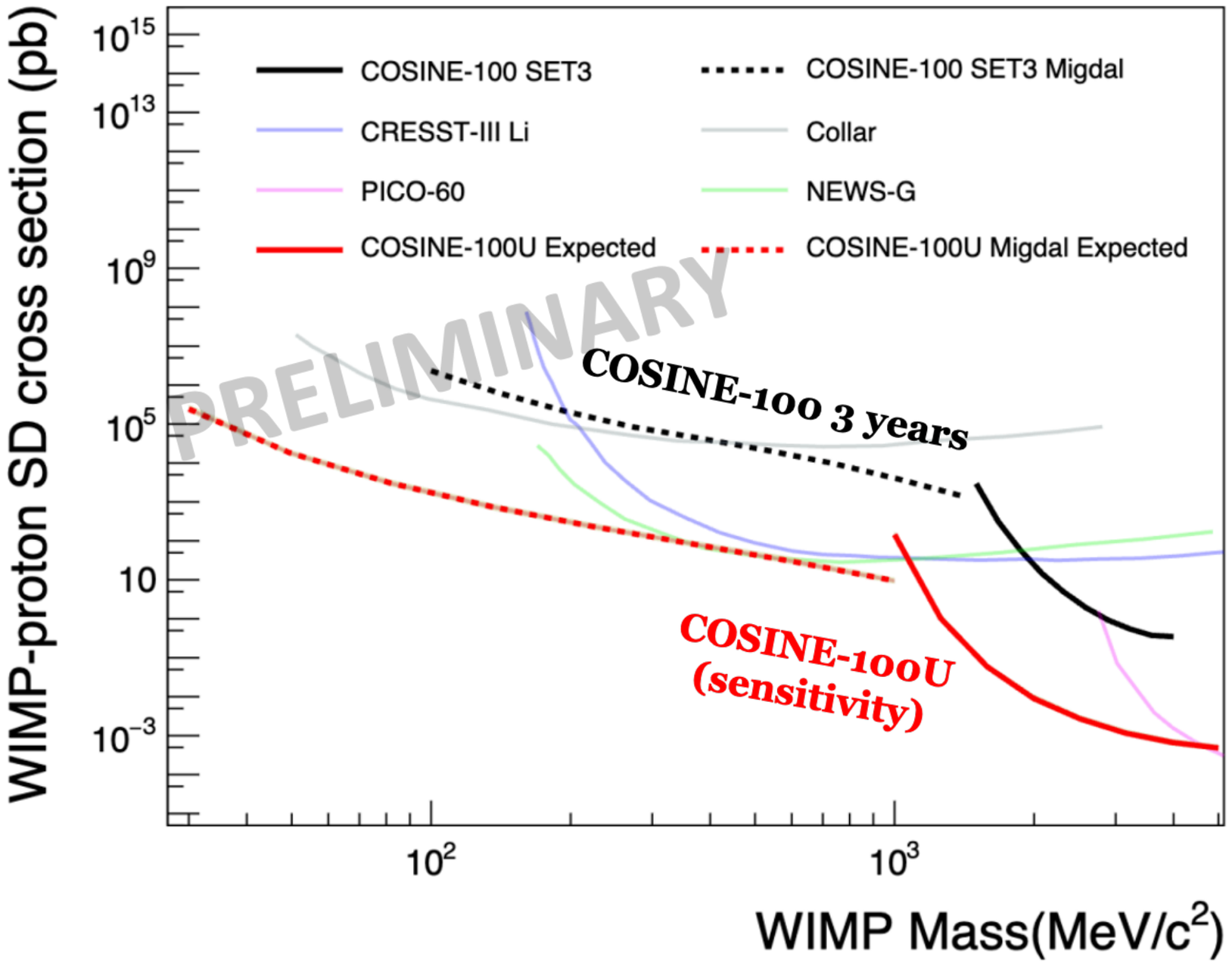


COSINE-100U schedule

	2024-(1-3)		2024-(4-6)		2024-(07-08)		2024-09		2024-10	2024-11
Crystals			Assembling & Installation				T E S T			
Liquid Scintillator		PMT Install LS Production				Pouring LS			→	
Lead Shield	Bottom		Side					Top	Physics operation!!	
Electronics				Server, HVS, Monitoring						
Muon detector			holder				PS install			

- All crystals were encapsulated already
- We plan to start COSINE-100U in October/2024

Sensitivity of COSINE-100U



Summary

Two major experiments in Yemilab.
- KU is one of core universities.

- **AMoME for 0νββ search**
  - AMoRE-II is being prepared to start its 1st stage data taking in 2024, using 90 ea (27 kg) of $Li_2{}^{100}MoO_4$ crystals.
  - Background level at ROI~10^{-4} counts/keV/kg/year.
  - Discovery potential of 0νββ with 500 $kg_{Mo\text{-}100}$·year exposure: $T_{1/2}$~4×10^{26} years, $m_{\beta\beta}$ ~ 20-35 meV.
- **COSINE for dark mater search**
  - COSINE-100 ruled out DAMA/LIBRA with significance above 3 sigma in model-independent analysis
  - COSINE-100U will have world competitive sensitivities for low-mass dark matter searches

謝謝

Low temperature detector for AMoRE

- Metallic magnetic calorimeter (MMC) + SQUID operating at ~10 mK.

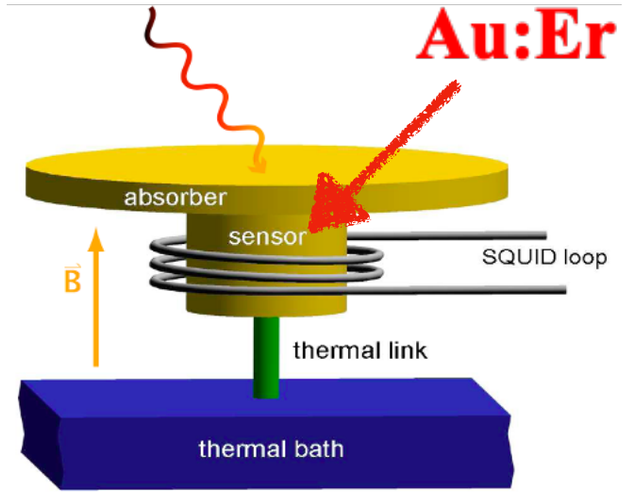
Principle of operation

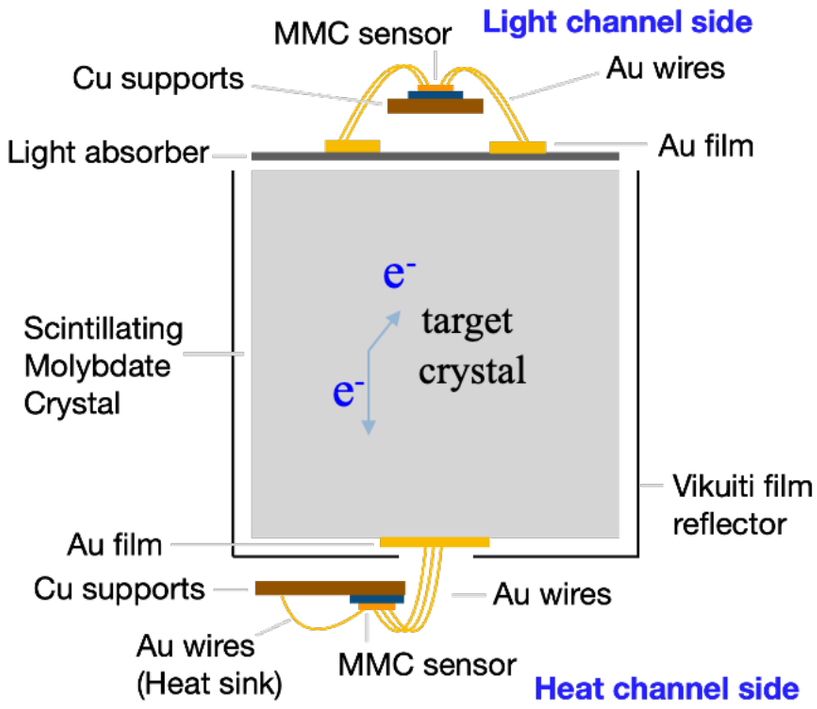
1. Energy absorption in crystal.
2. Phonon & Photon generation.
3. Temperature increase (gold film).
4. Magnetization of MMC decrease.
5. SQUID pickup the change.

Advantage of MMC

- Fast rising signal : ~0.5 ms (critical to reduce 2νββ random coincidence)
- Fairly easy to attach to absorber.
- Excellent Energy resolution

paramagnetic sensor:

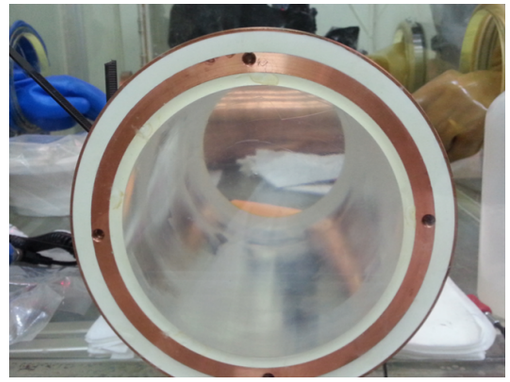


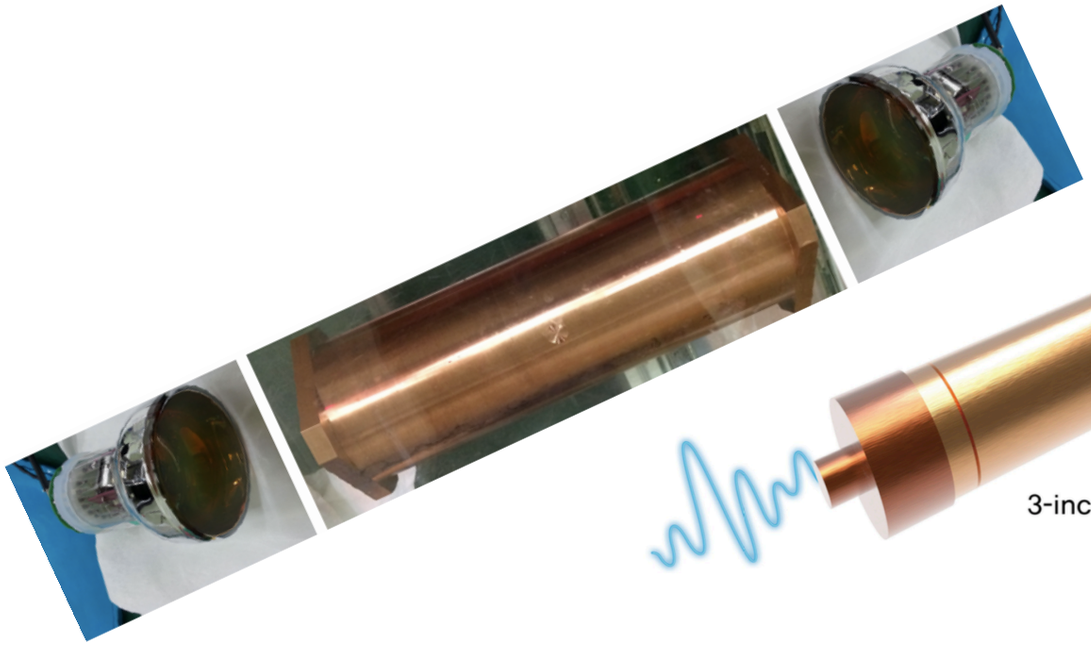


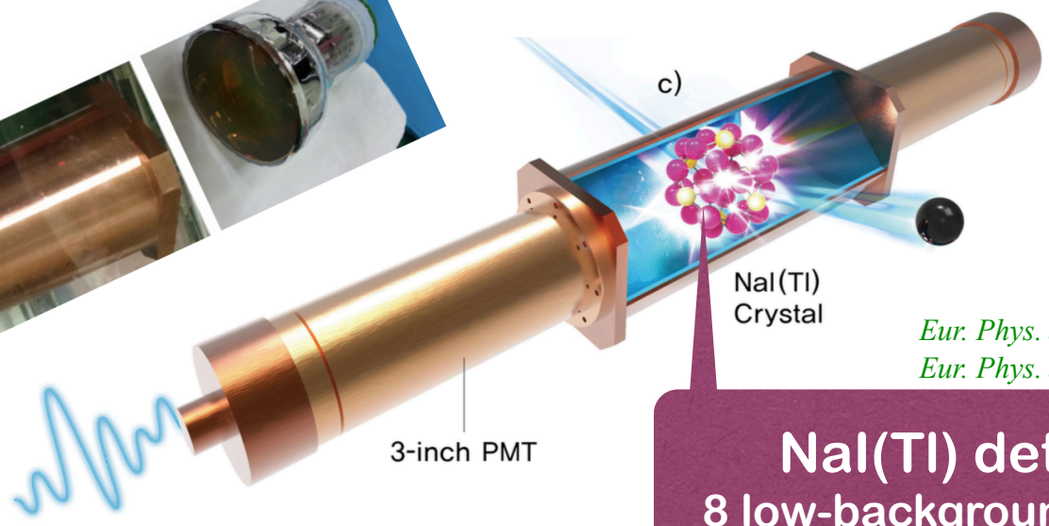
COSINE-100

Detector Configuration

- 8 low-background NaI(Tl) crystals w/ 106 kg in total
  - 2-3 times higher background compared to DAMA
    - Less U/Th/K level
    - Higher total α rate (~ ^{210}Pb)
  - Higher light yield than DAMA







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

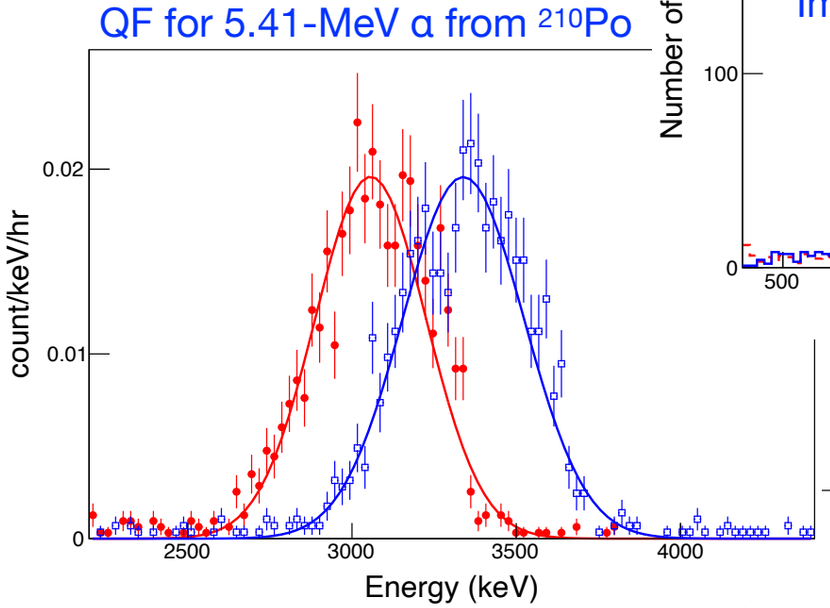
NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

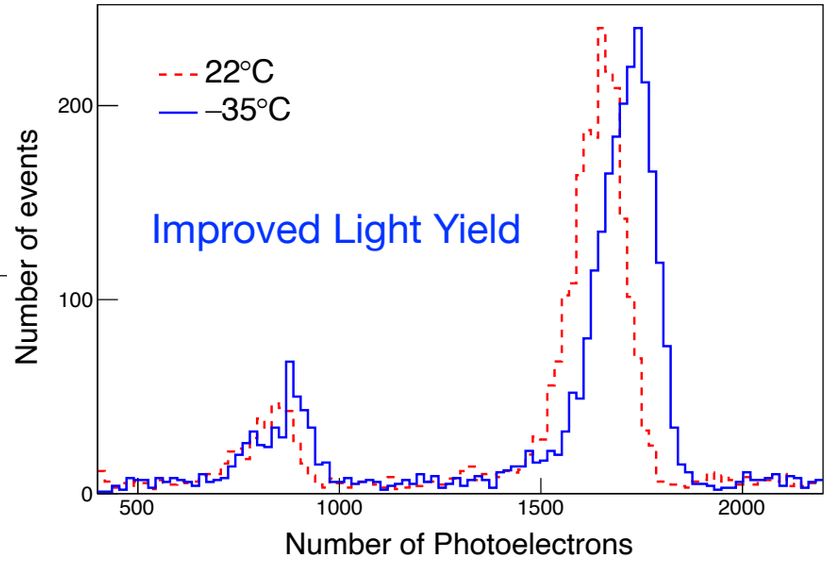
Plans for COSINE-100 Upgrade

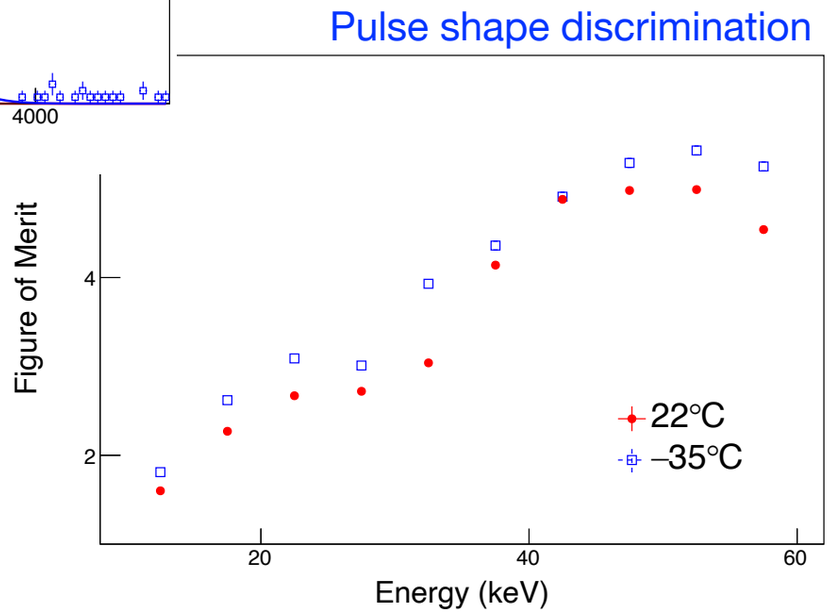
Operation at -35°C

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

- Better performance at -35°C
  - ~4.7% increased light yield
  - ~9.3% increased QF for α
  - Improved n-γ discrimination
- Installation refrigerator







Next Phase, COSINE-200

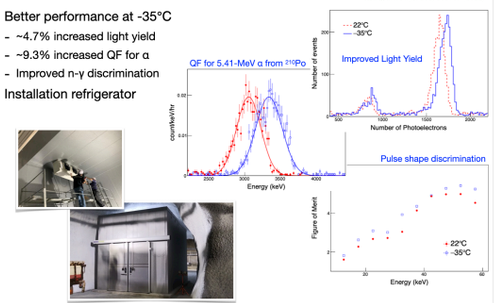
Crystal Development

COSINE-200

COSINE-100 upgrade

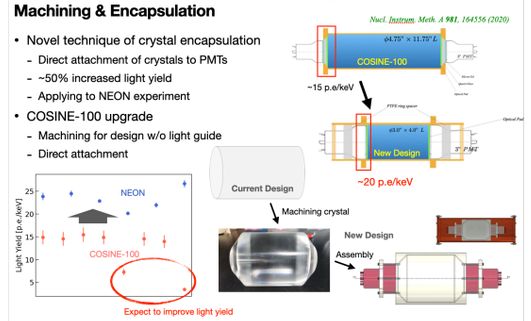
Plans for COSINE-100 Upgrade
Operation at ~35°C

- Better performance at ~35°C
  - ~4.7% increased light yield
  - ~9.3% increased QF for α
  - Improved n-γ discrimination
- Installation refrigerator



Plans for COSINE-100 Upgrade
Machining & Encapsulation

- Novel technique of crystal encapsulation
  - Direct attachment of crystals to PMTs
  - ~50% increased light yield
  - Applying to NEON experiment
- COSINE-100 upgrade
  - Machining for design w/o light guide
  - Direct attachment



Crystal Development

- Goal: Lower background than DAMA
- In-house development for entire process
  - NaI Purification
  - Crystal growing
  - Detector assembly
- Full size grower

Expected background