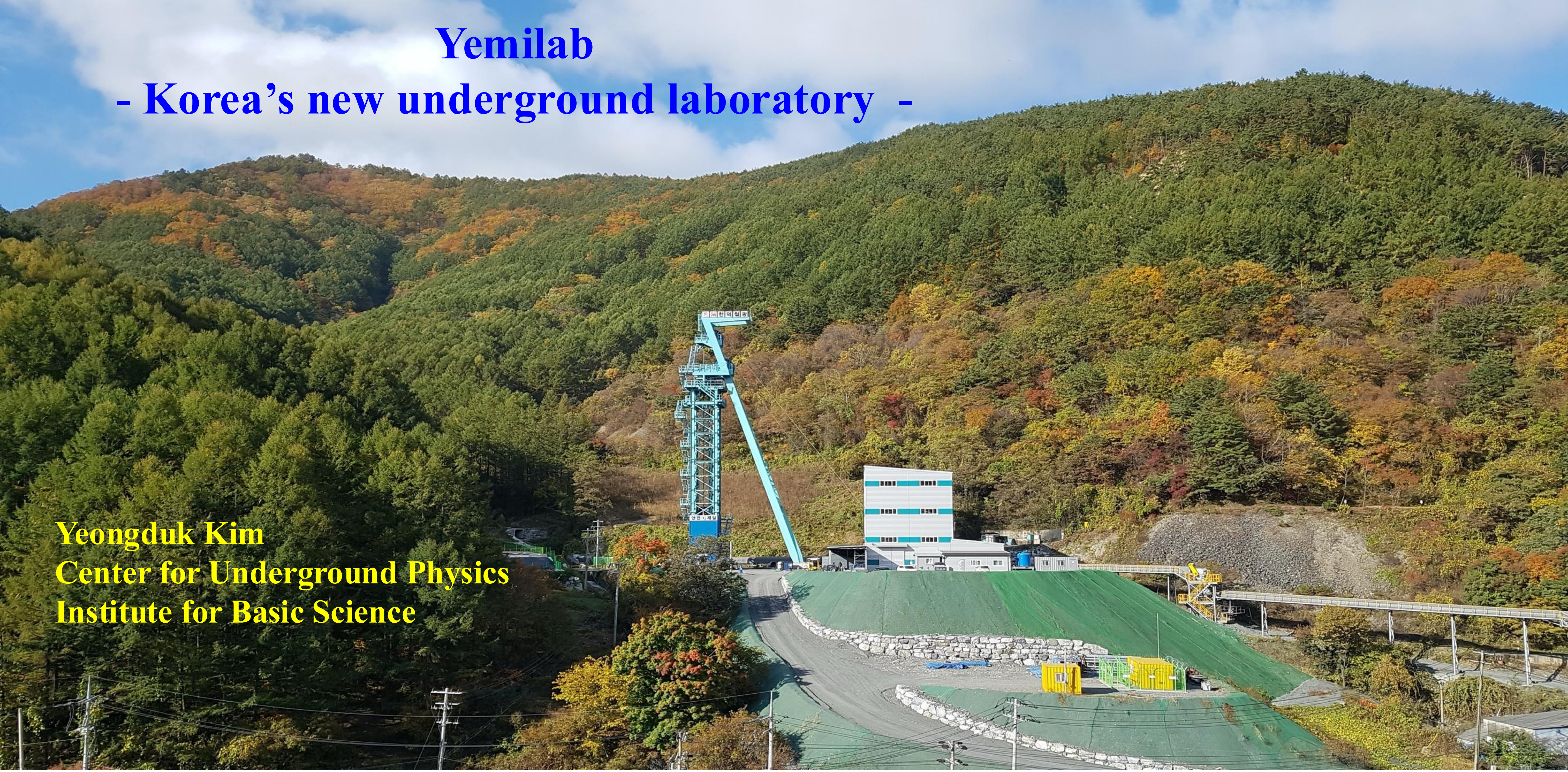
Yemilab
- Korea's new underground laboratory -



Yeongduk Kim
Center for Underground Physics
Institute for Basic Science

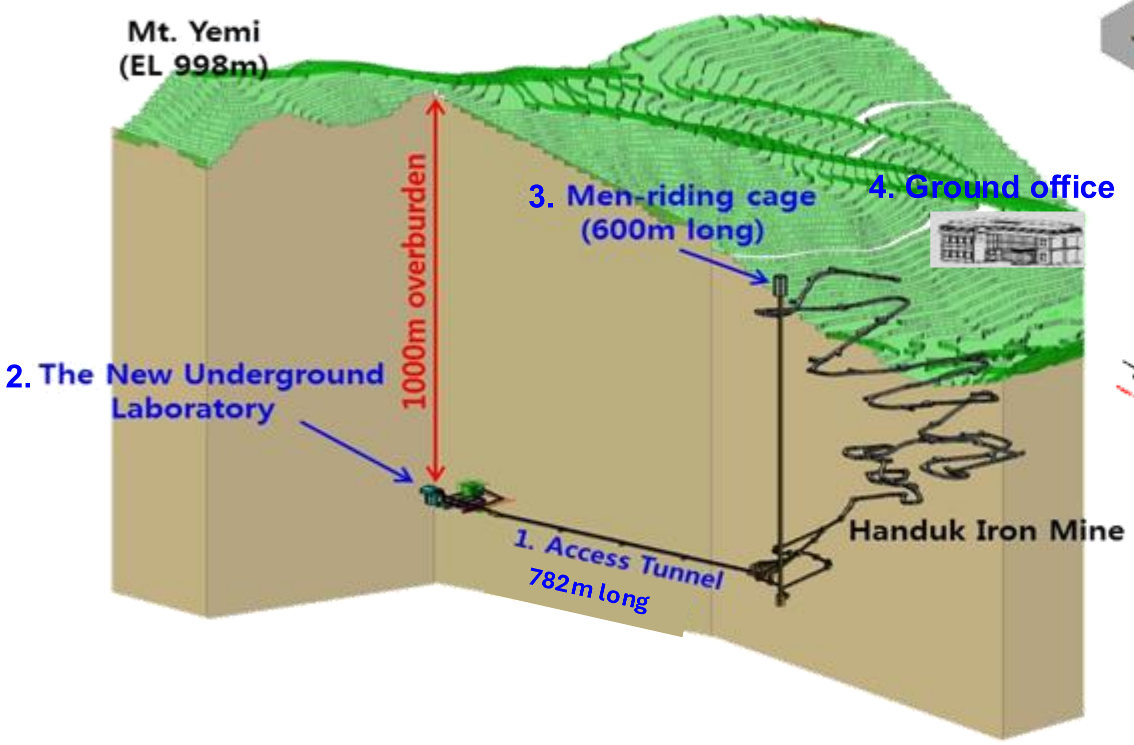
2025. 5. 30. INPC 2025, DCC, Daejeon, Korea

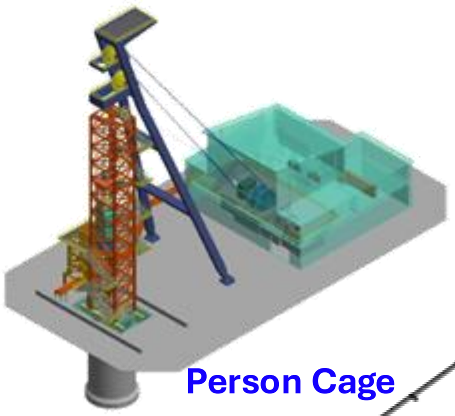
Brief history of underground laboratories

- **Y2L was constructed in 2003 to house KIMS dark matter search experiment.**
- **2013 : CUP established.**
- **2020 : Yemilab Phase-I constructed.**
- **2022 : Yemilab Phase-II constructed.**
- **2023 : Y2L moved to Yemilab.**
- **2025 : Yemilab Operation Center established.**

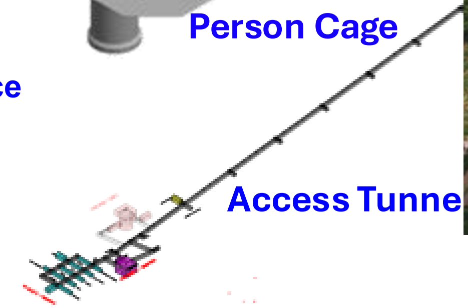
Yemilab Overview

1. Access Tunnel, 782 m long with 12% down slope
2. Underground Lab: 3000 m^2
3. Person Cage, running vertical 587 m
4. Ground Office: 2500 m^2



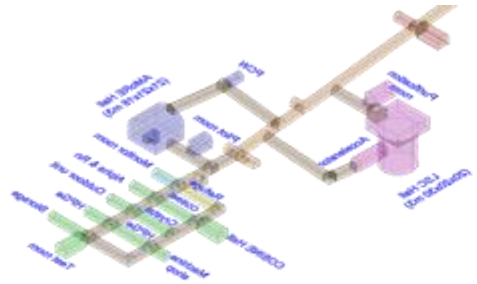


Person Cage

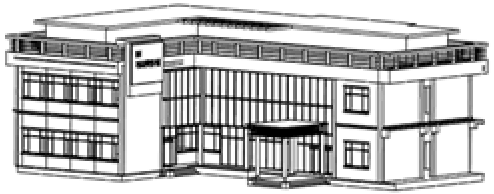


Access Tunnel

Bird view of Handeok Iron Mine



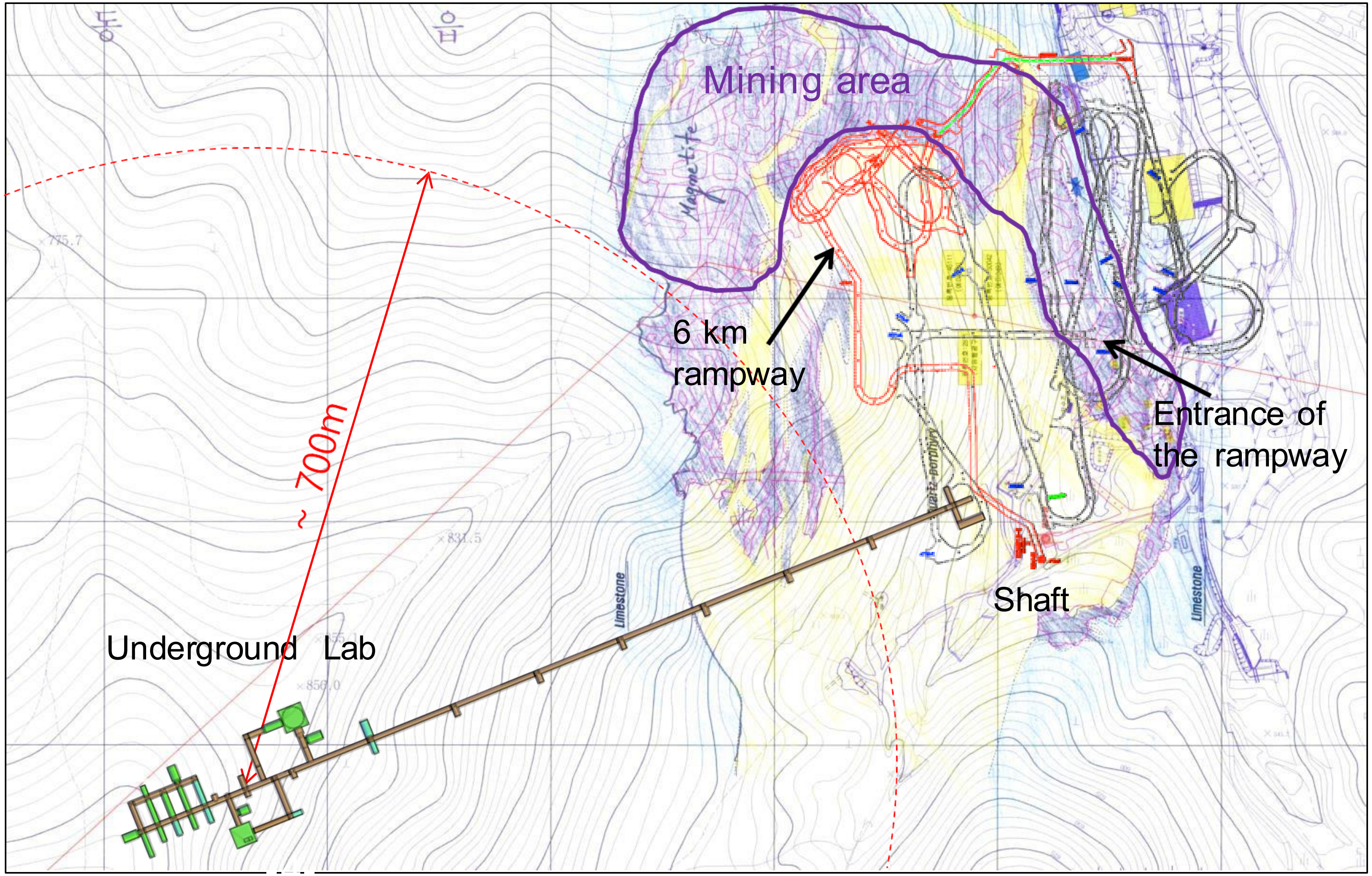
Underground Lab



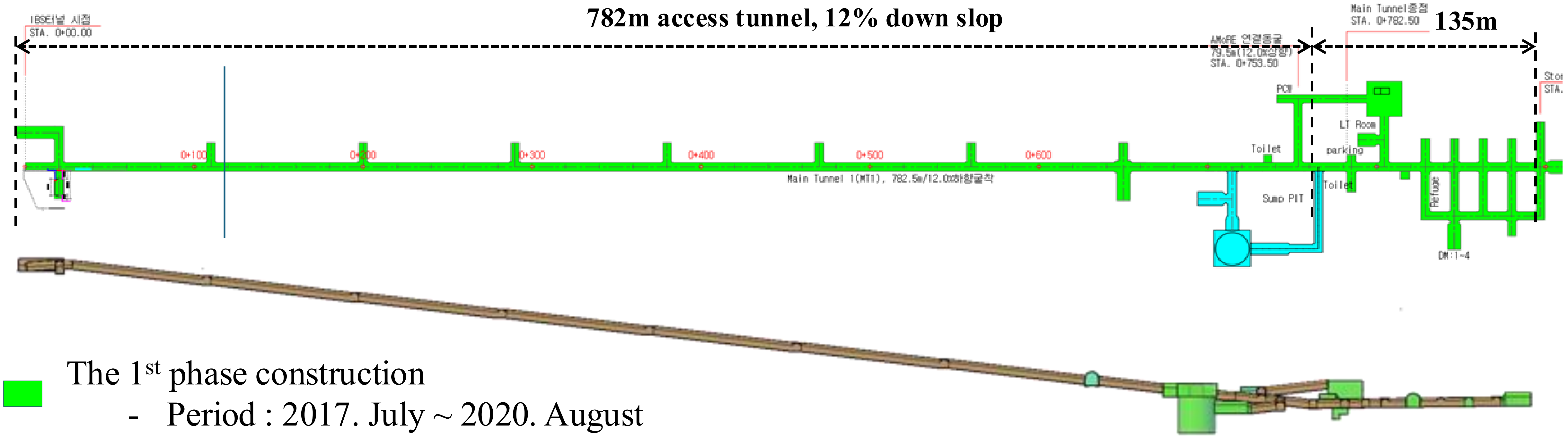
Ground office

Mine vs Yemilab

➢ The UL is going to be located further away from the active mining area by ~ 700 m



Construction of the Yemilab



The 1st phase construction

- Period : 2017. July ~ 2020. August
- Cage installation in the shaft
- 1st phase Excavation : 2000m²

The 2nd phase construction

- Period : 2021. May ~ 2022. July
- 2nd phase excavation : 1000m²
- Electricity and machinery
- Ground office renovation

Access to Yemilab

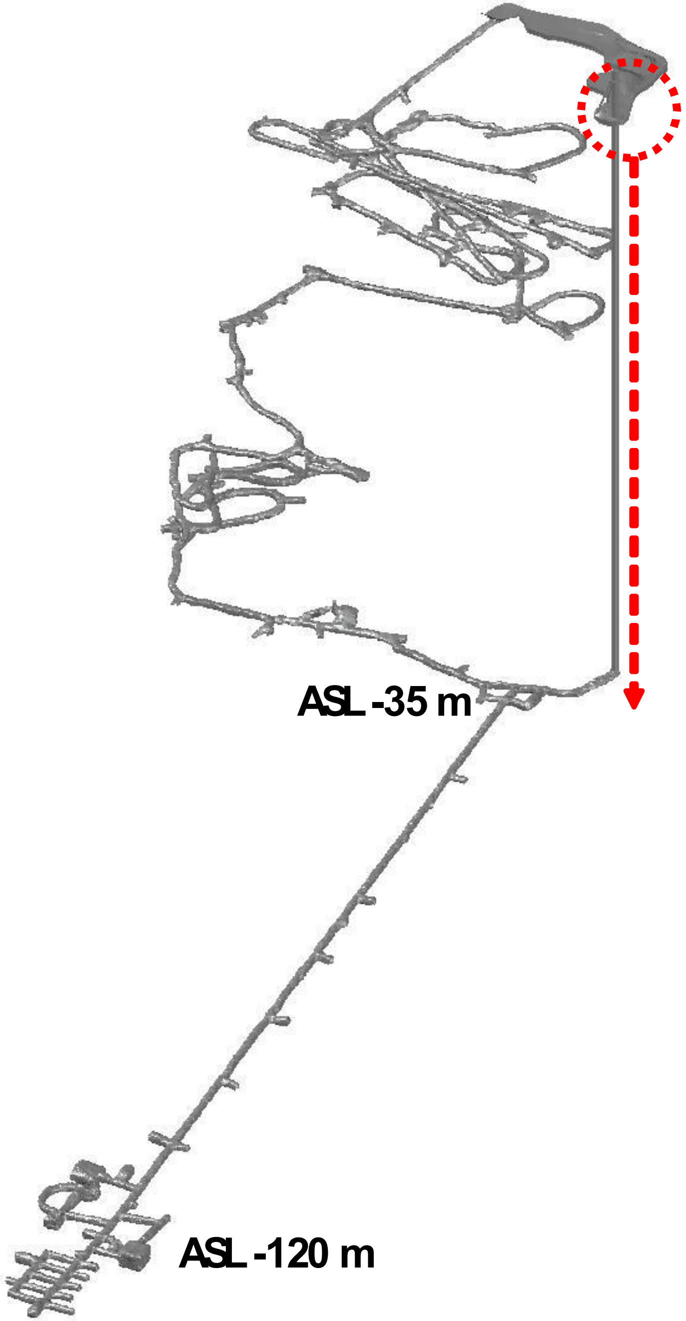
Access to Yemilab

Through 600-meter vertical sha

- Φ 6 m, skip for transporting ore

Man riding cage

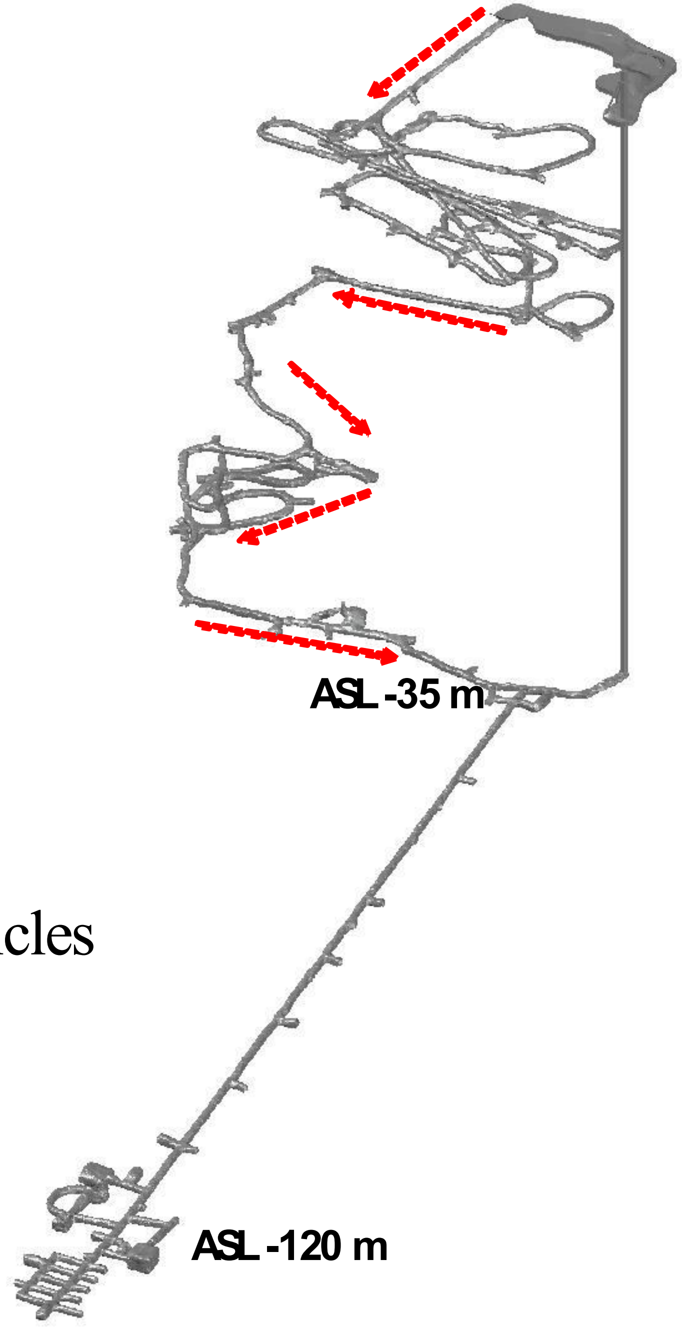
- Manufactured by SIEMAG
- 8 people, < 1.5 ton
- 4 m/s, 2.5 mins



Access to Yemilab

Through ramp way

- Unpaved road used by mining vehicles
- ~6 km to Yemilab, 20 mins by car
- Transporting cargo
- 5 m x 5 m tunnel cross-section
- Radio communication



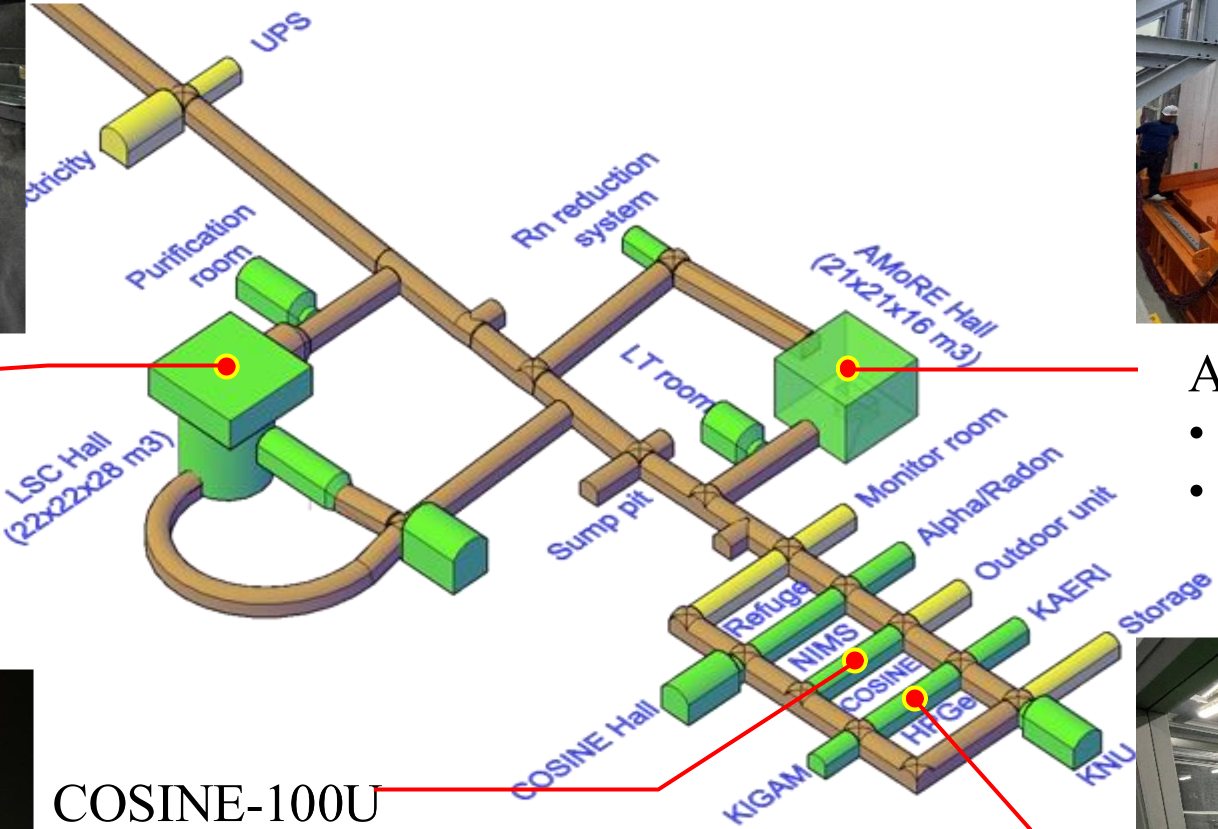
Experimental area of Yemilab

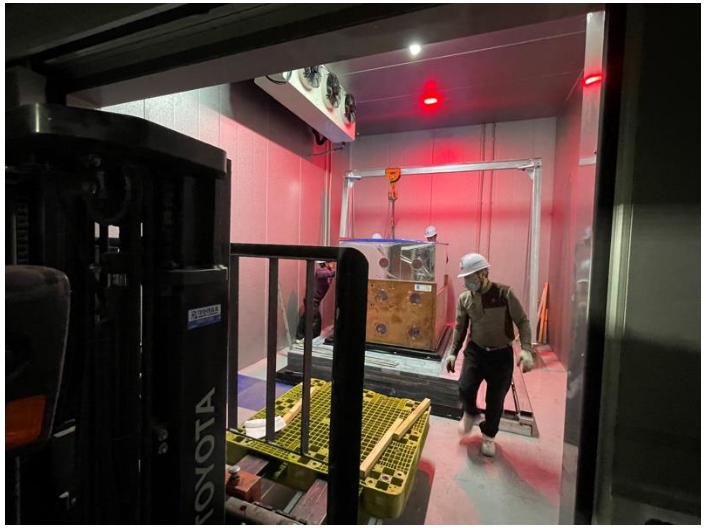
LSC Hall 10-ton crane

- Completion June 2023

AMoRE-II

- Shield structure done
- Late 2025, commissioning





COSINE-100U

- -30°C low-temp. room
- Moving Y2L detector to the room
- 2025, commissioning

HPGe

- Moving from Y2L
- Feb. 2024, start

Infrastructures

Electricity
- Power: 2500 KVA
- Backup generator (360 KW)
- 2 UPSs (80 + 180 KVA)

Air supply
- 39,000 m3/h circulation near vertical shaft
- 6,000 (radon-less air) m3/h at summer season

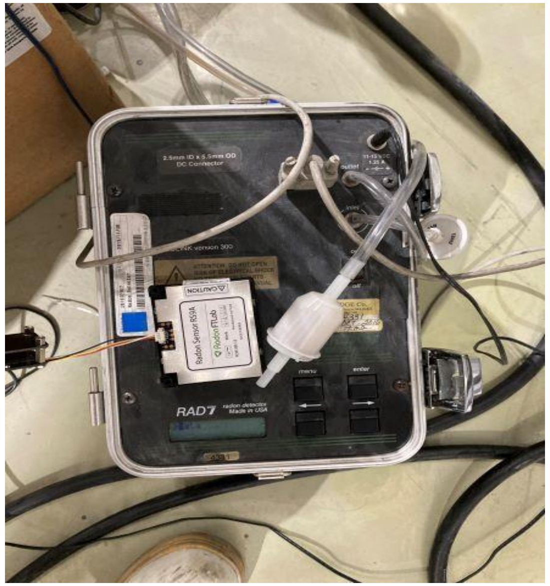
Communication
- Full mobile communication (LTE)
- 1 GB optical network to ground office
- Radio communication for emergency

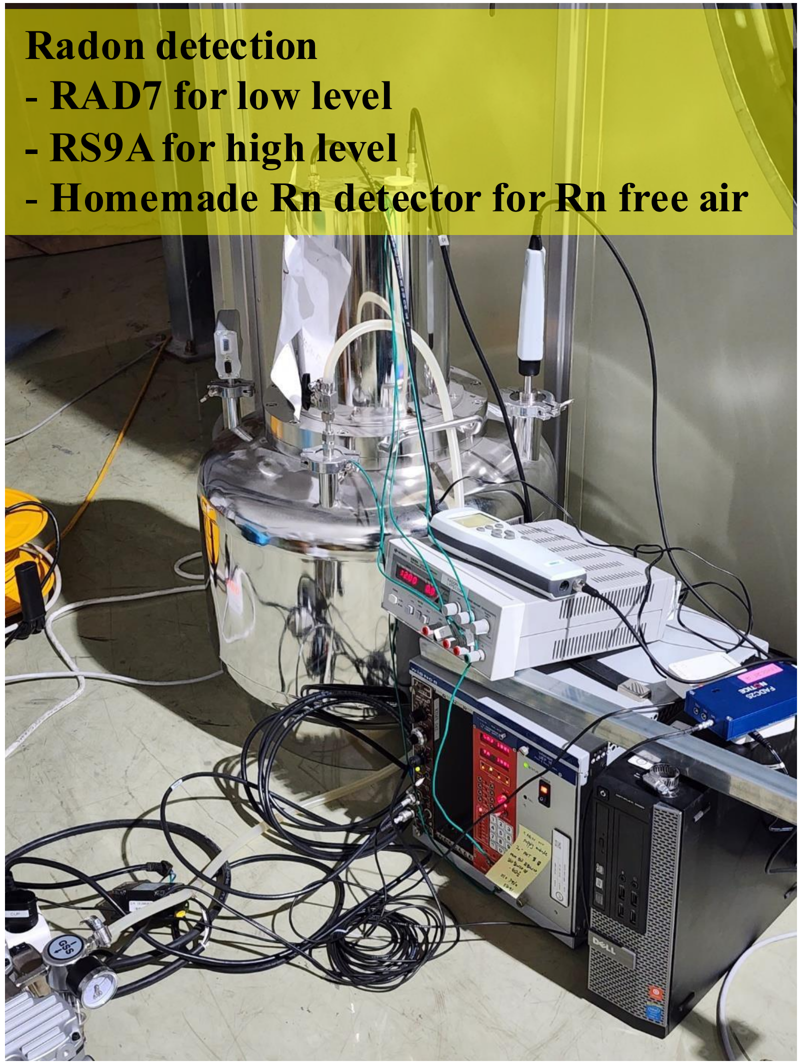
Radon Reduction System (RRS)
- 50 m3/h, 1/500 reduction
- **200 m3/h RRS is under consideration**

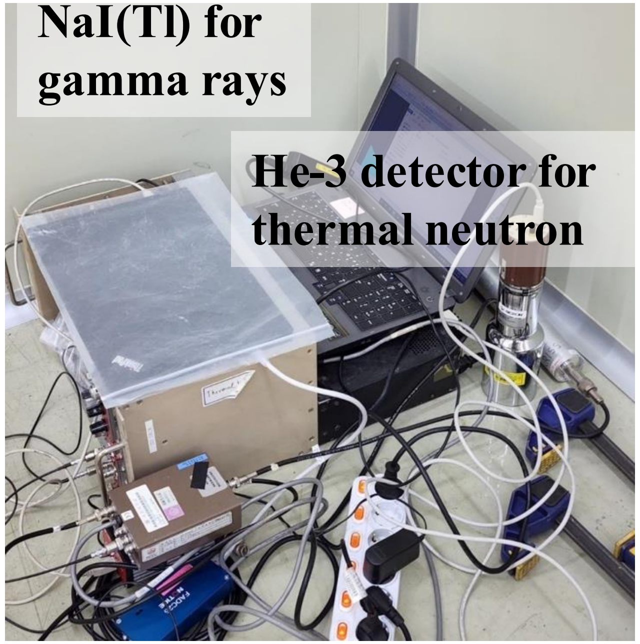
LN2 generators for cryostat and HPGe

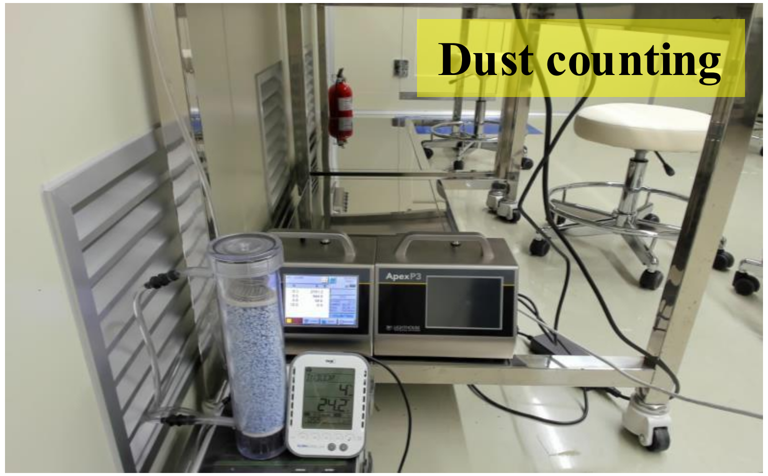
Refuge
- 40 people for 72 hours
- Normally used as a dining or meeting room

Environmental measurements

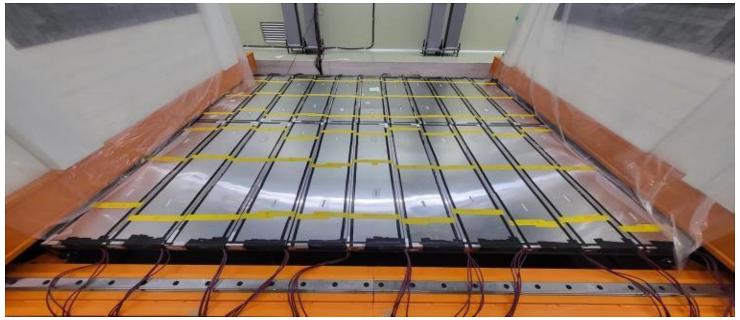








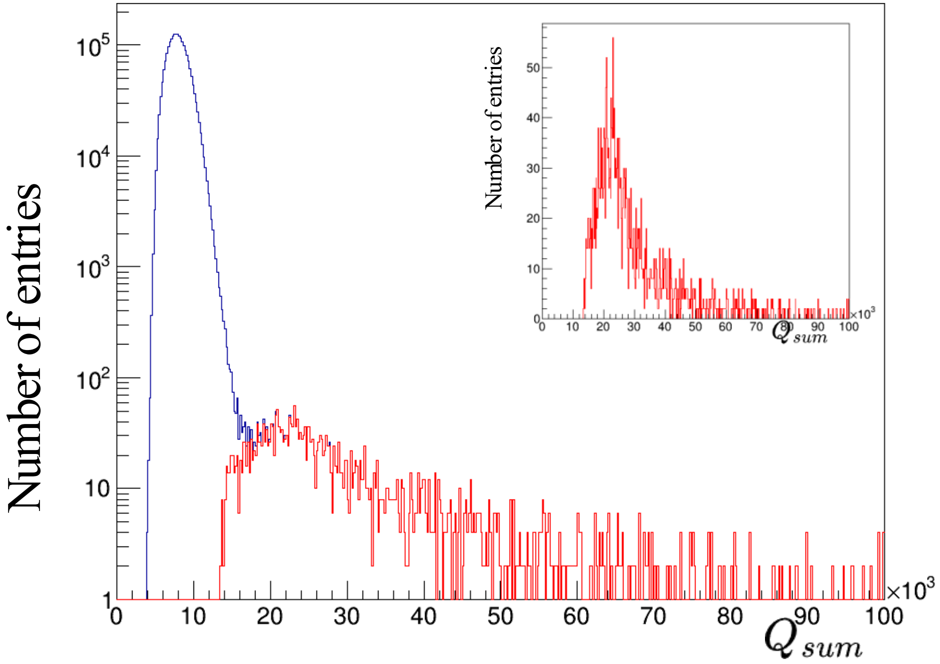
Muon Flux

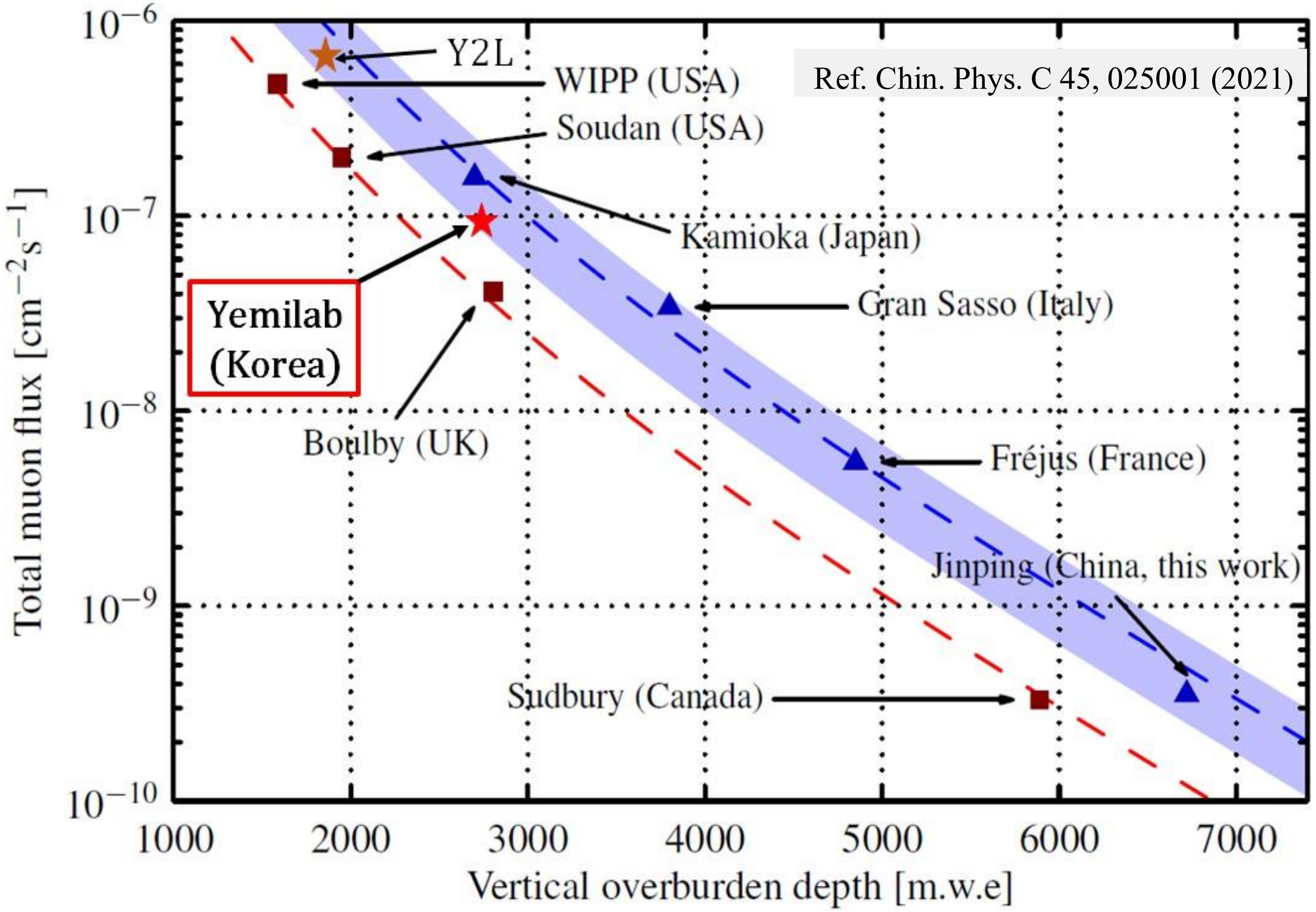


22 plastic scintillator panels (170 × 30 cm^2 for each, 11.2 m^2)

Preliminary muon rate at AMoRE Hall: $8.8 \times 10^{-8}/cm^2/sec$

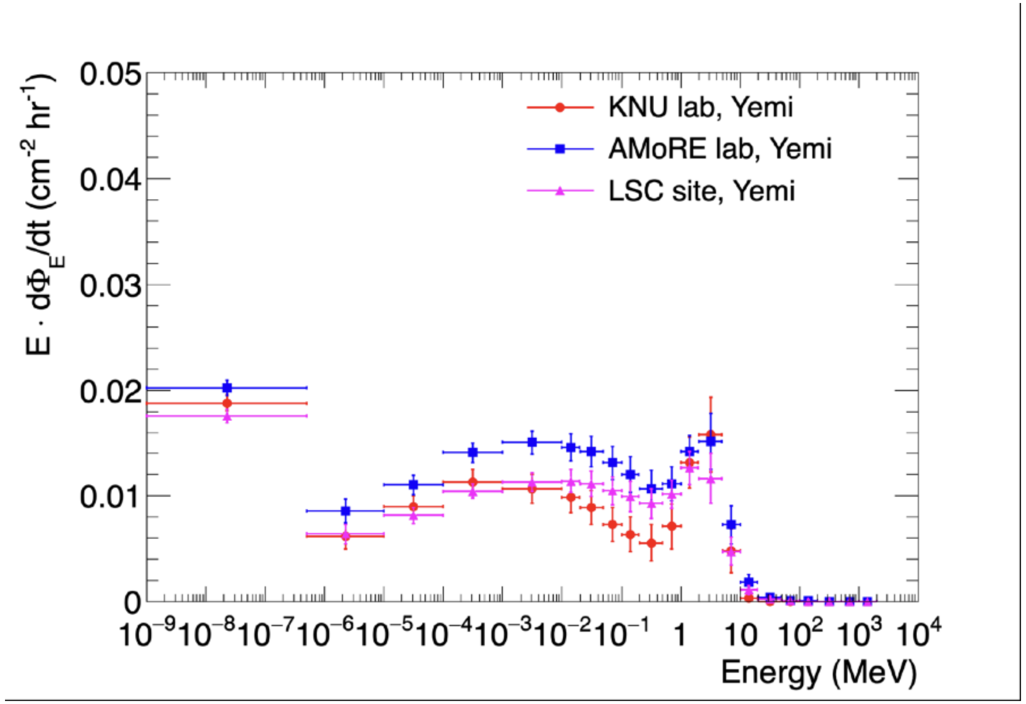
- Y2L: $3.8 \times 10^{-7}/cm^2/sec$



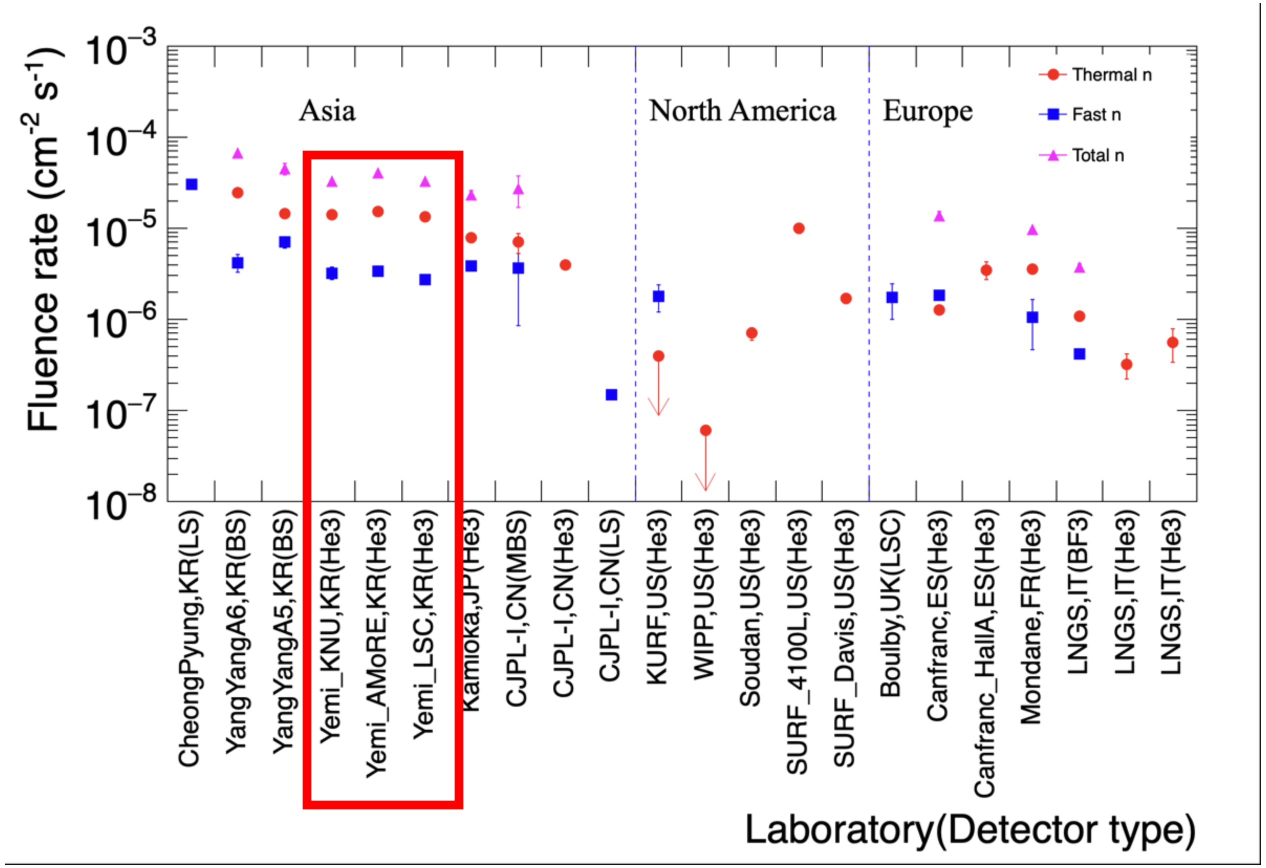


Neutron Flux @ Yemilab

High-sensitivity neutron spectrometer by KRISS

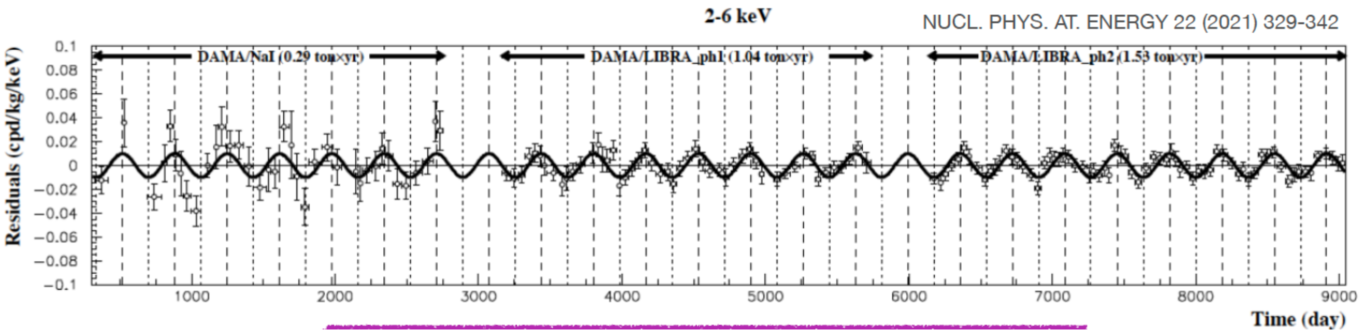


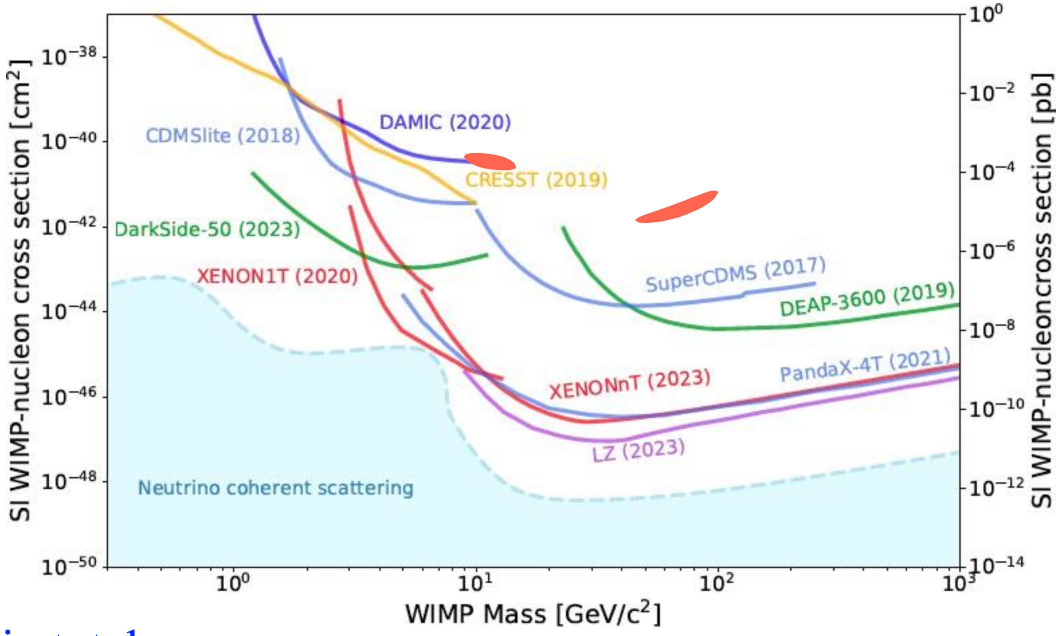
- Yemilab : A few hundreds of tons Shotcrete
  ~ 180 tons on AMoRE cavern
  High Rn level during summer season



COSINE-100 experiment (2016~2023) @ Y2L

DAMA/LIBRA's annual modulation signal has not been directly tested.





8 NaI(Tl) crystals, 106 kg in total

- Y2L
  - October/2016 ~ March/2023
- Decommissioning
  - Moved to Yemilab
  - Upgrade of detector for high light yield

Modulation fit results

6.4 years of COSINE-100 data were fot with decaying background model and modulation signal.

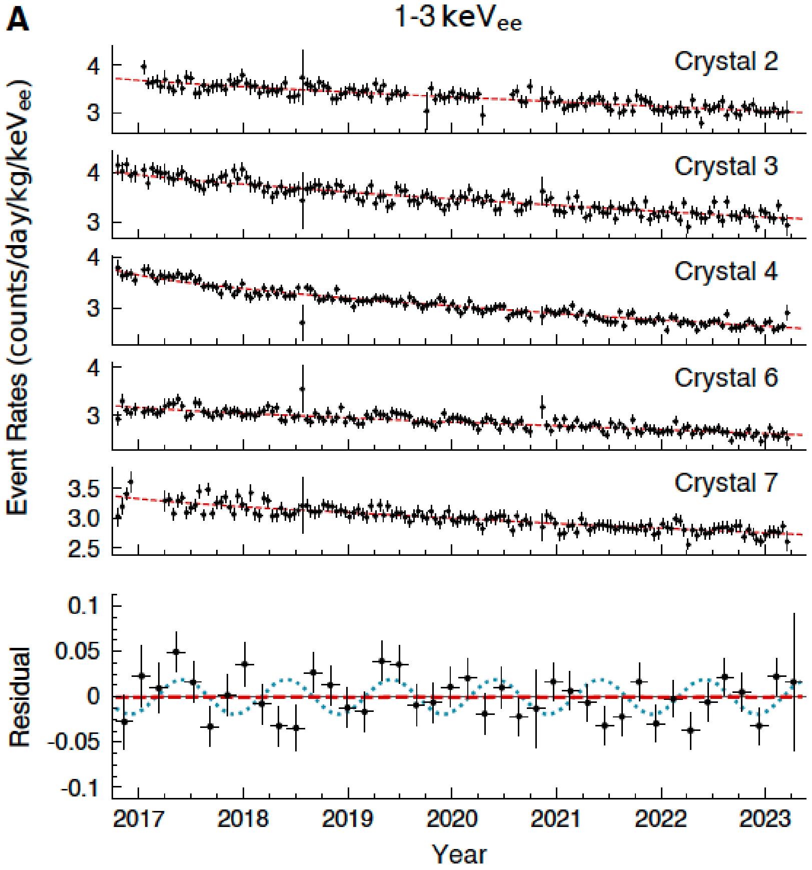
"COSINE-100 Full Dataset Challenges the Annual Modulation Signal of DAMA/LIBRA", N. Carlin et al., arXiv:2409.13226

$$R_i(t) = A\cos\left(\frac{2\pi(t-\phi)}{T}\right) + \sum_j C_{ij}e^{-\lambda_{ij}t}.$$

Modulation signals

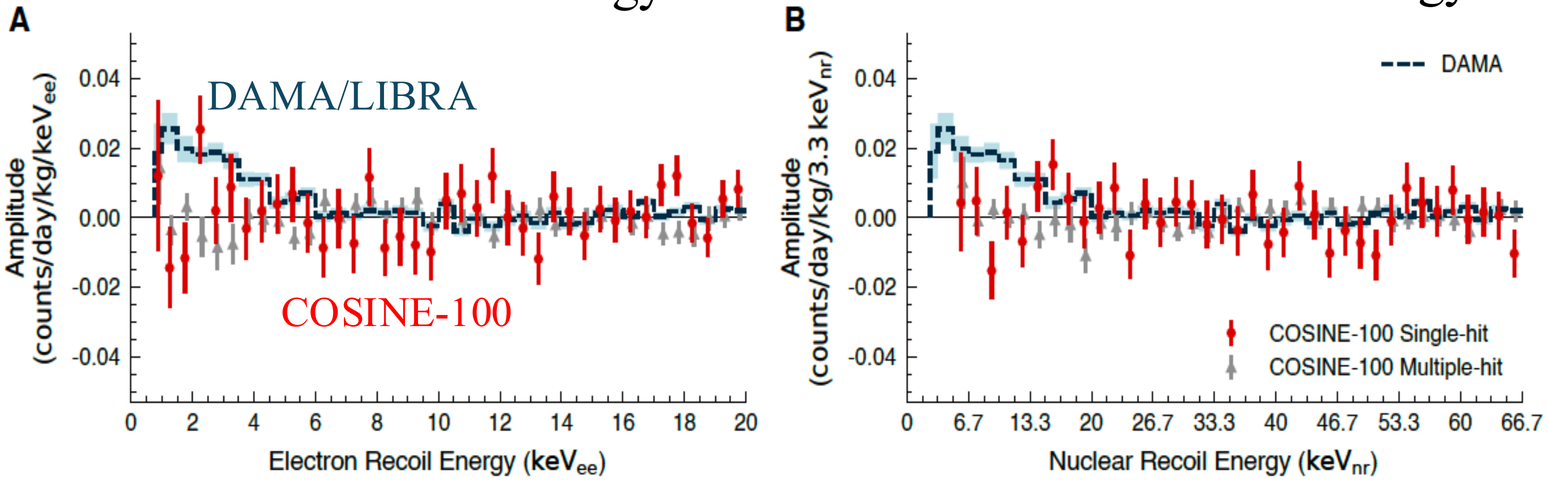
10 time-dependent components

→ No modulation signal observed !!



Electron Recoil Energy

Nuclear Recoil Energy



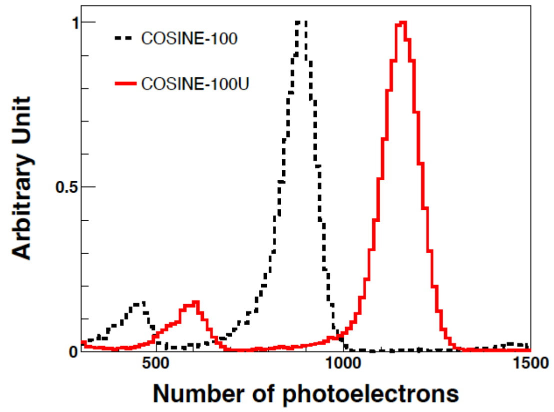
***E* (keV$_{ee}$)**	***A* (counts/day/kg/keV$_{ee}$)**	
	COSINE-100	DAMA/LIBRA
1~3	**0.001 ± 0.005**	0.019 ± 0.002
1~6	**0.002 ± 0.003**	0.010 ± 0.001
2~6	**0.005 ± 0.003**	0.010 ± 0.001

E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	0.001 ± 0.003	0.010 ± 0.001

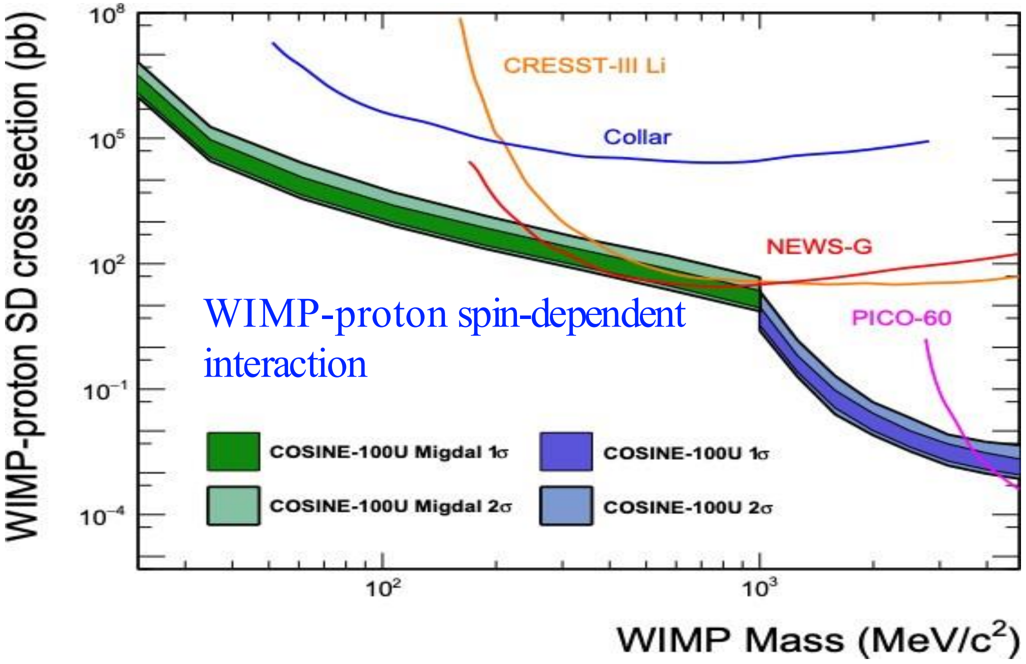
COSINE-100U

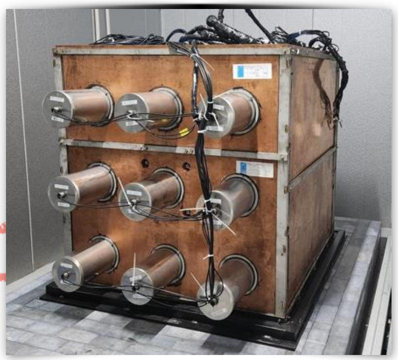
Updated experiment @ Yemilab

- Light yield improved by coupling update and lower temperature (-35^{o}C)
- Experiment will begin in 2025.

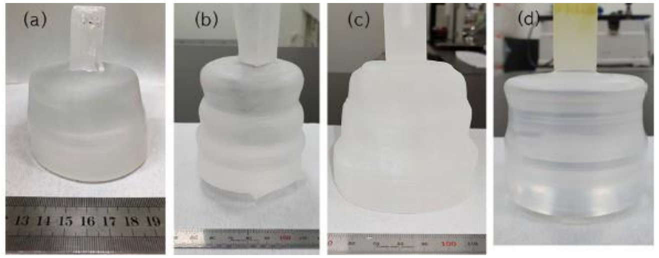


14.9 ± 1.5 → **20.1 ± 0.5** PE/keV
~40% increase in light yield.





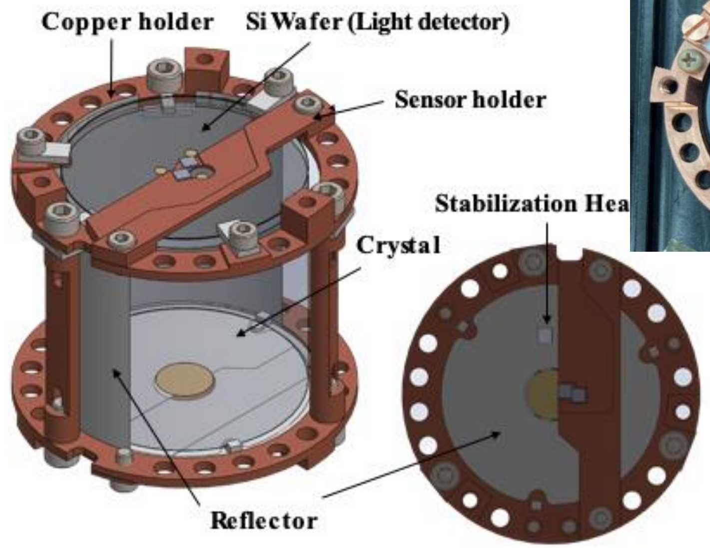
COSINE-200 with new crystals.



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

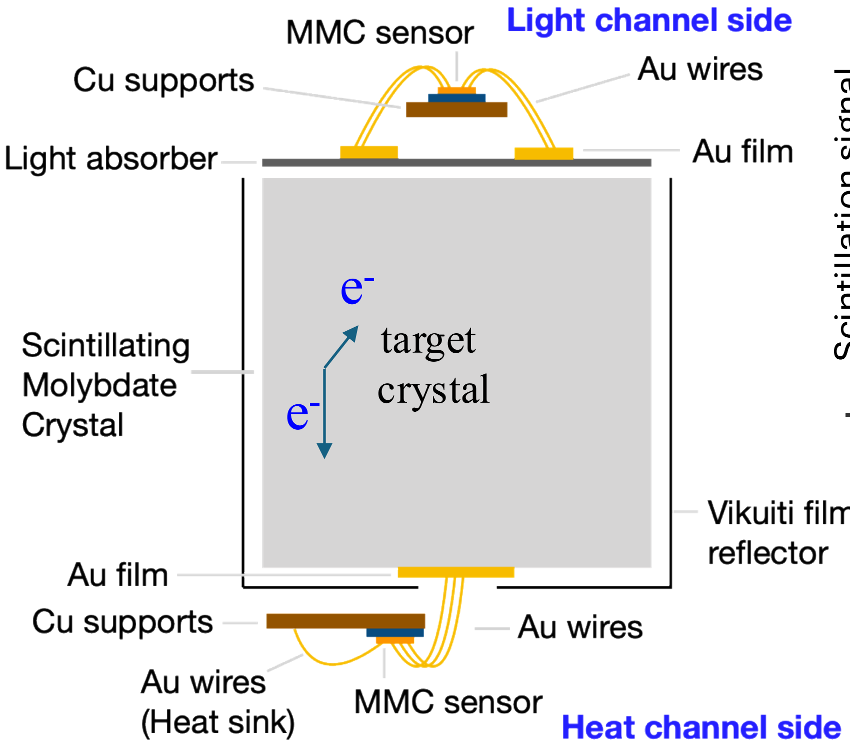
AMoRE Experiment

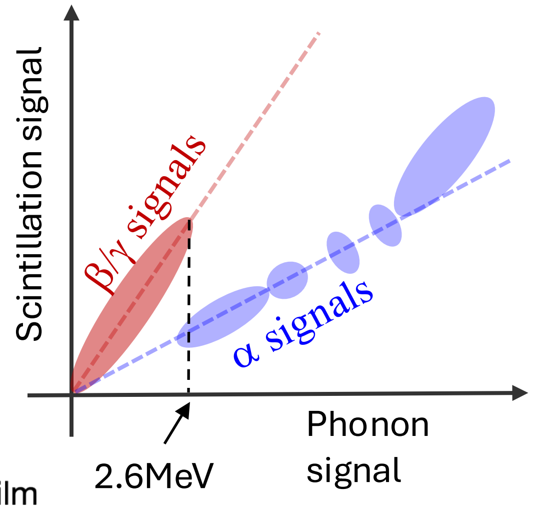
- **Discovery of neutrinoless double beta decay (0νββ)**
- **However, various mechanisms can produce 0νββ, thus observation in multiple isotopes is necessary.**
- **For next decades, multi-ton scale experiments will be constructed.**



Basics of AMoRE:

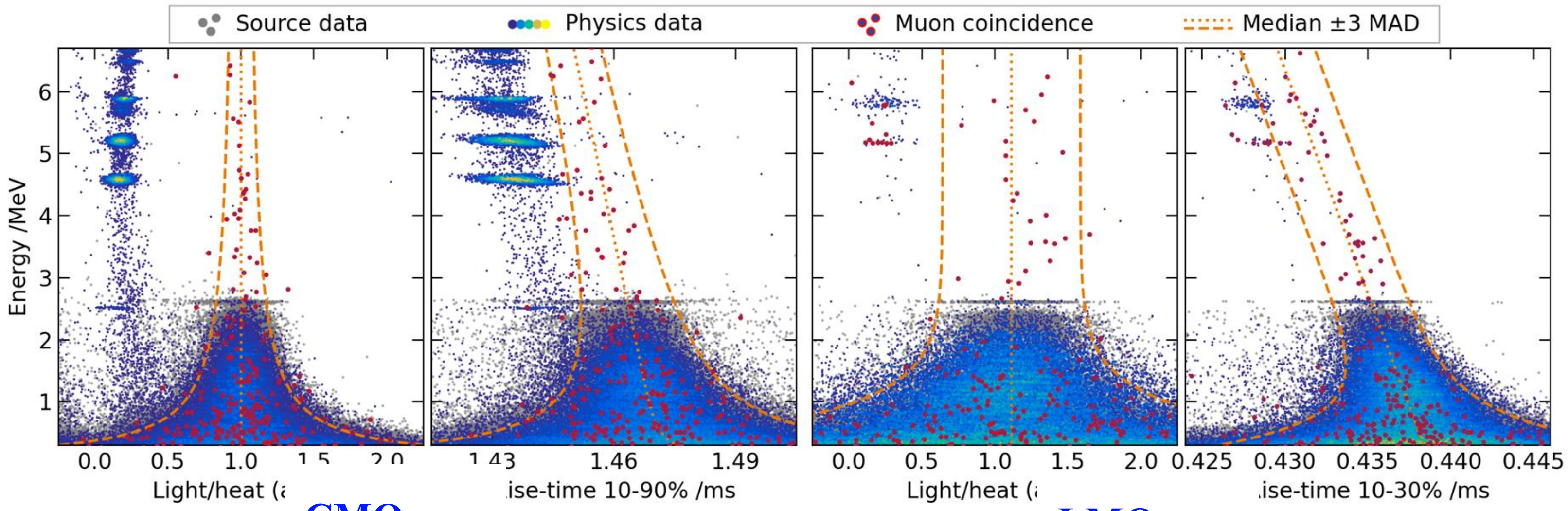
- ^{100}Mo (Q = 3.034 MeV, Natural 9.74%).
- Use scintillating bolometer with $^{40}Ca^{100}MoO_4$(CMO) and $Li_2{}^{100}MoO_4$(LMO) to have good energy resolution (<10 keV (FWHM))
- ~ 100 kg of ^{100}Mo Run





Surface alphas are continuous in energy and can be rejected by scintillation measurement.

AMoRE-I experiment: Run @Y2L, 2019-2022



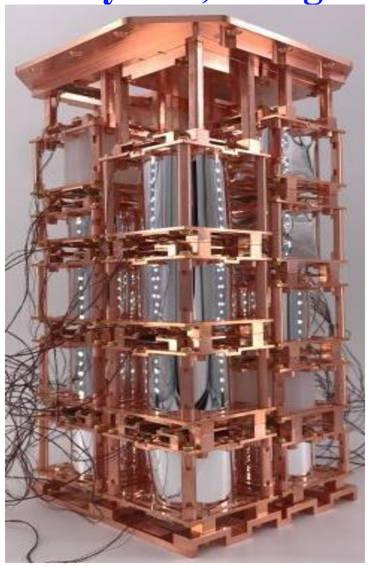
CMO

LMO

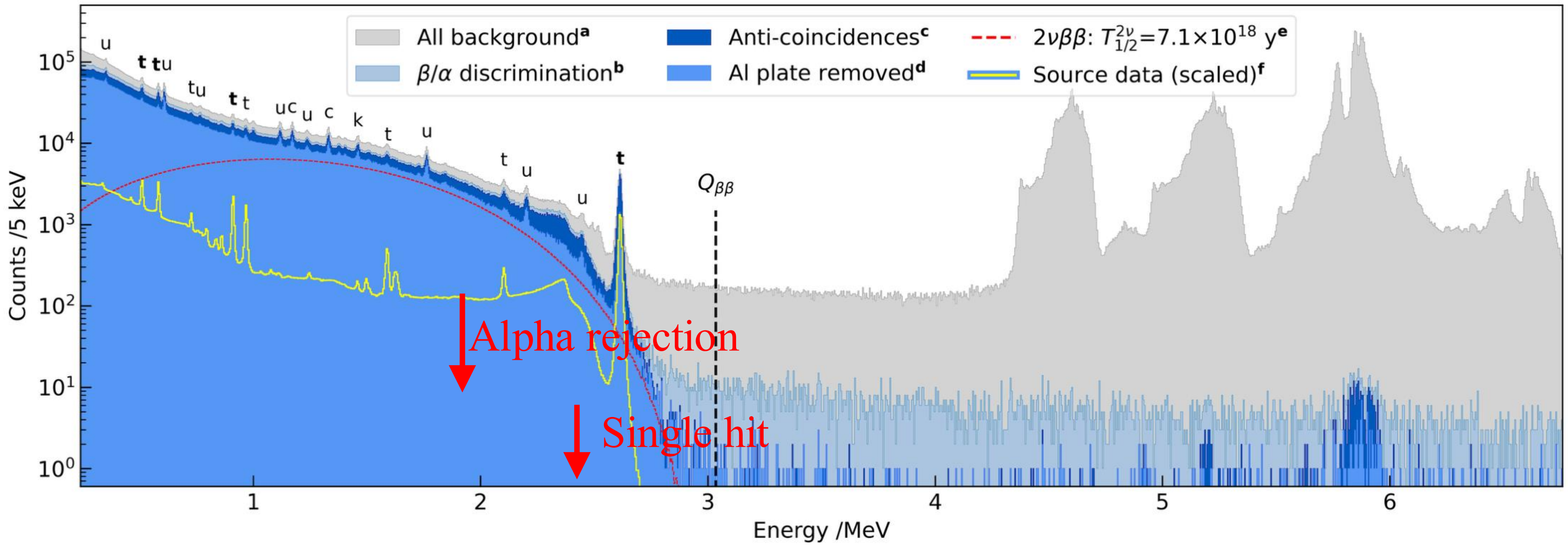
- Cryogen-free dilution refrigerator @12 mK
  - 17 crystals excluding one LMO,
  - Exposure = 3.88 $kg_{100Mo} \cdot yr$
  - CMO has higher alpha backgrounds and rejection power is high.
  - LMO has lower alpha backgrounds and rejection power is low.

AMoRE-I setup

18 crystals, 6.2 kg



- $\Delta E(FWHM) = 10 - 20\ keV\ @2614\ keV$

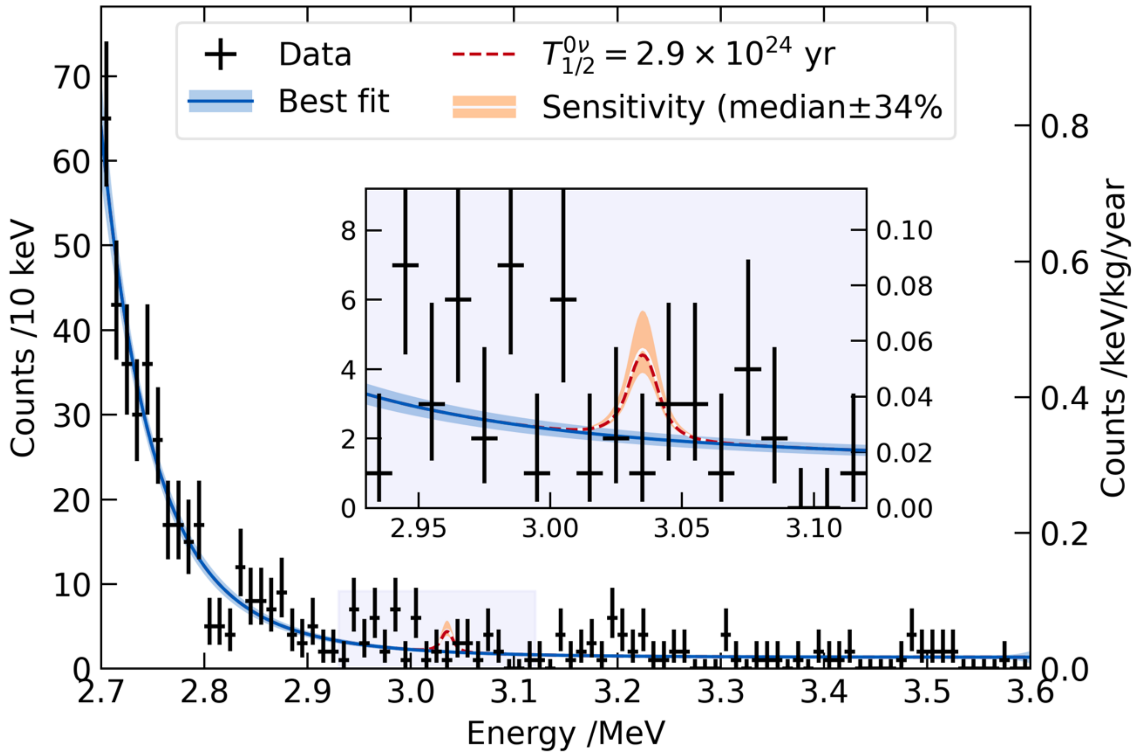


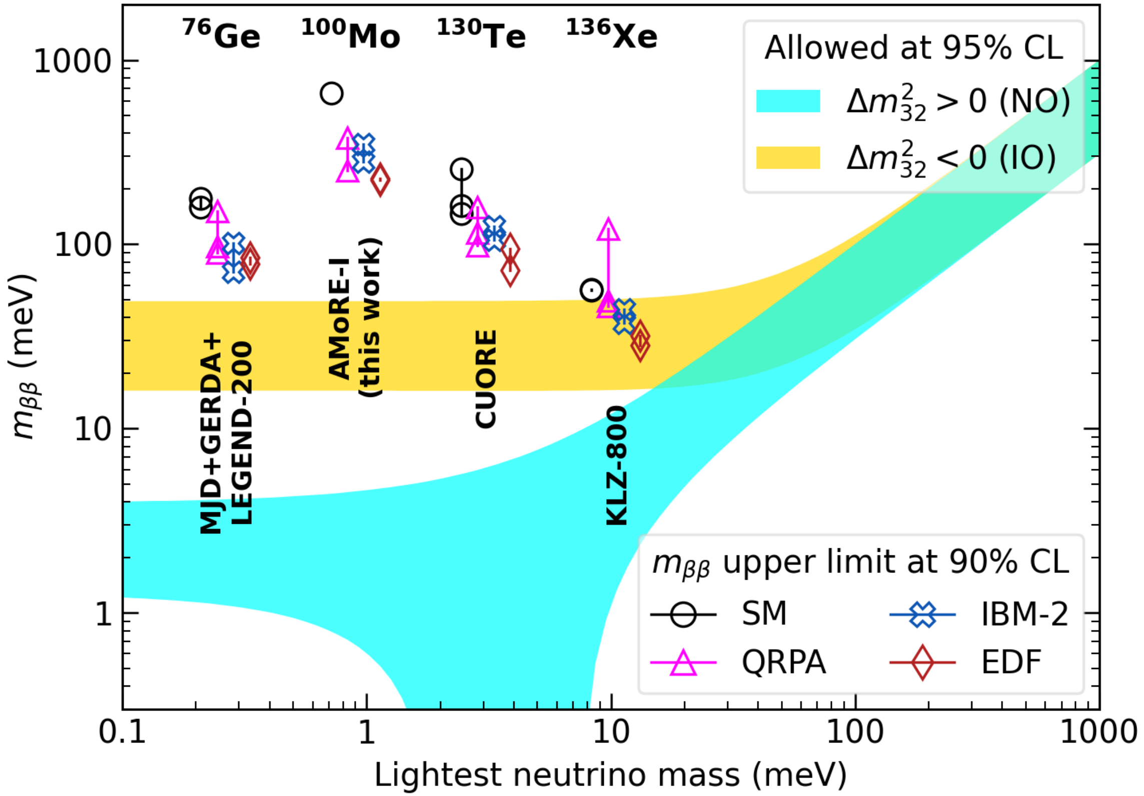
AMoRE-I improved the limit of ^{100}Mo 0νββ Half-life.

Agrawal et al., PRL 134, 082501 (2025)

$T_{1/2}^{0\nu} > 2.9 \times 10^{24}$ *years*

Cf. previous best limit 1.8× 10^{24} *years*



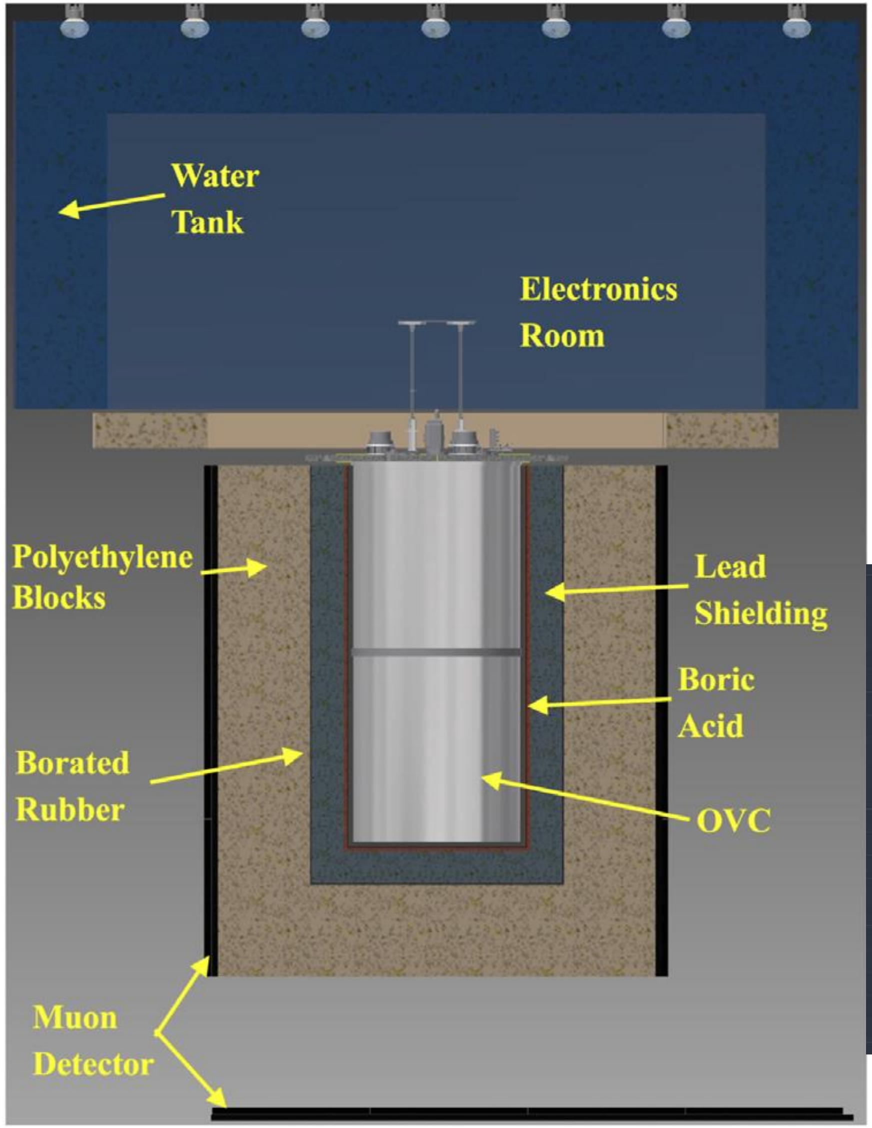


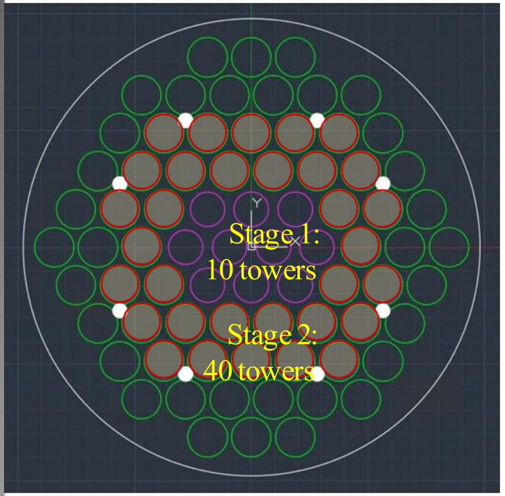
AMoRE-II experiment: @Yemilab, 2025-2030

10 Countries, 25 Institutions, 110 members
- Korea, Germany, USA, Ukraine, Russia, China, Thailand, Indonesia, India, Pakistan

Overview

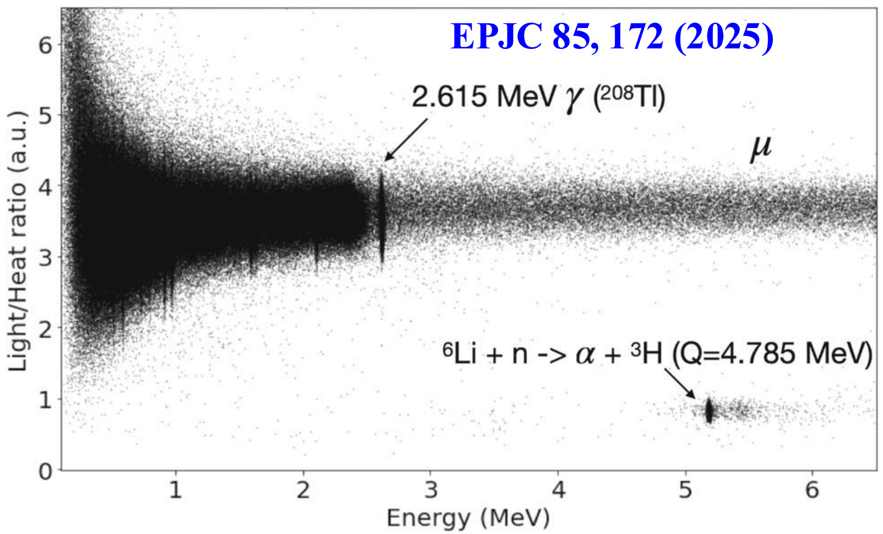
- 360 crystals (~85 kg ^{100}Mo)
- Backgrounds
  - Goal < 10^{-4} count/keV/kg/year
  - Main backgrounds are Pileup.
- Sensitivity w/ 5 yeas run: 4.5×10^{26} years (90% CL) → $m_{\beta\beta} < 17 - 49\ meV$
- Schedule
  - Stage1: 90 crystals, 2025-2026
  - Stage2: 360 crystals, 2026-2030

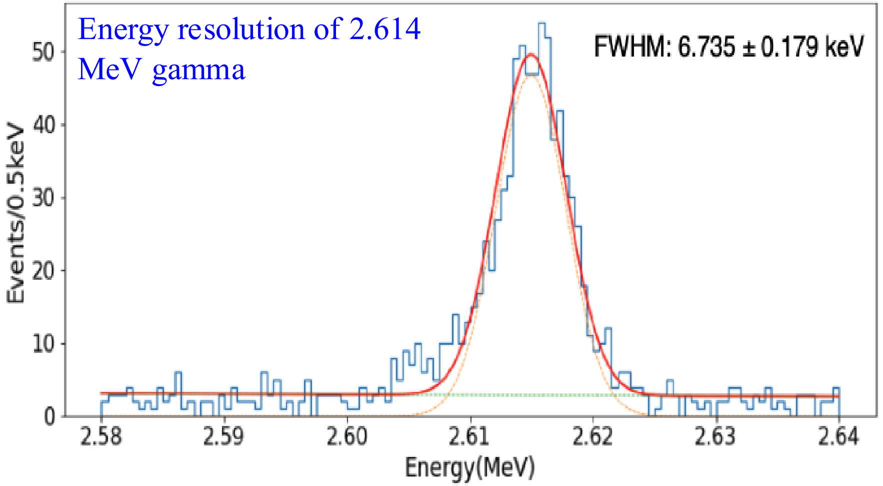


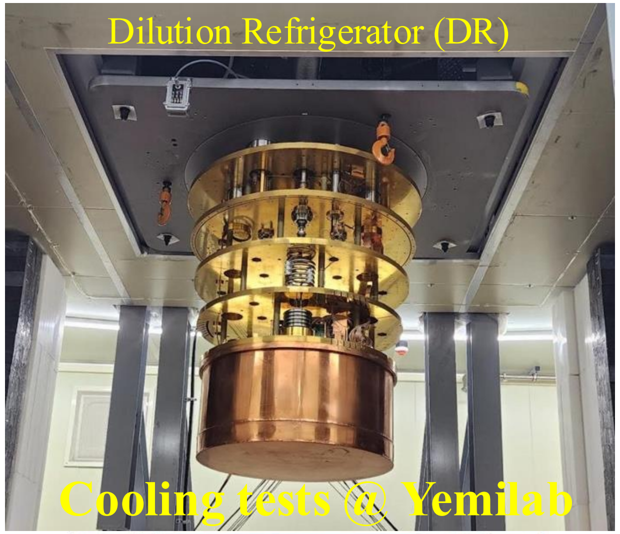


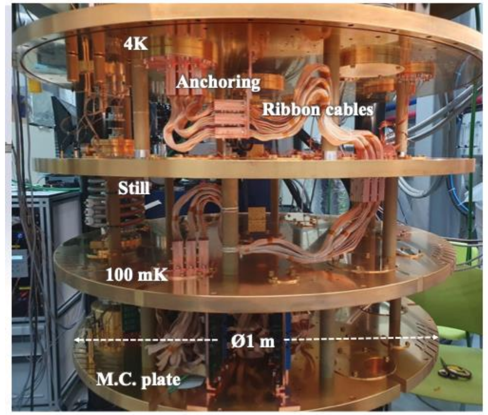
AMoRE-II under construction

Tests at ground showed satisfactory energy resolution and alpha rejection power.



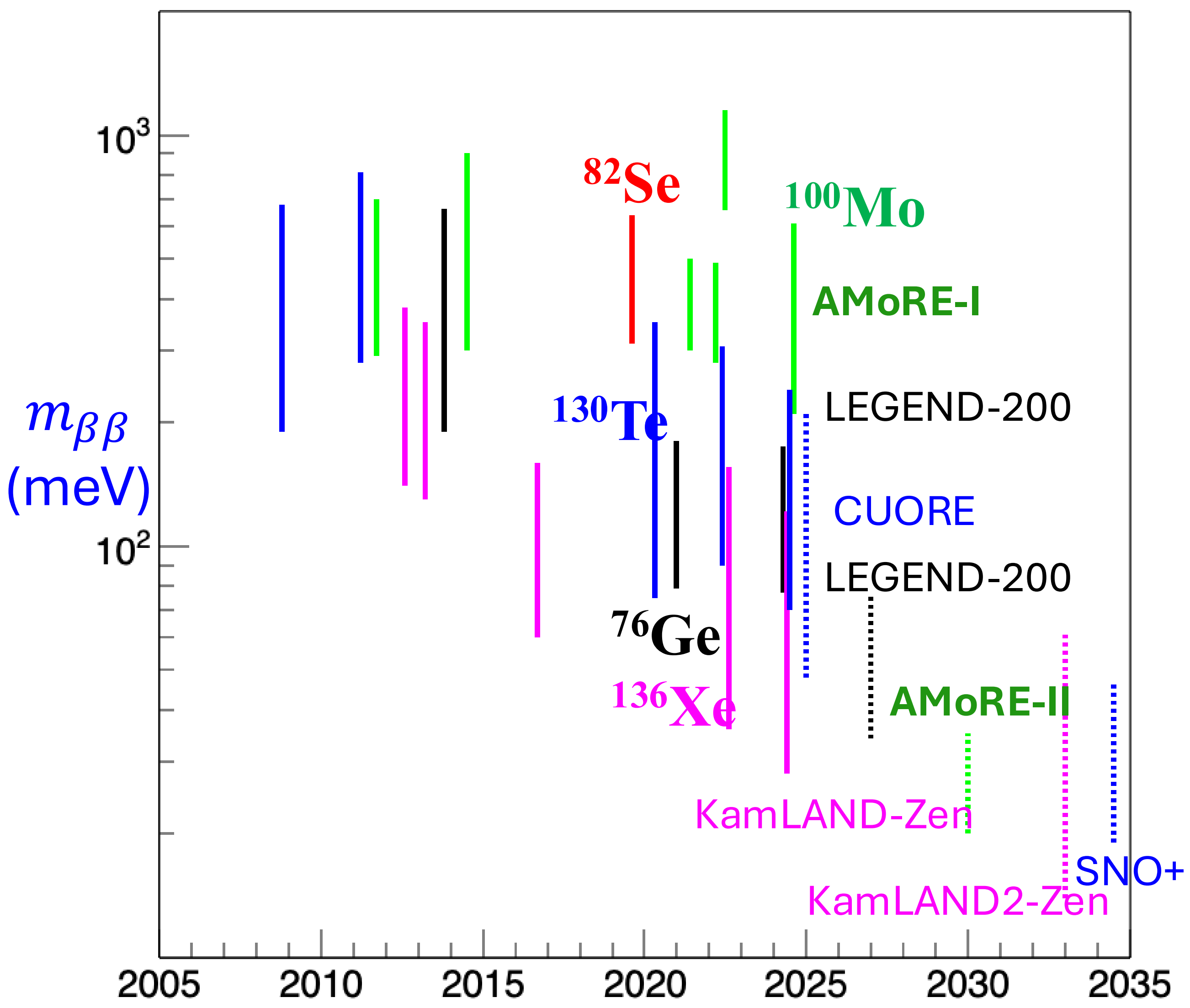






More than 200 MMCs and SQUIDS are tested.

Perspectives for 0νββ



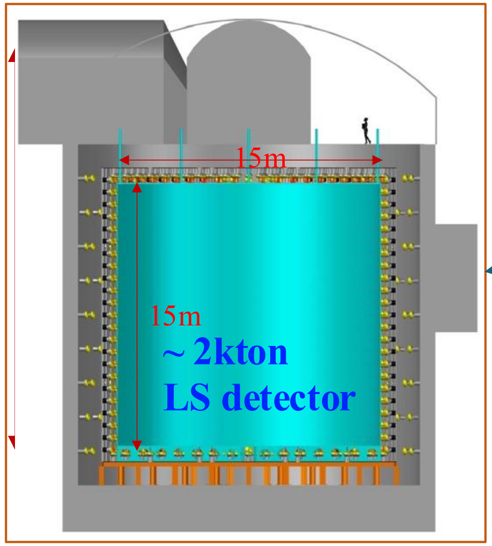
- In 2024, new data from KamLAND-Zen (^{136}Xe) and LEGEND-200 (^{76}Ge) came out at neutrino 2024 conference. AMoRE-I submitted new data in archive.
- For next decades, multi-ton scale experiments will be constructed.

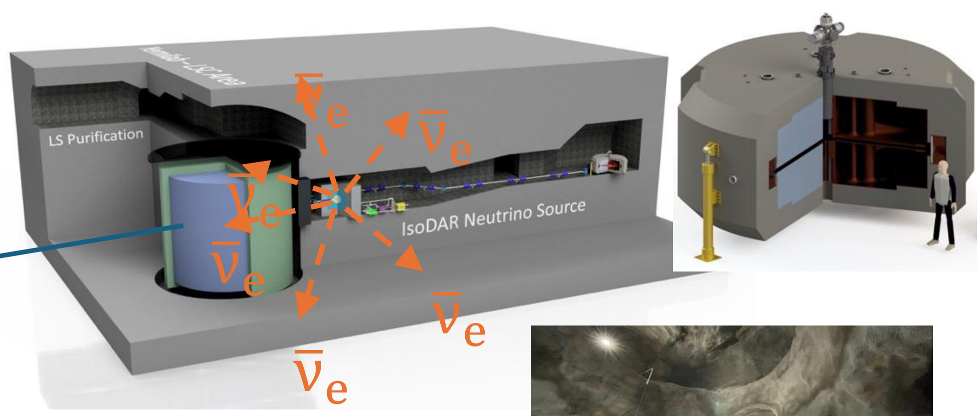
Expected with 5 years run.
Not comprehensive.

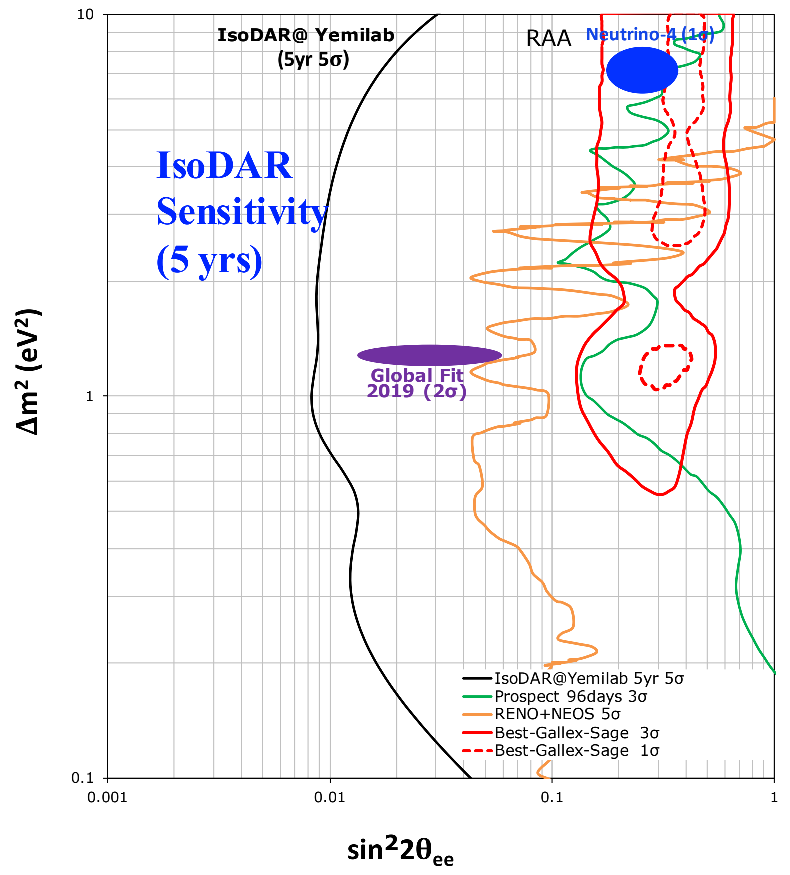
Neutrino Detector at Yemilab

- The current experimental status of ~ eV sterile neutrino is complex and confusing. Need a facility with a higher sensitivity.
- IsoDAR(isotope decay at rest) uses ^{8}Li Isotope Decay-at-rest neutrinos driven by proton cyclotron.
- Fist high power accelerator + Large underground detector

- “Neutrino Physics Opportunities with the IsoDAR Source at Yemilab”, PRD 105, 052009 (2022)
- “IsoDAR@Yemilab: Preliminary Design Report - Vol1:Cyclotron Driver”, arXiv:2404.06281





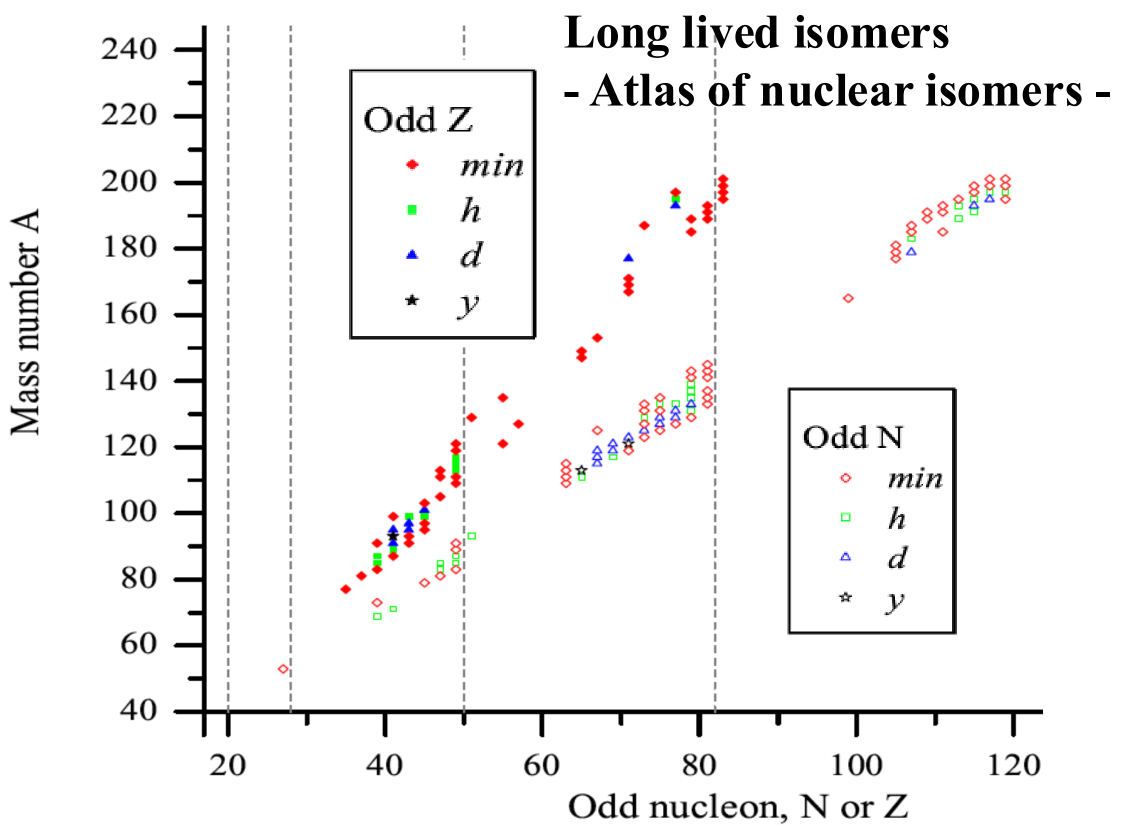


- For each IBD ($\bar{\nu}_e p \rightarrow e^+ n$) event, measure the energy (E) and vertex(L) of neutrinos. → L/E
- Assume : $\sigma(E) \sim 6.4\,\%/\sqrt{E(\text{MeV})}$, $\sigma(\text{vertex}) = 12\text{cm}/\sqrt{E(\text{MeV})}$

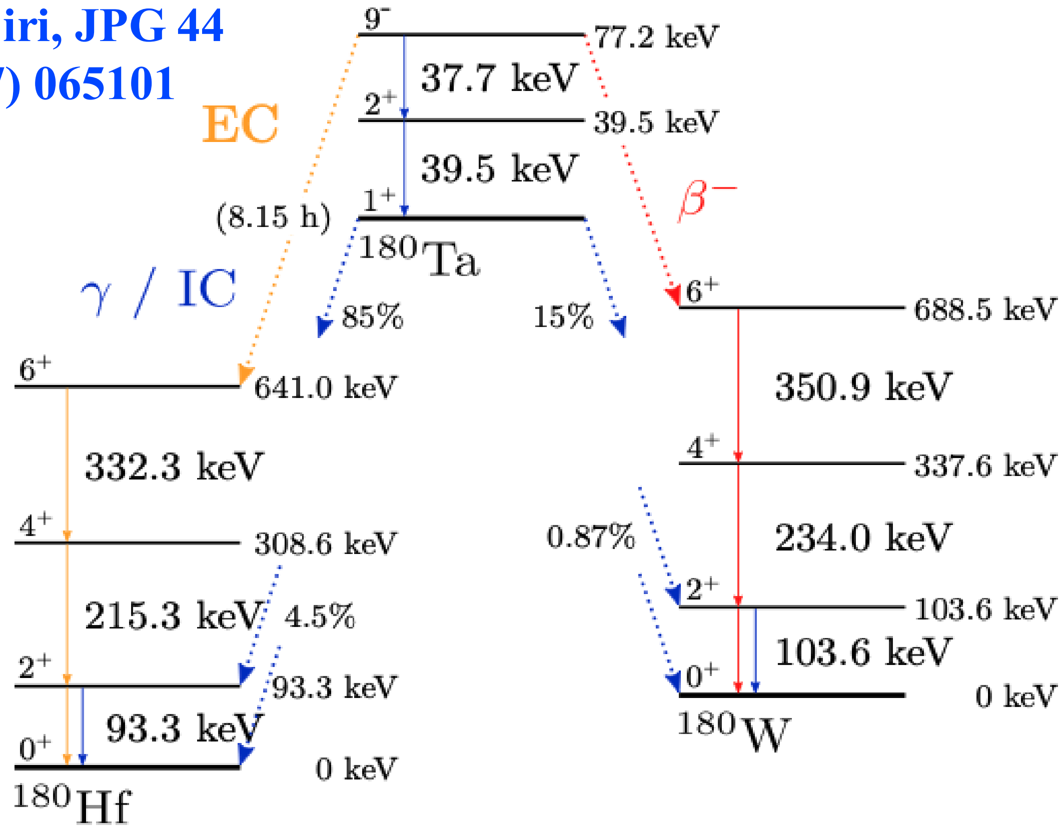
- Before IsoDAR installation, ~ 100 kCi ^{144}Ce antineutrino source can be installed. A little worse sensitivity than IsoDAR. (E. Won)

^{180m}Ta decay ?

1. ^{180m}Ta is the rarest isotope (0.012%) and the only isomer naturally abundant.
2. Its decay has never observed yet. (EC ?, B- ?, IC ?)
3. The abundance is not explained well in nucleosynthesis. s-process, p process, nu-process ?
4. Decay mode and lifetime will help to understand the astrophysical origin of this isotope.

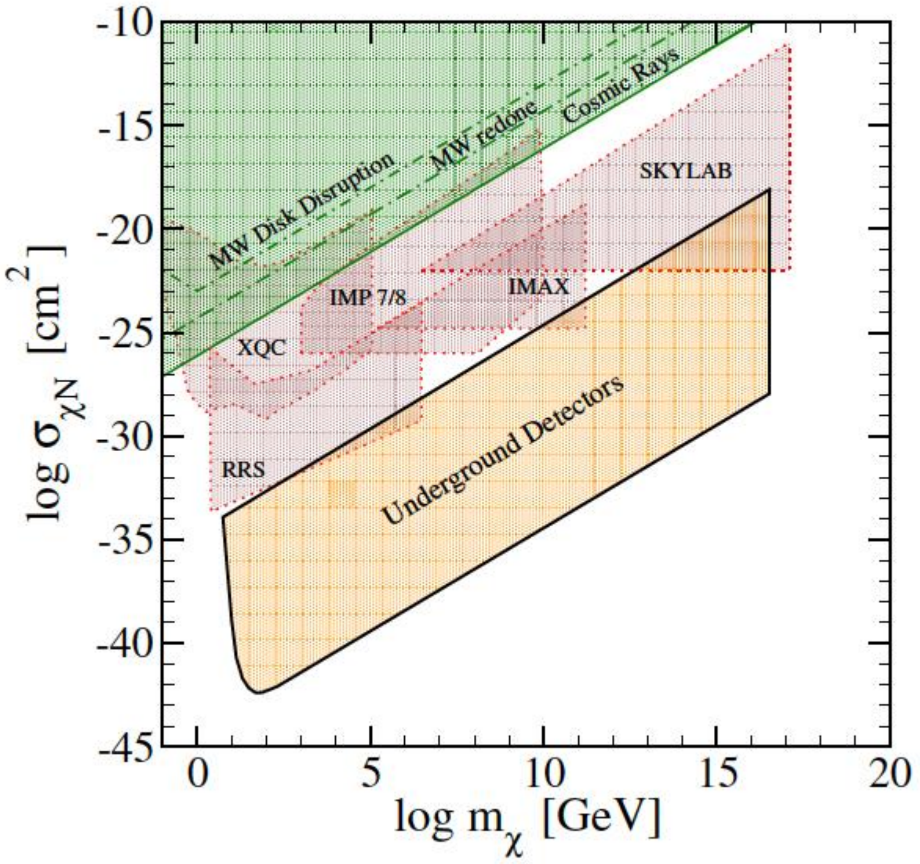


H. Ejiri, JPG 44 (2017) 065101

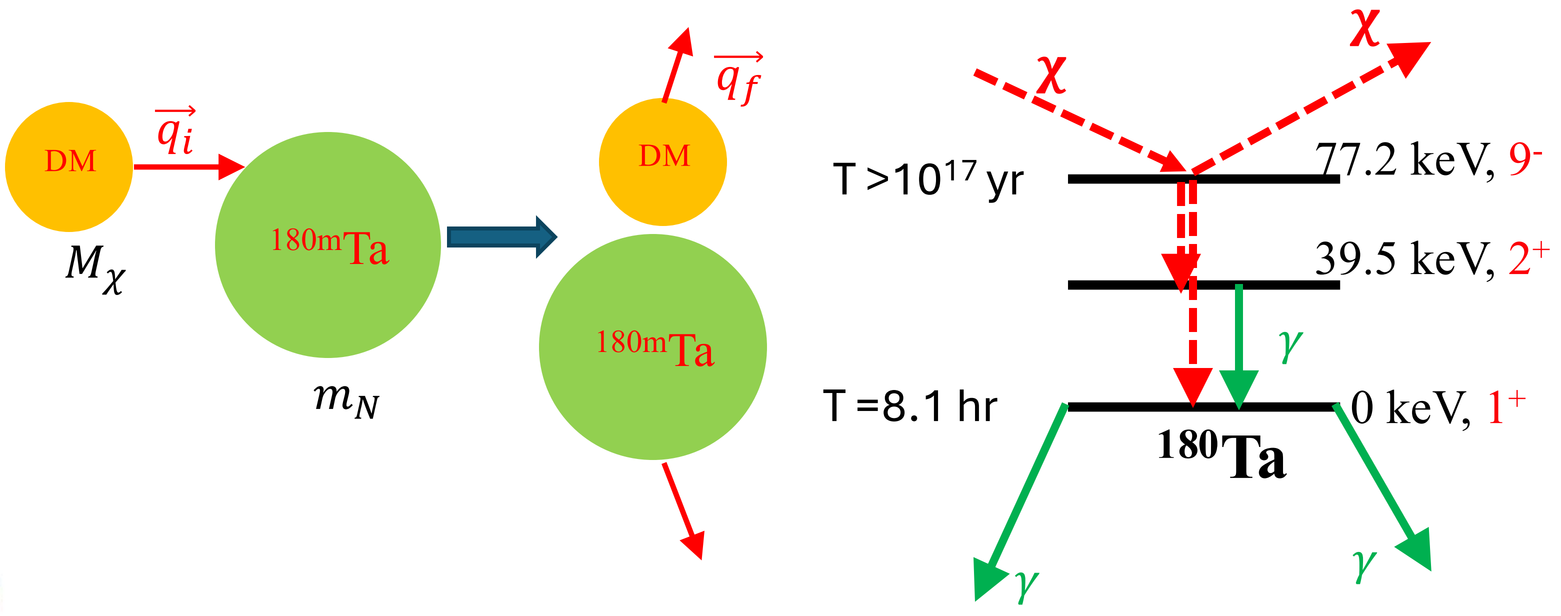


Dark matter with ^{180m}Ta

- Parameter space not explored yet for the Strongly Interactive Massive Particles (SIMP).
- SIMPs interacts strongly, so can't reach the underground detectors.
- Ground experiments limits the SIMP-nucleon cross sections.



Heavy, thermalized dark matter particle can deplete ^{180}Ta isomeric state to ground state.

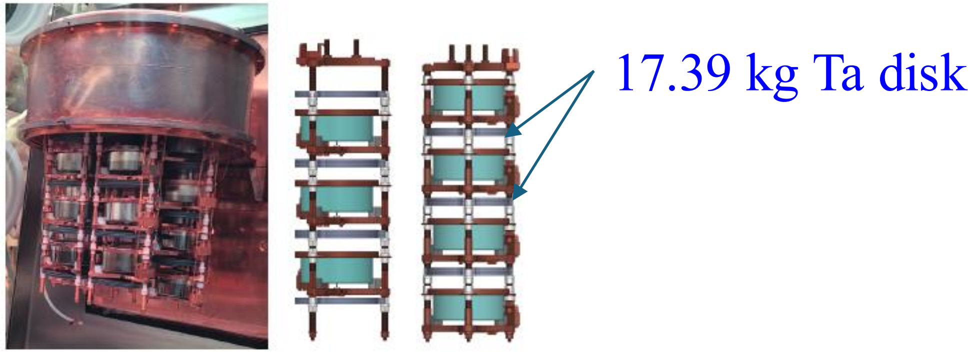


Pospelov, Nucl. Phys. B 1003 (2024) 116476

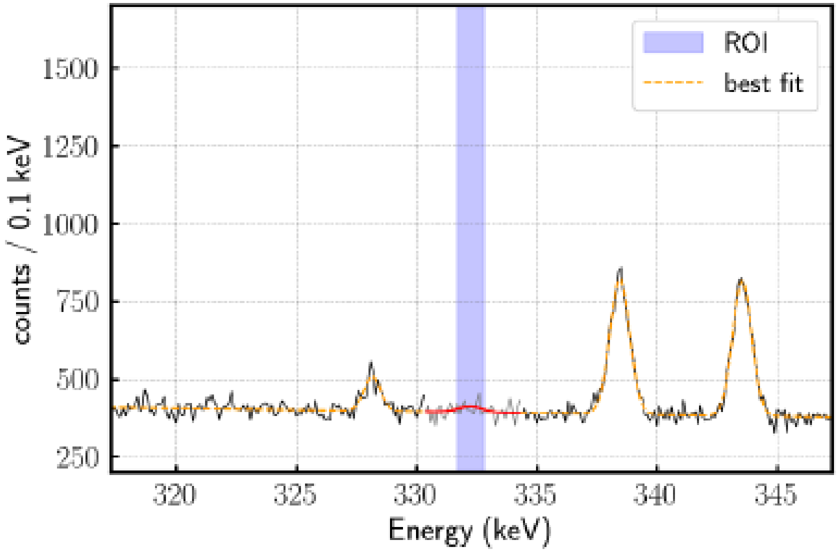
Los Alamos group used HPGe detector

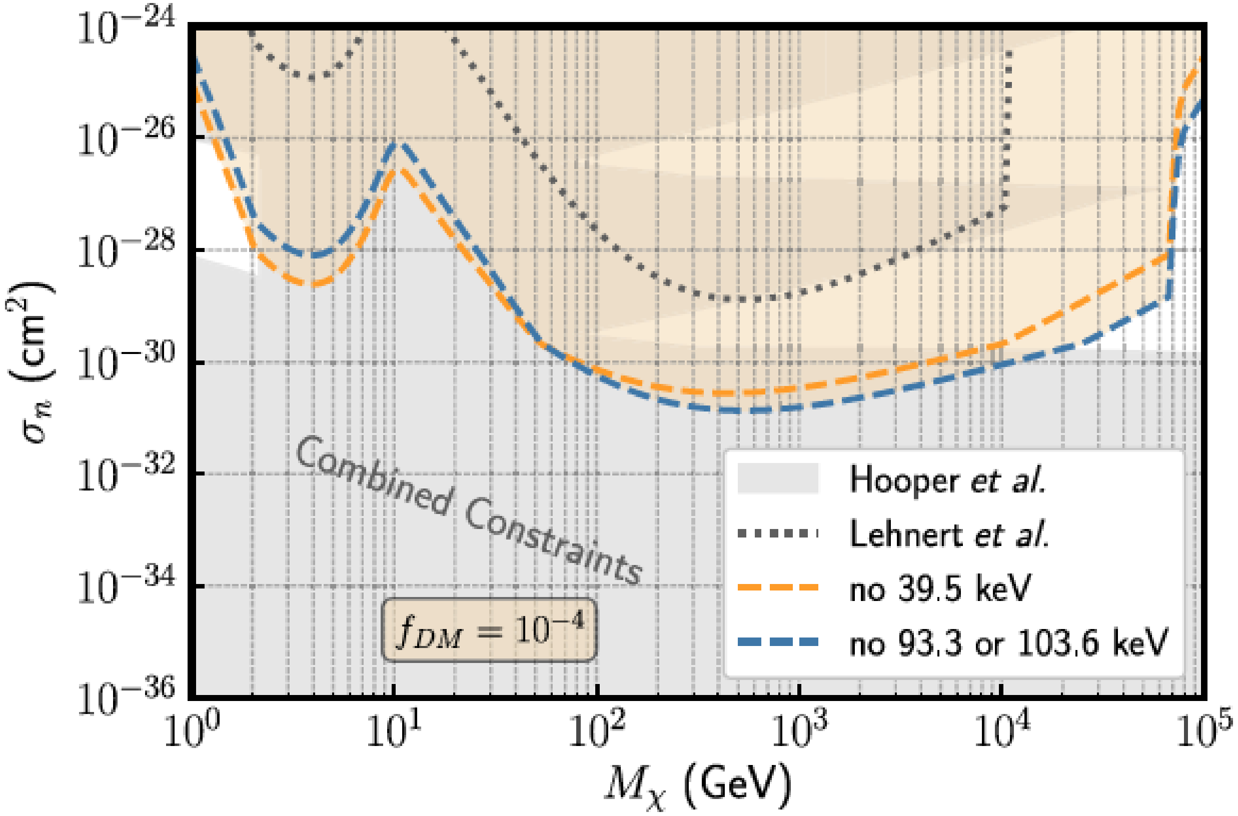
Arnquist et al., PRL 131, 152501 (2023)

Majorana Demonstrator Detector



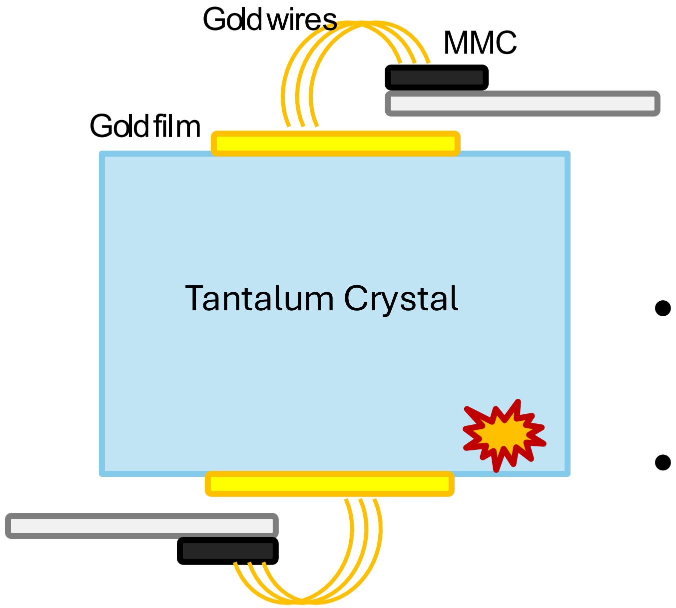
(years)	EC	B-	IC
Result (90%)	$>1.33\times10^{19}$	$>1.54\times10^{19}$	$>6.7\times10^{17}$
Theory	10^{23}	10^{20}	10^{18-19}



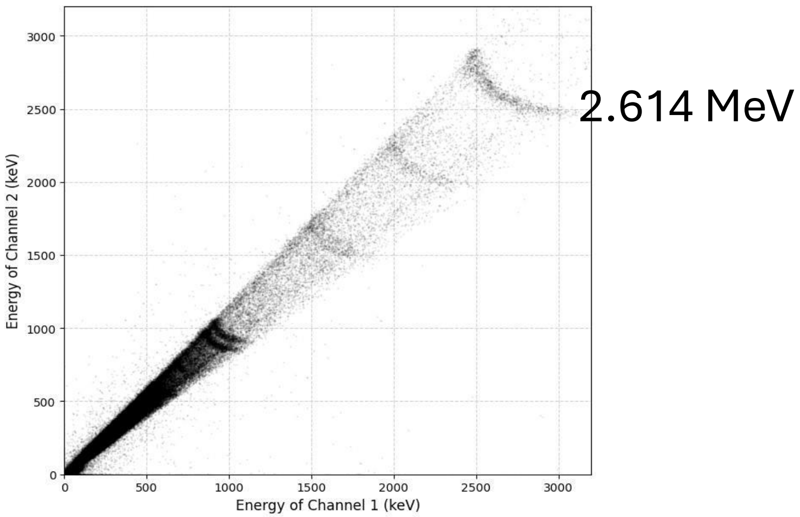


A plan to measure ^{180m}Ta decay

Our Plan
Try to measure IC with cryogenic detector similar to AMoRE detector
Detection efficiency > 80%



Quasiparticle recombination ➔
Dual phonon channels



- Initial tests show promising result, but needs to improve the energy reolution.
- Enrichment is possible with Thermal Diffusion Column up to 5% from 0.012%.
  - **5% enriched Ta-180m (1gram)**
  - **Background <5 count/keV/kg/day**
  - **ΔE <2 keV (FWHM)**

  ➔ > 5σ for 5x10^{19} years.

Fig. 1. Isotopic production facility, lower level of the column equipment.

Conclusion

- A new underground l^{abor}atory, Yemilab, is built in Korea, which will be a playground for dark matter and neutrino physics.
- We have strong contradiction to DAMA/LIBRA annual modulation and further improve with COSINE-100U and COSINE-200.
- Low mass dark matter searches with cryogenic detector is under preparation.
- keV sterile neutrino searches with ^{3}H, ^{63}Ni, and ^{87}Rb are on-going.
- AMoRE-II experiment is under construction and will give competent limits with Ge and Xe experiments.
- eV Sterile neutrino searches can be done with large scintillator detector and strong neutrino souce at underground.
- ^{180m}Ta decay can be discovered with a new cryogenic detector combined with enrichment.

Neutron on ^{180m}Ta

INelastic Neutron Acceleration (INNA) observed.

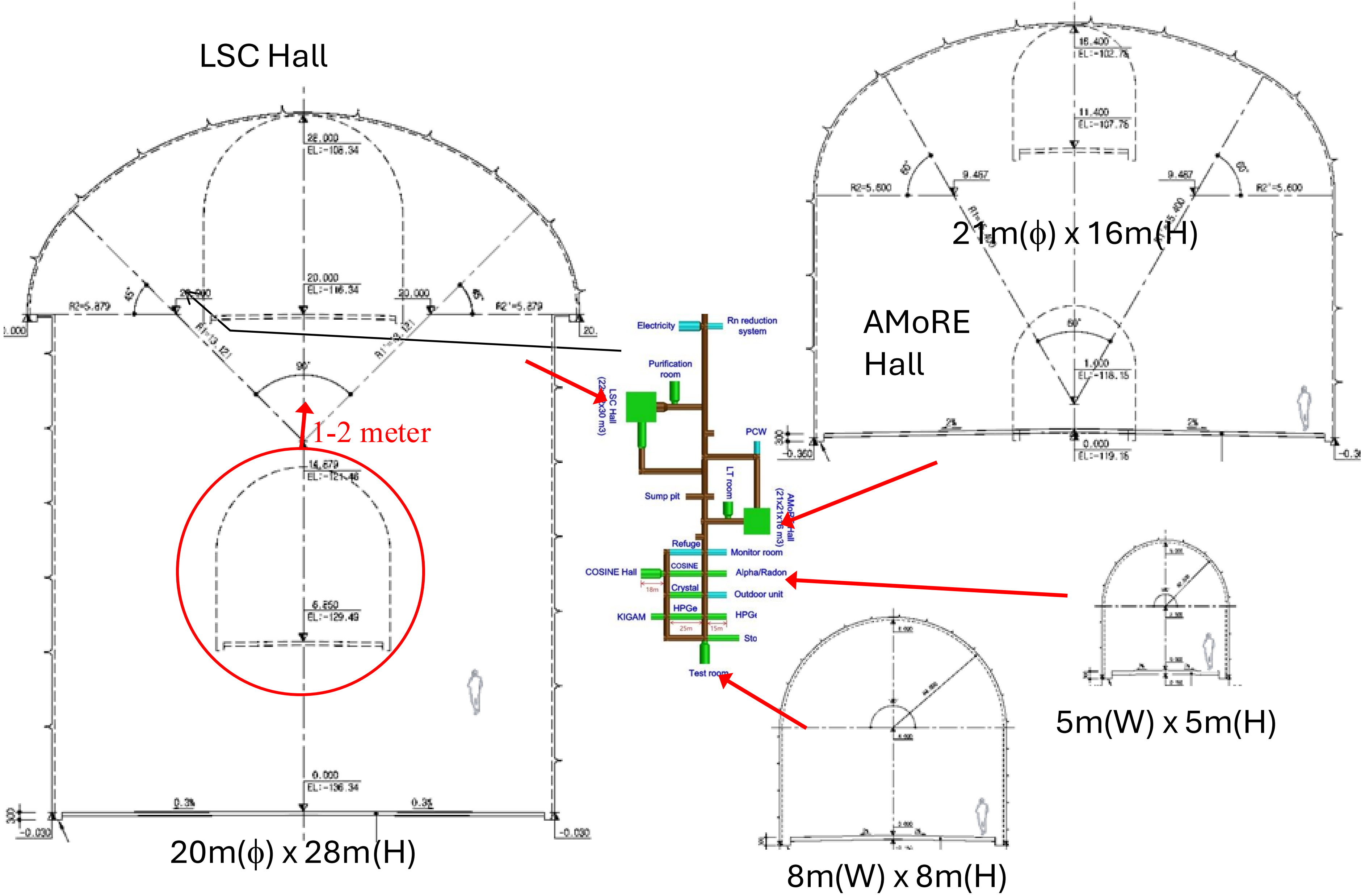
"ACCELERATION OF THERMAL NEUTRONS BY ISOMERIC NUCLEI (180Hfm)"
Kondurov et al., PLB 106, 383 (1981)

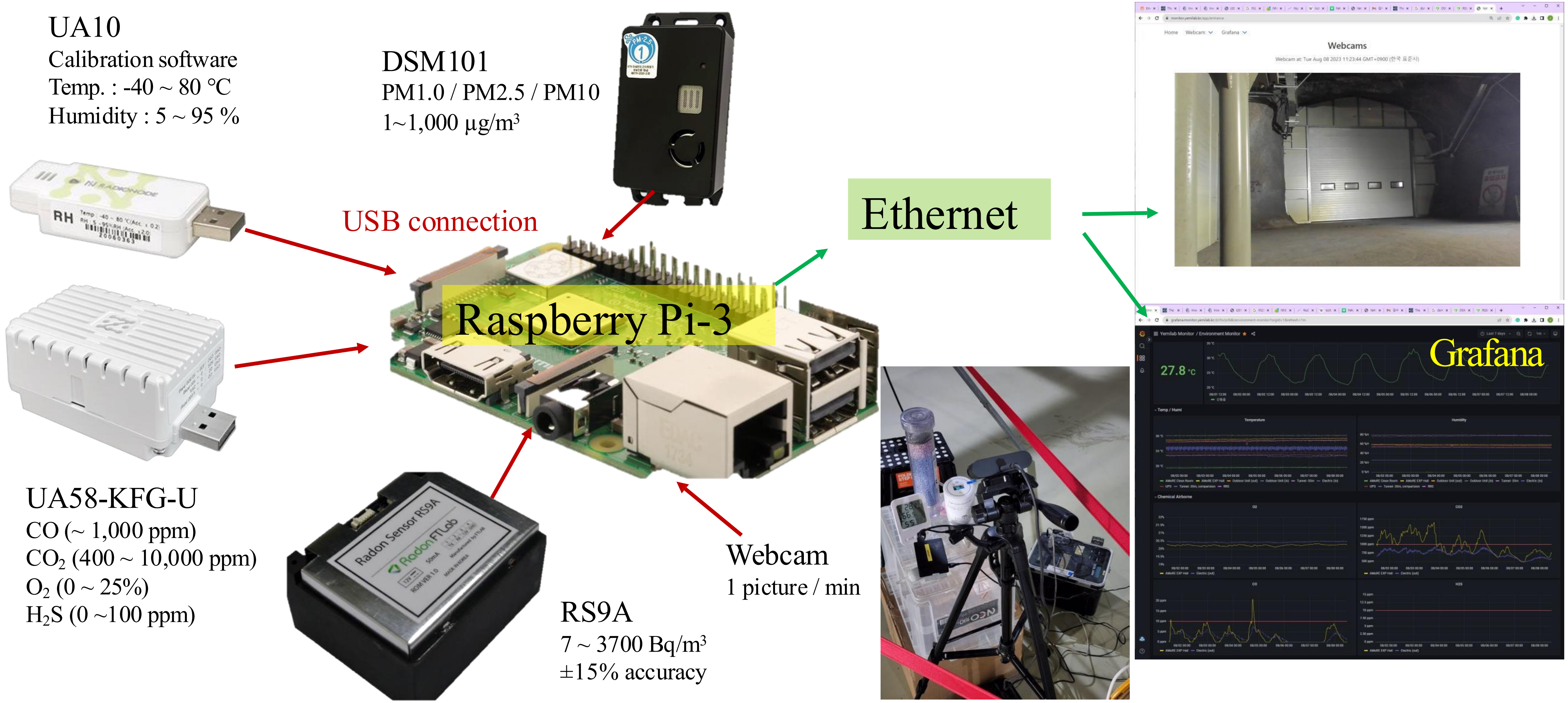
"Evidence for inelastic neutron acceleration by the 177Lu isomer"
Roig et al., RC 74, 054604 (2006)

^{177m}Lu: Ex=970 keV, T1/2=160 days, 23/2-

$$\sigma_{INNA} = 258 \pm 58\ b$$

Standard cross sections




UA10
Calibration software
Temp. : -40 ~ 80 °C
Humidity : 5 ~ 95 %
DSM101
PM1.0 / PM2.5 / PM10
1~1,000 μg/m³
USB connection
Raspberry Pi-3
Ethernet
Webcams
Grafana
UA58-KFG-U
CO (~ 1,000 ppm)
CO₂ (400 ~ 10,000 ppm)
O₂ (0 ~ 25%)
H₂S (0 ~100 ppm)
Radon Sensor RS9A
RadonFTLab
RS9A
7 ~ 3700 Bq/m³
±15% accuracy
Webcam
1 picture / min

Rock Radioactivity

HPGe

Bq/kg	^{226}Ra	^{40}K	^{228}Ac	^{228}Th	^{210}Pb	^{54}Mn
Rock	58.0±5.2	1,161±232.3	52.6±7.5	50.7±5.1	N. A.	N. A.
Cement	26.0±1.3	216.3±10.9	24.0±1.2	21.5±1.1	N. A.	0.36±0.02
Sand	24.6±1.2	848.9±42.5	57.0±2.9	53.5±2.7	N. A.	0.81±0.05
Stone	8.9±0.5	54.8±2.8	9.9±0.5	8.9±0.5	N. A.	0.13±0.01

ICP-MS

			^{238}U	^{232}Th	^{40}K	Sample location
2020.08.19.	Handuk limestone A	KIGAM	1.17	3.43	11400	@AMoRE Cavern top
	Handuk limestone B	KIGAM	0.68	3.50	13800	@AMoRE Cavern left
	Handuk limestone C	KIGAM	0.66	2.87	10200	@AMoRE Cavern right
average			**0.84 (10.4 Bq/kg)**	**3.27 (13.3 Bq/kg)**	**11800 (365.8 Bq/kg)**	

HPGe

CMD424.1 Dust near Yemi cage 220802 Mass: 1.45 kg , M. day : 1 day CC1

$^{226}Ra(^{238}U)$	^{234}Th	^{40}K	^{228}Ac	^{228}Th	^{210}Pb
24.61 ± 1.23 Bq/kg	28.12 ± 1.46 Bq/kg	226.08 ± 11.33 Bq/kg	15.21 ± 0.77 Bq/kg	13.61 ± 0.68 Bq/kg	17.82 ± 2.31 Bq/kg

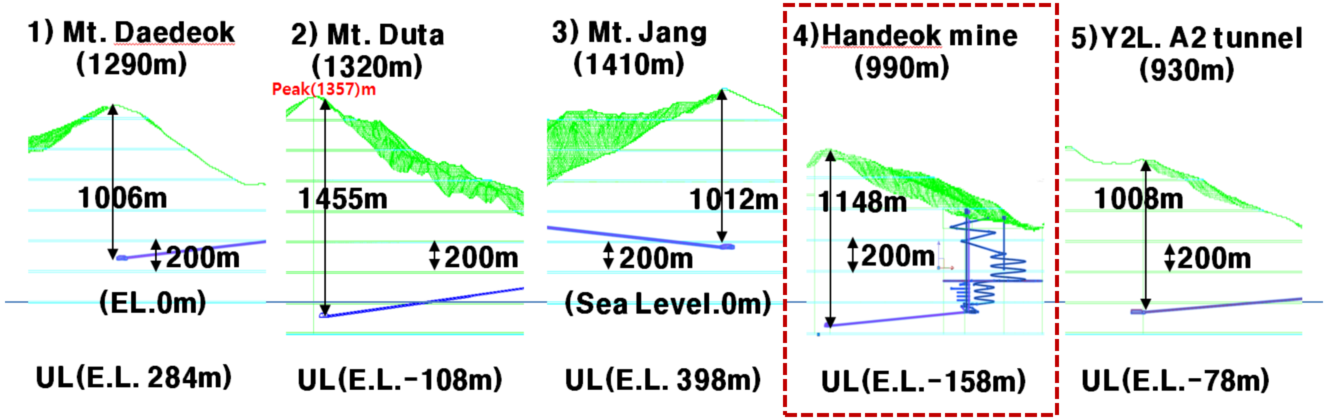
CMD424.2 Dust near AMoRE PCW 220803 Mass: 0.083 kg , M. day : 3 day CC1

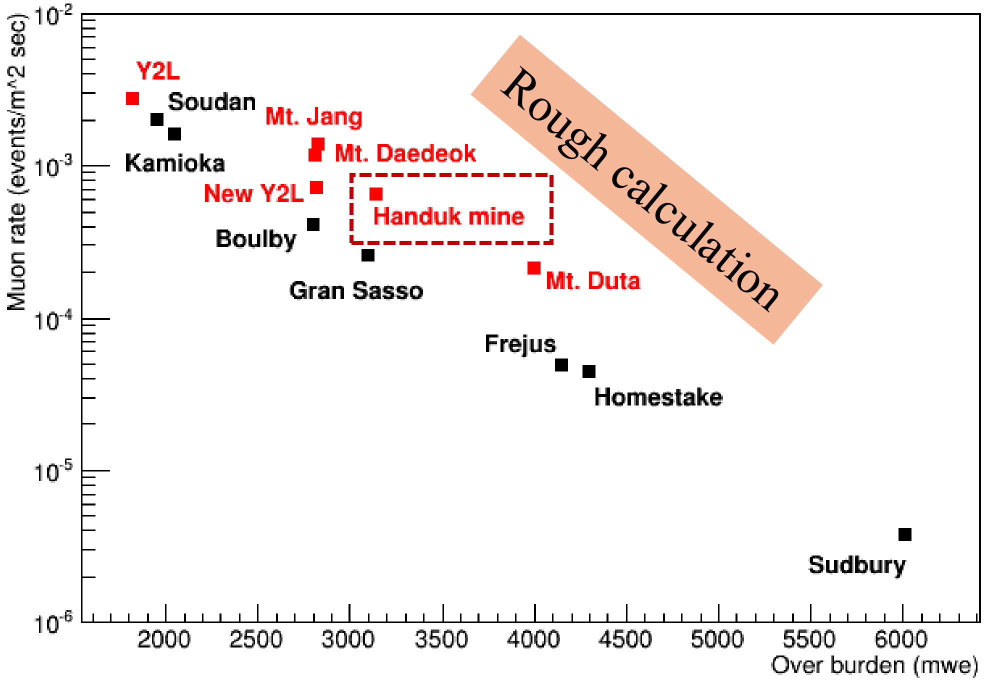
$^{226}Ra(^{238}U)$	^{234}Th	^{40}K	^{228}Ac	^{228}Th	^{210}Pb	^{54}Mn
24.99 ± 1.26 Bq/kg	39.62 ± 2.15 Bq/kg	407.21 ± 20.52 Bq/kg	22.88 ± 1.18 Bq/kg	23.07 ± 1.16 Bq/kg	164.78 ± 9.17 Bq/kg	0.33 ± 0.04 Bq/kg

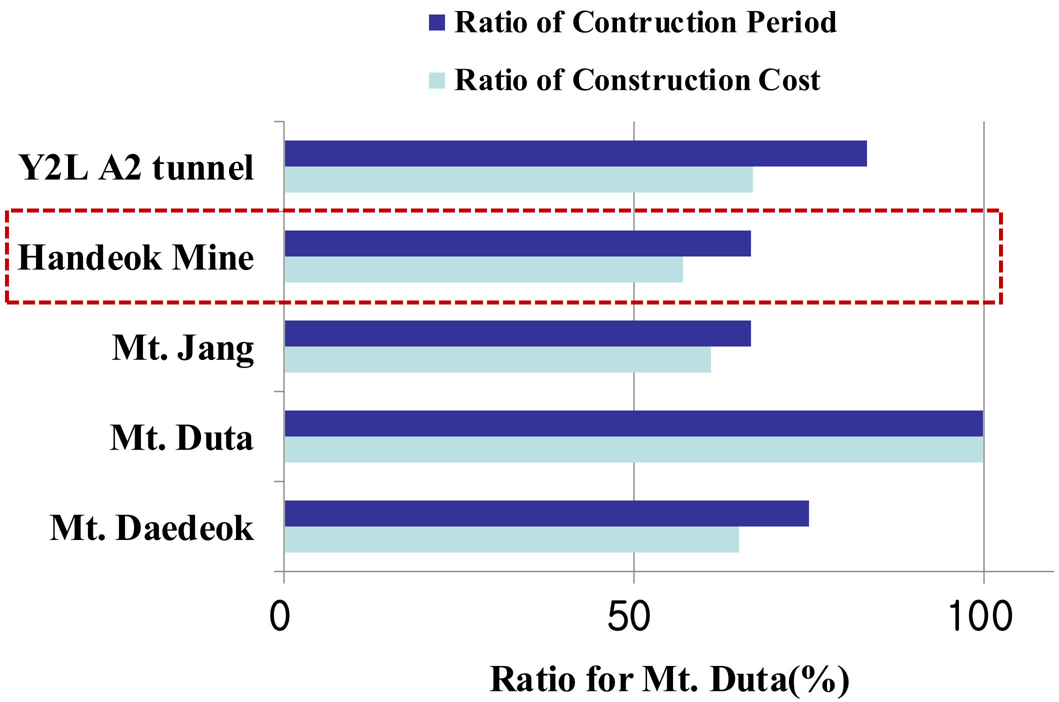
Contents

1. Y2L, Yemilab
   - Y2L
   - Construction of Yemilab
   - Status of Yemilab
2. Dark Matter Searches
   - 2-1 COSINE contradicts DAMA
   - 2-3 Low Mass Dark Matter Searches
3. Neutrino oscillation and sterile neutrino searches
   - 3-2 nEYE, IsoDAR
4. Double beta decay experiments, AMoRE
5. Nuclear Astrophysics programs
   1. Ta180m

A new underground laboratory







The Handuk mine

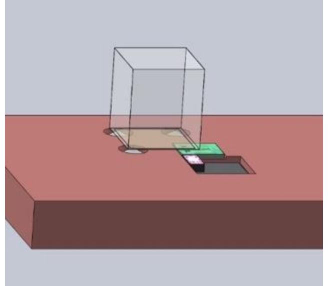
1. Cost effectiveness
2. Acceptable overburden
3. Limestone for less radioactivity

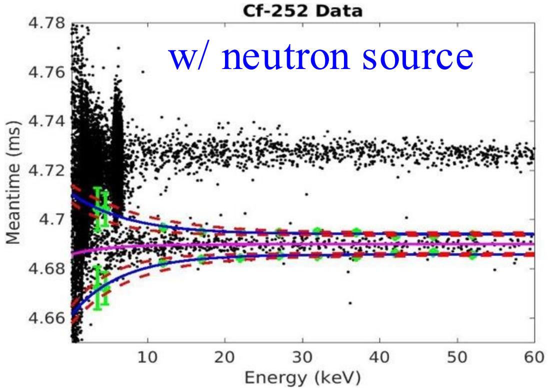
Ground Laboratory, Houses

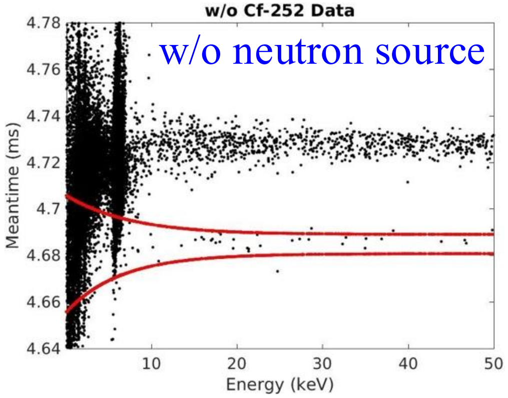
-2.5 km from Handeokmine
-Offices, labs (general, chemistry), auditorium, recreation room, storage, …

Low mass DM and sterile neutrino searches with low temp. sensors.

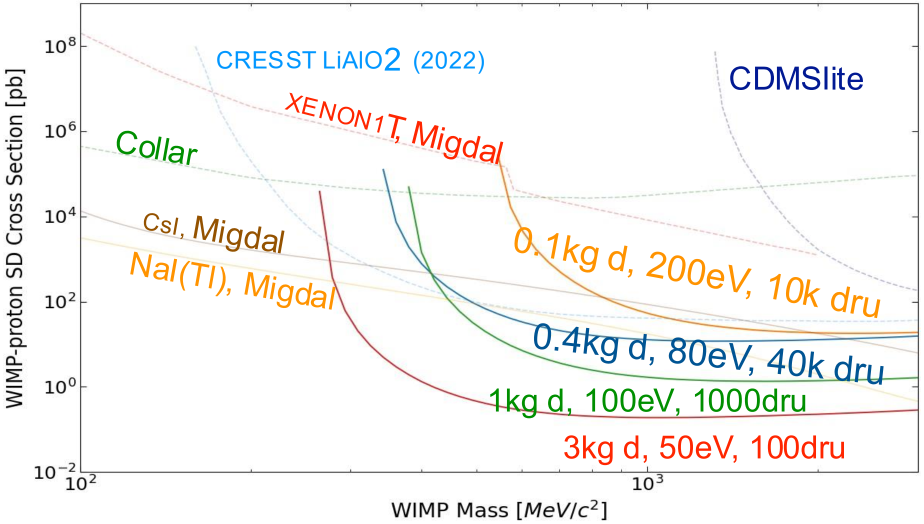
- Crystals: LiF, CaF_2, Al_2O_3,..Li and F are proton spin isotope.
- CaF_2 crystal ($5\times5\times5$ mm^3, 0.4g) coupled directly to MMC+SQUID, 30 mK at ground laboratory.
- Preliminary energy threshold ~ 50 eV and good PSD w/o light detector.



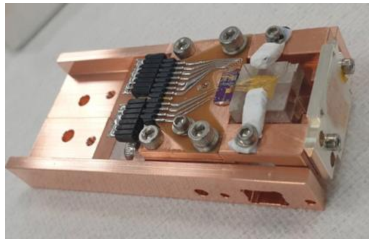




Expected: WIMP-proton spin-dependent interaction

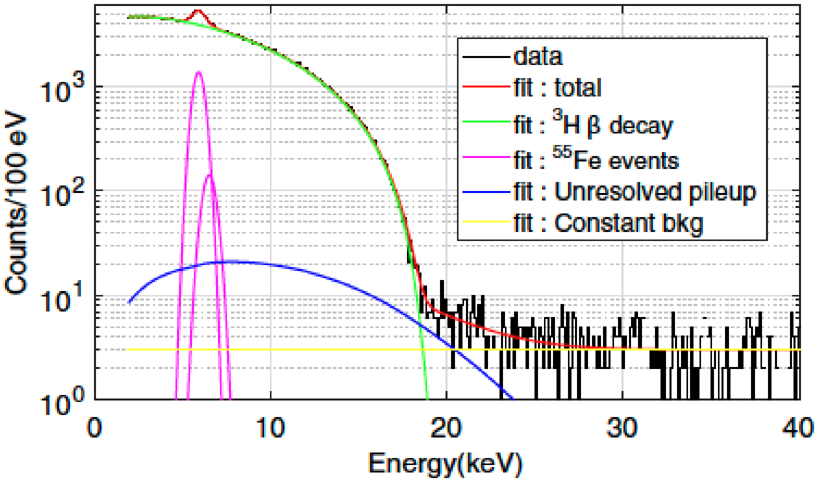


~keV sterile neutrino searches with low temp. calorimeter



LiF crystal irradiated by neutron → ^3H produced inside crystal.
Measured by MMC+SQUID

^{63}Ni (Q_β=67.0 keV) sandwiched by Au foil will be studied too. Sensitive to higher mass.



Y.C. Lee et al., JLTP 209, 919 (2022)