AMoRE-II at Yemilab

Jaison Lee

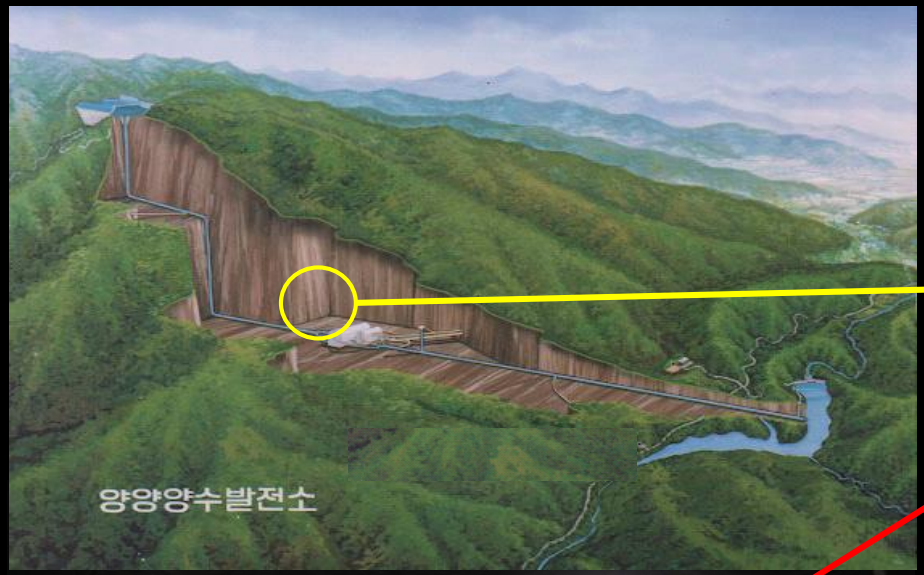
CUP / IBS

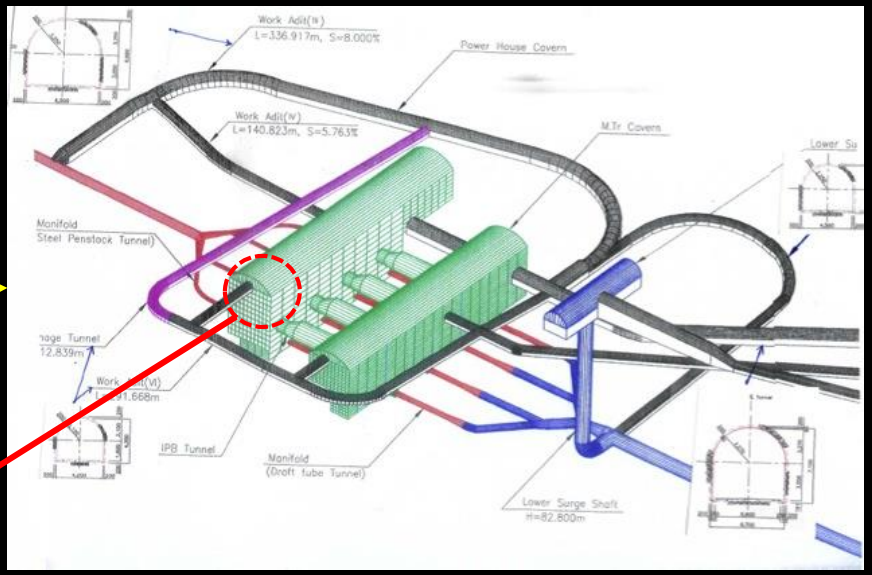
Content

- Yemilab
- AMoRE-II


Yemilab
EST.
2022
Less Muon
Better Flavor

Y2L (Yangyang Underground Lab.)

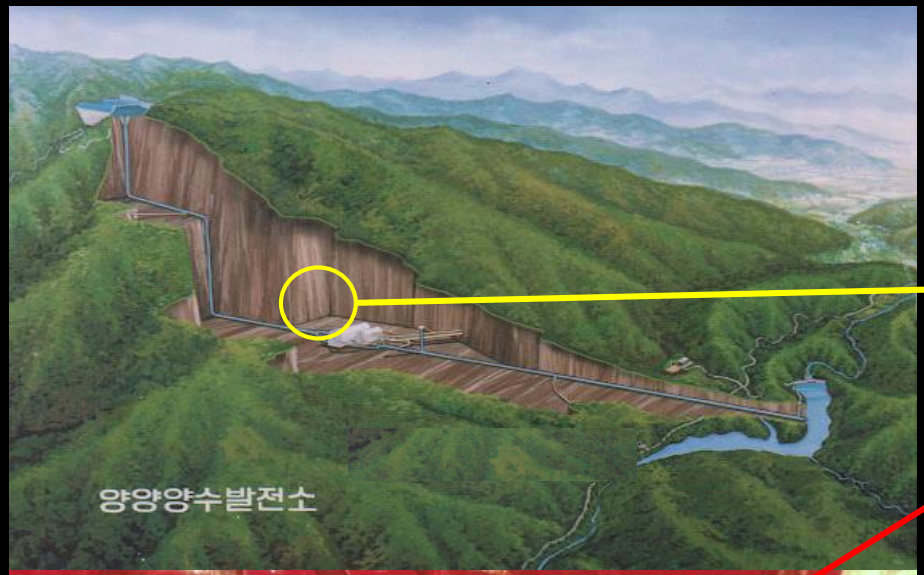


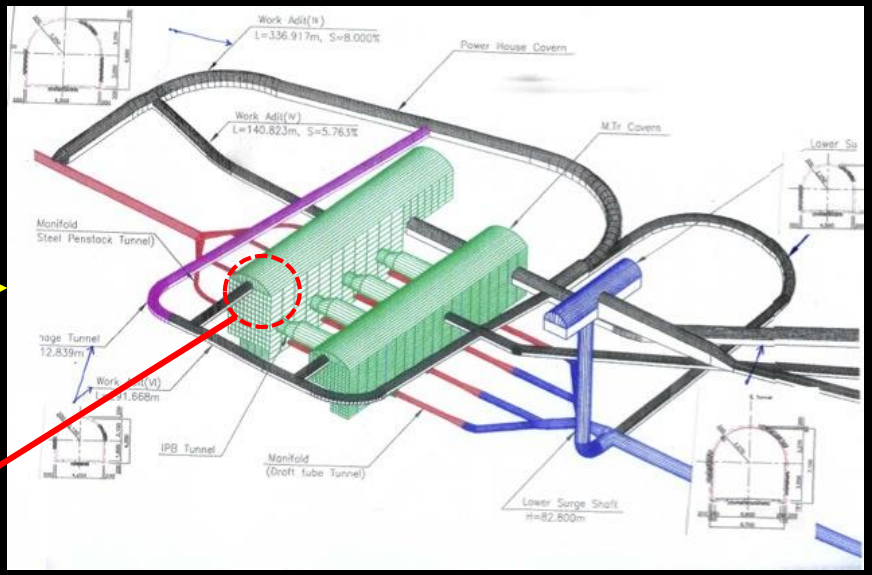


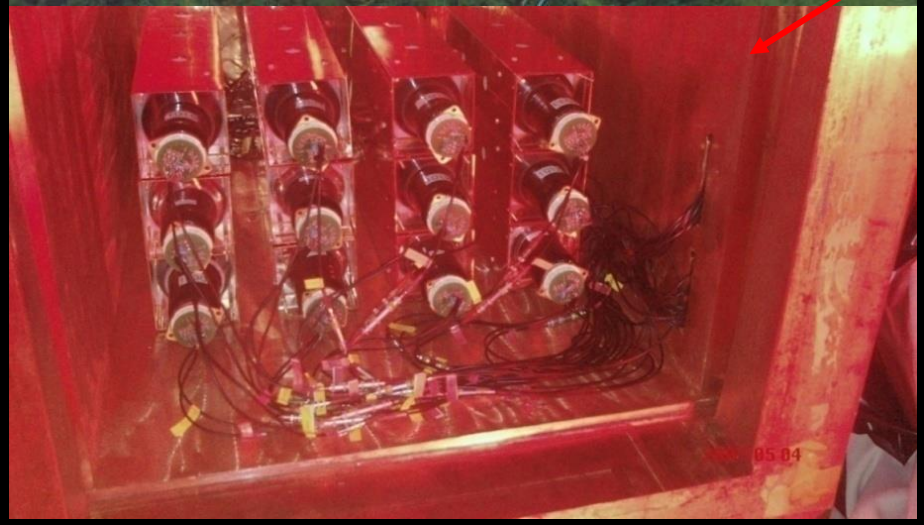
Y2L phase 1 (A6 tunnel)

- 2003 ~ 2023
- **600 m overburden**
- 100 m^2 area
- Access by car for 2km

Y2L (Yangyang Underground Lab.)

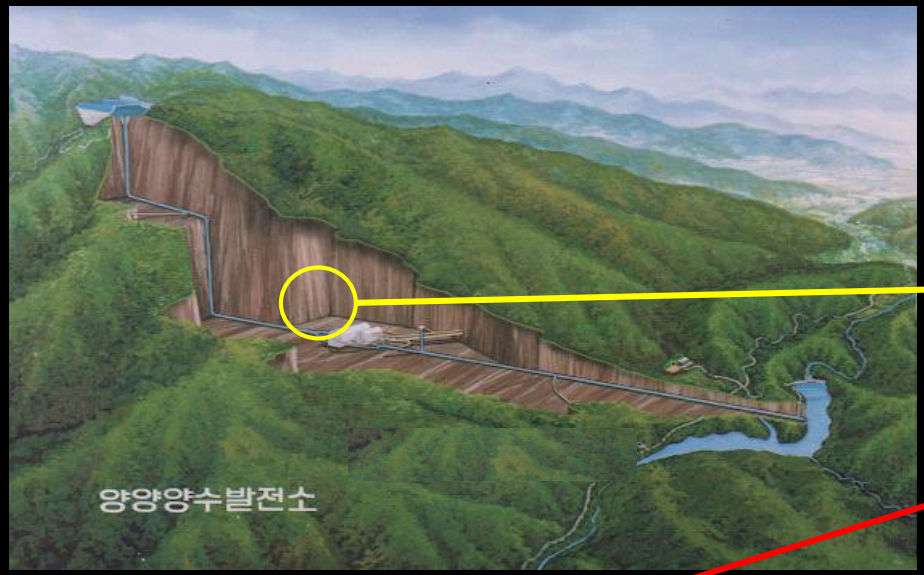


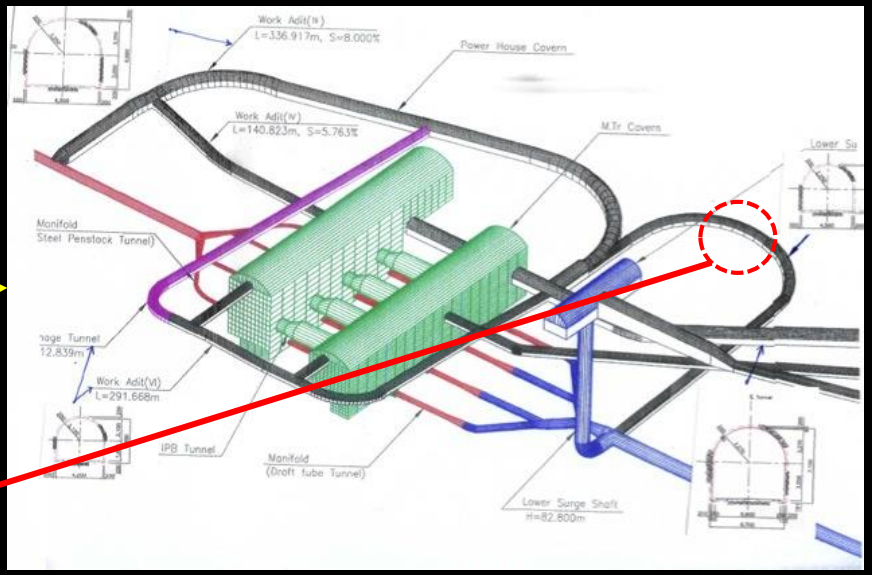


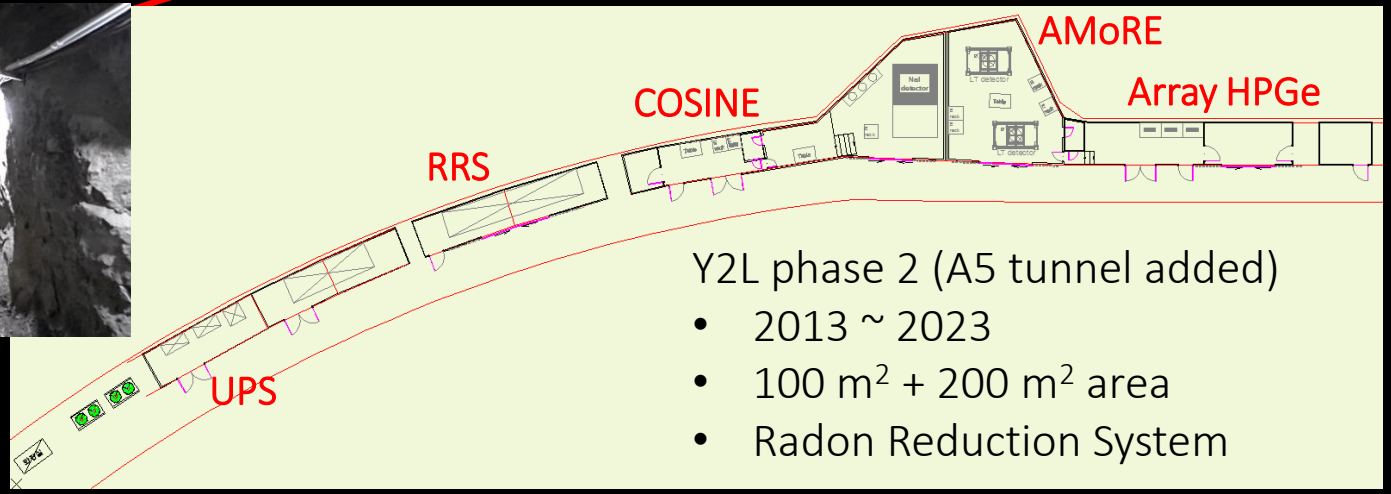


- KIMS experiment start.
  - CsI(Tl) scintillator
- HPGe for radio-assay
- $CaMoO_4$ crystal R&D

Y2L (Yangyang Underground Lab.)



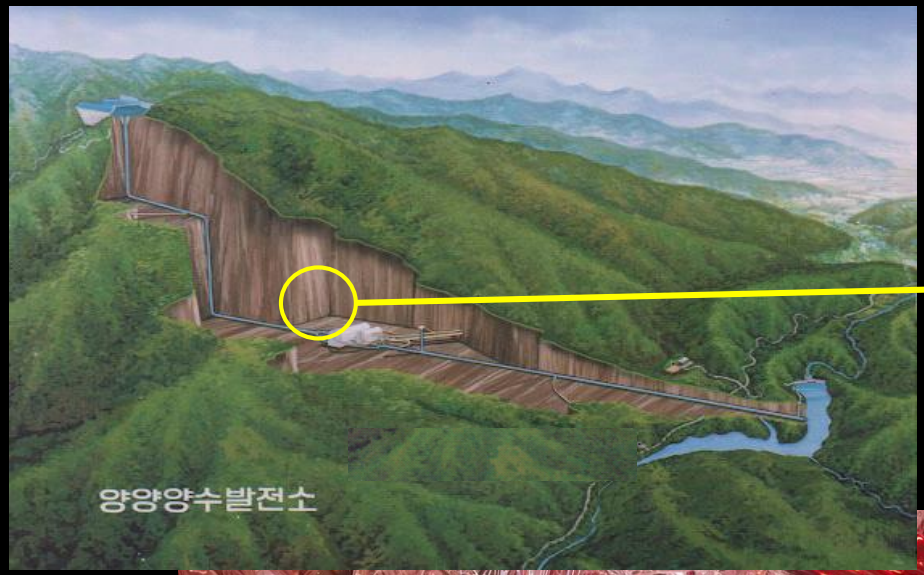


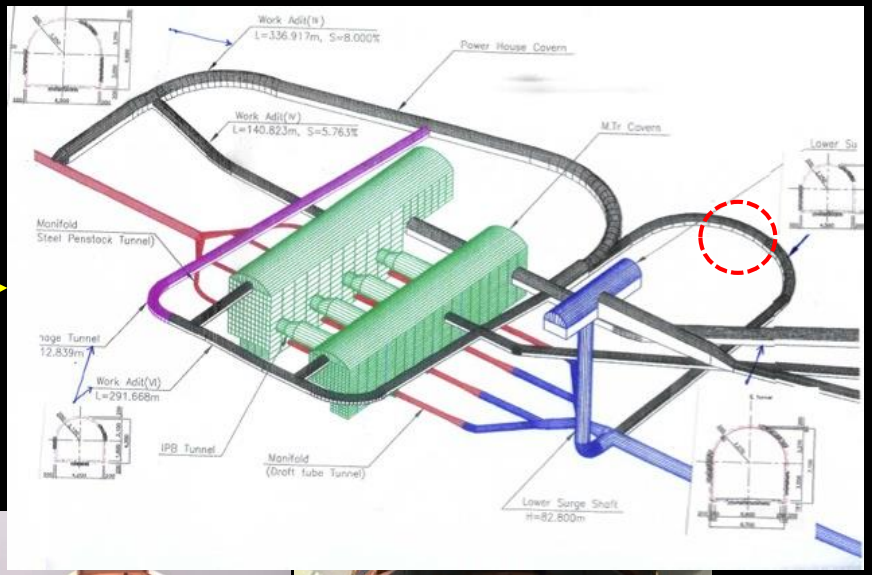


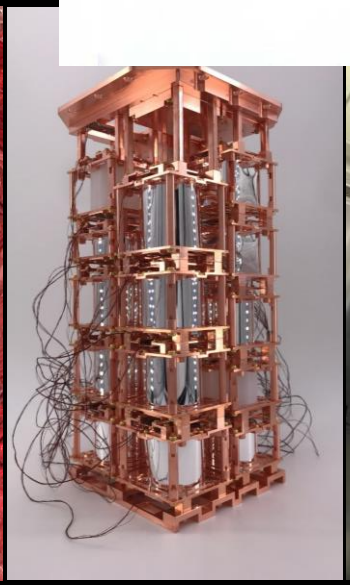
Y2L phase 2 (A5 tunnel added)

- 2013 ~ 2023
- 100 m^2 + 200 m^2 area
- Radon Reduction System

Y2L (Yangyang Underground Lab.)

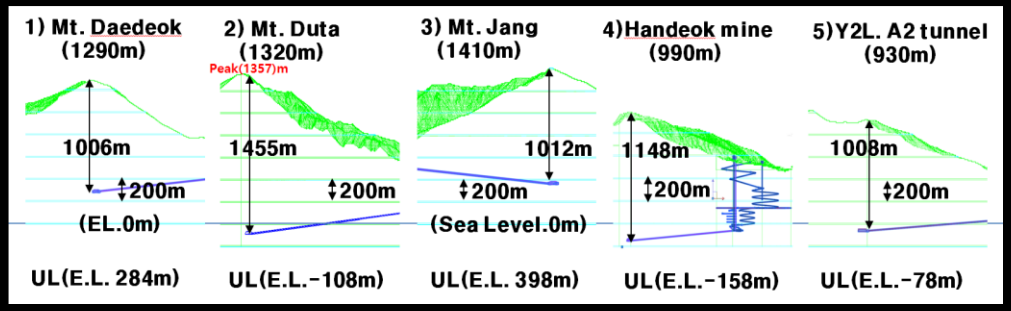


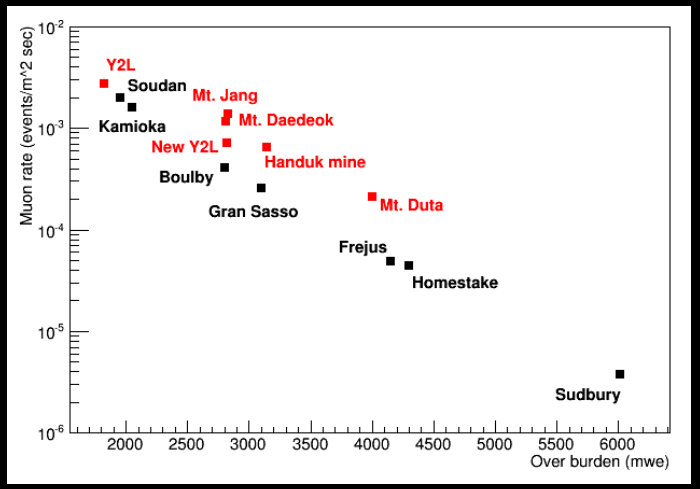




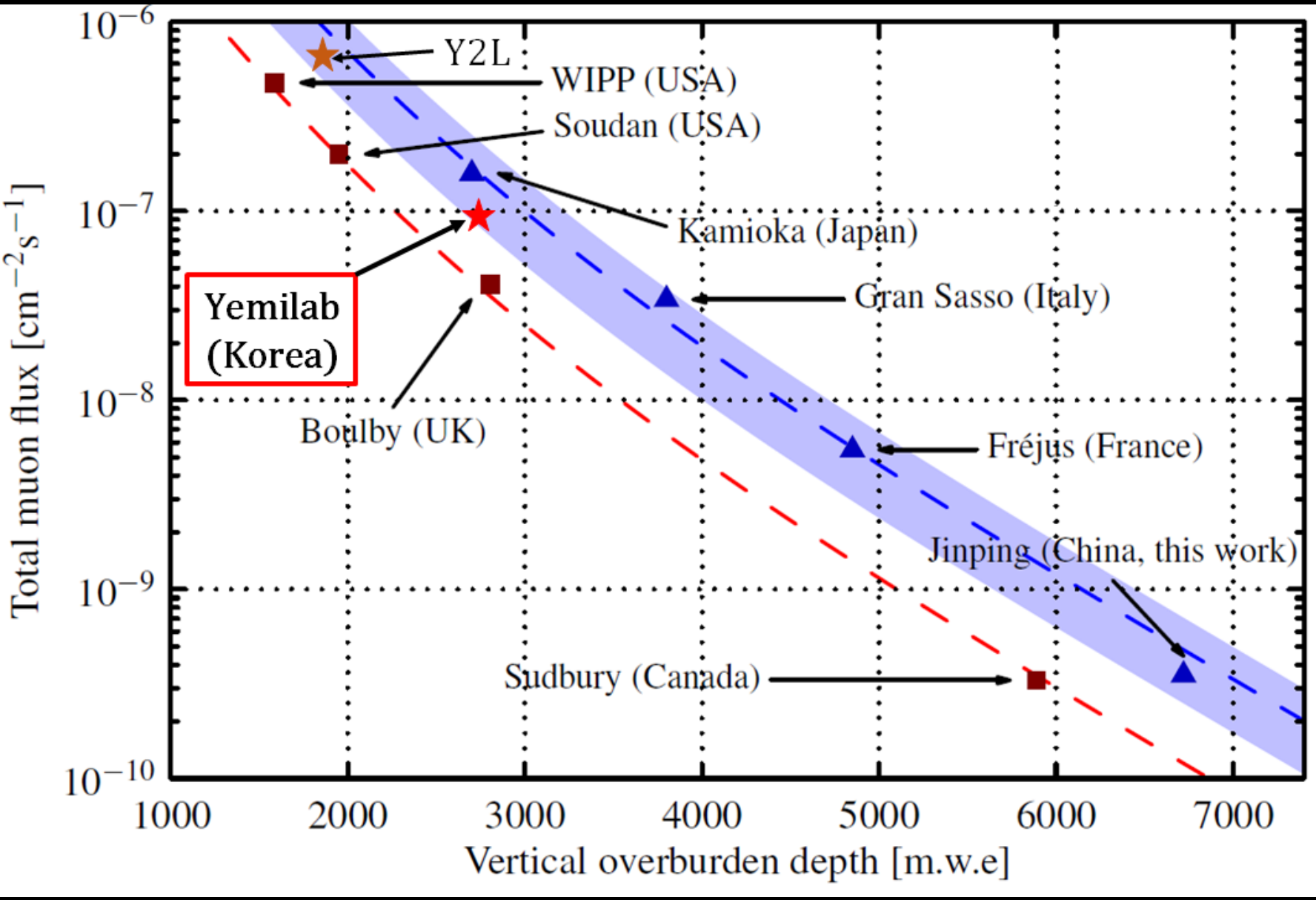
New Underground Lab.

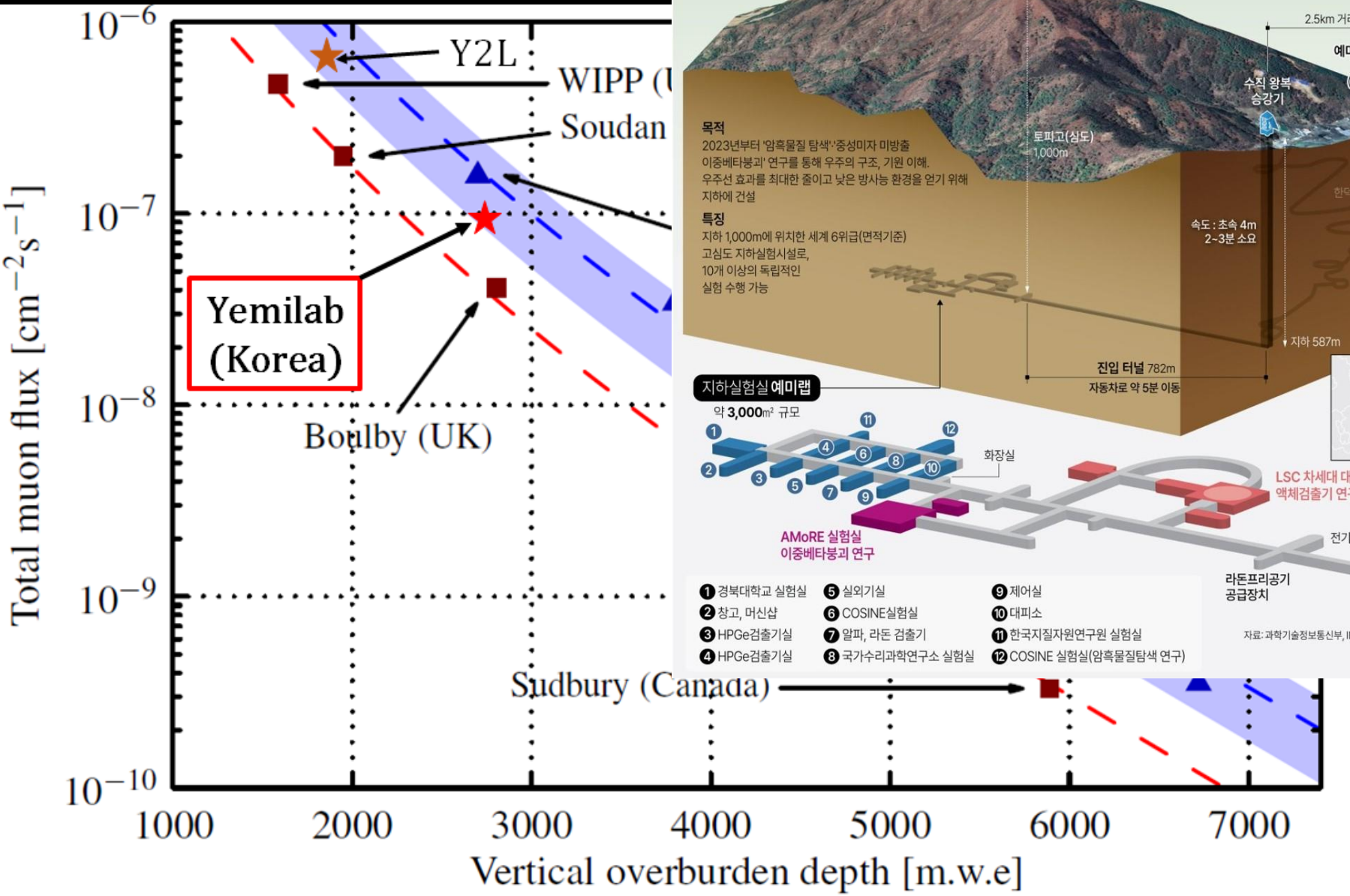
Deeper! Larger! But cheap??





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


Y2L
WIPP (USA)
Soudan (USA)
Kamioka (Japan)
Yemilab
(Korea)
Gran Sasso (Italy)
Boulby (UK)
Fréjus (France)
Jinping (China, this work)
Sudbury (Canada)
Total muon flux [cm^{-2}s^{-1}]
Vertical overburden depth [m.w.e]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
7000


Y2L
WIPP (U
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(Korea)
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Total muon flux [cm^{-2}s^{-1}]
Vertical overburden depth [m.w.e]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
7000

지하 1,000m 지하실험실 '예미랩'
예미산
989m
2.5km 거리
예미랩 지상연구실
3층 건물
(연면적 2,500m²)
수직 왕복
승강기
토파고(심도)
1,000m
한덕철광 광산갱도
목적
2023년부터 '암흑물질 탐색'·'중성미자 미방출
이중베타붕괴' 연구를 통해 우주의 구조, 기원 이해.
우주선 효과를 최대한 줄이고 낮은 방사능 환경을 얻기 위해
지하에 건설
특징
지하 1,000m에 위치한 세계 6위급(면적기준)
고심도 지하실험시설로,
10개 이상의 독립적인
실험 수행 가능
속도 : 초속 4m
2~3분 소요
지하 587m
진입 터널 782m
자동차로 약 5분 이동
강원도
정선군
지하실험실 예미랩
약 3,000m² 규모
화장실
LSC 차세대 대용량
액체검출기 연구
AMoRE 실험실
이중베타붕괴 연구
전기실
라돈프리공기
공급장치
❶ 경북대학교 실험실
❷ 창고, 머신샵
❸ HPGe검출기실
❹ HPGe검출기실
❺ 실외기실
❻ COSINE실험실
❼ 알파, 라돈 검출기
❽ 국가수리과학연구소 실험실
❾ 제어실
❿ 대피소
⓫ 한국지질자원연구원 실험실
⓬ COSINE 실험실(암흑물질탐색 연구)
자료: 과학기술정보통신부, IBS(기초과학연구원)

Yemilab Construction

Milestones

2015. New underground facility site chosen as Handuk iron mine LTD

2016.12 Agreement signed with Handuk for the establishment and utilization of Yemilab within Handuk mine

2017.09 –2018.12 Building the human riding cage

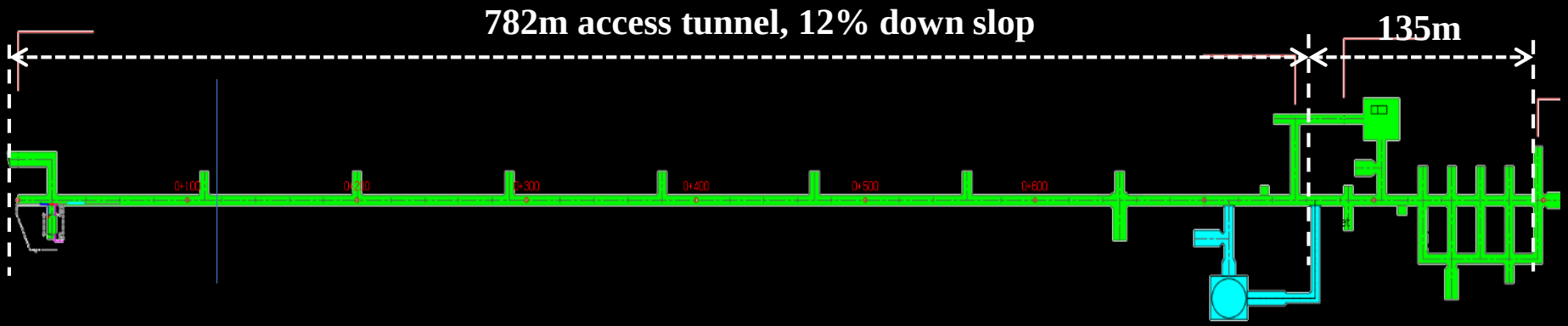
2018.12 –2020.08 The 1st construction for excavation of the main tunnels

2021.06 –2023.07 The 2nd construction for LSC & electricity, machinery etc..

2022.10 Renovation of the ground office

2022.10.05 The construction completion ceremony

Yemilab Construction



- The 1st phase construction
  - Period : 2017. July ~ 2020. August
  - Cage installation in the shaft
  - 1st phase Excavation : 2000 m^2 (lab. area)

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

Yemilab Construction: AMoRE Cavern

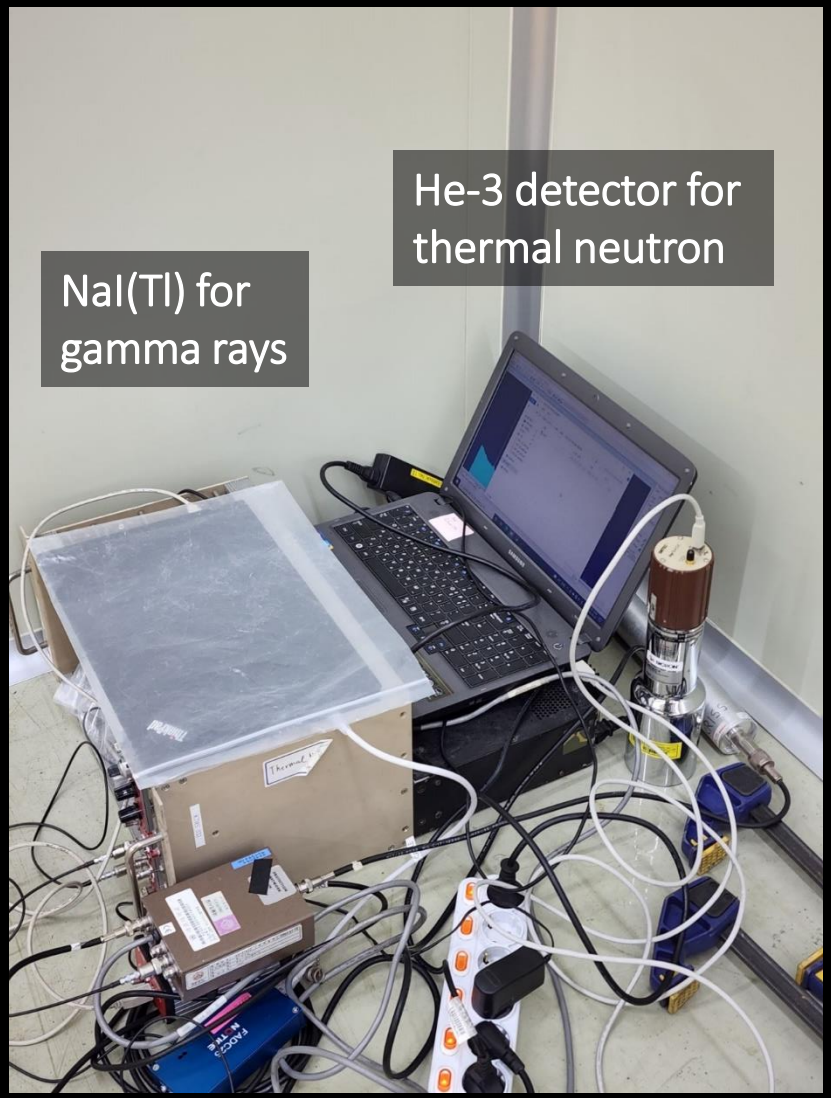
The Yemilab

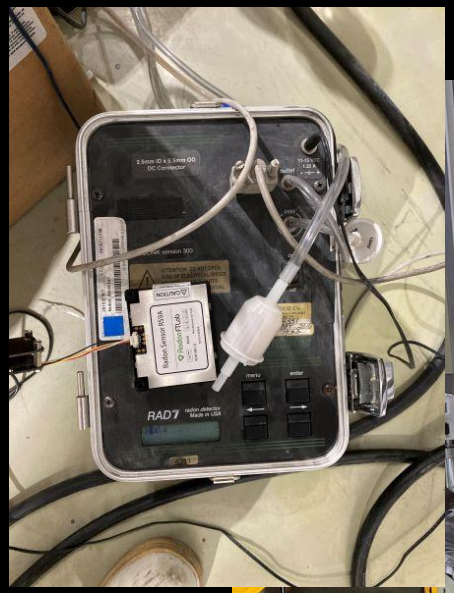
Access by EV
The LSC cavern
(20 × 25 m³)
RRS (50m³/h)
COSINE (future)
Refuge
AMoRE cavern
(21 × 21 × 15 m³)
COSINE
HPGe
Network
O.D.U.
KNU cavern
(8 × 8 × 12 m³)

Yemilab Infrastructures

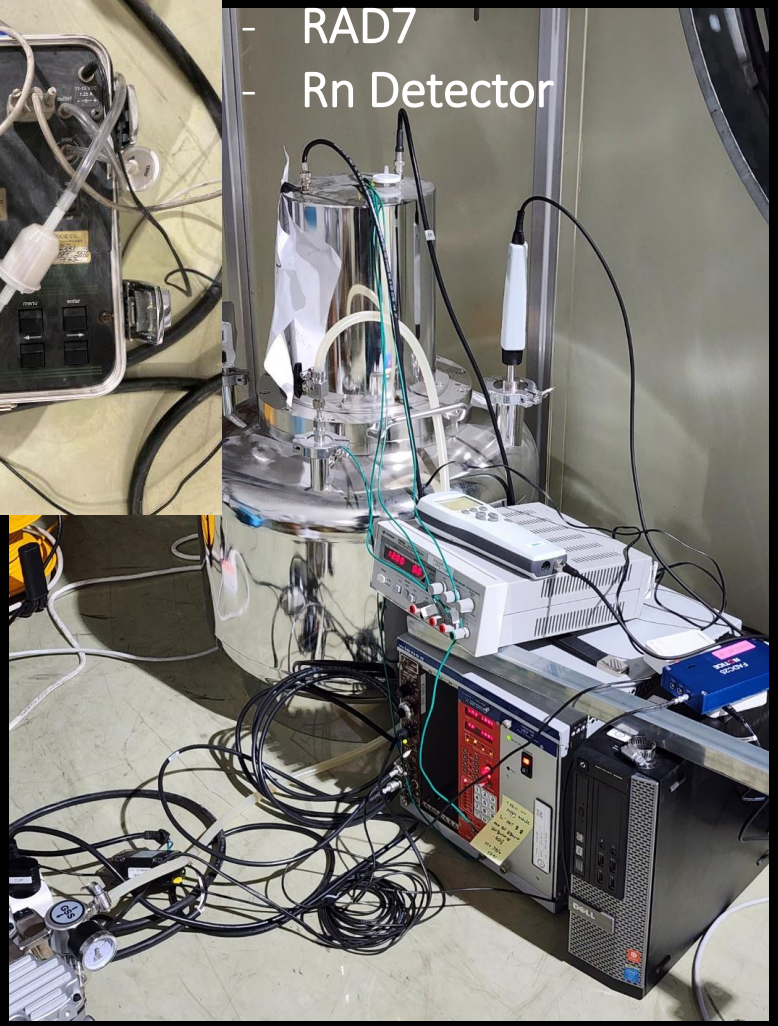
- Full mobile communication (LTE)
- Network connection
- Radon reduction system (50 m^3/h, 1/500 reduction)
  - Will be upgraded to 200 m^3/h
- LN2 generators for cryostats and HPGe
- Dust proof doors
- Electric vehicles for dust proof area
- Cranes for the large caverns (for large construction, 5/10 ton)
- Refuge (40 people for 72 hours, Dried food, water, air, UPS, …)
- Toilets
- …

Radiation Measurements

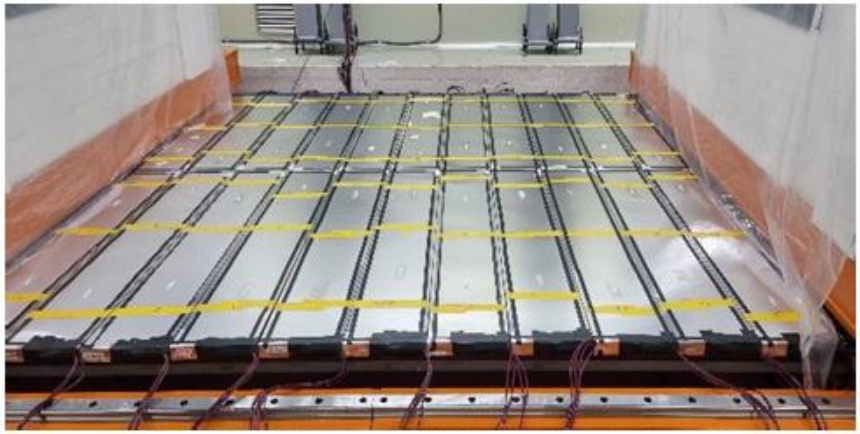


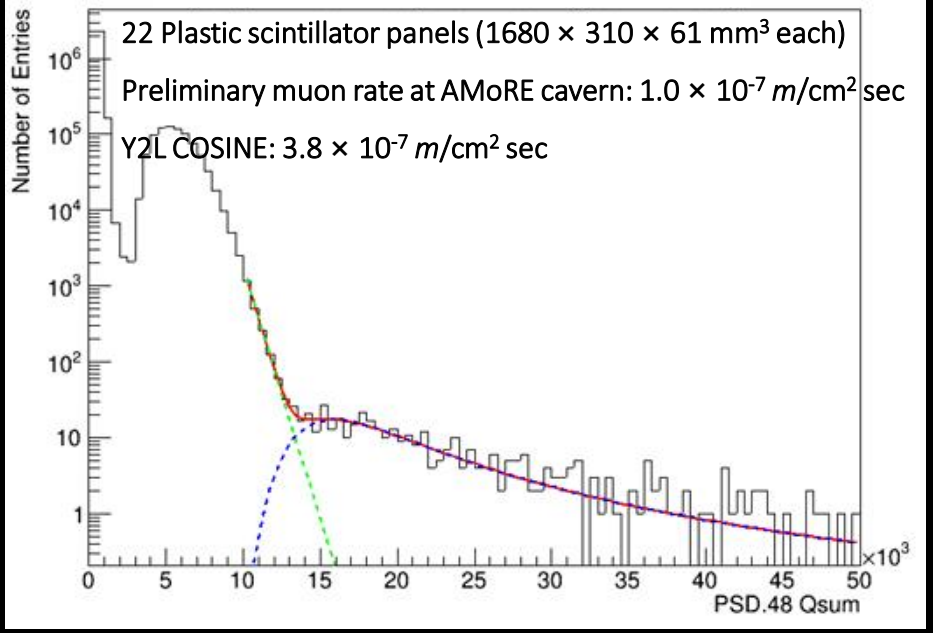


Rn monitors
- RAD7
- Rn Detector

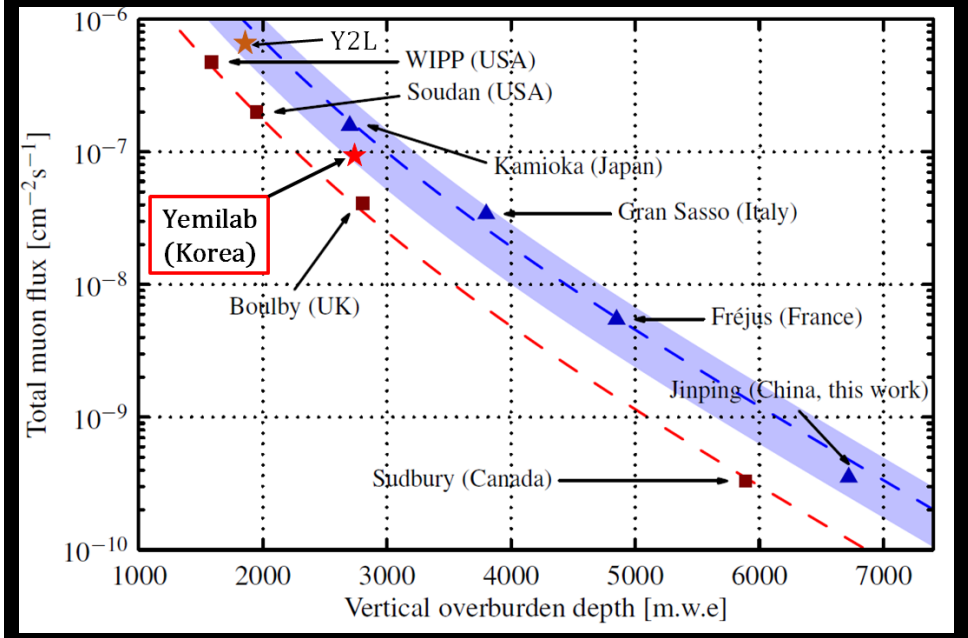


Muon Flux

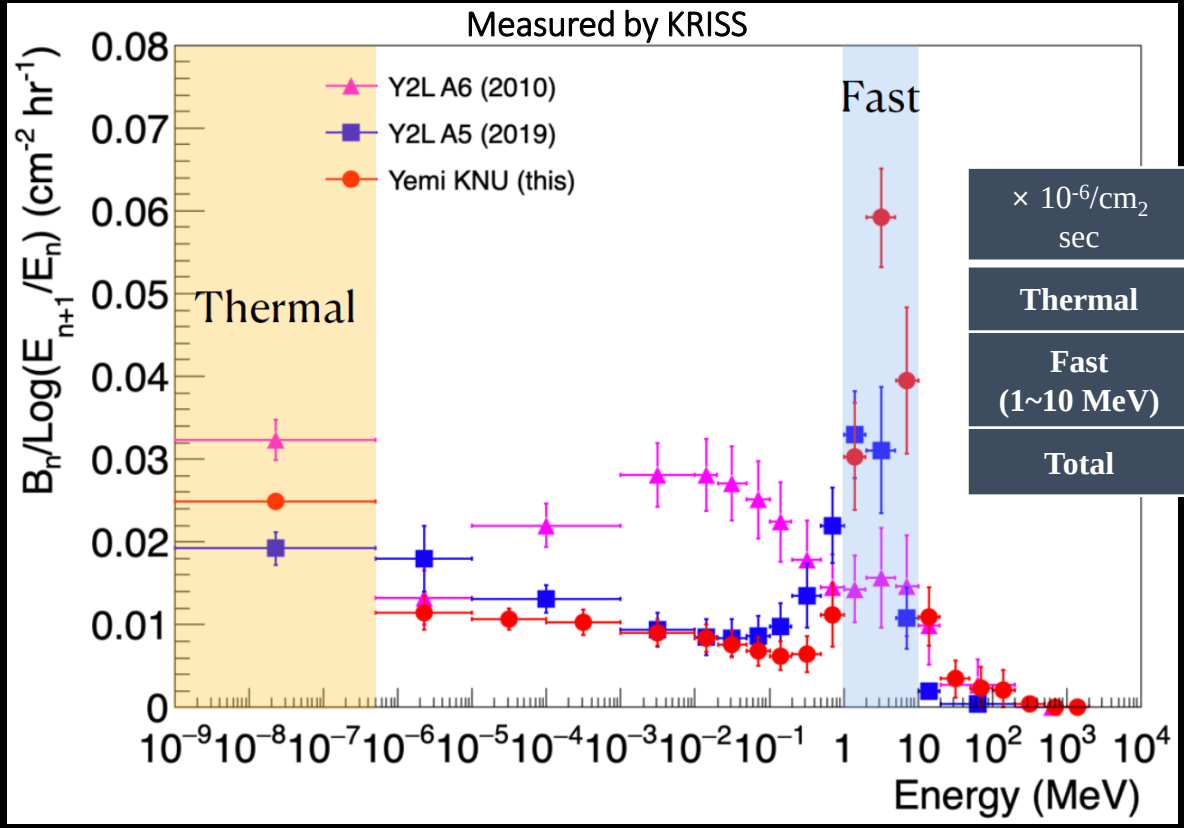




U.L.	Gran Sasso	SNO lab	SURF	Kamioka	Boulby	Yemilab
Depth (mwe)	3,800	6,000	4,300	2,700	2,850	2,500
Volume (m³)	180,000	37,000	7,800	56,500	14,000	25,000



Neutron Flux



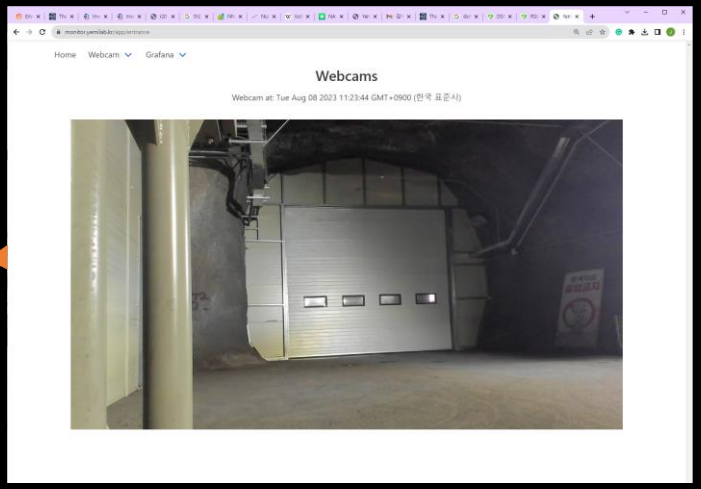
× $10^{-6}/cm_2$ sec	Y2L A6	Y2L A5	Yemilab
Thermal	24.2 ± 1.8	14.4 ± 1.5	**18.6 ± 0.8**
Fast (1~10 MeV)	4.2 ± 0.9	7.1 ± 1.0	**12.4 ± 1.1**
Total	67.2 ± 2.2	44.6 ± 6.6	**49.5 ± 1.8**

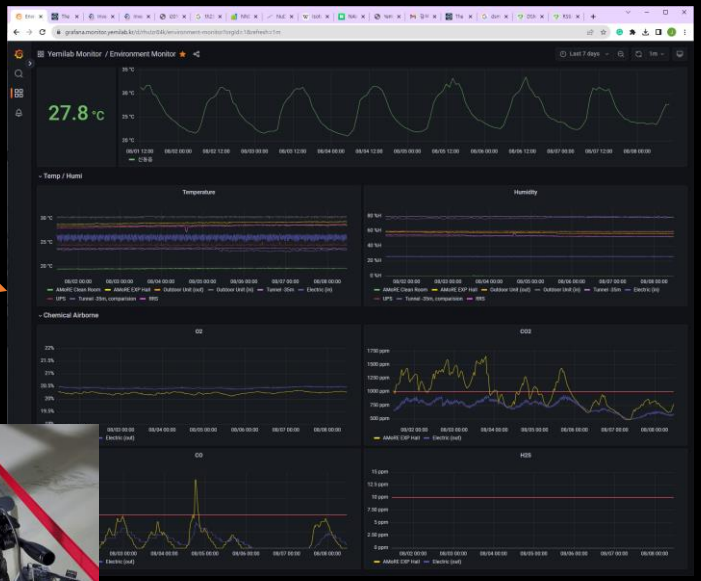
Y2L : More moderation by equipment
Yemilab : A few hundreds of tons Shotcrete
~ 180 tons on AMoRE cavern

Environmental Monitoring

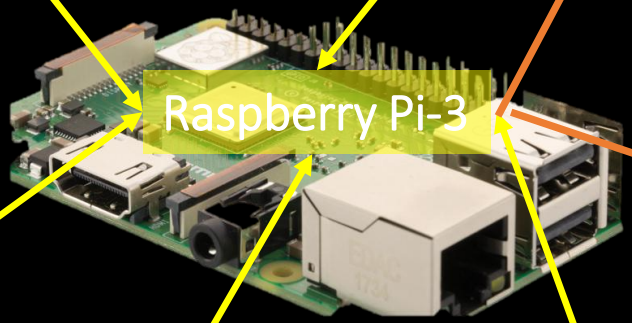
UA10
Temp. : -40 ~ 80 ℃
Humidity : 5 ~ 95 %

DSM101
PM1.0 / PM2.5 / PM10
1~1,000 $\mu g/m^3$





UA58-KFG-U
CO (~ 1,000 ppm)
CO_2 (400 ~ 10,000 ppm)
O_2 (0 ~ 25%)
H_2S (0 ~100 ppm)



USB Connection

RS9A
7 ~ 3700 Bq/m^3
±15% accuracy

Webcam
1 picture / min

Yemilab Summary

- The new underground laboratory has been started in Korea.
  - Overburden: ~ 2,700 m.w.e.
  - Total Area: 3,000 m^2
- The measurement of the radiation environment is continued.
  - The rock and construction material radio-assay is ongoing.
  - Muon flux : 1.0×10^{-7} m/cm^2 sec (Preliminary)
  - Neutron flux : $4.95 (\pm 1.8) \times 10^{-7}/cm^2$ sec (Preliminary)
  - Raspberry-pi based online monitoring
- A permanent air circulation system is under considering.
- Y2L had been moved to Yemilab.

AMoRE-II

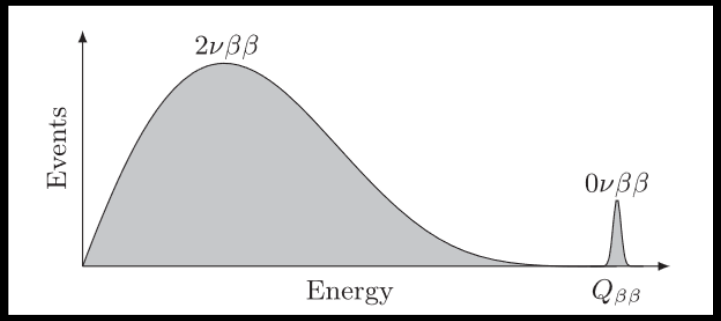
Total 107 members, from 24 institutes, at 10 countries

0νββ of ^{100}Mo

- Discovery of 0νββ
  - Neutrinos are Majorana fermions
  - Lepton number violation
  - Beyond the standard model
- To discover 0νββ, we need a good energy resolution, extremely low background at that energy and mass·time exposure.
- Molybdenum-100:
  - $Q_{\beta\beta}$ = 3034 keV, $T_{1/2}^{2\nu} = 7.1 \times 10^{18}$ years
  - Natural abundance ~ 9.7%
  - Possible to be a scintillation crystal, $CaMoO_4$, Li_2MoO_4
  - $T_{1/2}^{0\nu} > 1.8 \times 10^{24}$ years at 90% CL. by CUPID-Mo

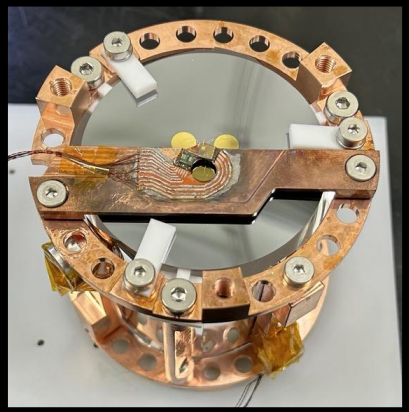
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}|M_{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

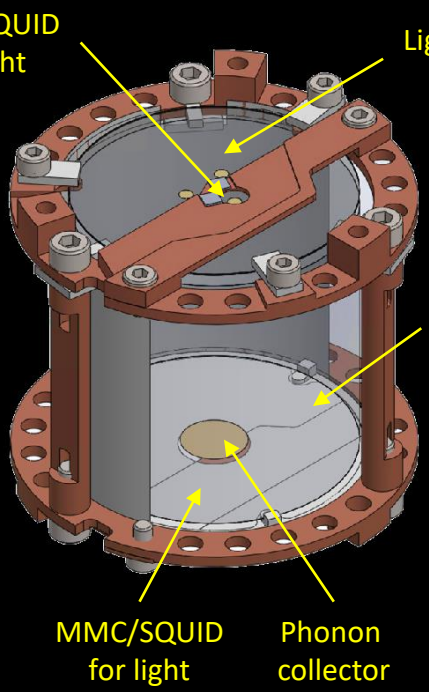
$$T_{1/2}^{0\nu} \propto \sqrt{\frac{MT}{b\Delta E}}$$



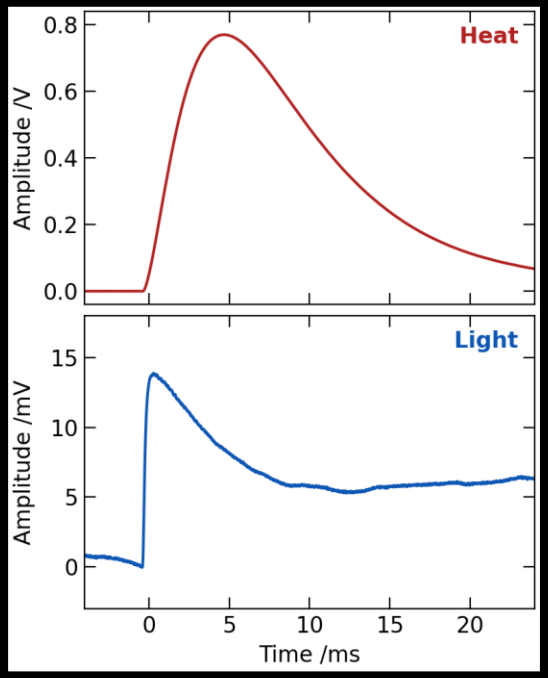
AMoRE Detector

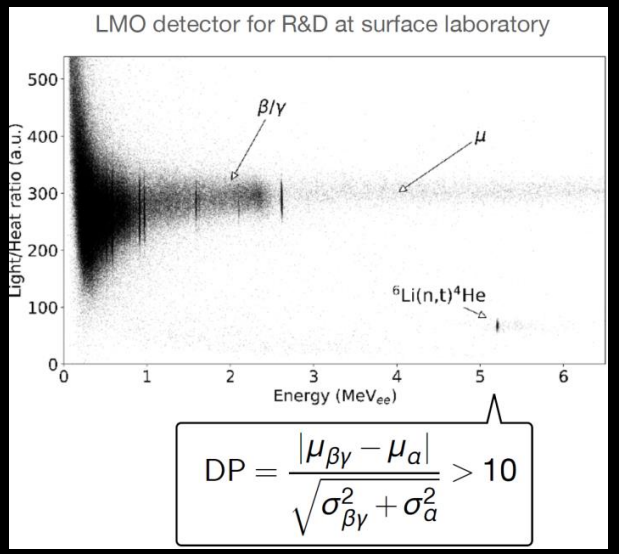
- Heat and light signals at low temperature
  - $Li_2{}^{100}MoO_4$ (LMO) scintillation crystal as a source and target at ~10 mK
  - Detection of head and light signal using MMC+SQUID





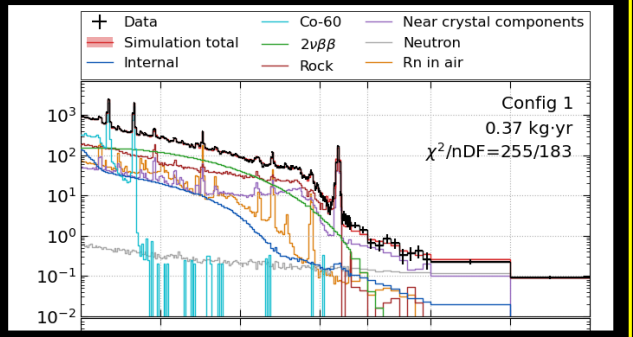
Averaged 2.6 MeV γ signal of a LMO detector of AMoRE-I





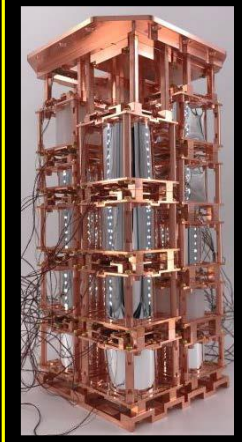
AMoRE-Pilot
2015 – 2018

6 $^{48dep}Ca^{100}MoO_4$ crystals: 1.9(0.88 ^{100}Mo) kg of CMO

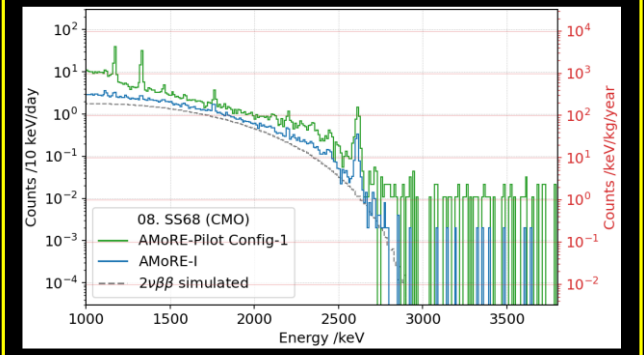


Y2L
Live exposure: ~0.32 kg_{100Mo}·yr
Background: ~0.5 ckky
$T_{1/2}^{0\nu} > 3.2 \times 10^{23}$ years at 90% CL.

AMoRE-I
2020 – 2023

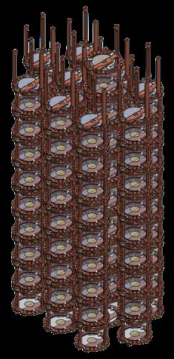


13 CMOs & 5 LMOs: 6.2(3.0 ^{100}Mo) kg of XMO



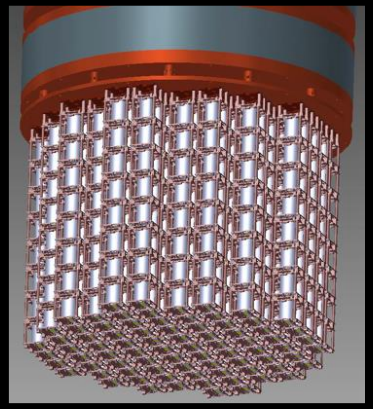
Y2L
Live exposure: ~4 kg_{100Mo}·yr
Background: ~0.025 ckky
$T_{1/2}^{0\nu} > 3.0 \times 10^{24}$ years at 90% CL.

AMoRE-II
2025 –



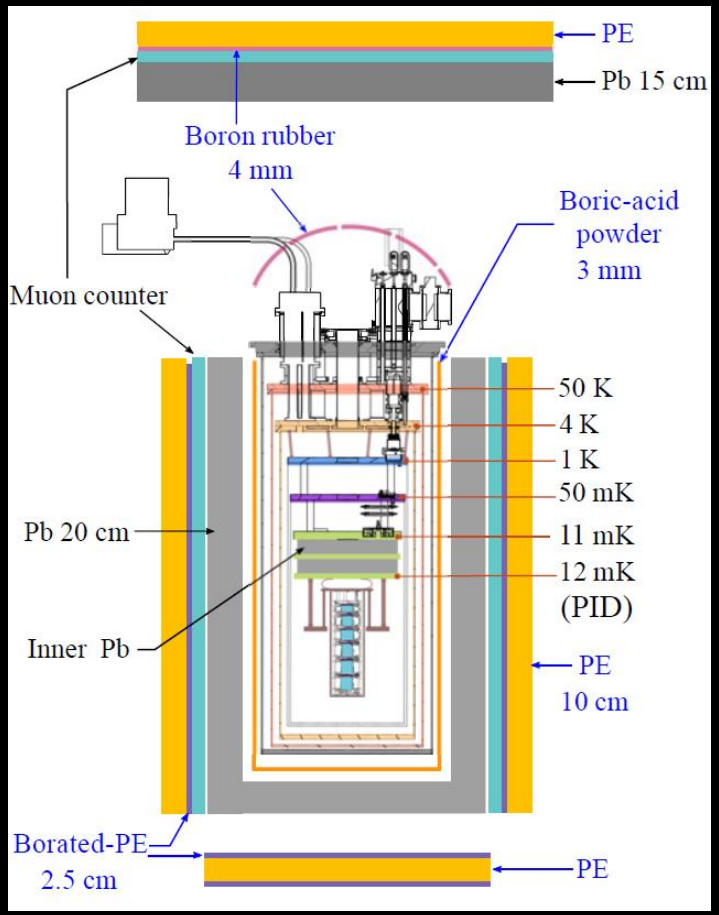
Stage 1: 90 LMOs (27 kg)

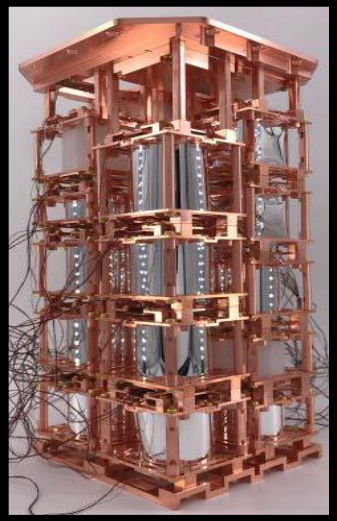
Stage 2: 360 LMOs (157 kg)



Yemilab
Live exposure: > 500 kg_{100Mo}·yr
Background: ~10^{-4} ckky

AMoRE-I @ Y2L

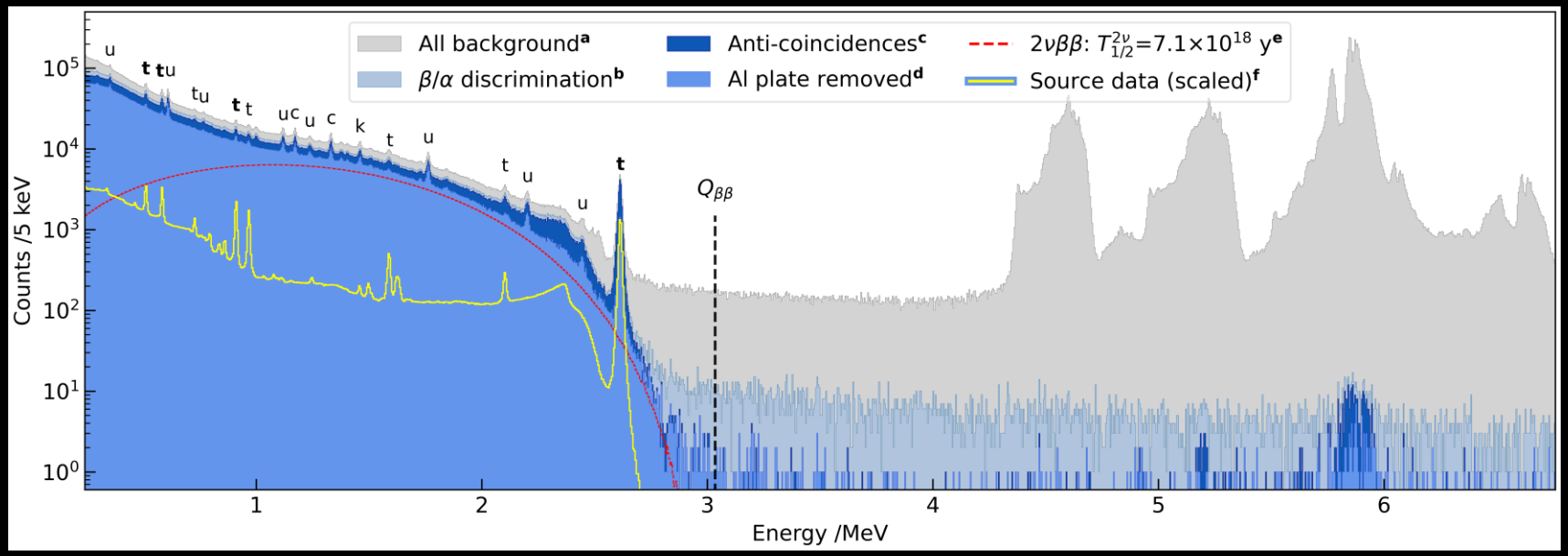


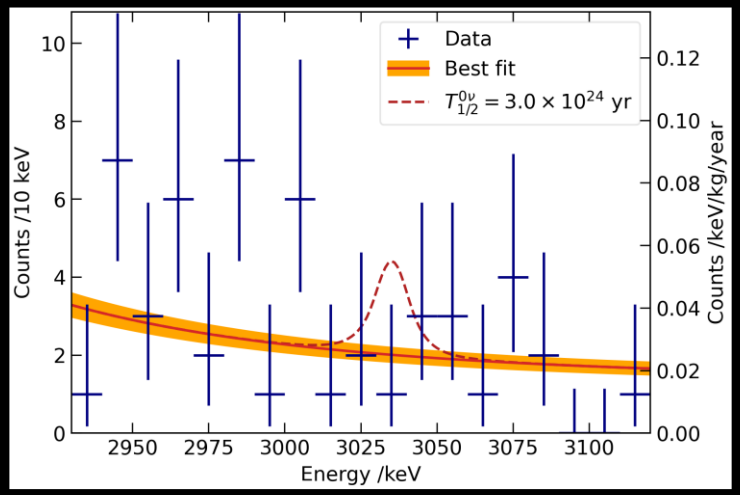


To check detector performance & backgrounds

- Run @ Yangyang Underground Lab. (Y2L), 2020 - 2023
- 13 CMO (4.6 kg) and 5 LMO (1.6 kg) crystals
- 20 cm Pb shielding + neutron shields (PE + b.PE)
- Muon veto detector (plastic scintillator + PMT)
- Confirmed stable operation of MMC+SQUID @ 12 mK

AMoRE-I





Total exposure: 3.89 kg_{100Mo}·year

Results:

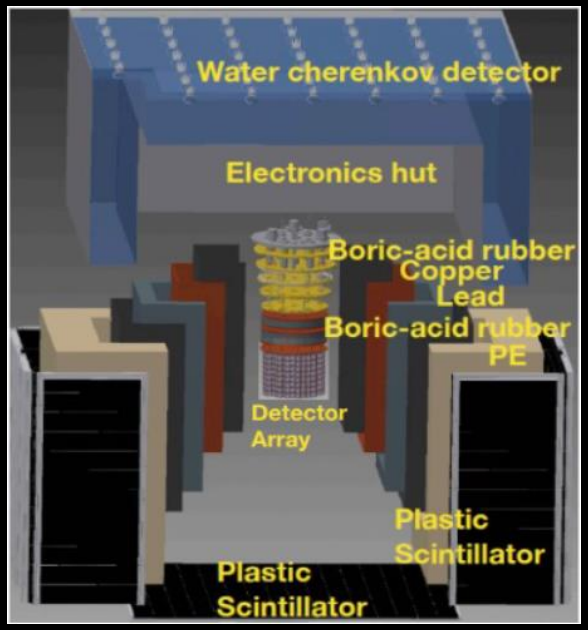
- Background: 0.025 ckky
- $T^{0\nu}_{1/2} > 3.0 \times 10^{24}$ years at 90% CL.

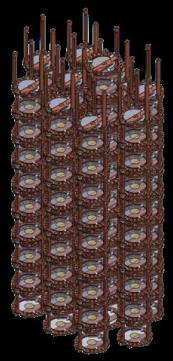
Agrawal *et al.*, arXiv:2407.05618, submitted to PRL

ckky: counts/kev/kg/year

AMoRE-II Overview

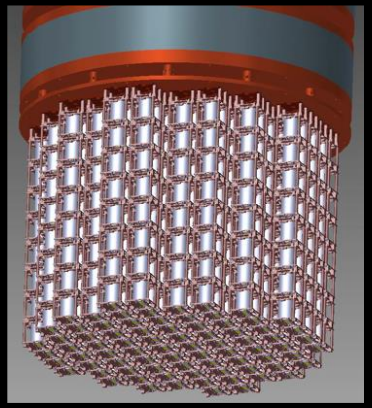
- @ Yemilab, 1000 m overburden
- 360 crystals (LMOs + 13 CMOs)
  - MMC+SQUID for heat & light signals
  - Si wafer for light detector
- Cryostat from Leiden
- Shielding with Pb, PE, and water
  - Lower: Pb (25 cm) + boric-acid rubber (1 cm) + PE (70 cm)
  - Upper: Inner Pb (26 cm) + water (~70 cm)
- Muon veto system
  - Lower: Plastic Scintillator Muon Detector (PSMD)
  - Upper: Water Cerenkov Muon Detector (WCMD)
- Backgrounds: Goal < 10^{-4} ckky
- Sensitivity: $T_{1/2}^{0\nu} \sim 4 \times 10^{26}$ years, 90% CL.
- Schedule
  - Stage 1: 90 crystals, 2024-25
  - Stage 2: 360 crystals, 2026 - 2030





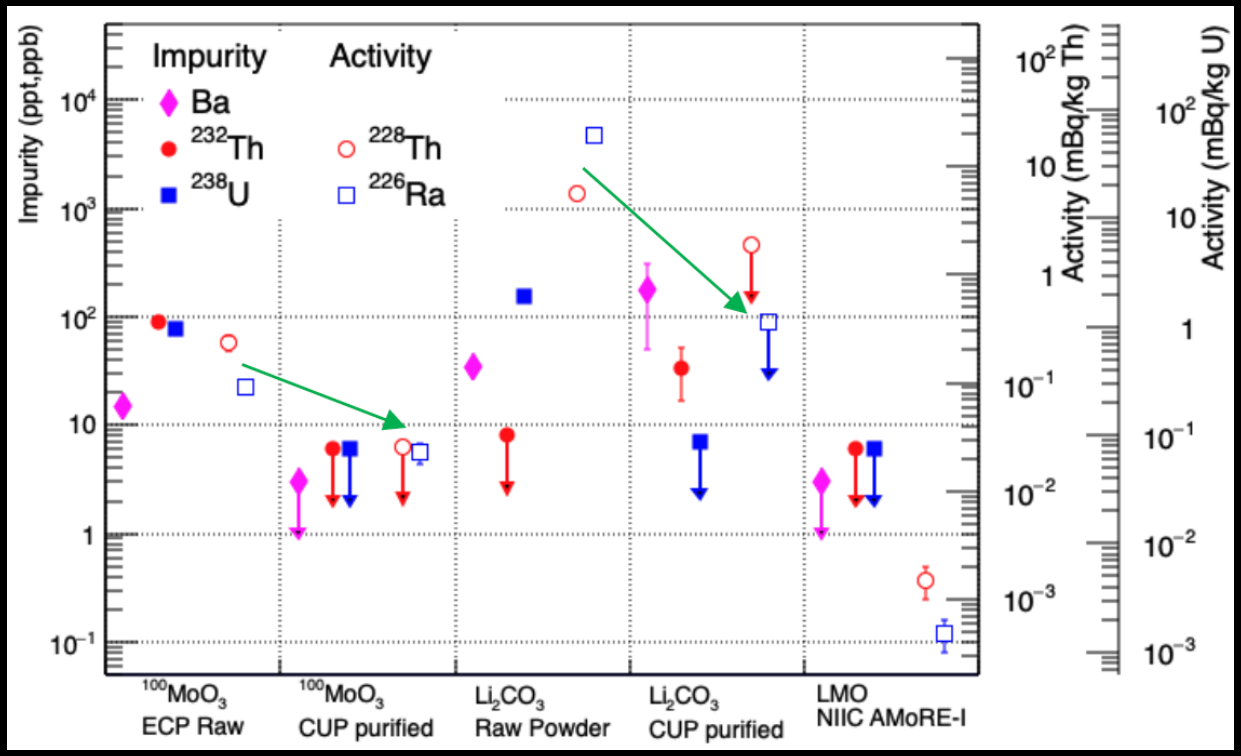
Stage 1:
90 LMOs
(27 kg)

Stage 2:
360 LMOs
(157 kg)



Radiopure Enriched Crystals

- Purification of raw materials
  - Purification of both powders, $^{100}MoO_3$ and Li_2CO_3
  - 120 kg of enriched MoO3 powder is purified in wet chemistry
  - Re-purification of crystal melts and wastes is going on

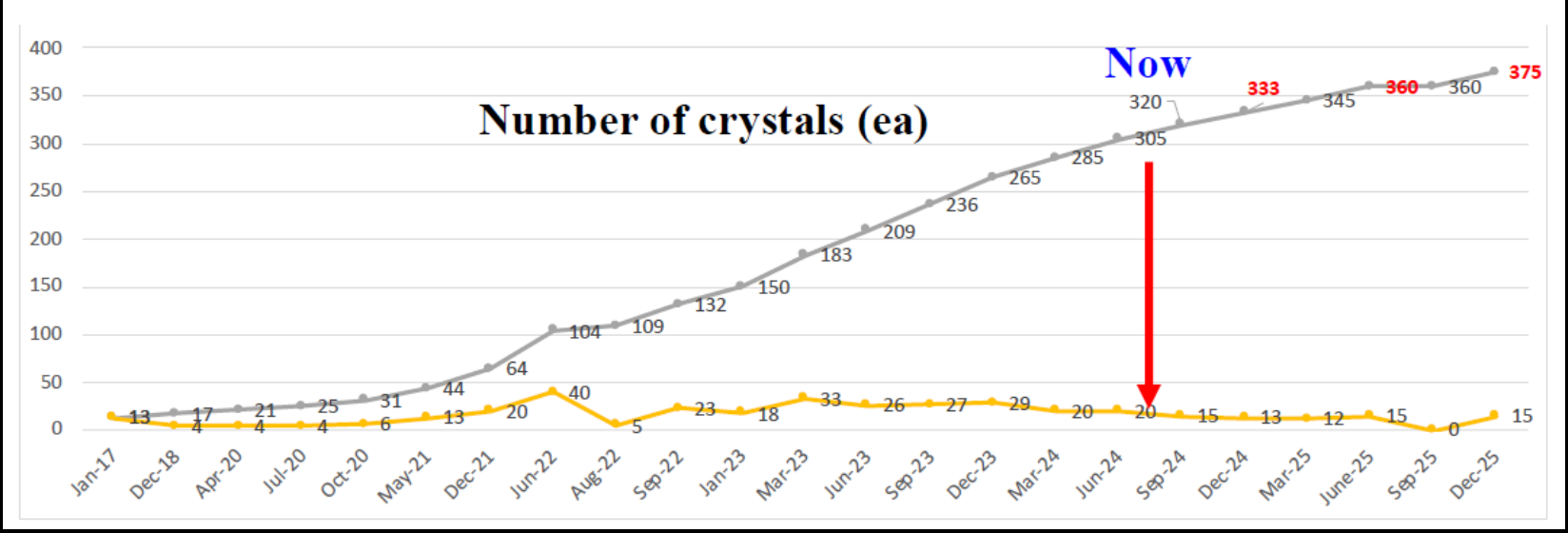


MoO_3 powder \ Activity (μBq/kg)	Raw	Purified
Ac-228	260 ± 50	< 27
Th-228	210 ± 50	< 16
Ra-226	260 ± 50	110 ± 30
K-40	8500 ± 1400	1700 ± 340

Yeon H., et al. Front. Phys. 11, 1142136 (2023)

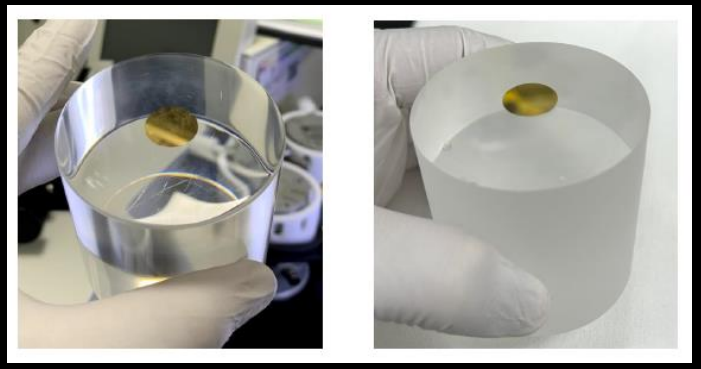
Crystal Productions

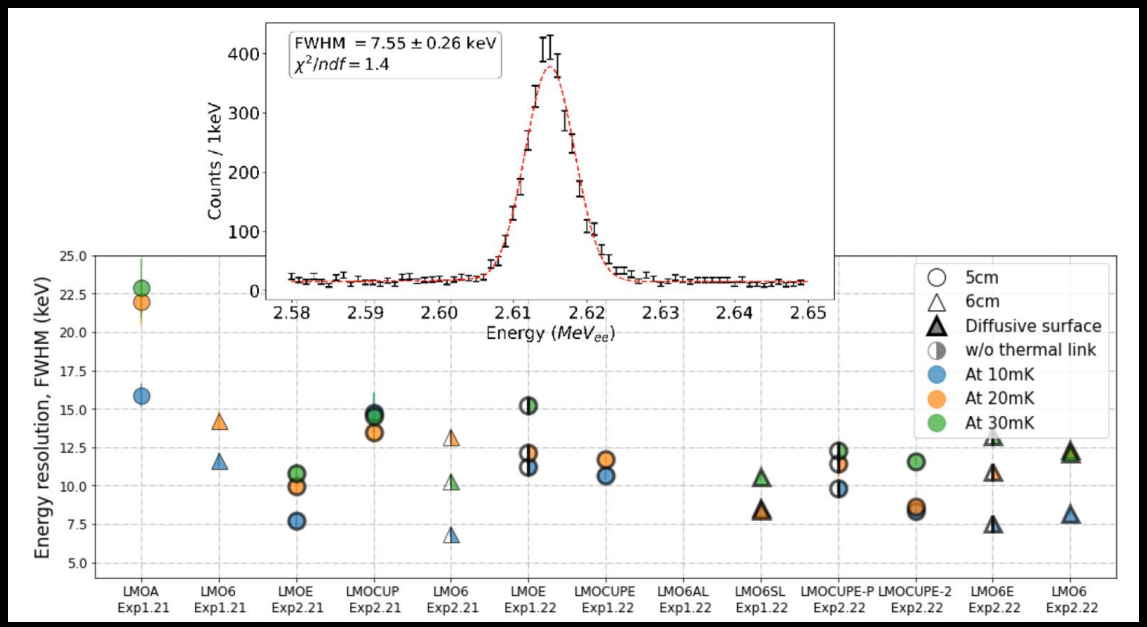
- Crystals produced at CUP/IBS and Nikolaev Institute of Inorganic Chemistry (NIIC, Russia).
- 100Mo enrichment = 95%
- 360 ea (157 kg, 84 kg of 100Mo) of crystals (including AMoRE-I CMOs) will be ready be mid-2025.

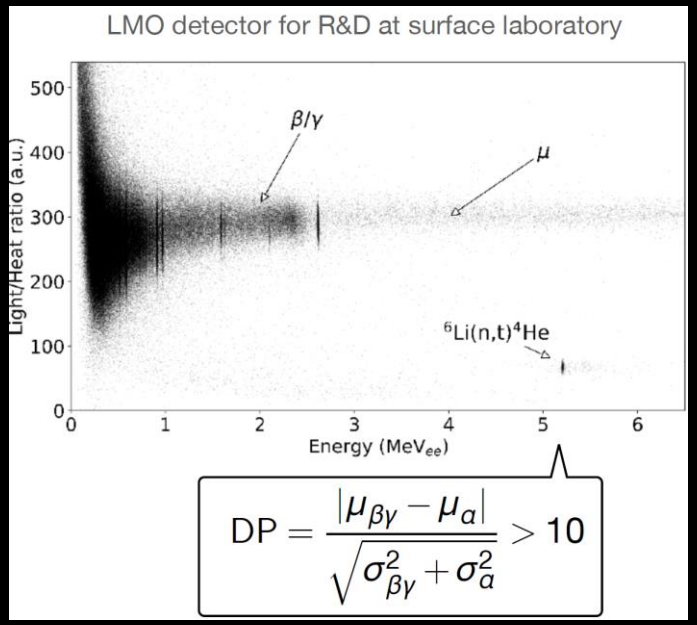


Detector R&D

- Optimized detector design
  - Crystal surface (polished, diffusive)
  - Crystal size (5 cm, 6 cm): pile-up background $< 3 \times 10^{-5}$ ckky
- Reach FWHM < 10 keV at 3.034 MeV & improve light detector performance
  - β/α discrimination power > 10

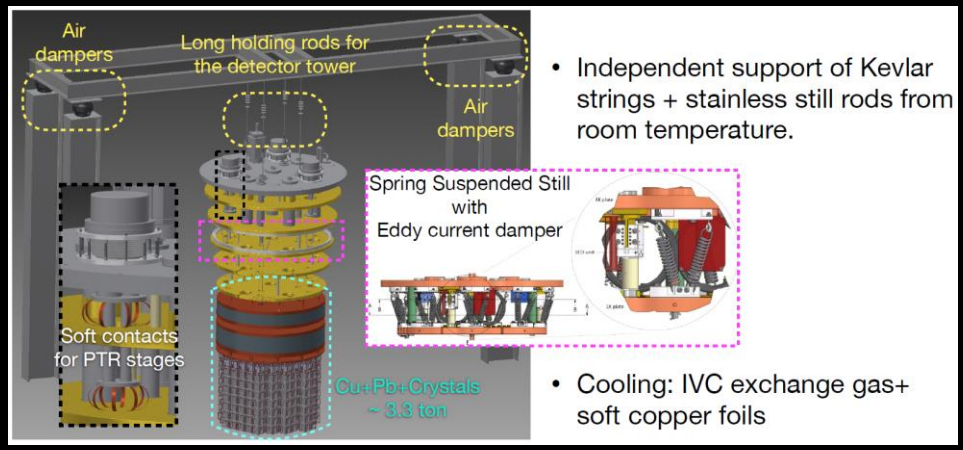


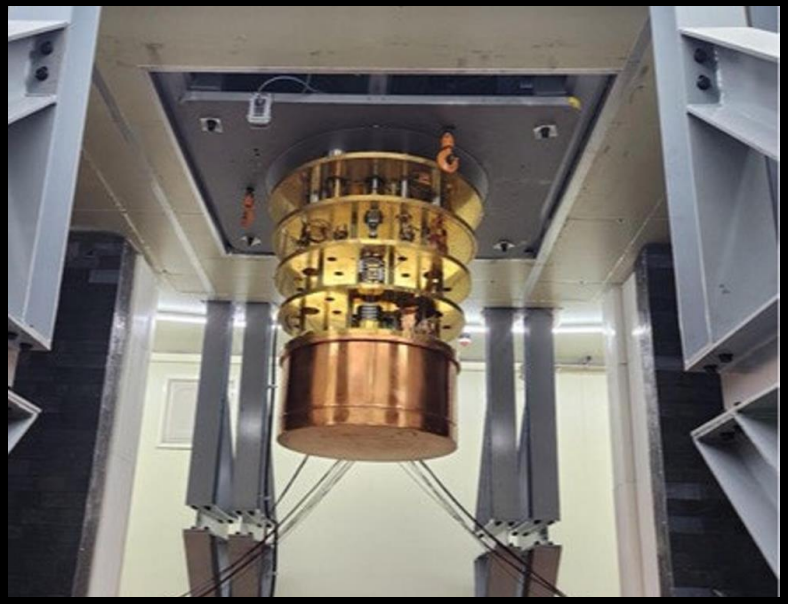




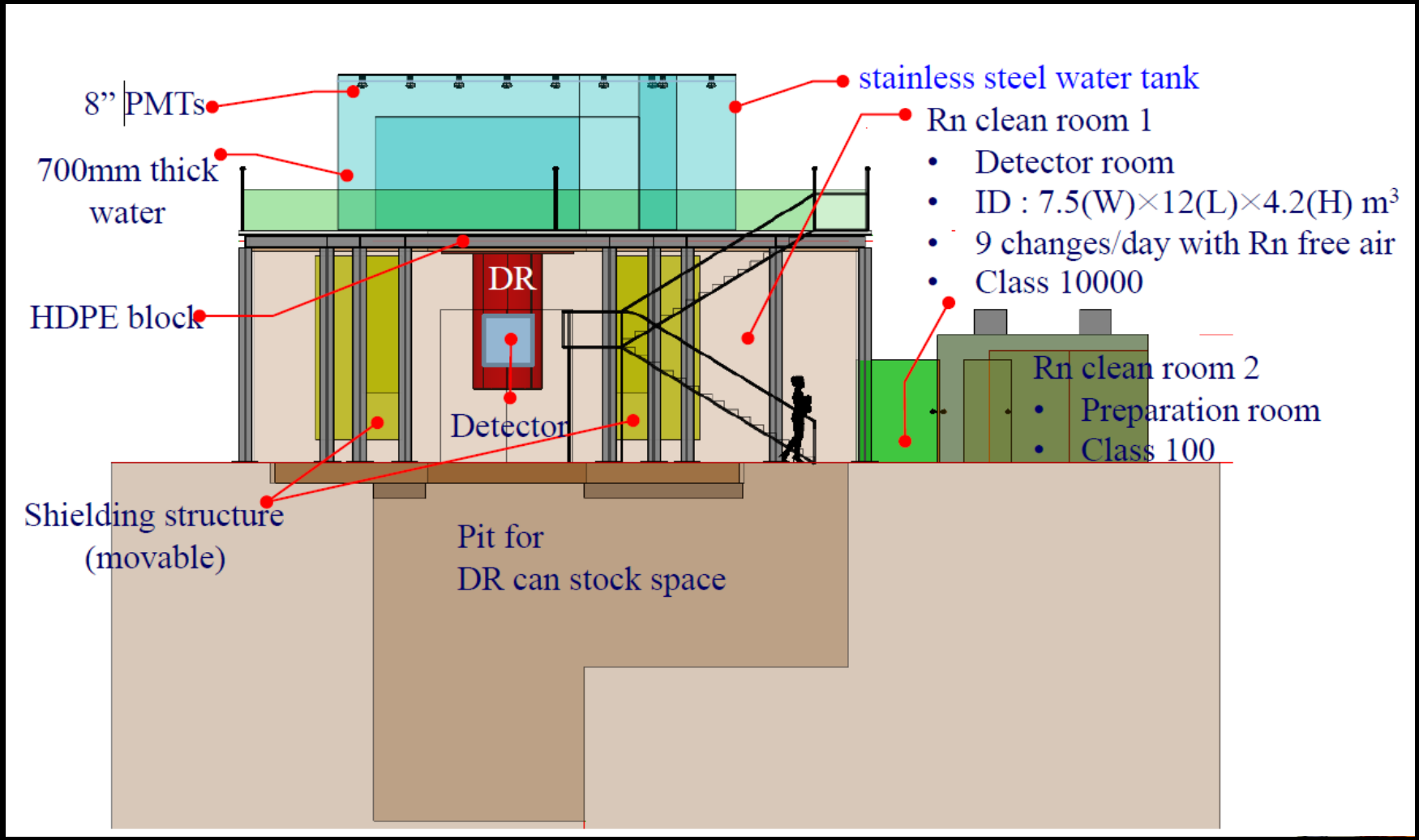
Dilution Refrigerator (DR)

- Large dilution refrigerator from Leiden
  - With three pulse tubes
  - Cooling power: 5 μW @ 10 mK
  - Base temperature: 6 mK
- Including vibration damping system
- Cabling: 27 wires X 360 detector
  - CuNi alloy30 (ϕ160 μm) with NOMAX wire between top plate & mixing chamber
- DR has been transferred to Yemilab and is currently undergoing various tests.





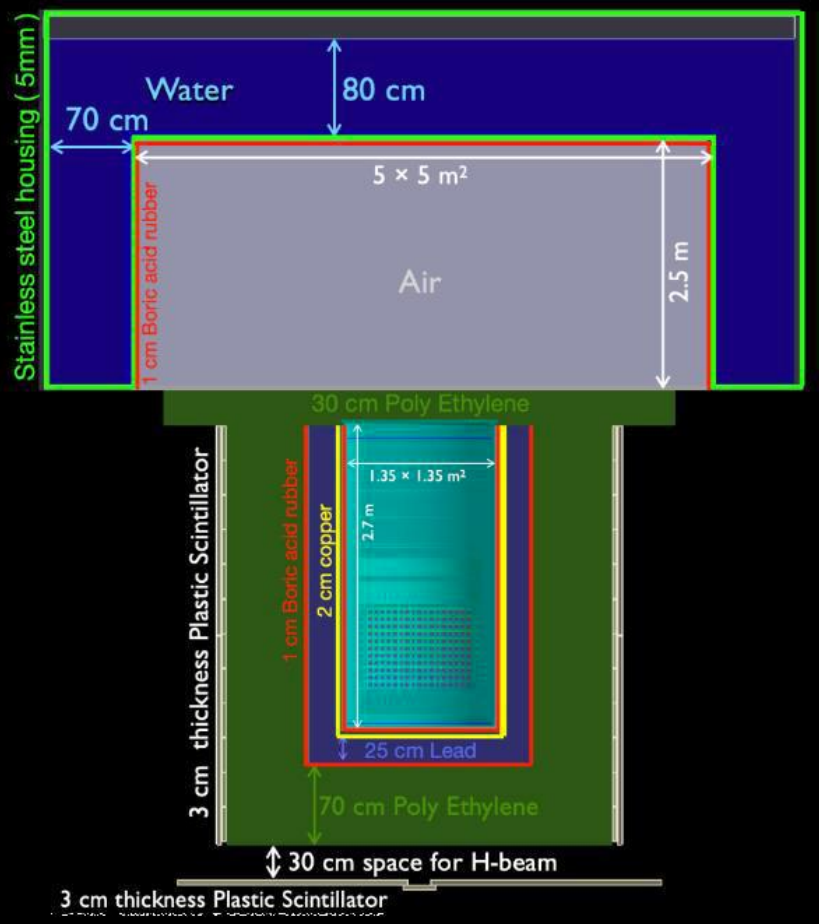
Structures


8” PMTs
700mm thick water
HDPE block
Shielding structure (movable)
DR
Detector
stainless steel water tank
Rn clean room 1
• Detector room
• ID : 7.5(W)×12(L)×4.2(H) m³
• 9 changes/day with Rn free air
• Class 10000
Rn clean room 2
• Preparation room
• Class 100
Pit for
DR can stock space

Structures

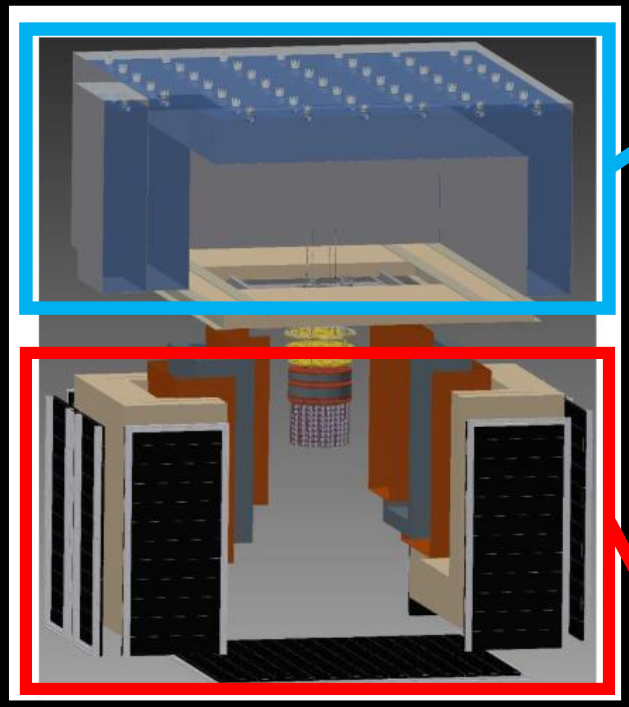
Shielding

- GEANT4 simulation for a realistic geometry with rock gamma, neutron and muon flux at Yemilab.
- Pb (26 cm) over the crystal towers, below the mixing chamber plate in IVC
- Lower: Pb (25 cm) < boric acid rubber (1 cm) < HDPE (70 cm)
- Upper: boric acid rubber (1 cm) < water (> 70 cm)
- Radon-less air supply
- At 1,000 m underground
  - Muon rate ~ 10^{-7} $cm^{-2}s^{-1}$



Muon Veto System

Water Cerenkov Muon Detector (WCMD)



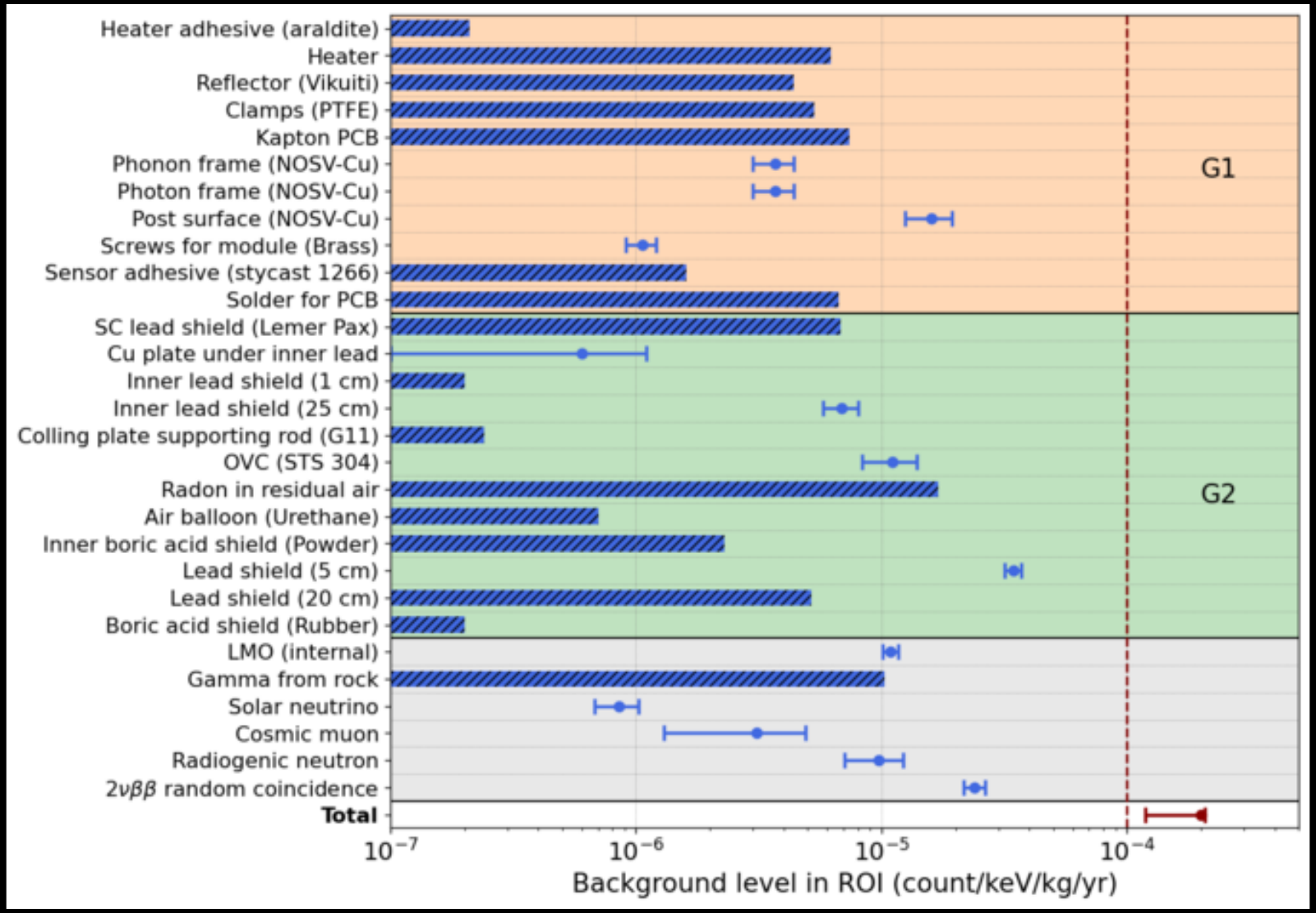
- 48 PMTs (8 & 10 inch)
- 60 tons of DI water
- Tyvek reflector inner surface

Plastic Scintillator Muon Detector (PSMD)

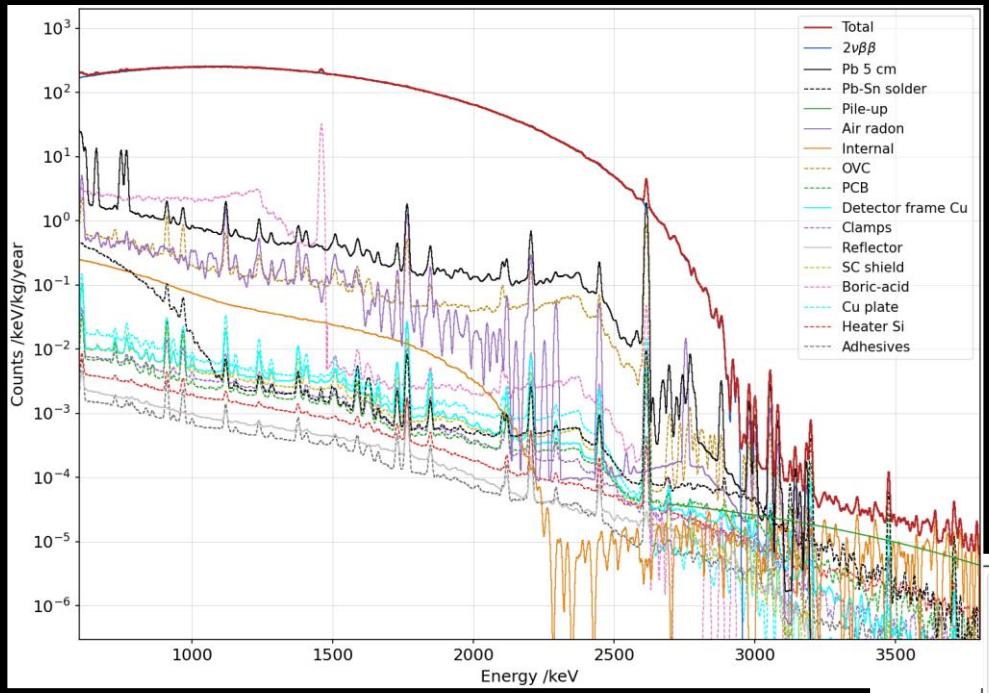
130 detectors

- 2 PS with wavelength shifting fibers and 4 SiPM
- 170 cm x 30 cm x 5 cm

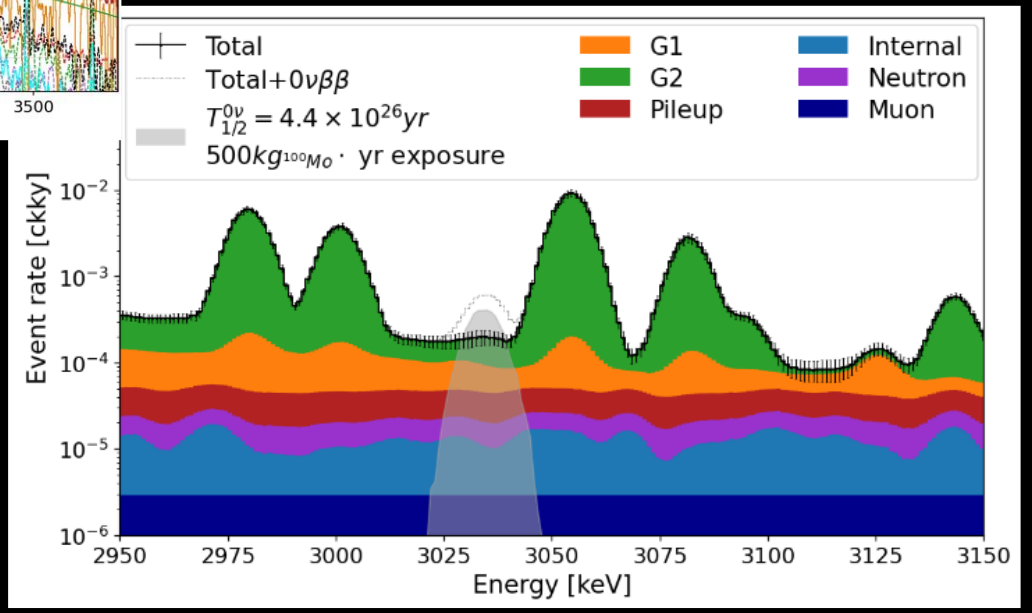
Background Estimation



Background Estimation

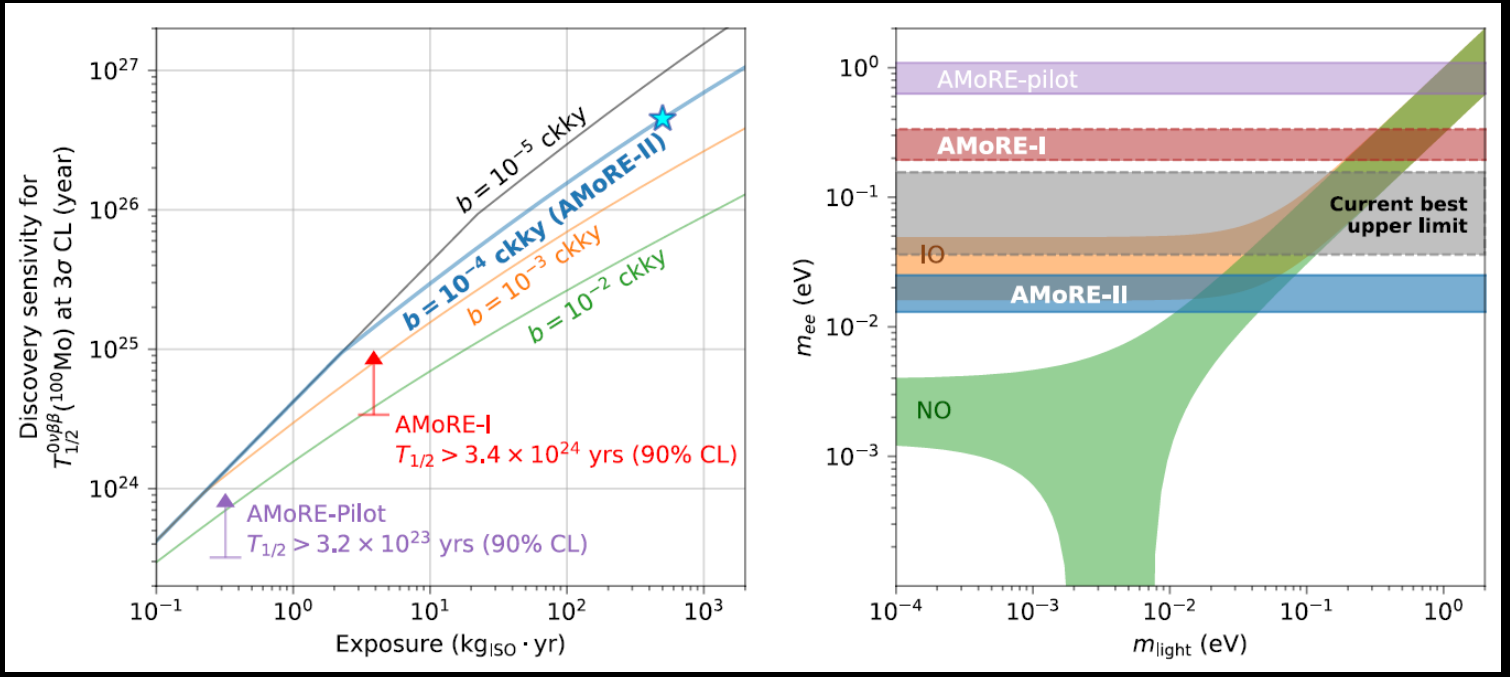


Bkg~10-4 ckky, σ_E=10 keV (FWHM)



AMoRE-II Plan

- Stage 1 with 27 kg of LMO for ~1 year
- Mass upgrade to 157 kg for stage 2
- > 5 years more data taking: > 500 $kg_{^{100}Mo}$·year
- Sensitivity goal:
  - $T_{1/2}^{0\nu} \sim 6 \times 10^{26}$ years (90% CL. Exclusion)
  - $T_{1/2}^{0\nu} \sim 4 \times 10^{26}$ years (3σ evidence)
  - $\langle m_{\beta\beta} \rangle \sim$ 20-35 meV



AMoRE-II Summary

- AMoRE-II is being prepared to start stage 1 in 2024 with 90 ea (27 kg) of LMO crystals
  - DR was installed at Yemilab and is being tested now
  - Assembling crystal detector is on-going at Yemilab
  - Installing crystal detector will be started soon
- Stage 2 will use 360 ea (157 kg) of LMO
  - Background level at ROI ~10-4 ckky
  - Discovery potential of 0νββ with 500 $kg_{^{100}Mo}$·year exposure: $T_{1/2}^{0\nu} \sim 4 \times 10^{26}$ years, $\langle m_{\beta\beta} \rangle \sim$ 20-35 meV

Thank you