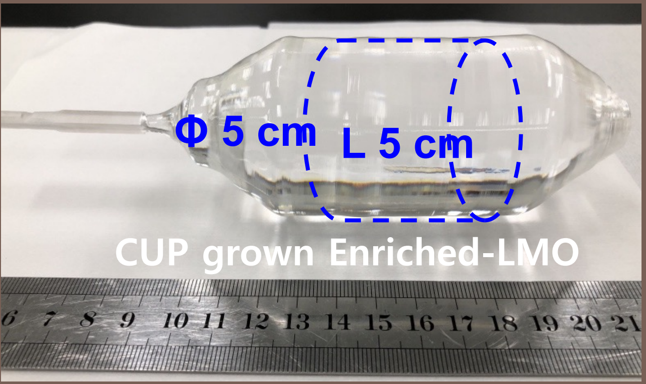

AMoRE (Neutrinoless Double Beta Decay Search Experiment)

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Daejeon, Korea

2022. 12.16

2022 KPS DPF meeting, SKKU (Seoul)

AMoRE Collaboration

V. Alenkov et al., Technical Design Report for the AMoRE 0ν2β Decay Search Experiment, arXiv:1512.05957v1

23rd AMoRE Collaboration meeting
Zoom, Feb. 23-25 2022

9 countries, 25 Institutes, ~107 collaborators

15th AMoRE Collaboration meeting
Jeongseon, Jan. 18-19, 2018

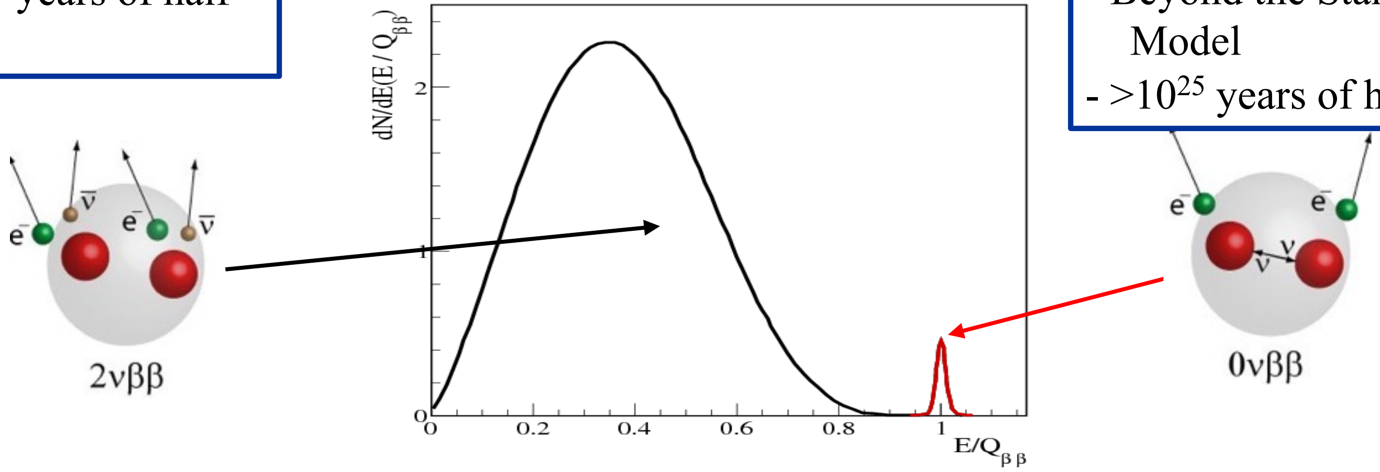
11th AMoRE Collaboration meeting
Pattaya, Feb. 27-28, 2016

AMoRE: Neutrinoless double beta decay

The goal of **AMoRE** is to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.

$2\nu\beta\beta$ decay
- 2nd order beta decay
- Rare nuclear decay
- (>10^{18} years of half life)

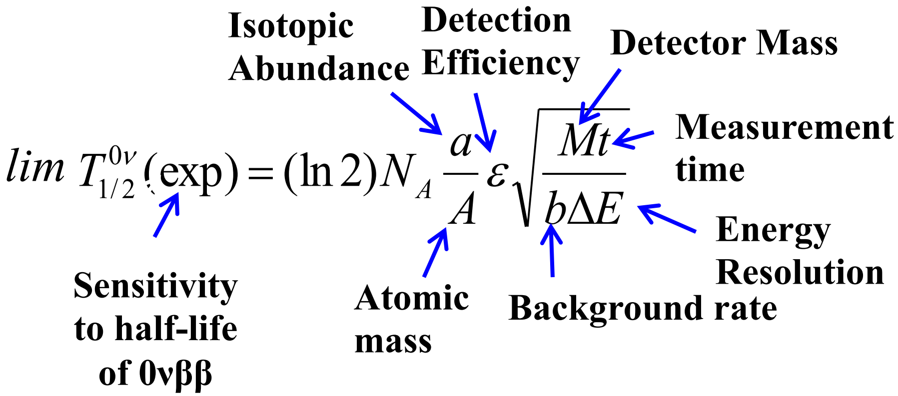
$0\nu\beta\beta$ decay
- Lepton number violation
- Massive neutrino
- Majorana particle
- Beyond the Standard Model
- >10^{25} years of half-life



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

AMoRE Experimental Approach

- **Sizable background case:**

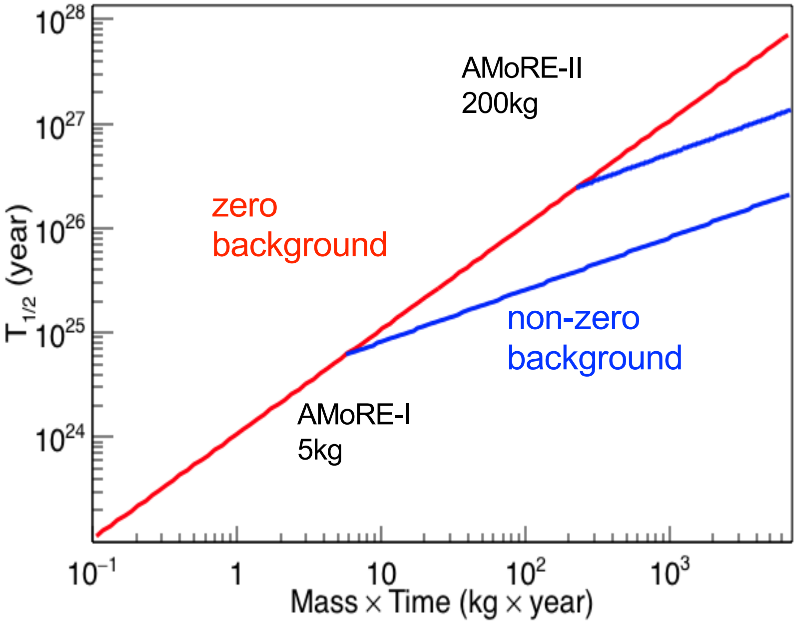


$$\lim T^{0\nu}_{1/2}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{Mt}{b\Delta E}}$$

- **“Zero” background case:**

When b is ~ O(1),

$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon M t$$



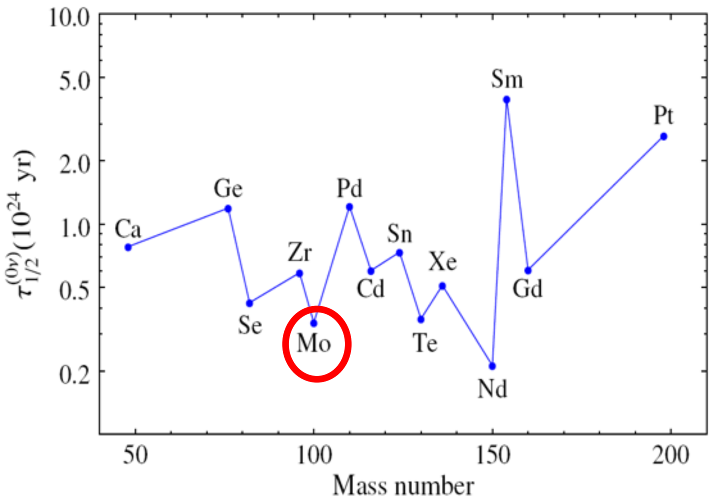
AMoRE is aiming for zero background.

Why we use ^{100}Mo for 0νββ search ?

- High Q-value (ββ) of 3034.40 (12) keV.

(^{208}Tl→^{208}Pb, the highest & intensive 2.614 MeV γ from nature)

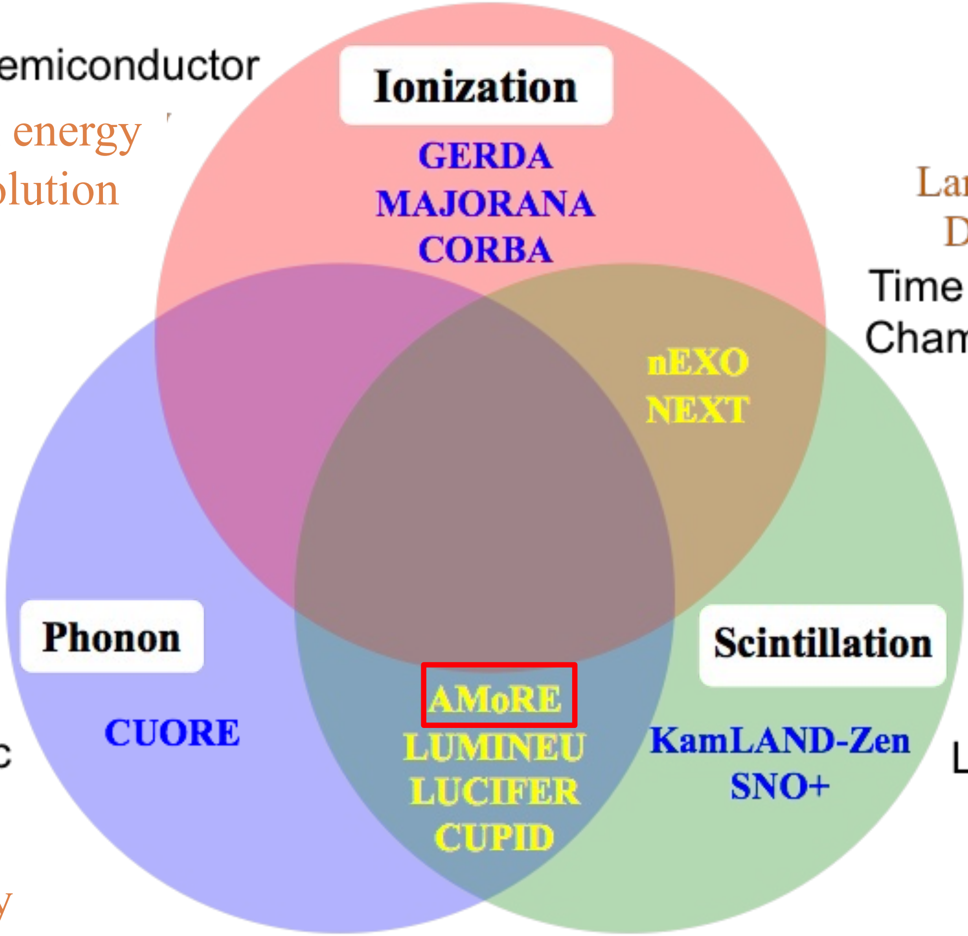
- High natural abundance of 9.7%.
- Relatively short (0νββ) half life expected from theoretical calculation.



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



Semiconductor

High energy
resolution

Ionization

GERDA
MAJORANA
CORBA

Large Mass
Detector

Time Projection
Chamber (TPC)

nEXO
NEXT

Phonon

Scintillation

Cryogenic
detector

CUORE

AMoRE
LUMINEU
LUCIFER
CUPID

KamLAND-Zen
SNO+

Large Mass
Detector

Liquid scintillator

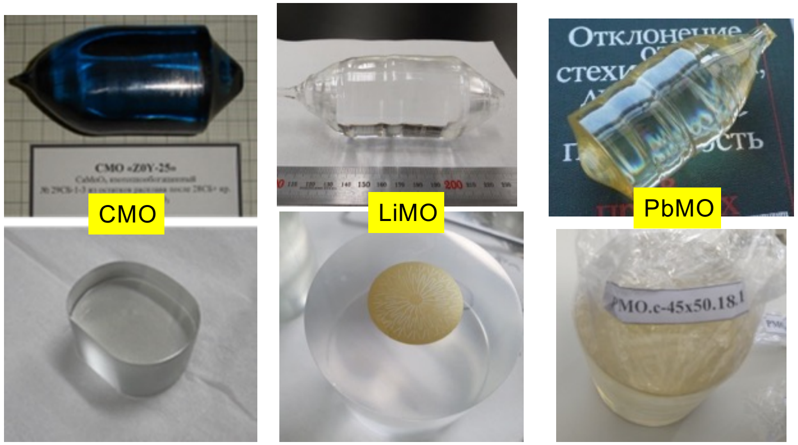
High energy
resolution

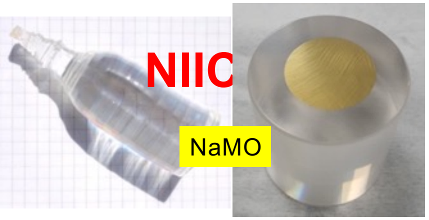
Scintillating bolometer

Excellent Particle
Identification

AMoRE parameters

- Crystals: $^{40}Ca^{100}MoO_4$(CMO) or XMO (X: Li, Na, or Pb)
  - ^{100}Mo enriched: > 95%
  - ^{48}Ca depleted: < 0.001% (N.A. of ^{48}Ca:0.187%)
- Low temperature detector: 10 – 30 mK
- Energy resolution: ~5 keV @ 3MeV, Excellent PSD



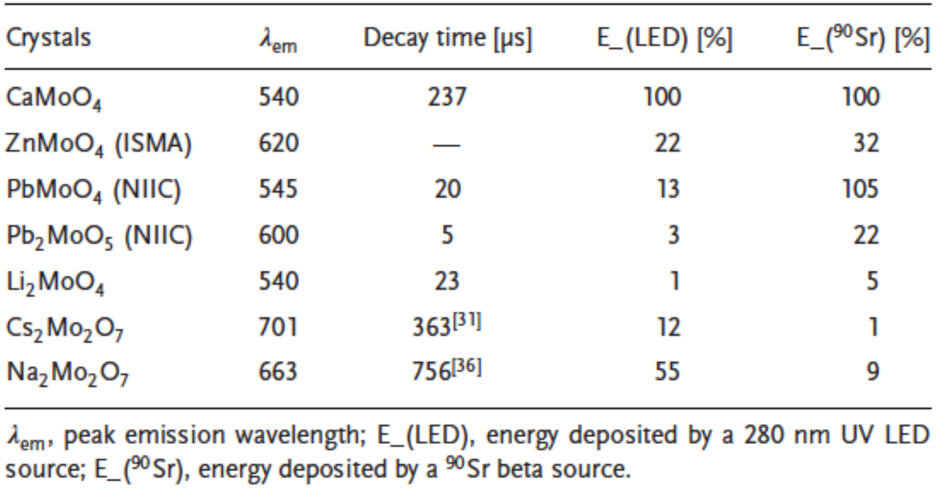


The AMoRE Plan

	Pilot	Phase I	Phase II
Mass (Crystal)	**1.9 kg CMO**	**6 kg (CMO + LMO)**	**188 kg LMO + 4 kg CMO**
Bkg [keV ·kg· year]$^{-1}$	**< 10^{-1}**	**< 10^{-2}**	**< 10^{-4}**
$T^{0\nu}_{1/2}$ Sensitivity [years]	**~3.2×10^{23}**	**~1.05×10^{24}**	**~5.0×10^{26}**
Location	**Y2L (700 m depth)**		**Yemilab (1000m depth)**
Schedule	**2015 - 8**	**2020 - 2023**	**2023 -**

Crystals R&D for AMoRE-I & II

- ☐ Even though CMO ($CaMoO_4$) is a very good detector material which has the largest light output among Mo based crystal scintillators, there are other Mo crystals suitable for AMoRE-II experiment besides CMO. CMO has disadvantage that we have to purchase ^{48}Ca depleted isotopes, expensive.
- ☐ We worked on R&D of various molybdate crystals including Li_2MoO_4, $Na_2Mo_2O_7$, $PbMoO_4$ and other compounds.
- ☐ Decided to use Li_2MoO_4 due to low-background level and easiness in growth at relatively low temperature even though its hygroscopic nature requires a careful handling during the preparation and operation in a dry environment.

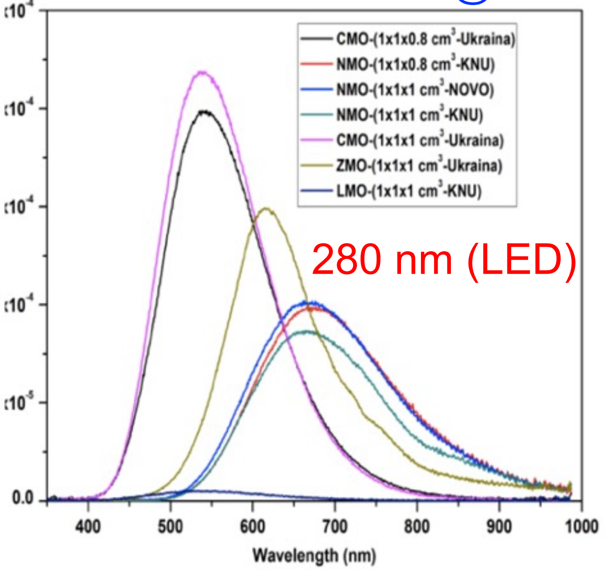


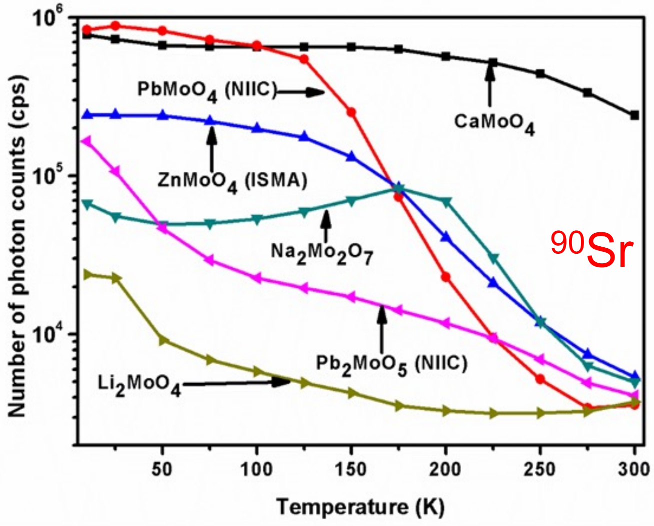
Crystals	λ_{em}	Decay time [μs]	E_(LED) [%]	E_(^{90}Sr) [%]
$CaMoO_4$	540	237	100	100
$ZnMoO_4$ (ISMA)	620	—	22	32
$PbMoO_4$ (NIIC)	545	20	13	105
Pb_2MoO_5 (NIIC)	600	5	3	22
Li_2MoO_4	540	23	1	5
$Cs_2Mo_2O_7$	701	363[31]	12	1
$Na_2Mo_2O_7$	663	756[36]	55	9

λ_{em}, peak emission wavelength; E_(LED), energy deposited by a 280 nm UV LED source; E_(^{90}Sr), energy deposited by a ^{90}Sr beta source.

H.J. Kim et al., Crystal Research & Technology, Nov. 2019

H.J.Kim @SCINT2017





MMC (Metallic Magnetic Calorimeter) for LTD

S.J. Lee et al., Astroparticle Physics 34 (2011) 732–737

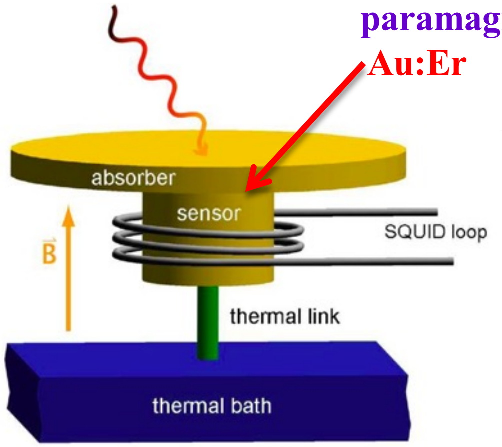
Principle of operation

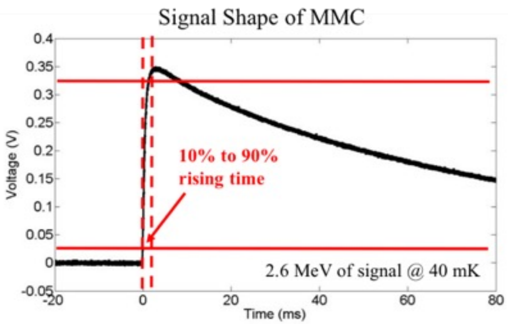
1. Energy absorption in an XMO crystal.
2. Phonon & Photon generation.
3. Temperature increase (gold film).
4. Magnetization in MMC decreases.
5. SQUID pickup the change.

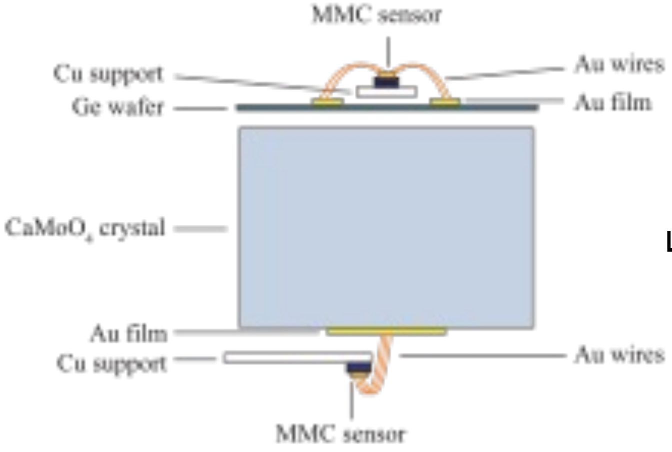
Advantage of MMC

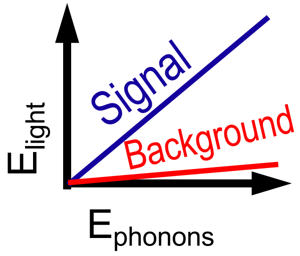
- Fast rising signal : ~0.5 ms (critical to reduce $2\nu\beta\beta$ random coincidence)
- Fairly easy to attach to absorber.
- Excellent Energy resolution

paramagnetic sensor:
Au:Er



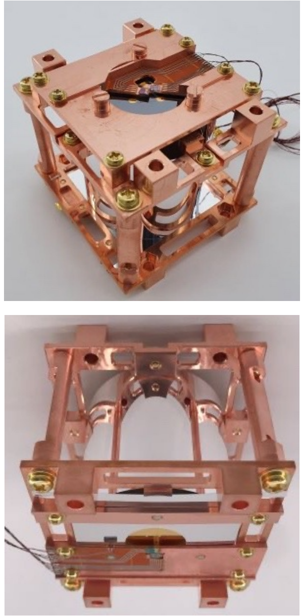


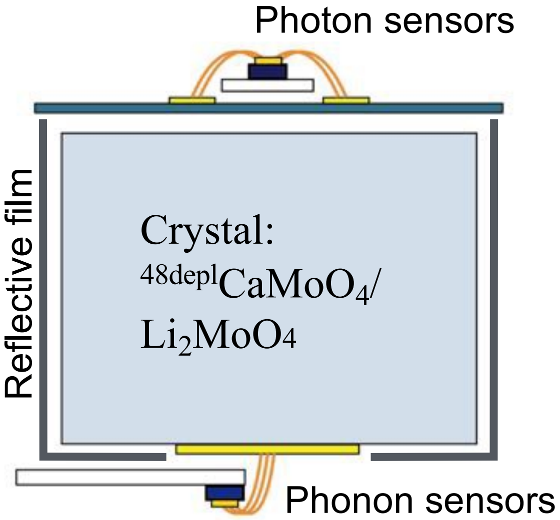


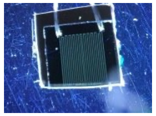


Detector module

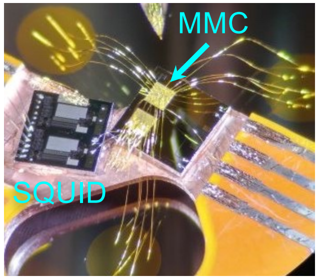
- Cylindrical CMO and LMO crystals, sizes vary $\Phi \geq 4$ cm / H $\lesssim 5$ cm.
  - CMO: ^{48}Ca depleted, $Q_{\beta\beta}$ (^{48}Ca) = 4271 keV.
- Metallic magnetic calorimeter (MMC) + SQUID:
  - Fast signal timing: a few millisecond rise-time for phonon signals at mK.
  - Low random coincidence background.
  - Energy resolution ~ 10 keV FWHM at 2.6 MeV.





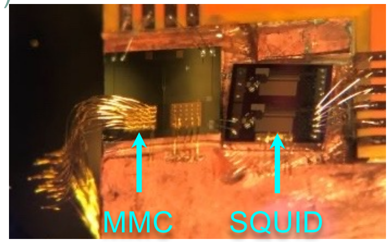


Stabilization heater

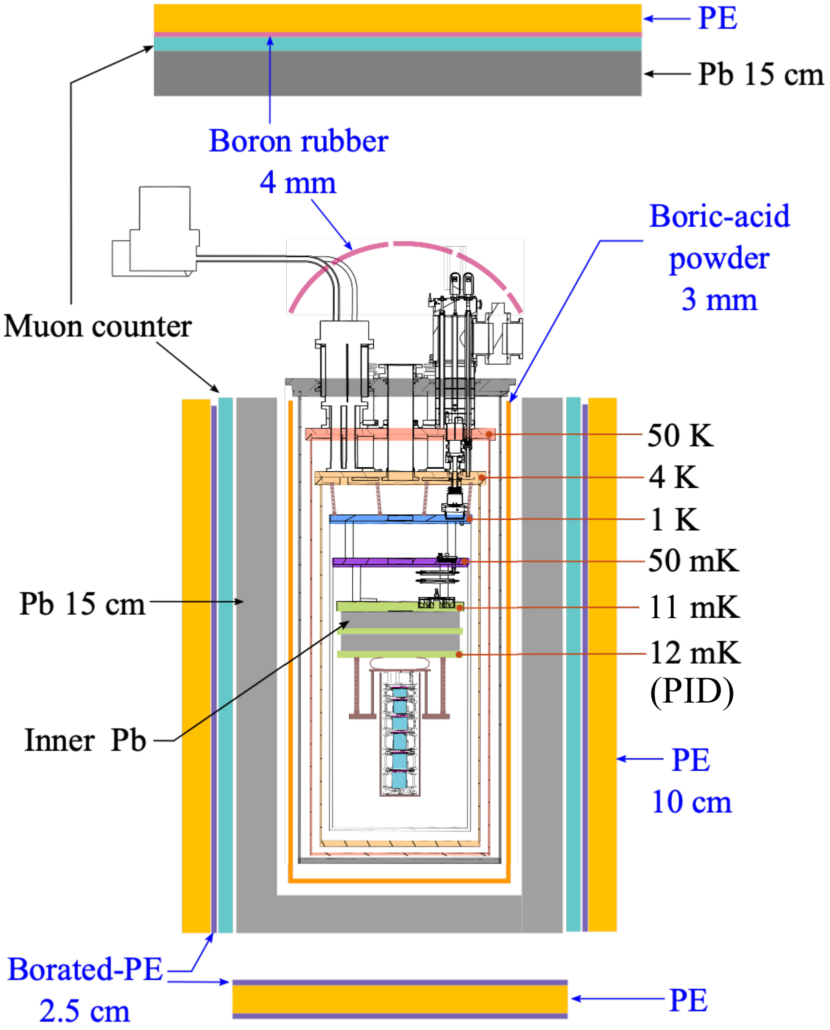


Light absorber (Ge/Si wafer)

Phonon collector (Au film)

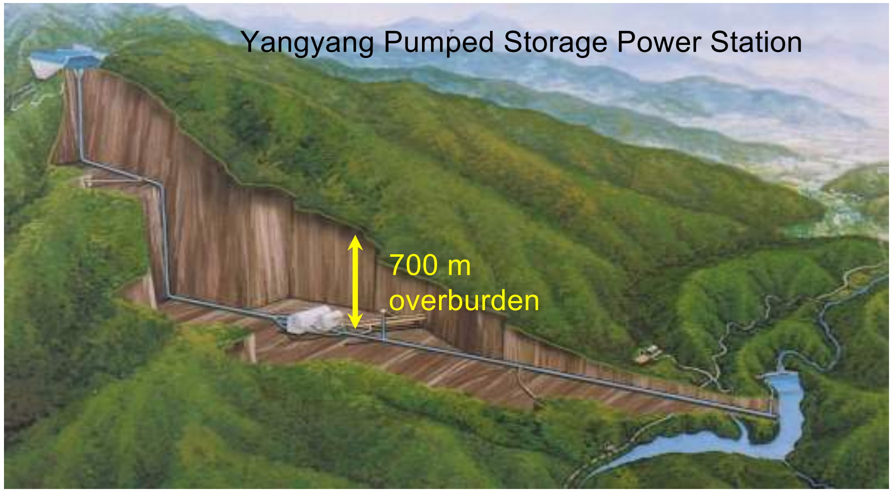


AMoRE-pilot/I cryostat / shielding

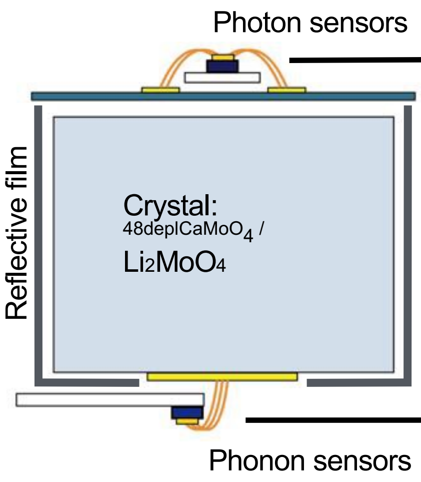


+ More enhanced shielding for AMoRE-I

- ☐ Cryogen-free dilution refrigerator.
- ☐ For AMoRE-pilot and AMoRE-I.
- ☐ Now operating at 10 mK with 1.2 μW cooling power.
- ☐ Pb (γ), boron, and polyethylene (n).
- ☐ Plastic scintillator muon counter.
- ☐ Yangyang underground laboratory (Y2L) at 700 m depth.

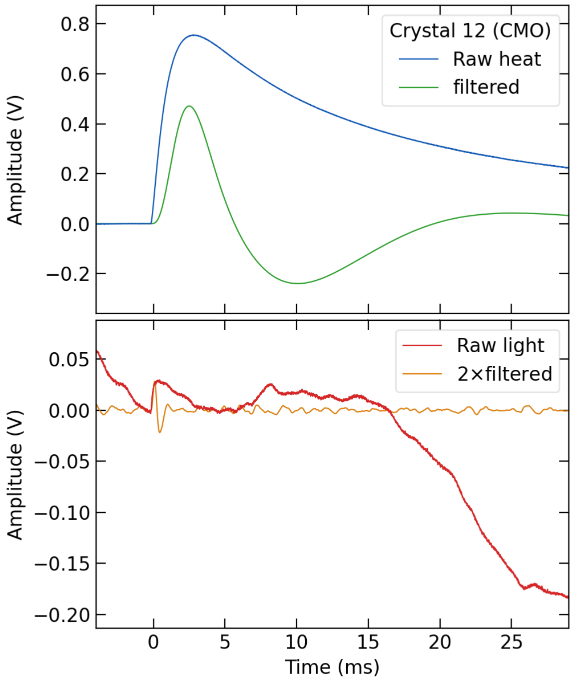


Signal processing and analysis



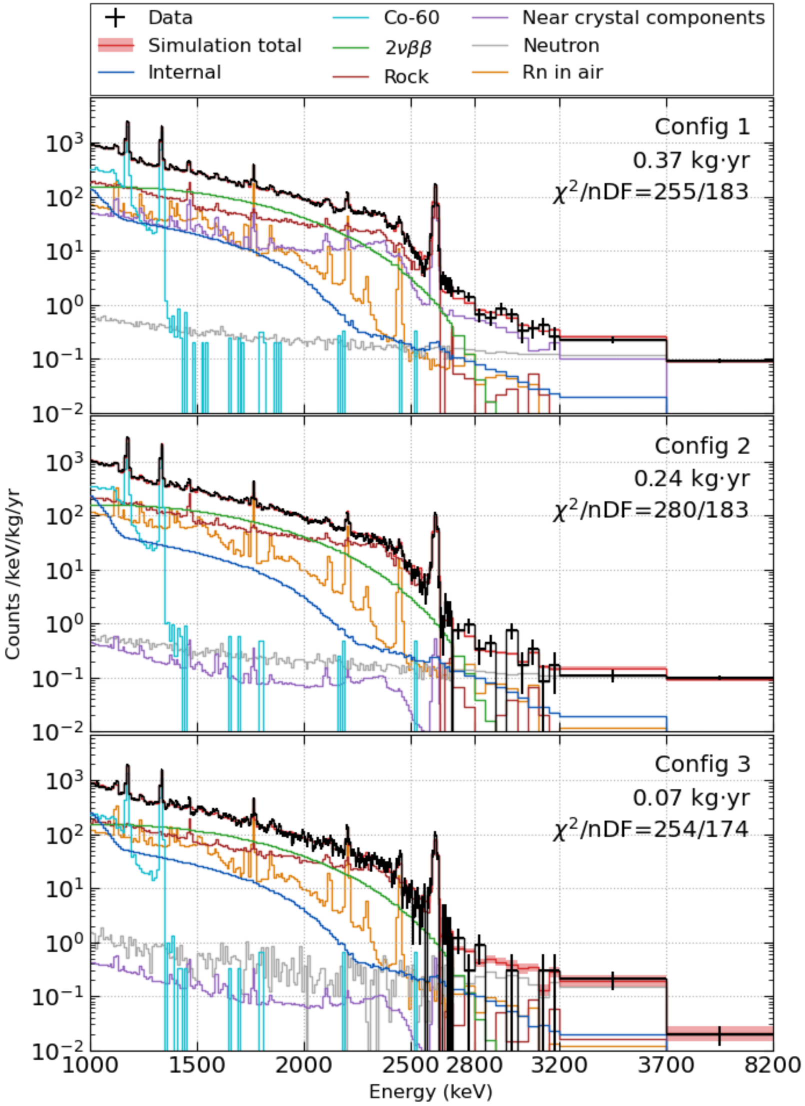
ADCs:
18-bit resolution,
100 kHz
sampling

- Software trigger for phonon signal, using Butterworth bandpass filter.
- Trigger threshold: 30-200 keV.

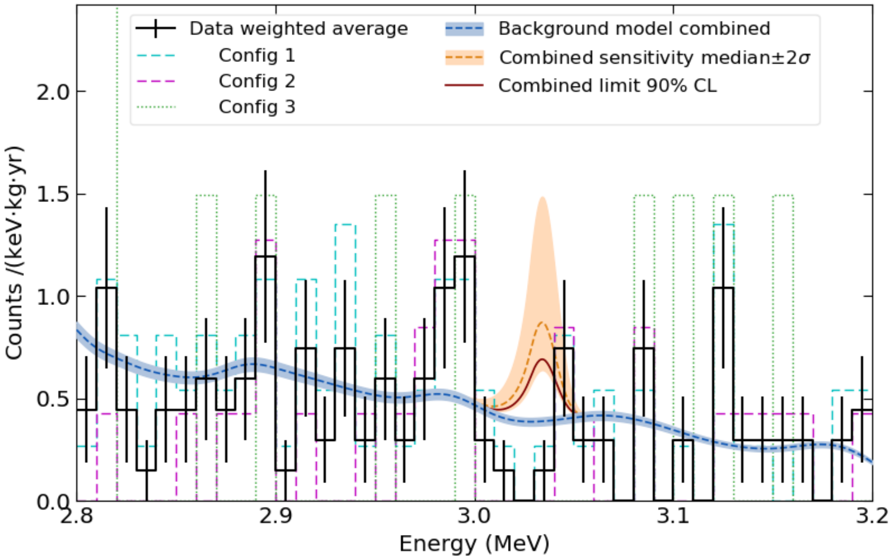


- ☐ Raw waveform:
  - Baseline/noise information.
  - Timings (rise/fall): pulse shape discrimination (PSD).
- ☐ Reconstruction for improving energy resolution and β/α discrimination power (DP):
  - Butterworth bandpass filter— mainly for noise suppression:
    - pulse amplitude: pulse height or a least square fit to the template signal.
  - Stabilization heater signal every 10 seconds for gain drift corrections.

AMoRE-pilot final result

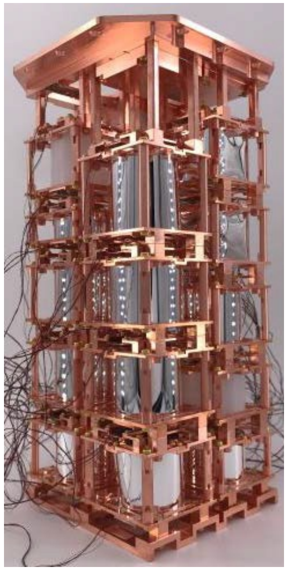


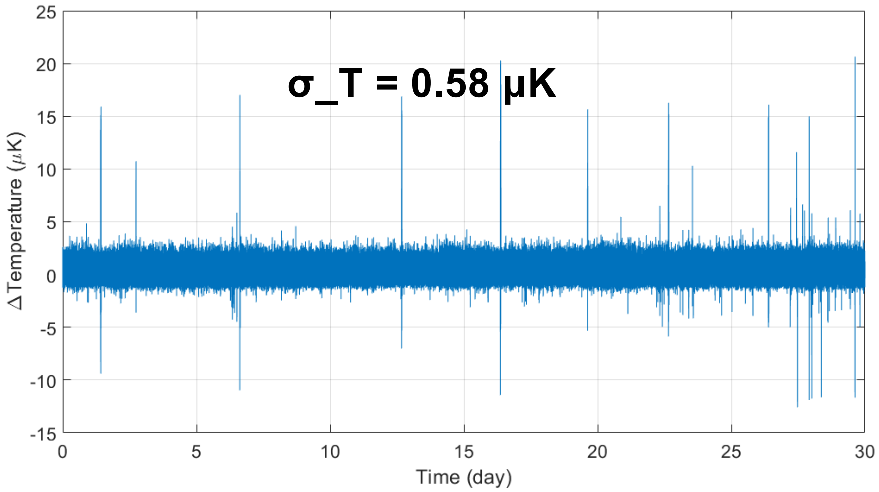
- ☐ Understanding of the background components and reduction of them.
- ☐ Background level of ~0.5 counts/keV/kg/yr at 2.8-3.2 MeV.
  - neutron-induced γ, crystals' internal contamination, rock/air-radon γ.
  - Internal background— arXiv:2107.07704
- ☐ $T^{0\nu}_{1/2} > 3.2 \times 10^{23}$ years at 90% CL.



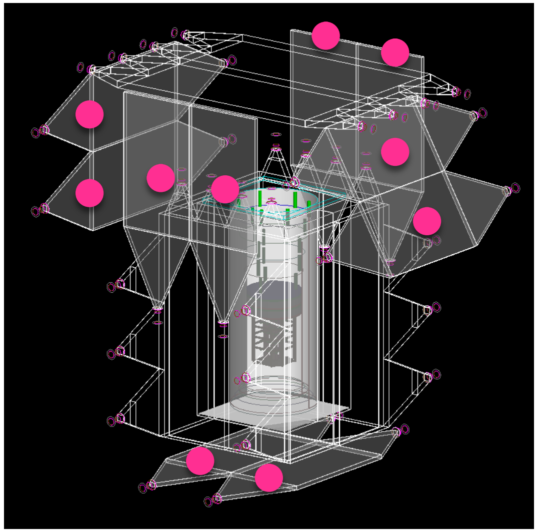
AMoRE-pilot → AMoRE-I

- ☐ 6 CMO (1.89 kg) → 13 CMO (4.58 kg) + 5 LMO (1.61 kg)
  - ◘ Total crystal mass = 6.19 kg, ^{100}Mo mass = 3.0 kg
- ☐ Stabilization heater for all crystals.
- ☐ MMC sensor: Au:Er → Ag:Er.
- ☐ Using same cryostat + two stage temperature control: ⟨ΔT⟩ < 1 μK.
- ☐ Shielding enhancements:
  - ◘ Outer Pb: 15 → 20 cm; neutron shields: boric acid silicon + more PE / B-PE.
  - ◘ More muon counter coverage.
  - ◘ Supply of Rn-free air.

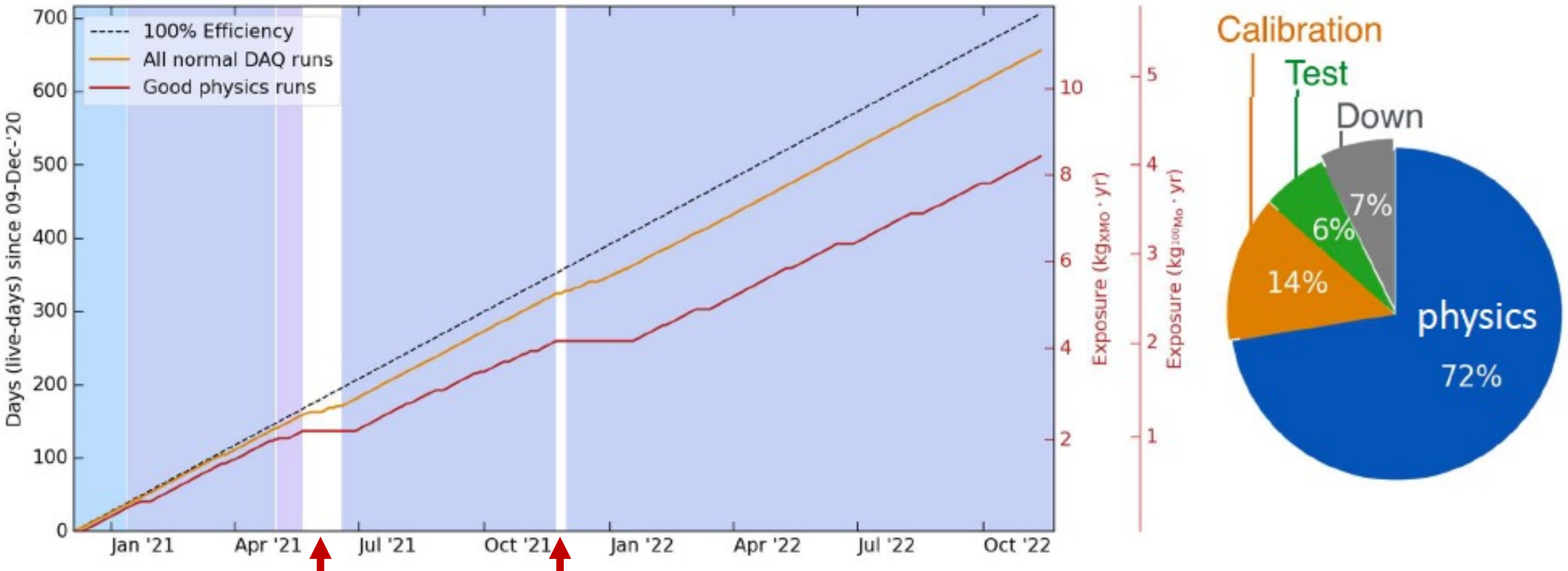




●Added muon counters



AMoRE-I data taking



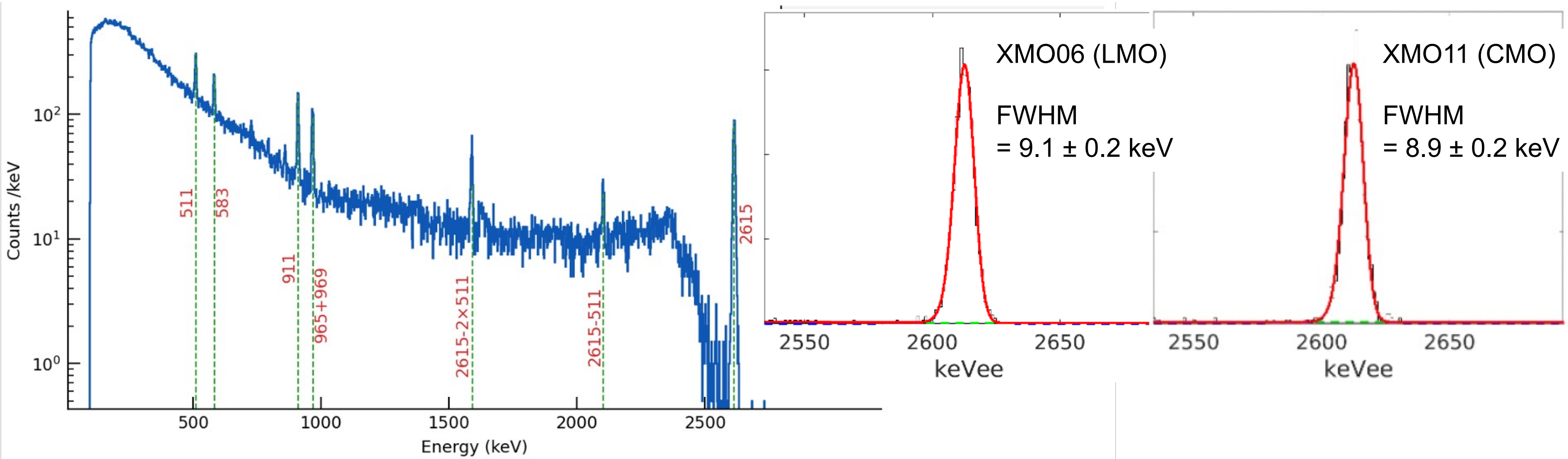
DR temperature control

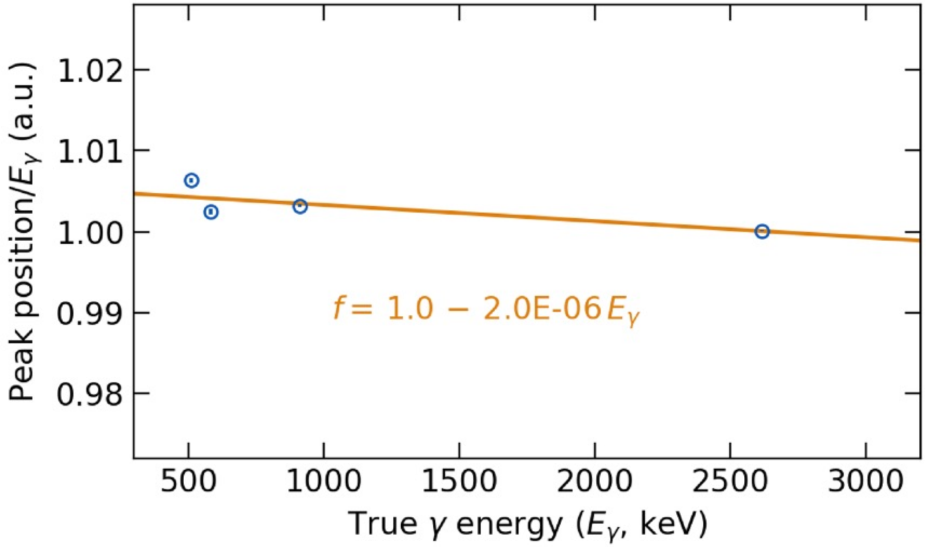
Recovery from power outage

☐ DAQ duty factor ~ 90%, good physics data ~ 72%.

☐ Data taking continues in 2023.

AMoRE-I: Energy calibration



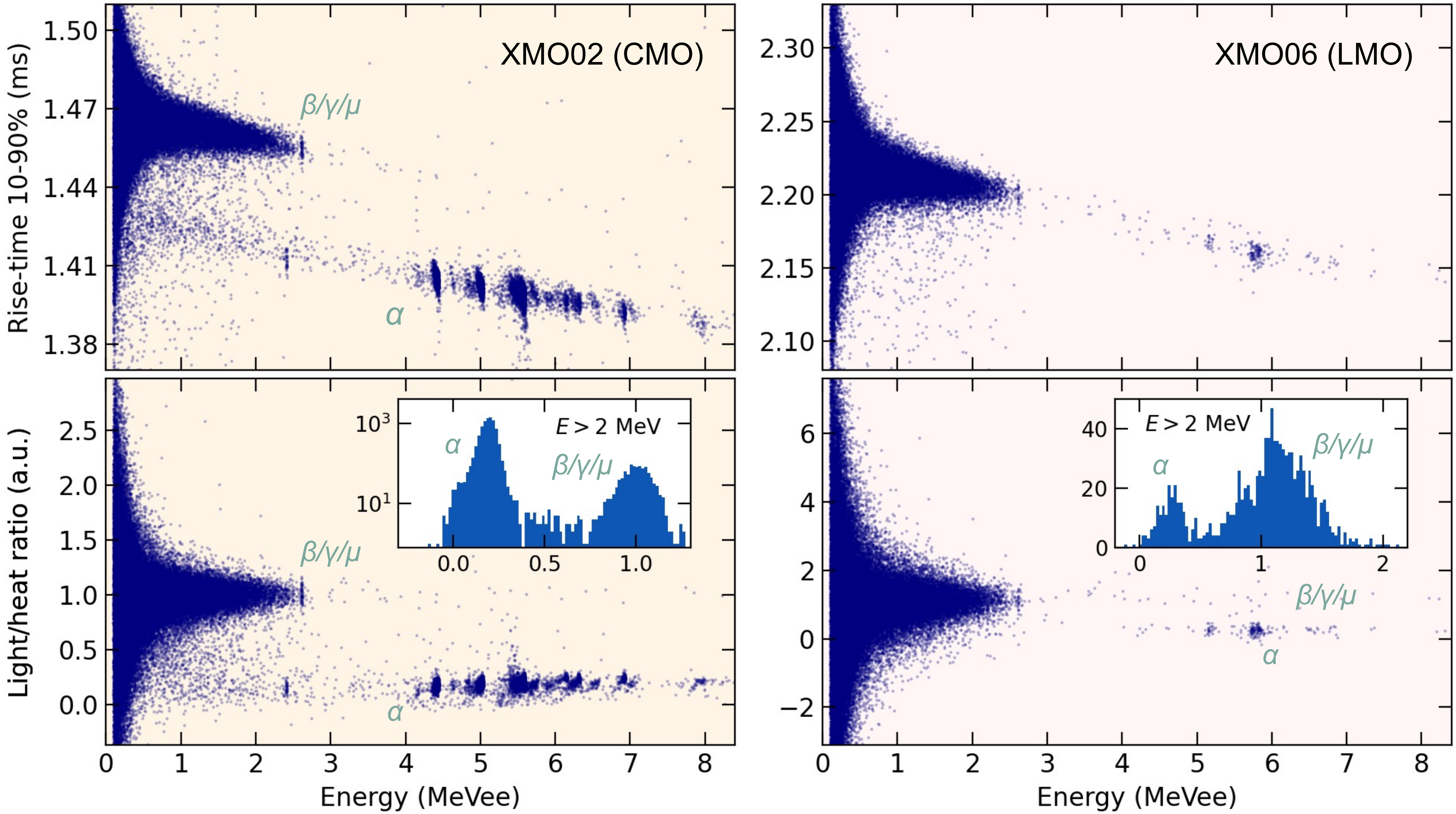


☐ Calibration source: ^{232}Th-rich welding rods just outside the outer vacuum chamber.

☐ Slight non-linearity between signal amplitude and energy.

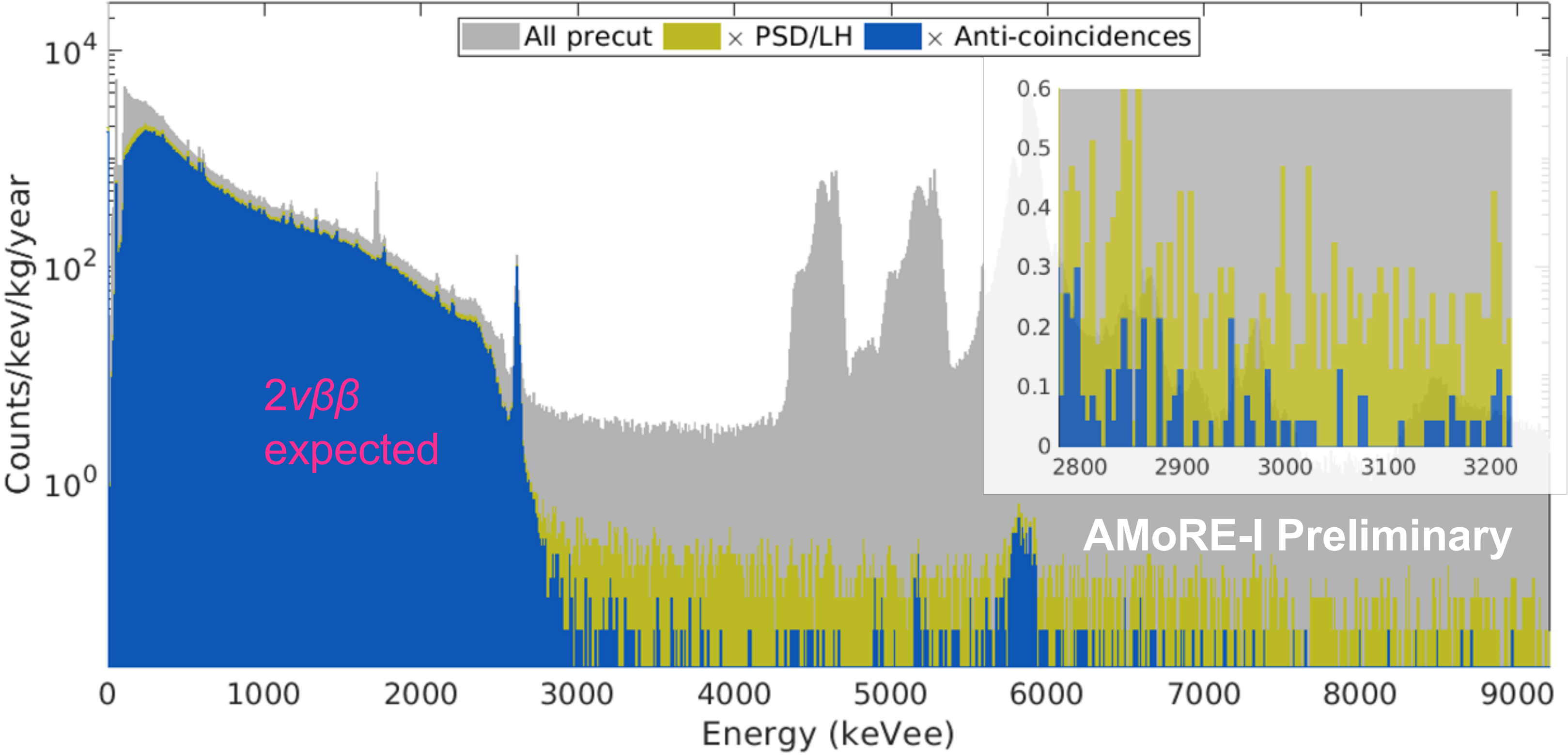
☐ Energy resolution: [8.9-32.7] keV FWHM at 2615 keV, ~15 keV in average.

Particle IDentifications, CMO and LMO



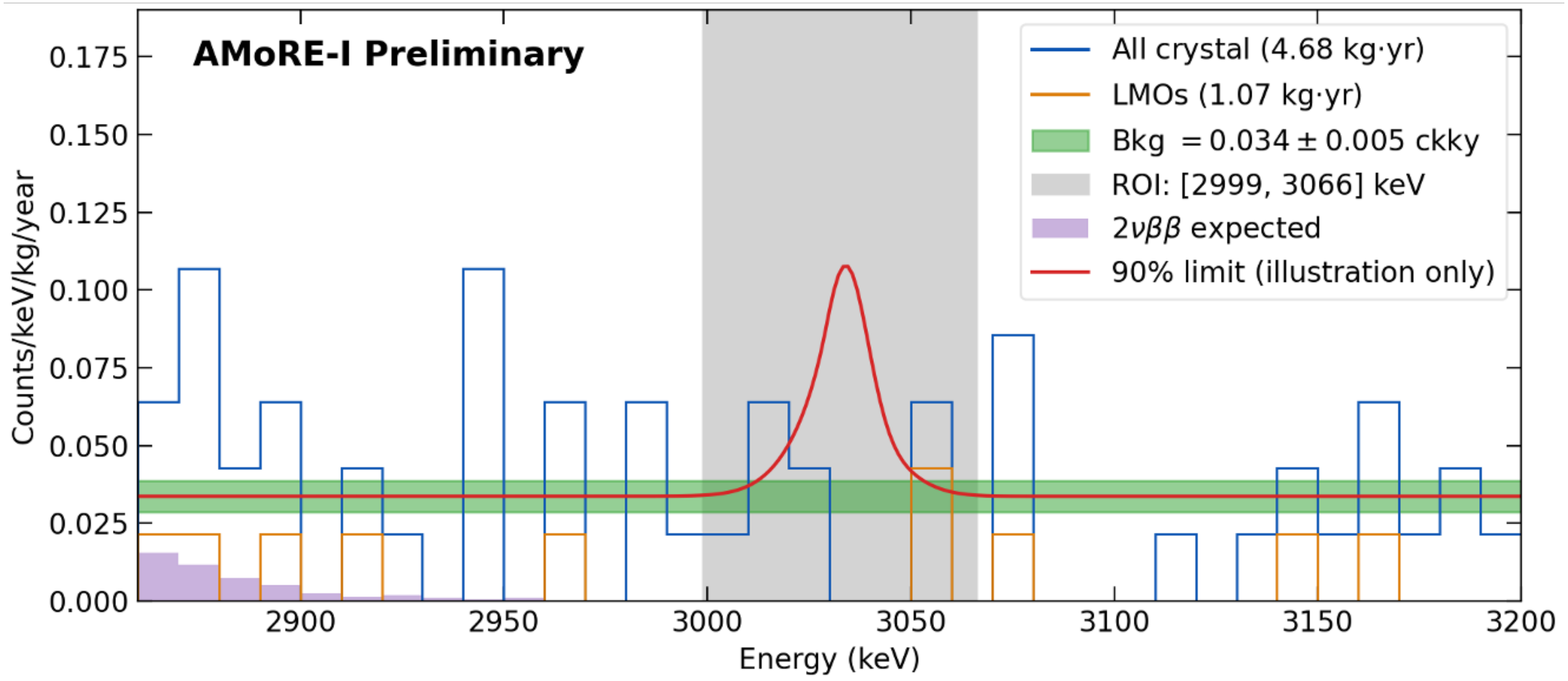
- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less α contamination.

Background spectrum



- All crystal excluding 1 LMO (with very poor β/α discrimination):
  - 13 CMO + 4 LMO: exposure = 4.68 kg_{XMO}·yr = 2.24 kg_{ISO}·yr.
- Anti-coincidence cuts reject events:
  - coincident at multiple crystals within 2 ms ($\varepsilon \sim 99\%$),
  - within 10 ms after a muon counter event ($\varepsilon \sim 99.7\%$),
  - within 20 minutes after a ^{212}Bi α-decay event candidate ($\varepsilon \sim 98\%$).

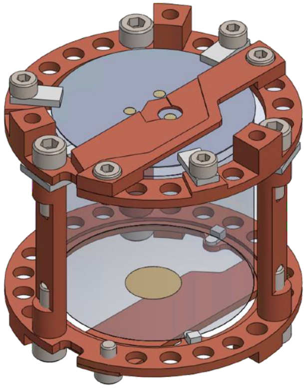
Preliminary 0νββ limit from AMoRE-I

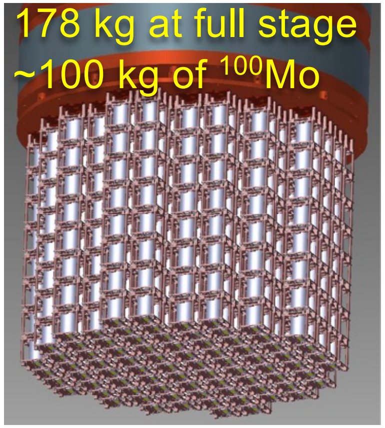


- ☐ ROI to contain most (> 99%) of the $0\nu\beta\beta$ signal peak, $\varepsilon_{\text{containment}} \sim 81\%$.
- ☐ Background = 0.034 ± 0.005 counts/keV/kg/year, from ROI side-band.
- ☐ Combining the result of counting analysis at ROI, with a flat background constraint from the side-band events for each crystal.
- ☐ $T_{1/2}^{0\nu} > 1.05 \times 10^{24}$ years at 90% CL.

AMoRE-II under construction

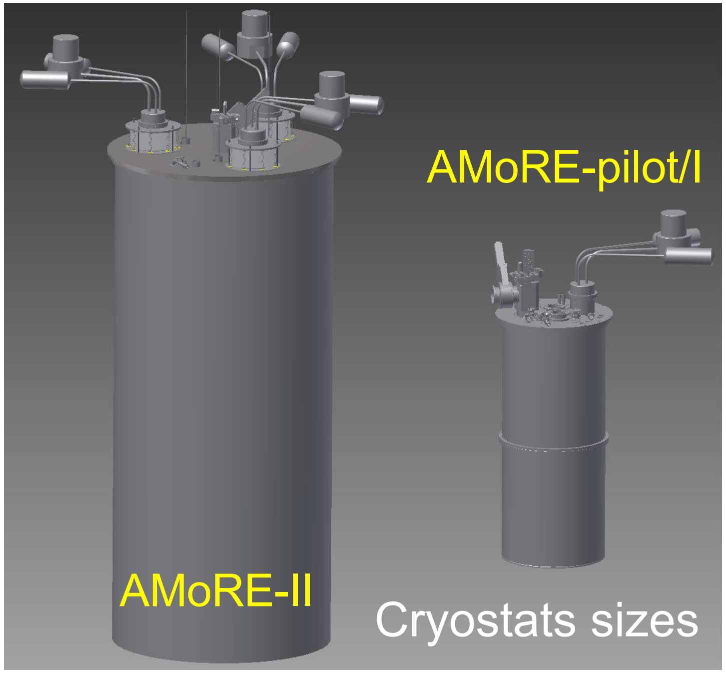
AMoRE-II
Detector module





178 kg at full stage
~100 kg of ^{100}Mo

90 modules (~27 kg LMO)
in the first stage

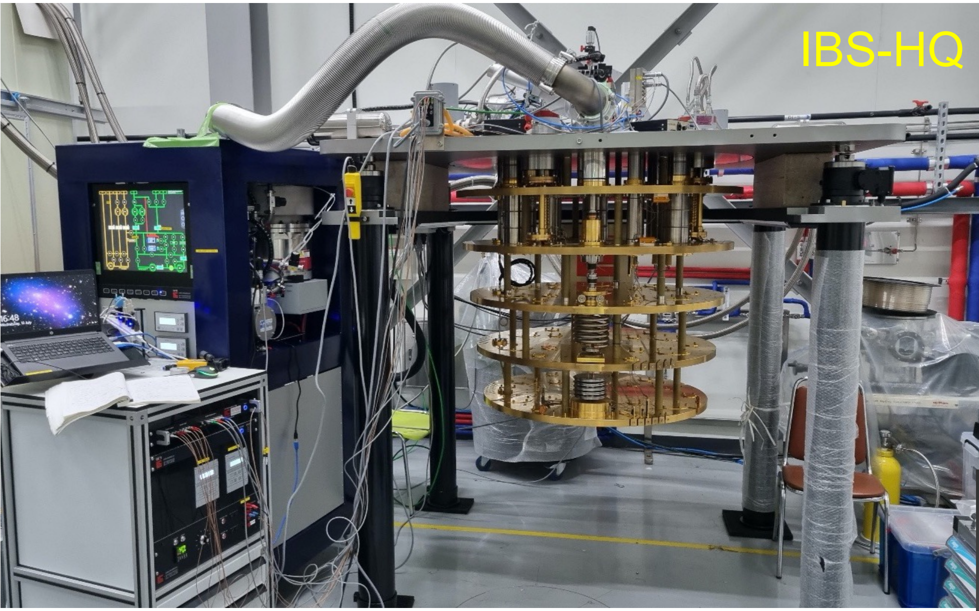


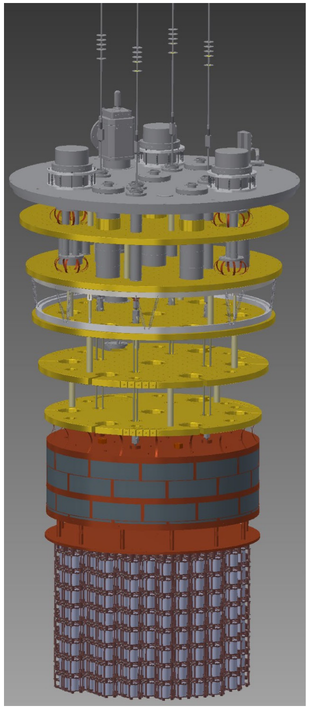
Cryostats sizes

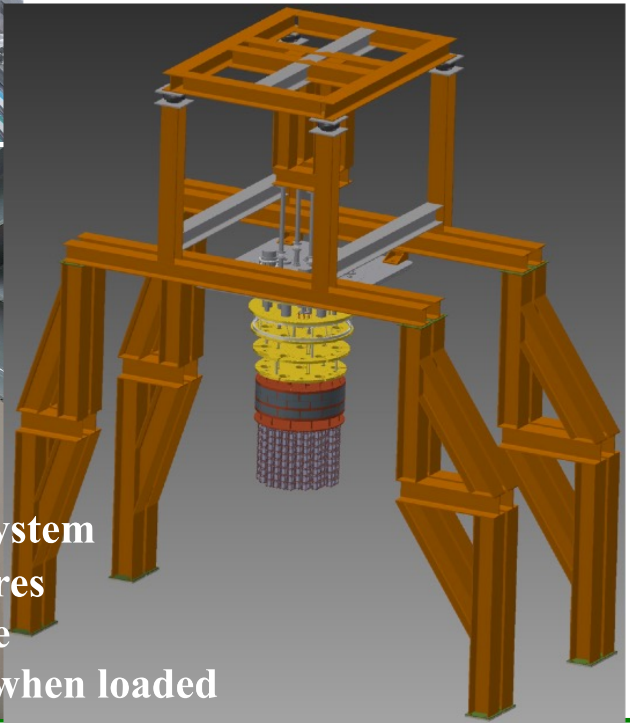
AMoRE-II cryostat and support system

Large cryogen-free dilution refrigerator

- ☐ 2.4 mW @120 mK, > 5 μW@10 mK
- ☐ Base temperature < 10 mK



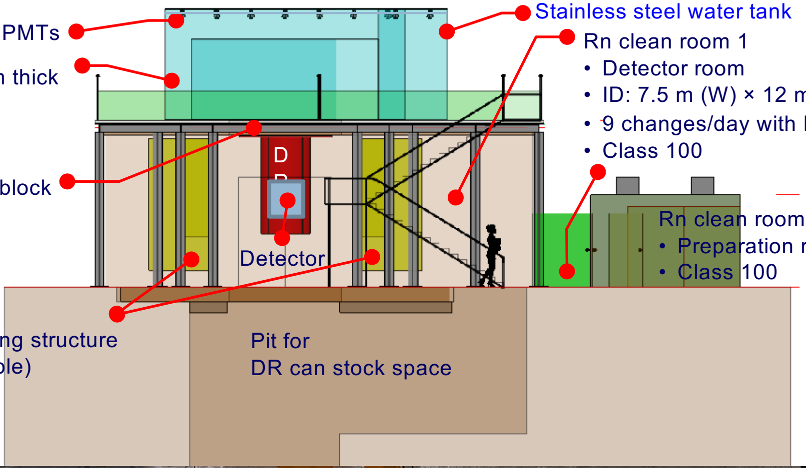




New vibration damping system

- ☐ Hanging by Kevlar wires
- ☐ Suspending ~ 3.4 tonne
- ☐ < 1 mm displacement when loaded

AMoRE-II in Yemilab



8” PMTs

700mm thick water

HDPE block

Stainless steel water tank

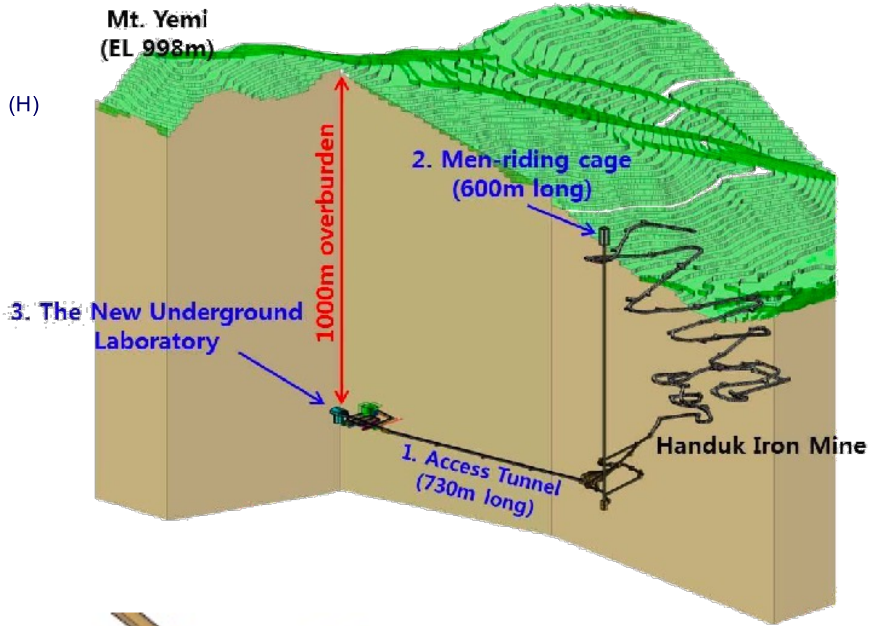
Rn clean room 1
- Detector room
- ID: 7.5 m (W) × 12 m (L) × 4.2 m (H)
- 9 changes/day with Rn free air
- Class 100

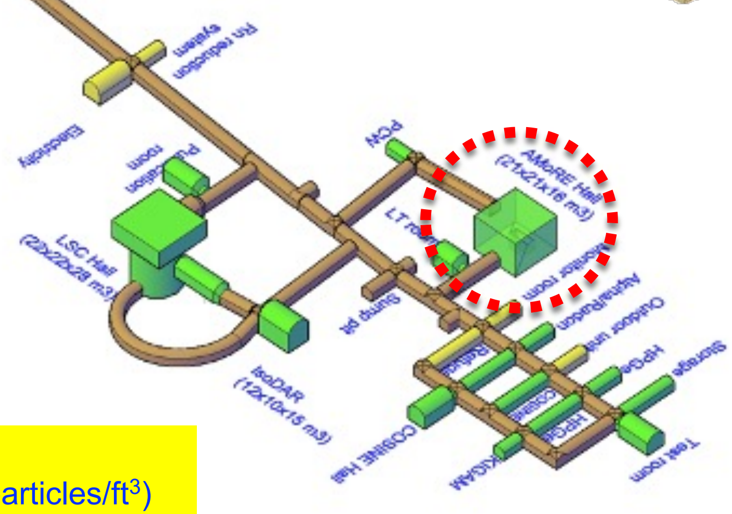
Detector

Rn clean room 2
- Preparation room
- Class 100

Shielding structure (movable)

Pit for DR can stock space

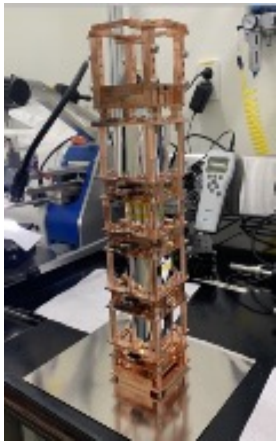


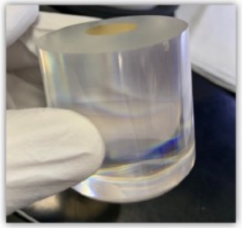


- ❑ Dust proof door & radon free air to the detector room.
- ❑ Cleanness: Hall (100 k), Detector room (10 k), Preparation room (100) (#particles/ft^3)

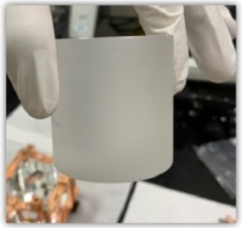
AMoRE-II crystal detector R&D

IBS HQ test setup for multi-crystals
(i.e., LiMO, PbMO, NaMO, CMO)

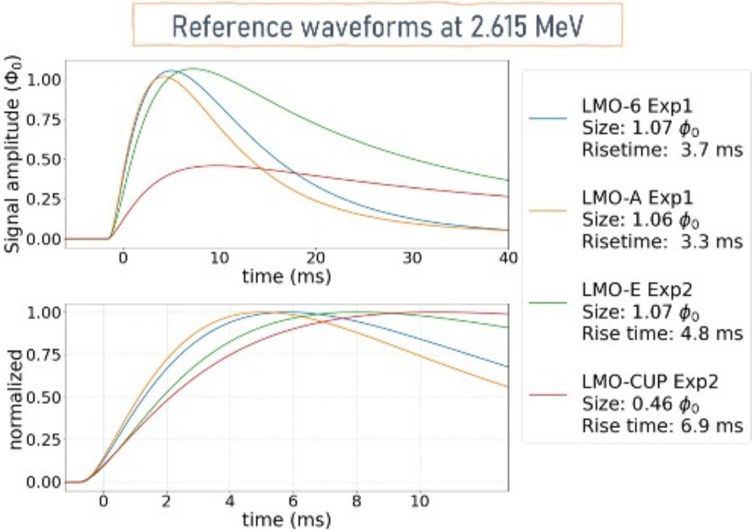




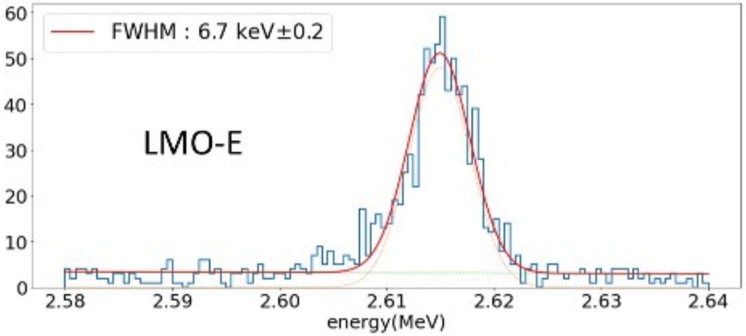
With lapping & polishing



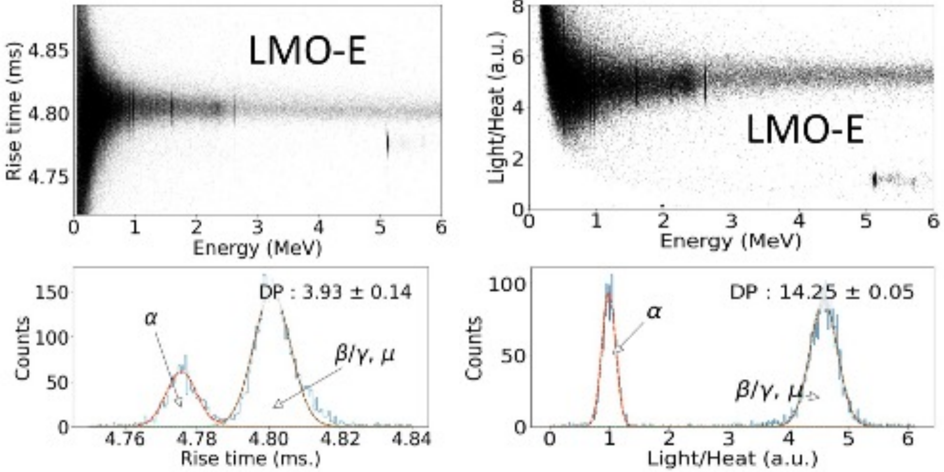
With lapping and no polishing



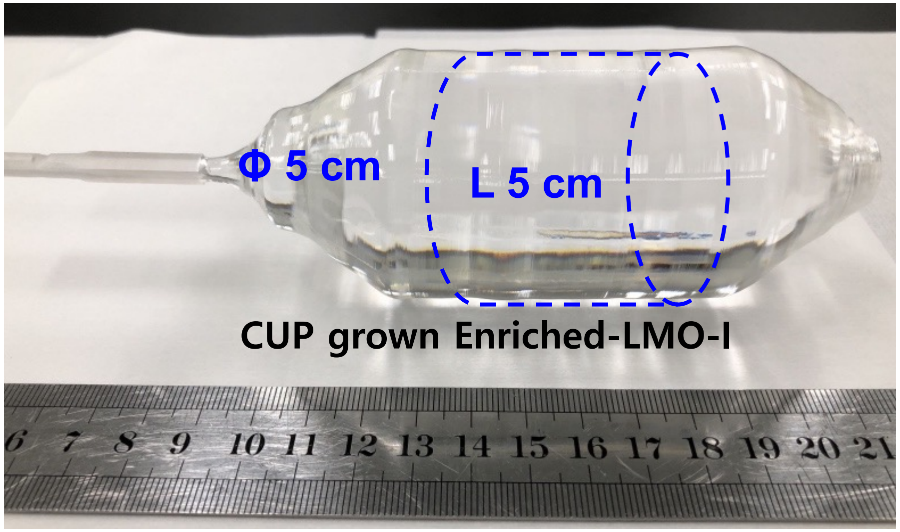
W.T. Kim et al. *JINST* 17 P07034 (2022)



PSD



LMO crystals with purified powders



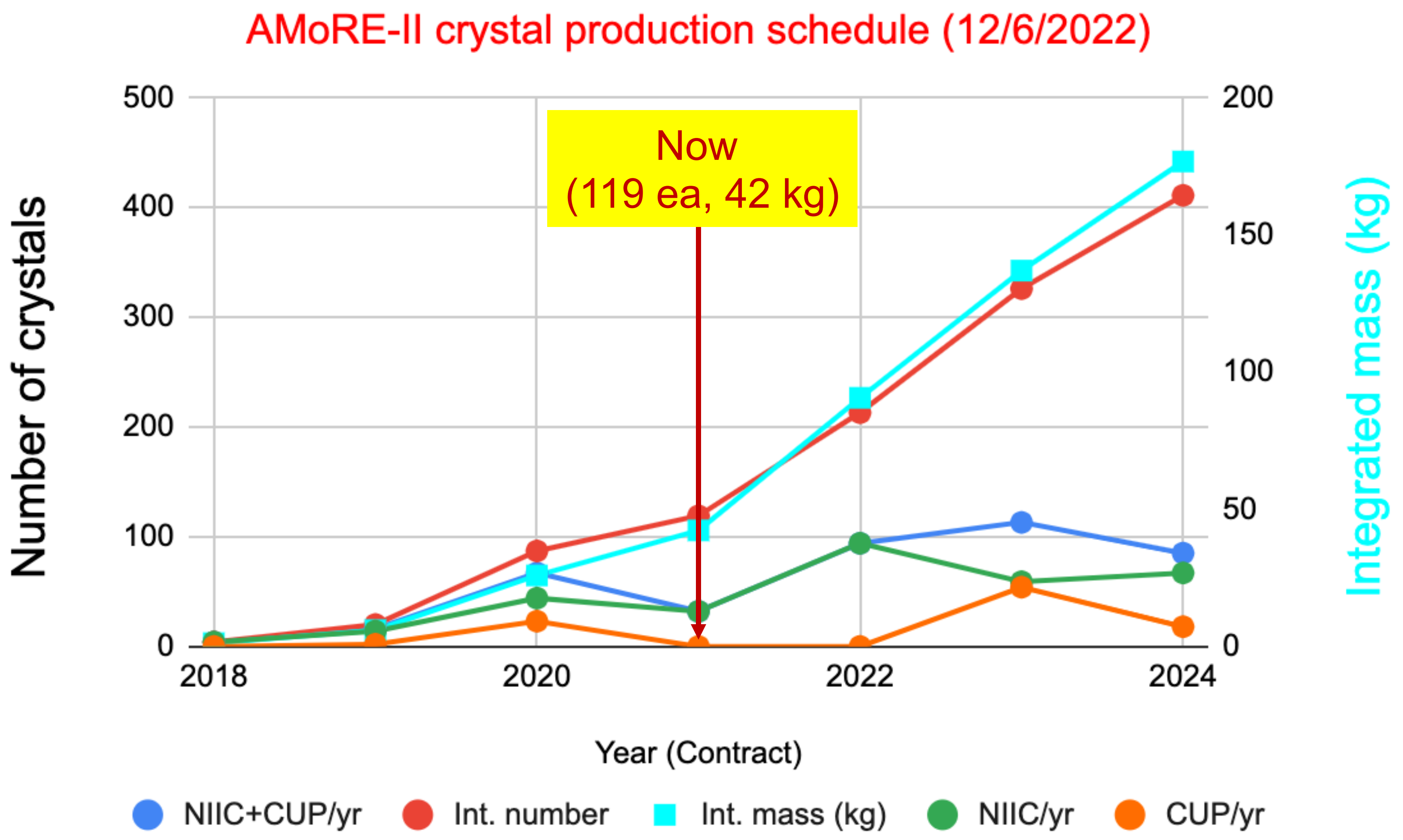
CUP grown Enriched-LMO-I

Czokralski grower at CUP

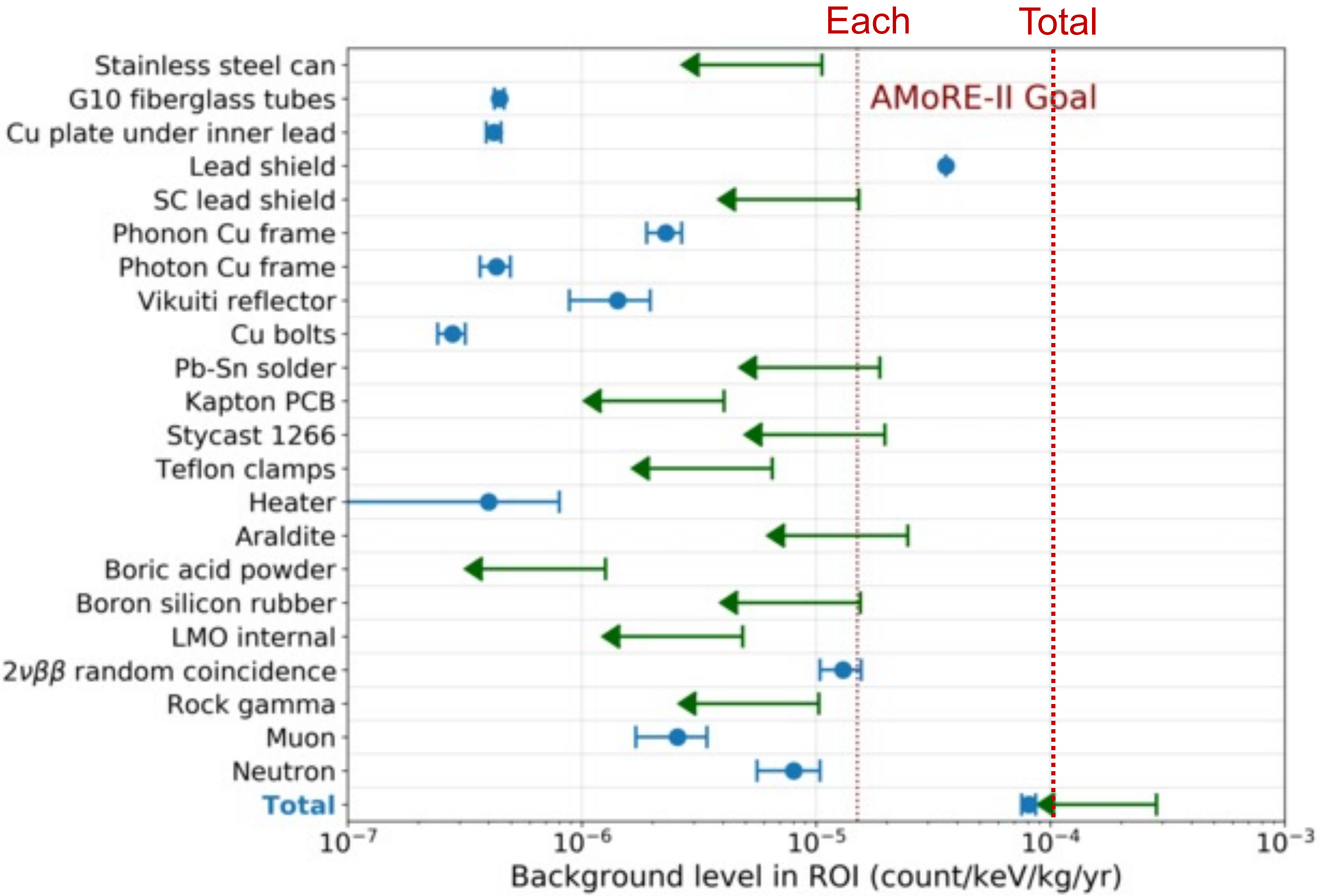
ICP-MS results of CUP grown LMO crystals

LMO sample name	K	Ba	Sr	Zr	Ir	Pb	Th	U
	(ppb)	(ppb)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)
CZ01-L2110ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2110ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2111ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2111ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2112ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2112ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2113ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2113ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6

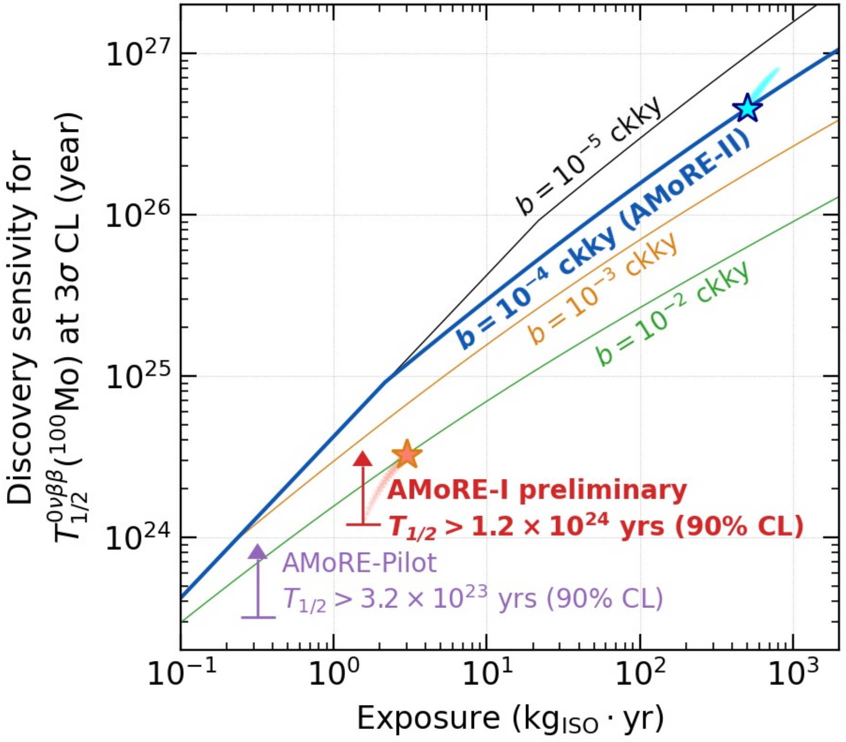
AMoRE crystal production schedule

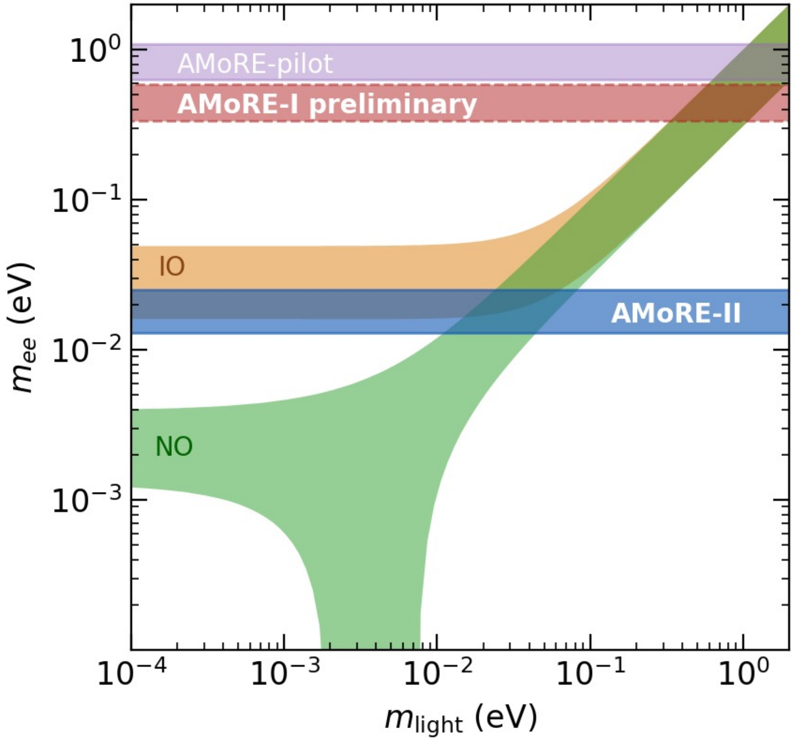


Background budget for AMoRE-II



Limits and sensitivities





- AMoRE-II for $T_{1/2}^{0\nu} > \sim 5 \times 10^{26}$ years by 100 kg of Mo-100 × 5 years running.
- Reduction of background level down below 10^{-4} ckky.

Summary

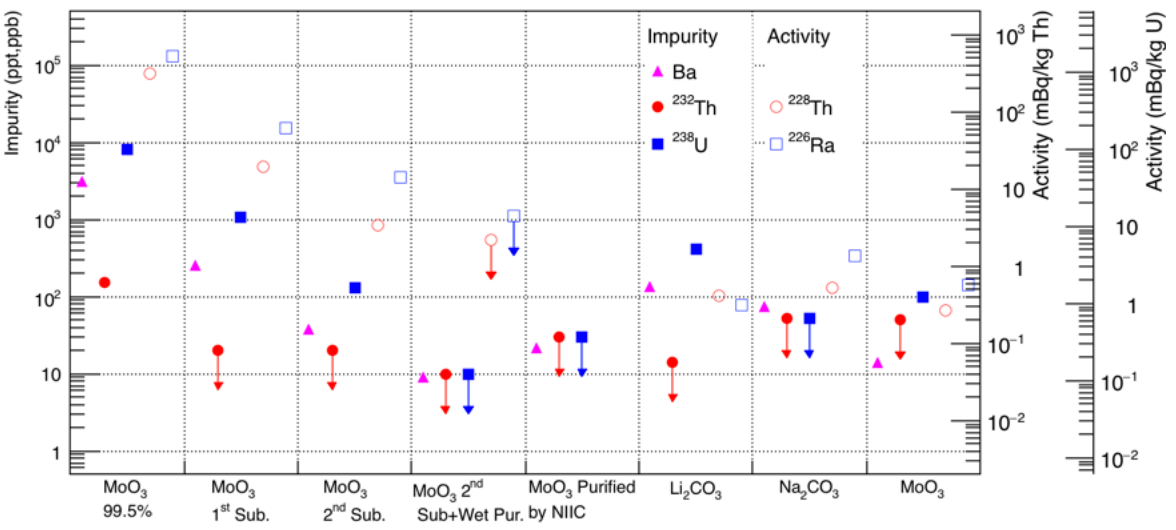
- AMoRE is searching for 0v$\boldsymbol{\beta\beta}$ decay to establish Majorana nature of neutrinos using Mo-100 based scintillation crystals at the low temperature detector system.
- Preliminary result of AMoRE-I at its mid-point:
  - Mass × time exposure: 4.68 (2.24) kg·yr XMO (^{100}Mo).
  - Background level ~ 0.034 counts/keV/kg/year at [2860-3200] keV.
  - $T_{1/2}^{0\nu} > 1.05\times10^{24}$ years.
  - AMoRE-I data taking will continue in 2023.
- AMoRE-II will starts at the newly built Yemilab to head for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years.
  - Mass-purification of MoO_3 and Li_2CO_3 powders started and on-going with measured purities.
  - Mass-production of Li_2MoO_4 crystals started both at NIIC and CUP aiming to prepare ~180 kg of crystals by mid 2024.

Backup

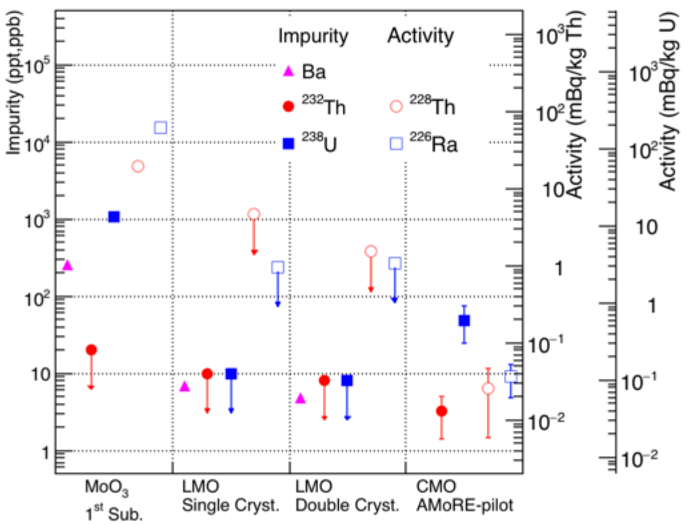
AMoRE-II: Purification for XMO crystals

- Ba is a good indicator for Ra since they are in the same family.
- We have a good progress toward AMoRE-II crystals.

Impurity and Activity



Impurity and Activity



AMoRE-II crystal requirement:

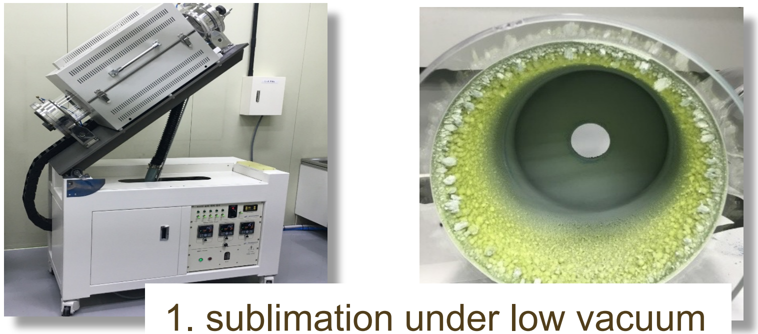
Mo based crystal with

- Good phonon resolution, high light yield and excellent PSD
- Extremely low background in ROI (< 0.0001 evt/kg/y)
- Easy to grow, low price for crystal growing.

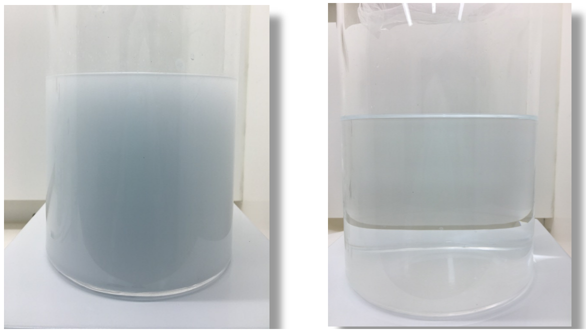
$^{48depl}Ca^{100}MoO_4$ (AMoRE-Pilot/I): Excellent but $^{48depl}Ca$ & Ca deep purification necessary .

Purification of $^{100}MoO_3$ powder

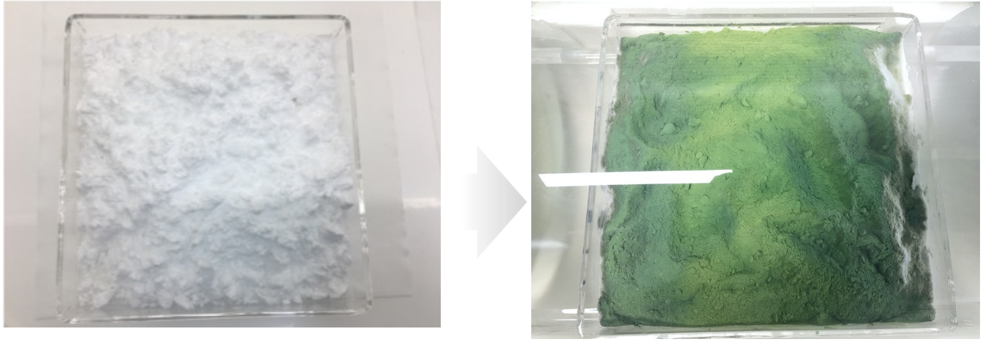
- ☐ Enriched molybdenum oxide purification, mass-production and analysis
- ☐ 5 kg/month purification capacity at CUP
- ☐ ~99% recovery efficiency for the process



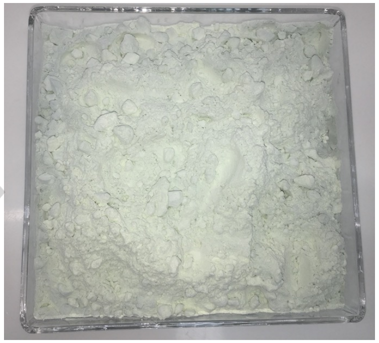
1. sublimation under low vacuum



2. dissolving, co-precipitation, filtering



3. synthesis of ammonium polymolybdate powder and its annealing



4. final $^{100}MoO_3$ powder collection and its storage at Y2L A5

ICP-MS and HPGe array measurements

CENTER FOR UNDERGROUND PHYSICS

experiment #	Al, ppb	K, ppb	Cr, ppb	Mn, ppb	Fe, ppb	Ni, ppb	Cu, ppb	W, ppb	Sr, ppb	Ba, ppb	Pb, ppb	Th, ppt	U, ppt
Raw ^{100}MoO$_3$ (lot #3497)	1399	938	<300	<30	504	1073	<200	670	4	11	4.0	70	257
Purified products (examples)													
1	585	409	<200	<30	39	<20	<200	33	<0.15	3.9	0.33	<10	<7
11	630	253	<400	<30	26	<20	<200	43	<0.20	<3.0	<0.20	<9	<6
21	<30	246	<200	<30	33	<20	<200	38	<0.15	<3.0	<0.5	<10	<7
31	<30	150	<200	<30	26	<20	<200	648	<0.15	<3.0	<0.5	<10	<7
51	<100	146	<200	<30	18	<20	<200	601	<0.15	<3.0	<0.4	<10	<7

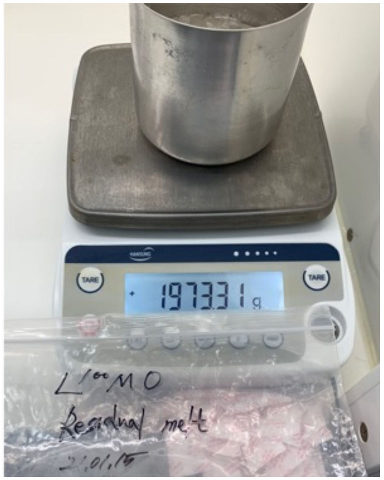
HPGe	**Unpurified #3172** (CC1, 1.6 kg, 14 days)	**Unpurified #3434** (CAGe, 9.6 kg, 75 days)	**Unpurified #3675** (CAGe, 9.8 kg, 93 days)	**Unpurified #3824** (CAGe, 12.7 kg, 183 days)	**Purified #3824** (CAGe, 12.0 kg, 152 days, preliminary)
^{228}Ac	< 1.0 (90% C.L.)	0.88 ± 0.13	0.703 ± 0.097	**0.274 ± 0.044**	< **0.030** (90% C.L.)
^{228}Th	< 1.0 (90% C.L.)	0.669 ± 0.089	0.773 ± 0.093	**0.234 ± 0.040**	< **0.026** (90% C.L.)
^{226}Ra	5.1 ± 0.4 (stat) ± 2.2 (syst)	1.19 ± 0.42	< 0.51 (90% C.L.)	**0.273 ± 0.036**	**0.069 ± 0.014**
^{40}K	< 16.4 (90% C.L.)	36.0 ± 4.1	17.5 ± 2.0	**8.8 ± 1.0**	**1.48 ± 0.27**
^{88}Y	Not observed	0.101 ± 0.016	0.090 ± 0.013	**0.0564 ± 0.0067**	**Not observed**
^{88}Zr	Not observed	Not observed	Not observed	**0.0354 ± 0.0074**	**Not observed**

Unit: mBq/kg (kg: powder)

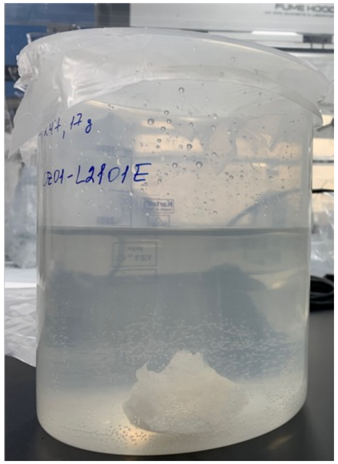
Reduced more than 4 times

ICP-MS	**Unpurified #3172**	**Unpurified #3434**	**Unpurified #3675**	**Unpurified #3824**	**Purified #3824**
^{232}Th	0.14	0.36	0.37	0.36	< 0.041
^{238}U	0.94	2.7	0.93	0.96	< 0.087
^{40}K	9.0	38	22	22	3.6 – 18.3

$^{100}MoO_3$ recovery from LMO melt



Residual LMO melt in the Pt-crucible



LMO melt dissolution

☐ 3 LMO crystal ingots are pulled from every crucible.

☐ The final melt is dissolved in DI-water, and insoluble impurities (Th, U, Pb, etc.) are filtered out with a membrane filter.

☐ Mo is separated from Li in form of molybdic acid (H_2MoO_4) via interaction with NH_4Cl.

☐ Separated molybdic acid is dissolved, purified with co-precipitation and recrystallized.

Element	Al	K	Ca	Ba	Sr	Pb	Th	U
Unit	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	ppt	ppt
LMO melt	1450	606	579	16	0.67	<0.4	<8	28
$^{100}MoO_3$ powder, **pure recovered**	<100	131	<200	<3	<0.15	<0.4	<10	<7
$^{100}MoO_3$ powder, **initial purified**	<100	146	-	<3	<0.15	<0.4	<10	<7

☐ Recovered $^{100}MoO_3$ powder is waiting for the HPGe array measurements.
☐ ~99% recovery efficiency for the process

Purification of Li_2CO_3

☐ Purification steps

Carbonization method → Column chromatography → Co-precipitation with tiny amount of Li_2CO_3 → Final Li_2CO_3 synthesis

☐ Purification results

sample	^{40}K, mBq/kg	^{228}Ac, mBq/kg	^{228}Th, mBq/kg	^{226}Ra, mBq/kg	K, ppb	Sr, ppb	Ba, ppb	Pb, ppt	Th, ppt	U, ppt
Huarui, 99.999%	HPGe@CUP				ICP-MS@CUP					
Initial	<16.59	6.33 ± 1.28	5.47 ± 0.67	57.38 ± 3.15	426	6	35	1397	8	156
PURIFIED	<6.02	<1.96	<1.86	<1.1	<60	0.5	61	<80	<6	<6
RF		>3	>2	>50	>7	>12		>17	>1.3	>26

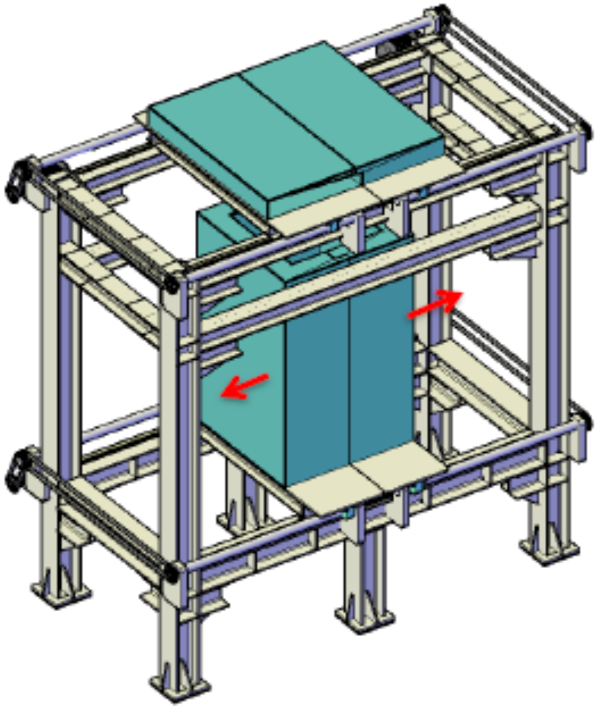
>2	>3	>50	>7	>17	>26	>1.3
^{228}Th	^{228}Ac	Ra	K	Pb	U	^{232}Th

Background requirements for AMoRE

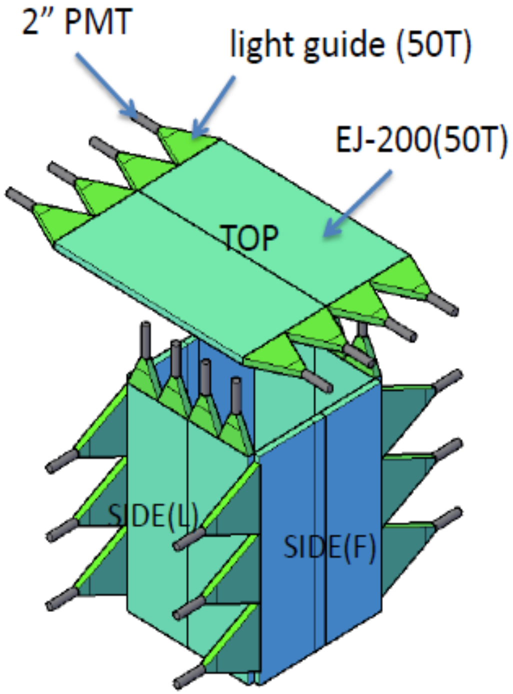
Phase	AMoRE-I	AMoRE-II
BKG Requirement	$<10^{-3}$ ckky in ROI	$<10^{-4}$ ckky in ROI
Mass of 100Mo	~ 3 kg ^{100}Mo	~ 100 kg ^{100}Mo
Number of crystals	18 crystals (5 LMO + 13 CMO)	~ 420 crystals
Contribution to background from Th and U chains [ppt]		
Internal crystal	<100	<10

- ☐ Assuming a segregation of the impurities in the melt after the crystal growing, the concentration of the contaminants in the raw powders is expected to be less than 100 ppt

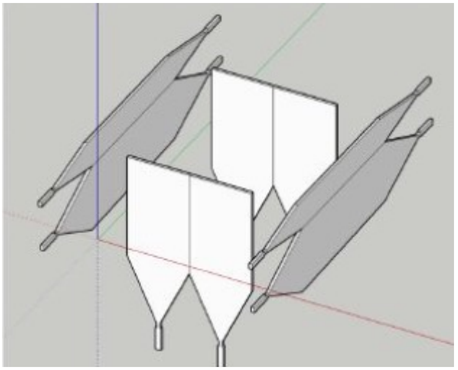
Shielding structure of AMoRE-pilot & AMoRE-I



15cm low background Pb



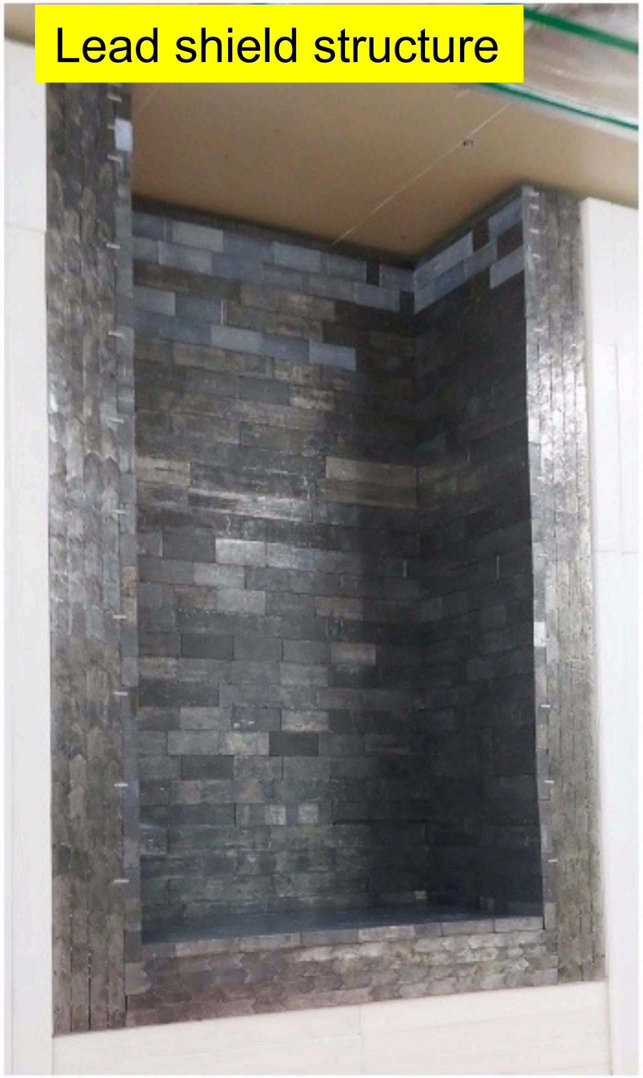
muon shielding structure



Additional muon counters
to cover gaps from AMoRE-I

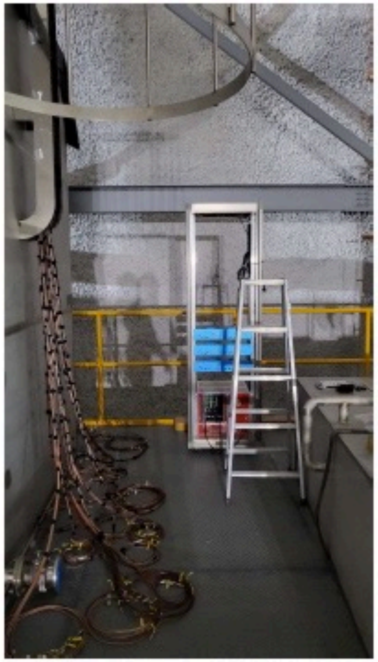
- ☐ PE, borated PE, borated rubber sheet and boric acid rubbers were also added for neutron shielding during AMoRE-pilot runs

AMoRE-II construction at Yemilab



Lead shield structure

Water Cherenkov Counter



Pastic Scintillator Muon Counter