The 21st Lomonosov Conference on Elementary Particle Physics
Moscow, 24 Aug – 30 Aug 2023

Status and perspectives of the AMoRE experiment

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AMoRE (Advanced Mo-based Rare process Experiment): search for 0ν2β-decay of ^{100}Mo isotope with scintillation cryogenic bolometer

China
Germany
India
Indonesia
Korea
Pakistan
Russia
Thailand
Ukraine

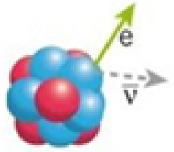
2003 – the beginning of works on $CaMoO_4$ scintillation crystals growth in Korea (and in Russia)

2009 – creation of International collaboration AMoRE

2006-2012 – JSC Fomos-Materials developed the technology of $^{48free}Ca^{100}MoO_4$ crystals growth.

2013 – Foundation of CUP (Center for Underground Physics IBS).

Motivation for the search for neutrinoless double beta decay process

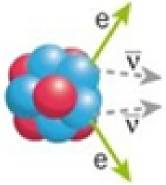


(Z,A) →(Z+1,A)+e⁻ +ν_e
^{3}T, ^{14}C, ^{40}K….

E. Rutherford
P. Curie
1898

Wolfgang Pauli
1930

M.Goeppert-Mayer
1935

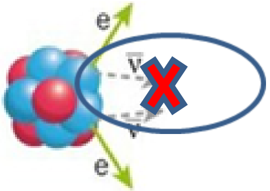


(Z,A) →(Z+2,A)+2e⁻ +ν_e
$T_{1/2}^{2\nu}$ > 10^{18} yr
(ΔL=0, allowed,
even-even ^{76}Ge, ^{130}Te, ^{100}Mo,…)

Ettore Majorana
1937

Jiulio Racah
1937

Wendell Furry
1939



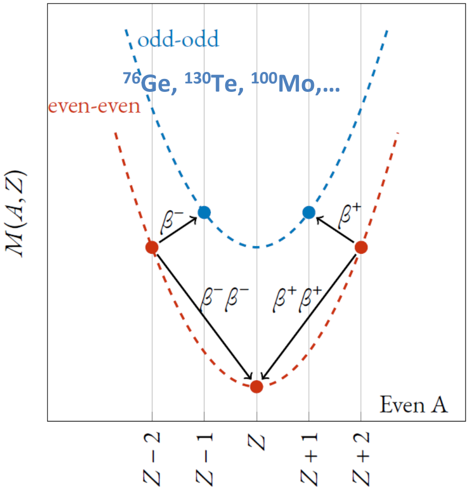
(Z,A) →(Z+2,A)+2e⁻
$T_{1/2}^{2\nu}$ > 10^{25} yr
(ΔL≠ 0 (L = 2), forbidden,
even-even ^{76}Ge, ^{130}Te, ^{100}Mo,…)

If the process exists: neutrino is Majorana particle (i.e. it is its own antiparticle) beyond the Standard Model.

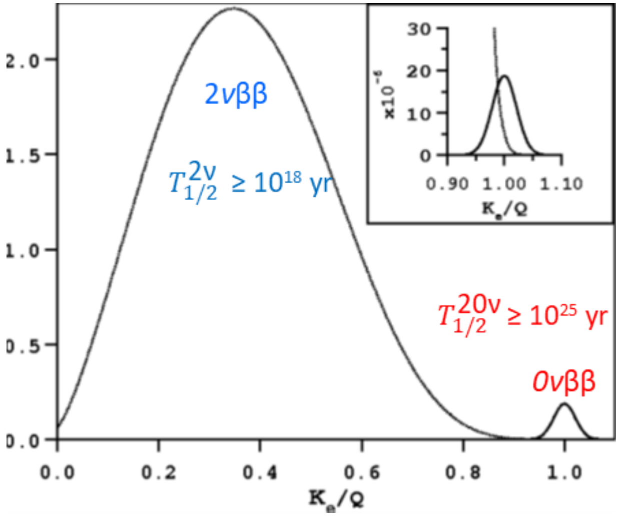
- *Violation of Lepton number conservation (ΔL=2): new physics*
- *Nature of neutrino (Majorana or Dirac particle?)*
- *The absolute neutrino mass scale (1/$T_{1/2}^{0\nu}$ ~ m_ν^2)*
- *CP- violation in the lepton sector*

To observe 2νββ decay, the single β-decay must be energetically forbidden due to energy conservation constraint →

In total 35 isotopes available and ~ 11 of them can be used for 0νββ search

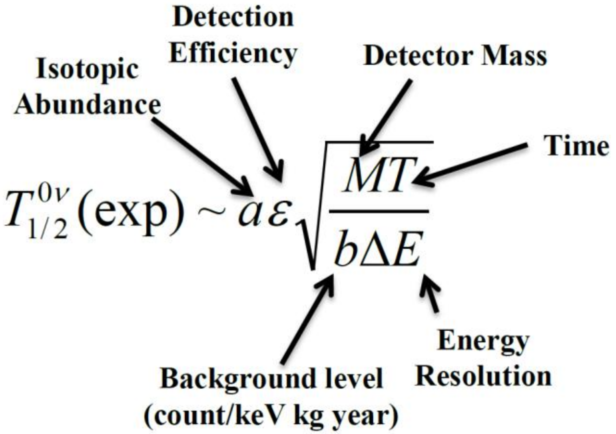


Experimental signature of 2νββ and *0νββ*

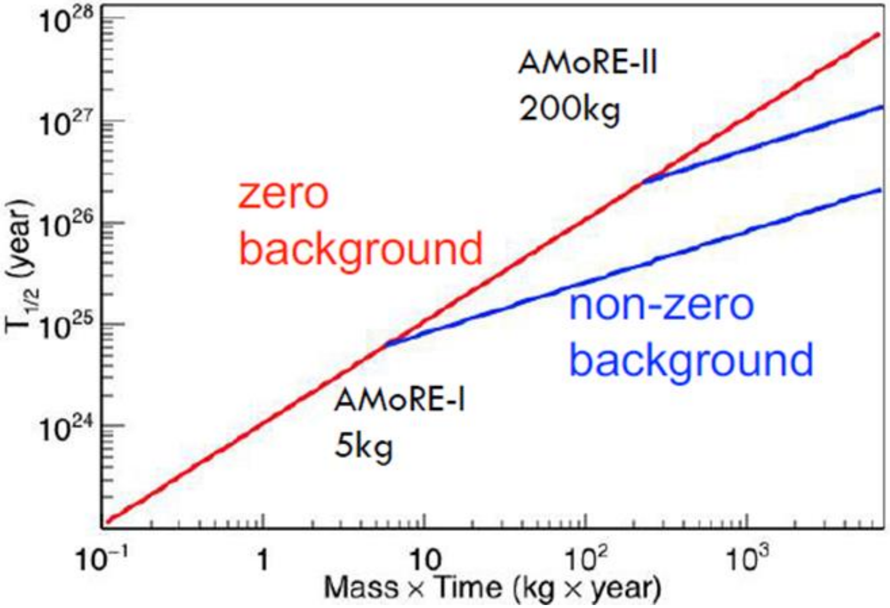


Sensitivity of 0ν2β-decay experiments: the problem of background and energy resolution

For “sizeable” background



$$T_{1/2}^{0\nu}(\exp) \sim a\varepsilon\sqrt{\frac{MT}{b\Delta E}}$$



“Zero” background

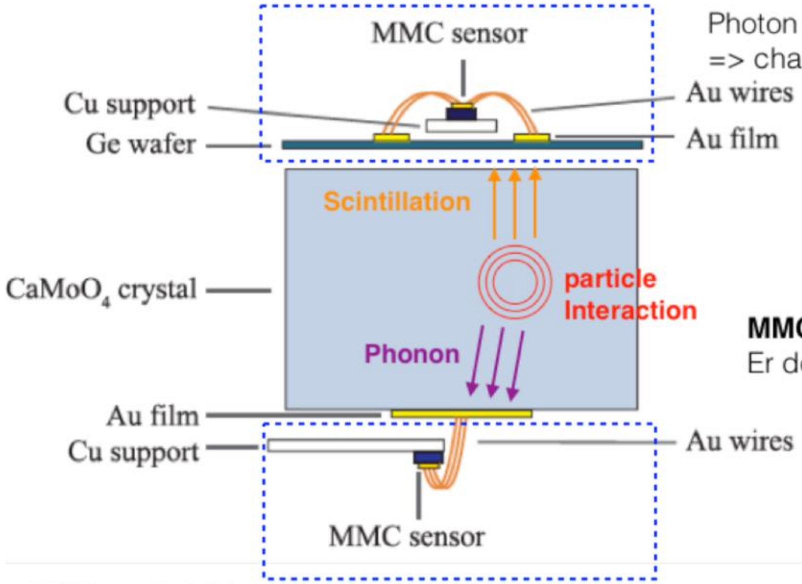
$$T_{1/2}^{0\nu}(\exp) \sim a\varepsilon\frac{MT}{n_{CL}}$$

AMoRE scintillation cryogenic detector

temperature sensor: MMC (Metallic Magnetic Calorimeter)
registration system: SQUID (Superconducting Quantum Interference Device) magnetometer

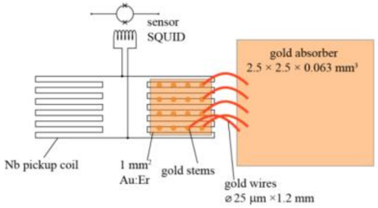
Simultaneous registration of two signals: phonon and light

Photon detector

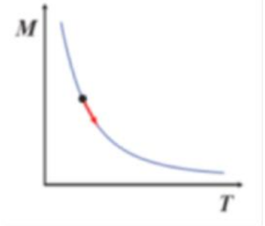


IEEE Trans. Nucl. Sci., 63, 539

Photon => heating wafer => heating MMC
=> change of Magnetization => SQUID

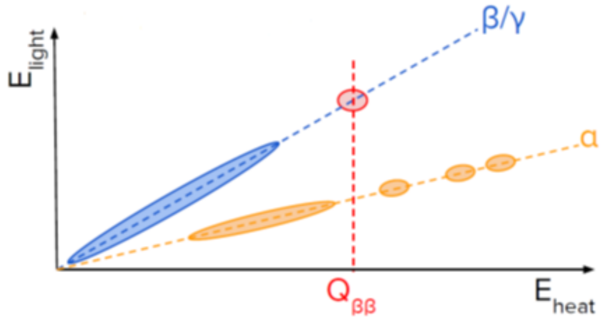


MMC (metallic magnetic calorimeter)
Er doped Au film, Er spin in B-field flips as T changes.



Phonon detector

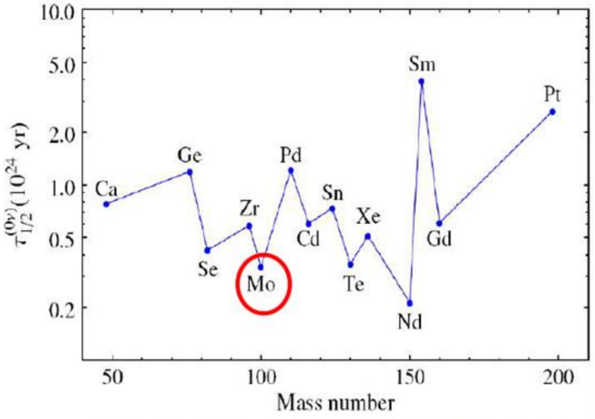
Phonon => heating MMC => change of Magnetization => SQUID



- Different light yield (LY) of α vs β/γ to actively suppress background: Rejection of α-induced background
- High energy resolution ~ 10 keV FWHM at 2.6 MeV.
- Fast signal timing: a few msec rise-time for phonon signals at mK
- Low random coincidence background.

Why is ^{100}Mo isotope chosen for AMoRE detector?

- ✓ High $Q_{\beta\beta}$ = 3034 keV > ^{208}Tl γ-line (2615 keV) from rock and materials).
- ✓ Relatively short half life (0νββ) expected from the theoretical calculation.
- ✓ High natural abundance: 9.7%
- ✓ Production of ^{100}Mo isotope@97% at industrial scale: centrifuges (ECP, Russia).



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

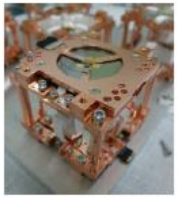
Isotope	Q (MeV)	Abundance,%
^{48}Ca	4,271	0,19
^{76}Ge	2,040	7,8
^{82}Se	2,995	8,7
^{100}Mo	3,034	9,7
^{116}Cd	2,802	7,5
^{124}Sn	2,228	5,8
^{130}Te	2,533	34,1
^{136}Xe	2,479	8,9
^{150}Nd	3,367	5,6

ECP (Zelenogorsk, Russia)

^{100}Mo-based scintillation crystals (XMoO4) operated under cryogenic temperature.

- ✓ ^{100}Mo-based scintillation crystals: $XMoO_4$ (XMO, X =**Ca, Li_2**, etc, …) with simultaneous detection of light/heat signal → rejection of α-background
- ✓ Detector = Source: high efficiency ~ 80÷85%.
- ✓ Technology of Czochralski crystal growth: High purity → very low intrinsic radioactive background.

Implementation of AMoRE experiment (Stages Plan)



Single module

→

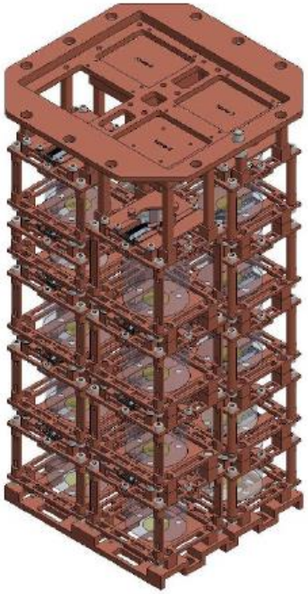
Completed
2015 ÷ 2018
6 CMO & 1.9 kg
$^{48depl}Ca^{100}MoO_4$

AMoRE-Pilot to demonstrate the potential for 0νββ probe

AMoRE-Pilot

→

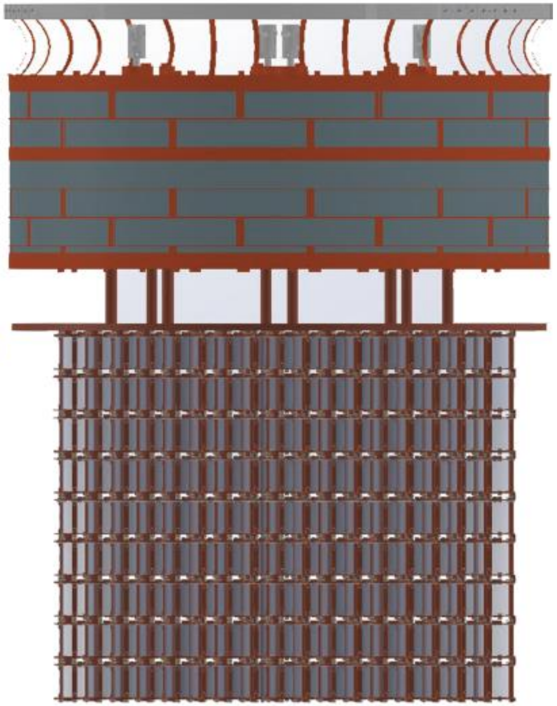
Completed
2020 – May 2023
13 CMO + 5 LMO
Total mass: 6.2 kg



AMoRE-I

→

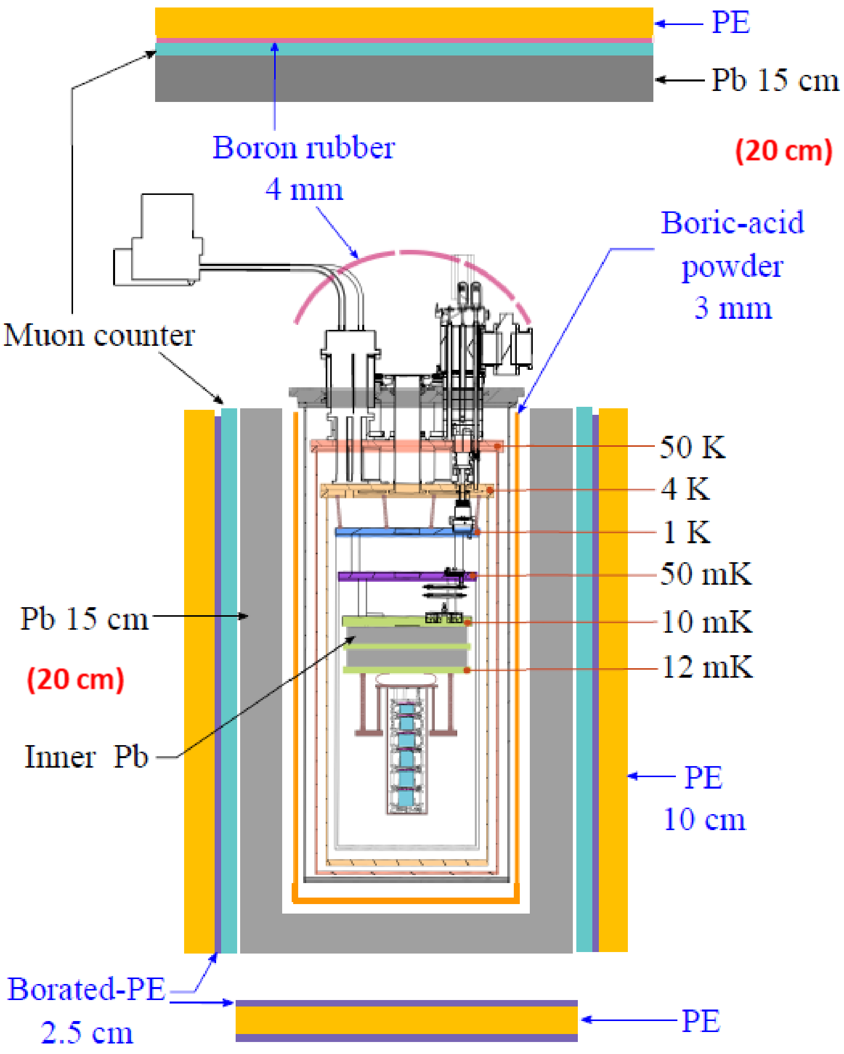
Planned since Dec 2023 →
1st stage of AMoRE-II - 90 crystals of LMO (10 towers)
Total mass of 178 kg XMoO4 (100 kg of ^{100}Mo)
40 towers ~ 360 $XMoO_4$ crystals

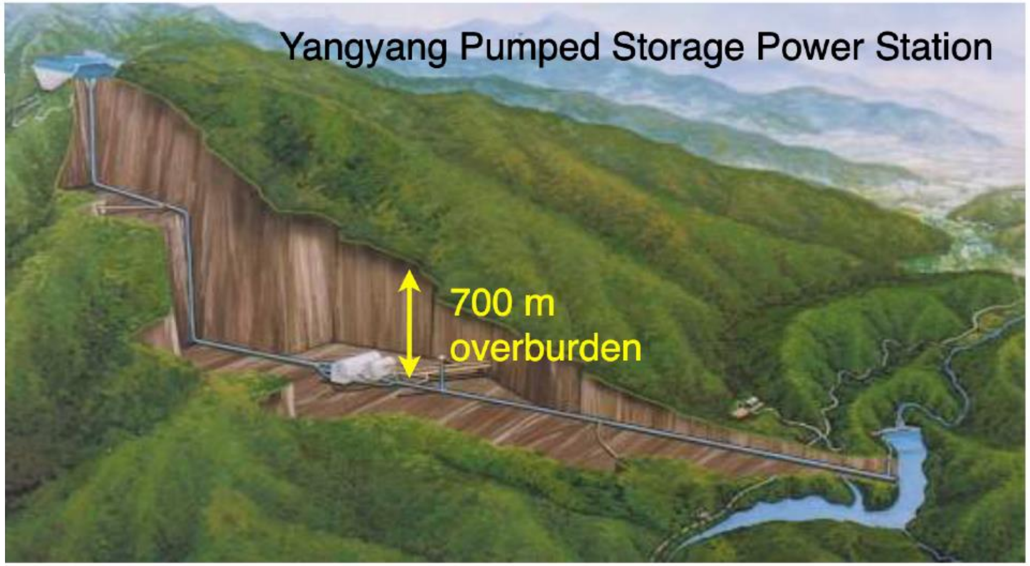


AMoRE-II
Being prepared

$^{48depl}Ca^{100}MoO_4 + Li_2MoO_4$ crystals
D 5 x 5 cm (~ 310 g)
D 6 x 6 cm (~ 520 g)

Cryostat with shielding/AMoRE-Pilot and AMoRE-I in YangYang lab





Pulse-tube dilution refrigerator:

Operating at 10 mK with 1.2 µW cooling power. Damping system to reduce vibration noise signals from the impulse tube of the CF-DR cryostat.

15-20 cm Pb (γ), boron and polyethylene (neutrons), Plastic scintillator muon counter (muons veto).

YangYang underground laboratory

-700 m minimum vertical depth (2000 m.w.e)

Radon free air supplied

AMoRE-I experiment

Period: Aug 2020 – April 2023

18 crystals:

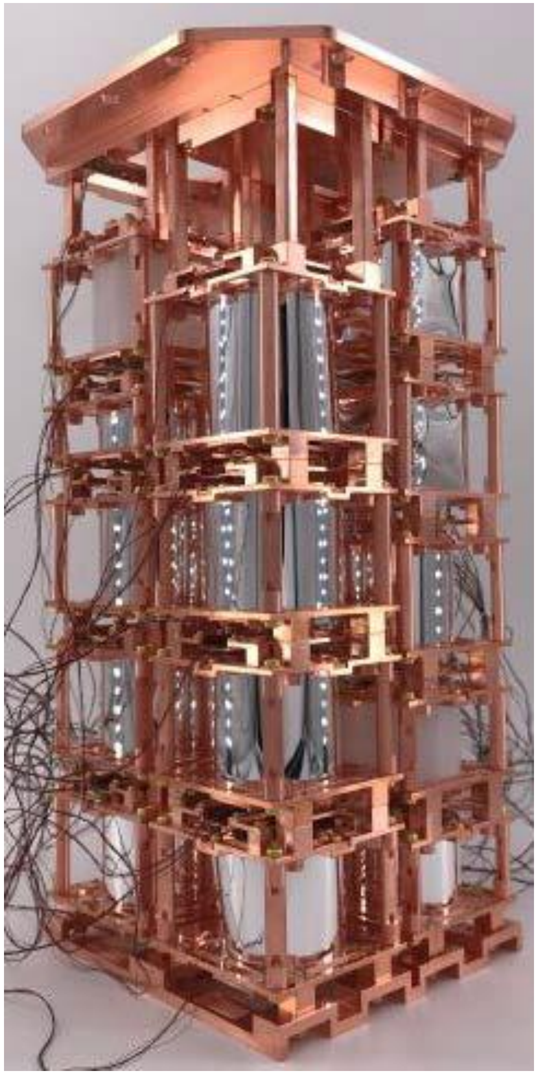
$^{48free}Ca^{100}MoO_4$:

13 from Fomos-Materials (4.58 kg)

$Li_2{}^{100}MoO_4$:

5 from NIIC + 1 from CUP (1.61 kg)

-**Total crystal mass = 6.19 kg, ^{100}Mo mass = 3.1 kg**

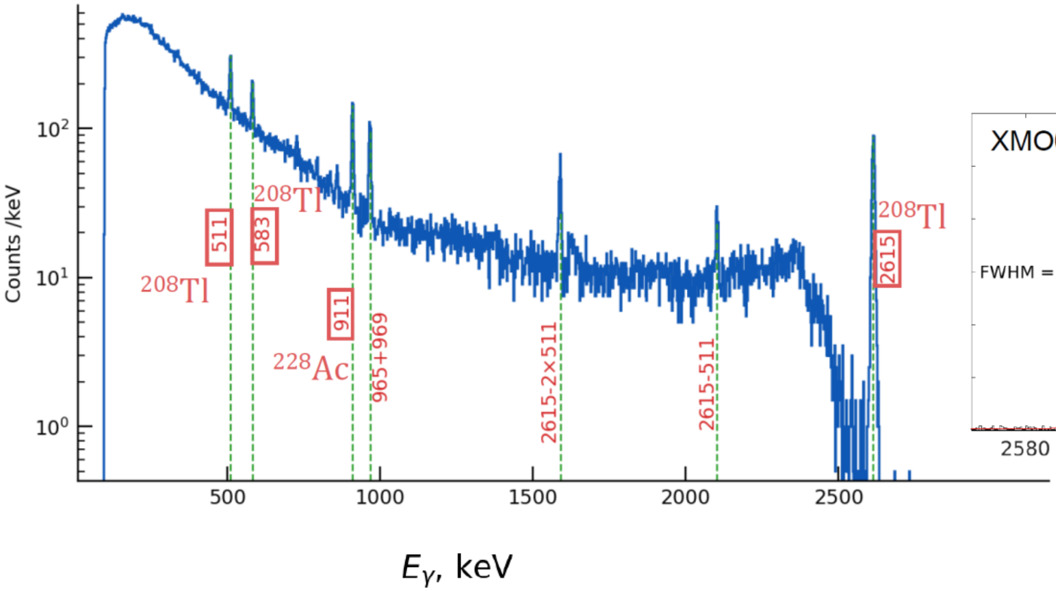


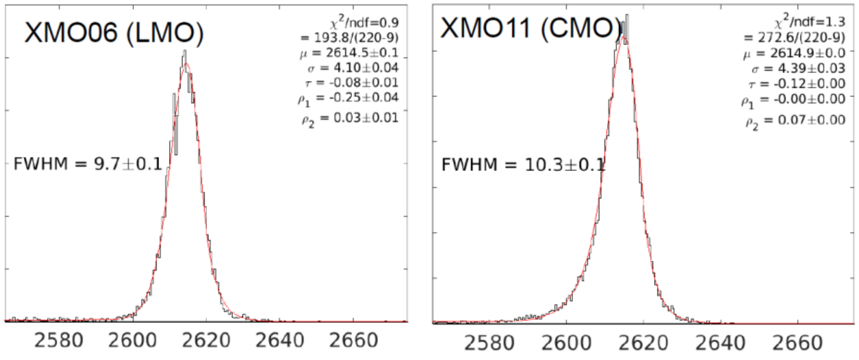
Upgrade from Pilot:

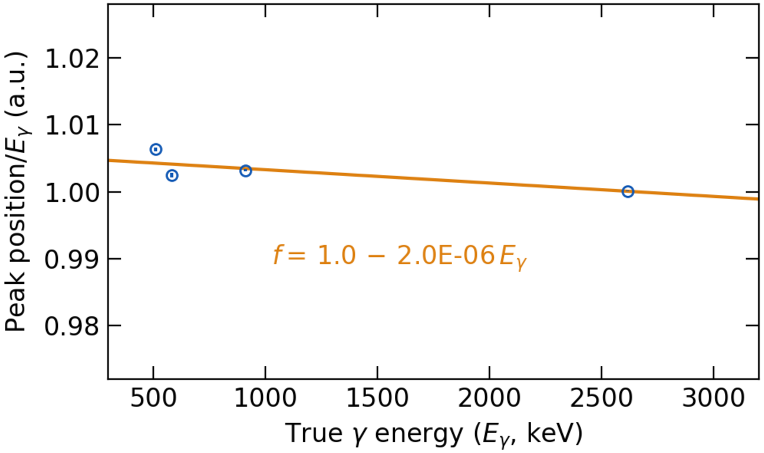
- Stabilization heater for all crystals.
- MMC sensor: AuEr ➔ AgEr.
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1\ \mu K$.
- Shielding enhancements:

-Outer Pb: 15 cm ➔ 20 cm;
- Neutron shields: boric acid silicon + more PE / Boron-PE.
- Better muon counter coverage (~ 4π).
- More supply of Rn-free air.

AMoRE-I detector performance (energy calibration & resolution)



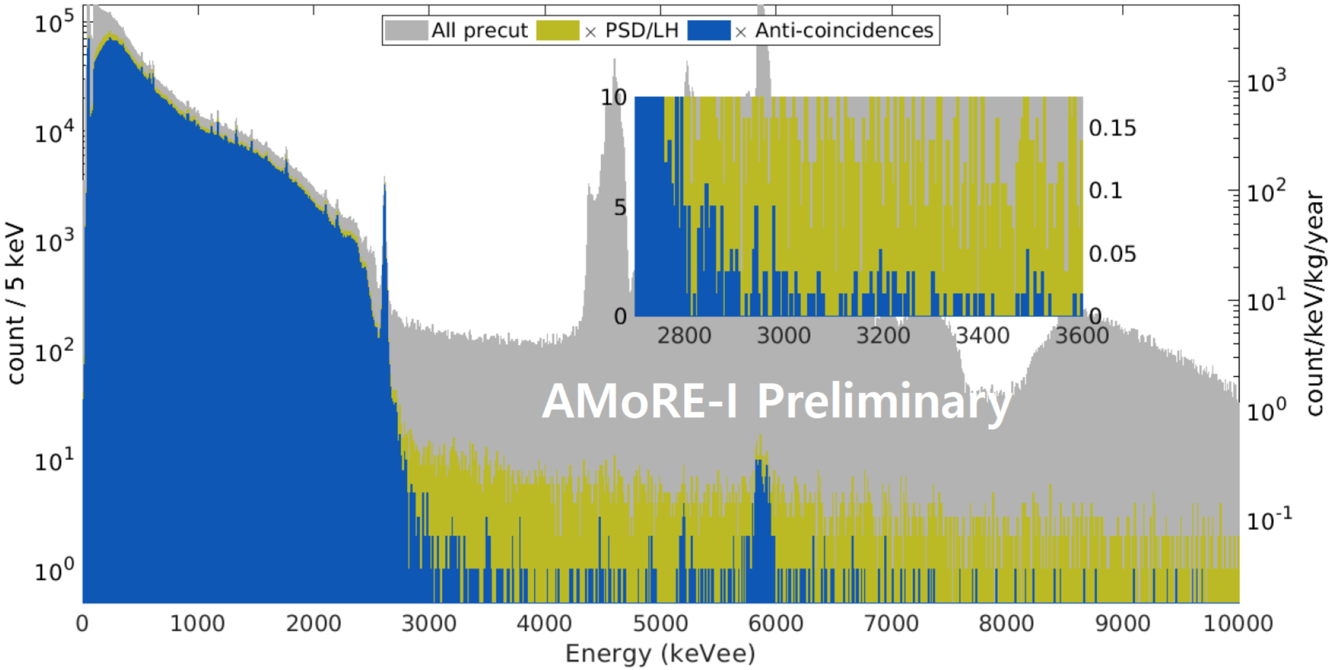




- **External γ source**: ^{232}Th-doped welding rods outside of OVC (Outer Vacuum System)
- Slight second order non linearity
- FWHM@2.6MeV ~ [8.9 ÷ 32.7] keV FWHM at 2615 keV, ~15 keV average

Best Measured 2.6 MeV γ scintillation energy is 2.5 keV (0.95 keV /MeV) for AMoRE II type LD

The background spectrum AMoRE-I



All crystal excluding 1 LMO for very poor β/α discrimination power:

13 CMO + 4 LMO: live exposure = **8.20 kg$_{XMO}$ · yr = 3.96 kg$_{ISO}$ · yr**

✓ Anti-coincidence cuts reject events:

- coincident at multiple crystals within 2 ms (ε ~ 99.8%)
- within 10 ms after a muon counter event (ε ~ 99,8%)

✓ α-tagging of internal ^{208}Tl background within 20 min after a ^{212}Bi α-decay event candidate (ε ~ 98%)

Background = 0.037 +/- 0.001 counts/keV/kg/year, from ROI side band

$T^{0\nu}_{1/2}$ > 3.7×10^{24} years at 90% C.L. (to be update)

AMoRE-II detector

Detector array: 100 (88) kg of ^{100}Mo, 178 (157) kg of LMO crystals (360 modules)

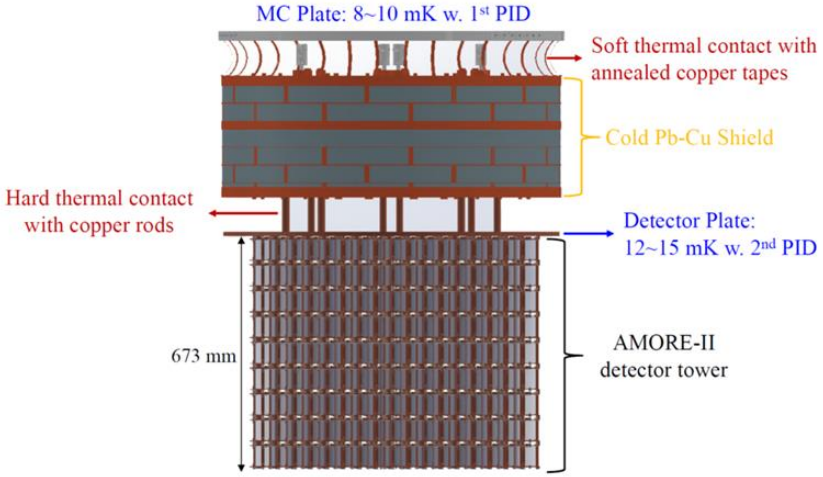
Scintillating molybdate crystals CMO from Fomos-Materials of different sizes and Li$_2$MoO$_4$ (LMO) by NIIC and CUP: D5 x 5 cm (310 gr) and D6 x 6 cm (~ 530 g)

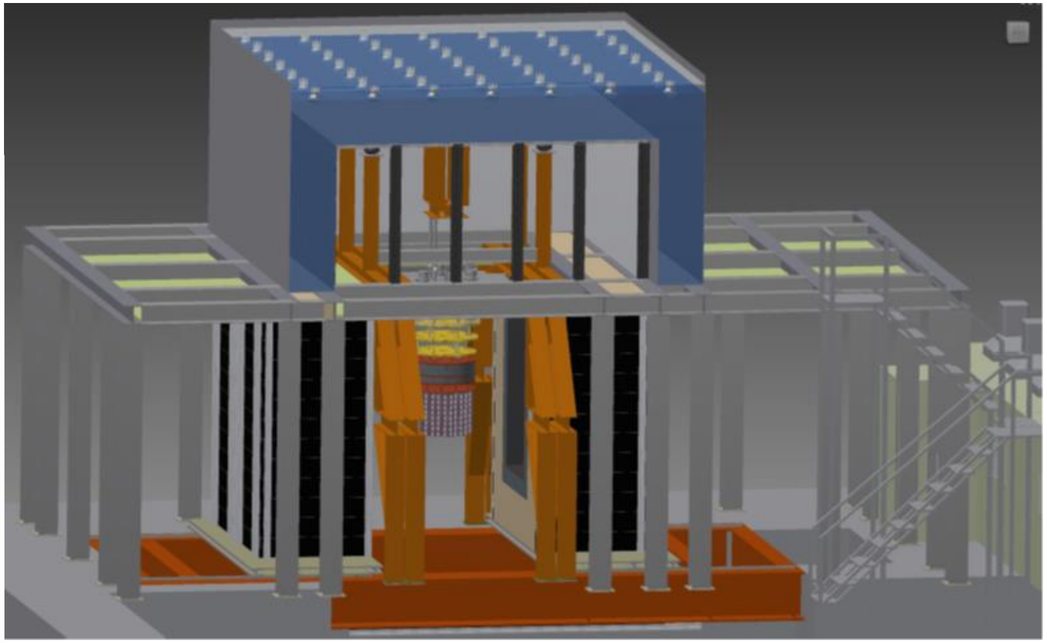
Recent R &D efforts at HQ (Daejeon): detector performance improved significantly:

- Energy resolution (FWHM) at 2.6 MeV: 7 ÷9 keV at 10 mK
- Light measurement: 0.8 - 0.95 keV/MeV
- Alpha particle Discrimination Power (DP): L/H ratio: 14 - 19.5 @ ~ 5MeV and PSD: ~5 @ ~ 5MeV
- Fast time response (rise time = 1 ÷ 2 ms @ 30 mK)

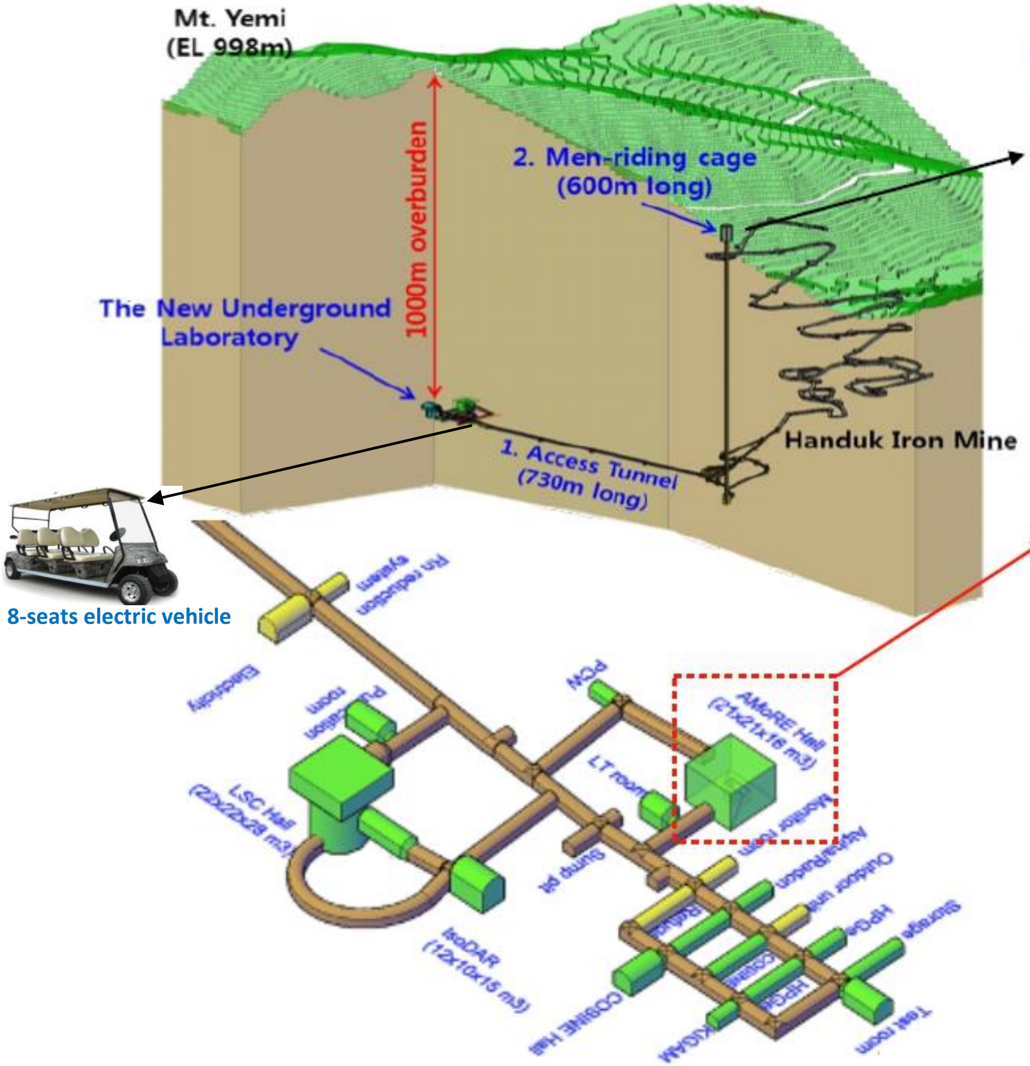
Jinju refrigerator:

- sample space: Ø1 m×H.1 m
- 26 cm thick inner lead shield

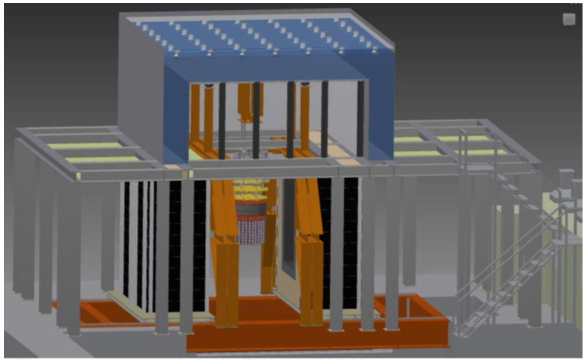




New Underground Laboratory Yemilab to host AMoRE-II



Transportation cage



The constructions have been done (2017.09 – 2022.07)

2,500 m^2 of experiment dedicated area

Since Sept 2022, the Yemilab is in operation

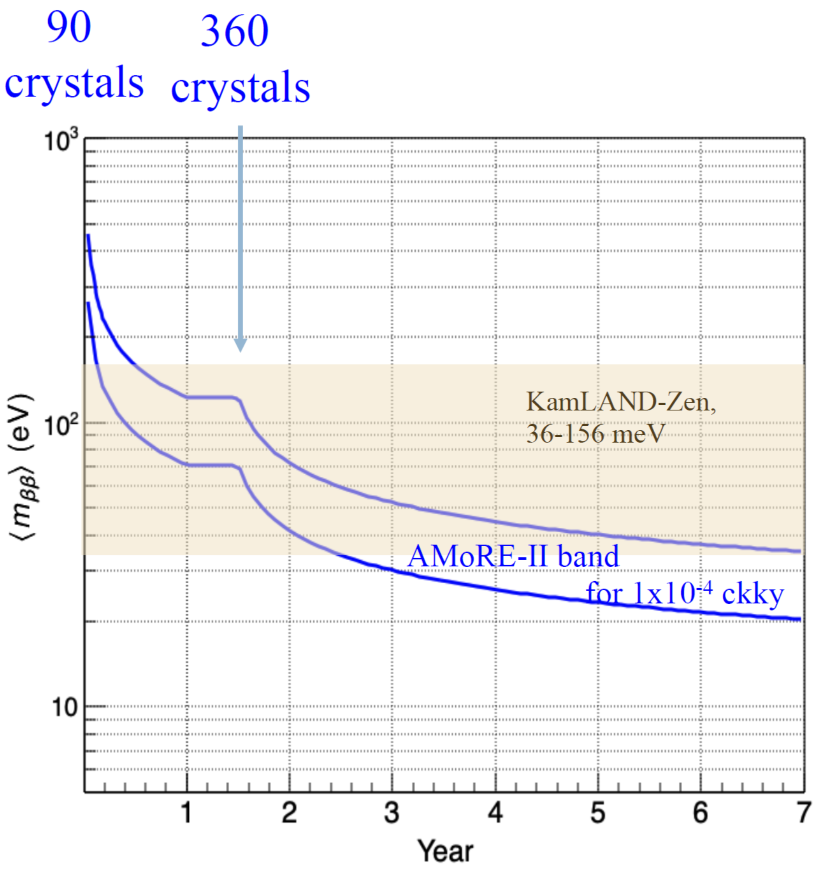
1000 m vertical depth (2500 m.w.e)

Radon Remove System

Preliminary muon rate at AMoRE hall: $1.0 \times 10^{-7}\ \mu/cm^2/sec$

AMoRE-II expected sensitivity and limits

YEONGDUK KIM
26th AMoRE collaboration meeting
16 Aug. 2023



Final results of AMoRE-I with further improvement

Background level ≤ 10^{-4} counts/keV/kg/year at 2860 ÷ 3200 keV

AMoRE-II for $T^{0\nu}_{1/2} > 5 \times 10^{26}$ years and 100 kg of ^{100}Mo x 5 years operation

Conclusions

AMoRE-I

- The AMoRE-I total effective exposure : 3.12 $\mathrm{kg}_{\mathrm{Mo100}}$ year (from Aug. 2020 for 2.5 years)
  - ✓ The background level in AMoRE-I is ~ 0.037 cnts/keV/kg//year (at ROI)
  - ✓ $T_{1/2}^{0\nu}$ >3.7×10^{24} years - best 90% limit for ^{100}Mo (to be update)

    (current best limit: 1.8 × 10^{24} of CUPID Mo)

AMoRE-II

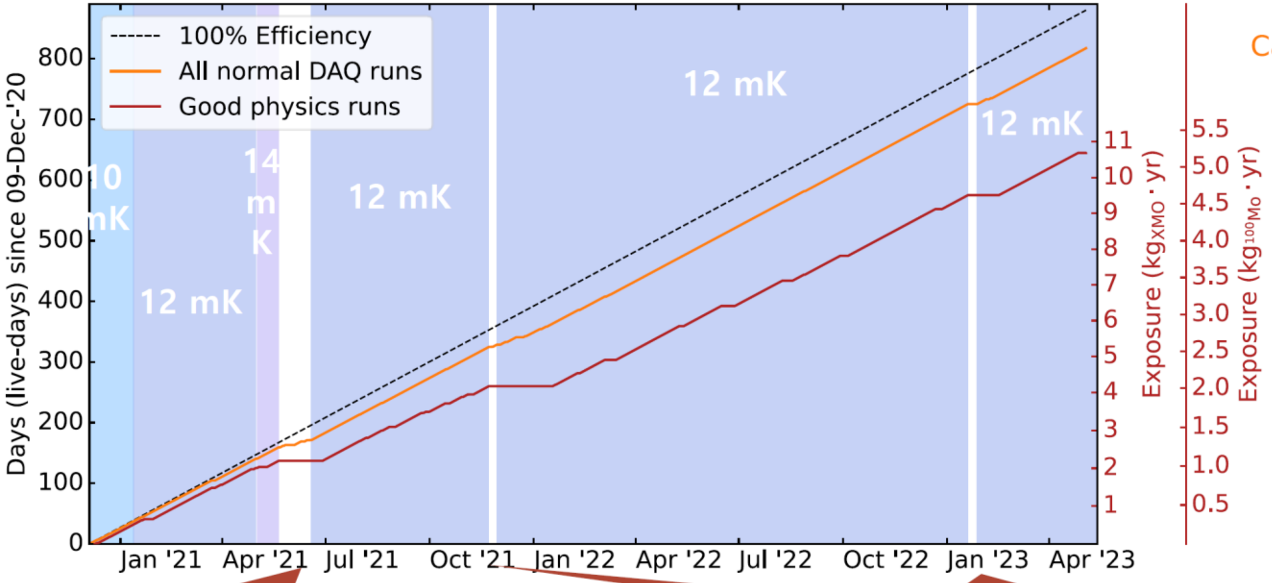
- Detector array: 100 kg of ^{100}Mo, 178 kg of LMO crystals (360 modules) Ø5cm×H.5cm (310 g) and Ø6cm×H.6cm (520 g)
- Expected background at the ROI down to 10^{-4} cnts/keV/kg/year
- AMoRE-II will run in two phases, aiming the final goal of $T_{1/2}^{0\nu}$ > 5 x 10^{26} years (m_{ee} ~ 2x10^{-2} eV).
- The first phase with 90 crystals (27 kg) of $X^{100}MoO_4$ will start at the end of 2023.
- The construction of major facilities and subsystem are almost completed.
- Preparing to install DR (Dilution Refrigerator).

Yemilab

- A new underground laboratory in Korea (Yemilab) to host AMoRE-II experiment: 2,500 m^2 of experiment dedicated area & 1000 m vertical depth (2500 m.w.e) & 1.0 × 10^{-7} μ/cm^2/sec

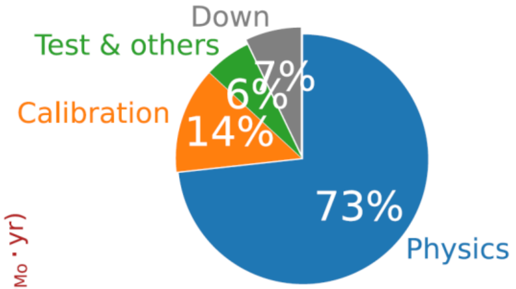
Back up slides

AMoRE-I data taking



DR temperature control

Recovery from power outage



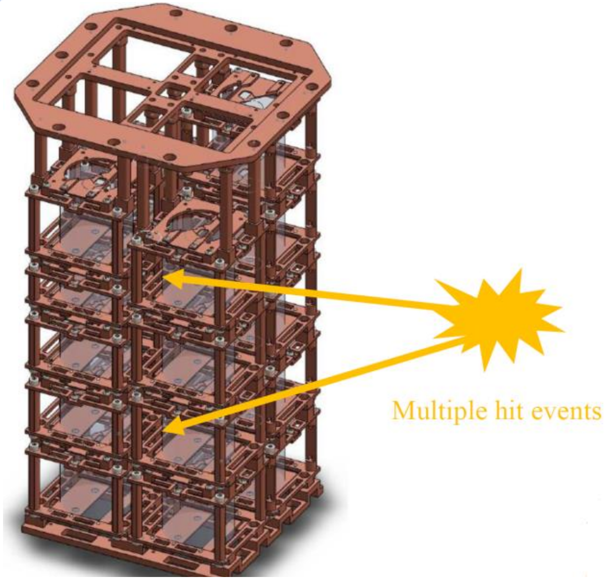
12 mK physics data	Exposure ($kg_{XMO}\cdot yr$)
Total	10.16
- Bad channels/runs*	8.76
- deadtime & anti-coincidence (= live exposure)	8.20
×efficiencies (= effective exposure)	6.44
in ^{100}Mo	3.11 ($kg_{ISO}\cdot yr$)

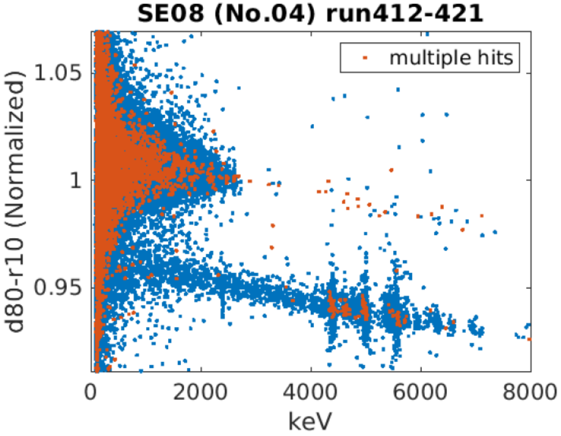
*: ex) Bad photon channel of LMOCUP, phonon ch. 3 not working before 1st outage, severe fluctuation runs, …

All Science Runs: Dec/2020 ~ Apr/2023

Hanbeom Kim (IBS/SNU) for 26th AMoRE Collab. Meeting
Aug. 16 – 18, 2023

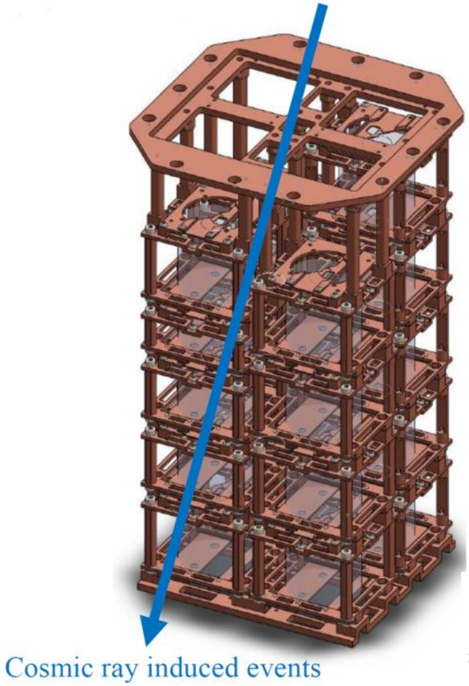
Particle identification: coincidence events - 1

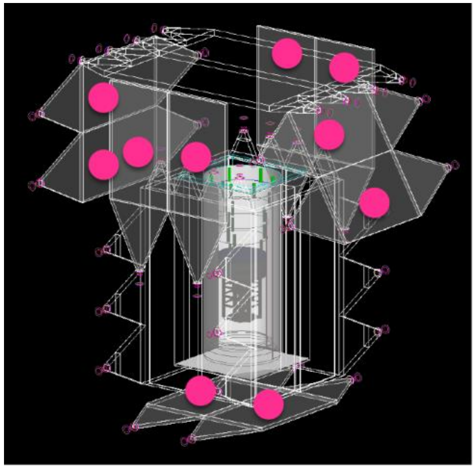




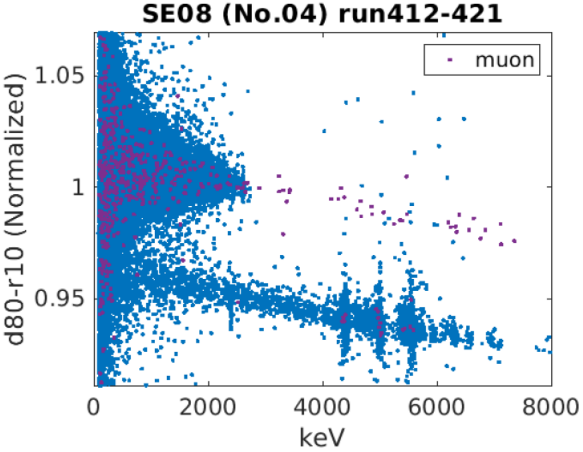
Multiple hits cut:
Events within ± 2ms time window to be coincidental

- ε ~ 99.8%





Muon Veto System

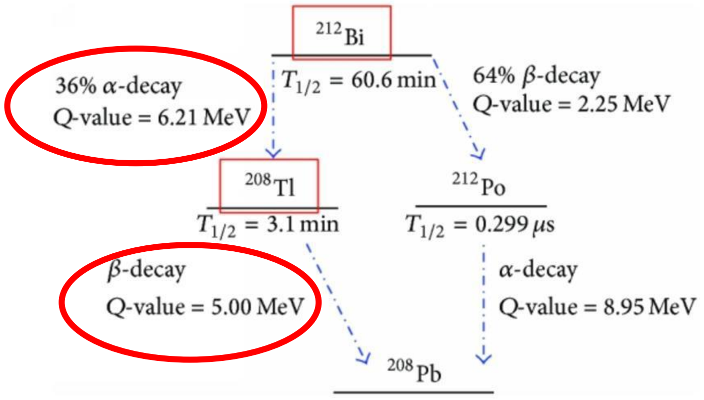


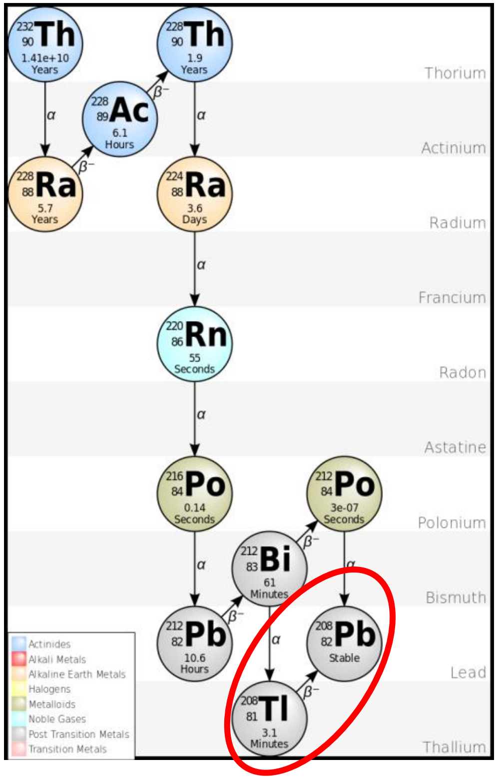
- Muon tagging data is obtained from Muon Veto System (MVS) installed outside of the cryostat
- ±10 ms windows are rejected
- ε ~ 99.8%

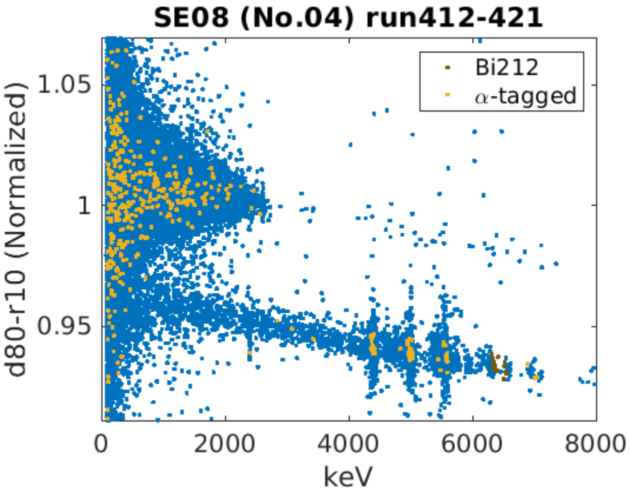
Hanbeom Kim (IBS/SNU) for 26th AMoRE Collab. Meeting
Aug. 16 – 18, 2023

Particle identification: coincidence events - 2

α-tagging of internal Tl-208 background





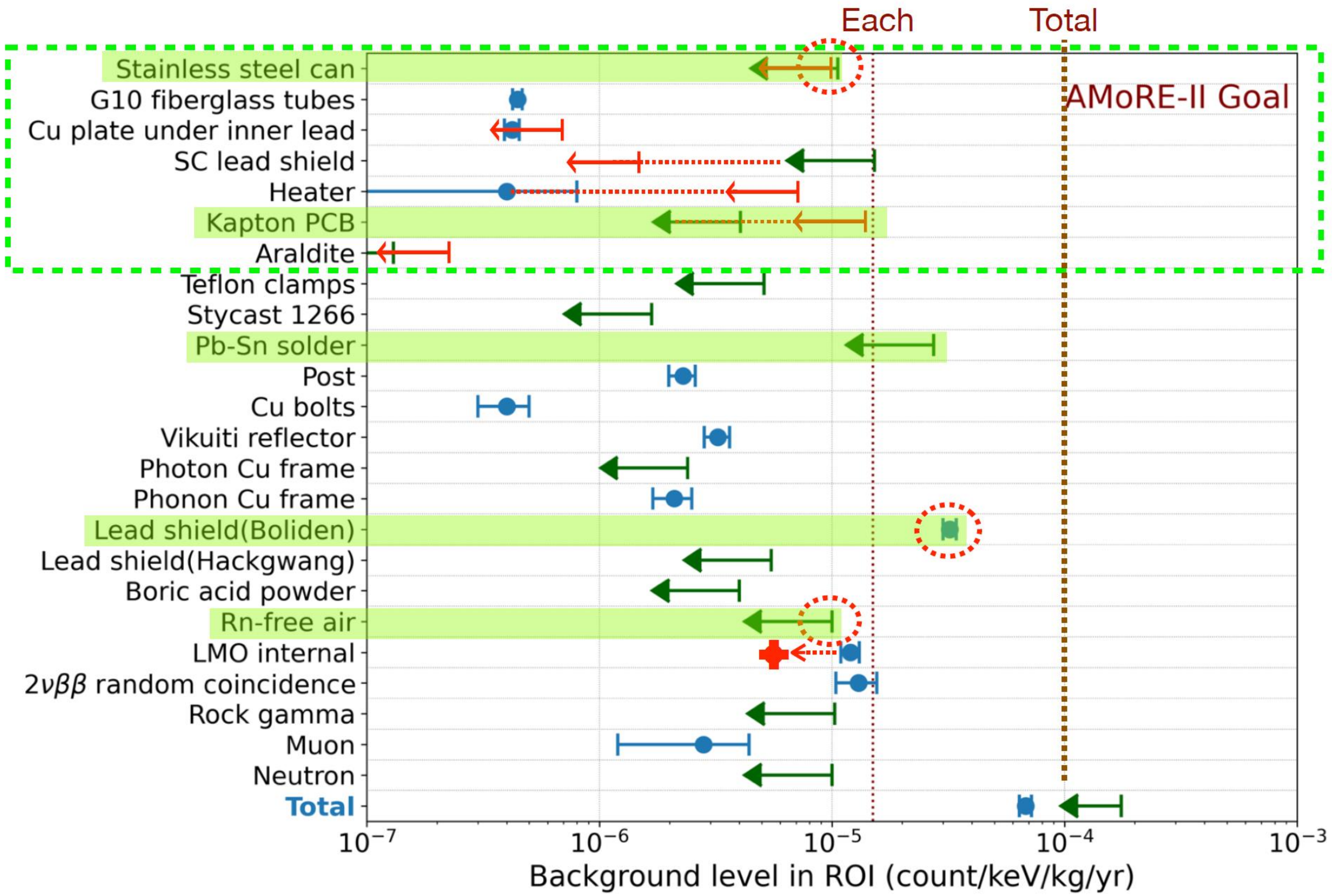


Hanbeom Kim (IBS/SNU) for 26th AMoRE Collab. Meeting
Aug. 16 – 18, 2023

^{212}Bi alpha can be used for α-tagging of internal ^{208}Tl background

- ^{212}Bi → ^{208}Tl (α 35.94%): $T_{1/2}$ =60.55 min, 6207.26 keV
- ^{208}Tl → ^{208}Pb (β): $T_{1/2}$ =3.053 min, Q ~ 5 MeV
- Events within 20 min window *(> 3.053 min x 5)* after each ^{212}Bi candidates are rejected
- ε ~ 98% (> 99% for many crystals, ~82% for the worst case (SB29))

AMoRE-II backgrounds estimation

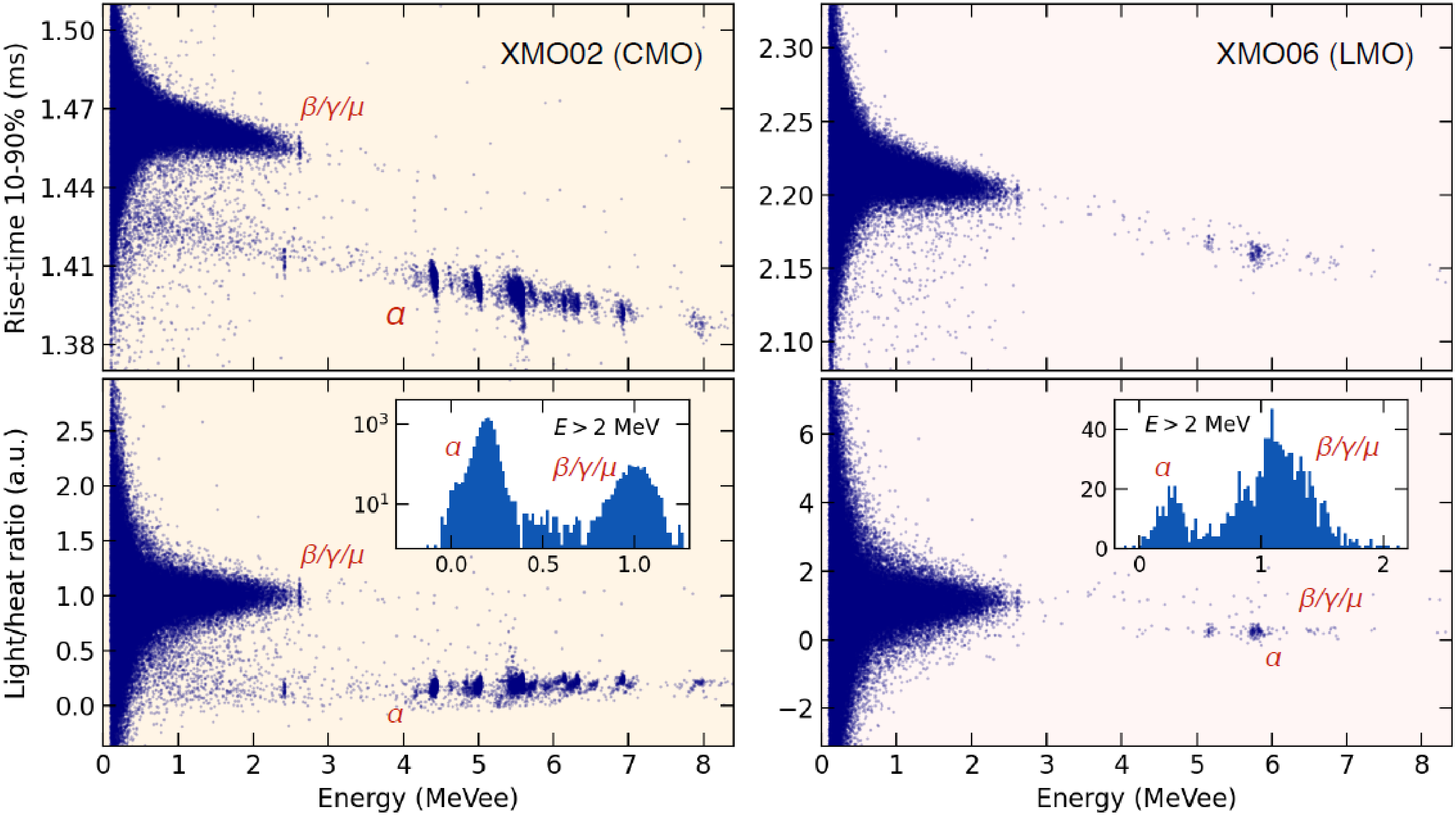


Newly updated with AMoRE-II simulation

Eunju Jeon, CUP/IBS

AMoRE Collab. Meeting @IBS HQ, 16-18 August 2023

Particle identification: Alpha rejection (two signals: phonon and light)



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

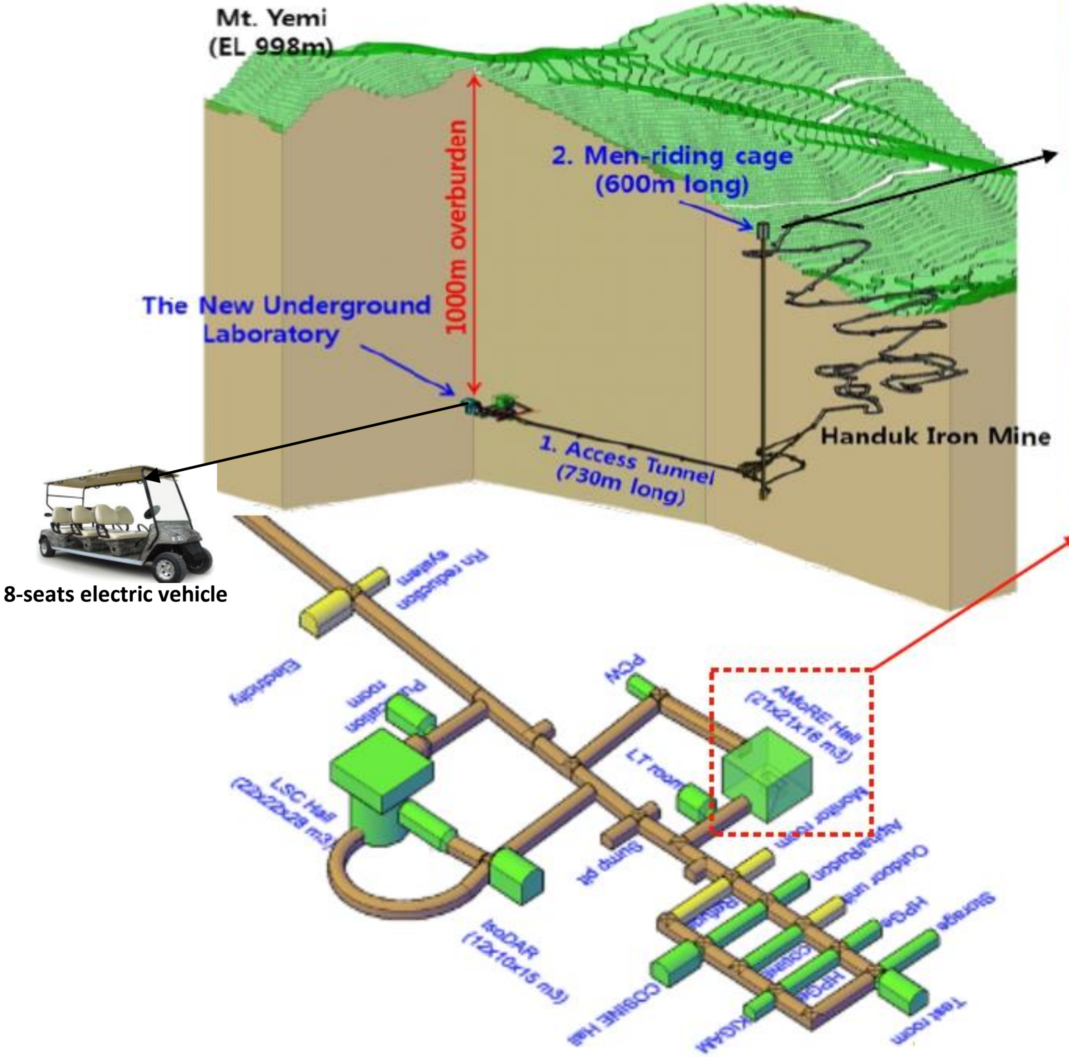
$$DP \equiv \frac{|\mu_{\beta/\gamma} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

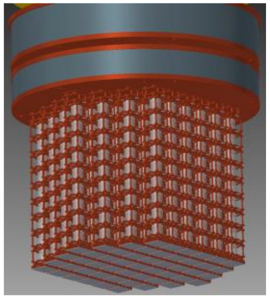
YangYang and Yemi (Handuk iron mine) underground laboratories

Bird view of Handeok Iron Mine

Handeok has two shafts for mining
1st shaft ~300 m long
2nd shaft 600 m long (NEW)

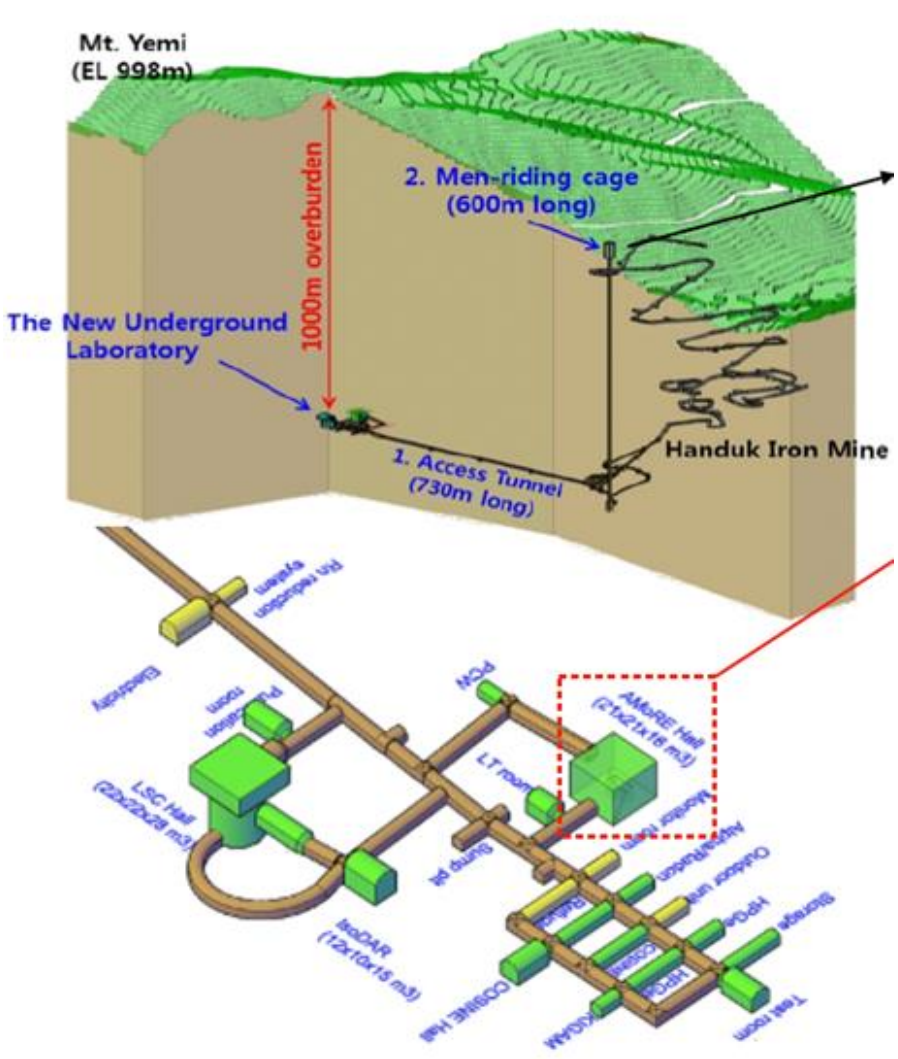
New Underground Laboratory Yemilab to host AMoRE-II

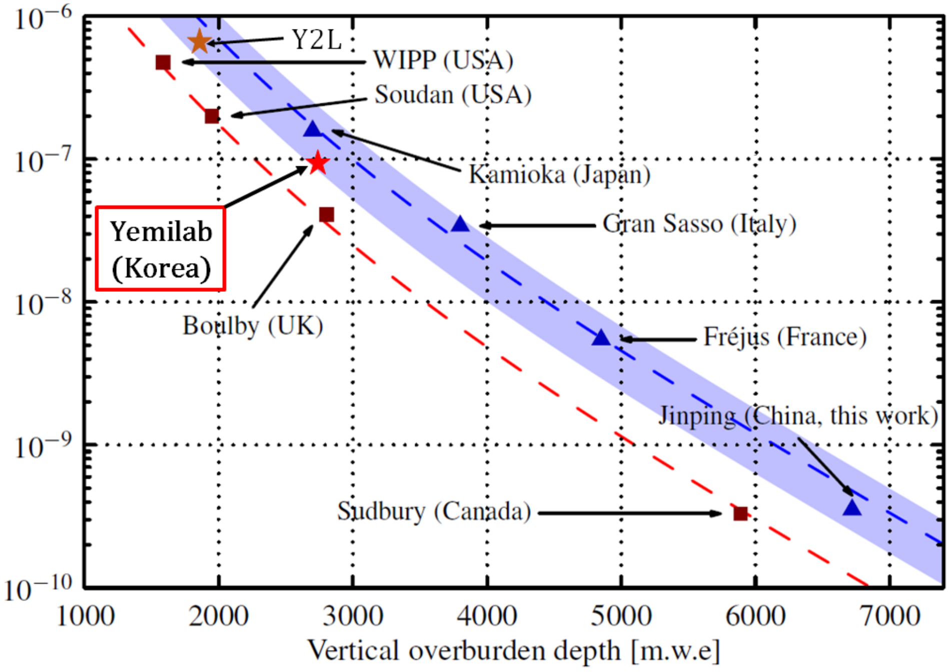




The constructions have been done
(2017.09 – 2022.07)
2,500 m^2 of experiment dedicated area
1,000 m of rock underground
Since Sept 2022, the Yemilab is in operation

New Underground Laboratory Yemilab to host AMoRE-II

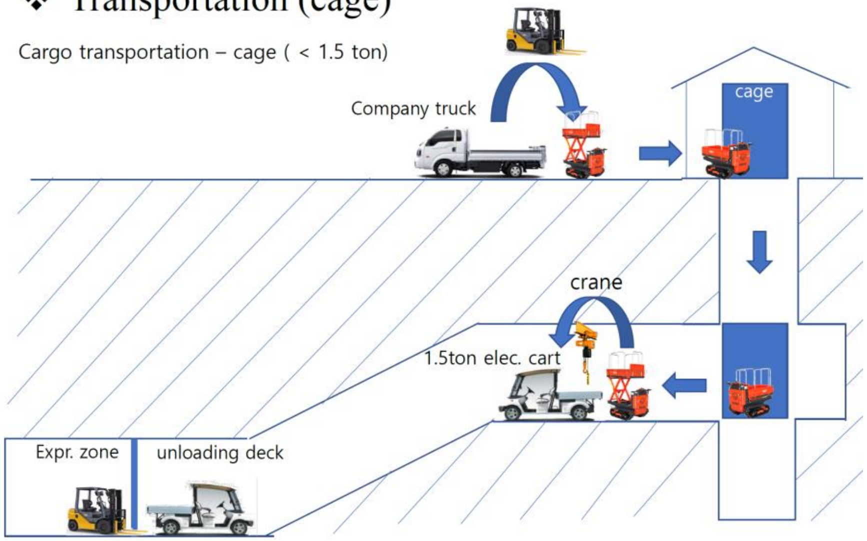




Transportation to Yemi lab/ AMoRE-II: cage and rampway

❖ Transportation (cage)

Cargo transportation – cage (< 1.5 ton)



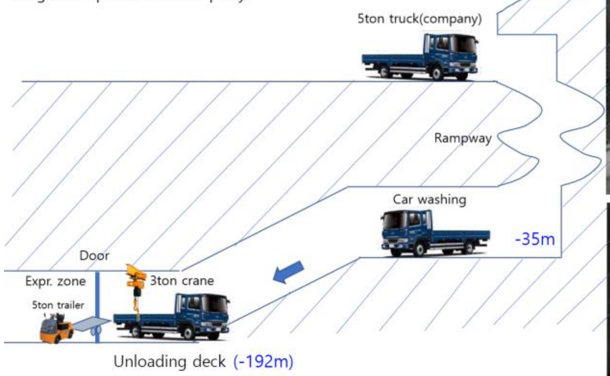
- ➢ All transportation vehicle will be ready by Oct.

K.S. Park
on behalf of operation team

26th AMoRE collaboration meeting, 16-18, Aug. 2023

❖ Transportation (rampway)

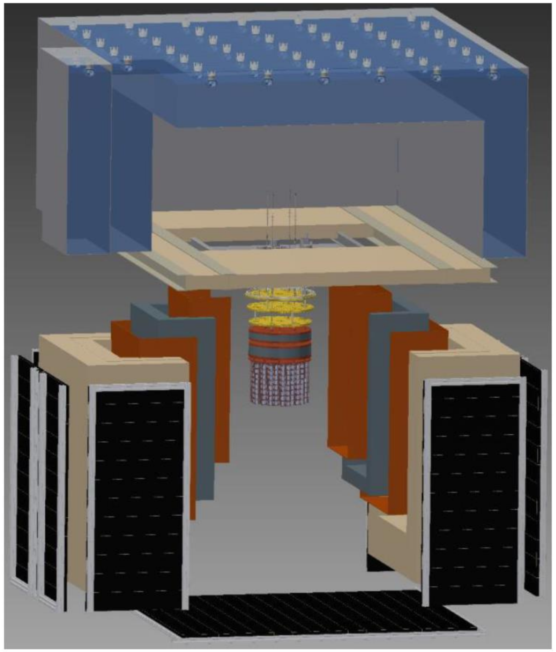
Cargo transportation – rampway

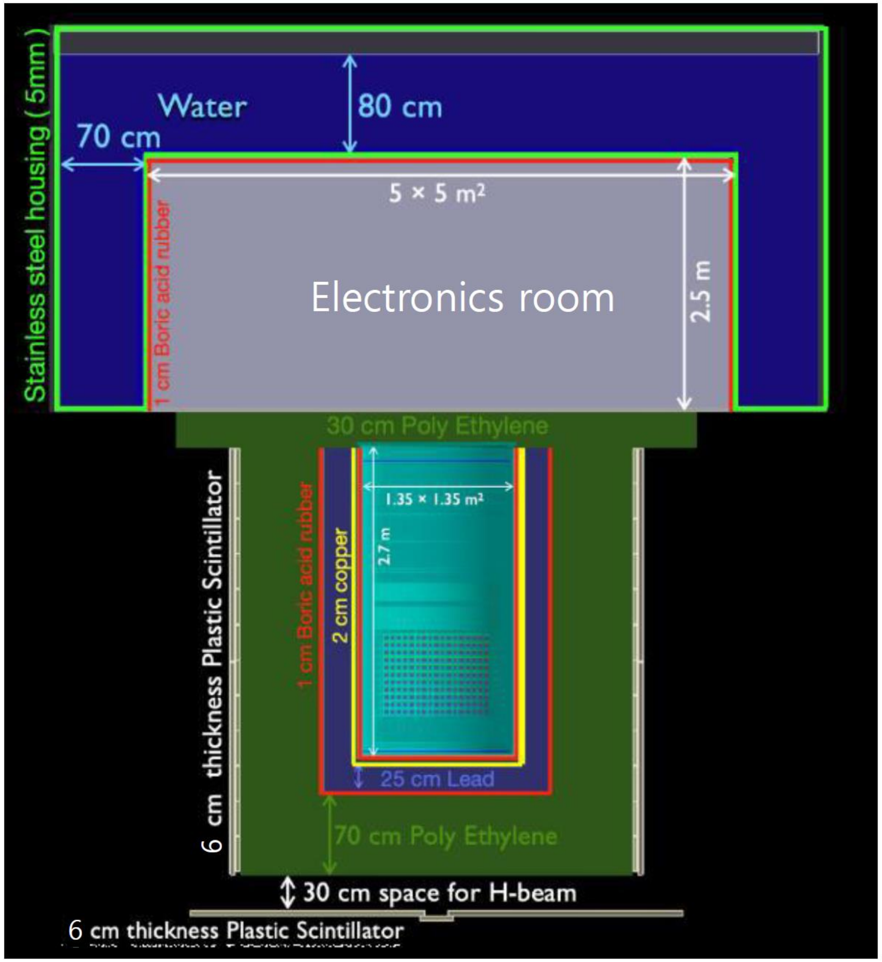


- ➢ The crane and trailer will be ready by Oct.

Car washing system (-35m)

AMoRE-II shielding system



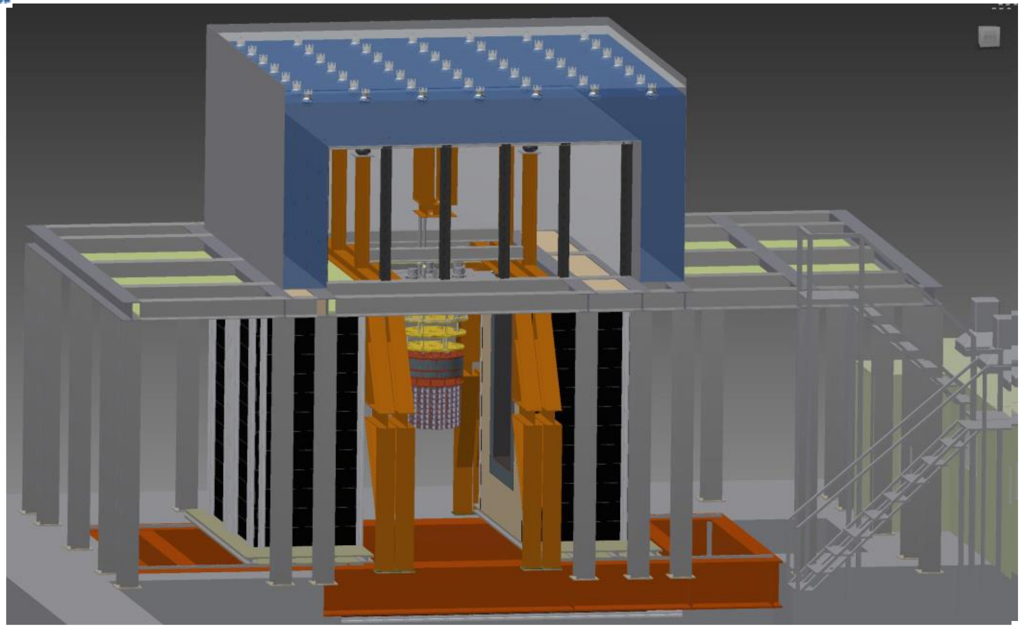


[inner] 1cm Boric acid rubber → 2cm Copper → 25cm Lead → 1cm Boric acid rubber → polyethylene [outer]

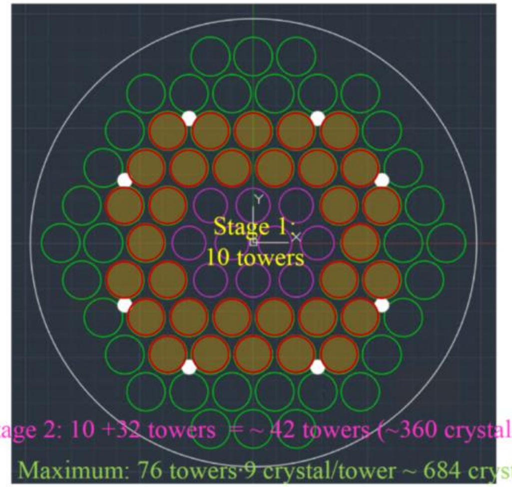
26th AMoRE Collaboration meeting (23.08.17)

G.W.Kim

AMoRE-II detector: main components



Towers arrangement

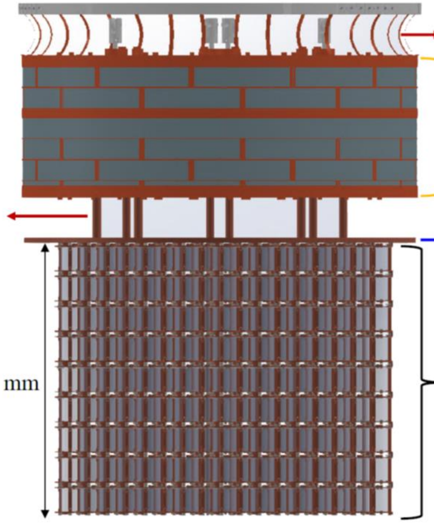


Stage 2: 10 +32 towers = ~ 42 towers (~360 crystals)

Maximum: 76 towers·9 crystal/tower ~ 684 crystals

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

Cold components



MC Plate: 8~10 mK w. 1st PID

Soft thermal contact with annealed copper tapes

Cold Pb-Cu Shield

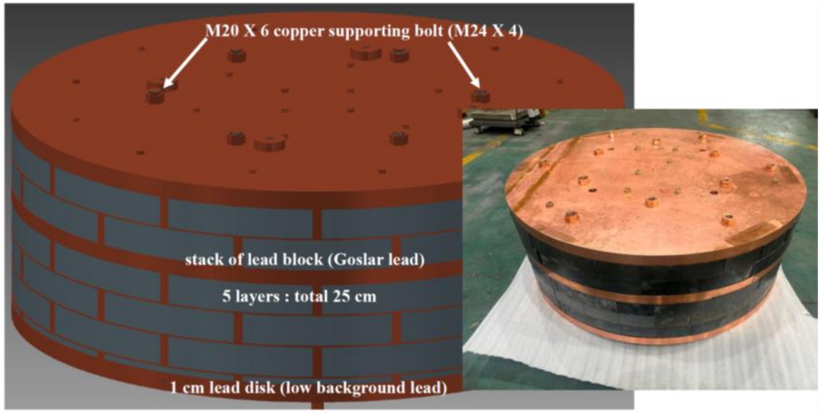
Hard thermal contact with copper rods

Detector Plate: 12~15 mK w. 2nd PID

673 mm

AMORE-II detector tower

Internal lead shield



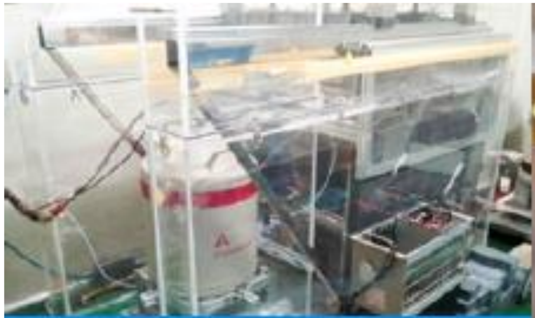
copper plates and parts : done

Staking of lead bricks : ready

1 cm thick disk with low-activity lead: being produced

Plan to finish in Sep/2023

Radioactivity measurement for AMoRE-II


HPGe (CC1)


HPGe (CC2)


HPGe (14 ch array)


ICP-MS (Agilent 7900)


α ionization counter (XIA)

Production of ^{100}Mo и ^{48depl}Ca

Production of ^{100}Mo: 120 kg (for CUP IBS) + 8,25 kg (for JSC “Fomos Materials”):

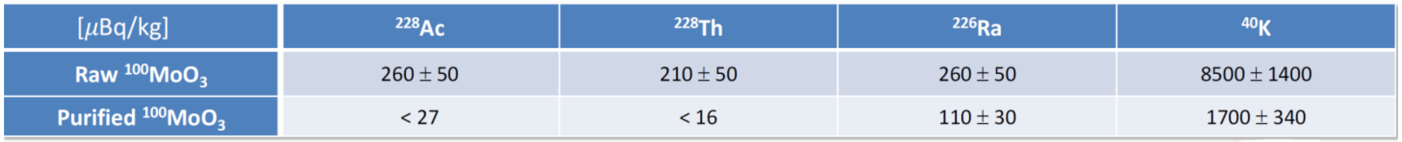
JSC «The Electrochemical Plant» (ECP), Zelenogorsk, Russia (https://www.ecp.ru/eng/)

In form of $^{100}MoO_3$ powder:

- Enrichment on ^{100}Mo: ~ 95%
- Radiopurity (ECP):

ICP-MS at CUP	U: ~ 0.2 ppb	Th: ~ 0,05ppb
HPGe at BNO INR RAS	^{226}Ra: $\leq$ 8 mBq/kg	^{228}Ac: $\leq$ 3.5 mBq/kg

ECP (BNO)
CUP



[μBq/kg]	^{228}Ac	^{228}Th	^{226}Ra	^{40}K
Raw $^{100}MoO_3$	260 ± 50	210 ± 50	260 ± 50	8500 ± 1400
Purified $^{100}MoO_3$	< 27	< 16	110 ± 30	1700 ± 340

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

Calcium carbonate enriched on ^{40}Ca and depleted on ^{48}Ca: 4,5 kg (for JSC “Fomos Materials”)

Elektrohhimpribor (EKP), Lesnoy, Russia (http://www.ehp-atom.ru/)

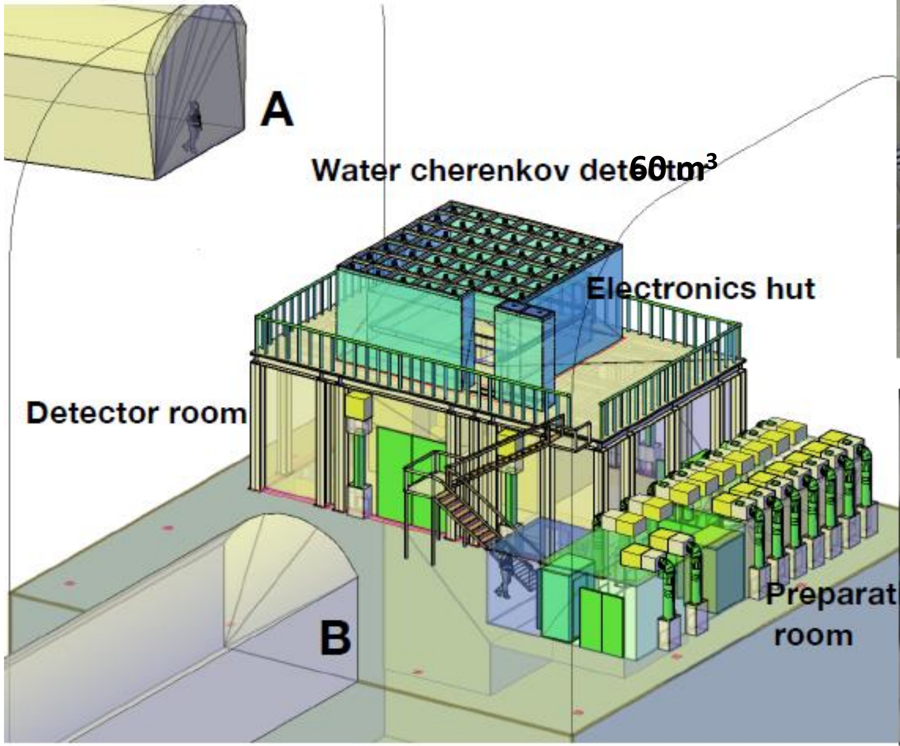
In form of $^{40}CaCO_3$ powder:

depletion on ^{48}Ca < 0,001%

- ✓ Radiopurity: U ≤ 0.1 ppb, Th ≤ 0,1 ppb, Sr= 1 ppm, Ba = 1 ppm,
- ✓ ^{226}Ra = 5 mBq/kg (NEOKHIM 1.4 mBq/kg), ^{228}Ac (^{228}Th) = 1 mBq/kg

AMoRE Hall in Yemilab (October 2022)

AMoRE Hall in Yemilab

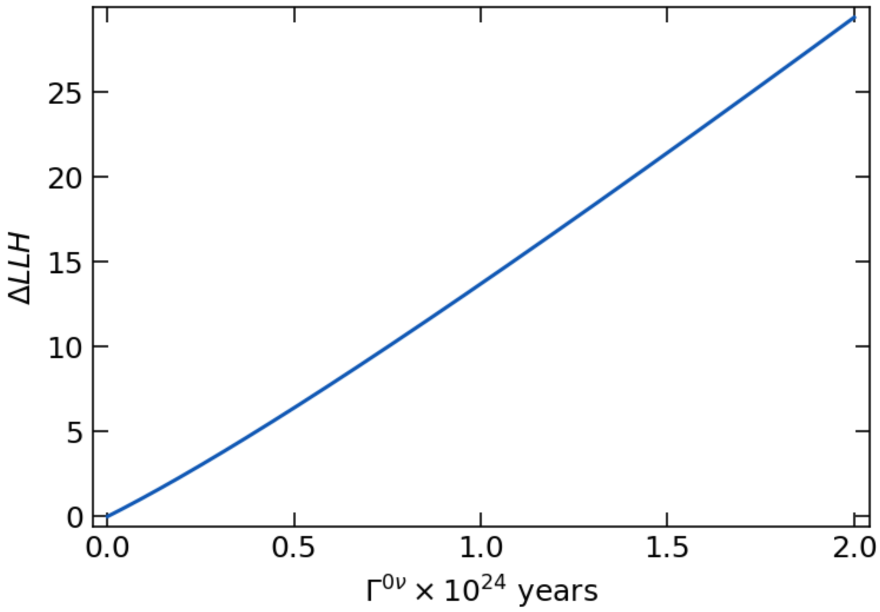


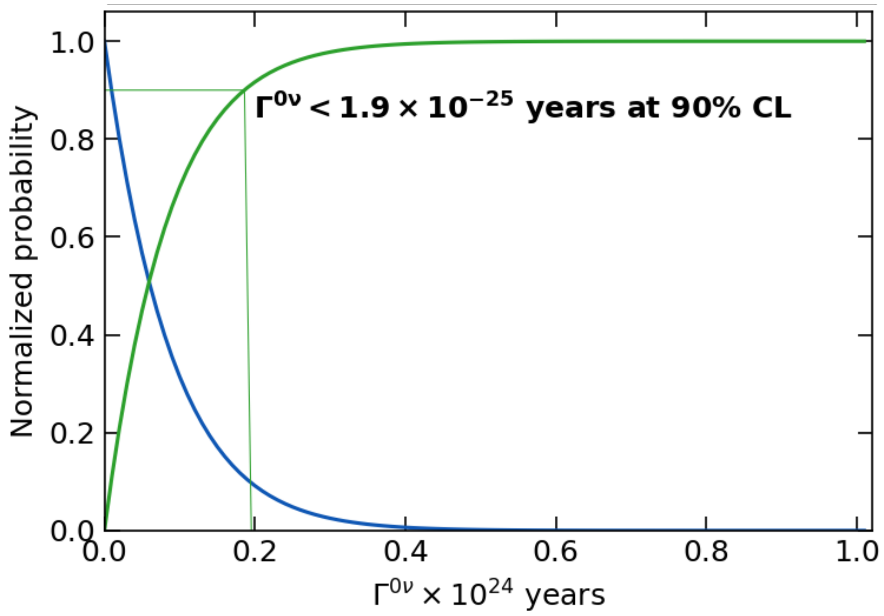
Radon reduction system
Clean room
(detector preparation in class 100)


Detector preparation room with Rn-free air supply


Current view from B

^{100}Mo 0νββ limit from AMoRE-I





- ROI to contain most (> 99%) of the 0νββ signal peak, ε ~ 81%
- ^{100}Mo effective exposure: 3.11 kg ▪ yr
- Background = 0.037 +/- 0.001 counts/keV/kg/year, from ROI side band.
- Bayesian method (marginalization of nuisance parameters): combining the result of shape analysis at ROI, with a flat & exponential background constraint from the side band events for each crystal.

$T_{1/2}^{0\nu}$ > 3.7×10^{24} years at 90% C.L. (Current best limit: 1.8×10^{24} of CUPID Mo)