Initial Performance test of AMoRE-II Muon Detector

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On behalf of

AMoRE collaboration

DARK SIDE OF THE UNIVERSE

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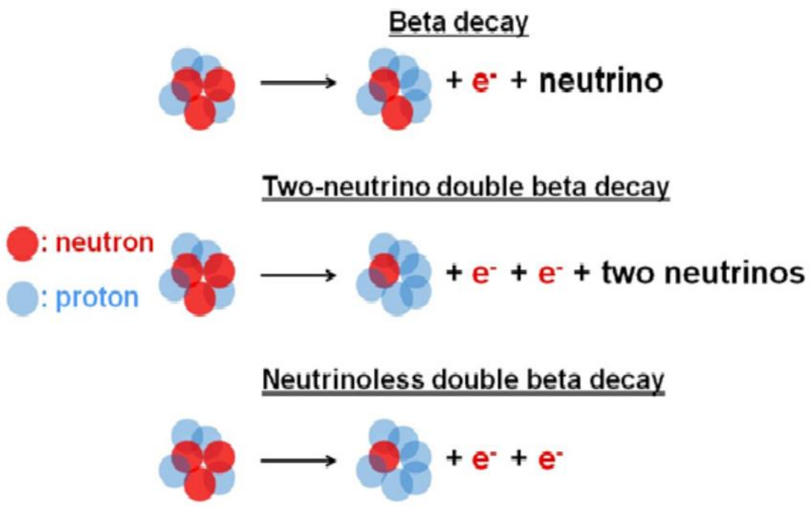
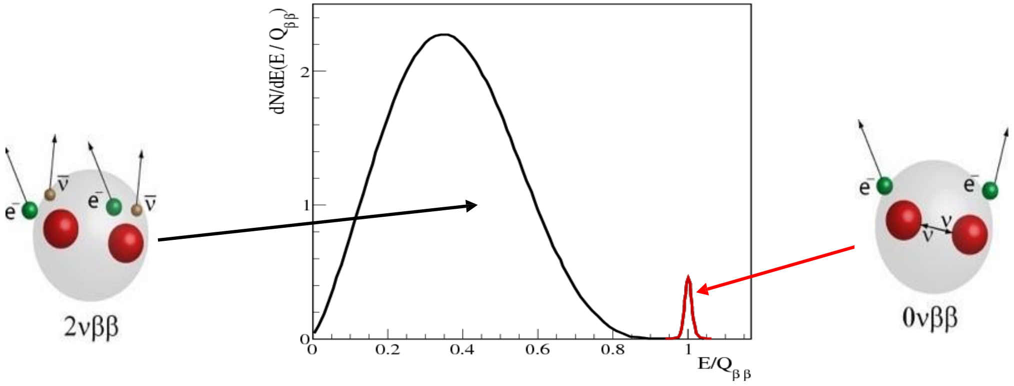
ICTP-EAIFR, Kigali, Rwanda

AMoRE (Advanced Molybdenum-based Rare process Experiment)

Goal: Search for neutrinoless double beta decay (0νββ) of Molybdenum (^{100}Mo) based scintillating crystals and low-temperature sensors.





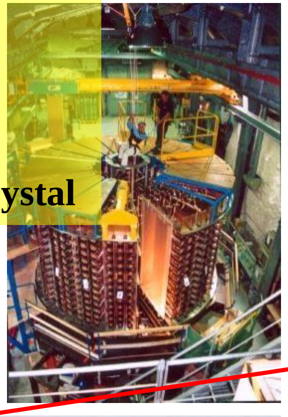
2νββ decay
- 2^{nd} order beta decay
- Rare nuclear decay
- $10^{18} < 10^{22}$ years of half life

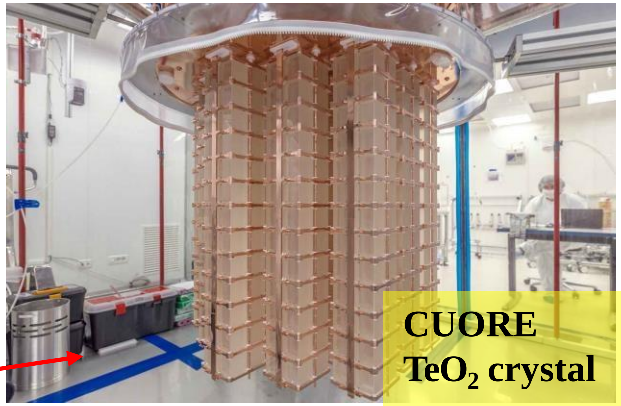
0νββ decay
- Lepton number violation
- Majorana particle
- Beyond the Standard Model
- $>10^{25}$ years of half-life

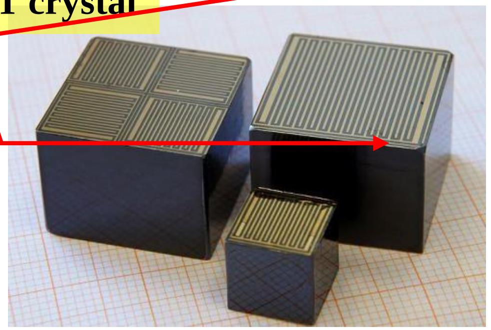
Other 0νββ Experiments

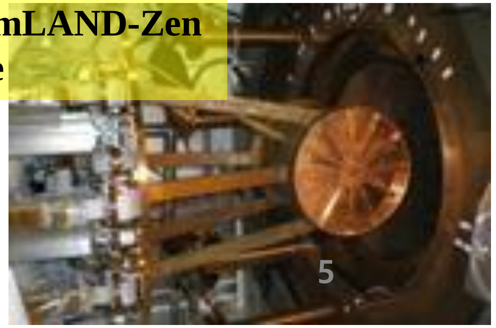
Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

【Current CANDLES detector】





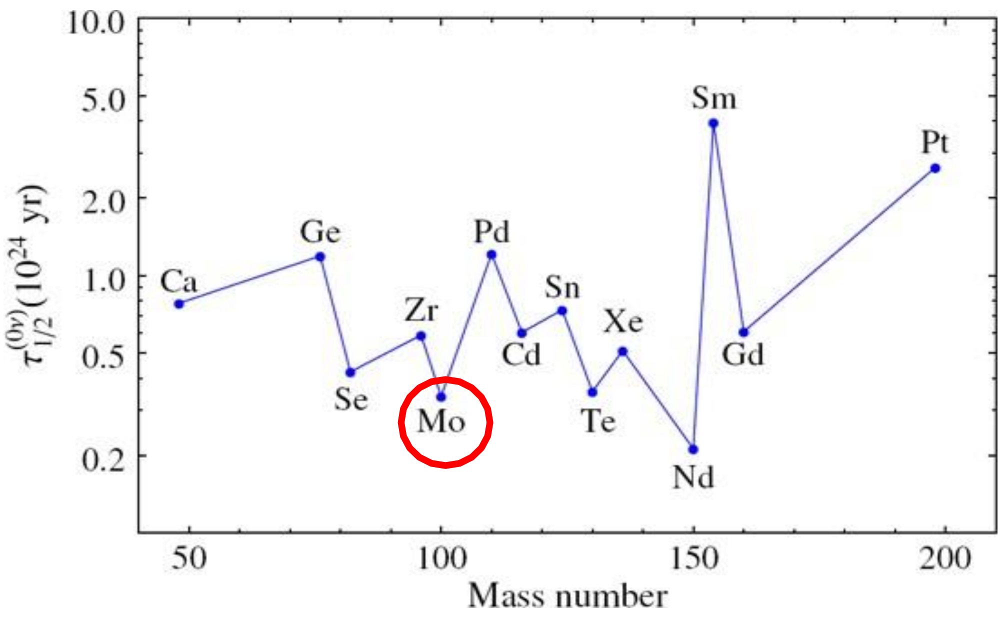




Why ^{100}Mo for AMoRE (0νββ)

- High Q-value (ββ) of 3.034MeV

  (^{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)

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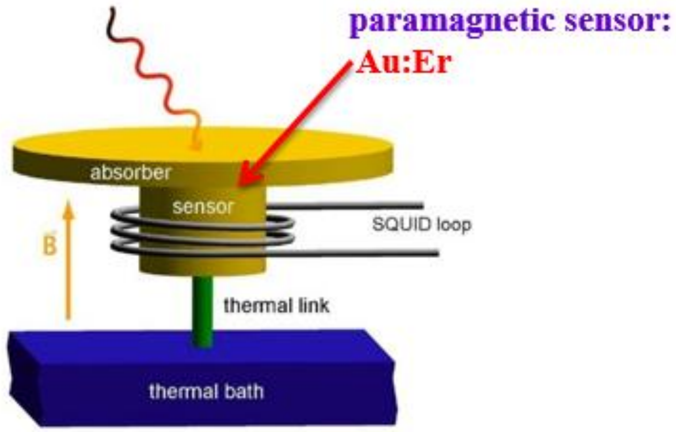
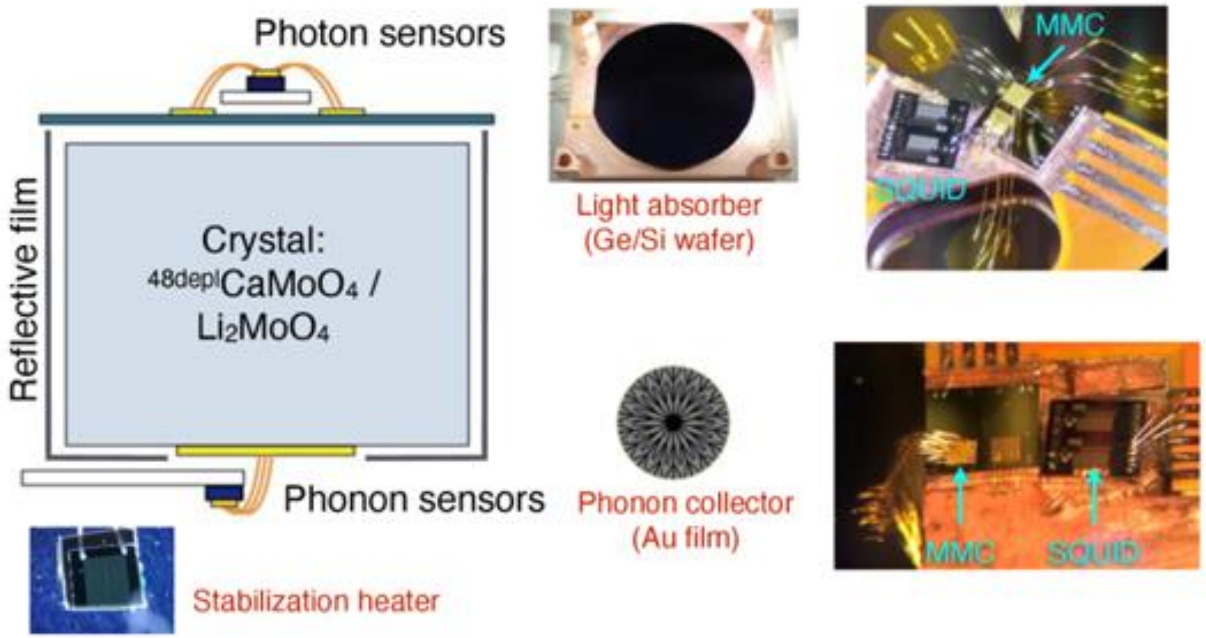
Crystal and Detector module for AMoRE-II





Principle of operation:

- Energy absorption (LMO crystal)
- Photon and phonon generation
- Temperature increase in gold film
- Decrease in magnetization in MMC
- SQUID pick up the changes

- Cylindrical crystal (Li_2MoO_4) size $\Phi \lesssim$ 5-6 cm/H $\lesssim$ 5cm
- Metallic Magnetic Calorimeter (MMC) + SQUID
- Phonon-Scintillation detection at mill Kelvin

AMoRE Collaboration

AMoRE Experimental Approach

- **Sizable background case:**

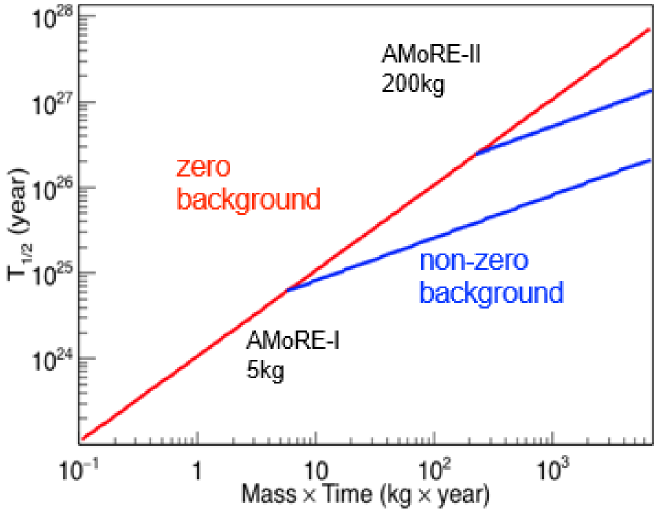
Isotopic Abundance, Detection Efficiency, Detector Mass, Measurement time, Energy Resolution, Background rate, Atomic mass, Sensitivity to half-life of $0\nu\beta\beta$

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

- **"Zero" background case:**

When b is ~ O(1),

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

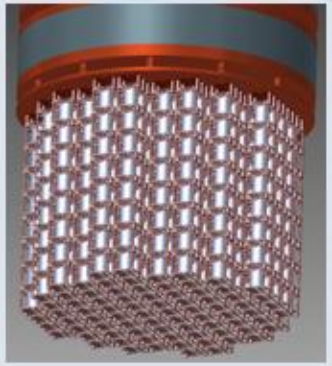


$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

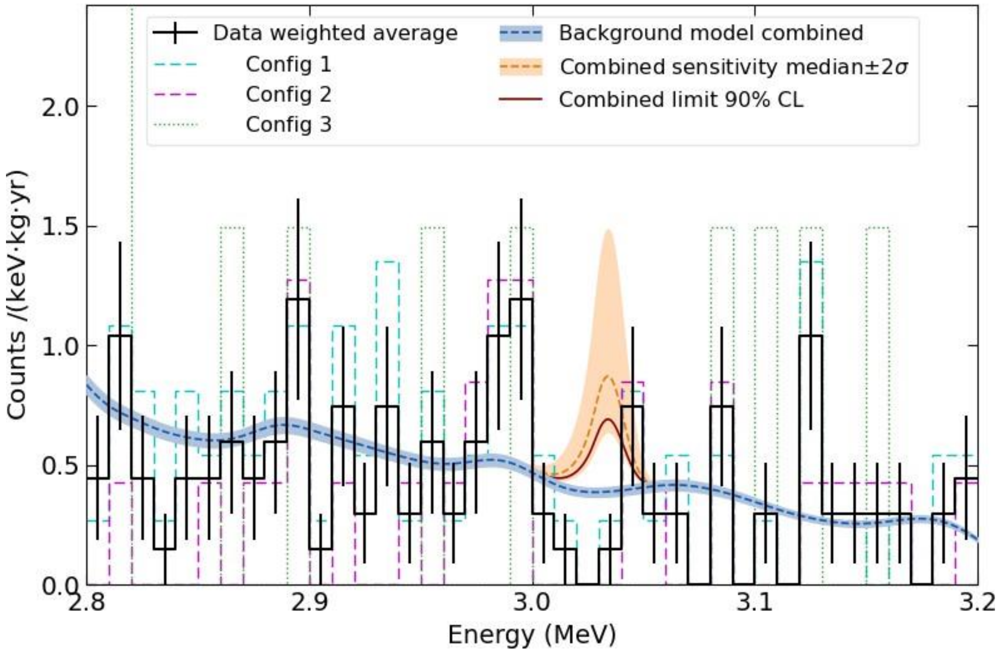
Half-life Measured; Phase factor; Nuclear Matrix Element; Effective $0\nu\beta\beta$ Neutrino Mass

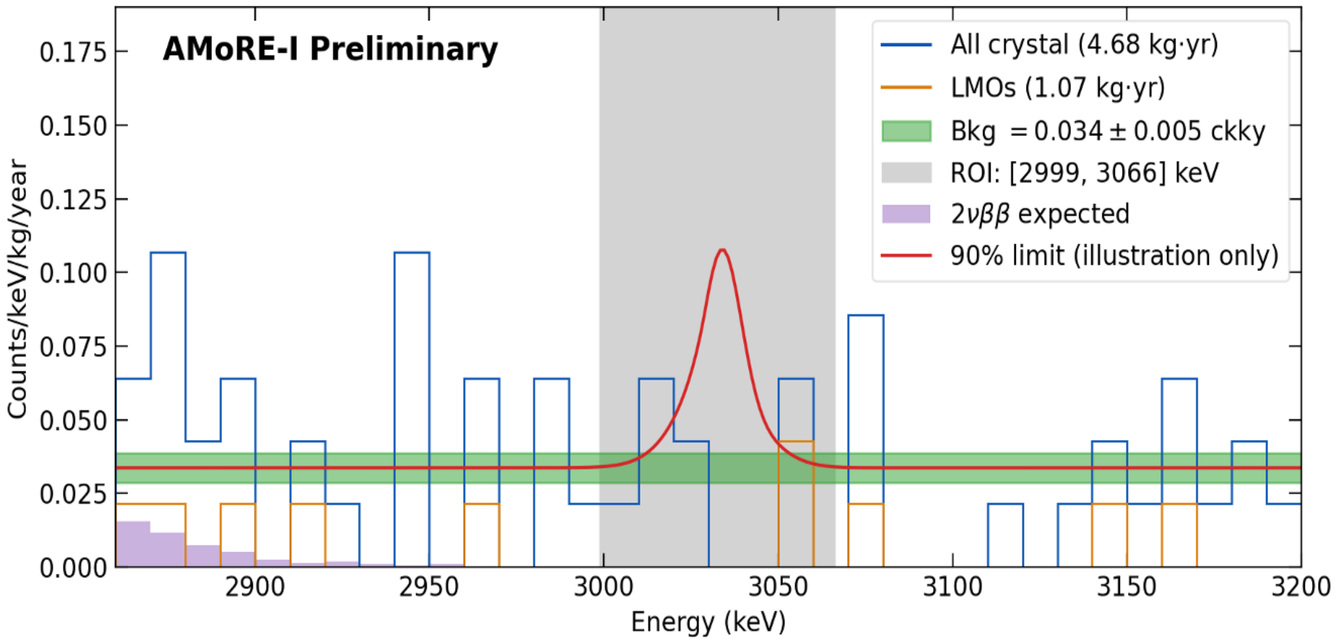
AMoRE is aiming for zero background.

AMoRE Phases

Phases	AMoRE-Pilot	AMoRE-I	AMoRE-II
Detector Setup (Not in scale)			
Crystals	$^{40}Ca^{100}MoO_4$ (CMO)	$(^{40}Ca,Li_2)^{100}MoO_4$	$Li_2{}^{100}MoO_4$ (LMO)
Crystal # & Mass	6, 1.9kg	18, 6.2kg	596, 178kg
Backgrounds (ckky)	$\sim 10^{-1}$	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$\sim 3.0\text{x}10^{23}$	$\sim 4.0\text{x}10^{24}$	$\sim 4.5\text{x}10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	170-320	17-31
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2022	Yemilab / 2024-2029

Results from AMoRE-pilot and AMoRE-I

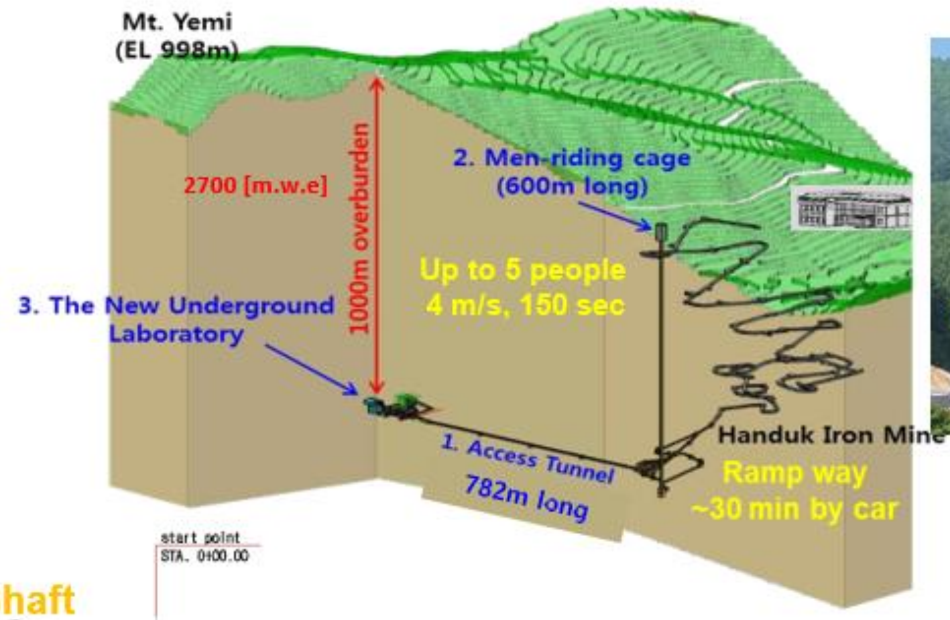


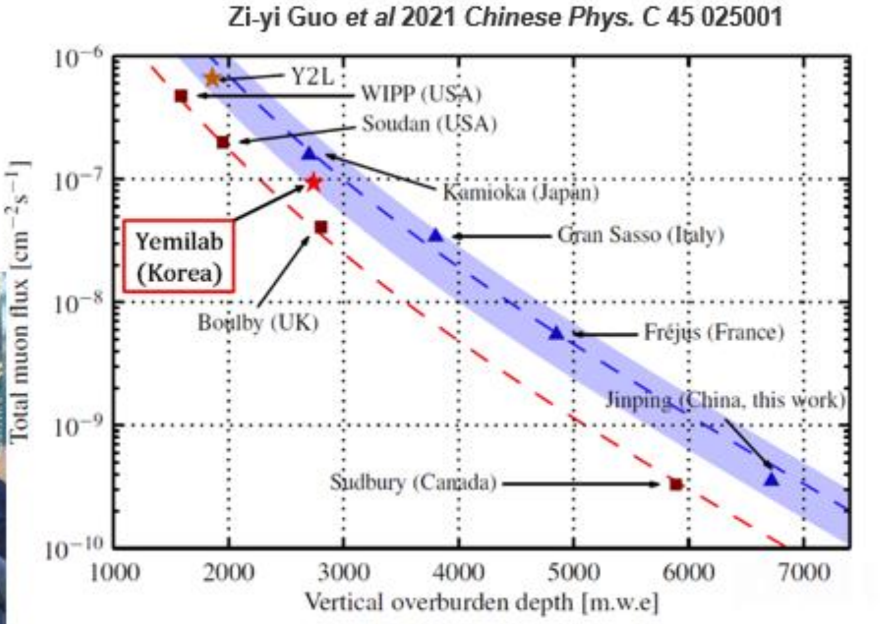


- Understanding background components and reduction of them
- Background level ≈ 0.5 ckky at 2.8 – 3.2 MeV (neutron-induced γ, crstal internal contamination, rock/air-radon γ)

- Increased number of crystals
- More shielding enhancement
- More muon counters
- Supply of Radon free air
- Background level ≈ 0.03 ckky

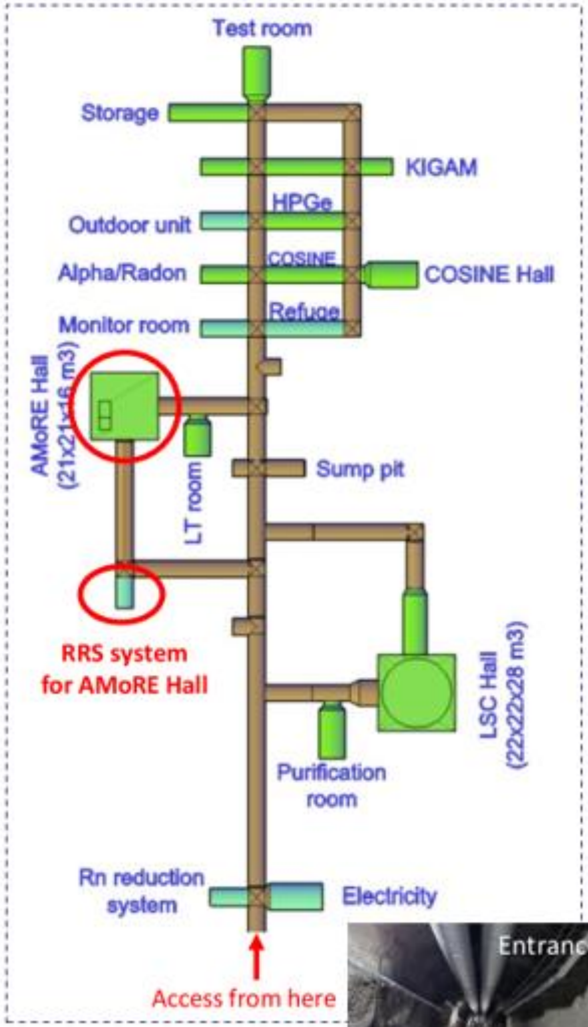
Yemilab (new underground laboratory)





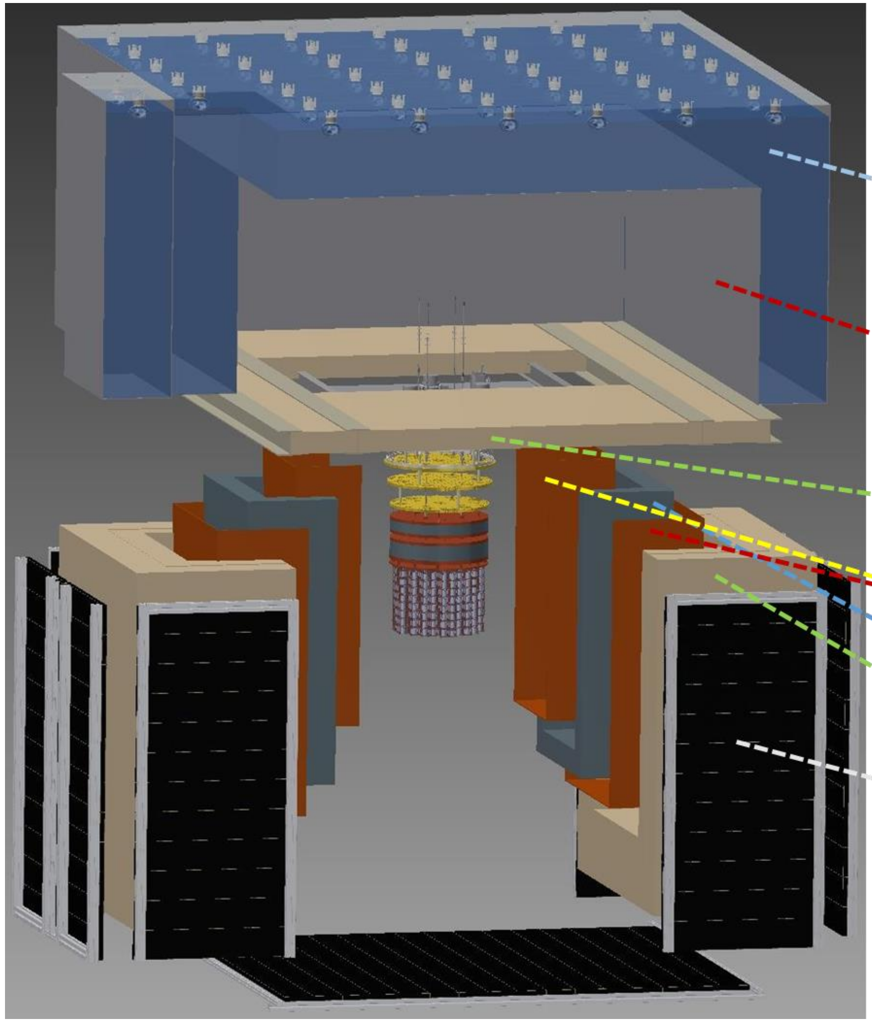
Yemilab

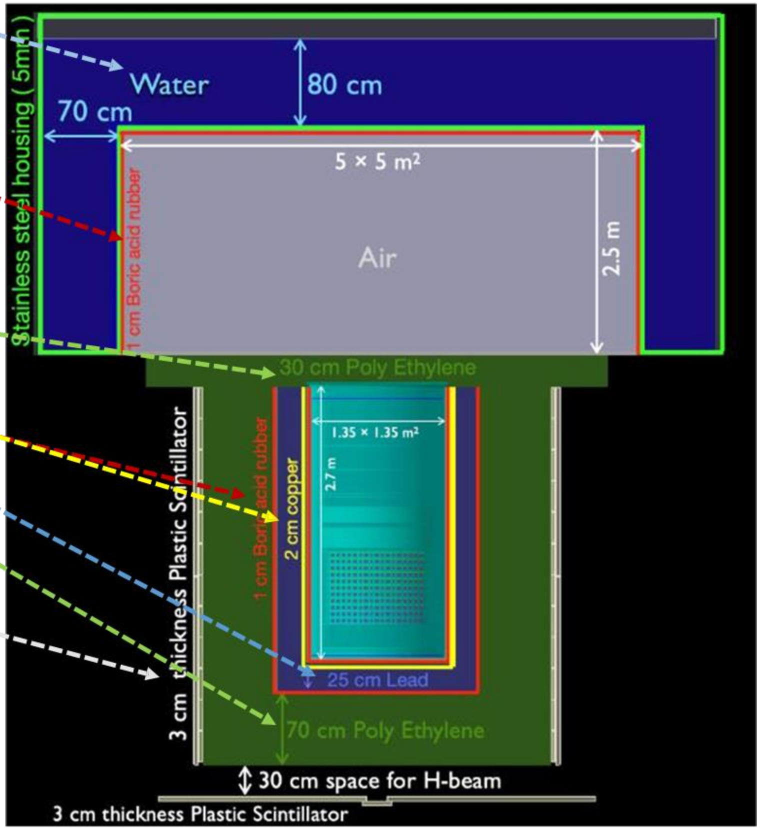
[Yemilab drawing]



Transportation
Electric car for
6 people

AMoRE-II shielding system





From outside:

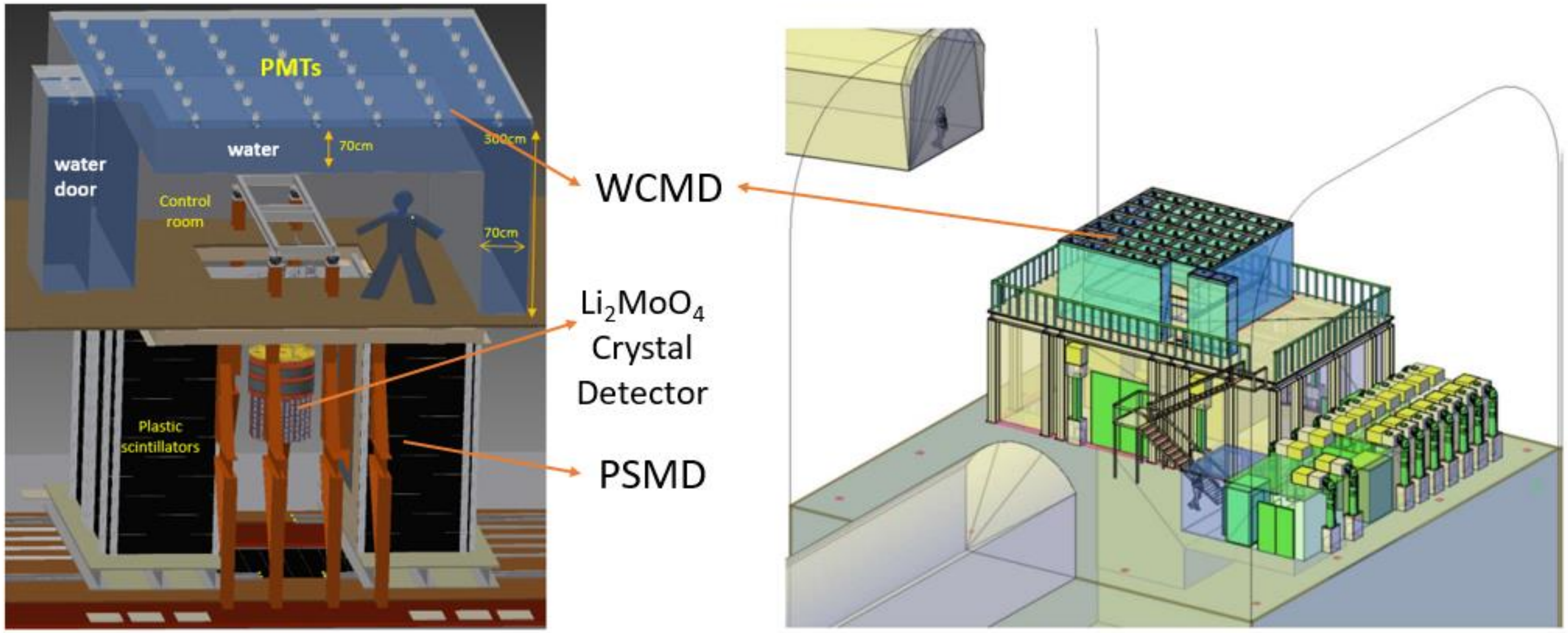
- Muon veto
- 70 cm high density Polyethylene (HDPE)
- 25cm Lead
- 1 cm Boric acid rubber

Muon Detectors

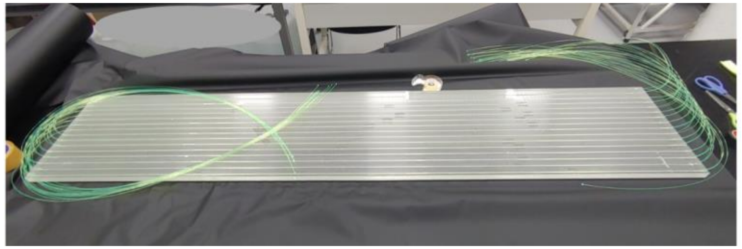
- Plastic Scintillator Muon Detector (PSMD)
- Water Cherenkov Muon Detector (WCMD)

PSMD: 2 extruded plastic Scintillator panels + 32 WLS fibers + 4 SiPM

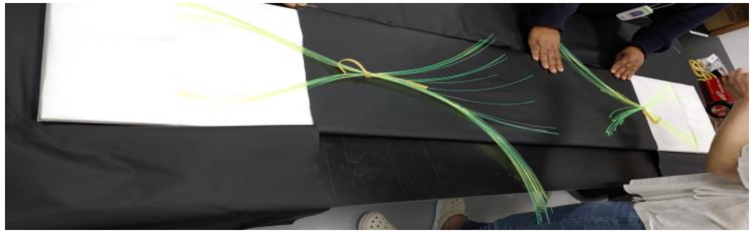
WCMD: Steel water tank (aligned with reflector-Tyvek) + DI water + 48PMTs



PSMD Construction

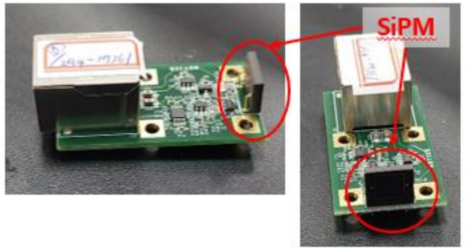


PS panel (167 x 30 x 1.5 cm) with 2 optical fibers per groove (16 grooves)

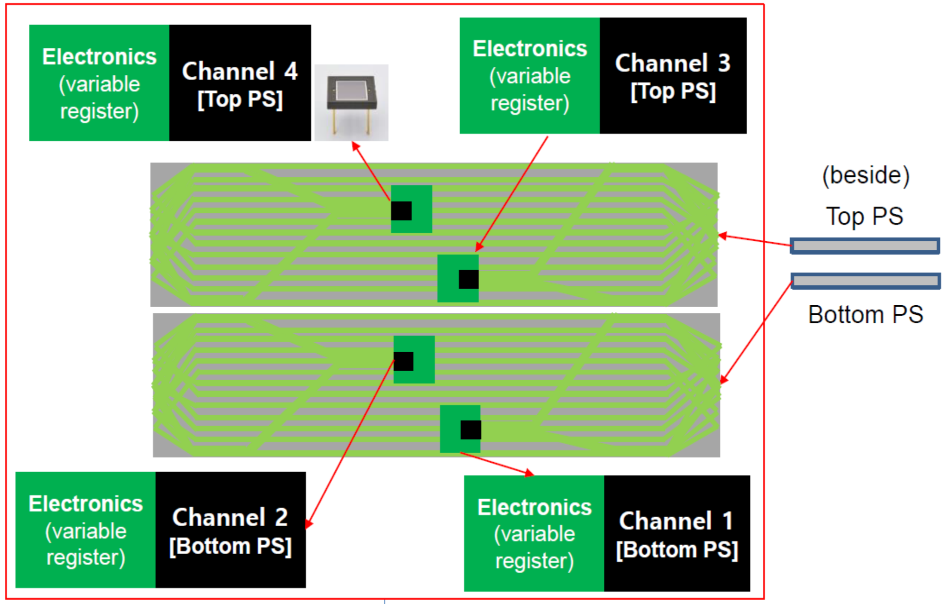


Covered with a reflector (Tyvek) and black sheet. Optical fibers are connected with 2 Sipm.

Two complete panels are mounted together with supporter in between (acrery blocks)

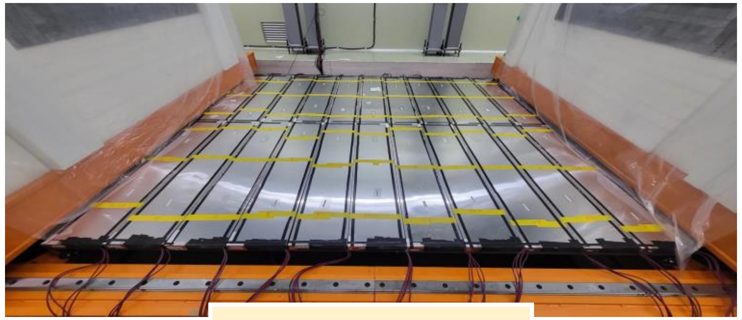


Two panels are installed in a box made of steel frame and aluminum sheets



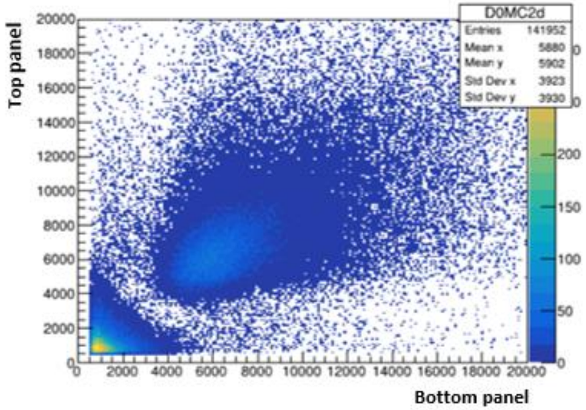
Appearance of 2 PS panels after fixing WLS fibers and SiPM

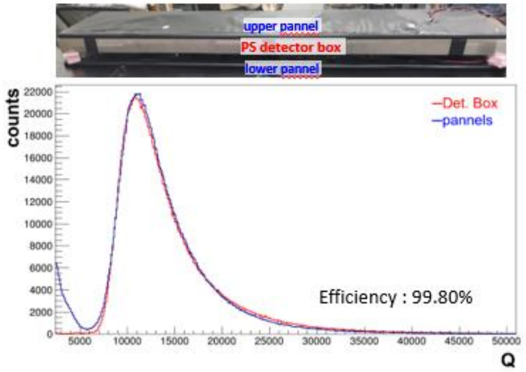
PSMD Installation and performance test



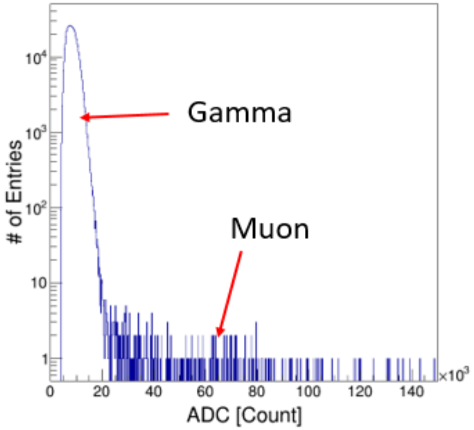
Bottom PSMD

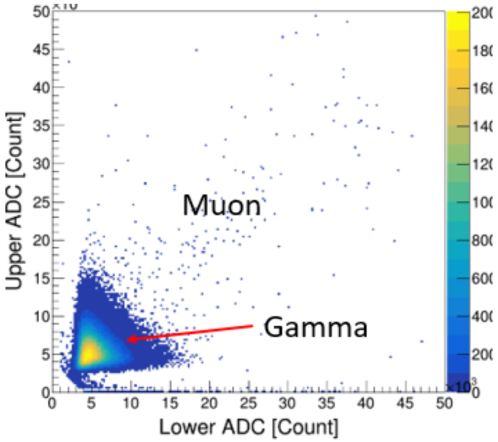
Ground

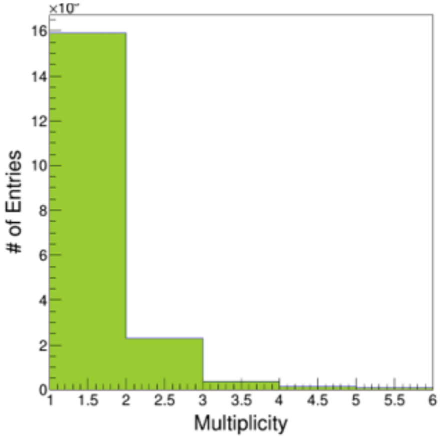




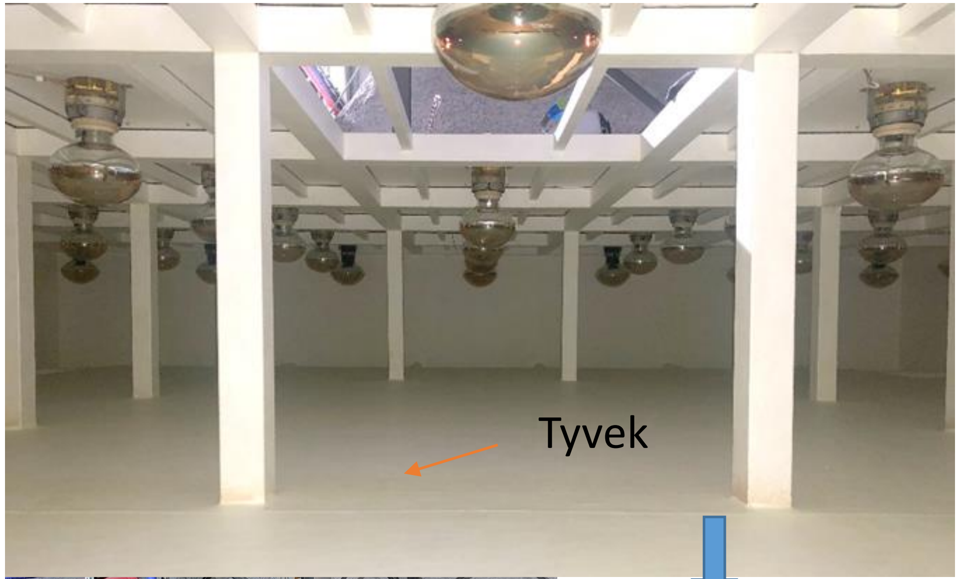
- Underground (rough estimation of muon rate ≈ 80 [$m^{-2}day^{-1}$]
- Reduced to a factor of 4 compared to Y2L)

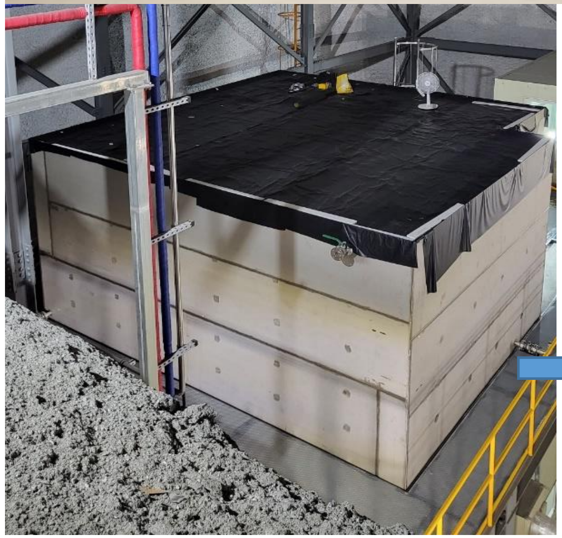






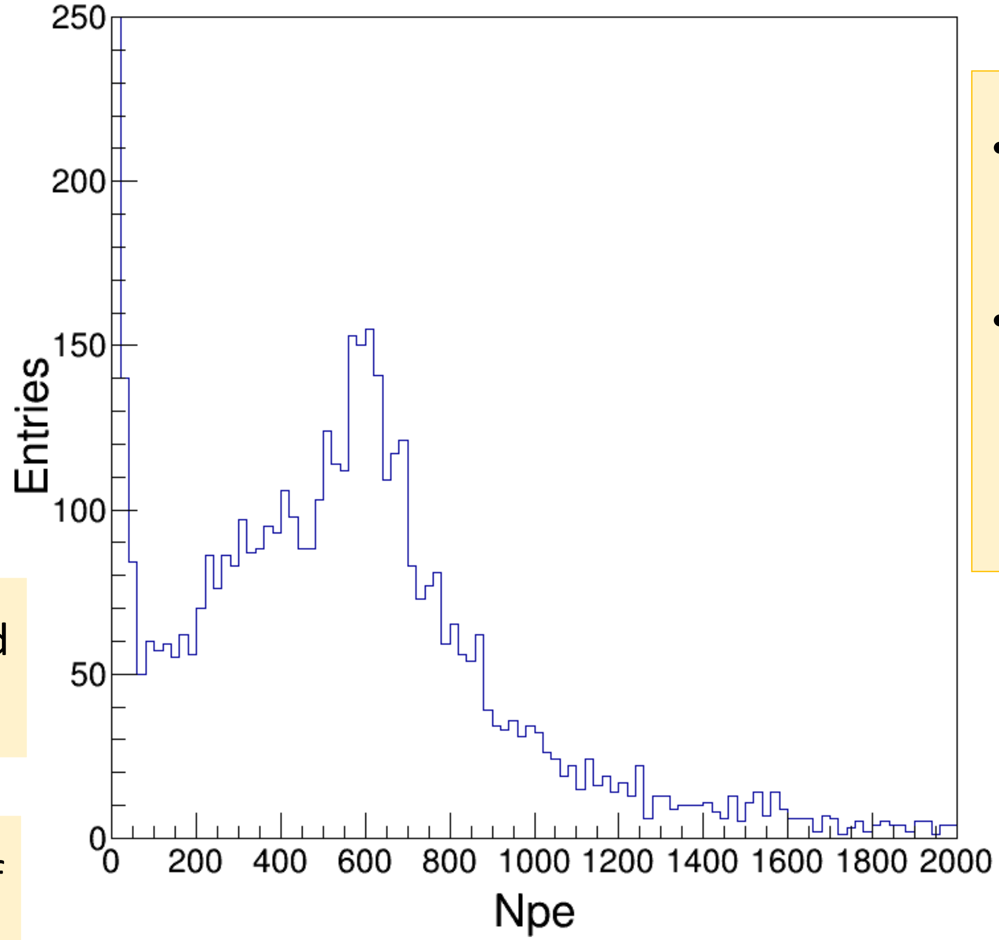
WCMD Installation and performance test





Water tank installed with 48 PMTs

filled with 60 tones of DI water



- Cherenkov light spectrum tested underground
- About 600 number of photoelectrons(npe) were counted

Summary

- AMoRE-II construction is still ongoing. The detector is expected to be installed in December 2023.
- Muon detector installation is completed and commissioning is ongoing.
- Muon flux is preliminary measured as $\sim$80 [$m^{-2}day^{-1}$].

Thank you for your attention!

Back up

More quantitatively…

for light neutrino exchange model.

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

Half-life Measured — $\left[T_{1/2}^{0\nu}\right]^{-1}$

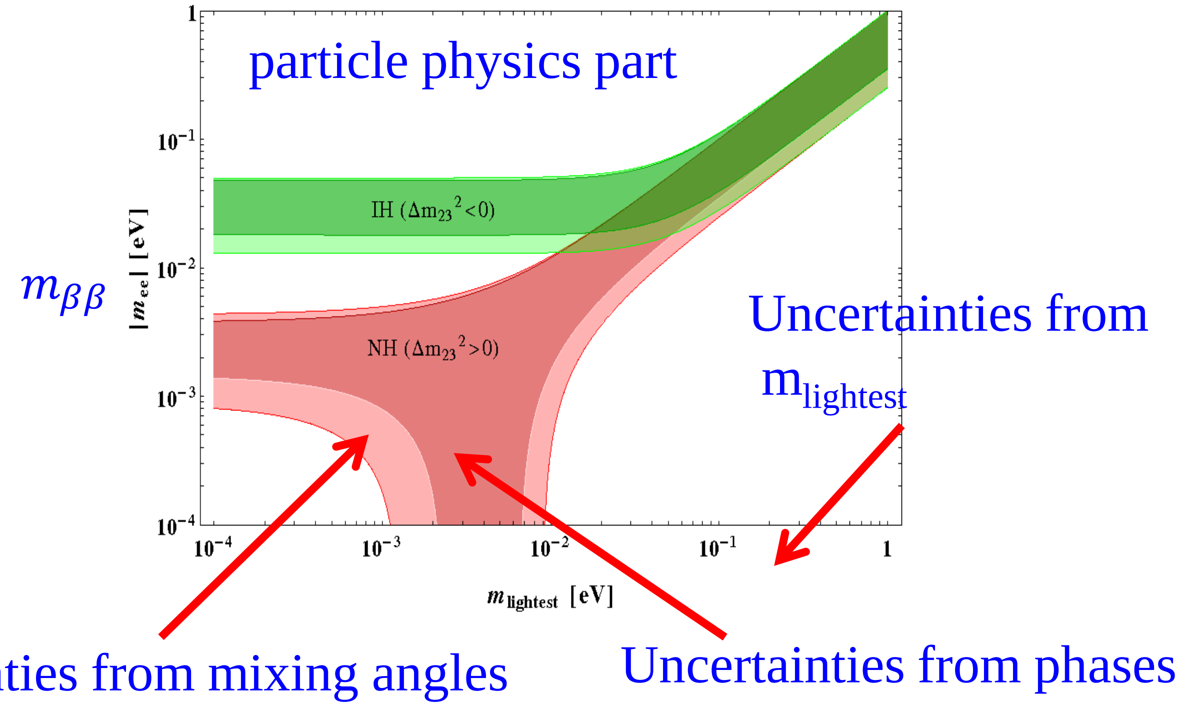
Phase factor — $G_{0\nu}$

Nuclear Matrix Element — $M_{0\nu}$

Effective 0νββ Neutrino Mass — $m_{\beta\beta}$

Effective 0νββ neutrino mass is ;

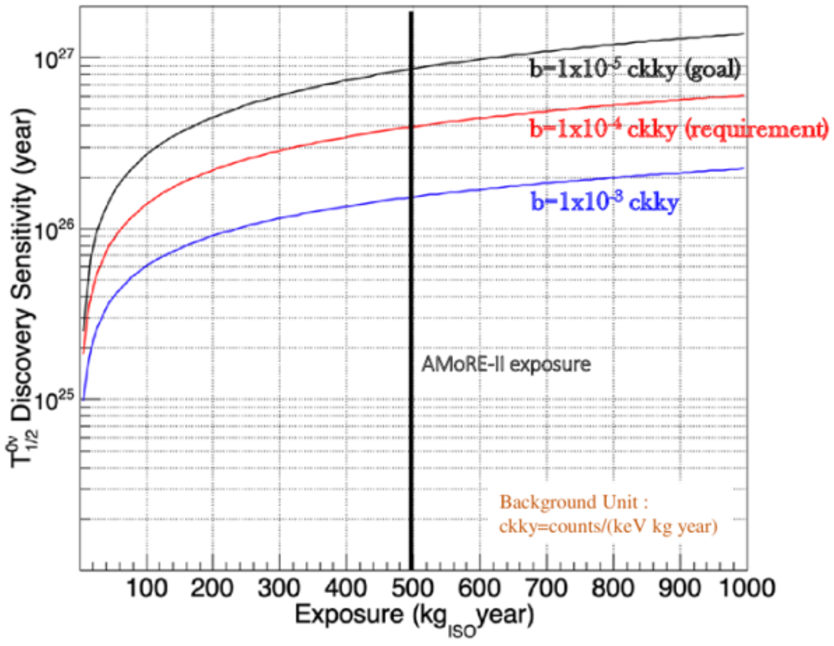
$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| = \left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$



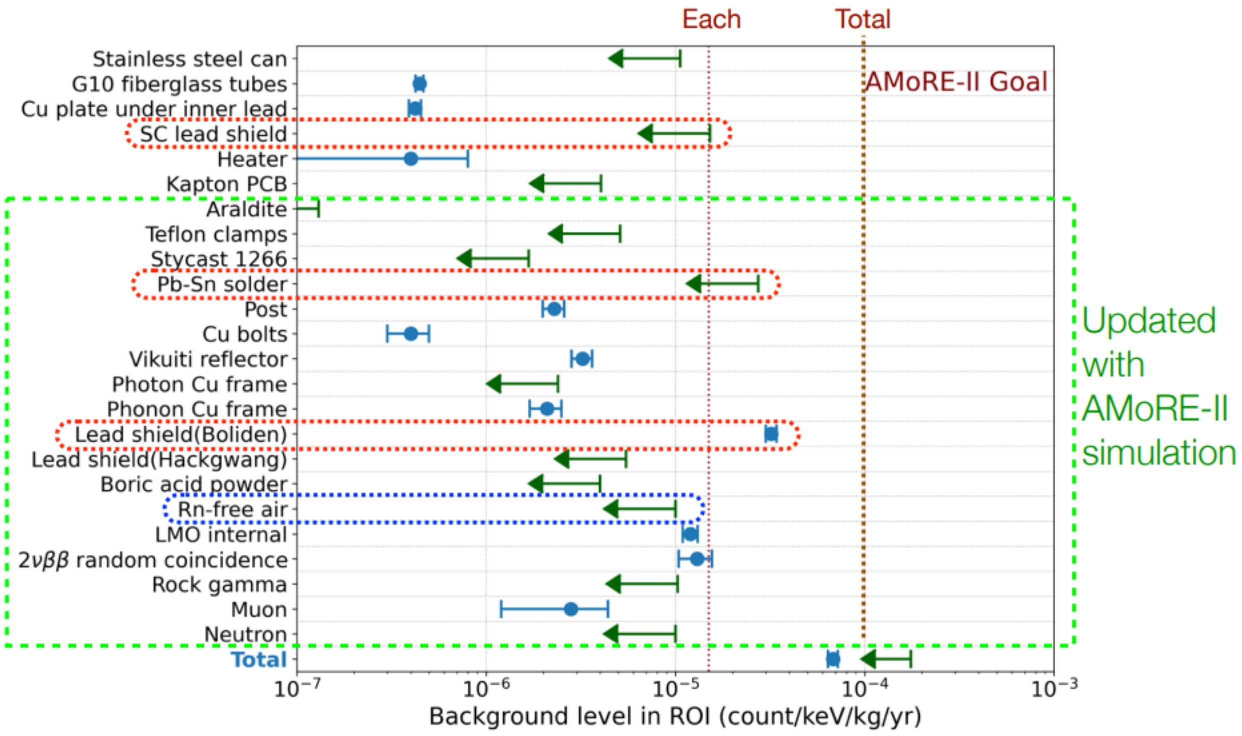
Sensitivity for AMoRE-II

- Discovery sensitivity depends on background and exposure
- AMoRE-II time schedule: 5yrs
- Background requirements: ~10^{-4} ckky

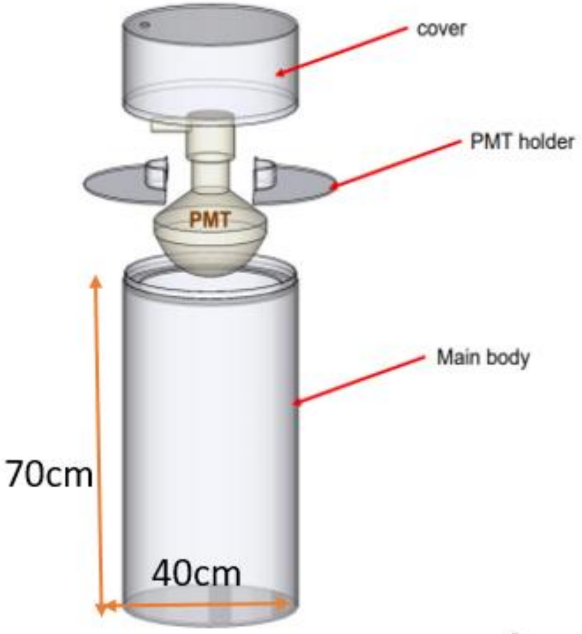
Discovery sensitivity with a significance of at least 3 sigma (99.7%).



Updated AMoRE-II backgrounds estimation



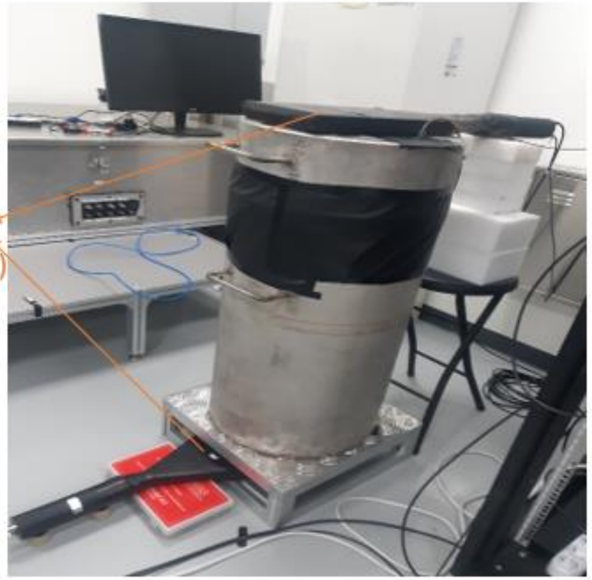
Experimental setup (R & D for WCMD)



- 5mm thick stainless steel tank.
- Inner part of the tank is covered by a reflector (Tyvek).

- 10 inch, hemispherical and water proof PMT.
- Detection wavelength range of 300nm – 650nm, max at 420nm. Quantum efficiency of 25% at 390nm.

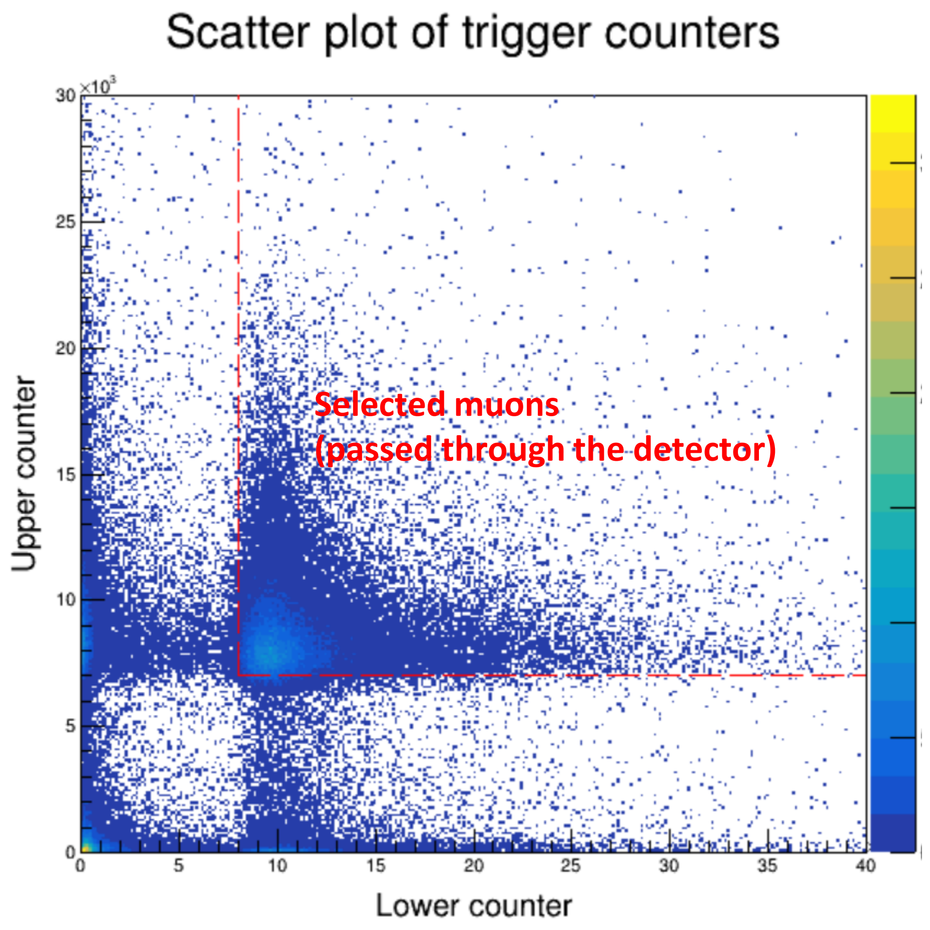
Trigger counters
(20cm x 30cm x 3cm)

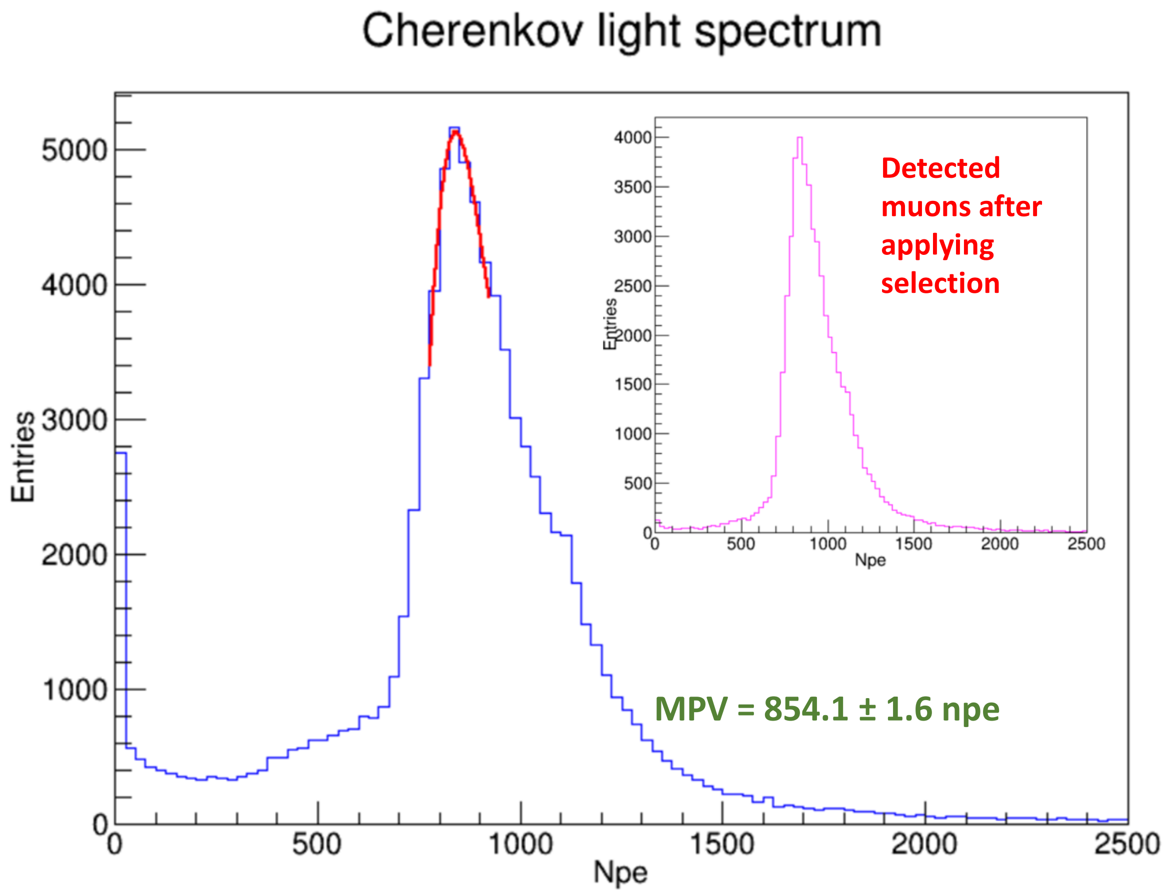


DI water filled up to 65cm high.

Using coincidence trigger condition, 100,000 events were triggered with trigger rate of 0.41Hz.

Muon detection efficiency for WCMD with DI water



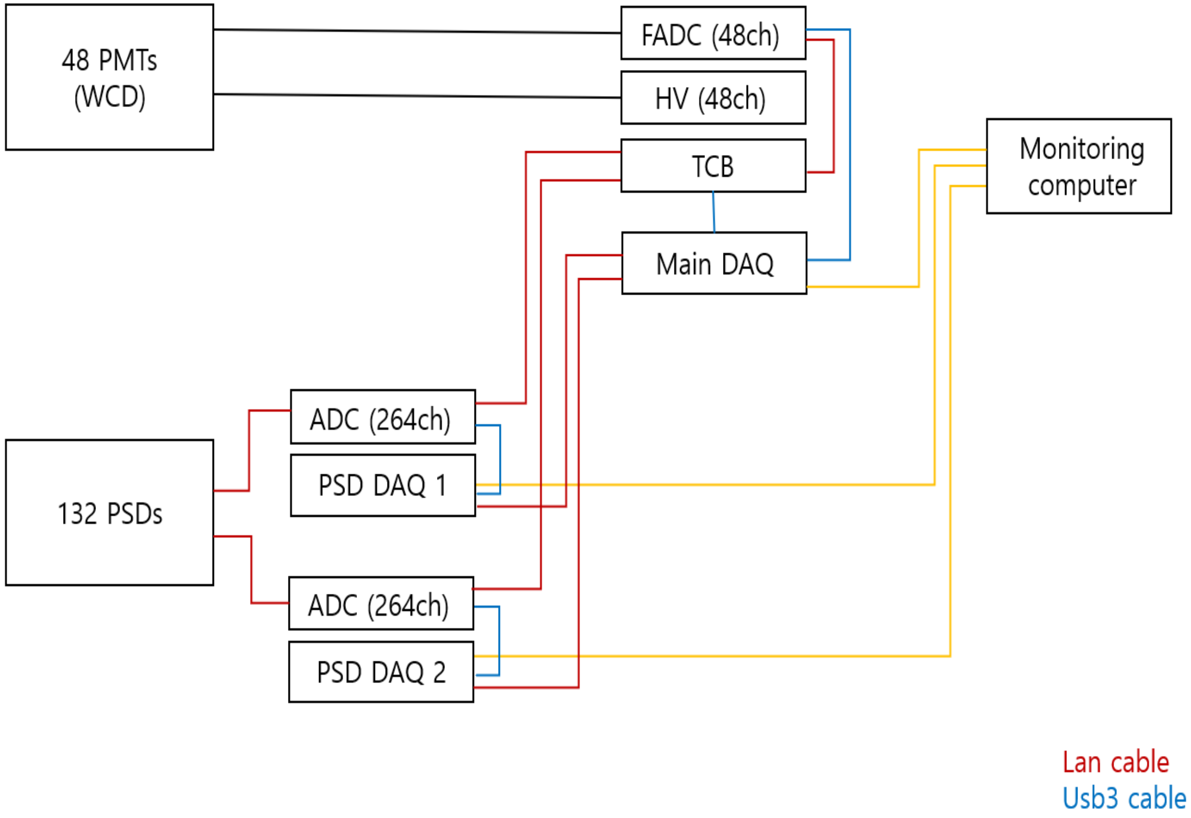


Muon selection was done by selecting charge Q(ADC counts) on upper counter > 7000 and lower counter > 8000.

- Detected muons calculated through integral of the Cherenkov spectrum.
- Detection Efficiency: 99.7%

AMoRE-II Construction at Yemilab

DAQ Schematic Diagram for Muon detector



ADC modules specifications

	PSMD	WCMD
		
Channels	40	4 (2 in 1)
Dynamic range	2Vpp	2.5Vpp
Resolution	12bit	12bit
Sampling rate	62.5Ms/s	500Ms/s