COSMO-18
August 27-31, 2018
IBS Science and Culture Center
Daejeon, Korea
The 22nd annual International Conference on Particle Physics and Cosmology

Center for Underground Physics
ibs

AMoRE

A neutrinoless double beta decay experiment

AMoRE (Advance Molybdenum-based Rare-process Experiment)

Moo Hyun Lee
Center for Underground Physics (CUP)
Institute for Basic Science (IBS)
Daejeon, Korea

AMoRE Collaboration

8 countries, 18 Institutes, ~90 collaborators

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

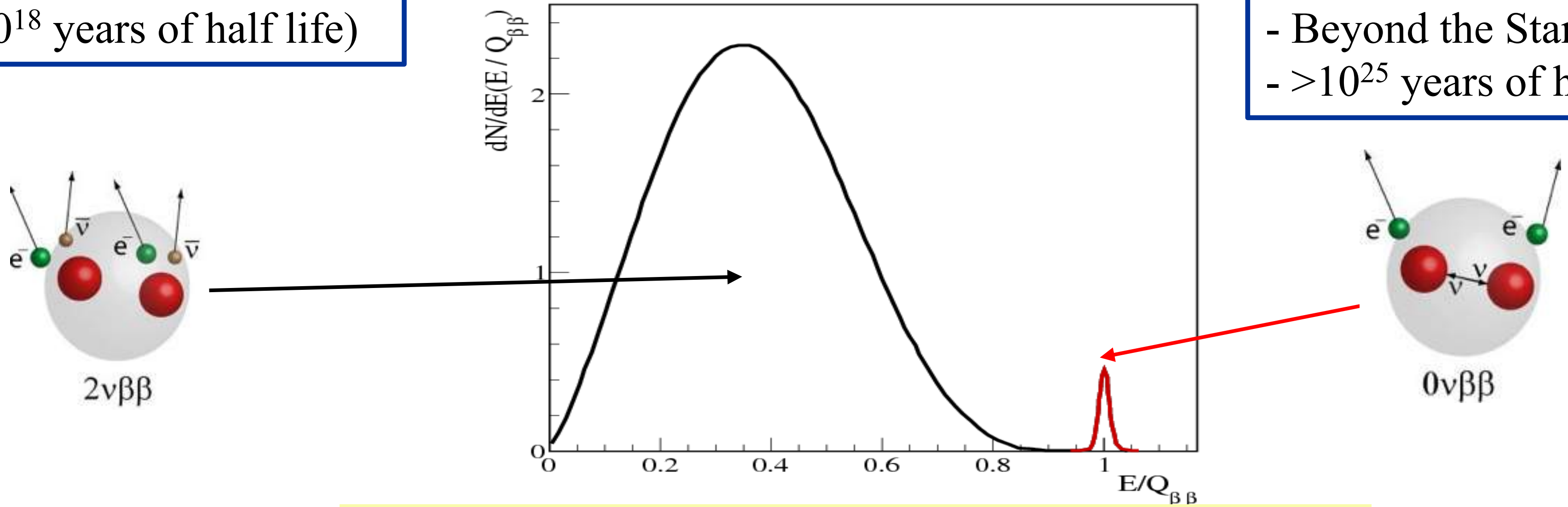
15th AMoRE Collaboration meeting
Jeongseon, Jan. 18-19, 2018

AMoRE: Neutrinoless double beta decay

The goal of **AMoRE** (**A**dvanced **Mo**-based **R**are process **E**xperiment) is to search for neutrinoless double beta decay (0υββ) 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)

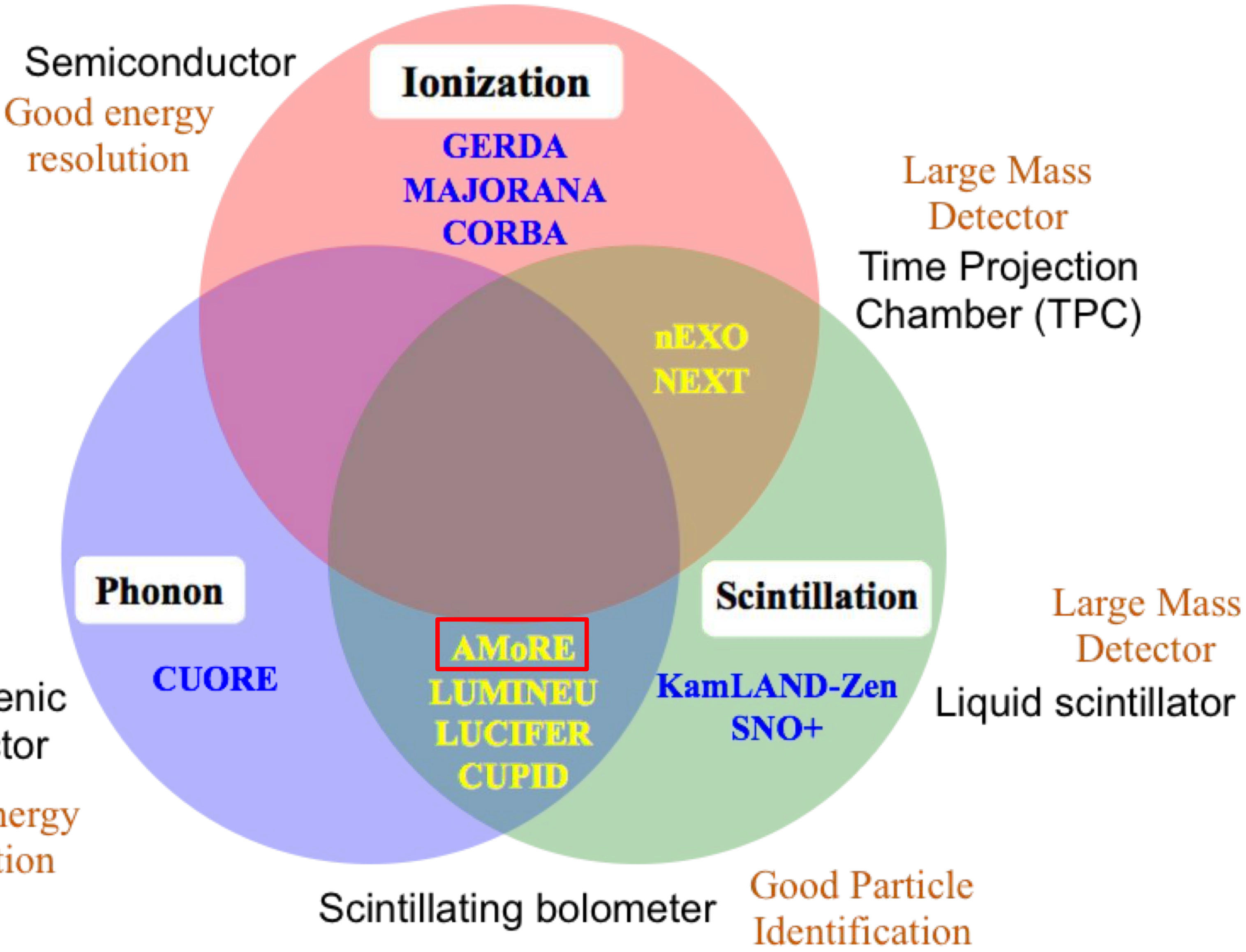
$0\nu\beta\beta$ decay
- Massive neutrino
- Majorana particle
- Beyond the Standard Model
- >10^{25} years of half-life



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

$(Z, A) \rightarrow (Z+2, A) + 2e^-$ ($\Delta L = 2$, violated)

Detection Techniques of 0νββ



Semiconductor

Good energy resolution

Ionization

GERDA
MAJORANA
CORBA

Large Mass Detector

Time Projection Chamber (TPC)

nEXO
NEXT

Phonon

CUORE

Cryogenic detector

Good energy resolution

AMoRE
LUMINEU
LUCIFER
CUPID

Scintillation

KamLAND-Zen
SNO+

Large Mass Detector

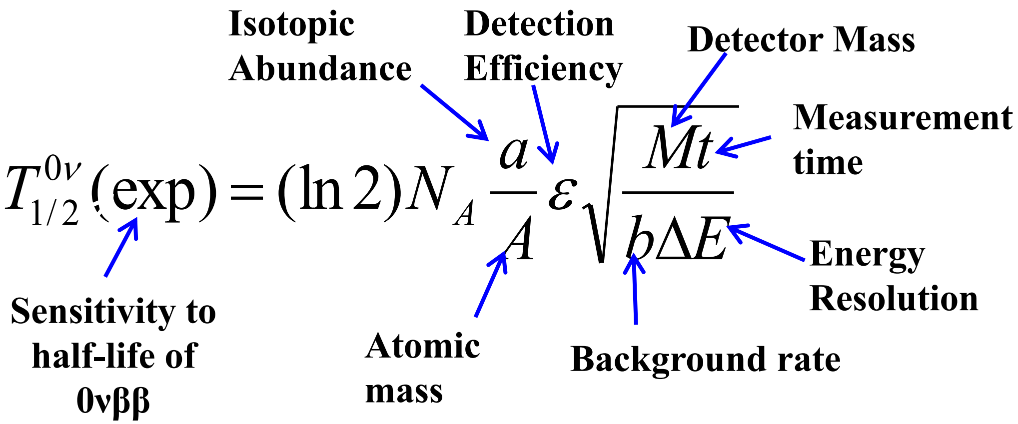
Liquid scintillator

Scintillating bolometer

Good Particle Identification

AMoRE Experimental Approach

- **Sizable background case:**

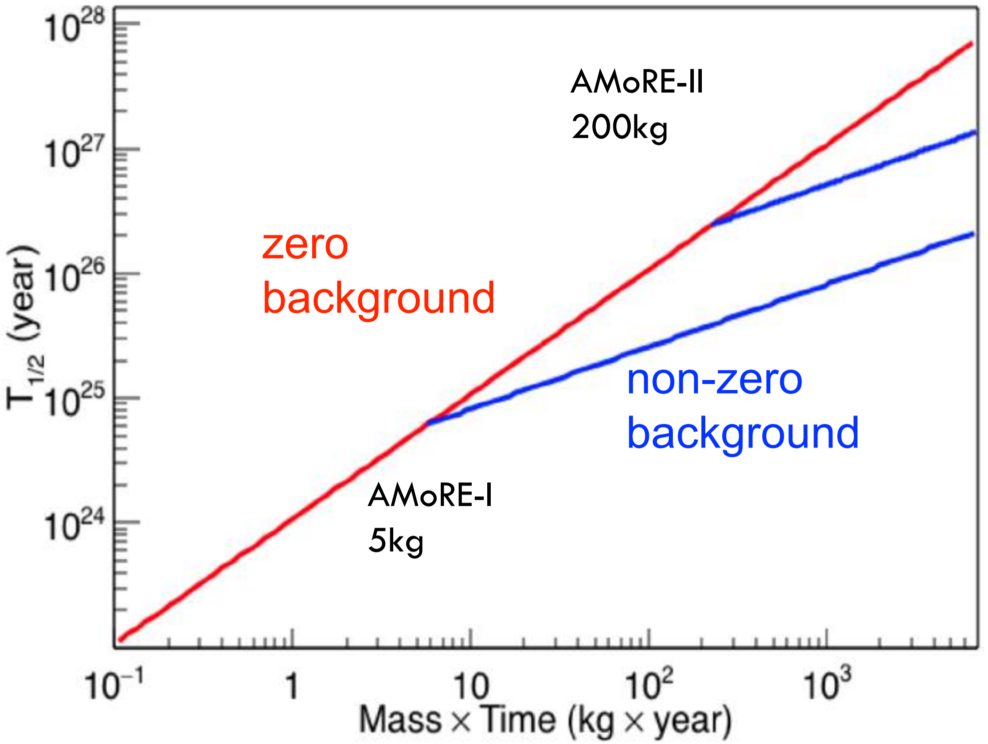


$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{Mt}{b \Delta E}}$$

- **"Zero" background case:**

When b is ~ O(1),

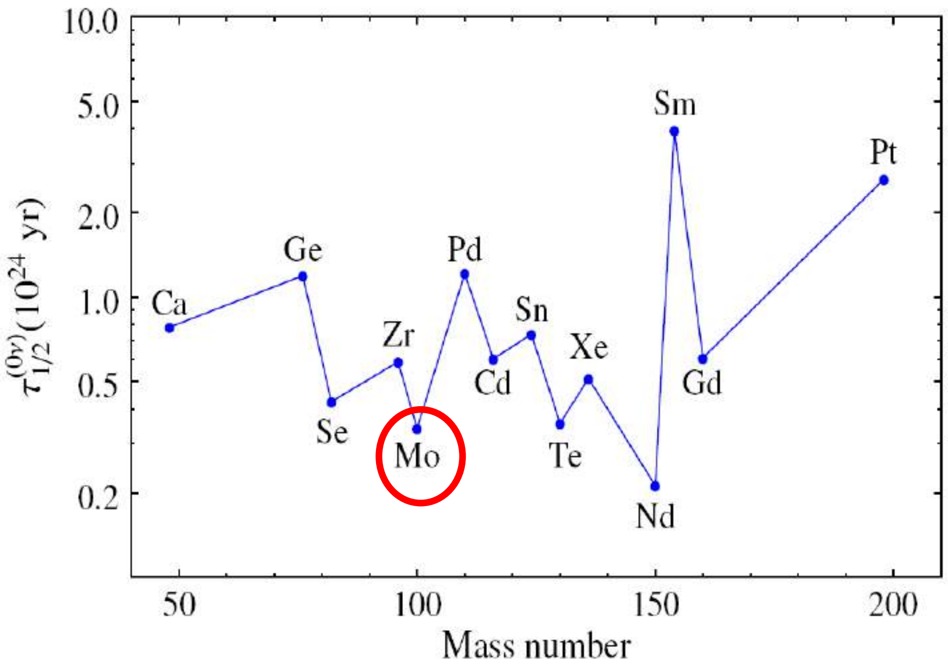
$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon M t$$



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 2.614 MeV γ-ray from nature)
- **High natural abundance of 9.7%.**
- **Relatively short half life (0νββ) expected from theoretical calculation.**

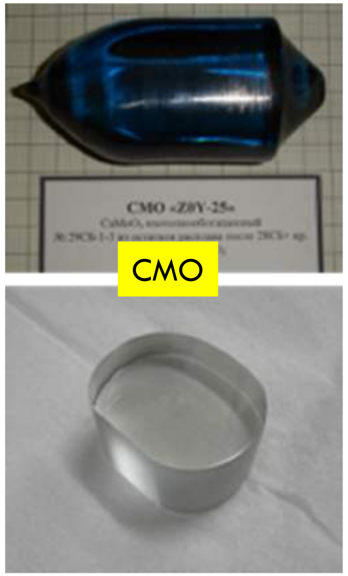


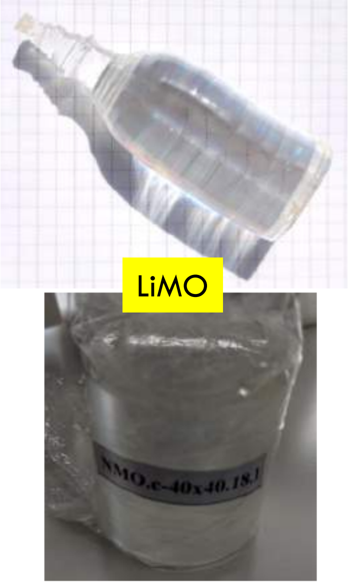
Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

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

AMoRE Parameters

- Crystals: $^{40}Ca^{100}MoO_4$(CMO) or XMO (X: Li, Na, 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
- The AMoRE Plan:

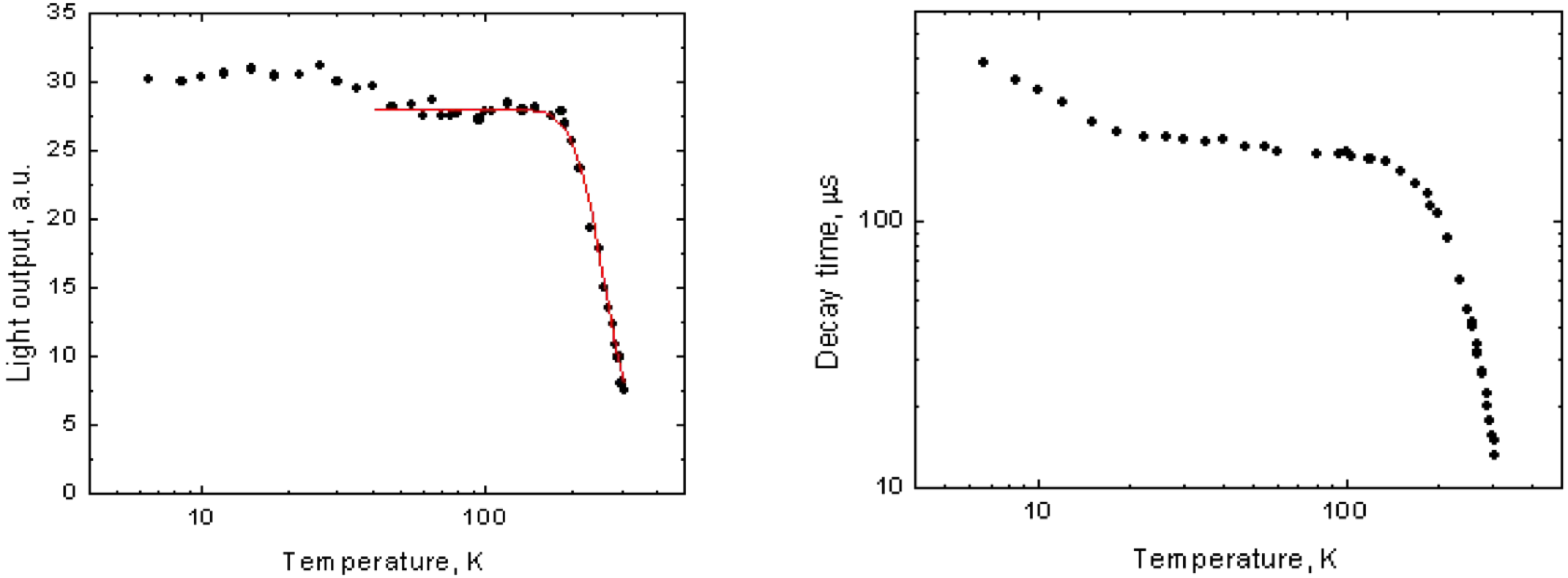




	Pilot	Phase I	Phase II
Mass (Crystal)	**1.9 kg CMO**	**6 kg (CMO + LMO)**	**200 kg XMO (X: Li, Na, Pb)**
Bkg [keV ·kg· year]$^{-1}$	**$<10^{-2}$**	**$<10^{-3}$**	**$<10^{-4}$**
$T_{1/2}$ Sensitivity [years]	**$\sim10^{24}$**	**8.2×10^{24}**	**8.2×10^{26}**
$<m_{\beta\beta}>$ Sensitivity [meV]	**380 - 719**	**130 - 250**	**13 - 25**
Location	**Y2L (700 m depth)**		**Yemi Lab (1100m depth)**
Schedule	**2015 - 8**	**2018 - 2020**	**2021 -**

Temperature dependence of $CaMoO_4$ light yield

- **From RT to 7K, light yield is increased by factor of 6.**
  (V.B. Mikhailik et al., NIMA 583 (2007) 350)



- **CMO absolute light yield:**

~ 4,900 ph/MeV @ Room Temp. (H.J. Kim et al., IEEE TNS 57 (2010) 1475)
~ 30,000 ph/MeV @ ~10 K

→ Highest light yield among Molybdate crystals.

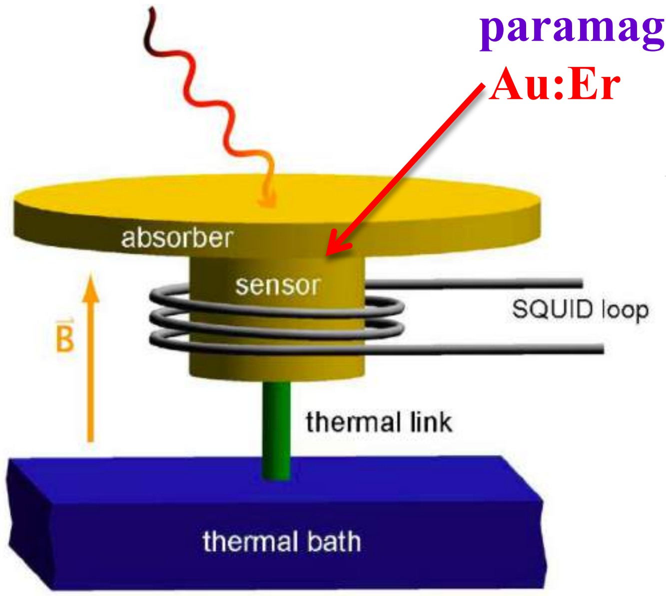
MMC (Metallic Magnetic Calorimeter) for LTD

Principle of operation

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

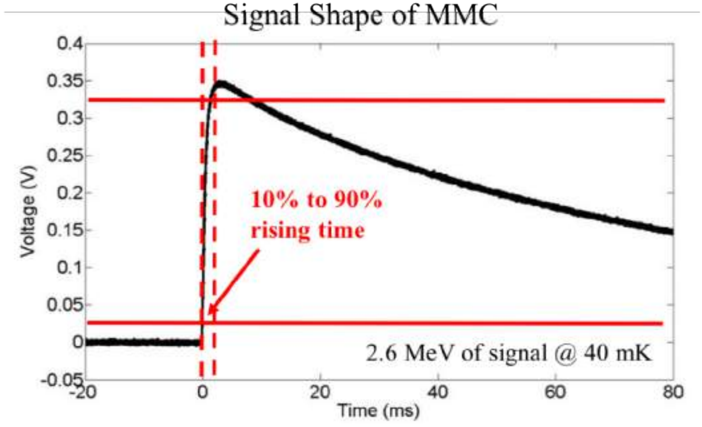
Advantage of MMC

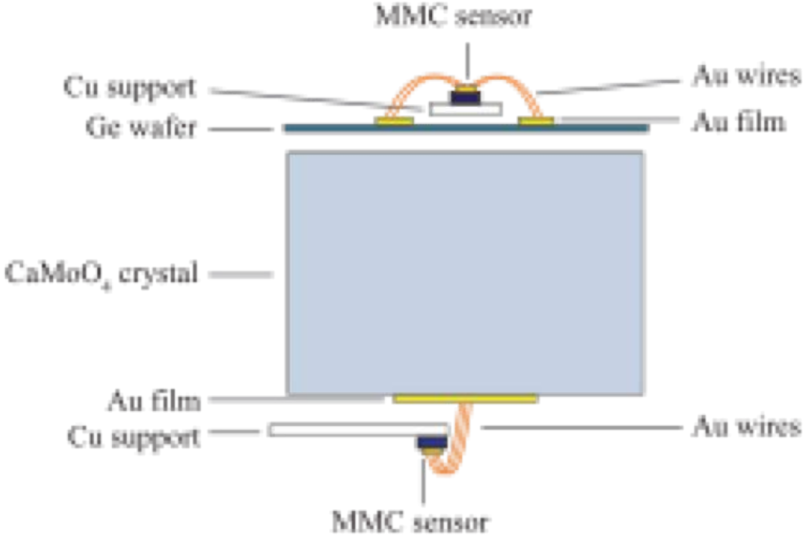
- Fast rising signal : ~0.5 ms (critical to reduce $2\nu\beta\beta$ random coincidence)
- Fairly easy to attach to absorber.
- Excellent Energy resolution

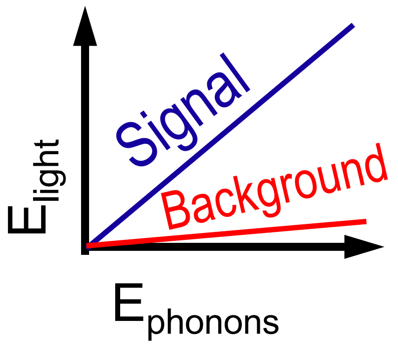


paramagnetic sensor:

Au:Er



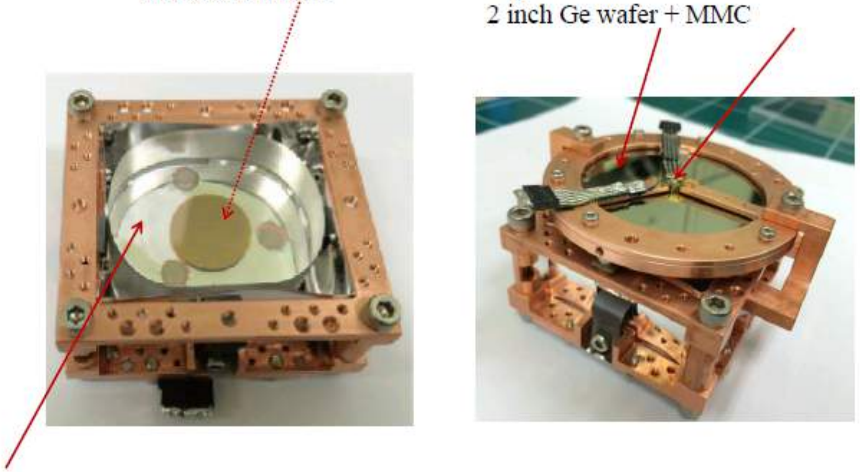




Prototype Detector and Above-ground Measurements

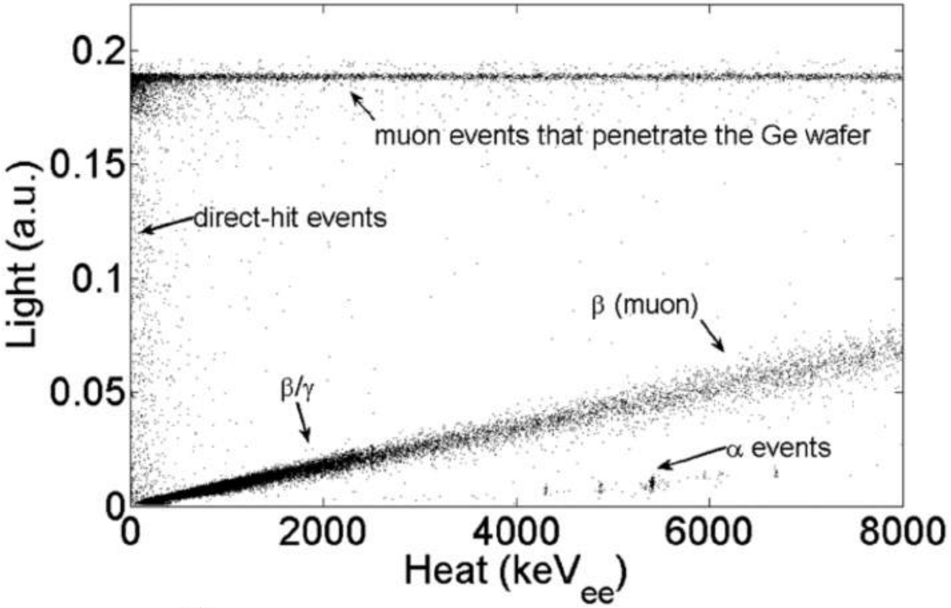
Phonon collector film on bottom surface

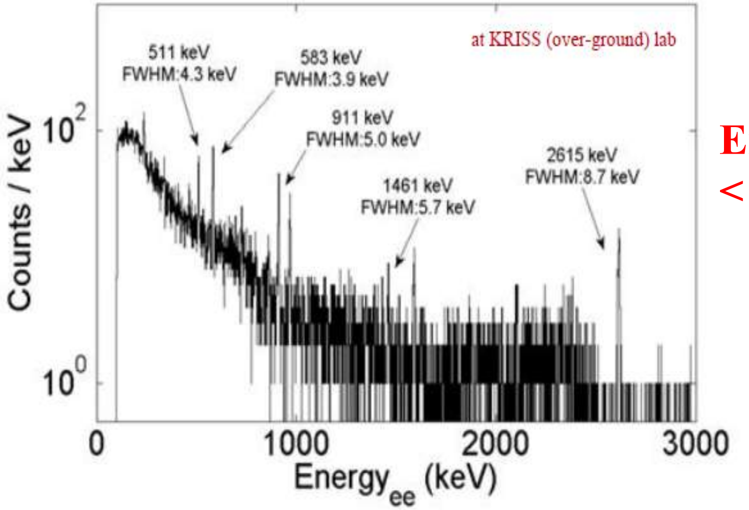
Light detector
2 inch Ge wafer + MMC



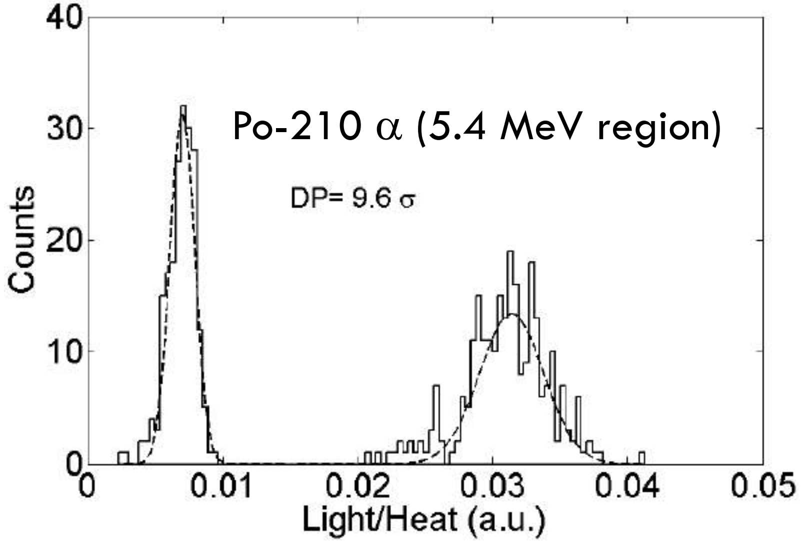
196 g $^{40}Ca^{100}MoO_4$
(doubly enriched crystal)

G.B. Kim et al., IEEE Trans. Nucl. Sci. (2016)





Energy resolution:
< 9 keV @2.6 MeV



Yangyang Underground Laboratory (Y2L)

YangYang Pumped Storage Power Plant

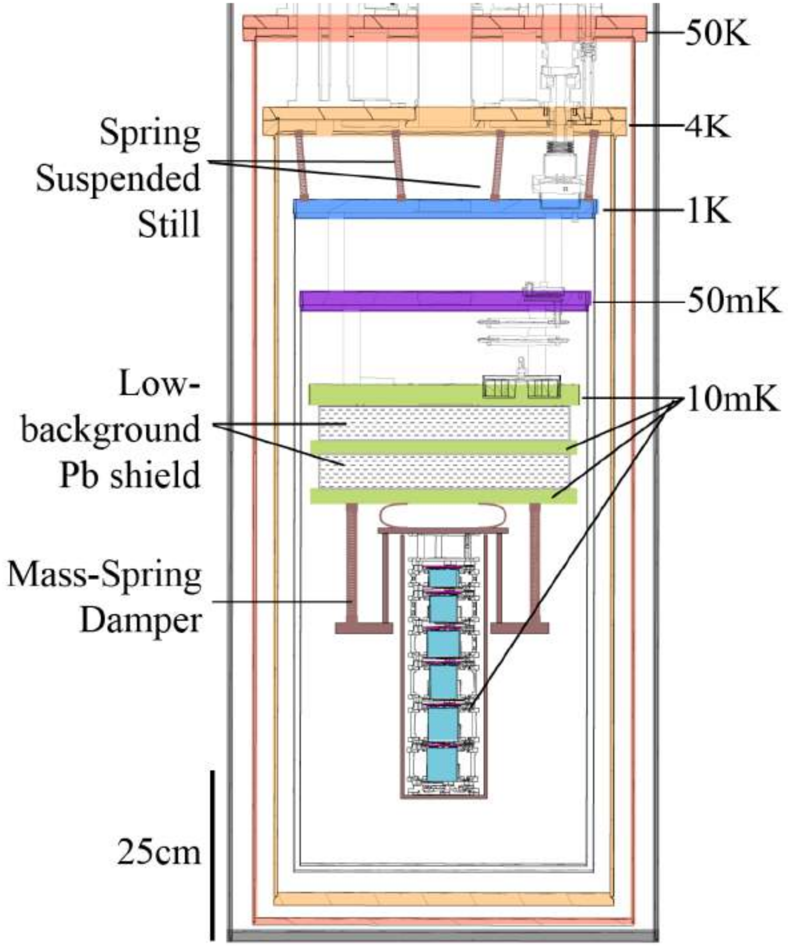
KIMS/COSINE (Dark Matter Search)

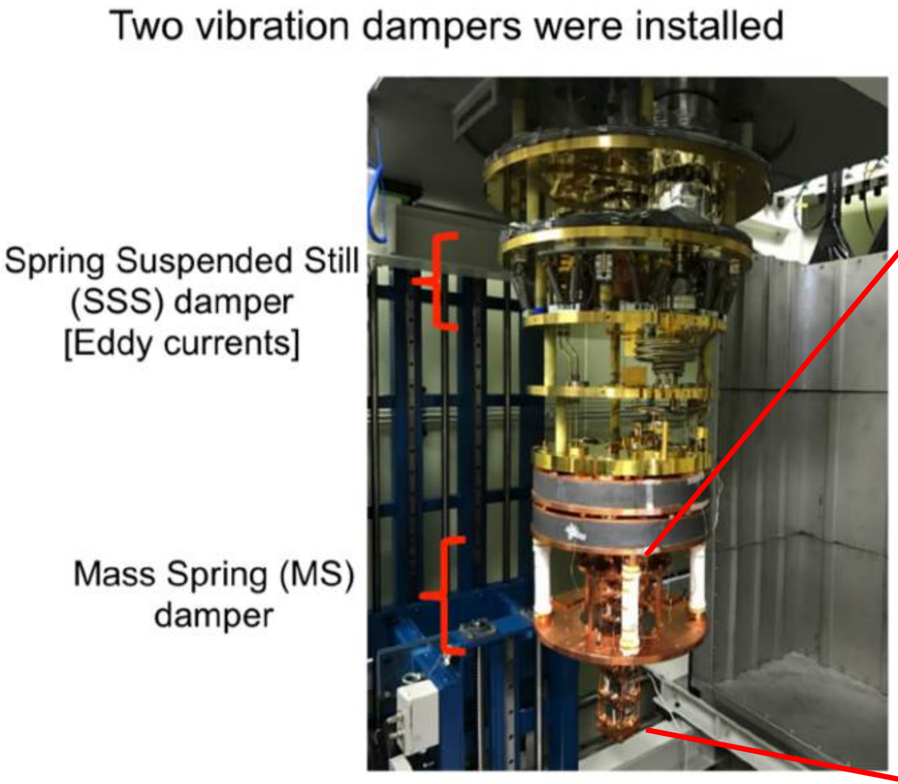
AMoRE (Double Beta Decay Experiment)

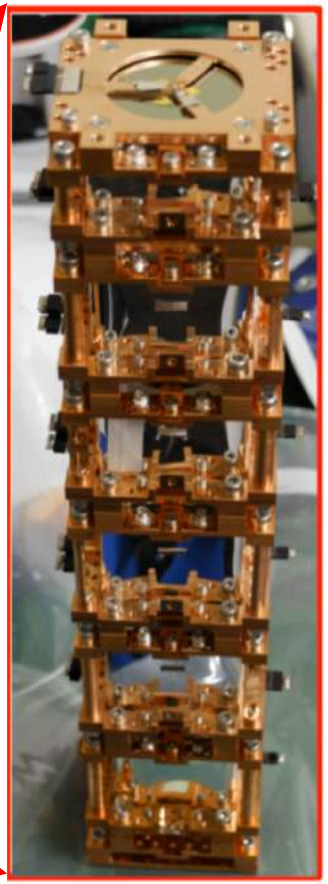
Minimum depth : 700 m / Access to the lab by car (~2km)

AMoRE-Pilot configuration (Run6)

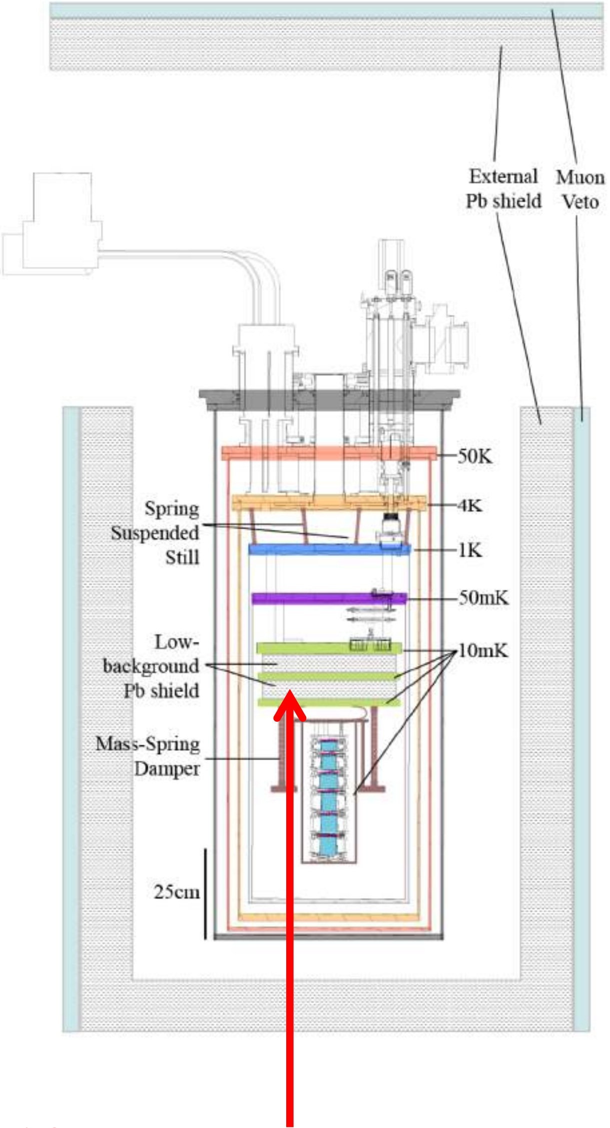
- Six CaMoO4 crystals with total mass of ~ 1.9 kg
- Two vibration dampers were installed



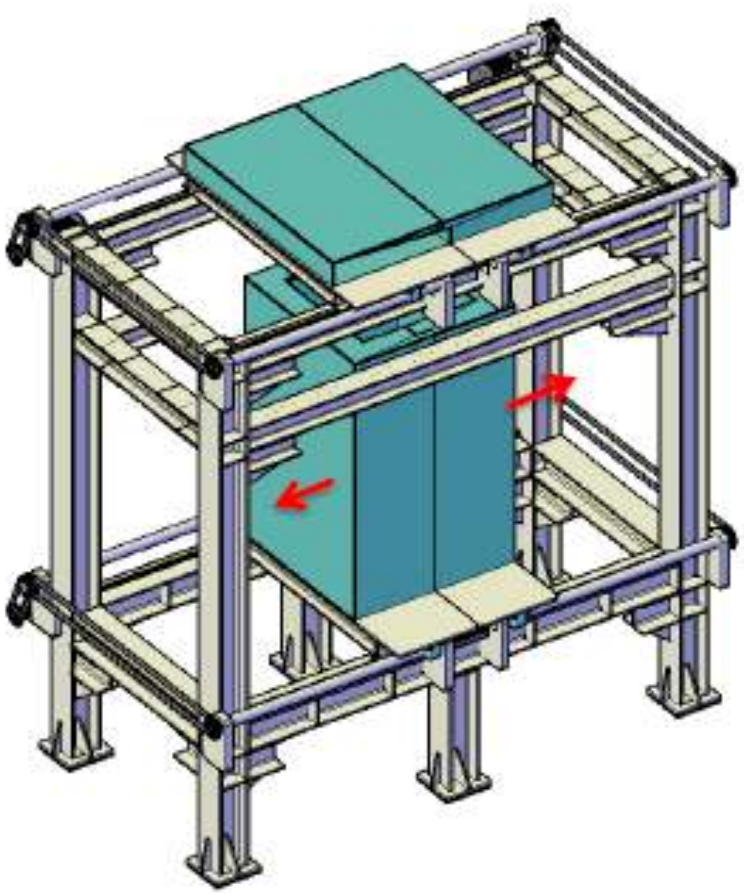




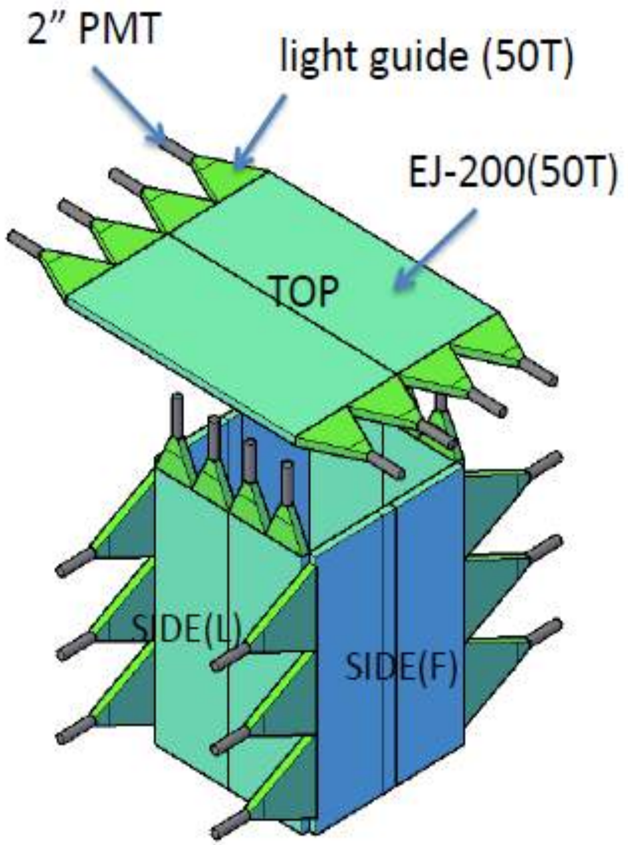
Shielding structure of AMoRE-pilot & AMoRE-I



10cm ultra-low background Pb

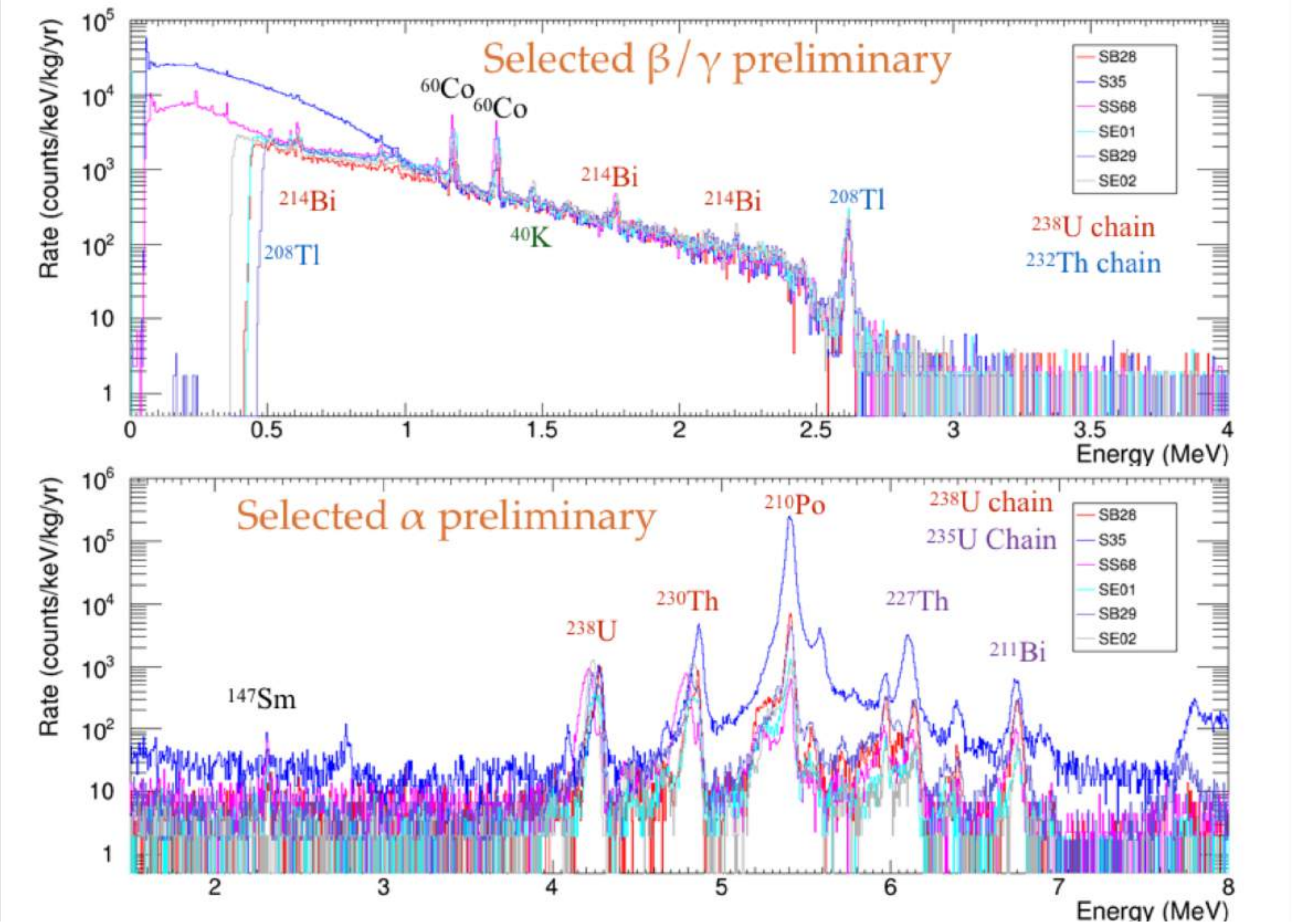


15cm low background Pb



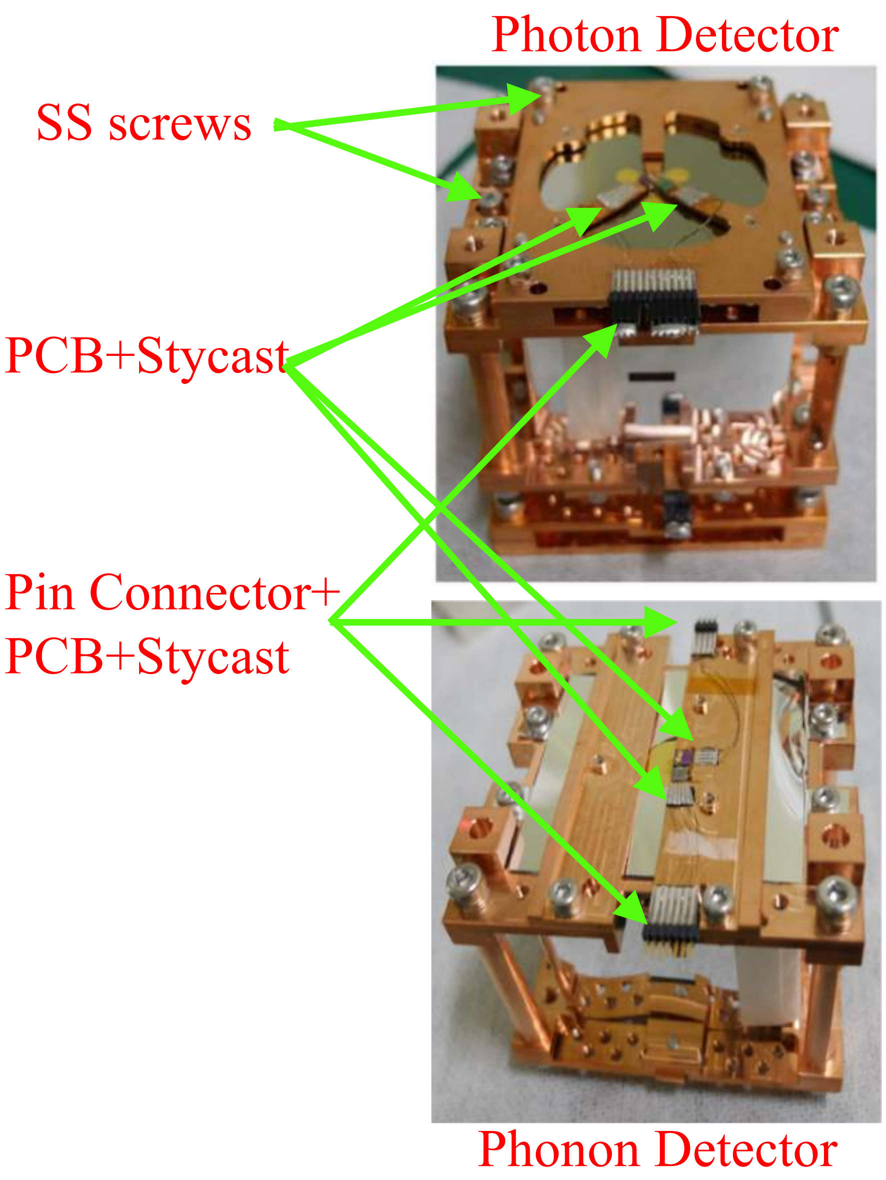
muon shielding structure

Selected β/γ and α Event Distributions



- After applying rejection and selection cuts, α and β/γ distributions were obtained in each crystal.

Backgrounds of AMoRE-Pilot Exp.



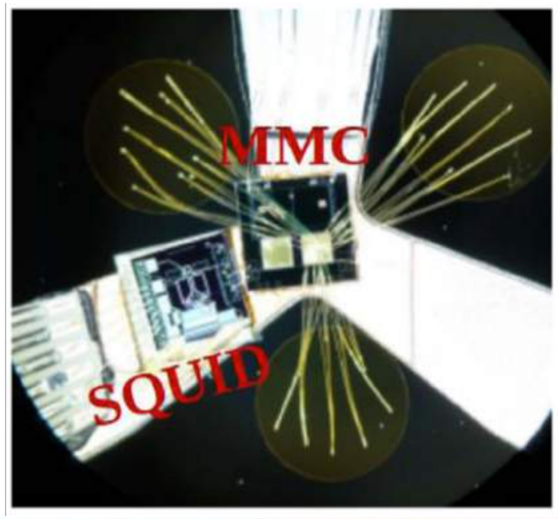
Photon Detector

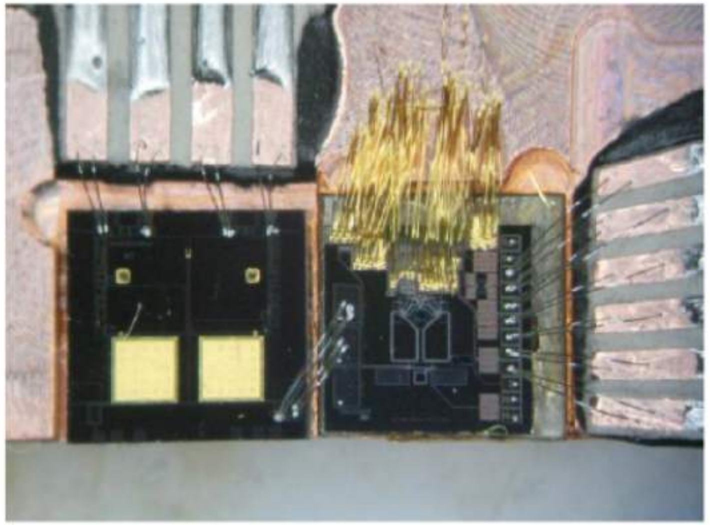
SS screws

PCB+Stycast

Pin Connector+
PCB+Stycast

Phonon Detector





Activities measured with HPGe

Total masses and activities of components in the AMoRE-Pilot Setup (up to Run5).

Item	Total mass (g)	A(Ra226) mBq	A(Ac228) mBq	A(Th228) mBq	A(K40) mBq
Pin connector	7.77	15.08	27.67	24.09	28.75
PCB	2.88	0.54	0.50	0.41	3.04
Stycast	0.69	0.20	0.26	0.25	0.20
SS Screws	200.00	0.16	< 0.42	0.42	< 0.38
SQUID	0.12	< 0.23	< 0.46	< 0.14	< 2.24
Phosphor bronze spring	4.73	< 0.01	< 0.01	< 0.01	< 0.01

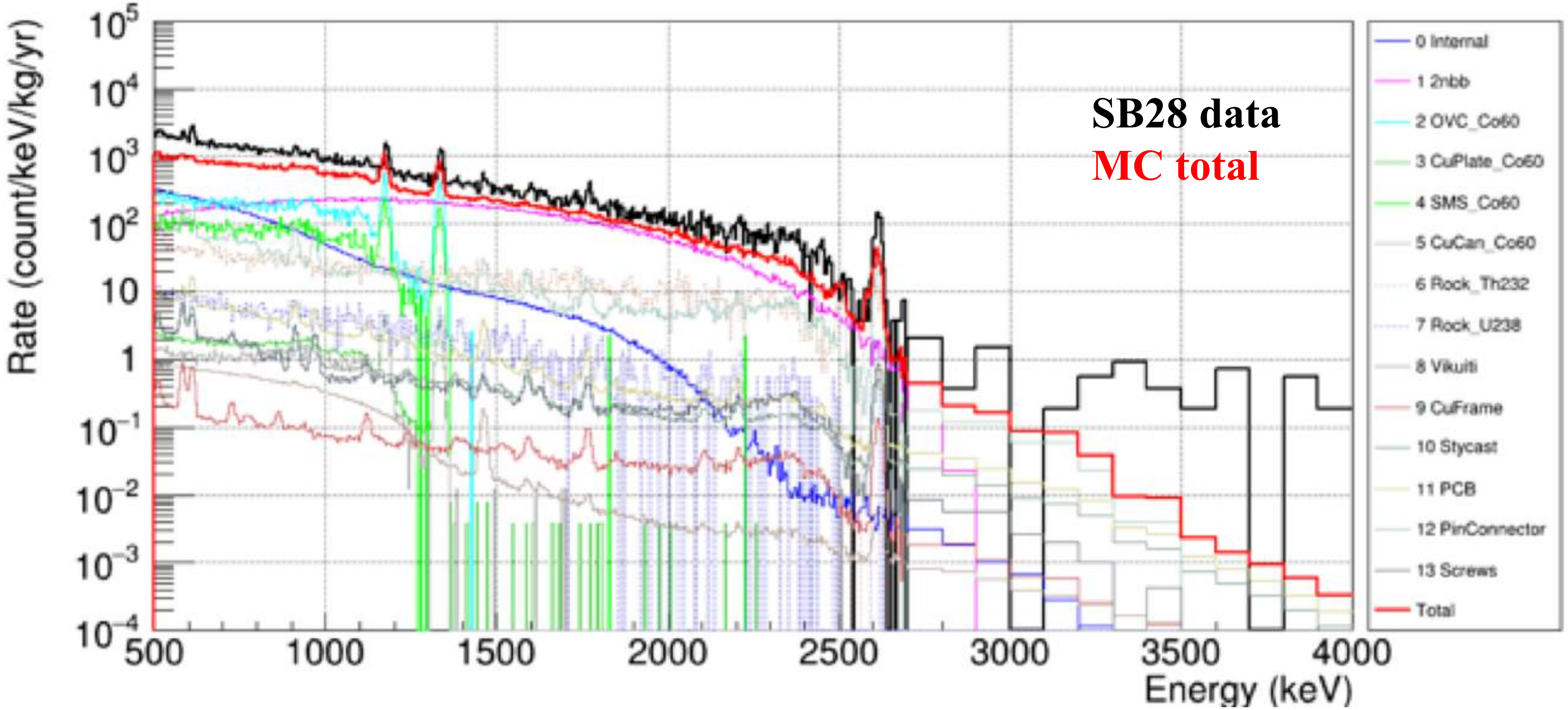
- Even though the amount is small, these components are major sources of background.
- Pin connector is the most active component.
- Most of the active components are replaced in the Run6 setup.

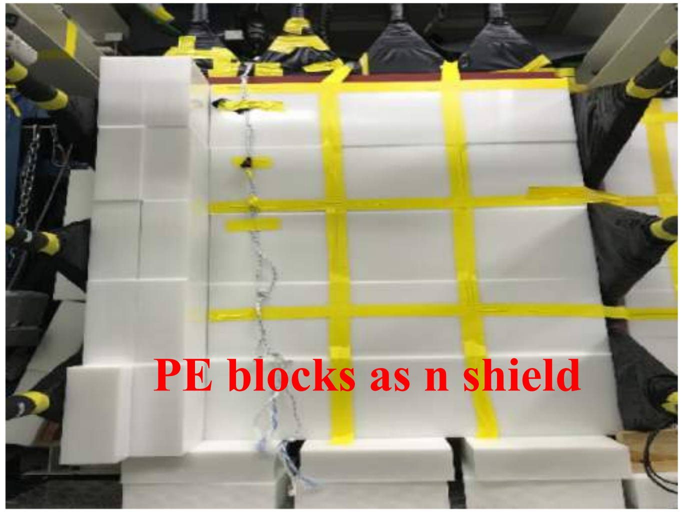
Radioactivity BKG study results

El	Decay	$T_{1/2}$	Q(MeV)	Mother	Chain	Comment
^{26}Al	EC	$7.4 \mathrm{x} 10^5$y	4.004	N/A		Long lifetime
^{56}Co	EC	0.21y	4.567	N/A		Short lifetime
^{88}Y	EC	0.29y	3.623	^{88}Zr (0.23 y)		Short lifetime
^{106}Rh	B-	30s	4.004	^{106}Ru(1.02y)		
^{126}Sb	B-	12.5d	3.670	^{126}Sn($2.3 \mathrm{x} 10^5$y)		Long lifetime
^{146}Eu	EC	4.61d	3.878	^{146}Gd (0.13 y)		Short lifetime
^{208}Tl	B-	3.05m	4.999	^{228}Th (1.91 y)	Th232	Main
^{209}Tl	B-	2.16m	3.970	^{233}U(159200y)	U233	2.1% branching
^{210}Tl	B-	1.3m	5.482	^{226}Ra(1600y)	U238	0.02% branching
^{214}Bi	B-	19.9m	3.269	^{226}Ra(1600y)	U238	Main

- Only Thorium and Uranium natural radioactivity are dangerous for Q > 3.02MeV. → Great advantage to run high Q-value nuclei!
- ^{110m}Ag(3010.5 keV) doesn't contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.

Run5 β/γ candidate events and MC



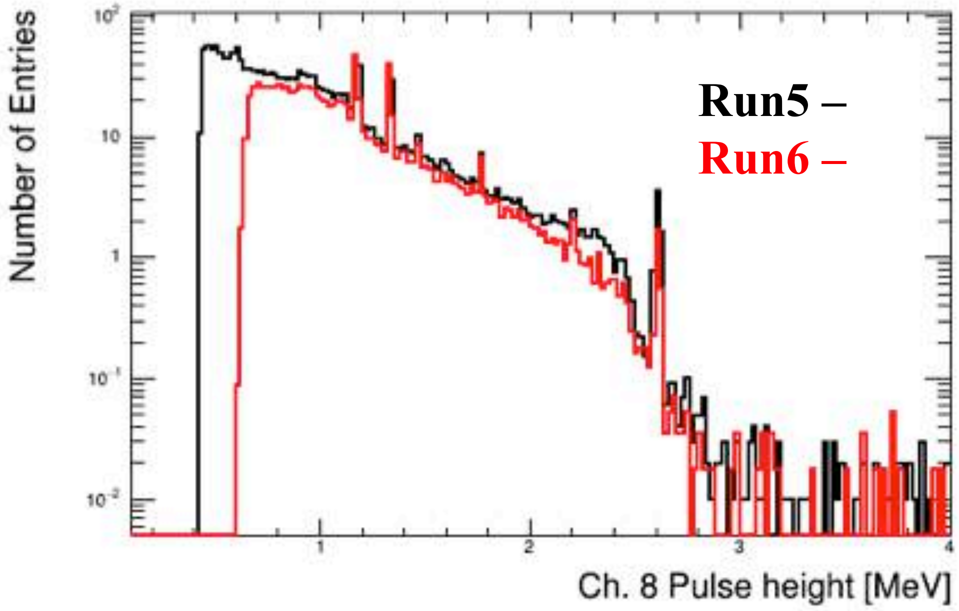


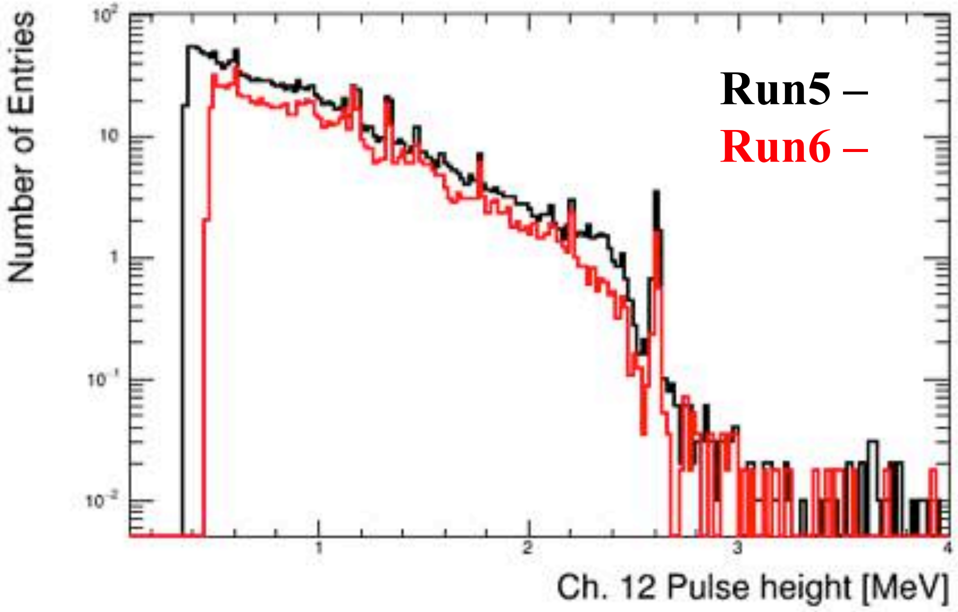
- MC distributions are estimated rates with measured activities except ^{60}Co.
- Level of ^{60}Co was estimated by likelihood fit with free parameters to match shapes.
- More background for data at higher energy than MC (E > 2.8 MeV). → Added PE, borated PE, borated rubber sheets, and boric acid as a neutron shield to block neutrons from the rock on August 15th.

AMoRE Pilot Run-6

Modifications in 6th commissioning run from the 5th run.

- Six $CaMoO_4$ crystals (total mass ~1.9 kg)
- Pin-connector, stycast, and PCB were replaced with Kapton, copper, and soldering with a high-purity solders.
- Some stainless steel bolts were replaced.
- Heaters were installed on crystals.



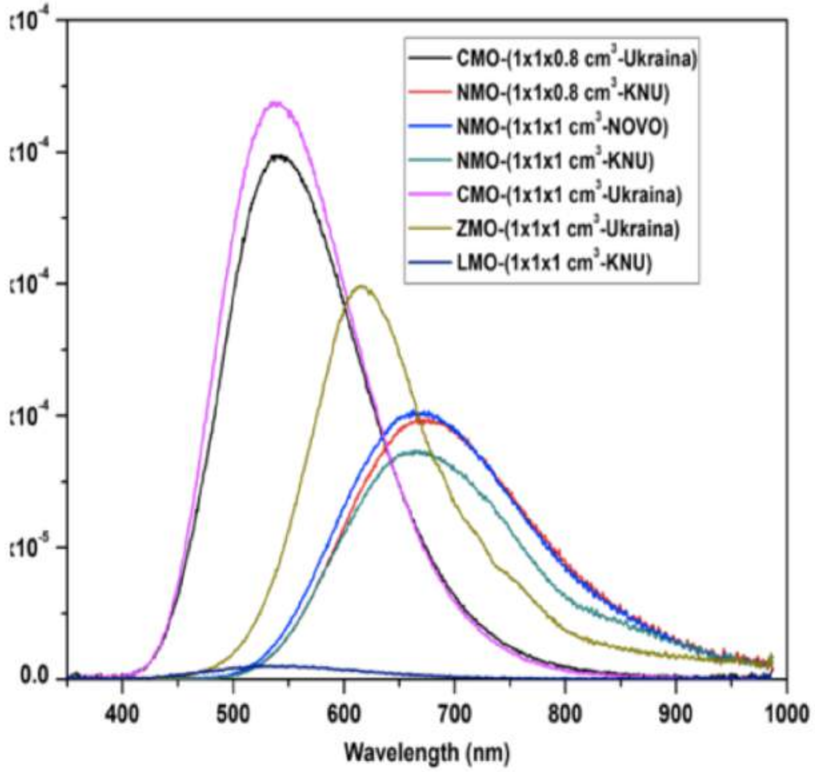


Event rate (ckky)	0.863±0.092	0.723±0.085
2.8 < E < 4 MeV	0.512±0.148	0.598±0.159

Crystals R&D for AMoRE-I & II

- ☐ Even though CMO ($CaMoO_4$) is a very good crystal which has the largest light output among Mo based crystals, 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.
- ☐ LUMINEU group decided to use LMO for their experiment, and we are working on Li_2MoO_4, $PbMoO_4$, and $Na_2Mo_2O_7$ crystals.

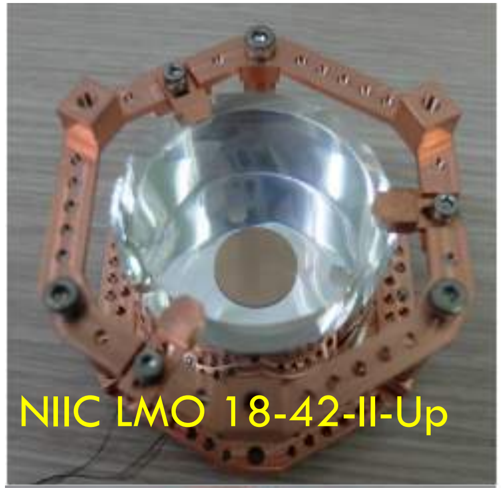
Crystal	Emission (nm)	LightYield @ 10K	density	Mo Fraction	Exp
$CaMoO_4$	538	100	4.34	0.49	AMoRE-1, II
$ZnMoO_4$	614	30-35	4.37	0.436	
Li_2MoO_4	533	5	3.03	0.562	LUMINEU AMoRE-II
$PbMoO_4$	590	~100	6.95	0.269	AMoRE-II
$Na_2Mo_2O_7$	663	~10	3.62	0.558	AMoRE-II

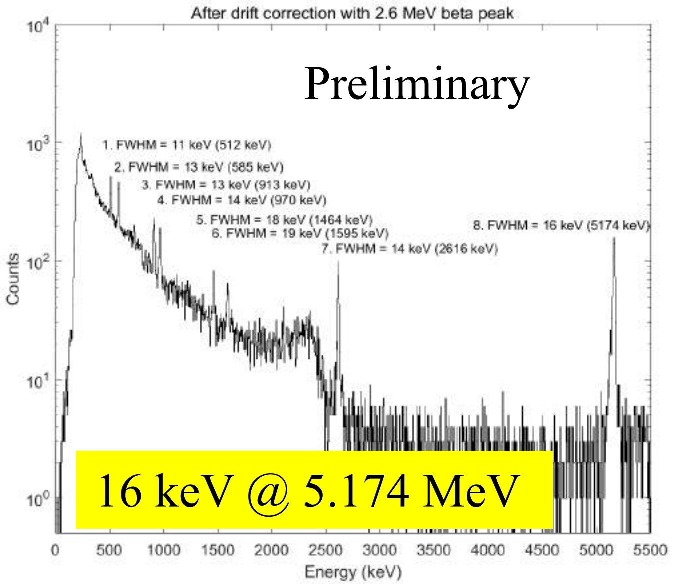


We are going to decide the crystal by the end of 2018.

Full size crystals tests at LT (~ 20 mK)

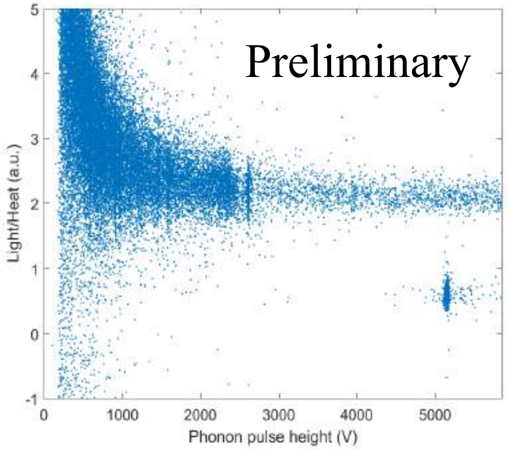
KRISS test for NIIC Li_2MoO_4 (Single crystal)



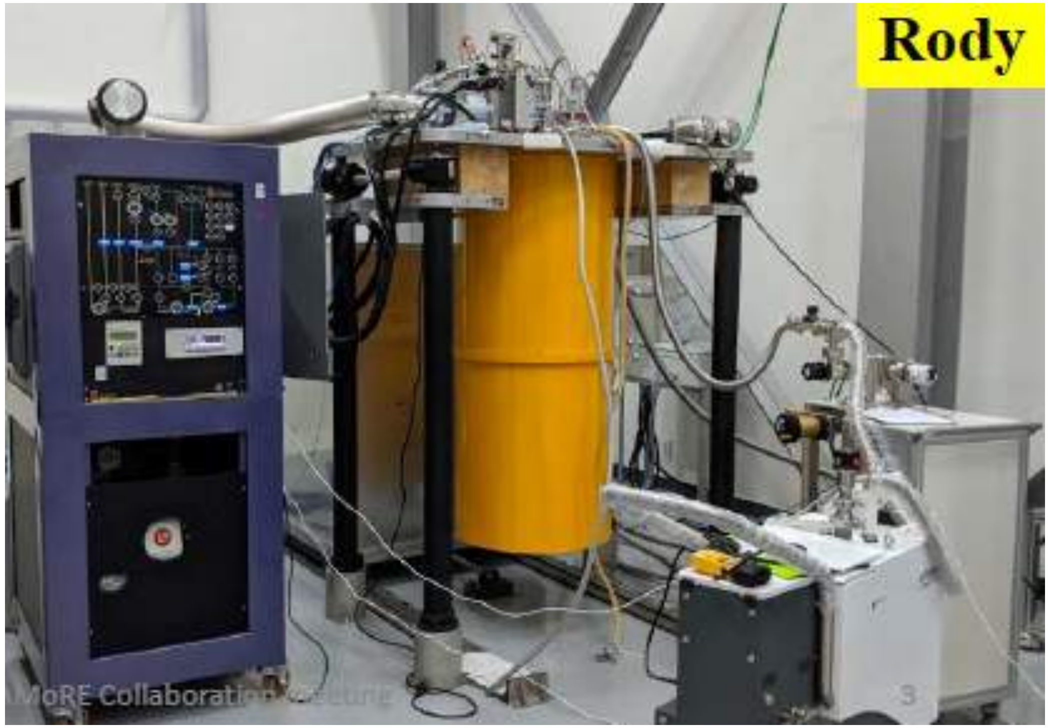


16 keV @ 5.174 MeV

Above ground under Thoriated W rode (3 days)



IBS HQ test setup for multi-crystals (PbMO, NaMO, CMO) being prepared for a cooling by the end of September



Gold deposition succeed after cleaning the surfaces with methanol and O_2 plasma asher.

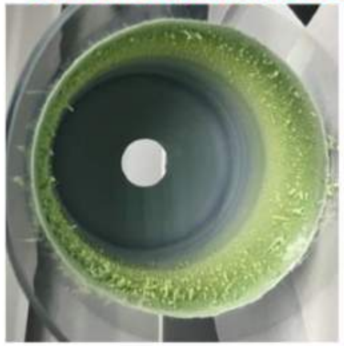
Low background Crystal growing facility at CUP

- ☐ Main goal
  - CaMoO$_4$ & Li$_2$MoO$_4$ crystal growing R&D for AMoRE-II
  - Other DBD or DM crystal R&D
- ☐ Deep purification of CaCO$_3$ and MoO$_3$ powders (< 50 μBq/kg for U,Th chain)
- ☐ Crystal growing equipment:
  1 Czochalski, 2 Kyropoulous, 1 Bridgman crystal growers.

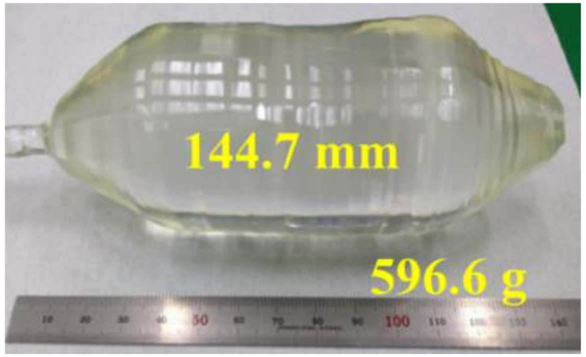
Lab tour (Tue. & Thr. 1-2 PM)

- ○ **Crystal growing lab**
- ○ **Purification chemistry lab**
- ○ **Low temperature detector lab**
- ○ **Etc…**
- ○ **Wait at the IBS cafeteria entrance for an escort!**

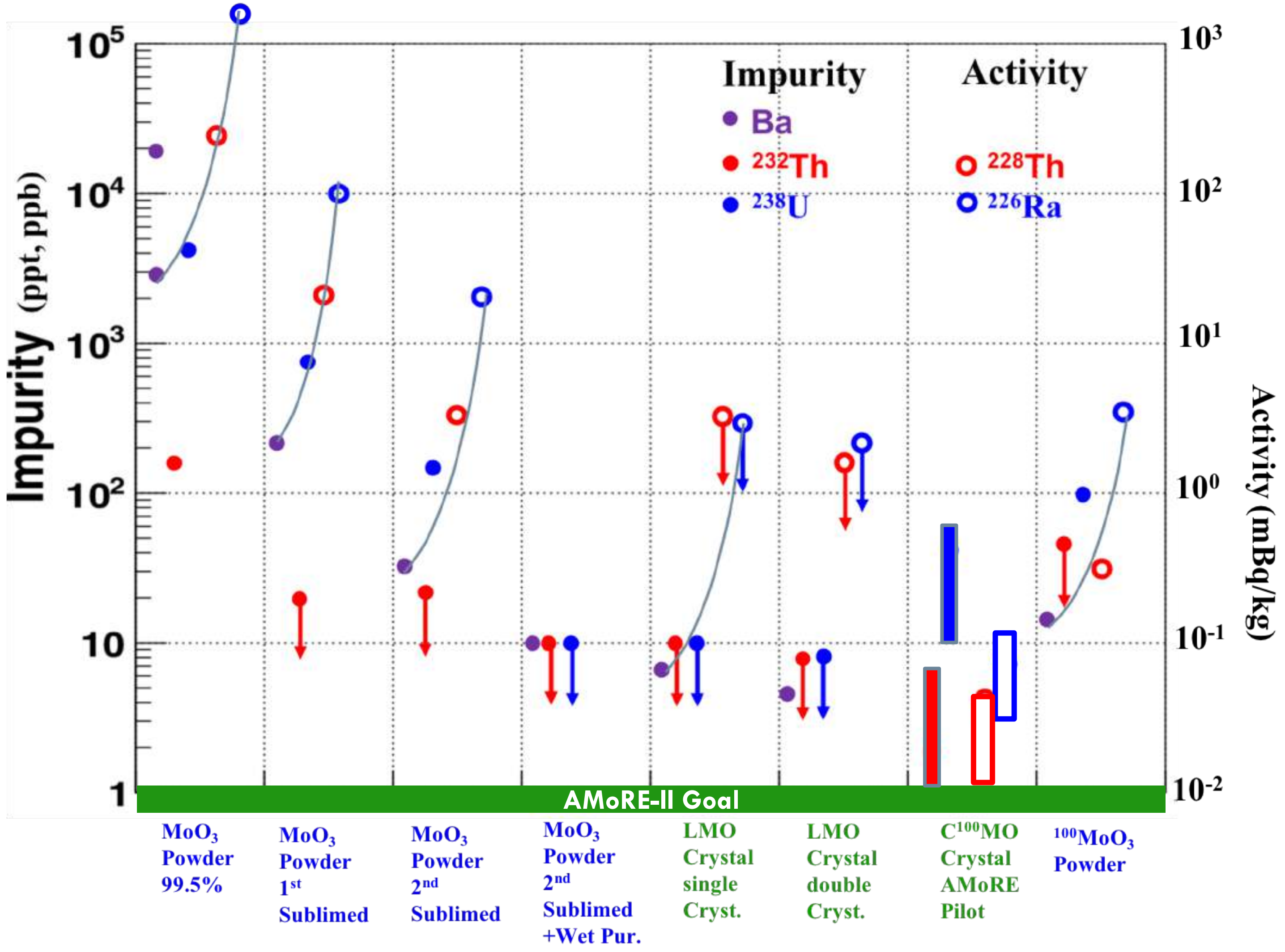
Purified powder after sublimation



CMO & LMO crystals by CUP



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.

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 .

AMoRE-I CMO crystals (FOMOS)

@ AMoRE-Pilot

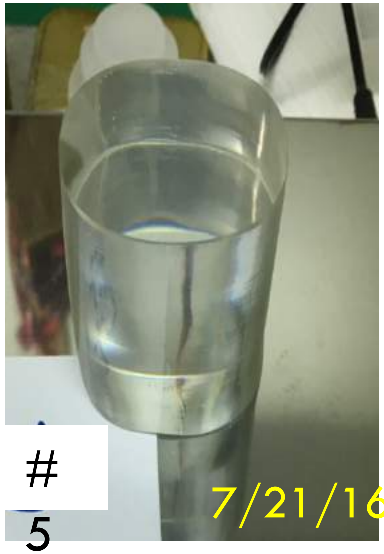

3/24/15 #1


7/8/15 #2


4/29/16 #3


#4 7/18/16

Total: 3.387 kg


#5 7/21/16


11/22/16 #6


12/13/16 #7


#8


#9

- 3 years for procurement.
- LY, resolution, transmittance, RT background measurements done.
- #3-9 to be installed at AMoRE-I together with #1-2.

AMoRE Phase I

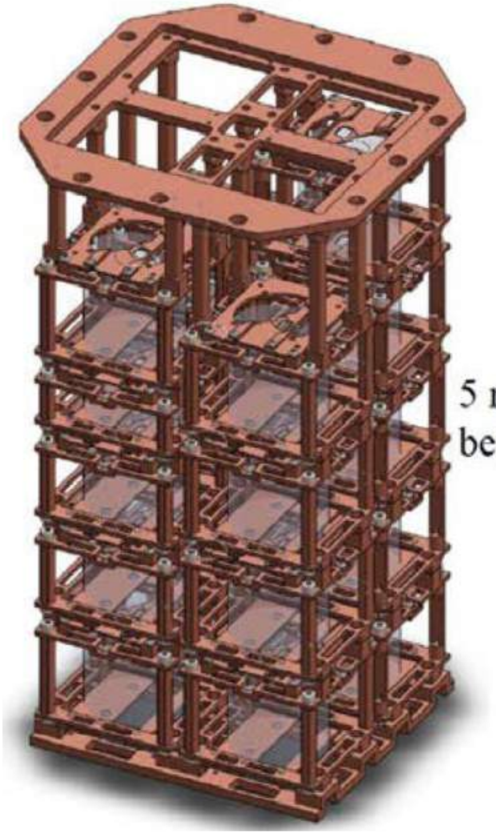
AMoRE-phase 1: A scaled-up version of Pilot

Six $^{40}Ca^{100}MoO_4$ crystals from Pilot : 1.886 kg
Seven new $^{40}Ca^{100}MoO_4$ crystals : 2.696 kg
Five extra crystals $Li_2{}^{100}MoO_4$: 1.5 kg

Total: 6 kg, 18 crystals with ~2.4 kg of ^{100}Mo

Plan: Depending on Pilot schedule (~October 2018)
3-4 months preparation time
3+ year measurement

Work required: MMC+SQUID wirings for 36 channels.
MMC production at IBS & KRISS
SQUIDs from PTB (AMoRE contribution) and IPHT(commercial)
Mass Spring Damper modification
New superconducting shield
Extra DAQ modules



5 mm distance between towers

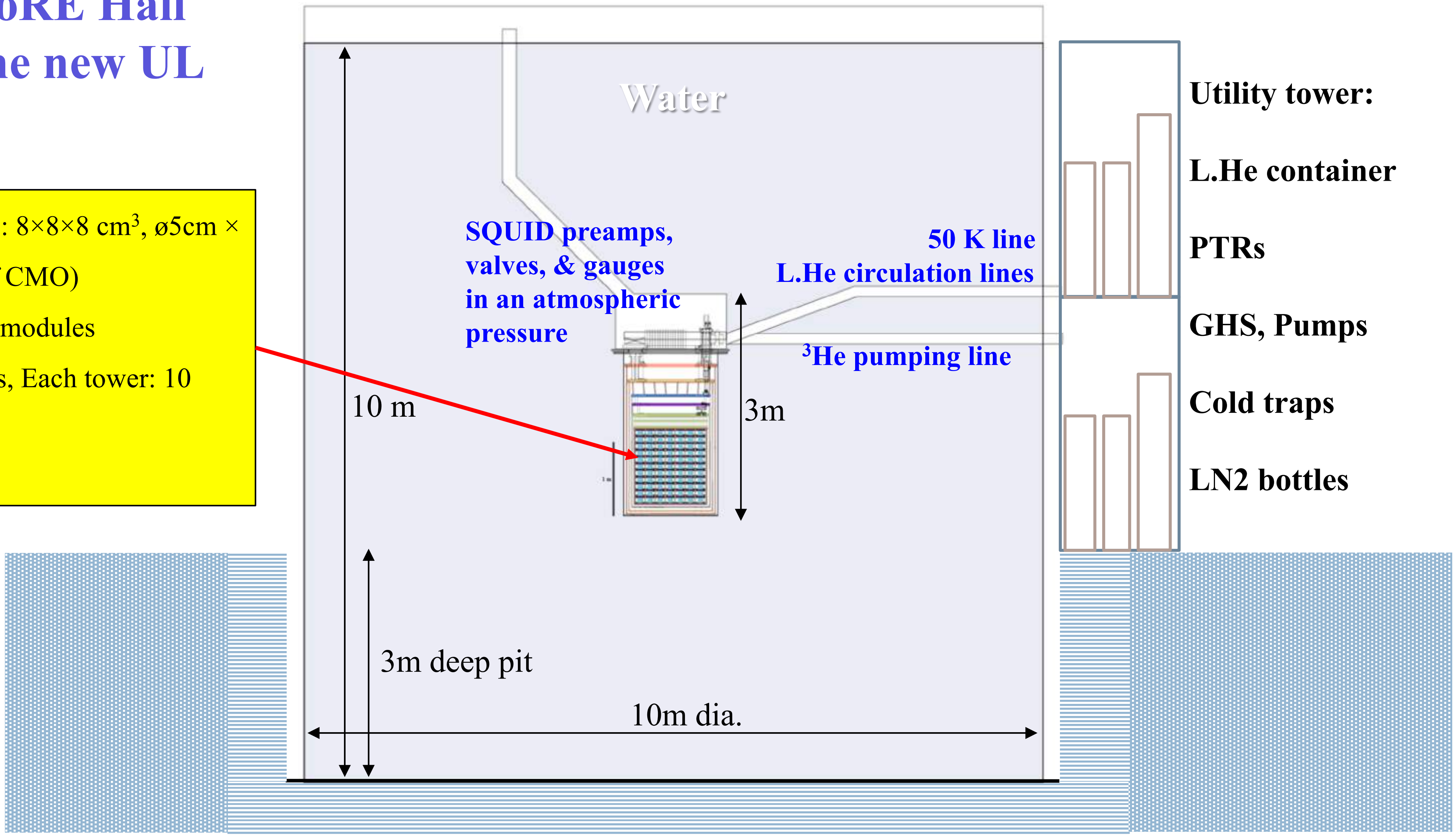
AMoRE-1 tower with 18 crystals

AMoRE-II design: cryostat in active water shield

AMoRE Hall
in the new UL

- ☐ Each module: 8×8×8 cm^3, ø5cm × 6cm (506g if CMO)
- ☐ 400 detector modules
- ☐ 40~44 towers, Each tower: 10 modules
- ☐ 800 channels

Tank top:
DAQs, Controllers, Power supplies



SQUID preamps, valves, & gauges in an atmospheric pressure

50 K line
L.He circulation lines

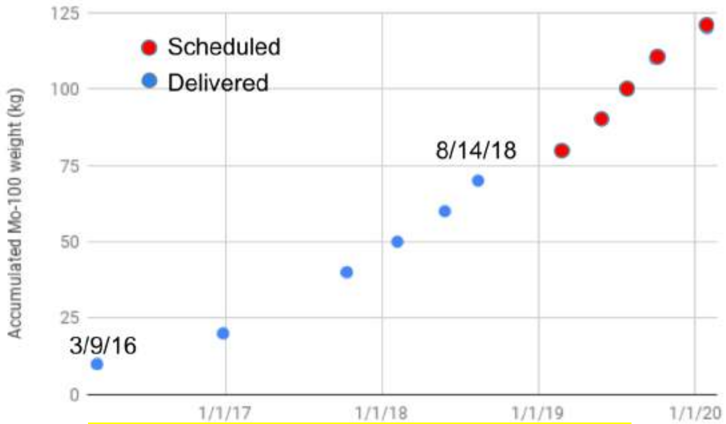
^{3}He pumping line

Utility tower:
L.He container
PTRs
GHS, Pumps
Cold traps
LN2 bottles

Mo-100 powder (ECP) for AMoRE-II

Contract Date (weight)	Lot#	Delivery@Y2L
2015 (10 kg)	#1(3172)	3/9/16
	#2(3328)	
2016 (10 kg)	3434	12/28/16
2016 (10 kg)	3497	10/12/17
2016 (10 kg)	3535	
2017 (10 kg)	3589	2/7/18
2017 (10 kg)	3649	5/29/18
2017 (10 kg)	3675	8/14/18

70 kg delivered out of 120 kg contracted



Last delivery ~Jan. 2020

HPGe Array meas. (9/13 – 11/28/2017)

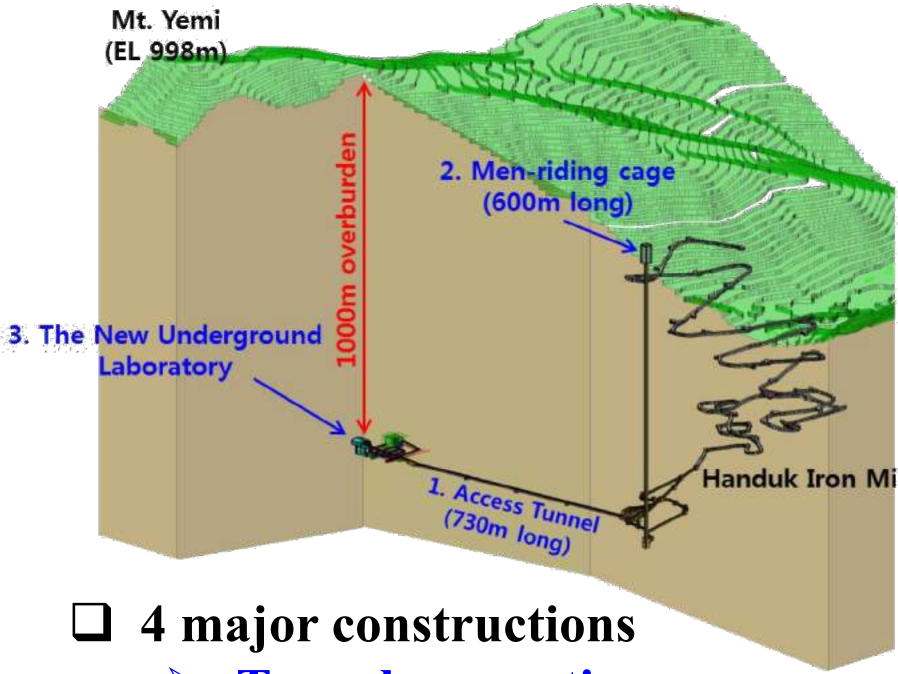
- ^{226}Ra chain (^{238}U):1.6 ± 0.3 mBq/kg
- ^{228}Th chain (^{232}Th): 244 ± 50 μBq/kg (first measurement)
- ^{88}Y: 33 ± 8 μBq/kg (cosmogenic)

Yemi Lab: A new Underground Lab in Handeok mine

☐ The only operating iron ore mine in Korea.

☐ A 600 m long 2nd shaft already constructed.

☐ 0.7 million tons of iron ores extracted per year

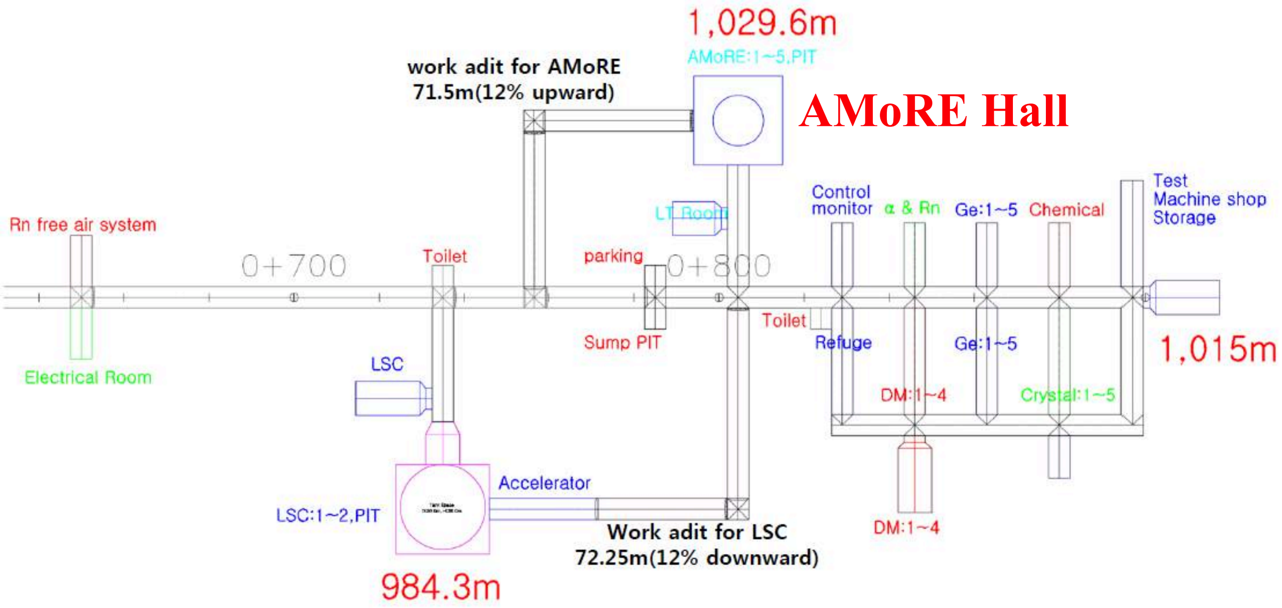


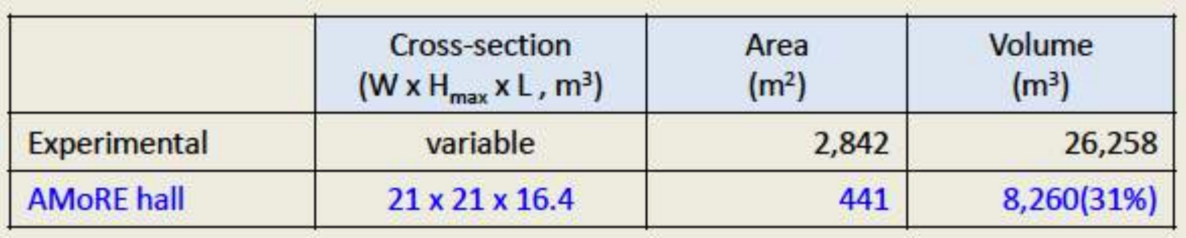
☐ **4 major constructions**

- ➢ **Tunnel excavation**
- ➢ **Shaft cage**
- ➢ **Underground lab**
- ➢ **Surface office/lab**

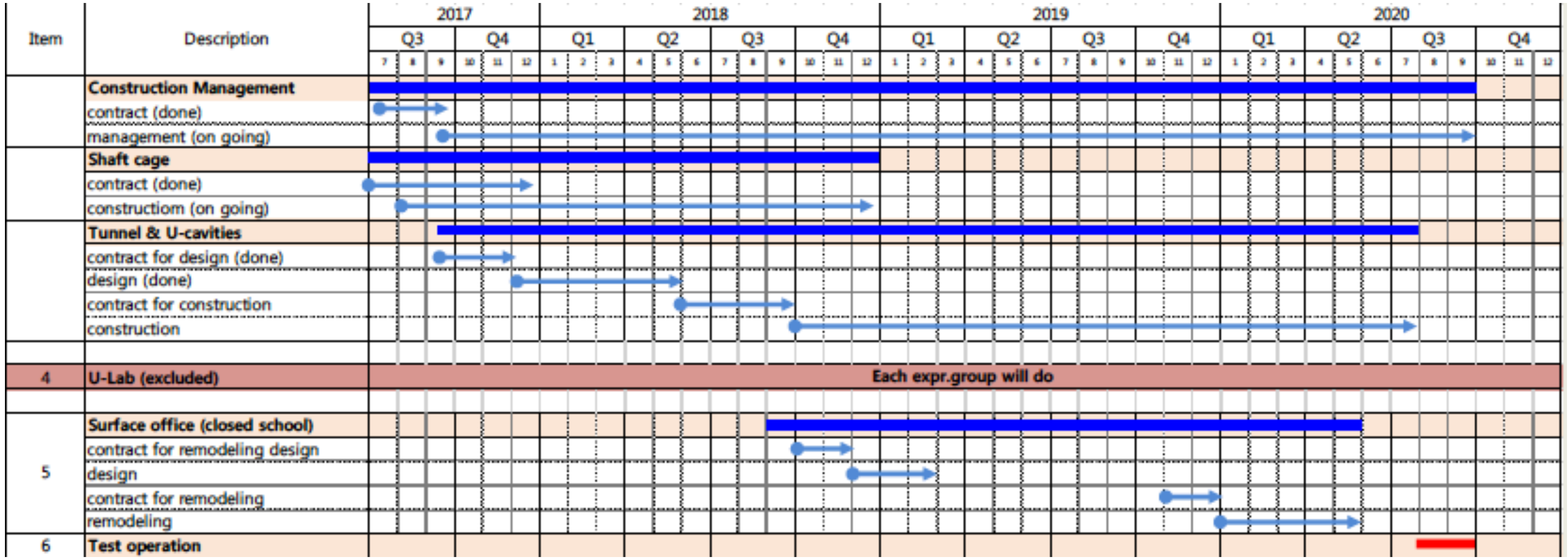
Handeok has two shafts for mining
1st shaft ~300 m deep
2nd shaft 600 m deep (NEW)

Yemi Lab: Floor Plan and schedule



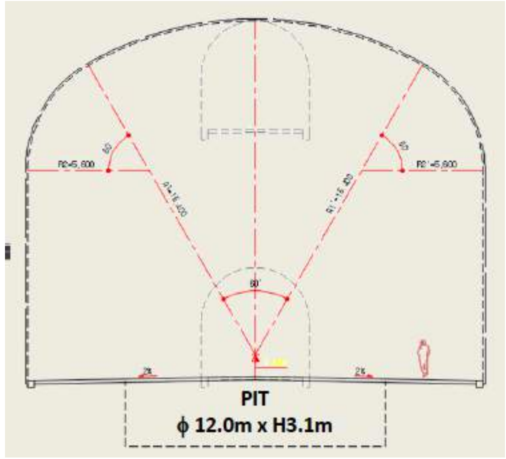


	Cross-section (W x H_{max} x L , m^3)	Area (m^2)	Volume (m^3)
Experimental	variable	2,842	26,258
AMoRE hall	21 x 21 x 16.4	441	8,260(31%)



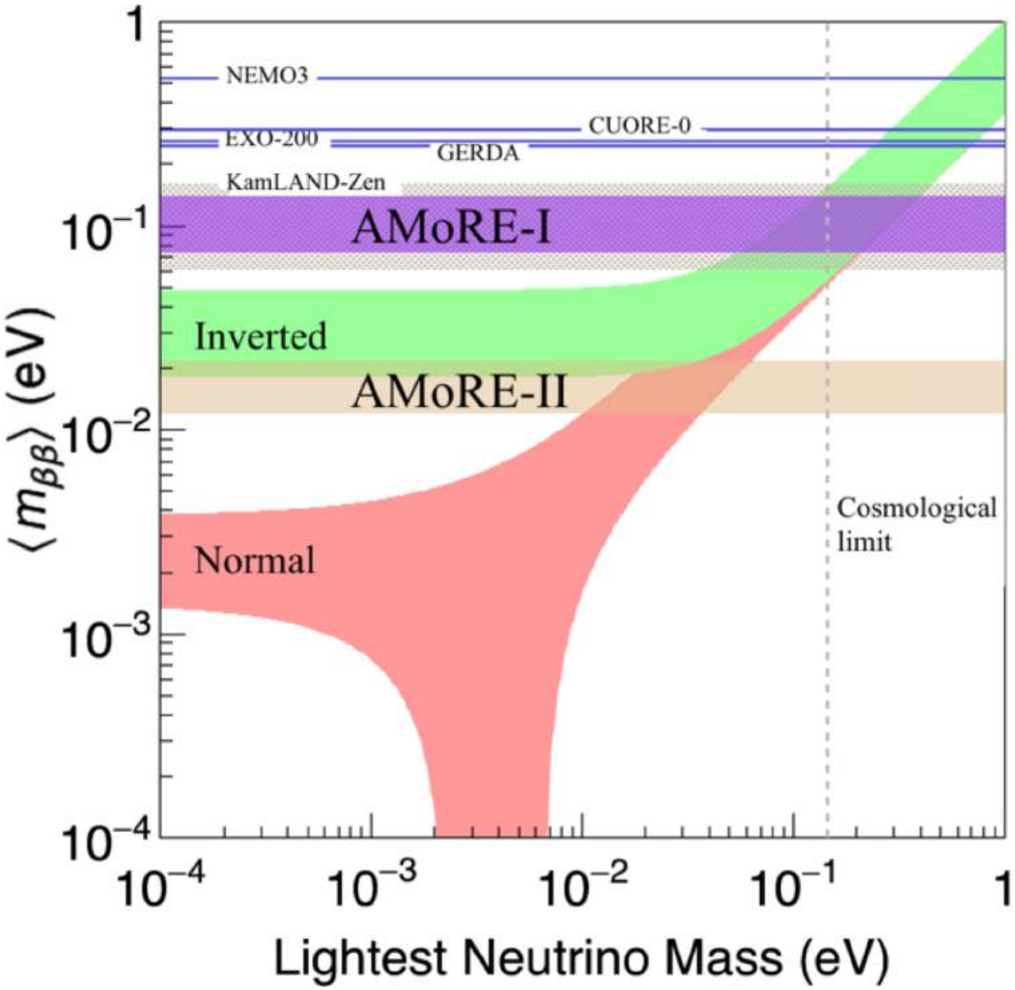
Item	Description
	Construction Management
	contract (done)
	management (on going)
	Shaft cage
	contract (done)
	construction (on going)
	Tunnel & U-cavities
	contract for design (done)
	design (done)
	contract for construction
	construction
4	**U-Lab (excluded)**
5	**Surface office (closed school)**
	contract for remodeling design
	design
	contract for remodeling
	remodeling
6	**Test operation**

Cross section of AMoRE Hall



Summary

- ☐ Five commissioning runs in AMoRE-pilot have been completed and the 6th run started last March after another system upgrades (radio-active components replacement).
- ☐ AMoRE-I is currently being prepared to start late this year.
- ☐ AMoRE-II preparation is ongoing in parallel together with the new ARF (Yemi Lab) construction.



- ◆ Nuclear Matrix Element: QRPA (Faessler et al., 2012)
- ◆ AMoRE-I: 5 kg and 5 years
- ◆ AMoRE-II: 200 kg and 5 years
- ◆ It was assumed as “zero-background”.