



# **AMoRE**

Search for neutrinoless double beta decay of <sup>100</sup>Mo using low-temperature molybdenum containing crystal detectors

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On behalf of the AMoRE Collaboration

# **AMoRE Collaboration**



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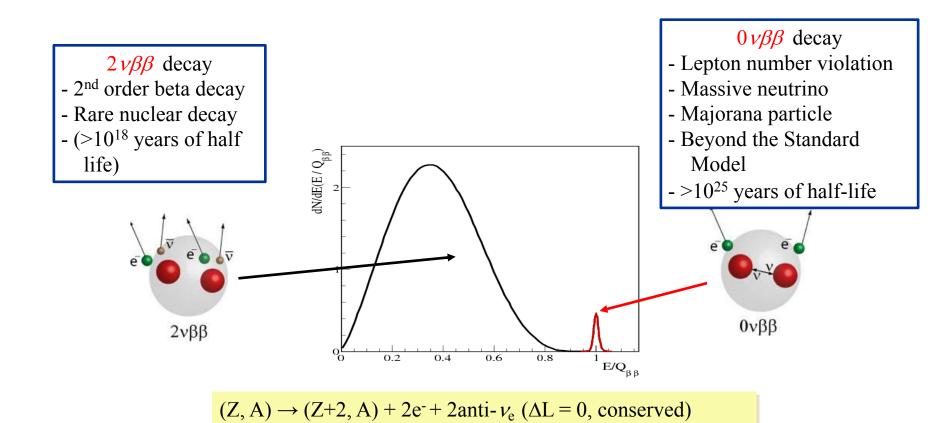
V. Alenkov et al., Technical Design Report for the AMoRE 0ν2β Decay Search Experiment, arXiv:1512.05957v1



## AMoRE: Neutrinoless double beta decay



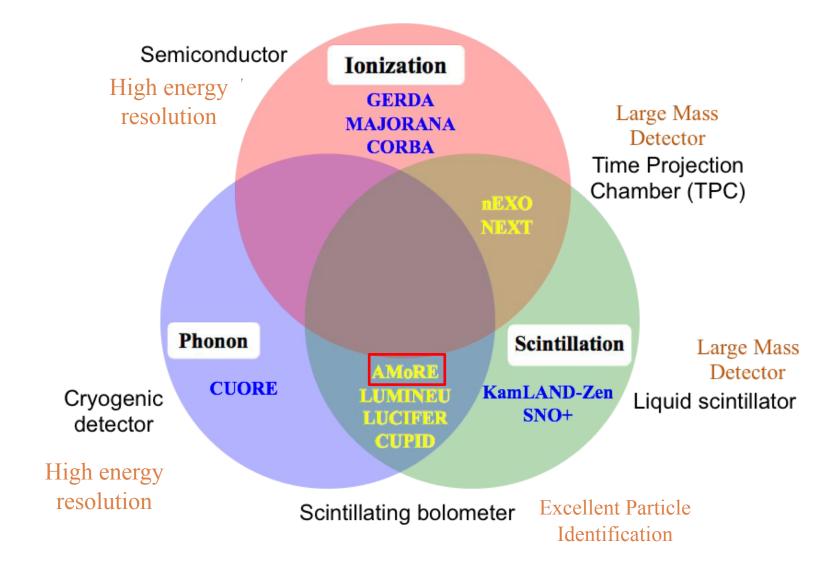
The goal of **AMoRE** is to search for neutrinoless double beta decay  $(0\nu\beta\beta)$  of  $^{100}$ Mo using Mo-based scintillating crystals and low-temperature sensors.



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

# Detection Techniques of 0vbb

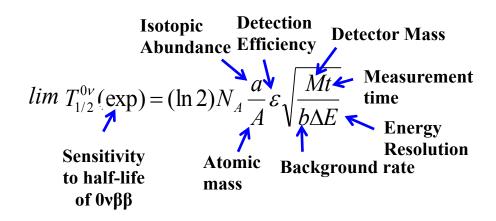




# **AMoRE Experimental Approach**



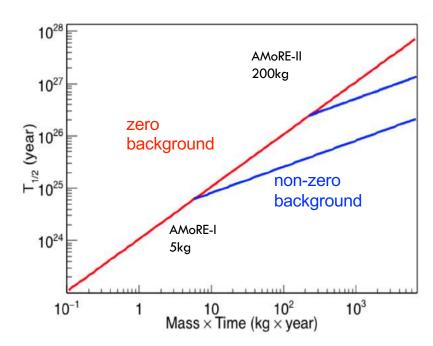
### Sizable background case:



### "Zero" background case:

When b is  $\sim O(1)$ ,

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

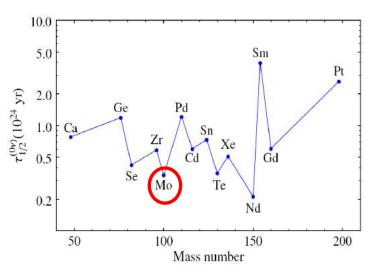


AMoRE is aiming for zero background.

# Why we use $^{100}$ Mo for $0\nu\beta\beta$ search ?



- High Q-value (ββ) of 3034.40 (12) keV. ( $^{208}\text{Tl}\rightarrow^{208}\text{Pb}$ , the highest & intensive 2.614 MeV  $\gamma$  from nature)
- High natural abundance of 9.7%.
- Relatively short half life  $(0\nu\beta\beta)$  expected from theoretical calculation.



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

Candidate	Q (MeV)	Abund. (%)
<sup>48</sup> Ca	4.271	0.19
<sup>76</sup> Ge	2.040	7.8
<sup>82</sup> Se	2.995	8.7
<sup>100</sup> Mo	3.034	9.7
<sup>116</sup> Cd	2.802	7.5
<sup>124</sup> Sn	2.228	5.8
<sup>130</sup> Te	2.533	34.1
<sup>136</sup> Xe	2.479	8.9
<sup>150</sup> Nd	3.367	5.6

# **AMoRE Parameters**

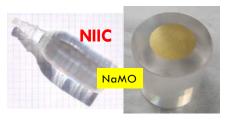


- □ Crystals: <sup>40</sup>Ca<sup>100</sup>MoO<sub>4</sub>(CMO) or XMO (X: Li, Na, or Pb)
  - $\square$  100Mo enriched: > 95%
  - $\blacksquare$  <sup>48</sup>Ca depleted: < 0.001% (N.A. of <sup>48</sup>Ca:0.187%)
- □ Low temperature detector: 10 30 mK
- □ Energy resolution: ~5 keV @ 3MeV, Excellent PSD









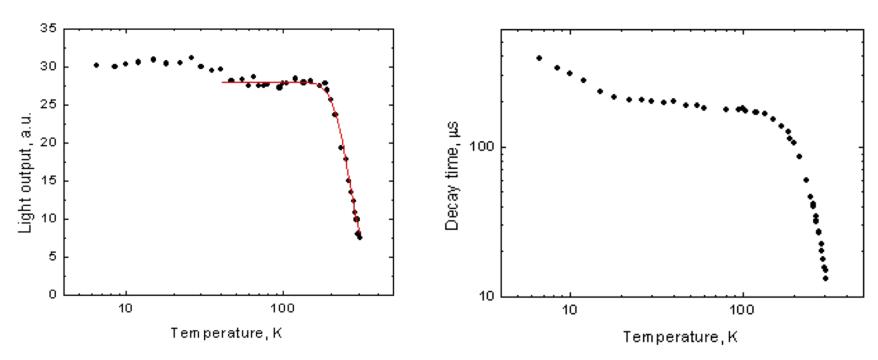
#### The AMoRE Plan

	Pilot	Phase I	Phase II
Mass (Crystal)	1.9 kg CMO	6 kg (CMO + LMO)	200 kg XMO (X: Li, Na, Pb)
Bkg [keV·kg· year]-1	<10-2	<10-3	<10-4
T <sub>1/2</sub> Sensitivity [years]	~10 <sup>24</sup>	~10 <sup>25</sup>	~8 ×10 <sup>26</sup>
<m<sub>ββ &gt; Sensitivity [meV]</m<sub>	400 - 700	100 - 300	13 - 25
Location	Y2L (700	m depth)	Yemilab (1100m depth)
Schedule	2015 - 8	2020 - 2021	2021 -

## Temperature dependence of CaMoO<sub>4</sub> light yield



■ From RT to 7 K, 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



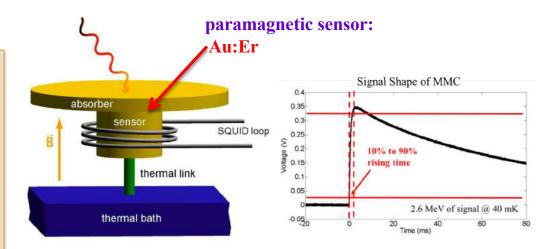
#### S.J. Lee et al., Astroparticle Physics 34 (2011) 732-737

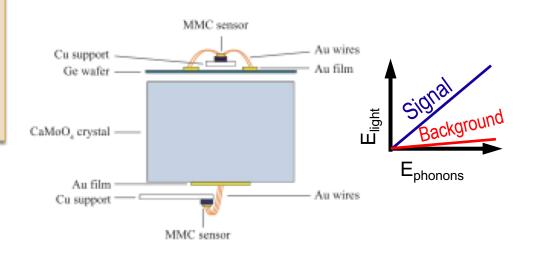
#### Principle of operation

- 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

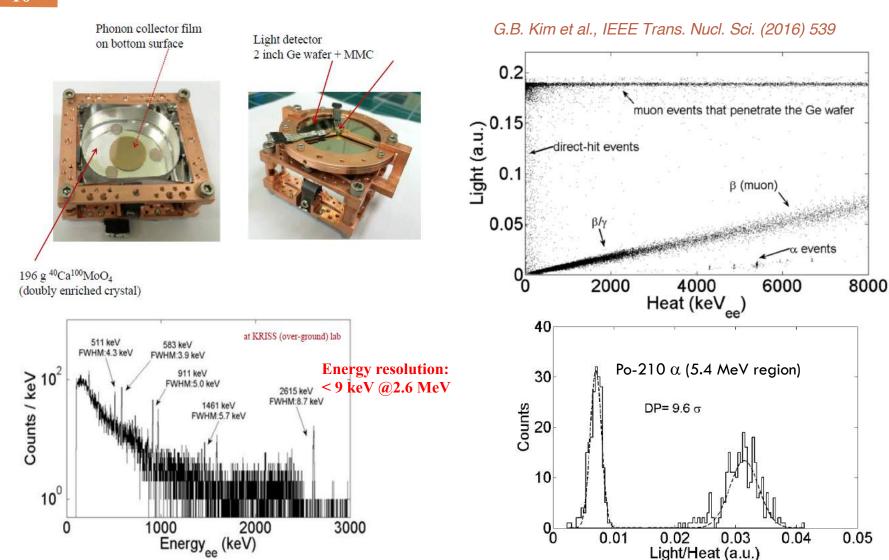
- Fast rising signal :  $\sim$ 0.5 ms (critical to reduce 2vββ random coincidence)
- Fairly easy to attach to absorber. (i.e. CMO)
- Excellent Energy resolution





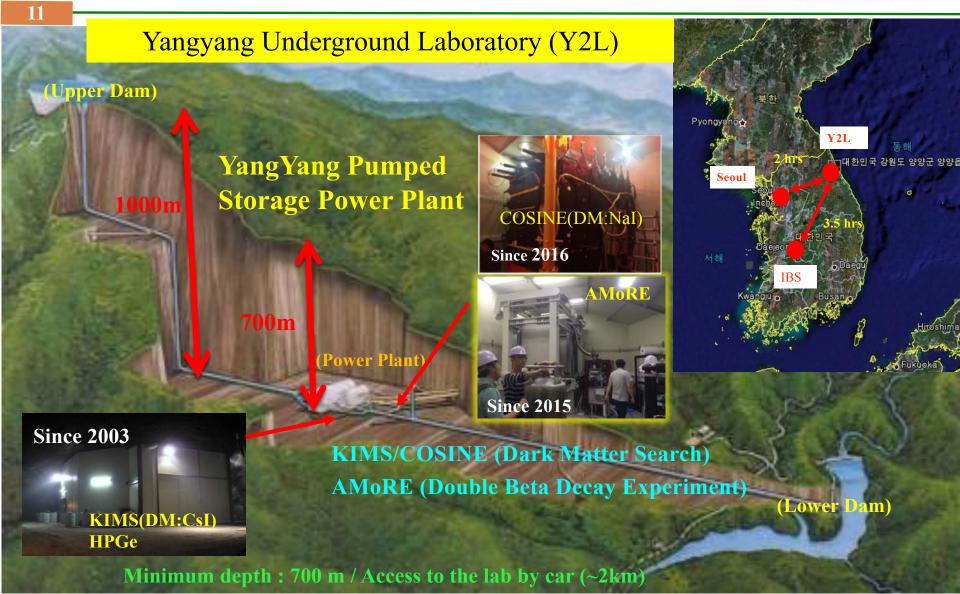
### **Prototype Detector and Above-ground Measurements**





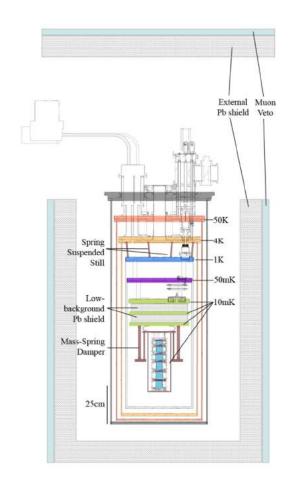
### AMoRE-Pilot/I at Y2L in Yangyang, Korea



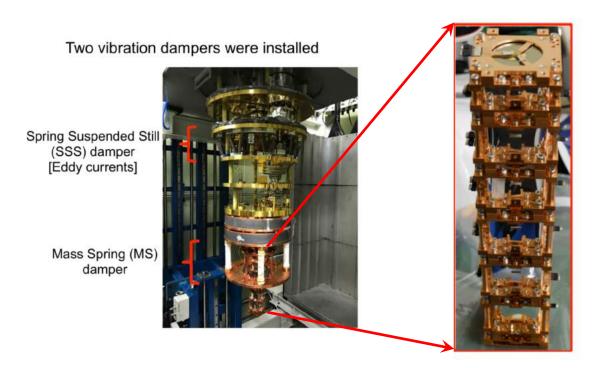


## **AMoRE-Pilot (Run6)**





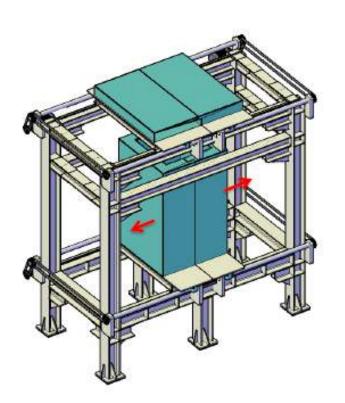
- Six CaMoO4 crystals with total mass of ~ 1.9 kg
- Two vibration dampers were installed

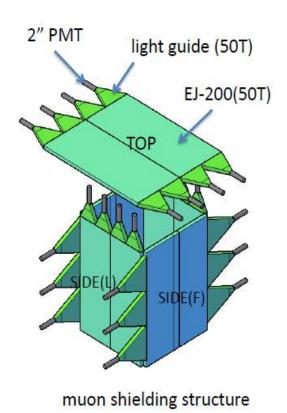


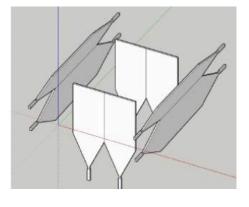
#### 10cm ultra-low background Pb

### Shielding structure of AMoRE-pilot & AMoRE-I









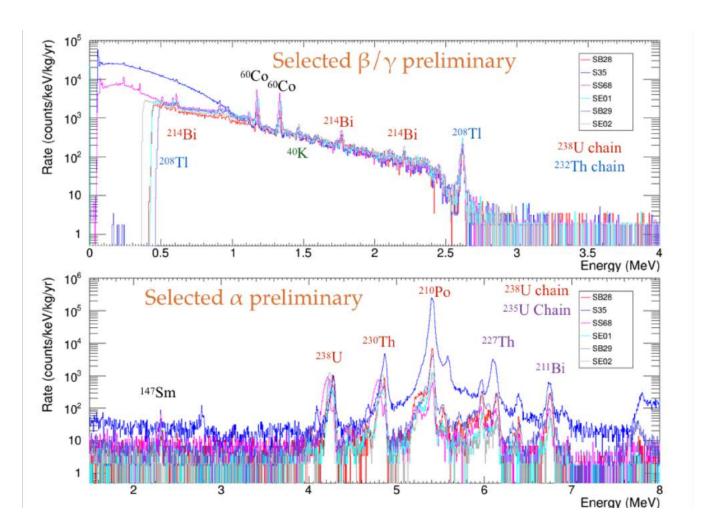
Additional muon counters to cover gaps from AMoRE-I

15cm low background Pb

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

## Selected $\beta/\gamma$ and $\alpha$ Event Distributions





After applying rejection and selection cuts,  $\alpha$  and  $\beta/\gamma$  distributions were obtained for each detector.

## **Backgrounds of AMoRE-Pilot Exp.**

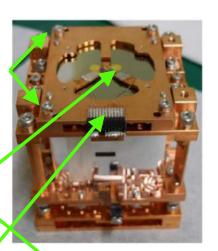


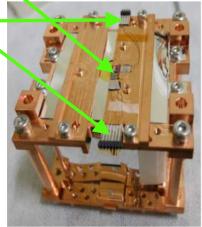
#### Photon Detector

SS(Stainless Steel) screws

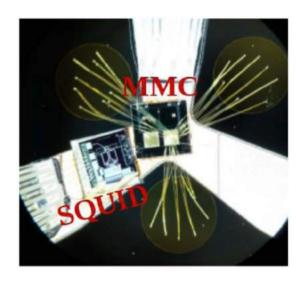
PCB (Printed circuit Board)+Stycast

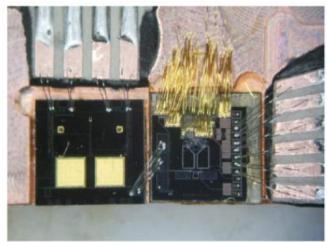
Pin Connector+ PCB+Stycast











## **Detector components radio-activities (HPGe)**



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

Item	Total mass (g)	<sup>226</sup> Ra (mBq)	<sup>228</sup> Ac (mBq)	<sup>228</sup> Th (mBq)	<sup>40</sup> K (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.

## Sources of background

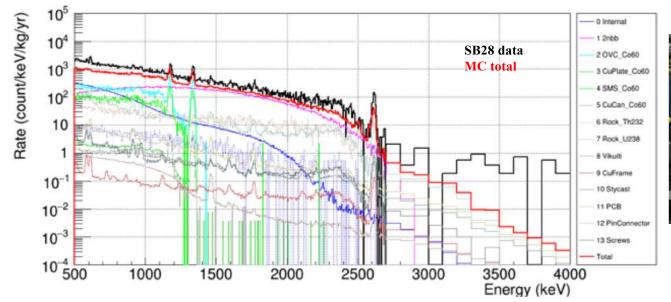


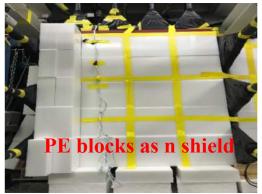
El	Decay	$T_{1/2}$	Q(MeV)	Mother	Chain	Comment
<sup>26</sup> Al	EC	$7.4 \times 10^5 \text{y}$	4.004	N/A		Long lifetime
<sup>56</sup> Co	EC	0.21y	4.567	N/A		Short lifetime
$^{88}Y$	EC	0.29y	3.623	<sup>88</sup> Zr (0.23 y)		Short lifetime
<sup>106</sup> Rh	B-	30s	4.004	$^{106}$ Ru(1.02y)		
<sup>126</sup> Sb	В-	12.5d	3.670	$^{126}$ Sn(2.3x10 $^{5}$ y)		Long lifetime
<sup>146</sup> Eu	EC	4.61d	3.878	<sup>146</sup> Gd (0.13 y)		Short lifetime
<sup>208</sup> Tl	B-	3.05m	4.999	<sup>228</sup> Th (1.91 y)	<sup>232</sup> Th	Major source
<sup>209</sup> Tl	B-	2.16m	3.970	<sup>233</sup> U(159200y)	$^{233}U$	2.1% branching
<sup>210</sup> Tl	В-	1.3m	5.482	<sup>226</sup> Ra(1600y)	$^{238}U$	0.02% branching
<sup>214</sup> Bi	B-	19.9m	3.269	<sup>226</sup> Ra(1600y)	$^{238}U$	Major source

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

## Run5 $\beta/\gamma$ candidate events and MC





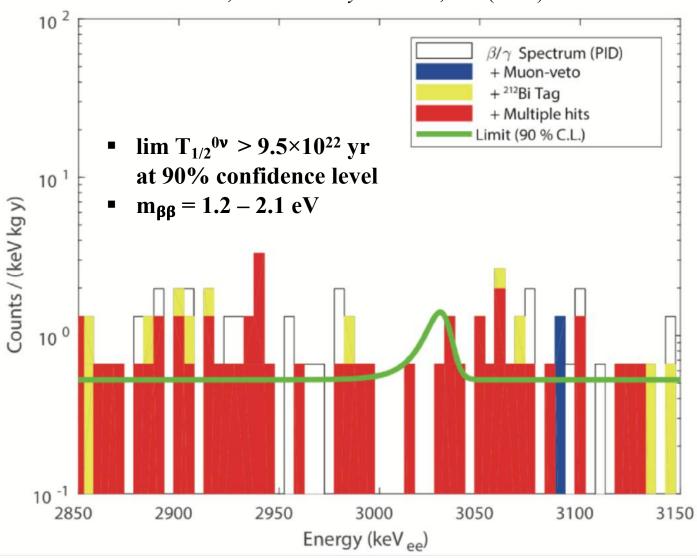


- ☐ MC distributions are estimated rates with measured activities except <sup>60</sup>Co.
- ☐ Level of <sup>60</sup>Co was estimated by likelihood fit with free parameters to match shapes.
- ☐ More background for data at higher energy than MC (E > 2.8 MeV).  $\rightarrow$  Added PE, borated PE, borated rubber sheets, and boric acid as a neutron shield to block neutrons from the rock on August 15<sup>th</sup>, 2018.

## Physics result from AMoRE-pilot run-5



V. Alenkov, et al. Eur. Phys. J. C 79, 791 (2019).

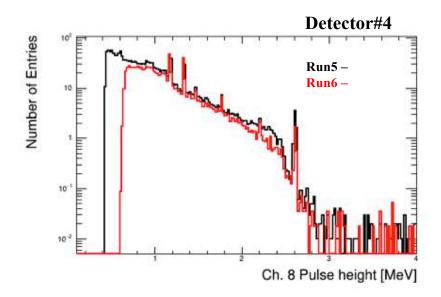


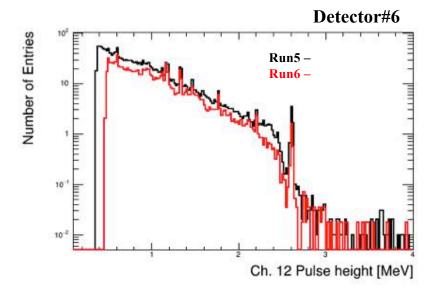
### **AMoRE Pilot Run-6**



Modifications in 6<sup>th</sup> commissioning run from the 5th run.

- Six CaMoO<sub>4</sub> 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) 2.8 < E < 4 MeV 0.863±0.092

0.512±0.148

0.723±0.085 0.598±0.159

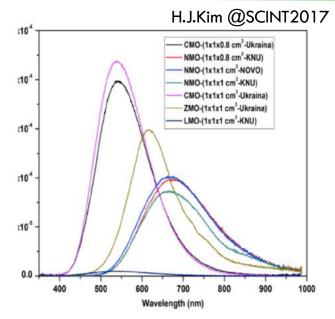


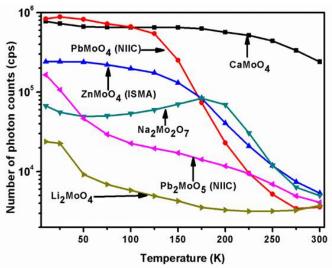
- Even though CMO (CaMoO<sub>4</sub>) is a very good detector material which has the largest light output among Mo based crystal scintillators, there are other Mo crystals suitable for AMoRE-II experiment besides CMO. CMO has disadvantage that we have to purchase <sup>48</sup>Ca depleted isotopes, expensive.
- We are working on R&D of various molybdate crystals including Li<sub>2</sub>MoO<sub>4</sub>, Na<sub>2</sub>Mo<sub>2</sub>O<sub>7</sub>, PbMoO<sub>4</sub> and other compounds..

Crystals	$\lambda_{em}$	Decay time [µs]	E_(LED) [%]	E_(90 Sr) [%]
CaMoO <sub>4</sub>	540	237	100	100
ZnMoO <sub>4</sub> (ISMA)	620	F	22	32
PbMoO <sub>4</sub> (NIIC)	545	20	13	105
Pb <sub>2</sub> MoO <sub>5</sub> (NIIC)	600	5	3	22
Li <sub>2</sub> MoO <sub>4</sub>	540	23	1	5
Cs <sub>2</sub> Mo <sub>2</sub> O <sub>7</sub>	701	363[31]	12	1
Na <sub>2</sub> Mo <sub>2</sub> O <sub>7</sub>	663	756[36]	55	9

 $<sup>\</sup>lambda_{\rm em}$ , 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 We are going to decide the crystal by mid. 2020.



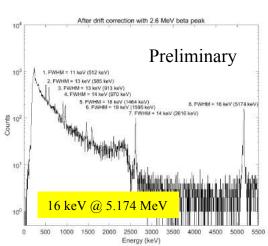


## Full size crystals tests at LT (~ 20 mK)

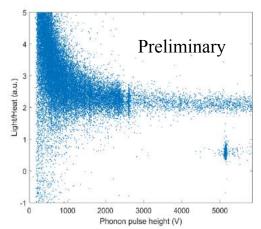


#### KRISS test for NIIC Li<sub>2</sub>MoO<sub>4</sub>





Above ground under Thoriated W rode (3 days)



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



### Low background Crystal growing facility at CUP



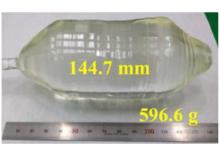
- Main goal
  - CaMoO<sub>4</sub> & Li<sub>2</sub>MoO<sub>4</sub> crystal growing R&D for AMoRE-II
  - Other DBD or DM crystal R&D
- Deep purification of CaCO<sub>3</sub>, Li<sub>2</sub>CO<sub>3</sub>, Na<sub>2</sub>CO<sub>3</sub> and MoO<sub>3</sub> powders (< 50 μBq/kg for U,Th chain)
- Crystal growing equipment:3 Czochralski, 2 Kyropoulous, 1 Bridgman crystal growing set-ups.











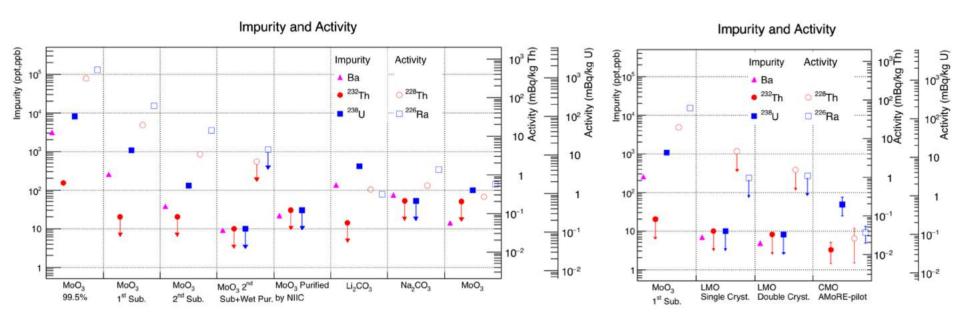
**CMO & LMO crystals by CUP** 

- O.Gileva's poster on purification at CUP
- D.Y. Kim's poster on crystal growth at 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
- $\square$  Extremely low background in ROI (< 0.0001 evt/kg/y)
- ☐ Easy to grow, low price for crystal growing.

<sup>48depl</sup>Ca<sup>100</sup>MoO<sub>4</sub> (AMoRE-Pilot/I): Excellent but <sup>48depl</sup>Ca & Ca deep purification necessary.

### **AMoRE Phase I: About to start**



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

Six <sup>40</sup>Ca<sup>100</sup>MoO<sub>4</sub> crystals from Pilot: 1.886 kg Seven new <sup>40</sup>Ca<sup>100</sup>MoO<sub>4</sub> crystals: 2.696 kg Five extra crystals Li<sub>2</sub><sup>100</sup>MoO<sub>4</sub>: 1.5 kg

Total: 6 kg, 18 crystals with ~2.4 kg of <sup>100</sup>Mo

#### Extra works to be done:

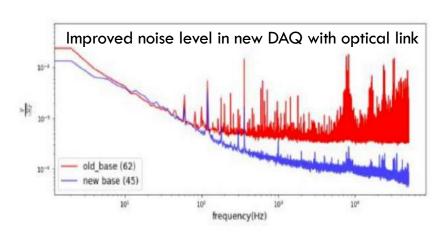
MMC+SQUID wirings for 36 channels.
MMC production at IBS
SQUIDs from PTB
Mass Spring Damper modification
New superconducting shield
Extra DAQ modules
Muon counters

#### Schedule:

Run starts from March, under preparation 3+ years measurement

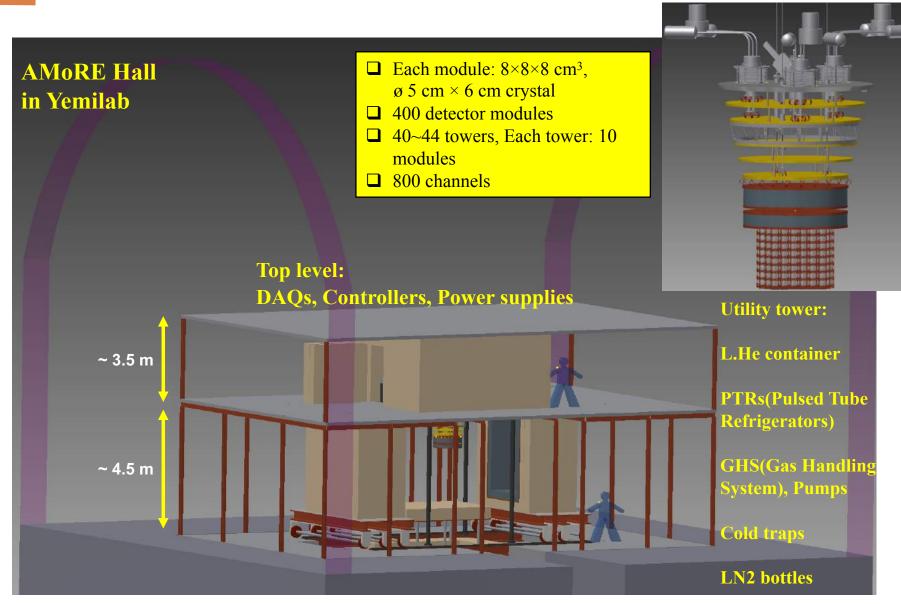






### AMoRE-II design: Cryostat, shield, clean room etc..

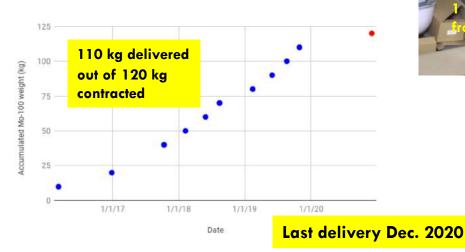




### Mo-100 powder for AMoRE-II



Lot	Delivery@Y2L	Wedight/kg
#1(3172)	3/9/16	10
#2(3328)	3/ 4/ 10	10
3434	12/28/16	10
3497	10/12/17	10
3535	10/12/17	10
3589	2/7/18	10
3649	5/29/18	10
3675	8/14/18	10
3741	2/13/19	10
3803	5/31/19	10
3824	8/20/19	10
3848	10/20/19	10







HPGe Array meas. (9/13 - 11/28/2017)

- $^{226}$ Ra chain ( $^{238}$ U): 0.78  $\pm$  0.19 mBq/kg
- <sup>228</sup>Th chain (<sup>232</sup>Th): 0.65 ± 0.15 mBq/kg (first measurement)
- $^{88}$ Y: 97 ± 25  $\mu$ Bq/kg (cosmogenic)

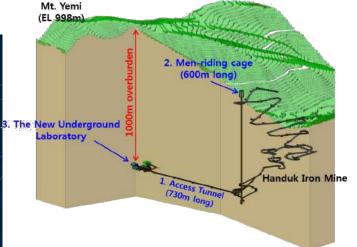
### Yemilab: A new underground lab in Handeok mine



- ☐ The only operating iron ore mine in Korea.
- □ 0.7 million tons of iron ores extracted per year
- ☐ A 600 m long 2<sup>nd</sup> shaft is in operation. Main route to the underground lab for scientists after the construction is completed.

□ A ~5 km rampway for mining shared with tunnel excavation and construction works.







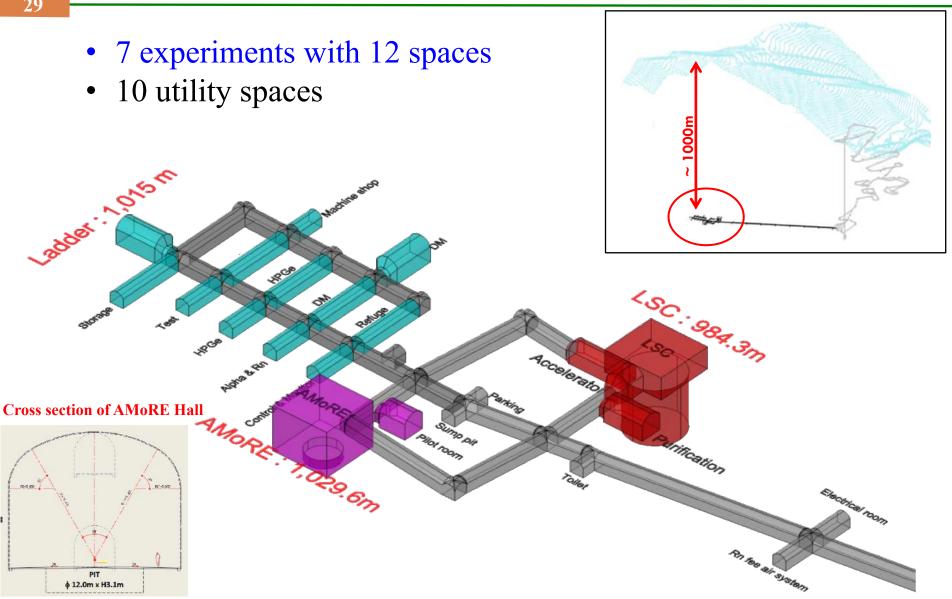
- Tunnel excavation
- **>** Shaft cage ✓
- Underground lab
- Surface office/lab



Handeok has two shafts for mining  $1^{st}$  shaft  $\sim 300$  m deep  $2^{nd}$  shaft 600 m deep (NEW)

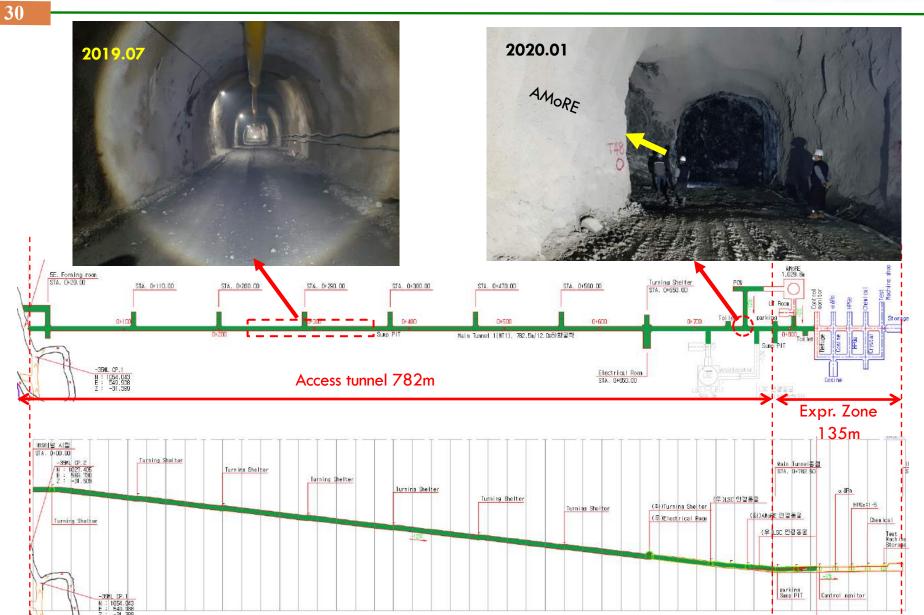






## Yemilab: Tunnel excavation (~75% now) by July 2020

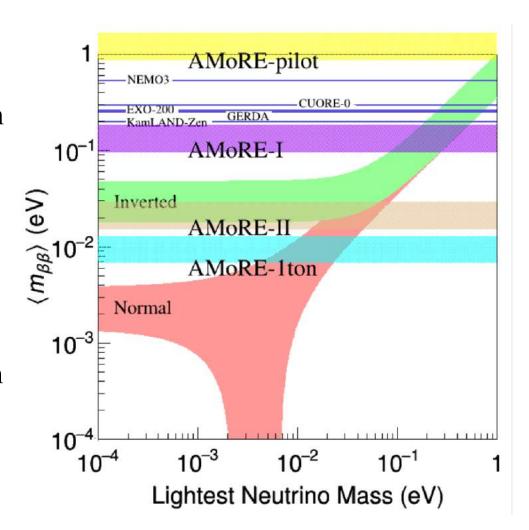




# Summary



- □ Seven commissioning runs in AMoRE-pilot have completed in December 2018. First physics result published in 2019. Analysis work on-going.
- □ AMoRE-I is currently being prepared to start from March.
- □AMoRE-II preparation is ongoing in parallel together with the Yemilab construction.



### **Backup slides**



### **AMoRE-I CMO crystals (FOMOS)**

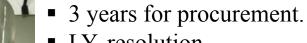




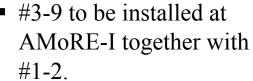








LY, resolution, transmittance, RT background measurements done.







Total: 3.387 kg

