Status of the AMORE double beta decay experiment

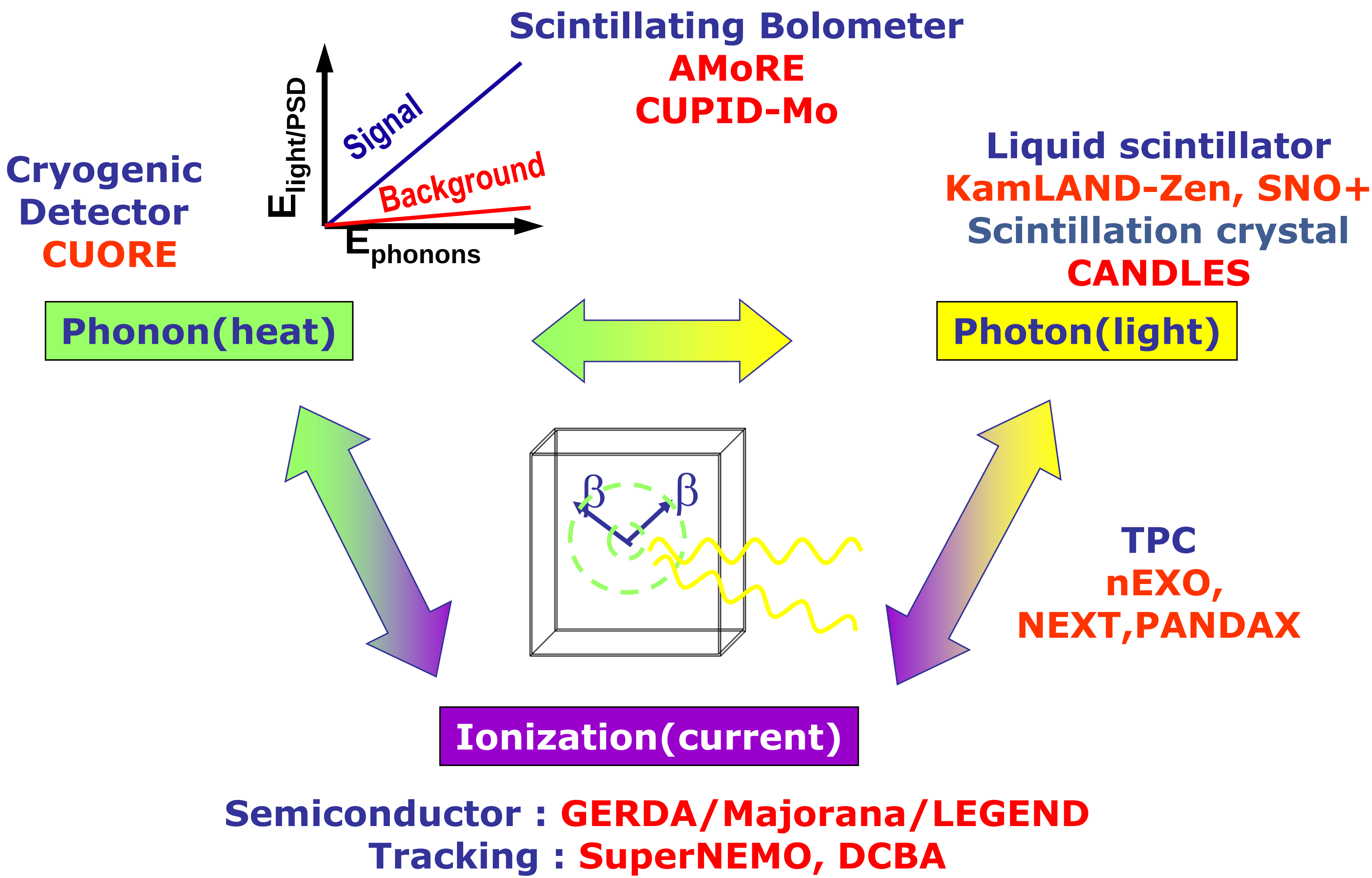
AMoRE (Advanced Mo-based Rare process Experiment)

HongJoo Kim
Kyungpook National University

On Behalf of AMoRE collaboration

6th Symposium on Neutrinos and Dark Matter
in Nuclear Physics (NDM18)
IBS, Daejeon, June 29th - July 4th, 2018.

Double beta decay detection technique



AMoRE Experimental sensitivity

For sizeable background case;

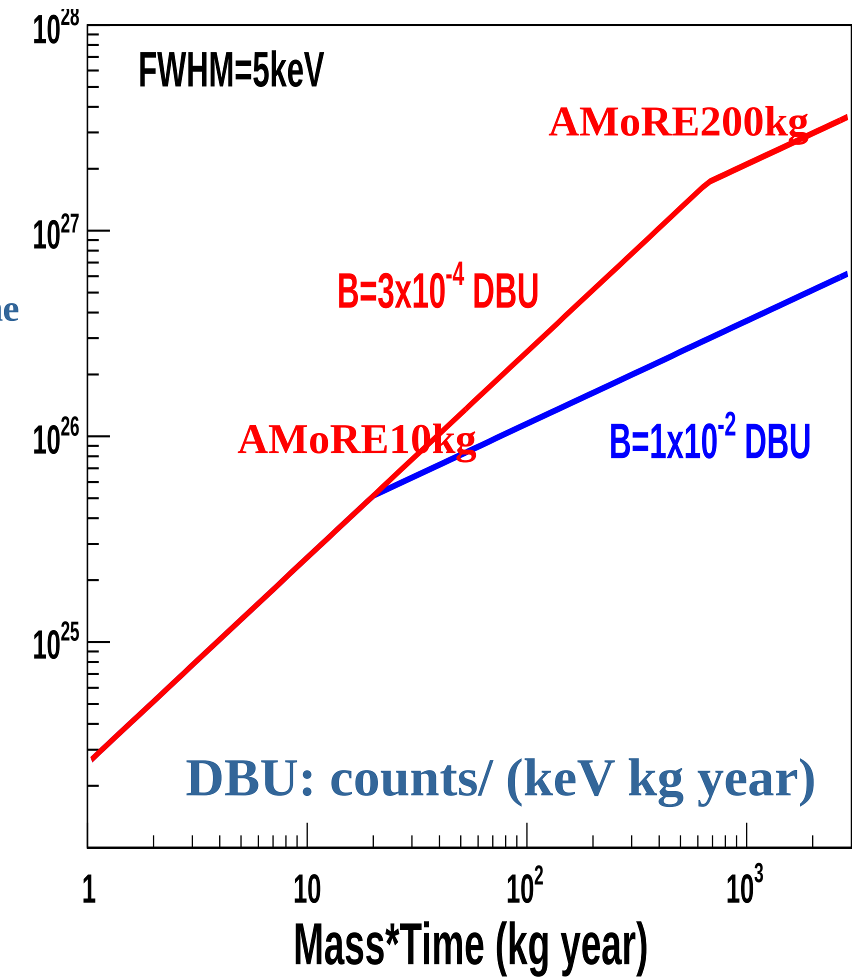
Isotopic Abundance — Detection Efficiency — Detector Mass — Time

$$T_{1/2}^{0\nu}(\exp) = (\log 2) N_a \frac{a}{A} e \sqrt{\frac{MT}{b \Delta E}}$$

Atomic mass — Background level (count/keV kg year) — Energy Resolution

For "zero" background case;
# of background events ~ O(1)
<- AMoRE goal

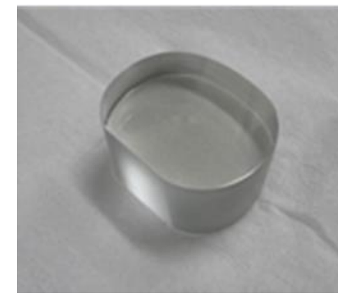
$$T_{1/2}^{0\nu}(\exp) = (\log 2) N_a \frac{a}{A} e \frac{MT}{n_{CL}}$$



AMoRE collaboration

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

AMoRE Parameters



- **Crystals: $^{depl}Ca^{100}MoO_4$ or other Mo-100 based crystals**
  - **^{100}Mo enriched: > 95%**
- **Cryogenic detector with MMC technique: 10 – 30 mK**
- **Energy resolution: ~5 keV @ 3MeV, Excellent PSD**
- **Aiming for zero background**

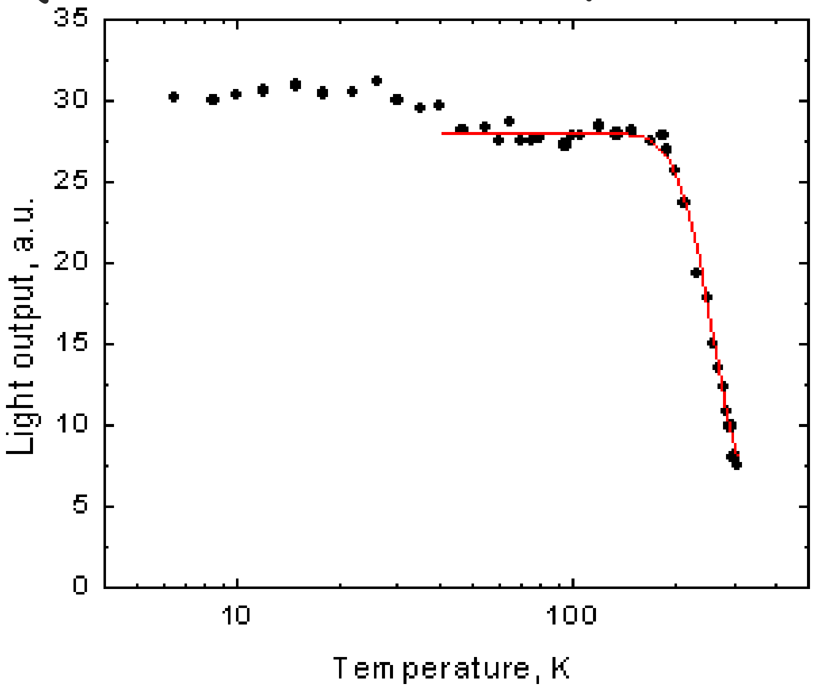
The AMoRE Plan:

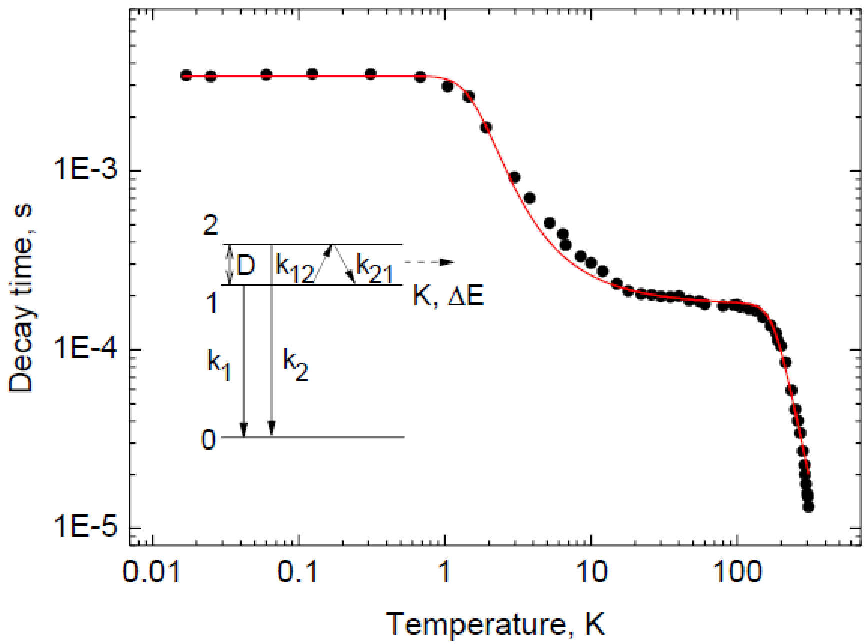
	Pilot	Phase I	Phase II
Mass	1.9 kg	6 kg	200 kg
Bkg [keV ·kg· year]$^{-1}$	$<10^{-2}$	$<10^{-3}$	$<10^{-4}$
$T_{1/2}$ Sensitivity [years]	$\sim10^{24}$	$\sim10^{25}$	$\sim8 \times 10^{26}$
$<m_{\beta\beta}>$ Sensitivity [meV]	400-700	100-300	13-25
Location	Y2L (700 m depth)		New ARF
Schedule	2016-8	2018 - 2020	2021- 2025

Temperature dependence of $CaMoO_4$

From RT to 7K, light yield increase factor 6

(V.B. Mikhailik et al., NIMA 583 (2007) 350, APL 106 (2015) 241904





CMO absolute light yield @RT: 4900±590 ph/MeV

(H.J. Kim et al., IEEE TNS 57 (2010) 1475)

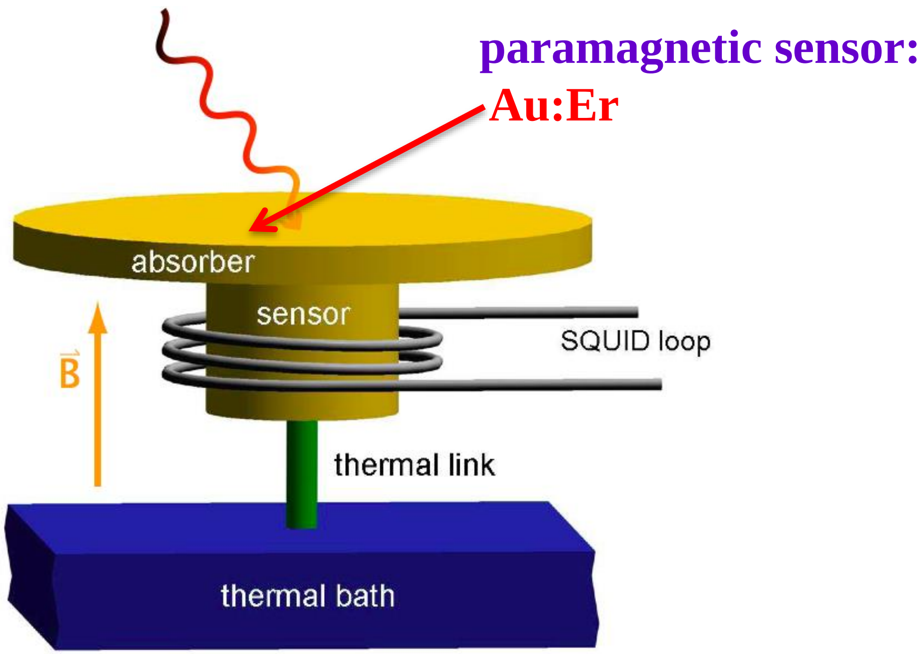
-> Light yield at cryogenic temp. : ~ 30,000 ph/MeV

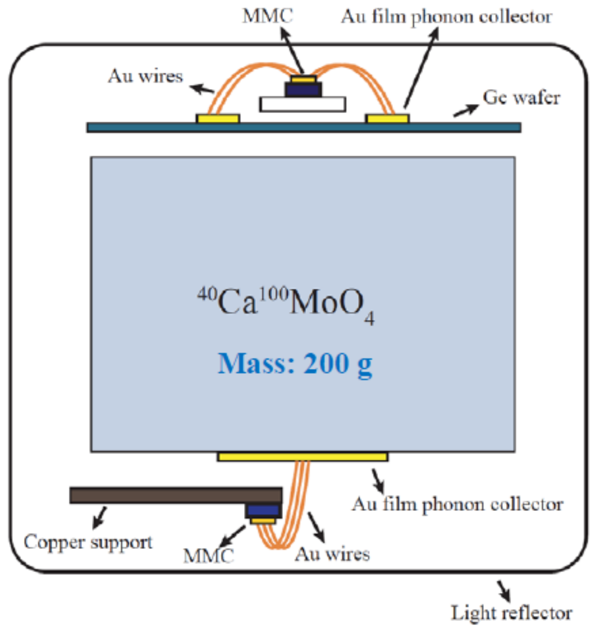
-> Highest light yield among Mo contained crystals.

(^{100}Mo, ^{48}Ca $0\nu\ \beta\beta$ decay, Dark matter search possible)

MMC (Metallic Magnetic Calorimeter) for LTD

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

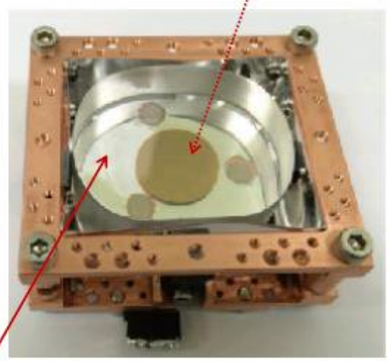




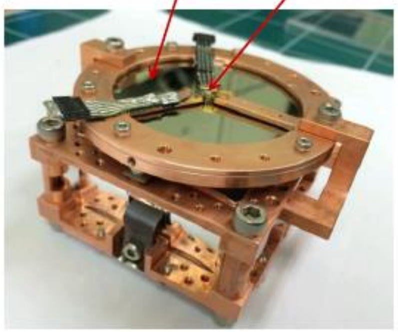
Advantage of MMC

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

Phonon collector film
on bottom surface



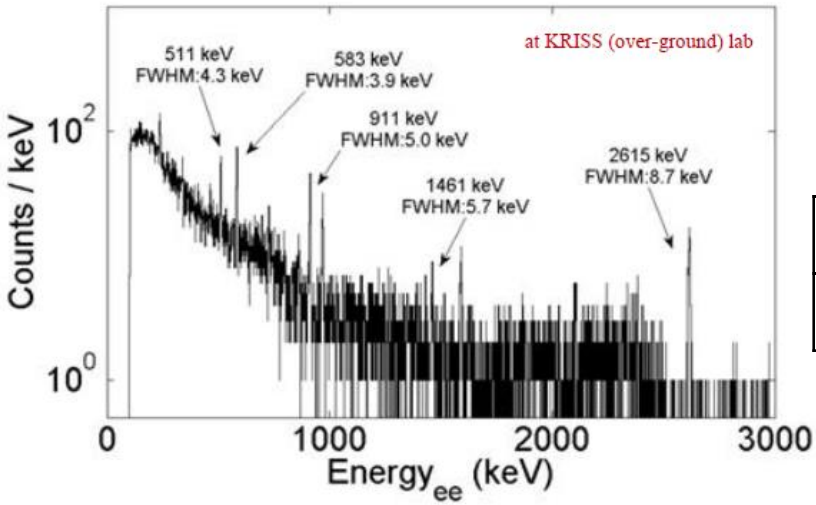
Light detector
2 inch Ge wafer + MMC



Poster 97: KIM, Inwook

MMC cryogenic technique for AMoRE

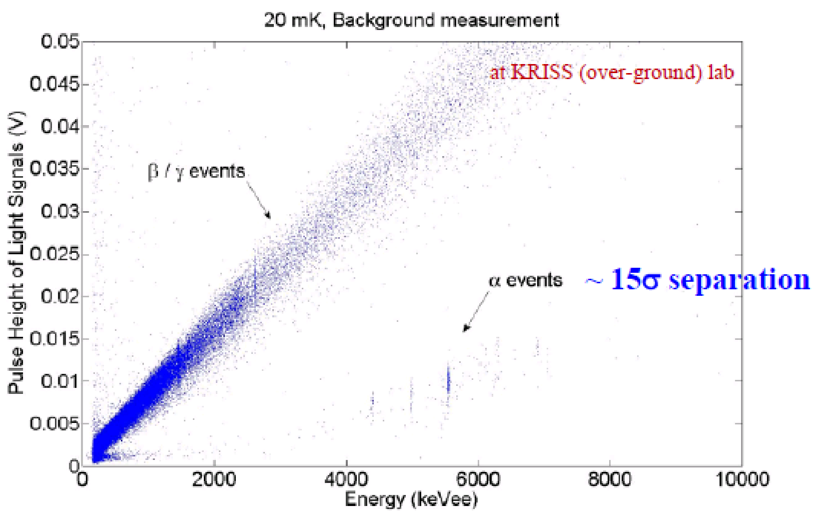
G. B. Kim, et al., IEEE Trans. Nucl. Sci. 63 (2016) 539

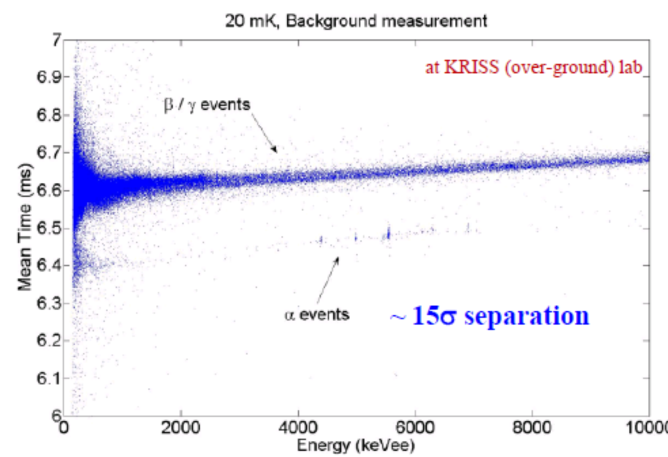


Overground test at KRISS @ 10 mK
Wet DR

Energy (keV)	511	1461	2615
FWHM (keV)	4.3	5.7	8.7

Energy resolution:
< 9 keV @2.6 MeV





Excellent α/e separation by both Light and PSD

Yangyang Underground Laboratory (Y2L)

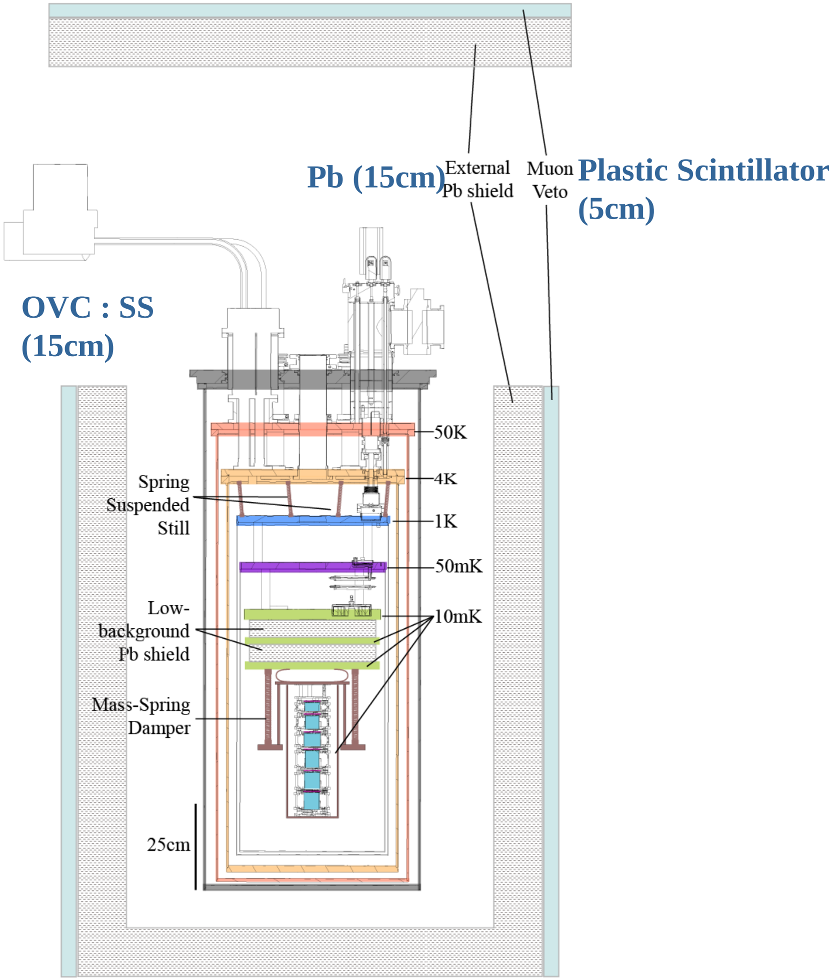
KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

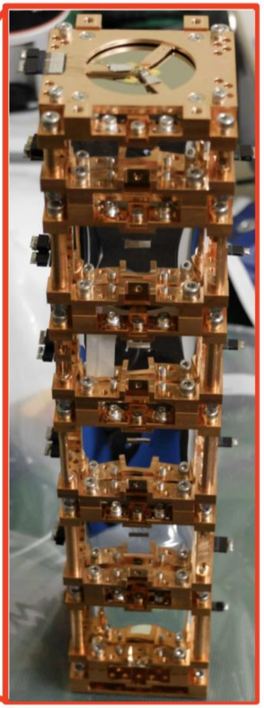
Minimum depth : 700 m / Access to the lab by car (~2km)

AMoRE-Pilot Setup

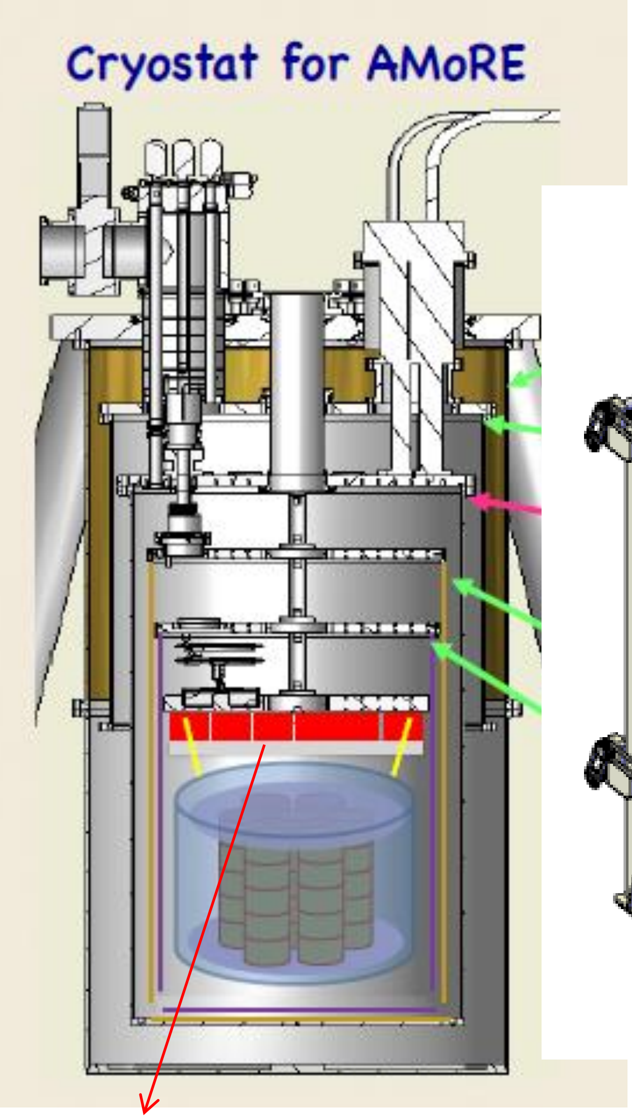
- 6 crystals making total mass 1.89 kg.
- Two vibration reduction systems are installed.



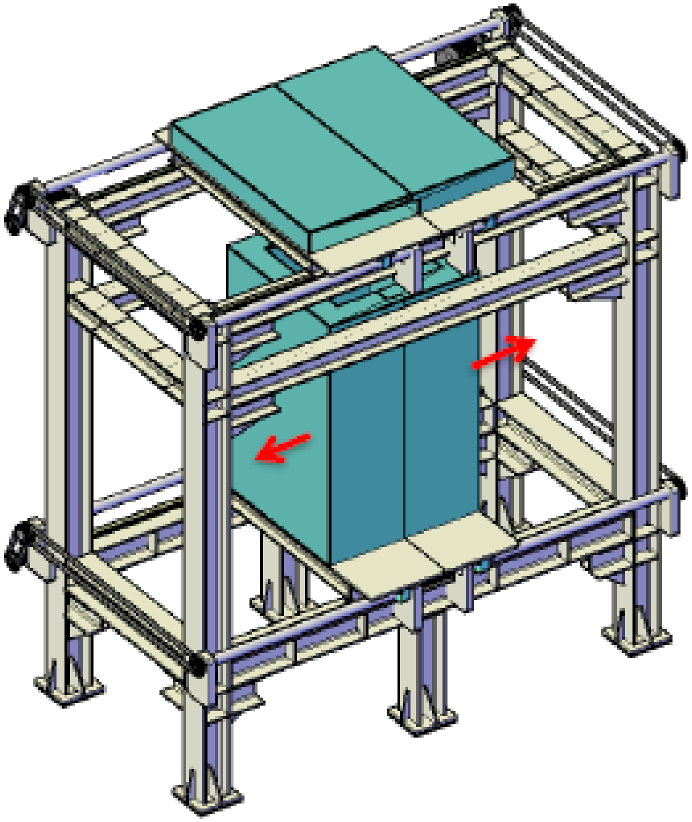
12 detector channels
(6 heat detectors + 6 light detectors)

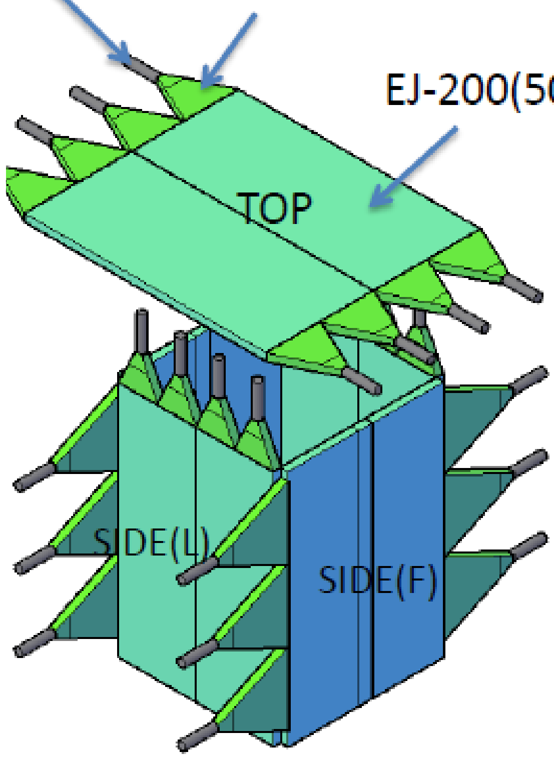


Shielding structure of AMoRE-pilot & AMoRE-I



Poster 100:
SEO, Kyungmin



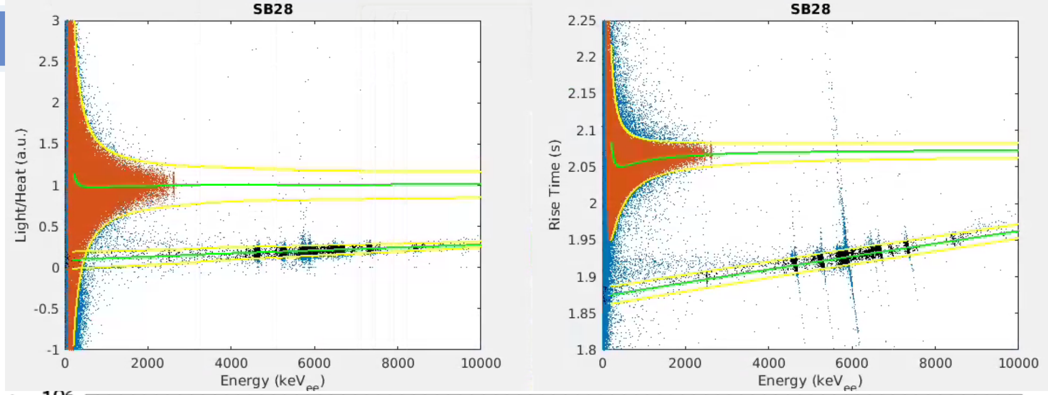


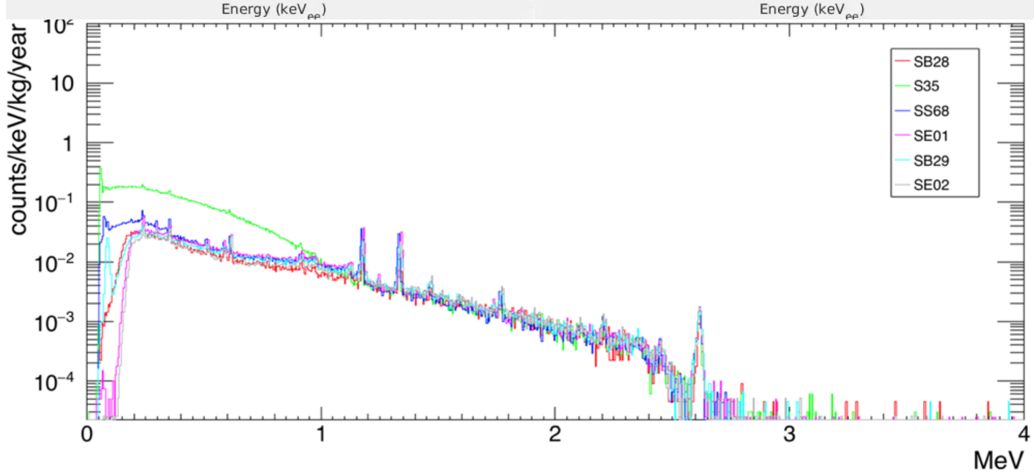
muon shielding structure

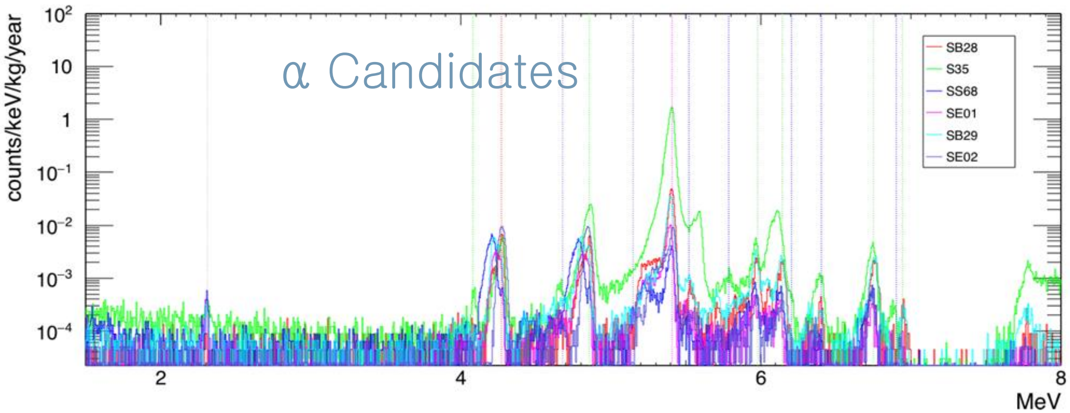
15cm low background Pb

10cm ultra-low background Pb

Selected β/γ and α Events Distributions



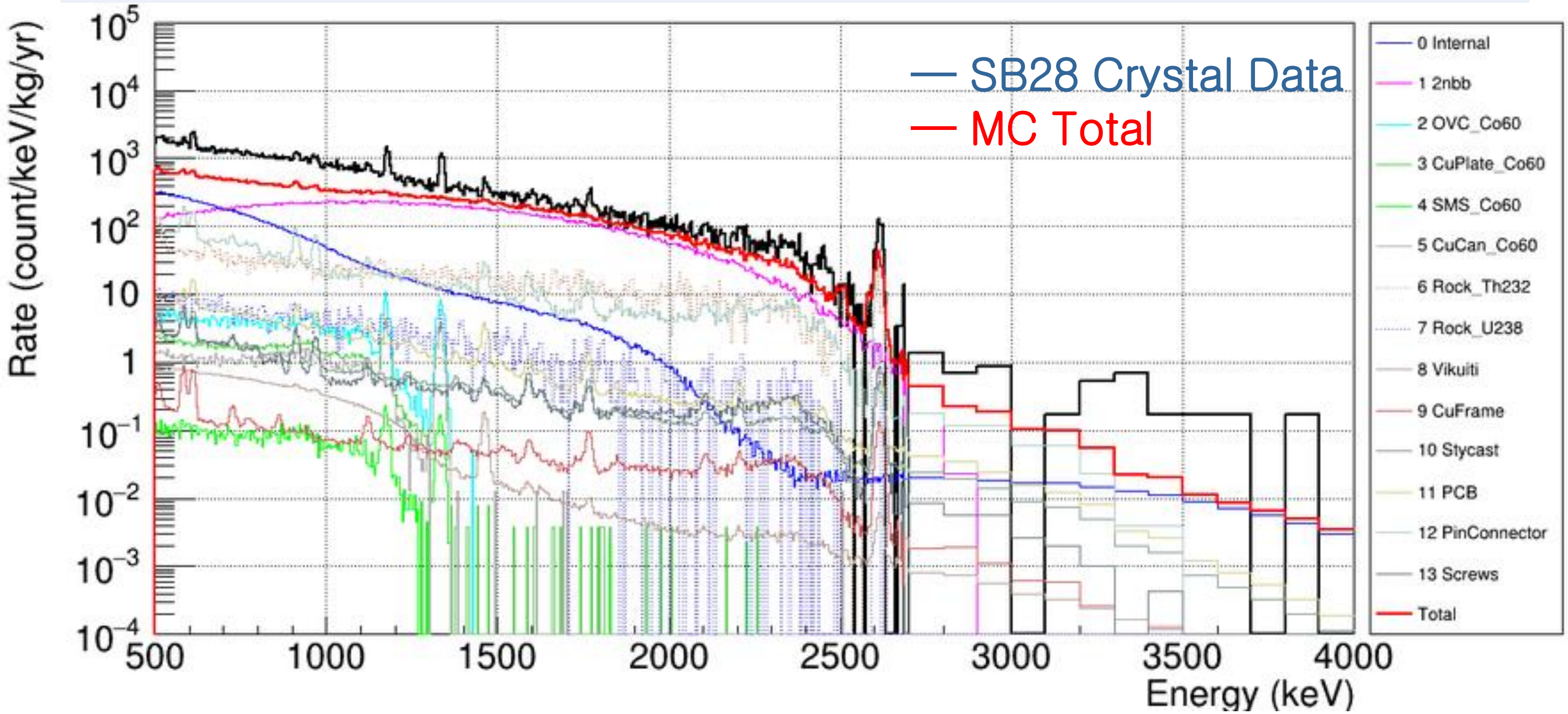




Poster 99:
SEO, Kyungmin

Comparison of Data with MC simulation

Simulated spectra from the radioactivity measurements vs data.



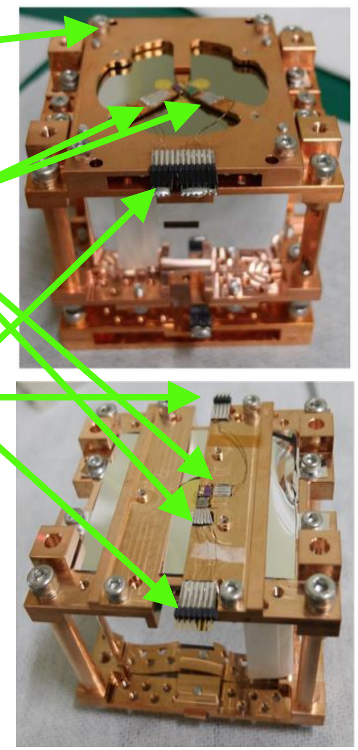
Comparison shows ;

- Active components should be one of dominant backgrounds @ ROI(region of interest).
- Data has more background at higher energy region (E>ROI) than the simulation.

Poster 85 simulation, HA, Daehoon, Poster 107: Dr. YOON, Young Soo

Radioactive components in AMoRE-Pilot Exp.

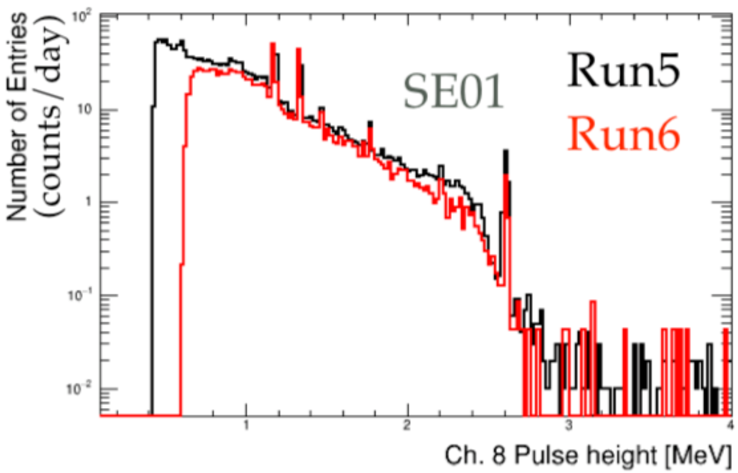
- Connectors, glue, and PCB boards were highly radioactive from HPGe measurements.
- Removed these parts for current run (run6) in Pilot setup.

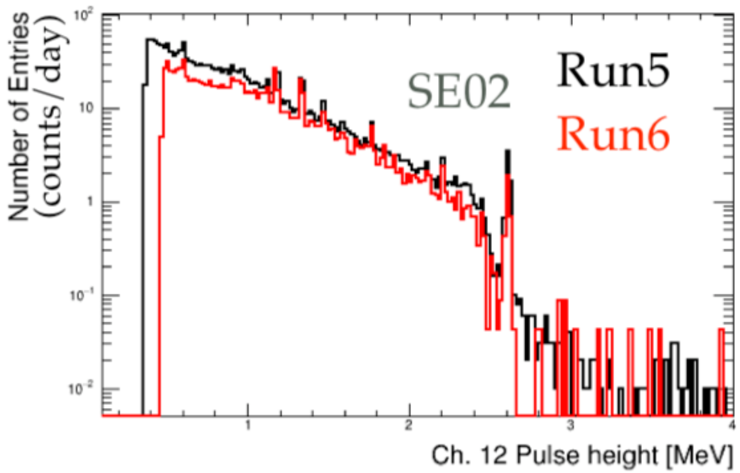


Poster 59 : Ms. LEE, Eunkyung

Background reduction in Pilot data

- **After removing active components inside IVC, the background around ROI is reduced by 0.1 – 0.2 ckky. (Preliminary)**
- **In next step, we will surround Pilot setup with Borated PE and PE blocks to reduce neutrons. We suspect neutron capture gammas from Fe and Cu may be the source of remaining background. (Similar to CUORE setup) Detail simulation is on-going.**





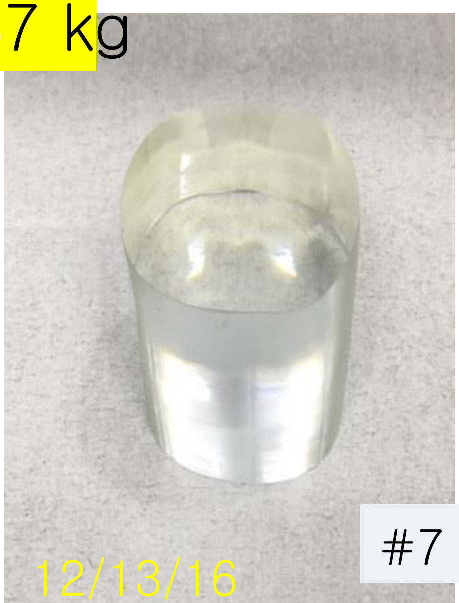
	SE01	SE02
Event Rate (ckky) 2.8 < E< 4 MeV	0.863±0.092	0.723±0.085
	0.512±0.148	0.598±0.159

Poster 107: Dr. YOON, Young Soo

AMoRE phase-I CMO crystals: all delivered

FOMOS Material, Russia

Total: 3.387 kg



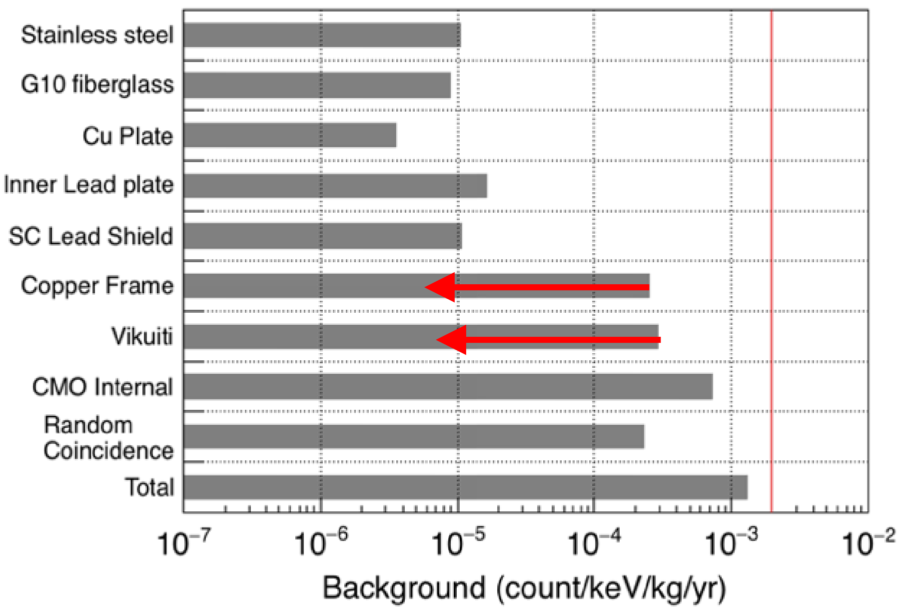
AMoRE-I CMO: RT measurement

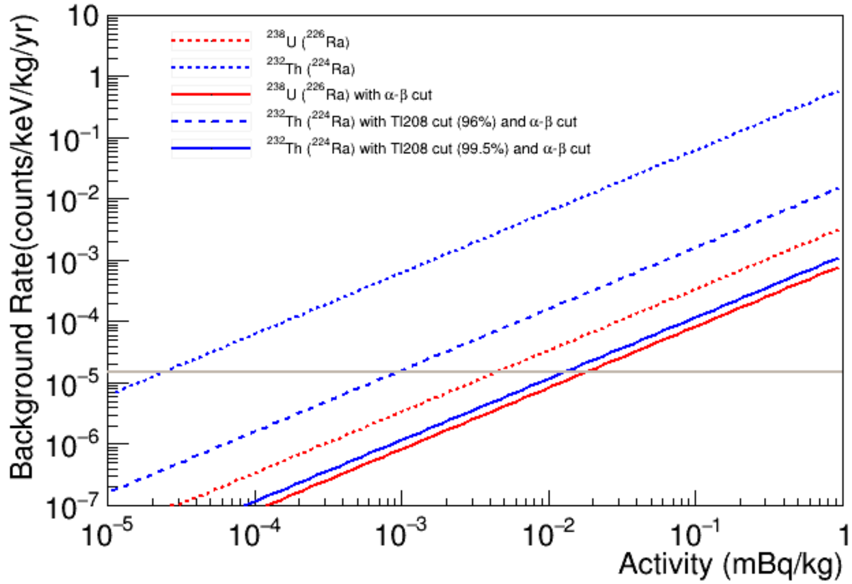
	^{227}Ac (^{215}Po) [μB/kg]	^{226}Ra (^{214}Po) [μB/kg]	^{228}Th (^{216}Po) [μB/kg]	Alpha [μB/kg]	Relative Light Yield
Qualification	<500	<100	<50	<1000	
SE1	60 ± 8	40 ± 6	50 ± 6		0.43
SE2	90 ± 10	20 ± 3	< 100		0.58
SE3	30 ± 6	6 ± 3	30 ± 6	28000	0.75
SE4	30 ± 6	10 ± 3	10 ± 3	3200	0.60
SE5	40 ± 6	10 ± 3	10 ± 3		0.70
SE6	35 ± 6	100 ± 10	70 ± 10		0.62
SE7	80 ± 10	30 ± 5	65 ± 10		0.60
SE8	40 ± 6	20 ± 5	40 ± 6		0.55
SE9	50 ± 6	<11	50 ± 6		0.66

Expect to have 10^{-3} counts/keV/kg/y at AMoRE-I *J.Y. Lee @ SCINT2017

Estimation for AMoRE-I backgrounds

- Tried to identify critical components in the setup for AMoRE-II experiment.
- Currently, “Crystal Bulk” has largest contribution in $CaMoO_4$ crystal case.
- For AMoRE-II, the Crystal Bulk activity for zero background has been set.





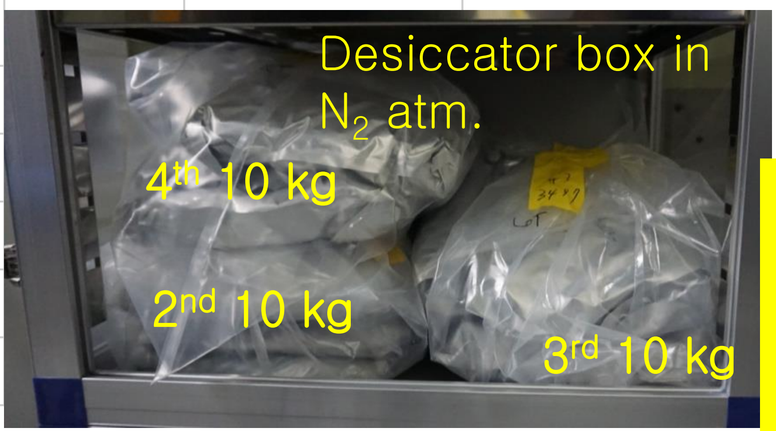
Luqman, A. et al., “Simulations of background sources in AMoRE-I experiment”, NIMA 855, 140 (2017)
“Technical design report for the AMoRE 0νββ Decay Search Experiment”, arXiv:1512.05957 (2016)
Lee, J.Y. et al., “A Study of Radioactive Contamination of $^{40}Ca^{100}MoO_4$ Crystals for the AMoRE Experiment”, IEEE Trans. Nucl. Sci. 63, 543-547 (2016)

Poster 98: AMoRE-II MC BAE, Hanwook

AMoRE-II Mo-100 powder

Contract Year (^{100}Mo quantity)	Lot	Delivery @Y2L
2015 (10 kg)	3172	3/9/16
	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)		
2017 (10 kg)		
2018 (10 kg)		
2018 (10 kg)		
2018 (10 kg)		
2018 (10 kg)		

60 kg delivered out of 120 kg contracted



Last delivery ~Jan. 2020

- ~10 kg in HPGe array (~3 months)
- ^{226}Ra: 1.7 ± 0.3 mBq/kg
- ^{228}Th: 0.27 ± 0.06 mBq/kg (The first measurement)
- ^{88}Y : 33 ± 8 μBq/kg (cosmogenic)

Identify critical radioactivity

- Go through all known nuclei decaying β *with* Q > 3.02MeV in NNDC database.
- ^{110m}Ag(3010.5 keV) doesn't contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.
- Only Thorium and Uranium natural radioactivity are critical for Q> 3.02MeV. → Great advantage to run high Q-value nuclei !

El	Decay	$T_{1/2}$	Q	Mother	Chain	Comment
			MeV	N/A		
^{26}Al	EC	7.4×10^5y	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(2.3×10^5y)		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

Ultra-low background crystals for AMoRE-II

Ultra-low background powder R&D is difficult
and need **quick feedback**

(Purification and measurement of 10 uBq/kg U-238, Th-232 & total radioactivity of alpha <1mBq)

CUP chemical & Clean room

Powder purification

CUP & underground lab

ICP-MS, HPGe,

No

Yes

CUP lab.

Crystal growing

Y2L Underground lab
Baksan lab.

Scintillation
(Phonon)

No

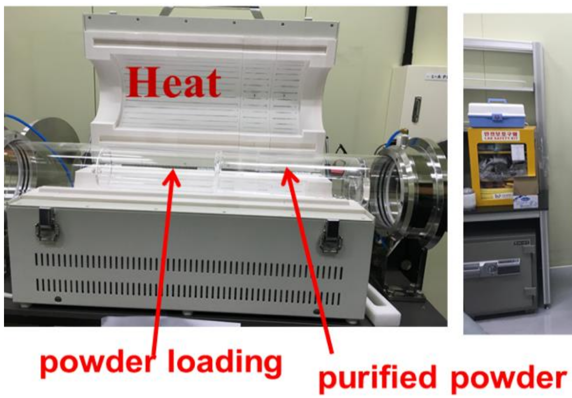
Yes

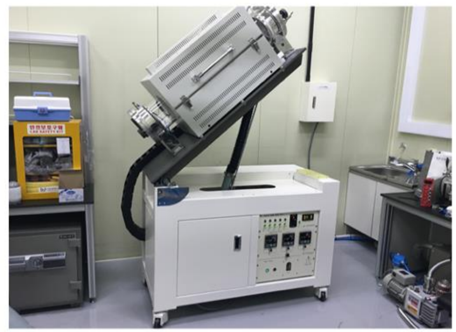
Company
(CUP lab.)

Crystal growing optimization
(Size and quality)

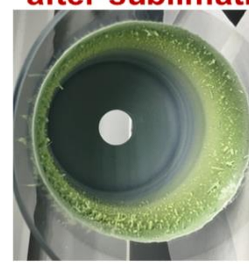
Purification, Ultra-clean crystals for AMoRE

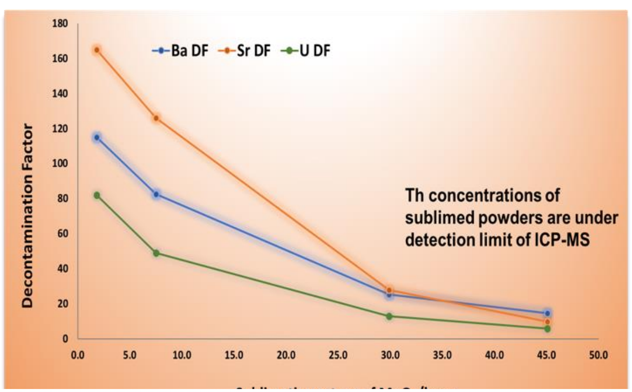
- Chemistry group has been successful in reducing powders for molybdate crystals.
- Sublimation, Co-precipitation are basic techniques.
- Recovery process from LMO are established for further purification.

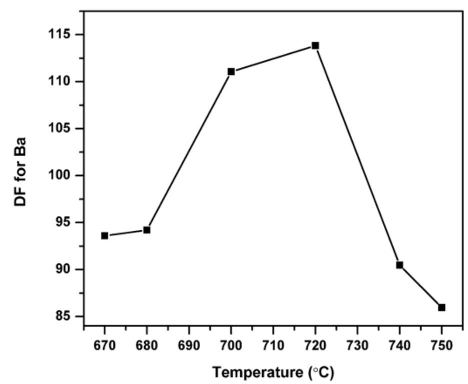




Purified powder after sublimation







Publications

Olga Gileva et al., “Investigation of the molybdenum oxide purification for the AMoRE experiment”, J. Rad. Nucl. Chem 314 1695 (2017)

Radioassay for AMoRE-I & II

Measurements of $^{100}MoO_3$ powder

- Very important to know the background level of $^{100}MoO_3$ powder.
- Previous HPGe measurements had ~ 1mBq/kg sensitivity.
- We can improve the sensitivity ~ tens of mBq/kg with the HPGe Array detector.

HPGe array measurement of Mo-100 powder

14 of 70% HPGe

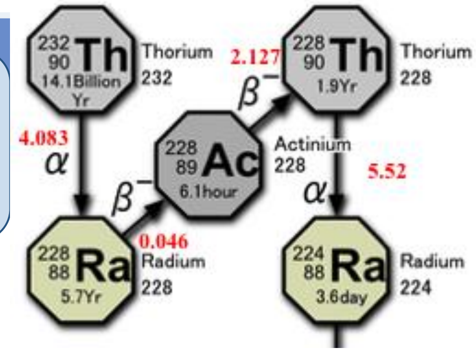
Results :
- ^{226}Ra : 1.7±0.3mBq/kg, ^{228}Th : 0.27±0.06mBq/kg. (First measurement)
- Observed $2\nu\beta\beta$ to the excited state of ^{100}Ru.
- Observed ^{88}Y produced by cosmic rays : 33±8 μBq/kg

Poster 59 : Ms. LEE, Eunkyung

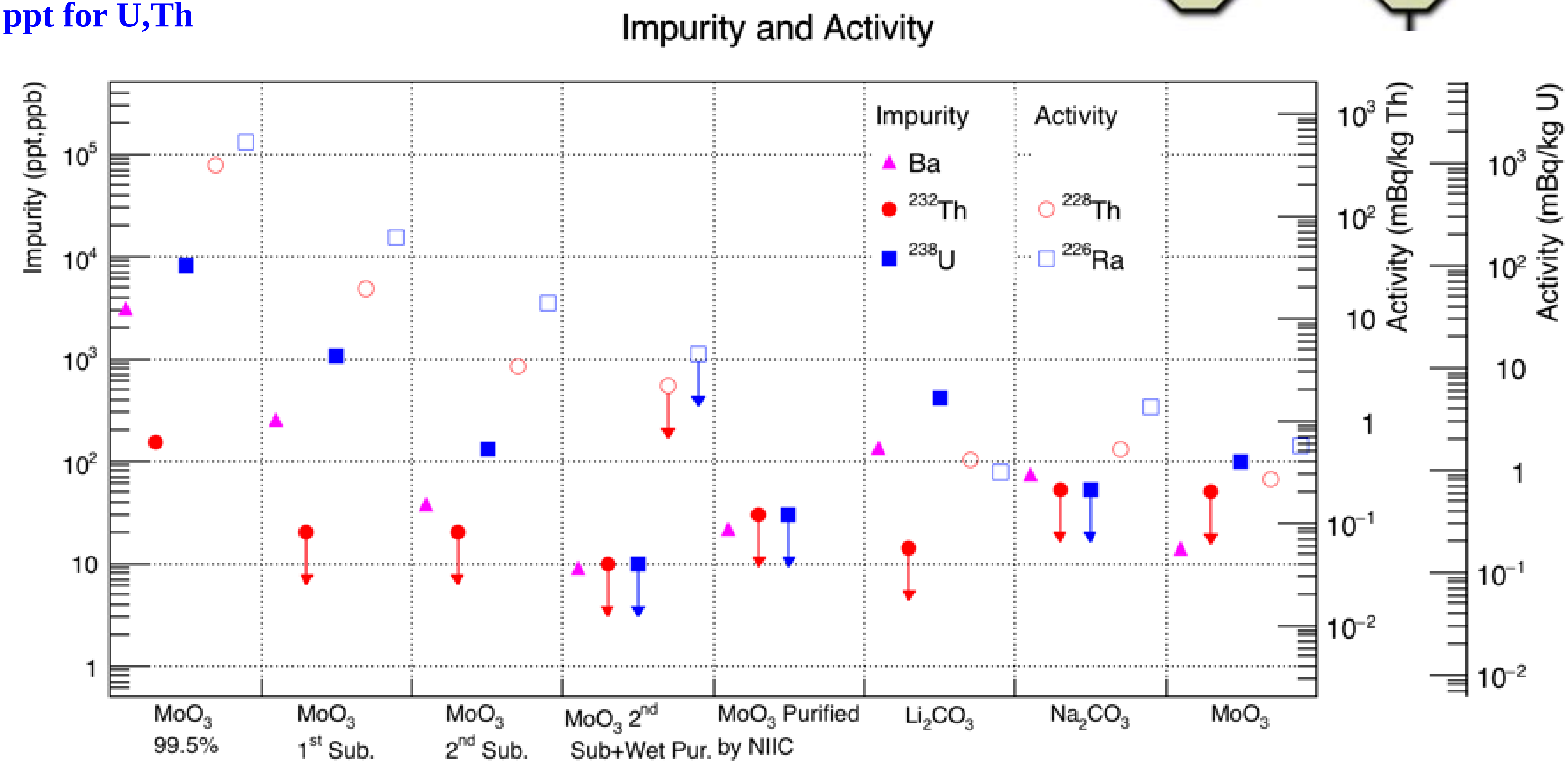
Poster 86: Ms. PARK, Su-yeon

Summary of Chemical Purification Results

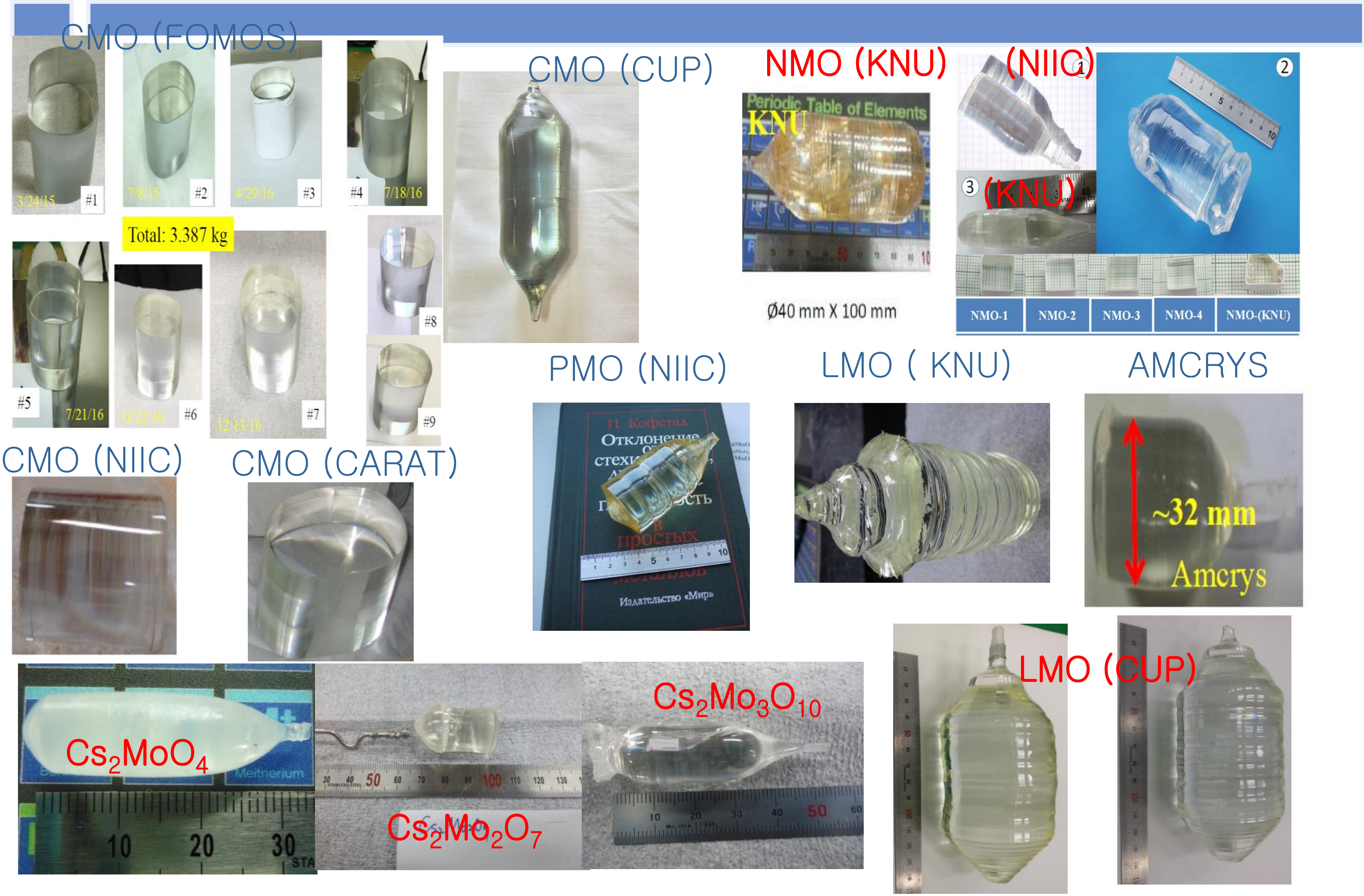
Ba is a good indicator for Ra since they are in the same family.
→ Both ^{226}Ra & ^{228}Ra (5.7 year) → ^{228}Th are related to Ba.



ppb for Ba
ppt for U,Th



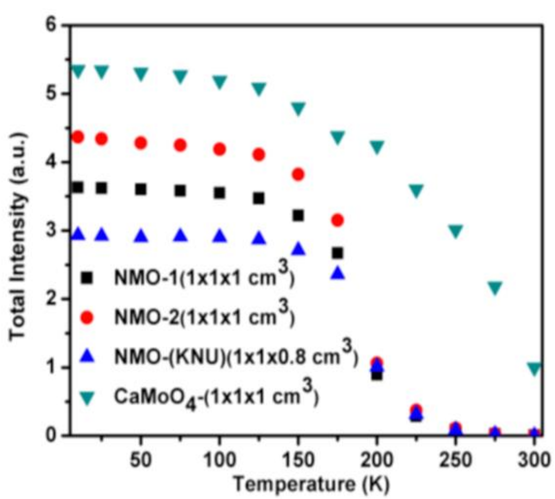
AMoRE-II: Mo crystals grown and tested

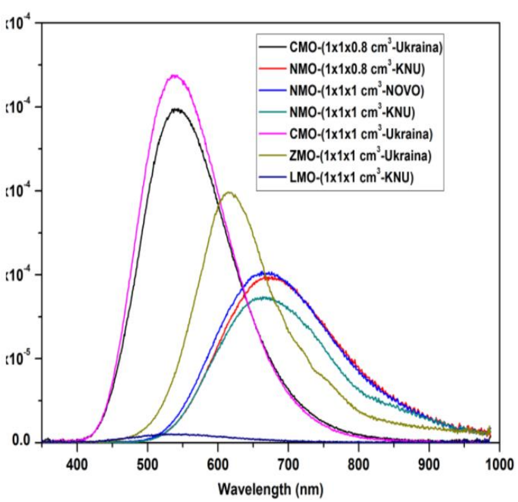


Decision on crystals for AMoRE-II

- CMO ($CaMoO_4$) is a very good crystal with the largest light output, but CMO has a disadvantage that we need ^{48}Ca depleted isotopes, expensive.
- CUPID-Mo group decided to use LMO (Li_2MoO_4), and we are working on LMO, PMO ($PbMoO_4$), & NMO ($Na_2Mo_2O_7$), crystals.

Crystal	Emission (nm)	LightYield(10K)		Decay time (μs)	density	Mo Fraction
		280nm	X-ray			
CMO(Ukra)	540	100	100	240	4.34	0.49
ZMO(NIIC)	614	63	35		4.37	0.436
LMO(KTI)	535	1	5	23	3.03	0.562
PMO(NIIC)	592	11	105	20	6.95	0.269
NMO(NIIC)	663	75	9	750	3.62	0.558





CMO ($CaMoO_4$)
LMO (Li_2MoO_4)
NMO ($Na_2Mo_2O_7$)
PMO ($PbMoO_4$)

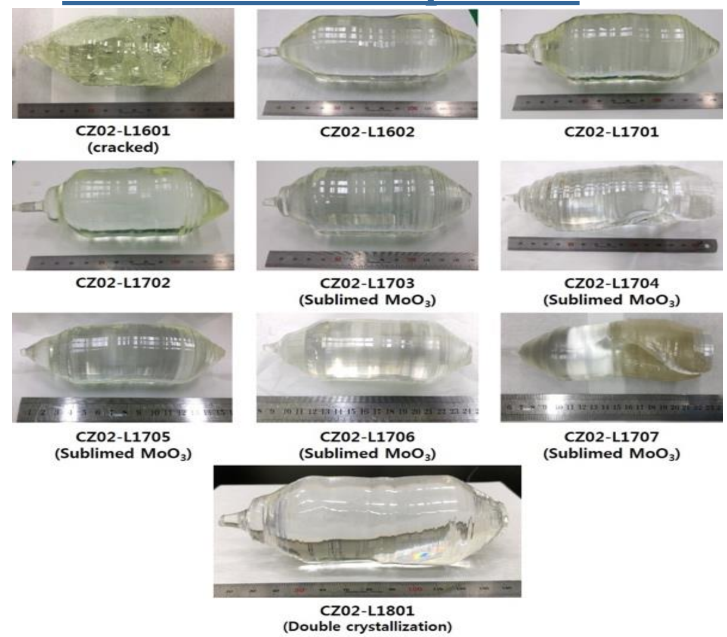
Publications :

Pandey et al., IEEE Trans. Nucl. Sci. (2018)
Pandey et al., Journal of Crystal Growth 480 (2017) 62-66
J.Y. Lee et al., IEEE Trans. Nucl. Sci. (2018)

Molybdate crystals at CUP.

- Crystal group has been successful in growing molybdate crystals. Growing time ~ 1 week.
- The purity of the grown crystals are measured by ICP-MS → Promising results
- We have a campaign to grow an enriched LMO crystal in this summer at NIIC and CUP.

Purified Mo and Li powders

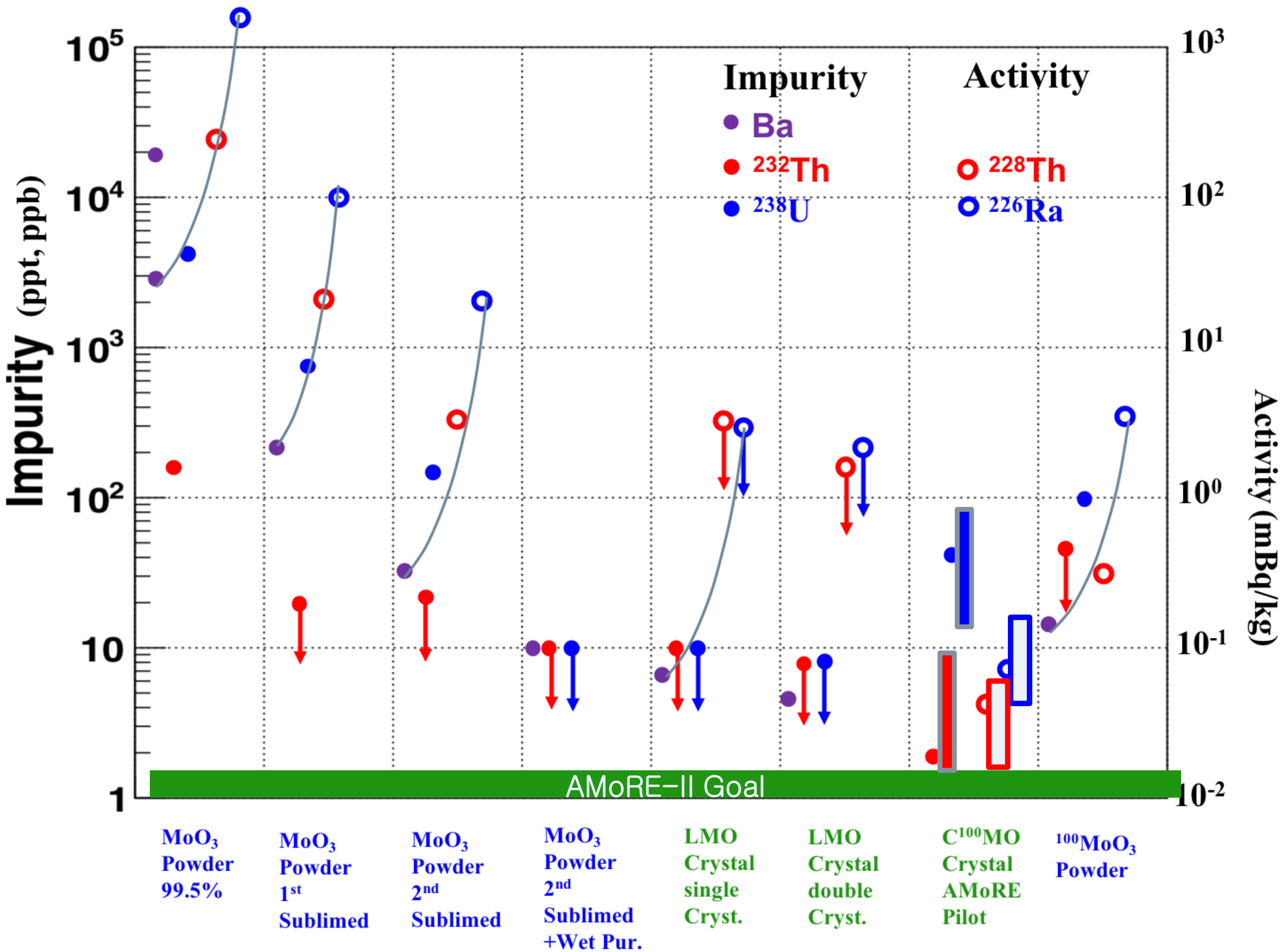


Unpurified Mo and Ca powders

Purified Mo and Na powder

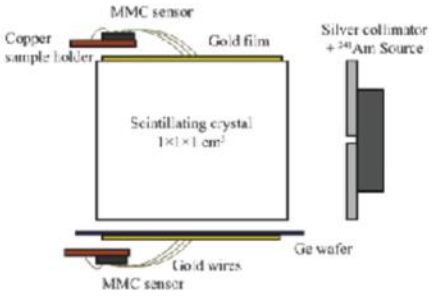
AMoRE: Purification for XMO crystals

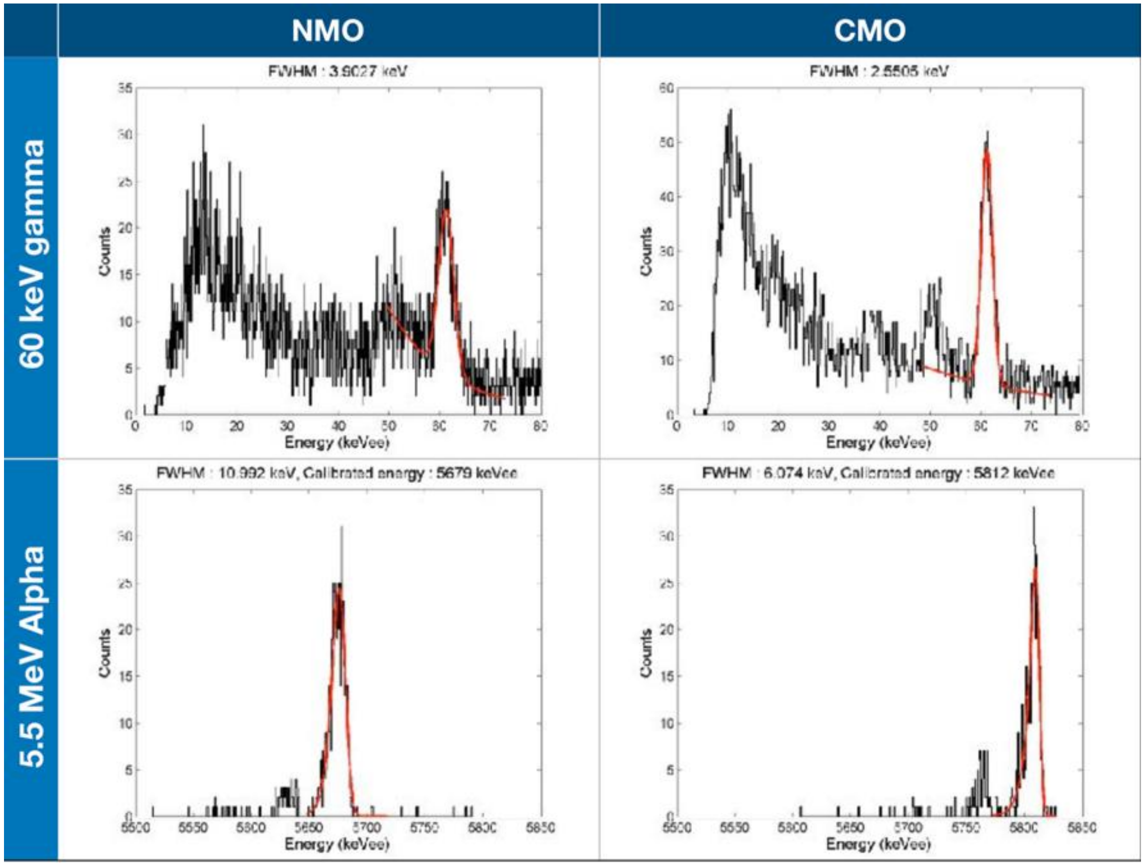
- Ba is a good indicator for Ra since they are in the same family.
- We have a good progress toward AMoRE-II crystals.



LT Test of NaMO cubic

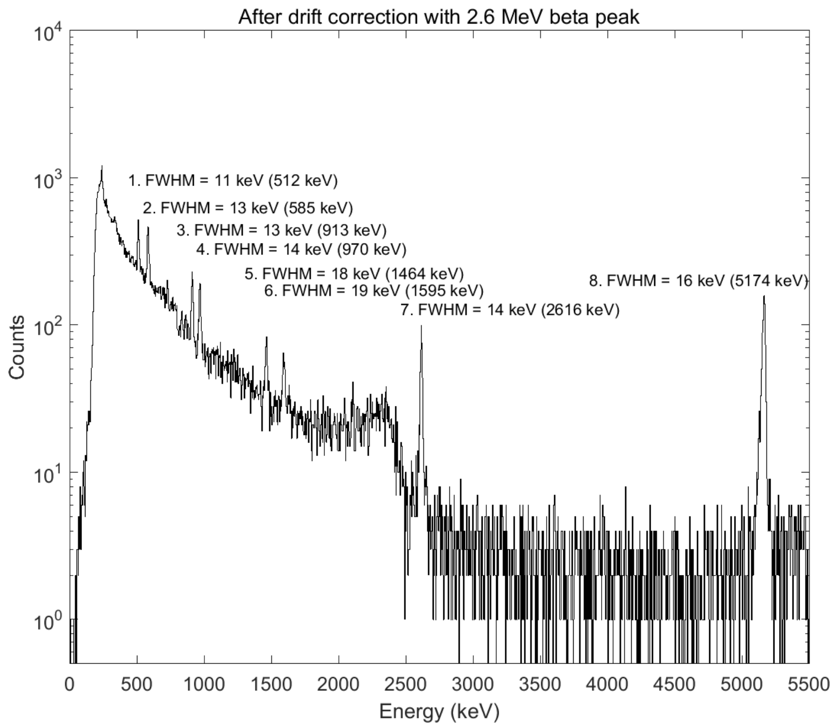
- Crystal : $CaMoO_4$, $Na_2Mo_7O_4$
- Crystal size : 10 × 10 × 10 mm^3
- Ge wafer size : 15 × 15 × 0.5 mm^3
- Ag collimator + Alpha source, External gamma source
- Al can for superconducting shield
- VM2000 (3M) for light reflector

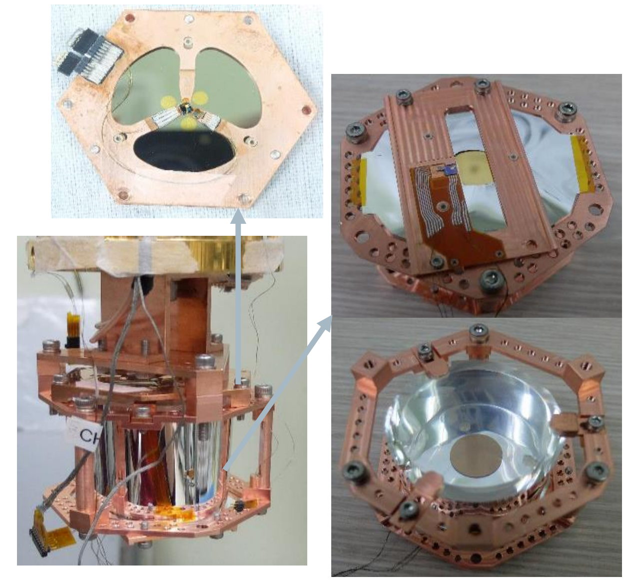


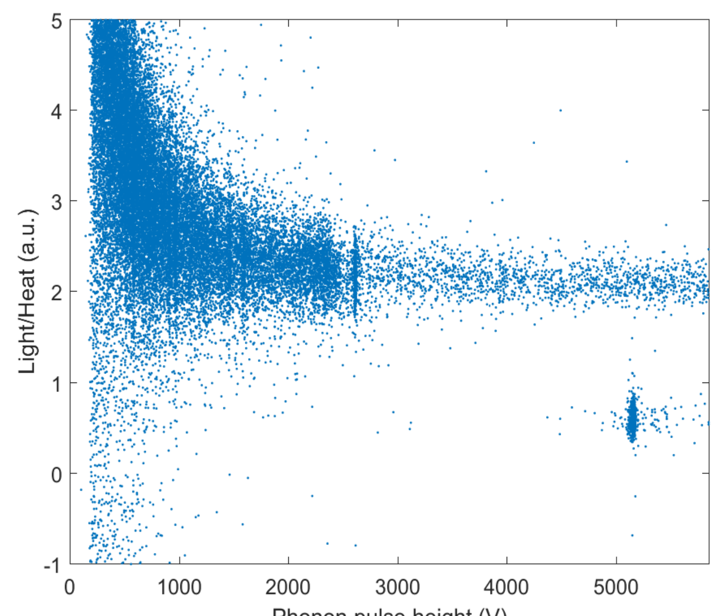


First LT measurement for NMO crystal → 10 keV energy resolution with 1cc crystal compared to 6 keV for CMO.

LMO Energy resolution and PSD (Pre-liminary)







- Neutron captured alpha events were used for drift correction.
- The resolution was calculated to be similar by different drift correction lines.

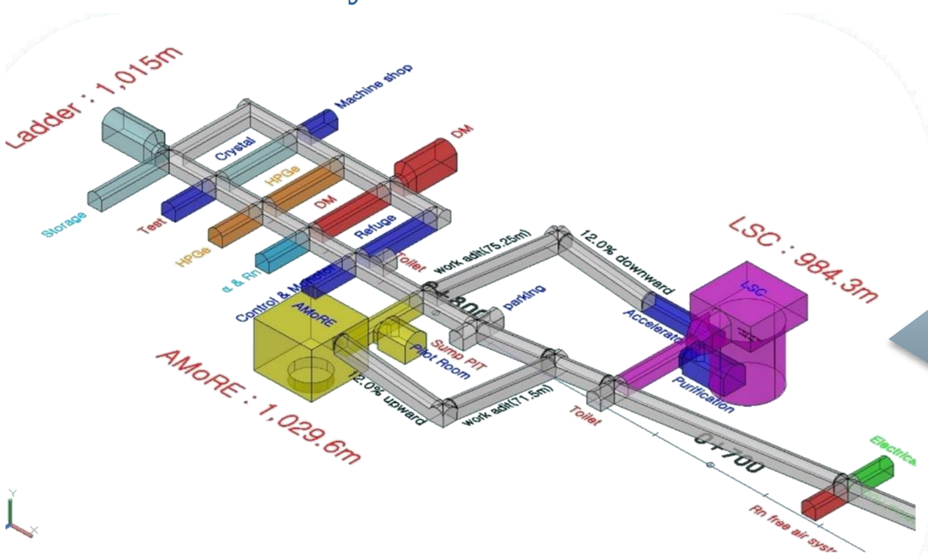
Poster 72 : KIM, Hyelim

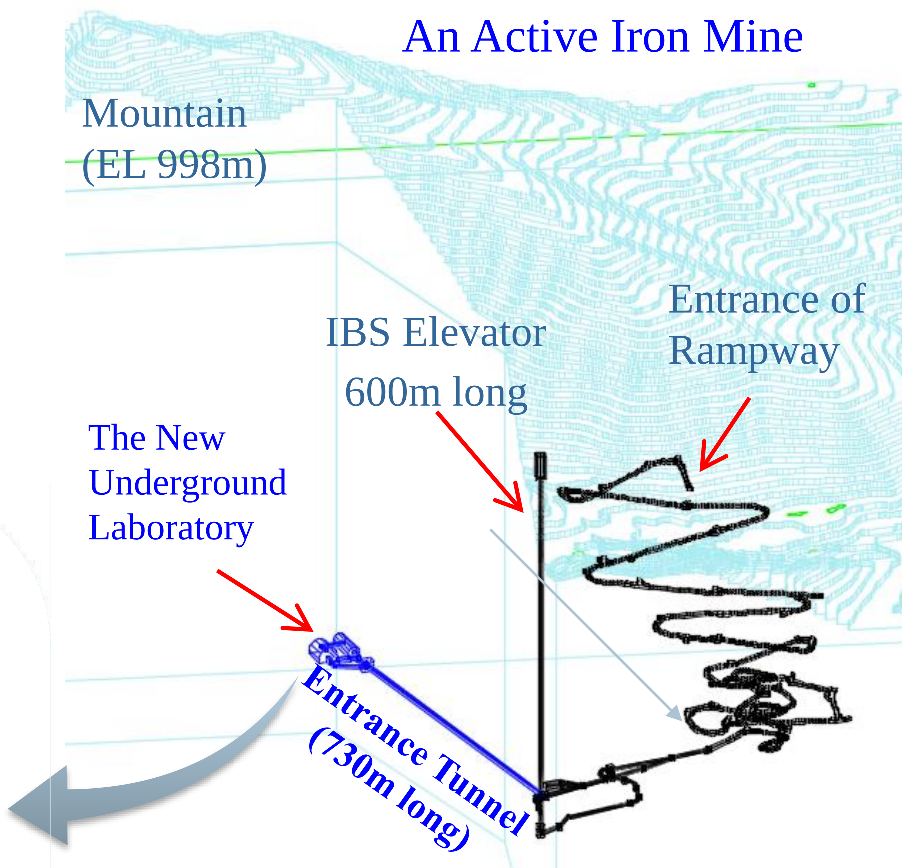
New underground lab.

- **Will have an independent entrance (human vertical elevator) from mine activity.**
- **The construction starts this year and completed early of 2020.**

Bird view of Handuk Iron Mine

Handuk mine, ~ 0.7milion tons iron ore a year

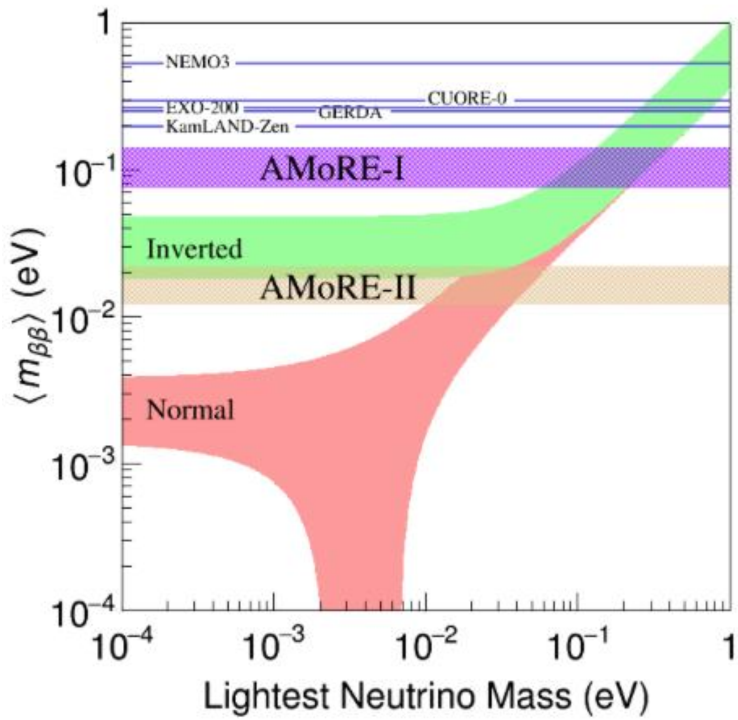




Large (>2000m^2), deeper (1100m depth)

AMoRE summary & prospect

- Large volume of low background $^{48depl}Ca^{100}MoO4$ (CMO) have been developed and cryogenic MMC technique with CMO is successful.
- We started AMoRE-pilot with 1.9kg of CMO and making good progress in detector performance and identifying the background sources.
- We are working on chemical purification & new crystal R&D for AMoRE-II.
- AMoRE-I will begin in the end of 2018 to confirm lower backgrounds and to test various Mo based crystals.
- AMoRE-II will begin end of 2020 at a new underground laboratory and aim to be sensitive to 10^{27} year range for ^{100}Mo isotope.

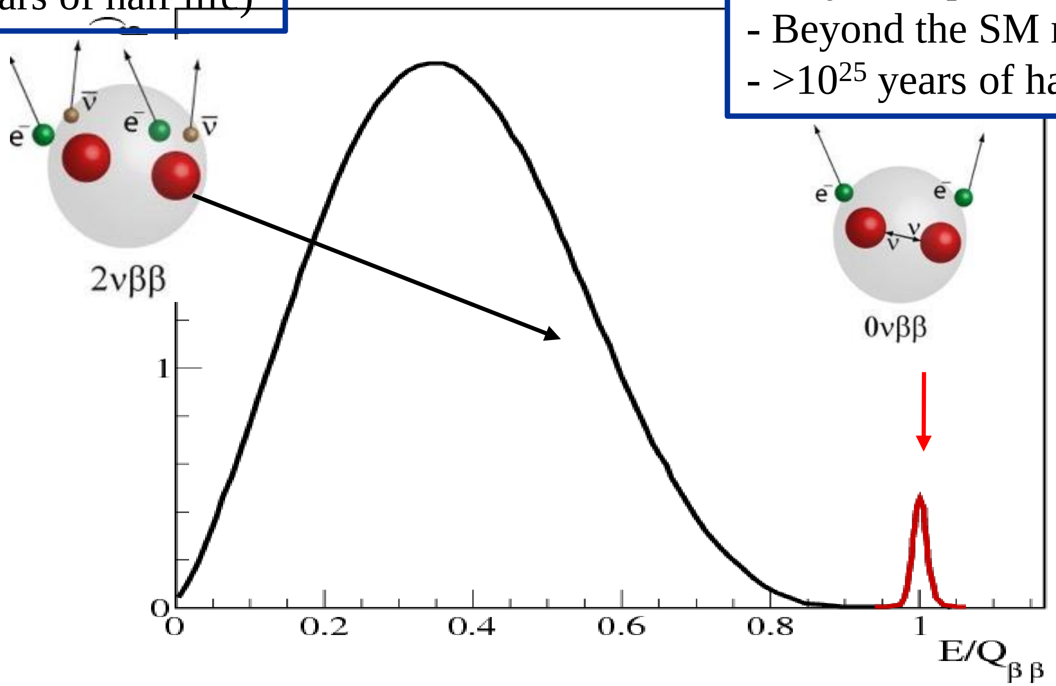


Thank you

Double beta decay

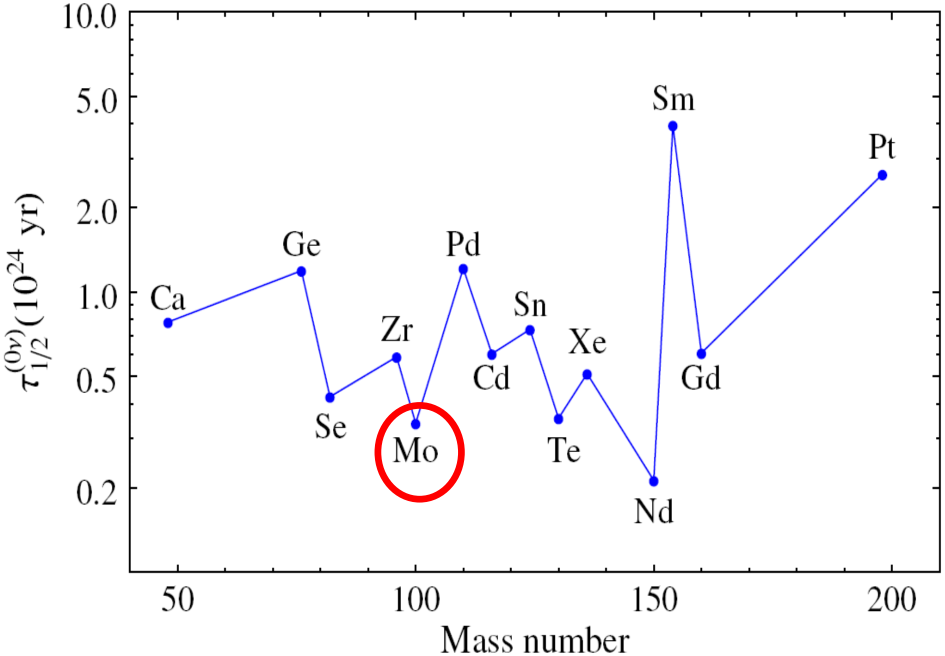
$2\nu\beta\beta$ decay
- 2nd order beta decay
- Rare nuclear decay
- (>10^{18} years of half life)

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



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.**

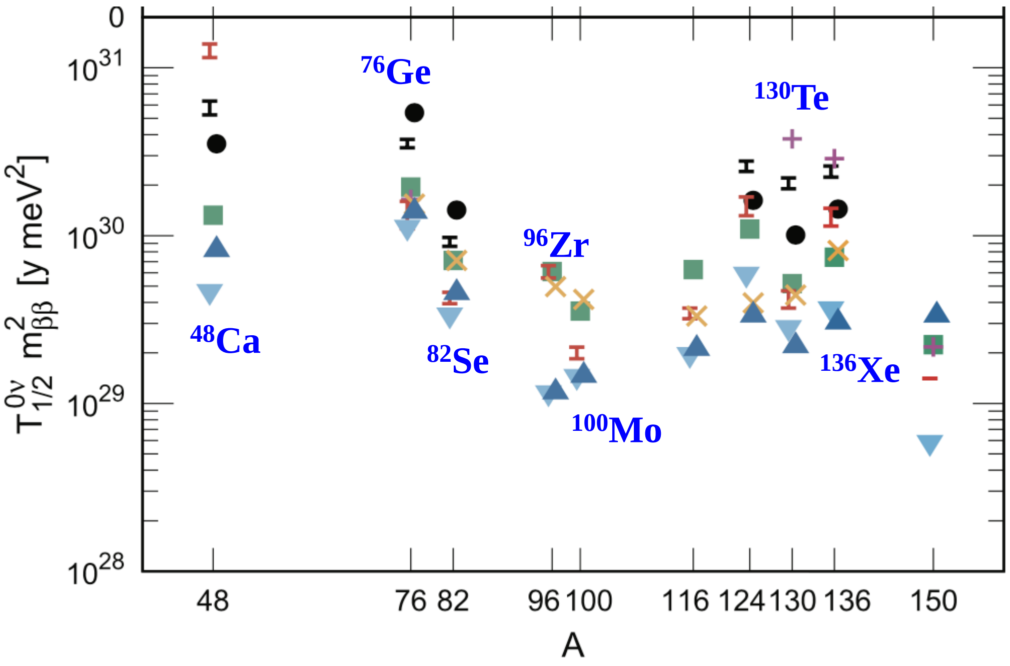


Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

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

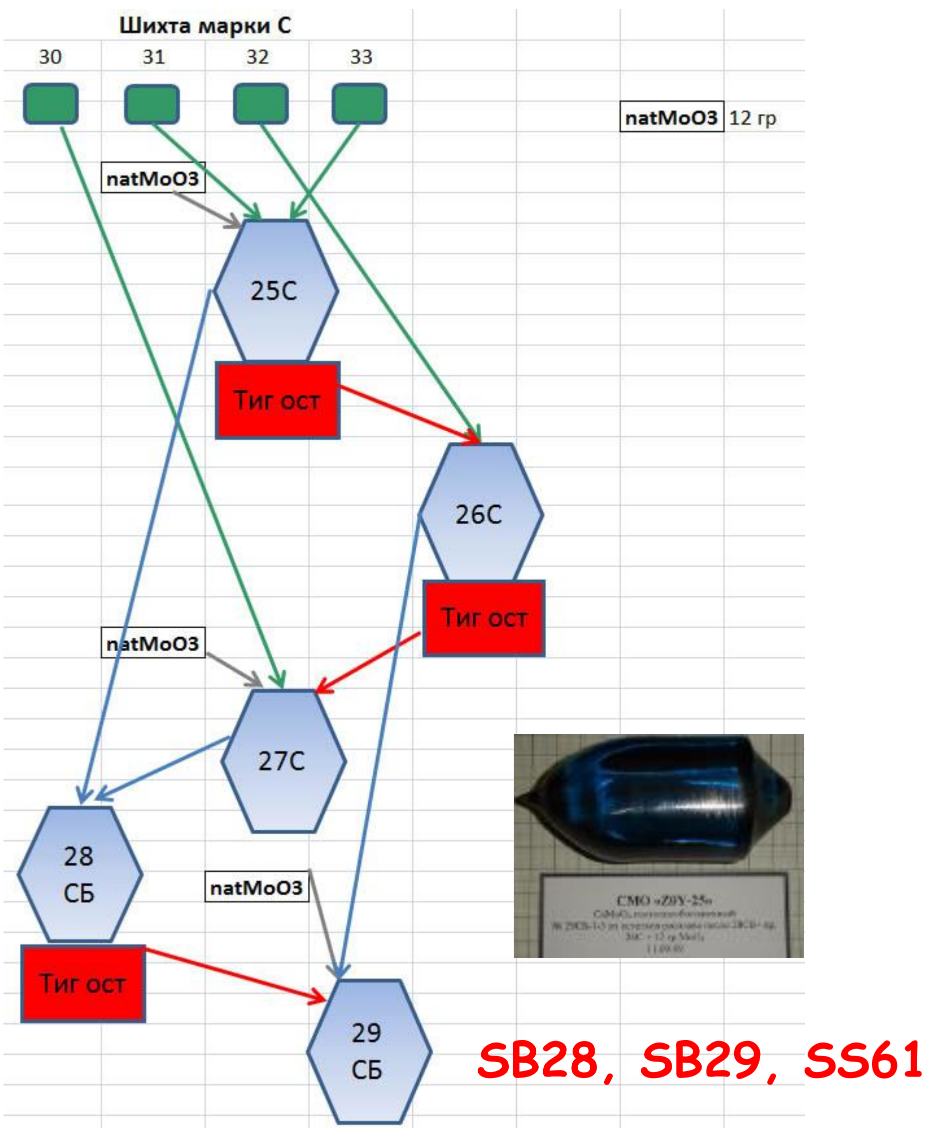
Why ^{100}Mo ?

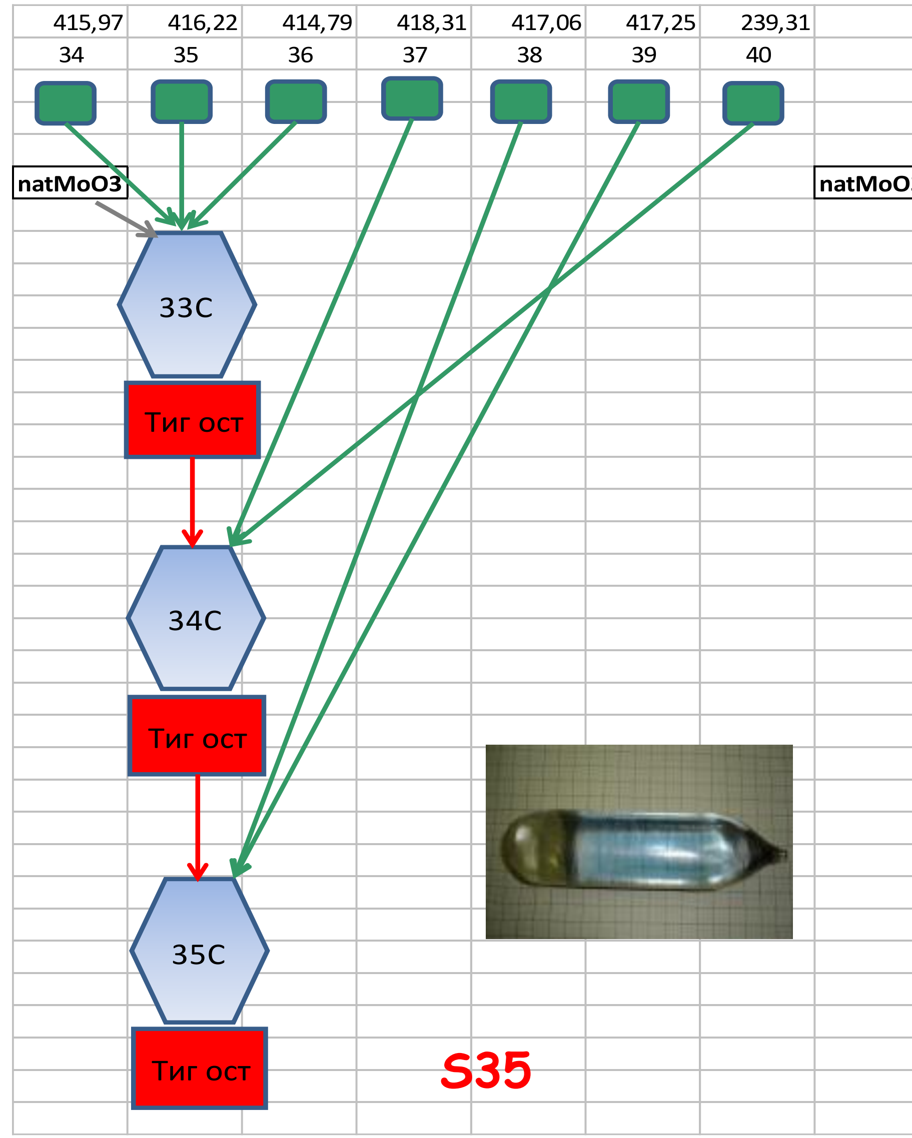
Expected Half-lives



- ^{100}Mo is expected to have a smallest half-life except ^{150}Nd.
- Natural abundance ~ 10 % → enrichment cost is moderate.
- Background will be low for Q>3MeV.
- We need data for multiple isotopes to study the various models with data if discovery is done for any isotope.

Crystal growing (Double crystalization)





^{100}Mo, ^{48depl}Ca materials

- ^{100}Mo isotope production:
  - ECP (Electro Chemical Plant), Krasnoyarsk, Russia
  - $^{100}MoO_3$ powder:
    - ^{100}Mo Enrichment: ~ 95%
    - Impurities:

ICP-MS at CUP	U: ~ 0.2 ppb	Th: < ~0.05 ppb
HPGe at Y2L	^{226}Ra: 8.3 mBq/kg	^{228}Ac < ~1.0 mBq/kg

- ^{40}Ca with depletion of ^{48}Ca isotope production:
  - ELEKTROCHIMPRIBOR (EKP), Lesnoy, Russia
  - $^{40}CaCO_3$ powder:
    - ^{48}Ca < 0.001%
    - Impurities: U ≤ 0.1 ppb, Th ≤ 0.1 ppb, Sr = 1 ppm, Ba = 1 ppm
    ^{226}Ra = 5 mBq/kg (1.4 by NEOKHIM later), ^{228}Ac(^{228}Th) = 1 mBq/kg

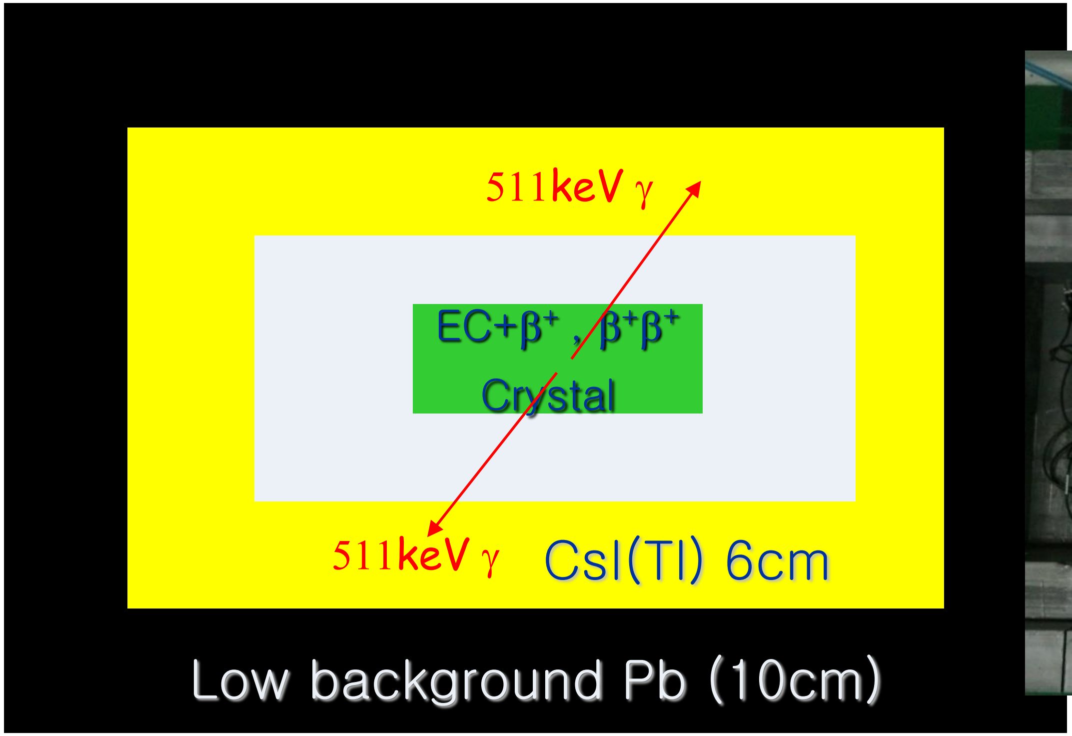
4π CsI(Tl) active setup with Pb shielding at Y2L

1) 2ν EC+β^+ , $\beta^+\beta^+$ study with 2 back to back γ tagging

(1) Sr-84 : $SrCl_2$ (4.6×10^{17} yr by 90%CL)

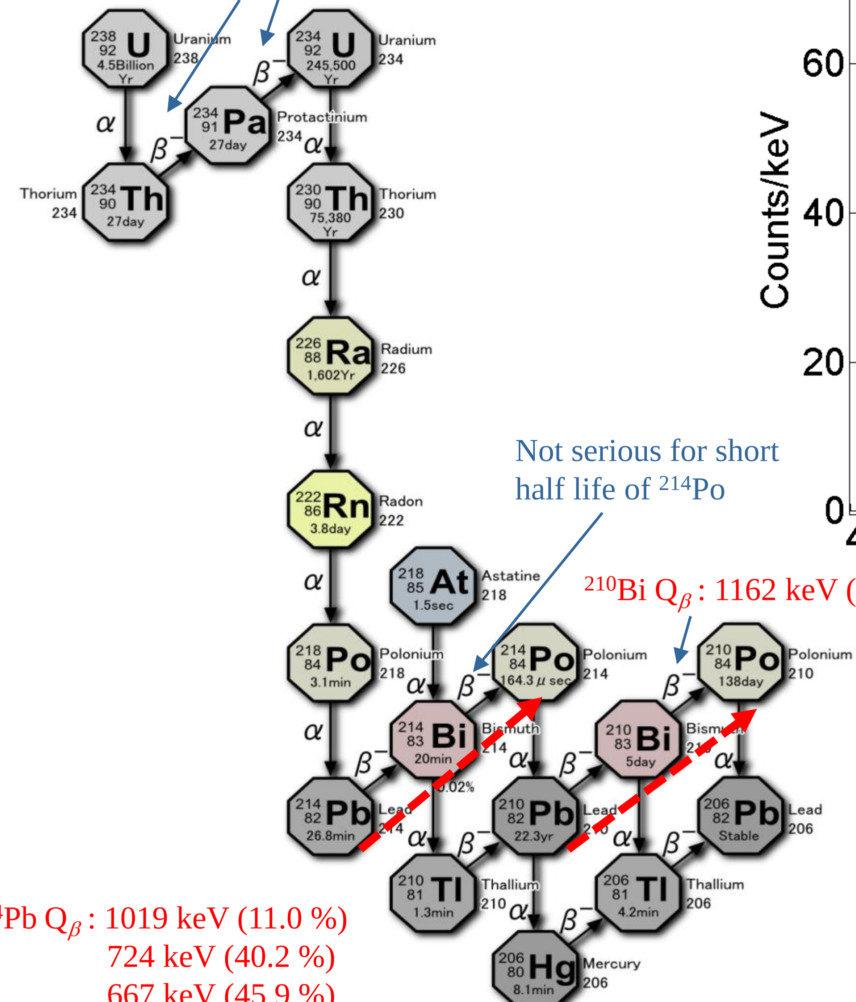
(2) Mo-92 : CaMoO4 (2.3×10^{20} yr NIMA 654, 157 (2011))

2) CMO internal background study with active veto



Considerable beta decays (^{238}U)

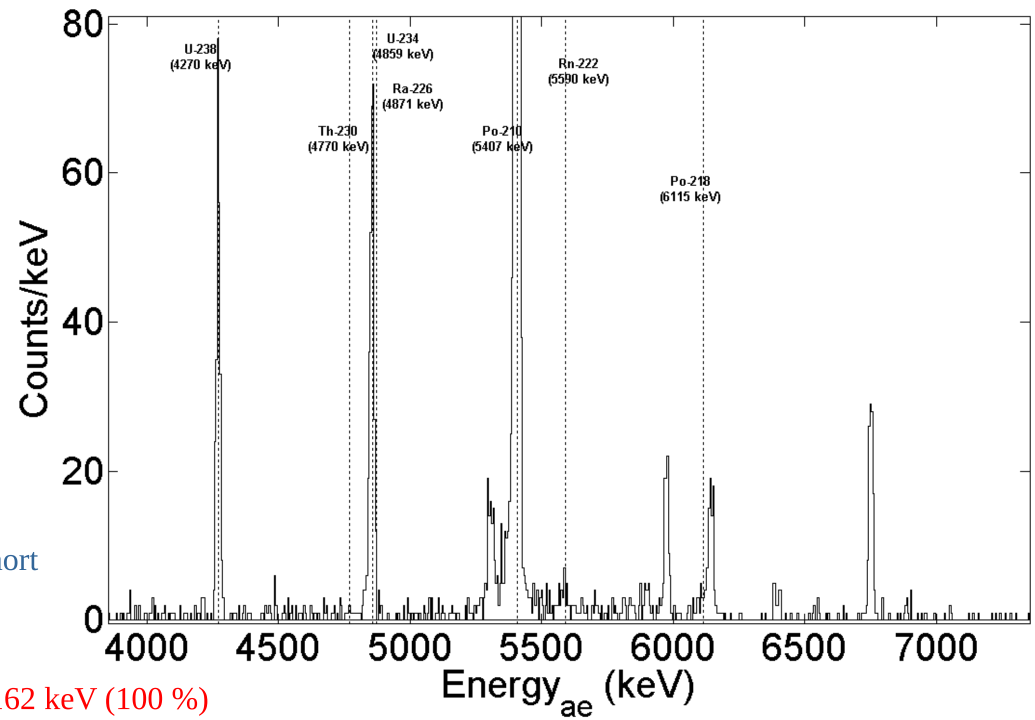
^{234}Th Q_β : 199 keV (78.0 %)
^{234}Pa Q_β : 2269 keV (97.6 %)



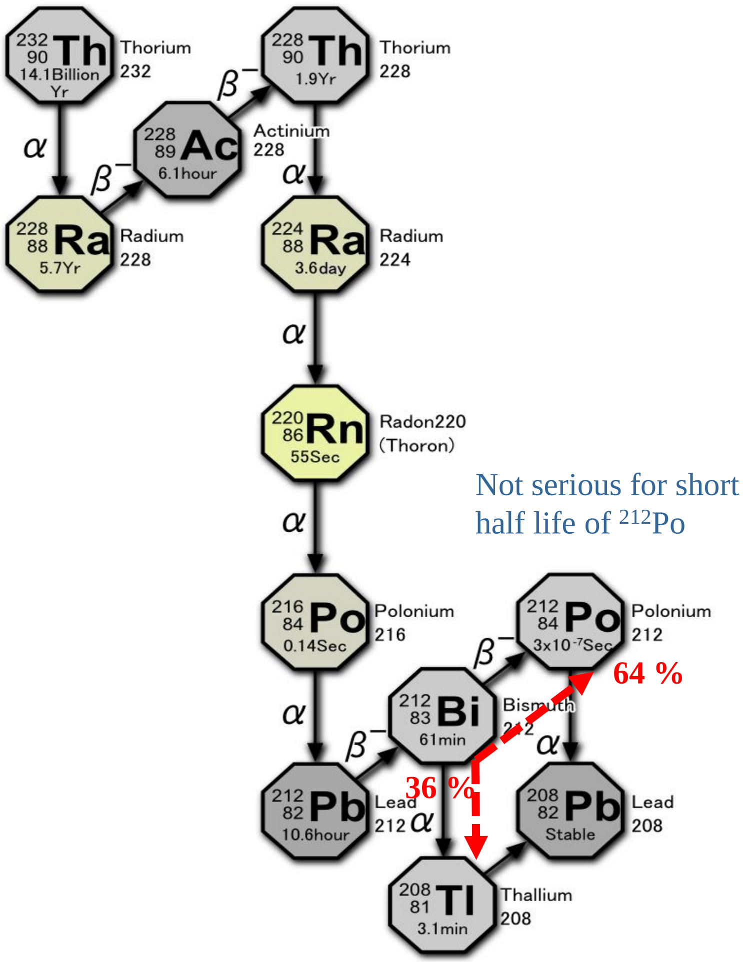
Not serious for short half life of ^{214}Po

^{210}Bi Q_β : 1162 keV (100 %)

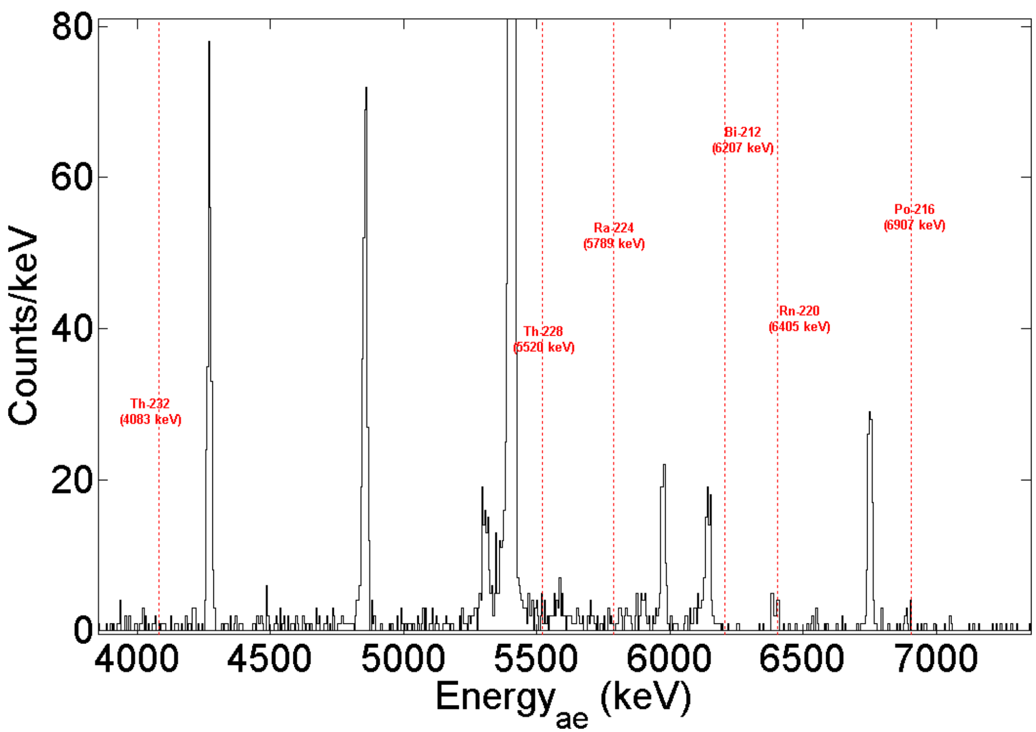
^{214}Pb Q_β : 1019 keV (11.0 %)
724 keV (40.2 %)
667 keV (45.9 %)



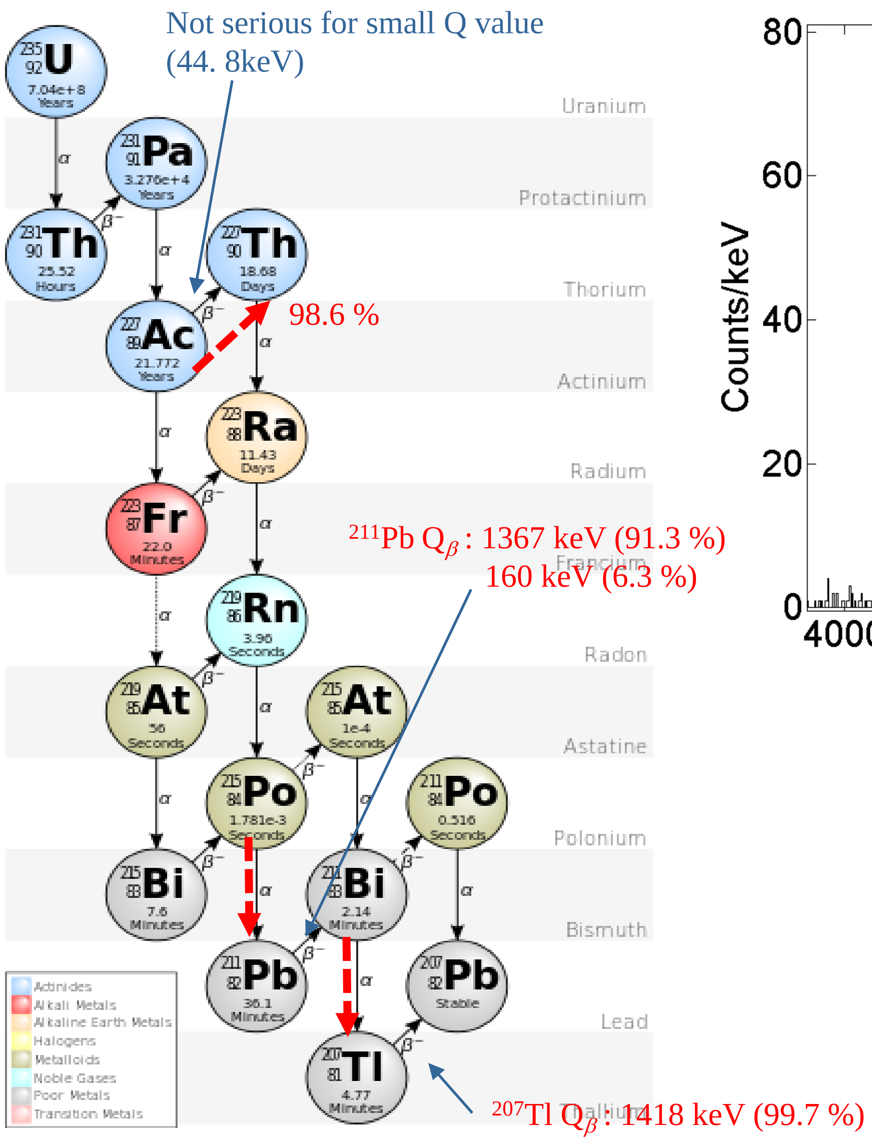
Considerable beta decays (^{232}Th)

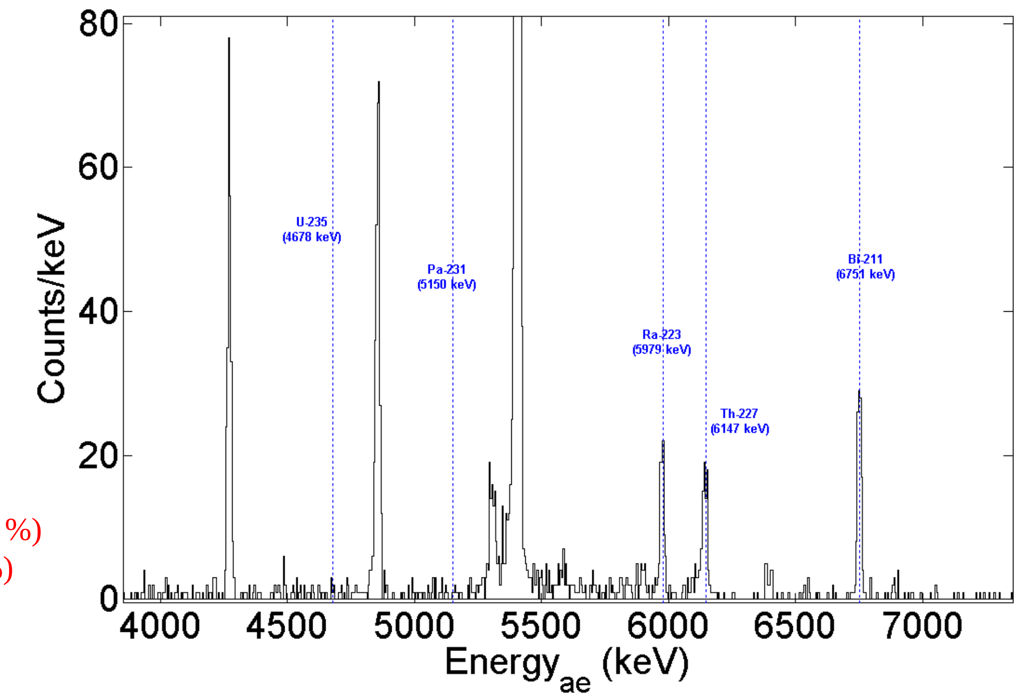


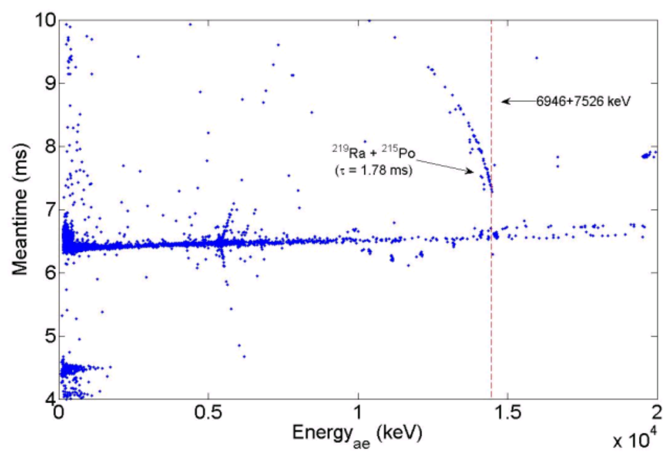
Not serious for short half life of ^{212}Po



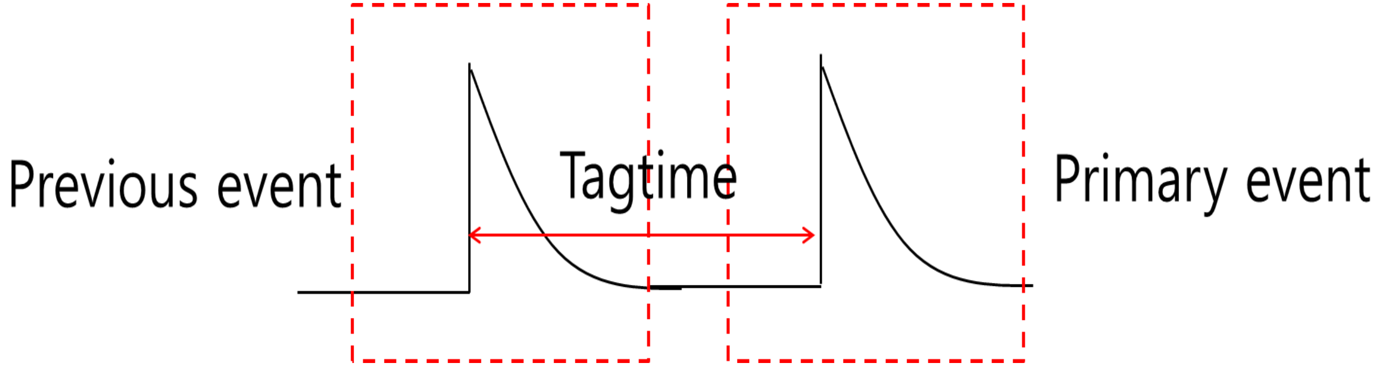
Considerable beta decays (^{235}U)







Time-Amplitude analysis method



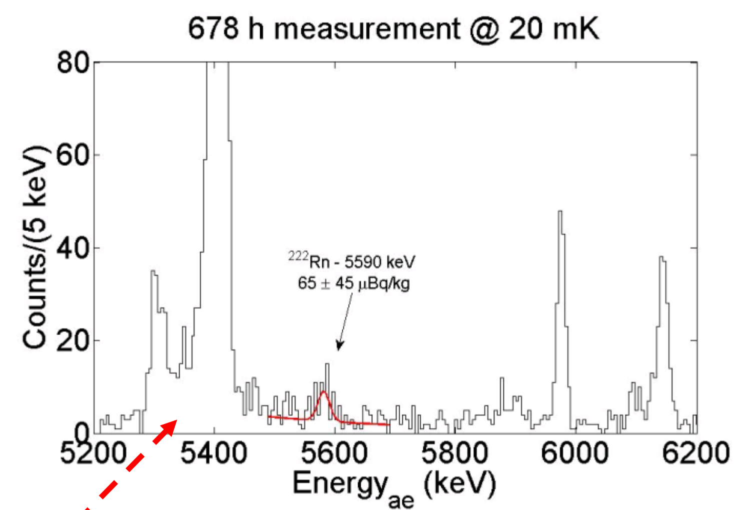
U-235 chain : Rn-219 (3.965 s) → Po-215 (1.78 ms) → Pb-211

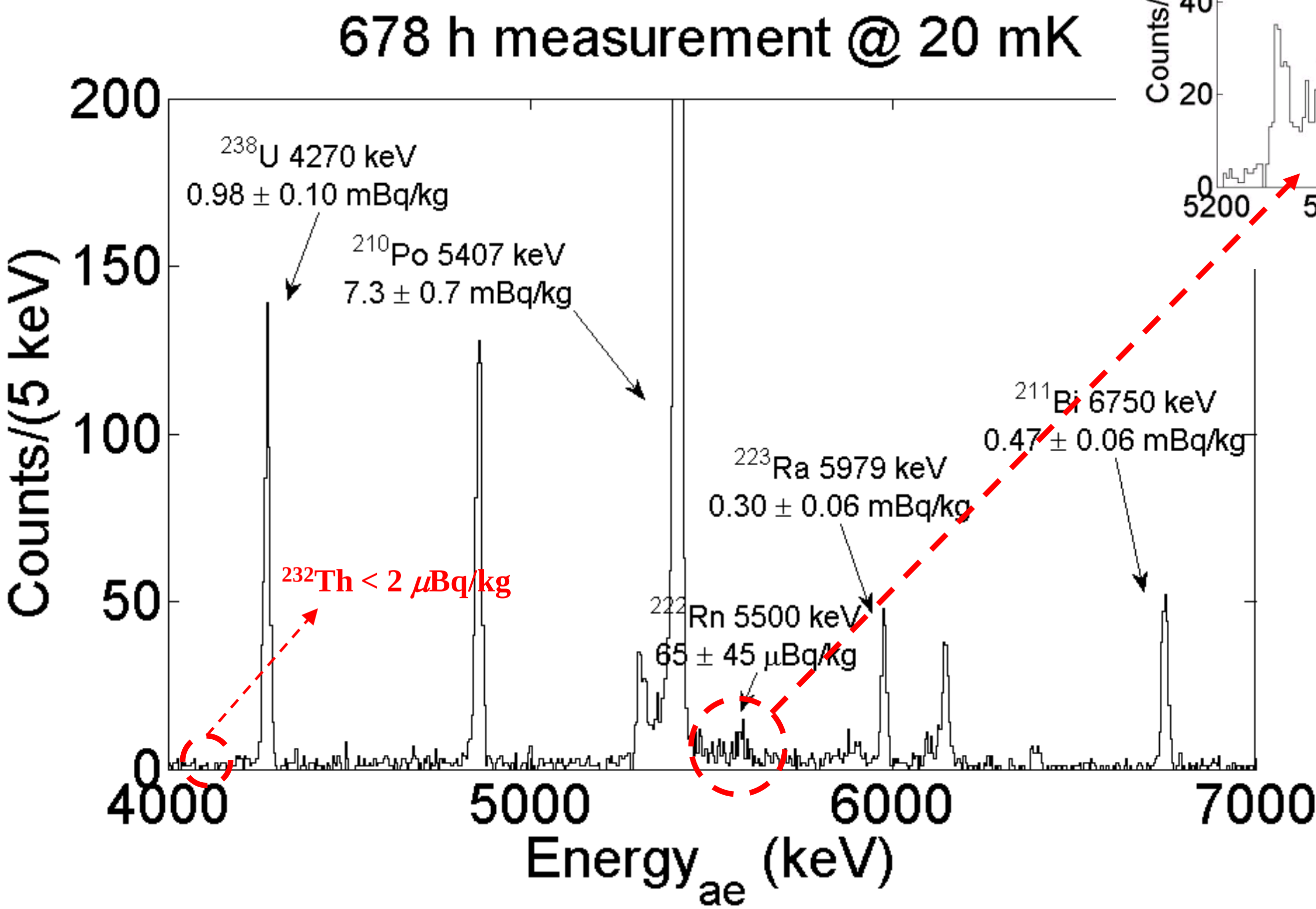
U-238 chain : Bi-214 (20 m) → Po-214 (164 us) → Pb-210

Th-232 chain : Rn-220 (55.6 s) → Po-216 (0.145 s) → Pb-212

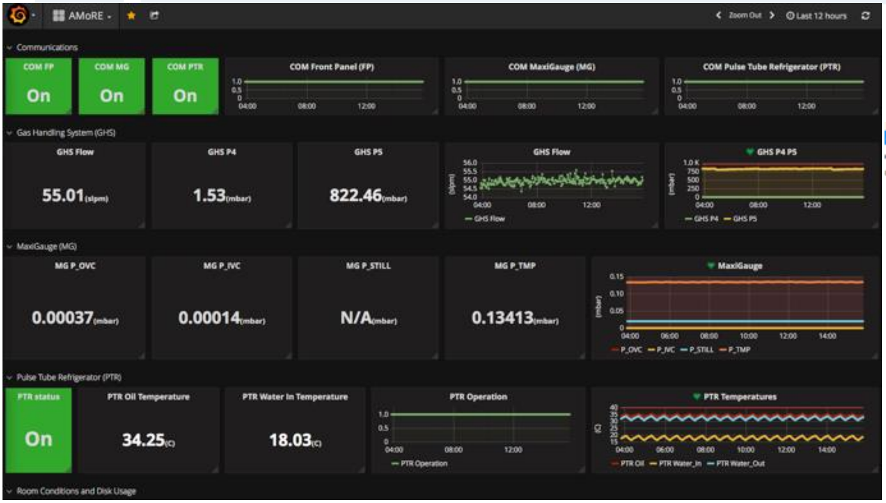
Internal alpha background of SB28

U−238 decay chain:
Consistent with 4π setup measurement
(80 uBq/kg)

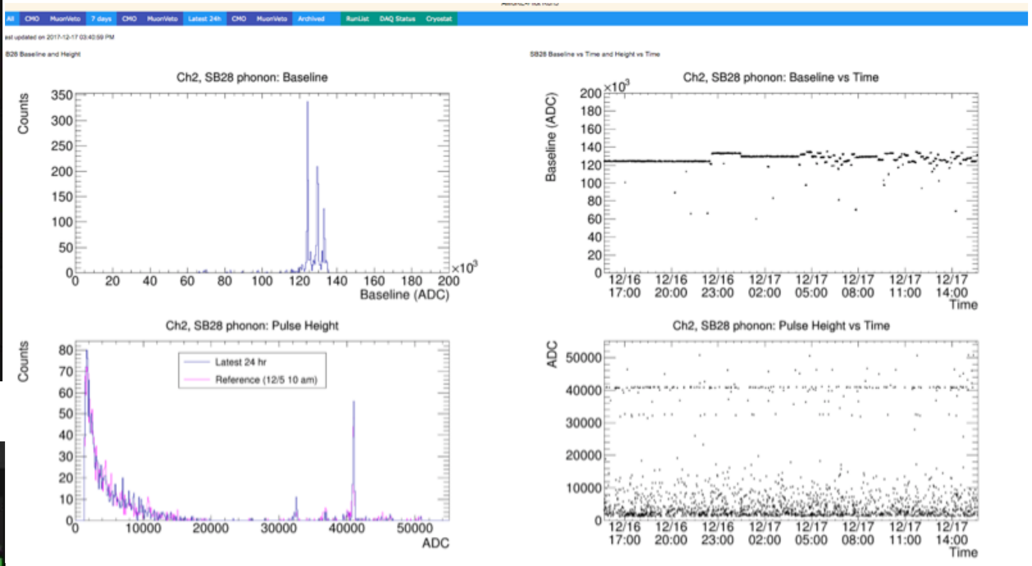




Monitoring AMoRE-Pilot

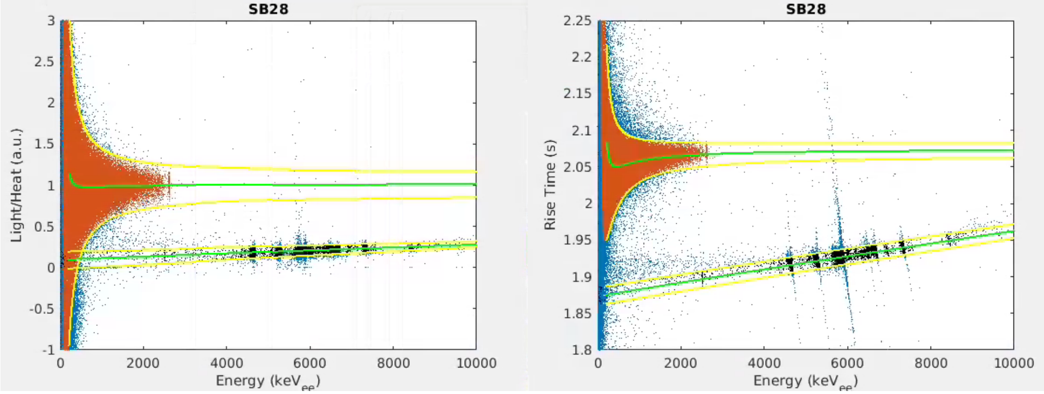


On-line: Housekeeping and DAQ

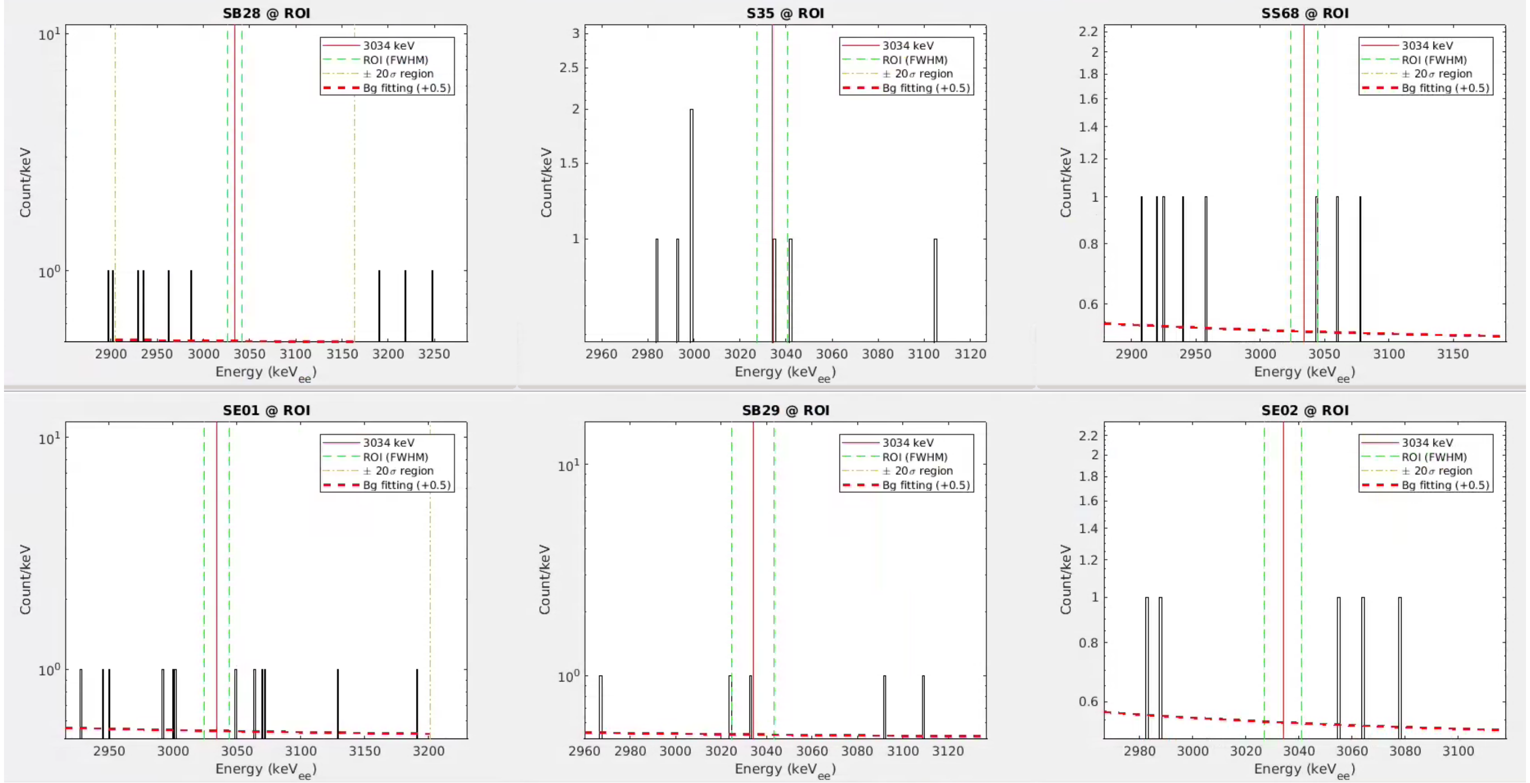


Data quality check: Baseline and Pulse height

Preliminary results



- After removing alpha backgrounds, alpha tagging, muon veto, beta-like events selected.
- Around Q-value, we have 0.2 – 0.6 ckky with 141 days data. Higher than expected.



Impurities measured with HPGe

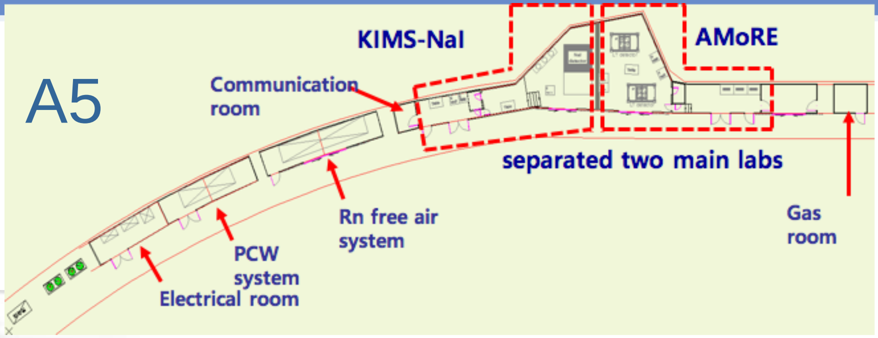
Total masses and activities of components in the AMoRE-Pilot Setup (up to Run5).

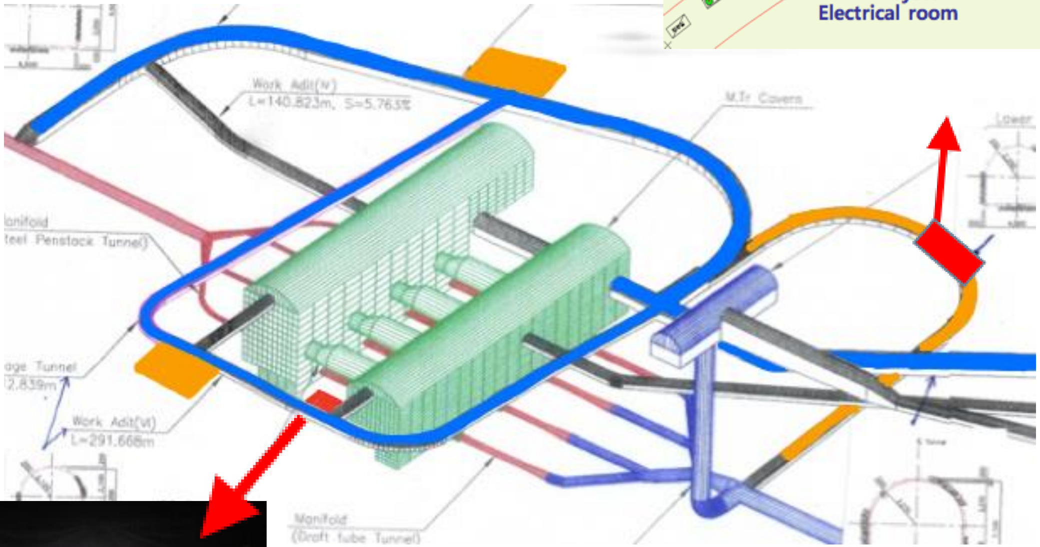
Item	Total mass (g)	A(Ra226) mBq	A(Ac228) mBq	A(Th228) mBq	A(K40) mBq
Pin connector	7.77	15.08	27.67	24.09	28.75
PCB	2.88	0.54	0.50	0.41	3.04
Stycast	0.69	0.20	0.26	0.25	0.20
SS Screws	200.00	0.16	< 0.42	0.42	< 0.38
SQUID	0.12	< 0.23	< 0.46	< 0.14	< 2.24
Phosphor bronze spring	4.73	< 0.01	< 0.01	< 0.01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

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

Experiments at the Y2L

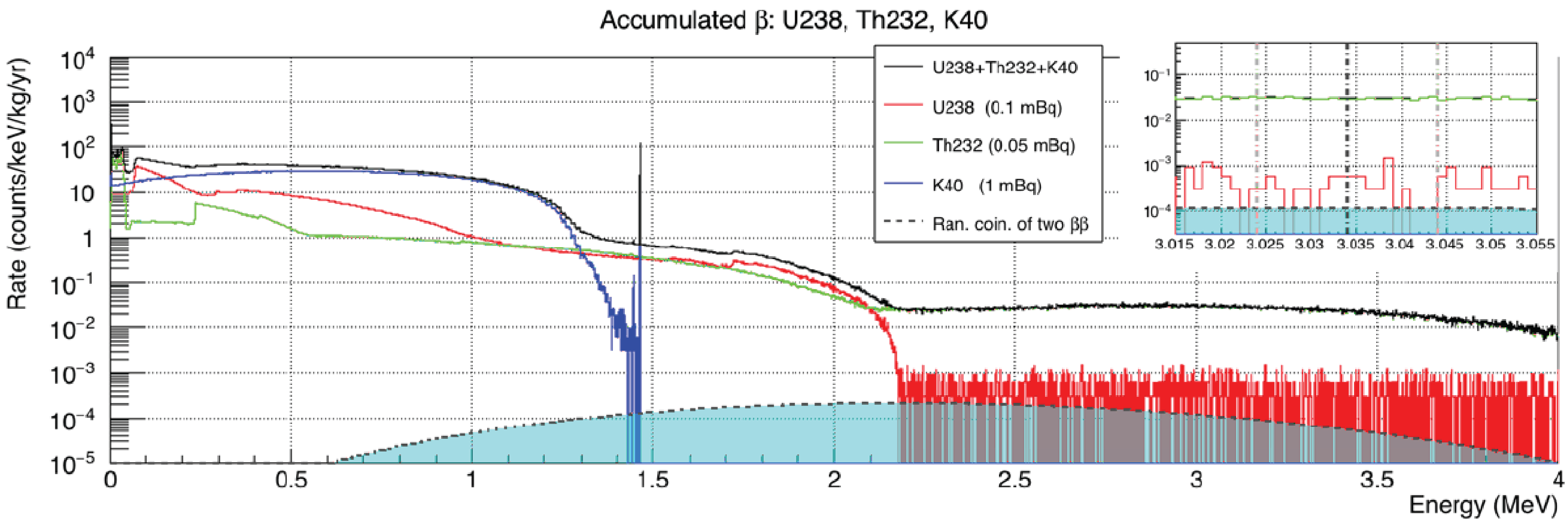
- New rooms in A5 tunnel were constructed for COSINE (38 m^2) and AMoRE (43 m^2) in late 2014.
- Currently the two experiments are running.

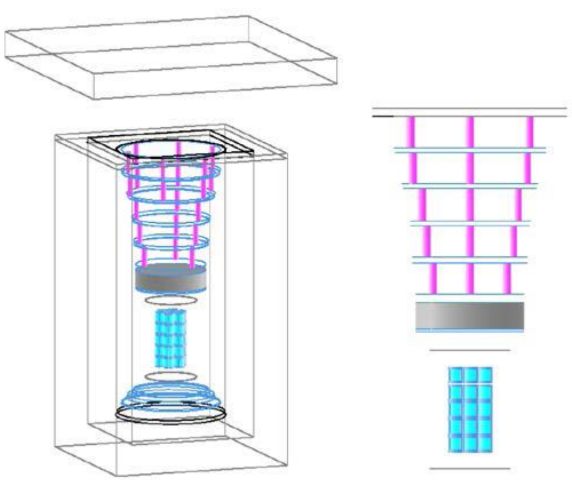




GEANT4 simulation for AMoRE-I

A. Luqman, et al., arXiv:1601.01249

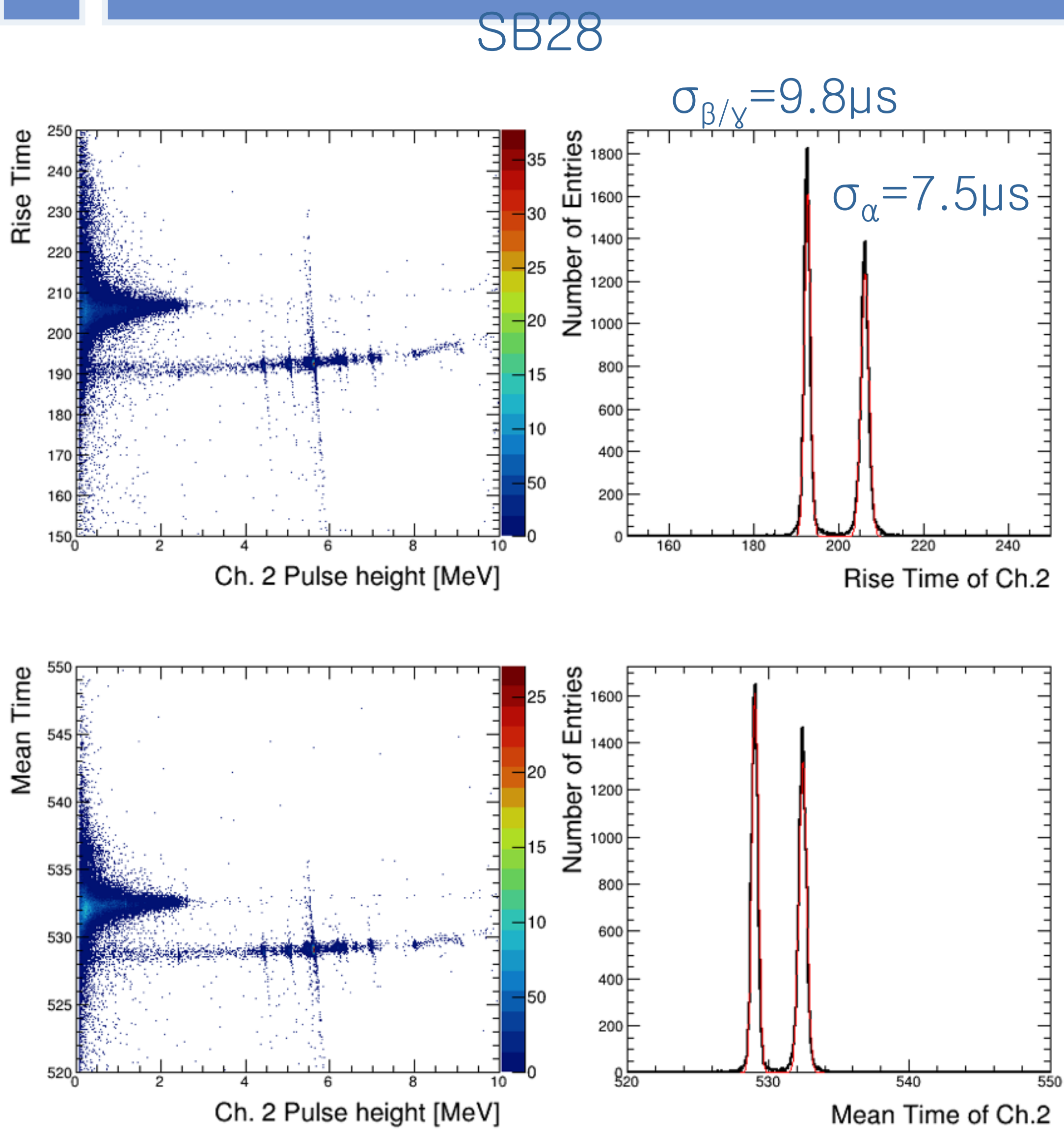




-> Goal of 0.001 DBU for AMoRE-I can be achieved

-> Zero background with 5kg of CMO, 3years

Pulse Height vs Risetime or Meantime

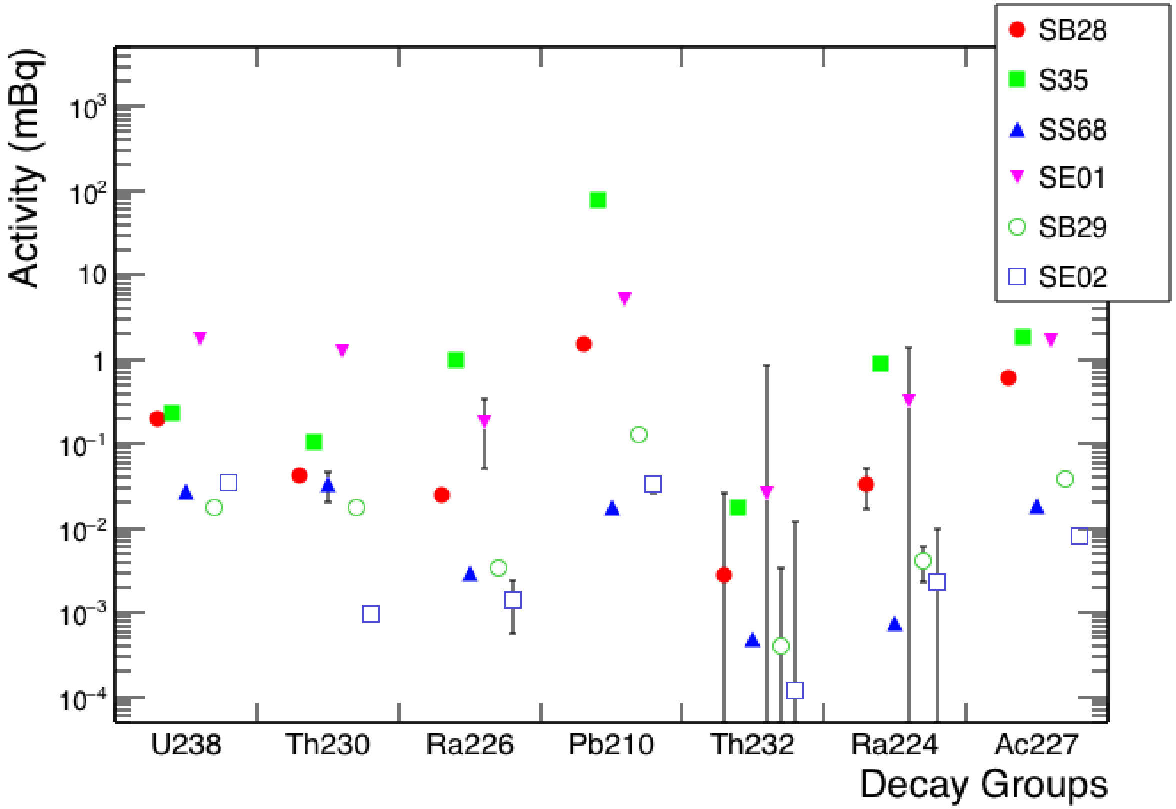


- Discrimination power

$$DP = \frac{|m_B - m_A|}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

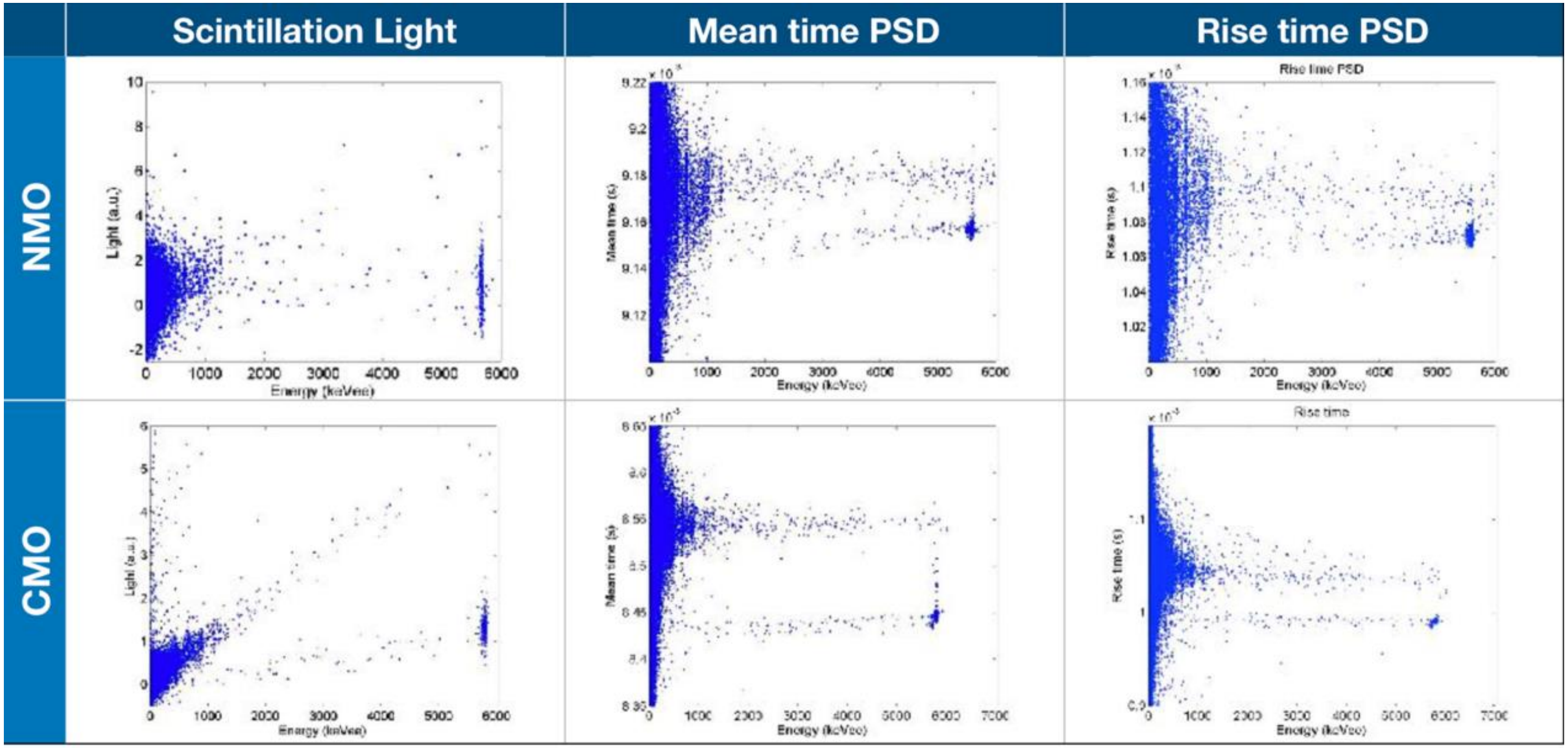
- Using risetime
  - DP = 11.0 ± 1.2
- Using meantime
  - DP= 9.23 ± 0.36

Internal Activity from α rates



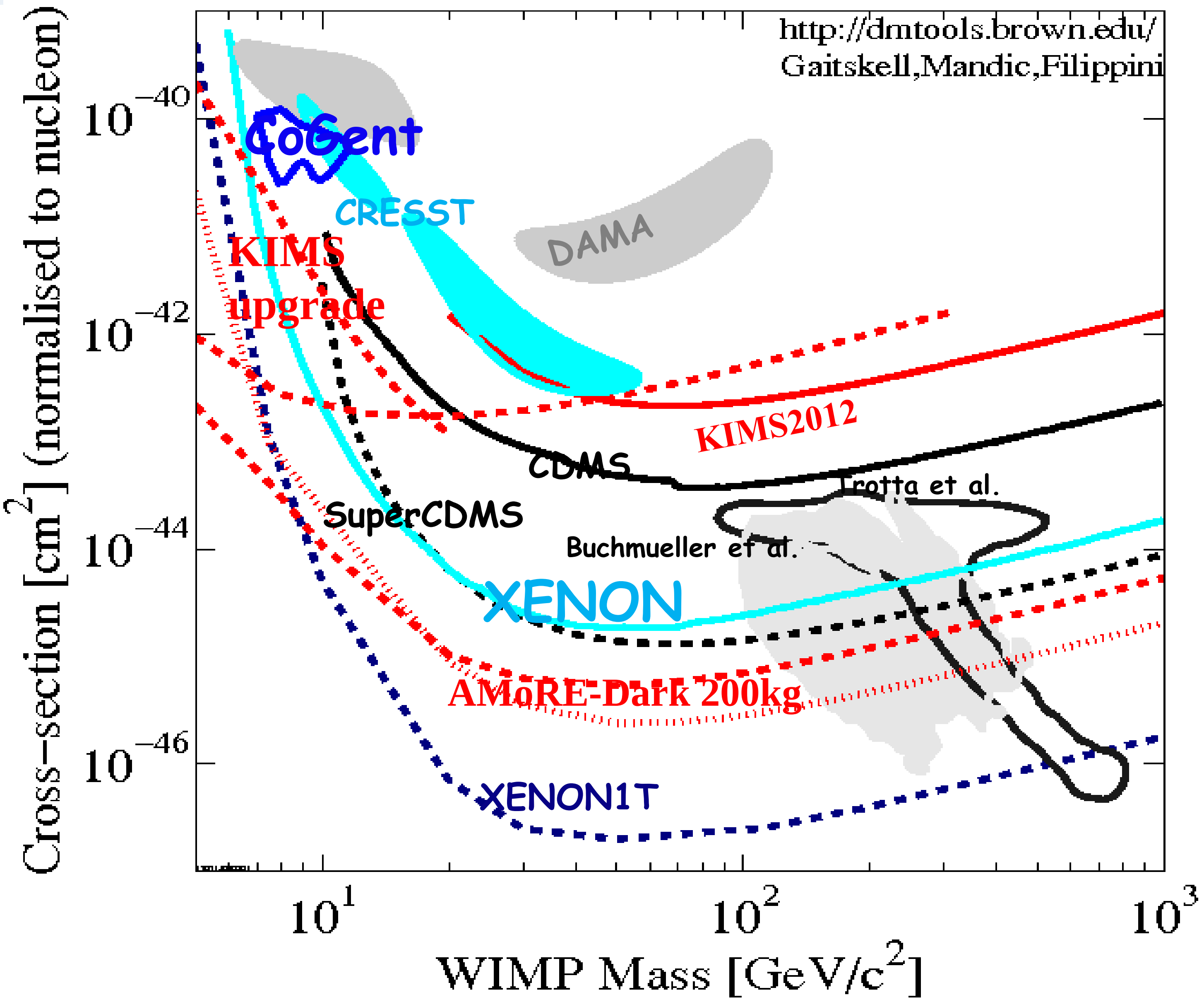
- Most of the Pb-210 are bulk contribution.
- Internal backgrounds between crystals differ more than an order, even two orders.

LT test of CMO and NMO cubics: Preliminary



- CMO has better separation power than NMO.
- CMO has ~ 7% energy in photon emission.
- Need more tests for various crystals for comparison.

Dark matter sensitivity of $CaMoO_4$ cryogenic experiment : AMoRE-DARK (KIMS-LT)



Conclusions (SWAPS2014 by Andrea Giuliani)

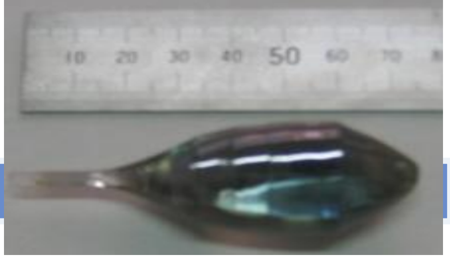
- **LUCIFER** – difficulties larger than expected in producing ZnSe crystals with the desired features in a reproducible way, complicated by geopolitical issues – now most of the technical problems have been solved - enriched crystal production starting from fall 2014 – about 36 crystals containing 10 kg of ^{82}Se (irrecoverable loss 35%) in Gran Sasso

- **LUMINEU** – excellent radiopurity and performance of the $ZnMoO_4$ crystals (natural and enriched) – irrecoverable loss negligible – pilot experiment with 1 kg of enriched Mo in Modane within 2015 – demonstrator with 10 kg of enriched Mo in Modane or Gran Sasso in 2016 $\Rightarrow$ MoU INFN – IN2P3 – ITEP

- **AMoRE**: excellent $^{40}Ca^{100}MoO_4$ detector performance – aggressive schedule foreseeing a 10 kg experiment at a 2 year scale and 200 kg at a 5 year scale

The scintillating bolometer technology has excellent prospects to reach zero background at the ton x year scale with high energy resolution and efficiency in more than one isotope

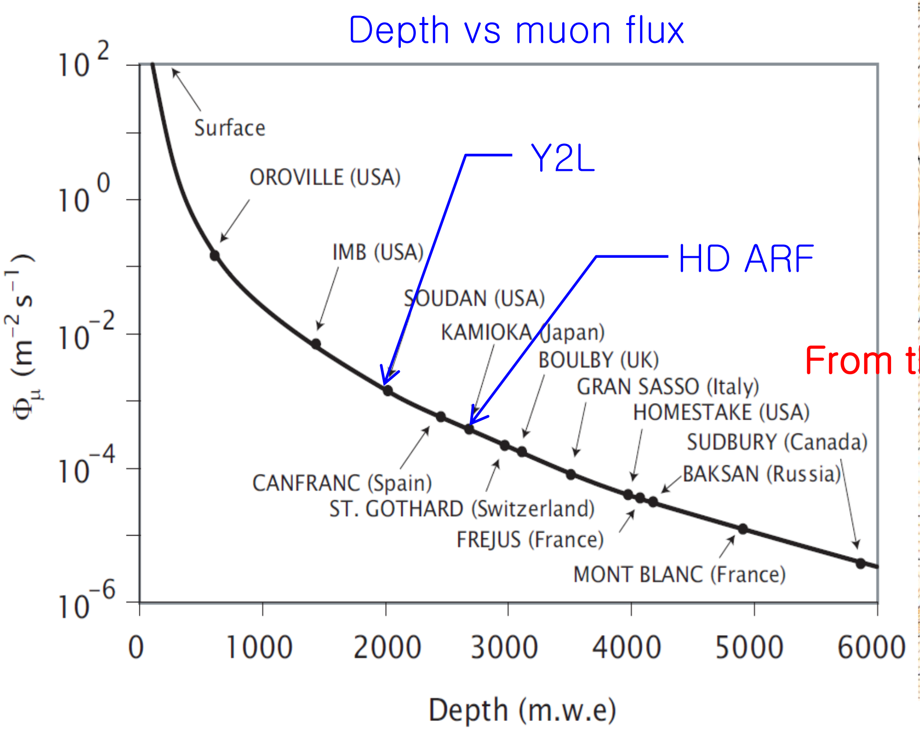
History of AMoRE

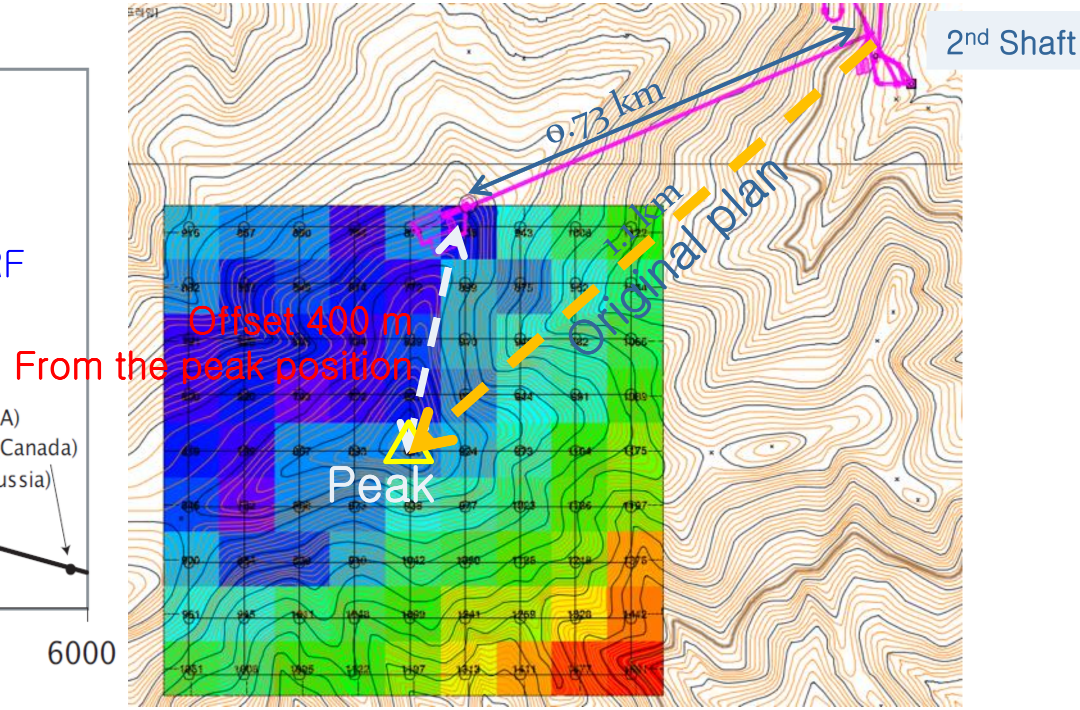


1) 2002 : First idea and try to grow $CaMoO_4$(CMO) in Korea
2) 2003 : Collaboration with V.Kornokov.
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of $XMoO_4$, cryogenic detector of CMO
4) 2005-2007 : Large CMO with 1st ISTC project
5) 2006 : Collaboration with F. Danevich group (CMO by Lviv)
6) 2007 : CMO R&D in cryogenic temperature started.
7) 2008 : 2nd ISTC project : 1kg of $^{48depl}Ca^{100}MoO_4$ crystal
8) 2009 : AMORE collaboration formed
9) 2010-11 : $^{48depl}Ca^{100}MoO_4$ internal background study
10) 2012 : Russian group (FOMOS) got funding for production line
11) 2013 : AMoRE project funded (Under Center for Underground Physics, Institute for Basic Science)
12) 2014 : Upgrade of Y2L lab for AMoRE-pilot and AMoRE-I
13) 2015 : AMoRE-pilot commissioning

Muon Flux Study for Location

- ❑ **Access tunnel with more overburden shortened to ~730 m by a simulation study considering a detail profile of the landscape.**





- ❑ **Muon reduction rate @ HD with a simulation: ~ 8 × 10^{-6}**

A new UL in Handeok mine

- ❑ The only operating iron ore mine in Korea.
- ❑ A 600 m long 2nd shaft already constructed.
- ❑ 0.7 million ton iron ores being produced per year

Bird view of Handeok Iron Mine

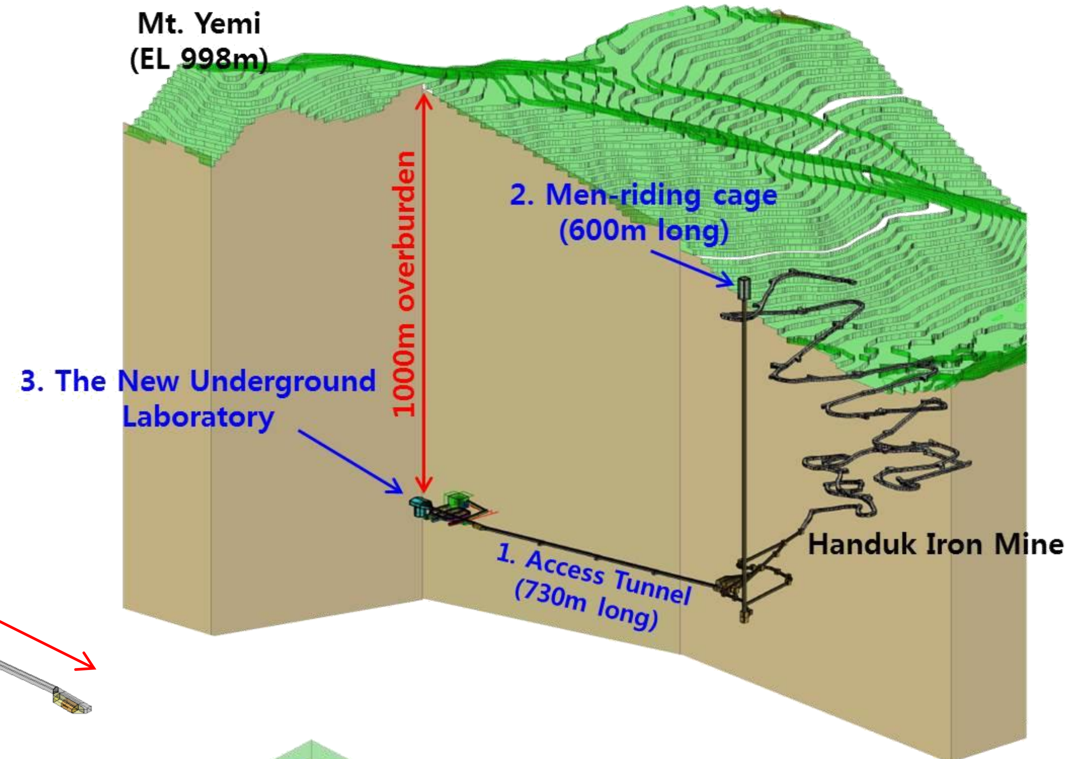
Handeok has two shafts for mining

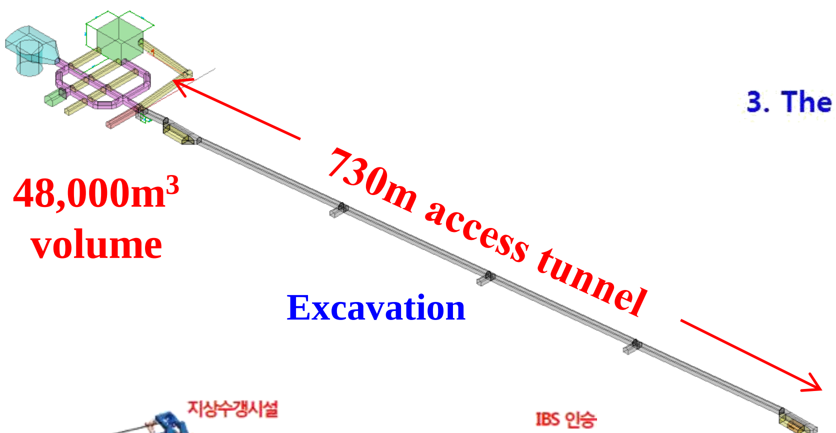
1st shaft ~ 300 m long

2nd shaft 600 m long (NEW)

New Underground Laboratory

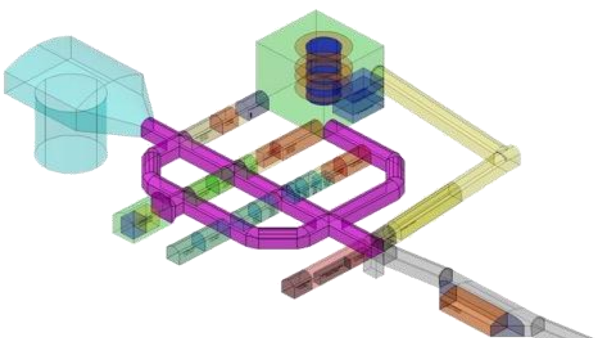
- 4 major constructions
  - Tunnel excavation
  - Men-riding cage
  - Underground lab
  - Surface office/lab





Excavation

Men-riding cage



Underground lab

Surface office/lab