# Status of the AMORE double beta decay experiment

**AMoRE (Advanced Mo-based Rare process Experiment)**

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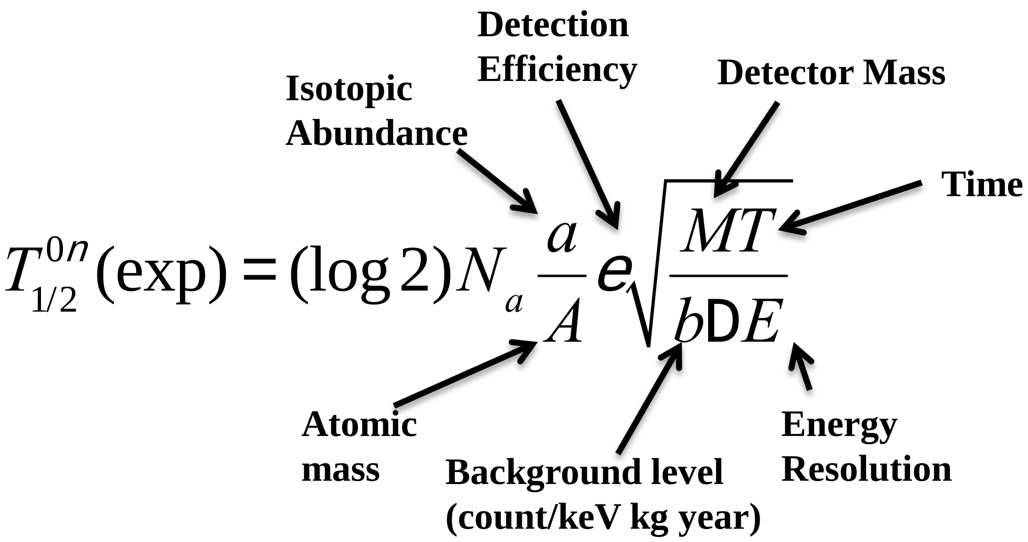
Kyungpook National University

On Behalf of AMoRE collaboration

International Conference on High Energy Physics
(ICHEP2016) Chicago, USA, August 4-11, 2016

# AMoRE Experimental sensitivity

## For sizeable background case;



$$T^{0n}_{1/2}(\exp) = (\log 2)N_a \frac{a}{A} e\sqrt{\frac{MT}{bDE}}$$

Isotopic Abundance

Detection Efficiency

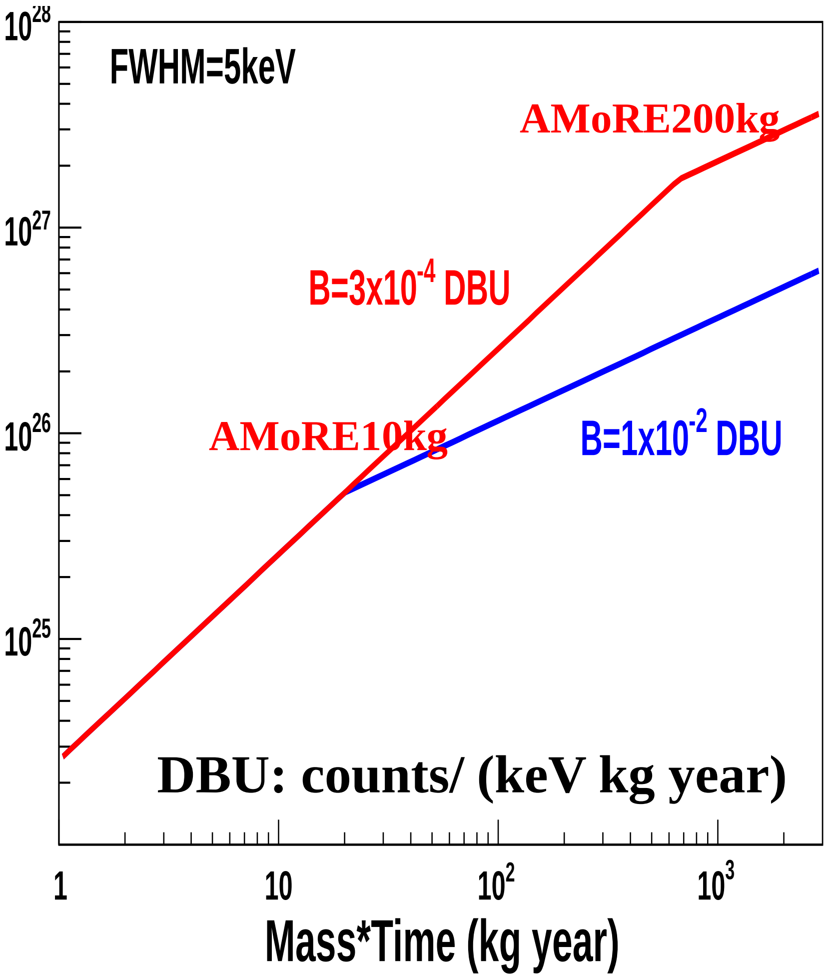
Detector Mass

Time

Atomic mass

Background level (count/keV kg year)

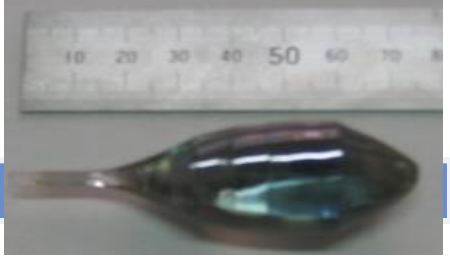
Energy Resolution



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

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

# History of AMoRE



1) 2002 : First idea and try to grow CaMoO4(CMO) in Korea
2) 2003 : Collaboration with V.Kornokov.
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of XMoO4, 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

# AMoRE collaboration

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

8 counties, 18 institutions, ~90 collaborators

# Yangyang(Y2L) Underground Laboratory

Korea Hydro & Nuclear Power Co.
Yangyang Pumped Storage Power Plant

**KIMS (Dark Matter Search)**

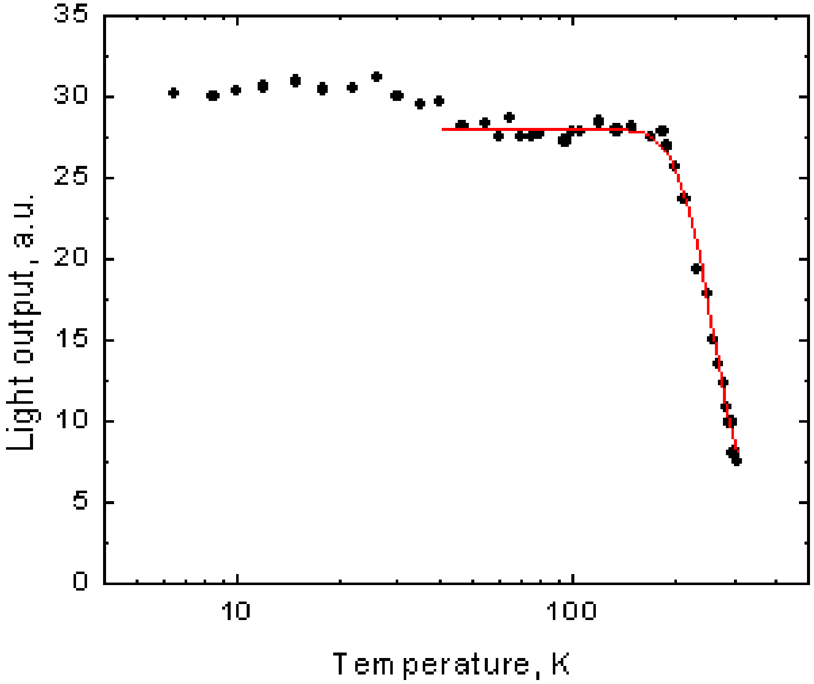
**AMoRE (Double Beta Decay Experiment)**

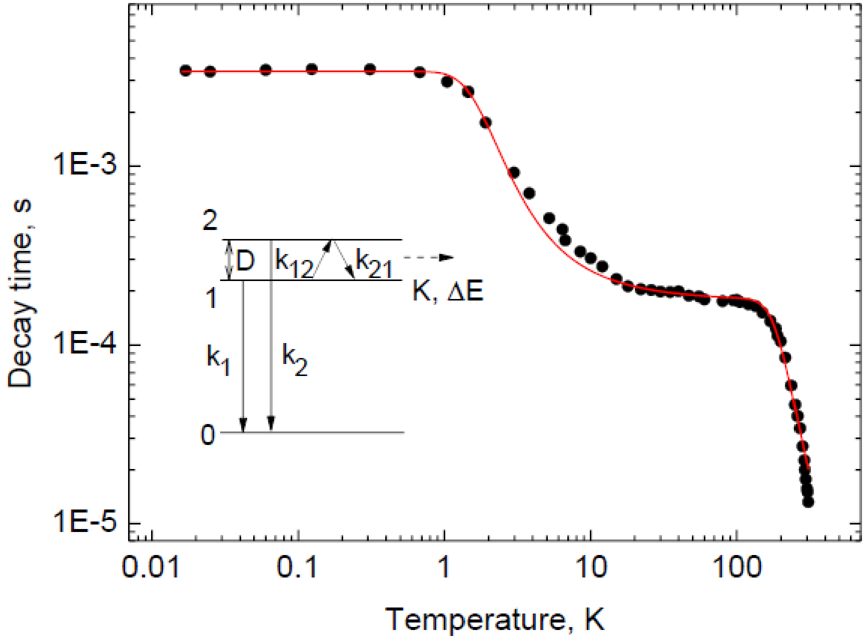
Minimum depth : 700 m / Access to the lab by car (~2km)

# 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 0ν ββ decay, Dark matter search possible)

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

Mo-100 isotope production:

The ECP (Electrochemical plant)
Zelenogorsk, Krasnoyarsky kray, Siberia

- $^{100}MoO_3$ oxide with mass of 2,5 kg

  1) Enrichment: Mo-100 = 96,1%

  2) Impurities (the results from ICP MS measurements):

  U < 0,07 ppb to < 0,2 ppb , Th < 0,1 ppb to < 0,7 ppb

  $^{226}$Ra < 2,3 mBq/kg, $^{228}$Ac < 3,8 mBq/kg

- Current capacity is 25-30 kg per year.

  CUP has contract with ECP for $^{100}$Mo delivery : 120 kg for AMoRE-II

Ca-48 isotope production

The industrial separator SU20, Lesnoy, Sverdlovky region

27 kg of Ca-48depl ($^{48depl}CaCO_3$) is available now at EKP, Lesnoy

Ca-48 < 0,001%

# Internal background levels from Y2L@RT

$\beta-\alpha$ decay in $^{238}$U (164 us)
$^{214}$Bi (Q-value : 3.27-MeV) → $^{214}$Po (Q-value : 7.83-MeV)

$\alpha-\alpha$ decay in $^{232}$Th (145 ms)
$^{220}$Rn (Q-value : 6.41-MeV) → $^{216}$Po (Q-value : 6.91-MeV)

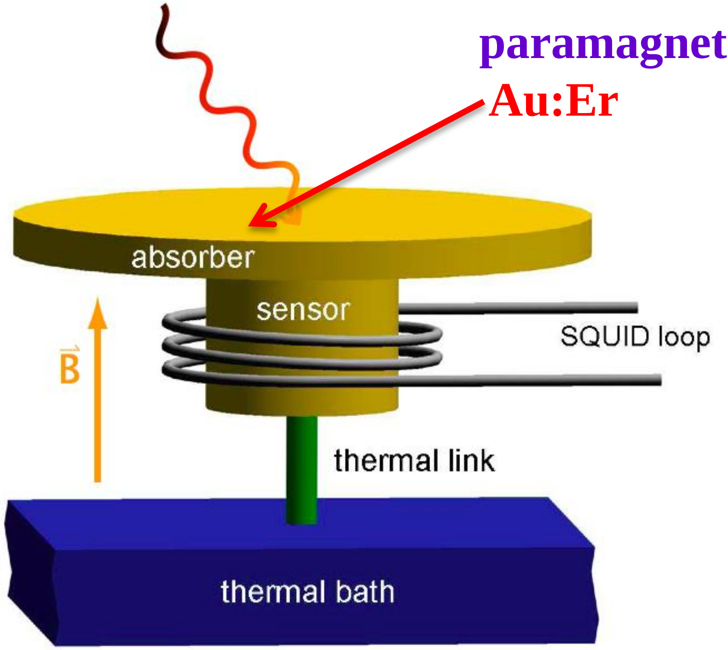
$\alpha-\alpha$ decay in $^{235}$U (1.78 ms)
$^{219}$Rn (Q-value : 6.23-MeV) → $^{215}$Po (Q-value : 7.38-MeV

| | U-238 chain | U-235 chain | Th-232 chain |
|---|---|---|---|
| Element | Po-214 | Po-215 | Po-216 |
| Activity (uB/kg)<br>SS68 | 60±8 | 200±14 | 30±7 |
| NSB29 | 200±14 | 700±26 | 80±9 |
| S35 | 4400±66 | 1200±35 | 500±22 |
| SB28 | 80±9 | N/A | 70±8 |
| SE1 | 40±12 | 60±8 | 50±15 |

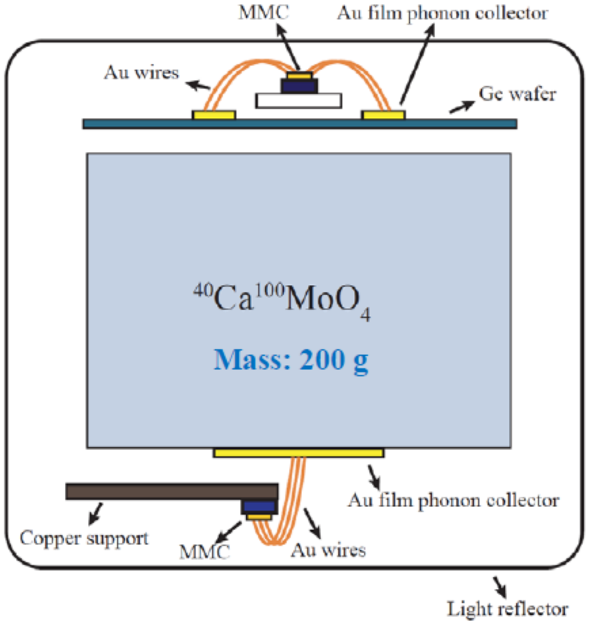
* J.Y. Lee et al., IEEE Trans. Nucl. Sci. 63, (2016) 543
*100 uBq/kg for U-238,50 uBq/kg for Th232 decay chain for AMoRE-I

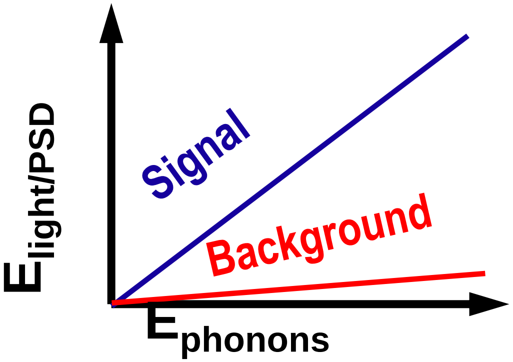
# MMC (Metallic Magnetic Calorimeter) for LTD

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

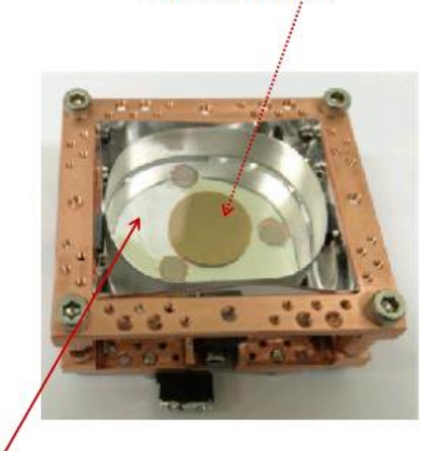


**paramagnetic sensor:**
**Au:Er**

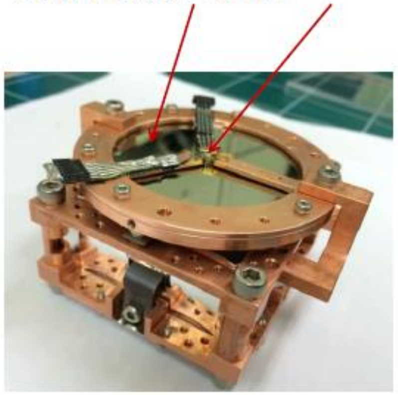




Phonon collector film
on bottom surface

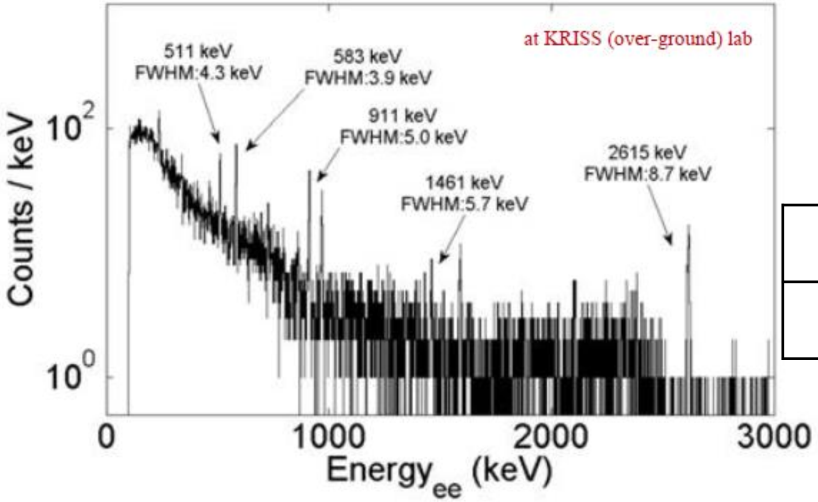


Light detector
2 inch Ge wafer + MMC



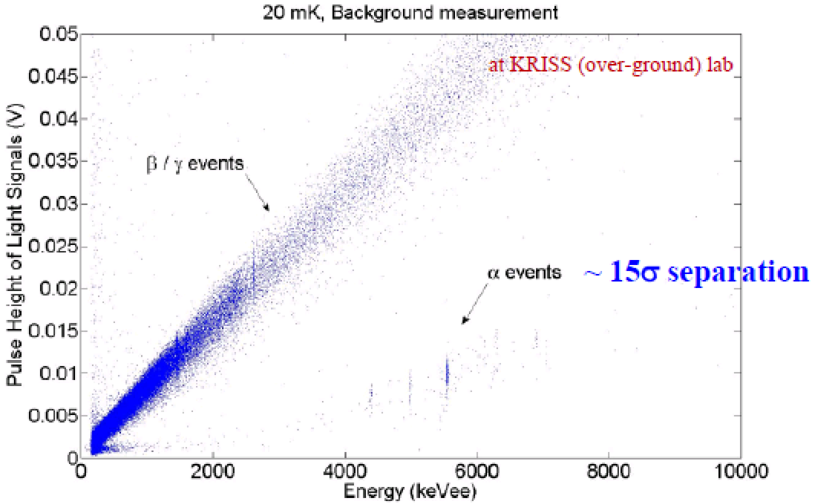
# MMC cryogenic technique for AMoRE

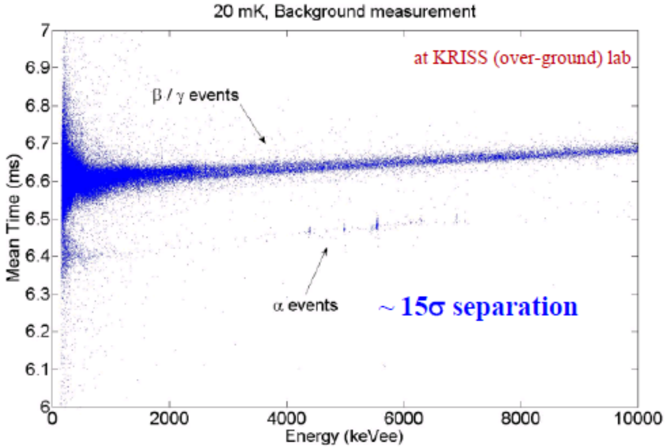
G. B. Kim, et al., IEEE Trans. Nucl. Sci. 63 (2016) 539



Overground test at KRISS @ 10 mK
Wet DR

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



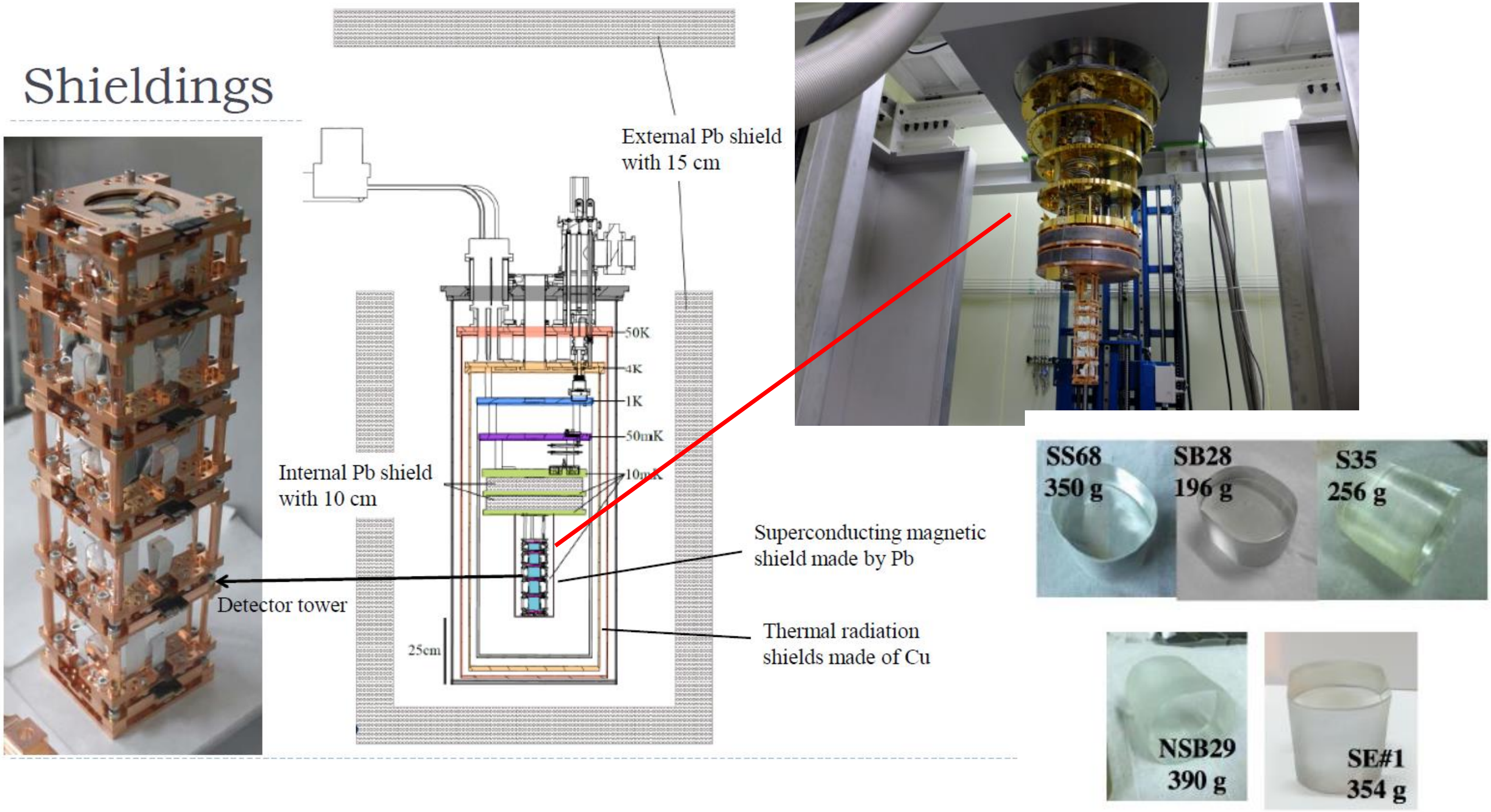


Excellent α/e separation by both Light and PSD

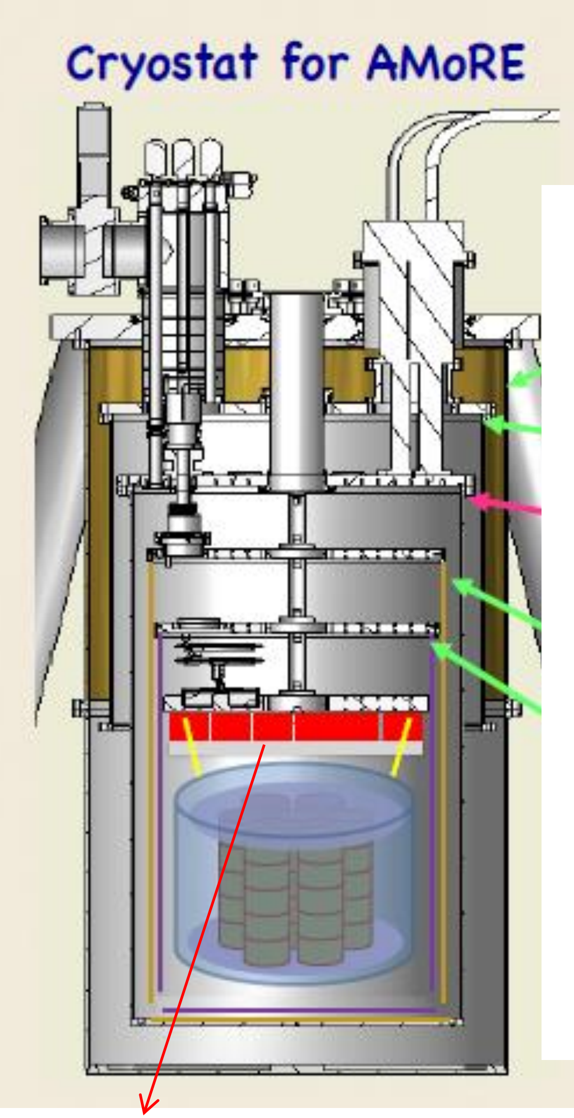
# AMoRE-Pilot Setup

AMoRE-pilot : five $^{40}Ca^{100}MoO_4$ crystals of 1.5kg

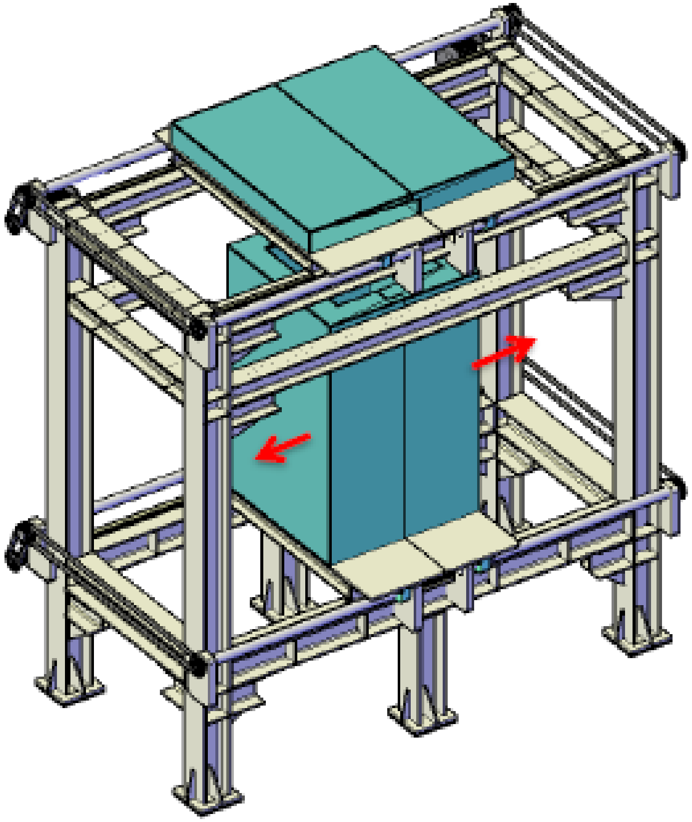
(SB28, S35, SS68, SE01, SB29) ; 5 phonon detectors + 6 photon detectors



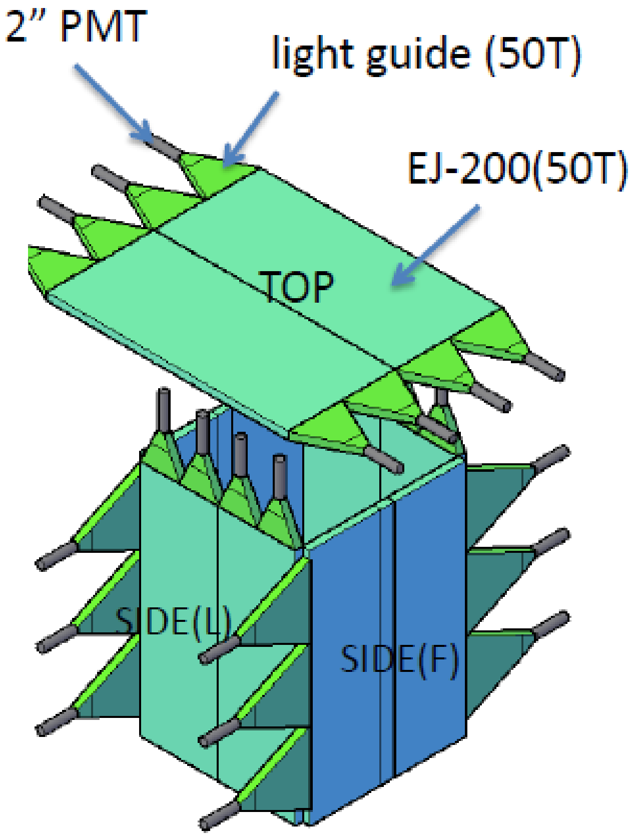
# Shielding structure of AMoRE-pilot & AMoRE-I



10cm ultra-low background Pb

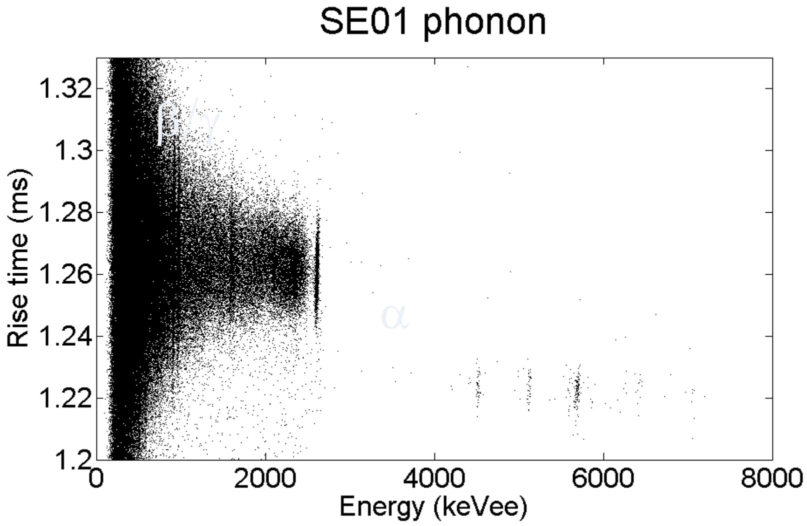


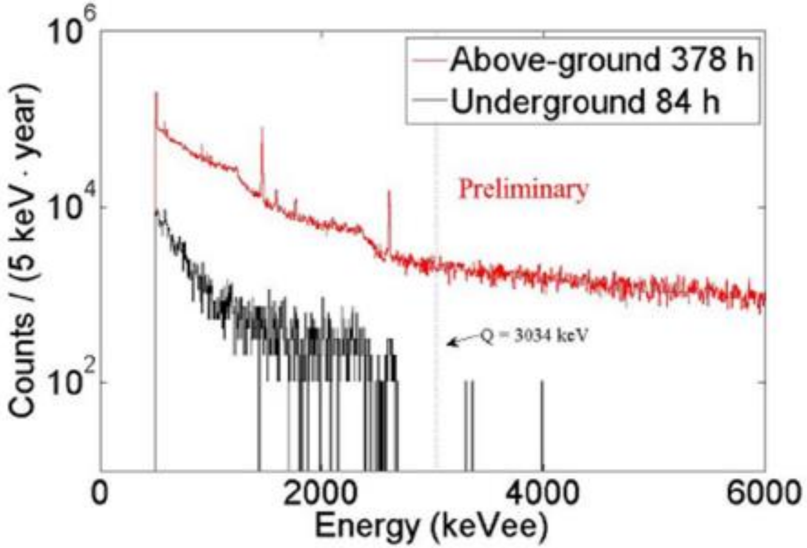
15cm low background Pb



muon shielding structure

# Preliminary results on AMoRE-pilot commissioning run





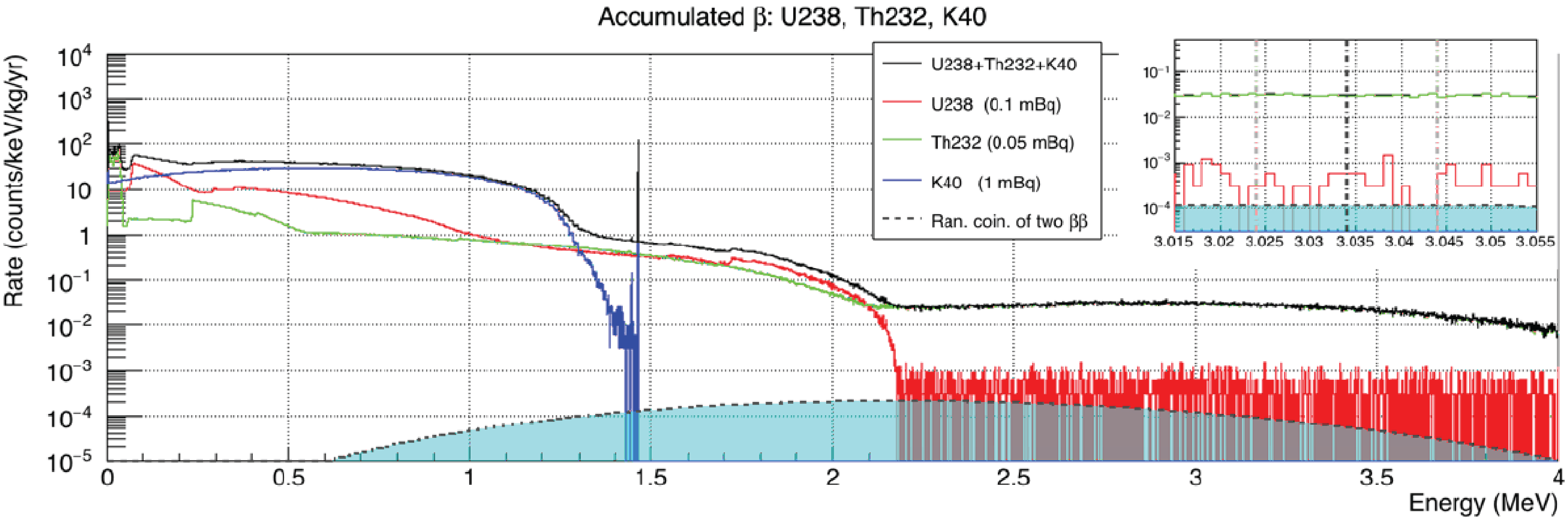
FWHM energy resolution at 2.6 MeV

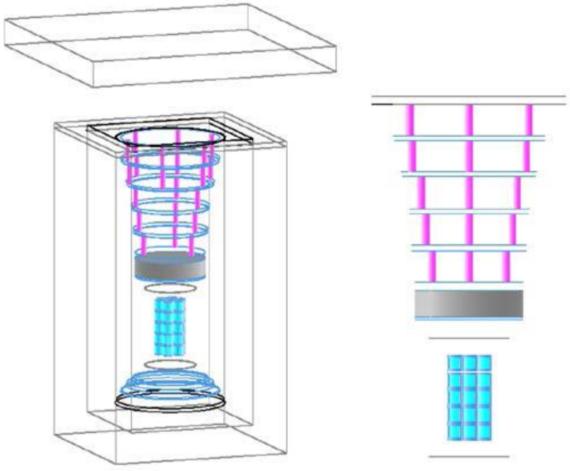
| Crystals | AMoRE-Pilot run-1 | AMoRE-Pilot run-2 |
|---|---|---|
| SB28 | 36.8 keV | 25.0 keV |
| S35 | N/A | 16.3 keV |
| SS68 | 52.6 keV | 24.2 keV |
| SE01 | 39.7 keV | 24.6 keV |
| NSB29 | 42.6 keV | N/A |

Background and vibration noise need to be improved

# 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

# Major backgrounds from radionuclides for AMoRE-II (GEANT4)

| **Background source** | **Activity** [ μBq/kg] | **Bg** [10$^{-4}$ cnt/keV/kg/yr] | **Bg reduced by PSD** [10$^{-4}$ cnt/keV/kg/yr] |
|---|---|---|---|
| Tl-208, internal | 10 ($^{232}$Th) | 0.36 | |
| Tl-208, in Cu | 16 ($^{232}$Th) | 0.22 | |
| BiPo-214, internal | 10 | 0.11 1) | ≤ 0.01 |
| BiPo-214, in Cu | 60 | 1.8 1) 2) | ≤ 0.18 |
| BiPo-212, internal | 10 ($^{232}$Th) | 0.08 1) | ≤ 0.01 |
| BiPo-212, in Cu | 16 ($^{232}$Th) | 0.36 1) 2) | ≤ 0.04 |
| Y-88, internal | 20 | 0.19 | |
| Σ int. (w/o 2β2ν ) | | 0.74 | ≤ 0.57 |
| Σ Cu | | 2.40 | ≤ 0.44 |
| Rand. coinc. from 2β2ν decays of $^{100}$Mo | 8.7×10$^3$ (single evts.) | 3.1 3) | 1.2 |
| **Total** | | **6.2** | **≤ 2.2** |

**1) Can be reduced x0.1 by alpha/beta PSD**

**2) Can be reduced by teflon coating of Cu (to remove surface alphas)?**

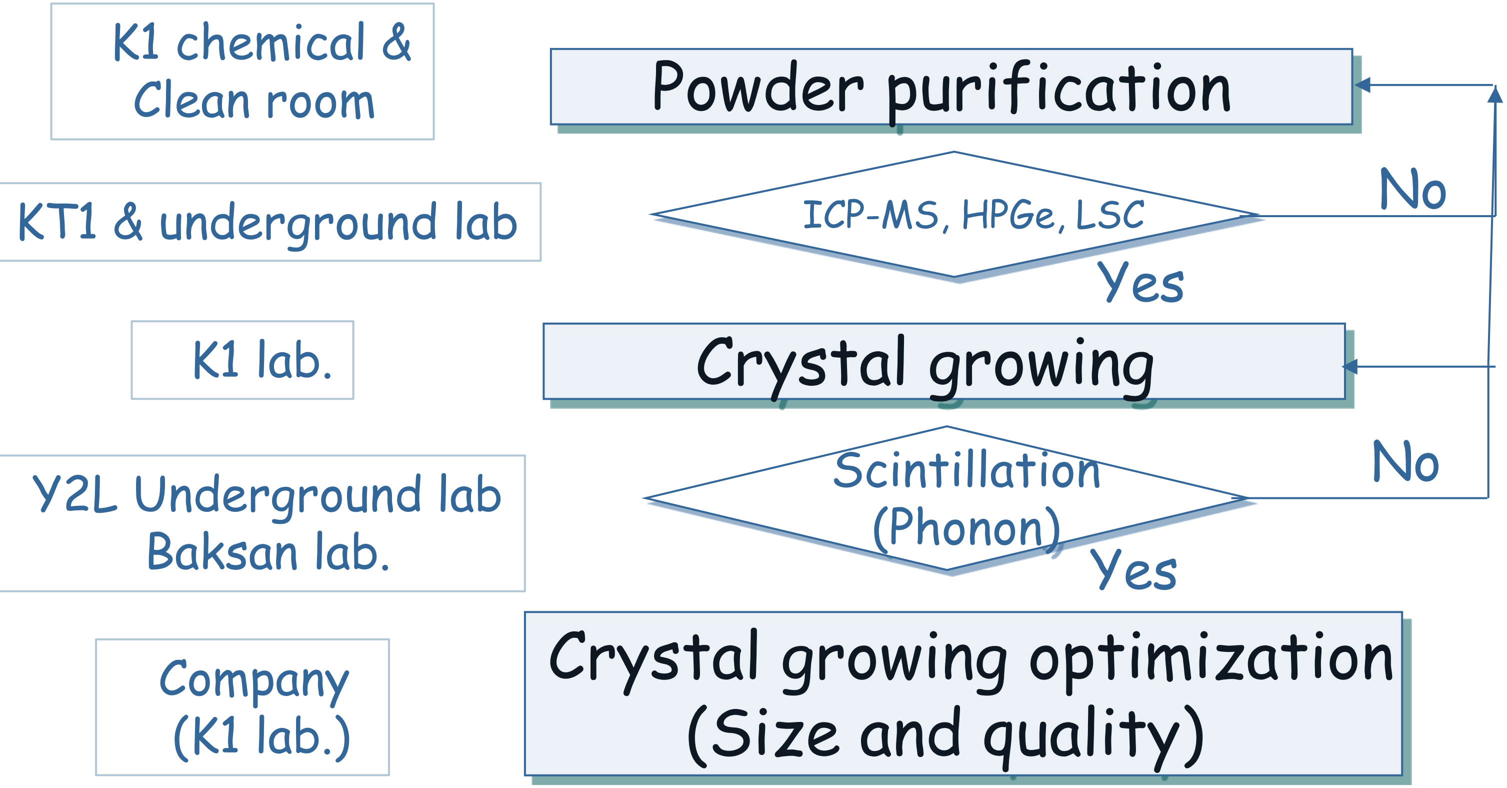
**3) Can be reduced by the leading edge separation with Δt=0.5 ms**

Muon background : ~1.4e$^{-4}$ counts/keV/kg/yr @Y2L

# 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)**


K1 chemical & Clean room

Powder purification

KT1 & underground lab

ICP-MS, HPGe, LSC

No

Yes

K1 lab.

Crystal growing

Y2L Underground lab
Baksan lab.

Scintillation
(Phonon)

No

Yes

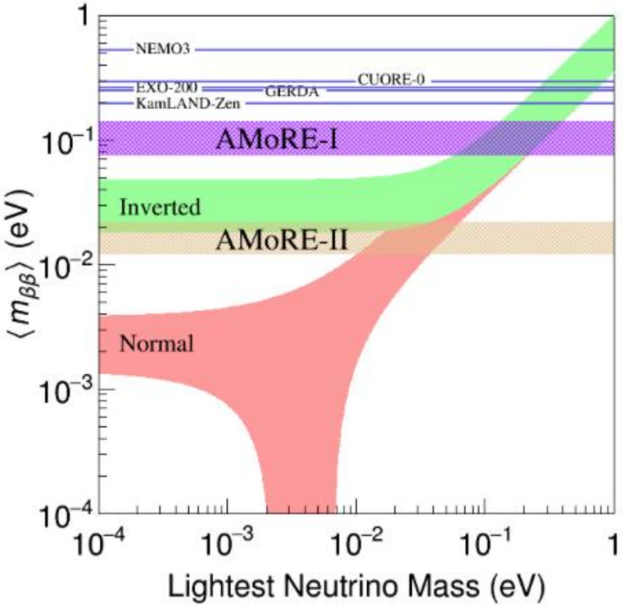
Company
(K1 lab.)

Crystal growing optimization
(Size and quality)

**=> See talk by Dr. H.K.Park instrumentation session**

# AMoRE summary & prospect

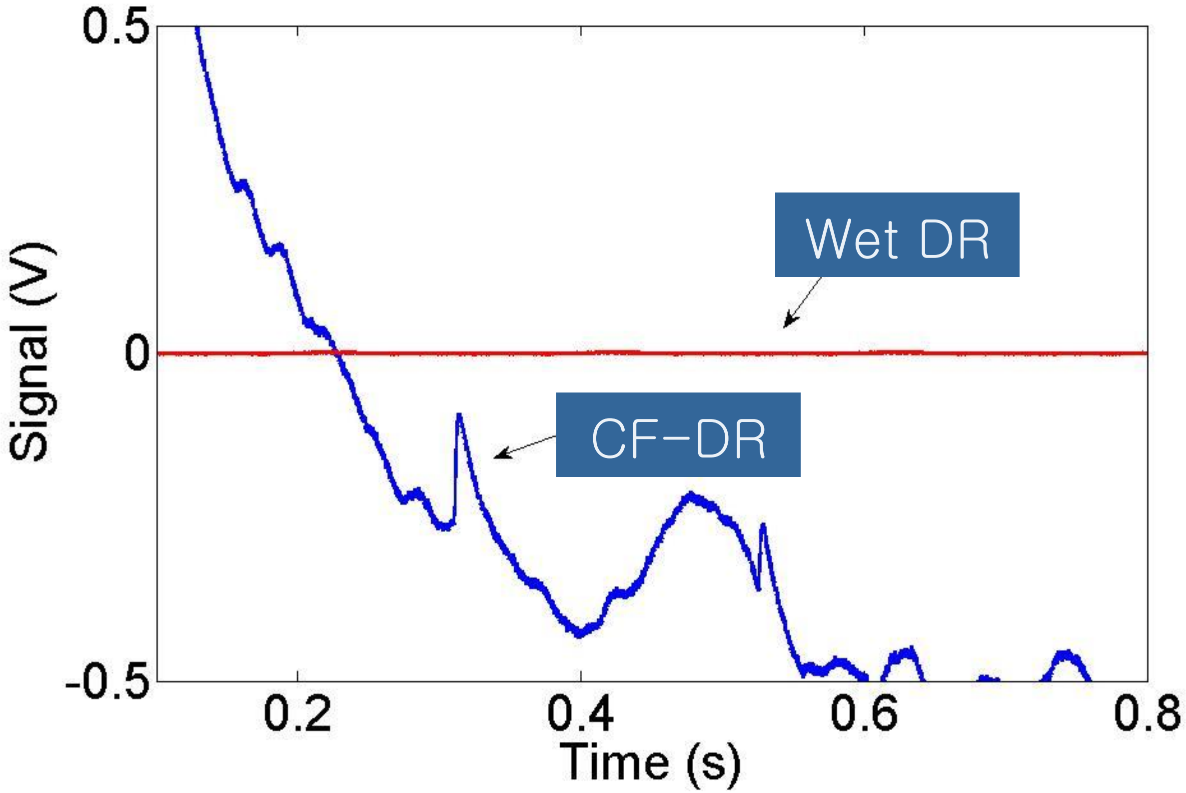
- Large volume of low background $^{48depl}Ca^{100}MoO4$ (CMO) have been developed.
- Cryogenic MMC technique with CMO is successful.
- We started AMoRE-pilot with 1.5kg of CMO.
- CMOs for AMoRE-I are under delivery and will be tested by the end of this year.
- We are working on R&D of chemical purification & new crystal R&D for AMoRE-II
- Fully funded up to AMoRE-II.



| | Pilot | Phase I | Phase II |
|---|---|---|---|
| Detector Crystal | $^{48depl}Ca^{100}MoO_4$ | $^{48depl}Ca^{100}MoO_4$ | New crystal? |
| Detector Mass | 1.5 kg | ~5 kg | ~200 kg |
| Background (keV /kg /year) | 0.01 | 0.001 | 0.0001 |
| Sensitivity of $T_{1/2}$ (year) | ~$10^{24}$ | $2.7x10^{25}$ | $1.1x10^{27}$ |
| Sensitivity of $M_{\beta\beta}$ (meV) | < 300–900 | 70–140 | 12–22 |
| Location | Y2L | Y2L | Handuk mine |
| Schedule | 2016–2017 | 2017–2019 | 2020–2025 |

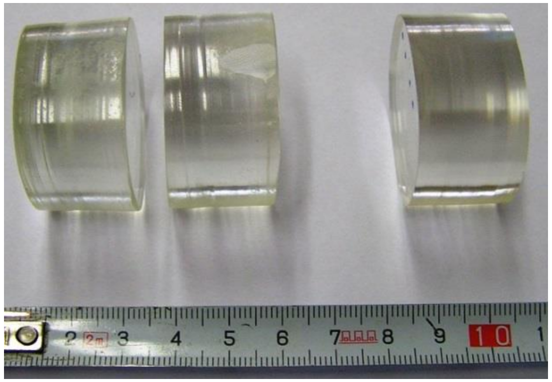
# Thank you

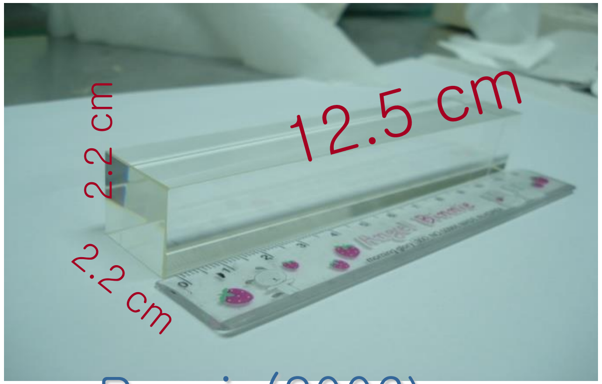
The main source of vibration noise is the pulse tube refrigerator of the CF-DR.
We are working on noise reduction such as new damping system.



# $CaMoO_4$ crystal development

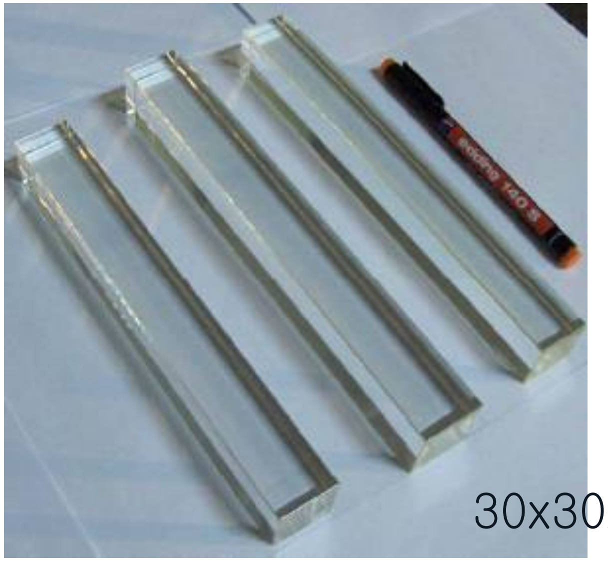

Korea(2003)


Ukraine-CARAT(2006)

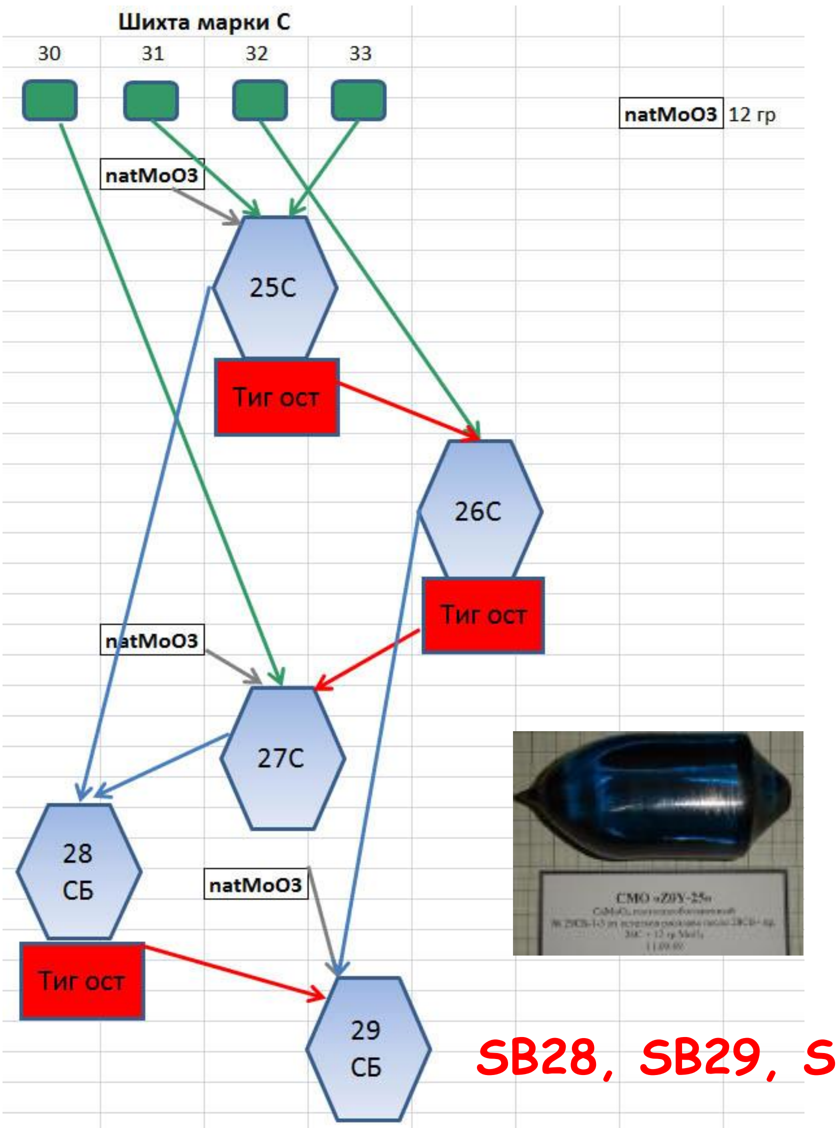


Russia(2006)

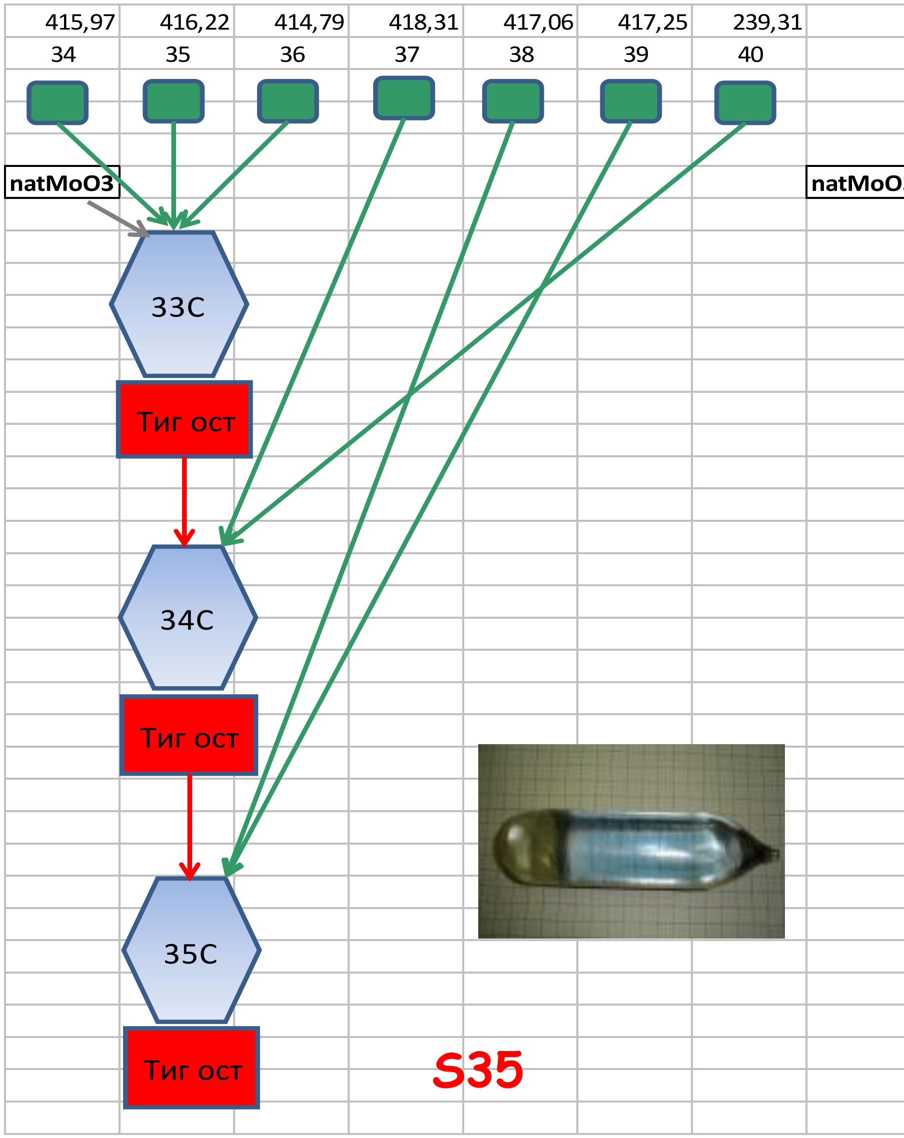

IEEE/TNS 2008


30x30x200mm

# Crystal growing (Double crystalization)



**SB28, SB29, SS61**



**S35**

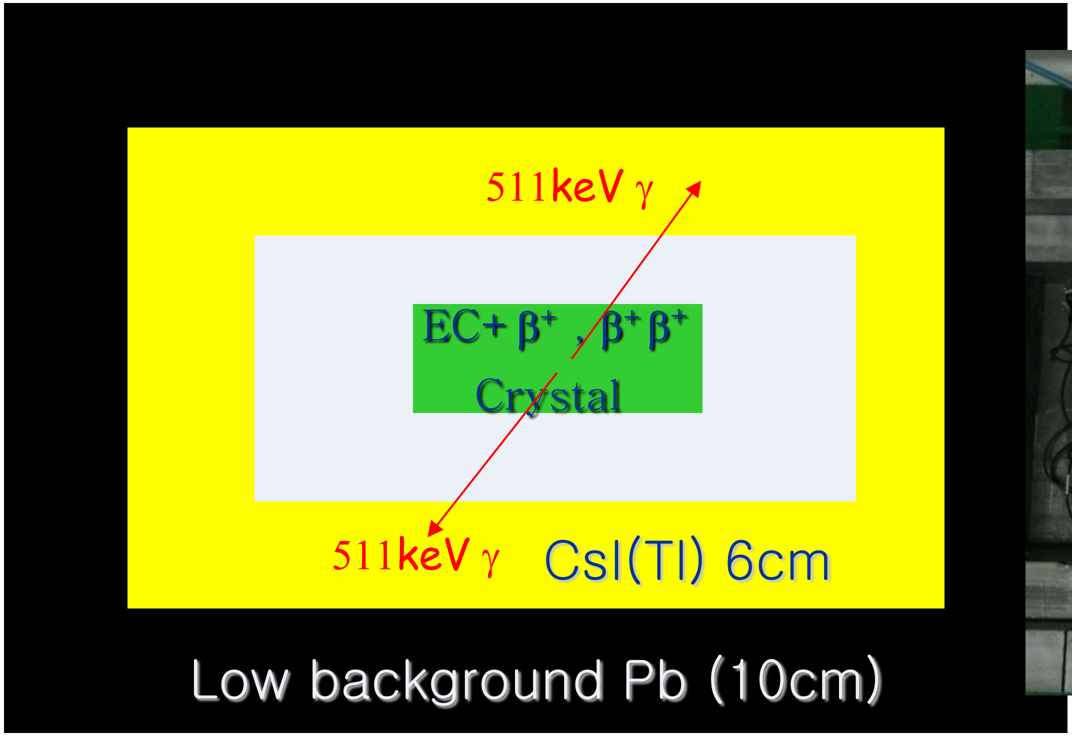
# $4\pi$ CsI(Tl) active setup with Pb shielding at Y2L

1) $2\nu$ EC+ $\beta^+$ , $\beta^+\beta^+$ study with 2 back to back $\gamma$ tagging

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

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

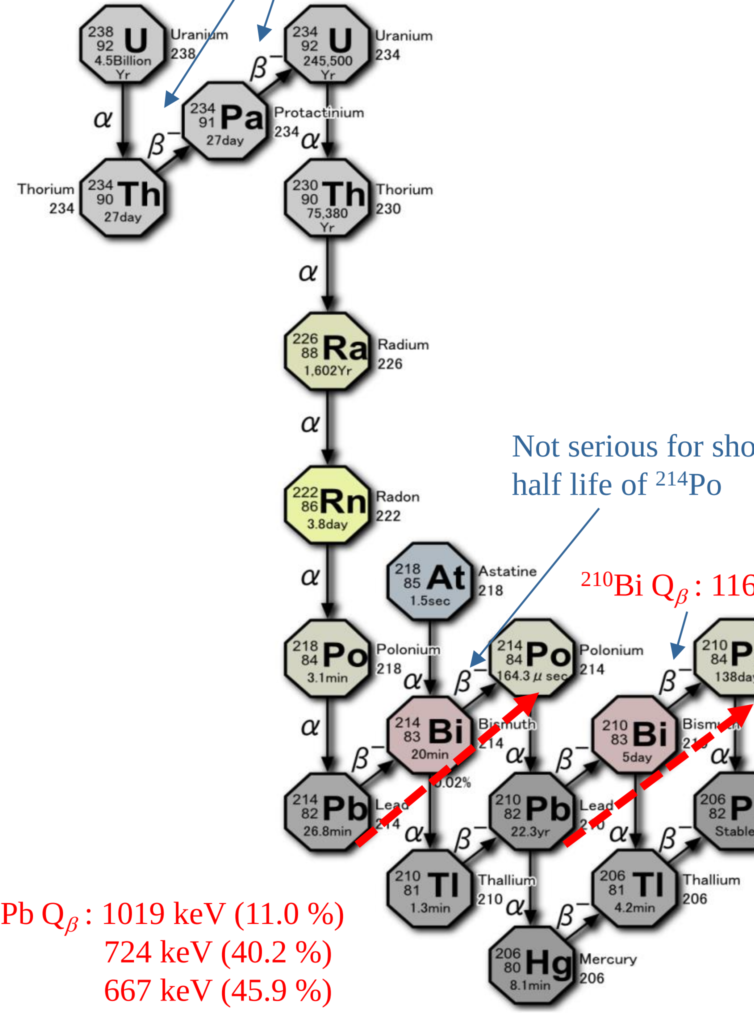
2) CMO internal background study with active veto



# Considerable beta decays ($^{238}$U)

$^{234}$Th $Q_{\beta}$ : 199 keV (78.0 %)

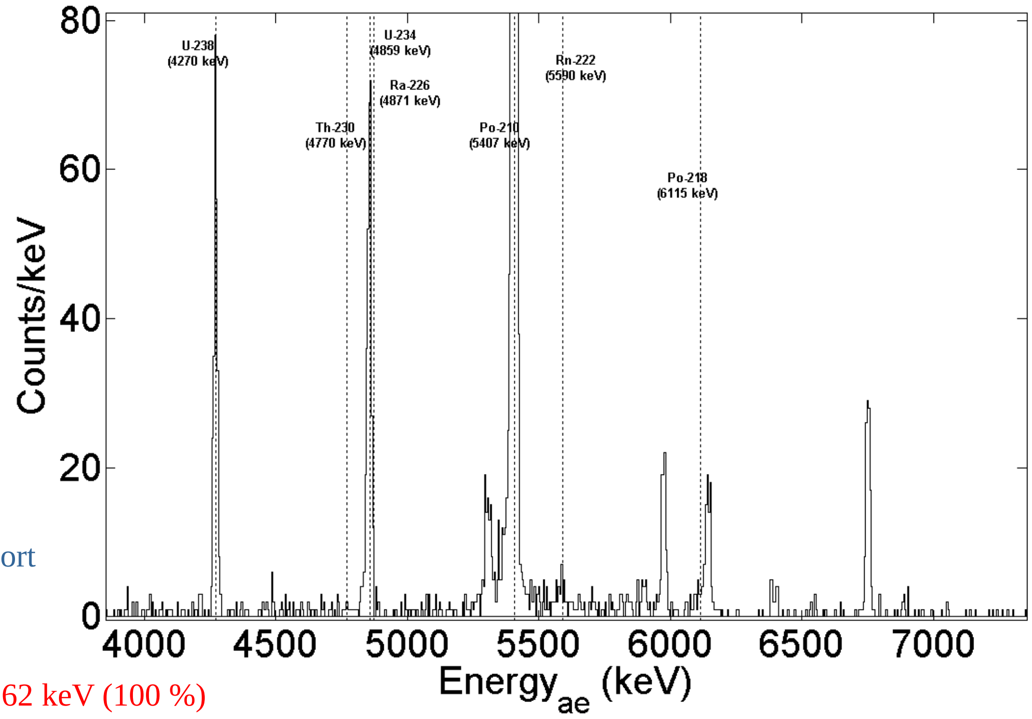
$^{234}$Pa $Q_{\beta}$ : 2269 keV (97.6 %)



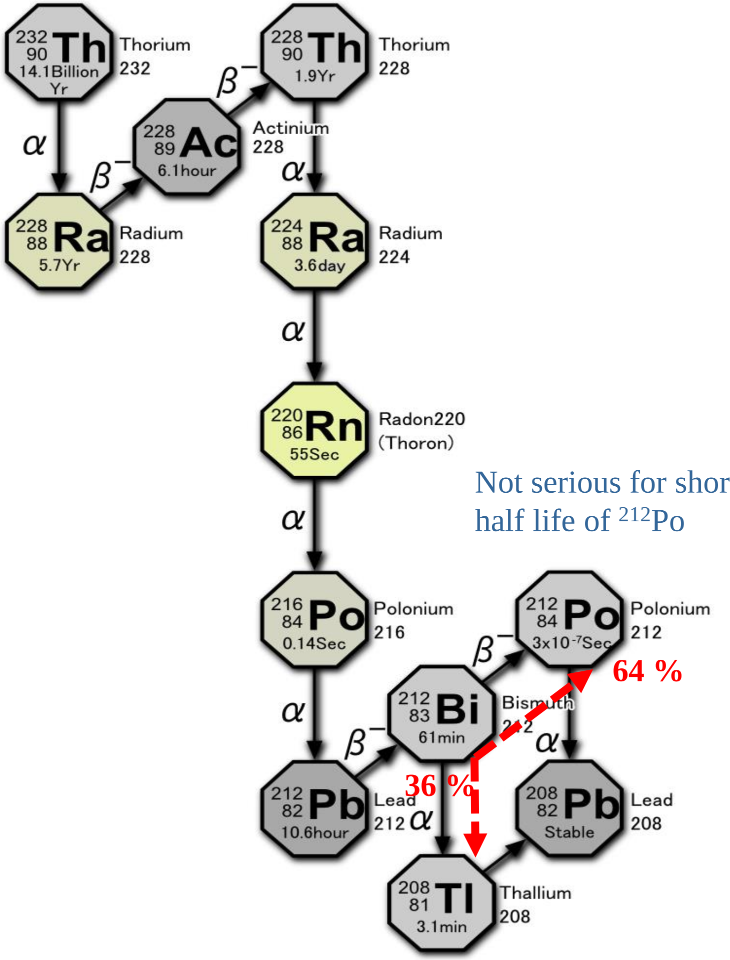
Not serious for short half life of $^{214}$Po

$^{210}$Bi $Q_{\beta}$ : 1162 keV (100 %)

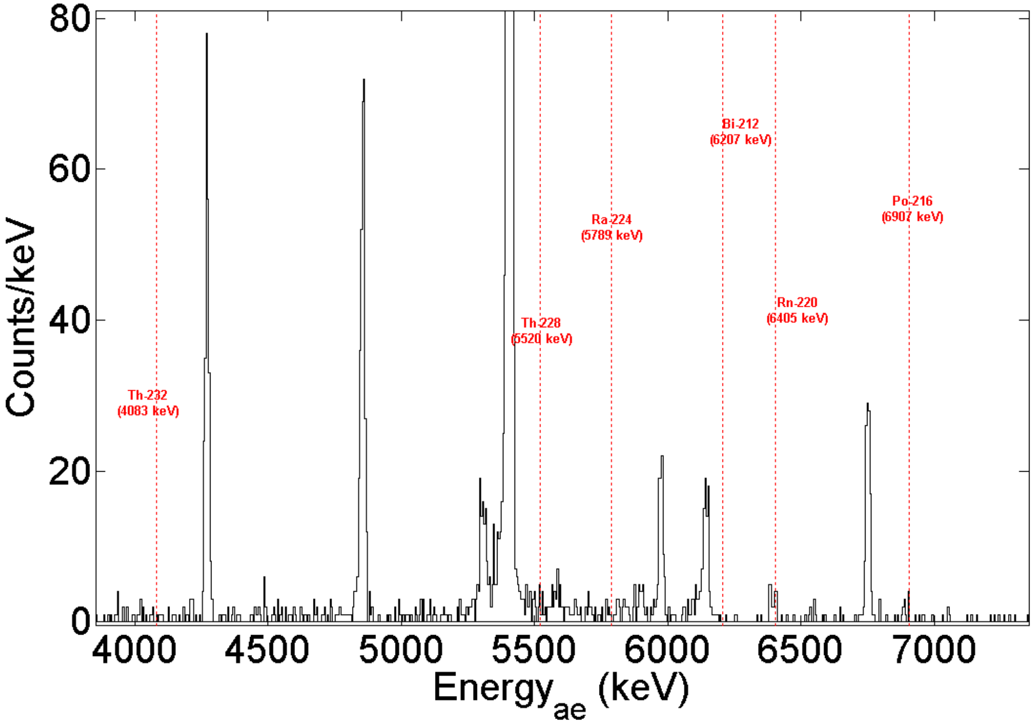
$^{214}$Pb $Q_{\beta}$ : 1019 keV (11.0 %)
724 keV (40.2 %)
667 keV (45.9 %)



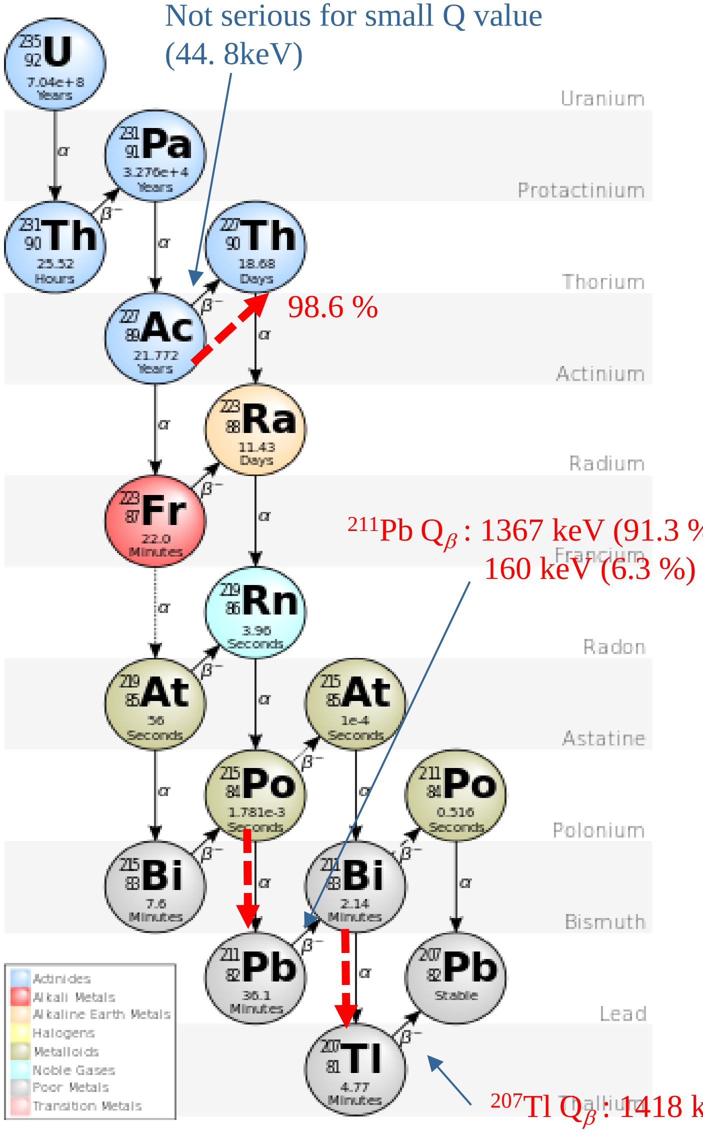
# Considerable beta decays ($^{232}$Th)



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



# Considerable beta decays ($^{235}$U)

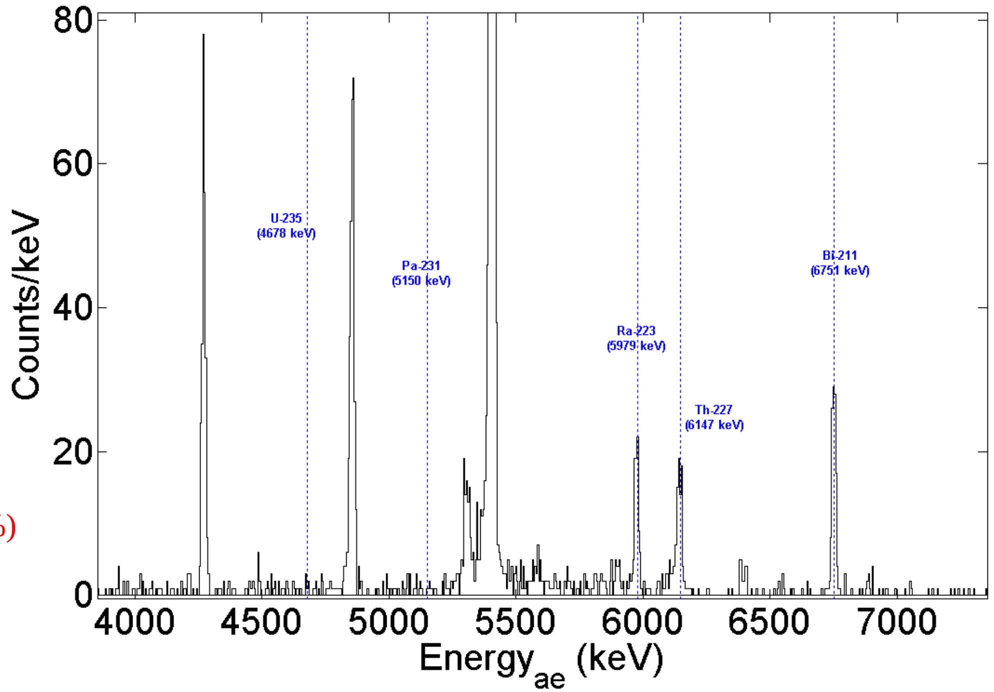


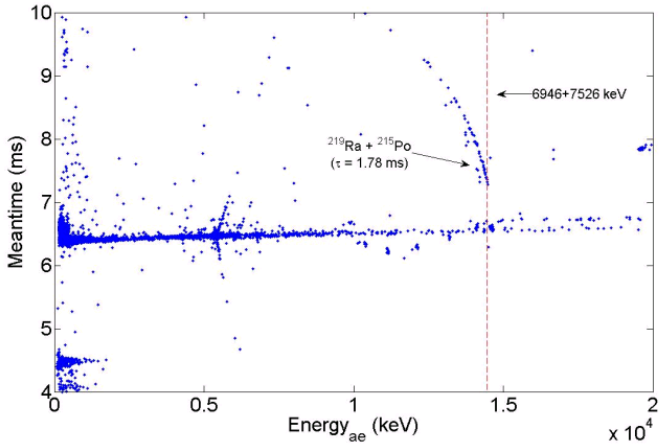
Not serious for small Q value (44. 8keV)

98.6 %

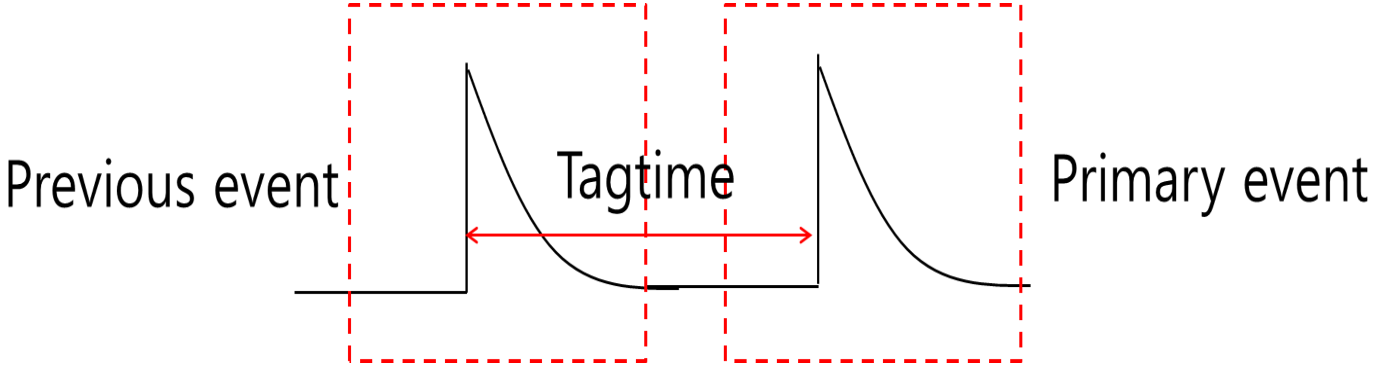
$^{211}$Pb $Q_\beta$ : 1367 keV (91.3 %)
160 keV (6.3 %)

$^{207}$Tl $Q_\beta$ : 1418 keV (99.7 %)





# 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

# CMO internal background measurement

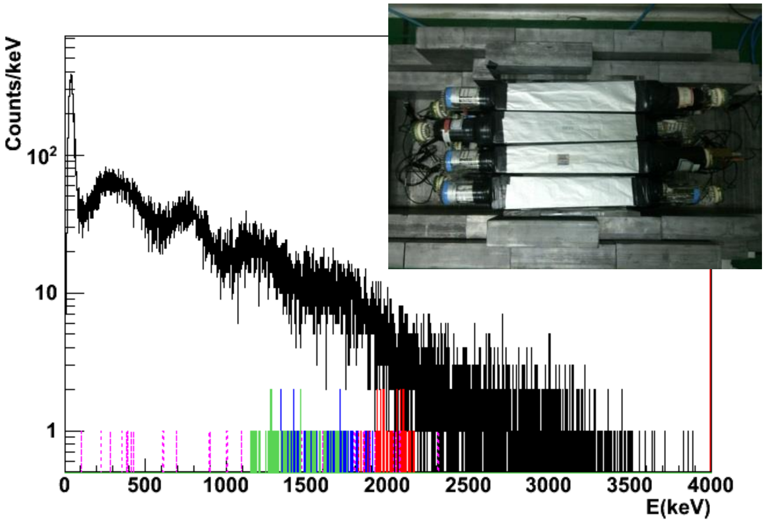
1) ICP/MS $^{238}U$, $^{235}U$, & $^{232}Th$ ~ppt level sensitivity

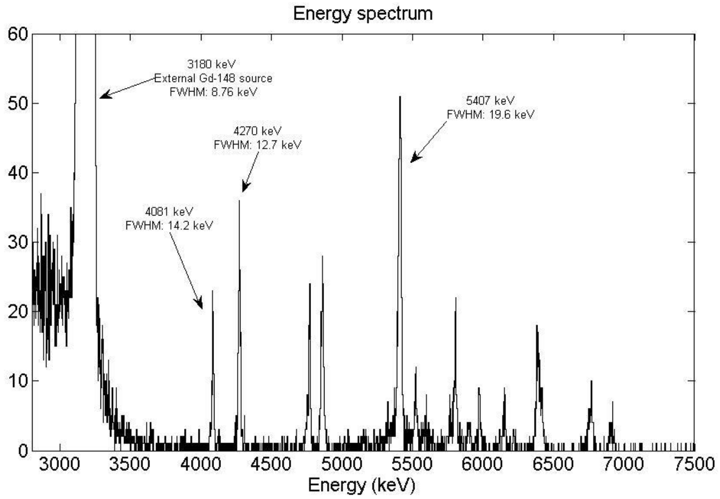
2) HPGe at Y2L (U,Th decay chains with $\gamma$, ~mBq/kg level)

3) $4\pi$ setup at Y2L vs Cryogenic measurement.

| | |
|---|---|
| 300K | 20mK |
| Easy to measure | Need time for setup |
| Limits on $\alpha$ tagging | $\alpha$ spectroscopy |

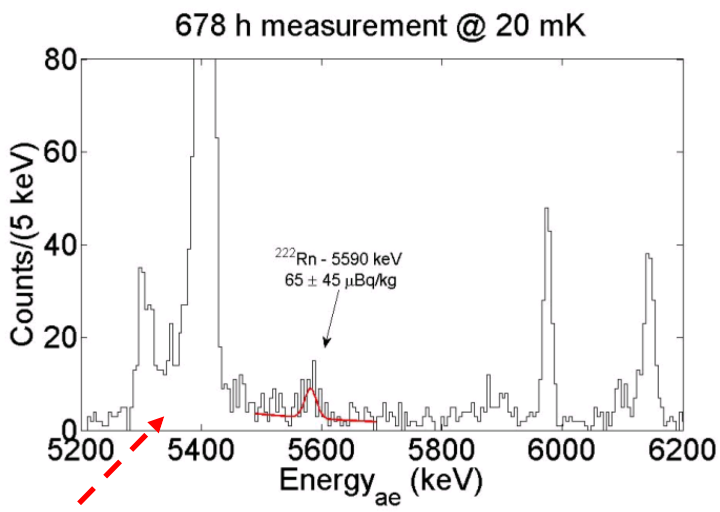
Similar sensitivity of $^{238}U$ & $^{232}Th$ decay chain (<10 uBq/kg)

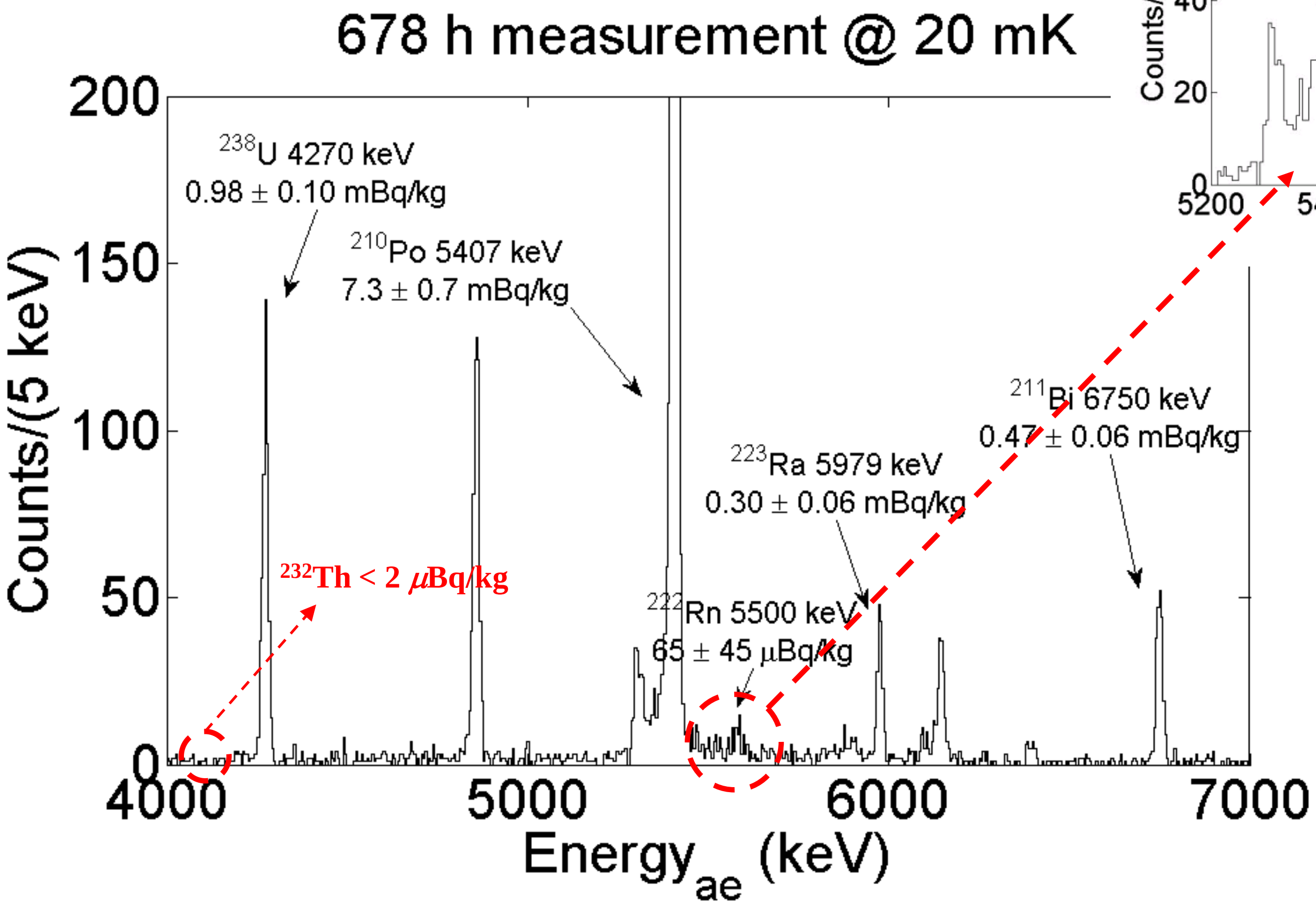




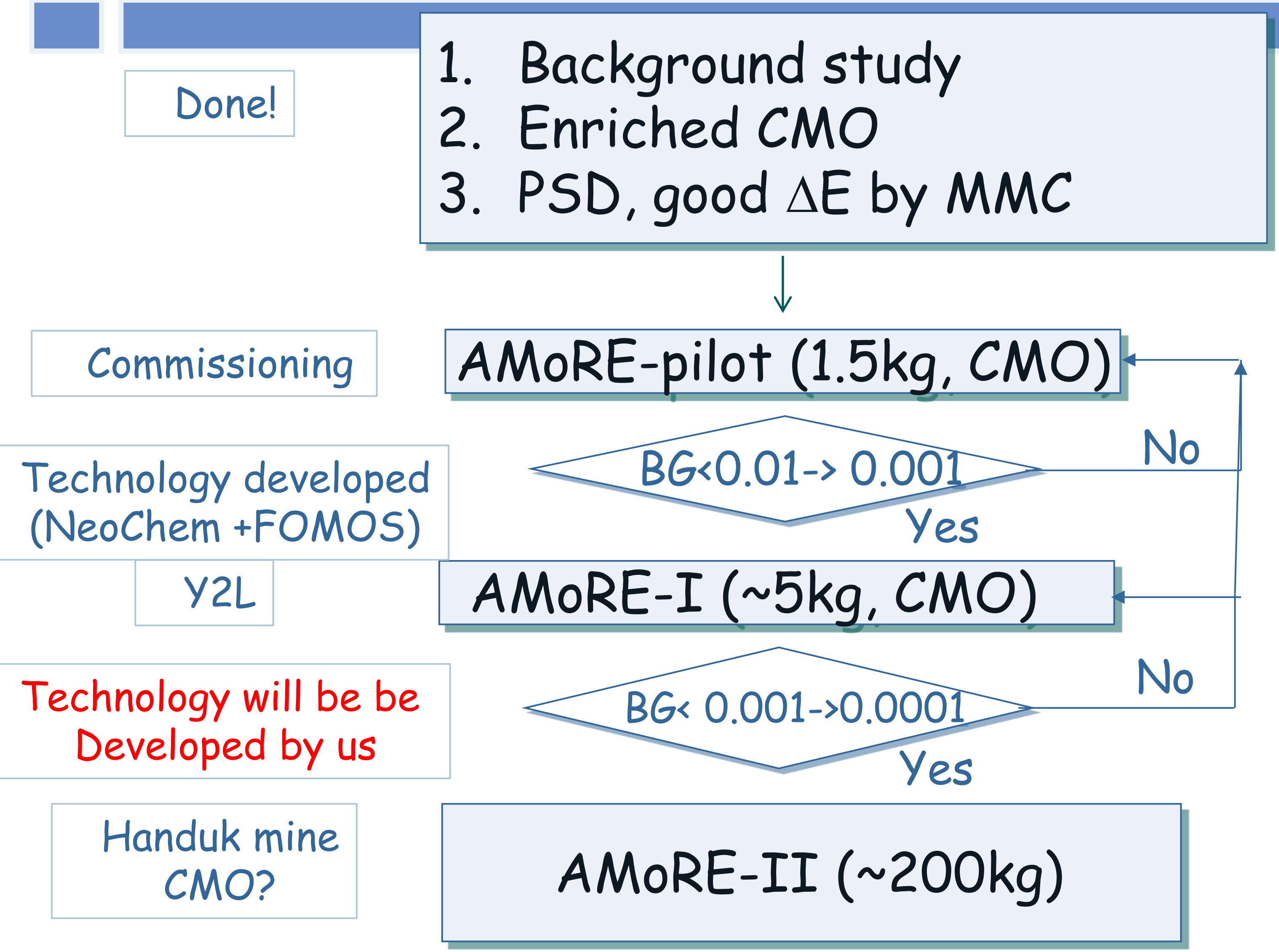
# Internal alpha background of SB28

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





# Plan for zero background for AMoRE



1. Background study
2. Enriched CMO
3. PSD, good ΔE by MMC

Done!

AMoRE-pilot (1.5kg, CMO)

Commissioning

BG<0.01-> 0.001

No

Yes

Technology developed (NeoChem +FOMOS)

AMoRE-I (~5kg, CMO)

Y2L

BG< 0.001->0.0001

No

Yes

Technology will be be Developed by us

AMoRE-II (~200kg)

Handuk mine CMO?

- Background reduction R&D with purification will be presented by Dr. H.K. Park in instrumentation section

# Chemical purification facility

- Deep purification of CaCo3 and MoO3 (<50uBq/kg for U,Th chain)
- Efficient CaMoO4 recovery
- People : 2 staff, 1 postdoc, 2 students, 1 technician

(+ Russia, Ukraine collaboration)

=> See talk by Dr. H.K.Park (Team leader)

Chemical room

Clean room

# Low background Crystal growing facility

- We have one Czochalski, 2 Kyropoulous and 1 Bridgman crystal growing equipment at KT 1 lab.

( 1 more Czochalski this year)

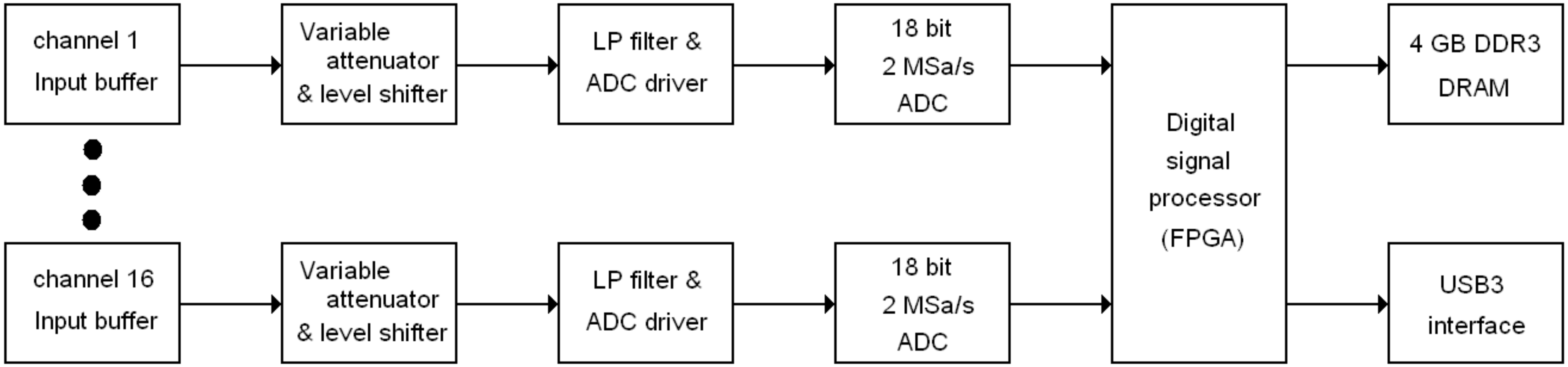
Main goal.

1) CaMoO4 crystal growing R&D
   for AMoRE-200
2) Other DB or DM crystal R&D

Currently we are focused on CaMoO4 crystal Growth

Czochalski machine

# AMoRE-ADC module development



channel 1 Input buffer

channel 16 Input buffer

Variable attenuator & level shifter

LP filter & ADC driver

18 bit 2 MSa/s ADC

Digital signal processor (FPGA)

4 GB DDR3 DRAM

USB3 interface

1 Input: ±10 V, 1 Mohm termination

2 16 ch/module, stand alone

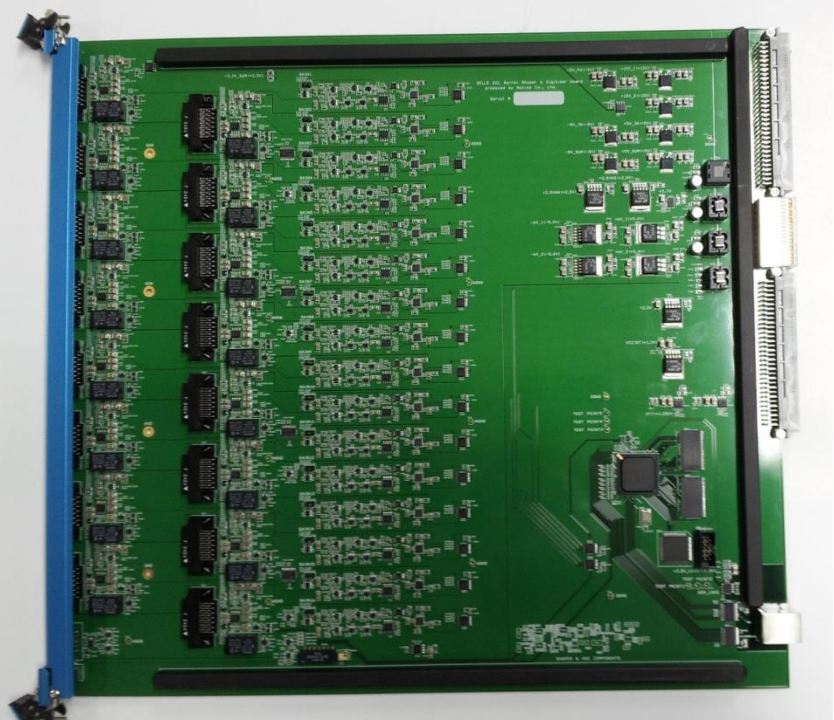
2. Variable attenuator

3. 18 bit, 2 Msa/s

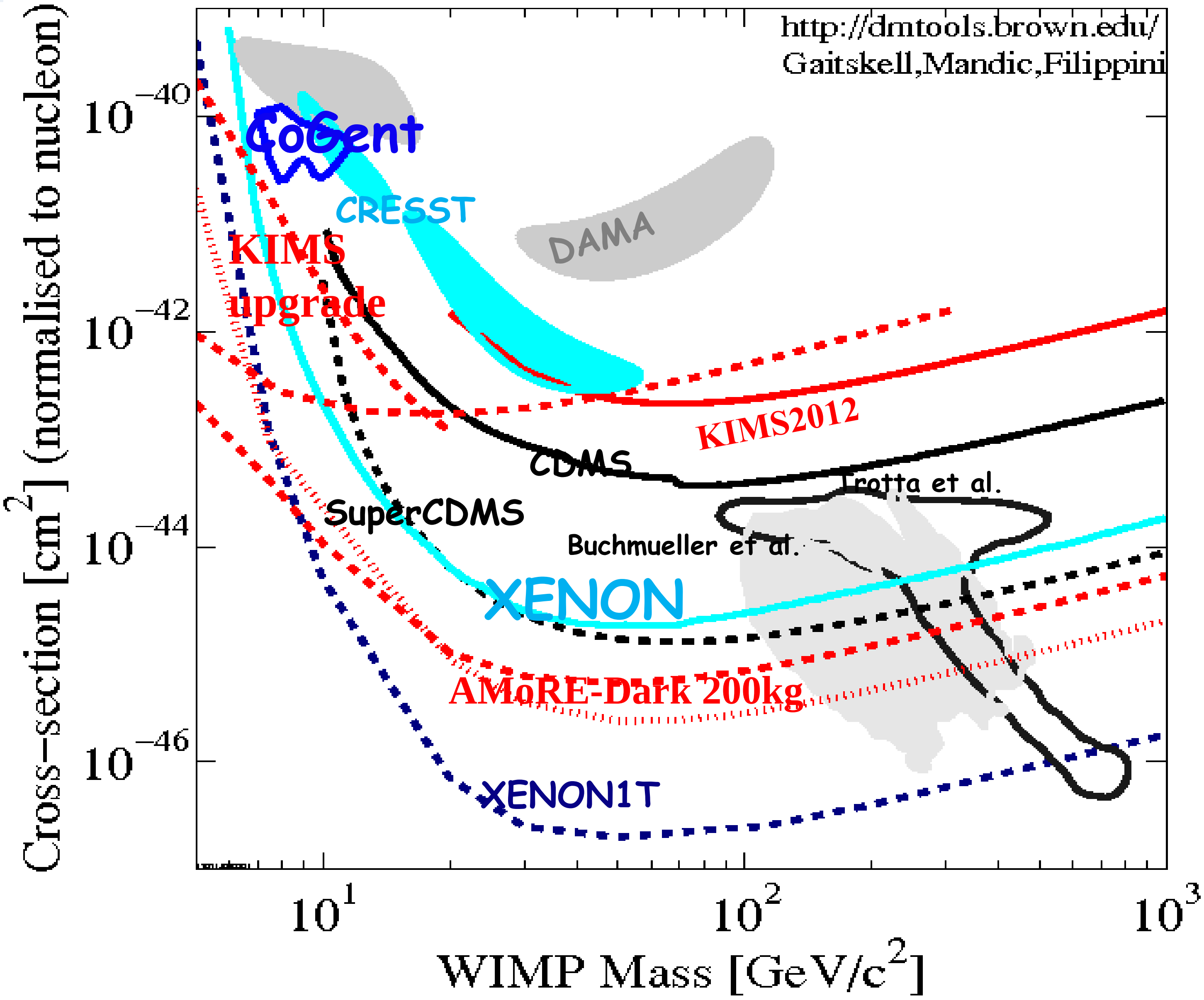
4. 4 Gbyte DDR3 DRAM buffer

5. Digital processing and trigger

6. Continuous sampling possible



# 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**