Development of low radioactivity $^{40}Ca^{100}MoO_4$ crystal scintillators for the AMORE double beta decay search

AMoRE (Advanced Mo-based Rare process Experiment)

HongJoo Kim
Kyungpook National University

For AMoRE collaboration

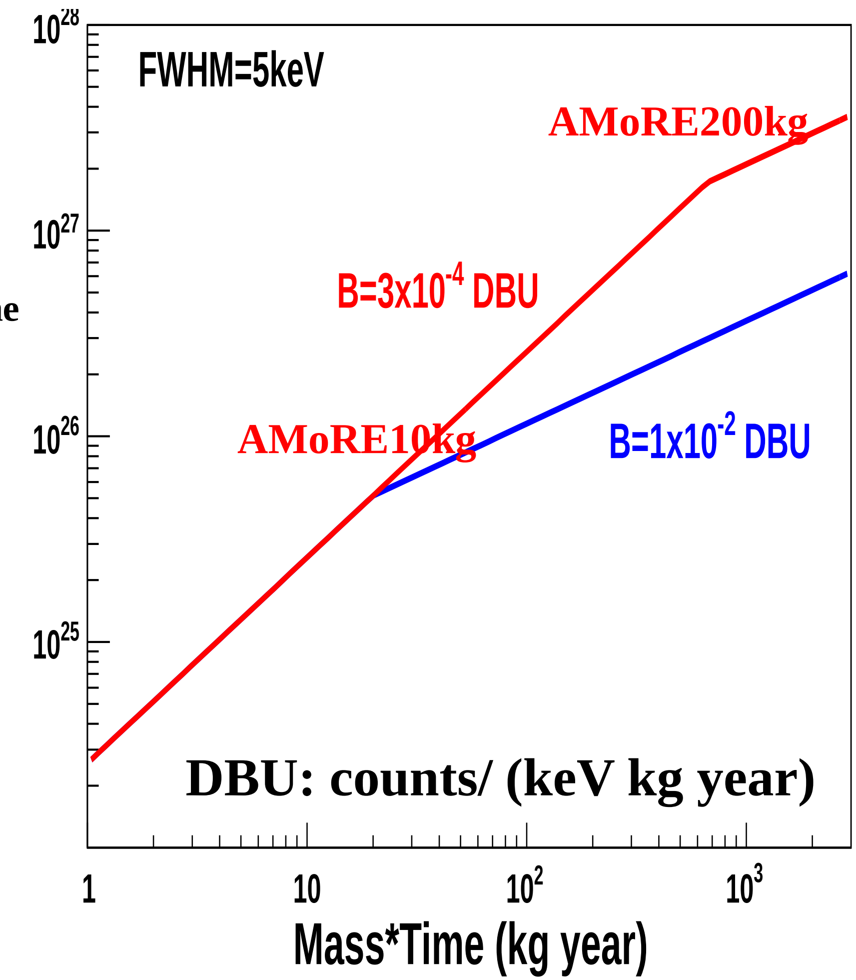
Low Radioactivity Techniques (LRT15)
University of Washington, USA, Mar 18-20, 2015

AMoRE Experimental sensitivity

For sizeable background case;

Isotopic Abundance — Detection Efficiency — Detector Mass — Time — Atomic mass — Background level (count/keV kg year) — Energy Resolution

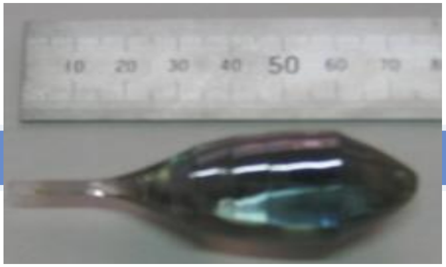
$$T_{1/2}^{0\nu}(\exp) = (\log 2) N_a \frac{a}{A} \epsilon \sqrt{\frac{MT}{b\Delta E}}$$



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

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

History of CaMoO4



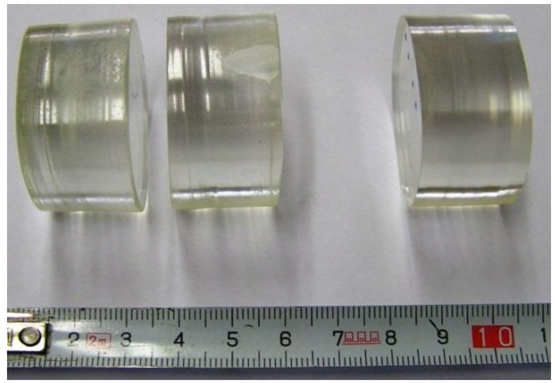
1) 2002 : Idea and try to grow CMO in Korea
2) 2003 : Collaboration with V.Kornokov.
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of XMoO4, cryogenic detector of CMO
4) 2005-2007 : Large CMO with 1st ISTC project
5) 2006 : Collaboration with F. Danevich group (CMO by Lviv)
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 : $^{40}Ca^{100}MoO_4$ 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 Scinece)
12) 2014 : Upgrade of Y2L lab for AMoRE-pilot and AMoRE-I

AMoRE collaboration

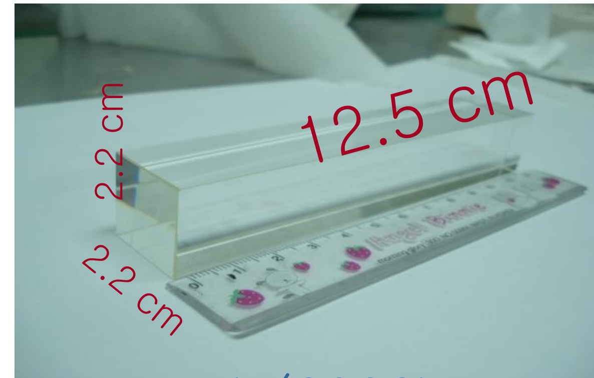
8 Countries
18 Institutions
~90 Collaborators

$CaMoO_4$ crystal development

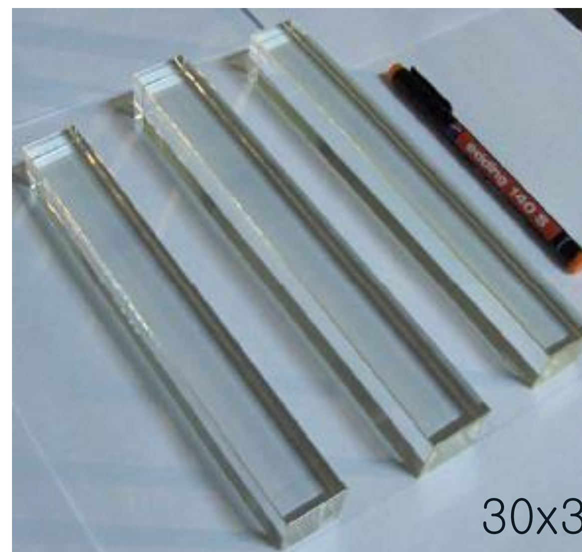
Korea(2003)



Ukraine-CARAT(2006)



Russia(2006)

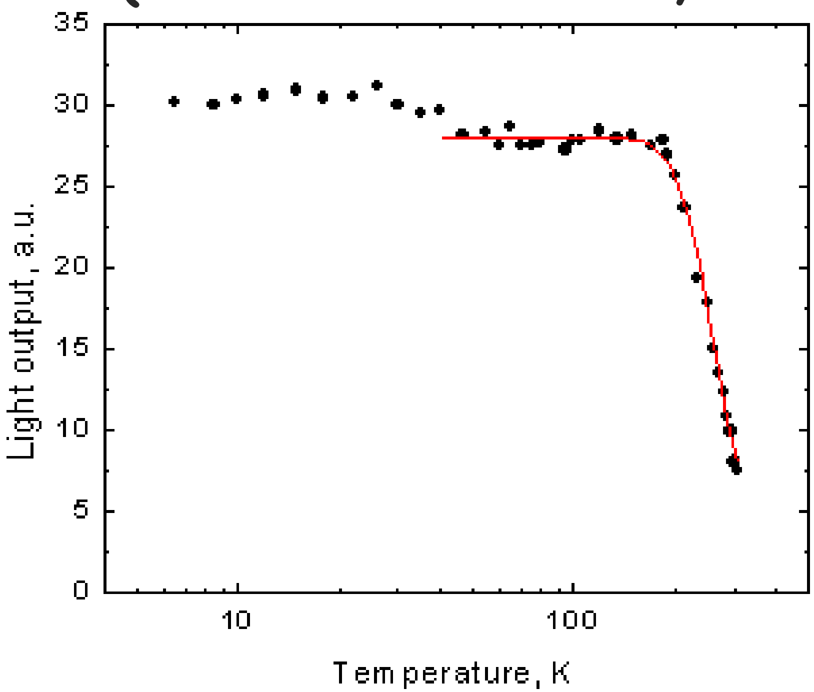


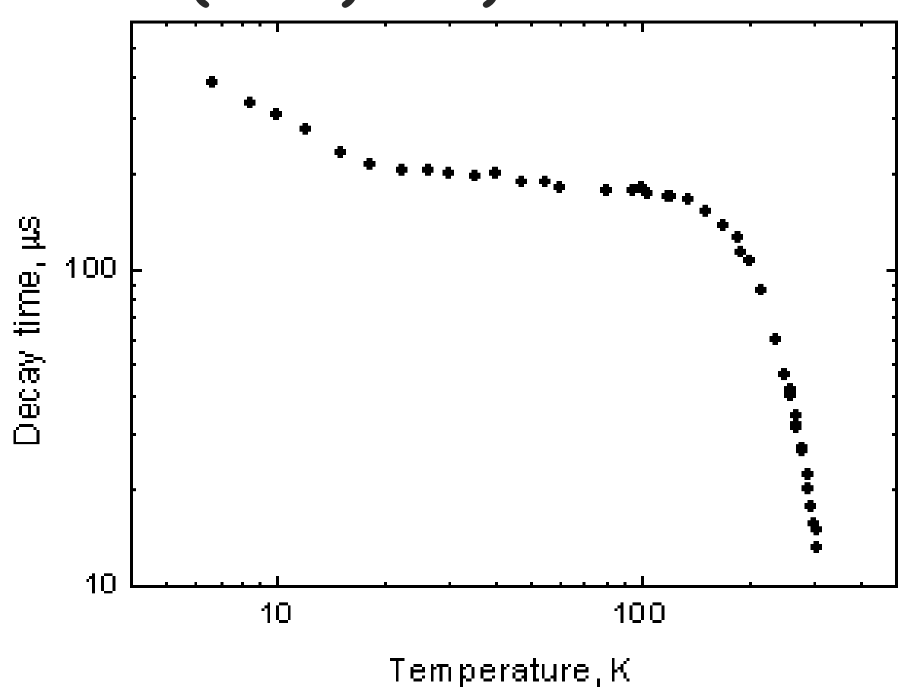
30x30x200mm

Temperature dependence of $CaMoO_4$

From RT to 7K, light yield increase factor 6

(V.B. Mikhailik et al., NIMA 583 (2007) 350)





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

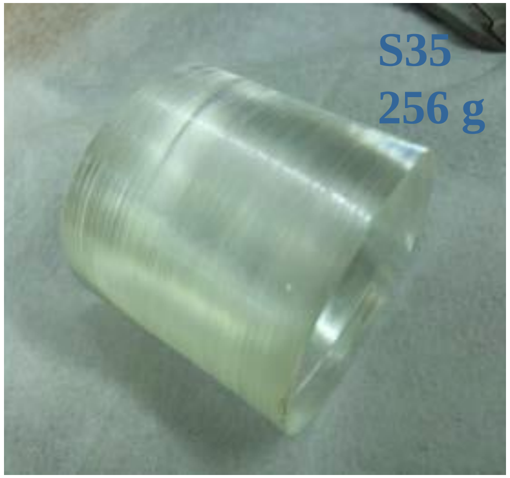
-> Highest light yield among Mo contained crystals.

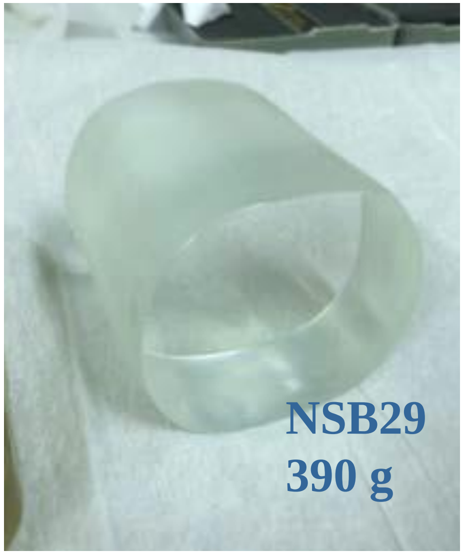
(^{100}Mo, ^{48}Ca $0\nu\beta\beta$ decay, Dark matter search poosible)

$^{40}Ca^{100}MoO_4$ for AMoRE-pilot by FOMOS

Total mass of crystals ~ 1.5 kg

Crystal	SS68	NSB29	S35
ΔE (%)	18.2	15.9	14.4
Rel. light	1.14	0.78	1



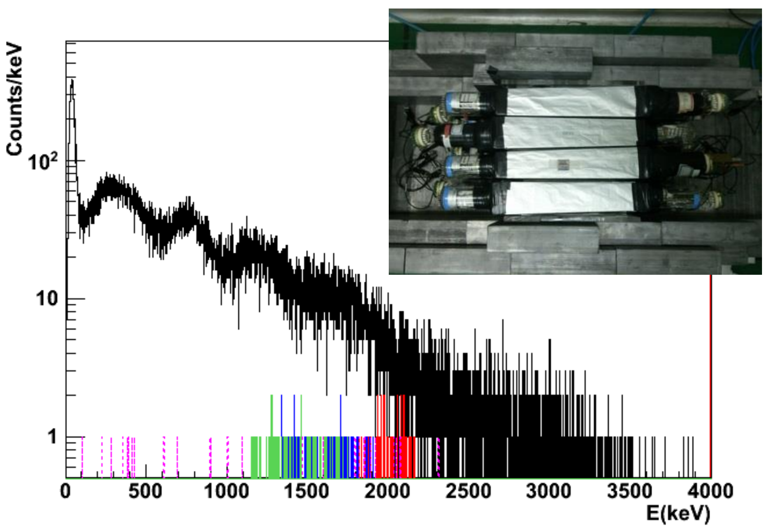


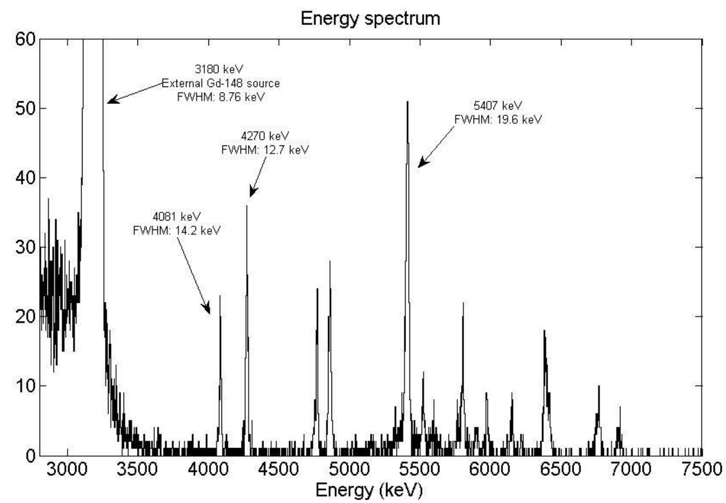
CMO internal background measurement

1) ICP/MS ^{238}U, ^{235}U, & ^{232}Th ~ppt level sensitivity
2) HPGe at Y2L (U,Th decay chains with γ, ~mBq/kg level)
3) 4π setup at Y2L vs Cryogenic measurement.

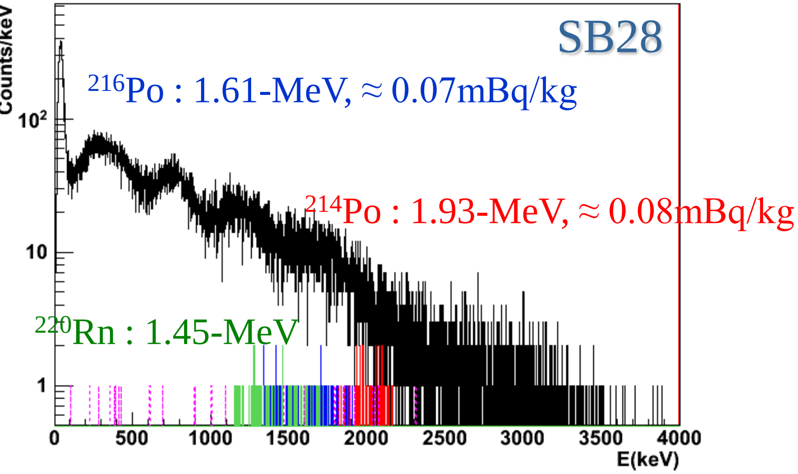
4π setup at Y2L	Cryogenic measurement
300K	20mK
Easy to measure	Need time for setup
Limits on α tagging	α spectroscopy

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





Internal background levels from Y2L@RT



***β–α* decay in ^{238}U (164 us)**
^{214}Bi (Q-value : 3.27-MeV) → ^{214}Po (Q-value : 7.83-MeV)

***α–α* decay in ^{232}Th (145 ms)**
^{220}Rn (Q-value : 6.41-MeV) → ^{216}Po (Q-value : 6.91-MeV)

***α–α* 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) SS68	61.8	237.1	26.7+-7
NSB29	229.1	667.6	24 ~ 40
S35	4488.7	1577.4	644.9
SB28	80	?	70

*100 uBq/kg for U-238,50uBq/kg for Th232 decay chain for AMoRE-10

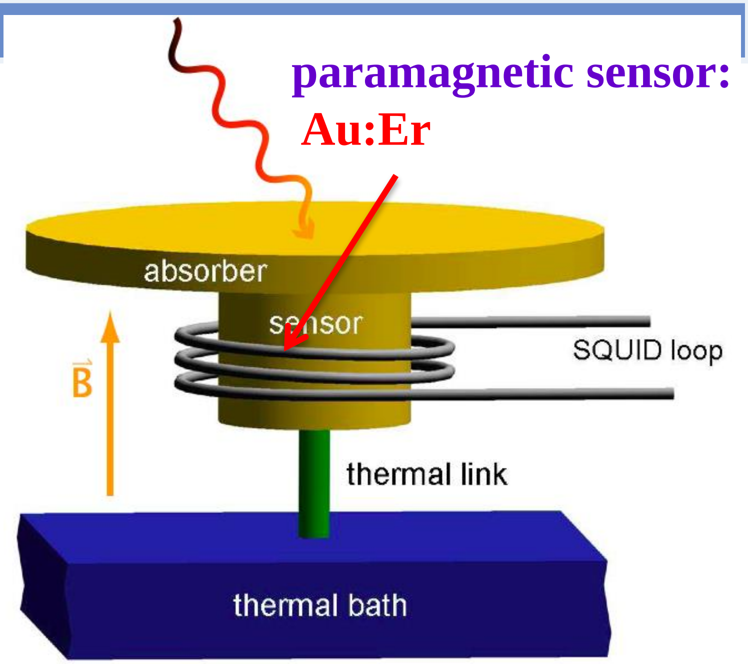
MMC (Metallic Magnetic Calorimeter) for LTD

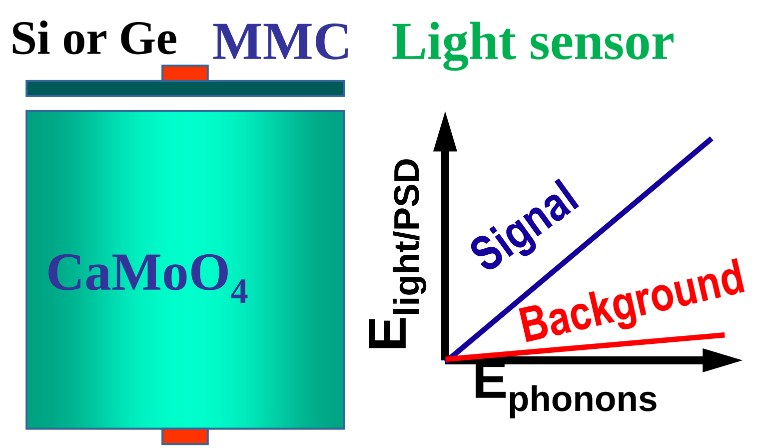
Principle of operation

1. Energy absorption in CMO crystal.
2. Phonon & Photon generation.
3. Temperature increase (gold film).
4. Magnetization of MMC decrease.
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

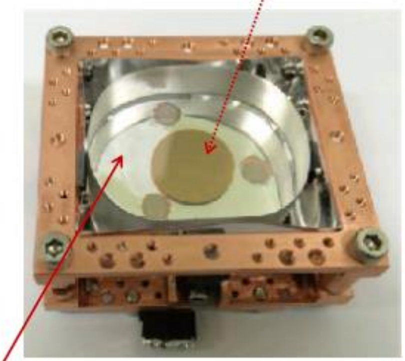




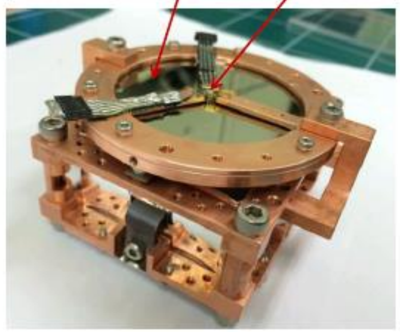
MMC Phonon sensor

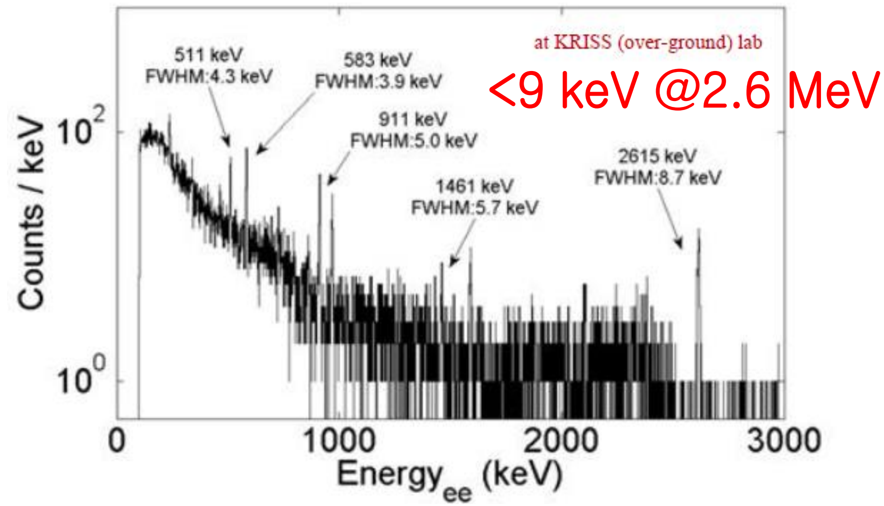
MMC cryogenic technique for AMoRE

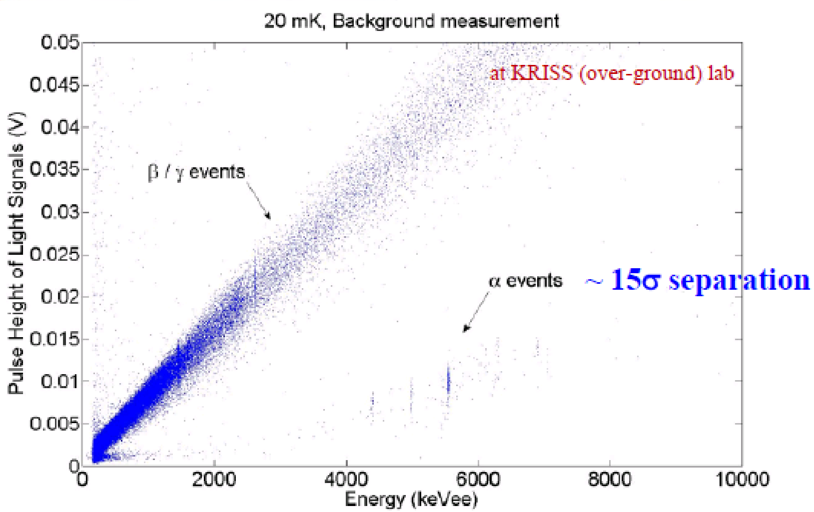
Phonon collector film
on bottom surface

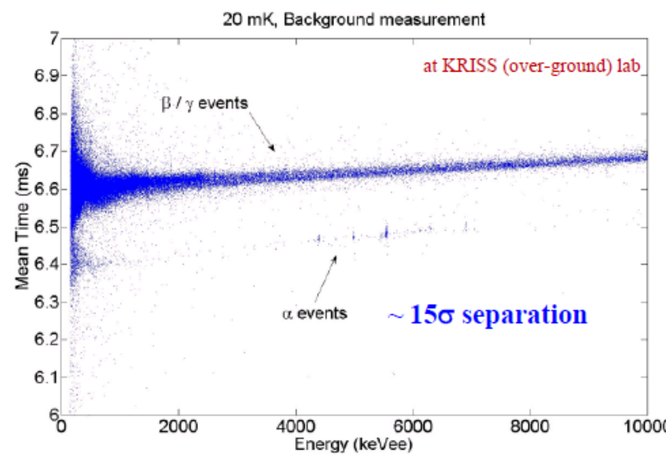


Light detector
2 inch Ge wafer + MMC





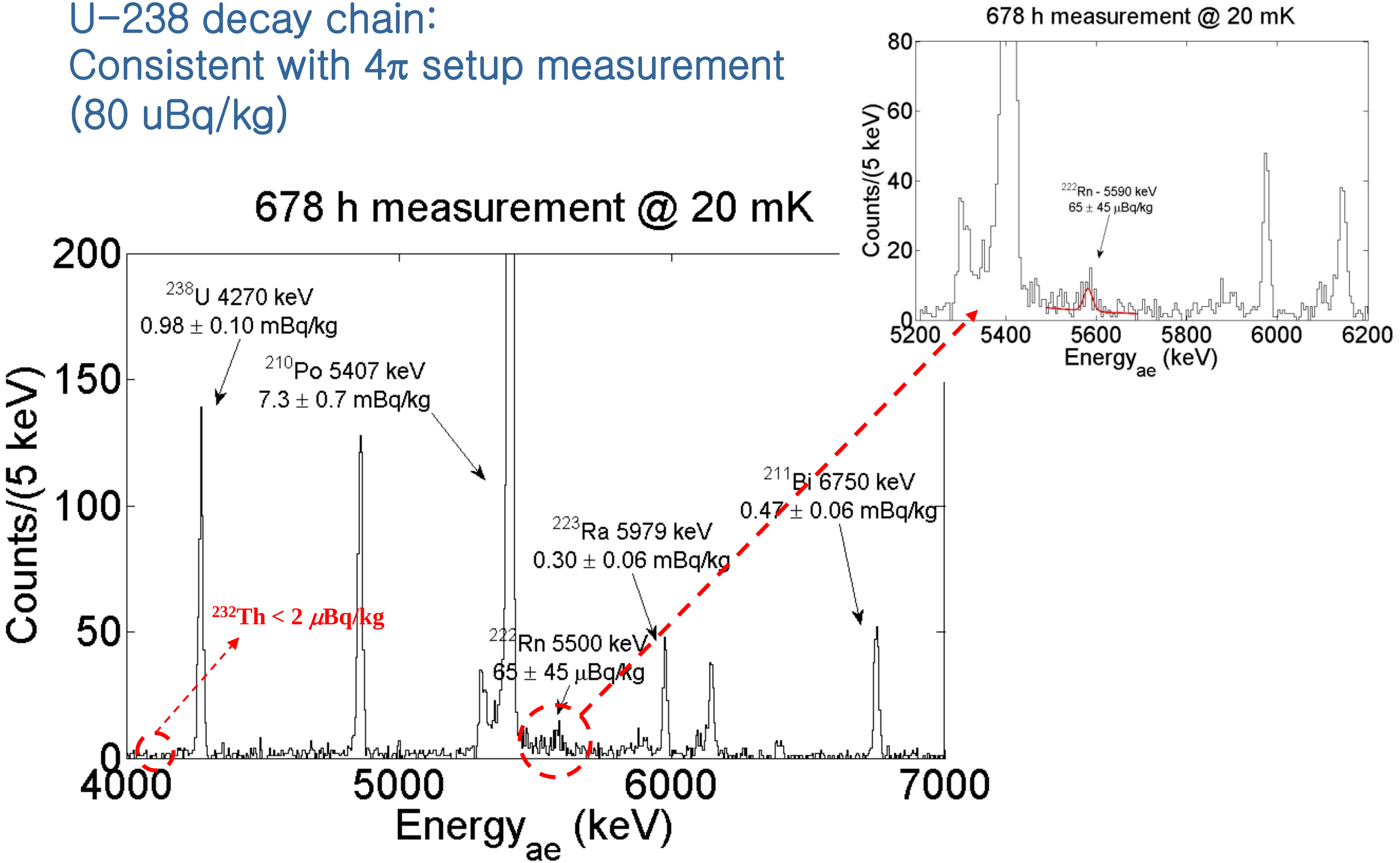




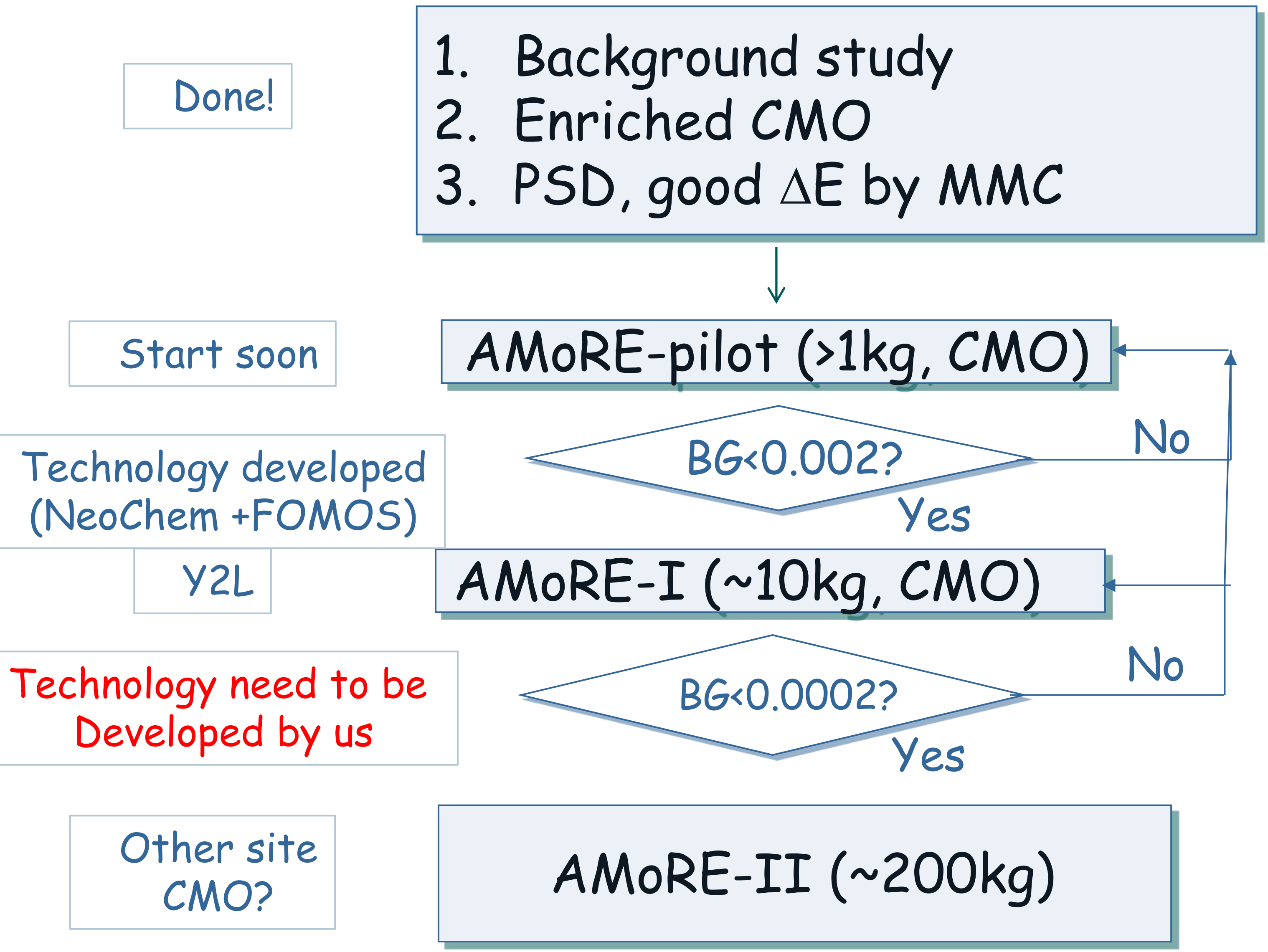
Excellent α/e separation by both Light and PSD

Internal alpha background of SB28

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

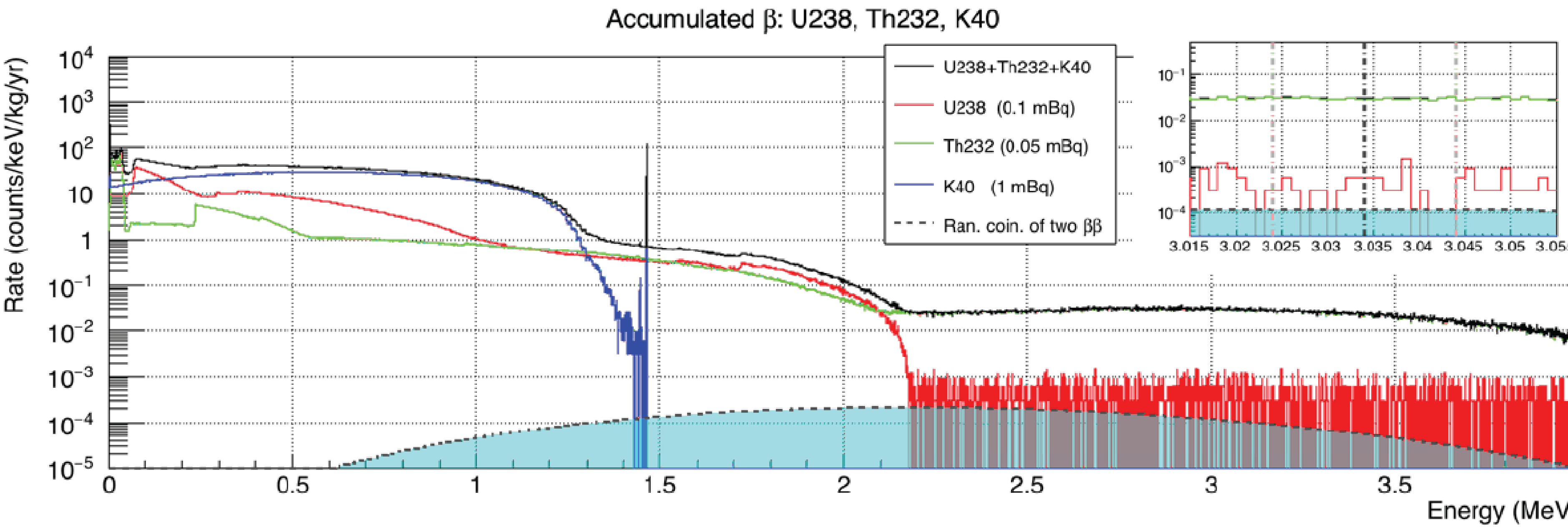


For zero background AMoRE experiment



GEANT4 simulation for AMoRE-I

		Pb210	U238	Th232	K40	U235
Concentration		10 mBq/kg	0.1 mBq/kg	50 µBq/kg	1 mBq/kg	1 mBq/kg



^{208}Tl with α-tagging : 0.0015 DBU.

Random coincidence of ββ of 100Mo: 0.00011 DBU

-> Goal of 0.002 for AMoRE-I can be achieved

-> Zero background experiment with 10kg 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 and other labs	ICP-MS (No → Powder purification; Yes → Crystal growing)
K1 lab.	Crystal growing
Y2L Underground lab Baksan lab	Scintillation (Phonon) (No → Powder purification; Yes → Crystal growing optimization)
Company (K1 lab.)	Crystal growing optimization (Size and quality)

Chemical purification facility

- Deep purification of CaCo3 and MoO3 (<50uBq/kg for U,Th chain)
- Efficient $CaMoO_4$ recovery
- People : 2 staff, 1 postdoc, 2 students, 1 technician

(+ Russia, Ukraine collaboration)

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

Chemical room

Clean room

Low background Crystal growing facility

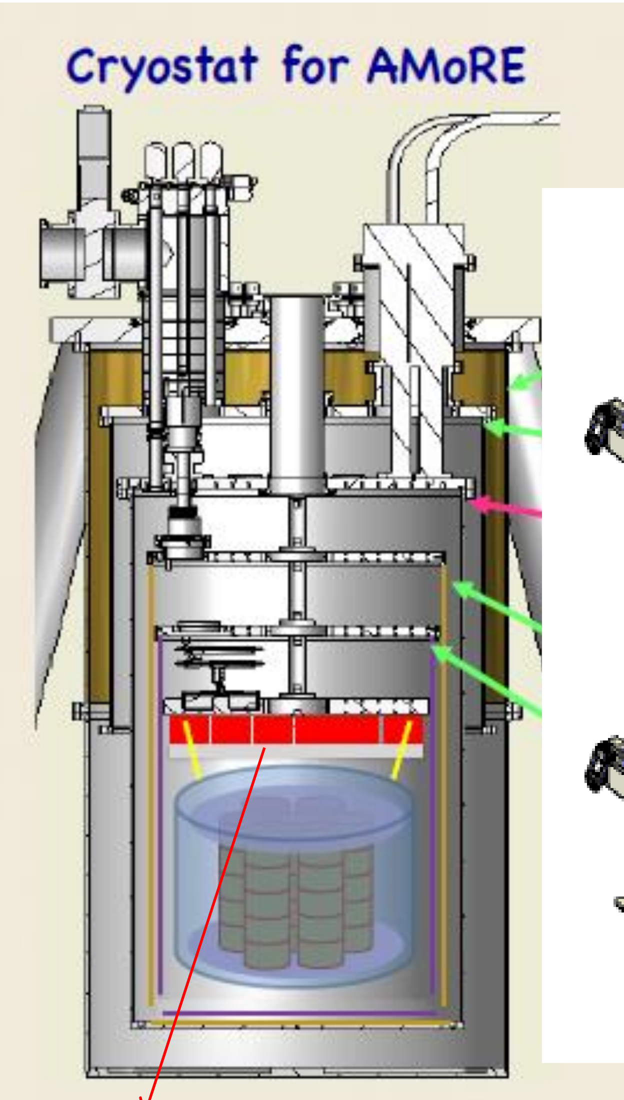
- We have one Czochalski, 2 Kyropoulous and 1 Bridgman crystal growing equipment at KT 1 lab.
(1 more Czochalski this year)

Main goal.
1) $CaMoO_4$ crystal growing R&D for AMoRE-200
2) Other DB or DM crystal R&D

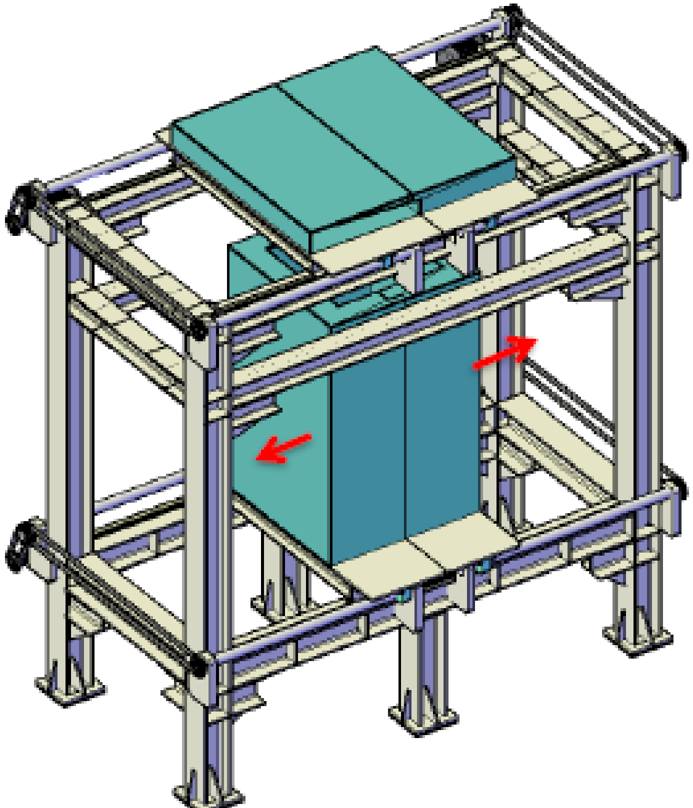
Currently we are focused on $CaMoO_4$ crystal Growth

Czochalski machine

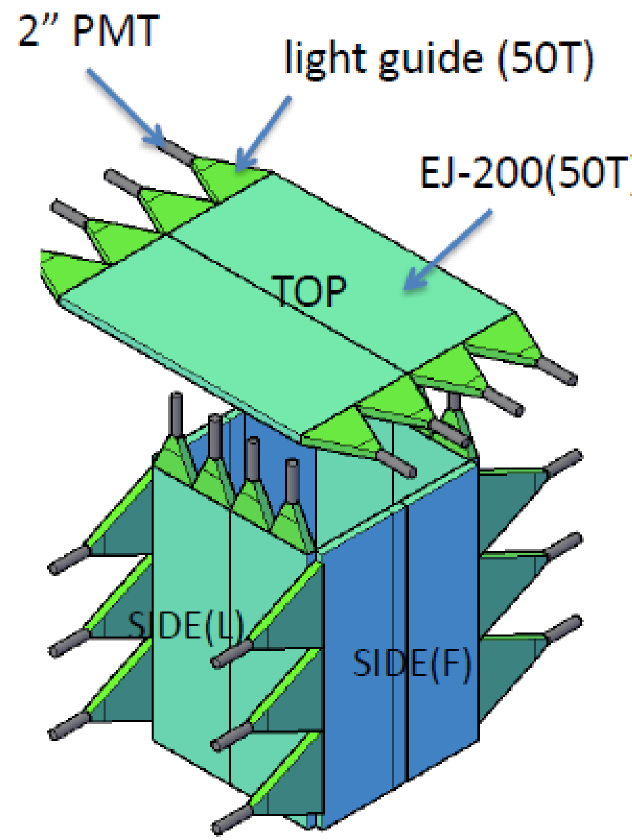
Shielding structure of AMoRE-pilot & AMoRE-I



10cm ultra-low background Pb



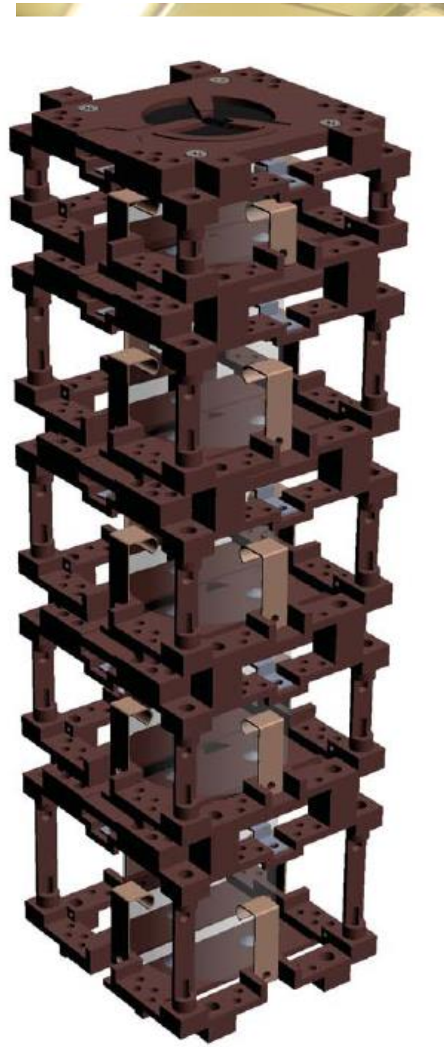
15cm low background Pb

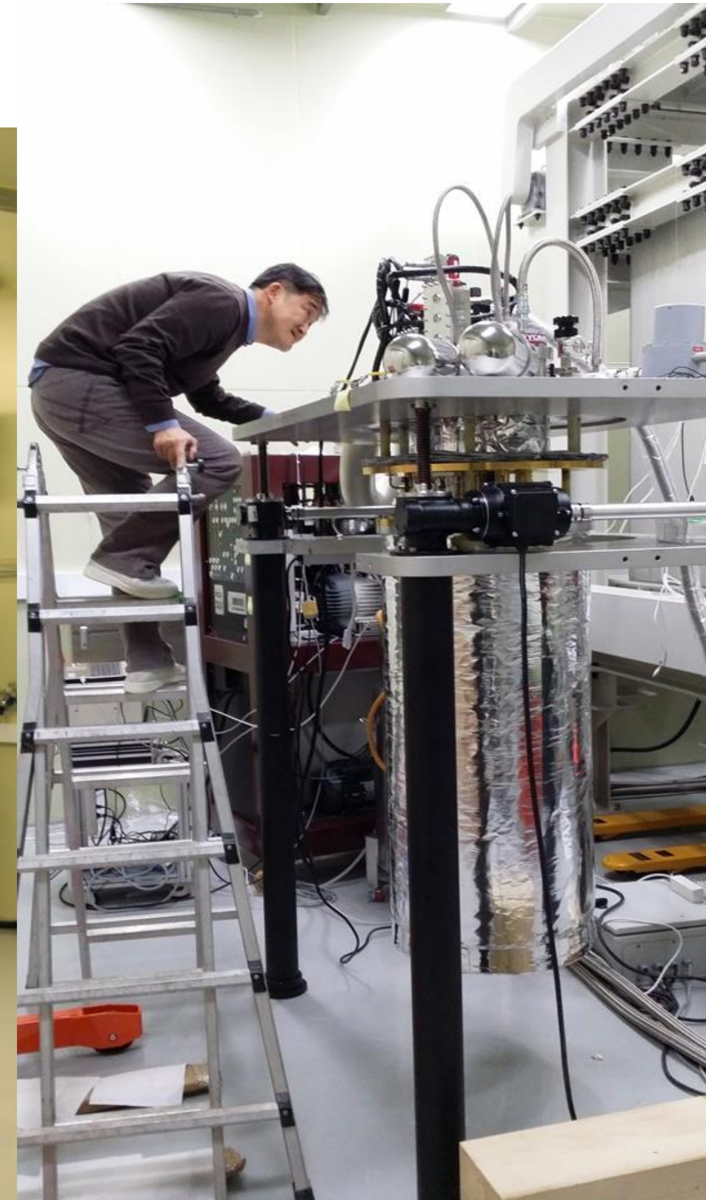


muon shielding structure

AMoRE-pilot (plan to start spring 2015)

4-5 enriched CMO





Summary and Prospect

- Large volume of low background $^{40}Ca^{100}MoO4$ have been developed and characterized.
- Cryogenic MMC technique with CMO is successful.
- We are working on R&D of chemical purification & crystal growth for AMoRE-II
- We will start AMoRE-pilot with>1.2kg of $^{48depl}Ca^{100}MoO4$ this year!

Prospect

	Mass	Place	Backgrounds (keV/kg/y)	Sensitivity (years)	Mass (eV)
AMoRE-pilot	1-1.5 kg CMO	A-5 Yangyang	0.01	>1.1x 10^24	<0.3 - 0.9
AMoRE-I	10 kg CMO	A-5 Yangyang	0.002	3x10^25	0.06 - 0.18
AMoRE-II	200 kg CMO(?)	Duta Mt. (plan)	0.0002	10^27	0.01 - 0.03

Thank you

Yangyang(Y2L) Underground Laboratory

(Upper Dam)

1000m

(Power Plant)

양양양수발전소

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

KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

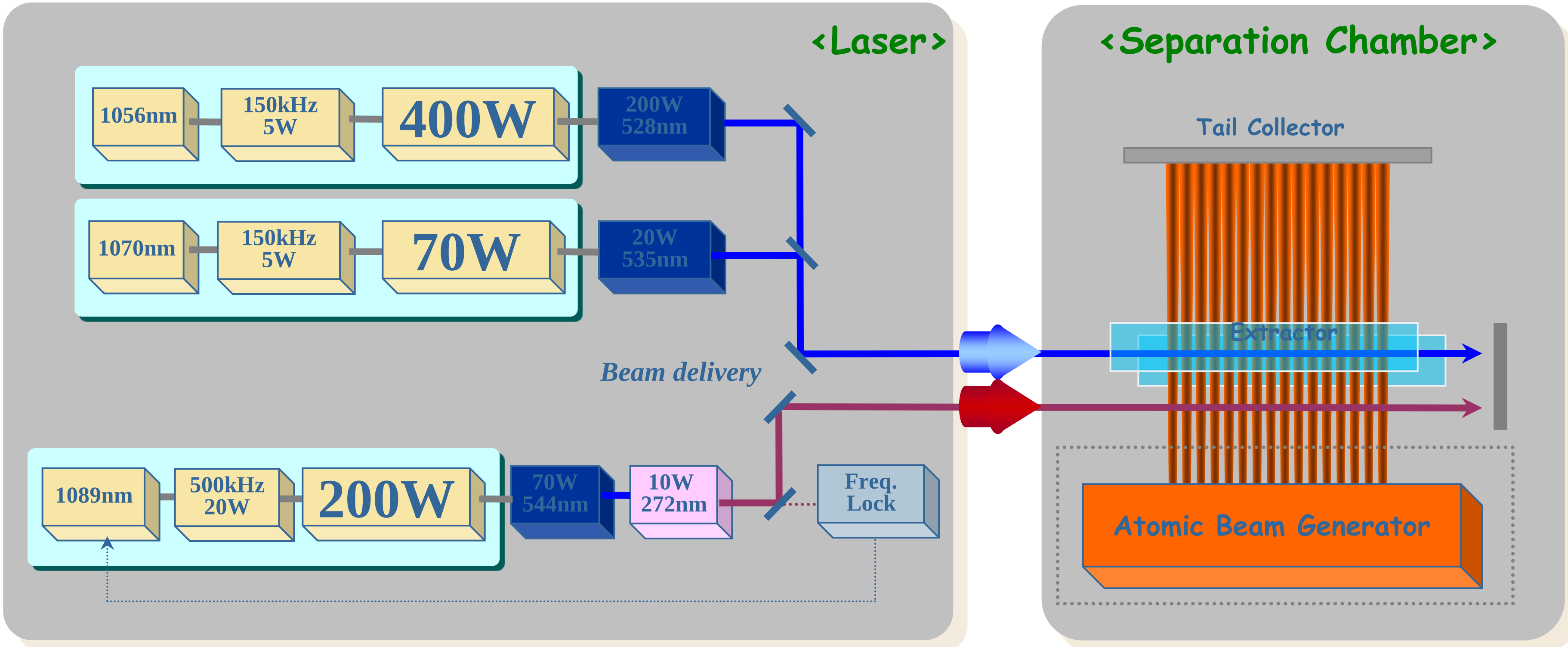
Minimum depth : 700 m / Access to the lab by car (~2km)

^{48}Ca Enrichment/Depletion at KAERI (Korea Atomic Energy Research Institute)

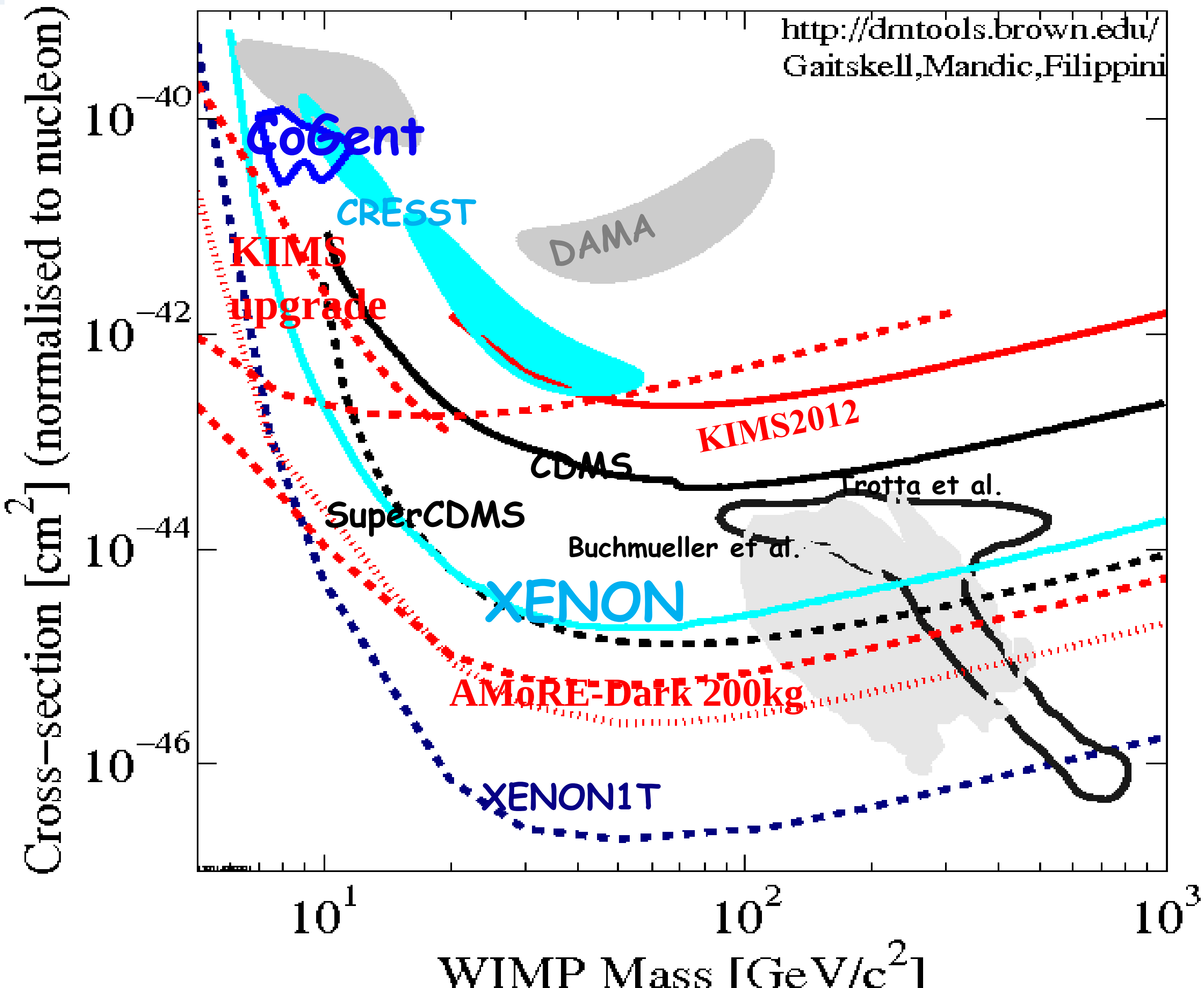
- ALSIS (Advanced Laser Stable Isotope Separation)

-> AMoRE-Ca (^{48}CaMoO4 crystal) for ^{48}Ca 0-DB search

Possible if ^{48}Ca enriched material can be obtained



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



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

Mo-100 isotope production:
The ECP (Electrochemical plant)
Zelenogorsk, Krasnoyarsky kray, Siberia

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

Enrichment: Mo-100 = 96,1%

Impurities (the results from ICP MS measurements):

U <= 0.00007 ppm (< 0,07 ppb) and <= 0.0002 ppm (< 0,2 ppb)
Th <= 0.0001 ppm (< 0,1 ppb) and <= 0.0007 ppm (< 0,7 ppb)
^{226}Ra < 2,3 mBq/kg, ^{228}Ac < 3,8 mBq/kg

Current capacity is 25-30 kg per year.

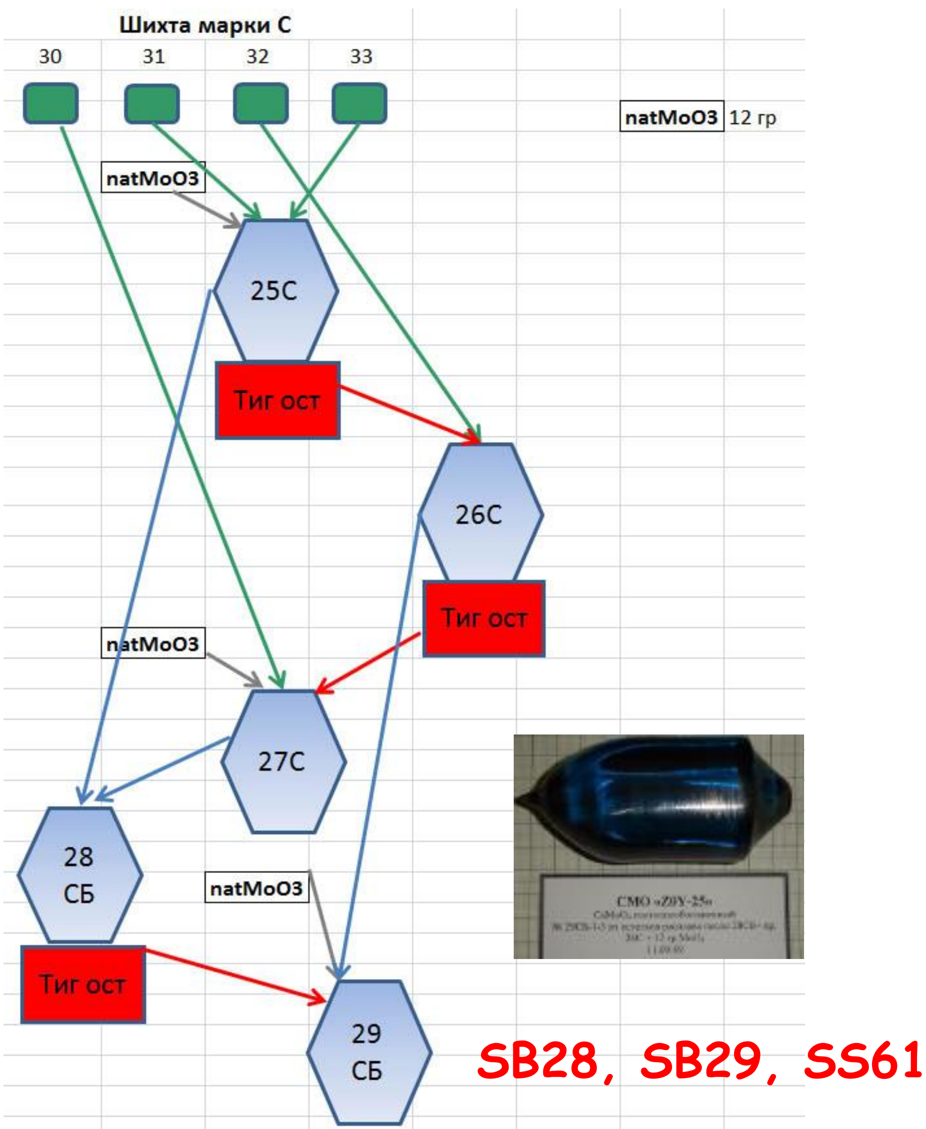
Other option for ^{100}Mo : URENCO Co. R&D stage for production

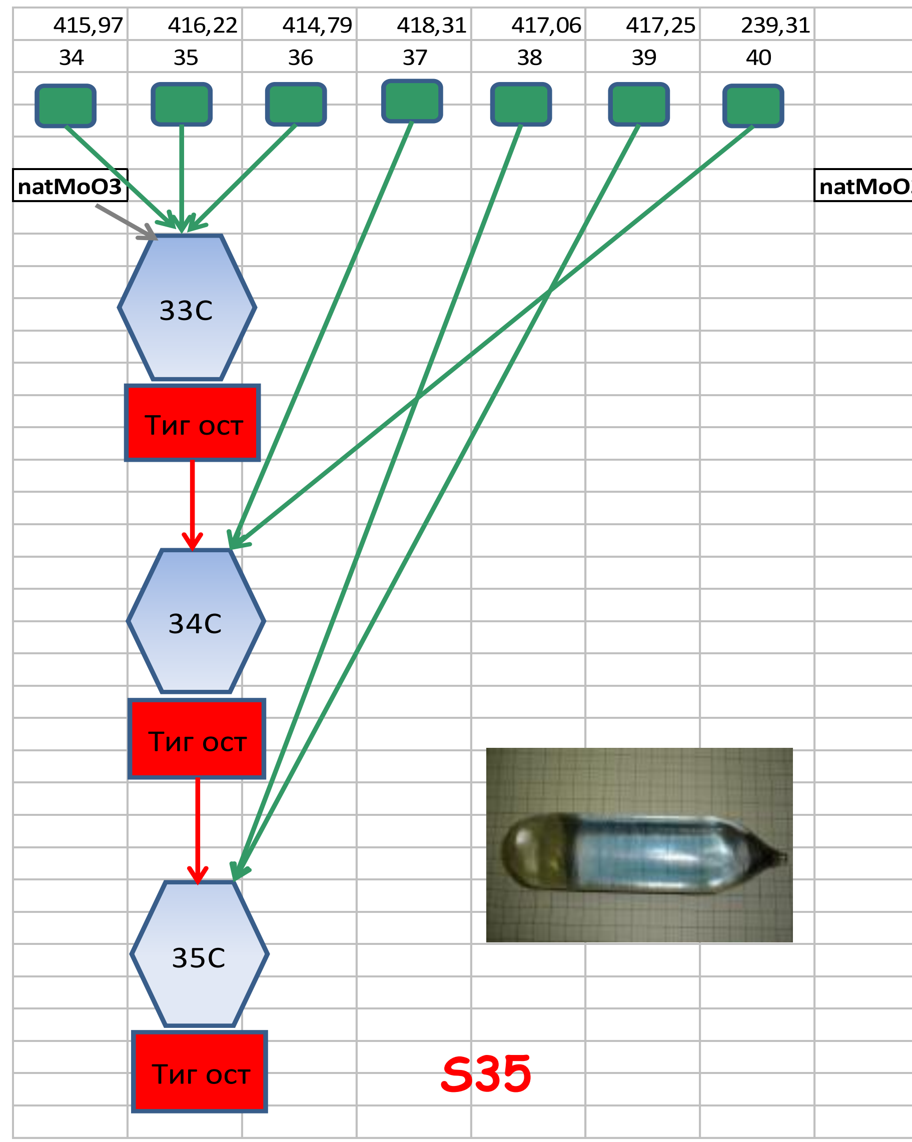
The industrial separator SU20
Lesnoy, Sverdlovky region

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

Ca-48 < 0,001%

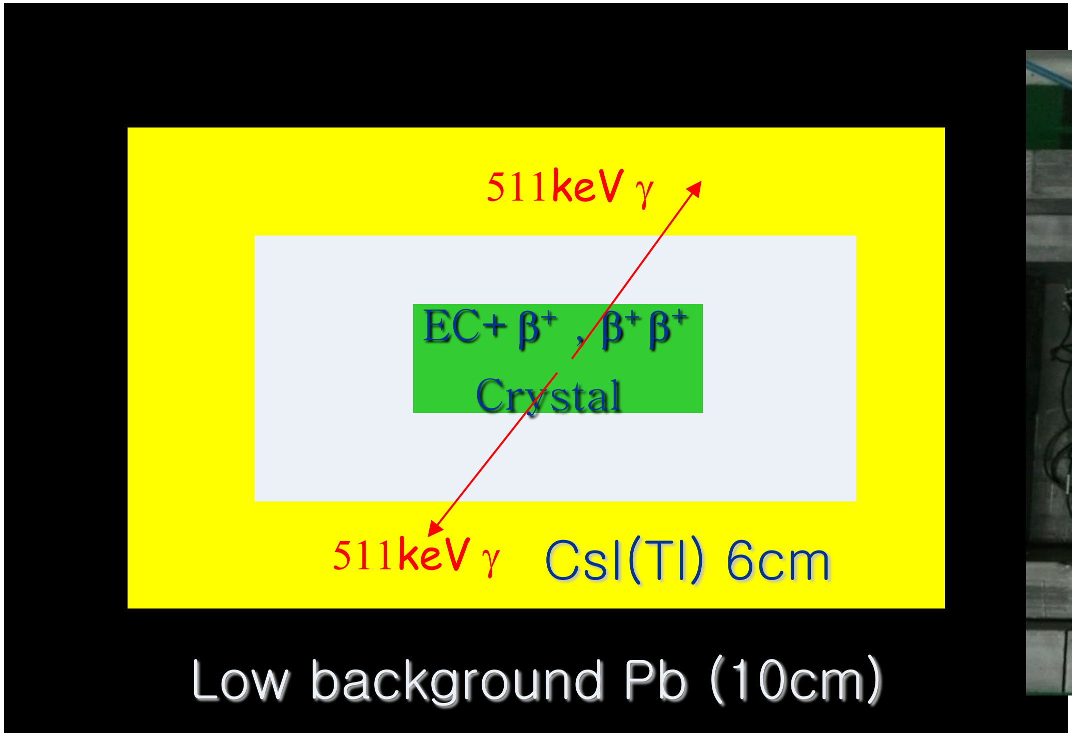
Crystal growing (Double crystalization)





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

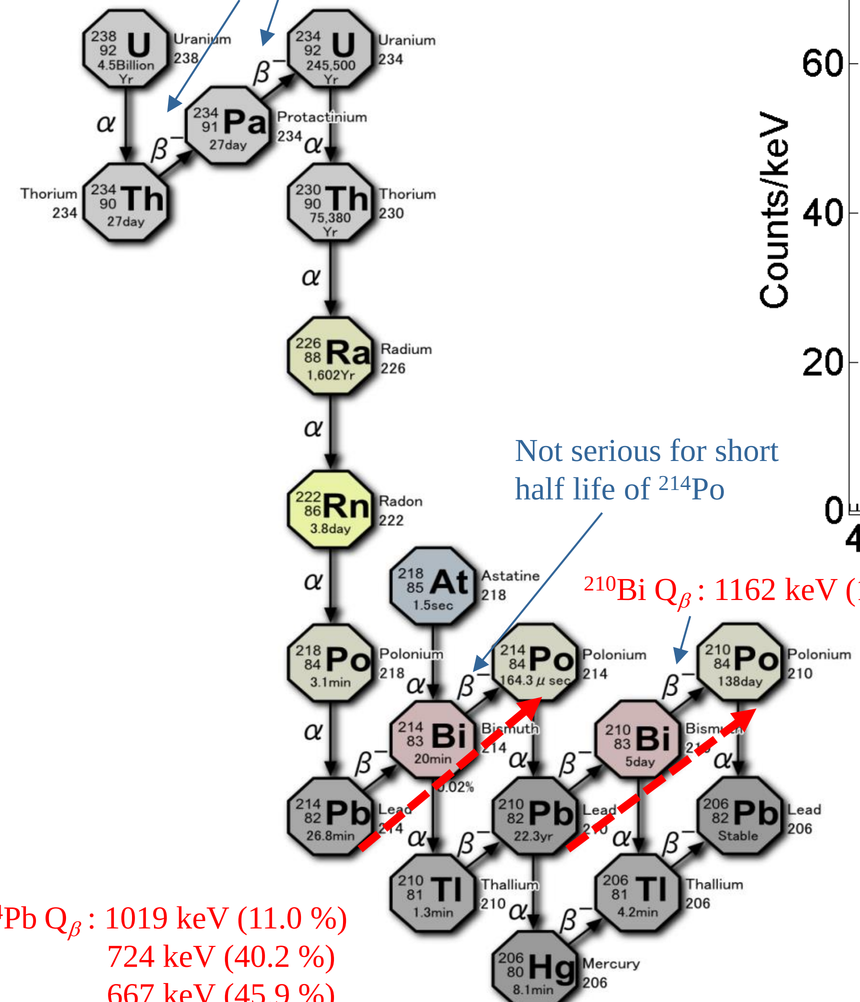
1) 2ν EC+ β^+ , $\beta^+\beta^+$ study with 2 back to back γ tagging
(1) Sr-84 : $SrCl_2$ (4.6×10^{17} yr by 90%CL)
(2) Mo-92 : CaMoO4 (2.3×10^{20} yr NIMA 654, 157 (2011))
2) CMO internal background study with active veto



Considerable beta decays (^{238}U)

^{234}Th Q_β : 199 keV (78.0 %)

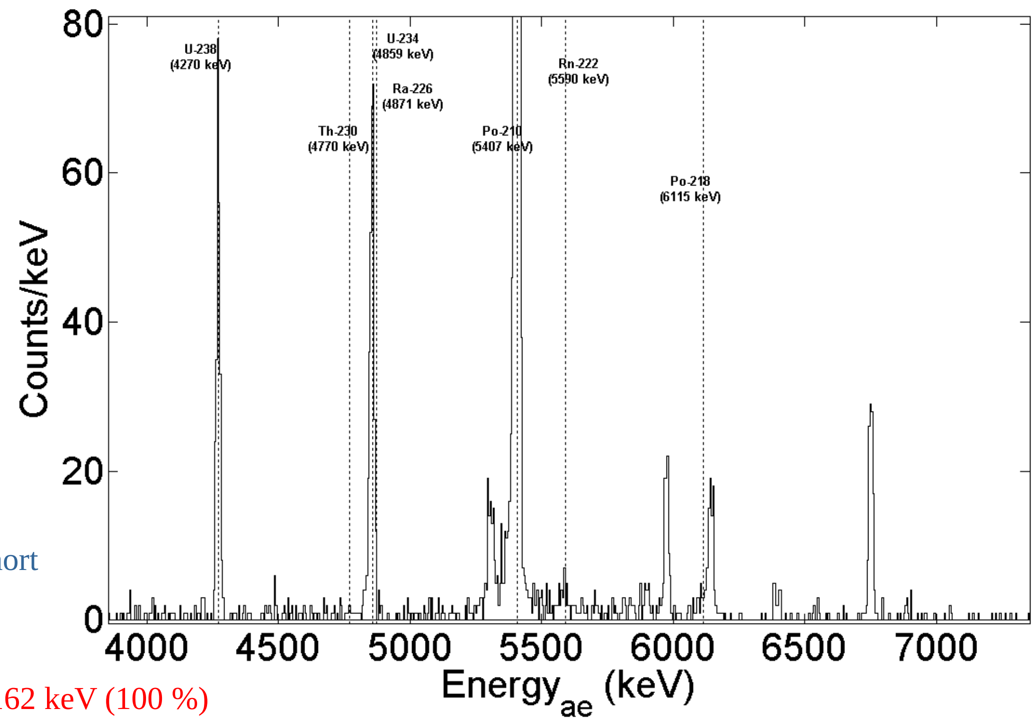
^{234}Pa Q_β : 2269 keV (97.6 %)



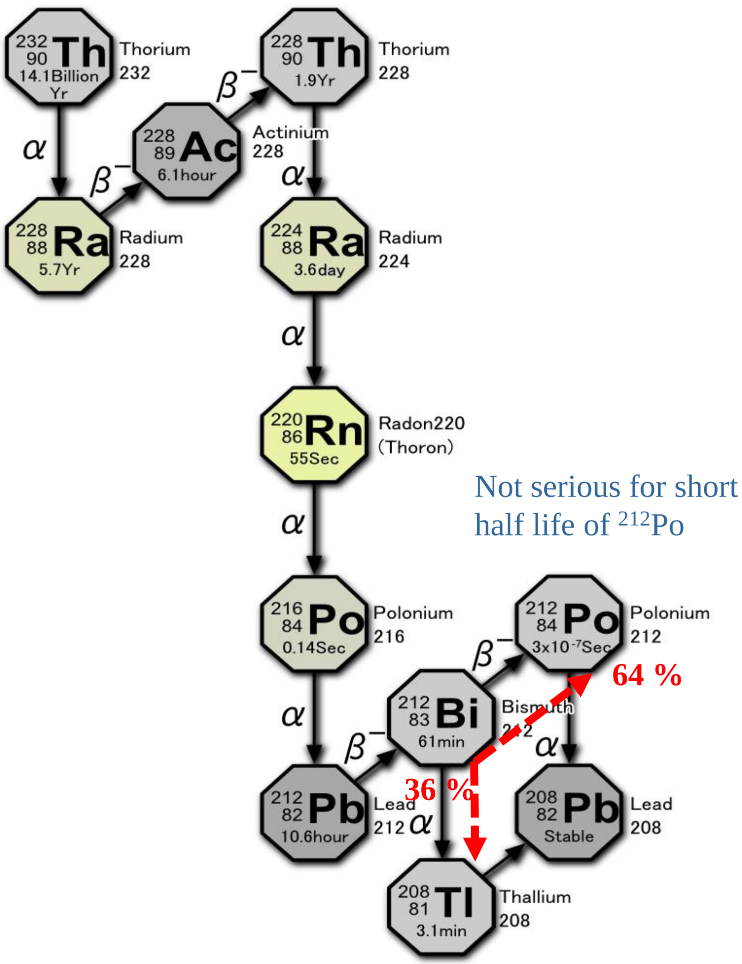
Not serious for short half life of ^{214}Po

^{210}Bi Q_β : 1162 keV (100 %)

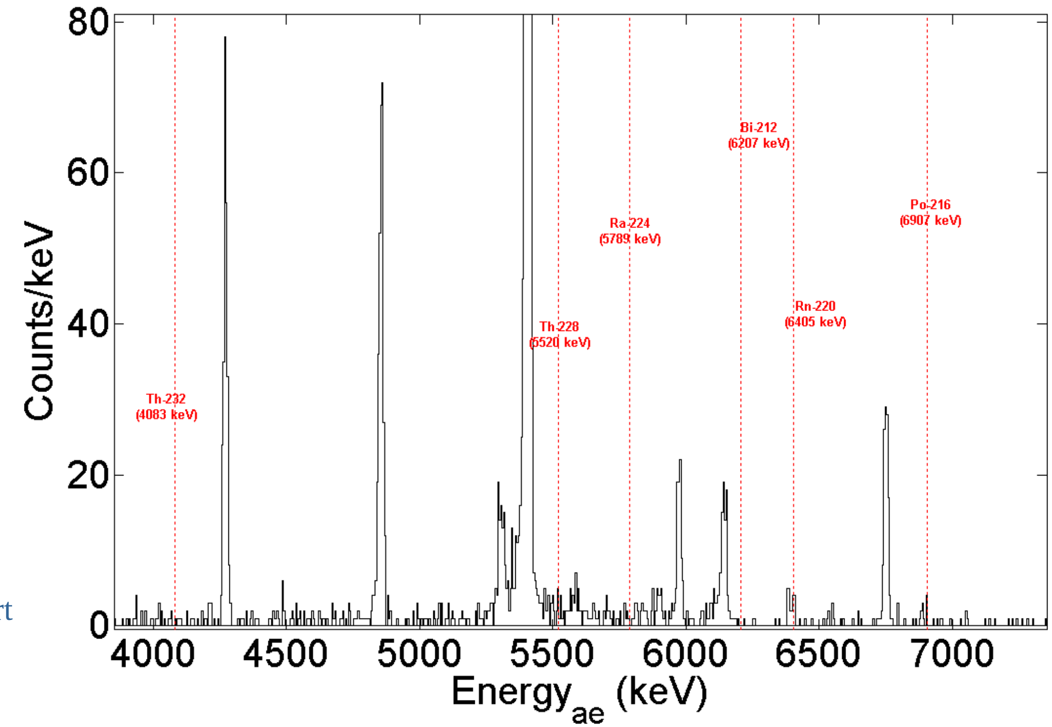
^{214}Pb Q_β : 1019 keV (11.0 %)
724 keV (40.2 %)
667 keV (45.9 %)



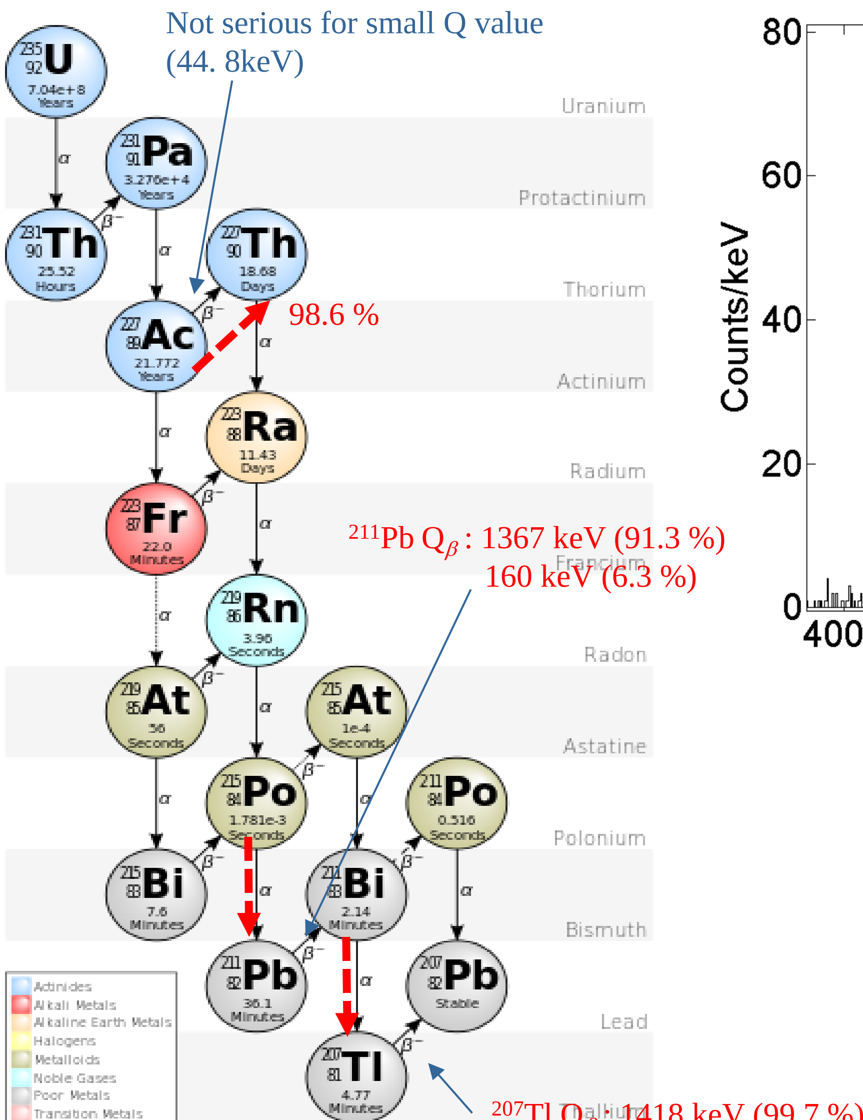
Considerable beta decays (^{232}Th)

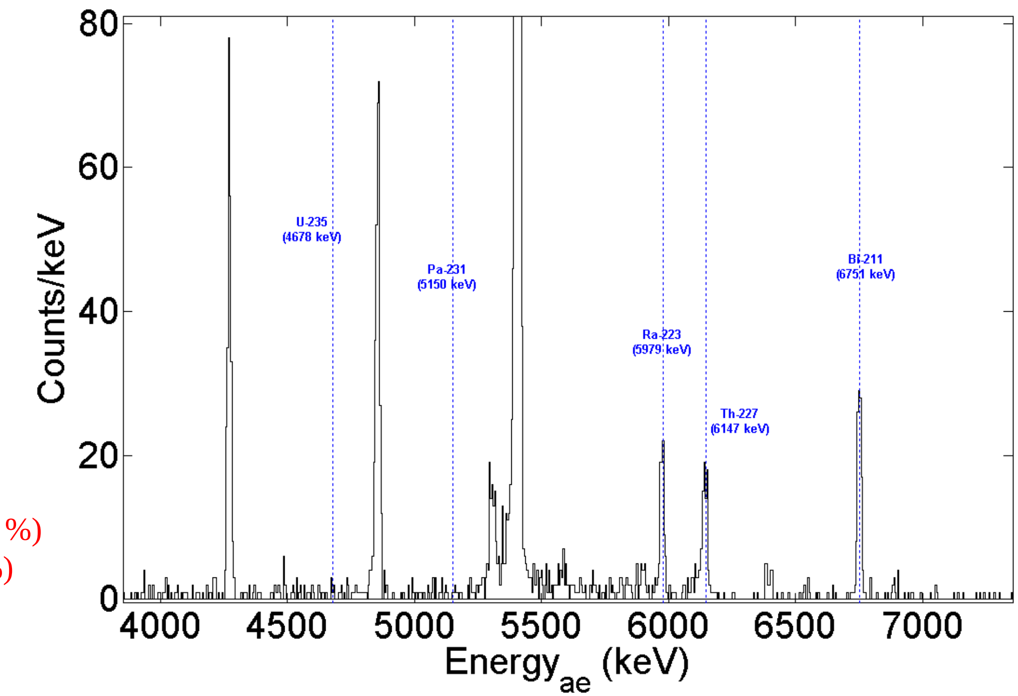


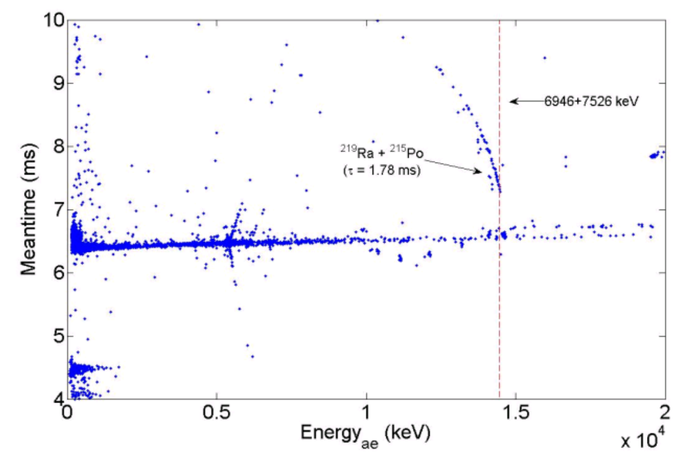
Not serious for short half life of ^{212}Po



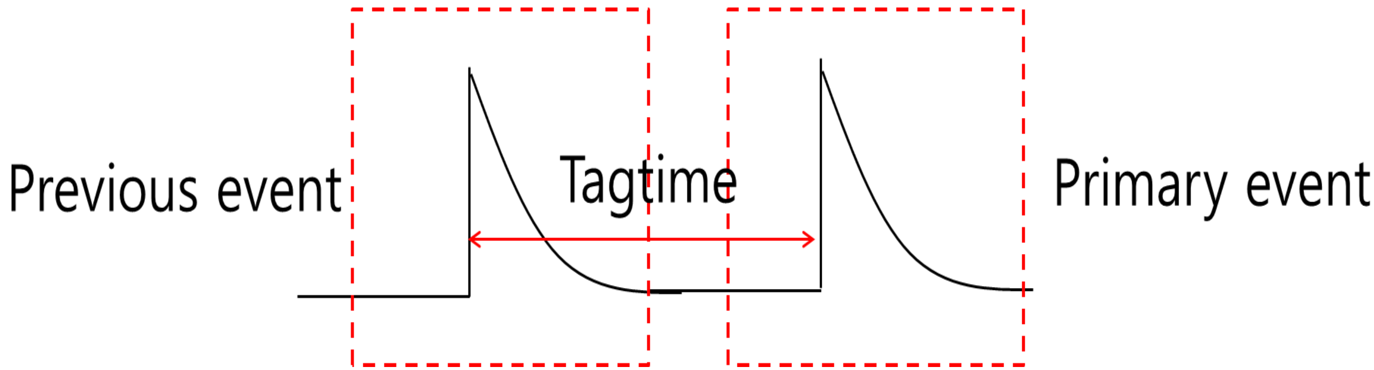
Considerable beta decays (^{235}U)







Time-Amplitude analysis method

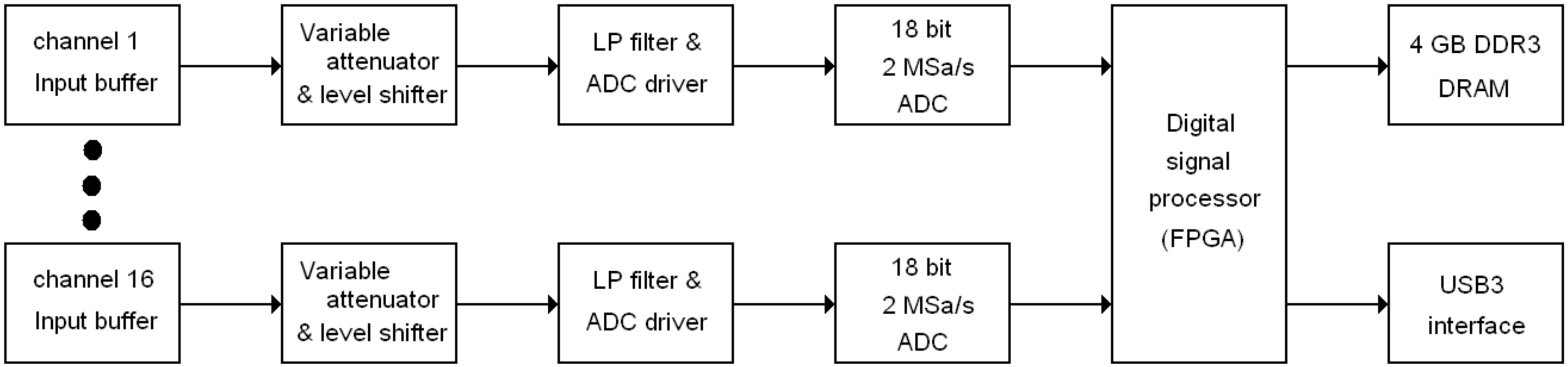


U-235 chain : Rn-219 (3.965 s) → Po-215 (1.78 ms) → Pb-211

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

AMoRE-ADC module development



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