AMoRE: Double Beta Decay Search with $CaMoO_4$

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DBD11, Osaka, Nov. 17, 2011

AMoRE Collaboration

Advanced Mo based Rare process Experiment

Korea
- Seoul National University
- Sejong University
- Kyungpook National University
- KRISS(Korea Research Institute of Standards and Science)

Russia
- ITEP(Institute for Theoretical and Experimental Physics)
- BNO(Baksan Neutrino Observatory)

Ukraine
- INR(Institute for Nuclear Research)

China
- Tsinghua University

Germany
- University of Heidelberg

5 countries
9 institutions
~70 collaborators

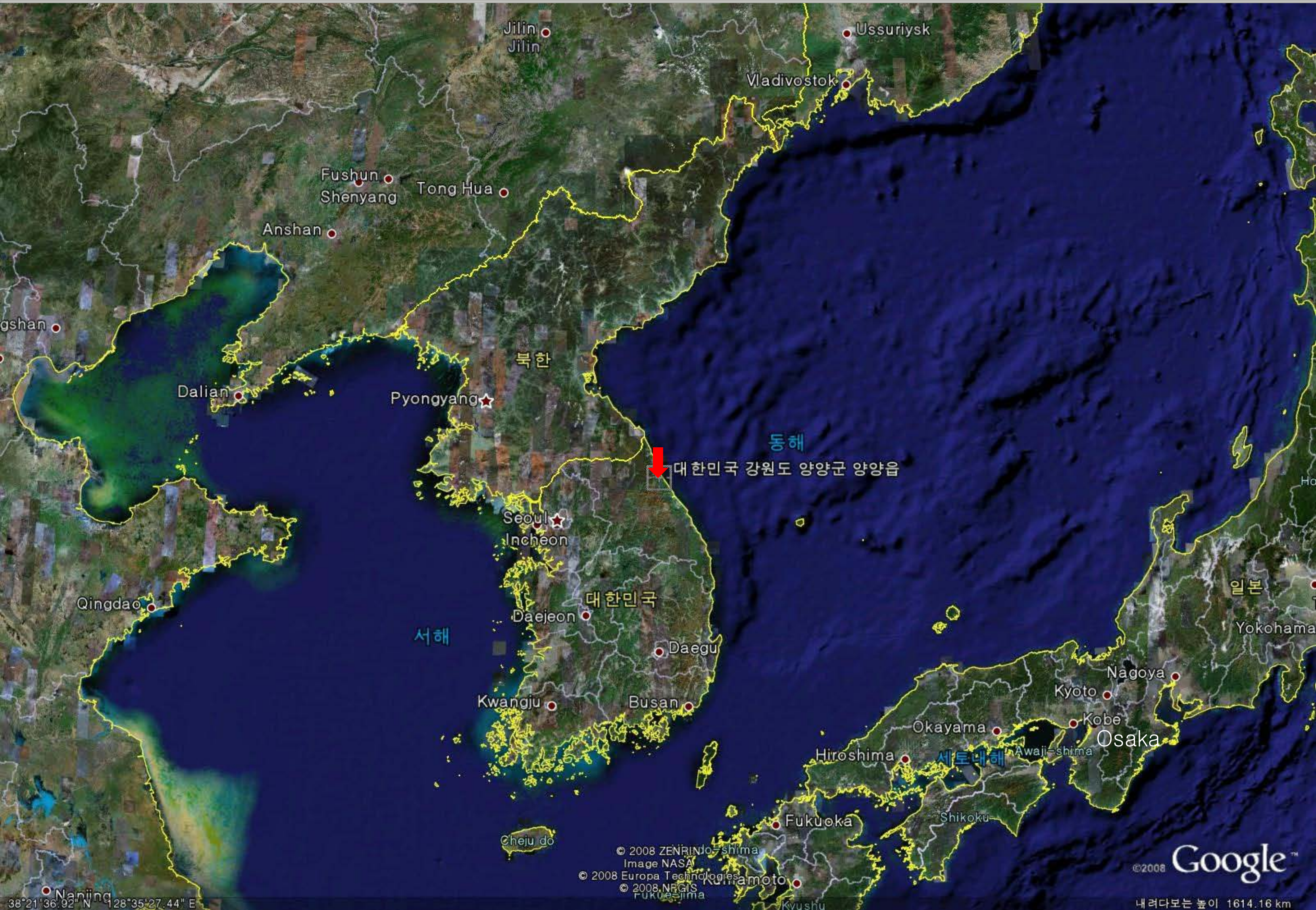
AMoRE

- Search for DBD of Mo-100
- WIMP search
- With $CaMoO_4$ crystal

International Workshop on Double Beta Decay Search
Oct. 15 ~ Oct. 17, SNU, Korea

Oct. 27, 2011 at INR, Kiev

Yangyang Underground Laboratory(Y2L)



YangYang Underground Laboratory(Y2L)

Y2L

- **Located in a tunnel of Yangyang Pumped Storage Power Plant Korea Middleland Power Co.**
- **Minimum vertical depth : 700 m**
- **Access to the lab by car (~2km)**
- **In operation since 2003**

Experiments:

- **KIMS: DM search exp. in operation**
- **AMORE: DBD Search exp. in preparation (additional laboratory space in design)**

DBD Searches at Y2L

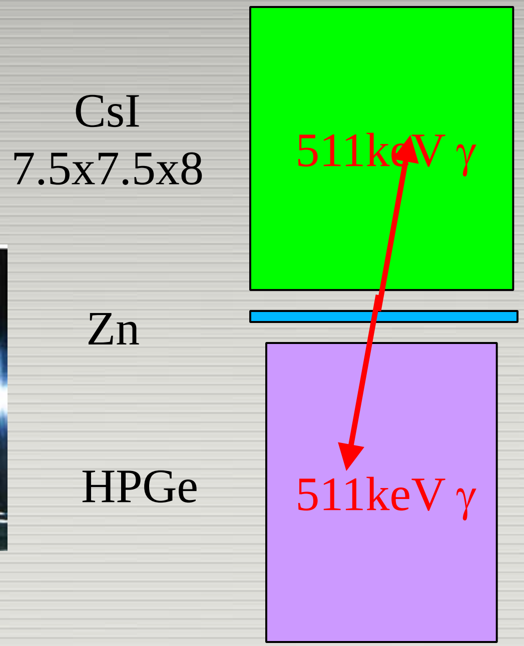
- Passive targets : HPGe + CsI(Tl) *[Nuclear Physics A 793 (2007)]*
  - ^{64}Zn EC+β^+ decay
  - ^{124}Sn $\beta\beta$ to excited states of ^{124}Te
  - ^{112}Sn EC+β^+ decay

- Active targets
  - ^{124}Sn 0v$\beta\beta$: Sn loaded Liquid scintillator *[Astropart. Phys. 31,412 (2009)]*
  - ^{84}Sr EC+β^+ decay : $SrCl_2$ crystal
  - ^{92}Mo EC+β^+ decay : $Ca^{nat}MoO_4$ crystal *[Nucl. Instr. Meth. A 654, 157 (2011)]*
  - ^{100}Mo 0v$\beta\beta$ decay : $Ca^{100}MoO_4$ crystal → AMoRE

Zn-64 EC+β⁺ decay

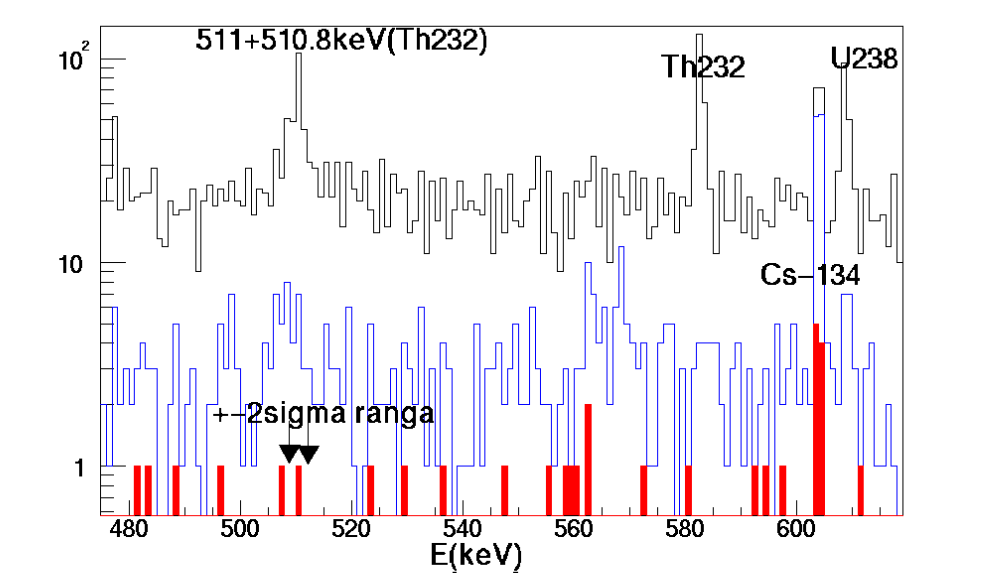
HPGe + Zn(8x8x1cm, 457g)+CsI(Tl) crystal

- 100% of HPGe
- 350m underground
- 10cm low background lead,
- 10cm copper and N2 flowing



Calibration by Na22 (β+ radioactive source)
Efficiency calculation by Geant4; 3%
1 week data;
Coincidence cut with 2 sigma range ; 1 event

⇒ 2×10^{20} year by 95% CL
Nucl. Phys. A 793 (2007)



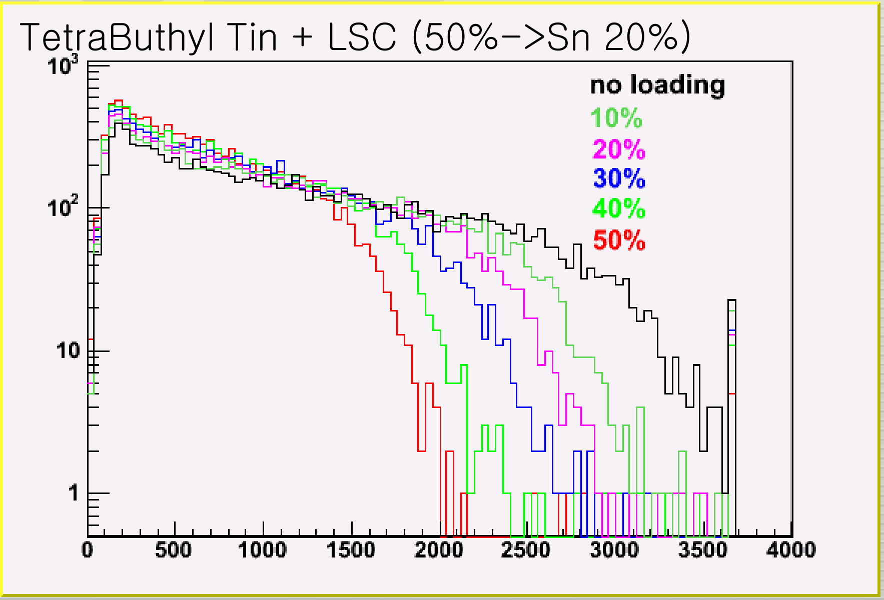
(1.1×10^{19} y) Positve evidence by I.BIKIT et.al,
App. Radio. Isot. 46, 455, 1995
<= 25% HPGe + NaI(Tl) with 350g Zn at surfac

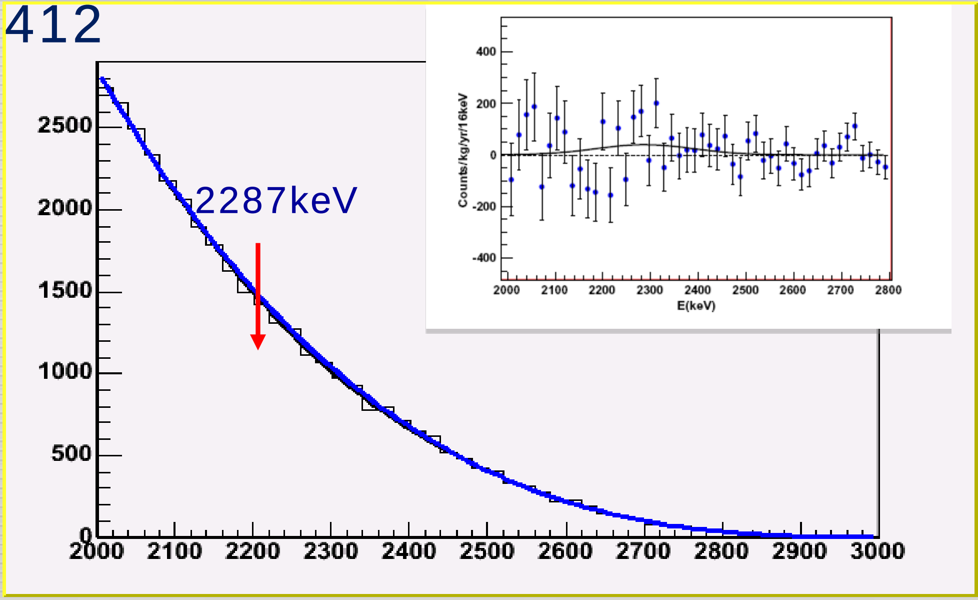
0ν bb search with Sn-loaded LSC

Double beta decay search with ^{124}Sn
Q = 2287 keV
5% of natural abundance

1.1 liter 33% Tin-loaded Liquid scintillator

- 9 Month data at Y2L inside of Pb shielding
- Astropart. Phys. 31 (2009) 412



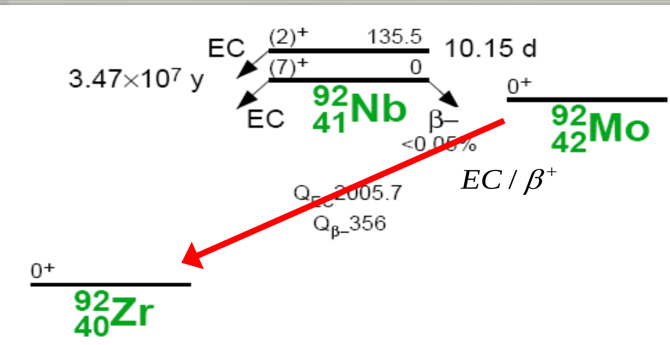


$T_{1/2}$ > 2.0x10^{19} yr at 90% C.L

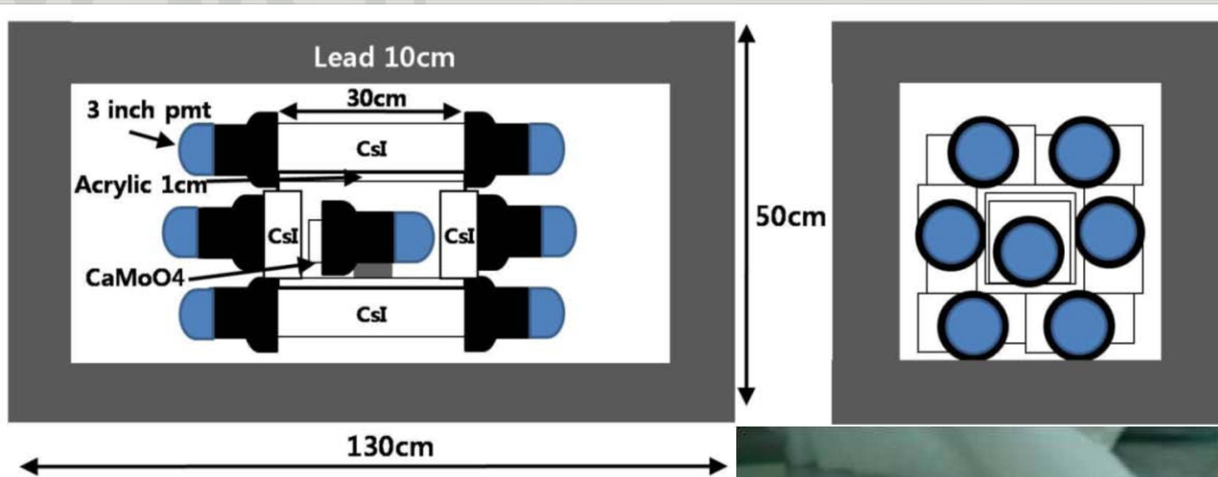
Previous limit:

$T_{1/2}$ > 2.4x10^{17} yr at 90% C.L

EC/β^+ decay of ^{92}Mo

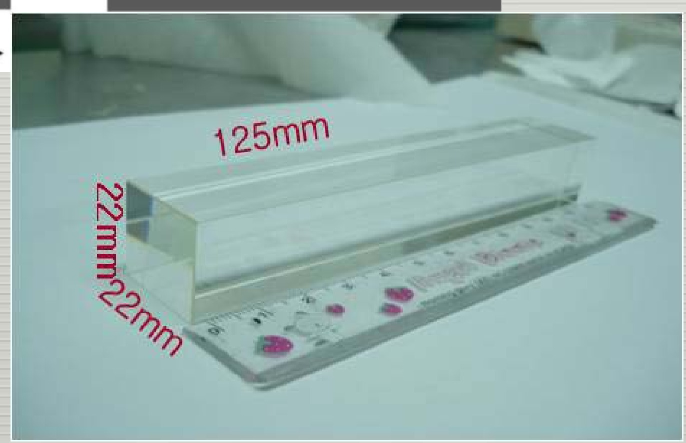


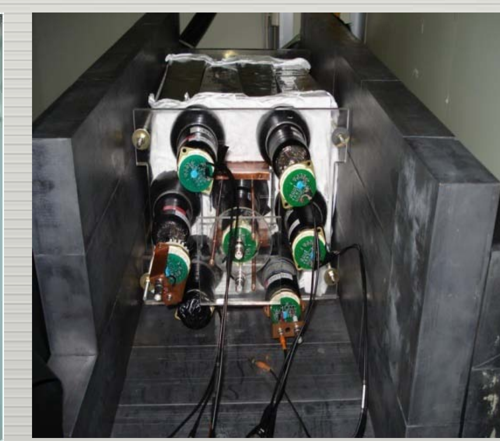
- (A, Z) + e^- -> (A, Z-2) + e^+ + 628keV(Q-value)
- e^+ stops in active($CaMoO_4$) Crystal.
- back to back 511 keV gammas at CsI(Tl)
- Abundance = ^{92}Mo: 14.84%, ^{100}Mo: 9.63%



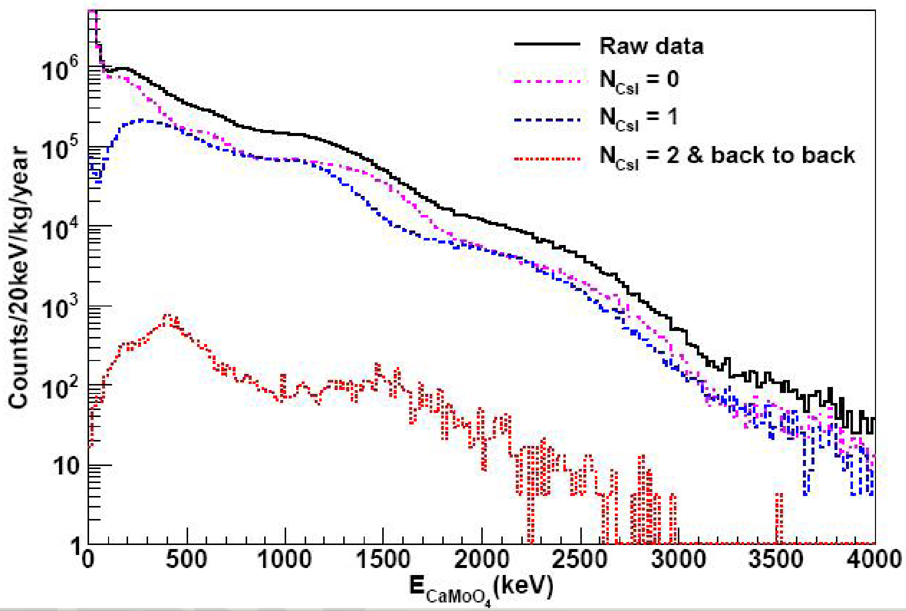
4pi coverage by CsI(Tl) crystal (not high radiopurity)

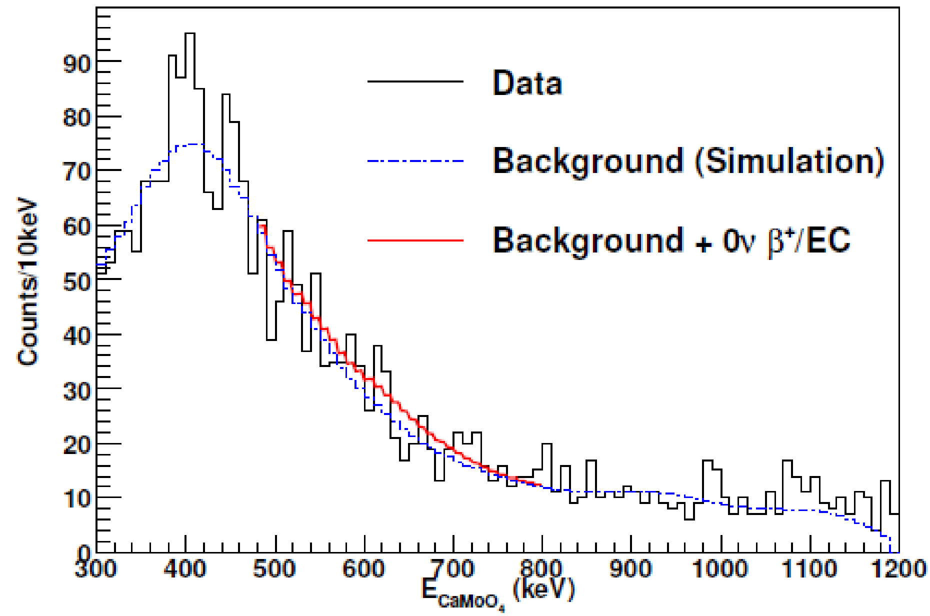
CaMoO4 crystal :
2.2x2.2x6cm (2) : 255g





Mo-92 EC





44.1 events at 90 % confidence level

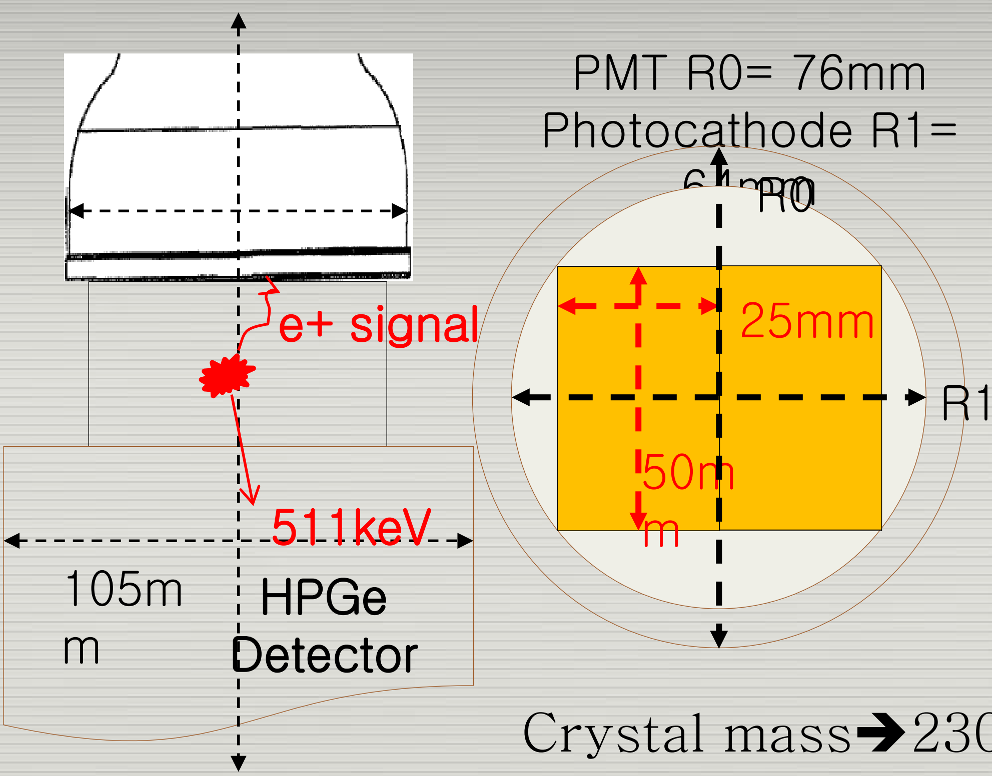
> 2.3×10^{20} years at 90 % confidence level

Nucl. Instr. Meth. A 654, 157 (2011)

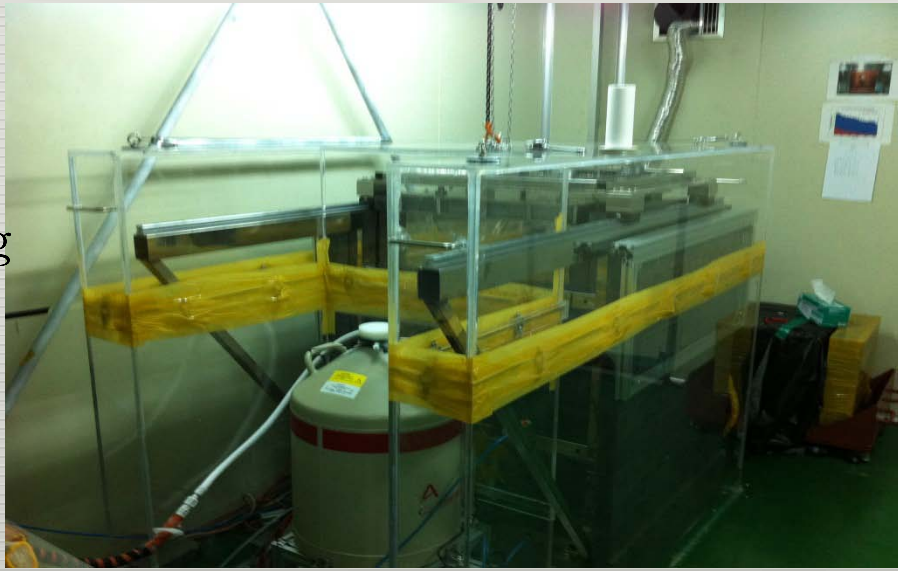
> $1.9\text{x}10^{20}$ years by Barabash et al.,

A.S. Barabash *et al.*, Z. Phys. A **357** 351-352 (1997)

New HPGe detector setup for Mo-92



Crystal mass➔230g

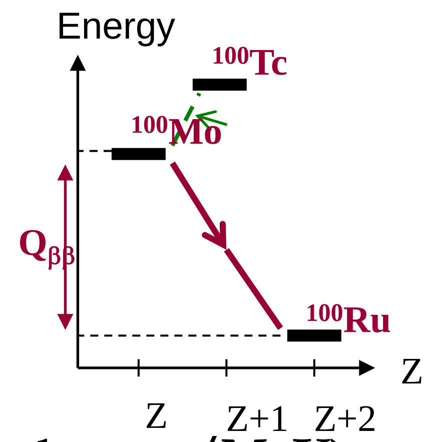


Mass	Diameter	Height
2.8kg	82.1 mm	90.7 mm

100% relative efficiency

$CaMoO_4$ for $0\nu\beta\beta$

$CaMoO_4$

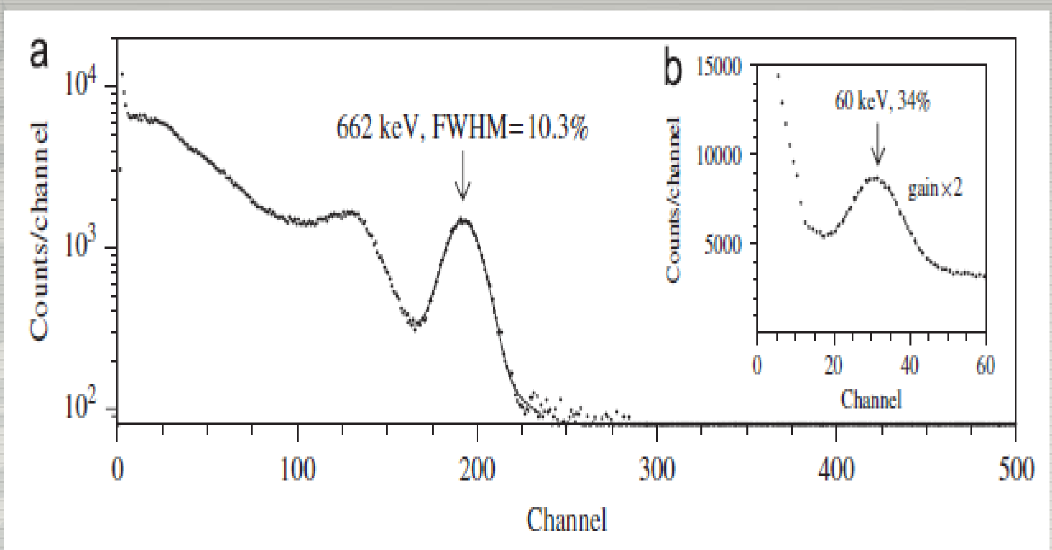


- DBD for Mo-100 (3034 keV), Ca-48(4272 keV)
  high Q-value → less background
- Mo-100 enrichment >90% not so difficult
- for Mo-100 search, <u>Ca-48 needs to be depleted</u>
- Scintillator
  - At room temp; 10-20% of CsI(Tl) at 20^o (9300 photons/MeV)
  - Decay time ; 16 μ sec
  - LY increases at lower temp. (almost the same as CsI(Tl))
  - Wavelength; 450-650ns-> RbCs PMT or APD
  - Pulse Shape Discrimination
- Can be used as cryogenic detector
  - Debye temperature: 438 K (Ge : 360 K, Si: 625 K)
  - Combining with Scintillation detection : NR, alpha/gamma separation
  - Good dark matter detector as well

$CaMoO_4$ crystal development

Crystal Characteristics

Nuclear Instruments and Methods in Physics Research A 584 (2008) 334–345



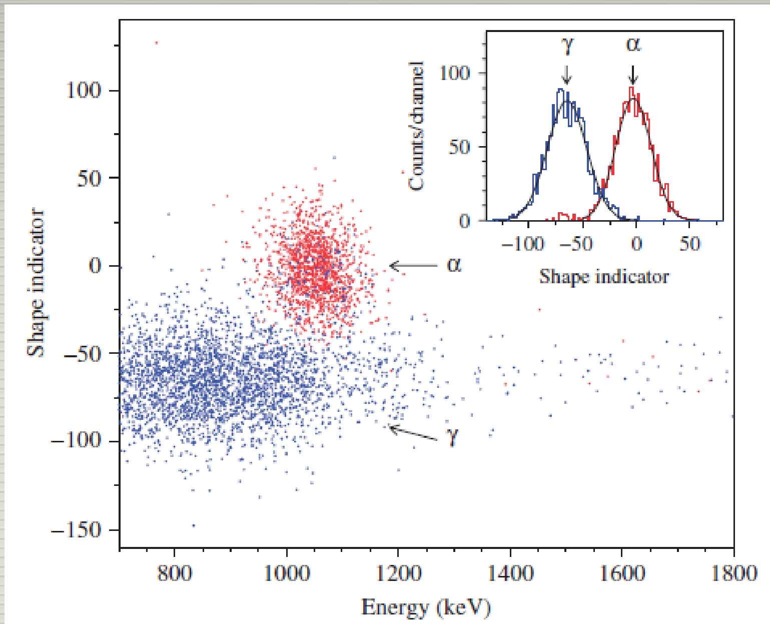


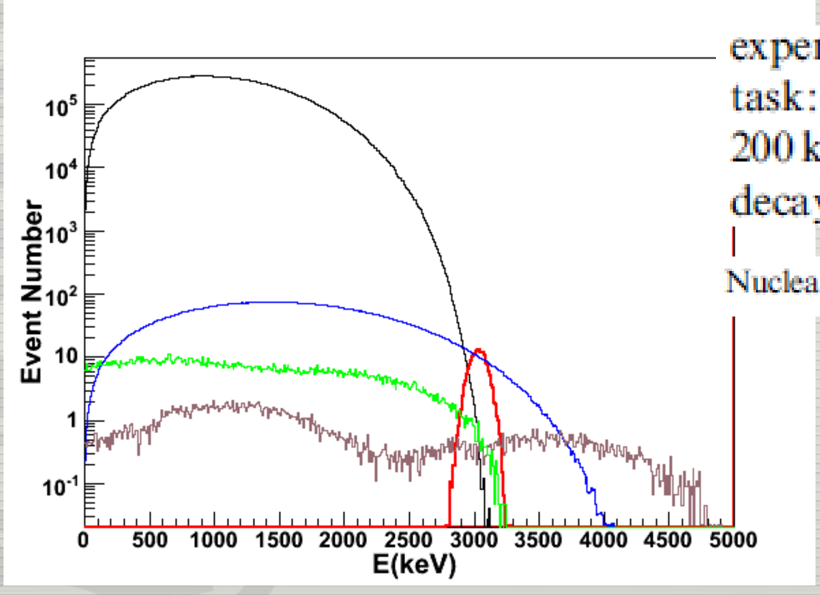
Table 4
Radioactive contaminations in $CaMoO_4$, $CaWO_4$, and $CdWO_4$ crystal scintillators

Source	Activity (mBq/kg)					
	CMO-2	CMO-3	CMO-4	CMO-5	CaWO [29]	CdWO [3,6,48,49]
^{232}Th	⩽0.7	⩽0.7	⩽0.9	⩽1.5	0.69(10)	0.053(5)
^{228}Th	0.23(10)	0.42(17)	0.4(4)	0.04(2)	0.6(2)	⩽0.004−0.039(2)
^{238}U	⩽0.5	⩽0.6	⩽0.6	⩽1.5	5.6(5)	⩽0.004
^{226}Ra	2.1(4)	2.5(5)	2.4(1.3)	0.13(4)	5.6(5)	⩽0.004
^{210}Pb	⩽398	⩽401	⩽550	⩽17	⩽430	⩽0.4
^{210}Po	420(10)	490(10)	550(20)	⩽8	291(5)	⩽0.4
^{40}K	⩽1.1	⩽2.1	⩽2.5	⩽3	⩽12	0.3(1)
^{90}Sr	⩽62	⩽178	⩽50	⩽23	⩽70	⩽0.2

Enrichment & Depletion

Mo-100 enrichemeinet : 96.1% (production capability : 30 kg/y)

Ca-48 depletion < 0.001% (Nantural abundance is 0.187%)



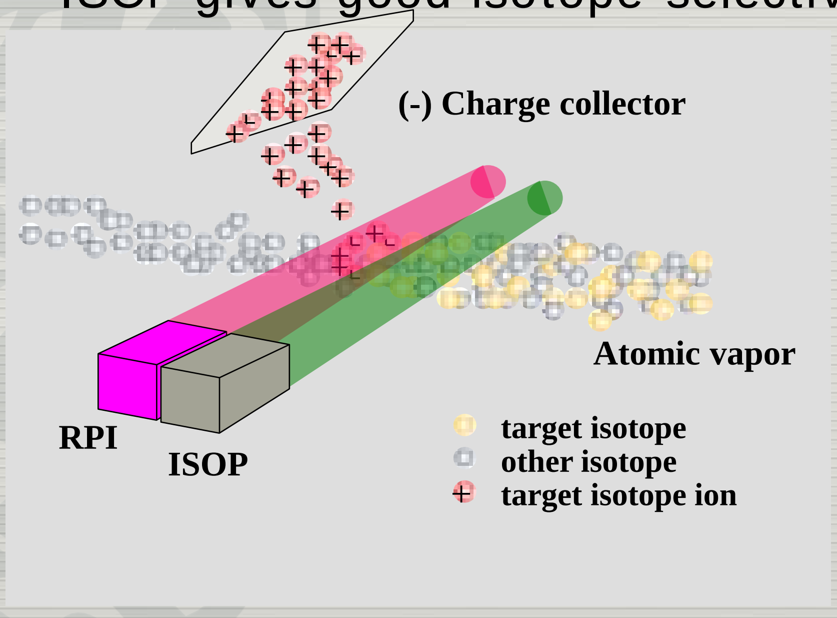
experiment. However, further improvement will be difficult task: the half-life limit of 10^{25} yr could be reached only with 200 kg yr statistics. More sensitive searches for ^{100}Mo $0\nu2\beta$ decay will evidently need the depletion of Ca in ^{48}Ca.[5]

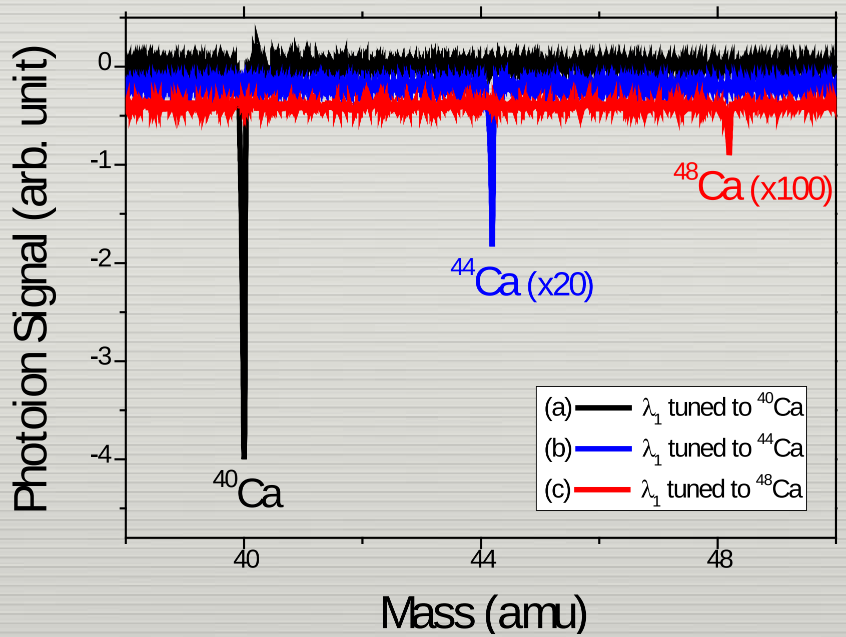
Nuclear Instruments and Methods in Physics Research A 584 (2008) 334–345

Depleted Ca : ~ 30 kg available (Ca-48 < 0.001%)
➔ Good for 100 kg CaMooO4 crystals

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

- ALSIS (**A**dvanced **L**aser **S**table **I**sotope **S**eparation)
  - Features : Isotope-Selective Optical Pumping (ISOP) followed by Non-selective Resonant Photoionization (RPI)
  - ISOP gives good isotope-selectivity and non-selective RPI high yield.

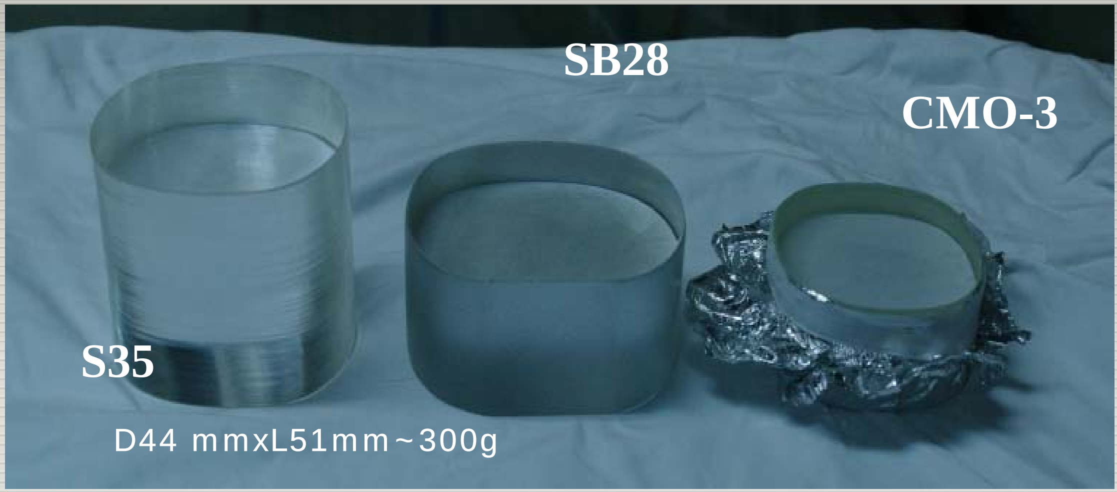




- Engineering Demonstration (2010~2012)

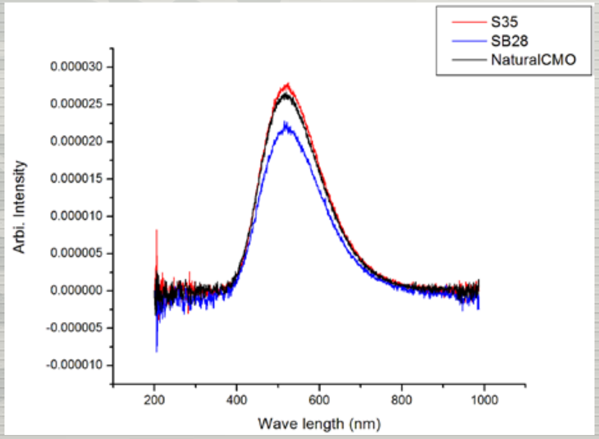
Production capability (Ca-48) : 1kg/yr

$^{40}Ca^{100}MoO_4$

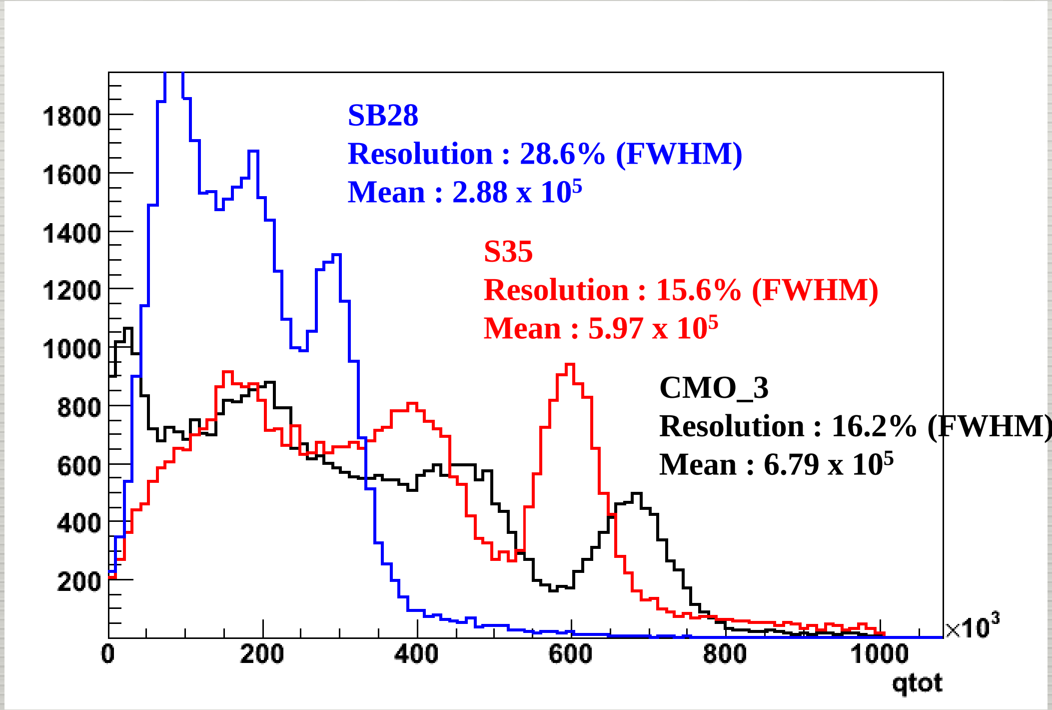


3 crystals with enriched material ~ 845g

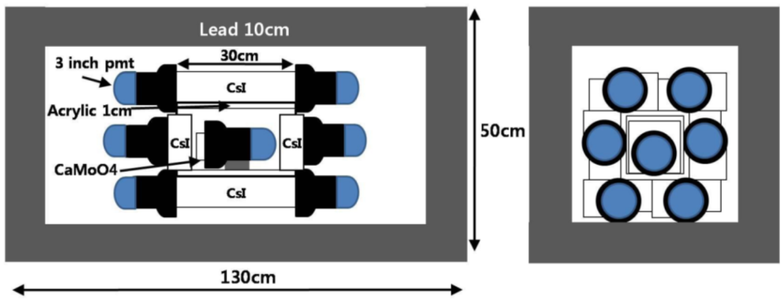
Good scintillation property

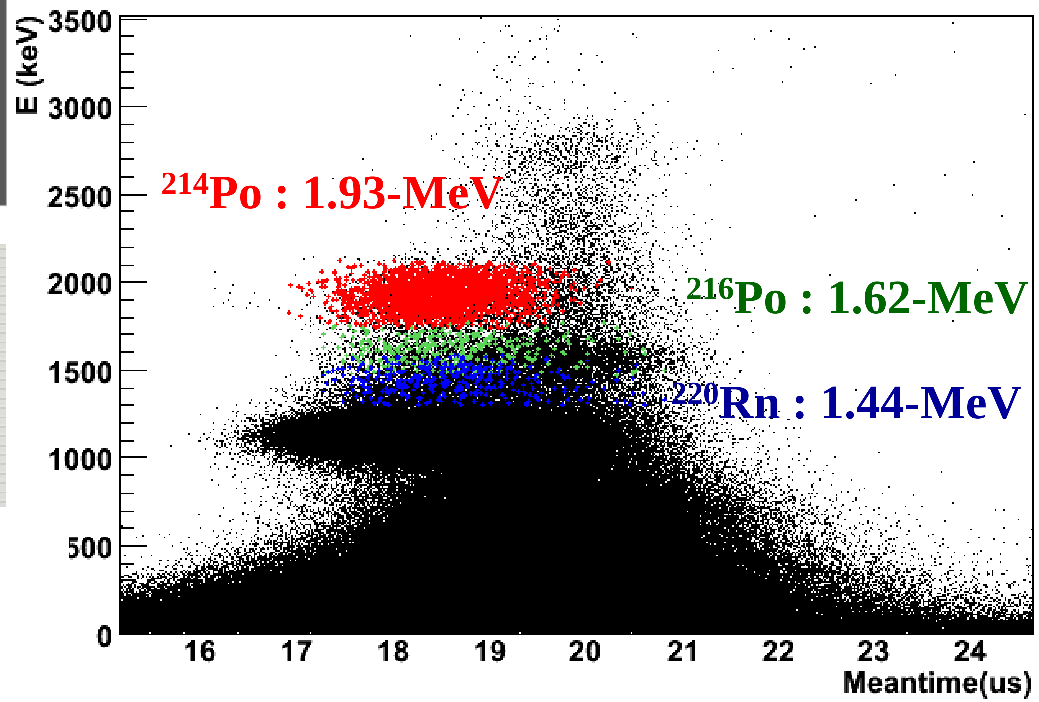


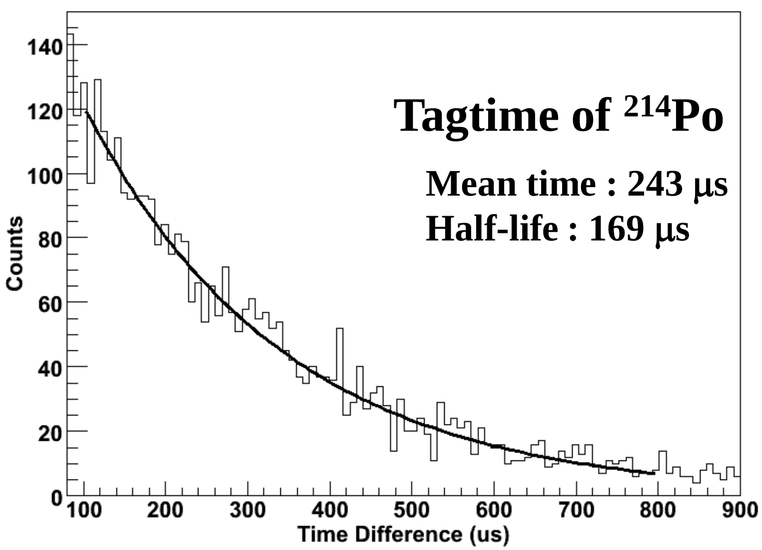
Emission spectra



Preliminary data analysis





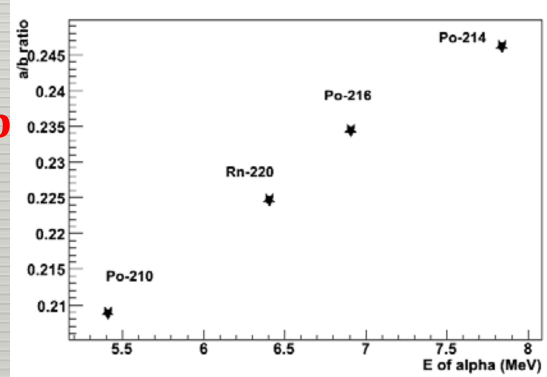


β–α **decay**

$^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$

***α*-decay of ^{214}Po**

Half life : 164 µs



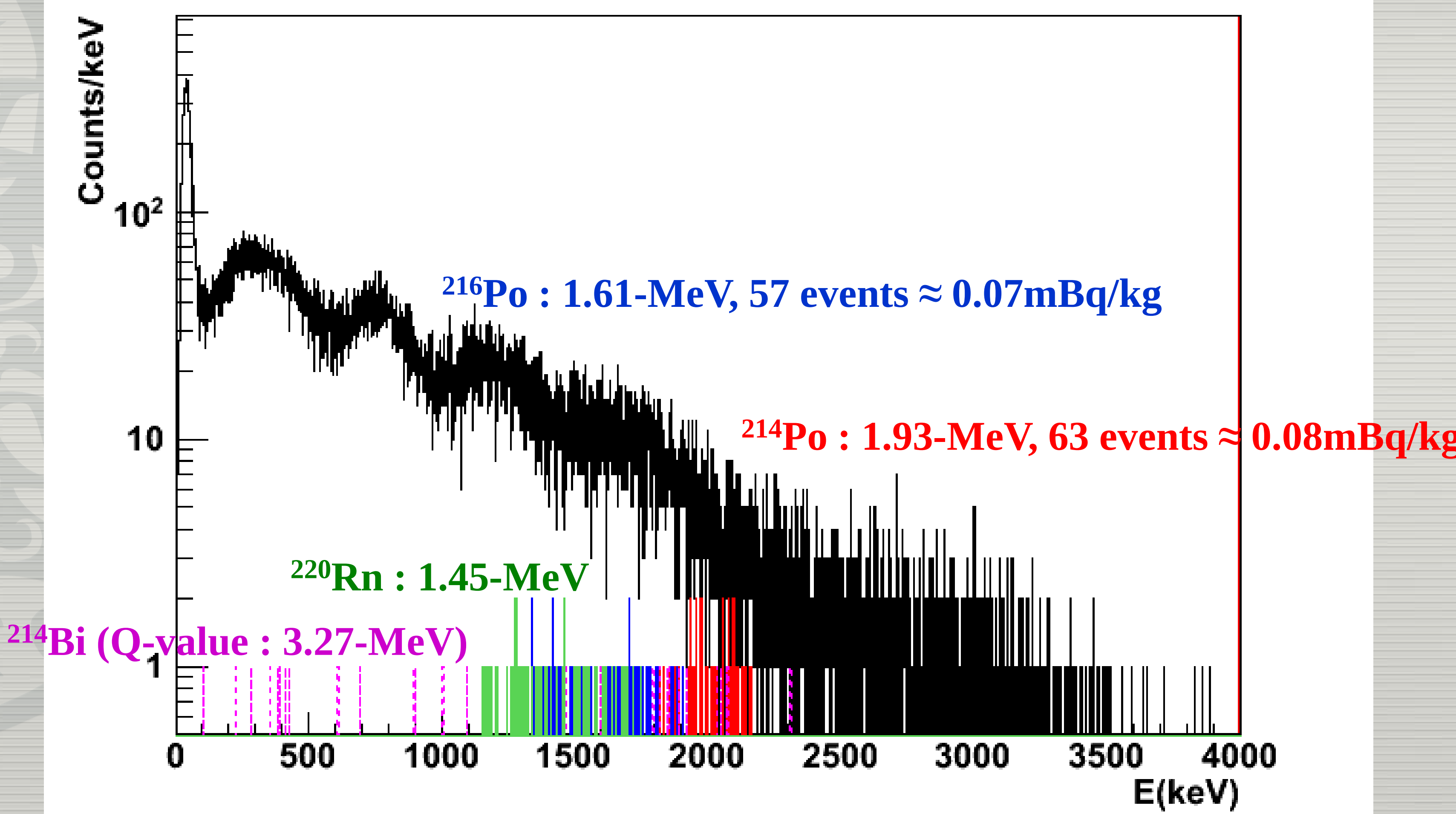
BG spectra of SB28

β–α decay in ^{238}U

^{214}Bi (Q-value : 3.27-MeV) → ^{214}Po (Q-value : 7.83-MeV)→ ^{210}Pb

α–α decay in ^{232}Th

^{220}Rn (Q-value : 6.41-MeV) → ^{216}Po (Q-value : 6.91-MeV)→ ^{212}Pb



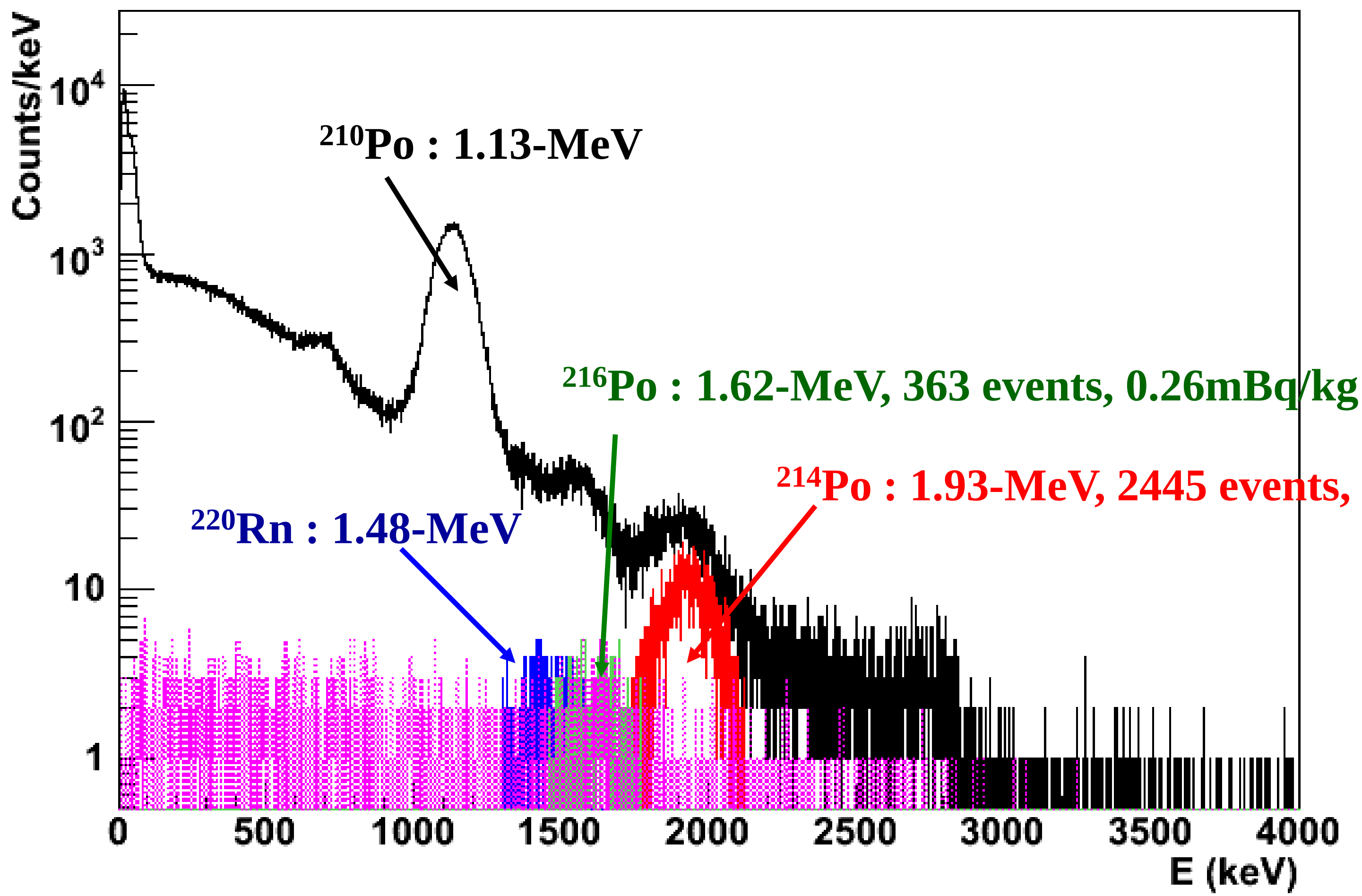
BG spectra of S35

β–α **decay in ^{238}U**

^{214}Bi (Q-value : 3.27-MeV) → ^{214}Po (Q-value : 7.83-MeV)→ ^{210}Pb

α–α **decay in ^{232}Th**

^{220}Rn (Q-value : 6.41-MeV) → ^{216}Po (Q-value : 6.91-MeV)→ ^{212}Pb



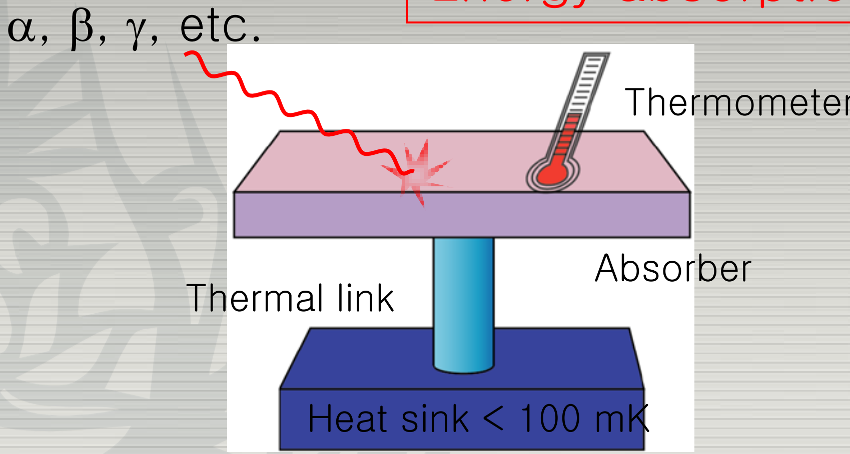
Background of $CaMoO_4$ crystals

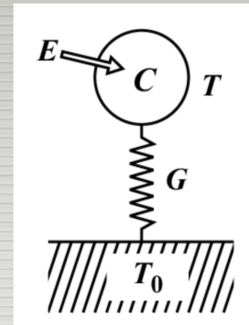
Crystal scintillator	^{226}Ra	^{228}Th	^{210}Po
$^{40}Ca^{100}MoO_4$ (S35)	1.74	0.26	57
$^{40}Ca^{100}MoO_4$ (SB28)	0.08	0.07	
$CaMoO_4$(IM [a])	2.1 – 2.5	0.2 – 0.4	420 – 550
$CaMoO_4$(ICMSAI [b])	0.13	≤ 0.04	≤ 8

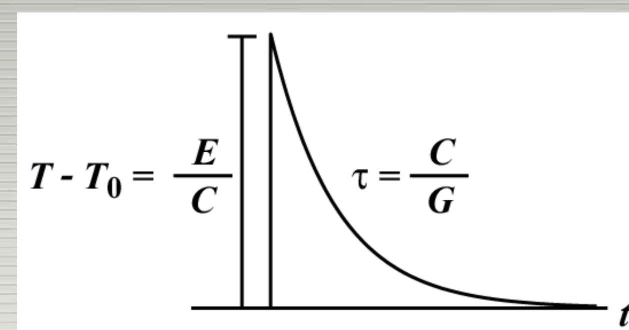
→ Setting up pilot experiment (Scintillation at 0^0C with S35 / SB28 /…)

Cryogenic Detector

Energy absorption ➔ Heat (Temperature)







At room temperature the specific heat of Si is 0.7 J/gK, so

$$E = 1 \text{ keV},\ m = 1 \text{ g} \quad \Rightarrow \quad \Delta T = 2 \cdot 10^{-16} \text{ K},$$

$$C \propto \left(\frac{T}{\Theta}\right)^3$$

Choice of thermometers

- **Thermistors (doped Ge, Si)**
- **TES (Transition Edge Sensor)**
- **MMC (Metallic Magnetic Calorimeter)**
- STJ, KID etc.

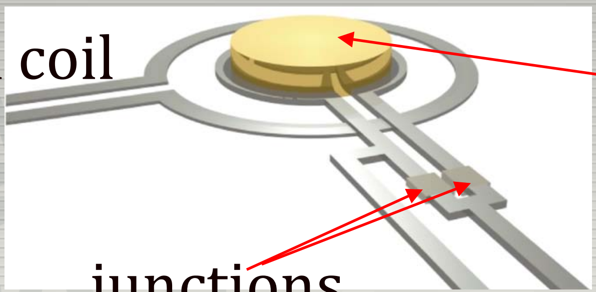
Example

$T = 0.1$ K

Si $\quad \Rightarrow \quad C = 4 \cdot 10^{-15}$ J/K

$E = 1$ keV $\quad \Rightarrow \quad \Delta T = 0.04$ K

Metallic Magnetic Calorimeter (MMC)



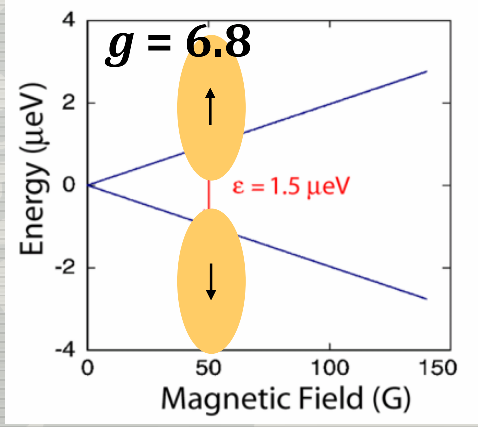
Magnetic material (Au:Er) in dc SQUID

Au:Er(10~1000ppm)

paramagnetic system

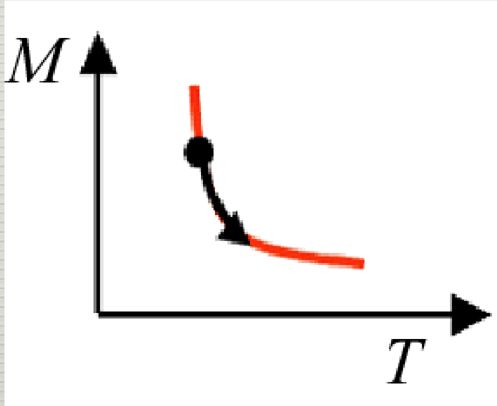
metallic host: fast thermalization (~ 1ms)

Can control heat capacity by magnetic field



5 mT → $\Delta\varepsilon$ = 1.5 μeV

1 keV → 10^9 spin flips

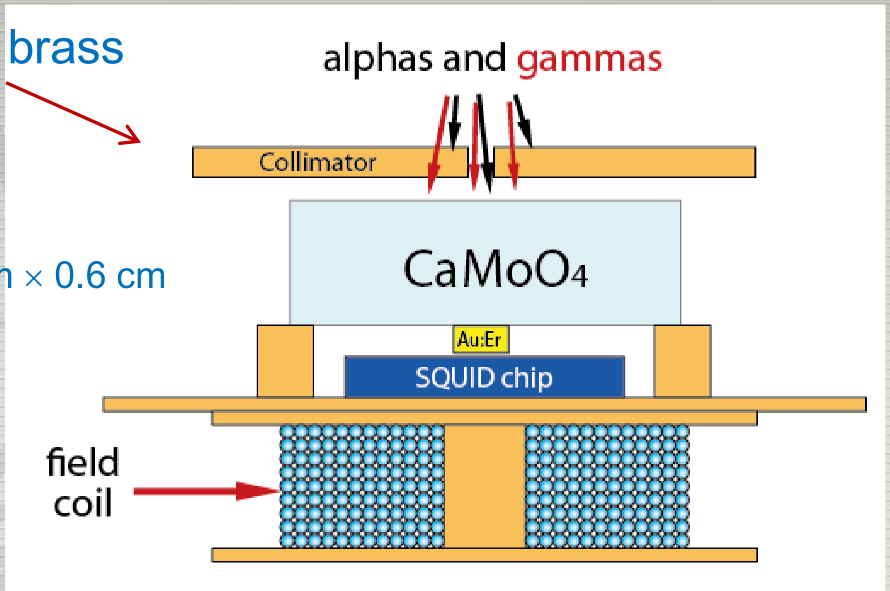


- **Fast**
- **Wide working temperature**
- **Absorber friendly**

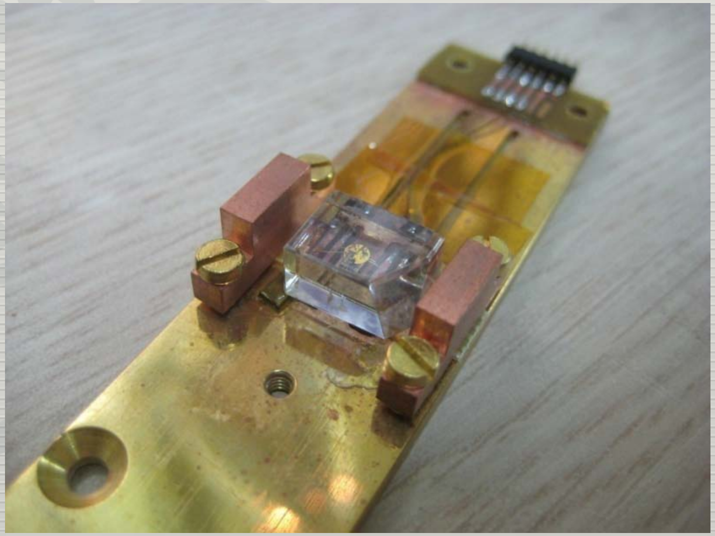
Experimental setup at KRISS with MMC to measure temperature changes

~ 500 μm thick brass

crystal size
~ 1 cm × 0.7 cm × 0.6 cm

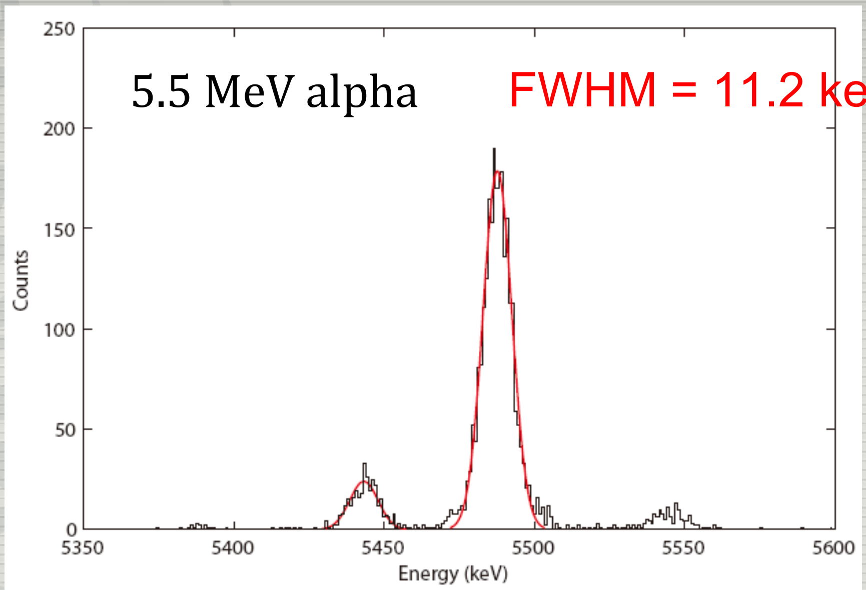


base temperature : 13 ~ 100 mK



Performance of CMO+MMC

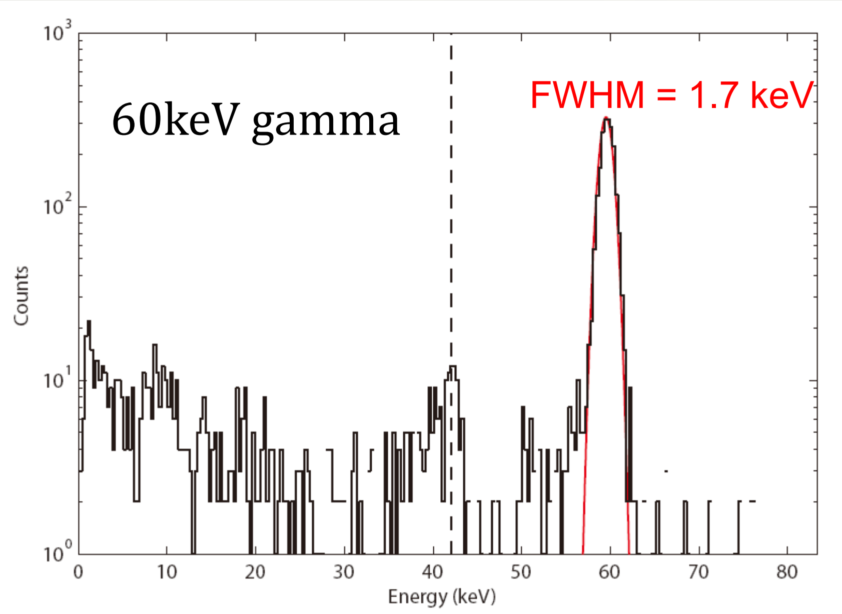
Astropart. Phys.34, 732, 2011



high energy resolution
suitable to search for Mo-100 0νββ

Emission line of Mo : 18keV

42 keV

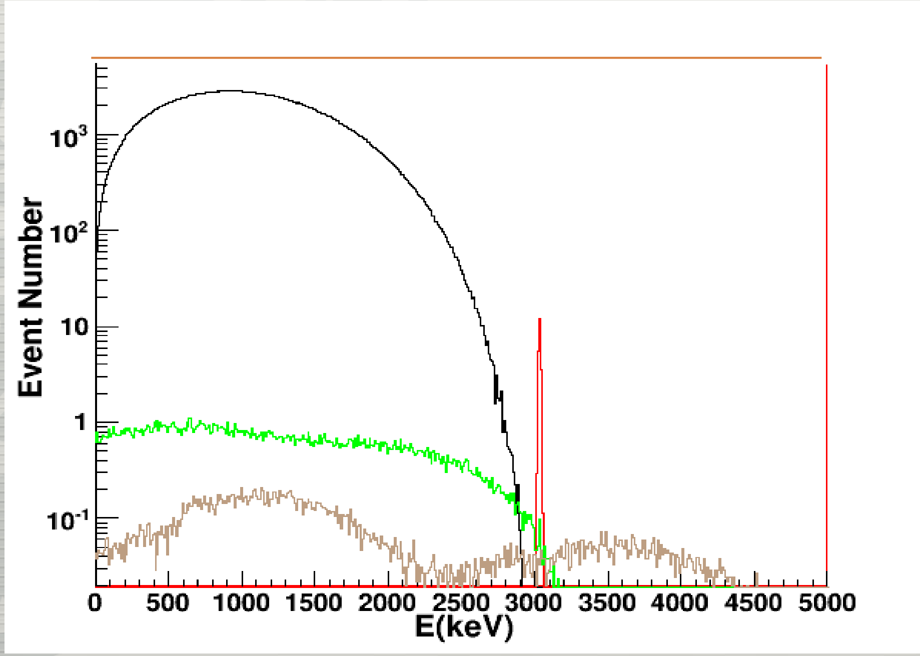


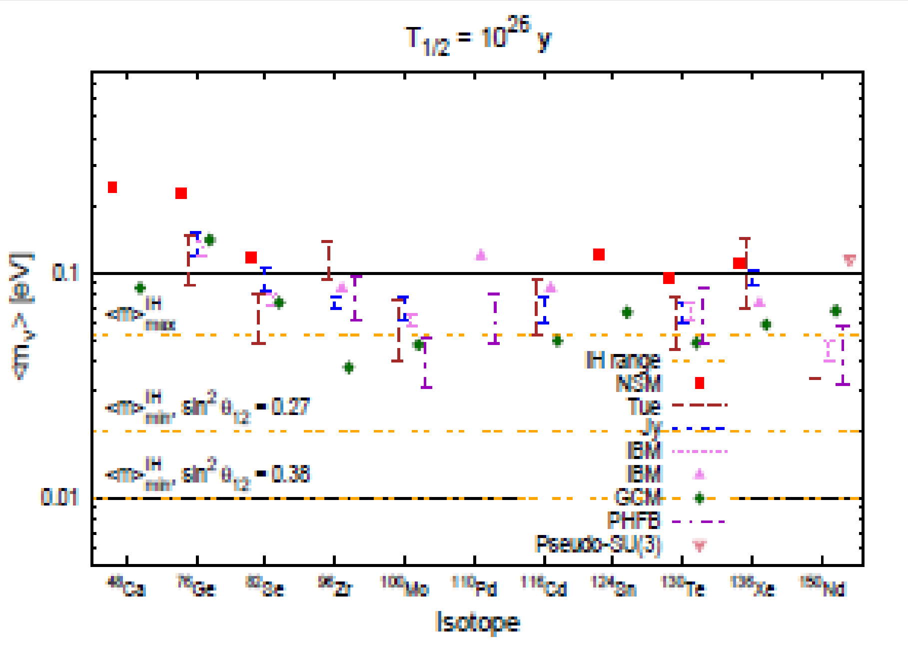
low energy thresold
suitable to search for WIMP

CaMoO4 DBD Sensitivity

100 kg CaMoO4 Cryogenic detector
Mo-100~ 50 kg
Efficiency ~ 0.8

5 years, 100 kg $^{40}Ca^{100}MoO_4$
3 x10^{26} years ~ 50 meV

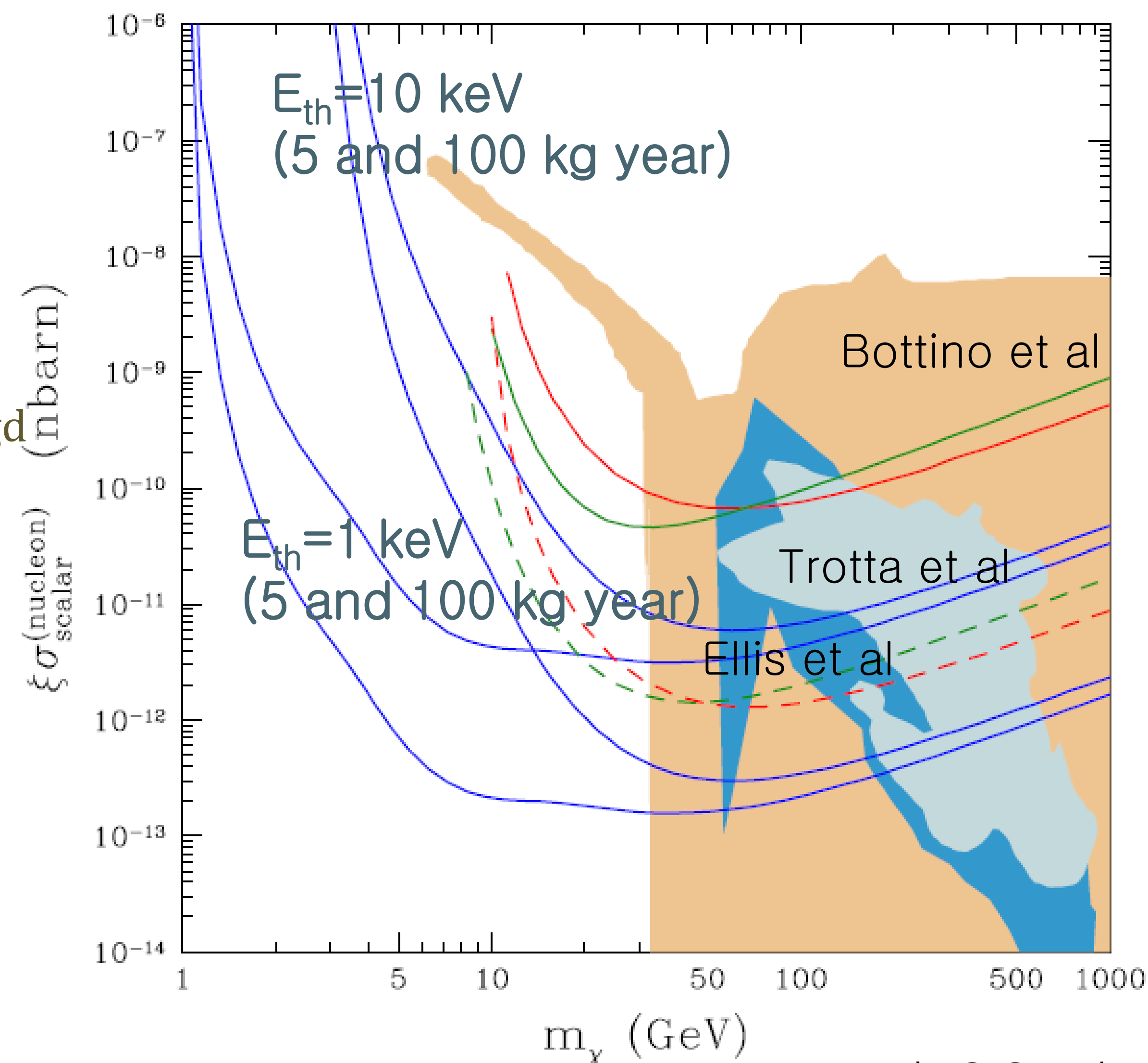




Werner Rodejohann, Int. J. M. Phys., 2011

Dark matter sensitivity of $CaMoO_4$ cryogenic experiment

- $CaMoO_4$
- CDMS 2008
- SuperCDMS 25kg
- XENON10 2007
- XENON100 6000 kgd
- CMSSM, Ellis et al
- CMSSM, Markov chain Trotta et al
- Effective MSSM, Bottino et al



by S. Scopel

Toward a full scale experiment

Crystal size: 0.6 cm³

Energy resolution
2keV (60keV)
11 keV (5.5MeV)

➔

Crystal size: ~ 60 cm³, 250 g

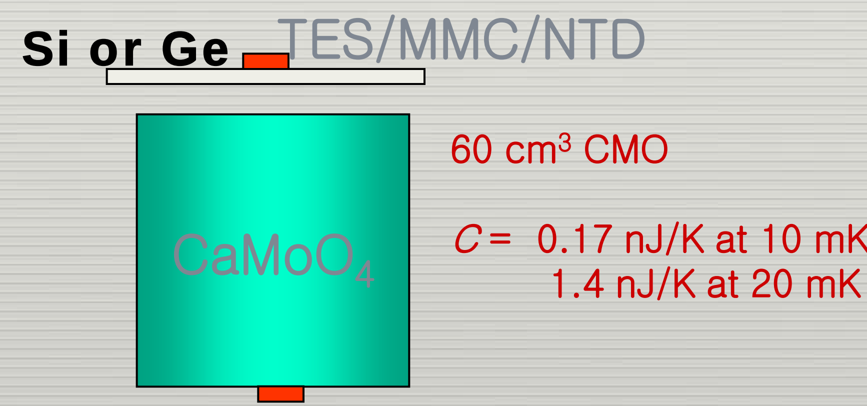
Energy resolution
<1 % @ 3 MeV

Additional light sensor

Time constant of phonon signal

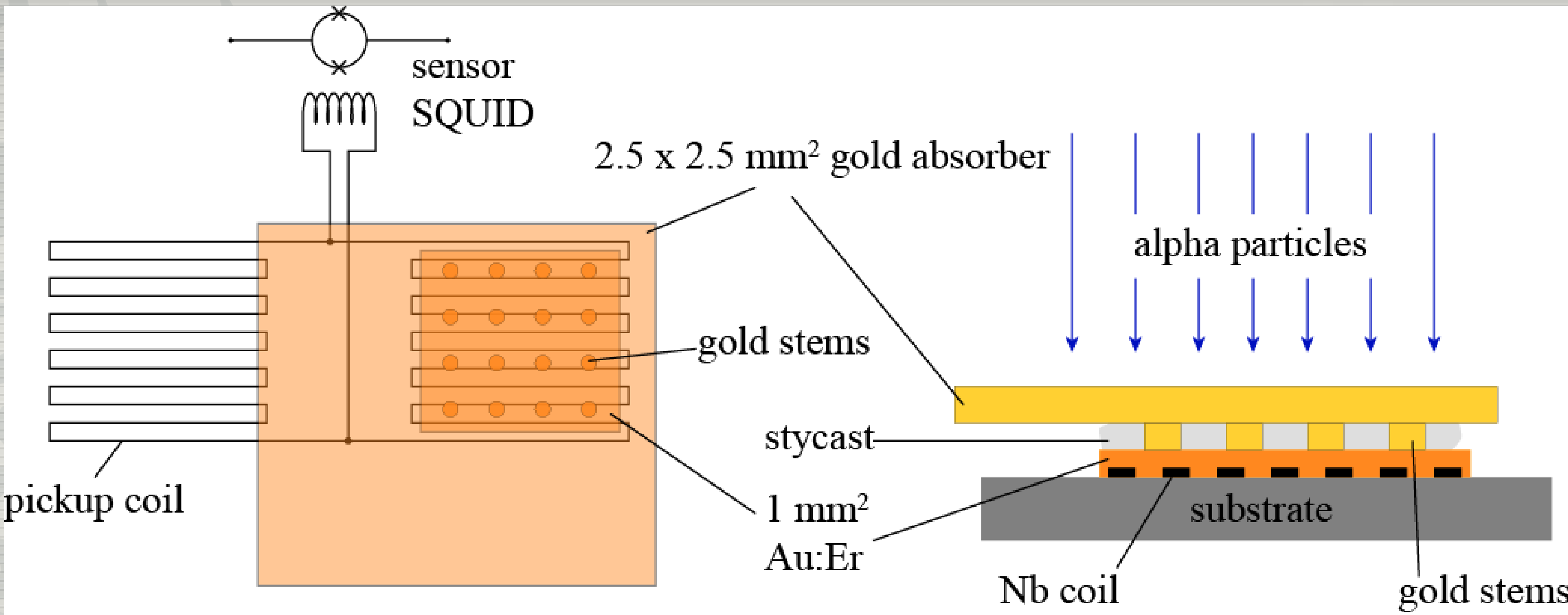
Efficiency ~ 0.8

		diameter, mm								
		30	35	40	45	50	55	60	65	70
height, mm	30	0.794	0.806	0.813	0.822	0.826	0.831	0.834	0.839	0.841
	35	0.799	0.808	0.821	0.829	0.833	0.839	0.843	0.846	0.849
	40	0.804	0.816	0.822	0.830	0.838	0.842	0.849	0.852	0.856
	45	0.808	0.819	0.829	0.835	0.841	0.847	0.851	0.856	0.860
	50	0.809	0.820	0.830	0.839	0.845	0.851	0.854	0.861	0.864
	55	0.809	0.823	0.834	0.841	0.848	0.856	0.857	0.864	0.868
	60	0.810	0.825	0.835	0.845	0.850	0.856	0.860	0.866	0.871
	65	0.813	0.825	0.838	0.846	0.851	0.859	0.863	0.869	0.873
	70	0.817	0.828	0.839	0.846	0.853	0.860	0.867	0.869	0.875



Phonon sensor (MMC)

New sensor for large heat capacity

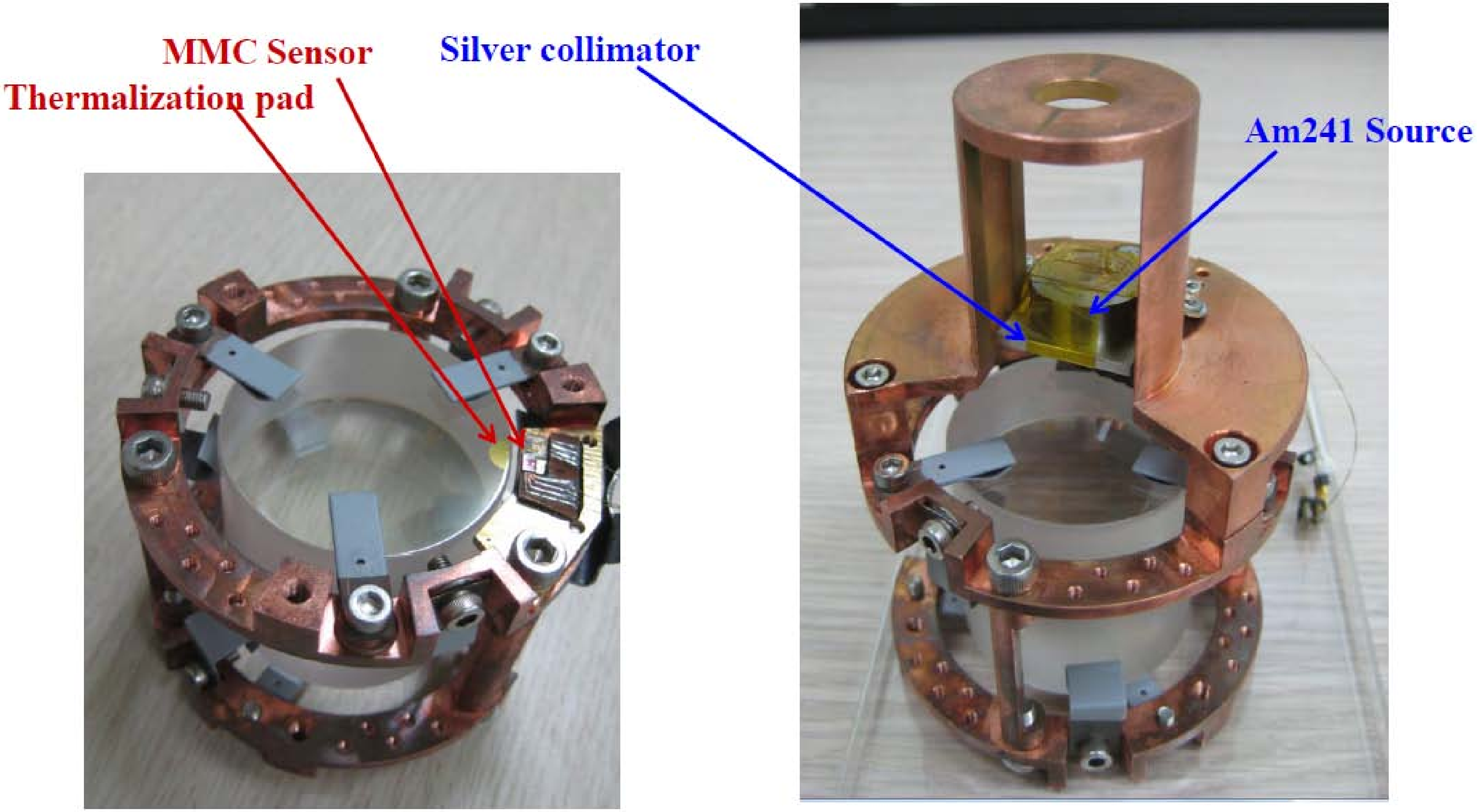


Meander is made in U. of Heidelberg.

2.5 x 2.5 x 0.07 mm³ gold foil

C = 0.6 nJ/K at 20 mK

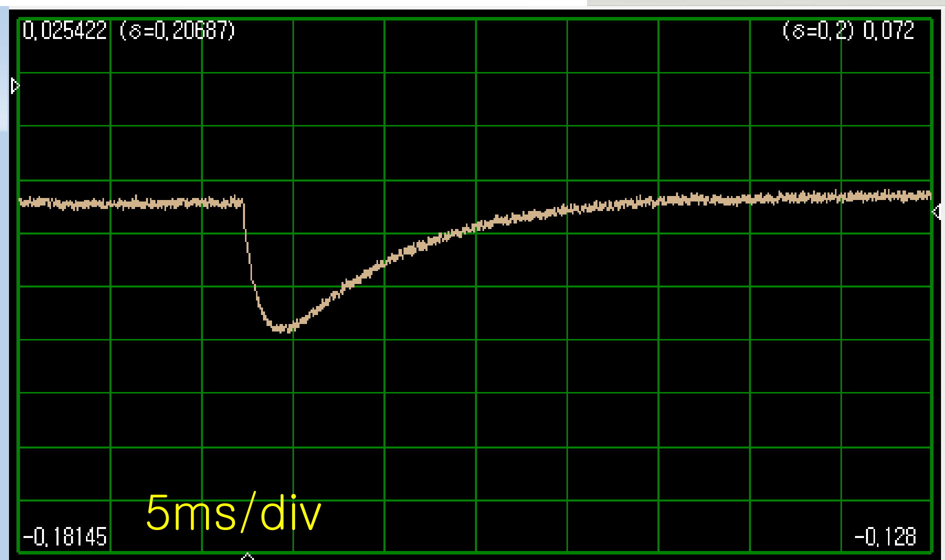
60 cm³ CMO
C = 0.17 nJ/K at 10 mK
1.4 nJ/K at 20 mK



4cm x 4 cm

Measurements in progress.

Toward the full scale experiment!



SUMMARY

- AMoRE : collaboration for DBD search with CaMoO4
- Large volume $^{40}Ca^{100}MoO_4$ crystals of high quality
  - ~ 0.85 kg crystal made of enriched material at Y2L
  - Existence of ~30 kg depleted Ca
- Pilot experiment of ~ 1 kg with scintillation technique

  + CsI(Tl) active veto is in preparation
- Development of cryogenic CaMoO4 detector
  - 2g crystal with MMC sensor – demonstrated the principle
  - > 200 g crystal setup in progress
- 100kg CaMoO4 cryogenic detector: achievable goal
  - ~3 x 10^{26} yrs (~ 0.05 eV)
  - Competitive dark matter search
  - Design of the experiment in progress: geometry, cryostat, simulation,…
  - Included in the National Facility Road Map

Thank you for your attention !

$^{238}U/^{232}Th$ decay chains