



Underground Experimental Program in Korea

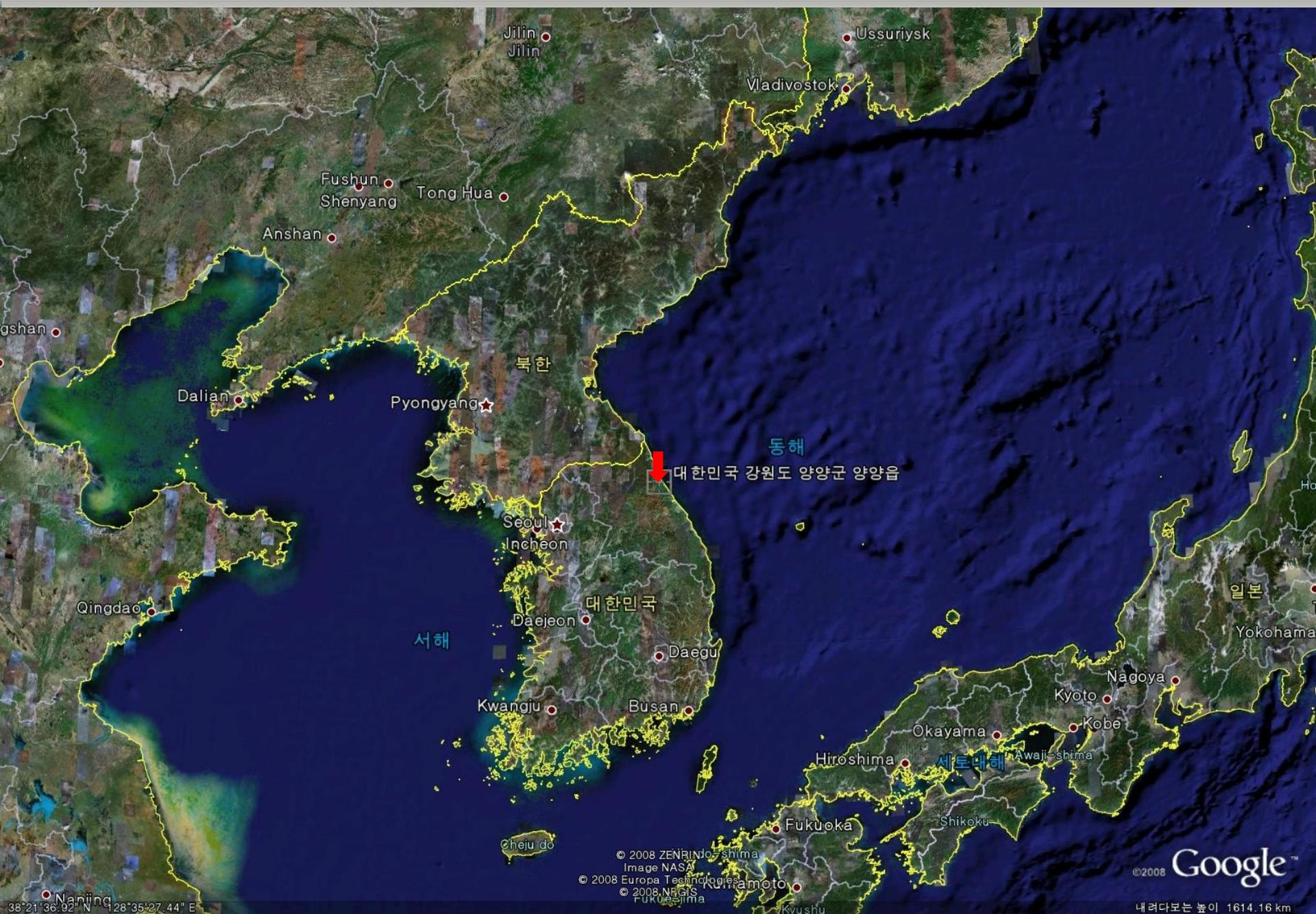
Sun Kee Kim
Seoul National University

ASPERA workshop, Zaragoza

Outline

- 
- **Y2L (*Yang Yang Underground Laboratory*)**
 - **KIMS (*Korea Invisible Mass Search*)**
 - Dark matter search with CsI(Tl) crystals*
 - Double beta decay search activities*
 - **AMoRE (*Advanced Molybdenum based Rare process Experiment*)**
 - *Development of CaMoO₄ crystals*
 - *Development of cryogenic detector with the CaMoO₄ crystal*
 - *Prospects*

Yangyang Underground Laboratory(Y2L)



Yangyang Underground Laboratory

(Upper Dam)

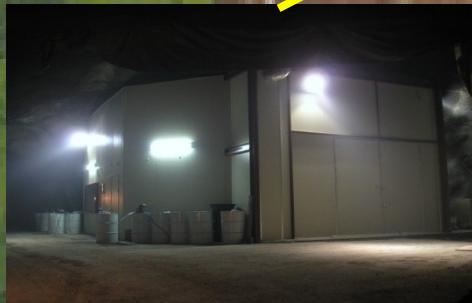
Yangyang Pumped Storage Power Plant

Korea Middleland Power Co.
→ Korea Hydro and Nuclear Power Co.

700m

(Power Plant)

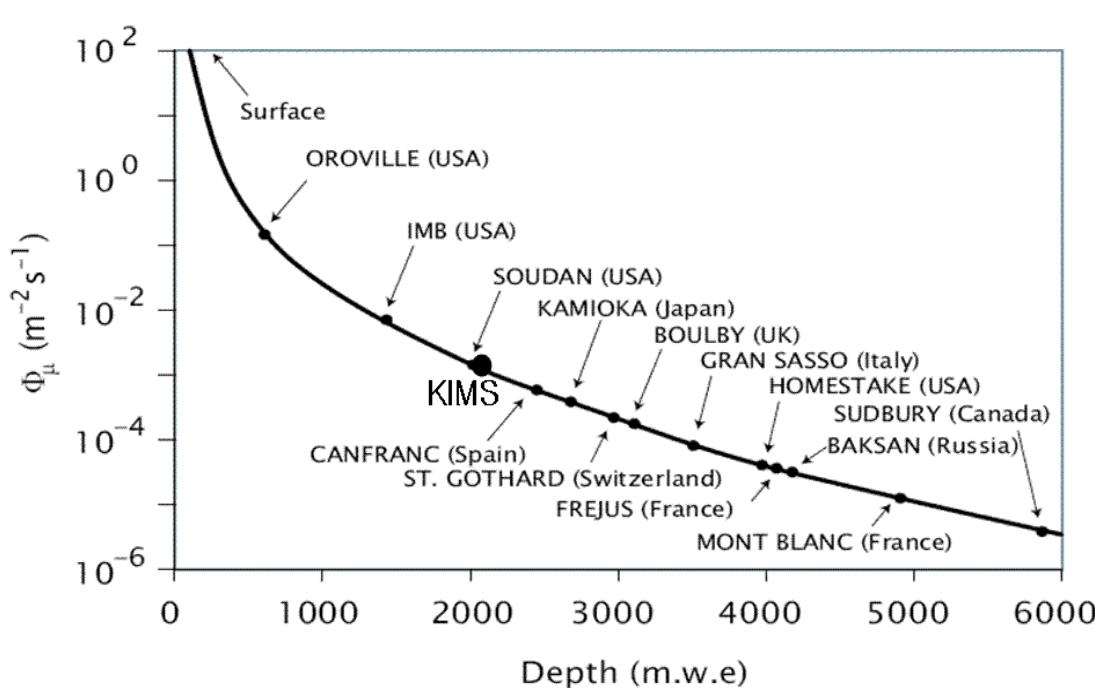
(Lower Dam)



양양양수발전소

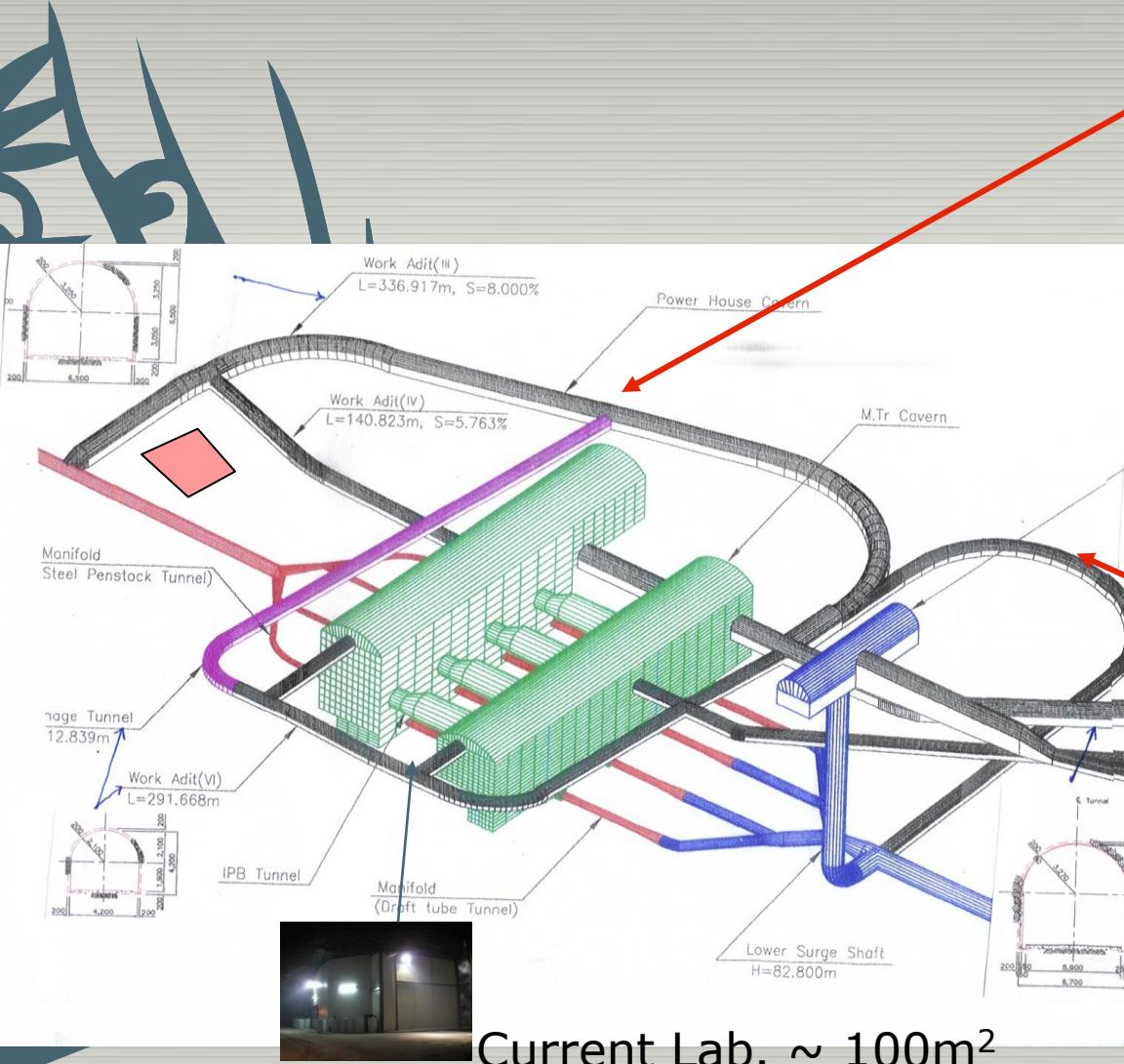
Vertical depth : 700 m / Access to the lab by car (~2km)
Constructed in 2003

Environment Parameters in Y2L

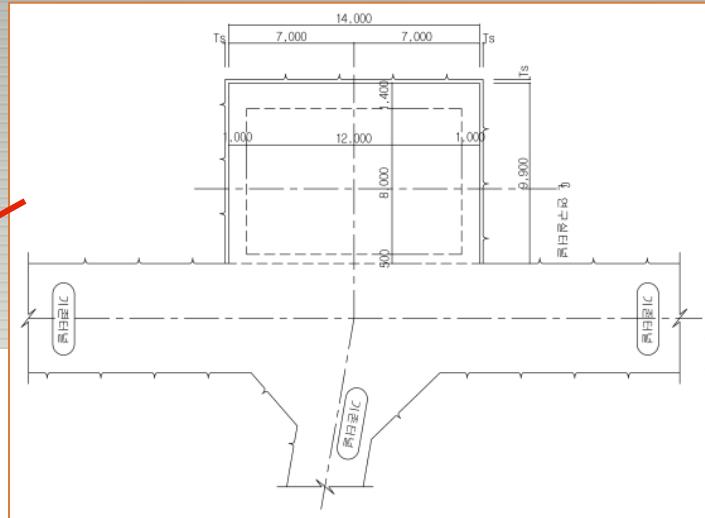


Depth	Minimum 700 m
Temperature	20 ~ 25 °C
Humidity	35 ~ 60 %
Rock contents	^{238}U less than 0.5 ppm ^{232}Th 5.6 ± 2.6 ppm ^{40}K 270 ppm
Muon flux	$2.7 \times 10^{-7} / \text{cm}^2/\text{s}$
Neutron flux	$8 \times 10^{-7} / \text{cm}^2/\text{s}$
^{222}Rn in air	1~2 pCi/liter

Underground Lab. Space



Current Lab. $\sim 100\text{m}^2$



New Lab. Space
under discussion
with KHNPC



KIMS(Korea Invisible Mass Search) WIMP search with CsI(Tl) Crystals

Easy to get large mass with an affordable cost

→ Good for AM study

High light yield $\sim 60,000/\text{MeV}$

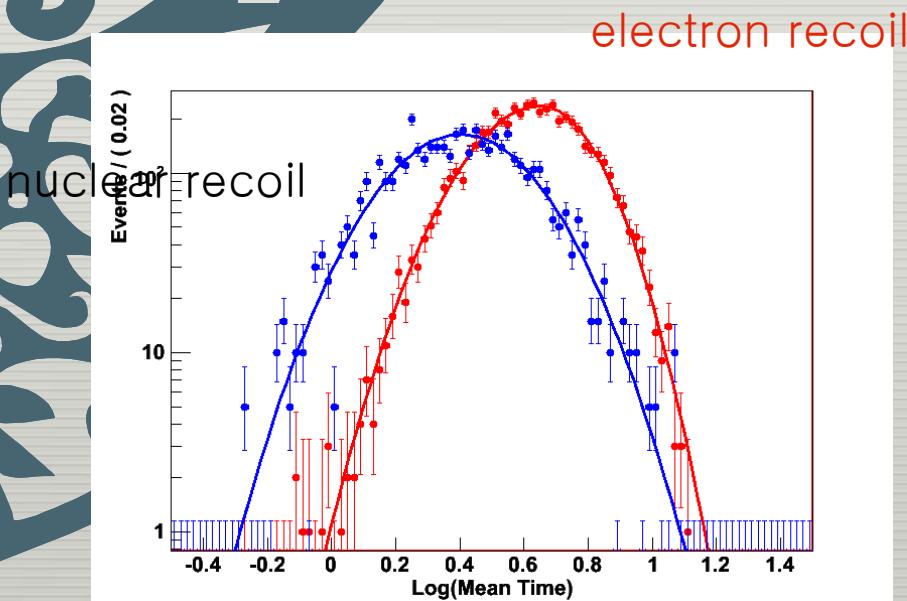
Pulse shape discrimination

→ Moderate background rejection

Easy fabrication and handling

Cs-133, I-127 (SI cross section $\sim A^2$)

Both Cs-133, I-127 are sensitive to SD interaction



Isotope	J	Abun	<Sp>	<Sn>
^{133}Cs	7/2	100%	-0.370	0.003
^{127}I	5/2	100%	0.309	0.075
^{73}Ge	9/2	7.8%	0.03	0.38
^{129}Xe	1/2	26%	0.028	0.359
^{131}Xe	3/2	21%	-0.009	-0.227

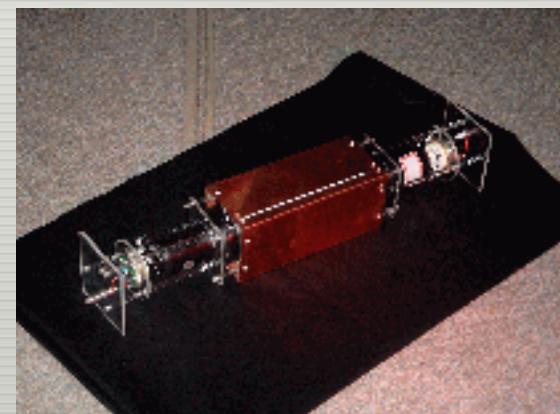
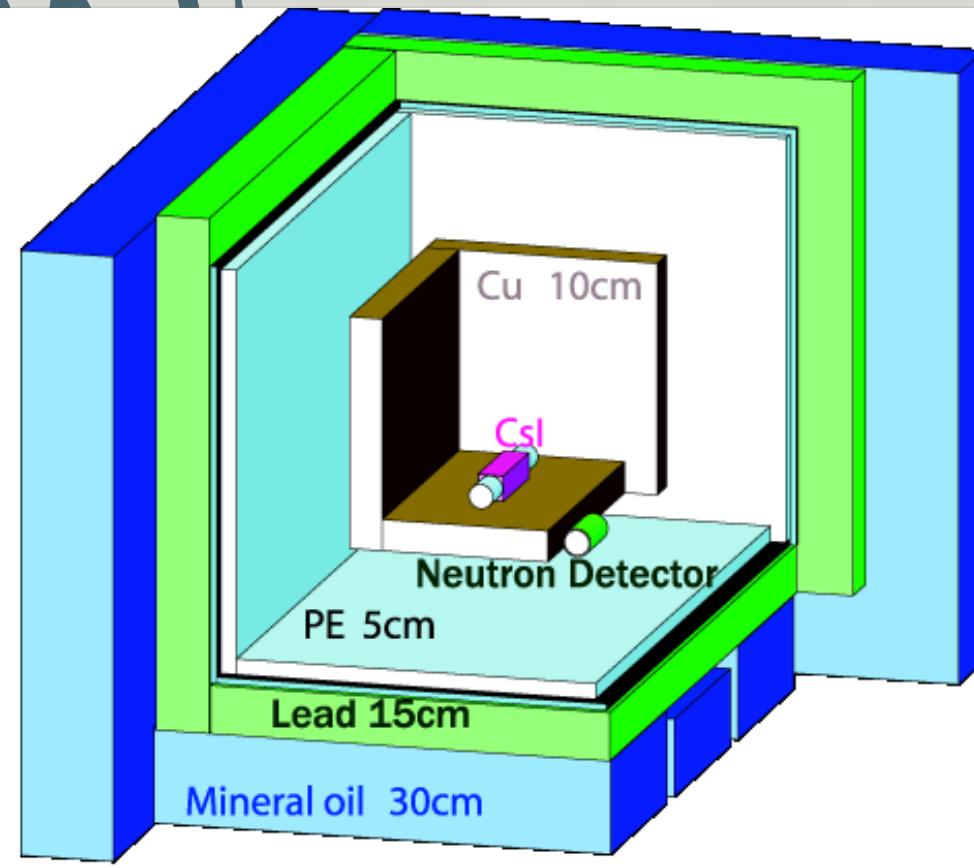
KIMS(Korea Invisible Mass Search)

DM search experiment with CsI crystal

CsI(Tl) Crystal 8x8x30 cm³ (8.7 kg)

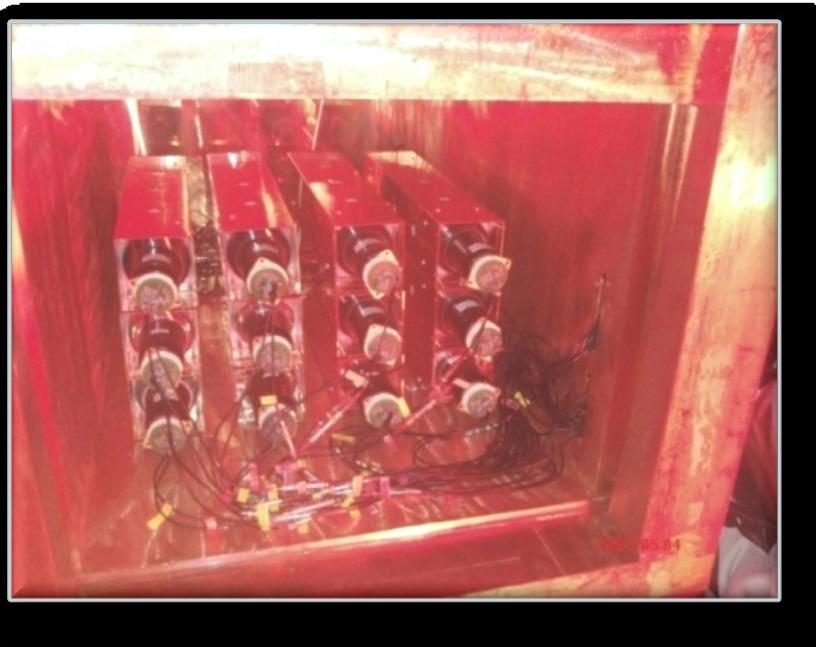
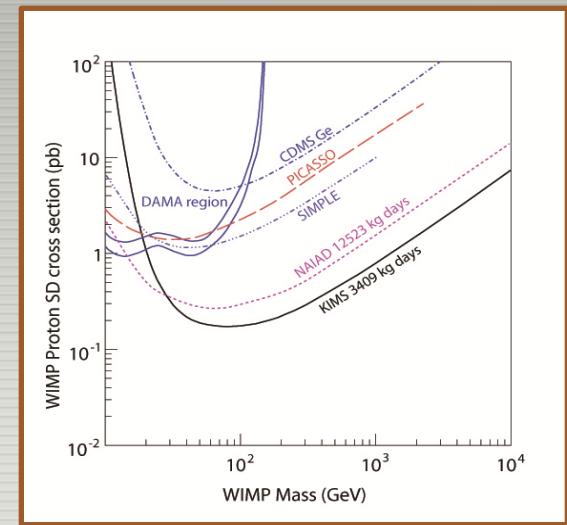
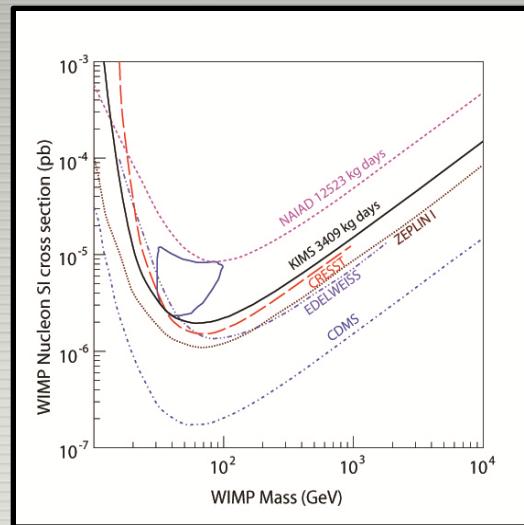
3" PMT (9269QA) : Quartz window, RbCs photo cathode

~5 Photo-electron/keV



*PR*L 99, 091301 (2007)

4 crystals, ~ 2months



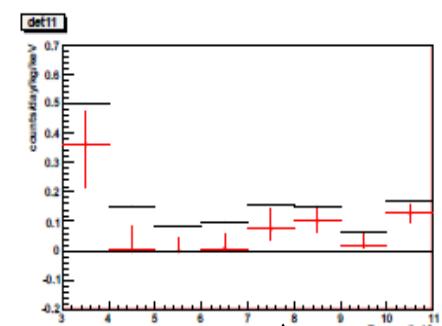
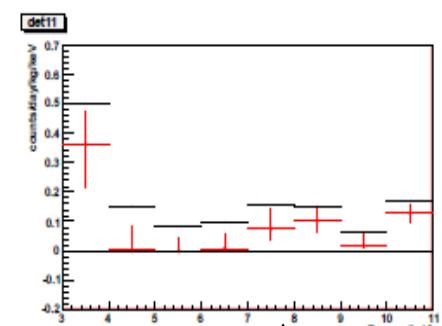
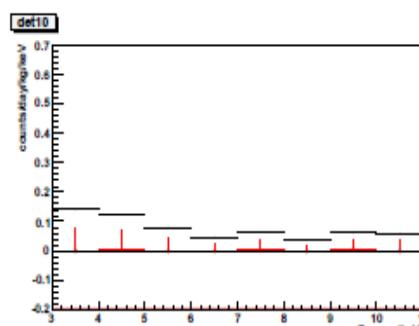
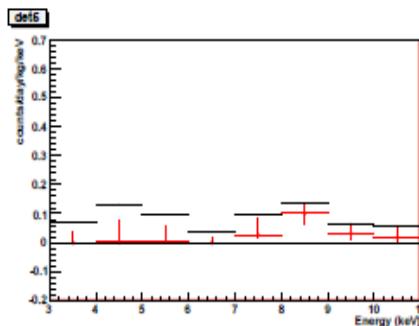
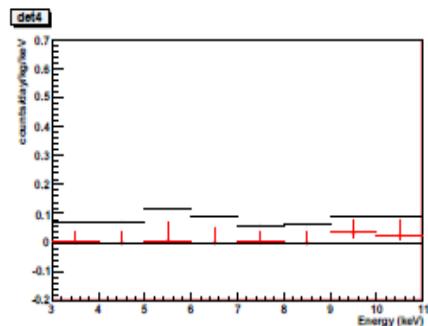
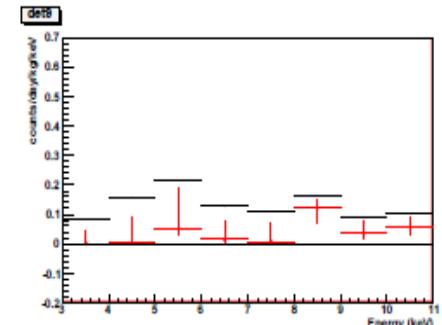
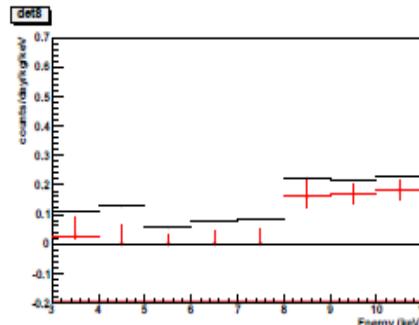
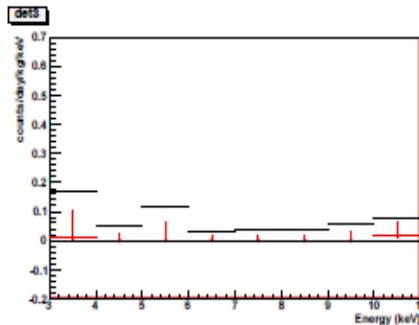
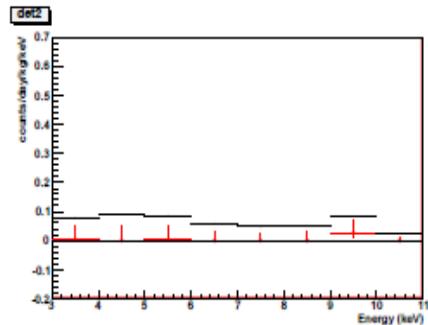
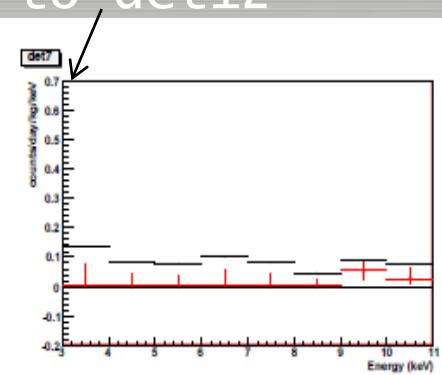
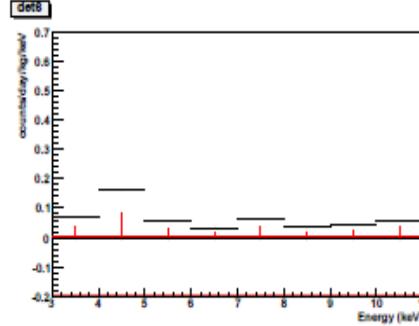
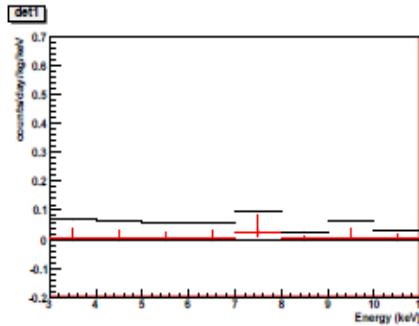
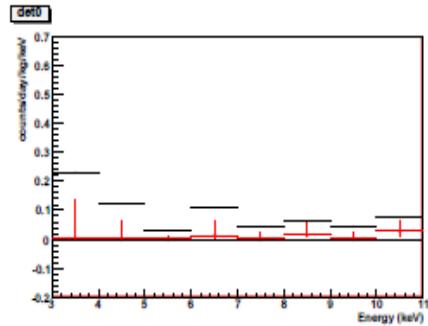
Data taking with 12 crystals

12 crystals(104.4kg) running (from 2008)
• Stable data taking for more than a year
• Unique experiment to test DAMA annual modulation

New result on WIMP search (PSD analysis) - Preliminary

NR events rate for det0 to det12

Counts/day/kg/keV



Bayesian method
-90% limit
-68% interval

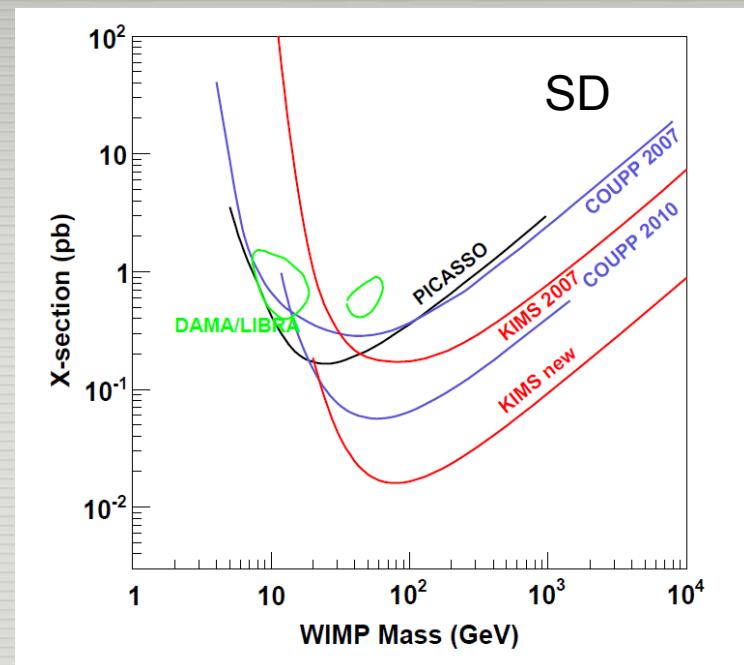
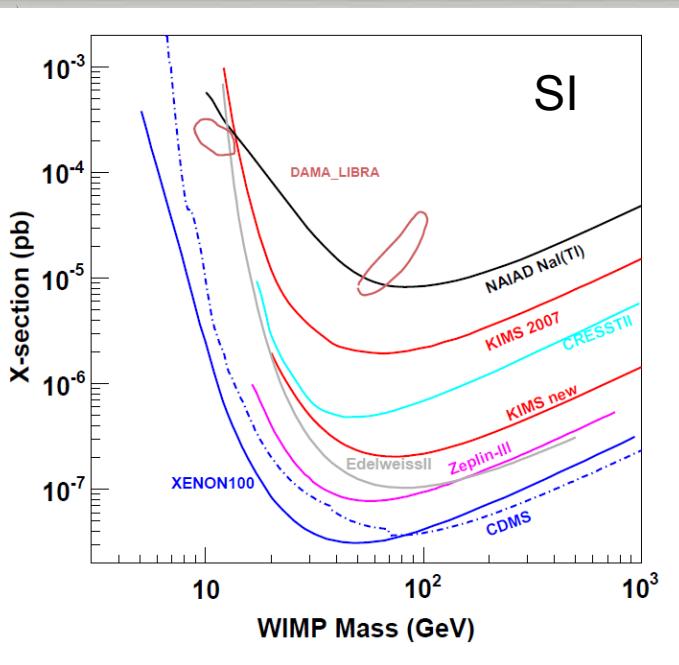
~ 1 year data

3-11 keV

10

New result on WIMP search (PSD analysis) - Preliminary

~ 1 year data, Total exposure: 32793 kg days

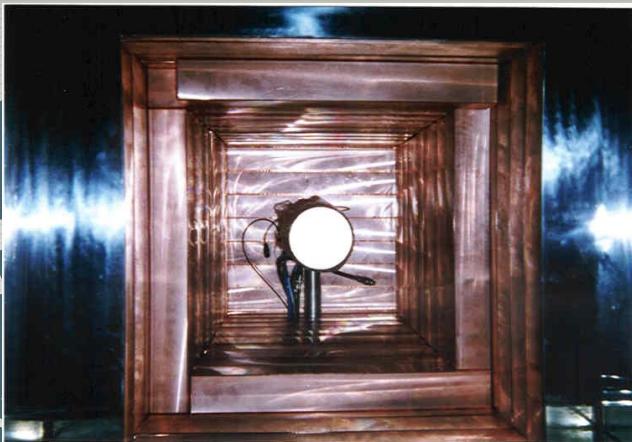


AM analysis after full 2 year data collection : ~ end of Aug.

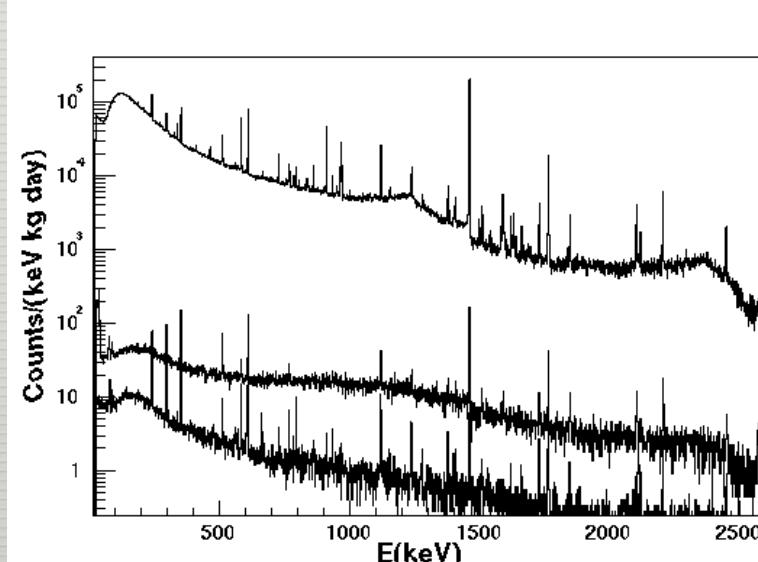
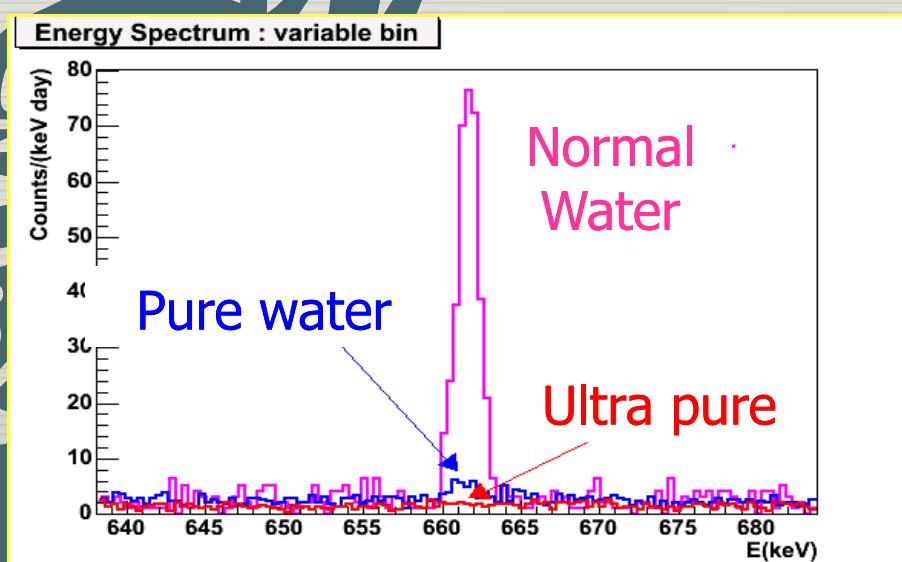
DBD Searches at KIMS

- 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 : $\text{Ca}^{\text{nat}}\text{MoO}_4$ crystal
 - ^{100}Mo 0v $\beta\beta$ decay : $\text{Ca}^{100}\text{MoO}_4$ crystal → AMoRE

HPGe at Y2L



- HPGe : 100% efficiency
- Shielding : 5 cm OFHC Cu + 15 cm Pb + N₂ gas flowing
- Low background measurement,
Double beta decay search



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

H.J.Kim et al., Nucl. Phys. A 793 (2007)

(1.1×10^{19} y) Positive evidence by I.BIKIT et.al,

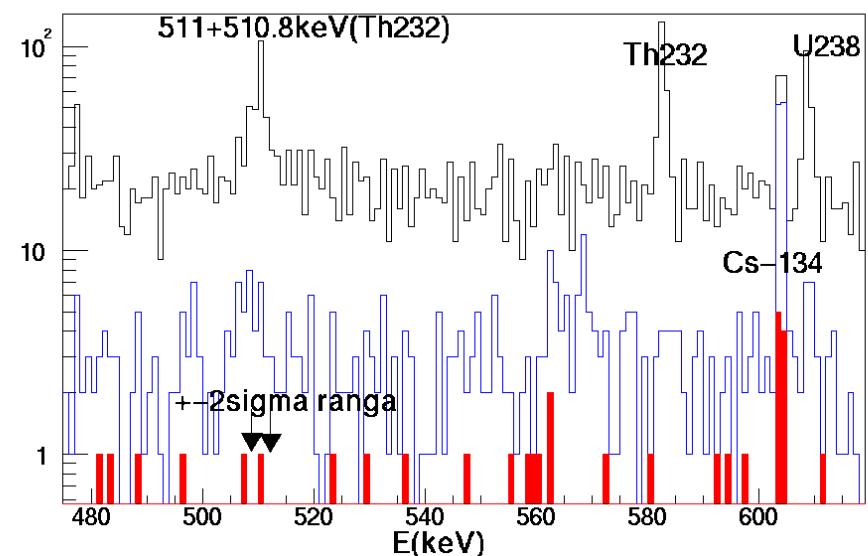
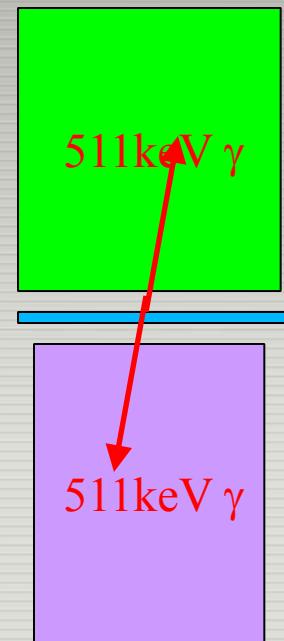
App. Radio. Isot. 46, 455, 1995

<= 25% HPGe + NaI(Tl) with 350g Zn at surface

CsI
7.5x7.5x8

Zn

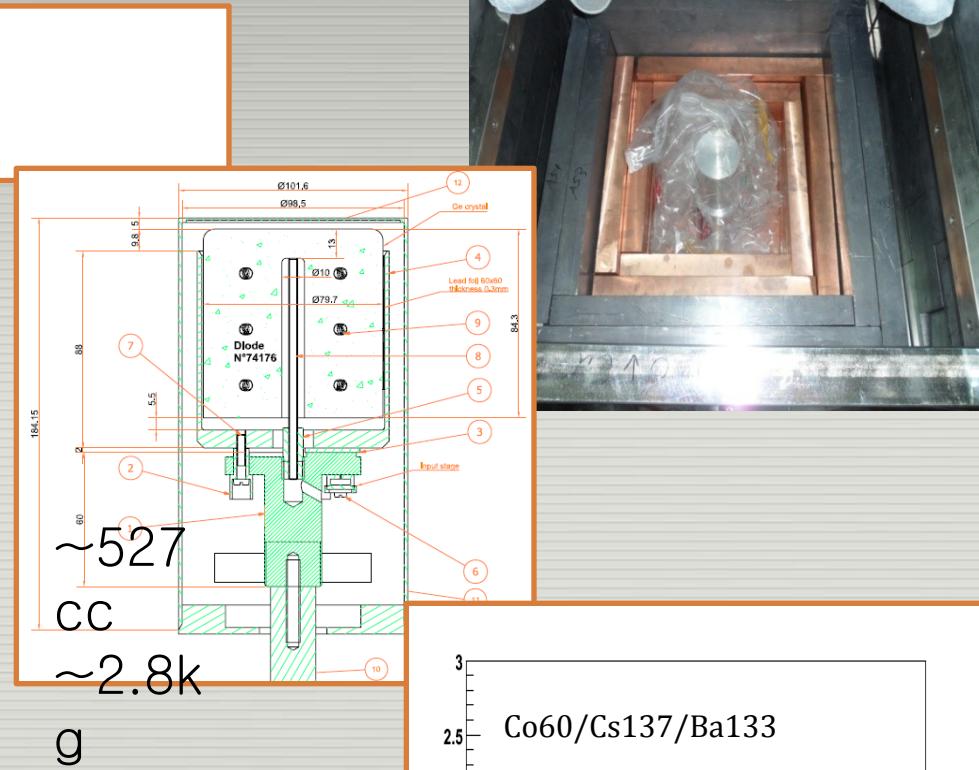
HPGe



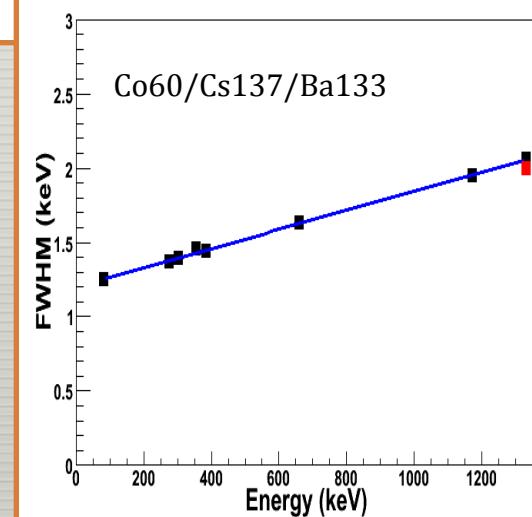
New HPGe detector at Y2L

Will be used for

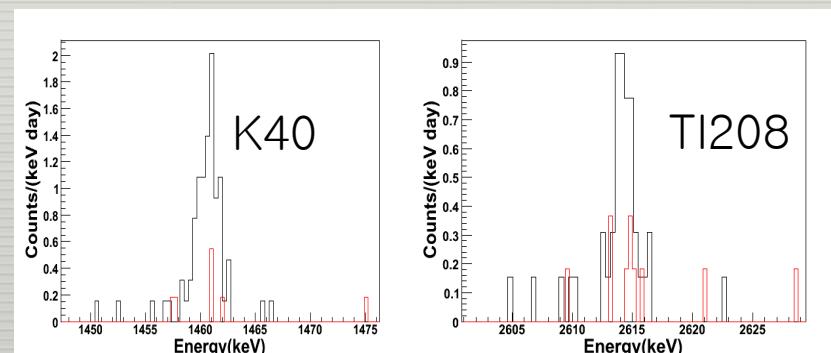
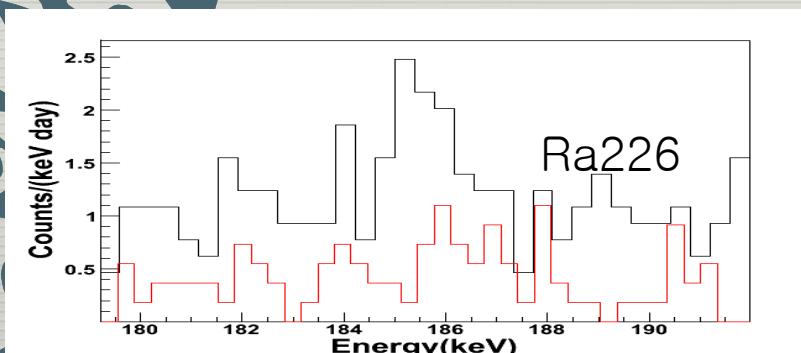
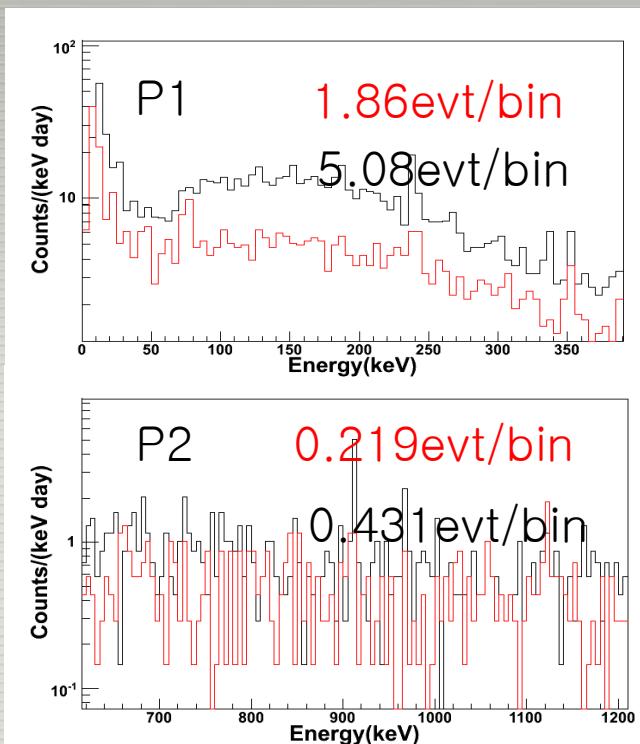
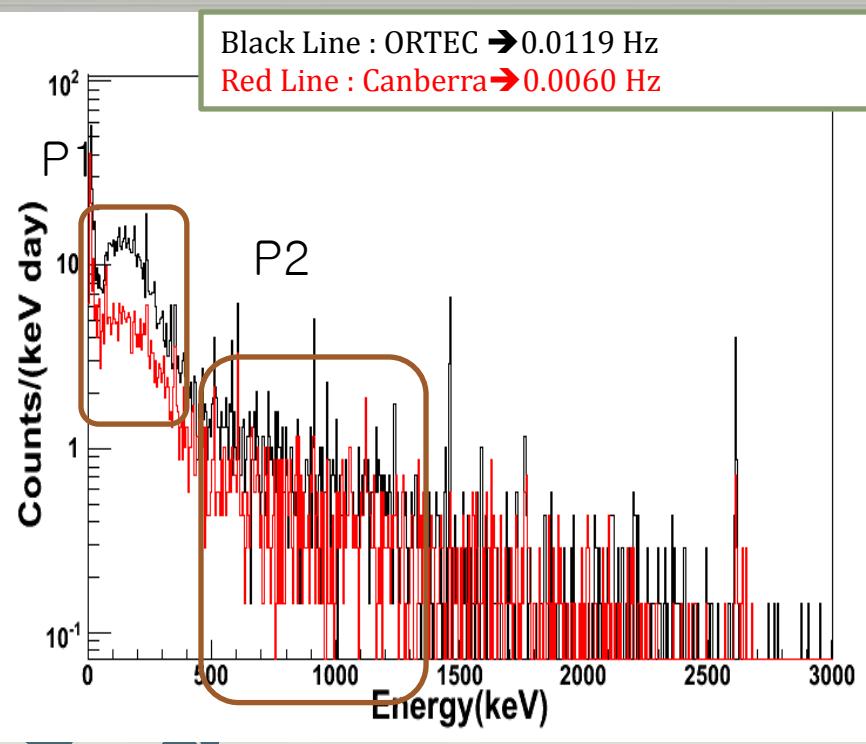
- Measurement of internal background
- DBD search with beta+



Energy
Resolution



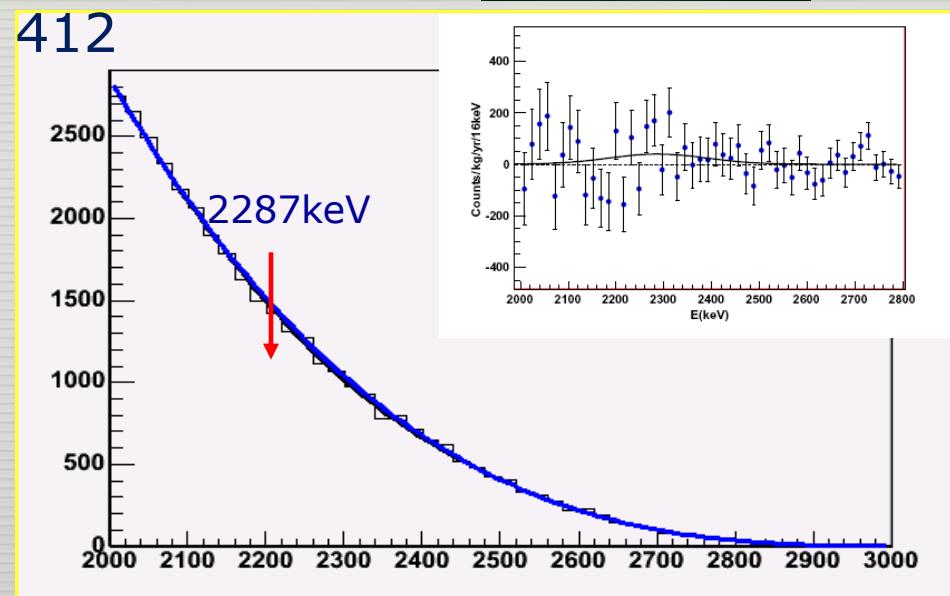
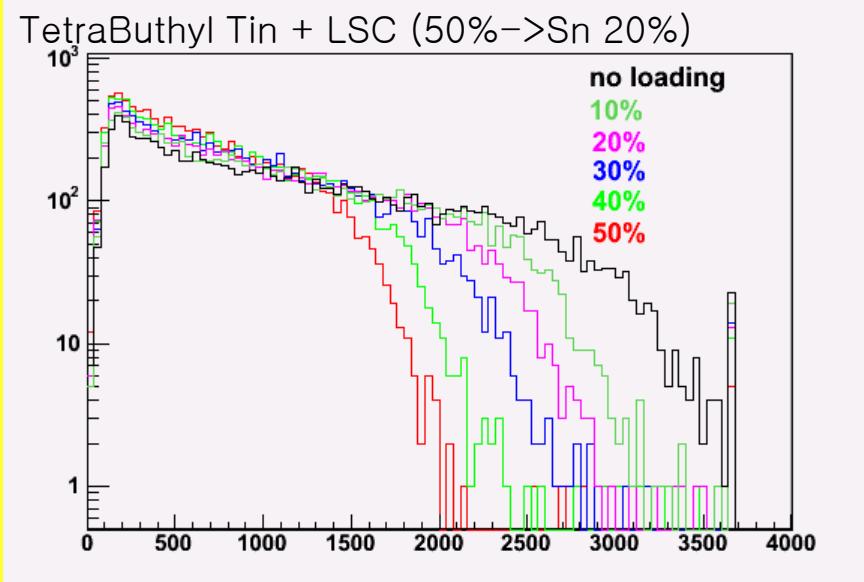
New HPGe detector at Y2L



0ν bb search with Sn-loaded LSC

Double beta decay search with ^{124}Sn
 $Q = 2287 \text{ keV}$
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

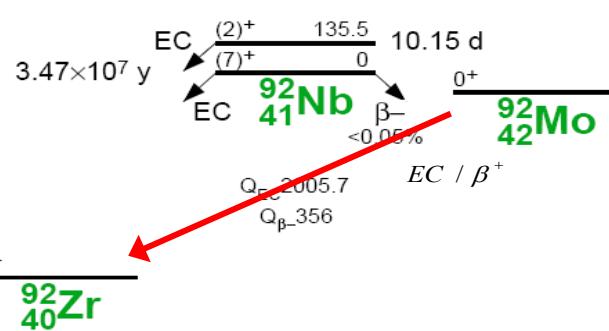


$T_{1/2} > 2.0 \times 10^{19} \text{ yr}$ at 90% C.L

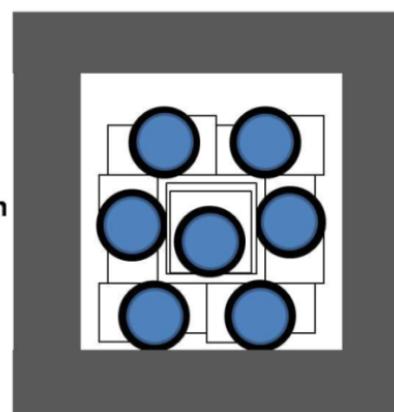
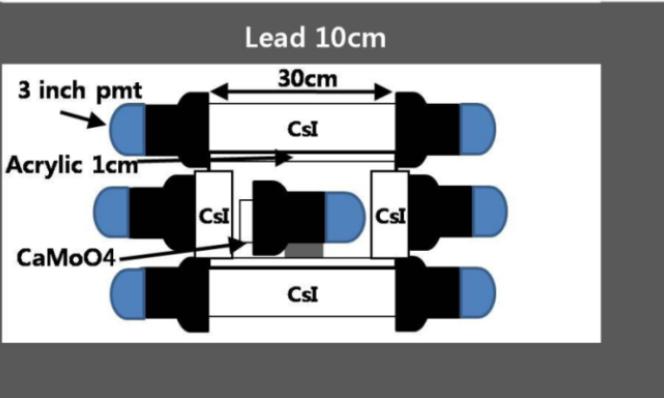
Previous limit:

$T_{1/2} > 2.4 \times 10^{17} \text{ yr}$ at 90% C.L

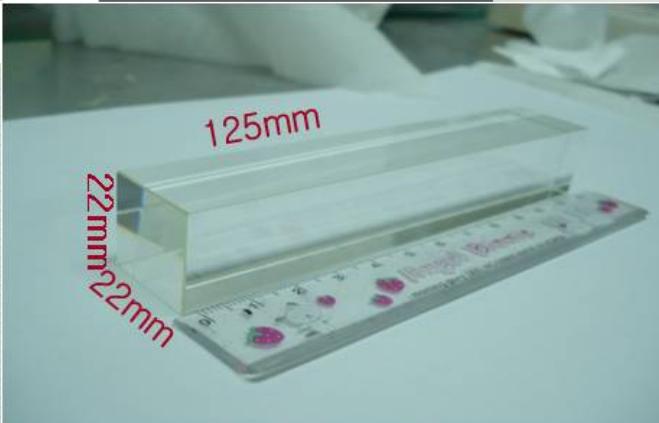
EC/ β^+ decay of ^{92}Mo



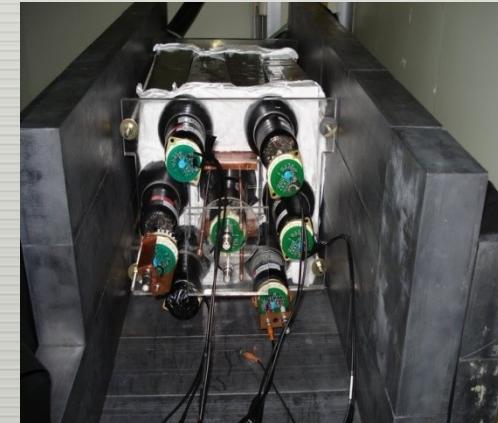
- $(A, Z) + e^- \rightarrow (A, Z-2) + e^+ + 628\text{keV}(Q\text{-value})$
- e^+ stops in active(CaMoO_4) Crystal.
- back to back 511 keV gammas at CsI(Tl)
- Abundance = ^{92}Mo : 14.84%, ^{100}Mo : 9.63%



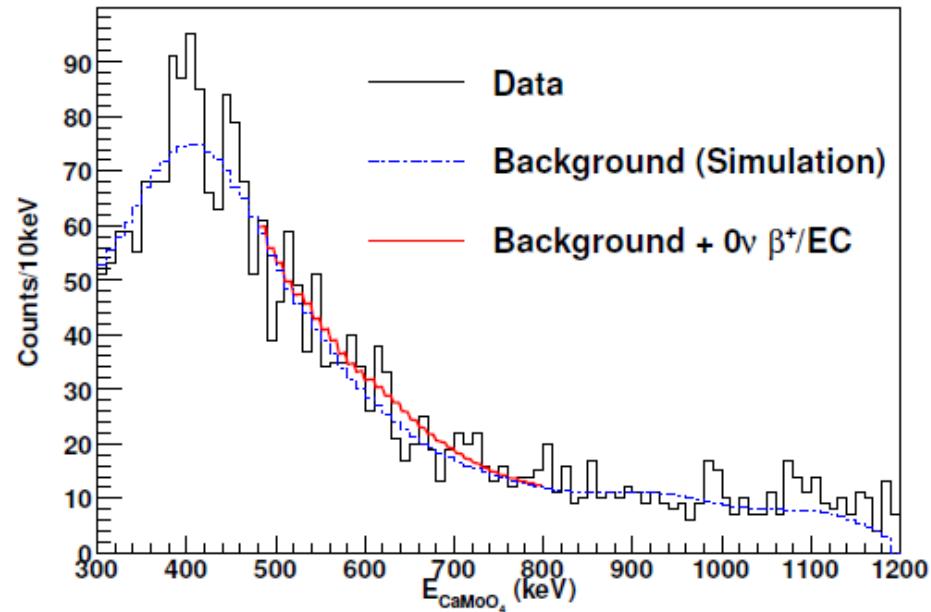
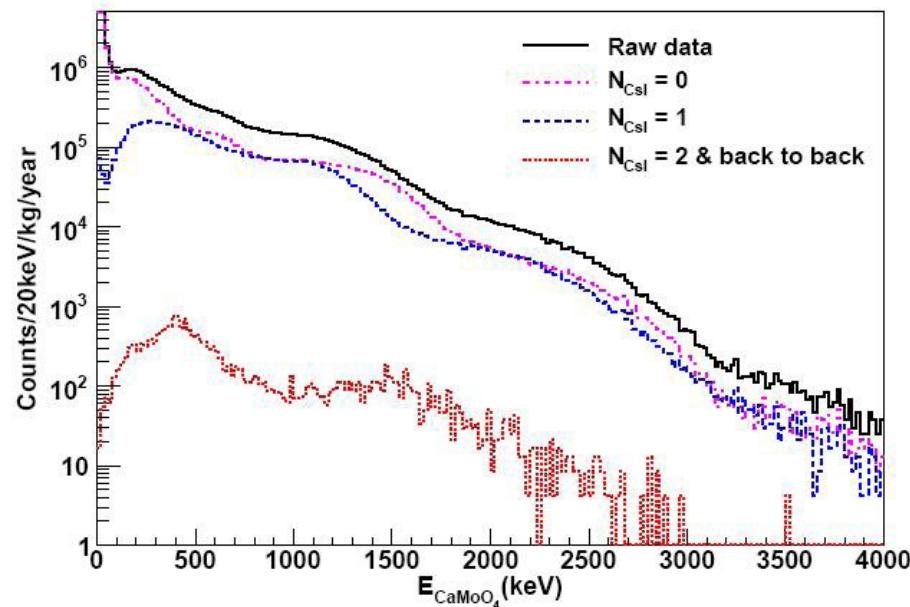
4pi coverage by CsI(Tl)
crystal (not high radiopurity)



CaMoO_4 crystal :
2.2x2.2x6cm (2) : 255g



Mo-92 EC



44.1 events at 90 % confidence level

$> 2.3 \times 10^{20}$ years at 90 % confidence level

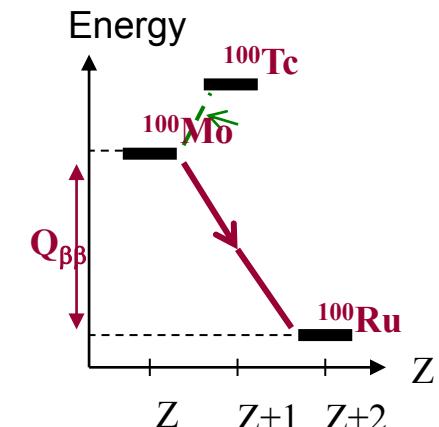
$> 1.9 \times 10^{20}$ years by Barabash et al.,

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

CaMoO₄ for 0νββ

CaMoO₄

- DBD for Mo-100 (3034 keV), Ca-48(4272 keV)
high energy → less background
- Mo-100 enrichment >90% not so difficult
- for Mo-100 search, Ca-48 needs to be depleted
- Scintillator
 - At room temp; 10-20% of CsI(Tl) at 20°
 - 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



Korea(2003)



Ukraine-CARAT(2006)



Russia(2006)



Russia (2007)



30x30x200mm

Crystal Characteristics

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

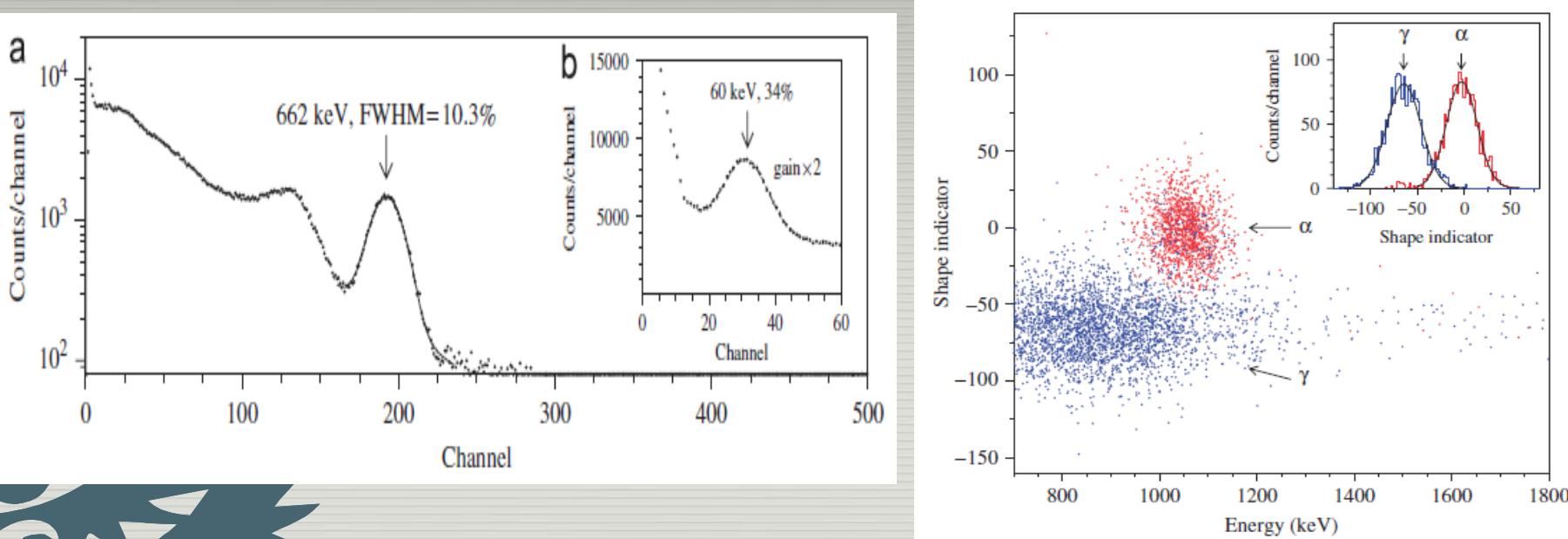


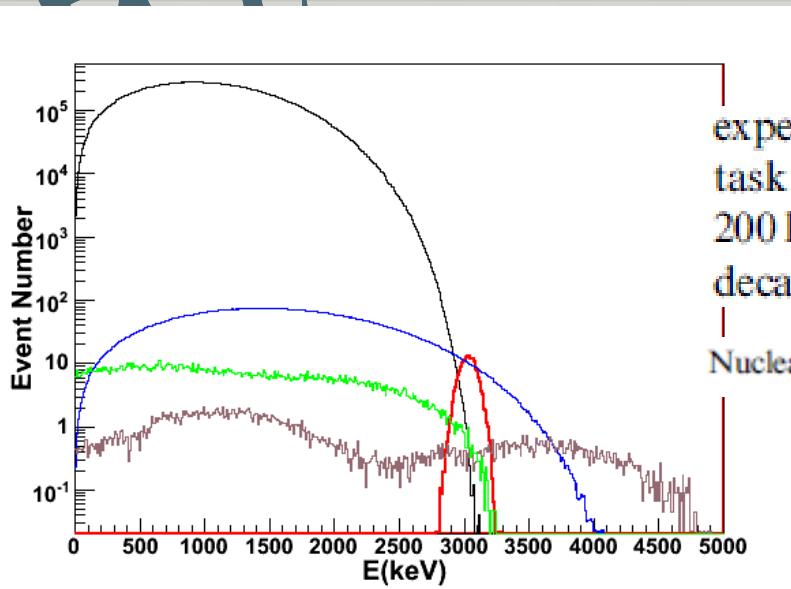
Table 4
Radioactive contaminations in CaMoO_4 , CaWO_4 , and CdWO_4 crystal scintillators

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

Enrichment & Depletion

Mo-100 enrichment : 96.1%

Ca-48 depletion < 0.001% (Natural 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
→ Good for 100 kg CaMooO₄ crystals

^{48}Ca Enrichment/Depletion at KAERI

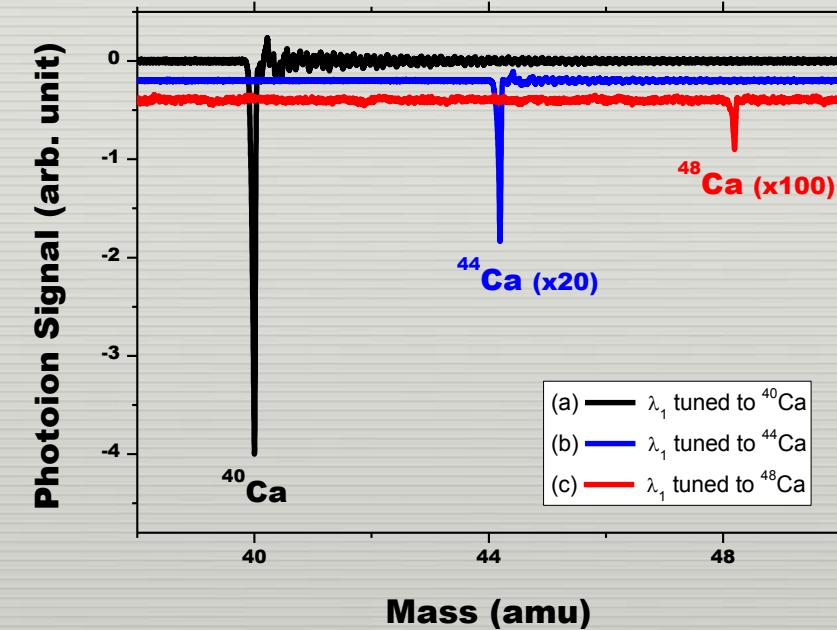
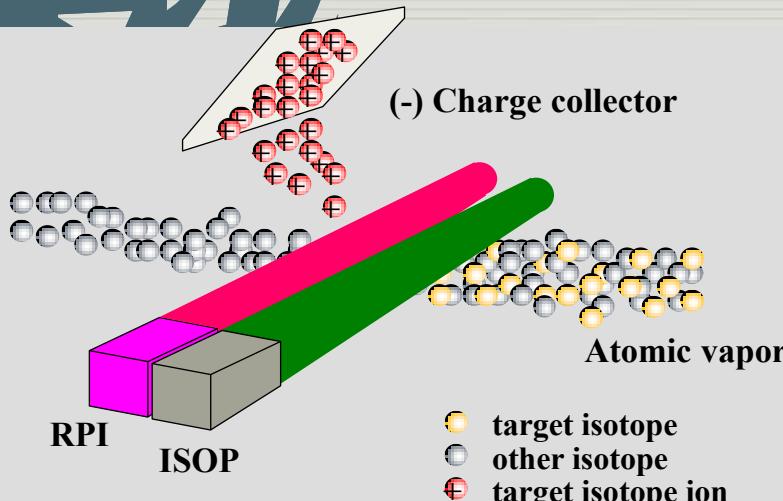
(Korea Atomic Energy Research Institute)

ALSIS (Advanced Laser Stable Isotope Separation)

- Features : Isotope-Selective Optical Pumping (ISOP)

- followed by Non-selective Resonant Photoionization (RPI)

- ISOP gives good isotope-selectivity and non-selective RPI high yield.



^{48}Ca Enrichment/Depletion at KAERI

- ◆ Special features of ALSIS
 - Isotope-selective optical pumping
 - followed by resonant photo-ionization
 - Ideal for ^{48}Ca Production
 - Fiber-based lasers : most advanced, maintenance-free
- ◆ Engineering Demonstration (2010~2012)
 - Production capability : 1kg/yr
- ◆ Production Demonstration for (2013 – 2014)
 - Production capability : 5 kg/yr

$^{40}\text{Ca}^{100}\text{MoO}_4$

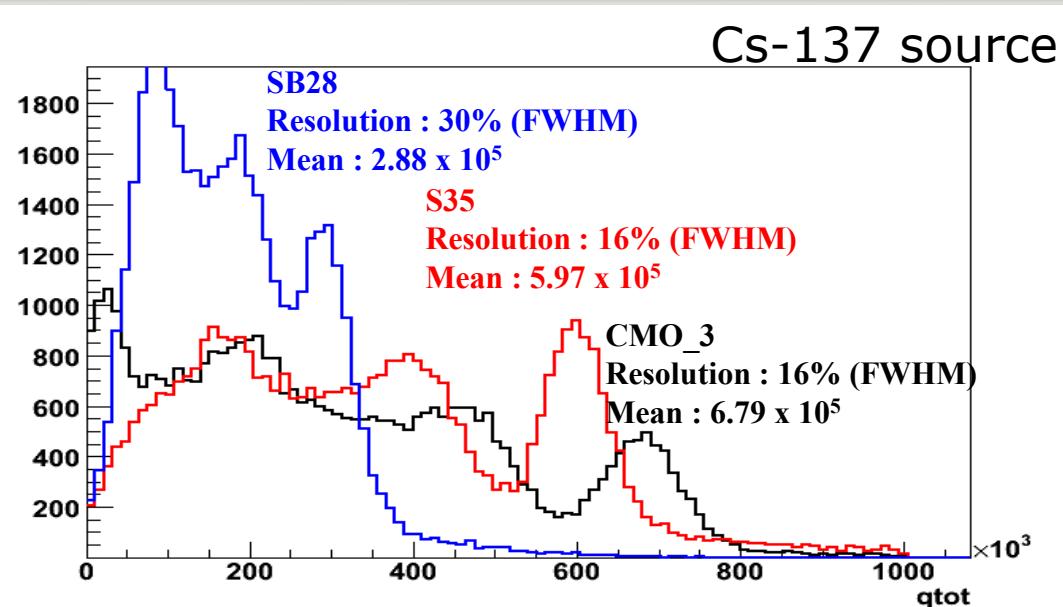
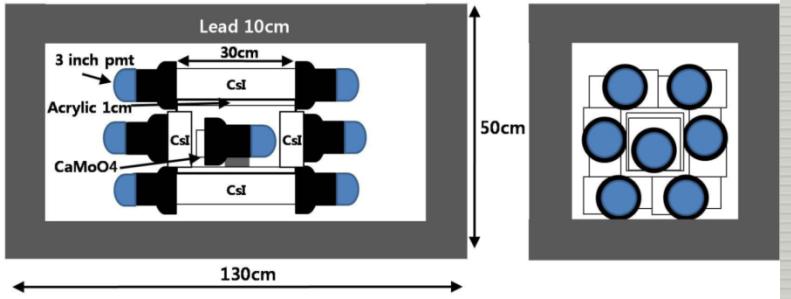
First $^{40}\text{Ca}^{100}\text{MoO}_4$ crystal
after big bang



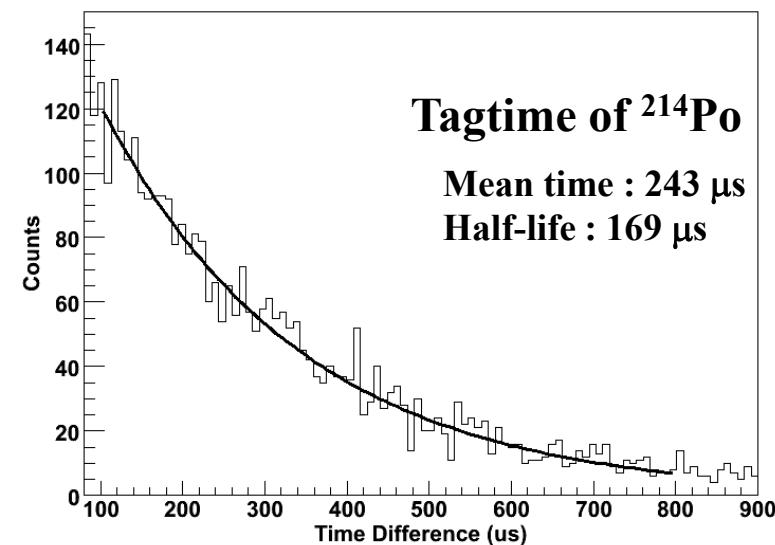
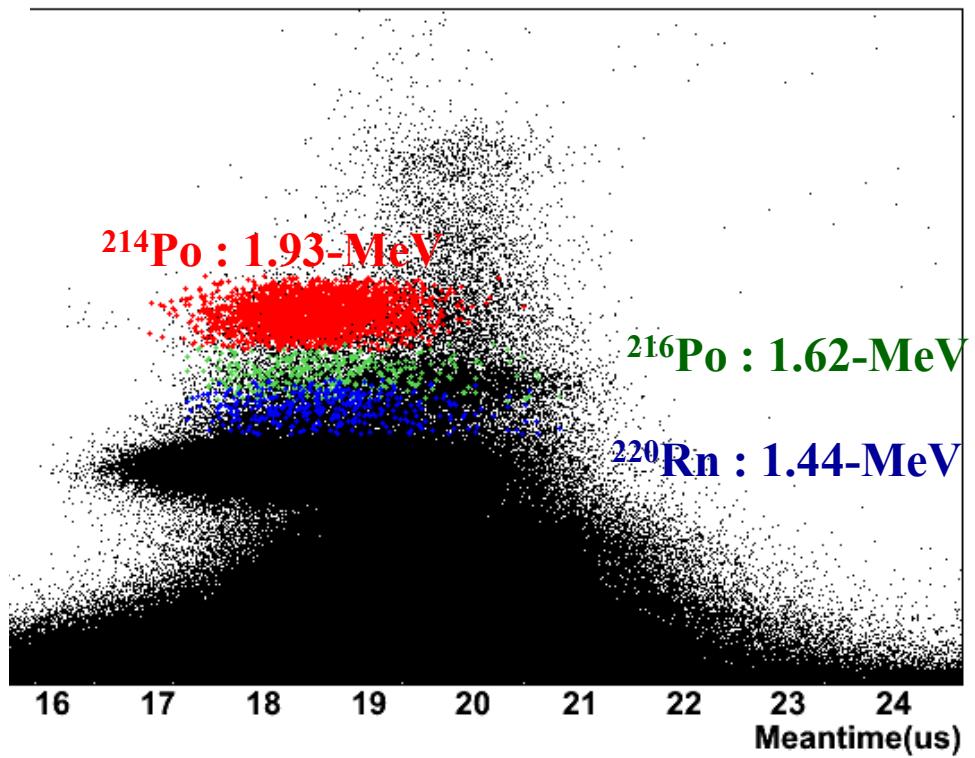
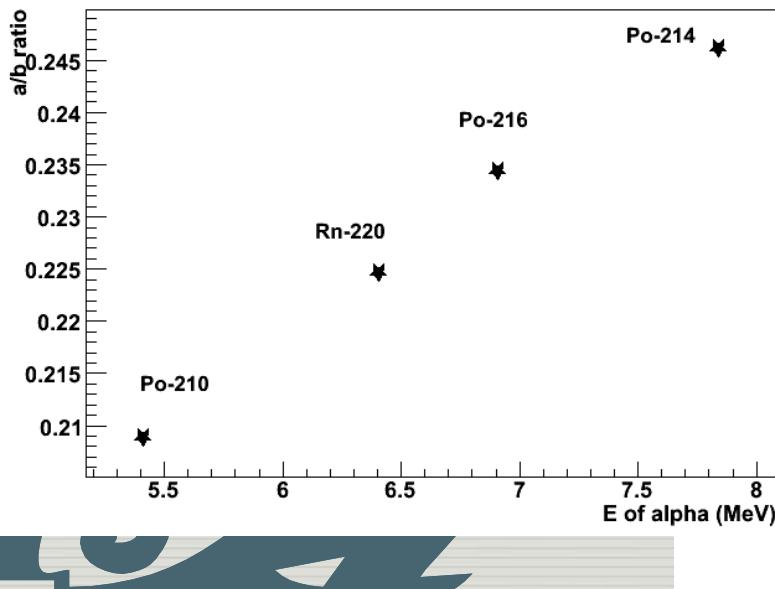
CMO «Z0Y-25»
CaMoO₄ изотопнообогащенный

3 crystals with enriched
material ~ 845g

Being tested at Y2L



Preliminary data analysis



$\beta-\alpha$ decay
 $^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$

α -decay of ^{214}Po
Half life : 164 μs

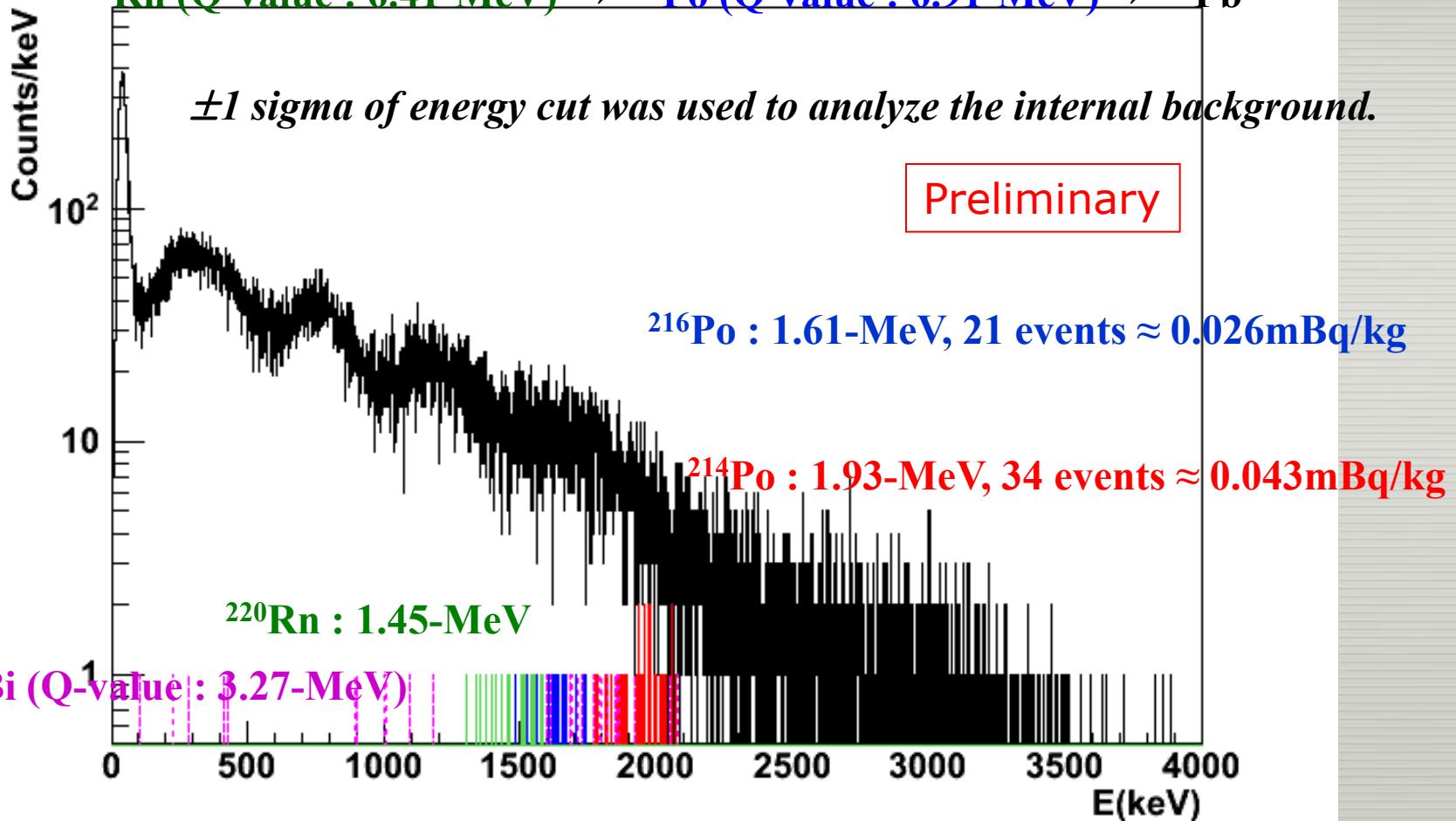
BG spectrum of SB28 with 47 days data

$\beta-\alpha$ decay in ^{238}U

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

$\alpha-\alpha$ decay in ^{232}Th

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

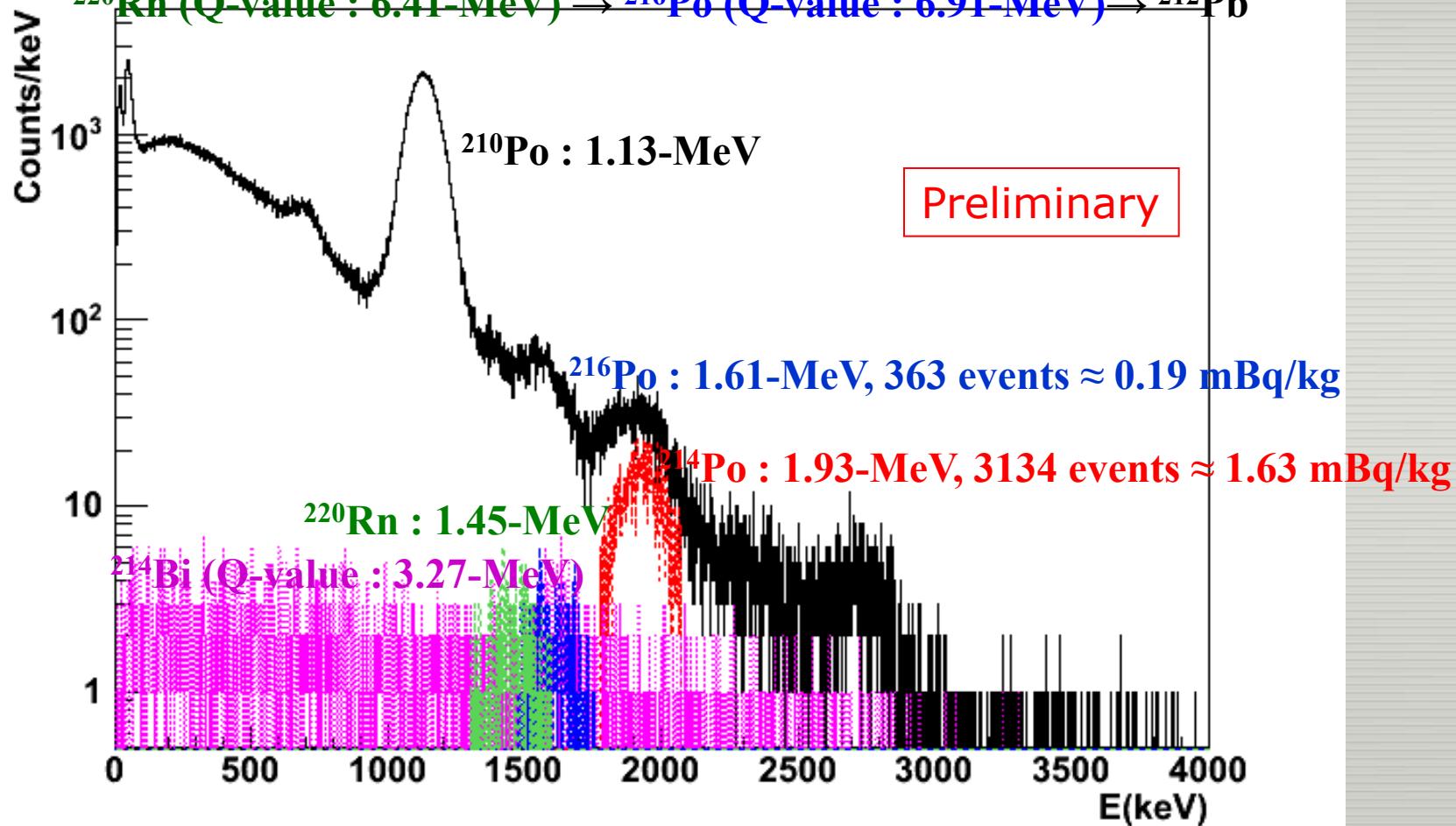
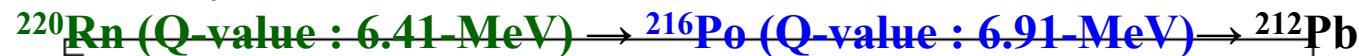


BG spectrum of S35 with 87 days data

$\beta-\alpha$ decay in ^{238}U



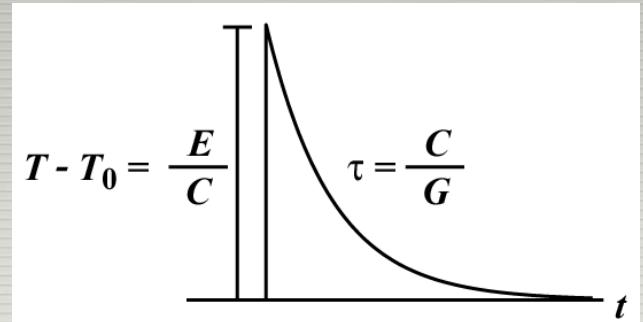
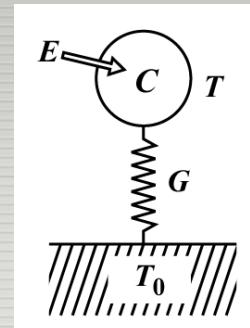
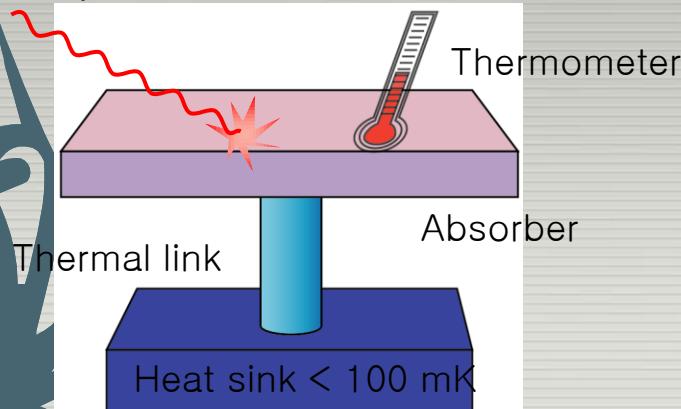
$\alpha-\alpha$ decay in ^{232}Th



Cryogenic Detector

Energy absorption → Heat (Temperature)

α, β, γ , etc.



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

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

Choice of thermometers

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

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

Example

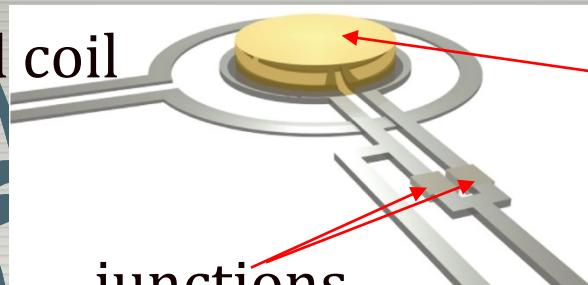
$$T = 0.1 \text{ K}$$

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

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

Metallic Magnetic Calorimeter (MMC)

Field coil



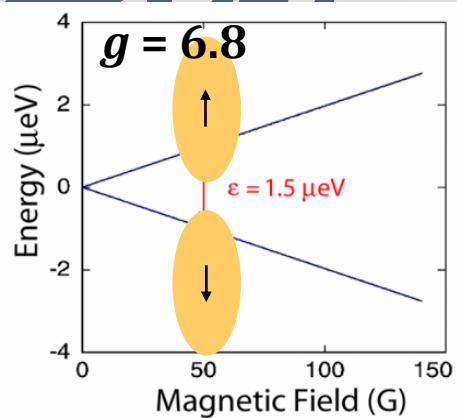
Magnetic material (Au:Er) in dc SQUID

Au:Er(10~1000ppm)

paramagnetic system

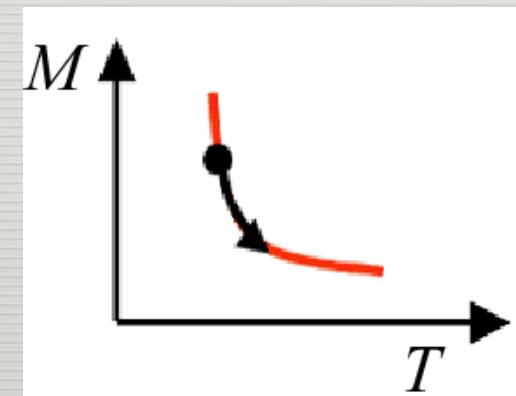
metallic host: fast thermalization ($\sim 1\text{ms}$)

Can control heat capacity by magnetic field



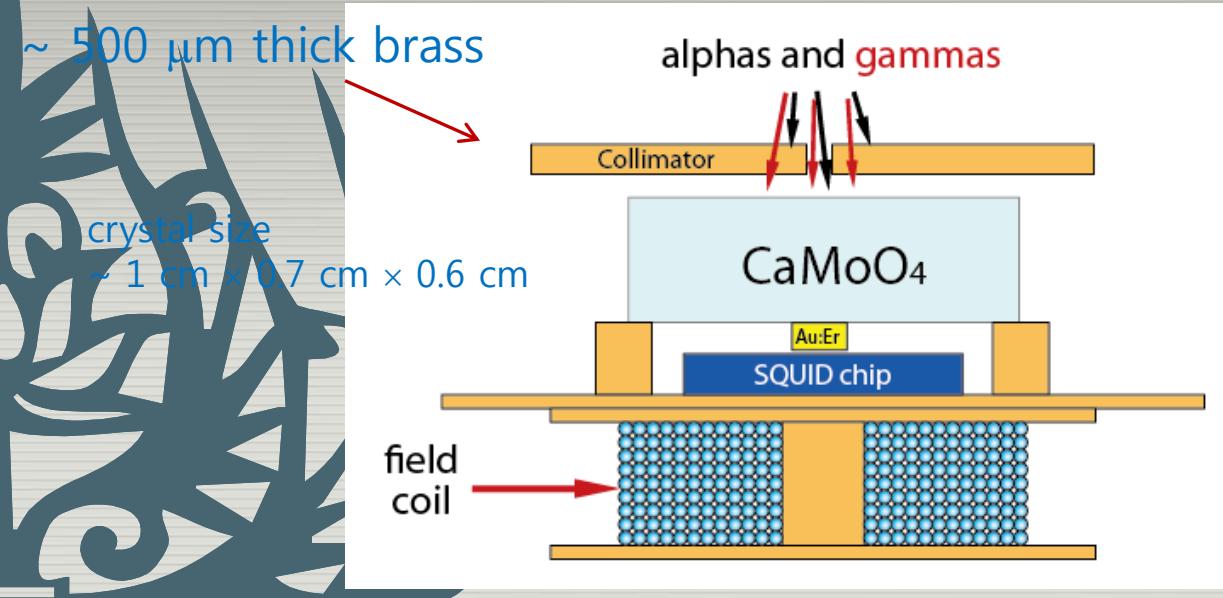
$$5 \text{ mT} \rightarrow \Delta\epsilon = 1.5 \mu\text{eV}$$

$$1 \text{ keV} \rightarrow 10^9 \text{ spin flips}$$

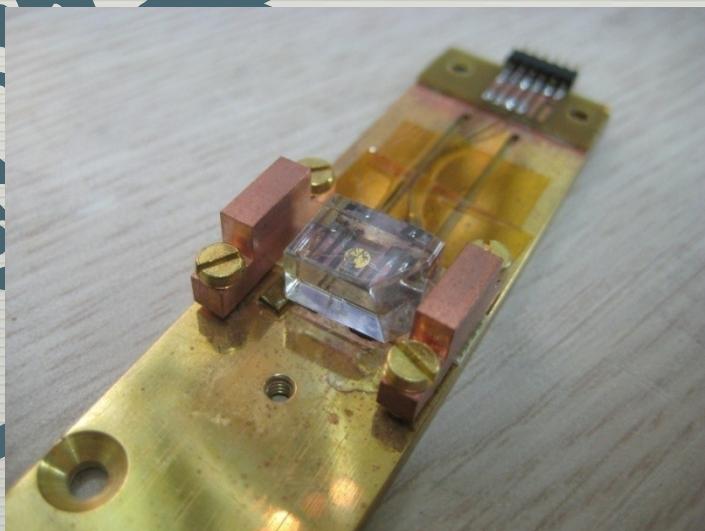


- **Fast**
- **Wide working temperature**
- **Absorber friendly**

Experimental setup at KRISS with MMC to measure temperature changes

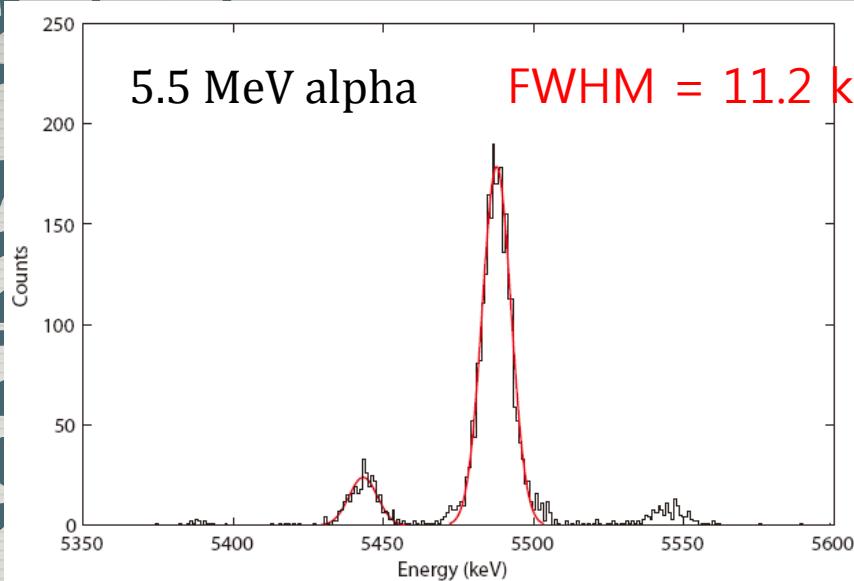


base temperature : 13 ~ 100 mK

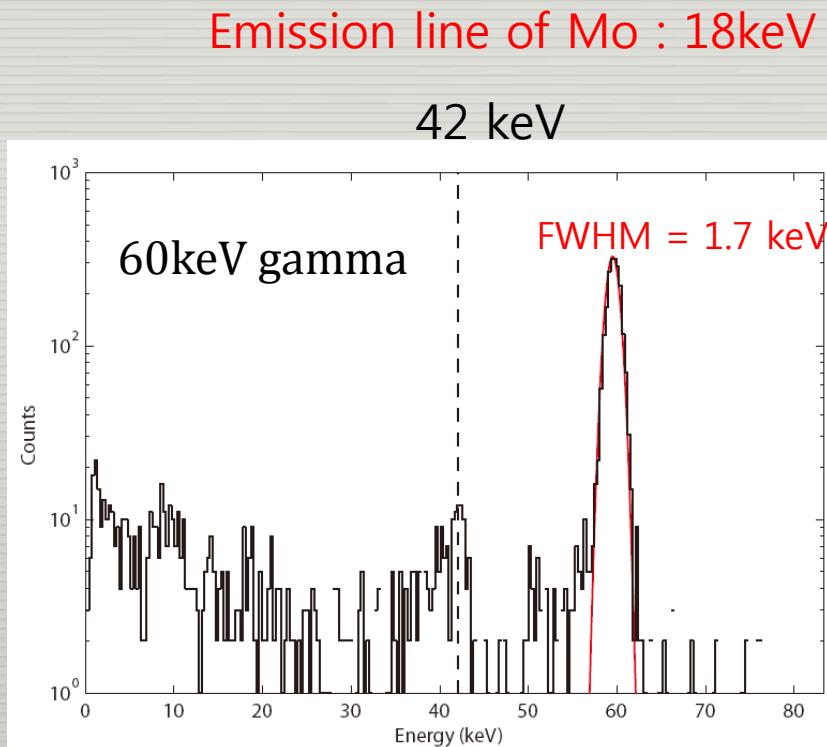


Performance of CMO+MMC

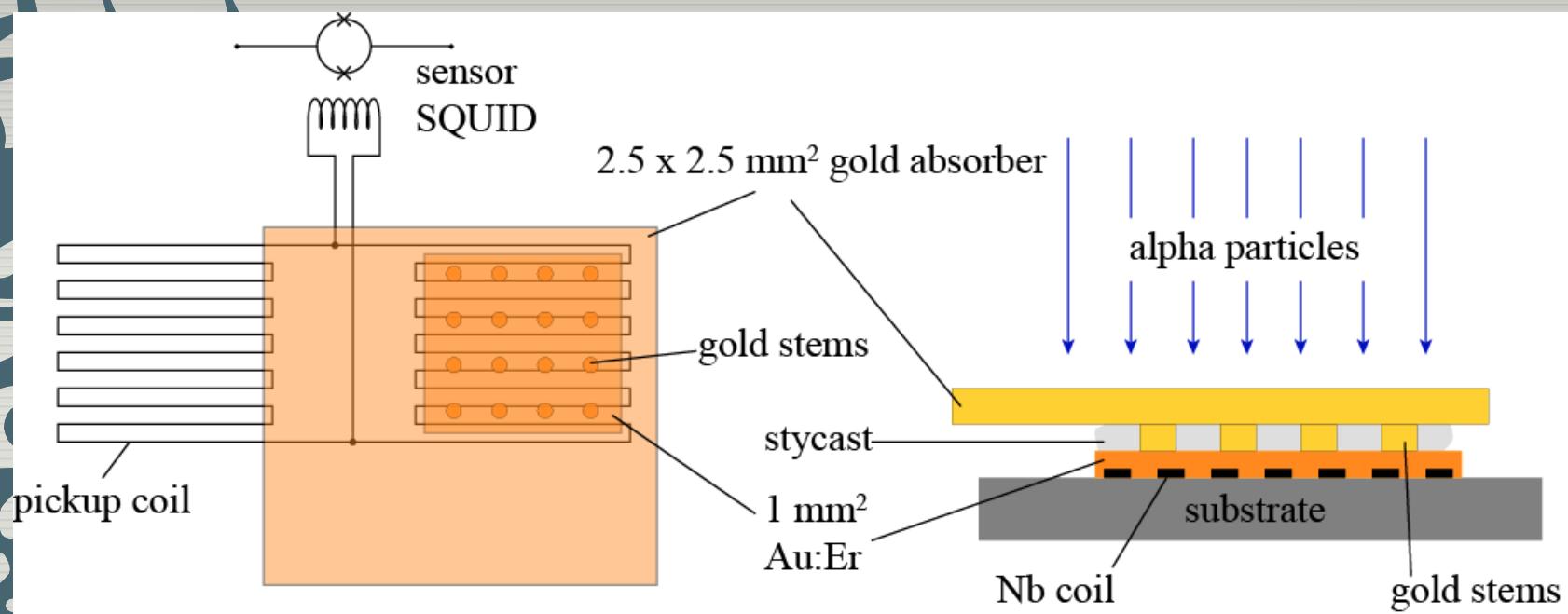
Astropart. Phys. 34, 732, 2011



low energy threshold
suitable to search for WIMP



New sensor for large heat capacity



Meander is made in U. of Heidelberg.

2.5 x 2.5 x 0.07 mm³ gold foil

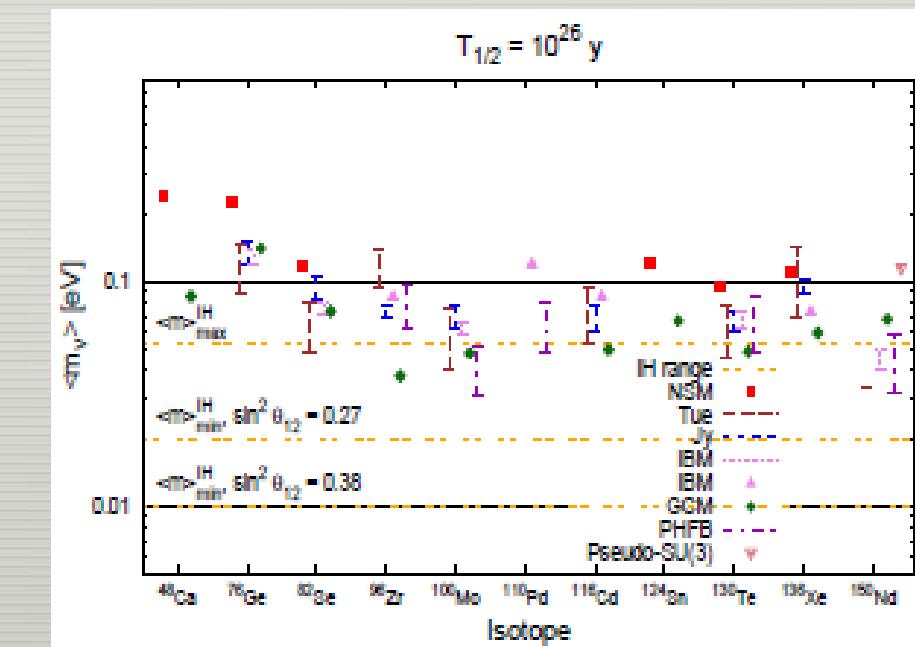
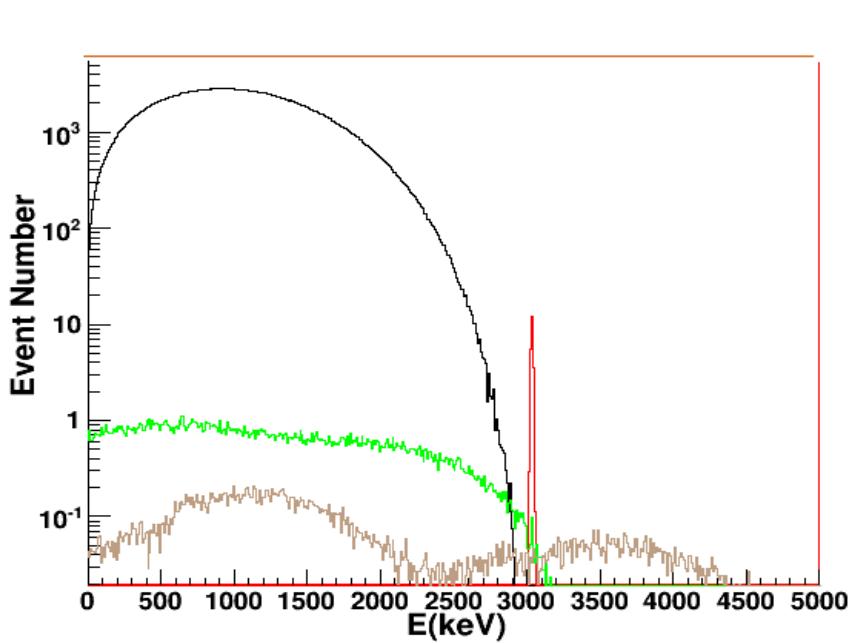
C = 0.6 nJ/K at 20 mK

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

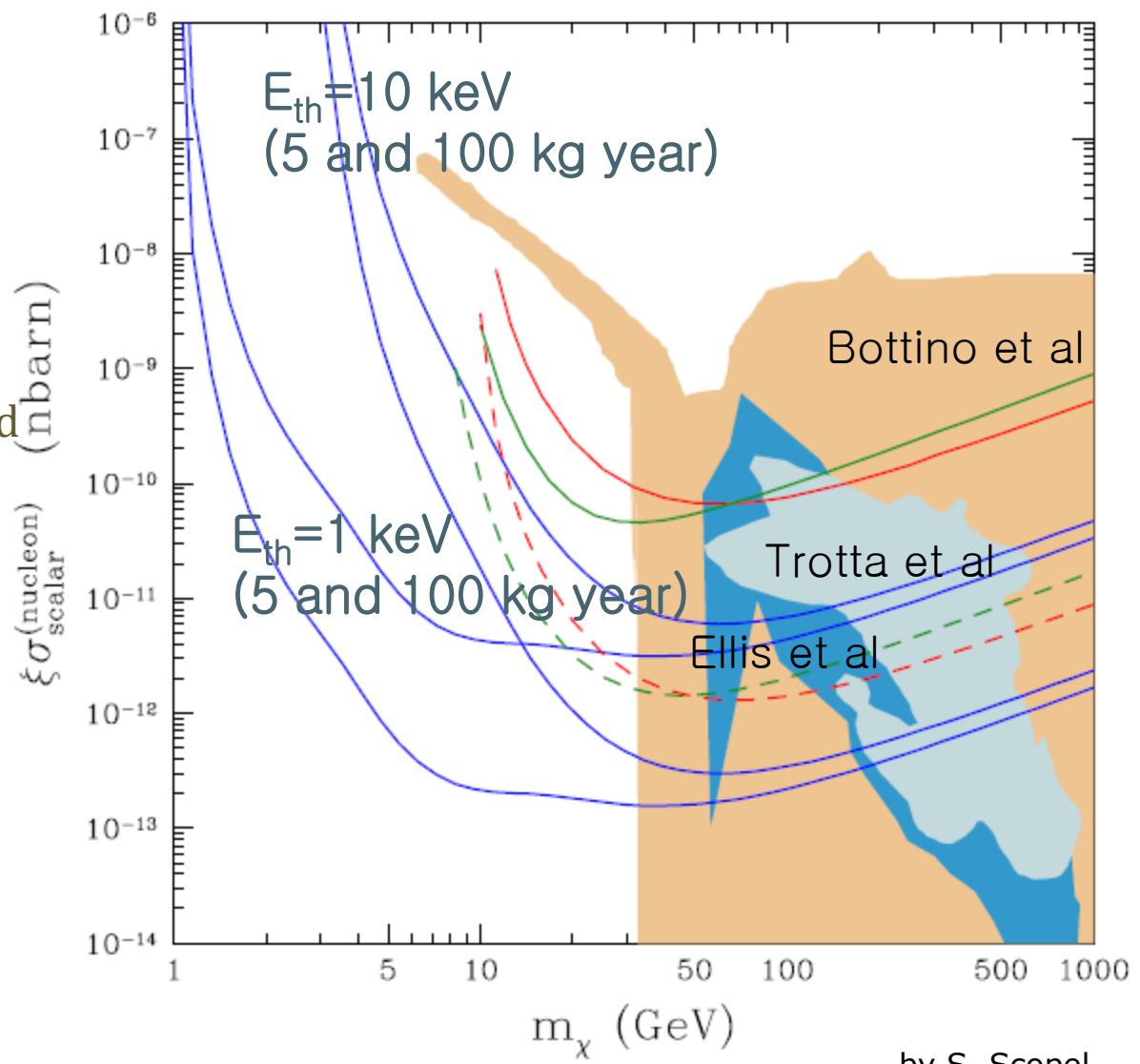
CaMoO₄ DBD Sensitivity

100 kg CaMoO₄ Cryogenic detector
Mo-100~50 kg
0.5% FWHM → 15 keV FWHM
Efficiency ~ 0.8

5 years, 100 kg ⁴⁰Ca¹⁰⁰MoO₄
 3×10^{26} years ~ 50 meV



Dark matter sensitivity of CaMoO₄ cryogenic experiment



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

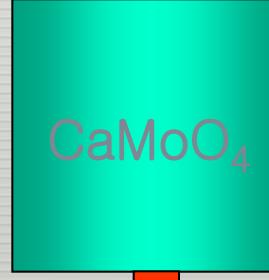
diameter, mm

	30	35	40	45	50	55	60	65	70
height, mm	0.794	0.806	0.813	0.822	0.826	0.831	0.834	0.839	0.841
30	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

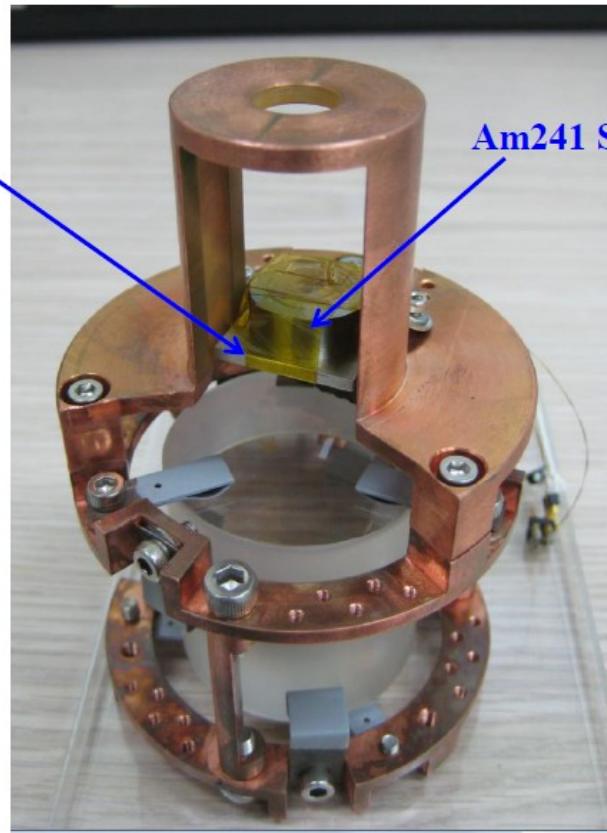
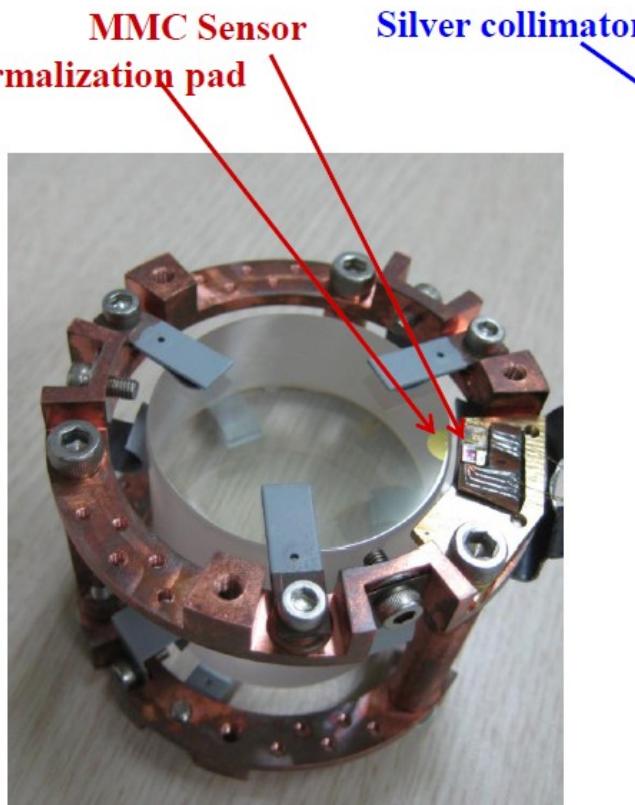
Si or Ge TES/MMC/NTD

60 cm³ CMO

$C = 0.17 \text{ nJ/K}$ at 10 mK
 1.4 nJ/K at 20 mK

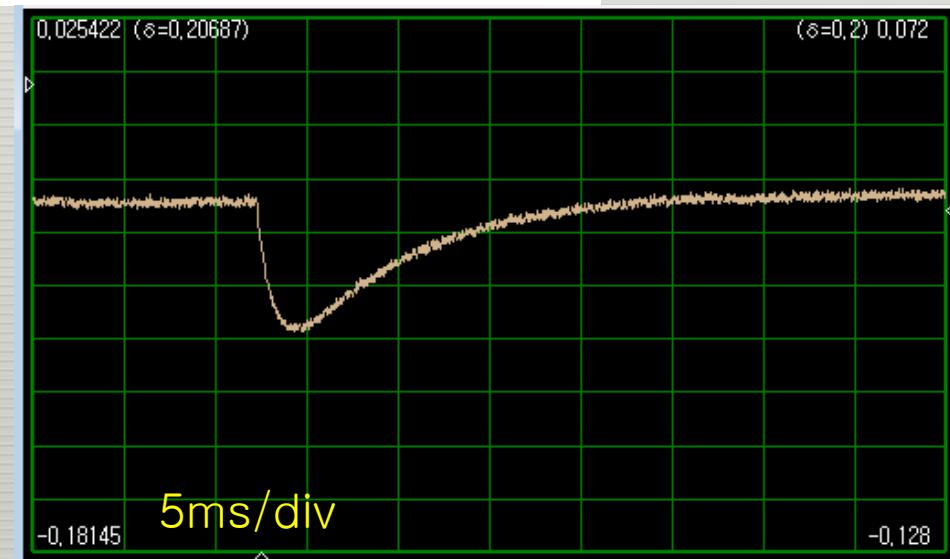


Phonon sensor (MMC)



4cm x 4 cm

Toward the full scale experiment!



KIMS(Korea Invisible Mass Search) collaboration



Seoul National University: H.C.Bhang, J.H.Choi, S.C.Kim, S.K.Kim, J.H.Lee, M.J.Lee, J.Lee, S.S.Myung
Sejong University: U.G.Kang, Y.D.Kim, J.I. Lee
Kyungpook National University: H.J.Kim, J.H.So, S.C.Yang
Yonsei University: M.J.Hwang, Y.J.Kwon
Wha Womans University: I.S.Hahn
orea Research Institute of Standard Sciences : Y.H.Kim, K.B.Lee, M. Lee
Institute of High Energy Physics J.Li
Tsinghua University : Y.Li, Q.Yue

AMoRE Collaboration

Korea (39)

Seoul National University : H.Bhang, S.Choi, M.J.Kim, S.K.Kim, M.J.Lee, S.S.Myung, S.Olsen, Y. Sato, K.Tanida, S.C.Kim, J.Choi, S.J.Lee, J.H.Lee, J.K.Lee, H.Kang, H.K.Kang, Y.Oh, S.J.Kim, E.H.Kim, K.Tshoo, D.K.Kim, X.Li, J.Li, H.S.Lee (24)

Sejong University : Y.D.Kim, E.-J.Jeon, K. Ma, J.I.Lee, W.Kang, J.Hwa (5)

Kyungpook national University : H.J.Kim, J.So, Gul Rooh, Y.S.Hwang(4)

KRISs : Y.H.Kim, M.K.Lee, H.S.Park, J.H.Kim, J.M.Lee, K.B.Lee (6)

Russia (16)

ITEP(Institute for Theoretical and Experimental Physics) : V.Kornoukhov, P. Ploz, N.Khanbekov (3)

Baksan National Observatory : A.Ganggapshev, A.Gezhaev, V.Gurentsov, V.Kuzminov, V.Kazalov, O.Mineev, S.Panasenko, S.Ratkevich, A.Verensnikova, S.Yakimenko, N.Yershov, K.Efendiev, Y.Gabriljuk (13)

Ukraine(11)

INR(Institute for Nuclear Research) : F.Danevich, V.Tretyak, V.Kobychev, A.Nikolaiko, D.Poda, R.Boiko, R.Podviianiuk, S.Nagorny, O.Polischuk, V.Kudovbenko, D.Chernyak(11)

China(2)

Tsinghua University : Y.Li, Q.Yue(2)

4 countries
8 institutions
68 collaborators



SUMMARY

■ Y2L

- In operation since 2003
- Expansion of the laboratory space in discussion

■ KIMS

- data taking with 100 kg CsI(Tl)
- PSD analysis is done
- AM analysis will be done for two full year data

■ AMoRE

- Large volume CaMoO₄ crystals with enriched material developed
- Pilot experiment of ~ 1 kg with scintillation technique + CsI(Tl) active veto is in preparation
- Development of cryogenic CaMoO₄ detector
- 100kg CaMoO₄ cryogenic detector: achievable goal
 - ~ 3×10^{26} yrs (~ 0.05 eV)
- Included in the National Research Facility Road Map



Thank you for your attention !