PROJECTS TO SEARCH WIMPS AND NEUTRINOLESS DOUBLE BETA DECAYS AT THE CENTER FOR UNDERGROUND PHYSICS.

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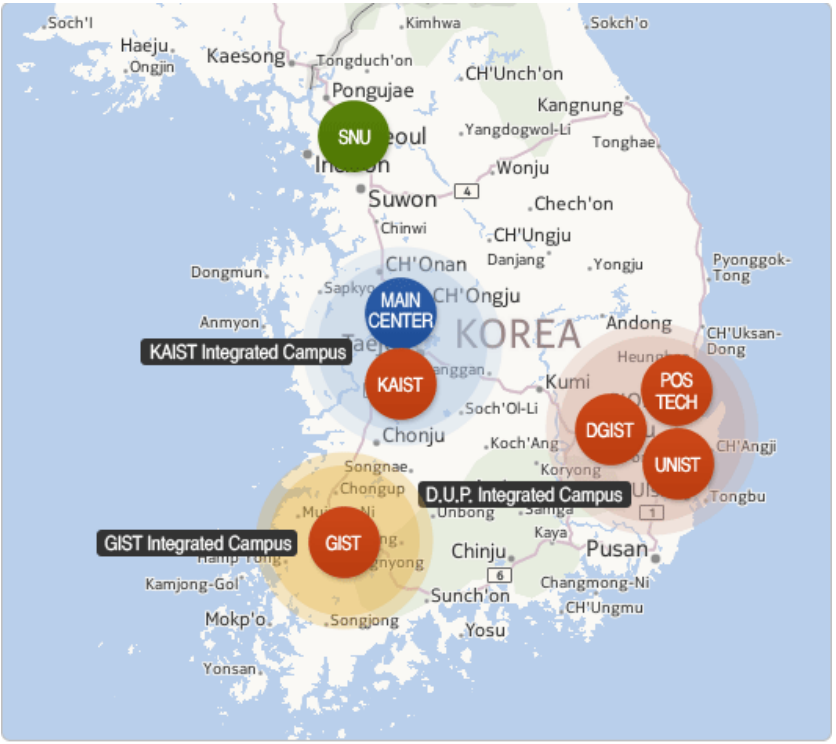
Fermi National Accelerator Laboratory

Outline

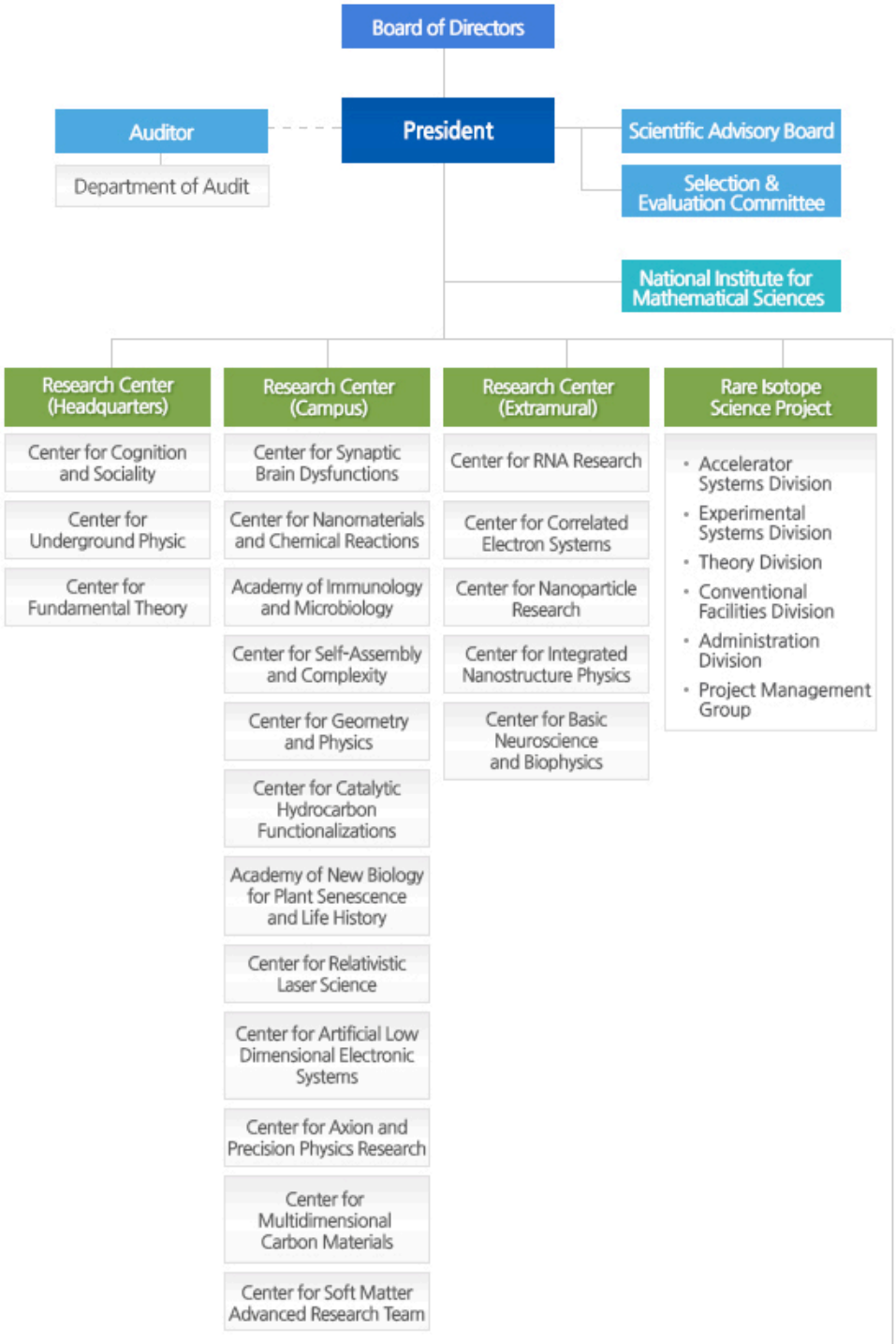
1. Introduction to CUP at IBS.
2. Underground Laboratory
3. Dark Matter Search - KIMS
4. $0\nu\beta\beta$ - AMoRE.
5. Summary.

3 Headquarter centers
12 Campus centers
5 Extramural centers

CUP is one of the headquarter centers.



Headquarters · Campus Research Centers · Extramural Research Centers



Center for Underground Physics (CUP)

- CUP began on July 2013
- Now, 17 Ph.Ds, 15 students, 3 technicians, 2 administrations.
- Director : Yeongduk Kim
- Group Leaders : Yong-Hamb Kim
- Research Area : Dark Matter, Double Beta Decay, Underground Nuclear Astrophysics, Sterile neutrino search at reactor, Low temperature Detector Development etc.
- Major Projects: **1. KIMS (ongoing dark matter search)**
  2. AMoRE (planed $0\nu\beta\beta$ search)

YangYang(Y2L) Underground Laboratory

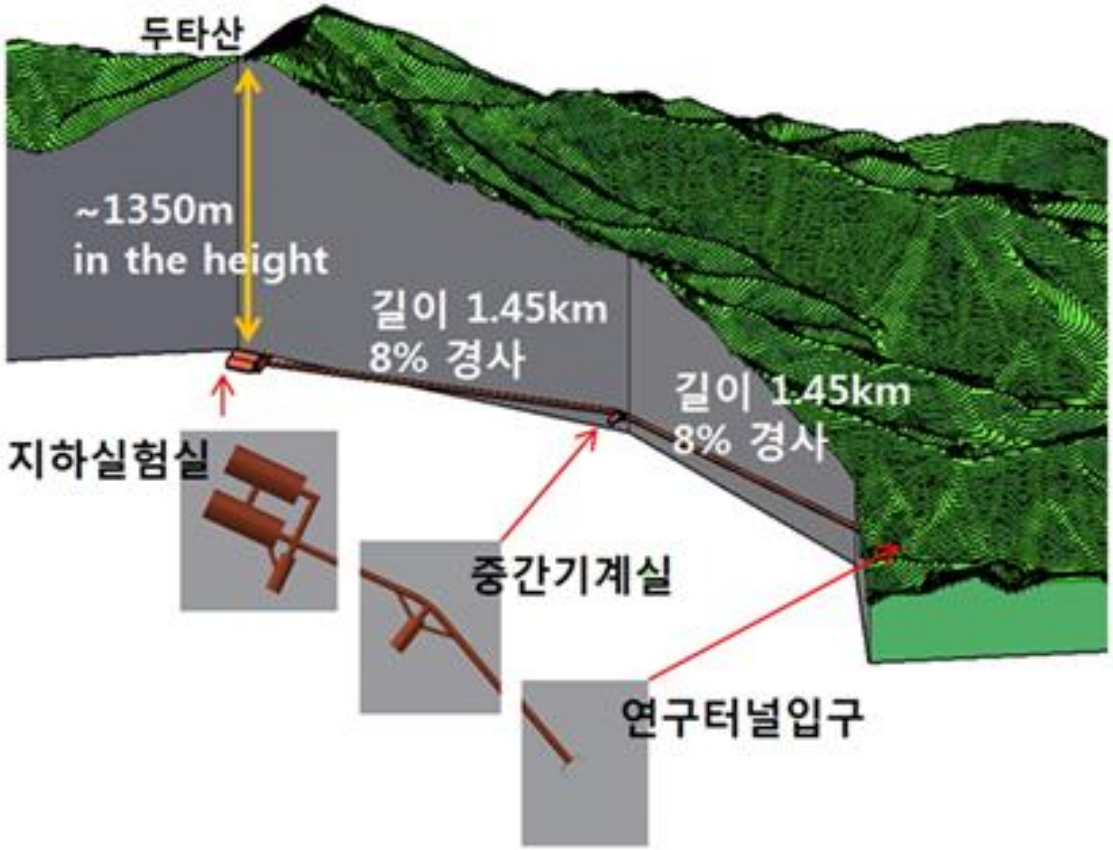
KIMS (Dark Matter Search)

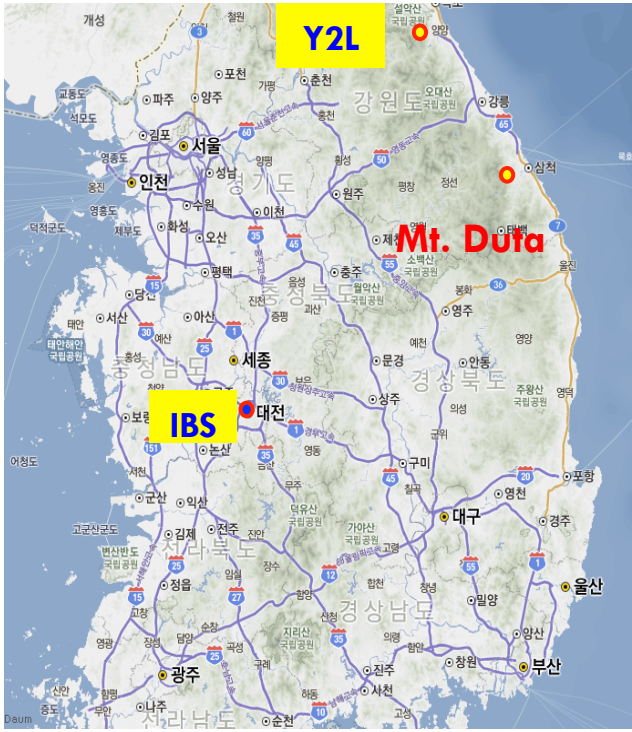
AMoRE (Double Beta Decay Experiment)

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

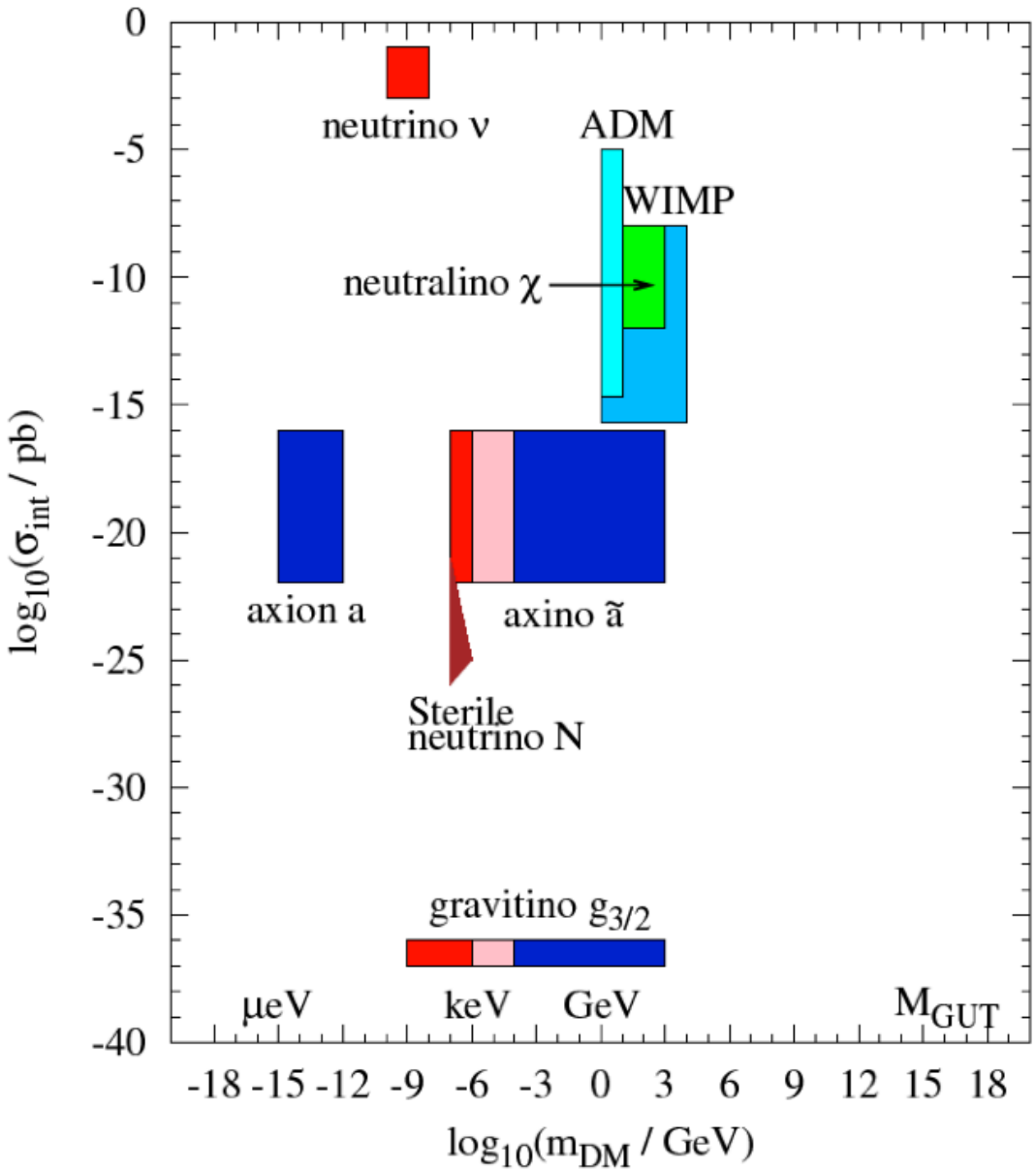
New Underground Laboratory

- A new underground laboratory is under consideration at Samcheok city since the expansion at Y2L seems to be not attractive compared to the new laboratory. – **Still need government approval.**





Particle candidates



Many candidates in many orders of magnitude of mass.

K.Y. Choi, JKPS 63, 1685(2013)

KIMS-CsI annual modulation data

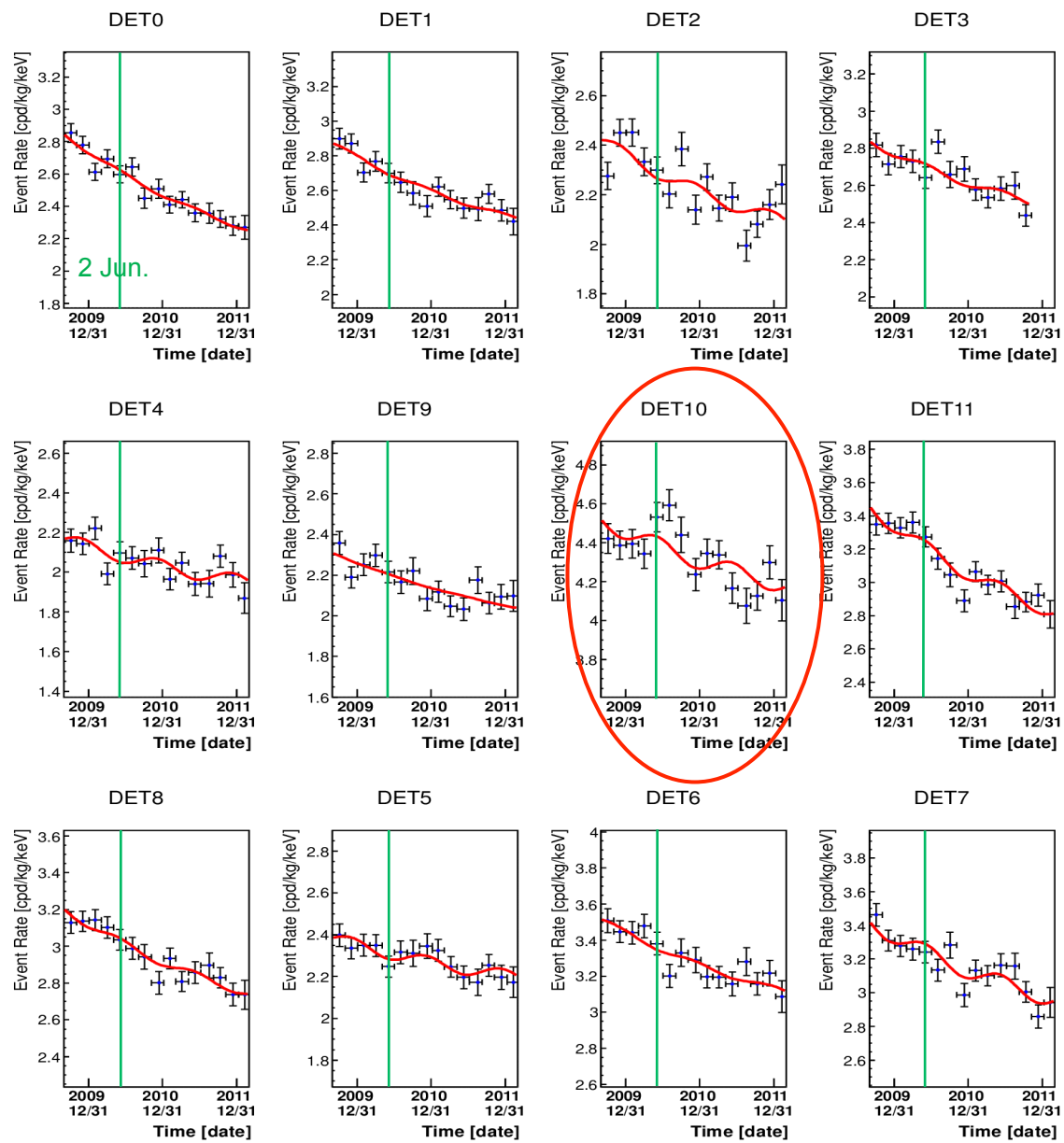
3-6 keV

$$R = A_{decay} e^{-\frac{t-t_0}{\tau}} + bkg + A\cos\frac{2\pi}{365}(t - t_{peak})$$

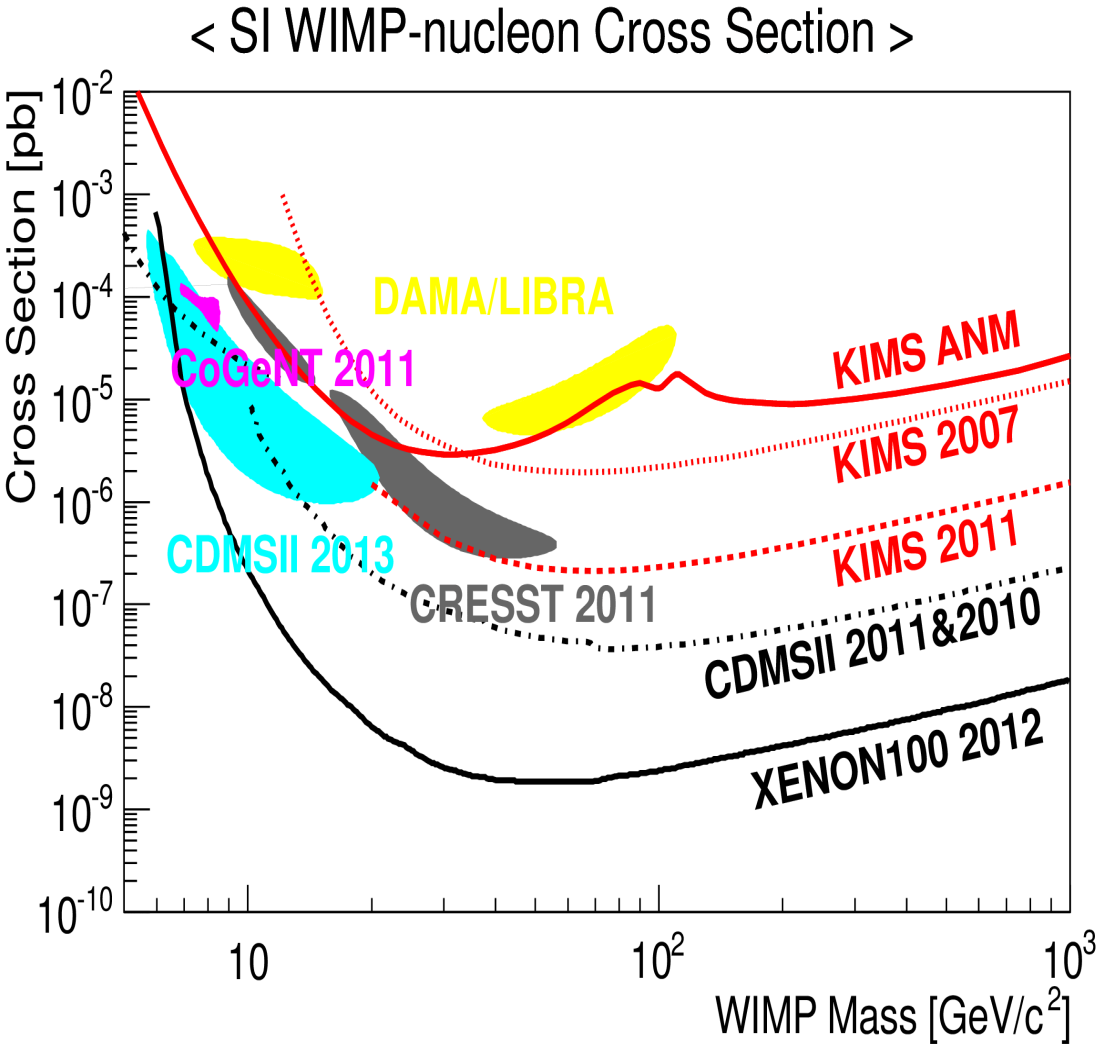
$$\tau = 2.980y,$$

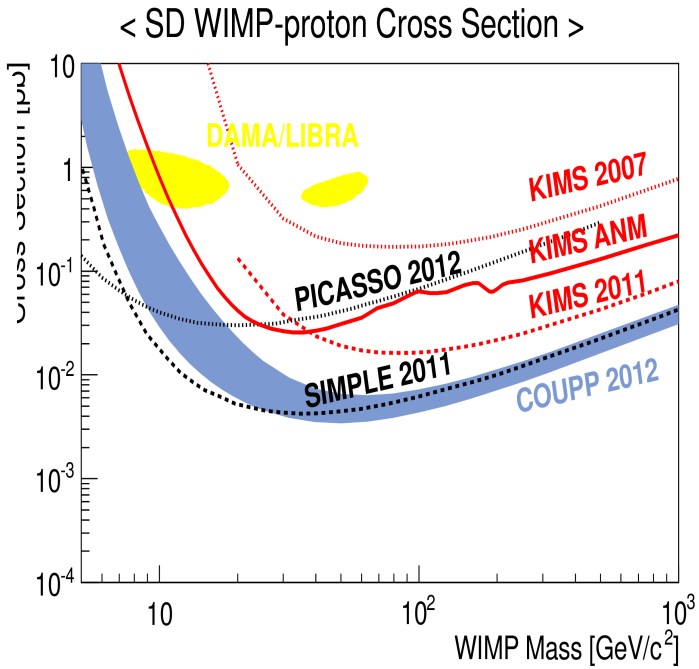
$$t_{peak} = 153(\text{June } 2)$$

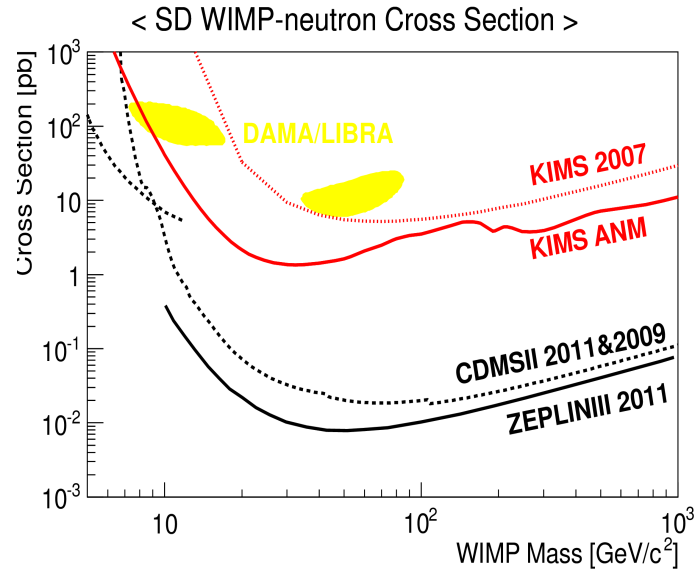
- **Annual modulation amplitude is obtained including the exponential decay of ^{134}Cs for 2.5 years of data.**
- **The mean amplitude from 3 keV to 6 keV is 0.0008±0.0068 cpd/kg/keV**



Cross Section Limit







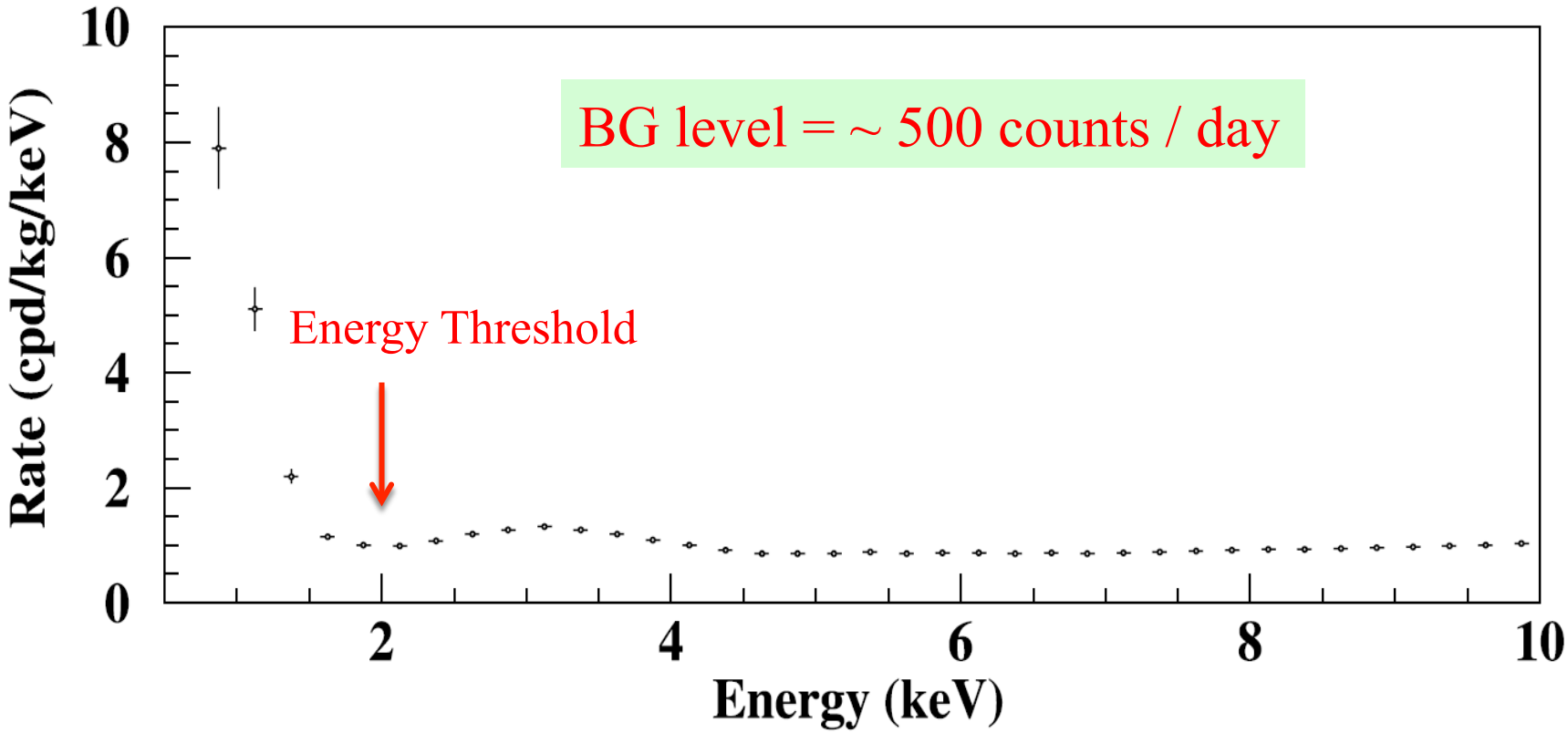
30 years (1985 -) of search -- Any Signals ?

- **Are these WIMP signals ?**
  1. **DAMA (~9σ)**
  2. **CoGeNT**
  3. **CRESST**
  4. **CDMS-Si**

VS

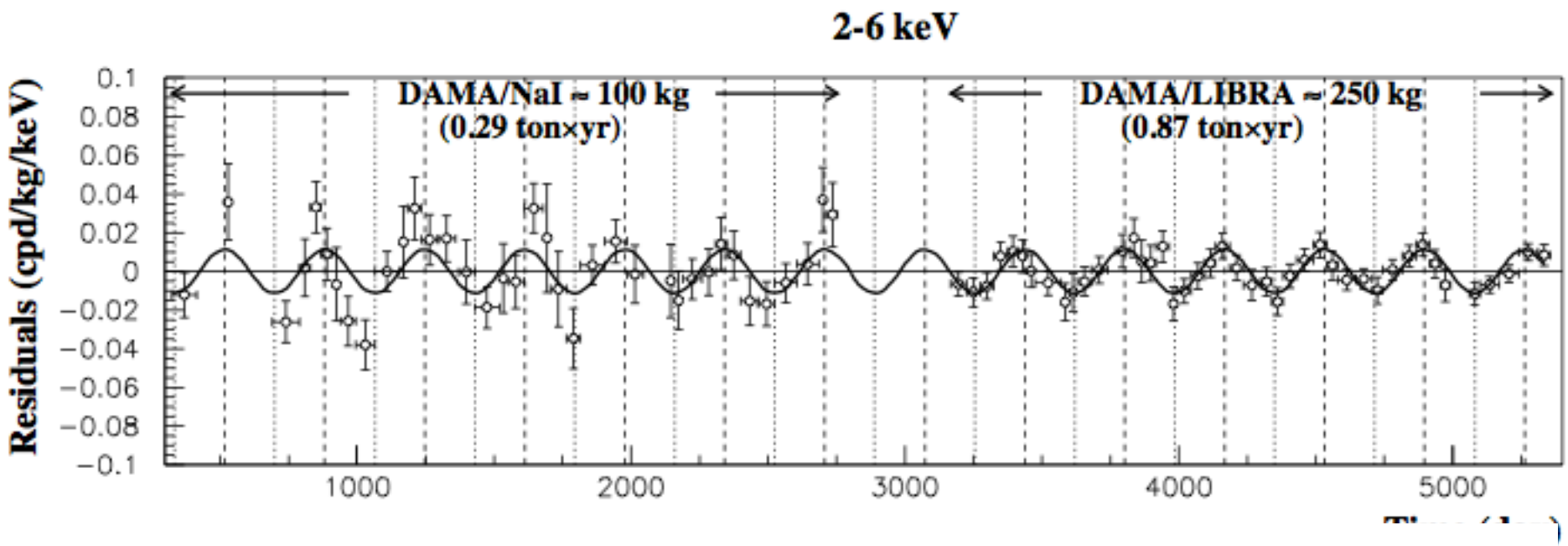
- **Only Limits.**
  1. **XENON 10+100**
  2. **KIMS**
  3. **CDMS-Ge**
  4. **LUX**
  5. **……..**

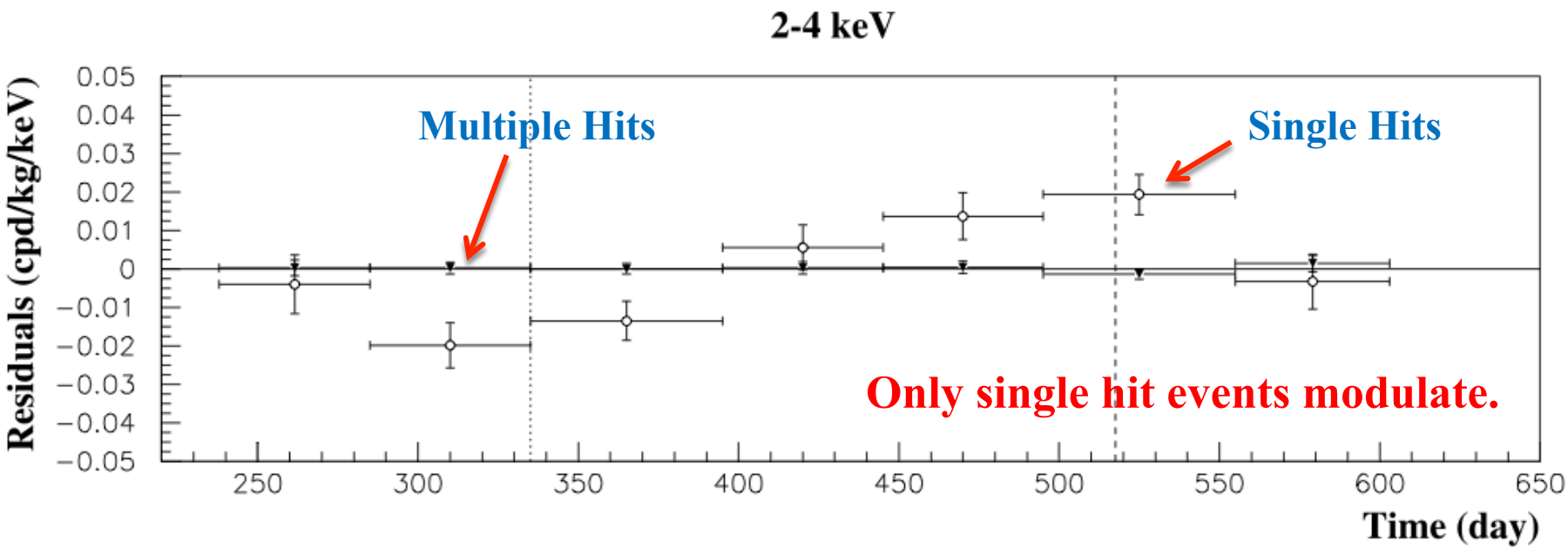
DAMA Background Spectrum



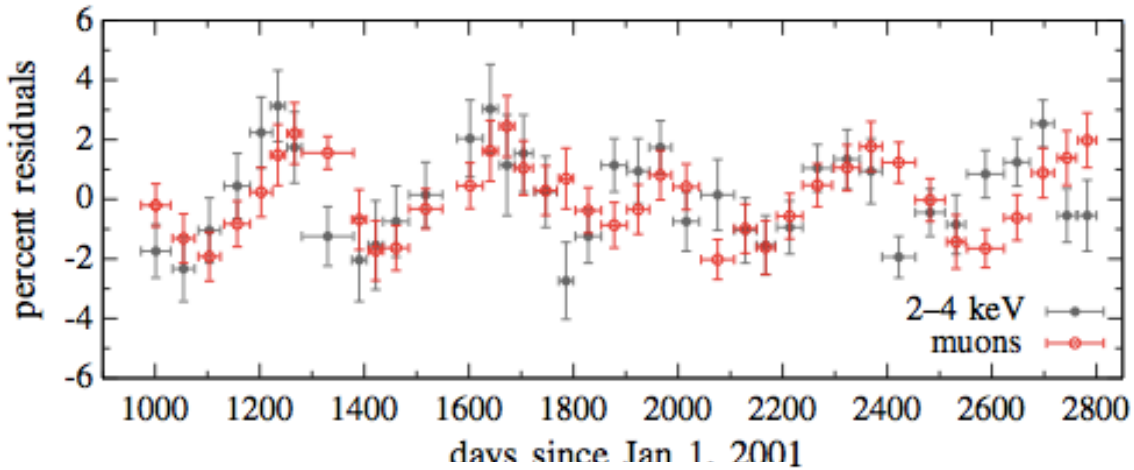
- No recoil energy shape observed.
- No recoil identification is possible.

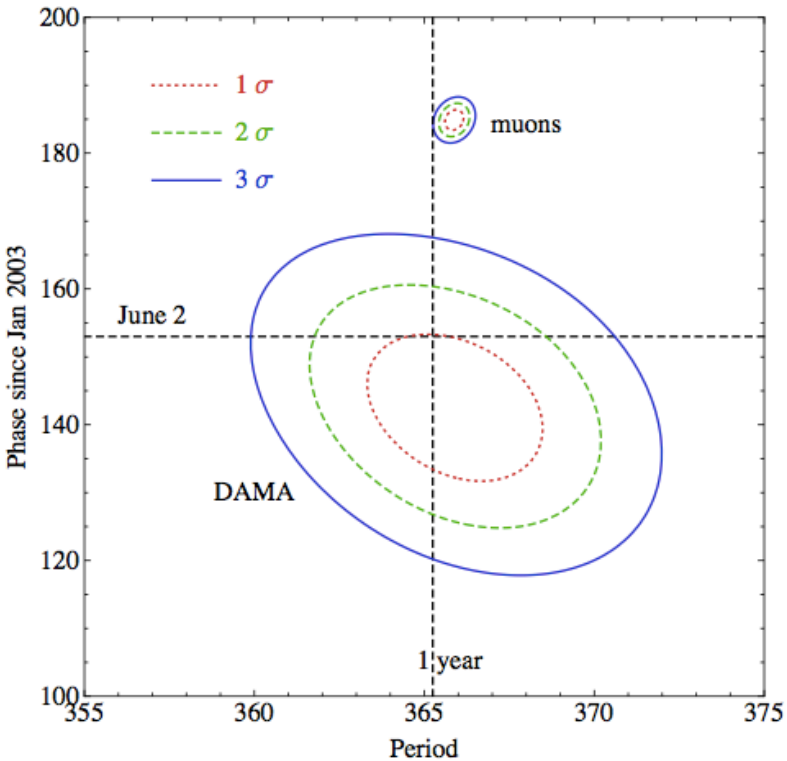
Is DAMA annual modulation due to WIMPs ?





Muon modulation ?

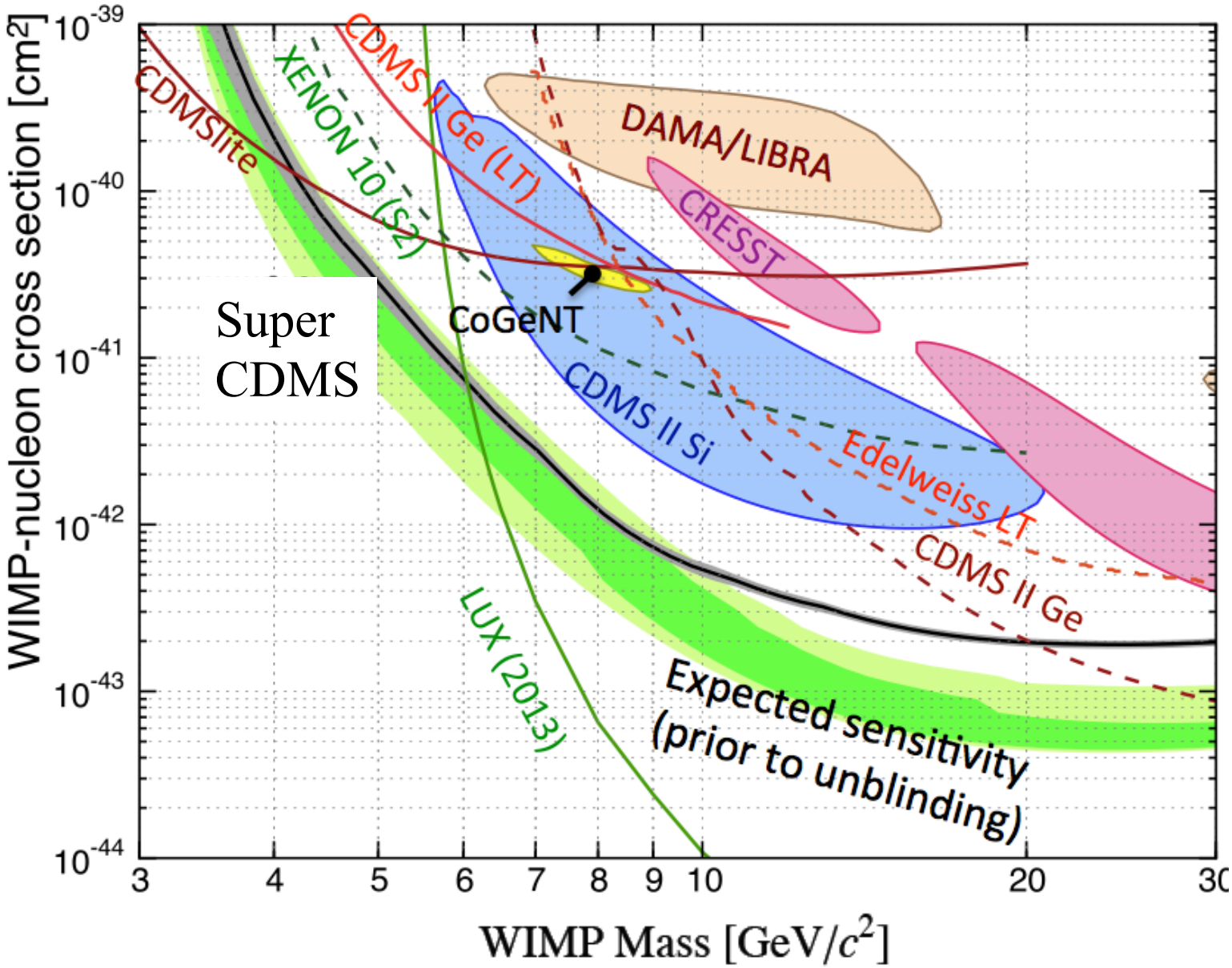




- Modulation amplitude similar.
- Phases are different.
- No clear mechanism suggested, yet muon effect is not completely ruled out.

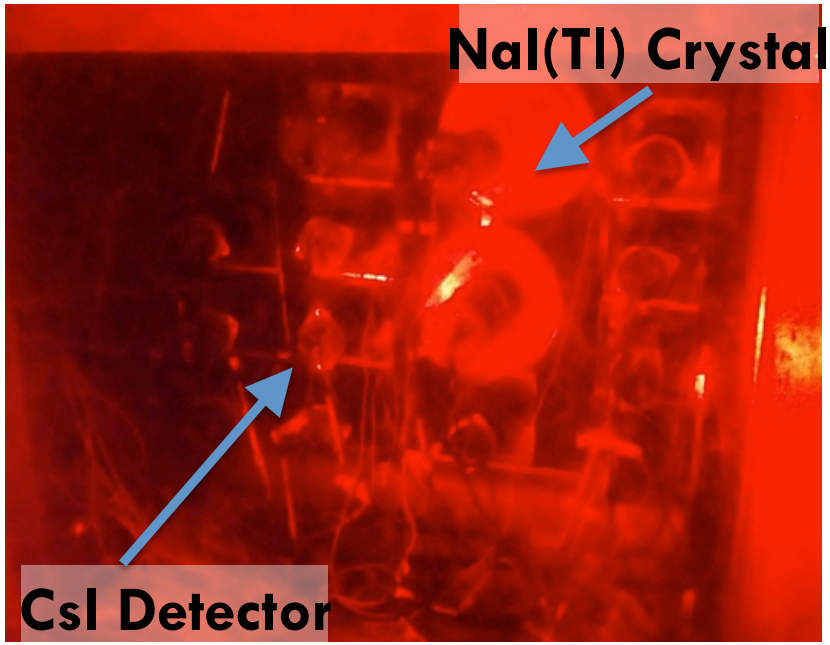
Fernandez-Martinez, JCAP 07, 029

Summary - Low mass WIMPs ?



KIMS-NaI Experiment @ CUP

- To verify the DAMA result using same NaI(Tl) crystals.
- Our strategy : Achieve lower background level and lower energy threshold than DAMA by factor 2.
- We can clarify the origin of the annual modulation unambiguously.



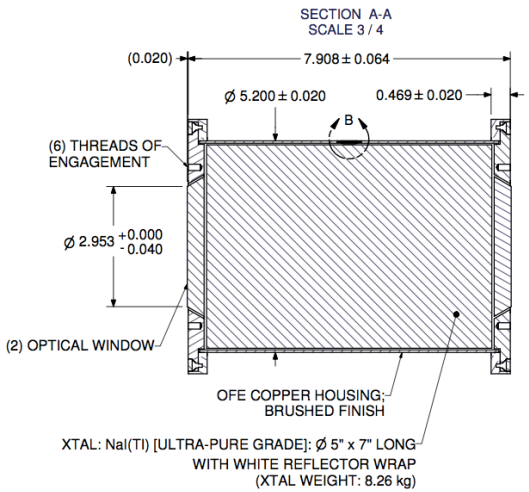
Phase I : CsI + NaI

Phase II : NaI in LS

Phase III : NaI Array in LS

Purification of the powder & crystals

- **New low-K NaI crystal is under R&D (ANAIS,DM-ICE,KIMS-NaI, SABRE).**
- **Alpha Spectra (AS) crystals**
- **BH will grow 5 crystals with Sigma-Aldrich powder.**
- **SICCAS is beginning to grow NaI crystals.**



Crystal delivered to KIMS

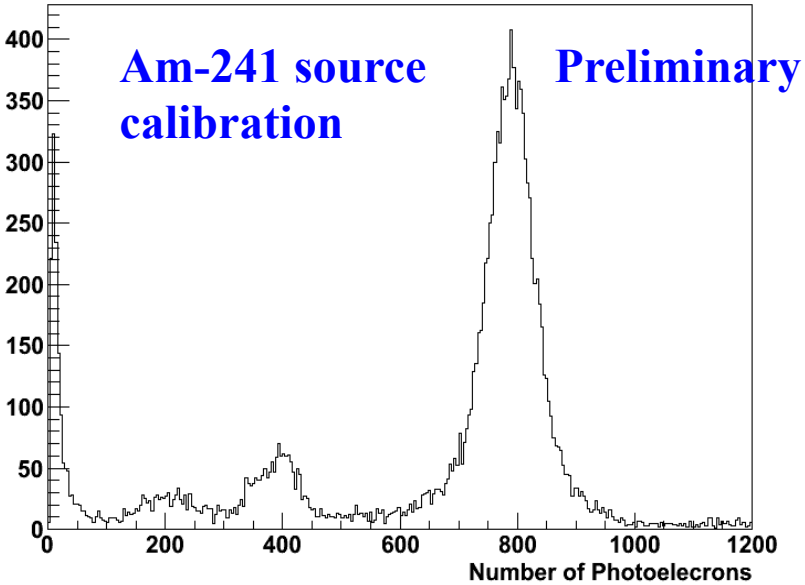
Powder Measurements

Samples	Measurements	^{nat}K (ppb)
Sigma Aldrich - crystal grade	HPGe(KIMS)	<266
Sigma Aldrich - Astro grade	HPGe(KIMS)	<183
Alpha Spectra, C	HPGe(KIMS)	<262
Sigma Aldrich – Astro grade	HPGe(DM-ICE)	<126
Sigma Aldrich – Astro grade	ICP-MS (SA)	~4

It's difficult to reach 10 ppb level measurements with powder !
Current plan is to grow crystals and measure K.

Light yields

	NaI1-Glass	NaI1-Metal	NaI2-Glass
Light yield	14.8±0.6 /keV	12.1 ± 0.9 /keV	15.7 ± 1.5 /keV
Resolution	5.0%	4.4±0.2%	5.3±0.2%
Dark Count rate	1.2 kHz	4.0 kHz	2.2 kHz



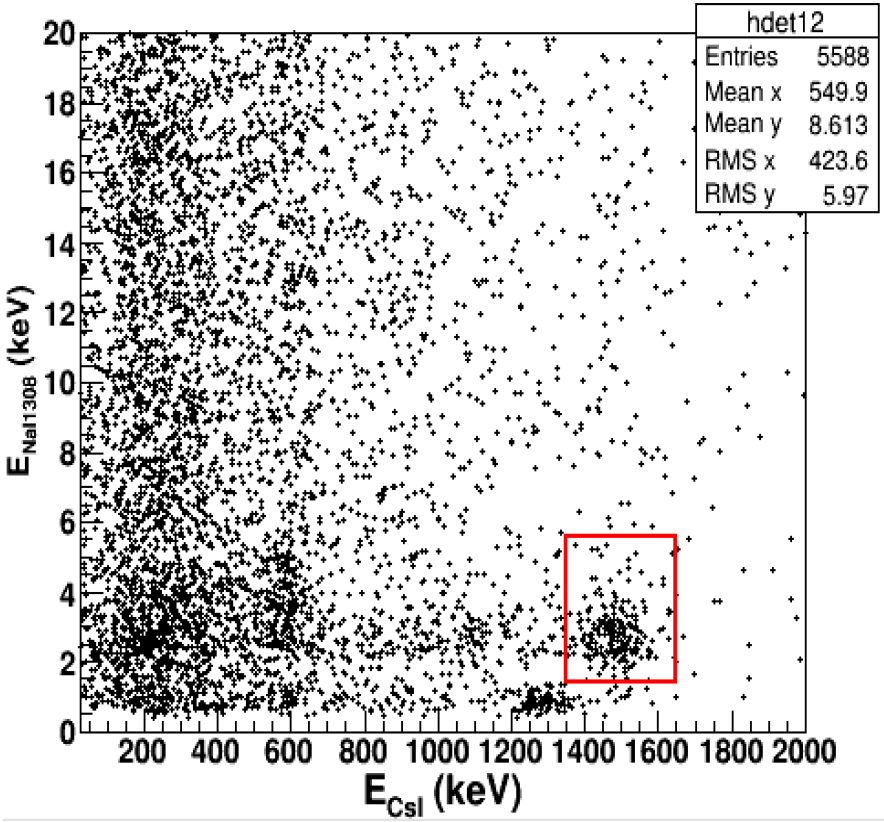
NaI1 :
5”(D) X 7”(L) = 8.26 kg
overall diameter = 15.9cm
same powder with ANAIS

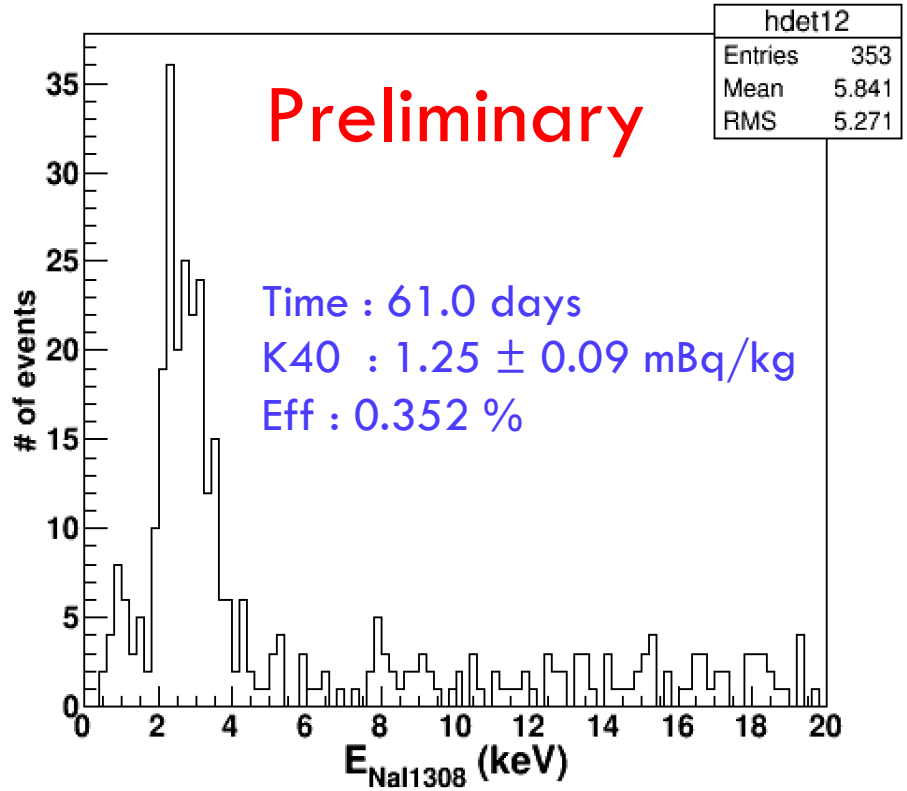
NaI2 :
4.2”(D) X 11”(L) = 9.2 kg
overall diameter = 13.8cm
less internal background than Crystal 1

consistent with ANAIS results
(arxiv: 1308.3478)

K-40 contamination – important background

- Coincidence events between NaI and CsI
- NaI (3keV X-rays) and CsI(1460 keV)





Eff : by Geant4 simulation

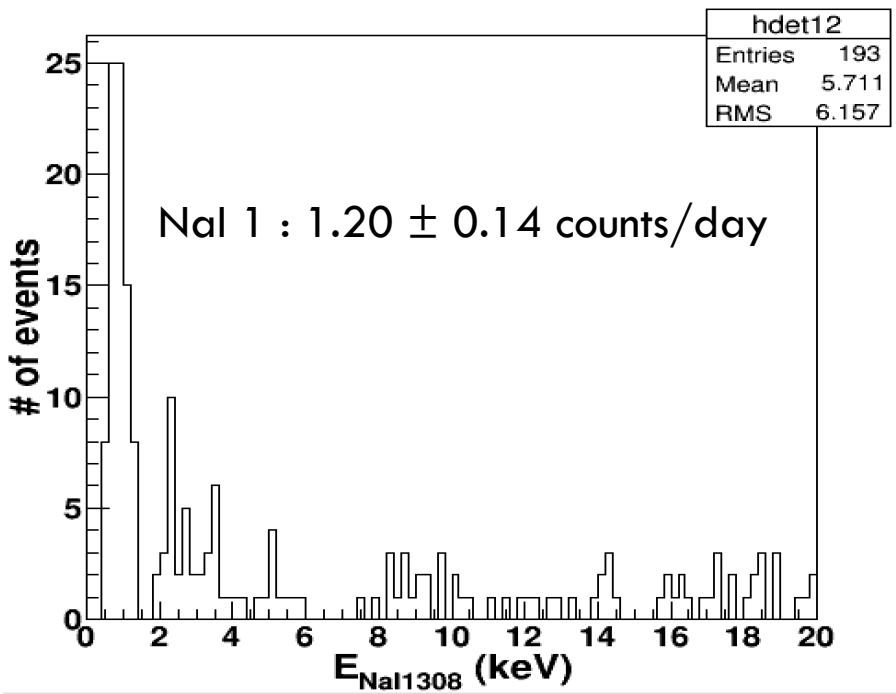
41.4 ± 3.0 ppb

- K level 41.4 ± 3.0 ppb is consistent with ANAIS group.
- Need to reduce below 10 ppb.

^{22}Na

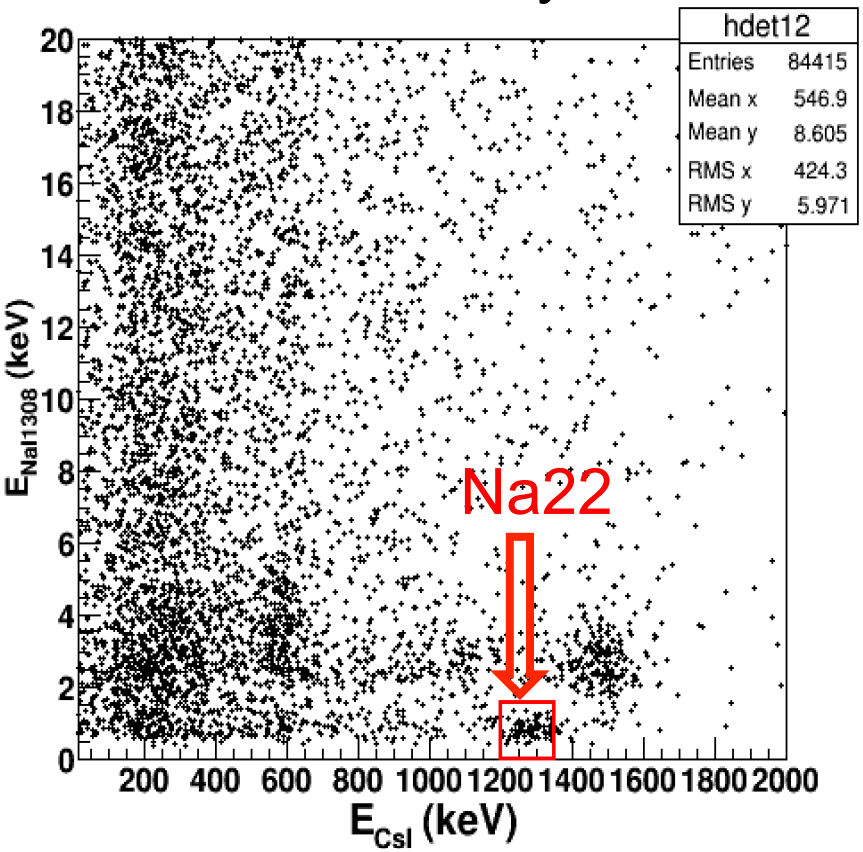
Coincidence Condition

- ❖ CsI Detector : 1274.5 γ-ray
- ❖ NaI Detector : X-rays (0.85 keV)

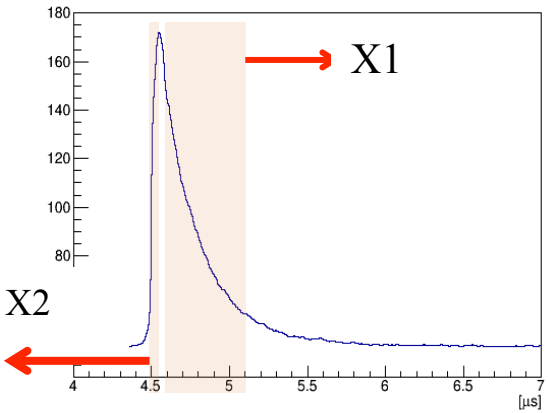


Half life = 2.6 years

NaI 1 crystal



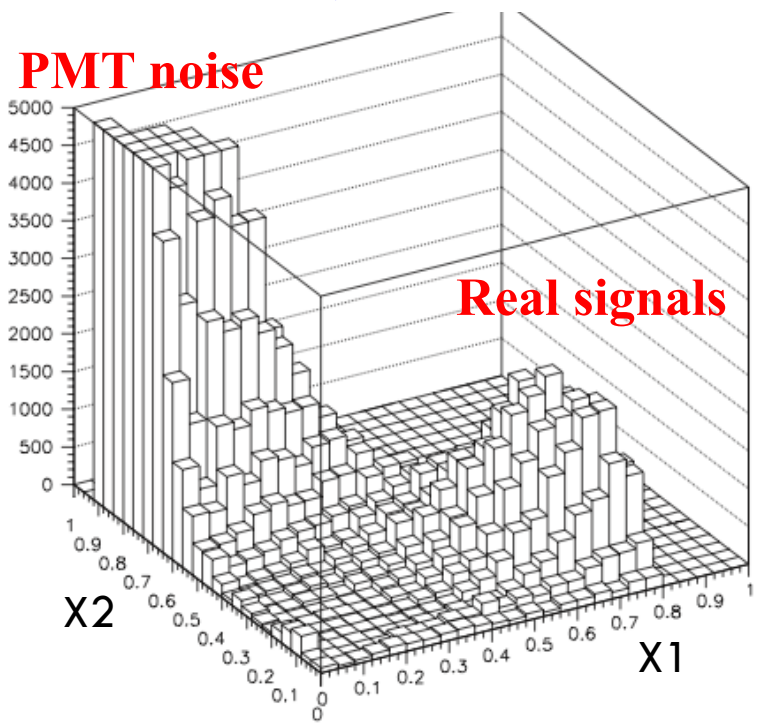
PMT noise reduction in background data.



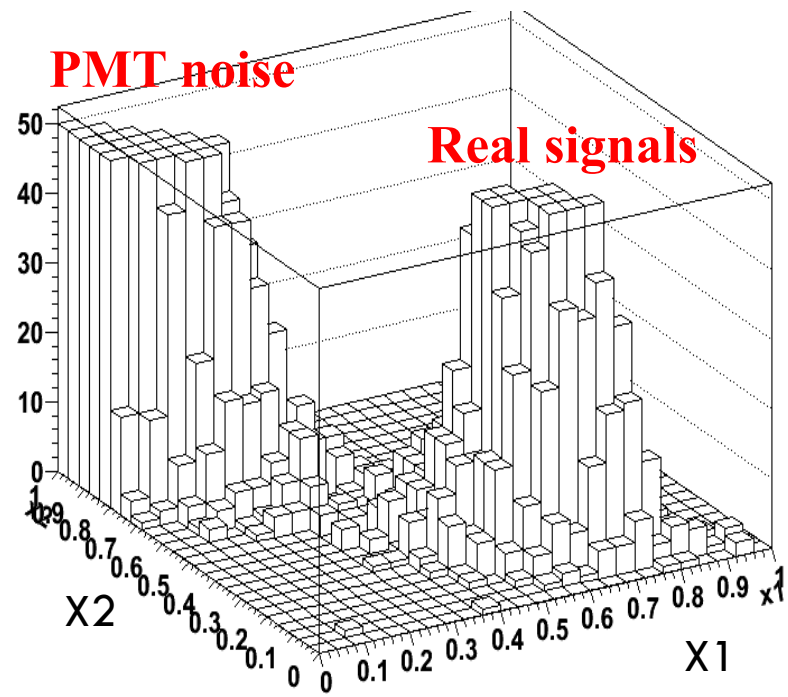
DAMA/LIBRA reported PMT noise reduction by introducing charge ratio parameters. We obtained the same results as DAMA.

$$X_1 = \frac{Area(100 \le t \le 600ns)}{Area(0 \le t \le 600ns)}, \quad X_2 = \frac{Area(0 \le t \le 50ns)}{Area(0 \le t \le 600ns)}$$

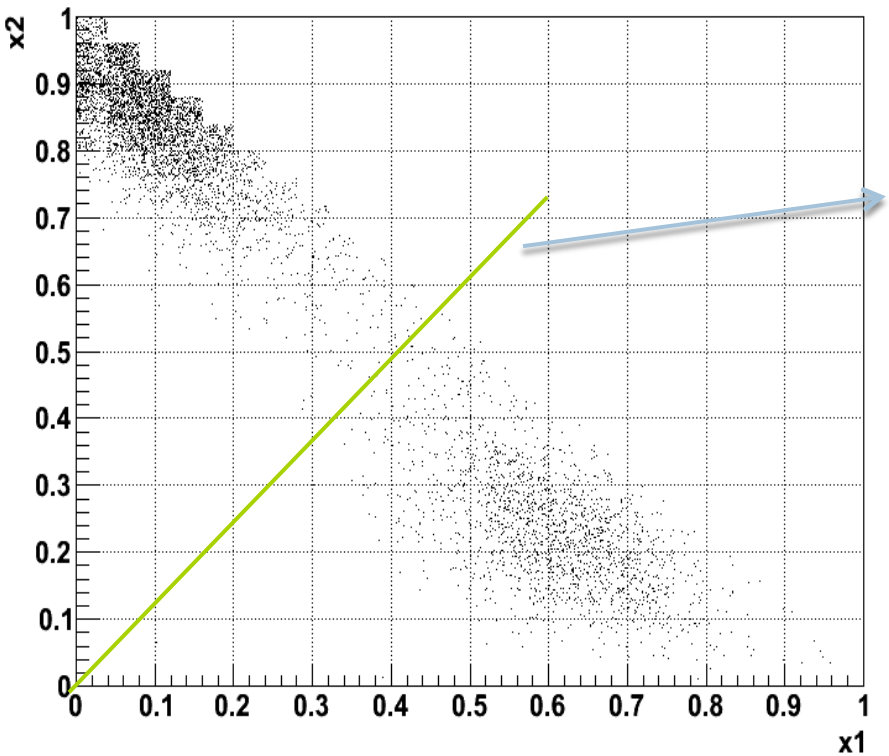
DAMA, E=2-4 keV



KIMS-NaI, E=2-4 keV



$$X_1 = \frac{Area(100 \le t \le 600ns)}{Area(0 \le t \le 600ns)}, \quad X_2 = \frac{Area(100 \le t \le 50ns)}{Area(0 \le t \le 600ns)}$$



$$\frac{X_2}{X_1} = \frac{Area(0 \le t \le 50ns)}{Area(100 \le t \le 600ns)} < 1.25$$

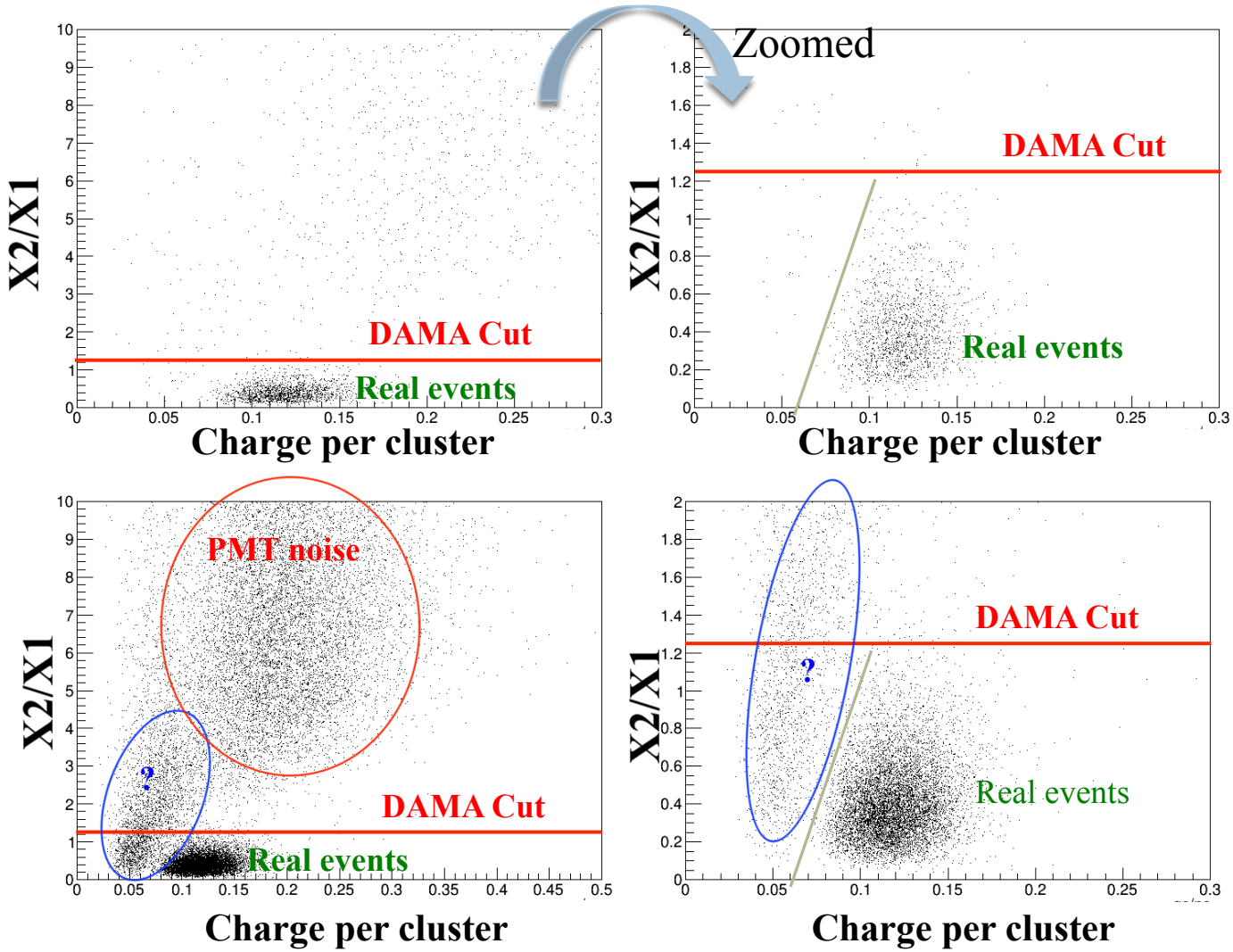
DAMA's 2-dimensional cut is reduced to 1-dimensional cut, X2/X1 < 1.25, basica lly same as (fast charge)/(slow charge)

Further reduction of PMT noise

Multiple hit events

2-4 keV

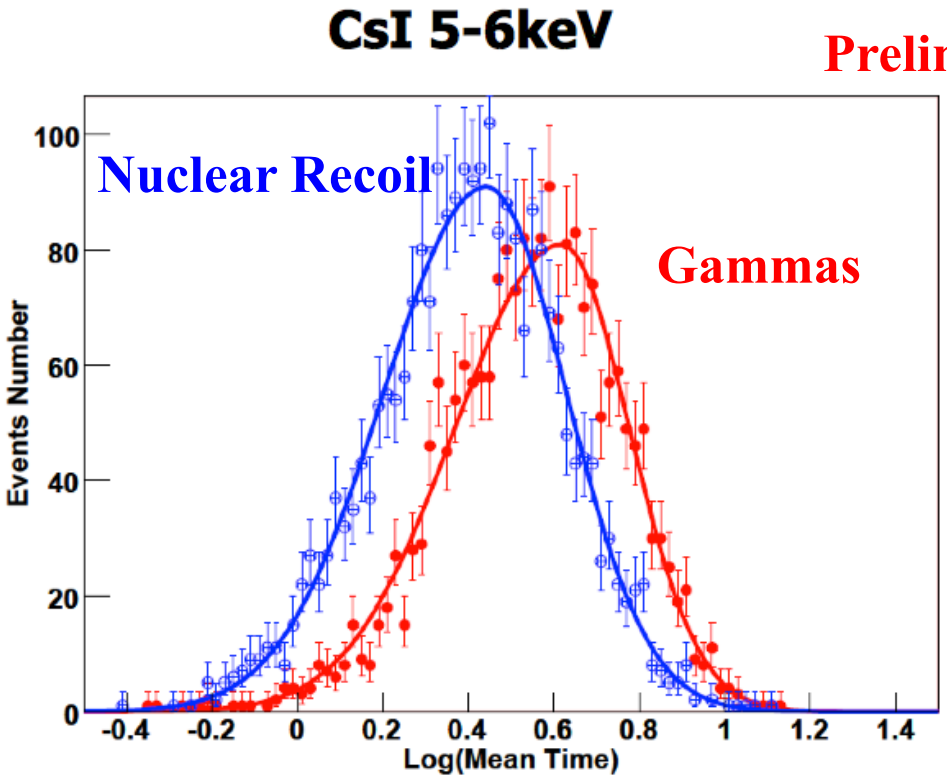
Single hit events

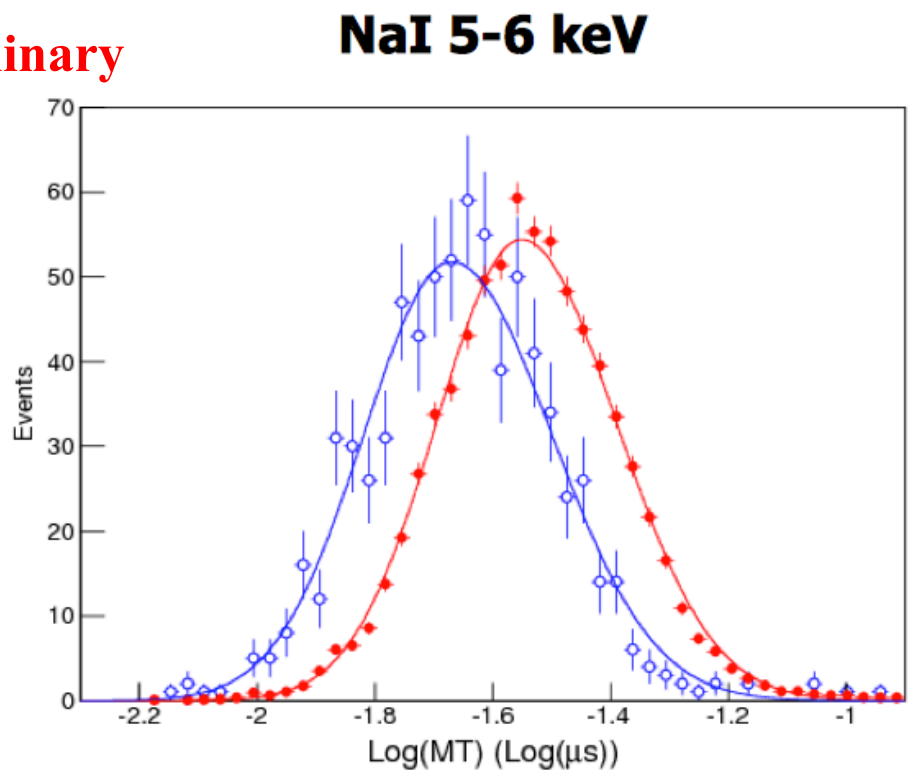


DAMA's cut, charge ratio cut, seems to be not enough to reject all PMT noise.

Pulse shape discrimination

- Pulse shape difference between nuclear recoil and backgrounds are measured.
- Due to high light yield, the separation powder is similar to CsI(Tl) crystals. This is a powerful advantage over DAMA.

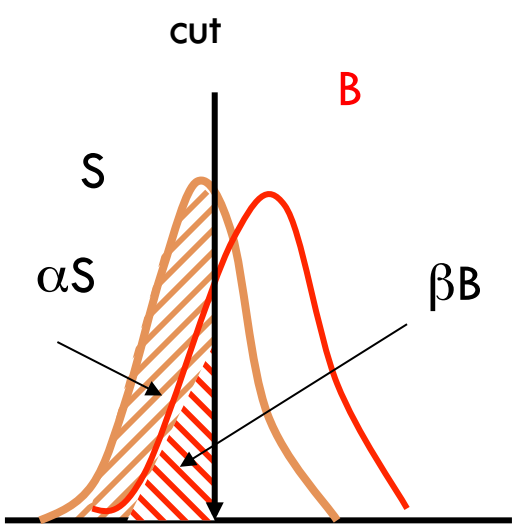


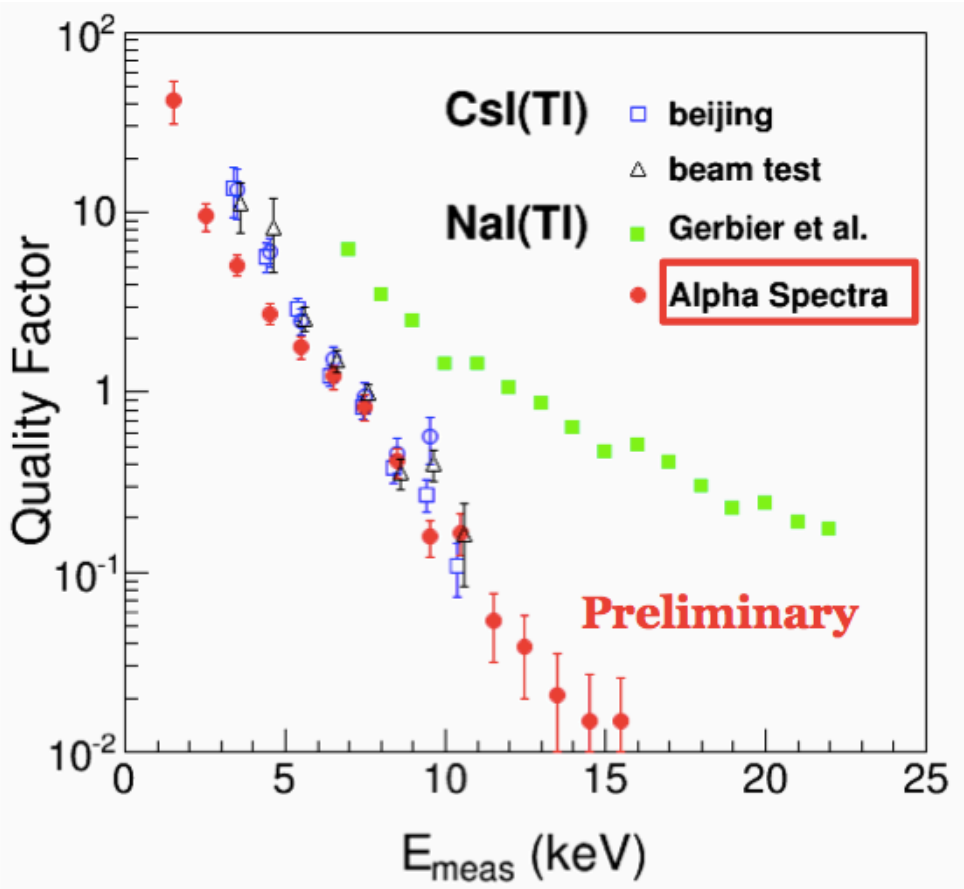


PSD power – Quality Factor

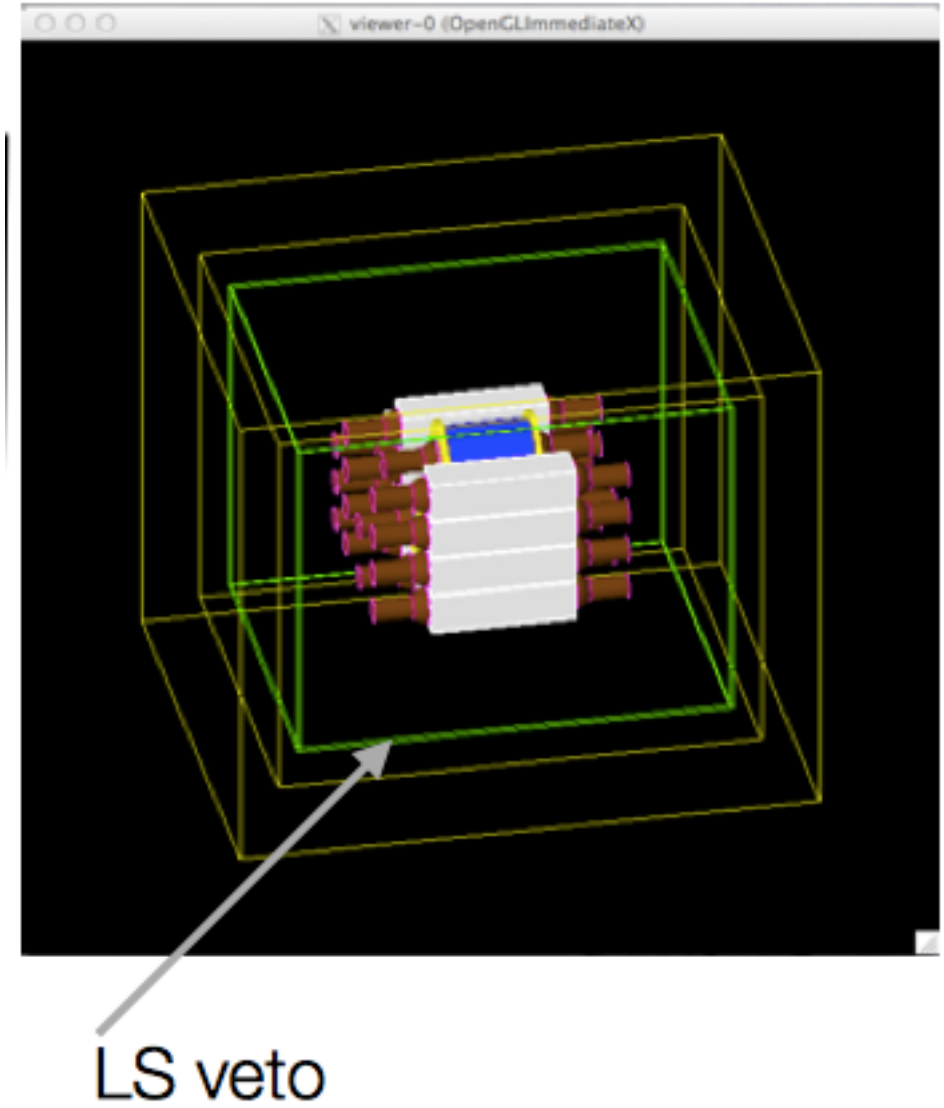
$$K = \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

Ideal detector
$\alpha \sim 1, \beta \sim 0$
$K << 1$



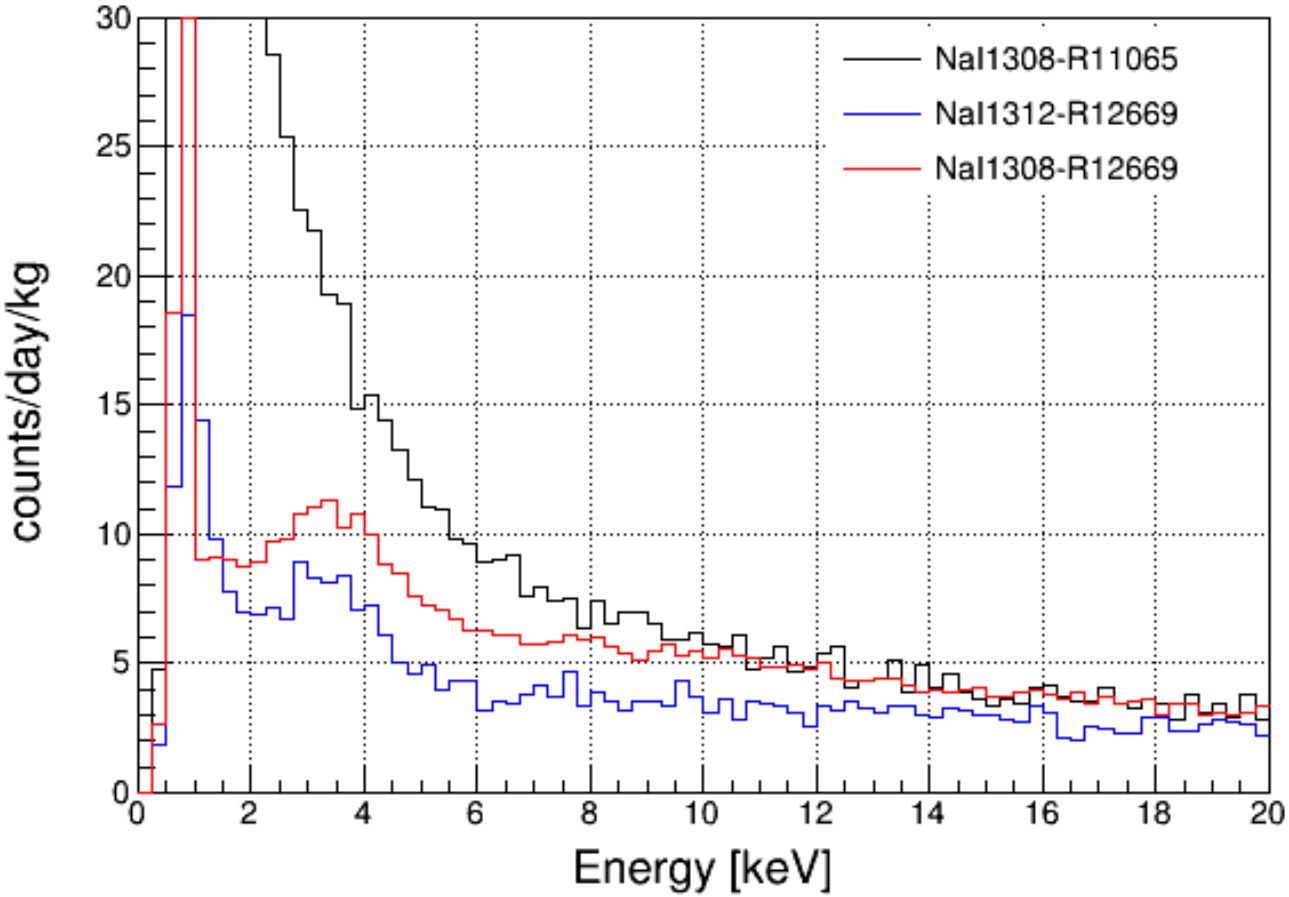


Consider active liquid scintillator veto



- NaI(Tl) array in ~ 20 cm thick LS.
- Veto efficiency for 0-10keV single hit events in case of PMT backgrounds.
  - 38% for ^{40}K
  - 78% for ^{238}U
  - 75% for ^{232}Th

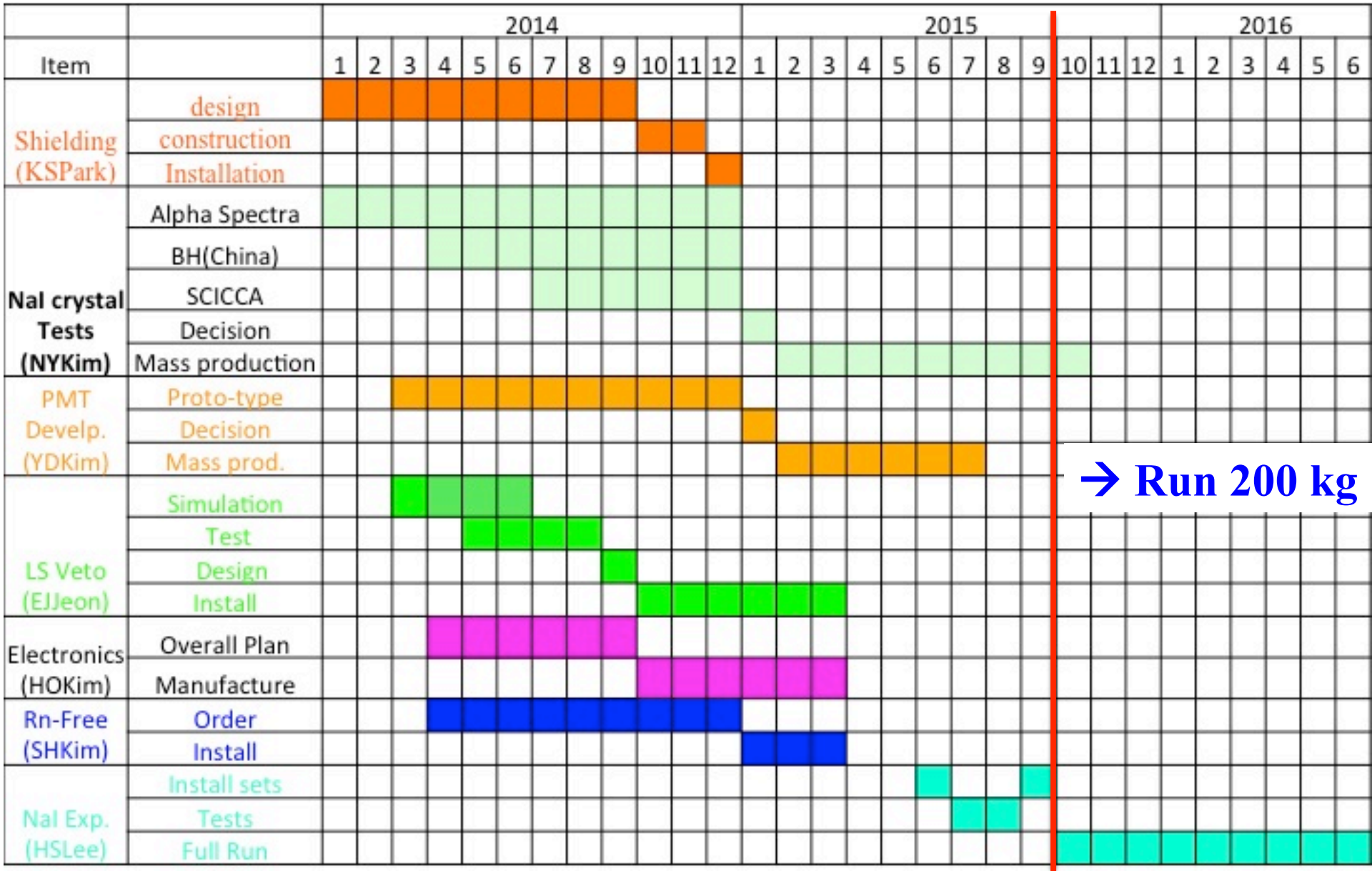
Background rates



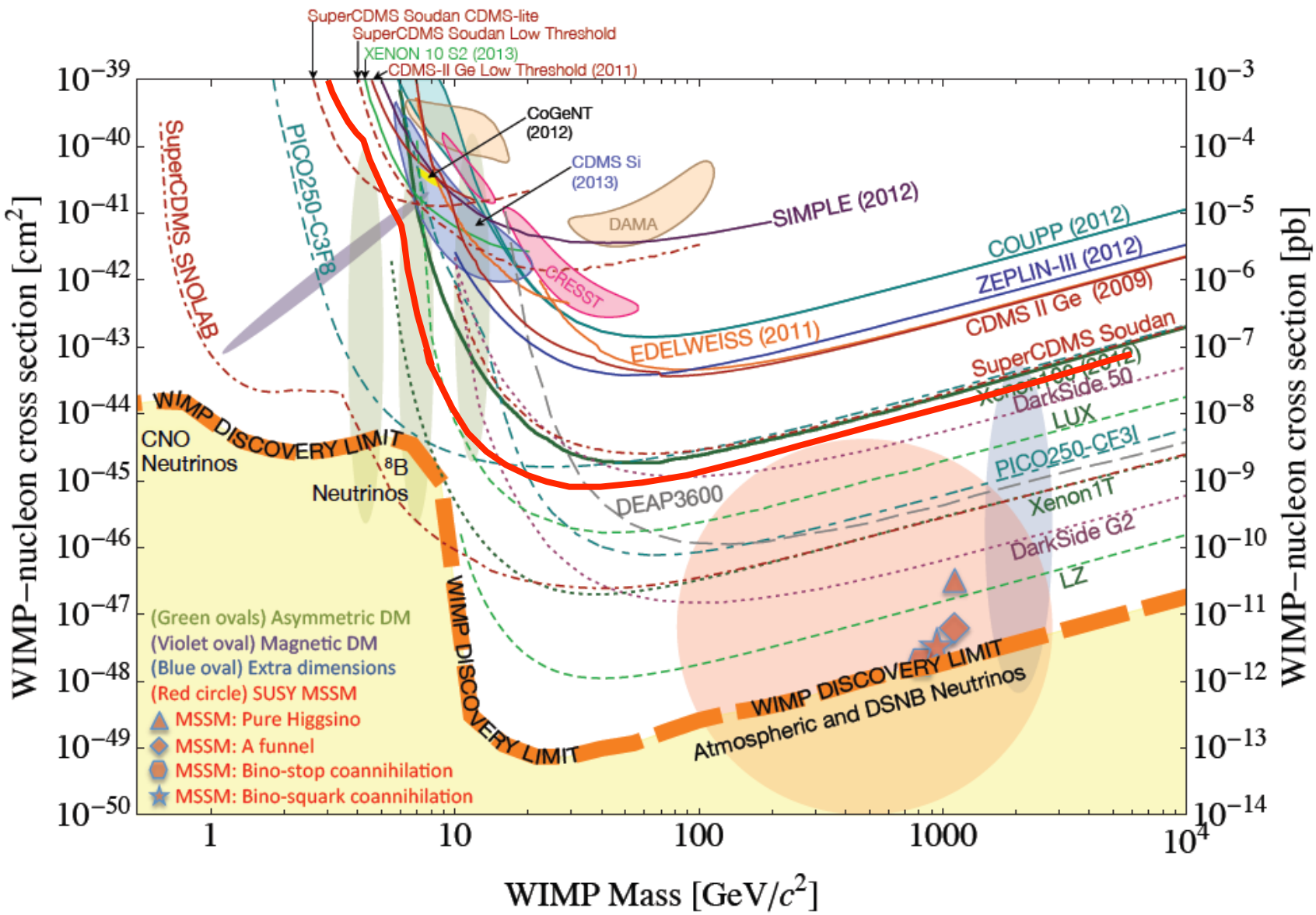
cut:
|t0(PMT0)-t0(PMT1)| <= 0.2 (det)
t0 > 4.0 μS (det)
t1-t0 <= 0.2 (pmt0, pmt1)
nc > 2 (pmt0, pmt1)
X2/X1 < 1.25
-0.6 < asymmetry < 0.6
qc/nc cut
Single hit

- Low threshold down to 1 keV achieved.
- With further powder purification, we expect to reduce the back ground level ~ 0.5 count/keV/kg/day.

Schedule for NaI exp.



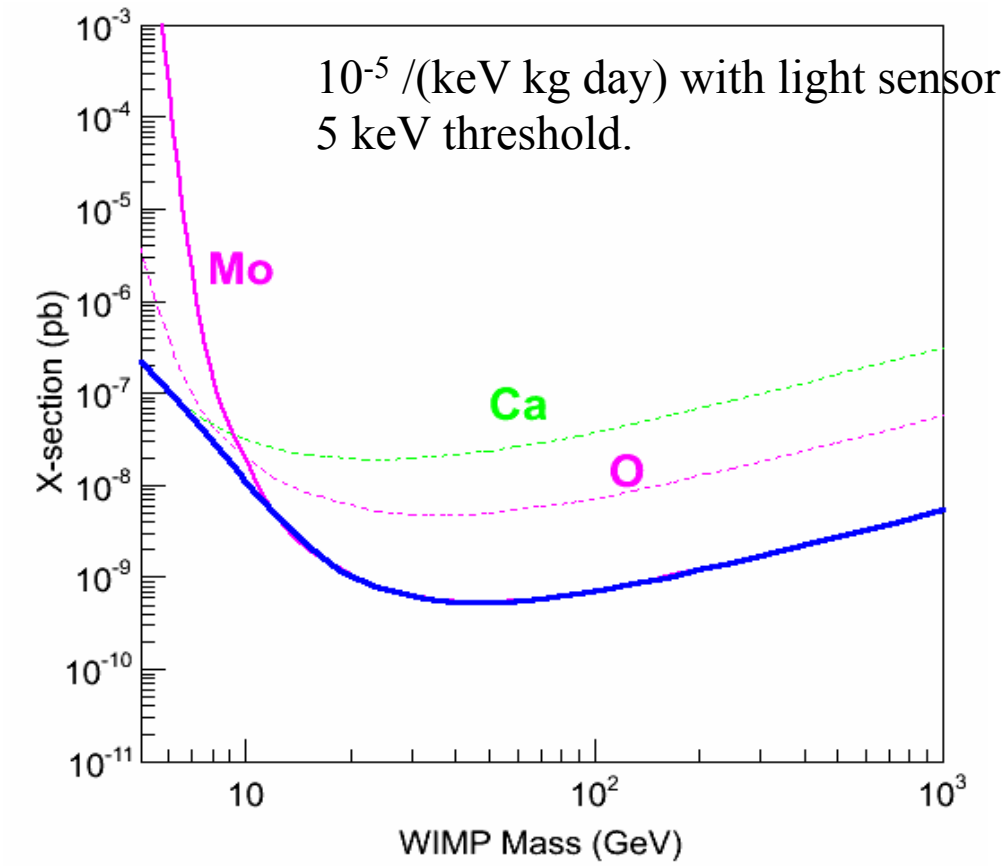
SNOWMASS projection for Dark Matter: next decade



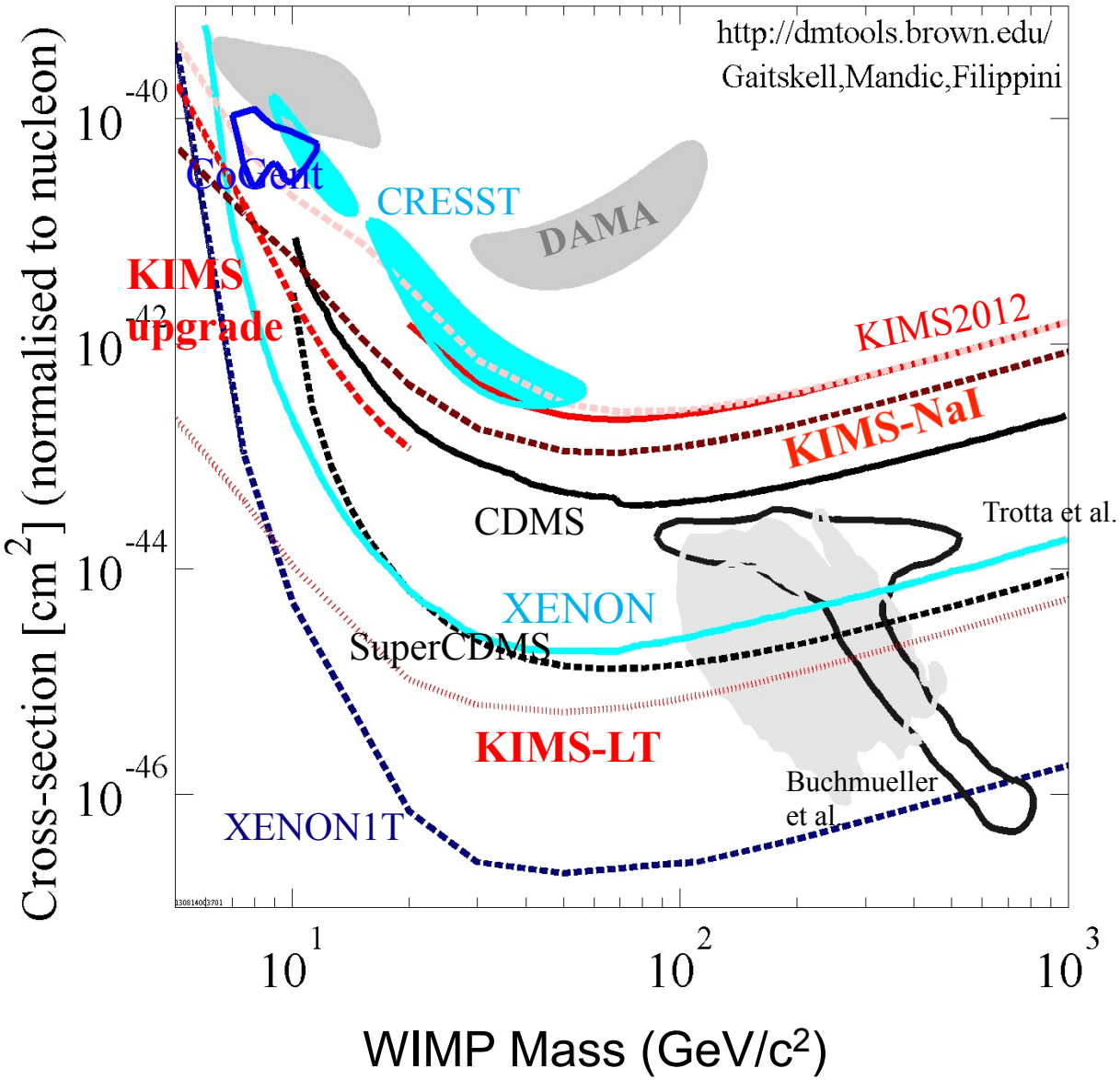
KIMS-LT @ CUP

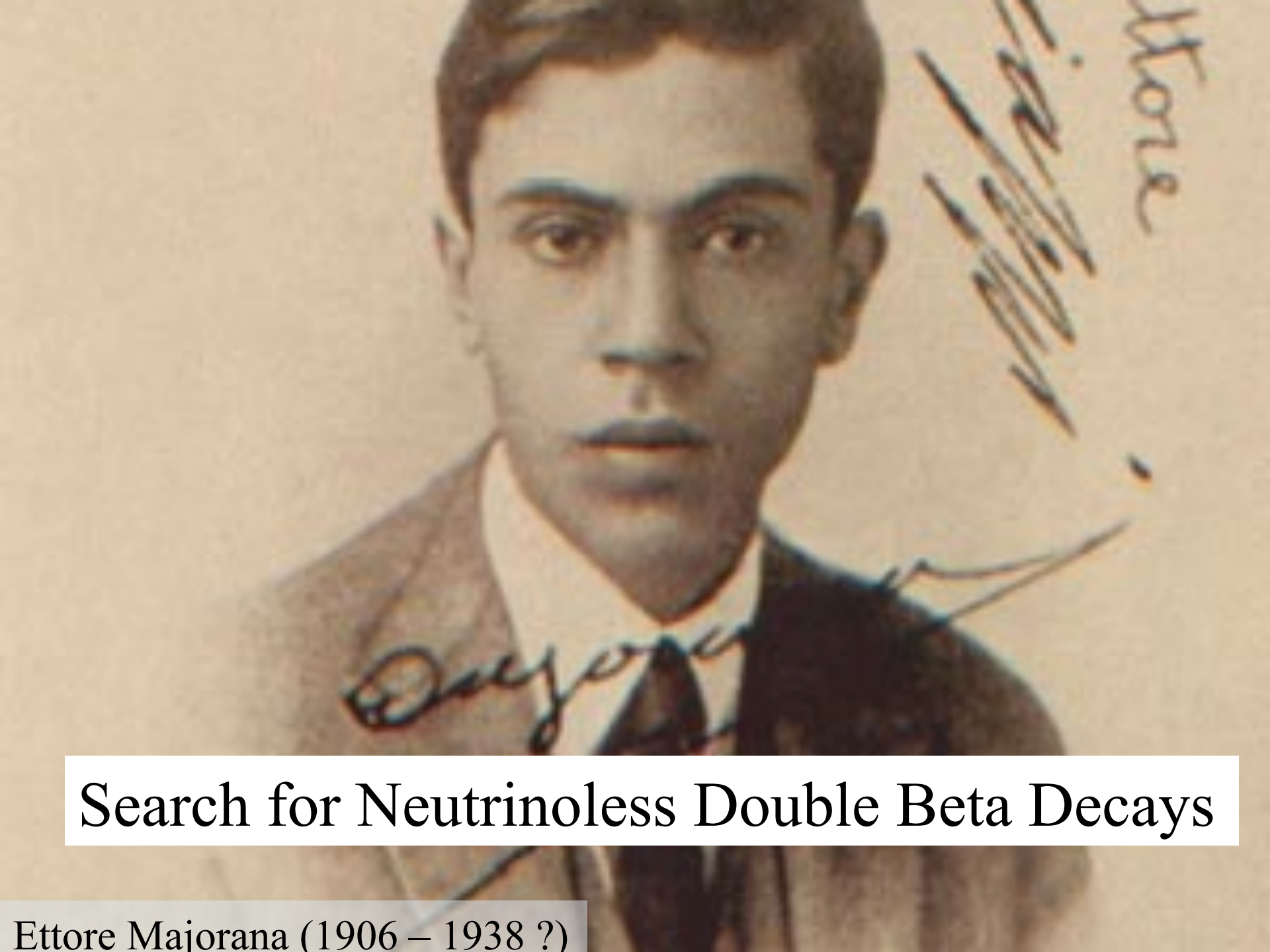
$^{nat}Ca^{nat}MoO_4$ crystals ~ 200 kg year.

- **High sensitivity in low mass WIMP.**
- **2019-2022**



Summary & Sensitivities of KIMS+



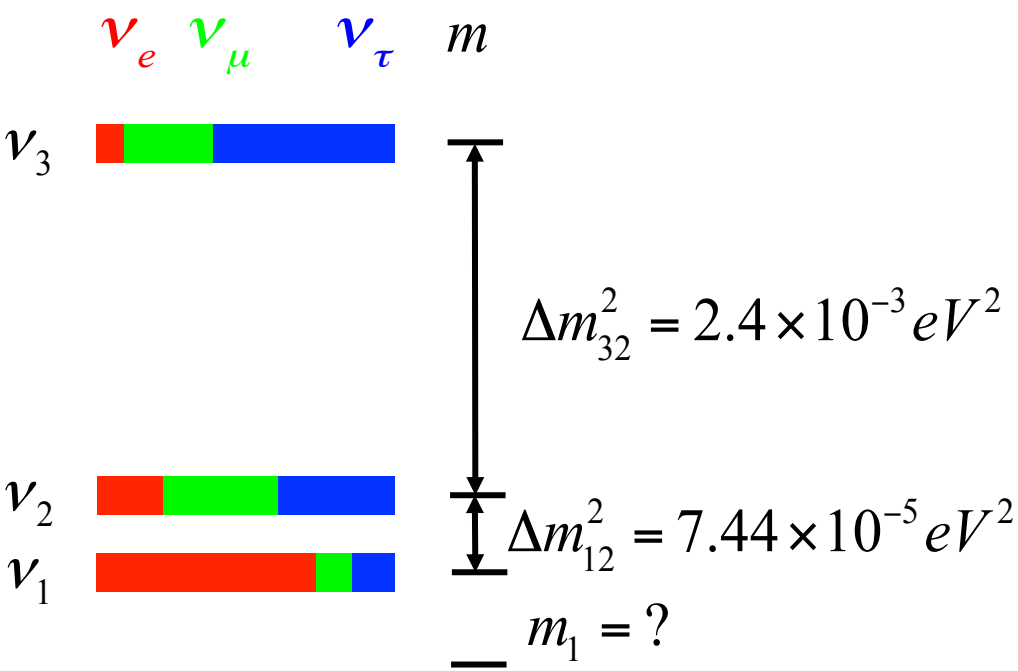


Search for Neutrinoless Double Beta Decays

Ettore Majorana (1906 – 1938 ?)

Neutrinos : mass, mixing, nature

Neutrinos oscillate, so are massive.
At least 3 neutrinos w/ different masses.



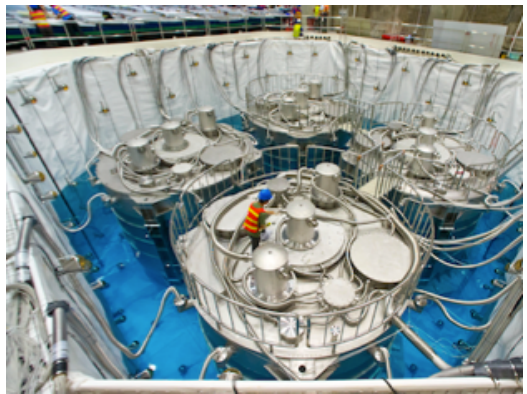
All mixing Angles are measured !

$$\sin^2\theta_{12} = 0.3$$

$$\sin^2\theta_{23} = 0.44$$

$$\sin^2\theta_{13} = 0.023$$

DAYA BAY



RENO

Search for Neutrinoless double beta decay (0νββ)

- **Observation of 0νββ will confirm**

  - Neutrinos are Majorana particles and have Majorana masses.

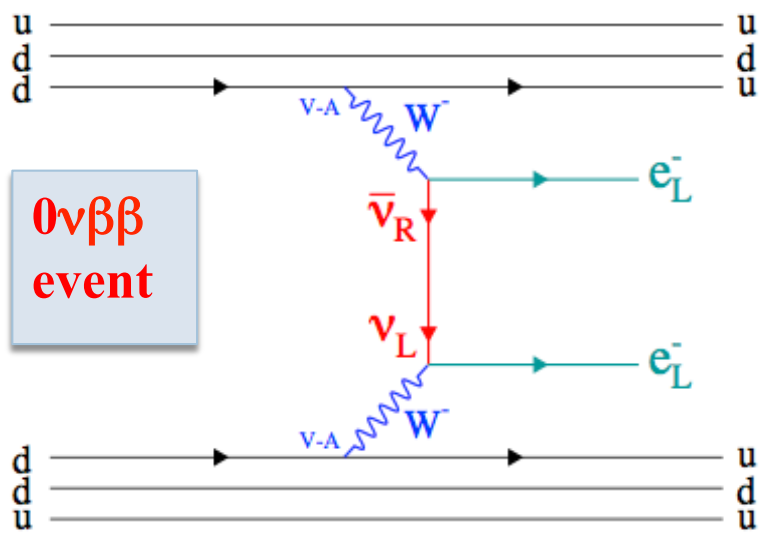
  - Lepton number L is not conserved.

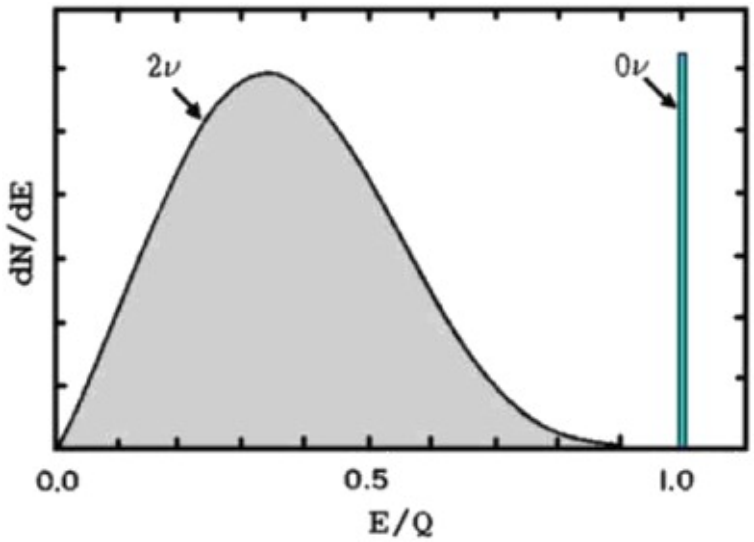
$$m_\nu \approx \frac{m_D^2}{m_N}$$

- **Observation of 0νββ will support more on**

  - See-Saw model of the neutrino mass.

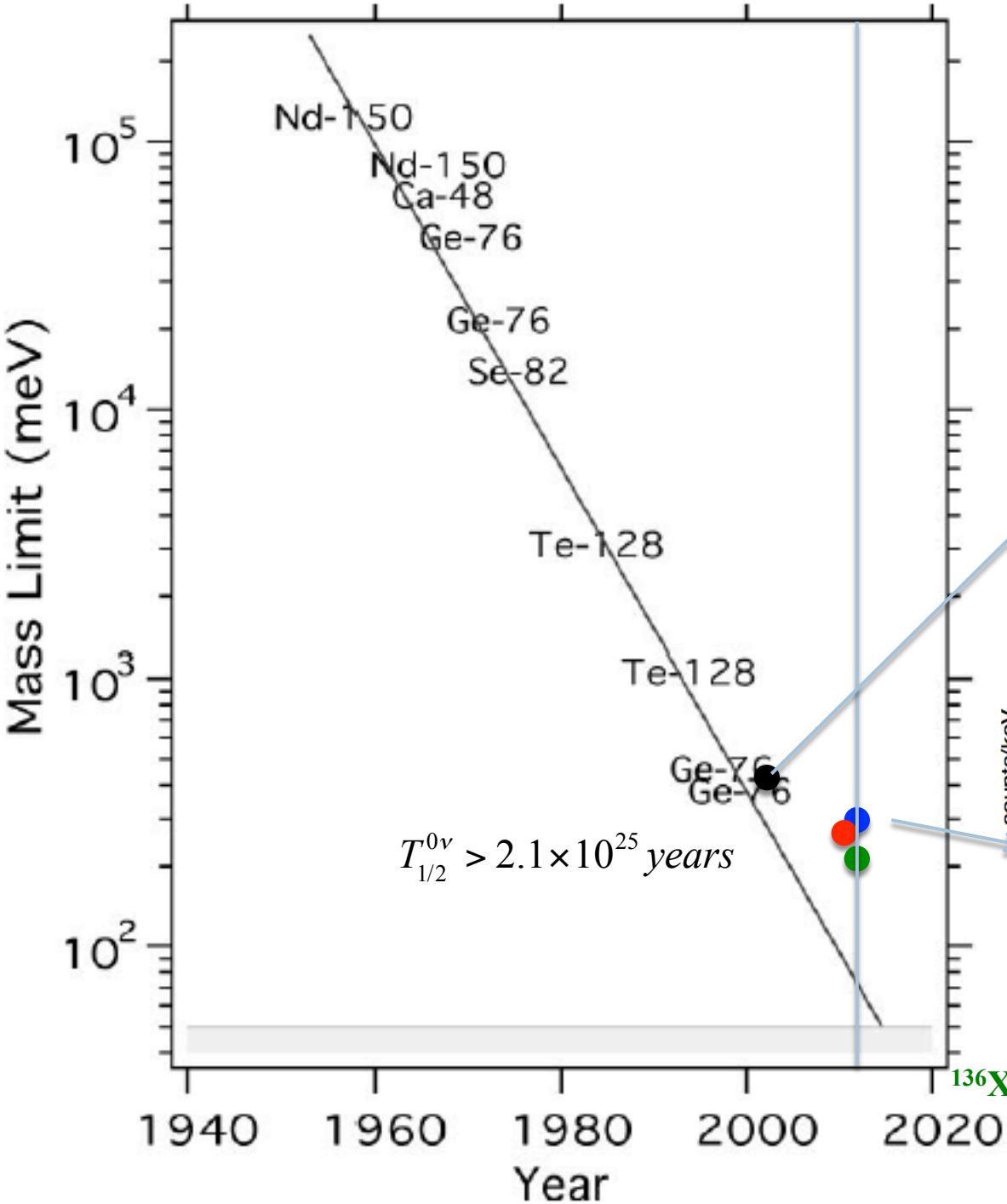
  - Leptogenesis, which may be the origin of the baryon asymmetry of the universe.

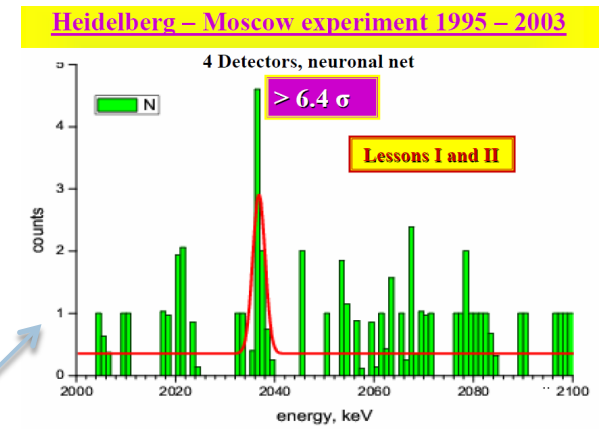


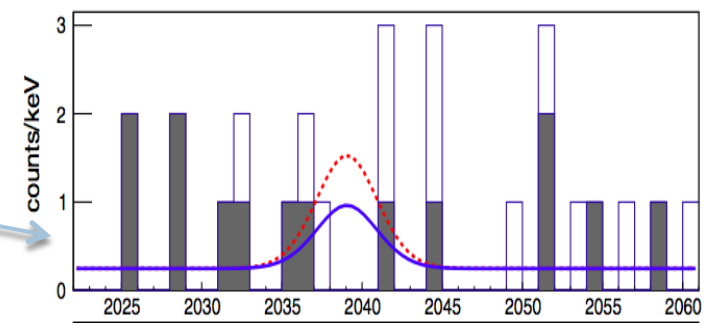


Moore's law for 0νββ ?

Elliott & Vogel, Ann, Phys. (2002)







^{76}Ge, Gerda (0.3) 2013.9

^{136}Xe, EXO (0.26) 2012.7

^{136}Xe, KAMLAND-ZEN (0.19) 2013.2

Which isotope for 0νββ experiment ?

- Half-lifves of 0νββ depends on phase factor and matrix element.

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Phase factor

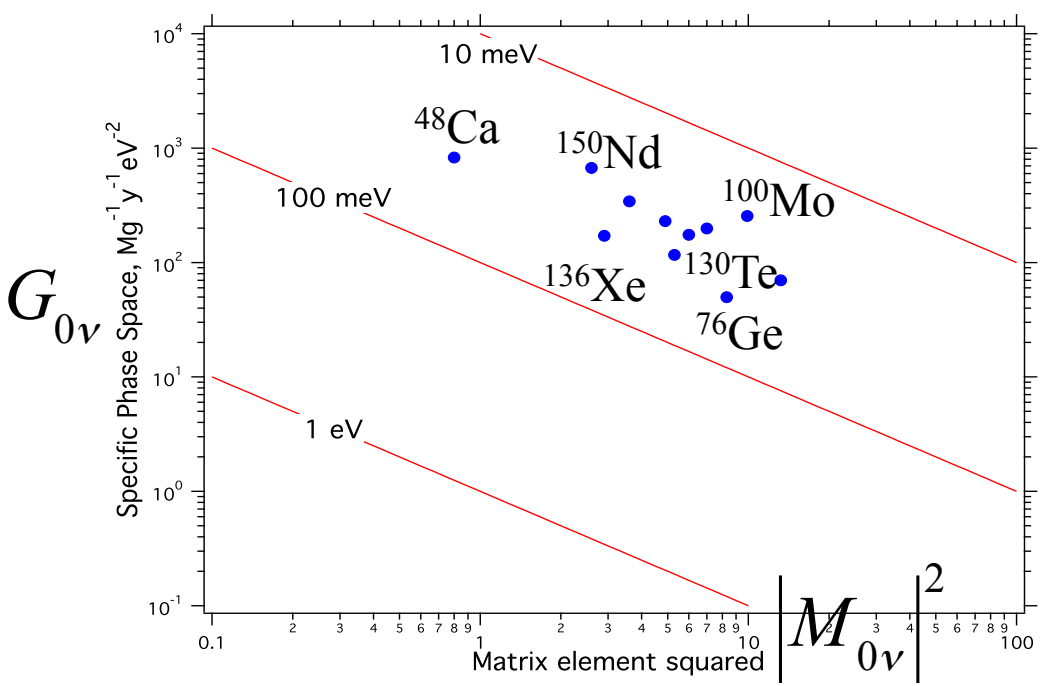
Half-life Measured

Nuclear Matrix Element

Neutrino Mass

$$T_{1/2}^{0\nu} \rightarrow m_{\beta\beta}$$

Lines are for 1event/(ton year)
→ Extremely low background required..



Isotope	Abundance
^{76}Ge	7.61
^{82}Se	8.73
^{100}Mo	9.63
^{116}Cd	7.49
^{124}Sn	5.79
^{130}Te	34.08
^{136}Xe	8.87
^{150}Nd	5.6

AMoRE Goal & Sensitivities

Aim at "Zero Background" experiment. ~ O(1 event)

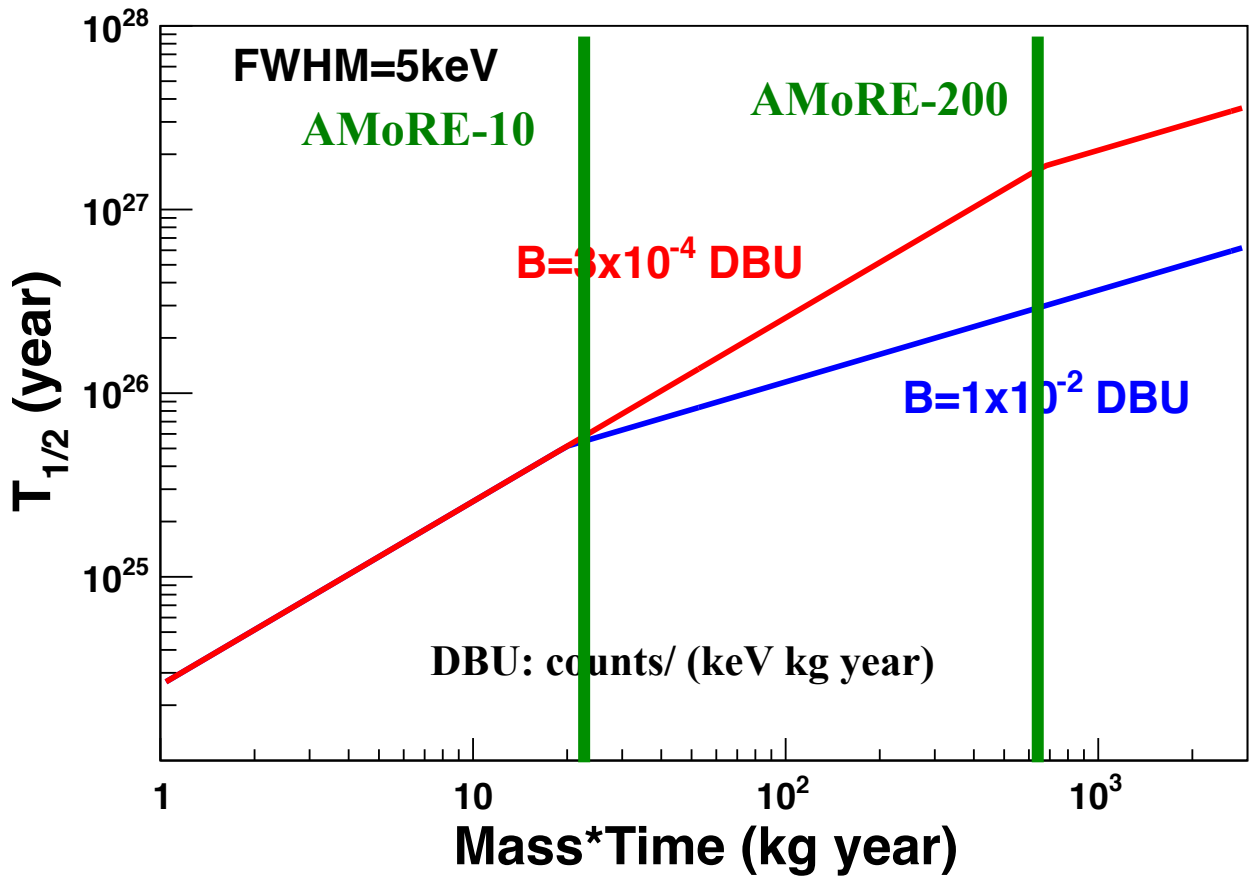
For 10kg CMO a 2 year run w/ 5 keV resolution → 0.01 count/(keV kg year)

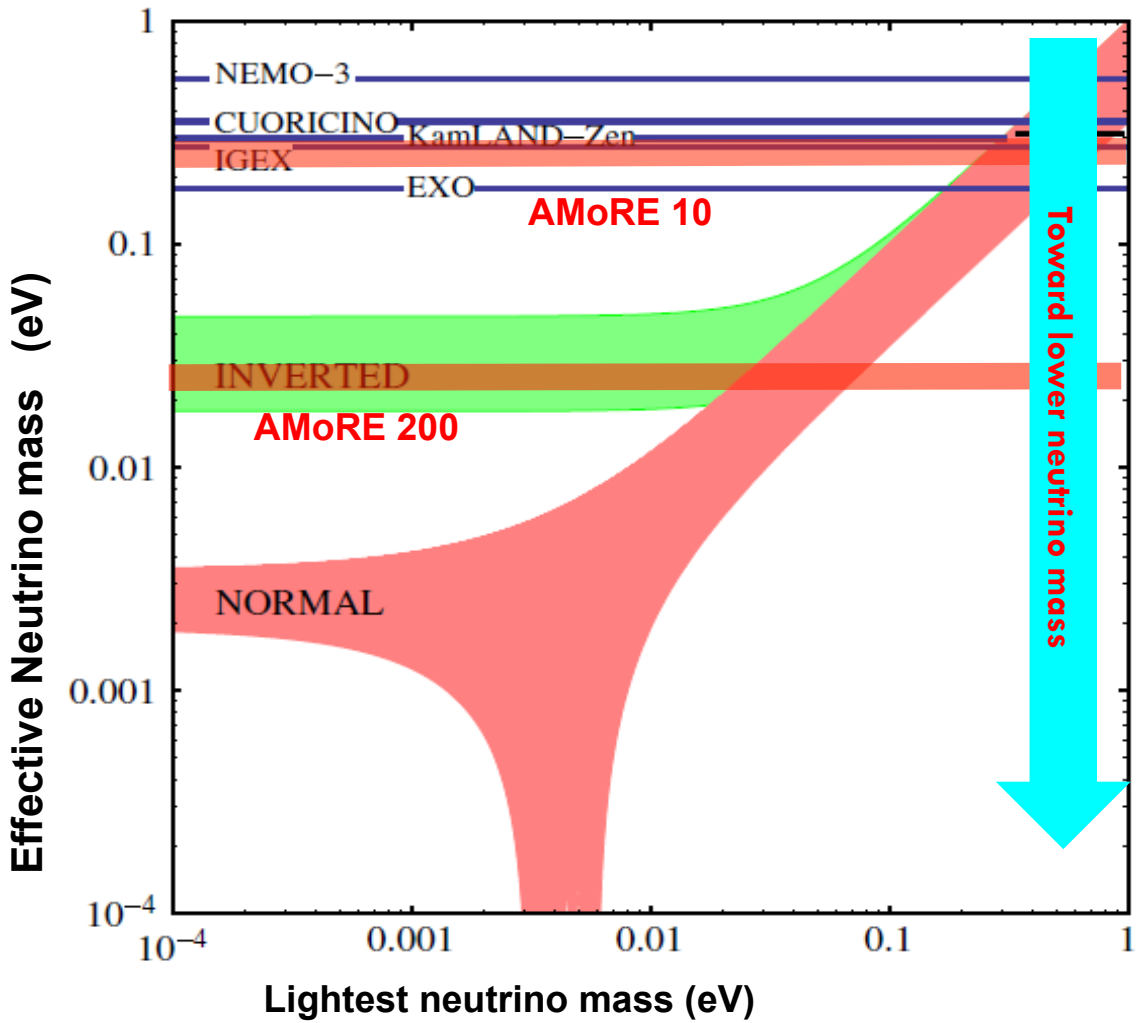
For 200 kg → 0.0003/(keV kg year)

$$S^{0\nu} = (log2)N_a \frac{a}{A} \epsilon \frac{MT}{n_{CL}},$$

Should achieve

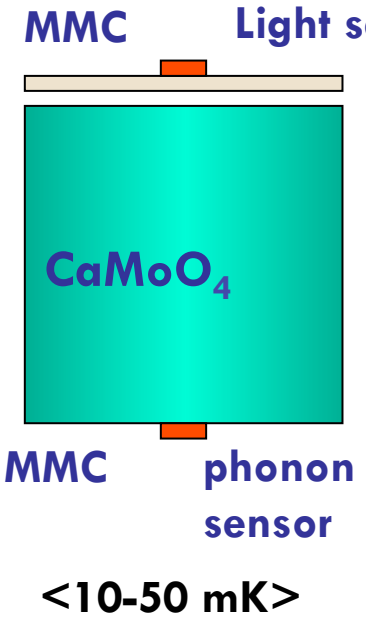
1. **5keV**
2. **Background**




NEMO−3
CUORICINO
KamLAND−Zen
IGEX
EXO
AMoRE 10
INVERTED
AMoRE 200
NORMAL
Toward lower neutrino mass
Effective Neutrino mass (eV)
Lightest neutrino mass (eV)
1
0.1
0.01
0.001
10^{-4}
10^{-4}
0.001
0.01
0.1
1

Overview of AMoRE-200kg project

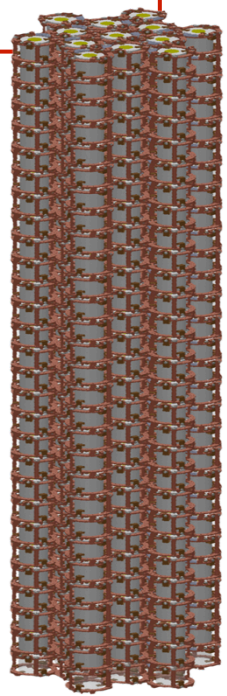
Scintillating Bolometer : $^{40}Ca^{100}MoO_4$ + MMC



$CaMoO_4$: highest light output among Mo based crystals

- Scintillating crystal
- High Debye temperature: T_D = 438 K, $C \sim (T/T_D)^3$
- ^{48}Ca, ^{100}Mo 0νββ candidates

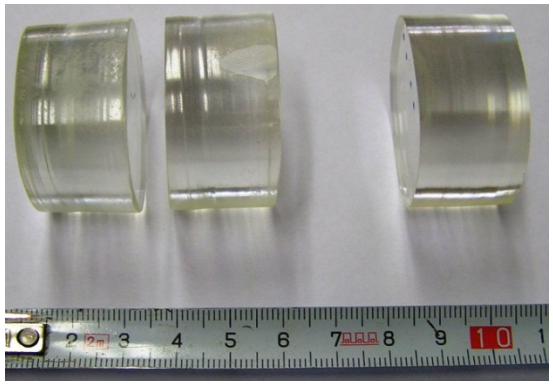
Detector Array 200kg



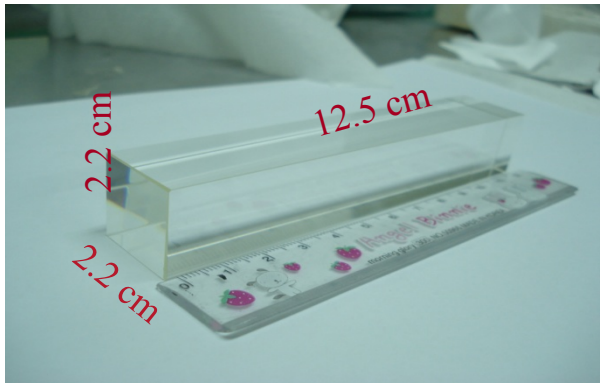
AMoRE-200 is the most massive experiment with enriched isotope having Q value > 3MeV.

$CaMoO_4$ crystal development

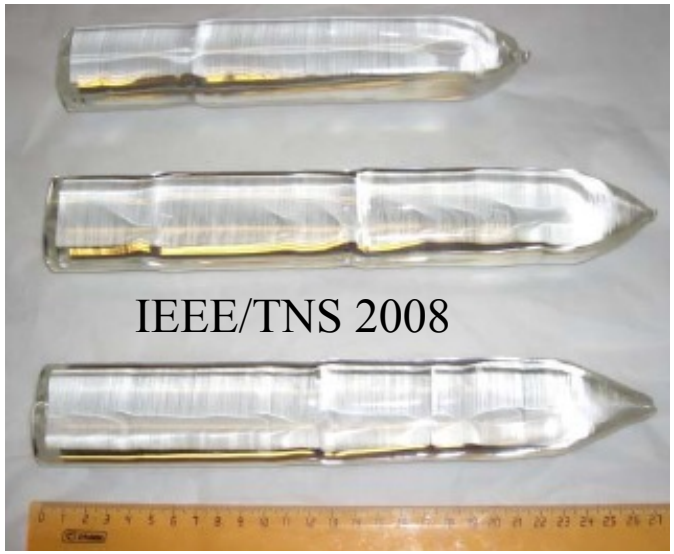
Korea(2003)

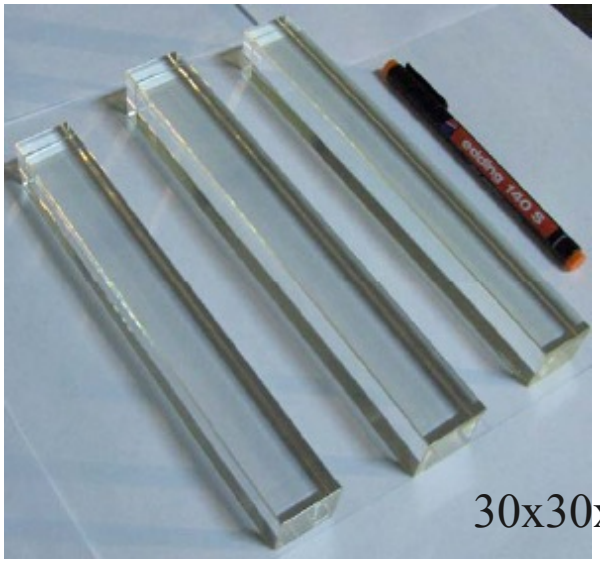


Ukraine-CARAT(2006)



Russia(2006)





30x30x200mm

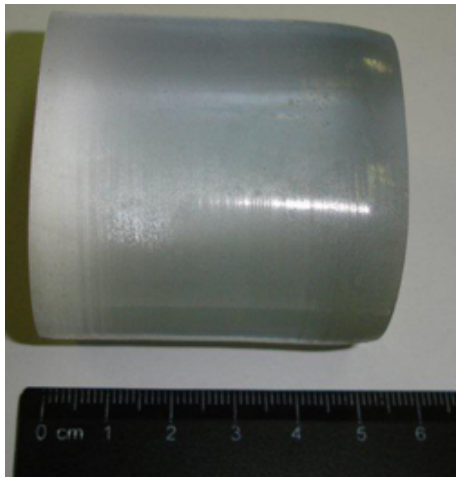
$^{40}Ca^{100}MoO_4$ crystals from Russia

- SB28

weight 196 g

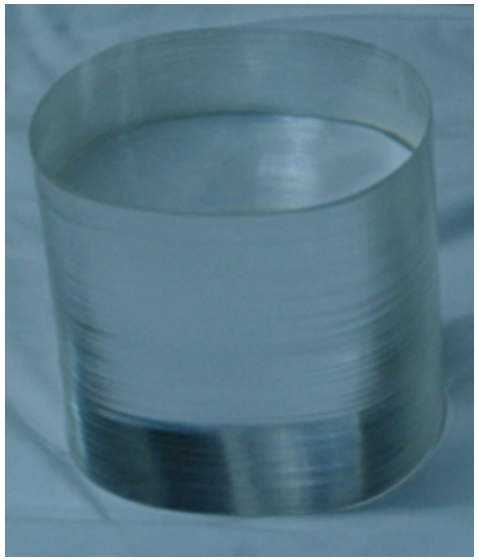
- SB29

weight 390 g



- S35

weight ~300 g

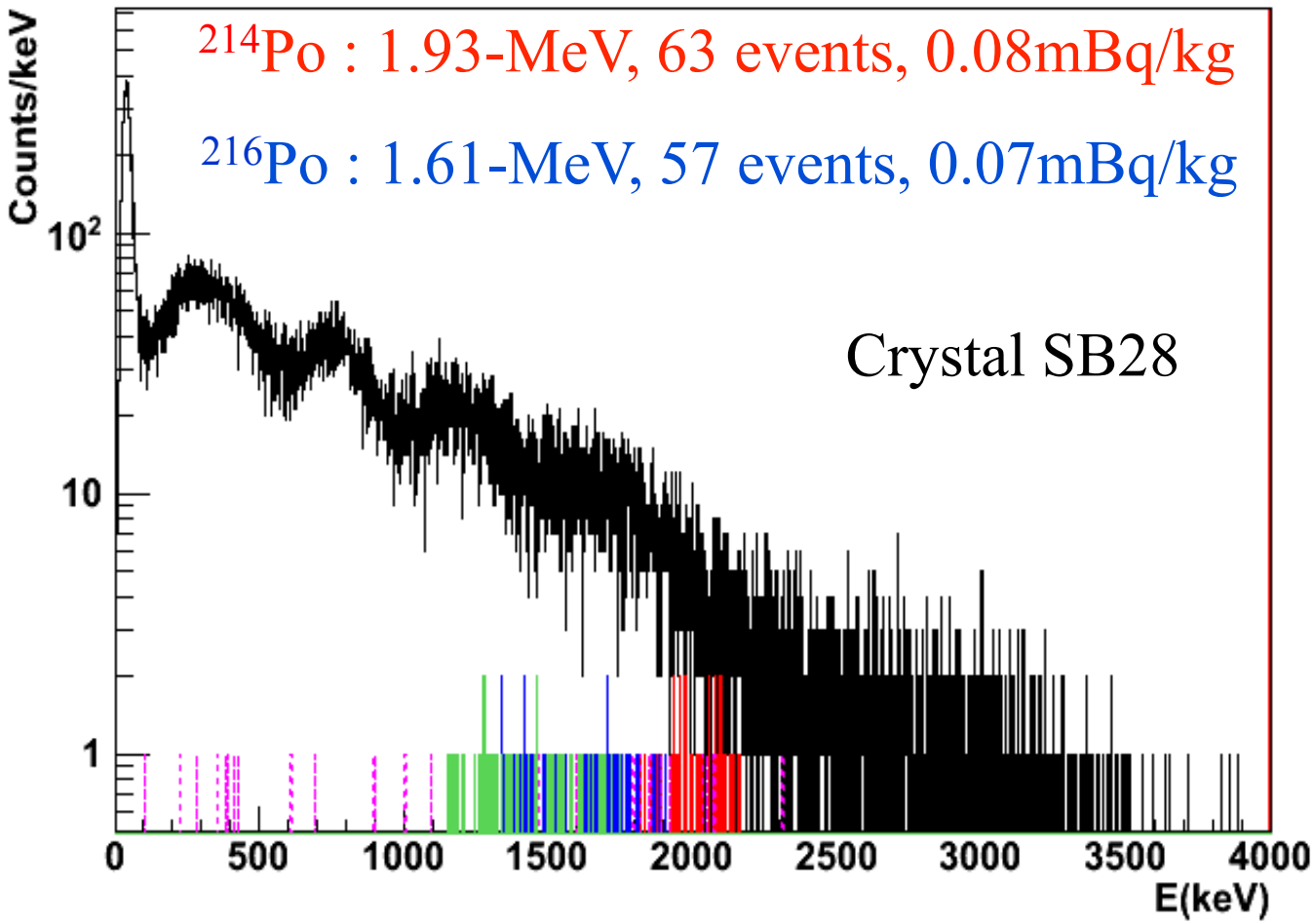


Simulation on Material Backgrounds

Background source	Activity Goal [μBq/kg]	Background [10^{-4} DBU]	After PSD
^{208}Tl, internal	10	0.36	0.36
^{208}Tl, in copper	16	0.22	0.22
^{212}BiPo, internal	10	0.08	<0.01
^{212}BiPo, in copper	16	0.36	<0.04
^{214}BiPo, internal	10	0.11	<0.01
^{214}BiPo, in copper	60	1.8*	<0.18
^{88}Y, internal	20	0.19	0.19
Random pileups from 2ν2β	**8.7×10^{3}**	**3.1**	**1.2**
Total		4.3	<2.2

* Can be reduced further by teflon coating on the Cu surface.

Internal backgrounds of $^{40}Ca^{100}MoO_4$ crystals



Factor 7 further reduction should be done for AMoRE-200.

Crystal Growing Facility

Motivation : difficulty to find a reliable and economical company. Will develop chemical purification and crystallization ourself insi de the center. (4 furnaces)

Czochralski Furnace

Bridgman Furnace

1st crystal (Sapphire) grown ~ 30kg !

Kyropoulos Furnace

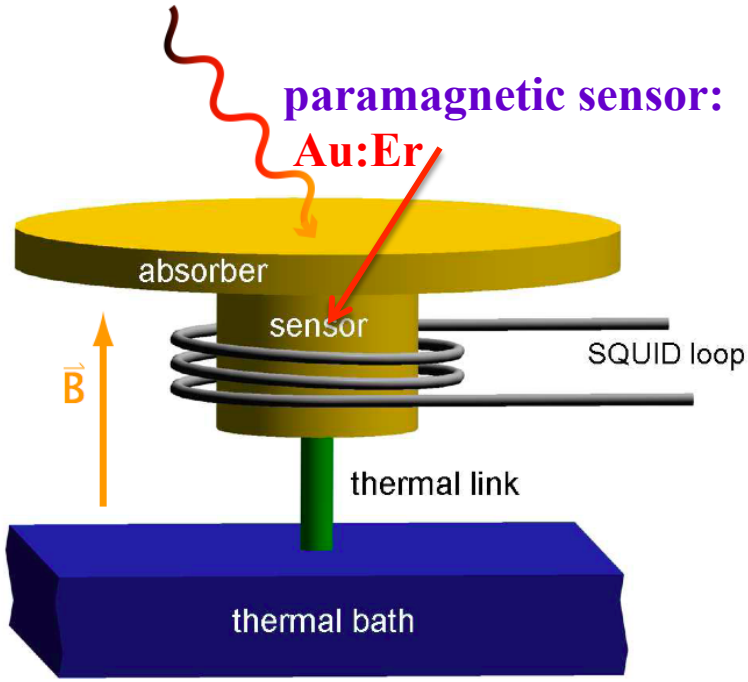
MMC (Metallic Magnetic Calorimeter)

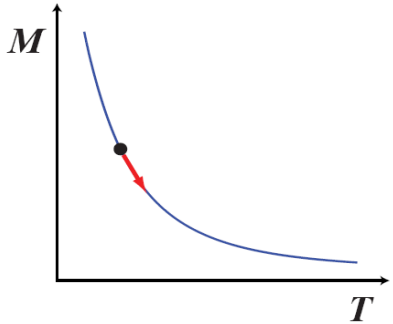
Principle of operation

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

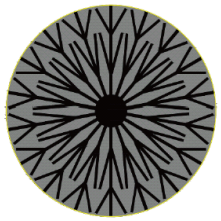
- **Fast signal. (critical for lower 2νββ random coincidence.)**
- **Fairly easy to attach to absorber.**



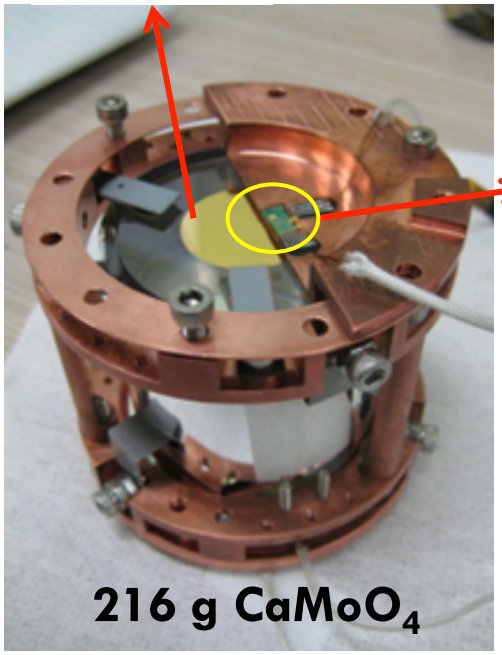


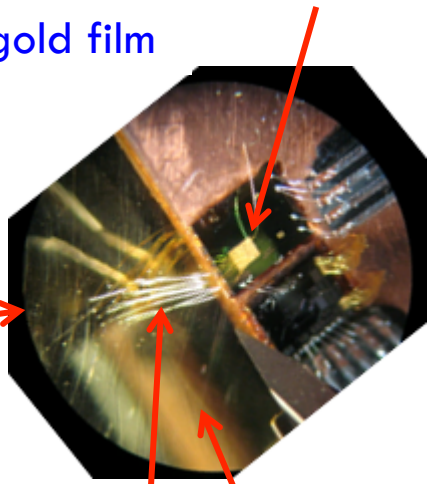
Advantage of MMC

Phonon sensor for AMoRE



Phonon collector
Patterned gold film

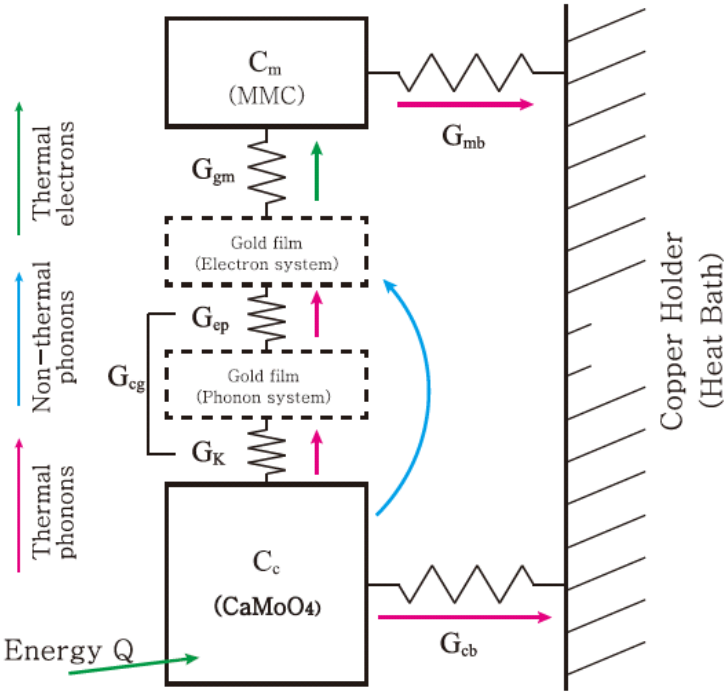


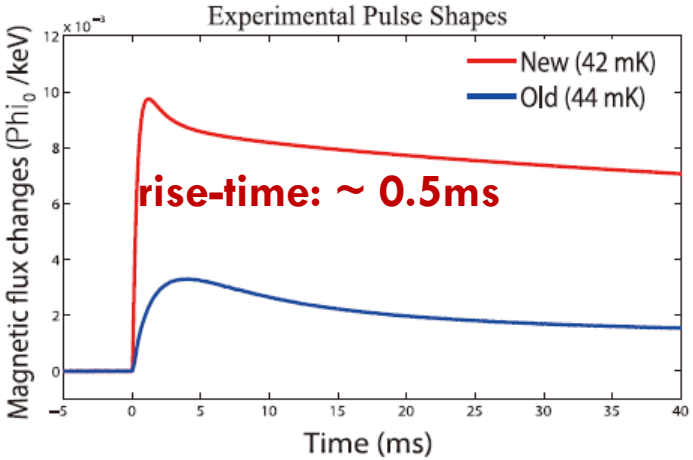


MMC

Gold film

Gold wires
(thermal connection)



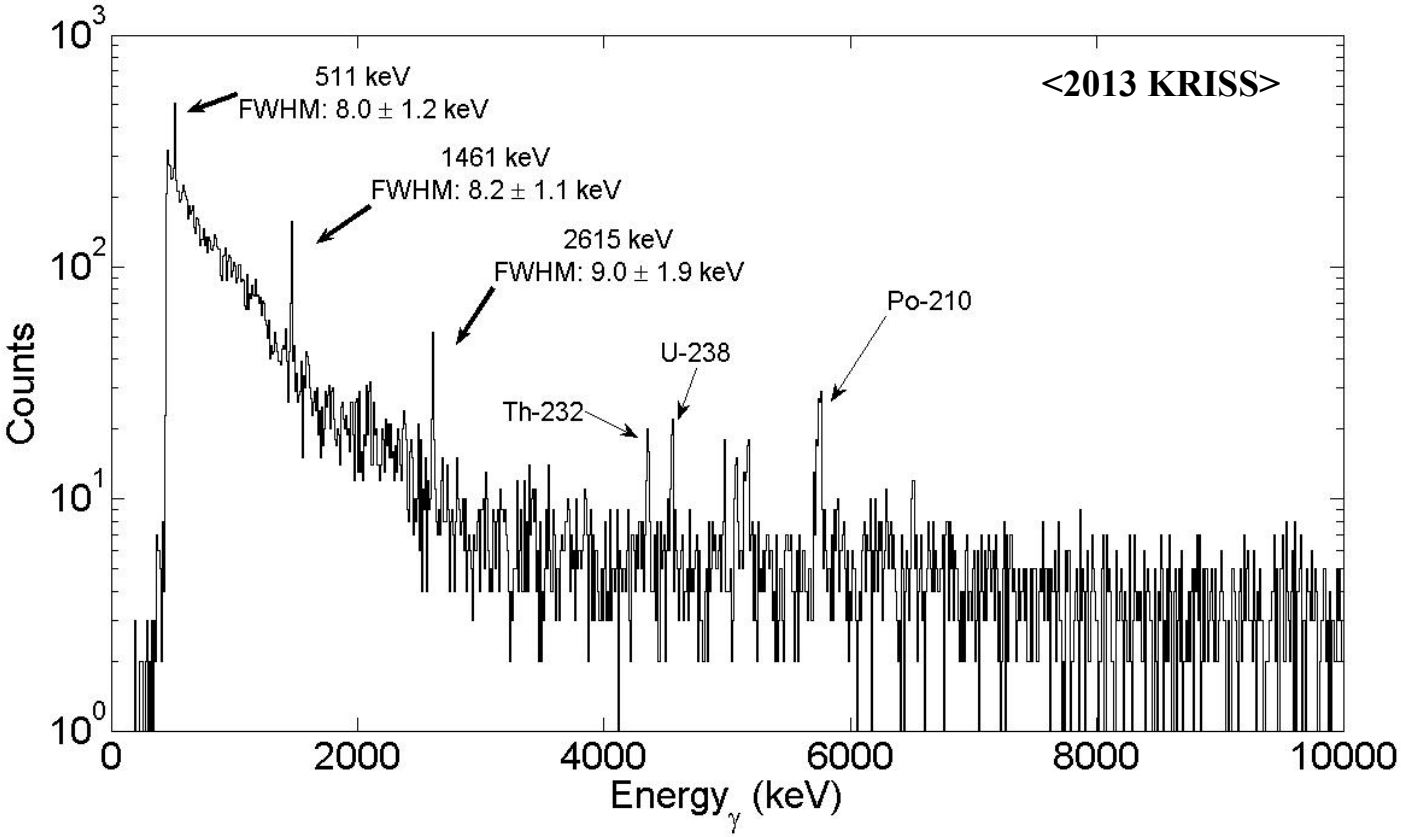


We measure both thermal an
d athermal phonons.

<Heat flow optimization>

Detector R&D in an over-ground lab

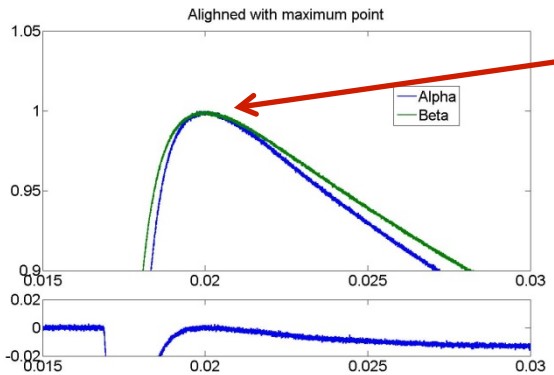
216 g $CaMoO_4$(natural) with a phonon sensor only.

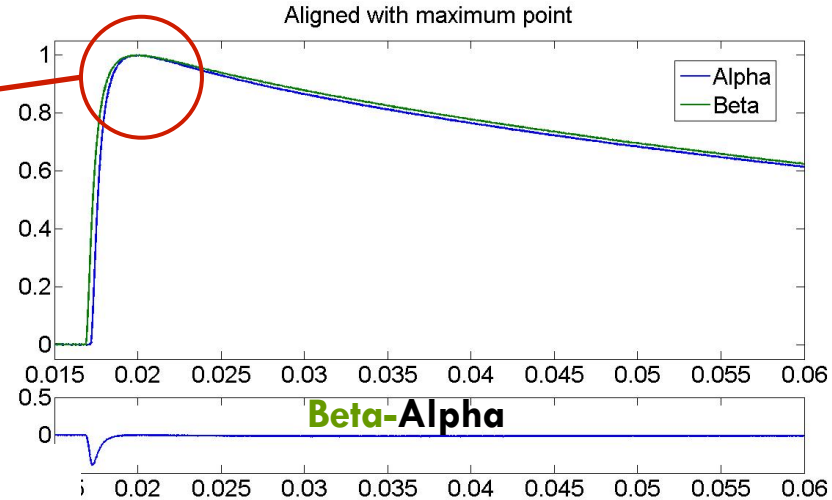


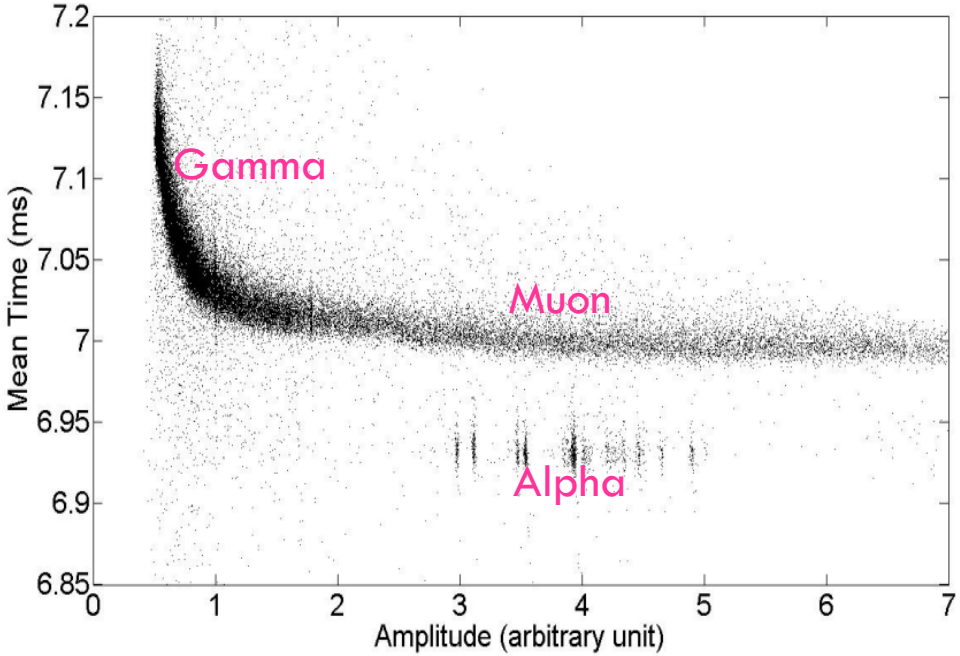
Energy (keV)	511	1461	2615
FWHM (keV)	8.0 ± 1.2	8.2 ± 1.1	9.0 ± 1.9

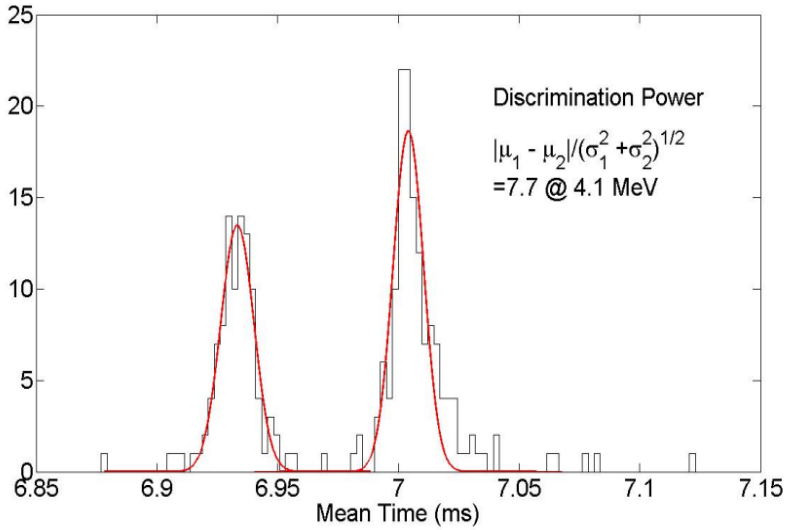
Pulse Shape Discrimination

α and β events show different pulse shapes in phonon signals.

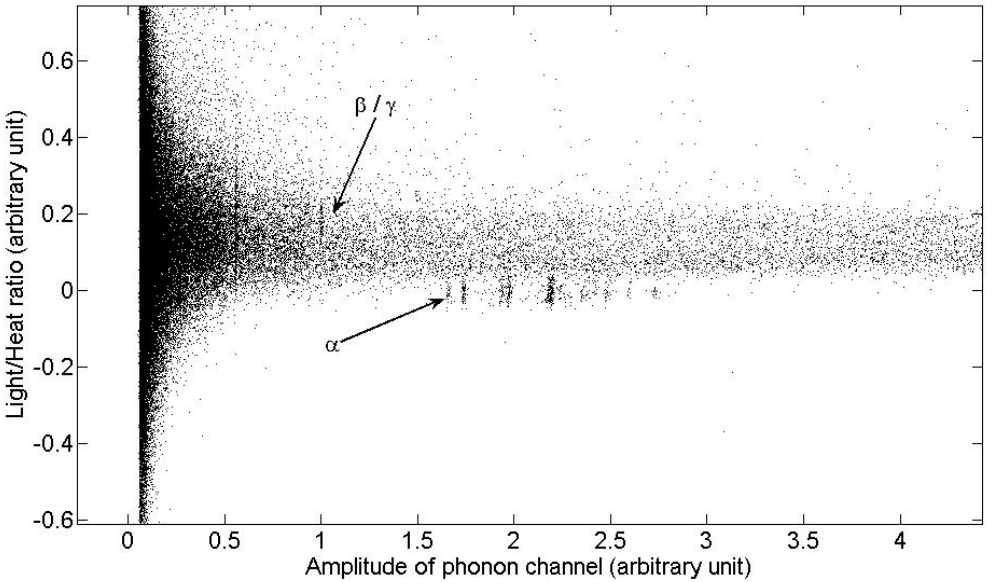


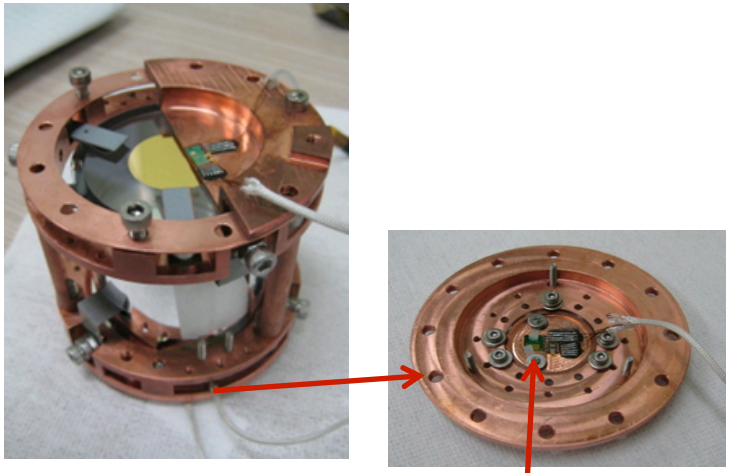






Photon Detector Measurement

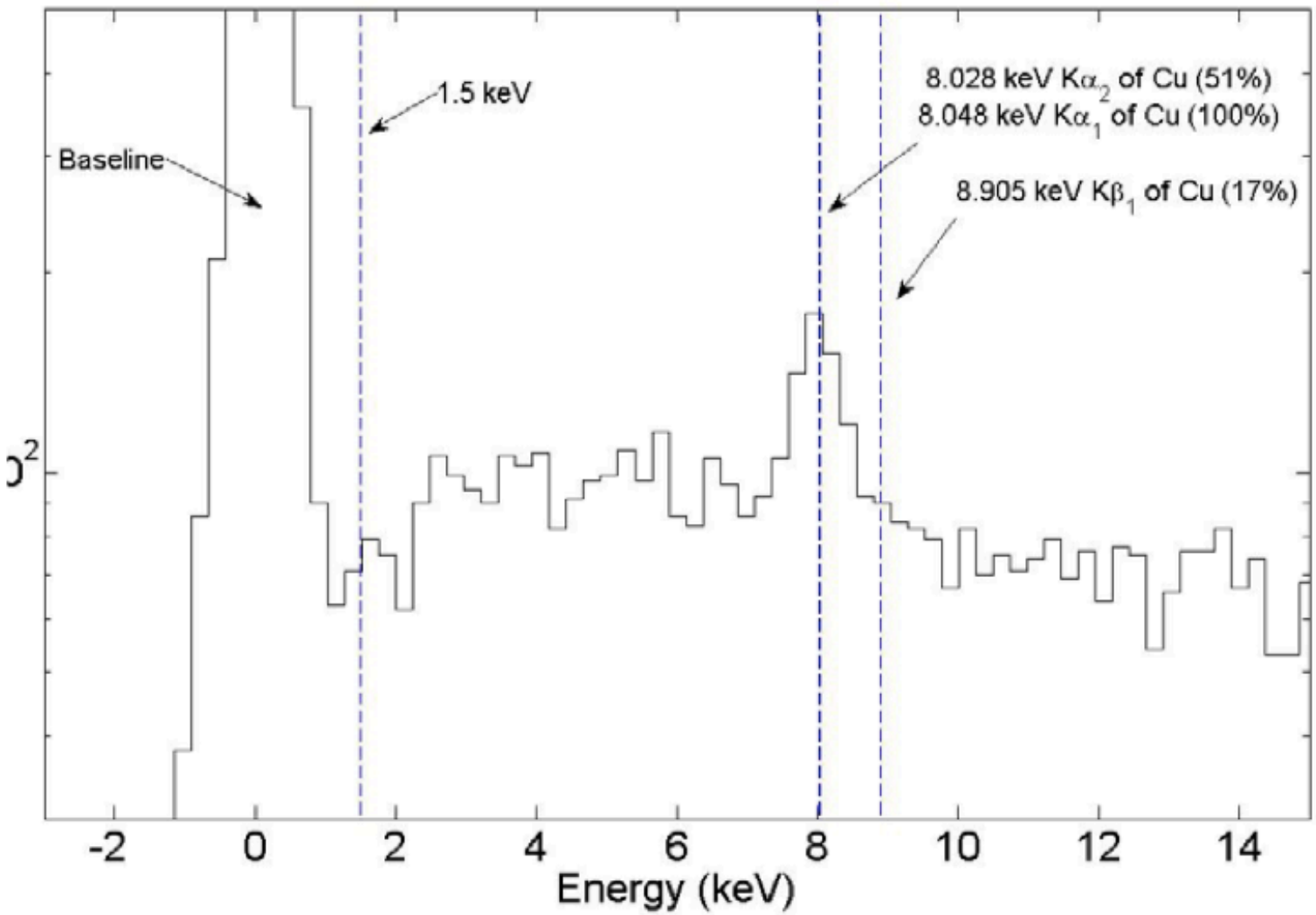




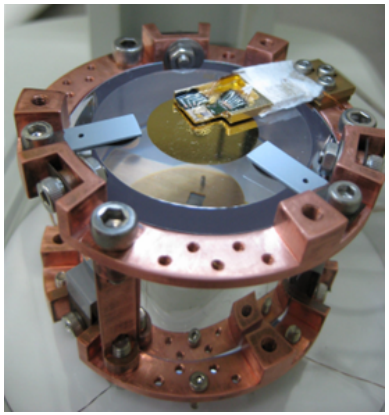
Photon detector

- We measured small photon signals because of small covering area (~2 0 mm^2).
- α and β particle events show different light yields.
- Now we are developing photon detectors with 1-2 inch Ge wafers.

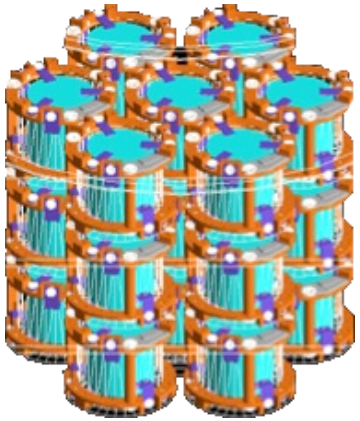
Low energy for DM



Now and Future AMoRE

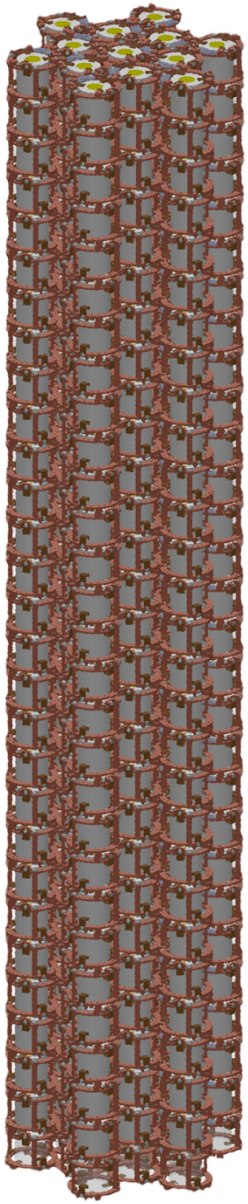


216 g
<Now, 2013>



CMO: ~ 300g
5 layers-7 columns

<AMoRE10, 2015~6>



Each Cell : D=70 mm, H=80 mm.
CMO (D=50mm, H=60mm, 506g)
30 layers(2.4 m height)-13 columns
or 20 layers(1.6 m height)-19 columns

<AMoRE200, 2018~9>

Summary of the AMoRE project

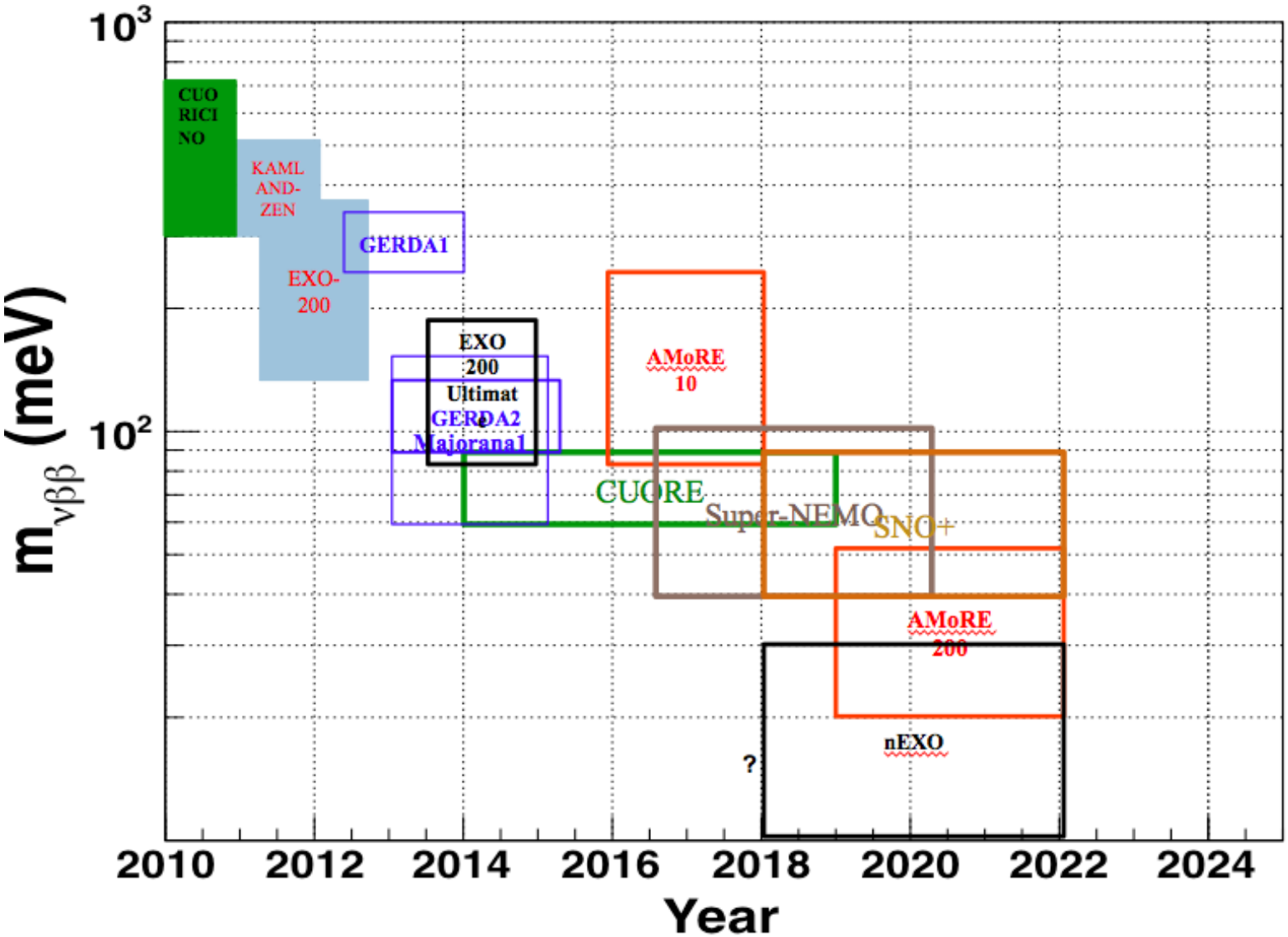
- Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals
- ^{100}Mo enrichment = 97%
- Temperature: 10-50 mK
- Energy Resolution: 5 keV @ 3 MeV

  (Now ~9keV w. one phonon only in over-ground)
- Single Detector Mass: 300-500g
- Location: AMoRE10 at Y2L, AMoRE200 at CUPID

	Phase I	**Phase II**
Mass	10 kg	200 kg
Background (keV kg year)$^{-1}$	10^{-2}	3×10^{-4}
Sensitivity(m_{ee}) (meV)	80-250	20-50
Schedule	in 3 years	in 8 years

Future experiments will reach 30meV ~ 2020.

Double Beta Decay Moor's Law is to be recovered as silicone industry.



Summary

- At CUP, we are preparing an NaI(Tl) exp to verify DAMA's claim unambiguously.
- A large scale low temperature scintillating phonon detector will be developed.
- AMoRE-200 experiment is a massive detector with Q-value>3MeV to reach inverted mass hierarchy.
- Please contact with me if you are interested in any of these experiment.