Development of low background CsI(Tl) and NaI(Tl) crystals for WIMP search

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On behalf of the KIMS Collaboration

Low Radioactivity Techniques 2015

KIMS (Korea Invisible Mass Search)

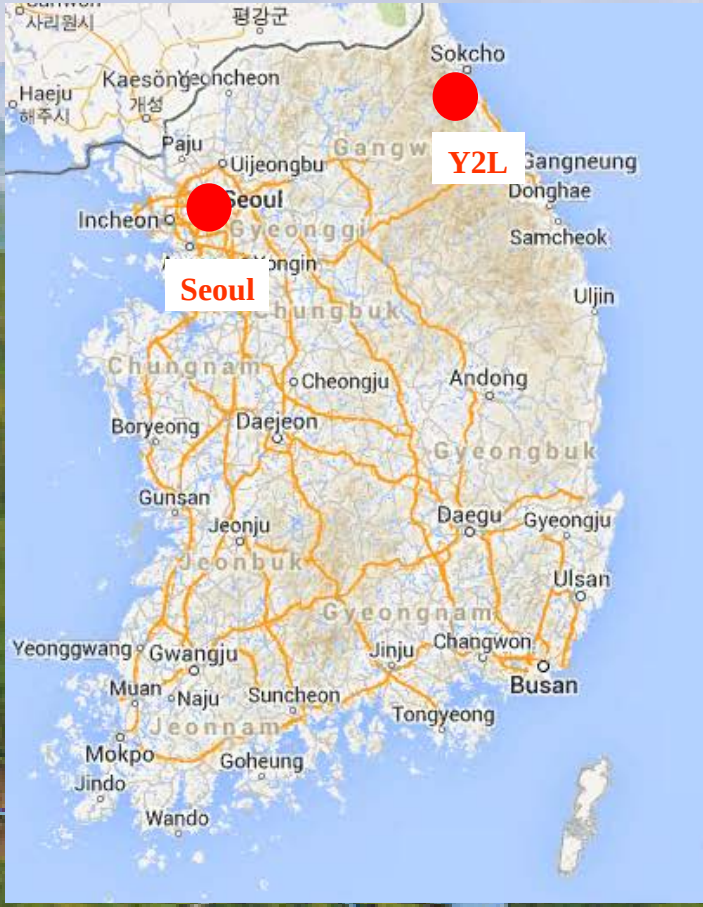
- Dark matter search at Yangyang underground laboratory
  - ❖ May have new laboratory in Samcheok
- Funded by National Research Foundation of Korea (2000)
  - ❖ Dark matter (DM) search with CsI(Tl) crystals (KIMS-CsI)
- Establishing the Center for Underground Physics (CUP) in the Institute of Basic Science (IBS) (2013)
  - ❖ Upgrade of KIMS-CsI
  - ❖ DM searches with NaI(Tl) crystals (KIMS-NaI)
  - ❖ DM searches with low temperature detector (KIMS-LT)

Yangyang Underground Laboratory

(Upper Dam)

Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant

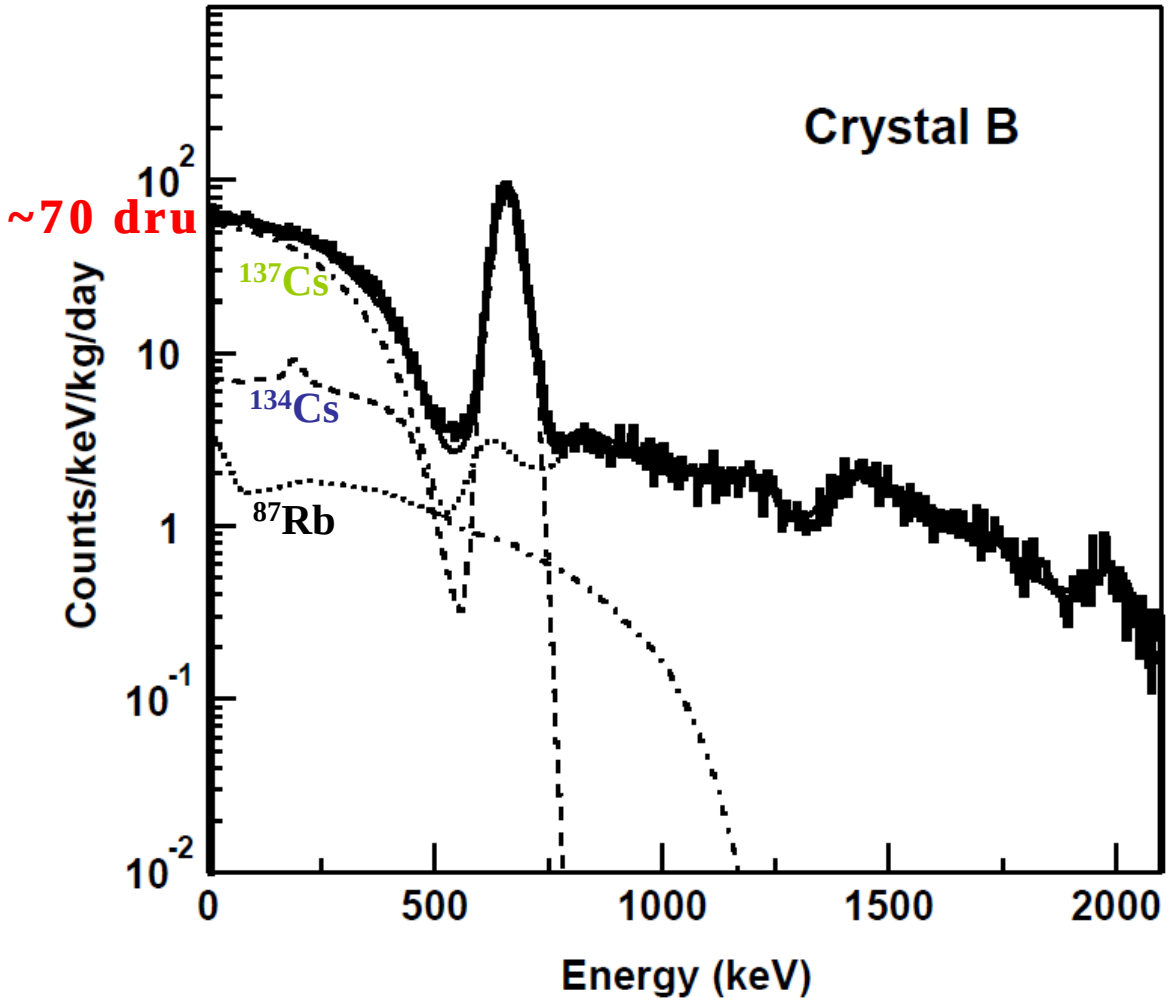
700 m
(Power Plant)

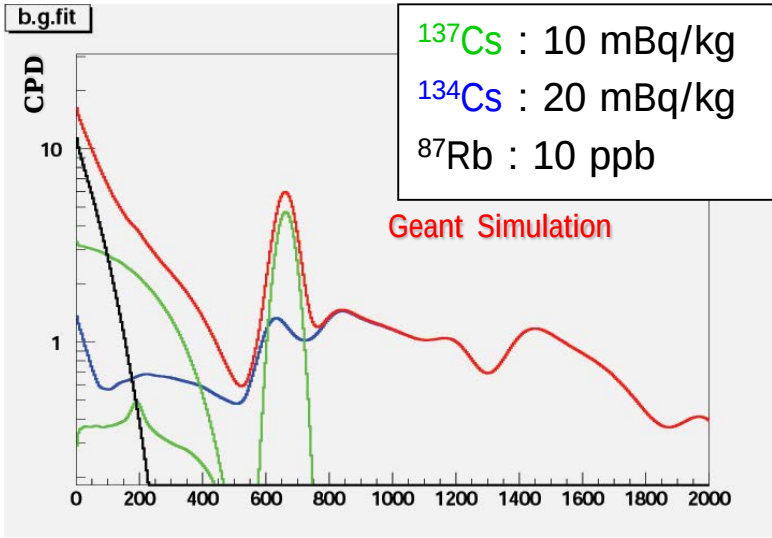


Minimum depth : 700 m
Access to the lab by car (~2km)

Internal background of CsI(Tl) crystals at beginning

The lowest background CsI(Tl) crystal in the market

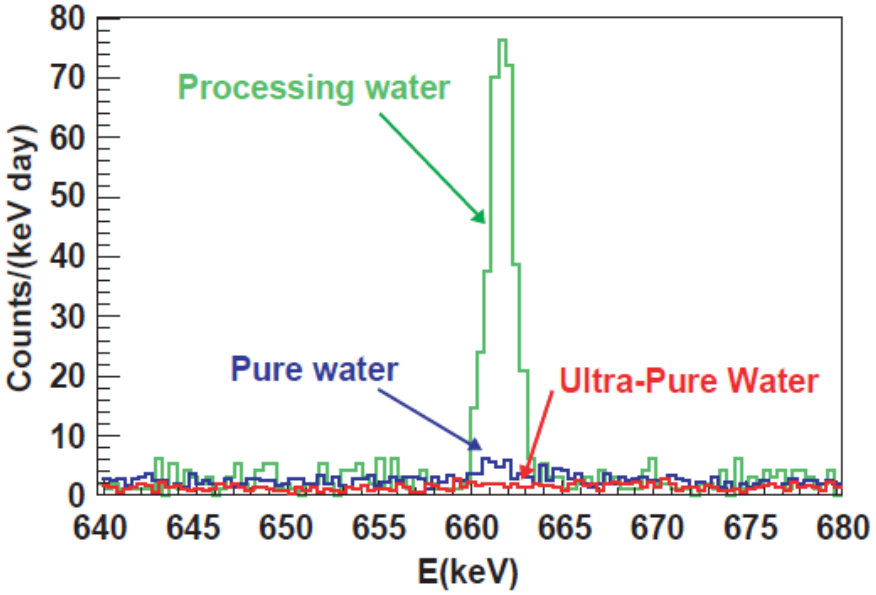




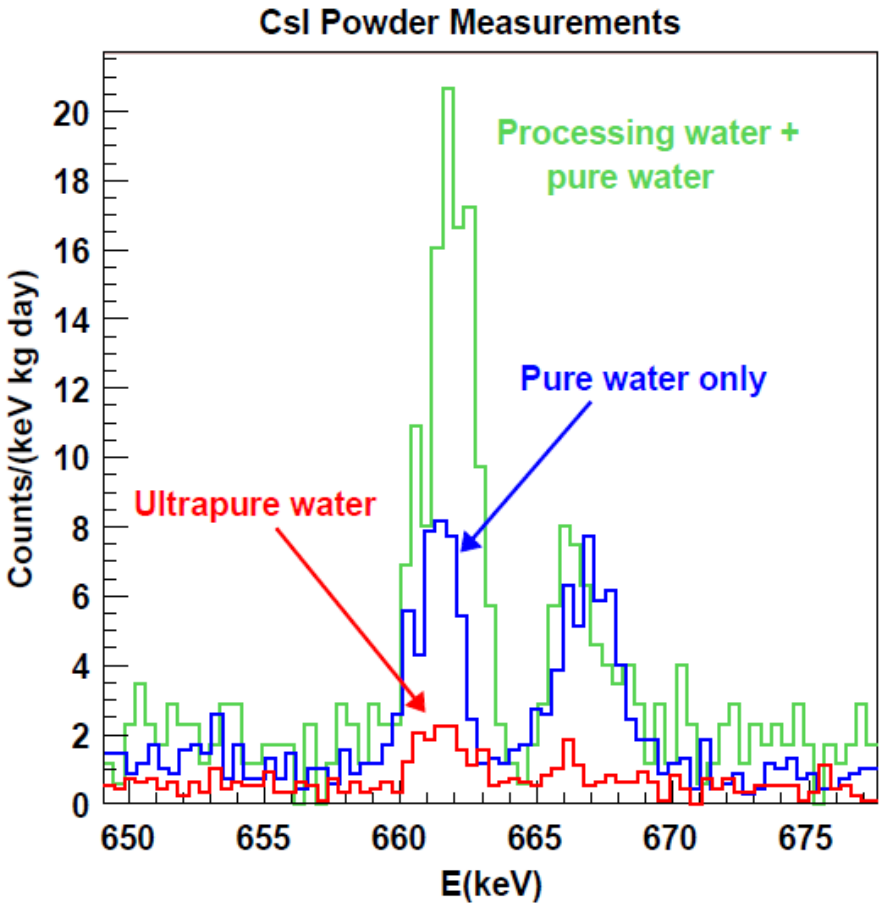
Nucl. Instrum. Meth. A 500 (2003) 337

^{137}Cs reduction

- Water is main source

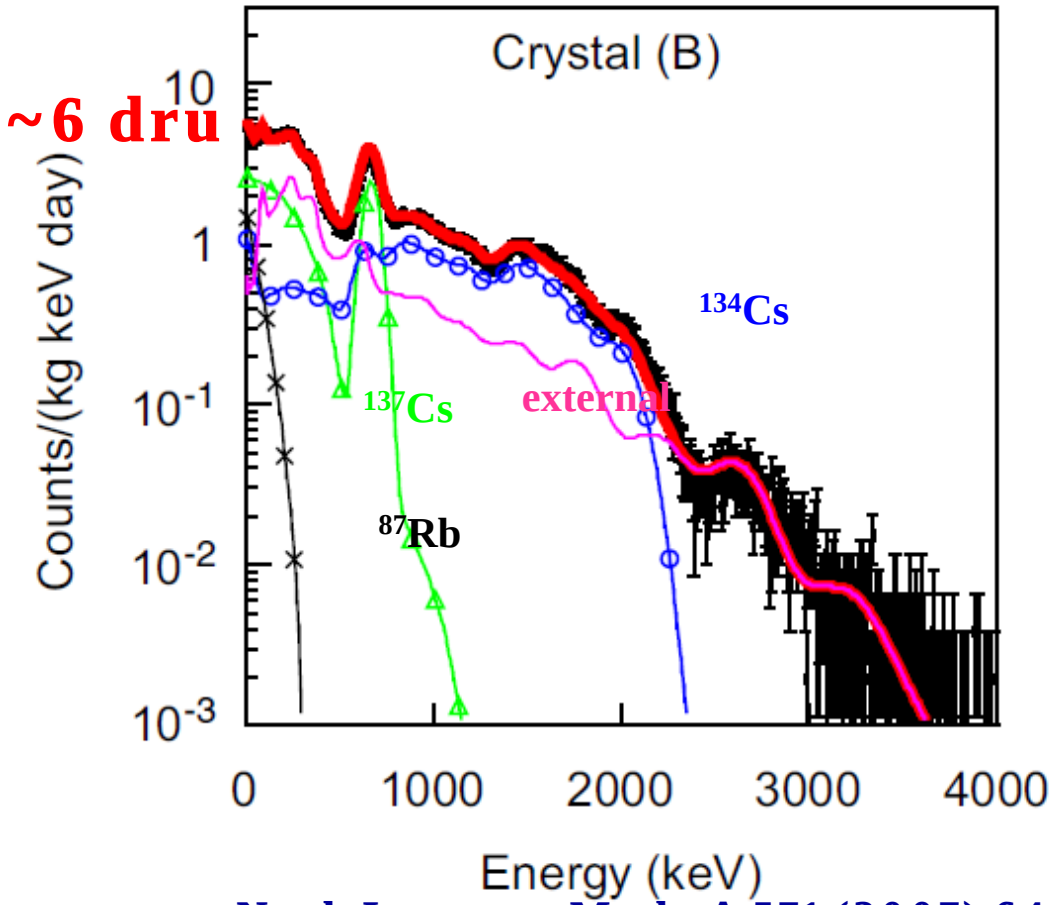


Nucl. Instrum. Meth. A 552 (2005) 456

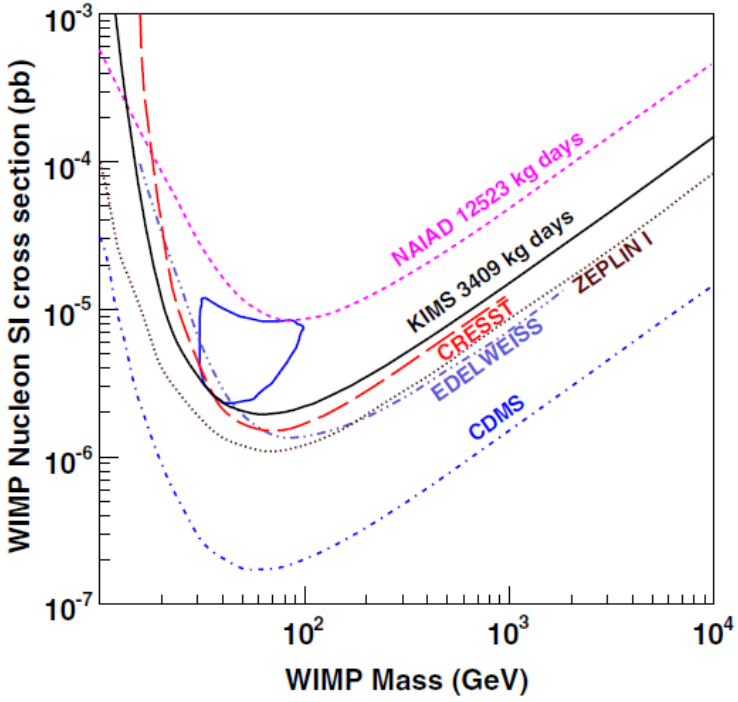


- With **purified water**, we can reduce the internal background

Internal background of CsI(Tl) crystal with “pure water”



Nucl. Instrum. Meth. A 571 (2007) 644



Phys. Rev. Lett. 99 (2007) 091301

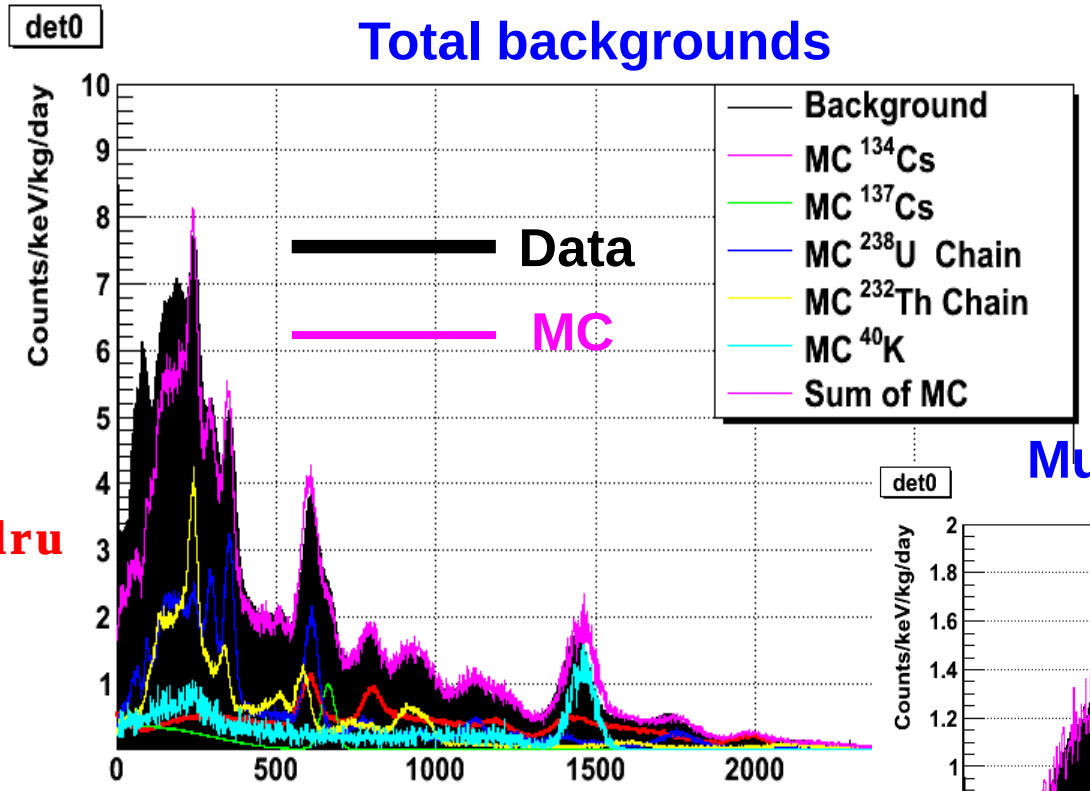
Phys. Lett. B 633 (2006) 201

- One test and Two full sized crystals were developed
- Physics results with pilot run

CsI(Tl) crystals with “ultra pure” water

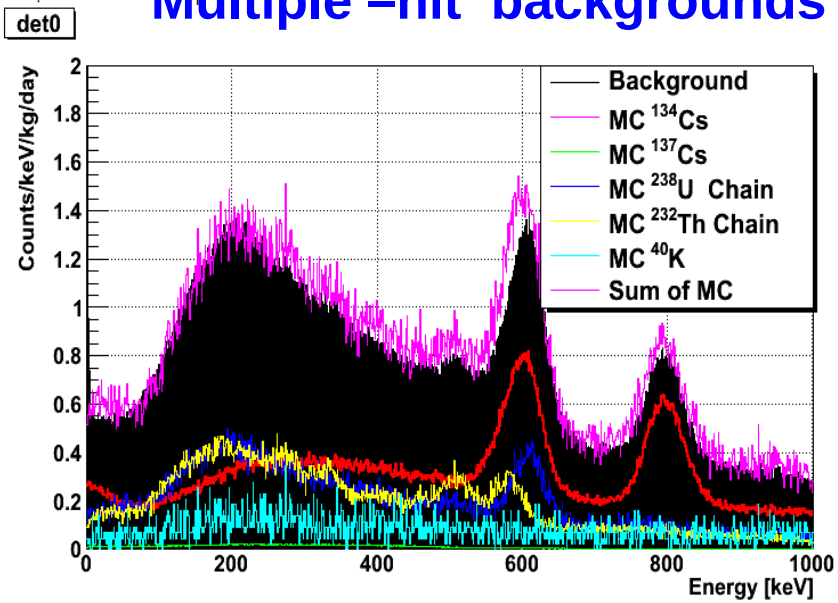
- Using “ultra-pure” water
- Growing twelve full sized crystals

Total backgrounds



~3 dru

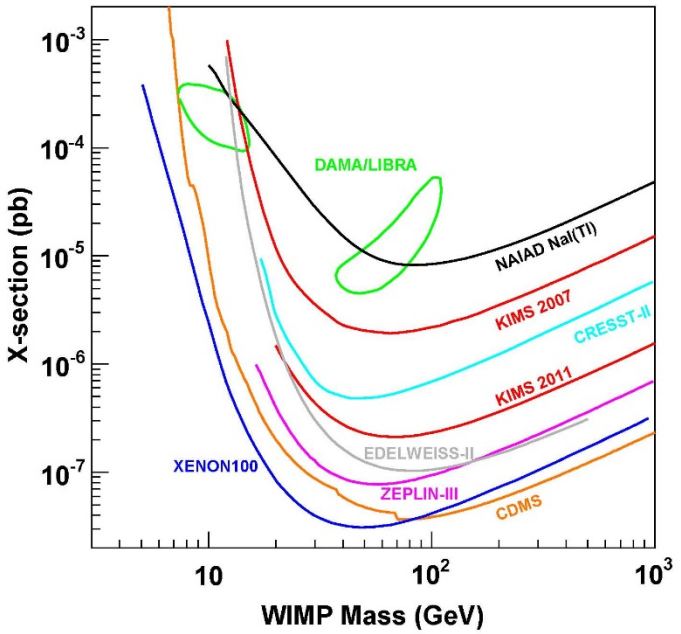
Multiple –hit backgrounds



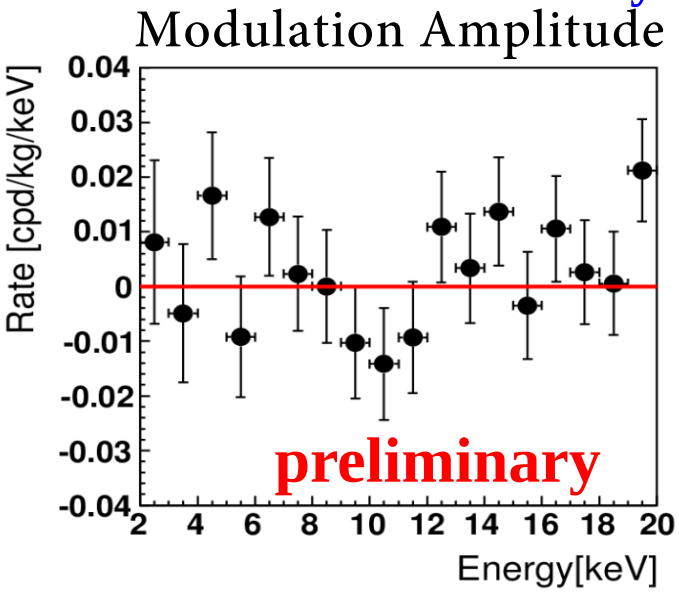
- Three years stable operation (2009-2012)

Physics results with a twelve CsI crystal array

SI cross section limit



Annual modulation analysis

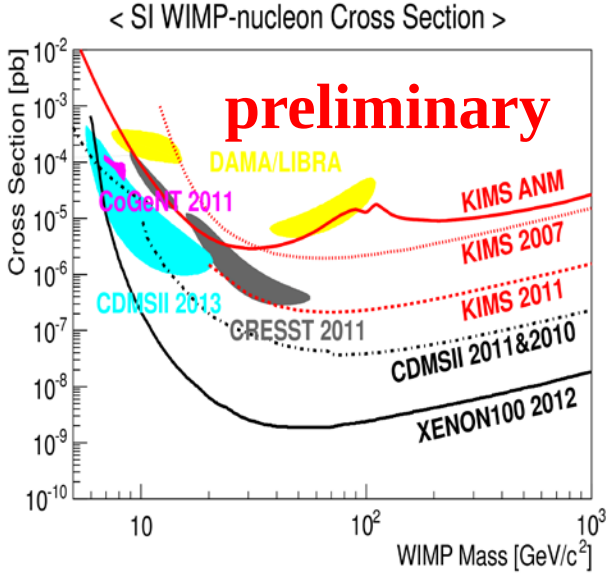


S.C. Kim et al., PRL 108 181301 (2012)

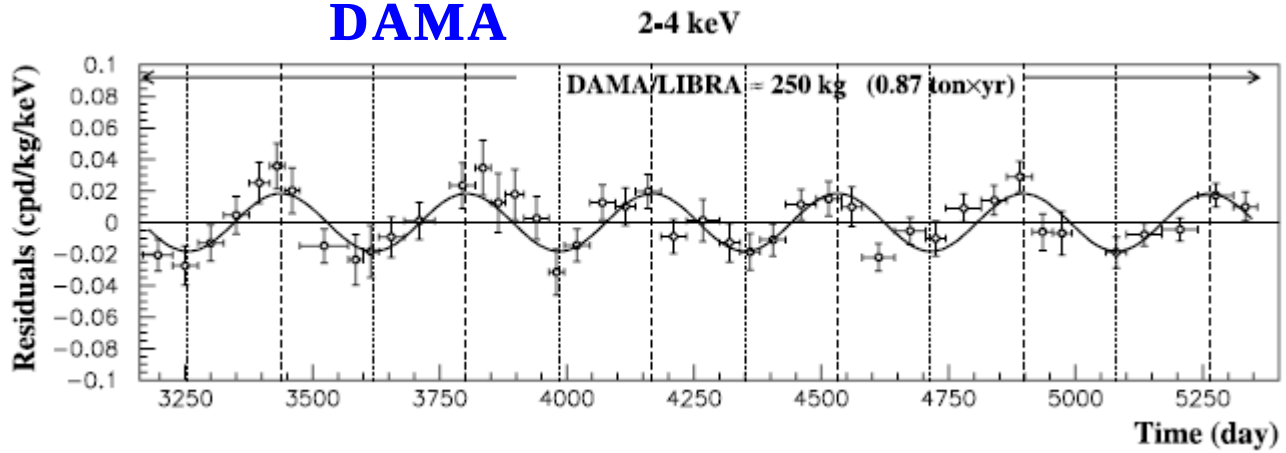
H.S. Lee et al., PRD 90 052006 (2014)

Used 1/3 data set

Full data set result soon will be out



KIMS-NaI experiment



- To confirm DAMA annual modulation signature
  - ❖ CsI is not enough for WIMP-Na interaction
  - ❖ Same NaI crystal for the same annual modulation signature

- Need to develop ultra-pure NaI(Tl) crystals
  - ❖ Goal is less than DAMA background (~1 dru = 1 counts/keV/kg/day)
  - ❖ 200 kg× 3 years data will prove DAMA signature without any ambiguity

KIMS-NaI crystals

- Development of low background NaI(Tl) crystals

	NaI-001	**NaI-002**	**NaI-003**	**NaI-004**	**NaI-005**	**NaI-006**
Mass	8.26 kg	9.15 kg	3.35kg	3.35kg	9.16 kg	11.44 kg
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG
Crystal	AS	AS	AS	AS	AS	BH
Arrive	2013.9	2014.1	2014.8	2014.8	2014.11	2014.12

K.W.Kim et al., Astropart. Phys. 62, 249 (2015)

Glossary

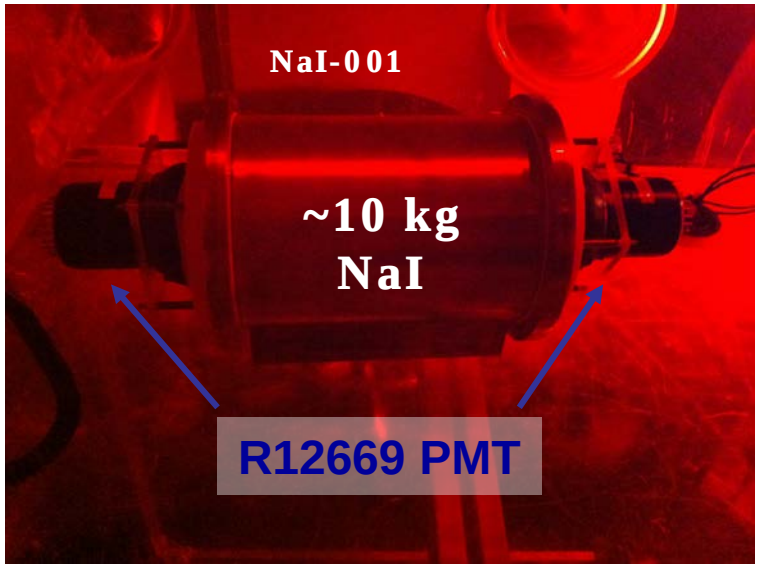
AS = Alpha Spectra Inc (US company)

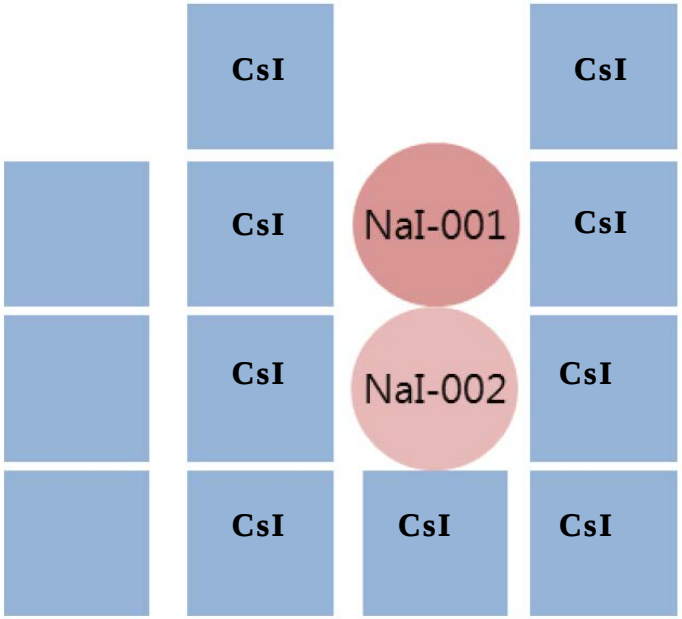
SA-AG = Sigma Adrich, Astro-grade (less K40)

SA-CG = Sigma Adrich, Crystal-grade

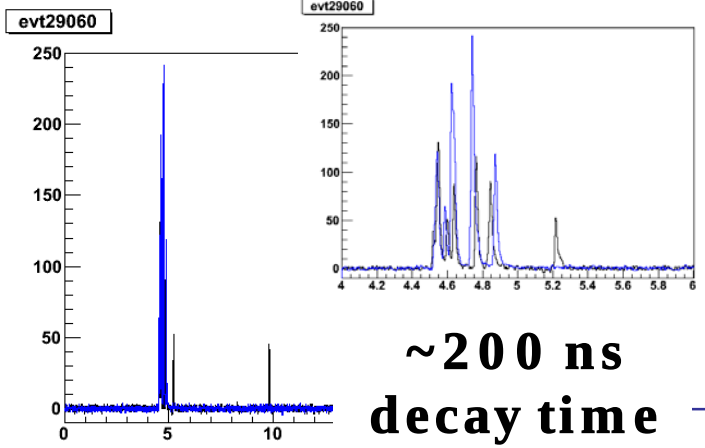
BH = Beijing Hamamatsu (China)

KIMS-NaI detector module





- Hamamastu R12669 PMTs are attached
  - ❖ Supposed same PMTs with recently upgraded DAMA PMTs
  - ❖ ~35% quantum efficiency at 420nm
- Light Yield: ~15 photoelectrons/keV
  - ❖ Consistent with ANAIS-25
- Data taking
  - ❖ 400MHz Flash ADC (Notice Korea)
    - ❑Flexible trigger logic with FPGA
    - ❑Trigger condition: 1 PE/PMT within 100ns



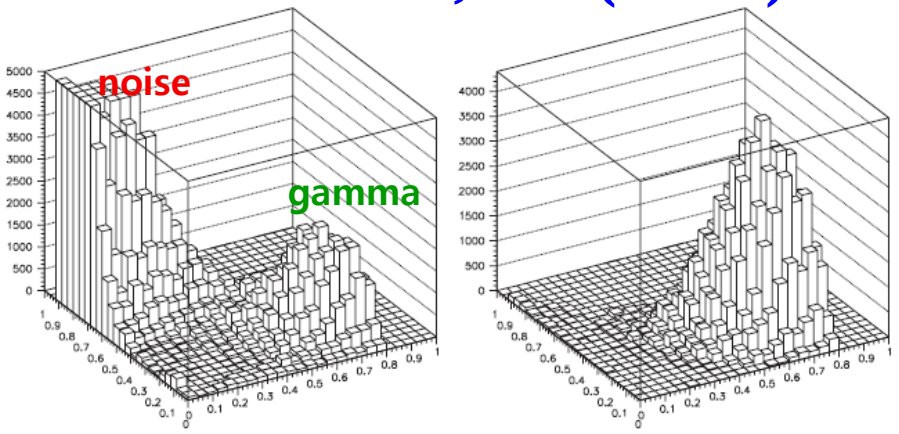
~200 ns decay time

PMT background

- **We can well identify PMT noise events using same parameter with DAMA**

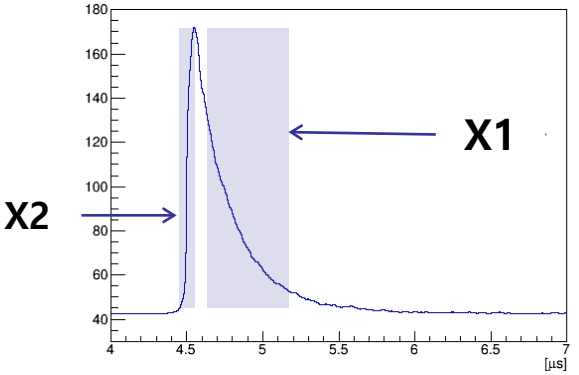
NIMA 592, 297 (2008)

DAMA



$$X_1 = \frac{\text{Area (from 100 to 600 ns)}}{\text{Area (from 0 to 600 ns)}}$$

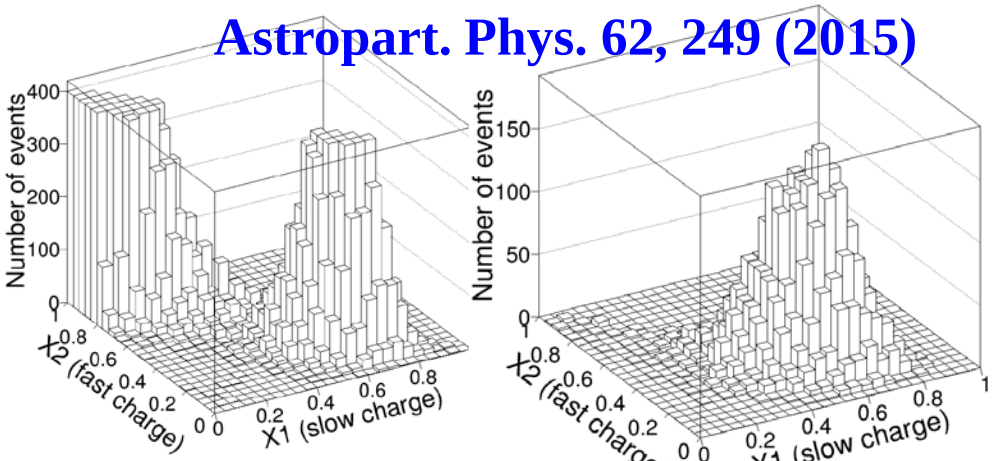
$$X_2 = \frac{\text{Area (from 0 to 50 ns)}}{\text{Area (from 0 to 600 ns)}}$$



2 keV≤ E ≤ 4 keV

Astropart. Phys. 62, 249 (2015)

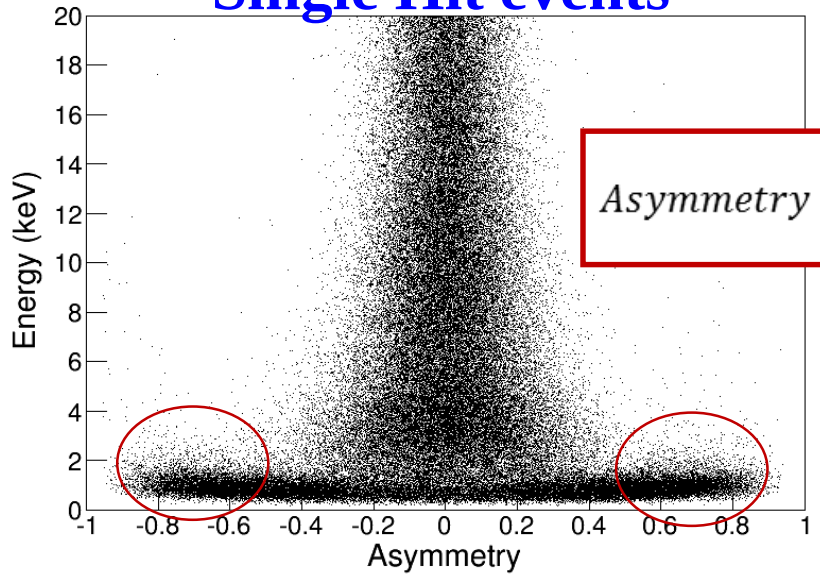
KIMS-NaI



Background data **X-ray source**

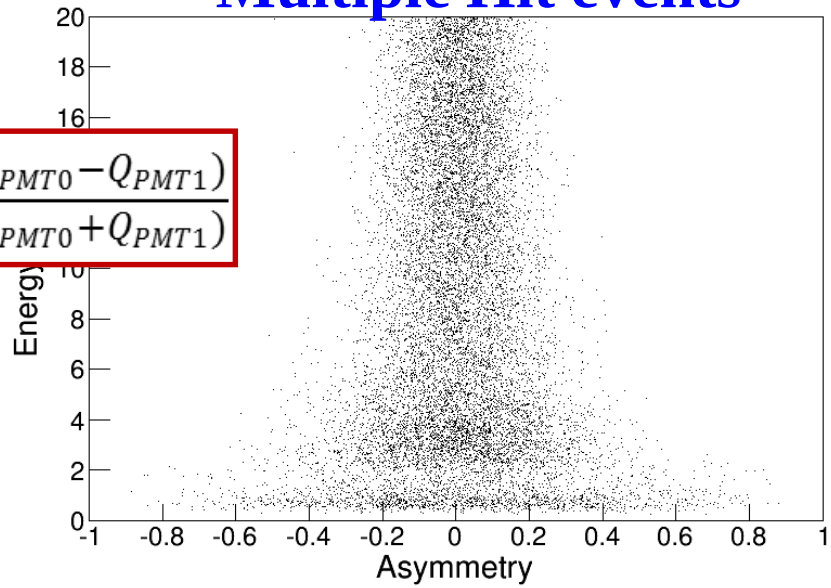
Remained noise?

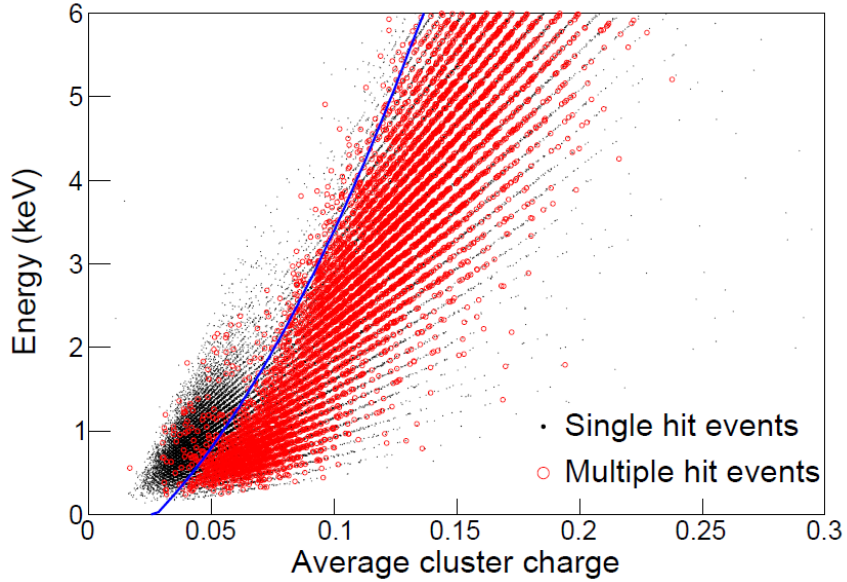
Single Hit events



$$Asymmetry = \frac{(Q_{PMT0} - Q_{PMT1})}{(Q_{PMT0} + Q_{PMT1})}$$

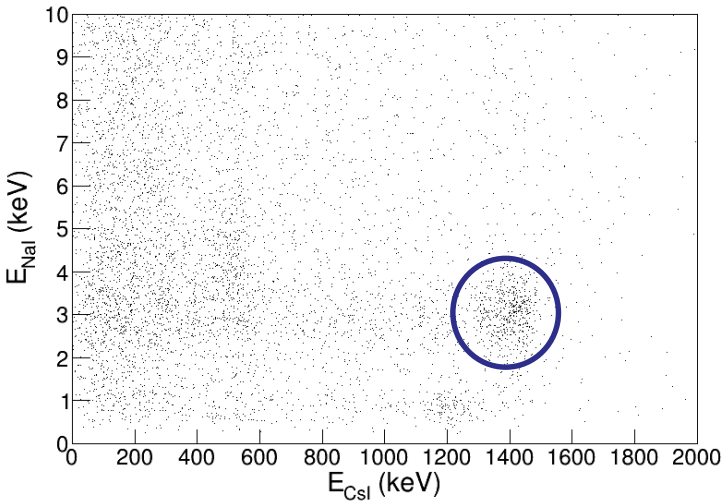
Multiple Hit events



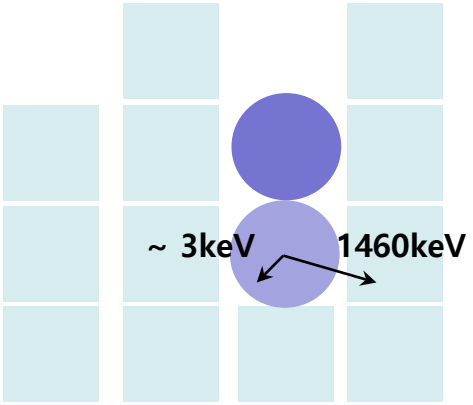


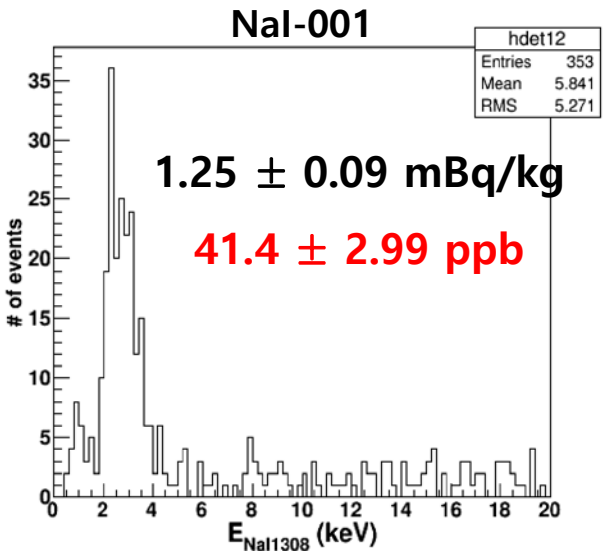
We should apply additional cuts to reject such noisy events

Intrinsic Background – ^{40}K



Coincidence signals





DAMA crystals :
10~20 ppb

Geant4 simulation
on efficiency

	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
K (ppb)	41.4 ± 3.0	49.3 ± 2.4	25.3 ± 2.4	> 110	40.1 ± 4.2	> 150

Intrinsic Background – ^{40}K

	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
K (ppb)	41.4 ± 3.0	49.3 ± 2.4	$\mathbf{25.3} \pm 2.4$	> 110	40.1 ± 4.2	> 150
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG
K (powder)	?	?	25.07	~200	?	~200

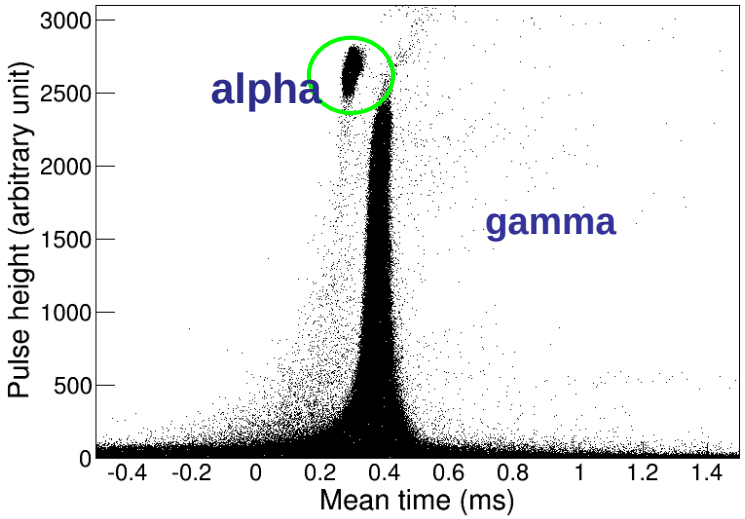
- NaI-003 used Sigma Adrich Astro-Grade (SA-AG) powder **25 ppb**
- NaI-004 & NaI-006 used **Crystal-Grade** (SA-CG) powder
- All Alpha Spectra prepared powders (NaI-001, NaI-002, NaI-005)

  ~ 40 ppb levels

NaI powder is a key of K contamination

- Will grow one another crystal using different batch of SA-AG powder
  - ~10 ppb from ICP-MS by Sigma Aldrich
- **K measurement technique** from powder is under development
- R&D to **reduce K in NaI powder** was just started!!

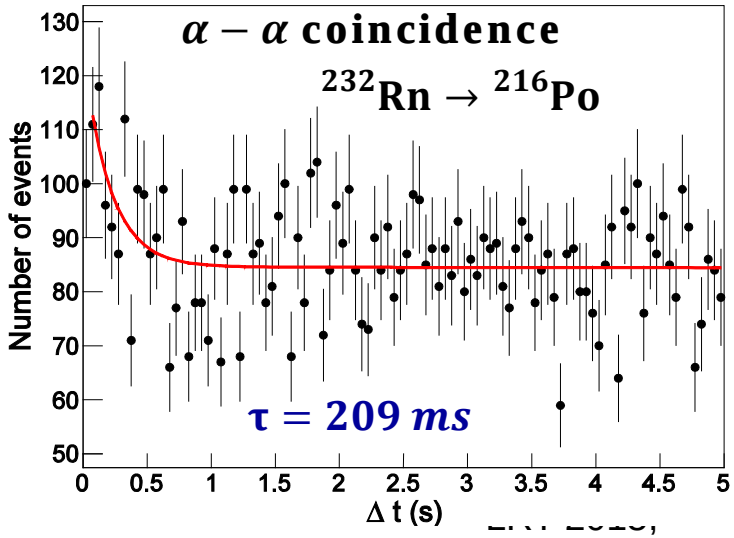
Intrinsic Background (alpha analysis)



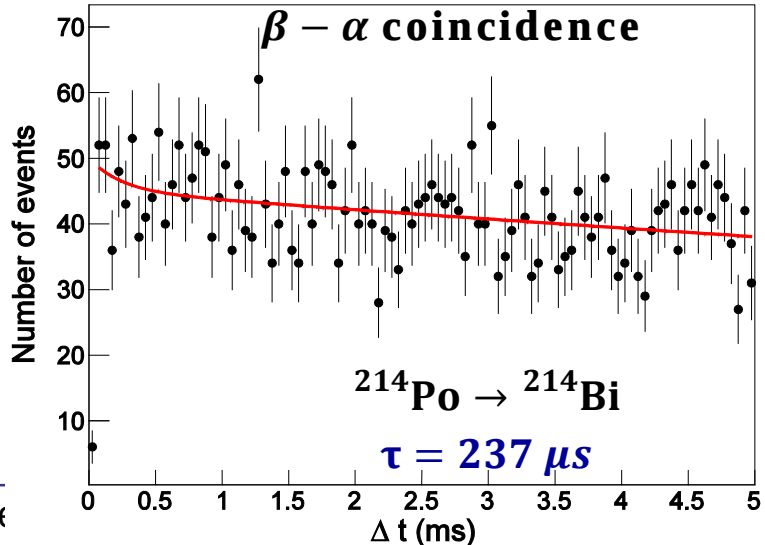
Radionuclei	NaI-001 [mBq/kg]	NaI-002 [mBq/kg]
^{238}U (^{214}Bi)	<0.007	<0.001
^{228}Th (^{216}Po)	<0.012	0.002±0.001
^{210}Po	3.28±0.02	1.76±0.01
Total alphas	3.29±0.02	1.77±0.01

^{238}U and ^{228}Th contaminations were very small!!

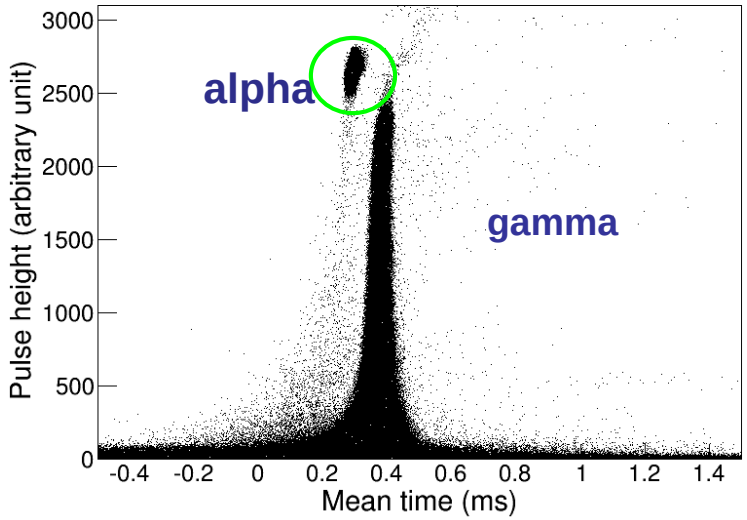
^{232}Th chain



^{238}U chain



Intrinsic Background – ^{210}Pb



- Most of alphas are coming from ^{210}Po
- Broken equilibrium (Rn-222 contamination) during powder or crystallization

	NaI-001	**NaI-002**	**NaI-003**	**NaI-004**	**NaI-005**	**NaI-006**
Total alpha (mBq/kg)	3.29 ± 0.01	1.77 ± 0.01	2.29 ± 0.03	-	0.47 ± 0.01	1.81 ± 0.02
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG

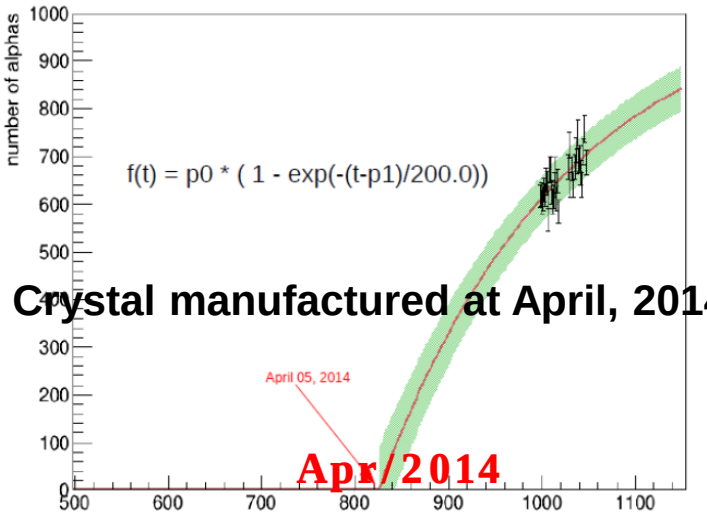
- **NaI-003, NaI-004, and NaI-005** had better treatment on air (Rn) contact during crystal growing
- **NaI-005** had better treatment of chemical process on powder

Intrinsic Background – ^{210}Pb

NaI-002

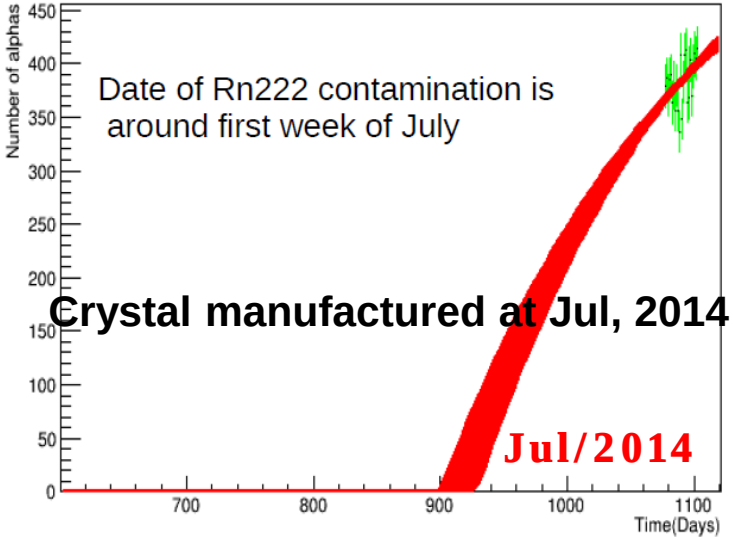
Crystal manufactured at April, 2013

NaI-003



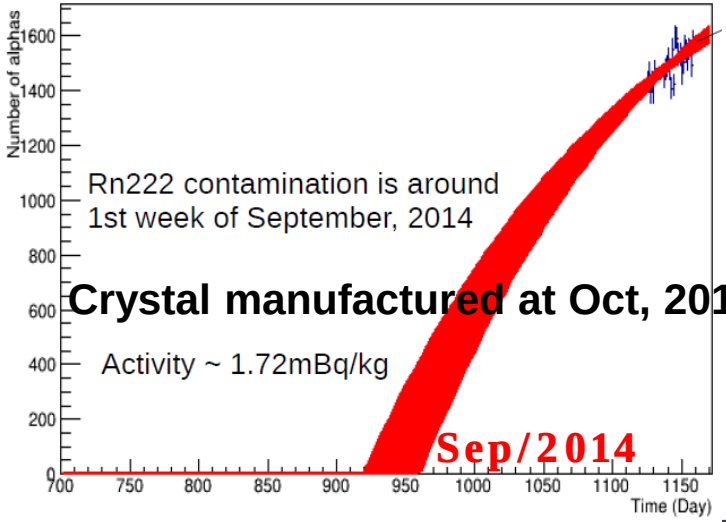
Crystal manufactured at April, 2014

NaI-005



Crystal manufactured at Jul, 2014

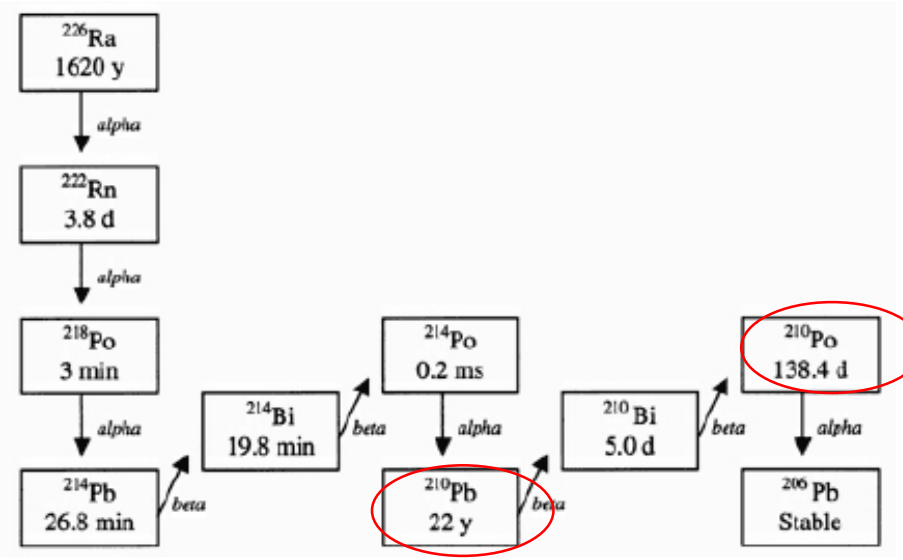
NaI-006



Crystal manufactured at Oct, 2014

Intrinsic Background – ^{210}Pb

- Main Source.. Powder production or crystal growing?
  - ❖ Should know ^{210}Pb in powder
  - ❖ **Alpha rate measurements** at powder
    - ❑ Buy High sensitive alpha counters
    - ❑ Developing ZnS detector
  - ❖ **46 keV gamma** measurement
    - ❑ Considering Well-type Ge or Si detectors



Kamland-pico demonstrates a reduction of ^{210}Pb in NaI powder with ion-exchange resin (arXiv:1407.3542): 50 μBq/kg in crystal

We just started ^{210}Pb reduction in powder with various resins
Co-worked with Russian chemists

NaI Powder purification

Sorbent	Matrix	Application
A	Inorganic, manganese dioxide	K^+, Pb^{2+}
B	Inorganic, zinc ferrocyanide	K^+
C	Organic macroporous anion exchange copolymer	Pb^{2+}
D	Organic macroporous chelating copolymer	Pb^{2+}
E	Organic, Resorcinol-formaldehyde	K^+

R&D for K and Pb purification

- First : Simple shaking for 24hrs with resins
  - Just done a week ago
- Next : Column chromatography

Shaking NaI solution with various resins

Preliminary result of purification

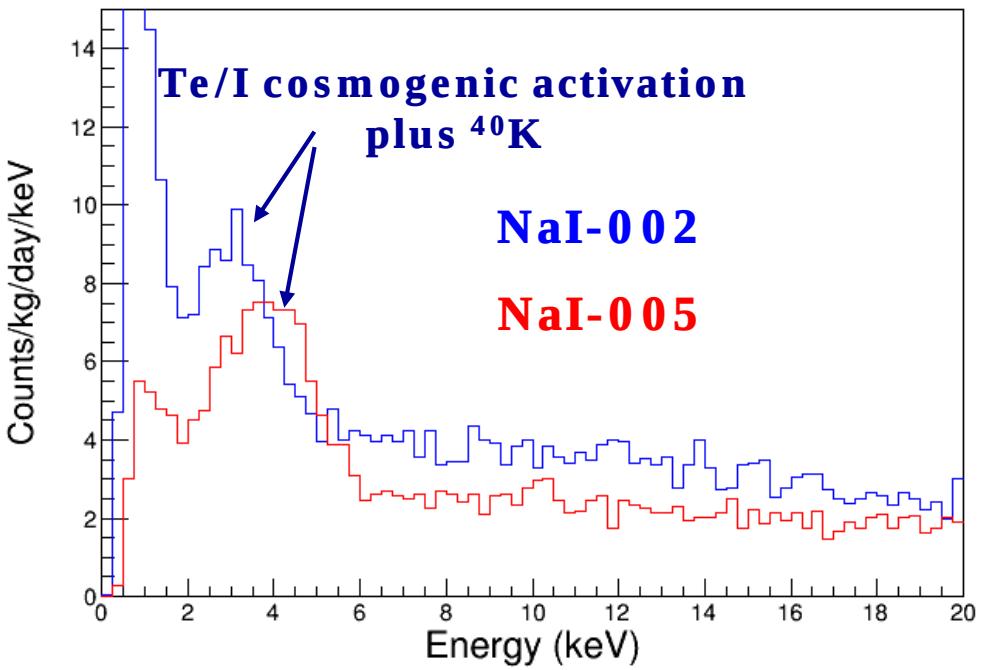
- Measurement with ICP-MS for K and Pb
  - ❖ We made NaI solution with some amounts of K and Pb

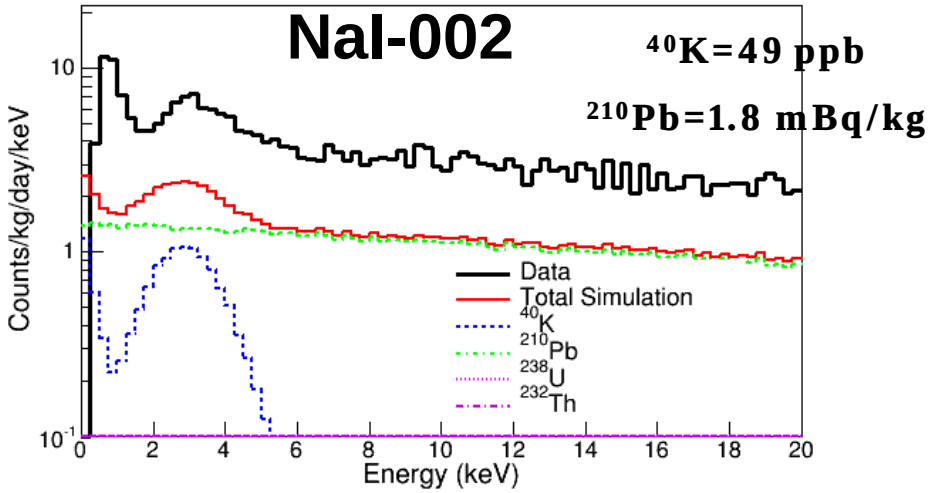
Resins	^{39}K (ppb)			^{208}Pb (ppb)			Applications
	Bef.	Aft.	DF	Bef.	Aft.	DF	
A	223	254	0.9	1275	19	67	K^+, Pb^{2+}
B	463	375	1.2	1693	1589	1.1	K^+
C	404	313	1.3	1653	5	330	Pb^{2+}
D	352	312	1.1	1619	33	49	Pb^{2+}
E	378	340	1.1	1661	898	1.8	K^+

- Reduction of **Pb** seems to **work very well**
- However, **K** seems to be **difficult**

- We will have much more experiences

Internal background



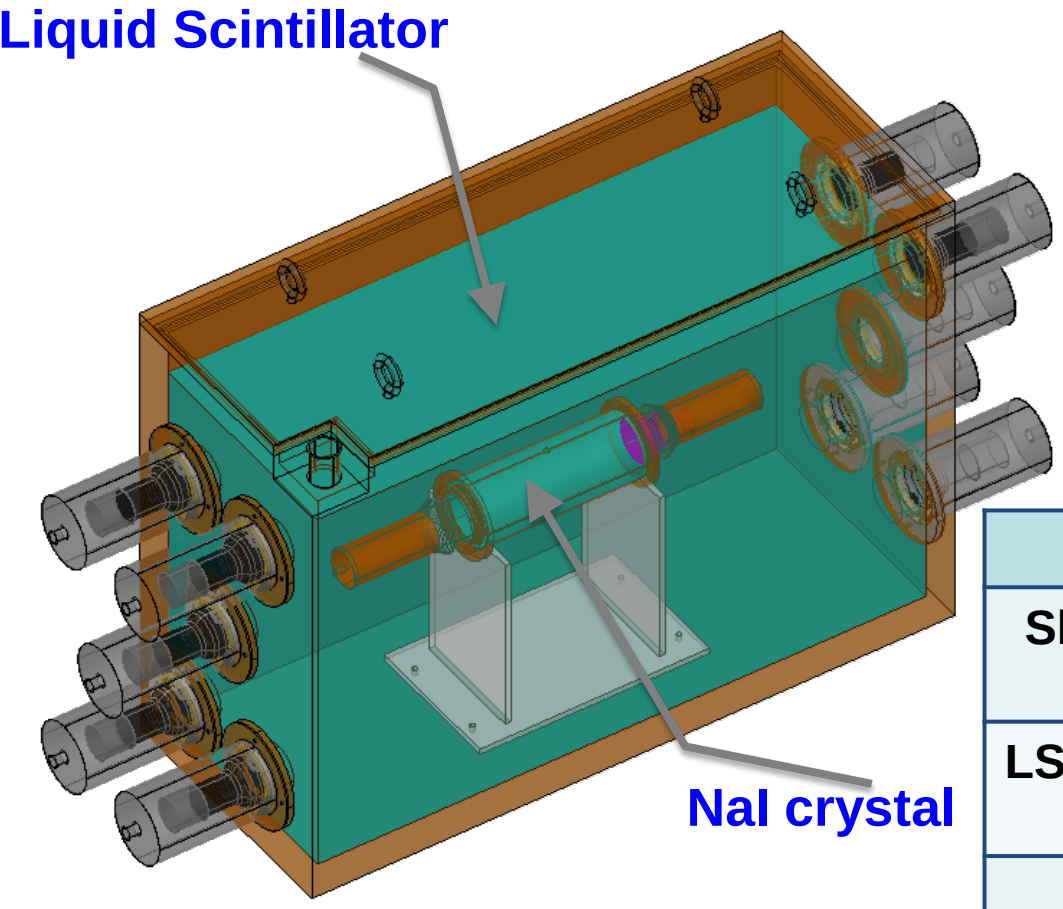


Simulation for external and cosmogenic activation is under development

- We achieved ~2 dru at 6keV
- ~ 0.5 dru caused by internal backgrounds (^{210}Pb)
  - ❖ Additional ~0.7 dru at 2-4 keV due to ^{40}K
- **~ 1.5 dru** caused by **external** (+cosmogenic)
- Goal : less than 1 dru (both less than 0.5 dru)

External background reduction

- We prepared liquid scintillator active veto system
  - ❖ Veto efficiencies for sources from PMT radioisotopes (U, Th, K) were greater than 80% at low energy (0-10 keV)



Less than 0.5 dru from external might be possible

	Feb/15	Mar/15	Apr/15	May/15
Shielding Box	Design & Construction			
LS base on LAB	Propagation & Insert			
Run			Run&Analysis	

Prospect of NaI(Tl) crystal development

- ^{40}K less than 10ppb
  - Astro-grade powders from Sigma-Adrich with ^{40}K less than 10ppb or our own purification (**<0.2 dru**@2-4 keV)
  - ~factor two reduction with liquid scintillator veto system
- ^{210}Pb less than 0.2 mBq/kg
  - Already 0.5 mBq/kg
  - At least factor 2 reduction with powder purification (**<0.25 dru**@2keV)
- External
  - **less than 0.5 dru** with liquid scintillator veto system
- **Goal : 200kg NaI detectors (less than 1 dru background)** within 2 years

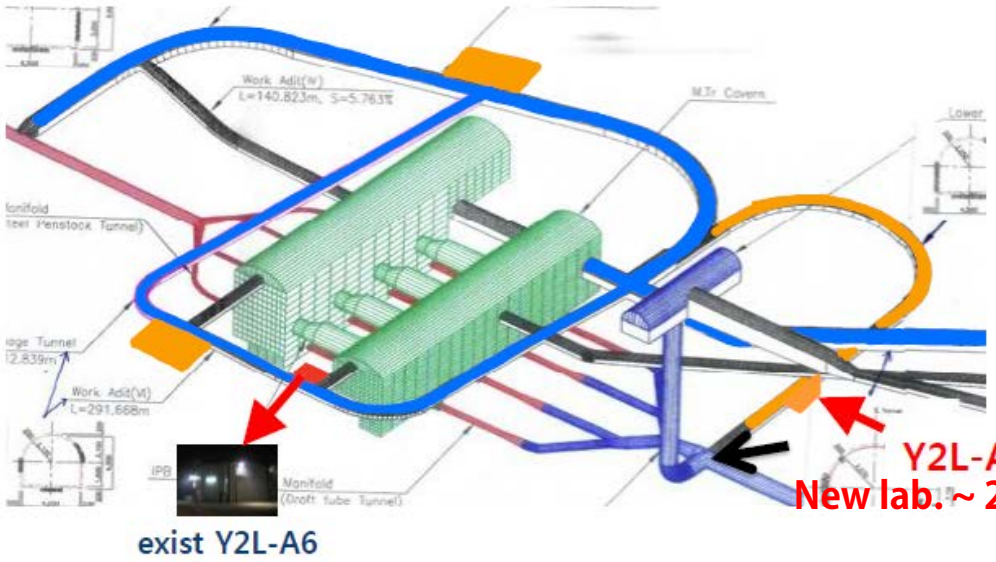
Conclusion

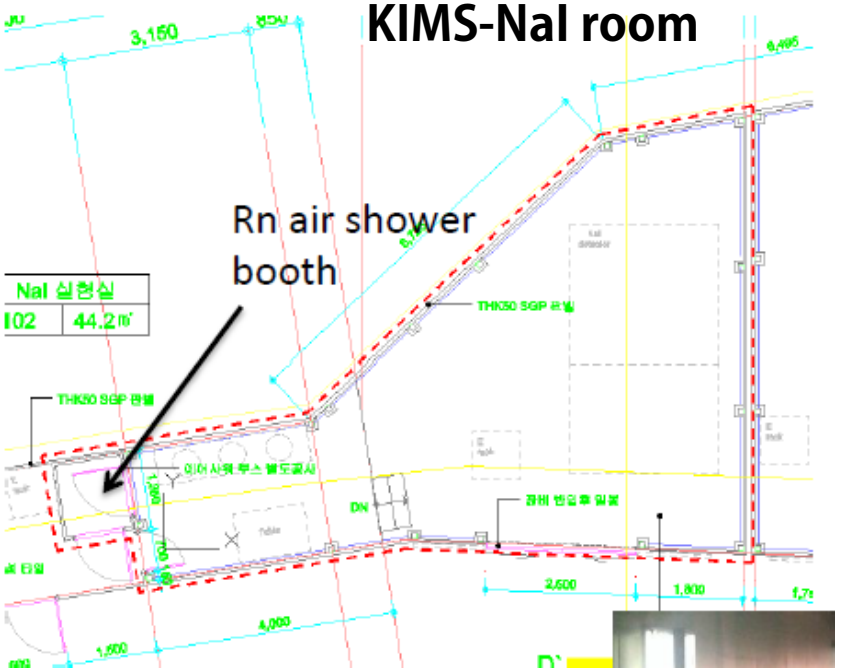
- KIMS collaboration successfully grew the low background CsI(Tl) crystals for the WIMP search
  - ❖ Have been contributed for understanding of DM nature during late decade

- **KIMS-NaI** collaboration start to grow the ultra-low background NaI(Tl) crystals for the WIMP search
  - ❖ Current ~2dru @ 6keV
  - ❖ Goal ~1dru @ 2keV (might be possible within one year)
  - ❖ We will **confirm the DAMA** signature within a couple of years

Backup

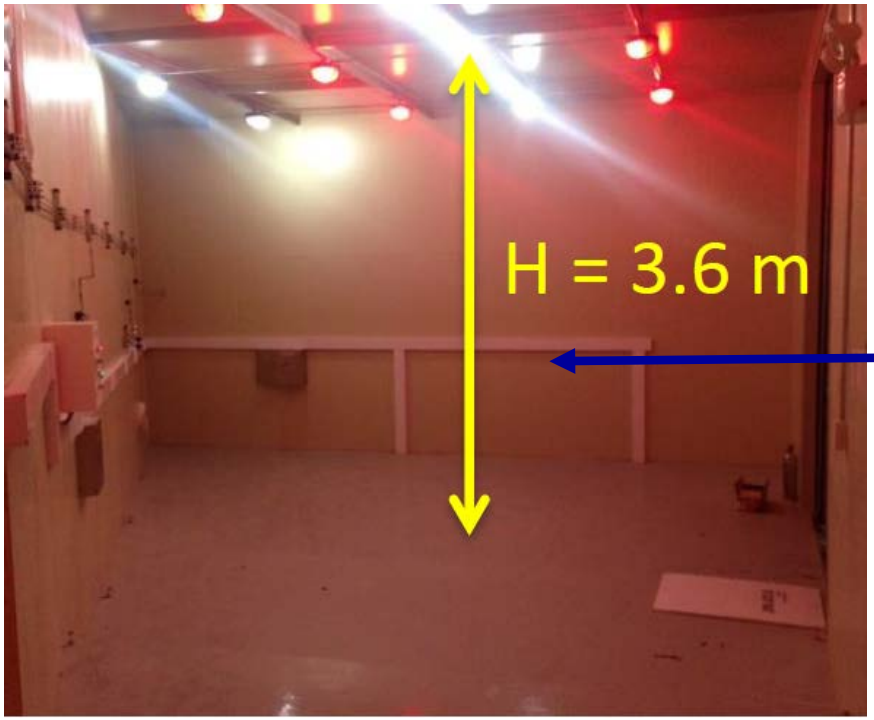
Underground laboratory

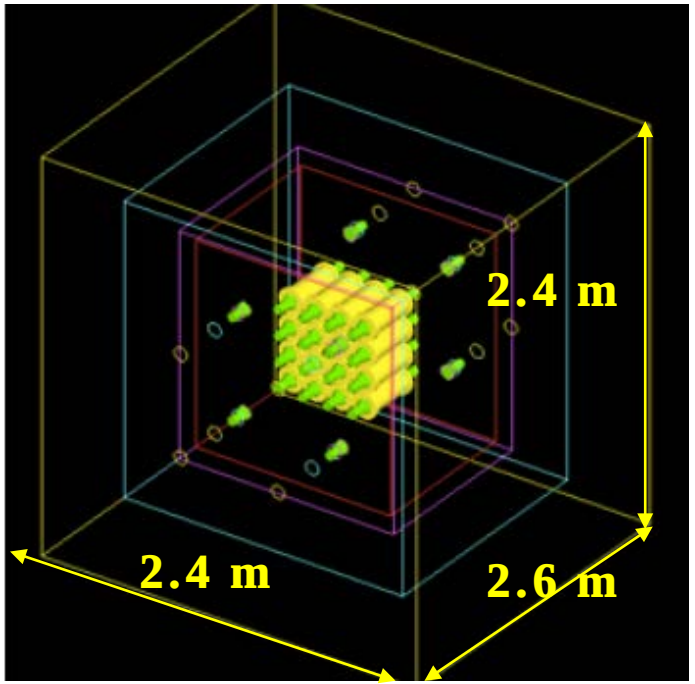




- **Underground space** for the KIMS-NaI was **already prepared** in Y2L
  - ❖ 10,000 class clean room
  - ❖ Rn free air will be supplied
  - ❖ Size of detector room ~50 m²

Preliminary design of KIMS-NaI





- 200 kg NaI
  - 30 cm liquid scintillator veto (Active veto)
  - 6 cm Cu
  - 20 cm lead
  - Muon veto (3 cm plastic scintillator)
  - 30 cm Polyethylen