Status of KIMS
(Korea Invisible Mass Search)

Moo Hyun Lee

Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

On behalf of the KIMS collaboration

2016.11.23 (Tue.)

Dark Matter from aeV to ZeV: 3rd IBS-MultiDark-IPPP Workshop

KIMS (Korea Invisible Mass Search)

- Dark matter search at Yangyang underground laboratory (Y2L) since 2003
  - R&D at CheongPyung Underground Laboratory (1999~2003)
  - Preparing new underground facility @ Handeok Iron mine (2018~)
- 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 for Basic Science (IBS) (2013)
  - DM searches with NaI(Tl) crystals (KIMS-NaI) ⇨ COSINE
  - DM searches with low temperature detector (KIMS-LT)

YangYang(Y2L) Underground Laboratory

(Upper Dam)

YangYang Pumped Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

1000m

700m

(Power Plant)

양양양수발전소

(Lower Dam)

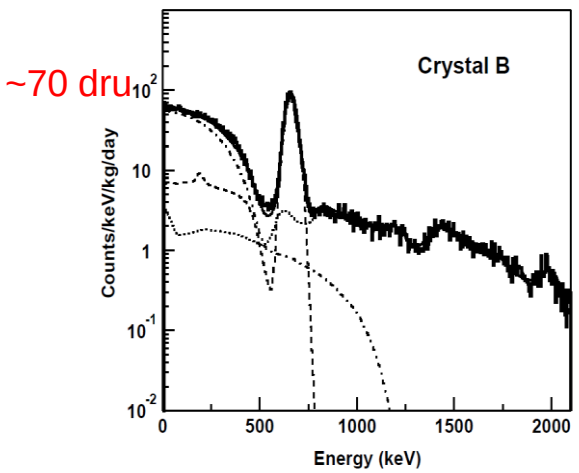
KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

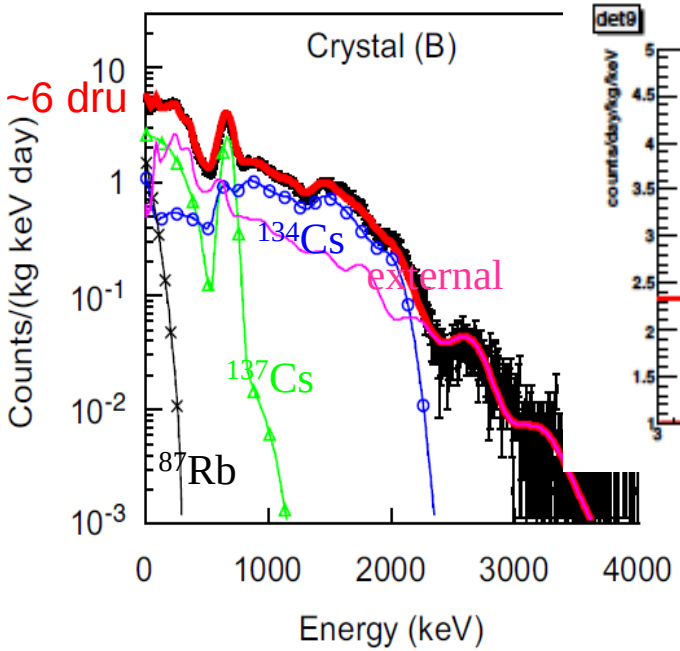
KIMS-CsI & Background

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

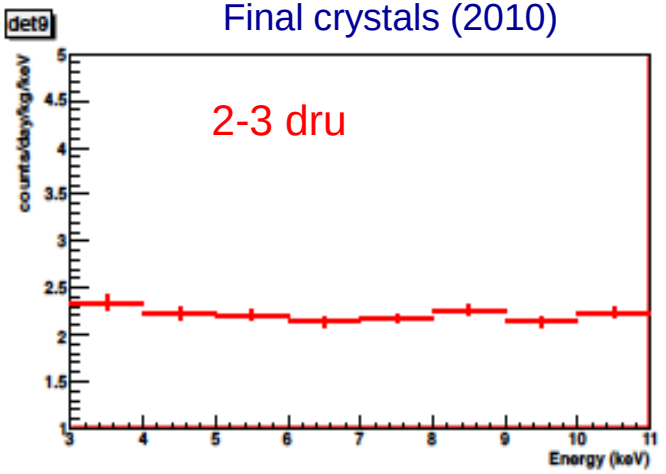


dru = events/kg/day/keV

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



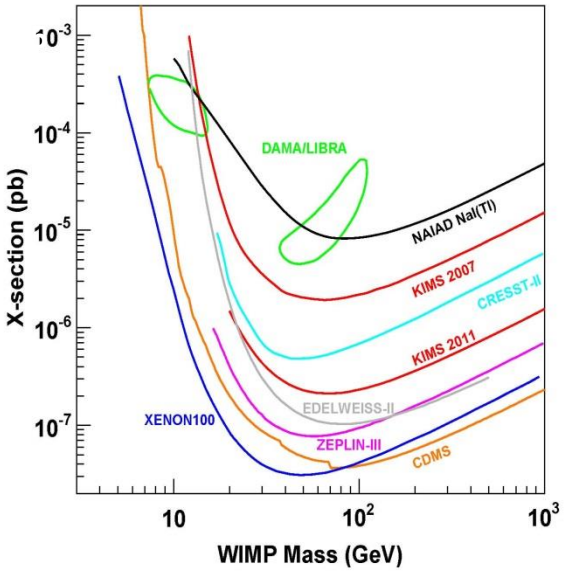
Final crystals (2010)



- Identified main sources of background
  - Internal ^{137}Cs, ^{134}Cs, ^{87}Rb
  - **^{137}Cs** was caused by processing water so, ^{137}Cs can be reduced by **purification of the water**
  - **^{87}Rb** was reduced by **recrystallization**
  - **^{134}Cs** can be **tagged** with surrounding crystals

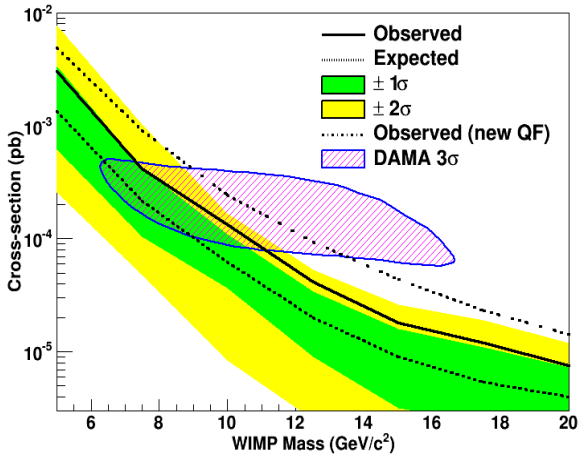
Physics of KIMS-CsI

PRL 108 181301 (2012)

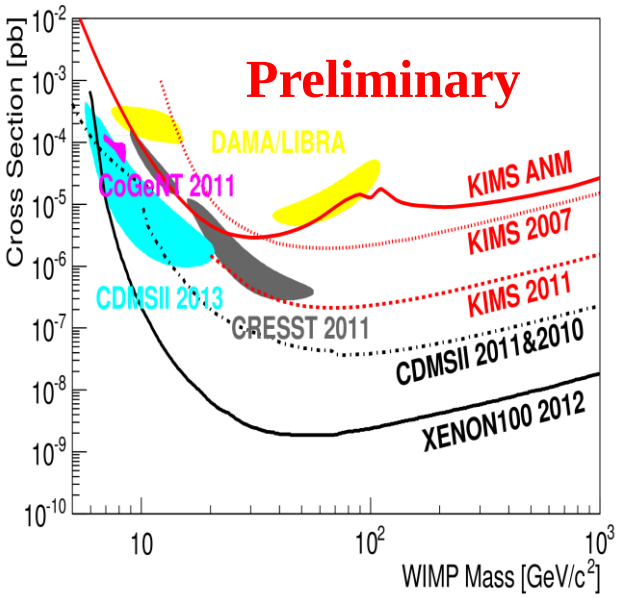


- 12 low-background CsI crystals (104.4 kg)
- 2.5 year data (2009-2012)
- Background : 2~3 count/kg/day/keV (dru)
- Model-independent rejection of DAMA signals interpreted as WIMP-Iodine interaction
- Solar axions search

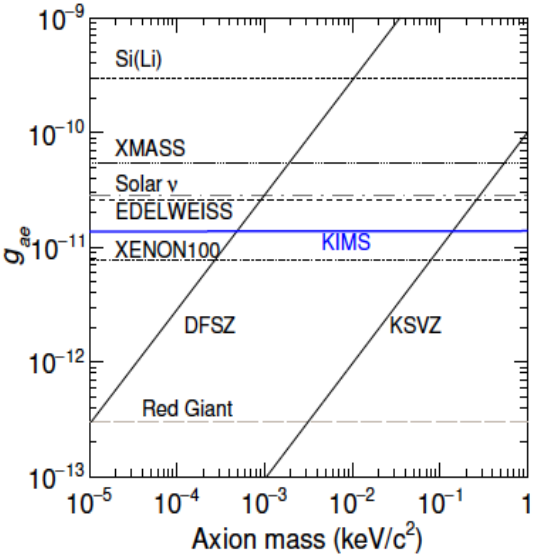
PRD 90 052006 (2014)



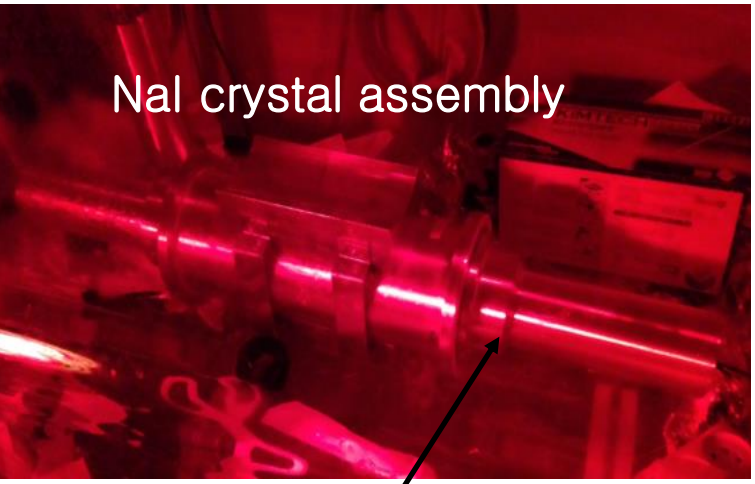
Annual Modulation

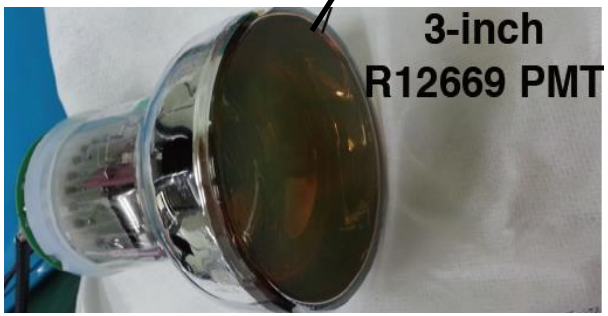


JHEP 06 011 (2016)



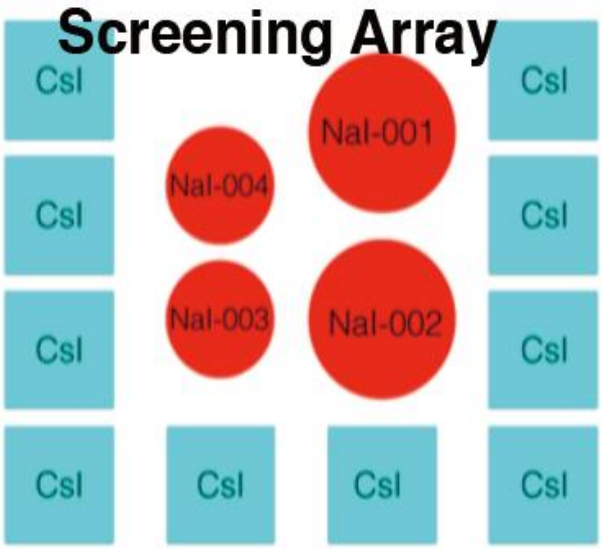
KIMS-NaI experiment (Since 2013~)



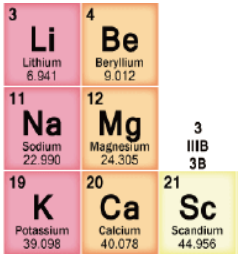


~35% Quantum Efficiency at 420nm

- Use the same NaI and analyze the same annual modulation as the DAMA
- Need to develop better detector than the DAMA
  - Background <1 dru (=counts/keV/kg/day)
  - Threshold <2 keV
- Use existing CsI&shield for R&D of NaI
- 15 R&D stage crystals were grown



^{40}K reduction



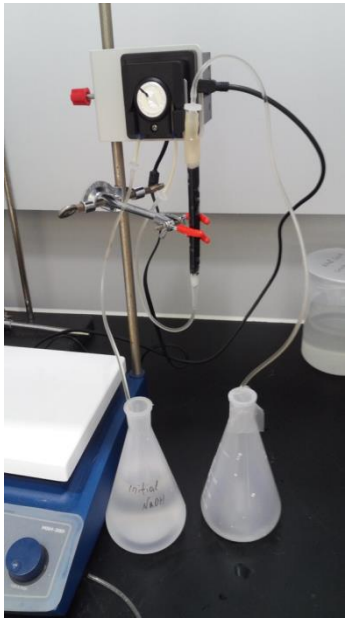
- Similar chemical properties with Na
- Can be separated with recrystallization

	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
Powder	AS-B	AS-C	SA-AG	SA-CG	AS-WS II	SA-CG
K (ppb) Crystal	41.4±3.0	49.3±2.4	**25.3**±3.6	>117	40.1±4.2	>127
K (ppb) Powder	?	?	**25.1**	~200	43	~200

	NaI-007	NaI-008	NaI-009	NaI-010	NaI-011	NaI-015
Powder	AS-WSII	SA-AG	SA-CG	AS-WSIII	AS-WSIII	SA-AG
K (ppb) Crystal	38.1±5.5	<17	639.1±51.4	18.0±11.7	18.5±3.2	<20
K (ppb) Powder	43	10	200-800	25	25	10

- We have **purified powder for ^{40}K already**!!
  - Goal ~ 20 ppb (less than 0.1 dru)
- We can effectively reduce contribution with active veto using liquid scintillator

Active reduction of Pb (Pb^{210}) and its measurement



- Goal is less than $\boldsymbol{100\ \mu Bq/kg}$ (<0.1 dru background)
- Purification of NaI powder with ion-exchange resin (chemical purification)
  - ~ 300 reduction of Pb with dirty NaI powder
  - ~10 reduction of Pb with normal NaI powder
  - Need to grow crystals with and without resin purification
- Powder measurements under progress (Alpha Counter, Well-type HPGe detector, ICP-MS)
- Recrystallization of NaI powder may also work

Crystal growing in Korea

Czochralski Furnace

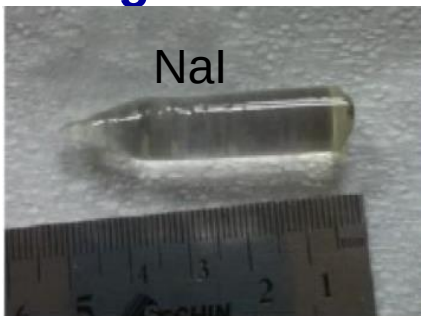
Under development

Bridgman Furnace

1st crystal (Sapphire) grown ~ 30kg !

Kyropoulos Furnace

Bridgman



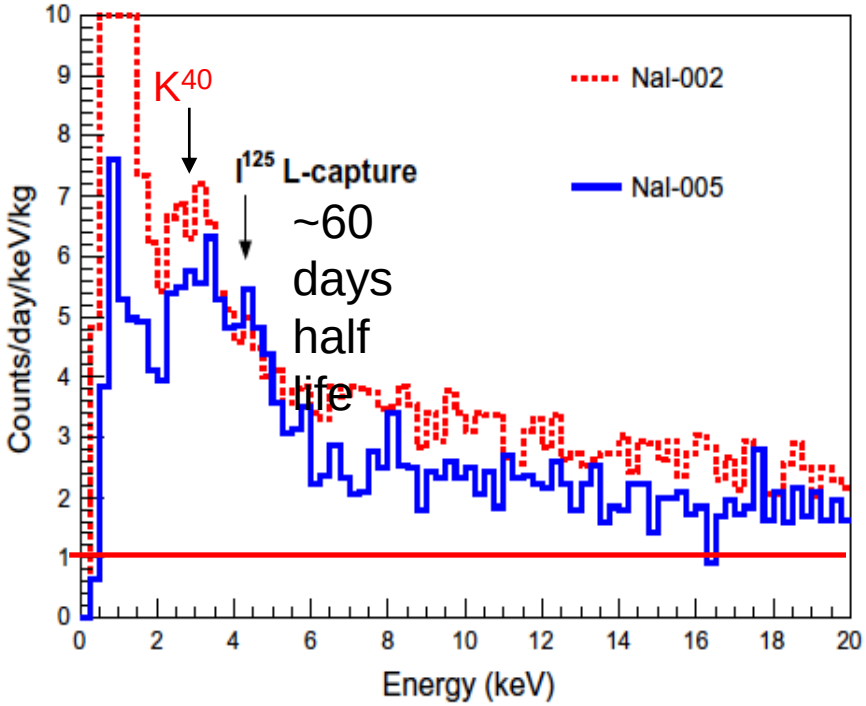
- A small NaI was grown in Korea
- We will try to grow **larger crystals**
  - A special Kyropoulos furnace is under procurement

- Whole procedure can be done by ourselves
  - ❖ Speed up the R&D of background reduction

Detector Development

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

P. Adhikari et al., EPJC 76, 185 (2016)



~ 2 keV energy threshold

~ 2 dru background @ 6keV

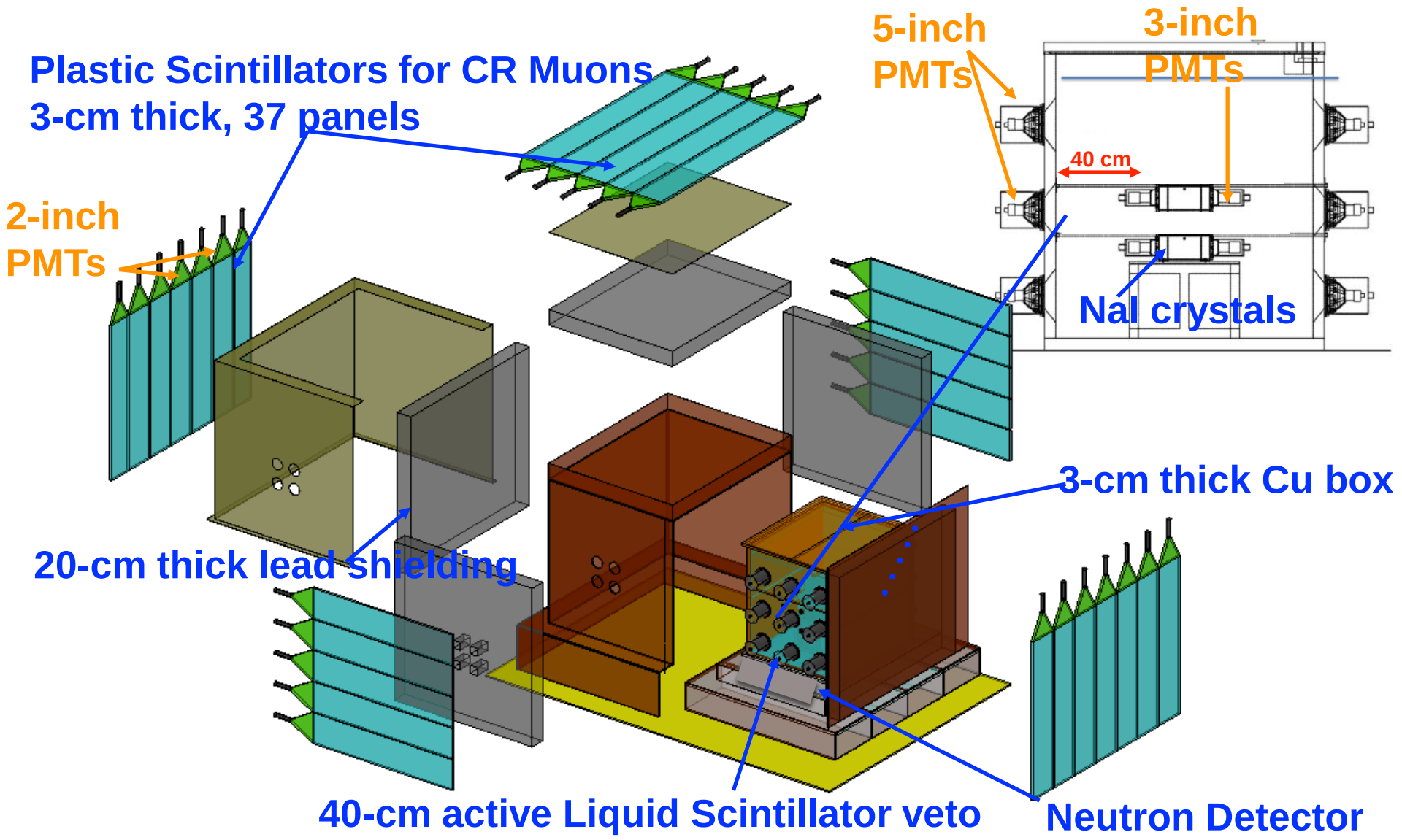
K^{40} and Pb^{210} are main background at low energy

DAMA level

- Understanding internal background very well
- ~2 counts/kg/day/keV level at 6 keV achieved

Developed crystals are used for COSINE-100

Full setup of NaI experiment



Installation of the NaI experiment at Y2L

- Physics run started from September 2016.
- Very stable for the last few weeks.

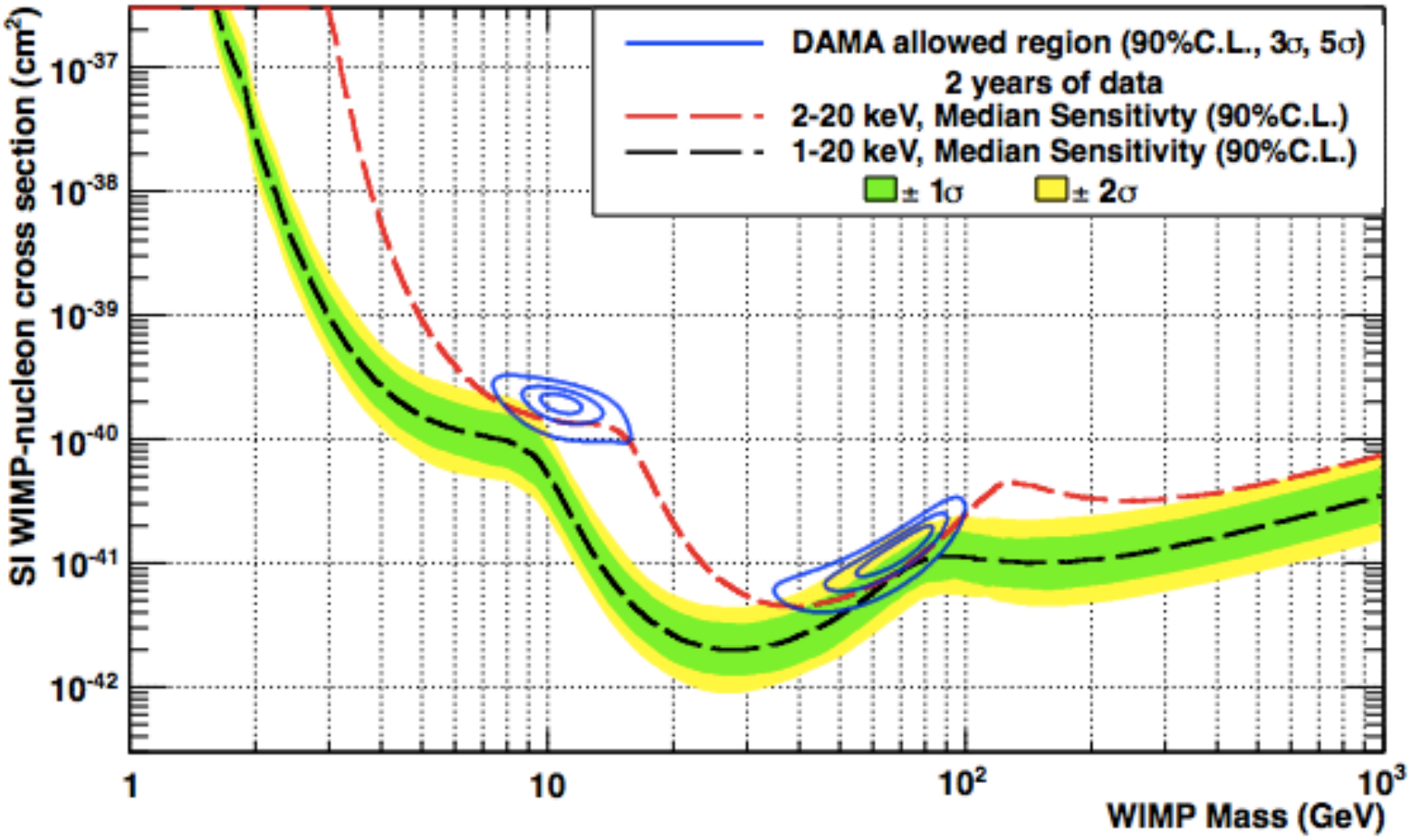
NaI crystals for Phase-I (~100kg)

KIMS

DM-ICE

Crystals need to be cleaned and assembled with PMTs before installing in the shielding.

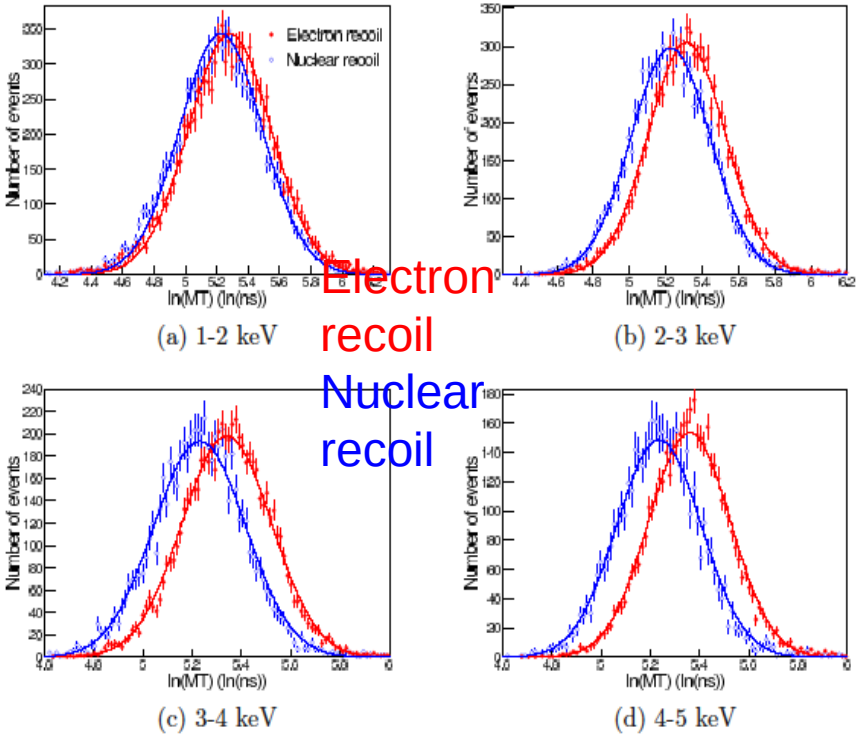
COSINE-100 sensitivity



Assumed 2 or 4 dru flat backgrounds depending on crystals

Pulse shape discrimination of NaI crystal

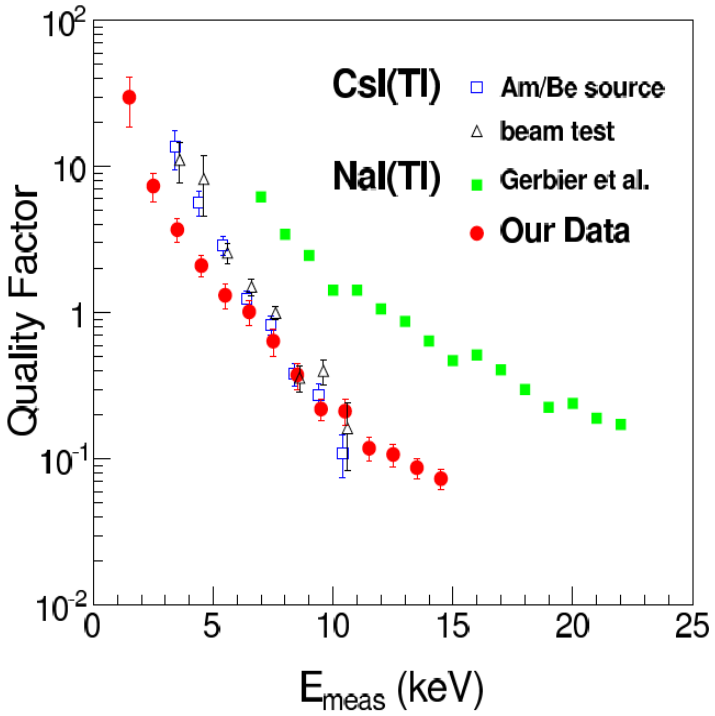
- Due to high light yield, we observe very good PSD performance **~ 15 photoelectrons/keV**



Electron recoil

Nuclear recoil

JHEP **08 093 (2015)**



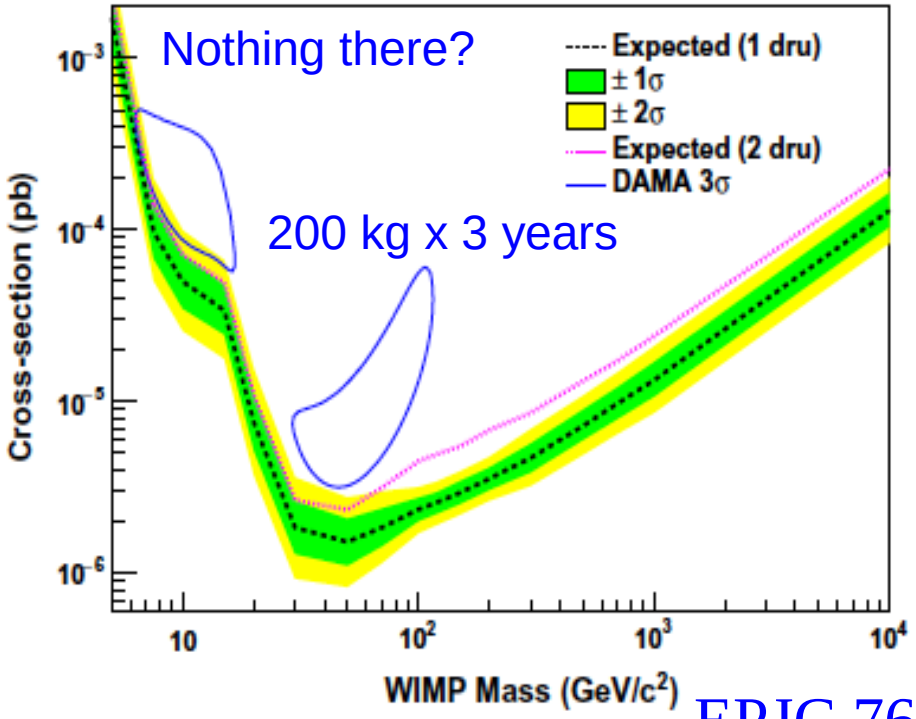
- If we **observe the same annual modulation** as the DAMA, we can check whether it is coming from nuclear recoil or electron recoil

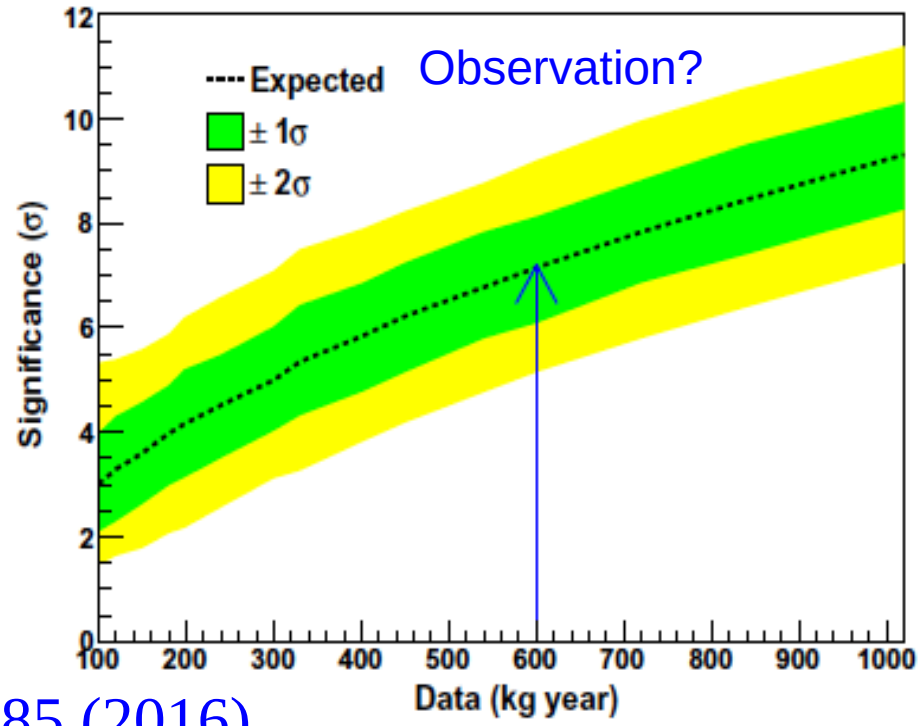
Toward phase-II NaI experiment (COSINE-200?)

- Active reduction of Pb^{210} in crystal
- Understanding & reduction of PMT background
- Crystallization & encapsulation

} 200 kg of NaI(Tl) crystal with less than 1 dru background

Sensitivity of phase-II experiments





EPJC 76 185 (2016)

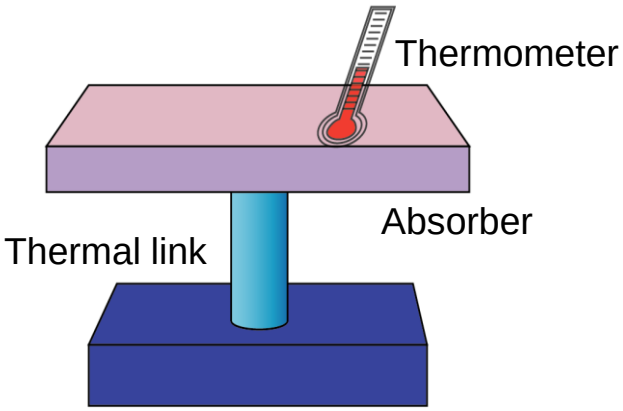
KIMS-LT experiment

MMC = Metallic Magnetic Calorimeter

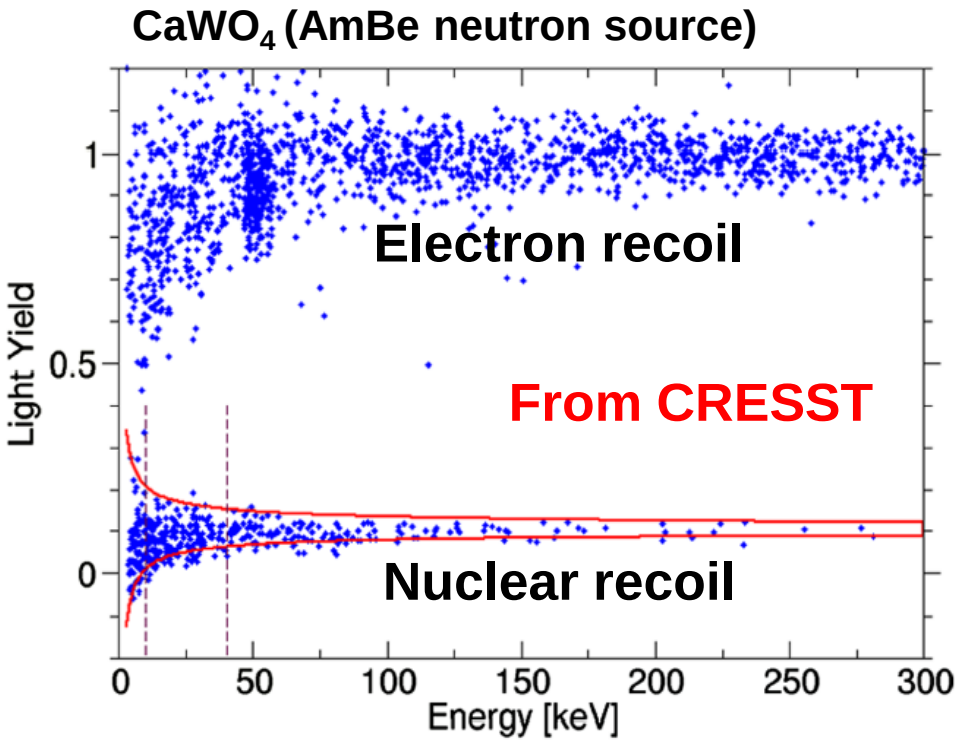
MMC Light sensor

MMC Phonon sensor

<10-50 mK>



- Scintillator detector @ 10-50 mK
- Ratio of heat-to-light signal make excellent discrimination between WIMP signal and background

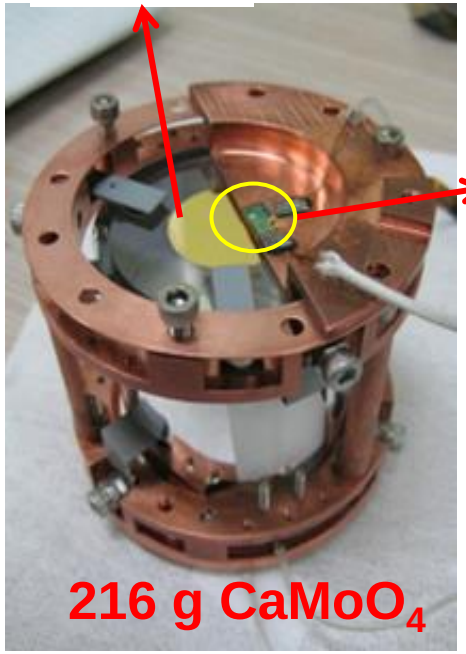


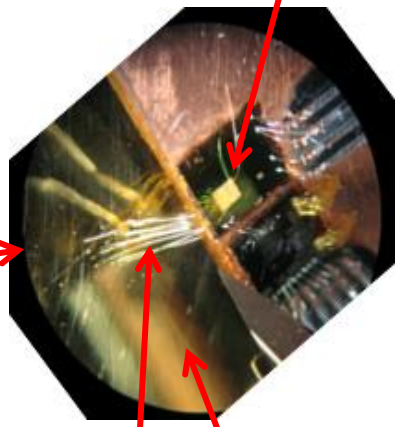
Phonon & photon sensors with $CaMoO_4$

Heat signal

Phonon collector
Patterned gold film

MMC

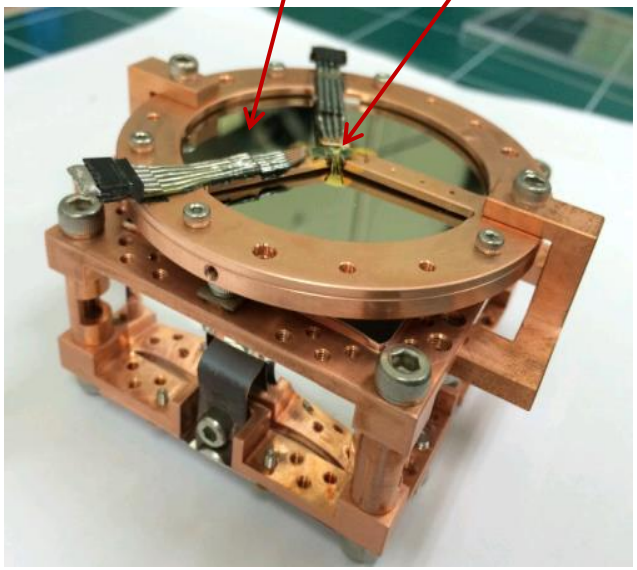




Gold film

Gold wires (thermal connection)

Light signal
2 inch Ge wafer + MMC

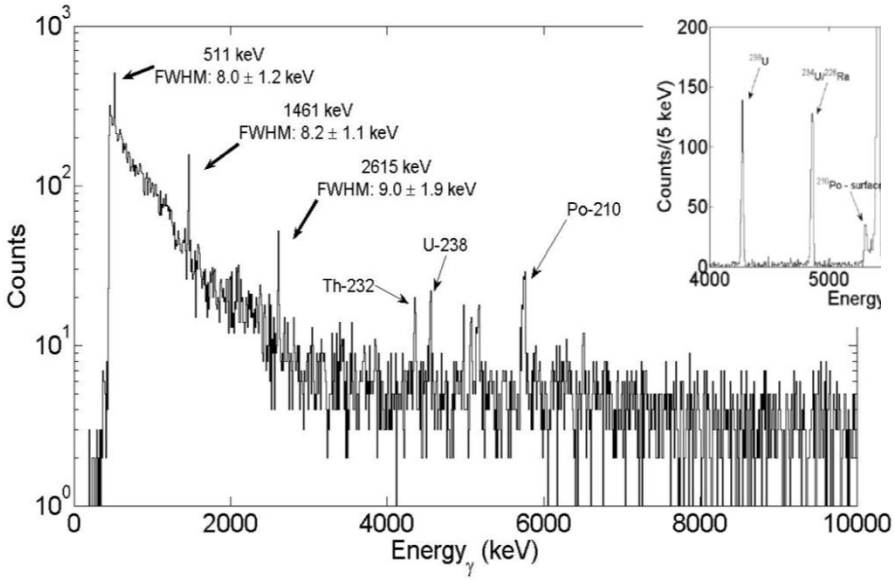


Active R&D to improve light sensor is underway

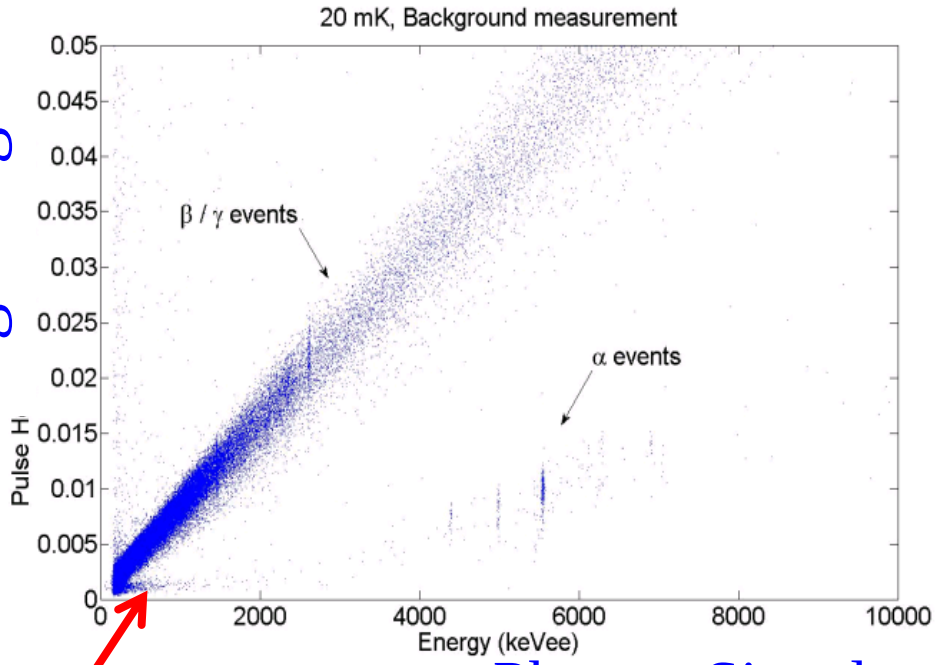
We measure both thermal and athermal phonons.

Light and Heat signals with $CaMoO_4$

At over-ground lab in Korea



Light Signal

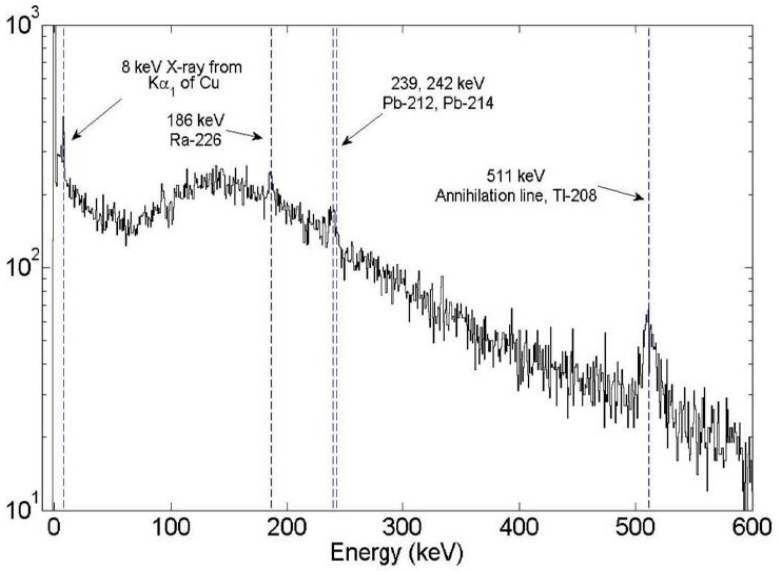


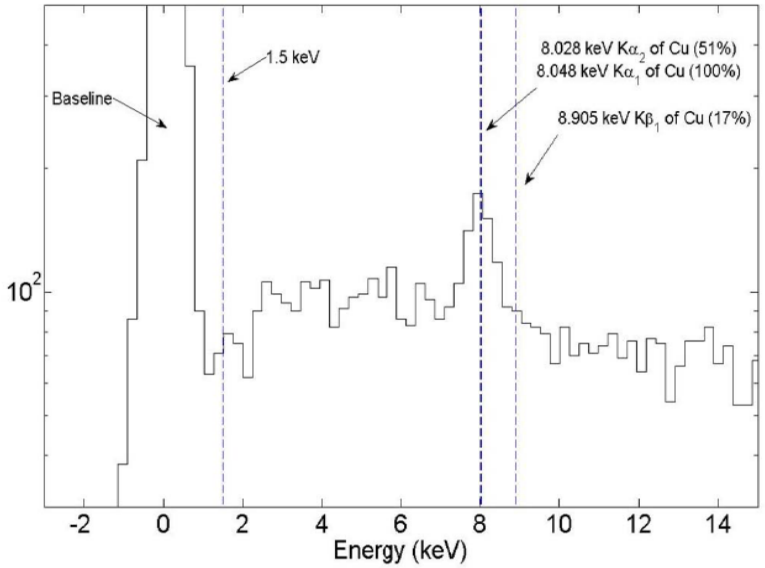
Phonon Signal

Nuclear recoil by neutrons ?

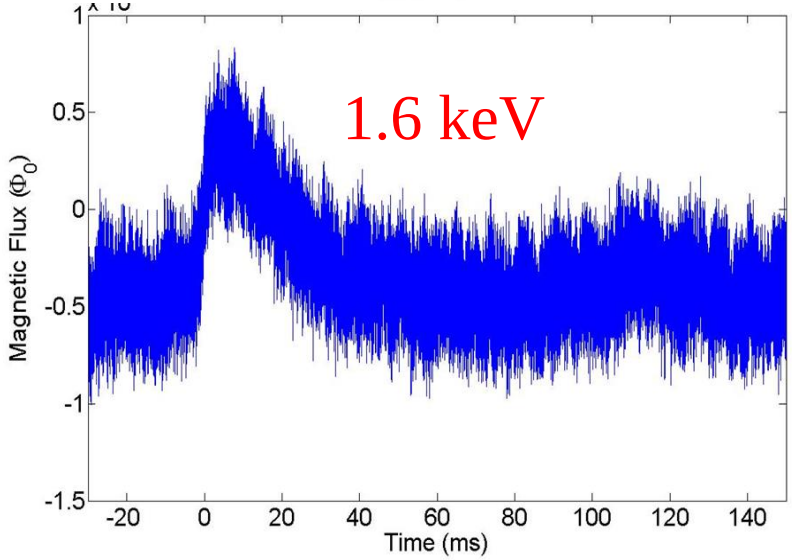
- Good energy resolution with phonon signals
- Need to optimize light sensor

Low energy heat signals





- ~ 1keV energy threshold is possible with phonon signal



Crystals for low temperature detectors

Materials	T(K)	E_g (eV)	E_λ(eV)	LY (ph/keV)	η %
NaI-Tl	295	5.9	3.0	44	13.2
CsI-Tl	295	6.4	2.3	57	13.1
$LaCl_3$-Ce	295	6.8	3.7	48	17.8
$Bi_4Ge_3O_{12}$	295	5.0	2.5	7.2	1.8
	9			22.7	5.7
$CaWO_4$	295	5.2	2.9	15.8	4.6
	9			28.7	8.3
$CaMoO_4$	295	4.0	2.3	8.9	2.0
	9			27.3	6.2
$CdWO_4$	295	4.2	2.6	27.4	7.1
	9			39.6	10.2

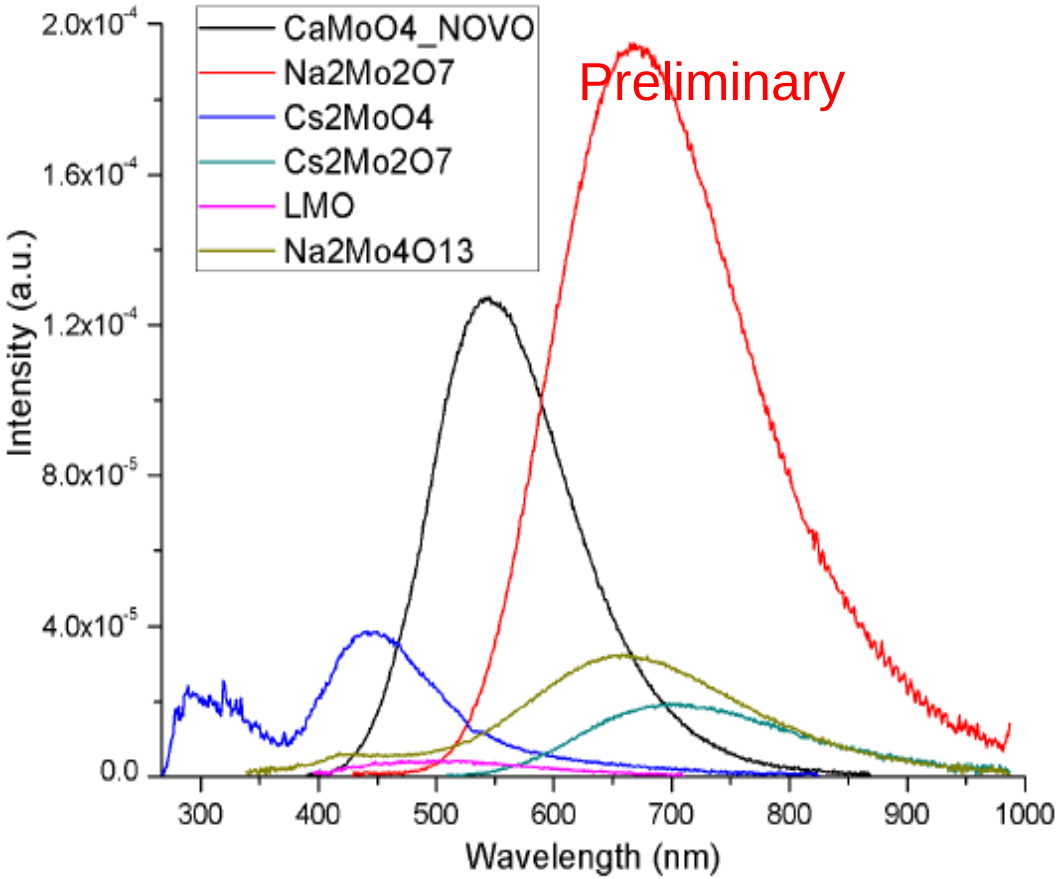
- $CaMoO_4$ is similar to $CaWO_4$ in scintillation efficiency.
- Also considering other candidates
  - $ZnWO_4$, $PbWO_4$, Li_2MoO_4, $PbMoO_4$, $Na_2Mo_2O_7$, Cs_2MoO_7
  - pure NaI, pure CsI
  - Start survey of possible crystals

Light Yield, Internal Background, Phonon signals …

Crystals for low temperature detectors

Materials
NaI-Tl
CsI-Tl
$LaCl_3$-Ce
$Bi_4Ge_3O_{12}$
$CaWO_4$
$CaMoO_4$
$CdWO_4$

Luminescence intensity @ 10 K



- $CaMoO_4$ is [redacted] ciency.
- Also consi
  - $ZnWO_4$, $PbWO_4$, Li_2MoO_4, $PbMoO_4$, $Na_2Mo_2O_7$, Cs_2MoO_7
  - pure NaI, pure CsI
  - Start survey of possible crystals

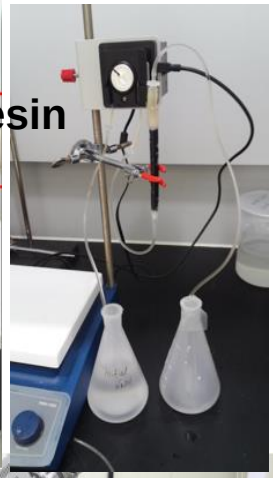
Light Yield, Internal Background, Phonon signals …

Active R&D for KIMS-LT experiment

Powder purification

Chemical purification, resin, chromatography, sublimation, recrystallization..

~10-1000 reduction of U and Th



Radiopurity measurement

- **2 Canberra HPGe (100%) are operating**
- **1 Ortec well-type HPGe (2016.7)**

Crystal growing

2 Kyropoulos ,1 Bridgman ,1 Czochralski in center + KNU + NIIC + ISM + FOMOS + Etc.

Annealing

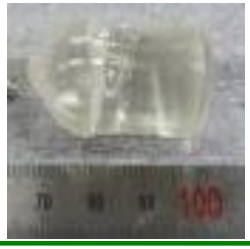
$CaMoO_4$

$PbMoO_4$

$Na_2Mo_2O_7$

Li_2MoO_4

$Cs_2Mo_2O_7$



Strategy for low-mass dark matter search

Low Mass WIMP detection

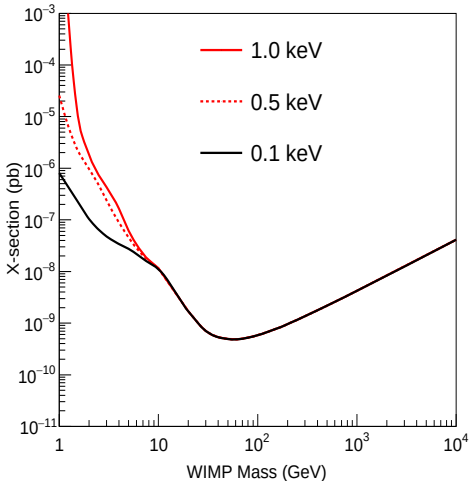
Lower Energy Threshold

Lower background

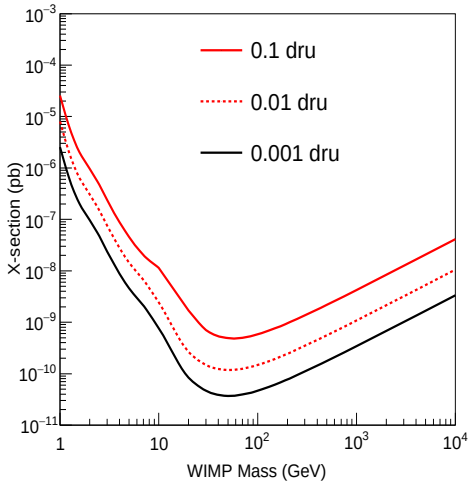
Larger detector volume

- Assuming $CaMoO_4$ and 1 year operation

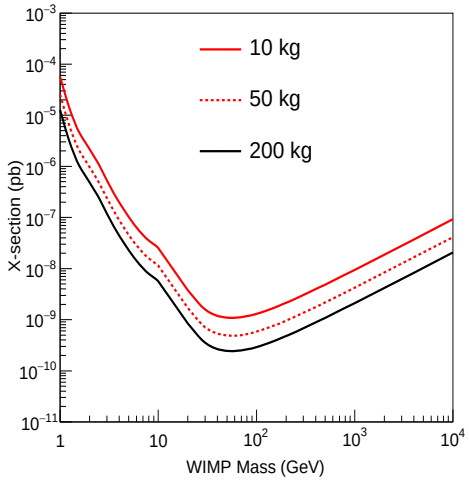
50 kg, 0.1 dru



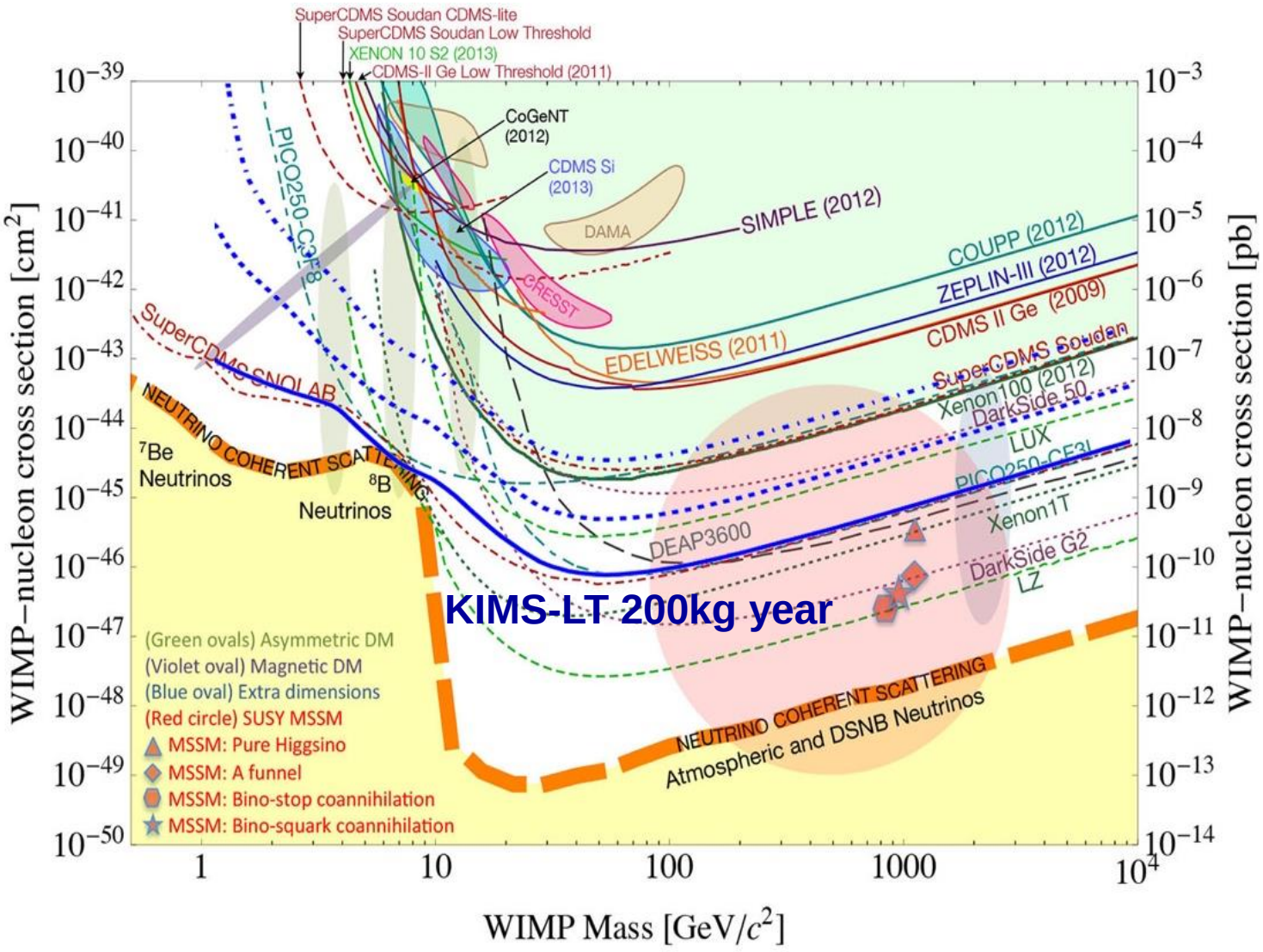
50 kg, 0.5 keV threshold



0.1 dru, 0.5 keV threshold



Sensitivity of KIMS-LT experiment



Goal to have the most sensitive detector for the low-mass DM

A new underground facility at Handeok Mine

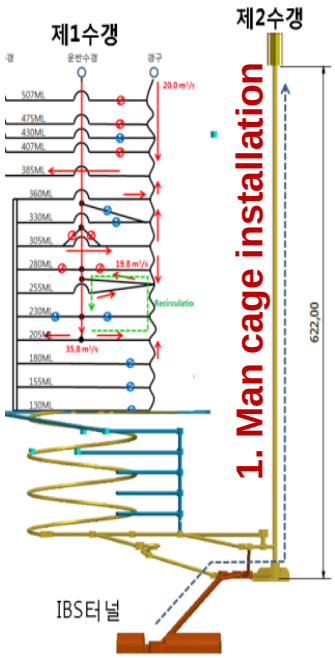
After extensive studies, we decided to build a new underground lab at the active iron mine, Handeok.

- **For the 2018 Winter Olympic, construction of a high-speed train from airport to the eastern shore has started.**
- **~ 3 hour from Incheon airport to Handeok Mine.**

Basic plan for a new underground facility

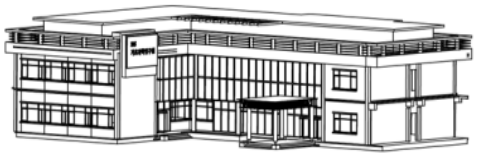
- Depth: 1100 m
- Existing Tunnels: 600m(Shaft), 6 km(Rampway)

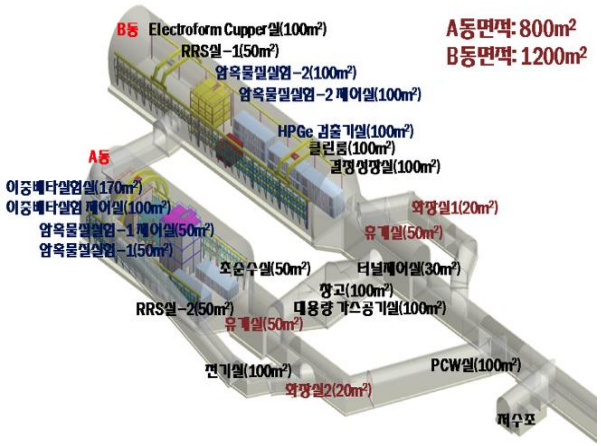
1. Man cage in the shaft
2. Access tunnel, 800m (10% descending)
3. Underground lab: 2000 m² (A 800 m² + B 1200 m²)
4. Ground office: 1000 m²



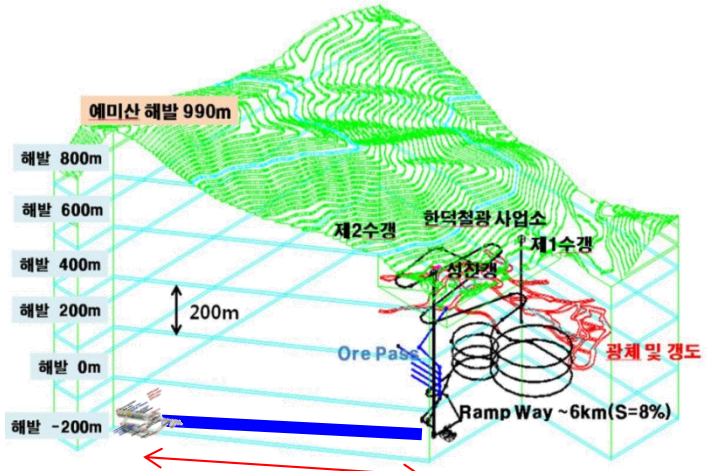
4. Ground office

지상연구소 (2층콘크리트 복합구조) 조감도



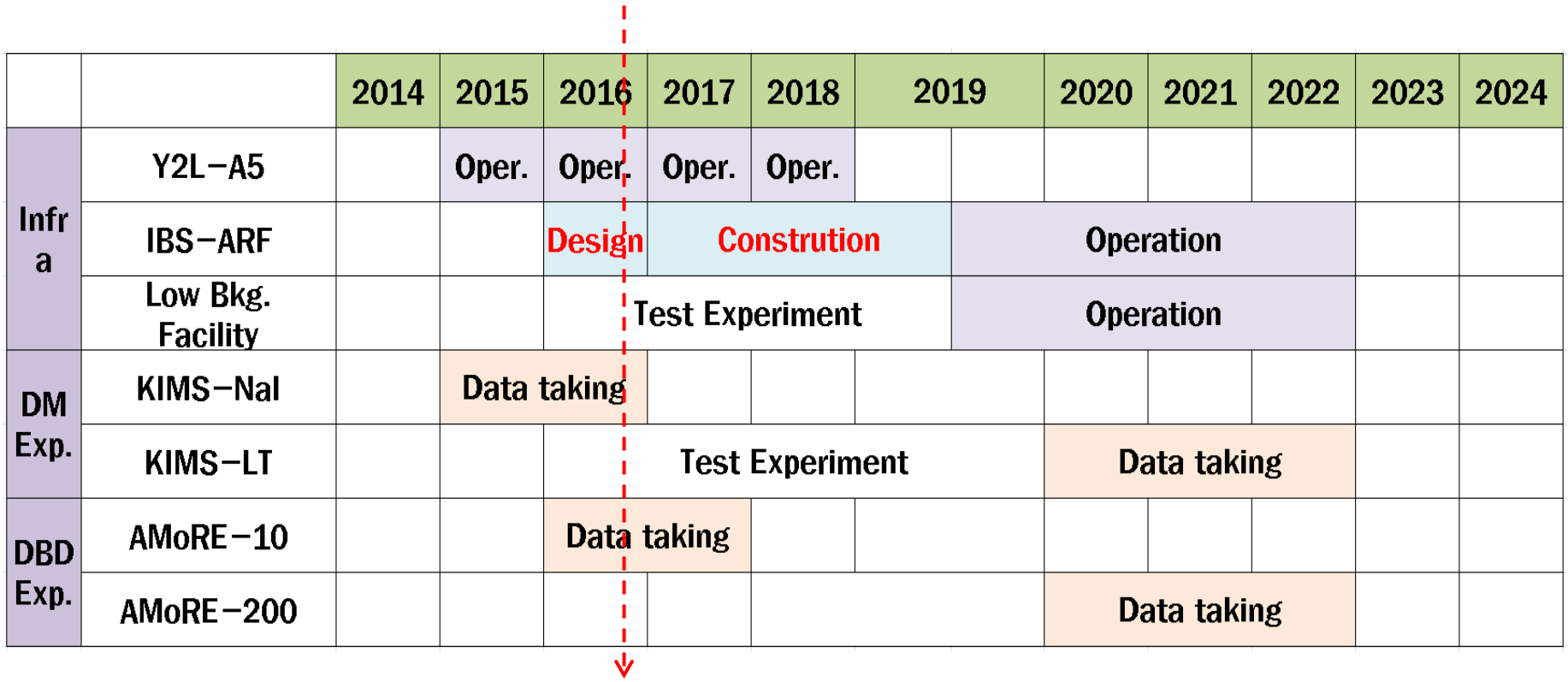


3. Underground lab (2000m²)



2. Access tnnel 800 m

A construction and experiments schedule



		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Infra	Y2L–A5		Oper.	Oper.	Oper.	Oper.						
	IBS–ARF			Design	Constrution			Operation				
	Low Bkg. Facility			Test Experiment				Operation				
DM Exp.	KIMS–NaI		Data taking									
	KIMS–LT			Test Experiment				Data taking				
DBD Exp.	AMoRE–10			Data taking								
	AMoRE–200							Data taking				

Summary

- **Korea Invisible Mass Search (KIMS)** experiment has been **running** more than **16 years** for dark matter search.

- **Active works** toward **better understanding of dark matter nature** are ongoing by **KIMS collaboration.**

Backup slides

Intrinsic Backgrounds

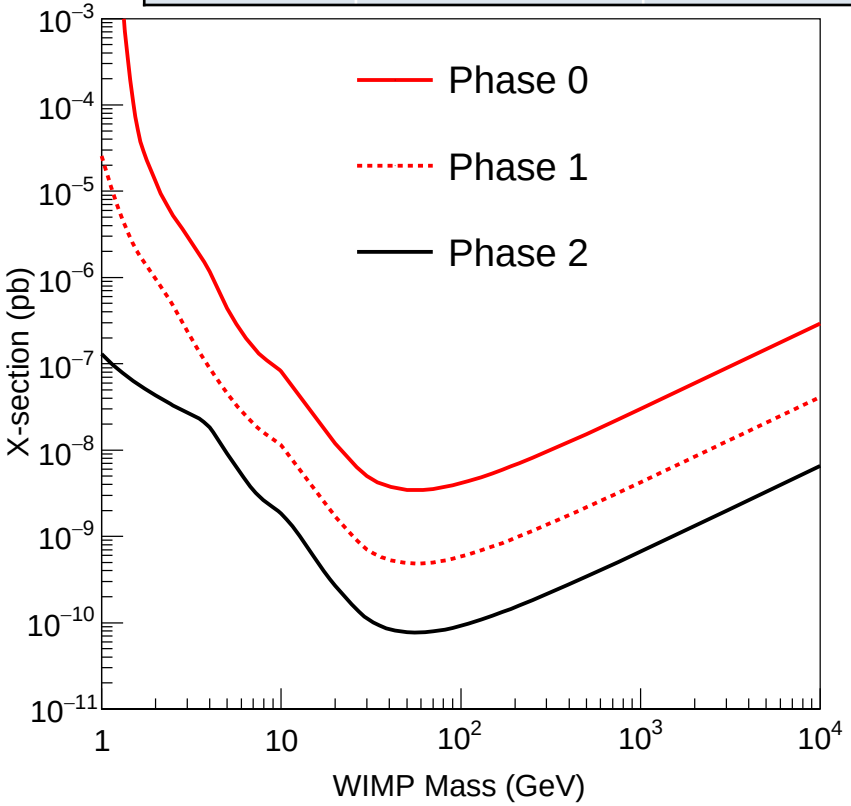
	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG
^{40}K (ppb)	41.4±3.0	49.3±2.4	**25.3**±3.6	<117	40.1±4.2	<127
^{40}K (powder)	?	?	**25.1**	~200	?	~200
^{238}U	<0.02	<1.04	<0.14	-	<0.04	<0.05
^{232}Th	<3.17	<0.48	0.46±0.07	-	0.19±0.002	8.9±0.04
α rate(mBq/kg)	**3.29**±0.01	**1.77**±0.01	2.43±0.01	-	**0.48**±0.004	1.53±0.01
LY(pe/keV)	12.1±0.9	15.1±1.1	12.6±0.1	3.8±0.4	11.3±0.2	4.8±0.4

- **^{40}K in powder and in crystal (NaI-003) are the same.**
- **All Alpha Spectra crystals are ~ 40 ppb ^{40}K levels.**
- **~10 ppb level ^{40}K powder is produced by SA.**
- **AS reduced ^{210}Pb by a factor of 4.**

AS = Alpha Spectra Inc.
SA-AG = Sigma Aldrich, Astro-grade (less K40)
SA-CG = Sigma Aldrich, Crystal-grade

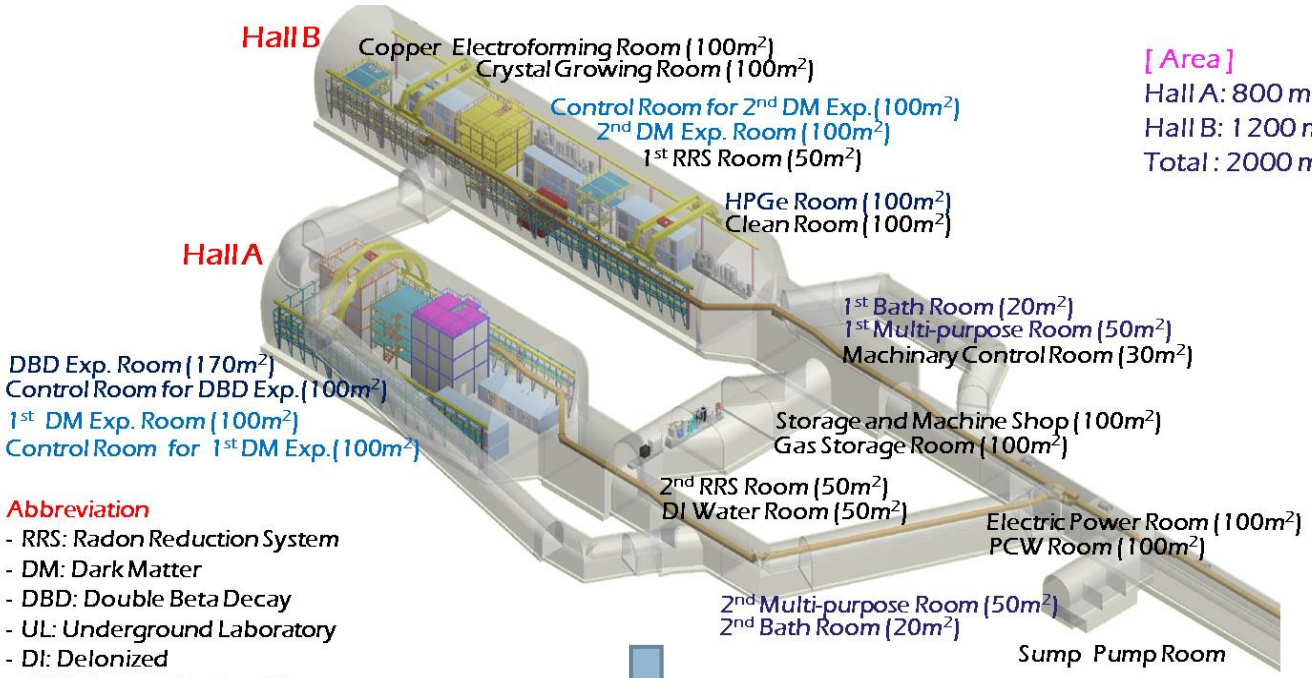
Backgrounds and sensitivities

	Threshold	Background	Mass	Time line
Phase0	1 keV	1.0 dru	10 kg	2~3 years
Phase1	0.5 keV	0.1 dru	50 kg	3~6 years
Phase2	0.1 keV	0.01 dru	200 kg	6~10 years



Background source	Radioactivity	Background [Counts/keV/kg/day]
$\beta\beta$ decays of 100Mo		$<10^{-5}$
Muon-induced neutrons		10^{-5}
^{238}U	10 μ Bq/kg	6×10^{-4}
^{232}Th	10 μ Bq/kg	4×10^{-4}
^{210}Pb	10 μ Bq/kg	0.002
Total		3×10^{-3}

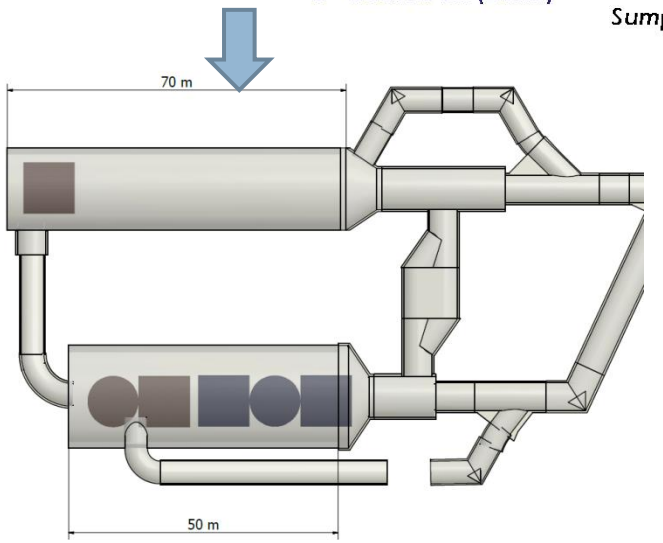
A Conceptual Layout of Underground Lab Space

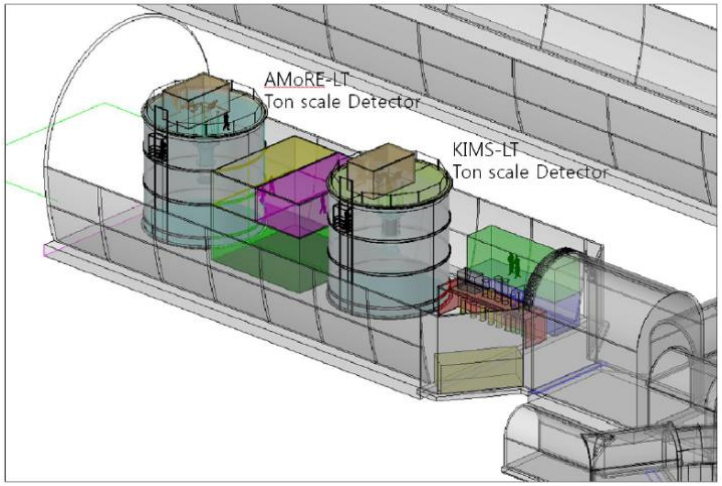


[Area]
Hall A: 800 m²
Hall B: 1200 m²
Total : 2000 m²

	Room Name	Area	Location
1	DBD Exp. Room	170 m²	Hall A
2	Control Room for DBD Exp.	100 m²	Hall A
3	1st DM Exp. Room	100 m²	Hall A
4	Control Room for 1st DM Exp.	100 m²	Hall A
5	2nd DM Exp. Room	100 m²	Hall B
6	Control Room for 2nd DM Exp.	50 m²	Hall B
7	HPGe Room	100 m²	Hall B
8	Clean room (50m2 x 2)	100 m²	Hall B
9	Crystal Growing Room	100 m²	Hall B
10	DI Water Room	50 m²	Hall B
11	Copper Electroforming Room	100 m²	Hall B
12	1st and 2nd RRS Room	100 m²	Aux. space
13	PCW Room	100 m²	Aux. space
14	Gas Storage Room	100 m²	Aux. space
15	Storage and Machine Shop	100 m²	Aux. space
16	Electric Power Room	100 m²	Aux. space
17	Multipurpose RoomX2	100 m²	Aux. space
18	Bath Room (20m2 x 2)	40 m²	Aux. space
19	Machinary Control Room	30 m²	Aux. space
	Total	1740 m²	

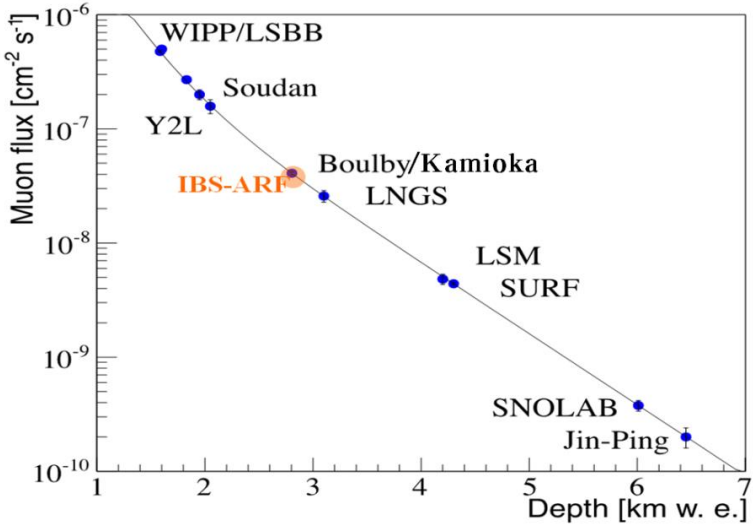
Abbreviation
- RRS: Radon Reduction System
- DM: Dark Matter
- DBD: Double Beta Decay
- UL: Underground Laboratory
- DI: Delonized
- PCW: Process Cooling Water



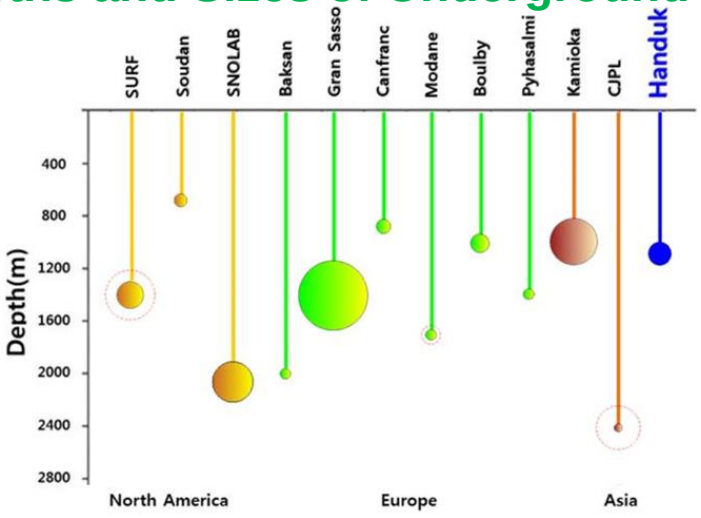


Underground Lab and Muon Flux

[Underground Labs and Muon Fluxes]

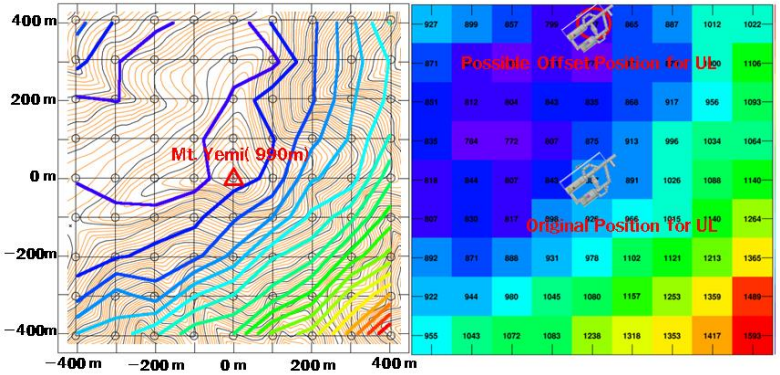


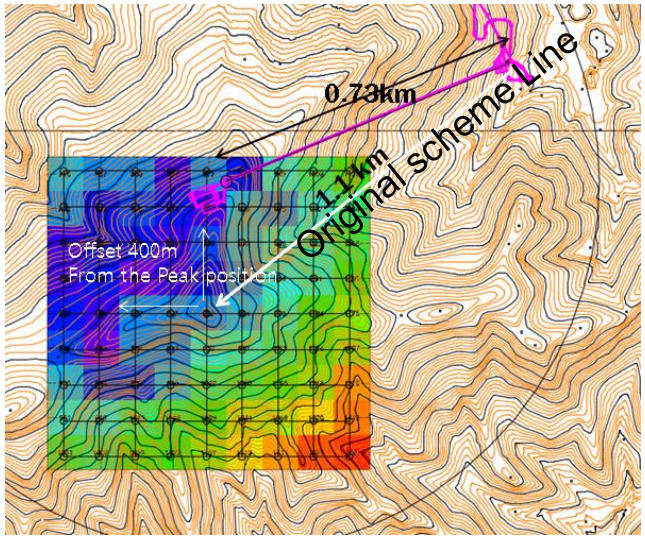
[Depths and Sizes of Underground Labs]



[Muon Fluxes in Handuk mine]

Distribution of Muon fluxes at 1010 m depth.





Tunnel length ~730m, 400m off from the peak