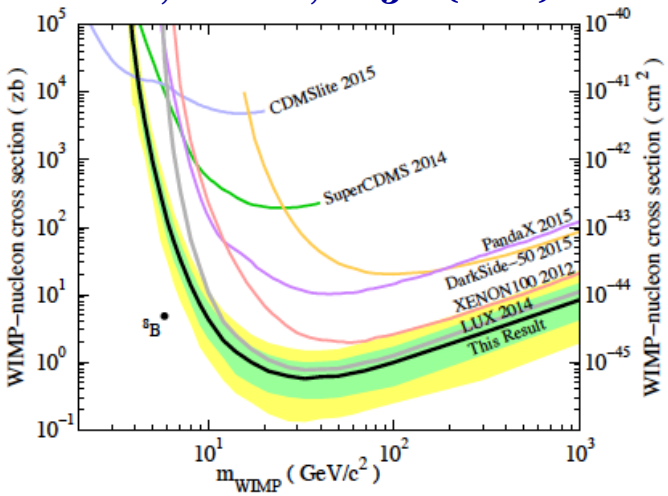
Rare Event Searches with ultra-low background scintillating calorimeter

Hyun Su Lee
Associate Director
Center for Underground Physics (CUP)
Institute for Basic Science (IBS)

Rare events?

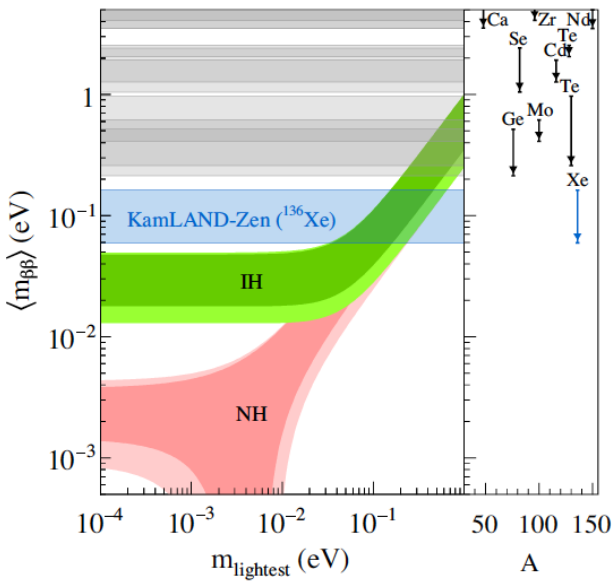
- **Direct detection of WIMP dark matter**
  - <O(1) events/(30 kg years)
  - Signal region <10 keV

LUX, PRL 116, 161301 (2016)



- **Neutrinoless double beta decay**
  - <O(1) events/(500 kg year)
  - Signal region ~ few MeV

KamLAND-Zen, arXiv:1605.02889



- Neutrino coherent scattering
  - ~O(1) events/(10 kg years)
  - Signal region <1 keV

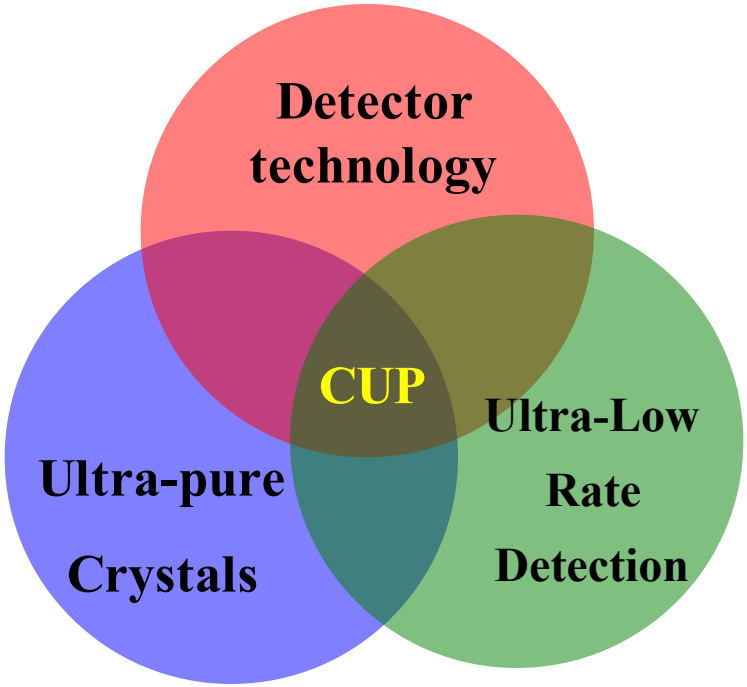
Key of rare event searches

- Background, Background, Background!!

- Go to Underground
- Heavy shield (Passive & Active)
- Internal background reduction
- Pulse shape discrimination

Strategy of our center for rare event searches

- To study rare events such as dark matter and neutrino, CUP is developing ultra-low background technology and infrastructure
- Ultra-low background technology can be realized with a combination of low background measurement and purification with the ultra-sensitive sensor



CUP will be unique research group to have all the technique in a center

KIMS (Dark Matter)

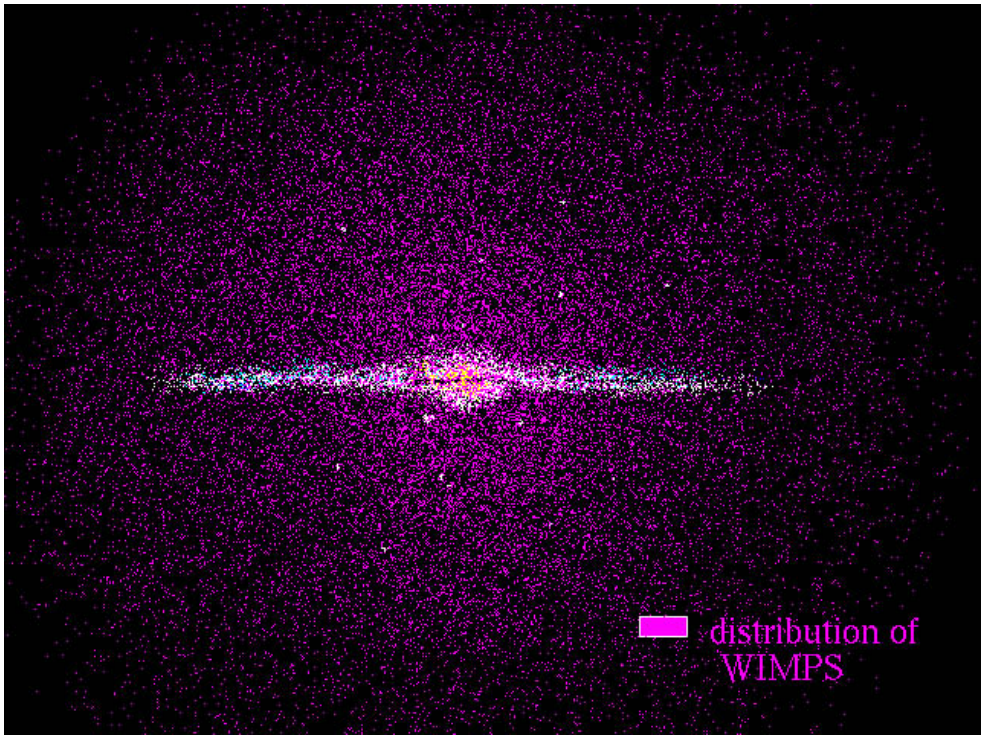
AMoRE ($0\nu\beta\beta$)

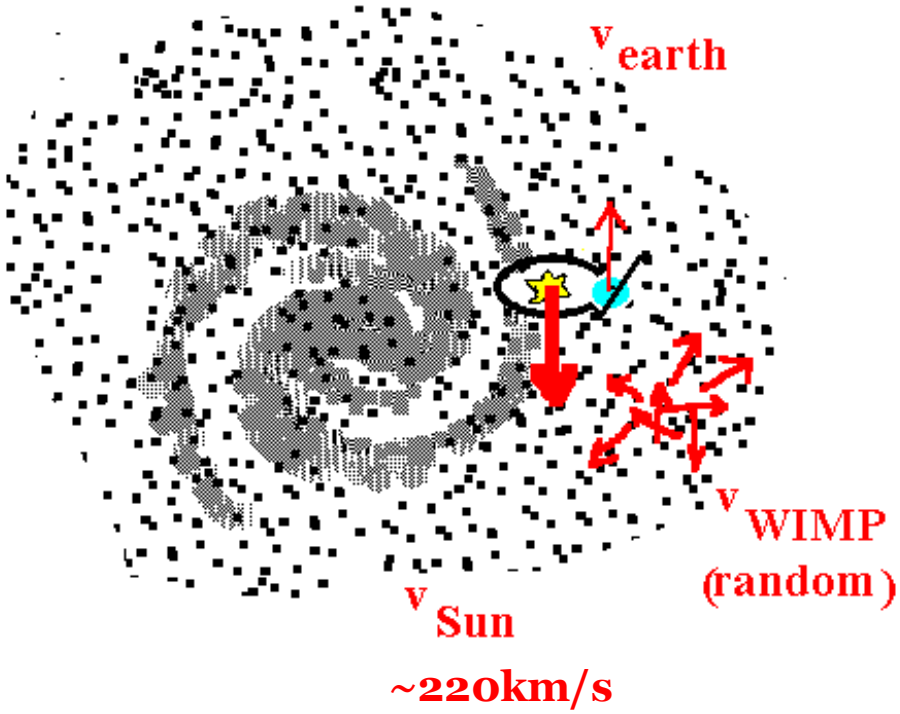
Inorganic scintillators for rare events searches

Experiment	Scintillator	Physics	Technique	Status	Site
DAMA/LIBRA	NaI	Dark Matter	PMTs	Running	LNGS, Italy
KIMS	CsI	Dark Matter	PMTs	Finished	**Y2L, Korea**
SABRE	NaI	Dark Matter	PMTs	R&D	LNGS, Italy/Stawell, Australia
KAMLAND-Pico	NaI	Dark Matter	Standard	R&D	Kamioka, Japan
ANAIS	NaI	Dark Matter	Standard	R&D	LSC, Spain
DM-Ice	NaI	Dark Matter	PMTs	R&D	South Pole
KIMS-NaI	NaI	Dark Matter	PMTs	R&D	**Y2L, Korea**
COSINE	NaI	Dark Matter	PMTs	R&D/Phase1	**Y2L, Korea/South Pole**
CRESST-II	$CaWO_4$	Dark Matter	Cryogenic	Running	LNGS, Italy
KIMS-LT	~MoO_4	Dark Matter	Cryogenic	R&D	Korea
TEXONO	CsI	Neutrino physics	PMTs	Running	KSNL, Taiwan
COHERENT	CsI/NaI	Neutrino physics	PMTs	R&D	SNS @ORNL
CANDLES	CaF_2	0ν2β	Standard	R&D	Kamioka, Japan
LUCIFER	ZnSe	0ν2β	Cryogenic	R&D	LNGS, Italy (?)
LUMINEU	$ZnMoO_4$	0ν2β	Cryogenic	R&D	LSM, France (?)
AMORE	$CaMoO_4$	0ν2β	cryogenic	R&D/Pilot	**Y2L, Korea**

- CsI/NaI for Dark Matter searches

Halo Model of WIMP dark matter

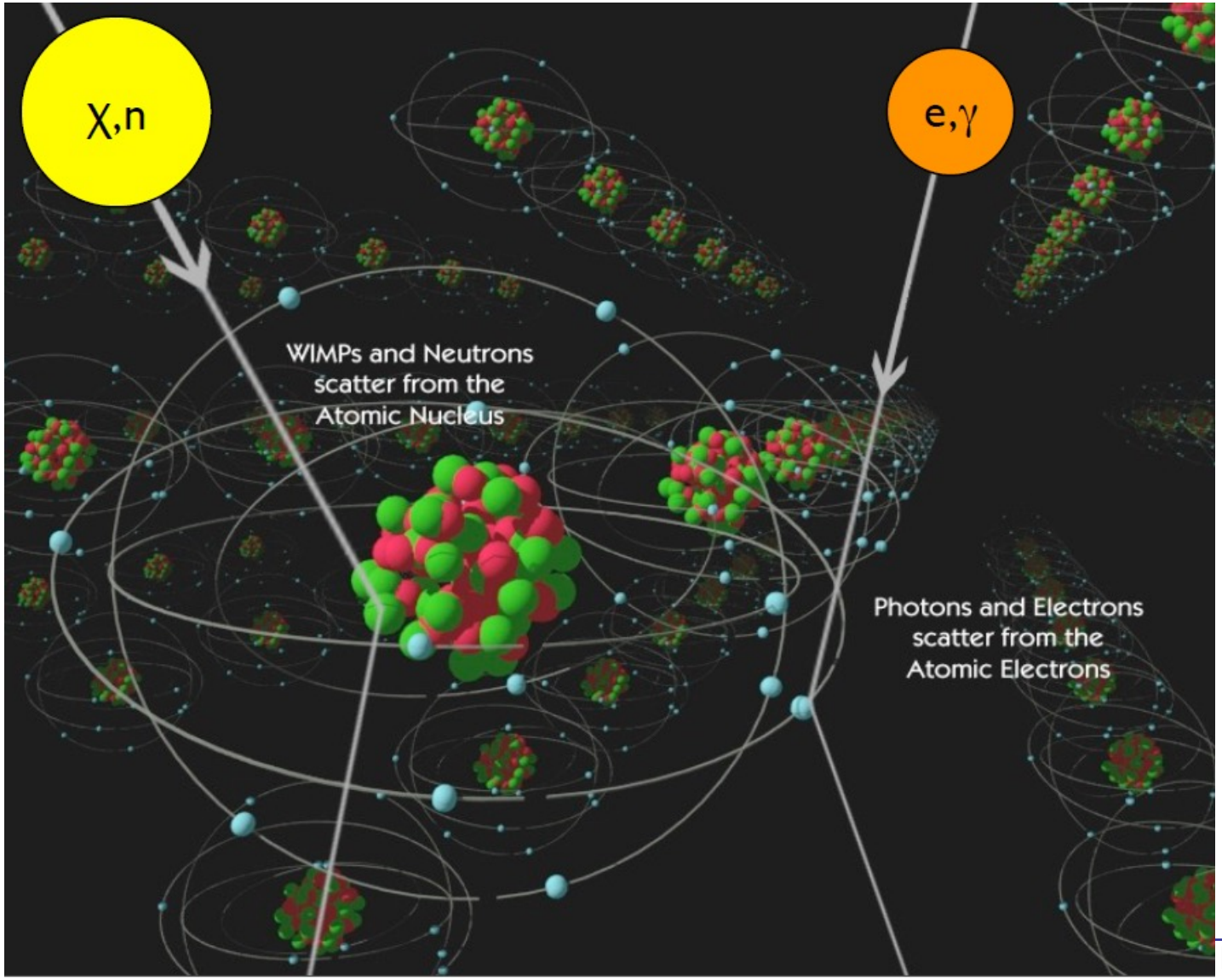




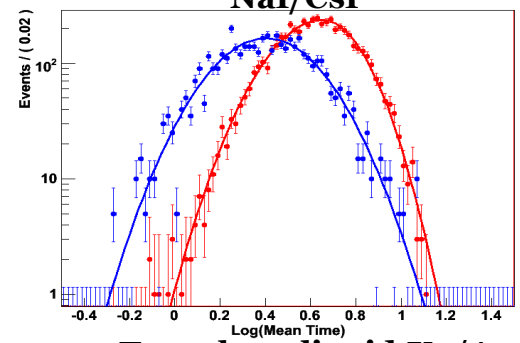
- Assuming Standard Halo Model
- Because of **rotation of the solar system**, we can have WIMP wind with average velocity of ~220km/s

Direct detection of WIMP dark matter

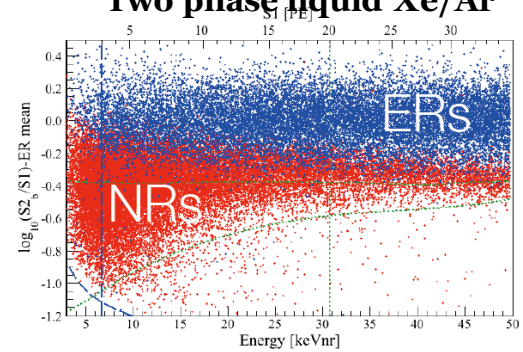
- WIMP-nucleus elastic-scattering



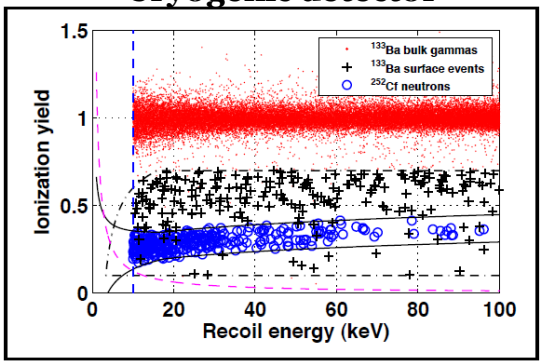
NaI/CsI



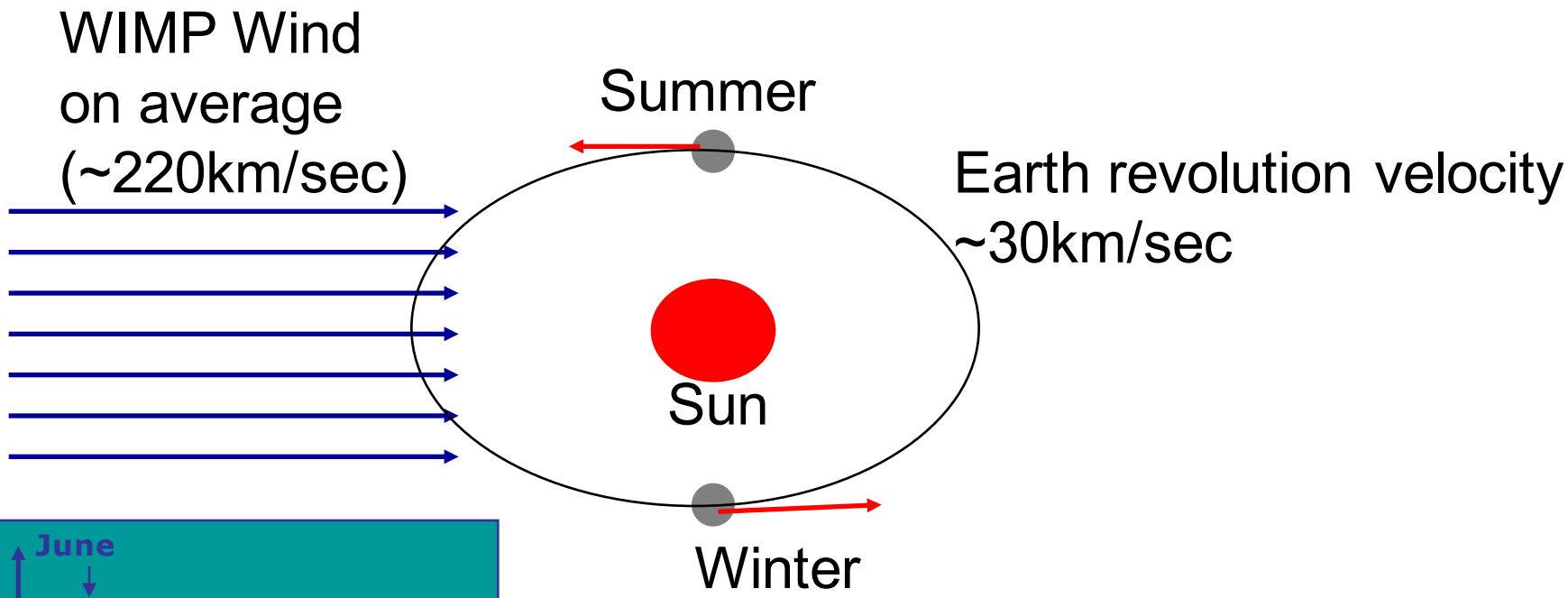
Two phase liquid Xe/Ar

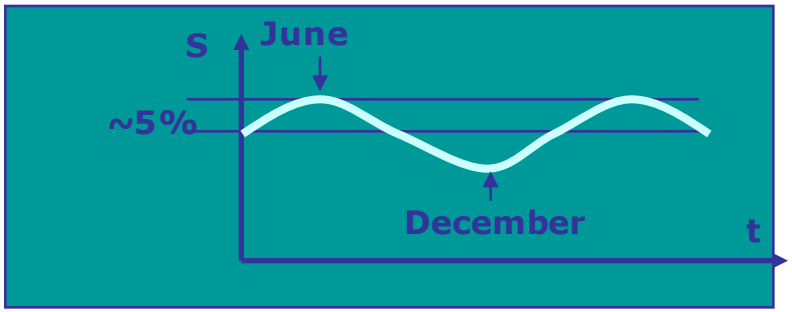


Cryogenic detector



Annual Modulation of WIMP dark matter

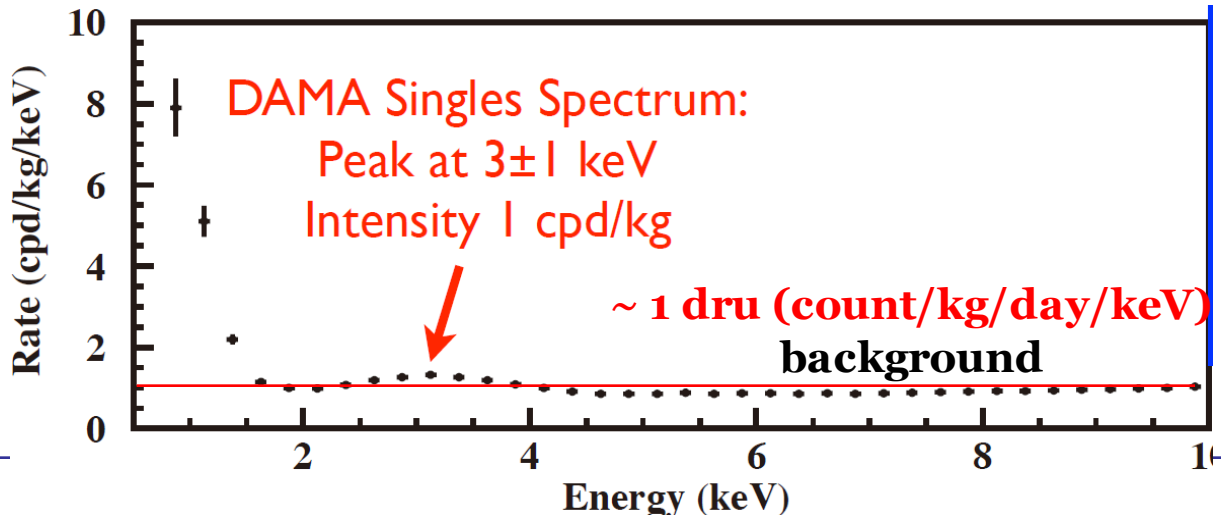




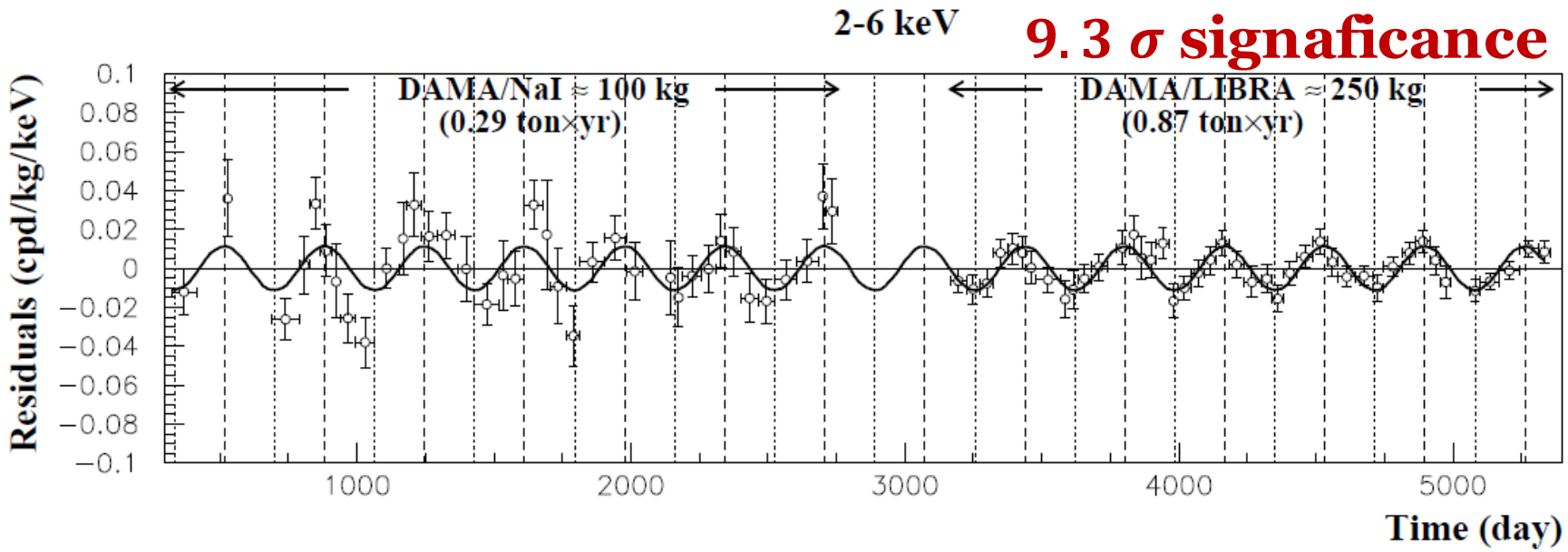
A few % annual modulation of WIMP signature

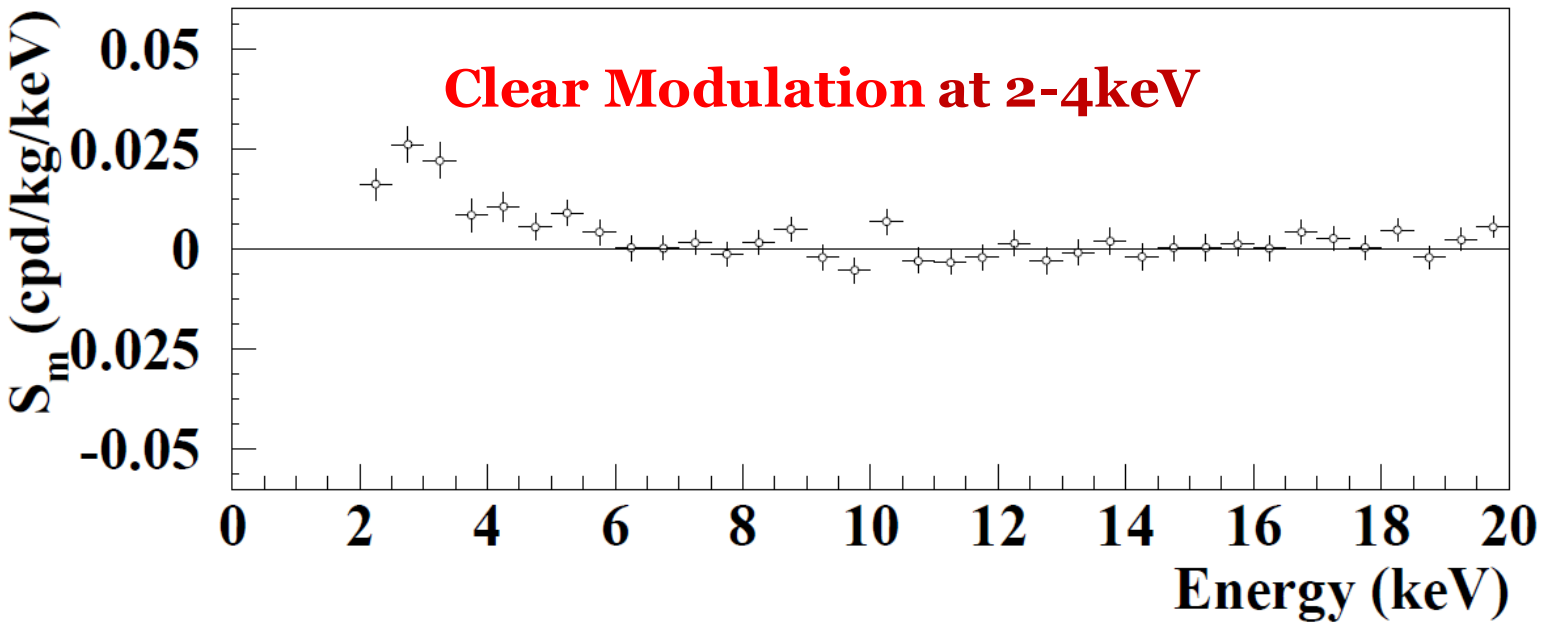
DAMA/LIBRA Experiment

- Annual Modulation Searches with NaI(Tl) crystal detectors
- DAMA/NaI
  - 100 kg target
  - 1997-2003
- DAMA/LIBRA
  - 250 kg target
  - 2003-2012 (phase I), 2013- (phase II)
- No discrimination of nuclear recoil events

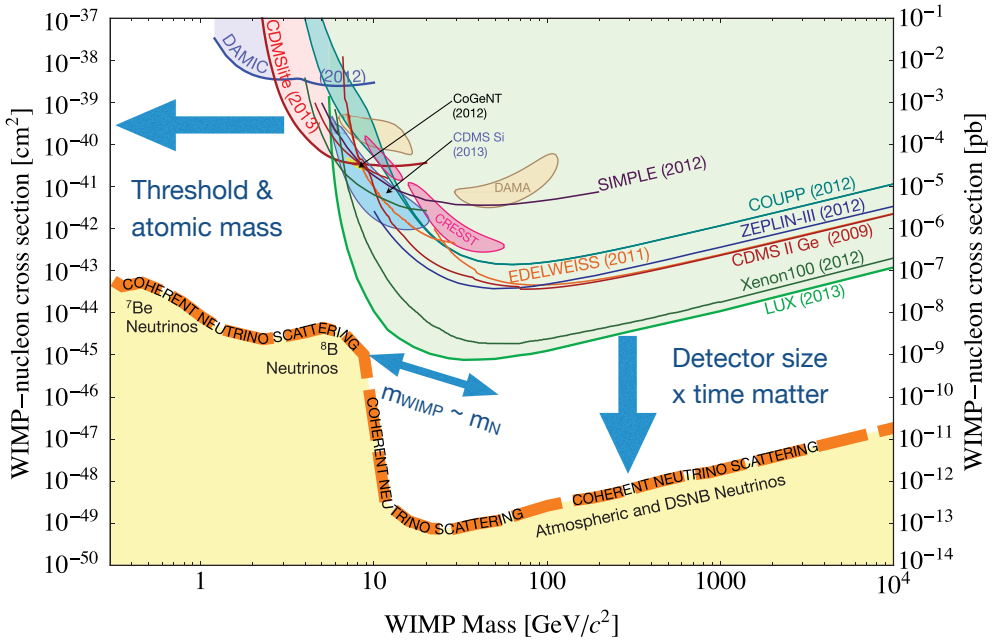


DAMA/LIBRA Experiment





DAMA/LIBRA was rejected?

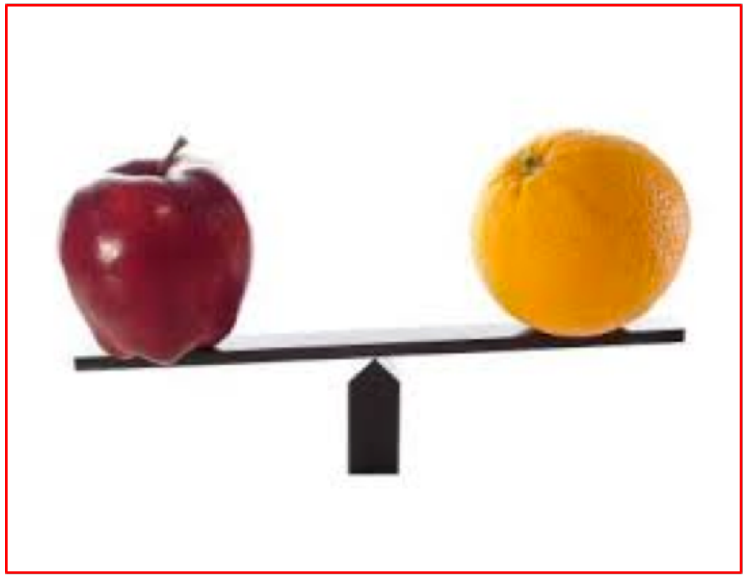


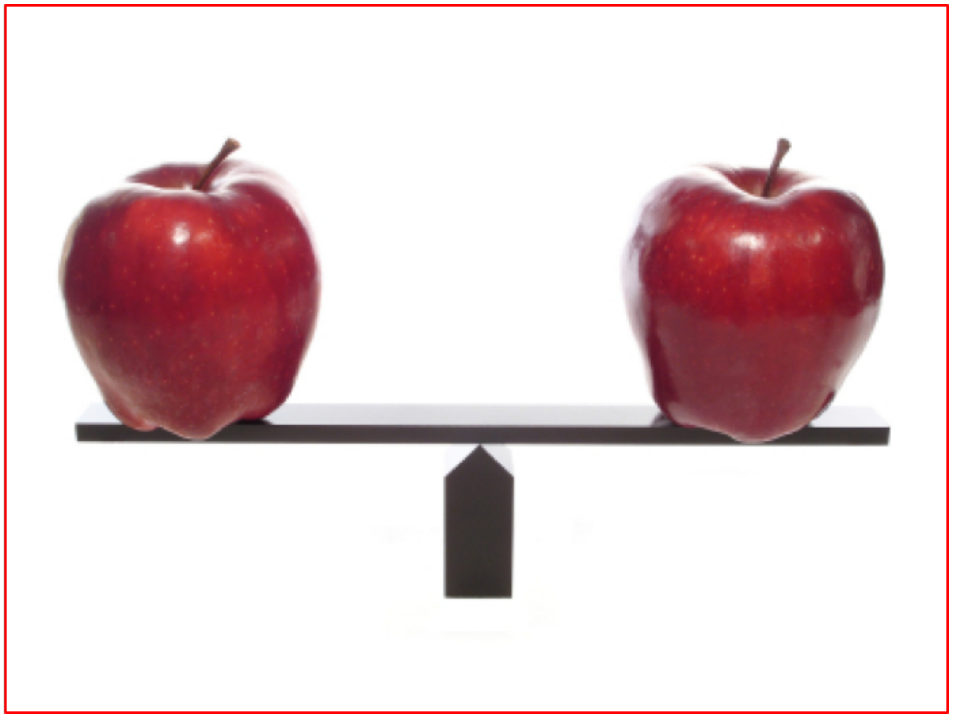
WIMP-Na interaction?

Quenching for nuclear recoil or other detector dependences?

Halo-model or dark matter model dependences?

Best way to prove/refute DAMA/LIBRA



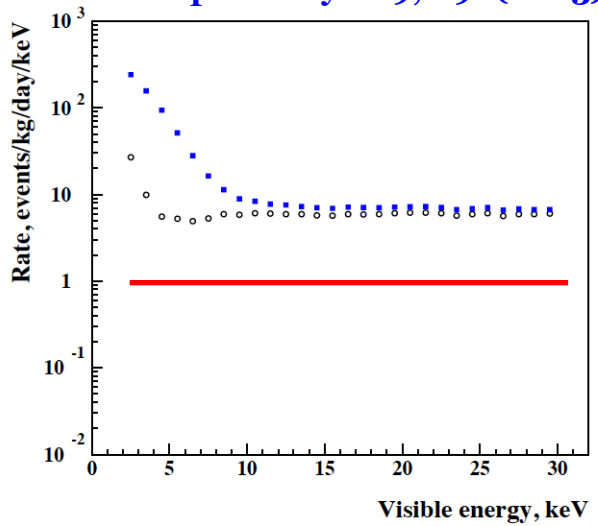


- Need exactly same experiment!!

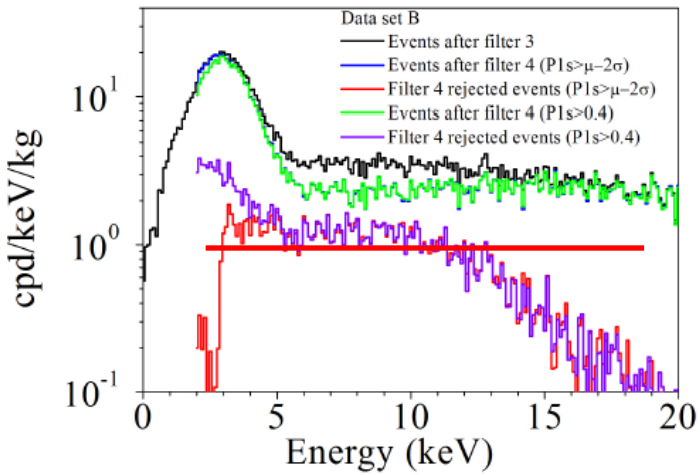
Why not yet?

- Background level of DAMA ~ 1 dru @ 2keV

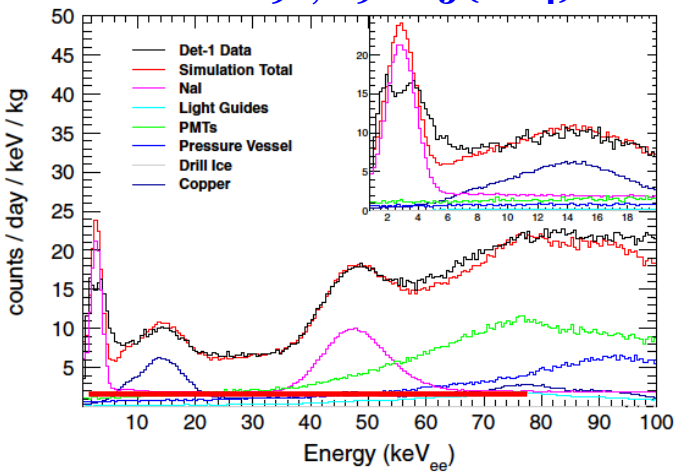
NAIAD Astropart. Phys. 19, 691 (2003)



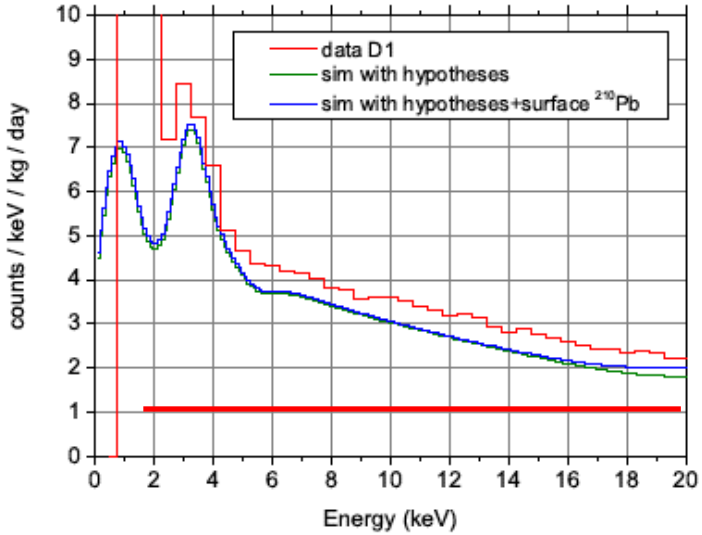
ANAIS EPJC 74, 3150 (2014)



DM-Ice PRD 90, 092005 (2014)



ANAIS arXiv:1604.05587 (2016)



KIMS (**K**orea **I**nvisible **M**ass **S**earch)

- Dark matter search at Yangyang underground laboratory since 2003
  - ❖ Proposed new underground laboratory @ Handuk 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 of 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

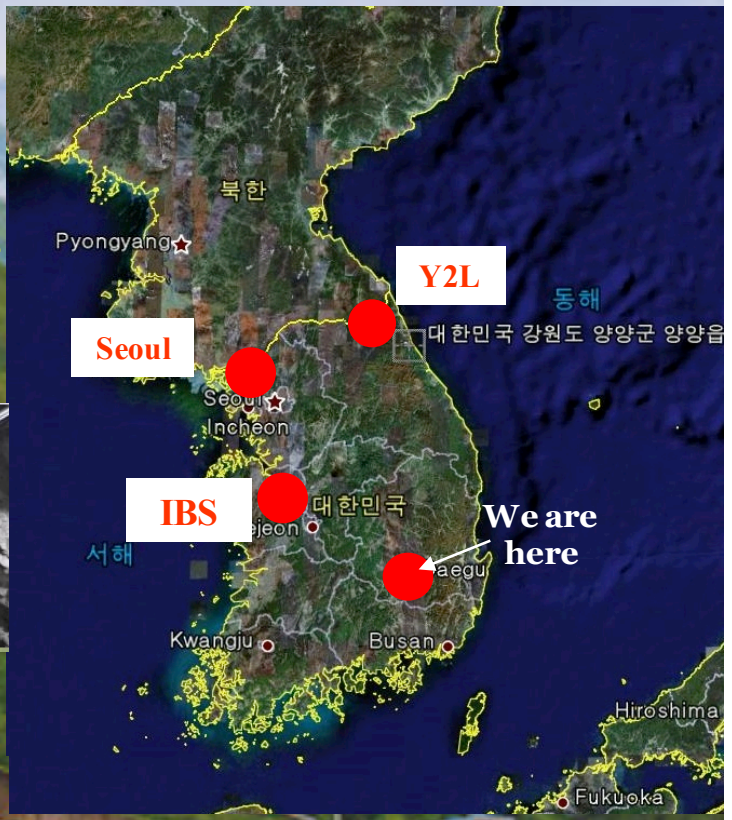
Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

1000m

700m



(Power Plant)

양양양수발전소

(Lower Dam)

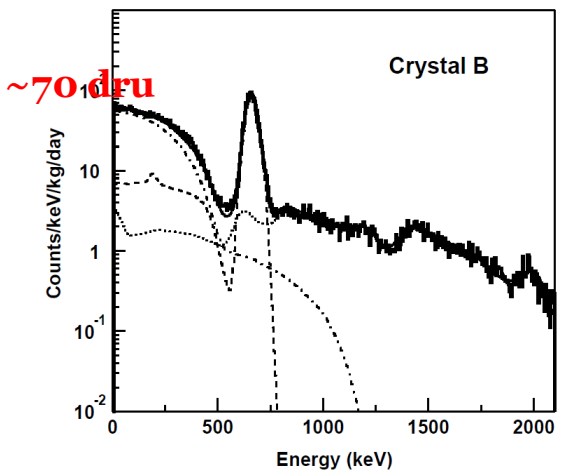
KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

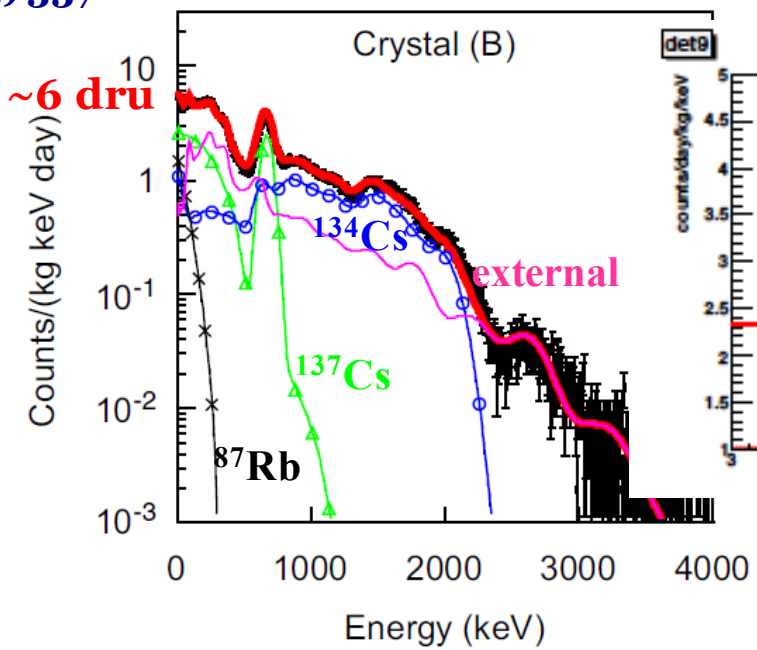
Minimum depth : 700 m / Access to the lab by car (~2km)

KIMS-CsI & Background

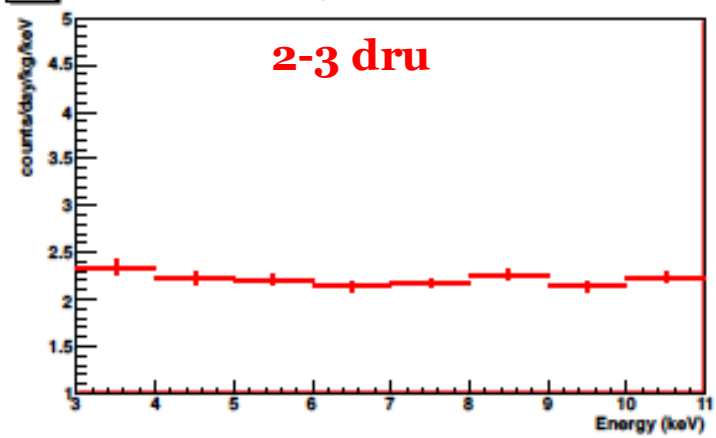
Nucl. Instrum. Meth. A 500 (2003) 337



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



Final crystals (2010)

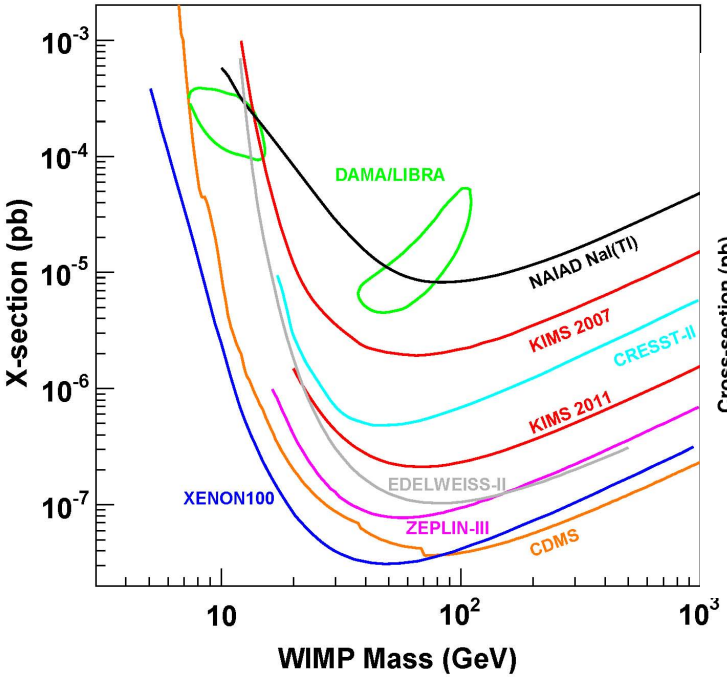


- Identified main sources of background
  - Internal ^{137}Cs, ^{134}Cs, ^{87}Rb
  - ^{137}Cs was caused by processing water so, purification of water can reduce
  - ^{87}Rb was reduced by recrystallization
  - ^{134}Cs can be tagged with surrounding crystals

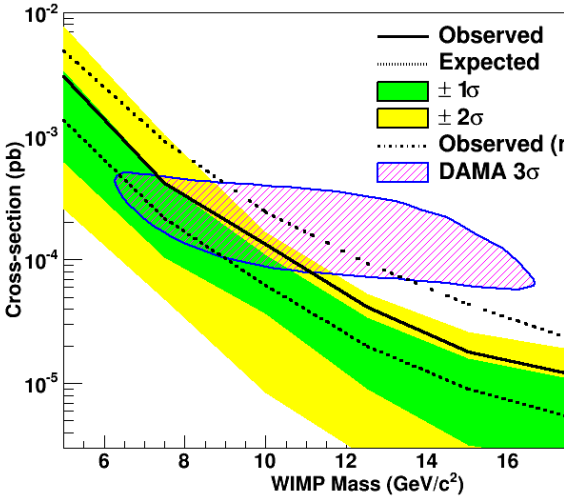
Physics of KIMS-CsI

- 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

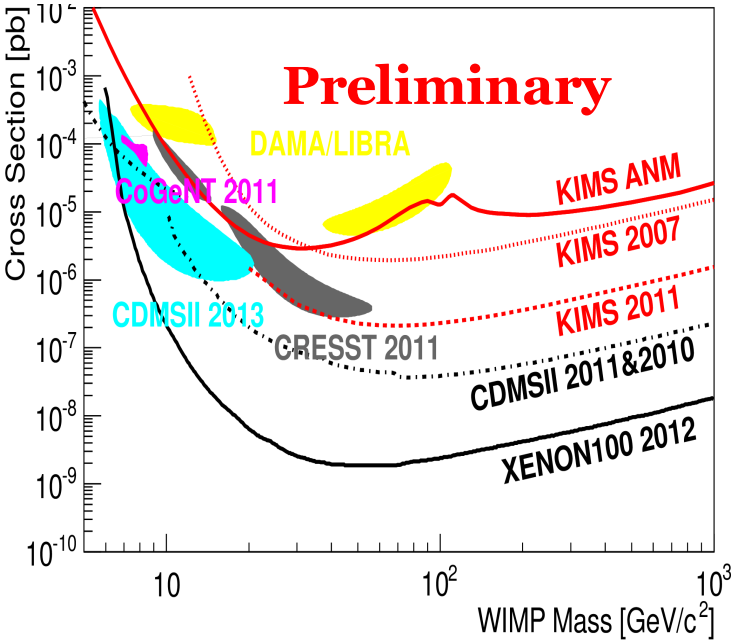
PRL 108 181301 (2012)



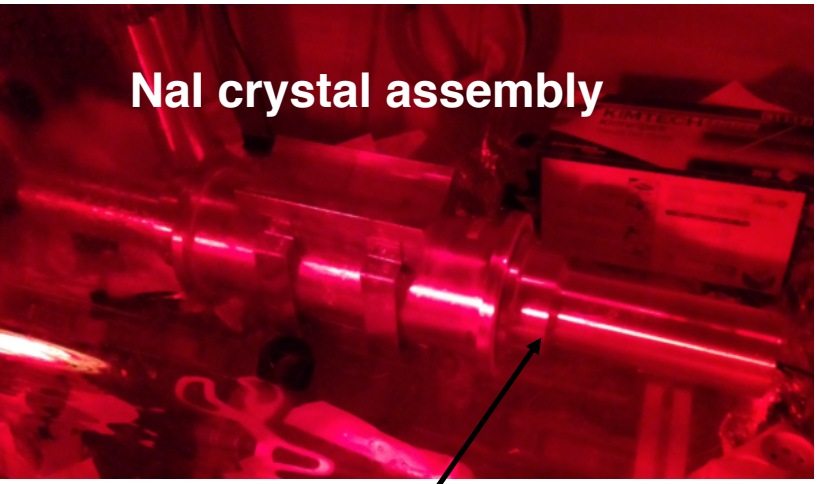
PRD 90 052006 (2014)

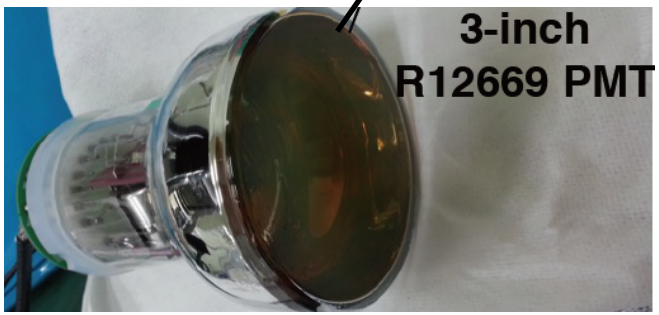


Annual Modulation

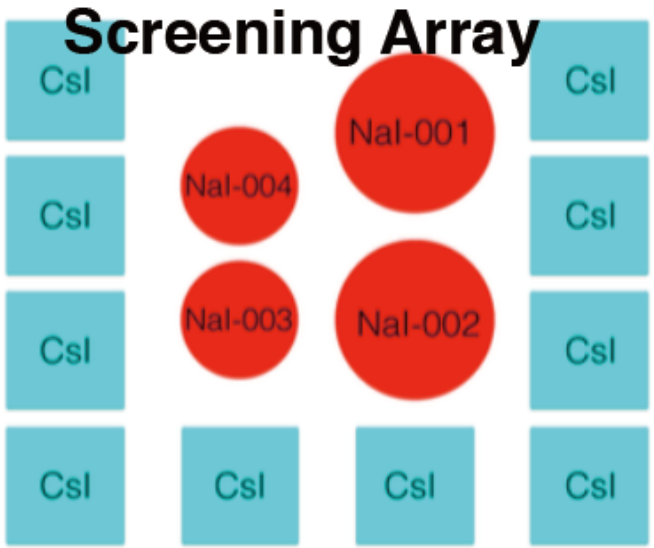


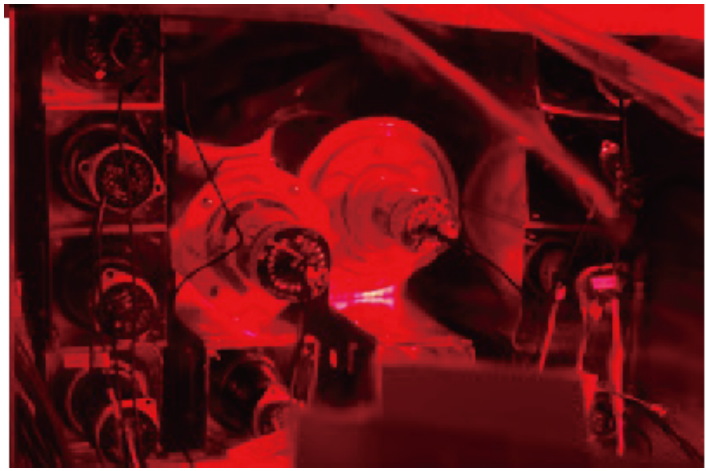
KIMS-NaI experiment (Since 2013~)





- Use same NaI crystal and analyze same annual modulation
- Need to develop better detector than 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

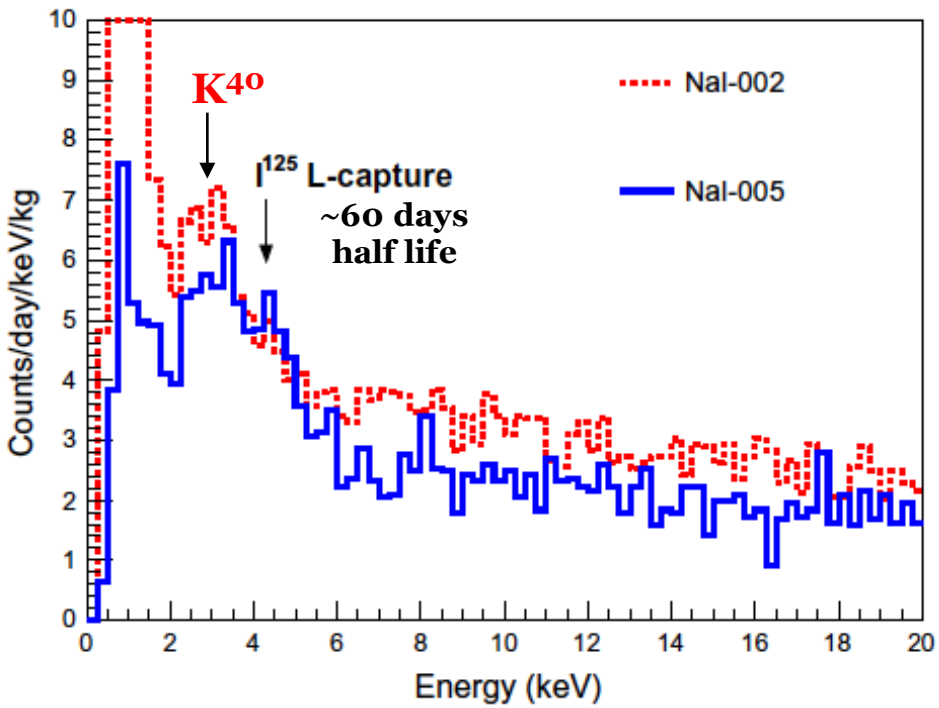




Detector Development

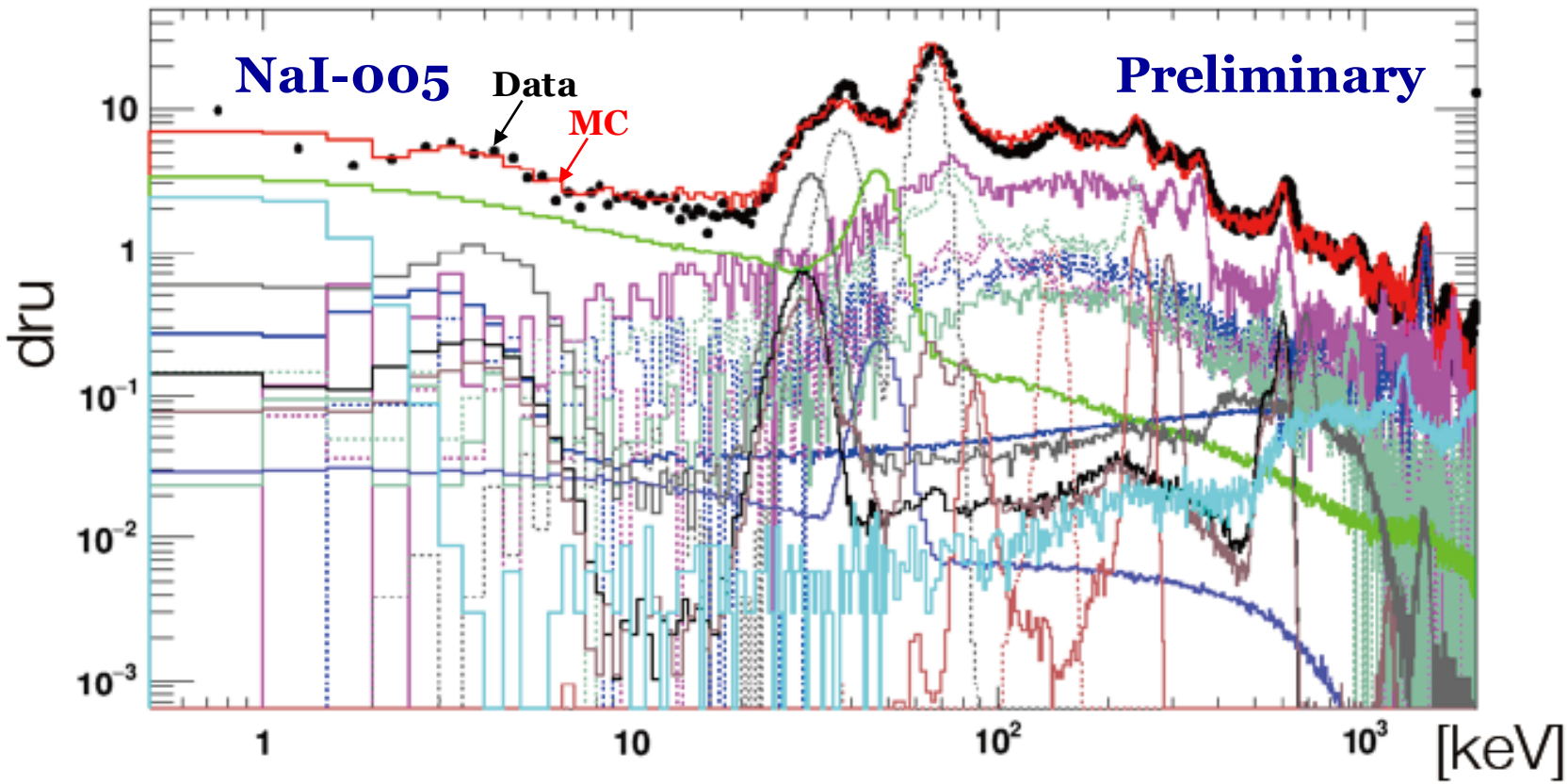
K.W.Kim et al., Astropart. Phys. 62, 249 (2015)

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



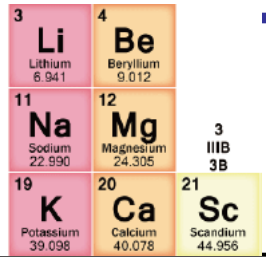
- Understanding internal background very well
- We achieved ~2 counts/kg/day/keV level at 6keV

Background understanding



- ^{40}K & ^{210}Pb are main sources

^{40}K



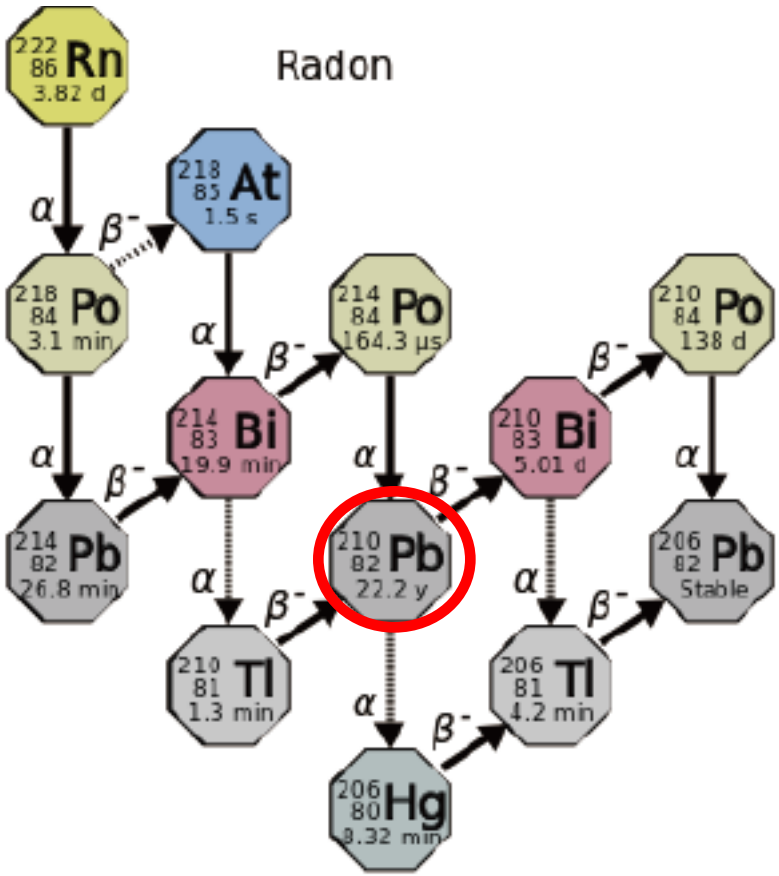
- Similar chemical properties with Na
- Can be separated with recrystallization

	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

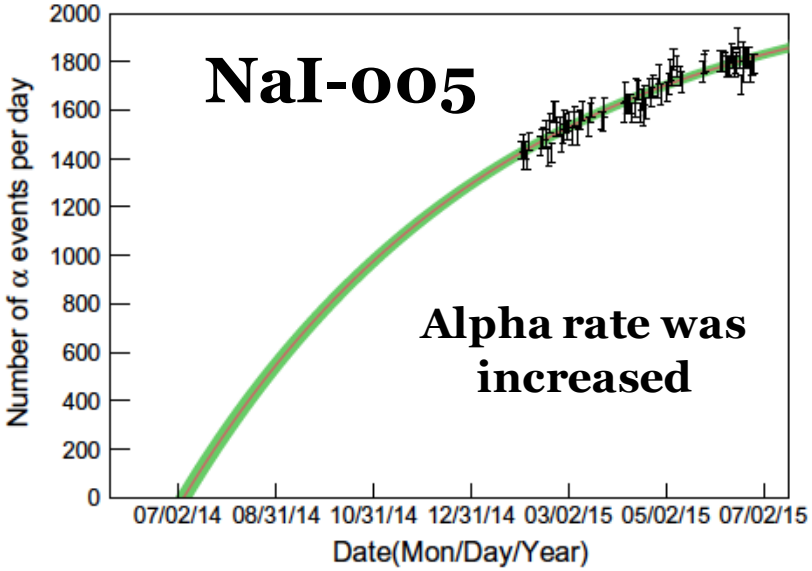
	NaI-007	NaI-008	NaI-009	NaI-010	NaI-011	NaI-015
Powder	AS-WSII	SA-AG	SA-CG	AS-WSIII	AS-WSIII	SA-AG
K (ppb) Crystal	38.1±5.5	<17	639.1±51.4	18.0±11.7	18.5±3.2	<20
K (ppb) Powder	43	10	200-800	25	25	10

- ^{40}K are originated by powder
- Purified powder are available
  - ❖ DAMA crystal has 10-20ppb of K

^{210}Pb

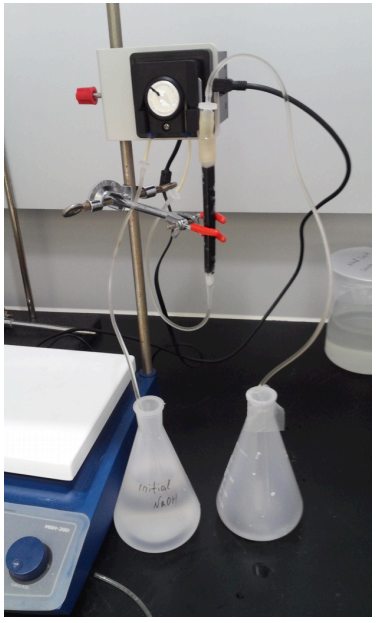


- ~ factor 3 reduction from starting
- ^{222}Rn contamination can cause ^{210}Pb contamination
  - ❖ Every process can make it
- Some Caveat



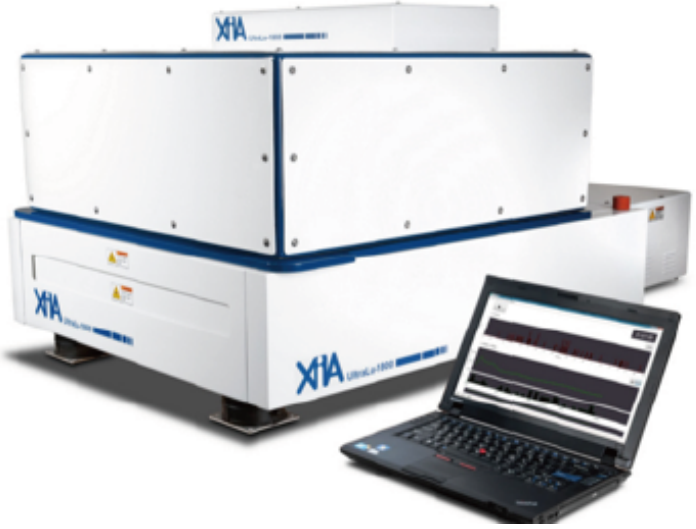
  - ❖ ^{222}Rn contamination or emanation
  - ❖ Removing ^{210}Po

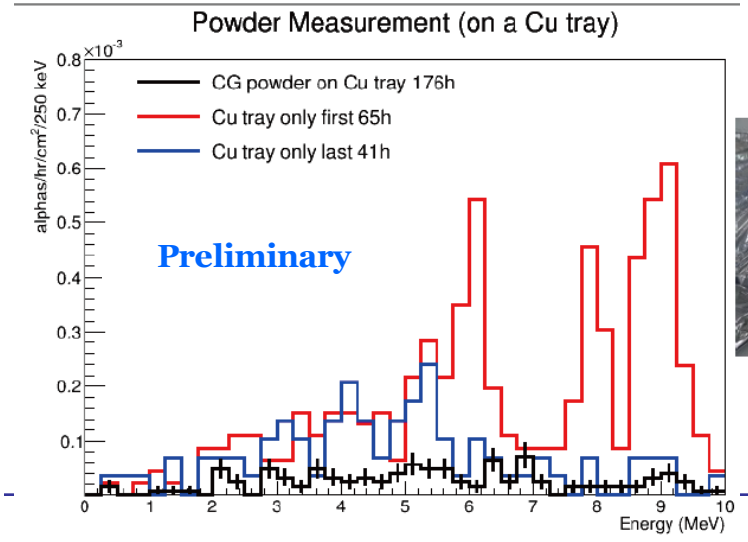
Purification of Pb and measurement



- 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
- Purification of TlI powder are also considered
- Powder measurements have started

XIA UltraLo-1800





100 gram of NaI Powder on a Cu container

Crystal growing by ourselves

Under development

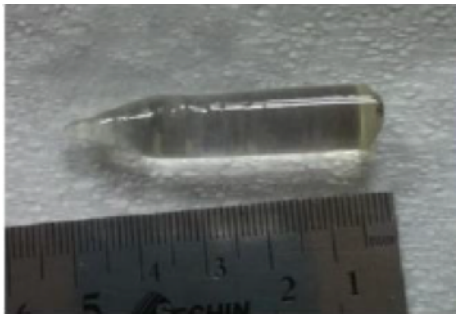
Czochralski Furnace

Bridgman Furnace

1st crystal (Sapphire) grown ~ 30kg !

Kyropoulos Furnace

Bridgman

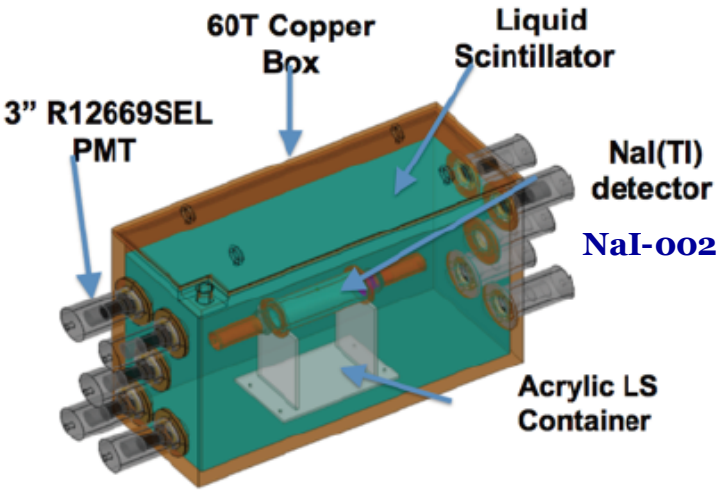


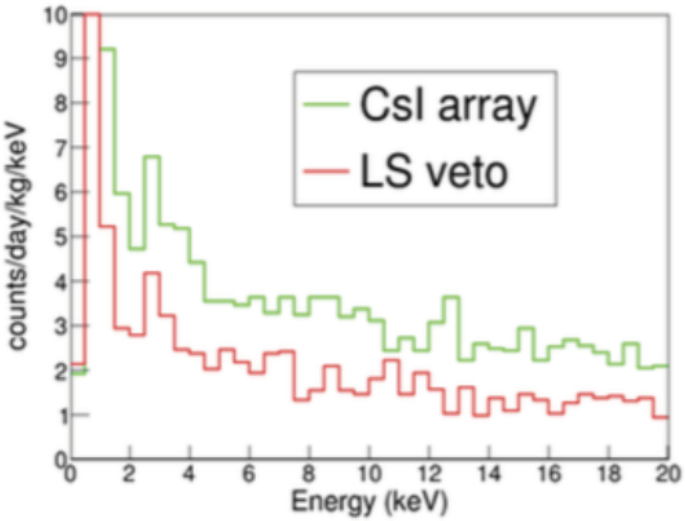
- Small NaI was grown in Korea
- We will try to grow **larger crystal**
  - ❖ Special Kyropoulos is under consideration

- Whole procedure will be controlled by ourselves
  - ❖ Speed up R&D of background reduction

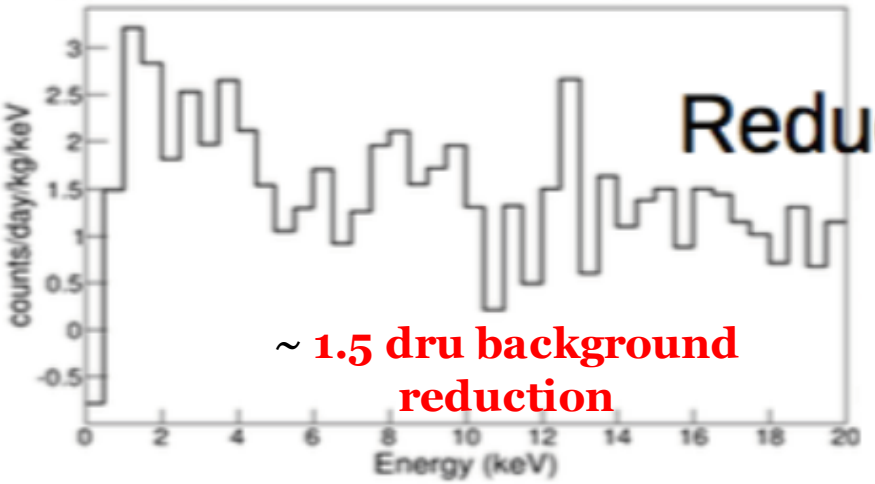
Compton suppressor

- Active veto with liquid scintillator (External & Internal gamma)

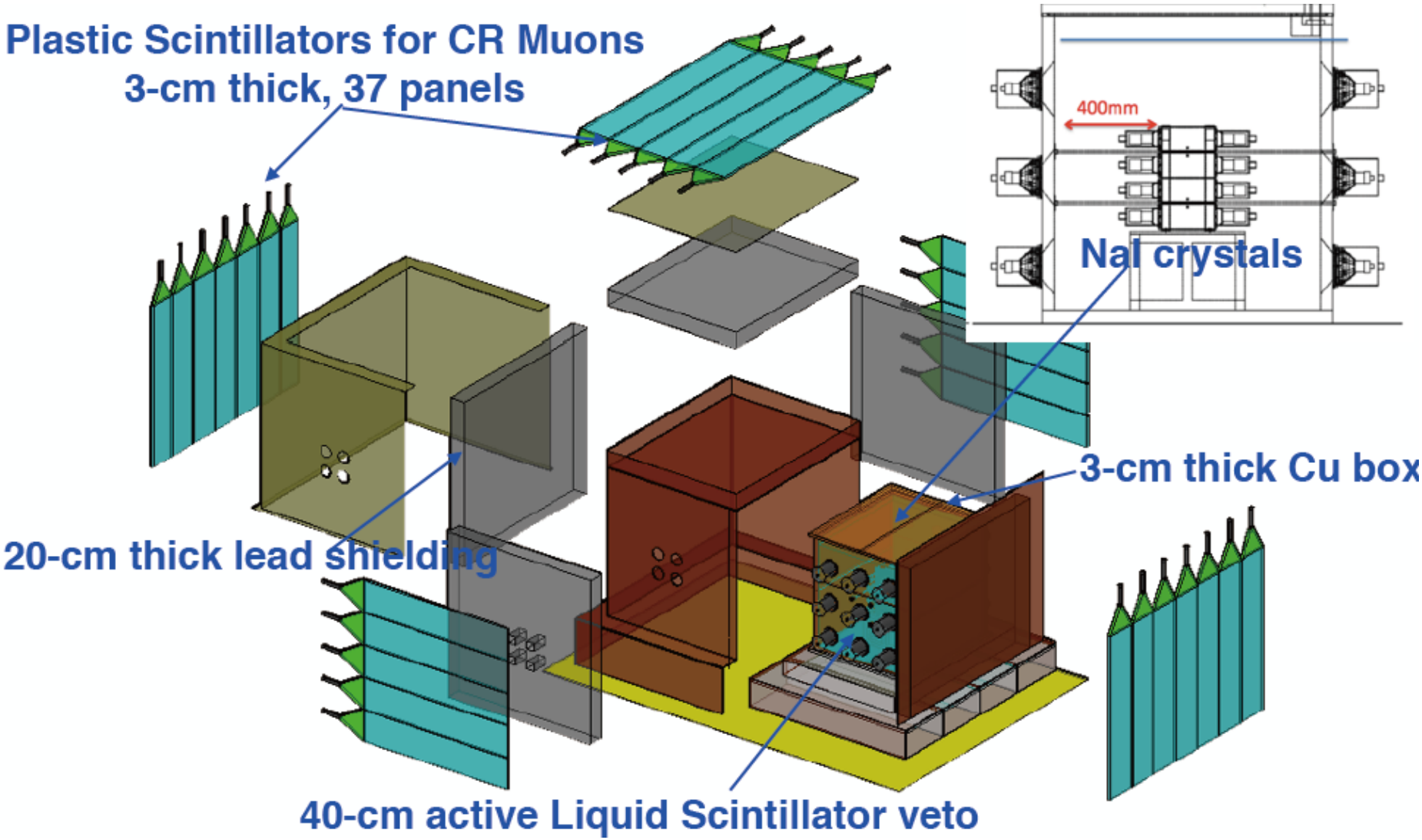




Prototype system with NaI-002 was installed



New shield for NaI experiment at Y2L



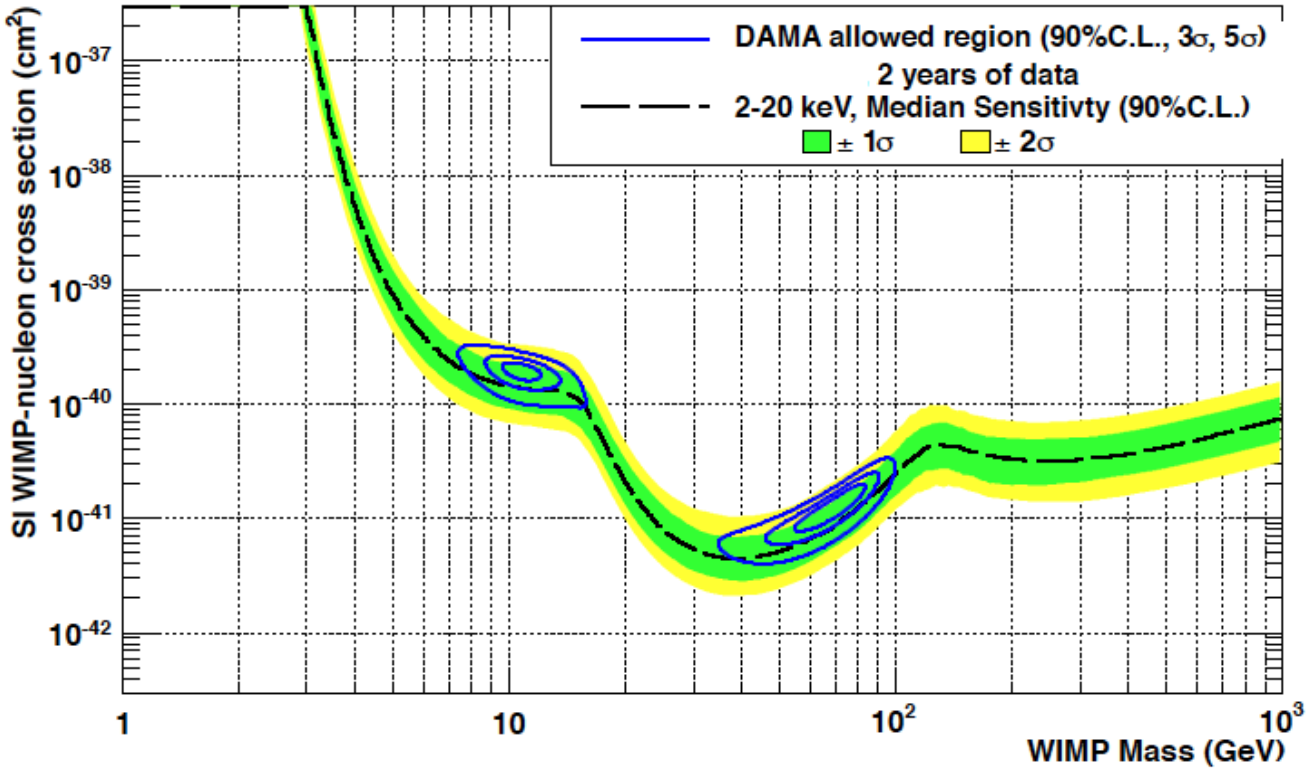
Construction was started from Dec/2015

NaI crystals for Phase-I (~100kg)

Installing of crystals are underway

COSINE-100 sensitivity

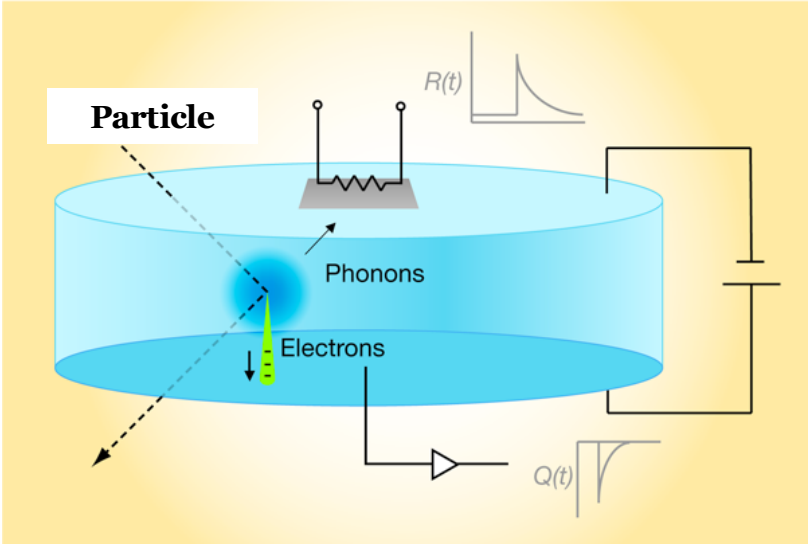
- **CO**nsortium (between KIMS and DM-Ice) **S**odium **I**odi**N**e **E**xperiment

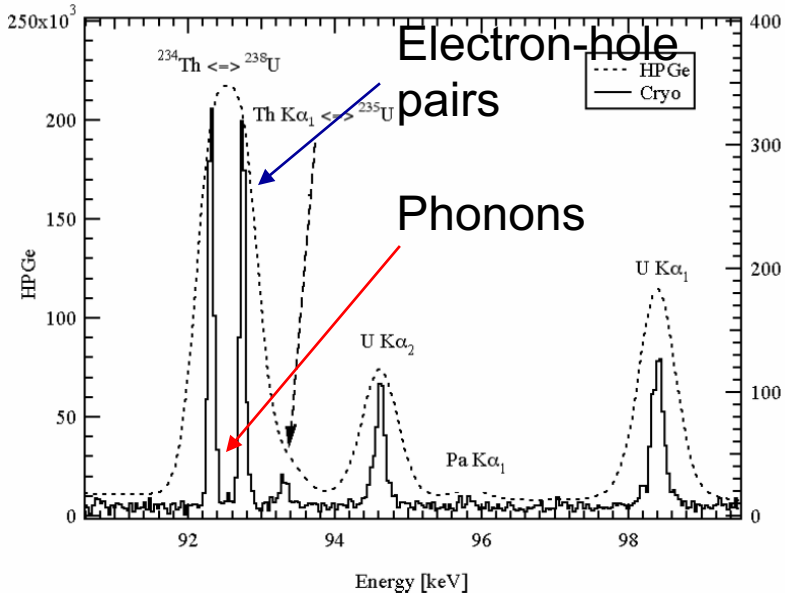


- Physics run will be started from June/2016 at Y2L
  - ❖ Consider South-Pole experiment depending on data
- Perform R&D for COSINE-200 (<1 dru background)

- Cryogenic bolometer

Cryogenic bolometer





Particle interaction bring electron-hole pairs and phonons

To make 1 e–h pair, we need 3.6 eV but, for 1 phonon it is ~meV

Statistically much more phonon

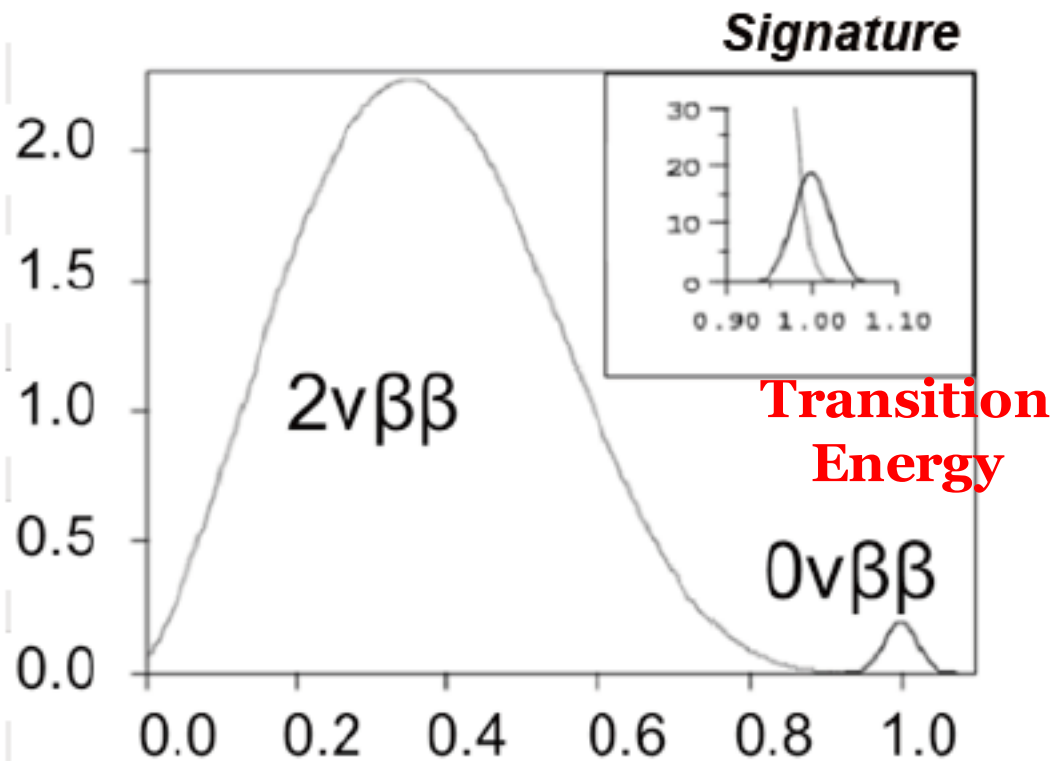
To avoid thermal noise, this should be almost zero K

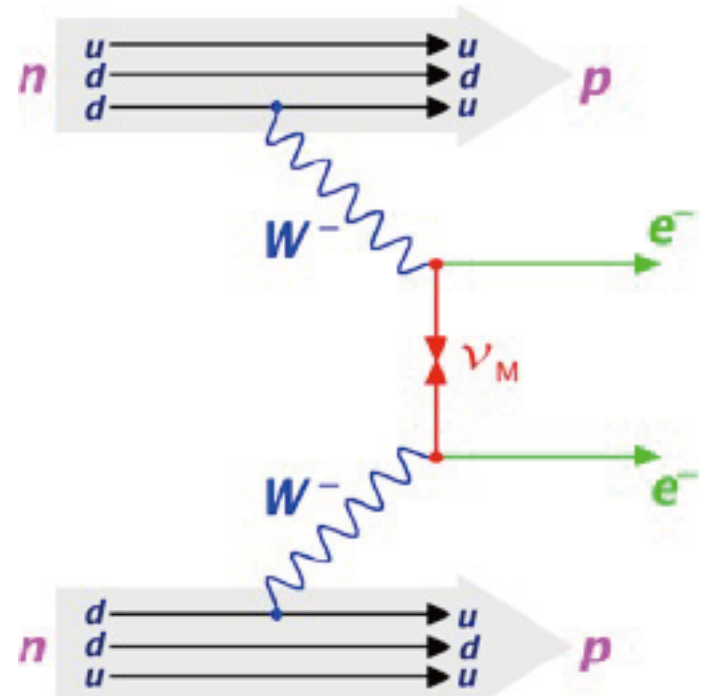
- Phonon measurements give excellent energy resolution

Neutrinoless double beta decay & phonon detector

- If neutrino is majorana particle, neutrino is same as anti-neutrino

$$2n \rightarrow 2p + 2e$$





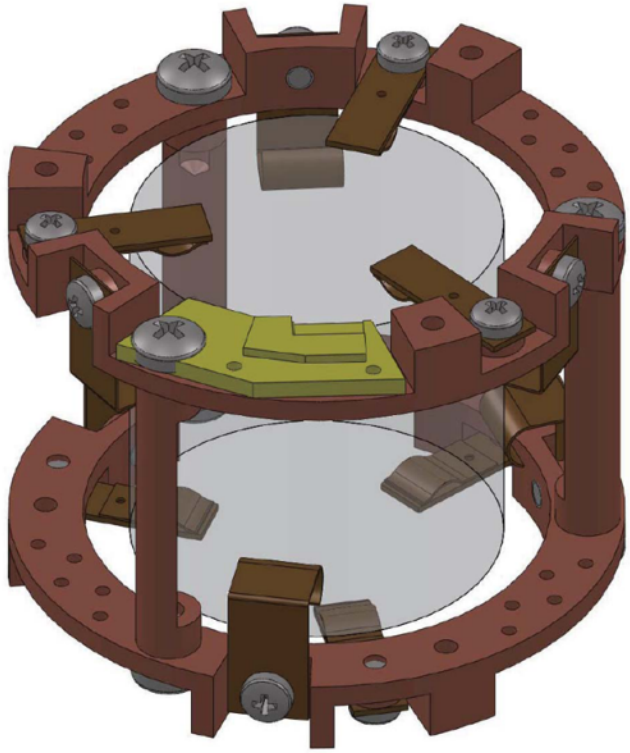
- Good energy resolution is mandatory
- LD has good advantage

AMoRE experiment

(Advanced Mo-based Rare process Experiment)

to search for neutrinoless double decay of ^{100}Mo

using cryogenic $CaMoO_4$ detectors



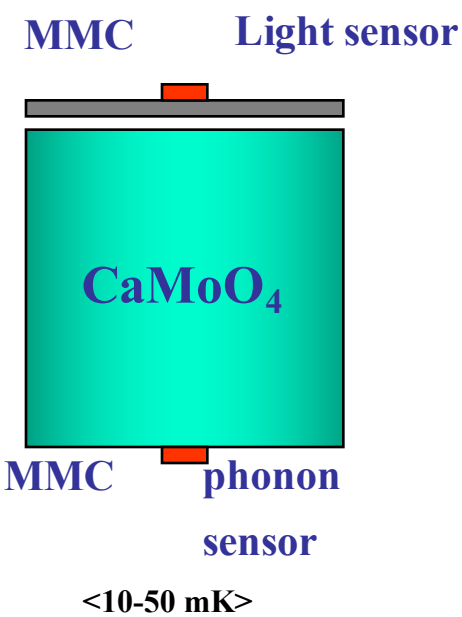
Ø4cmx4cm
$CaMoO_4$ crystal

AMoRE detector technology

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

Low Temp. Detector

Source = Detector



$CaMoO_4$

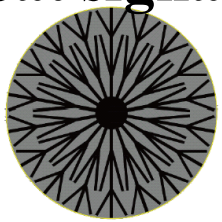
- Scintillating crystal
- High Debye temperature: $T_D = 438$ K, $C \sim (T/T_D)^3$
- ^{48}Ca, ^{100}Mo $0\nu\beta\beta$ candidates, Q-value=3035 keV
- AMoRE uses $^{40}Ca^{100}MoO_4$ w. enriched ^{100}Mo and depleted ^{48}Ca

MMC (Metallic Magnetic Calorimeter)

- Magnetic temperature sensor (Au:Er) + SQUID
- Sensitive low temperature detector with highest resolution
- Wide operating temperature
- Relatively fast signals
- Adjustable parameters in design and operation stages

Phonon & photon sensors

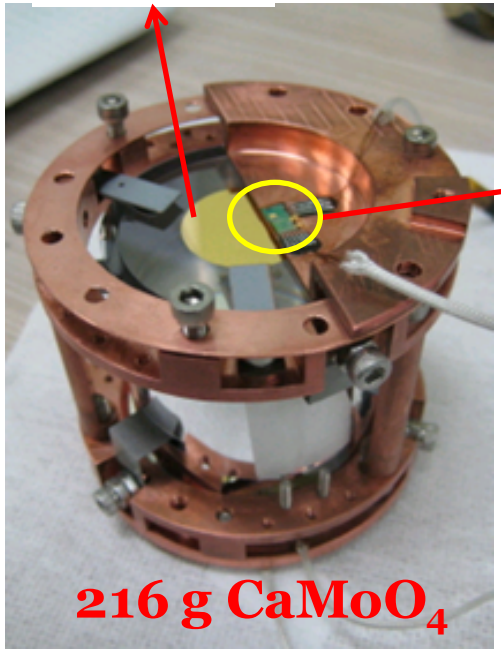
Heat signal

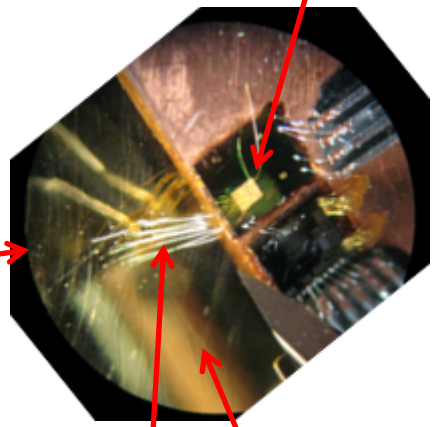


Phonon collector

Patterned gold film

MMC





Gold film

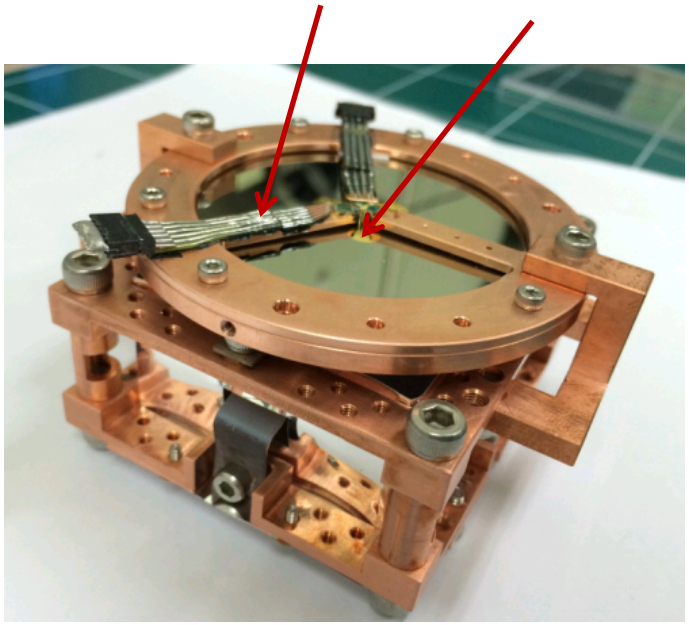
Gold wires

(thermal connection)

We measure both thermal and athermal phonons.

Light signal

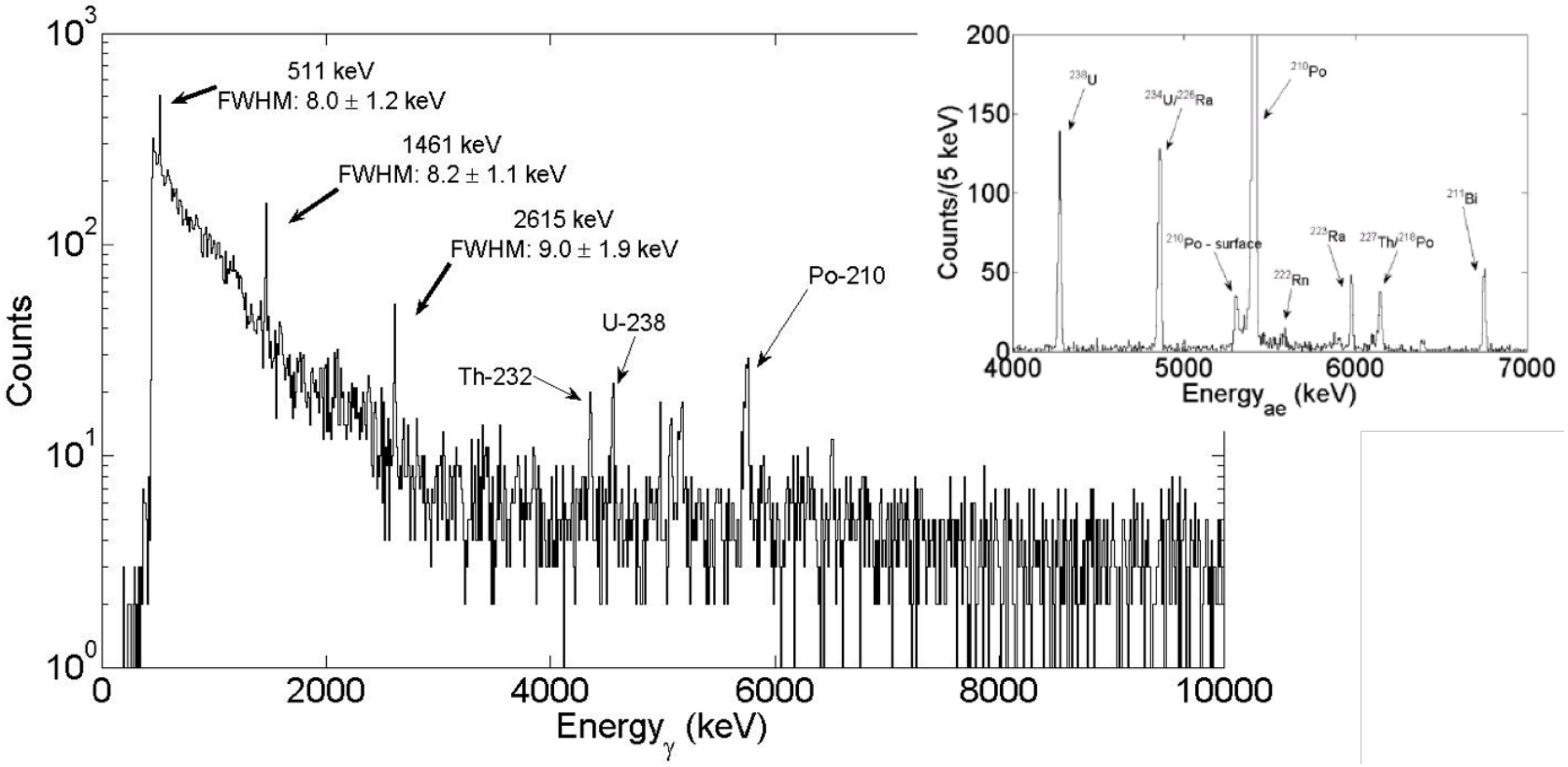
2 inch Ge wafer + MMC



Simultaneous measurement of heat and light signal make additional separation of high energy alpha

Detector R&D in an over-ground laboratory

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



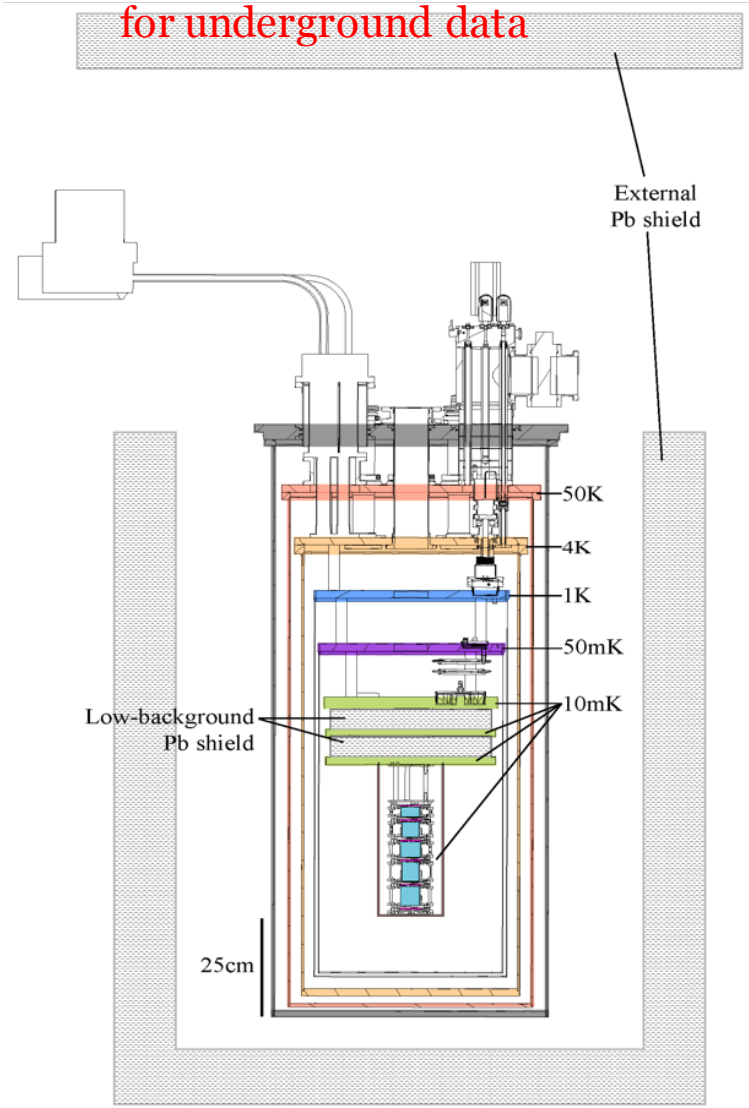
Energy (keV)	511	1461	2615
FWHM (keV)	8.0 +/-1.2	8.2+/-1.1	9.0+/-1.9

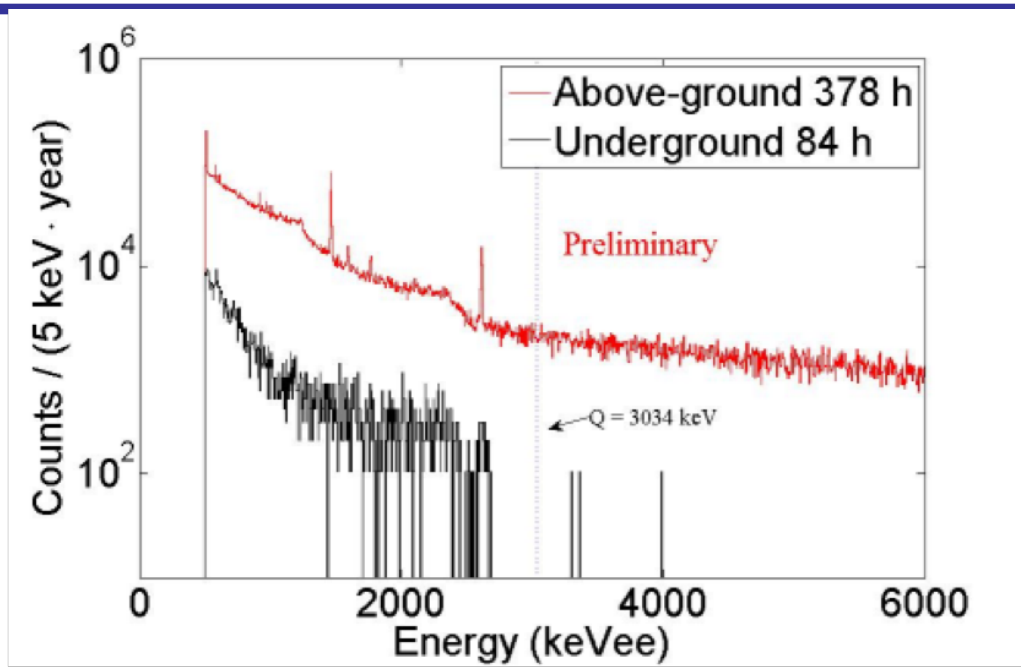
Underground Laboratory Construction

July 2015

AMoRE pilot : 1.5 kg of $^{40}Ca^{100}MoO_4$

See tomorrow **G.B. Kim's talk** for underground data





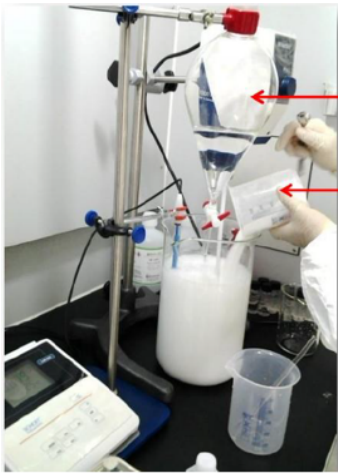
- Installed at underground and perform commissiong run
- Crystals were grown by Russian company(FOMOS)
- Additional 3.5 kg of crystals have been delivered for AMoRE-I

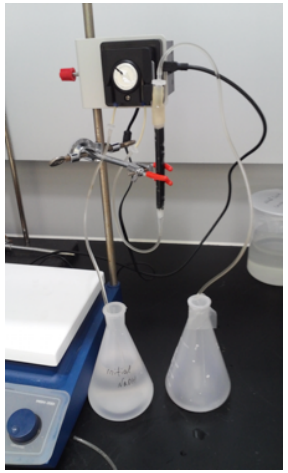
For AMoRE-II

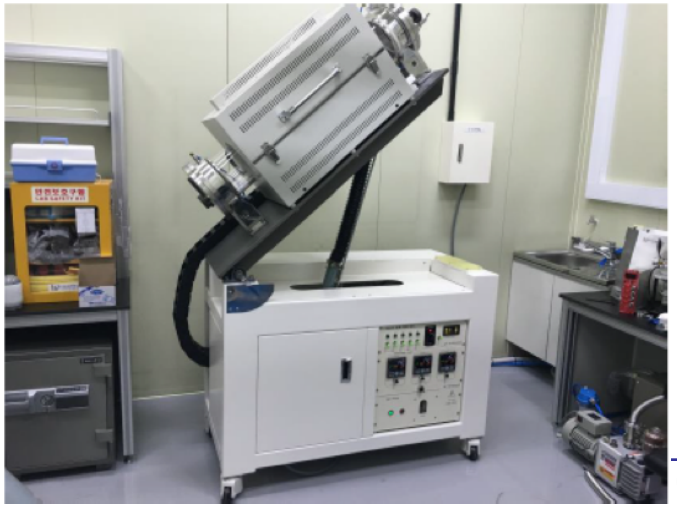
Powder purification

Chemical purification, resin, chromatography, sublimination, recrystallization..

~10-1000 reduction of U and Th







Radiopurity measurement

2 Canberra HPGe (100%) are operating

1 Ortec well-type HPGe (2016.8)

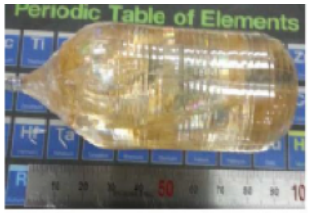
Crystal growing

2 Kyropoulos ,1 Bridgman ,1 Czochralski in center + KNU + Novosibirsk

$CaMoO_4$

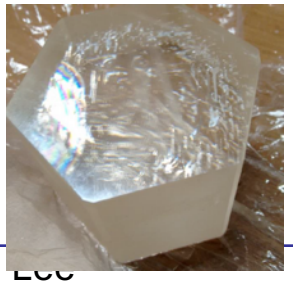
$PbMoO_4$

Na_2MoO_4



Ø40 mm X 100 mm

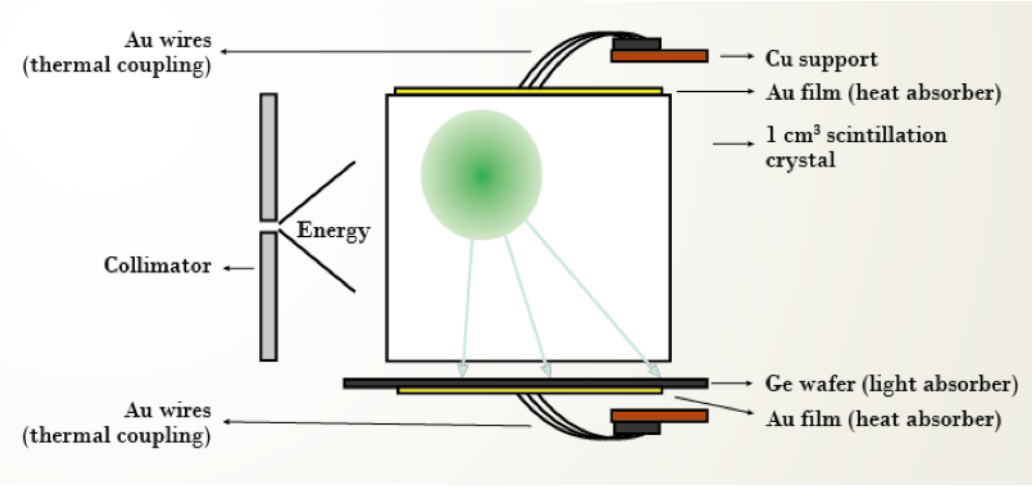
Li_2MoO_4

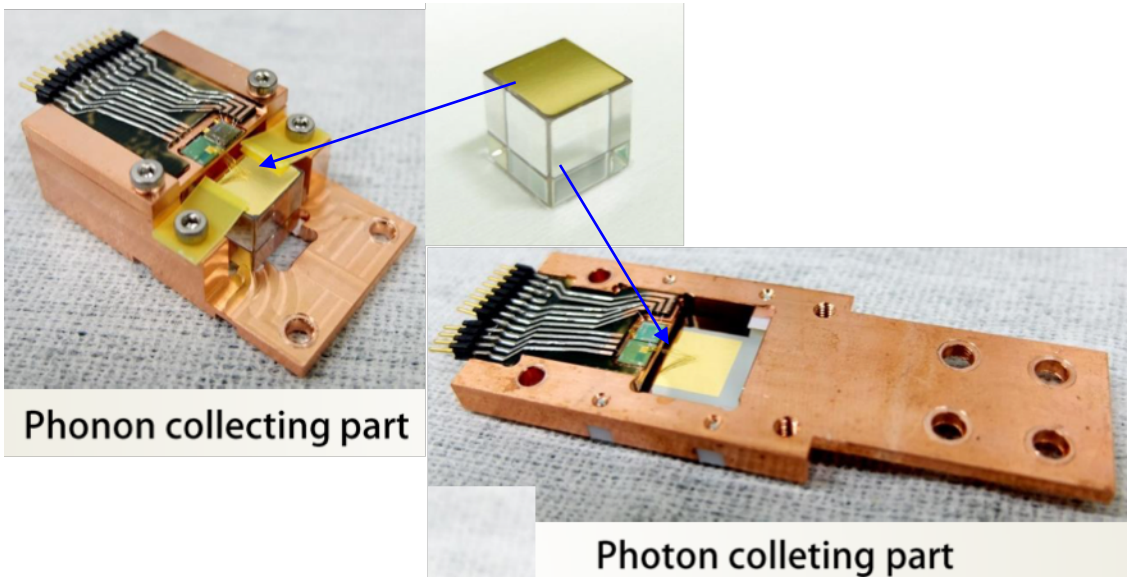


$ZnMoO_4$ from LUMINE

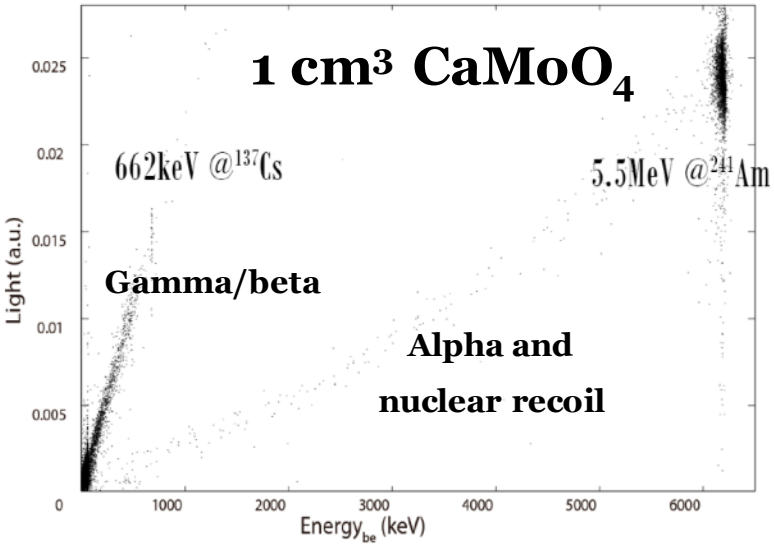
For AMoRE-II

Crystal screening at cryogenic environment





- We can measure 1cm^3 crystals for both photon and phonon within 2 weeks
- We plan to test various crystals

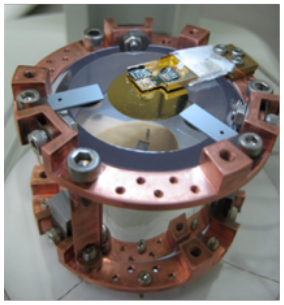


- Decision will be followed!!

AMoRE project schedule

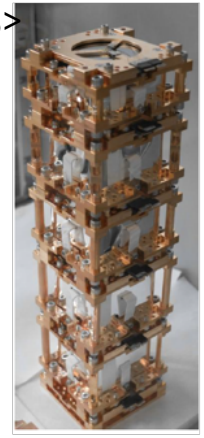
- Keep <1 expected backgrounds for all experiment

<2014>



216 g

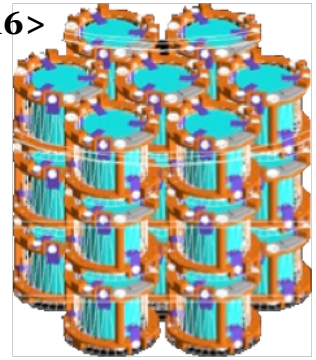
<2015>



5 CMOs: ~ 1.5 kg

<AMoRE Pilot>

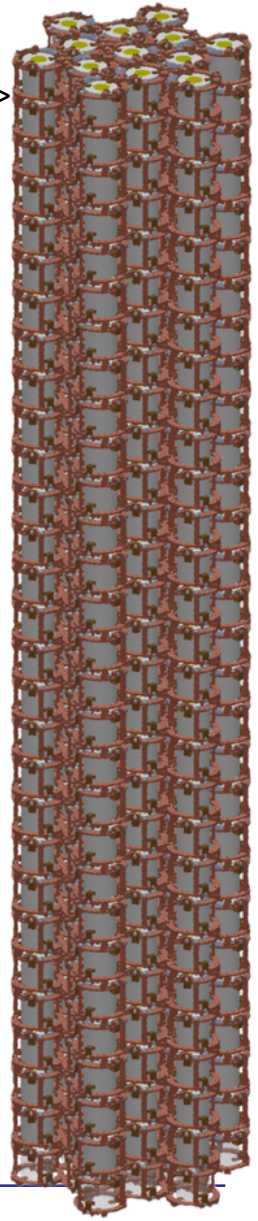
<2016>



CMO: ~ 5 kg

<AMoRE-I>

<2020>



<AMoRE-II>

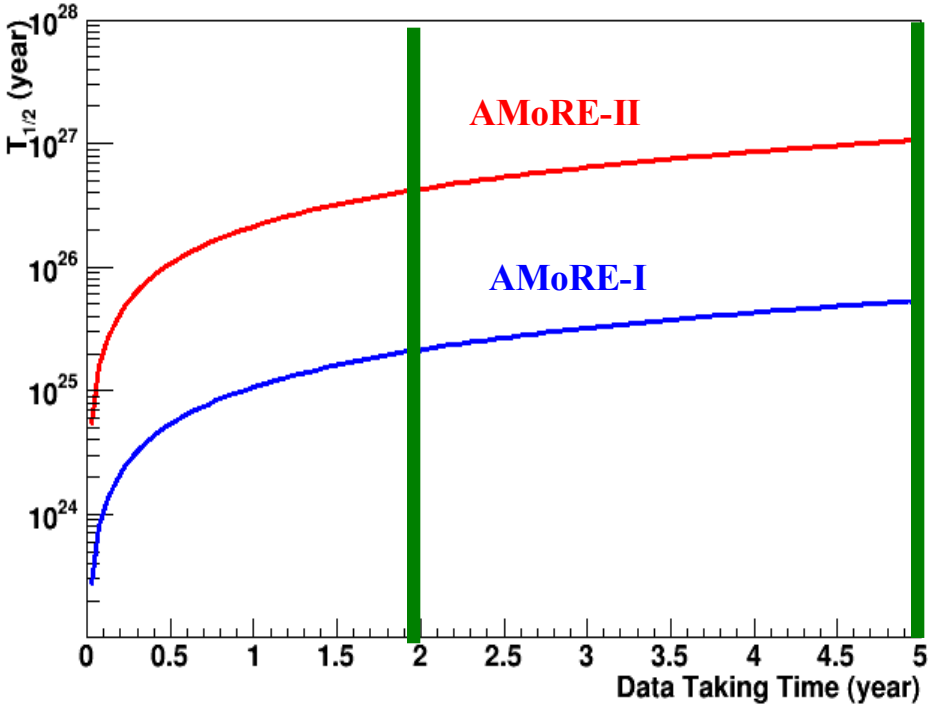
~ 200 kg

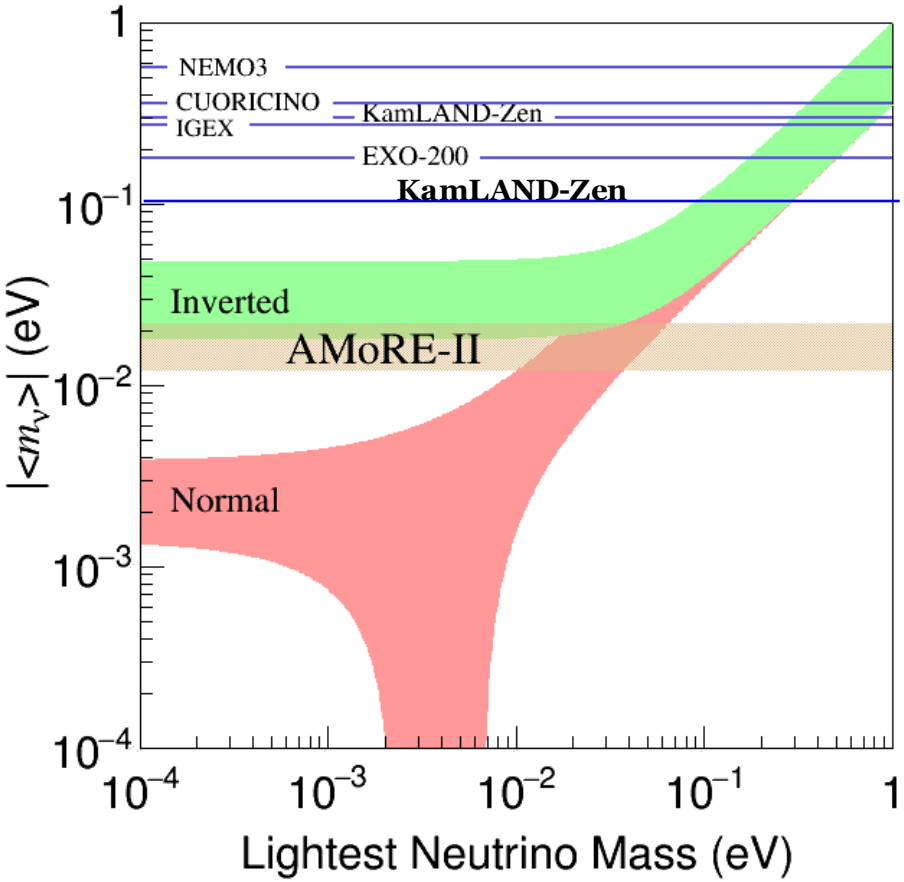
ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	200
Backgrounds(ckky)	10^{-2}	10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
$m_{\beta\beta}$ (meV)	380-719	130-250	13-25
Schedule	2015-2016	2016-2017	2019-2023

Goal & Sensitivities

- Aim "Zero Background" experiments (expected events <1)
- Good energy resolution & Ultra low background are mandatory
- Fully cover inverted mass hierarchy region





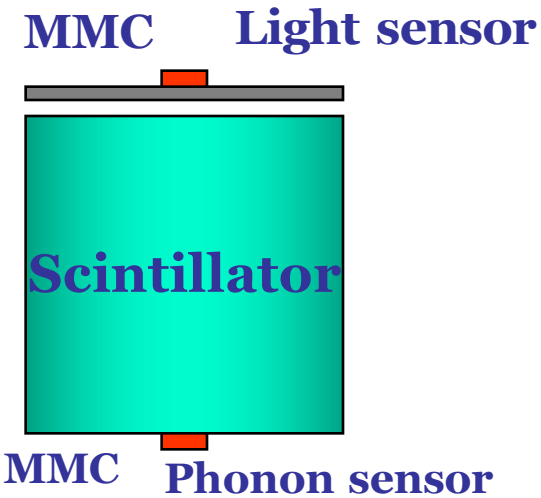
Summary

- Scintillating calorimeters are good detectors for rare event searches
- Background reduction is key to succeed experiments

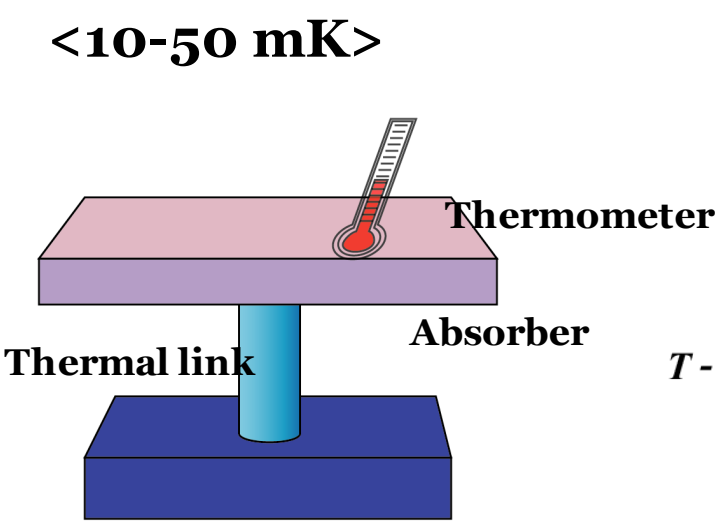
- Center for Underground Physics (CUP) of IBS at Korea are developing technologies for background reduction of scintillating calorimeter for rare event searches

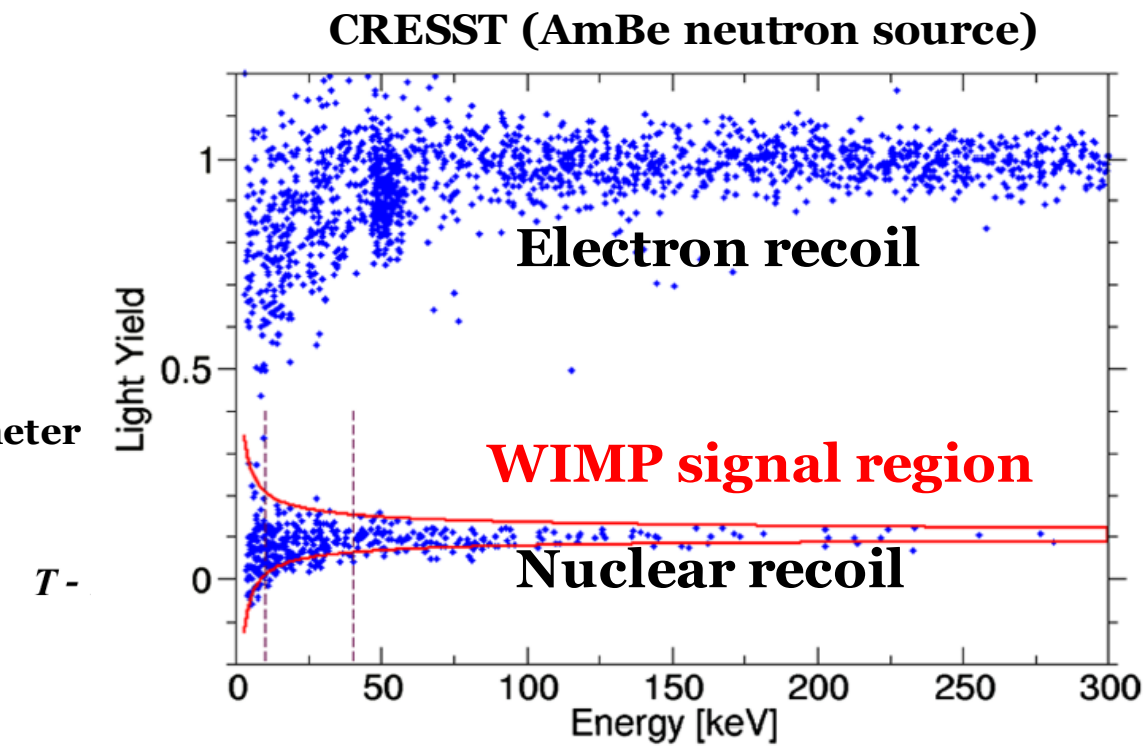
- Backup for KIMS-LT

KIMS-LT experiment



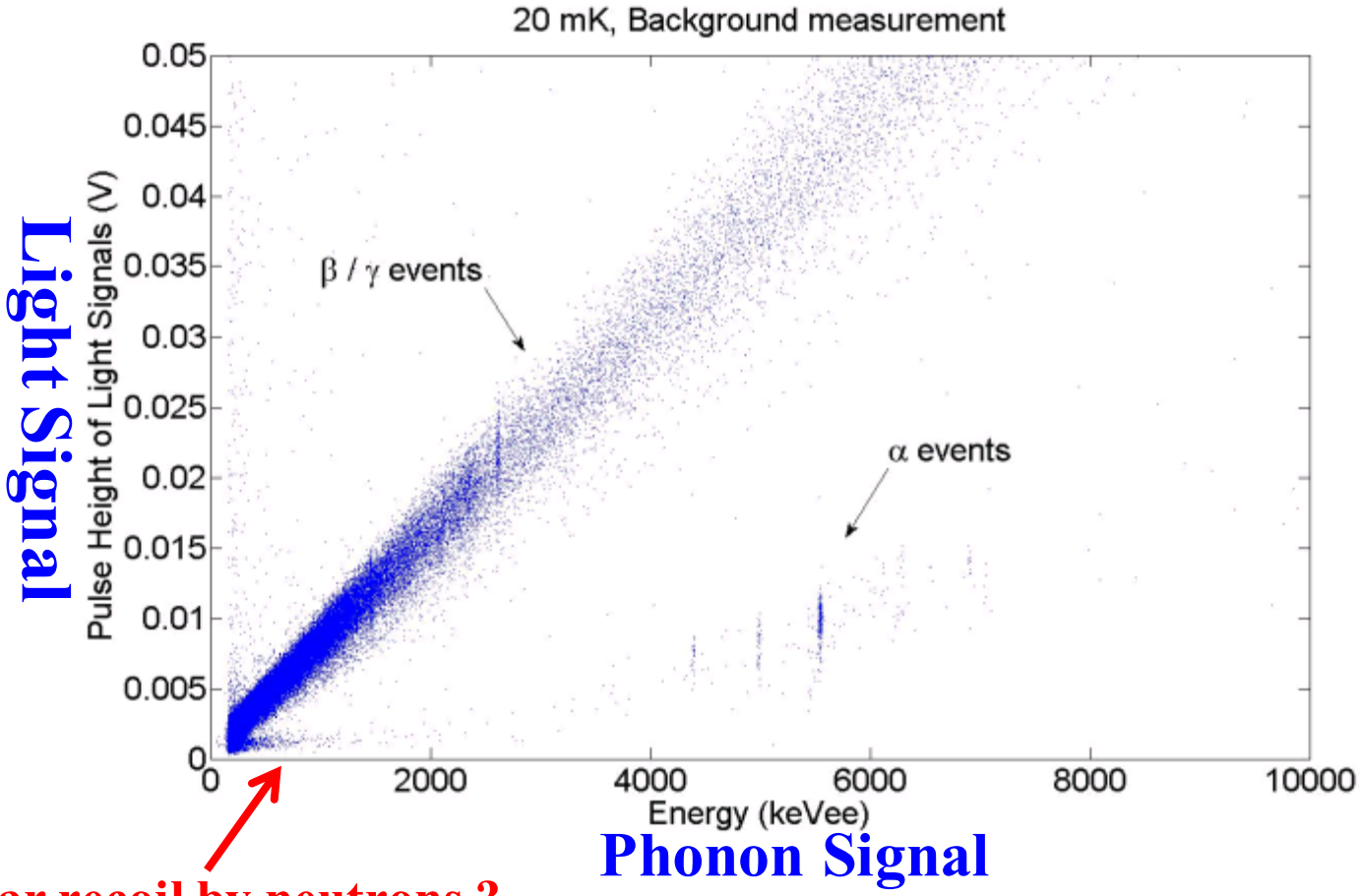
- Scintillator detector @ 10-50 mK
- Ratio of heat-to-light signal make excellent discrimination between WIMP signal and background





Light and Heat signals with our crystal

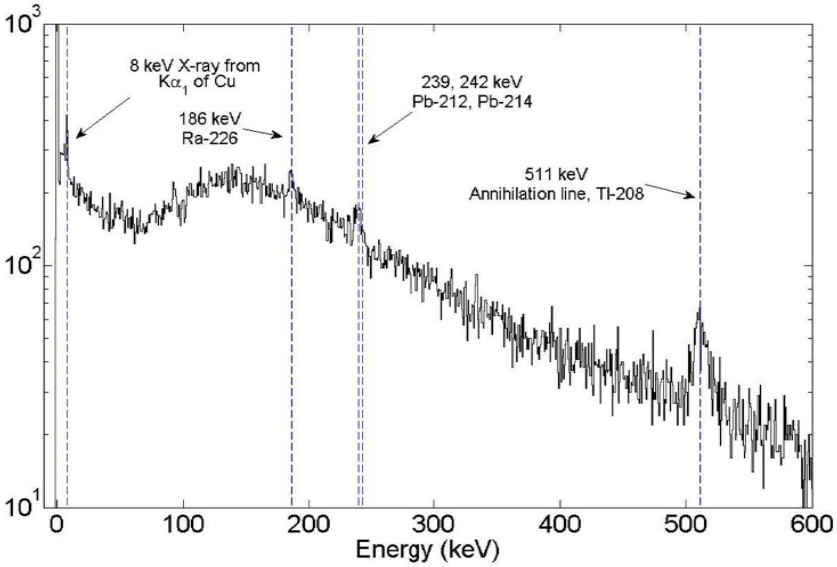
at KRISS (over-ground) lab

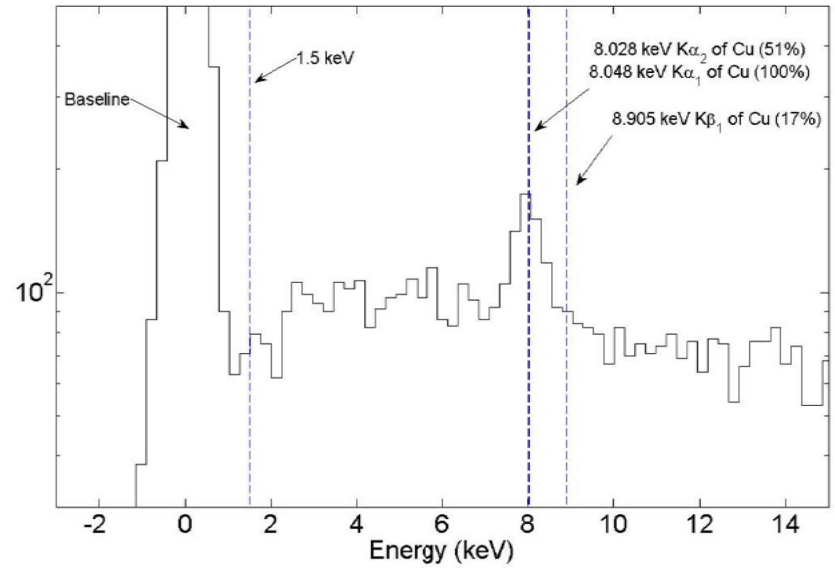


Nuclear recoil by neutrons ?

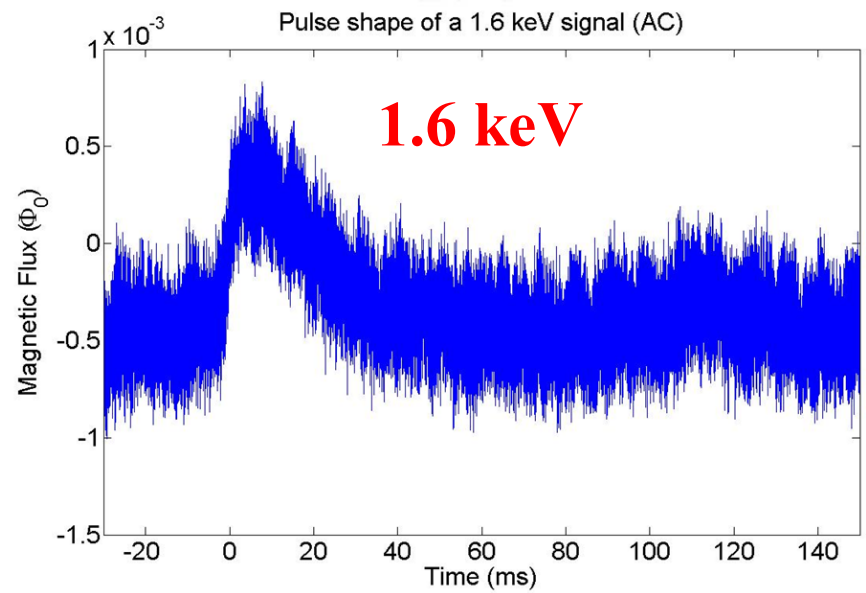
- Need to optimize at low energy

Low energy heat signals





- ~ 1keV threshold is possible with heat channel
- Need to improve our light detectors



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.
- Any other candidates?
  - $ZnWO_4$, $PbWO_4$, $Li_2Mo_7O_{16}$, pure NaI, pure CsI …
  - Start survey of possible crystals

Strategy for low-mass dark matter search

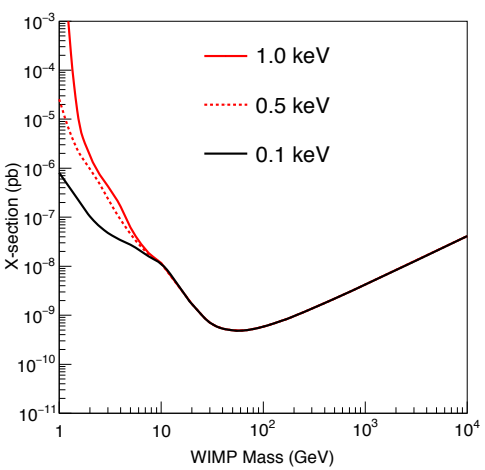
Low Mass WIMP detection

Lower Energy Threshold

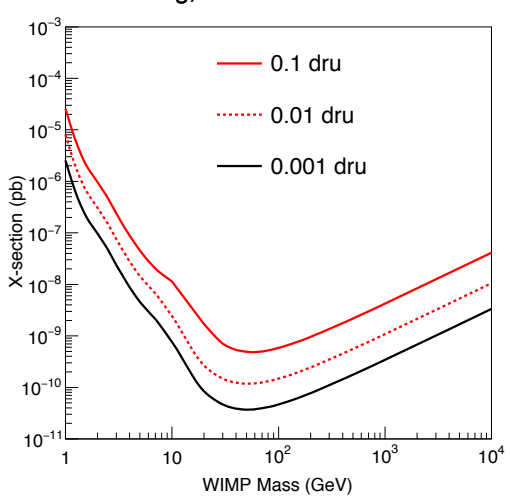
Lower background

Larger detector volume

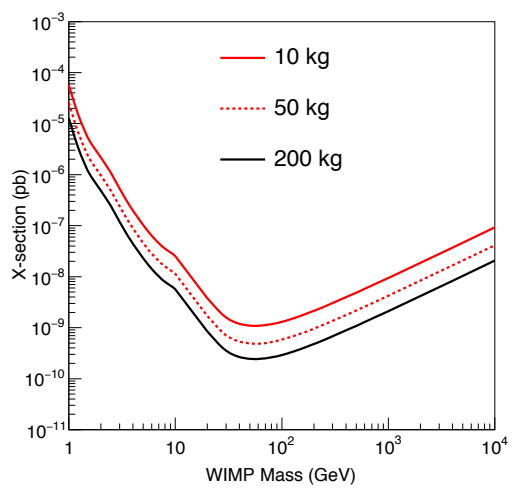
50 kg, 0.1 dru



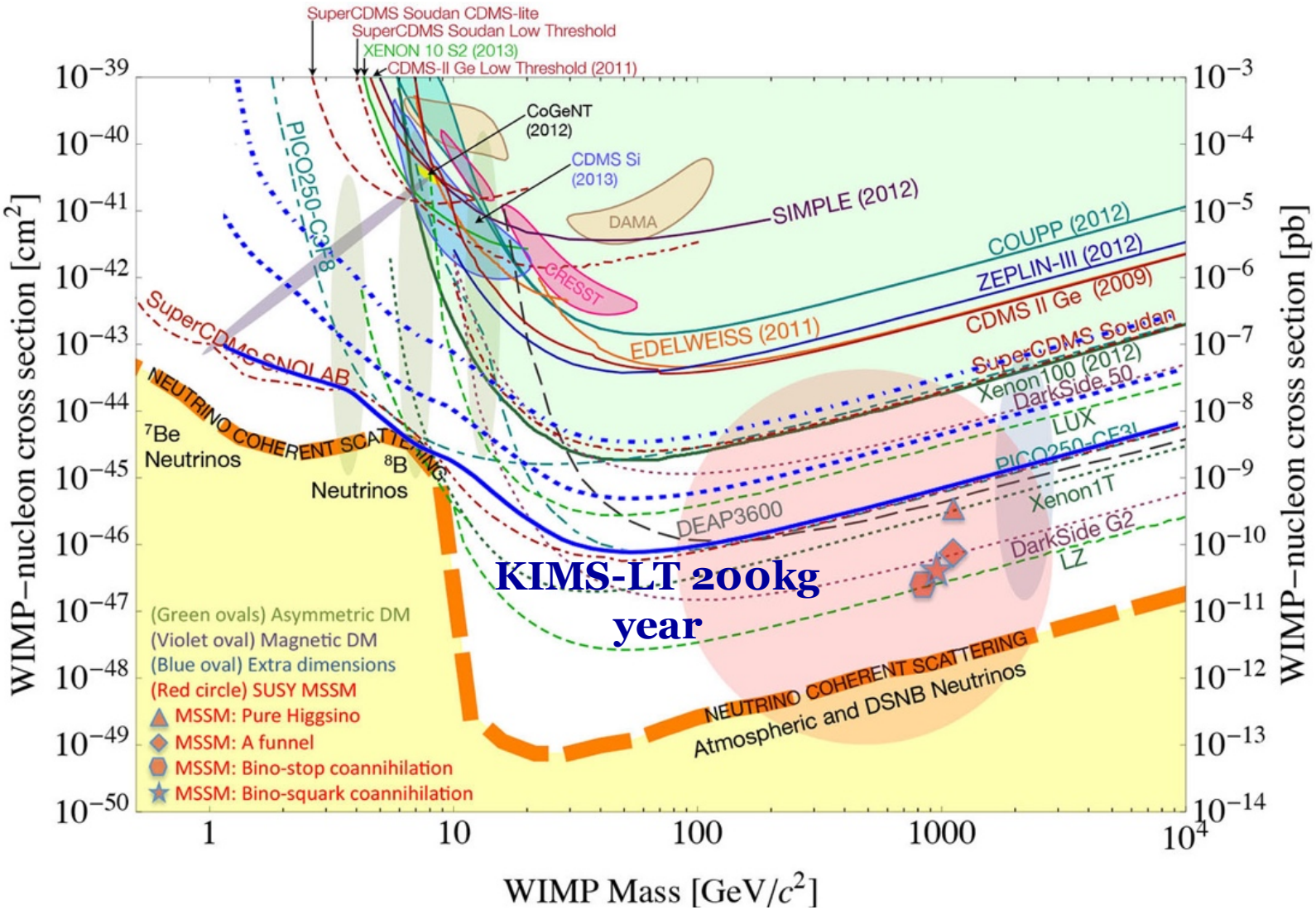
50 kg, 0.5 keV threshold



0.1 dru, 0.5 keV threshold



Sensitivity of KIMS-LT



Goal to have the most sensitive detector for the low-mass dark matter