Dark matter searches in XMASS

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On behalf of the XMASS collaboration

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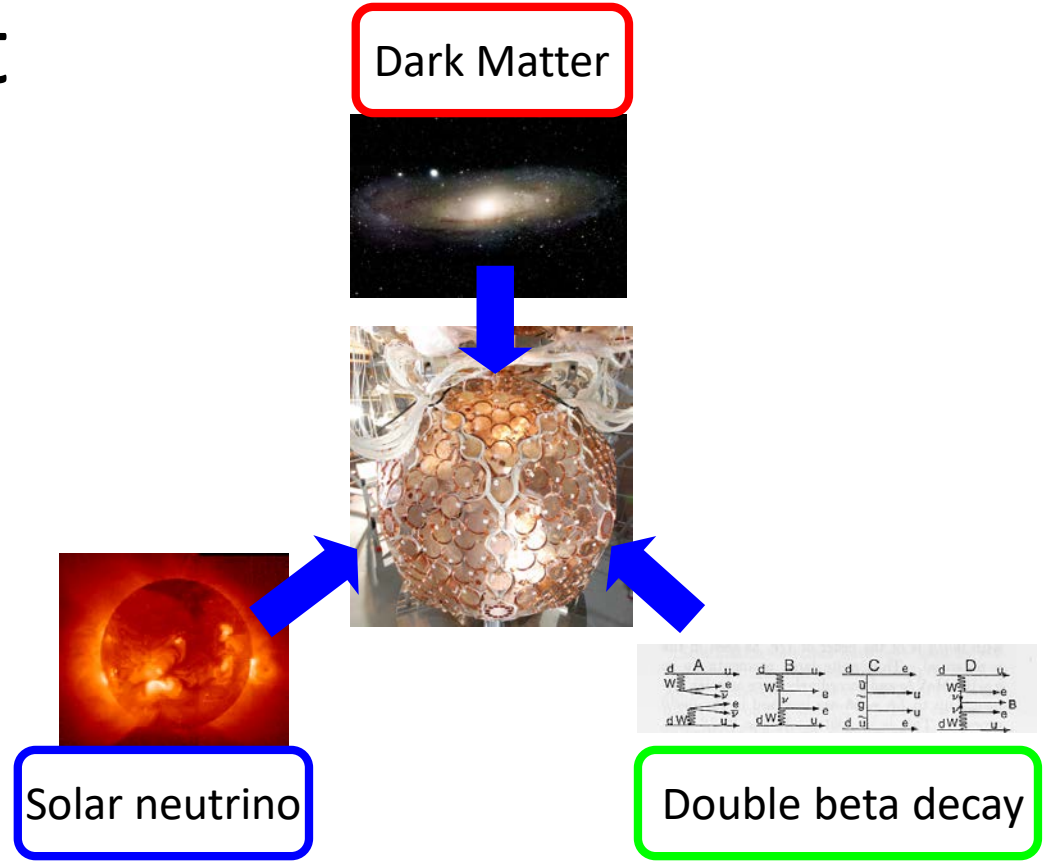
Seoul, South Korea

XMASS experiment

- XMASS

  Multi purpose low-background and low-energy threshold experiment with liquid Xenon
  - **X**enon detector for Weakly Interacting **MASS**ive Particles (**dark matter search**)
  - **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
  - **X**enon neutrino **MASS** detector (**ββ decay**)

Purpose of the first phase is the dark matter search.



history of XMASS

2010 2011 2012 2013 2014 2015 2016 2017 2018

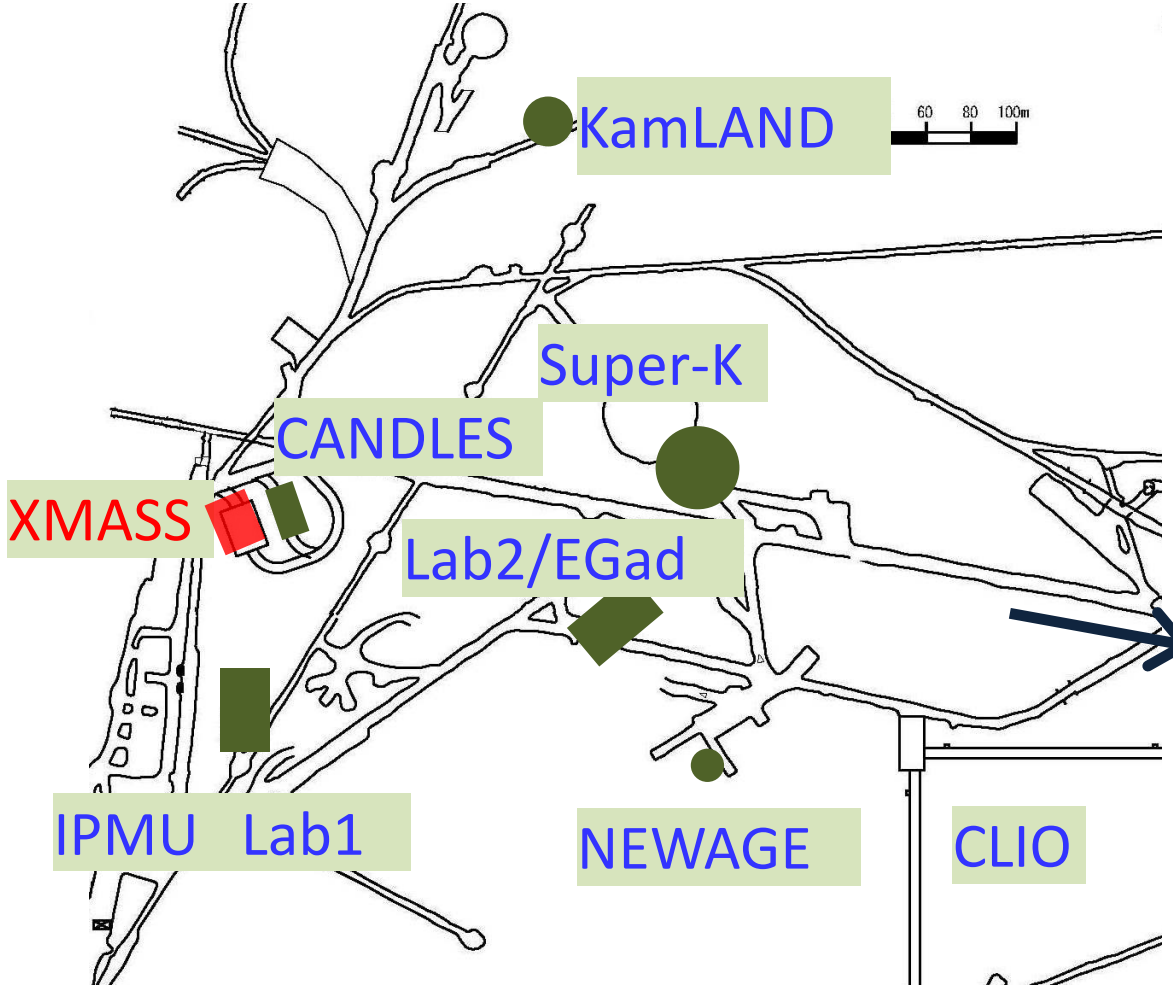
detector construction completed (Sep. 2010)

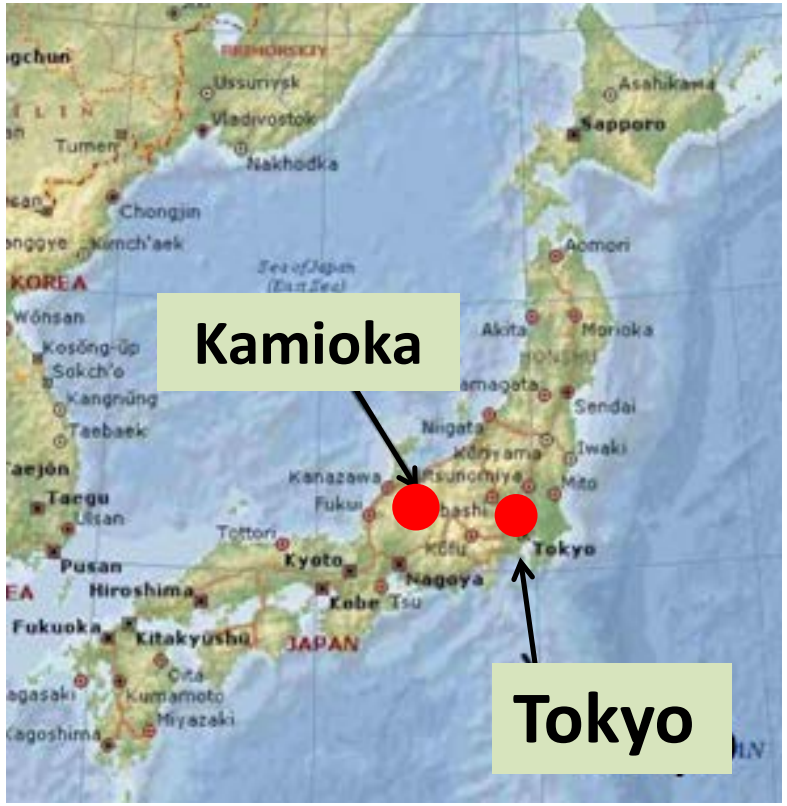
commissioning run (Dec. 2010 - May 2012)

detector refurbishment (Aug. 2012 - Oct. 2013)

- Resume data taking (Nov. 2013 -)
- We have already taken data for >4.5year.

Kamioka mine

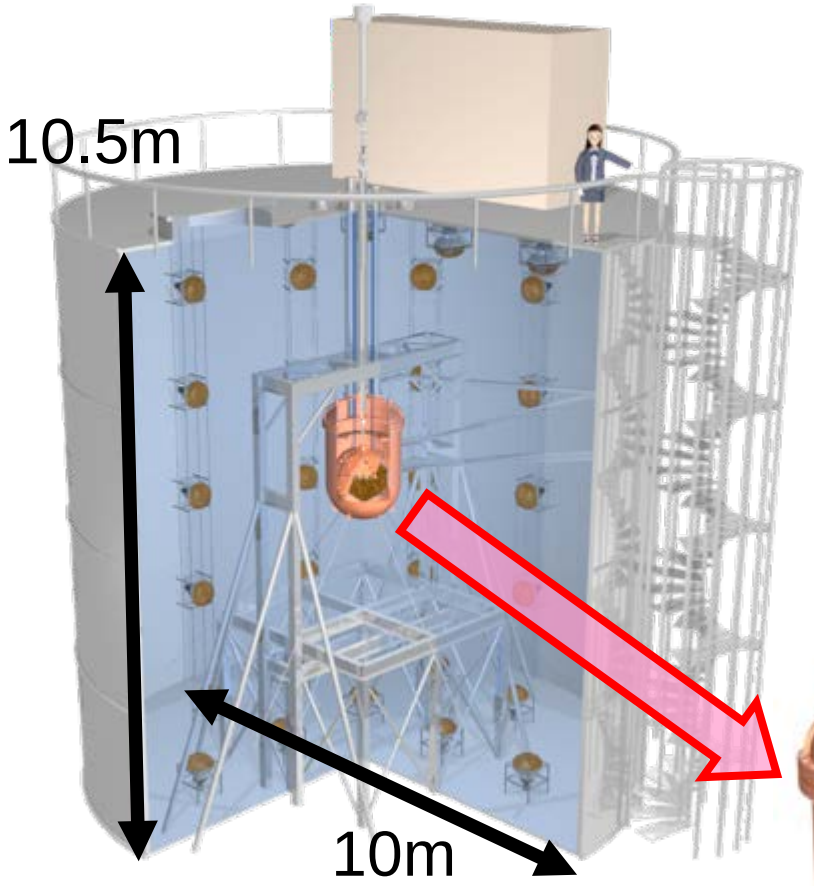


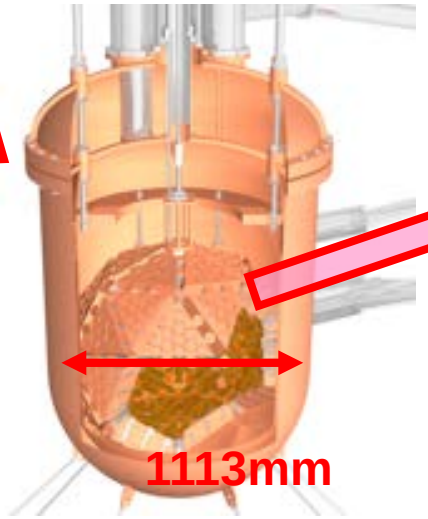


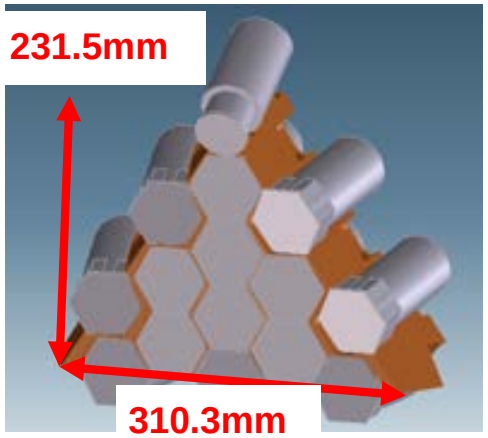
~1000m underneath Mt. Ikenoyama

XMASS detector

- Outer detector (OD, water tank)
  - 72 20-inch PMTs for cosmic-ray muon veto.
  - Water is also passive shield for gamma-ray and neutron from rock/wall.
- Inner detector (ID, Liquid Xe)
  - Liquid Xe surrounded by 642 2-inch PMTs.
    - Single phase
    - Observed scintillation light.
    - photo coverage: 62%
    - diameter: ~800mm
    - high light yield: 14.7 PE/keV







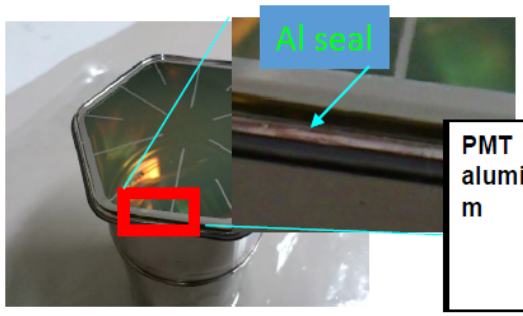
pentakisdodecahedron

Hexagonal PMT
Hamamatsu R10789

NIM A716, 78-85, (2013)

Background in XMASS

Only standard cut is applied



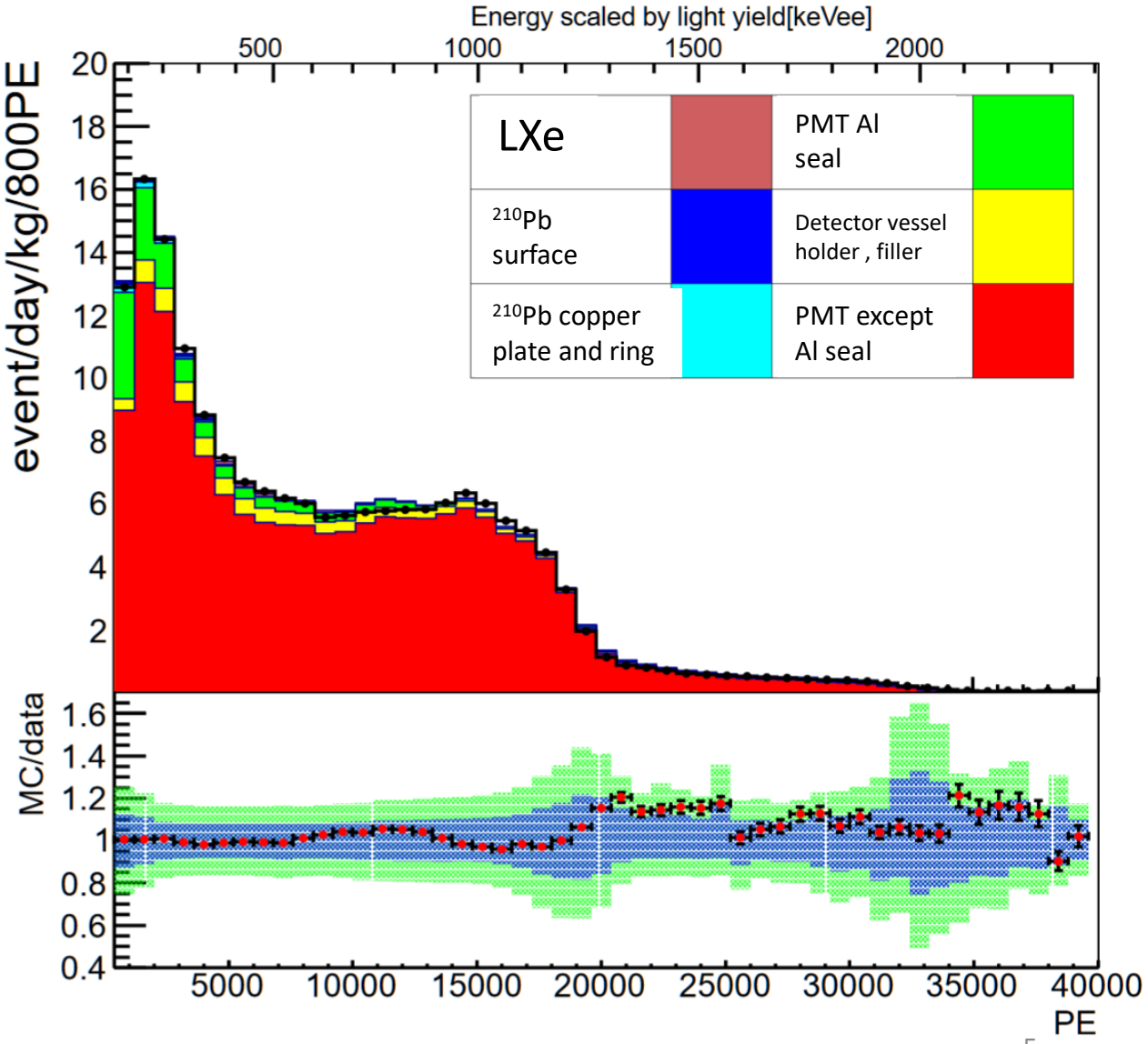
HPGe detector measurement & center value used in commissioning run analysis.

PMT aluminum	238U-230Th : 1.5+/-0.4Bq 210Pb : 2.85+/-1.15Bq 232Th : 96+/-18mBq 235U-207Pb : ~1.5Bq x 4.5%, correlated with U238

HPGe detector measurement for each parts and PMT whole.

PMT	232Th: 1.80+/-0.31mBq/PMT 60Co : 2.92+/-0.16mBq/PMT 40K : 9.10+/-2.15mBq/PMT 238U : 2.26+/-0.28Bq/PMT 210Pb : 200+/-100mBq/PMT

8

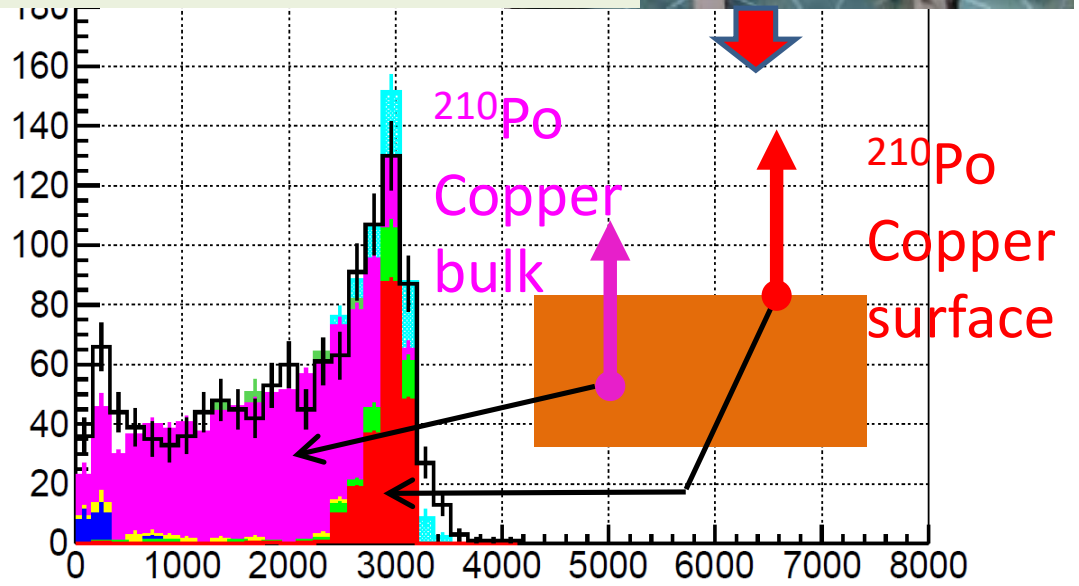


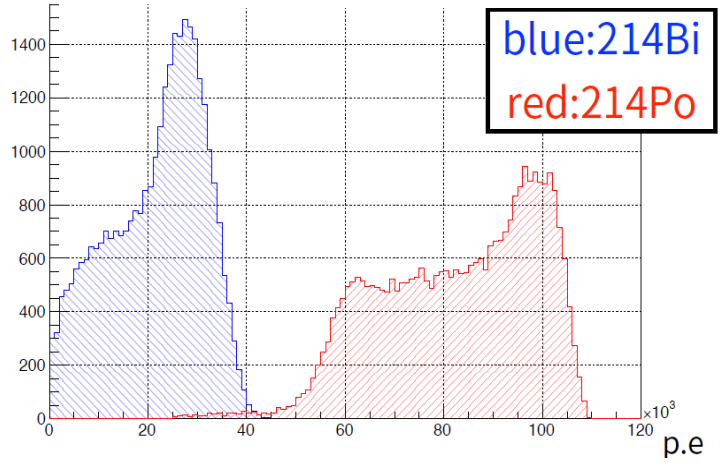
- RI screening of detector materials was done using HPGe detector.
- RI activity are estimated by spectrum fitting for > 400pe (~30keV) (full volume data) with constraints from the screening results.

Background in XMASS

- ^{210}Pb in copper surface & bulk.
  - Alpha-ray events are identified using scintillation decay time.
  - Copper surface/bulk ^{210}Pb concentration are estimated by alpha-ray from ^{210}Po decay (Alpha from bulk makes continuous spectrum.).
  - ^{210}Pb Contamination in the bulk oxygen-free copper was confirmed (~20 mBq/kg) by an alpha-particle counter -> See next page
- RI in liquid xenon.
  - Coincidence analysis is used for ^{222}Rn as ^{214}Bi-^{214}Po (164μs) decay, ^{85}Kr as beta-gamma (1.015μs, 0.434%).
  - Concentration of C14 and ^{39}Ar in LXe are estimated from spectrum fits.

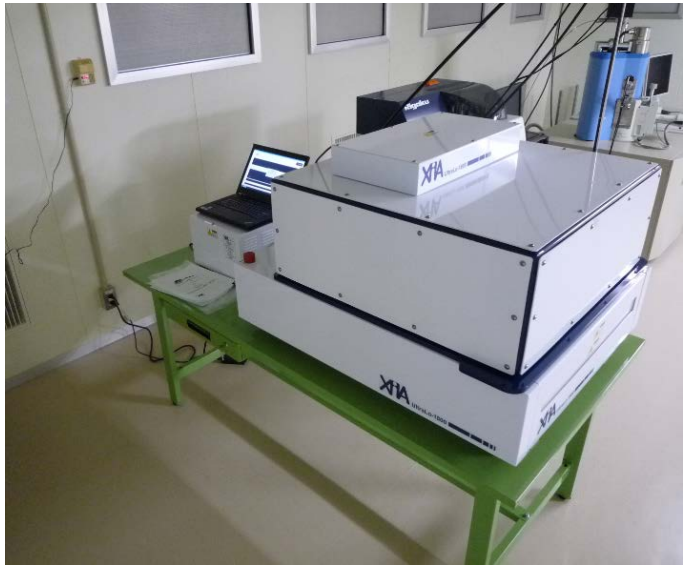
Alpha-like event sample





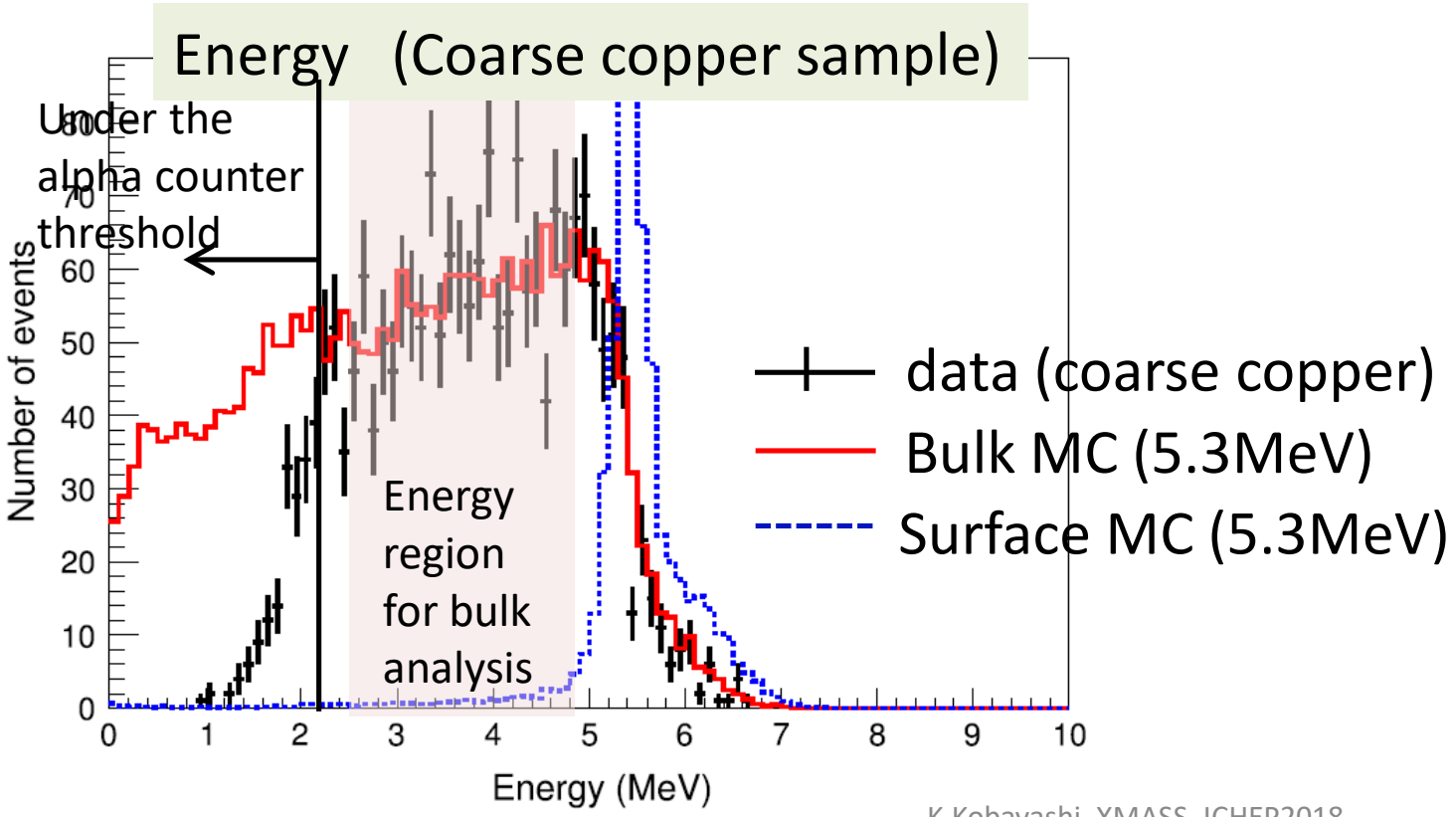
Measurement of ^{210}Pb in bulk copper by alpha counter

Not only the surface alpha events, but also bulk events can be observed! Sensitivity to ^{210}Pb is world best in screening (a few mBq/kg).

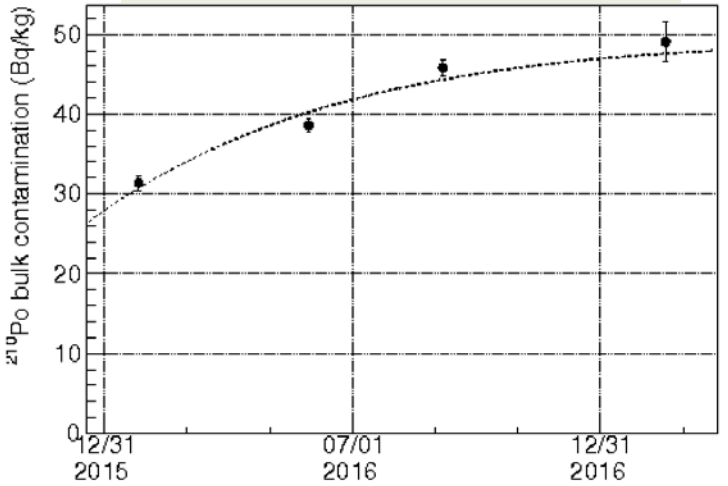


Low background alpha-counter
XIA Ultra-Lo-1800

Energy (Coarse copper sample)



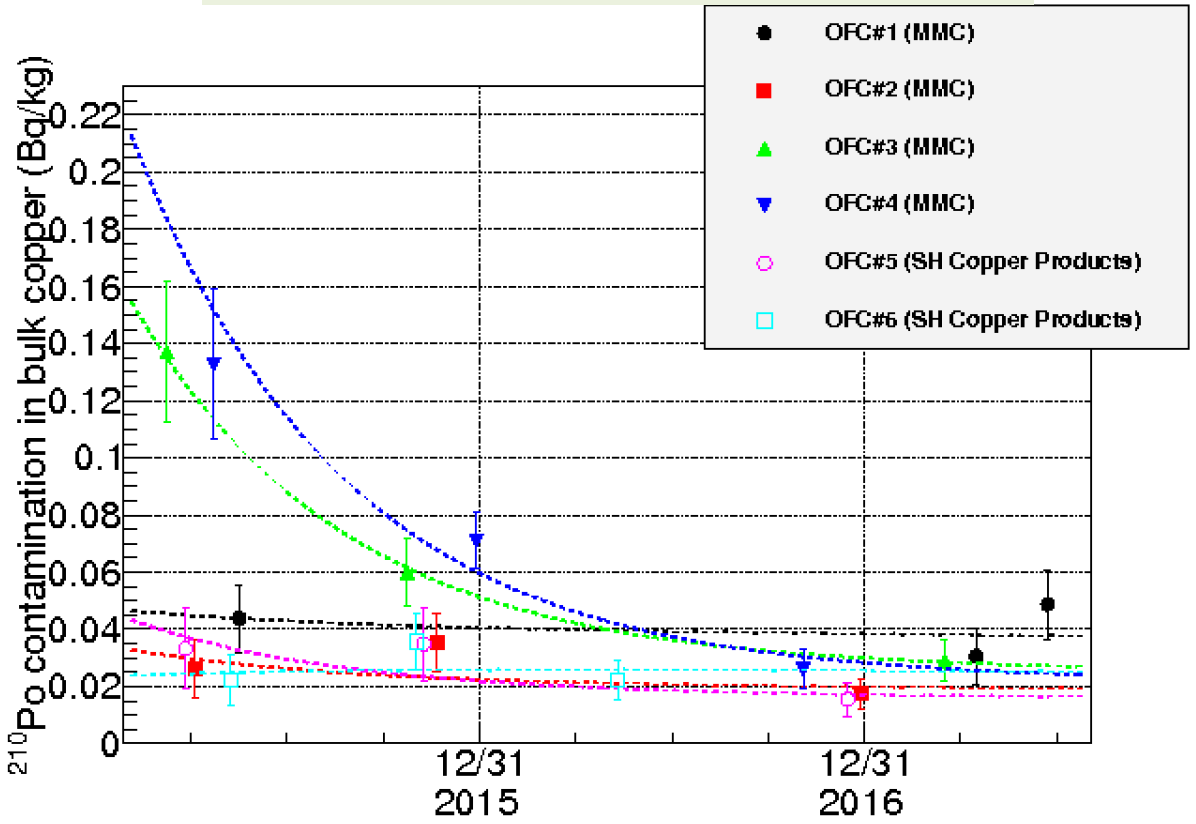
Time evolution (coarse copper)



^{210}Pb in bulk oxygen free copper is measured for the first time

- Many oxygen free copper samples are measured. ^{210}Pb contamination is 17-40 mBq/kg.
- Spare plate for XMASS detector is also measured to be 26±11mBqkg, which is NOT negligible in XMASS WIMP analysis. This is consistent to alpha-like events measurement in XMASS detector.
- This is the first measurement of ^{210}Pb contamination in oxygen free copper (NIMA884 (2018)157-161)

Time evolution
(oxygen free copper samples)



Event selection of WIMP search (arXiv: 1804.02180)

1. Standard cut

   remove electronic noise events, Cherenkov events, after pulse events, and so on.

2. Timing based vertex reconstruction R(T)

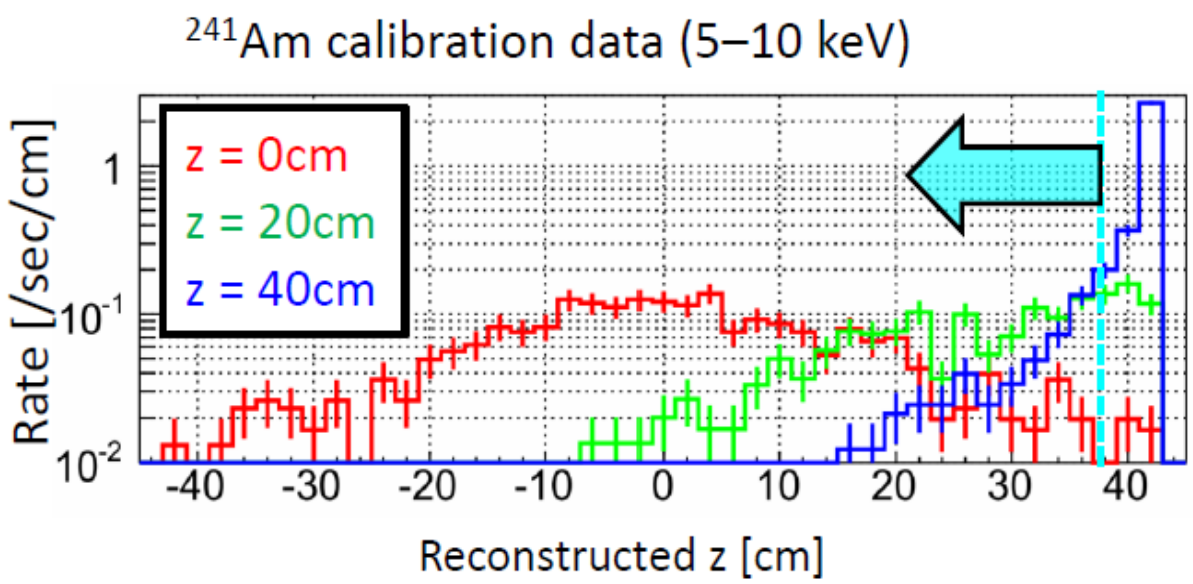
   First hit timing of each PMT is used. Position is fitted by likelihood. Events are selected if R(T)<38cm.

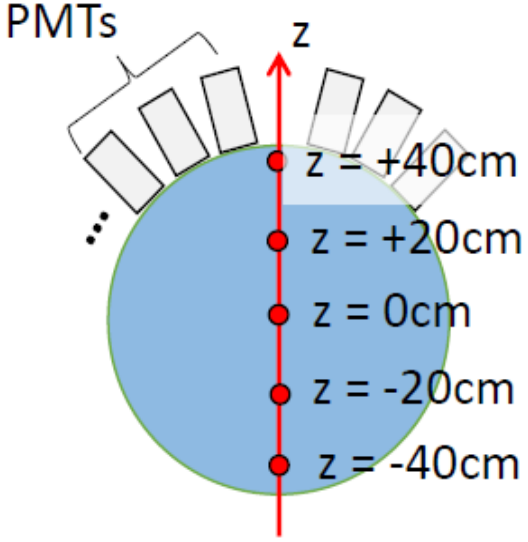
3. PE based vertex reconstruction R(PE)

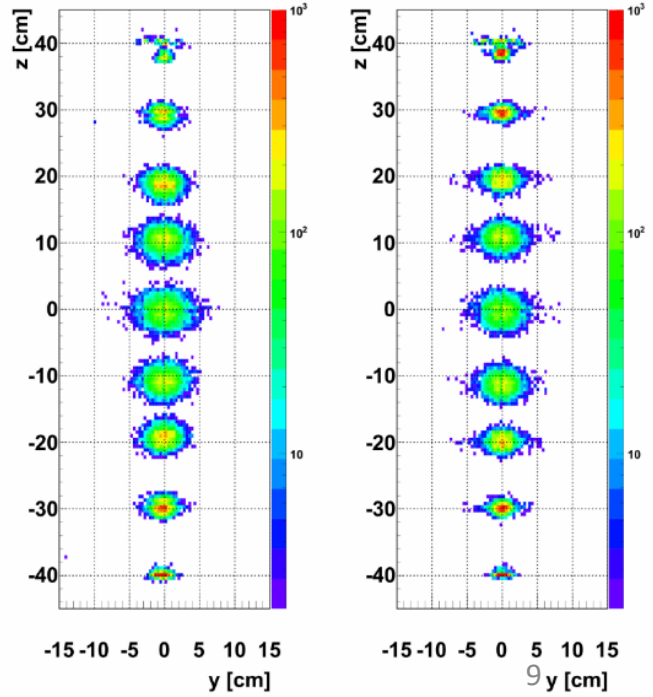
   PE map is made in each position using MC.

   Event vertex is calculated by likelihood.

   Energy is also reconstructed. Events are selected if R(PE)<20cm.



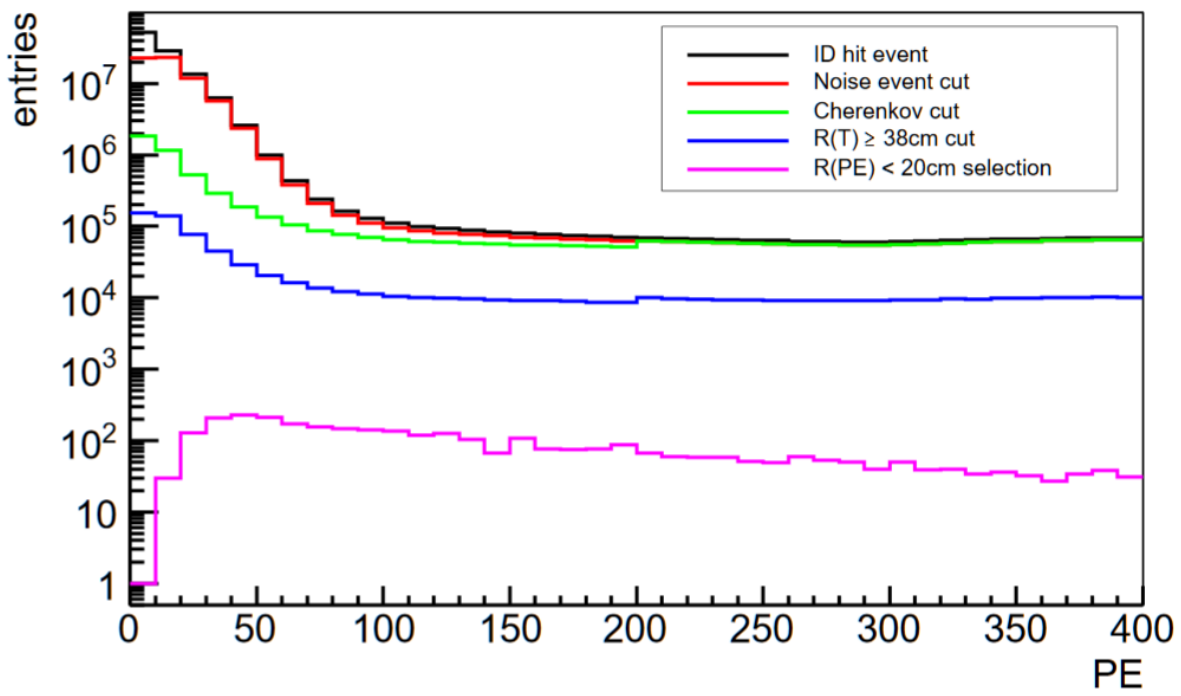




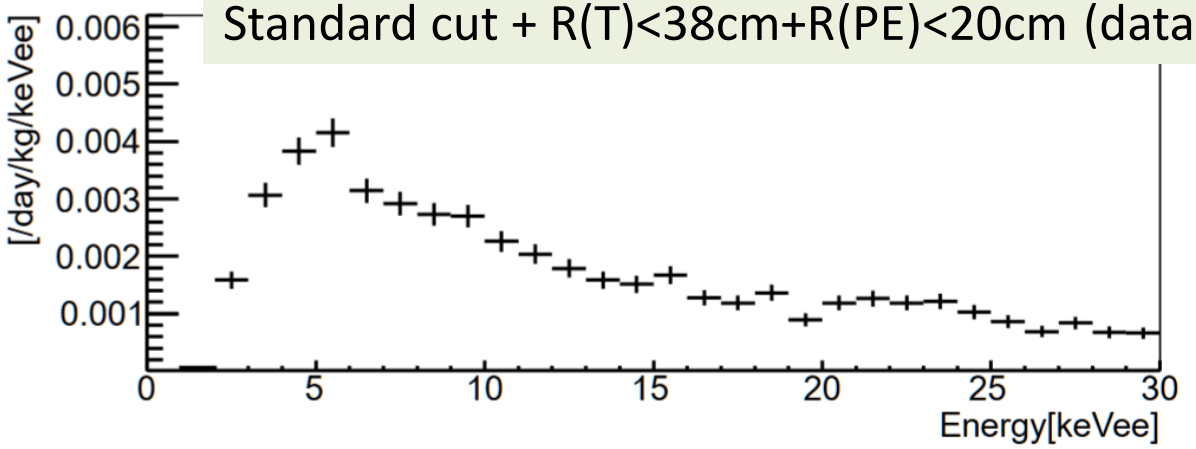
Data (WIMP search)

- Dataset
  - Nov. 20th, 2013 – Mar. 29th, 2016
- Livetime
  - 705.9days.
- After applying all the cuts (standard cut + R(T) cut + R(PE) cut), event rate becomes ~4×10^{-3} /day/kg/keVee @ 5-5.5keVee.

event selection (data)



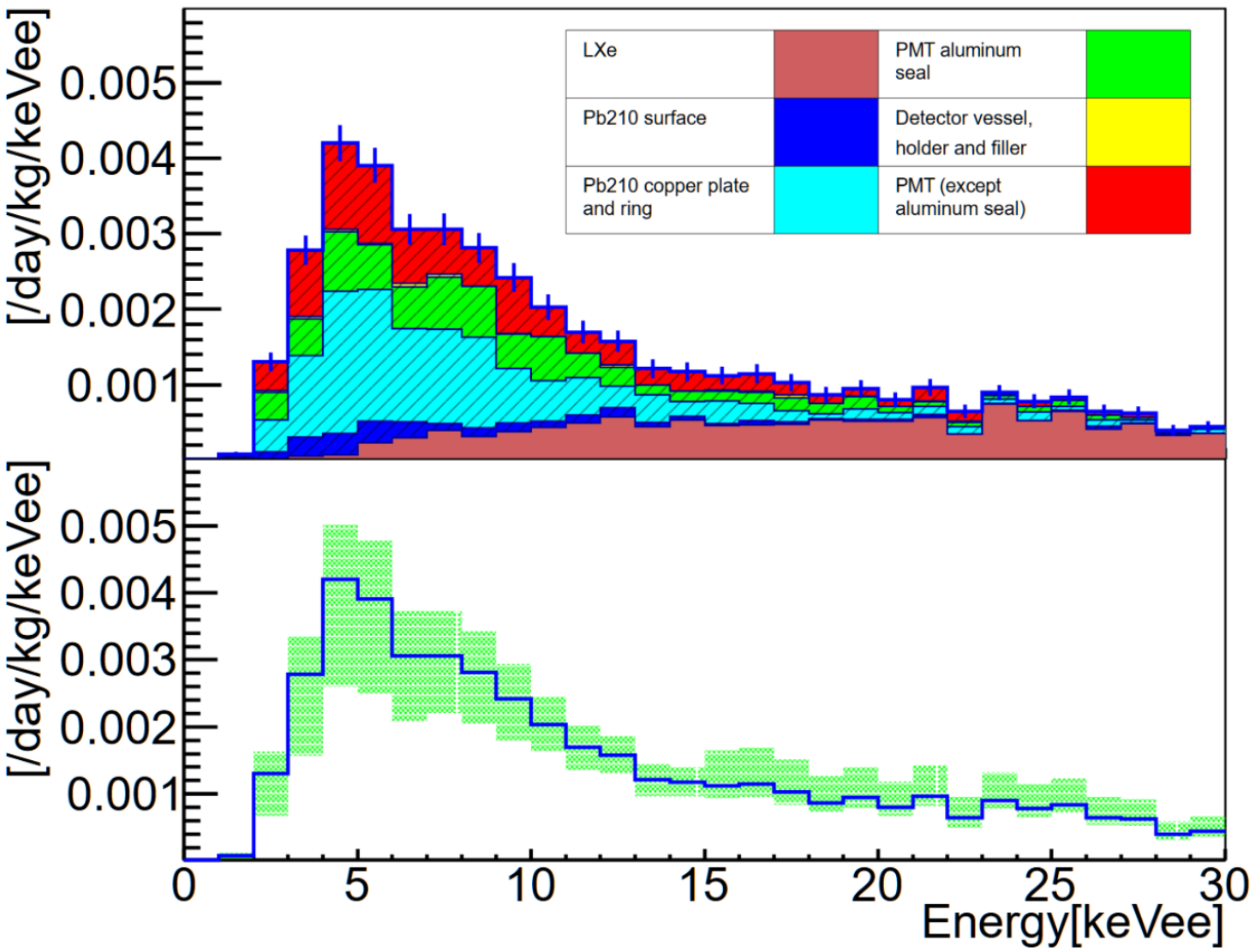
Standard cut + R(T)<38cm+R(PE)<20cm (data)



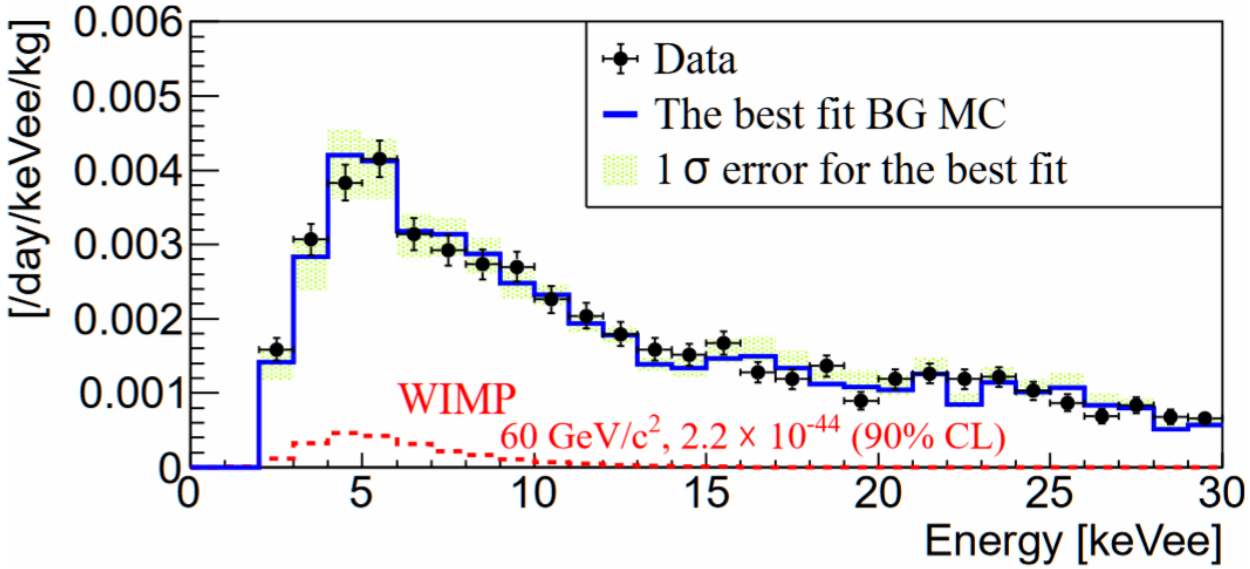
Background estimate of WIMP search

- Background MC is generated using XMASS MC for each RI's decay mode and its activity.
- Optical parameters of LXe are traced with our ^{57}Co57 and ^{60}Co regular calibration.
- Same event selection is applied to background MC, which has the same livetime as the dataset.
- ~90% of remaining BG is of detector surface origin (not internal BG). => mis-reconstructed events.

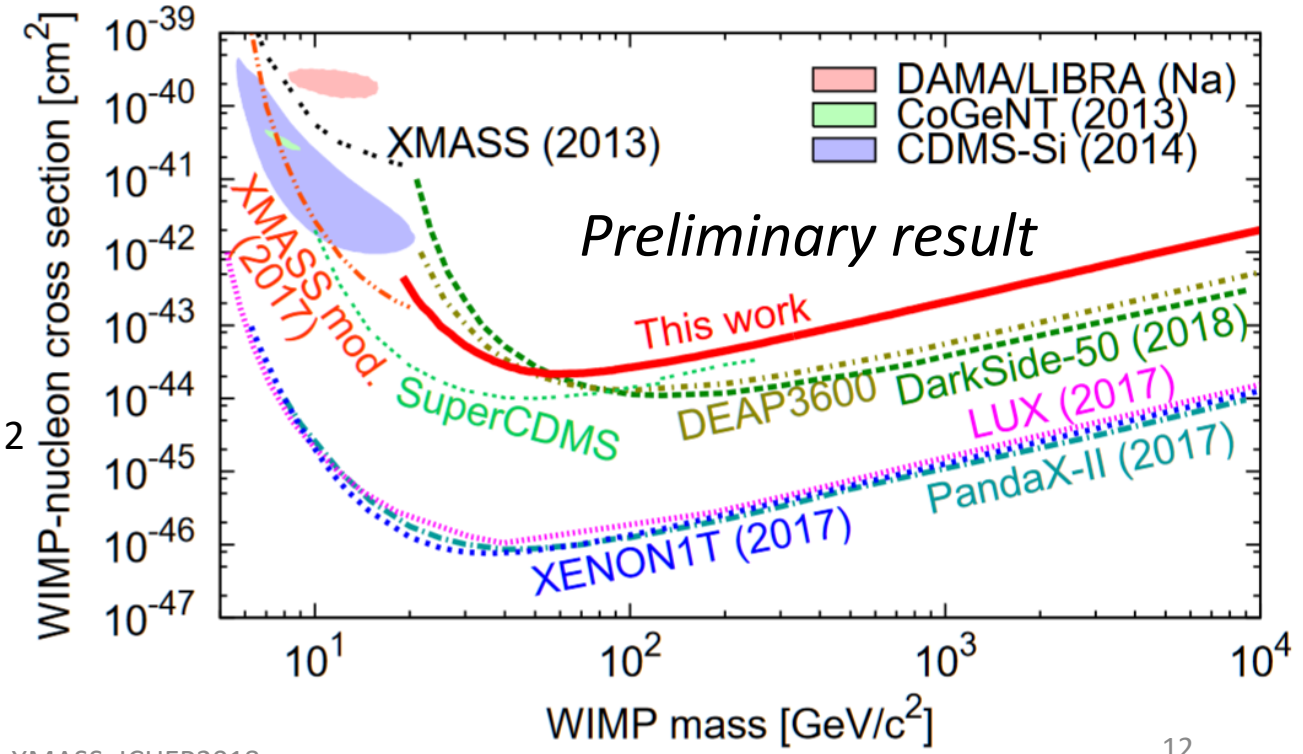
Standard cut + R(T)<38cm+R(PE)<20cm (MC)



Search for WIMPs with background evaluation in the fiducial volume.

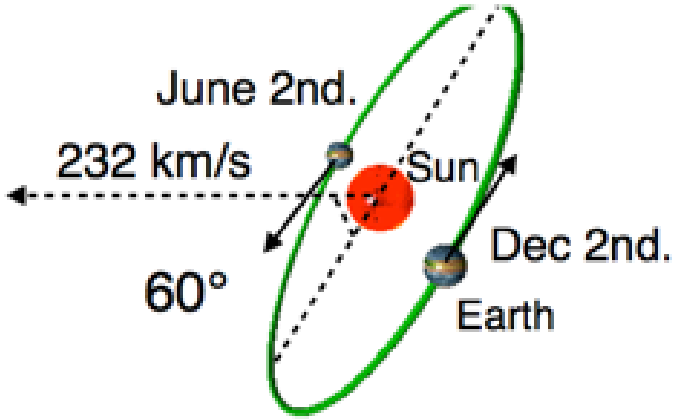


- Data is consistent with background expectation.
- The energy spectrum of the data was fitted with background MC plus WIMP MC in the energy range of 2-15keVee.
- Our exclusion limit at 90% CL is 2.2×10^{-44}cm^2 at 60GeV WIMPs mass.
- The result can be found at arXiv: 1804.02180.



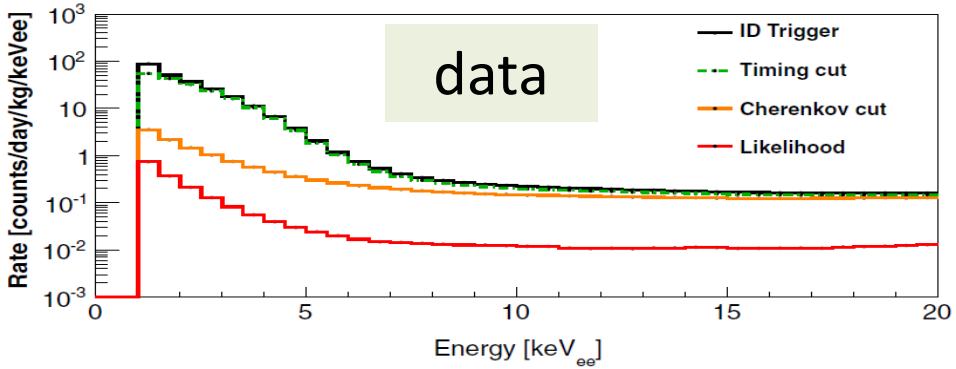
Annual modulation search

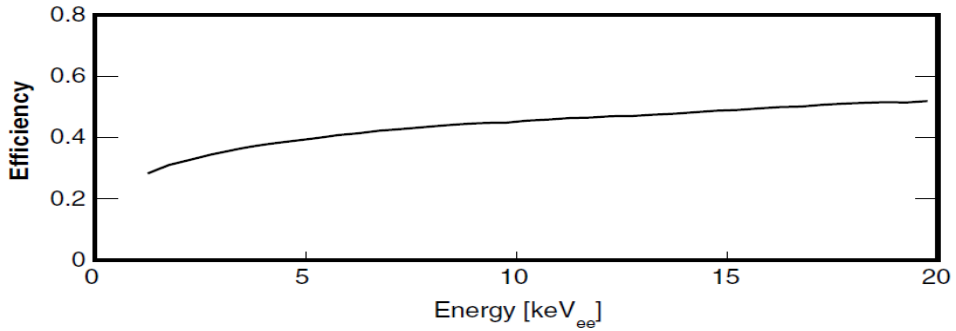
Dark matter event rate is expected to modulate annually due to relative motion of the Earth around the Sun. Annual modulation claimed by DAMA/LIBRA phase1+phase2 with 11.9σ significance (1.04+1.13 ton・year, 13 cycles).



Search in XMASS (PRD97 (2018) 102006)

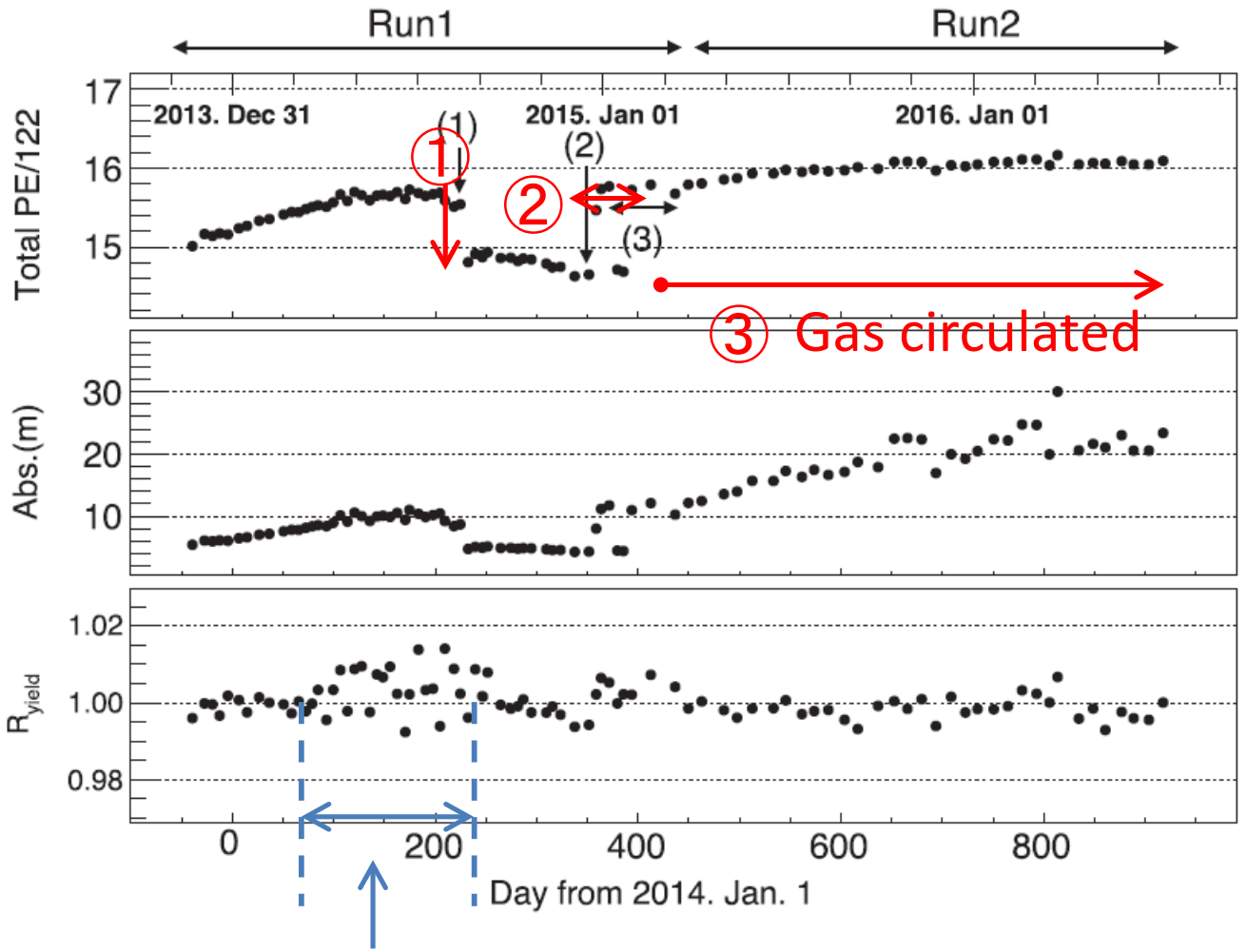
- >2year cycle data (1.82ton・year) with low threshold (1.0keVee, =4.8keVnr)
- No particle ID (just like DAMA/LIBRA)





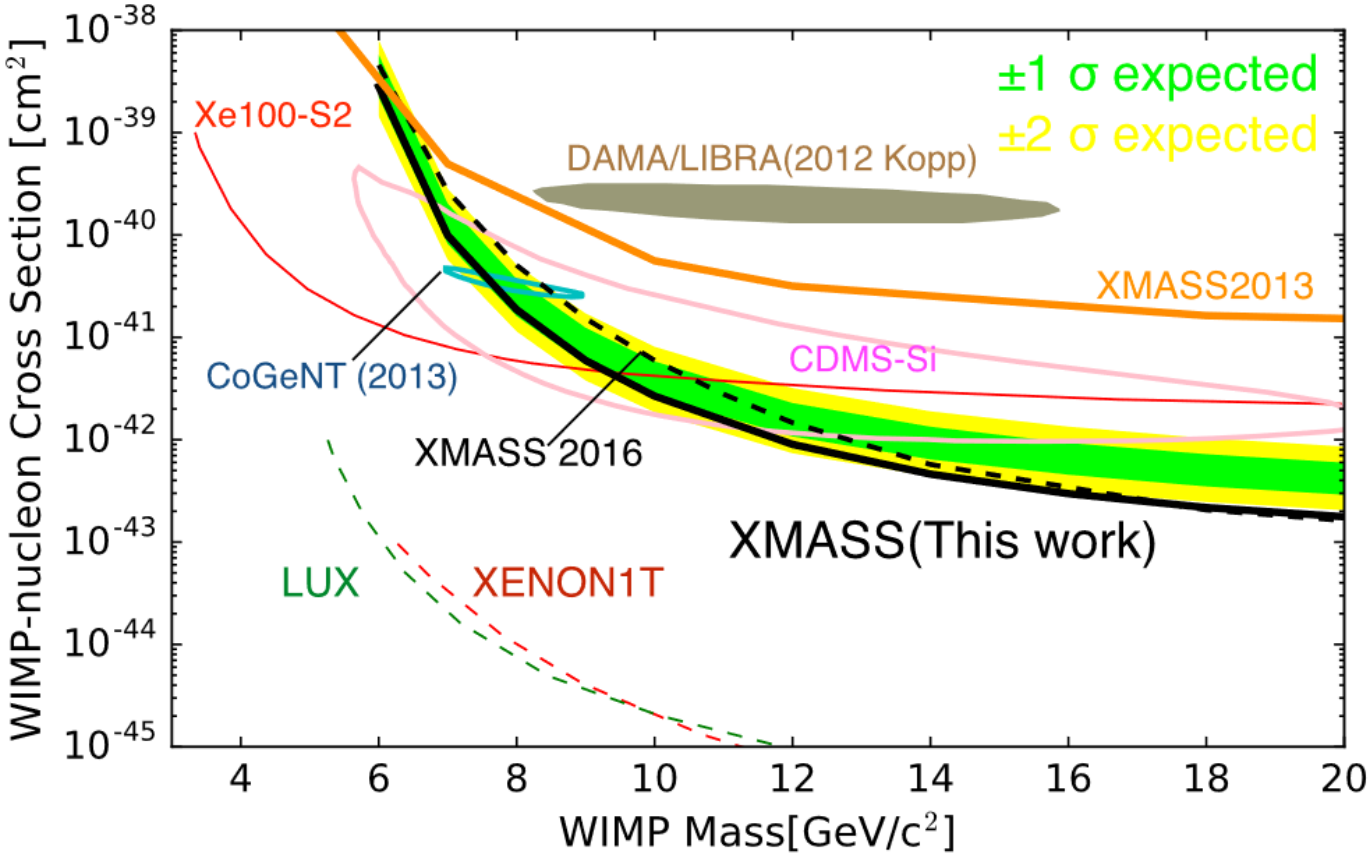
Detector stability

- We observed PE yield changes using Co57 source calibration.
  - ①Sudden drop at the power failure
  - ②Purification work
  - ③Continuous gas circulation.
- Run2 is more stable (Run1 is used in previous result (PLB2016)).
  (RMS of P.E. yield : 0.5%)
- Using the calibration and MC, estimated the detector stability.
  - The PE yield change is described by the change of absorption length.
  - RMS of deduced relative light yield : Run1 - 0.6%, Run2 - 0.3%



Relatively unstable due to different gain calibration

Standard WIMP search by modulation



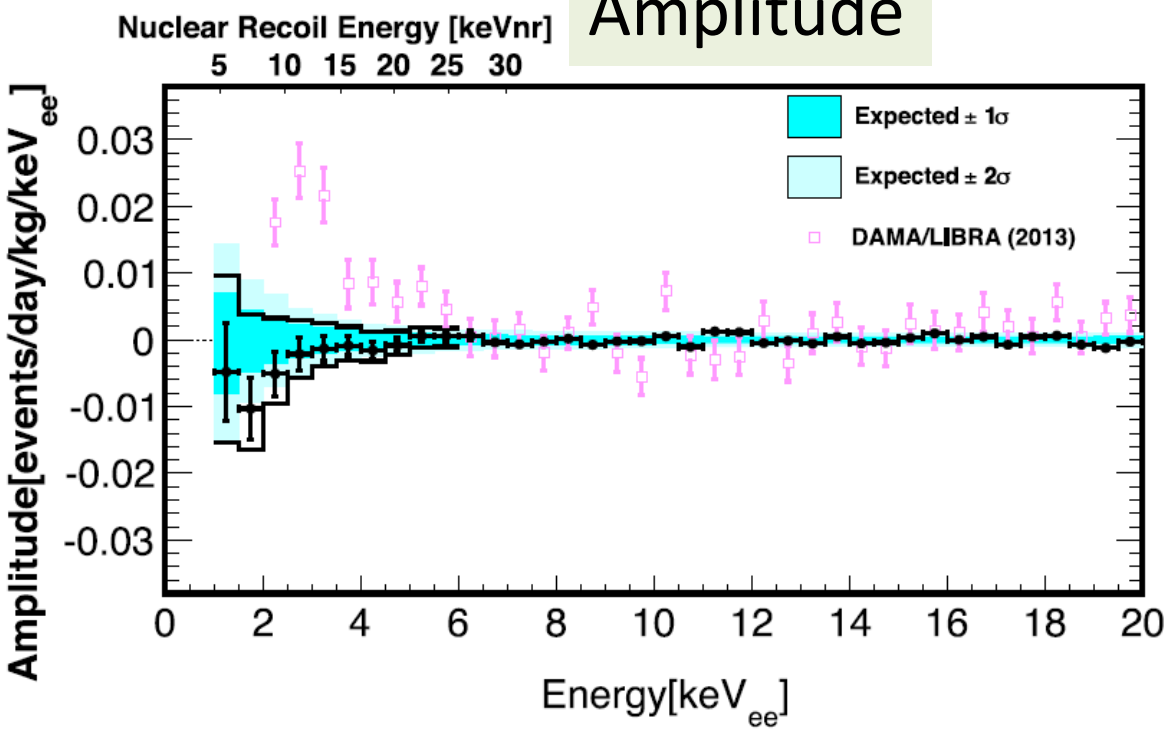
- Leff uncertainty is taken into account.
- DAMA/LIBRA region is excluded by our measurement.

Model assumption

T:1year, t0=152.5day (fixed)
V_0: 232.0 km/s
V_{esc}: 544 km/s
ρ_{dm}: 0.3 GeV/cm^3
Lewin, Smith (1996)

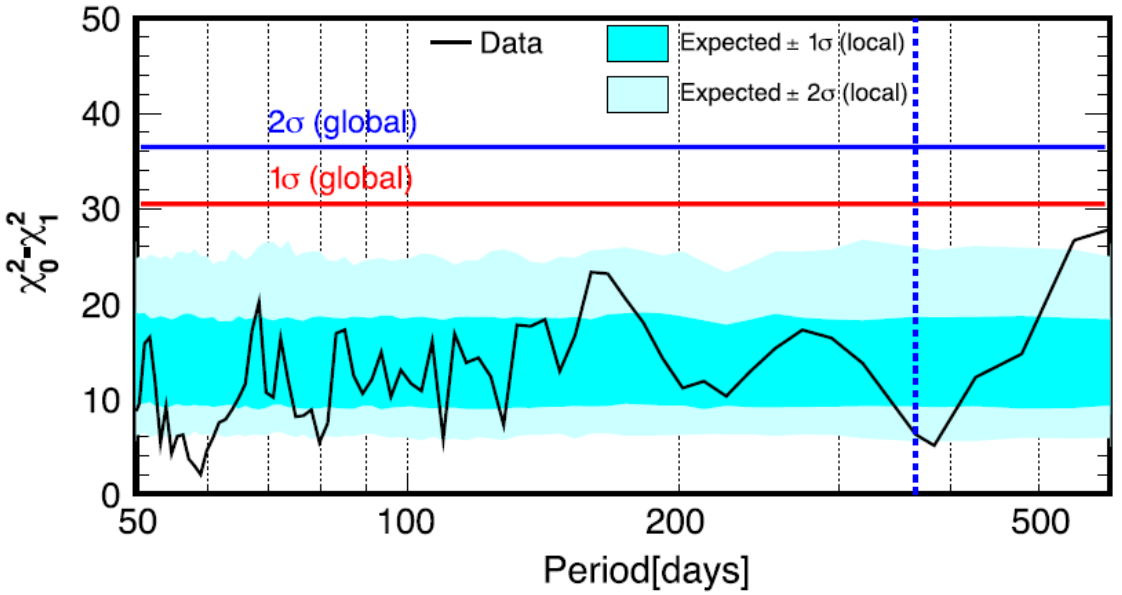
Model independent results of annual modulation search

Amplitude



Experiments	Amplitude(events/day/kg/keV$_{ee}$)
DAMA/LIBRA	~0.02 at 2.0-3.5keV$_{ee}$
XENON100	$1.67 \pm 0.73 \times 10^{-3}$ at 2.0-5.8keV$_{ee}$
XMASS	$<(1.3\text{-}3.2) \times 10^{-3}$ at 2-6keV$_{ee}$

Power spectrum



- Phase t_0 : free parameter. 1–6 keV$_{ee}$
- Test statistics : $\Delta\chi^2$ of model independent analysis between null and periodic hypotheses.
- No significant period was found between 50 and 600 days.

Hidden photon (HP) and Axion-like particle (ALP) dark mater search: motivation

HP (vector boson super-WIMPs)

- Cross section (σ_{abs}) is:

$$\frac{\sigma_{\mathrm{abs}} v}{\sigma_{\mathrm{photo}}(\omega = m_V)c} \approx \frac{\alpha'}{\alpha}$$

(α' : the vector boson analogue to the fine structure constant. v: velocity of the vector boson)

- Can be detected by absorption of the particle, which is similar to the photoelectric effect.
- The counting rate (S_v) in the detector is:

$$S_v \approx \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left(\frac{\mathrm{keV}}{m_V}\right) \left(\frac{\sigma_{\mathrm{photo}}}{\mathrm{barn}}\right) \mathrm{kg}^{-1}\,\mathrm{day}^{-1}$$

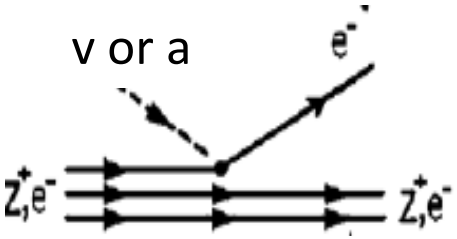
(A: atomic mass, standard local matter density: 0.3GeV/cm^3)

Pospelov et, al. Phys. Rev. D 78 115012 (2008)

ALP (pseudo-scalar boson super-WIMPs)

- Cross section (σ_{abs}) is:

$$\frac{\sigma_{\mathrm{abs}} v}{\sigma_{\mathrm{photo}}(\omega = m_a)c} \approx \frac{3m_a^2}{4\pi\alpha f_a^2}$$



(v: velocity of the vector boson, m_a: pseudoscalar mass, f_a: dimensionful coupling constant.)

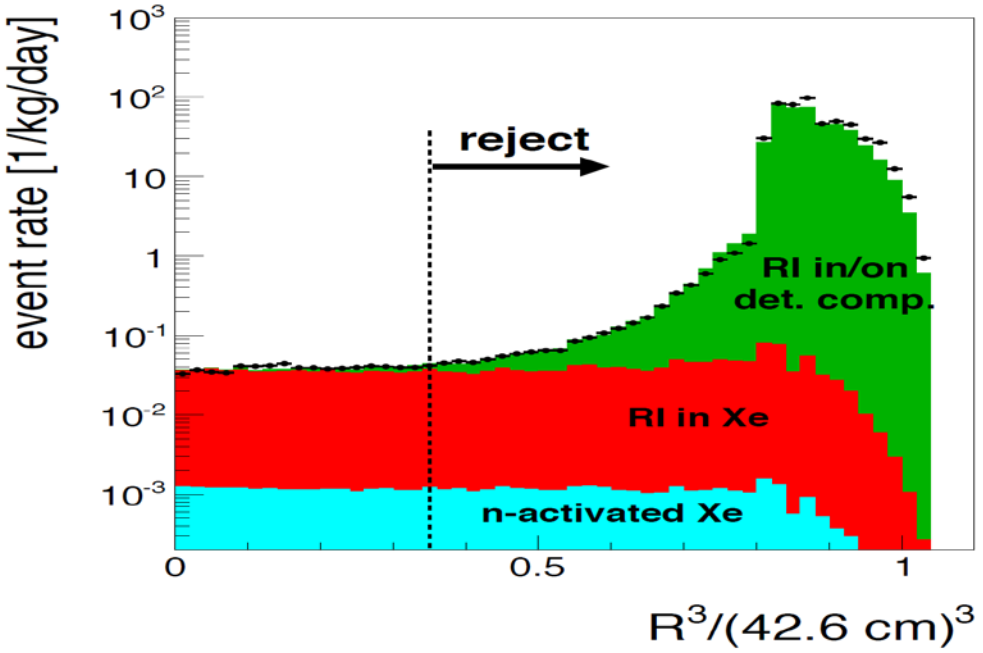
- The counting rate in the detector is:

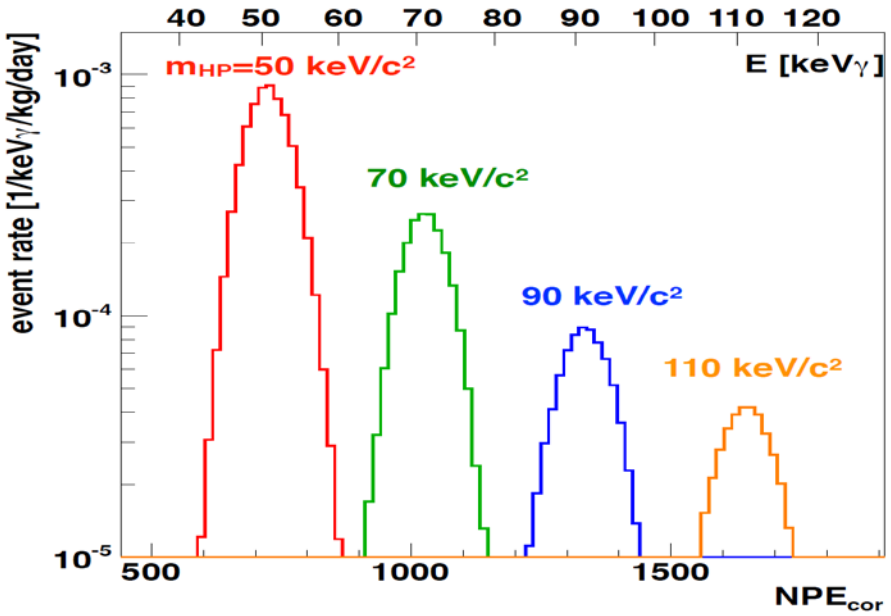
$$S_a \approx \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{\mathrm{photo}}}{\mathrm{barn}}\right) \mathrm{kg}^{-1}\,\mathrm{day}^{-1}$$

($g_{aee}=2m_e/f_a$, m_e: electron mass)

Hidden photon and axion-like particle search: method

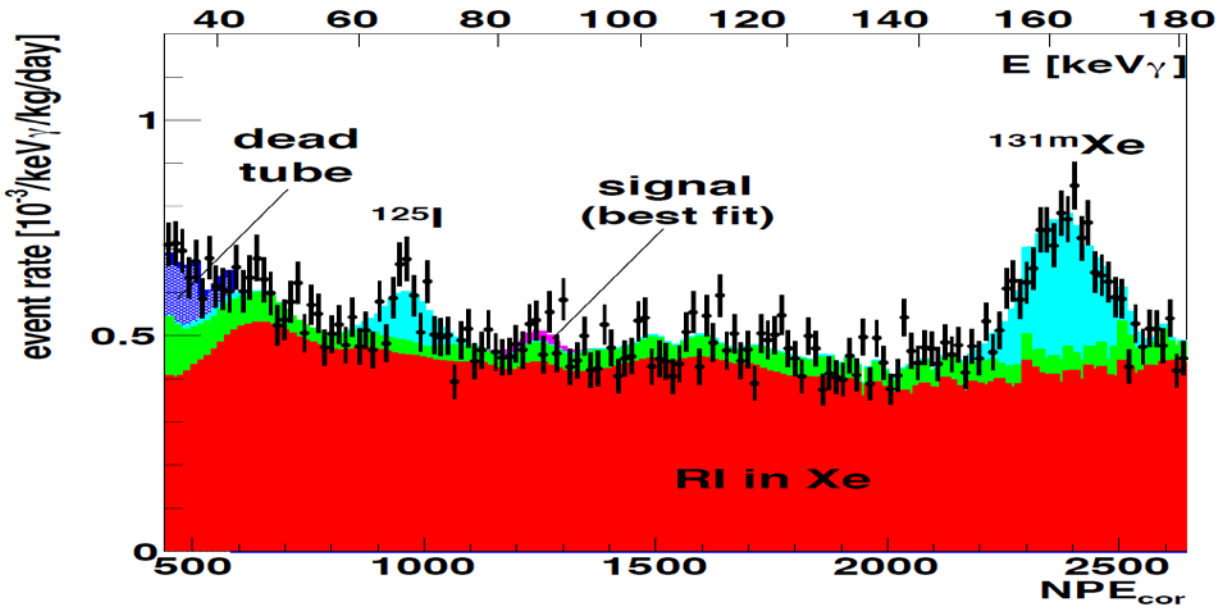
- Dataset: Nov. 2013 – Jul. 2016 (livetime 800days)
- Selection criteria: standard cut + fiducial volume cut (R<30cm) (327kg FV)
- Peak is expected in the NPE distribution.

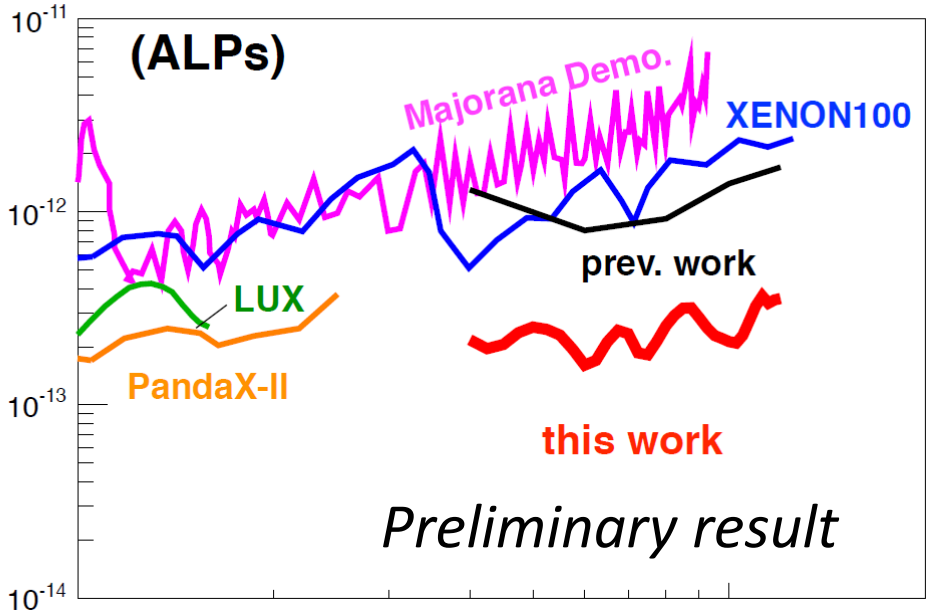


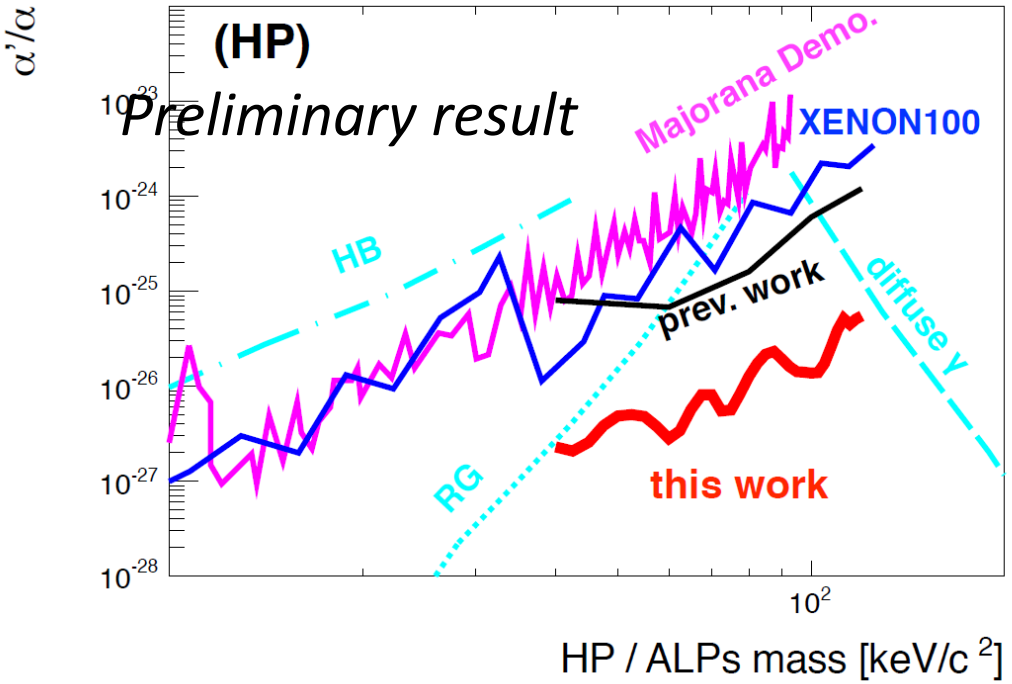


Hidden photon and axion-like particle search: result

- Peak search with signal + background model by fitting at 440-2650NPE$_{corr}$ (30-180keV γ).
- No candidates are found. Best constraint in 40-120keV/c^2 in both searches.







summary

- A WIMP dark matter search has been conducted based on background understanding. No WIMP singal is observed and the exclusion limit is calculated to be $2.2 \times 10^{-44} cm^2$ for 60GeV WIMPs.
- Annual modulation analysis has been performed using large exposure, 1.82ton·year data. No significant modulated WIMP signal has been observed. The result excluded DAMA/LIBRA allowed region.
- The best constraint is obtained at 40-120keV/c^2 for hidden photon and axion like particle dark matter search.
- We continue to take data. Various kind of dark matter candidates /physics topics has been searched for! We also continue to study various kinds of physics because XMASS has large exposure and is sensitive to both nuclear recoil and beta/gamma.

backup

XMASS collaboration

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Tokushima University	K. Fushimi
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Nihon University	H. Ogawa
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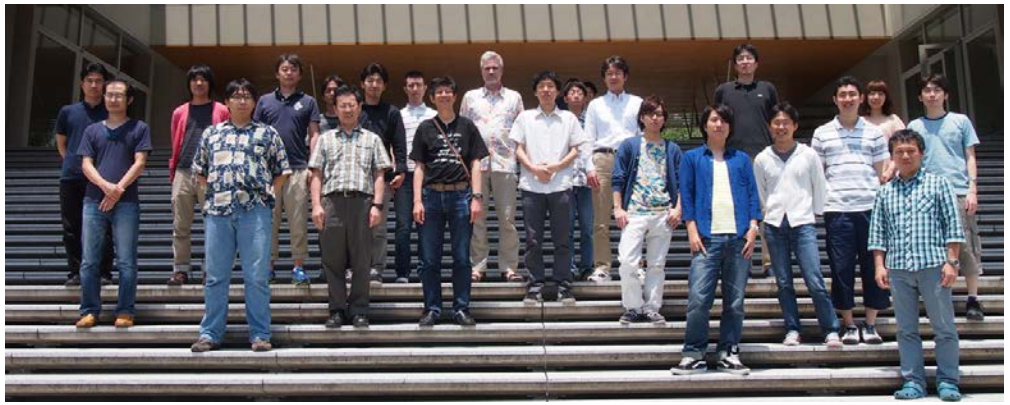
IBS	N.Y. Kim, Y. D. Kim
KRISS	Y. H. Kim, M. K. Lee, K. B. Lee



11 institutes, 36 collaborators

WIMP search in the fiducial volume

Location of RI	RI	Activity [mBq/detector] initial value of the fit	Activity [mBq/detector] the best fit value
LXe	^{222}Rn	-	8.53±0.16
	^{85}Kr	-	0.25±0.04
	^{39}Ar	-	0.65±0.04
	^{14}C	-	0.19±0.01
copper plate and ring	^{210}Pb	-	$(6.0\pm1.0)\times10^{2}$
copper surface	^{210}Pb	-	0.7±0.1
PMT quartz surface	^{210}Pb	-	6.4±0.1
PMT	^{238}U	$(1.5\pm0.2)\times10^{3}$	$(2.0\pm0.2)\times10^{3}$
(except aluminum seal	^{232}Th	$(1.2\pm0.2)\times10^{3}$	$(1.1\pm0.3)\times10^{3}$
and quartz surface)	^{60}Co	$(1.9\pm0.1)\times10^{3}$	$(1.6\pm0.2)\times10^{3}$
	^{40}K	$(5.8\pm1.4)\times10^{3}$	$(9.6\pm1.7)\times10^{3}$
	^{210}Pb	$(1.3\pm0.6)\times10^{5}$	$(2.2\pm0.7)\times10^{5}$
PMT aluminum seal	^{238}U	$(1.5\pm0.4)\times10^{3}$	$(9.0\pm4.1)\times10^{2}$
	^{235}U	$(6.8\pm1.8)\times10^{1}$	$(4.1\pm1.8)\times10^{1}$
	^{232}Th	$(9.6\pm1.8)\times10^{1}$	$(5.5\pm2.2)\times10^{1}$
	^{210}Pb	$(2.9\pm1.2)\times10^{3}$	$(3.4\pm1.2)\times10^{3}$
Detector vessel,	^{238}U	$(1.8\pm0.7)\times10^{3}$	$(9.0\pm7.6)\times10^{2}$
holder and filler	^{232}Th	$(6.4\pm0.7)\times10^{3}$	$(6.4\pm3.2)\times10^{3}$
	^{60}Co	$(2.3\pm0.1)\times10^{2}$	$(3.0\pm1.9)\times10^{2}$
	^{210}Pb	-	$(3.8\pm0.5)\times10^{4}$

Contents	Systematic error	
	2-15 keV_{ee}	15-30 keV_{ee}
(1) Plate gap	+6.2/-22.8%	+1.9/-6.9%
(2) Ring roughness	+6.6/-7.0%	+2.0/-2.1%
(3) Copper reflectivity	+5.2/-0.0%	+2.5/-0.0%
(4) Plate floating	+0.0/-4.6%	+0.0/-1.4%
(5) PMT aluminum seal	+0.7/-0.7%	-
(6) Reconstruction	+3.0/-6.2%	-
(7) Timing response	+4.6/-8.5%	+0.4/-5.3%
(8) Dead PMT	+10.3/-0.0%	+45.2/-0.0%
(9) LXe property	+0.7/-6.7%	+1.5/-1.1%