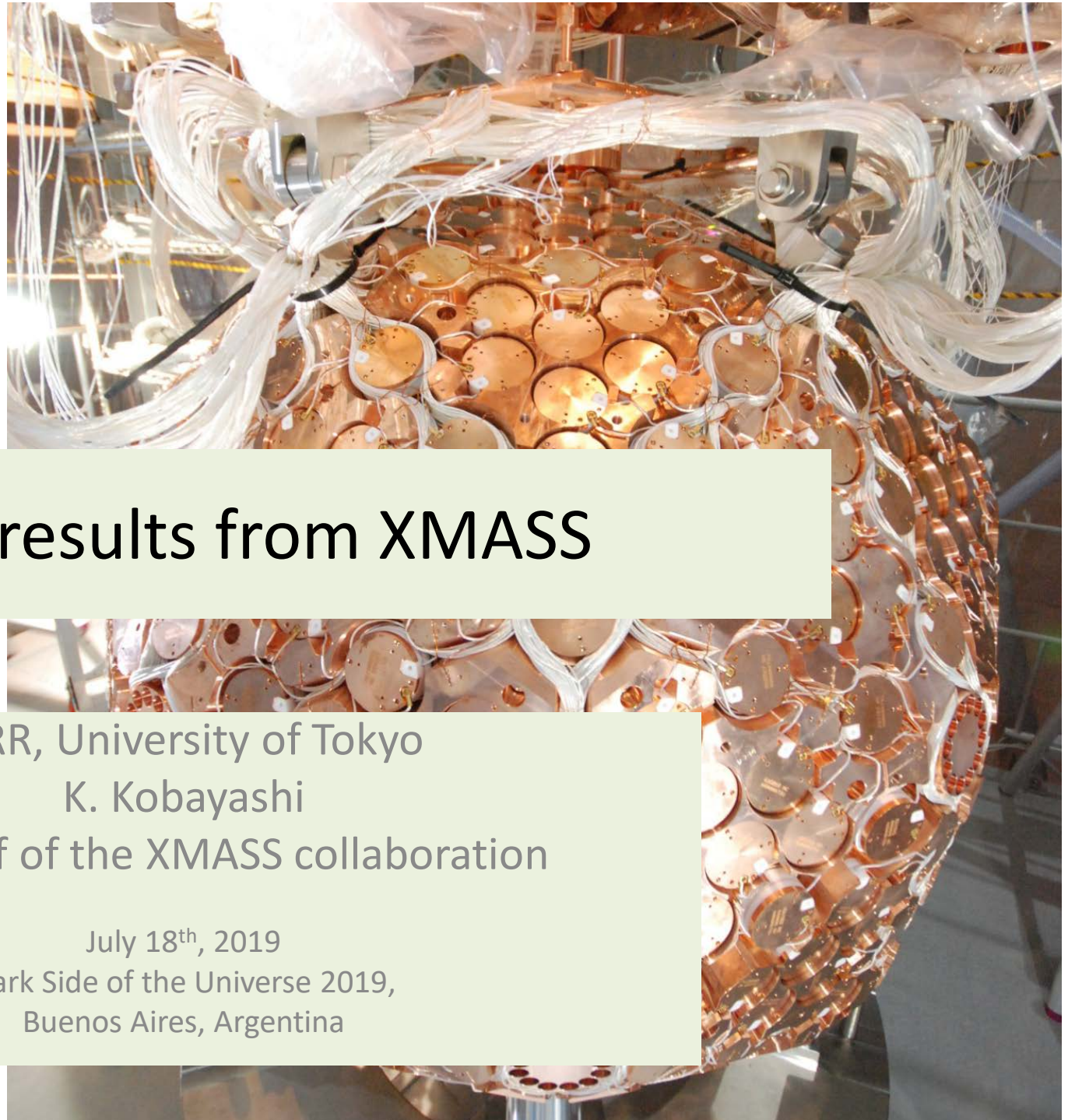


Latest results from XMASS

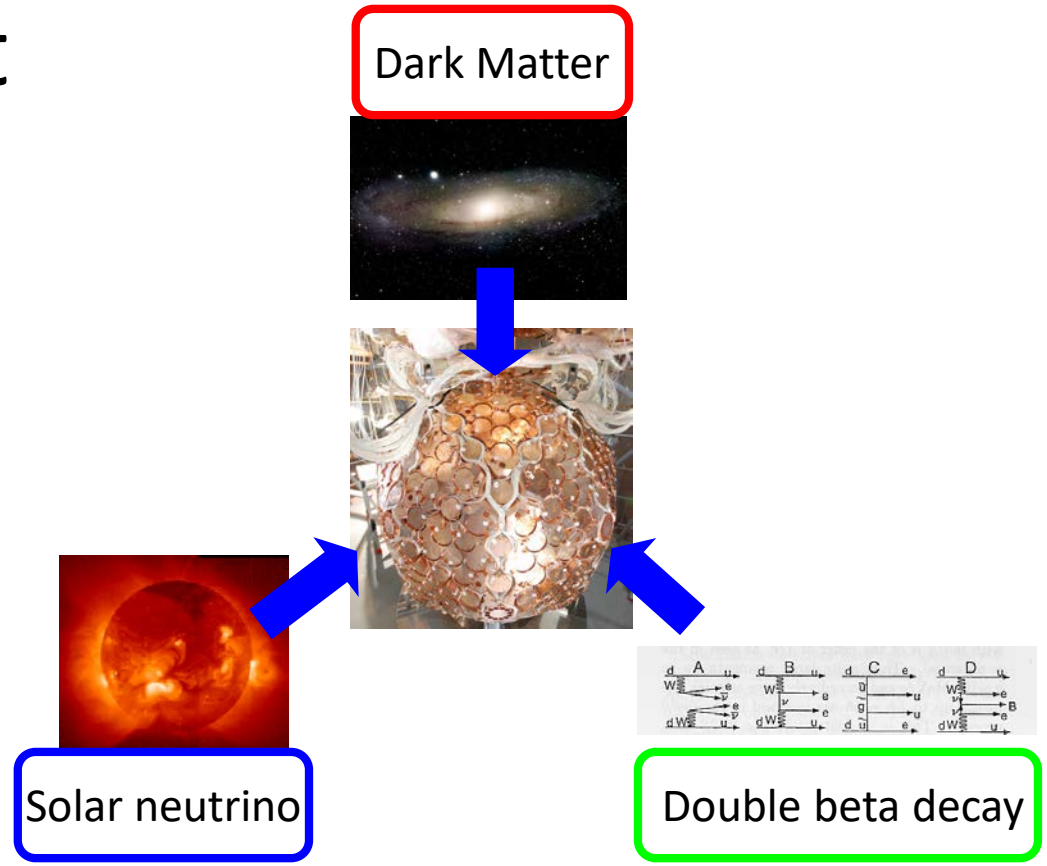
ICRR, University of Tokyo
K. Kobayashi
On behalf of the XMASS collaboration

July 18th, 2019
Dark Side of the Universe 2019,
Buenos Aires, Argentina

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**)



history of XMASS

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

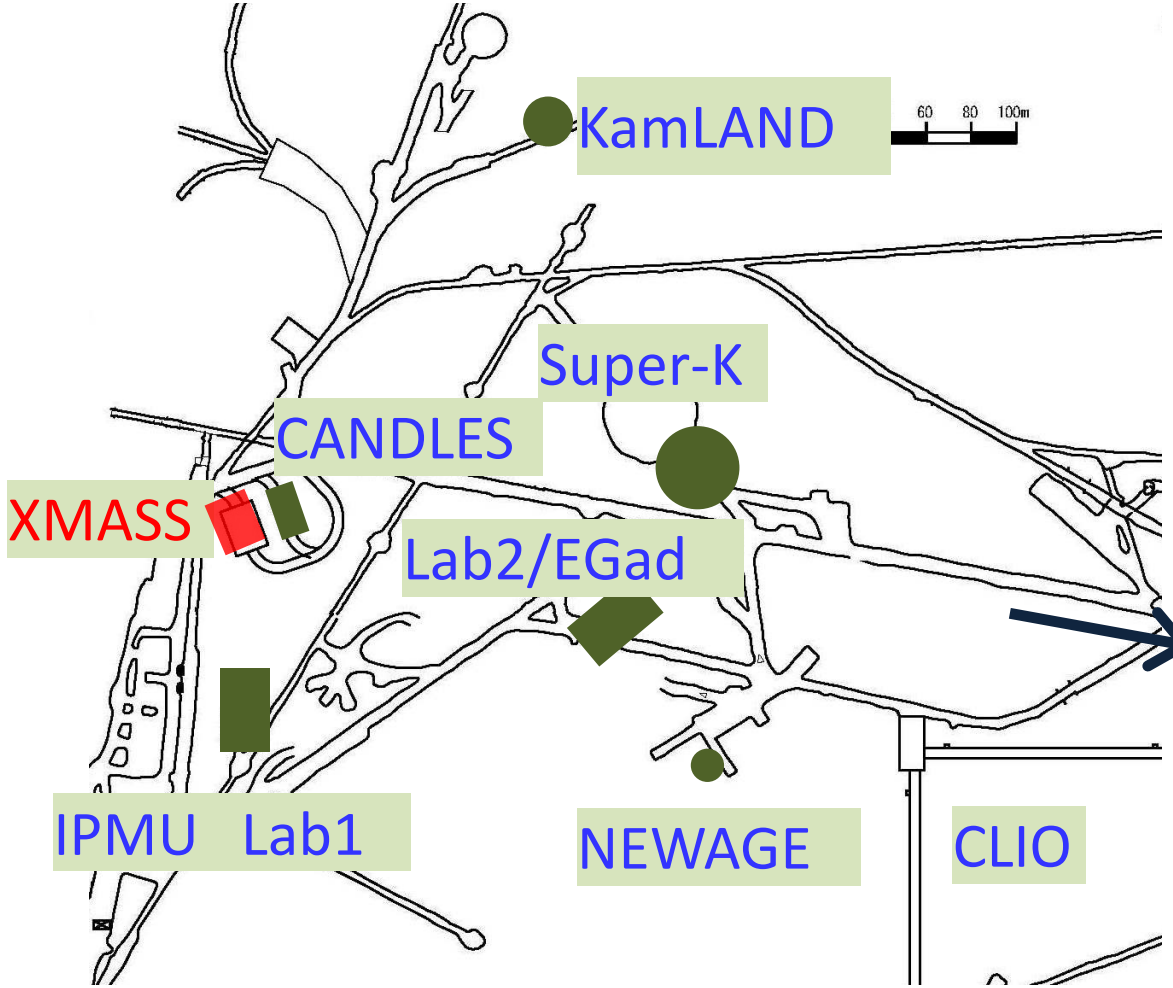
detector construction completed (Sep. 2010)

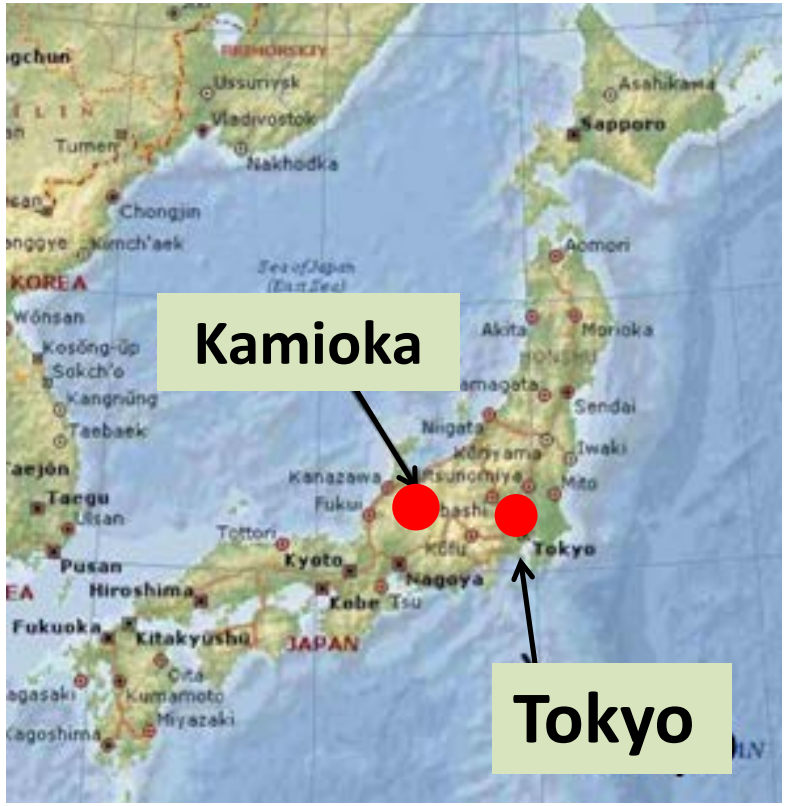
commissioning run (Dec. 2010 - May 2012)

detector refurbishment (Aug. 2012 - Oct. 2013)

- Data taking (Nov. 2013 – Feb. 2019)
- We have taken data for >5year.

Kamioka mine

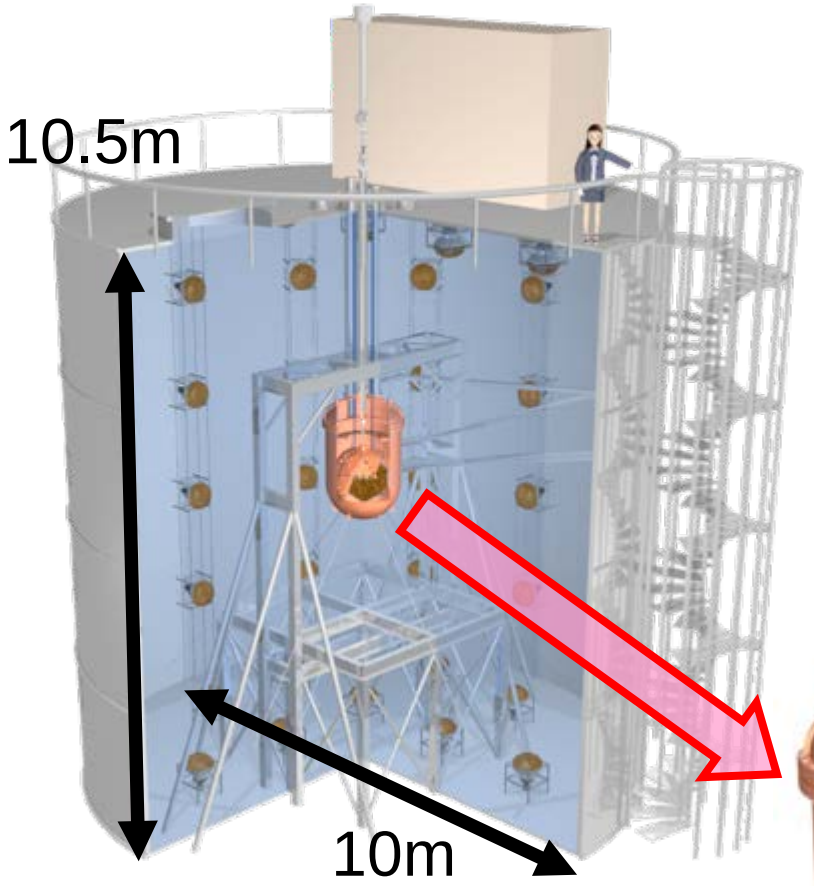


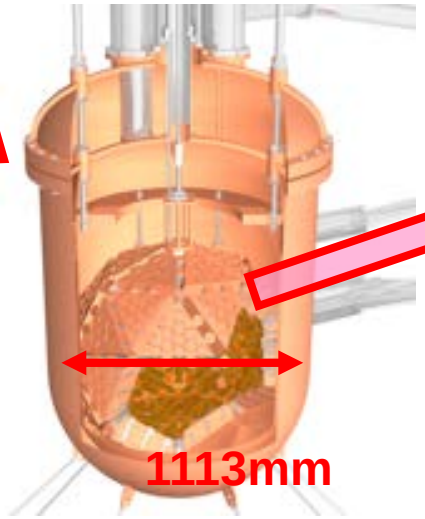


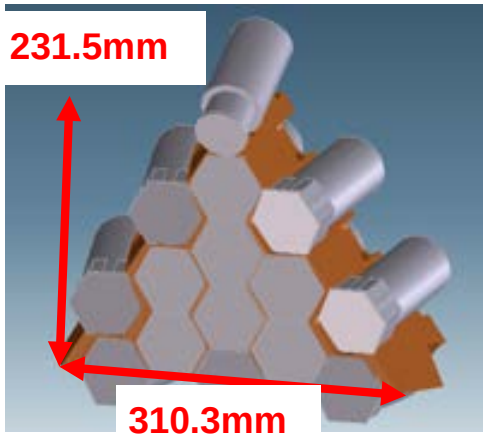
~1000m underneath Mt. Ikenoyama

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 A922 (2019) 171-176

NIM A716 (2013) 78-85

Calibration system

RI sources

	energy [keV]	diameter [mm]	Source geometry
Fe-55	5.9	10	2pi
Cd-109	8, 22, 25, 88	5	2pi
Am-241	17.8, 59.5	0.17	2pi/4pi
Co-57	59.3 (W X-ray)122	0.21	4pi
Cs-137	662	5	Cylindrical

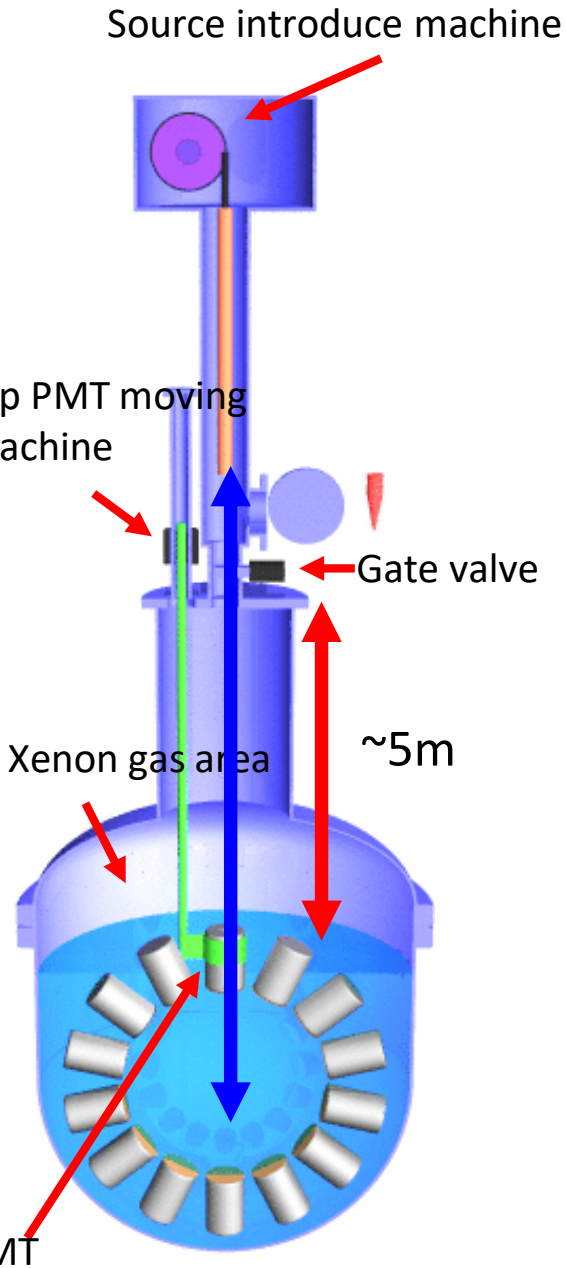
Source rod

adaptor(SUS304)

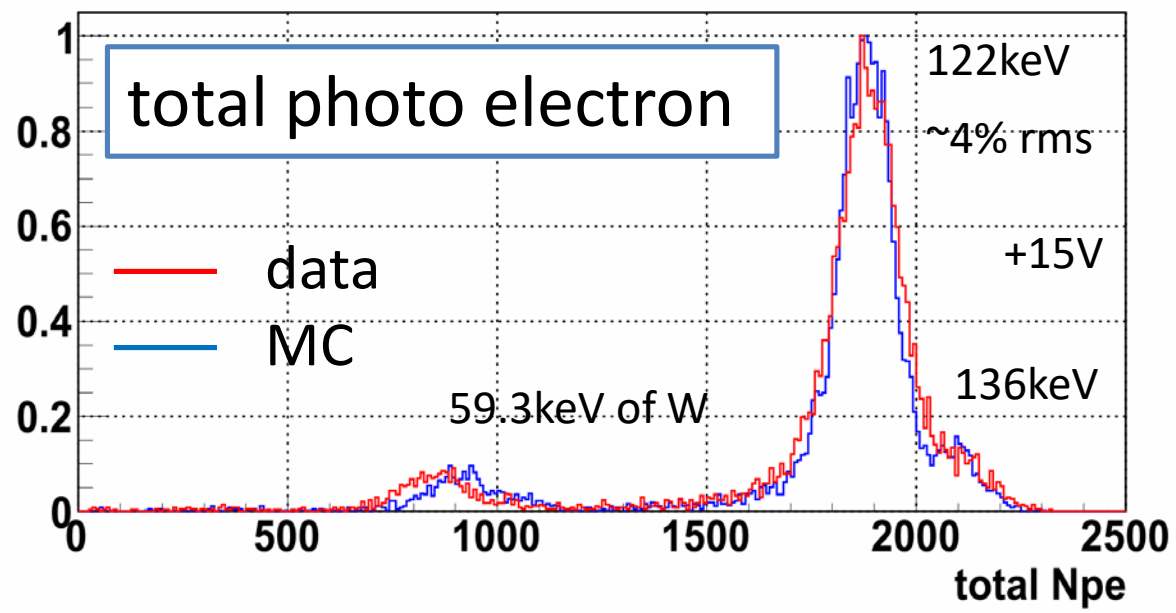
Source rod (Ti)

RI source is 1.8mm edge of pin

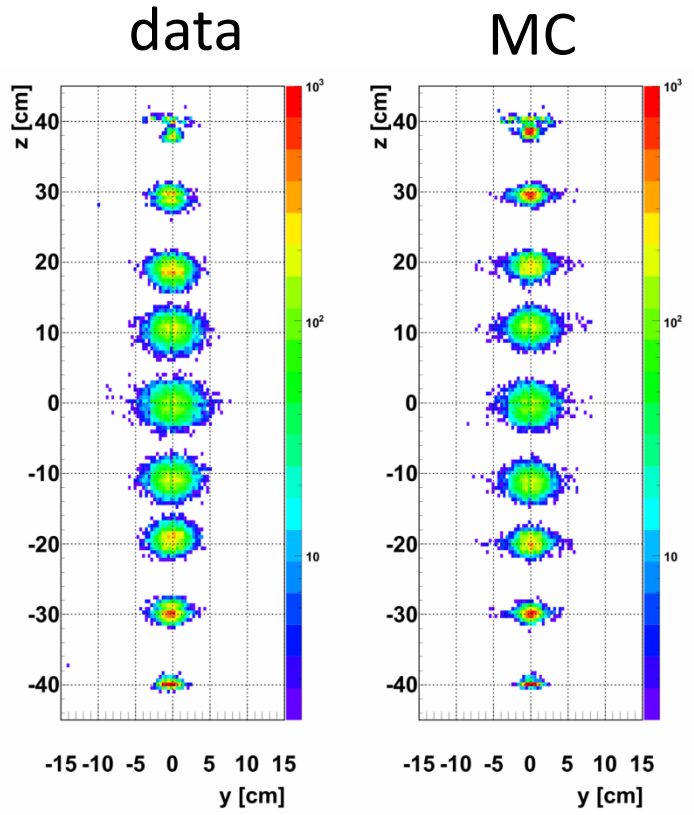
We also use outer calibration system using Co-60 for monitoring light yield.



Detector response for a point-like source



reconstructed vertex



- ^{57}Co source at center gives a typical response of the detector.
- ~14p.e./keV$_{ee}$
- The pe dist. well as vertex dist. were reproduced by a simulation well.

Search for WIMPs in the fiducial volume: event selection

1. Standard cut

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

2. Timing based vertex reconstruction R(T)

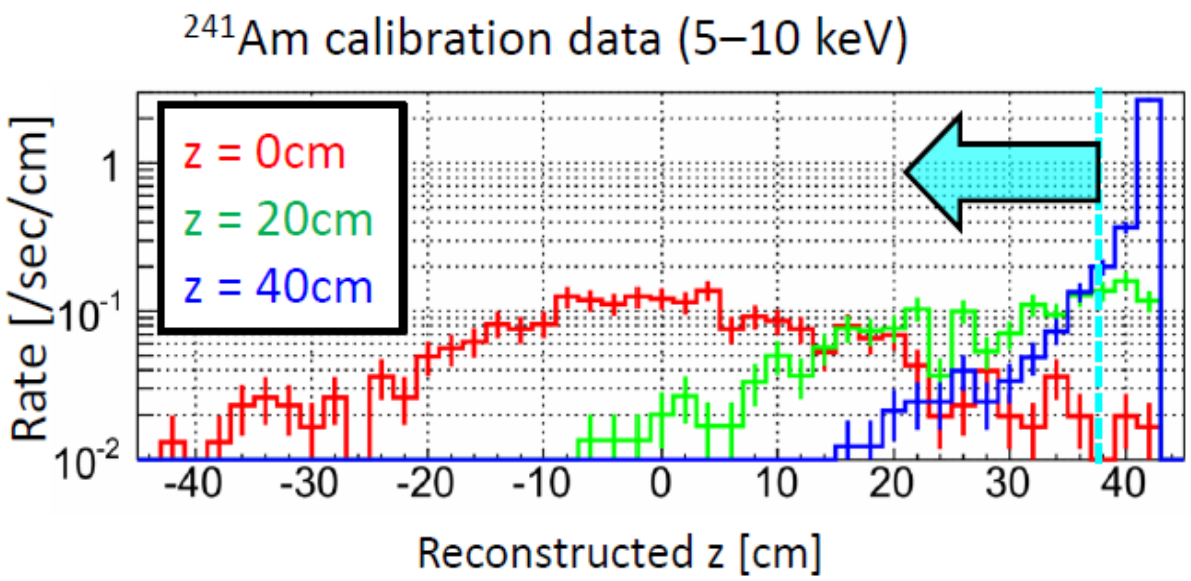
   First hit timing of each PMT is used. Position is fitted by likelihood. Events are selected if R(T)<38cm.

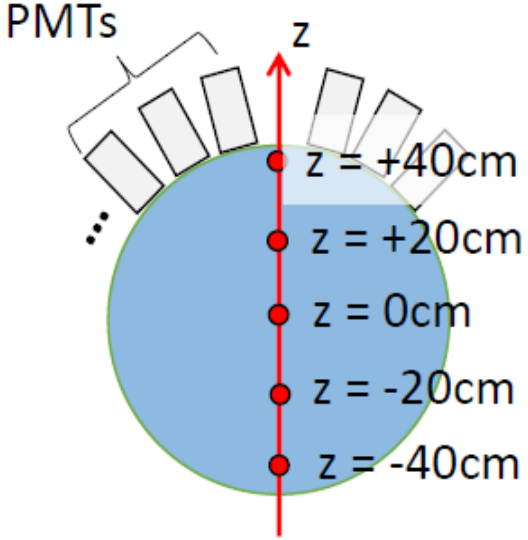
3. PE based vertex reconstruction R(PE)

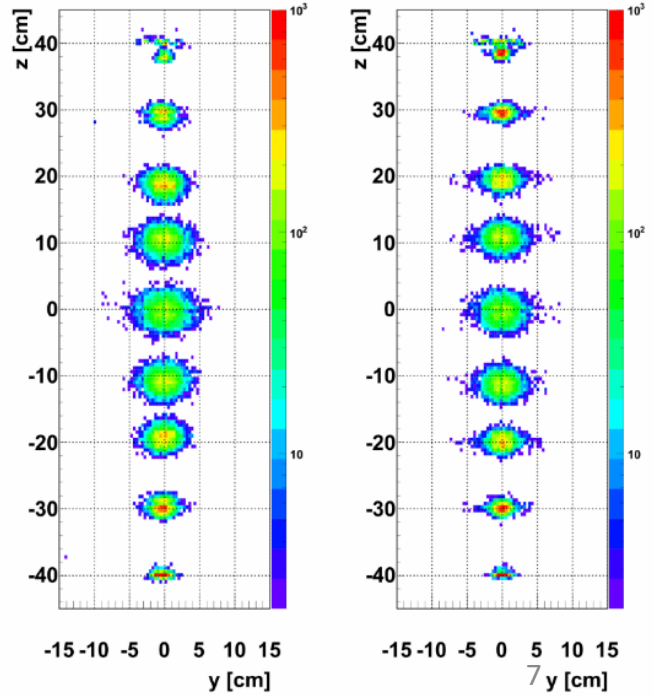
   PE map is made in each position using MC.

   Event vertex is calculated by likelihood.

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



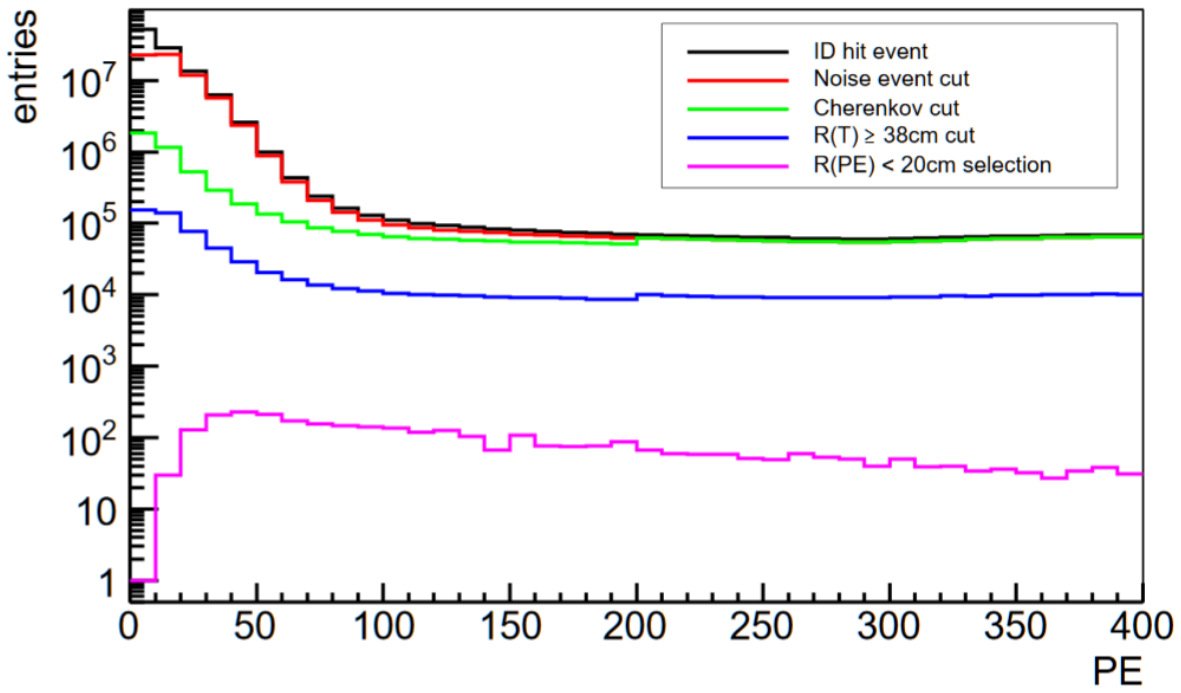




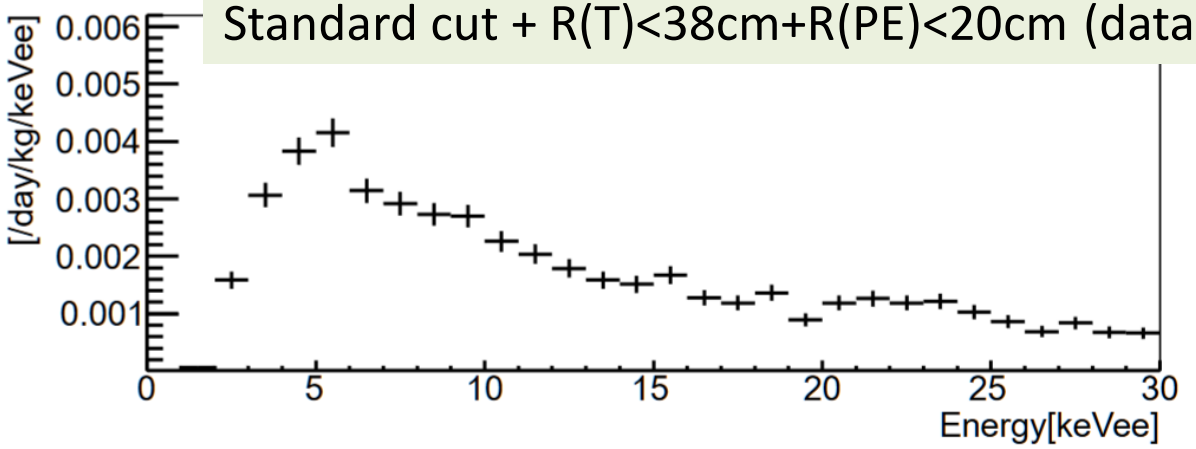
Search for WIMPs in the fiducial volume: data

- 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)



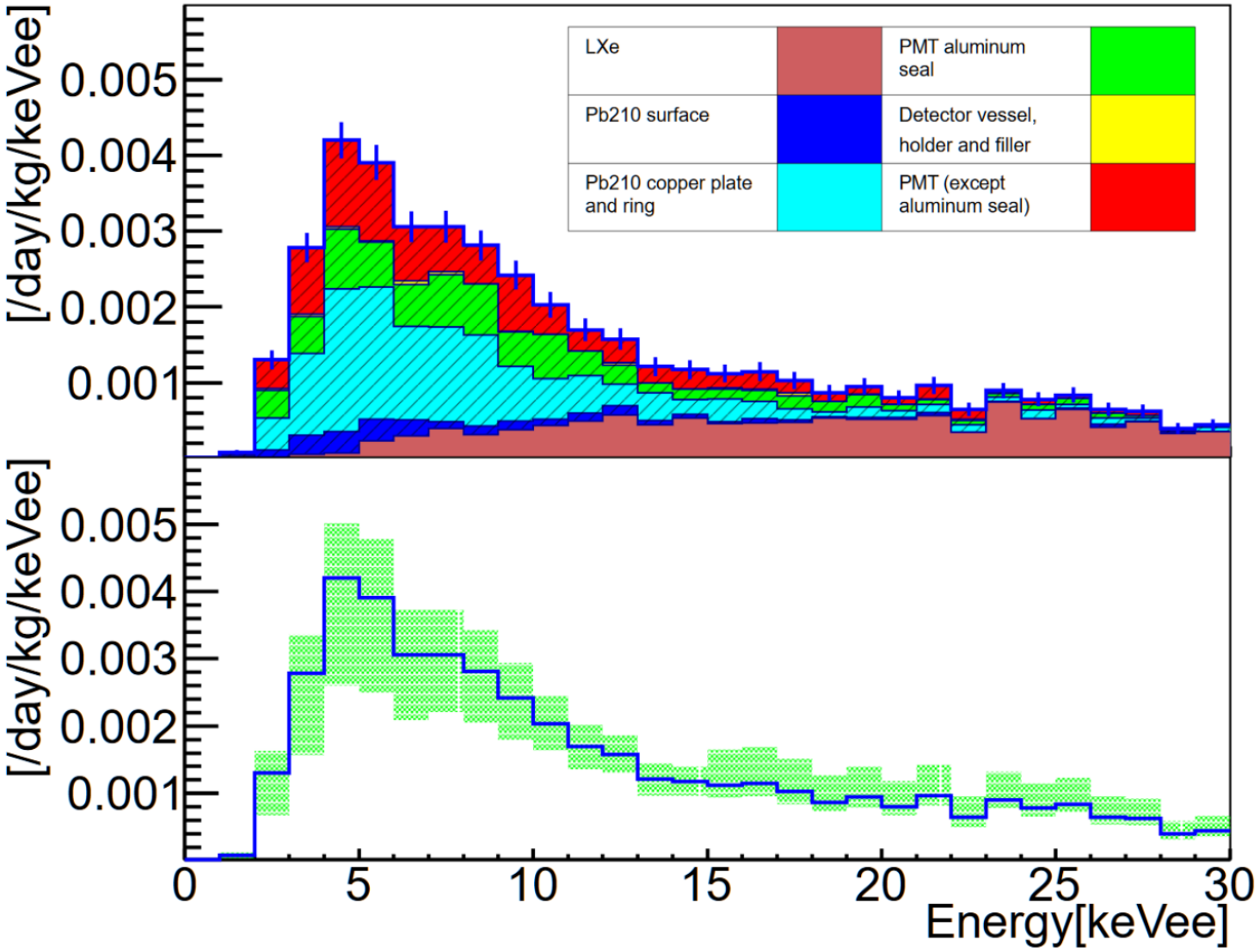
Standard cut + R(T)<38cm+R(PE)<20cm (data)



Search for WIMPs in the fiducial volume: background estimate

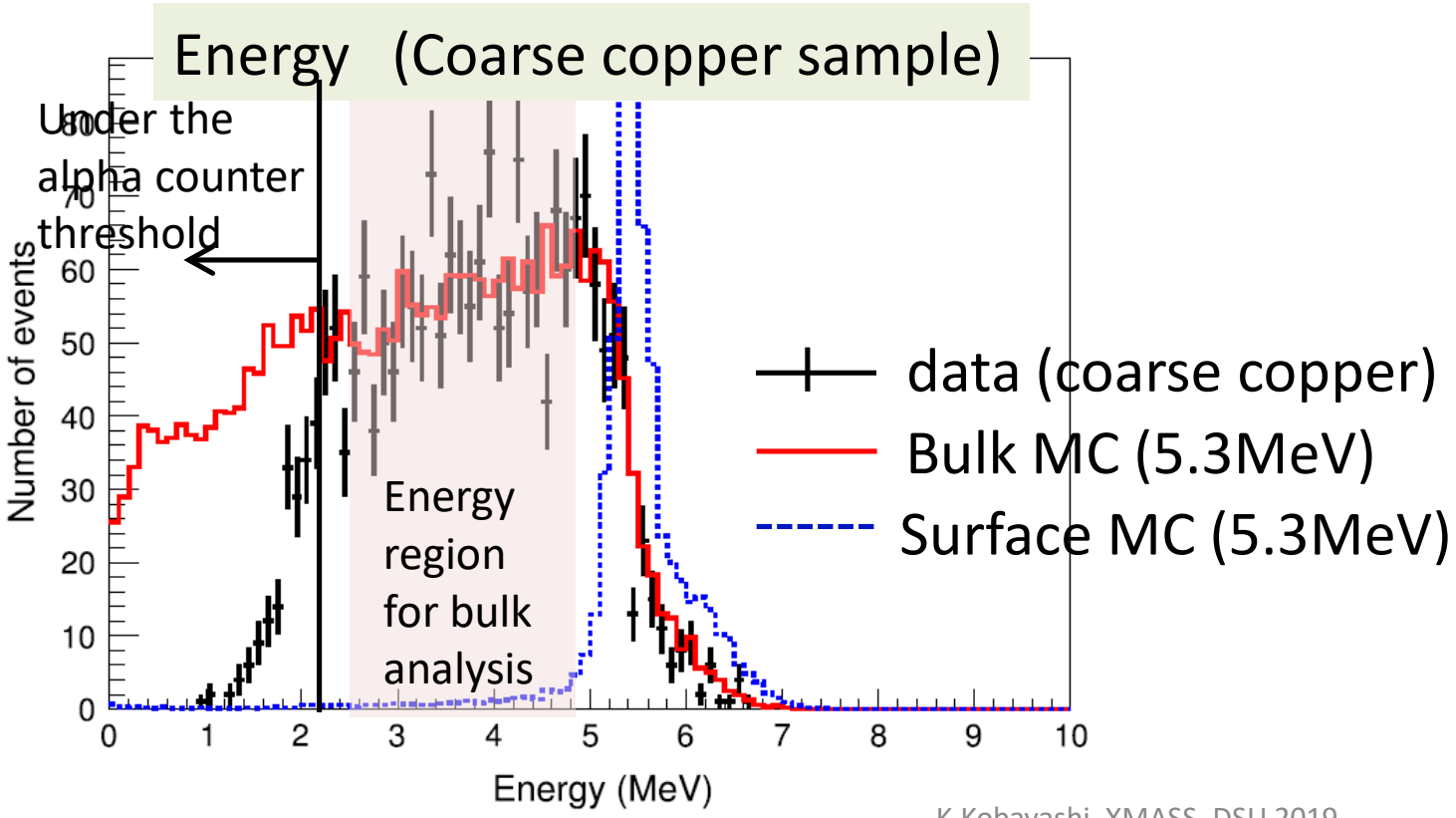
- Background MC is generated using XMASS MC for each RI's decay mode and its activity.
- Optical parameters of LXe are traced with our ^{57}Co57 and ^{60}Co regular calibration.
- Same event selection is applied to background MC, which has the same livetime as the dataset.
- ~90% of remaining BG is of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

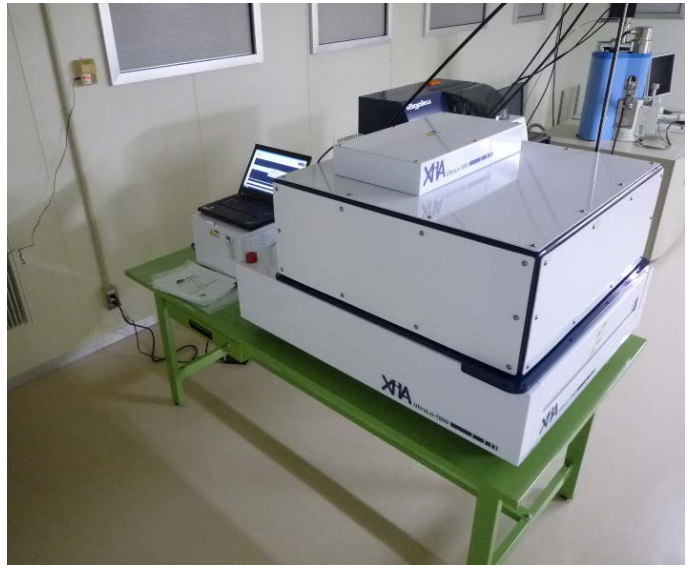
Standard cut + R(T)<38cm+R(PE)<20cm (MC)



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

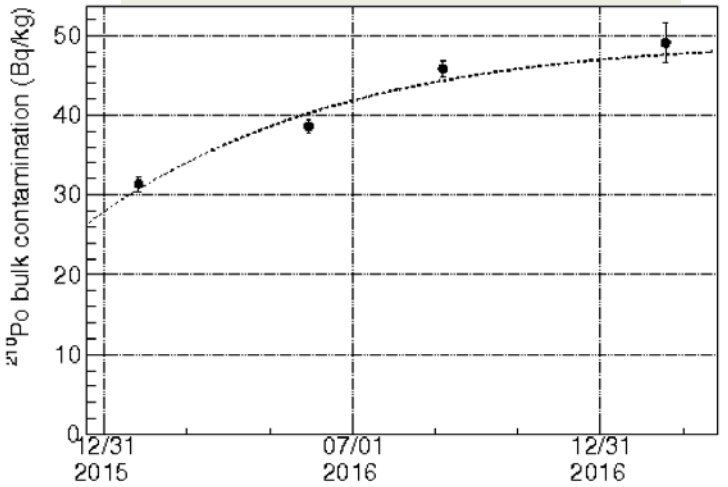
Not only the surface alpha events, but also bulk events can be observed! Sensitivity to ^{210}Pb is world best in screening (a few mBq/kg).





Low background alpha-counter XIA Ultra-Lo-1800

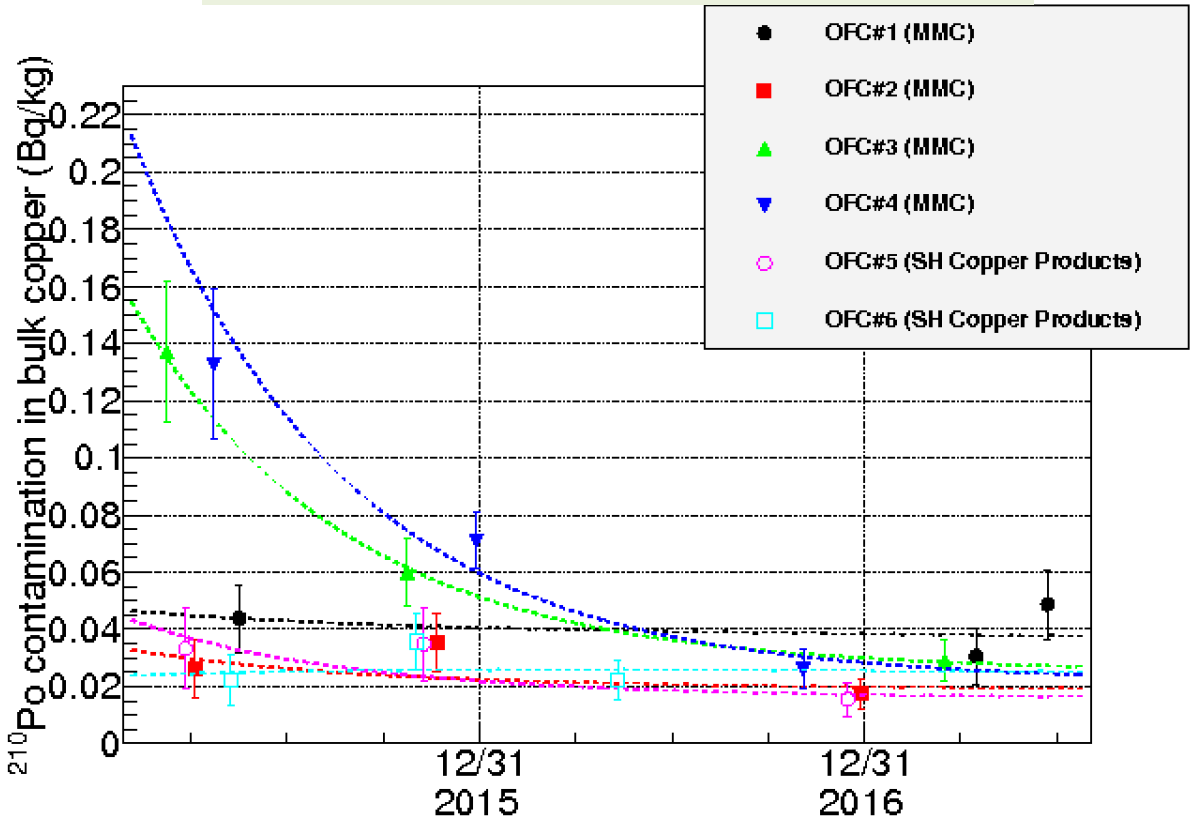
Time evolution (coarse copper)



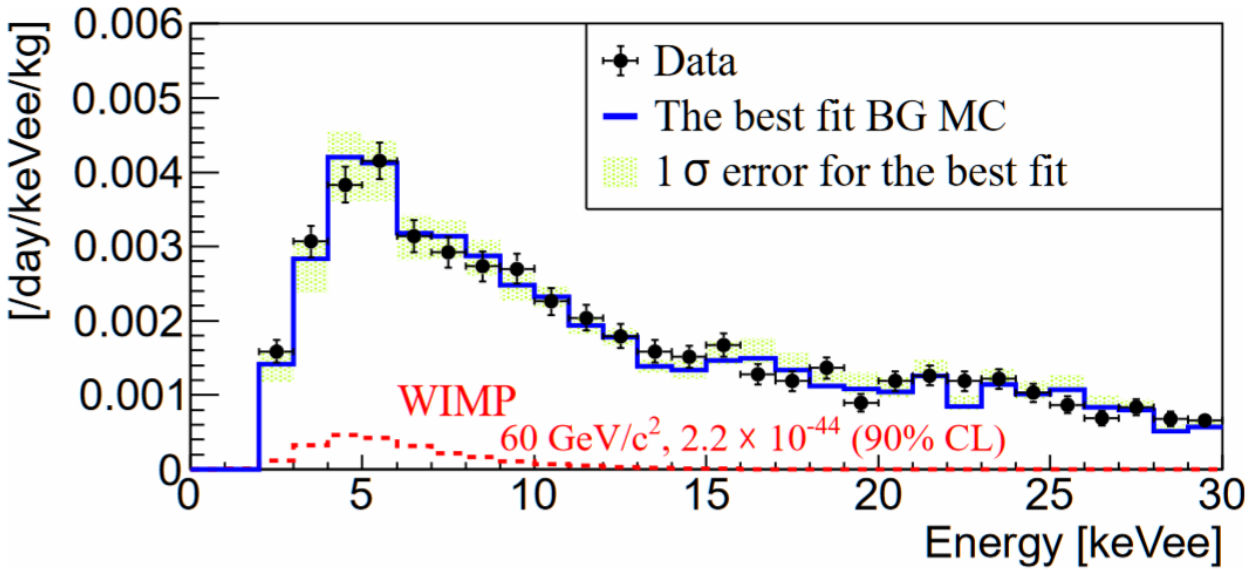
^{210}Pb in bulk oxygen free copper is measured for the first time

- 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 dominant background 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)

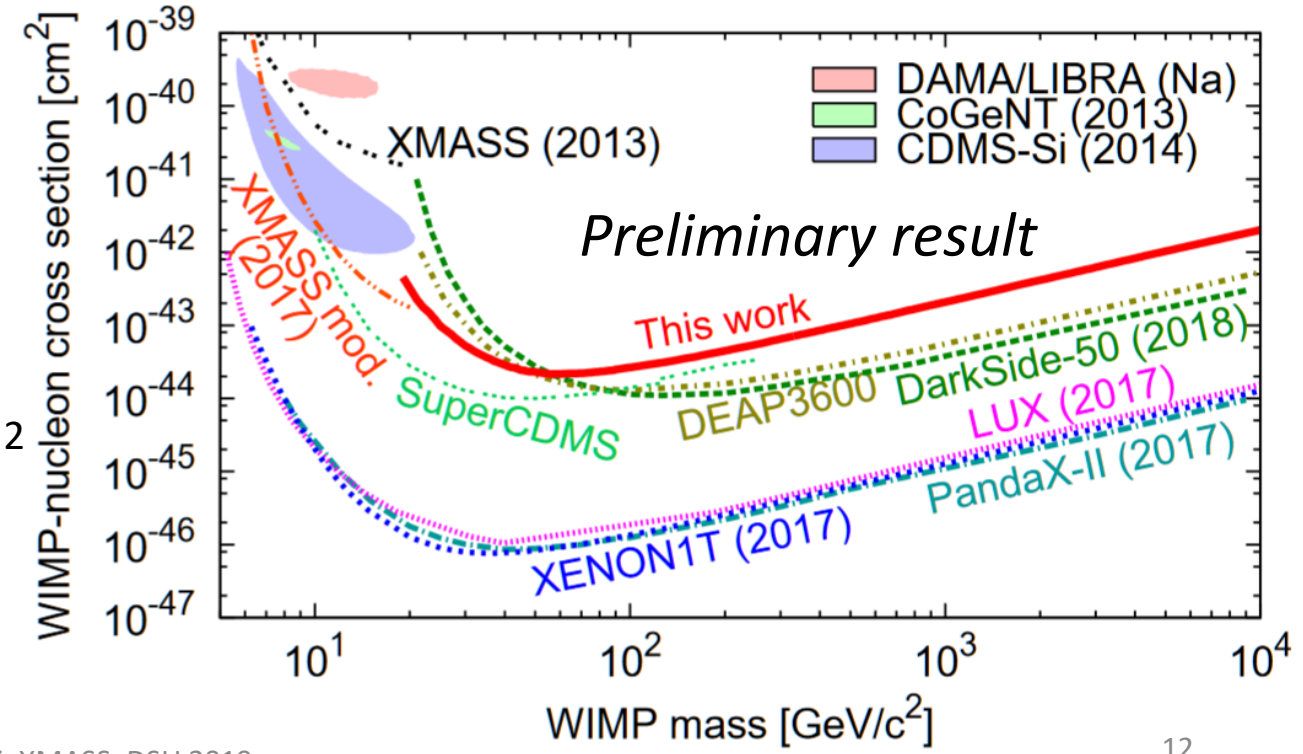


Search for WIMPs in the fiducial volume: result



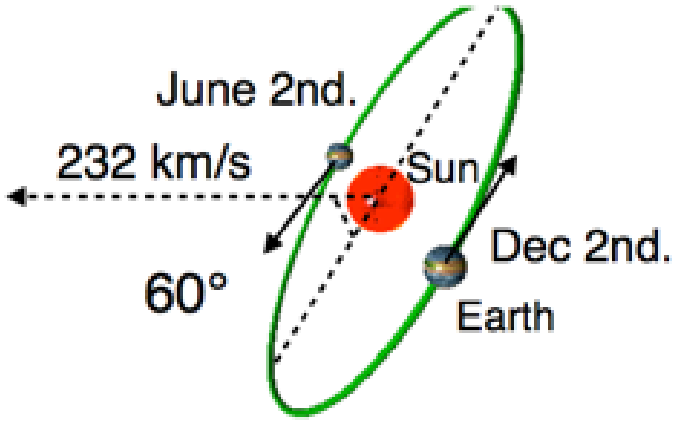
- Data is consistent with background expectation.
- The energy spectrum of the data was fitted with background MC plus WIMP MC in the energy range of 2-15keVee.
- Our exclusion limit at 90% CL is 2.2×10^{-44}cm^2 at 60GeV WIMPs mass.

PLB789 (2019) 45-53



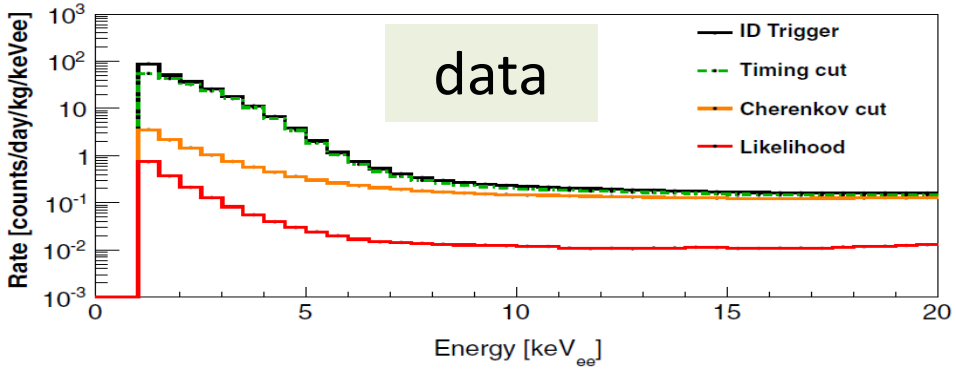
Annual modulation search

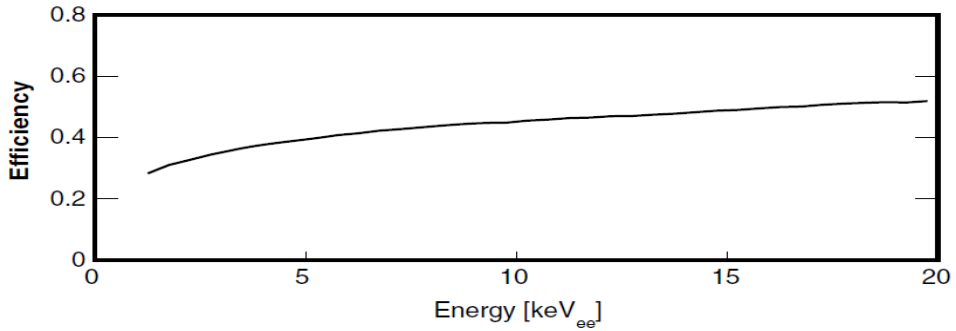
Dark matter event rate is expected to modulate annually due to relative motion of the Earth around the Sun. Annual modulation claimed by DAMA/LIBRA phase1+phase2 with 11.9σ significance (1.04+1.13 ton・year, 13 cycles).



Search in XMASS (PRD97 (2018) 102006)

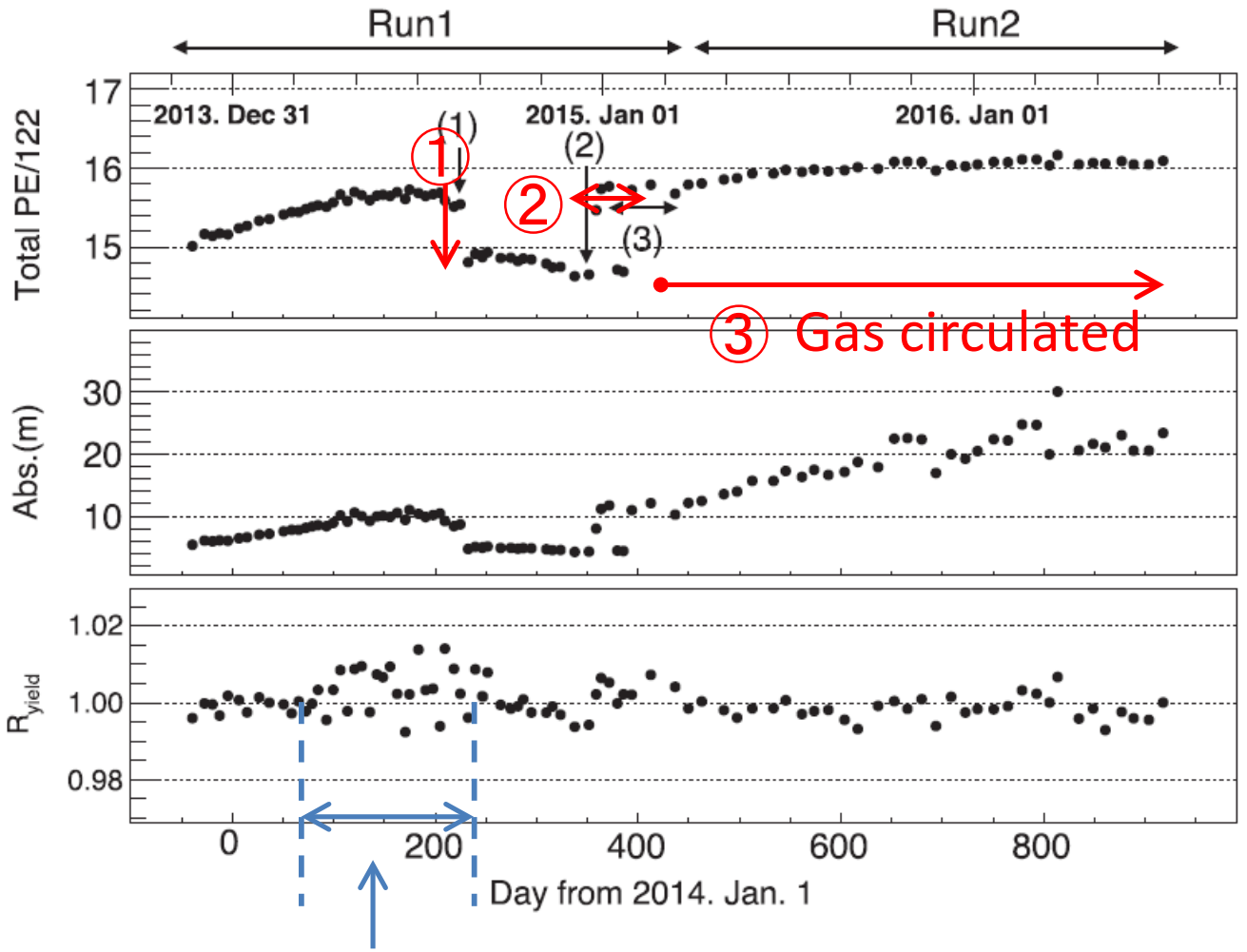
- >2year cycle data (1.82ton・year) with low threshold (1.0keVee, =4.8keVnr)
- No particle ID (just like DAMA/LIBRA)





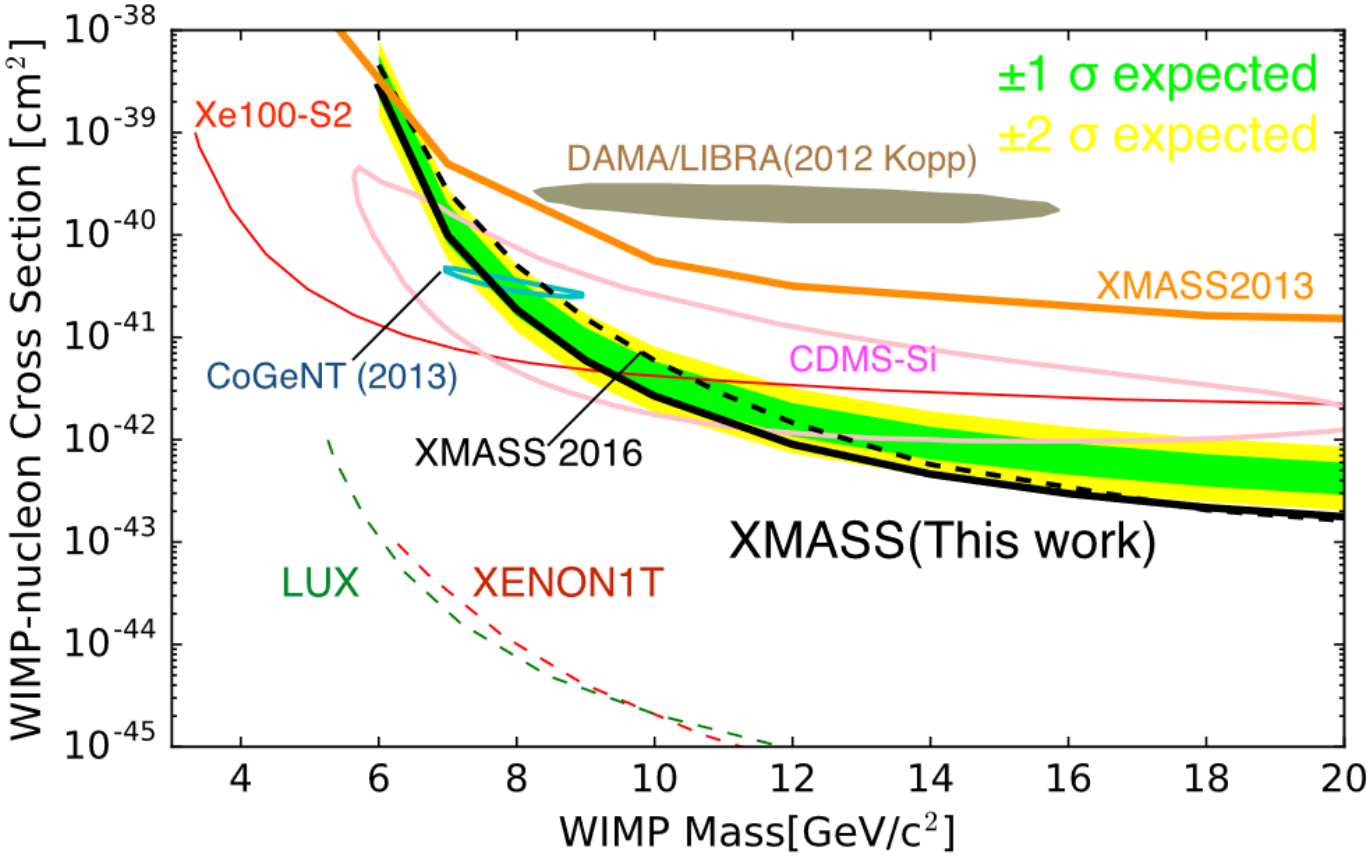
Detector stability

- 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



PRD97, 102006 (2018)

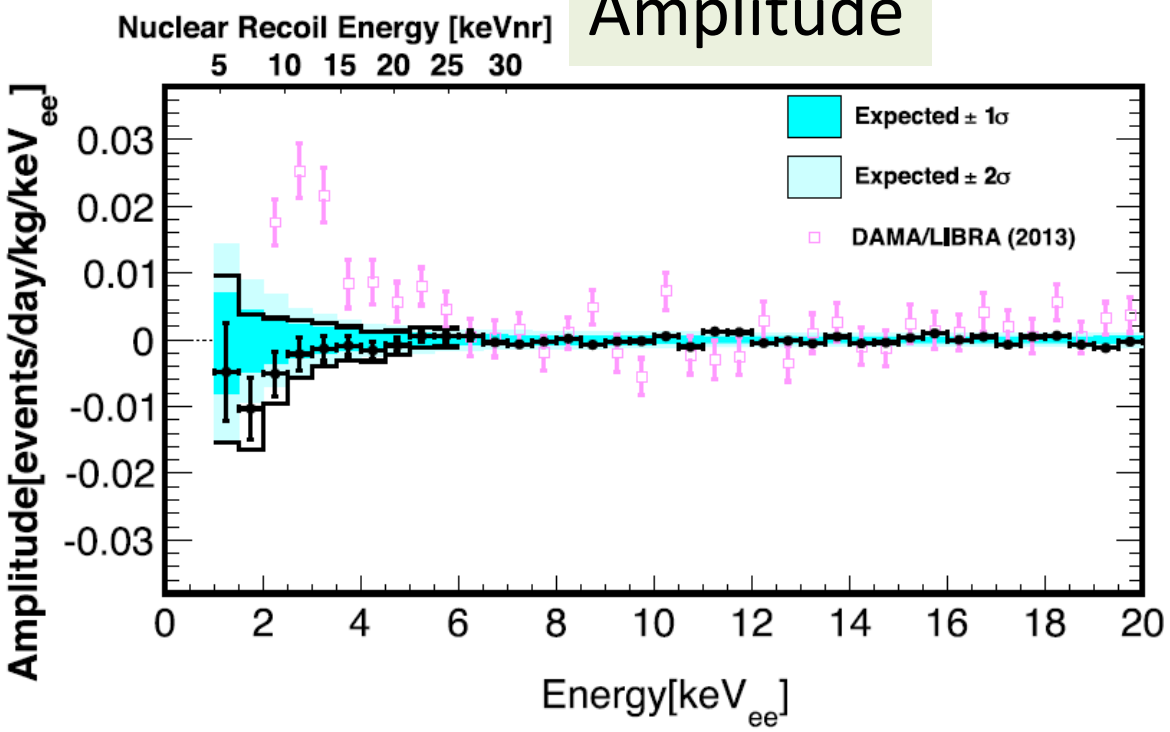
- Leff uncertainty is taken into account.
- DAMA/LIBRA region is excluded by our measurement.

Model assumption

T:1year, t_0=152.5day (fixed)
V_0: 232.0 km/s
V_{esc}: 544 km/s
ρ_{dm}: 0.3 GeV/cm^3
Lewin, Smith (1996)

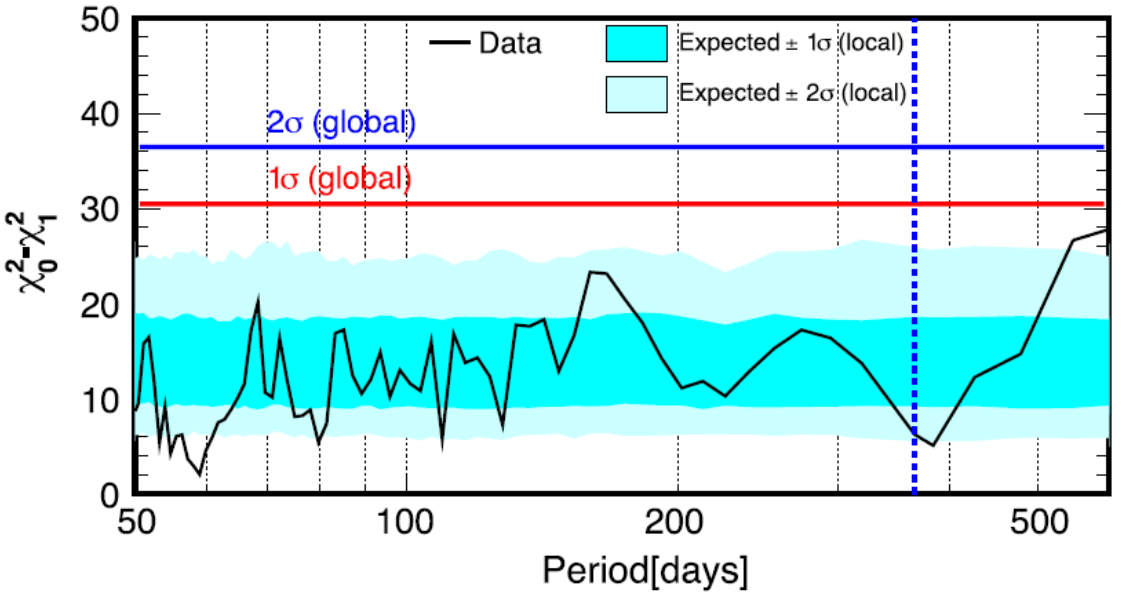
Model independent results of annual modulation search

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.

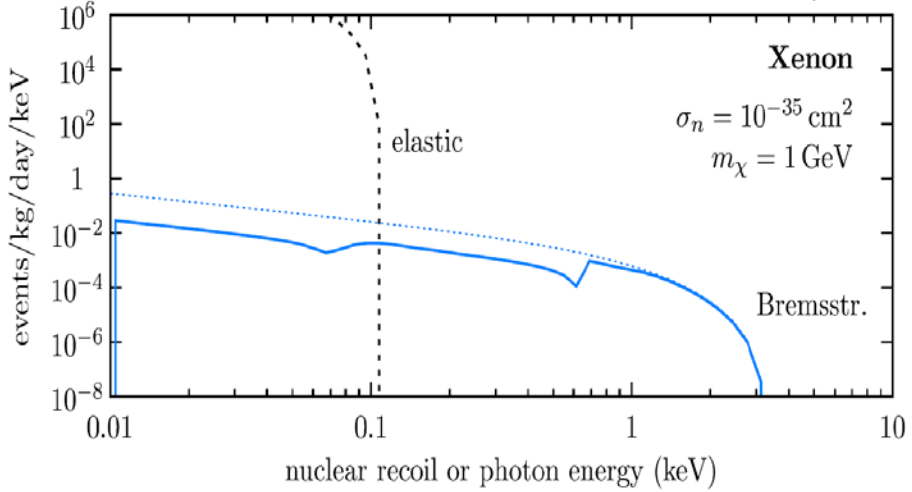
Search for sub-GeV dark matter: motivation

It is difficult to search for WIMP with m<4GeV when we use scintillation light from recoiled nucleon.
-> new approach to search for WIMP with m<4GeV

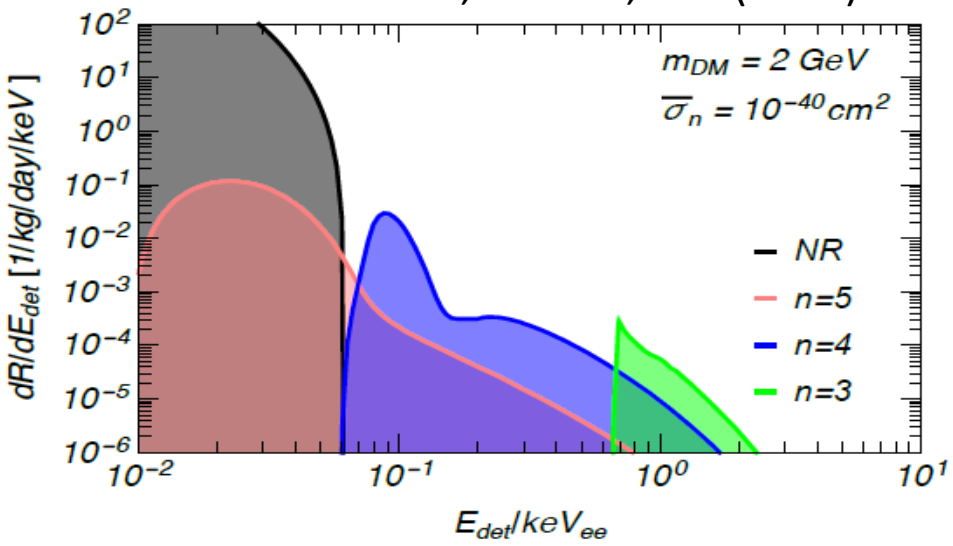
- Bremsstrahlung photon (PRL 118, 031803 (2017))
  - C. Kouvaris and J. Pradler, PRL 118, 031803 (2017)
- Electron by Migdal effect (JHEP03, 194 (2018))
  - M. Ibe et al., JHEP03, 194 (2018)

-> At this moment, XMASS use this Bremsstrahlung photon.

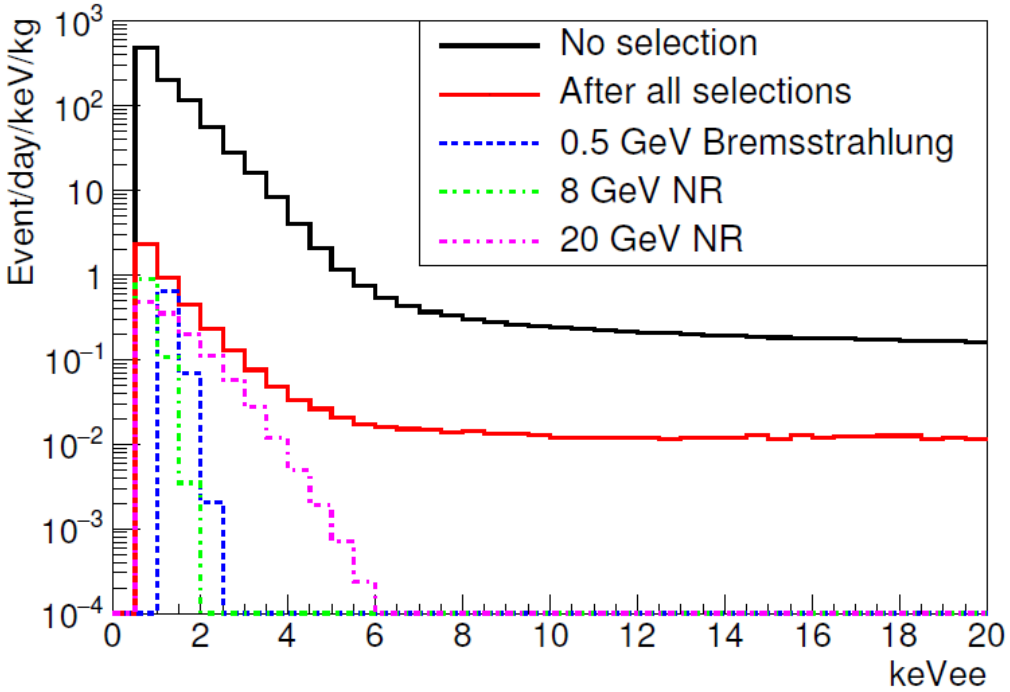
C. Kouvaris & J. Pradler, PRL 118, 031803 (2017)

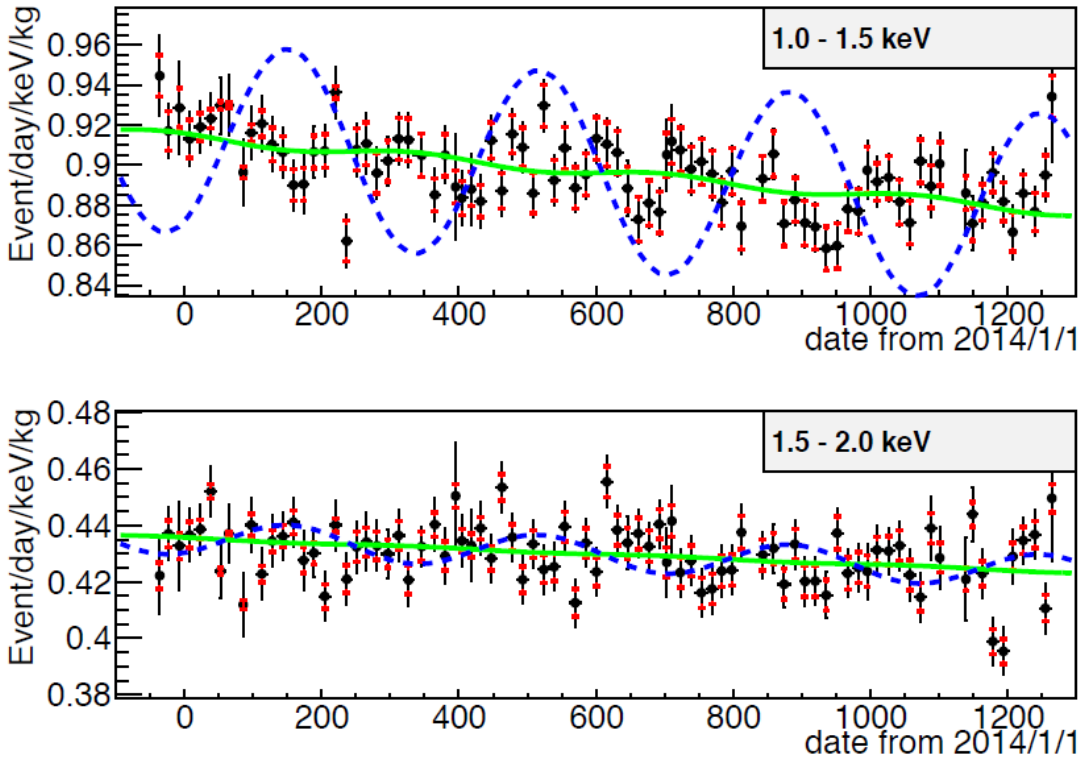


M. Ibe et al., JHEP03, 194 (2018)



Search for sub-GeV dark matter: method





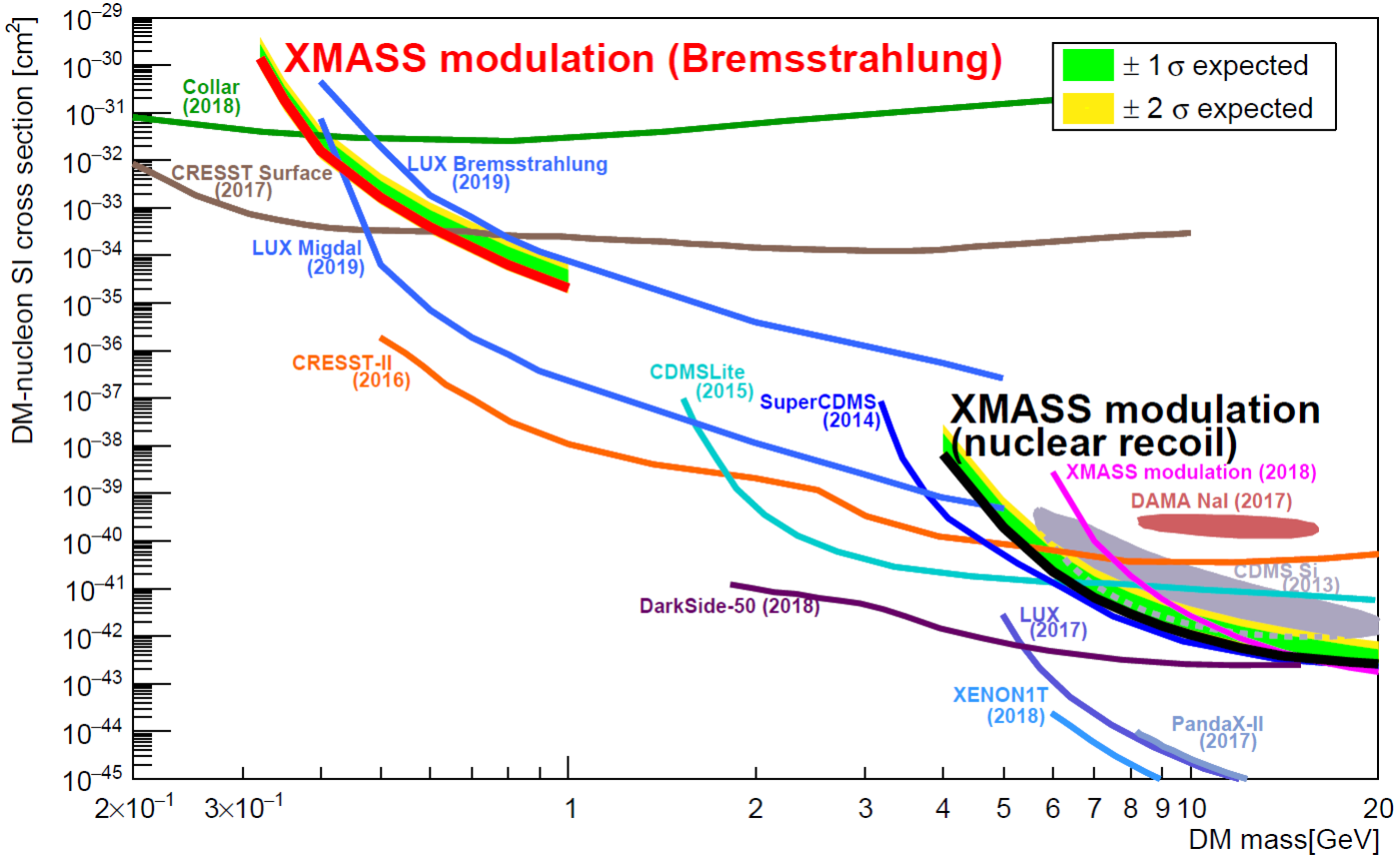
+ Data

-- Best fit time variation

-- Expected time variation (σ=3x10^{-32} cm^2)

- Search for annual modulation signal using 2.8year data (3.5 calendar year)
- E>1keVee region is used.

Search for sub-GeV dark matter: result



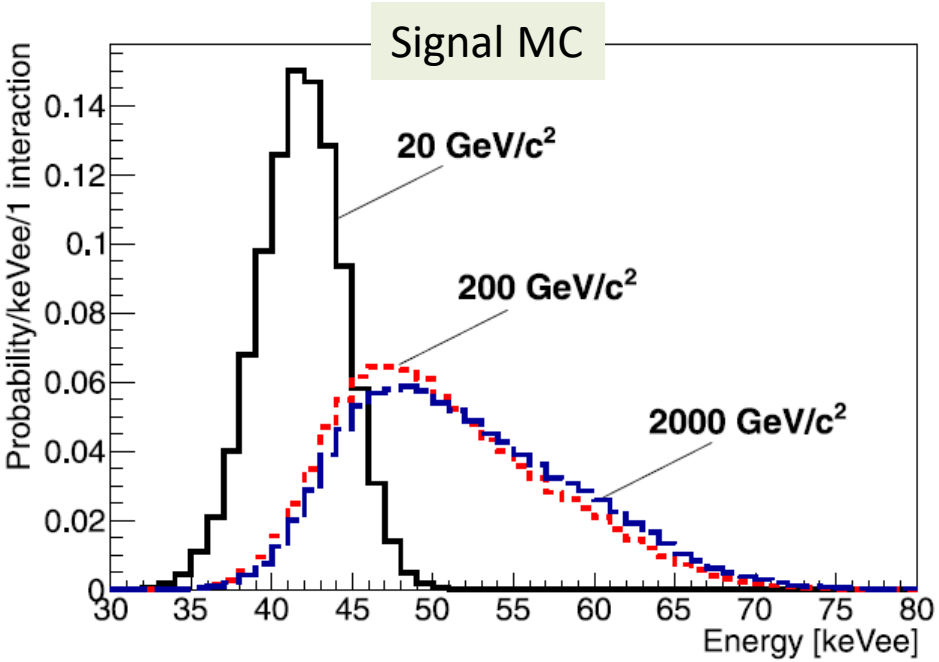
- First search for bremsstrahlung photon emission
- Limit on $\sigma<1.6\times10^{-39}$ cm^2 (for 0.5 GeV/c^2).
- Multi-GeV region is also searched for using lower threshold. Limit on $\sigma<2.9\times10^{-42}$ cm^2 (for 8 GeV/c^2)

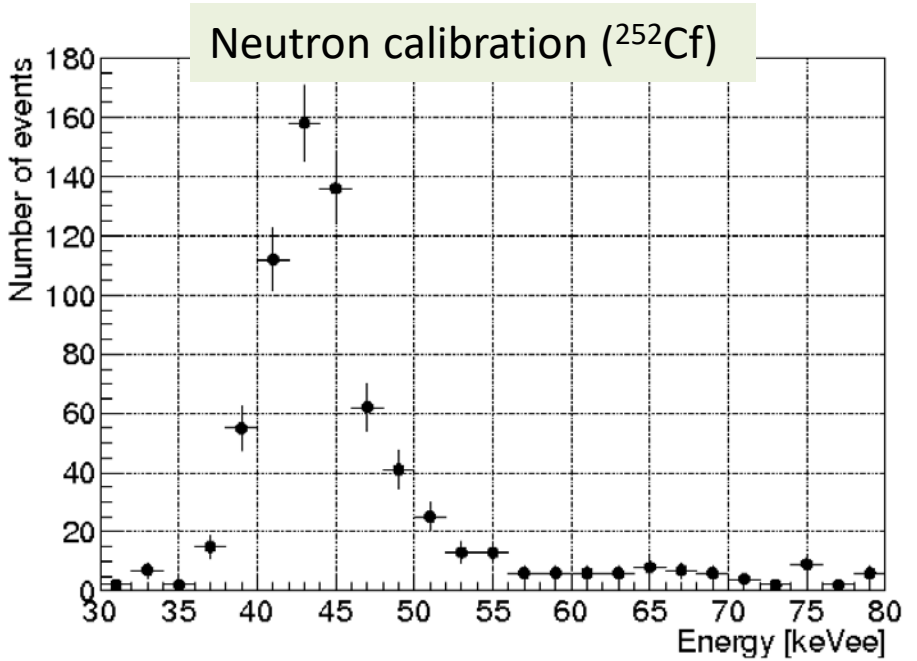
PLB 795 (2019) 308-313

Search for WIMP-^{129}Xe Inelastic scattering: motivation

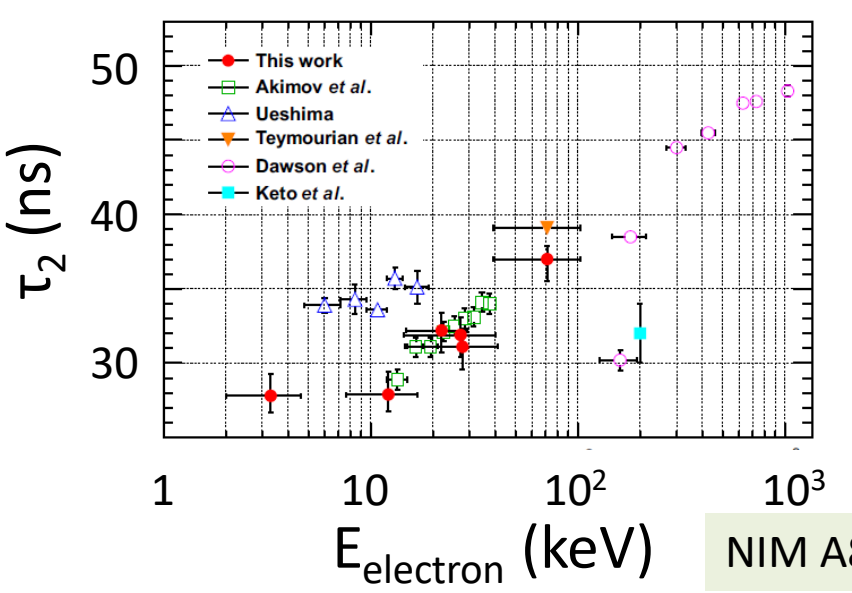
- WIMP-^{129}Xe Inelastic scattering would be direct evidence of spin dependent interaction mechanism (cf. natural abundance of ^{129}Xe: 26%).
- WIMP-^{129}Xe Inelastic scattering signal is nuclear recoil + 39.6keV gamma-ray from nuclear excitation.
  - $\chi + {}^{129}\mathrm{Xe} \rightarrow \chi + {}^{129}\mathrm{Xe}^*$

    ${}^{129}\mathrm{Xe}^* \rightarrow {}^{129}\mathrm{Xe} + \gamma$ (39.6keV)

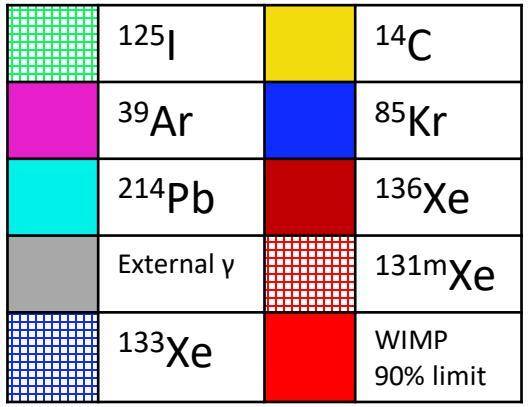


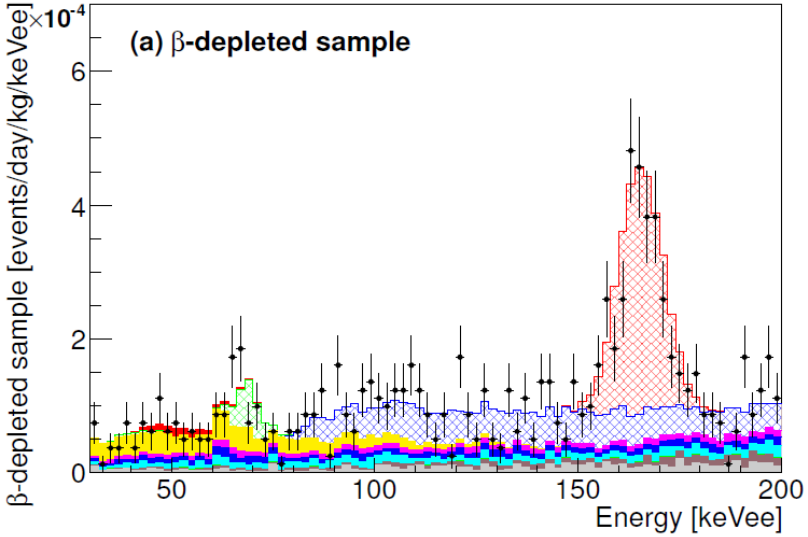


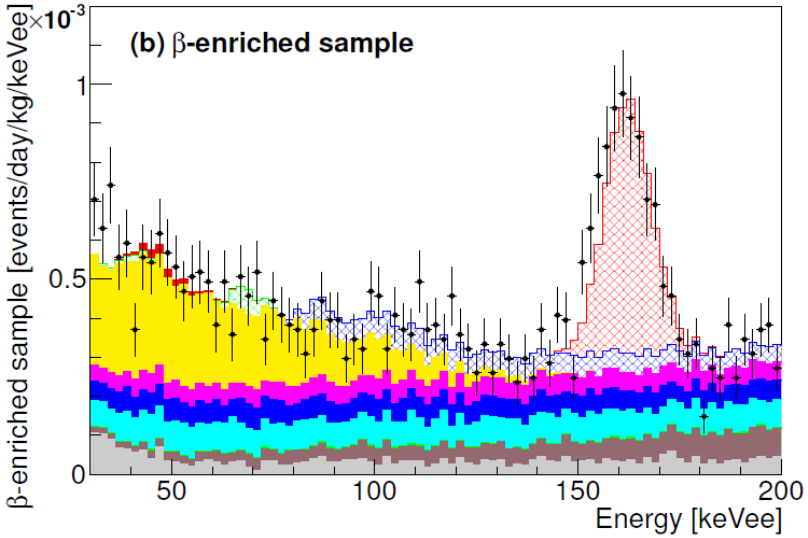
Search for WIMP-^{129}Xe Inelastic scattering: method



NIM A834 (2016) 192



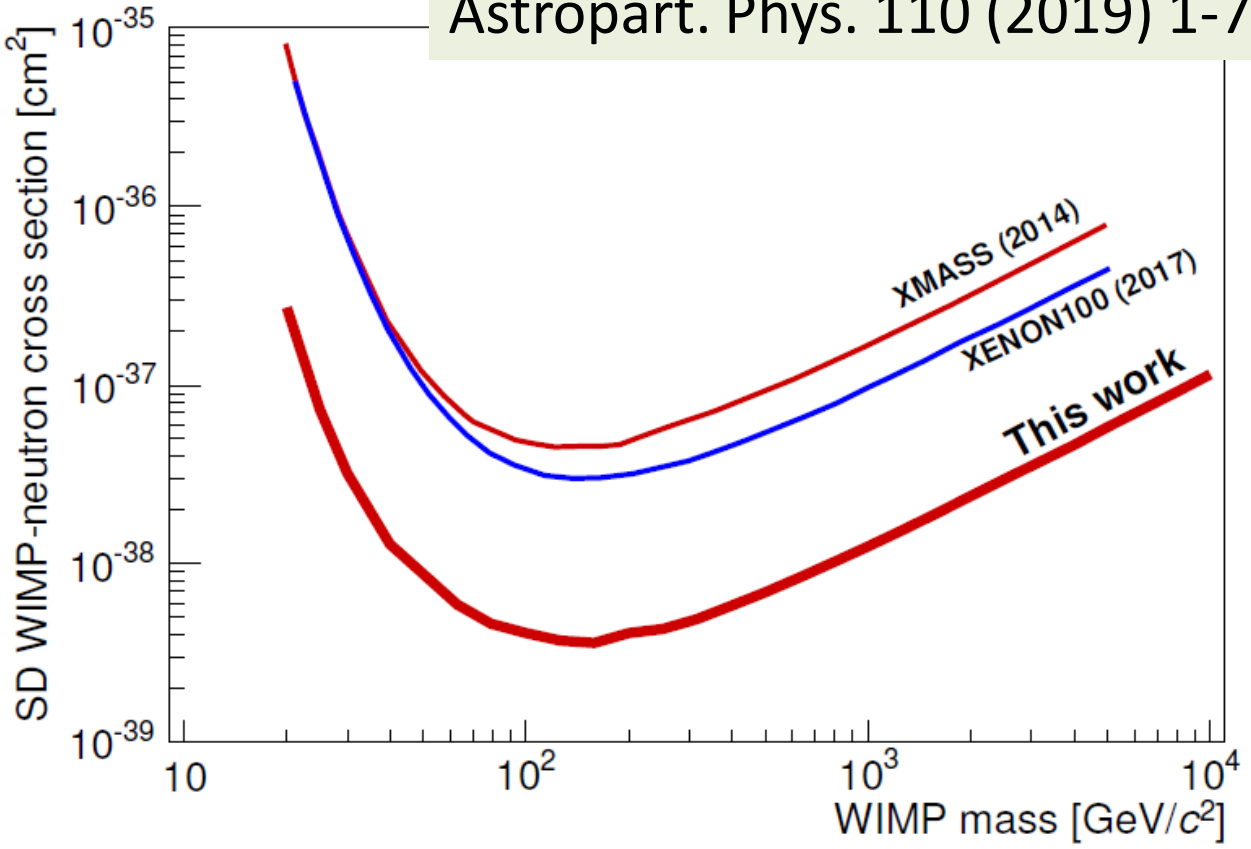




- In addition to standard cut, β-ray/γ-ray particle ID using scintillation decay time profile is used to reduce background.
- Because both γ-ray and ^{129}Xe decay times are shorter than β-ray when the scintillation light yields are same, β-ray background can be removed. S/N ratio improves by factor 5.
- β-depleted/enriched sample are used to fit background and the signal is searched for.

Search for WIMP-^{129}Xe Inelastic scattering: result

Astropart. Phys. 110 (2019) 1-7



- 800days data x 327kg are used (x48 larger exposure than XMASS (2014)).
- No significant signals are found.
- Limit on $\sigma<4.1\times10^{-39}$ cm^2 for 200 GeV/c^2.
- This is most stringent limit in the SD inelastic search.

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:

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

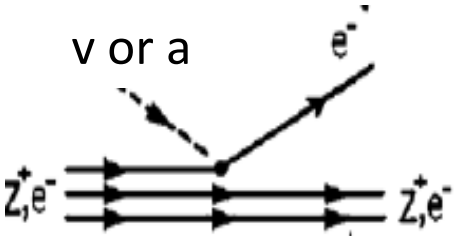
(A: atomic mass, standard local matter density: 0.3GeV/cm^3)

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.)

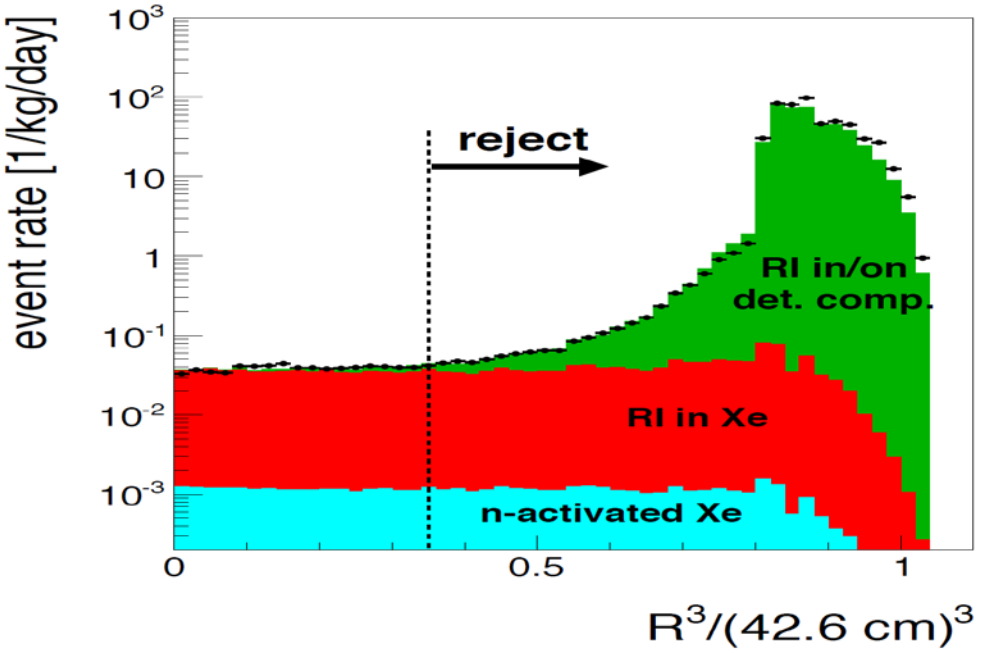
- The counting rate in the detector is:

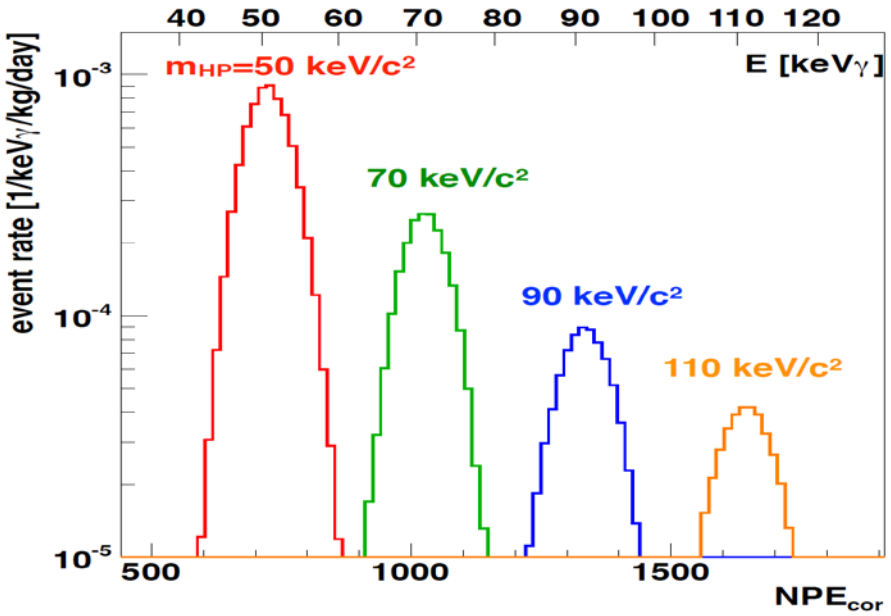
$$S_a \approx \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{\mathrm{photo}}}{\mathrm{barn}}\right) \mathrm{kg}^{-1}\,\mathrm{day}^{-1}$$

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

Hidden photon and axion-like particle search: method

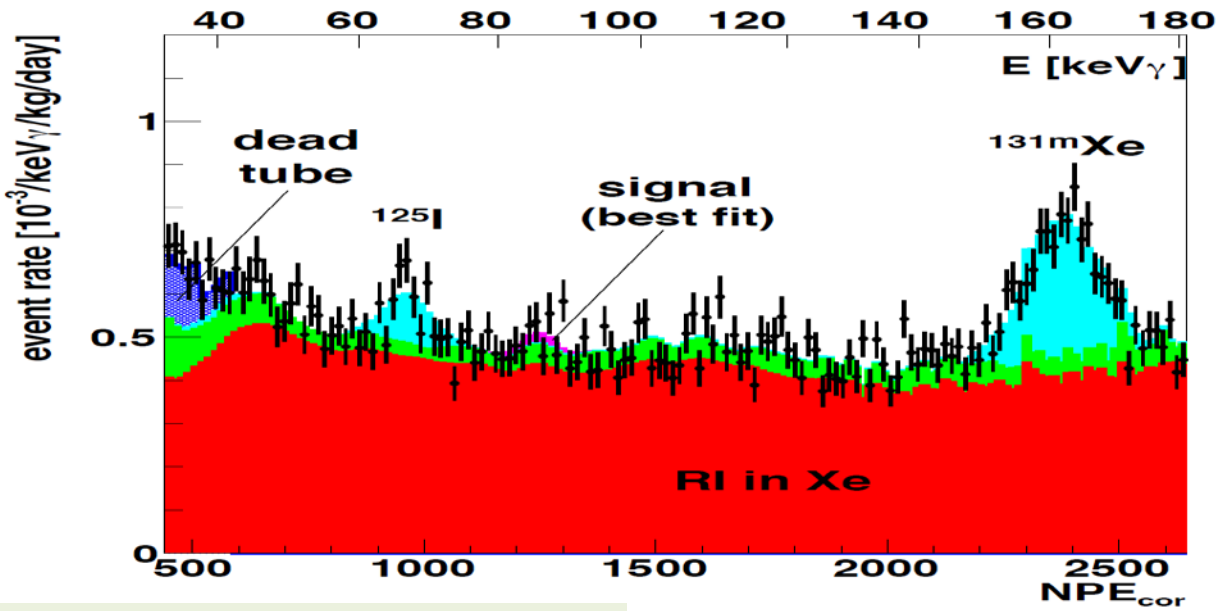
- Dataset: Nov. 2013 – Jul. 2016 (livetime 800days)
- Selection criteria: standard cut + fiducial volume cut (R<30cm) (327kg FV)
- Peak is expected in the NPE distribution.



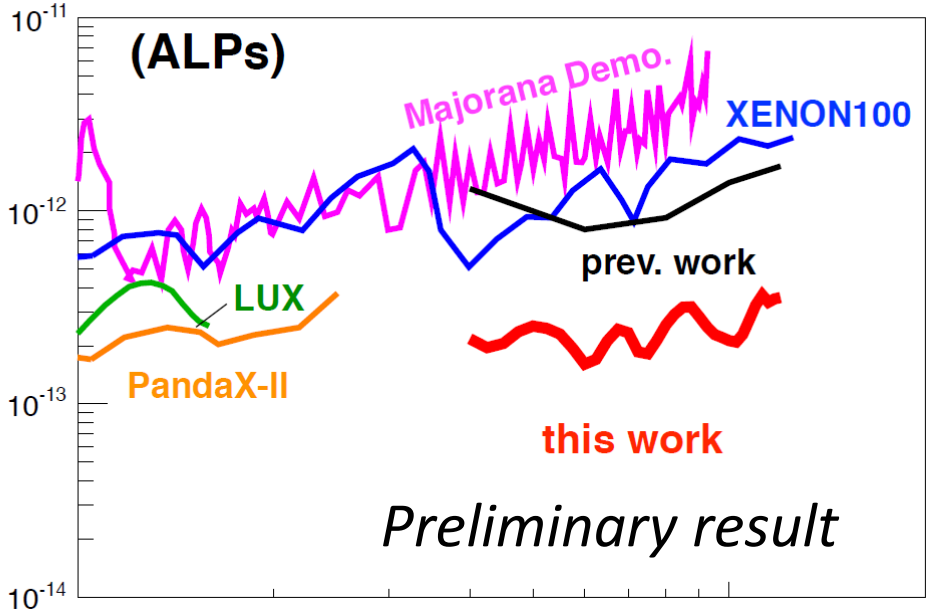


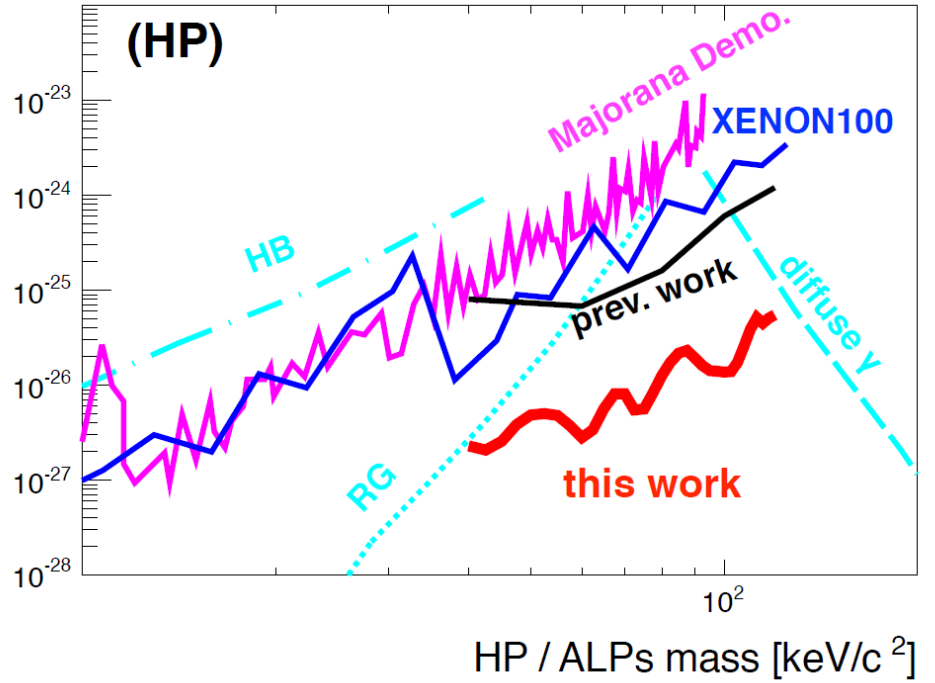
Hidden photon and axion-like particle search: result

- 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.



PLB787 (2018) 153-158.





summary

- XMASS has taken data for >5years with 832kg liquid xenon at Kamioka underground.
- We have been searched for various kinds of dark matter:
  - Standard WIMP (Phys. Lett. B789 (2019) 45-53)
  - WIMP-Xe inelastic scattering (Astropart. Phys. 110 (2019) 1-7)
  - Low mass WIMP with annual modulation (Phys. Rev. D97 (2018) 102006)
  - Sub-GeV dark matter via bremsstrahlung (Phys. Lett. B795 (2019) 308-313)
  - Hidden photon and axion like particles (Phys. Lett. B787 (2018) 153-158)
- We also have been studied other topics:
  - Solar KK-axion search (PTEP (2017) 103C01)
  - ^{124}Xe 2ν double electron capture (PTEP (2018) 053D03)
- Data taking has been completed in February 2019. Various kind of dark matter candidates /physics topics has been searched for! We also continue to study various kinds of physics using XMASS data.

backup

XMASS collaboration

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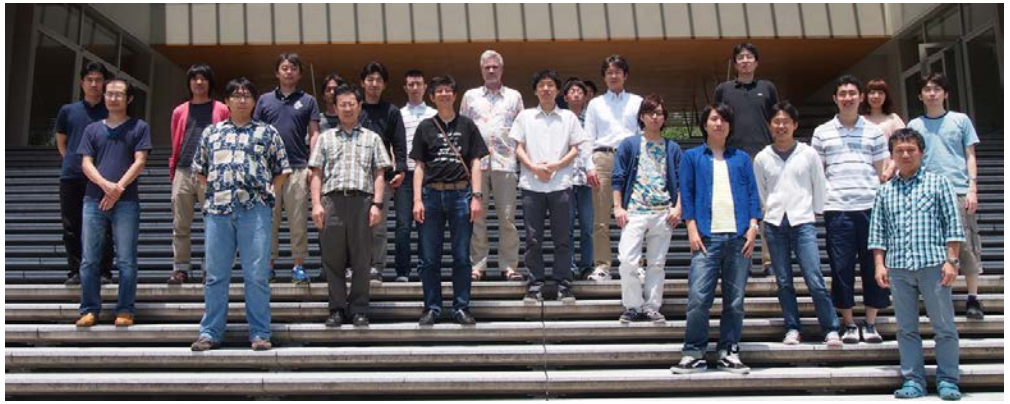

11 institutes, 36 collaborators

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%