WIMP search from XMASS-I fiducial volume data with background prediction

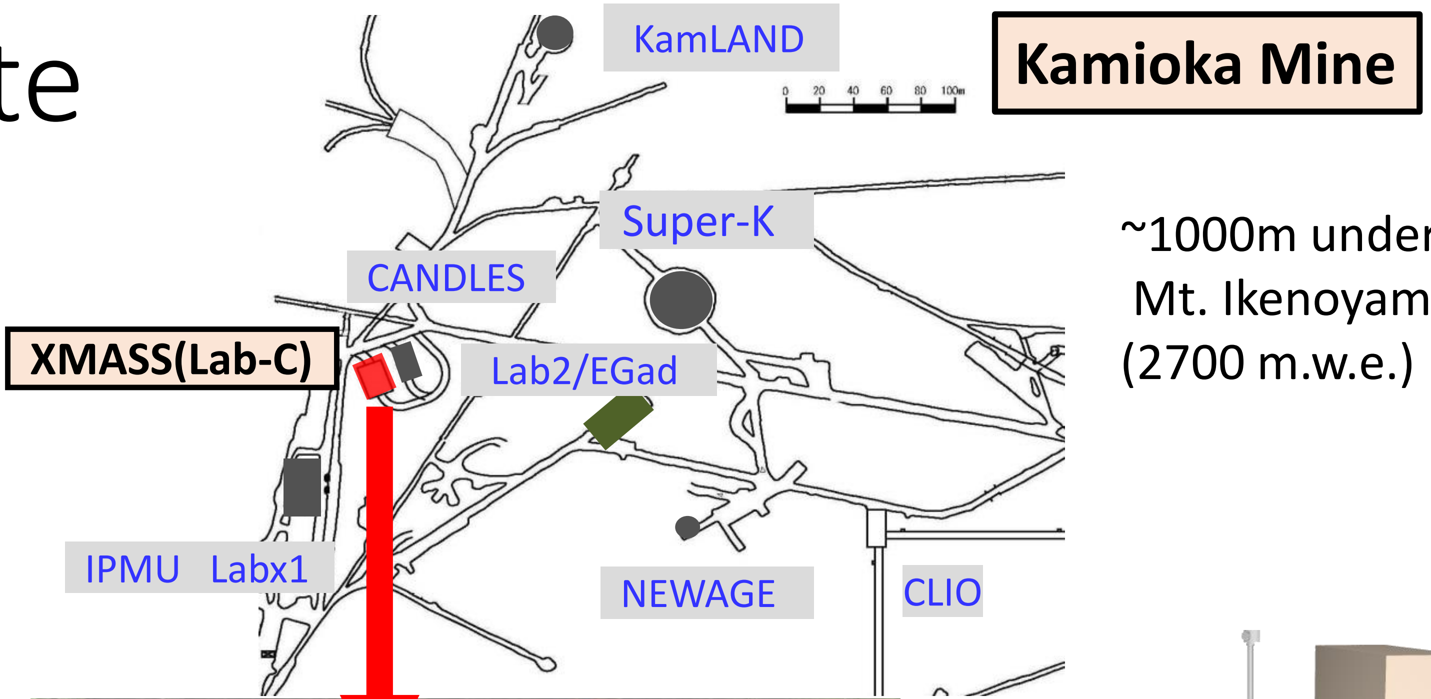
15th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2017)
Jul. 24–28, 2017,
Sudbury, ON, Canada

26th of Jul. 2017 (14:45–15:00)

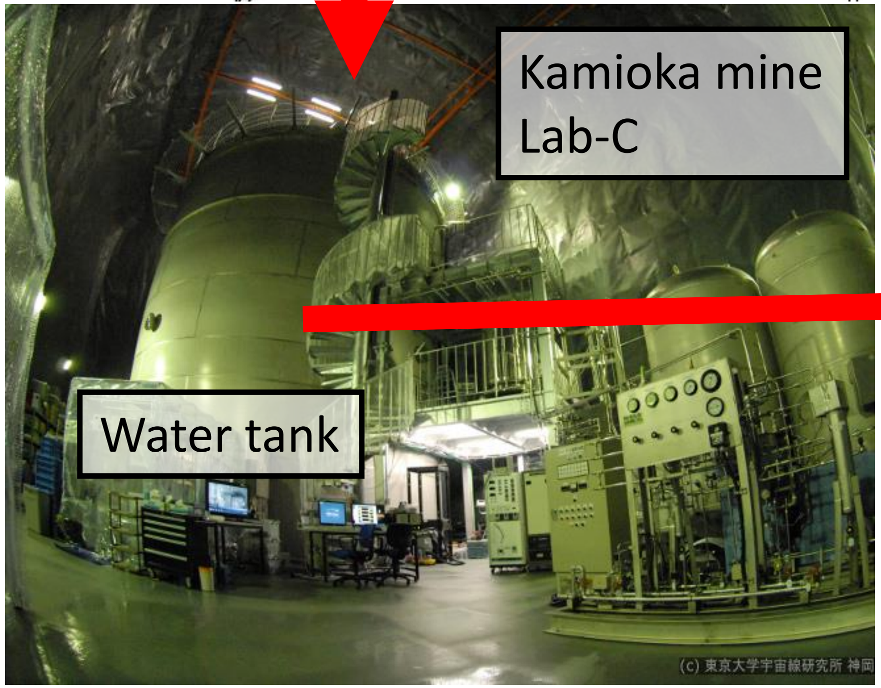
A. Takeda for the XMASS Collaboration

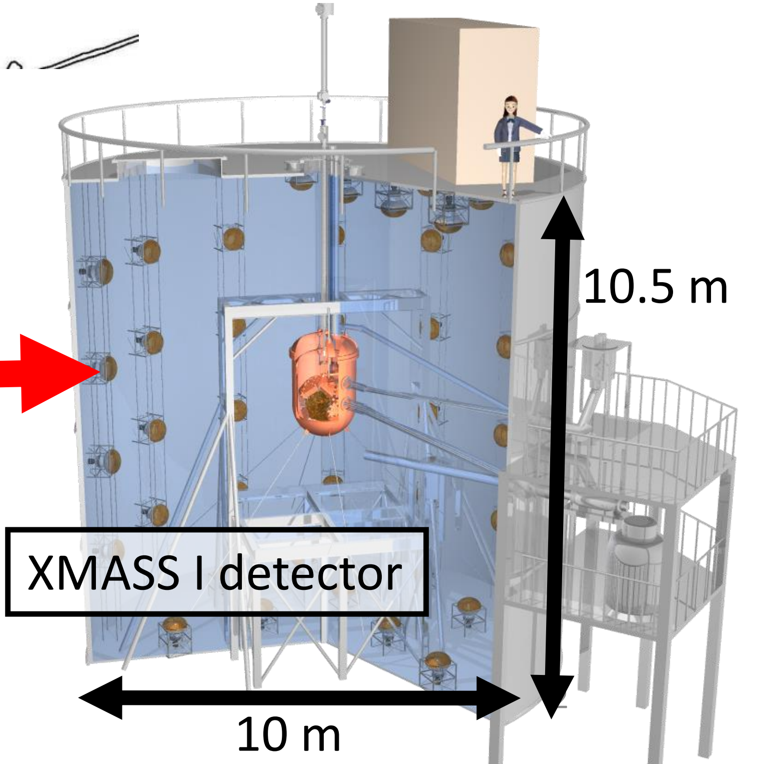
Dark Matter Search

Experimental site



~1000m underneath
Mt. Ikenoyama.
(2700 m.w.e.)

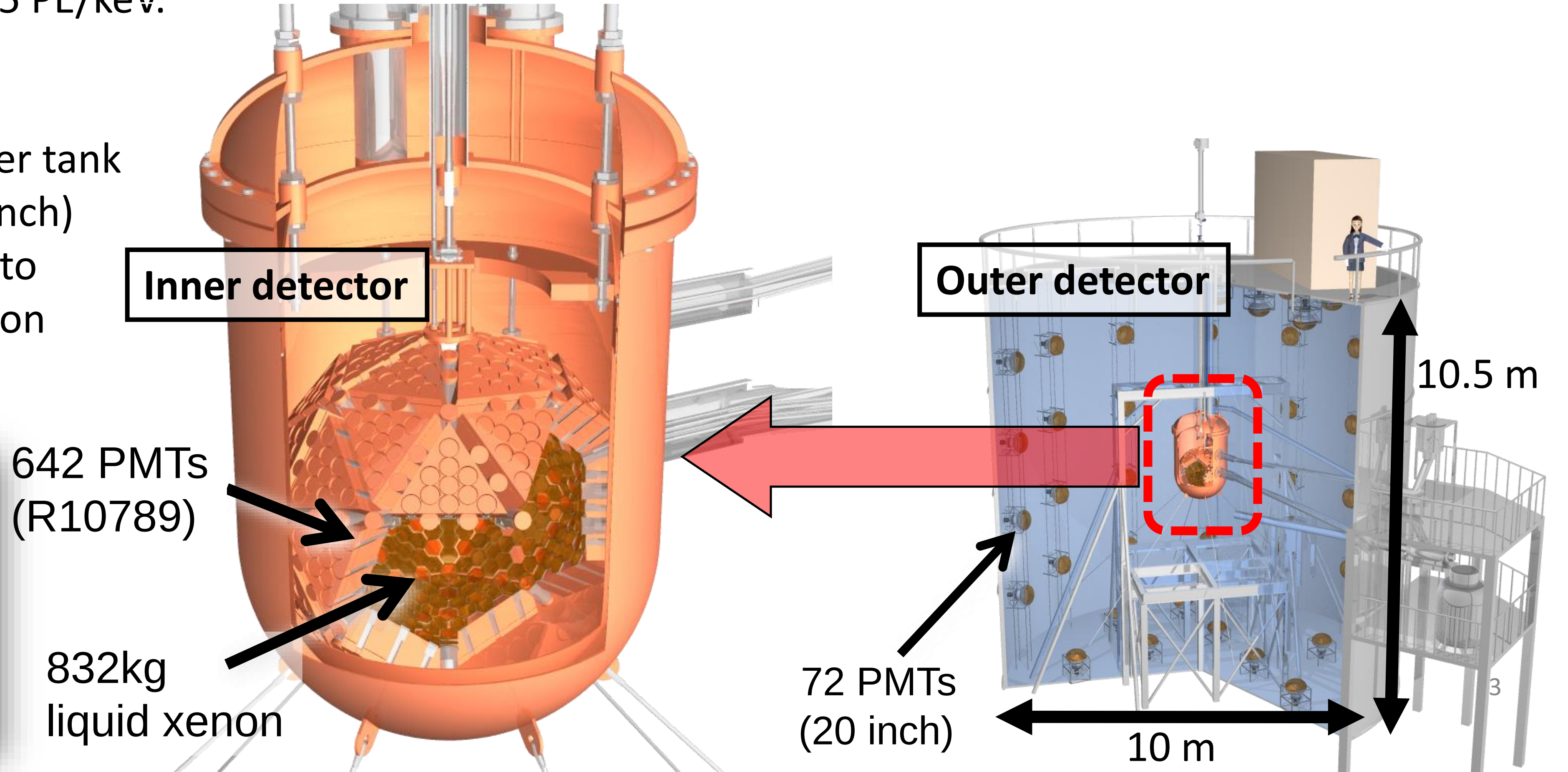




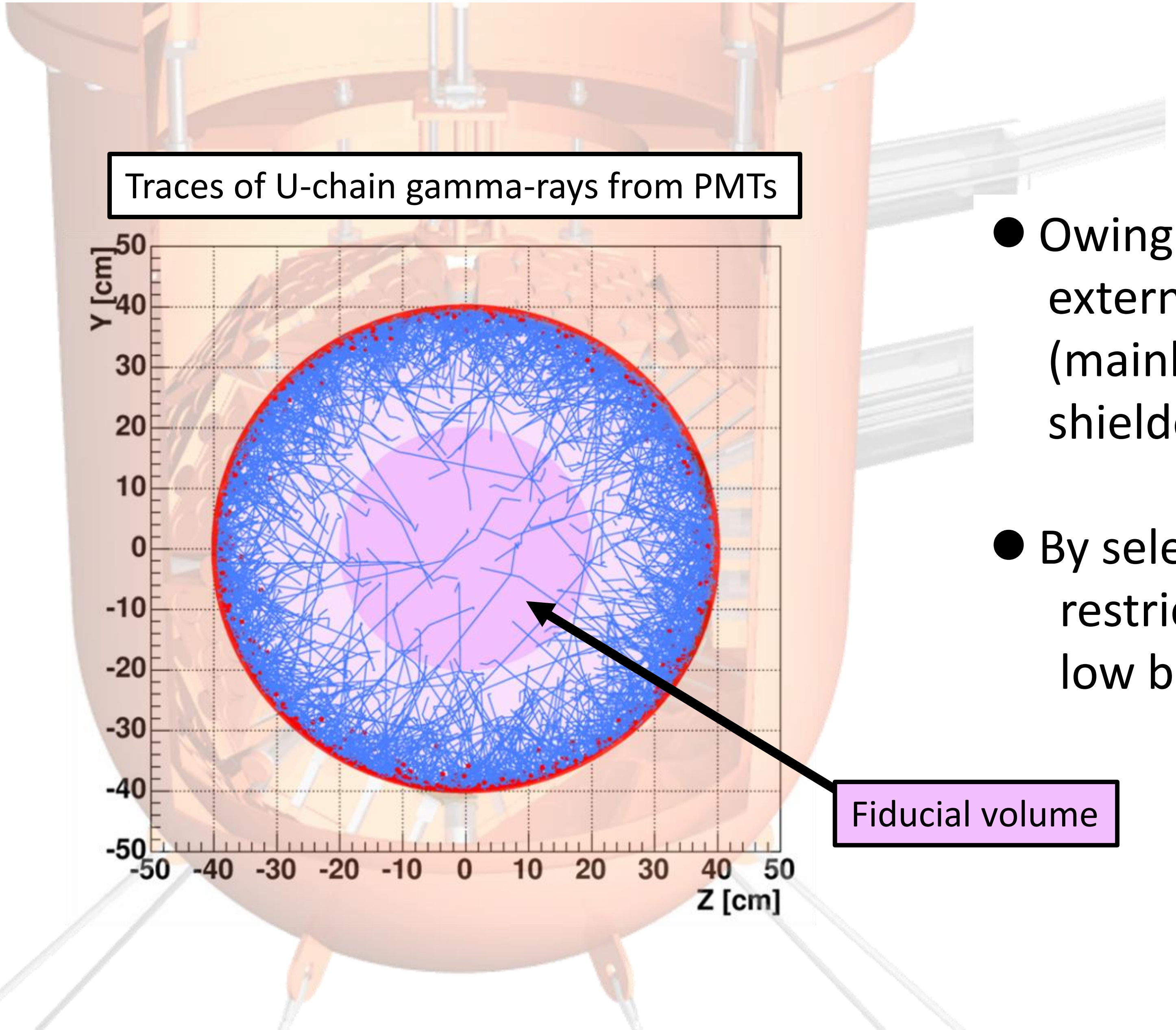
XMASS-I detector

- **Inner detector**
  - Single phase liquid xenon detector. (832 kg xenon for sensitive region)
  - 642 low background PMTs. (2 inch, HAMAMATSU R10789)
    → each PMT signal is recorded by 10-bit 1GS/s waveform digitizers.
  - High light yield: ~15 PE/keV.

- **Outer detector**
  - 10 m x 10.5 m water tank with 72 PMTs (20 inch) for active muon veto and passive radiation shield.



Self-shielding of γ-ray background



- Owing to high atomic number (Z=54), external gamma-ray background (mainly coming from PMTs) can be shielded by liquid xenon itself.
- By selecting events occurred in the restricted inner volume (fiducial volume) low background can be achieved.

Detector calibration

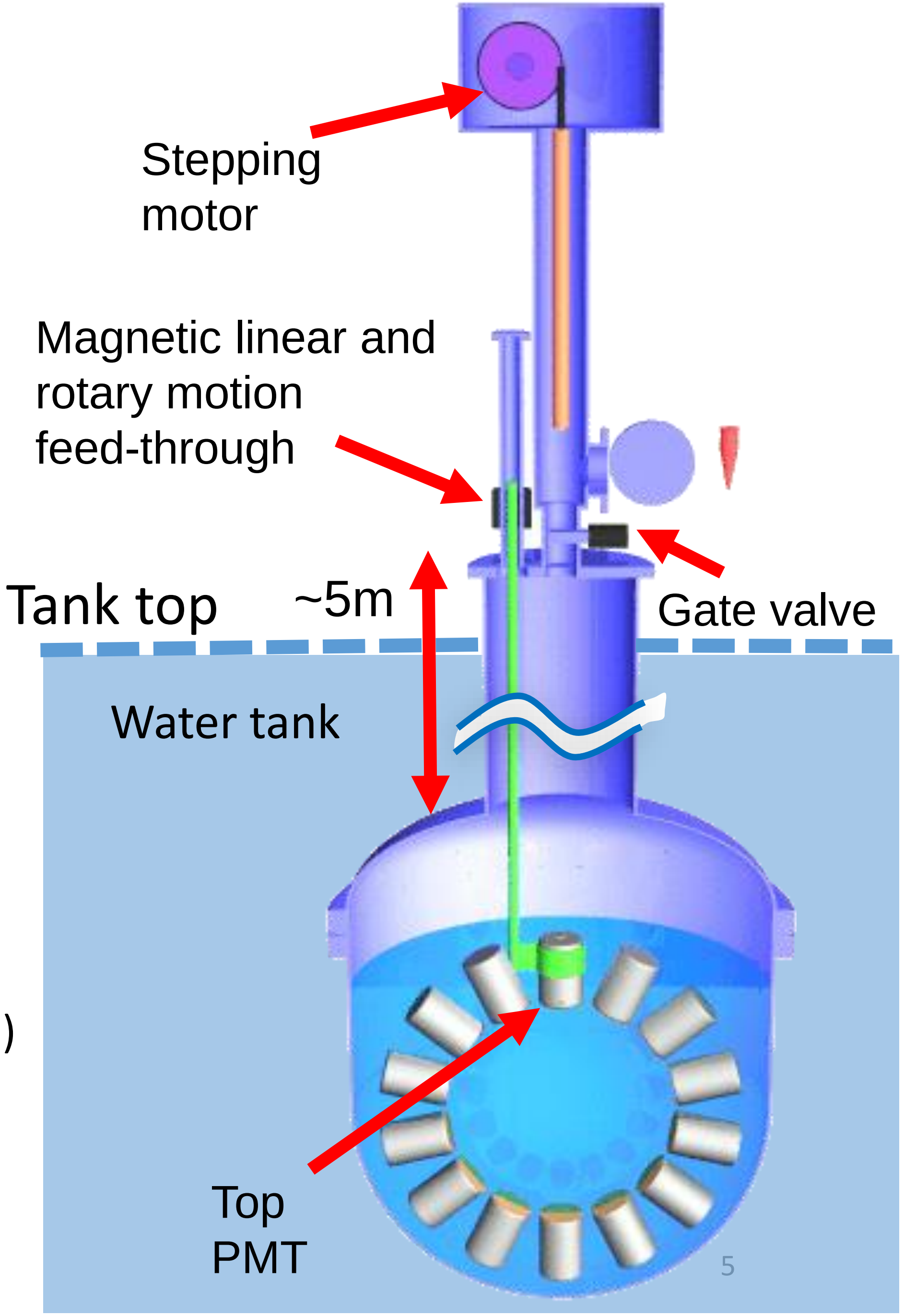
- Various RI sources can be inserted inside the sensitive volume w/o interrupting detector operation.
- Used for light yield monitoring, optical parameter tuning, energy and timing calibration etc.

RI	Energy [keV]	diameter [mm]	Geometry
(1) ^{55}Fe	1.65(*1), 5.9	10	2pi source
(2) ^{109}Cd	8, 22, 25, 88	5	2pi source
(3) ^{241}Am	17.8, 59.5	0.17	2pi/4pi source
(4) ^{57}Co	59.3(*2), 122	0.21	4pi source
(5) ^{137}Cs	662	5	cylindrical

(*1) 4.2 keV (averaged) L-shell X-ray escape from 5.9 keV K-shell X-ray.
(*2) Tungsten K-shell X-ray used for detector housing.

^{57}Co source

N.Y. Kim et al., NIM A 784 (2015) 499–503



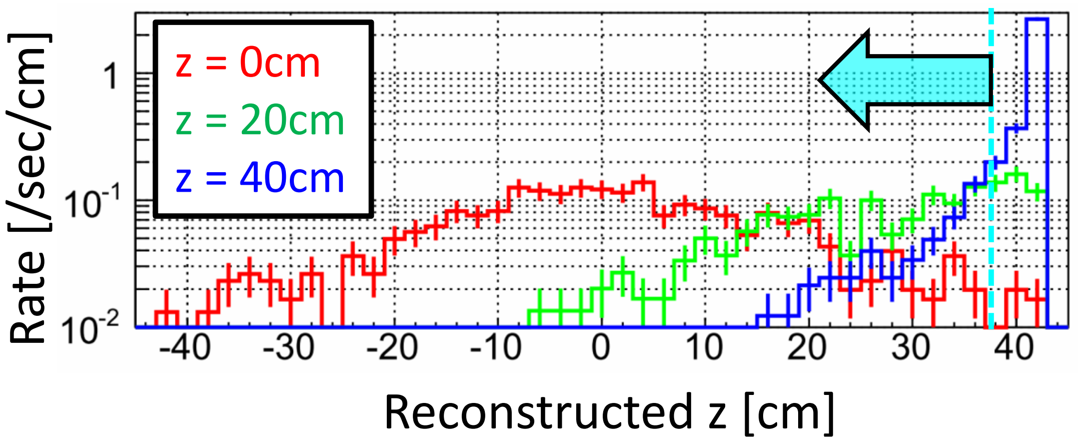
Vertex reconstruction (based on timing, R(T))

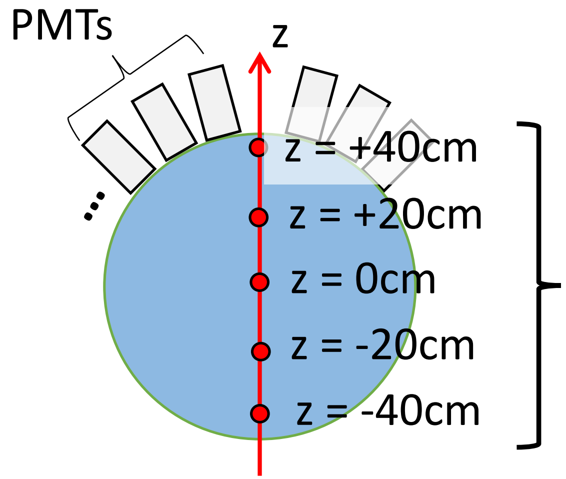
- Using FADC hit timing of each PMT.
- Timing constant for 2–10 keV events: 25±2ns.
- Position reconstruction is done by using likelihood method from probability density function for each PMT.

$$L(\vec{X},T) = \prod_{i=1}^{Nhits} P\left(t_i - \frac{\left|\vec{x}_i - \vec{X}\right|}{v_g} - T \right)$$

P(τ) : probability density function
x_i, t_i : PMT position and hit time
v_g : group velocity in Lxe (110mm/ns)

^{241}Am calibration data (5–10 keV)





detector calibration

Source position along vertical axis (z-axis)

→ Surface events > 38 cm are effectively removed from this distribution.
R(T) < 38 cm selection is used for event reduction.

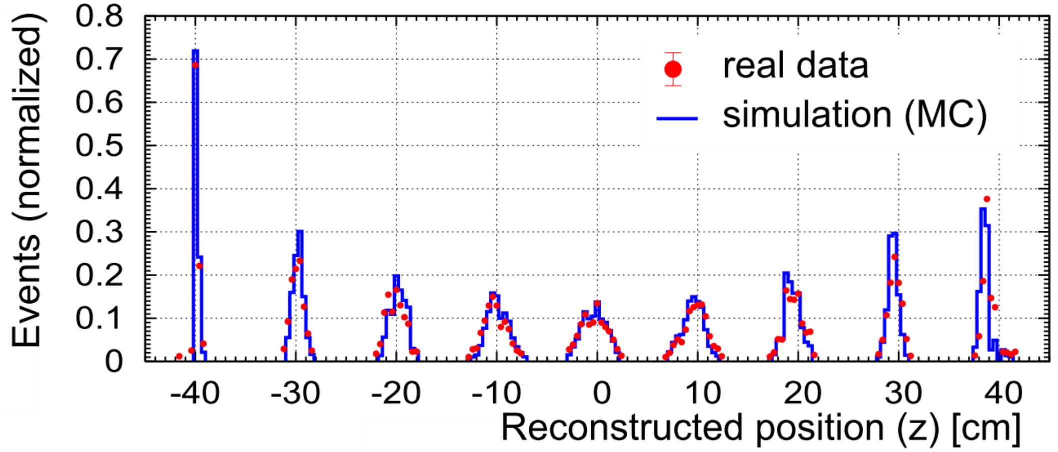
Vertex reconstruction (based on photo electron, R(PE))

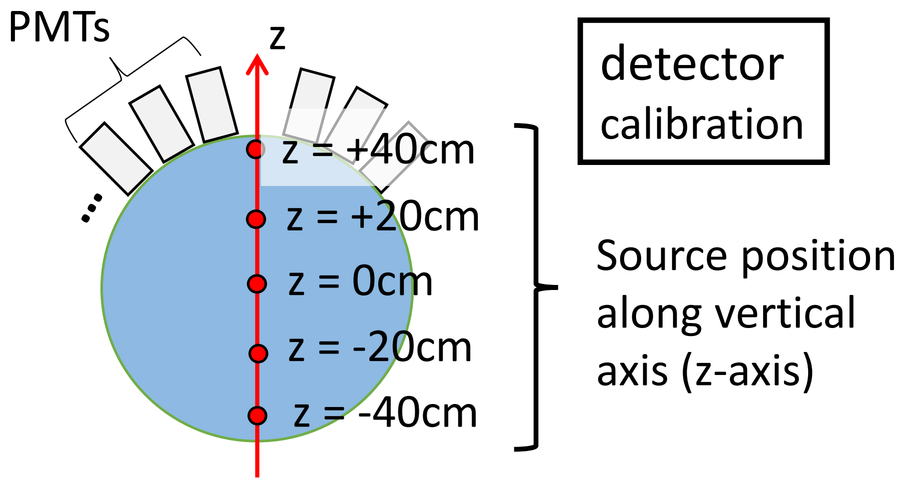
- Position reconstruction
  (1) Making acceptance map: Many grid points are defined inside whole detector volume including detector surface. Events are generated at each grid point and photo-electrons (pe) expected in each PMT are calculated by our MC.
  (2) From measured pe and scaled acceptance map (μ) in (1), position is calculated where following likelihood is maximum.

$$\log(\mathrm{L}) = -\sum_{\mathrm{PMT}} \log\left(\frac{\exp(-\mu)\mu^{\mathrm{pe}}}{\Gamma(\mathrm{pe}+1)}\right)$$

Γ(x): Gamma function
(Γ(n) = (n-1)!, n>0)

Reconstructed position distribution of ^{57}Co events (122 keV)





Evaluation of RI activities in XMASS-I (1/2)

- Based on RI screening for detector materials mainly with HPGe detector.
- RI activities are evaluated by spectrum fitting for > 400 pe (~30 keV) between data and MC with constraints from screening results.

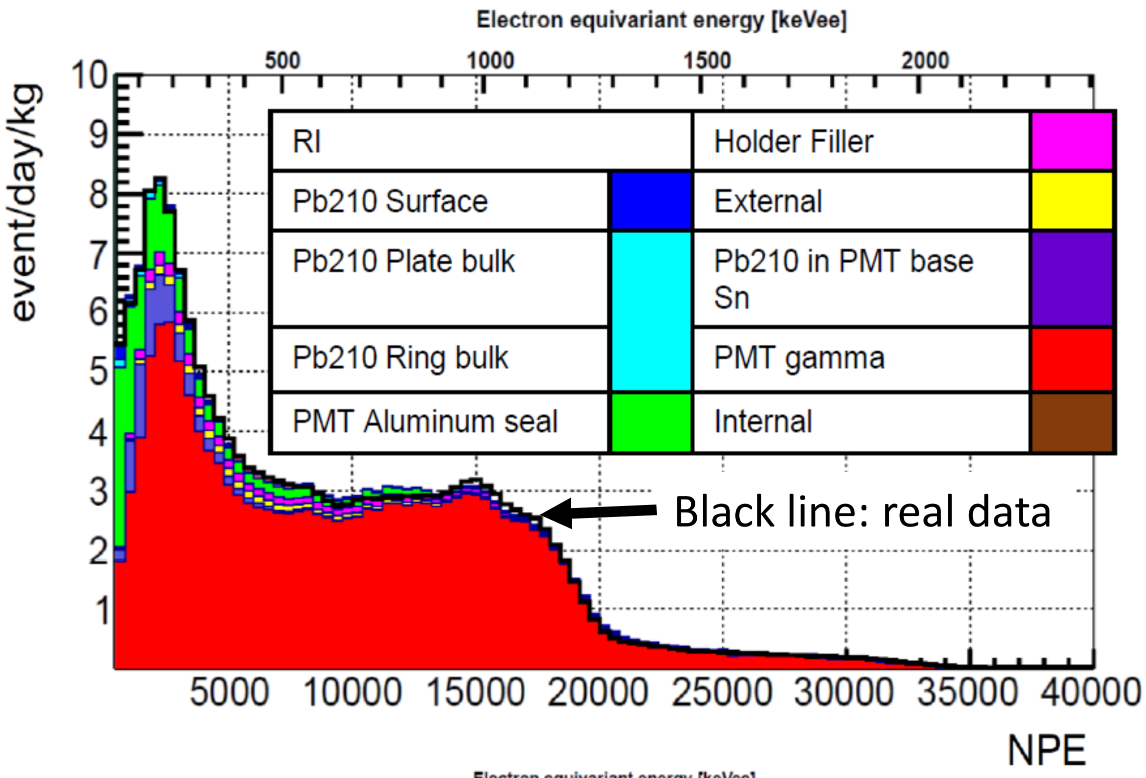
ex. RI screening results for PMT with HPGe detector.

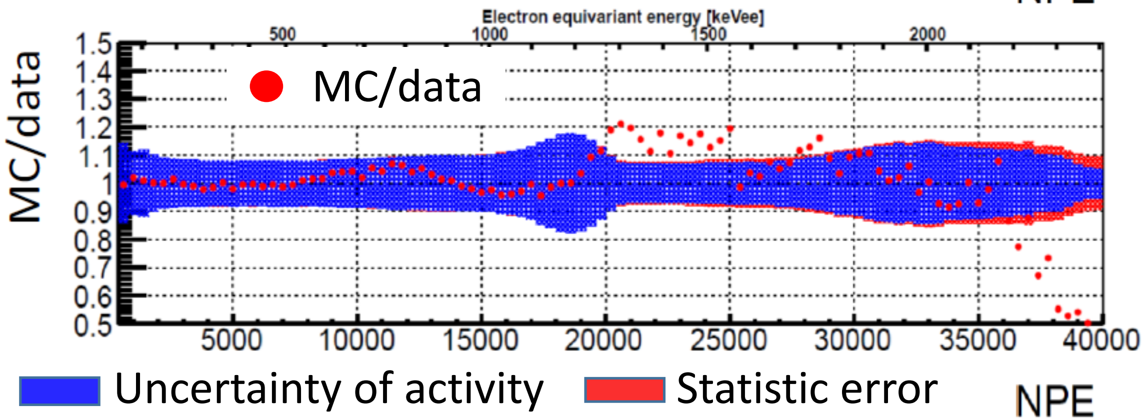
- PMT aluminum seal

	Bq
^{238}U–^{230}Th	1.5±0.4
^{210}Pb	2.85±1.15
^{232}Th	0.096±0.018
^{235}U–^{207}Pb	~1.5 x 4.5%

- PMT + base (whole measurement)

	mBq/PMT
^{232}Th	1.80±0.31
^{238}U	2.26±0.28
^{210}Pb	200±100
^{60}Co	2.92±0.16
^{40}K	9.10±2.15



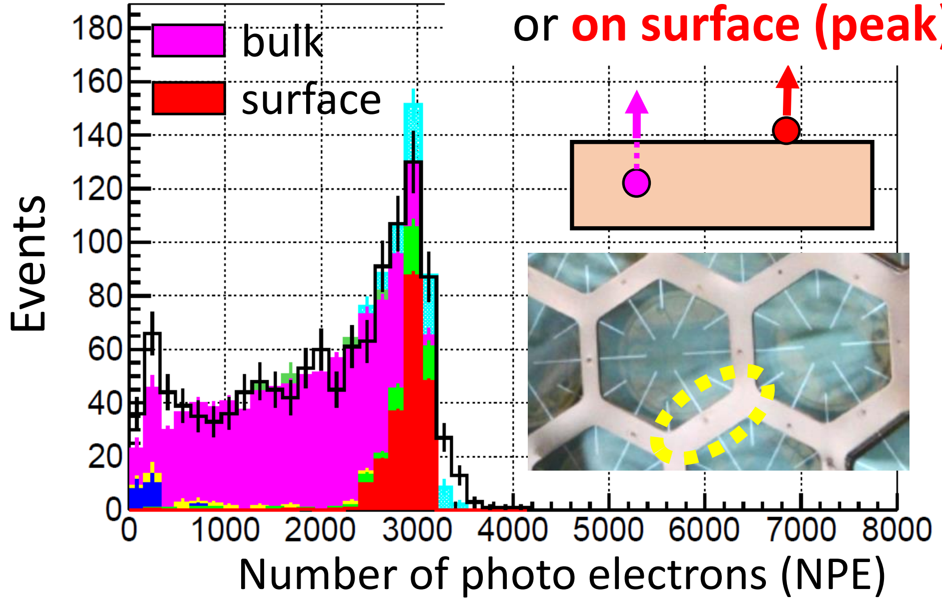


Evaluation of RI activities in XMASS-I (2/2)

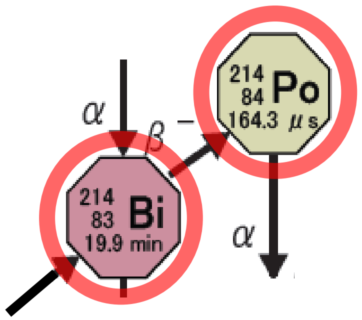
- **^{210}Pb in copper surface and bulk**
  - α events selection from scintillation decay time.
  - ^{210}Pb in copper surface/bulk were estimated from shape of energy spectrum caused by ^{210}Po α decay.
  - ^{210}Pb in the bulk of OFHC copper was also measured independently by a low background α-particle counter. (XIA Ultra-Lo-1800)

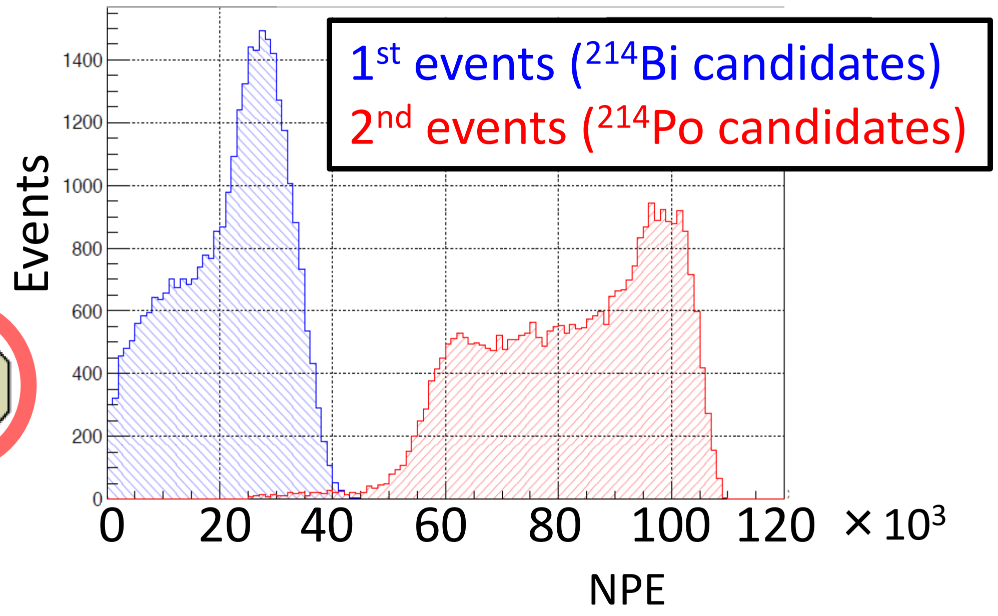
- **RI in liquid xenon**
  - Coincidence analysis was used.
    - ^{222}Rn: ^{214}Bi – ^{214}Po (164 us)
    - ^{85} Kr: β–γ (1.015 us, 0.343%)
  - ^{14}C and ^{39}Ar were estimated from spectrum fitting.

^{210}Po in copper bulk (continuous) or on surface (peak)



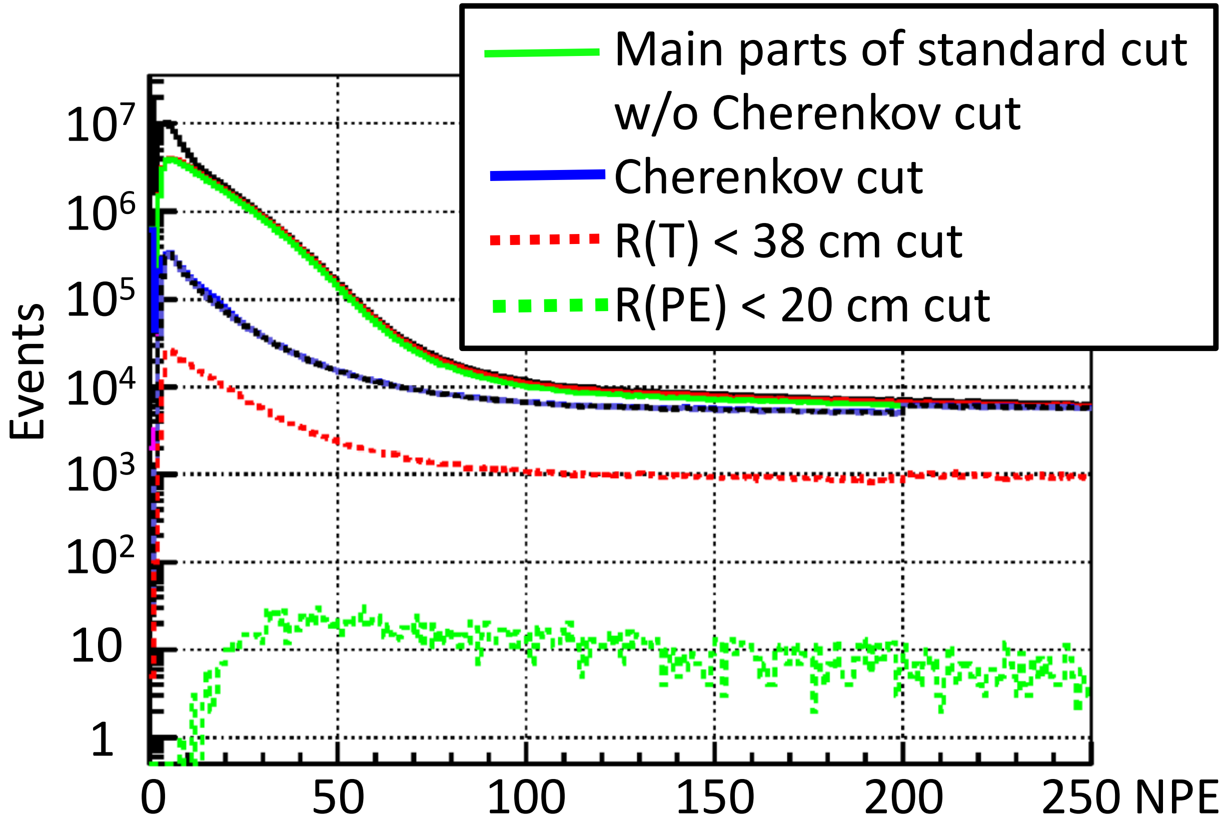
Down stream of ^{222}Rn

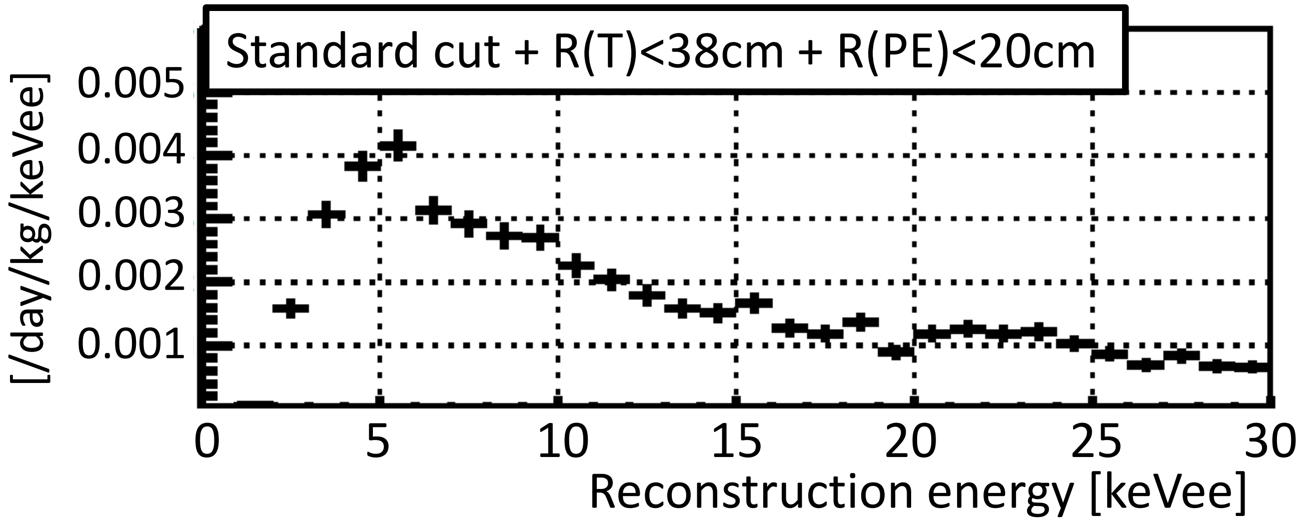




Data reduction

- **Live time**: 705.88 days
  2013/Nov. /20 – 2016/Mar./29
- **Standard cut**:
  - Reduction of Cherenkov event is effective.
    Main origin of Cherenkov events is
    β-ray in PMT quartz window emitted from
    ^{40}K in PMT photo-cathode.
- **R(T) < 38 cm and R(PE) < 20 cm cuts** give
  another O(10^{-3}) reduction.
- **Event rate after applying all cuts**:
  ~4×10^{-3} /day/kg/keVee
  @5–5.5 keVee
  (signal efficiency: ~30%)

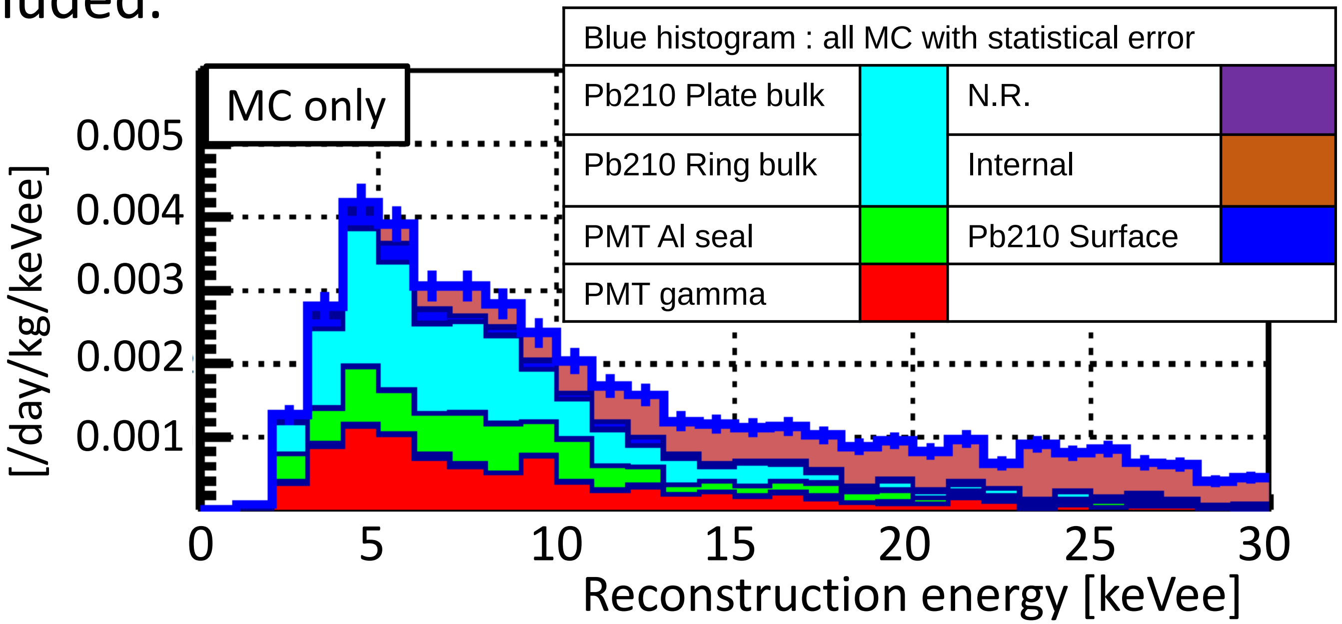




Background prediction with MC

- XMASS MC based on Geant4.
  - Detail detector geometry and responses of PMT and DAQ were included.
  - Optical parameters of LXe were traced with our periodical calibration (^{57}Co and ^{60}Co).
  - RI activities for each material were implanted.
  - Same live time as that of data.
  - Same reduction as that for data was applied.

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

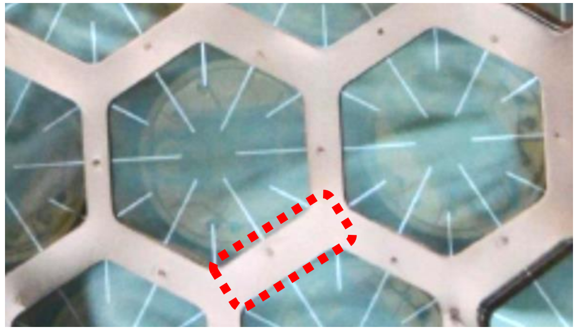


→ Main BG origin is not internal but detector surface events (miss-reconstructed events).

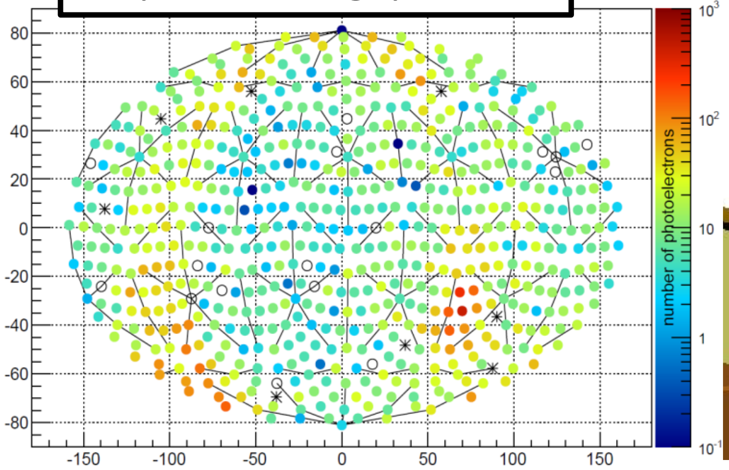
Miss-reconstructed events

- Events occurring on surface of copper plate are wrongly reconstructed to inside of the fiducial volume with some probabilities because closest PMT has small solid angle for these events.
- Light leakage from a gap around boundary between plate and plate makes special pattern, but, sometimes wrongly reconstructed inside the fiducial volume.

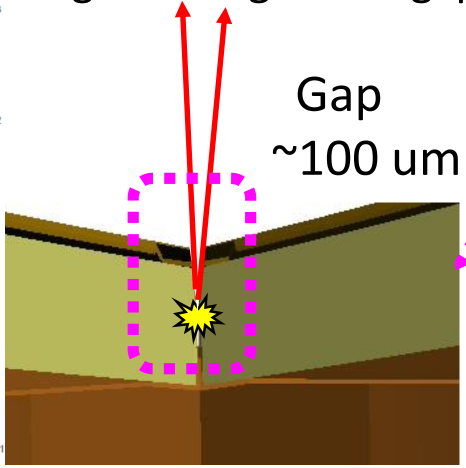
Structure around PMT



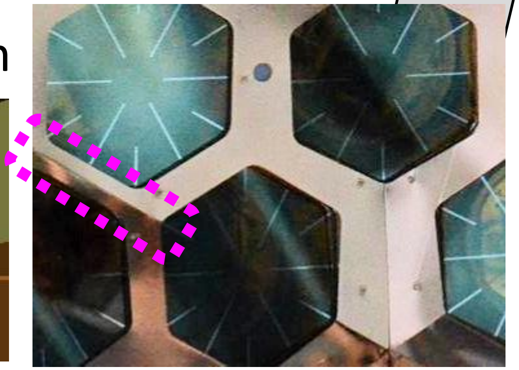
PE pattern of gap event

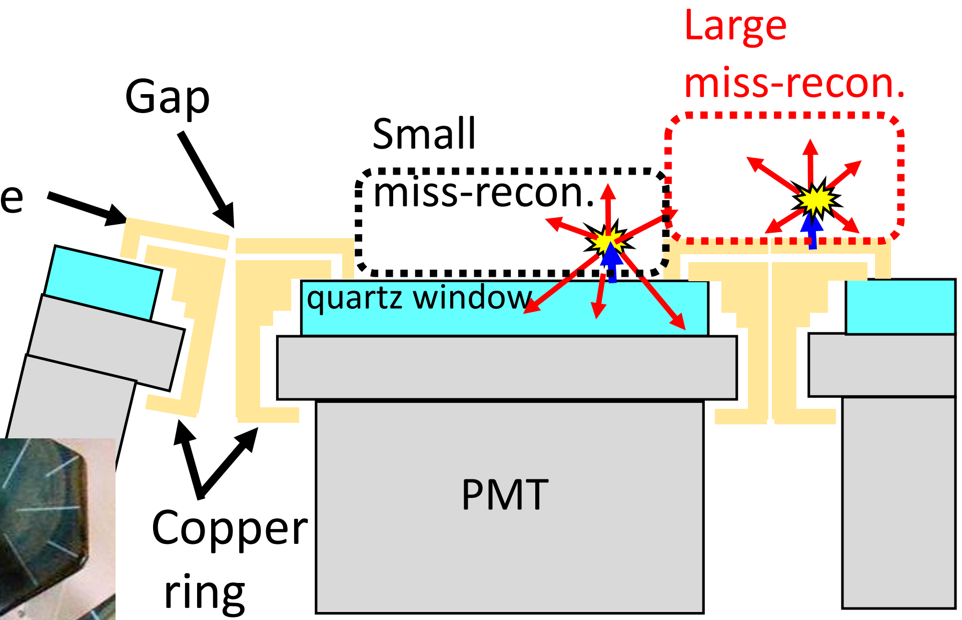


Light leakage from gap



Gap
~100 um





Position where scintillation happens
Scintillation photons

Systematic error evaluation

All the possible systematic errors were evaluated

- **Related to surface condition**: it mainly affects to miss-reconstruction rate.
  - (1) Geometry of gap between plates coming from installation accuracy of plates.
  - (2) Roughness of ring surface inside the gap.
  - (3) Reflection of plate surface.
  - (4) Floating of plate coming from installation accuracy of each plate.
- (5) Geometry and property of aluminum seal
- (6) Related to reconstruction: grid dependency and rate of miss-reconstruction.
- (7,8) Uncertainty for scintillation decay time and response of PMT.
- (9) Optical parameters of LXe.
- (10) Effect of dead PMTs (10 dead PMTs exist)
- (11) for ^{206}Pb recoil from ^{210}Po α decay on copper surface.

Contents	Systematic error	
	2-15 keVee	15-30 keVee
(1) Plate gap geometry	+6.2/-22.8%	+1.9/-6.9%
(2) Ring roughness	+6.6/-7.0%	+2.0/-2.1%
(3) Cu ref dependence	+5.2/-0.0%	+2.5/-0.0%
(4) Plate floating	+0.0/-4.6%	+0.0/-1.4%
(5) Al seal dependence	+0.7/-0.7%	+0.0/-0.0%
(6) Reconstruction	+3.0/-6.2%	+0.0/-0.0%
(7) Timing (decay time, TTS)	+4.6/-2.9%	+0.4/-5.3%
(8) Timing (response in detector surface)	+0.0/-8.0%	+0.0/-0.0%
(9) Absorption & scattering	+0.7/-6.7%	+1.5/-1.1%
(10) Dead tube origin	+10.3/-0.0%	+45.2/-0.0%
(11) N.R.	+0.7/-0.7%	+0.0/-0.0%

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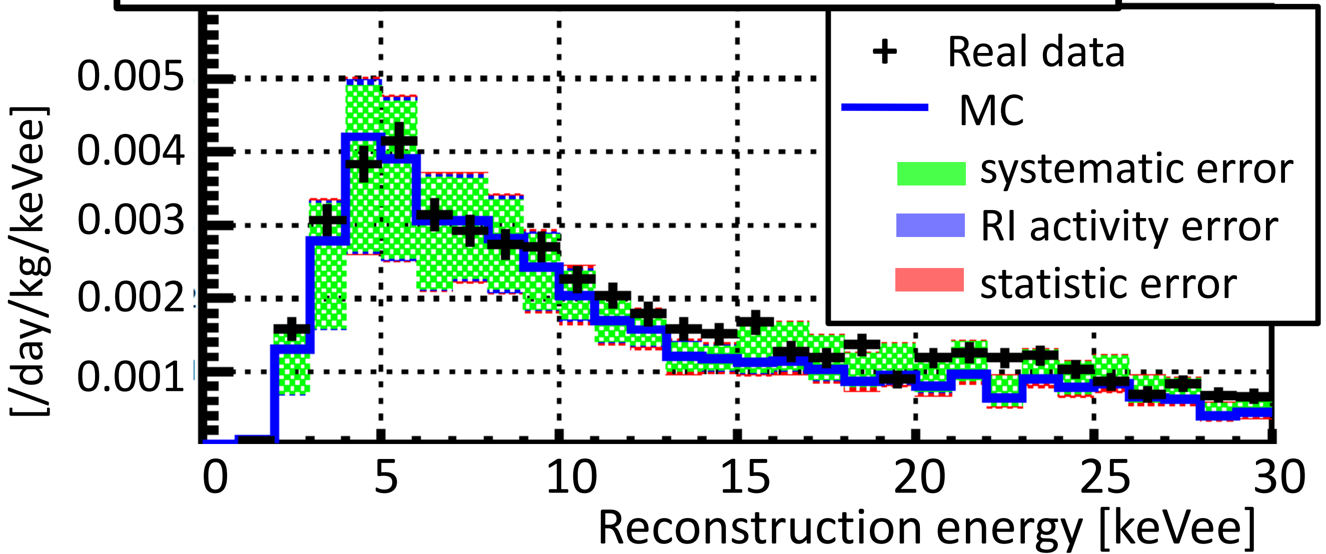

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← Real data is well explained with background MC.

WIMP search with background evaluation in fiducial volume

- 705.88 live days data applying fiducial volume data reduction were used. (standard + R(T)<38cm + R(PE) < 20cm cut)
- Energy spectrum of data was fitted with background MC and WIMP MC in the energy range of 2–15 keVee considering systematic error in both background and WIMP MC.
- Best fit result is consistent with no WIMP case, then 90% C.L. upper limit on the WIMP-nucleon cross section was derived.
- Our preliminary limit is 2.2×10^{-44} cm^2 for 60 GeV WIMP mass.