Direct dark matter search in XMASS-I

The 16th International Workshop on the Dark Side of the Universe (DSU 2022)
Dec. 5-9, 2022,
UNSW, Sydney, Australia

5th of Dec. 2022 (14:40–15:00)

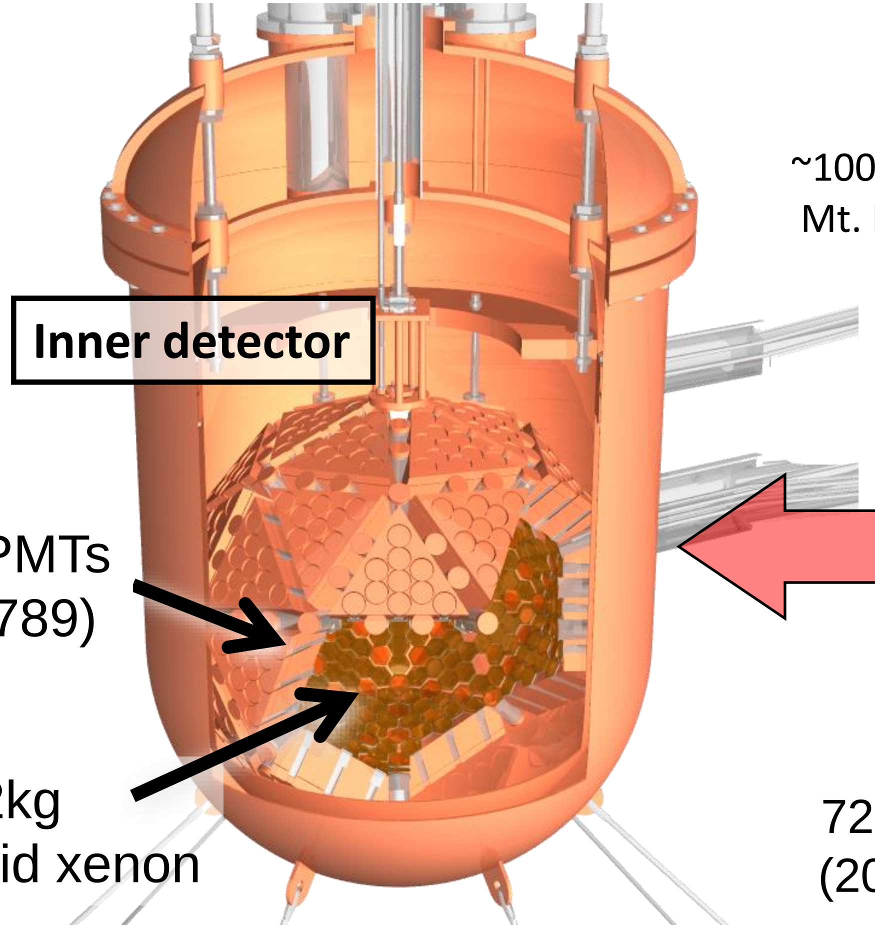
A. Takeda for the XMASS Collaboration

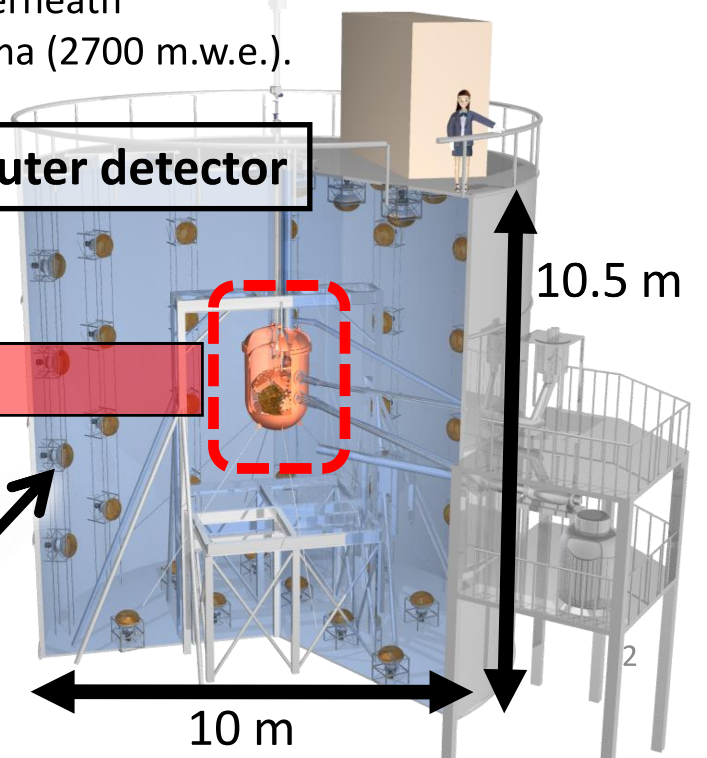
XMASS-I detector

- **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: ~14 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.

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



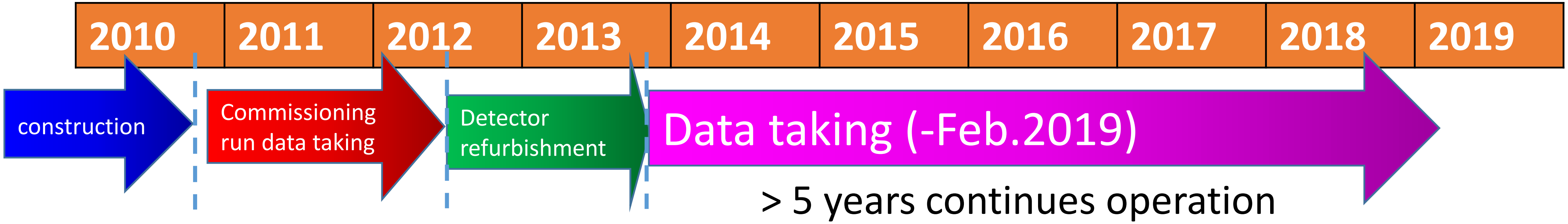


XMASS-I experiment

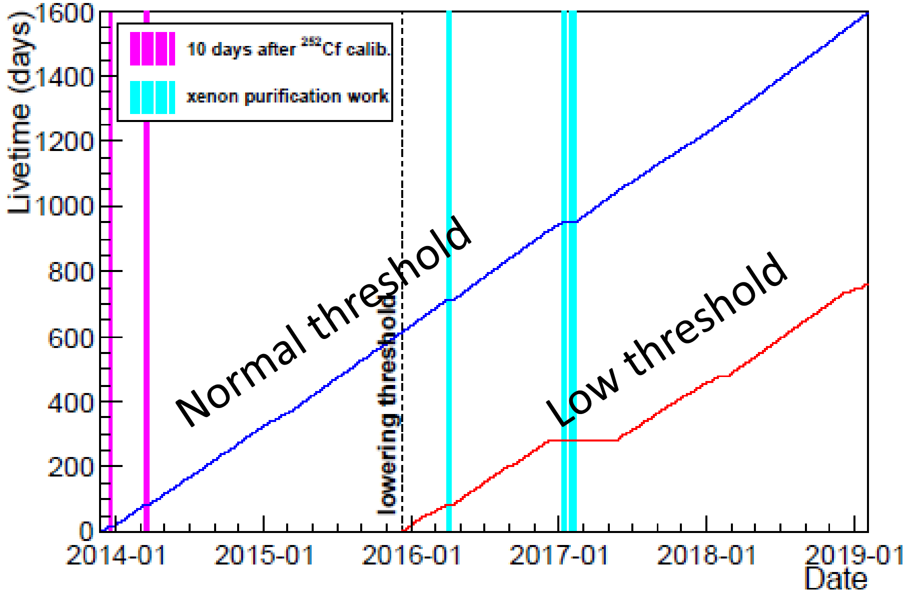
- **Unique experiment**
  - Using only scintillation photon with single phase liquid xenon detector.
  - Large volume, ~1 ton.
  - Long stable observation period, > 5 years.
    - 2013/11~2019/2
  - Large light yield, ~14 PE/keV, and low threshold, ~0.5 keVee.

- **Variety of rare events search**
  - Dark matter, modulation, low mass, inelastic, and hidden photon
  - Solar axion, 2νECEC, GW, and exotic neutrino interaction

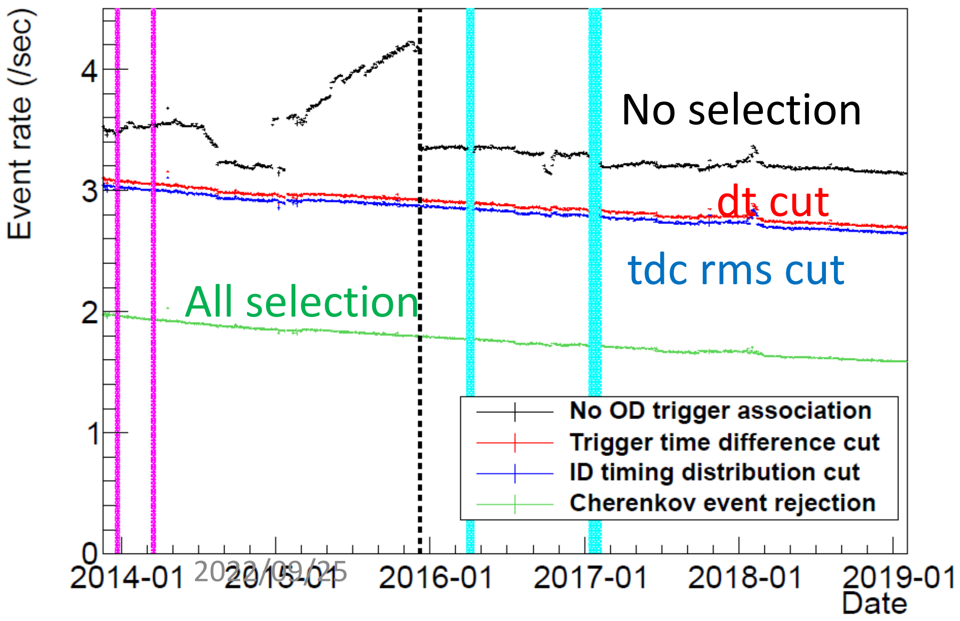
Wide variety results are quite important for present dark matter search



Full data set of analysis

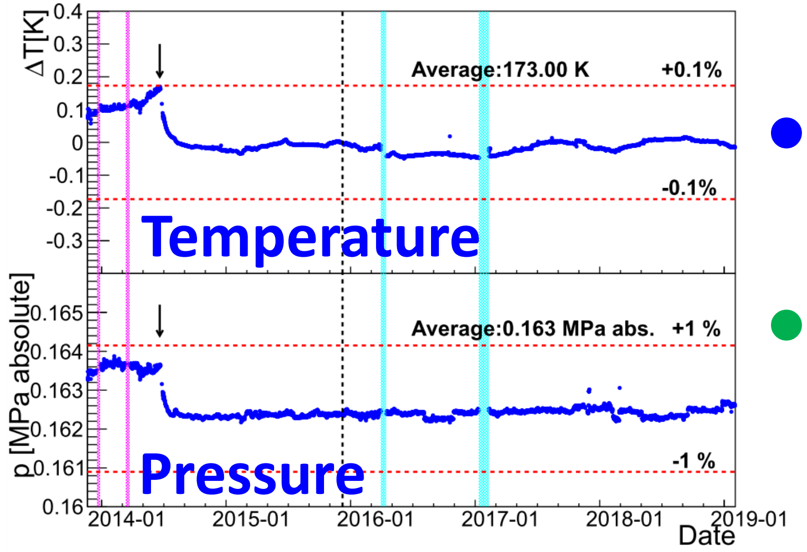


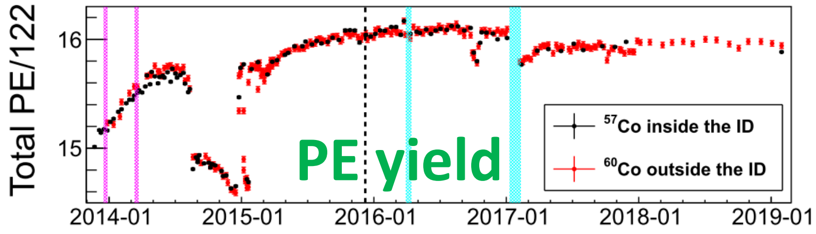
- 2013/11/20 ~ 2019/2/1 (~5 years)
  - Normal threshold (4 hits ~1 keV_{ee})
    - 1590.9 live days.
  - Low threshold (3 hits ~0.5 keV_{ee})
    - 768.8 live days.
    - Started from middle of the experiment.

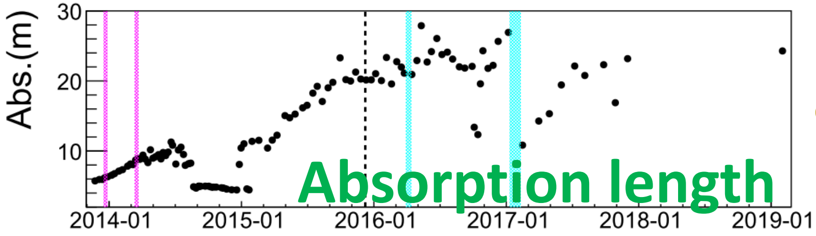


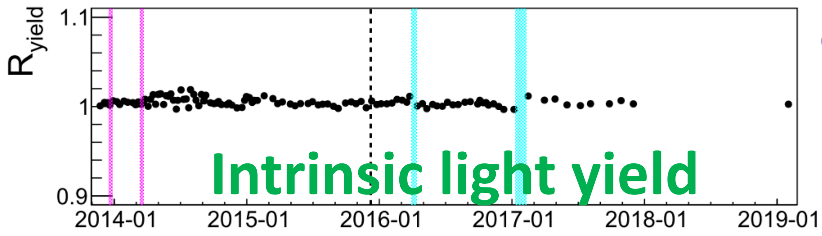
- Stable observation was realized
  - Steadily accumulated data.
  - Relatively longer down time came from xenon purification work for impurity removal.
  - Trigger rate change for before selection disappeared after noise removal.

Detector stability

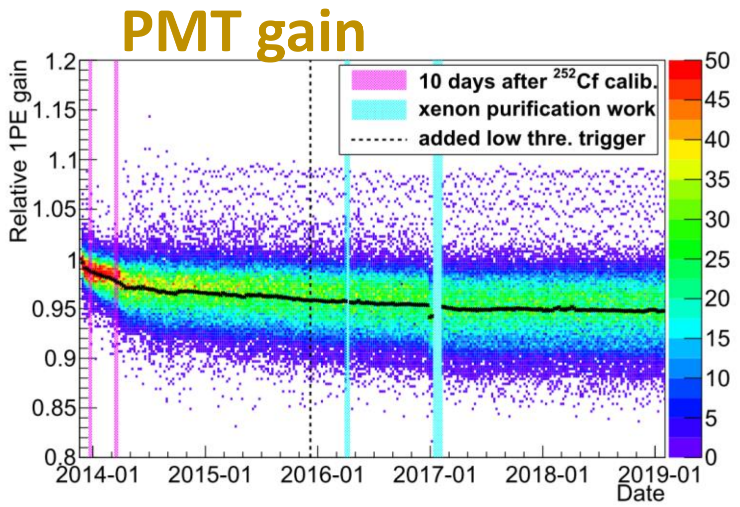


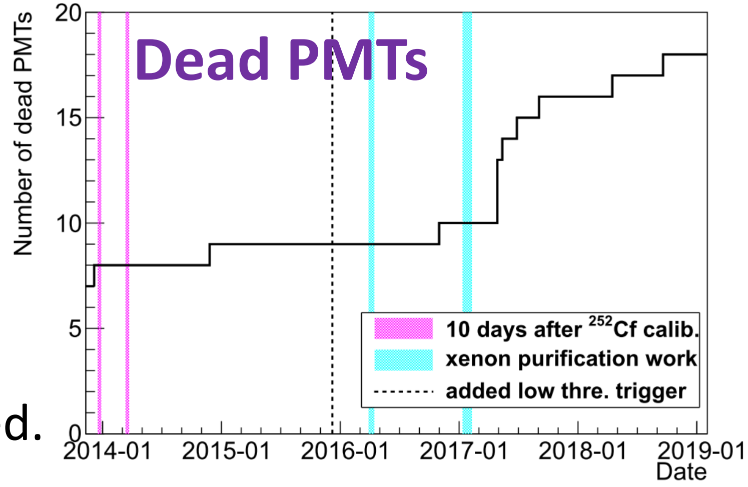




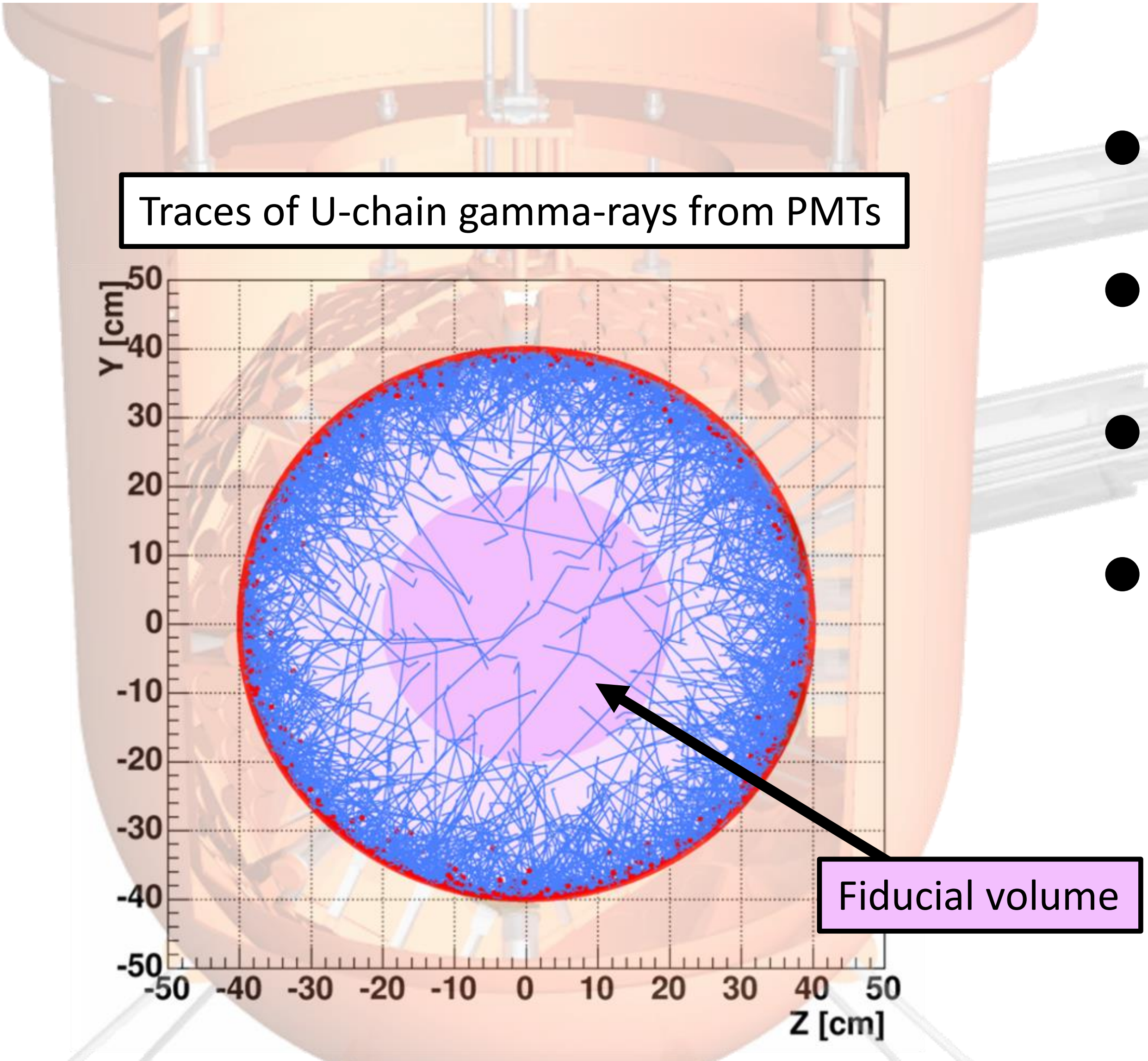


- **Temperature and pressure**
  - Stable except one drop caused by change of reference sensor for controlling the refrigerator.
- **Optical parameter of liquid xenon**
  - **PE yield**
    - Large change due to power outage and subsequent work.
    - Latter half was quite stable.
  - **Absorption length** gradually increased by gas circulation.
  - **Intrinsic relative light yield** was not changed within 2% estimation error.
- **PMT gain monitored by LED**
  - Small decreasing was observed.
  - Correction in the analysis.
- **Dead PMTs**
  - Increased in later part.
  - Effect to BG evaluation was considered.

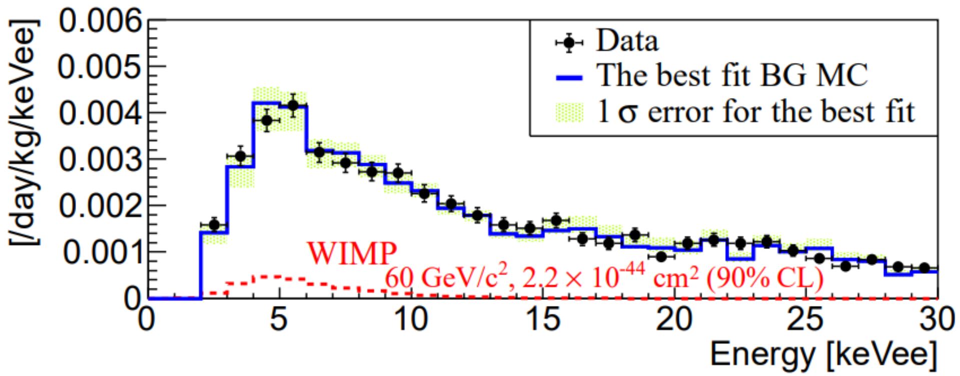




Fiducial volume WIMP search



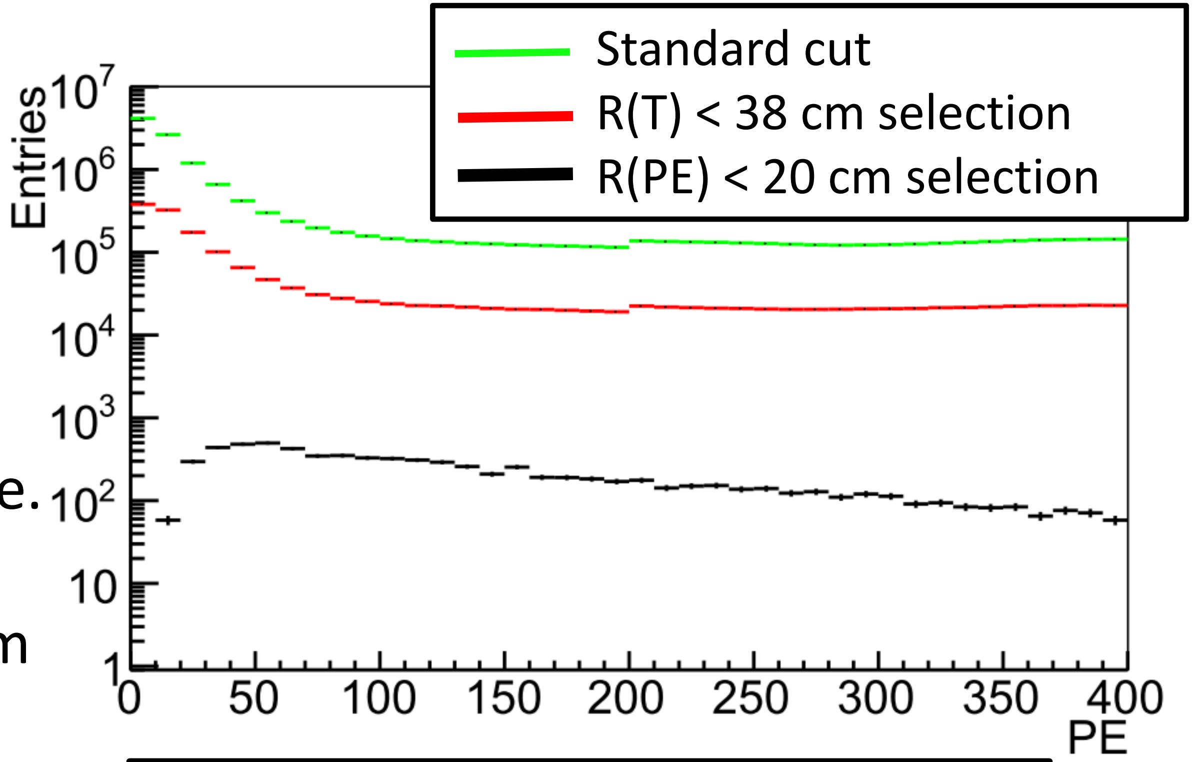
- Select fiducial volume events by using reconstructed position information.
- BG from outside can be stopped by the outside shielding region.
- Search signal by fitting data with BG + expected WIMP signal.
- Previous results: PLB 789 (2019) 45-53 (705.9 live days)



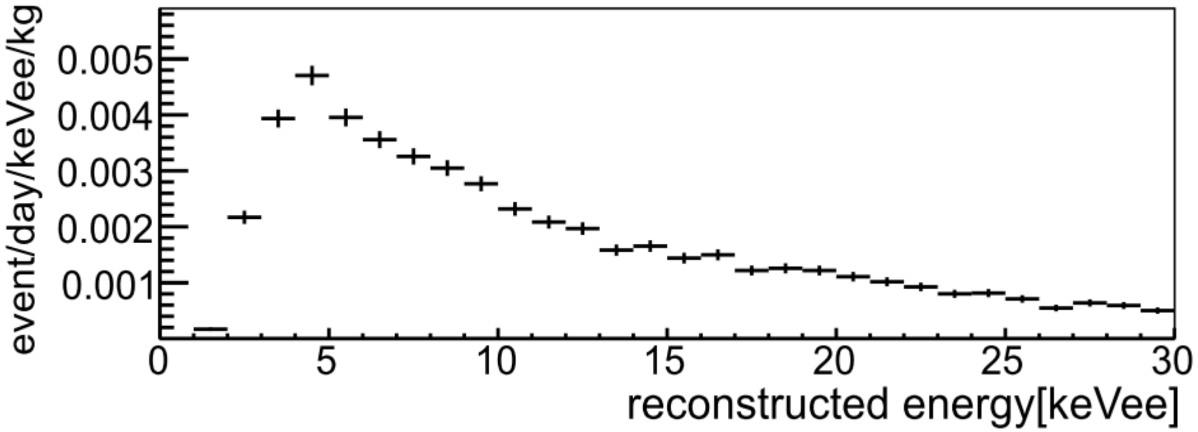
2019 XMASS results, PLB 789 (2019) 45-53

Data reduction

- **Live time**: 1590.9 days
  2013/Nov. /20 – 2019/Feb./1
- **Standard cut**:
  - Reduction of Cherenkov events is effective.
    Main origin of Cherenkov events is
    β-ray in PMT quartz window emitted from
    ^{40}K in PMT photo-cathode.
- **Fiducial selection (R(T) < 38 cm + R(PE) < 20 cm)**
  give another $O(10^{-3})$ reduction.
- **Event rate after applying all reductions**:
  $\sim 5 \times 10^{-3}$ /day/kg/keVee
  @5–5.5 keVee
  (signal efficiency: ~30%)



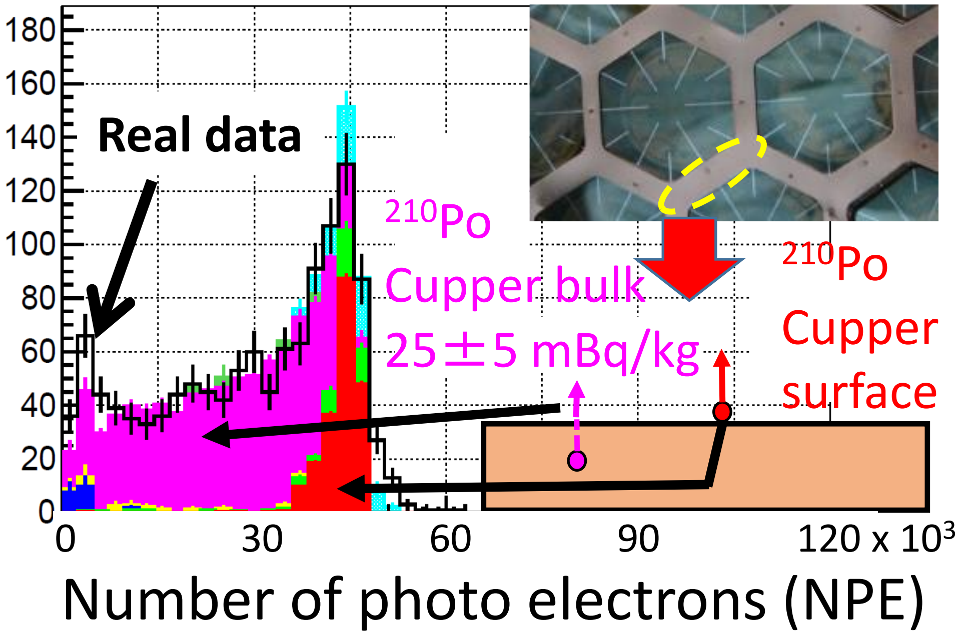
Standard cut + R(T)<38cm + R(PE)<20cm



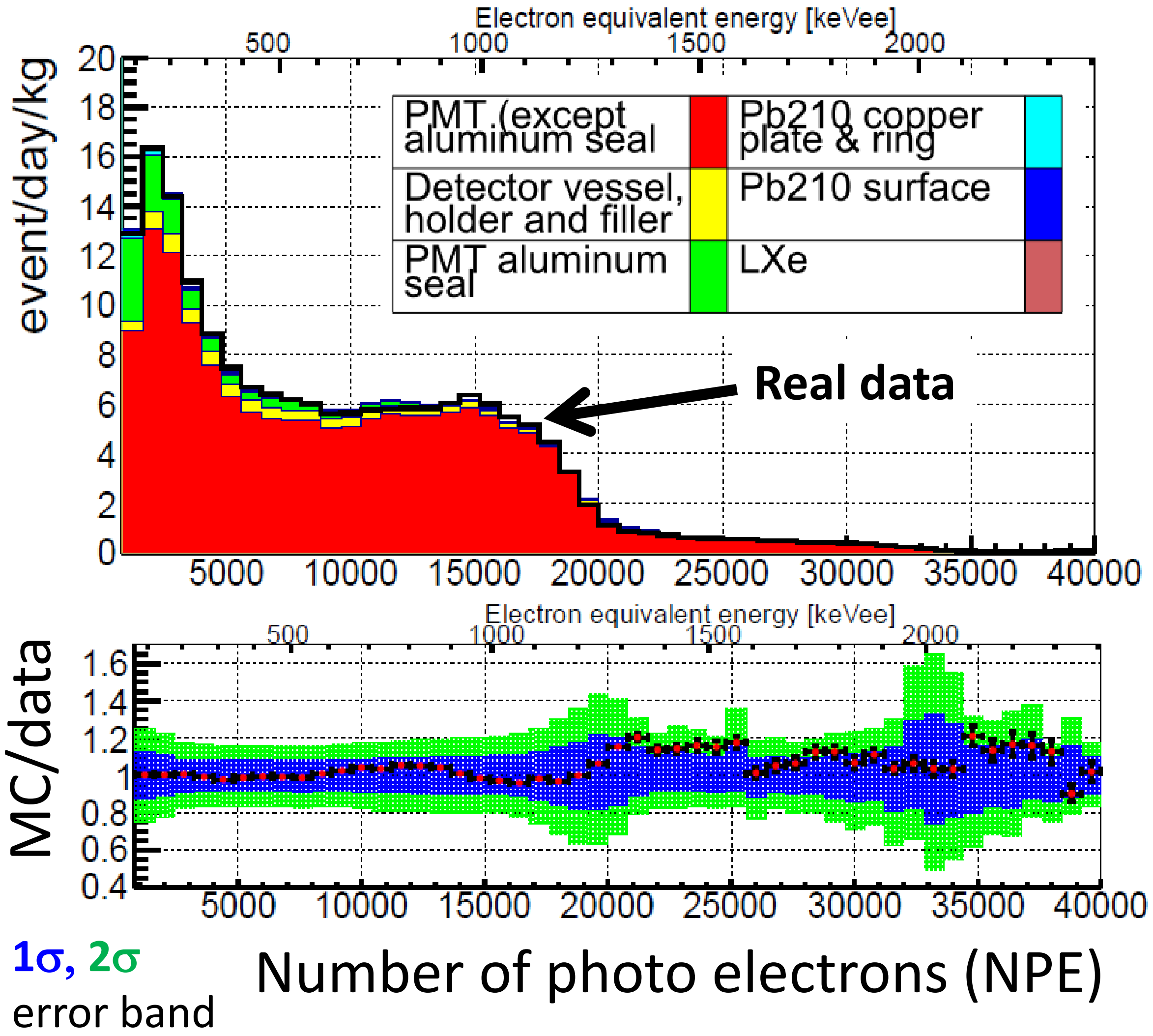
Background modeling

- Evaluation by using side-band data and MC.
- NPE distribution larger than 400 PE (~ 30 keVee) was fitted with BG MC based on RI assay by HPGe.
- ^{210}Pb in coper was also evaluated from analyses of α-like events and high sensitivity surface α counter.
- Impurities in liquid xenon: ^{222}Rn, ^{85}Kr, ^{39}Ar, ^{14}C.
- Contribution from neutron was negligible.

NPE distribution from α-like evens from PSD



Whole detector volume

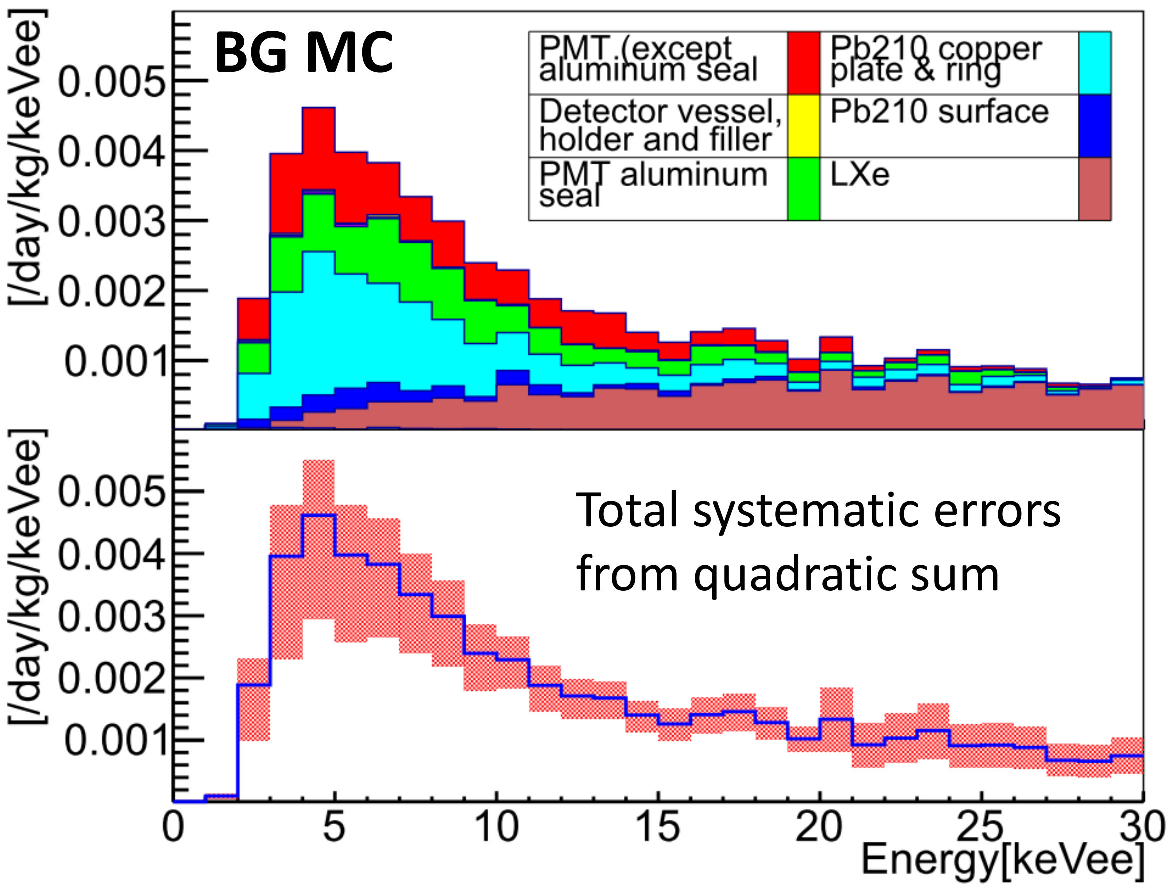


Background prediction with MC

- Main background origin within fiducial volume in low energy (< 10 keVee) was not internal.
  - Detector surface events were miss-identified inside the fiducial volume.
  - Largest contribution was ^{210}Pb in copper bulk around PMTs.
- All the possible systematic (9 components) errors were evaluated:

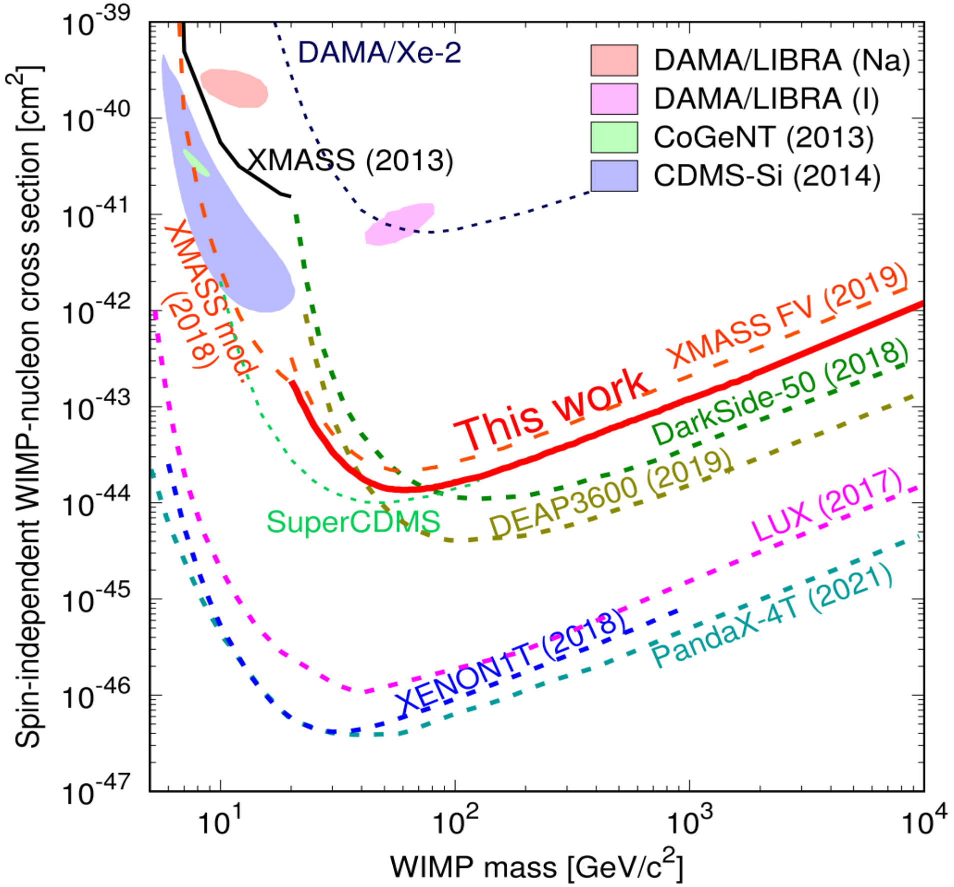
Component	Evaluated systematic errors			
	2-5 keV_{ee}	5-10 keV_{ee}	10-15 keV_{ee}	15-30 keV_{ee}
(1) Plate gap	+9.1/-33.4%	+5.2/-19.1%	+3.1/-11.3%	+1.6/-6.0%
(2) Ring roughness	+9.7/-10.3%	+5.6/-5.9%	+3.3/-3.5%	+1.8/-1.9%
(3) Cu reflectivity	+3.6/-0.0%	+5.9/-0.0%	+4.4/-0.0%	+2.4/-0.0%
(4) Plate floating	+0.0/-6.7%	+0.0/-3.8%	+0.0/-2.3%	+0.0/-1.2%
(5) PMT aluminum seal	+1.0/-1.0%	+0.3/-0.3%	+0.0/-0.0%	+0.0/-0.0%
(6) Reconstruction	+8.9/-8.9%	+1.4/-7.8%	+2.8/-2.8%	+2.8/-2.8%
(7) Timing response	+3.1/-9.9%	+7.6/-11.3%	+0.4/-5.3%	+0.4/-5.3%
(8) Dead PMT	+7.5/-7.5%	+11.9/-11.9%	+11.4/-11.4%	+28.3/-28.3%
(9) LXe optical property	+0.9/-6.7%	+0.9/-6.7%	+0.8/-6.7%	+1.5/-1.1%

After fiducial selection (standard cut + R(T)<38cm + R(PE)<20cm)

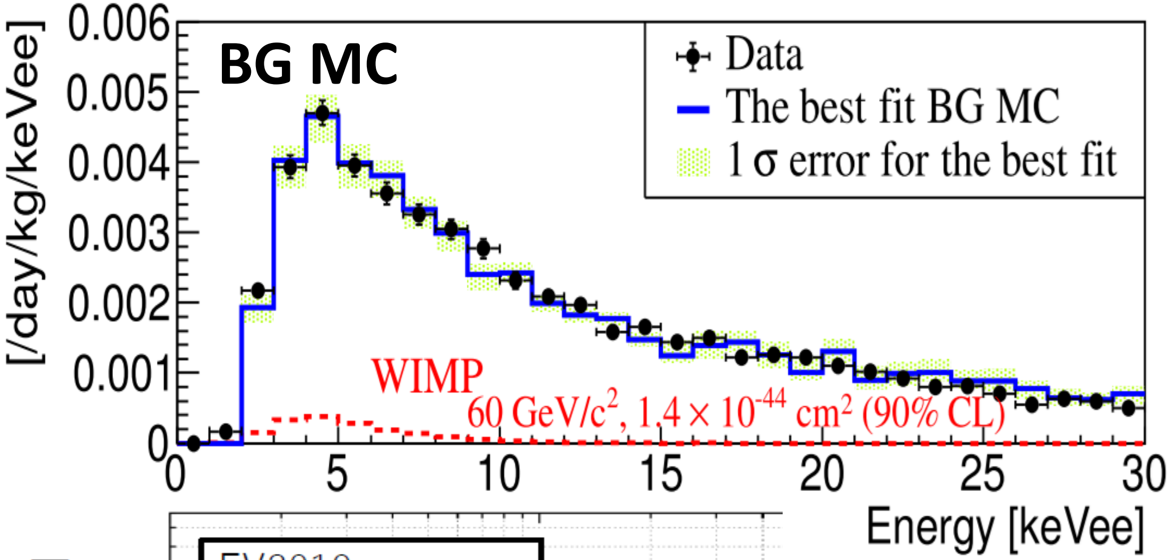


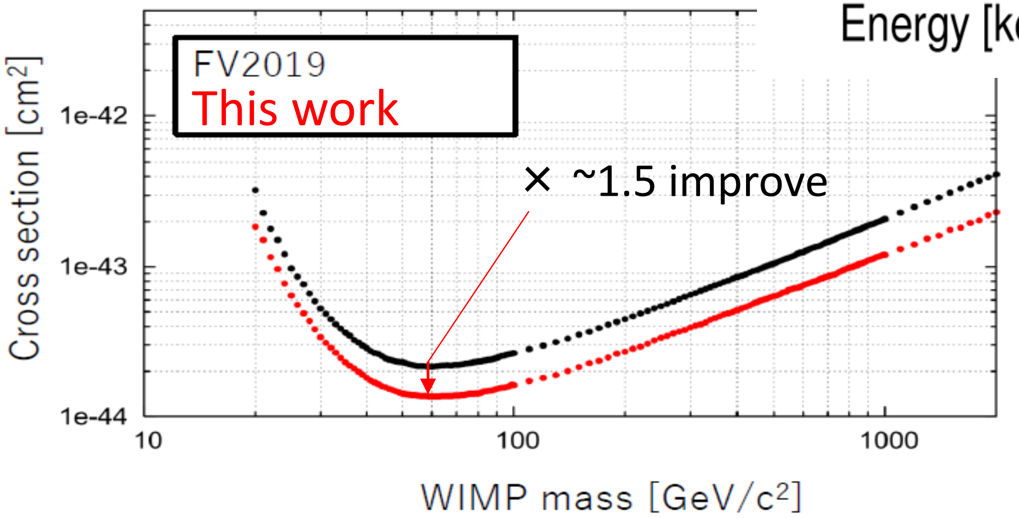
Results of fiducial volume analysis

- FV data was well explained by BG MC w/o WIMPs.
- 90% CL upper limits were derived.
- Factor 1.5 improve from 2019 results.

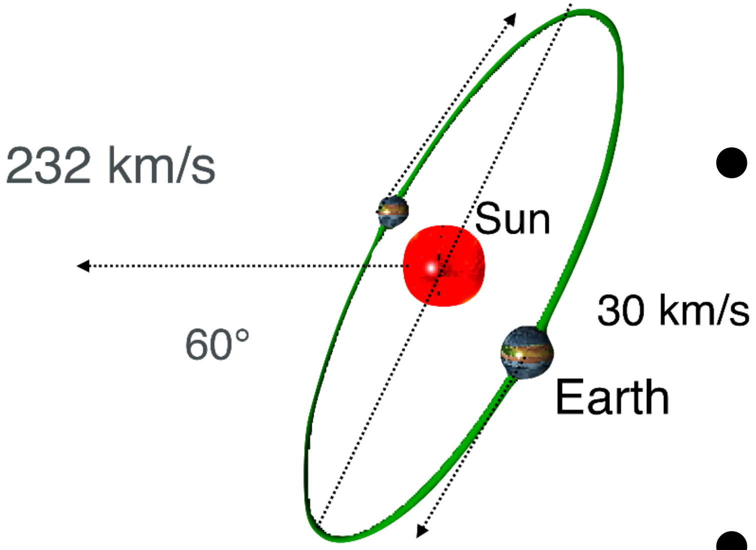


After fiducial selection (standard cut + R(T)<38cm + R(PE)<20cm)

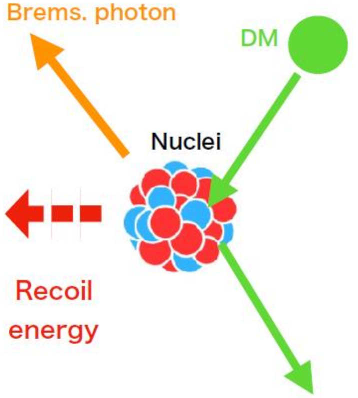




Modulation WIMP search



- Results so far by XMASS
  - Search for nuclear recoil:
    - **PRD 97, 102006 (2018)** : 2.7 years (800 live days)
  - Search for signal from Bremsstrahlung:
    - **PLB 795 (2019) 308-313** : 3.5 years (2.8 live years)
- In addition to update of above results, search for signal from Migdal effect was newly added.

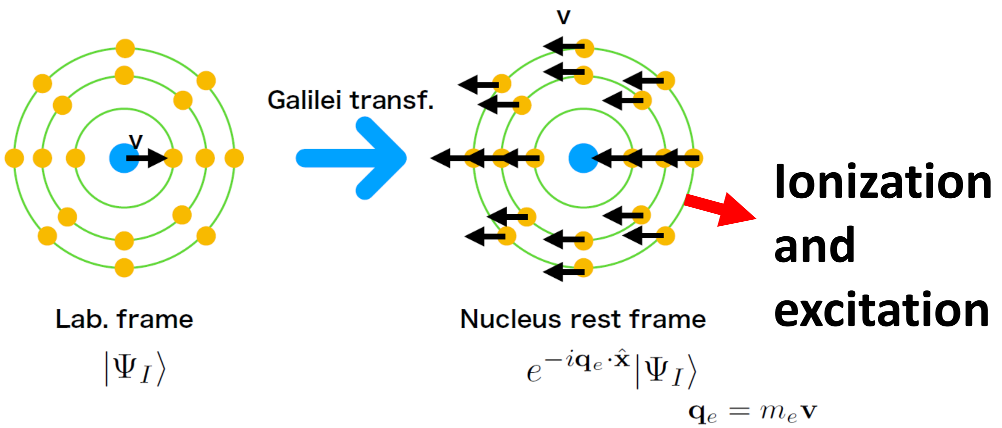


C. Kouvaris and J. Pradler PRL. 118, 031803

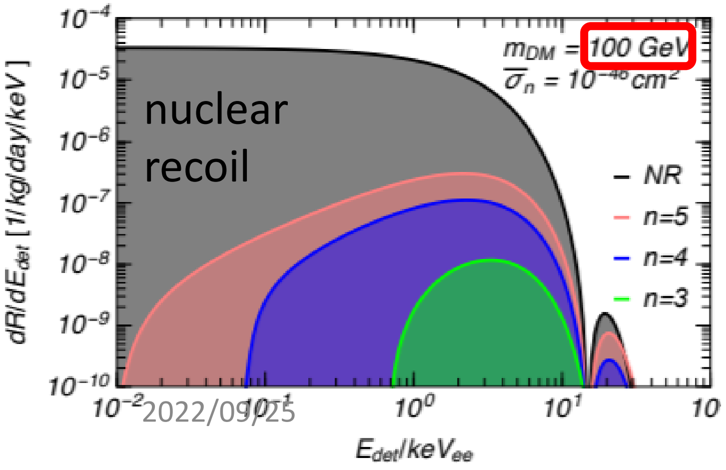
Migdal effect A. B. Migdal (1939)

$$Z_{FI}(q_e) = \langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle$$

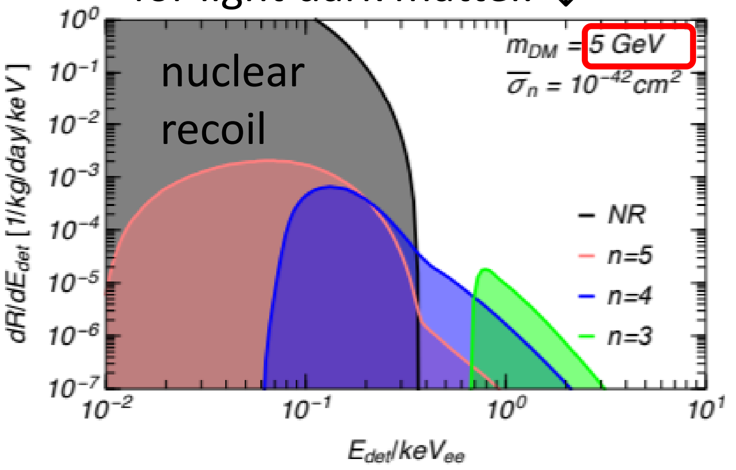
electron wave functions



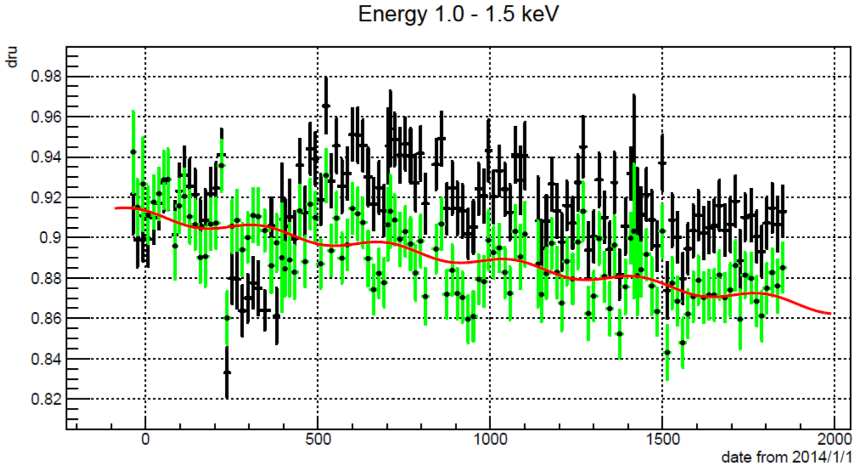
M.Ibe et al., arXiv:1707.07258v3 [hep-ph]

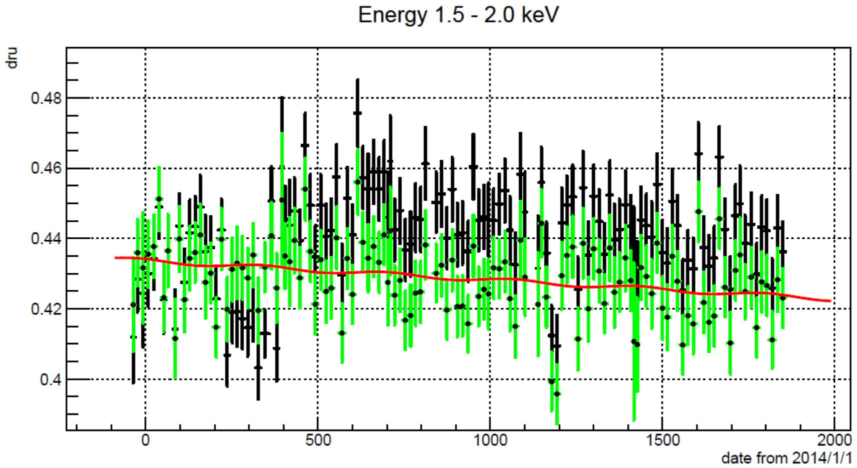


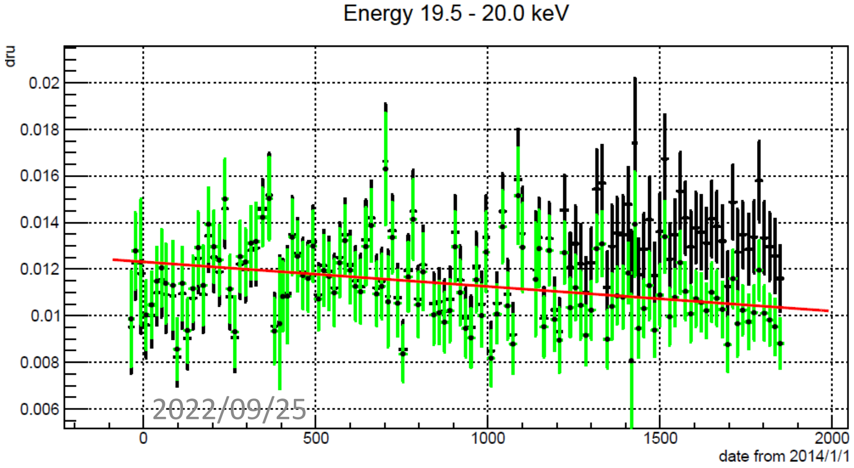
Larger energy loss is expected for light dark matter. ↓



Search for Migdal signal

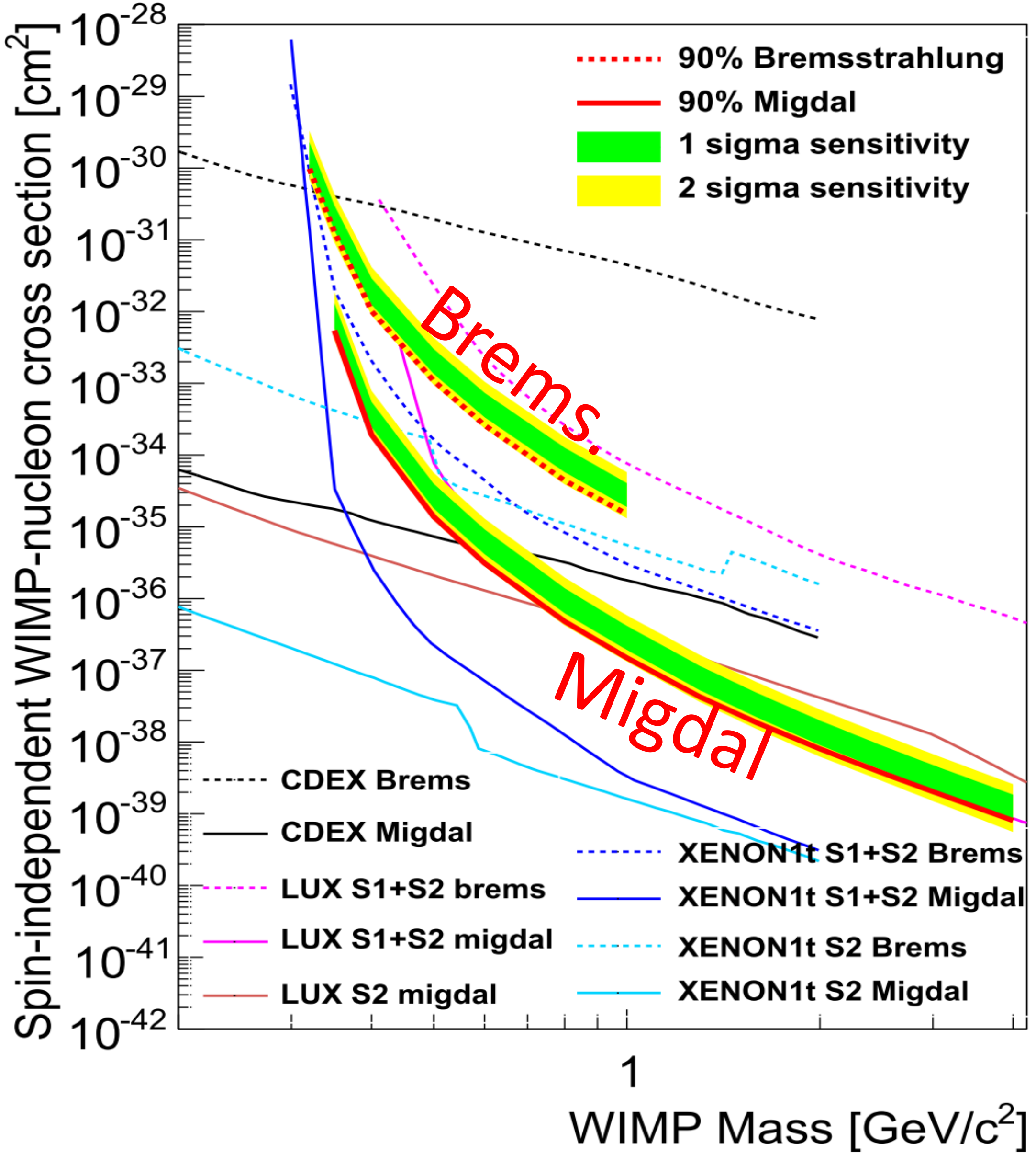






- Best fit result for Migdal signal.
- DM mass: 0.5 GeV/c^2.
- Data was fitted with BG (assume decrease over time) + signal (with modulation)
- 1~20 KeVee range
- **Observed data (black)** was **corrected (green)** considering PE yield change and increasing of dead PMTs.
- Linearly decreasing BG + modulated signal
- No significant signal was found and upper limits were derived.

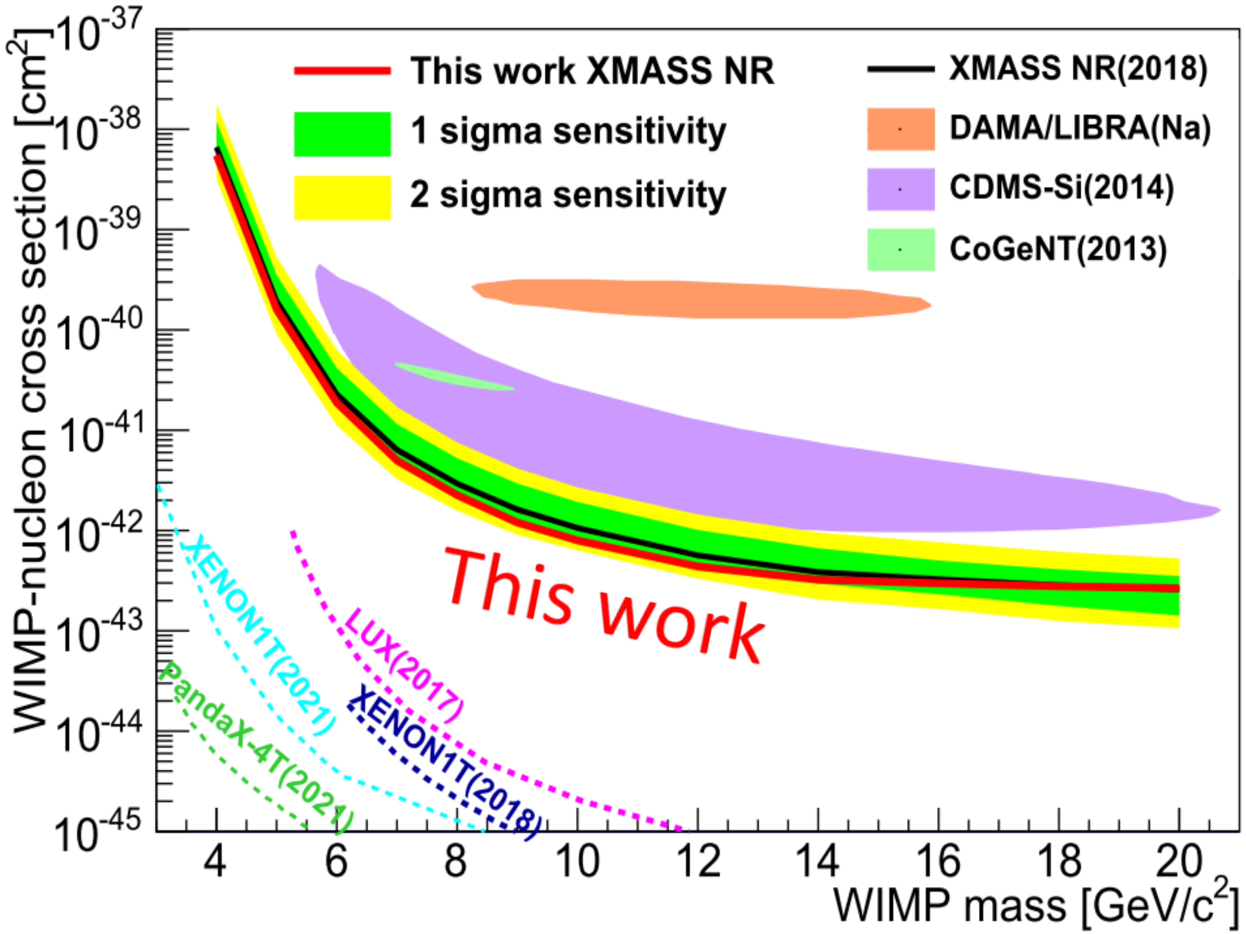
Results of Migdal and Brems. analysis



- 90% CL upper limits
- Sub-GeV region
  - 0.35~4 GeV/c^2 for Migdal
  - 0.32~1 GeV/c^2 for Brems.

- Migdal: new results
  - 2 orders better than Brems. as expected.
- Brems.: Factor ~2 improvement from XMASS 2018 results (PLB 795 (2019) 308-313)

Results of nuclear recoil analysis

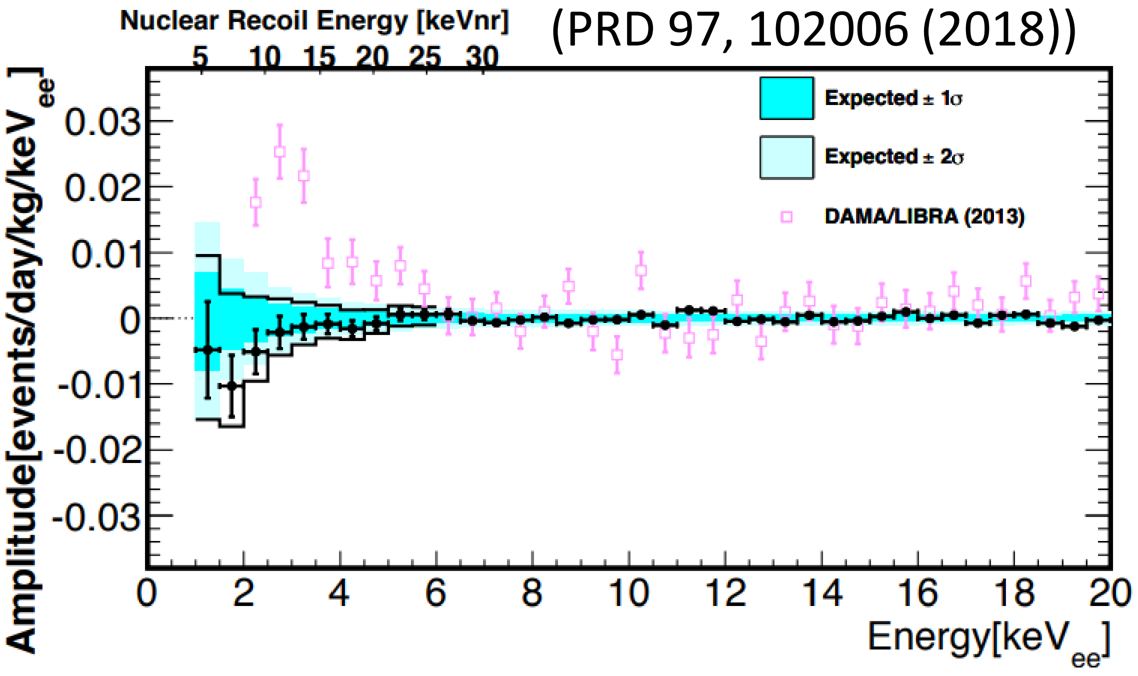


- Multi GeV region (4~20 GeV/c^2)
- Lowest energy bin was used:
  - 3 hits low threshold data
  - 0.5~20 keVee regions were searched
- At most ~1.4 improvement from 2018 XMASS results (PRD 97, 102006 (2018))

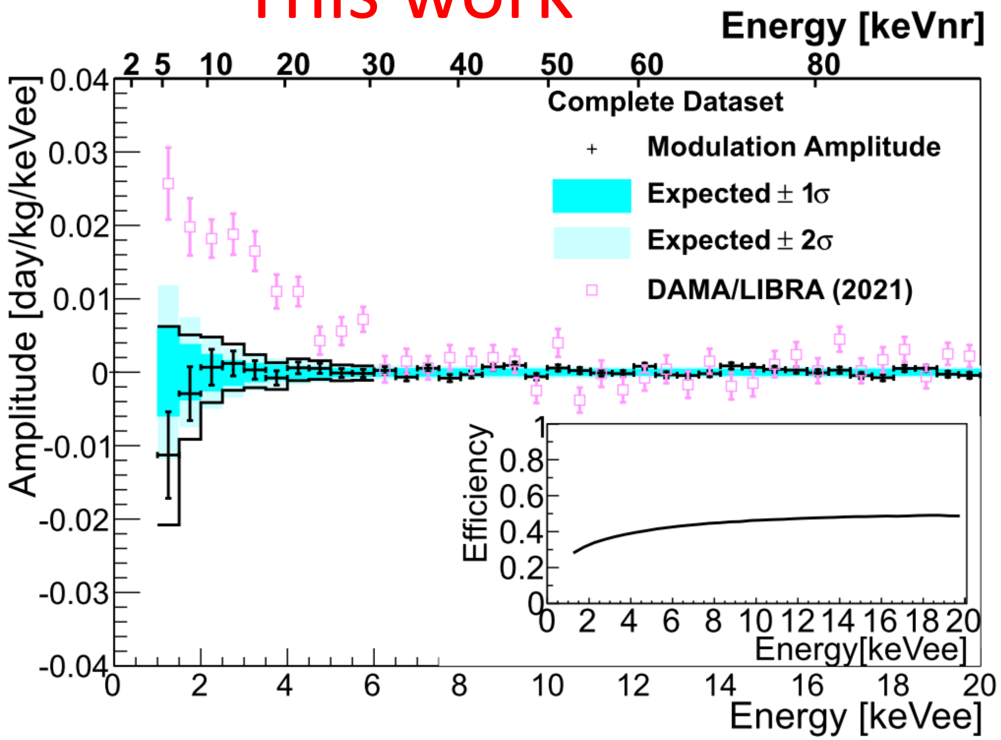
Results of model-independent analysis

- To look for variety of candidate, amplitude of modulation components was simply extracted.
- Cycle and period were fixed:
  - t_0 = 152.5 days (~Jun. 2nd) and T = 1 year

2018 XMASS results
(PRD 97, 102006 (2018))



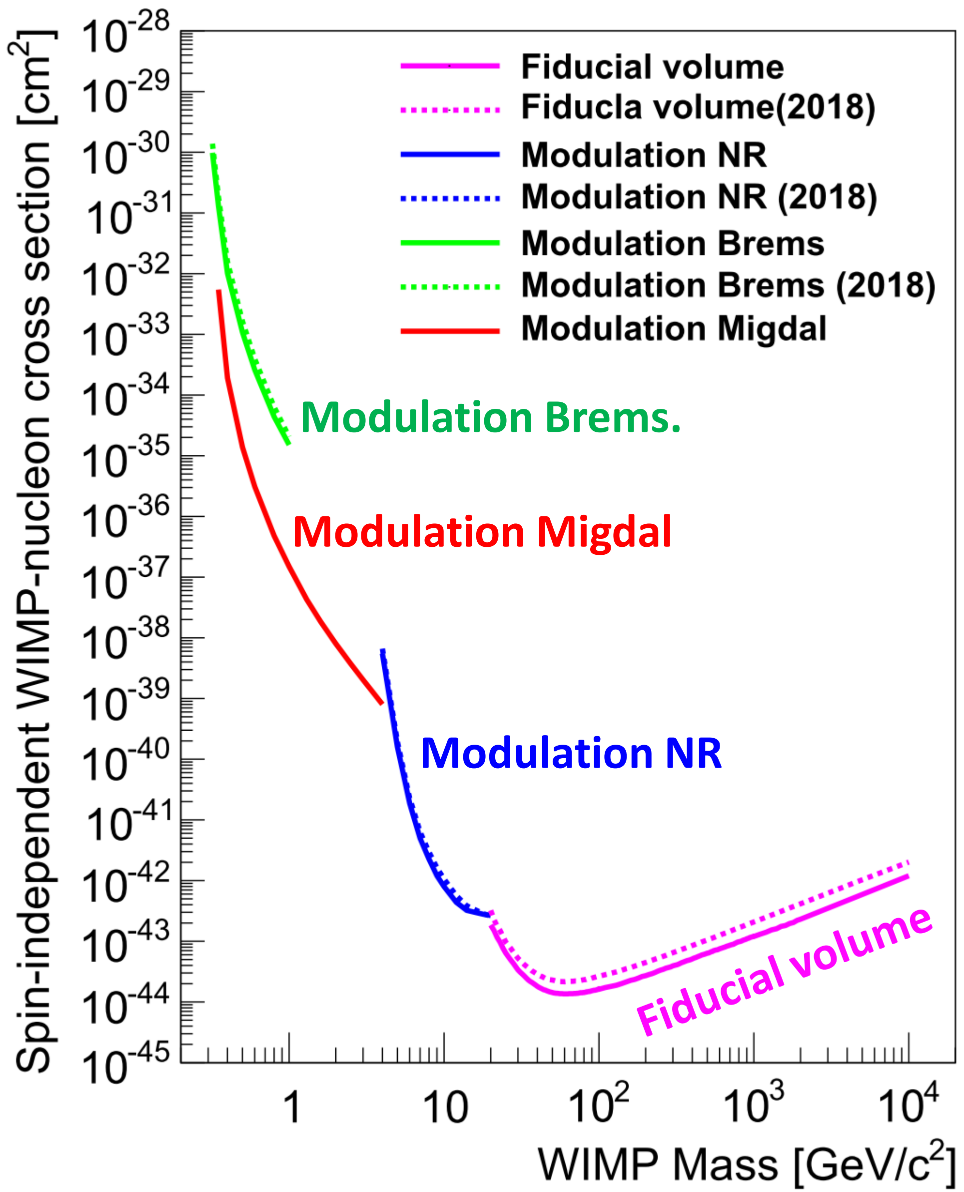
This work



Summary

- **XMASS-I experiment**
  - Unique experiment
  - Single phase, large volume liquid xenon detector.
  - 5 years long stable searches from 2013/11 to 2019/2
    - 1590.9 live days
    - Stable DAQ and detector status
- **Dark matter searches with full data set**
  - **Fiducial volume** analysis
    - Factor ~1.5 improve from 2019 results
  - Modulation analysis
    - Update **nuclear recoil**, **Brems.** and model independent
    - Add **Migdal effect** signal search
    - World best modulation limit
- **Paper was submitted (arXiv:2211.06204)**

Limits obtained from the various analyses



Backup

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

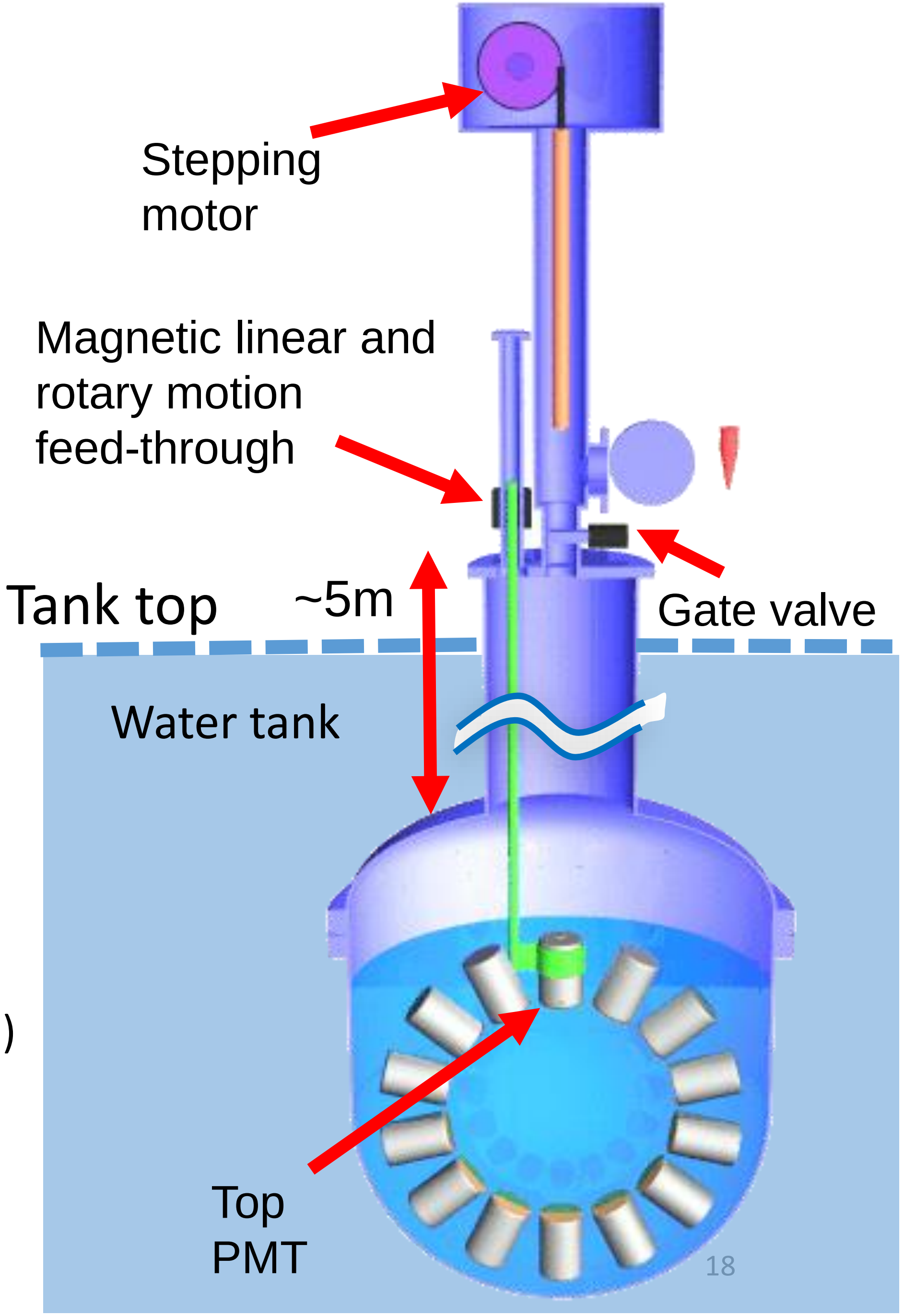
(*1) 4.2 keV (averaged) L-shell X-ray escape from 5.9 keV K-shell X-ray.
(*2) Tungsten K-shell X-ray used for detector housing.

^{57}Co source

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

Source rod (Ti)

Active region is concentrated on 1.8 mm edge region



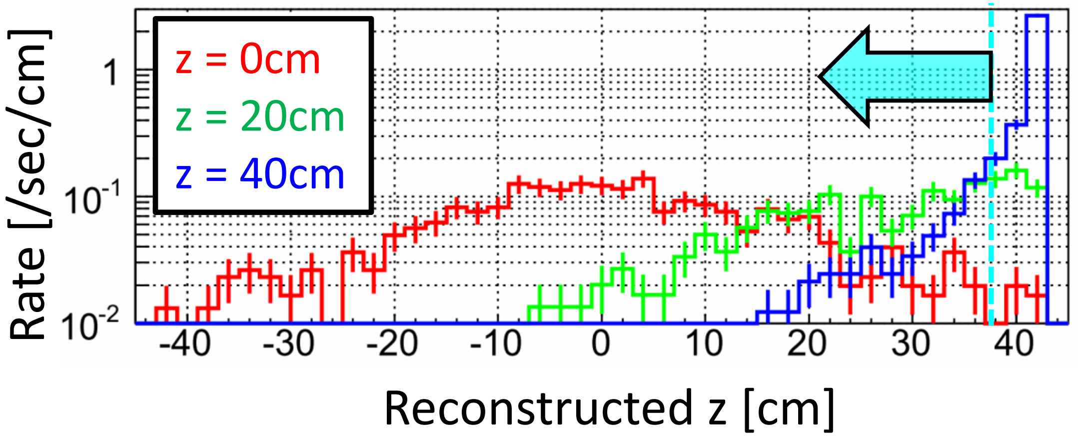
Vertex reconstruction (based on timing, R(T))

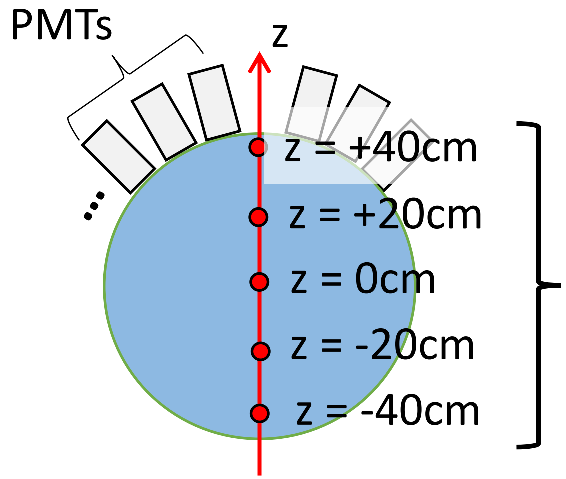
- Using FADC hit timing of each PMT.
- Timing constant for 2–10 keV events: 25±2ns.
- Position reconstruction is done by using likelihood method from probability density function for each PMT.

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

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.

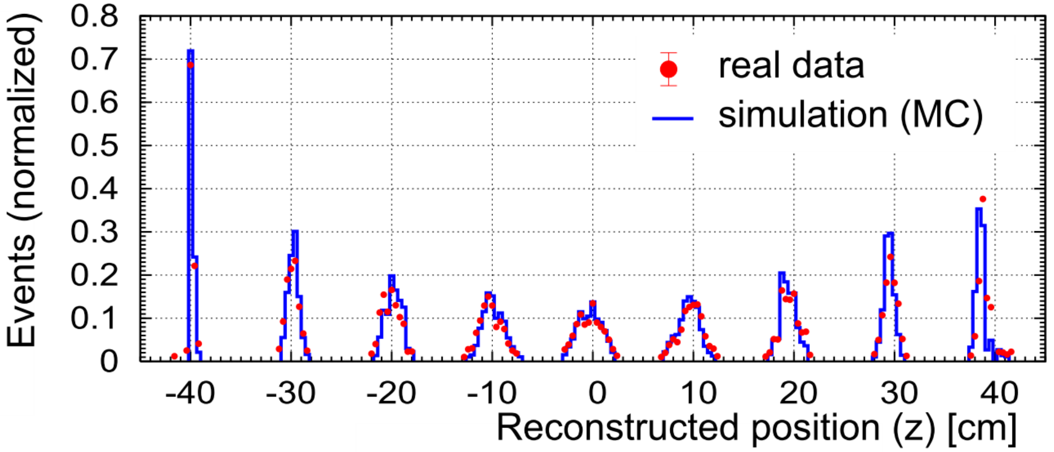
Vertex reconstruction (based on photo electron, R(PE))

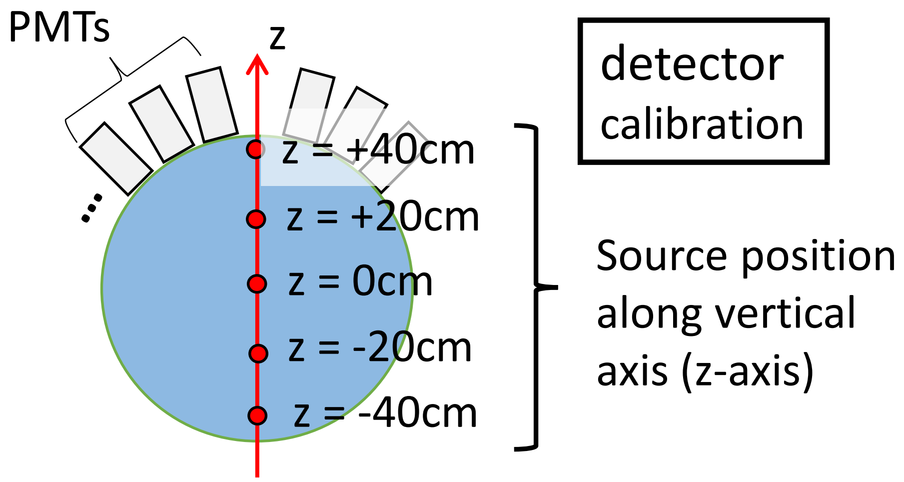
- Position reconstruction
  (1) Making acceptance map: Many grid points are defined inside whole detector volume including detector surface. Events are generated at each grid point and photo-electrons (pe) expected in each PMT are calculated by our MC.
  (2) From measured pe and scaled acceptance map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

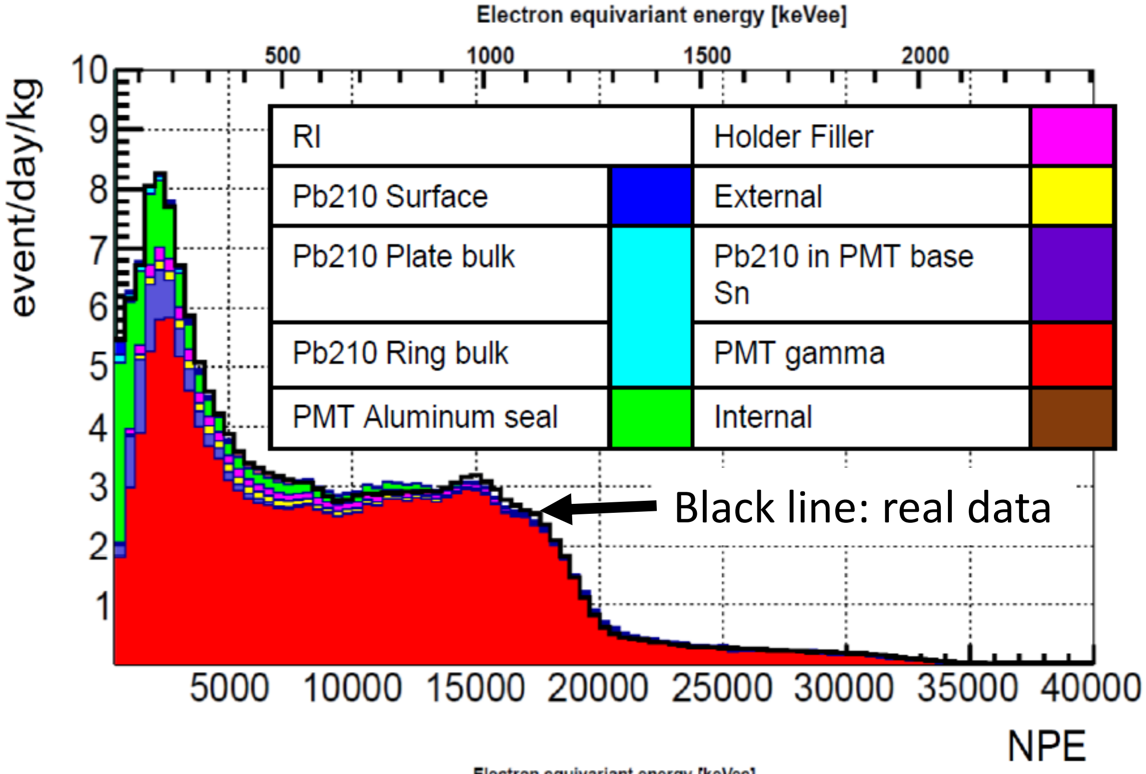
ex. RI screening results
for PMT with HPGe detector.

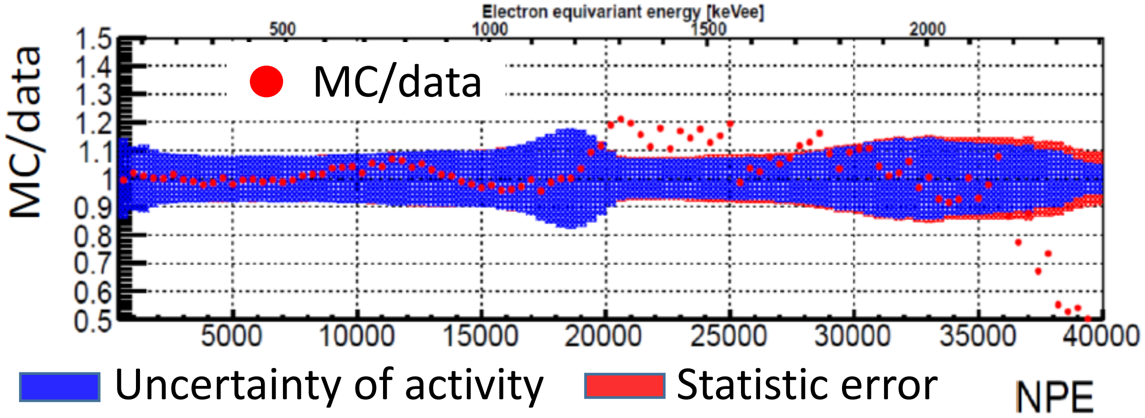
- PMT aluminum seal

	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



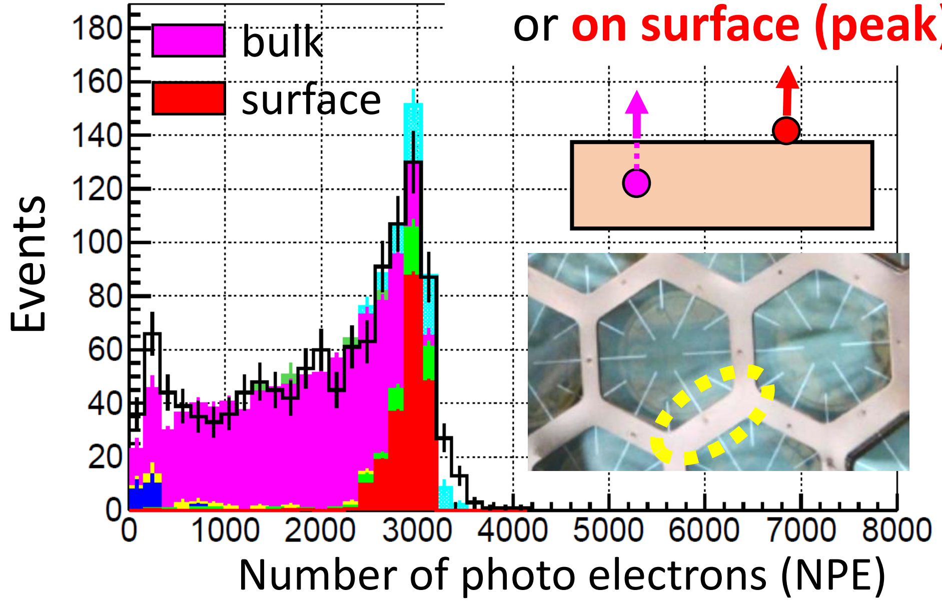


Evaluation of RI activities in XMASS-I (2/2)

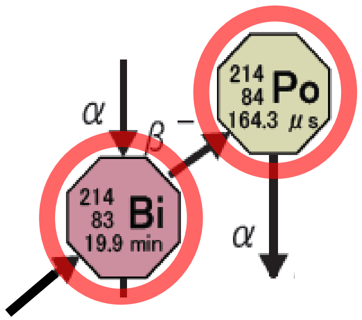
- **^{210}Pb in copper surface and bulk**
  - α events selection from scintillation decay time.
  - ^{210}Pb in copper surface/bulk were estimated from shape of energy spectrum caused by ^{210}Po α decay.
  - ^{210}Pb in the bulk of OFHC copper was also measured independently by a low background α-particle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

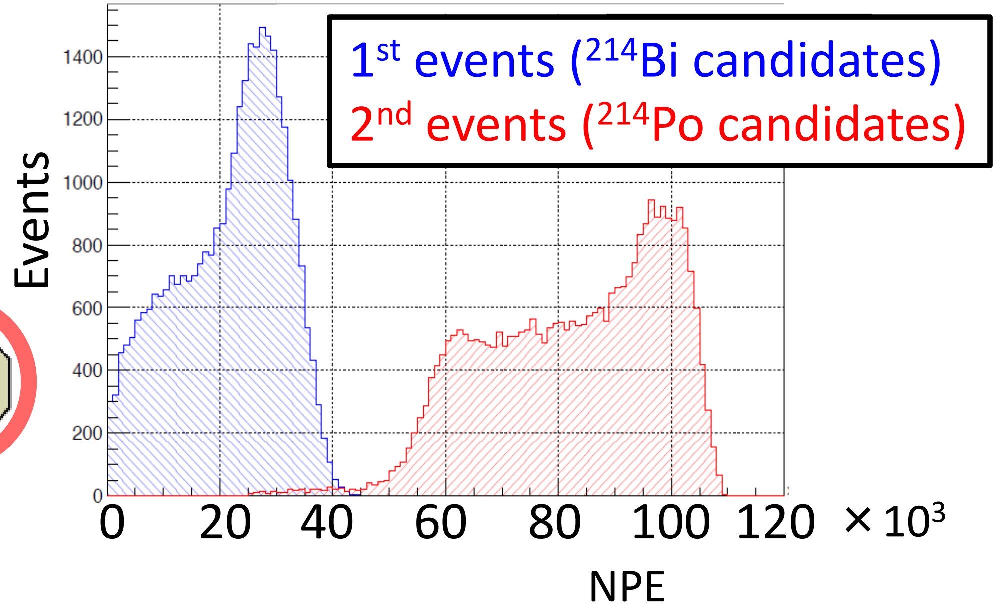
- **RI in liquid xenon**
  - Coincidence analysis was used.
    - ^{222}Rn: ^{214}Bi – ^{214}Po (164 us)
    - ^{85} Kr: β–γ (1.015 us, 0.343%)
  - ^{14}C and ^{39}Ar were estimated from spectrum fitting.

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



Down stream of ^{222}Rn

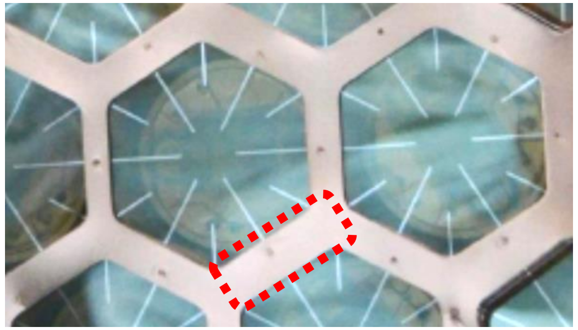




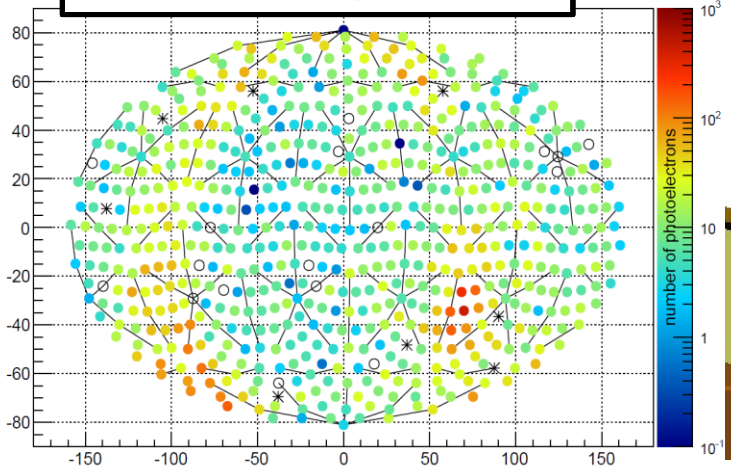
Miss-identified events

- 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.

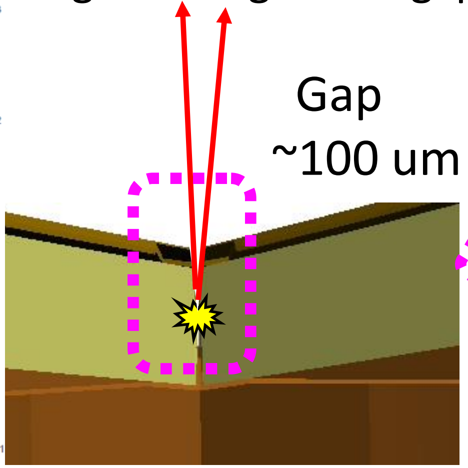
Structure around PMT



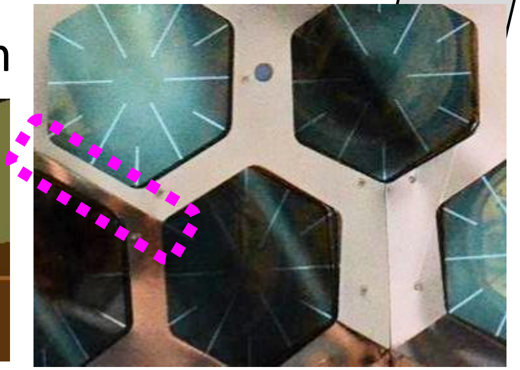
PE pattern of gap event

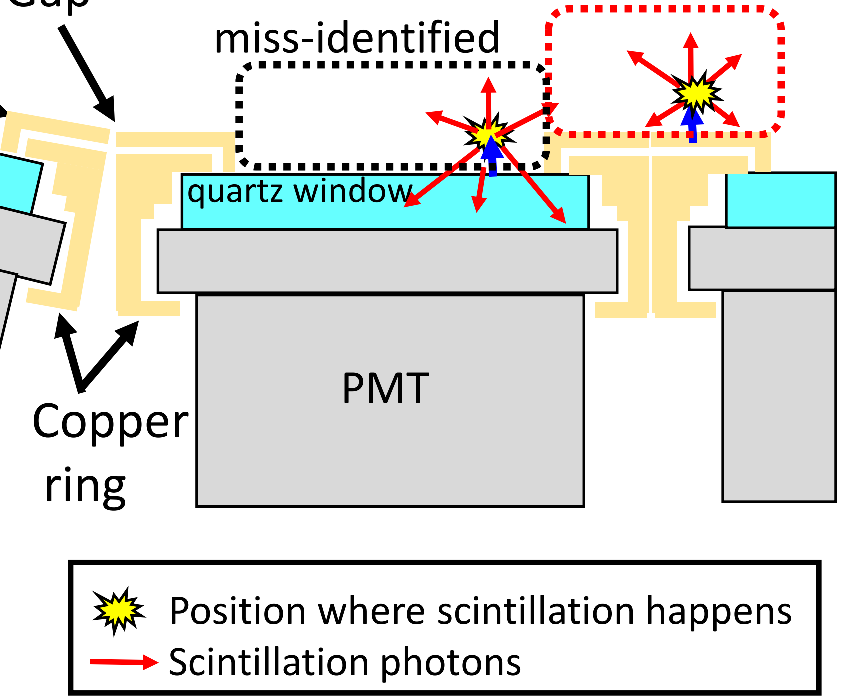


Light leakage from gap



Gap
~100 um



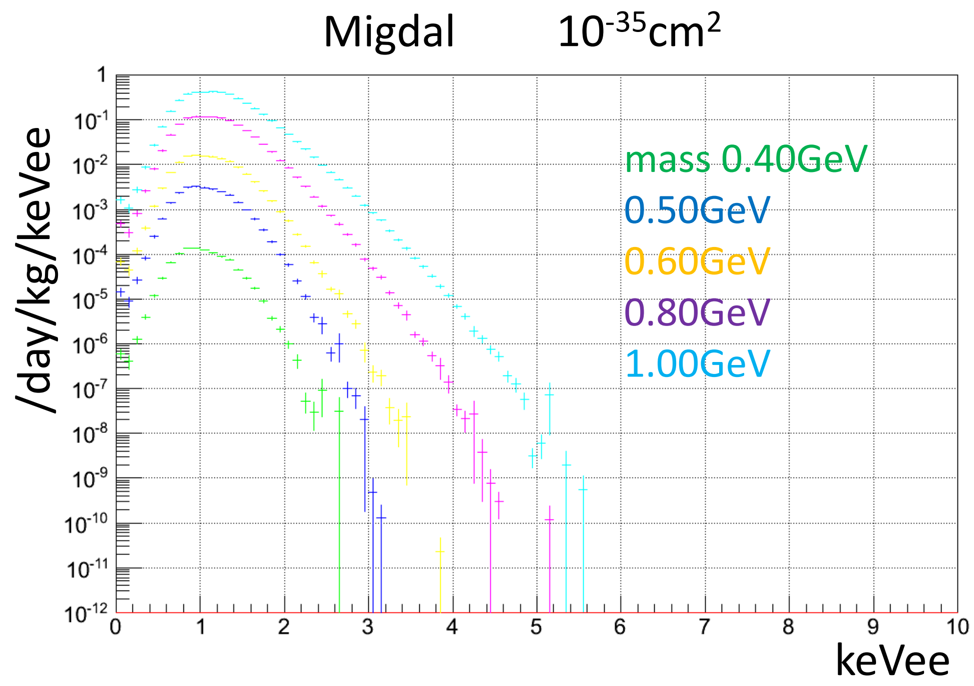


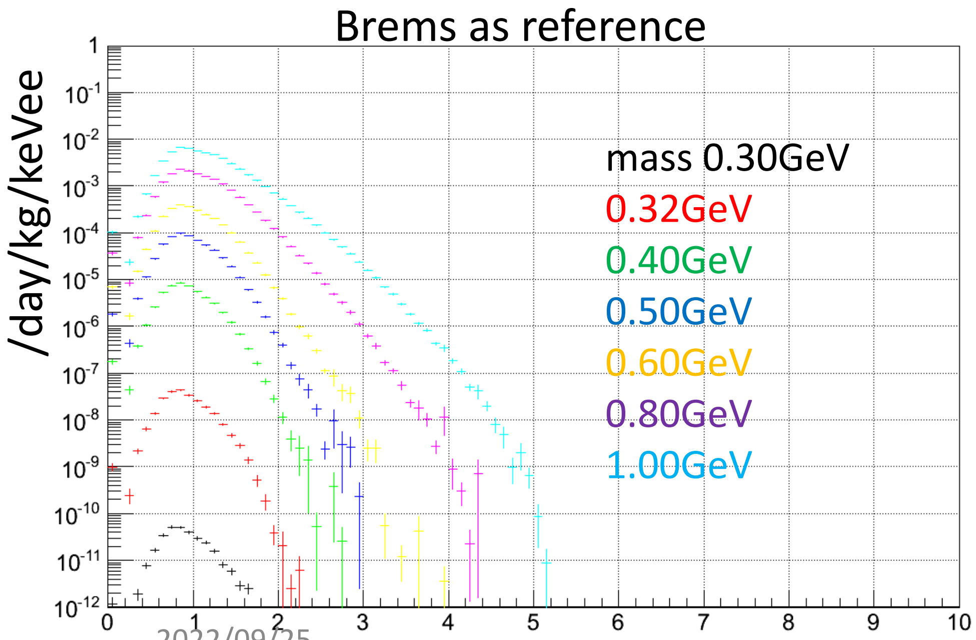
Systematic error evaluation

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) Uncertainty for scintillation decay time and response of PMT.
- (8) Effect of dead PMTs (from 7 to 18 over the total data-taking period)
- (9) Optical parameters of liquid xenon.

Component	Evaluated systematic errors			
	2-5 keV_{ee}	5-10 keV_{ee}	10-15 keV_{ee}	15-30 keV_{ee}
(1) Plate gap	+9.1/-33.4%	+5.2/-19.1%	+3.1/-11.3%	+1.6/-6.0%
(2) Ring roughness	+9.7/-10.3%	+5.6/-5.9%	+3.3/-3.5%	+1.8/-1.9%
(3) Cu reflectivity	+3.6/-0.0%	+5.9/-0.0%	+4.4/-0.0%	+2.4/-0.0%
(4) Plate floating	+0.0/-6.7%	+0.0/-3.8%	+0.0/-2.3%	+0.0/-1.2%
(5) PMT aluminum seal	+1.0/-1.0%	+0.3/-0.3%	+0.0/-0.0%	+0.0/-0.0%
(6) Reconstruction	+8.9/-8.9%	+1.4/-7.8%	+2.8/-2.8%	+2.8/-2.8%
(7) Timing response	+3.1/-9.9%	+7.6/-11.3%	+0.4/-5.3%	+0.4/-5.3%
(8) Dead PMT	+7.5/-7.5%	+11.9/-11.9%	+11.4/-11.4%	+28.3/-28.3%
(9) LXe optical property	+0.9/-6.7%	+0.9/-6.7%	+0.8/-6.7%	+1.5/-1.1%





Modulation analysis with Migdal effect

- Step of expected signal calculation
  1. **Expected energy loss calculation**
     1. Energy from emitted electron and de-excitation are considered separately.
     2. Calculate energy loss spectrum for each.
  2. **Apply detector response**
     1. Apply MC based response to each energy loss.
     2. Only above 1 keVee energy loss was used.
     3. Limit from our detector calibration (escape X-ray from 55Fe)
     4. De-excitation component was negligible.

- Two order large expected signal than Bremsstrahlung.