THE XMASS EXPERIMENT

MAR. 8TH, 2019

Y. KISHIMOTO ON BEHALF OF XMASS COLLABORATION

KAMIOKA OBS., ICRR, THE UNIV. OF TOKYO

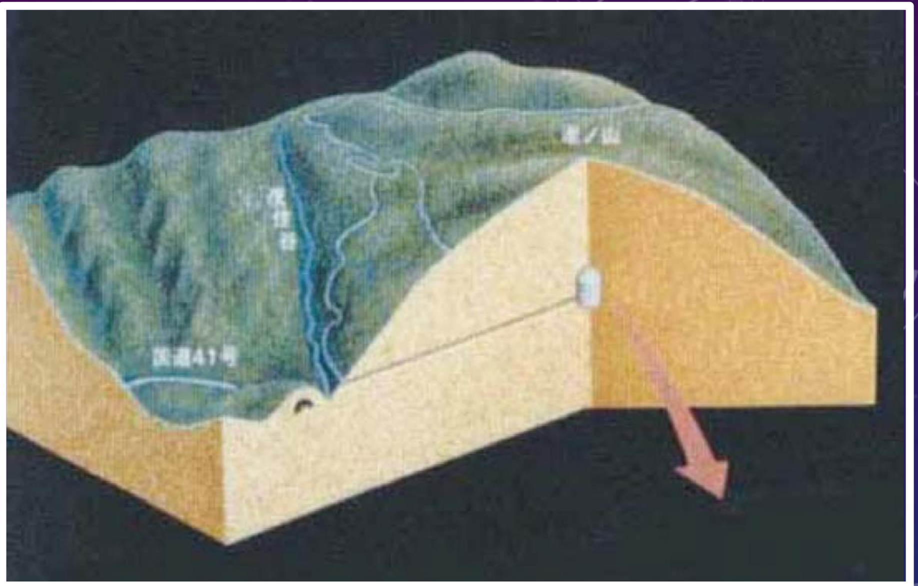
KAVLI IPMU, THE UNIV. OF TOKYO

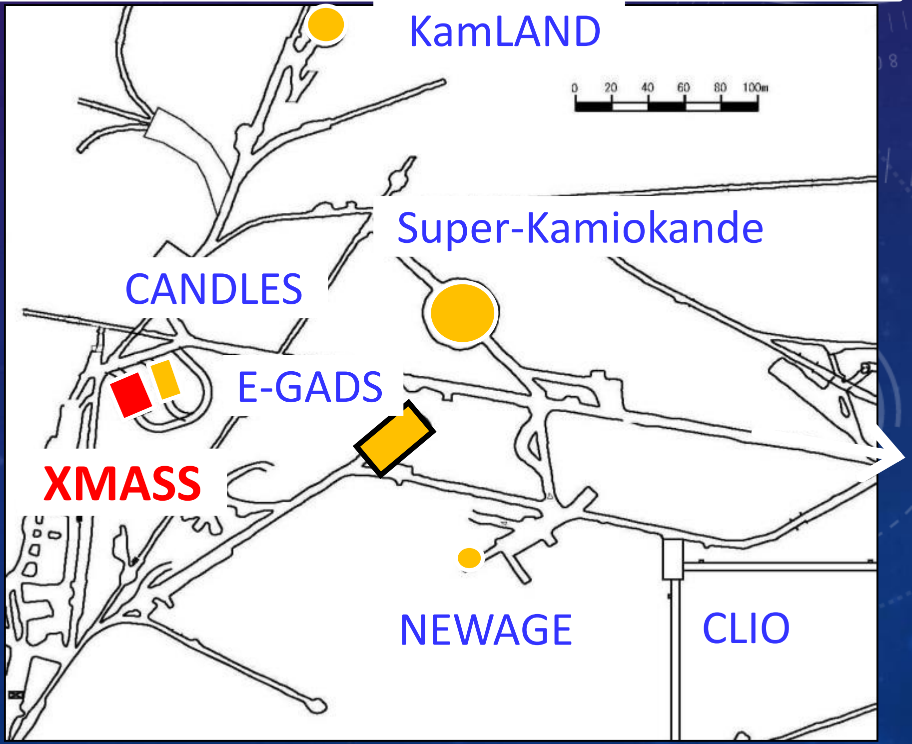
CONTENTS

- XMASS project
- Physics results from XMASS
- Low background technique in XMASS
- Summary

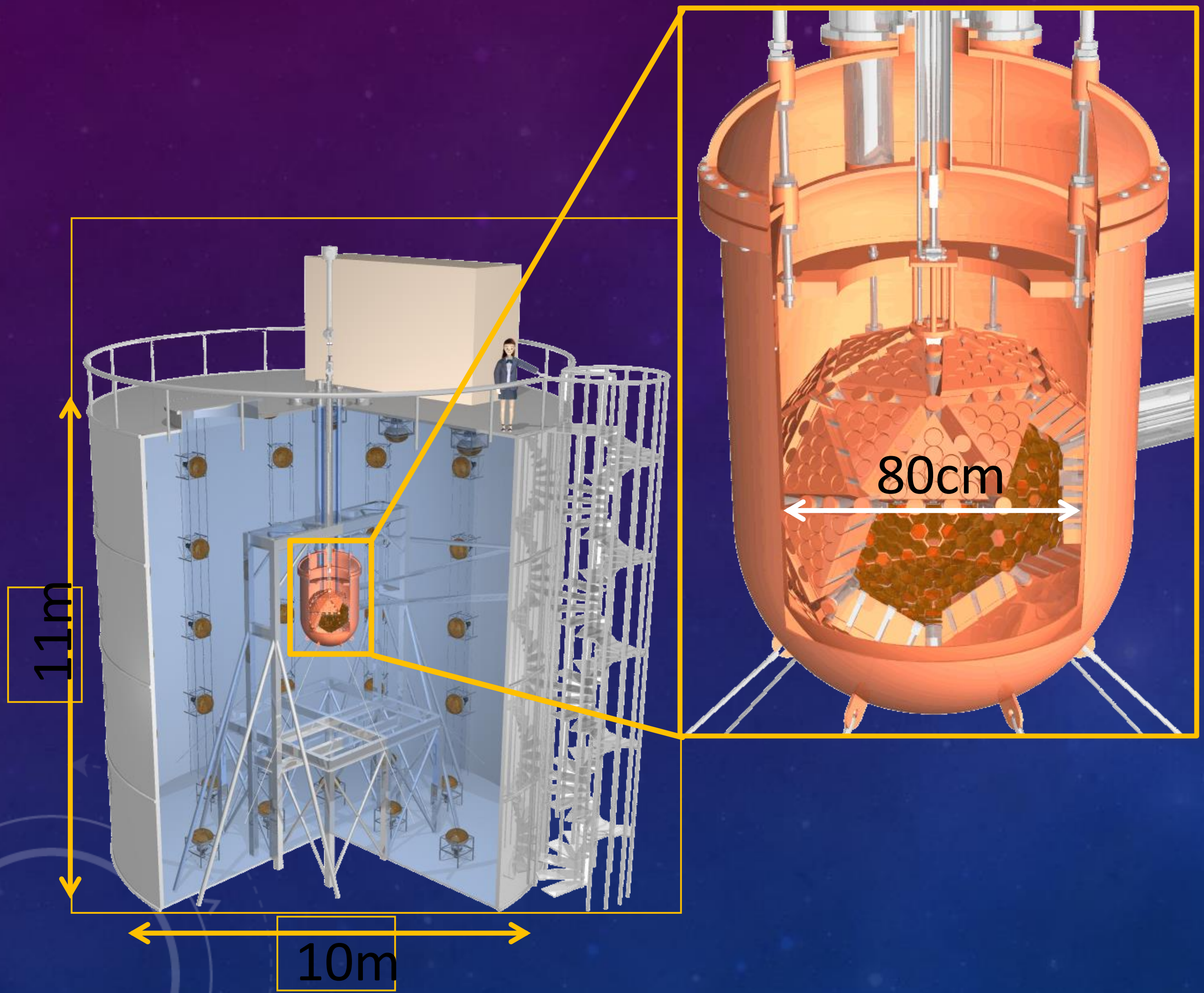
THE XMASS PROJECT

- XMASS: a multi purpose experiment with liquid xenon
  - Dark matter
  - Solar neutrino (pp/7Be)
  - 0ν ββ
- Located 1,000 m underground (2,700 m.w.e.) at the Kamioka Observatory in Japan
- Features
  - Scalability
  - Low energy threshold (~0.5keVee)
  - Sensitive to e/γ events as well as nuclear recoil





XMASS-I DETECTOR



- **Liquid xenon detector**
  - 832 kg of liquid xenon (-100 ^{o}C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers
- **Water Cherenkov detector**
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ

HISTORY OF XMASS-I DATA-TAKING

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

Dec.

May

Nov.

Run end on Feb. 20th

Const-ruction

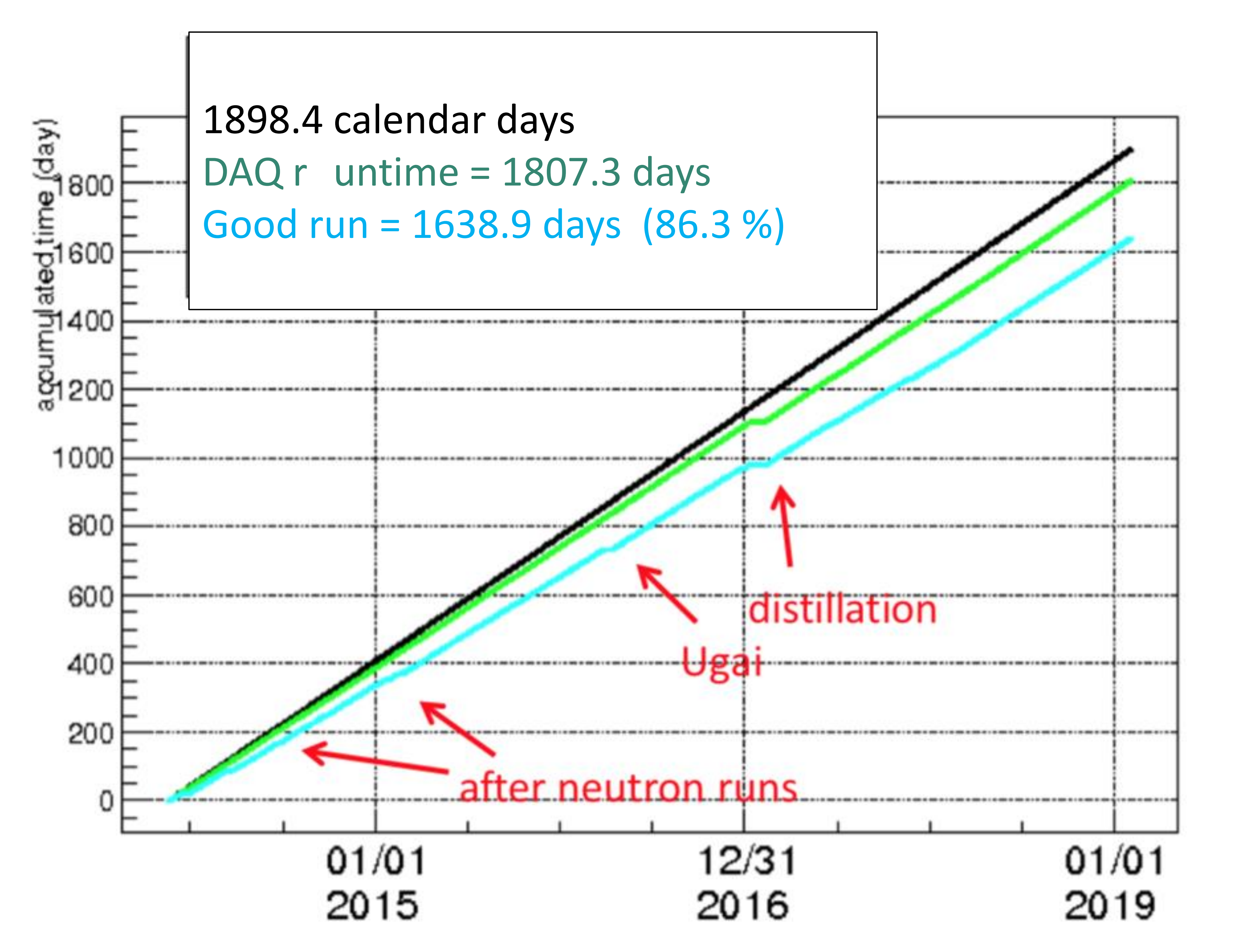
Commissioning data taking

Detector refurbish

Data taking

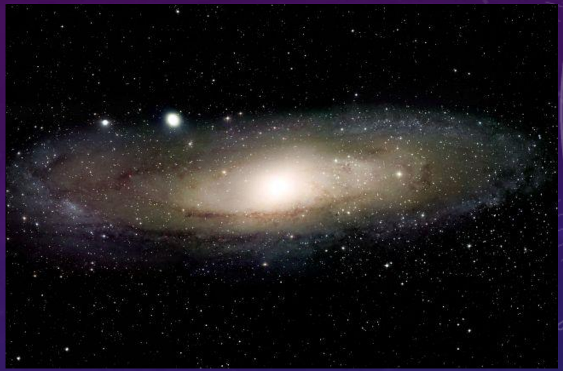
Rn calibration Feb. 1st ～20th.

- **Stable data taking from 2013 Nov. to 2019 Feb. (LT=1807.3 day)**
- **We achieved the objectives of XMASS-1 and shut down on Feb. 20th, 2019.**

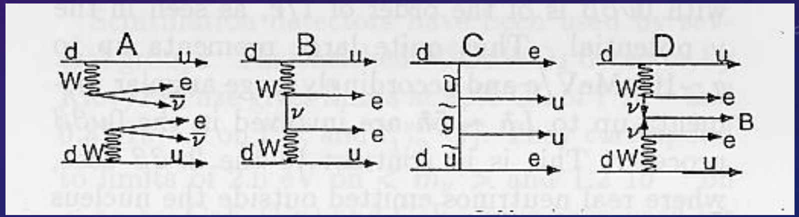


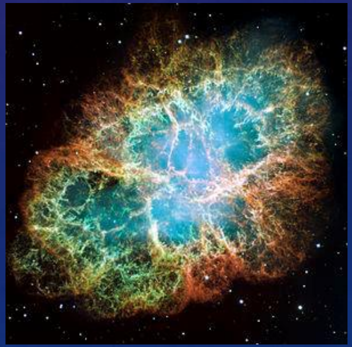
1898.4 calendar days
DAQ r untime = 1807.3 days
Good run = 1638.9 days (86.3 %)
accumulated time (day)
0
200
400
600
800
1000
1200
1400
1600
1800
01/01
2015
12/31
2016
01/01
2019
distillation
Ugai
after neutron runs

ACHIEVEMENTS IN XMASS-I



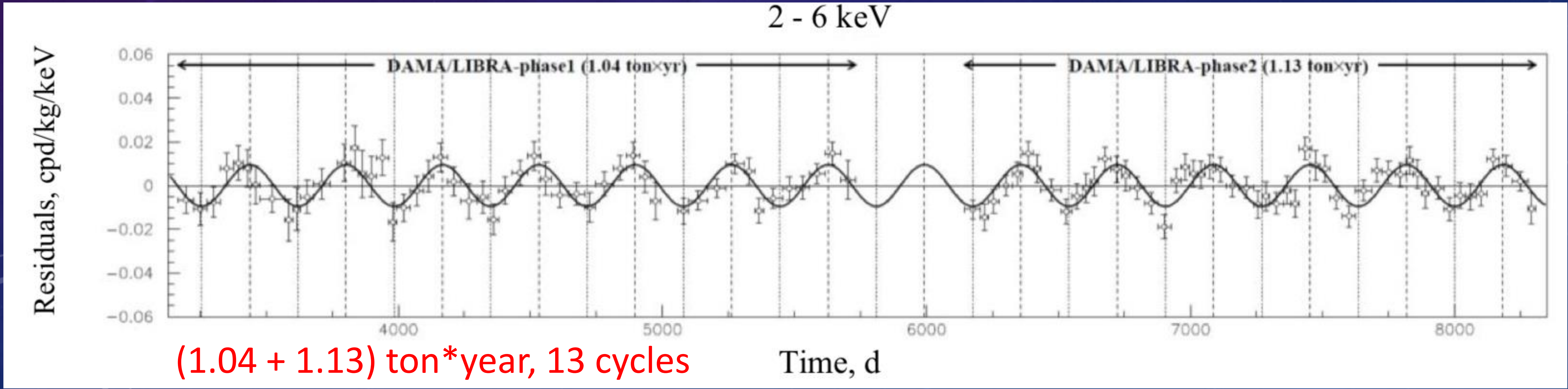
- Dark matter searches
- Neutrino studies
- Other exotic physics (Axion, …)
  - Solar axion, KK axion,
- Neutrino observatory
- Low background technology





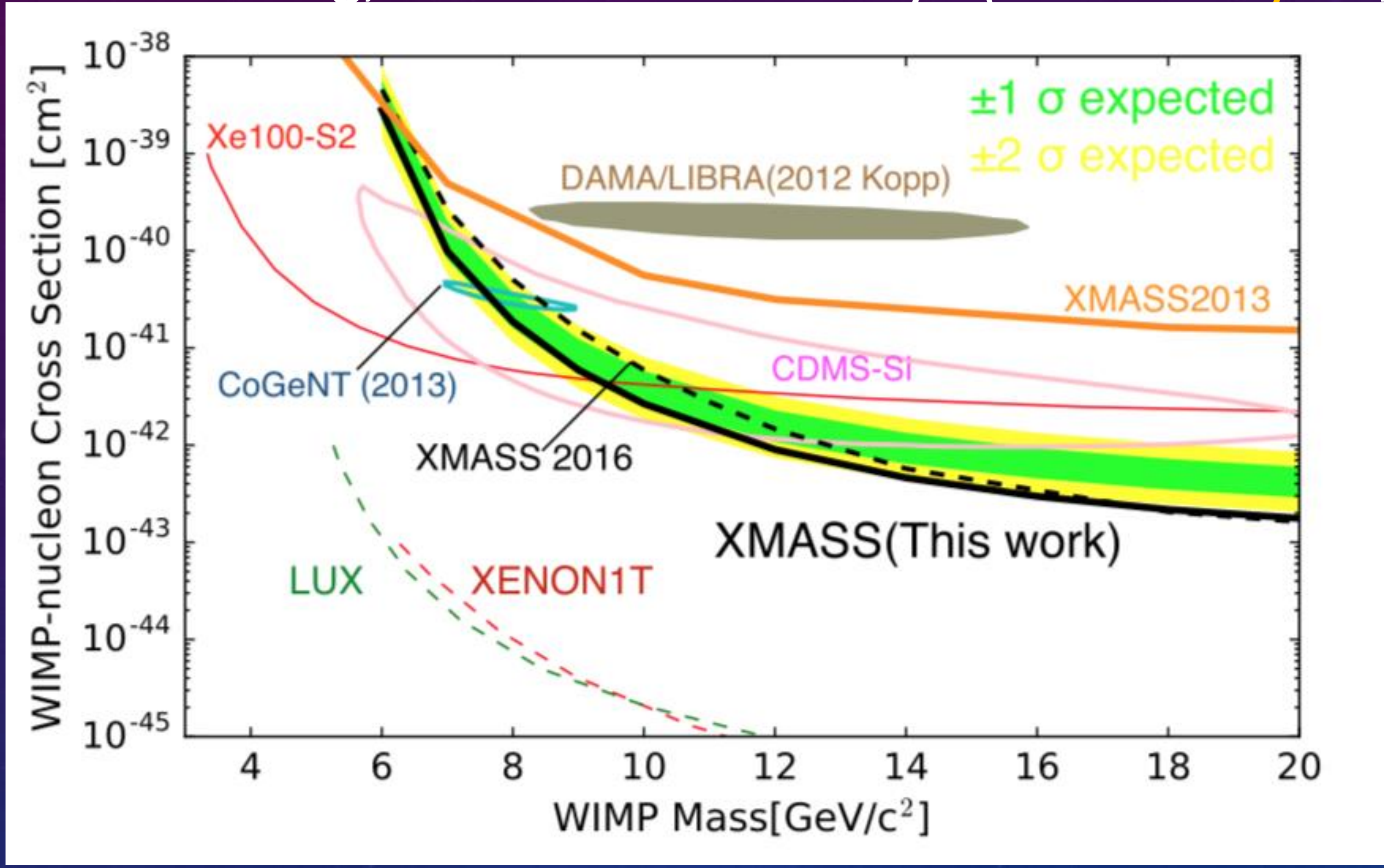
DARK MATTER SEARCHES IN XMASS-I -- ANNUAL MODULATION

- DAMA/LIBRA's claim (https://doi.org/10.15407/jnpae2018.04.307)
  - The data of the new DAMA/LIBRA-phase2 confirm a peculiar annual modulation of the *single-hit* scintillation events in the (1 - 6) keV energy region satisfying all the many requirements of the DM annual modulation signature; …

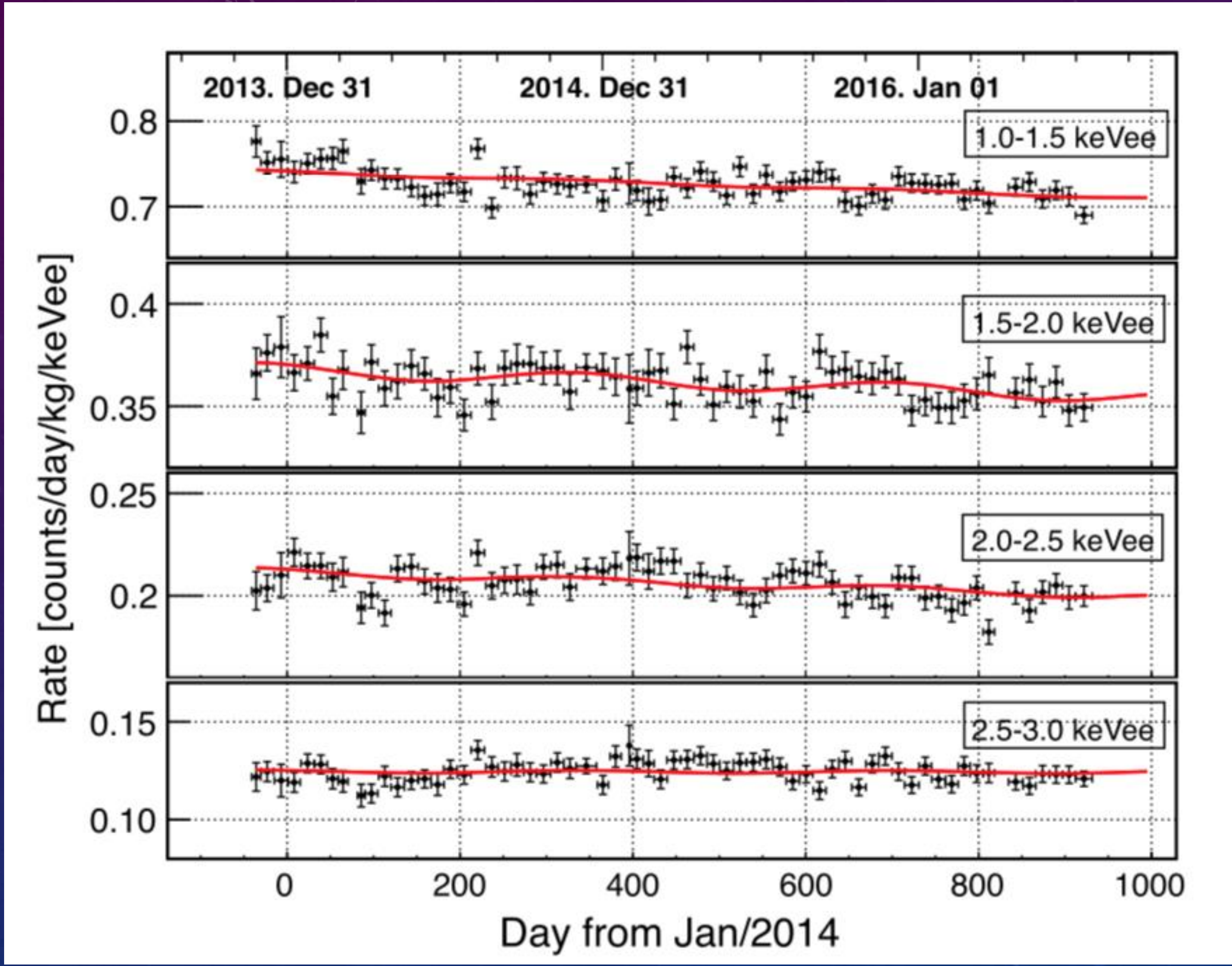


(1.04 + 1.13) ton*year, 13 cycles

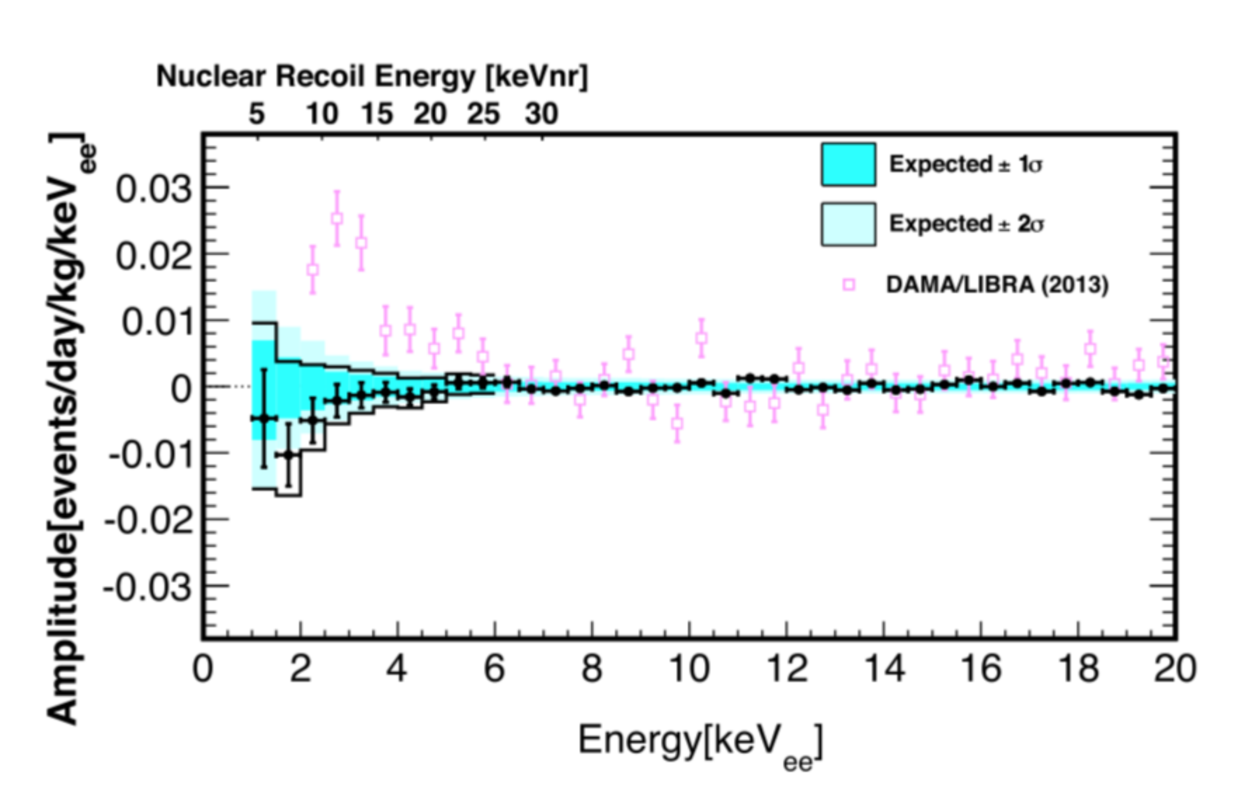
- Annual modulation search with the XMASS (10.1103/PhysRevD.97.102006)
  - Target volume = 800 kg, Livetime = 800 days (1.82 ton*year, 2.2 cycle)

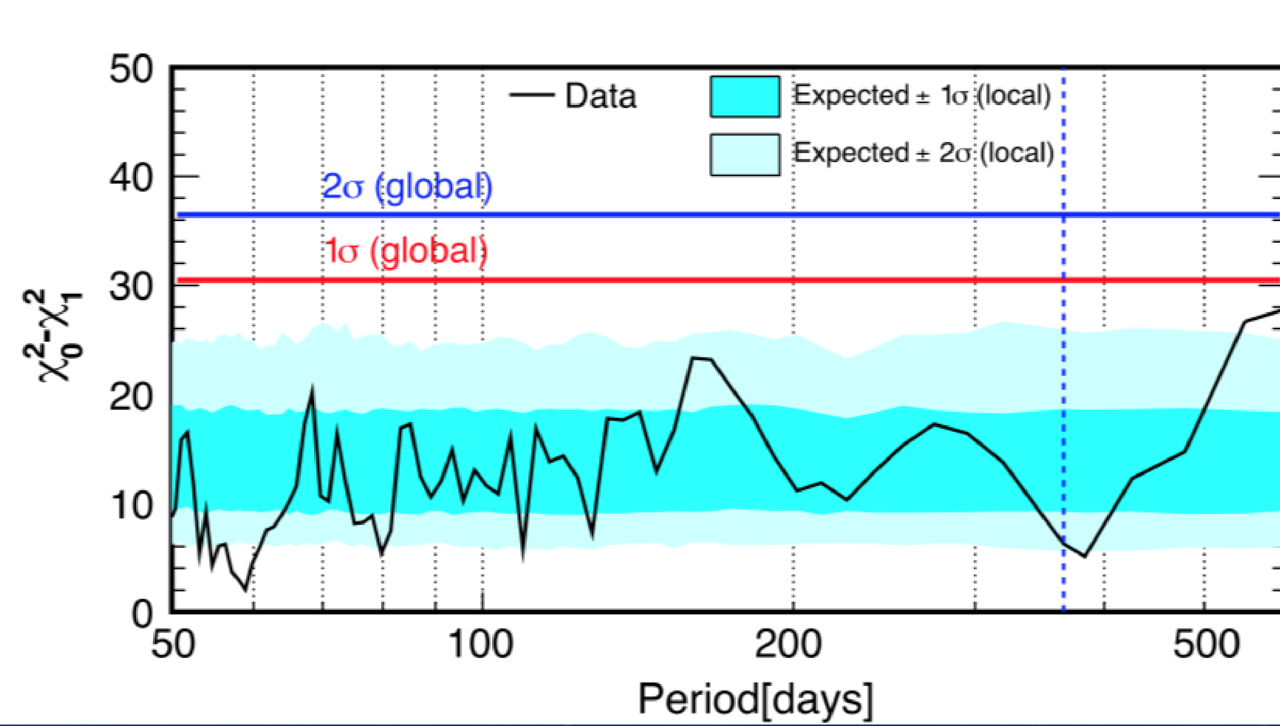


Assuming WIMP DM, we excludes DAMA/LBRA allowed region at 3σ level by annual modulation.


2013. Dec 31
2014. Dec 31
2016. Jan 01
1.0-1.5 keVee
1.5-2.0 keVee
2.0-2.5 keVee
2.5-3.0 keVee
Rate [counts/day/kg/keVee]
Day from Jan/2014
0.8
0.7
0.4
0.35
0.25
0.2
0.15
0.10
0
200
400
600
800
1000

In model independent analysis, we found no periodicity in data.





DARK MATTER SEARCHES IN XMASS-I -- ANALYSIS WITH EVENT RECONSTRUCTION

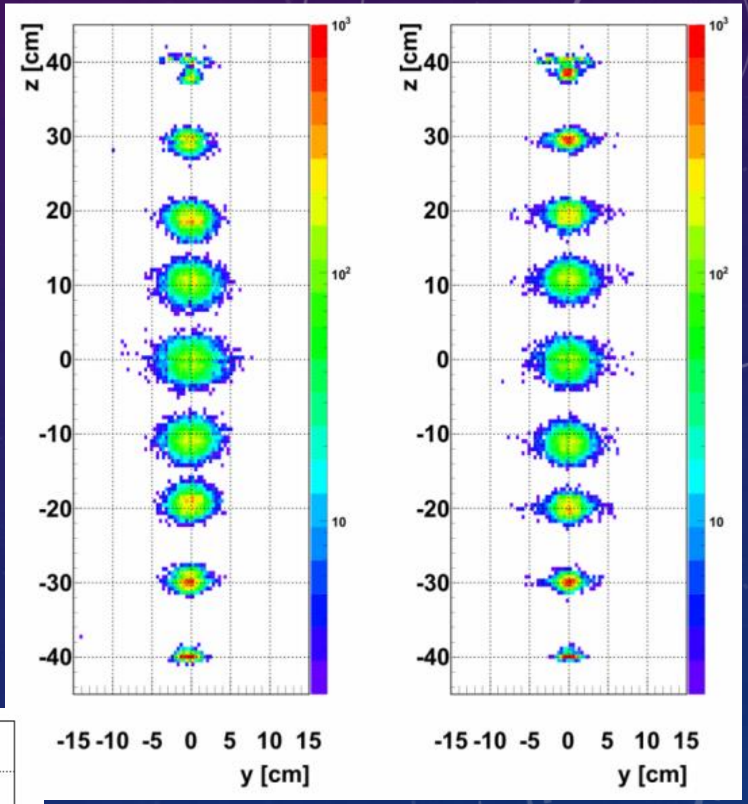
- Event reconstruction in XMASS:
  - Event energy and position can be reconstructed with numbers of P.E. in each PMTs.

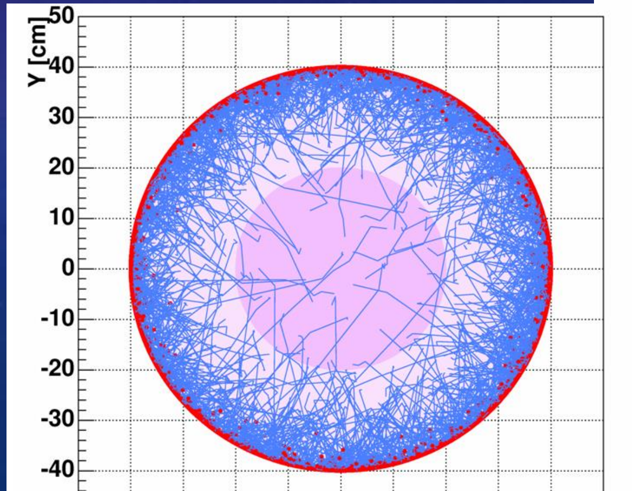
$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

p_i (n) : probability that the *i*-th PMT detects *n* PE

- Strong self-shielding could lead small numbers of BG at the center region, r<20 cm.

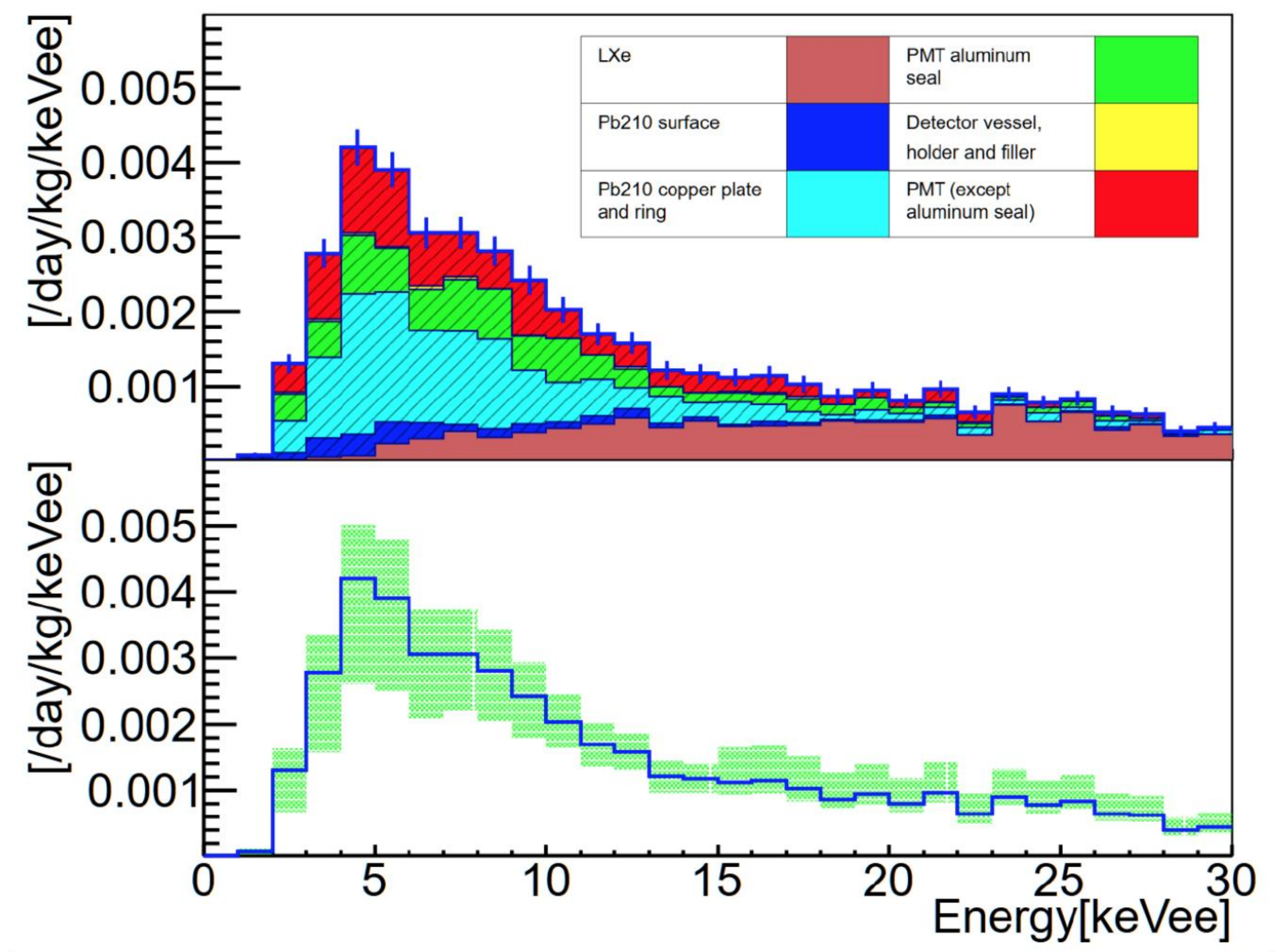
^{57}Co 122keV





RESULTS: ENERGY SPECTRUM IN THE FIDUCIAL VOLUME

- 706 live days taken in Nov. 2013 – Mar. 2016
- Fiducial mass 97kg (R<20cm)

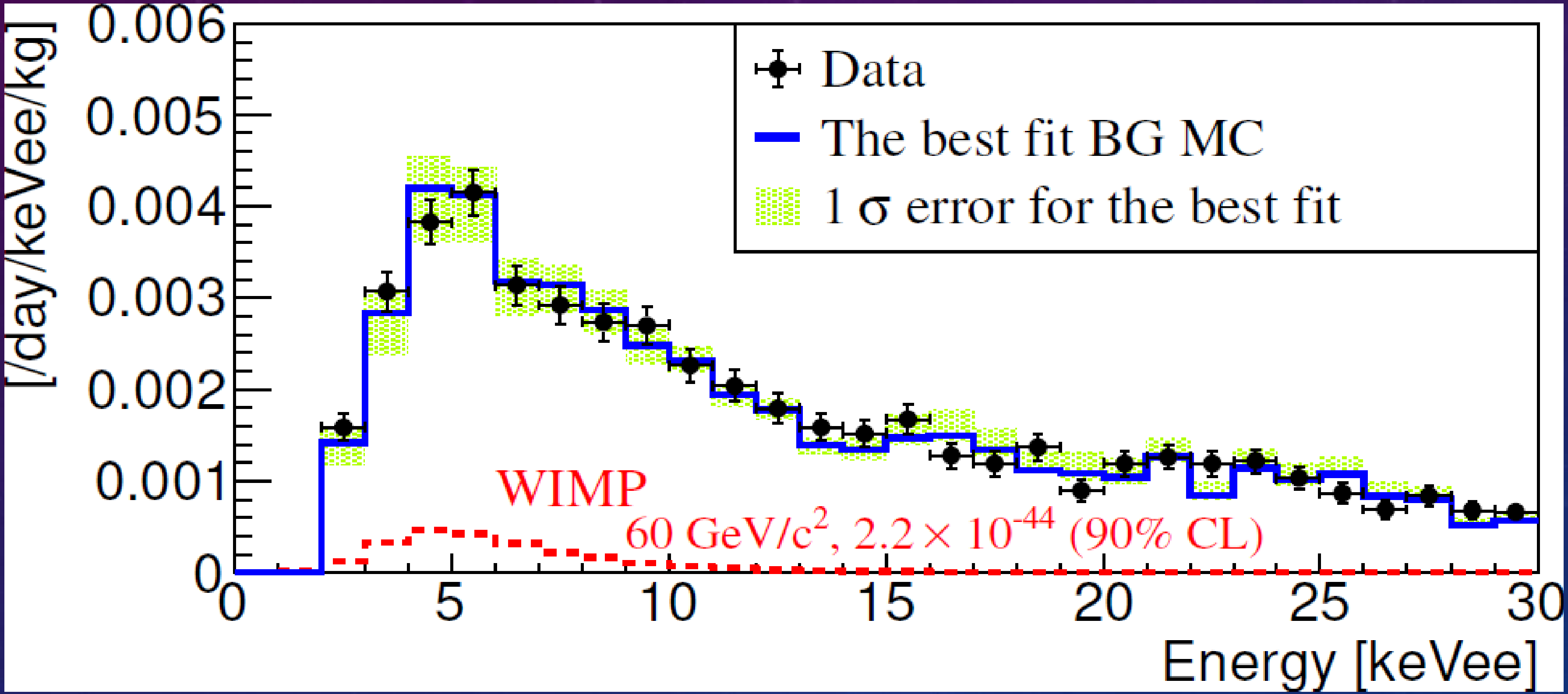


- Main background in the WIMP search region
  - ^{210}Pb in the copper
  - γ-rays from PMTs
  - Neutrons, alpha-rays are negligible

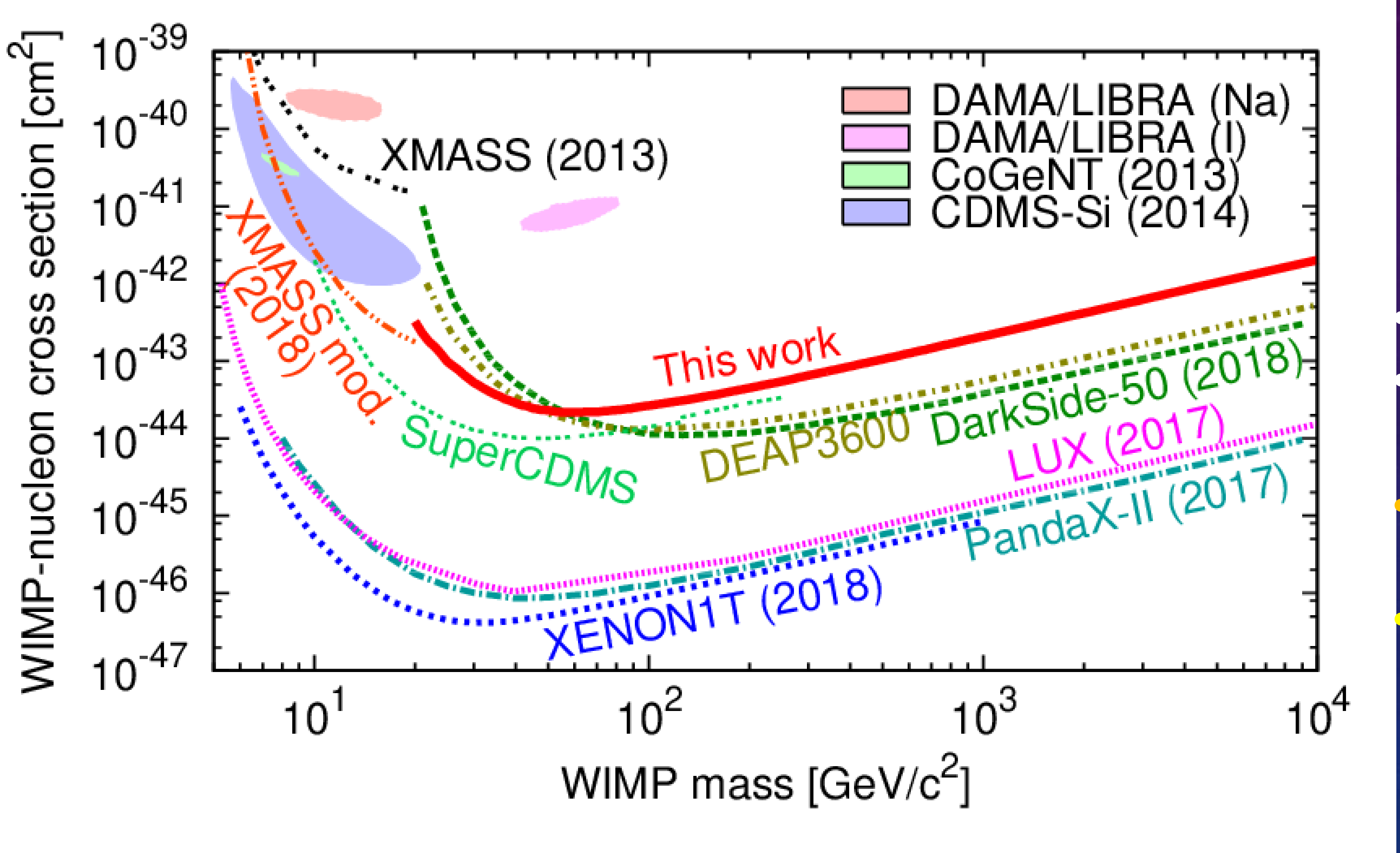
10.1016/j.physletb.2018.10.070

RESULTS: ENERGY SPECTRUM IN THE FIDUCIAL VOLUME

- 706 live days taken in Nov. 2013 – Mar. 2016
- Fiducial mass 97kg (R<20cm)



- The energy spectrum at 2-15 keV$_{ee}$ is fitted with signal + background.
- Systematic uncertainties are taken into account as nuisance parameters in the fit.
  - Detector surface conditions (gap, roughness) are dominant.



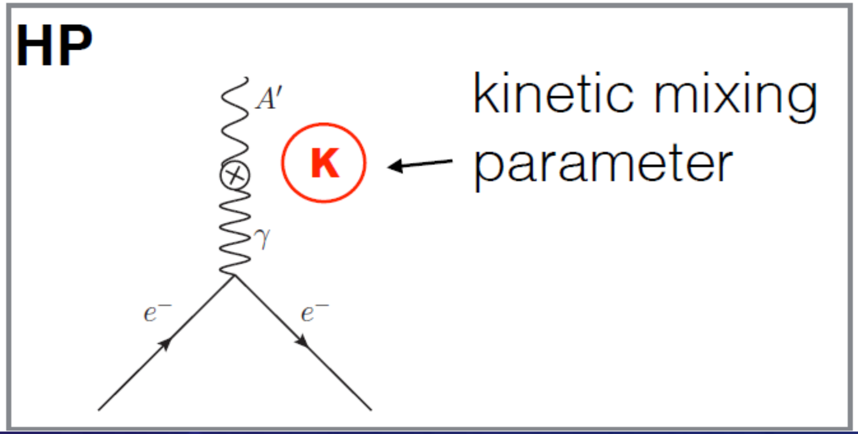
- 97kg x 706 days exposure
- 90% CL upper limit on SI WIMP-nucleon cross section
- $\sigma_{SI} < 2.2 \times 10^{-44}$ cm^2 @60 GeV/c^2
- First stringent constraint by a single-phase LXe detector.

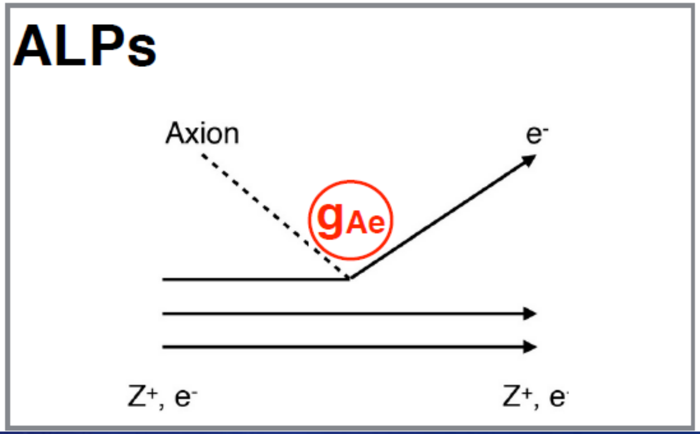
DARK MATTER SEARCHES IN XMASS-I
-- HIDDEN PHOTONS & AXION-LIKE PARTICLES DARK MATTER

- Hidden photon (HP): gauge boson of hidden U(1)
  Axion-like particles (ALPs): pseudo-Nambu-Goldstone boson

Both are the cold dark matter candidates.

- Both bosons can be absorbed in the detector medium with emission of an electron. ➔ analogue to photoelectric effect



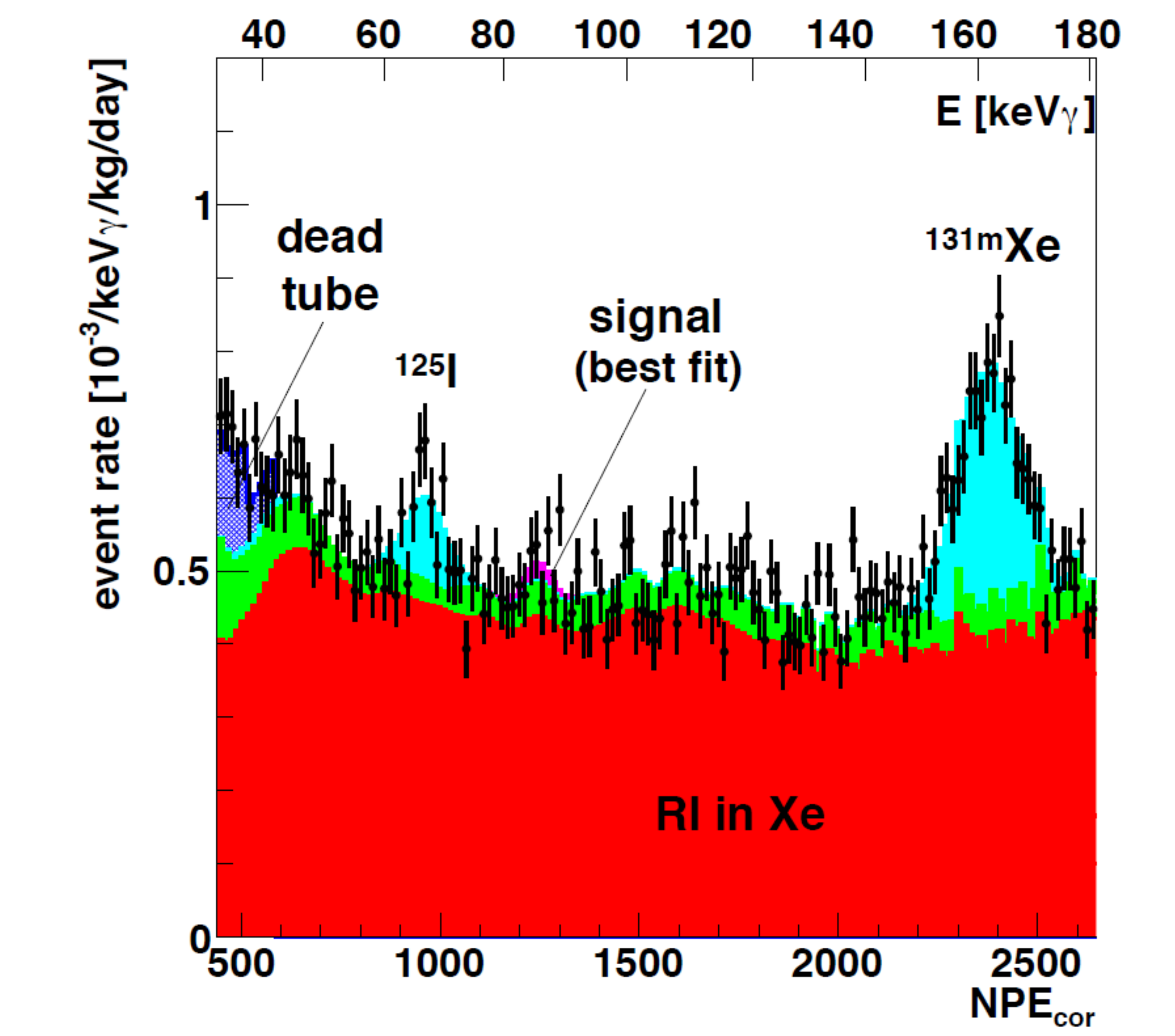


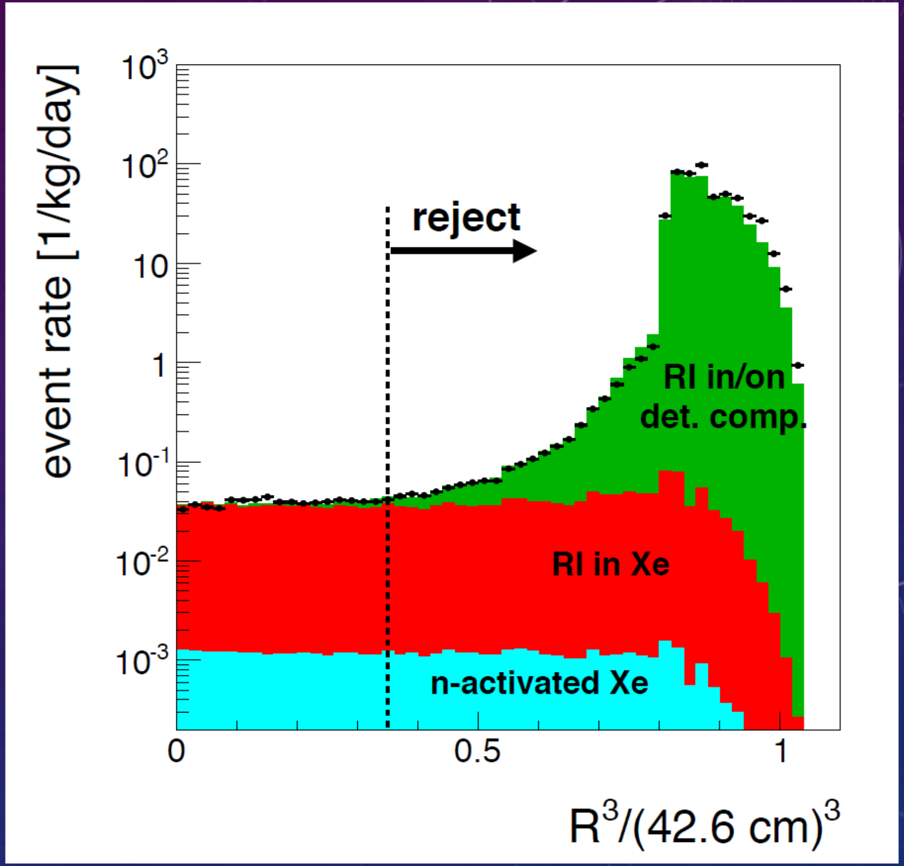
$$\frac{\sigma_{abs}v}{\sigma_{pe}(\omega = m_{HP})c} = \frac{\alpha'}{\alpha} \qquad \frac{\sigma_{abs}v}{\sigma_{pe}(\omega = m_{ALP})c} = \frac{3m_{ALP}^2}{16\pi\alpha m_e^2} \times g_{Ae}^2$$

- Event rate ∝ $(a'/a)/m_{HP}$ or $g_{Ae}^2 \times m_{ALP}$

THE RESULTS

- 800 live days of data (Nov. 2013 – Jul. 2016)
- Fiducial volume was extended to R<30cm (327 kg of LXe)
- Fitting energy range 30-180 keV

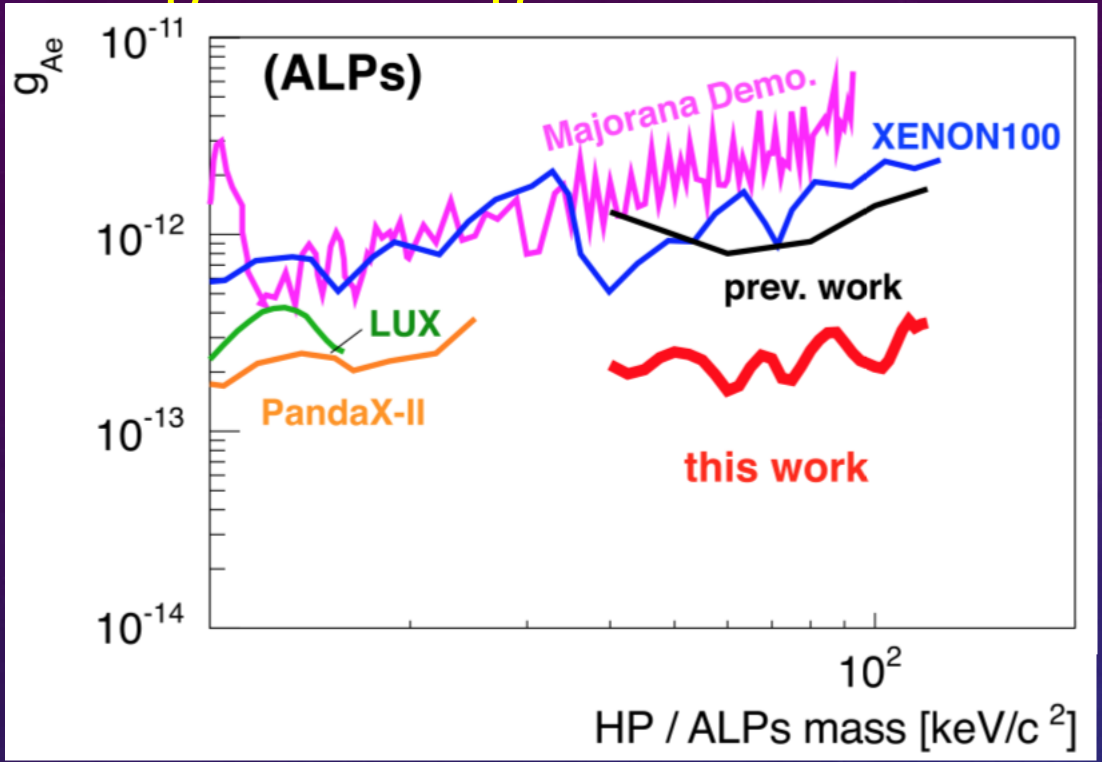


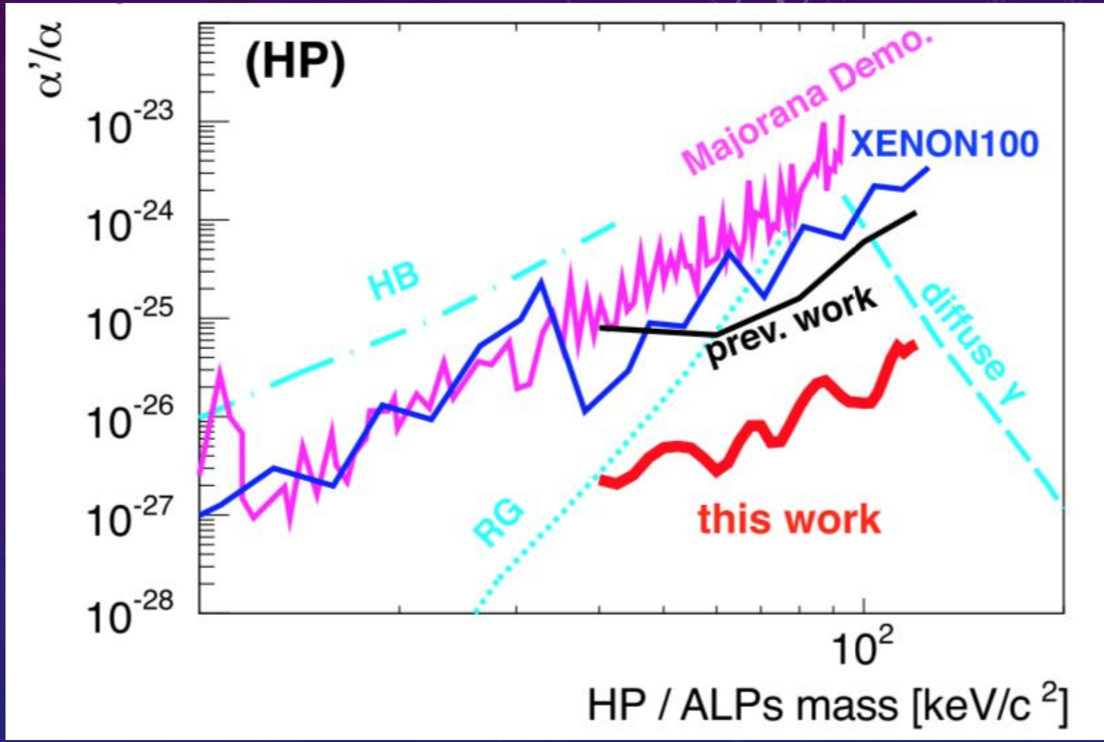


- A peak search by fitting the energy spectrum with the signal + background model.
- Scanning mass every 2.5 keV/c^2 in 40-120 keV/c^2

https://doi.org/10.1016/j.physletb.2018.10.050

No significant signal was observed.





- Axion-like particles DM
  - $g_{Ae} < 4\times10^{-13}$ (90% CL) for 40-120 keV/c^2
  - Cover higher mass region than LUX and PandaX-II
- Hidden photon DM
  - $\alpha'/\alpha < 6\times10^{-26}$ (90% CL) for 40-120 keV/c^2
  - Cover a region where indirect searches are weak

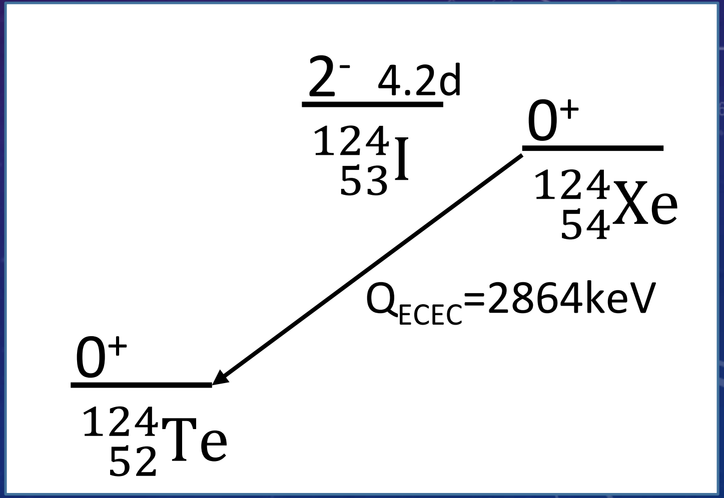
- **The best constraint in 40-120 keV/c^2 for both cases.**
- For HP, no possibility for thermal production mechanism for the first time in the world in the previous work in 2014. (DOI: 10.1103/PhysRevLett.113.121301)

STUDIES ON NEUTRINO PROPERTIES WITH XMASS -- DOUBLE ELECTRON CAPTURE

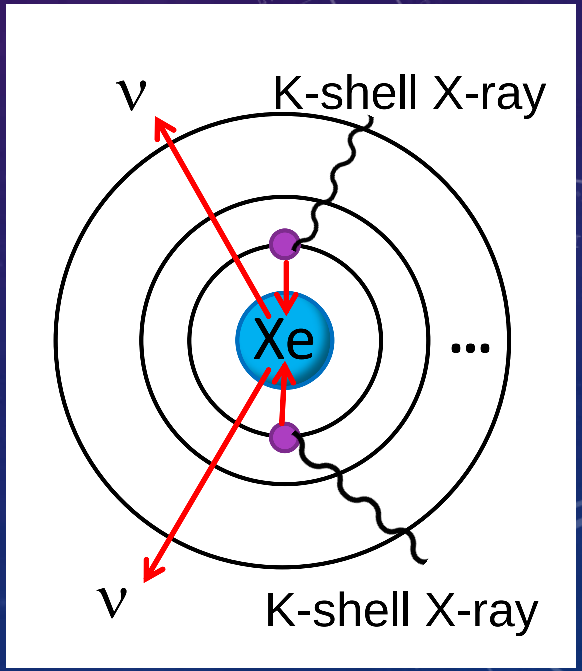
- Natural xenon contains ^{124}Xe (N.A.=0.095%) and ^{126}Xe (N.A.=0.089%) which can undergo double electron capture.

$$^{124}\mathrm{Xe}\ (\text{g.s., } 0^{+}) + 2e^{-} \rightarrow {}^{124}\mathrm{Te}\ (\text{g.s., } 0^{+}) + (2\nu_e) + 2864\,\text{keV}$$

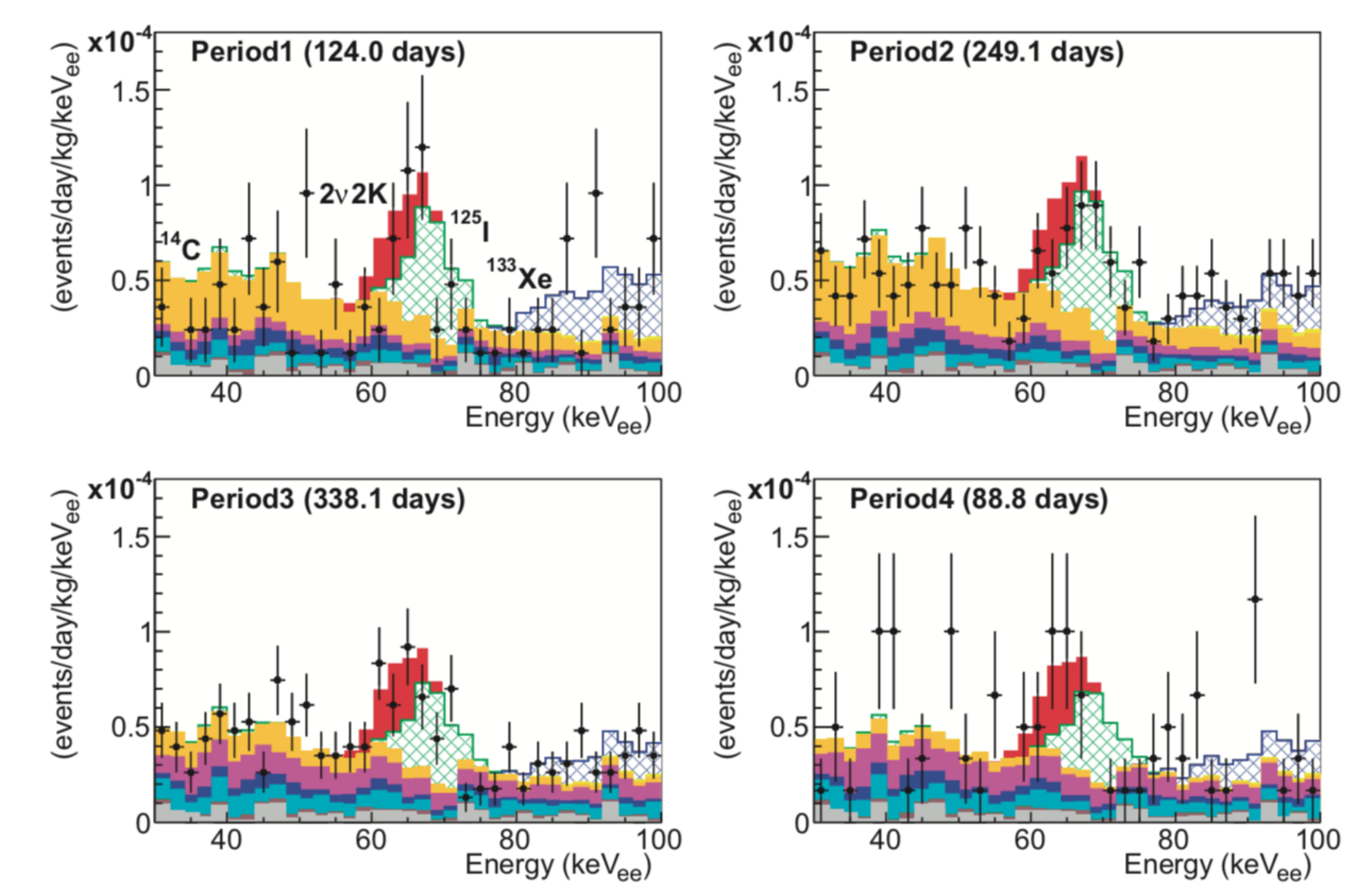
- 0ν mode → Evidence of lepton number violation
  2ν mode → New input for nuclear matrix element calculation
- None of the modes are overserved yet.



- ^{124}Xe 2ν double electron capture from K-shell (2ν2K)
  - Total deposit energy of **63.6 keV by X-rays/Auger electrons**
  - Expected half-life is **10^{20}-10^{24} years.**
  - **It may be possible to find out the 2v2K.**
  - Main BG: **^{125}I**
    - ^{125}I + e^- → ^{125}Te + ν + 185.77 keV, $T_{1/2}$=59.4 day
    - It is created by thermal neutron capture of ^{124}Xe outside the water shield.
    - It gives a peak at 67.5 keV$_{ee}$.

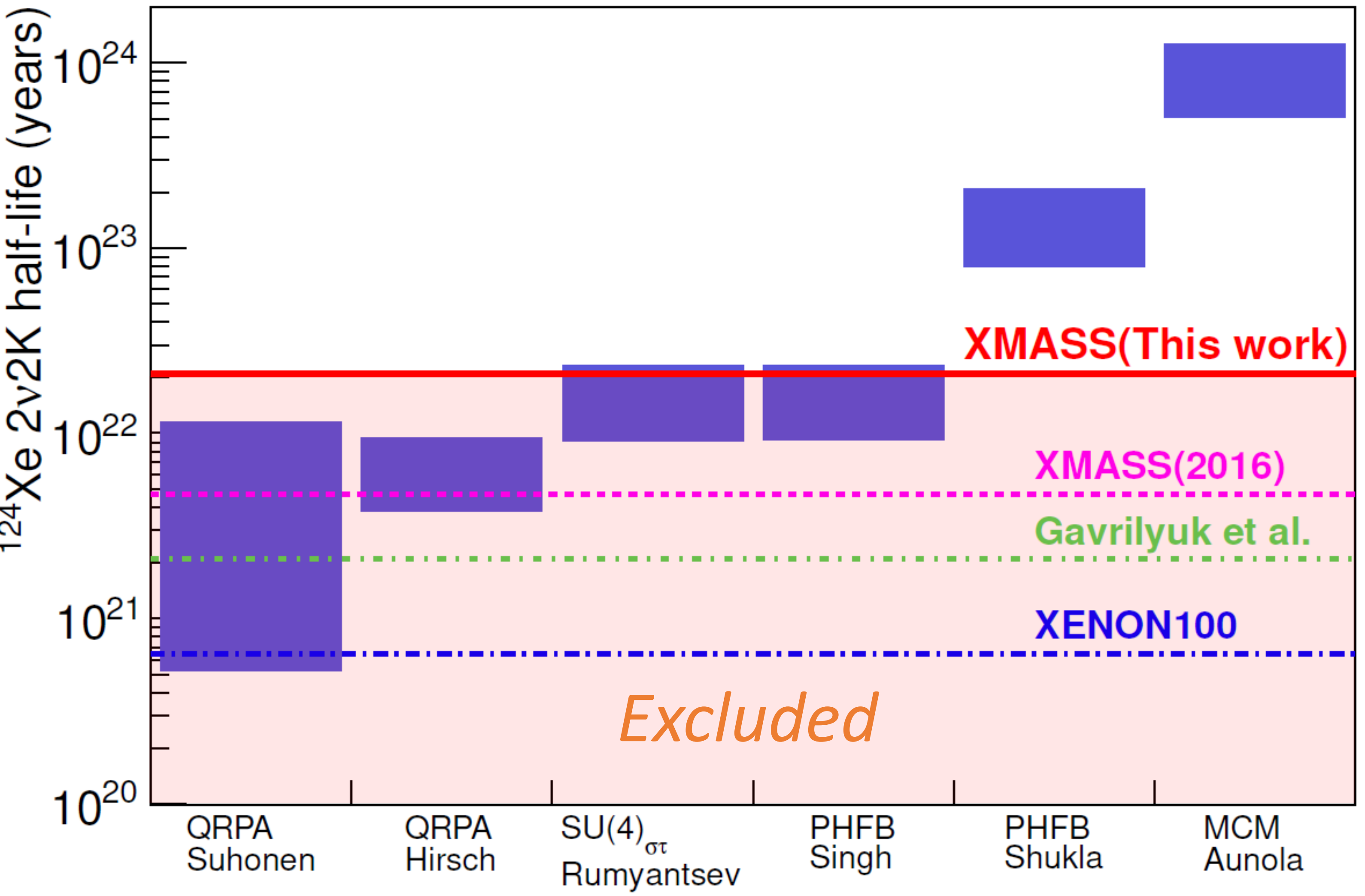


Result (DOI: 10.1093/ptep/pty053)



We divided the data into 4 by operation modes.
In each operation modes, thermal neutron flux is measured by independent measurement.

- **No significant signal was observed.**



- **The most stringent limit to date**
  - $T_{1/2}^{2\nu 2K}(^{124}Xe)>2.1\times10^{22}$ yrs
  - $T_{1/2}^{2\nu 2K}(^{126}Xe)>1.9\times10^{22}$ yrs

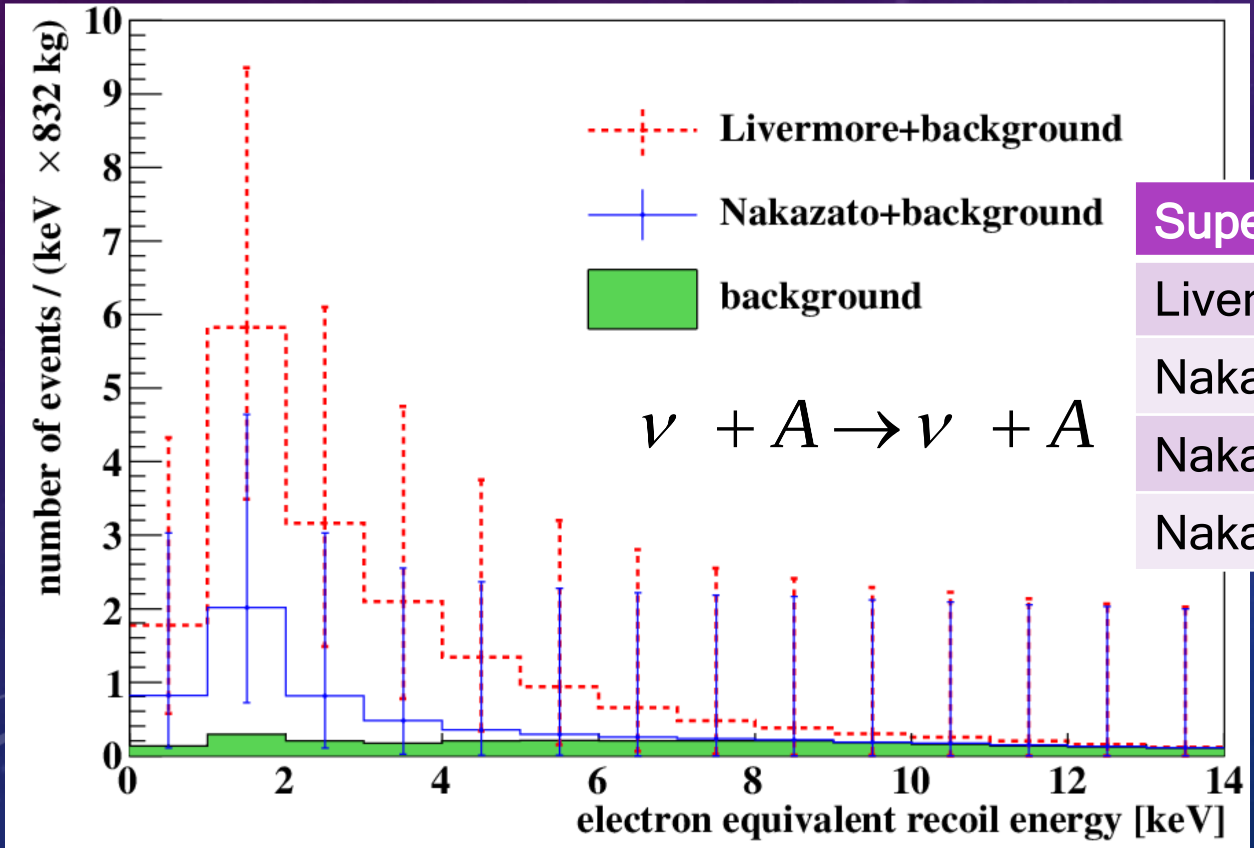
The result ruled out some theoretical predictions.

Note on theoretical predictions:

- g_A= 1.26(lower) – 1(upper)
- Probability of 2K-capture= 0.767

NEUTRINO OBSERVATORY, XMASS

- XMASS has the sensitivity to detect neutrino burst from a supernova around 10 kpc via neutrino coherent scattering

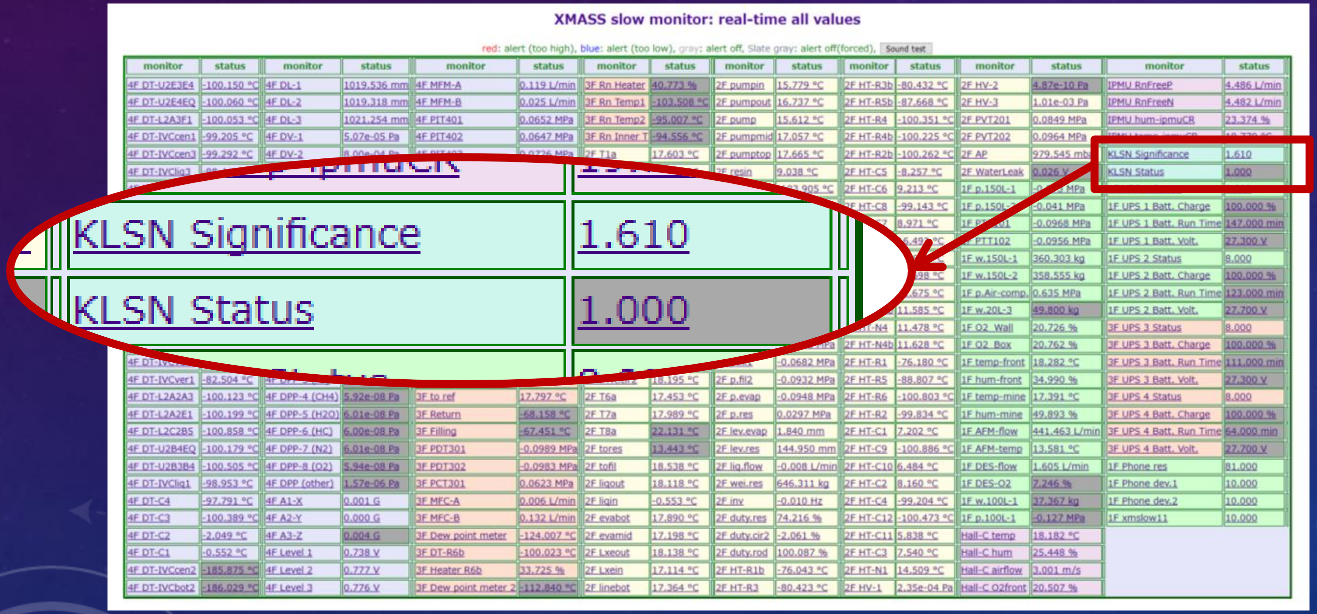


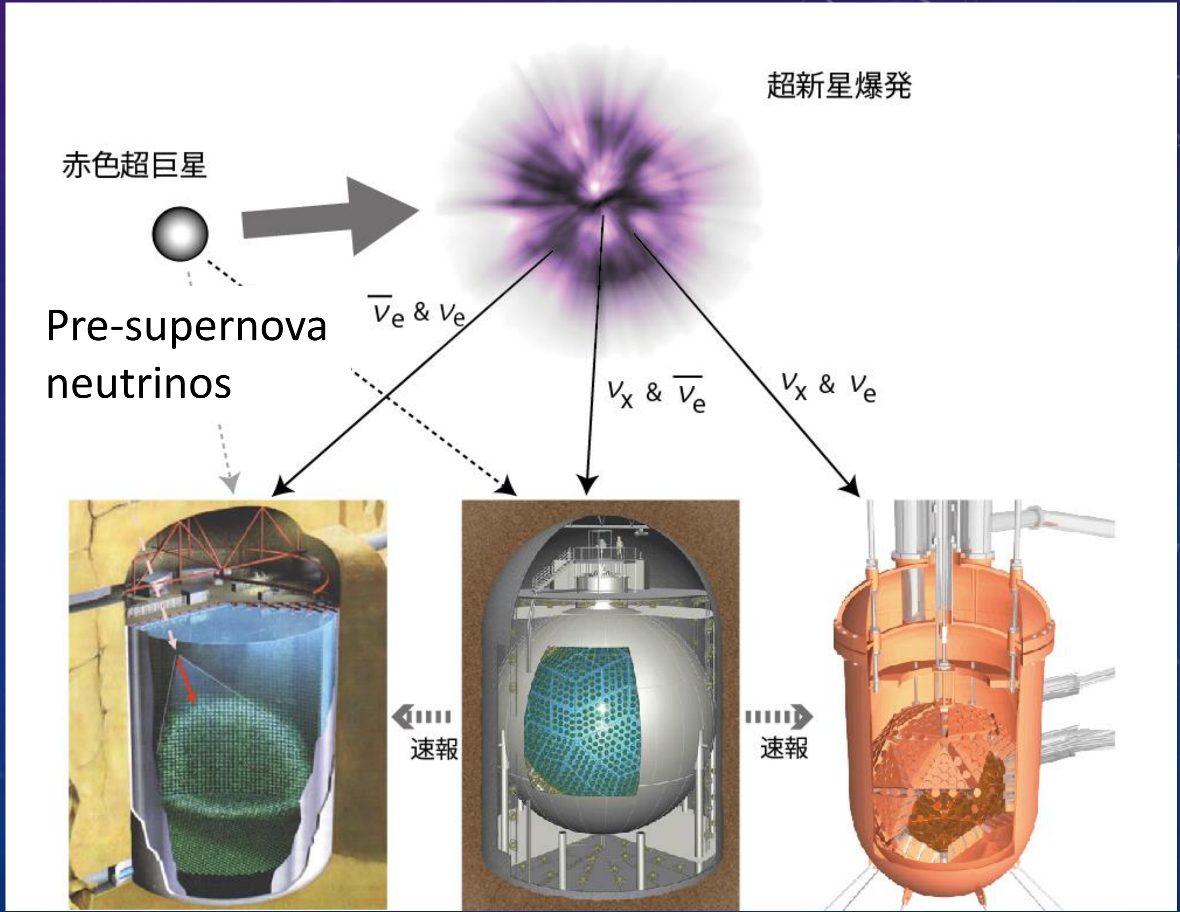
$$\nu + A \rightarrow \nu + A$$

Supernova model	d=10 kpc	d=196 pc
Livermore	15	3.9×10^4
Nakazato ($20M_{solar}$, Z=0.02, t_{rev}=100ms)	3.5	0.9×10^4
Nakazato ($30M_{solar}$, Z=0.02, t_{rev}=300ms)	8.7	2.3×10^4
Nakazato (black hole)	21	5.5×10^4

K. Abe et al. (XMASS Collaboration), Astropart. Phys. 89 (2017) 51-56

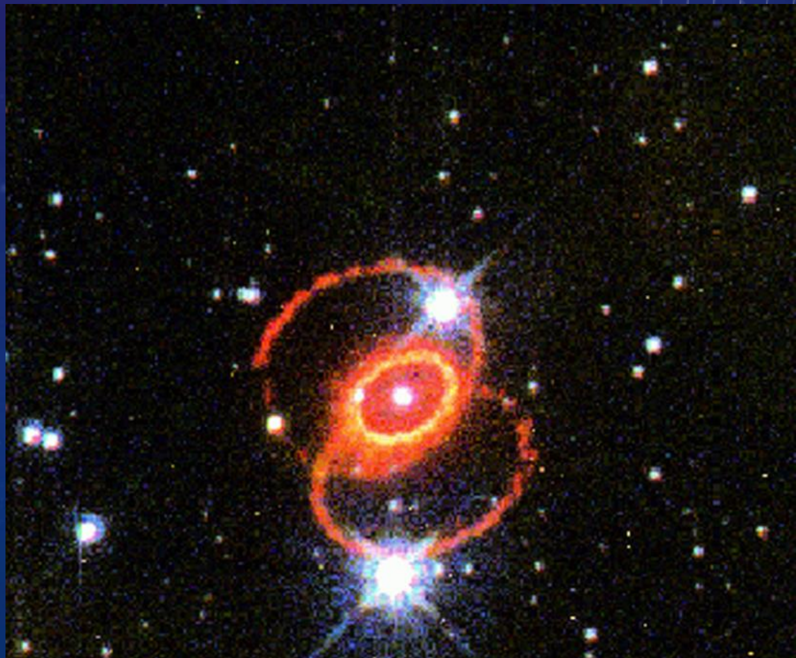
- Especially for nearby-supernova case,
  - KL can measure pre-SN ν to distribute SN alert.
  - XMASS can measure 10^4 events
- We established SN monitoring network in Kamioka.
  - Monitor SN alert provided by KL in 24 hours.



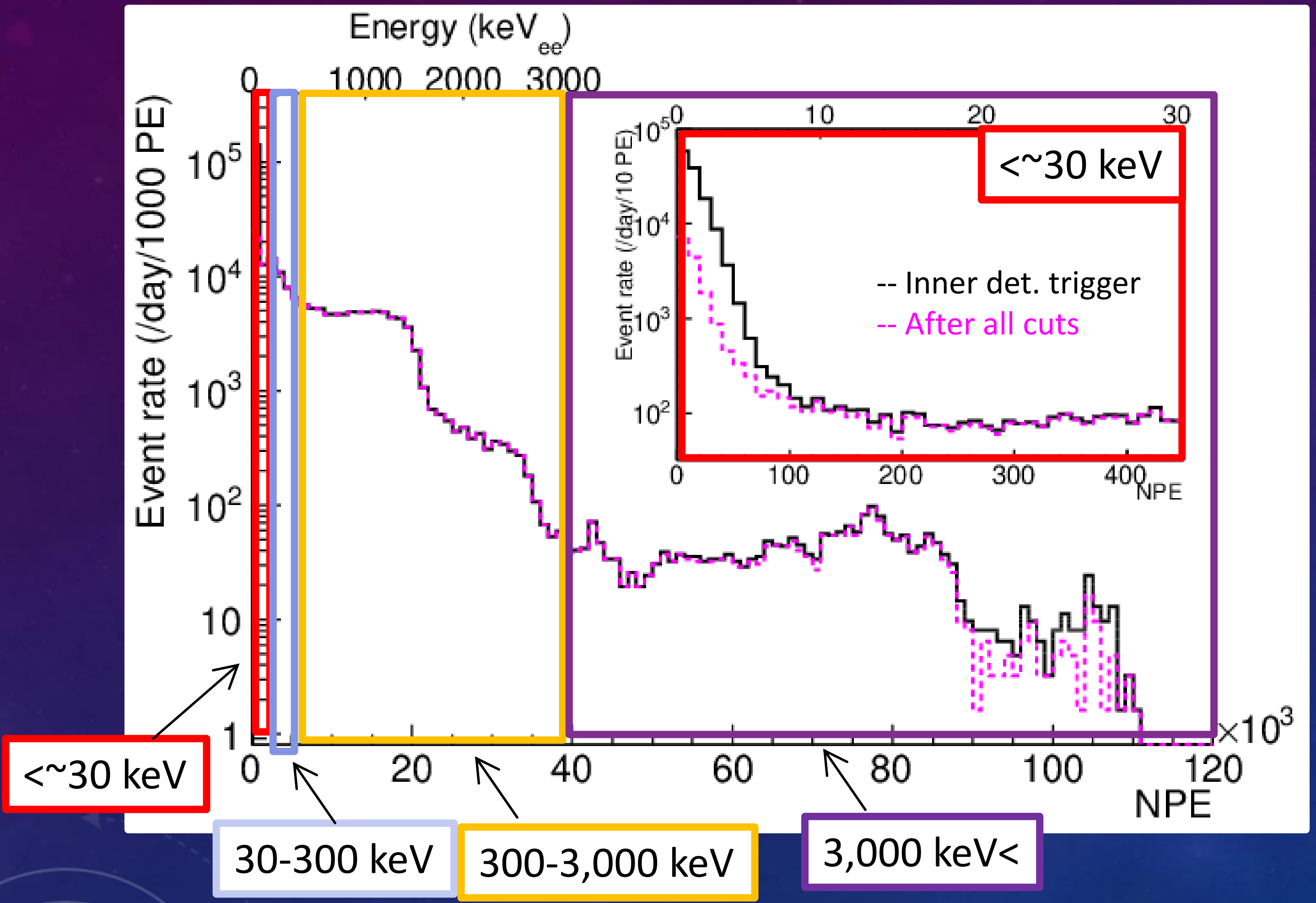


- The result:

  - We are *not* lucky enough to observe any SN ν in this 30 years.
  - But it is shown by XMASS that a large scale DM detector is potentially utilized as SN ν observatory.



- Other astrophysical object:
  - We searched for event bursts related to GW170817.



- Around GW170817 (Aug. 17 2017 12:41:04UTC) in [-400, +10,000] sec
- Simple data reduction:
  - Full volume
  - No OD trigger
  - Removing PMT after pulses
  - Remove Cherenkov events
- Four evet regions
  - <~30 keV 0.22 event/s
  - 30-300 keV 0.56 event/s
  - 300-3000 keV 0.99 event/s
  - >~3000 keV 0.02 event/s
- Analysis Window
  - Vary from 20 ms to 10 s to find bursts.

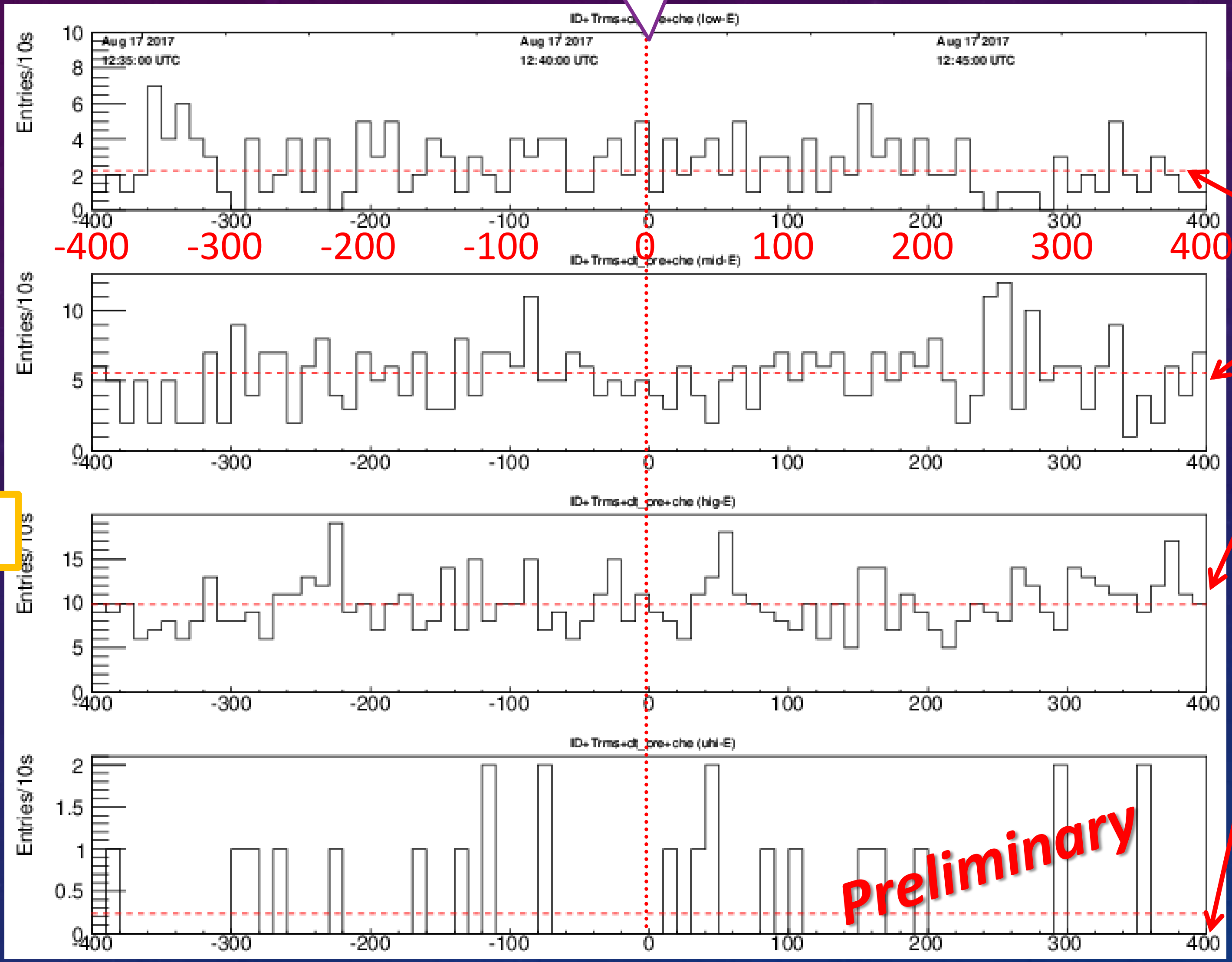
GW170817

<~30keVee

30-300keVee

300-3000keVee

>~3000keVee



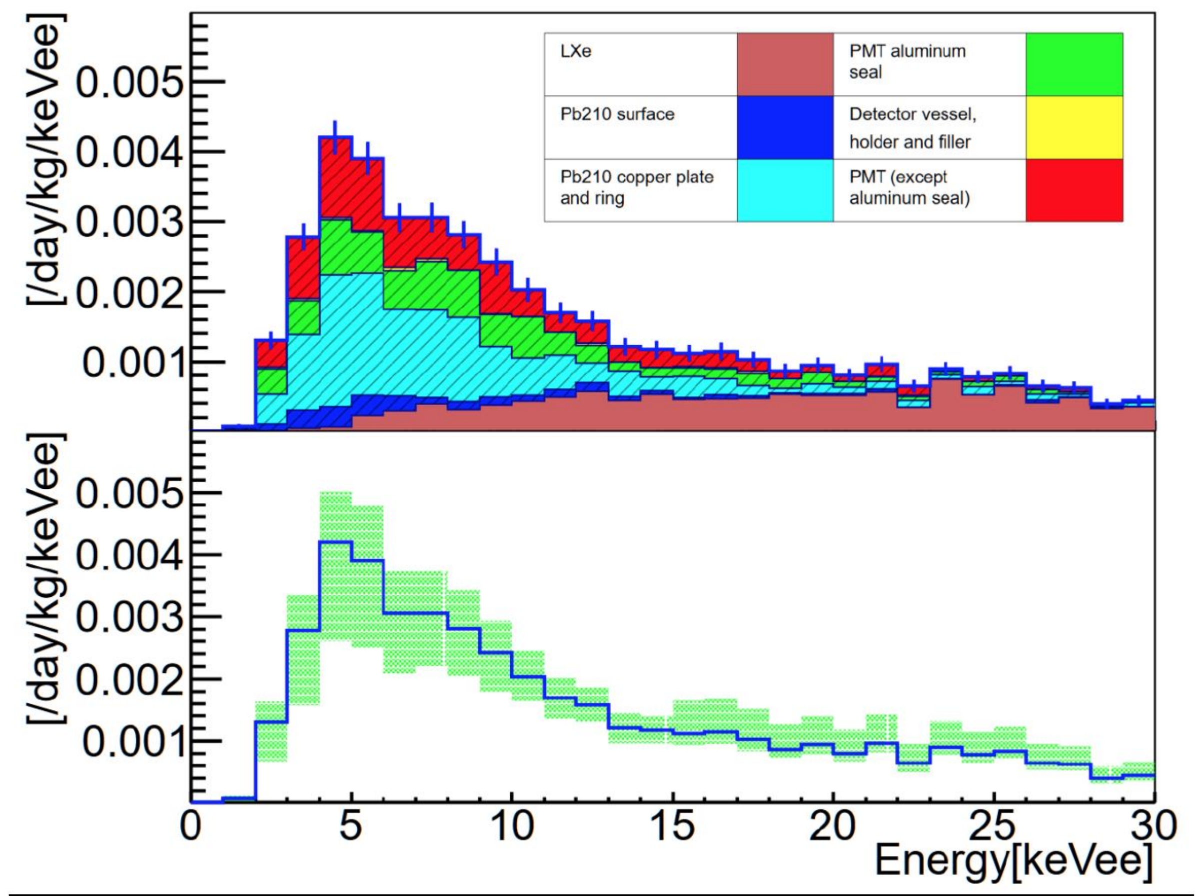
BG rate estimated from pre-window of GW170817

To be published soon!

No bursts were found.

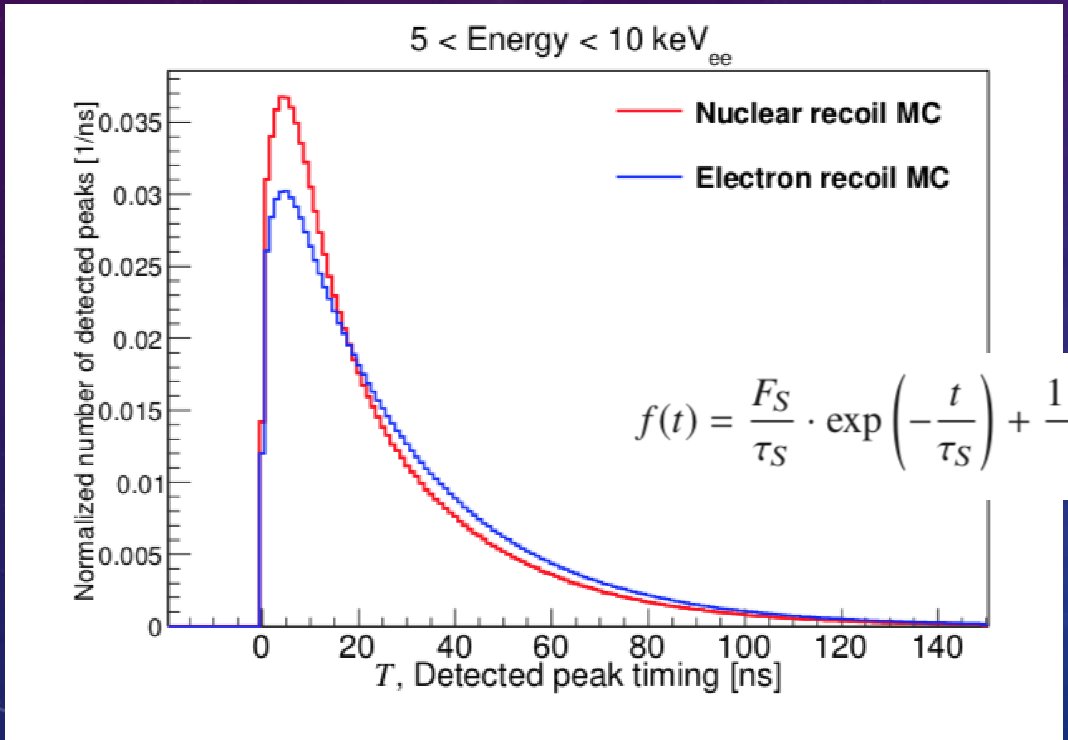
LOW BG TECHNOLOGY

- Introduction:
  - The main backgrounds of the XMASS detector are
    - ^{210}Pb from cupper and
    - RI's from the PMT.
  - We have lots of efforts.
  - <u>Three topics in this talk:</u>
    - New 3" round-shape PMTs
    - Particle ID by Xe scintillation property
    - Ultra low level α counter

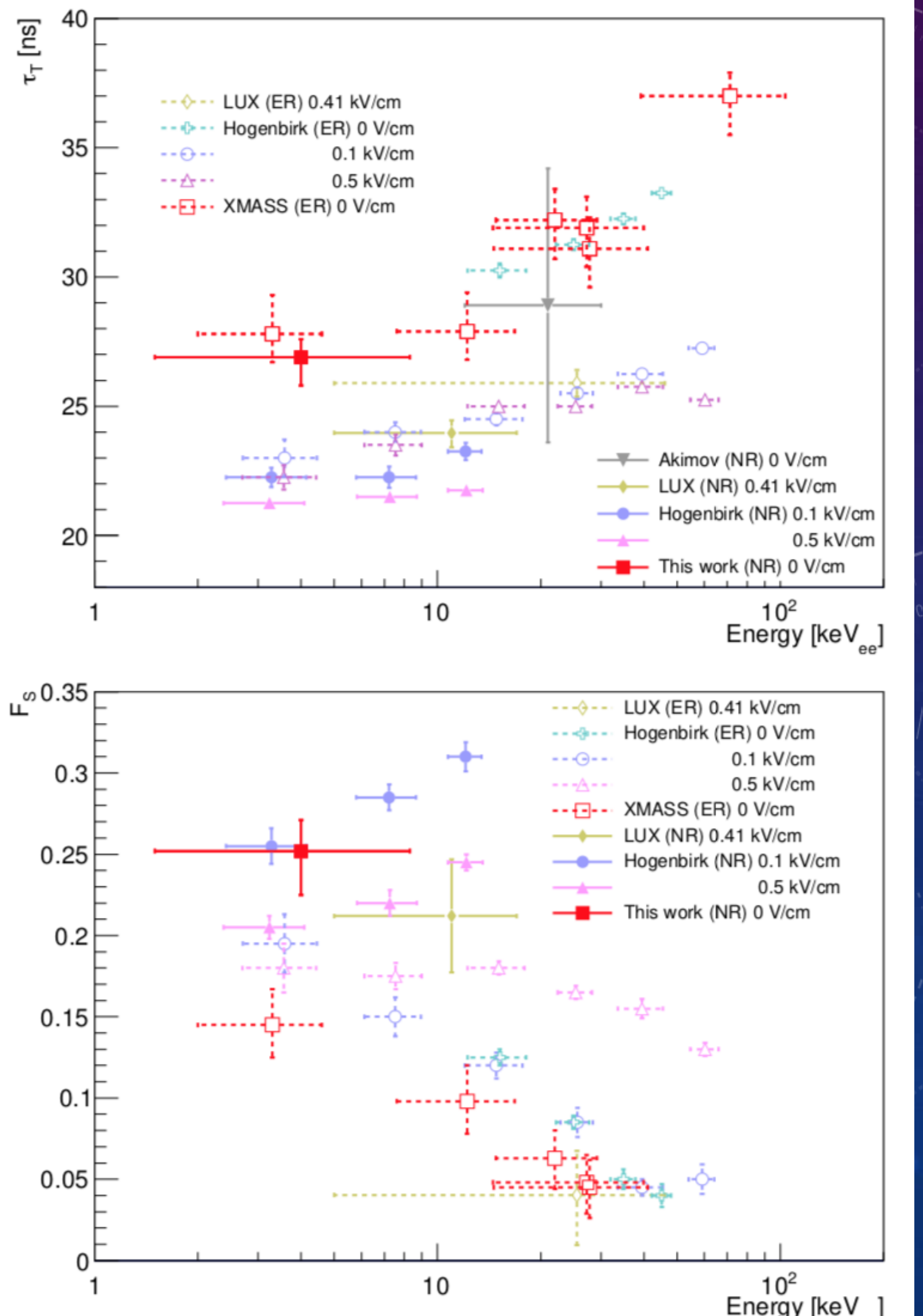


LOW BG TECHNOLOGY
-- PARTICLE ID BY XE SCINTILLATION LIGHT

- Nuclear scattering from electron scattering
  - With neutron source, scintillation time profile are measured.

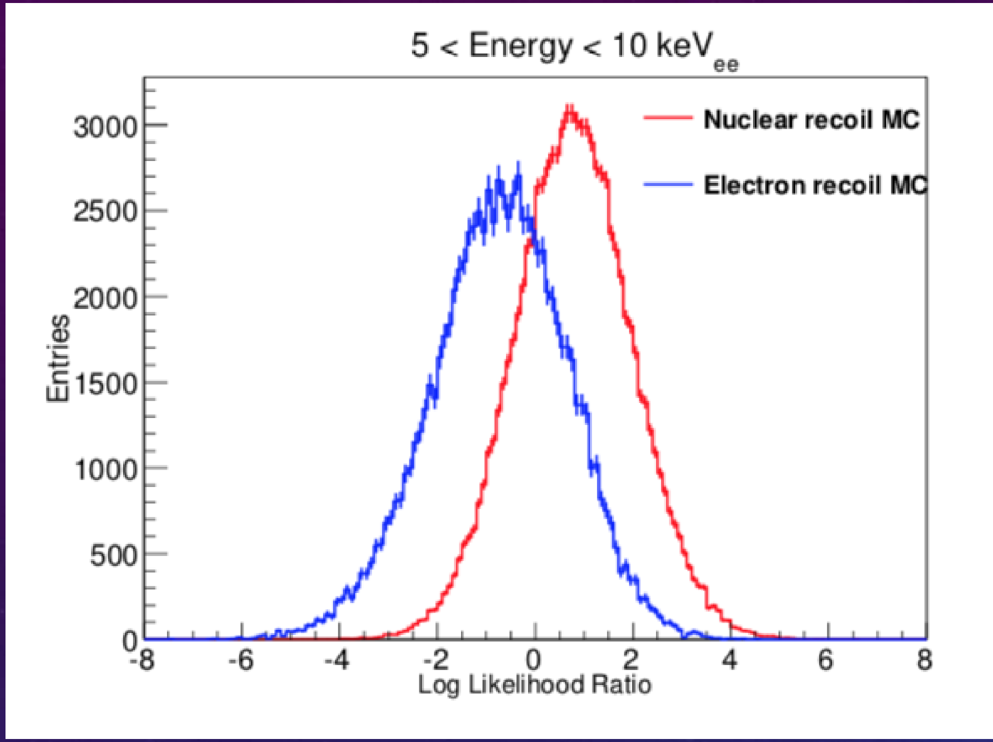


$$f(t) = \frac{F_S}{\tau_S} \cdot \exp\left(-\frac{t}{\tau_S}\right) + \frac{1 - F_S}{\tau_T} \cdot \exp\left(-\frac{t}{\tau_T}\right).$$

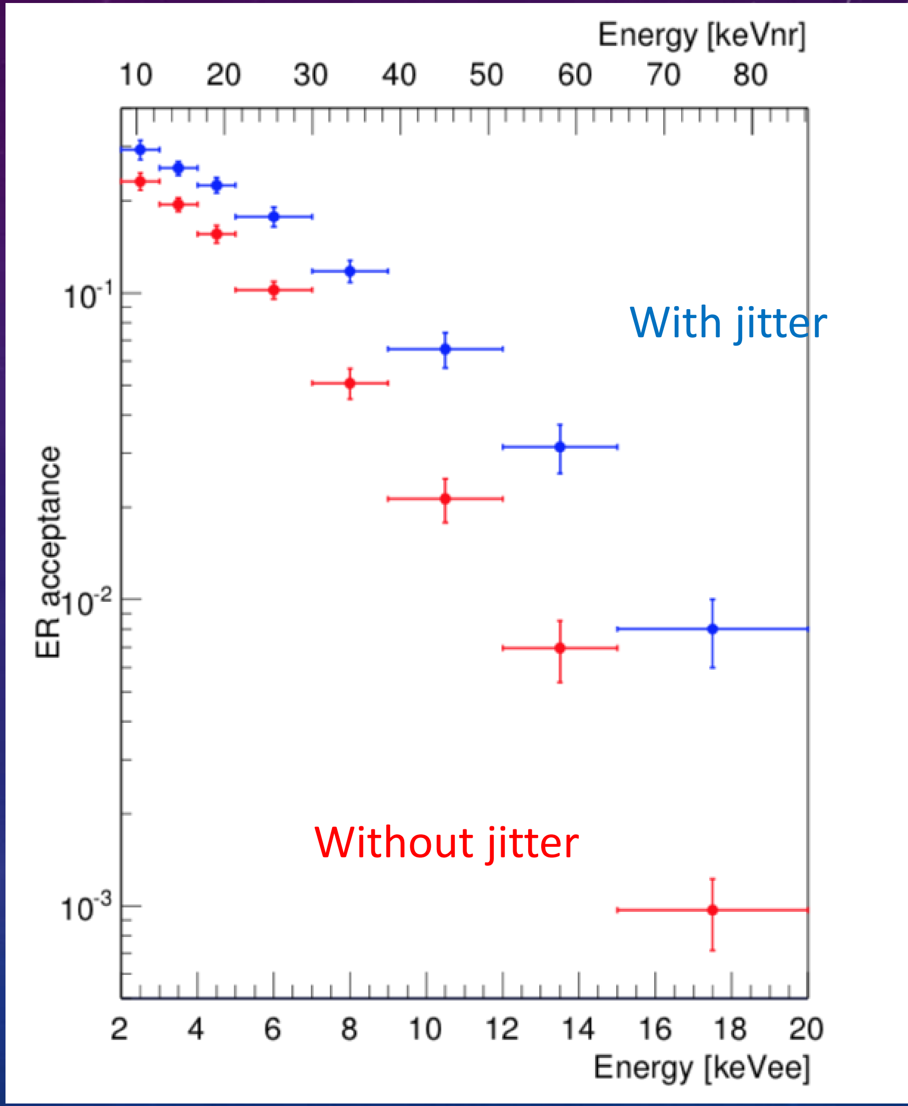


https://doi.org/10.1088/1748-0221/13/12/P12032

- Log likelihood ratio



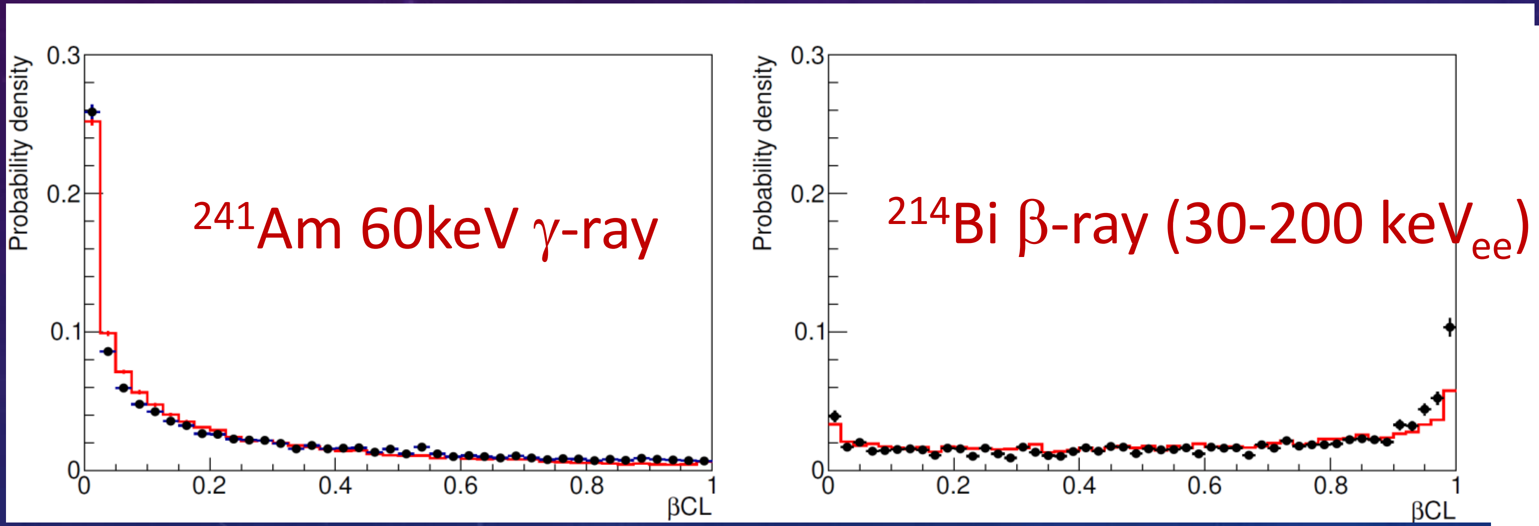
- Acceptance of electron recoil events assuming 50% acceptance of 100 GeV WIMPs.

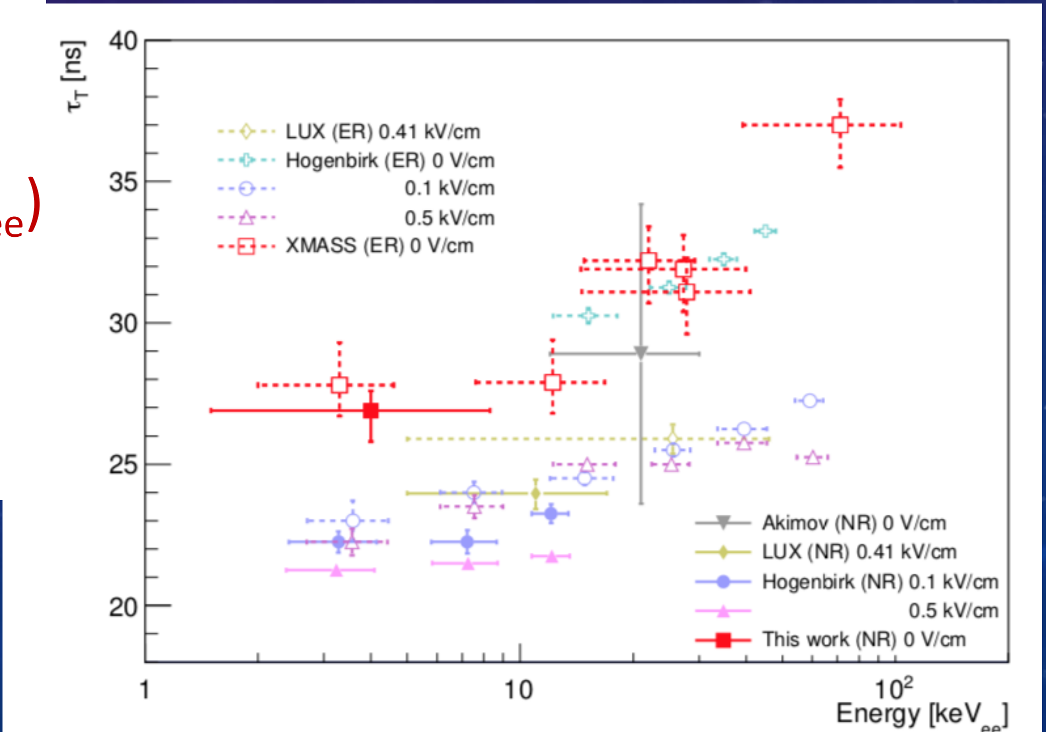


It is not easy to distinguish NR from ER at lower energy region.

- Electron event from gamma evet
  - Gamma ray interacts with electrons and looses the energy.
  - This reads the time profile difference between gamma and electron.

$$\beta\mathrm{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$



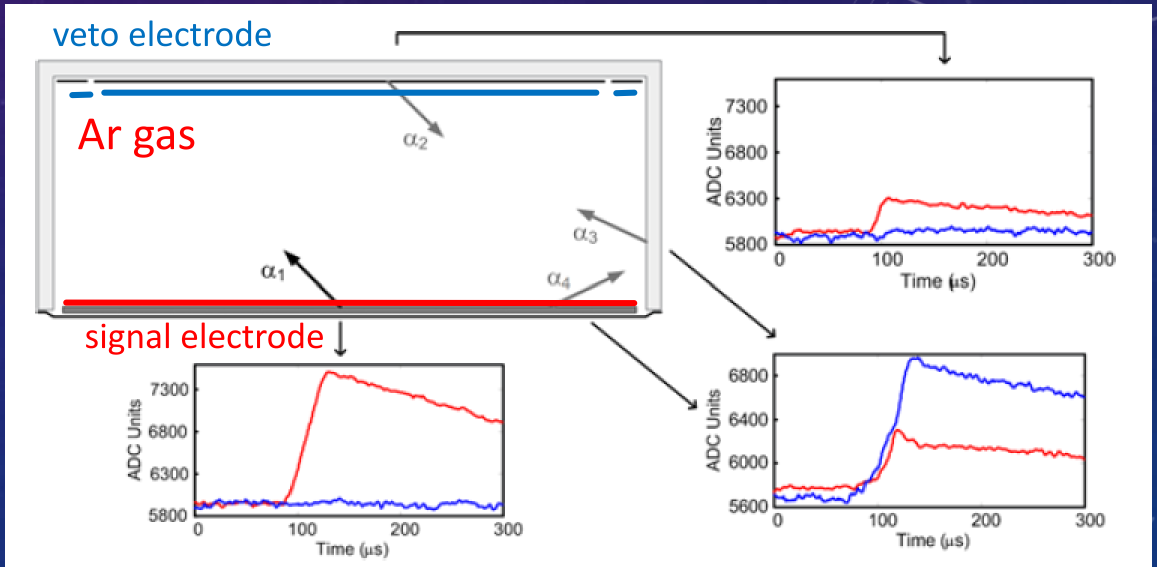


This method is applied to the ^{124}Xe 2ν2K analysis.
S/N is improved by factor 5.

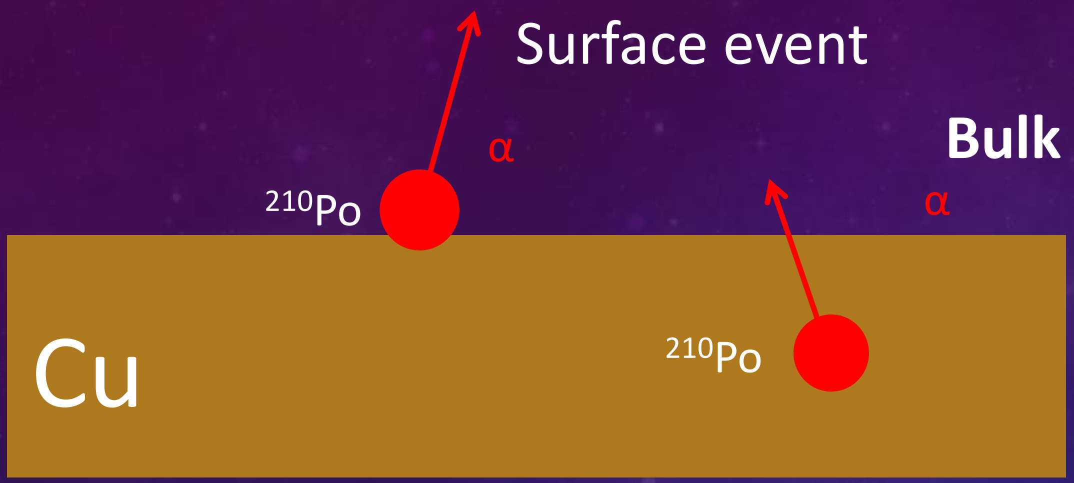
LOW BG TECHNOLOGY -- ULTRA-LOW ALPHA-RAY COUNTER

- XIA Ultra-Lo-1800
  - Measure ionization signal of Ar by induction.
    - Wall event rejection by pulse shape
  - Installed in Kamioka mine in 2015.
    - It was the first time installation into the underground experimental lab.

	Specification
efficiency	>90% of 2π
ΔE	<9% FWHM at 4.6MeV
E range	1-10MeV
Max. sample size	707cm^2 (ϕ30cm disk)、1800cm^2 (42cm*42cm)
Max. sample weight	9kg
Max. sample thickness	6.3mm
Sensitivity	$10^{-4}\alpha/cm^2/hr$ ~ 0.56 mBq of ^{210}Po on 1 m^2 surface

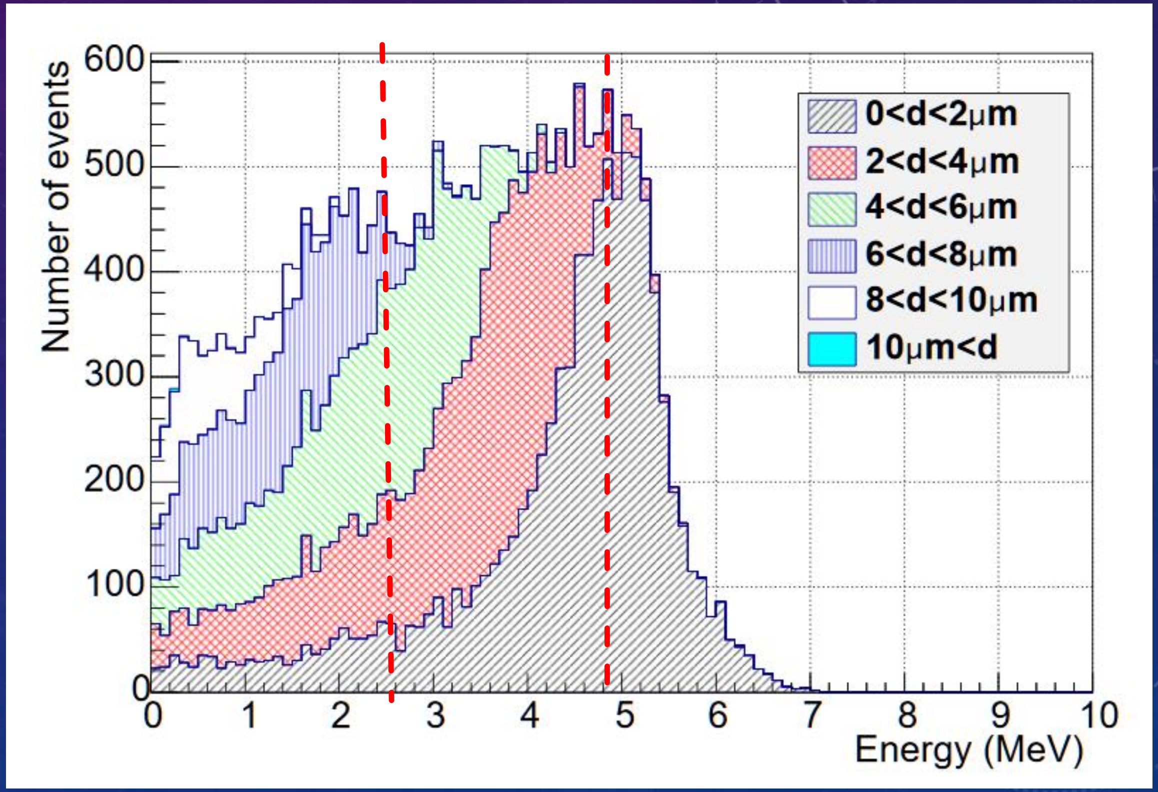


- We found that <u>the alpha counter is also sensitive for α-rays *from bulk*.</u>



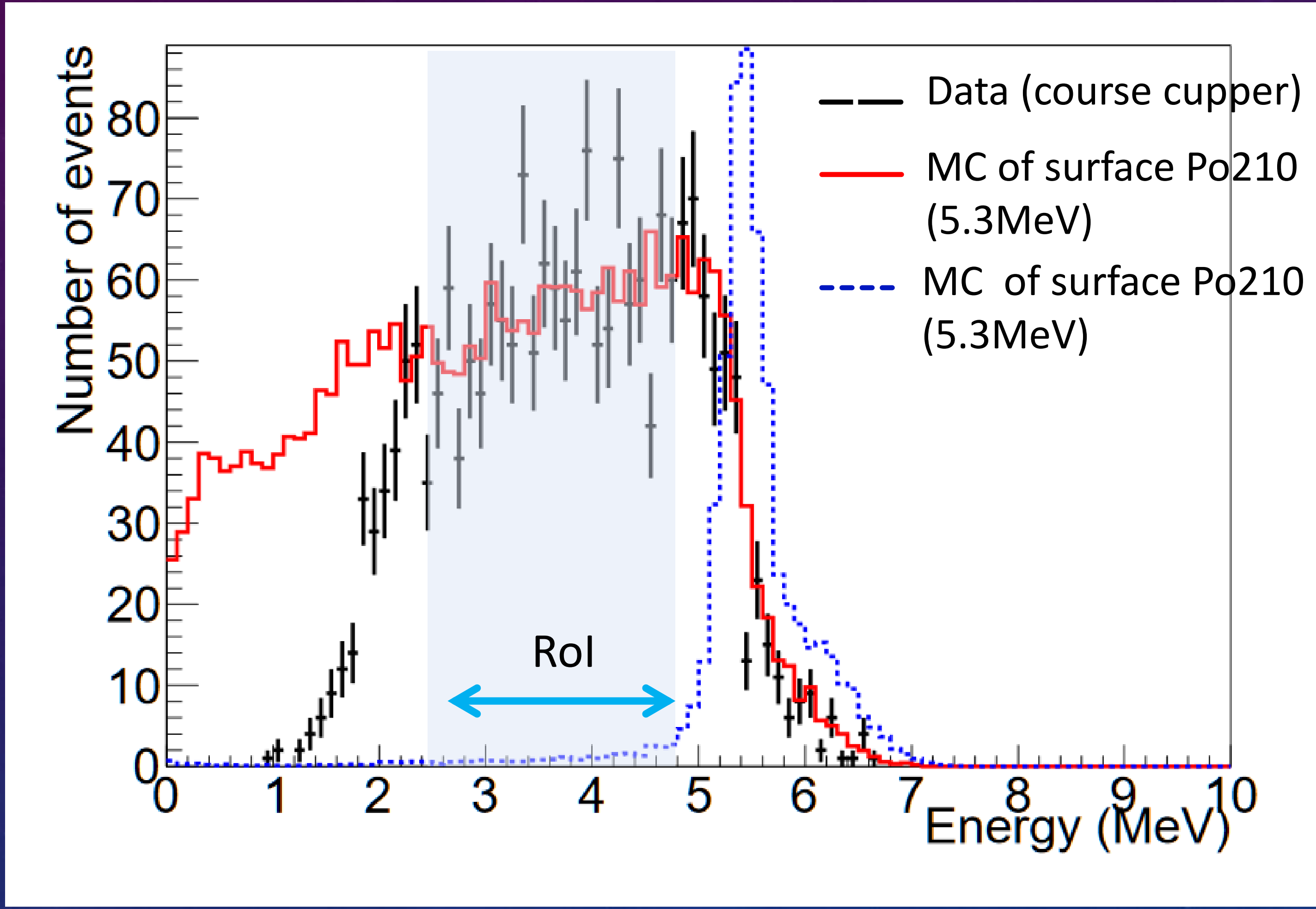
According to MC, α-ray comes from d=2〜6 μm can be measured at E=2.5〜4.8 MeV under some conditions:

- An α counter must be low-BG itself.
- Sample surface must be low-BG.
- Sample roughness << 10 μm
- Ris other than ^{210}Po can be ignorable.



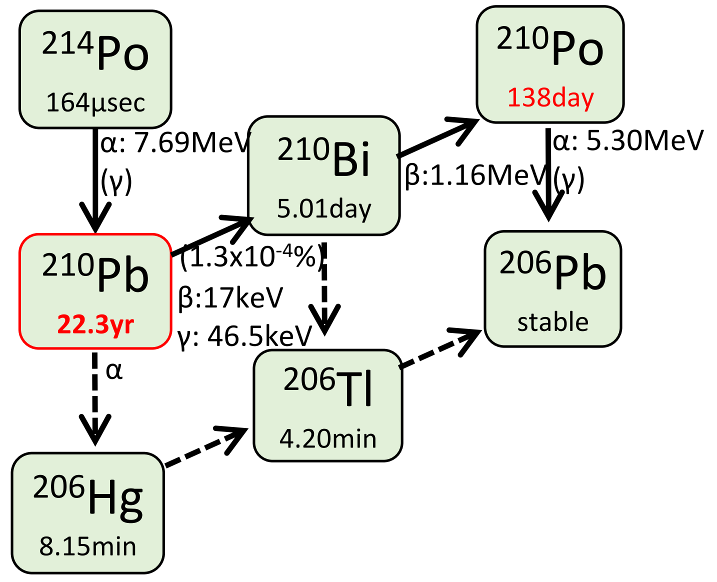
https://doi.org/10.1016/j.nima.2017.12.015

- Measure ^{210}Po count rate several time

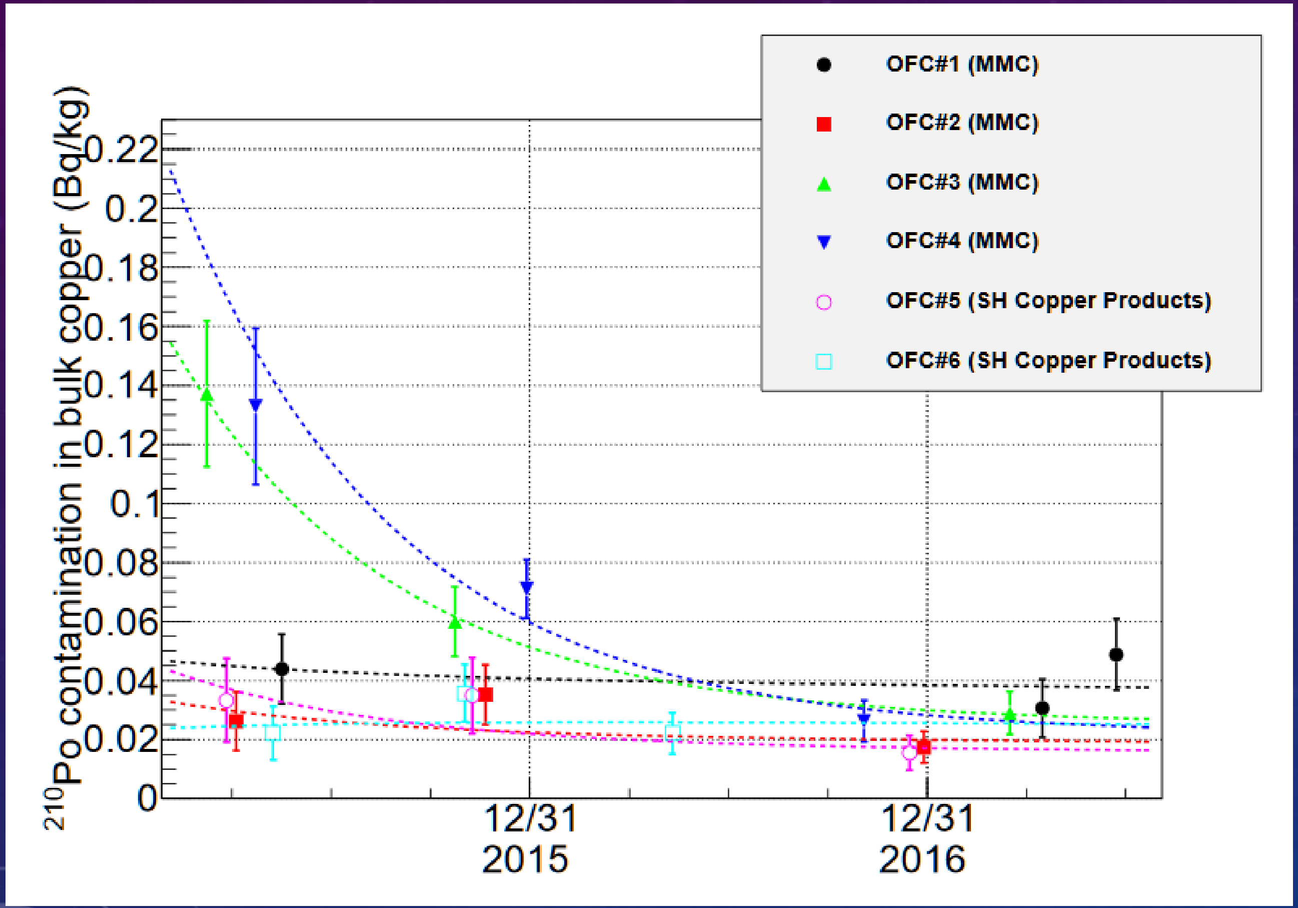


$$N_{\mathrm{Pb}}(t) = N_{\mathrm{Pb}}(0)e^{-k_{\mathrm{Pb}}t}$$

$$N_{\mathrm{Po}}(t) = N_{\mathrm{Pb}}(0)\frac{k_{\mathrm{Pb}}}{k_{\mathrm{Po}} - k_{\mathrm{Pb}}}\left(e^{-k_{\mathrm{Pb}}t} - e^{-k_{\mathrm{Po}}t}\right) + N_{\mathrm{Po}}(0)e^{-k_{\mathrm{Po}}t}$$



- Calculate ^{210}Pb and ^{210}Po in the material.



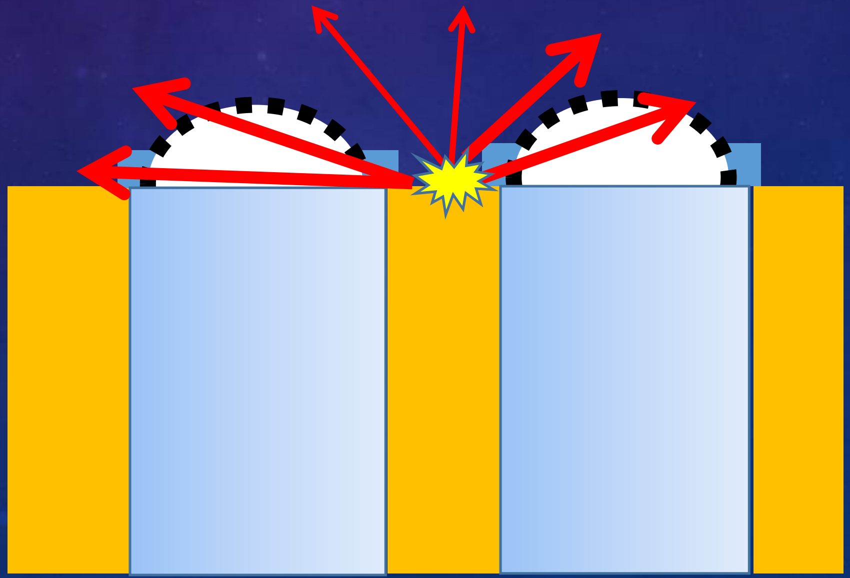
	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)
OFC#1 (MMC)	40±8	47±21
OFC#2 (MMC)	20±6	33±14
OFC#3 (MMC)	27±7	160±30
OFC#4 (MMC)	23±8	220±40
OFC#5 (SH copper products)	17±6	44±18
OFC#6 (SH copper products)	27±8	24±17

^{210}Pb in cupper is measured with high sensitivity.

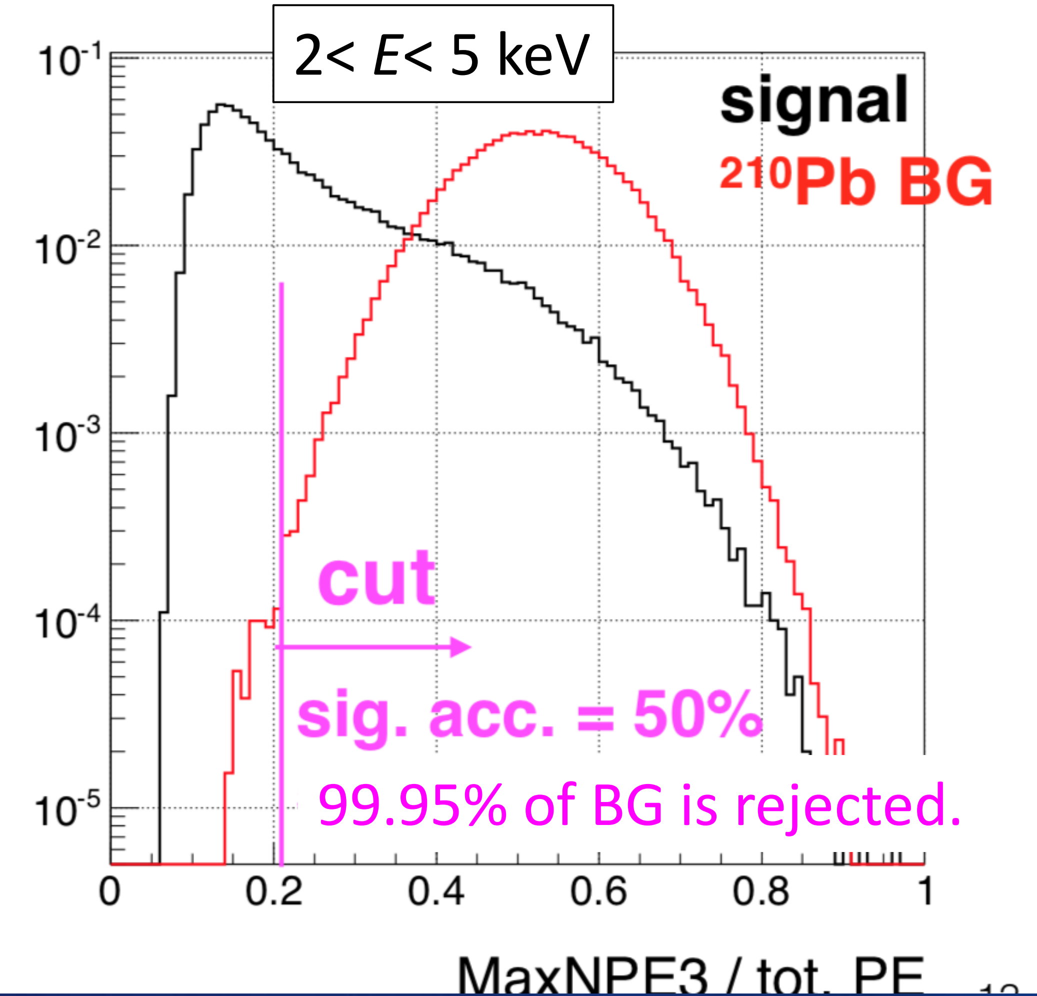
This technique is applicable to other conductive material. (Non-conductor?➔ Future R&D item)

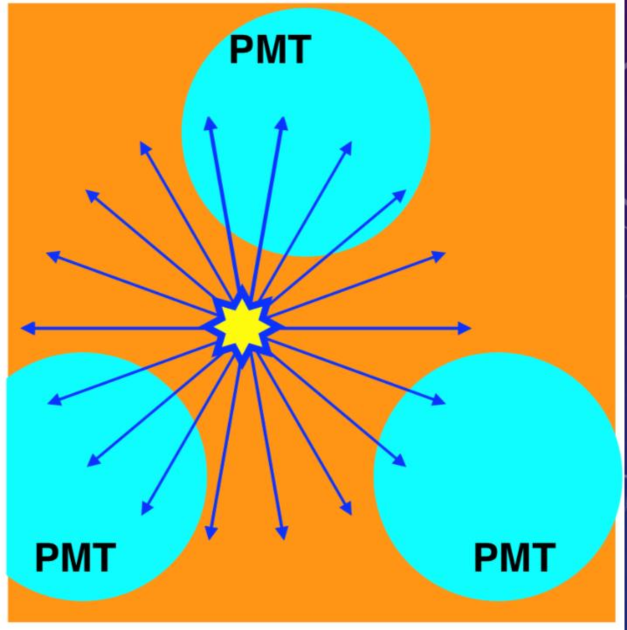
LOW BG TECHNOLOGY
-- 3" ROUND SHAPE PMT FOR FUTURE DETECTOR

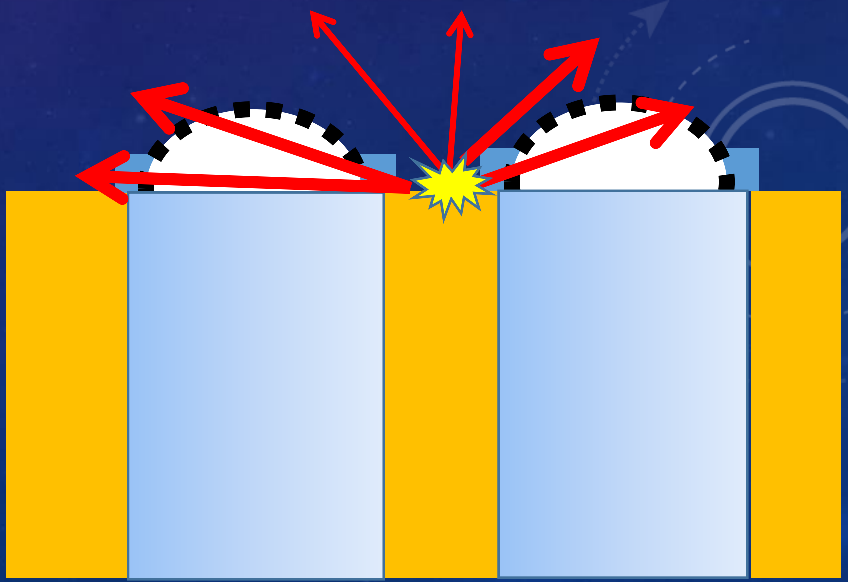
- We have developed a new low PMT, R13111, for a future detector with Hamamatsu.
  - Low RIs
  - Round shape
  - Larger photo-cathode



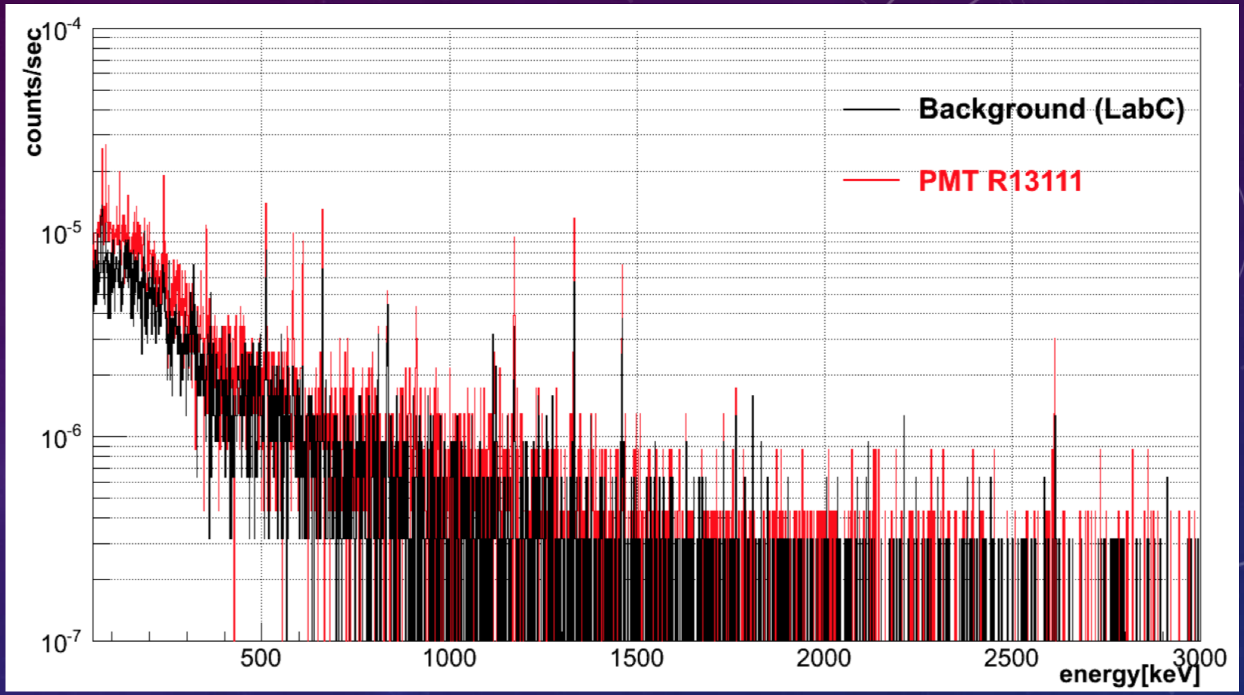
- Why round shape?
  - The BG from detector wall can be removed







- Low BG
  - We screened materials with Ge-detectors, GD-MS, and ICP-MS.
  - A low BG PMT, R113111, is developed successfully .



(Unit: mBq)	^{226}Ra	^{238}U	^{210}Pb	^{228}Ra (^{232}Th)	^{40}K	^{60}Co
Produced in 2015	0.38 (0.07)	<1.6	<32	0.29 (0.06)	<1.4	0.22 (0.05)
Produced in 2016	0.44 (0.06)	<1.4	<24	0.20 (0.06)	2.0 (0.5)	0.13 (0.04)
XMASS-I PMT (R10789)	1.2 (0.3)	-	-	<0.78	9.1 (2.2)	2.8 (0.2)

～1/10

Paper will be published soon.

SUMMARY

- XMASS project
- Physics results from XMASS
- Low background technique in XMASS

Thank you for your supports to XMASS-I.