New experiment for two neutrino emission double beta decay using Zirconium-96

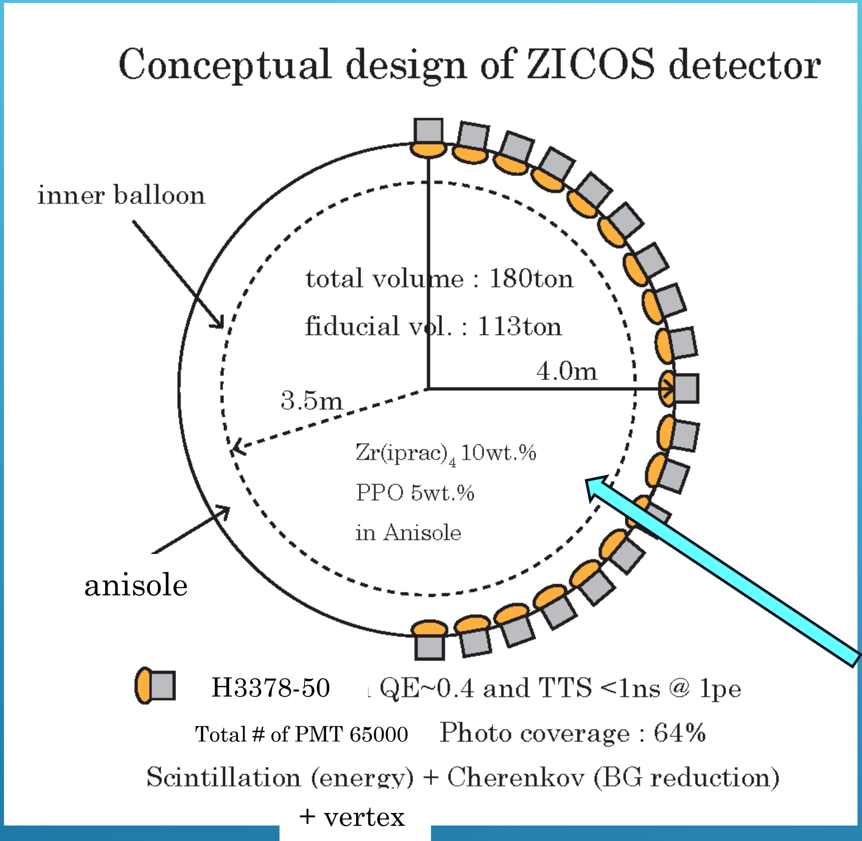
The 30th edition of the International Workshop on Weak interaction and Neutrinos (WIN2025) Brighton, UK

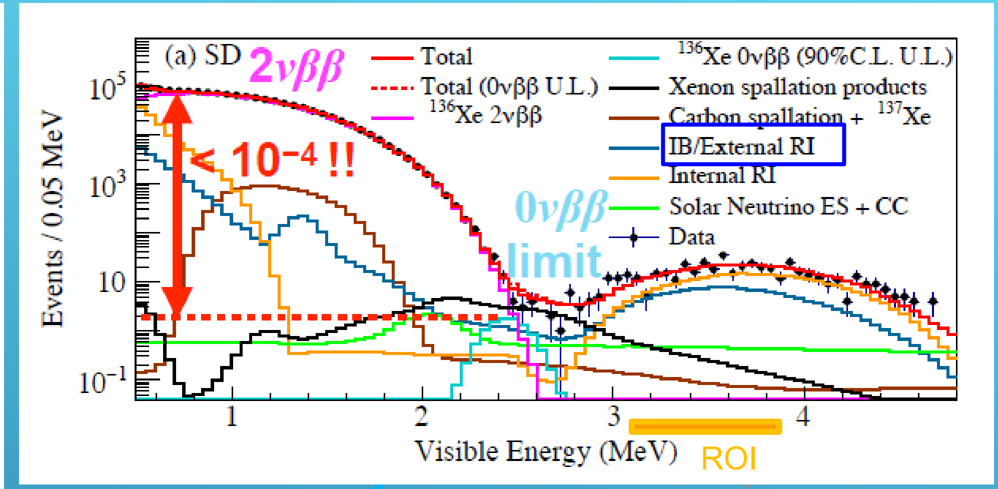
June 12, 2025

Grant-in-Aid for Scientific Research on Innovative Areas
19H05093 and 20H05241
Scientific Research (B) 22H01243/23K22514
Grant-in-Aid for Transformative Research Areas(A) 25H02166

Miyagi University of Education Y. Fukuda
Kamioka Observatory, ICRR, Univ. of Tokyo S. Moriyama, K. Hiraide
University of Fukui I. Ogawa
Tokyo University of Science T. Gunji
Institute for Materials Research, Tohoku University S. Kurosawa
University of Toyama Y. Nakano

ZICOS experiment for ^{96}Zr 0νββ observation





I.Shimizu, Plenary talk at Neutrino2024 conference.

Liquid scintillator loaded ^{96}Zr

NEMO3 : $T^{0\nu}_{1/2} > 9.1 \times 10^{21}$ yrs

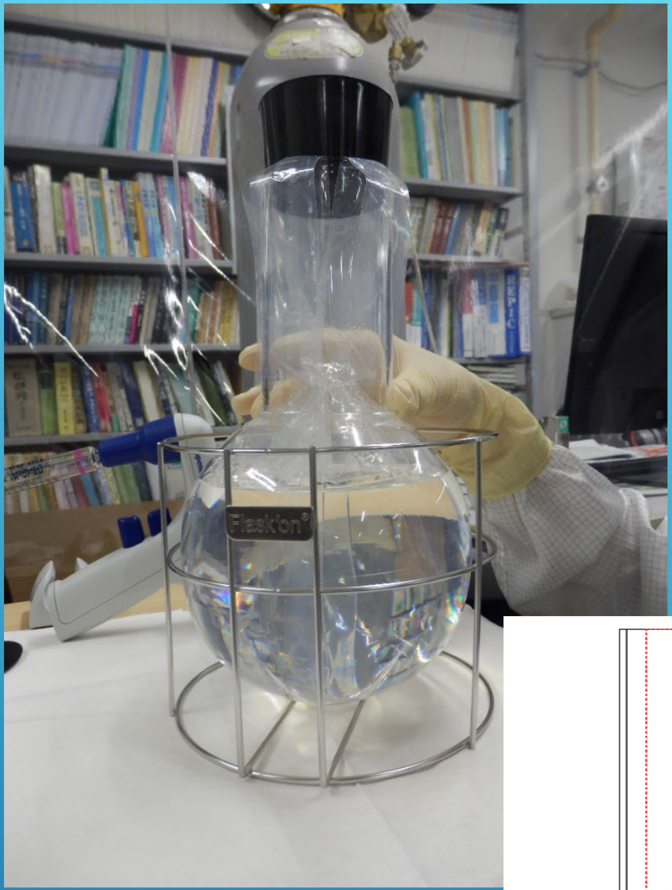
^{96}Zr : 45 kg (nat.) → 865 kg(50 % enrich)→1/20 BG

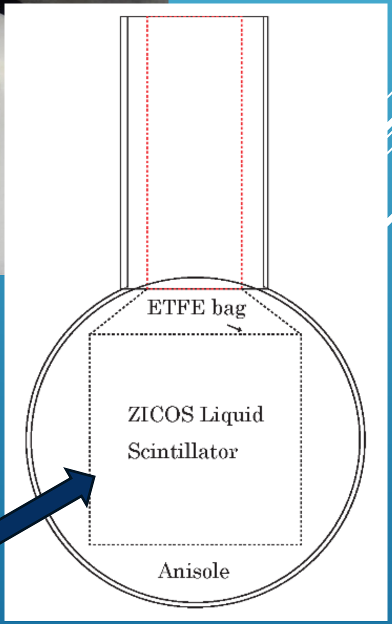
$T^{0\nu}_{1/2} > 4 \times 10^{25}$ yrs → 2×10^{26}yrs → ~1 $\times 10^{27}$yrs

Setup for 2ν-ZICOS detector

- 20 2” Ultra Low BG PMT Hamamatsu R10789.
- 16 cm diameter round bottom flask using pure Quartz.
- 2L of ZICOS LS loaded 200g of $Zr(iPrac)_4$ including ^{96}Zr 0.74g has been already prepared.

Setup for 2ν-ZICOS detector

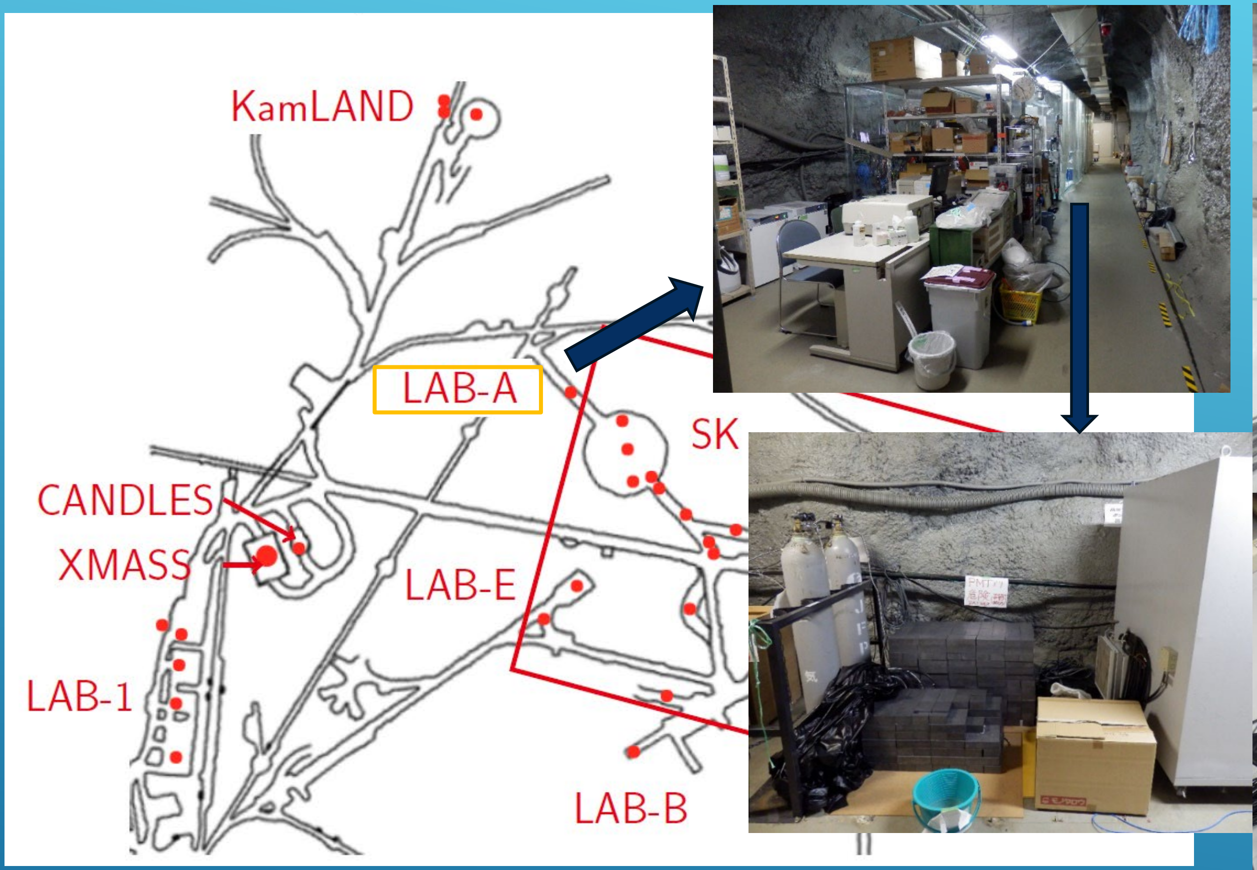


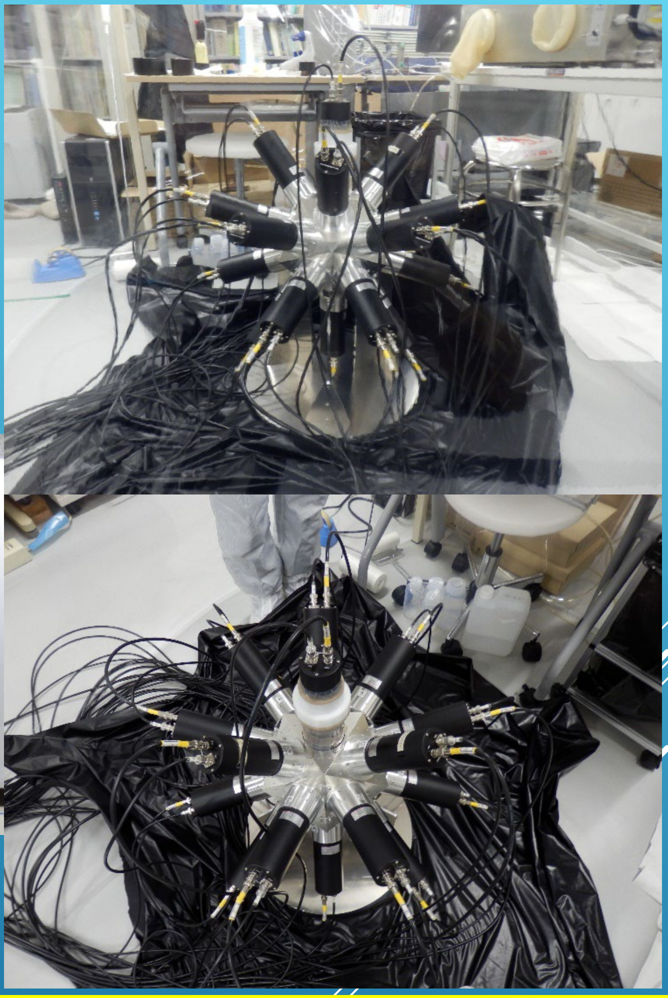


- 20 2” Ultra Low BG PMT Hamamatsu R10789.
- 16 cm diameter round bottom flask using pure Quartz.
- 2L of ZICOS LS loaded 200g of $Zr(iPrac)_4$ including ^{96}Zr 0.74g has been already prepared.

ETFE bag for reducing BG contains 0.73L ZICOS LS which includes ^{96}Zr 0.27g.

2ν-ZICOS for measurement of 2νββ half-life





In Kamioka mine LAB-A : Behind of LINAC control room

Now we are testing on the ground.

Why 2ν-ZICOS should do in Kamioka mine?

There is huge backgrounds for the observation of 2νββ events on the surface of earth due to cosmic muons.

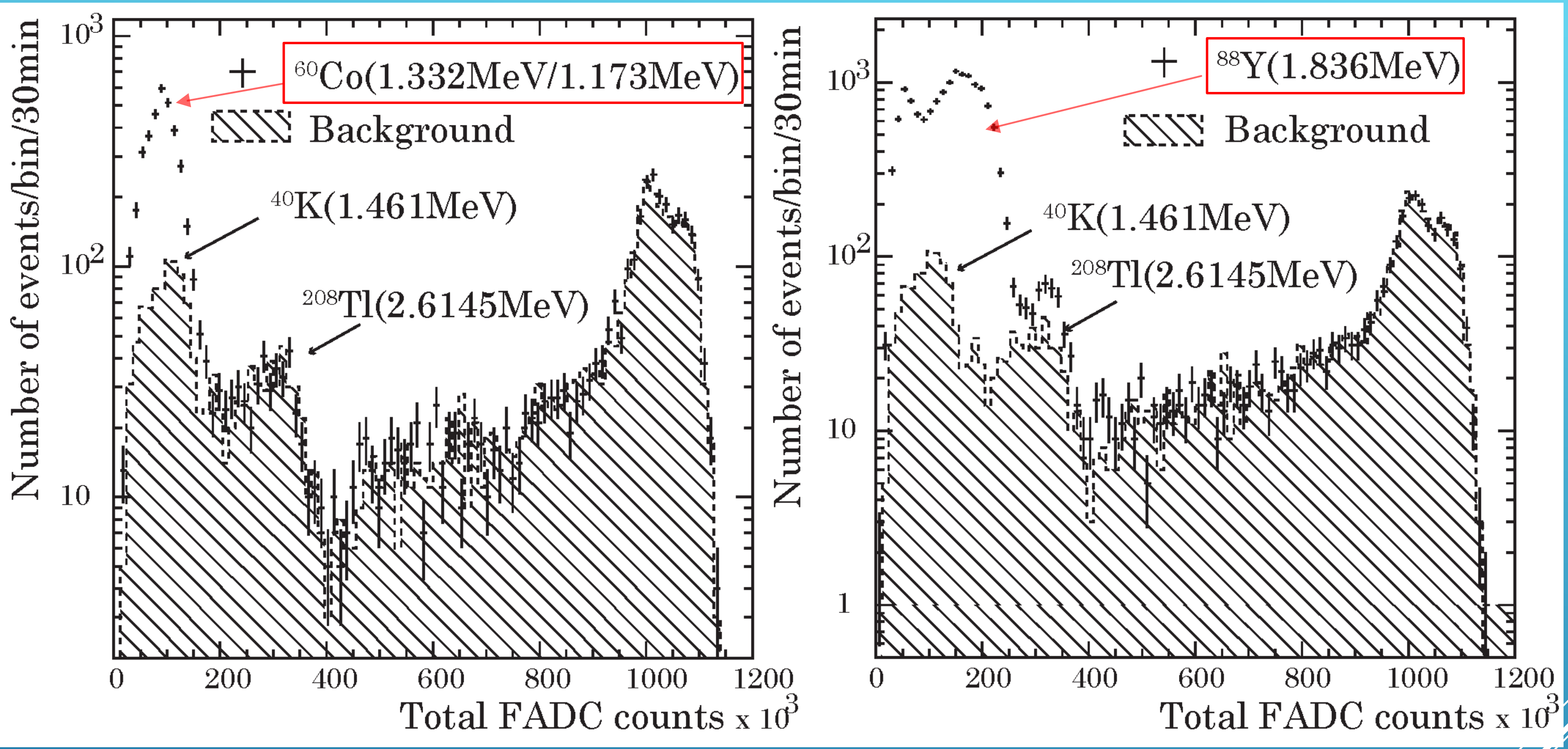
- Cosmic muon rate is ~2Hz on the surface of earth.
- Most significant spallation product is ^{11}C which decays in beta plus and emits total energy ~2MeV.
- The half-life of ^{11}C is 1200sec and the detector should have no live-time if veto for all muons.
- In the mine, the cosmic muon rate will be 2×10^{-5}Hz, so dead-time is about 2.4% even if veto for all muons.
- Expected event rate due to ^{11}C, which is caused by neutron produced by muon spallation, is ~20 events/yr using measured neutron flux. (same expected number was obtained by KamLAND data. Ref:Phys.RevC.107.054612)

Are we ready to start 2ν-ZICOS in the mine?

To show the detector performance of 2ν-ZICOS experiment, we measured following things.

1. Using calibration source, is observed energy spectrum consistent with simulation?
2. Does energy scale have a linearity?
3. Is the reconstructed vertex position consistent with simulation?
4. Is averaged angle, which is topological info of Cherenkov light used for BG event reduction, consistent with simulation?
5. Is background events low enough?
6. Is background spectrum understood?

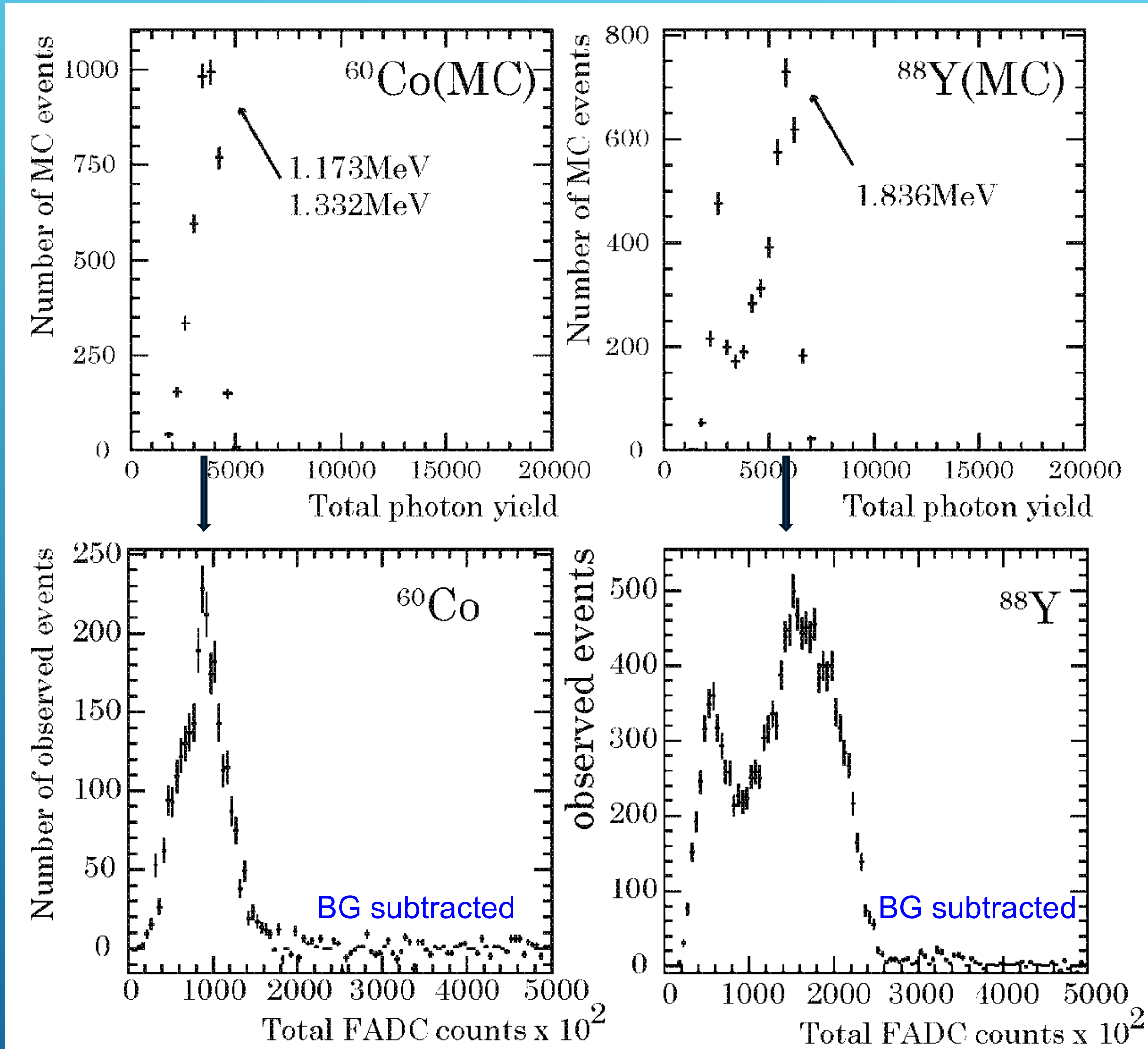
Energy spectra for 2ν-ZICOS detector



- Energy spectra for BG and calibration source
- Compton edges of both BG ^{40}K / ^{208}Tl gamma and calibration source were observed.

Energy scale looks good.

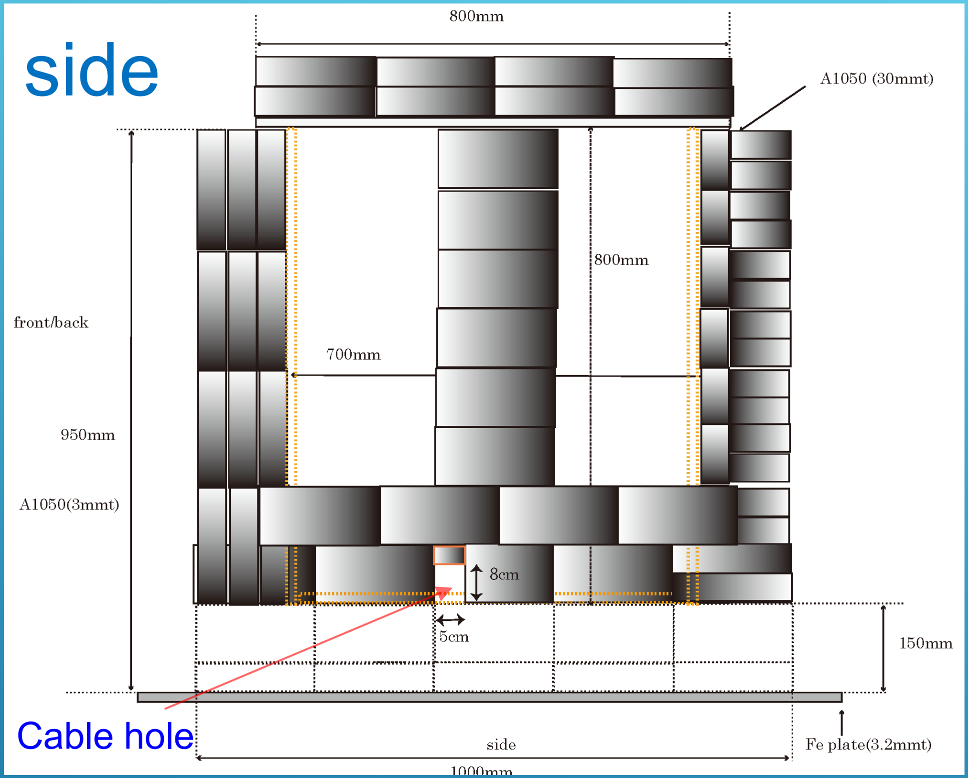
Energy calibration for 2ν-ZICOS detector

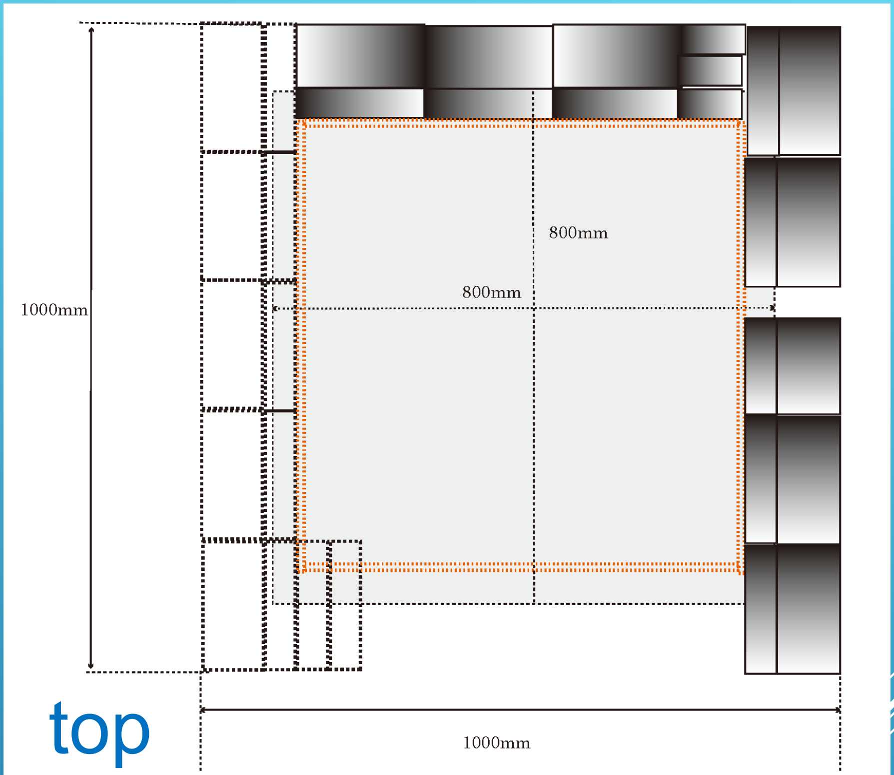


- Found clear Compton edge of gamma sources.
- Trigger simulation was also applied for MC data.
- Energy resolution was worth than simulation which does not consider the fluctuation of light intensity for PMT.

Energy spectrum seems to be reproduced by simulation.

Pb shield for 2ν-ZICOS experiment



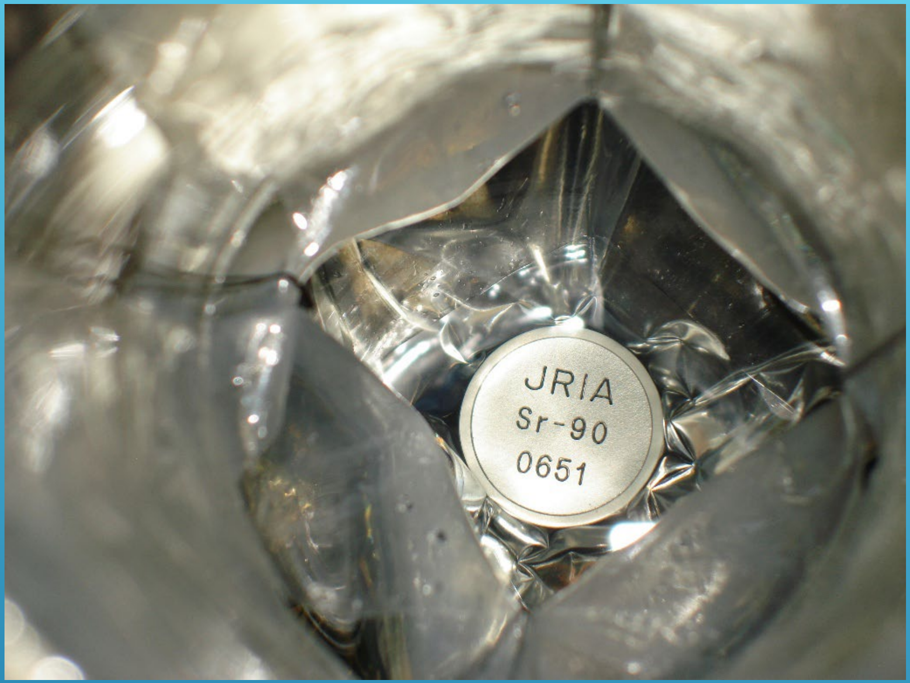


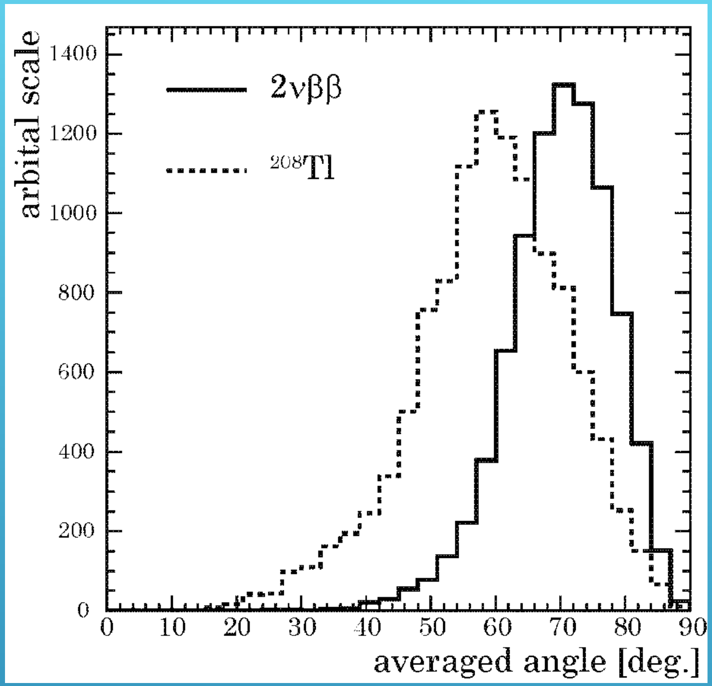
- 15cm thickness of Pb shield will be constructed.
- A1050 aluminum box for both structure of Pb shield and N_2 gas filling for safety issue.
- 20cm thickness of Pb shield and oxygen free copper will be used for world highest sensitivity measurement in next year.

Gain adjustment for vertex reconstruction

- Measure the scintillation caused by electron (β) emitted by ^{90}Sr source via narrow hole.
- All PMT gains will be adjusted within a few % by High voltage.
- Verify the consistency of vertex distribution between data and simulation.
- Confirm the averaged angle distribution as expected.

Gain adjustment for vertex reconstruction





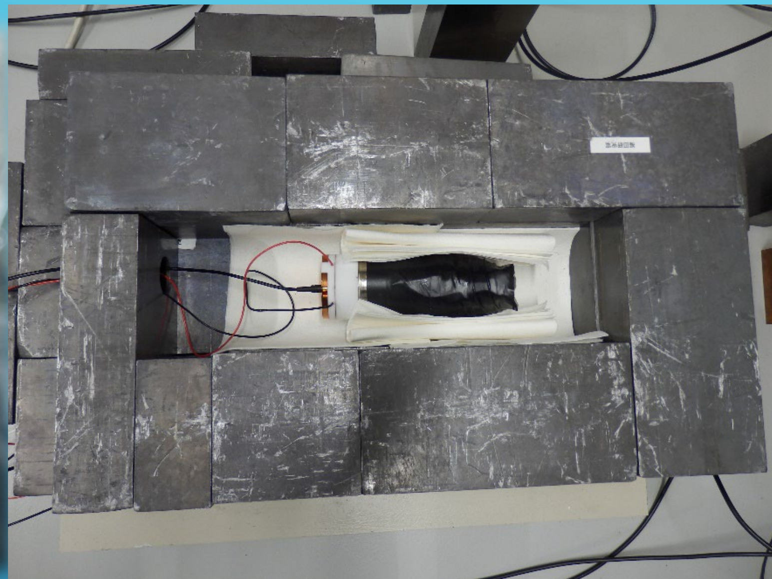
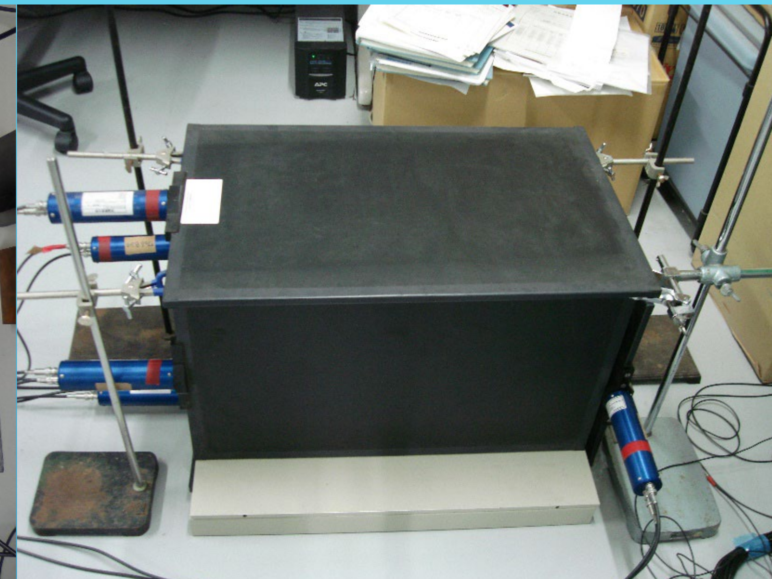
- Measure the scintillation caused by electron (β) emitted by ^{90}Sr source via narrow hole.
- All PMT gains will be adjusted within a few % by High voltage.
- Verify the consistency of vertex distribution between data and simulation.
- Confirm the averaged angle distribution as expected.

Are we ready to start 2ν-ZICOS in the mine?

To show the detector performance of 2ν-ZICOS experiment, we measured following things.

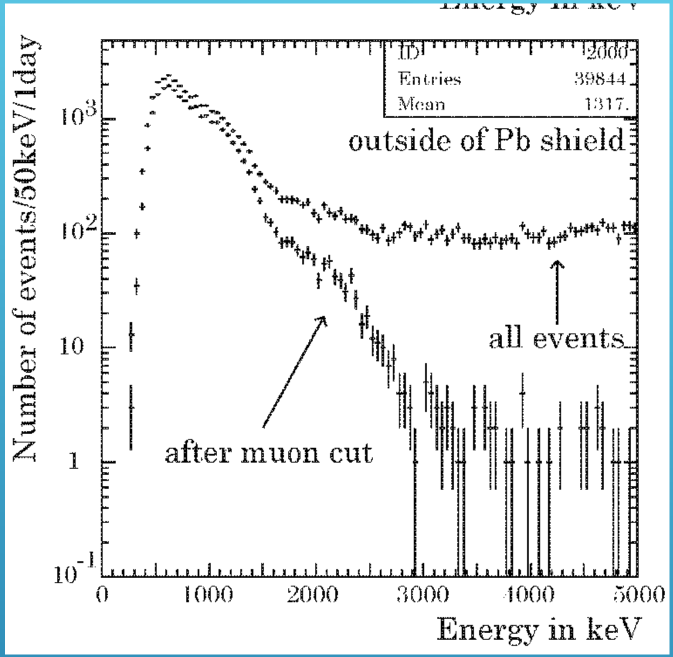
1. Using calibration source, is observed energy spectrum consistent with simulation?
2. Does energy scale have a linearity?
3. Is the reconstructed vertex position consistent with simulation?
4. Is averaged angle using Cherenkov light, which is topological ingo used for BG reduction, consistent with simulation?
5. Is background events low enough?
6. Is background spectrum understood?

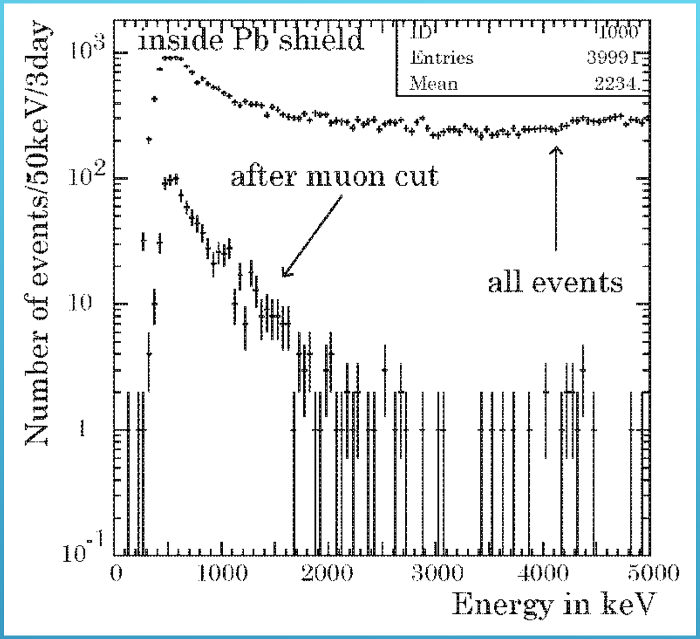
BG measurement using 20mL quartz vial

- Difficult to measure BG events for 2ν-ZICOS detector inside of Pb shield due to limit of number of Pb block.
- 17.5mL ZICOS LS filled in 20mL quartz vial.
- The vial contacted with XMASS PMT R10789 covered by Myra film.
- 10cm thickness of Pb radiation shield was prepared.
- In order to veto cosmic muons, plastic scintillators were located around Pb shield.

Energy spectra using Quartz vial detector



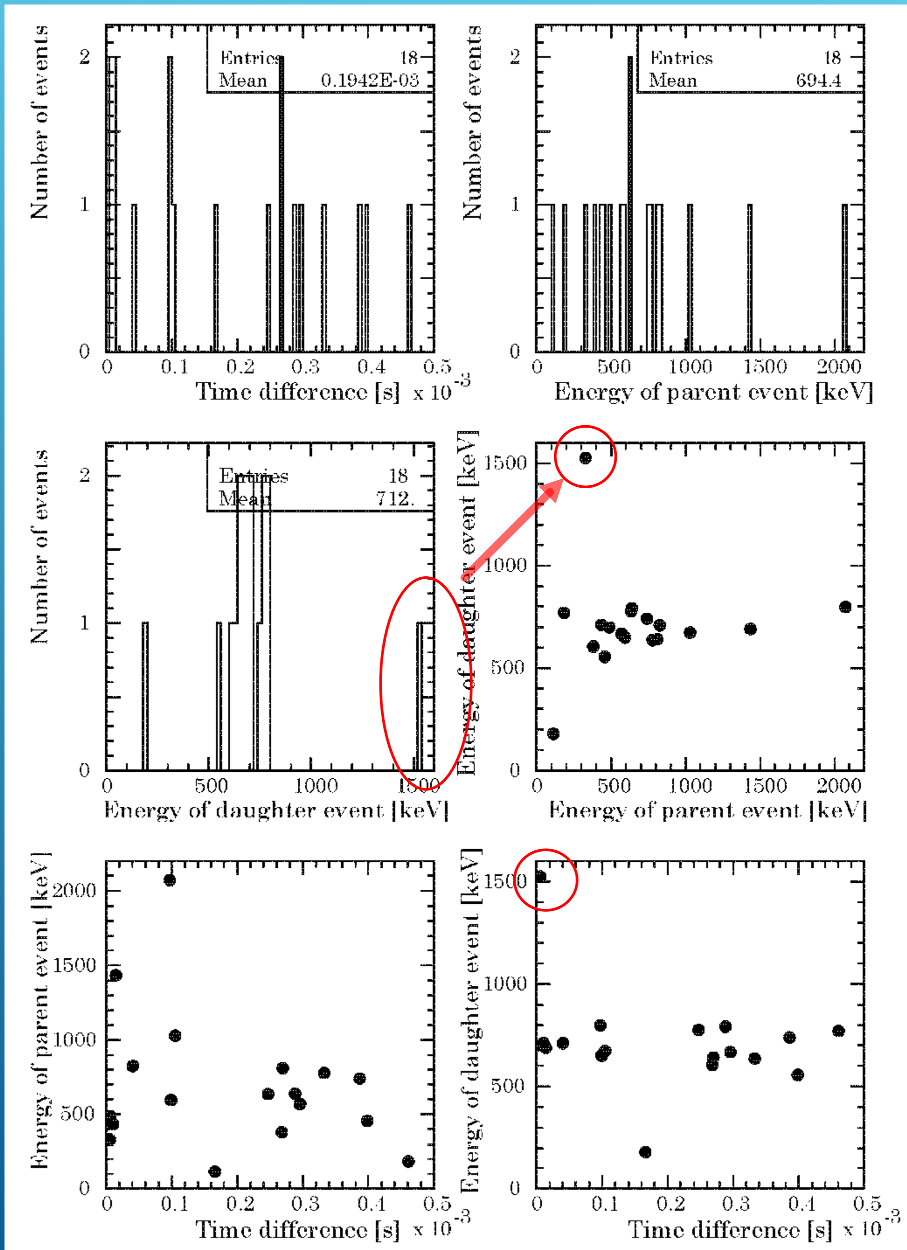


Outside of shield

Inside of shield

- Compton scattering gammas from natural ^{40}K and ^{208}Tl decay were observed for outside of Pb shield.
- Some background events were found inside of Pb shield.
- Assuming these events from U/Th in LS, we should search for ^{214}Bi -^{214}Po candidates (τ=1.643 × 10^{-4}sec)

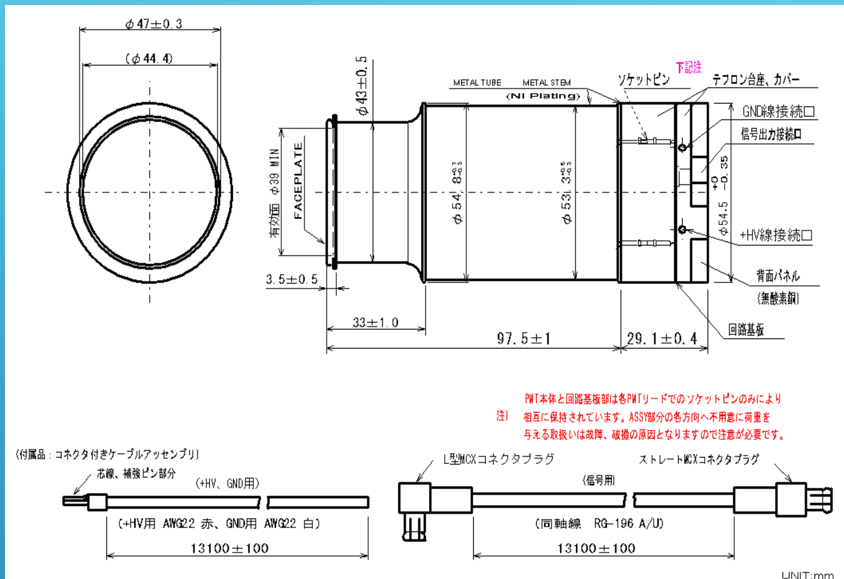
Search for ^{214}Bi-^{214}Po candidates

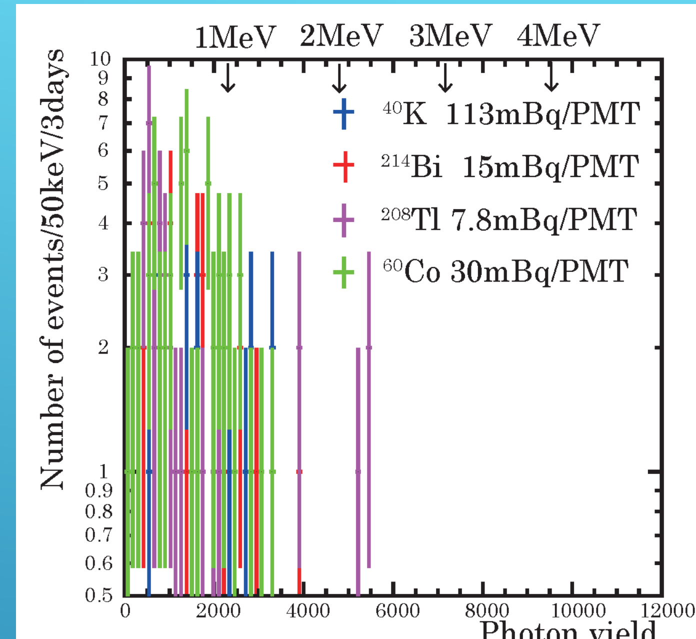


- 18events have time difference < 5×10^{-4} s except parent muon
- Parent events have wider energy distribution than daughter events
- Daughter events have narrow distribution (like α quenching)

17events looks ^{214}Bi-^{214}Po candidates. But they don’t contribute residual events.

BG events from PMT R10789





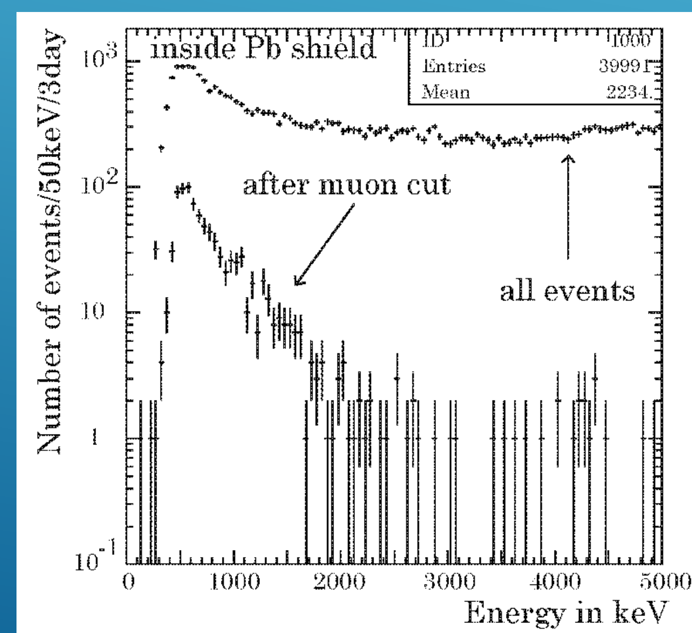
Ref: NIMA 922(2019)171-176

1.2 ± 0.3 mBq/PMT of ^{226}Ra

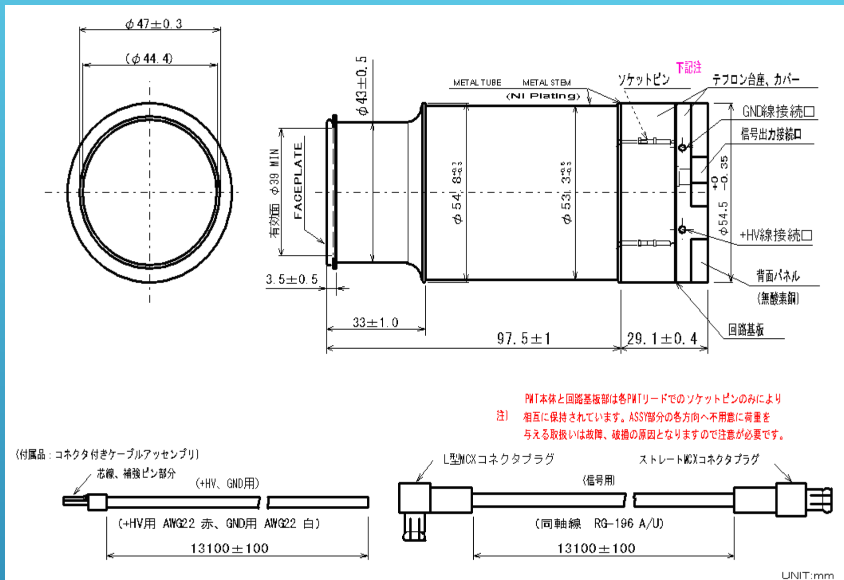
< 0.78 mBq/PMT of ^{228}Ra

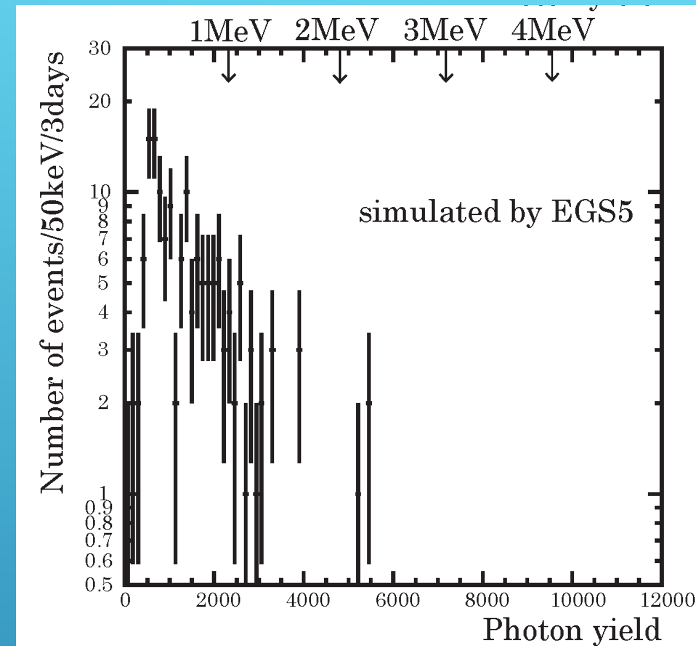
9.1 ± 2.2 mBq/PMT of ^{40}K

2.8 ± 0.2 mBq/PMT of ^{60}Co.



BG events from PMT R10789





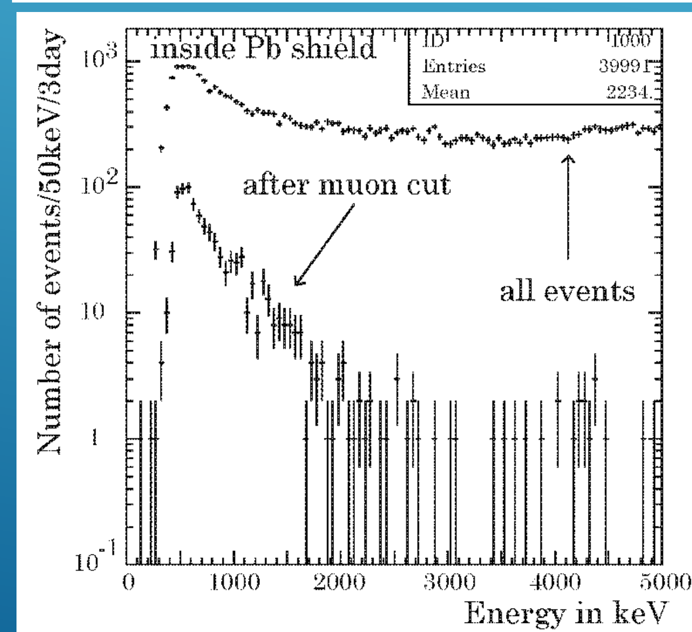
Ref: NIMA 922(2019)171-176

1.2 ± 0.3 mBq/PMT of ^{226}Ra

< 0.78 mBq/PMT of ^{228}Ra

9.1 ± 2.2 mBq/PMT of ^{40}K

2.8 ± 0.2 mBq/PMT of ^{60}Co.



Need ~40 times larger BG events to explain the residual events.

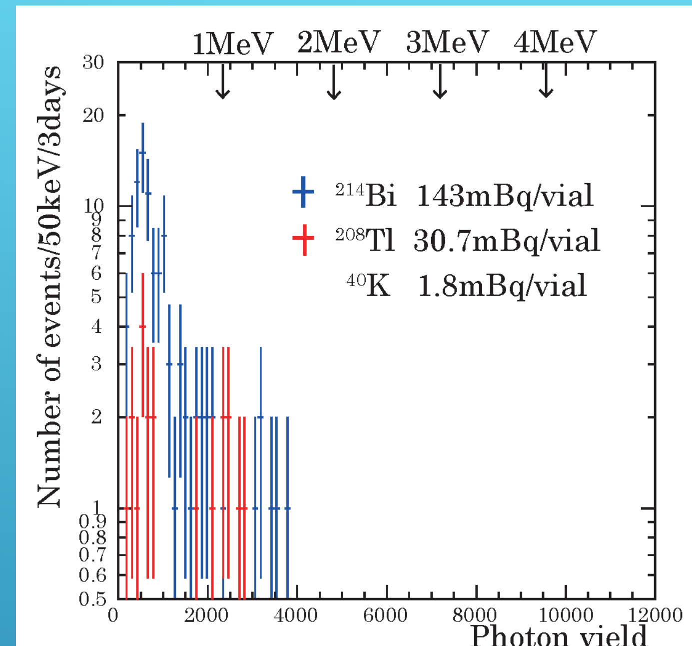
BG events from Quartz

表　分析結果

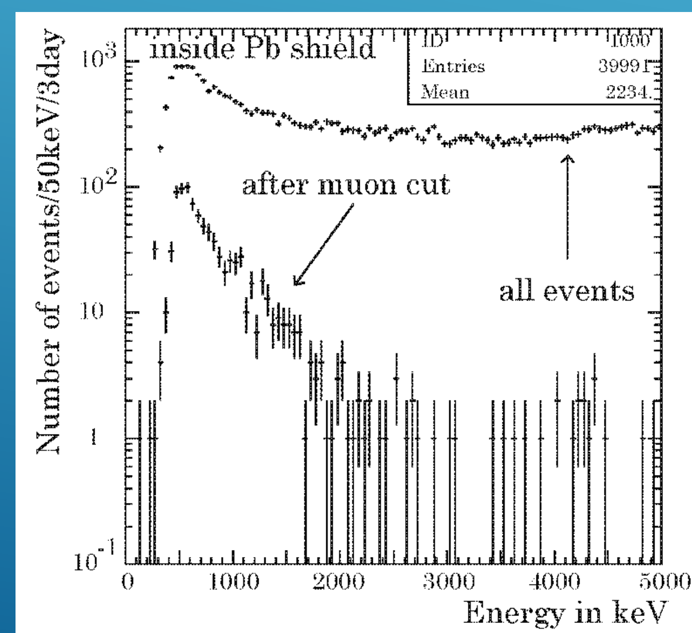
単位：ng/g

試料名	K	Th	U
RQ200	330	42	64
GE214	180	15	29
定量下限	5	1	1

Measured by Toshiba analysis using IPC mass spectrometer



14.3mBq/vial of ^{214}Bi
3.07mBq/vial of ^{208}Tl
0.18mBq/vial of ^{40}K



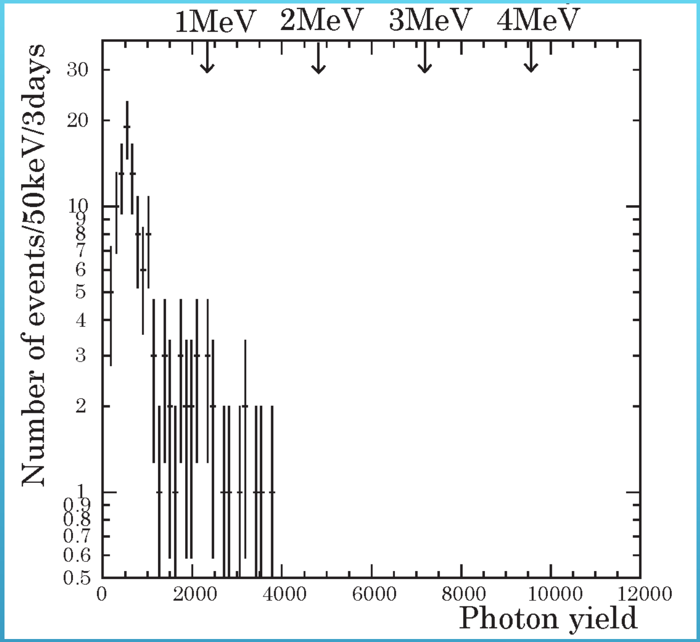
BG events from Quartz

表　分析結果

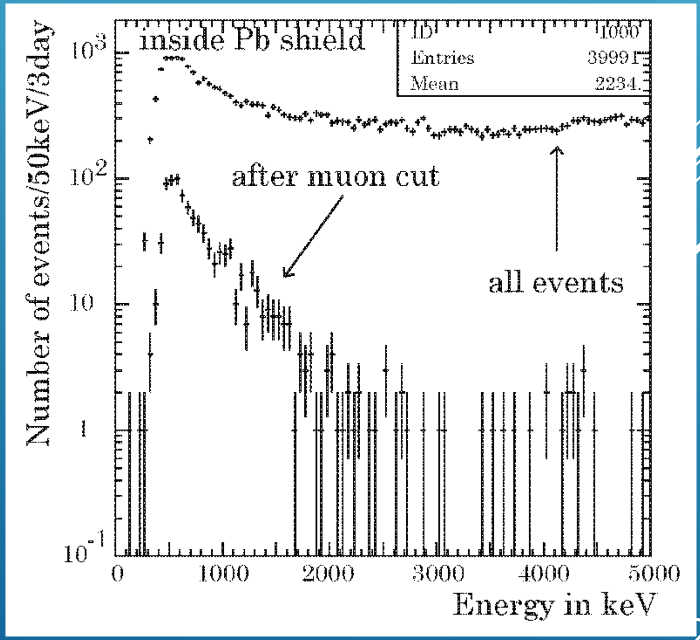
単位：ng/g

試料名	K	Th	U
RQ200	330	42	64
GE214	180	15	29
定量下限	5	1	1

Measured by Toshiba analysis using IPC mass spectrometer

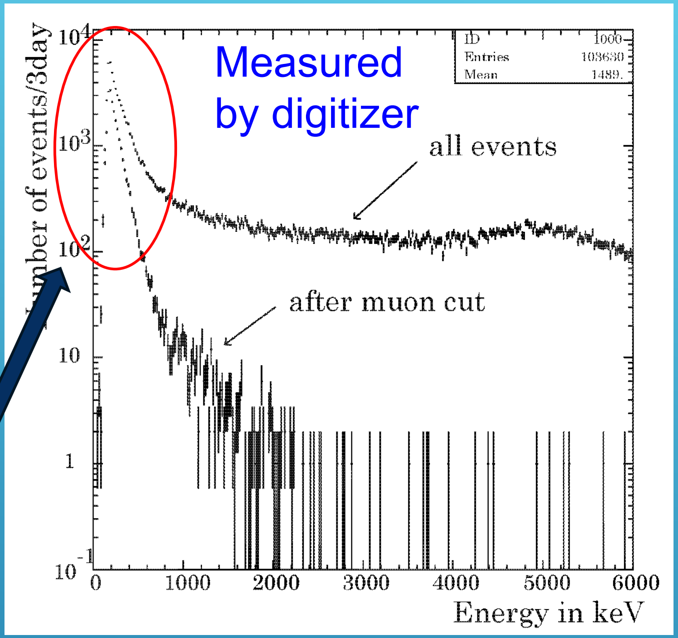


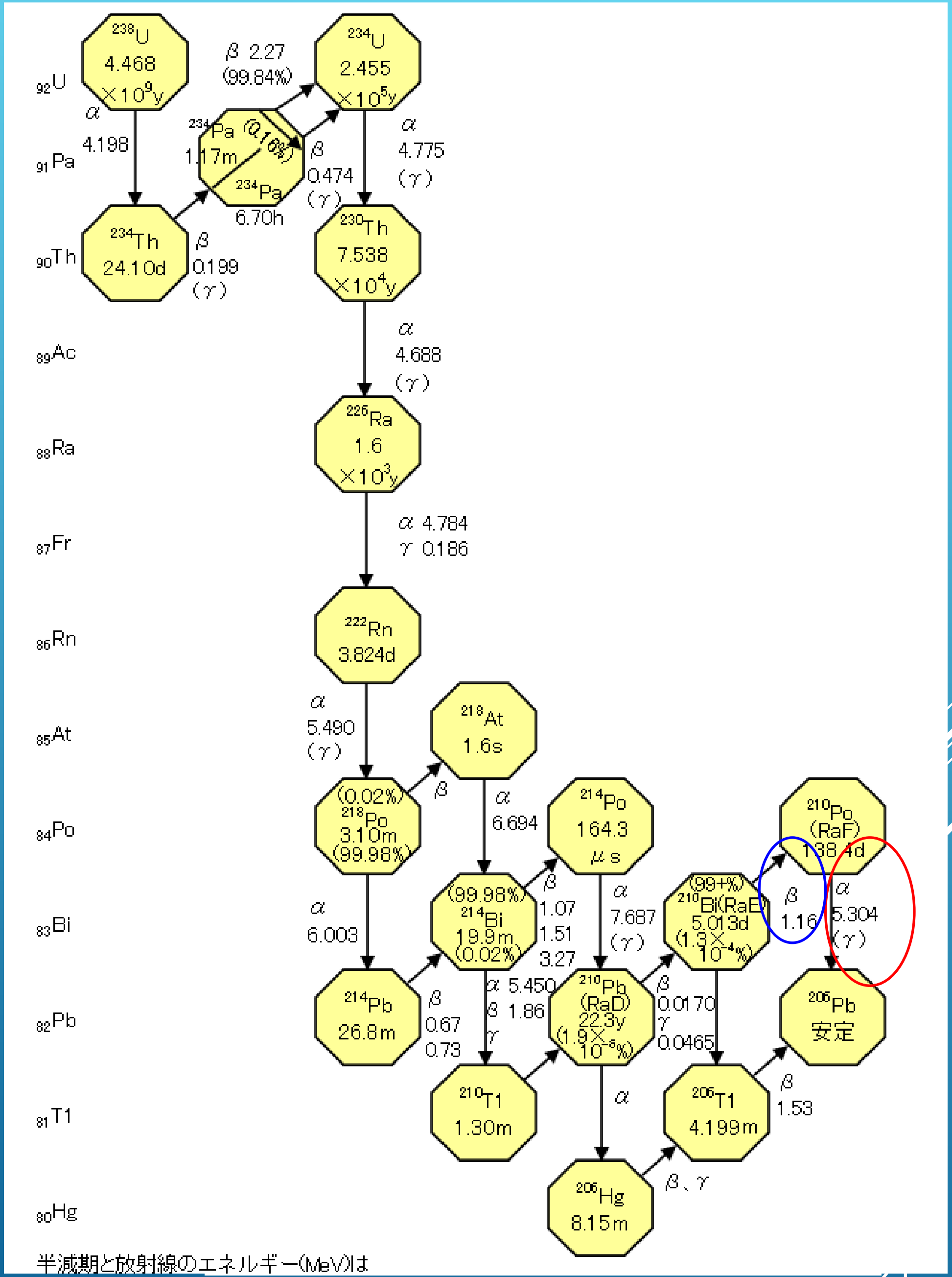
14.3mBq/vial of ^{214}Bi
3.07mBq/vial of ^{208}Tl
0.18mBq/vial of ^{40}K



Even more 50 times larger BG events could not explain the residual events.

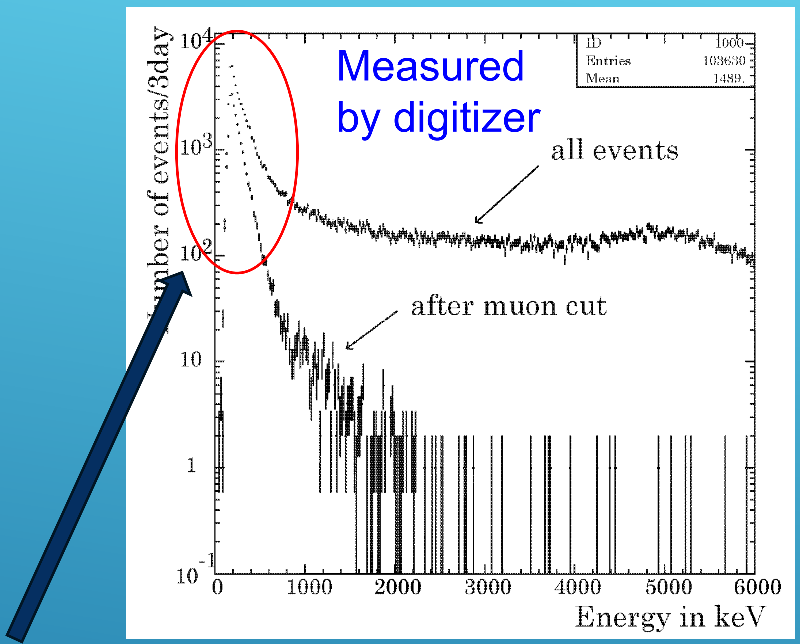
BG events from surface of Quartz

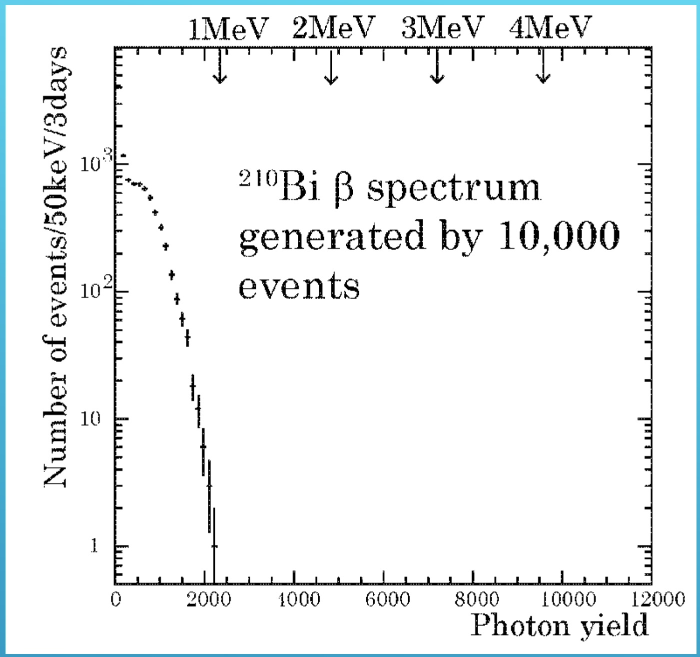




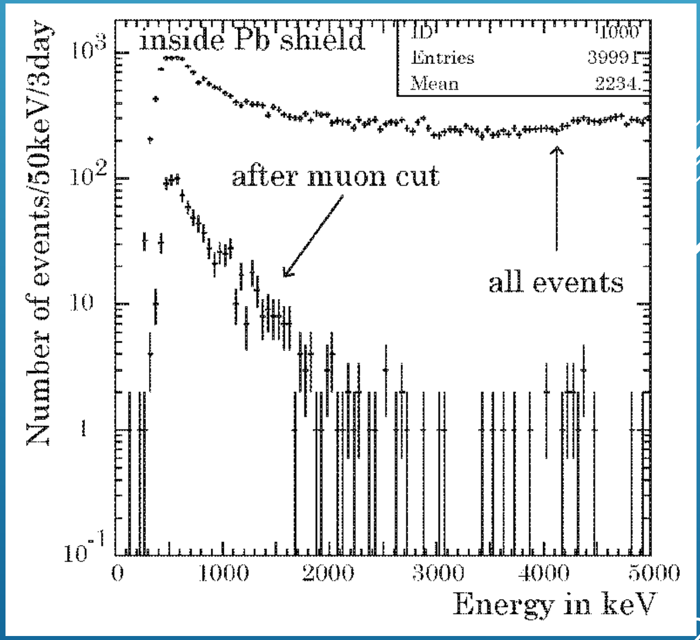
α from ^{210}Po? if so, β from ^{210}Bi should be observed by same order of events.

BG events from surface of Quartz



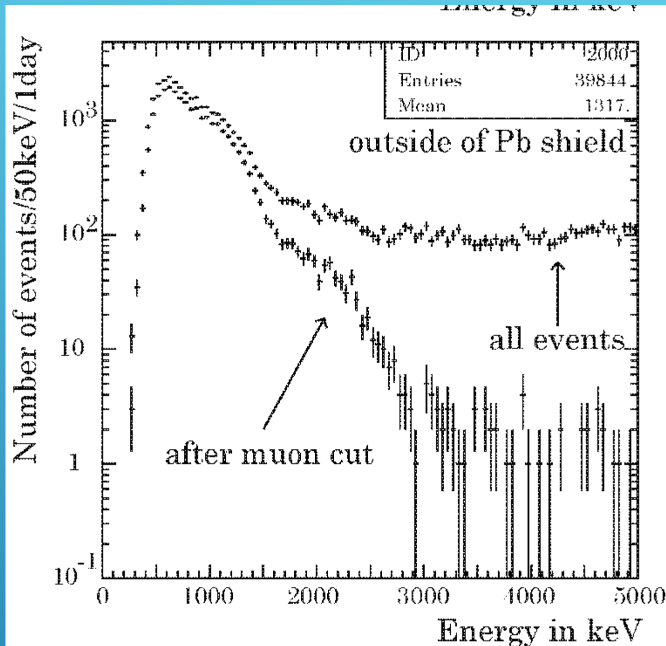


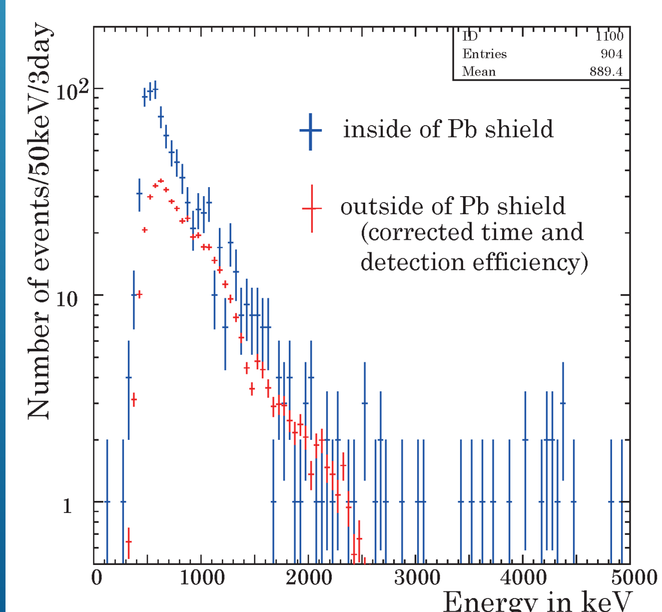
α from ^{210}Po? if so, β from ^{210}Bi should be observed by same order of events.



Observed rate correspond to 2mBq/cm^2, but XMASS estimated as 1μBq/cm^2.

Comparing distributions using natural gamma





Almost the energy spectrum of residual events is consistent with natural gammas observed at outside of shield.

No obvious BG event exists except similar natural gamma, we are still investigating the source of residual events. (At least, it is not internal BG.)

Summary

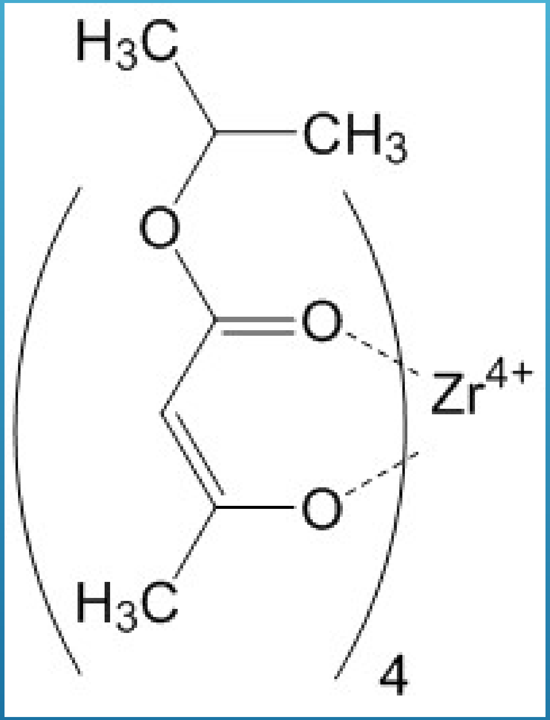
- Use ultra low BG PMT Hamamatsu R10789 in order to avoid U/Th/K BG events.
- Observed 17 events as ^{214}Bi-^{214}Po candidate, which is consistent with result of ^{226}Ra 2.72 $\pm$ 1.33 mBq/kg measured by Ge detector in Kamioka mine. (https://doi.org/10.1093/ptep/ptad136)
- BG events from U/Th/K in both PMT R10789 and Quartz vial are quite few.
- Surface event rate is inconsistent with XMASS estimation.
- Residual events seem to not be internal BG events.
- Most of things to do before starting 2ν-ZICOS experiment seem to be done, so we will be ready to move all equipment to Kamioka at the end of this month.
- Safety equipment will be also prepared by September.
- The observation will start at this Autumn. Stay tuned!

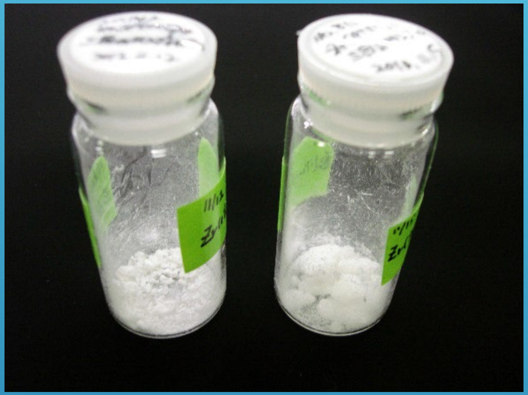
backup

Zirconium β-keto ester complex

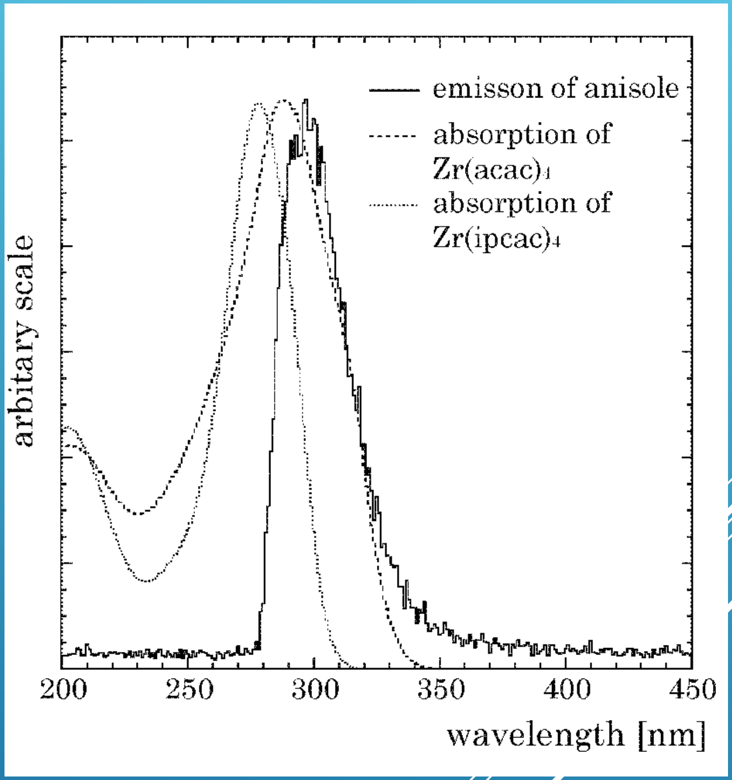
$Zr(CH_3COCHCOOCH(CH_3)_2)_4$ = $Zr(iPrac)_4$ mw : 663.87

Tetrakis(isopropyl acetoacetate) Zirconium





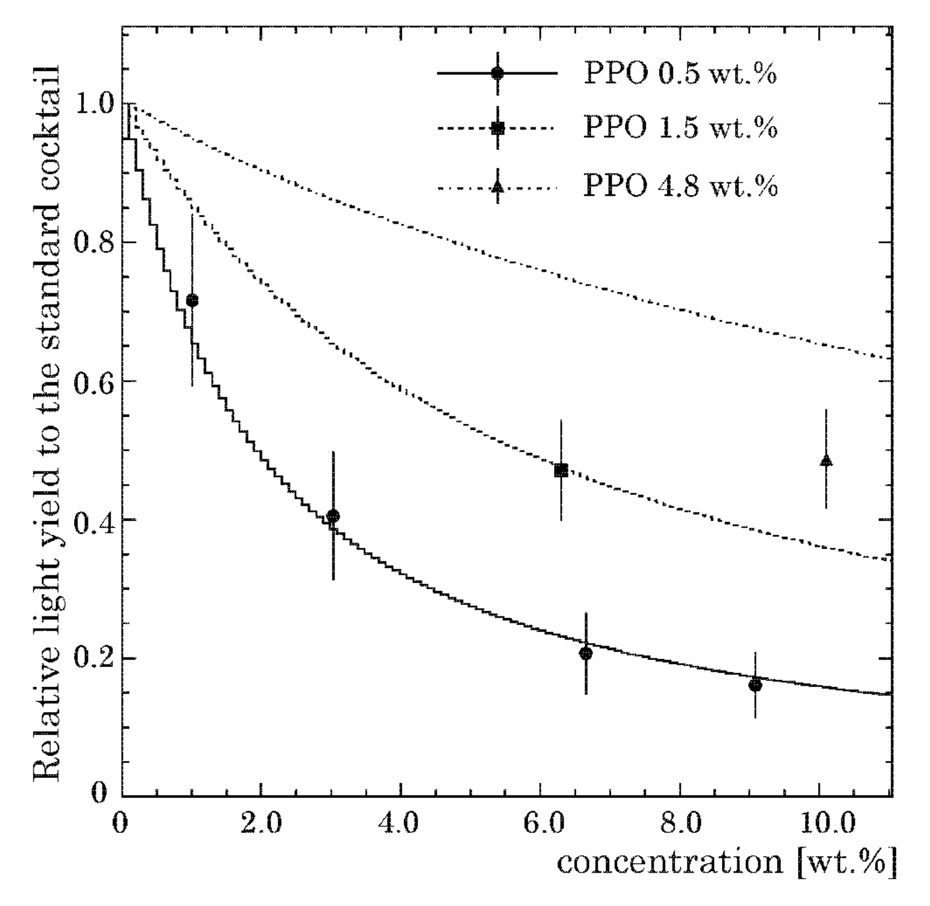
Synthesized by Prof. T.Gunji (Tokyo University of Science)

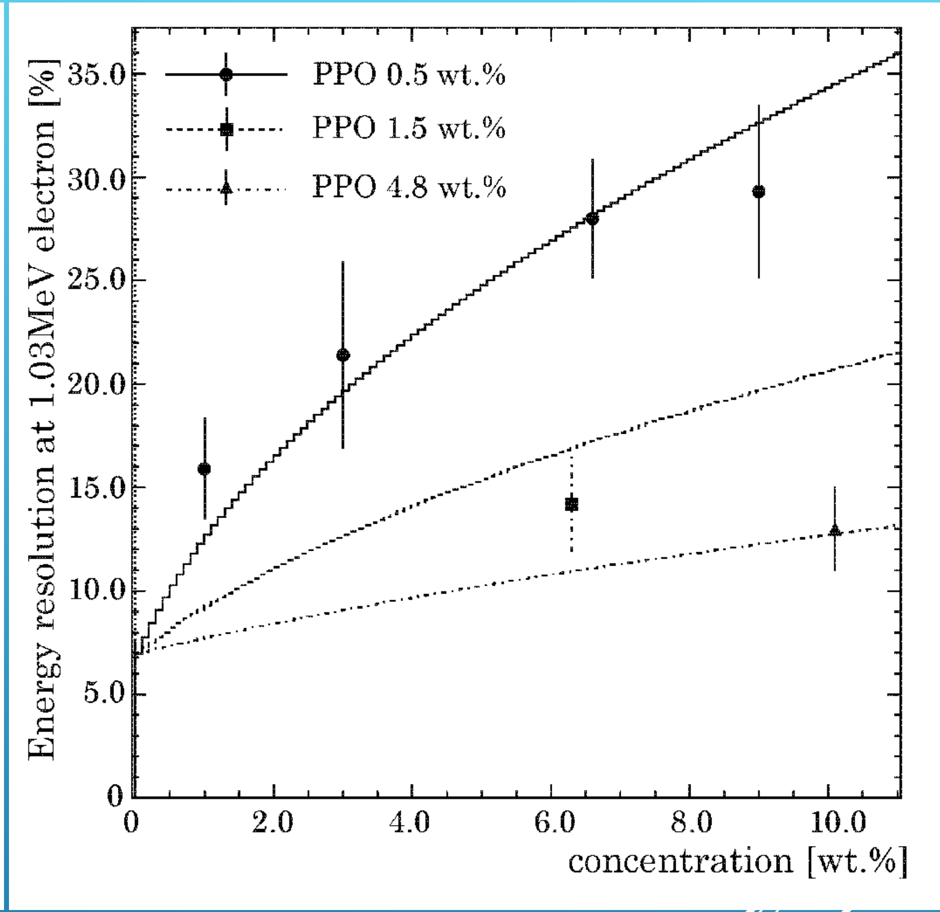


No commercial product

Shorter wavelength for absorbance

Improve of light yield and resolution



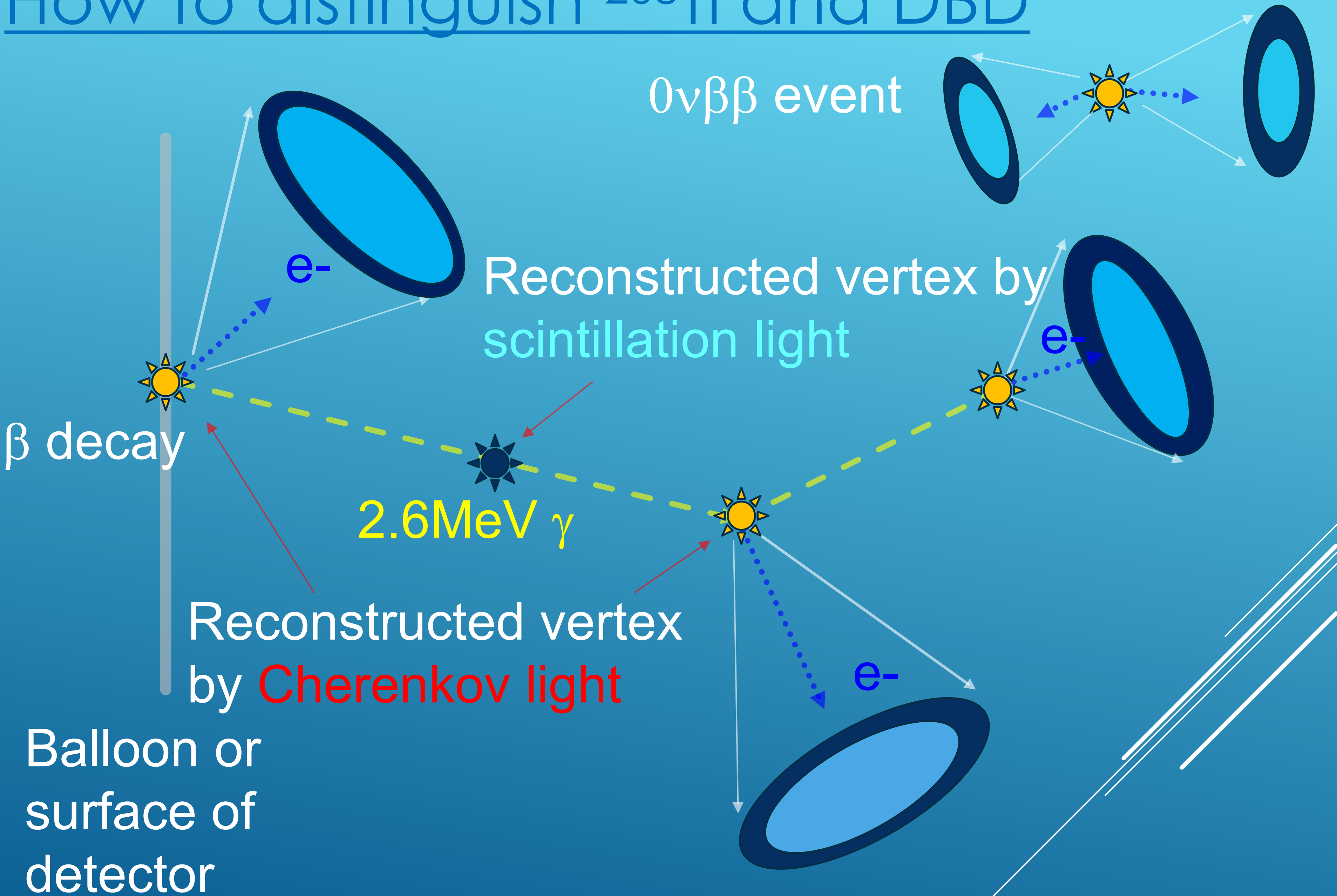


Zr(iPrac)$_4$ absorbs the scintillation photon and makes the energy resolution worth, however PPO could improve them.

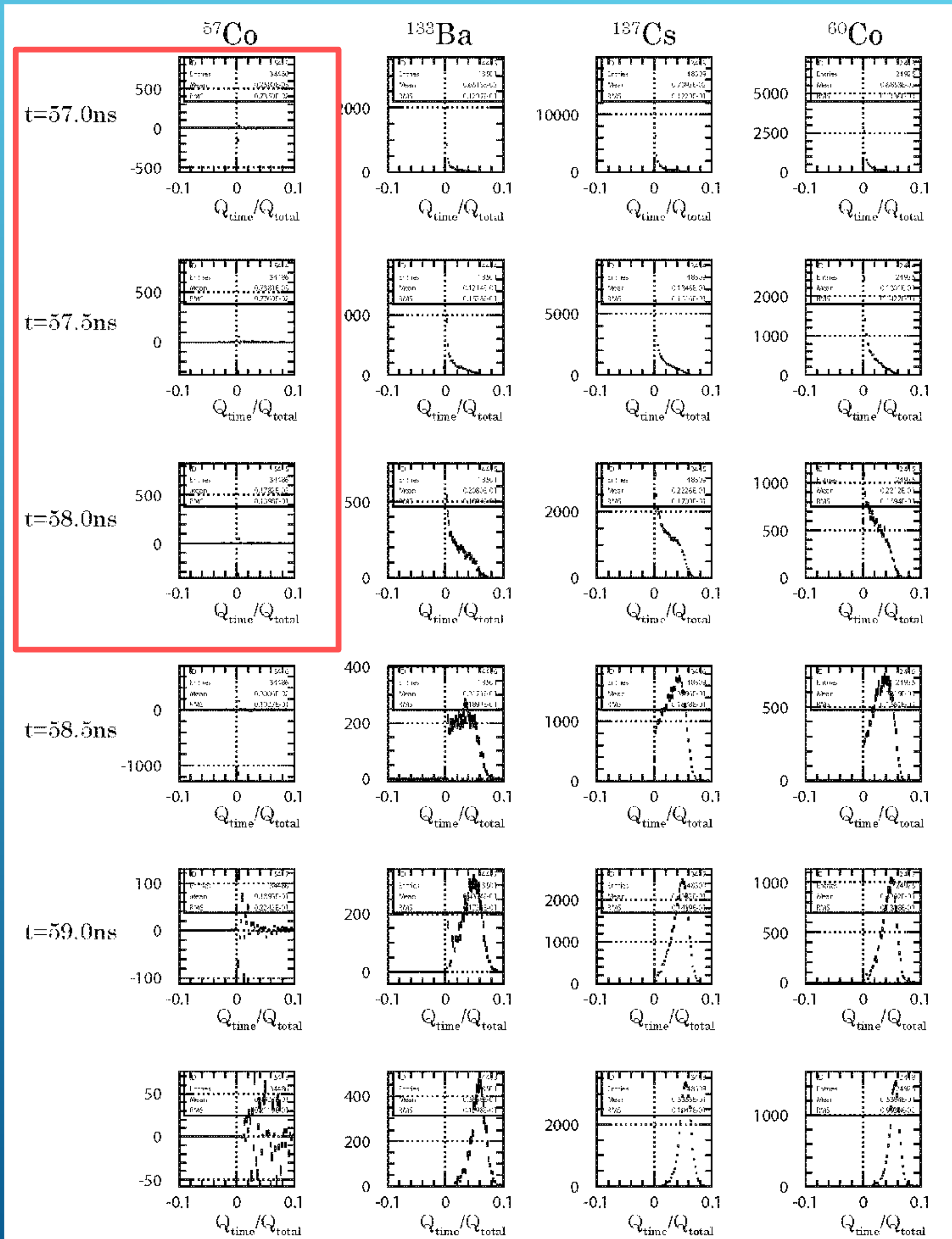
$$\frac{13.0\pm2.0\%}{\sqrt{40\%/9\%*0.72*3.35\text{MeV}/1.03\text{MeV}}}$$

$= 4.1\pm0.6\%$ at 3.35MeV

How to distinguish ^{208}Tl and DBD



ZICOS LSを用いたガンマ線事象の立ち上がり

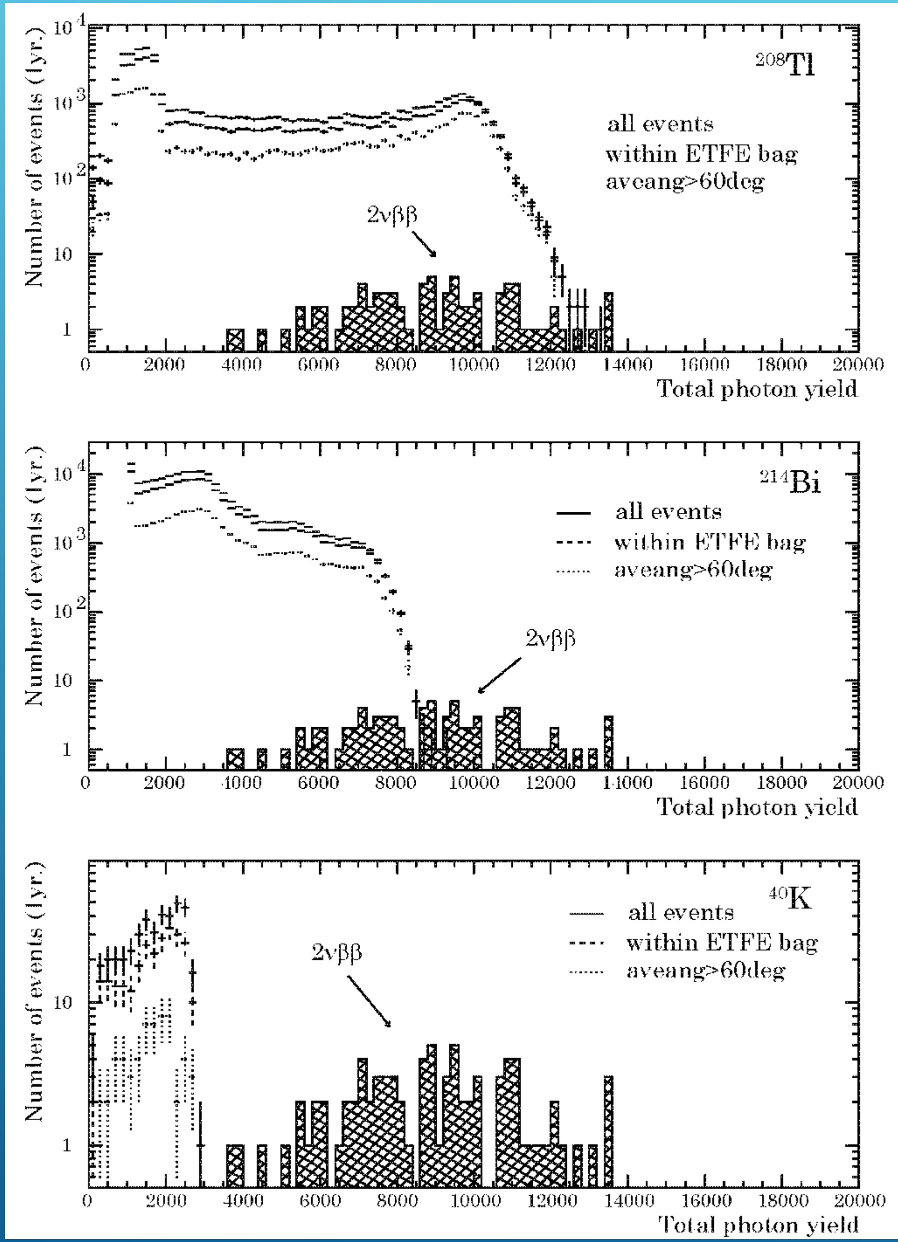


- t=57ns~58nsの時間帯で立ち上がり方に違いが見える
- エネルギーが大きいほど立ち上がり方も大きい
- t>58.5nsの波形はエネルギーによらず一定

t=57ns~58nsの波形はチェレンコフ光が優勢と考えられる。

^{57}Coの波形をシンチレーション光のテンプレートとして作成

BG simulation in worst case

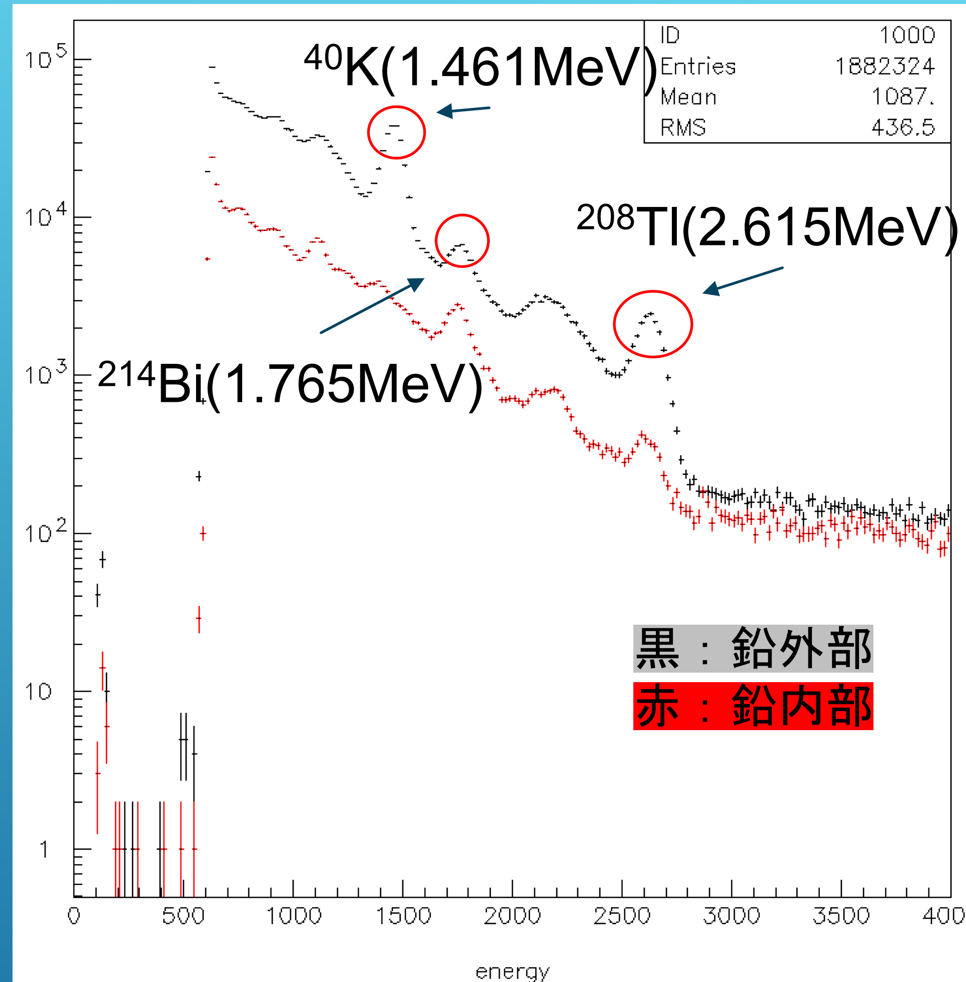


Assuming BGs from flask

- ^{40}K affects only part of $2\nu\beta\beta$ observation.
- ^{214}Bi is significant BG, but small fraction of $2\nu\beta\beta$ events should be observed.
- ^{208}Tl is most serious BG for $2\nu\beta\beta$. A few events might be observed.

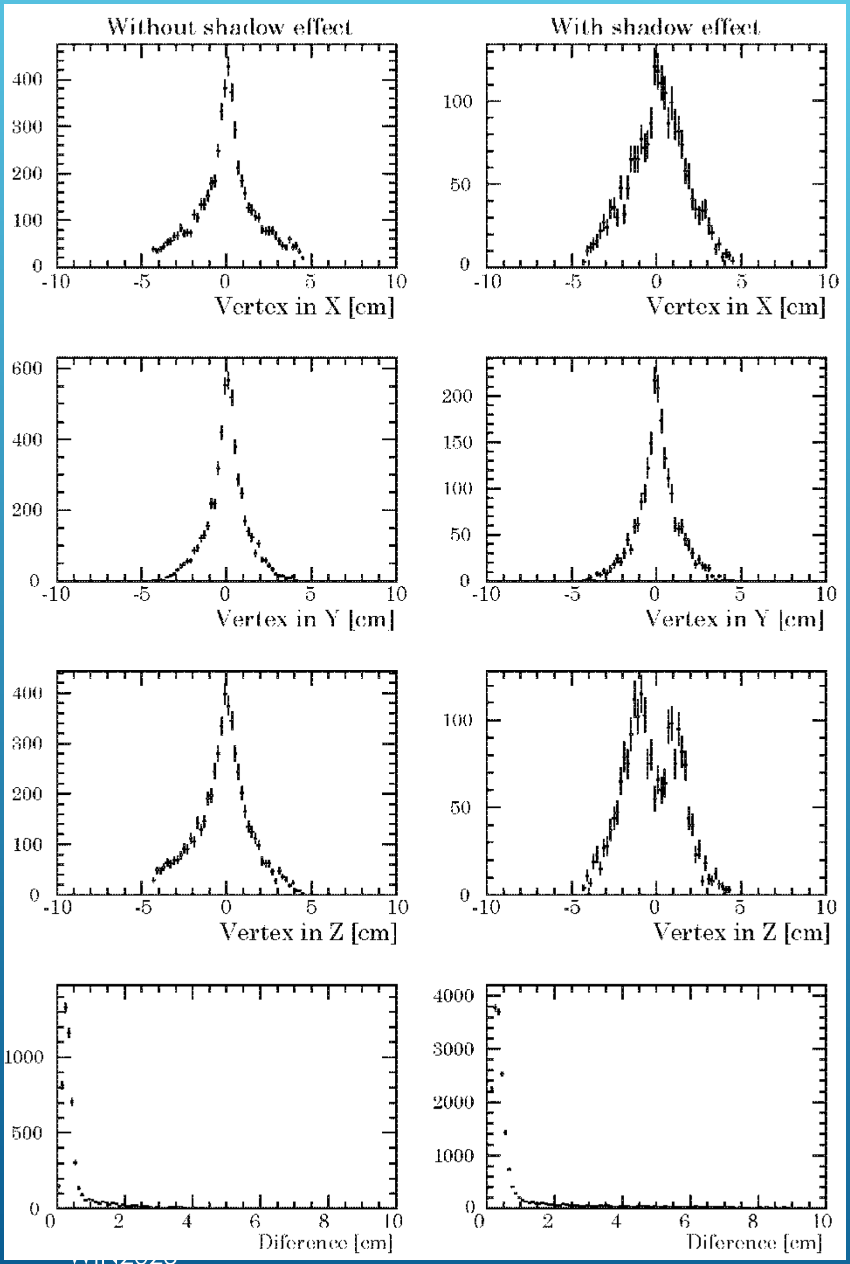
Need actual measurement for ^{96}Zr $2\nu\beta\beta$

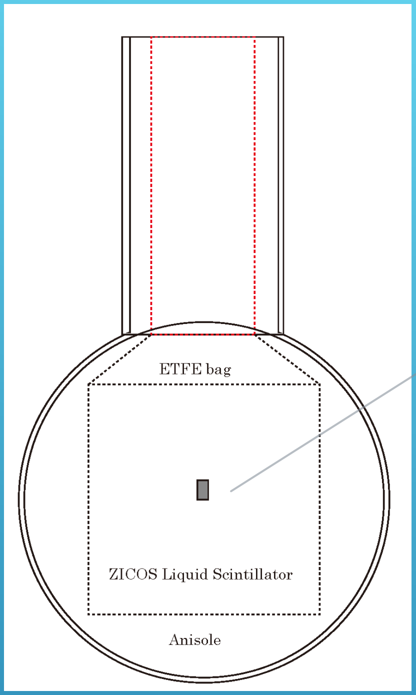
10cm mini Pb shield and CsI detector

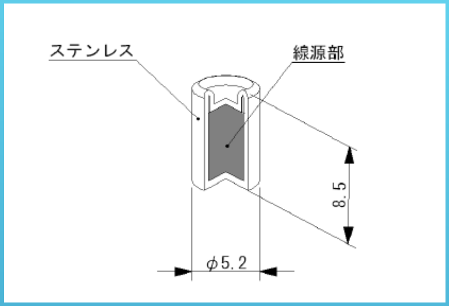


Due to limit of number of Pb block, we will use 15cmm thickness

Calibration of vertex reconstruction





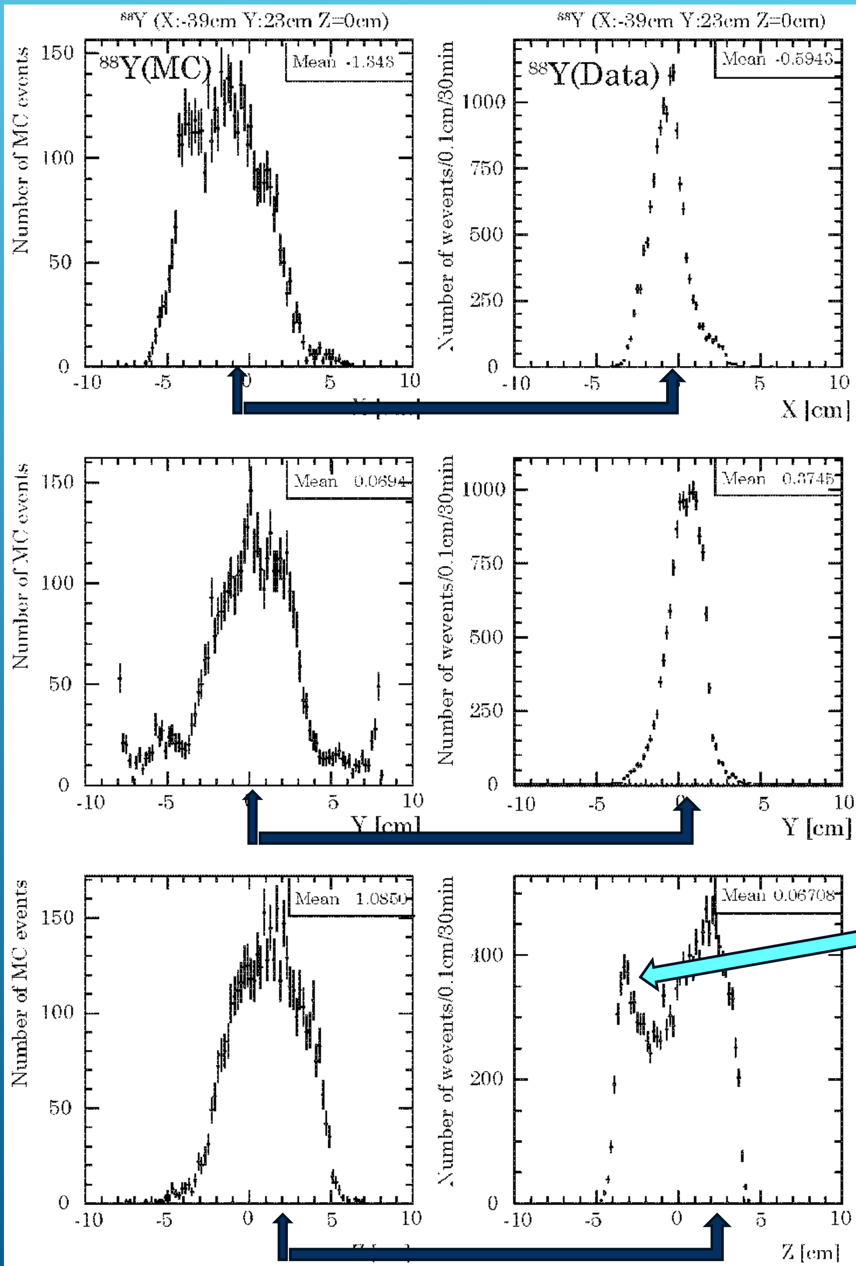


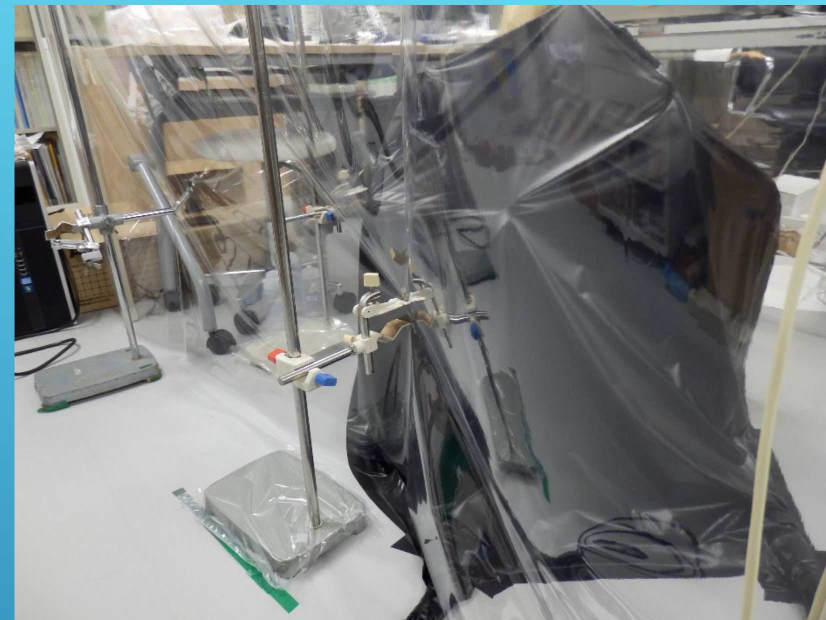
日本アイソトープ協会　標準ガンマ線　516タイプ

100kBq！

Larger pulse signal from ^{137}Cs type 516 source will be used for calibration of vertex reconstruction.

Vertex reconstruction using calibration data

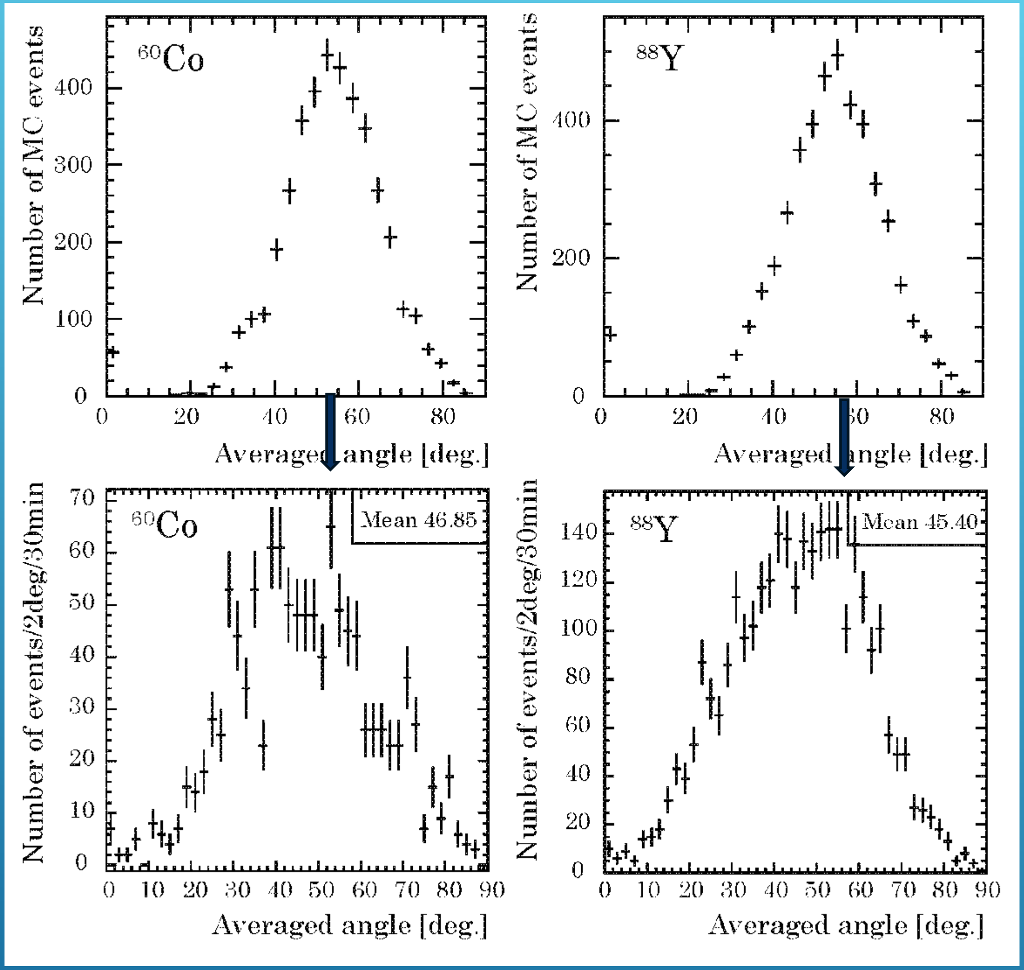


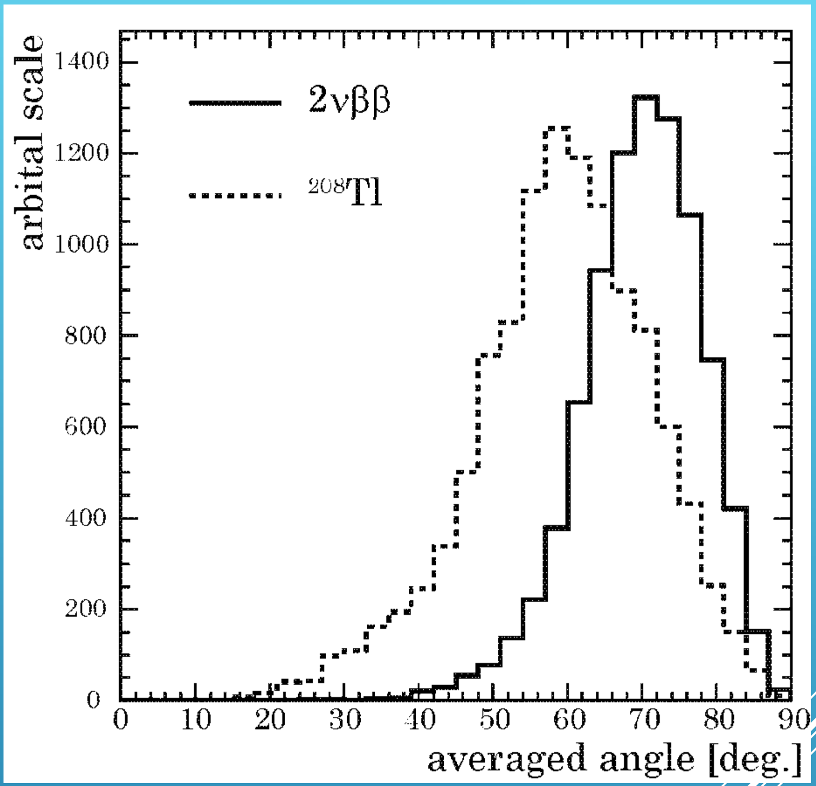


- Simulation vertices roughly reproduce the data.
- Extra cluster was found at Z<-3cm for data.

Need precise tuning or adjustment of PMT gain.

Averaged angle using calibration data





The peak position were seen at 58 and 70 degree for $2\nu\beta\beta$ and ^{208}Tl β decay, respectively.

Averaged angle of simulation seems to roughly reproduce the calibration data (Selection of PMT which receives Cherenkov light might be OK), but vertex still does not reproduce well.