DEMONSTRATION OF REDUCTION METHOD FOR TL-208 BACKGROUNDS USING TOPOLOGICAL INFORMATION OF CHERENKOV LIGHT FOR ZICOS EXPERIMENT

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Miyagi University of Education **Y. Fukuda, Narengerile, A. Obata, Y. Kamei, D. Anzai**

Kamioka Observatory, ICRR, Univ. of Tokyo **S. Moriyama, K. Hiraide**

Fukui University **I. Ogawa**

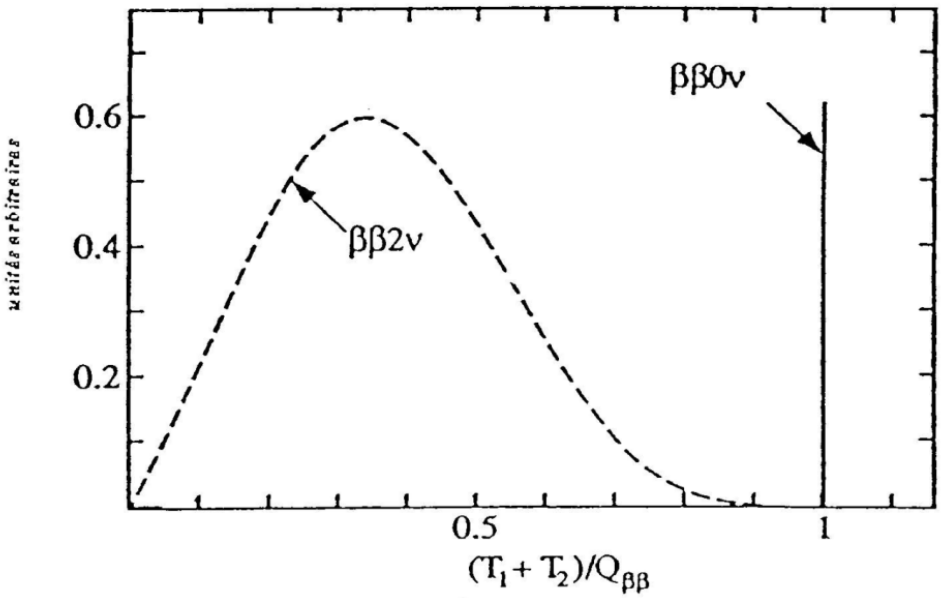
Tokyo University of Science **T. Gunji, S. Tsukada, R. Hayami**

Institute for Materials Research, Tohoku University **S. Kurosawa**

Neutrinoless double beta decay

$\beta\beta$ emitters with $Q_{\beta\beta}$ >2 Mev

Transition	$Q_{\beta\beta}$ (keV)	Abundance (%) ($^{232}Th = 100$)
$^{110}Pd \rightarrow ^{110}Cd$	2013	12
$^{76}Ge \rightarrow ^{76}Se$	2040	8
$^{124}Sn \rightarrow ^{124}Te$	2288	6
$^{136}Xe \rightarrow ^{136}Ba$	2479	9
$^{130}Te \rightarrow ^{130}Xe$	2533	34
$^{116}Cd \rightarrow ^{116}Sn$	2802	7
$^{82}Se \rightarrow ^{82}Kr$	2995	9
$^{100}Mo \rightarrow ^{100}Ru$	3034	10
$^{96}Zr \rightarrow ^{96}Mo$	3350	3
$^{150}Nd \rightarrow ^{150}Sm$	3667	6
$^{48}Ca \rightarrow ^{48}Ti$	4271	0.2



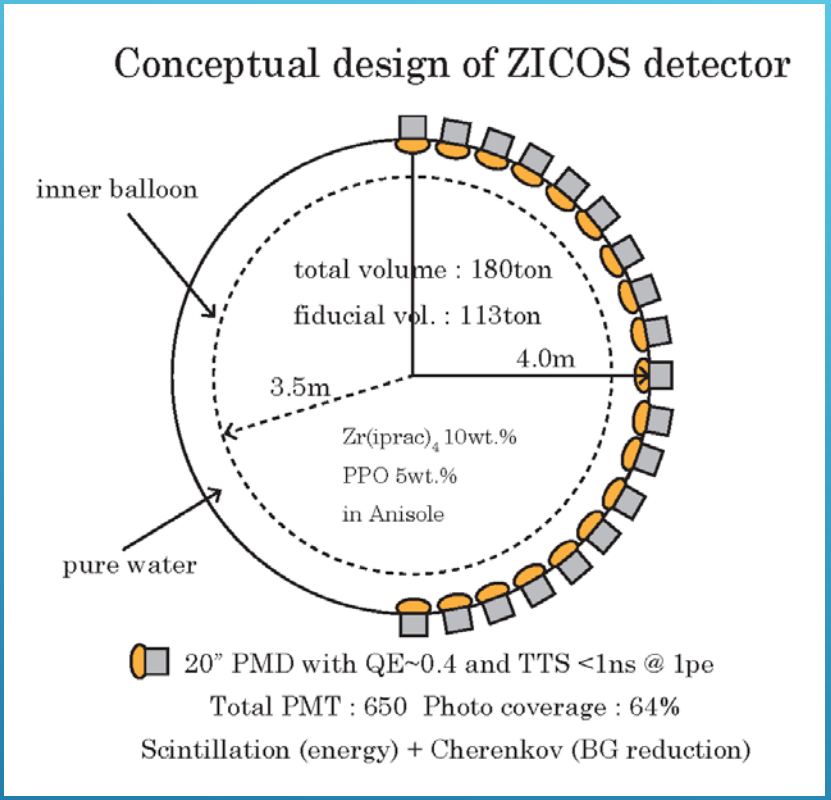
$$[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G_{0\nu}(E_0, Z) \mid M_{0\nu} \mid^2 \langle m_\nu \rangle^2 / m_e^2$$

$T_{1/2} \sim a(Mt/\Delta E \cdot B)^{1/2}$ a: abundance M: target mass

t: measuring time ΔE: energy resolution B: BG rate

Requirement : Low BG, Large target mass, High E-resolution

Conceptual design of ZICOS detector



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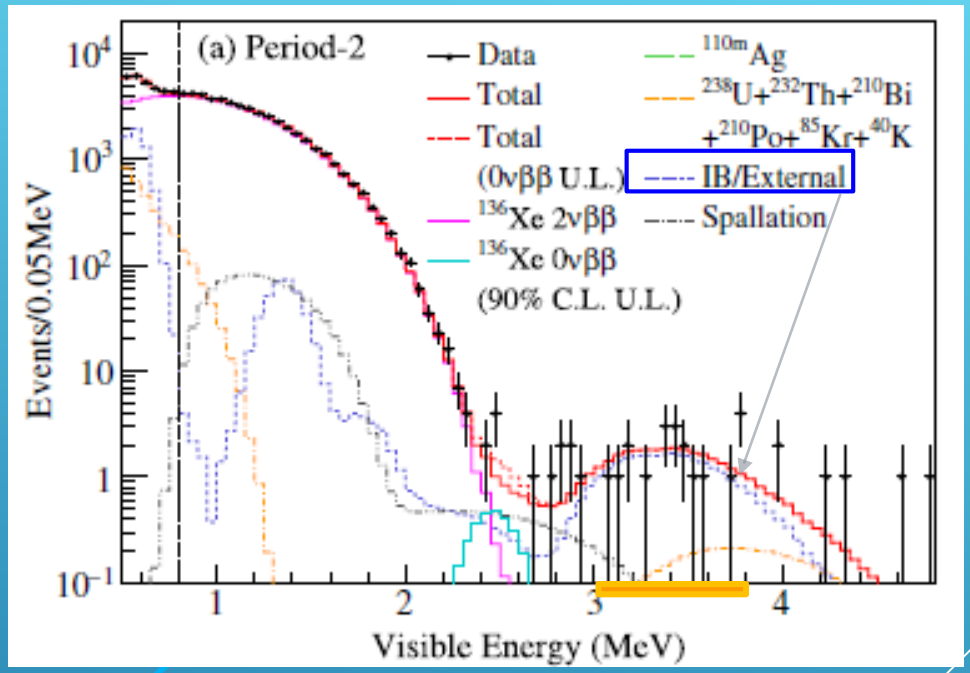


NEMO3 : $T_{1/2}^{0\nu} > 9.1 \times 10^{21}$ yrs

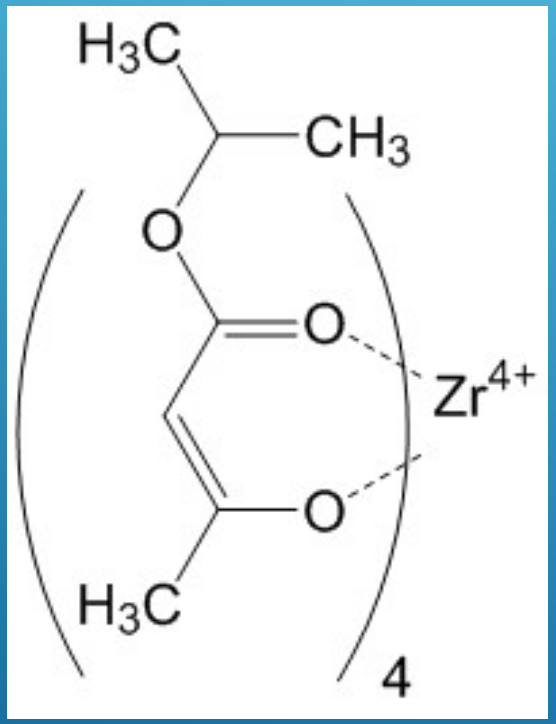
^{96}Zr : 45kg (nat.) → 865kg(50% enrich)→1/20 BG

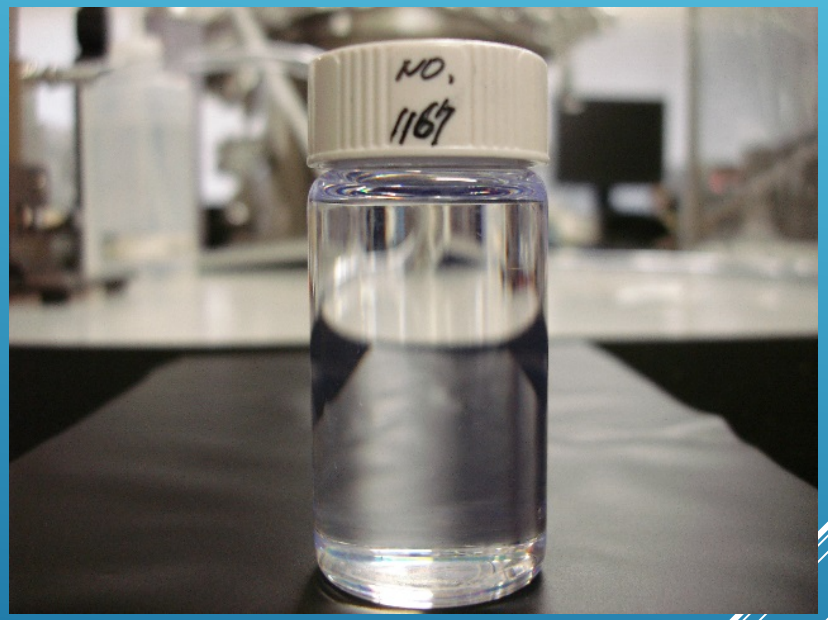
$T_{1/2}^{0\nu} > 4 \times 10^{25}$ yrs → 2×10^{26}yrs → ~1 $\times 10^{27}$yrs

Liquid Scintillator solving $Zr(iPrac)_4$

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

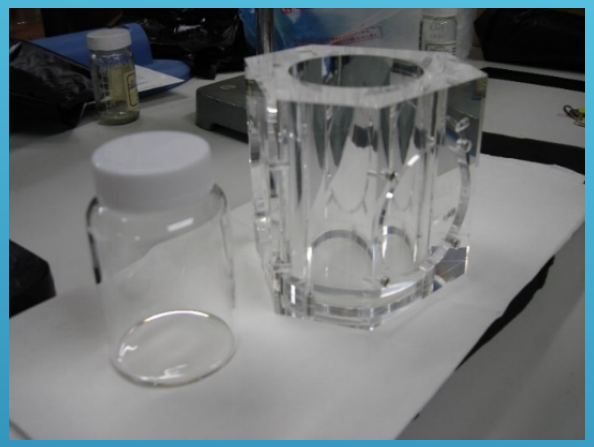
$Zr(iprac)_4$ 2242mg, PPO 999mg and POPOP 10mg solved in 20mL Anisole

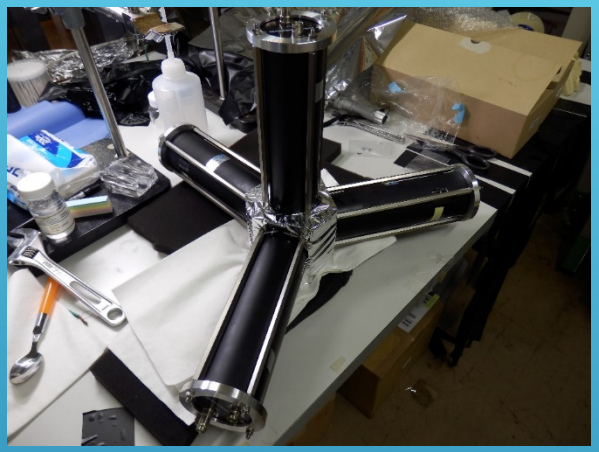




> 70g/L of Zirconium could be solved in anisole.

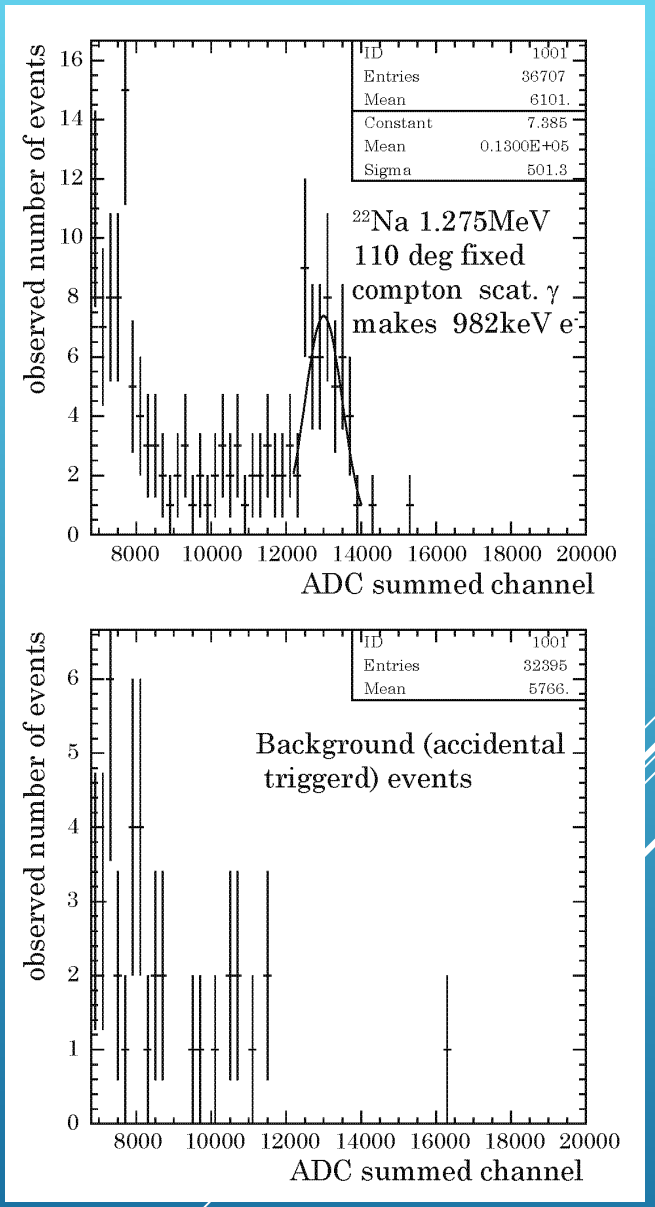
Measurement for energy resolution by 20% photo coverage



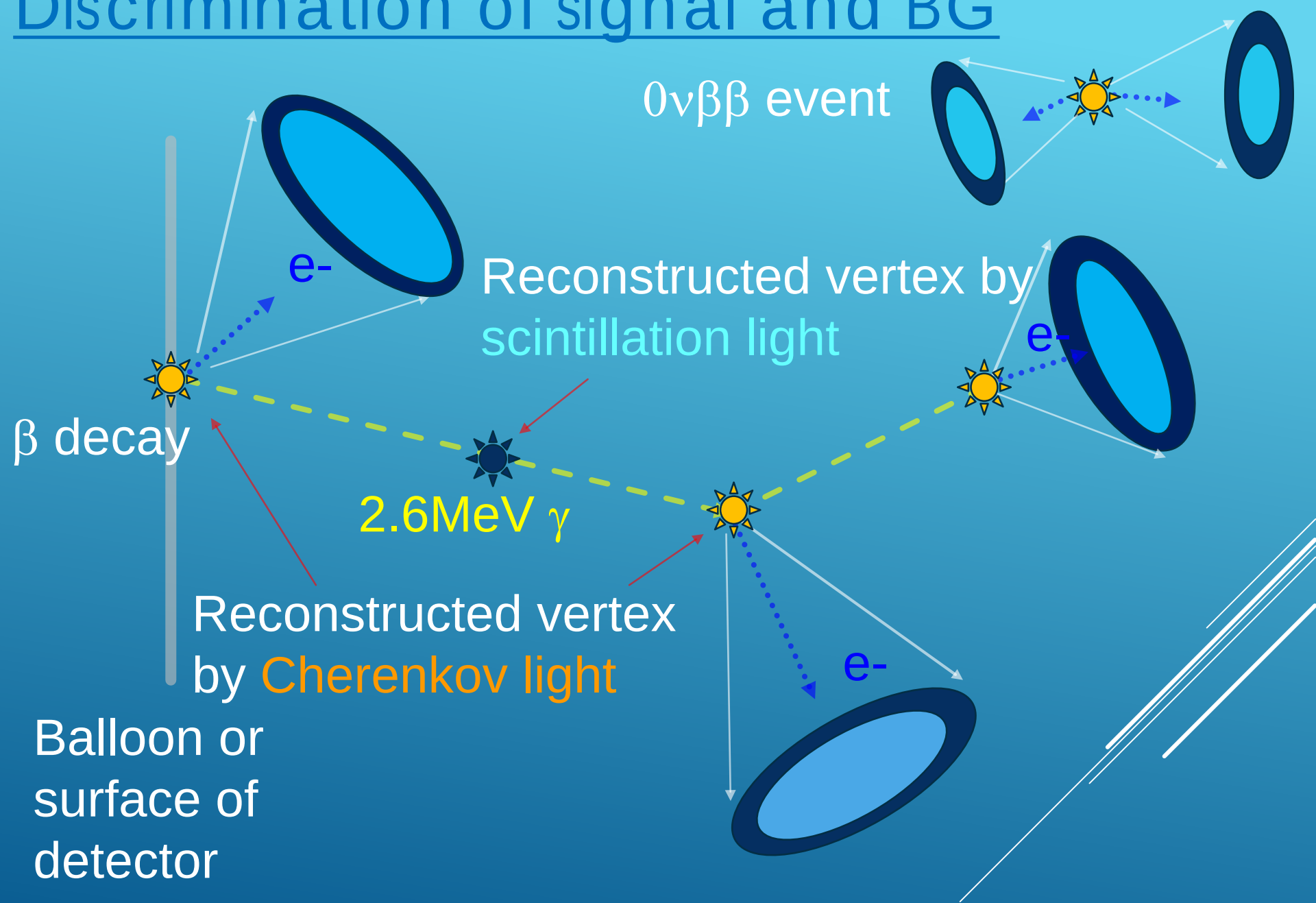


σ/E=7.0%@982 keV&20%photo coverage

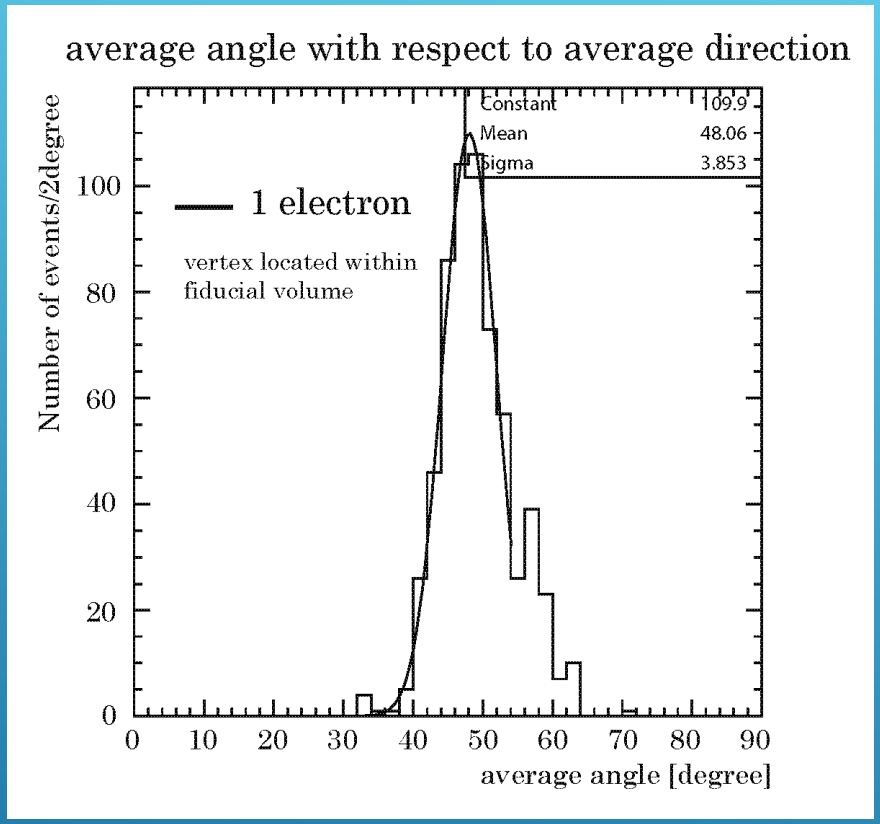
2.2%@3.35MeV &60% photo coverage



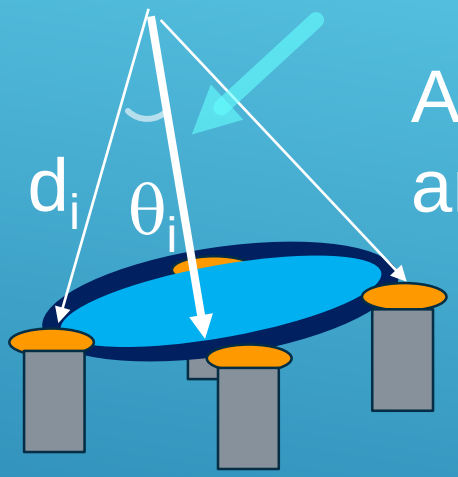
Discrimination of signal and BG



Topological info. : averaged angle



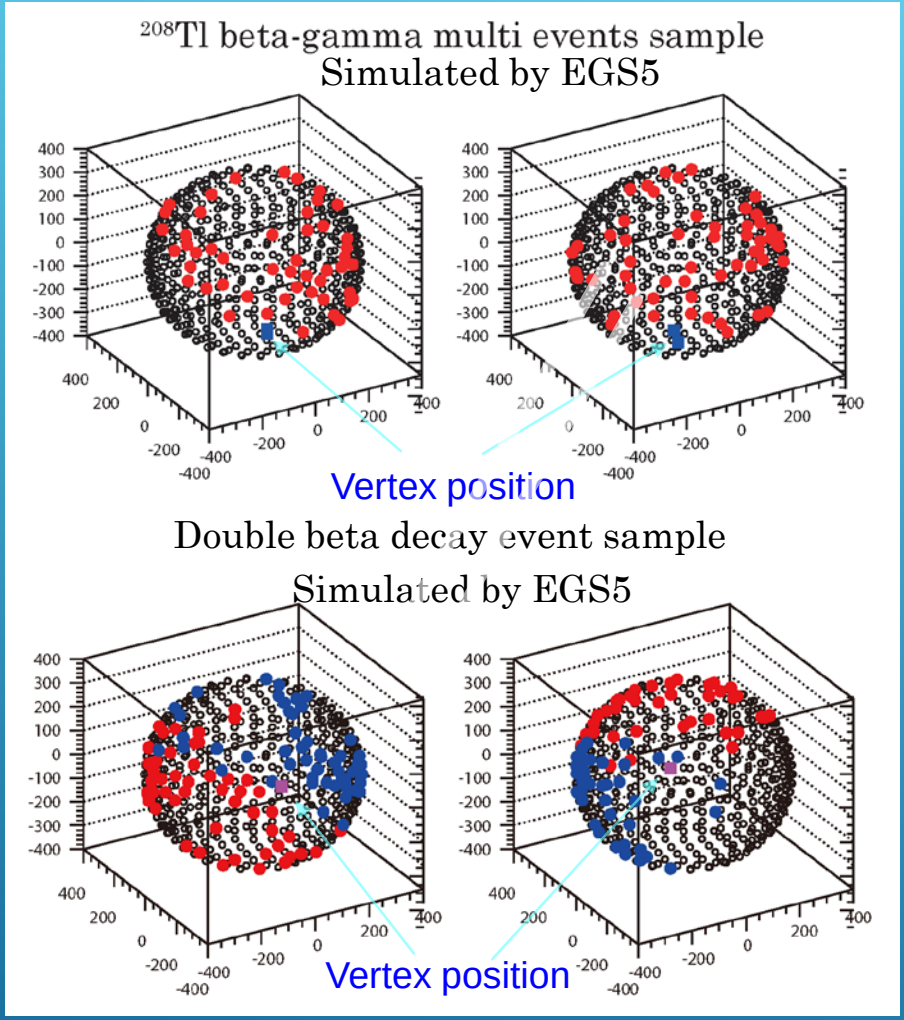
Average direction
$= \Sigma d_i$

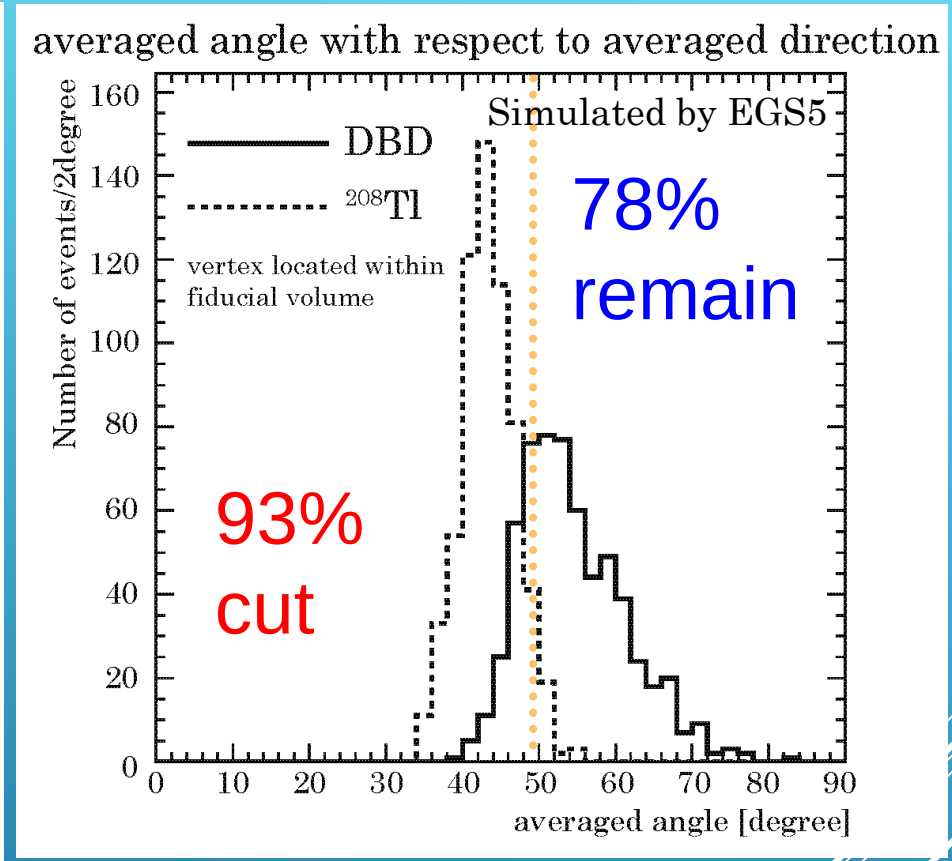


Averaged angle= $\frac{\Sigma \theta_i}{\text{Nhit}}$

Average angle with respect to averaged direction for single electron seems to have a peak at 48 degree which is almost same as Cherenkov angle.

BG reduction using topological information



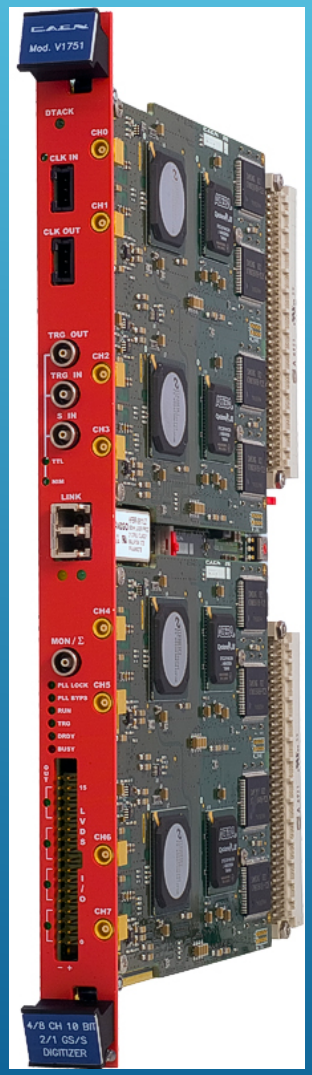


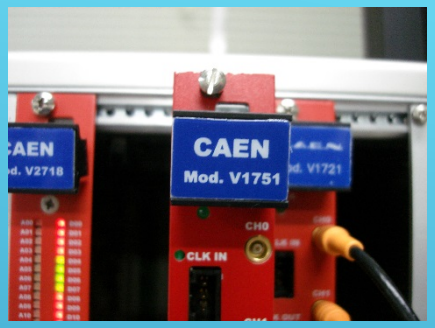
PMT hit pattern of ^{208}Tl BG and 0νββ signal

Topological information from PMT position which received Cherenkov lights could be used for reduction of ^{208}Tl BG.

Measurement of pulse shape difference

FADC digitizer: CAEN V1751

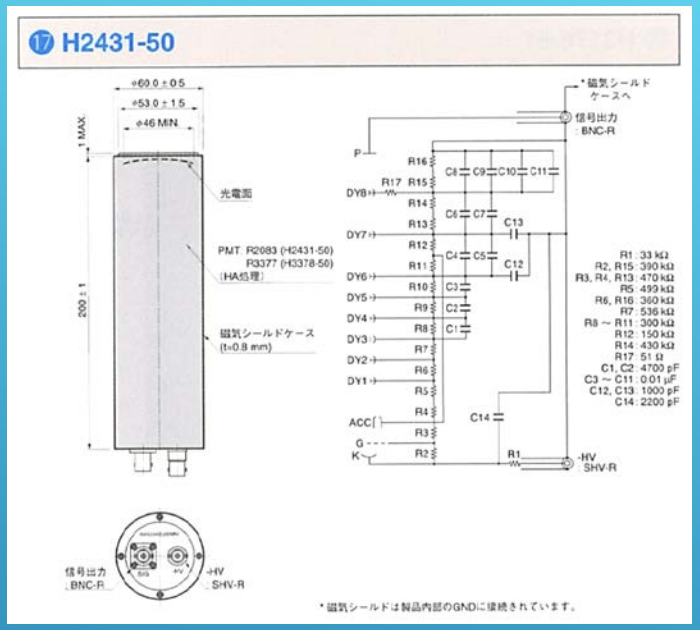




- **10 bit 2 GS/s (interleaved)** ~~– 1 GS/s ADC~~
- 4-8 channel
- FPGA for real time Digital Pulse Processing:
  - Pulse Shape Discrimination (DPP-PSD)
  - Zero Length Encoding (DPP-ZLEplus)
- 0.2 or 1 Vpp input dynamics single ended or 1 Vpp differential
- 16-bit programmable DC offset adjustment: ±0.5 V / ±0.1 V
- Trigger Time stamps
- Memory buffer: up to 14.4 MS/ch (28.8 MS/ch @2 GS/s)
- Programmable event size and pre-post trigger adjustment
- Analog Sum/Majority and digital over/under threshold flags for Global Trigger logic
- Front panel clock In/Out available for multiboard synchronisation (direct feed through or PLL based synthesis)
- 16 programmable LVDS I/Os
- Optical Link interface (CAEN proprietary protocol)
- VME64X compliant interface
- **A2818(PCI) / A3818 (PCIe) Controller available for handling up to 8/32 modules Daisy chained via Optical Lin**
- Firmware upgradeable via VME/Optical Link
- Libraries, Demos (C and LabView) and Software tools for Windows and Linux

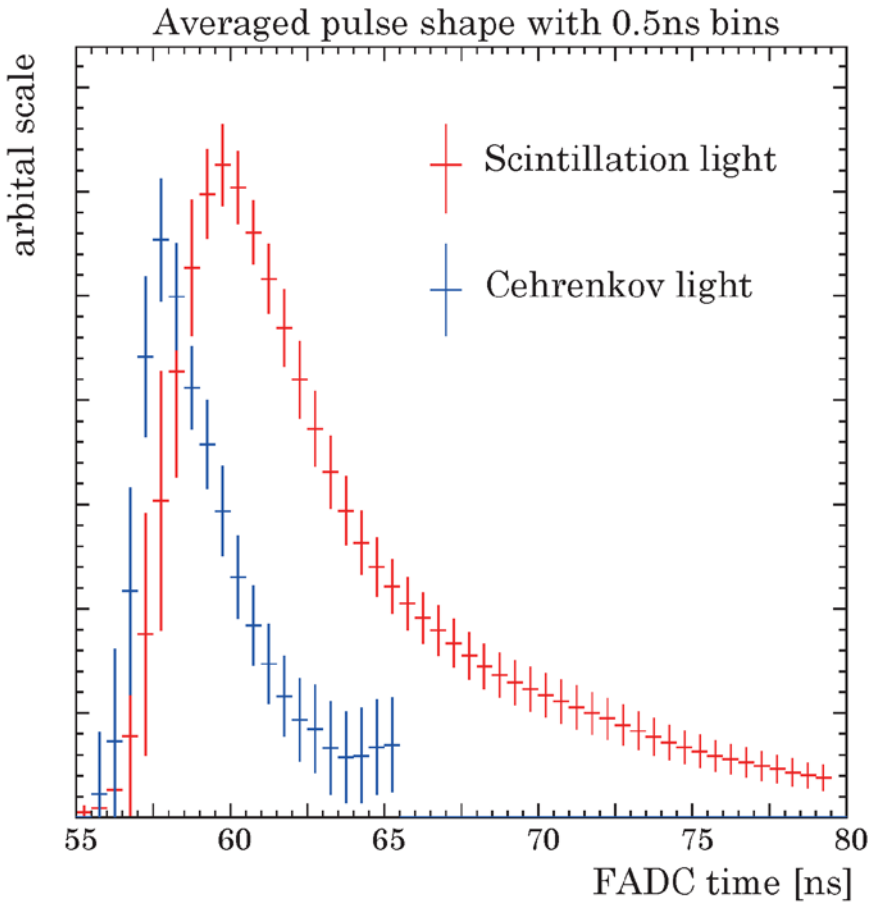
Measurement of pulse shape difference

Photomultiplier : Hamamatsu H2431-50 (R2083)



- Spectral response ：400K QE: 25% at peak
- Dynode structure : linear focused/8 dinodes
- High voltage ：3000V
- Gain：2.5×10^6 dark current :100nA (H6410:10nA)
- Time response ：0.37ns(TTS) 0.7ns（rise time）

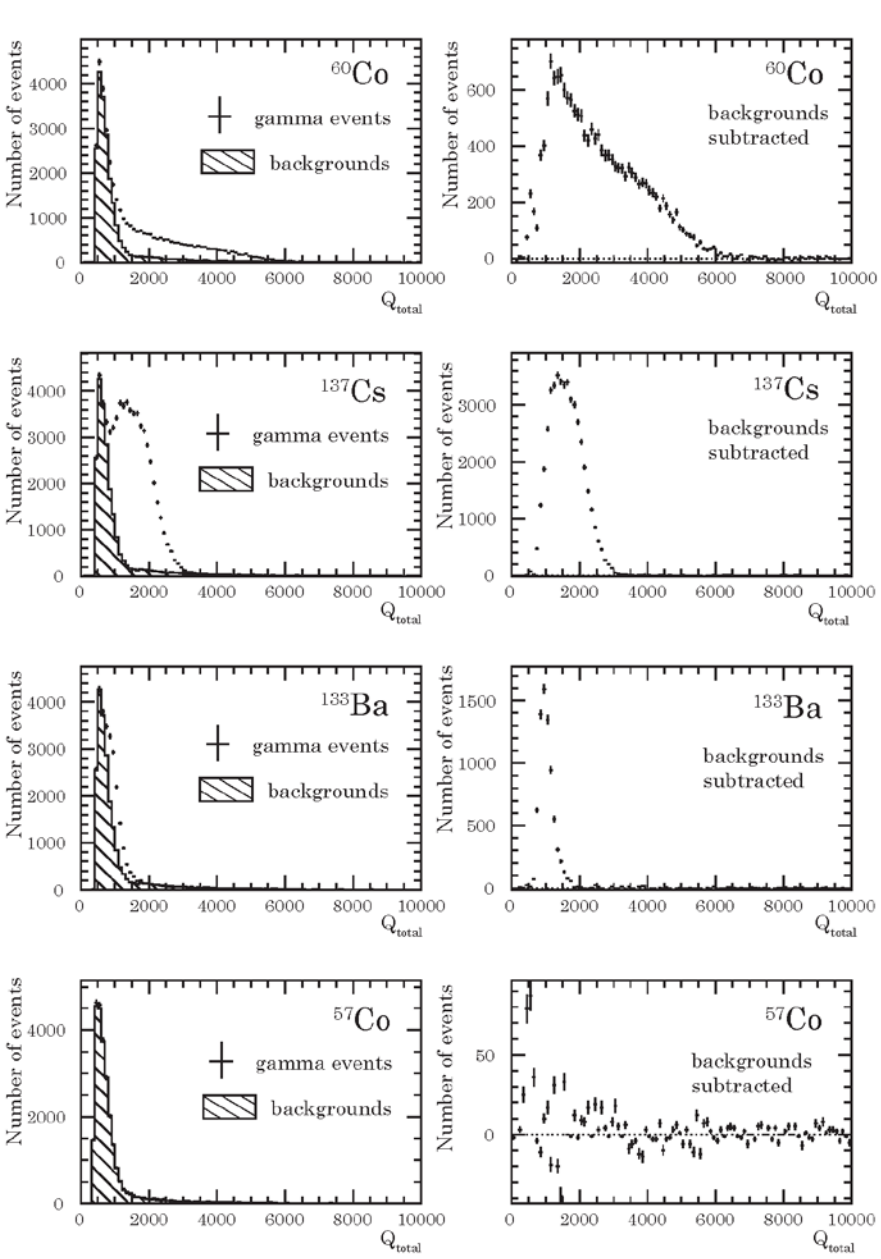
Pulse shape of Cherenkov and scintillation

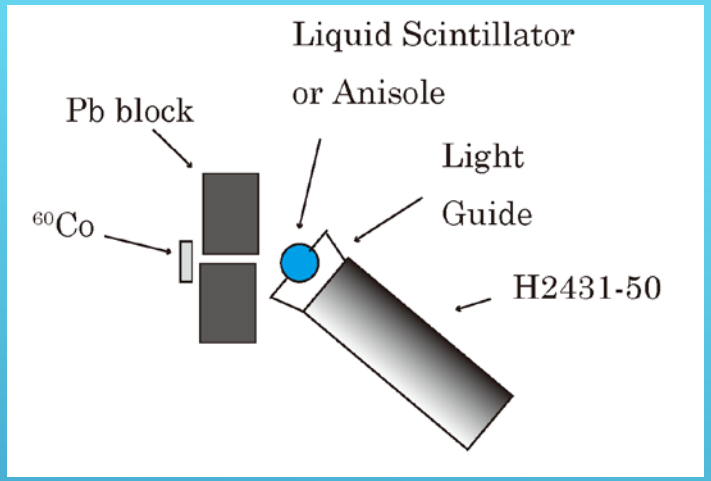


- Pulse shape of ^{90}Sr using H2431-50 measured by V1751 with DES mode (2GS/s)
- Decay time of scintillation : 4.57ns and 8.38ns
- Rise time of scintillation : 1.45ns
- Rise time of Cherenkov : 0.75ns

Use the charge ratio Q_{time}/Q_{total}. Here, Q_{time} is FADC value in each time, and Q_{total} is sum of FADC value between 55ns and 80ns.

Q_{total} distribution for γ sources

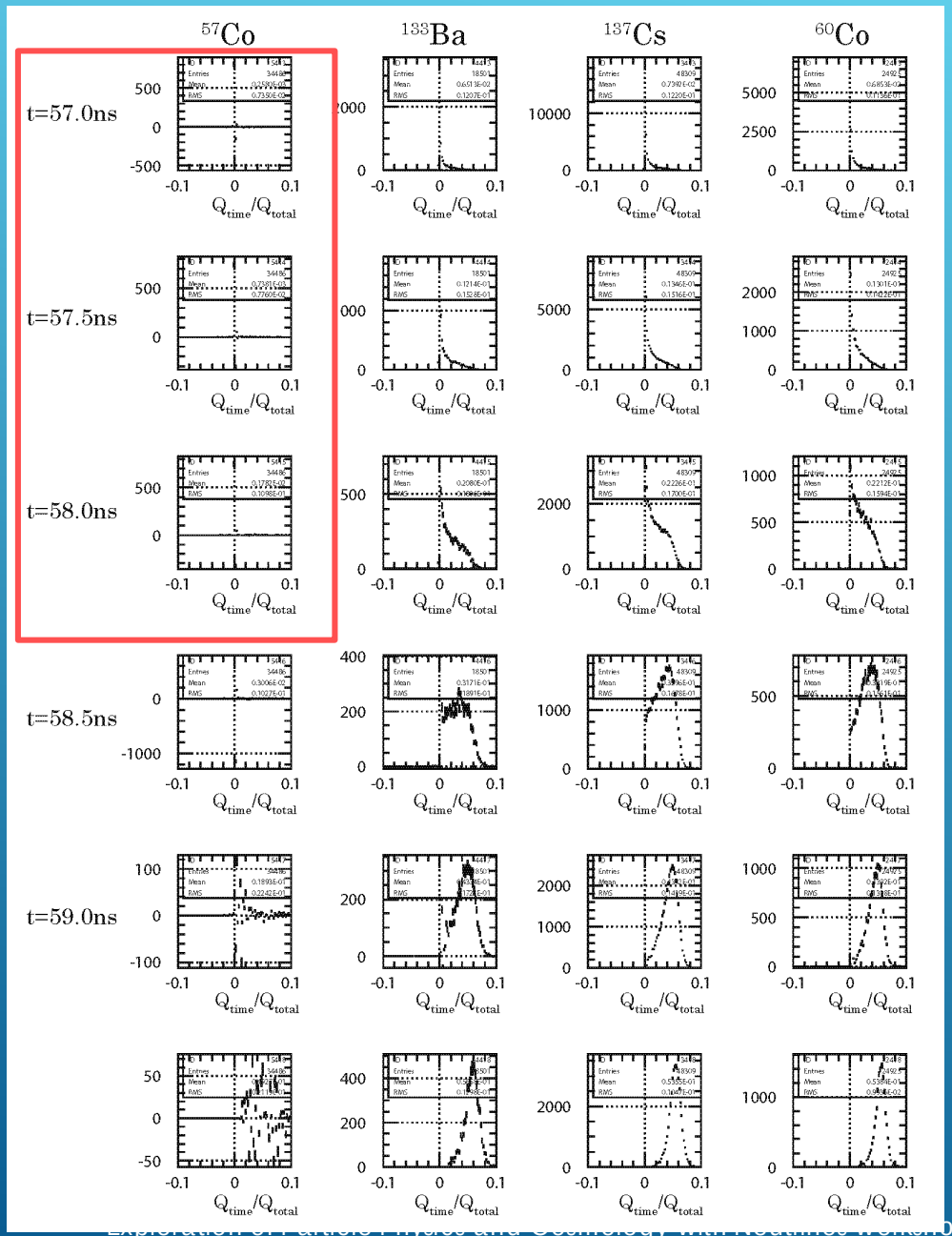




- ^{60}Co (1.17MeV/1.33MeV)
  Compton edge: 1.04MeV
- ^{137}Cs (662keV)
  Compton edge: 478keV
- ^{133}Ba (356keV)
  Compton edge: 207keV
- ^{57}Co (122keV)
  Under Cherenkov threshold (169kev)

Pulse shape with charge ratio in each FADC time.

Charge ratio in rise time using ZICOS LS

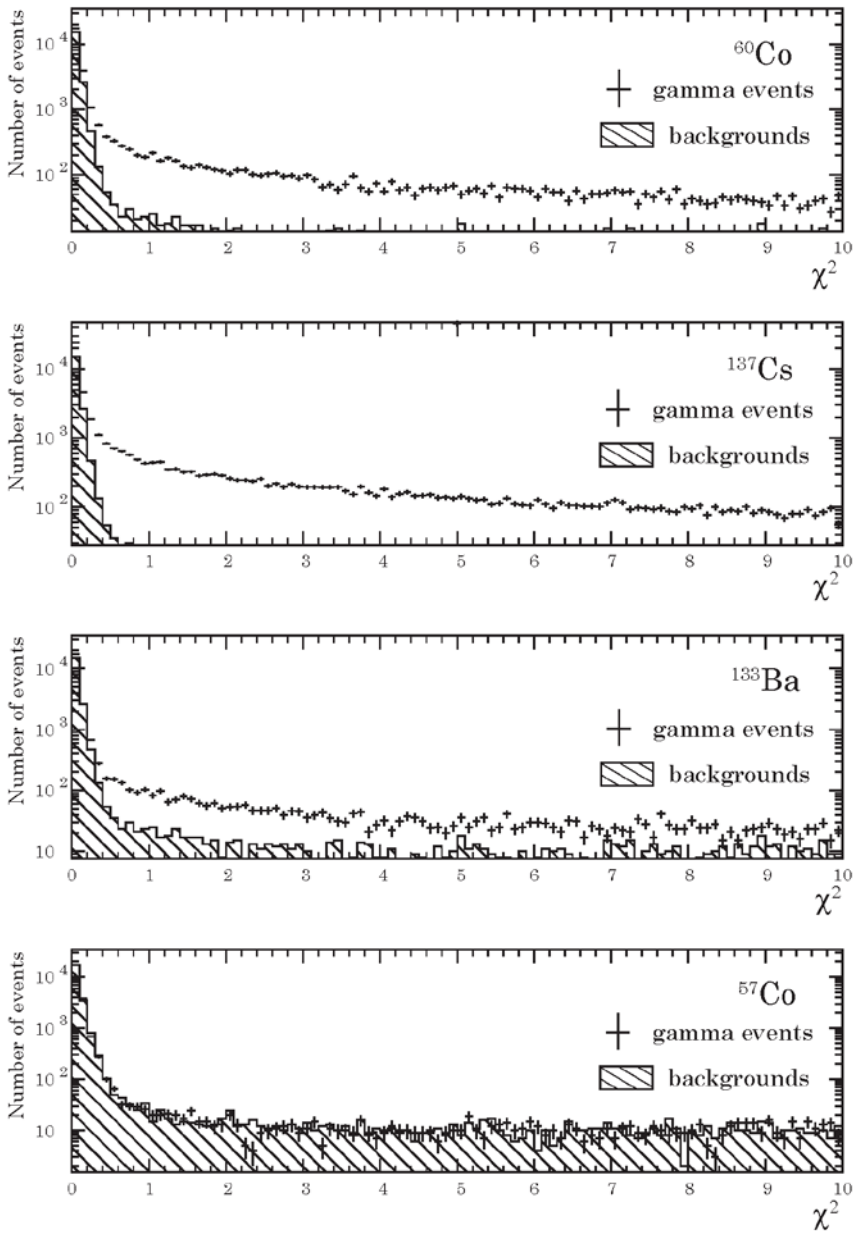


- There is difference of shape between t=57ns and 58ns
- Charge ratio looks depend on the energy
- For t>58.5ns, all shapes were almost same.

Cherenkov looks dominant between 57ns and 58ns.

Template waveform of scintillation between 57.0ns and 58.0ns for ^{57}Co.

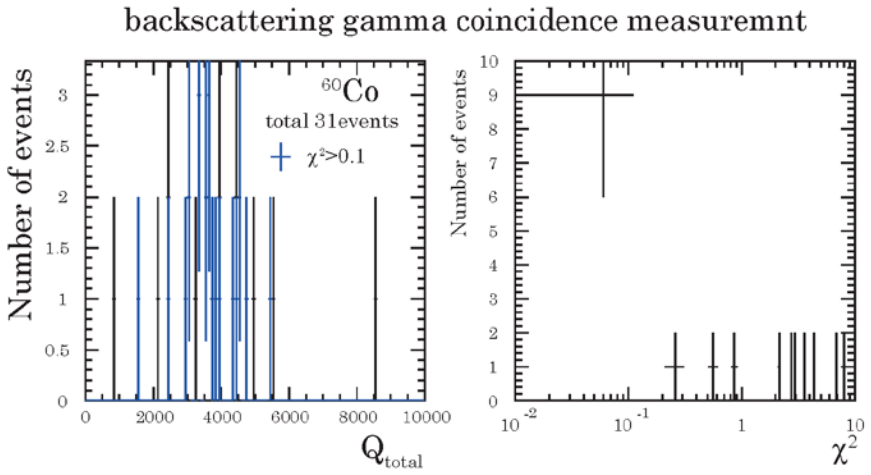
χ^2 distribution using ^{57}Co template



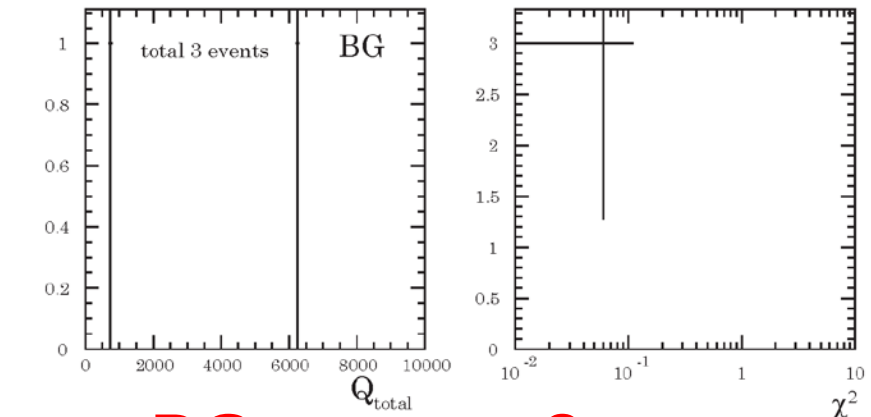
- Most of backgrounds have lower χ^2 than 1.0
- Most of backgrounds have lower energy than Cherenkov threshold, then only scintillation was seen.

It seems to events with Cherenkov lights should have large χ^2 value.

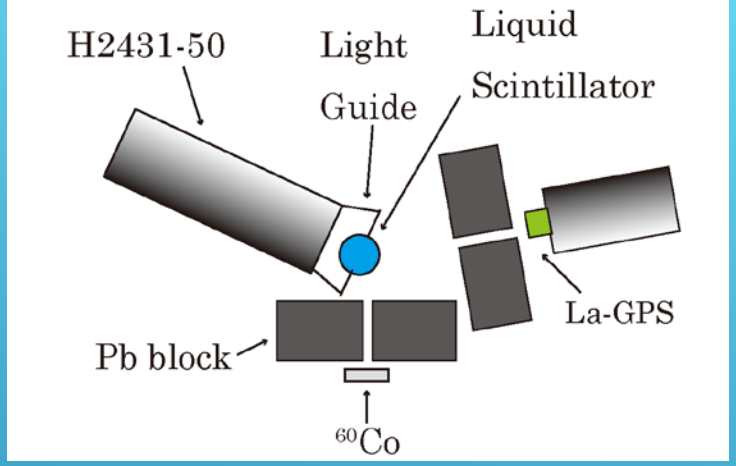
Measured by fixed energy fixed direction events



χ^2>0.1：22events/28events =78.6%



BG events=3evets

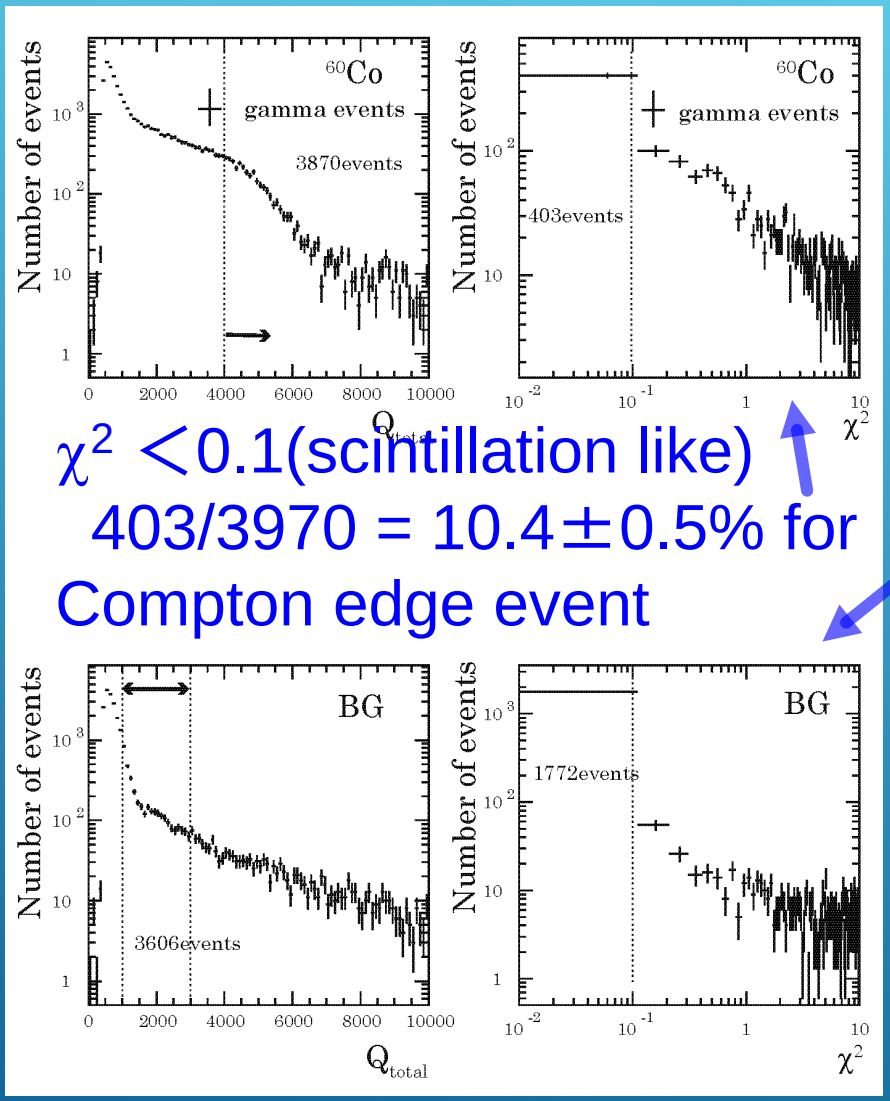


Fixed energy : 835keV

ADC ch~3400cn

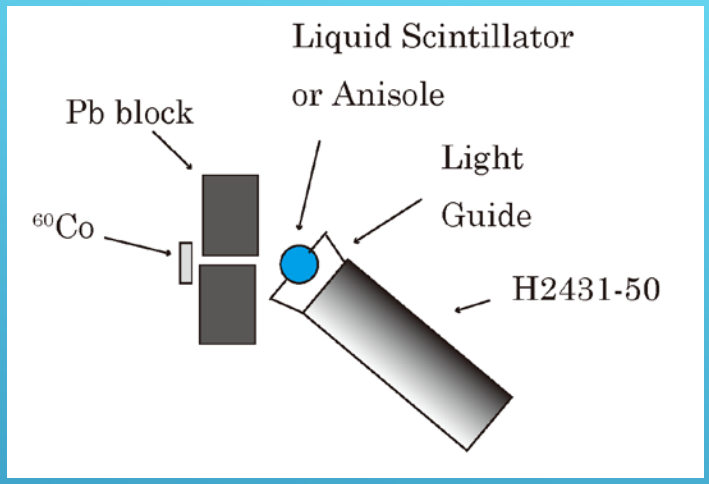
If the events with χ^2>0.1 should have Cherenkov lights, is this inefficiency 21.4±9.6% correct?

Measured by Compton edge event and BG sample



χ^2 ＜0.1(scintillation like)

403/3970 = 10.4±0.5% for Compton edge event

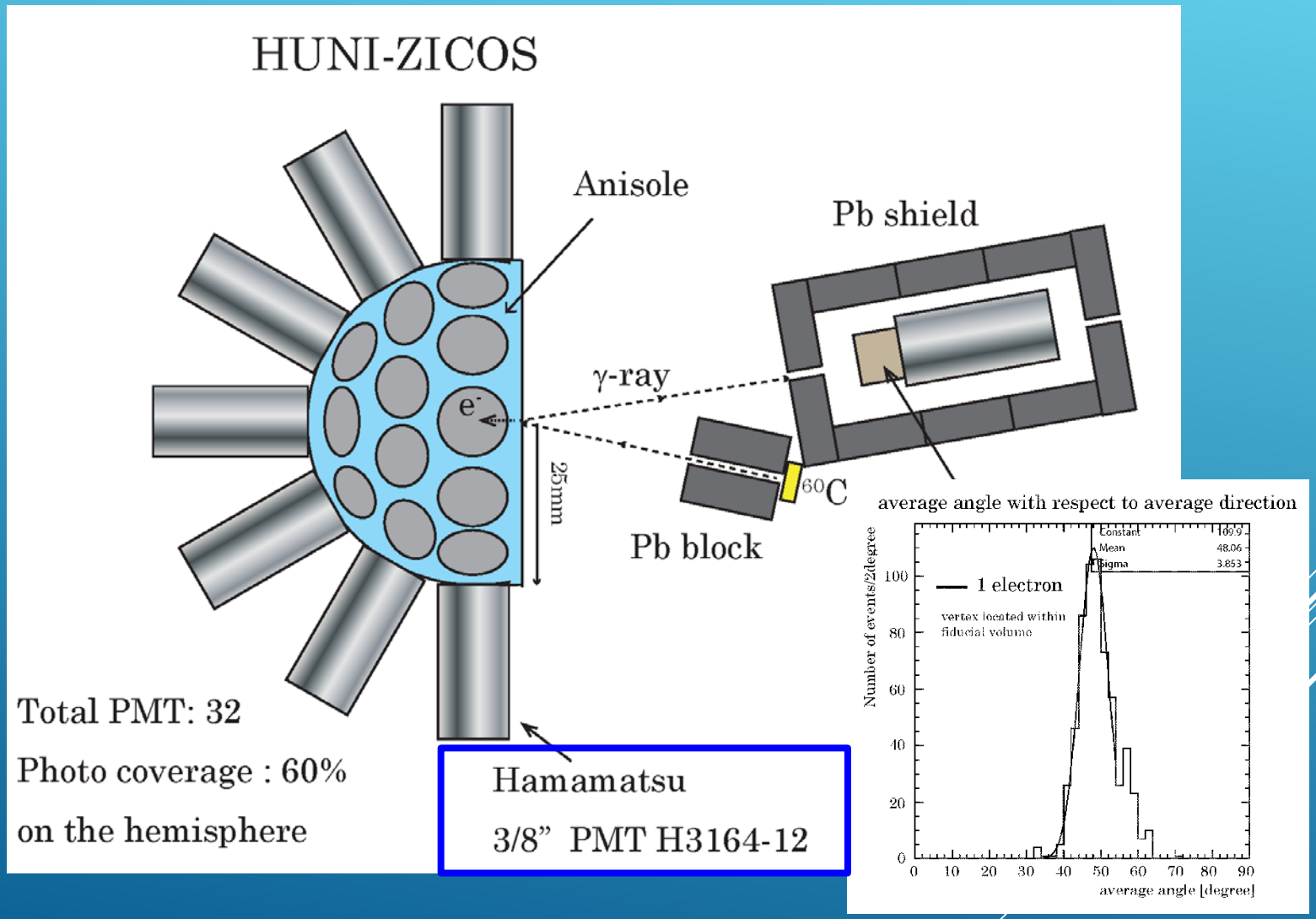


1772/3606=49.1±1.4% for BG sample

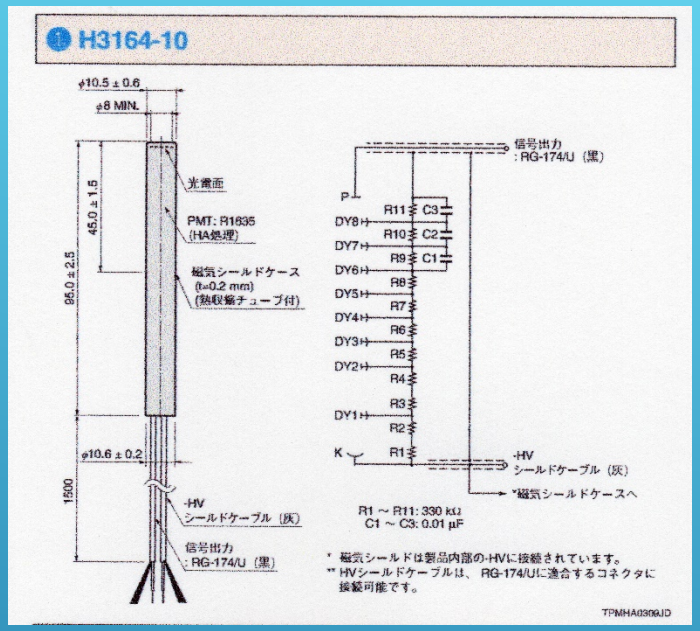
Inefficiency value between Compton edge and BG sample differs with 2.86σ.

Topology of Cherenkov lights for O(1)MeV e^- was confirmed.

Measurement of topological information (averaged angle) using HUNI-ZICOS



3/8” photomultiplier H3164-12(R1635)

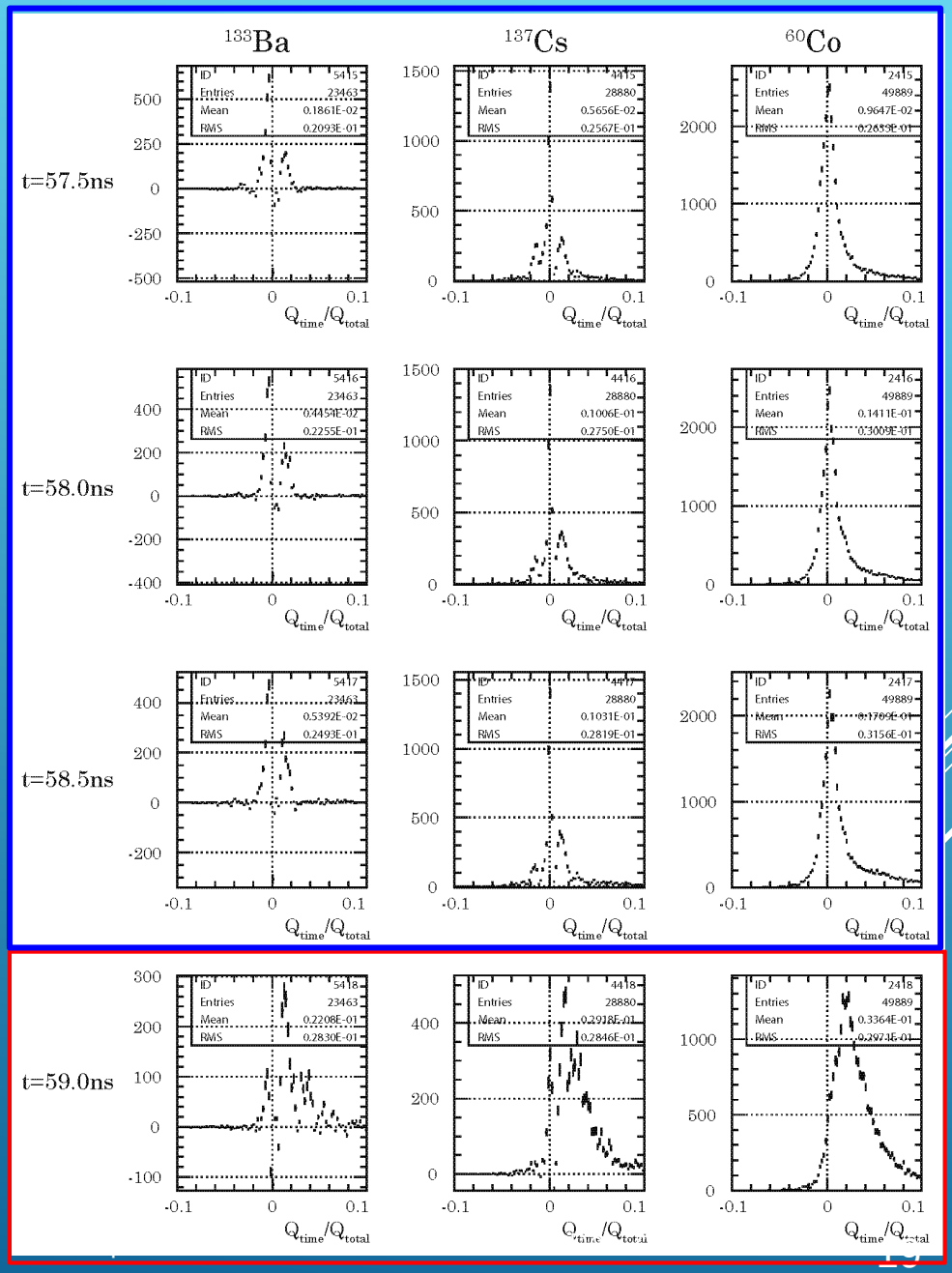


- Sensitivity：400K
- Dynode type : Line focus/8dynode
- Applied voltage：1250V
- Gain：1.0×10^6 Dark current:50nA
- Time characteristics：0.5ns(TTS) 0.8ns（rise time）

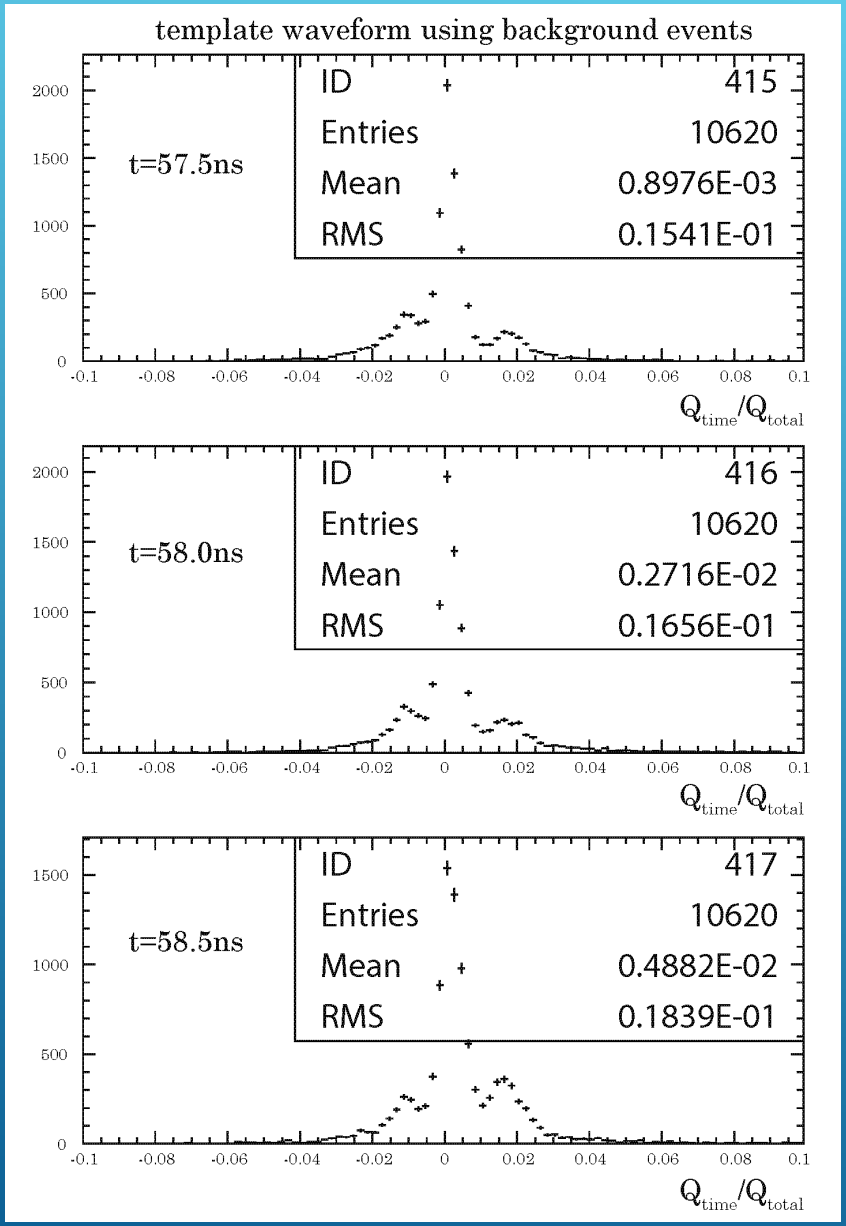
Pulse shape measurement by H3164-12

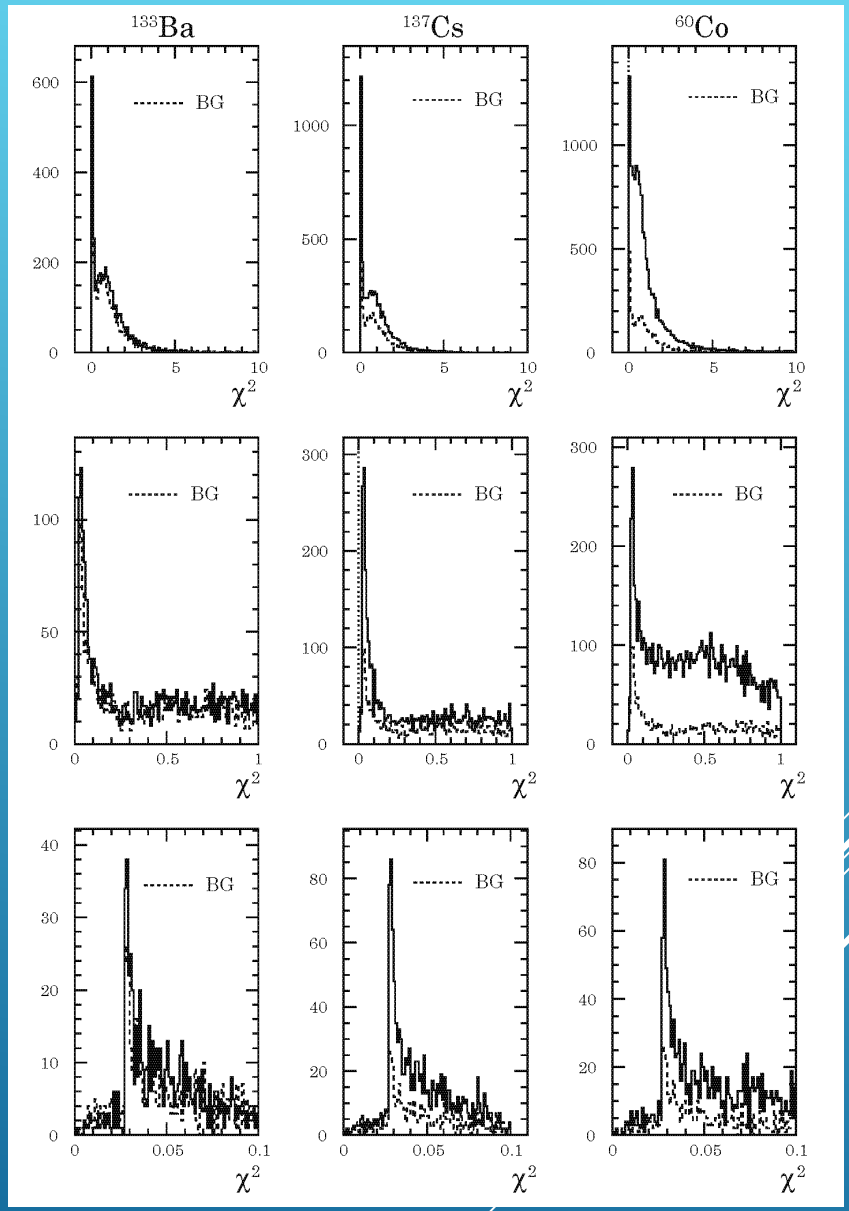
Cherenkov dominant

Scintillation dominant



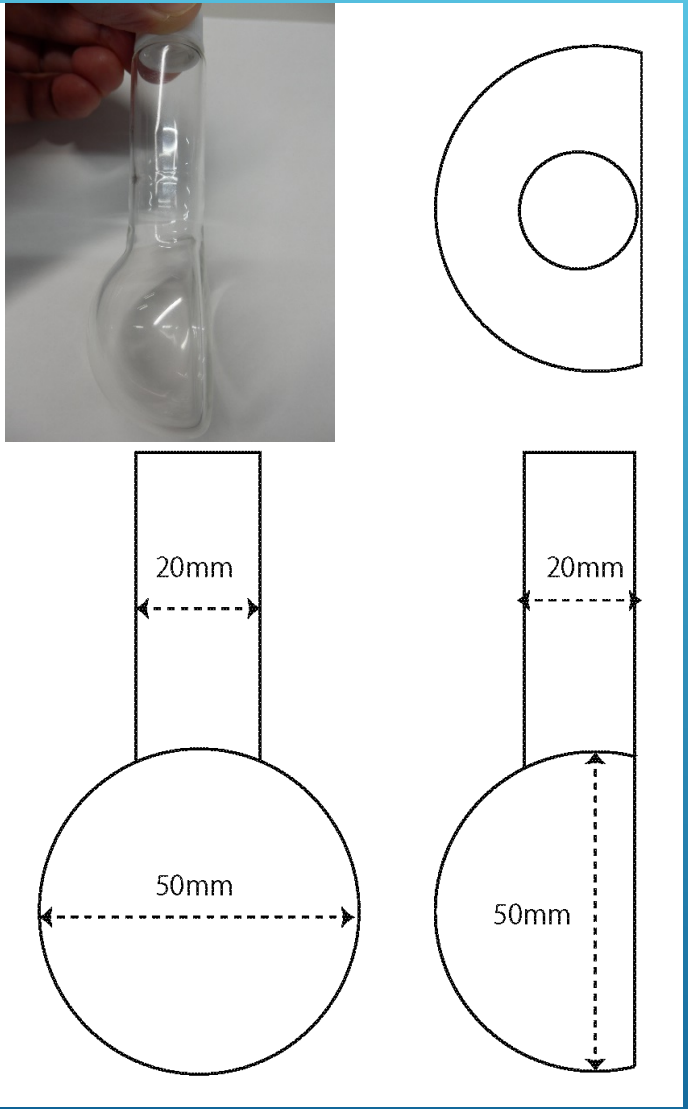
Pulse Shape Discrimination using H3164-12

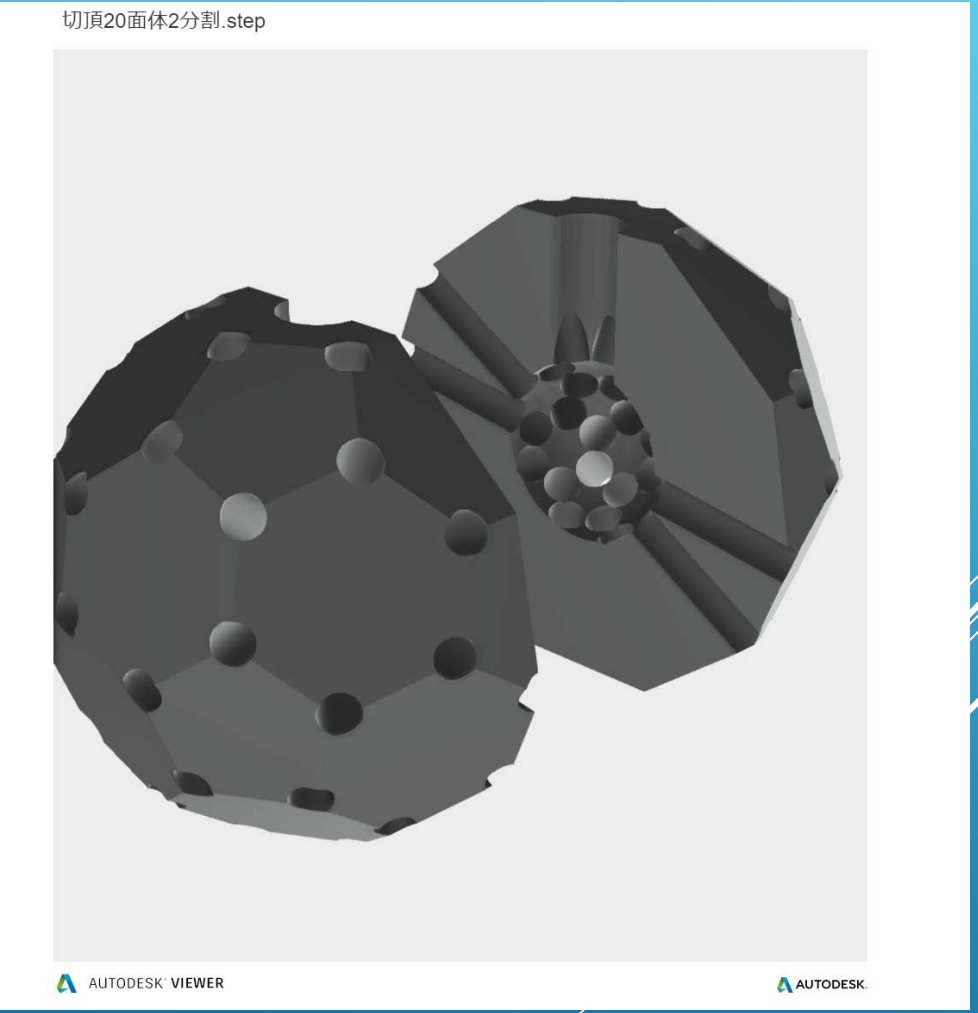




Possible but need tuning.

Hemisphere flask and PMT fixing jig for HUNI-ZICOS





Flash ADC V1742 and PMT HV system

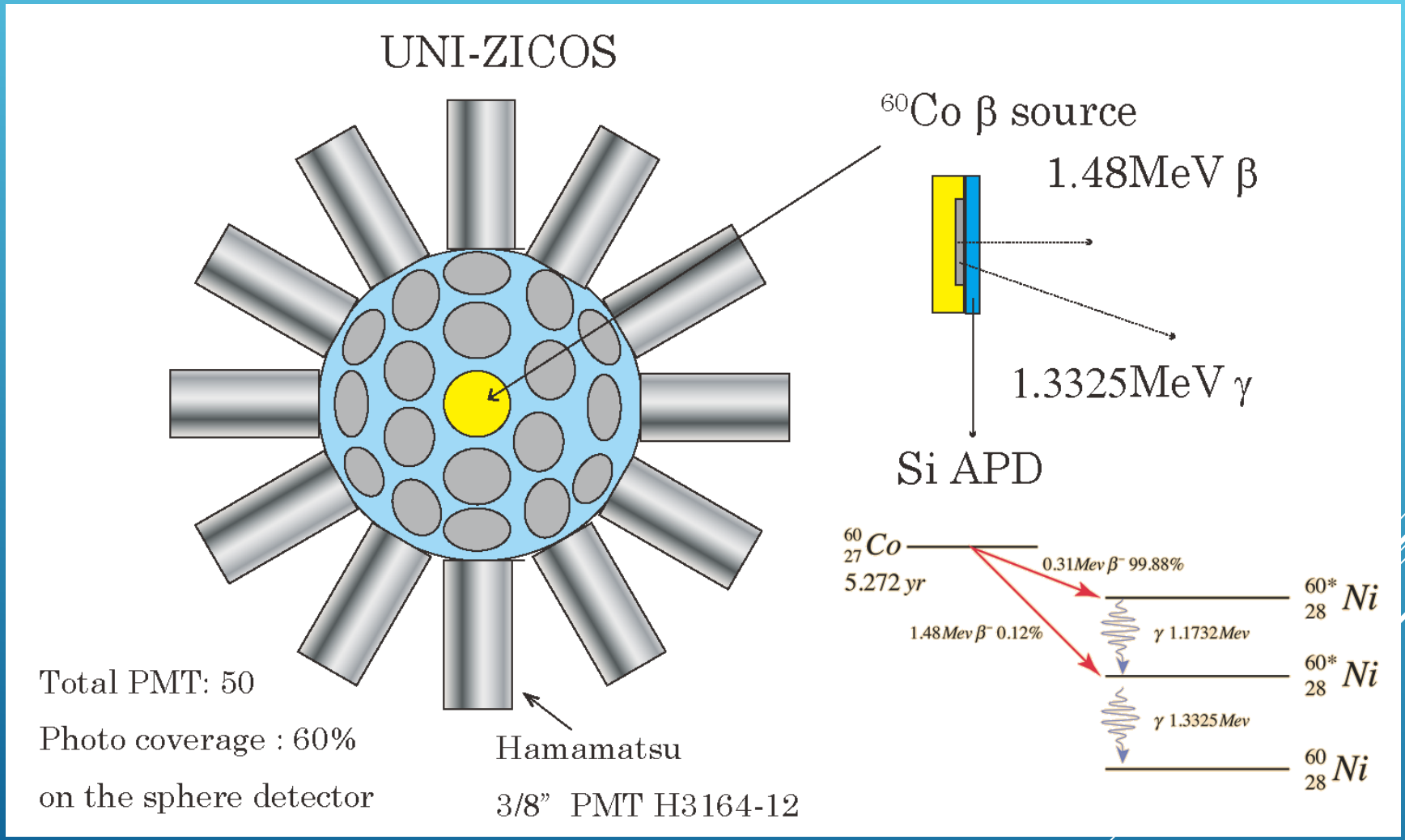
HV system worked well, but FADC was not checked yet, because the delivery was delayed due to COVID19.

Summary

- High Zr concentrated liquid scintillator is available.
- Expected energy resolution 2.2%@3.35MeV+60% photo coverage
  → need to confirm with real 60% Photo coverage
- To establish background reduction technique for ^{208}Tl decay
  → topological information using Cherenkov lights is useful.
  ① Pulse shape discrimination for selection of PMT which receives Cherenkov lights : almost done
  ② Confirmation of topological information : HUNI-ZICOS will be ready to measure soon
  ③ Demonstration of βγ events reduction using topological information : UNI-ZICOS will do next year

Demonstration of BG reduction of ^{208}Tl

- Direct reduction for βγ events by UNI-ZICOS



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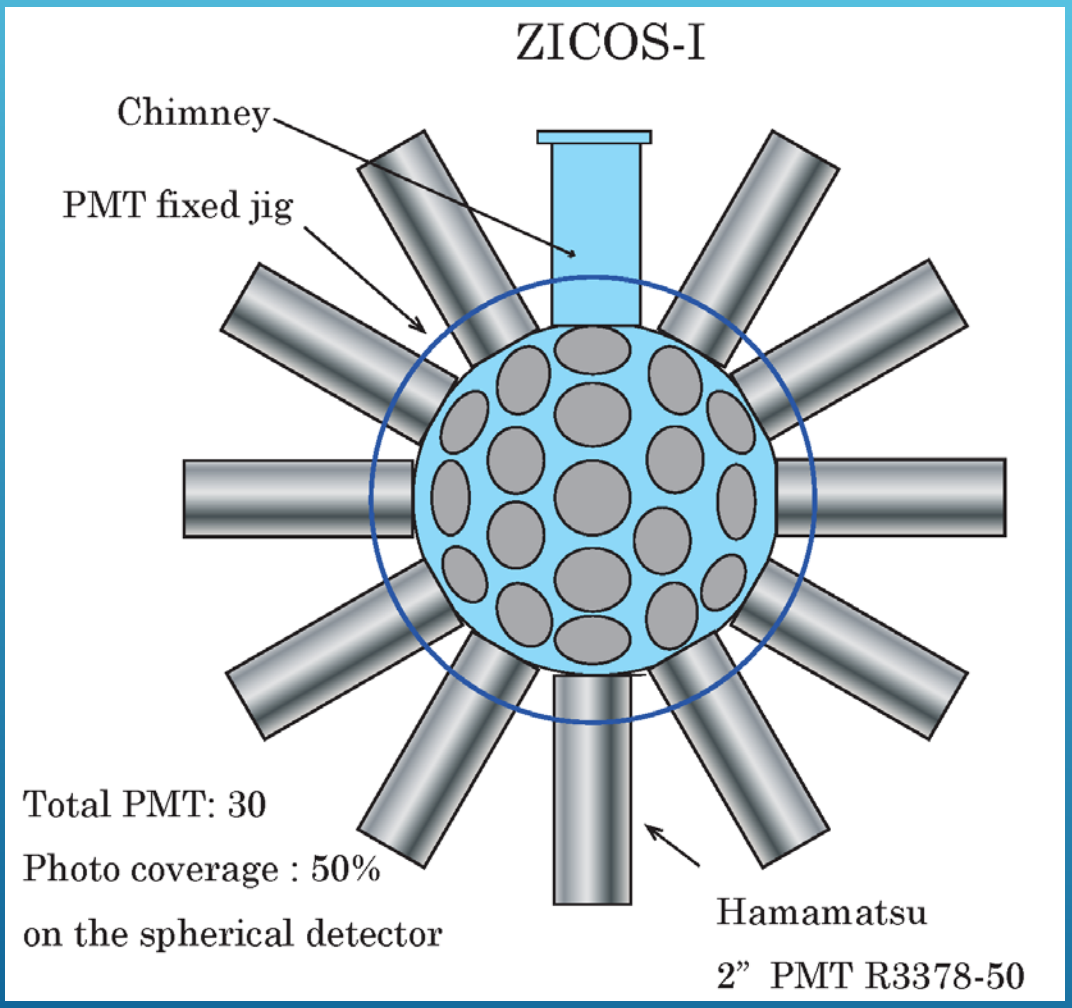
- Physics program (^{96}Zr $2\nu\beta\beta$ $T_{1/2}$ measurement) with ZICOS-I will start and get results within 5 years. Stay tuned!

Measurement of $T_{1/2}$ for ^{96}Zr $2\nu\beta\beta$ using ZICOS-I

- First physics program for confirmation of NEMO-3



- 20cm diameter flask using Ultra-pure quartz and 30 low BG PMT R3378-50
- 300g of $Zr(iPrac)_4$ corresponds to 1g ^{96}Zr
- According to NEMO-3 results, could expect 200 $2\nu\beta\beta$ events with 1 year measurement
- location : Kamioka mine

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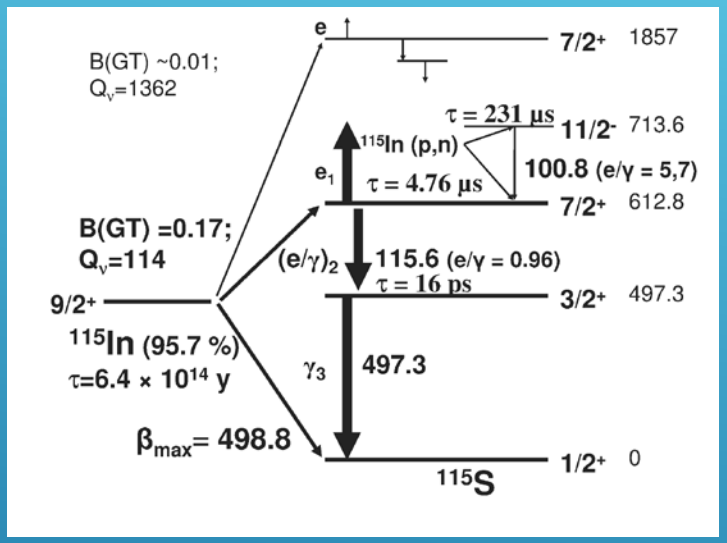
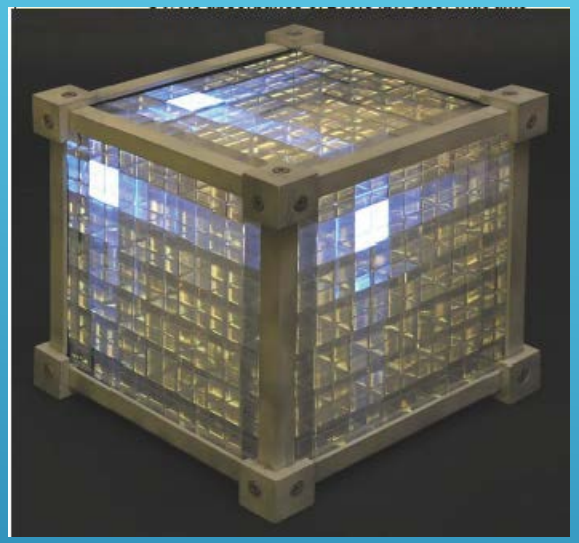
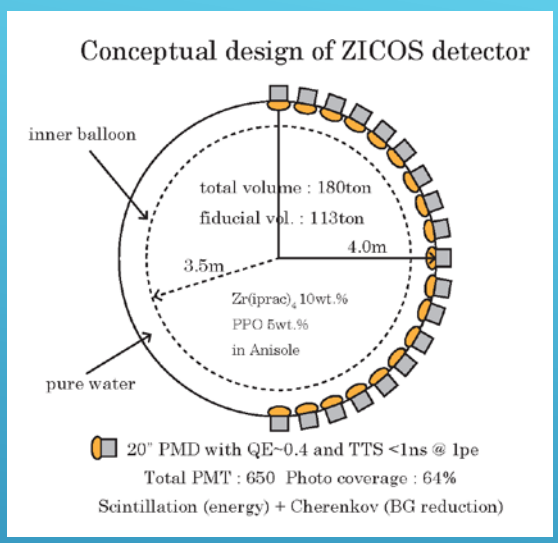
- Physics program (^{96}Zr $2\nu\beta\beta$ $T_{1/2}$ measurement) with ZICOS-I will start and get results within 5 years. Stay tuned!
- ^{115}In loaded LS for pp solar-ν will be evaluated by new tech. using topological information from multi Compton.

Evaluation of ^{115}In loaded in liquid scintillator for solar pp neutrino







本研究でO(1MeV)程度の電子から放射されるチェレンコフ光も位相幾何学情報を有していることが示唆されたことから、^{115}Inのニュートリノ捕獲で遷移した^{115}Sn*から放出する497keVのガンマ線が光電吸収や多重コンプトン散乱しても、その距離が20cm以内であり、散乱電子からチェレンコフ光を放射すれば、離れた場所で^{115}Inの自然ベータ崩壊が同時に発生し、各々の電子がチェレンコフ光を放出する場合とチェレンコフ光の位相幾何学的情報が異なるはずであり、In(iPrac)$_3$含有の大型単相LS検出器でも、チェレンコフ光による平均角を用いれば、検出器を細分化することなくsolar ppνが観測できる可能性があることを着想した。

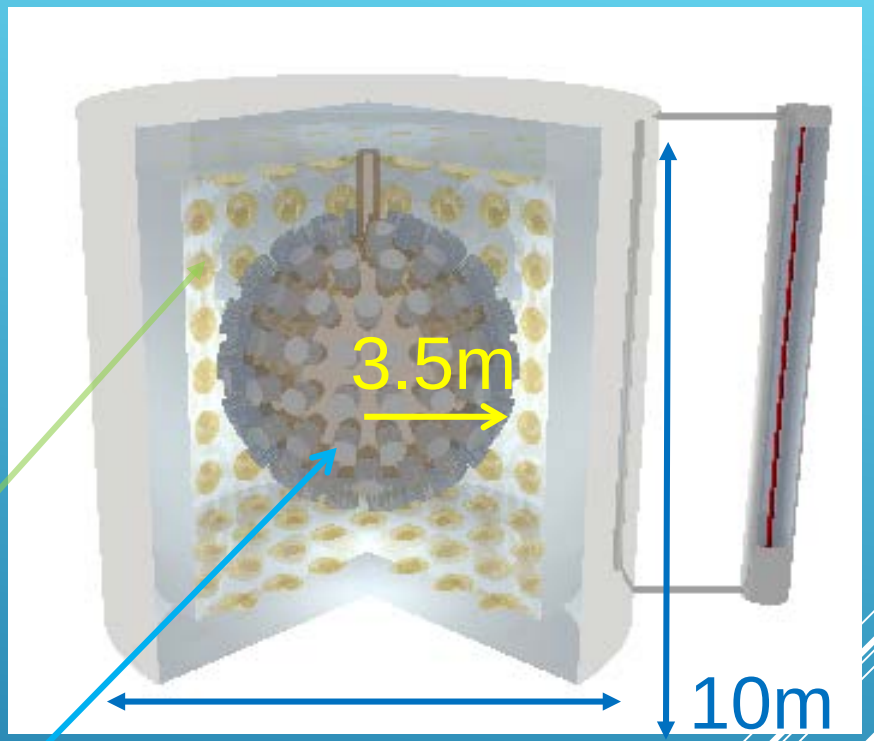
Backup slides

^{9}ZICOS experiment for neutrinoless double beta decay using ^{96}Zr

Liquid Scintillator:
(1) 10 wt.% $Zr(iprac)_4$ loaded in Liquid Scintillator
(2) 3~4% at 3.35MeV of energy resolution with 64% photo coverage and long attenuation length.

Pure water surrounding inner detector in order to veto muons and external backgrounds.

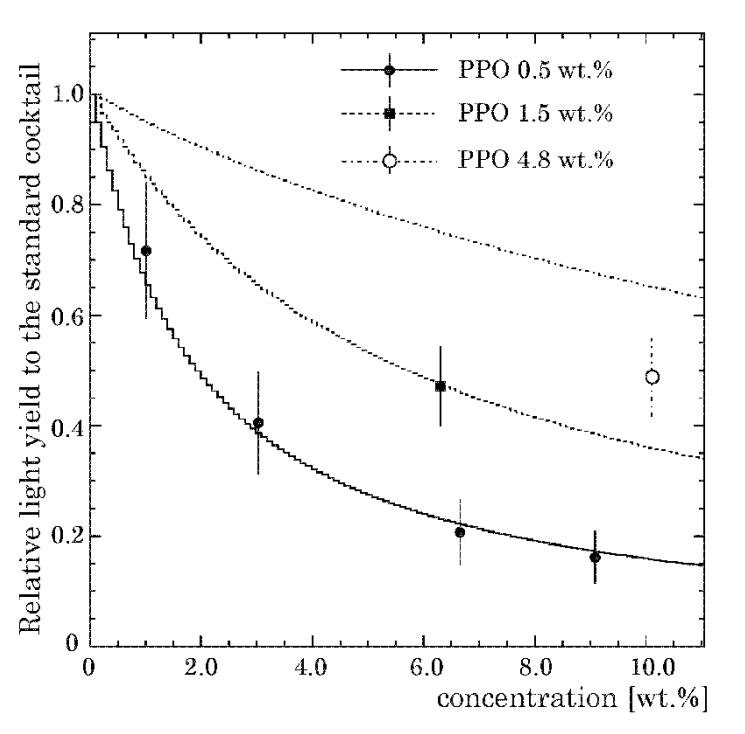
Inner detector with ~64% photo coverage 20" PMT including 1.7ton Zirconium loaded 113 tons LS in fiducial volume. (Total vol. : 180 tons)

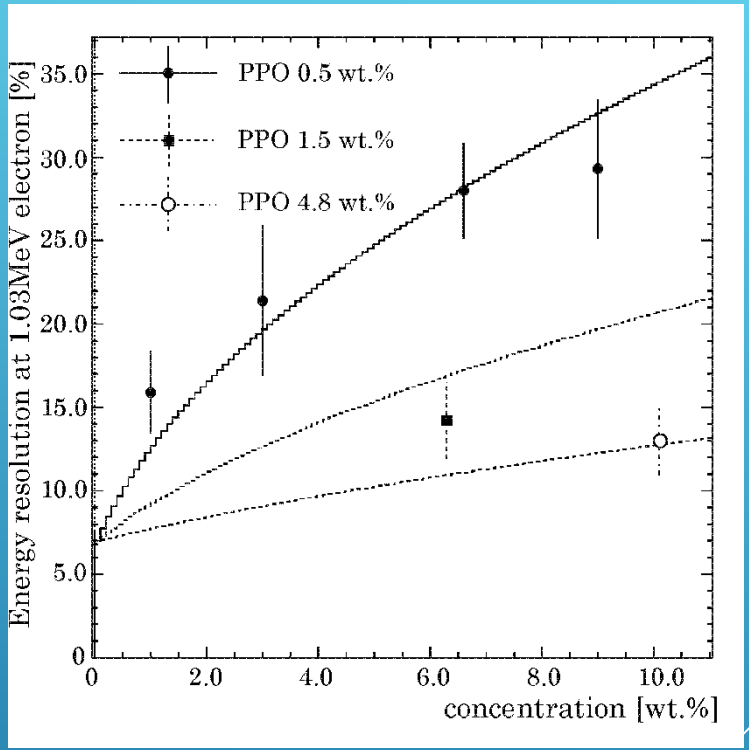


Purpose:
① **Direct measurement of $0\nu\beta\beta$**
② **Confirm parameter of nuclear matrix element model**

Performance of liquid scintillator

Measured at several conditions of PPO concentration

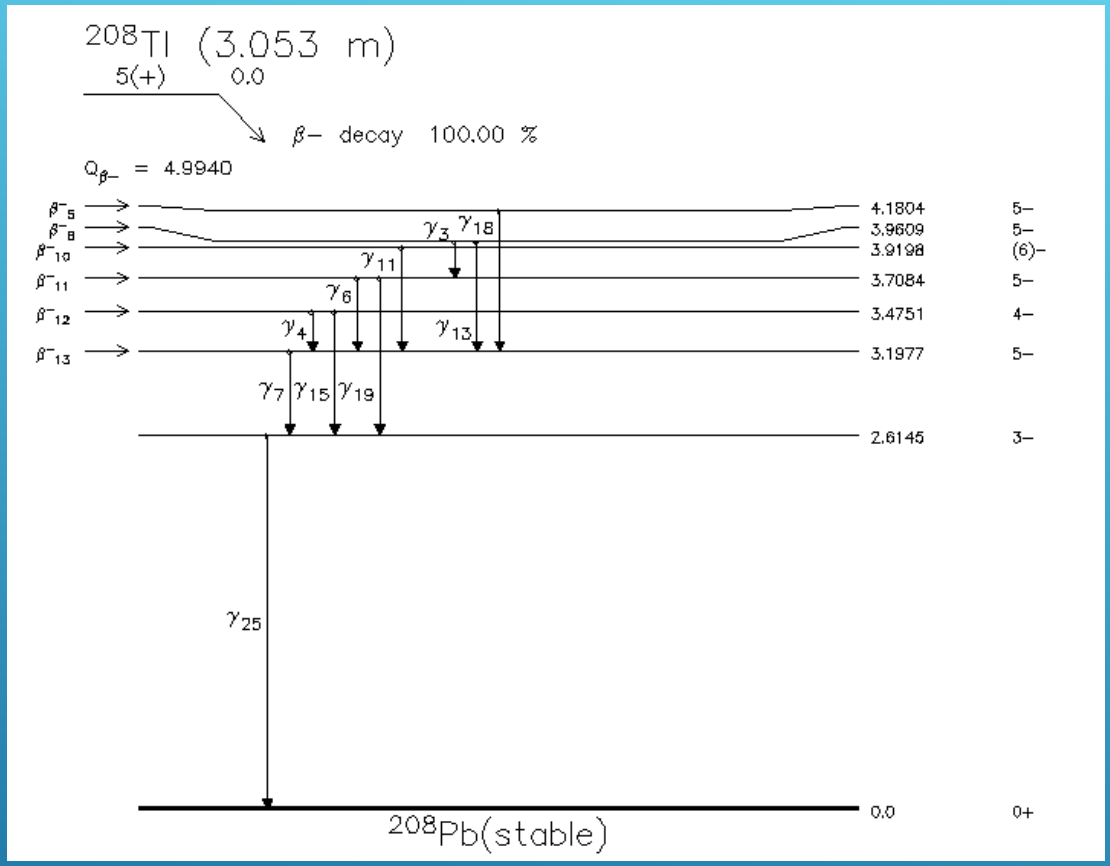




48.7±7.1% light yield to standard cocktail was obtained at 10wt.% concentration.

$$\frac{13.0\pm2.0\%}{\sqrt{(64\%/9.2\%)\times(3.35\text{MeV}/1.03\text{MeV})}} = 2.7\pm0.4\% \text{ at } 3.35\text{MeV}$$

Decay scheme of ^{208}Tl



Radiations	y(i) (Bq-s)$^{-1}$
beta- 5	2.27×10^{-03}
beta- 8	3.09×10^{-02}
beta- 10	6.30×10^{-03}
beta- 11	2.45×10^{-01}
beta- 12	2.18×10^{-01}
beta- 13	4.87×10^{-01}
ce-K, gamma 3	4.04×10^{-03}
gamma 4	6.31×10^{-02}
ce-K, gamma 4	2.84×10^{-02}
ce-L, gamma 4	4.87×10^{-03}
gamma 6	2.26×10^{-01}
ce-K, gamma 6	1.97×10^{-02}
ce-L, gamma 6	3.32×10^{-03}
gamma 7	8.45×10^{-01}
ce-K, gamma 7	1.28×10^{-02}
ce-L, gamma 7	3.51×10^{-03}
gamma 13	1.81×10^{-02}
gamma 15	1.24×10^{-01}
ce-K, gamma 15	2.80×10^{-03}
gamma 19	3.97×10^{-03}
gamma 25	9.92×10^{-01}

The vertex position reconstructed by scintillation might be within fiducial volume due to gammas.