VERIFICATION OF TL-208 BACKGROUNDS REDUCTION FOR NEUTRINOLESS DOUBLE BETA DECAY WITH HALF-LIFE 10 TO 27TH YEARS USING ZR-96

研究会「ニュートリノを伴わない二重ベータ崩壊とその周辺」

12th February, 2021

Grant-in-Aid for Scientific Research on Innovative Areas

19H05093 and 20H05241

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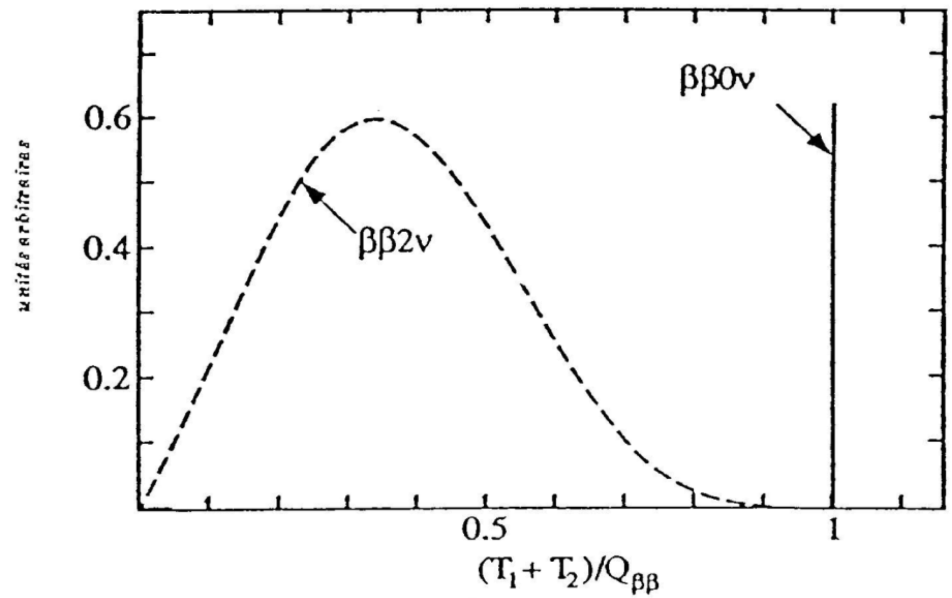
Neutrinoless double beta decay

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

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



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

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

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

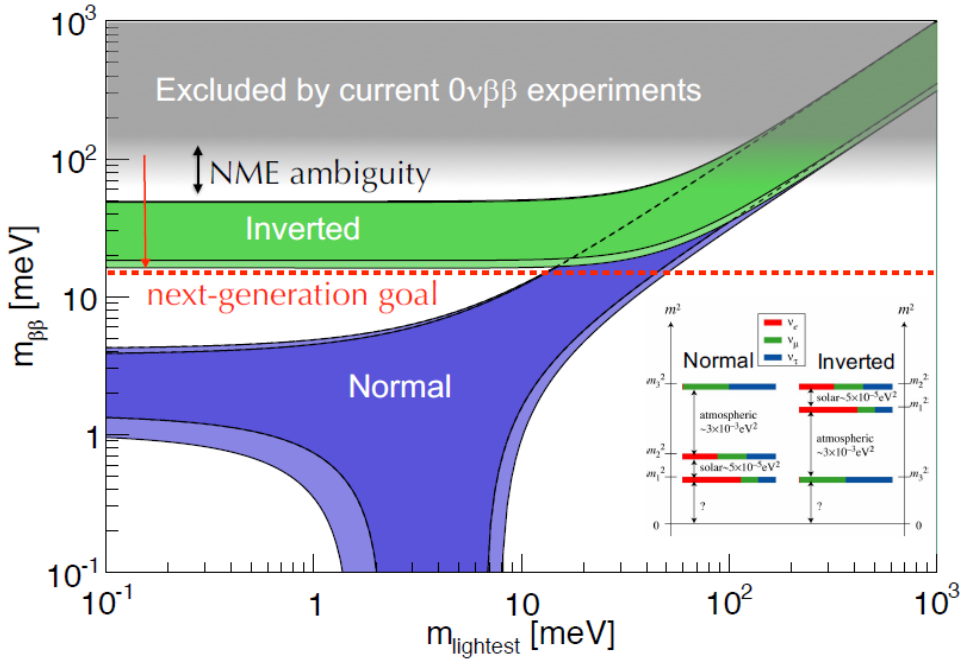
Requirement : Low BG, Large target mass, Good E-resolution

Future Neutrinoless double beta decay experiments

Current limits and future goal

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M^{0\nu}_{\text{cont}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



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- To cover IH region, measure $T_{1/2} \geqq 10^{27}$ years
- To reach NH region, need $T_{1/2} \sim 10^{28}$ years measuring

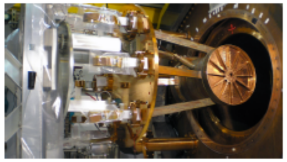
Techniques for Neutrinoless double beta decay experiment

Experimental Techniques

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO) MTD
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

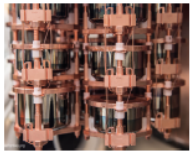

KamLAND-Zen

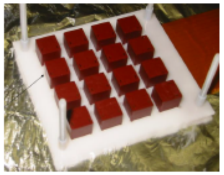

CANDLES

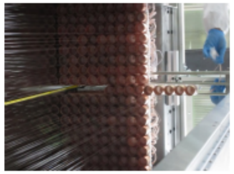

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

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Experiments

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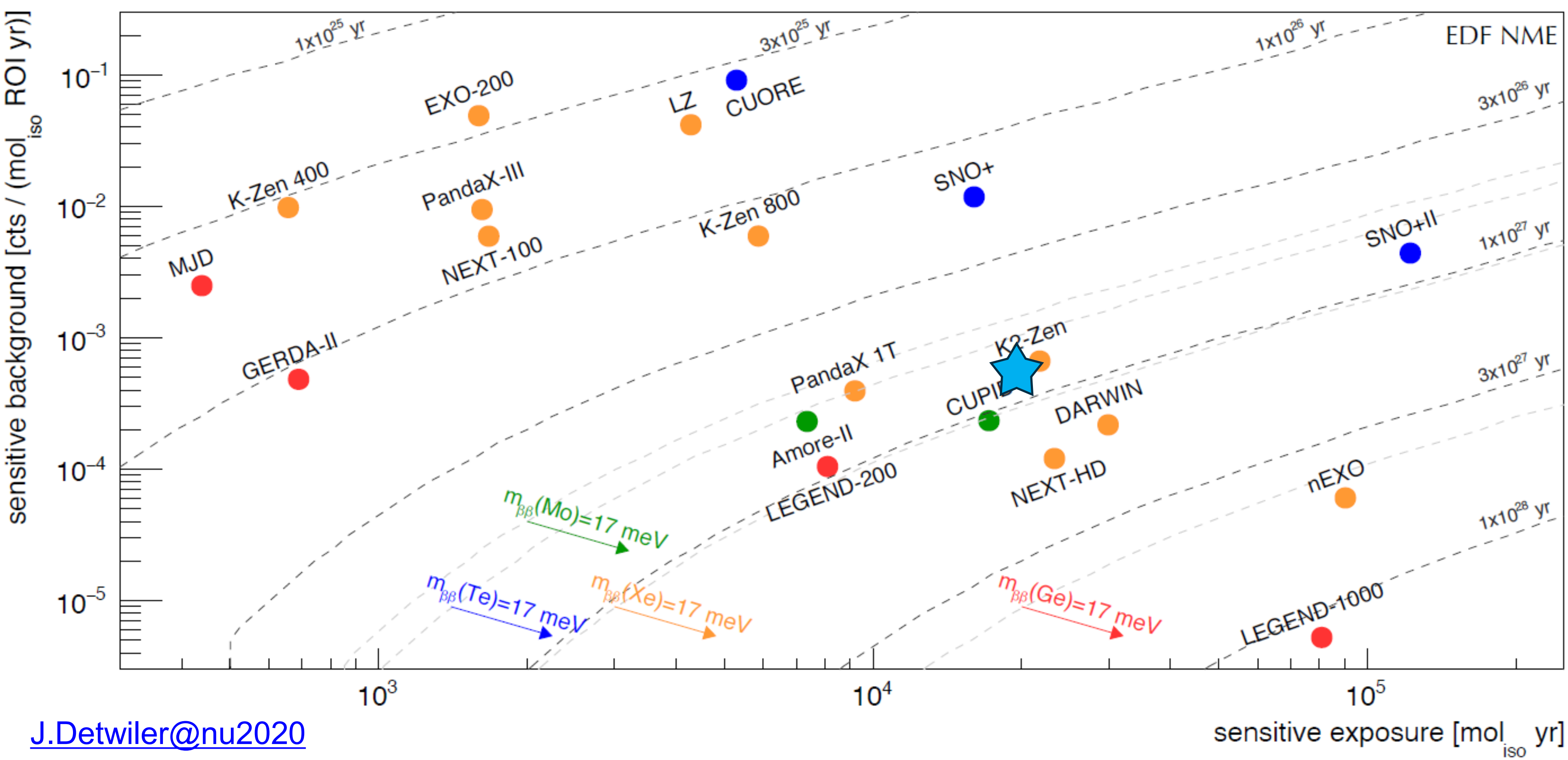
Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D | Construction | Operating | Complete

Sensitivity for some experiments

Discovery Sensitivity Comparison



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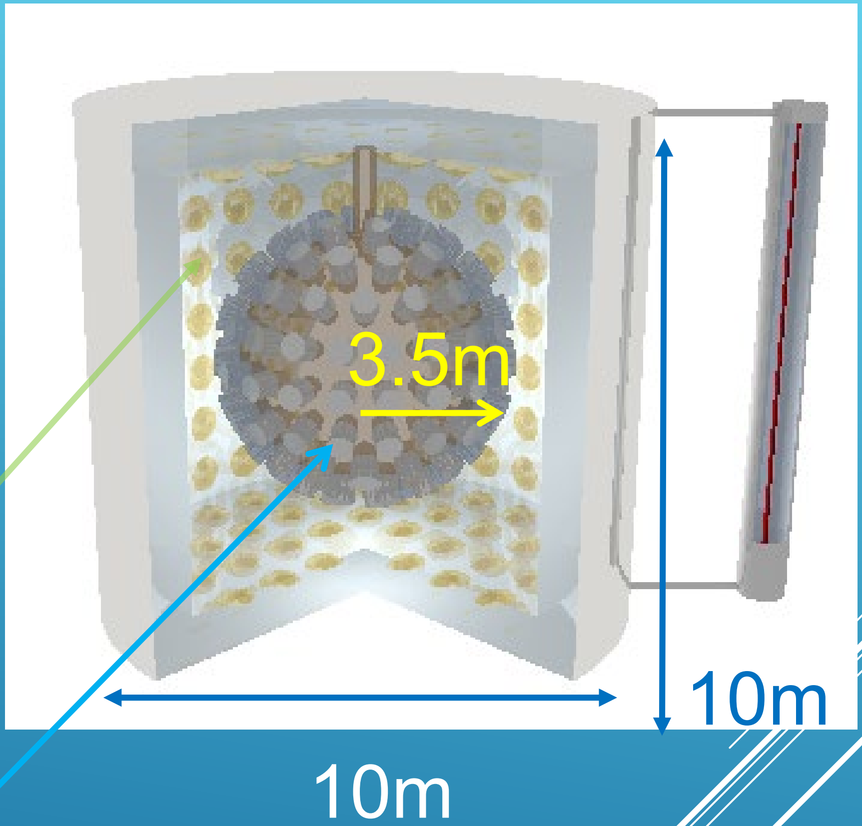
ZICOS experiment for neutrinoless double beta decay using ^{96}Zr

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)

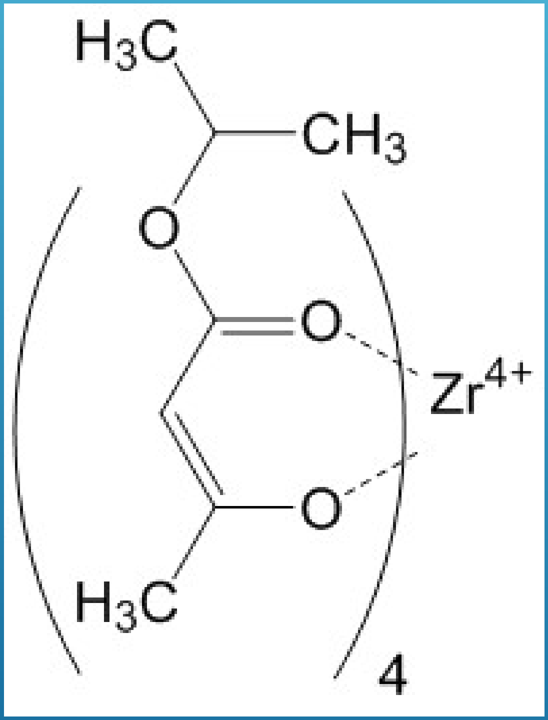


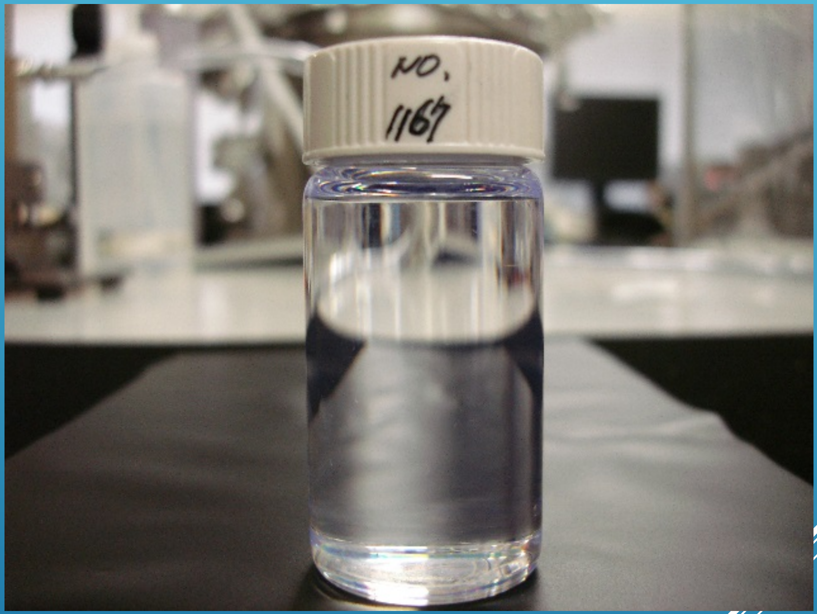
Purpose:
① Direct measurement of 0νββ
② Confirm parameter of nuclear matrix element model

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

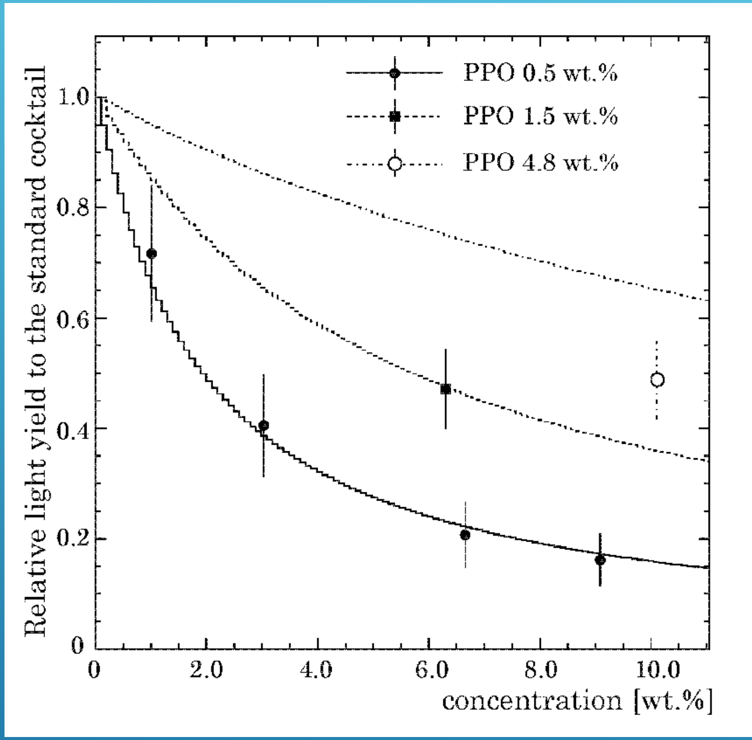


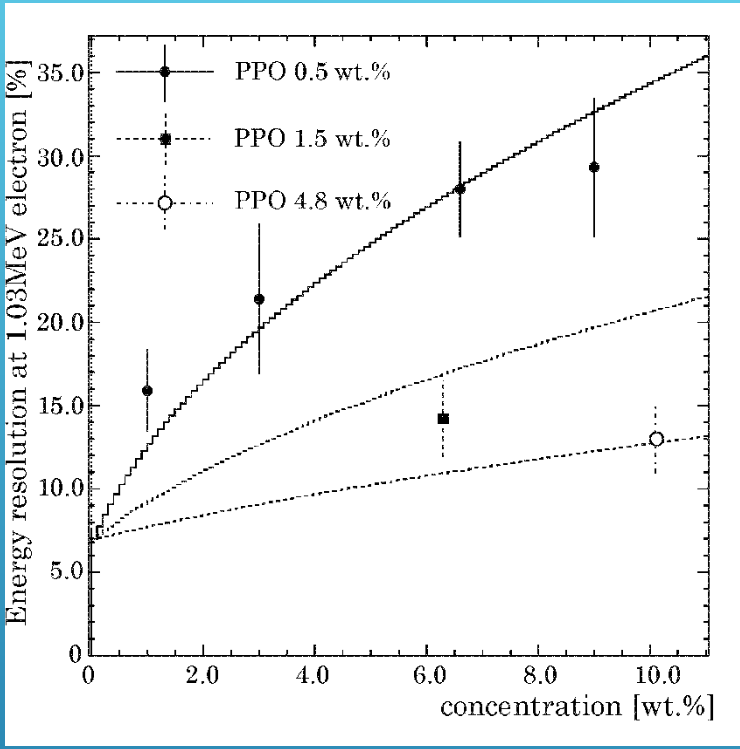


> 70g/L of Zirconium could be solved in anisole.

Performance of liquid scintillator

Measured at several conditions of PPO concentration

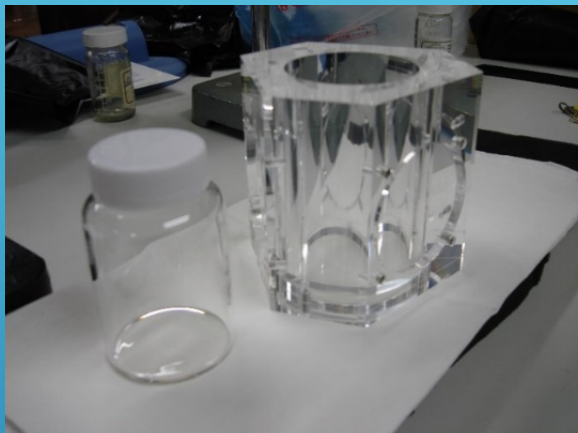


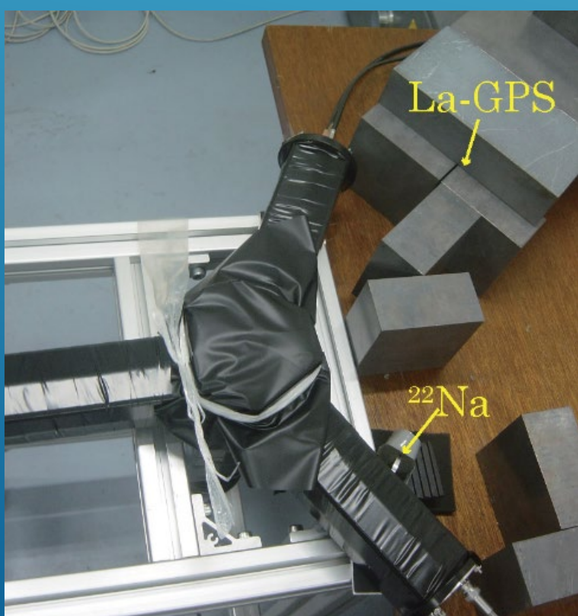


48.7±7.1% light yield to standard cocktail was obtained at 10wt.% concentration.

$$\frac{13.0 \pm 2.0\%}{\sqrt{(64\%/9.2\%) \times (3.35\mathrm{MeV}/1.03\mathrm{MeV})}} = 2.7 \pm 0.4\% \text{ at } 3.35\mathrm{MeV}$$

Measurement for energy resolution by 20% photo coverage

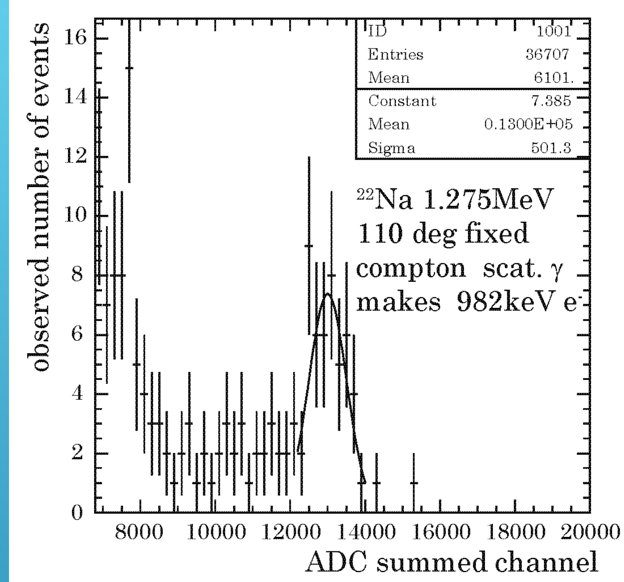


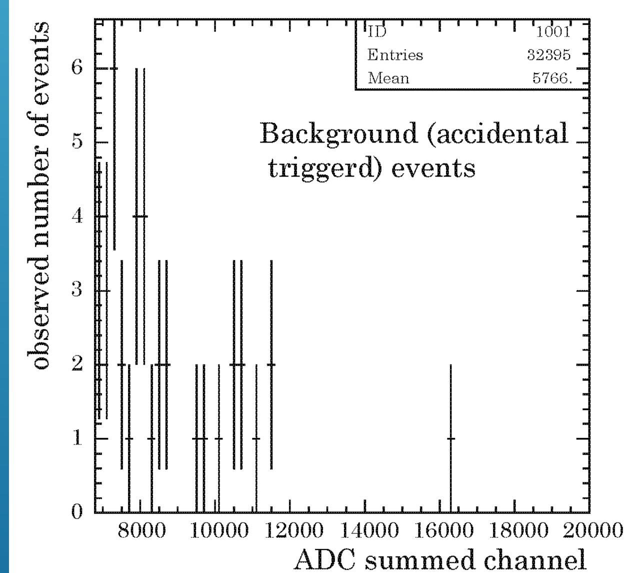


σ/E=7.0%@982 keV&20%photo coverage

⬇

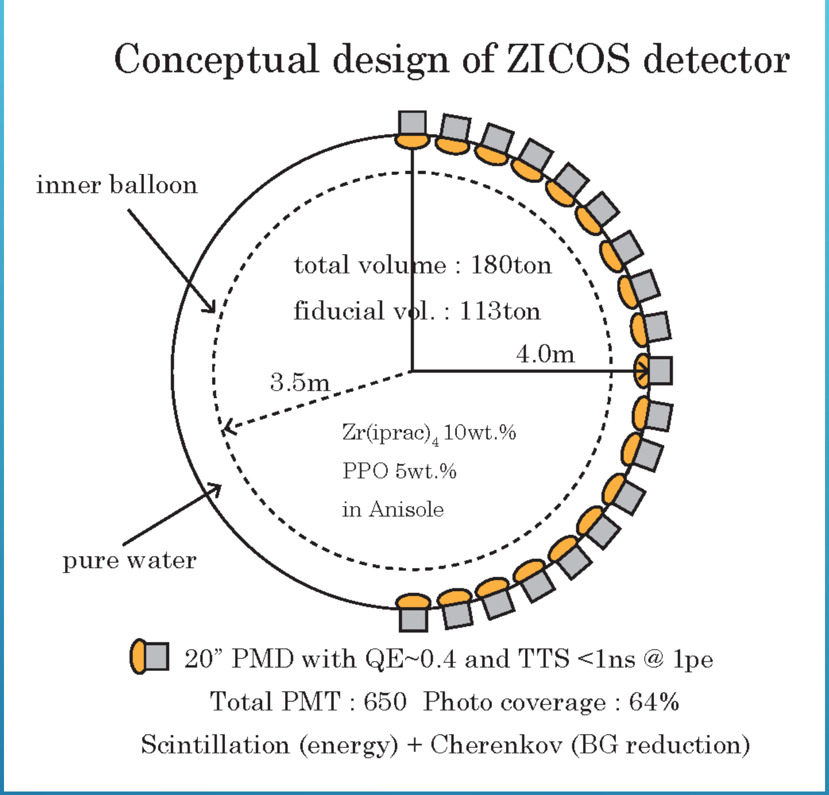
2.2%@3.35MeV &60% photo coverage

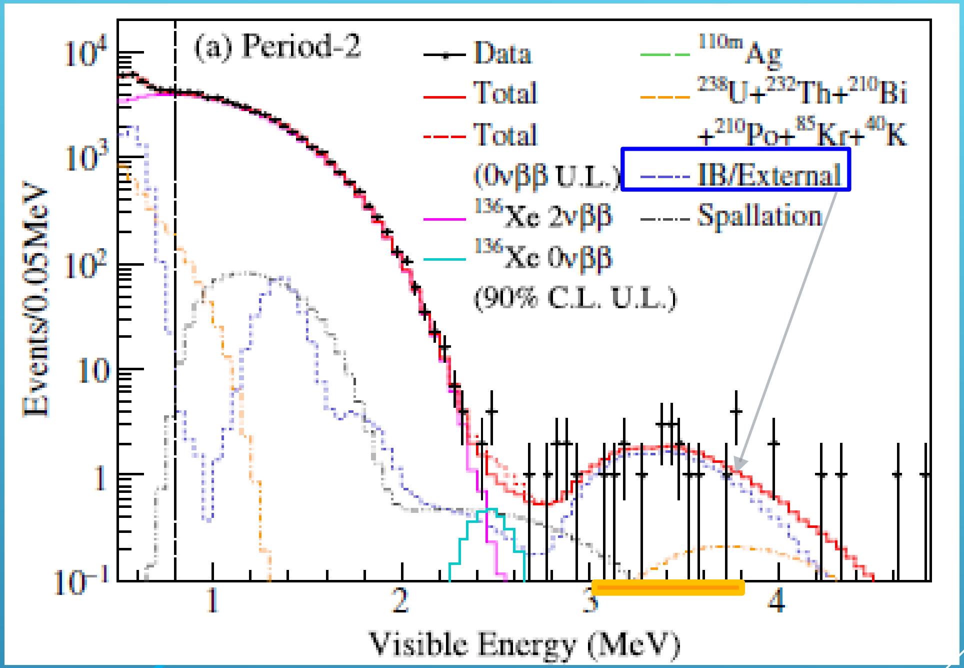




Conceptual design of ZICOS detector

Phys.Rev.Lett. 117 (2016) 082503



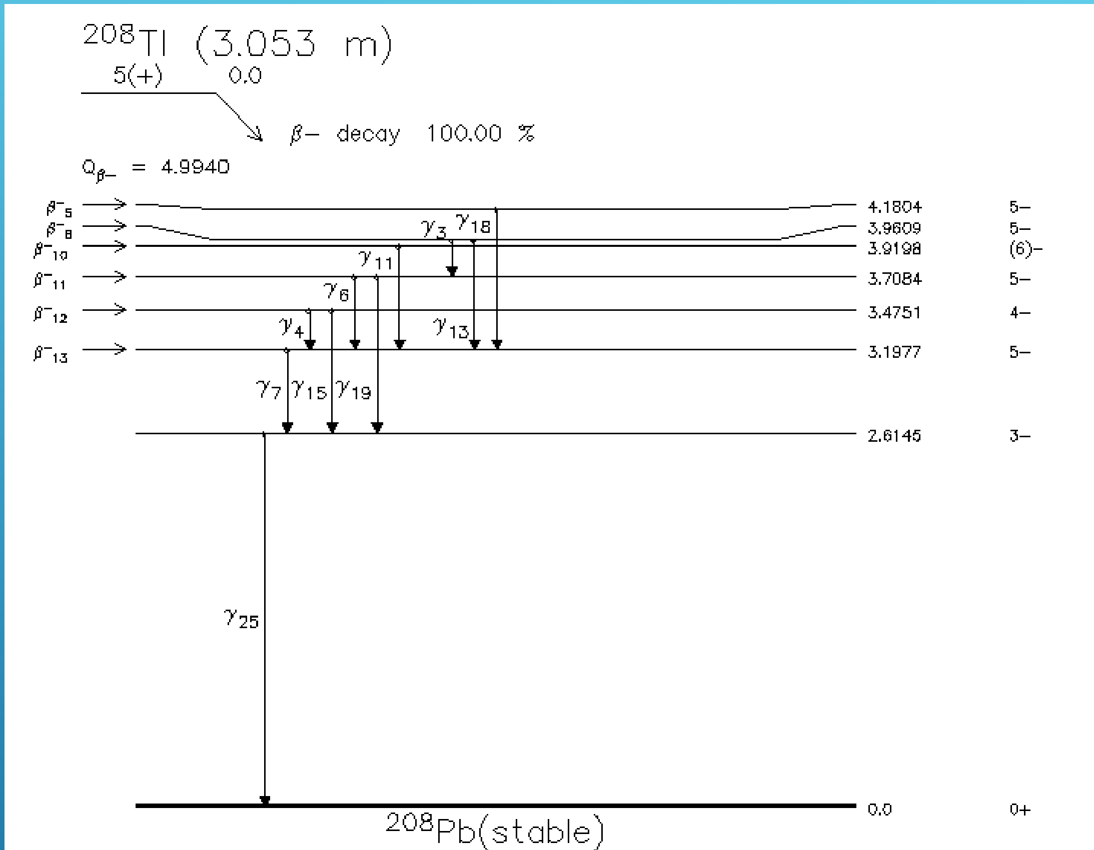


NEMO3 : $T_{1/2}^{0\nu} > 9.1 \times 10^{21}$ yrs

^{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 × 10^{27}yrs

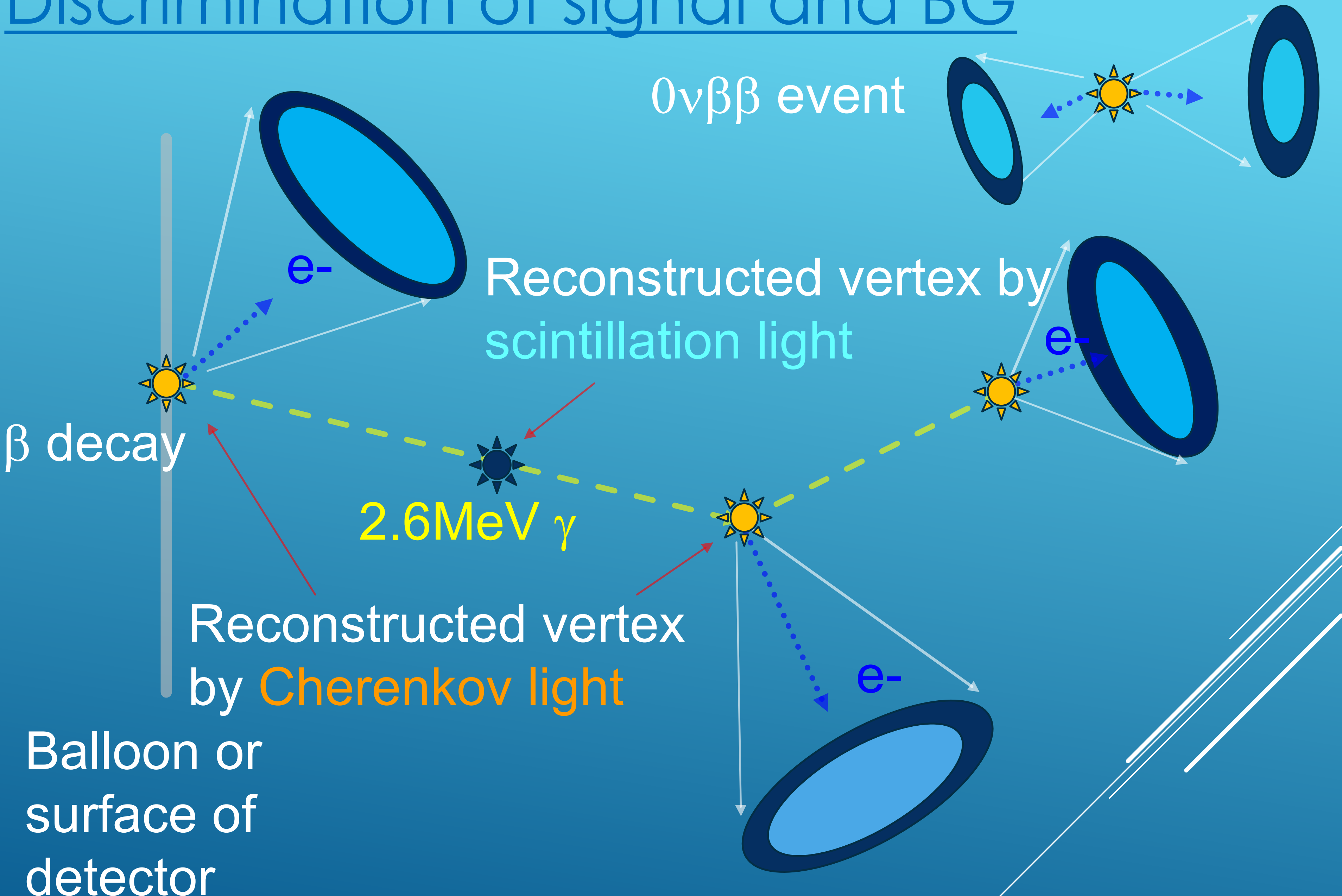
Decay scheme of ^{208}Tl



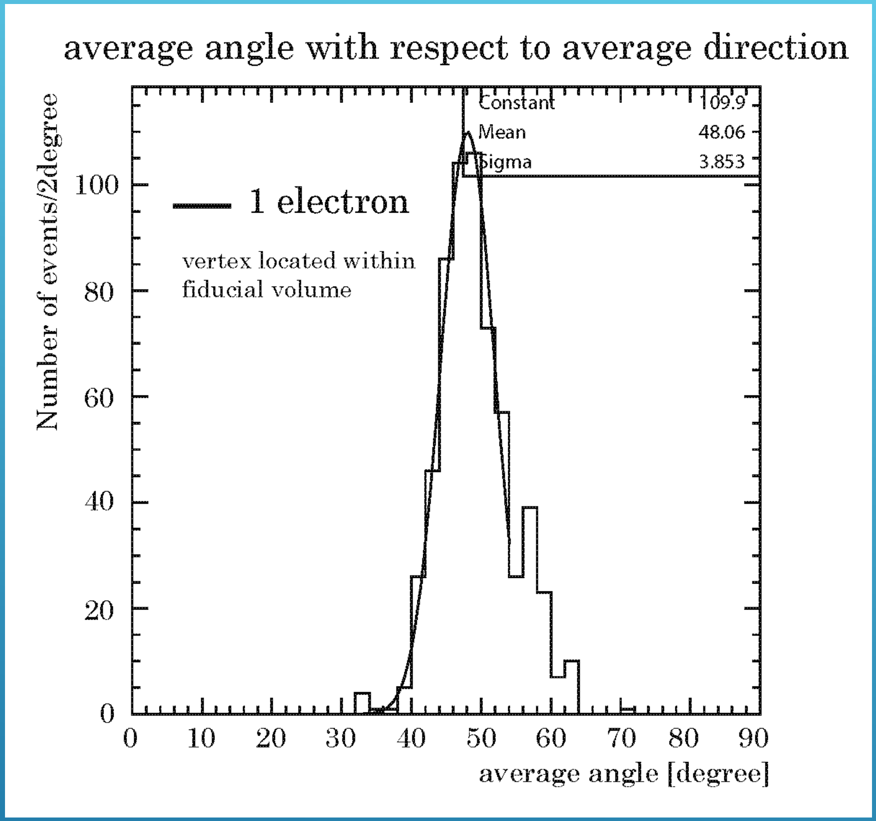
Radiations	y(i) $(Bq\text{-}s)^{-1}$
beta- 5	2.27×10^{-03}
beta- 8	3.09×10^{-02}
beta- 10	6.30×10^{-03}
beta- 11	2.45×10^{-01}
beta- 12	2.18×10^{-01}
beta- 13	4.87×10^{-01}
ce-K, gamma 3	4.04×10^{-03}
gamma 4	6.31×10^{-02}
ce-K, gamma 4	2.84×10^{-02}
ce-L, gamma 4	4.87×10^{-03}
gamma 6	2.26×10^{-01}
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}

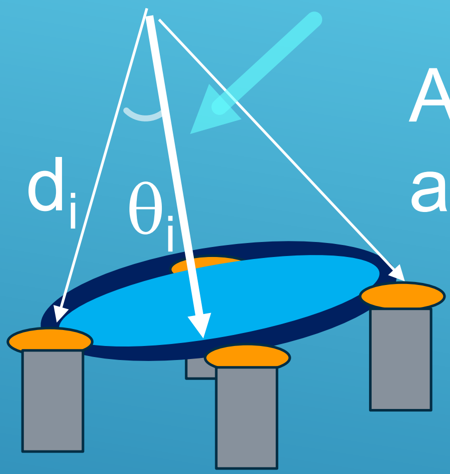
The vertex position reconstructed by scintillation might be within fiducial volume due to gammas.

Discrimination of signal and BG



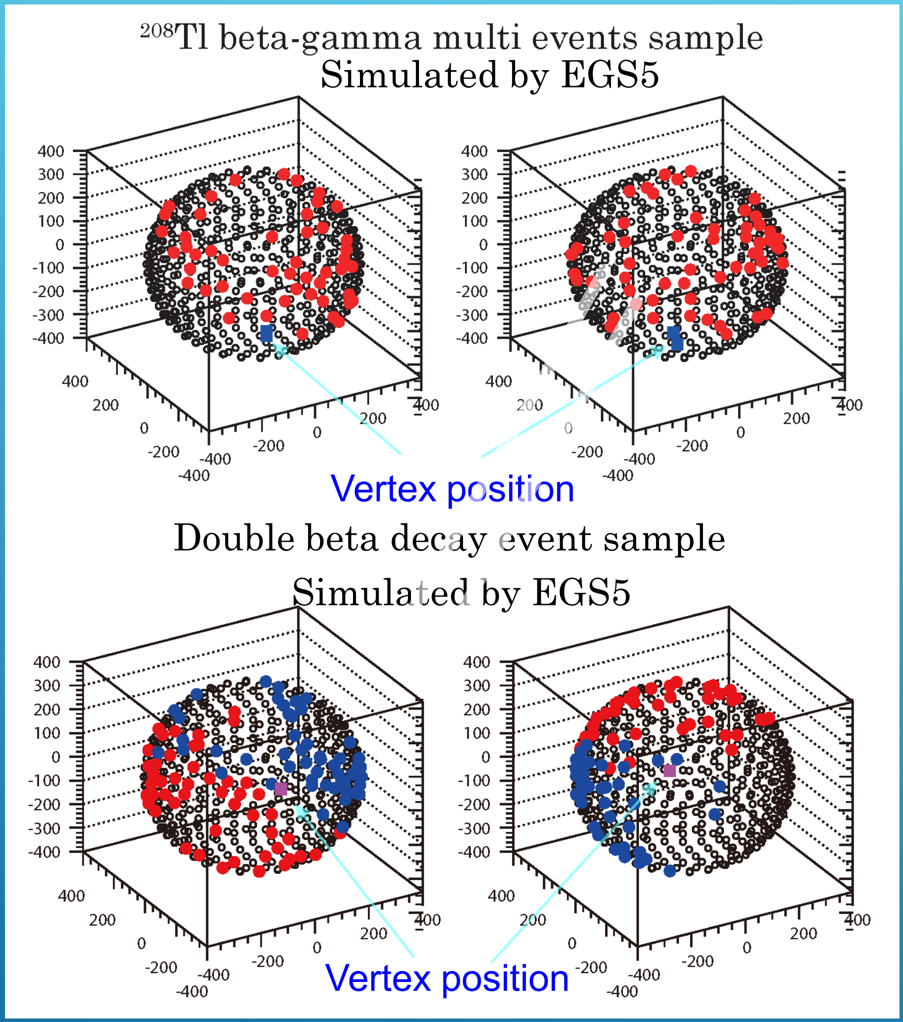
Topological info : averaged angle

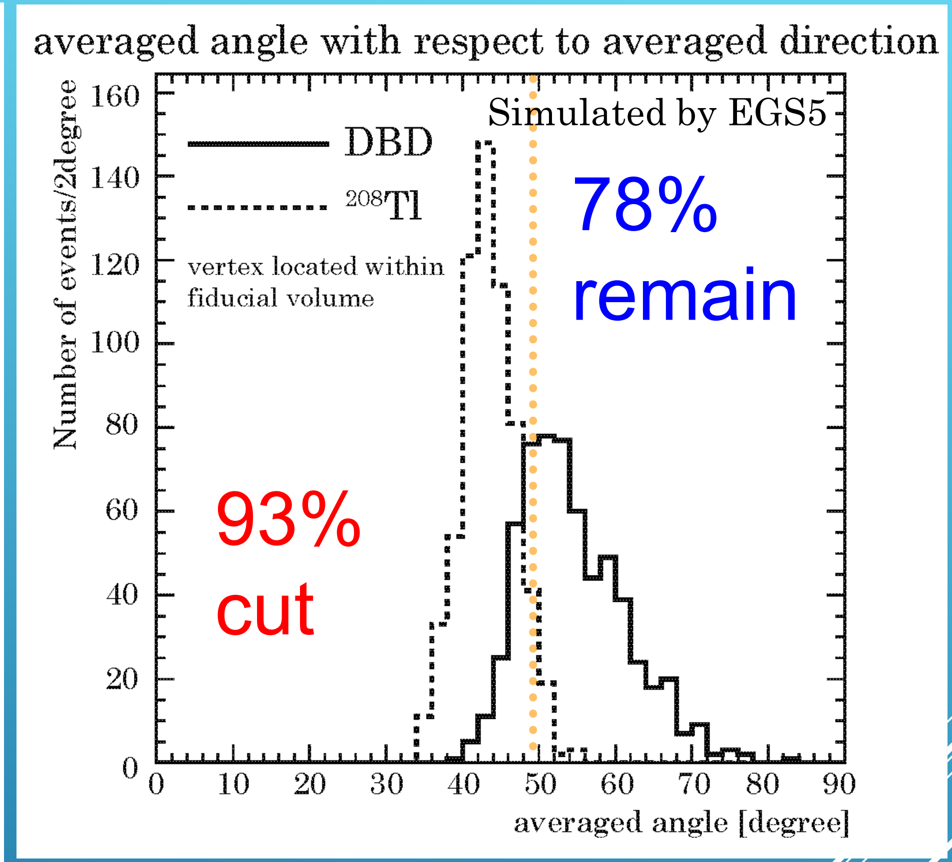




Average angle with respect to averaged direction for single electron seems to have a peak at 48 degree which is almost same as Cherenkov angle.

BG reduction using topological information



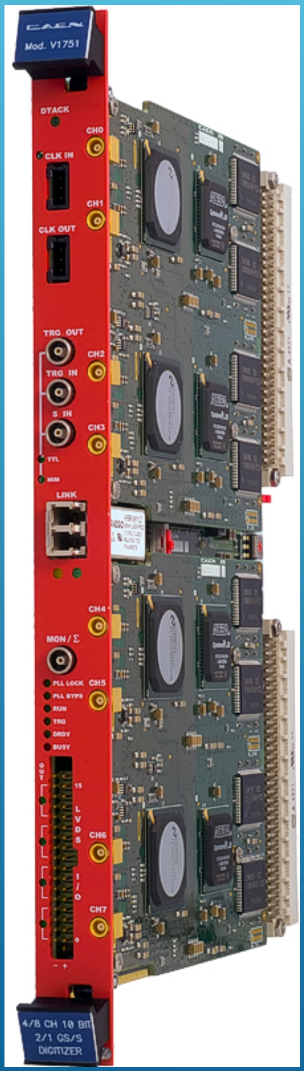


PMT hit pattern of ^{208}Tl BG and $0\nu\beta\beta$ signal

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

Measurement of pulse shape difference

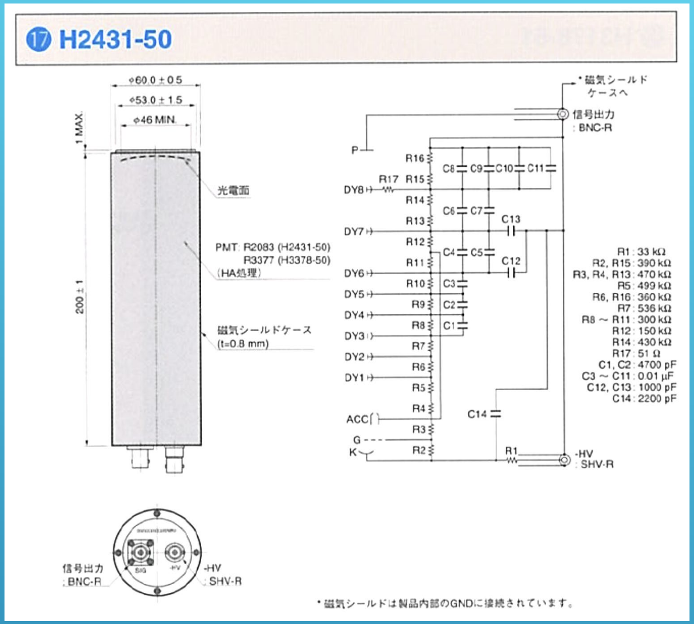
FADC digitizer: CAEN V1751



- **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

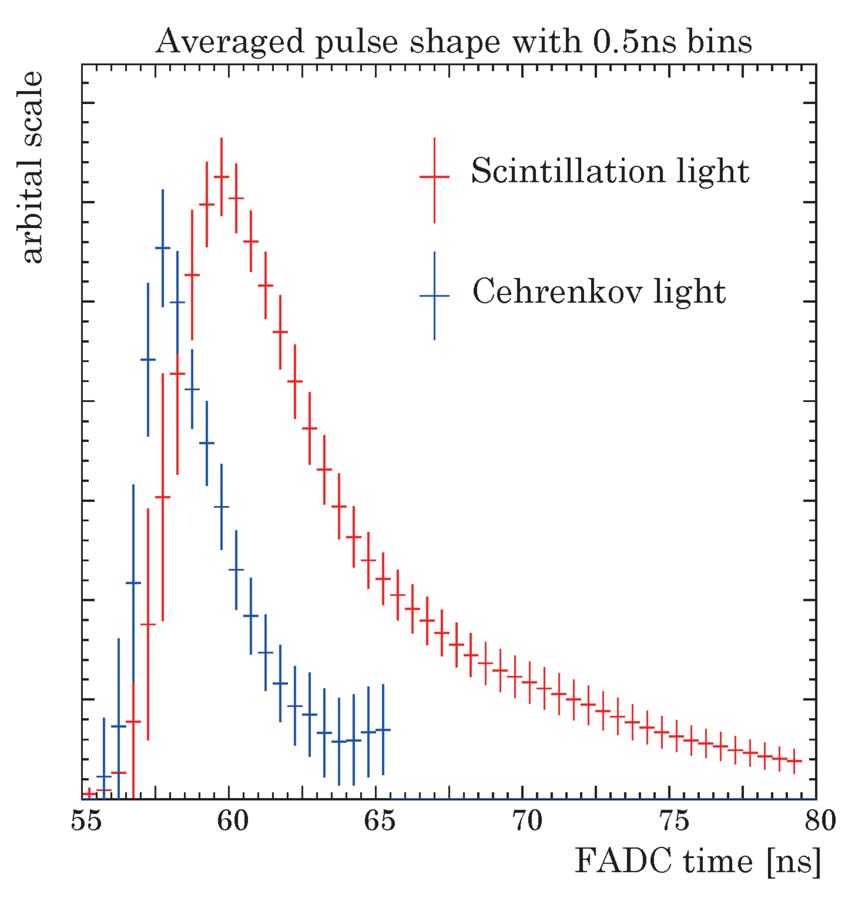
Measurement of pulse shape difference

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）

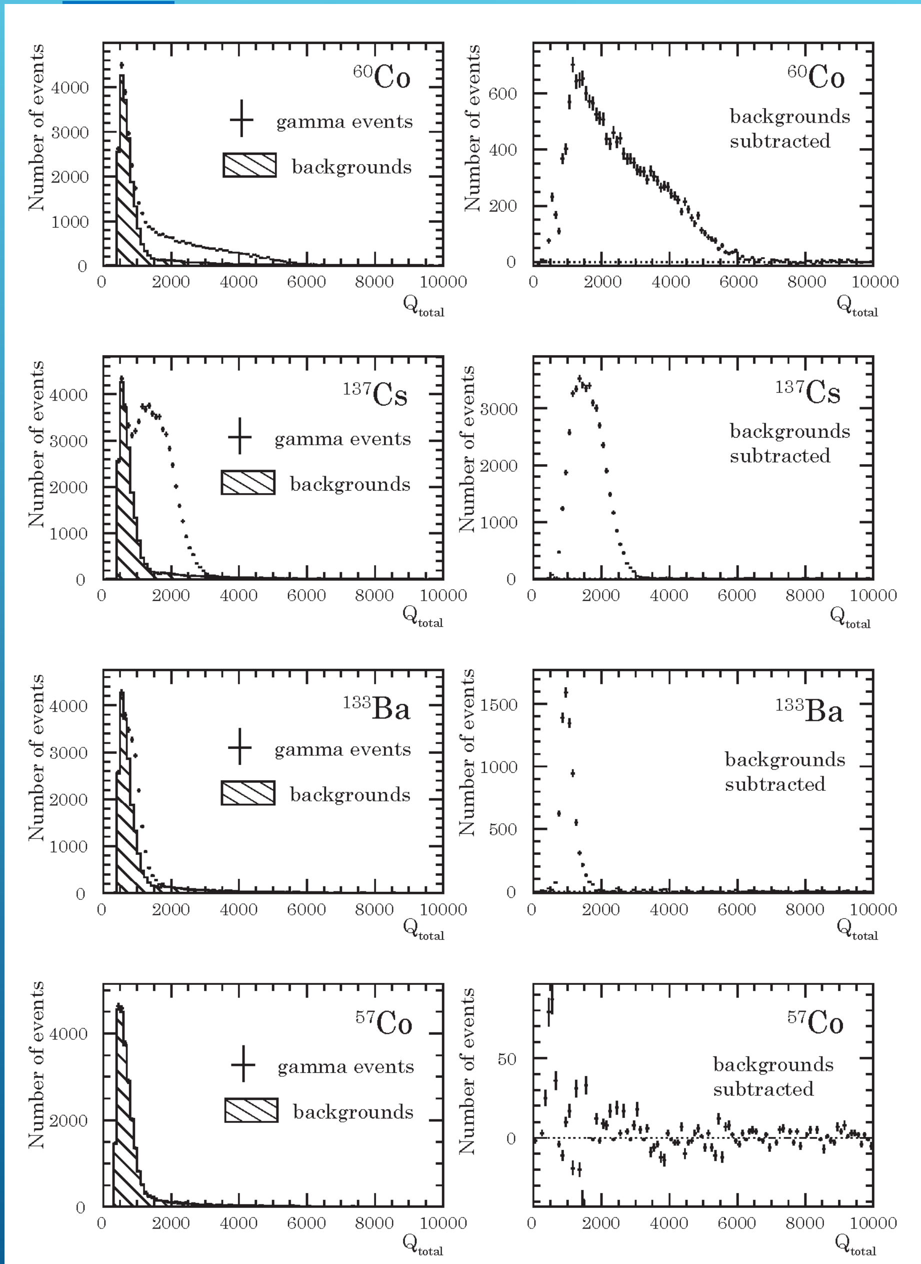
Pulse shape of Cherenkov and scintillation

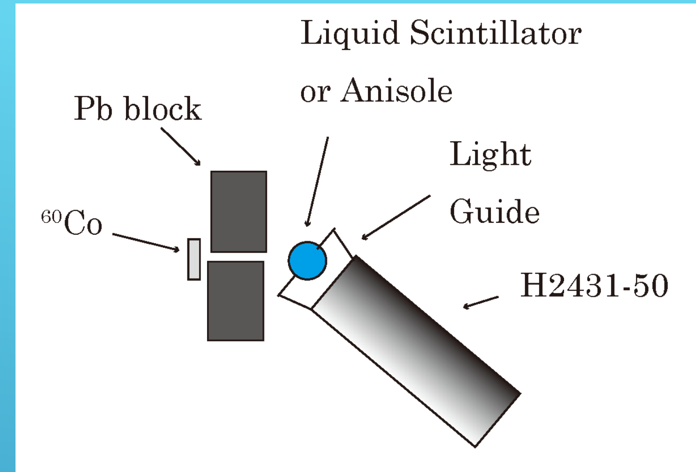


- Pulse shape of ^{90}Sr using H2431-50 measured by V1751 with DES mode (2GS/s)
- Decay time of scintillation : 4.57ns and 8.38ns
- Rise time of scintillation : 1.45ns
- Rise time of Cherenkov : 0.75ns

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

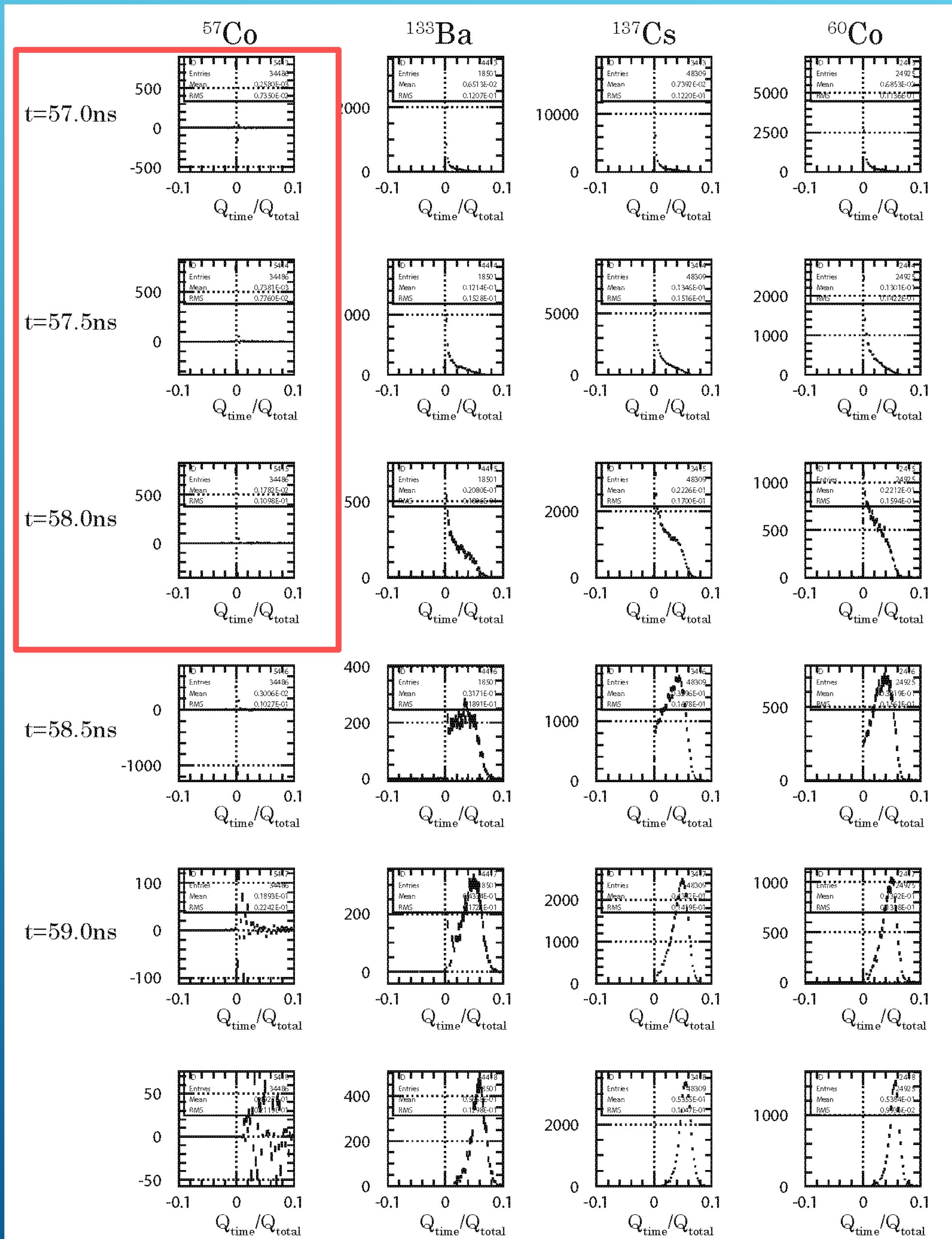




- ^{60}Co (1.17MeV/1.33MeV)
  Compton edge: 1.04MeV
- ^{137}Cs (662keV)
  Compton edge: 478keV
- ^{133}Ba (356keV)
  Compton edge: 207keV
- ^{57}Co (122keV)
  Under Cherenkov threshold (169kev)

Pulse shape with charge ratio in each FADC time.

Charge ratio in rise time using ZICOS LS

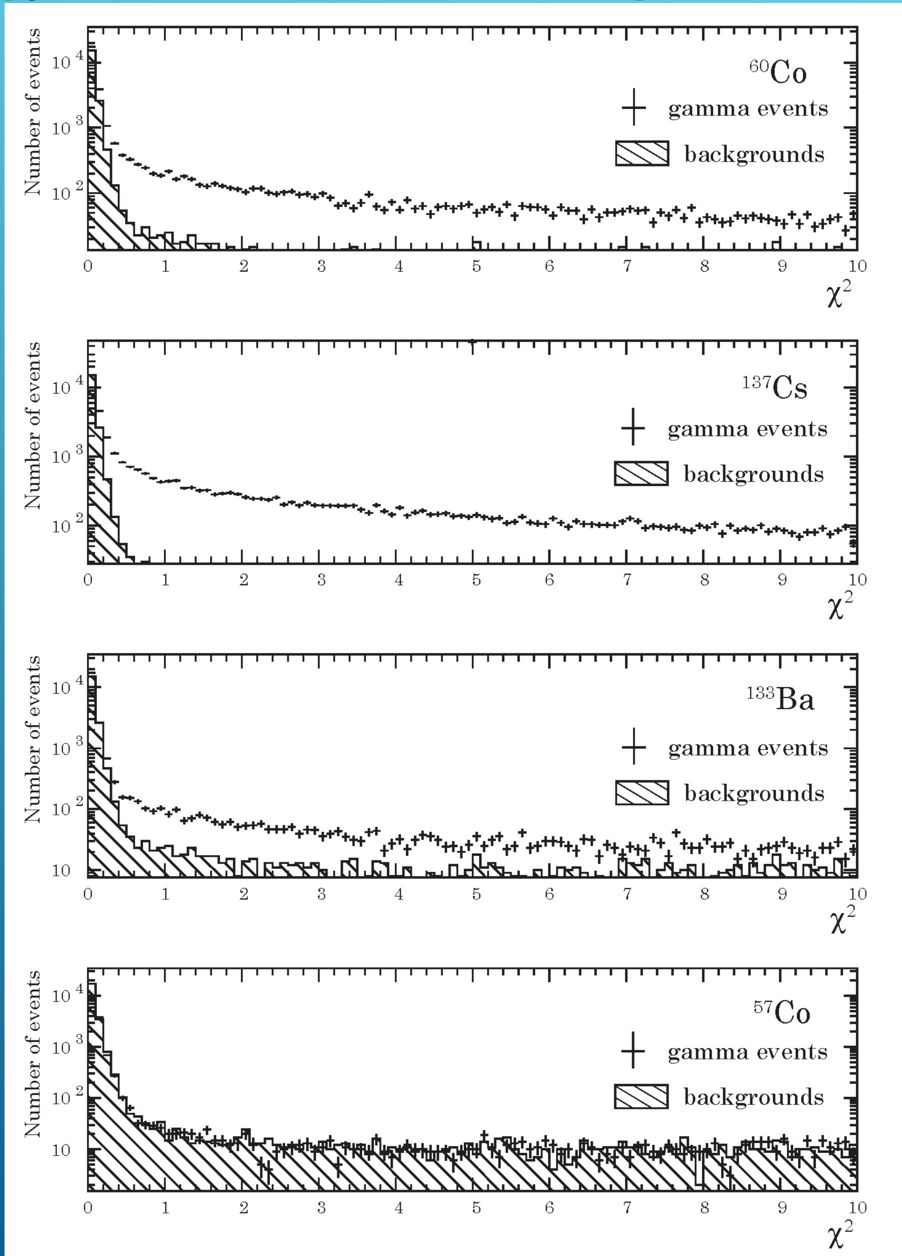


- There is difference of shape between t=57ns and 58ns
- Charge ratio looks depend on the energy
- For t>58.5ns, all shapes were almost same.

Cherenkov looks dominant between 57ns and 58ns.

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

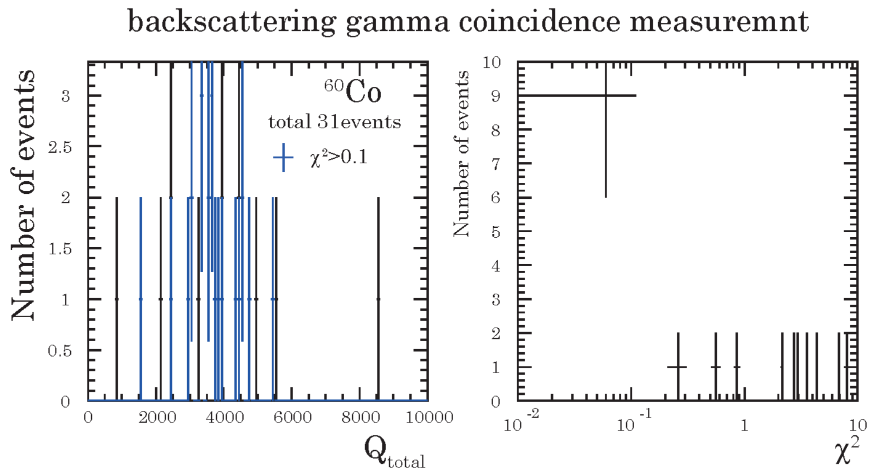
χ^2distribution using ^{57}Co template



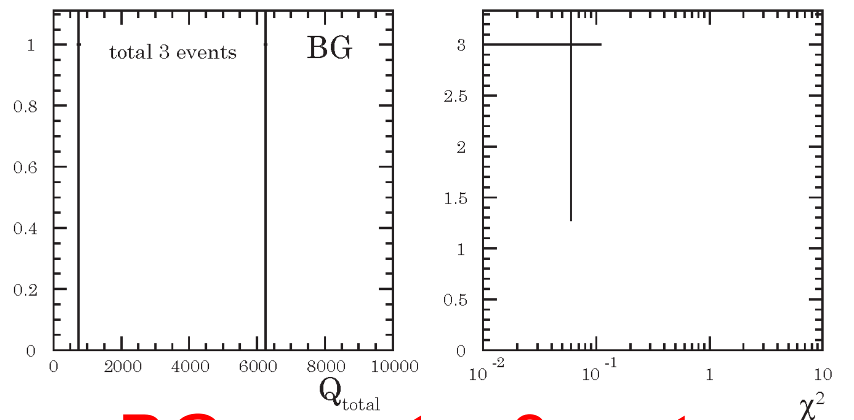
- Most of backgrounds have lower χ^2 than 1.0
- Most of backgrounds have lower energy than Cherenkov threshold, then only scintillation was seen.

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

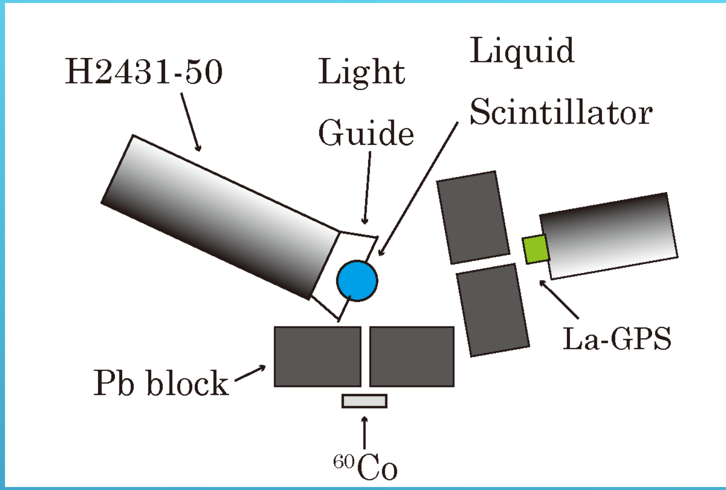
Measured by fixed energy fixed direction events



χ^2>0.1 : 22events/28events =78.6%



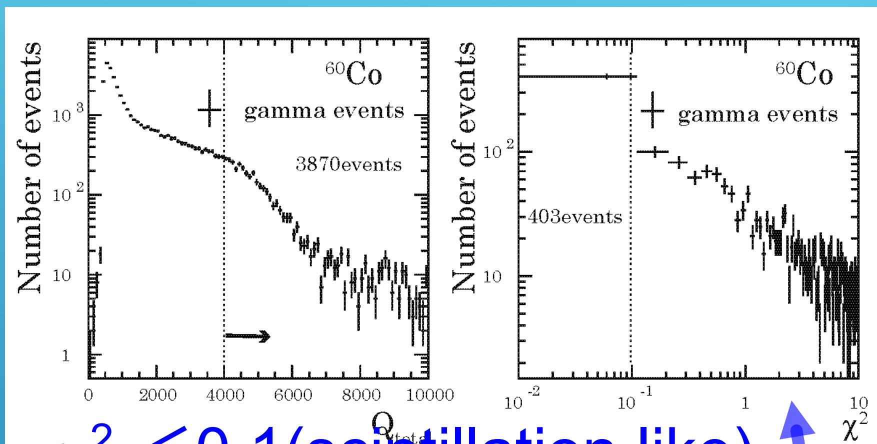
BG events=3evets



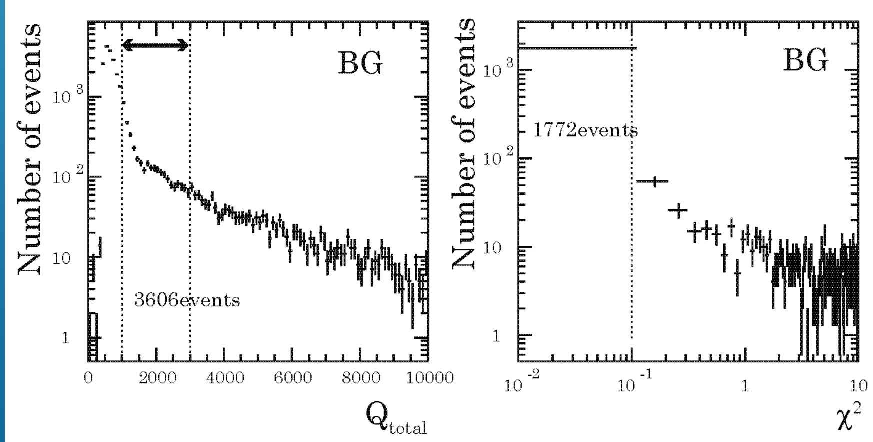
Fixed energy : 835keV
ADC ch~3400cn

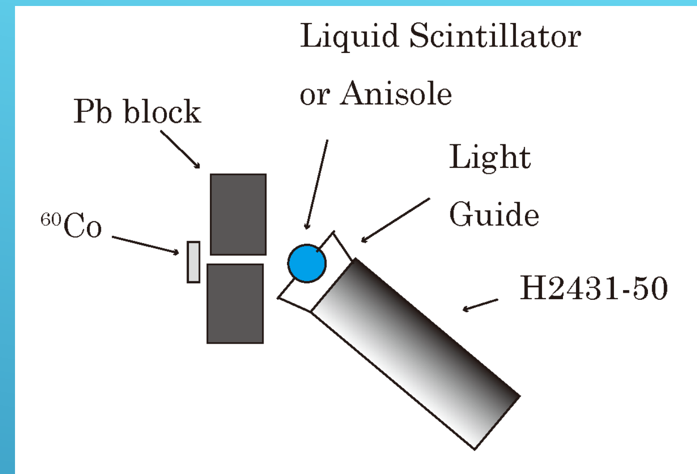
If the events with χ^2>0.1 should have Cherenkov lights, is this inefficiency 21.4±9.6% correct?

Measured by Compton edge event and BG sample



$\chi^2 < 0.1$(scintillation like)
403/3970 = 10.4±0.5% for
Compton edge event



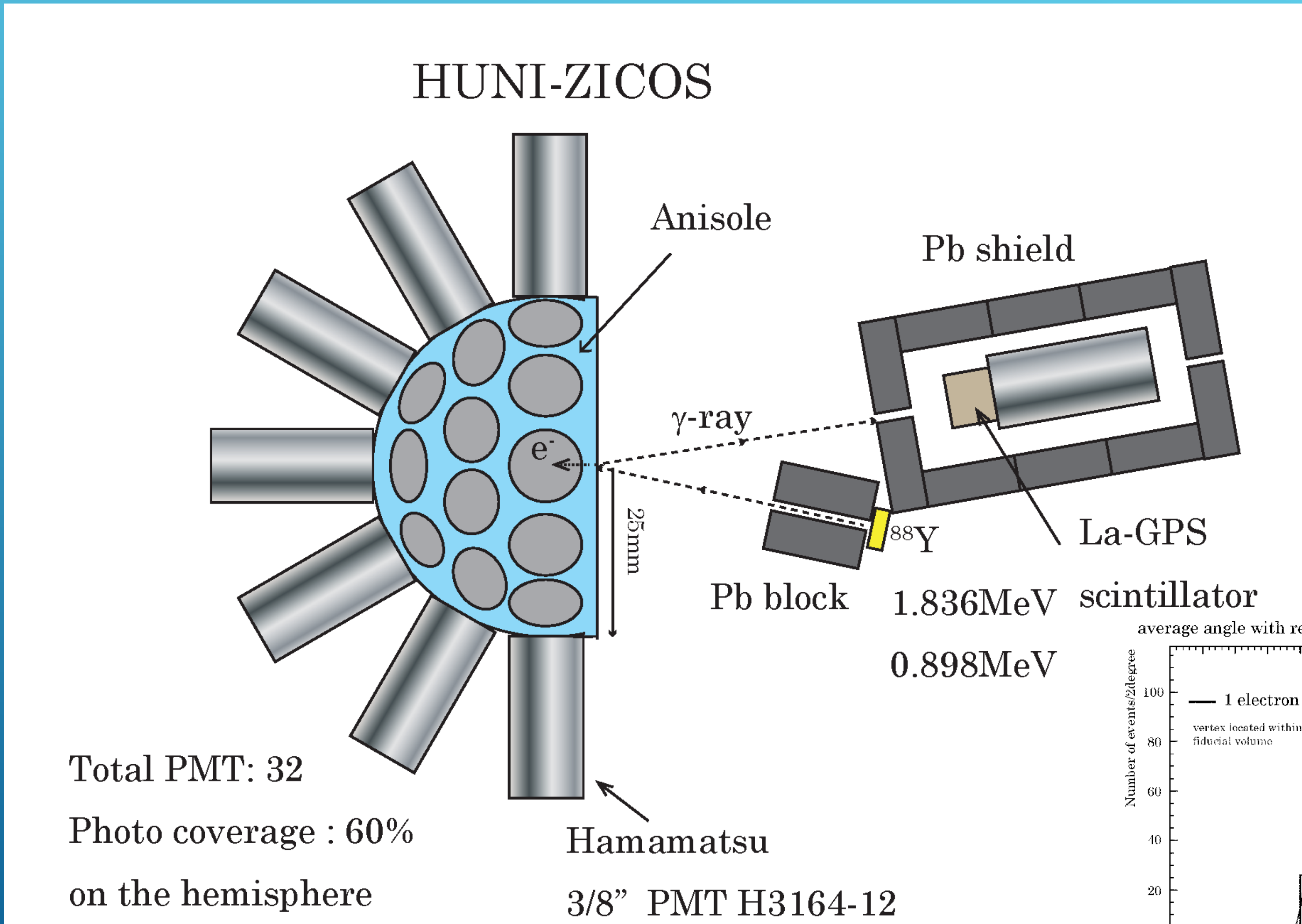


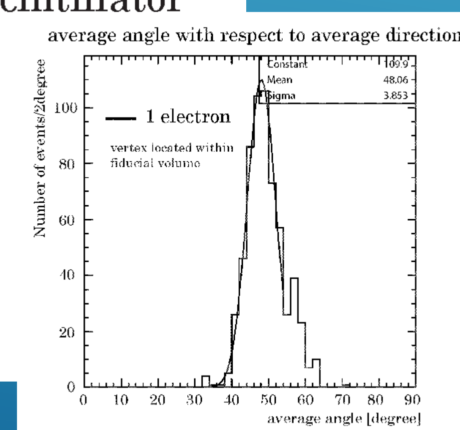
1772/3606=49.1±1.4% for BG sample

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

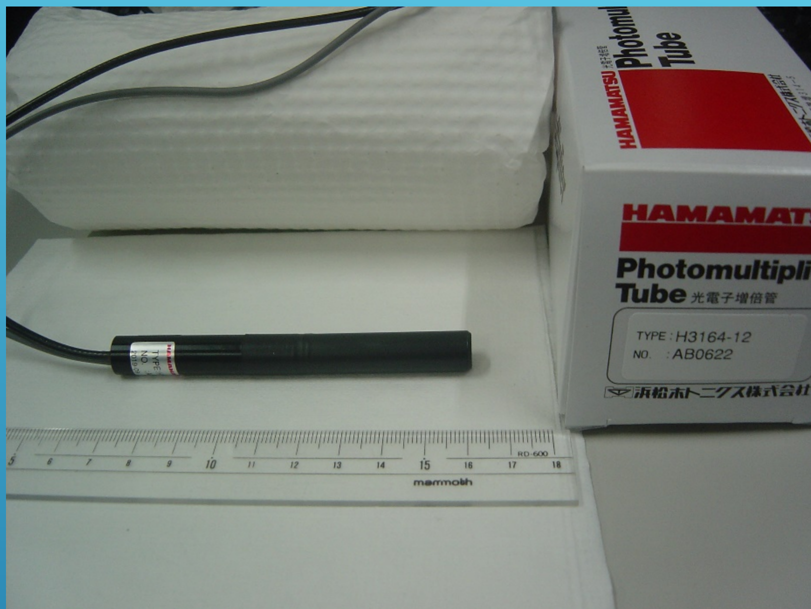
Topology of Cherenkov lights for O(1)MeV e$^-$ was confirmed.

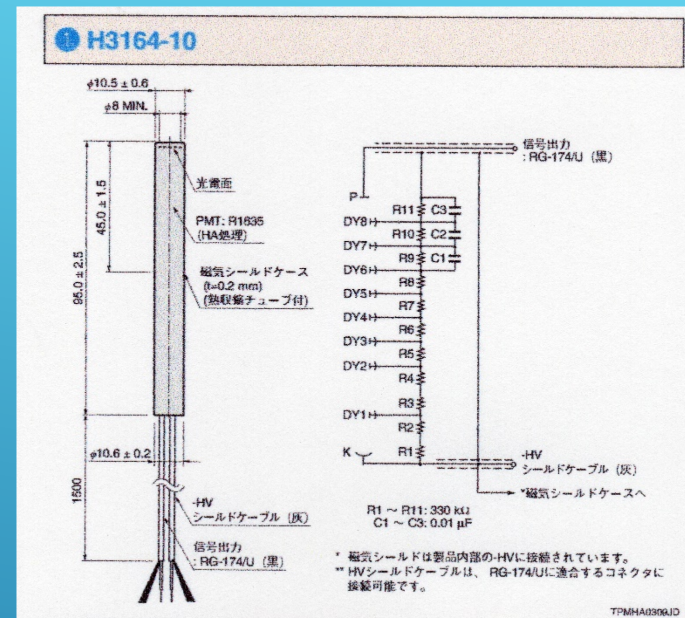
Measurement of topological information (averaged angle) using HUNI-ZICOS





3/8” photomultiplier H3164-12(R1635)



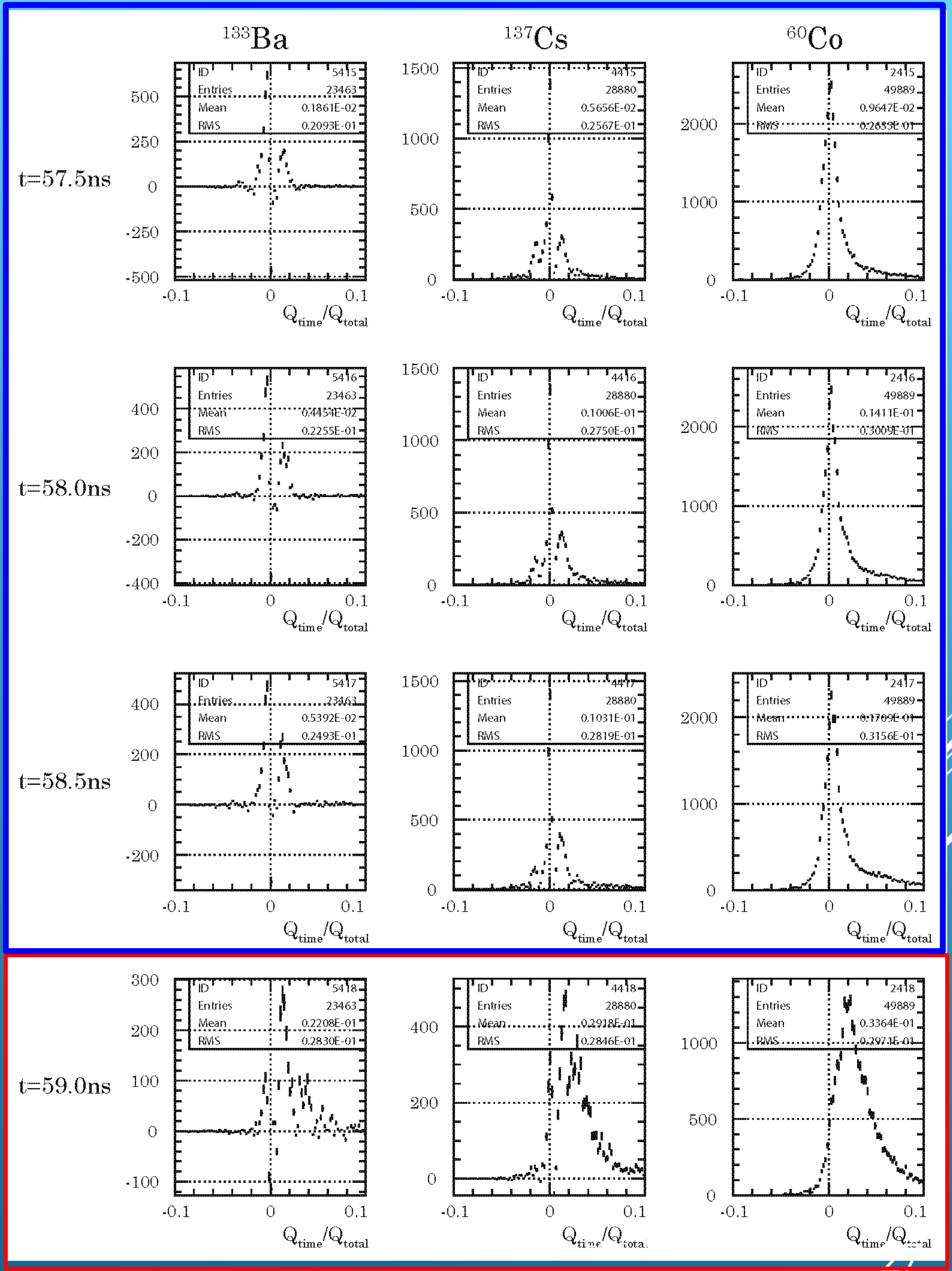


- Sensitivity：400K
- Dynode type : Line focus/8dynode
- Applied voltage：1250V
- Gain：1.0×10^6 Dark current: 50nA
- Time characteristics：0.5ns(TTS) 0.8ns（rise time）

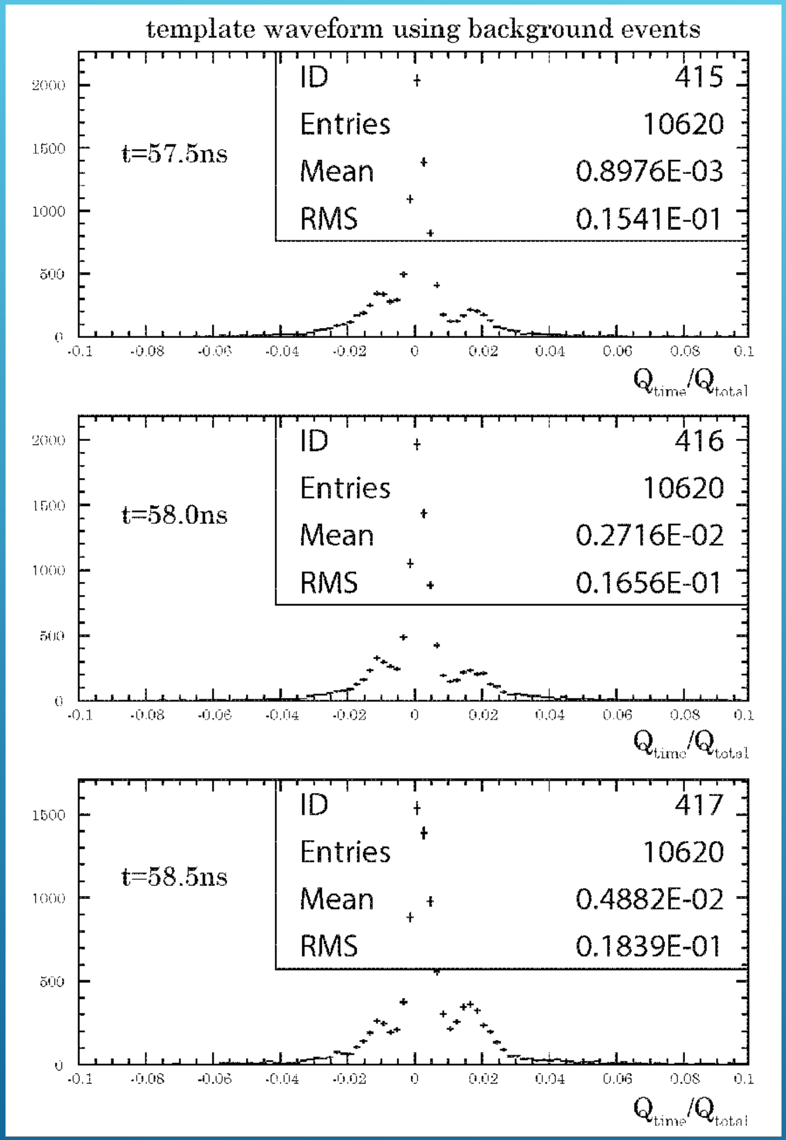
Pulse shape measurement by H3164-12

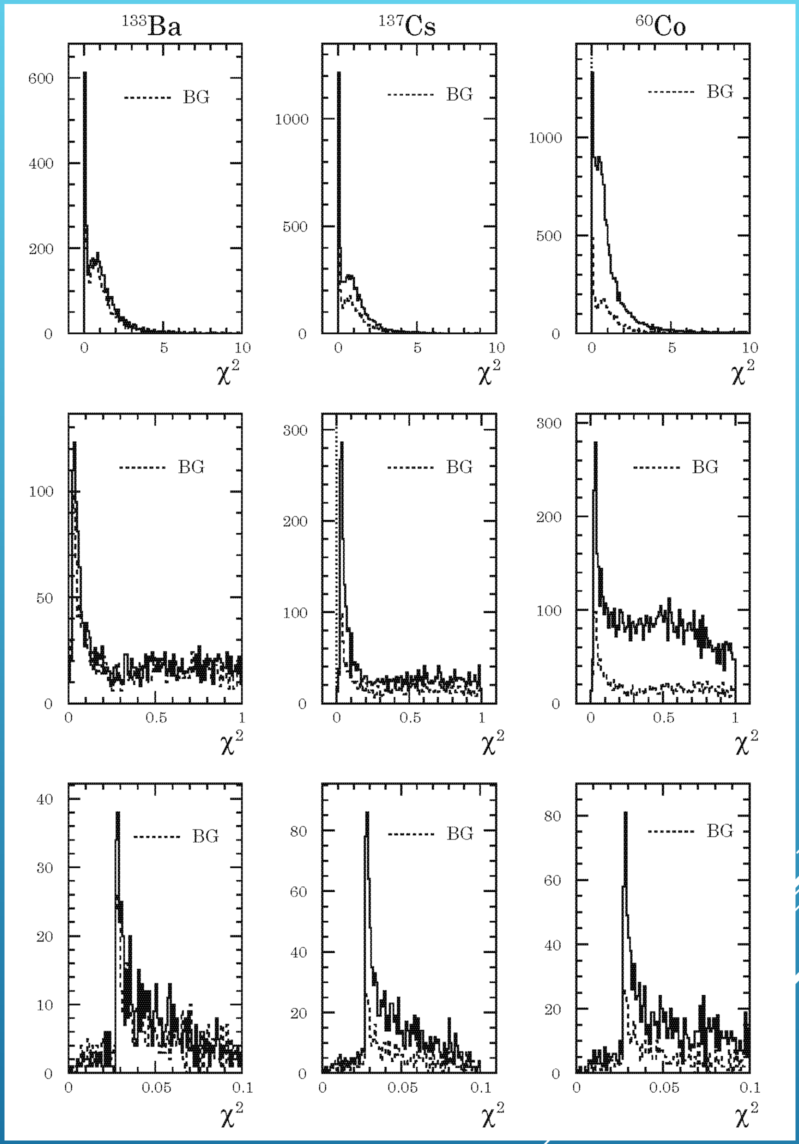
Cherenkov dominant

Scintillation dominant



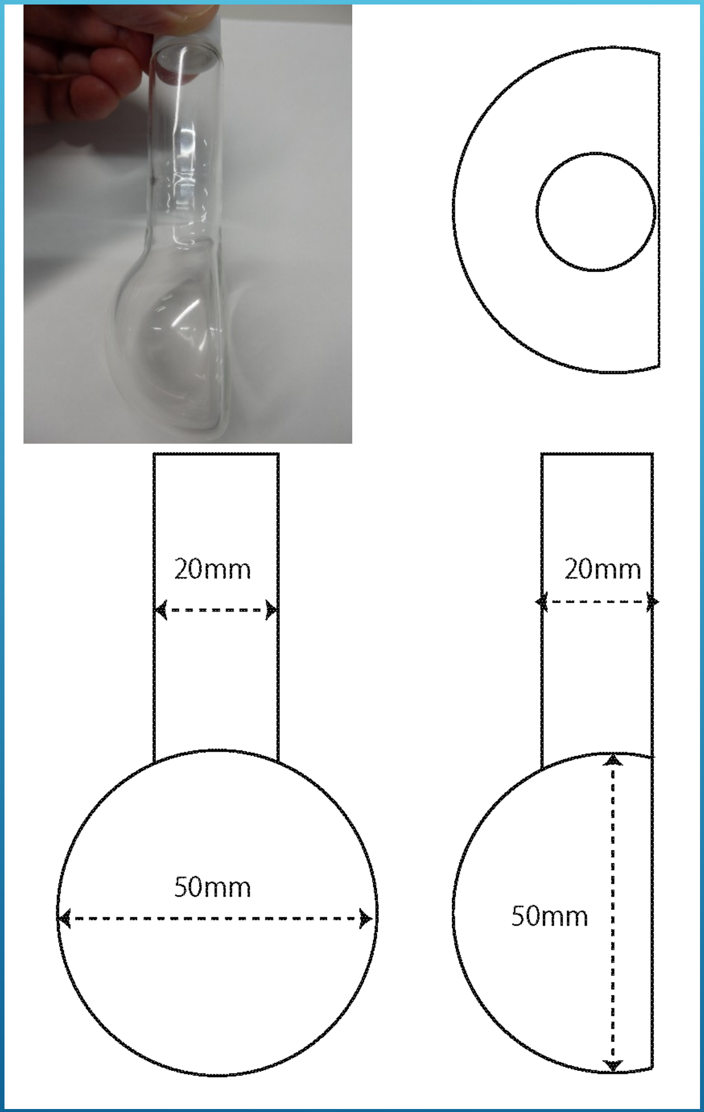
Pulse Shape Discrimination using H3164-12

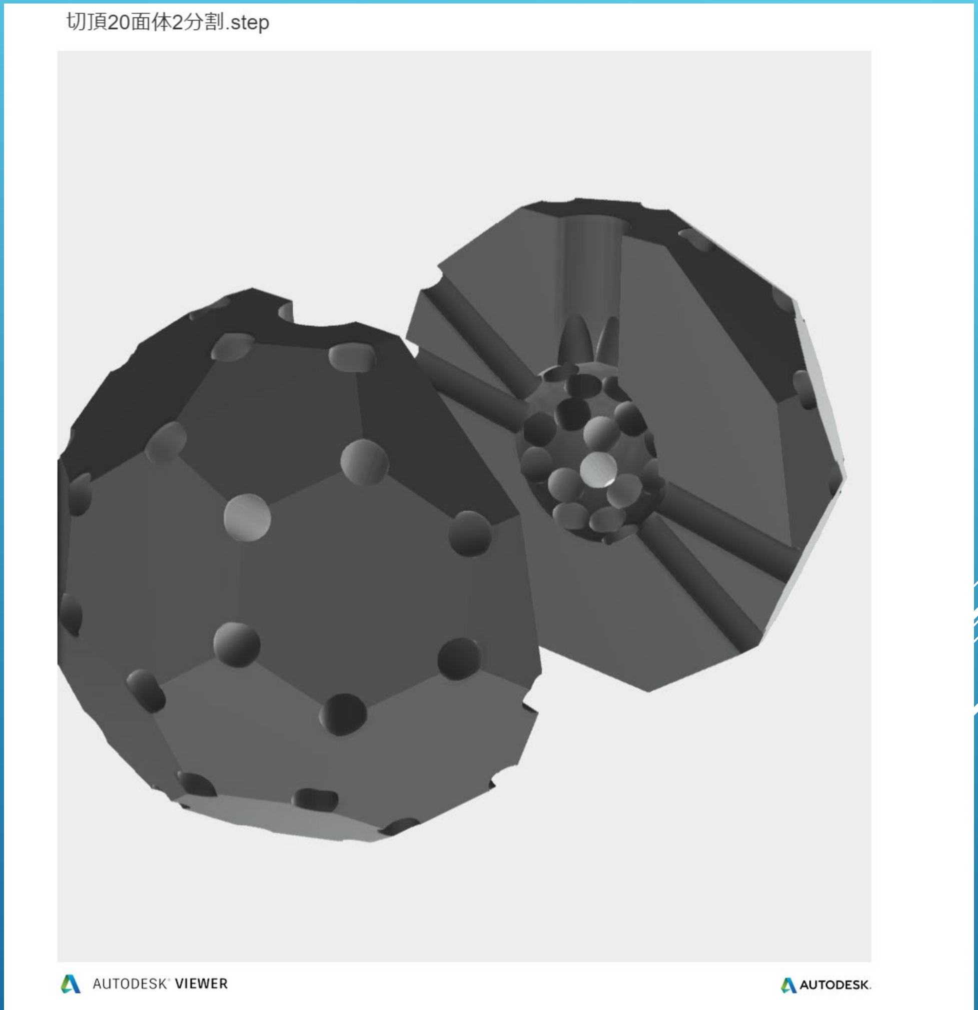




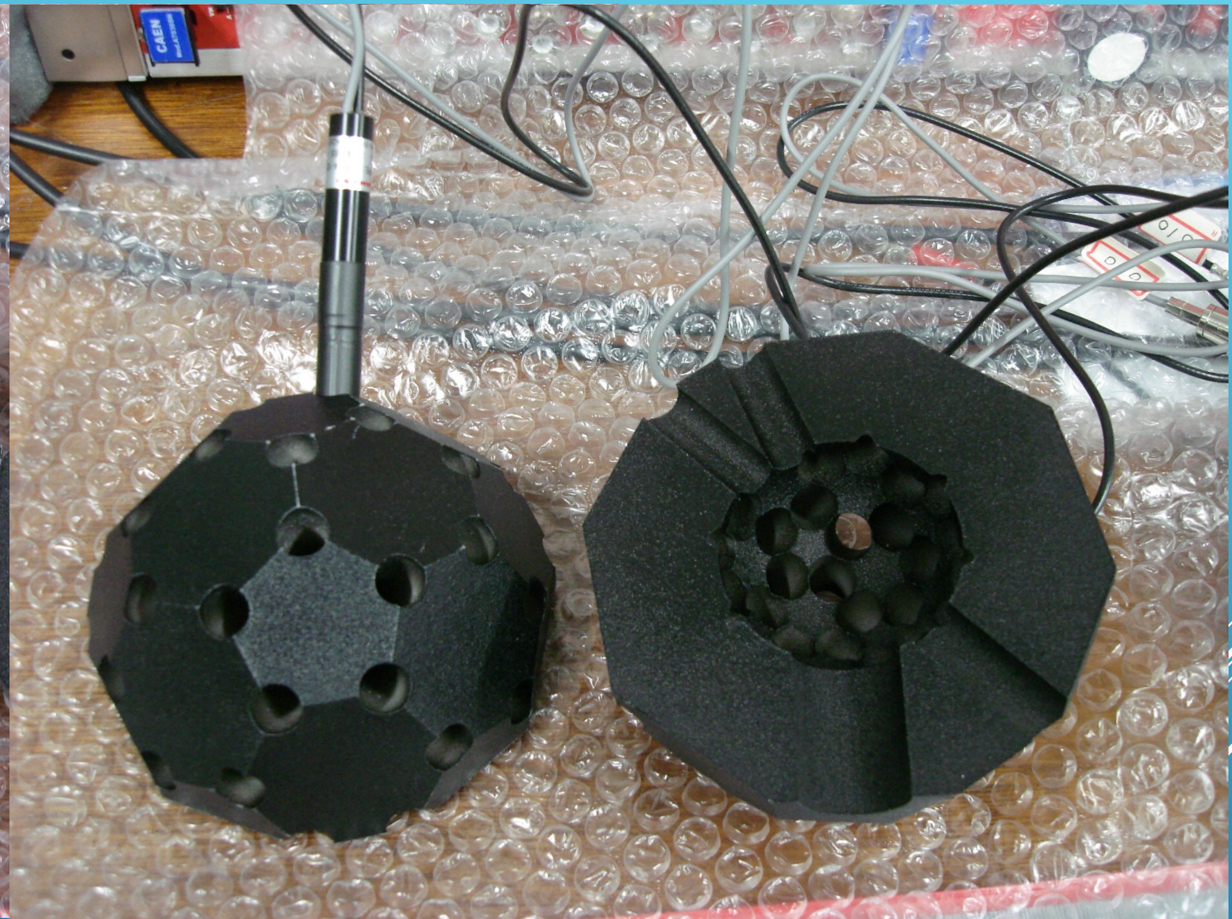
It's possible but need tuning.

Hemisphere flask and PMT fixing jig for HUNI-ZICOS





Extension sharpening for hemisphere flask and PMT



- Extension sharpening for hemisphere flask was almost done.
- Some extensions for PMT hole should be necessary.

Flash ADC V1742 and PMT HV system

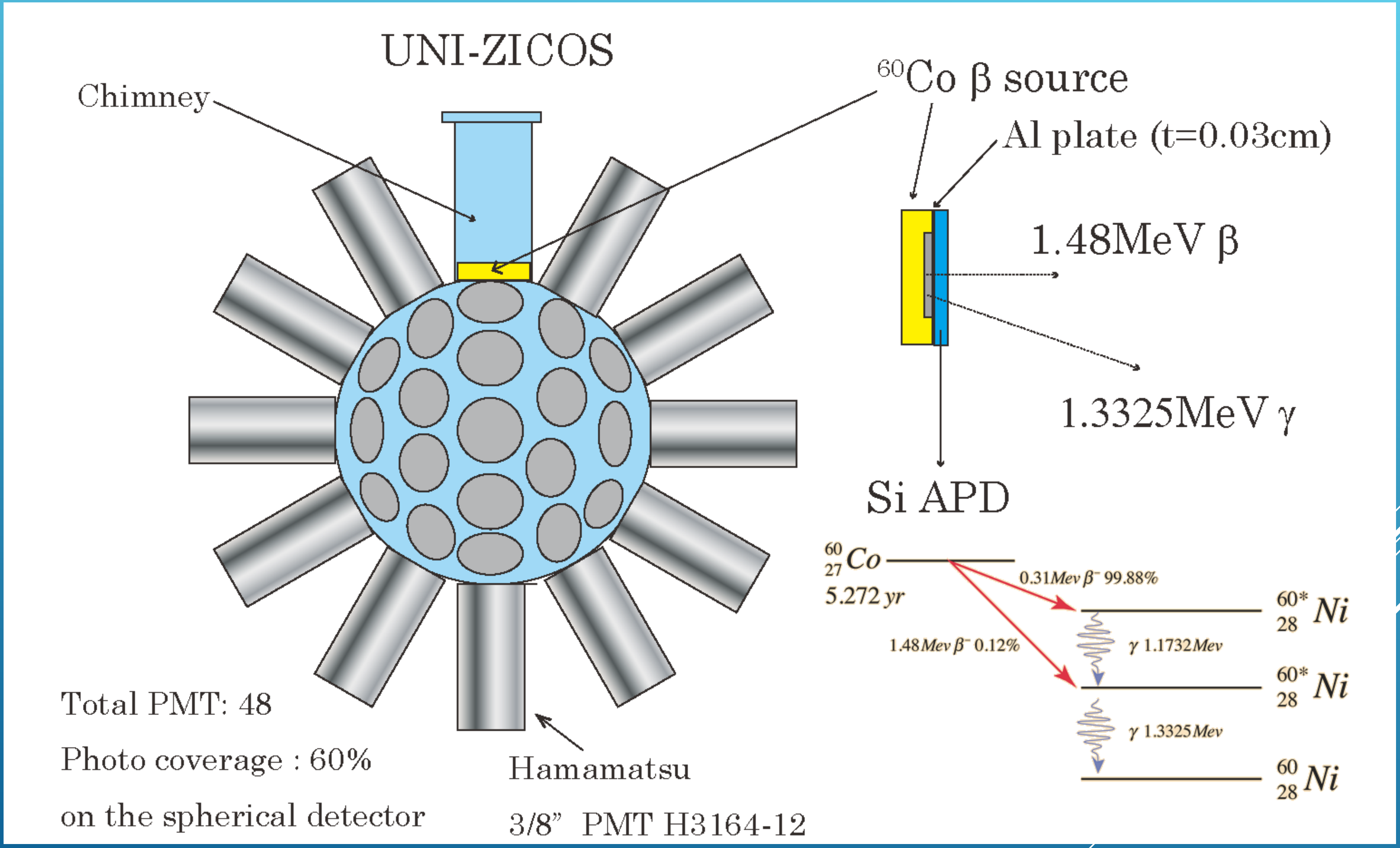
Both CAEN HV AG7030SN and FADC V1742 32ch (5Gs/s!) were checked and ready for the measurement.

Summary

- High Zr concentrated liquid scintillator is available.
- Expected energy resolution 2.2%@3.35MeV&20% 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 Verification of βγ events reduction using topological information : UNI-ZICOS will start in next fiscal year.

Verification of ^{208}Tl BG reduction

- Direct measurement using βγ events by UNI-ZICOS



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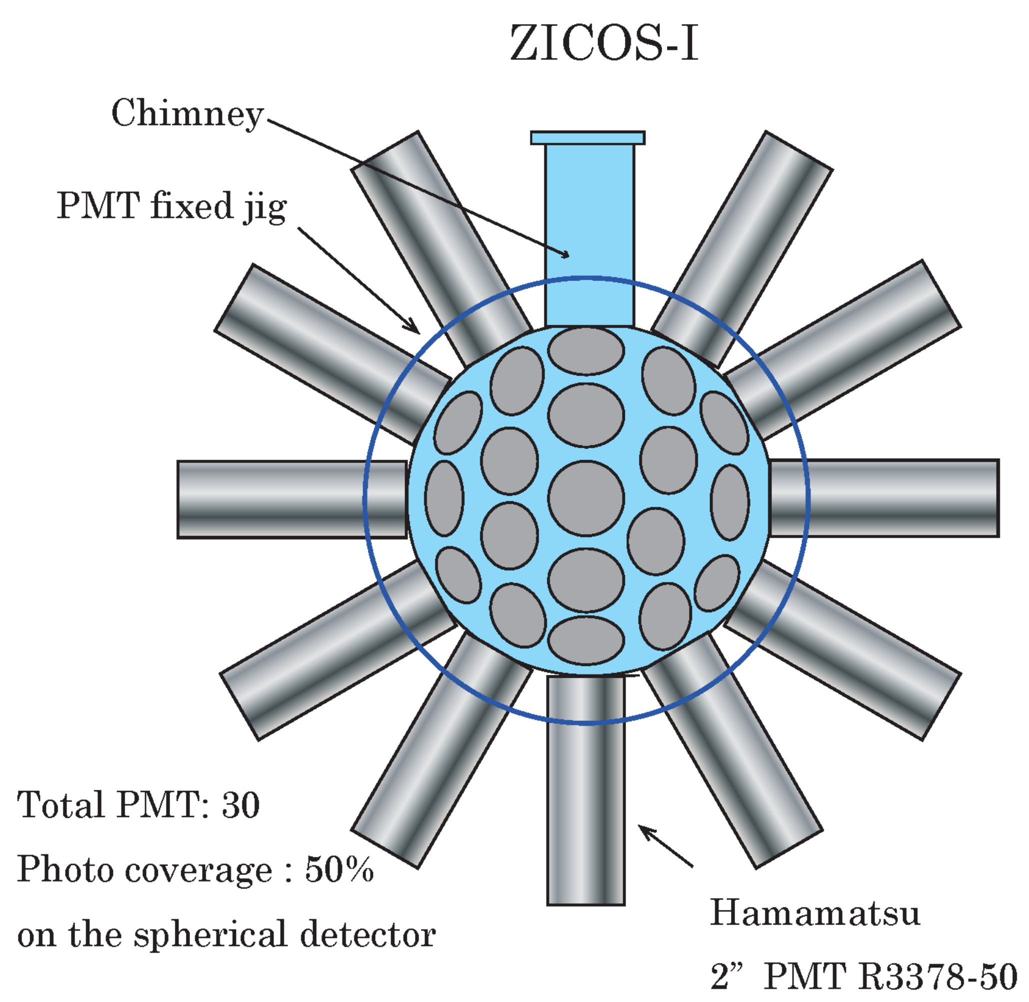
Measurement of $T^{2\nu}_{1/2}$ for ^{96}Zr using ZICOS-I

- First physics program to measure $T^{2\nu}_{1/2}$ for ^{96}Zr



・20cm diameter flask using Ultra-pure quartz and 30 low BG 2” PMT R3378-50 (R2083)

・Synthesis $Zr(iPrac)_4$ 300g which corresponds to ^{96}Zr isotope1g

・According to NEMO-3 result, expect 200 $2\nu\beta\beta$ events/year

・Location: Kamioka mine

Stay tuned!

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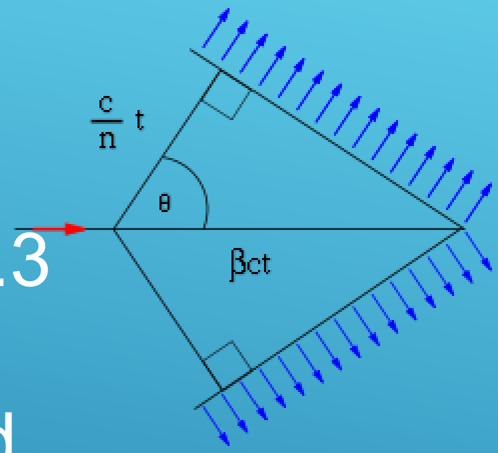
- Physics program (measurement of ^{96}Zr $2\nu\beta\beta$ $T_{1/2}$) with ZICOS-I will start soon and get results within 5 years.
- Future program for $0\nu\beta\beta$ search will start after ZICOS-I with 100g~1kg of ^{96}Zr using ZICOS-II detector. (need enrichment)

Backup slides

Property of Cherenkov light

- Refractive index of anisole : n=1.518
- Cherenkov angle is determined by cosθ= 1/nβ
- Assuming 1.65MeV electron, then β=0.972 and Cherenkov angel θ=47.3 degree are expected.
- Cherenkov light should be measured. (400nm – 600nm : 100 photon/MeV)

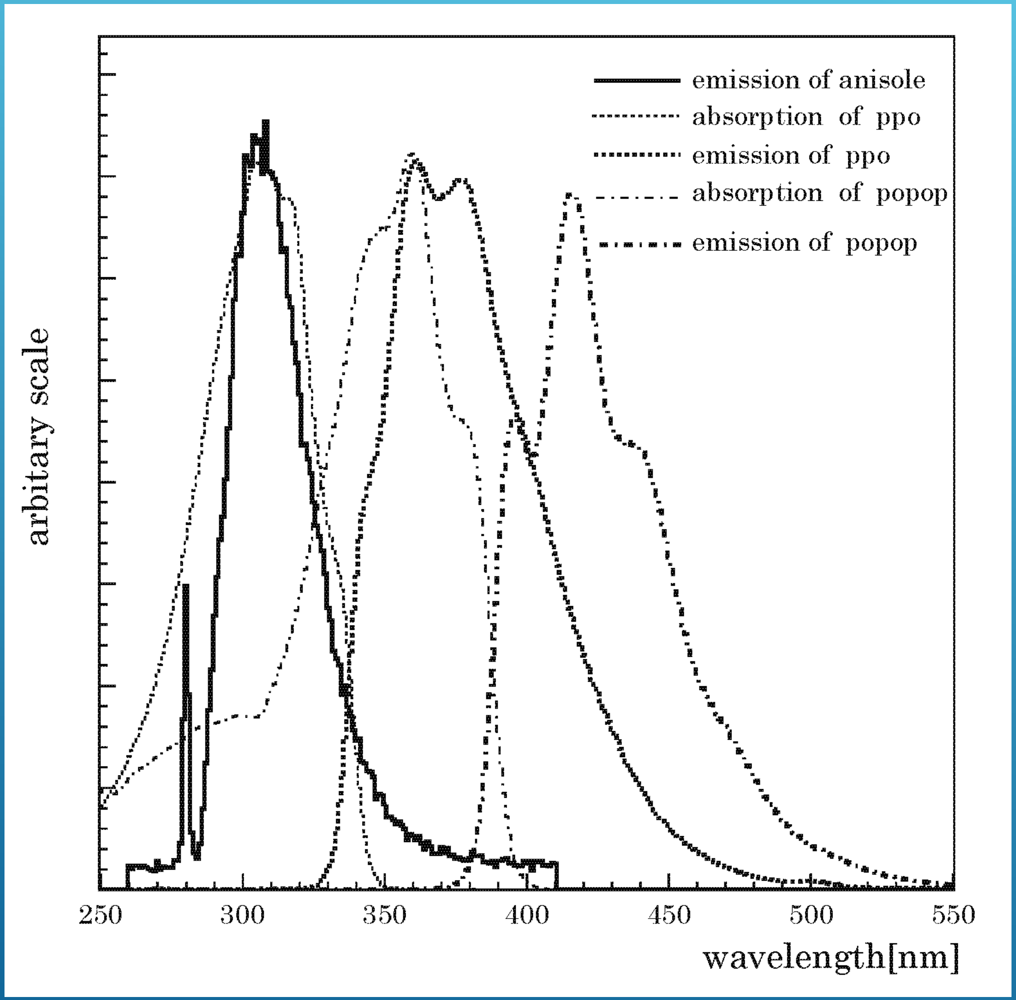


$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2\theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2\theta_c \text{photon}/\text{cm}$$

c.f. Light yield of Scintillation : ~12000photon/MeV

Cherenkov light = 1~2% of scintillation light

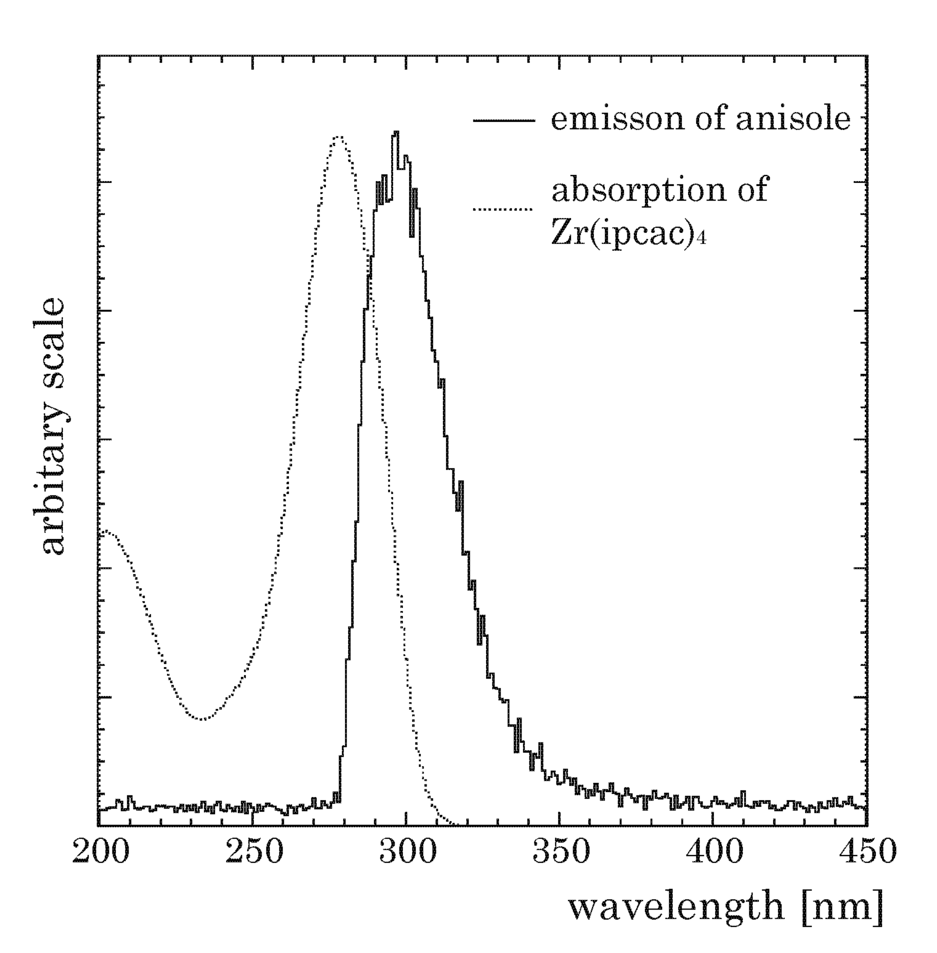
Emission and absorption spectra for solvent and solute in standard cocktail



PPO absorbed most of emission lights from anisole.

Effectively the energy was transferred to the secondary scintillator.

Absorbance spectra for Zr(iprac)$_4$



Absorption peaks of Zr(iprac)$_4$ was found around at 278nm. However, overlapped region with emission of anisole was existed.

Zr(iprac)$_4$ works as a quencher for the liquid scintillator system.