ZICOS – NEW PROJECT FOR NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENT USING ZIRCONIUM COMPLEX IN ORGANIC LIQUID SCINTILLATOR –

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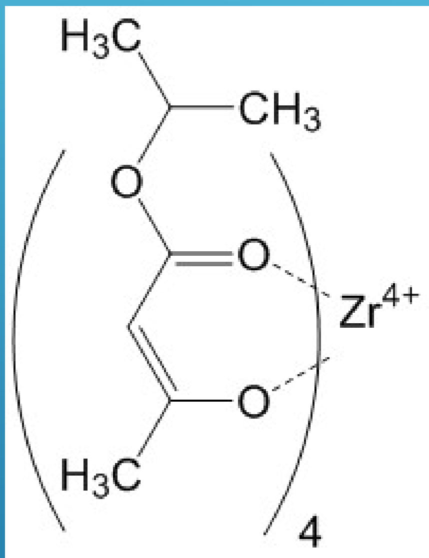
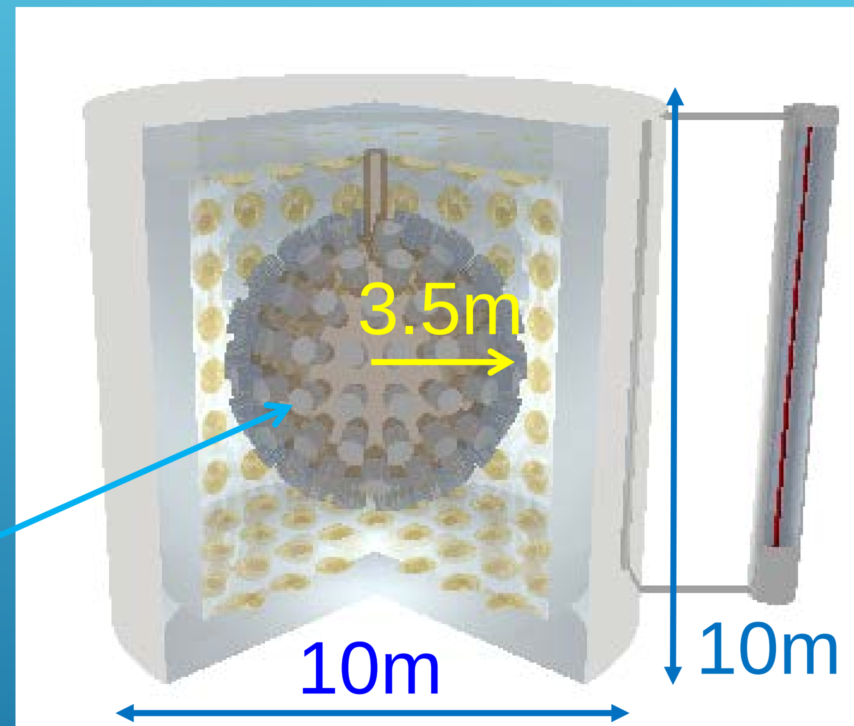
ZICOS- Zirconium Complex in Organic Liquid Scintillator for neutrinoless double beta decay



Tetrakis(iso-propyl acetoacetate) zirconium : $Zr(iprac)_4$

MW : 663.87

LS: Zr(iprac)4 10wt.% and PPO 5 wt.% solved in anisole.



Estimated energy resolution ~2.8%@3.35MeV assuming 64% photo coverage.

Neutrino mass sensitivity of ZICOS experiment

Total mass : 180ton (fiducial volume : 113ton)
Measurement time: 2years
10wt.% $Zr(iprac)_4$ = 12.6ton includes 1.7ton of
Zirconium = 45 kg of ^{96}Zr **(natural abundance 2.6%)**

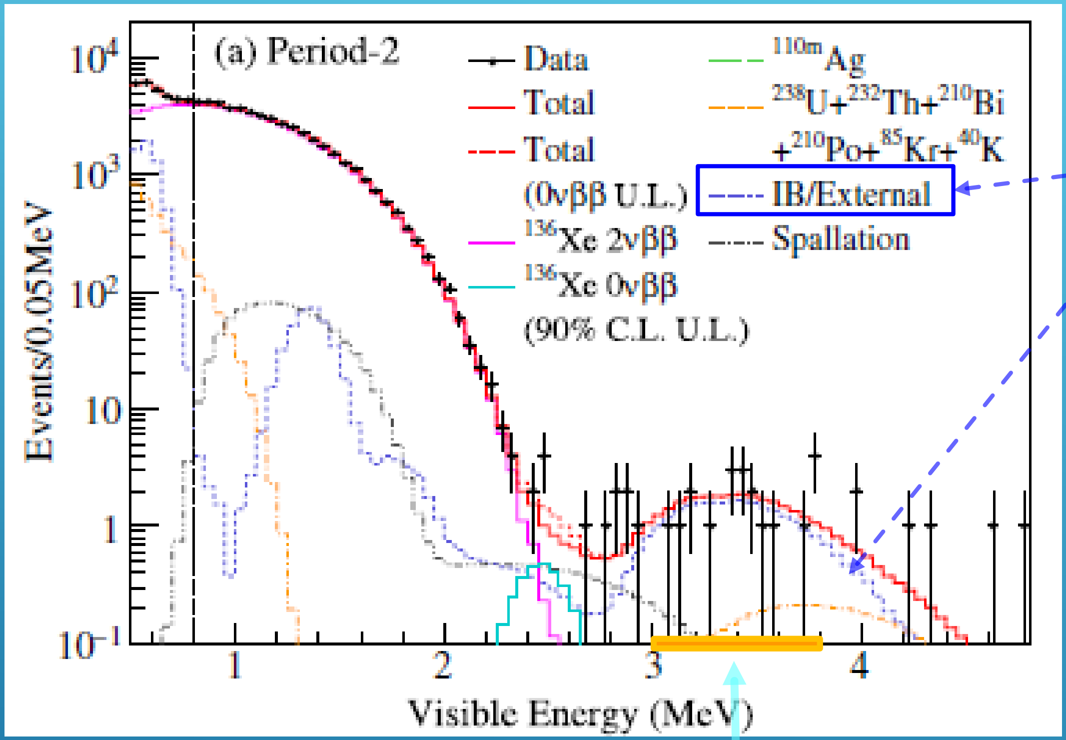
$T_{1/2}^{0\nu} > 4 \times 10^{25}$y ← Not enough for $0\nu\beta\beta$ search

1) Zr enrichment
50% enrichment of ^{96}Zr (e.g. 57.3% for NEMO-3)
^{96}Zr will be 865kg then $T_{1/2}^{0\nu} > \sim 2 \times 10^{26}$y

2) BG (^{208}Tl) reduction
BG level < 1/20 × KL-Zen
then $T_{1/2}^{0\nu} > \sim 1 \times 10^{27}$y Today's talk

Backgrounds around signal region

Measured by KamLAND-Zen



Phys.Rev.Lett. 117 (2016) 082503

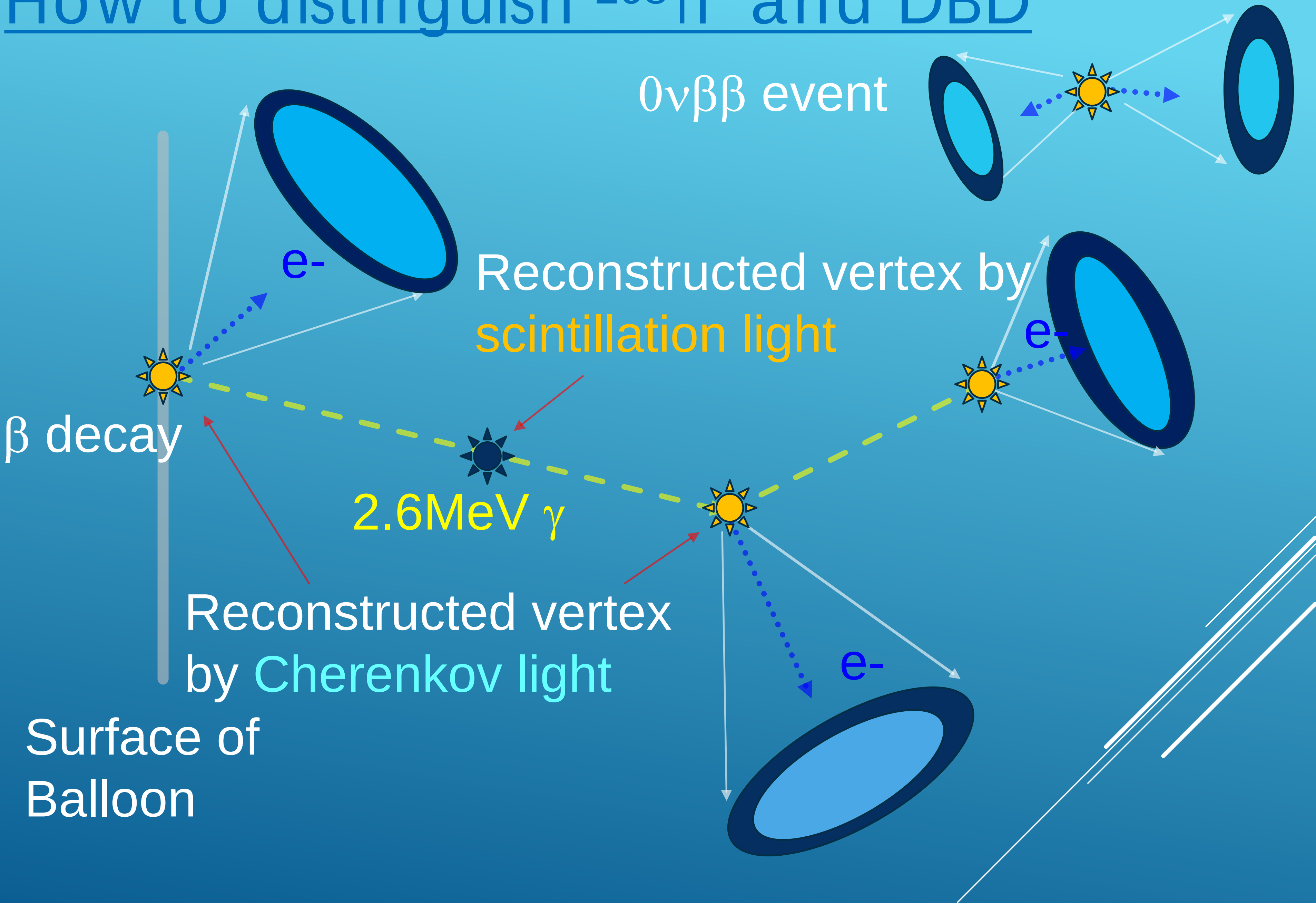
^{208}Tl on surface of balloon

Necessary same clean material as KamLAND-Zen, but … need further BG (^{208}Tl) reduction

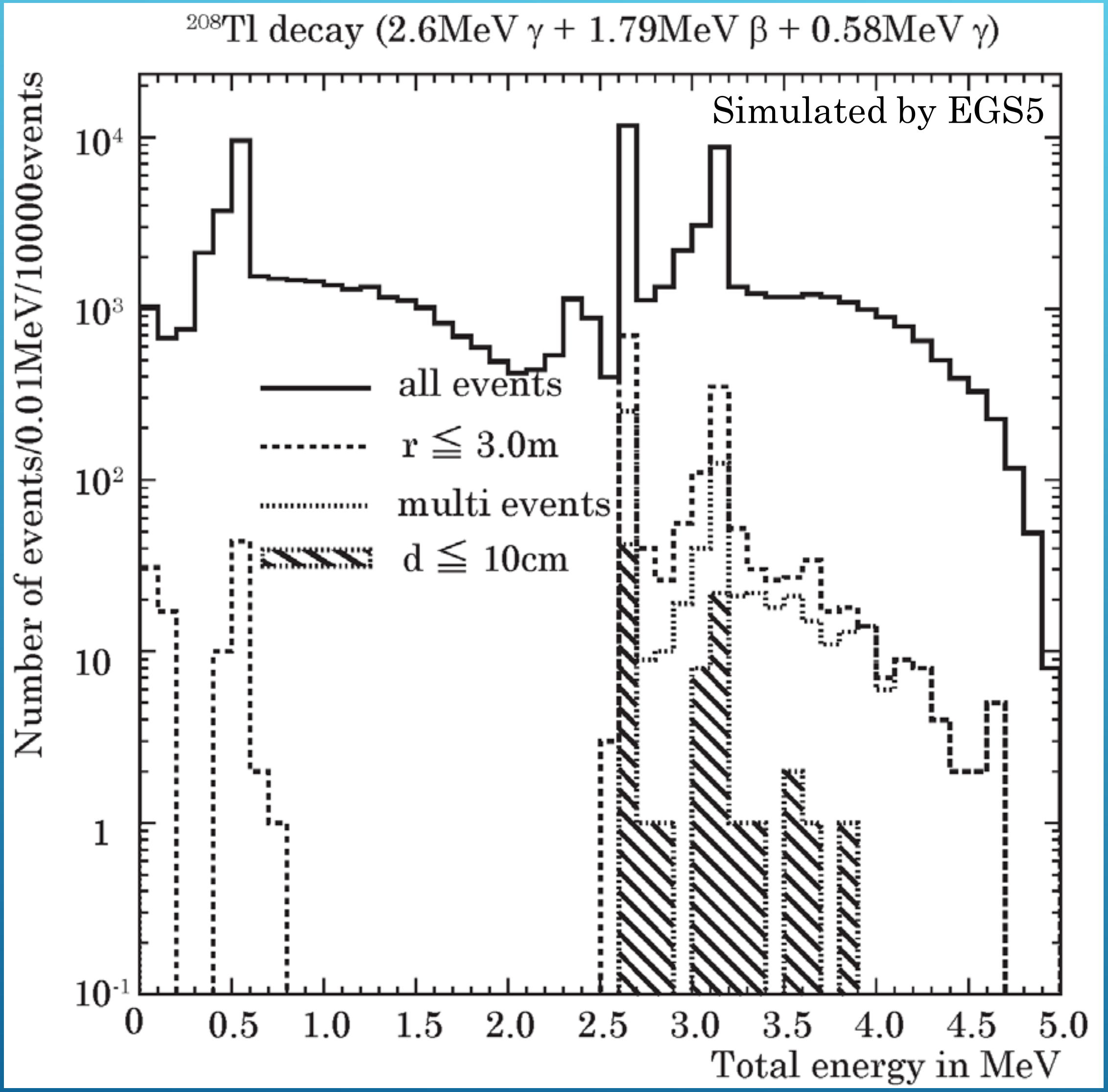
0νββ signal region for ^{96}Zr

Require an additional technique other than the energy spectral shape obtained by scintillation.

How to distinguish ^{208}Tl and DBD



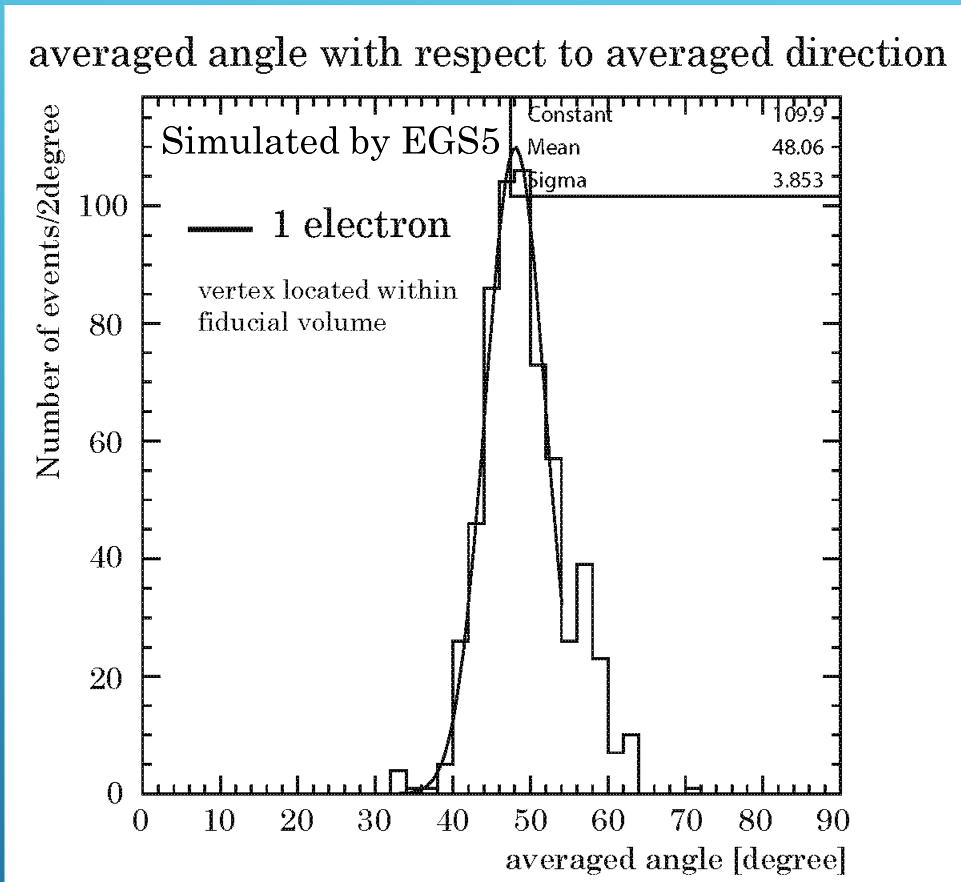
Reduction of ^{208}Tl decay



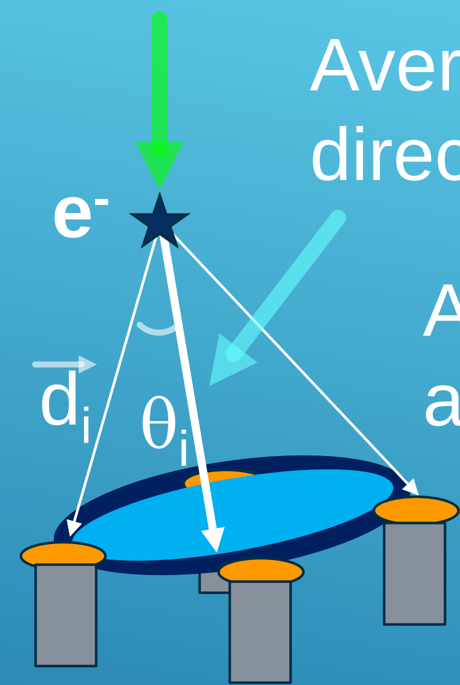
1) E : 3.0-3.7MeV
   17925 events
2) Fiducial volume
   628 events
3) Multi events
   263 events
4) Closer events (d≦10cm)
   35 events

~1/20 BG reduction could be achieved by using the information from Cherenkov light.

Averaged angle of Cherenkov hit



Vertex position obtained by scintillation

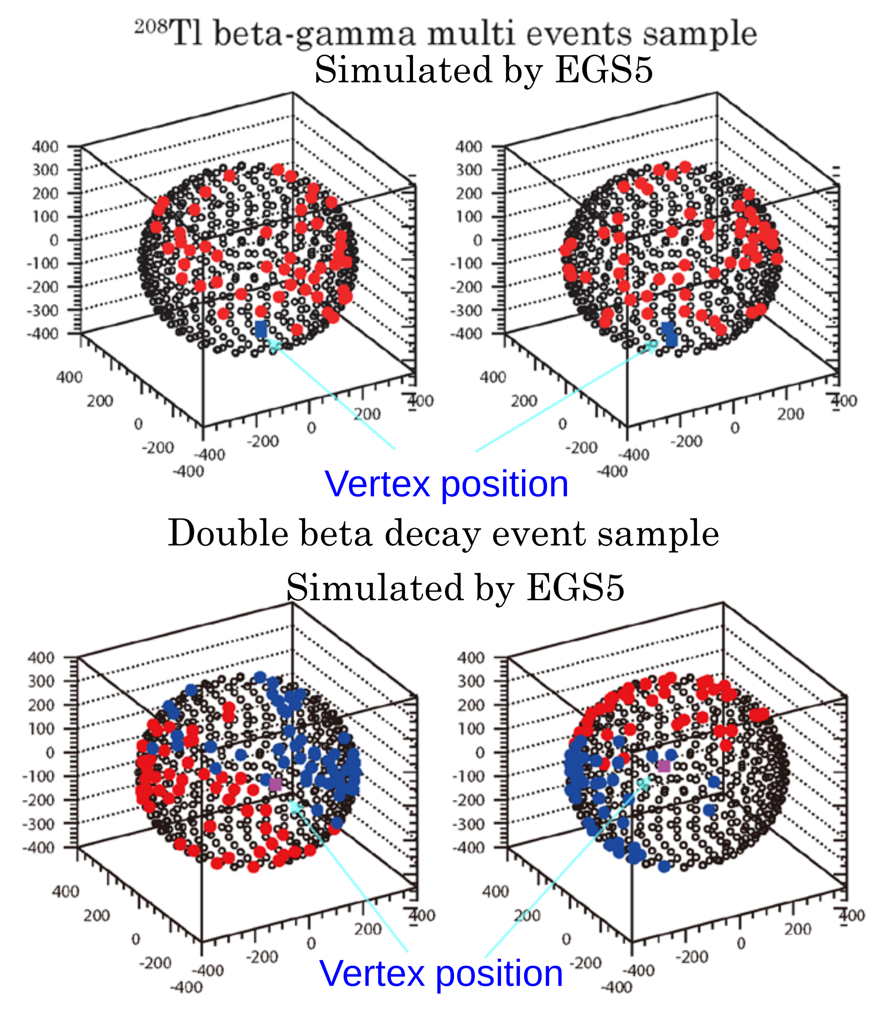


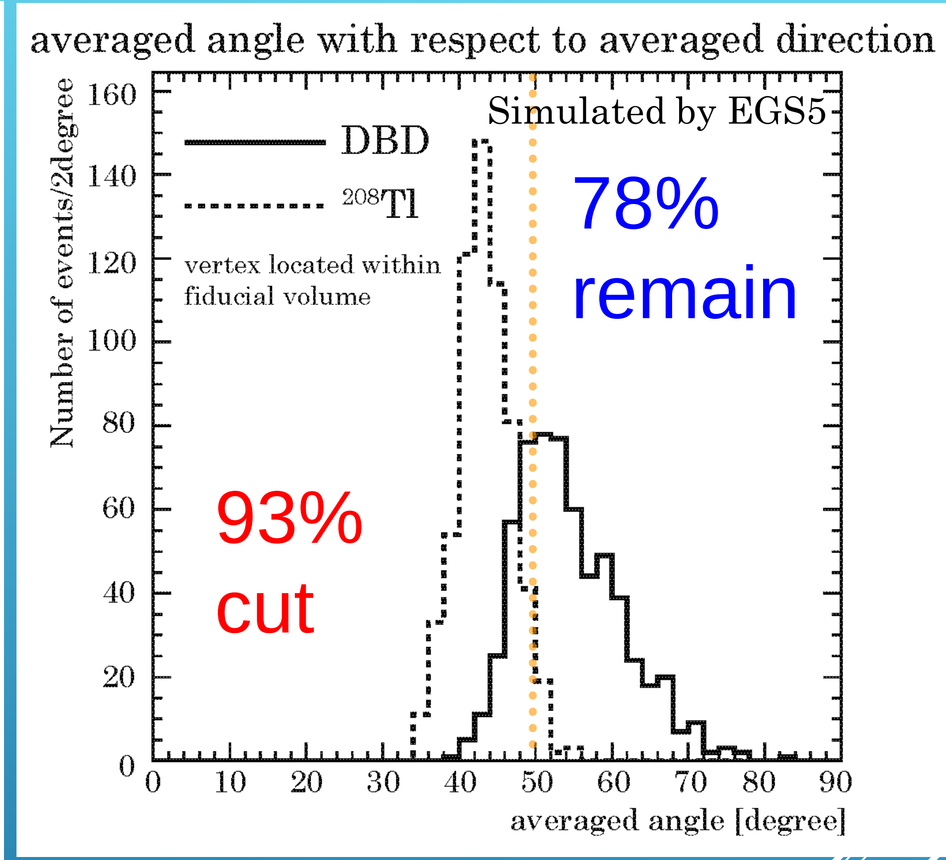
Averaged direction = $\Sigma \vec{d_i}$

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

Averaged angle distribution with respect to averaged direction for single electron has a peak at ~48 degree, which is almost same as Cherenkov angle.

Hit pattern of ^{208}Tl decay and DBD



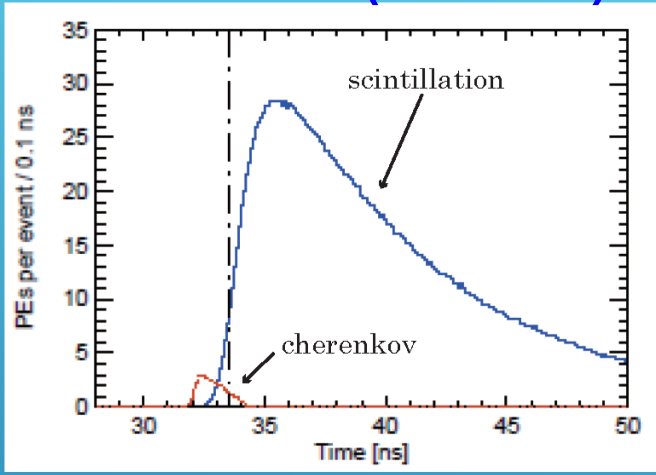


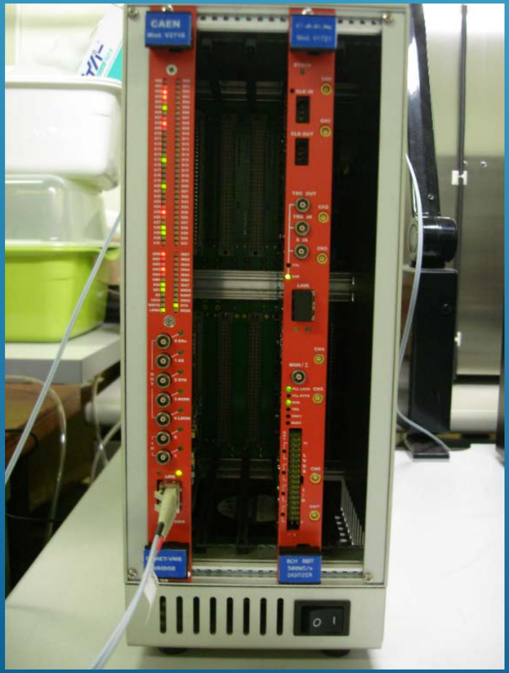
Hit pattern of Cherenkov lights for ^{208}Tl decay looks different from DBD .

Averaged angle of ^{208}Tl decay is smaller values than that of DBD.

Separation of Cherenkov and Scintillation

arXiv:1609.0986(simulation)



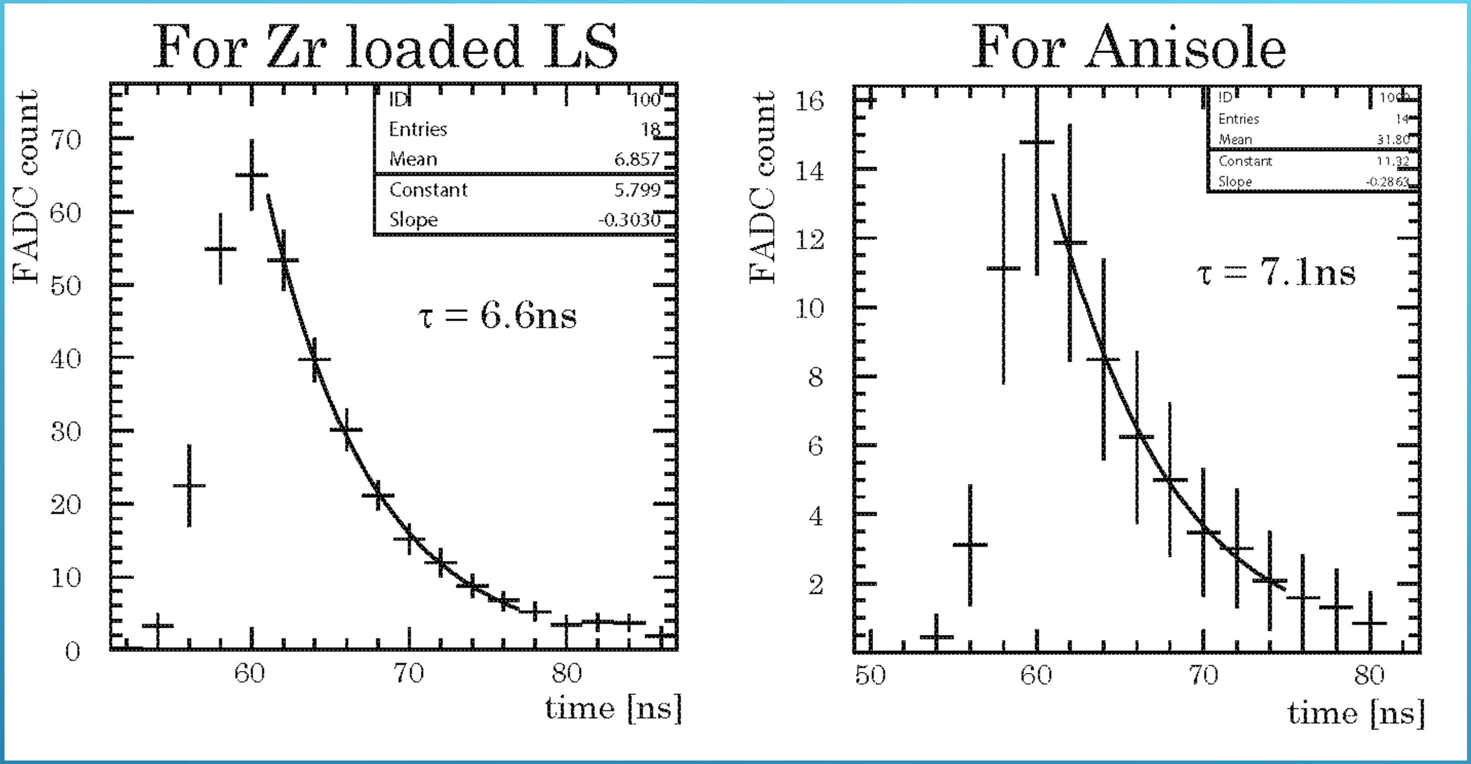


- Rise time of Cherenkov light : an order of a few 100 pico second due to the electro-magnetic process
- Rise time of Scintillation light: an order of nano seconds in general.

Possible to extract PMT hits received Cherenkov lights by Pulse Shape Discrimination.

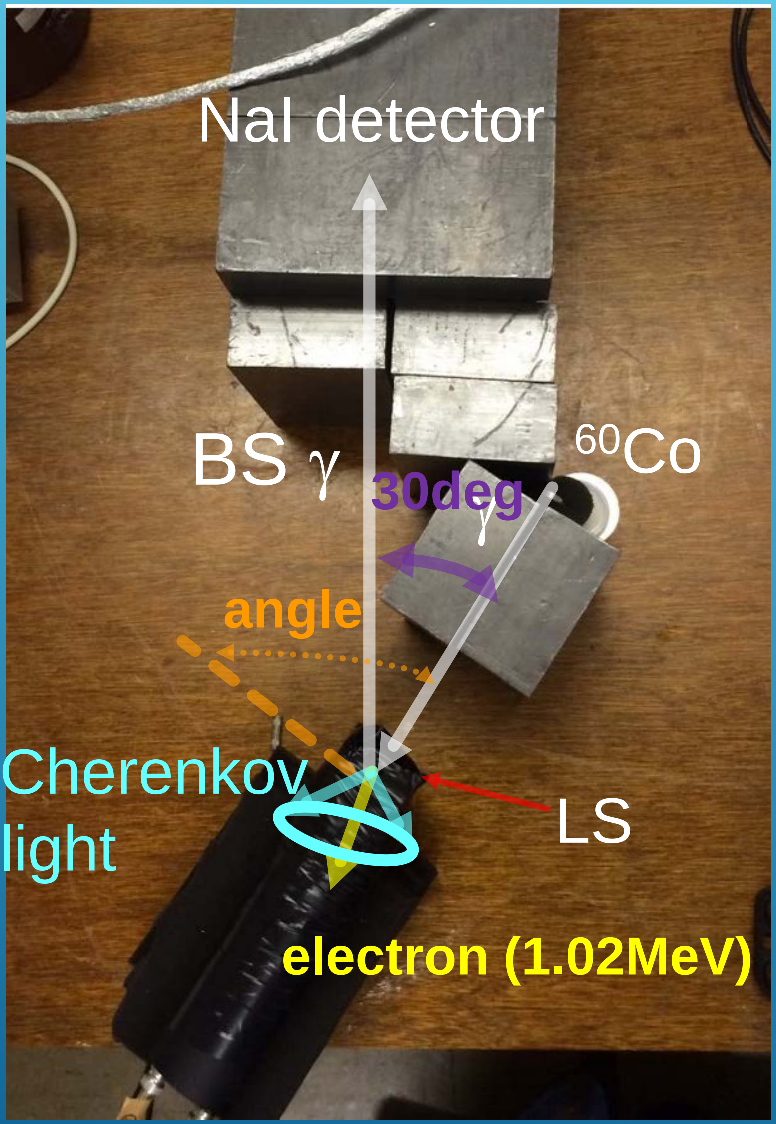
- CAEN V1721 8 channel 8bit 500MS/s FADC
- CAEN V2718 VME-PCI Optical Link Bridge

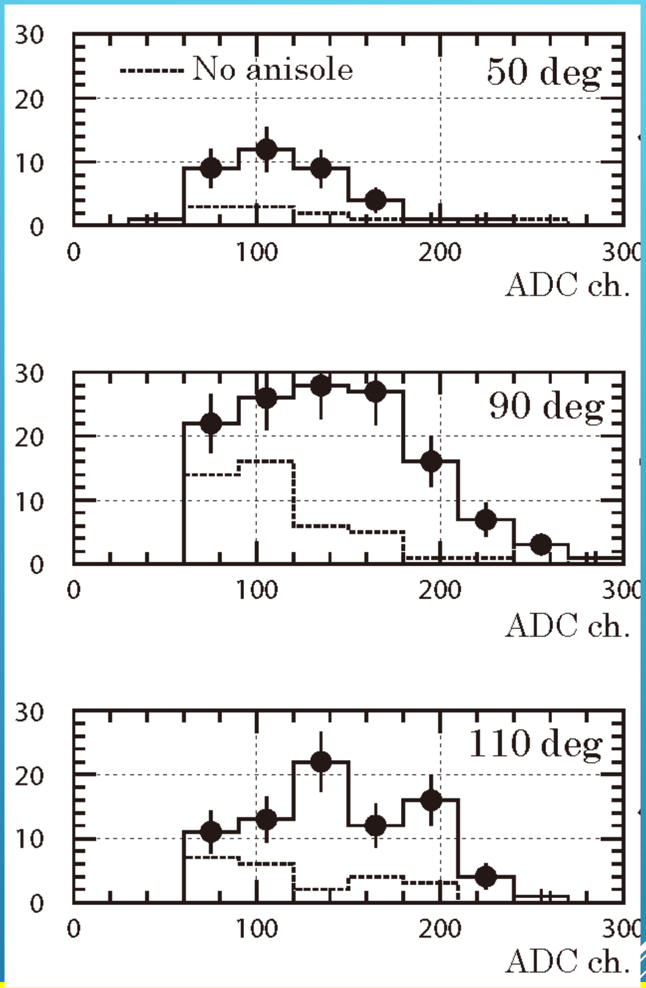
Pulse shape of scintillation light



- Templates of FADC timing pulse shape for scintillation light were obtained for both case.
- Both decay time of scintillation light are same, and it was about 7ns.

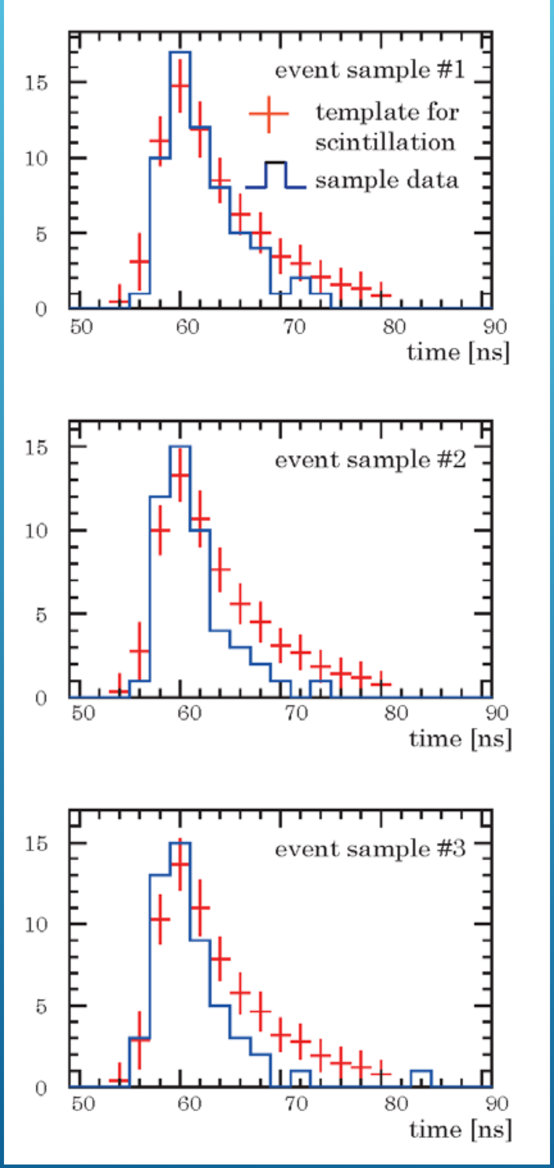
Observation of Cherenkov lights





Cherenkov lights from O(1MeV) electron seem to have a directionality.

Pulse shape observed for Anisole

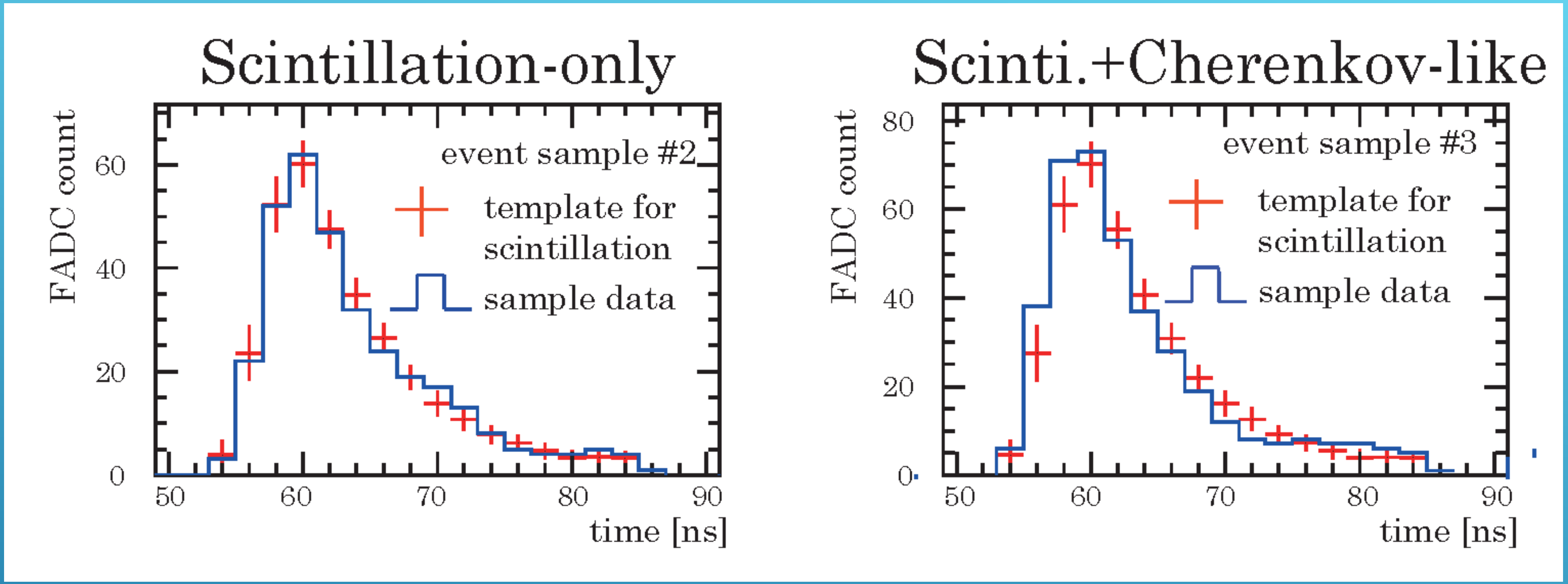


- Most of observed events have a different pulse shape from that of scintillation light.
- It is faster rise time and decay time.

Those events mainly consist of Cherenkov lights, because of low QE for wave length of scintillation light (300nm).

Same pulse shapes were also observed in H_2O.

Pulse shape observed for Zr loaded LS

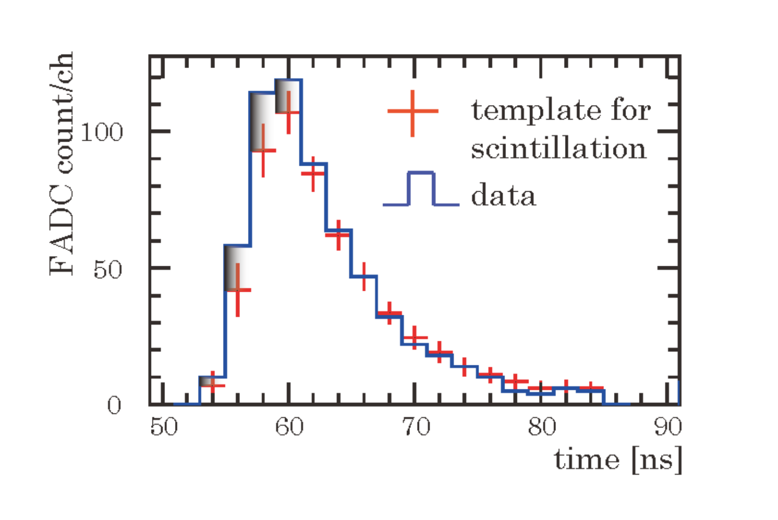


Mainly two types of pulse shape (Scintillation-only and Scinti.+Cherenkov-like) were observed.

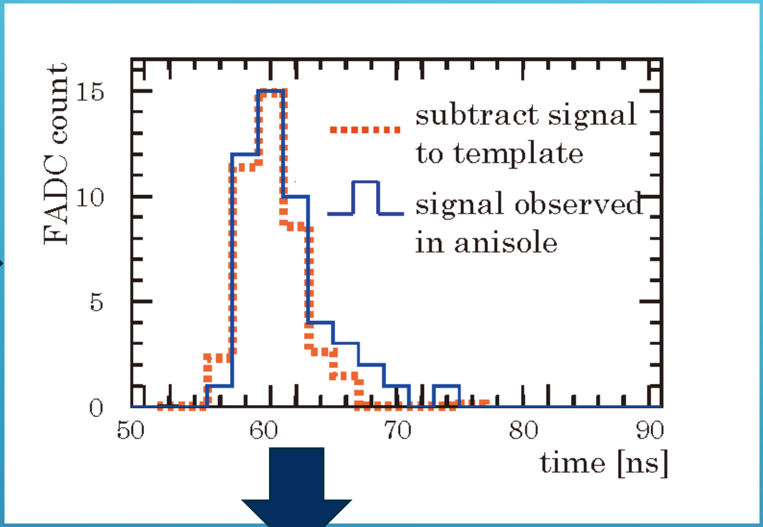
We maybe use pulse shape discrimination for the selection of events which include Cherenkov lights.

Pulse shape discrimination

Typical pulse shape of Scinti.+Cherenkov-like



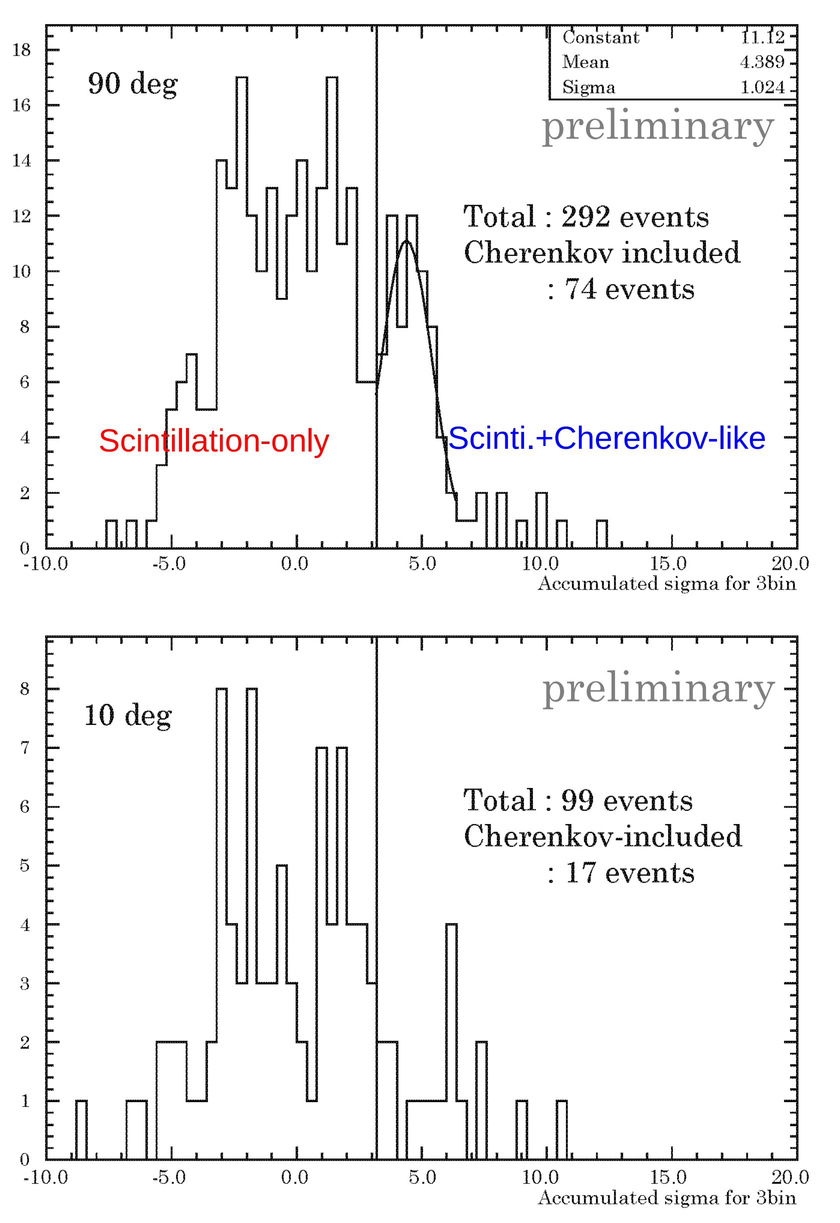
Comparison of excess pulse shape and signal for anisole



Excess pulse shape seems to be consistent with the pulse which was seen in Anisole (see p12).

Excess of sigma between data and template were accumulated for first 3 bins : accumulated sigma

Accumulated sigma distribution



Ratio of Scintillation+Cherenkov

- 90deg 25.3 ± 3.3 %
- 10deg 17.2 ± 4.5 %

Significance : 1.5σ

Scinti.+Cherenkov-like might be discriminated by acc. sig. method… but

The difference of ratio was smaller than expected by Anisole.

There seems to exist some different conditions between anisole and LS.

Summary

- Conceptual design of ZICOS detector (10 wt.% $Zr(iprac)_4$ loaded Liquid Scintillator has 2.8% @3.35MeV energy resolution assuming 64% photo coverage of 20” PMT) for next generation DBD experiment.($T_{1/2}(0\nu\beta\beta) > 10^{27}$years).
  - ^{96}Zr : 45kg (nat.) ➡ 865kg(50% enrich)
  - Further 1/20 reduction of ^{208}Tl backgrounds using PMT hit pattern of Cherenkov lights.
- PSD could be useful for the extraction of Cherenkov lights, however still need to study for confirmation.
- If PSD works, then BG reduction using PSD should be checked by prototype for next step.

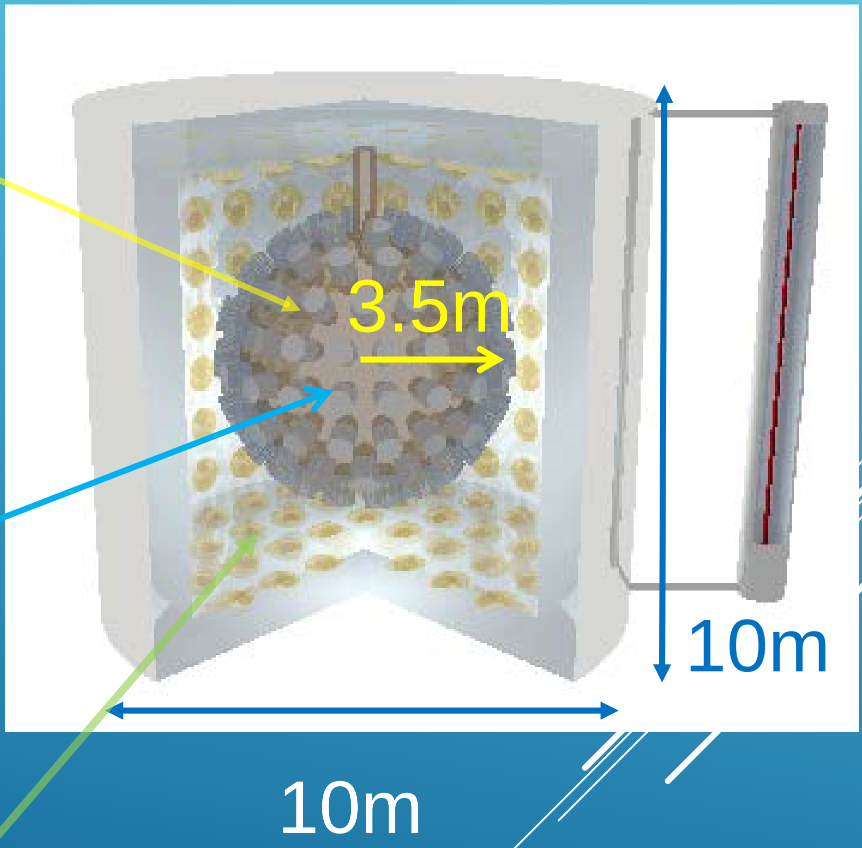
BACKUP

ZICOS- Zirconium Complex in Organic Liquid Scintillator for neutrinoless double beta decay

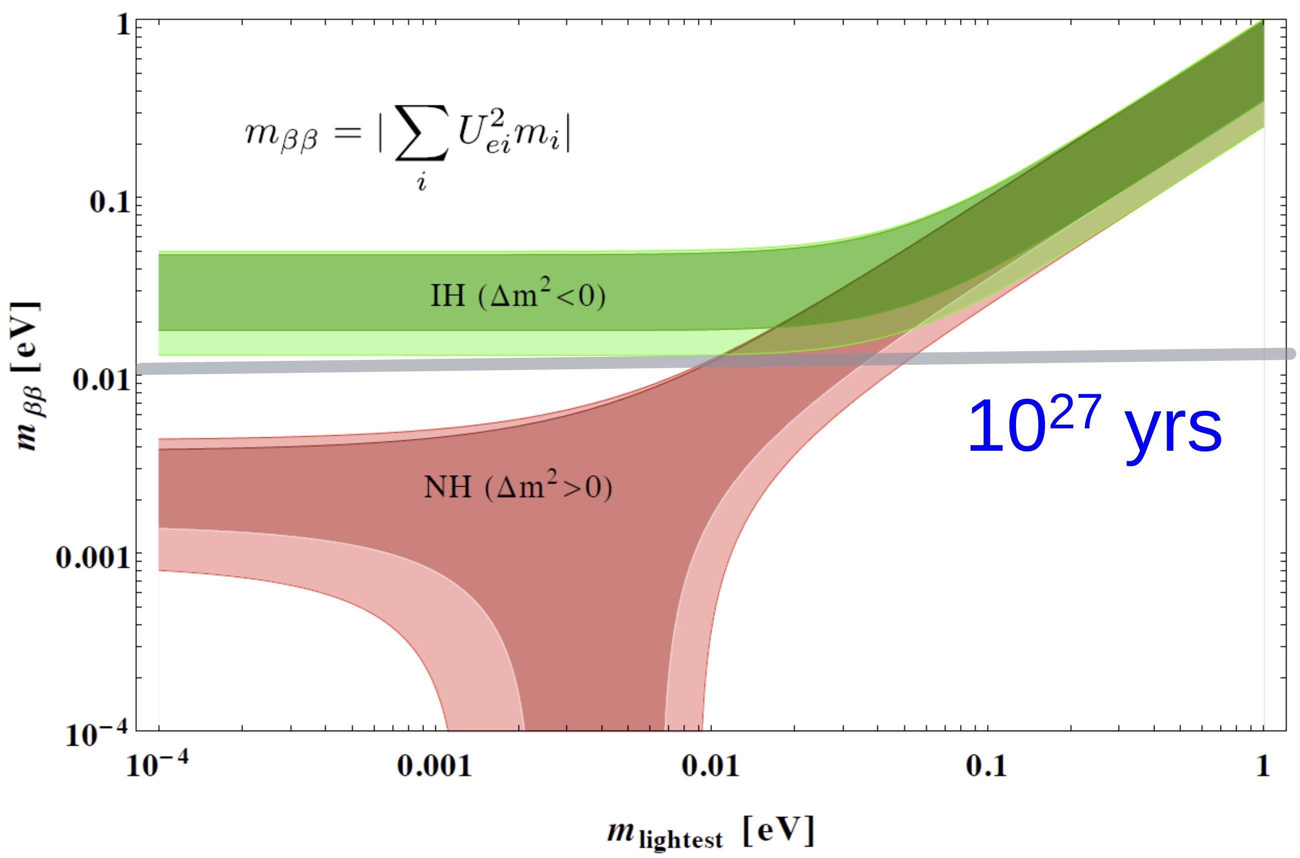
1.5wt.% Zr loaded Liquid Scintillator :
Light yield of 48.7±7.1% for BC505, and an energy resolution of 2.8±0.4% at 3.35 MeV assuming 64% photo coverage of the photomultiplier

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

Outer detector : active veto using pure water surrounding inner detector in order to veto muons and external γ-ray backgrounds.



Future 0νββ experiments



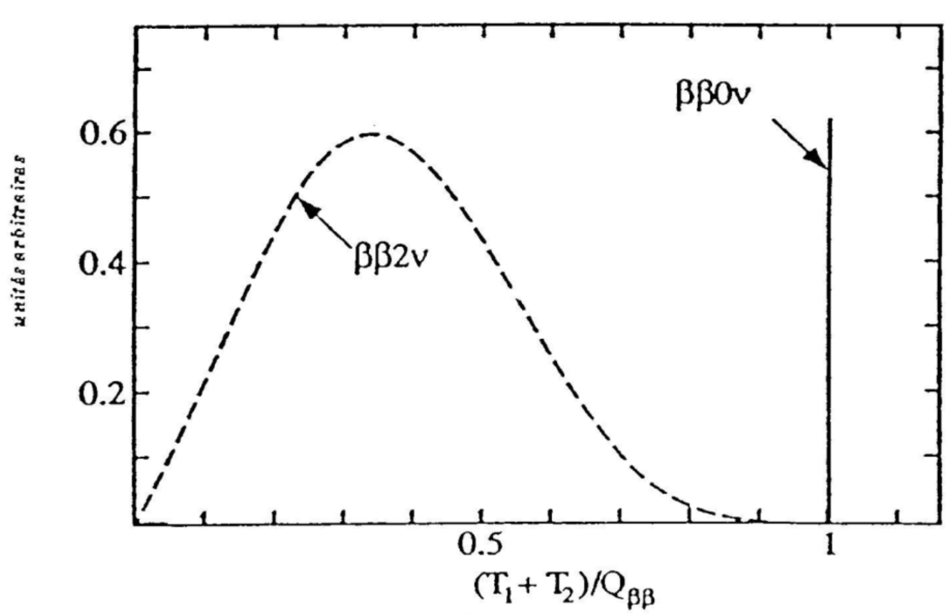
S. Dell'Oro, S. Marcocci, F. Vissani, Phys. Rev. D90, 033005 (2014)

~tons of target and ~zero BG detector will be necessary for next generation 0νββ experiment.

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



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

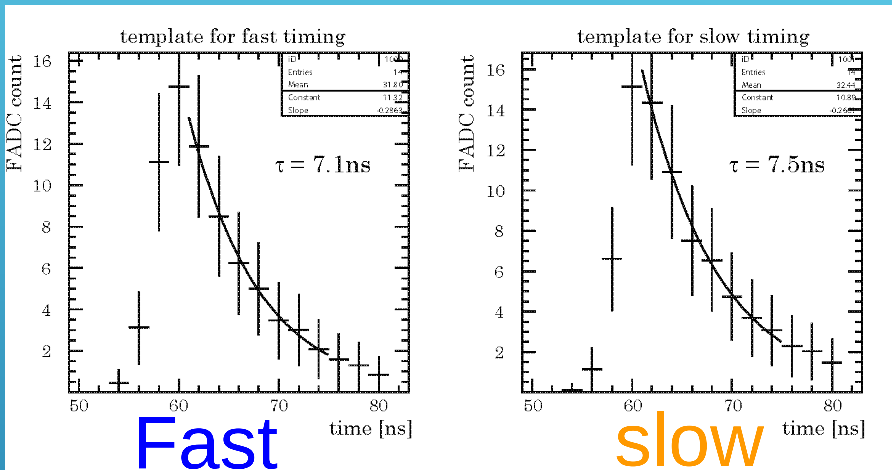
$T_{1/2} \sim a(Mt/\Delta E \cdot B)^{1/2}$ a: abundance M: target mass

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

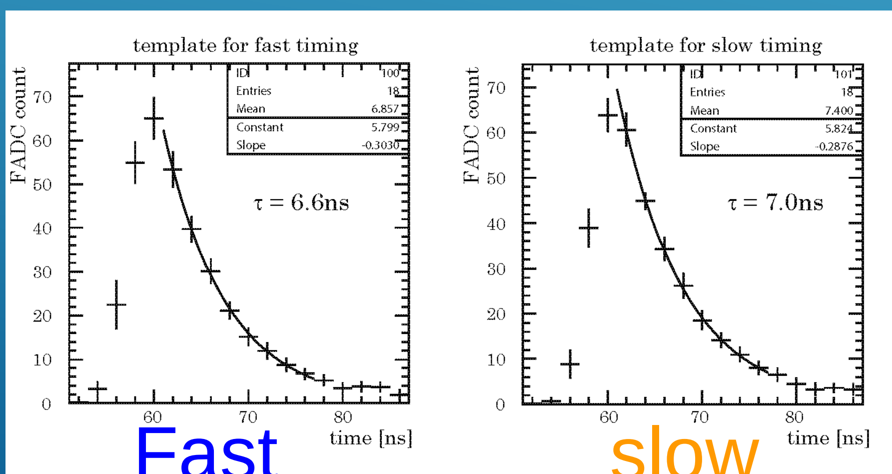
Requirement : Low BG, Large target mass, High E-resolution

Pulse shape of timing information

Anisole only

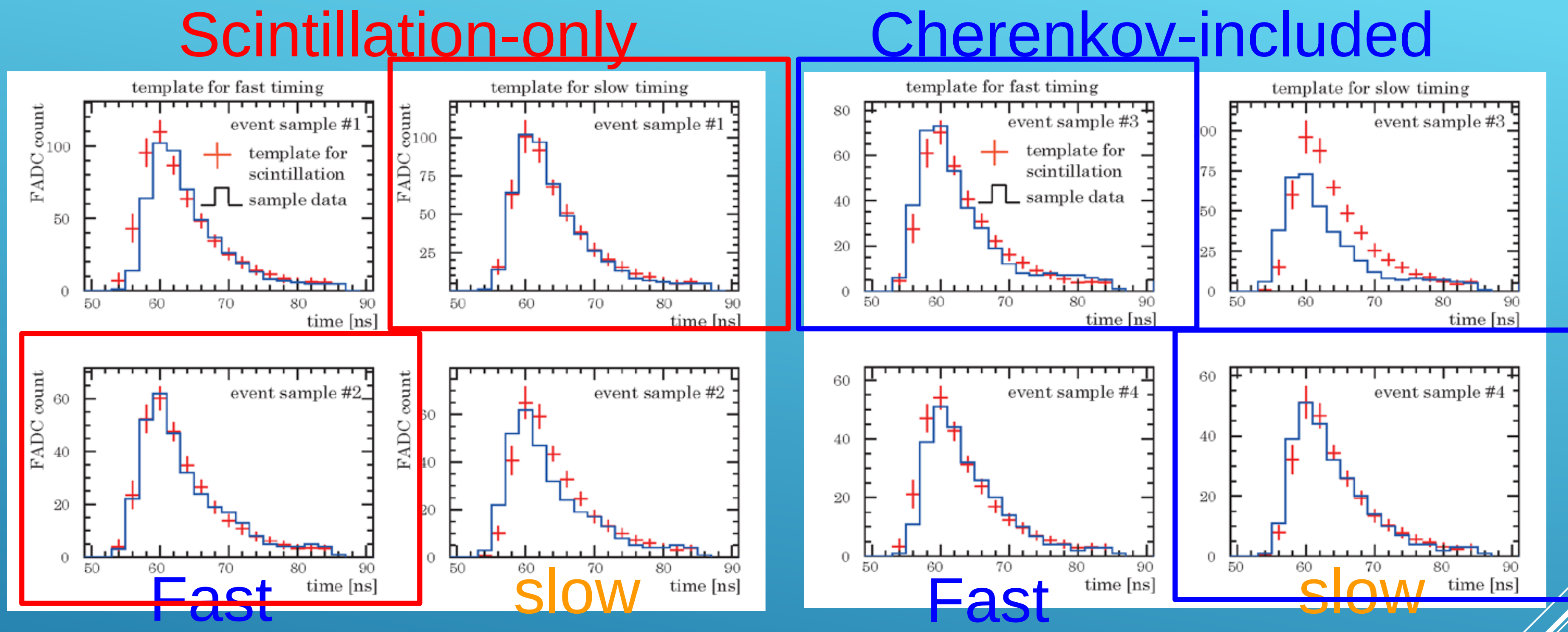


Zr(iprac)$_4$ loaded LS



- Templates of pulse shape of timing information for scintillation light were obtained by FADC.
- Fast and slow rise time component were observed due to FADC resolution.
- Both decay time of scintillation light are about 7ns.

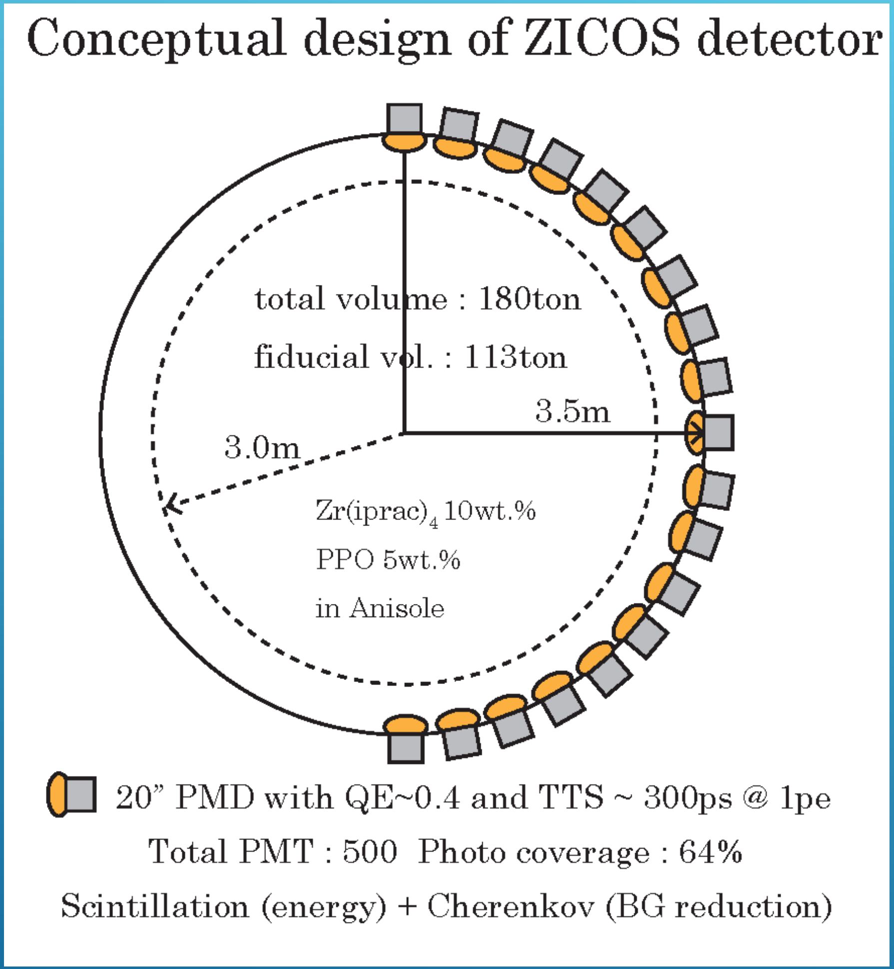
Pulse shape observed in Zr loaded LS



Two types of pulse shape (Scintillation-only and Cherenkov-included) were observed.

We can use pulse shape discrimination for selection of events which include Cherenkov lights.

Design of ZICOS detector



Natural abundance of ^{96}Zr : 2.6%

Detector :

1) 180tons LS : 1.5 wt.% Zr and 5wt.% PPO in Anisole .
2) Need 500 of 20" PMT with high QE ~0.4 and TTS ~300ps@1pe for 64% photo coverage.

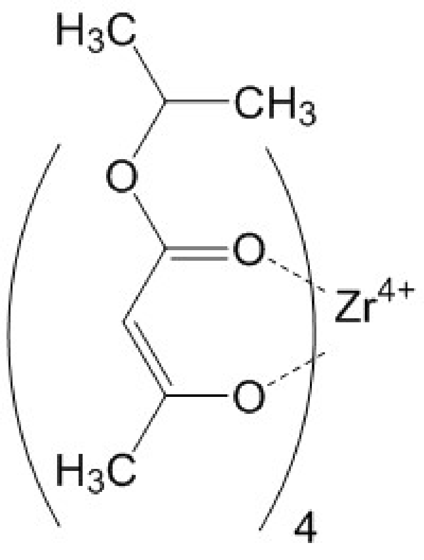
Expected performance :

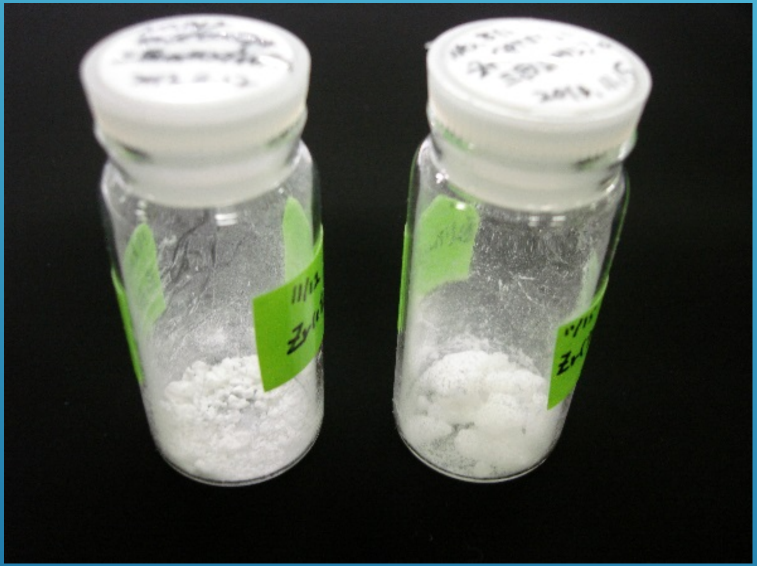
1) Energy resolution ~2.8%@3.35MeV
2) $T_{1/2}(0\nu\beta\beta)$ > **10^{27}years,** if both 1/20 BG reduction and 50% ^{96}Zr enrichment could be achieved.

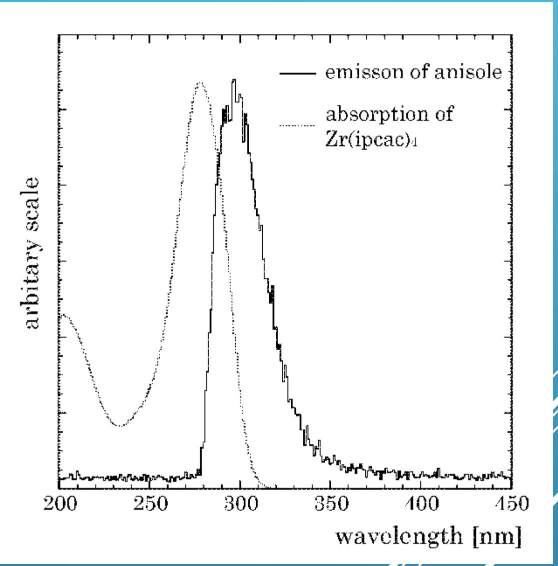
tetralkis(isopropyl acetoacetate) zirconium

$Zr(CH_3COCHCOOCH(CH_3)_2)_4$: $Zr(iprac)_4$

Molecular weights : 663.87







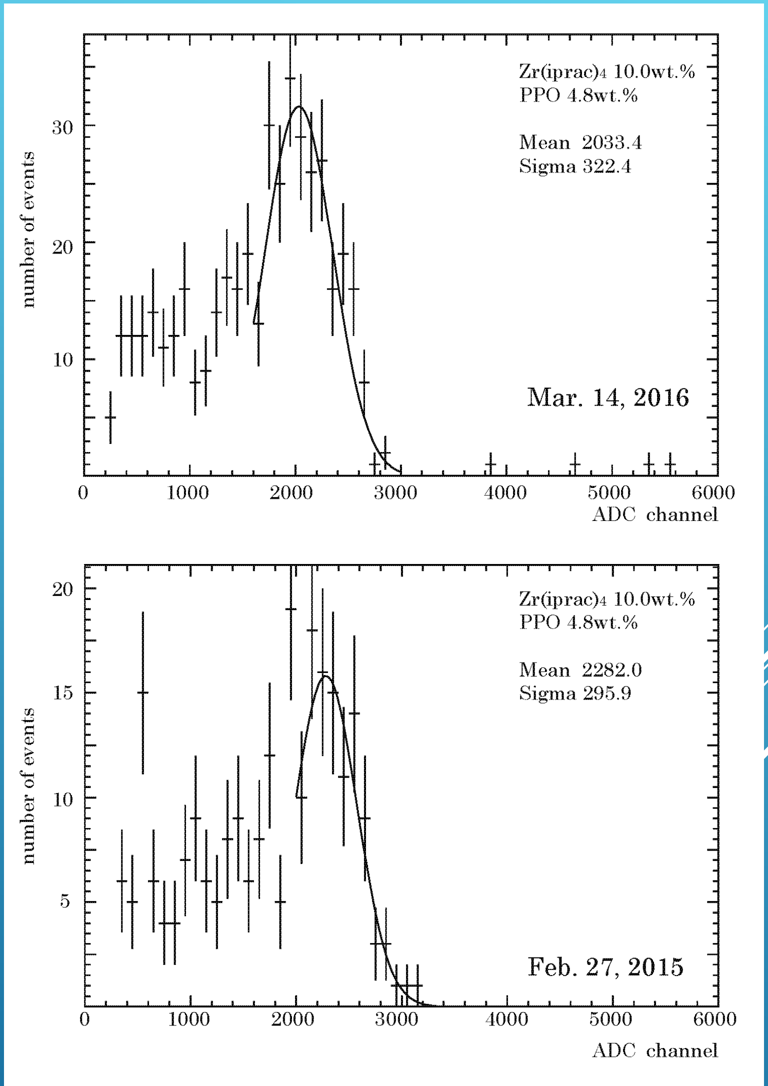
LS = $Zr(iprac)_4$: 10 wt.% PPO: 5wt.%
(POPOP: 0.05wt.%)

Zr loaded liquid scintillator

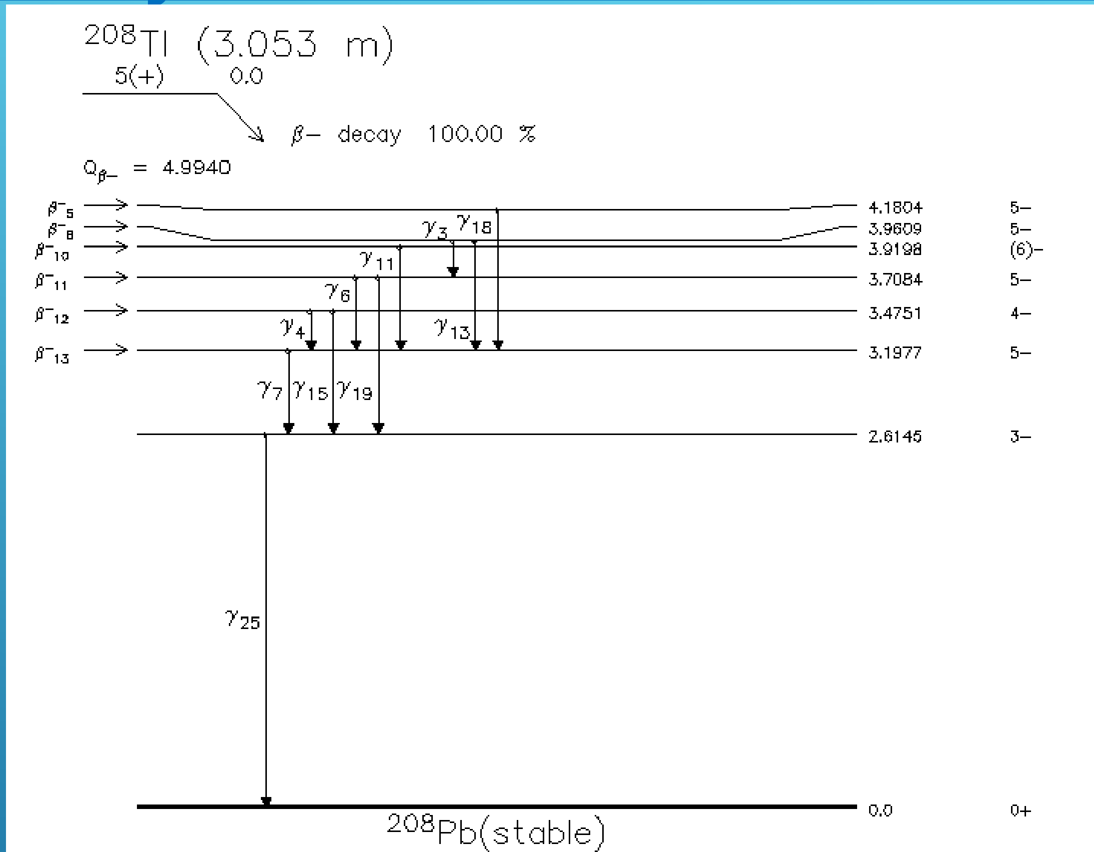
Feb. 27,2015

Mar. 14, 2016

Light yield of 48.7±7.1% for BC505, and an energy resolution of 4.1±0.6% at 3.35 MeV assuming 40% photo coverage of the photomultiplier



Decay branch of Thallium-208

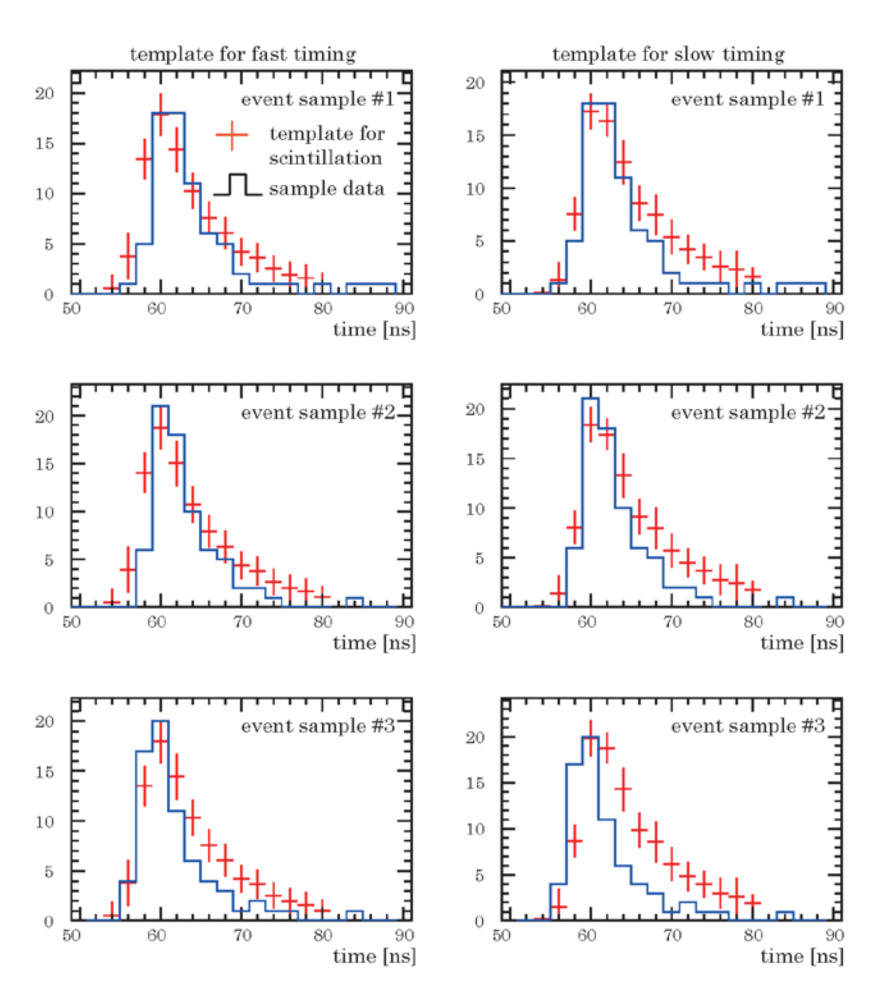


Radiations	y(i) (Bq-s)$^{-1}$
beta- 5	2.27×10^{-03}
beta- 8	3.09×10^{-02}
beta- 10	6.30×10^{-03}
beta- 11	2.45×10^{-01}
beta- 12	2.18×10^{-01}
beta- 13	4.87×10^{-01}
ce-K, gamma 3	4.04×10^{-03}
gamma 4	6.31×10^{-02}
ce-K, gamma 4	2.84×10^{-02}
ce-L, gamma 4	4.87×10^{-03}
gamma 6	2.26×10^{-01}
ce-K, gamma 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 reconstructed by scintillation make it within fiducial volume due to mis-fitting of gammas.

Pulse shape observed in H_2O

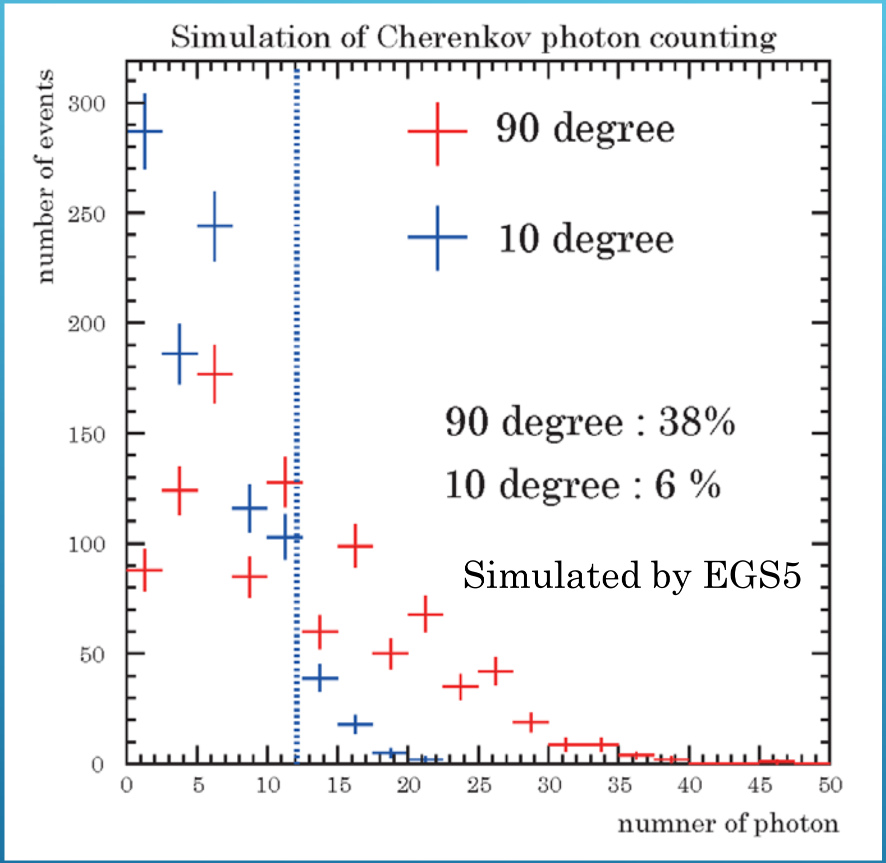
90deg



- Same pulse shape of timing as anisole was observed.
- This signal should be caused by Cherenkov light, because of no scintillation in H_2O.

This pulse shape is made by Cherenkov lights.

Monte Carlo Simulation



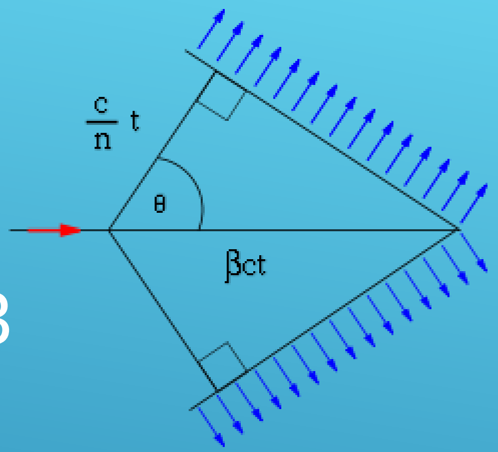
Number of event received Cherenkov light in Anisole has a clear difference between 90deg and 10deg, because of directionality of Cherenkov light.

Maybe different situation in Liquid Scintillator.

Photon could be scattered by high concentration of solute.
We have to simulate such kind of effect.

Property of Cherenkov light

- Refractive index of anisole : n=1.518
- Cherenkov angle is determined by cosθ= 1/n'β (Ee>0.7MeV) n'>n
- Assuming 1.65MeV electron, then β=0.972 and Cherenkov angel θ=47.3 degree are expected.
- Number of Cherenkov photon :
  100 photon/MeV (400nm – 600nm)

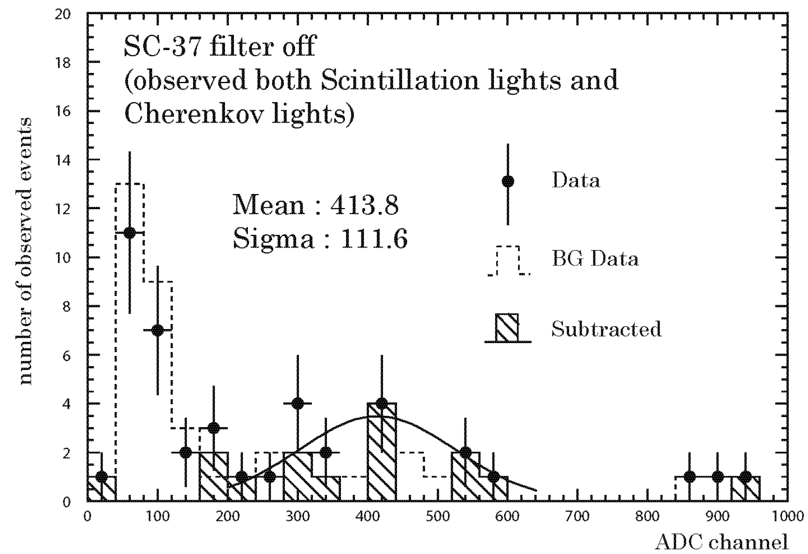


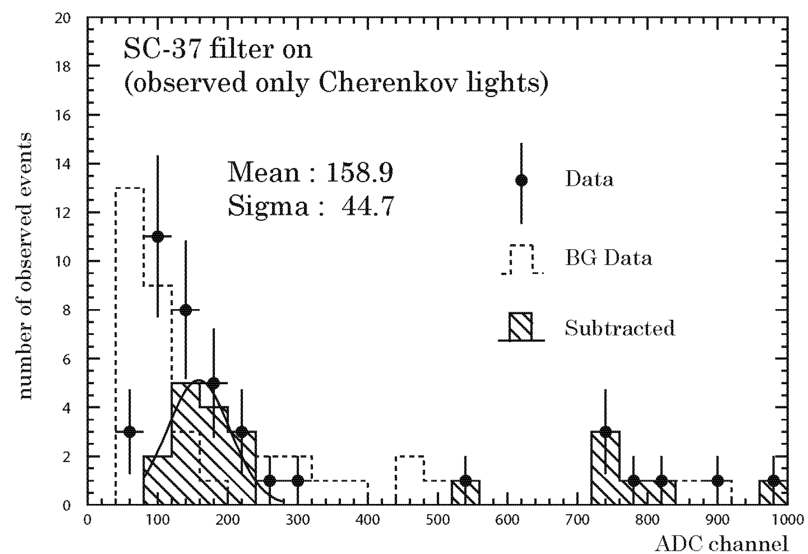
$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2\theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2\theta_c \mathrm{photon/cm}$$

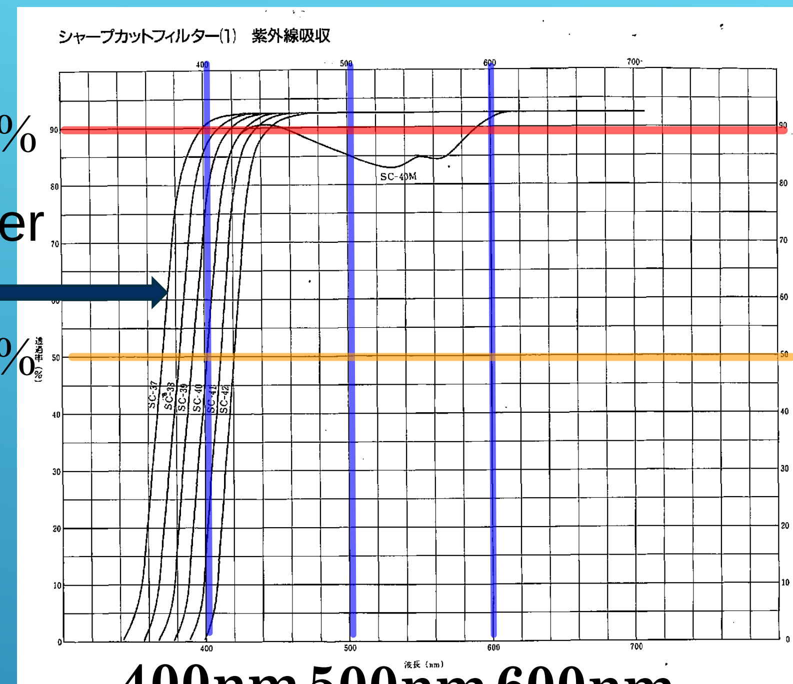
c.f. Light yield of Scintillation : ~12000photon/MeV

Cherenkov light = ~1% of scintillation light

Light yield of Cherenkov lights





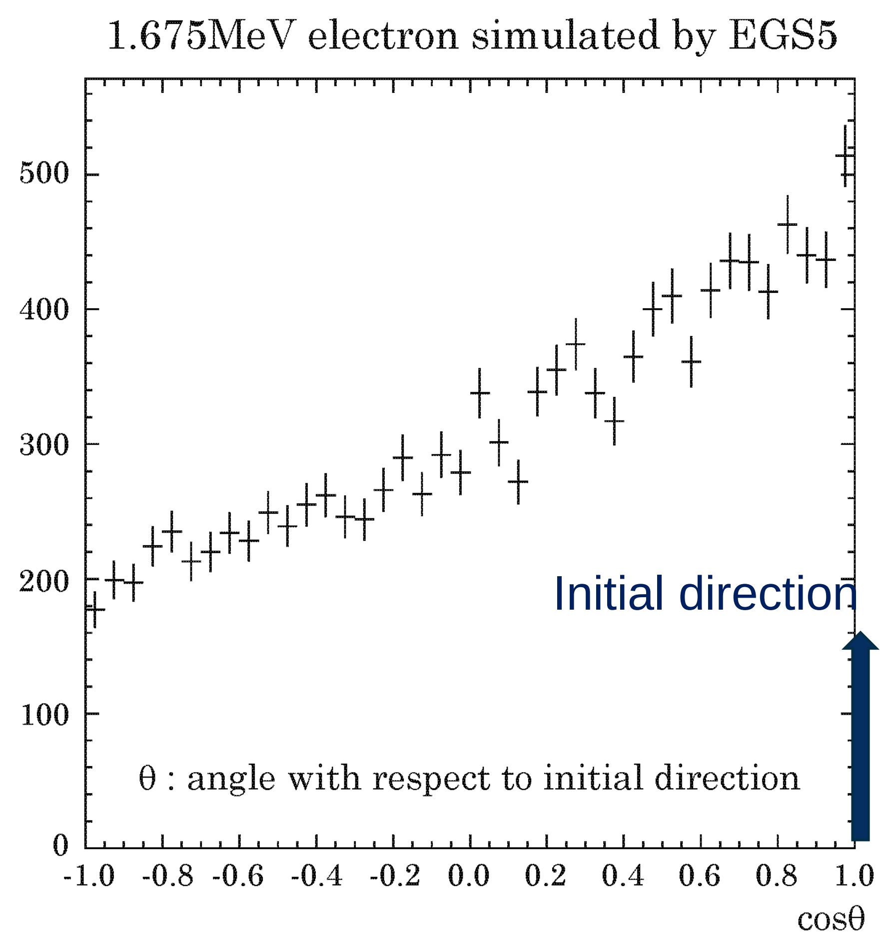


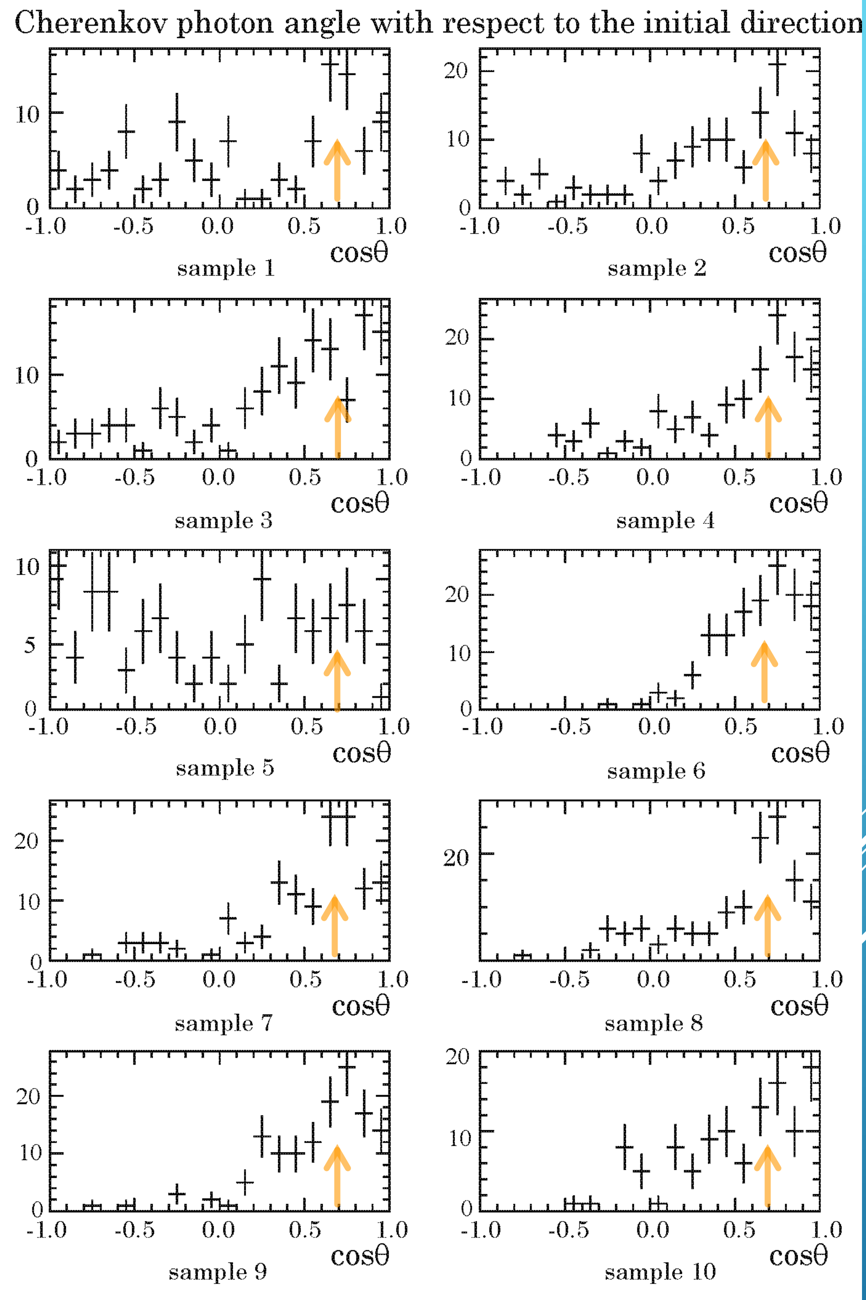
Cherenkov light yield (λ>400nm)

Scintillation light yield of anisole

= ~0.02 ≡ ~200 photon/MeV

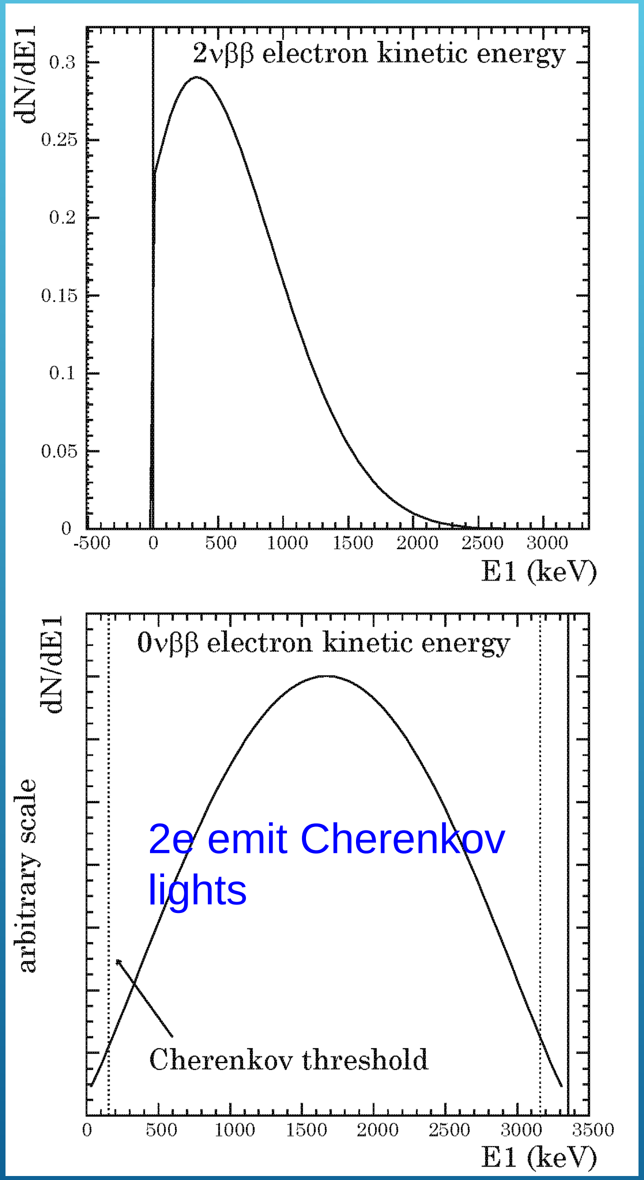
Multiple scattering





Even though multiple scattering of electrons, Cherenkov photons look have some clusters.

kinetic energy spectrum of electron



For calculation of 2νββ,

$$\frac{d\omega}{dk_1 dk_2 d\cos\theta} \sim \mathcal{F}(Z,\varepsilon_1)\mathcal{F}(Z,\varepsilon_2)k_1^2 k_2^2 (W_0-\varepsilon_1-\varepsilon_2)^5(1-\beta_1\beta_2\cos\theta)$$

k_i, electron momenta
$\varepsilon_i = \mathrm{sqrt}(k_i^2+m_e^2)$: electron energy
$W_0=Q+2m_e$: total release energy
Q : Q value m_e: electron mass
θ : opening angle $\mathcal{F}$: Fermi func.

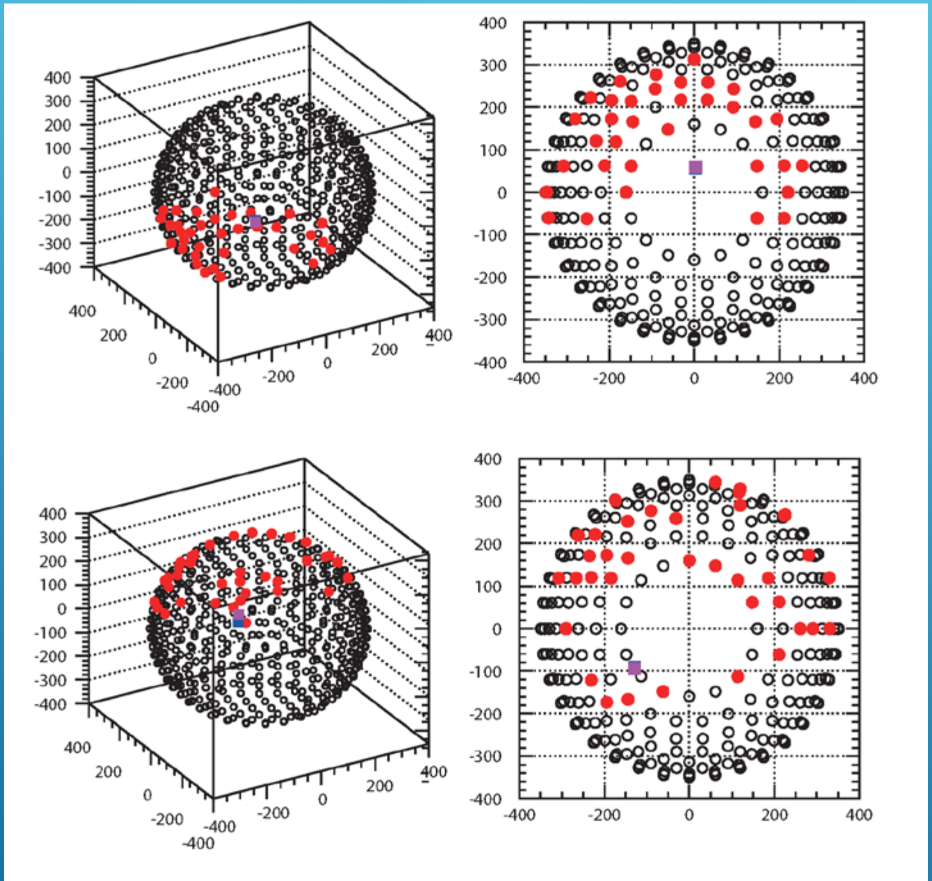
ε_i can generate independently within energy conservation.

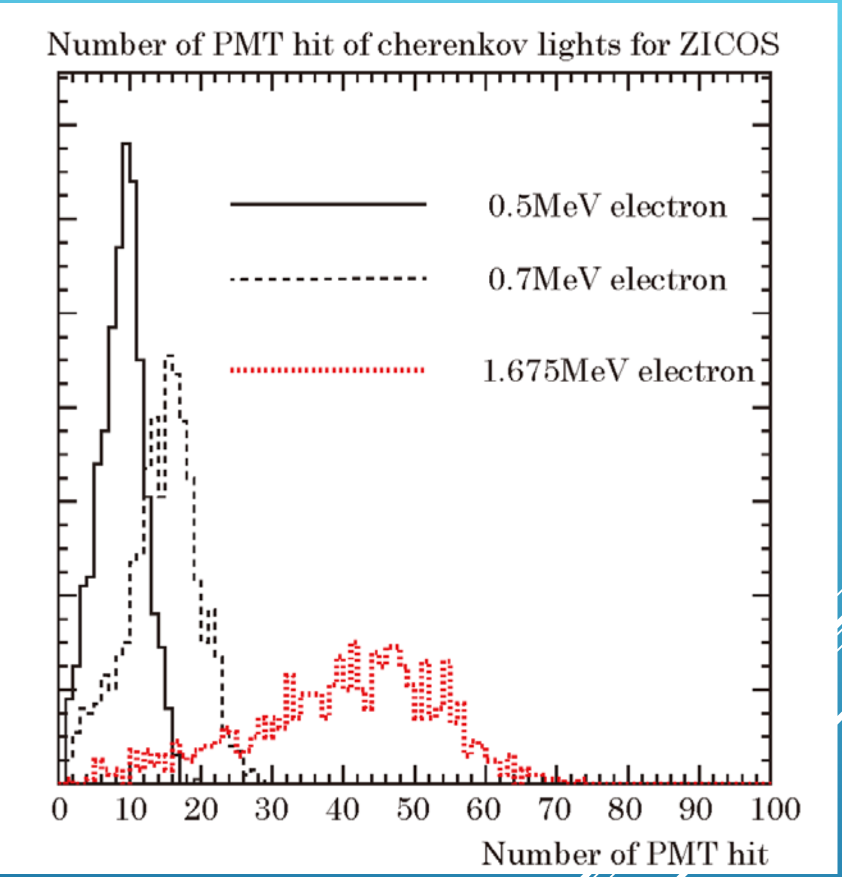
For calculation of 0νββ,

Same calculation but ε_i can only generates with $\varepsilon_1+\varepsilon_2=W_0$.

Simulation of Cherenkov lights

Simulated by EGS5 (kinetic energy 1.675MeV)

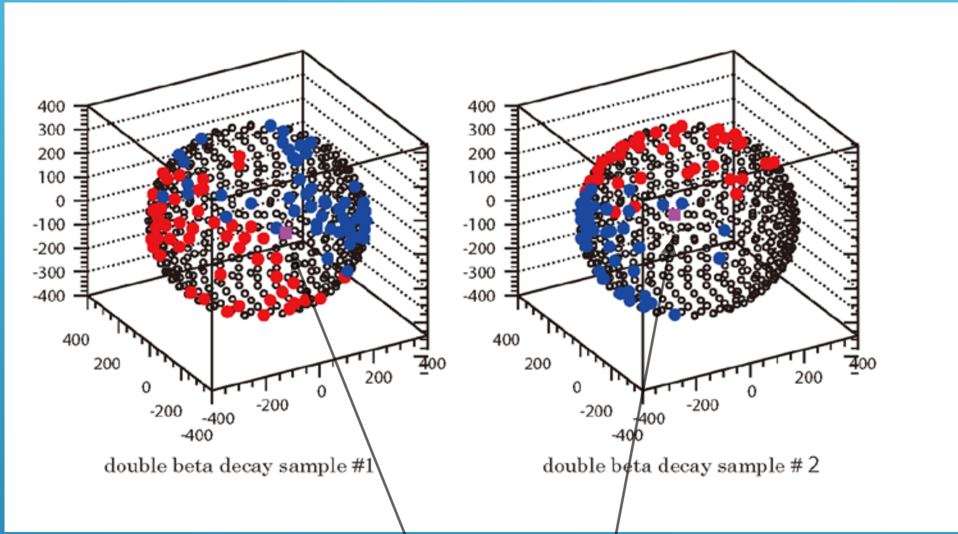




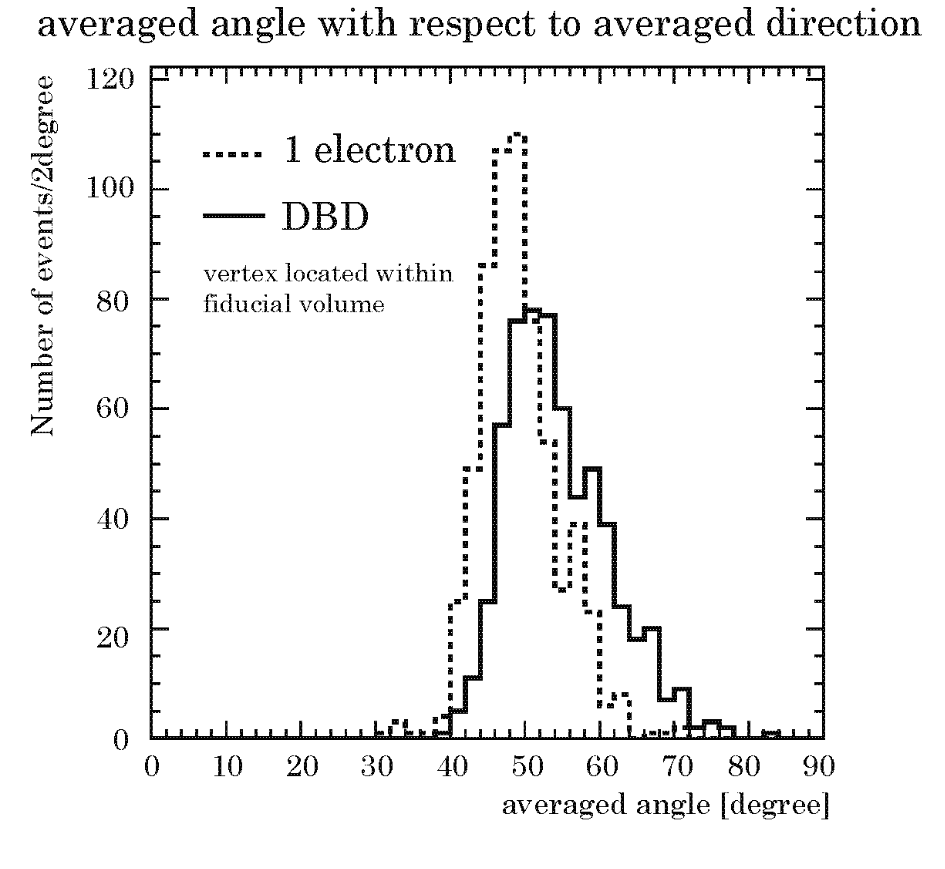
Hard to detect Cherenkov events below 0.5MeV.

Hit pattern of DBD (opposite and half E)

Simulated by EGS5 (kinetic energy 1.675MeV)

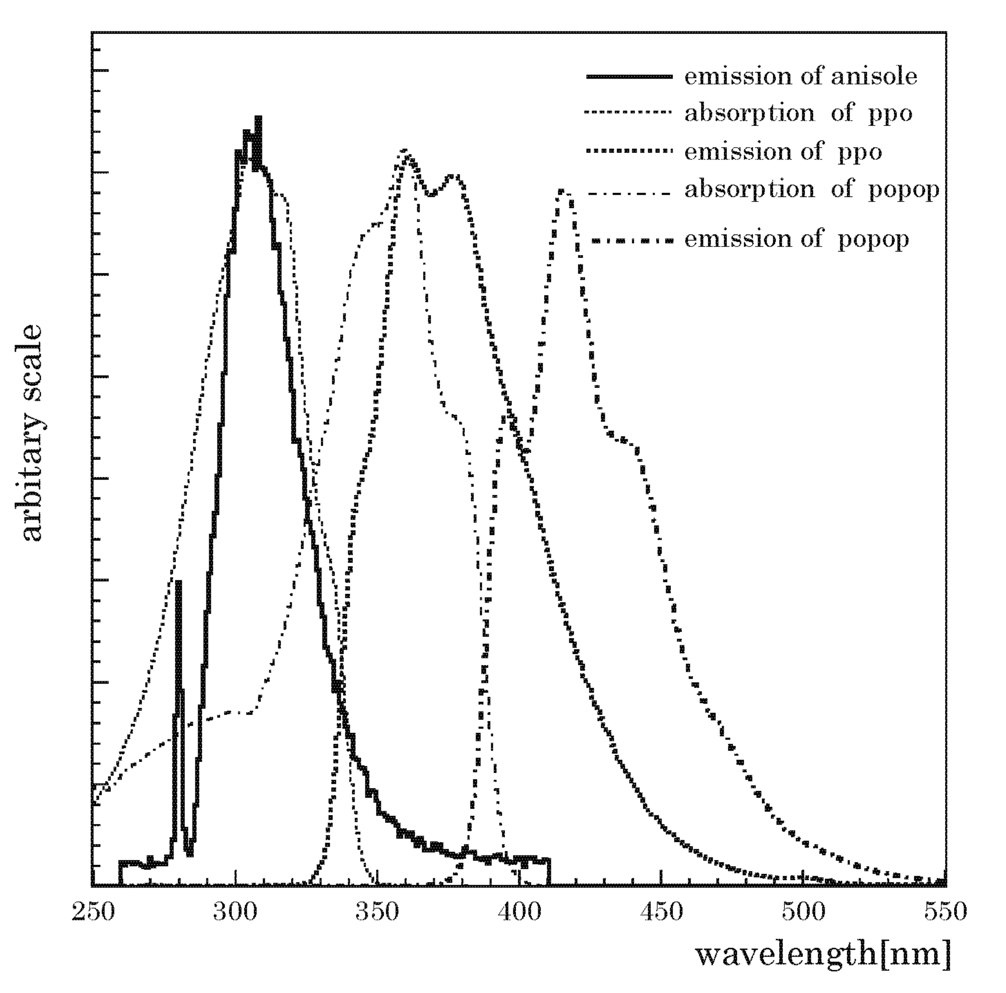


Generate position of DBD



Multi events from DBD tend to have a slightly larger values of averaged angle than single e^-.

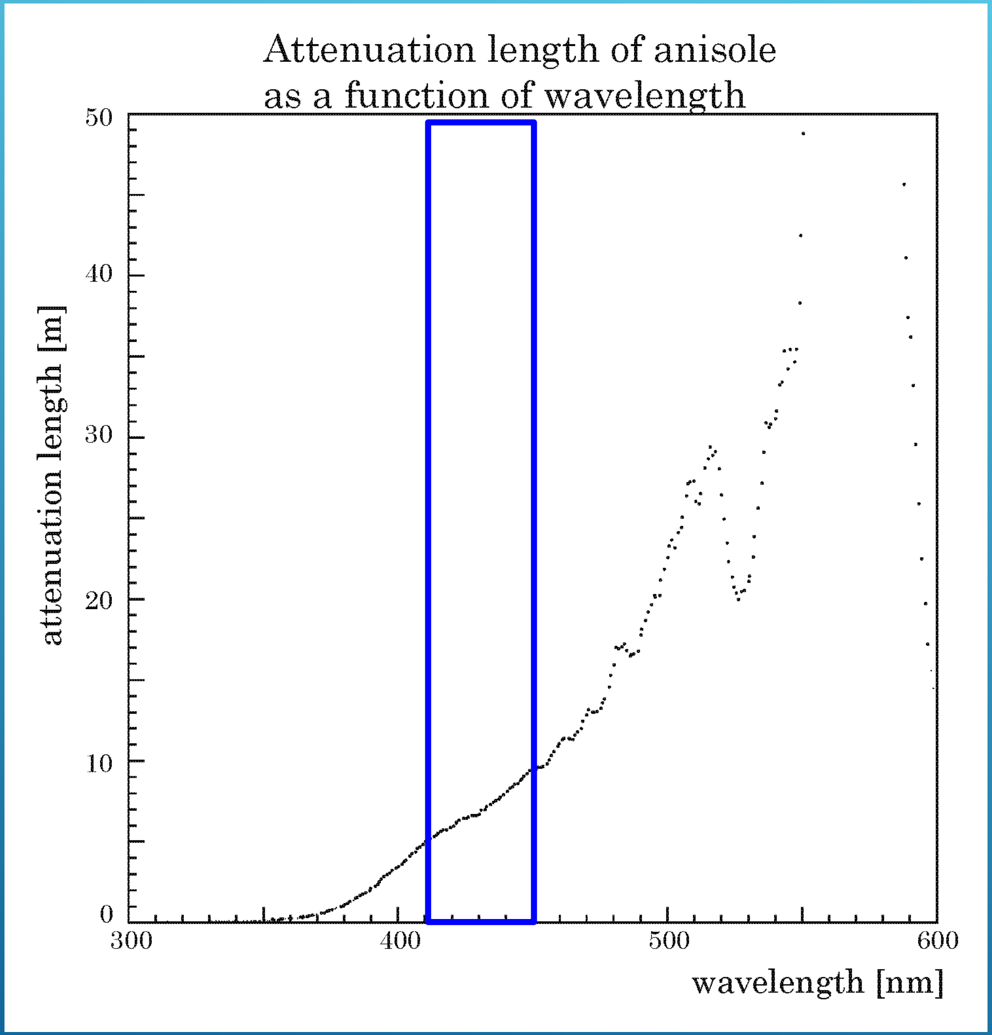
Emission and absorption spectra for solvent and solute in standard cocktail



PPO absorbed most of emission lights from anisole.

Effectively the energy was transferred to the secondary scintillator.

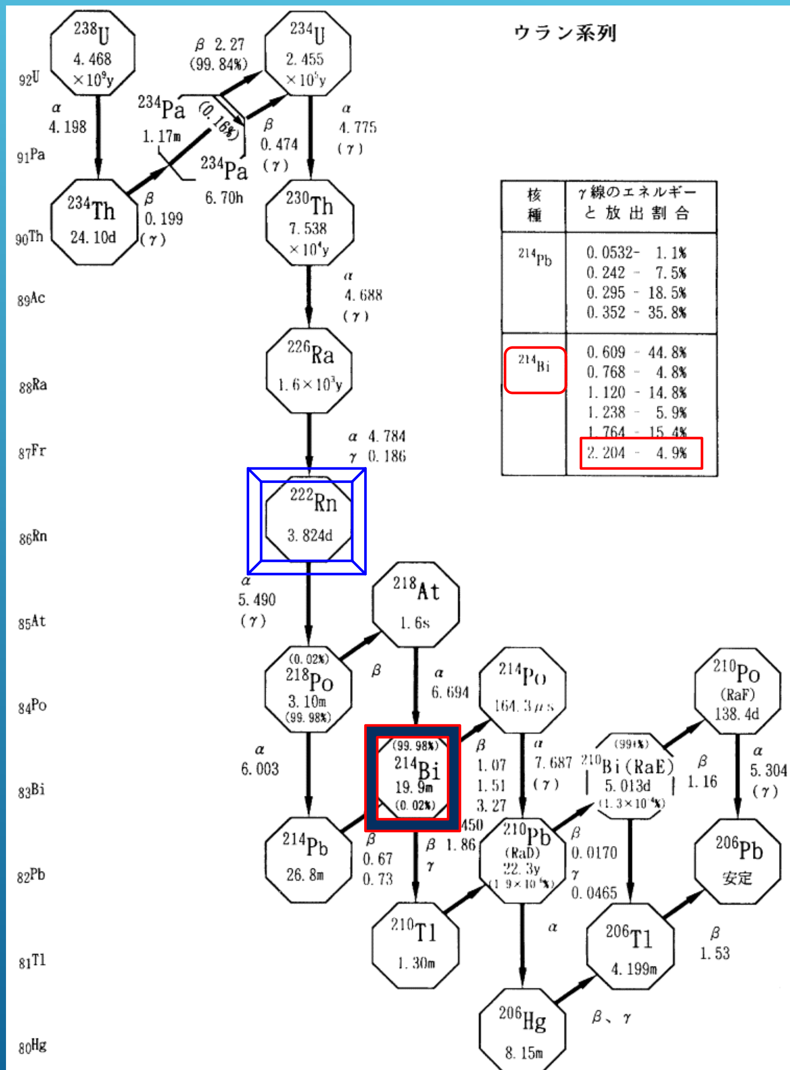
ATTENUATION LENGTH OF ANISOLE



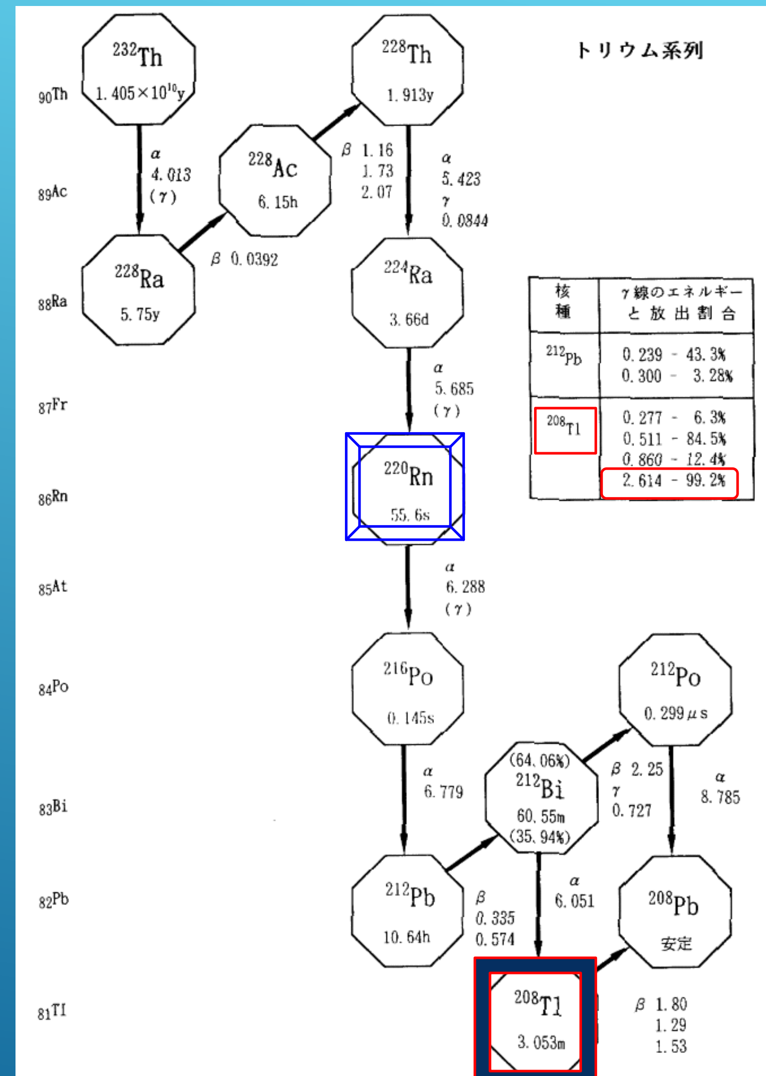
Attenuation length of scintillation light from POPOP (~450nm) was obtained as ~6m.

No problem for radius of ZICOS detector.

Natural radiative U/Th decay chain

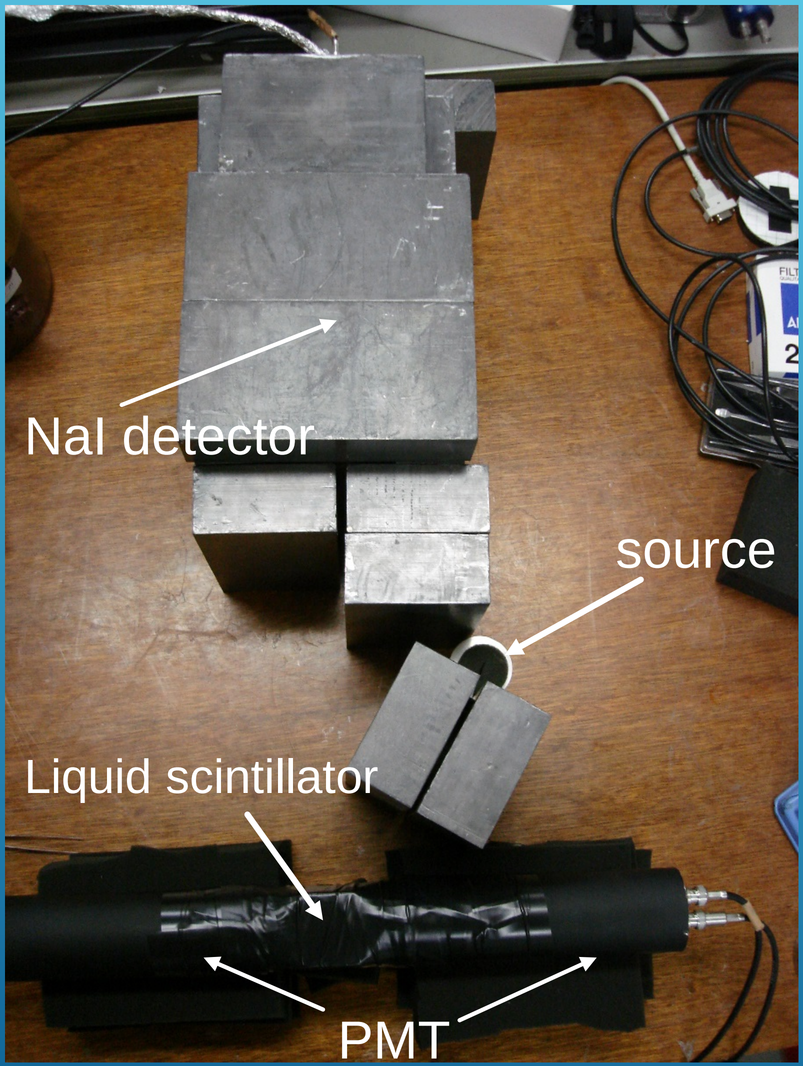


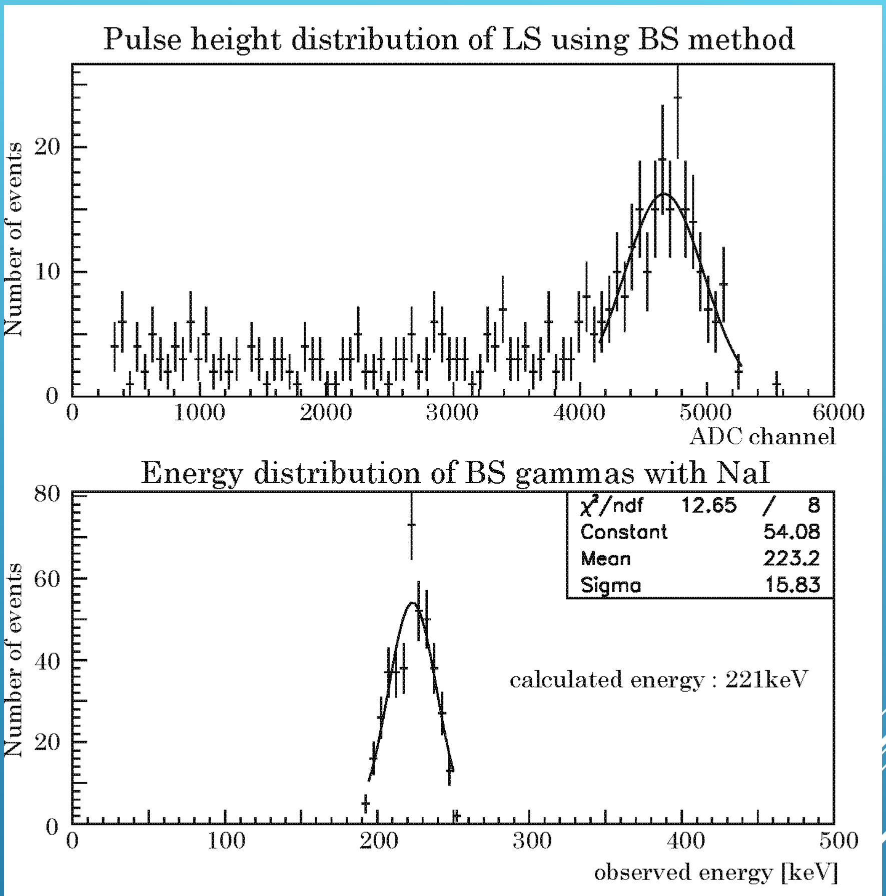
核種	γ線のエネルギーと放出割合
^{214}Pb	0.0532 - 1.1% 0.242 - 7.5% 0.295 - 18.5% 0.352 - 35.8%
^{214}Bi	0.609 - 44.8% 0.768 - 4.8% 1.120 - 14.8% 1.238 - 5.9% 1.764 - 15.4% 2.204 - 4.9%



核種	γ線のエネルギーと放出割合
^{212}Pb	0.239 - 43.3% 0.300 - 3.28%
^{208}Tl	0.277 - 6.3% 0.511 - 84.5% 0.860 - 12.4% 2.614 - 99.2%

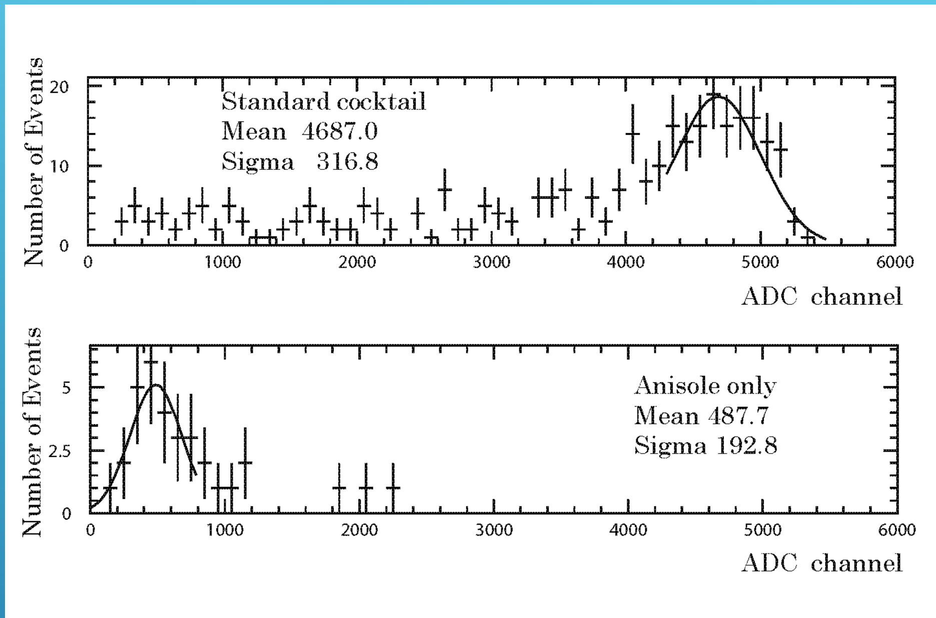
Backscattering method

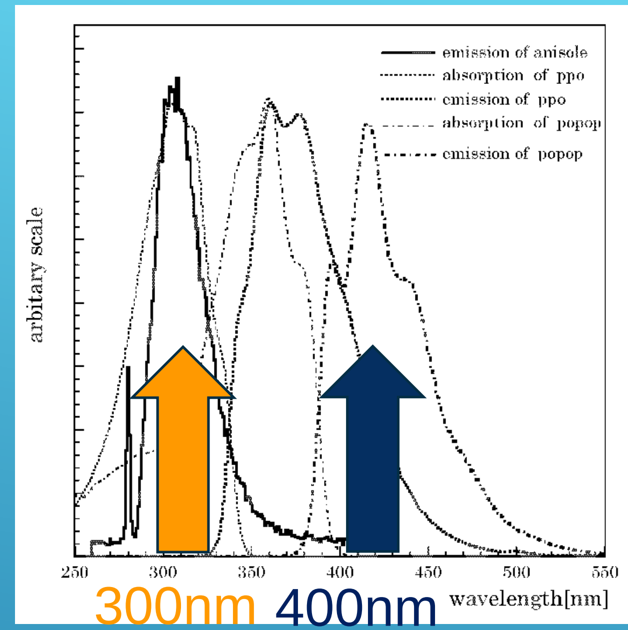


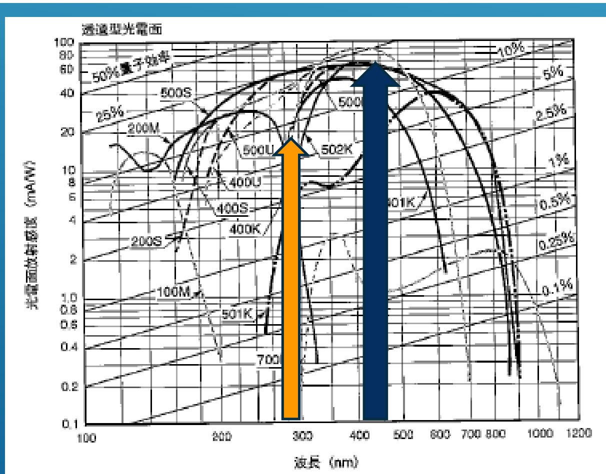


Single peak could be used even in liquid scintillator.

Light yield of scintillation in anisole

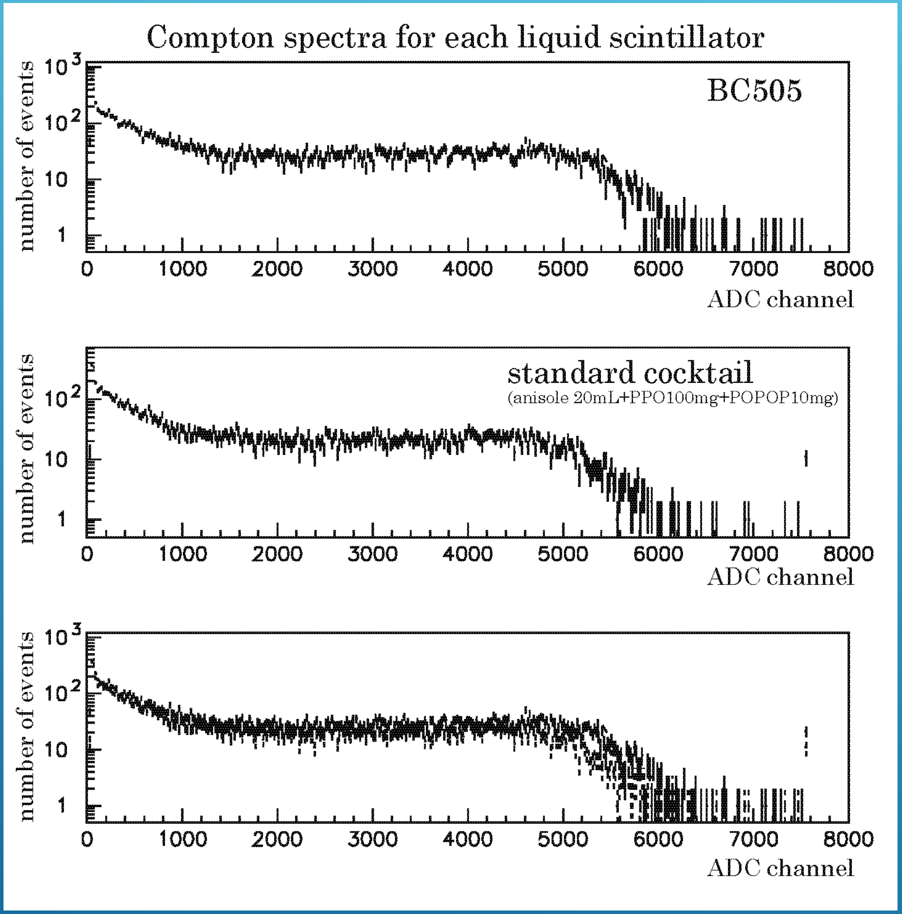






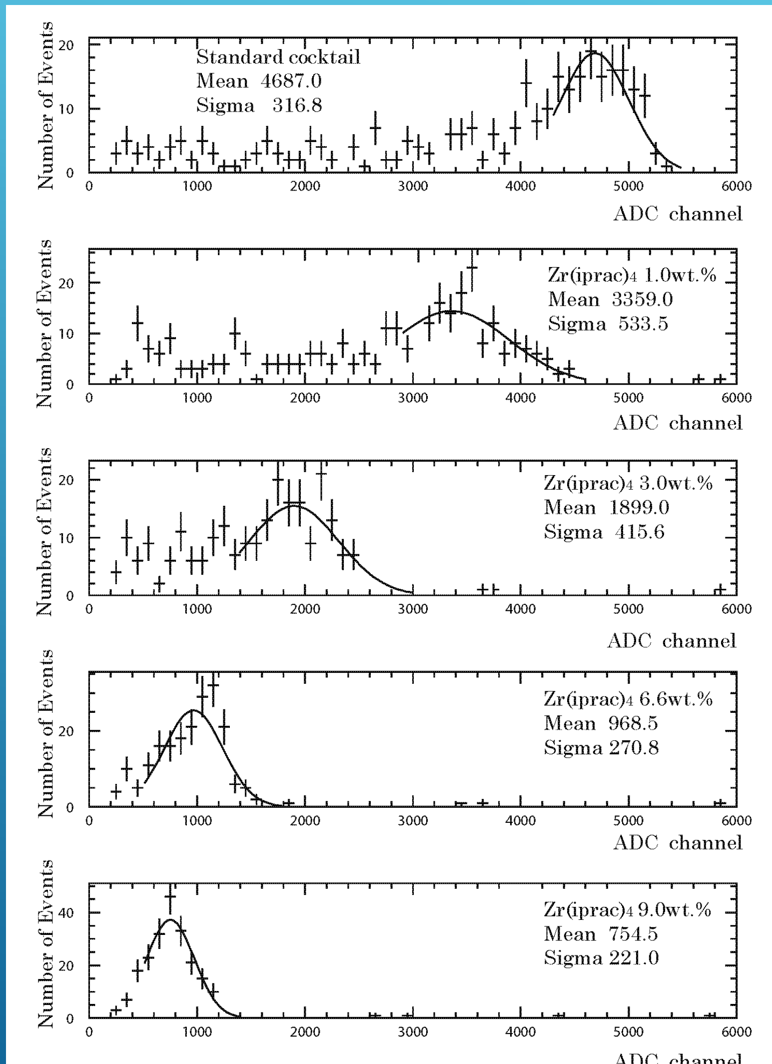
Relative scintillation light yield of anisole is 9.8% to standard cocktail (due to difference of quantum efficiency of PMT)

LIGHT YIELD COMPARISON BETWEEN BC505 AND STANDARD COCKTAIL



Light yield of BC505 and our standard cocktail (100mg PPO and 10mg POPOP solved in 20mL anisole) is almost same quality.

ENERGY SPECTRA FOR SEVERAL CONCENTRATION OF ZR(IPRAC)4



Peak values decreased as a function of the concentration of $Zr(iprac)_4$.

Energy resolutions are also getting worth as a function of the concentration of $Zr(iprac)_4$.

Physical constants of Liquid Scintillator

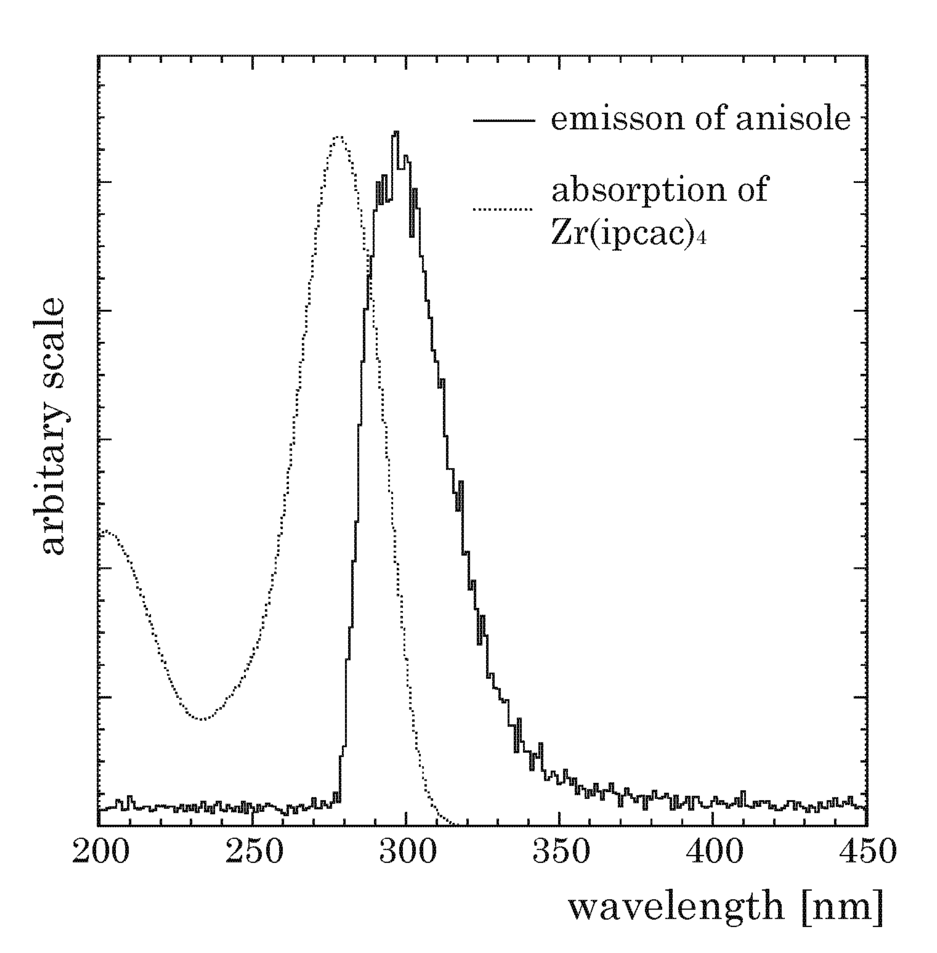
Physical Constants of SGC Liquid Scintillators

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	H:C Ratio	Loading Element	Density	Flash Point °C
BC-501A	78	425	3.2[1]	1.212		0.87	26
BC-505	80	425	2.5	1.331		0.877	48
BC-509	20	425	3.1	.0035	F	1.61	10
BC-517L	39	425	2	2.01		0.86	102
BC-517H	52	425	2	1.89		0.86	81
BC-517P	28	425	2.2	2.05		0.85	115
BC-517S	66	425	2	1.70		0.87	53
BC-519	60	425	4	1.73		0.87	63
BC-521	60	425	4	1.31	Gd (to 1%)	0.89	44
BC-523	65	425	3.7	1.74	Nat. ^{10}B (5%)	0.916	-8
BC-523A	65	425	3.7	1.67	Enr. ^{10}B (5%)	0.916	-8
BC-525	55	425	3.8	1.56	Gd (to 1%)	0.88	91
BC-531	59	425	3.5	1.63		0.87	93
BC-533	51	425	3	1.96		0.80	65
BC-537	61	425	2.8	0.99 (D:C)	^{2}H	0.954	-11

* Anthracene light output = 40-50% of NaI(Tl)   [1] Fast component; mean decay times of first 3 components = 3.16, 32.3 and 270 ns

LY of NaI(Tl) : 4×10^4 photon/MeV → LY of BC505 : 1.2×10^4 photon/MeV

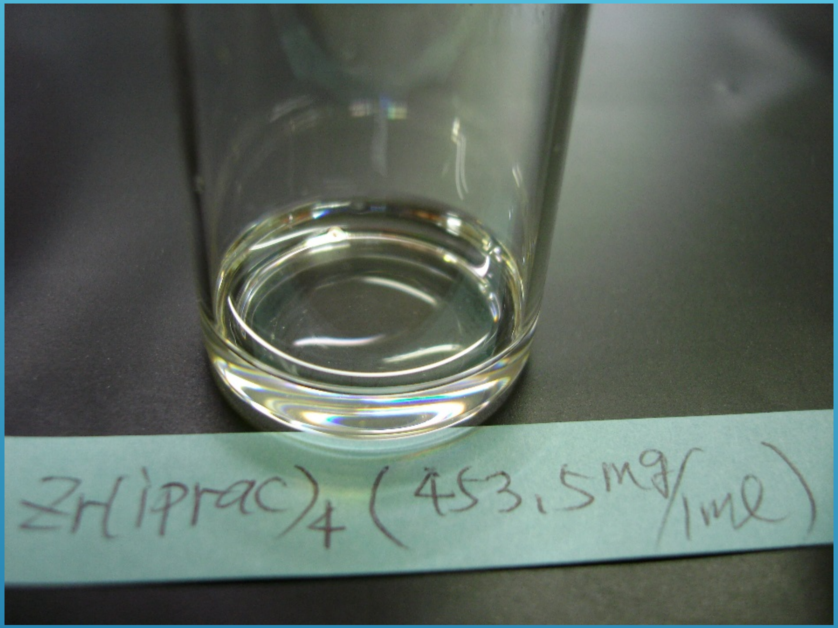
Absorbance spectra for Zr(iprac)$_4$

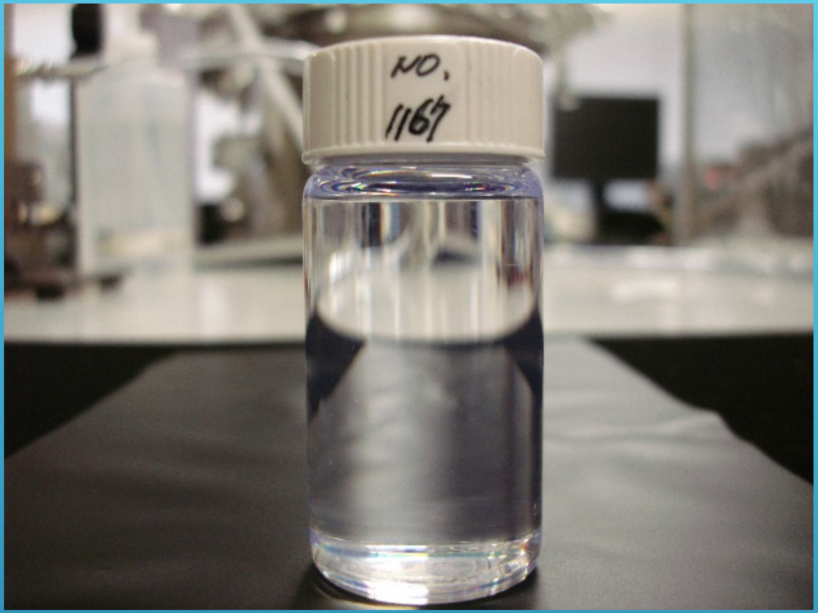


Absorption peaks of Zr(iprac)$_4$ was found around at 278nm. However, overlapped region with emission of anisole was existed.

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

Solubility of $Zr(iprac)_4$ for anisole





Solubility > 31.2 wt.%

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

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

Light yield quenching by $Zr(iprac)_4$

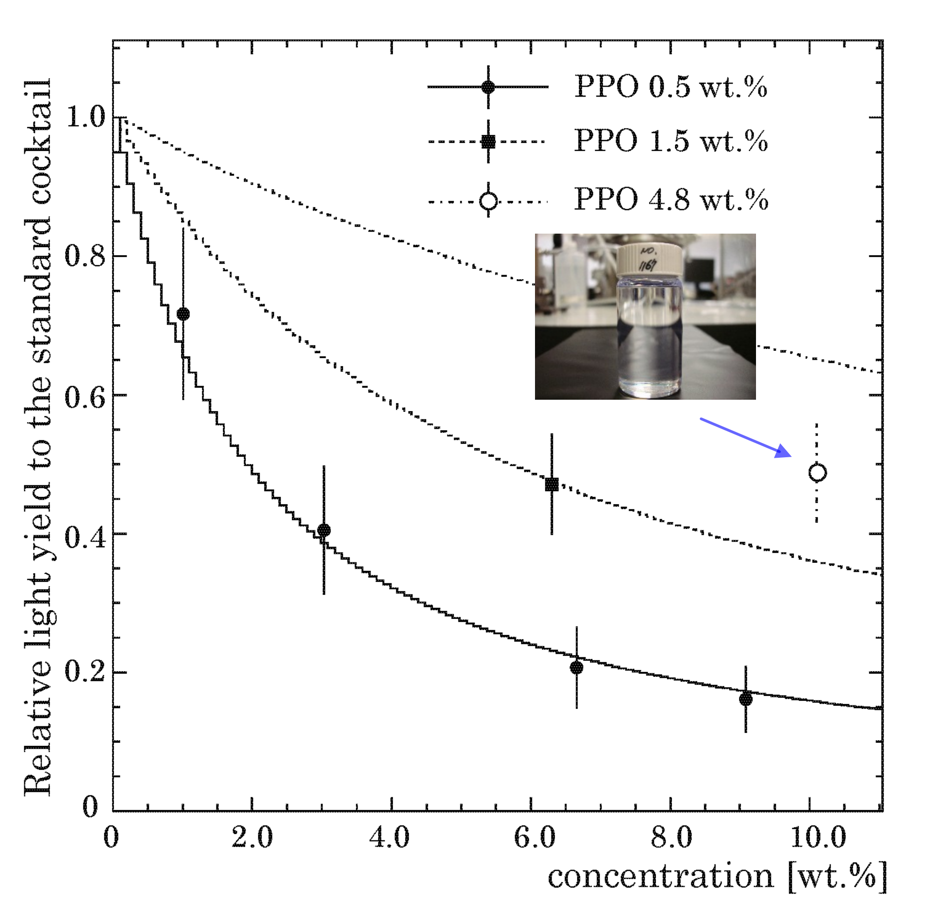
$$\text{Light yield} = L_0 \times \frac{\sigma_1 N_{ppo}}{\sigma_1 N_{ppo} + \sigma_2 N_{Zr}}$$

L_0 : Light yield of anisole
N_{ppo} : Number of PPO molecular in mole
N_{Zr} : Number Zr complex molecular in mole
σ_1 : absorbance of PPO (mol^{-1})
σ_2 : absorbance of Zr complex (mol^{-1})

PPO would help the recovering light yield.

Recovering the light yield

Measured at several conditions of PPO concentration

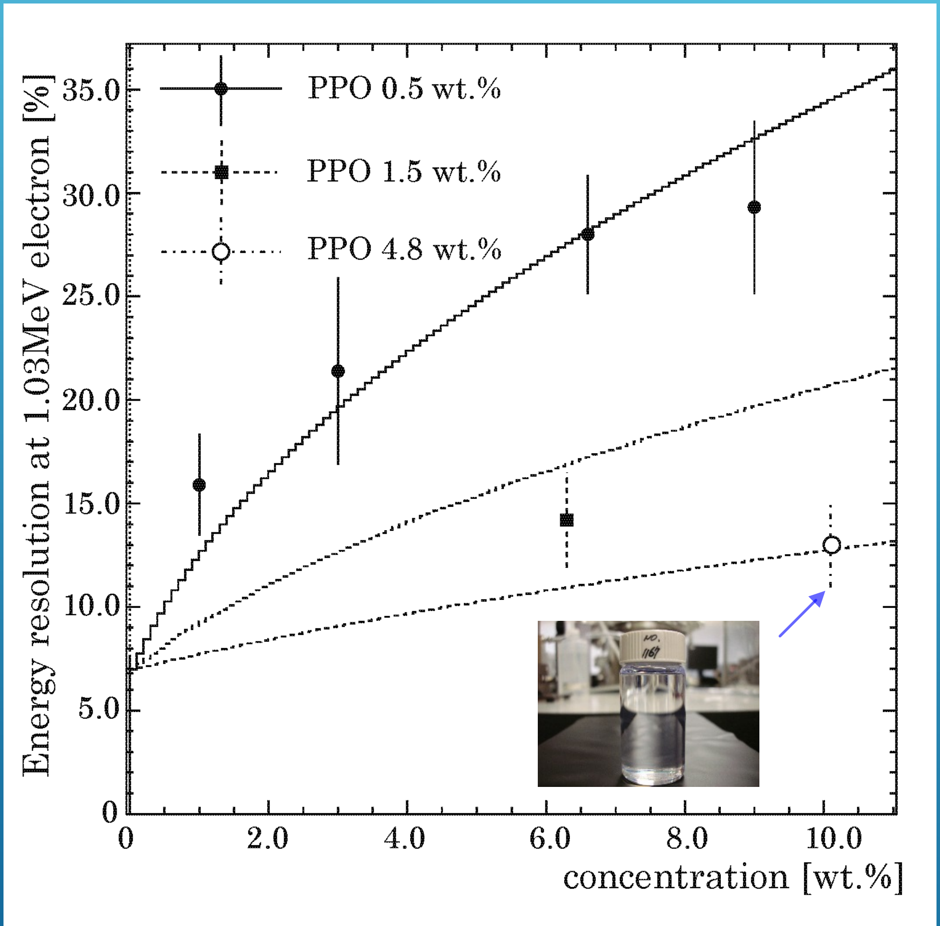


5wt.% PPO helps actually recovering the scintillation light yield.

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

Recovering the energy resolution

Measured at several conditions of PPO concentration



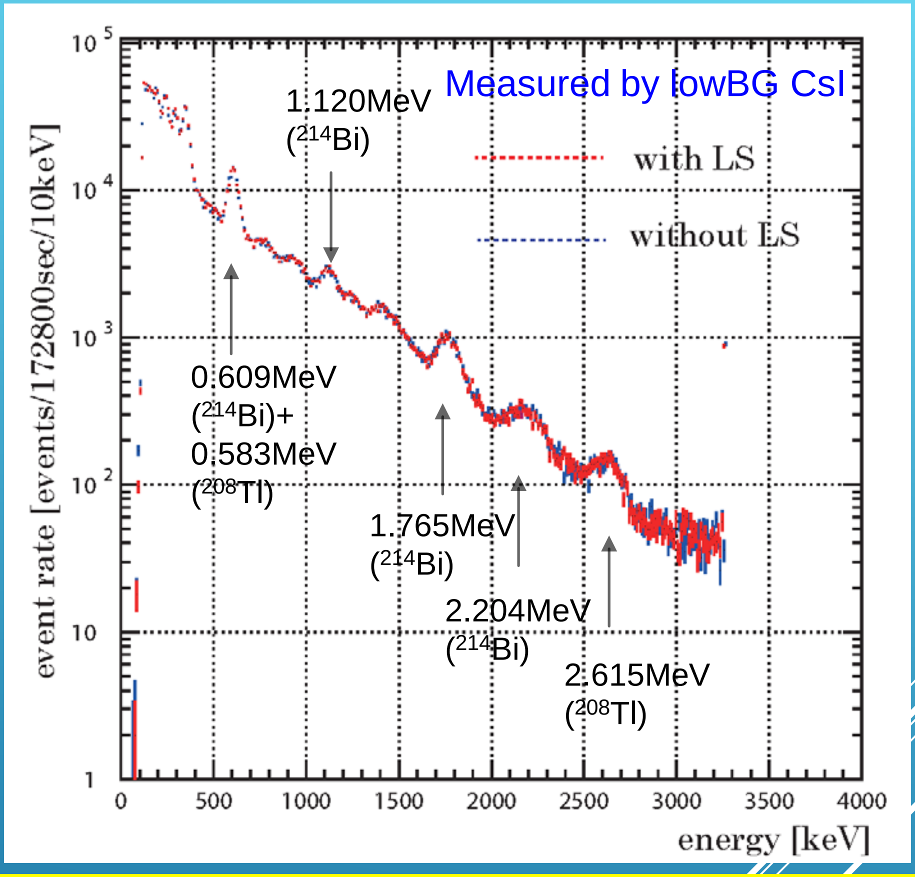
5wt.% PPO helps again the energy resolution 35% → 13%. at 10wt.% of $Zr(iprac)_4$.

$$\frac{13.0\pm2.0\%}{\sqrt{(40\%/9.2\%)\times(3.35\text{MeV}/1.03\text{MeV})}}$$

= 3.5±0.5% at 3.35MeV

Achieved goal !

Measurement of backgrounds from LS



Using subtracted # of events around 2.6MeV and 2.2MeV
^{214}Bi < 4.9x10^{-20}g/g ^{208}Tl < 2.7x10^{-22} g/g
(^{238}U < 6.4x10^{-6} g/g) (^{232}Th < 7.4x10^{-7} g/g) (c.f. KL 10^{-18}g/g)