Development of an imaging detector to reduce the long-lived spallation background in the KamLAND2-Zen experiment

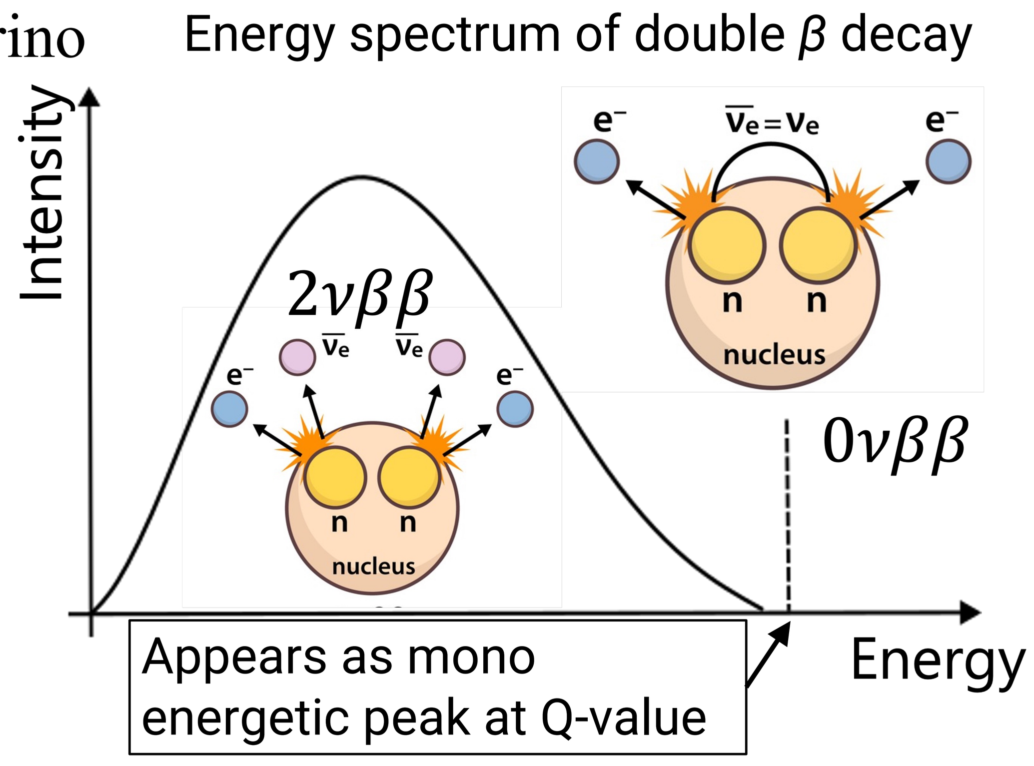
Daiki Morita RCNS
Tohoku Univ. Japan

Abstract Observation of $0\nu\beta\beta$ decay is essential to confirm the Majorana nature of neutrinos, with significant implications for the Standard Model and cosmology. The KamLAND-Zen experiment, which uses a liquid scintillator with dissolved ^{136}Xe, currently provides the most stringent limit on the $0\nu\beta\beta$ half-life & effective Majorana mass. Its successor, KamLAND2-Zen, is under development but faces a challenge: long-lived spallation background caused by cosmic muon interactions with Xe. To address the issue, we designed a new detector to image scintillation spread and evaluated its performance via simulations. The results show the design can reduce spallation background by over 90%.

1. Background & Motivation

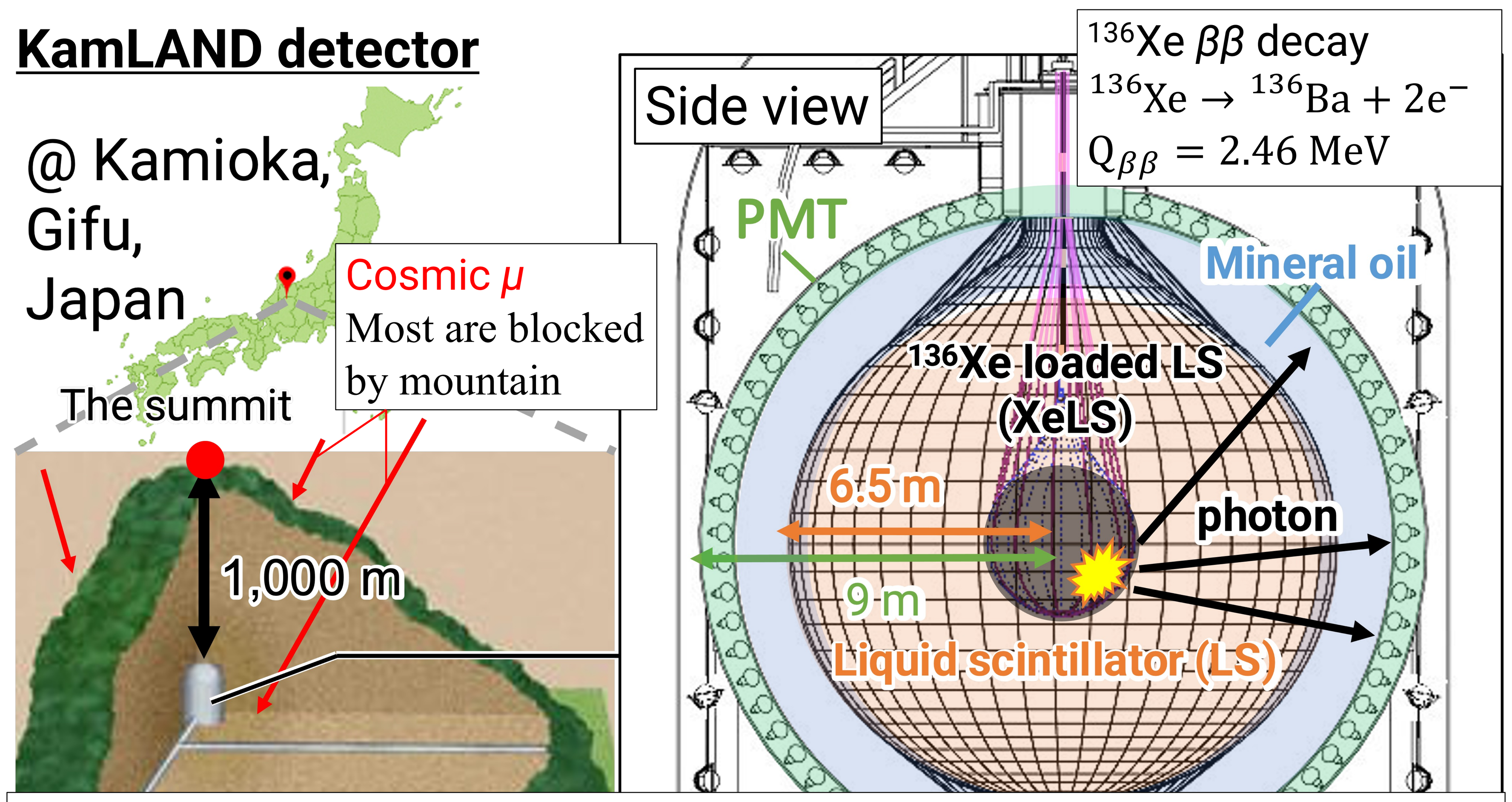
Physics target : $0\nu\beta\beta$ decay

- Double β decay w/o neutrino
- Only happen if neutrino has the Majorana nature
  → Implication for
  - Beginning of Matter dominant universe
  - Neutrino mass
- Very rare event
  To observe $0\nu\beta\beta$, low background environment is needed !



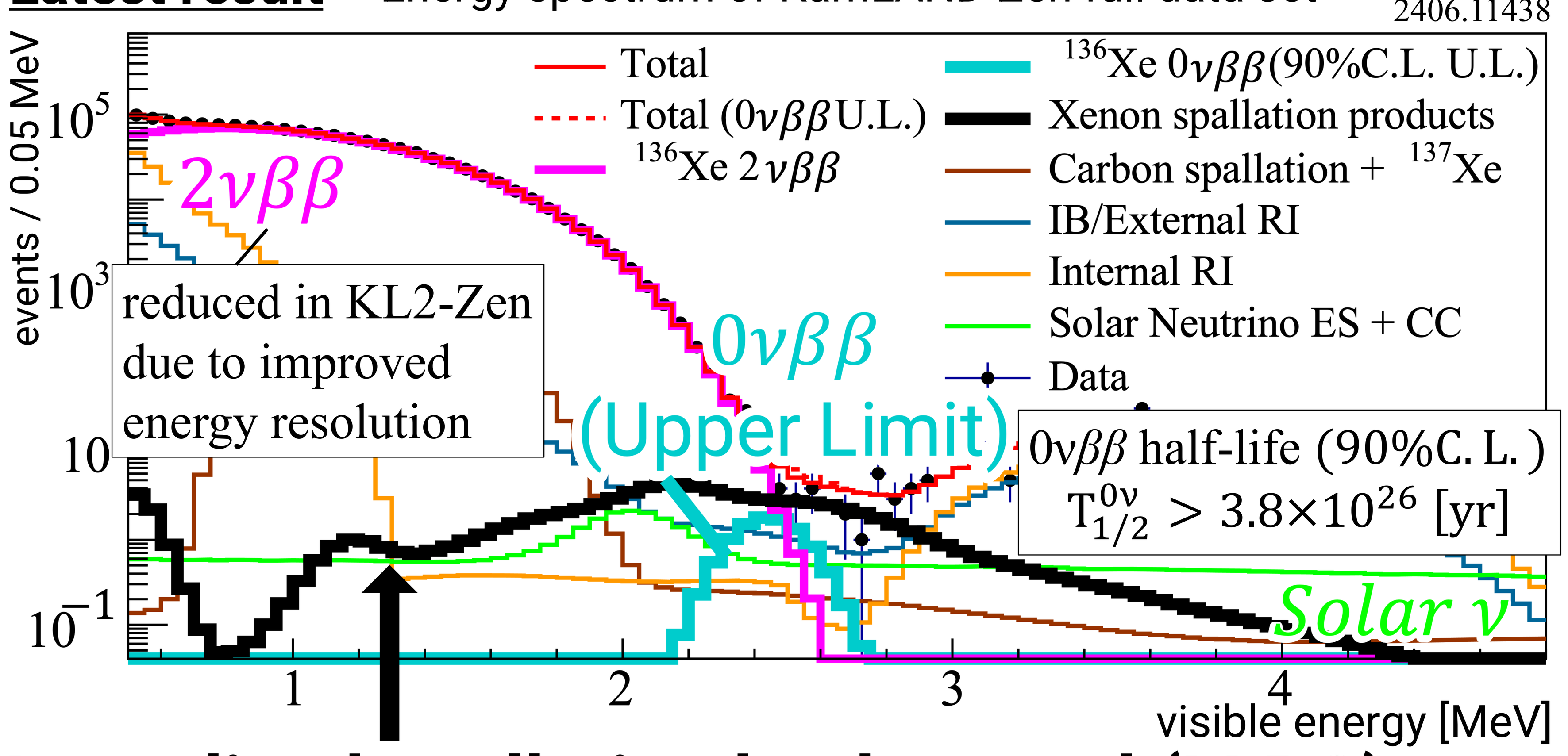
KamLAND-Zen & KamLAND2-Zen

KamLAND detector



KamLAND2-Zen (KL2-Zen) upgrade plan of KamLAND-Zen
- Improving energy resolution due to increased light collection
- Reduction of RI with new equipment
- See also E18 2/18 14:25~ J.Nakane talk

Latest result Energy spectrum of KamLAND-Zen full data set [1] [1] arXiv: 2406.11438



Long-lived spallation background (LLBG)

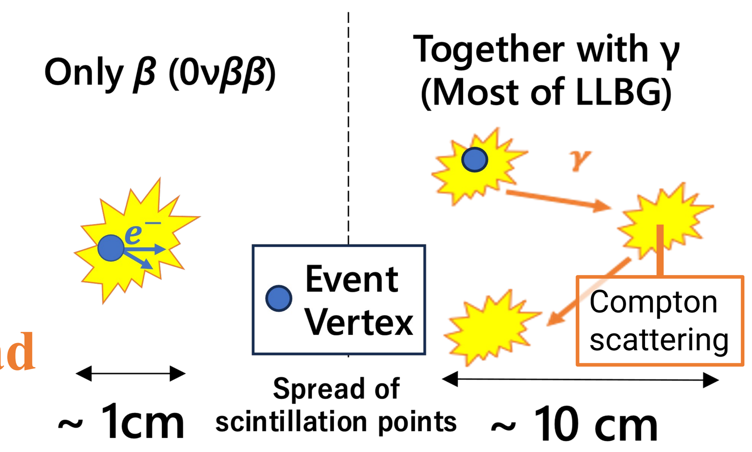
- Xe spallation products by cosmic-μ
  - Long half-life (a few min. ~ days)
  - Generated naturally
- Rejection efficiency is not high in the current detector. (47.1 ± 8.7% [1])
- Expected to be main BG of KL2-Zen

Top 3 of LLBG nuclides	Rate [day⁻¹kton⁻¹(XeLS)] ROI 2.35 - 2.7 [MeV]
^{124}I (EC/β^+ γ)	0.18
^{130}I (β^- γ)	0.17
^{122}I (EC/β^+ γ)	0.11
Total (32 species)	1.06

*estimated by FLUKA & Geant4

New idea for reduce LLBG

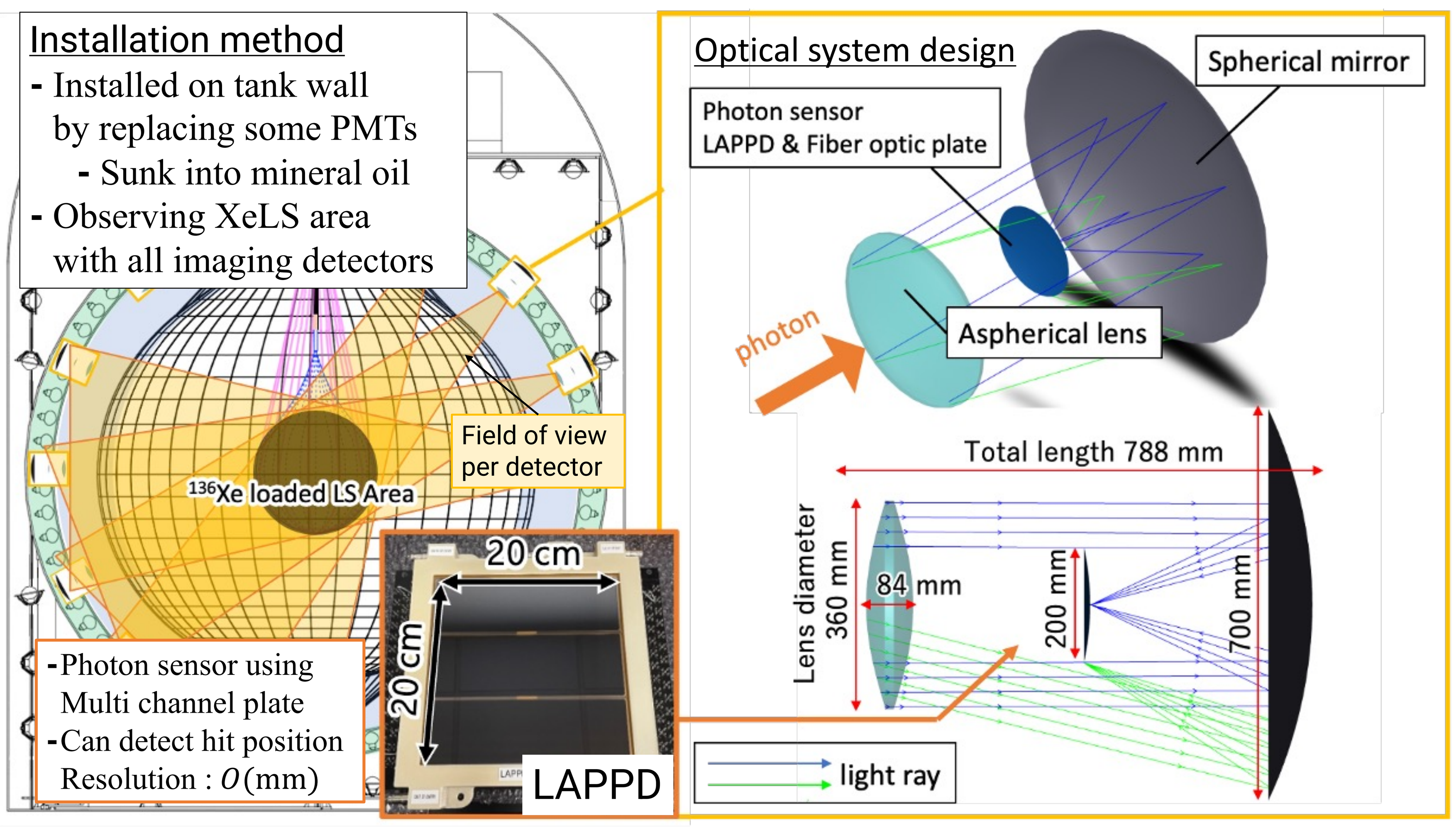
- Identifying events from the spread of scintillation points
  - The spread depends on the particle type.
- **Goal**
  - **Developing method to detect the spread**
  - **Reducing LLBG 90%**



2. Imaging detector development

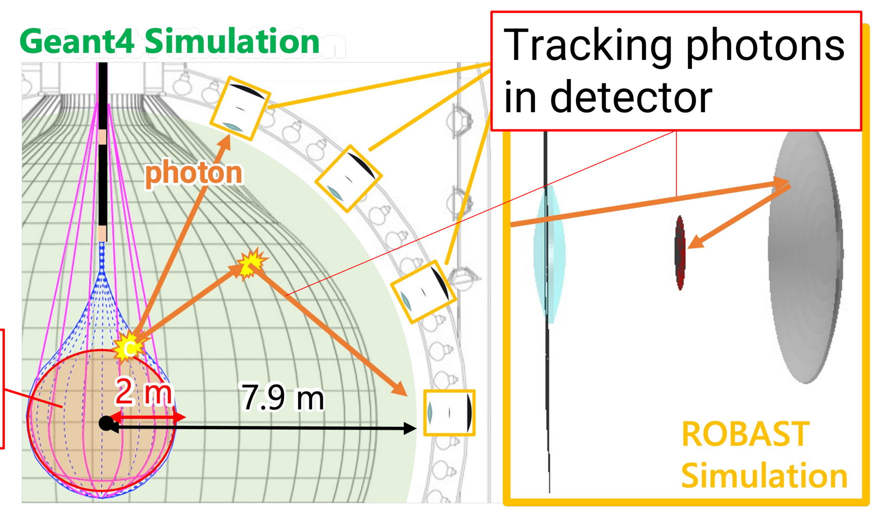
New detector's design

- Designed camera-like detector using with PMTs in KL2-Zen
- It can detect the spatial structure of scintillation by "Imaging"



Estimating performance via simulation

- Simulating decay of nuclides, photon transport and detection, and calculating reduction efficiency from the results



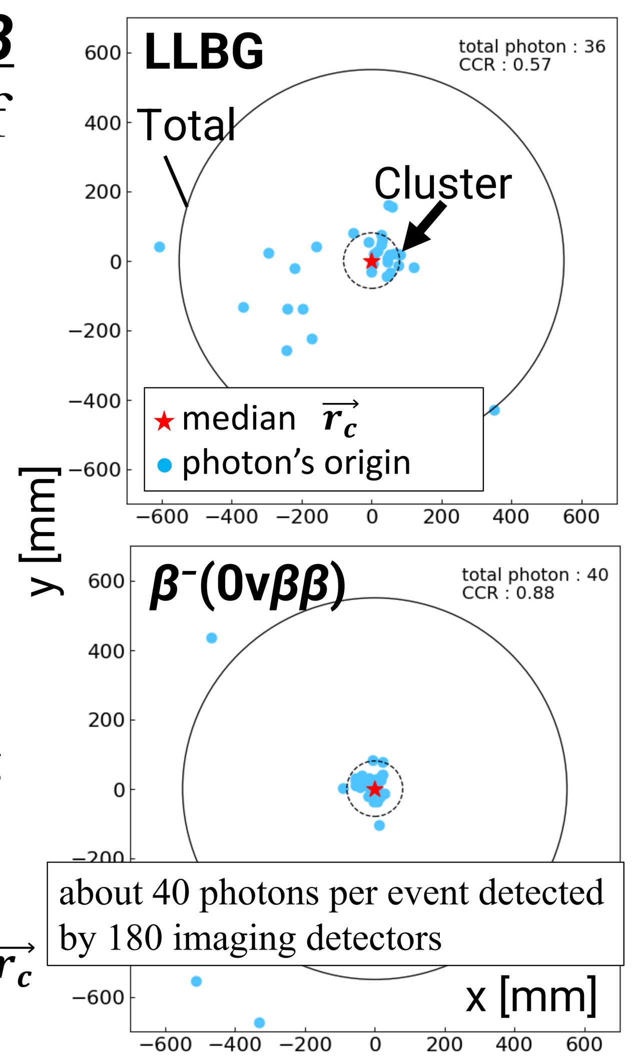
Assumptions
- 180 of imaging detector using (10% of PMTs replaced)
- KL2-Zen environment (1.5k p.e./MeV, PMT & imaging detector)

Method to discriminate LLBG from $0\nu\beta\beta$
- "CCR" is defined to describe the spread of scintillation points quantitatively

1. Reconstruct the origin of each photon detected by the imaging detectors
2. Determine the median ($\vec{r_c}$) of each photon's origin
3. Categorize all photon's origin into "cluster", "total", or other based on its distance from $\vec{r_c}$
4. Calculate CCR

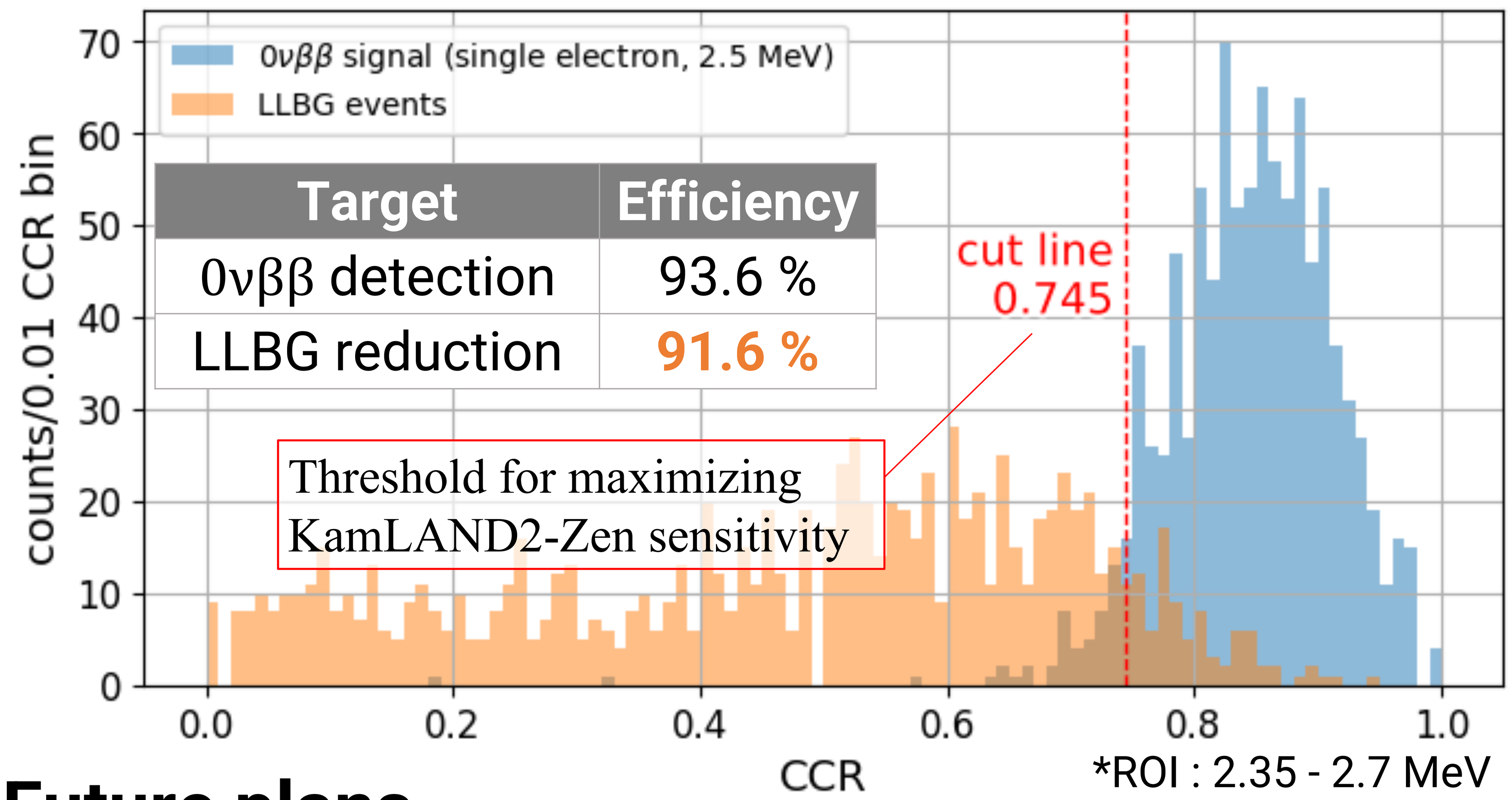
$$\text{Cluster Charge Ratio (CCR)} = \frac{N_{Cluster}}{N_{Total}}$$

5. Set the threshold from the FoM calculation assuming LLBG as the main BG of KL2-Zen, classifying high CCR as β-like and low CCR as LLBG-like



(Right figs) Ex. of distance distribution from $\vec{r_c}$ to reconstructed photon's origin (simulation)

Result CCR distribution (1,000 events)



Target	Efficiency
0νββ detection	93.6 %
LLBG reduction	91.6 %

Future plans

- Building the prototype with this design
- Testing the principle in a lab.

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Author mail address : morita@awa.tohoku.ac.jp