Geo-neutrino observation in KamLAND & new detectors

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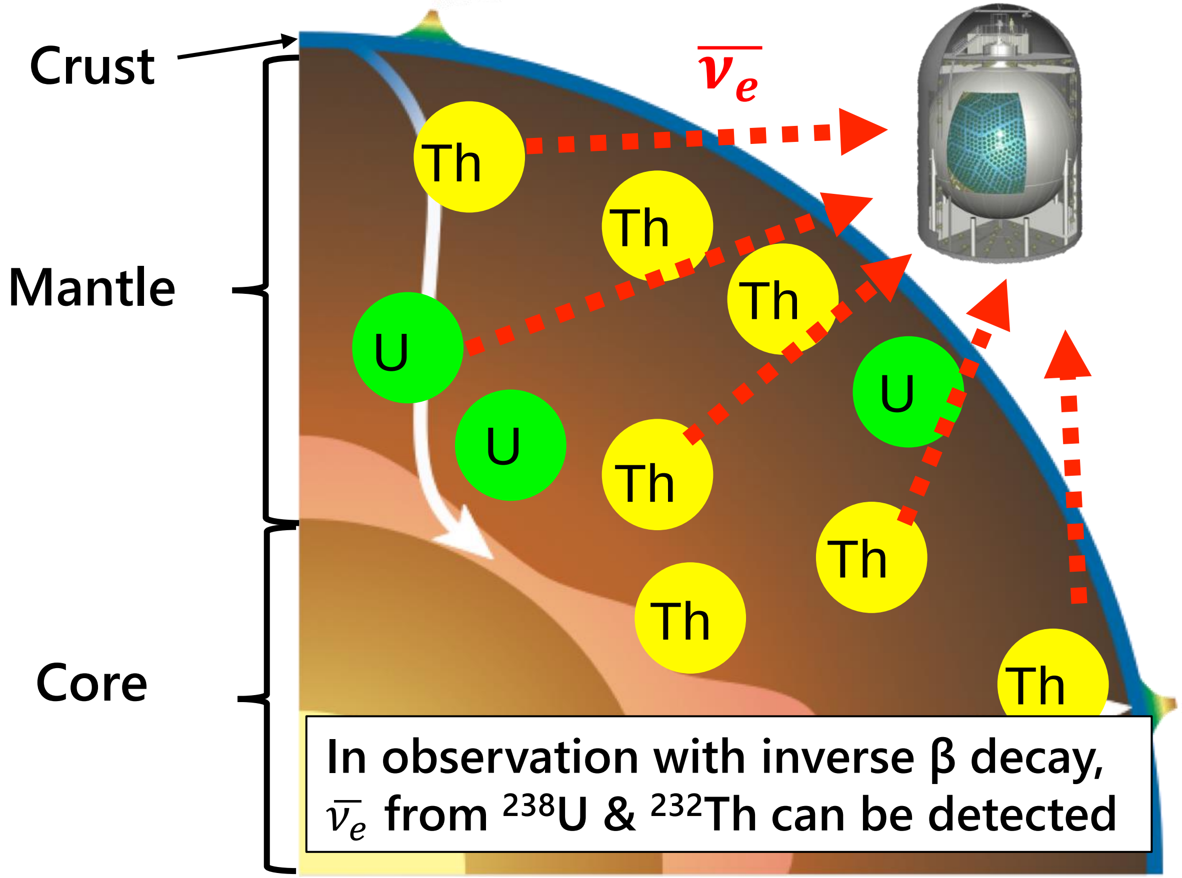
Introduction : Geo-ν overview

- Geo-ν is $\bar{\nu}_e$ from β decay of isotopes in the Earth, especially $\bar{\nu}_e$ from ^{238}U & ^{232}Th.
- Geo-ν can directly measure the amount of Earth's engine power source.

Earth's structure & Geo-ν



In observation with inverse β decay, $\bar{\nu}_e$ from ^{238}U & ^{232}Th can be detected

Earth's heat

Primordial heat
The residual heat from Earth's formation

+

Radiogenic heat
Energy from radioactive decay

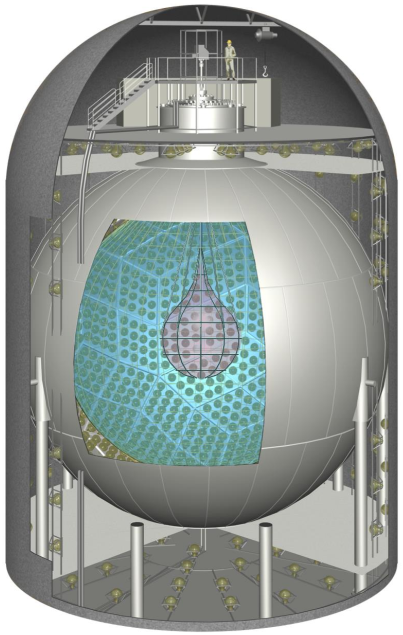
These heat drives
- Mantle convection
- Geomagnetism
- Plate tectonics

However, these ratio and distribution are unknown…

Q : How do we measure ?
→ Geo ν flux is proportional to U & Th
→ The amount of radiogenic heat can be estimated!

Today’s outline

- I will talk about status of KamLAND Geo-ν observation and new detector ideas for more precise measurements.



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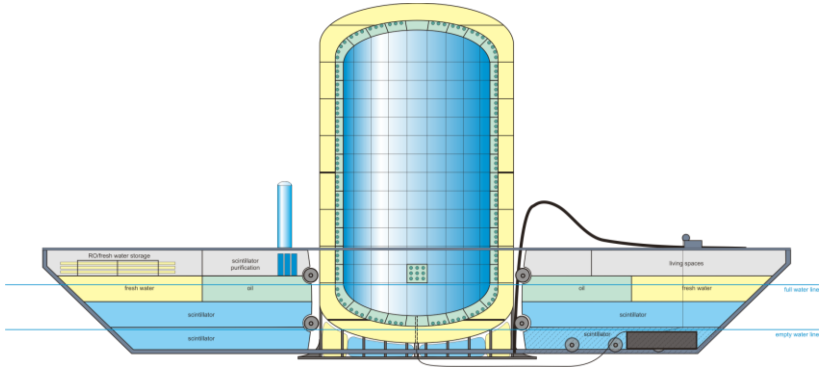
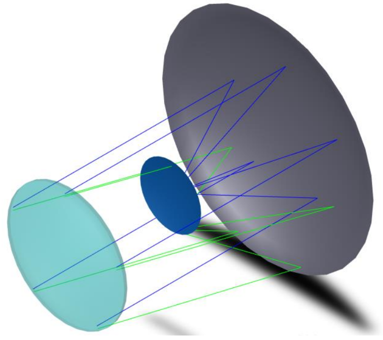
2. New detectors
   - OBD : Ocean bottom detector
   - Imaging detector



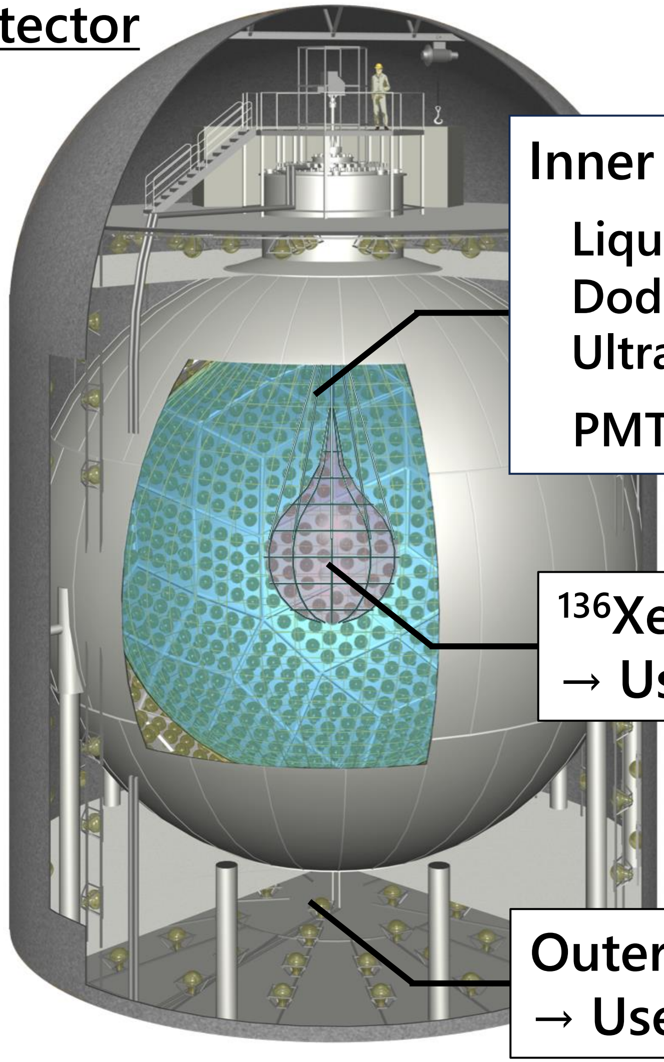


1. Geo-neutrino observation in KamLAND

KamLAND Kamioka Liquid Anti-Neutrino Detector

- Large liquid scintillator detector in ultra-low radioactivity environment

Detector



Inner detector

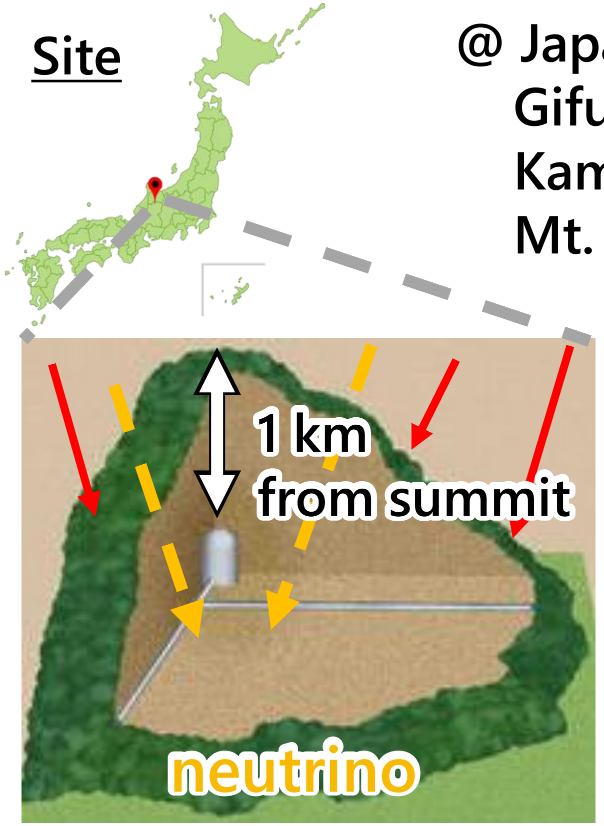
Liquid scintillator : 1 kt
Dodecane (80%) + PC (20%) + PPO
Ultra low impurity

PMT : 17inch 1,325 + 20inch 554

^{136}Xe loaded scintillator (2011~)
→ Used for 0νββ observation

Outer detector : Water Cherenkov
→ Used for Muon veto, shield

Site



@ Japan,
Gifu,
Kamioka,
Mt. Ikenoyama

cosmic-μ

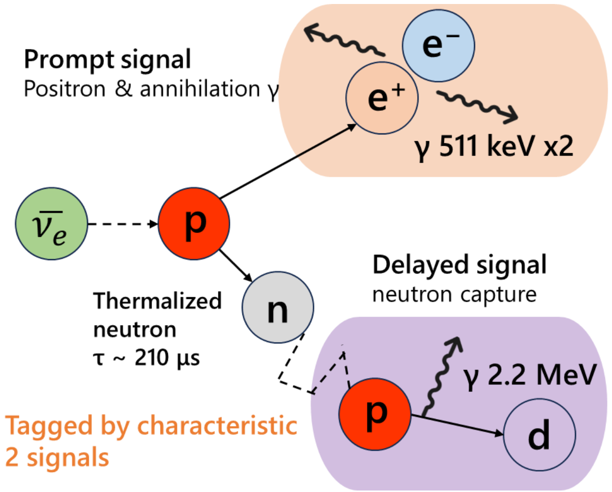
Status

DAQ has been completed in this August !!

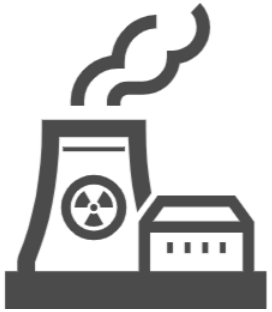
How to observe $\bar{\nu}_e$ & Background events

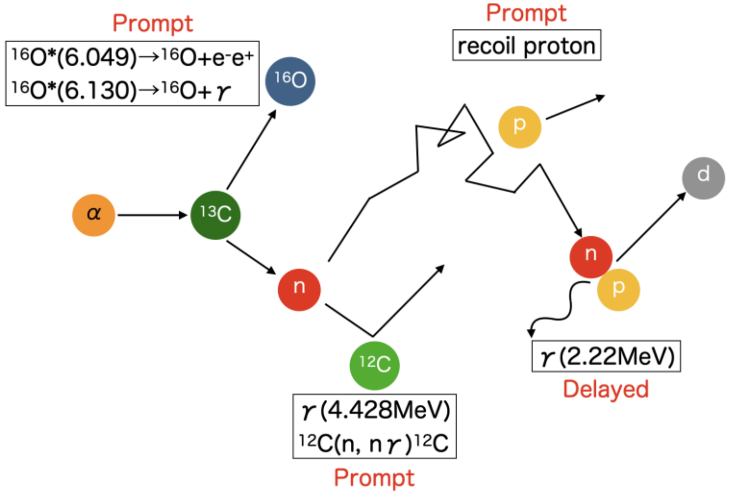
- KamLAND observes $\bar{\nu}_e$ by delayed coincidence (DC).
- Reactor ν, $^{13}C(\alpha,n)^{16}O$, Spallation, Accidental are main background of Geo-ν observation.

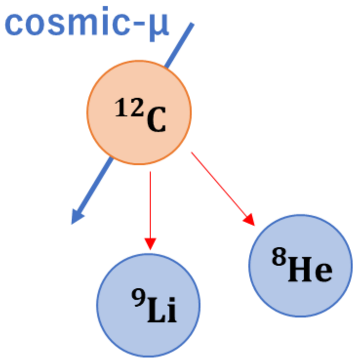
Delayed coincidence

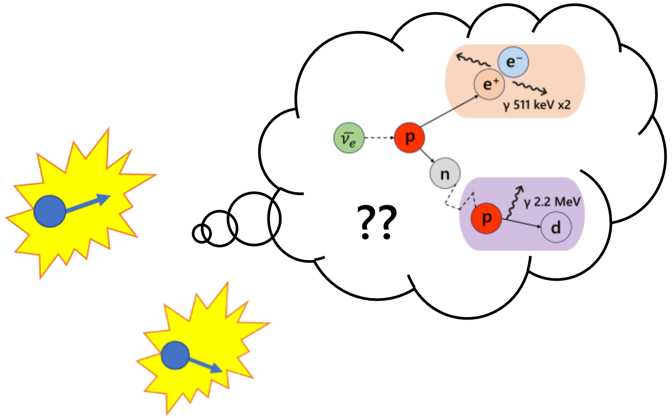


Background of Geo ν observation (Representative)









Reactor ν

$\bar{\nu}_e$ from reactor

$^{13}C(\alpha,n)^{16}O$

Series of reactions triggered by α decay of radioactive impurities

Spallation from ^{12}C

β^-+n reaction by nuclei produced from crushed ^{12}C

Accidental

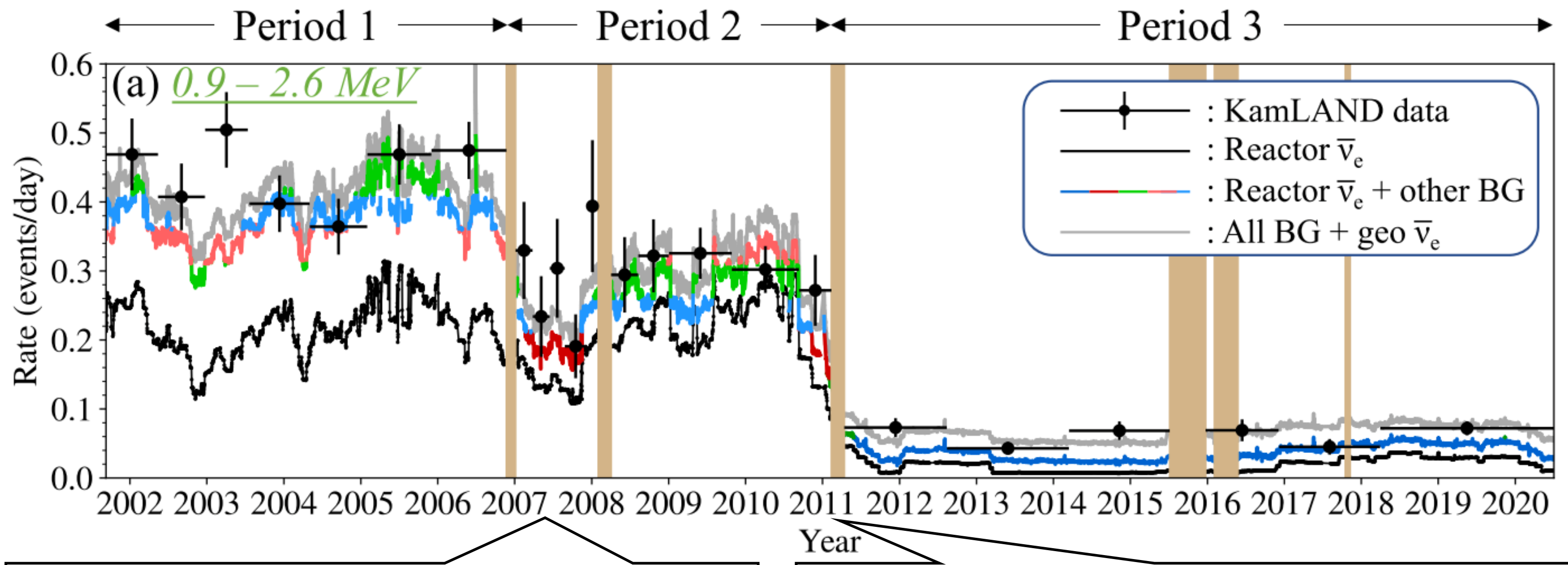
Not inverse β decay event, but two events which meets delayed coincidence selection

Latest result : Energy spectrum & Event rate trend

Abe et al.(2022), GRL,49,e2022GL099566.

- KamLAND achieved Geo-ν observation with low BG.

Event rate trend

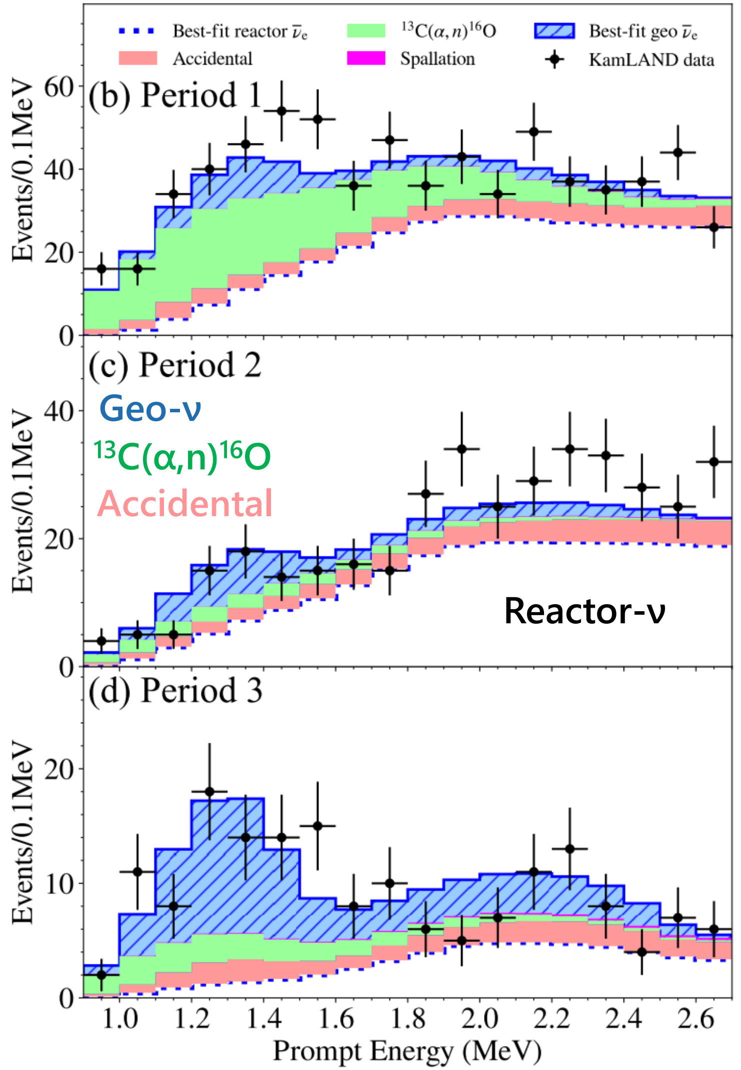


Liquid scintillator distillation
→ Reducing radioactive impurity

Huge earthquake occurred in Japan
→ stopped Most of Japan reactors
→ Reactor ν was decreased

Dataset : Mar, 2002-Dec, 2020
Livetime : 5,227 days
(low-reactor phase : 2,590 days)

Energy spectrum (best fit)

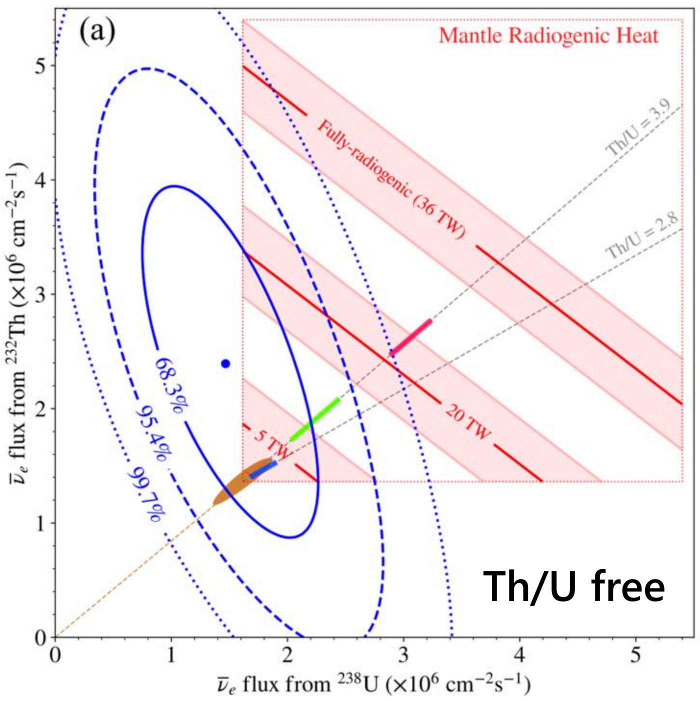


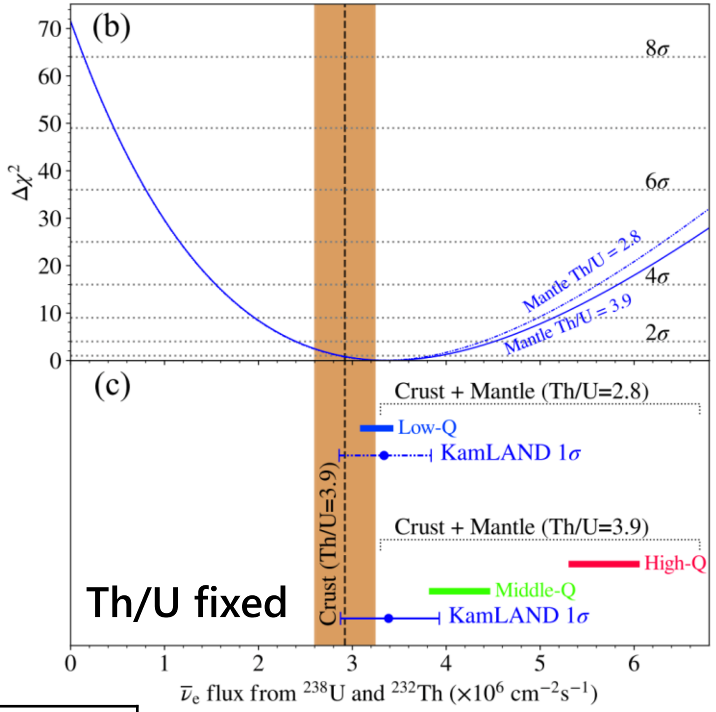
Latest result : Neutrino flux from ^{238}U & ^{232}Th

Abe et al.(2022), GRL,49,e2022GL099566.

▪ KamLAND constrained heat contribution from U & Th.

Best fit for ^{238}U & ^{232}Th Geo-ν flux





	N of event	0 signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+31}_{-29}	8.3σ

High-Q (Rich-H) rejected at 99.76 % C.L. (homogeneous mantle)

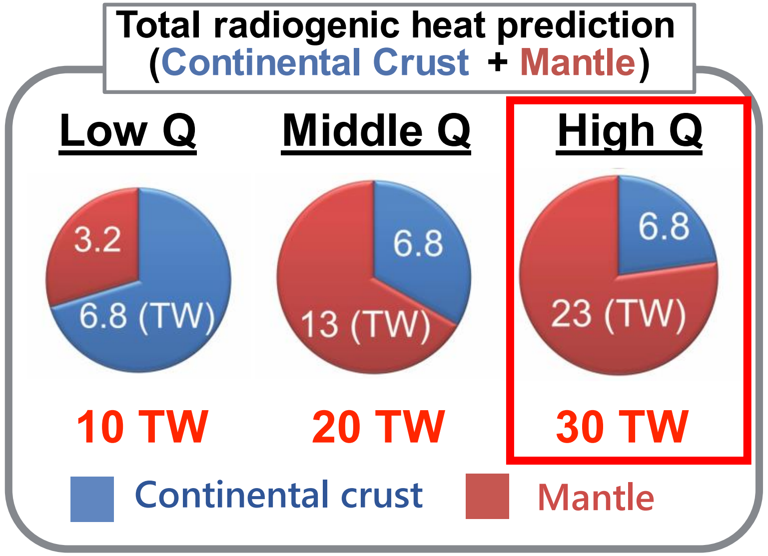
97.9% C.L. (concentrated at CMB)

Radiogenic heat calculation

Adding heat estimate from crust

^{238}U : 3.35 TW ^{232}Th : 3.61 TW

$$Q^{U} = 3.3^{+3.2}_{-0.8}\ \text{TW}$$
$$Q^{Th} = 12.1^{+8.3}_{-8.6}\ \text{TW}$$
$$Q^{U} + Q^{Th} = 15.4^{+8.3}_{-7.9}\ \text{TW}$$



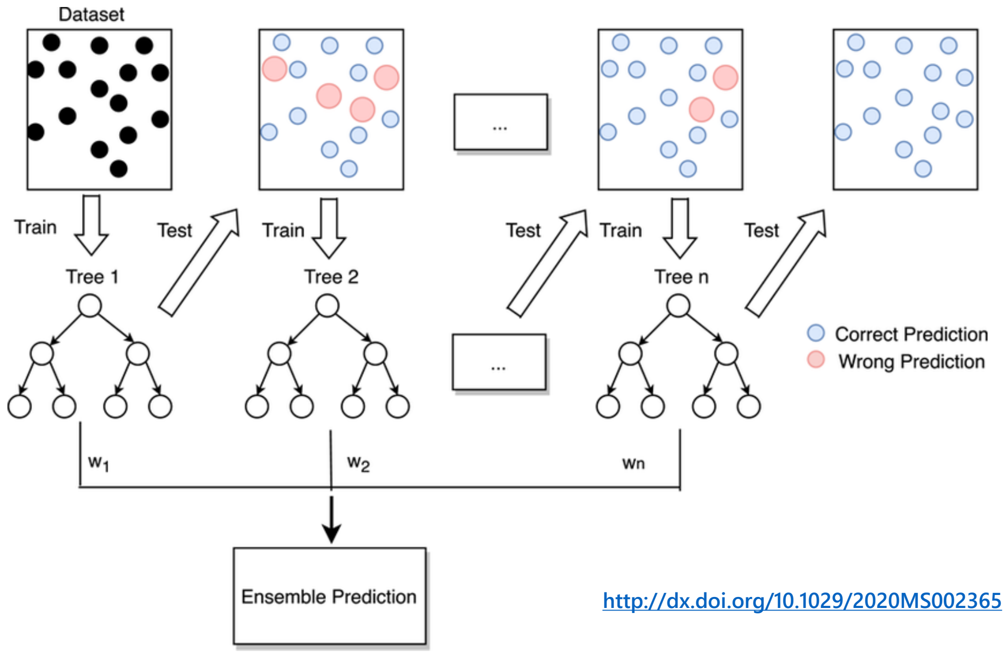
Near future : BG reduction with machine learning

- Gradient boosting decision tree is powerful algorithm for BG reduction.

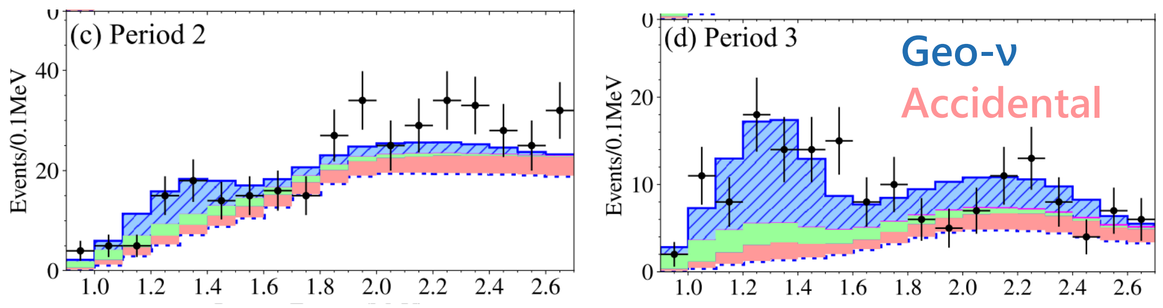
GBDT: Gradient Boosting Decision Tree

- Machine learning model using
  - **Decision tree**
    Model that breaks down data into hierarchically smaller subset based on the data's features
    It becomes tree like structure
  - **Boosting**
    Creating weak learner (e.g. decision tree) iteratively to correct the errors in previous learning result
  - **Gradient descent**
    Optimization algorithm used to minimize a function
    In GBDT, iteratively adding correction value to prediction

- Can be used for regression, classification
  → being applied to accidental BG reduction



http://dx.doi.org/10.1029/2020MS002365

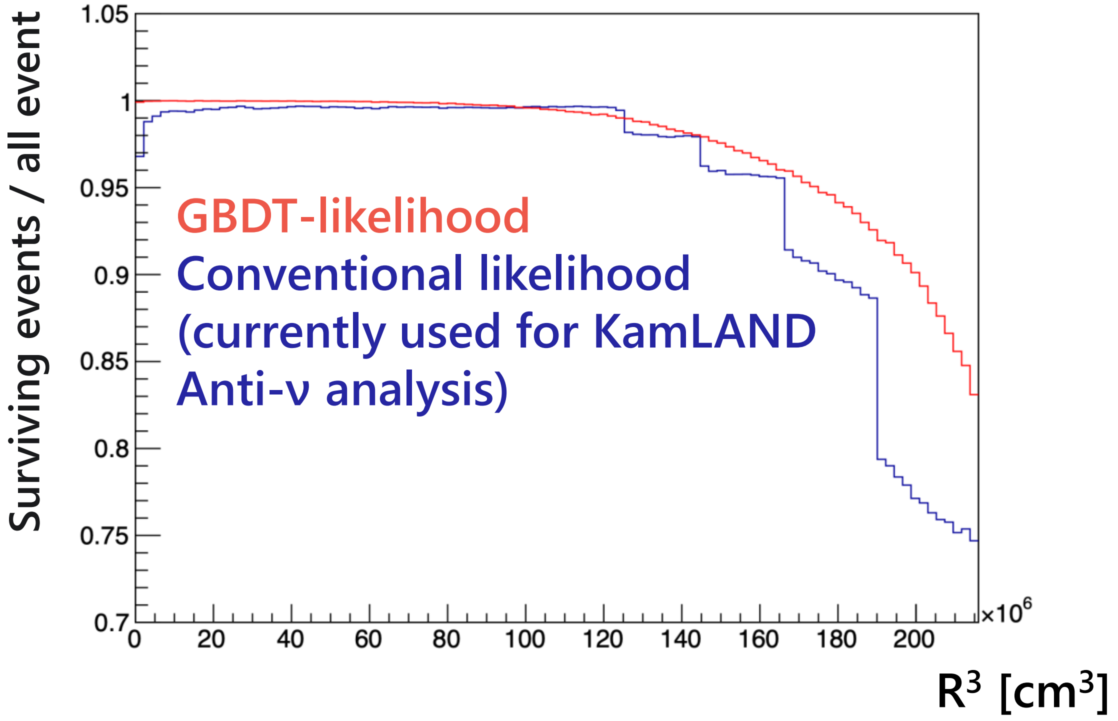


prompt energy [MeV]

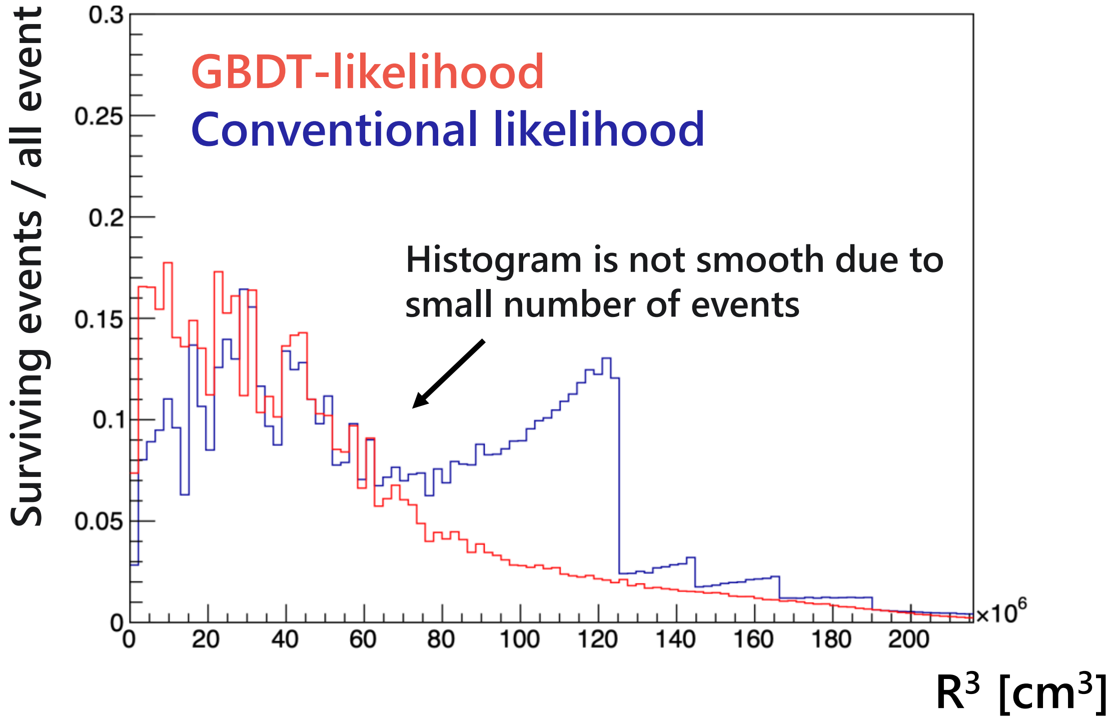
Accidental background identification with GBDT

- GBDT remarks higher reduction efficiency than conventional likelihood.

Anti-neutrino signal (MC)



Accidental background (off-time delayed coincidence)



GBDT-likelihood using $(E_p, X_p, Y_p, Z_p, E_d, X_d, Y_d, Z_d, \Delta R, \Delta T)$

conventional likelihood PDF using $(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$

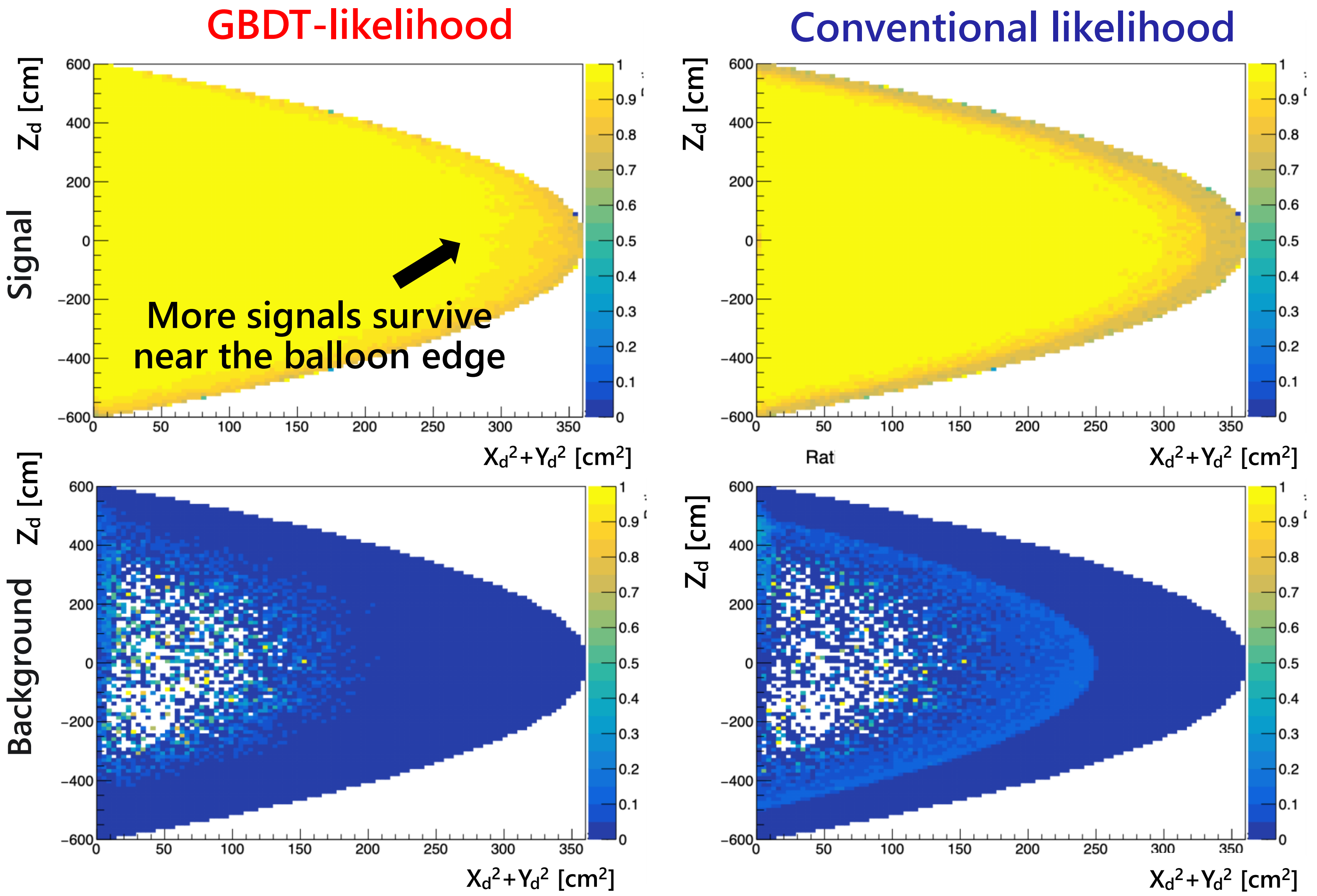
When GBDT use, Accidental : 40 % decrease

Signal : 8 % increase

Accidental background identification with GBDT

Distribution of remaining ratio in KamLAND

Z axis $= \dfrac{\text{Surviving events}}{\text{All event}}$



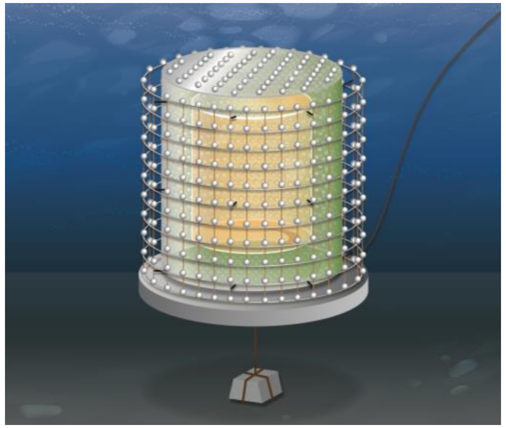
GBDT improves sensitivity !→ KamLAND full data analysis with GBDT is ongoing !

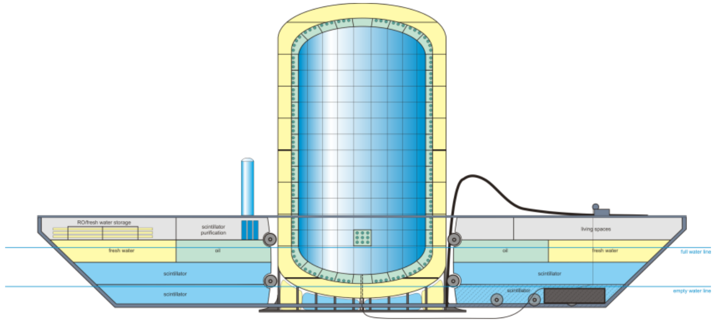
2. New detector

Challenge for more precise Geo-ν observation

- Large uncertainty of ν from crust
  - Geo-ν comes from mantle & crust.
  - Uncertainty of crustal flux model is larger than that of Geo-ν observation.
    → difficult to obtain insight on the mantle
  - Continental detectors have ~20% contribution from crust

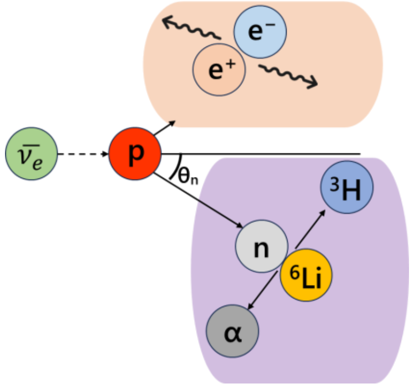
Ocean bottom detector

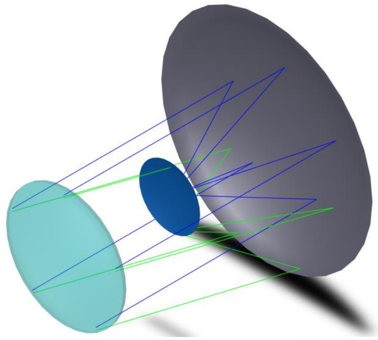




- Reactor ν identification
  - Reactor ν and Geo-ν make same signal in liquid scintillator.
  - However, arrival direction is different.

$\bar{\nu}_e$ direction detection with imaging (imaging detector)





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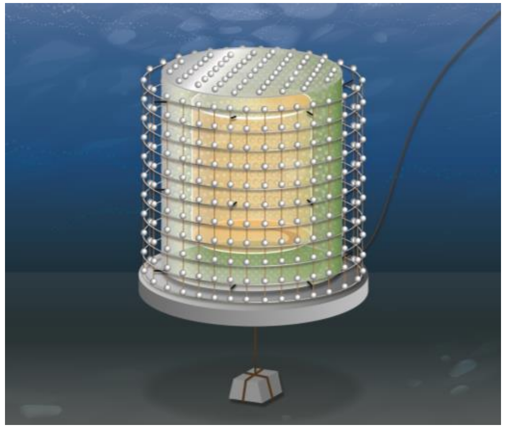

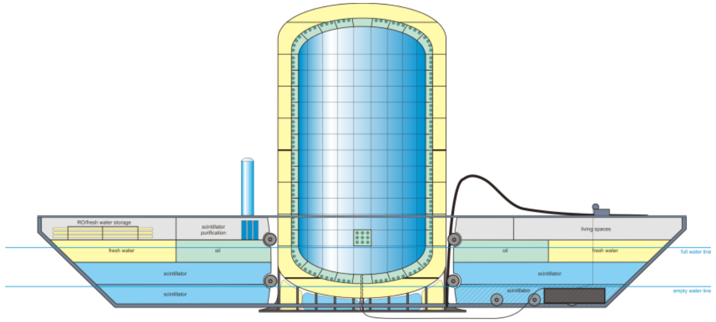

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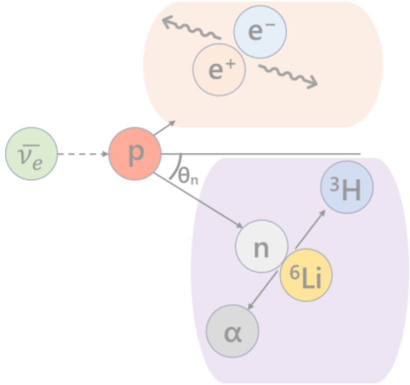
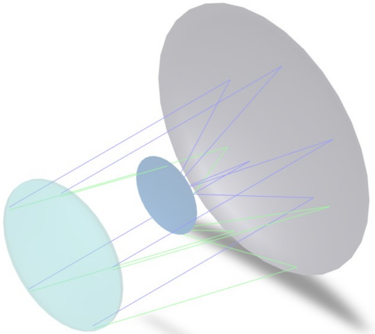




OBD Ocean Bottom Detector

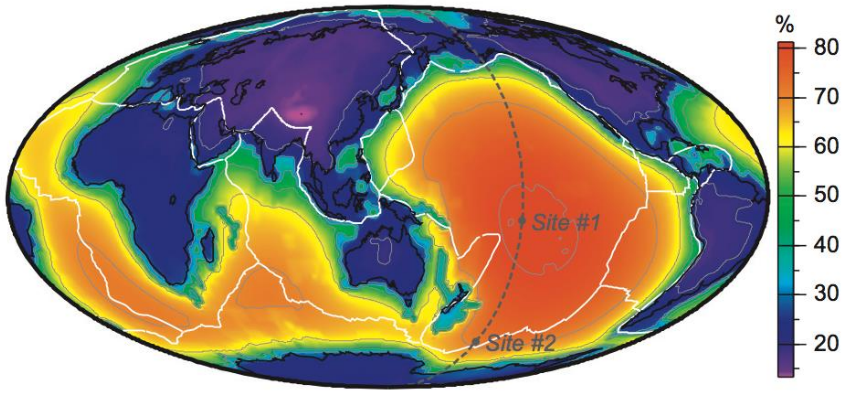
- Liquid scintillator detector in deep sea to observe Mantle Geo-ν

Merit of Geo-ν observation in deep sea

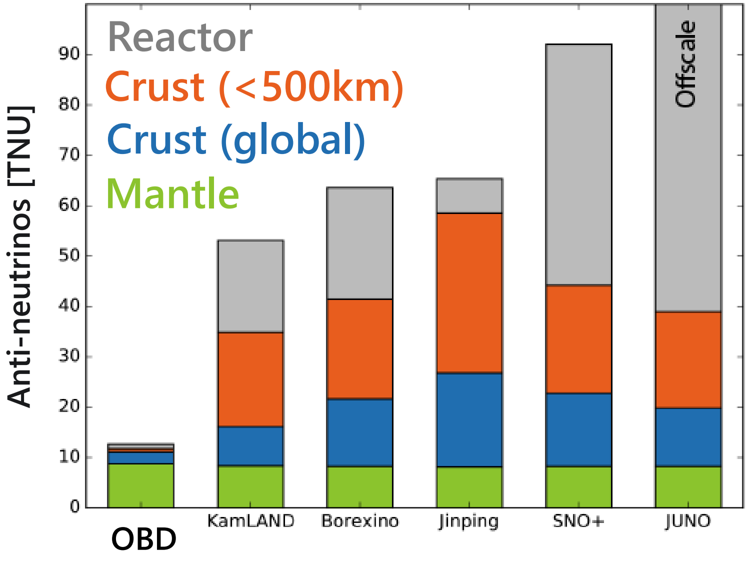
- Oceanic crust is thinner than continental crust
- U & Th in oceanic crust is lower than continental crust
  → Mantle ν contribution is greater than in continental observation
- Far away from any reactors
  → Low BG environment

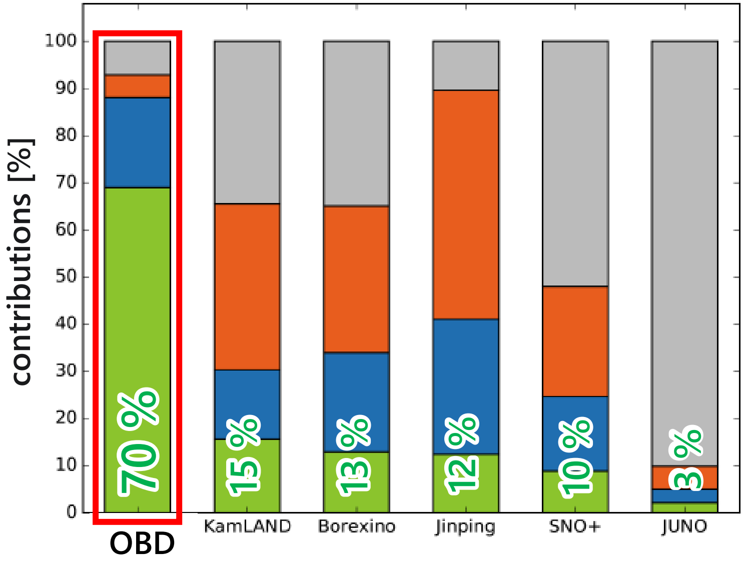
Ocean bottom is suitable site for Mantle ν observation.

Ratio of Geo ν flux : Mantle/Total



Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001





R&D of OBD

- Protype detector is now R&D phase.

Goal of OBD

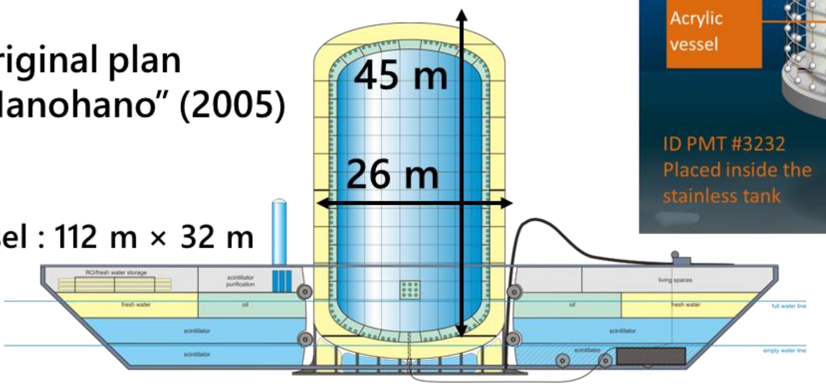
- 10 ~ 50 kt of liquid scintillator
- 1 ~ 5 km under the pacific ocean
- Movable

Current progress

- Researching property of detector component
- Planning to begin prototype detector (~20kg LS) testing in deep sea within 1 year

Intermediate target
1.5 kt design OBD

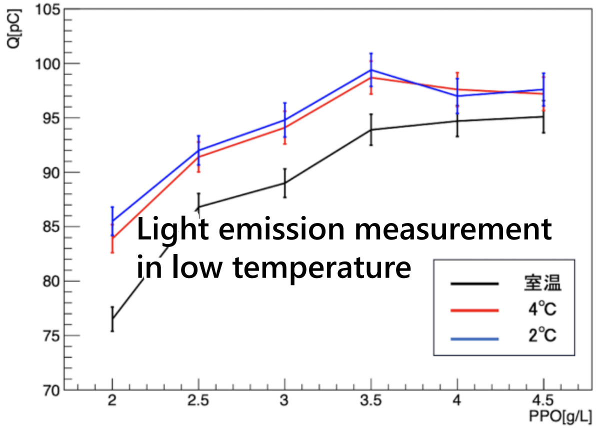
Original plan
"Hanohano" (2005)



Vessel : 112 m × 32 m

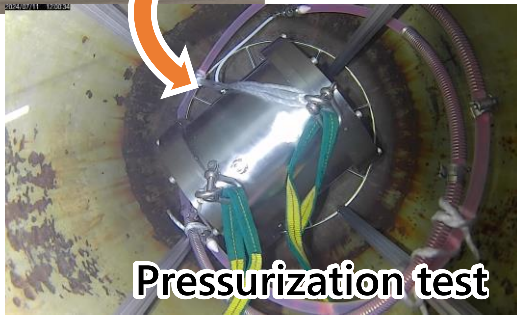
U. Hawaii & Makai Ocean Engineering

Liquid scintillator R&D

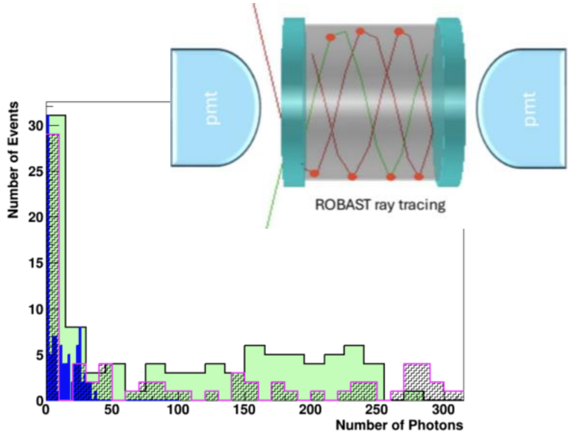


Pressure test for the component

Compensation tube
for LS volume decreasing



Photon simulation



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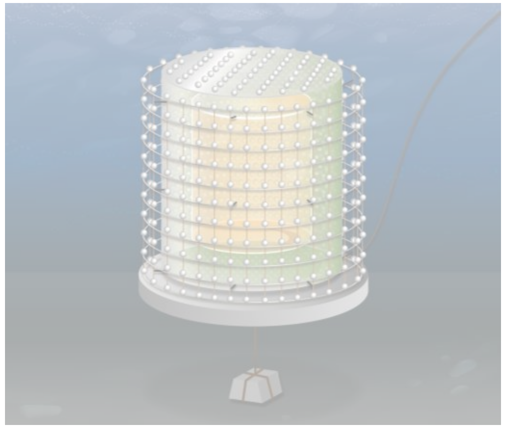
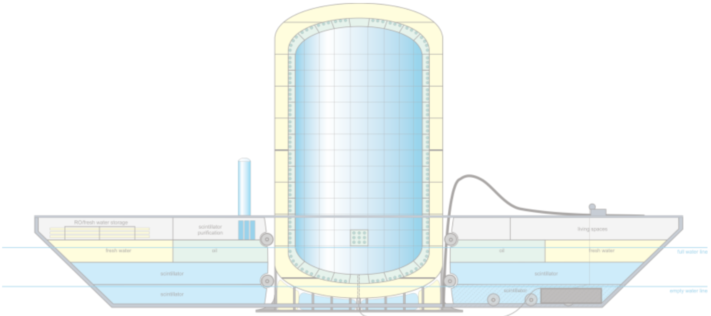
Ocean bottom detector





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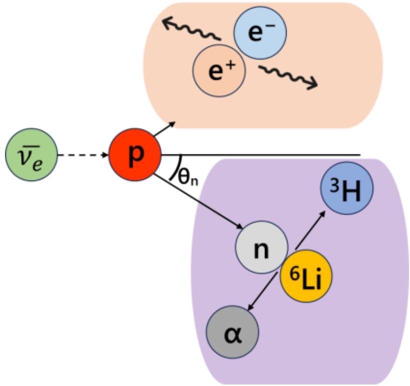
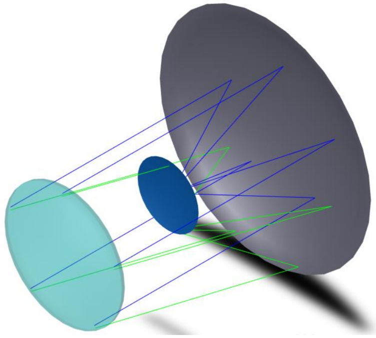
$\bar{\nu}_e$ direction detection with imaging (imaging detector)



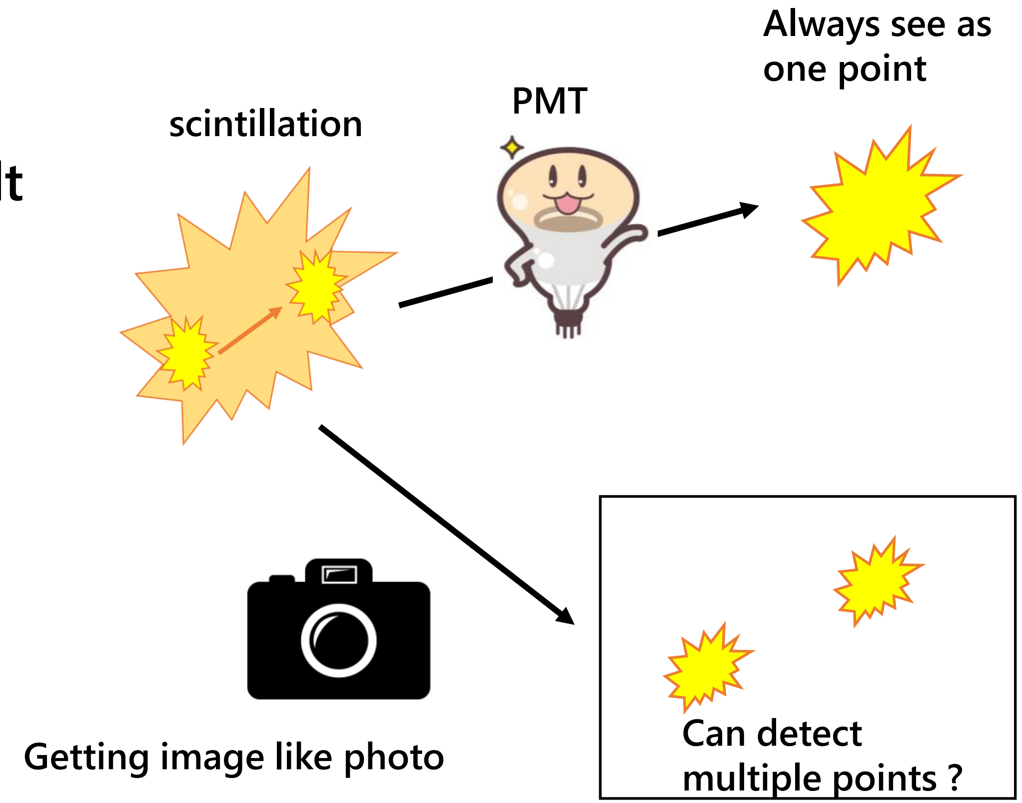


Concept of imaging detector

▪ Camera-like detector to image scintillation directly

<u>Current KamLAND (by PMT) detection</u>

- Event vertex is reconstructed from the time difference between photons being detected by each PMT.
  → Vertex resolution : $\frac{13.7}{\sqrt{E\ [\mathrm{MeV}]}}\ [\mathrm{cm}]$
- Assuming scintillation occurs at one point
  → Detecting microstructure of scintillation is difficult



By imaging scintillation directly,
imaging detector may improve vertex resolution
and detecting microstructure of scintillation

$\bar{\nu}_e$ direction detection with imaging scintillation

- Improved vertex resolution through imaging enables $\bar{\nu}_e$ direction detection

Principle of direction detection

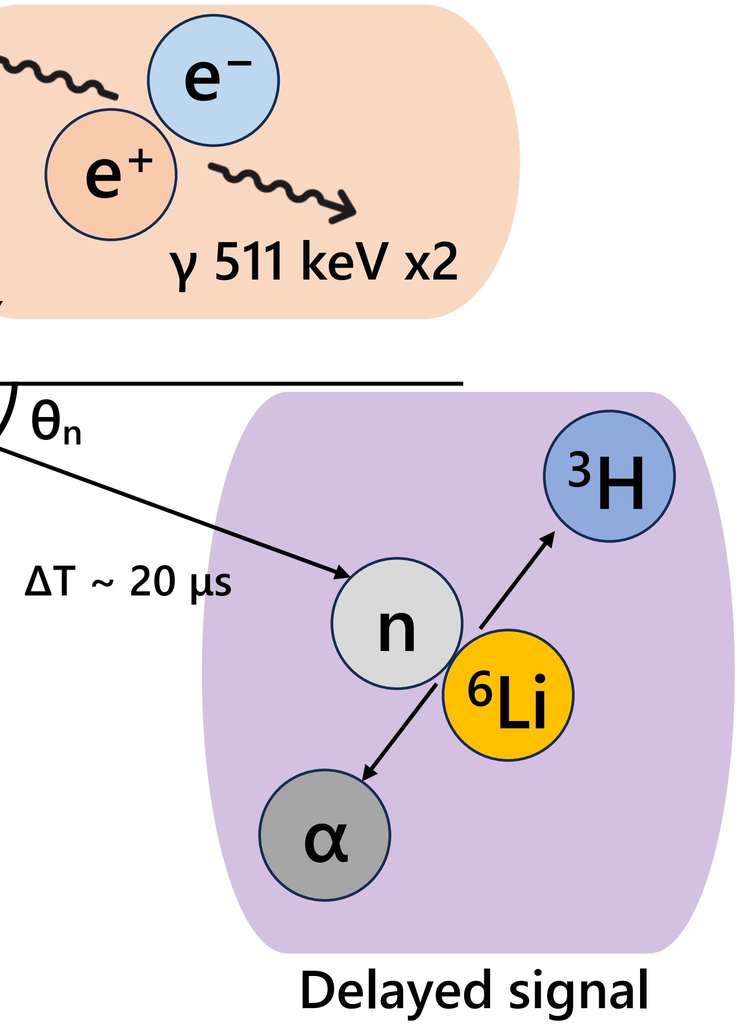
- If cross section for neutron capture becomes large, capture time becomes shorter. (e.g. ^{6}Li-doped LS)
- Neutron conserves initial ν's momentum, so initial ν's direction can be regarded as the direction connecting prompt signal's and delayed signal's vertex.

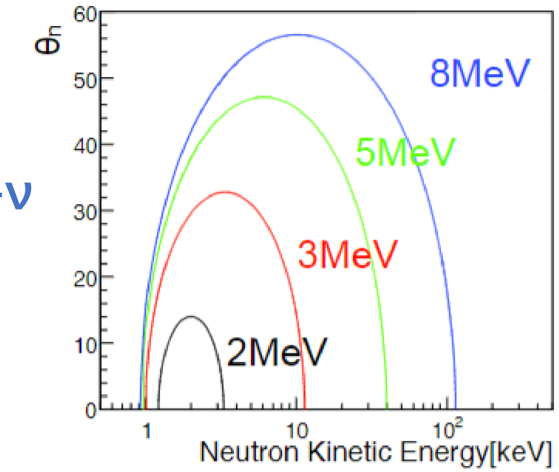
- However, it needs more vertex resolution. $O(1\ \mathrm{cm})$

▼

Imaging improves the vertex resolution.
Becoming distinguishable Reactor ν and Geo-ν
Keeping research

Inverse β decay in ^{6}Li-doped liquid scintillator

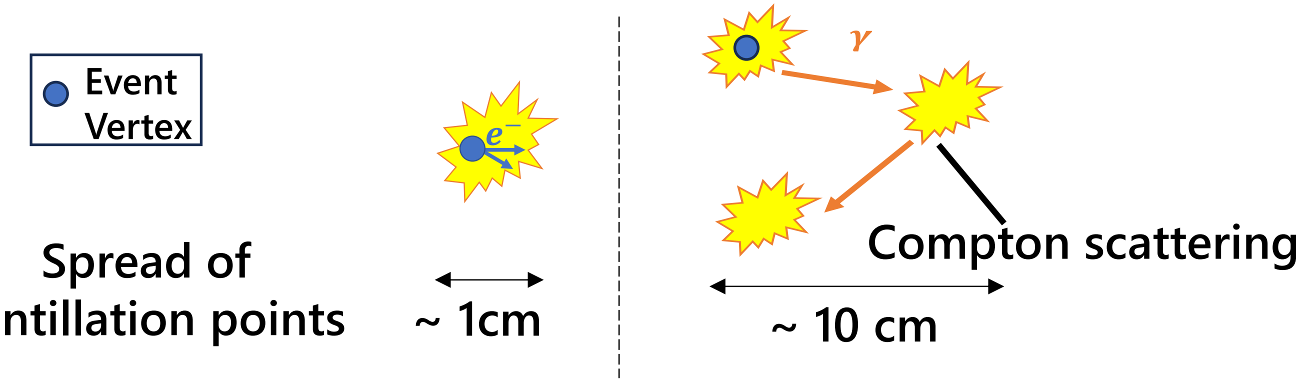




Another application of imaging detector

- Imaging technics also can be applied to particle identification.

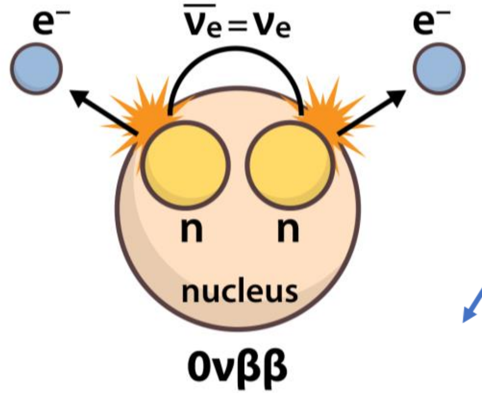
Difference of scintillation



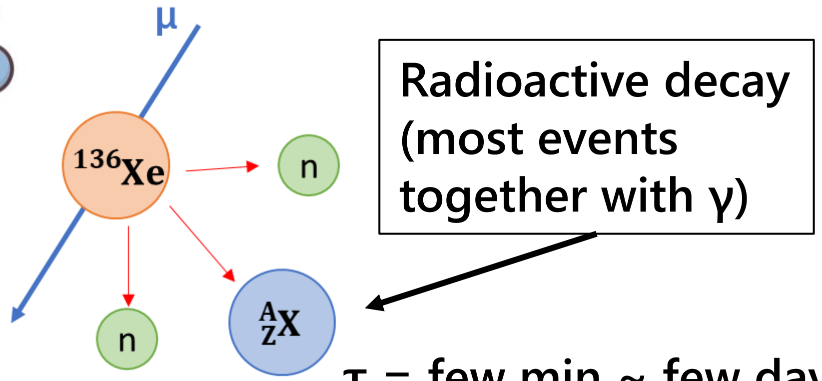
By capturing the spread of the emission, β and γ may be distinguishable.

Application BG reduction for 0νββ observation

Signal

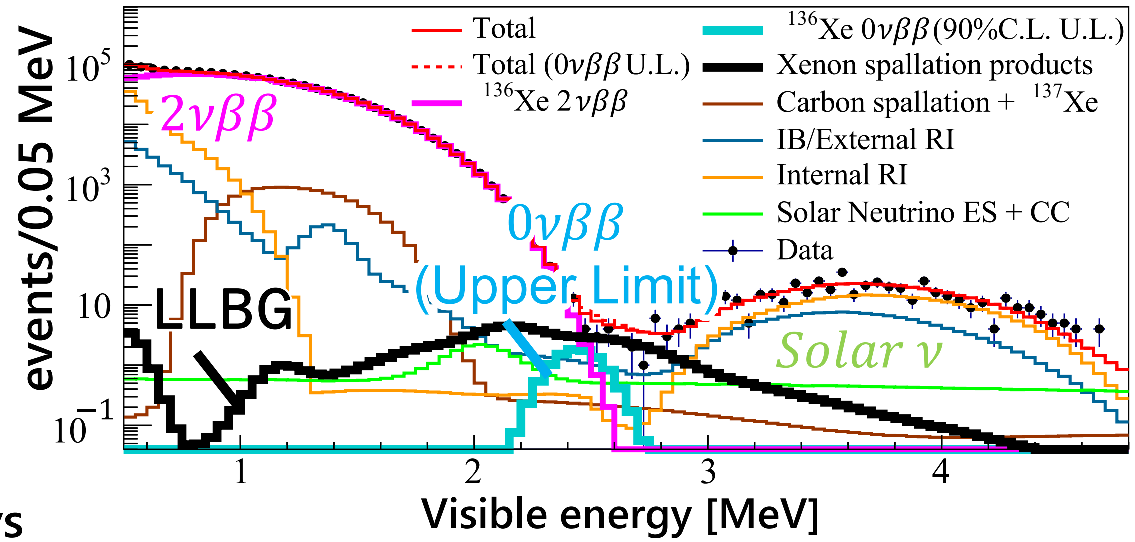


BG : long-lived spallation (LLBG)

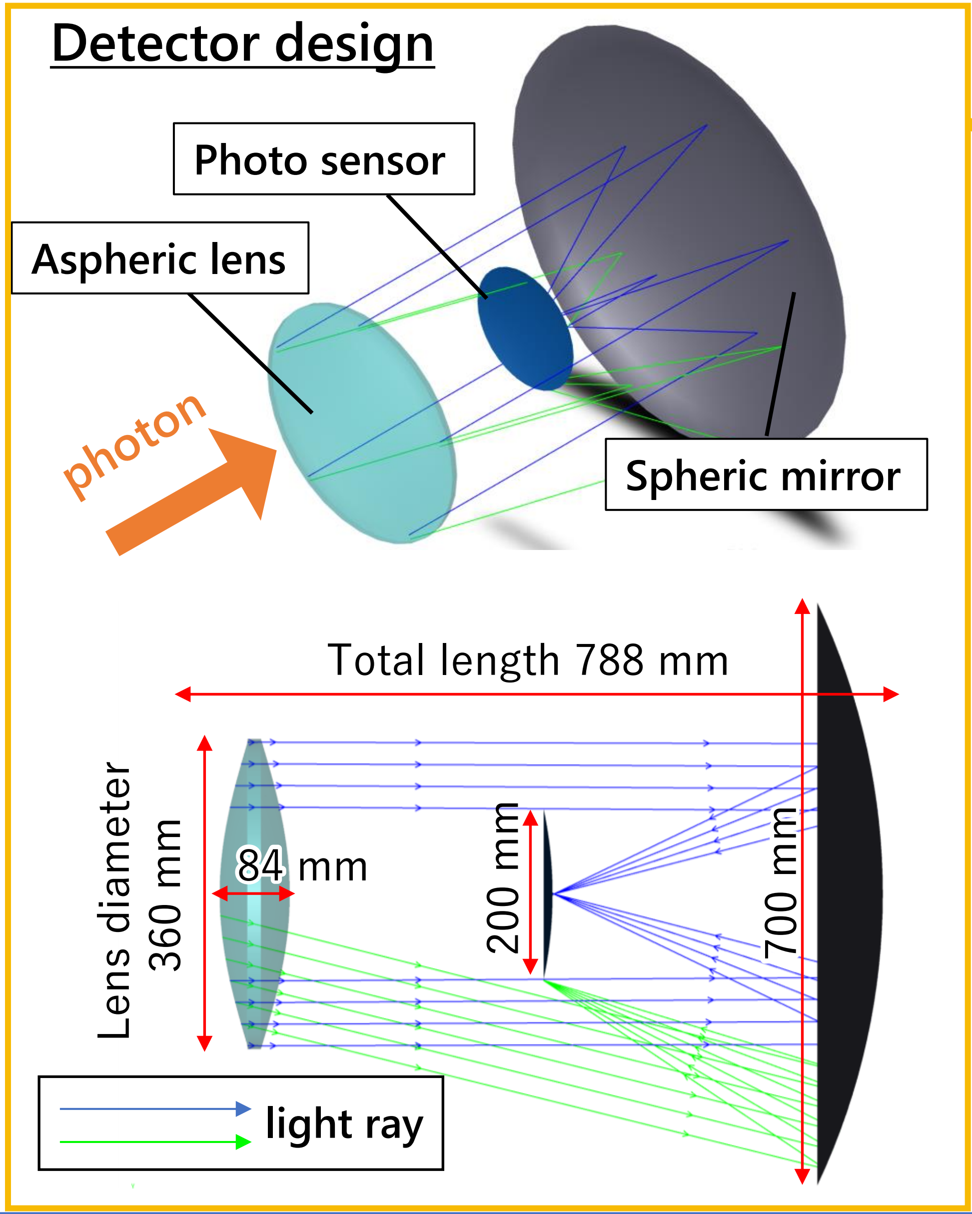


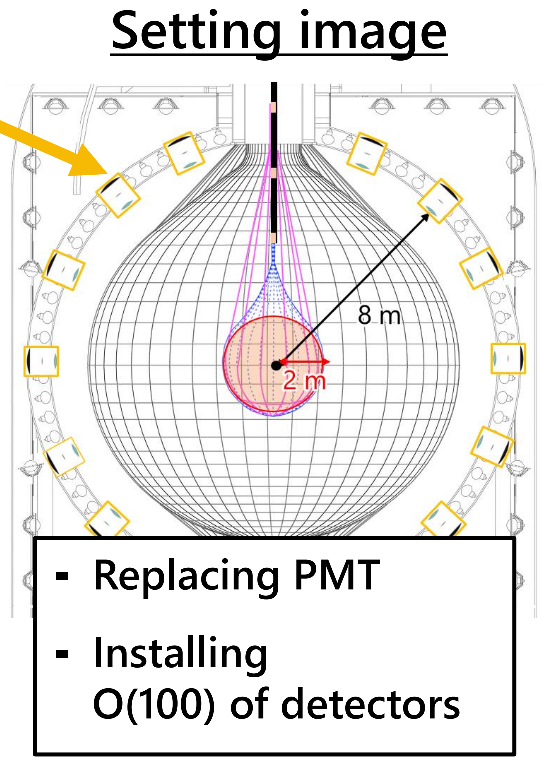
τ = few min ~ few days

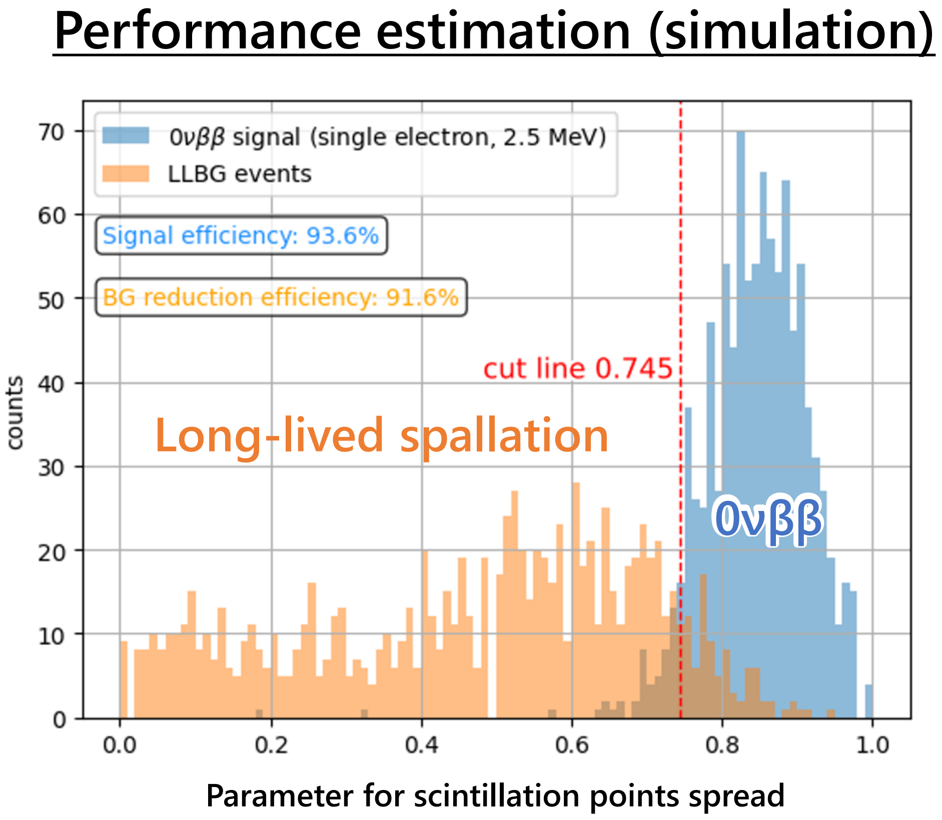
Energy spectrum of KamLAND-Zen



Current progress







- The design for using KamLAND2 has been created.
  - KamLAND2 : Upgraded KamLAND detector, Now being prepared
- Simulation shows this design can reduce long-lived spallation more than 90%.

Summary

Geo-ν observation in KamLAND

- KamLAND realized Geo-ν observation with ultra-low background.
- We measured ν flux from U & Th,
  and constrained their contribution and the amount of radiogenic heat.
- Now, full data analysis with machine learning is ongoing.

Ocean bottom detector

- Ocean bottom is suitable site to observe Mantle Geo-ν.
- “OBD” is liquid scintillator detector plan for ν observation in deep sea.
- Now, R&D phase. Property of prototype components are being researched.

Imaging detector

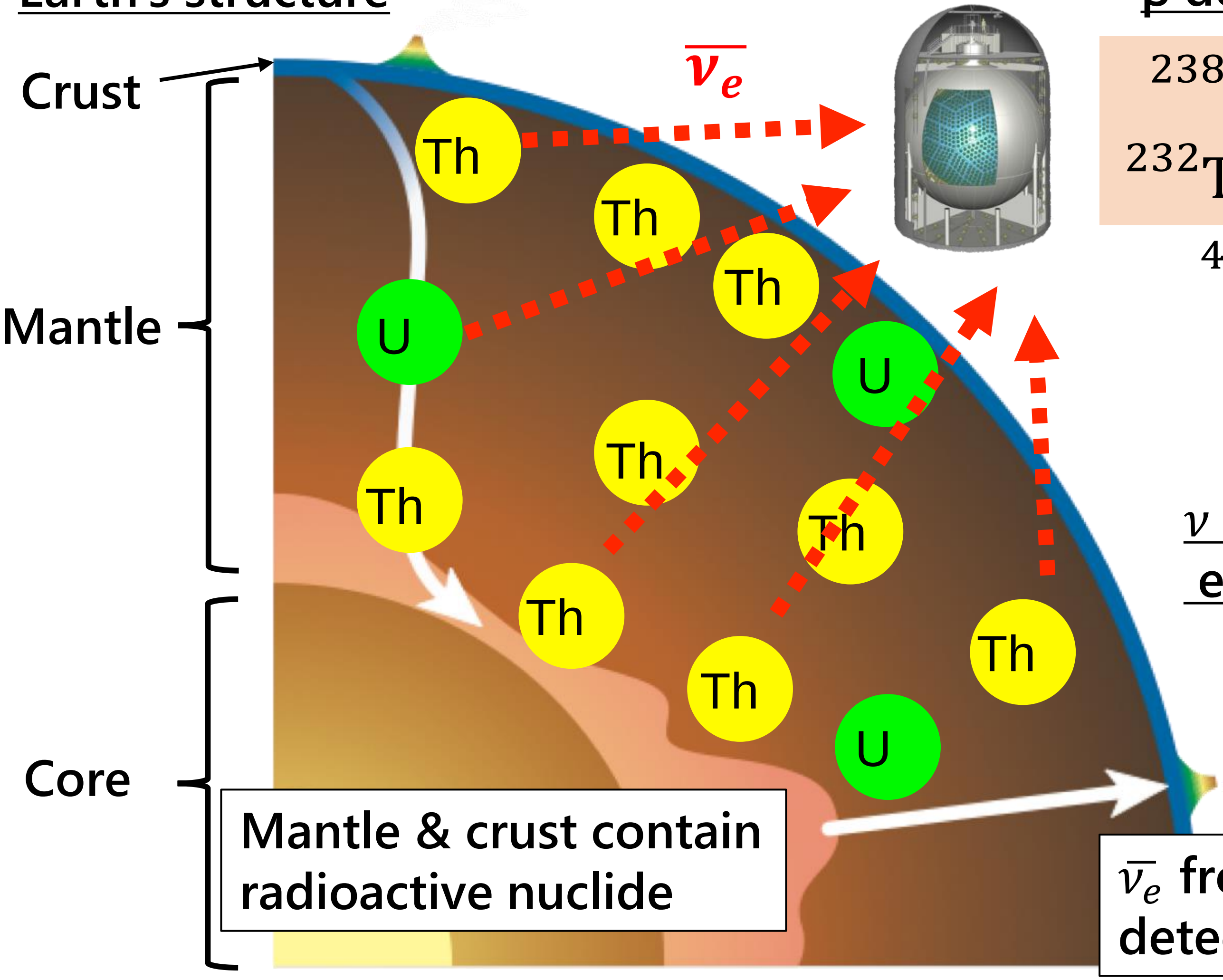
- It is camera-like detector to image scintillation directly
  to improve vertex resolution and capture scintillation structure.
- Using with LS which has short neutron capture time,
  it enables ν direction detection.
- Now, it designs for BG reduction of 0νββ observation by detecting
  the difference of scintillation spread.

Back Up

What's Geo-neutrino ?

- $\overline{\nu_e}$ from β decay of isotopes inner Earth

Earth's structure



Mantle & crust contain radioactive nuclide

β decay to stable nuclide (Representative isotope)

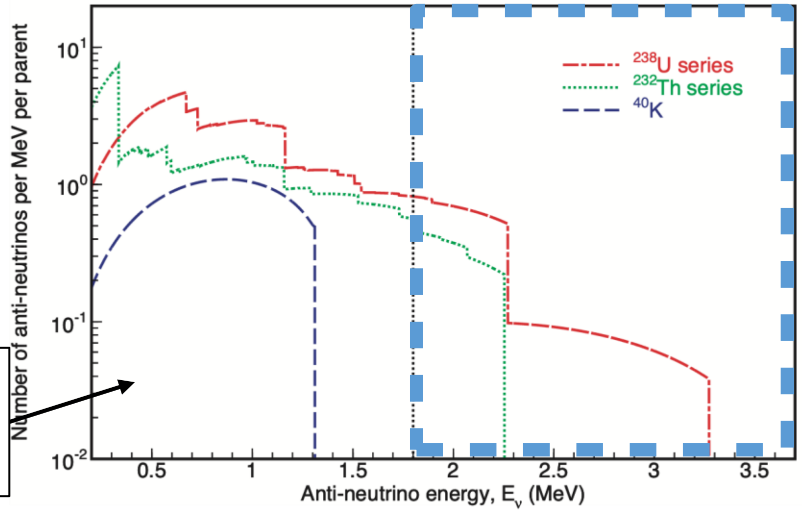
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$\bar{\nu}_e$ is observed by inverse β decay
$\bar{\nu}_e + p \rightarrow e^+ + n$ Energy threshold : 1.806 MeV

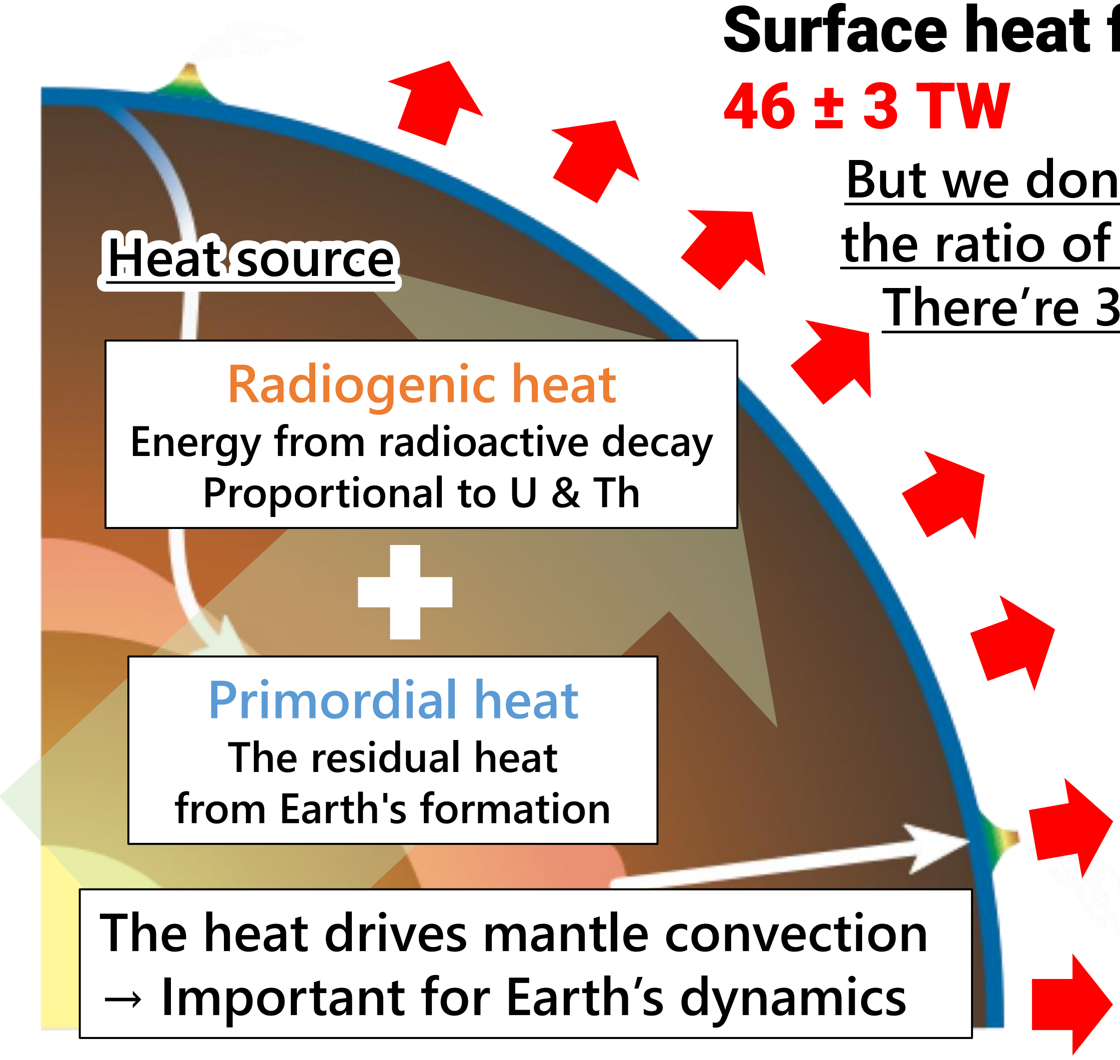
ν flux from each nuclide



$\bar{\nu}_e$ from ^{40}K can't detect now

Merit of Geo-neutrino observation

- Geo-ν can directly measure the amount of Earth’s engine power source.

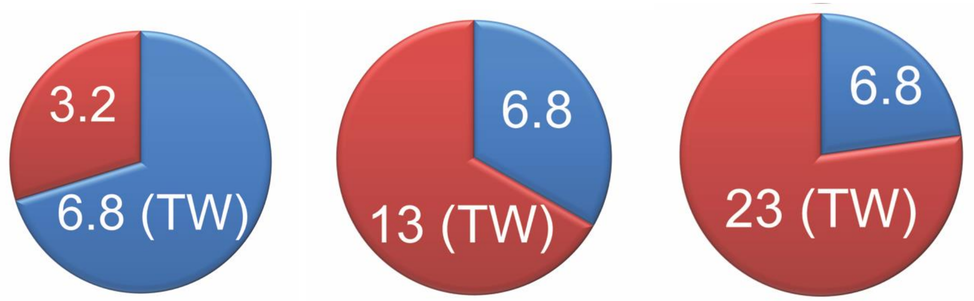


Surface heat flow
46 ± 3 TW

But we don’t know
the ratio of source…
There’re 3 models.

Total radiogenic heat prediction
(Continental Crust + Mantle)

Low Q	Middle Q	High Q



10 TW	20 TW	30 TW

Continental crust   Mantle

Q : How much radioactive nuclides are left in mantle?
→ Geo ν can measure its amount directly !