# Geoneutrino measurement with KamLAND

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# What formed our planet ?

◆ **Traditional geoscientific approaches**

Credit: Getty Images/iStockphoto

Seismology:

- Structual modeling by earthquake analysis
  - "Core—mantle—crust" layers in the Earth

Geochemistry / Cosmochemistry

- Compositional estimation based on rock samples and chondrite meteorites

Geothermology

- Heat flux measurement at the surface to study geothermal activities.

**There still be some open questions for our planet!!**

- Which type of meteorites formed the Earth?

→ **Need for direct test of deep-Earth composition**

- What powers the geodynamics?
- How much layers the mantle have?

→ **Understanding the amount and sources of heat inside the Earth is important.**

**Geoneutrino is a key of these questions.**

# Earth's heat budget

- The history of the Earth is a global cooling process.
- The geodynamics are powered by heat inside the Earth.

**Understanding the heat amount and its source inside the Earth is important.**

**Heat inside the Earth**

- Total heat flux: 46±3 TW by surface heat flux measurement
- Source: **primordial heat +** **radiogenic heat** **the breakdown is unknown**

**Radiogenic heat:** Heat generated by radioactive elements

- Past amount is calculated from the present value.
- Different predictions from geophysics and geochemistry

**BSE models** (Sramek et. al. 2013)

Predict mantle heat and radioactive element abundance inside the Earth.

- **Low-Q** (10-15 TW): Based on compositional analysis of enstatite chondrites
- **Middle-Q** (17-22 TW): Based on compositional analysis of CI carbonaceous chondrites
- **High-Q** (>25 TW): Based on balancing mantle viscosity and heat dissipation.

**Direct measurement is necessary!**

# Motivation for geoneutrino observation

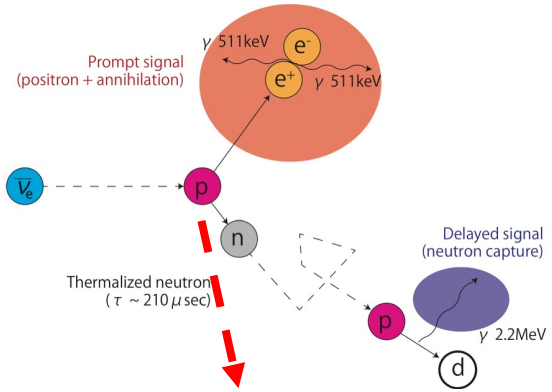
**Geoneutrino**: $\bar{\nu}_e$ from the decay of radioactive materials in the Earth

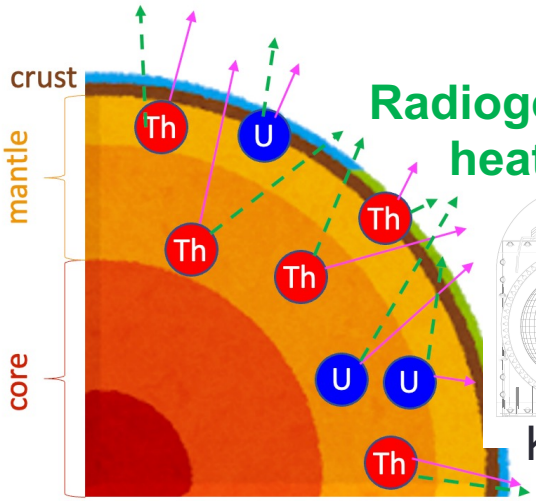
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + \mathbf{6\bar{\nu}_e} + 51.7\ \mathrm{MeV}$$

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

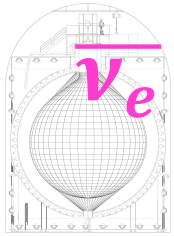
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$\bar{\nu}_e$ can be detected by inverse β-decay (IBD)!



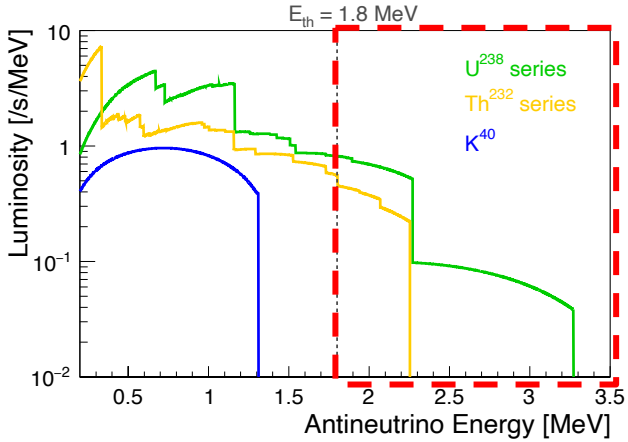




Radiogenic heat




KamLAND

$\bar{\nu}_e$ flux
∝ U, Th
∝ Radiogenic heat




✓ Measurement of the geoneutrino total flux

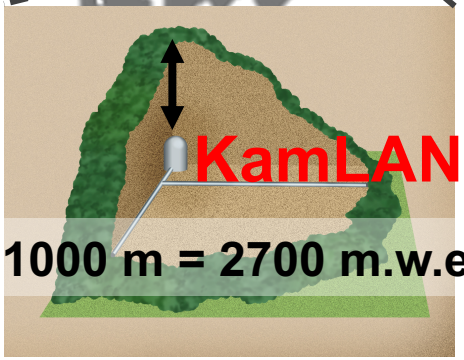
→ **Test of Earth's heat budget**

✓ Measurement of the geoneutrino flux from U and Th separately

→ **Test of Earth's chemical composition**

# KamLAND/KamLAND-Zen Collaboration

**Kamioka,**
**Gifu, Japan**





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大阪大学 OSAKA UNIVERSITY
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THE UNIVERSITY OF TENNESSEE KNOXVILLE
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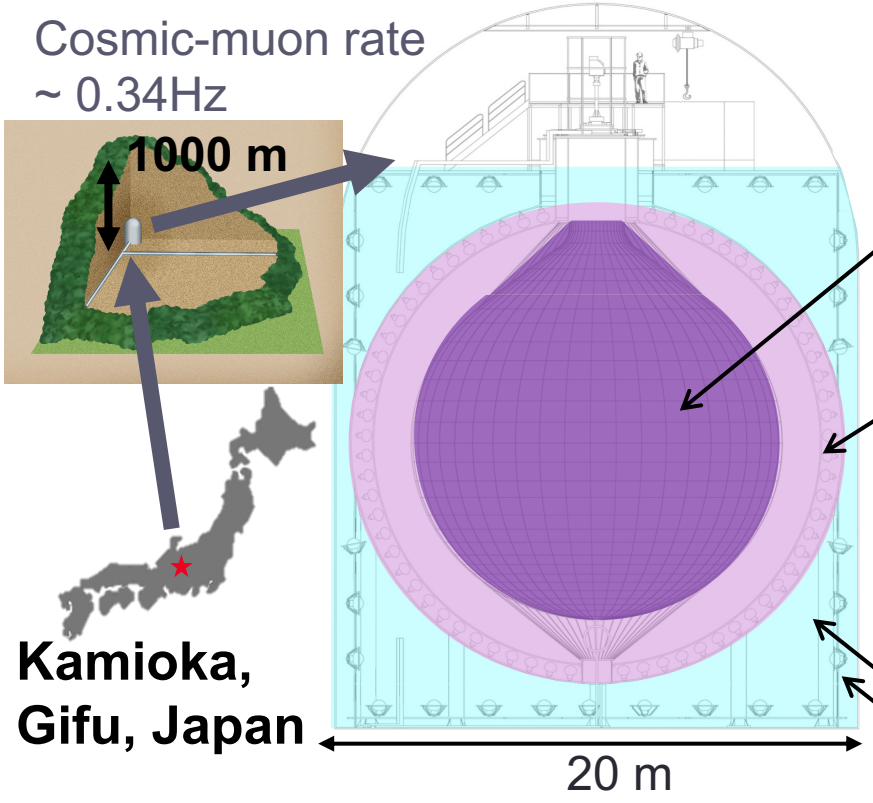
# KamLAND

## *Kam*ioka *L*iquid Scintillator *A*nti-*N*eutrino *D*etector




**Scintillation Inner Detector:**

**Physics observation**

1kton purified liquid scintillator

$^{238}$U~5.0x10$^{-18}$ g/g

- $^{232}$Th~1.8x10$^{-17}$ g/g

1879 PMTs

6.7%/√E, 13.7 cm/√E

**Water-Cherenkov outer detector:**

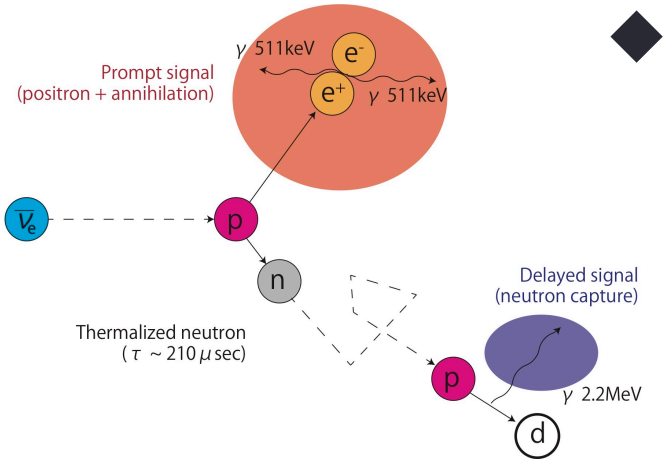
**Active cosmic-μ veto**

3.2kton purified water

225(140), 20-inch PMTs

- KamLAND completed DAQ on Aug. 27, 2024
- We started detector upgrades in 2024 and plan to launch KamLAND2 in 2028!!

# Geoneutrino measurement in KamLAND

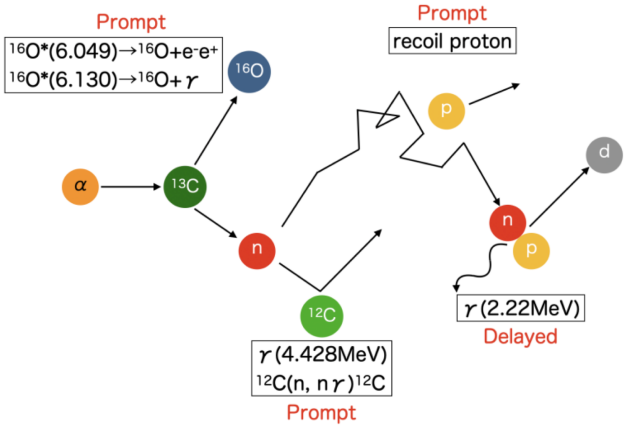



## ◆ Observe $\bar{\nu}_e$ by delayed coincidence

- Significant background reduction by two-fold coincidence
- Neutrino energy reconstruction from prompt signal

## ◆ Main Background

- **Reactor neutrino**
- **$^{13}C(\alpha, n)^{16}O$:** Originating from alpha particles emitted by natural radioactive isotopes (mainly $^{210}Po$) in detector structural materials.




- **Accidental:** Accidental IBD-like BG from detector radioactivity ($^{214}Bi$, $^{208}Tl$ and $^{40}K$).
- **Cosmic-ray muon spallation products:** $^{9}Li$ and $^{8}He$

# History of neutrino geoscience in KamLAND

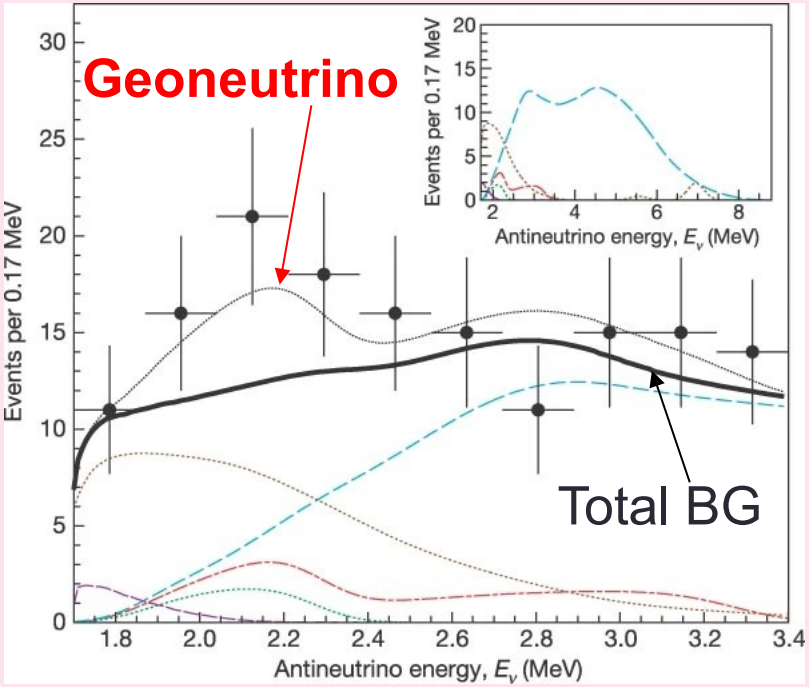
2002 **2005** 2011 2022 2025 2028

**KamLAND start**

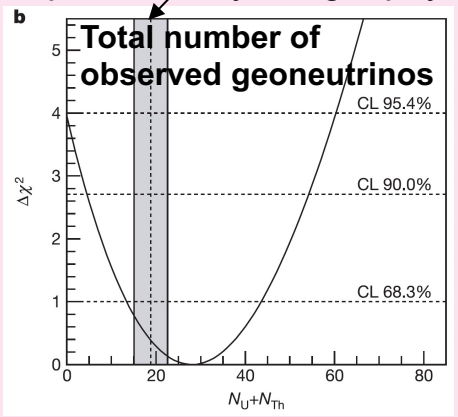
**KamLAND2 start**

## *First evidence of geoneutrino detection*

Nature 436, 499–503




predicted by the geophysical model.





**$28.0^{+15.6}_{-14.6}$ events (56% error)**
**749 days, 0.71 x $10^{23}$ proton-year**

**The beginning of neutrino geoscience**

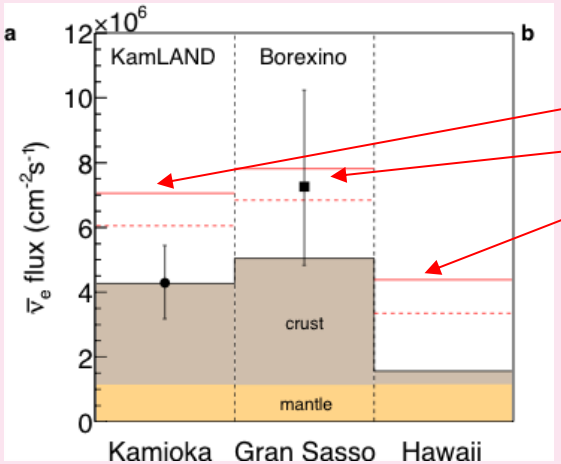
# History of neutrino geoscience in KamLAND

2002 2005 **2011** 2022 2025 2028

**KamLAND start**

**KamLAND2 start**

## *First evidence of partial radiogenic Earth*




Nature Geoscience 4, 647–651

Expected flux if all geothermal heat is generated by radioactivity inside earth.

**$106^{+29}_{-28}$ events (27% error)**
**2135 days, 3.49 x $10^{32}$ proton-year**
**Radiogenic heat: $20.0^{+8.8}_{-86}$ TW**

- The result indicates that the radiogenic heat inside the Earth accounts for about half of the total heat flow at the surface.

→ **There is residual primordial heat inside the Earth. Our planet is cooling.**

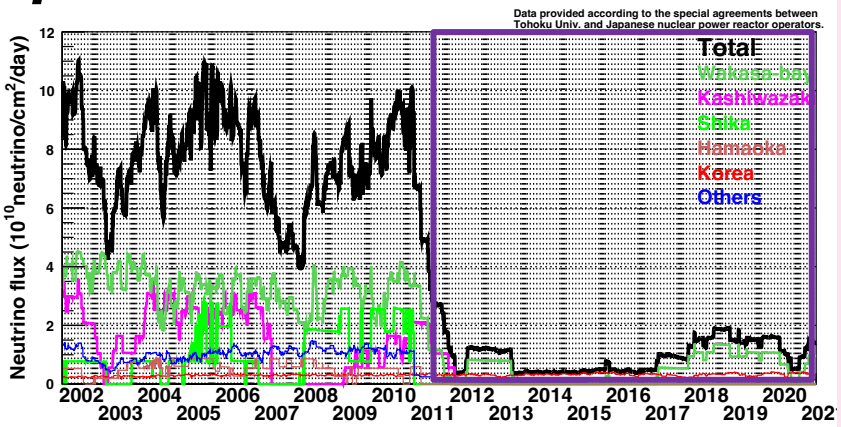
# History of neutrino geoscience in KamLAND

2002 2005 2011 **2022** 2025 2028

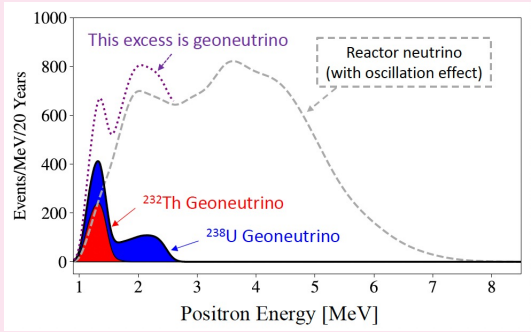
**KamLAND start**

**KamLAND2 start**

## *Improved observation in low-reactor period*



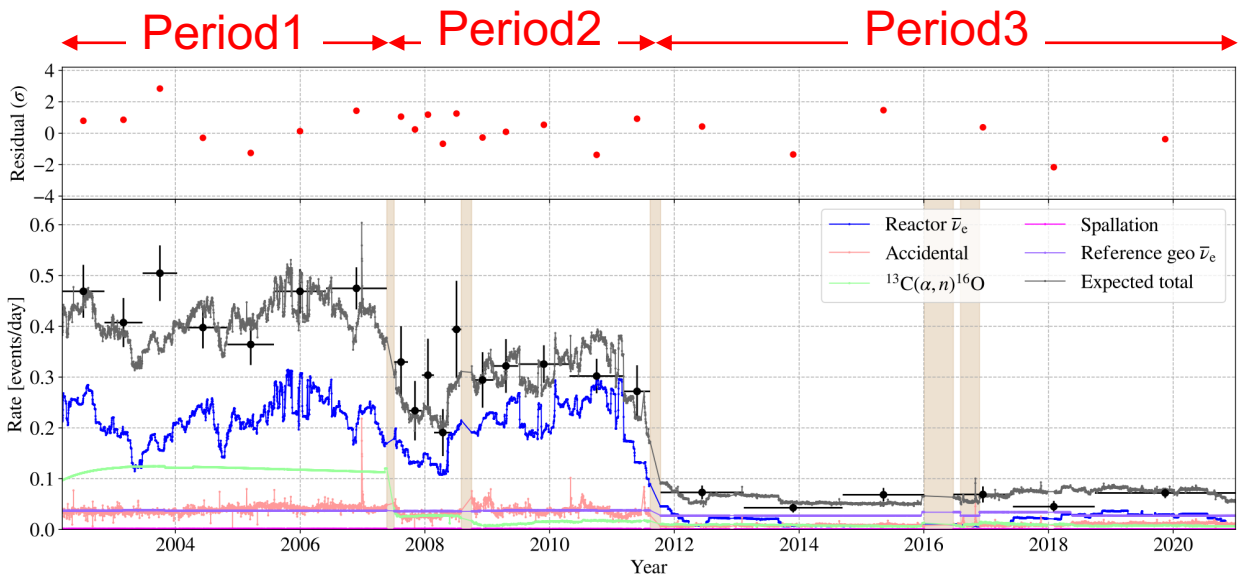

Geophysical Research Letters, 49, Issue 16, e2022GL099566




- Reactor neutrinos are the dominant background in geoneutrino detection.
- Most of the Japanese reactors have been shut down due to the huge earthquake in Japan in 2011.
- The reactor-off period significantly improved the observation accuracy.

# Best fit result

## Time variation




### Number of BG events from best-fit result

| | Period1 | Period2 | Period3 | All Period |
|---|---|---|---|---|
| energy range [MeV] | 0.9–2.6 | 0.9–2.6 | 0.9–2.6 | 0.9–2.6 |
| live time [day] | 1485.5 | 1151.5 | 2590.0 | 5227.0 |
| Reactor $\bar{\nu}_e$ | 325.75 | 229.64 | 48.97 | 604.36 |
| $^{13}C(\alpha,n)^{16}O$ | 177.66 | 20.42 | 22.18 | 222.26 |
| Accidental | 59.35 | 40.53 | 24.79 | 124.67 |
| Spallation ($^{8}He/^{9}Li$) | 1.52 | 1.05 | 1.69 | 4.26 |
| Background total | 620.21 | 334.07 | 171.98 | 1126.26 |
| observed | 651 | 363 | 164 | 1178 |

**Period1→Period2**

- $^{13}C(\alpha, n)^{16*}O$ BG was greatly reduced by LS distillation campaign.

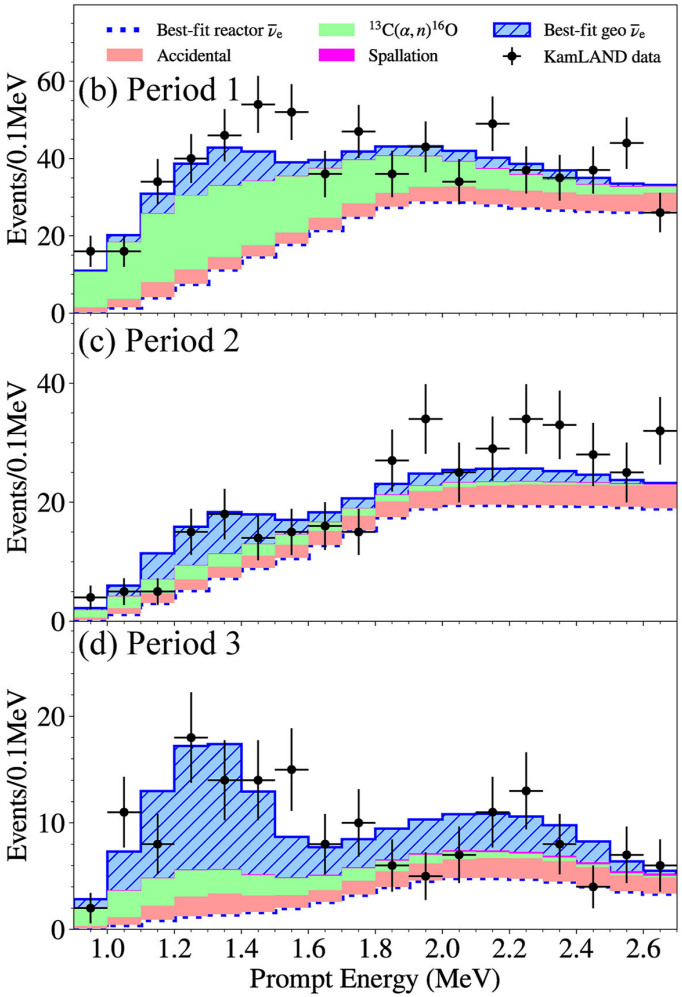
**Period2→Period3**

- Reactor $\bar{\nu}_e$ decreased due to reactor shutdowns in Japan.
- Reduced reactor $\bar{\nu}_e$ + Optimized likelihood selection

→ Fewer accidental backgrounds

# Best fit result

## Rate + Shape + Time un-binned Likelihood




### Conditions

- Energy: 72 bins in $0.9 \leq Energy_{prompt} \leq 8.5$ [MeV]
- Time: each KamLAND run (~24 hours bin)
- Scan Parameter: geo $\bar{\nu}_e$ signal (U, Th)
- Fit Parameter: $\Delta {m_{21}}^2$, $\theta_{12}$, $\theta_{13}$, BGs, systematics

**Simultaneous scan of the oscillation parameters and geoneutrinos**

Number of BG events from best-fit result

| | Period1 | Period2 | Period3 | All Period |
|---|---|---|---|---|
| energy range [MeV] | 0.9–2.6 | 0.9–2.6 | 0.9–2.6 | 0.9–2.6 |
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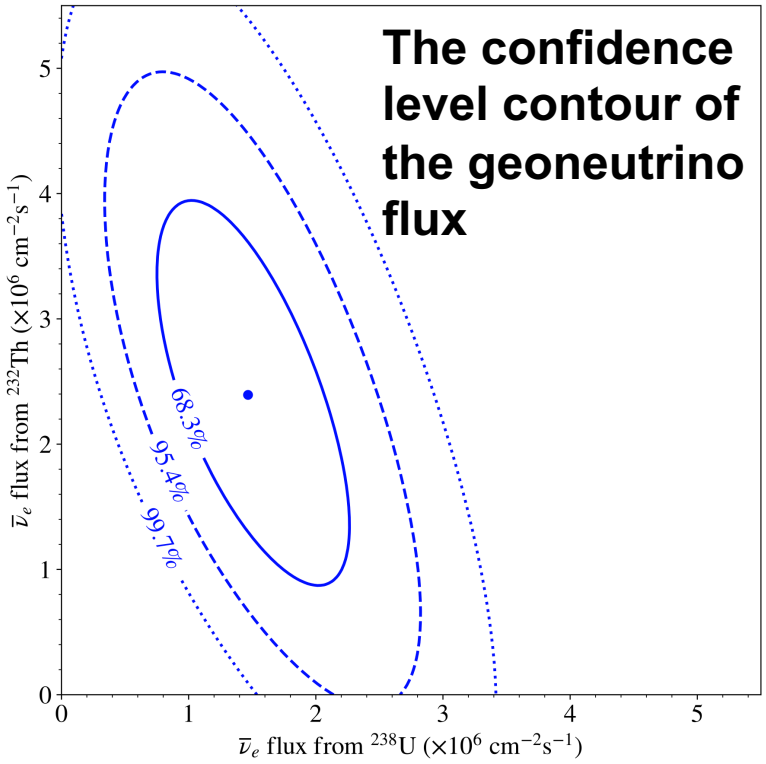
# Geoneutrino flux measured by KamLAND




## Number of geoneutrinos from best-fit result

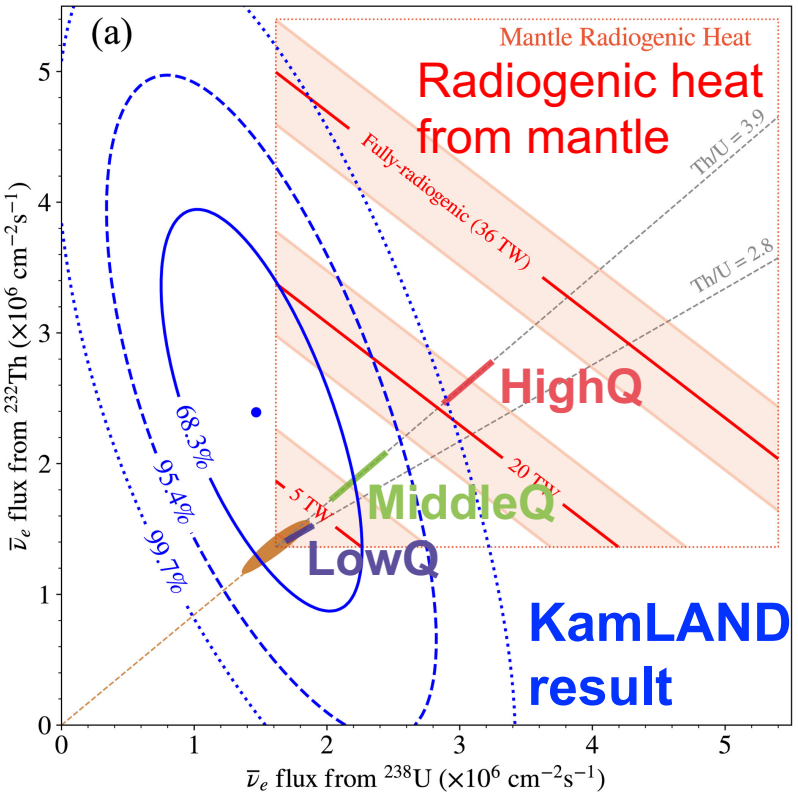
| | $N_{\mathrm{U/Th}}$ [event] | flux [$\times 10^5$ cm$^{-2}$s$^{-1}$] | flux [TNU] | 0-signal rejection |
|---|---|---|---|---|
| U | $116.6^{+41.0}_{-38.5}$ | $14.7^{+5.2}_{-4.8}$ | $19.1^{+6.7}_{-6.3}$ | $3.343\sigma$ |
| Th | $57.5^{+24.5}_{-24.1}$ | $23.9^{+10.2}_{-10.0}$ | $9.7^{+4.1}_{-4.1}$ | $2.386\sigma$ |
| U + Th | $173.7^{+29.2}_{-27.7}$ | $32.1^{+5.8}_{-5.3}$ | $28.6^{+5.1}_{-4.8}$ | $8.3\sigma$ |

TNU=1 [event/year/$10^{32}$ target proton]

**Best-fit U+Th: $174^{+31}_{-29}$**

- KamLAND detected significant geoneutrino signals from both uranium and thorium inside the Earth.
- Spectroscopic measurement of geoneutrinos from uranium and thorium was achieved.

# Radiogenic heat measurement




**Crust estimation**

mean value: Enomoto 2007

uncertainty: Rudnick & Gao 2014

Th/U ratio : Wipperfurth et al 2018

$$Q^{\mathrm{U,Th}} = Q^{\mathrm{U,Th}}_{\mathrm{crust}} + Q^{\mathrm{U,Th}}_{\mathrm{mantle}}$$

Conversion coefficients between flux and radiogenic heat in homogeneous mantle

$$Q^{\mathrm{U,Th}}_{\mathrm{mantle}} = \left(\Phi^{\mathrm{U,Th}} - \Phi^{\mathrm{U,Th}}_{\mathrm{crust}}\right) \frac{\mathrm{d}Q^{\mathrm{U,Th}}_{\mathrm{mantle}}}{\mathrm{d}\Phi^{\mathrm{U,Th}}_{\mathrm{mantle}}}$$

**measured flux at the surface** — flux estimate in crustal model

$Q^{\mathrm{U}}_{\mathrm{crust}} = 3.4$ TW, $Q^{\mathrm{Th}}_{\mathrm{crust}} = 3.6$ TW

$Q^{\mathrm{U}} = 3.3^{+3.2}_{-0.8}$ TW

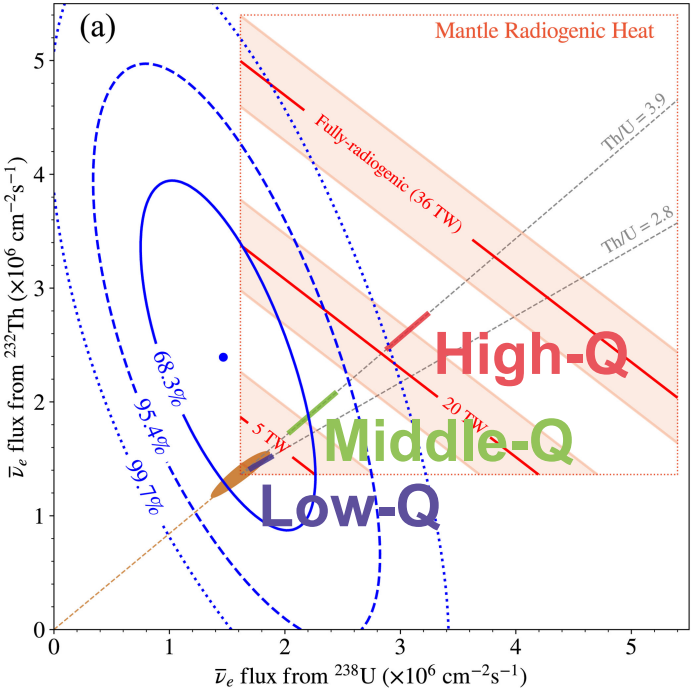
$Q^{\mathrm{Th}} = 12.1^{+8.3}_{-8.6}$ TW

$Q^{U} + Q^{Th} = 15.4^{+8.3}_{-7.9}$ TW

**U, Th heat separated measurement achieved!!**

# Estimation of radiogenic heat production in the Earth

**Compared to radiogenic heat predictions from some earth models.**




## BSE models (Sramek et. al. 2013)

◆ **Low-Q** (10-15 TW)

Based on compositional analysis of enstatite chondrites and isotopic constraints

(U : 12±2 ppb, Th : 43±4 ppb)

◆ **Middle-Q** (17-22 TW)

Based on compositional analysis of CI carbonaceous chondrites and earth samples

(U : 20±4 ppb, Th : 80±13 ppb)

➢ **Consistent with the KamLAND data.**

◆ **High-Q** (>25 TW)

Based on balancing mantle viscosity and heat dissipation (1-layer mantle convection).

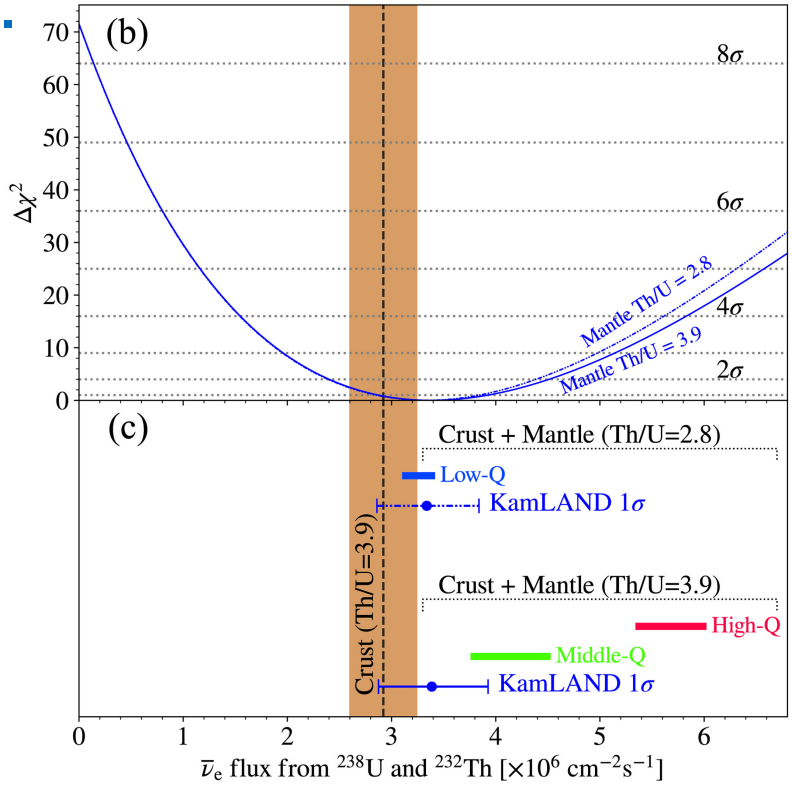
(U : 35±4 ppb, Th : 140±14 ppb)

➢ **Inconsistent with the KamLAND data.**

# Comparison to Earth models

Assuming homogeneous mantle composition,
**High-Q model is disfavored at 99.76%.**

Assuming U and Th concentration at the mantle-core boundary,
**High-Q model is disfavored at 97.9%.**




- **Implies that the seismic interpretation underlying the High-Q model (density and viscosity) needs revision.**

**The KamLAND data favor Low-Q, Middle-Q model.**

- **Suggest mantle multi-layer convection.**

# Summary

- KamLAND measured geoneutrinos from uranium and thorium.
- The KamLAND results are consistent with Low-Q and Middle-Q model based on chondrites compositional analysis.
- The High-Q model is excluded at the 99.76% C.L. assuming a homogeneous mantle, implying layered mantle convection.

**We are ongoing KamLAND completed dataset analysis !!**


https://higgstan.com

# Back Up

# Earth's chemical composition

- The Bulk Silicate Earth (BSE) model provides the average composition of the Earth's **crust** + **mantle.**

Estimated from Earth samples.

Estimated by subtracting crustal elements from the BSE composition.

## Candidate material of the Earth: chondrites

**CI carbonaceous chondrite:**
- compositional similarity to solar atmosphere
- abundant volatile elements

**Enstatite chondrite:**
- isotopic similarity to the Earth
- abundant iron

**The choice of the Earth's material is critical.**
**Need for direct test of deep-Earth composition !!**