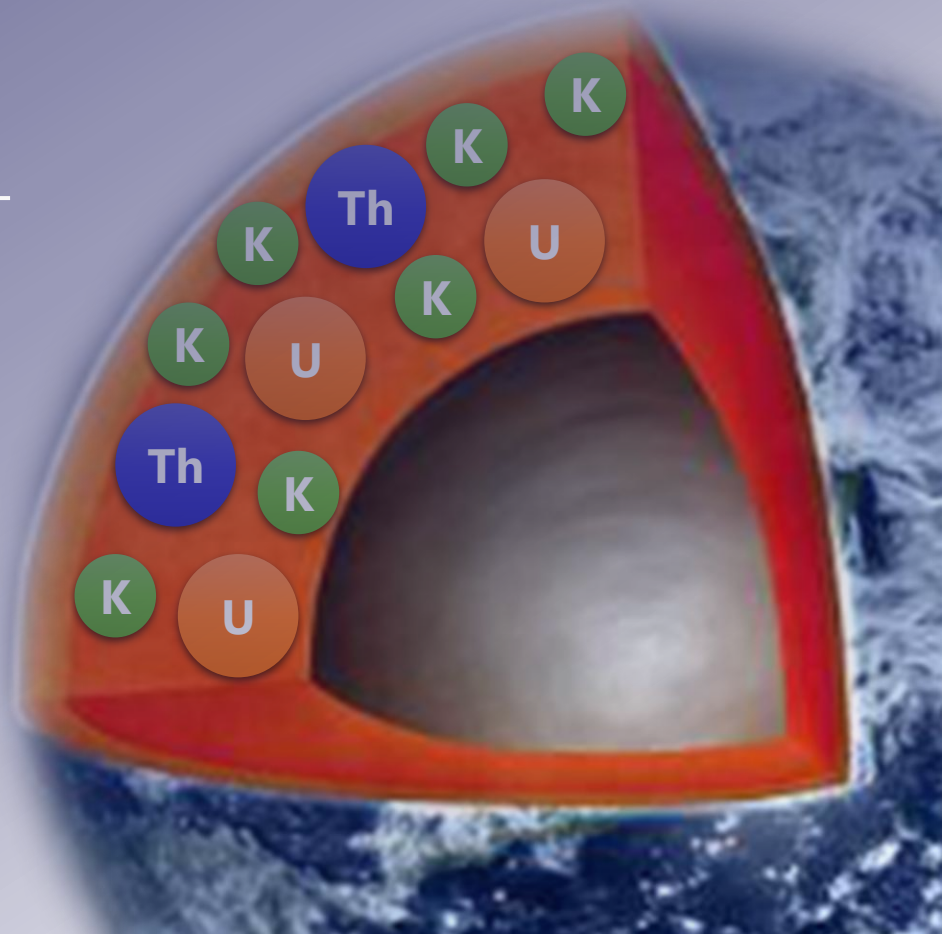
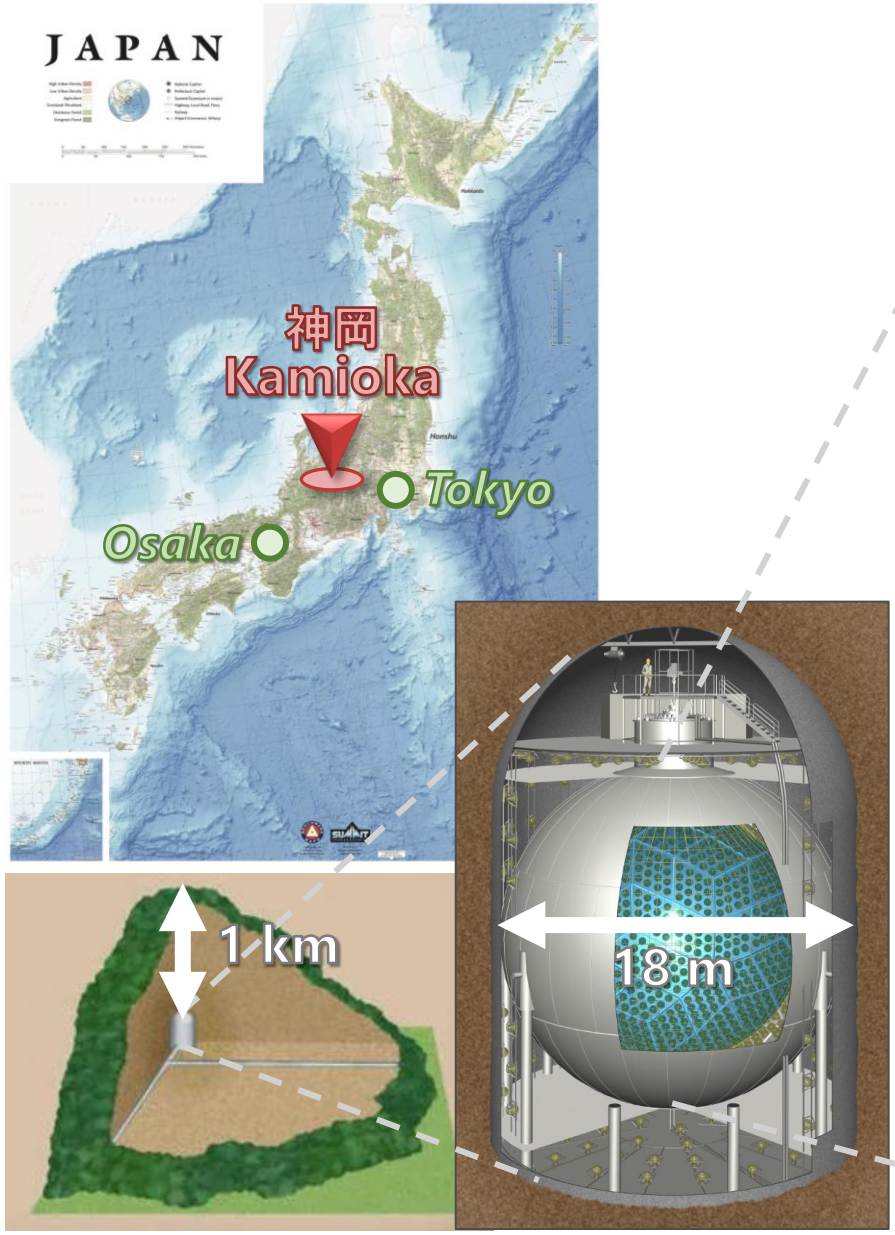
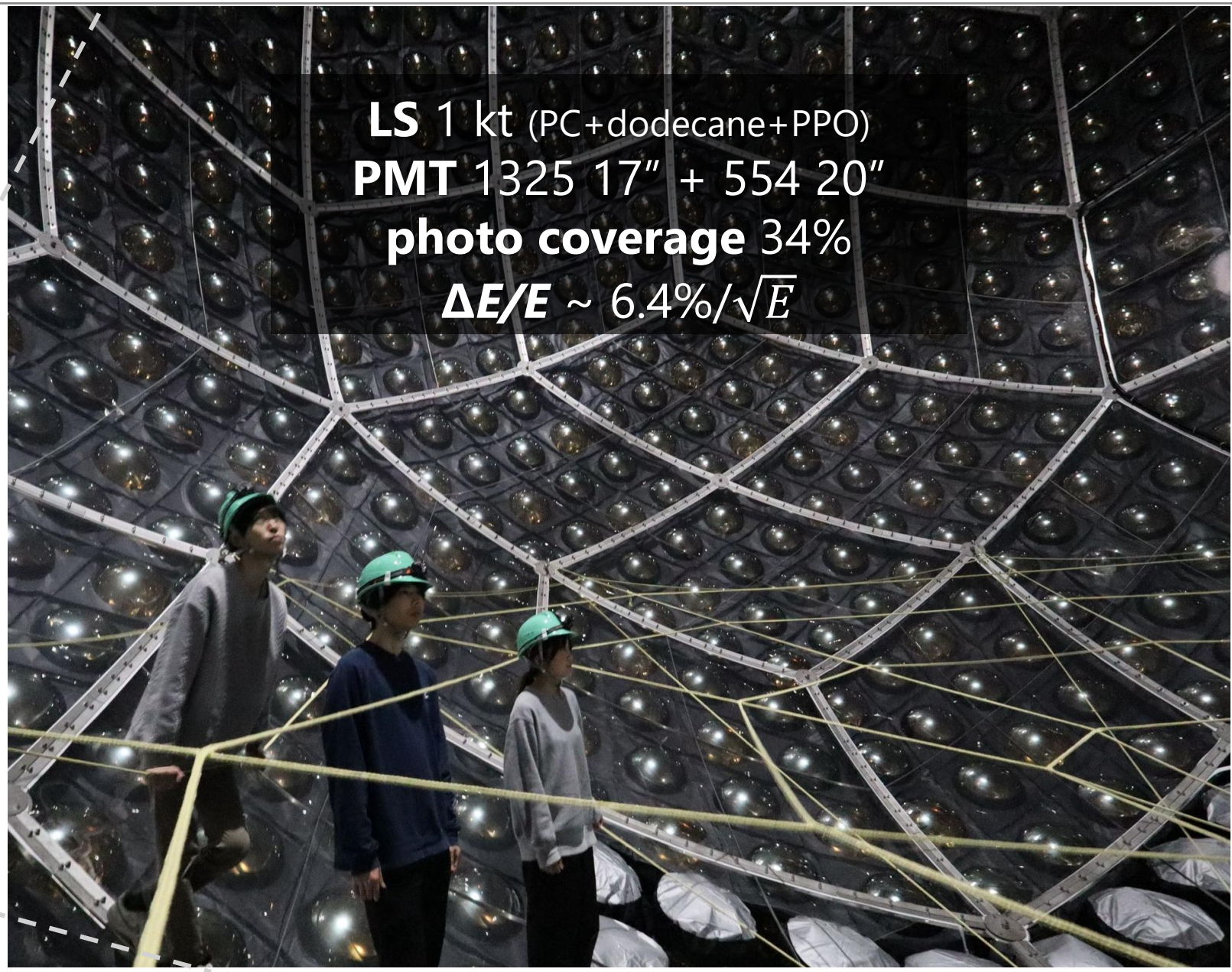
Two Decades of Geoneutrino Measurements at KamLAND

Zhihao Xu (许智豪, M2) for KamLAND Collaboration
Tohoku University (日本东北大学)



Kamioka Liquid Scintillator Anti-Neutrino Detector





Kamioka Liquid Scintillator Anti-Neutrino Detector

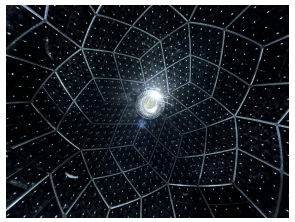


D. Chernyak[1], T. Eda[1], M. Eizuka[1], R. Endo[1], A. Gando[1,2], Y. Gando[1,2], T. Hachiya[1], F. Haneishi[1], K. Hata[1], T. Hirai[1], K. Hosokawa[1], K. Ichimura[1], H. Ikeda[1], K. Inoue[1], K. Ishidoshiro[1], Y. Kamei[1,24], N. Kawada[1], Y. Kishimoto[1], M. Koga[1,3], K. Mikami[1], H. Miyake[1], K. Mizukoshi[1], D. Morita[1], K. Nakamura[1,25], R. Nakamura[1], J. Nakane[1], Y. Nakano[1], N. Obata[1], Y. Ota[1], K. Saito[1], I. Sakaki[1], I. Shimizu[1], J. Shirai[1], A. Suzuki[1], K. Tachibana[1,26], A. Takeuchi[1], K. Tamae[1], H. Watanabe[1], Z. Xu[1], S. Yoshida[4], S. Umehara[5], K. Fushimi[6], K. Kotera[7,27], Y. Urano[7,28], S. Kurosawa[8], H. Ozaki[9], B.E. Berger[10], B.K. Fujikawa[3,10], J.G. Learned[11], J. Maricic[11], Z. Li[11], Z. Fu[12], S. Ghosh[12], J. Smolsky[12], L.A. Winslow[12], Y. Efremenko[3,13], H.J. Karwowski[14,15,16,17], D.M. Markoff[14,15,16,17], W. Tornow[3,14,15,16,17], S. Dell'Oro[18], T. O'Donnell[18], J.A. Detwiler[3,19], S. Enomoto[1,19], M.P. Decowski[20], K.M. Weerman[20], C. Grant[21], Ö. Penek[21], H. Song[21], A. Li[22], S.N. Axani[23], M. Garcia[23], M. Sarfraz[23], and C. Lin[23]
(KamLAND Collaboration)

Kamioka Underground Observatories

- Not only KamLAND, but also various experiments and facilities!

KamLAND



1-kt LS detector

KERNEL

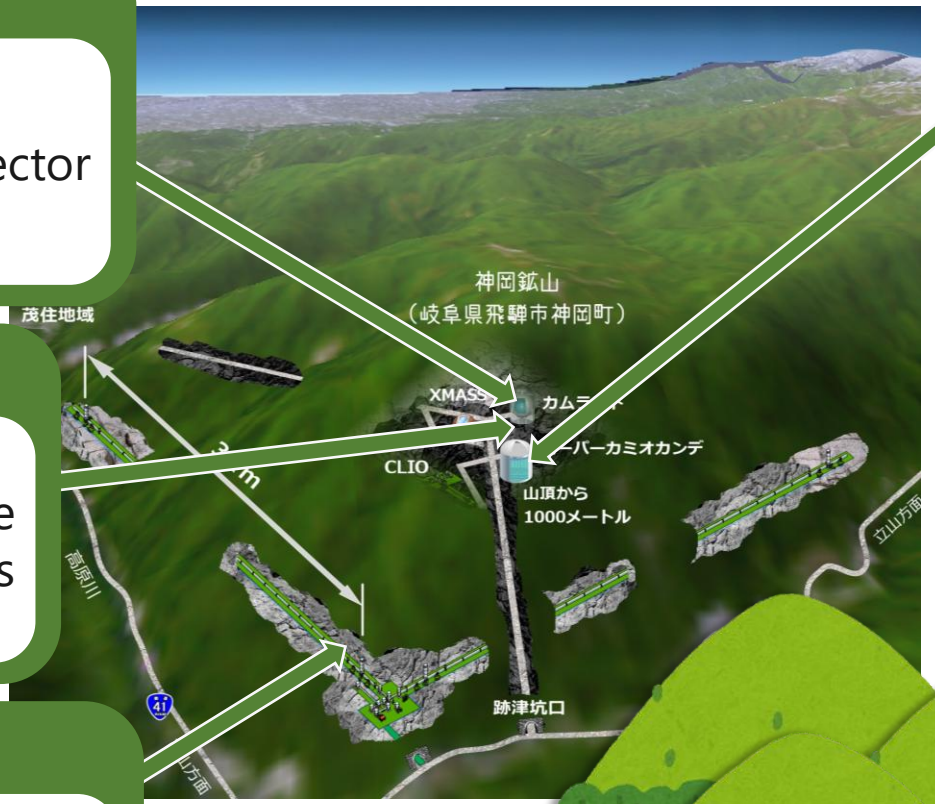


Experimental space for low-BG studies

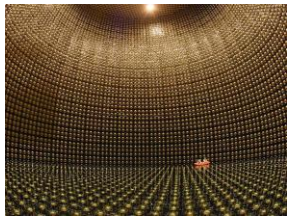
KAGRA



Gravitational wave telescope



Super-Kamiokande



50-kt water Cherenkov detector

PICOLON
PIKACHU
NEWAGE
CANDLES
XMASS
.....

Hyper-Kamiokande (2028~)

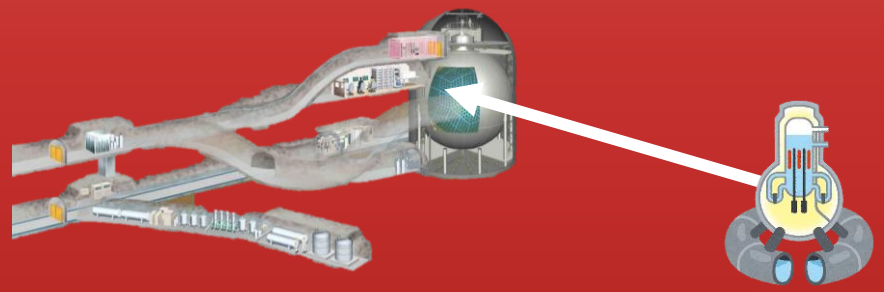
260-kt water Cherenkov detector

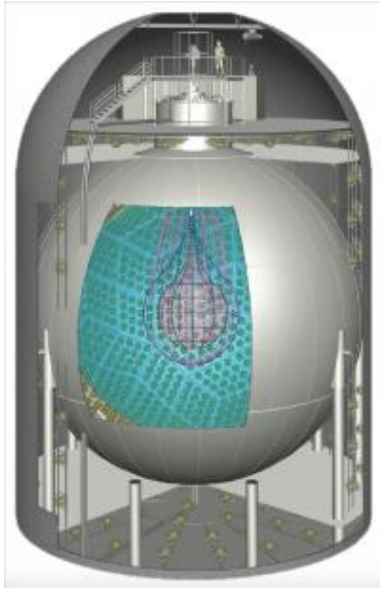


Physical Goals

Oscillation Parameter

$\Delta m^2_{21}, \theta_{12}$

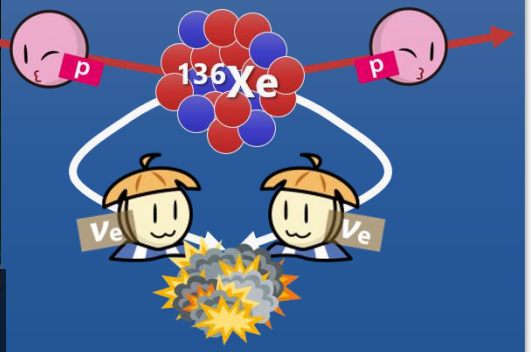




0νββ



^{136}Xe ~800 kg



Astrophysics

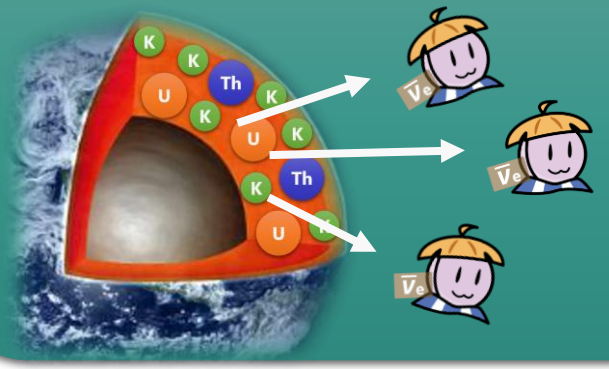


Sun



Supernova

Geoneutrino



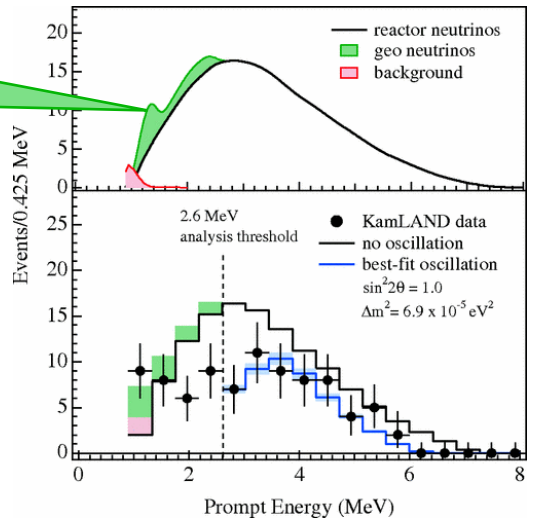
Exotic Particle Physics

DM search
Majoron
Strange axial coupling
Invisible neutron decay
……

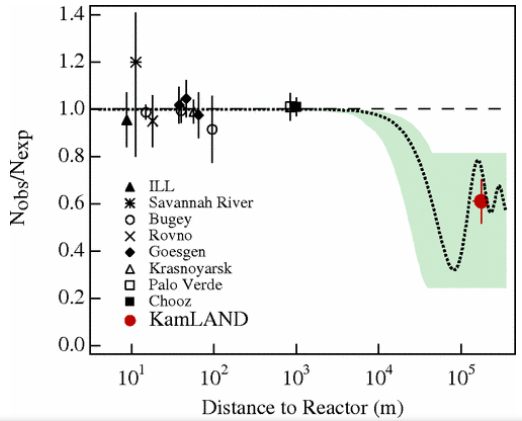
Timeline

Already found ~**9 geo-$\bar{\nu}$** in 2003!
More analyses to be done…

for 145.1 days, 0.162×10^{32} proton-yr



Eguchi *et al.* (2003),
Phys. Rev. Lett. **90**, 021802



First evidence for reactor-$\bar{\nu}$ disappearance!

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND

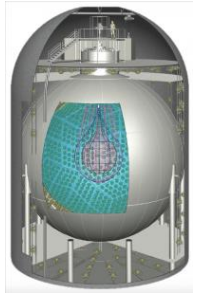
Kamiokande
(Utokyo + *etc*)
1983～1995



Pure water 3 kt

The same site, but different tech.

KamLAND
(TohokuU + *etc*)
2002～2024



LS 1 kt

Timeline

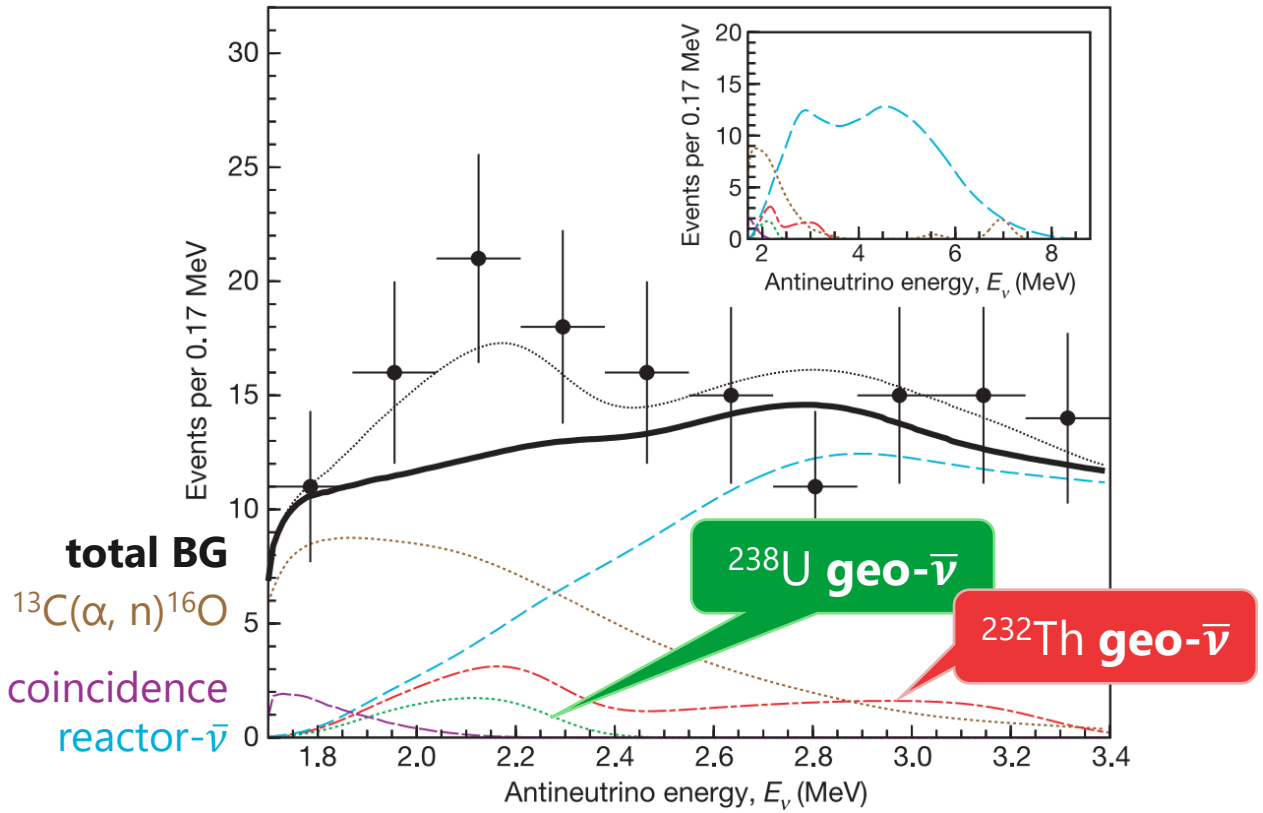


Araki *et al.* (2005),
Nature **436**, 499-503

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND



$28.0^{+15.6}_{-14.6}$ events
for 749 days, 0.71×10^{32} proton-yr

First evidence of geo-$\bar{\nu}$!

Timeline



Araki *et al.* (2005),
Nature **436**, 499-503



Prof. Sanshiro Enomoto
(榎本三四郎 教授)

Hmm… How should we interpret our measurement?

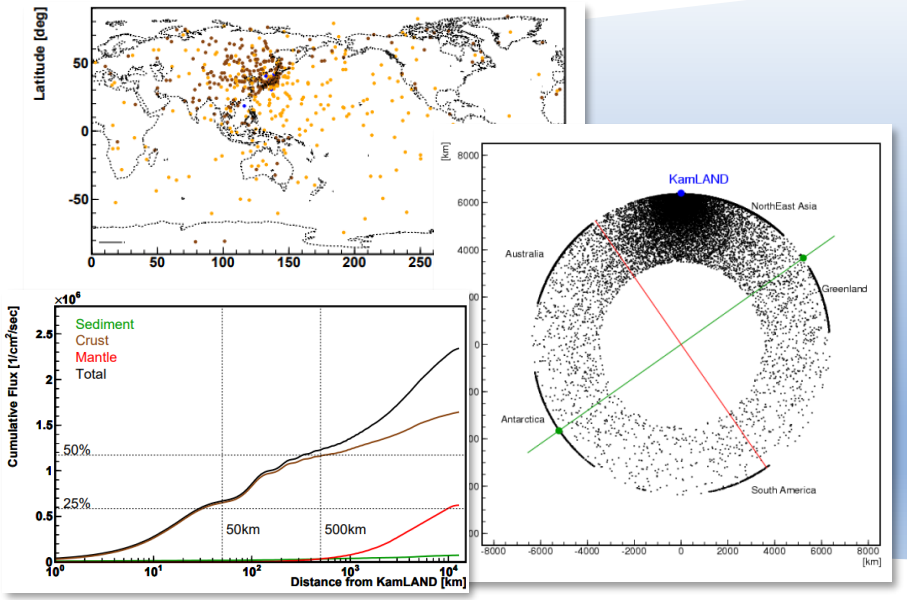
There's no U & Th map in ready to be used!

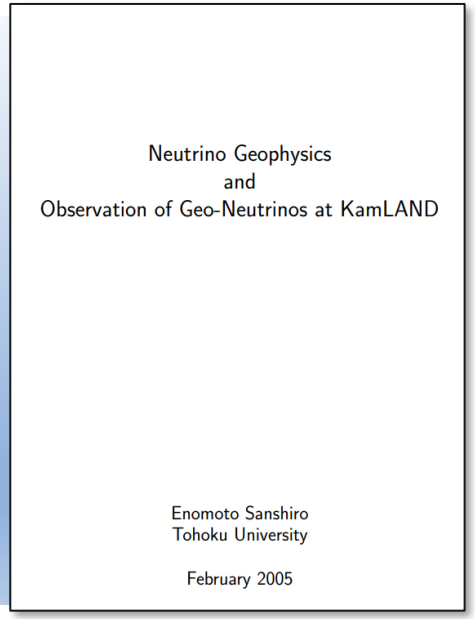
Let's do it by ourselves!!

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND





Timeline



Araki *et al.* (2005),
Nature **436**, 499-503



Hey, guess what?
We have constrained
the Earth's radiogenic heat to
<60 TW (99% U.L.)!

physicists

Well, we **already know**
the Earth's total heat
is ~47 TW.....



geologists

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND

Improving measurement precision is needed

Timeline



Araki *et al.* (2005),
Nature **436**, 499-503

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND

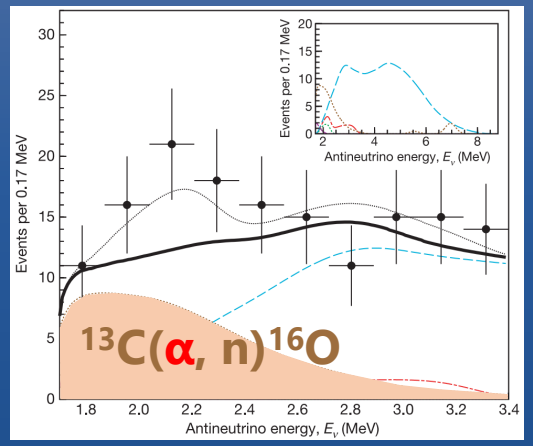
- 2 big problems!

Statistics was not enough

$$\text{uncertainty} \propto 1/\sqrt{N}$$

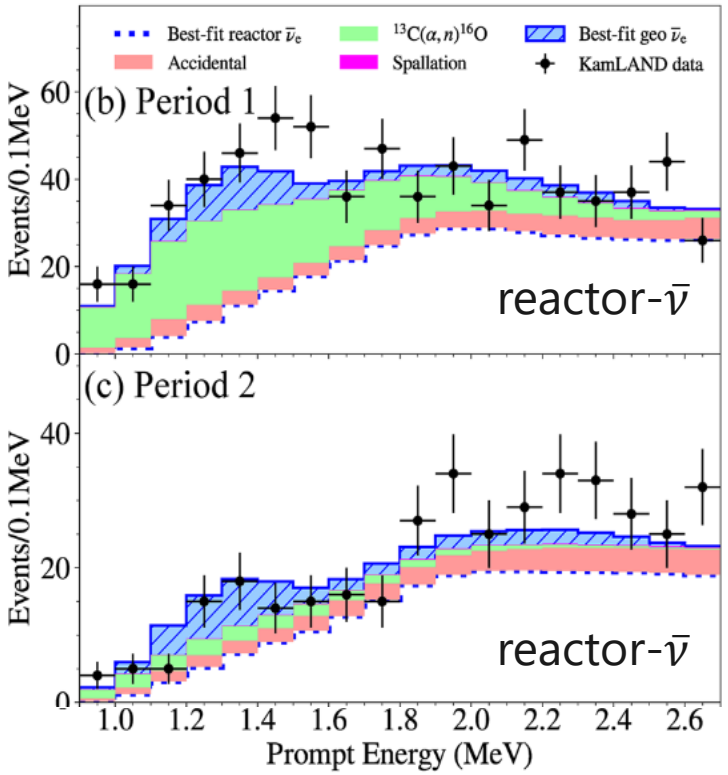
Solution: Be patient, wait and wait

LS was extremely dirty



**Solution:
Remove Rn
by purifying LS**

Timeline



LS purification (2007 & 2008)

	Period1	Period2
energy range [MeV]	0.9–2.6	0.9–2.6
live time [day]	1485.5	1151.5
Reactor $\bar{\nu}_e$	325.75	229.64
$^{13}C(\alpha,n)^{16}O$	177.66	20.42
Accidental	59.35	40.53
Spallation ($^{8}He/^{9}Li$)	1.52	1.05
Background total	620.21	334.07
observed	651	363

Rn was successfully removed by 1 order!

Timeline

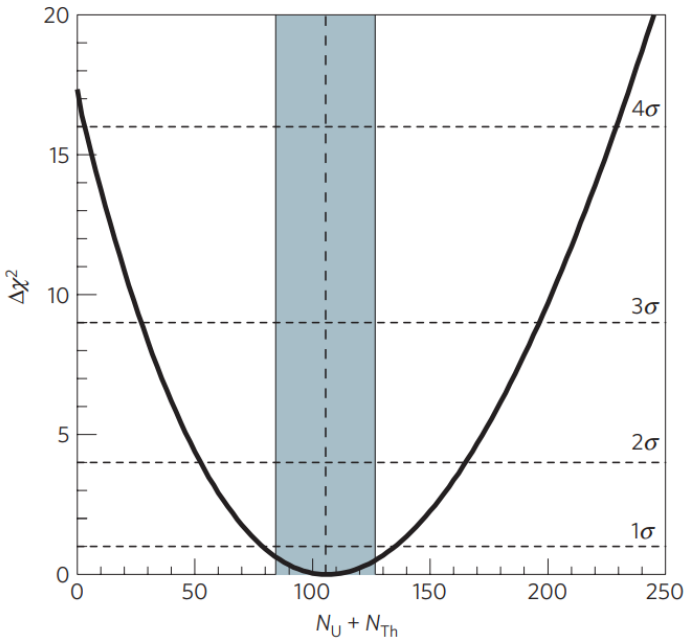
2011
Partial radiogenic Earth confirmed

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

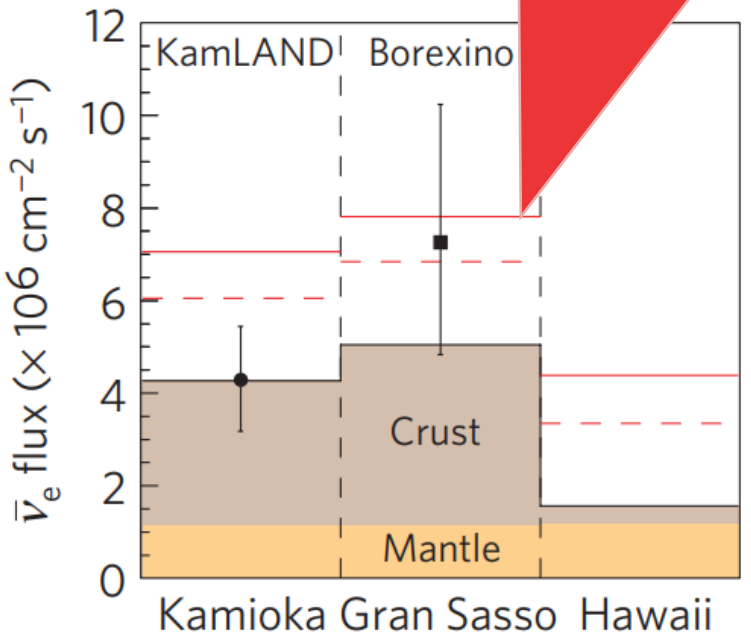
2002
Beginning of KamLAND

The KamLAND Collaboration (2011),
Nat. Geosci. **4**, 647-651



106^{+29}_{-28} events
for 2135 days, 3.49×10^{32} proton-yr

Expected flux if all heat is generated by radioactivity



Fully radiogenic hypothesis is disfavored at **98% C.L.**

First evidence of partial radiogenic Earth!

Timeline

2022
Measurement in low-reactor-BG period

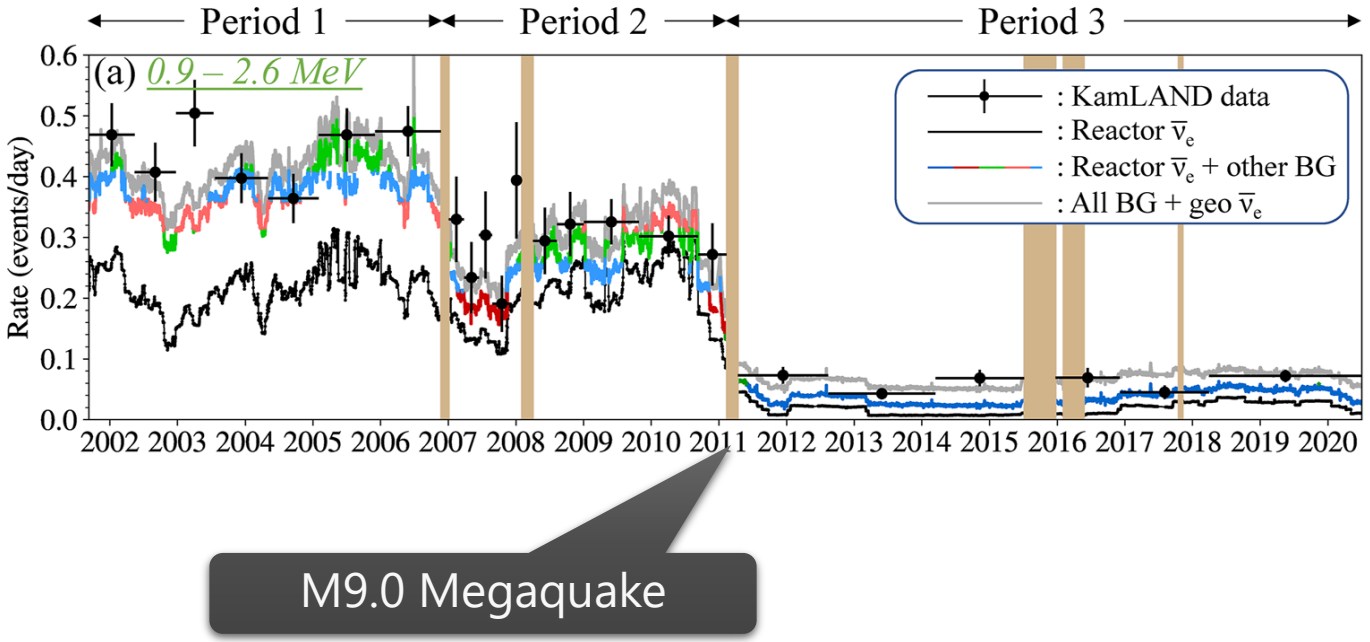
2011
Partial radiogenic Earth confirmed

2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND

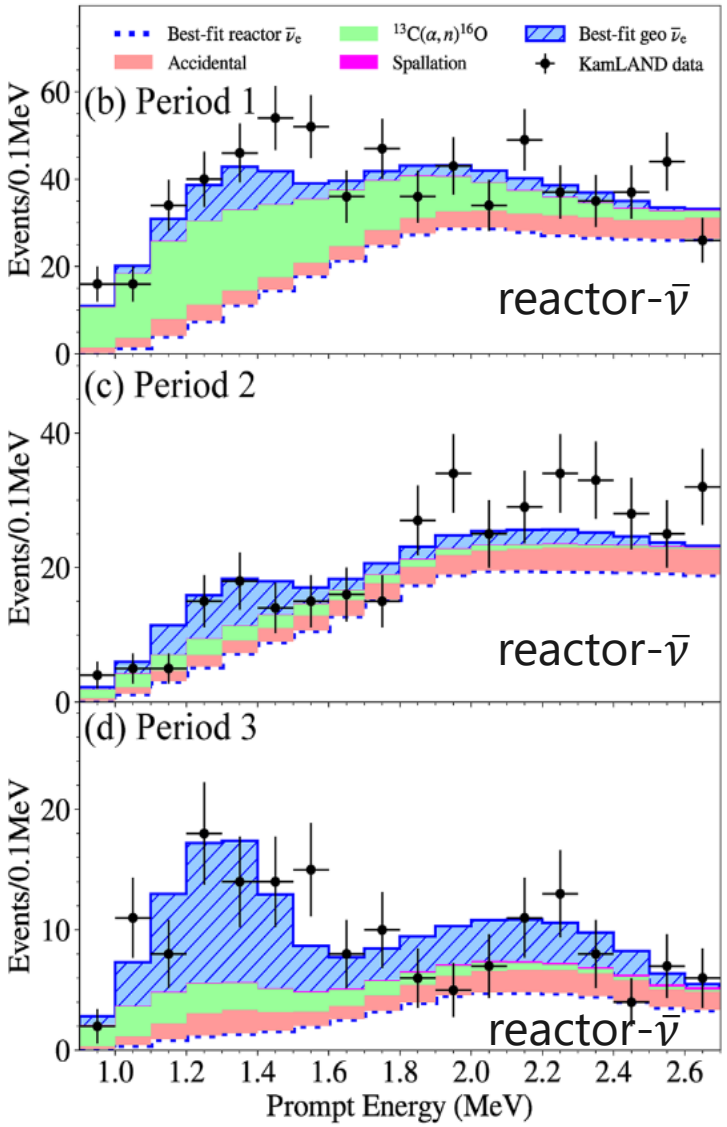
Abe *et al.* (2022),
Geophys. Res. Lett. **49**, e2022GL099566



Most of Japanese reactors
have been shut down from 2011

Low-background period

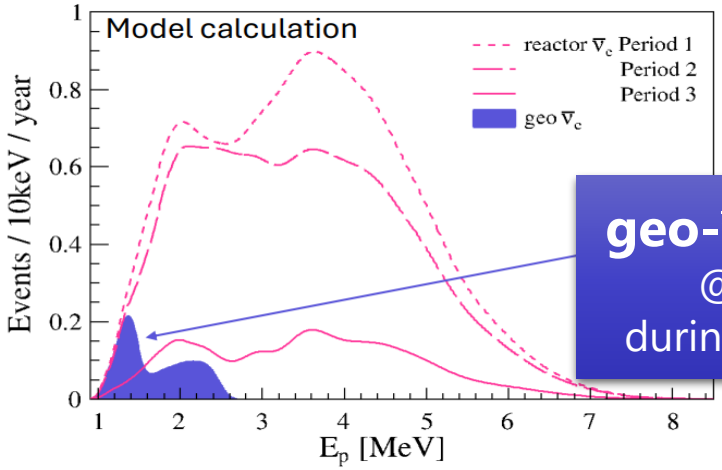
Results up to 2022



LS purification (2007 & 2008)

Reactors shut down (2011~)

	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

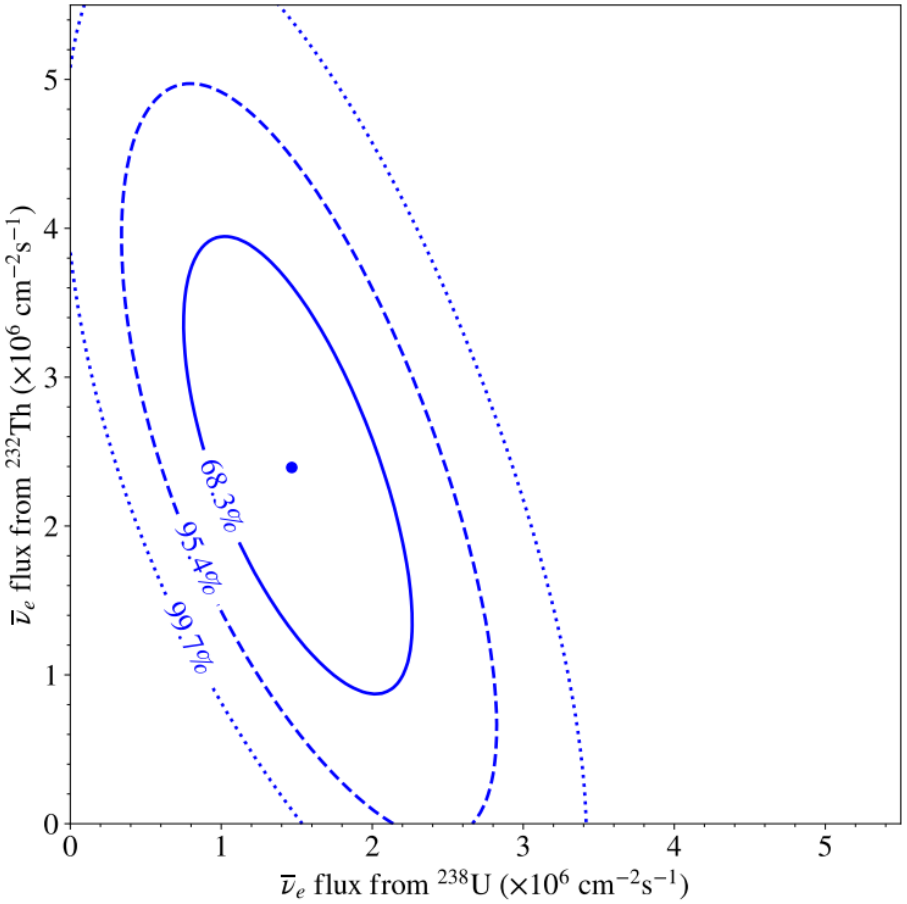


geo-$\bar{\nu}$ > reactor-$\bar{\nu}$
@low *E* range
during low-BG period

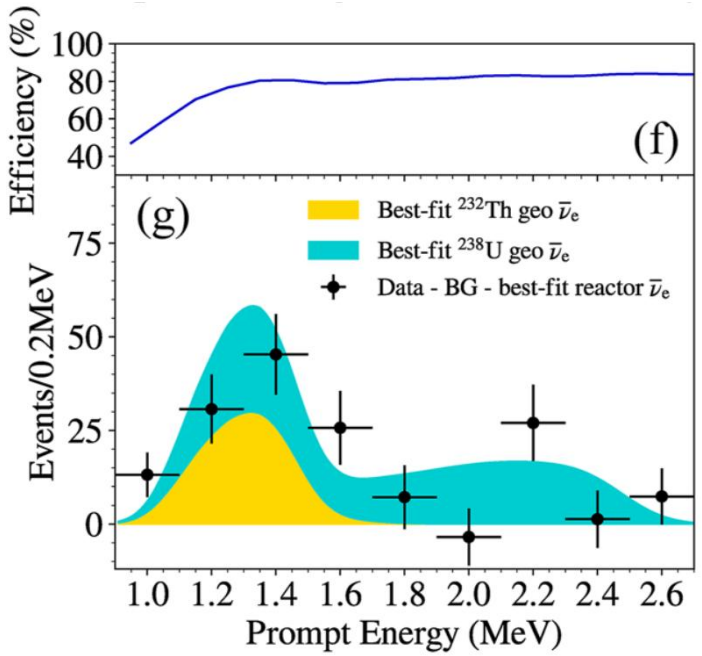
S/B ratio significantly improved!

Results up to 2022

Abe *et al.* (2022),
Geophys. Res. Lett. **49**, e2022GL099566



$173.7^{+29.2}_{-27.7}$ events
for 5227 days, 6.39×10^{32} proton-yr



^{232}Th geo-$\bar{\nu}$
$57.5^{+24.5}_{-24.1}$ events
0-signal rejection: 2.4σ

^{238}U geo-$\bar{\nu}$
$116.6^{+41.0}_{-38.5}$ events
0-signal rejection: 3.3σ

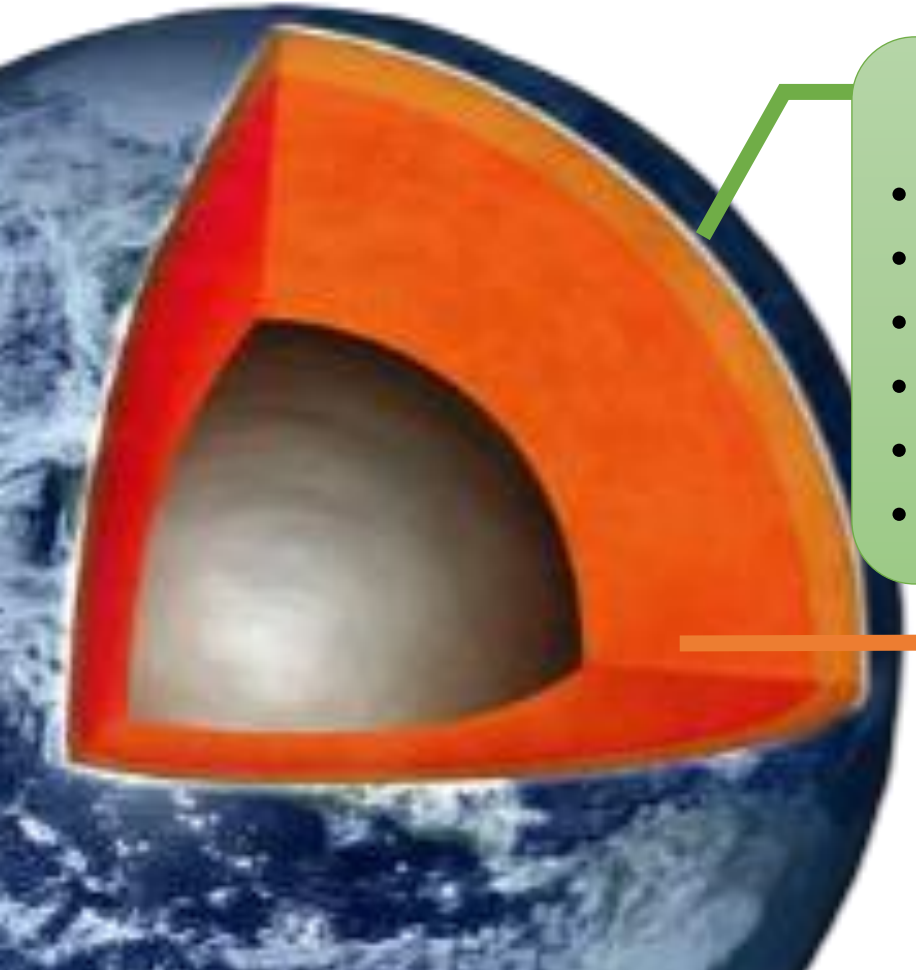
Spectroscopic measurement of geo-$\bar{\nu}$ was achieved!

How to interpret the data?

- Measured total flux ≈ crustal component + mantle component

$$S_{\text{total}}(\boldsymbol{r}) = S_{\text{crust}}(\boldsymbol{r}) + S_{\text{mantle}}(\boldsymbol{r})$$

$$Y = X + b$$



Crustal component

- Rock samples
- Seismic velocity
- Heat flux
- Gravity
- Magnetic field
- ……

HPE & density can be predicted with high accuracy

Mantle component

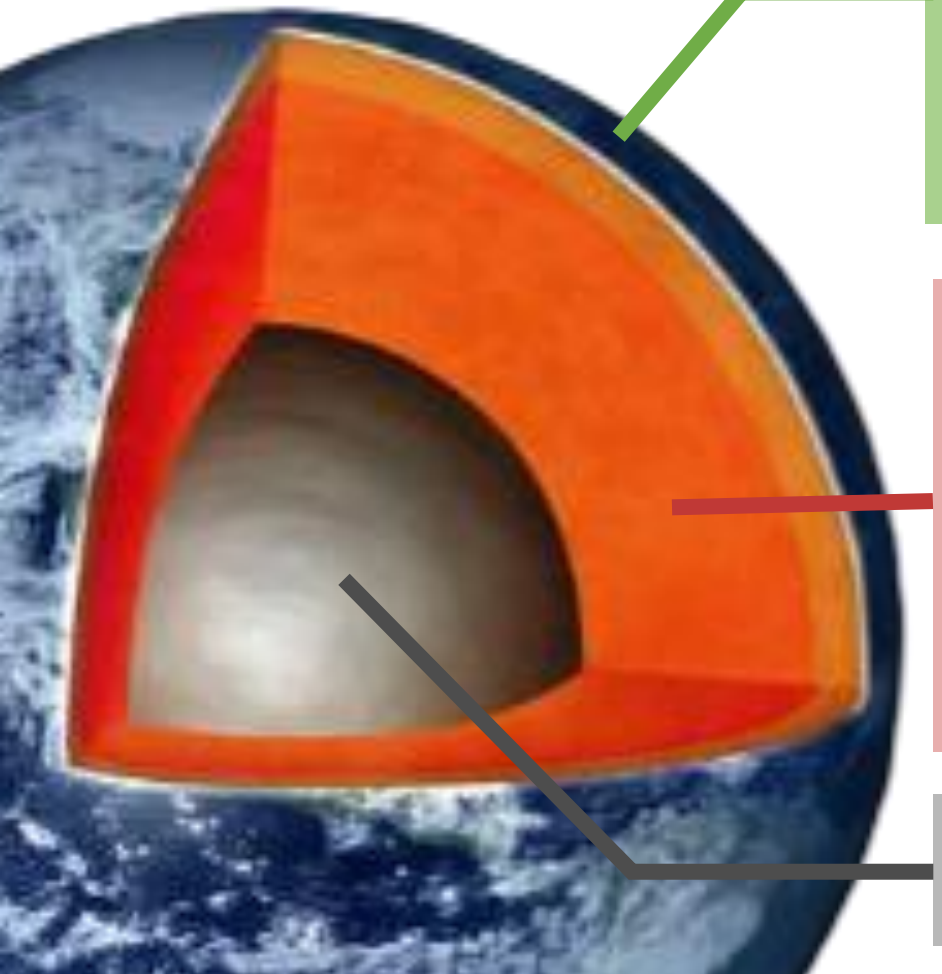
Can be treated as free parameters

↓

Estimate HPE abundances in the mantle

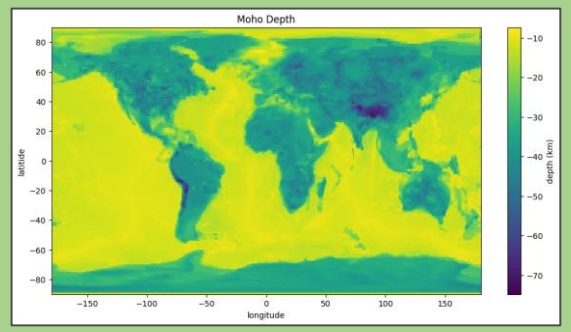
How to interpret the data?

$$S_{\mathrm{total}}(r) = S_{\mathrm{crust}}(r) + S_{\mathrm{mantle}}(r)$$



crust

CRUST1.0

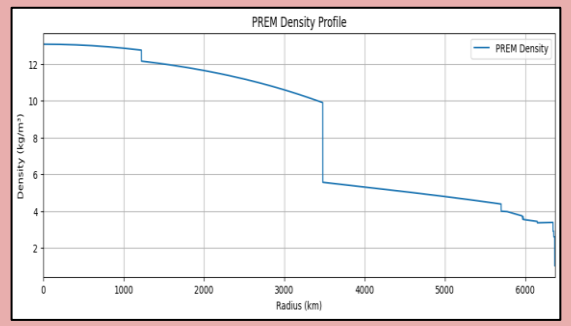


Region		U [ppm]	Th [ppm]
Sediment		1.73±0.09	8.10±0.59
Continental crust	Upper	2.7±0.6	10.5±1.0
	Middle	$0.97^{+0.58}_{-0.36}$	$4.86^{+4.30}_{-2.25}$
	Lower	$0.16^{+0.14}_{-0.07}$	$0.96^{+1.18}_{-0.51}$
Oceanic crust		0.07±0.02	0.21±0.06

Huang, et al. (2013)

mantle

Density: PREM



Th/U ratio unfixed or fixed at 3.9

Free parameter

Th & U abundance

core

Due to their negligible abundance, U and Th are ignored.

Geoscientific interpretation

- For normalization, the event counts should be converted into event rates.

KamLAND detector parameters

LS mass	LS density	Proton number density
m_{LS}	ρ_{LS}	n_{p}

KamLAND proton number

$$N_p = \frac{m_{\mathrm{LS}}}{\rho_{\mathrm{LS}}} n_{\mathrm{p}} = (5.98 \pm 0.13) \times 10^{31}$$

Geoneutrino event rate from KamLAND

$$n_{\mathrm{geo}\,\bar{\nu}} = (3.3^{+0.6}_{-0.5}) \times 10^{-2} \text{ cpd}$$

KamLAND detection efficiency

$$\varepsilon_{\mathrm{eff}}$$

Geoneutrino event rate (in TNU)

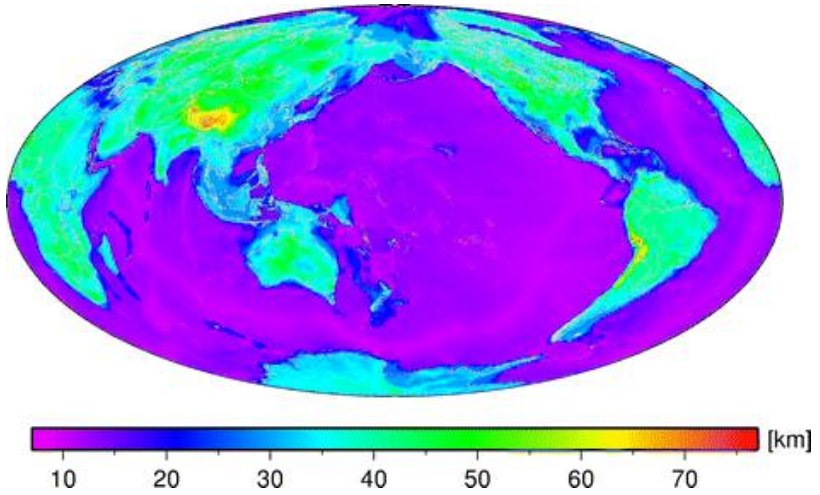
$$S_{\mathrm{geo}\,\bar{\nu}} = \frac{n_{\mathrm{geo}\,\bar{\nu}}}{\varepsilon_{\mathrm{eff}}} \times \frac{10^{32}}{N_p} \times 365 \text{ day}$$
$$= \mathbf{28.6^{+5.1}_{-4.8}\ TNU}$$

1 TNU = 1 geo-$\bar{\nu}$ event/10^{32} protons/year

Geoscientific interpretation

- Then, let's predict crustal component using geoscientific models.

Structure & density: CRUST1.0



Radioisotope abundance: global average

Region		U [ppm]	Th [ppm]
Sediment		1.73±0.09	8.10±0.59
Continental crust	Upper	2.7±0.6	10.5±1.0
	Middle	$0.97^{+0.58}_{-0.36}$	$4.86^{+4.30}_{-2.25}$
	Lower	$0.16^{+0.14}_{-0.07}$	$0.96^{+1.18}_{-0.51}$
Oceanic crust		0.07±0.02	0.21±0.06

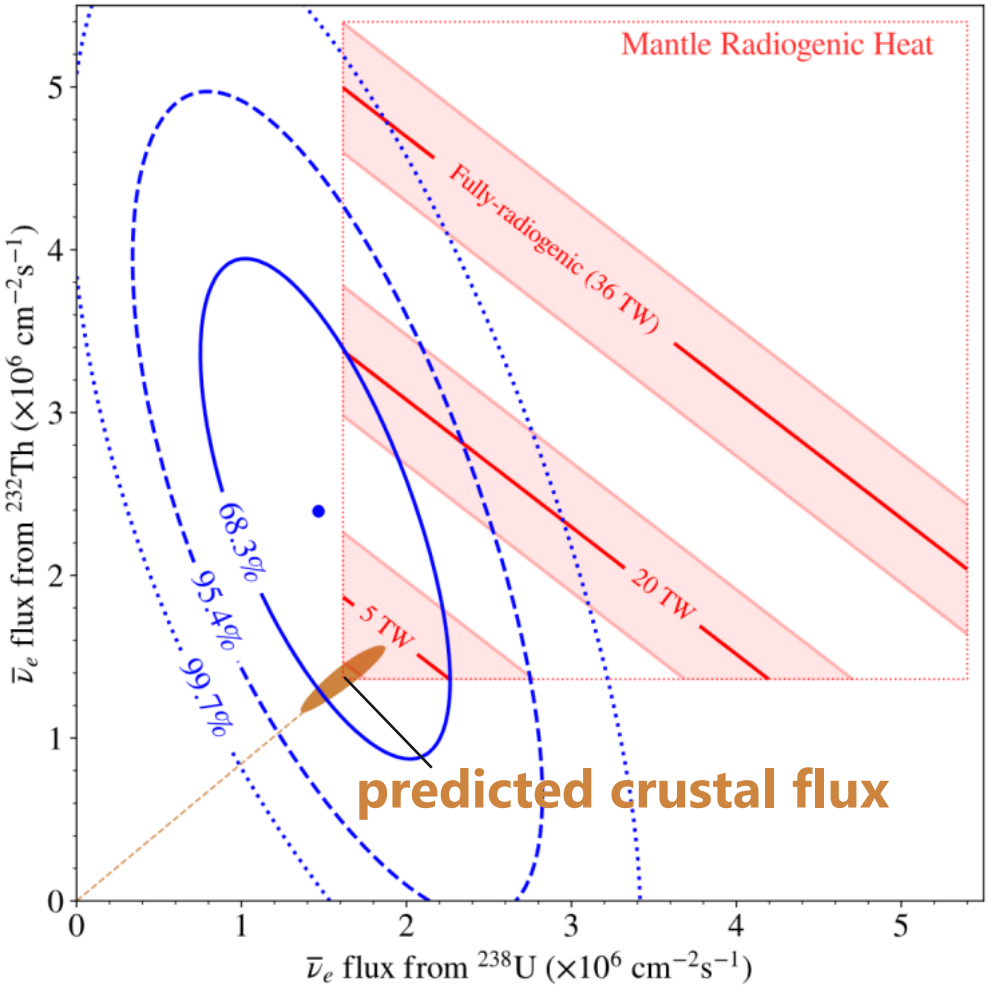
$$S(\boldsymbol{r}) = \sum_{X\in\mathrm{HPE}} L_X \int_E dE_\nu \int_{D(\theta)} d\boldsymbol{r}' \frac{dn_X(E_\nu)}{dE_\nu} \sigma_{\mathrm{IBD}}(E_\nu) P_{ee}(E_\nu, |\boldsymbol{r}-\boldsymbol{r}'|) \frac{A_X(\boldsymbol{r}')\rho(\boldsymbol{r}')}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}$$

$S_{\mathrm{crust}}(\mathrm{U}) = 18.9^{+5.2}_{-4.1}$ TNU
$S_{\mathrm{crust}}(\mathrm{Th}) = 5.7^{+1.7}_{-1.3}$ TNU

→ $\boldsymbol{S_{\mathrm{crust}} = 24.6^{+6.6}_{-5.2}}$ **TNU**

Geoscientific interpretation

- Then, we may extract signals from the mantle, and estimate radiogenic heat in the Earth.



$$S_{\mathrm{mantle}} = S_{\mathrm{total}} - S_{\mathrm{crust}} = 4.0^{+7.3}_{-8.2}\ \mathrm{TNU}$$

$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 9.2^{+9.0}_{-4.6}\ \mathrm{TW}$$

w/ crust model from Wipperfurth et al. (2020)

- Results vary depending on the constraints applied.

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

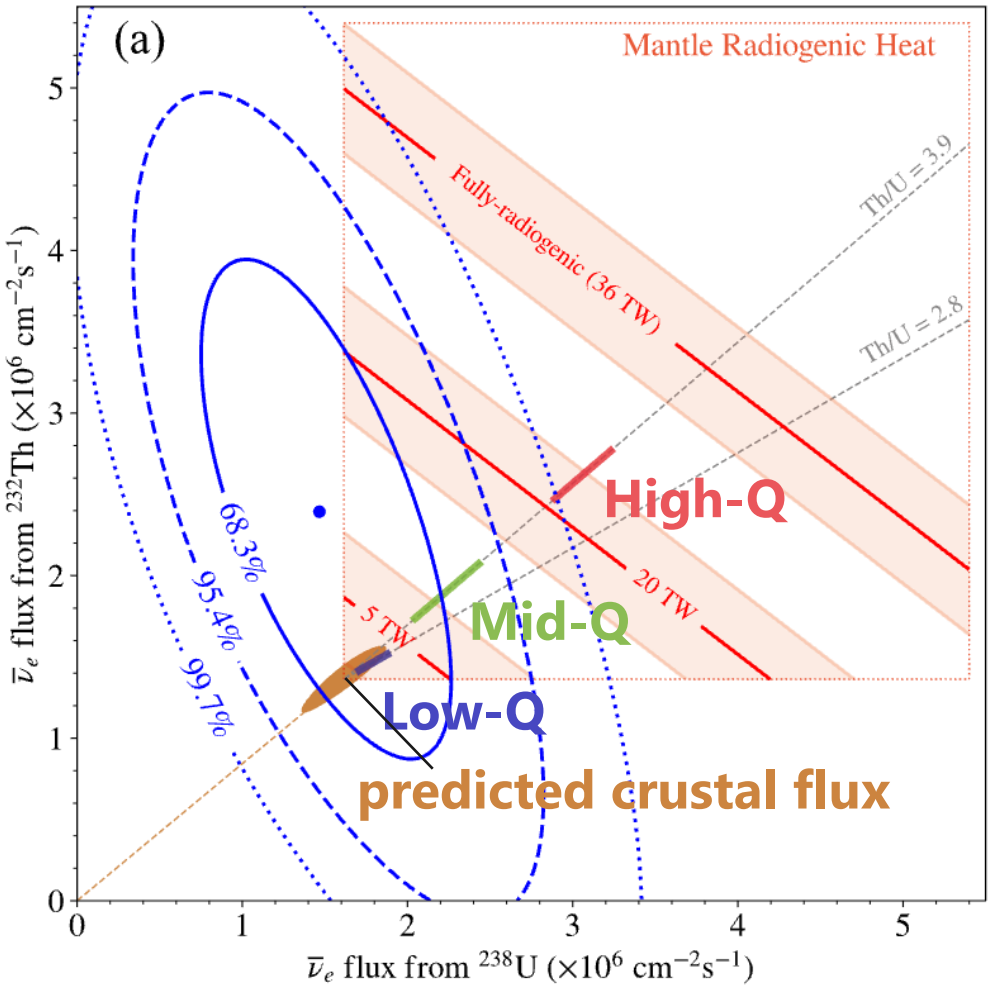
w/ crust model from Enomoto et al. (2007)

$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 10.6^{+6.2}_{-4.2}\ \mathrm{TW}$$

w/ crust model from Enomoto et al. (2007),
Th/U mass ratio fixed at 3.9

Geoscientific interpretation

- Finally, we may compare the result with BSE models.



DISFAVORED

High-Q (Geodynamics model)
>25 TW

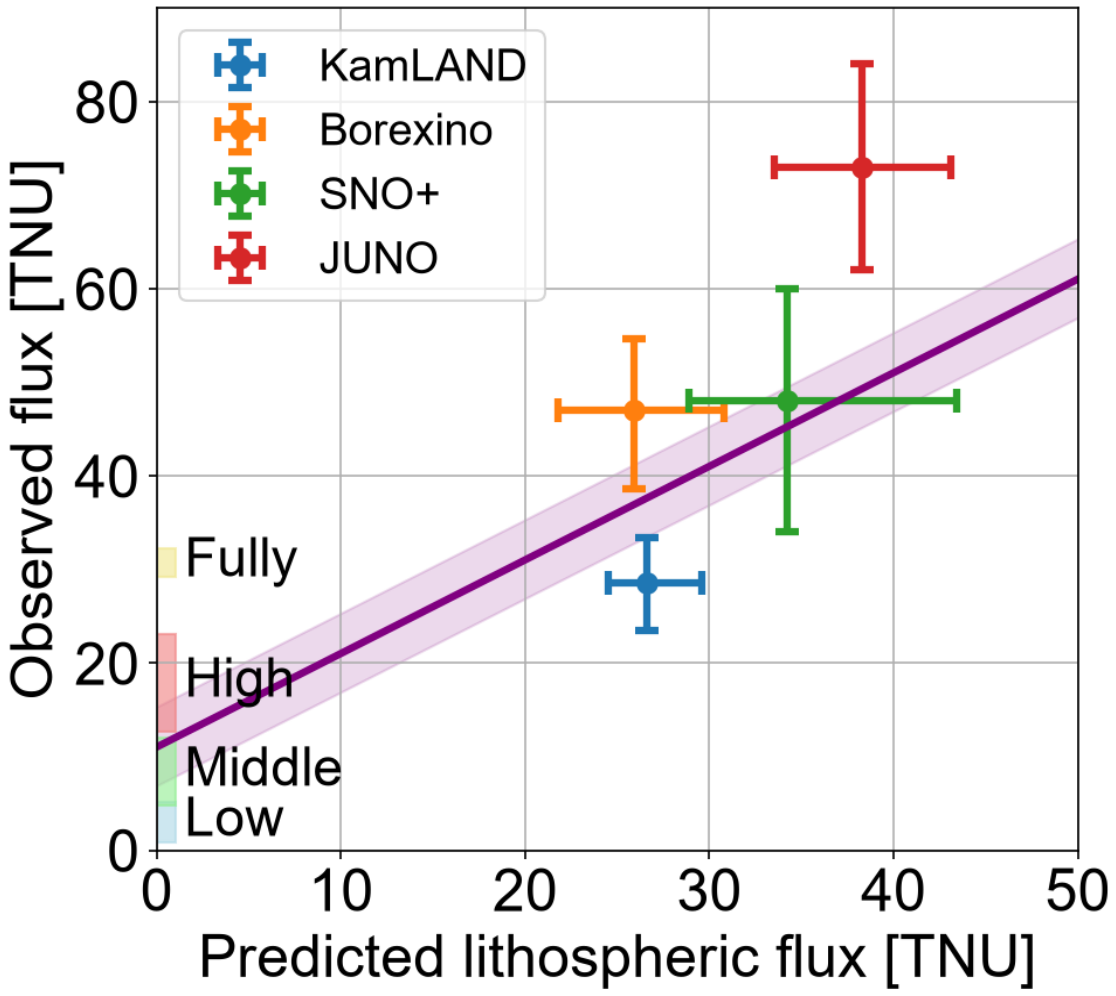
FAVORED

Mid-Q (Geochemical model)
17~22 TW

FAVORED

Low-Q (Cosmochemical model)
10~15 TW

Global fit: Comparison with other experiments



Crustal models:

- *KamLAND: Bellini et al. (2021)*
- *Borexino: Agostini et al. (2020)*
- *SNO+: Strati et al. (2017)*
- *JUNO: Gao et al. (2020)*

- If the mantle is a homogeneous part, then

$$S_{\text{total}}(\boldsymbol{r}) = S_{\text{crust}}(\boldsymbol{r}) + S_{\text{mantle}}(\boldsymbol{r})$$

$$Y \quad = \quad X \quad + \quad b$$

- **Result**

Mantle radiogenic heat
14.7 ± 6.0 TW

Total Earth radiogenic heat
21.8 ± 6.1 TW

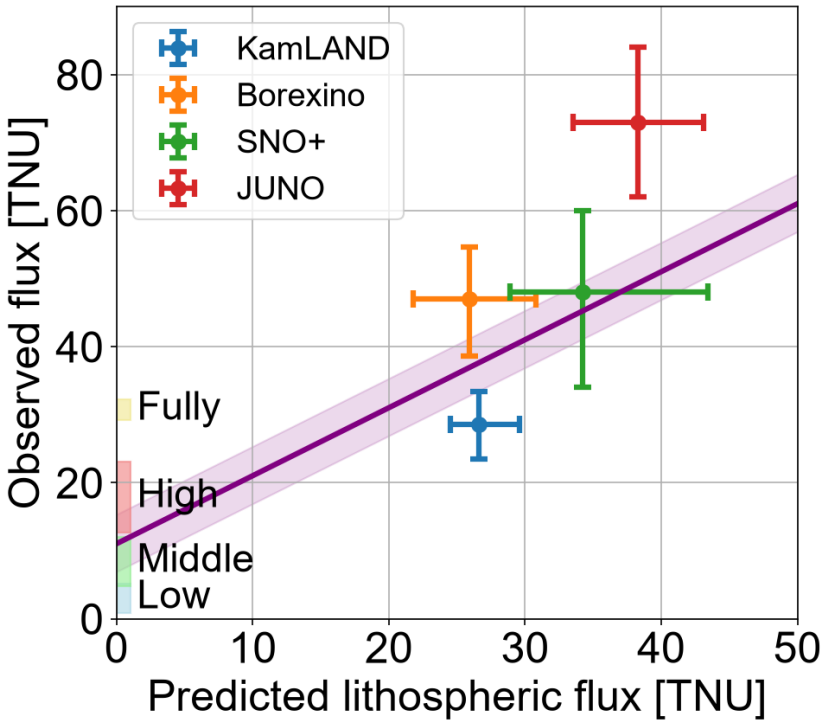
Mantle U abundance
13.3 ± 5.4 ppb

Uncertainties are so huge!

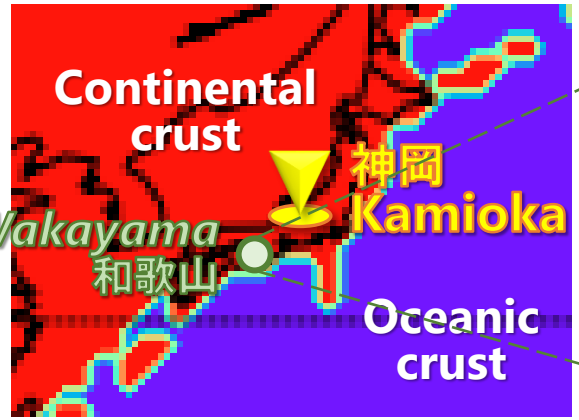
And the data points are
inconsistent with each other!



(a) New crustal models



Can be better predicted with more accurate crustal models

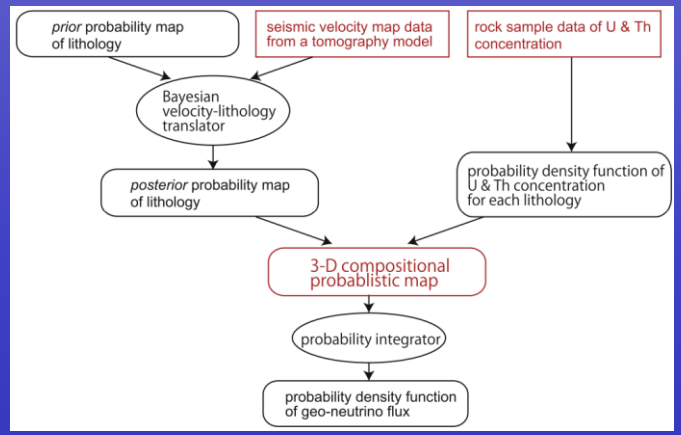


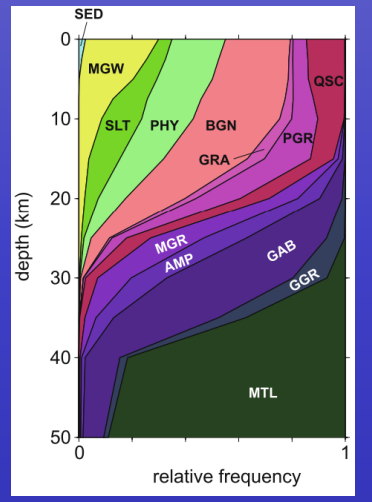
Japan is classified as **continental crust** in CRUST1.0



green schist (绿片岩) originated from **oceanic crust**

Stochastic modeling method (Bayesian inference)





Takeuchi *et al.* (2019), *Phys. Earth Planet. Inter.* **288**, 37-57

Also see Sanshiro's talk (18th 10:50)

(b) KamLAND full-dataset analysis

2024
KamLAND DAQ finished

2022
Measurement in low-reactor-BG period

New data!
Under analysis with **new methods**...

2011
Partial radiogenic Earth confirmed

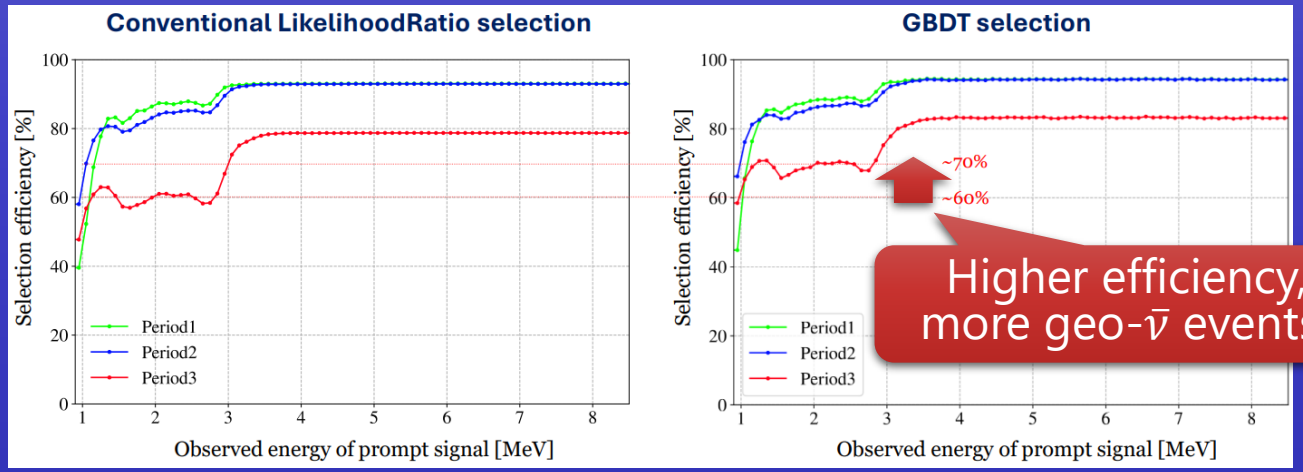
2005
First evidence of geoneutrino

2003
Evidence for reactor $\bar{\nu}$ disappearance

2002
Beginning of KamLAND

IBD selection with GBDT
(Gradient Boosted Decision Tree)

An ensemble method combining multiple decision tree to improve prediction accuracy.

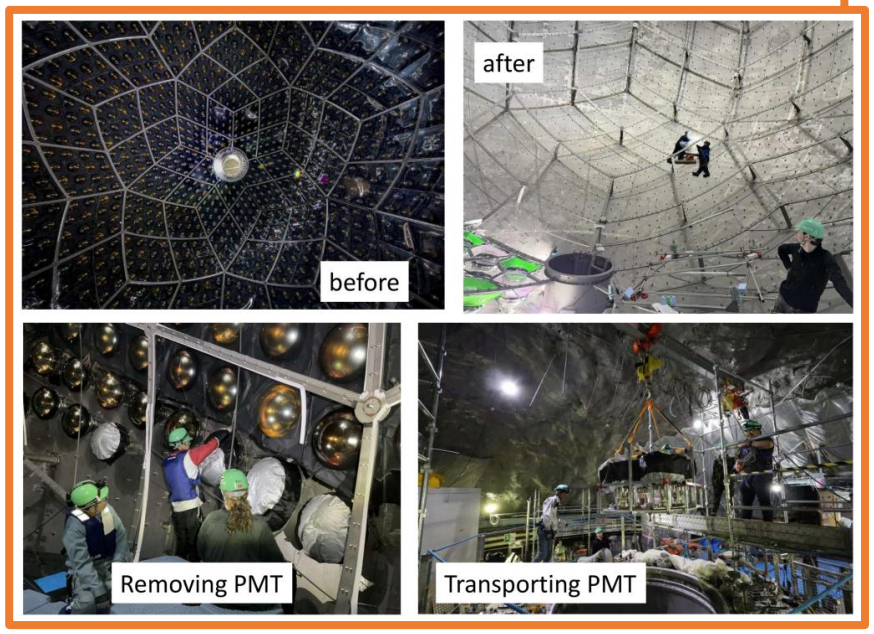


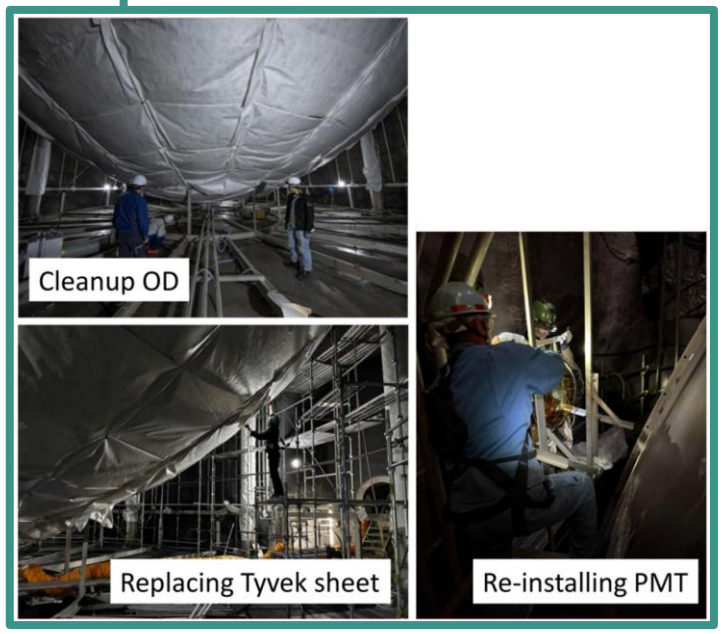
(c) KamLAND2

KamLAND decommission | **KamLAND2 construction** | **KL2-Zen construction**

2024 2025 2026 2027 2028 2029

Xe extraction
KamLAND DAQ stop
OD dismantling
LS & BO extraction
PMT removal
OD reconstruction
PMT & light-collection mirror installation
LS & BO installation
DAQ system installation
KamLAND2 start
Mini-balloon installation
Xe loading
KamLAND2-Zen start







(c) KamLAND2

High-performance PMTs

High-QE 20" PMTs
(~2x light capture)



Upgraded DAQ electronics



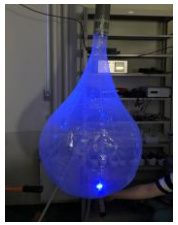
for stronger
BG removal

Light-collecting mirrors

(~2x light yield)



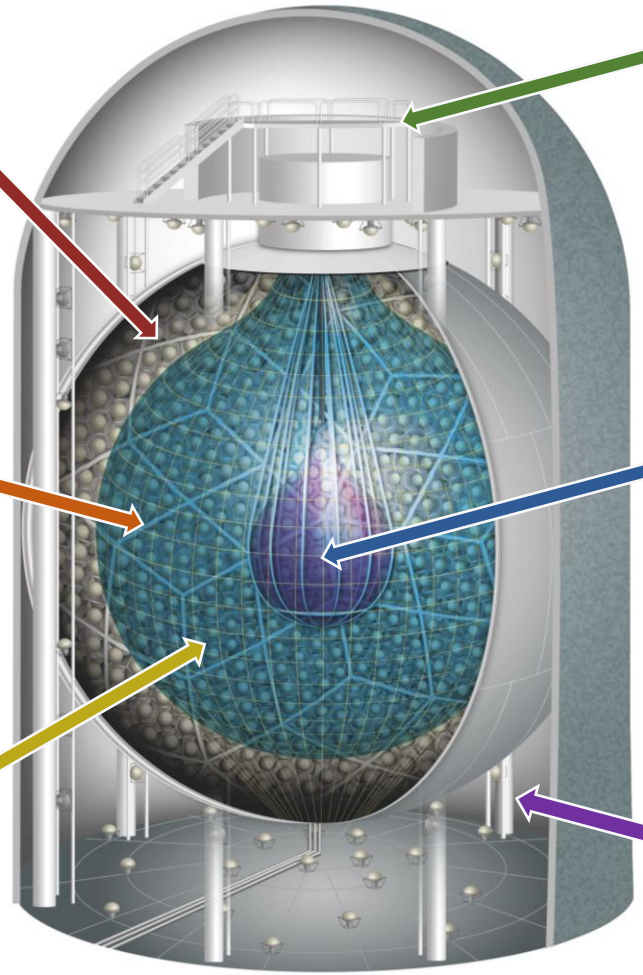
Scintillating balloon (for 0νββ)



PEN film
tags and removes
alpha backgrounds

Wavelength-shifting LS

Shifts light spectrum
for easier neutrino detection



Upgraded Outer Detector (OD)



Enhanced coating &
waterproofing
for stable experiment

DAQ start from 2028!

Thank you.

