# KamLAND : Geo-Neutrino Measurement in Japan

Muon and Geo-Radiation Physics for Earth Studies

Nov. 12, 2014

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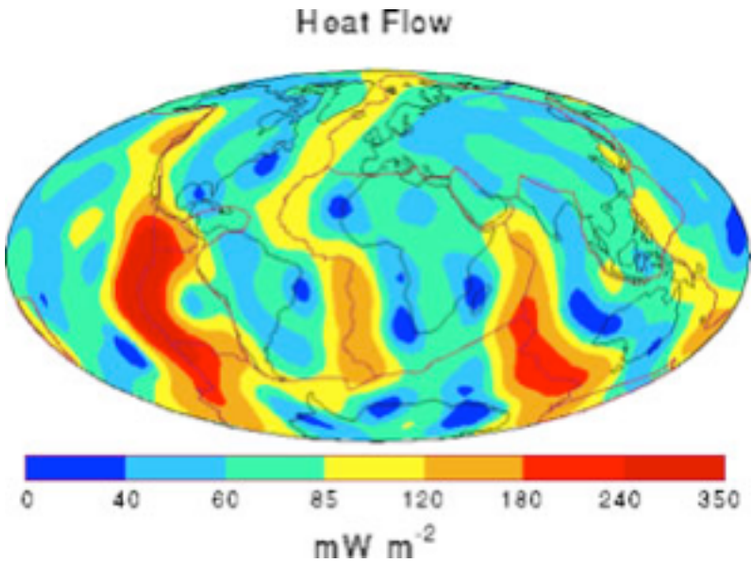
# Geologically Produced Anti-Neutrino

Beta-decay of radioactivities (U, Th, K) in the Earth

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ (100\%)$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}\ (100\%)$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ (89.28\%)$$

$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\mathrm{MeV}(10.72\%)$$



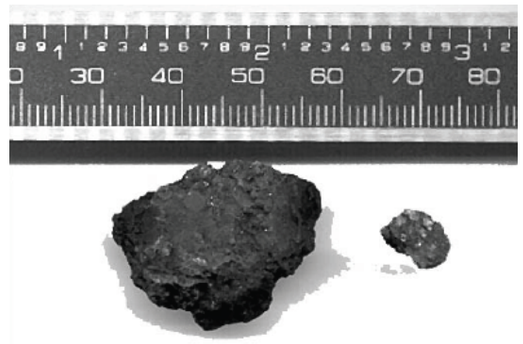

Bulk Silicate Earth (BSE) model

chondrite meteorite

U : 8 TW

Th : 8 TW

K : 3 TW



Surface heat flow

47 ± 2 TW

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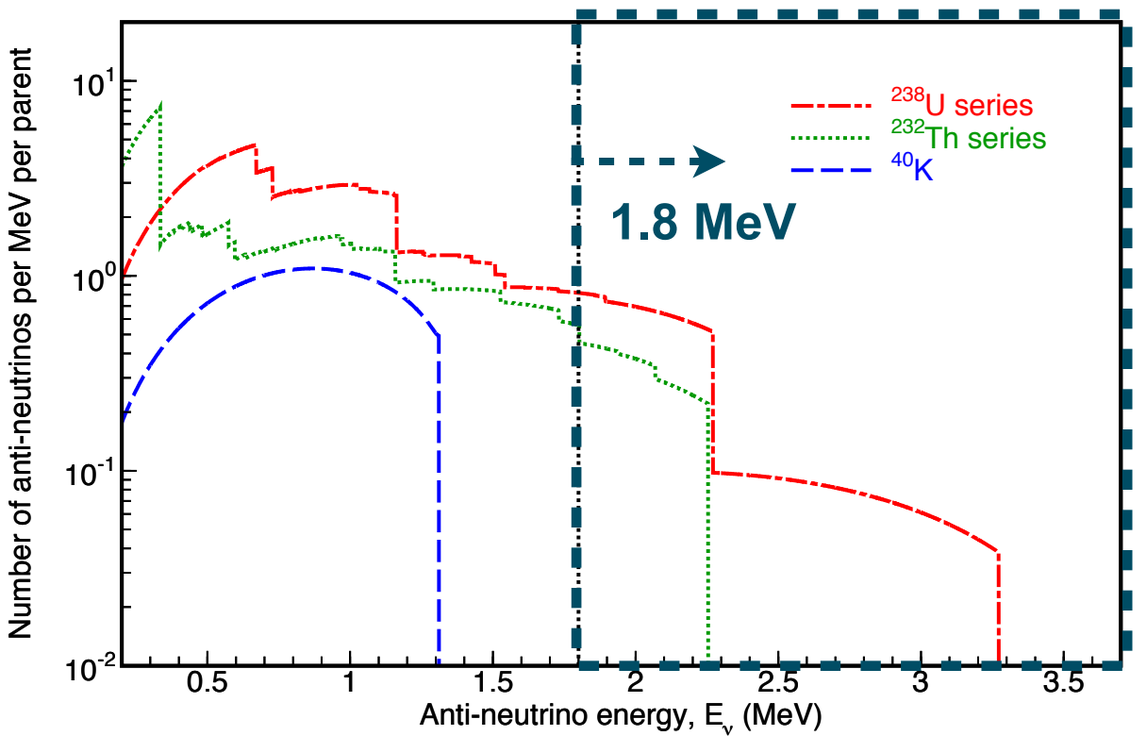
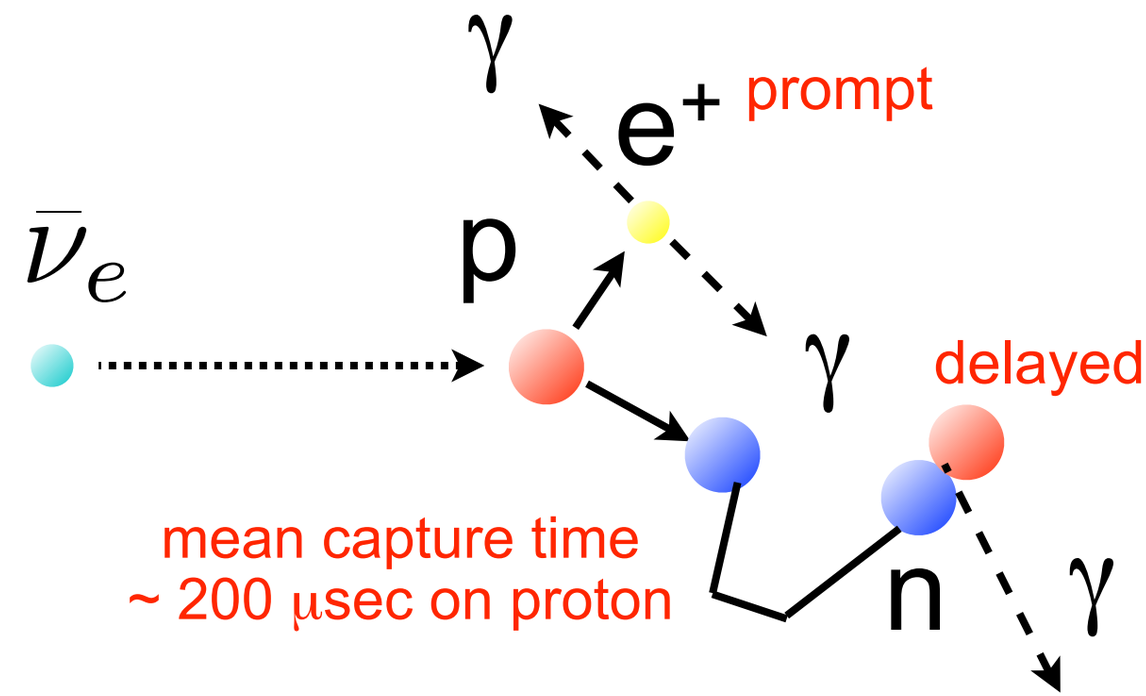
Radiogenic heat

19 TW

# Geo Neutrino

- G. Eder (1966) — **first calculation in science literature**
- G. Marx (1969)
- L. Krauss et al. (1988)
- M. Kobayashi, Y. Fukao (1981) — **systematic search of target detector material**
- R. Raghavan et al. (1998) — **feasible plan in KamLAND and Borexino**
- Rothschild et al. (1998)
- G. Fiorentini et al. (2003) — **detailed neutrino flux calculations**



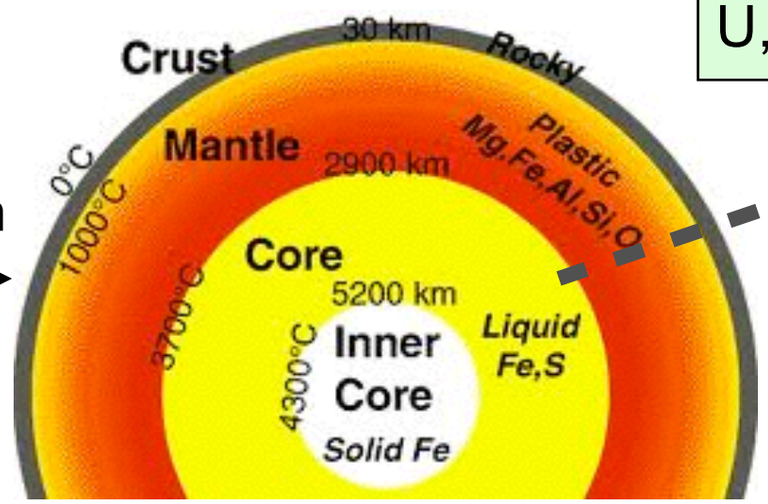

anti-neutrino detection by inverse beta-decay

# Neutrino Geoscience

## Heat sources in the Earth

~ 4 billion years ago

Earth formation →




Energy release by radioactive decay of U, Th, K → **radiogenic heat**

Release of gravitational energy through metallic core separation → **primordial heat**

still remain ?

## 5 Big Questions:

- What are earth's K/U & Th/U ratios?
  *planetary volatility curve*
- Radiogenic contribution to heat flow?
  *secular cooling*
- Distribution of reservoirs in mantle?
  *whole vs layered convection*
- Radiogenic elements in the core??
  *Earth energy budget*
- Nature of the Core-Mantle Boundary?
  *hidden reservoirs*

15 July 2009 McDonough-Trieste-2009

geo reactor

Experimentally investigated

Geo neutrino detector

- KamLAND (Japan)
- Borexino (Italy)

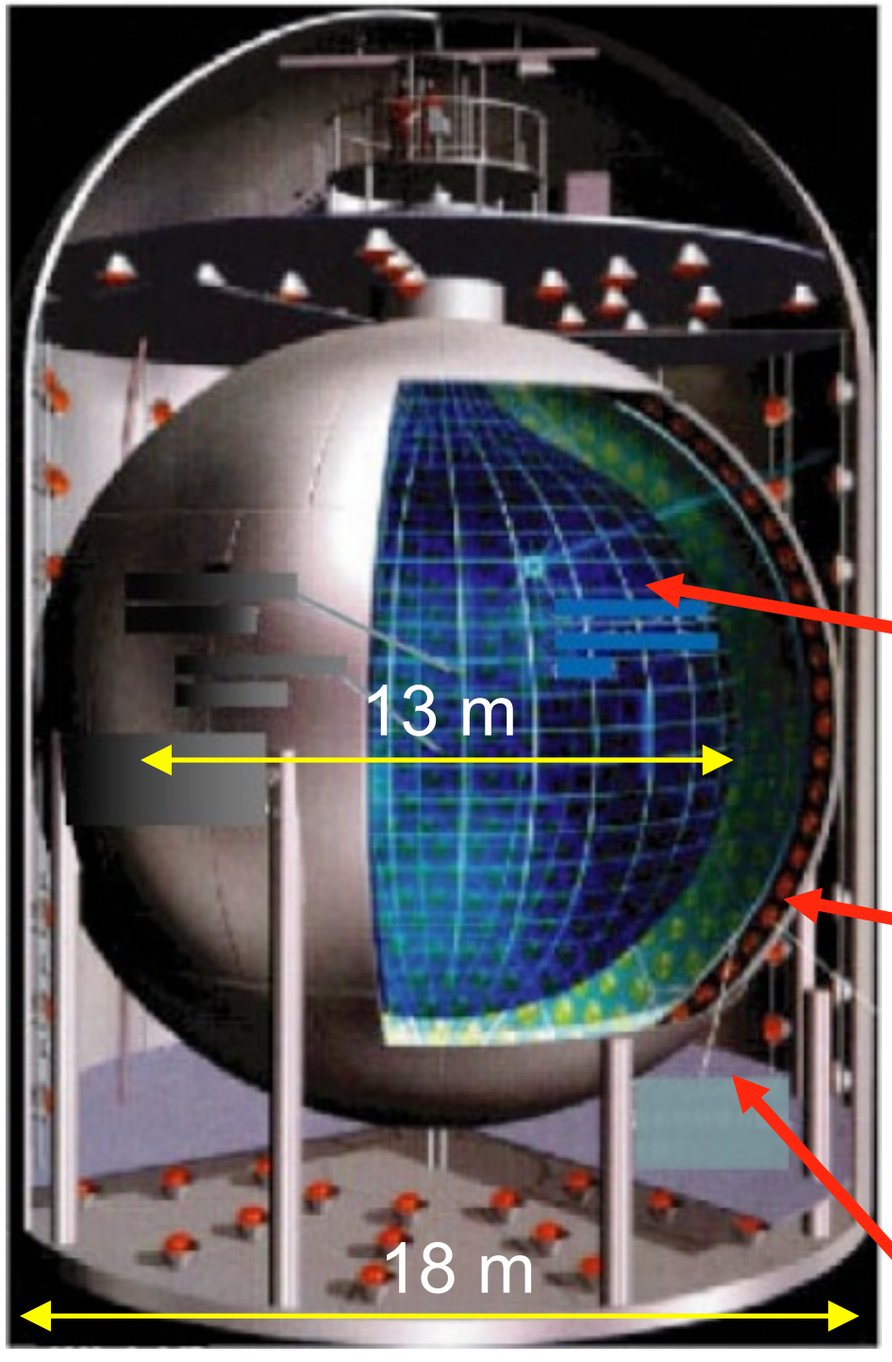
Geo neutrino experiment will play a key role in answer all the questions !

KamLAND

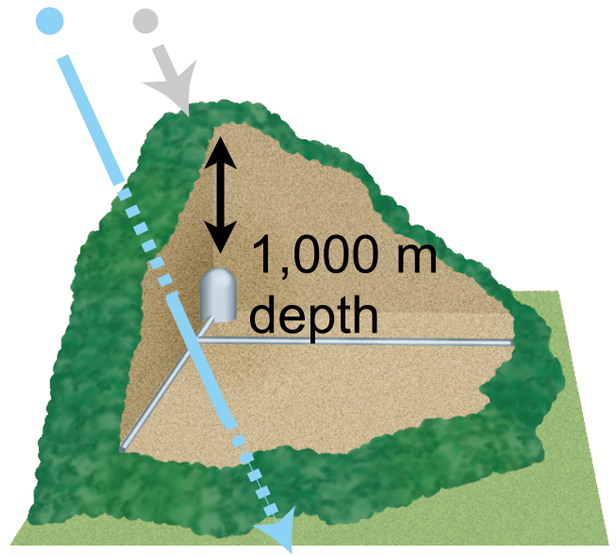
# KamLAND

## Kamioka Liquid Scintillator Anti-Neutrino Detector

operated since 2002








1,000 ton Liquid Scintillator

Dodecane (80%)  Pseudocumene (20%)  PPO (1.36 g/l)

1,325 17 inch + 554 20 inch PMTs

commissioned in February, 2003

photocathode coverage : 22% → 34%

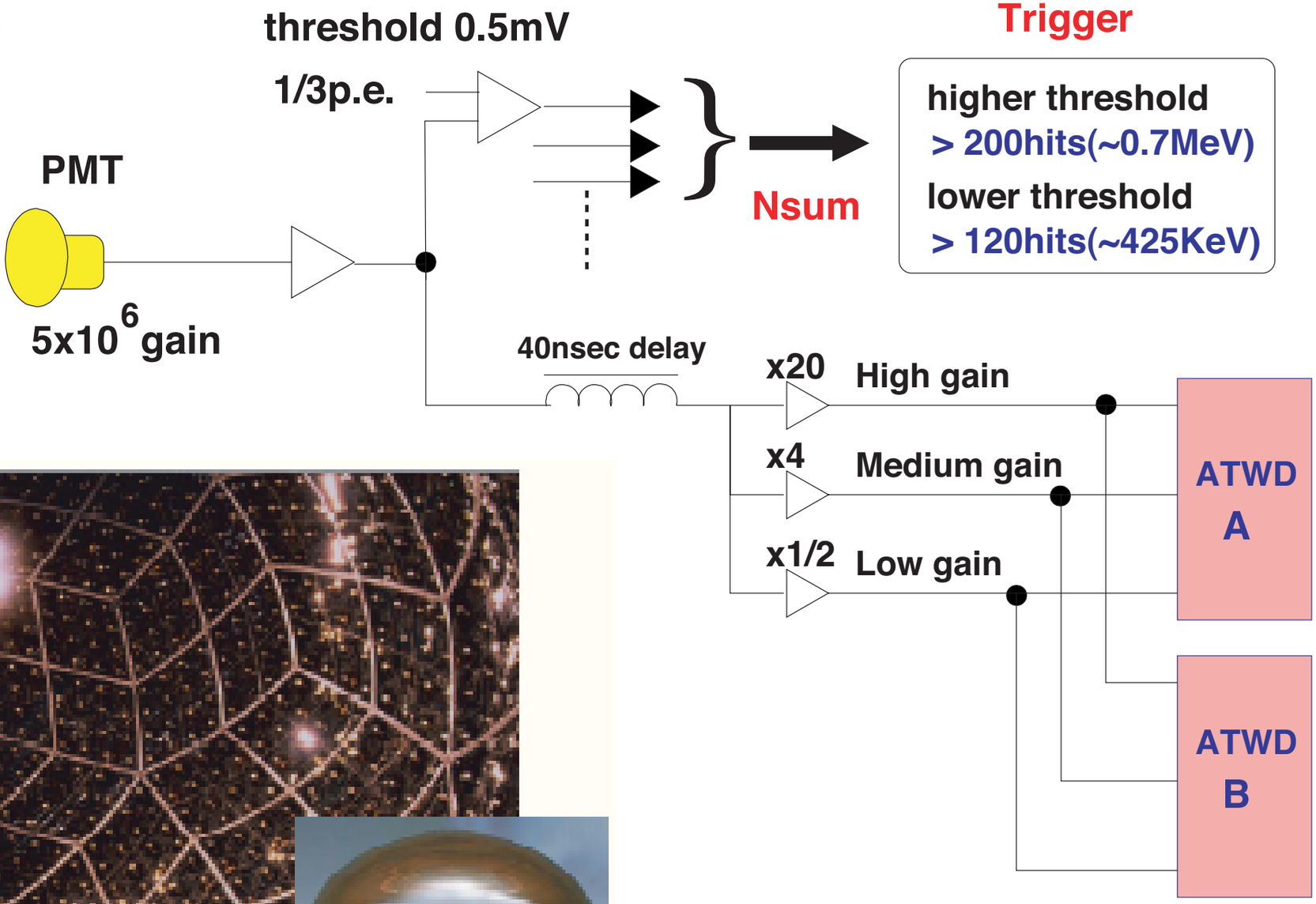
Water Cherenkov Outer Detector

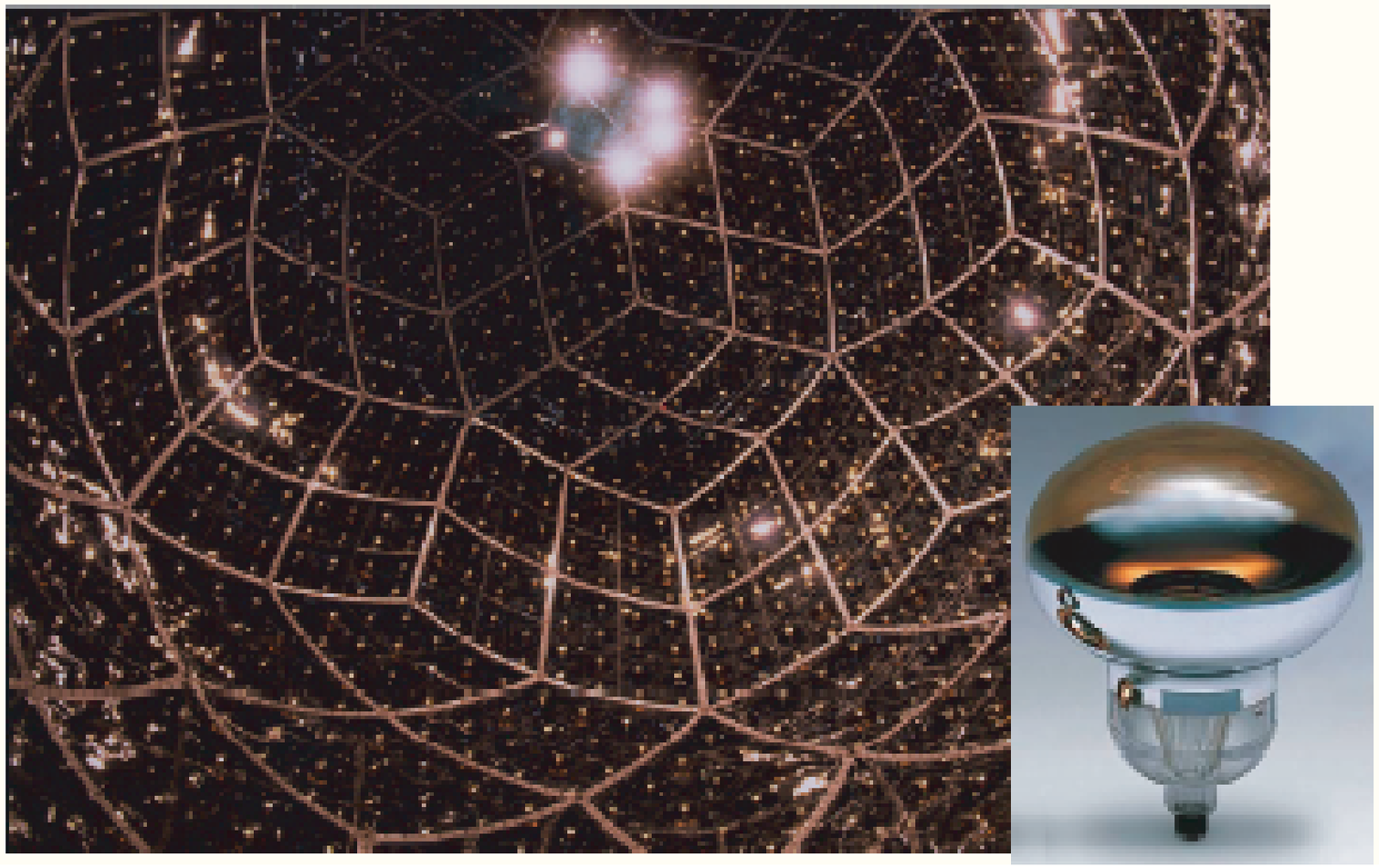
# Scintillation Signal Record

Large Area PMT

17-inch 1325

20-inch 554



cover signals from wide dynamic range
0.1 ~ 1000 p.e.

# Reference Earth Model

UCC U : 2.8 ppm / Th : 10.7 ppm

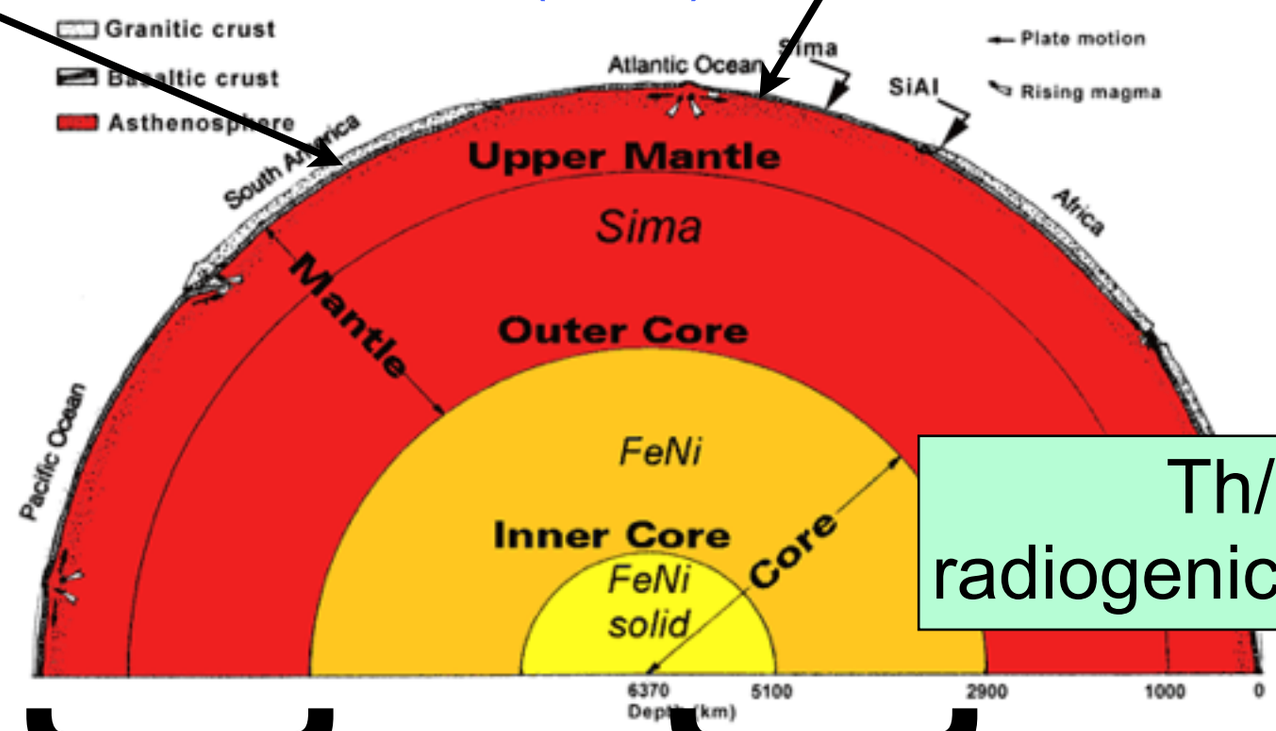
MCC U : 1.6 ppm / Th : 6.1 ppm

LCC U : 0.2 ppm / Th : 1.2 ppm

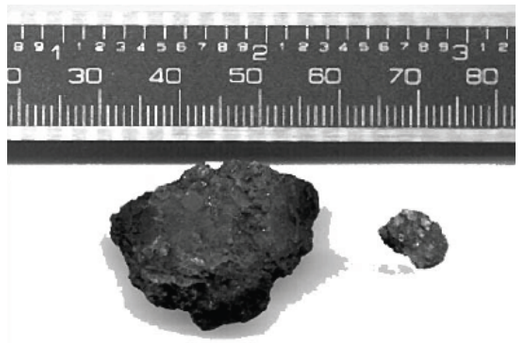
Rudnick et al. (1995)

continental crust

oceanic crust
U : 0.10 ppm / Th : 0.22 ppm




chondrite meteorite



Th/U ~ 3.9
radiogenic heat ~ 16 TW

mantle

U : 0.012 ppm / Th : 0.048 ppm

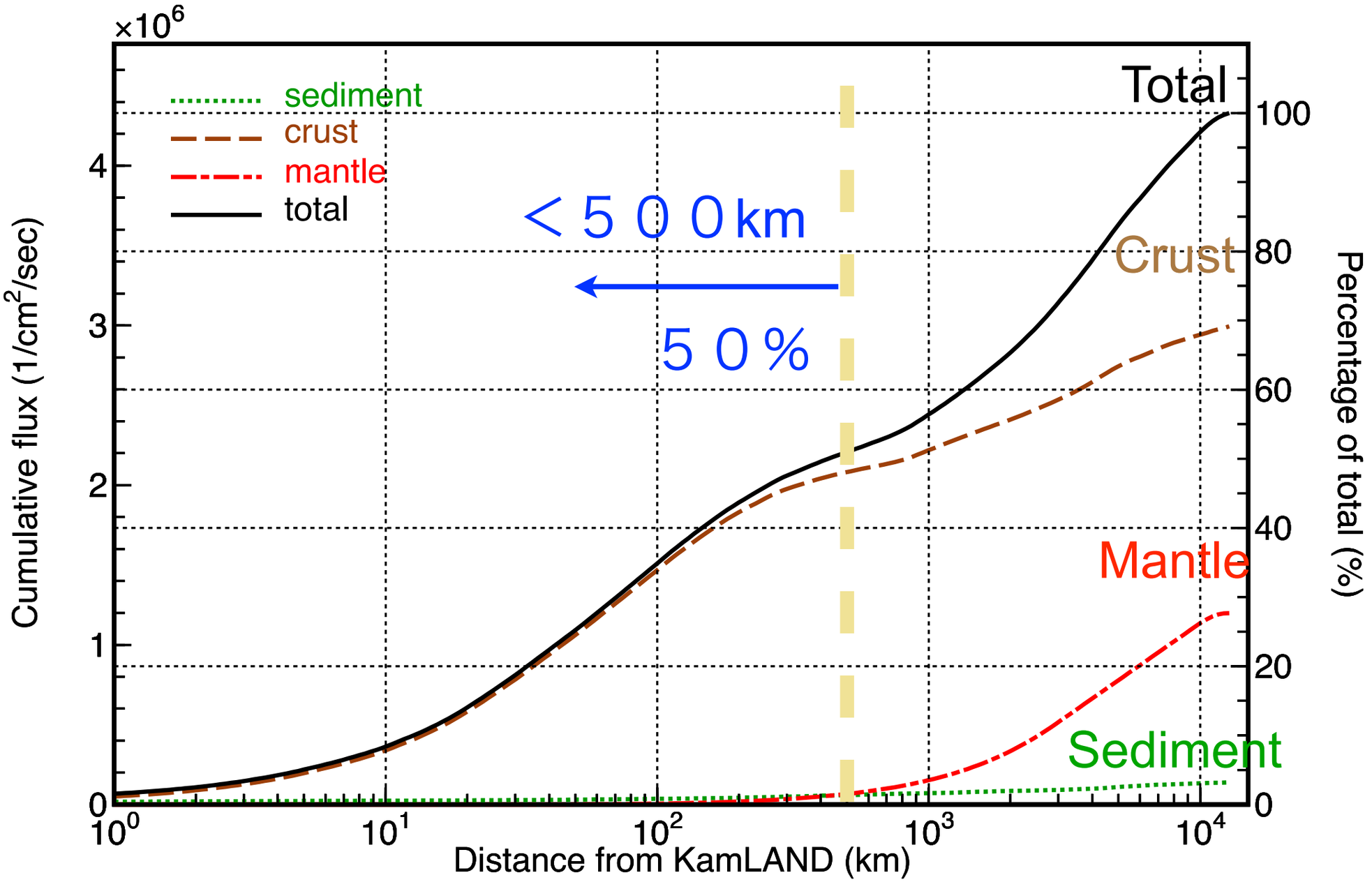
core

U : 0 ppm / Th : 0 ppm

no U/Th in core

***Mantle = BSE (Primitive Mantle) − Crust***

# Distance and Cumulative Flux



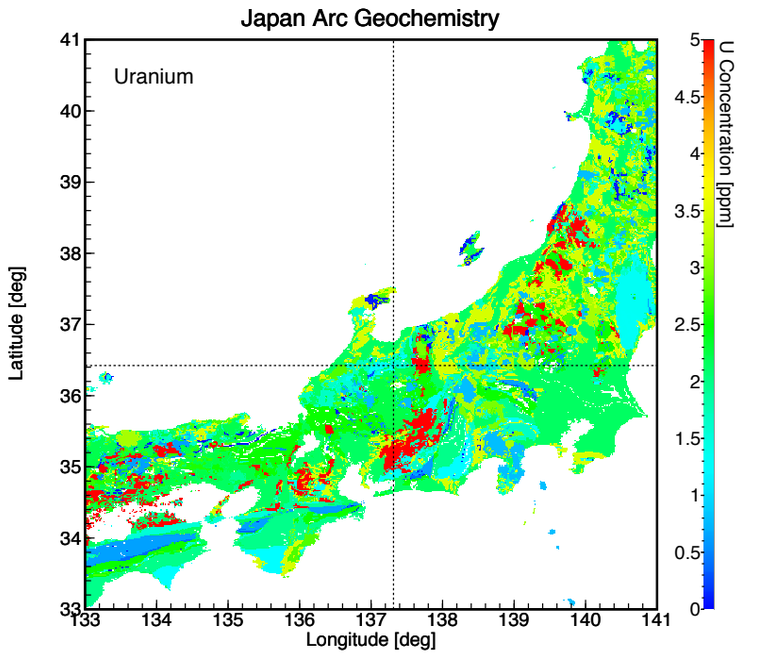

neutrino oscillation

$$P(E, L) \sim 1 - \frac{1}{2} \sin^2 2\theta_{12}$$ (constant suppression)

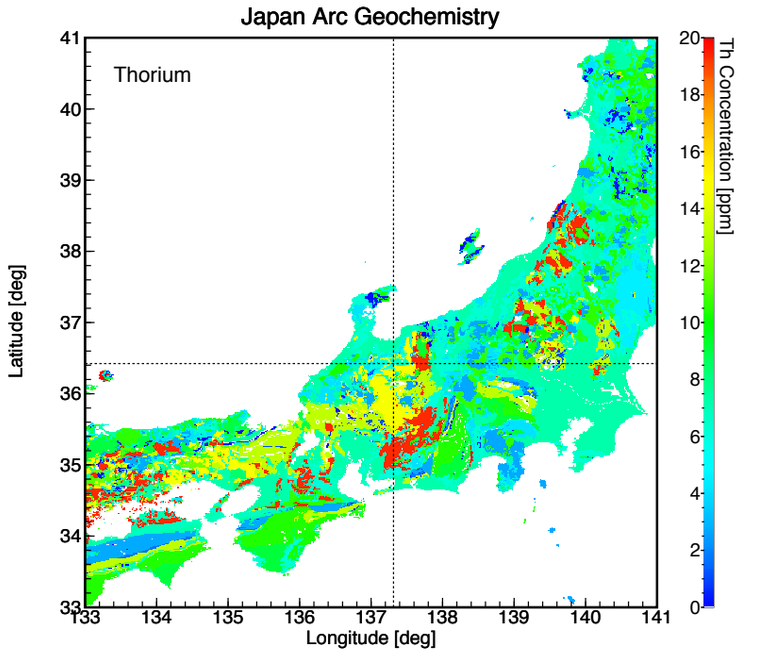
50% of the total flux originates within 500 km

# Effect of Local Geology

## Uranium




## Thorium

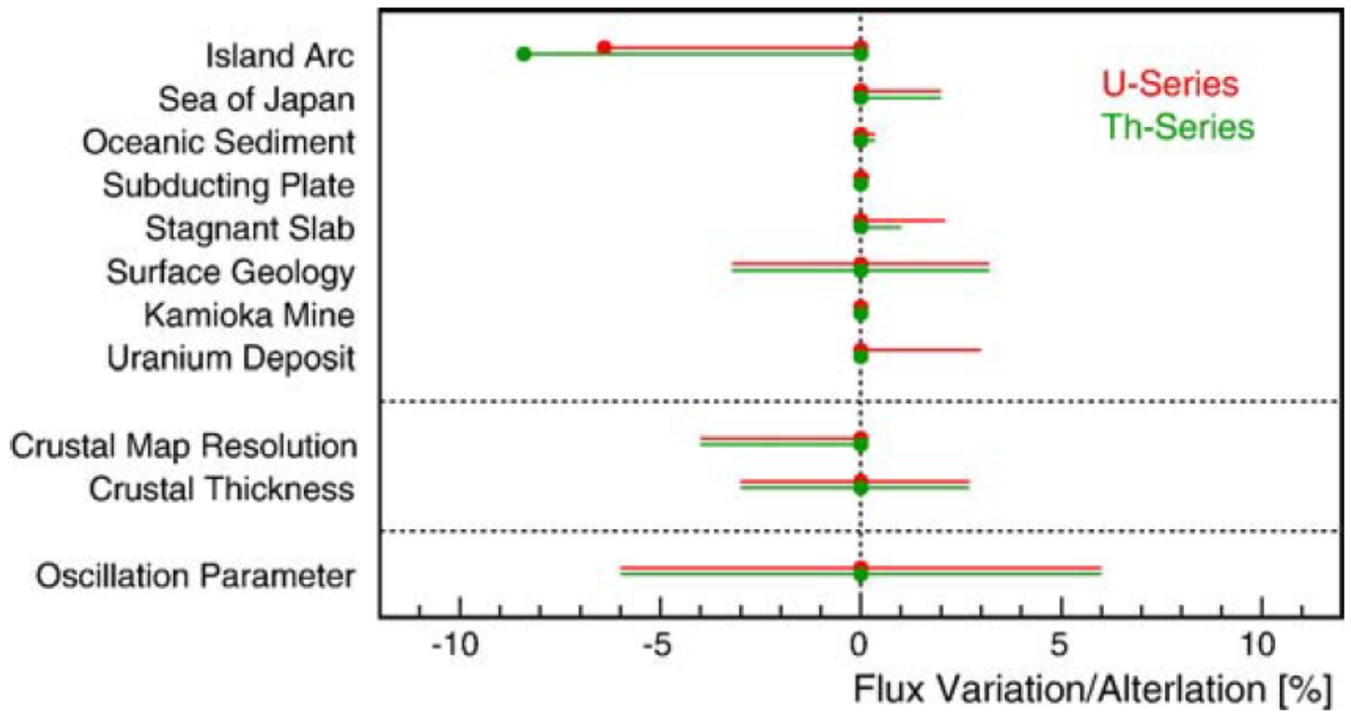



## weighted average of surface contamination

geological map + rock samples (Togashi et al.)

U : 2.32 ppm  Th : 8.3 ppm

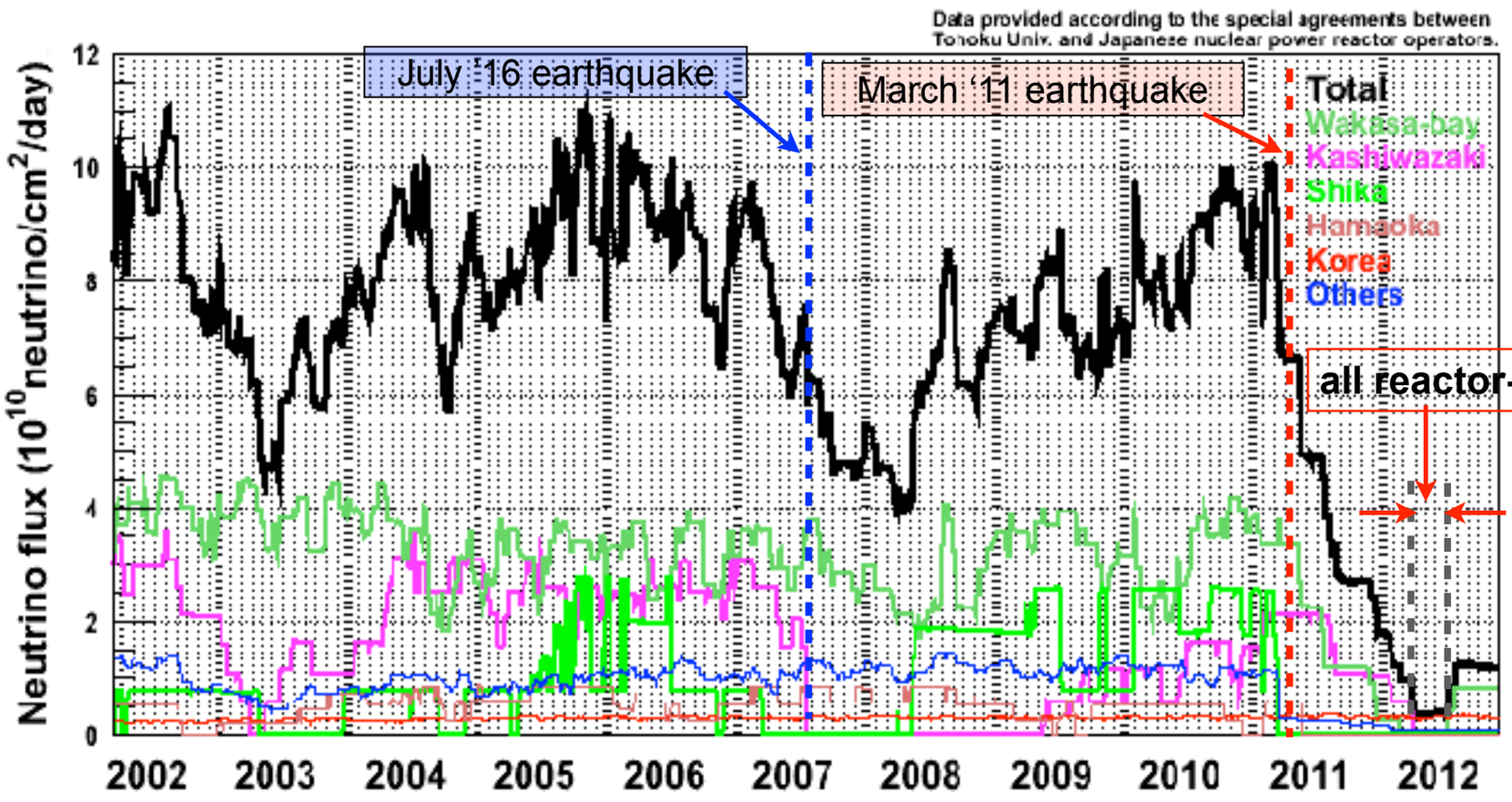
EPSL 258, 147 (2007)

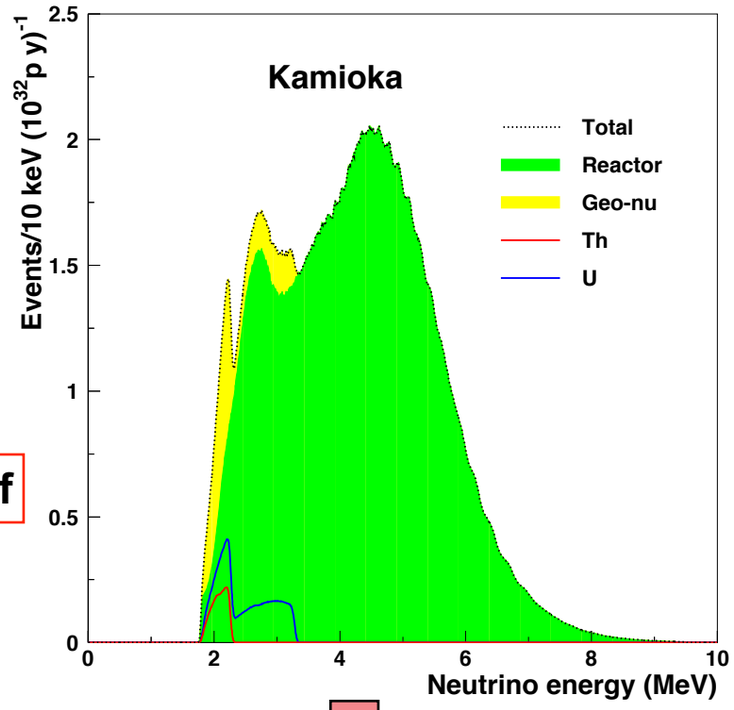



< 10% fluctuation
from global average

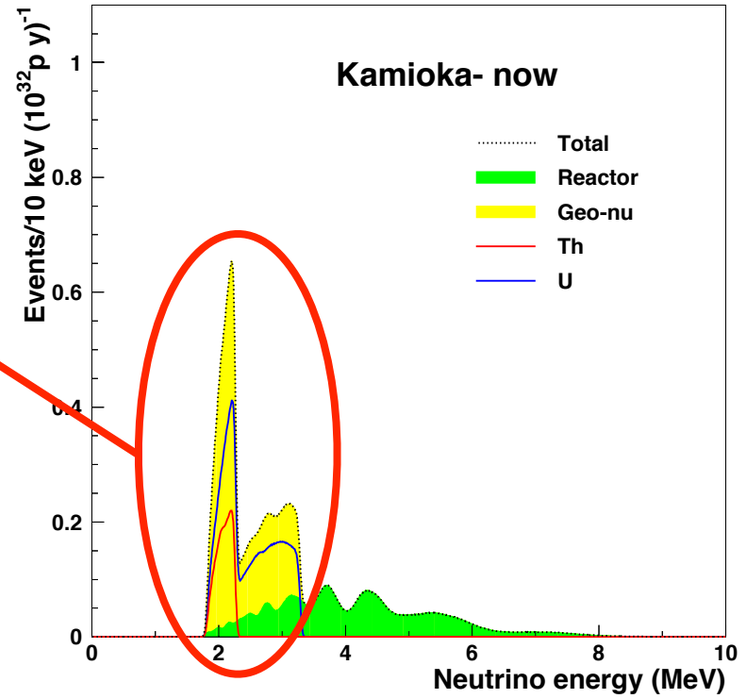
# Anti-Neutrino Flux in Kamioka

## time variation of reactor anti-neutrino flux




decrease of reactor neutrino




significant reduction of anti-neutrino flux from reactors after Fukushima-I accident

good data for geo neutrino observation

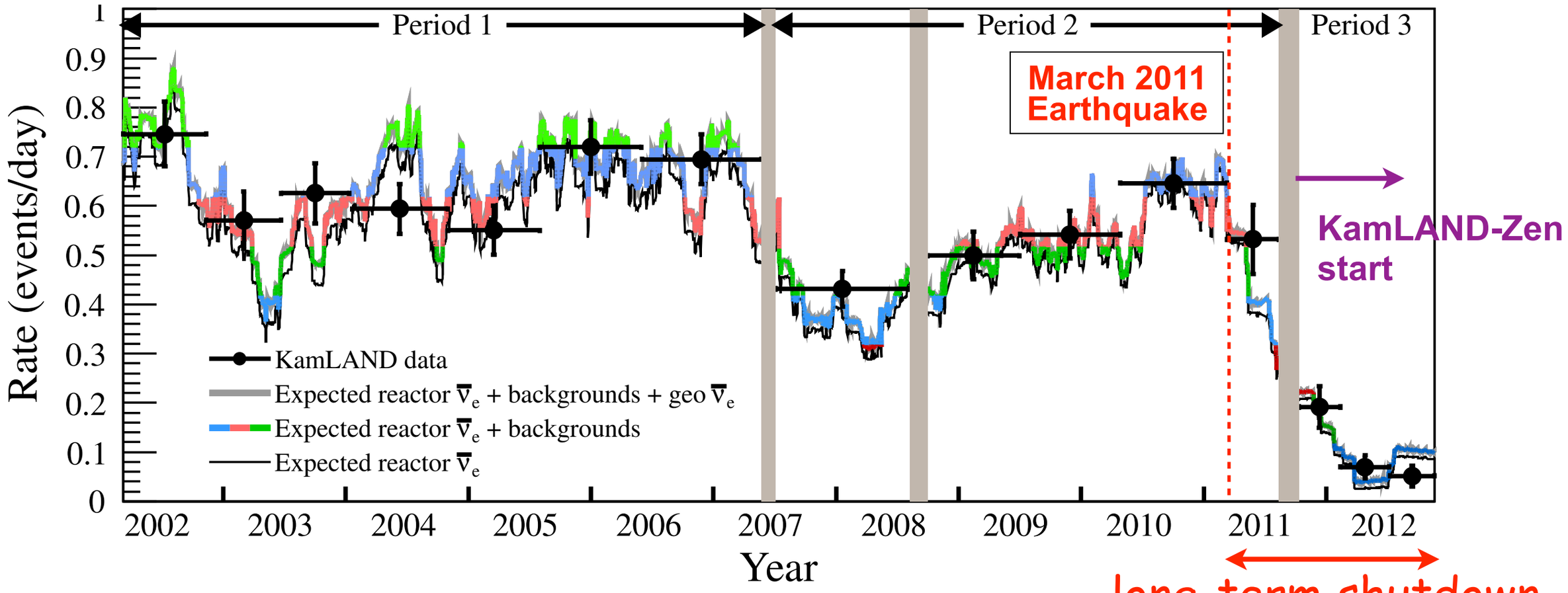
"Reactor on-off" study for neutrino oscillation and geo neutrino analysis

# Time Variation of Event Rate

Total livetime
2991 days

Period 1: Mar. 2002 - May 2007
Period 2: May 2007 - Aug. 2011 (after LS purification)
Period 3: Oct. 2011 - Nov. 2012 (after KamLAND-Zen start)

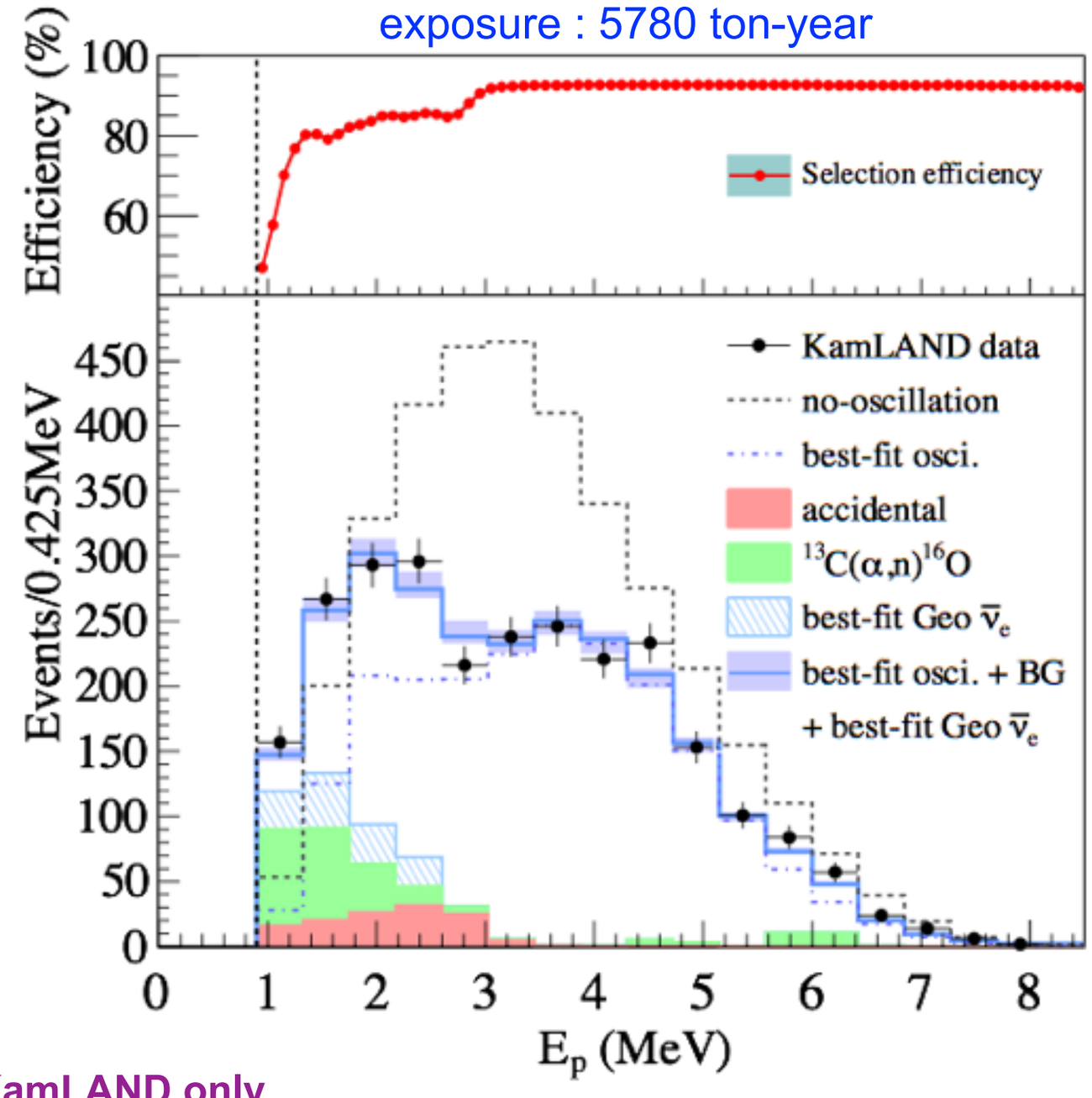
$2.6 < E_p < 8.5$ MeV




Data have good agreement with expected rate

# Observed Energy Spectrum

exposure : 5780 ton-year



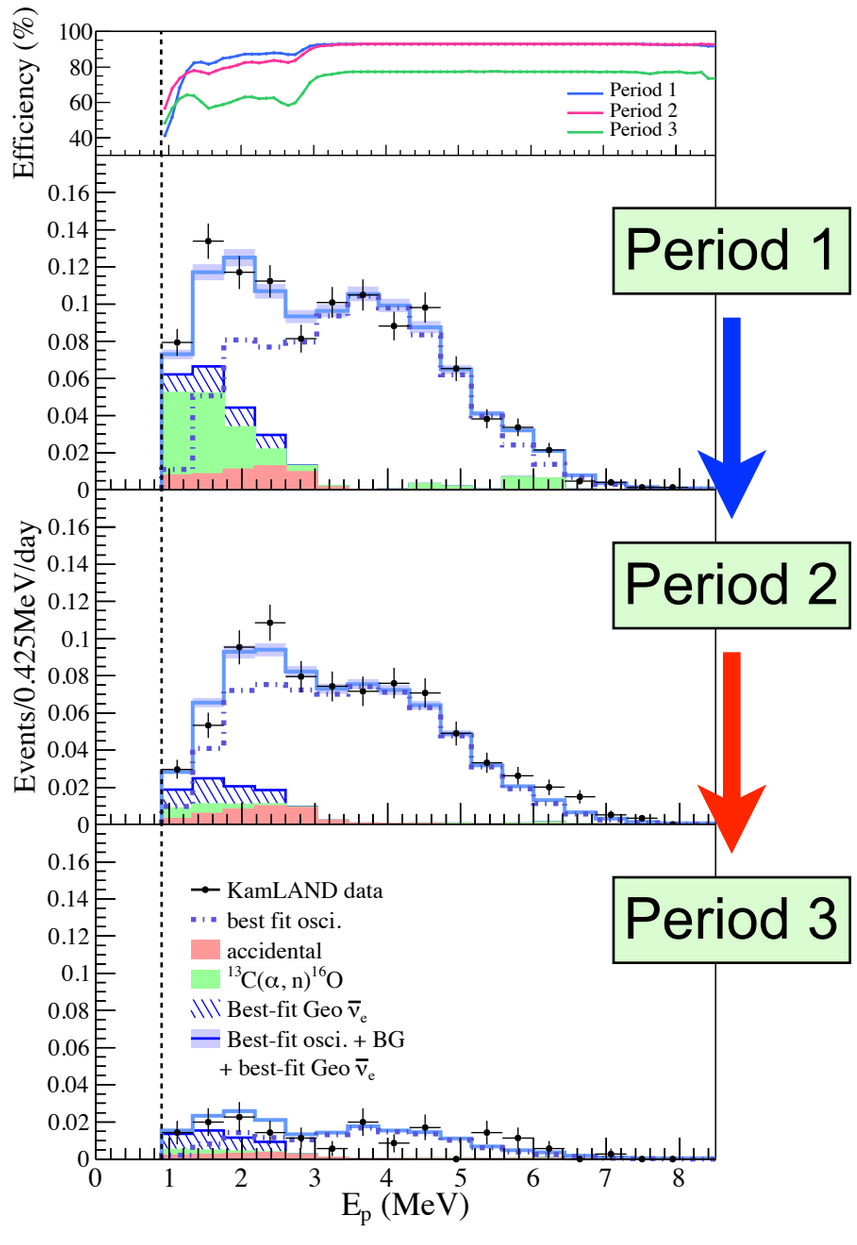

**KamLAND only**

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

| | |
|---|---|
| **No osci. expected** | **3564 ± 145** |
| **Background (w/o geo neutrino)** | **364 ± 31** |
| **Observed events** | **2611** |

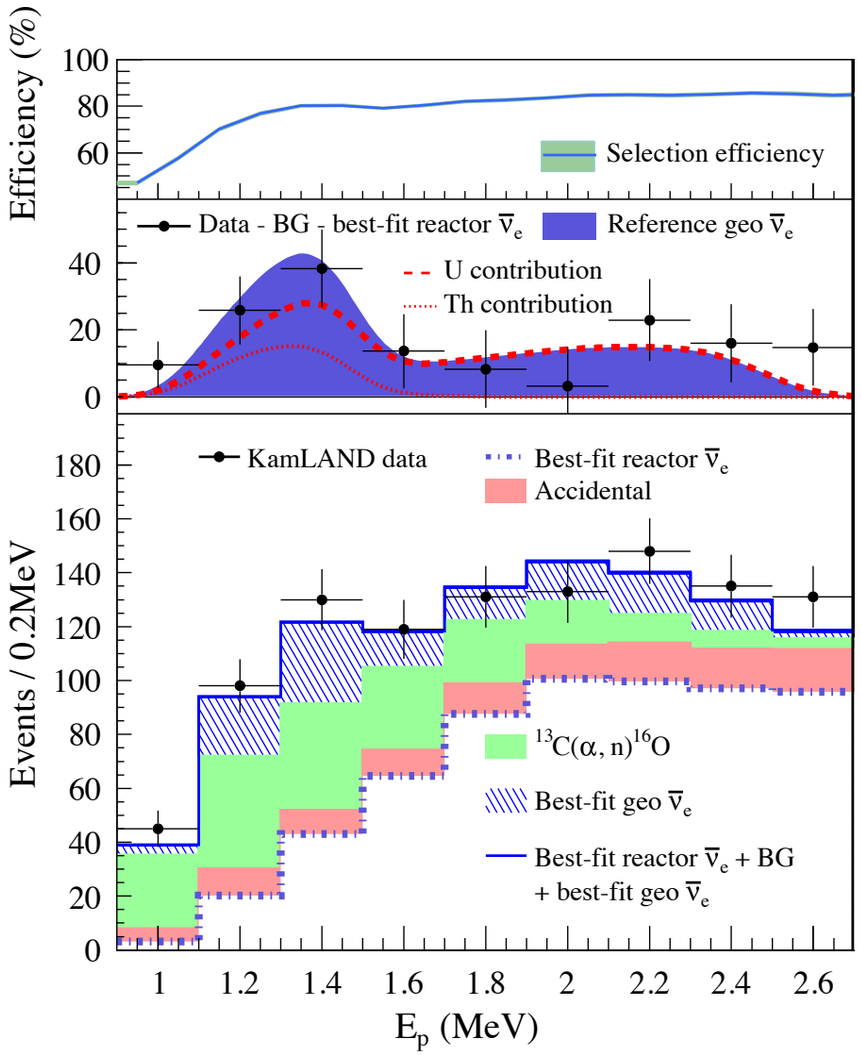
**purification** **(α,n) ↓**

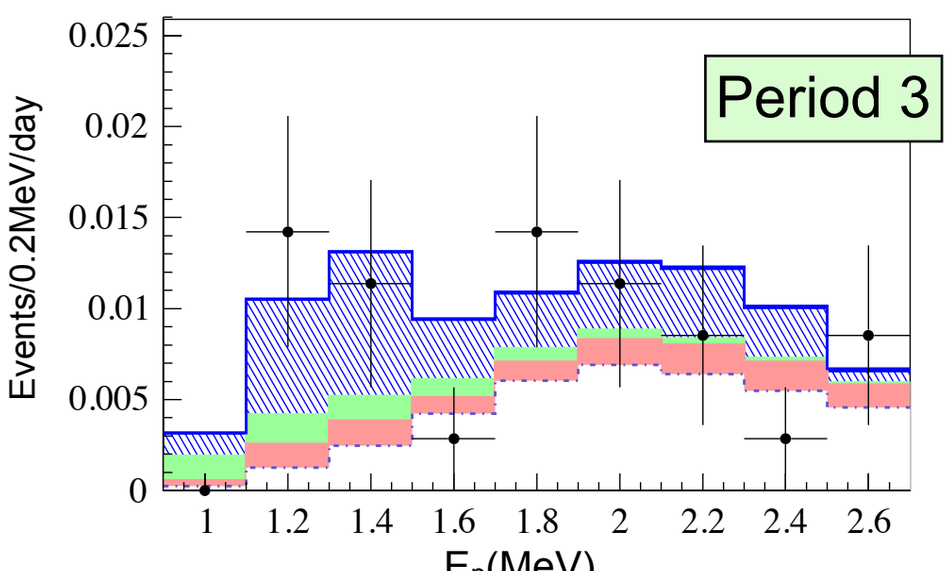
**earthquake** **reactor ↓**



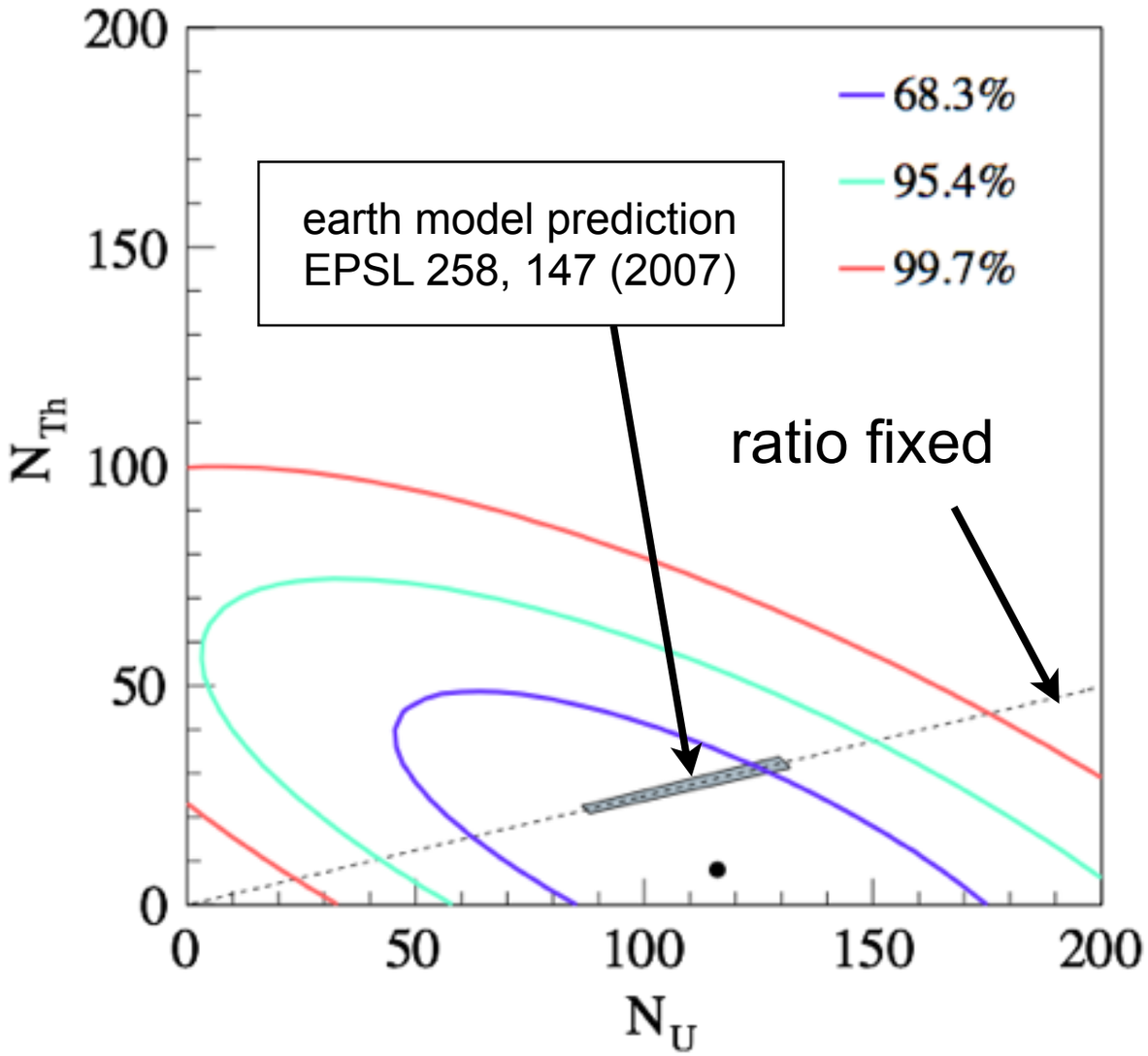

significant reduction

# Geo Neutrino Flux




best-fit $(N_U, N_{Th}) = (116,8)$




$N_{geo} = 116\ ^{+28}_{-27}$ events

$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6$ /cm$^2$/sec

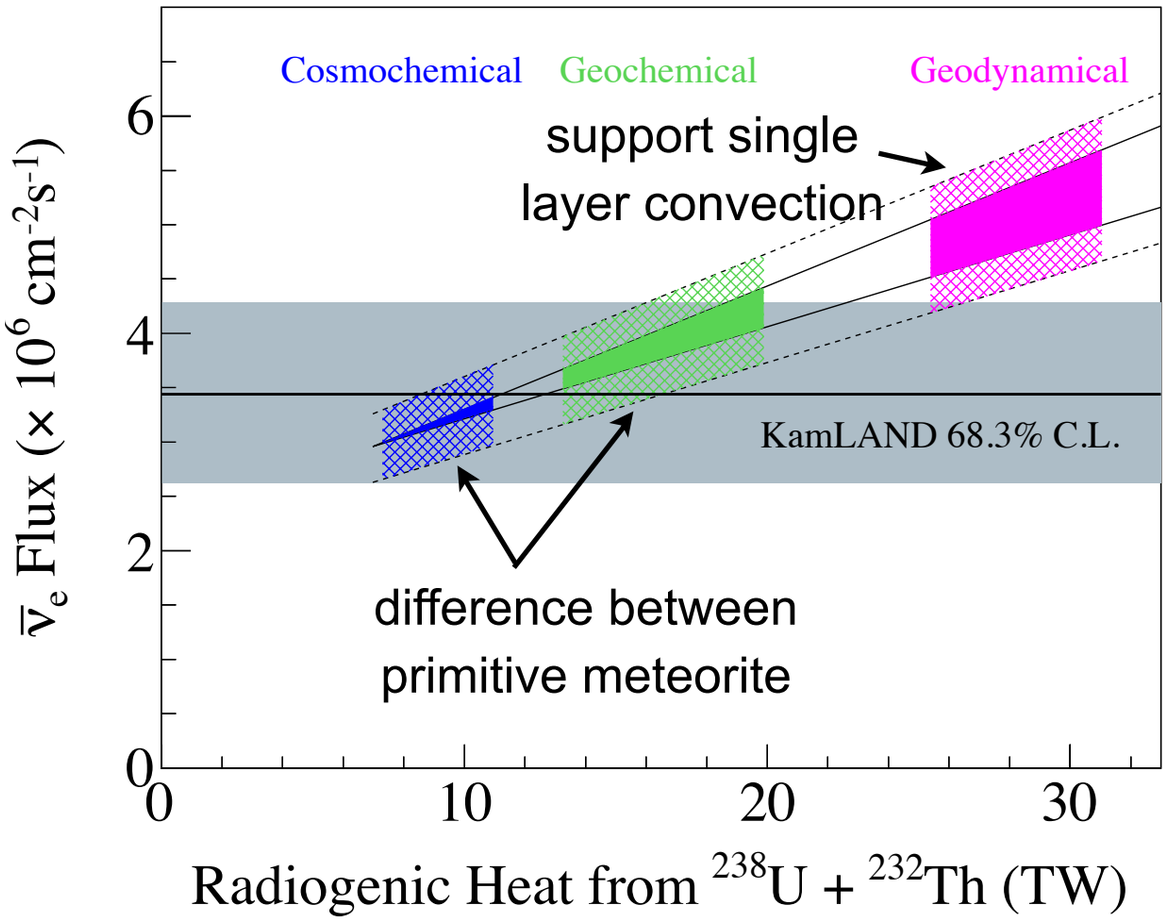
$(30.7\ ^{+7.5}_{-7.3}$ TNU$)$

# Earth Model Comparison

**Three classes BSE compositional estimates**

O. Šramek et al. Earth. Plan. Sci. Letters 361 (2013) 356–366

| Model | Cosmochem. | Geochem. | Geodyn. |
|---|---|---|---|
| A | 12 ± 2 | 20 ± 4 | 35 ± 4 |
| A | 43 ± 4 | 80 ± 13 | 140 ± 14 |
| A | 146 ± 29 | 280 ± 60 | 350 ± 35 |
| Th/U | 3.5 | 4 | 4 |
| K/U | 12000 | 14000 | 10000 |
| Tot. Power (TW) | 11 ± 2 | 20 ± 4 | 33 ± 3 |
| Mantle power (TW) | 3.3 ± 2.0 | 12 ± 4 | 25 ± 3 |
| Mantle Urey ratio | 0.08 ± 0.05 | 0.3 ± 0.1 | 0.7 ± 0.1 |




KamLAND result

**radiogenic** $14.2^{+7.9}_{-5.1}$ **TW**

heat flow from Earth's surface 47±2 TW

Geodynamical prediction with homogeneous hypothesis is disfavored at 89% C.L.

All composition models are still consistent within ~2σ

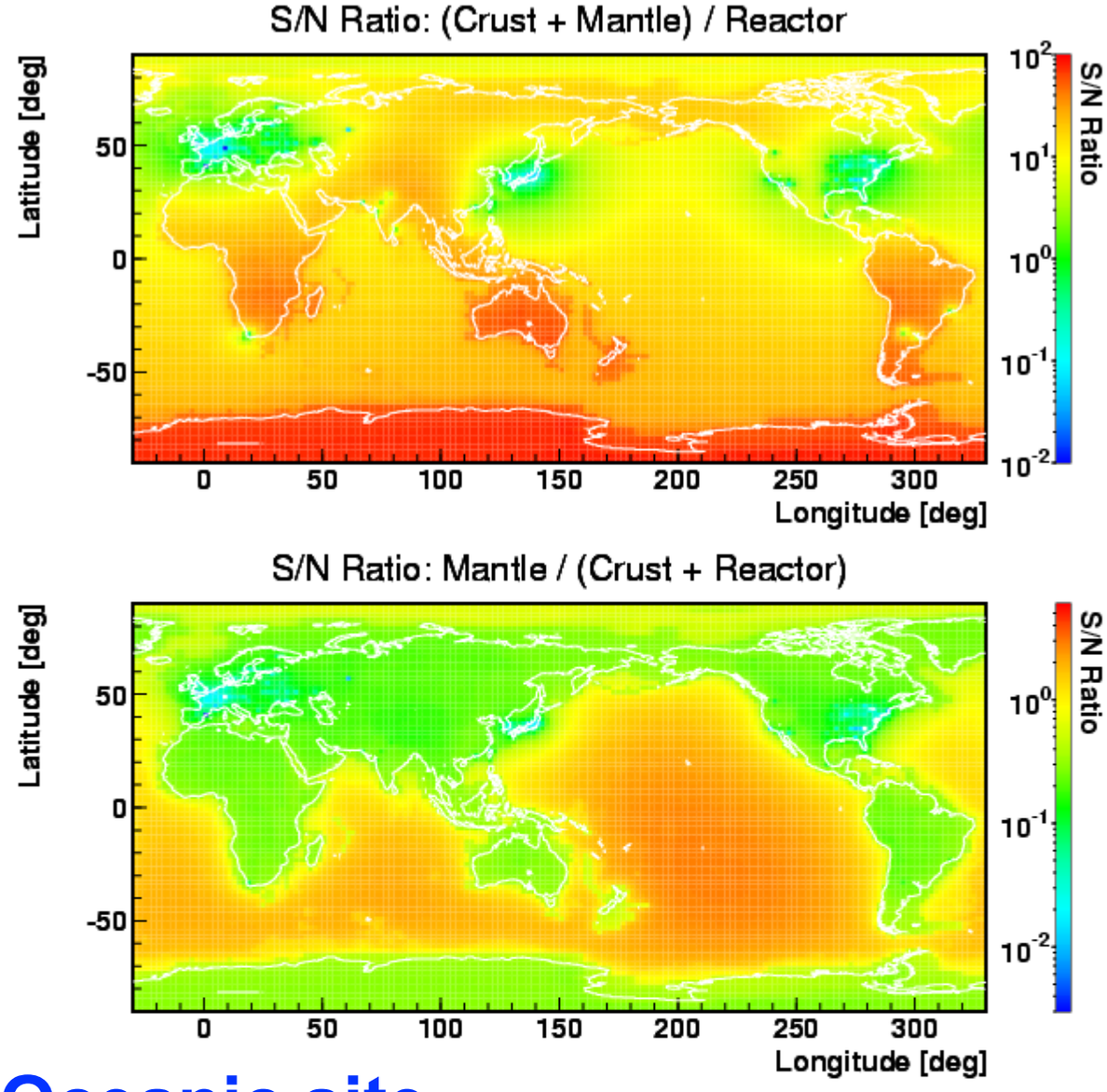
Geo-ν measurement is in agreement with BSE models

# Future Prospect

# Future Geo Neutrino Detector

| Project | Location | Mass (kton) | Depth (m.w.e.) |
|---|---|---|---|
| KamLAND | Kamioka / Japan | 1.0 | 2700 |
| Borexino | Gran Sasso / Italy | 0.3 | 3700 |
| SNO+ | Sudbury / Canada | 0.7 | 5400 |
| Hano-hano | Hawaii / U.S. | 10 | 4000 |
| BNO | Baksan / Russia | 1.0 | 4800 |
| LENA | Phyasalm / Finland<br>Nestor / Greece | 50 | 4000<br>4000 |
| HSD | Kimballton / U.S.<br>Homestake / U.S.<br>Soudan / U.S. | 100 | 1850<br>4200<br>2070 |

S. Enomoto @ Neutrino Geoscience 2007




**Large detector (> 50 kton size)**

aim to reduce the statistical uncertainty of flux down to < 10%

**Oceanic site**

Hawaii is a good candidate to measure the contribution from the mantle

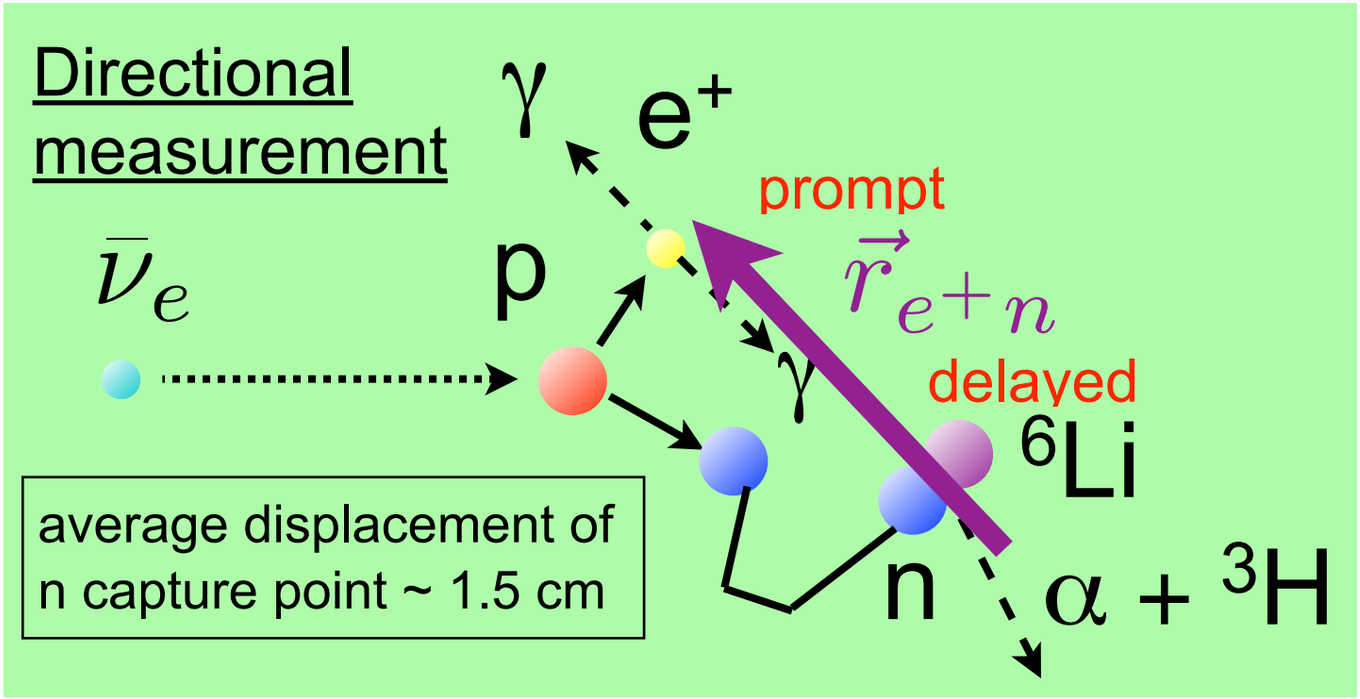
**Multi-site measurement**

useful to avoid the flux uncertainties from local geology ~ 10%

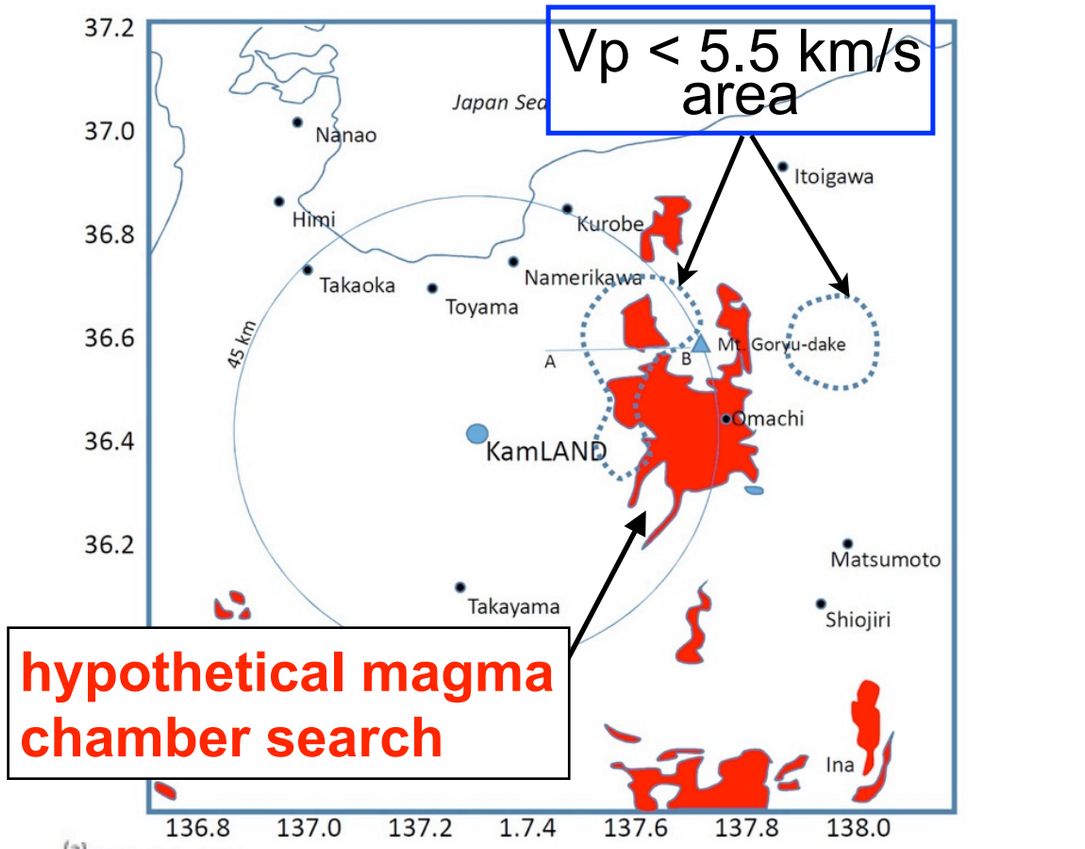
**Directional sensitivity**

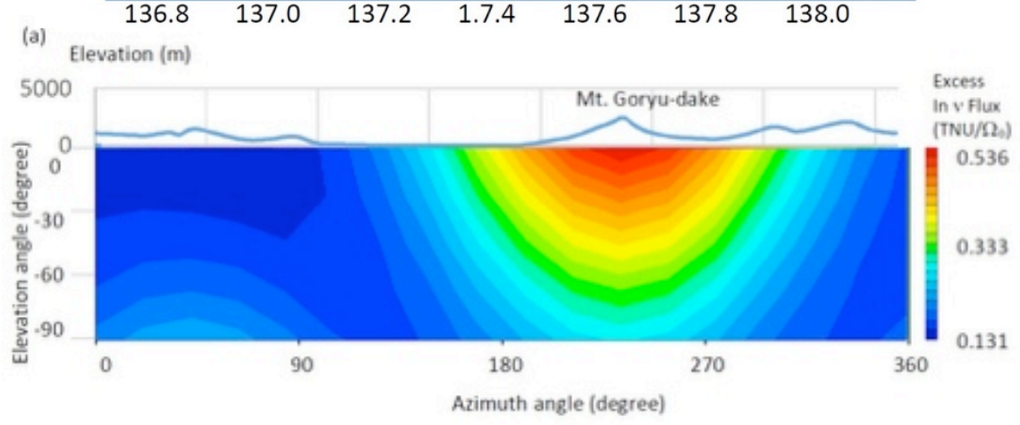
can be powerful tool to reduce the backgrounds from reactor or crust

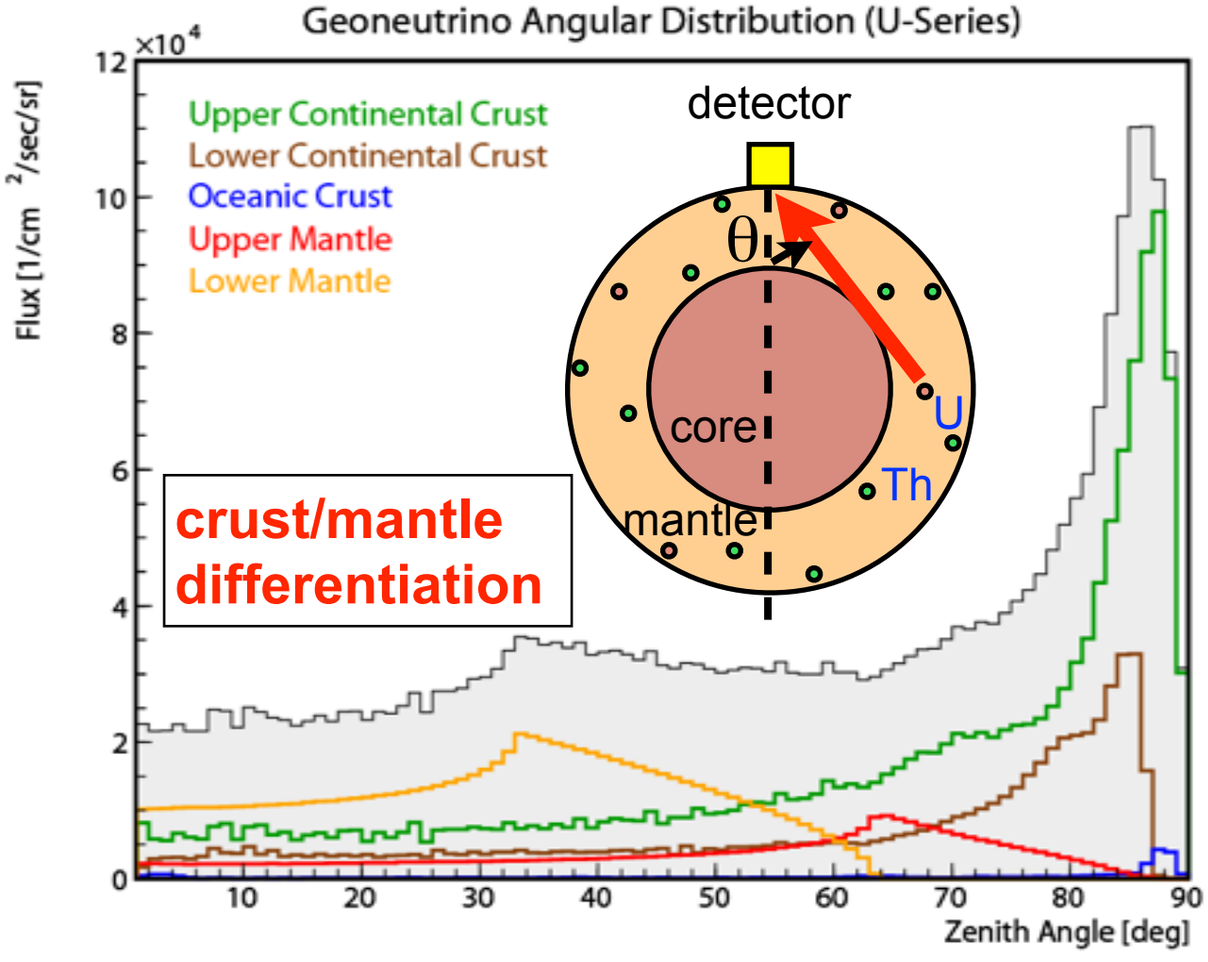
# Directional Study




Tanaka H. K. M. and Watanabe H. Scientific Reports 4, 4708 (2014)




- U/Th distribution can be investigated by directional measurement
- We are now developing $^6$Li-loaded directionally sensitive detector

# Summary

- KamLAND showed the geo neutrino results.

  - Observed flux is fully consistent with Earth model

  - Radiogenic heat contributes only half of Earth's total heat flow → fully-radiogenic models are disfavored

**Observed geo-neutrino event** **$\underline{116^{+28}_{-27}\ \text{events}}$**

**flux** **$\underline{3.4^{+0.8}_{-0.8} \times 10^{6}\ /\text{cm}^2/\text{sec}}$**

**(mass Th/U = 3.9)**

- Tests of primitive meteorite and mantle convection model are the next target.
- Multi-site measurements at geologically different locations (e.g. Japan and Italy) will be important for the tests.