Neutrinos from the Earth
- Observation -

1. Geoneutrino Physics with KamLAND
2. KamLAND Detector Design and Data Analysis
3. Future Prospects

Sanshiro Enomoto
Research Center for Neutrino Science, Tohoku University

The Fourth COE Symposium, Sendai, 28-30 June 2006

Geoneutrinos:
A New Tool to Explore the Earth Interior

- Generated by radioactivity inside the Earth

$$^{238}U \rightarrow \; ^{206}Pb + 8\,^{4}He + 6\,e^{-} + 6\,\bar{\nu}_e + 51.7\ [MeV]$$

$$^{232}Th \rightarrow \; ^{208}Pb + 6\,^{4}He + 4\,e^{-} + 4\,\bar{\nu}_e + 42.7\ [MeV]$$

$$^{40}K \rightarrow \; ^{40}Ca + e^{-} + \bar{\nu}_e + 1.3\ [MeV]$$

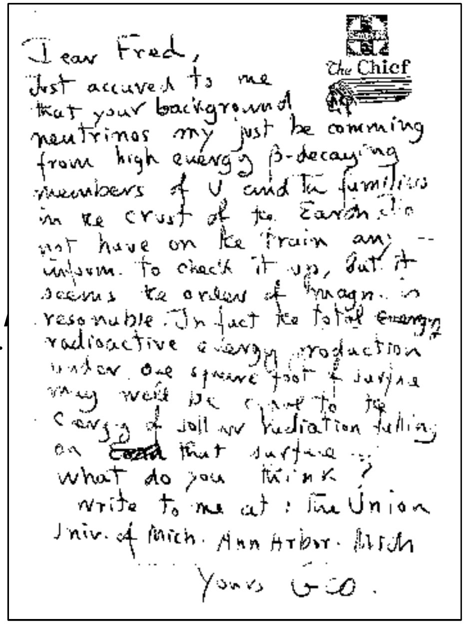
- Radiogenic heat dominates Earth energetics
  - Measured terrestrial heat flow ~ 44 TW
  - Estimated radiogenic heat (model prediction)
    ^{238}U ~8 TW / ^{232}Th ~8 TW / ^{40}K ~ 3 TW ???

- The only direct geochemical probe
  - The deepest borehole reaches only ~12 km
  - The deepest rock sample originates ~200 km

Long History of the New Tool

Geoneutrino Predawn (50′s ~ 60′s)

- G.Gamow (1956)
  - → First mention of “neutrinos from the Earth’


Dear Fred,
Just occurred to me
that your background
neutrinos may just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. I do
not have on the train any
uniform to check it up, but it
seems the order of magn. is
resonable. In fact the total energy
radioactive energy production
under one square foot of surface
may well be equal to the
energy of soil ... radiation falling
on that surface...
what do you think?
Write to me at: The Union
Univ. of Mich. Ann Arbor. Mich.
Yours Geo.

To: Reines
From: Gamow
(1956)

- G.Eder (1966)
- G.Marx (1969)
  - → First discussion on geoneutrinos
- C.Avilez et al. (1981)
- L.Krauss et al. (1984)
- M.Kobayashi, Y.Fukao (1991)
  - → Neutrino application for Earth Science
  - → “Not practical for the present” because of
    - – Too low geoneutrino energy (<3.3 MeV)
    - – Requirement of huge target mass (kilo tons)

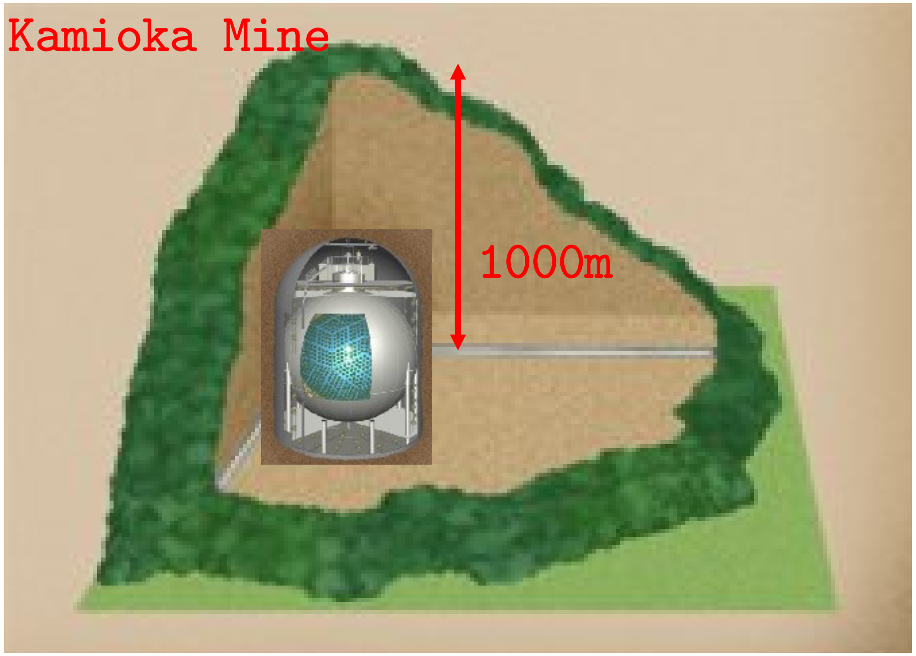
Geoneutrino Epoch (late 90′s)

→ Huge scintillator detectors (KamLAND / Borexino) are proposed
→ Practical discussion based on actual detector designs

- R.Raghavan, S.Enomoto et al. (1998)
- C.Rothschild et al. (1998)
- G.Fiorentini et al. (2003)

The KamLAND experiment makes it

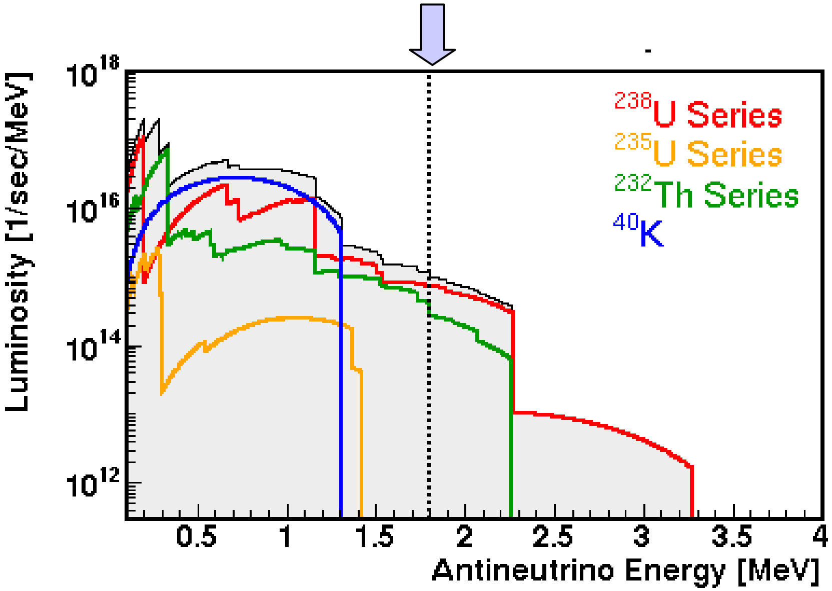
- observes low energy anti-neutrinos in the Kamioka Mine, Hida, Japan
- consists of 1000ton Liquid Scintillator, surrounded by 1845 PMT’s



Reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Threshold: 1.8 MeV



large-volume, ultra-pure liquid scintillator

→ enables detecting weakly interacting low energy neutrinos

discriminative sensitivity to antineutrinos

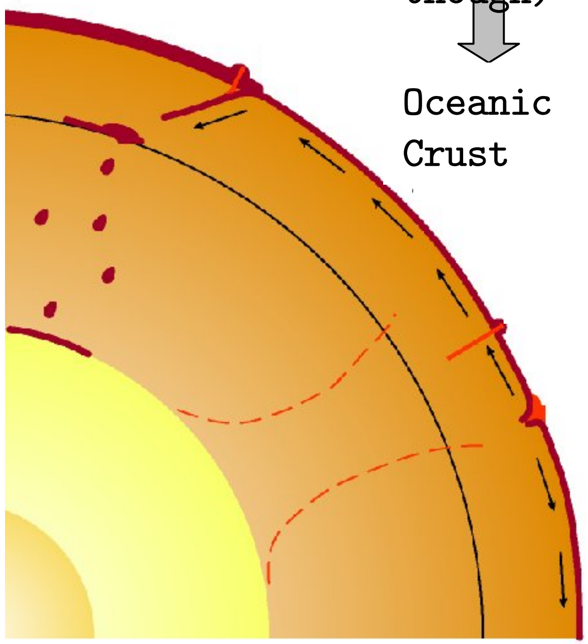
→ avoids overwhelming solar neutrino backgrounds

July 2005: The First Experimental Result

The first detection of geoneutrinos from beneath our feet is a landmark resul
It will allow better estimation of the abundances and distributions of radioa
elements in the Earth, and of the Earth's overall heat budget.
- William F. McDonough

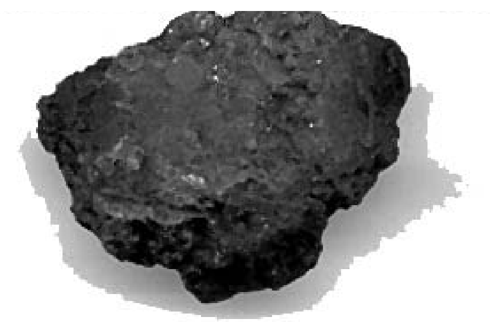
What do we know about the Earth interior?

Rock samples are available
(representativeness of the samples are questionable though)



High-Density Fe-Ni alloy;
Lithophile elements (U and Th) are hardly contained
(results from high-pressure petrologic experiments)

The Ingredient of the Earth
CI-Chondrite Meteorite

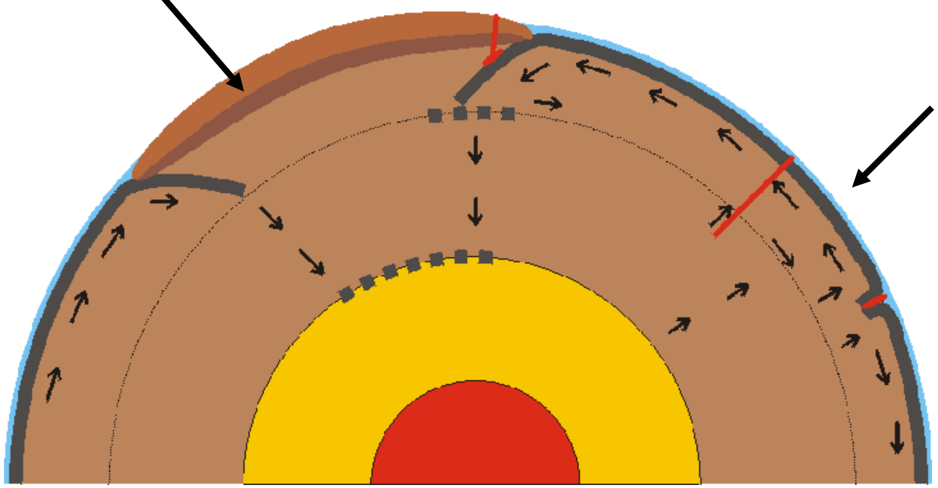


tells the composition of the
Bulk Silicate Earth (BSE)
(fundamental paradigm of geochemistry)

A Reference Earth Model (that I made up)

Upper C.C. U: 2.8ppm / Th: 10.7ppm
Middle C.C. U: 1.6ppm / Th: 6.1ppm
Lower C.C. U: 0.2ppm / Th: 1.2ppm

tentatively taken from Rudnick et al. (1995)



Oceanic Crust
U: 0.08ppm / Th: 0.32ppm

Obtained by
BSE − C.C. − O.C.
assuming uniform mantle

Mantle U: 0.012ppm / Th: 0.048ppm

Inner/Outer Core U: 0ppm / Th: 0ppm

As commonly believed...

- Half of U and Th are concentrated in the Continental Crust
- Total Ragiogenic Heat: U: 7.7 TW, Th: 8.5 TW

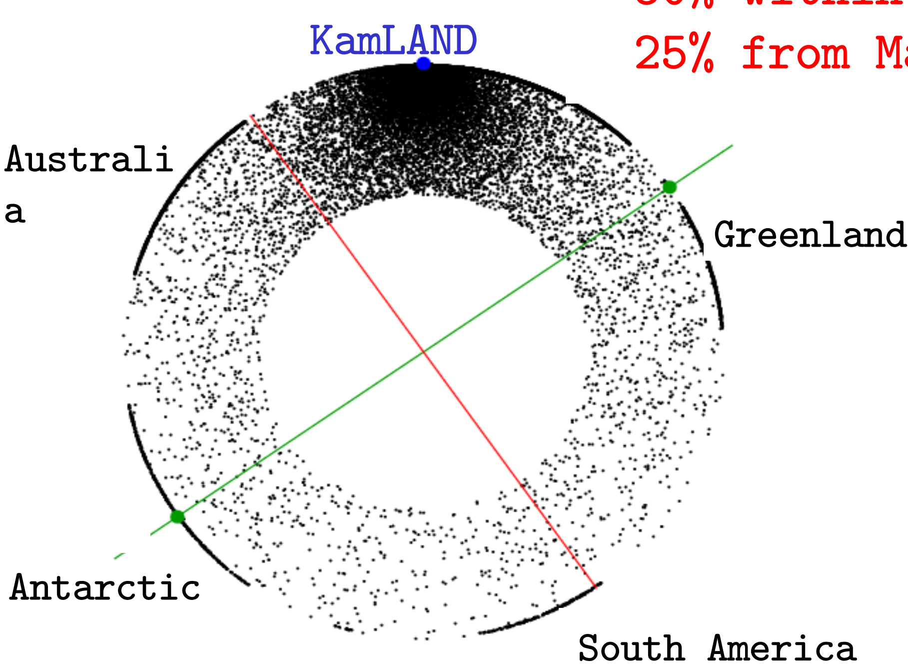
Event Rate Prediction with Earth Model

$$F_{U/Th} = A \cdot \int_{Earth} \frac{\rho_{U/Th}(\vec{r})}{4\pi \, |\vec{r} - \vec{r}_{KamLAND}|^2} P(\bar{\nu}_e \to \bar{\nu}_e) \, dV$$

Neutrino Oscillation

Geoneutrino Origination Points
Detectable at KamLAND (MC)

50% within 500km
25% from Mantle



Expected Geoneutrino Flux

- U-Series
  2.3×10^6 [1/cm^2/sec]
- Th-Series
  2.0×10^6 [1/cm^2/sec]

With 10^{32} target protons,

- U-Series
  32 events / year
- Th-Series
  8 events / year

Neutrino Detection Method

$$\bar{\nu}_e + p \to e^+ + n$$

$$e^+ + e^- \to 2\gamma \ \text{(0.511MeV)}$$

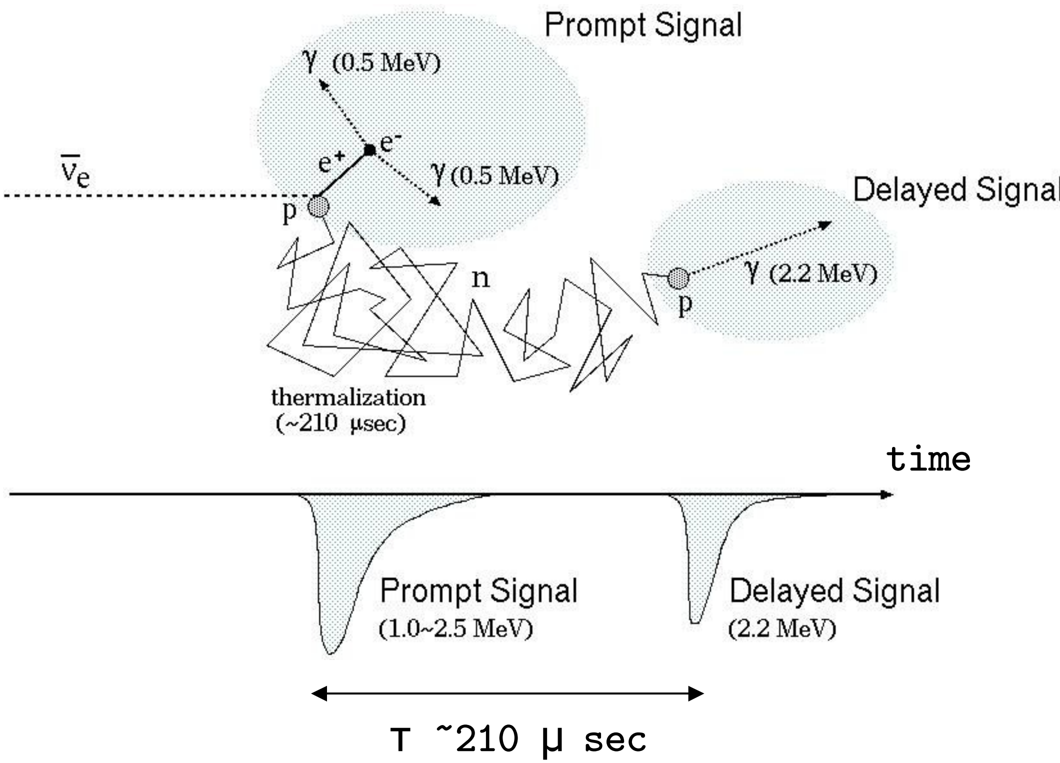
$$n + p \to d + \gamma \ \text{(2.2MeV)}$$

τ ~210 μ sec

$$E_{threshold} = 1.8 \text{ MeV}$$

$$E_{prompt} = E_{\nu_e} - 0.8 \text{ MeV}$$

$$E_{delayed} = 2.2 \text{ MeV}$$



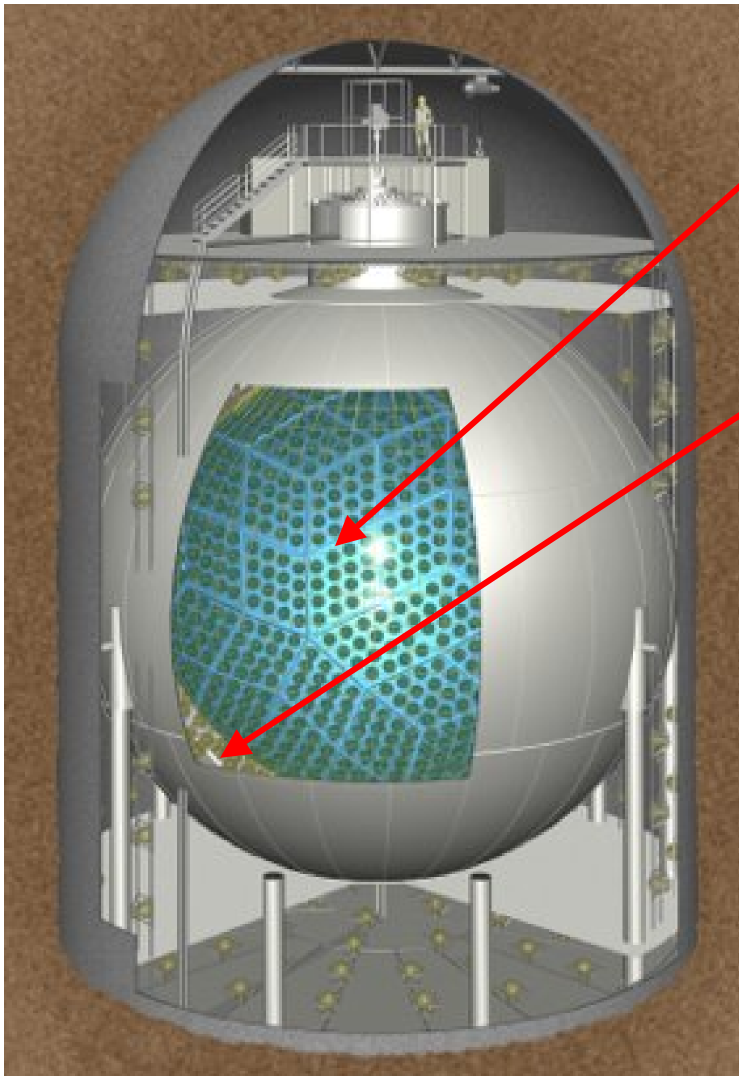
Two characteristic signals

⇩

Clear event identification

Great BG suppression

KamLAND Detector



20m

Detector Center

Liquid Scintillator 1000 ton

Contained in plastic balloon

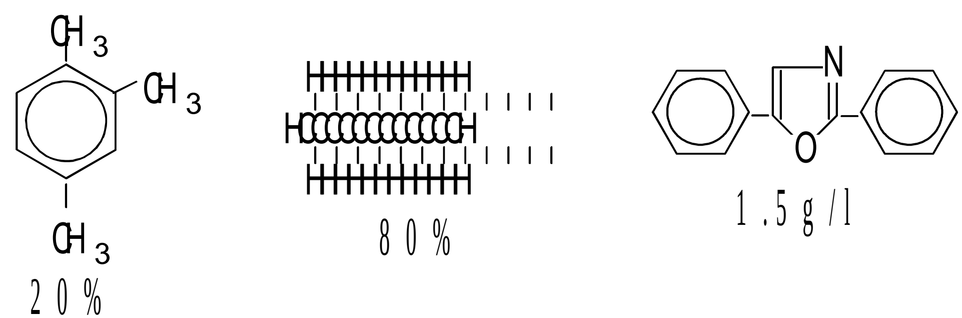
Surrounded by

17-inch PMT 1325

20-inch 554

(PMT : Photo Multiplier Tube, a photo sensor)

Liquid Scintillator

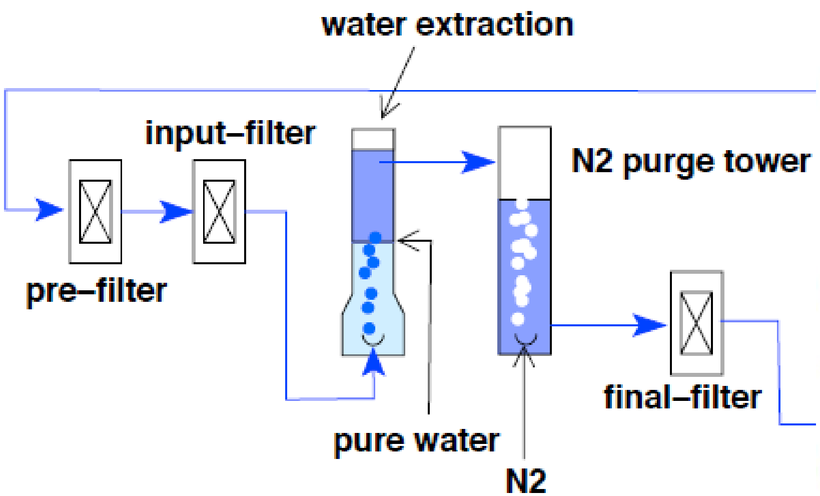


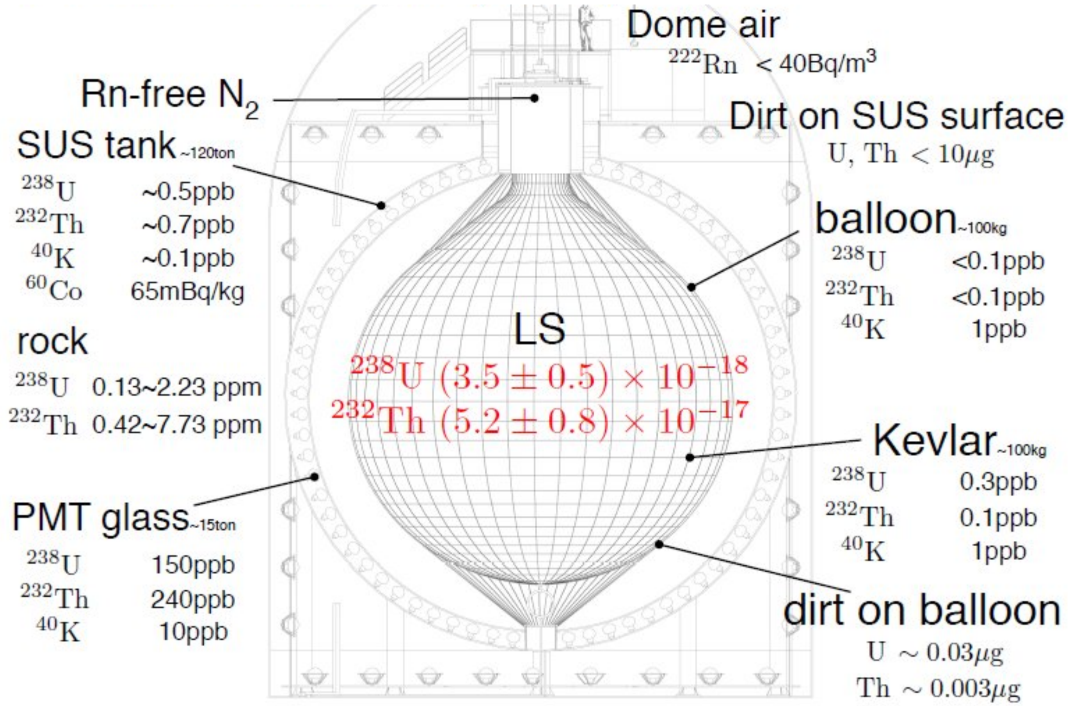
- Large light output (8000 photons / MeV)
- Mainly consists of only C and H

↑ neutrino target

LS Purification and Radioactive Impurity

For low-energy neutrino detection, purification is the key





before

U: ~10^{-10} g/g, Th: <10^{-12} g/g, K: 7×10^{-11} g/g

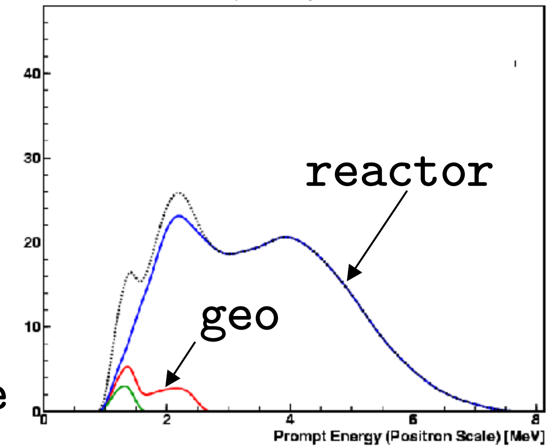
⇩

after

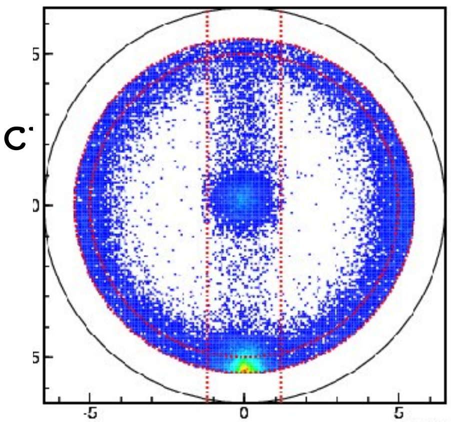
U: 3.5×10^{-18} g/g, Th: 5.2×10^{-17} g/g, K: 2.7×10^{-16} g/g

measurable only with KamLAND itself !

Backgrounds



- Reactor Neutrinos (80.4¡ 7.2)
  - Largest background, no way to discriminate
  - Very well understood



- Accidental Coincidence (2.38¡ 0.01)
  - Tighter selection criteria is applied to rejec
- (α ,n) Reaction (42.4¡ 11.1)
  - Produced by:
    1) ^{210}Po (descendant of ^{222}Rn) emits α (5.3MeV)
    2) ^{13}C(α ,n) generates neutron (max 8MeV)
    3) Neutron scatters protons: prompt signal
    4) Neutron is captured on another proton: delayed signal
  - Large contribution, large uncertainties

More Backgrounds, as many as we can think of

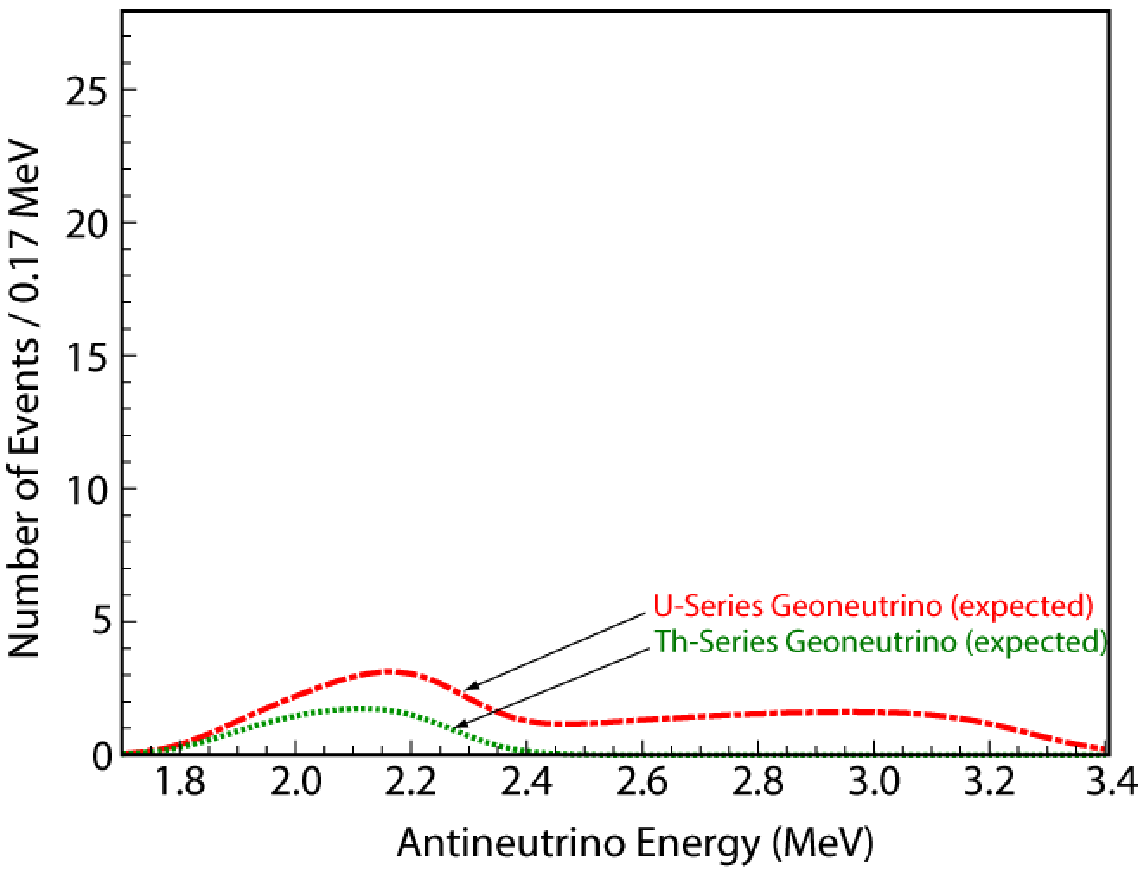
- Neutrinos
  - Reactor: 80.4¡ 7.2
  - Spent Fuel : 1.9¡ 0.2
- Cosmic Muon Induced
  - Fast neutron (from outside): < 0.1
  - Spallation products (^{9}Li): 0.30¡ 0.05
- Radioactive Impurity
  - Accidental coincidence 2.38¡ 0.01
  - Cascade decay negligible
  - Spontaneous fission < 0.1
  - (α ,n) reaction 42.4¡ 11.1
  - (γ ,n) reaction negligible
- Even More
  - ^{12}C breakup by cosmic neutrinos negligible
  - ^{2}H disintegration by solar neutrinos negligible

Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%

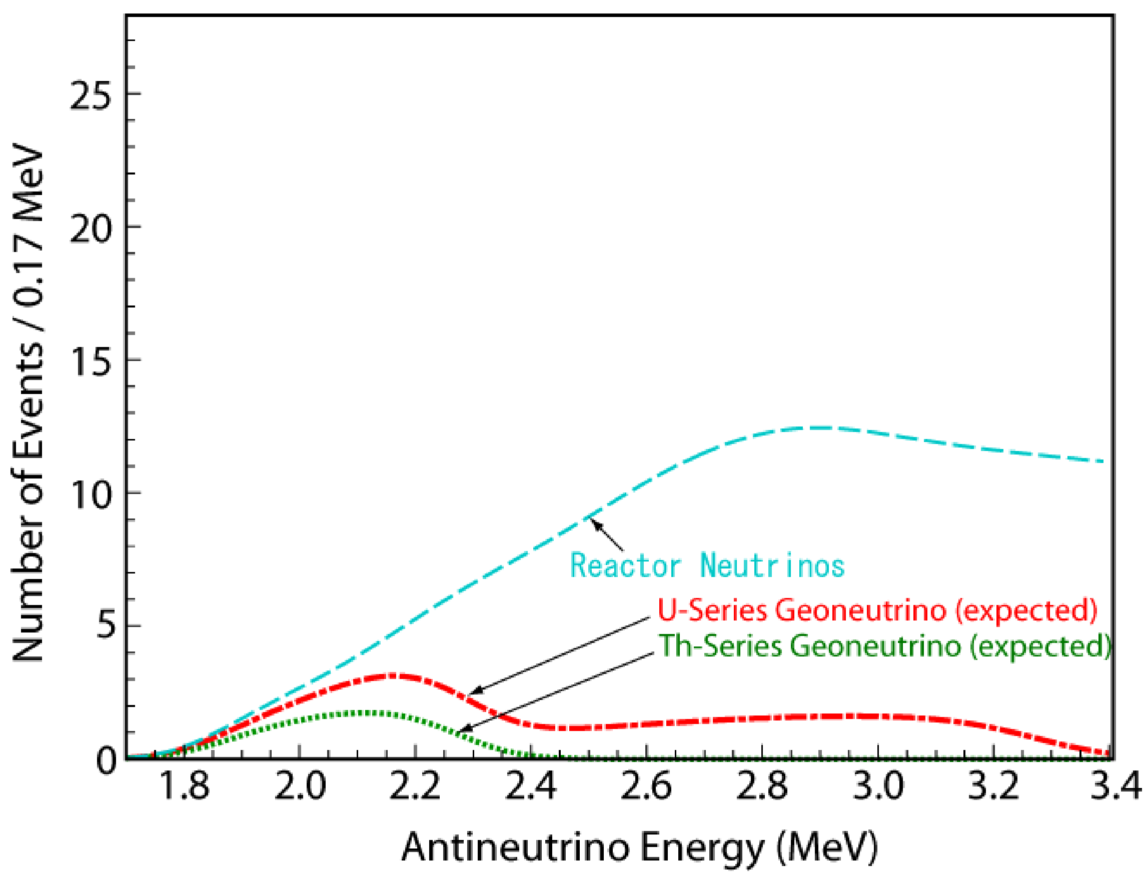
Expected Geoneutrinos

- U-Series : 14.9
- Th-Series : 4.0



Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

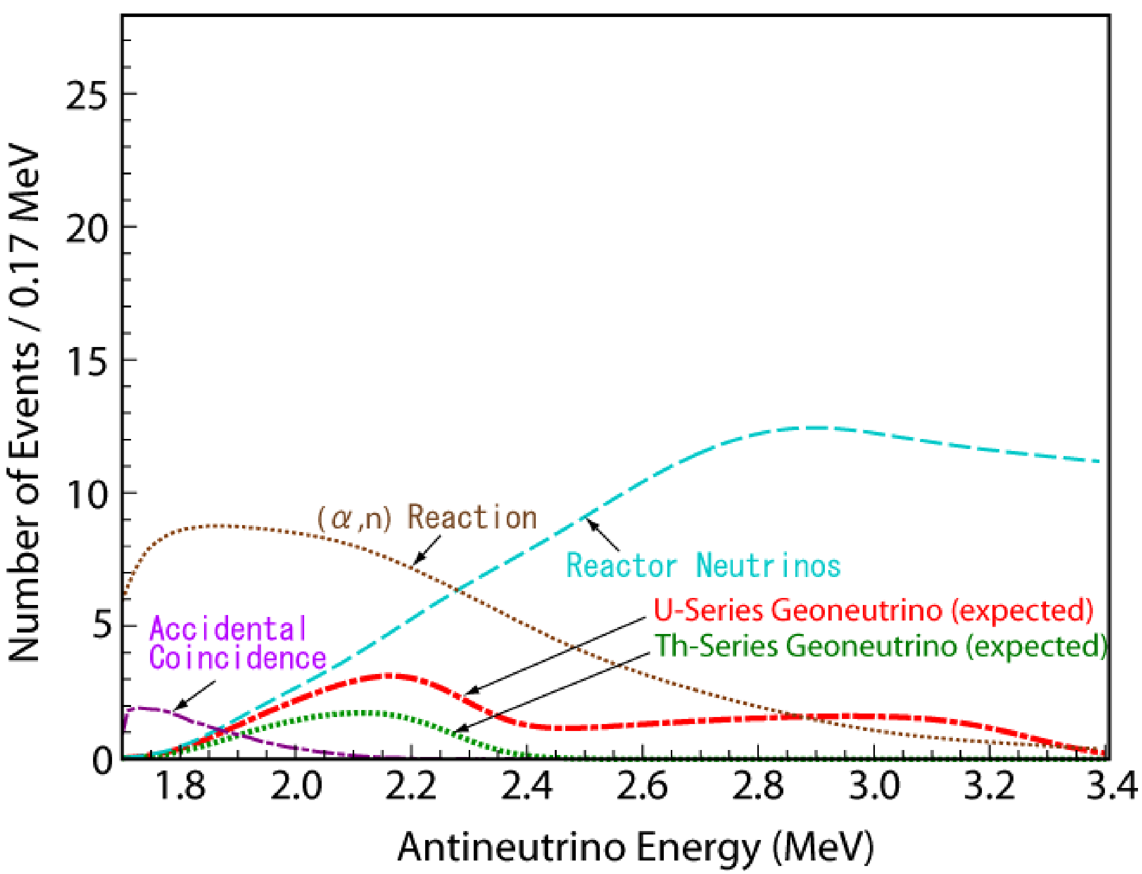
- U-Series : 14.9
- Th-Series : 4.0

Backgrounds

- Reactor : 82.3¡ 7.2

Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

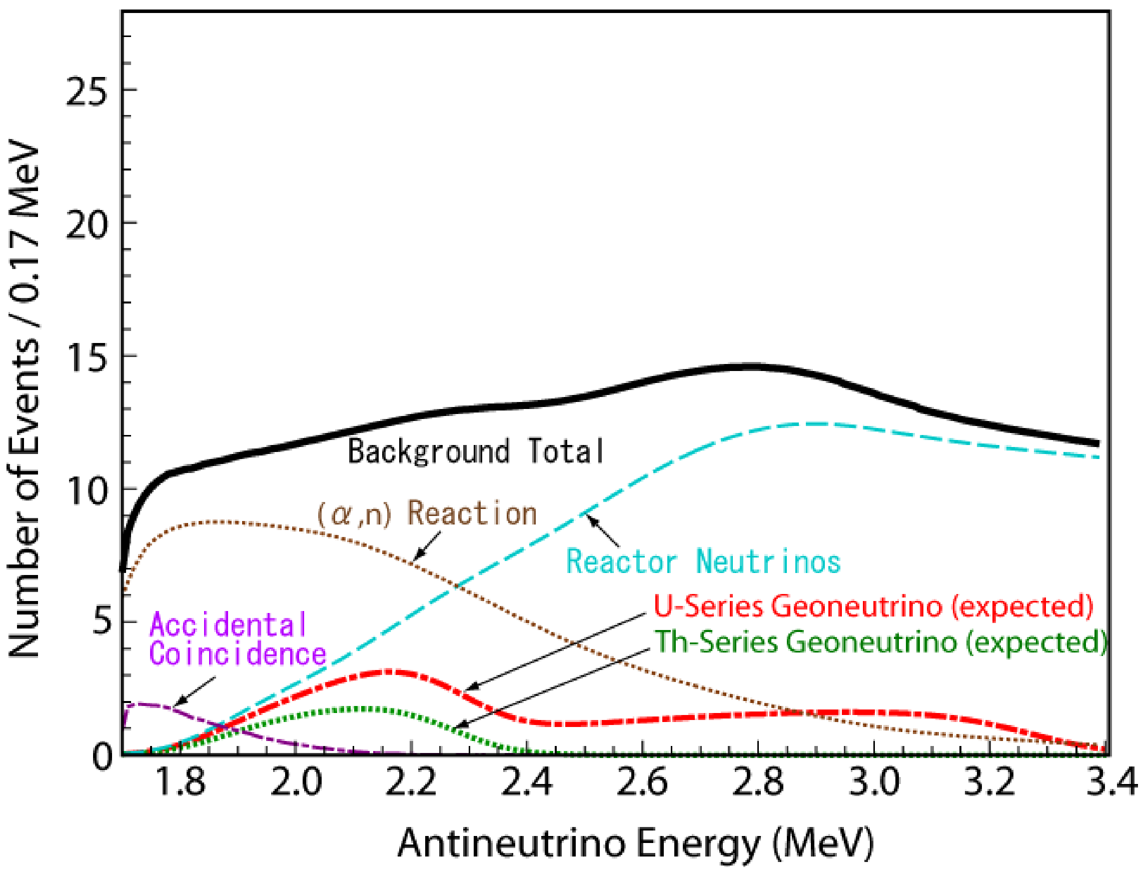
- U-Series : 14.9
- Th-Series : 4.0

Backgrounds

- Reactor : 82.3¡ 7.2
- (ɑ ,n) : 42.4¡ 11
- Accidental : 2.38¡ 0.01

Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

- U-Series : 14.9
- Th-Series : 4.0

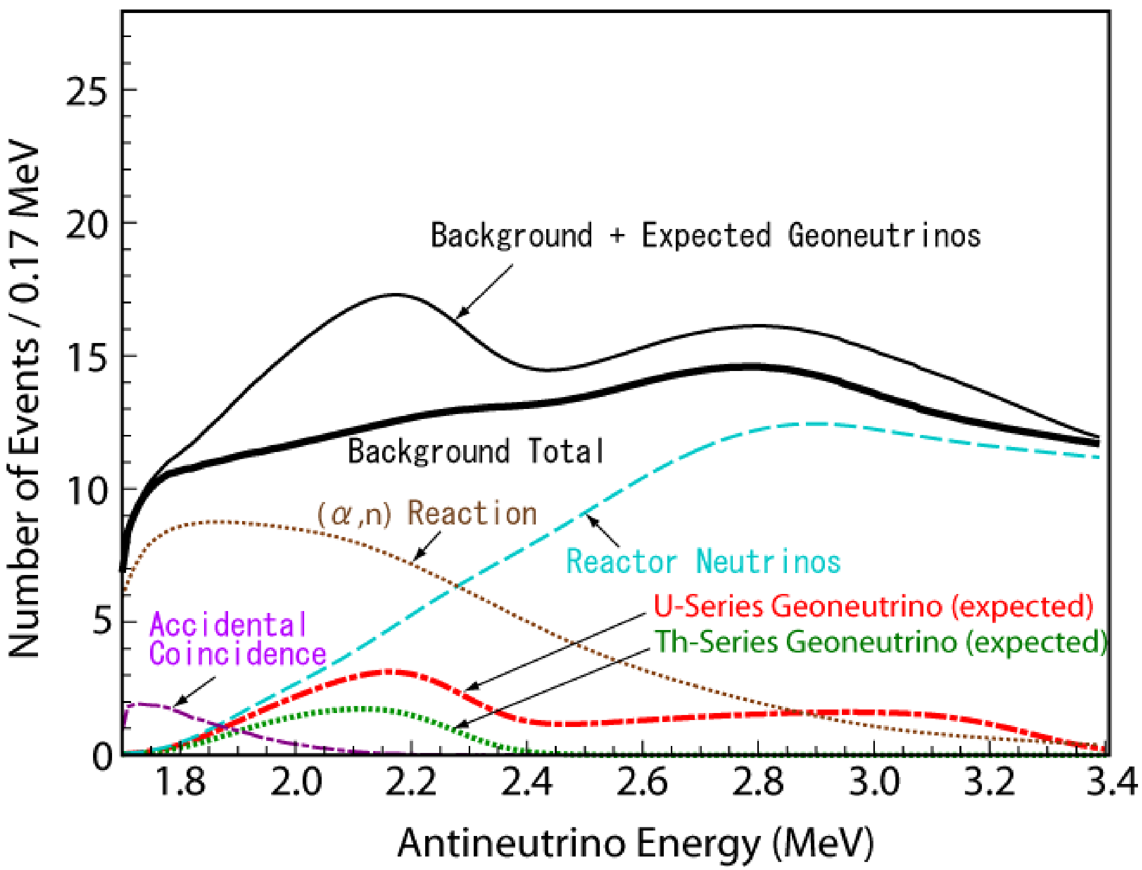
Backgrounds

- Reactor : 82.3¡ 7.2
- (α ,n) : 42.4¡ 11
- Accidental : 2.38¡ 0.01

BG total : 127.4¡ 13.3

Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

- U-Series : 14.9
- Th-Series : 4.0

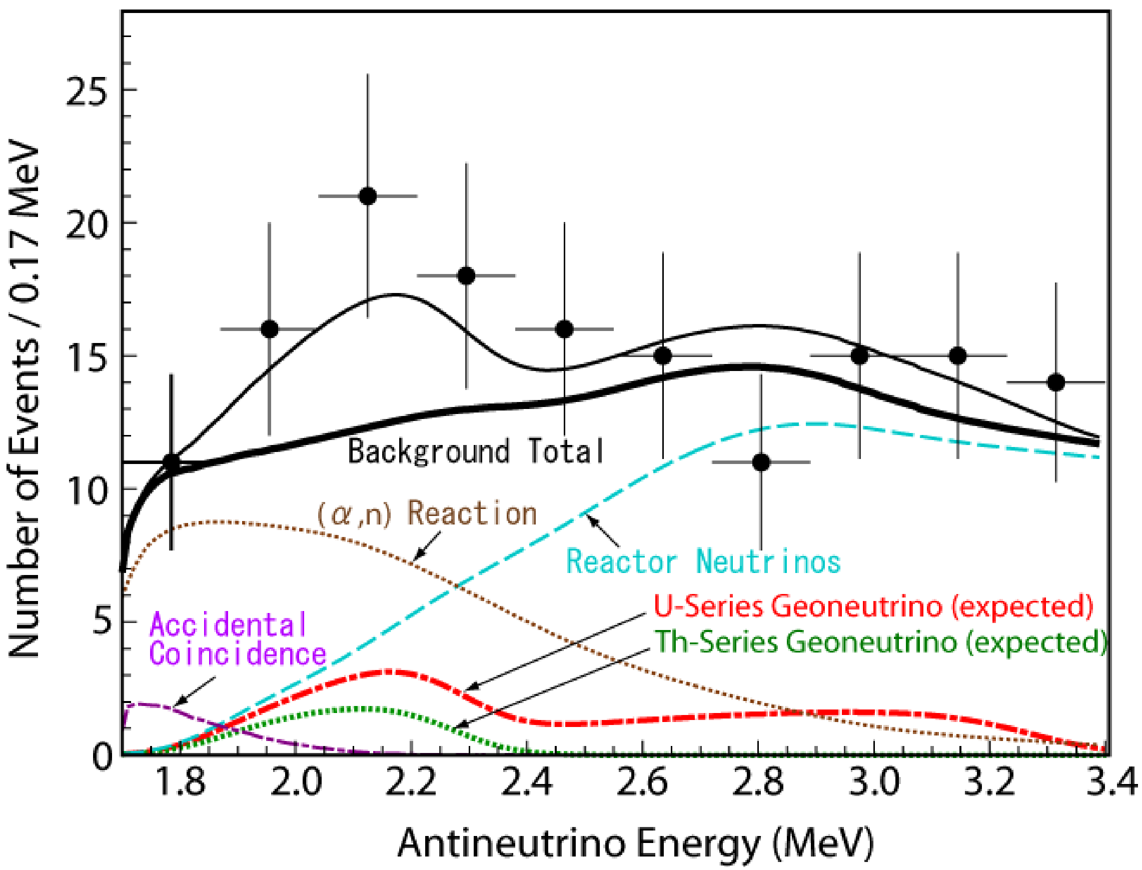
Backgrounds

- Reactor : 82.3¡ 7.2
- (α ,n) : 42.4¡ 11
- Accidental : 2.38¡ 0.01

BG total : 127.4¡ 13.3

KamLAND Observation

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

- U-Series : 14.9
- Th-Series : 4.0

Backgrounds

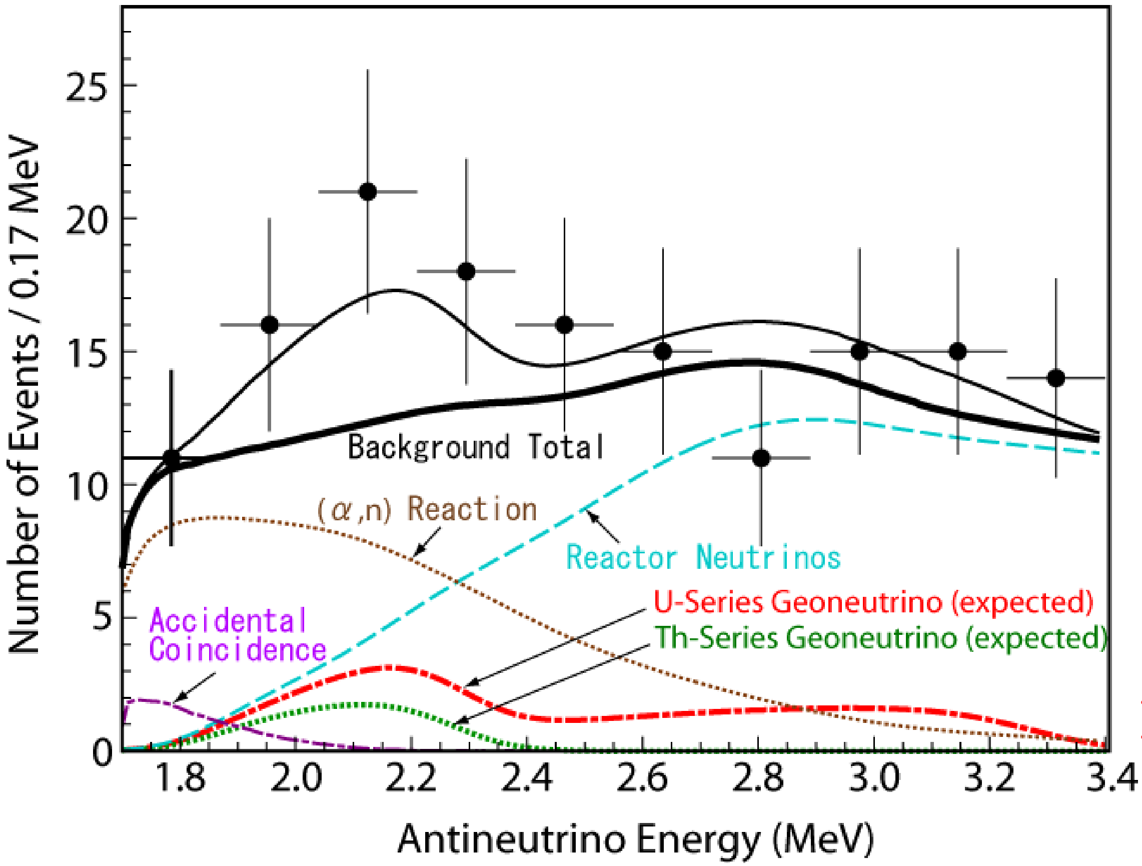
- Reactor : 82.3¡ 7.2
- (α ,n) : 42.4¡ 11
- Accidental : 2.38¡ 0.01

BG total : 127.4¡ 13.3

Observed : 152

KamLAND Observation

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%



Expected Geoneutrinos

- U-Series : 14.9
- Th-Series : 4.0

Backgrounds

- Reactor : 82.3¡ 7.2
- (α ,n) : 42.4¡ 11
- Accidental : 2.38¡ 0.01

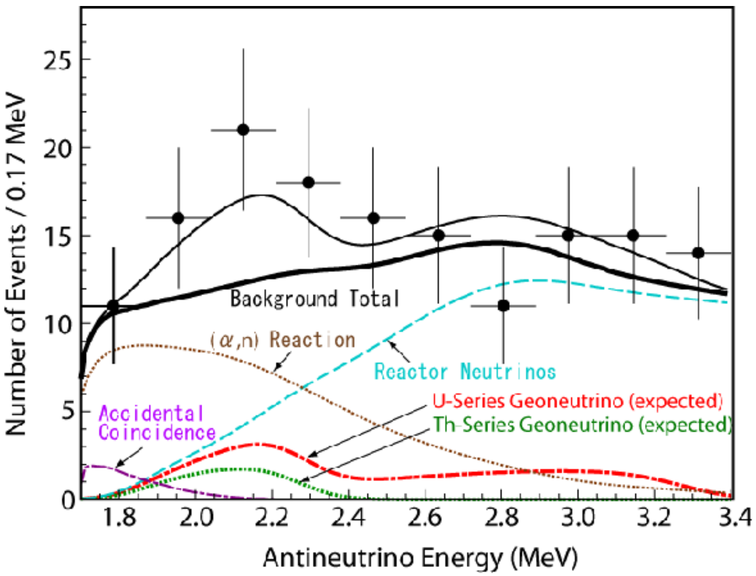
BG total : 127.4¡ 13.3

Observed : 152

Number of Geoneutrinos:

25^{+19}_{-18}

Spectrum Shape Analysis

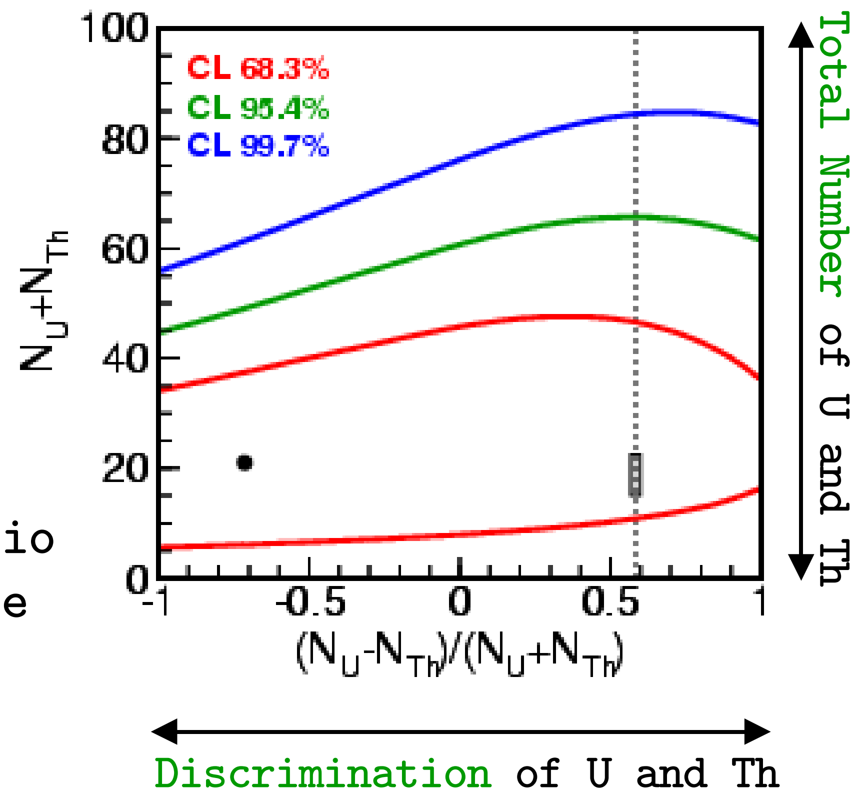


Parameters

N_U, N_{Th}: Number of Geoneutrino

$\sin^2 2\theta$, Δm^2 : Neutrino Oscillation

α_1, α_2: Backgrounds Uncertai

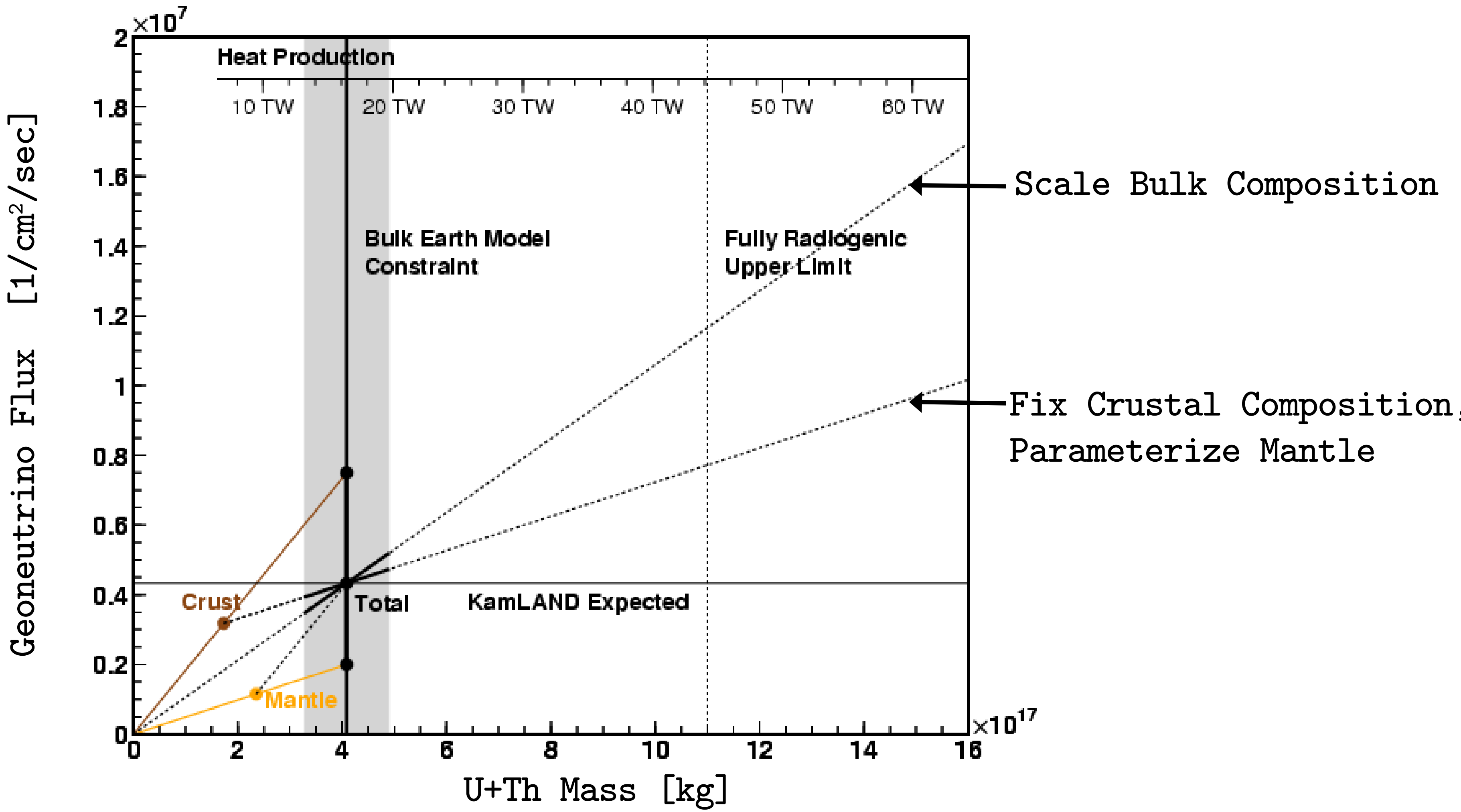


- KamLAND is insensitive to U/Th ratio

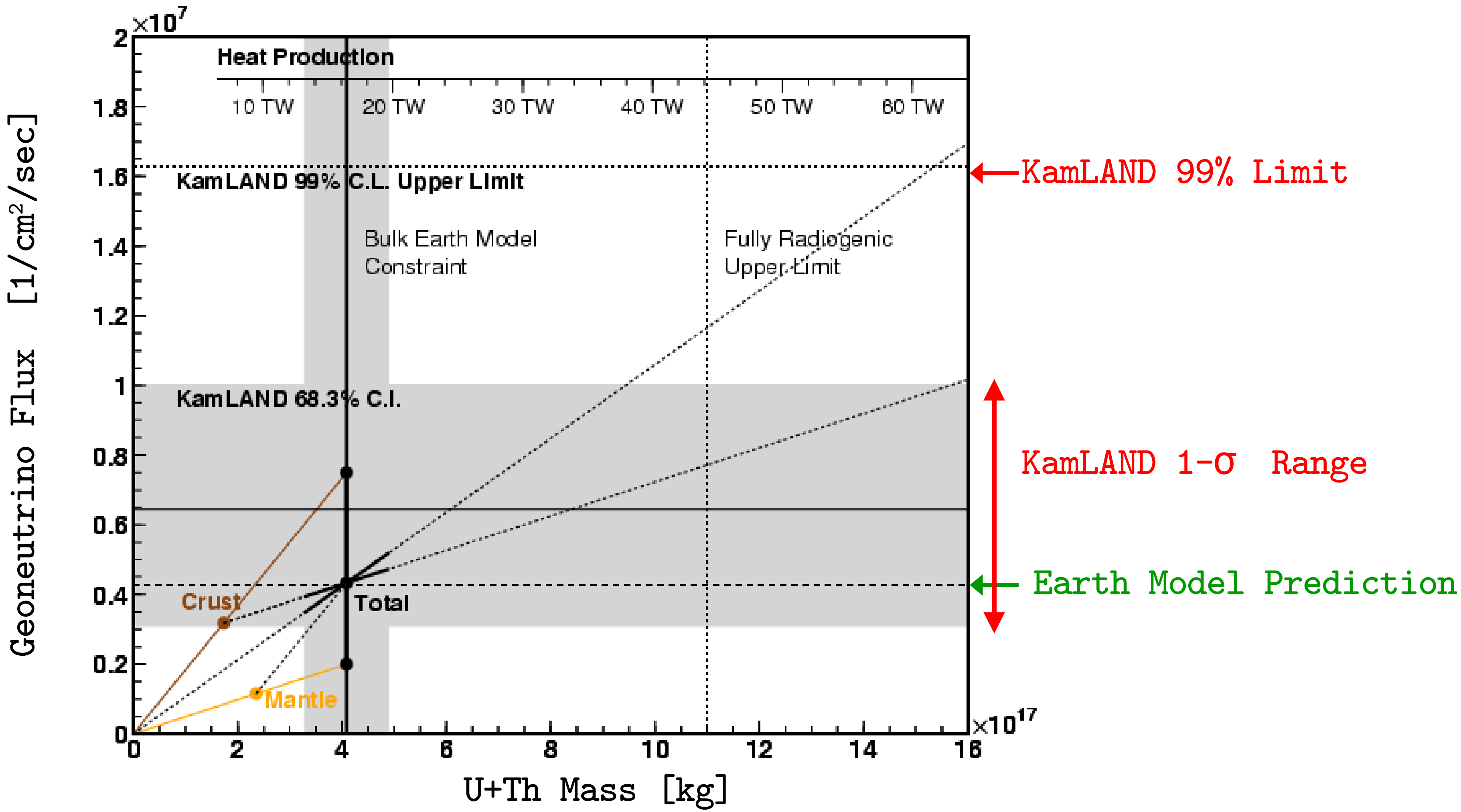
→ adopt U/Th ~ 3.9 from Earth science

- Number of Geoneutrinos : $28.0^{+15.6}_{-14.6}$
- 99% C.L. upper limit : 70.7 events
- Significance 95.3% (1.99-sigmas)

Comparison with Earth Model Predictions

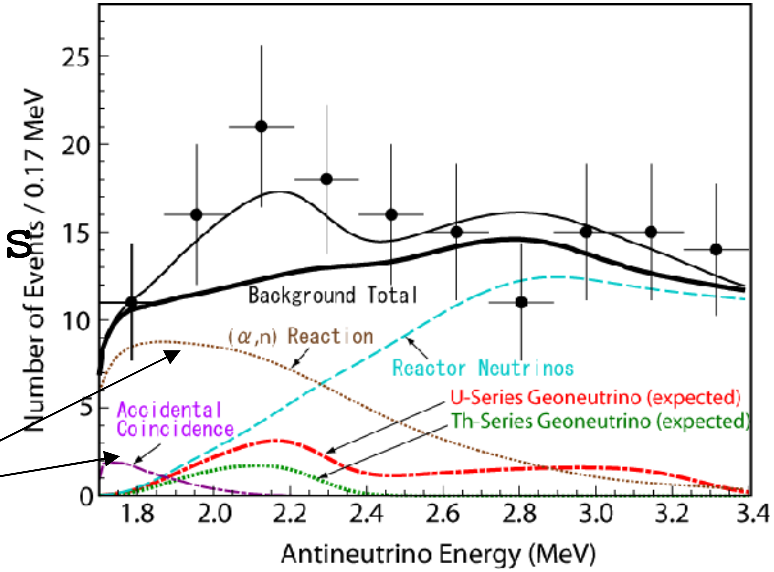


Comparison with Earth Model Predictions



- Consistent with BSE model predictions
- 99%C.L. upper limit too large to be converted to heat production (No Earth models applicable)

KamLAND Future Plan

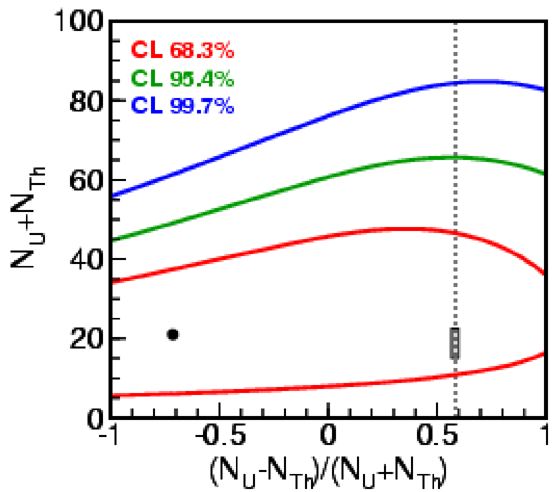


Further LS purification in progress
(distillation, N_2 purging, etc)

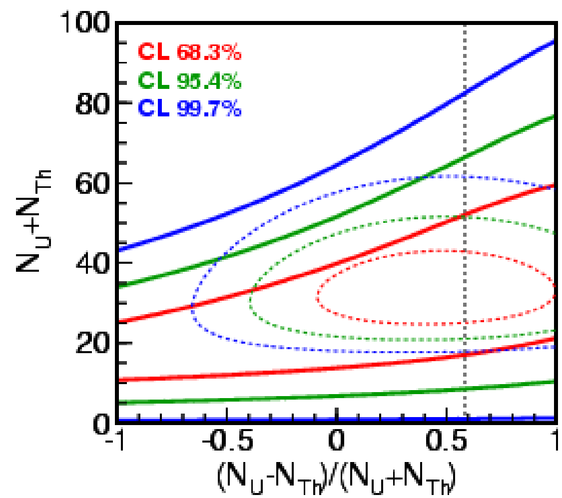
⇒ removes radioactivity by 10^{-5}

we remove these

BEFORE



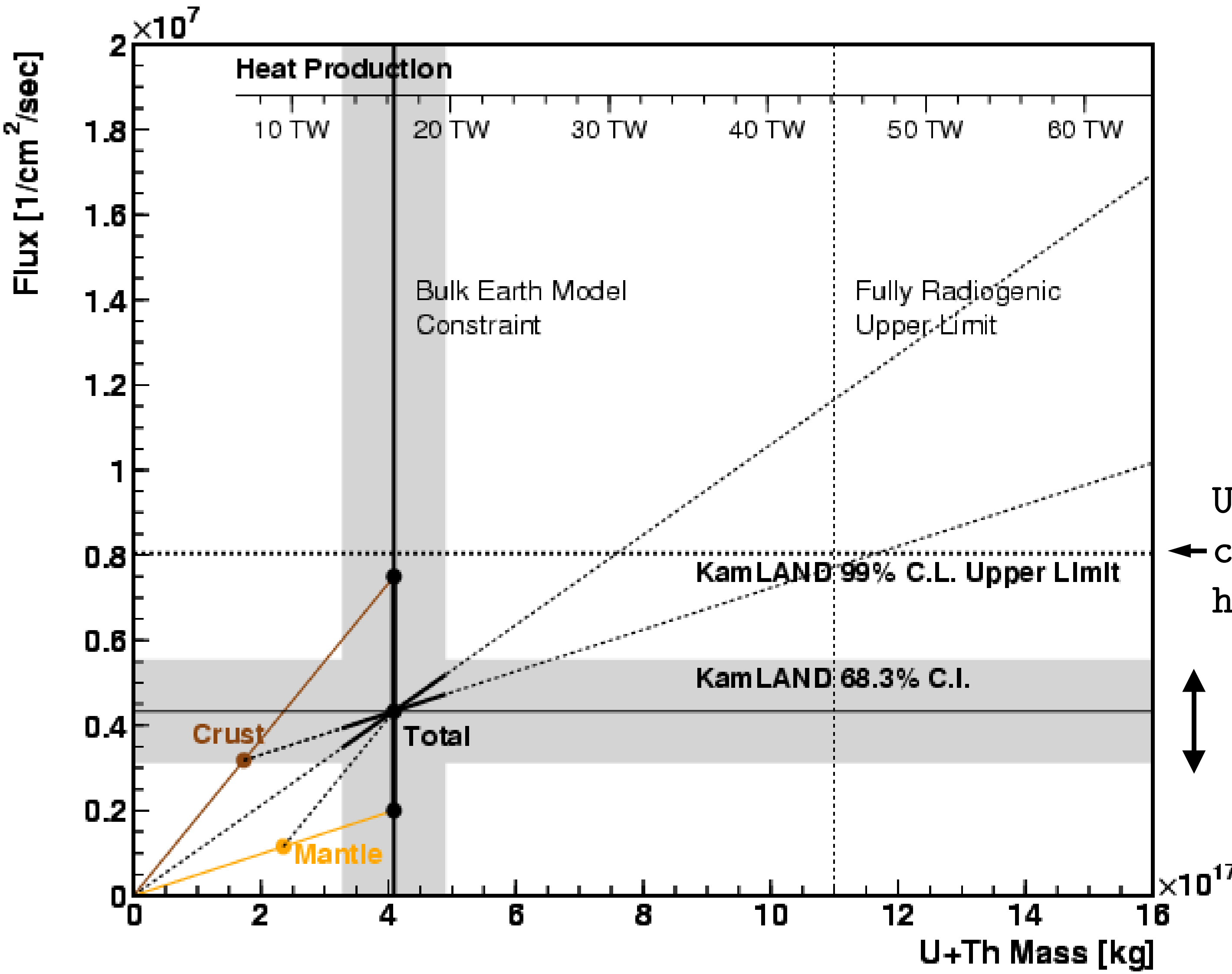
AFTER



Another 749 days operation after purification,

- Error is reduced : from 54% to 28% (error is dominated by reactor neutrinos
- Significance : 99.96%

KamLAND Prospects

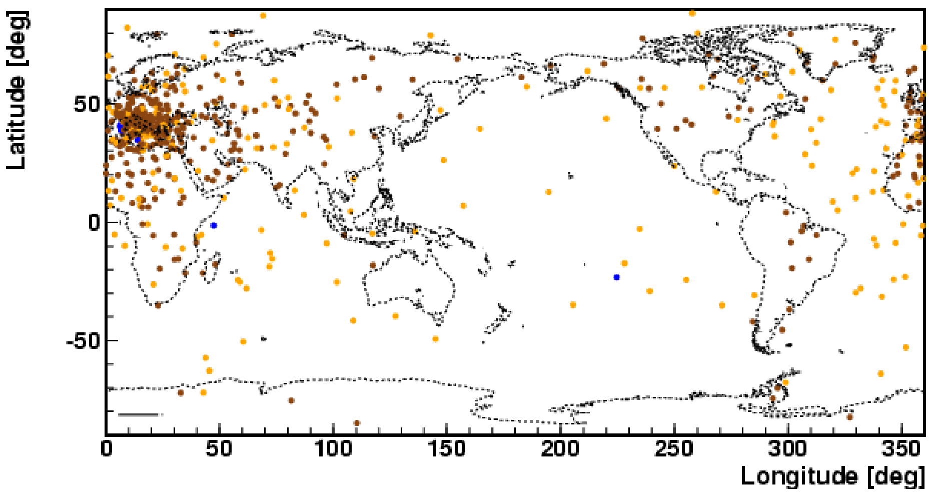


Upper limit (~40TW) comparable with heat flow (~40TW)

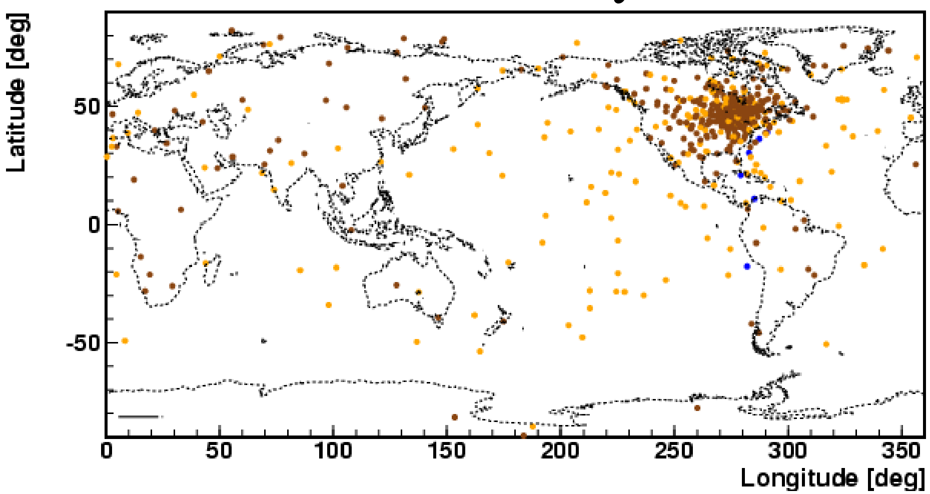
28% uncertainty

Next Geoneutrino Experiments

Borexino @ Gran Sasso



SNO+ @ Sudbury



- Detectors are located in the middle of the continental crust (80% of geoneutrinos come from continental)

- Flux is determined by average composition of ~500km radius

⇩

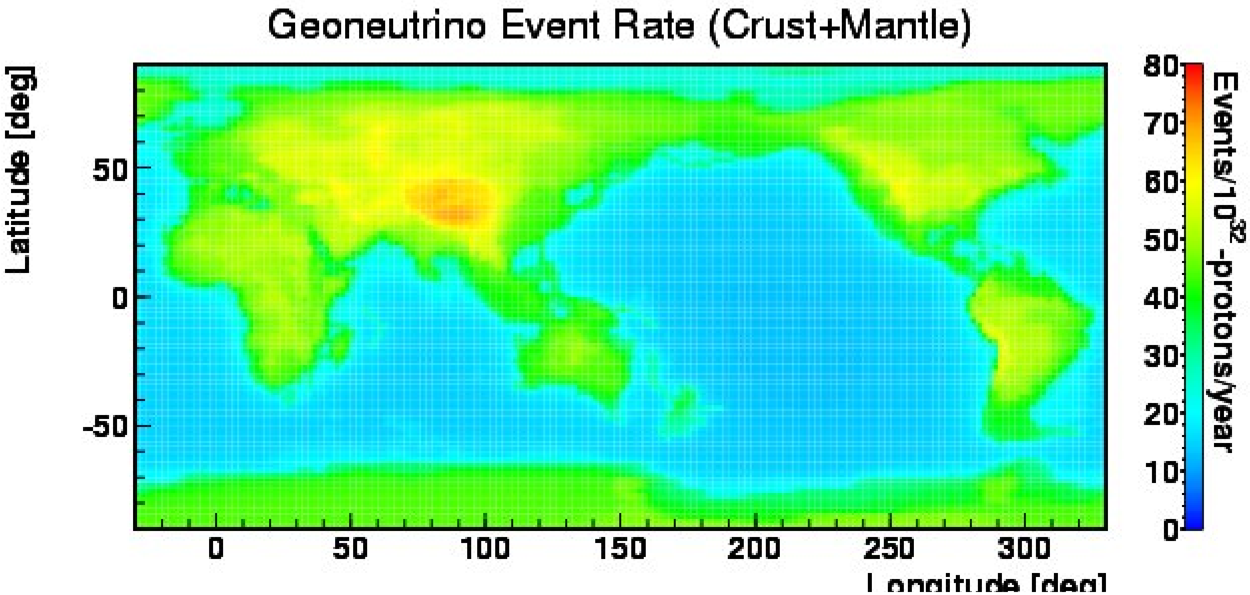
Unbiased crustal composition can be seen

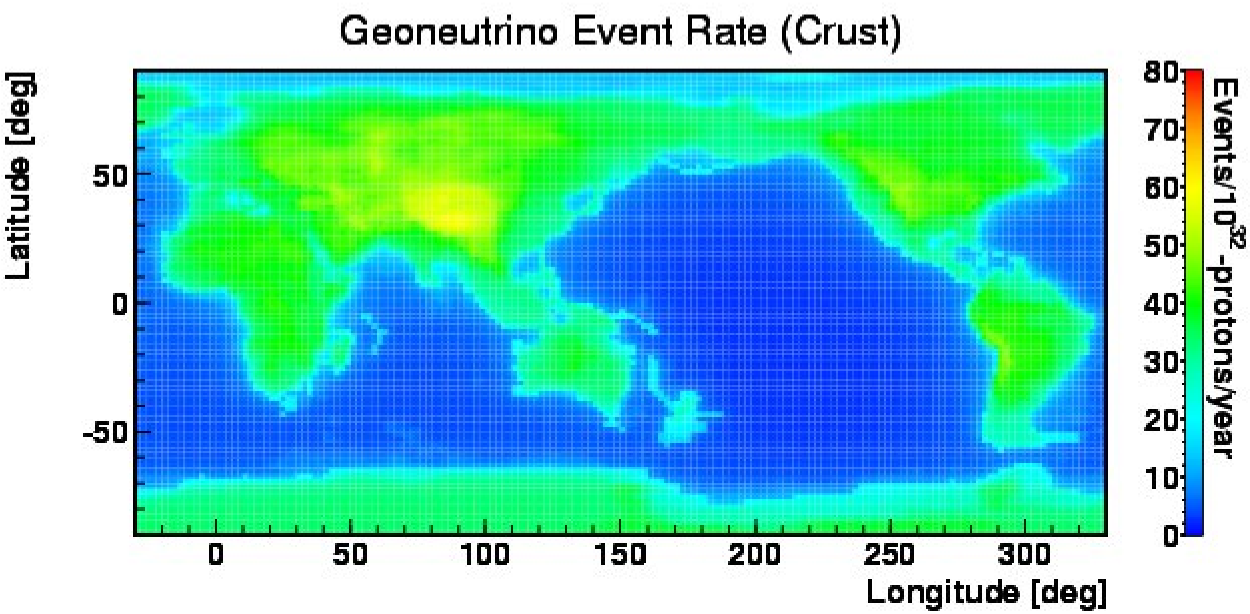
(Geochemical studies are based on “ rock samples”)

Future Geoneutrino Experiments

Project	Location	Mass (kton)	Depth (m.w.e.)	Start
KamLAND	Kamioka / Japan	1.0	2700	2002
Borexino	Gran Sasso / Italy	0.3	1500	200?
SNO+	Sudbury / Canada	0.7	5400	Under Discussion
Hano-hano	Hawaii / U.S.	4	3000 (?)	Under Discussion
BNO	Baksan / Russia	1.0	4800	Under Discussion
LENA	Phyasalm / Finland Nestor / Greece	60	4000 4000	Still Dream
HSD	Kimballton / U.S. Homestake / U.S. Soudan / U.S.	100	1850 4200 2070	Still Dream

The World Map of Geoneutrino Flux





Typical Rate

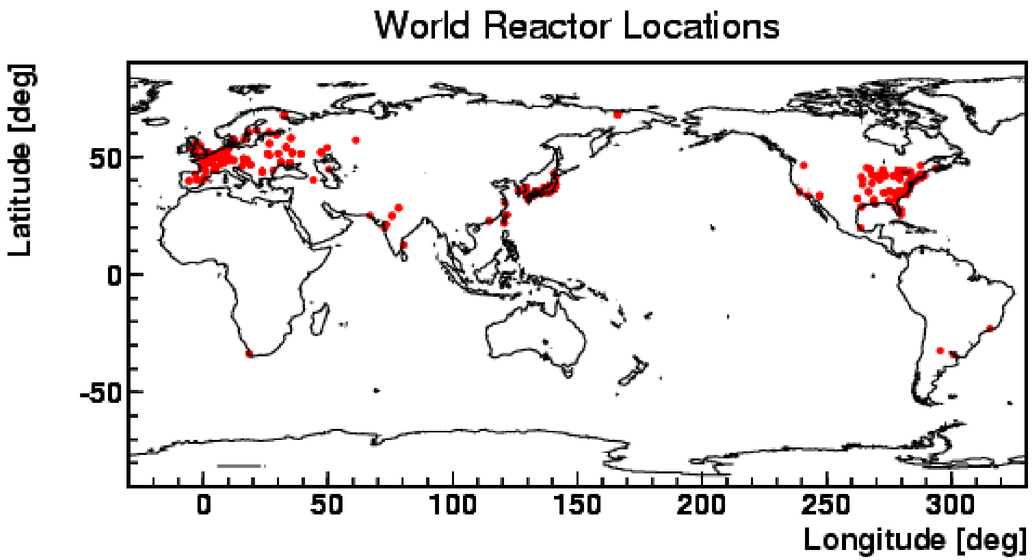
from Mantle

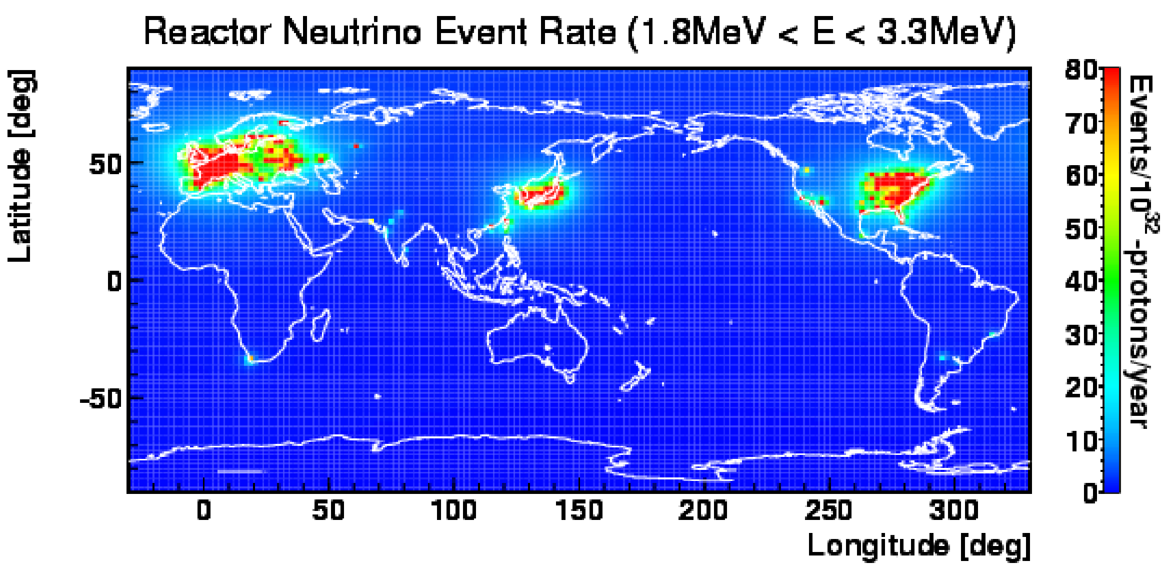
~10 /10^{32}P/year

from Crust

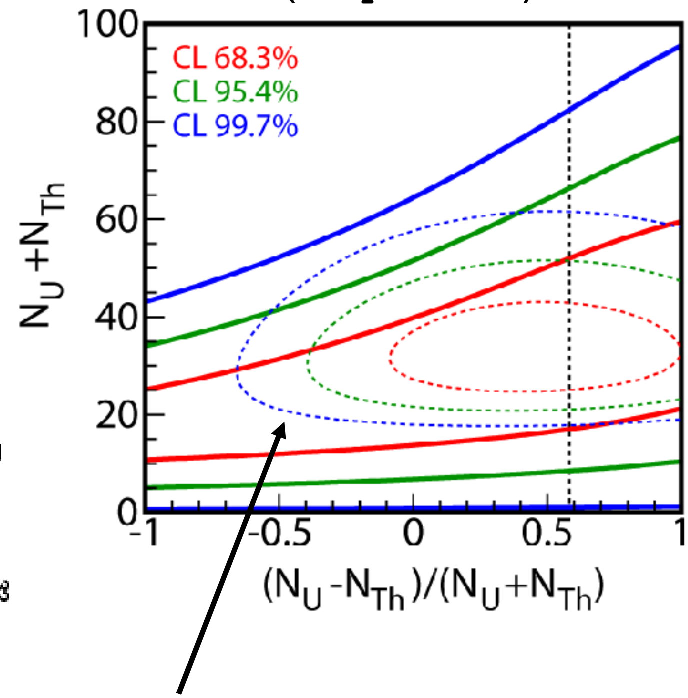
30~70 /10^{32}P/year

Reactor Neutrino Backgrounds



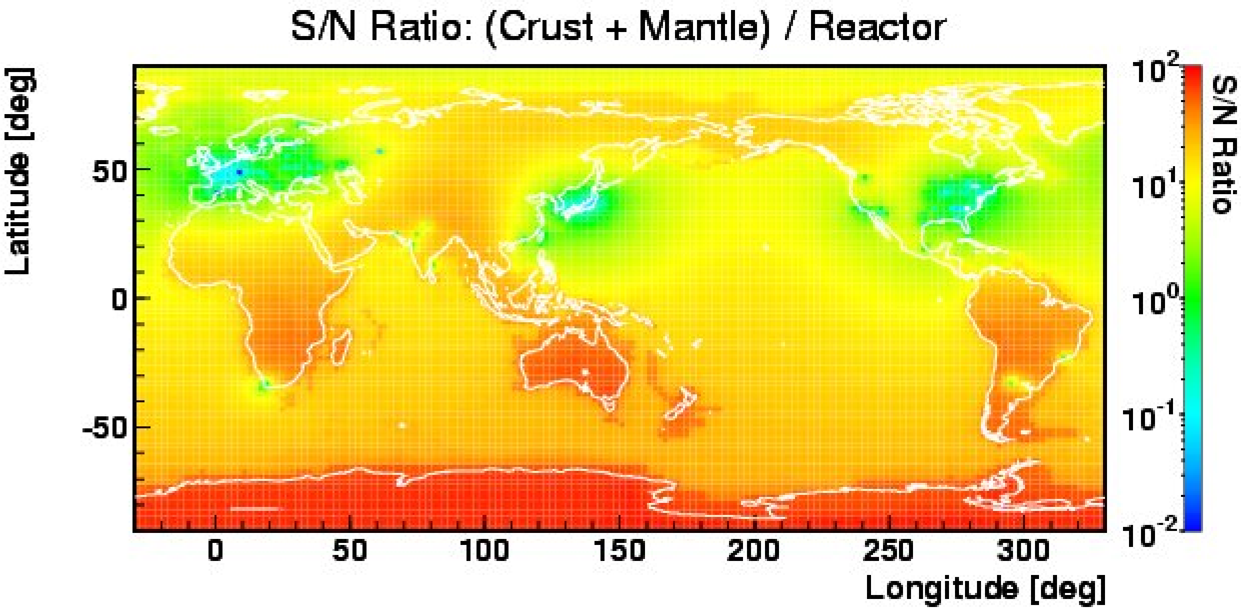


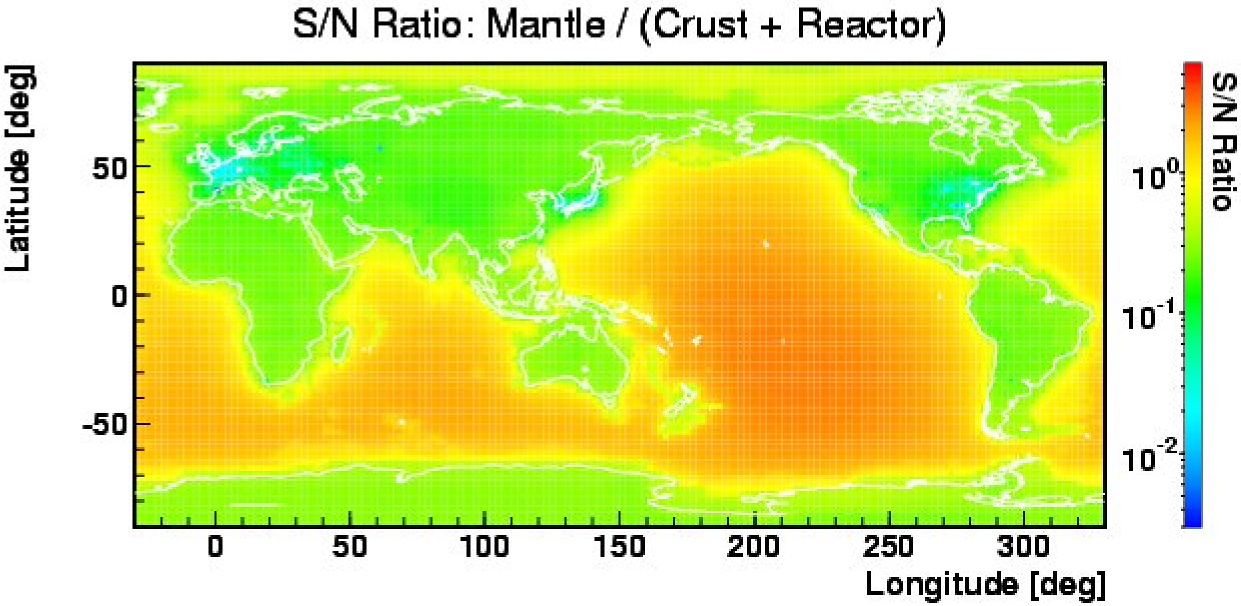
KamLAND-II 750 days
(expected)



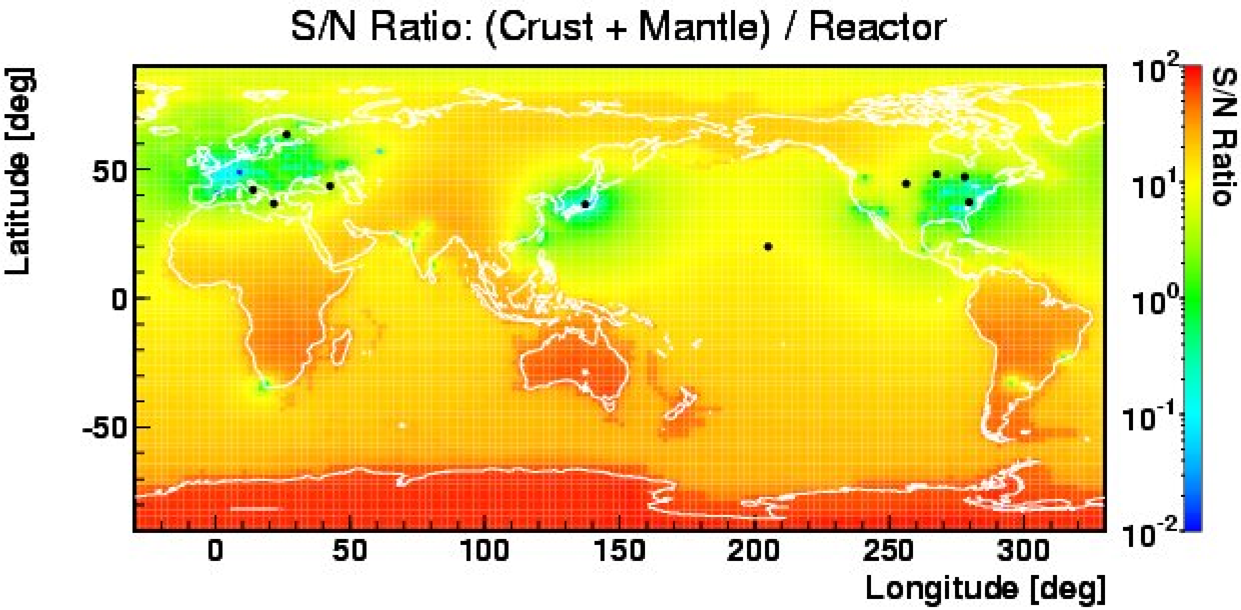
without reactor BG

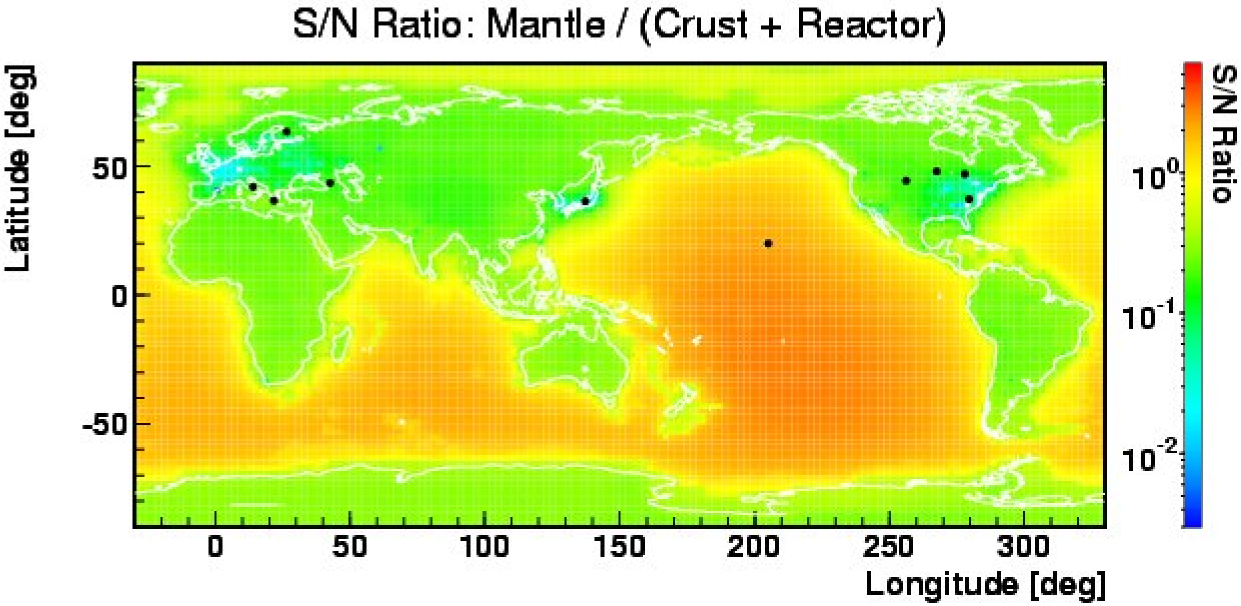
The World Map of Geoneutrino S/N Ratio



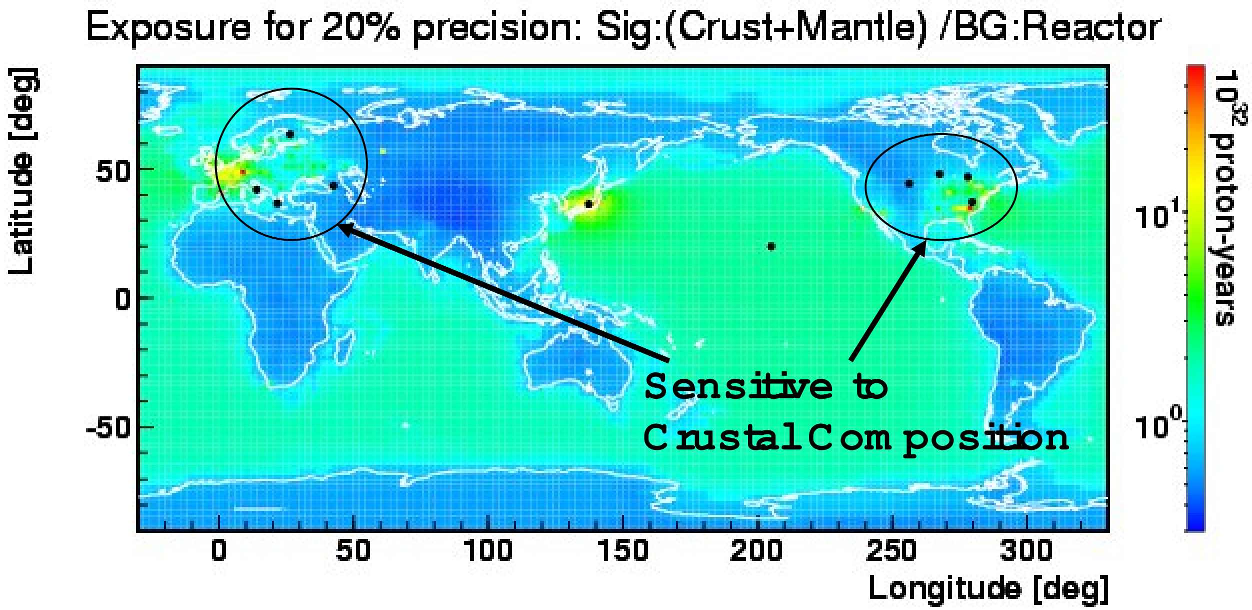


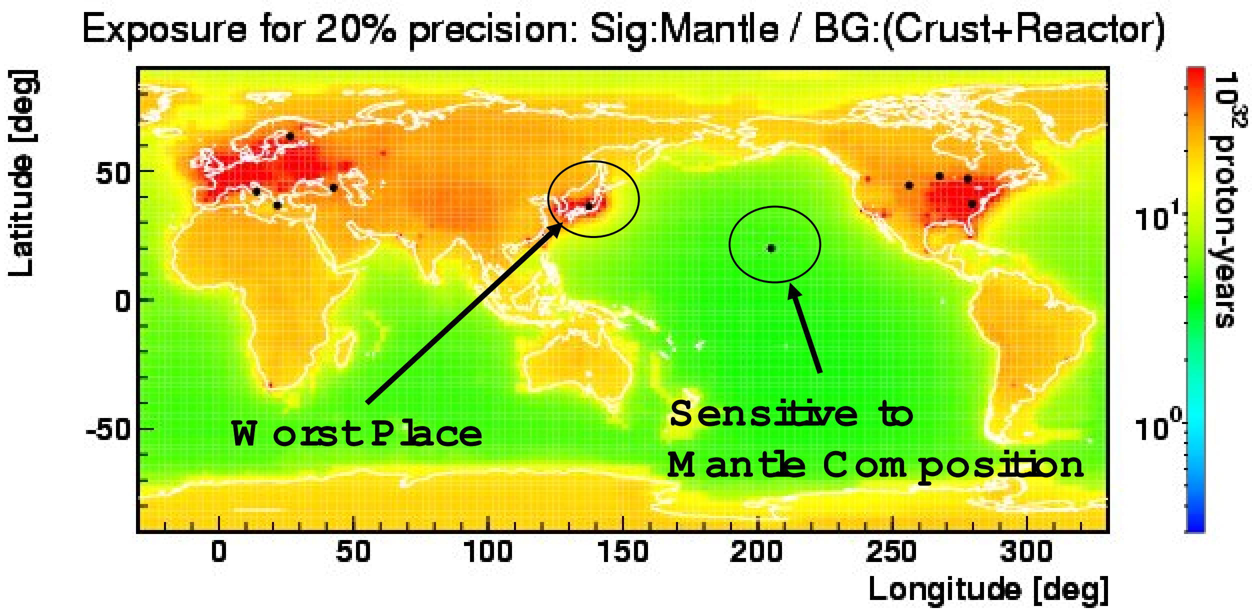
The World Map of Geoneutrino S/N Ratio





Required Exposure for 20% precision determination





Typical Time

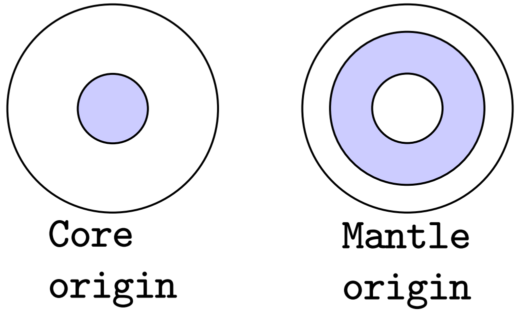
on CC, estimate BSE
0.5~1 [10^{32}P· year]

on CC, estimate M
~30 [10^{32}P· year]

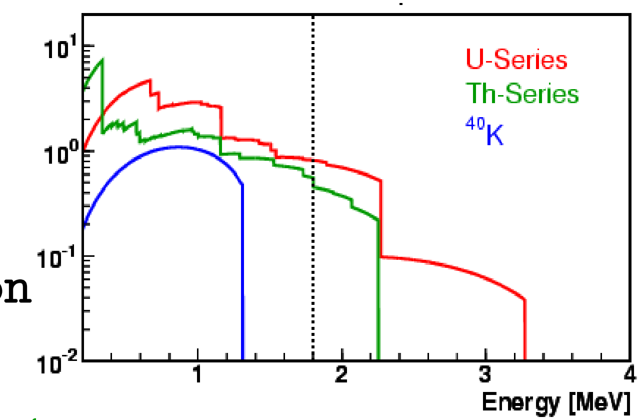
on OC, estimate M
4.5 [10^{32}P· year]

Future Themes

- Directional Sensitivity
  - Composition of Mantle beneath Crsut
  - Separation of Mantle and Core
  - Towards " Earth Tomography"



- ^{40}K (E_{max}=1.3MeV) Neutrino Detection
  - Importance heat source (3TW ~ 20TW)
  - Poor Earth model predictions
  - A key to understand planetary formation



- Portability (multiple-site observation)
  - Underwater detector
  - Cosmic ray tolerance (shallow site)
  - Small (dead-)volume detector

Summary

- KamLAND has made the first experimental study of geoneutrinos
- 749 days exposure of KamLAND results in
  - ✓ 90% Confidence Interval: 4.5 to 54.2 events
  - ✓ 99% C.L. upper limit: 70.7 events
  - ✓ Consistent with predictions by Earth models
- Further purification is in progress: with another 749 days,
  - ✓ Significance will reach 99.96%
  - ✓ Measurement error will be around 28%
  - ✓ 99% upper limit will be around 40TW heatflow-equivalent
- A number of new geoneutrino experiments are proposed. Stay attuned!