Using Neutrinos to Study the Earth
- Geoneutrinos -

Un altro modo di guardare il ~~cielo~~ globo

1. Neutrino Geophysics
2. KamLAND Results
3. Near Future Prospects (Borexino, SNO+, ...)
4. Far Future Dreams

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Geoneutrinos

Generated by beta-decay chain of natural isotopes (U, Th, K)

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

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

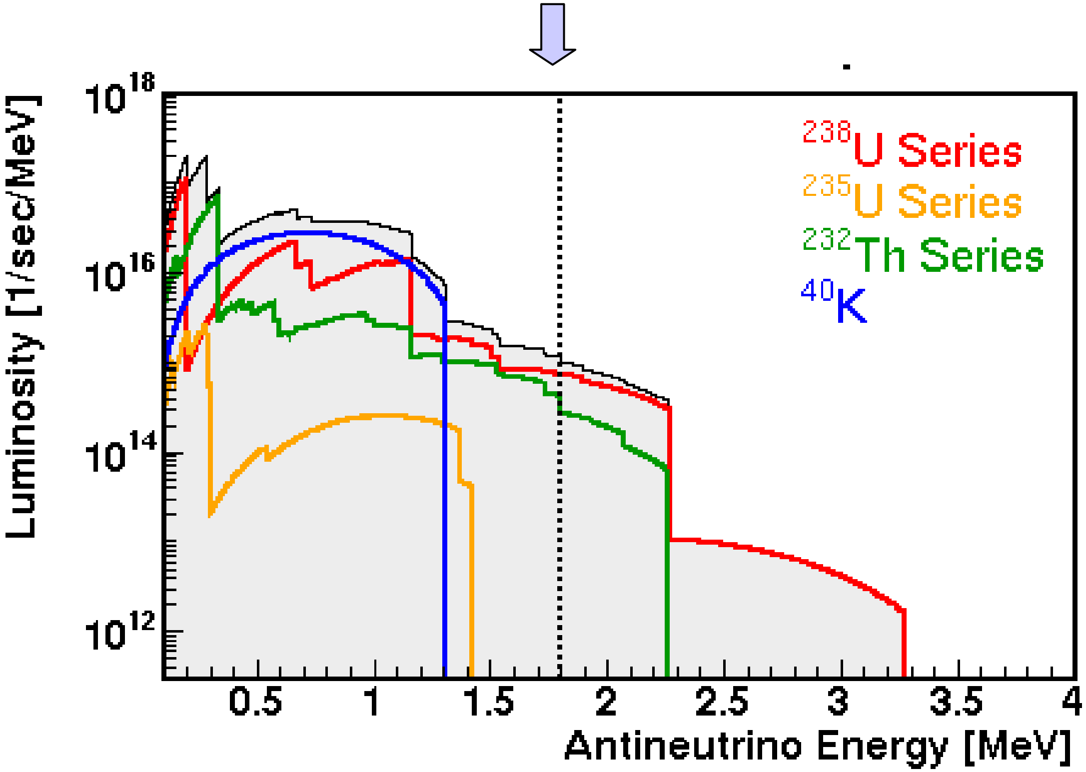
$$^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e$$

With organic scintillator, detected by inverse-beta decay reaction

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

No directional info.

Threshold: 1.8 MeV



Discovery of radioactive isotopes in the Earth??

Geoneutrinos:
A New Tool to Explore the Earth Interior

- Generated by radioactivity inside the Earth

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

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

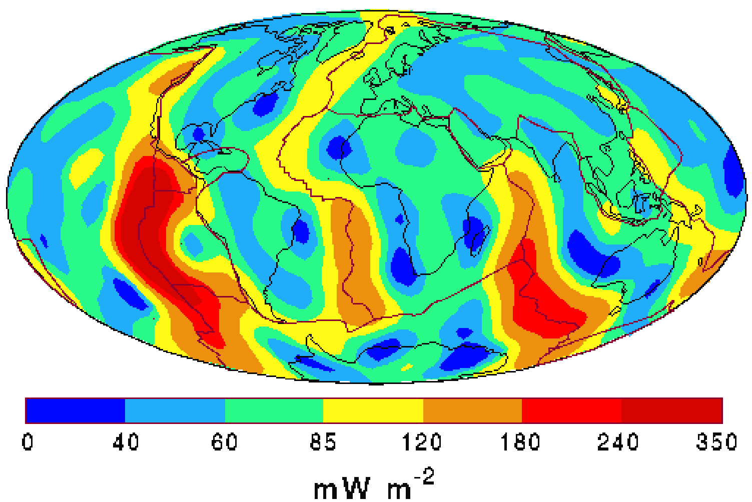
$$^{40}K \rightarrow \ ^{40}Ca + e^{-} + \bar{\nu}_e + 1.3\ [MeV]$$

- 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

Heat Producing Element (HPE) and Energy Balance

Heat Release from the Surface



- 24774 bore-hole measurements
- Corrections of hydrothermal circulation

⇩

44.2±1 TW Total Heat Flux
(Recent Challenge 31±1 TW)

The Ingredient of the Earth
CI-Chondrite Meteorite

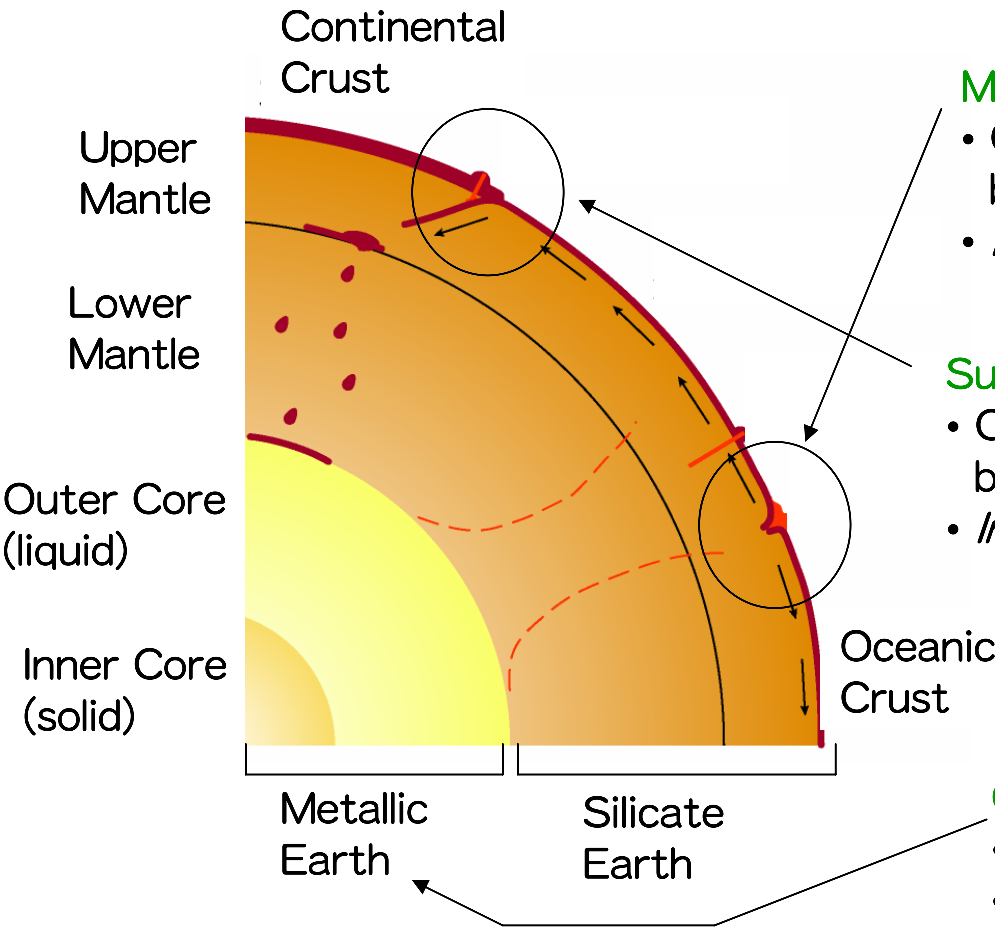
tells the composition of the
Bulk Silicate Earth (BSE)
(fundamental paradigm of geochemistry)
[McDonough et al, Chem.Geo.120,223 (1995)]

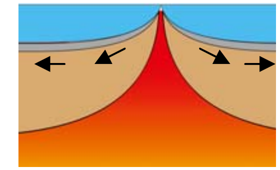
⇩

~20 TW Radioactive Heat
(U: ~8TW, Th: ~8TW, K: ~3TW)

- Core heatflow (solidification etc.) estimated 5~15 TW ???
- Secular cooling 18±10 TW ???

Earth Evolution (Differentiation) and Present Structure



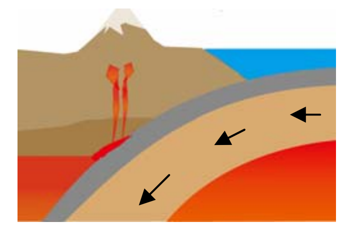


Mid-Ocean Ridge

- Oceanic crust is being created by partial melting of mantle
- *Incompatible* elements (U, Th, K) extracted

Subduction Zone (Japan etc)

- Continental crust is being created by partial melting of oceanic crust and mantle
- *Incompatible* elements (U, Th, K) extracted



Core

- High density Fe-Ni alloy
- *Lithophile* elements (U. Th, K) are hardly (almost never) contained

Result of 4.5Ga Planetary Evolution

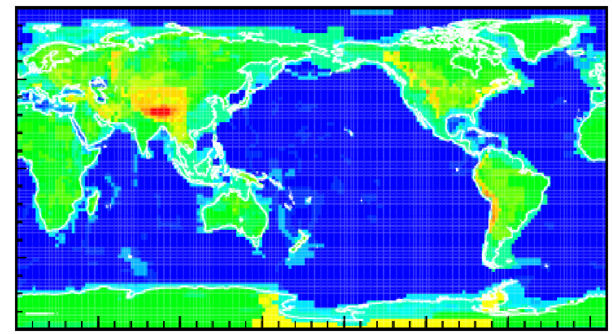
- Half of U and Th are contained in Continental Crust
- Mantle ???
  uniform or layered, depleted or recycled, something on the bottom ???

Start Point: A Reference Earth Model

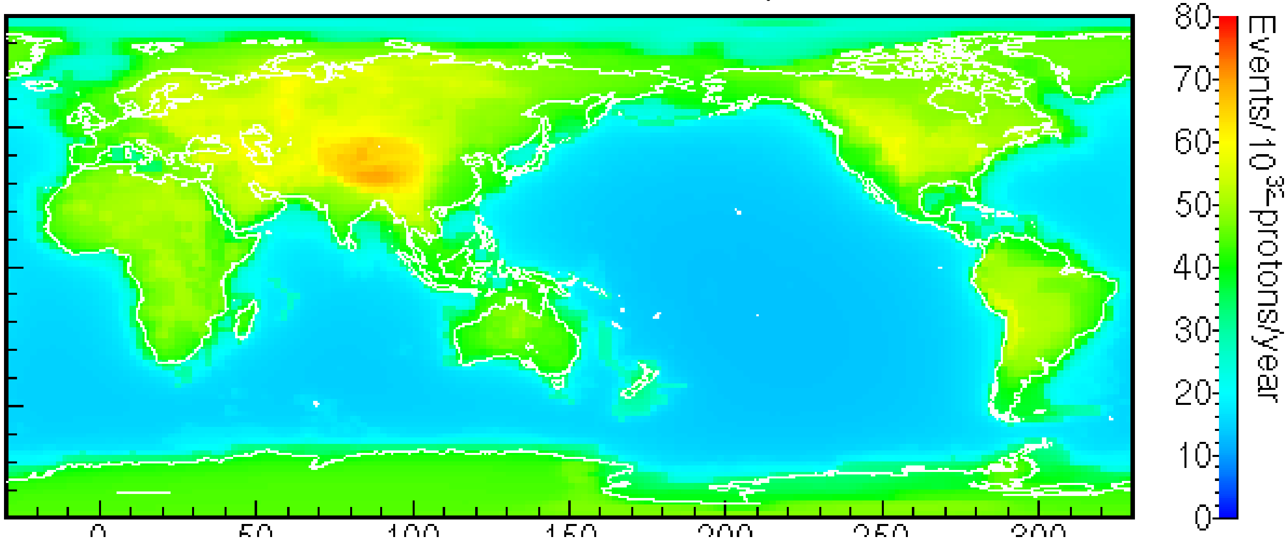
- BSE composition by [McDonough1999]
- Crustal composition by [Rudnick et al. 1995]
- Crustal thickness by CRUST 2.0
- Uniform Mantle model assumed
- No U/Th in the Core

- Local Geologies Not Considered

Crustal Thickness
(CRUST 2.0 data set)



Geoneutrino Flux Map



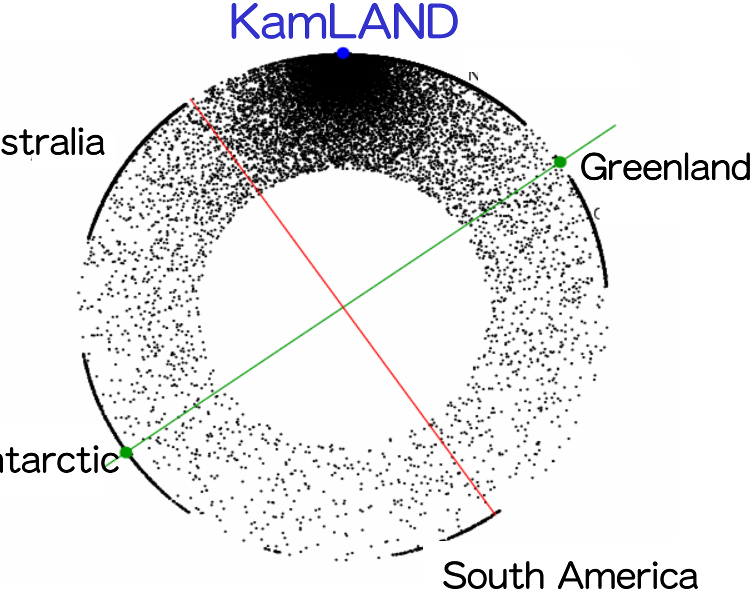
Typical Rate

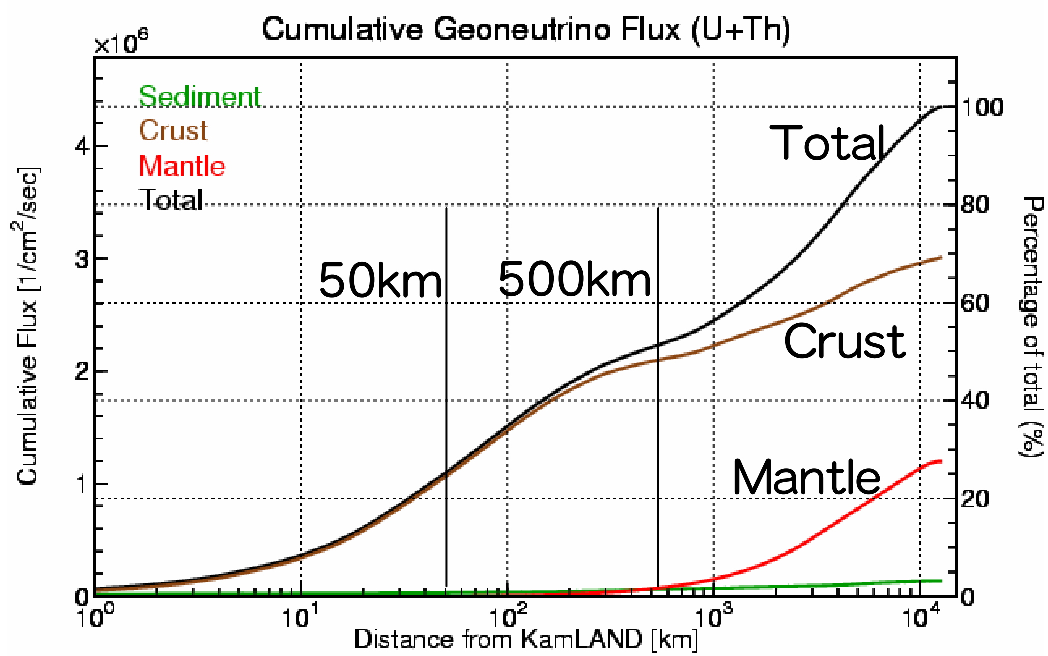
from Crust
$30\sim70\ /10^{32}$P/year

from Mantle
$\sim10\ /10^{32}$P/year

Geoneutrino at Kamioka

Simulated
Geoneutrino Origination Points



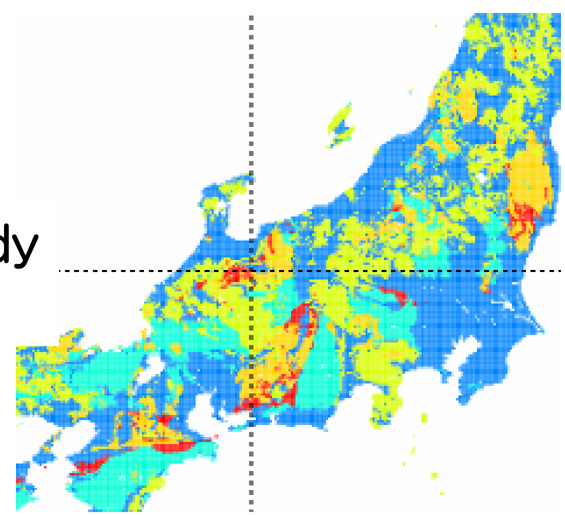


50% within ~500km
25% within ~50 km
~25% from Mantle

With 10^{32} target protons,
- U-Series
  32 events / year
- Th-Series
  8 events / year

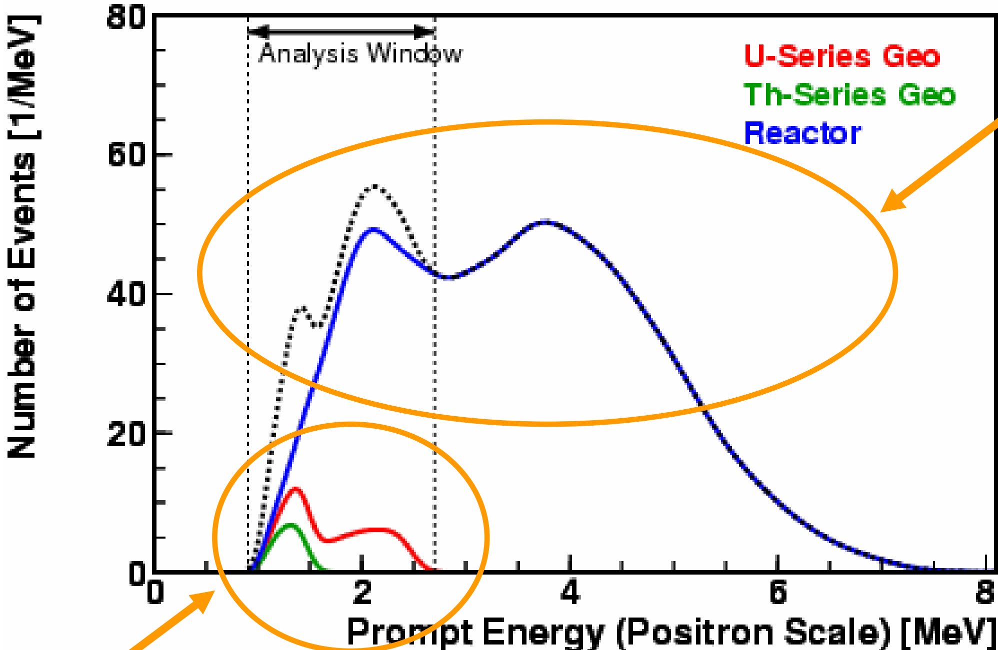
Extensive geology study confined error to <5%,

Local characteristic depletion 6~8%

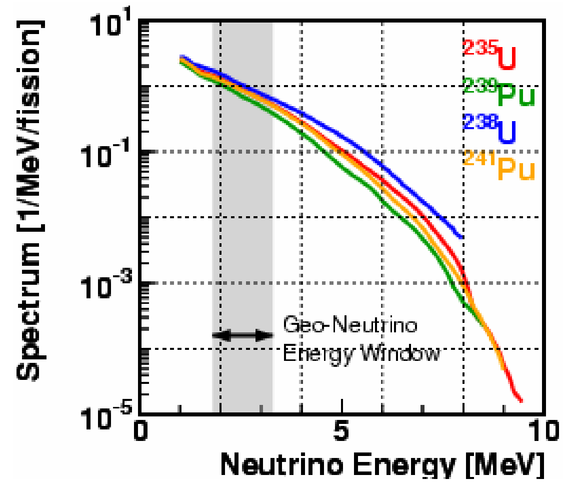


[Enomoto et al., EPSL 258, 147 (2007)]

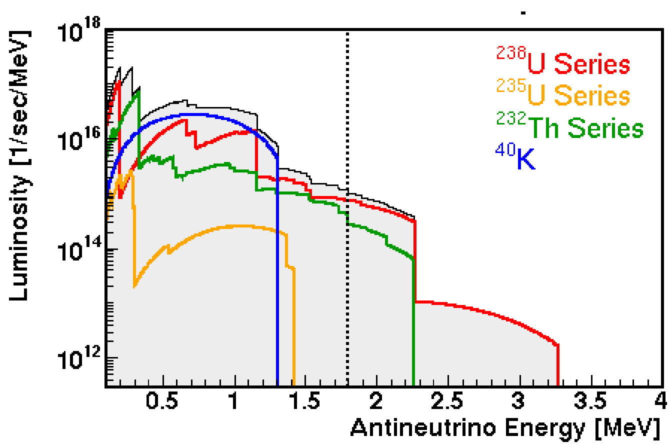
KamLAND Antineutrino Spectrum (expected)



Reactor Neutrinos



Geoneutrinos

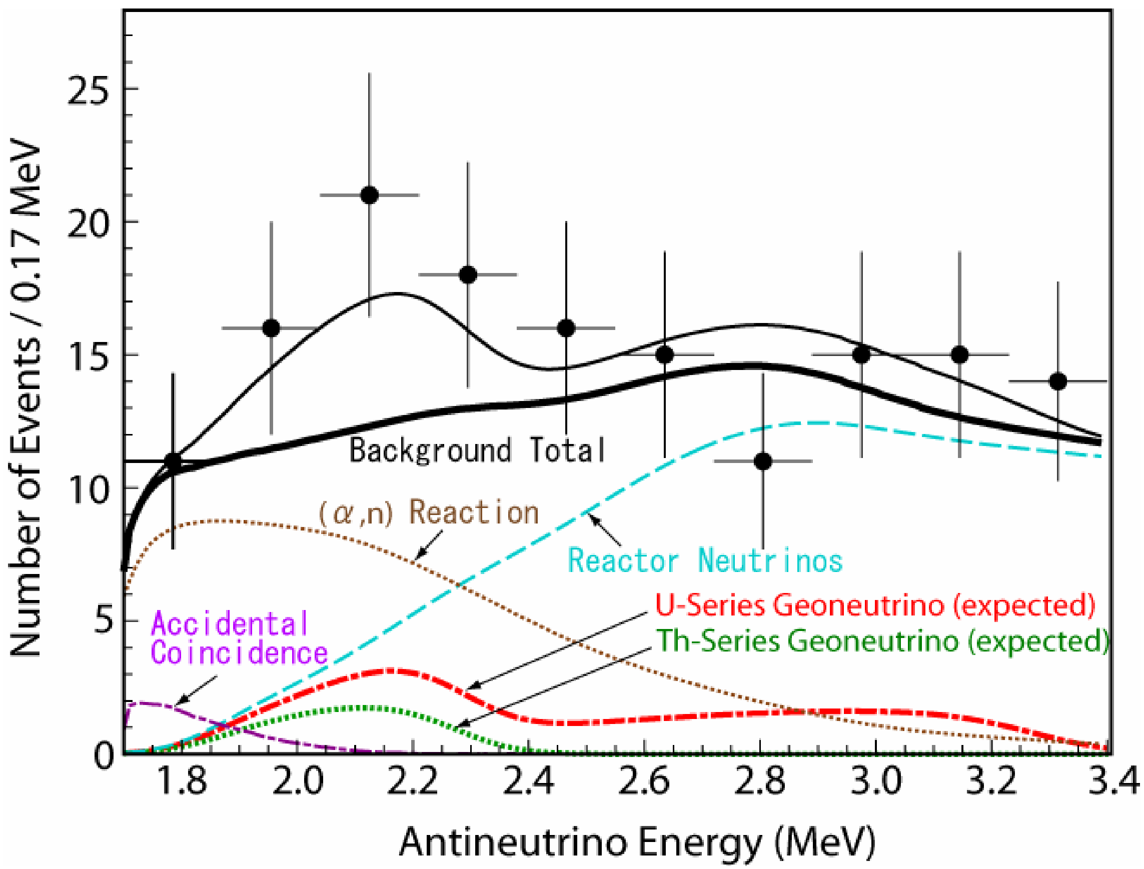


- Japanese reactor operation data provided
- Korean reactor (3.4%) calculated from published electrical output

⇒ Total 2% error (conservative)

KamLAND Geoneutrino 1st Result [Nature 436, 499 (2005)]

- 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±11.1
- Accidental : 2.38±0.01

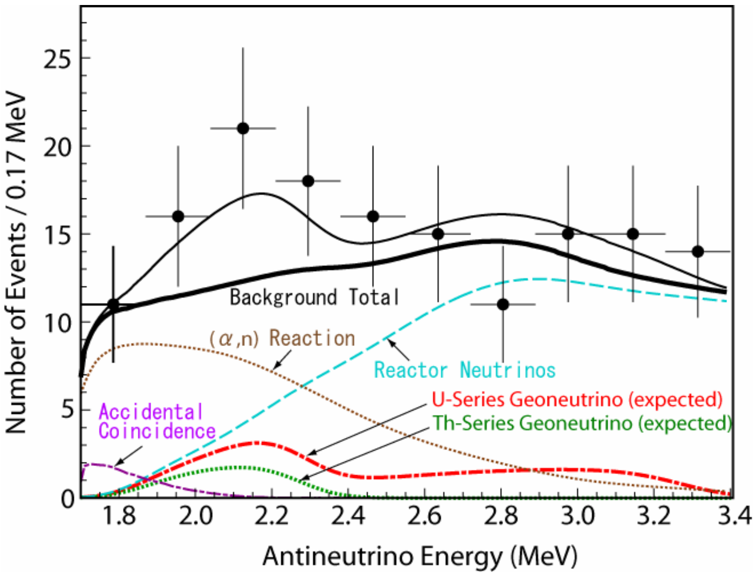
BG total : 127.4±13.3

Observed : 152

Number of Geoneutrinos:

25^{+19}_{-18}

KamLAND Spectrum Analysis [Nature 436, 499 (2005)]

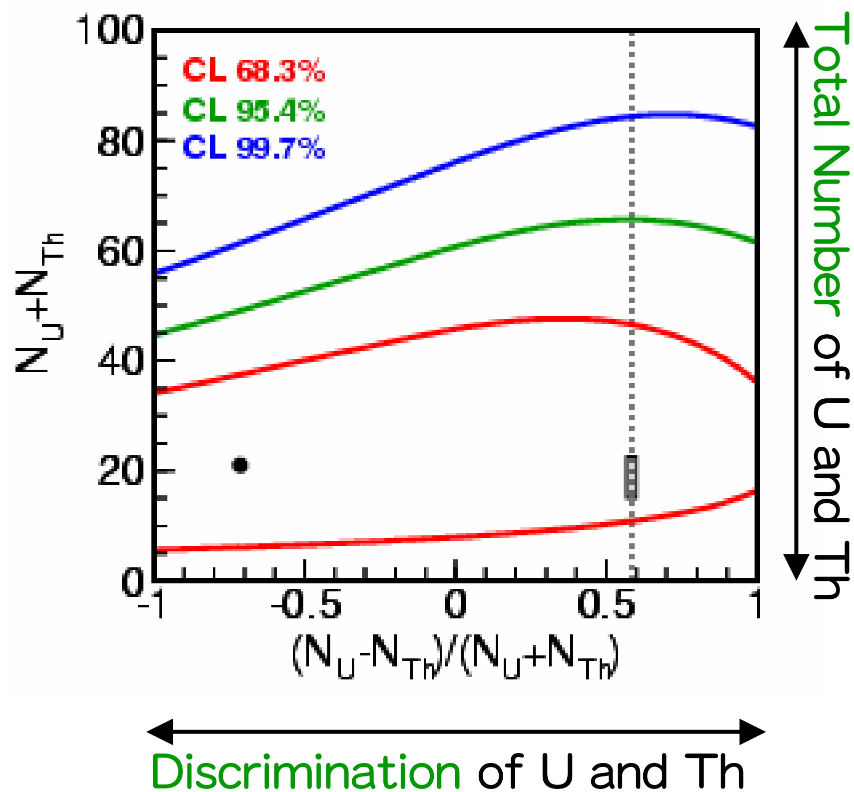


Parameters

N_U, N_{Th}: Number of Geoneutrinos

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

α_1, α_2: Backgrounds Uncertainties

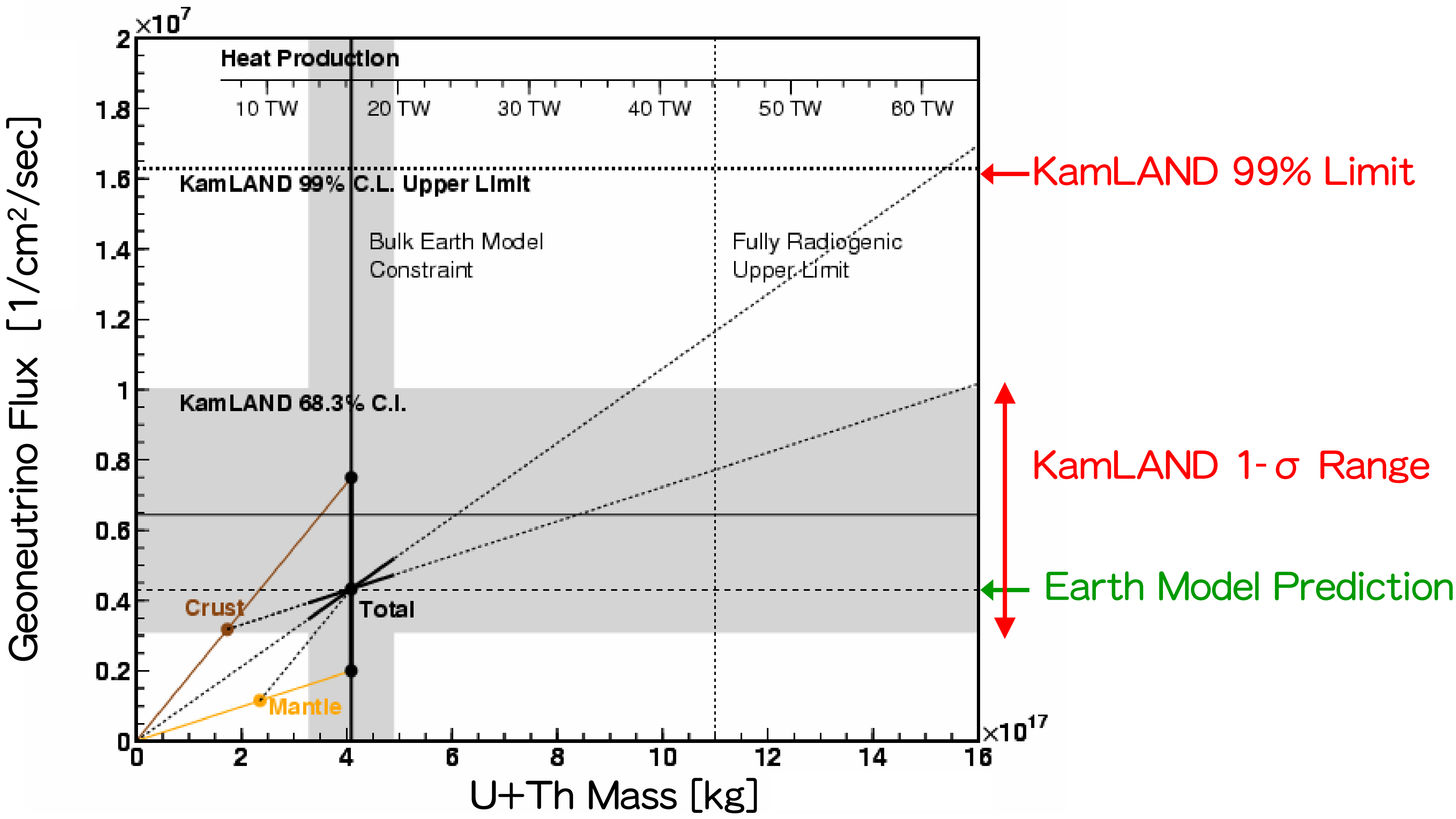


- KamLAND is insensitive to U/Th ratio

→ 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)

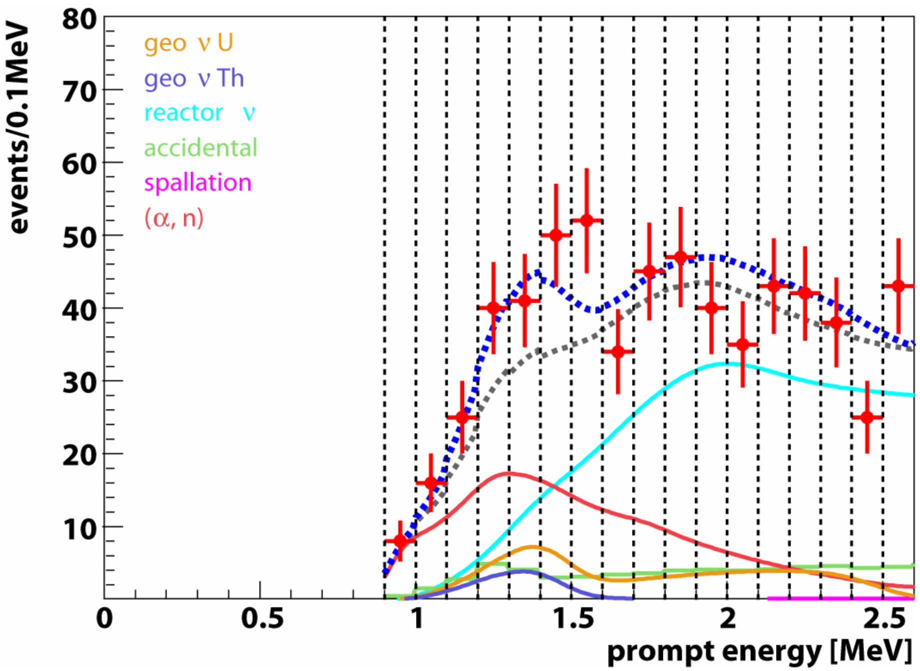
Comparison with Earth Model Predictions

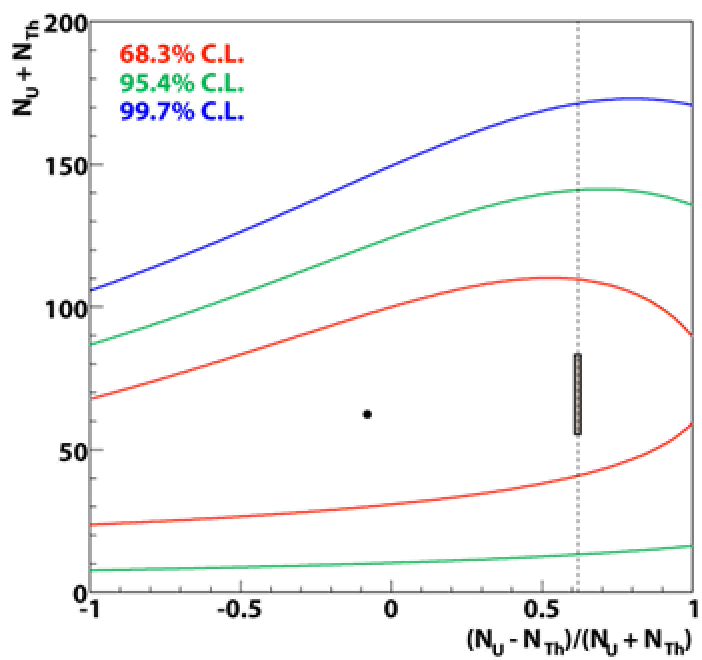


- Consistent with BSE model predictions
- 99%C.L. upper limit too large to be converted to heat production (No Earth models applicable)

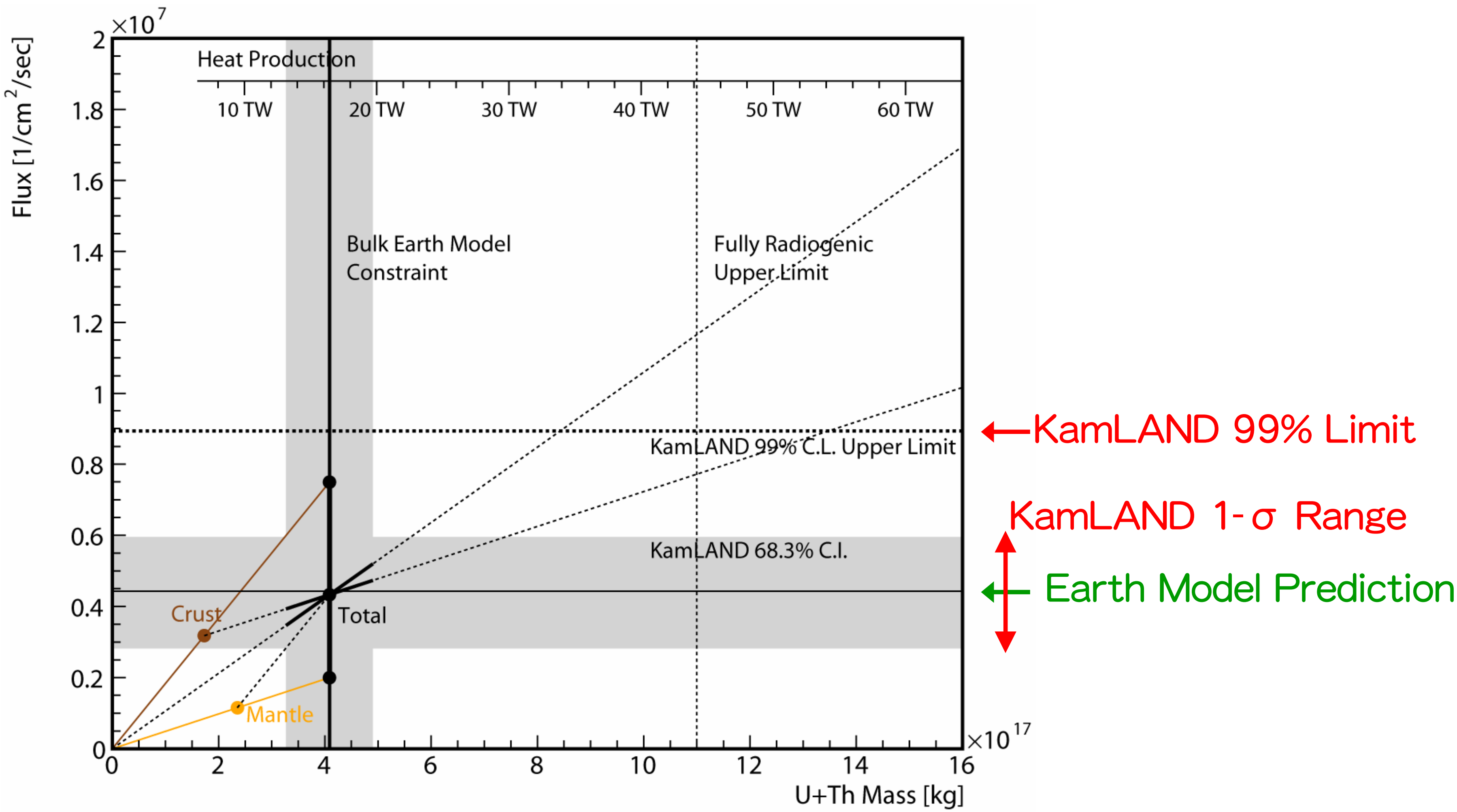
Recent Improvements [PRL 100, 221803 (2008)]

- More statistics accumulated: 749 day to 1491 day
- (α,n) error reduced: ~26% to ~11%
- Reconstruction improved (off-axis calibration)
- Analysis improved:
  - Fiducial volume increased
  - Time variation included
  - Optimal event selection with figure-of-merit basis





Geophysics with Improved Results

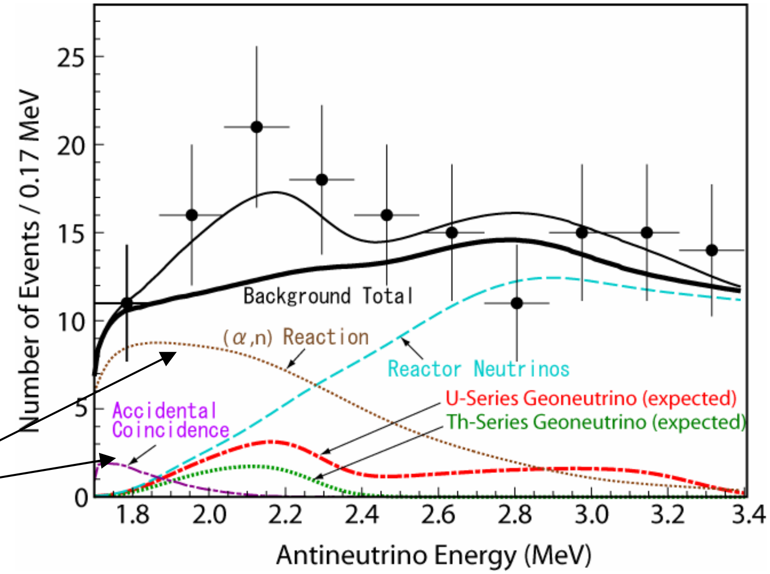


- Error is reduced from 56% to 36%
- Consistent with BSE model predictions
- 99%C.L. upper limit is approaching to the total terrestrial heat

KamLAND On-going Effort

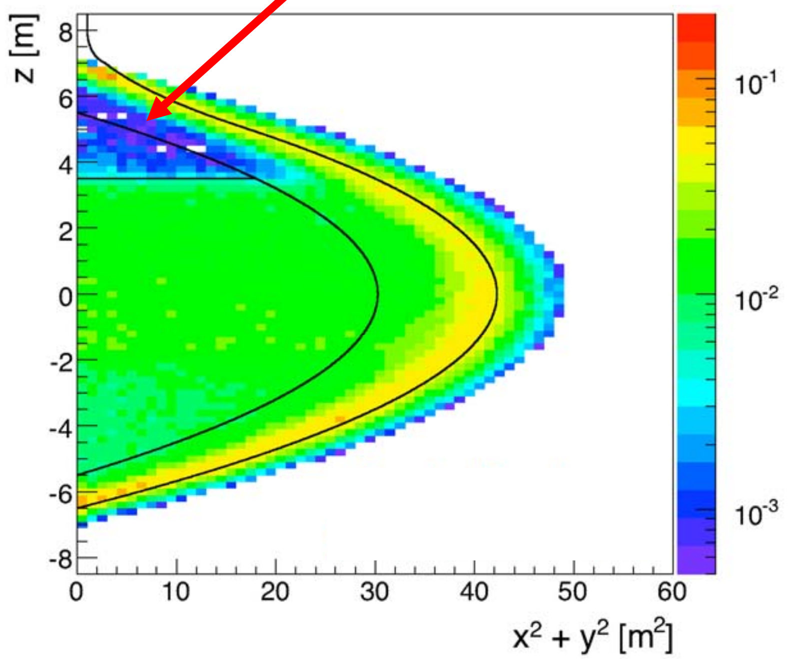
LS Distillation in Progress

⇒ removes radioactivity by 10^{-5}



we remove these

distilled scintillator

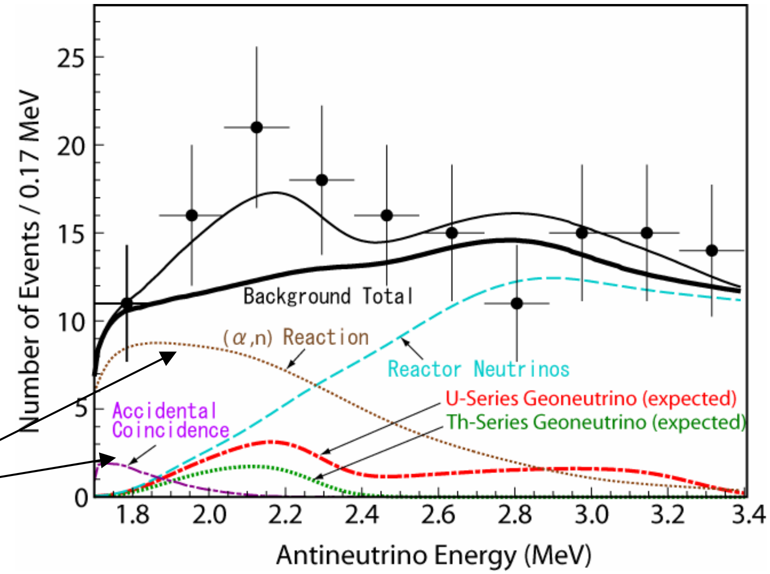


KamLAND Prospects

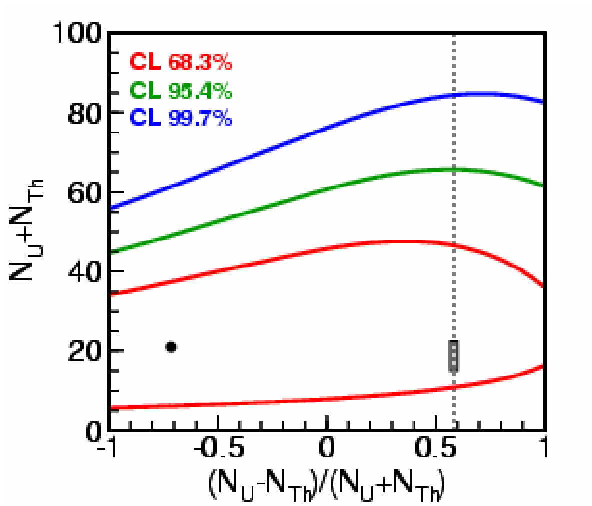
Assuming:

- 10^{-4} reduction of ^{210}Pb
- Enlarged fiducial volume (5.5m)
- Improved selection criteria
- 749 days livetime

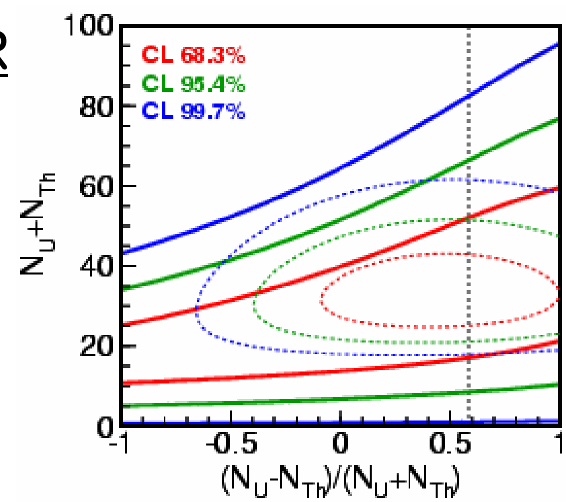
we remove these



BEFORE



AFTER

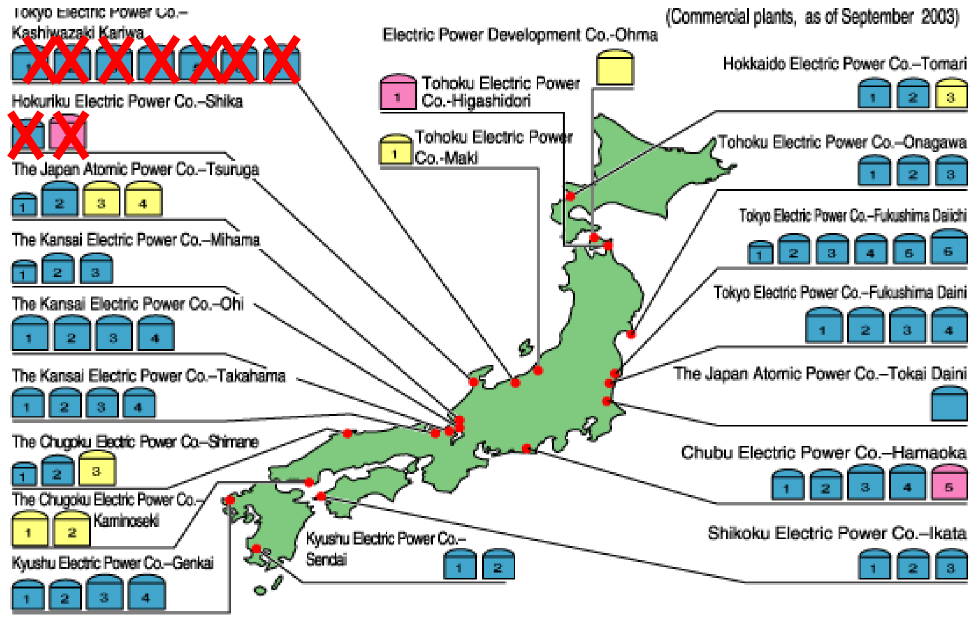


If combined with the current 1491 day data,

- Error is reduced : from 36% to 25% (error is dominated by reactor neutrinos)
- Significance : 99.992% (3.96 sigmas)

Another ~~Good~~ News: Reactors Stopped

- July 2007: Earthquake hit the world largest reactors (Kashiwazaki)
- March 2007: Earthquake hit the closest reactors (Shika)

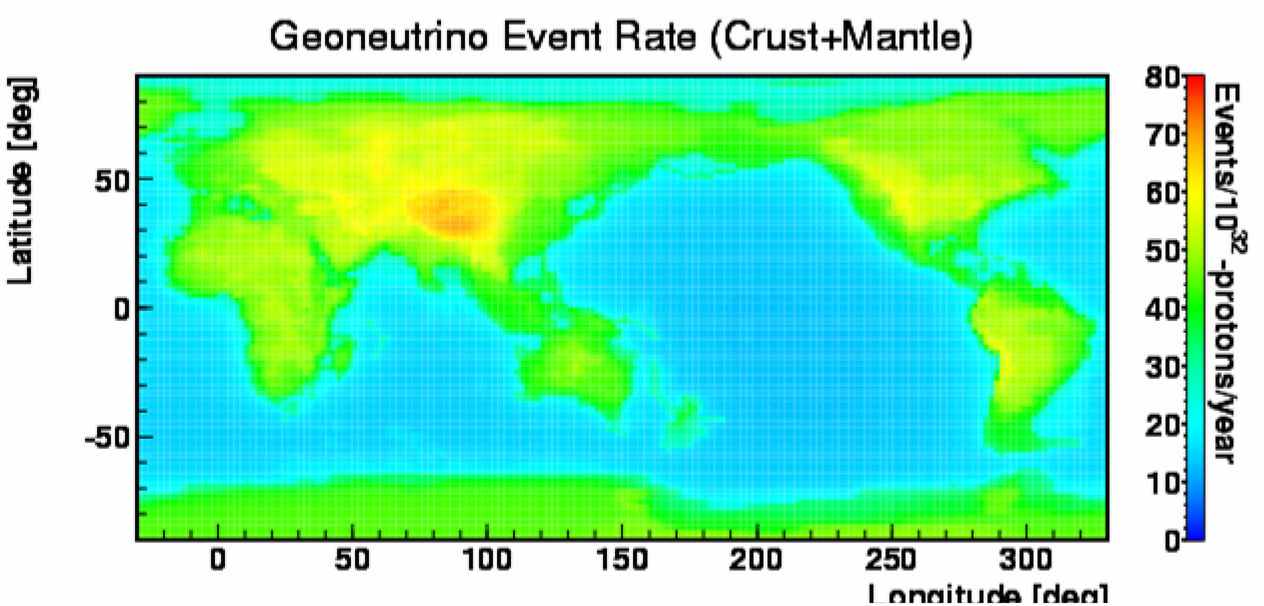


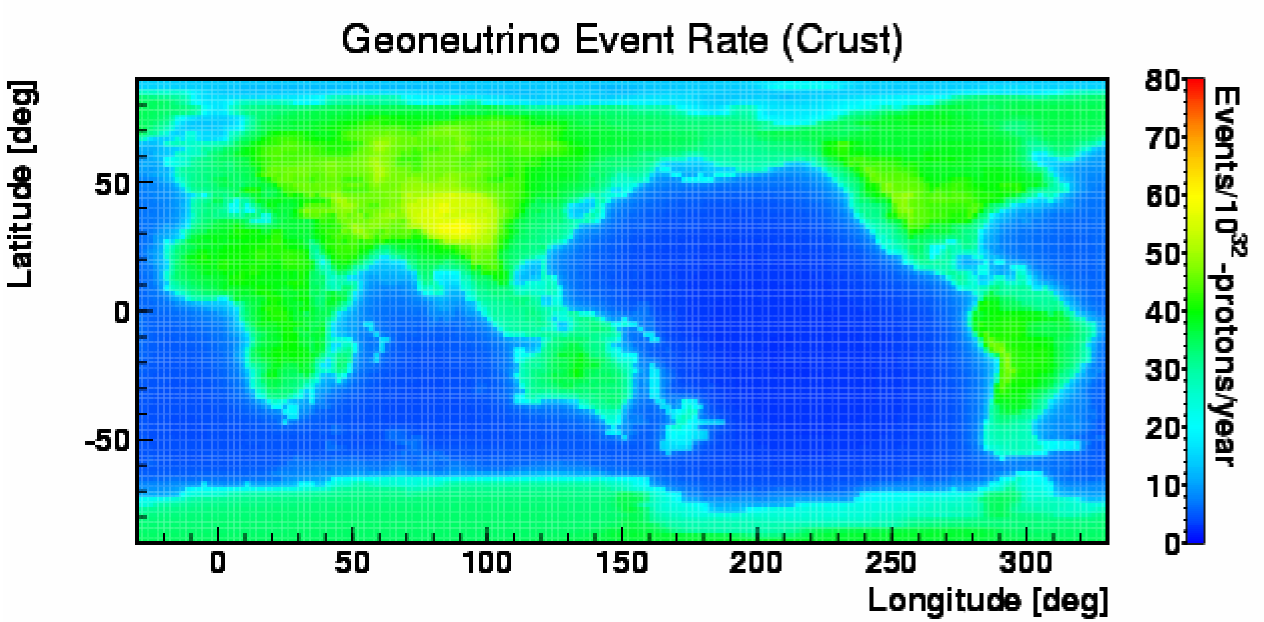
⇒ ~40% reactor flux reduced

More Geoneutrino Experiments

Project	Location	Mass (kton)	Depth (m.w.e.)	Status
KamLAND	Kamioka / Japan	1.0	2700	Running (~7 years)
Borexino	Gran Sasso / Italy	0.3	3700	Running (~ 2 years)
SNO+	Sudbury / Canada	1.0	5400	Soon
Hanohano	Hawaii / U.S.	>10	~4000	?
LENA	Somewehere in Europe	50		?
BNO	Baksan / Russia		4800	?
	Homestake / U.S. Kimballton / U.S. Soudan / U.S.		4200 1850 2070	?

The World Map of Geoneutrino Flux



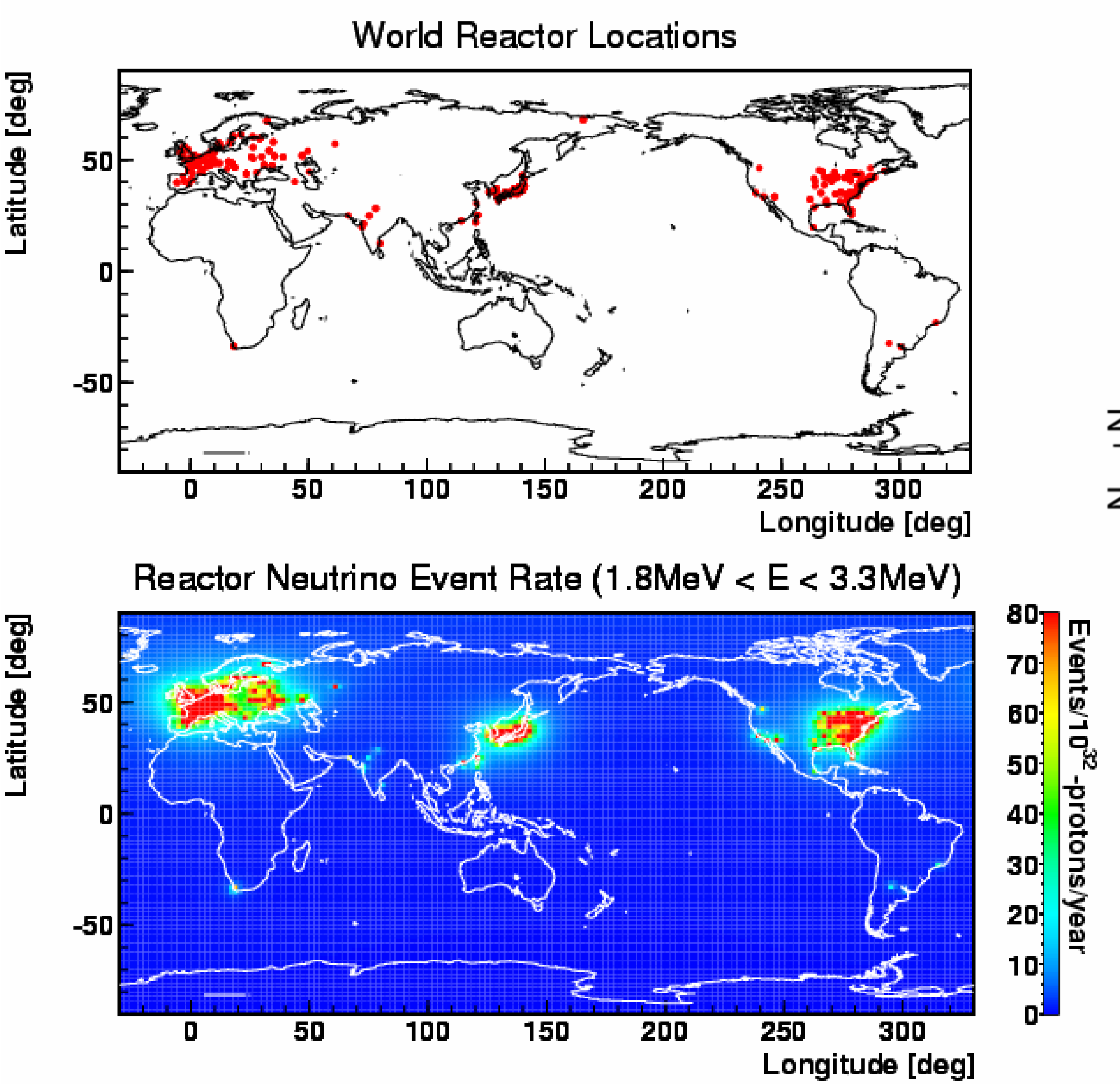


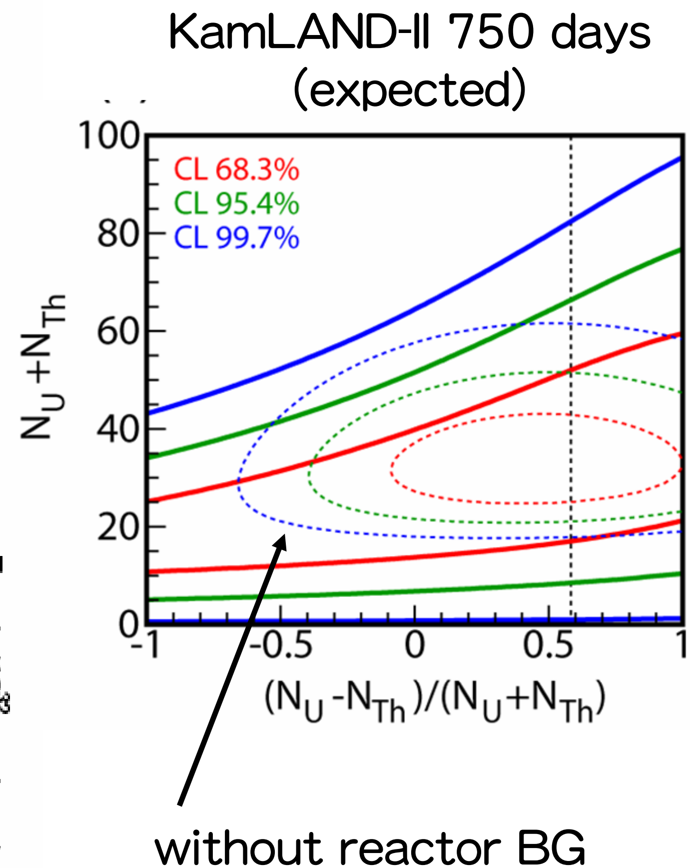
Typical Rate

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

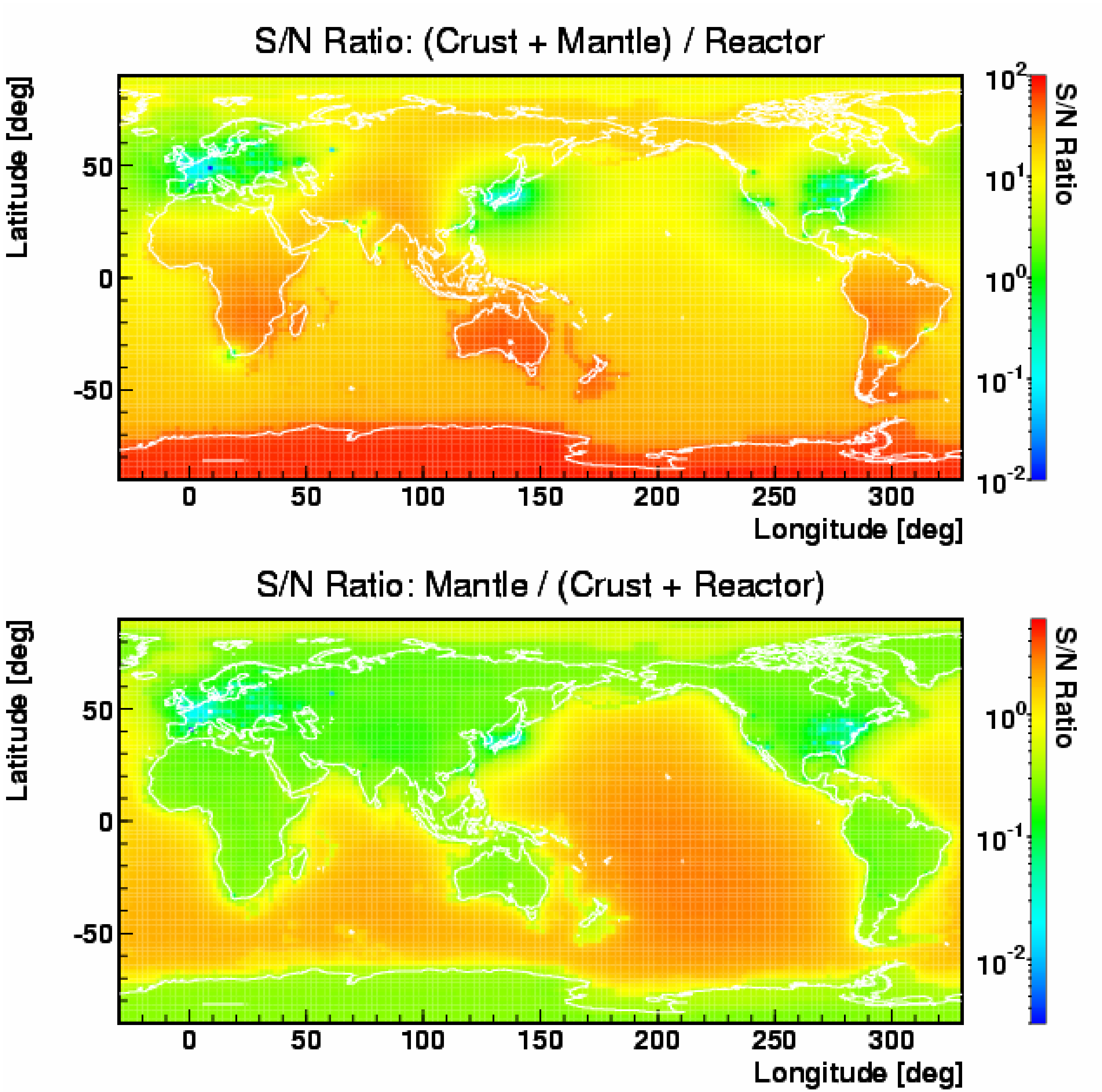
from Mantle
~10 /10^{32}P/year

Reactor Neutrino Backgrounds

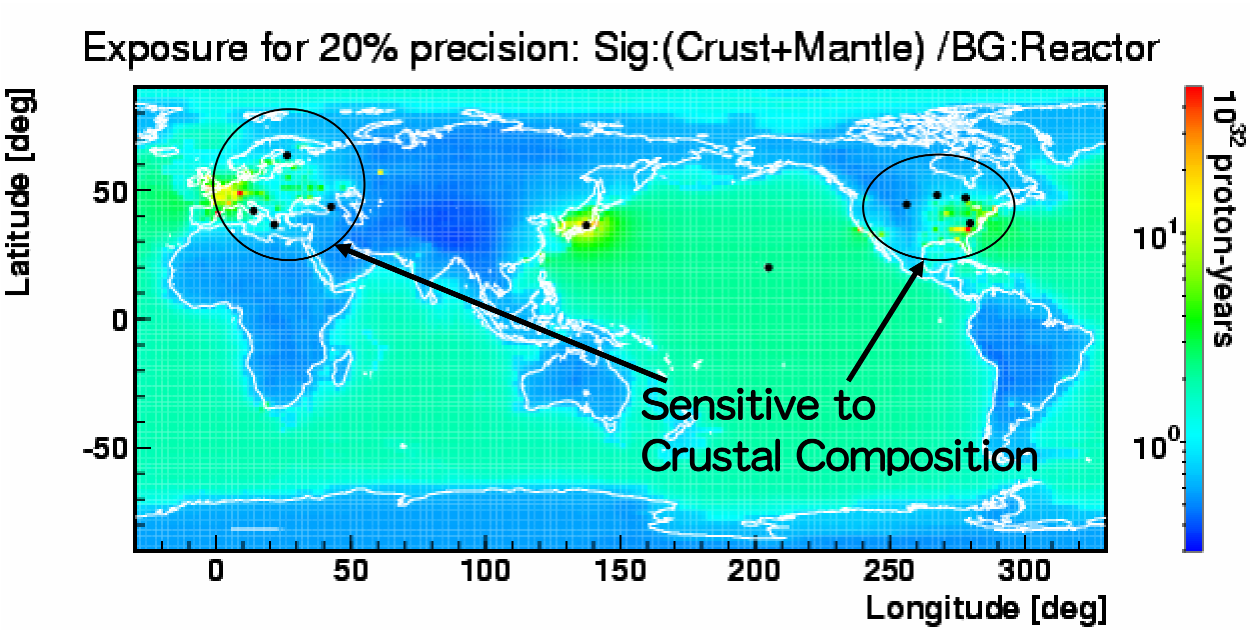


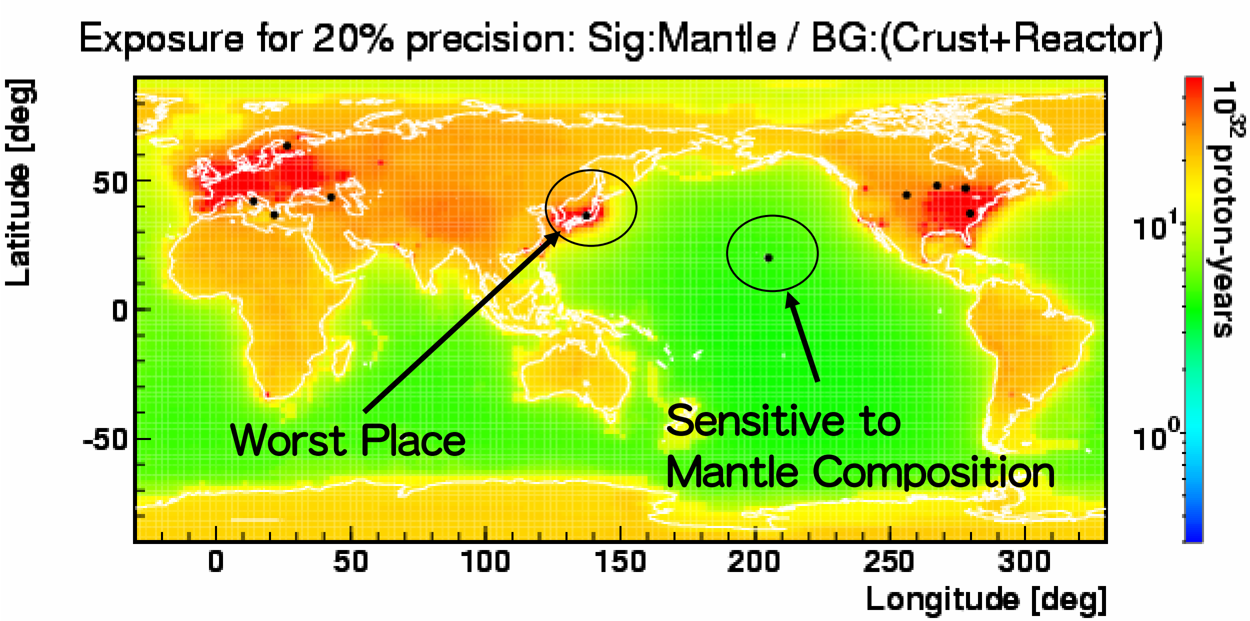


The World Map of Geoneutrino S/N Ratio



Required Exposure for 20% precision determination





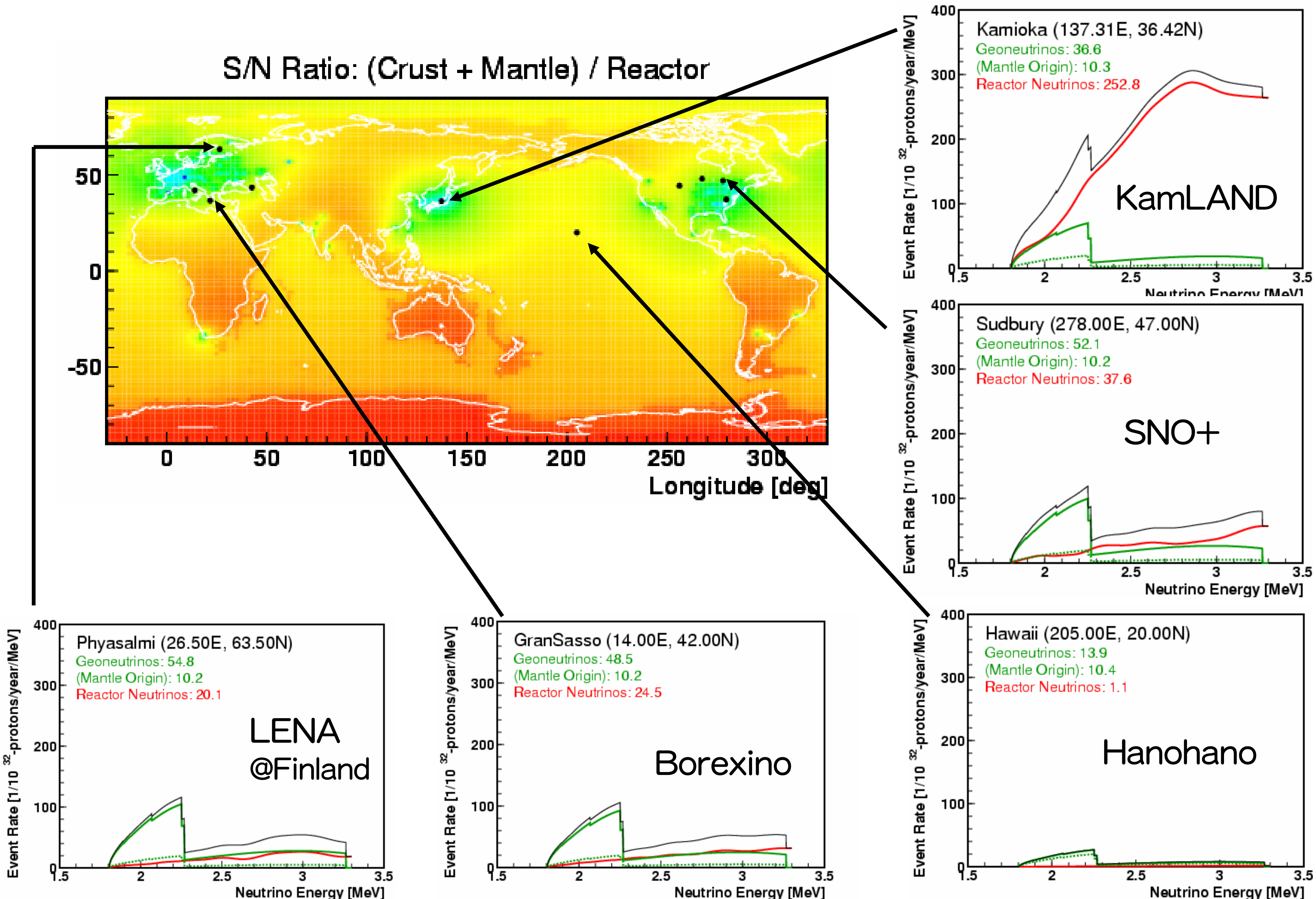
Typical Time

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

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

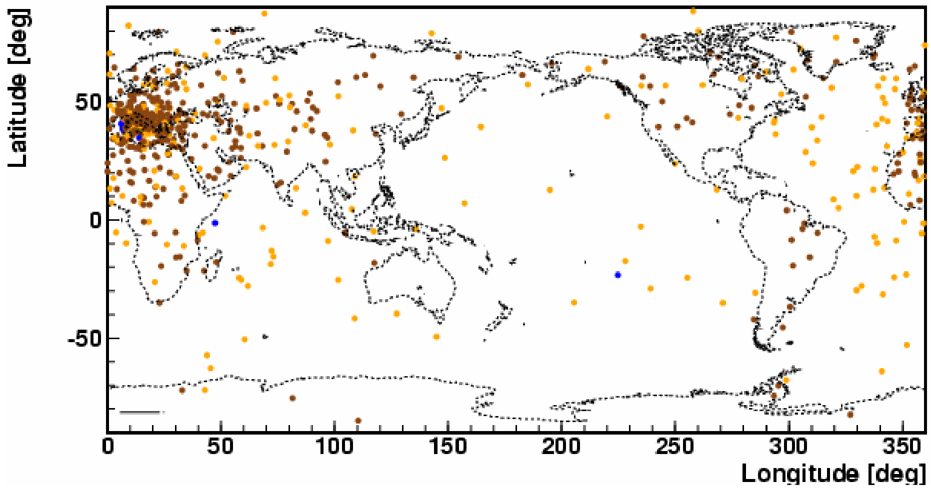
on OC, estimate M
4.5 [10^{32}P • year]

Geoneutrino Flux @ Future Detector Sites

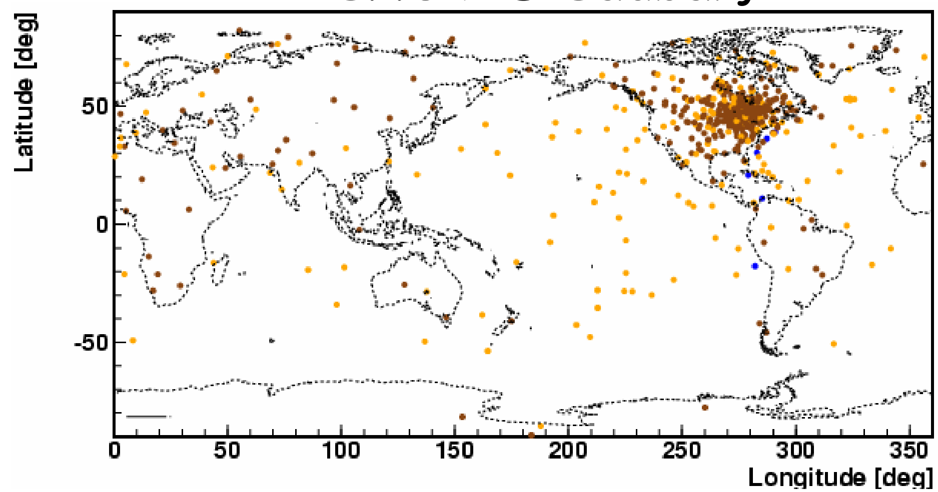


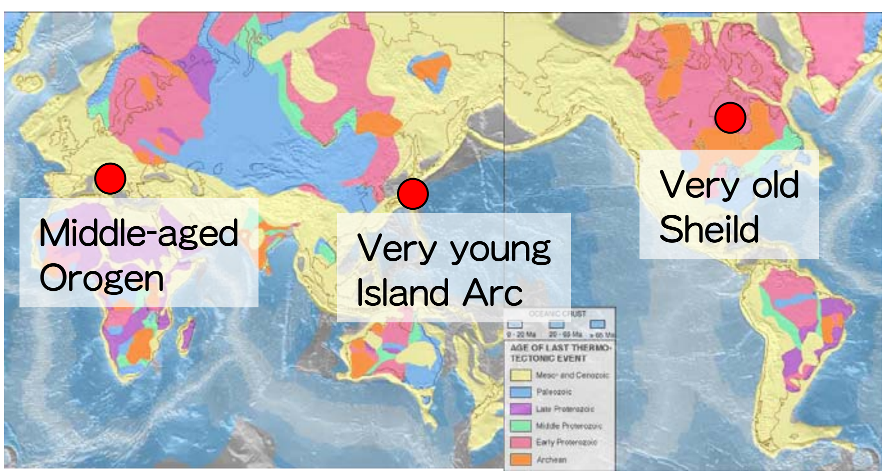
KamLAND, Borexino and SNO+: Crustal Neutrino Probing

Borexino @ Gran Sasso

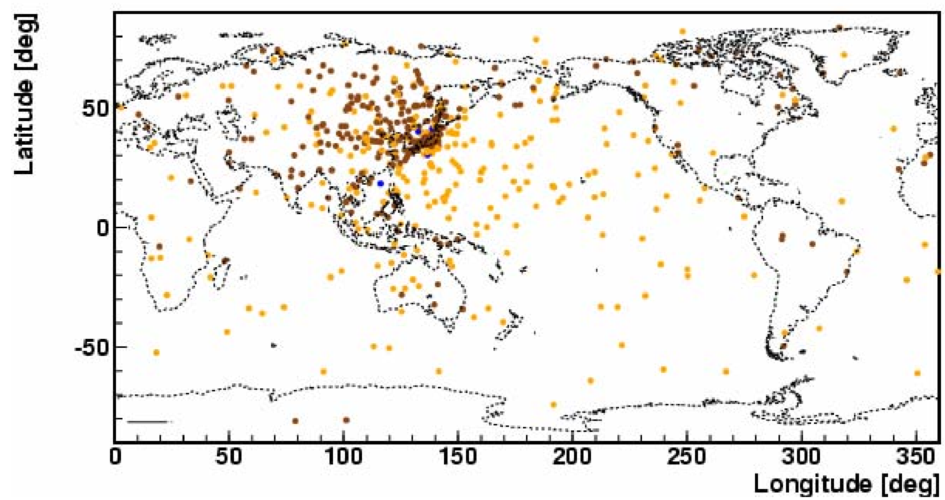


SNO+ @ Sudbury



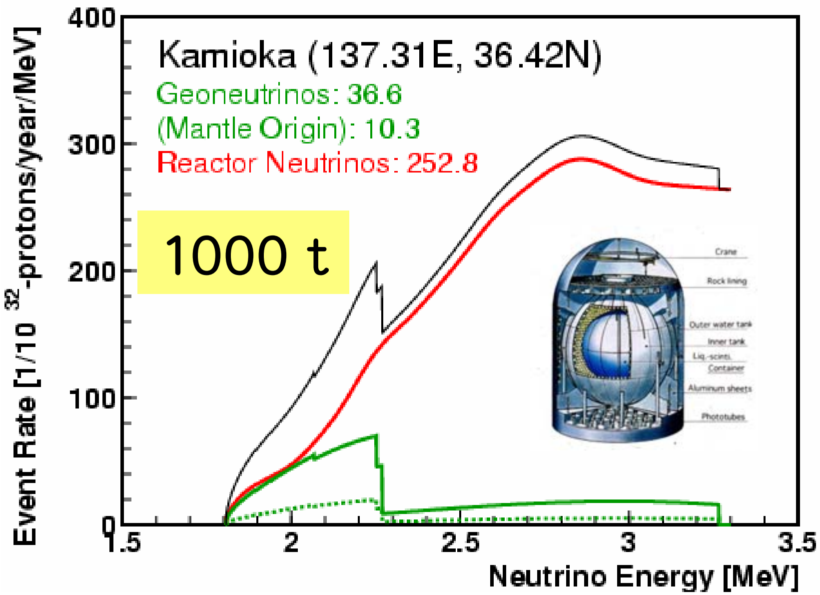


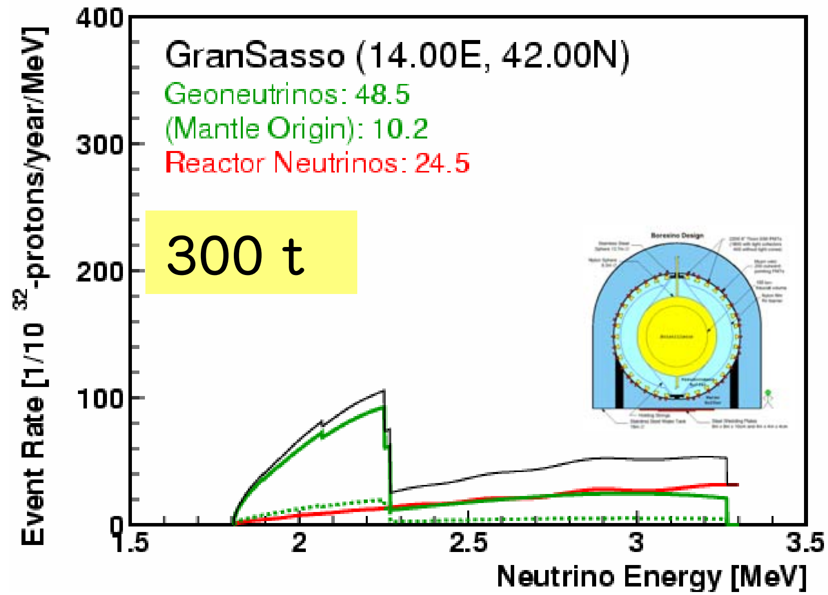
KamLAND @ Kamioka

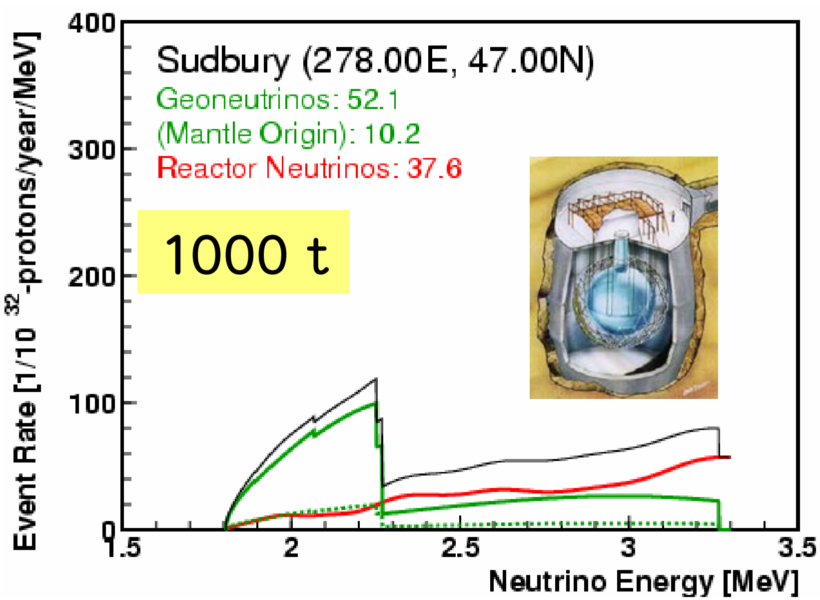


Different type / age of crusts ⇒ key to understand planetary evolution

Sensitivity (S/N) Comparison



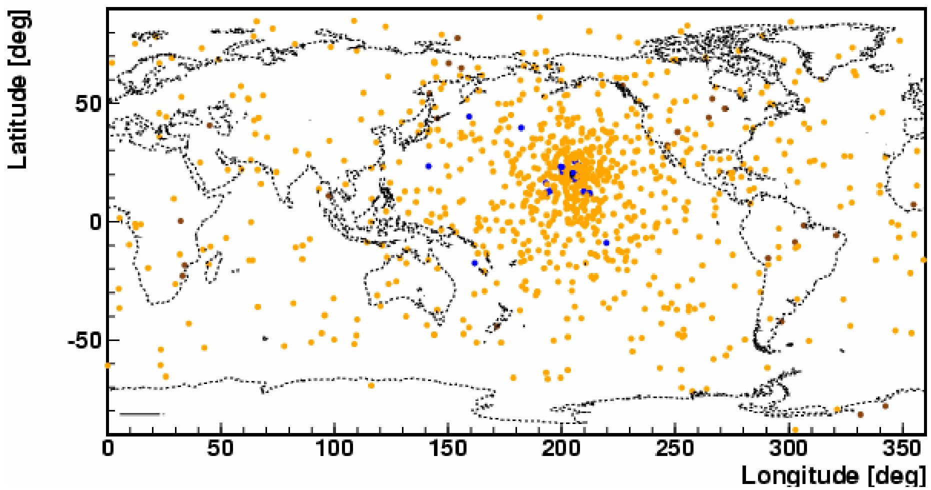


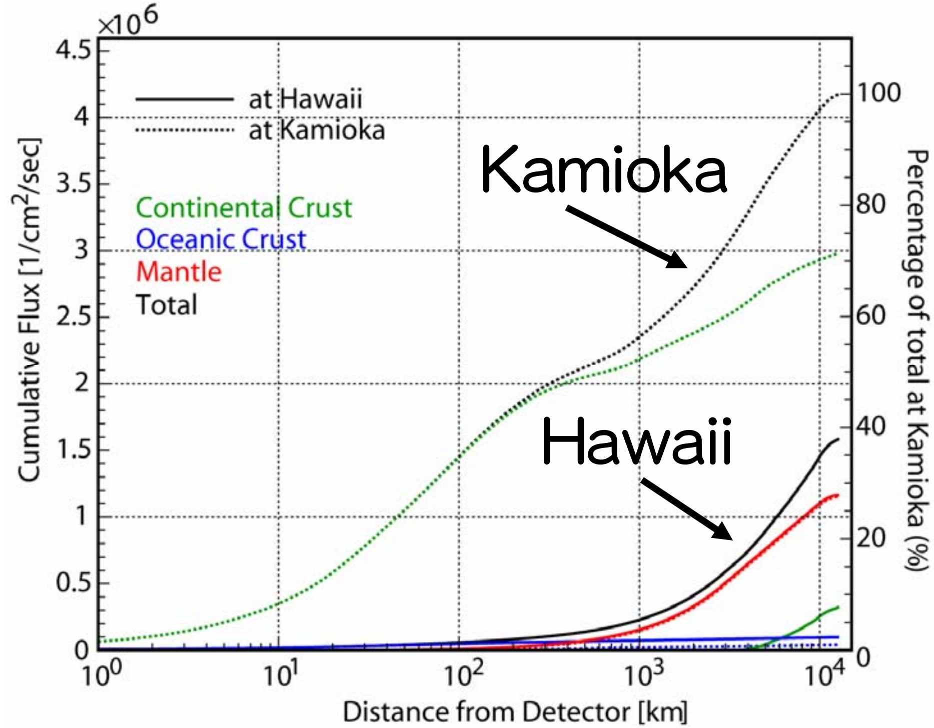


Time to reach 20% precision with simple rate analysis
(efficiency / FV fraction NOT considered)

	Crust	Mantle
KamLAND	12 y	161 y
Borexino	4.2 y	131 y
SNO+	1.4 y	96 y

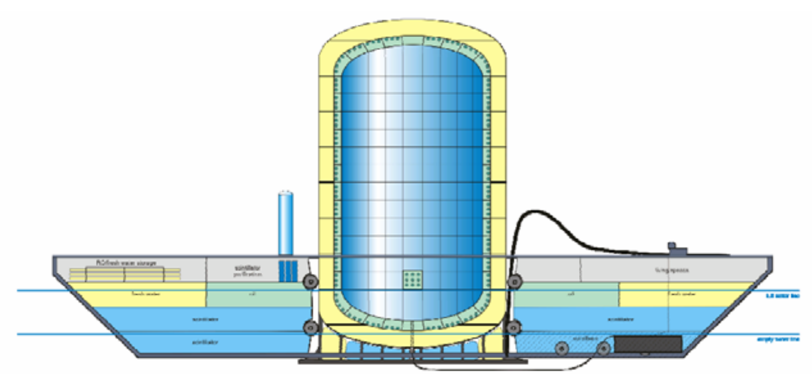
Future 1: Mantle Neutrino Probing (Hanohano)





Hawaii Antineutrino Observatory
(Hanohano)

- ＞ 10 kton LS detector
- Mobile, sinkable and retrievable

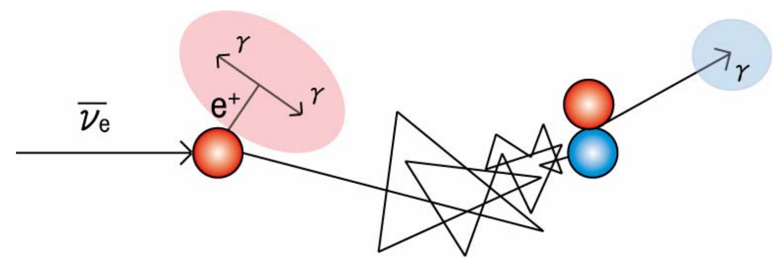


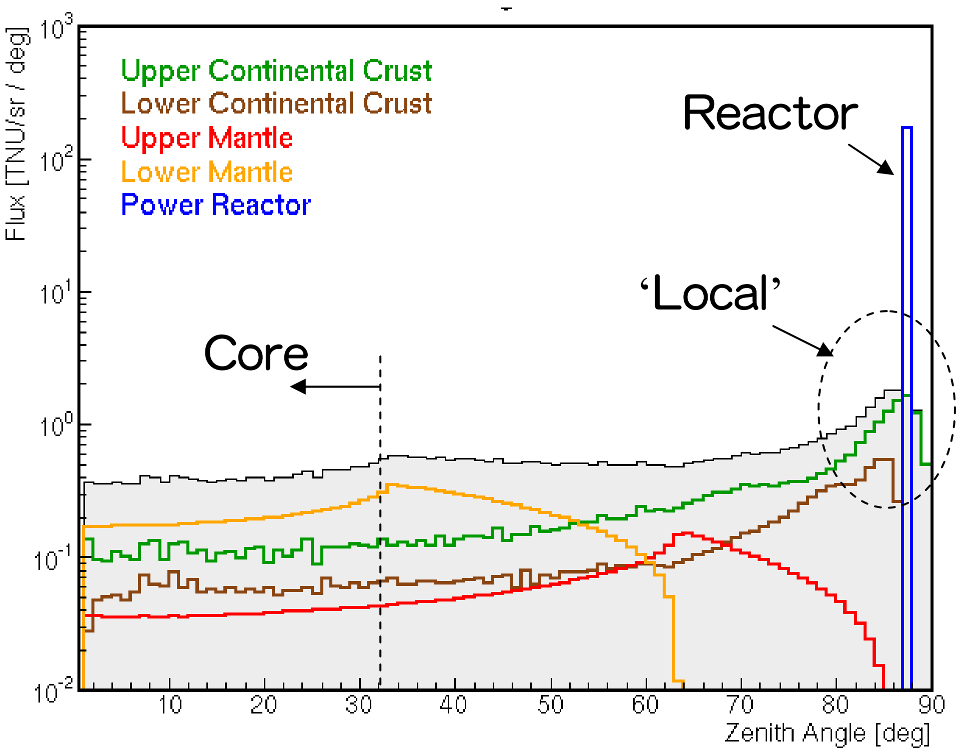
- 75% from Mantle
- 50% from Lower Mantle
- No Reactor BG
- Simple local geology

Far Future Dreams: Directional Sensitivity

- Mantle under continental crust
- Core / Mantle separation
- Rejection of reactor BG
- Local geology separation
- Earth tomography ??

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





Recoiled neutron remembers direction

Problems:

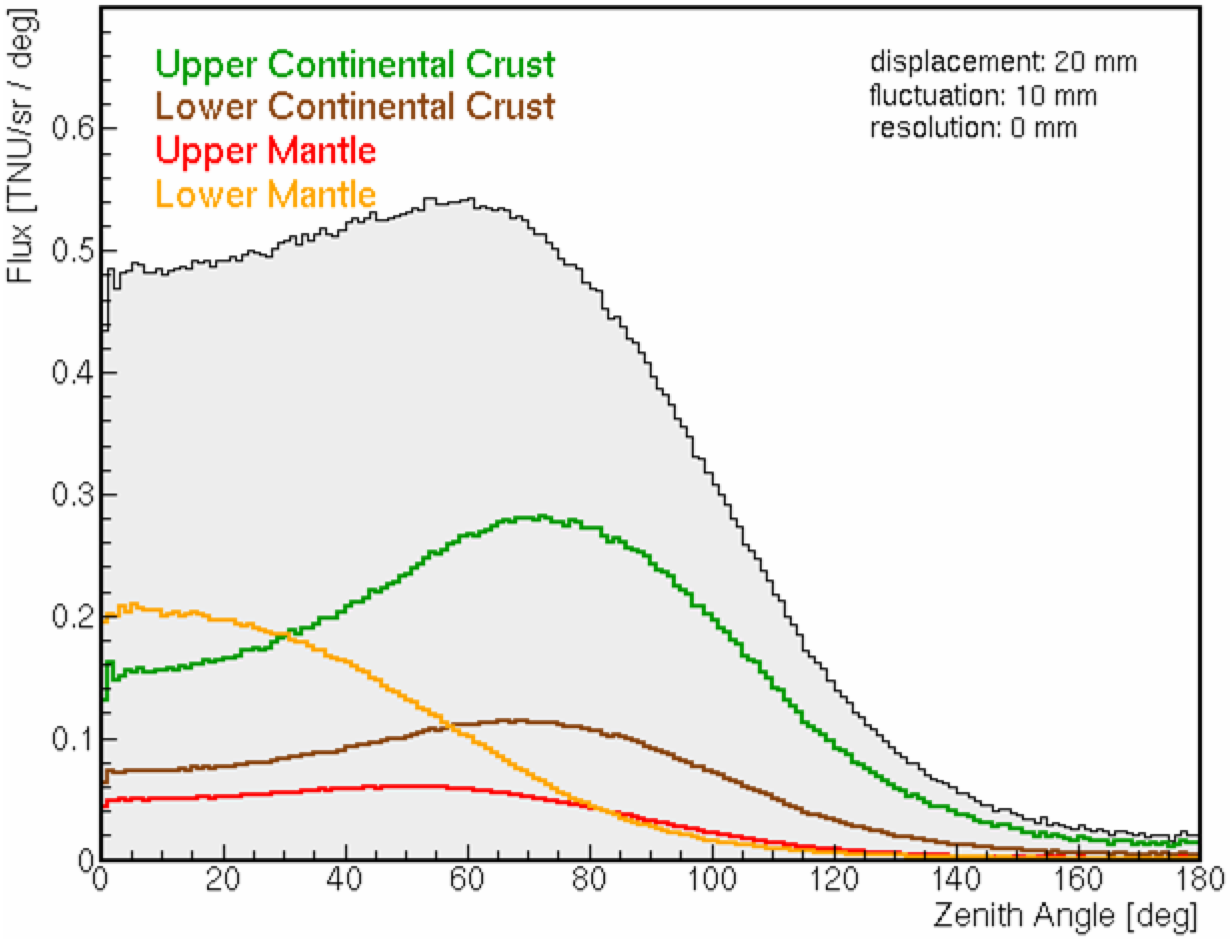
- Thermalization blurs the info
- Gamma diffusion spoils the info
- Reconstruction resolution is too poor

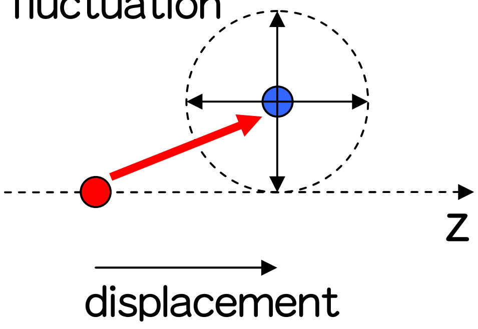
Wish List:

- large neutron capture cross-section
- (heavy) charged particle emission and
- good resolution detector (~1cm)

LS Directionality and Geoneutrinos

If we achieve
- 20 mm vertex displacement
- 10 mm vertex fluctuation
- Perfect resolution (≪~10mm)



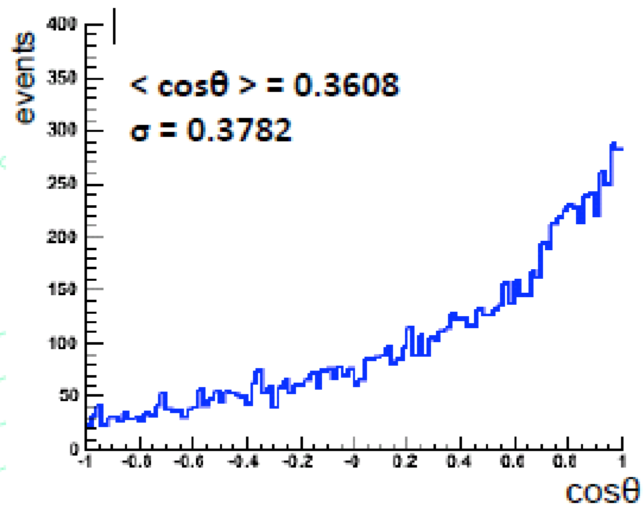


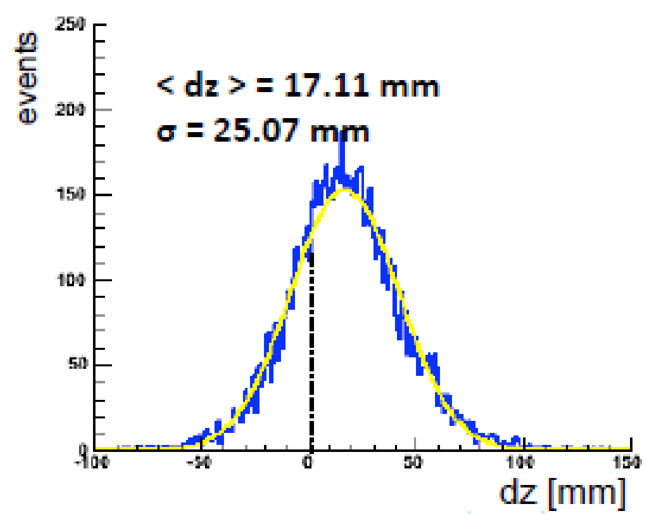
Towards Directional Sensitivity 1

^{6}Li loading helps preserving directional information

- Large neutron capture cross-section: 940 barn
- ^{6}Li + n → α + T : no gamma-ray emission
- Natural abundance 7.59%, enrichment possible

Li 2.0 wt% (^{6}Li 0.15wt%) Angular Resolution (MC)





LS development at Tohoku U. (under progress)

PC + PPO + POE + LiBr + H_2O (POE: surfactant)

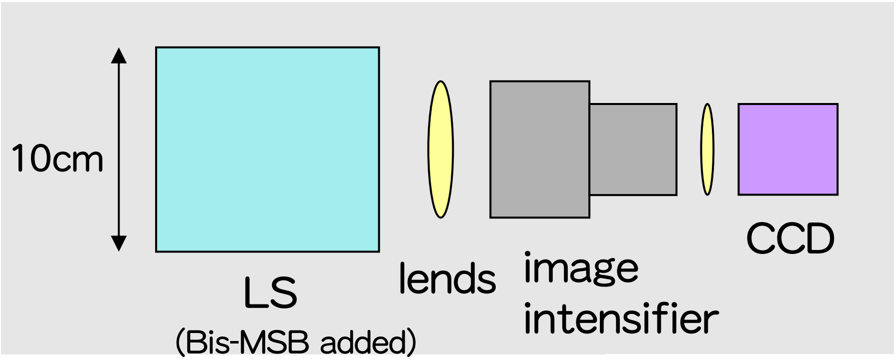
0.8 wt% Li,
transparency 65cm@400nm, light yield 45% KamLAND LS

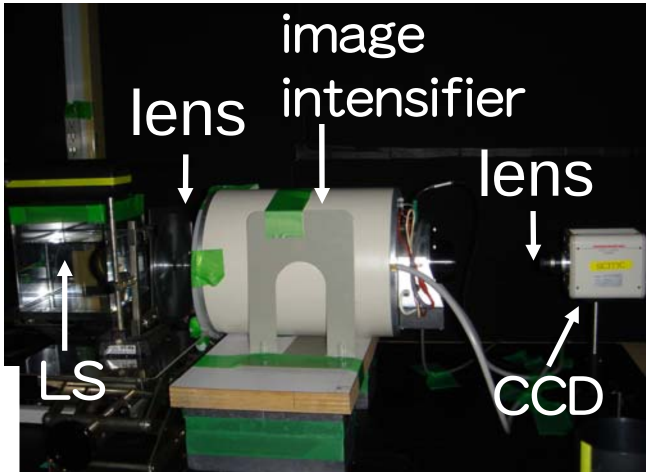
Towards Directional Sensitivity 2

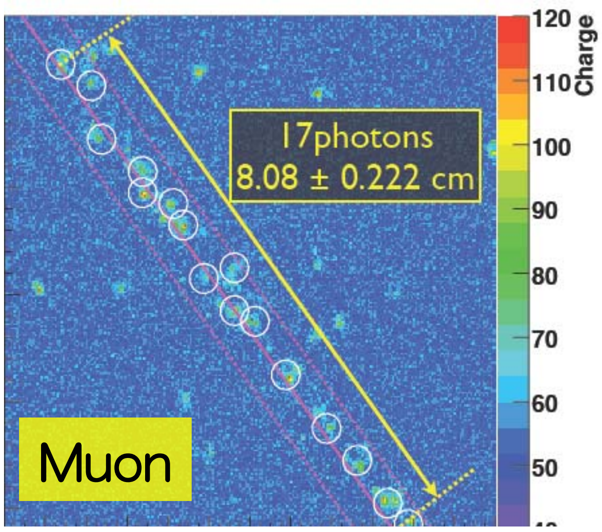
~1M pixel imaging can achieve 1 cm resolution

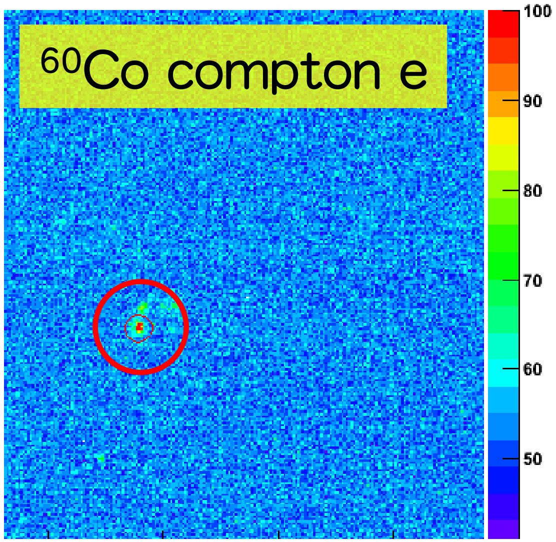
- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging…(150cc test bench at Tohoku U.)







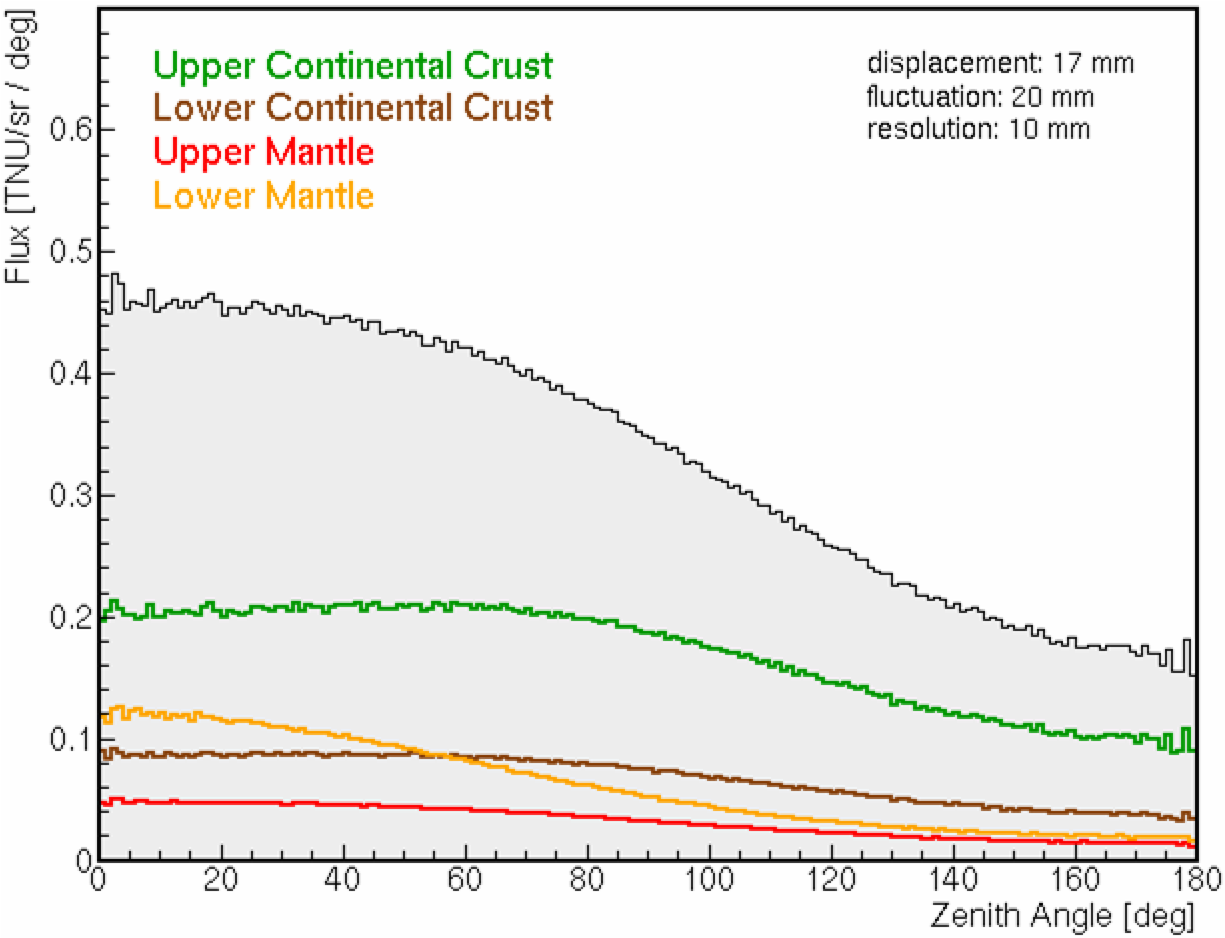


Directionality: Current Achievement (Tohoku U.)

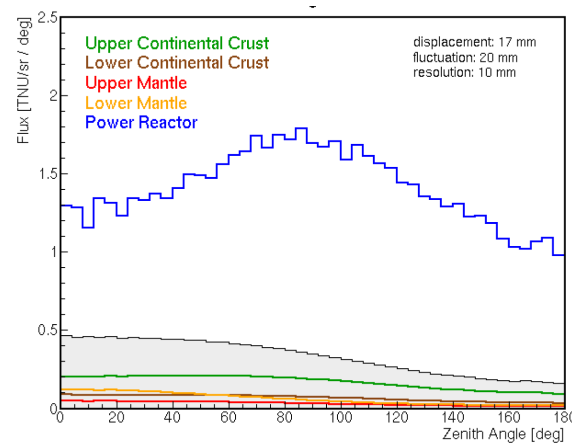
- 17 mm vertex displacement
- 20 mm vertex fluctuation
- 10 mm resolution

Li loading:
- 0.8 wt% Li
- Transparency 65 cm @ 400 nm
- Light yield 46% of KamLAND LS

Optics
- 150cc test bench / CCD & II



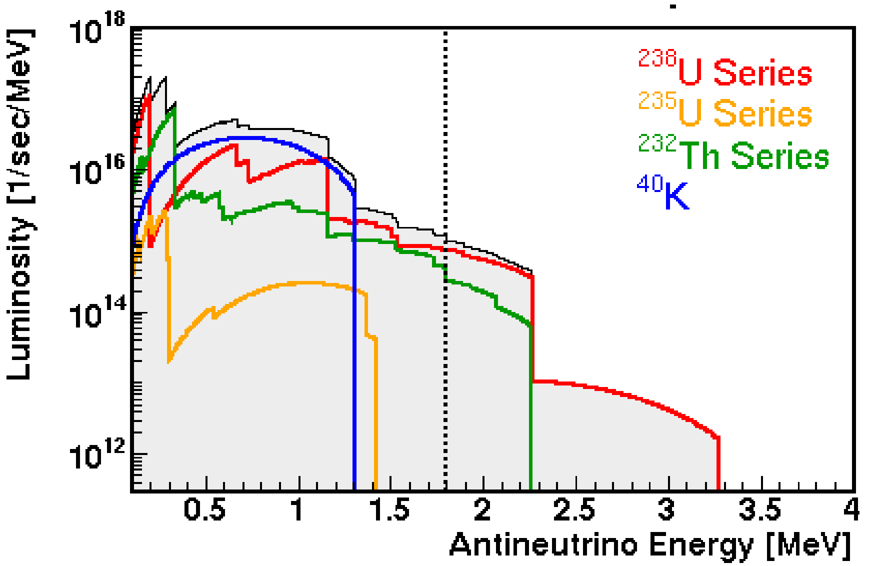
Reactor BG
@ Kamioka



More info extracted from:
- horizontal distribution
- energy spectrum
- time variation

^{40}K Neutrino Detection

- Emax : 1.31 MeV
  (inverse β minimum: 1.02 MeV)
- Overwhelmed by solar neutrinos
  (inverse β might be only way)



Low Q_β, low *ft* isotopes searched…

	Natural Abundance	Ethresh [MeV]	Amount for ~100 ev/yr
^{187}Os	1.6%	1.025	16 Gton
^{3}He	<0.01%	1.041	7.4 ton
^{107}Ag	51.8%	1.055	1.7 Gton
^{151}Eu	47.8%	1.098	680 kton
^{93}Nb	100%	1.114	6.8 Gton
^{171}Yb	14.3%	1.119	98 kton
^{14}N	99.6%	1.179	98 Mton
^{79}Br	50.7%	1.181	2.1 Gton
^{35}Cl	75.8%	1.190	4.9 Mton
^{135}Ba	6.6%	1.227	470 Gton
^{155}Gd	14.8%	1.268	550 Mton
^{33}S	0.76%	1.271	14 kton
^{106}Cd	1.2%	1.216	~10 kton

Kobayashi et al, Geophys.Res.Lett. 18, 633 (1991)

Chen, Neutrino Science 2005

Summary

- Geoneutrinos provide with a direct measurement of heat producing elements (HPE)
- Geoneutrinos are chemical probe to deep Earth

- KamLAND currently 2 σ, 4 σ expected in 2y
- Borexino operational (2y), SNO+ soon

- Future Dreams:
  - Oceanic Detector / Mobile Detector
  - Multiple Site / Large Detector
  - Directionality
  - ^{40}K Neutrino Detection
  - …