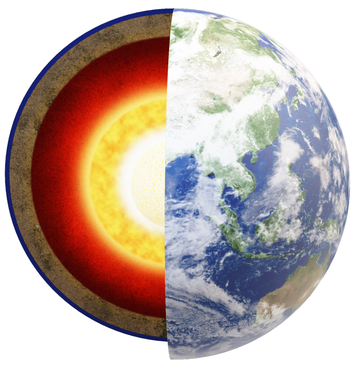
Validation of earth models by measuring geoneutrino fluxes

Tokyo University of Science　Ryoya Tamura　Hideyuki Suzuki

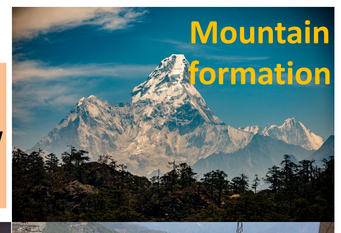
1. Introduction

Heat flow from the ground surface

46 ± 3 TW



Large reactor for power generation of 1 million kW 16,000 units



Understanding geothermal energy is an important issue

Earth's radioactive decay

$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6e^{-} + 6\,\bar{\nu}_e + 51.7$ MeV　(α-ray, β-ray, neutrino)

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

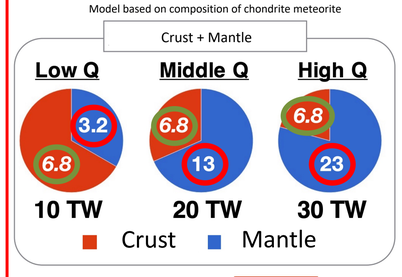
$^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e + 1.311$ MeV

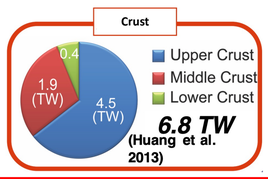
$^{40}K + e^{-} \rightarrow {}^{40}Ar + \nu_e + 1.505$ MeV

Analyzing Radioactive Materials in the Earth's Interior Leading to an understanding of geothermal heat

Bulk Silicate Earth (BSE) models

Model based on composition of chondrite meteorite





Heat flow from the ground surface

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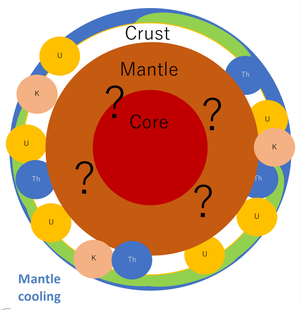
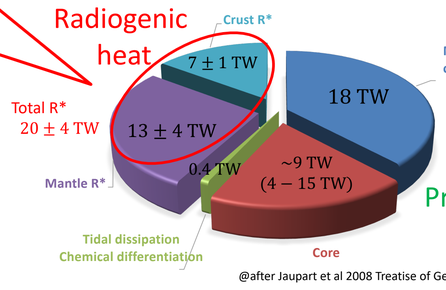


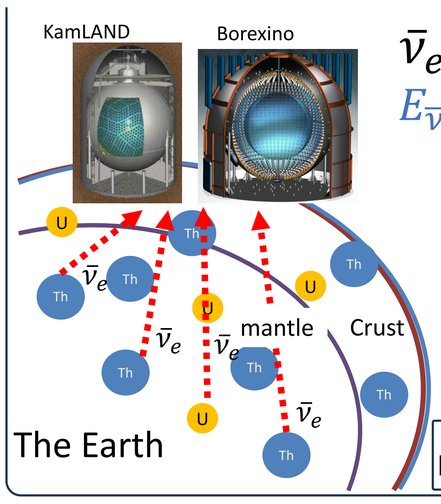


@after Jaupart et al 2008 Treatise of Geophysics

Example of heat flow breakdown (Middle-Q model)

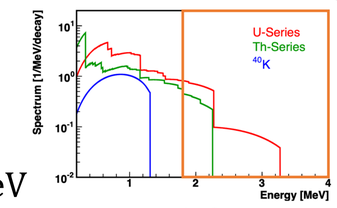
2. Method

Observation Methods

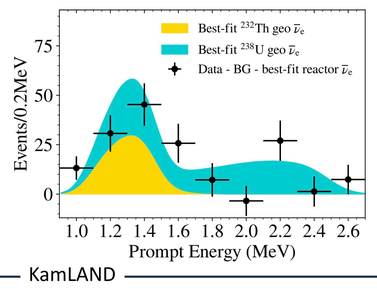


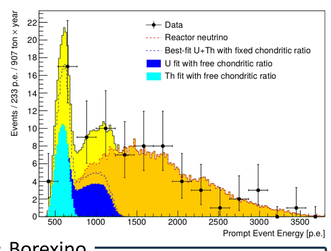
$\bar{\nu}_e + p \rightarrow n + e^{+}$

$E_{\bar{\nu}_e}$　1.3 MeV　0.5 MeV



$E_{\bar{\nu}_e} > 1.8$ MeV





KamLAND		Borexino	
$[\mathrm{cm^{-2}s^{-1}}]$	$3.4^{+0.8}_{-0.8}\times10^{6}$ (Th/U=3.9)	$4.4^{+0.8}_{-0.8}\times10^{6}$ (Th/U=4.3)	$5.3^{+1.1}_{-0.7}\times10^{6}$ (Th/U=3.9)	$6.8^{+1.1}_{-0.7}\times10^{6}$ (Th/U=4.3)

Calculation Methods

$$\Phi_i(\vec{r}) = A_i \cdot n_i \int \frac{a(\vec{r'})\rho(\vec{r'})}{4\pi|\vec{r} - \vec{r'}|^2} P(|\vec{r} - \vec{r'}|) d^3\vec{r'} \quad (i : U, Th)$$

@S.Enomoto et al. (2007)

$\vec{r}$: Location of observers

KamLAND (North latitude 36.43°、East longitude 137.31°、Sea level 358m)

Borexino (North latitude 42.45°、East longitude 13.58°、Sea level 900m)

A_i :Decay rate per unit mass of U and Th

$A_U = 1.24 \times 10^{7}\ \mathrm{s^{-1}\,kg^{-1}}$, $A_{Th} = 4.06 \times 10^{7}\ \mathrm{s^{-1}\,kg^{-1}}$

n_i : Number of neutrinos emitted during decay

$n_U = 6$, $n_{Th} = 4$

$P(|\vec{r} - \vec{r'}|)$:Survival probability due to neutrino oscillation after migration

$P \cong 0.554$ — A global calculation would approximate this value @Abe,S et al. (2022)

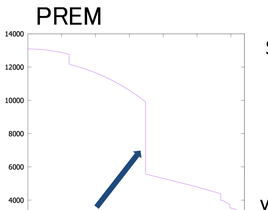
$\rho(\vec{r'})$:Density [kg/m³]

$a(\vec{r'})$: Ratio of mass of U , Th to unit mass（Concentrations）

$\rho(\vec{r'})$:Density

CRUST1.0 for surface to crust and PREM density data for mantle to core

CRUST1.0



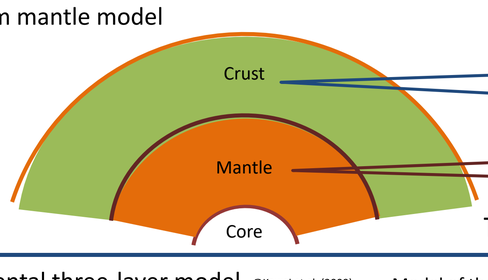
Eight regions of the Earth's interior, divided by depth

- water: upper sediments / middle sediments / lower sediments
- ice: upper crust / middle crust / lower crust

PREM

Spherically symmetric density data that depends only on the distance from the center of the earth, studied using seismic velocities in the earth's interior

Uniform mantle model



Model of the Earth's crust

Enomoto model (high concentration) @Enomoto et al. (2005)	Huang model (low concentration) @Huang et al. (2013)

Model of the Earth's mantle

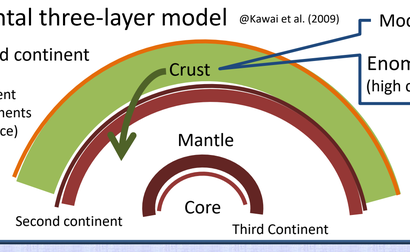
Enomoto model (high concentration) / Huang model (low concentration)

Low-Q、Middle-Q、High-Q model

Total 8 models

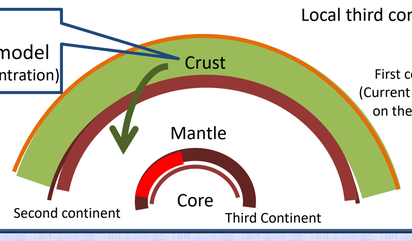
Continental three-layer model @Kawai et al. (2009)

Unified third continent



Model of the Earth's crust: Enomoto model (high concentration) / Huang model (low concentration)

Local third continent



Total 4 models

3. Result

Uniform mantle model

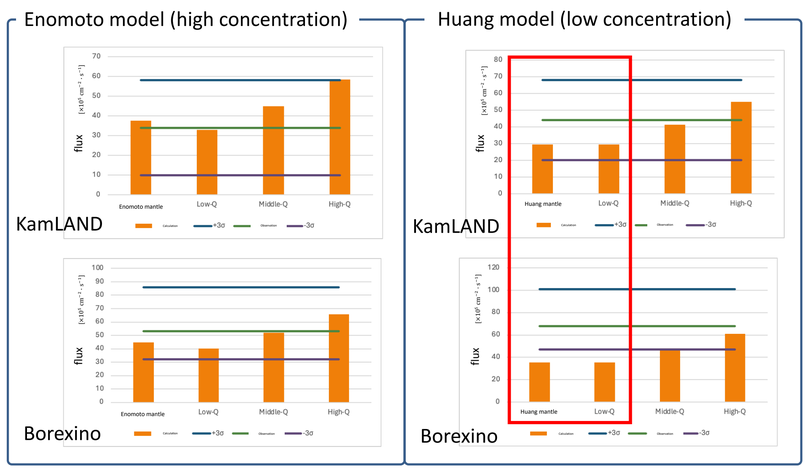
Models

Crust : Huang
Mantle : Huang

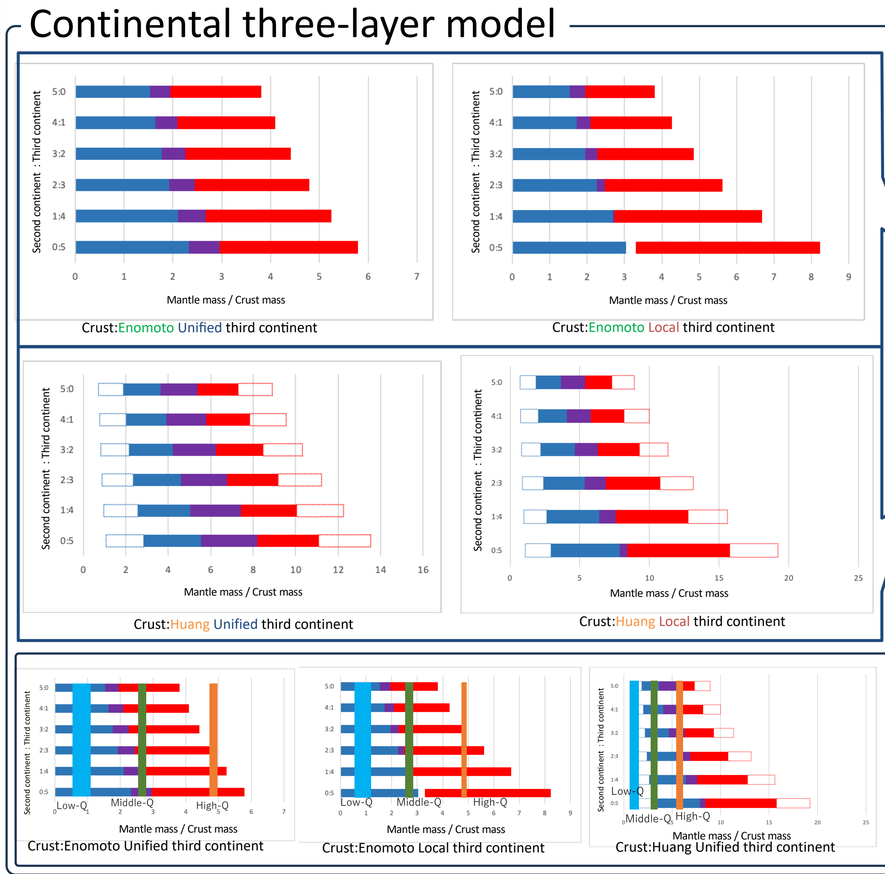
And

Crust : Huang
Mantle : Low-Q

were found to be unsuitable 99.76% of the time



Continental three-layer model



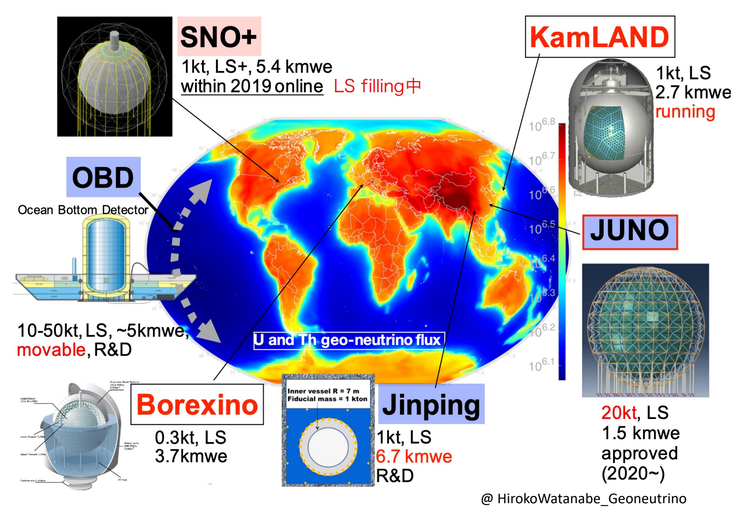
Blue : KamLAND
Red : Borexino
Purple : Fitting from two observers

Crust : Enomoto model
Mantle mass / Crust mass
About 1.5~3.0 times
Uncertainty calculated at 1 sigma

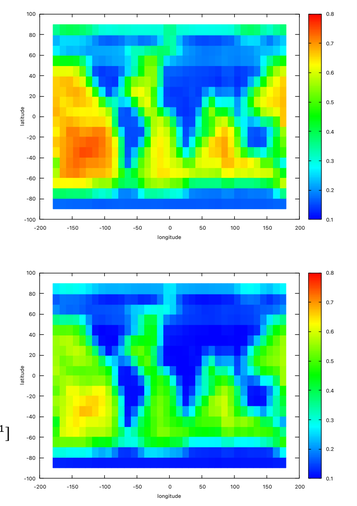
Crust : Huang model
Mantle mass / Crust mass
About 3.4~8.4 times
Uncertainty calculated at 2 sigma

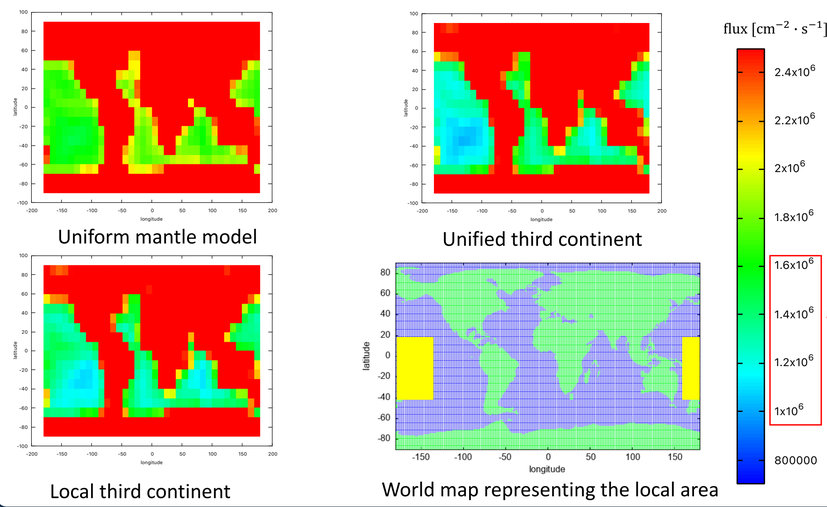
Correspondence of heat content to model

Geoneutrino Observation Location



Observing Geoneutrinos in the oceans makes mantle models easier to understand





It was found that the model could be restricted if Geoneutrinos could be observed with an accuracy of $\sim 10^{5}\ \mathrm{cm^{-2}s^{-1}}$

4. Summary

Conclusion

- In the uniform mantle model, the crust:Huang, mantle:Low-Q model is found to be inadequate 99.76% of the time.
- In the continental three-layer model, we find a model consistent with the KamLAND and Borexino observations.
- It was found that the model could be restricted if the Earth neutrinos could be observed offshore in the Pacific Ocean with an accuracy of $\sim 10^{5}\ \mathrm{cm^{-2}s^{-1}}$.

Future Challenges

- When observational data other than KamLAND and Borexino are gathered It is necessary to consider a model that is consistent with the observed data.