Geoneutrino Flux From Earth's Mantle And Its Detectability

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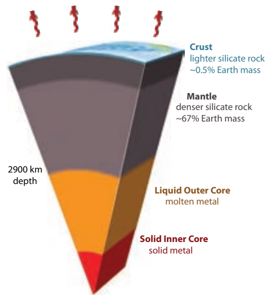
1. Earth Structure And Present-Day Energy Budget

Earth loses heat at a rate of **46±3 TW** [1],
which includes **heating by long-lived radioactivity** (^{238}U, ^{232}Th, ^{40}K),
and **primordial heat** remnant after accretion and core–mantle differentiation.



How much radiogenic heating?

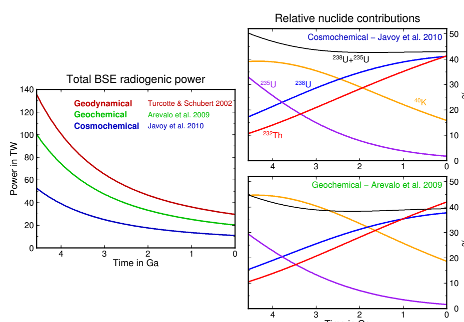
Most likely **no U/Th/K in the core**.

Bulk Silicate Earth ("primitive mantle") compositional estimates [2]:

"Cosmochemical" BSE: 11±2 TW
based on enstatite chondrite composition (also "collisional erosion" model)

"Geochemical" BSE: 20±4 TW
measured rock sample abundances + C1 chondritic RLE ratios

"Geodynamical" BSE: 33±3 TW
parameterized thermal evolution models



Radioactivity in the highly enriched **Continental Crust** accounts for **7.8±0.9 TW**.

Oceanic Crust only outputs 0.21±0.02 TW.

(Calculated from abundances of refs. [3, 4, 5] and CRUST2.0 crustal structure.)

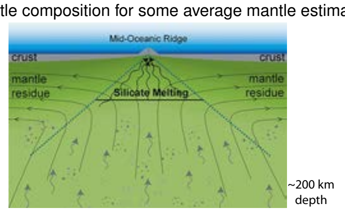
Average mantle ("= BSE − Crust") abundances account for **1 to 28 TW**:

"Cosmochemical" mantle: 3±2 TW

"Geochemical" mantle: 12±4 TW

"Geodynamical" mantle: 25±3 TW

Compositional estimates for **shallow mantle** ("depleted mantle"), based on analysis of basalts erupted at mid-oceanic ridges, suggest heterogeneity in mantle composition for some average mantle estimates.



We use three depleted mantle (DM) compositional estimates,
"low" [6], "medium" [7], and "high" [8] in terms of U+Th abundances [2].

Fundamental questions:

- How much radioactivity is there in Earth's mantle? OR more broadly: What is Earth made of?
- How is mantle radioactivity spatially distributed? Is the mantle compositionally uniform? layered? 3-D compositional structures?

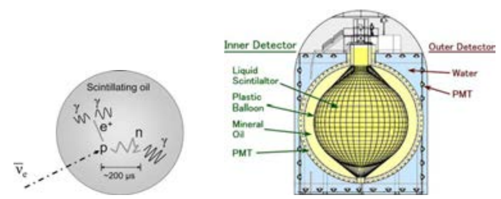
Crucial for understanding the power available for mantle convection & plate tectonics, Earth's thermal history, planetary accretion.

2. Geoneutrinos

Electron anti-neutrinos ($\bar{\nu}_e$) emitted in β-decays of natural radionuclides.

$$\begin{aligned}
{}^{238}_{92}\mathrm{U} &\longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV},\\
{}^{235}_{92}\mathrm{U} &\longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\,\mathrm{MeV},\\
{}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\,\mathrm{MeV},\\
{}^{40}_{19}\mathrm{K} &\xrightarrow{89.3\,\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV},\\
{}^{40}_{19}\mathrm{K} + e &\xrightarrow{10.7\,\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\,\mathrm{MeV}.
\end{aligned} \tag{1}$$

The higher energy geoneutrinos from ^{238}U and ^{232}Th decay chains detectable with large liquid scintillator detectors using inverse beta decay reaction:
Direct assessment of Earth radioactivity!



To-date detections:
KamLAND (Kamioka, Japan) [9, 10] and **Borexino** (Gran Sasso, Italy) [11]

Combined analysis assuming site-independent mantle flux yields mantle signal of **23±10 TNU** [12]

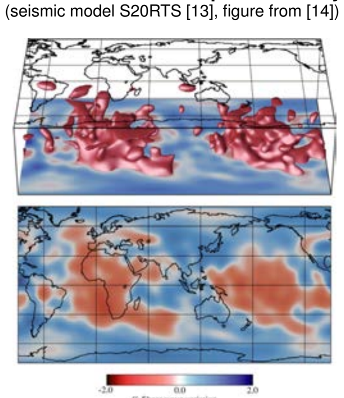
[1 TNU (terrestrial neutrino unit) = 1 event per 10^{32} free protons per year at 100% detection efficiency]

SNO+ (Sudbury, Canada) experiment under construction

Proposed detectors: LENA (Pyhäsalmi, Finland), Homestake (South Dakota), Baksan (Caucasus, Russia), Daya Bay II (China), Hanohano (Hawaii)

3. Seismic Image of the Mantle

Shear-wave seismic speed anomaly
(seismic model S20RTS [13], figure from [14])



Two anomalous structures in deep mantle, below Pacific and below Africa

Character of the anomaly suggests a compositional component.

4. Geoneutrino Flux Predictions (^{238}U + ^{232}Th)

We calculate geoneutrino flux Φ at Earth's surface:

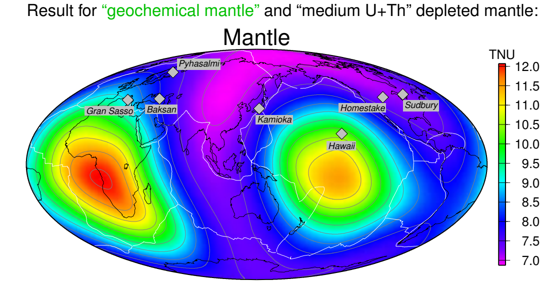
$$\Phi(\vec{r}) = \frac{n_\nu \lambda \langle P \rangle}{4\pi} \int_\Omega \frac{a(\vec{r}')\rho(\vec{r}')}{|\vec{r} - \vec{r}'|^2} \mathrm{d}\vec{r}', \tag{2}$$

where n_ν ... number of antineutrino per decay chain, λ ... decay constant, $\langle P \rangle$ ... average survival probability, a ... radioactive isotope abundance, ρ ... rock density.

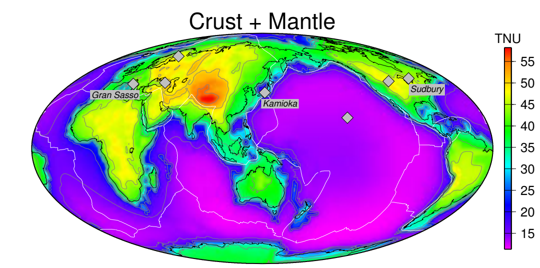
Assumption: seismically imaged deep-mantle structures can be compositionally distinct from ambient mantle.

Abundance of U & Th calculated from available estimates for average mantle and depleted mantle. PREM density used.

Result for "geochemical mantle" and "medium U+Th" depleted mantle:

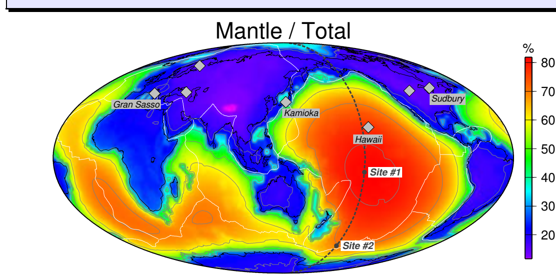


Lateral variation in mantle flux

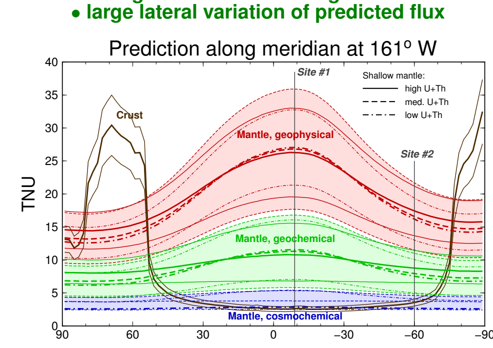


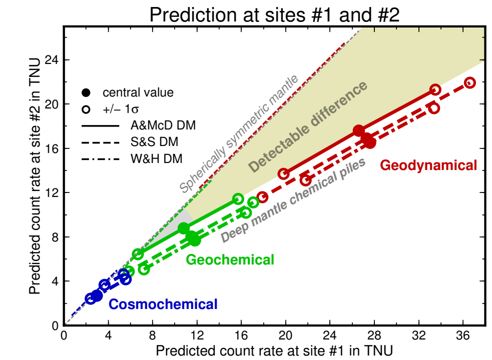
Geoneutrino signal dominated by continental crust

5. Detectability of Mantle Flux



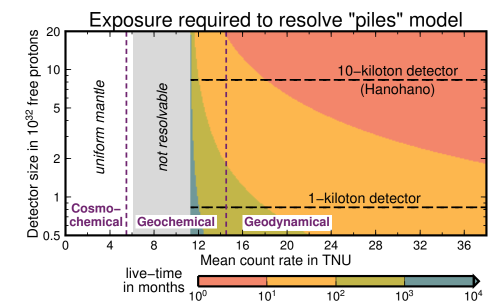
Two detection sites in Pacific basin proposed to benefit from:
- **high mantle-to-crust signal ratio**
- **large lateral variation of predicted flux**





Two- (multiple-) site oceanic measurements can resolve BSE models.

Resolvable difference between uniform mantle and mantle with chemical piles.



Summary

- Detection of geoneutrinos can provide new meaningful constraints on mantle radioactivity.
- New model of geoneutrino emission from Earth's mantle, constrained by geophysics and geochemistry is presented [2].
- Existing compositional estimates result in mantle flux patterns ranging from low-amplitude spatially uniform to high-amplitude laterally variable.
- Predicted lateral variation in mantle flux is resolvable for "geophysical" mantle and the high-abundance end of "geochemical" mantle by a two-site measurement in the Pacific.
- Existing geoneutrino data reject "cosmochemical" BSE model at 1σ level.

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