New technologies provide transformative insights into global geochemistry

Seema Kumari
National Postdoctoral Fellow
Centre for Earth Sciences
Indian Institute of Science, Bangalore

International Symposium, Frontier of Understanding Earth's Interior and Dynamics
Hosted by Tohoku Forum for Creativity

INDIAN INSTITUTE OF SCIENCE
भारतीय विज्ञान संस्थान

TOHOKU FORUM for CREATIVITY

TOHOKU UNIVERSITY

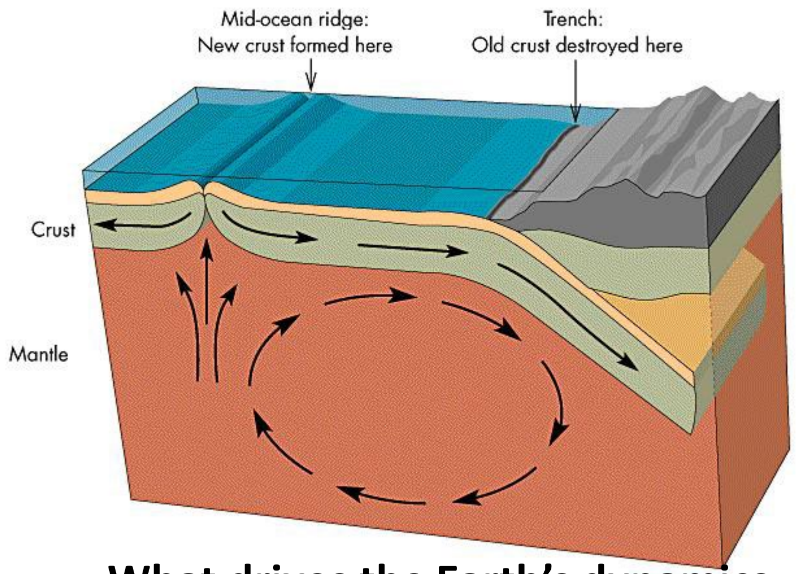
Geoneutrino flux

Defines Radiogenic Power

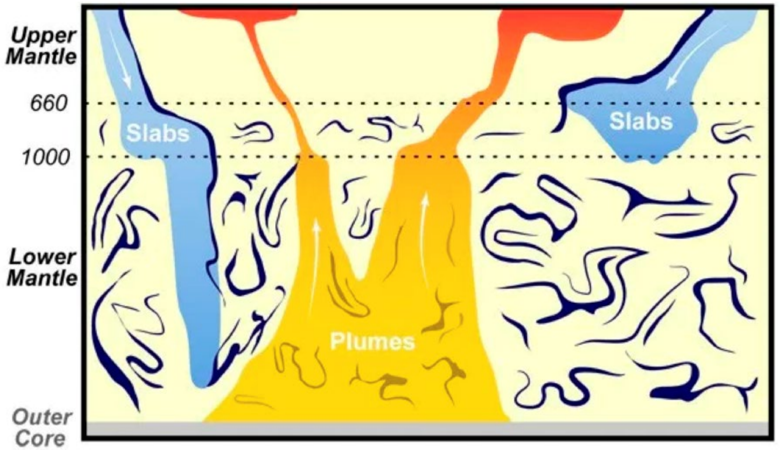
Constrains Bulk Earth Composition

Why Geochemist should care???

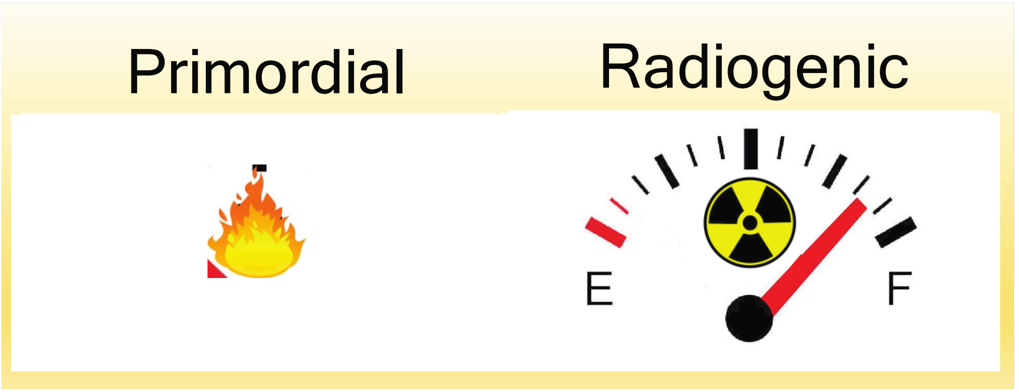
Major Questions



What drives the Earth's dynamics

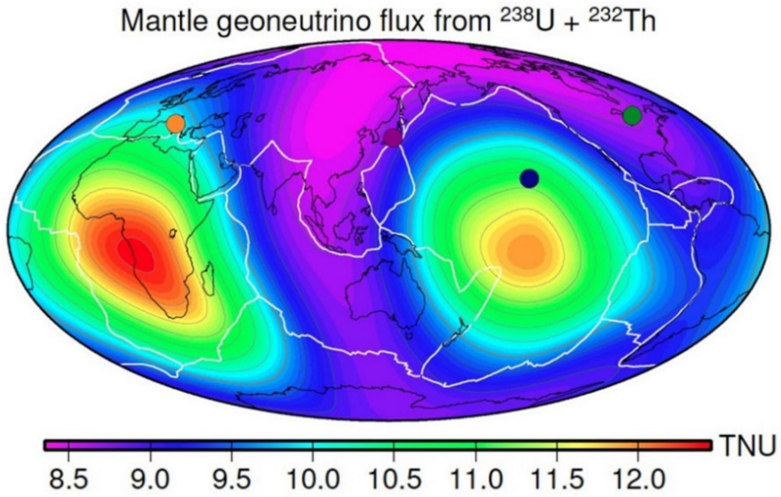


Mantle structures: whole VS layered convection



Current surface heat flux = **46 ± 3 TW**

Earth's radiogenic power



Interdisciplinary approach

Earth's Thermal History

Primordial Heat

- Planetary accretion
- core formation

Radiogenic Heat

- Short-lived isotopic decay, ^{26}Al, ^{60}Fe
- Decay of U, Th, and K

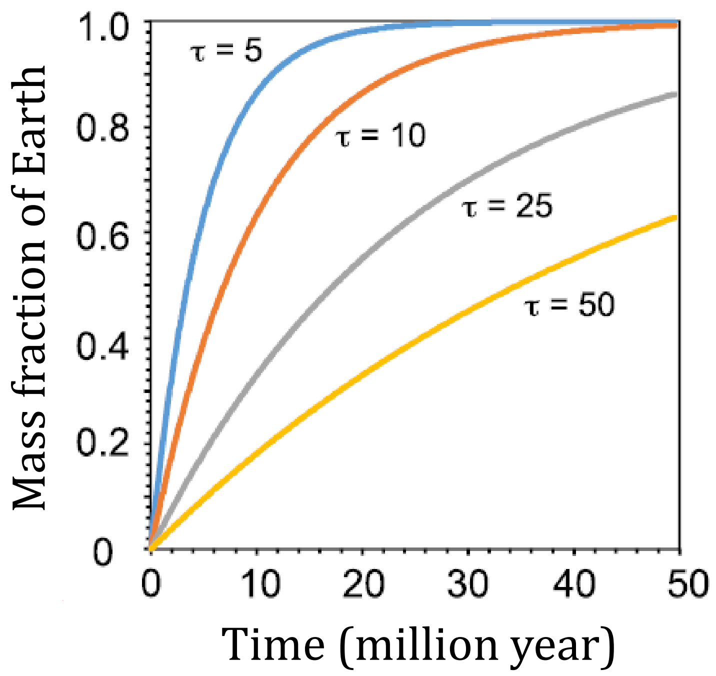
sets the Initial condition

How much fuel is left to drive the plate tectonics ??

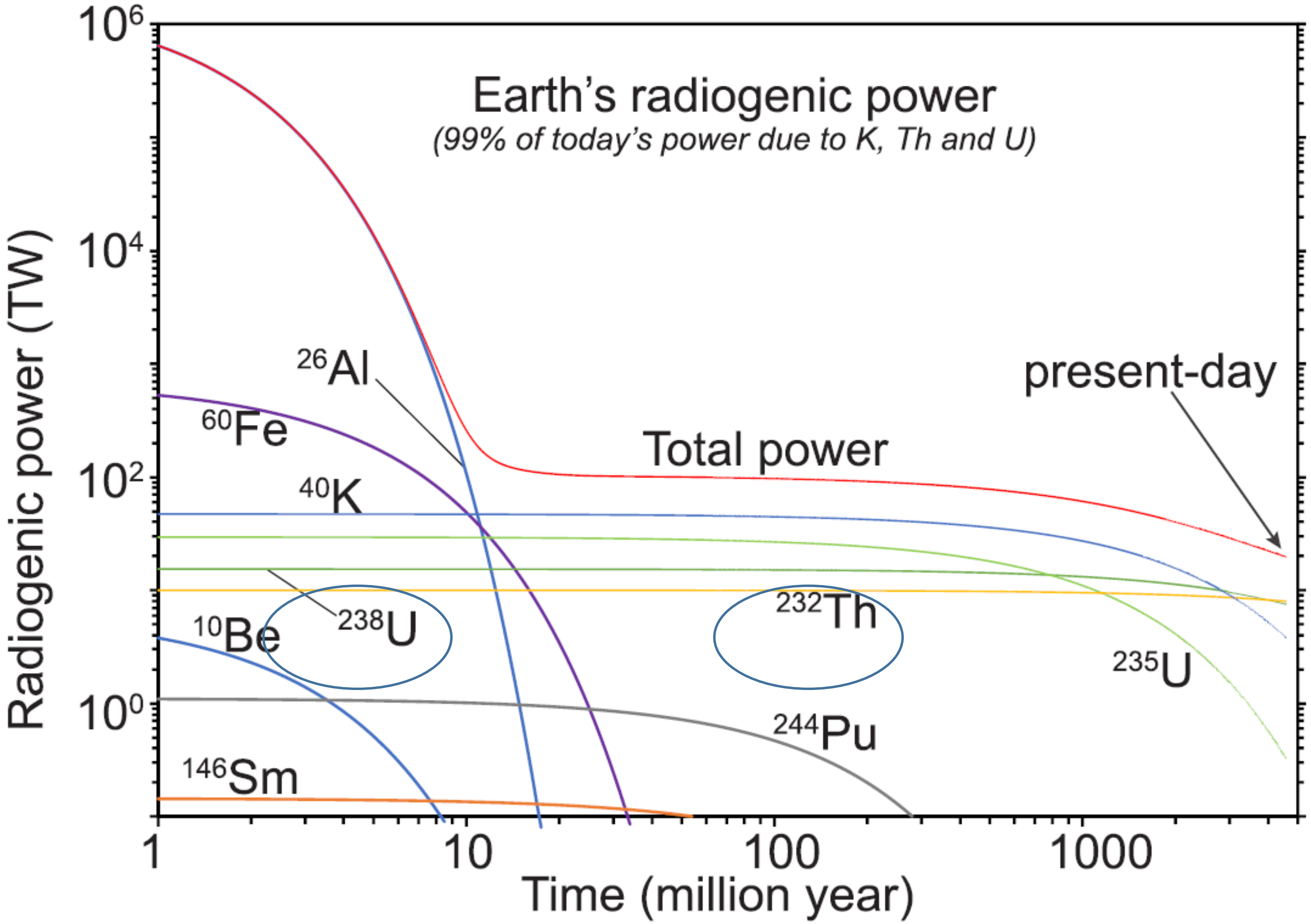
throughout the Earth's Evolution

Assumptions:

Earth's tau-age = 10 Myr



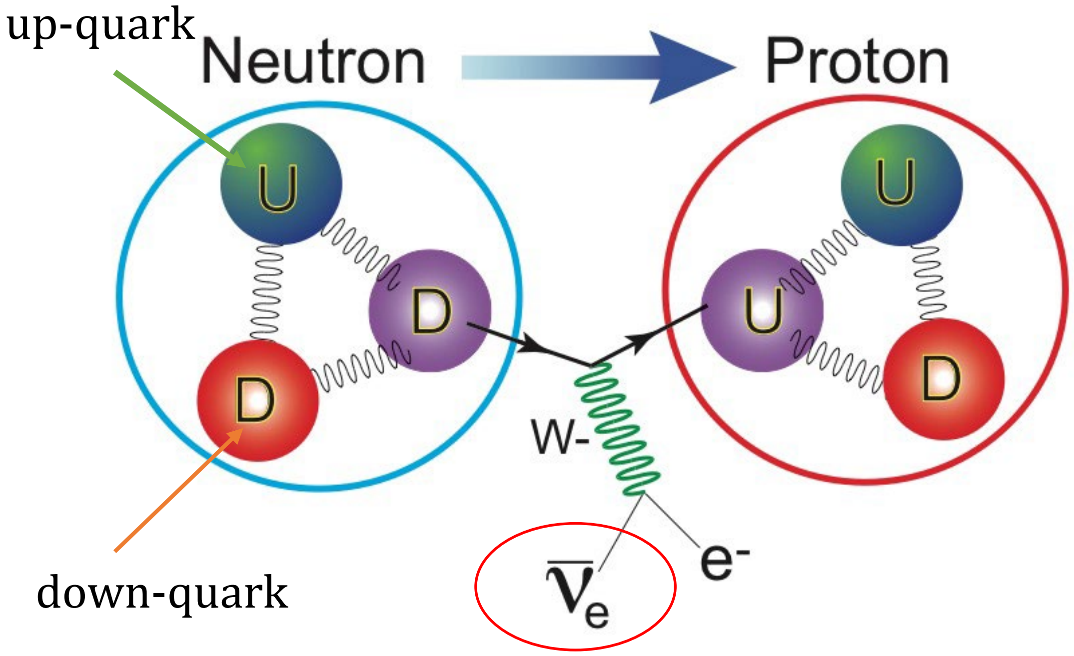
$$M(t)/M_{\text{final}} = 1 - \exp(-t/\tau)$$



McDonough et al. (2020), G-cube

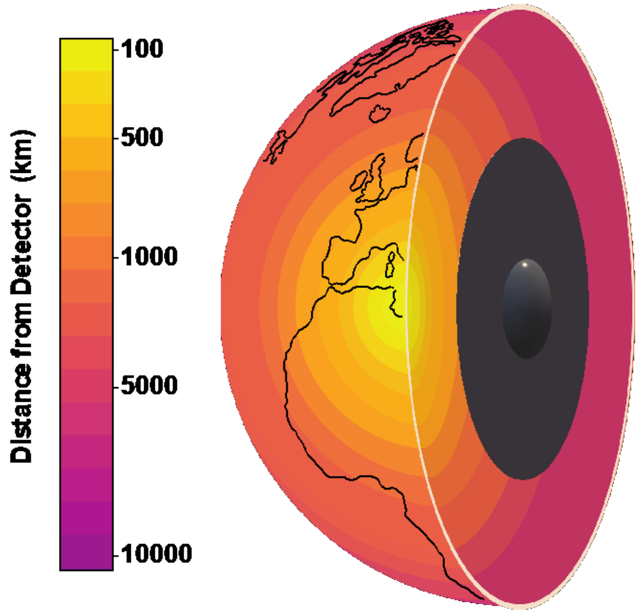
Particle physics endeavors in estimating the U, Th

β^- decay process (e.g., U, Th, K, Re, Lu, Rb)



Electron anti-neutrino
Geoneutrino

Antineutrino flux spectrum $d\Phi/dE_\nu$ at position r from a given radionuclide distributed with abundance A in the Earth



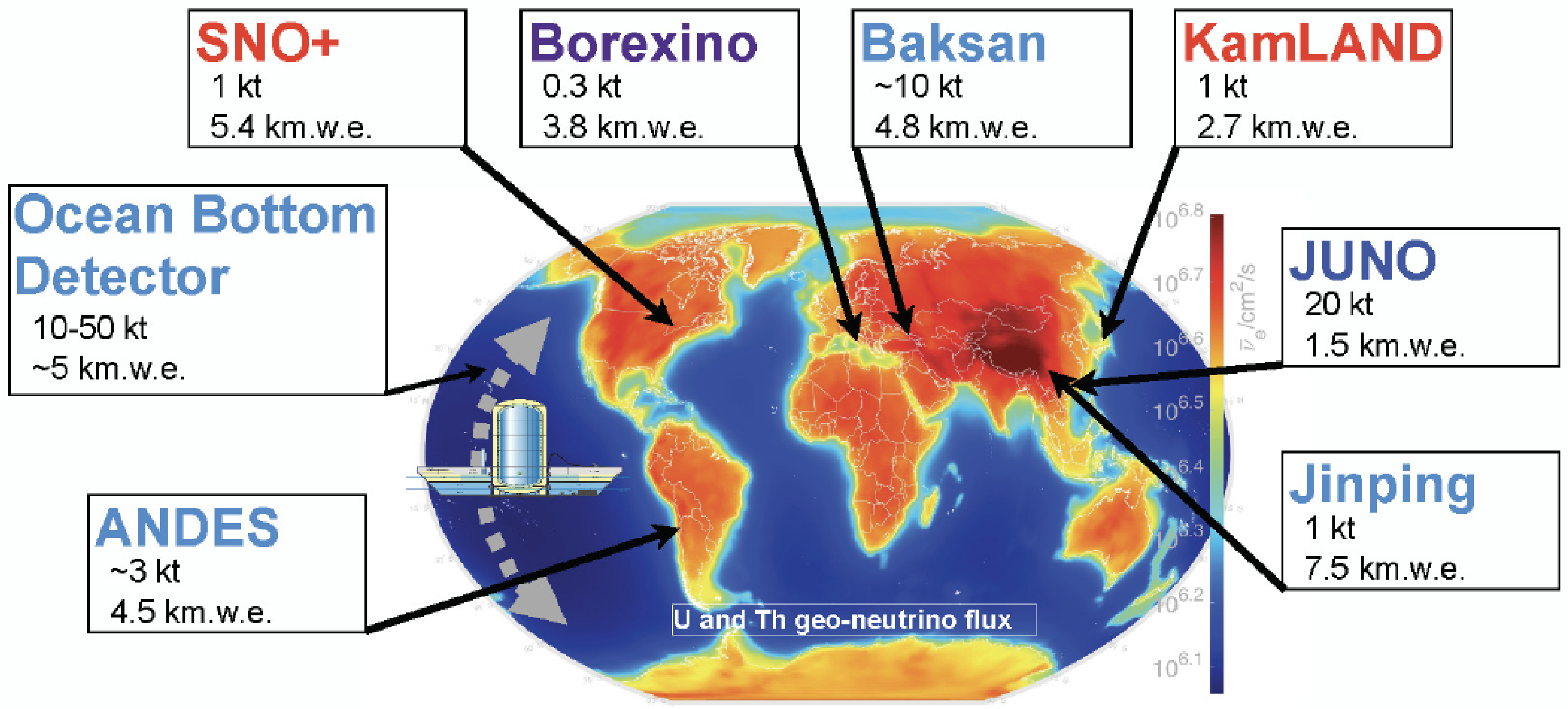
Inputs from geoscience:
- chemical abundances A
- density ρ

Inputs from nuclear/particle physics:
- decay rate D
- antineutrino intensity spectrum dn/dE_ν,
- antineutrino survival probability P_{ee}

$$\frac{d\phi(\boldsymbol{r},E_\nu)}{dE_\nu} = D\frac{dn(E_\nu)}{dE_\nu}\iiint \frac{A(\boldsymbol{r}')\rho(\boldsymbol{r}')P_{ee}(E_\nu,|\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}\,d^3\boldsymbol{r}'$$

geoneutrino flux = global measure of present-day U and Th

Global distribution of inland underground detectors



Red-detectors counting geoneutrino

Purple- have counted

Blue- in the development and/or planning stage

Bold blue- JUNO, in the construction phase.

Geoneutrino emission and relative contribution

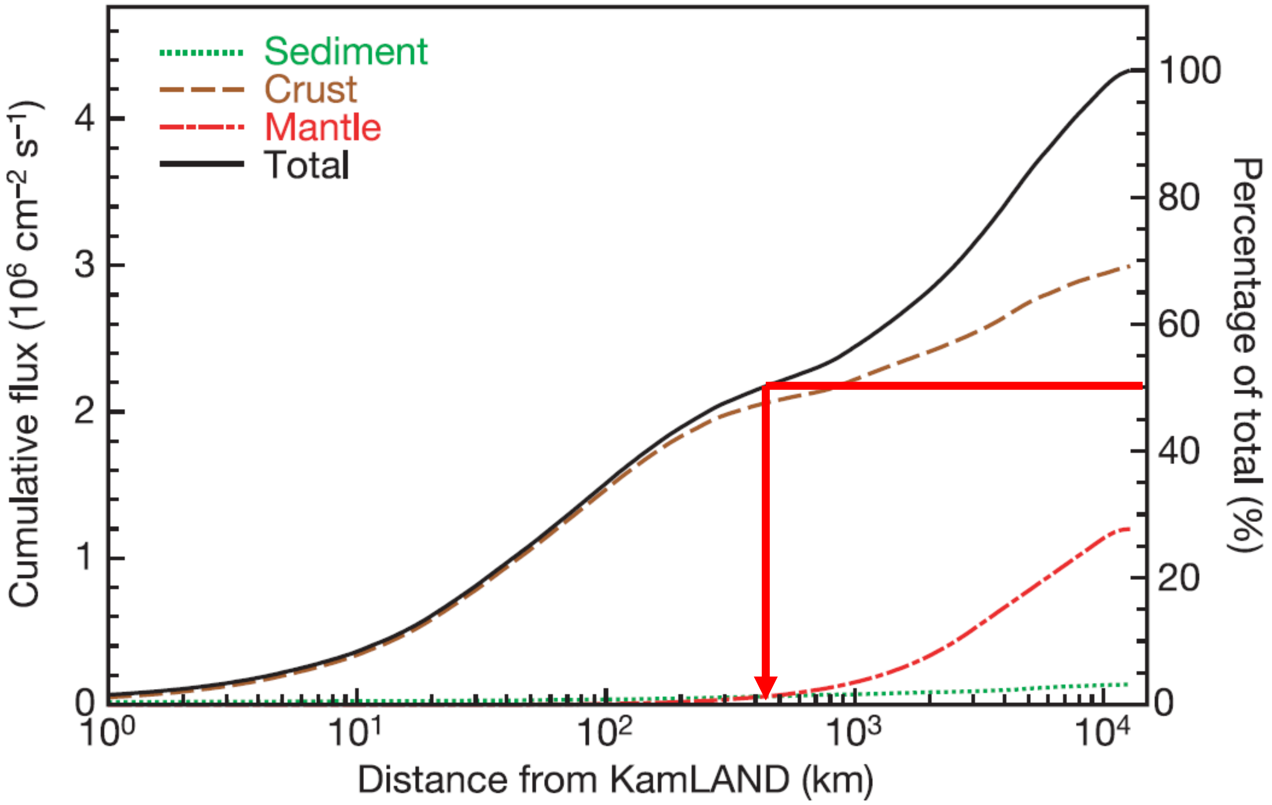
Total geoneutrino emission:

$$S_{total} = S_{lithosphere} + S_{mantle} + \cancel{S_{core}}$$

$$S_{lithosphere} = S_{Near\ Field\ L} + S_{far\ Field\ L}$$

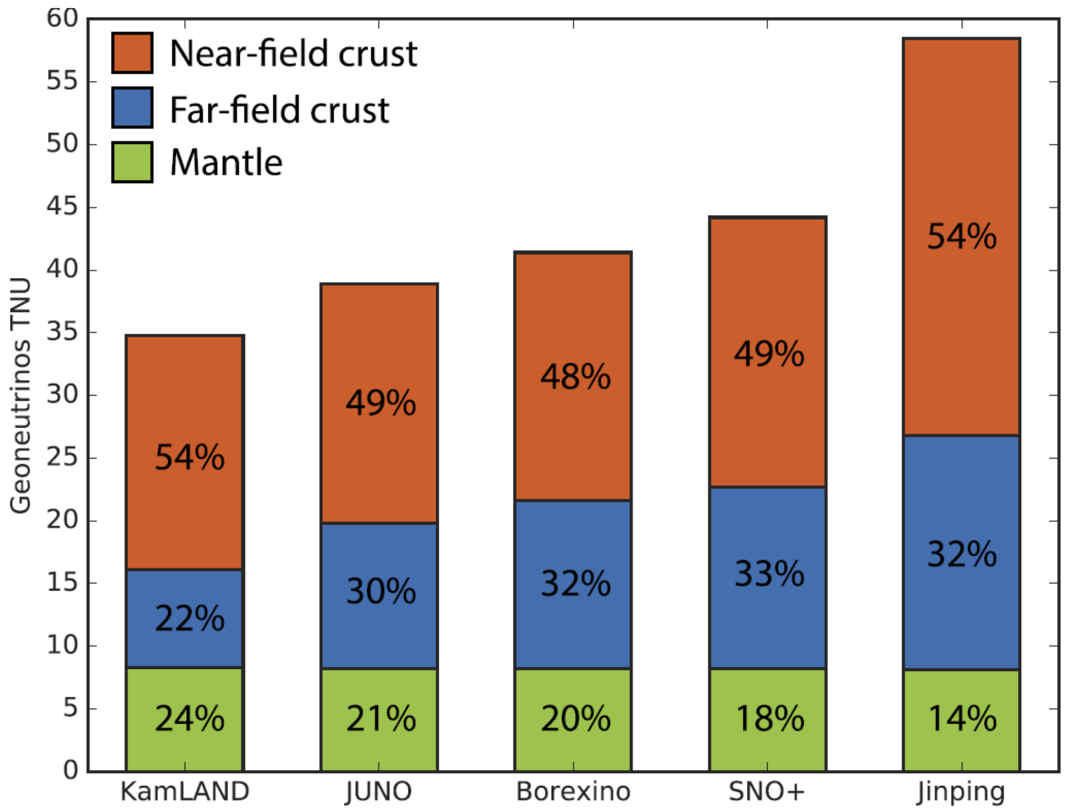
$$S_{total} - S_{lithosphere} = S_{mantle}$$

Relative Contributions



Araki et al. (2005), *Nature*

Near-field crust ~50%



Šrámek et al. (2005), *Nature*

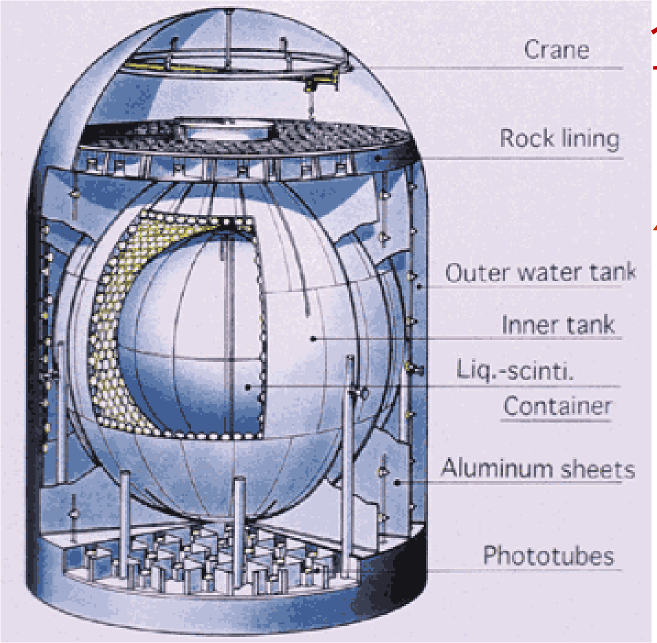
KamLAND

Total

Borexino

$14.6^{+5.2}_{-4.2}$ TW

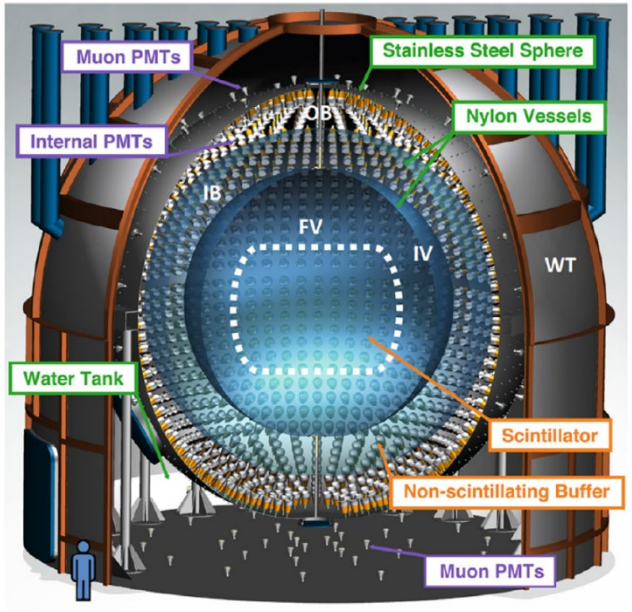
$38.2^{+13.6}_{-12.7}$ TW



Mantle

8 TW

30 TW



KamLAND ≠ Borexino

1 kt liquid Scintillator

0.3 kt liquid Scintillator

Why this discrepancy??

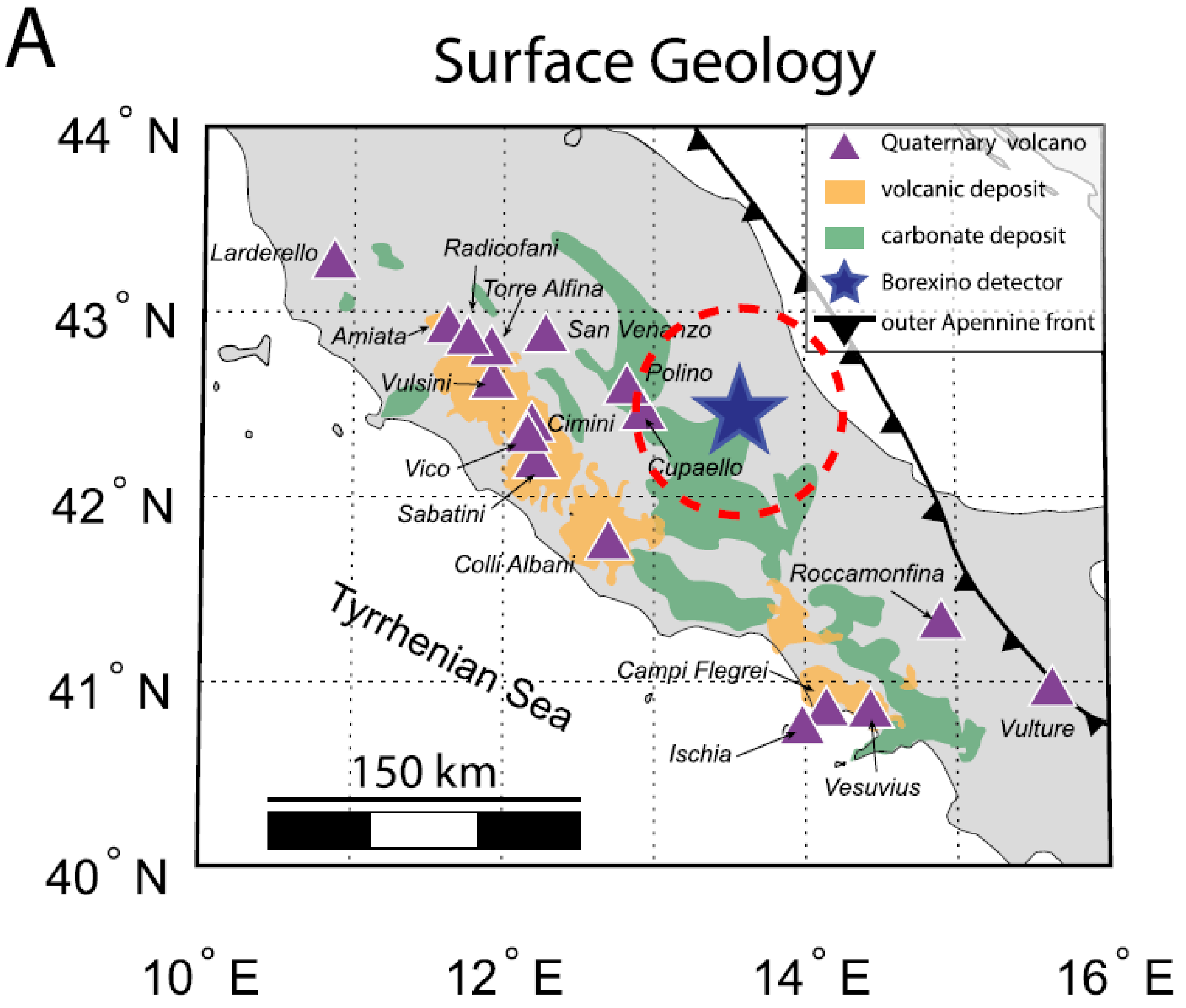
Geologic model: Borexino

Agostini et al. (2020, Phy. Rev. D.)

HPE-poor, carbonate-rich; no igneous component

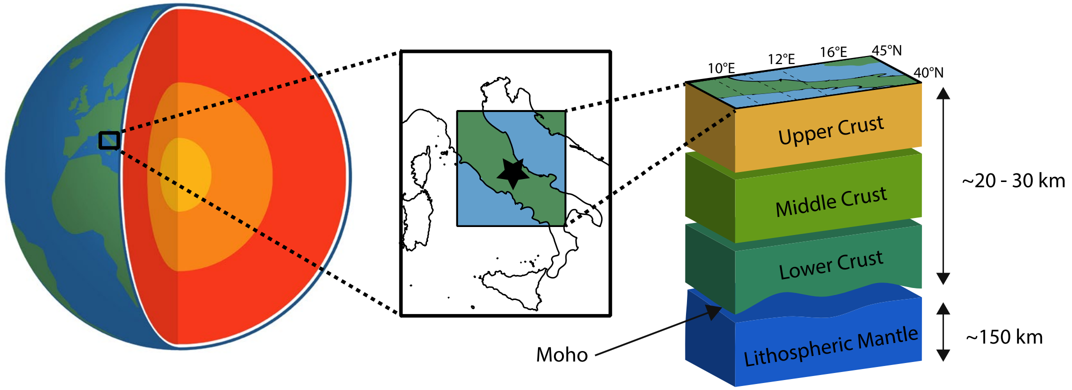
Sammon & McDonough (2022, EPSL)

rich in potassic magmatism

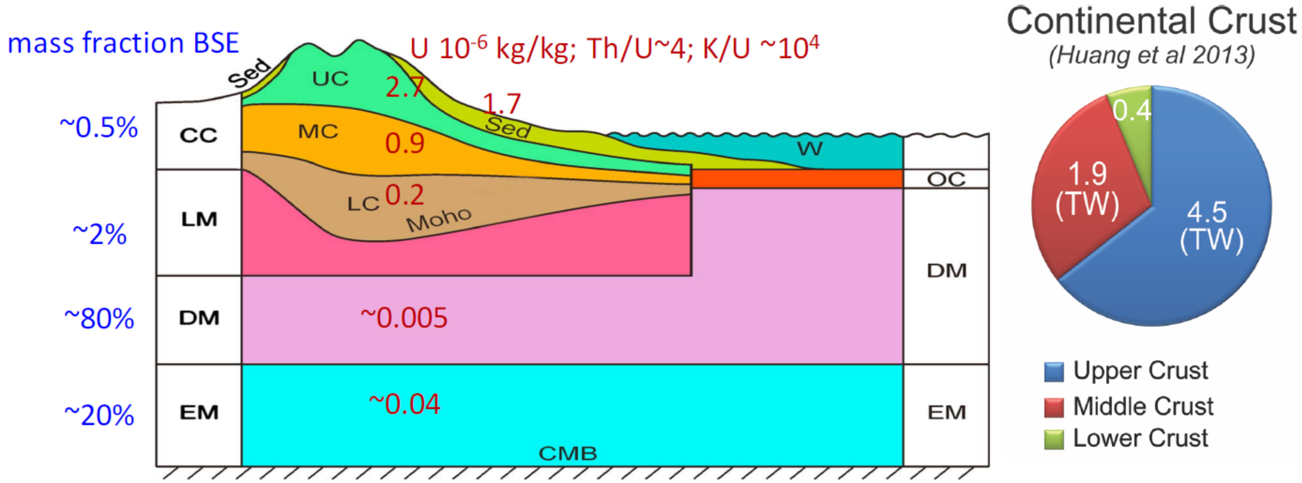


Sammon and McDonough (2022); *EPSL*

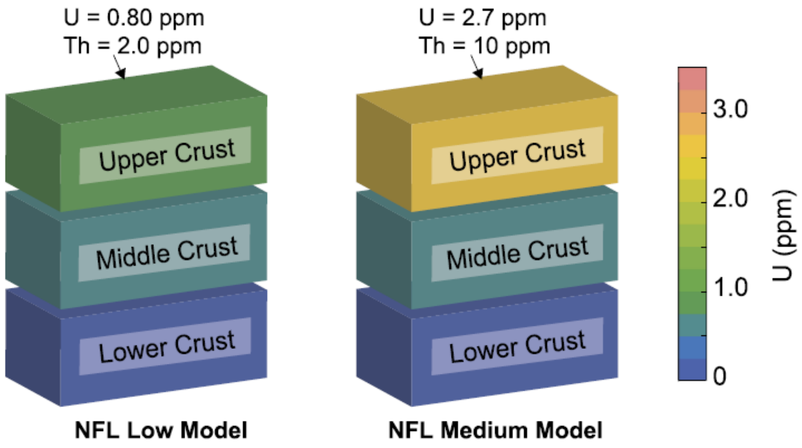
$$\frac{\mathrm{d}\phi(\boldsymbol{r},E_\nu)}{\mathrm{d}E_\nu} = D\frac{\mathrm{d}n(E_\nu)}{\mathrm{d}E_\nu}\iiint \frac{\boxed{A(\boldsymbol{r}')\rho(\boldsymbol{r}')}P_{ee}(E_\nu,|\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}\mathrm{d}^3\boldsymbol{r}'$$

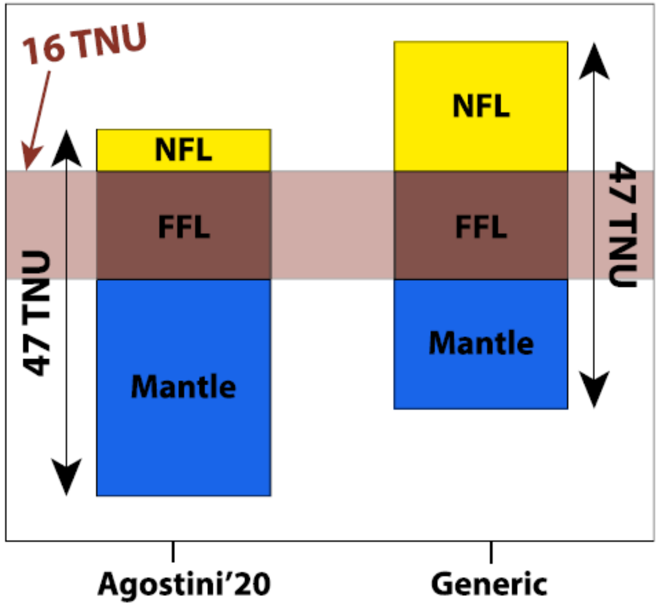


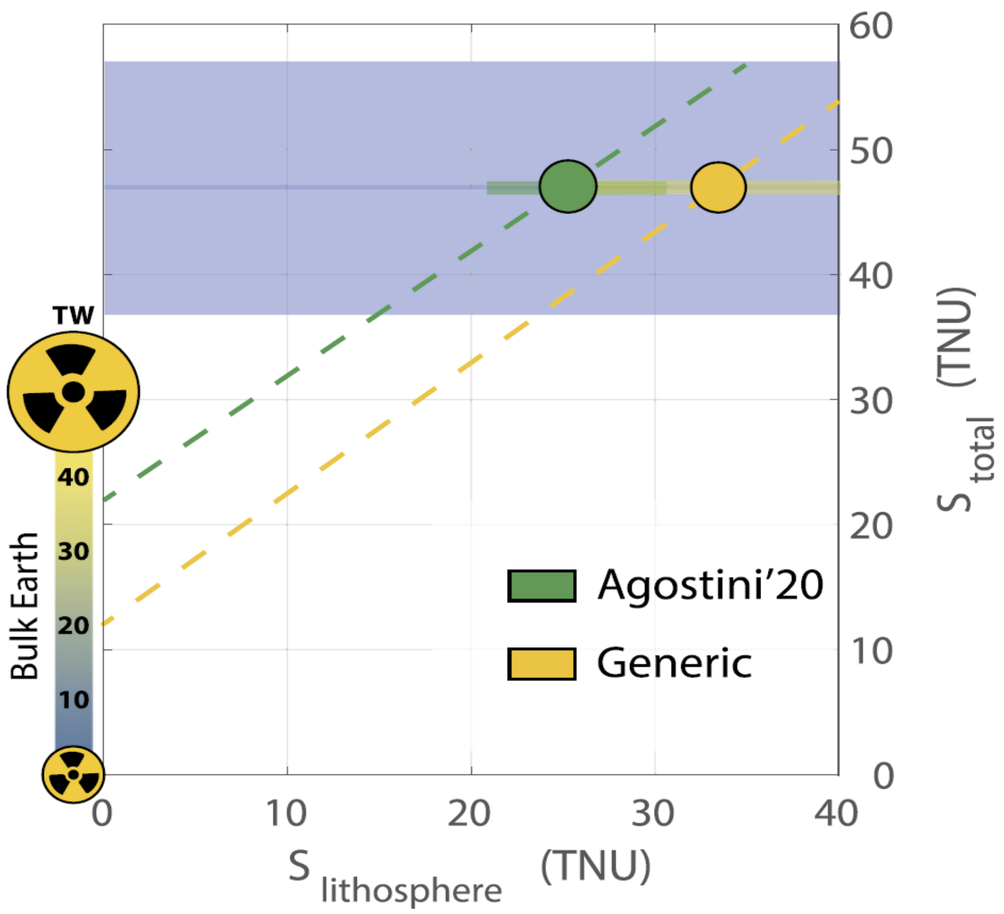
Local crust (<500 km) contributes ~50% of the total signal, and mostly the upper crust



Agostini’20 -vs- Generic







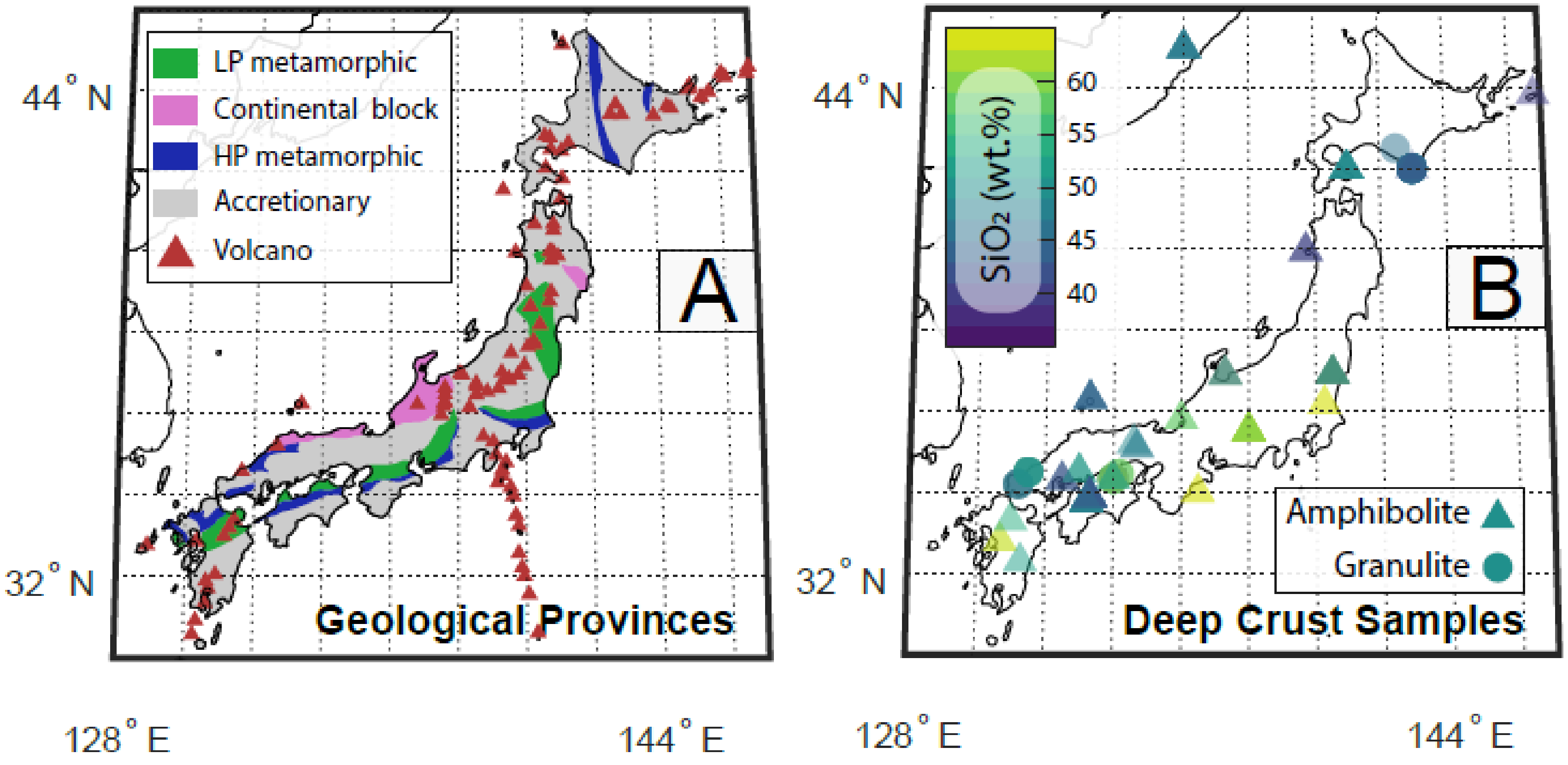
Sammon and McDonough (2022, *EPSL)*

Hi-resolution crustal model is essential

Geologic Model: KamLAND

Surface Sediments: average upper continental crust, **Rudnick and Gao (2014)**

Deep crustal model: Sammon and McDonough (2021)



Mantle Geoneutrino Flux : $\mathbf{9.2^{+5.2}_{-6.5}}$ **TNU or** $\mathbf{10.2^{+3.6}_{-4.5}}$ **TW**

U = 12.8 ppb, Th = 48.8 ppb

Assume, $(K/U)_{BSE}$ = 13800 ± 1300,

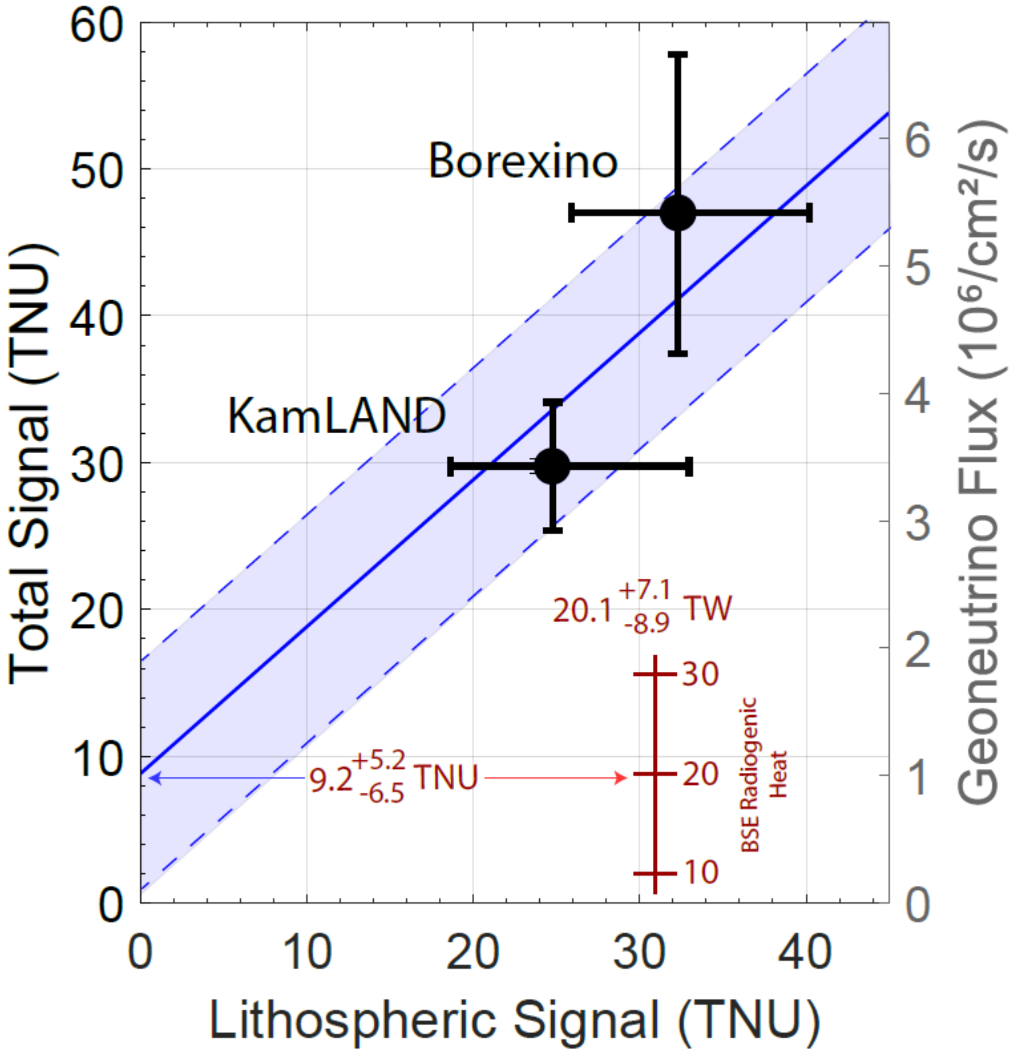
Total mantle radiogenic power: $\mathbf{12.6^{+4.6}_{-5.7}}$ **TW**

Lithosphere + mantle: $\mathbf{20.1^{+7.1}_{-8.9}}$ **TW from U, Th, and K**

Total radiogenic power (U + Th): $\mathbf{16.3^{+5.8}_{-7.2}}$ **TW**

U = 20.5 ppb, Th = 77.3 ppb

~ peridotite (MS95), U = 20.3 ppb, Th = 79.5 ppb



Silicate Earth = 2.7 × CI carbonaceous chondrites

Implication of understanding Bulk Earth Composition

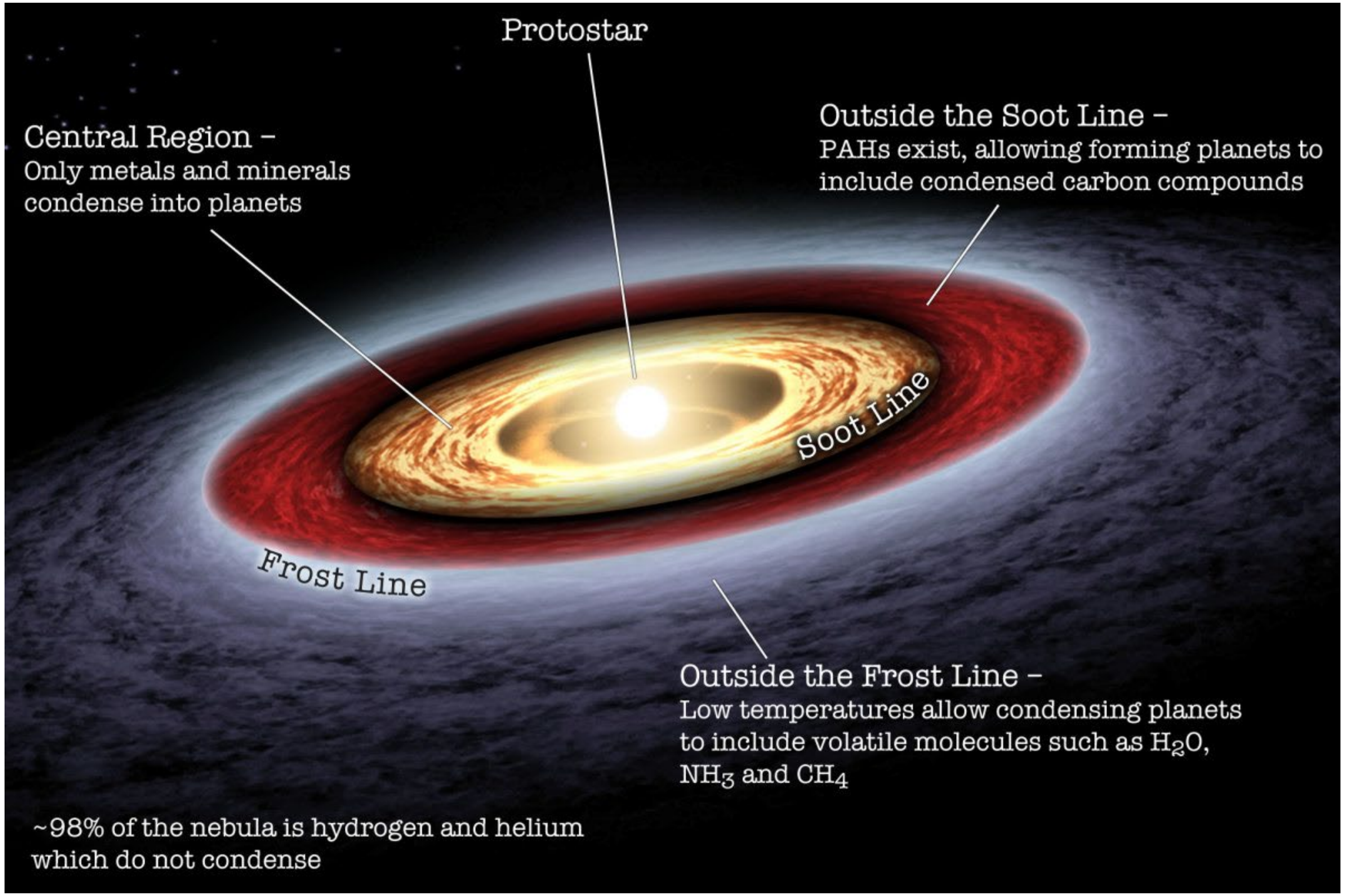
Nature of accretion of material in inner nebula

↓ + other planets formation

astronomical model of planet formation

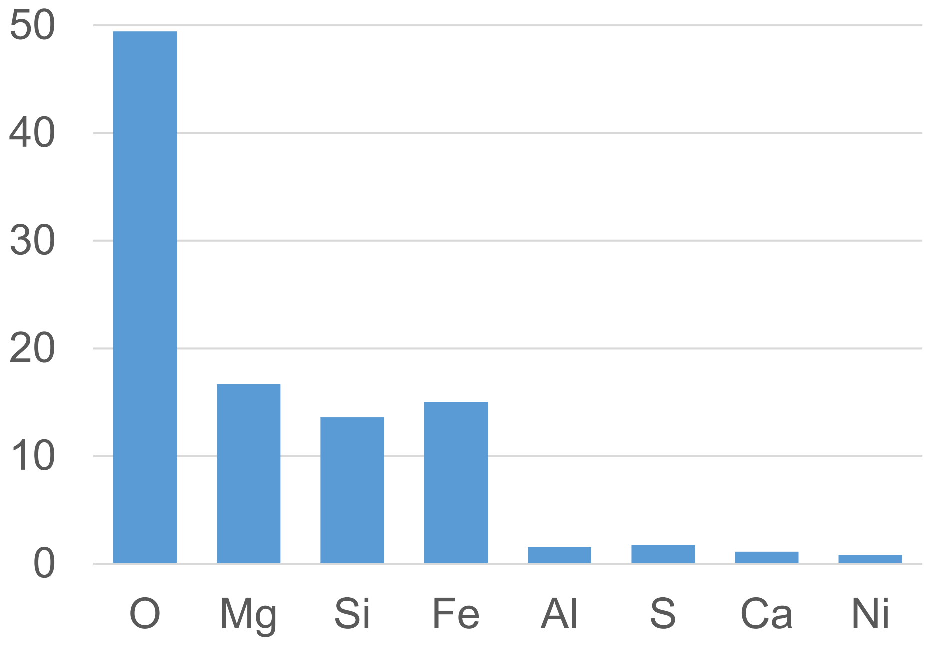
↓

Understanding of our solar system's planets
(discovering life elsewhere)



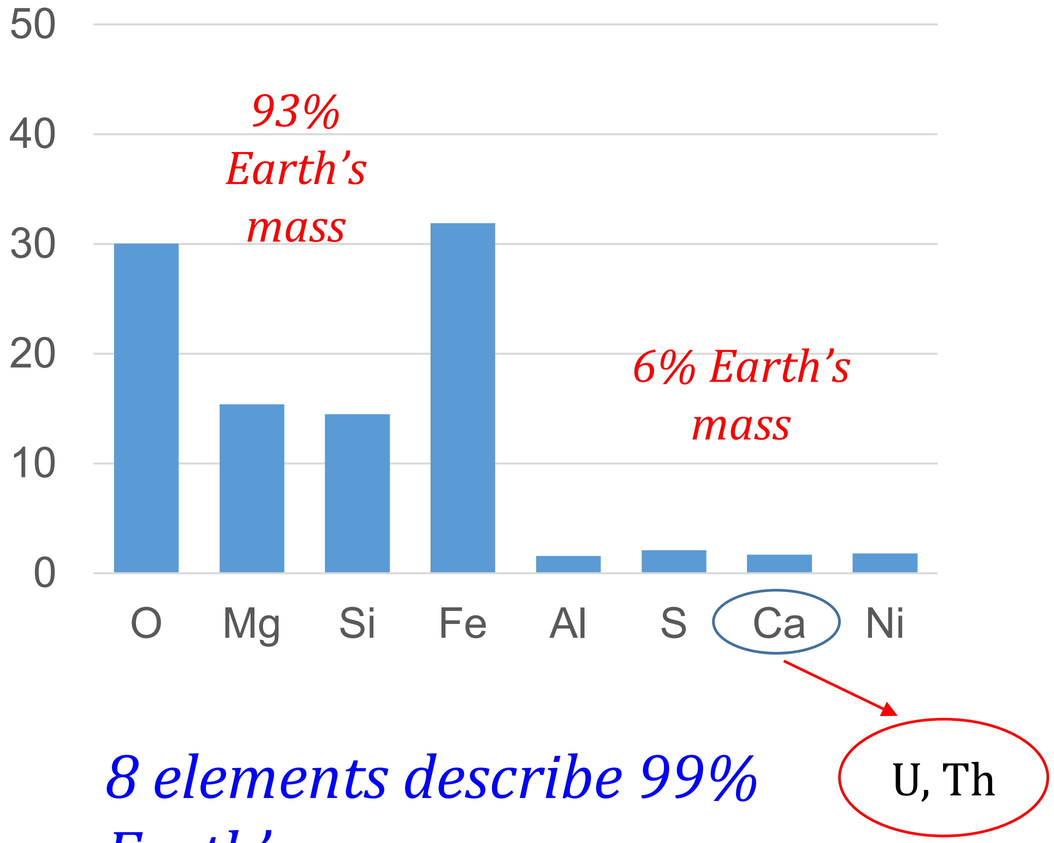
Compositional model of Earth

Earth: atom%



One out of every two atoms in Earth is oxygen

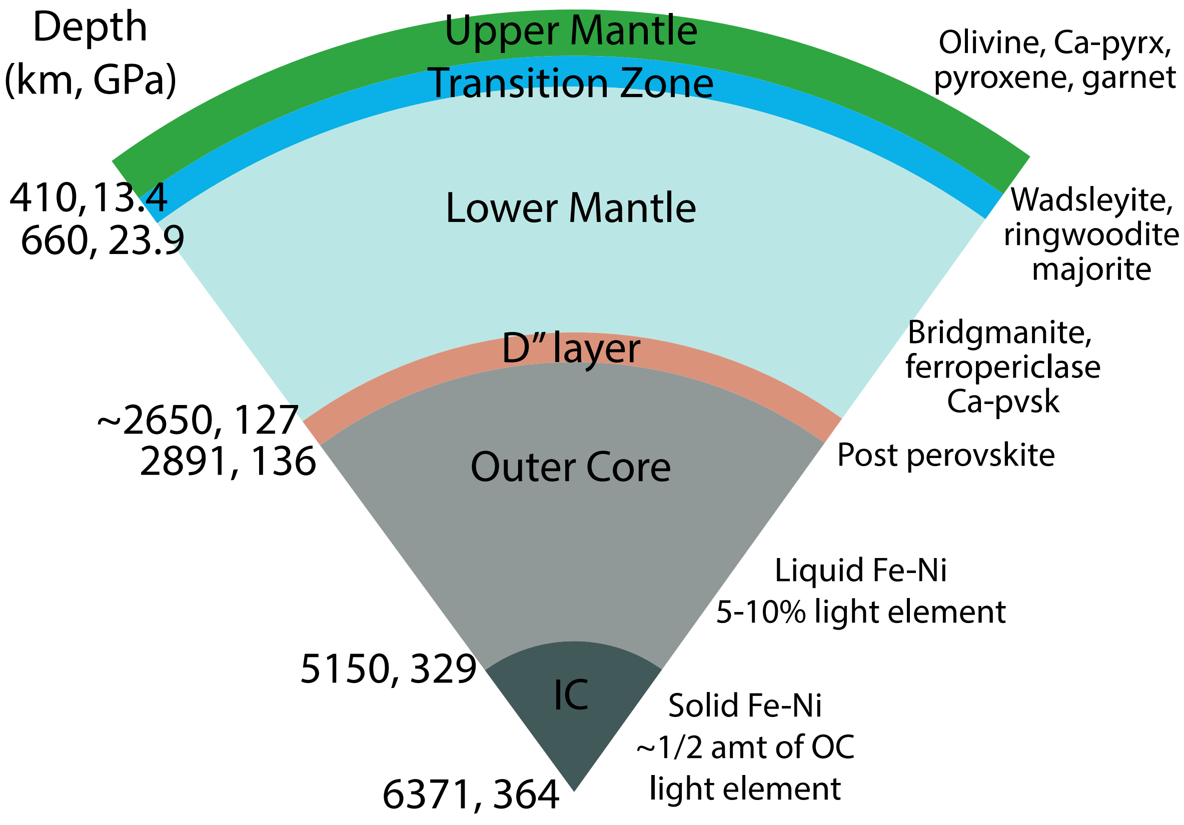
Earth: weight%

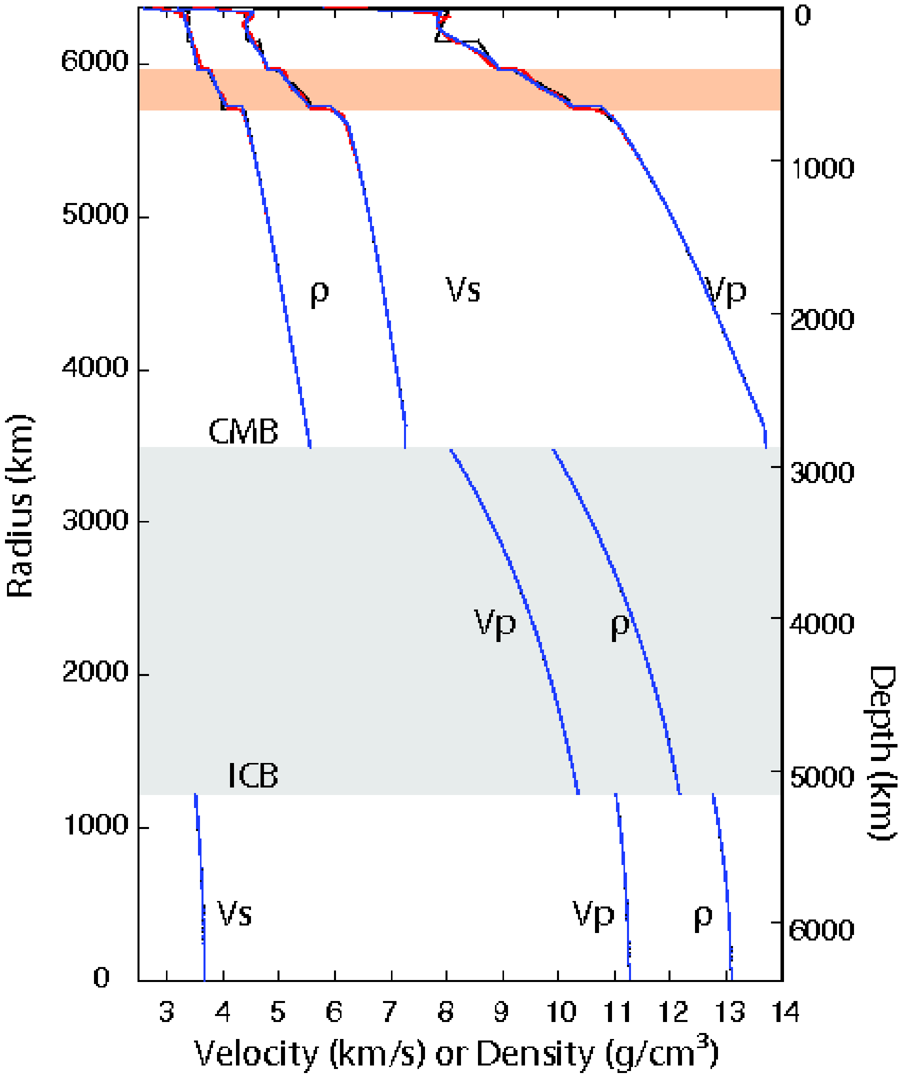


8 elements describe 99% Earth's mass

Compositional model of Earth

Mineralogy



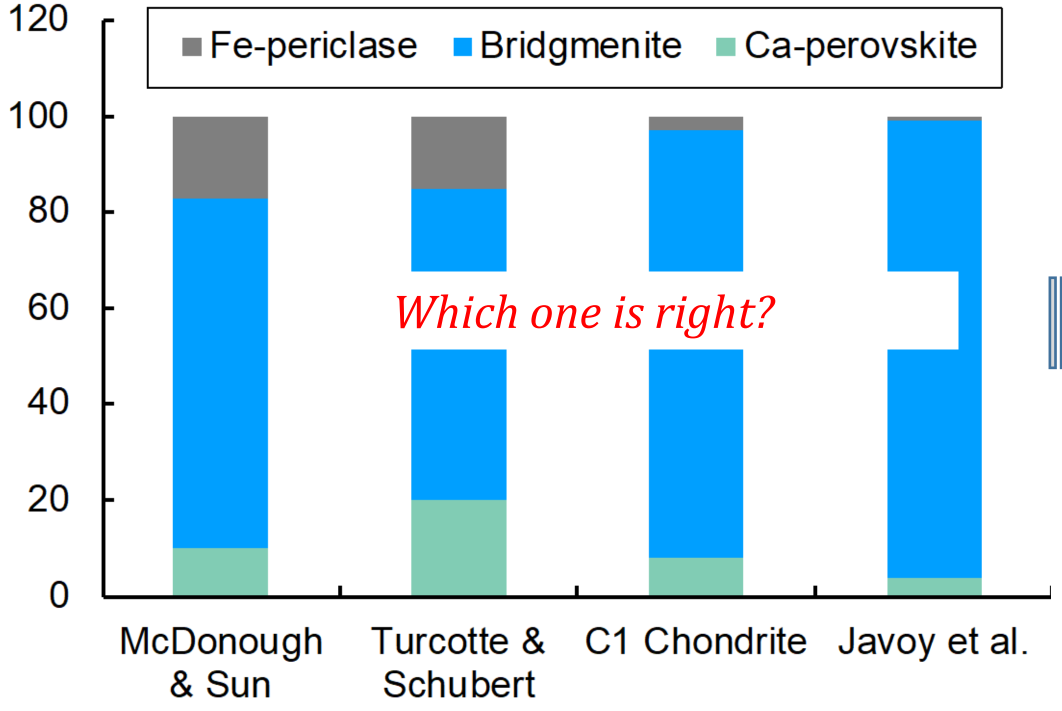


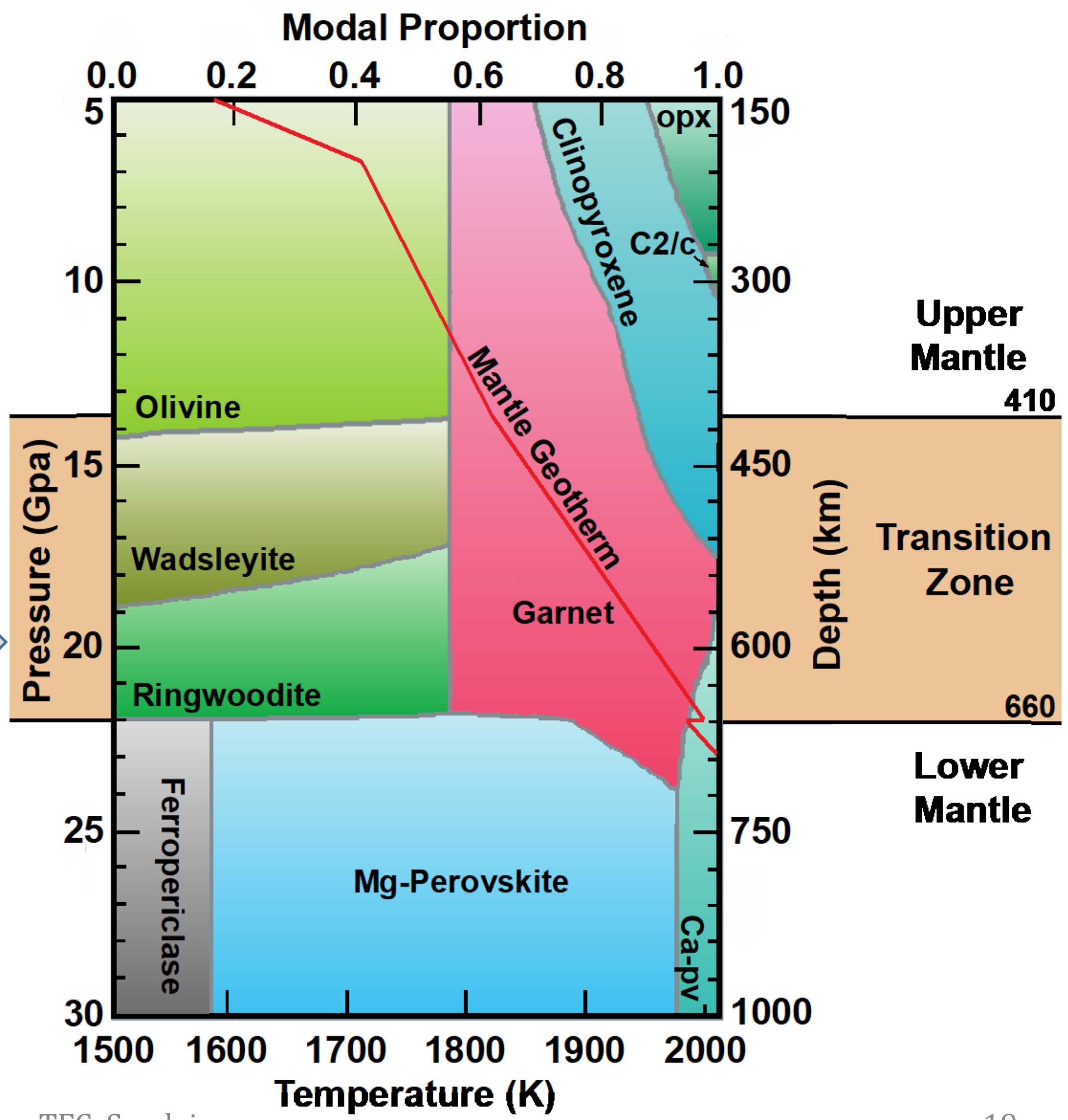
Earth: seismically defined

Compositional model of Earth

Mineralogy

Seismic wave discontinuities are coincident with major phase changes





Compositional model of Earth

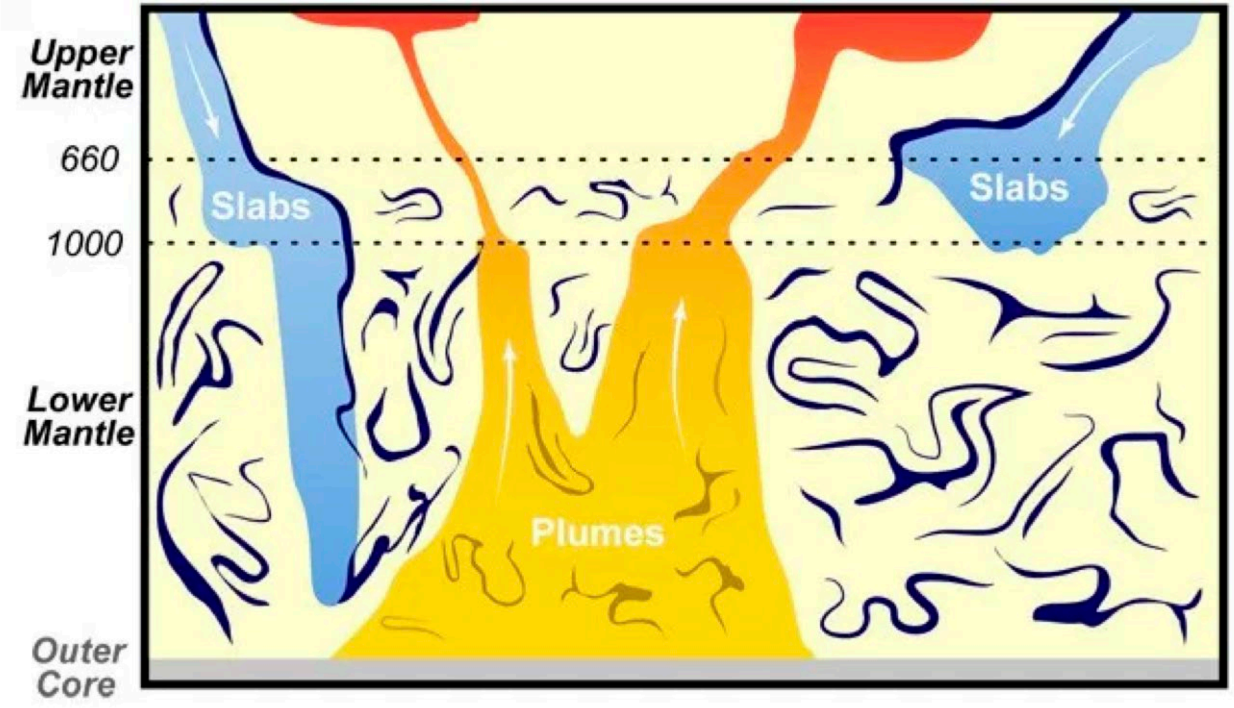
Earth's model -vs- Geoneutrino

Model	Low Q (Javoy et al., 2010)	Med Q (McD&S, 1995)	High Q (T&S, 2014)	$\bar{\nu}_e$ Flux
Radiogenic Power (TW)	10	20	30	20.1
U_{BSE} (in ppb)	11	20	30	20.5
Enrichment factor relative to CI Chondrites	1.5	2.7	3.9	2.7

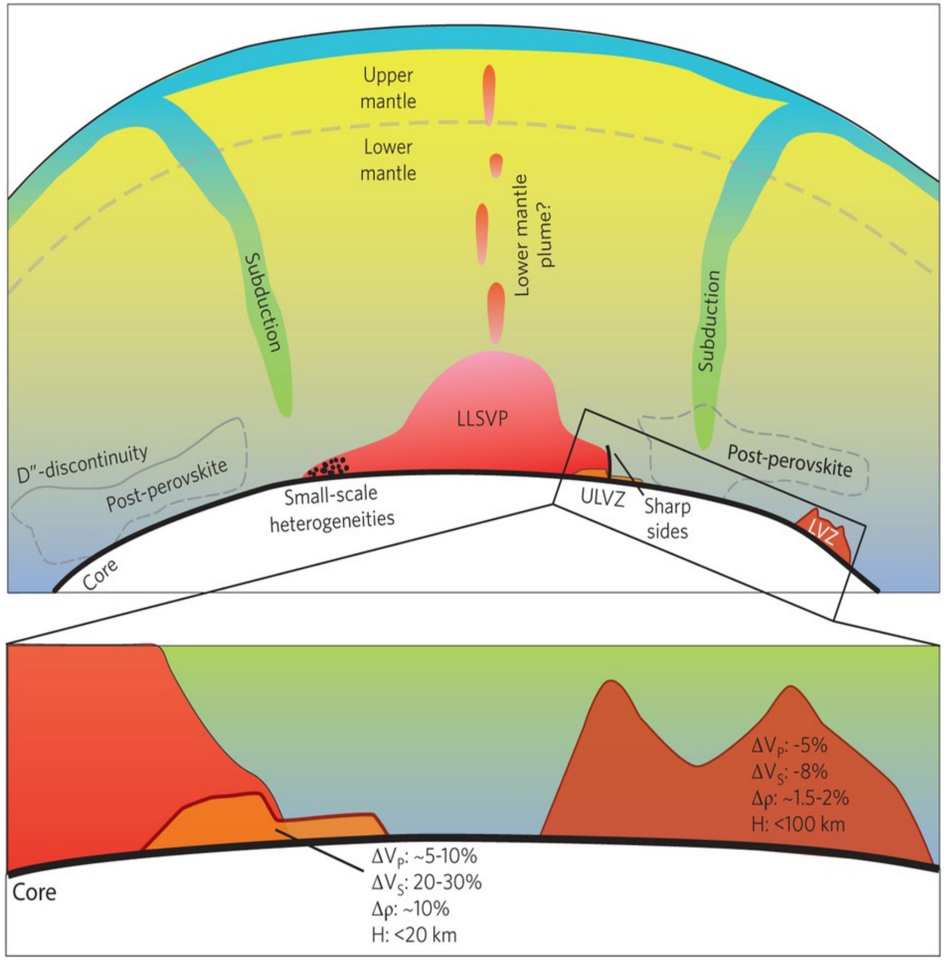
Two independent method, same conclusion

Compositional model of Earth

Mantle heterogeneity

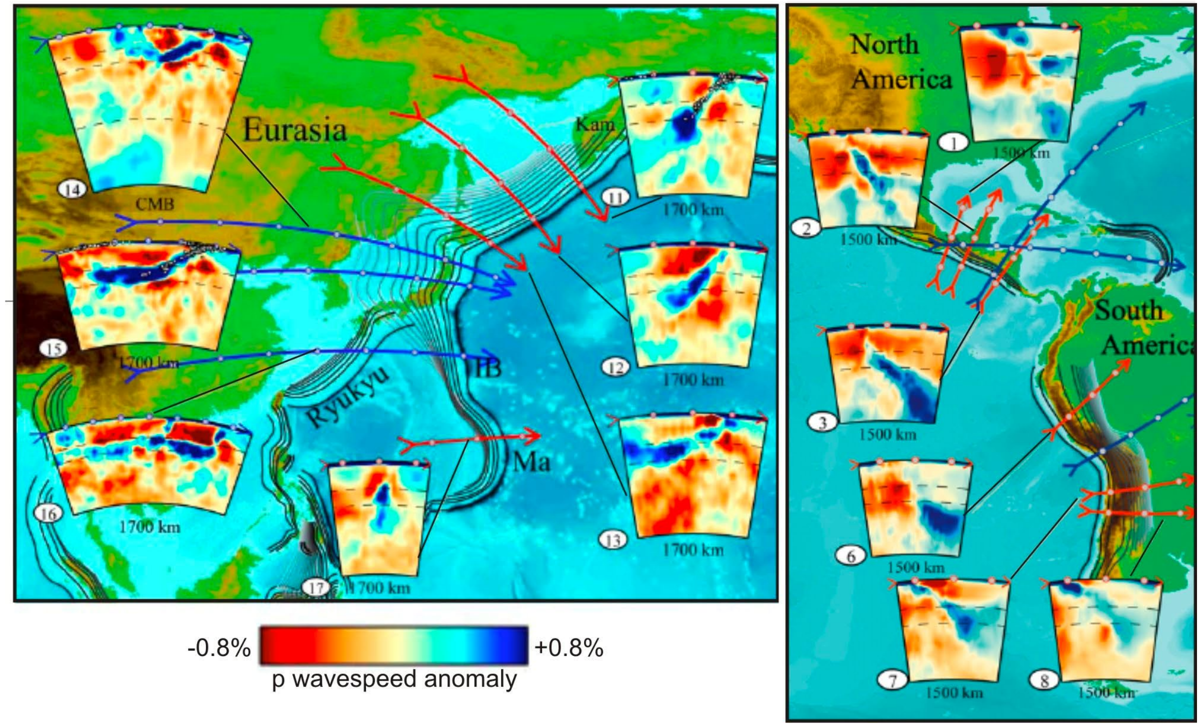


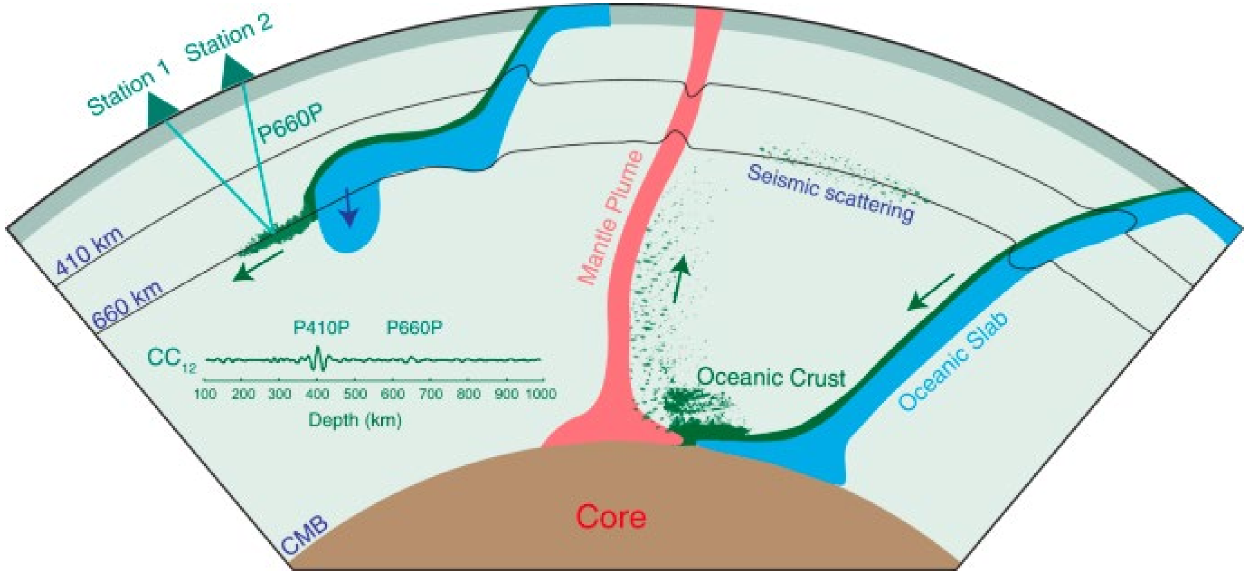
Kellogg et al. (1999); *Science*



Presence of geochemically heterogenous domains

Mantle heterogeneity

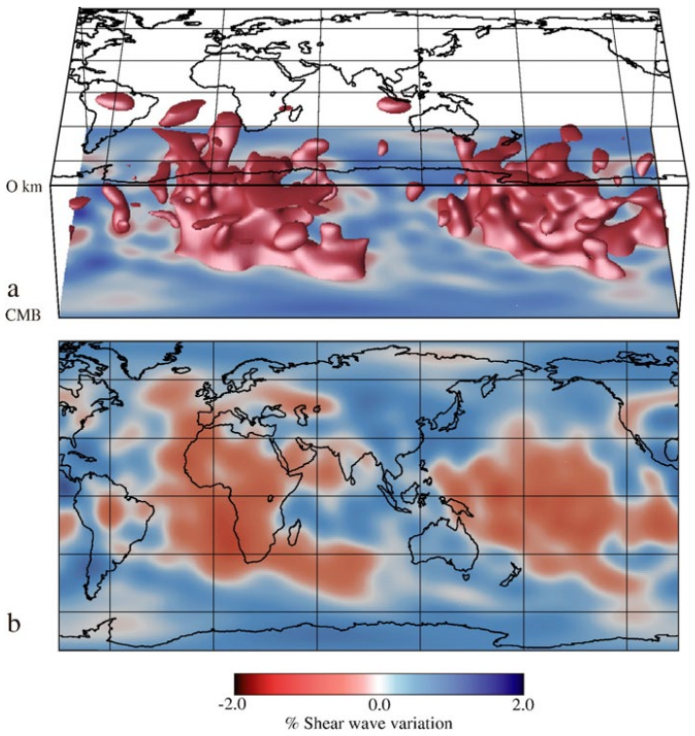




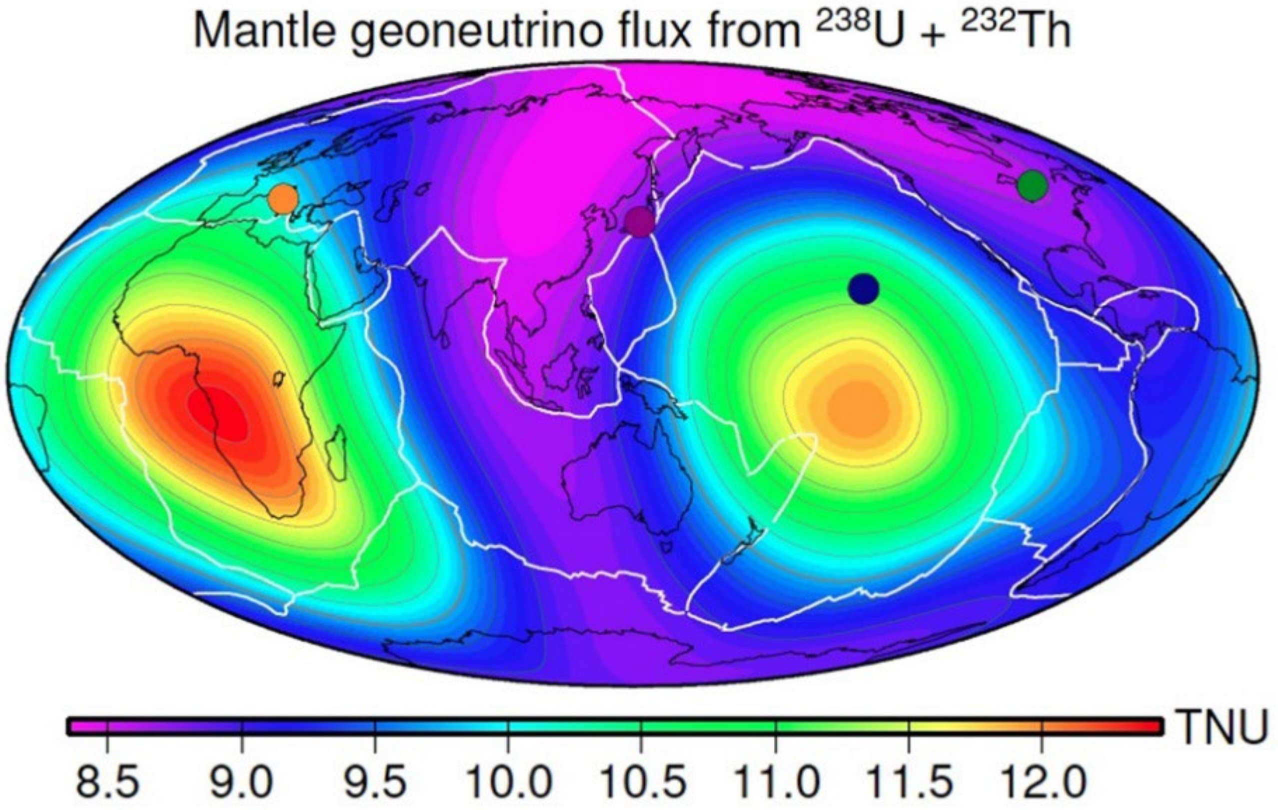
Feng et al (2021, *Nat. Comm.)*

Subducting plate stagnates at variable depths

Mantle heterogeneity



Bull et al (2009); *EPSL*



Šrámek et al. (2013); *EPSL*

Can we detect such variation in geoneutrino flux??

Mantle geoneutrino prediction (excluding crustal signals)

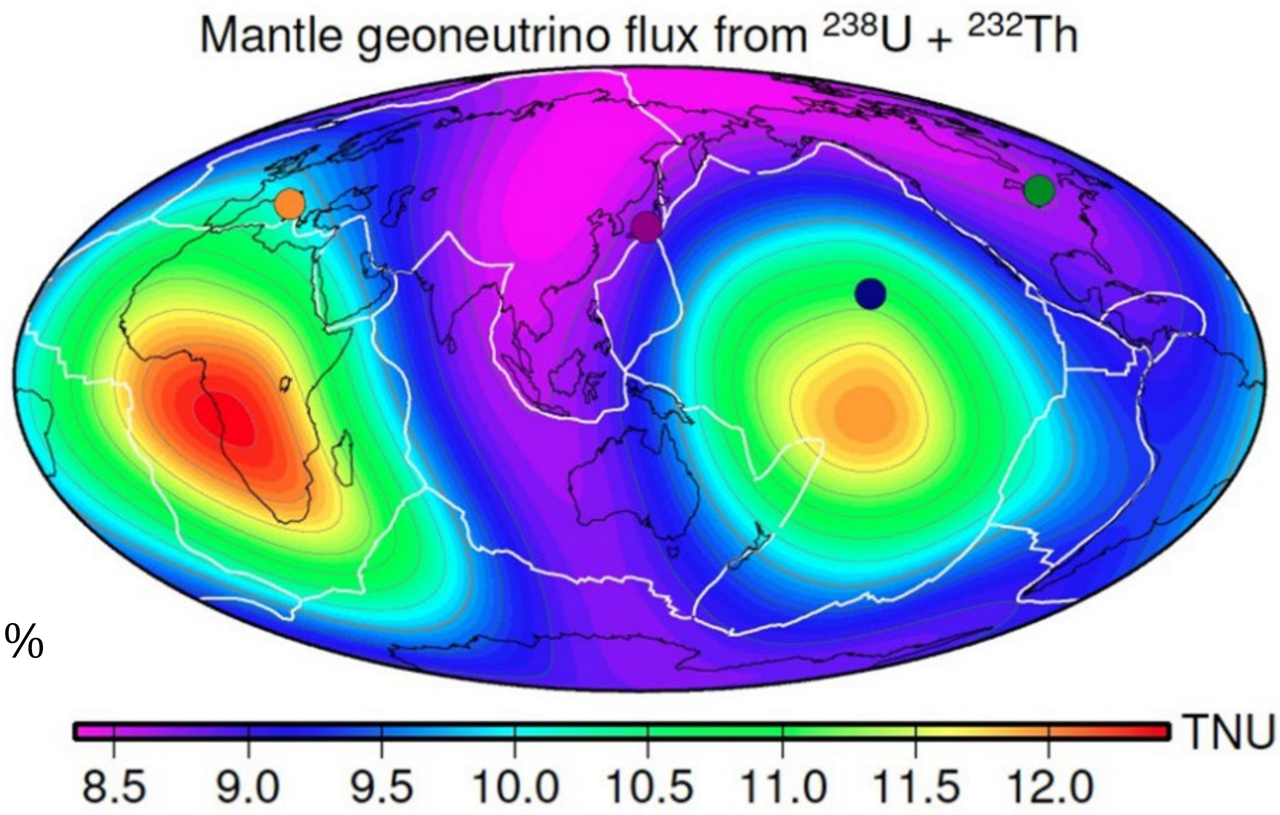
Mantle heterogeneity

Assumptions:

Geochemical BSE and A&McD depleted mantle abundances

Seismic tomographic model S20RTS (Ritsema et al., 1999)

Enriched mantle
- V_S anomaly less than -0.25% relative to PREM
- Deeper than 1500 km



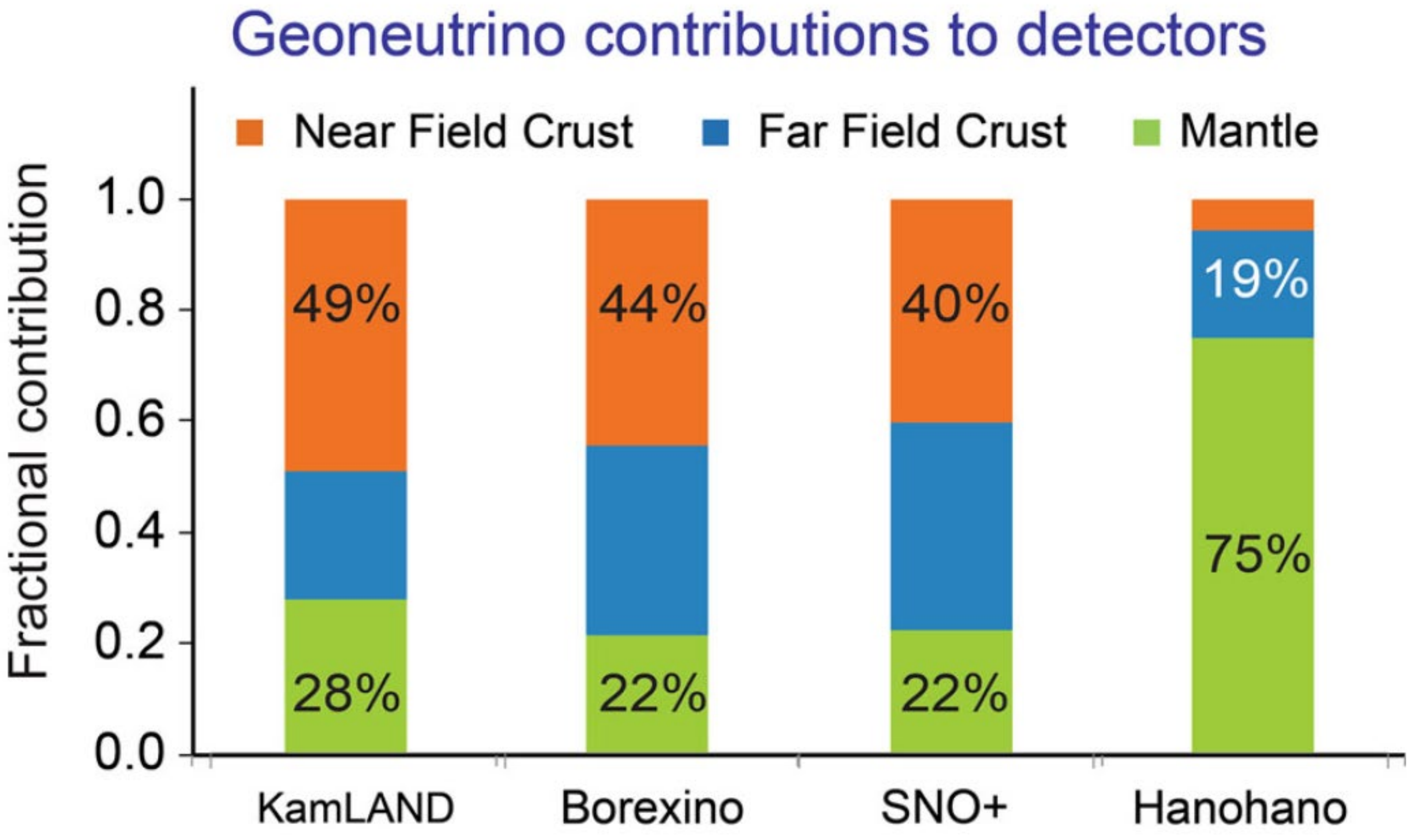
Šrámek et al. (2013); *EPSL*

Can we detect such variation in geoneutrino flux??

Mantle geoneutrino prediction (excluding crustal signals)

Necessity of Ocean Bottom Detector (OBD)

Detector gets a “mostly-mantle“ signal



Geoneutrino flux

- ❑ Defines Radiogenic Power : Proper geological assessment
- ❑ Constrains Bulk Earth Composition : Independent of Earth's structure

ANEKĀNTAVĀDA

Sanskrit: “non-one-sidedness” or “many-sidedness”

Truth depends on one’s point of view

No single point of view comprises the complete truth

These views are not wrong, merely incomplete.