Earth and its energy budget

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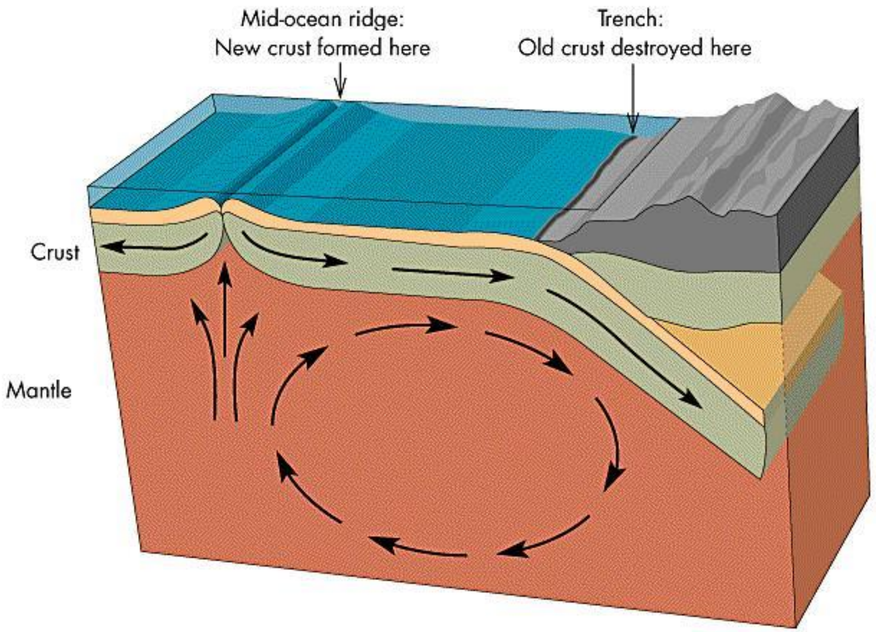
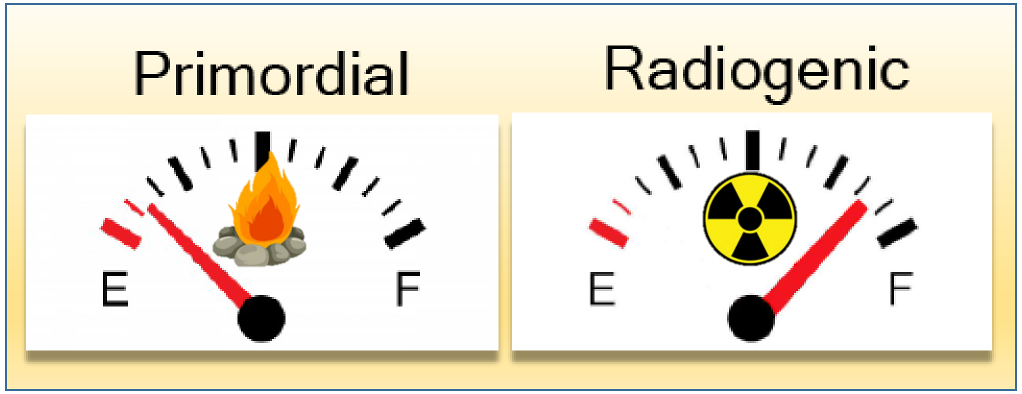
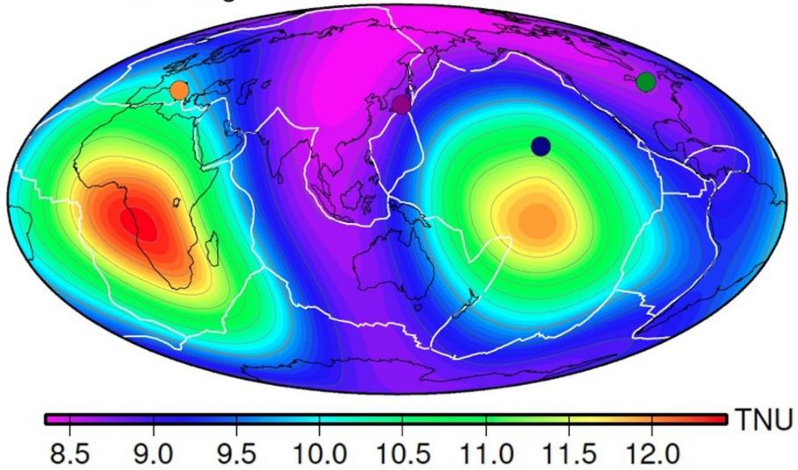
How much fuel is left to drive Plate Tectonics?

46±3 TW





Mantle geoneutrino flux from ^{238}U + ^{232}Th



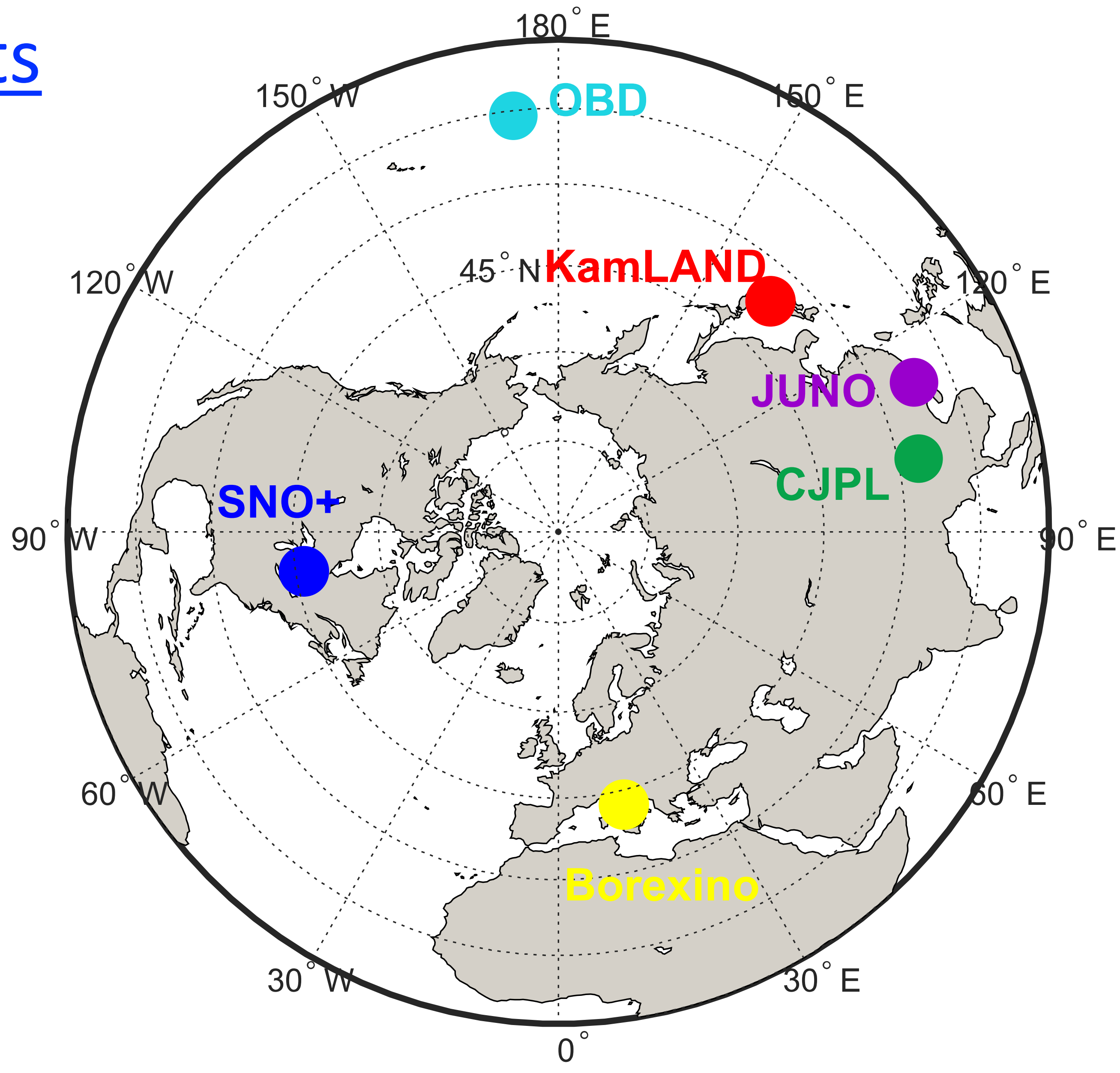
Geoneutrino experiments

KamLAND	counting
Borexino	finished
SNO+	counting*

JUNO filing!!,
and counting August '25

CJPL	development
OBD	development

** reporting in 2025*



Geoneutrino Flux on Earth Surface

Activity and number of produced geoneutrinos

Volume of source unit

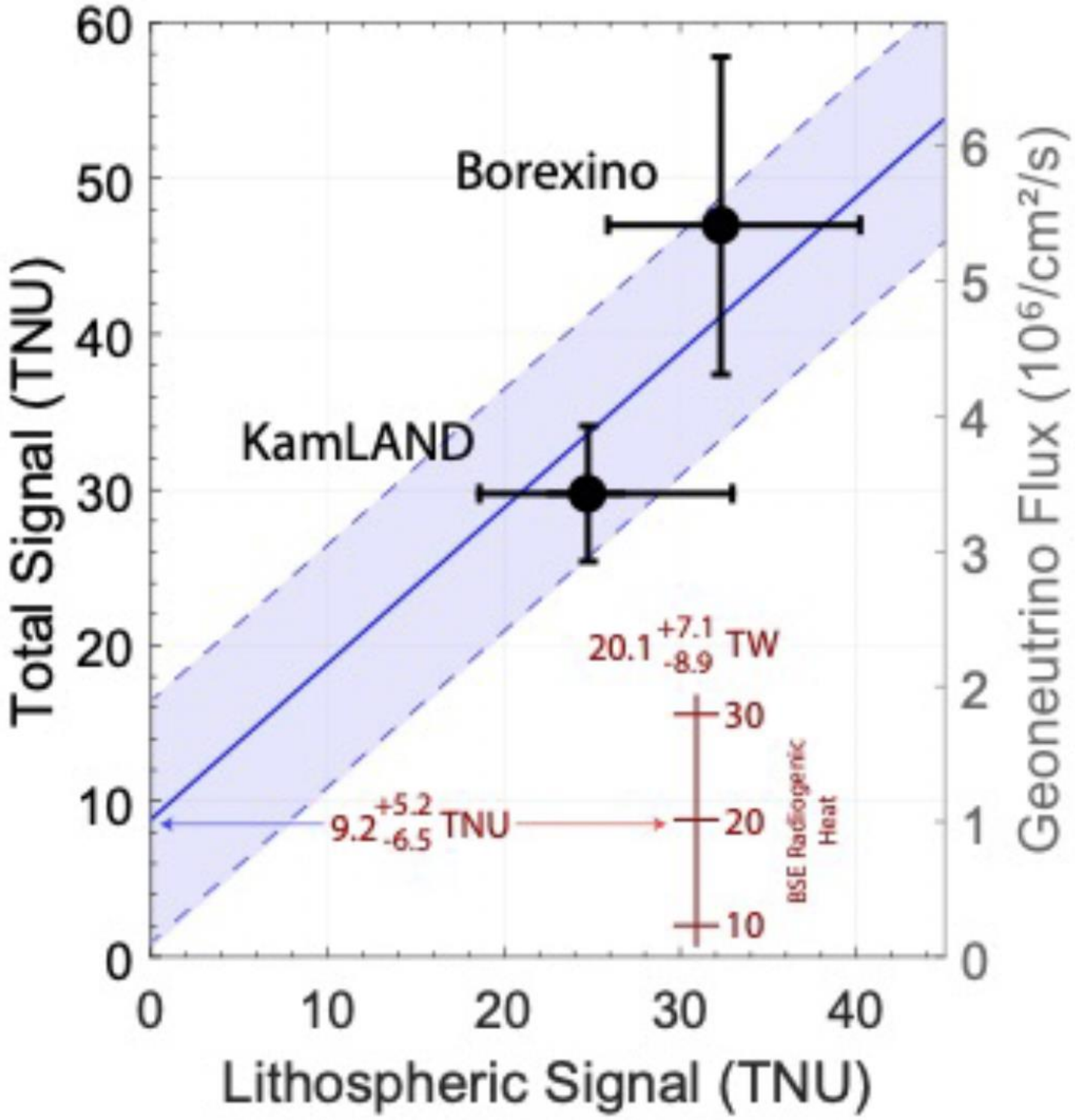
$$\frac{d\phi(E_\nu, \mathbf{r})}{dE_\nu} = A \frac{dn(E_\nu)}{dE_\nu} \int_{V_\oplus} d^3\mathbf{r}' \frac{a(\mathbf{r}')\rho(\mathbf{r}')P(E_\nu, |\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|^2}$$

Survival probability function

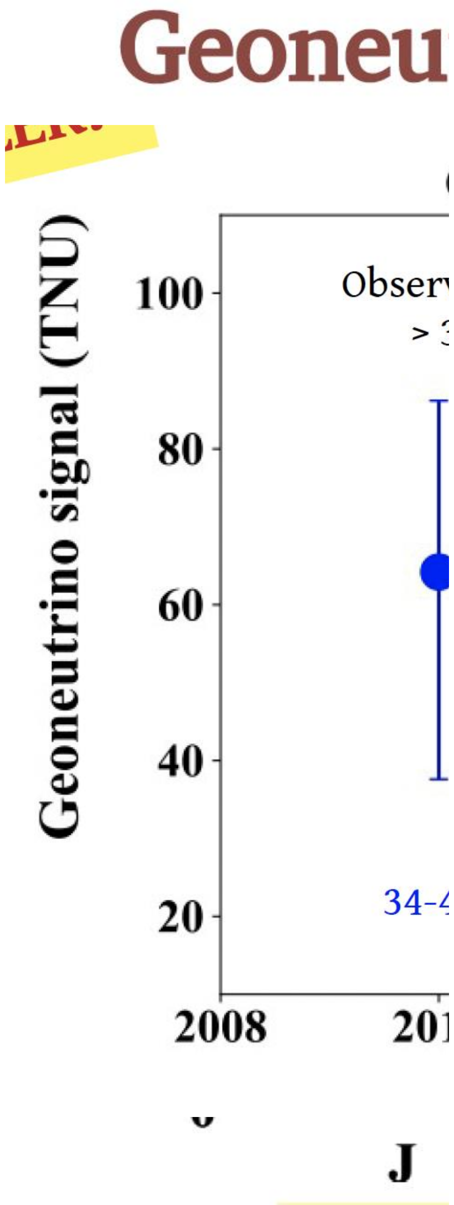
Abundance and density of the source unit

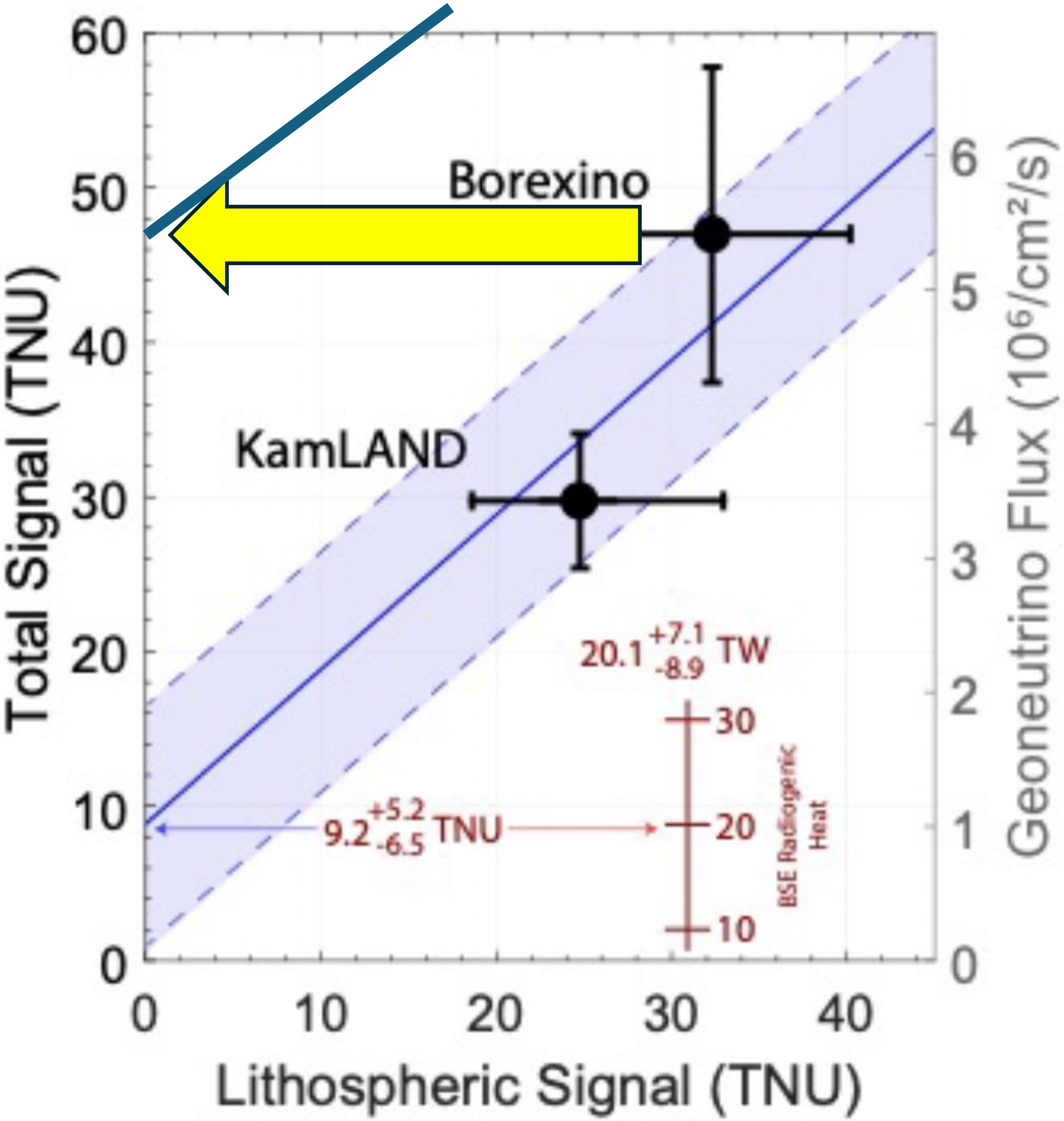
Distance between source unit and detector

Earth structure (ρ and L) and **chemical composition** (a)


Borexino
KamLAND
Total Signal (TNU)
Lithospheric Signal (TNU)
Geoneutrino Flux (10^6/cm^2/s)
$20.1^{+7.1}_{-8.9}$ TW
$9.2^{+5.2}_{-6.5}$ TNU
BSE Radiogenic Heat
0
10
20
30
40
50
60
1
2
3
4
5
6

2019


Geoneutrino signal (TNU)
100
80
60
40
20
2008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BSE Radiogenic Heat

Presented by J. Manei

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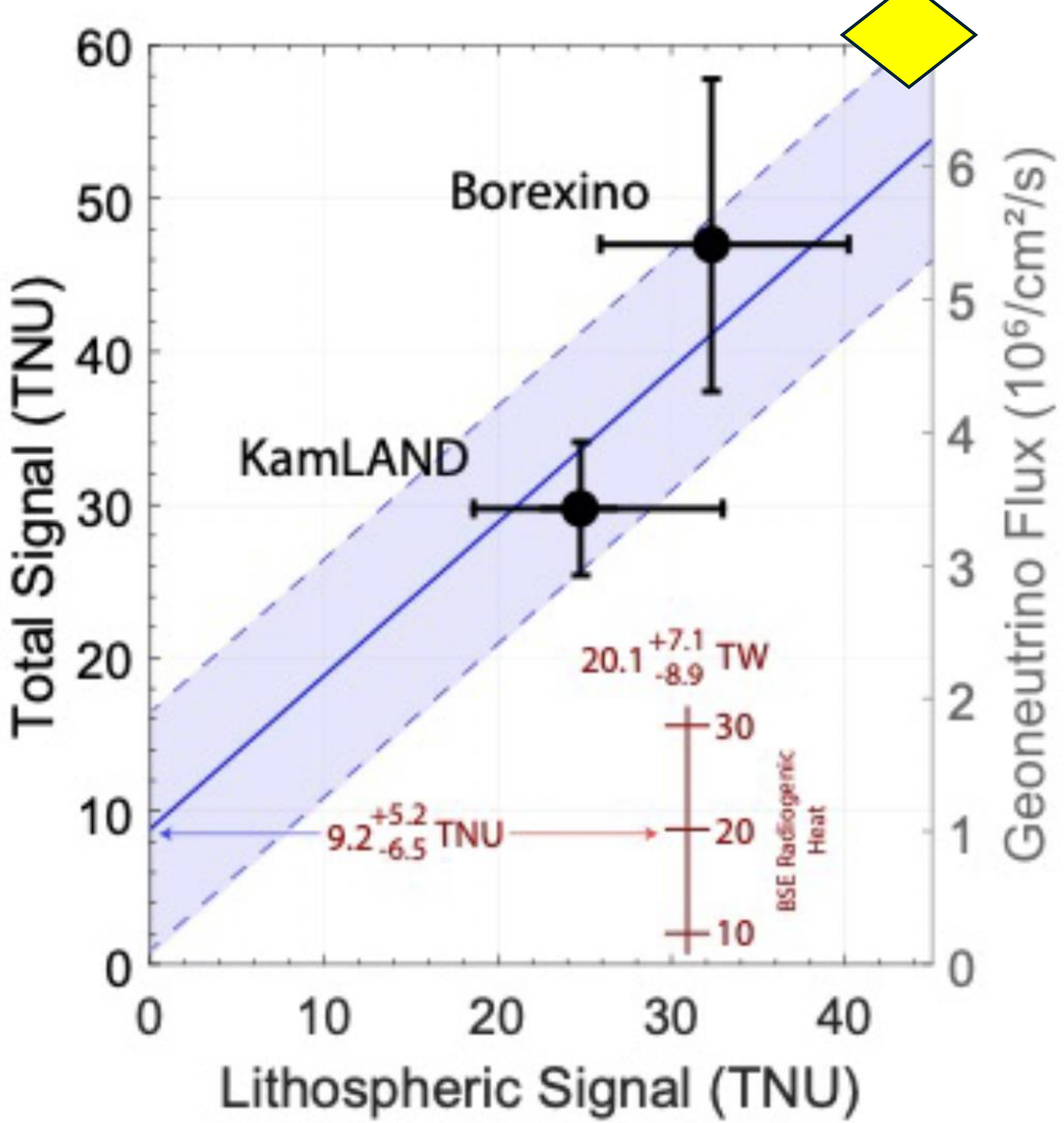
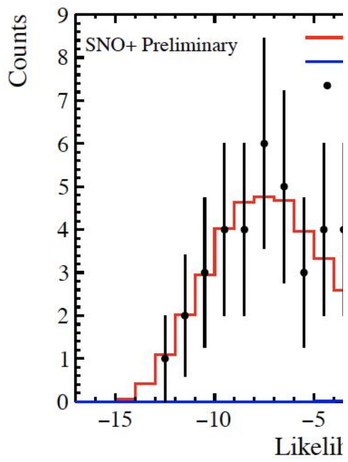
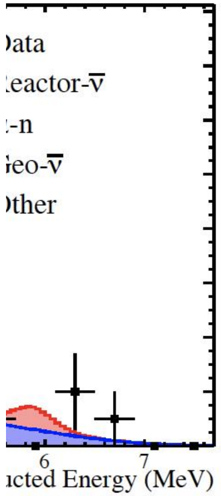
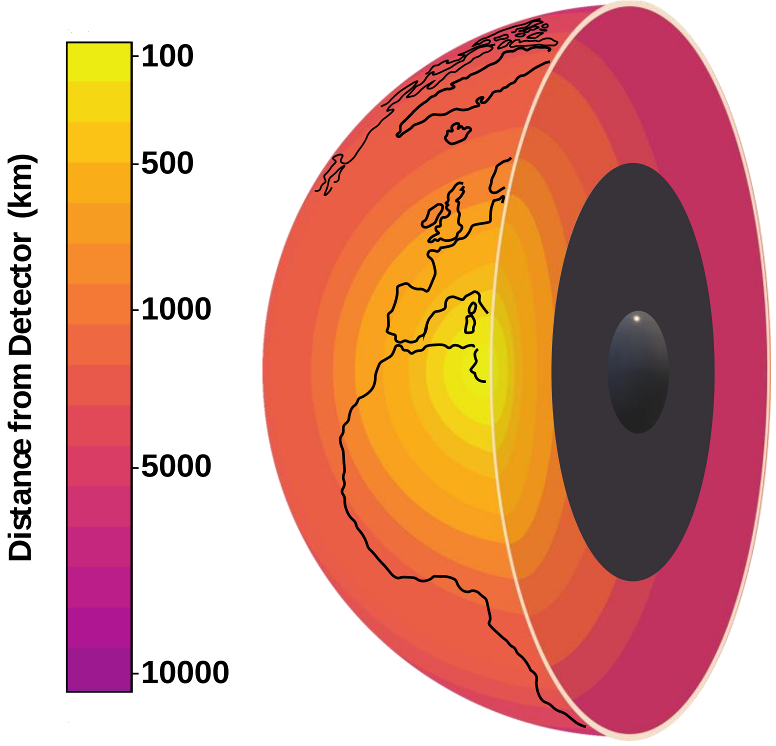


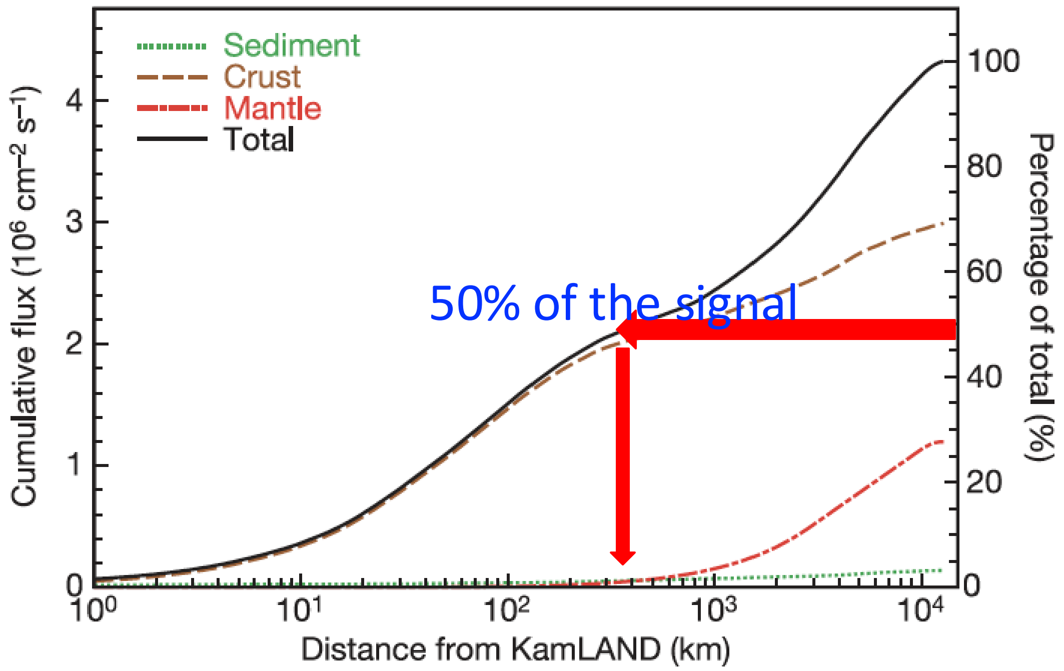




$$S_{total} = S_{lithosphere} + S_{mantle} + S_{core}$$

$$S_{lithosphere} = S_{Near\ Field\ Lithosphere} + S_{Far\ Field\ Lithosphere}$$





$$S_{total} \propto \int_{V\oplus} \frac{\alpha[U] + \beta[Th]}{r^2}$$

"… Borexino estimate of the total radiogenic heat of the Earth is $38.2^{+13.6}_{-12.7}$ TW…" Borexino collaboration (2020, PRD)

Quantifying Earth's radiogenic heat budget

Laura G. Sammon [a,*], William F. McDonough [a,b]

Earth and Planetary Science Letters 593 (2022) 117684

Italian surface rocks

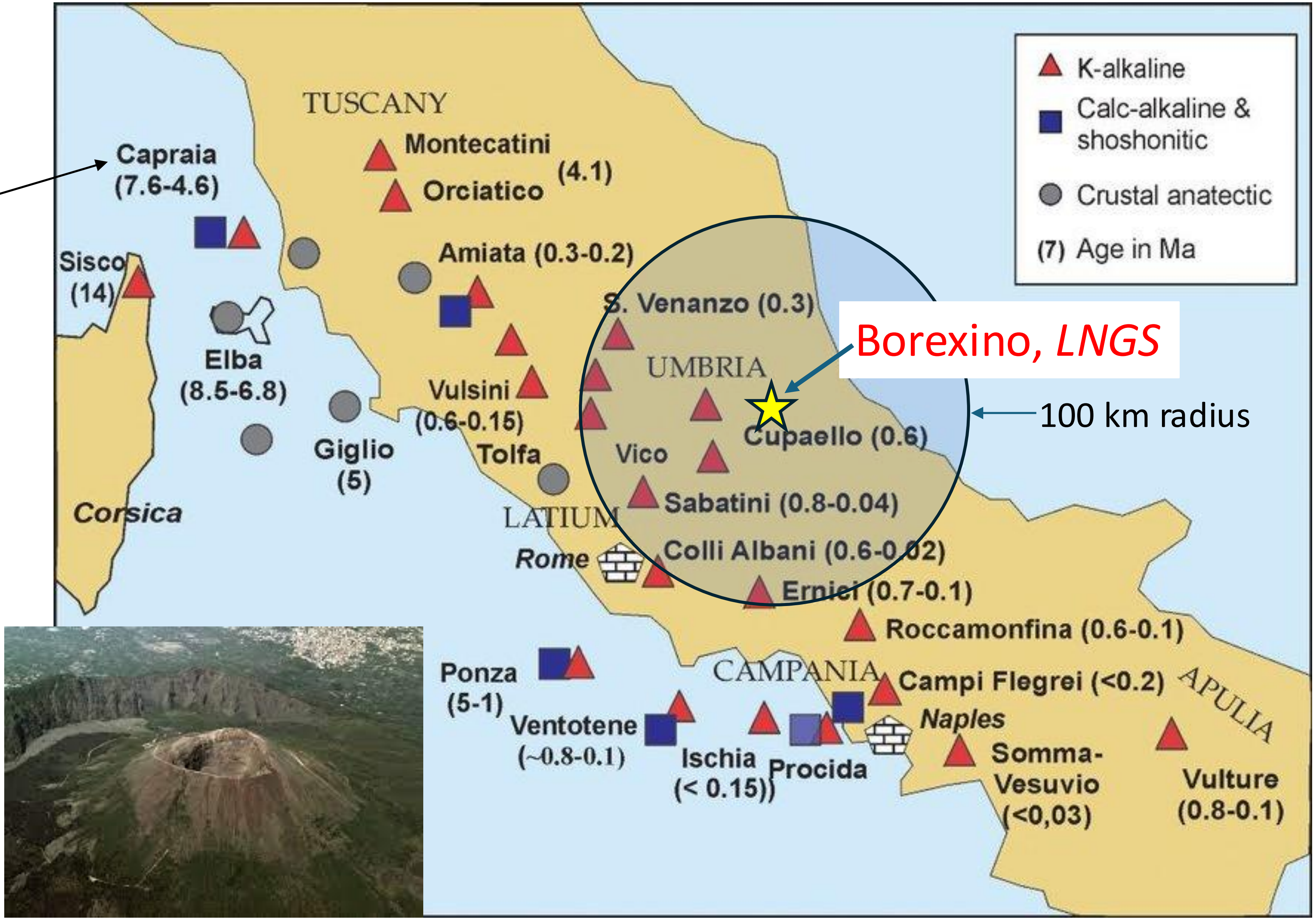
Names of volcanoes
ages (Myrs)

Median Concentration (ppm)		count
Th	35.0	2808
U	8.5	1854

Avg. upper crust: Th 10.5 ppm
U 2.7 ppm

Th/U values		count
Th/U	4.1 ± 3.4	1845
Kappa	4.2 ± 3.5	1845
$Kappa_{Pb}$	4.06 ± 0.07	386

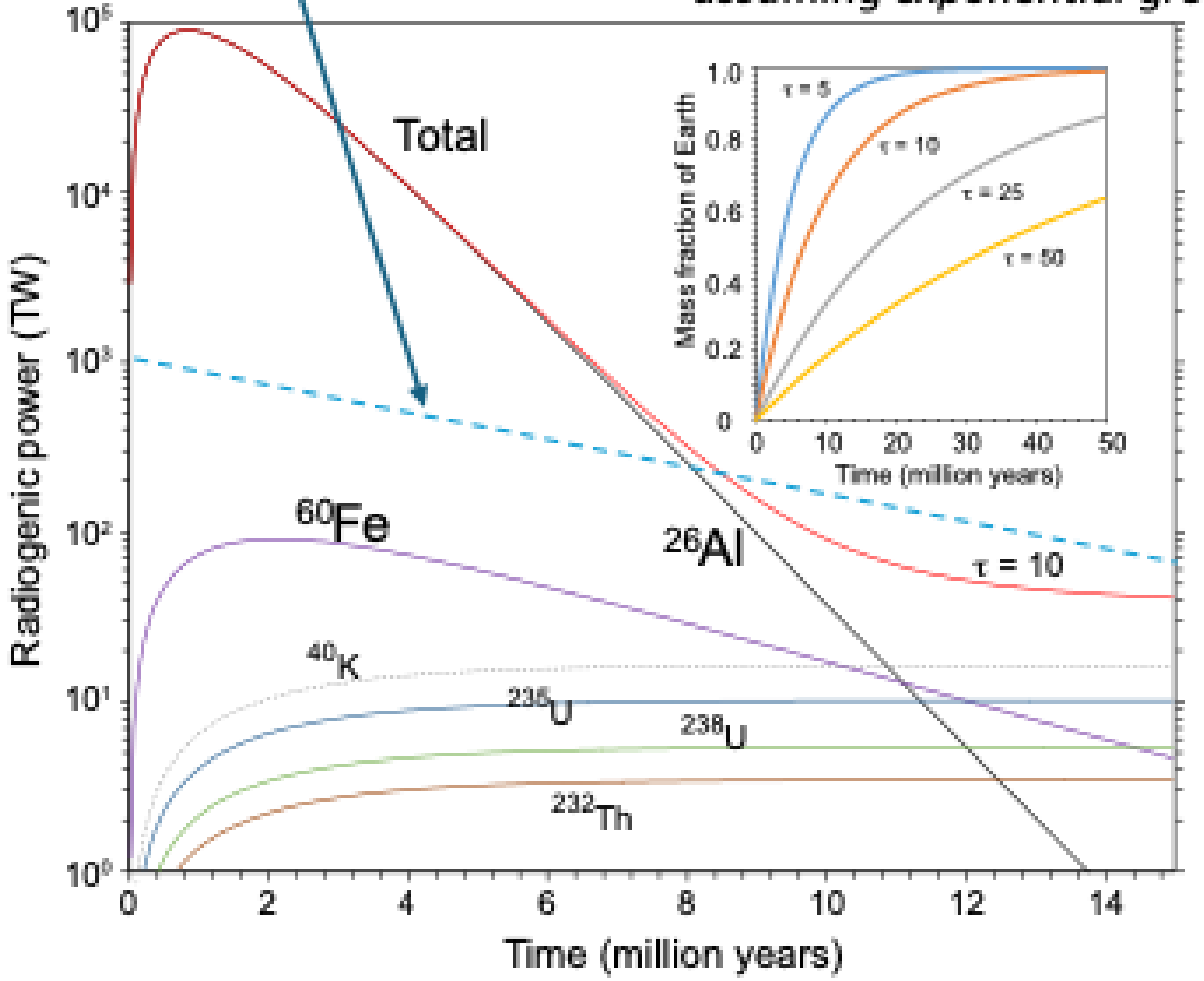
It is important to do the geology!



Agostini et al., (2020; Phys Rev D) reported no surface igneous rocks in the region!!!

Simple primordial accretion energy curve

$M_{(t)}/M_{final} = 1 - \exp(-t/\tau)$
assuming exponential growth



assumes Earth's $\tau_{accretion}$ = 10 million years

first 15 million years

Model reported in McDonough et al 2020

Thermal evolution of the Earth

Current condition

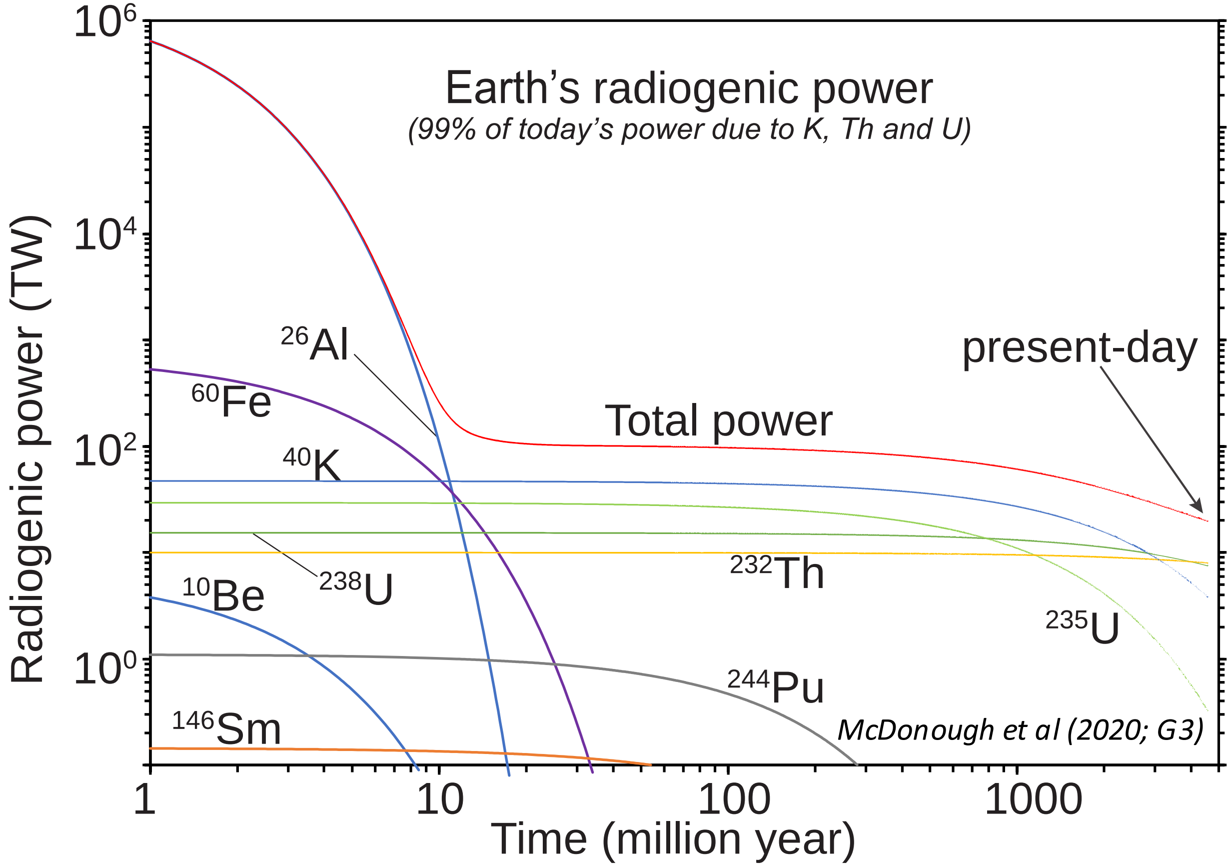
Earth's heat flux	TW
$^{total}Q_{surface\ flux}$	46
$^{core}Q_{cooling}$	13
$^{mantle}Q_{cooling}$	13
$^{mantle}Q_{radiogenic\ heating}$	13*
$^{crust}Q_{radiogenic\ heating}$	7*

**assuming McDonough and Sun (1995, CG) Earth model*

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

assuming exponential growth

Earth's τ age = 10 Ma



Current state

- KL counting, but negligible change
- BX finished
- SNO+ counting (exciting!)
- <u>**JUNO: 2 NFL estimates**</u>

  Strati et al (2015)

  Wipperfurth et al (2020)

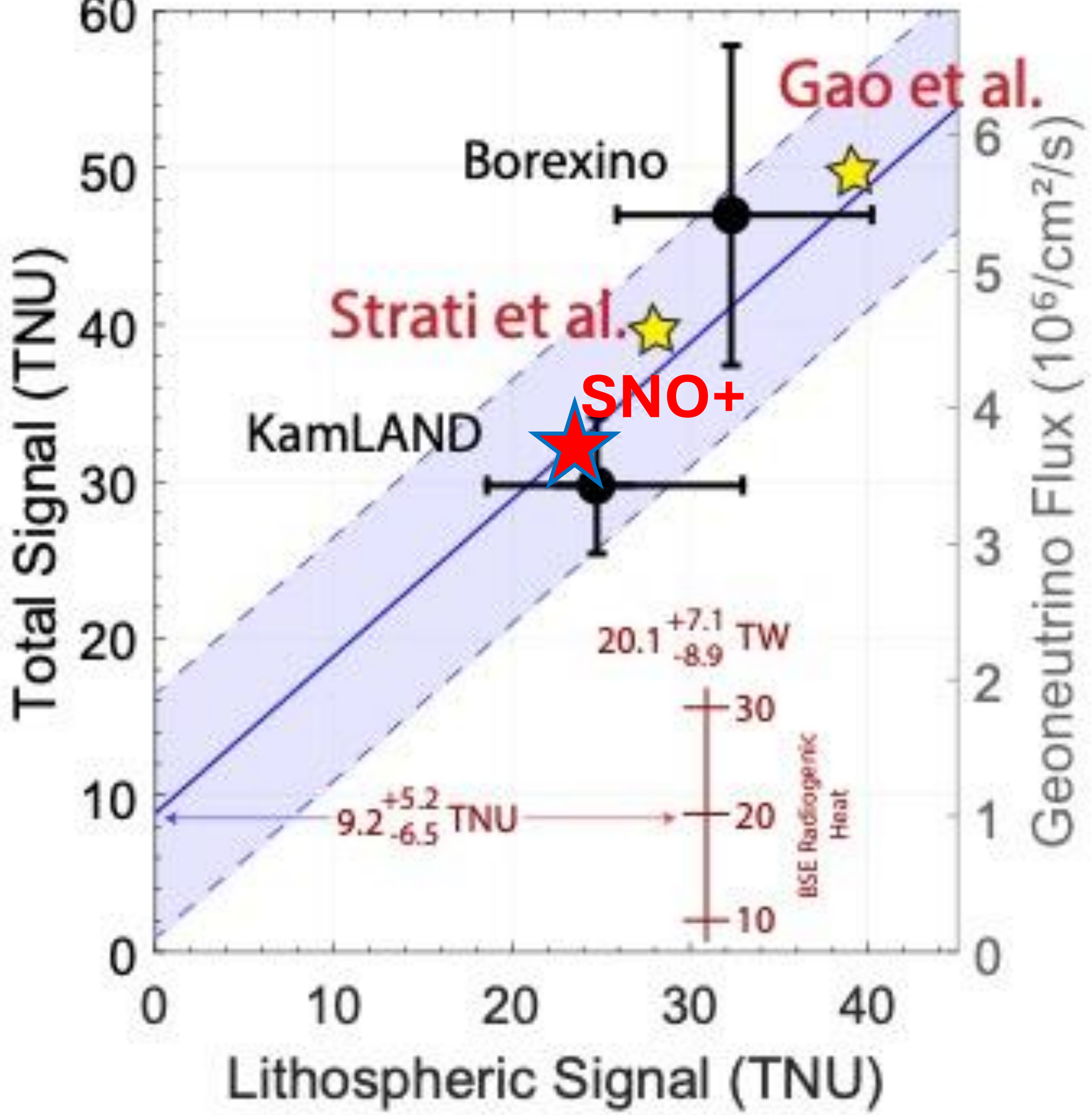
  vs

  Gao et al (2020)

<u>What is next?</u>

- JUNO begins counting 8/25
- SNO+ reports results 2025

McDonough and Sammon (2024, review)



SUMMARY

Earth's radiogenic (K, Th & U) power *(assuming Th/U=3.9; K/U = 14,000)*

21^{+7}_{-8} TW - Borexino 20^{+6}_{-7} TW – KamLAND

: 20^{+7}_{-9} TW, 20.5 ppb U, 77 ppb Th, & 2.7 x CI abundances

-- Future is bright—

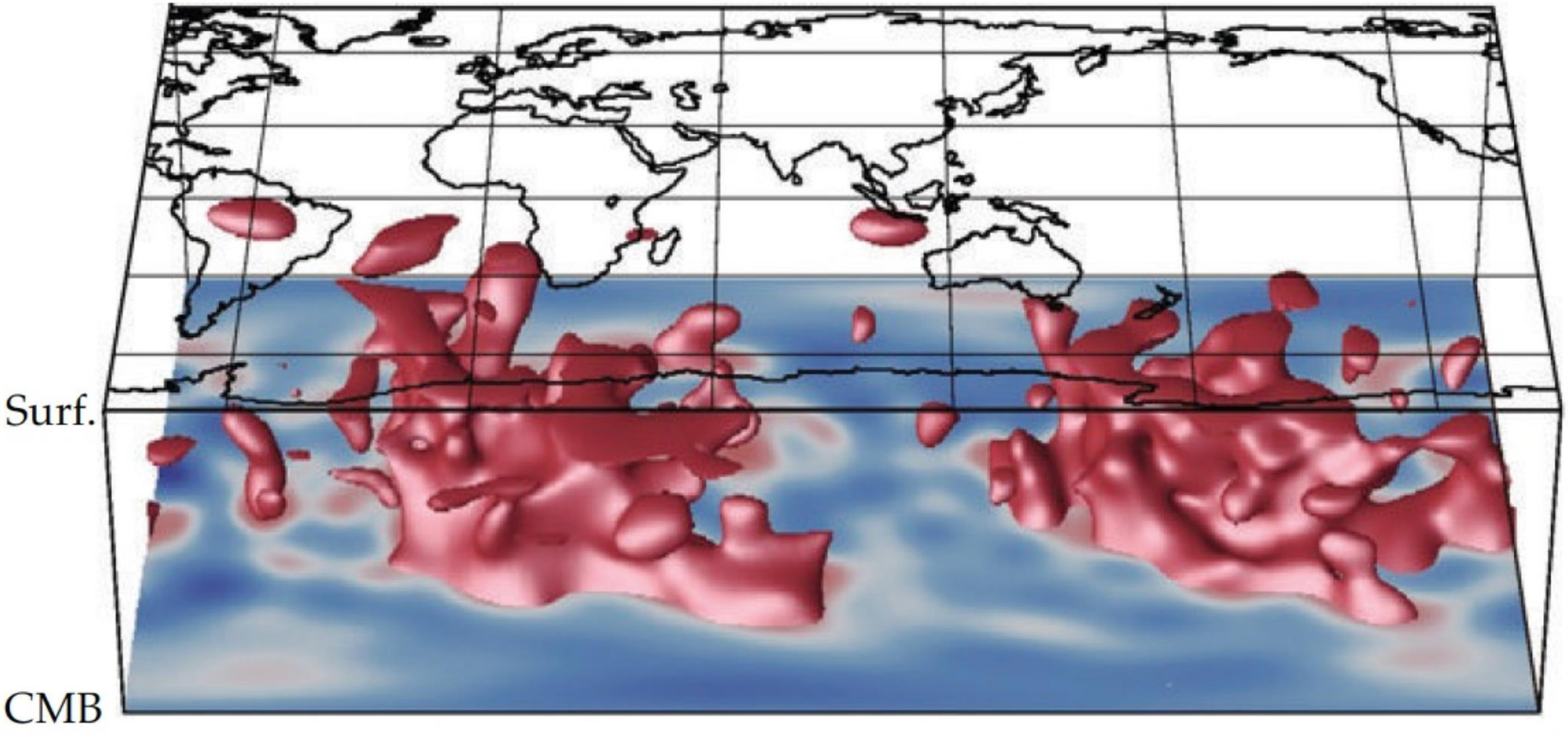
On-line and next generation GEO-NEUTRINO experiments:

- **SNO+** online since late 2022, ☺ expects to report 2025
- **JUNO**: 2025, enormous detector & big background…
- **CJPL**: 2030(?), superb experiment, great for crust & mantle
- **OBD**: looks only at the mantle

What's hidden in the mantle?

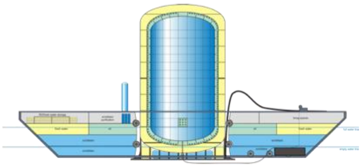
Can we image it with geonus?

Seismically slow "red" regions in the deep mantle

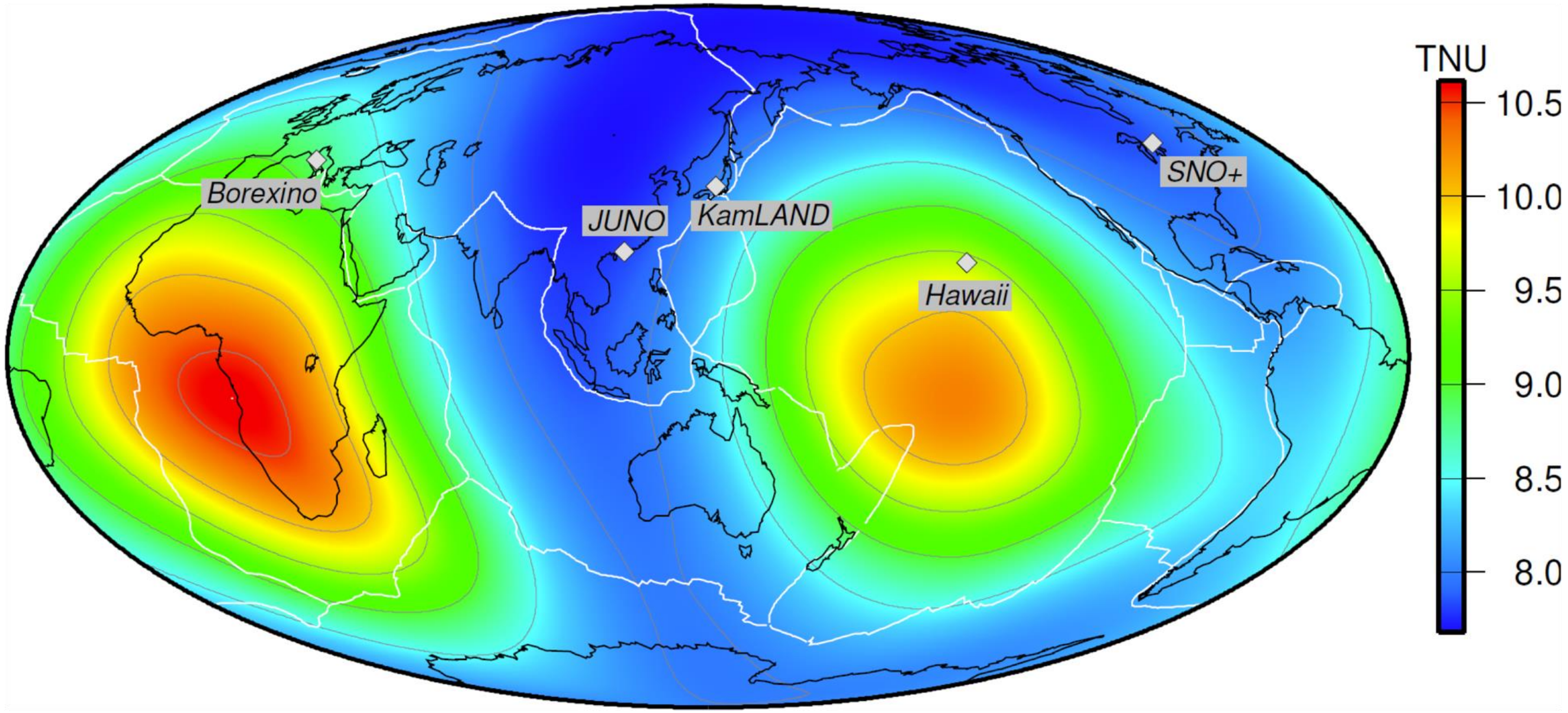


From Alan McNamara after Ritsema et al (Science, 1999)

Testing Earth Models



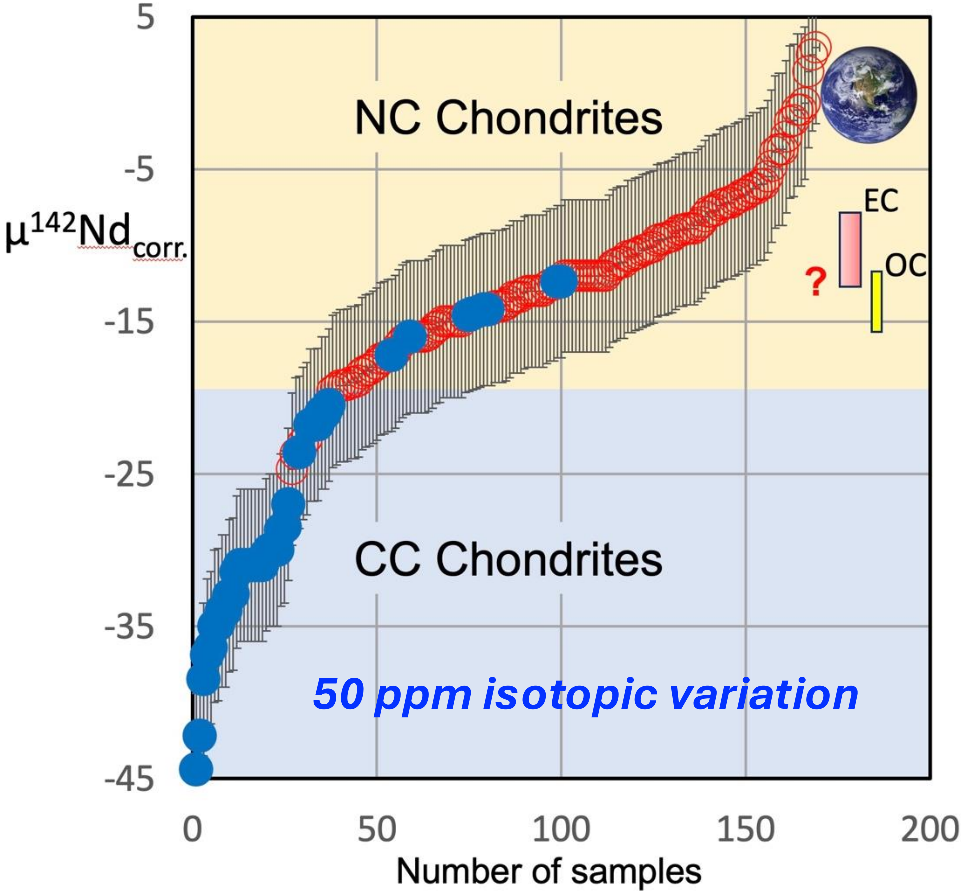
Mantle geoneutrino flux (^{238}U & ^{232}Th)



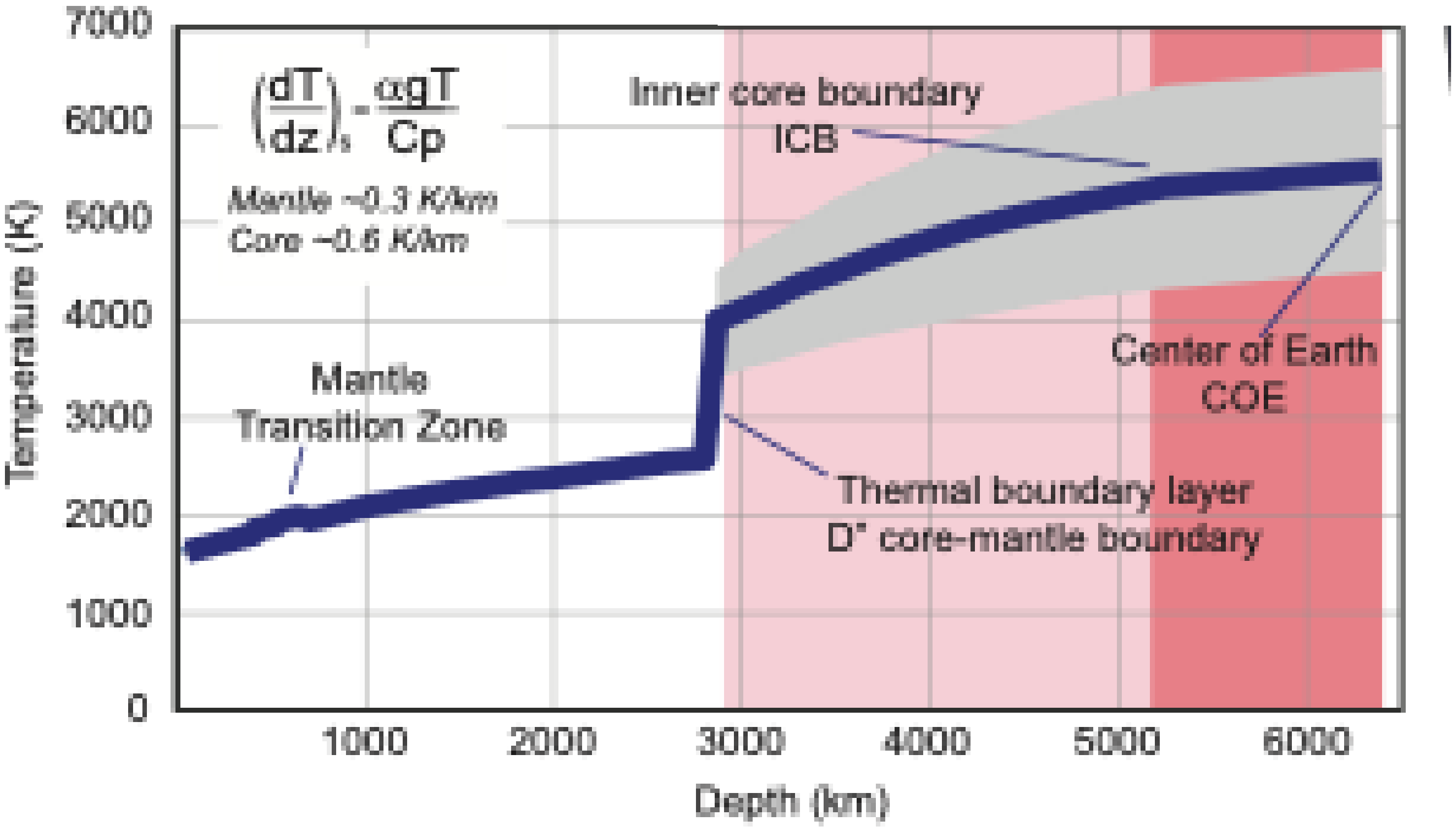
Šrámek et al (2013) EPSL, 361: 356–366, [10.1016/j.epsl.2012.11.001](https://doi.org/10.1016/j.epsl.2012.11.001)

Heat budget

Neutrino data constrains the sources of radiogenic energy



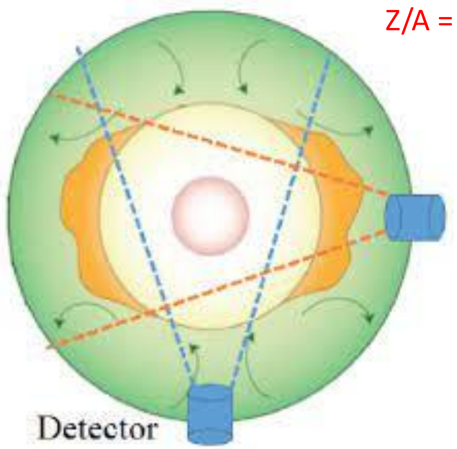
Can we measure temperature at depth in the Earth?

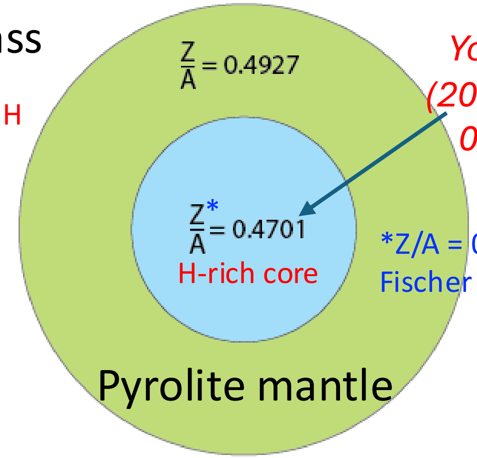


Electron density:
testing the H content of the Earth

Z = proton#, A = atomic mass

Z/A = 1 for H
Z/A = 0.5



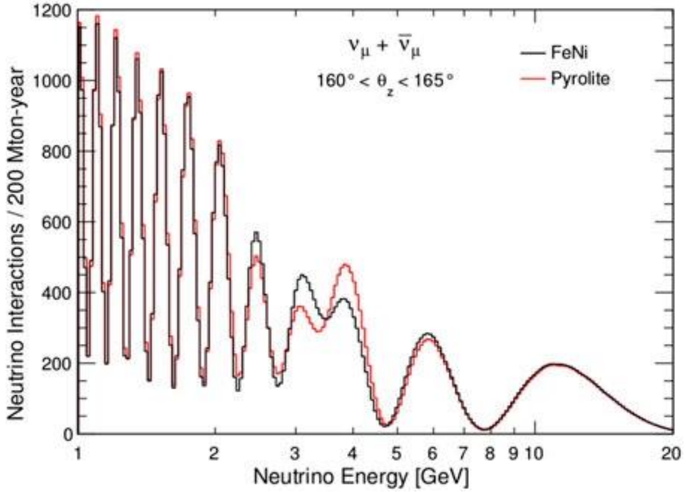


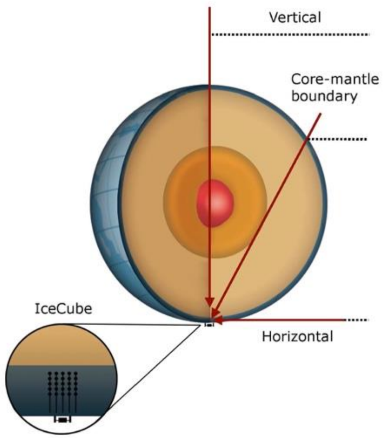
Young et al. (2023; Nature) 0.5 wt% H

*Z/A = 0.4611
Fischer & McDonough 2025

Neutrino oscillation studies

B 2-8 GeV oscillation spectrum

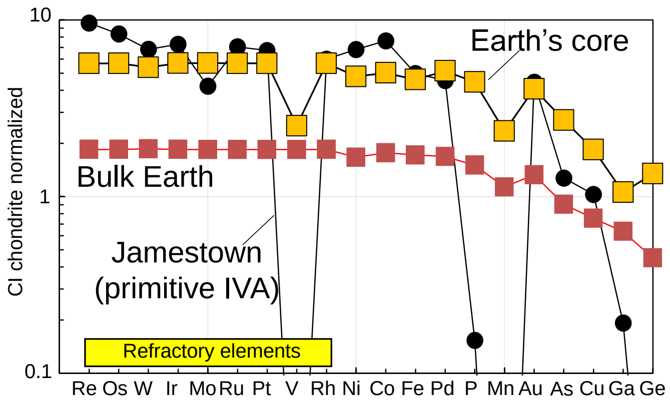




Earth's core

Radius :	3483 ± 5 km
Inner core radius:	1220 ± 10 km
Mass:	1.93 x 10^{24} kg
CMB heat flux	60-110 mW/m^2
CMB heat flux	13 ± 3 TW
Ellipticity @ CMB	2.5 x 10^{-3}
Core surface topography	<3 km

Fischer & McDonough, 2025



	* wt%	at %
Fe	85	80
O	1.0	3.3
Si	3.5	6.5
S	3.3	5.5
Ni	5.2	4.6
Co, Cr, P…	1.5	0.02

[#1545010] Tytrice Faison[1] | Laura Sammon[1] | William F McDonough[1,2]

The Geoneutrino Surface Flux Calculator

GEONU is a user-friendly, MATLAB live script for modeling data from geoneutrino experiments; it is used to generate a global prediction for the amount of radioactive power in the mantle.

GEONU uses existing global crust models and is equipped with full descriptions of each coding statement. Users may select from a series of predefined inputs, or define their own!

GEONU boasts a flexible experience where non-specialists can learn step-by-step and experts have full access to customize their model!

https://github.com/LSKgeo/GEONU

Conclusions

Neutrino geophysics provide the following insights:

- Define the compositional model of the **bulk Earth** (e.g., U=15 and Th=55 ppb; Ca = 1.63 wt%, Al = 1.55 wt%)
- Constrain Earth's thermal evolution
- Confirm planet's chondritic ratio of refractory elements (e.g., $(Th/U)_{molar}$ = 3.88) and proportion 2.7* CI