Quarter of century of geoneutrinos & future prospects

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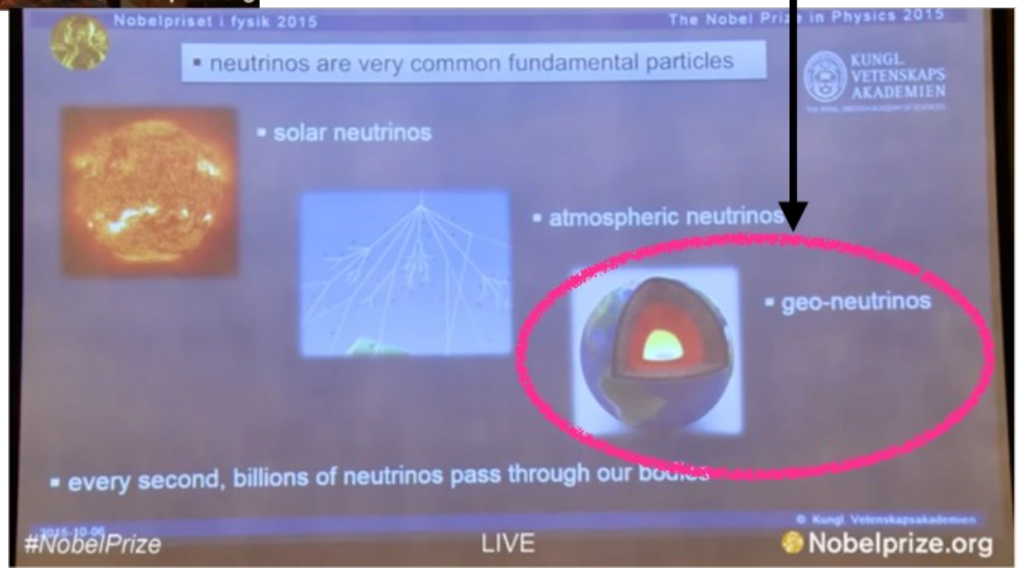
Science with impact

Nobel Prize Winners for 2015 Announced

Geoneutrinos!!!



World Class Science

Charles Lyell
geologist

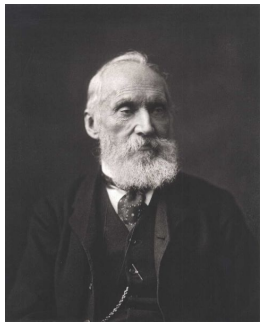
The great debate on the age of the Earth

1860s

Lord Kelvin
physicist

More than a century of collaboration!

AGE OF THE EARTH
thermal evolution



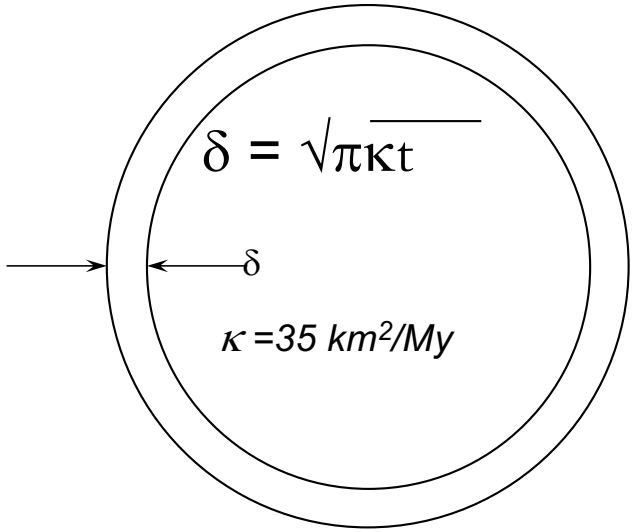
Lord Kelvin

1862

Conductive cooling of a **solid** planet

Age of Earth ~100 My

Heat loss depends on thermal boundary layer thickness δ



John Perry

1895

Conductive cooling of a planet with a **convecting** interior

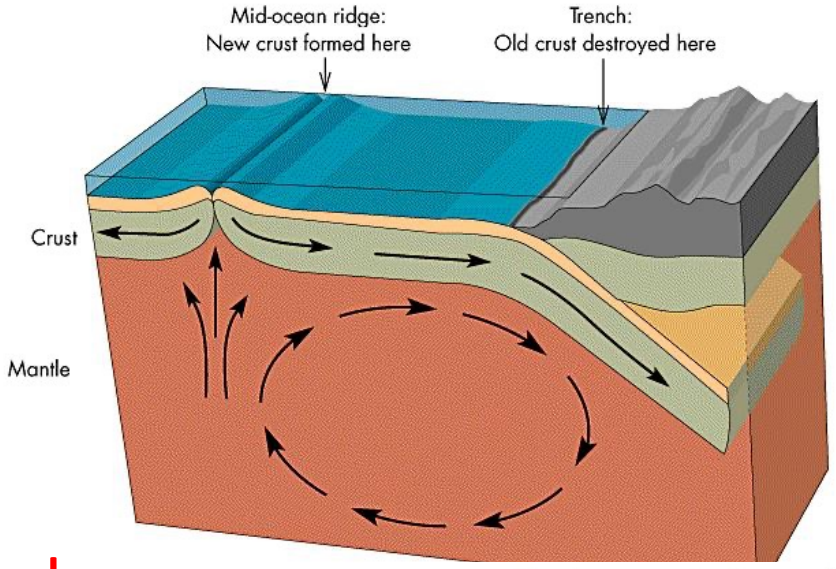
Age of Earth ~1 Gy

Outline

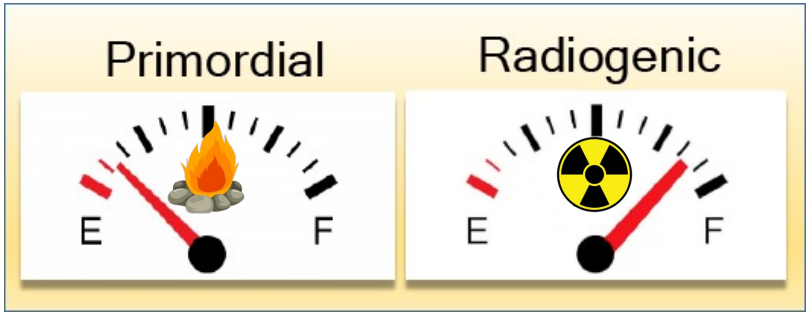
- Surface heat flux: 46 ± 3 TW
- **Primordial** vs **radiogenic** – proportions?
- Continents vs mantle sources
- Measuring the Earth's geoneutrino flux

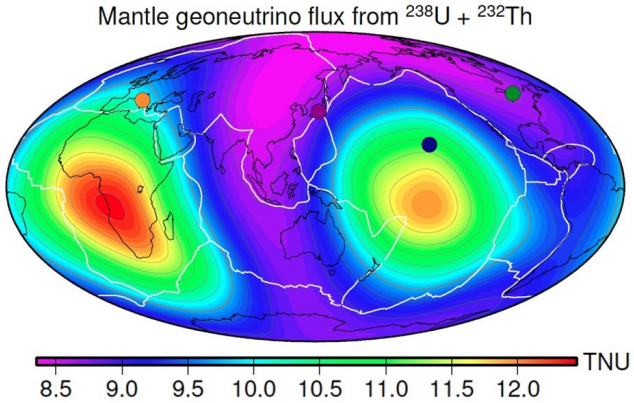
How much fuel is left to drive Plate Tectonics?

46±3 TW



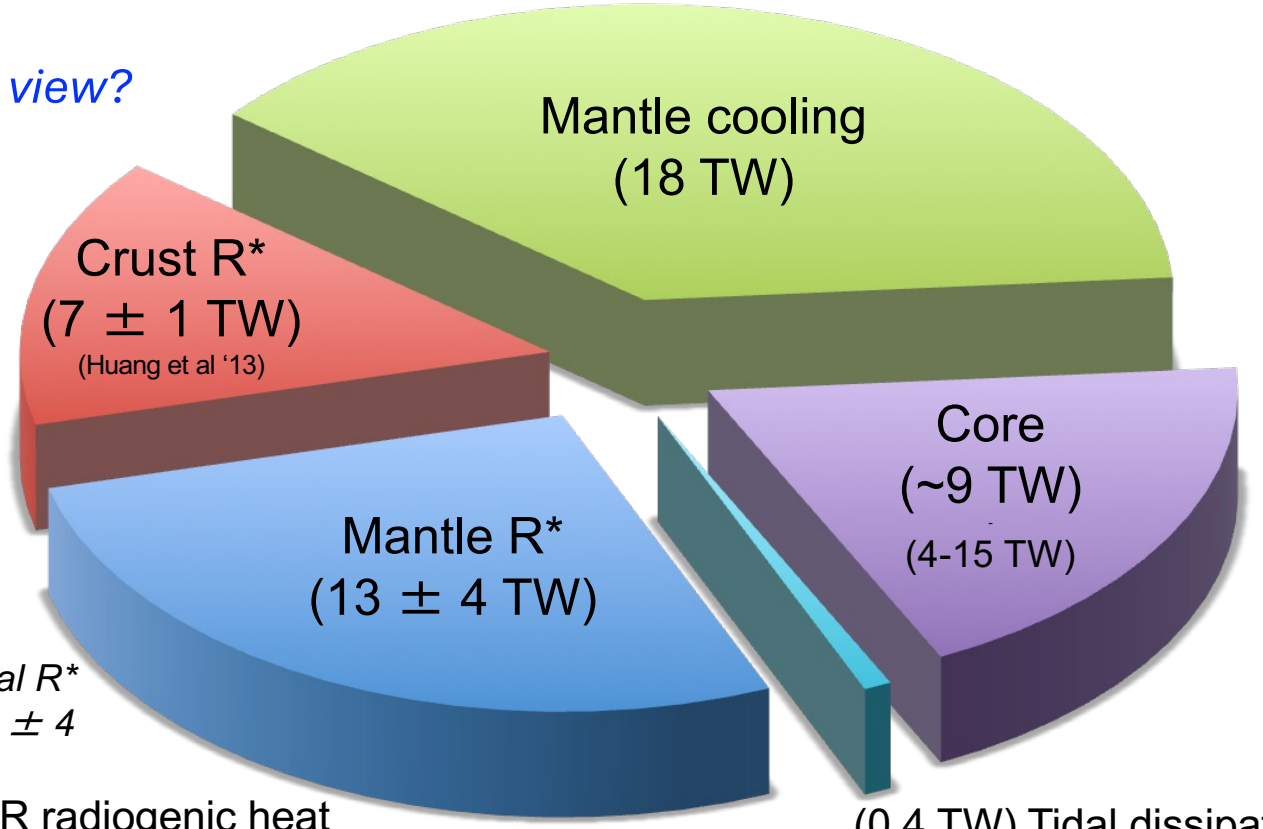
Primary Goal: building a fuel gauge





Earth's surface heat flow 46 ± 3 TW

Conventional view?



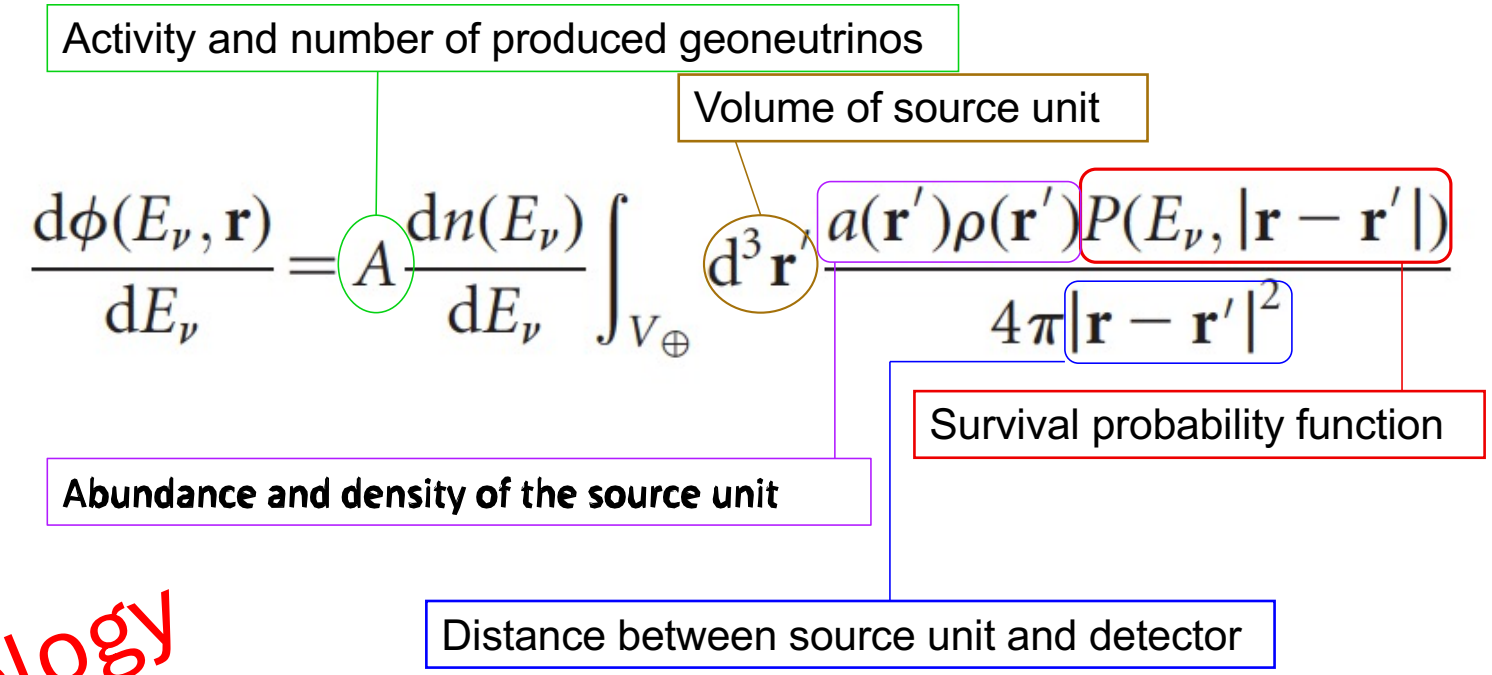
*total R**
20 ± 4

*R radiogenic heat
(after McDonough & Sun '95)

(0.4 TW) Tidal dissipation
Chemical differentiation

after Jaupart et al 2008 Treatise of Geophysics

Geoneutrino Flux on Earth's Surface

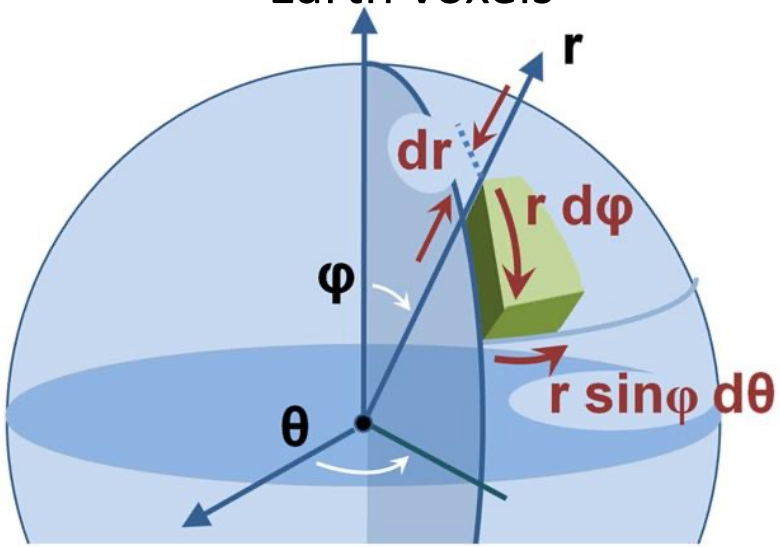


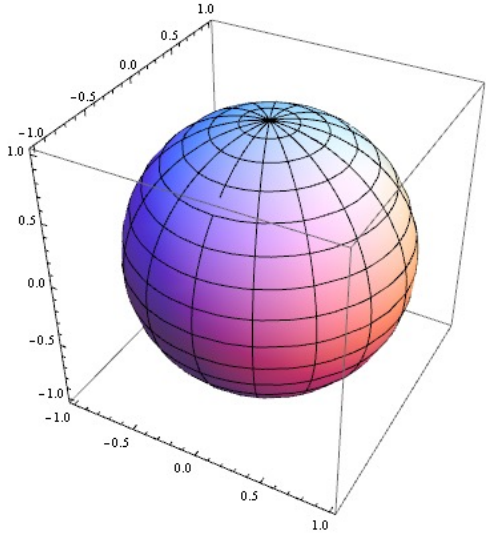
Geology

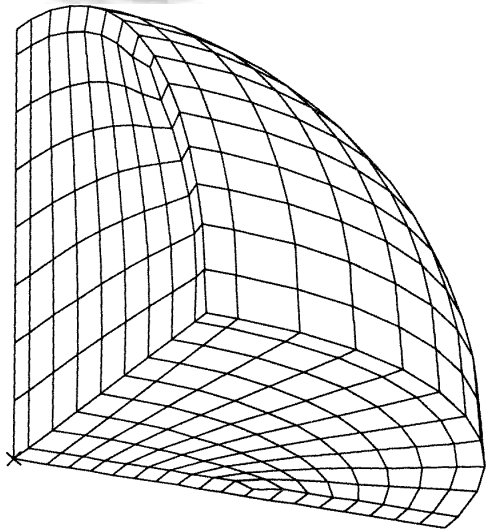
Earth structure (ρ and L) and **chemical composition** (a)

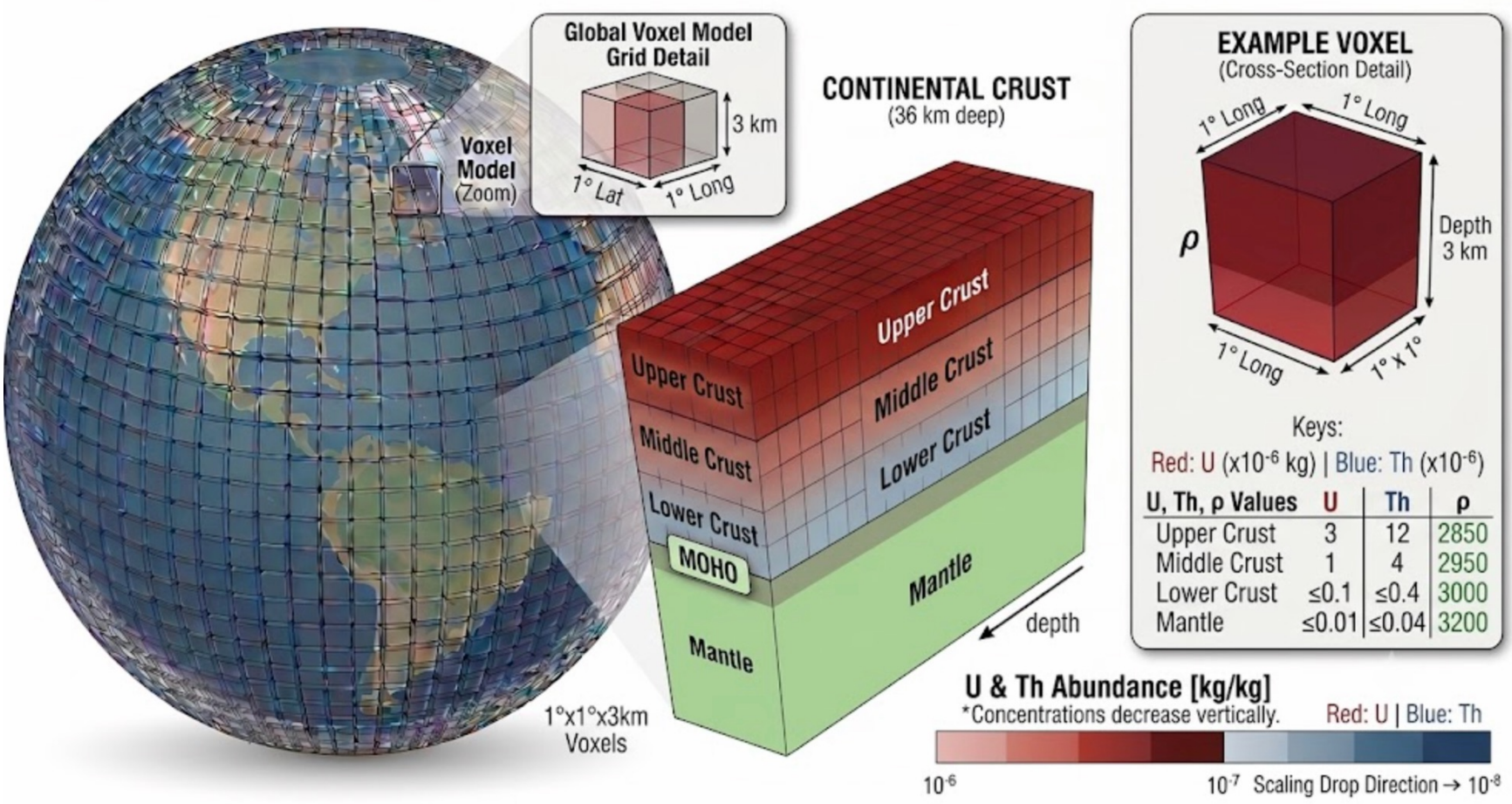
Constructing a 3-D reference model Earth

assigning chemical and physical states to Earth voxels

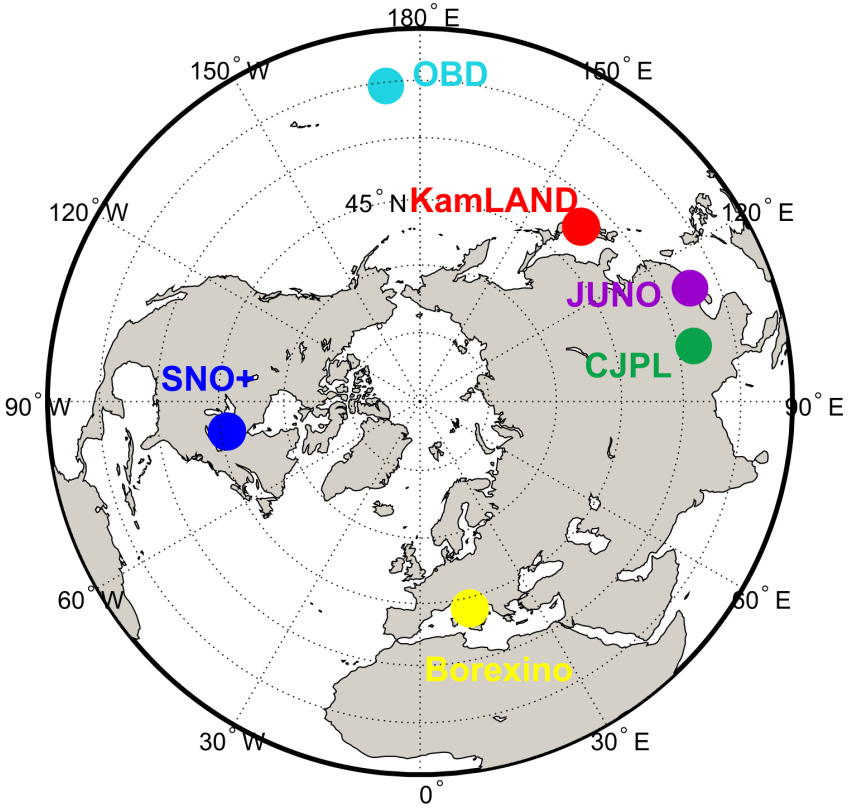







Global Voxel Model
Grid Detail
3 km
1° Lat
1° Long
Voxel
Model
(Zoom)
CONTINENTAL CRUST
(36 km deep)
Upper Crust
Middle Crust
Lower Crust
MOHO
Mantle
depth
1°x1°x3km
Voxels
EXAMPLE VOXEL
(Cross-Section Detail)
1° Long
1° Long
ρ
Depth
3 km
1° Long
1° X 1°
Keys:
Red: U (x10-6 kg) | Blue: Th (x10-6)
U, Th, ρ Values | U | Th | ρ
Upper Crust | 3 | 12 | 2850
Middle Crust | 1 | 4 | 2950
Lower Crust | ≤0.1 | ≤0.4 | 3000
Mantle | ≤0.01 | ≤0.04 | 3200
U & Th Abundance [kg/kg]
*Concentrations decrease vertically.
Red: U | Blue: Th
10-6
10-7 Scaling Drop Direction → 10-8

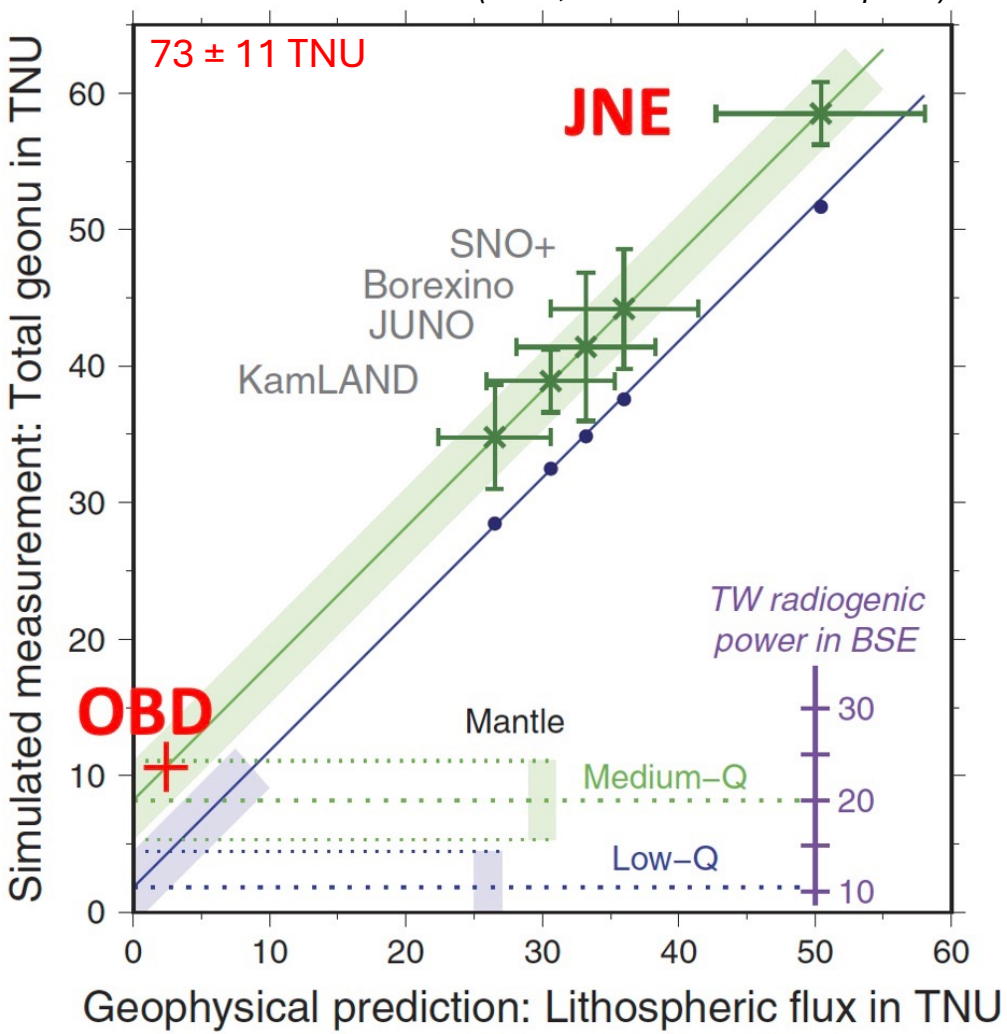
Sammon & McDonough (2022, EPSL)



2 component system

$S_{Mantle} + S_{Lithosphere} = S_{Total}$

Sramek et al (2016, Nature Scientific Reports)



Lessons from Borexino

- Coltorti et al (2011, GCA) initial geological survey
- Their conclusion: low content of Th & U in the crust surrounding Borexino
- Agostini et al (2020, PRD): Earth 38 TW of radiogenic power!

Coral reef ➡ 13 km Limestone rocks

BX upper crust prediction
(no igneous rocks)

- Sammon & McDonough (2022, EPSL): new geological survey

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

Earth has ~20 TW

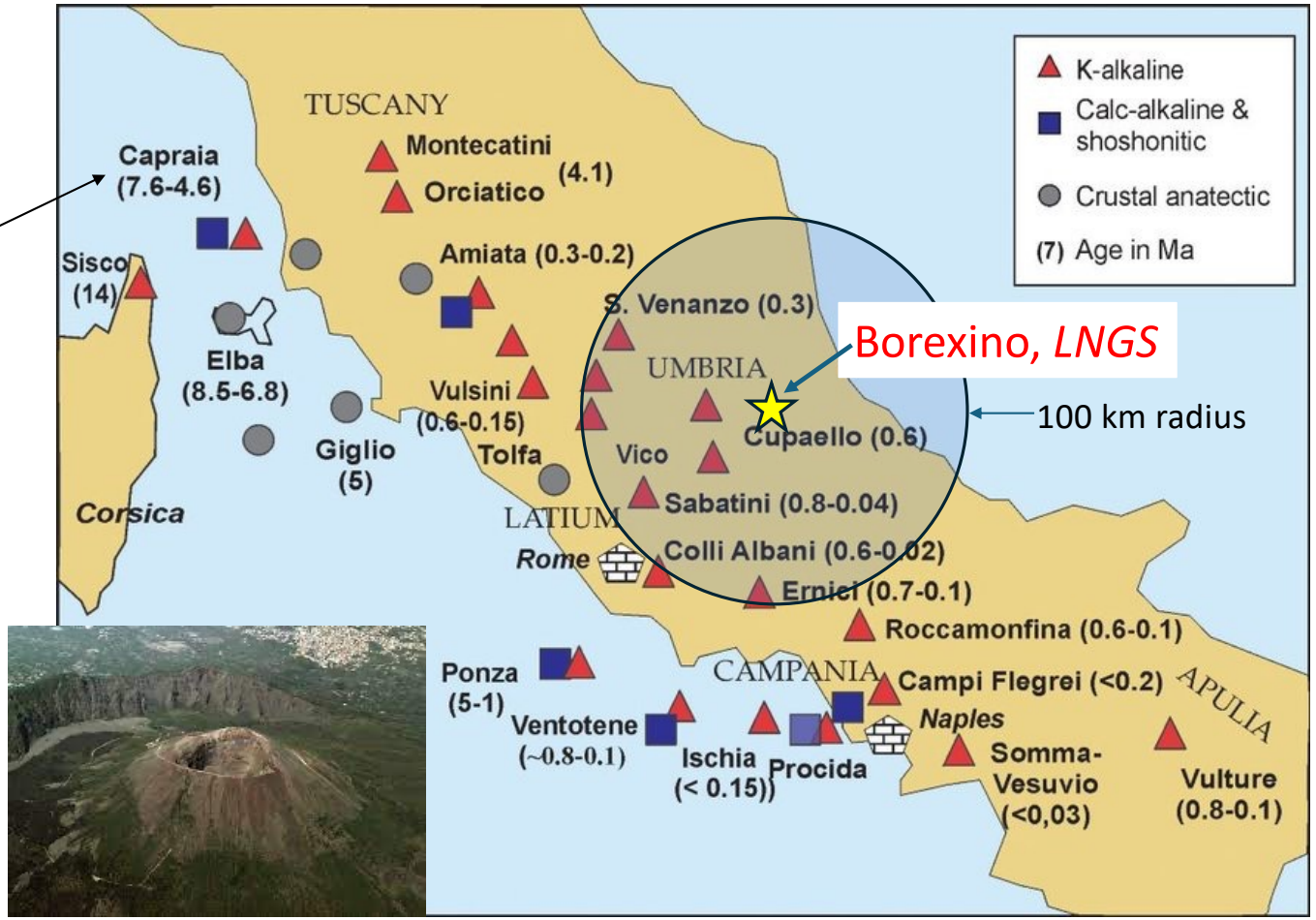
Italian surface rocks

Names of volcanoes
ages (Myrs)

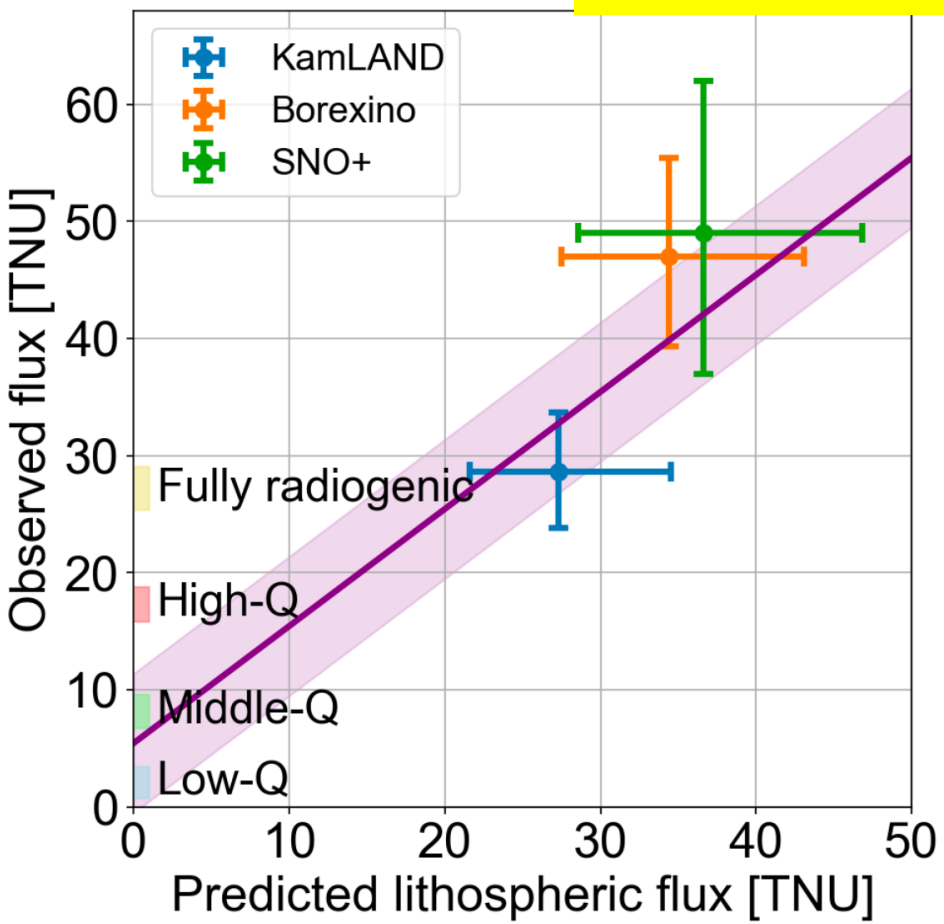
	Median Concentration (ppm)	count
Th	35.0	2808
U	8.5	1854

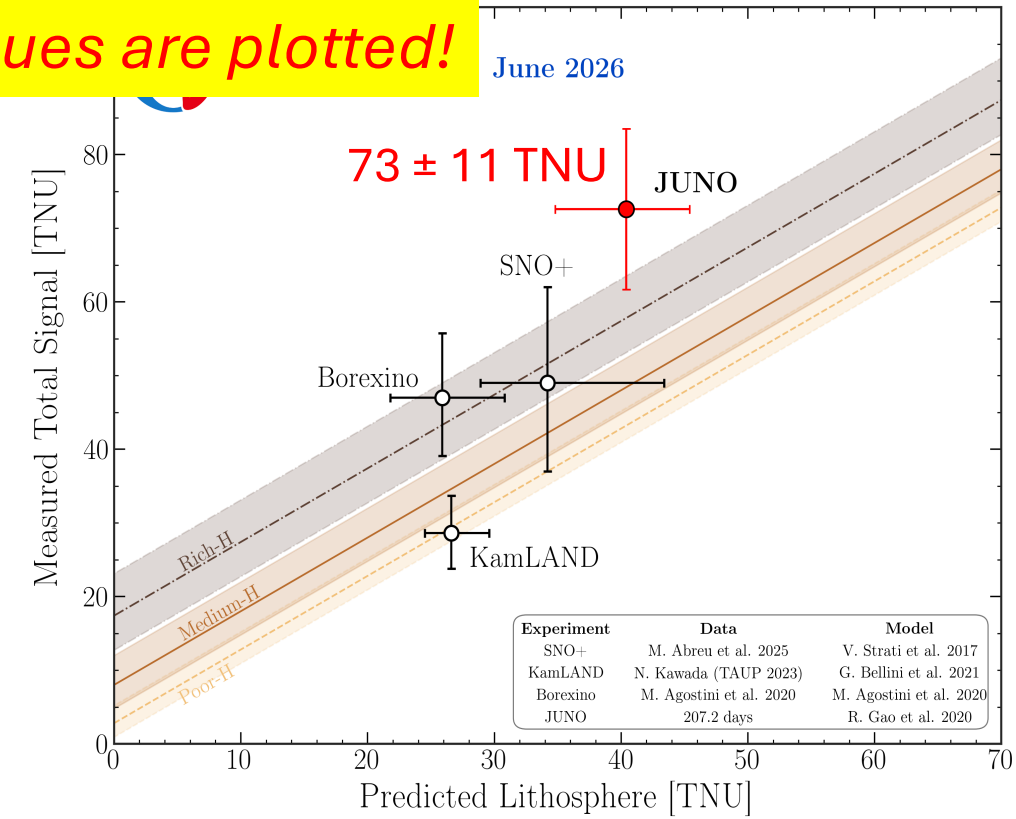
Avg. upper crust: Th 10.5 ppm
U 2.7 ppm

Important to do the geology!



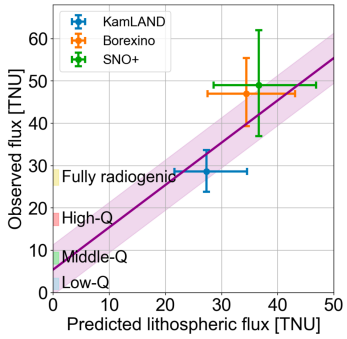
Different values are plotted!





location	Observed (TNU)	reference	Predicted Lithospheric (TNU)
KamLAND*	$28.6^{+5.1}_{-4.8}$	(Abe et al., 2022)	$27.3^{+7.2}_{-5.7}$
Borexino*	$47.0^{+8.4}_{-7.7}$	(Agostini et al., 2020)	$34.4^{+8.7}_{-6.9}$
SNO+*	49.0^{+13}_{-12}	(Abreu et al., 2025)	$36.6^{+10.2}_{-8}$
JUNO**	73^{+11}_{-11}	(Wang, 2026)	40^{+6}_{-6}

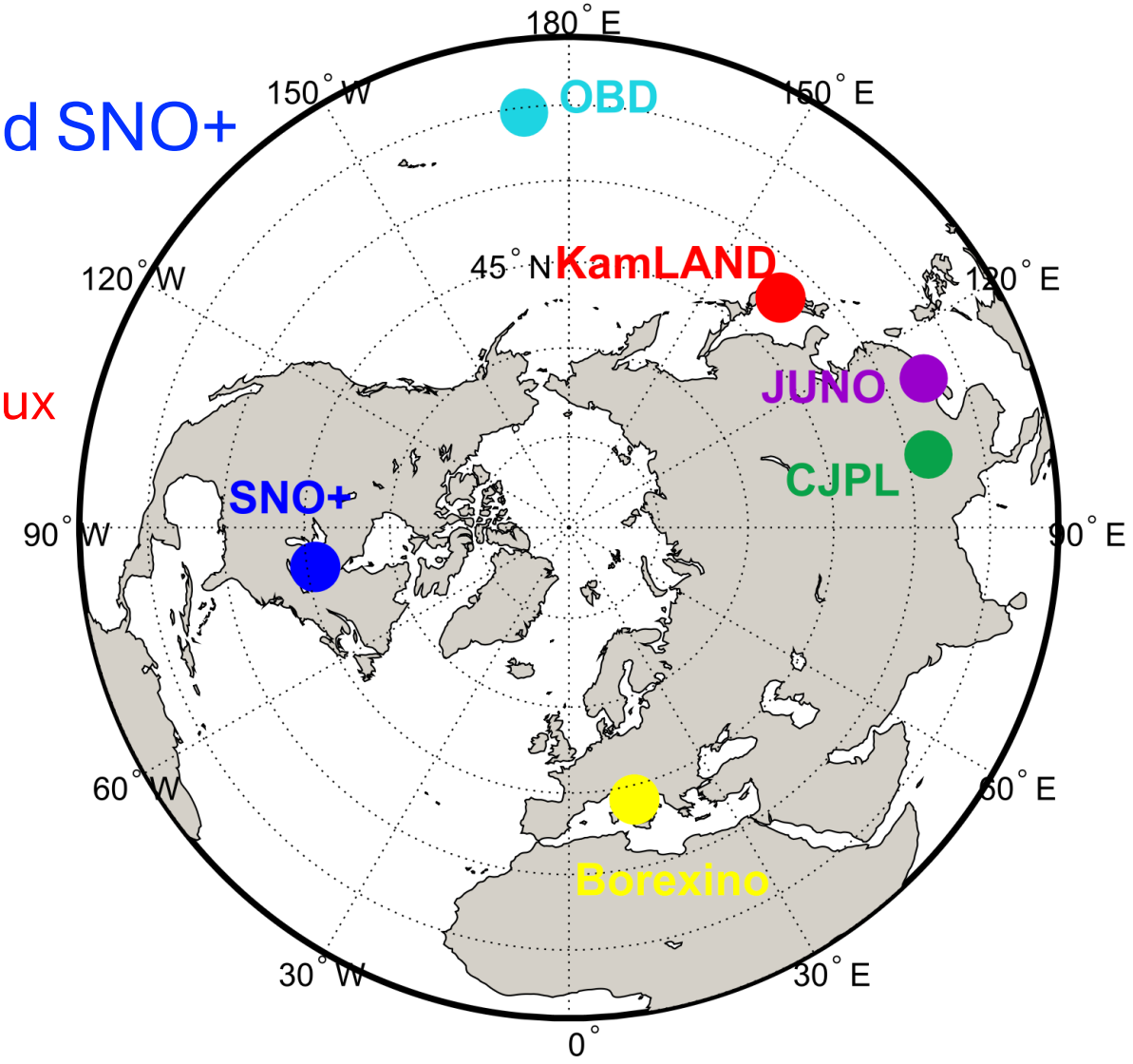
KamLAND, Borexino and SNO+



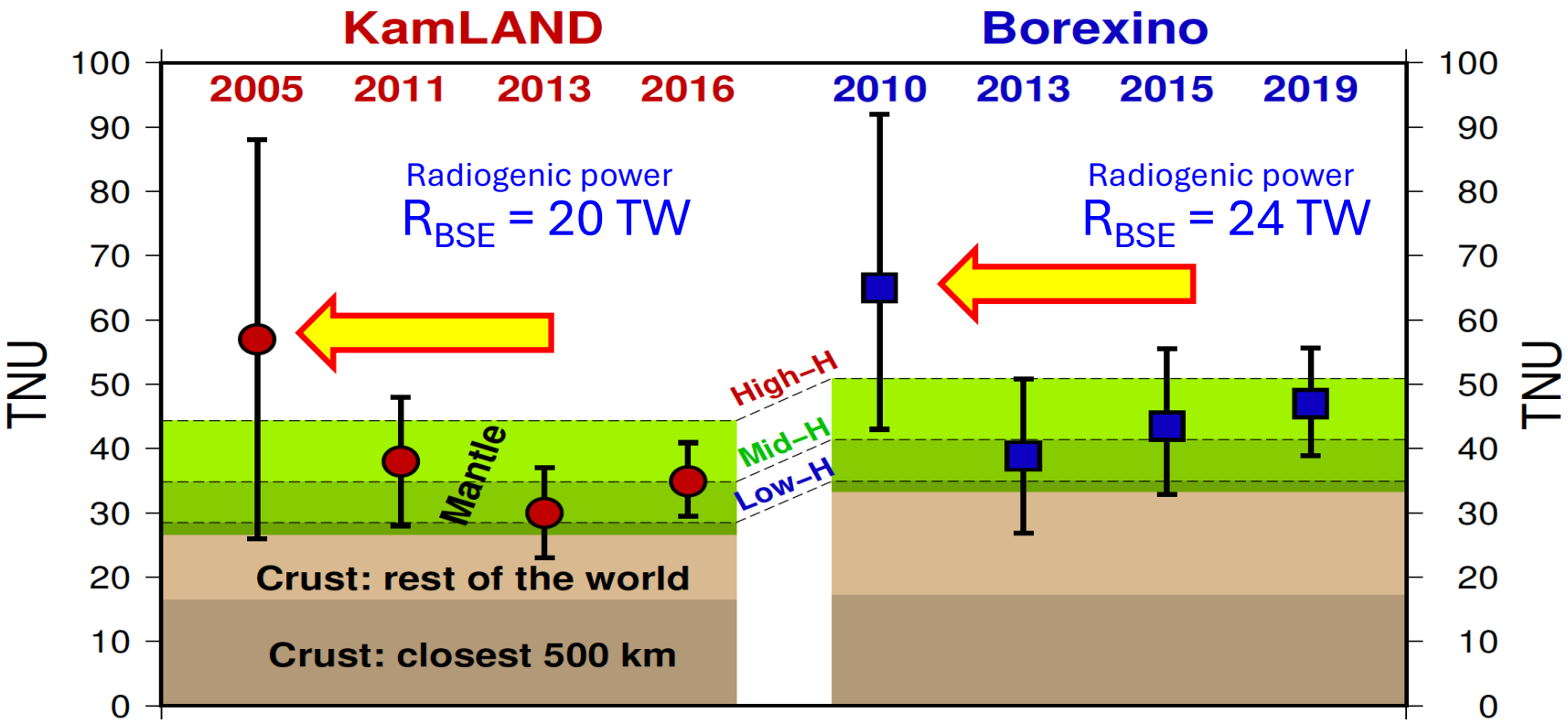
Mantle flux
homogeneous flux
~8 ± 8 TNU

KL – JUNO: separation distance
~ 2/3 of a mantle depth

JUNO high geonu flux possibly due to local geological feature



Evolution of the signal



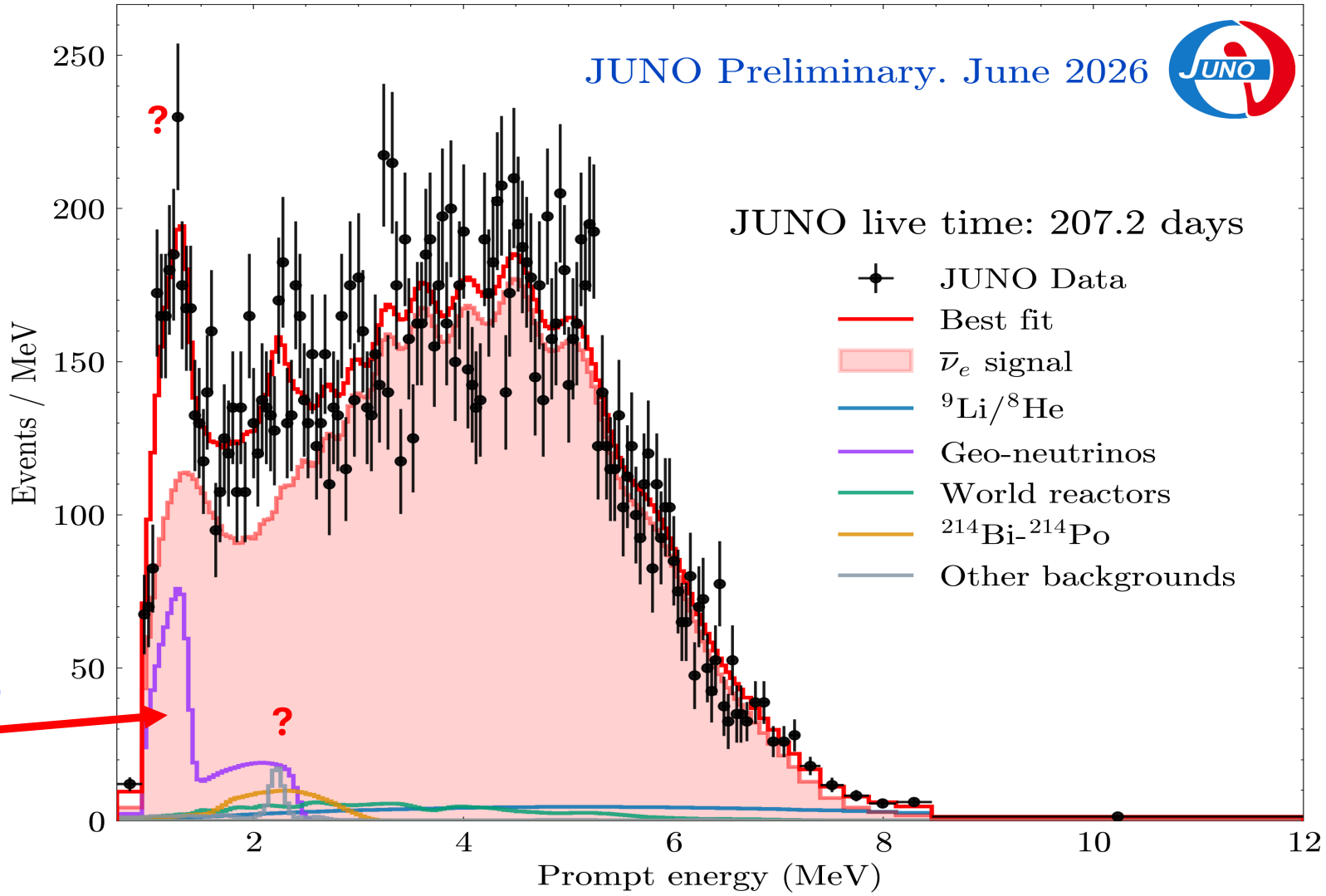
Lessons learned: SNO+

Evolution of SNO+ geoneutrino results:

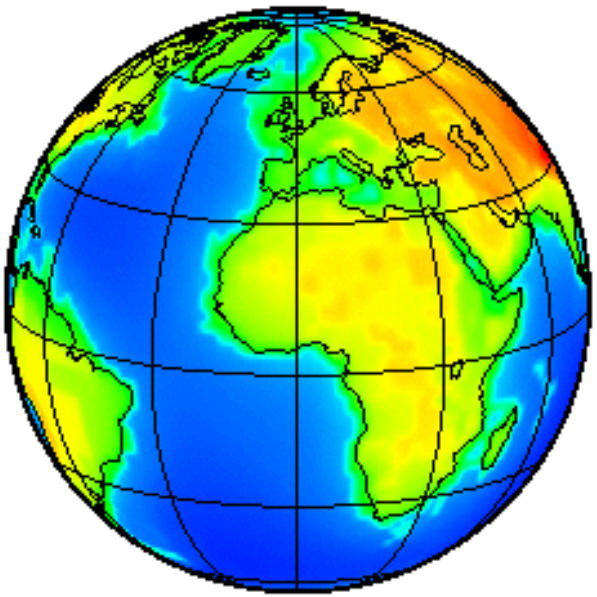
- 2023 Dissertation doc: **109 ± 35 TNU**
- 2024 TAUP and arXiv: **$73\ ^{+47}_{-34}$ TNU**
- 2025 Neutrino G'25: **61 ± 22 TNU**
- 2025 November arXiv : **$49\ ^{+13}_{-12}$ TNU**

Still challenges to be address

Geoneutrino window

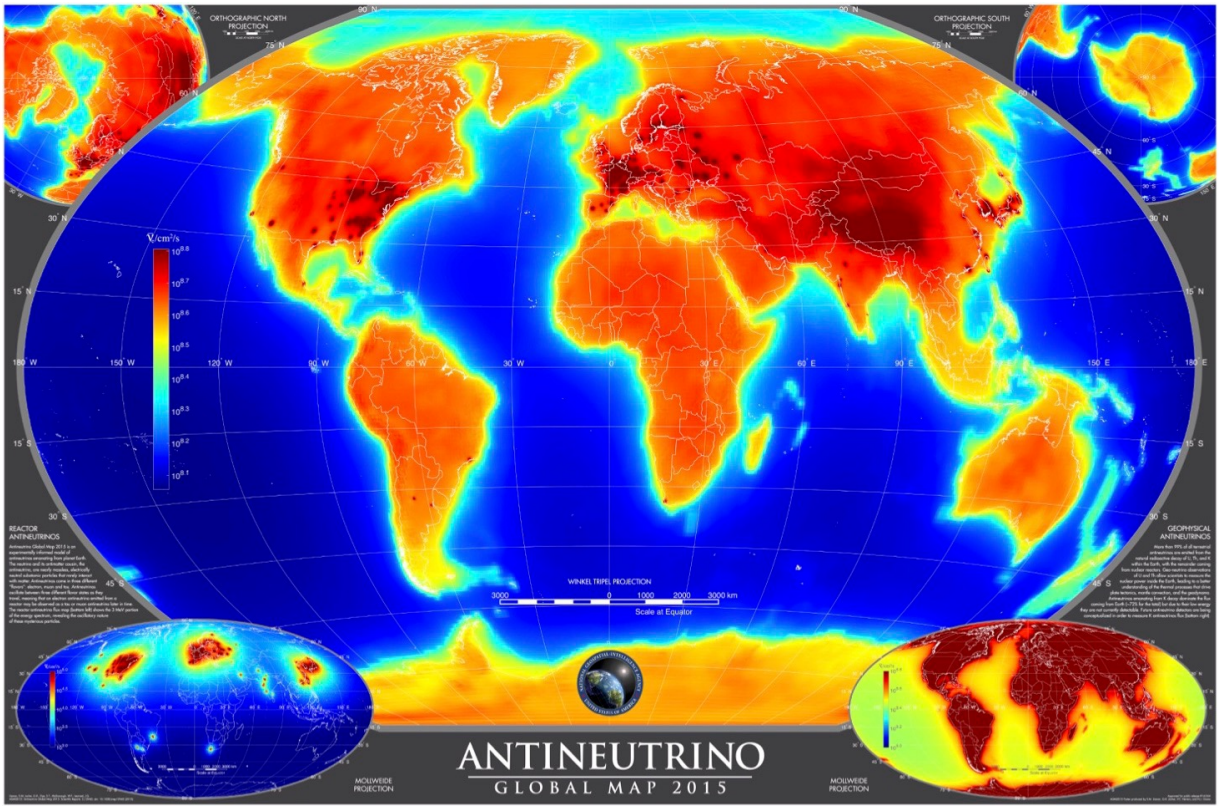


Geoneutrinos: a success story (mostly)



Crust

Antineutrino Map: geoneutrinos + reactor neutrinos



Time-dependent change in mantle temperature (dT/dt)

uncertainties

~23% ~50% ~21%

$$\frac{dT}{dt} = \frac{h_m(t) + Q_c(t) + Q_s(t)}{C_m}$$

~10%

approaching 100%

Future studies

- K geoneutrino detection:

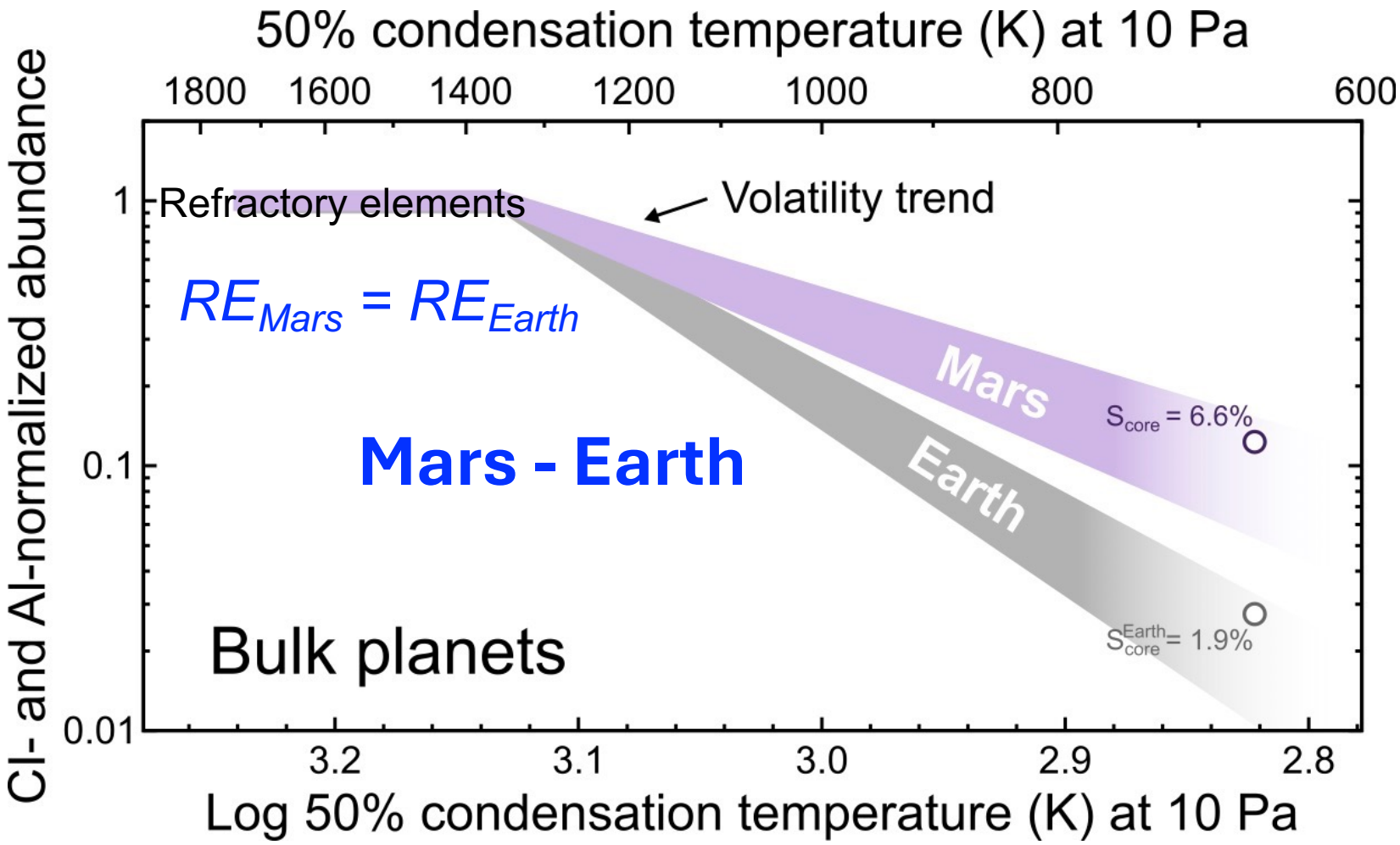
  (*breaking the 1.8 MeV IBD barrier*)

  Discovery-level science

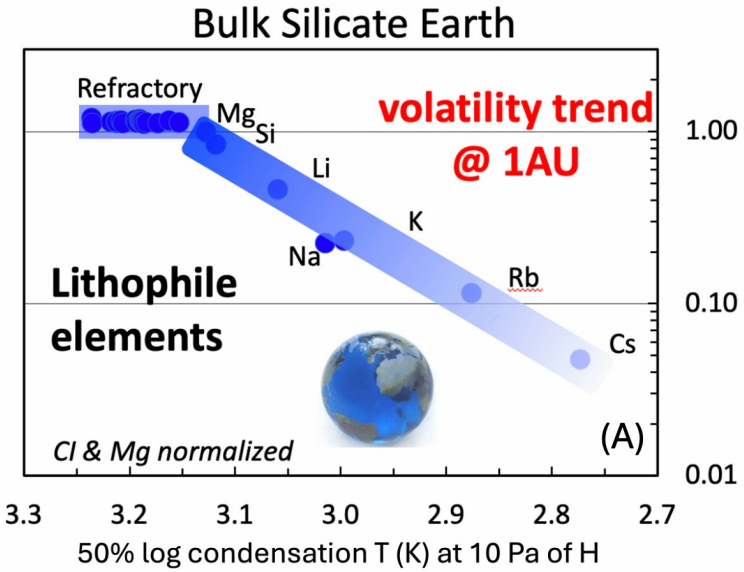
- Ocean bottom detector:

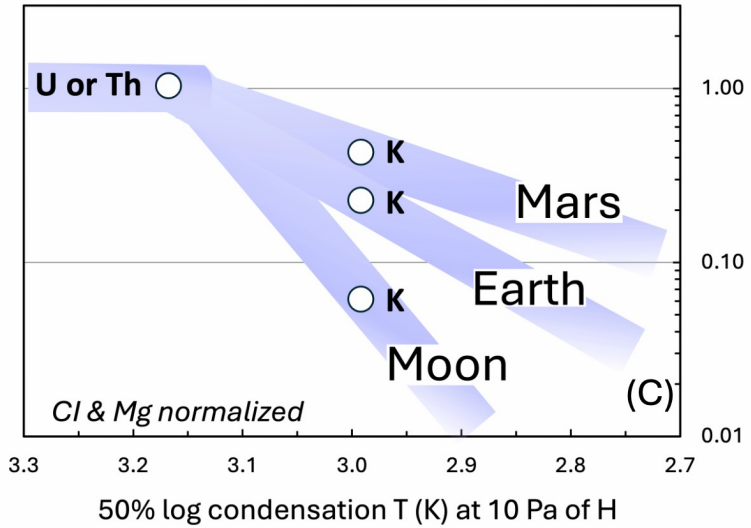
  (*in search of a mantle only signal*)

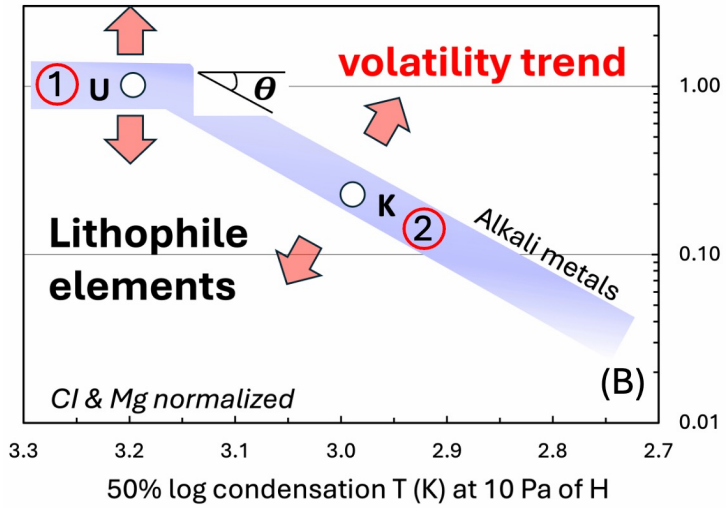
  A Grand challenge



Yoshizaki & McDonough (2021) Geochemistry



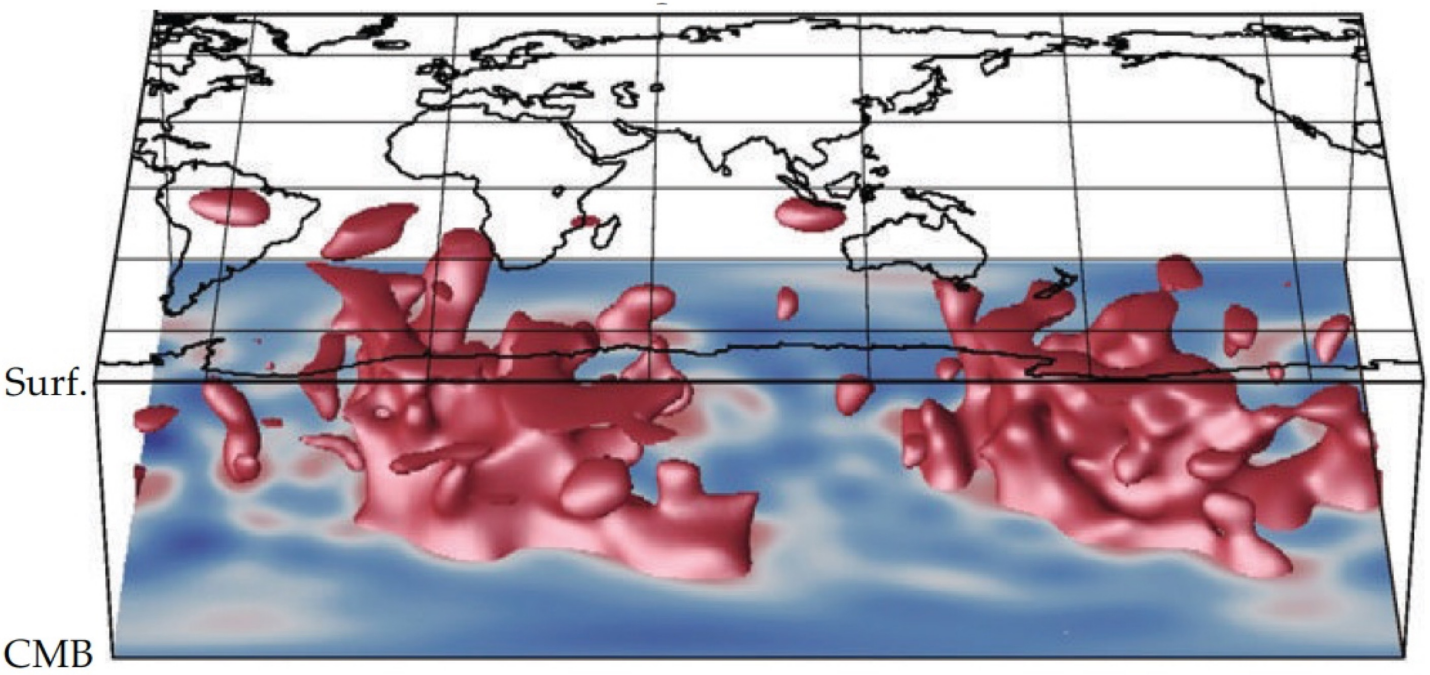




Th/U=3.8*	U (ppm)	K (ppm)	K/U	K/Th
Earth	0.020	260	13,000	3450
Moon	0.020	50	2500	660
Mars	0.018	360	20,000	5300
Mercury*	0.035	450	12,800	5200
Venus	0.020	150	7200	2000

*Th/U = 2.5 ± 0.9 MESSENGER (Peplowski et al., 2011)

Are these structures (**LLSVP**) primordial or recent?



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

Many ideas, few constraints

Denser: Debatable

Compositionally distinct: likely

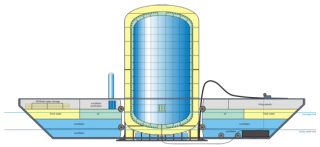
Ancient: could be

Product of recycling: maybe

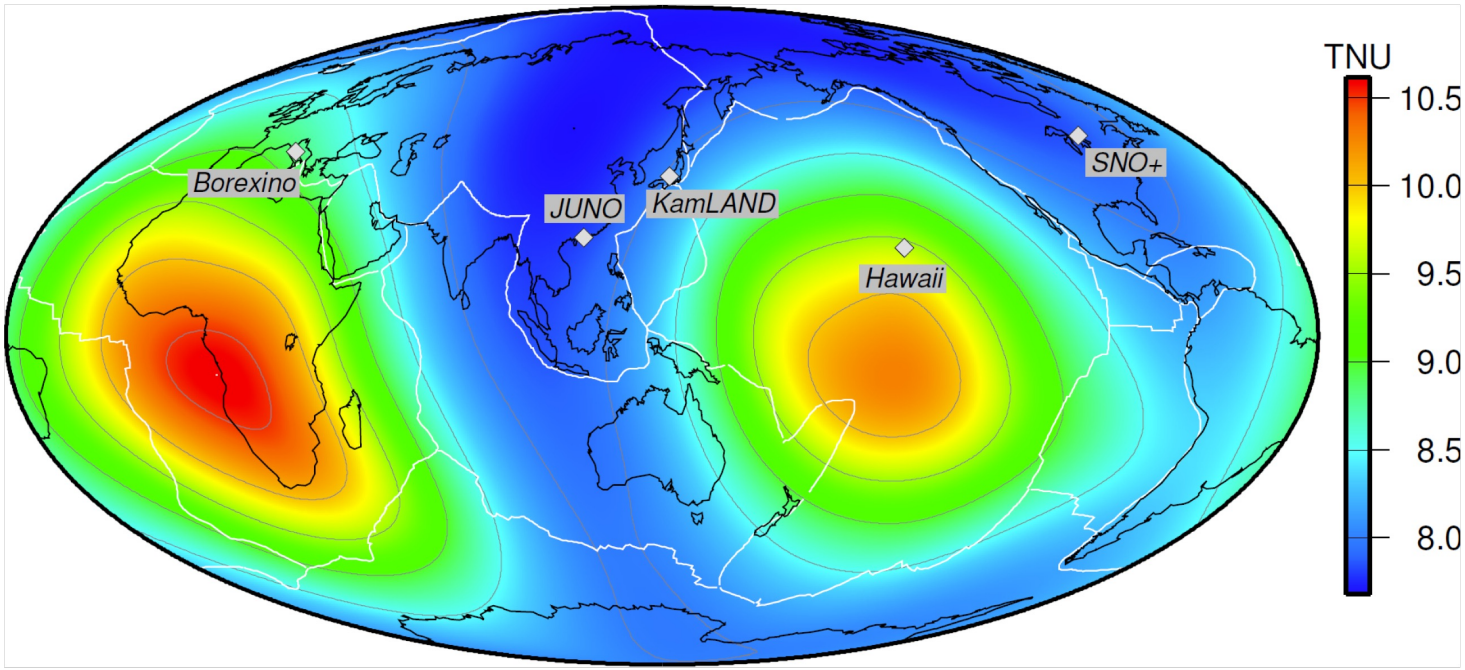
Volume: 2-8% of mantle

OIB sources: seems likely

Testing Earth Models

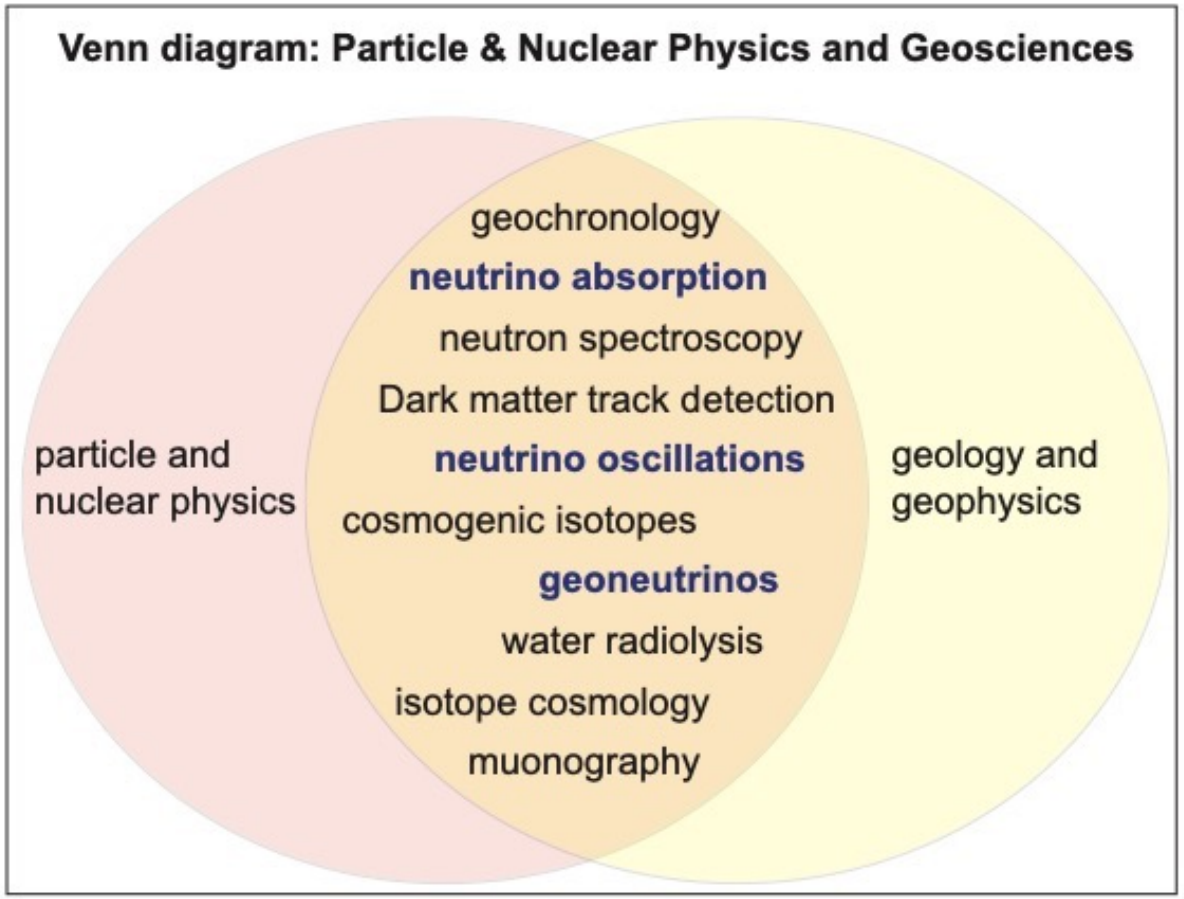


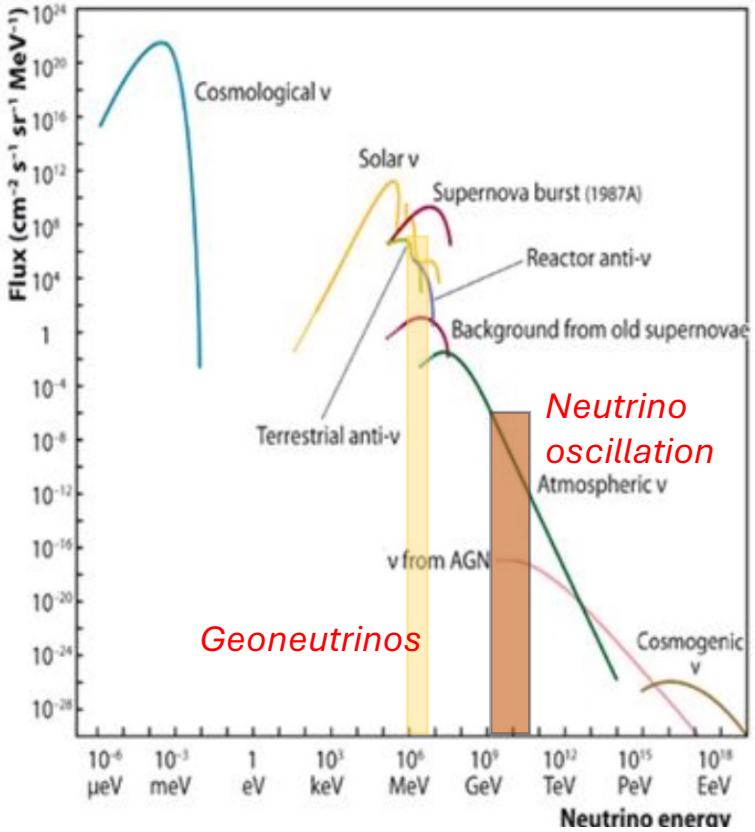
Mantle geoneutrino flux (^{238}U & ^{232}Th)



Šrámek et al (2013) EPSL, 361: 356–366, 10.1016/j.epsl.2012.11.001

Shared science and experiences over many centuries





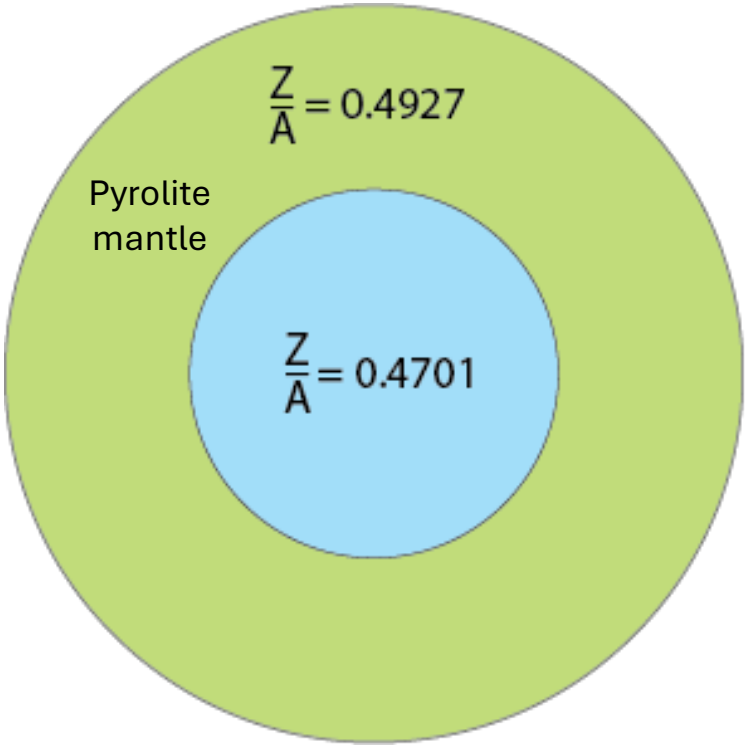
Electron density: testing the H content of the Earth

Neutrino oscillation studies

Sensing hydrogen in the core

	core		silicate Earth	
	wt%	at %	wt%	at %
Fe	89.5	68.6	6.3	2.4
O	0.8	2.2	44.0	57.9
Mg	0.0	0.0	22.8	19.8
Si	3.8	5.8	21.0	15.7
Ni	5.5	4.0	0.2	0.1
Ca	0.0	0.0	2.5	1.3
S	0.0	0.0	0.0	0.0
Al	0.0	0.0	2.5	2.0
H	0.5	19.5	0.0	0.8
	100.0	100.0	99.4	100.0

Core composition from Young et al (2023, Nature)



Z = proton#, A = atomic mass

Conclusions

- Are the **refractory lithophile elements** in chondritic proportions (e.g., Th/U = 3.8), if not, why not?
- Are **U** & **Th** abundances in the Earth 2.7 x CI chondrite?
- What is the Earth's **K/U** value? $\begin{matrix}\sim 14{,}000 \\ < 10{,}000\end{matrix}$ **?**
- What proportion of the Earth's ***HPE*** are in continents?
- Neutrino Geophysics has a bright future!