Geoneutrinos and heat production in the Earth

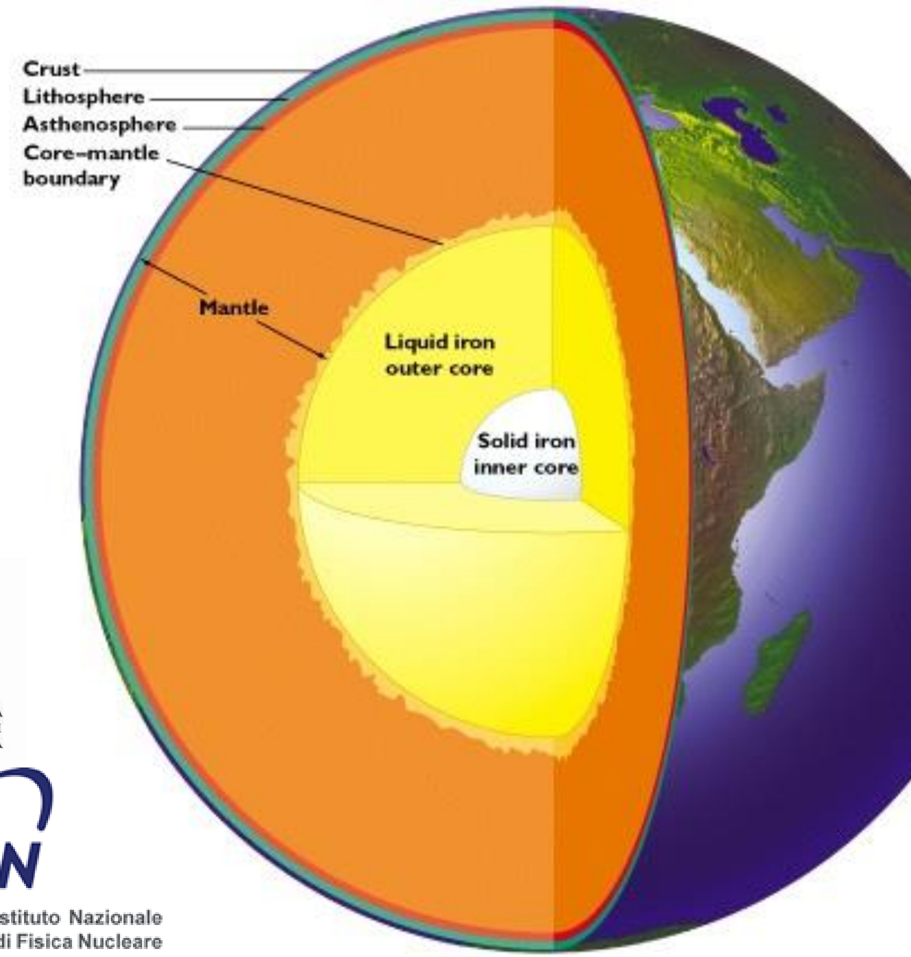
Bill McDonough, *Scott Wipperfurth **Yu Huang
Geology, U Maryland

+Ondřej Šrámek
Geology, Physics, Charles Univ, Prague

Fabio Mantovani and **Virginia Strati
Physics, U Ferrara and INFN, Italy

John Learned & Steve Dye
Physics, U Hawaii

*graduate student, **former
+former post-doc



Antineutrino Map: geoneutrinos + reactor neutrinos

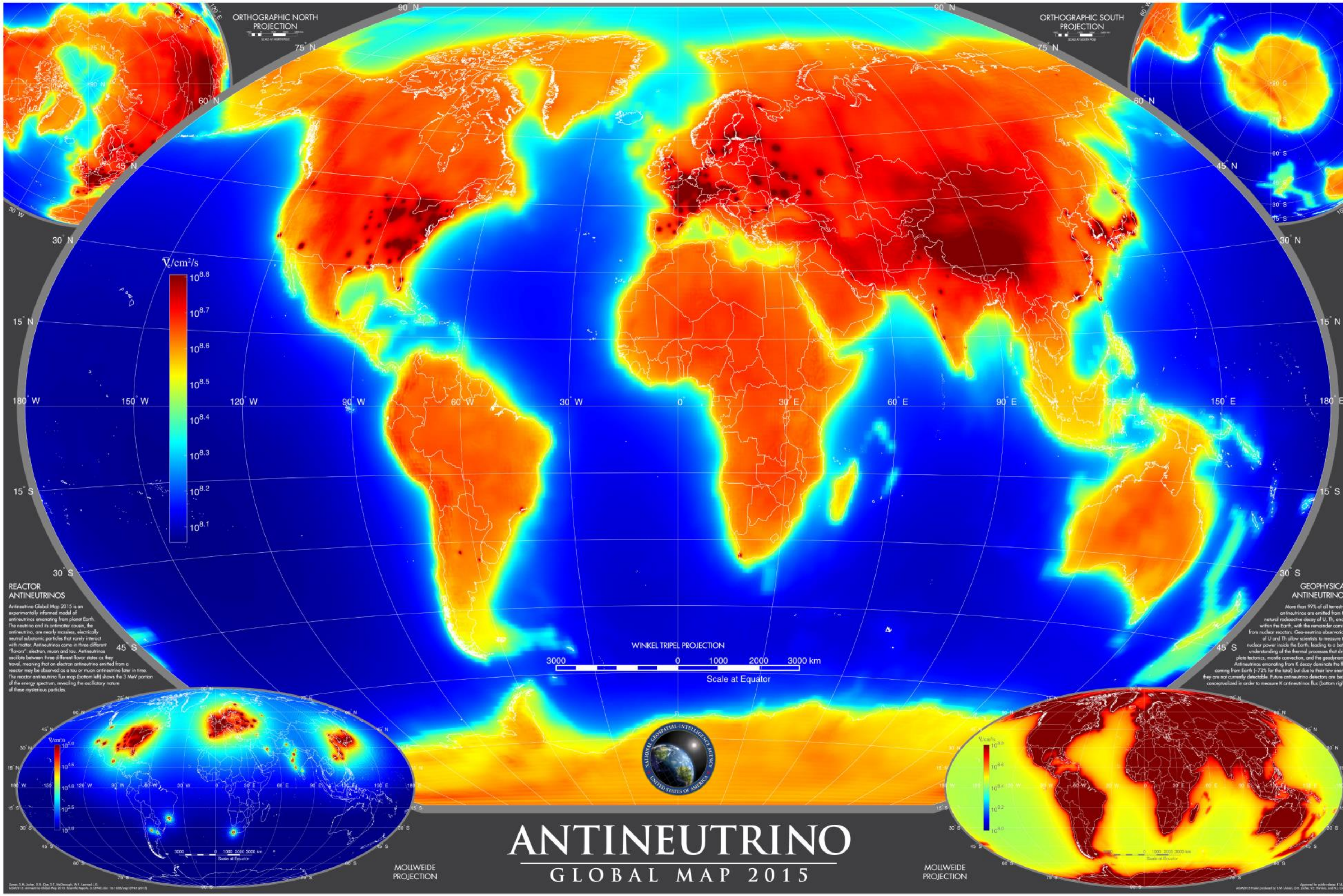
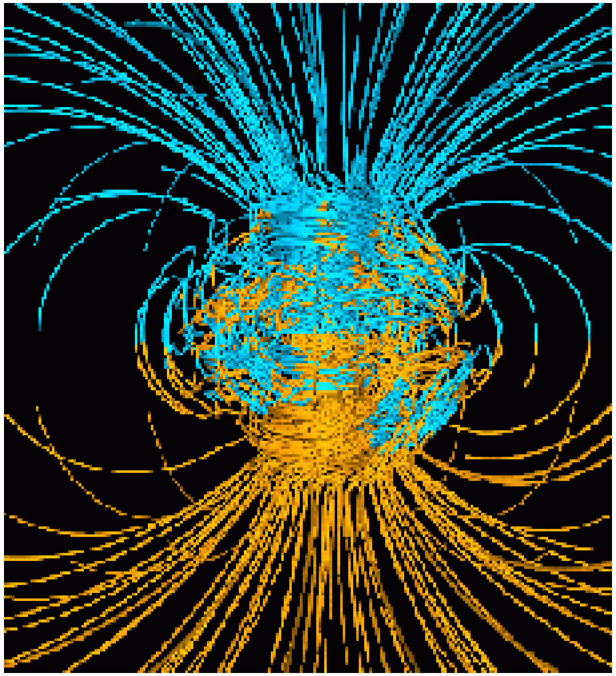
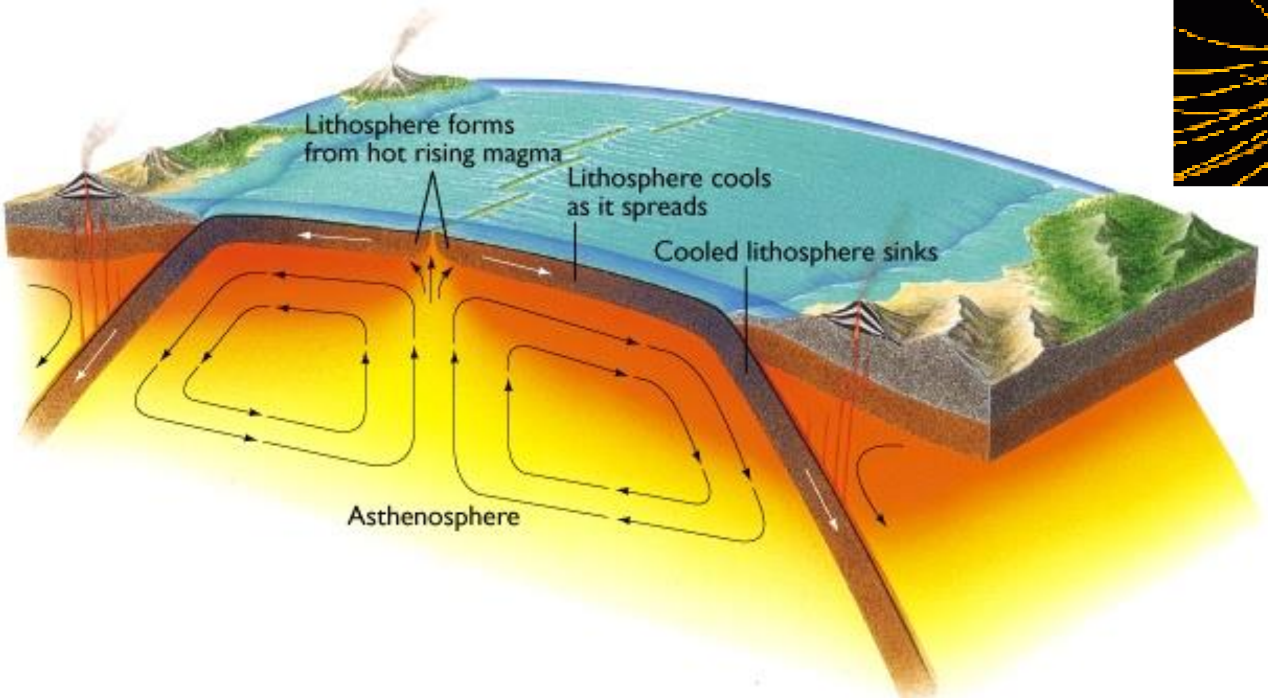
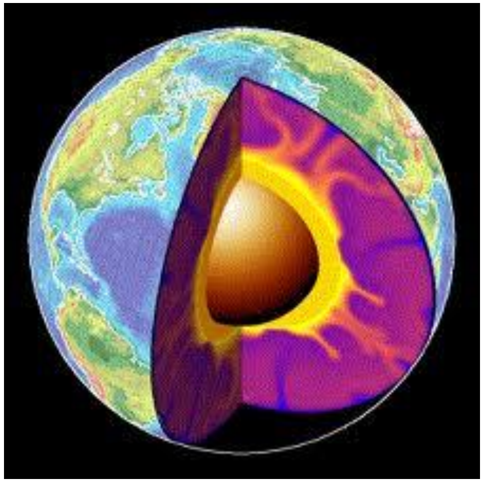


Plate Tectonics, Convection, Geodynamo







Radioactive decay driving the Earth's engine!

K, Th & U!

Nature & amount of Earth's thermal power

radiogenic heating vs secular cooling

- abundance of heat producing elements (K, Th, U) in the Earth

estimates of BSE from 9TW to 36TW

- clues to planet formation processes

constrains chondritic Earth models

- amount of radiogenic power to drive mantle convection & plate tectonics

estimates of mantle 1.3TW to 28TW

- is the mantle compositionally layered? or has large structures?

layers, LLSVP, superplume piles

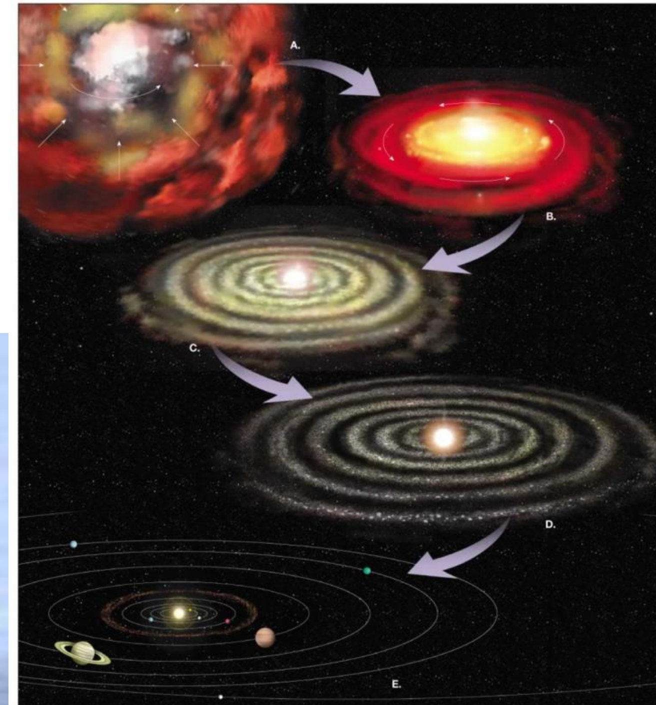
the future is… *Geoneutrino studies*

Disagreement with "chondritic" Earth Models

Murakami et al (May - 2012, *Nature*): "…the lower mantle is enriched in silicon … consistent with the [CI] **chondritic Earth model**."

What is the composition of the Earth? and where did this stuff come from?

Nebula

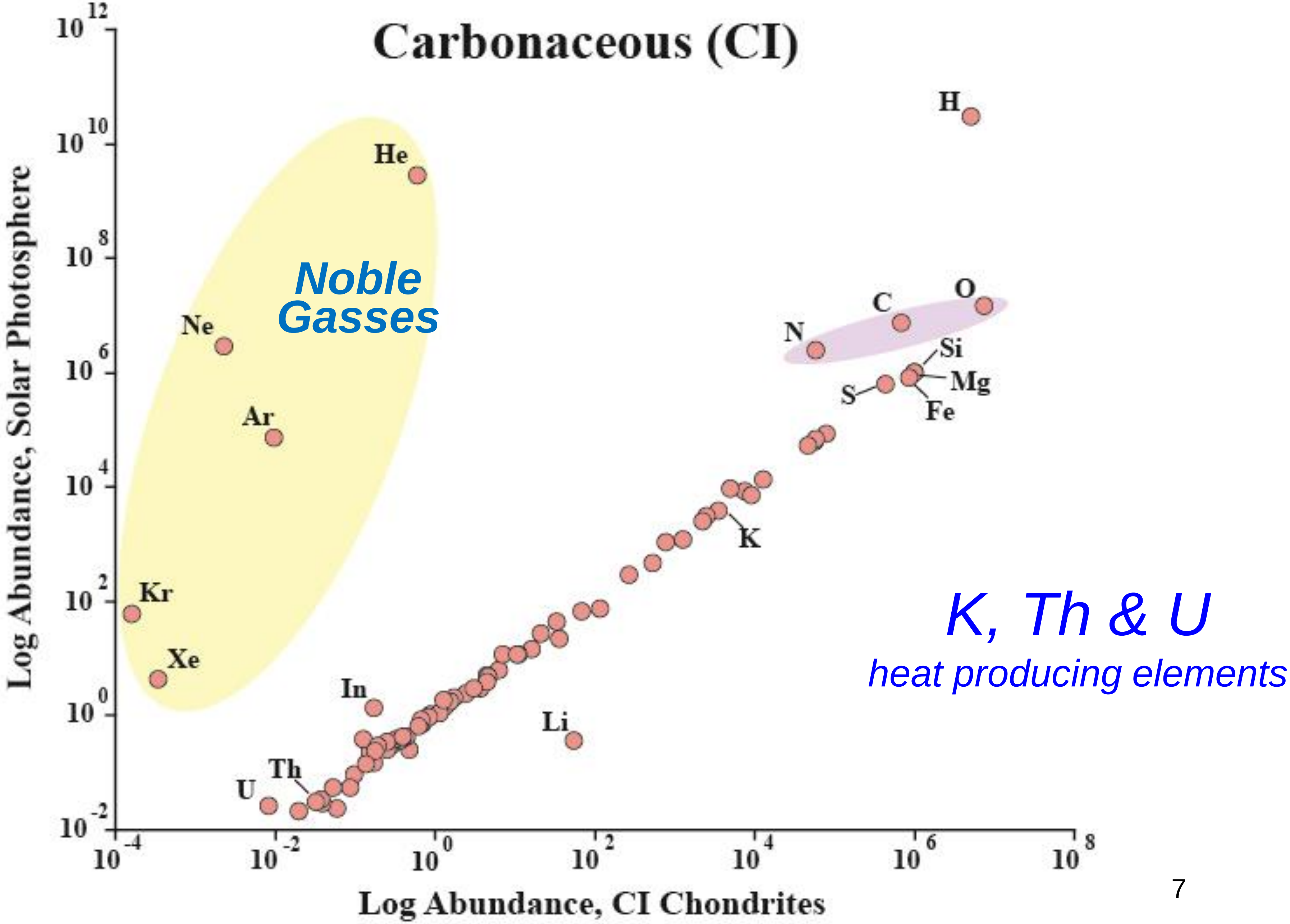


Meteorite

Heterogeneous mixtures of components with different formation temperatures and conditions

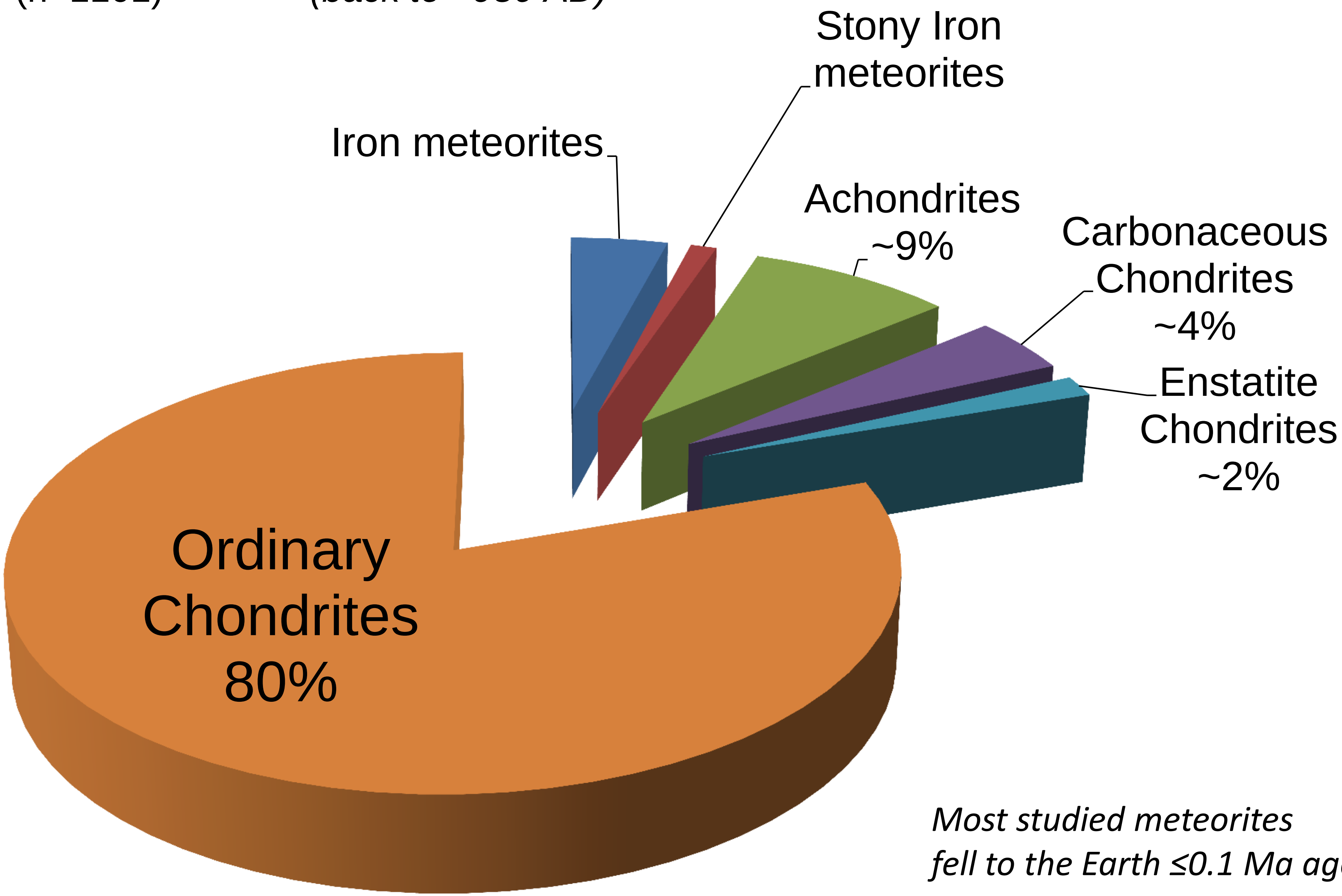
Planet:
mix of metal, silicate, volatiles

Sun and Chondrites are related



Meteorite: Fall statistics

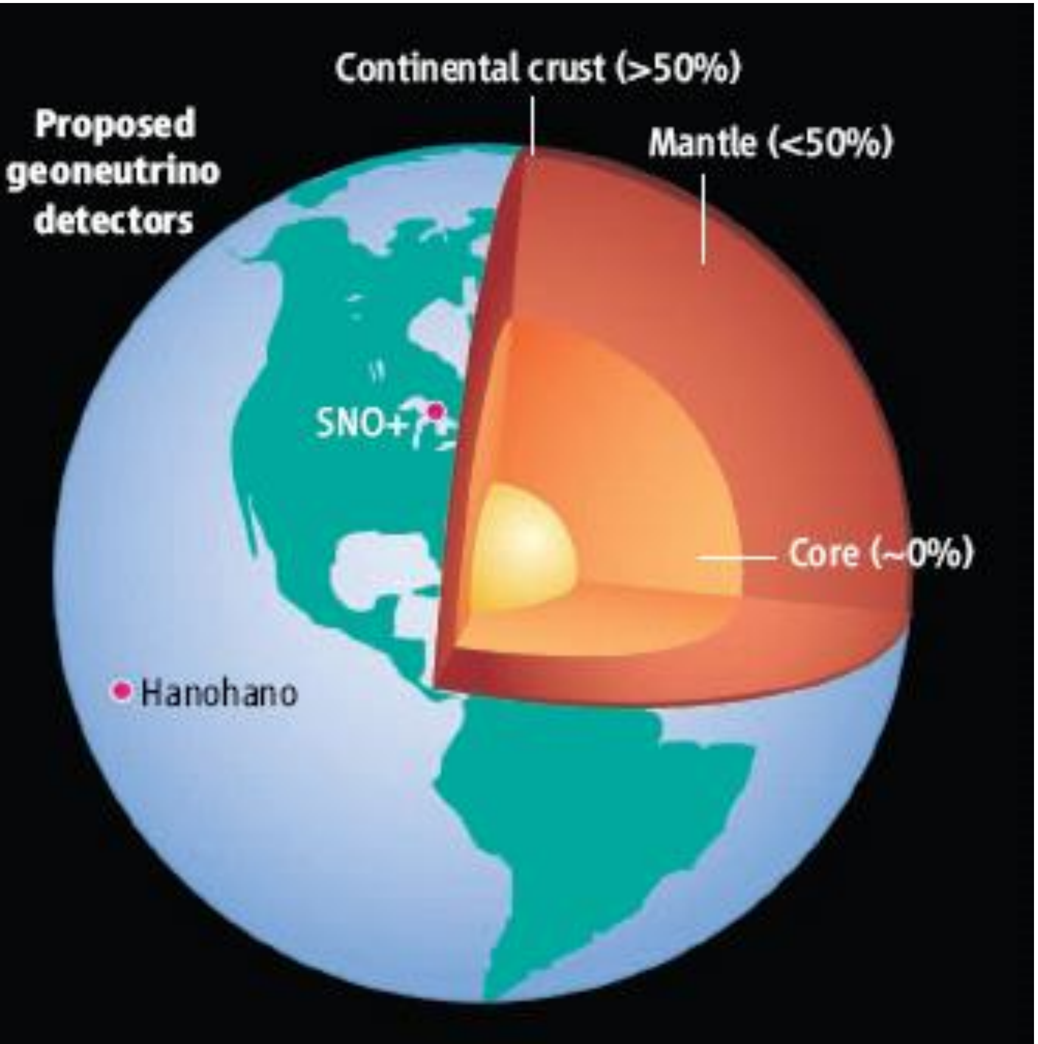
(n=1101) *(back to ~980 AD)*



Most studied meteorites fell to the Earth ≤0.1 Ma ago

U in the Earth:

[Th/U = 3.9, K//U = 1.3 x 10^4]



~13 ng/g U in the Earth

Metallic sphere (core)
<<<1 ng/g U

Silicate sphere
20* ng/g U

**O'Neill & Palme (2008)* *10 ng/g*

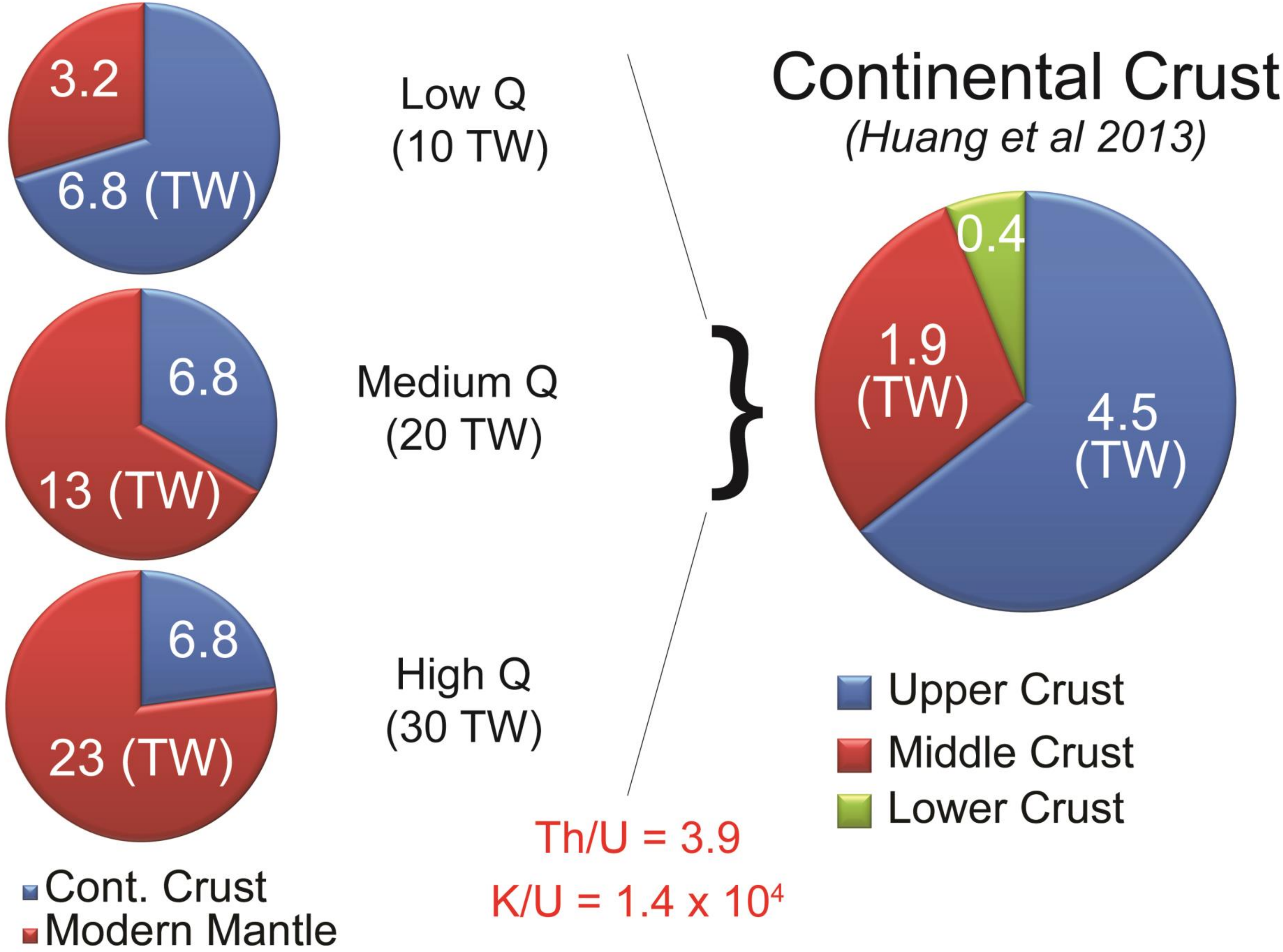
**Turcotte & Schubert (2002)* *31 ng/g*

Continental Crust
1300 ng/g U (~7 TW)

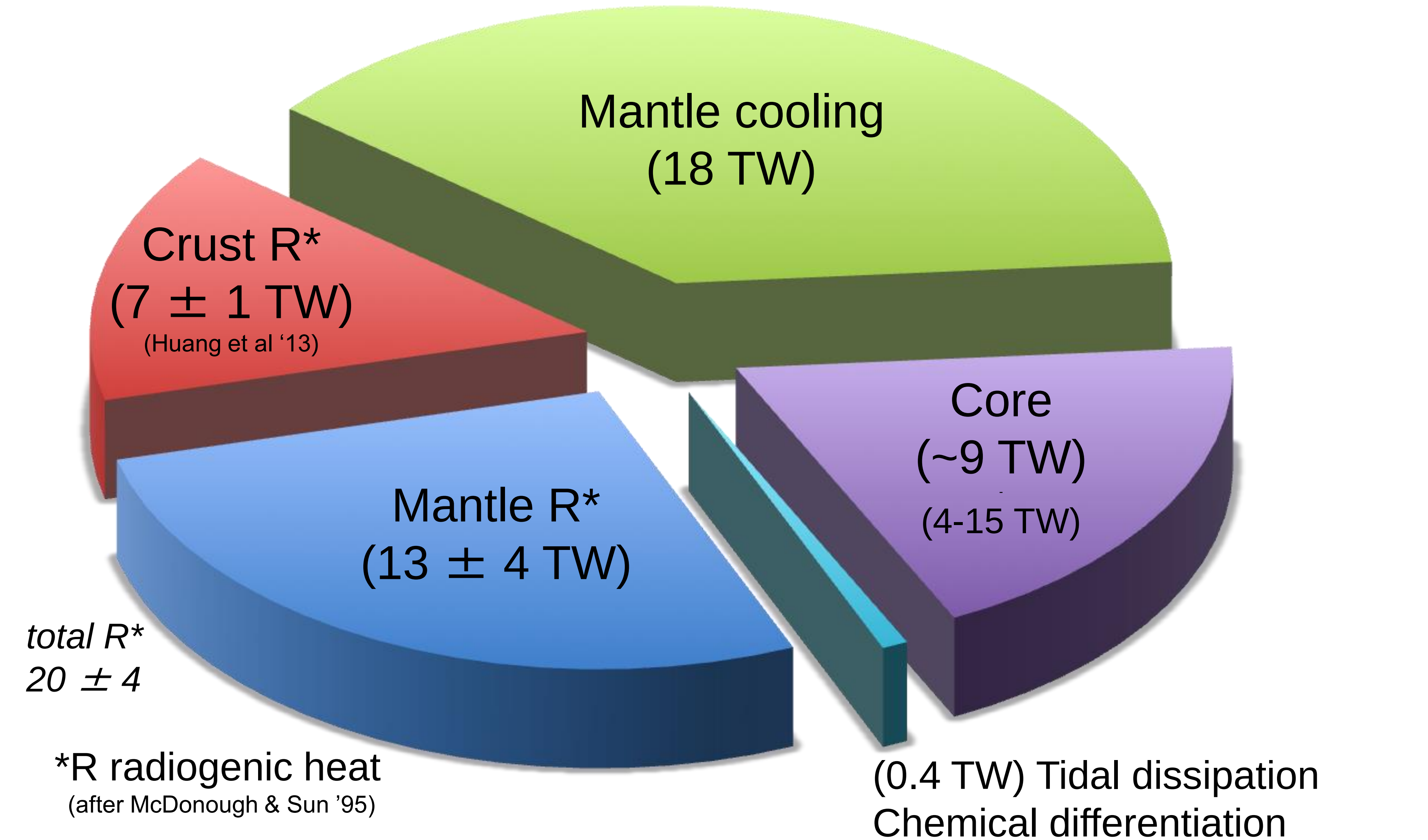
Mantle
~13* ng/g U (~13 TW)

Mantle could have as little 1-3 TW or as much as 28 TW

Bulk Silicate Earth Models



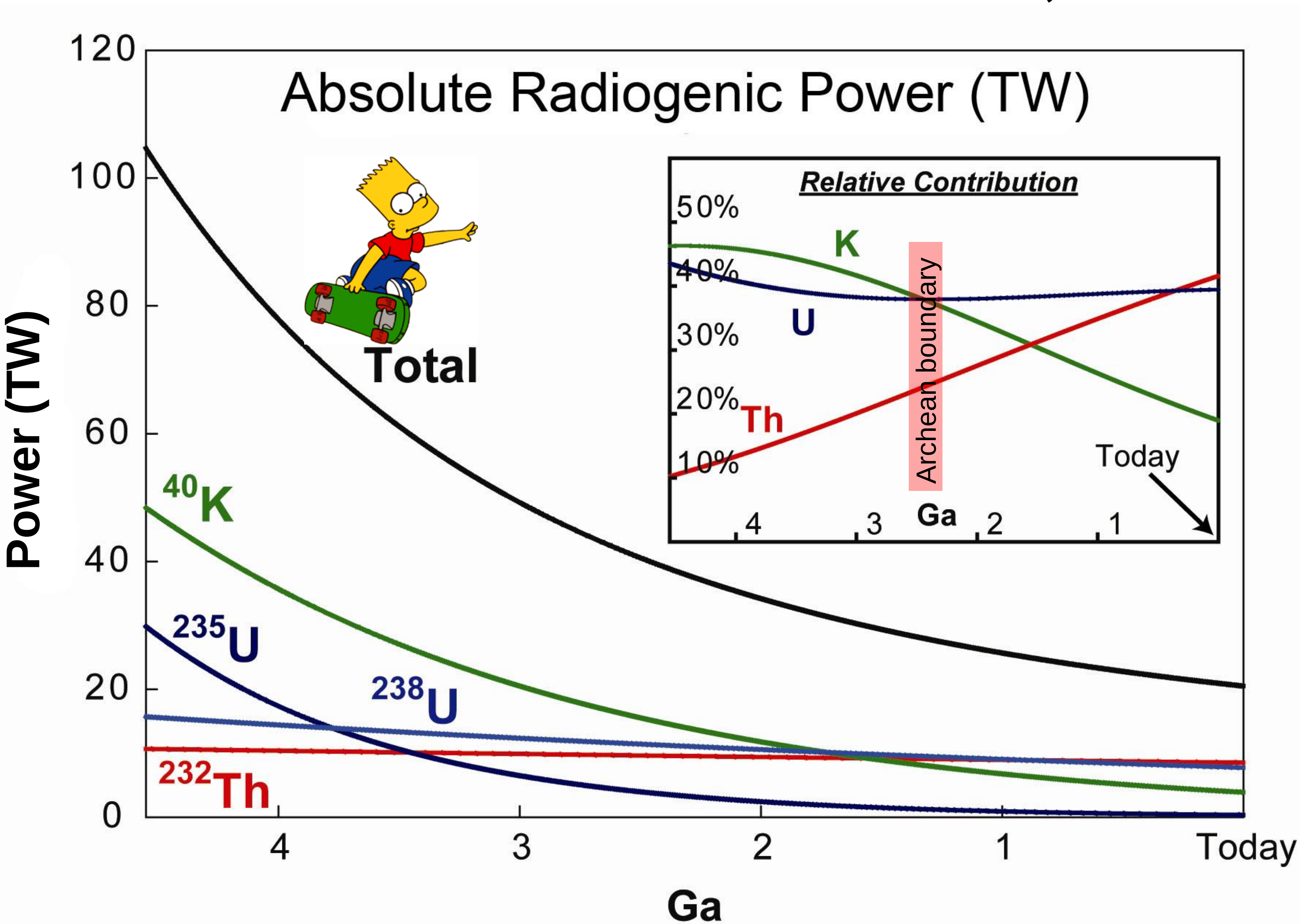
Earth's surface heat flow 46 ± 3 (47 ± 1) TW



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

after Jaupart et al 2008 Treatise of Geophysics

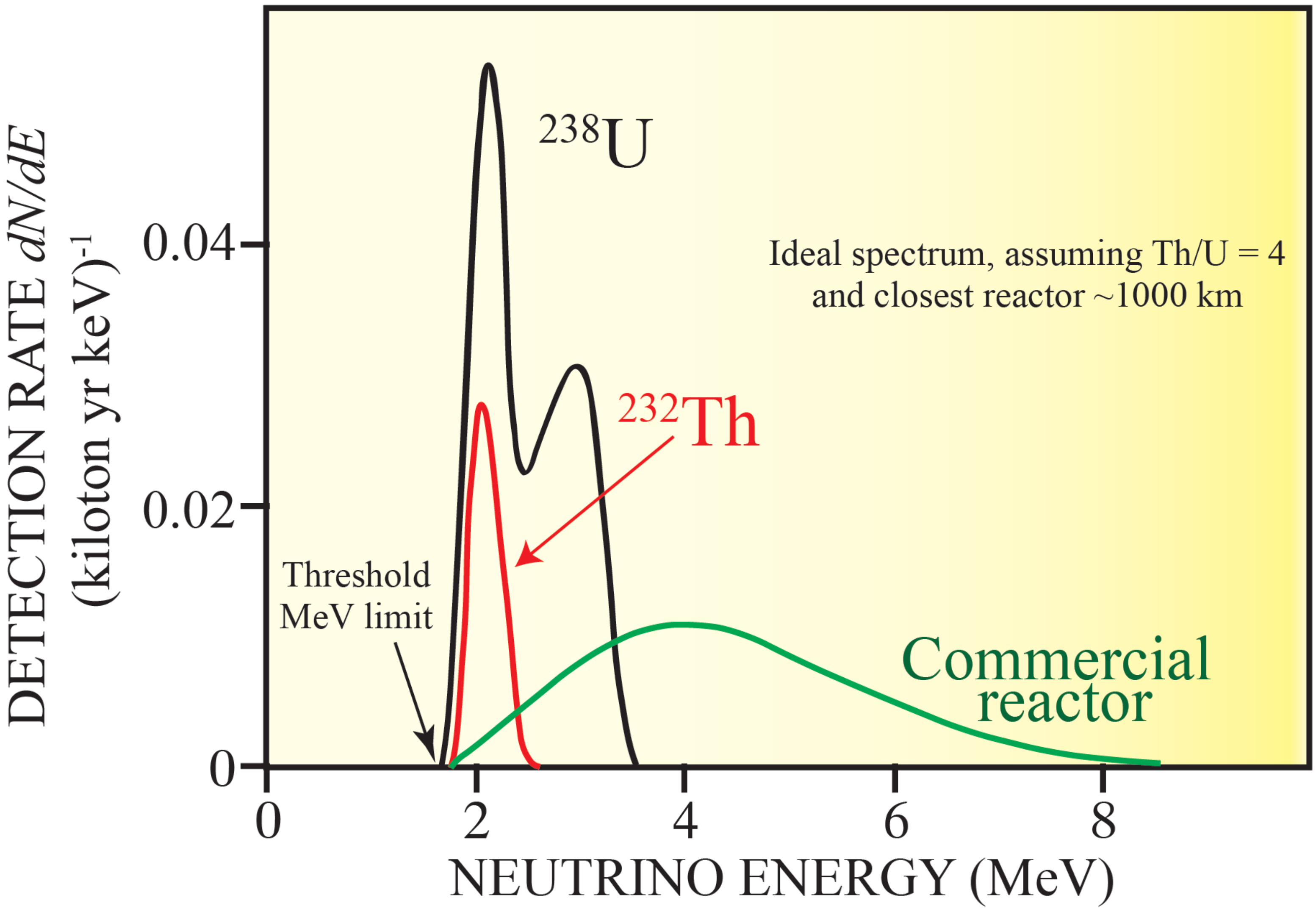
Earth's thermal evolution: role of K, Th & U



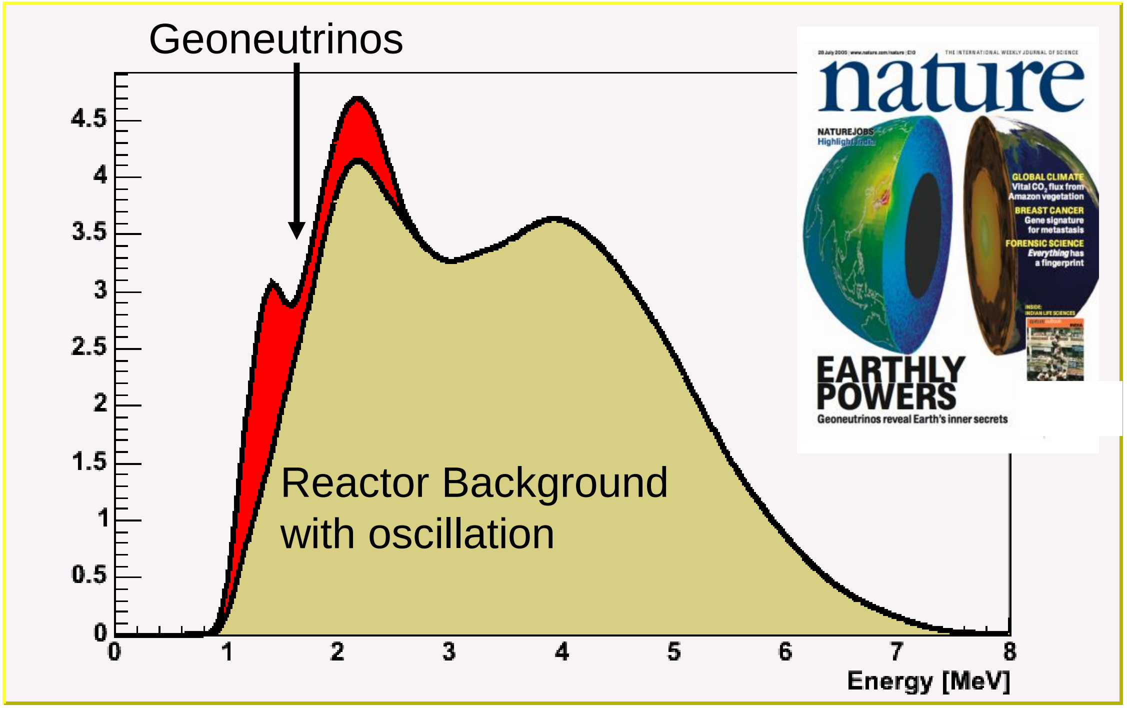
Arevalo, McDonough, Luong (2009) EPSL doi:10.1016/j.epsl.2008.12.023

Antineutrinos - Geoneutrinos

$$\overline{\nu}_e + p^+ \longrightarrow n + e^+$$



Reactor and Earth Signal

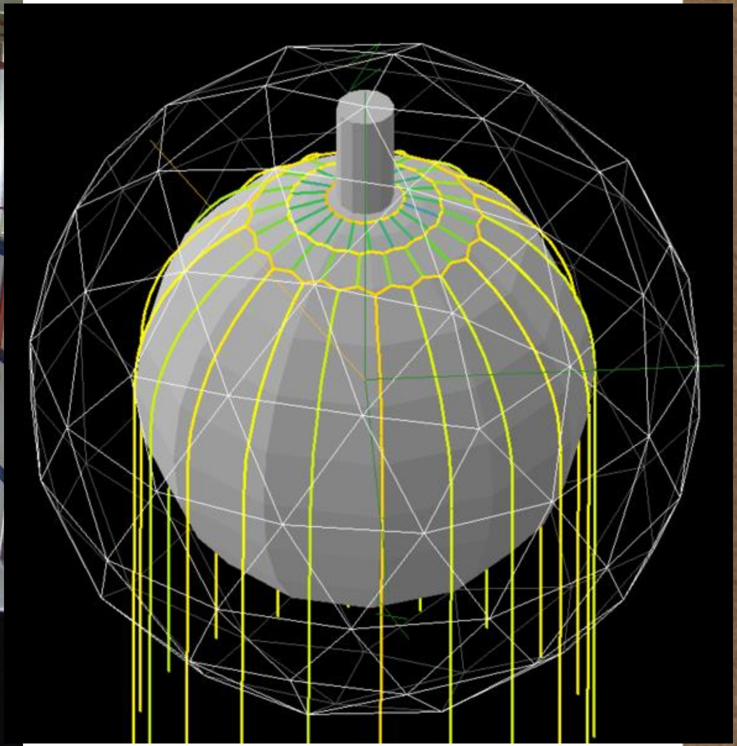


- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant contributor to the total signal.

Present LS-detectors, *data update*

Borexino, Italy (0.3kt)

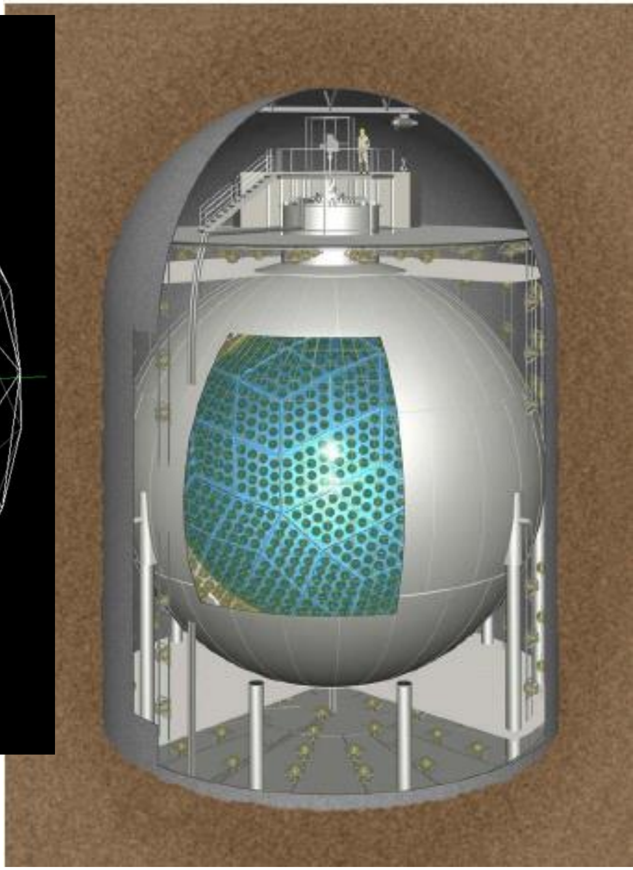
SNO+, Canada (1kt)



under construction

(online later this yr?)

KamLAND, Japan (1kt)



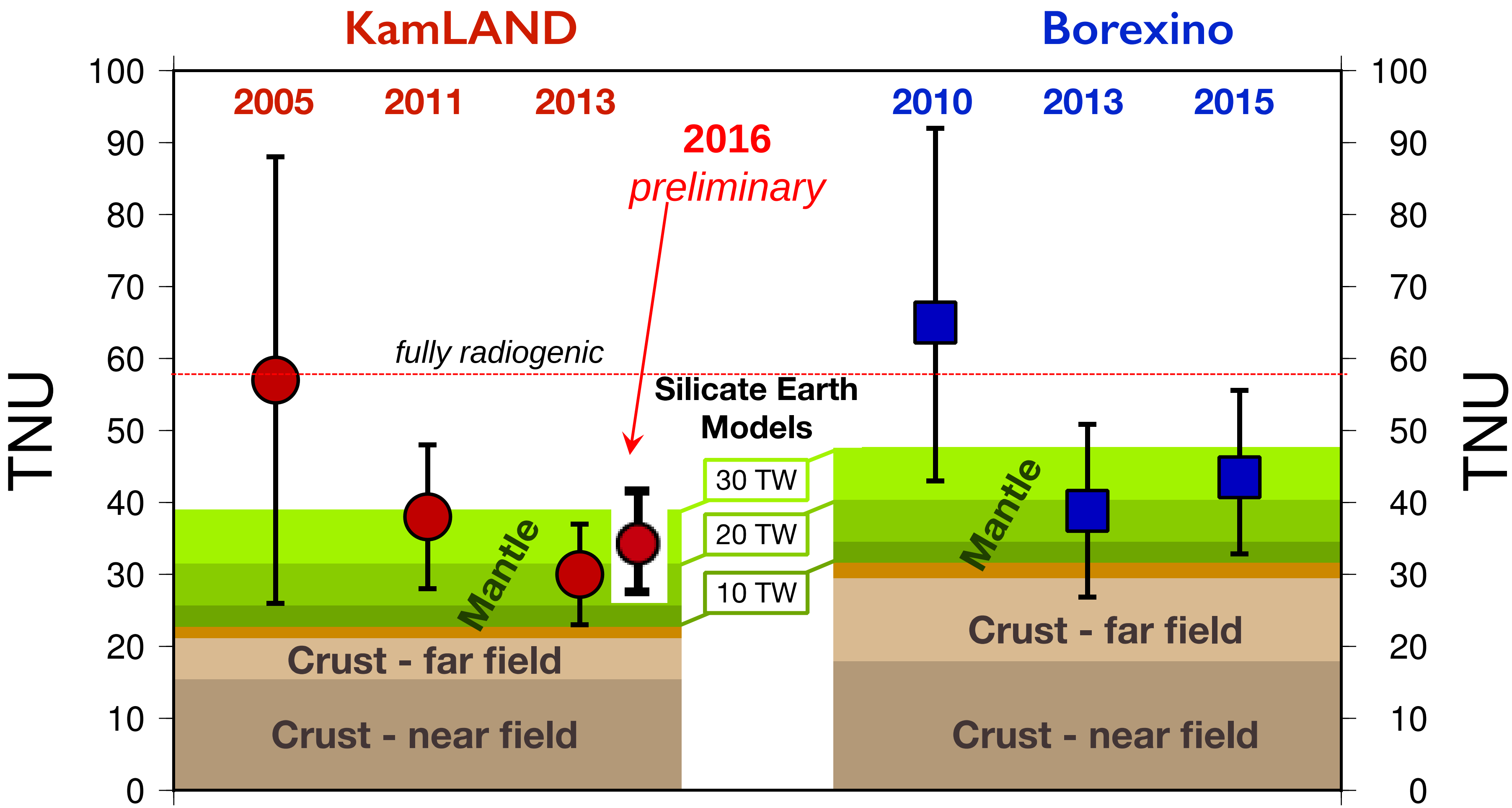
$23.7^{+6.5}_{-5.7}$ counts

from May '07 - March '15

164^{+28}_{-25} counts

From Mar '02 to Dec '15

Summary of geoneutrino results



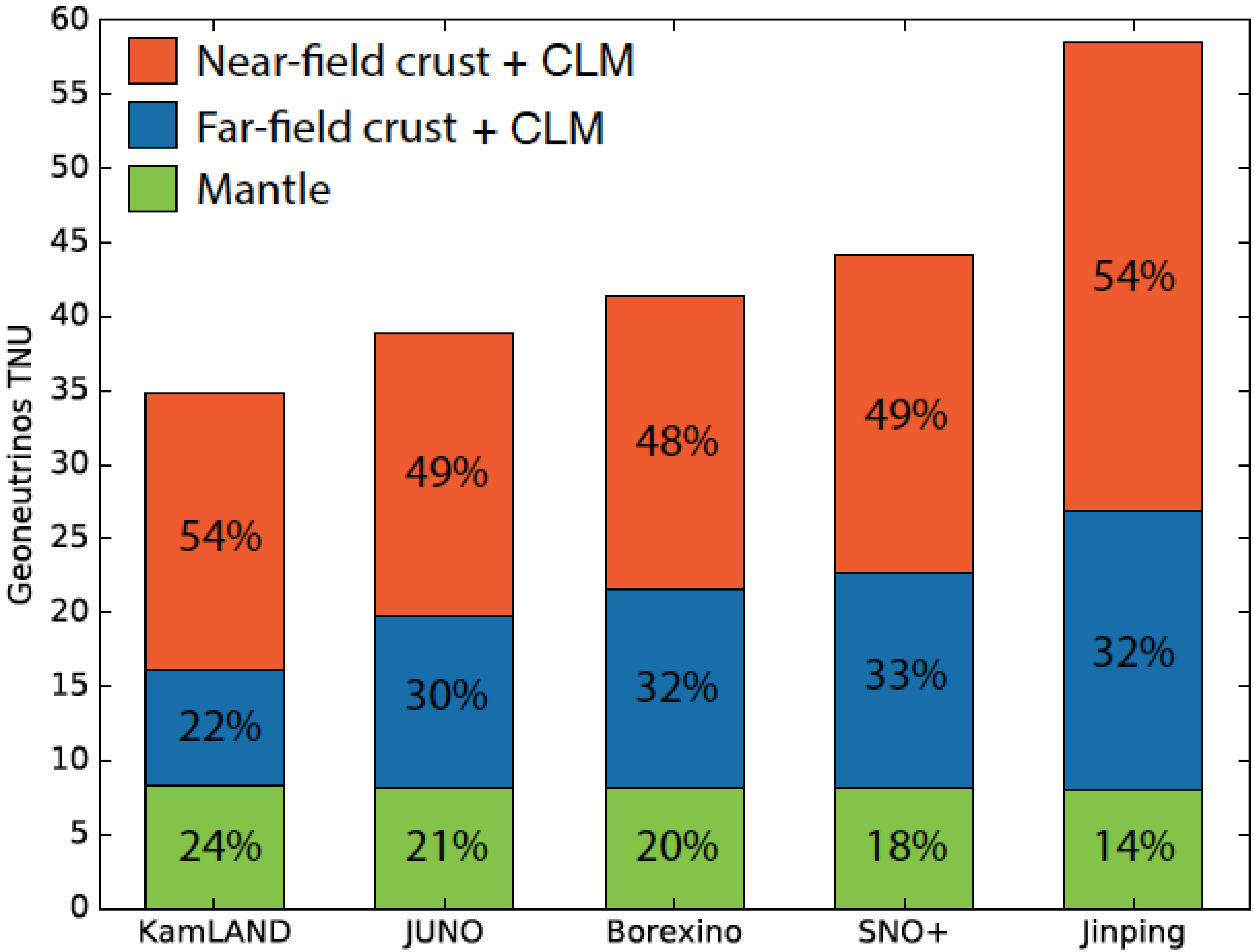
SILICATE EARTH MODELS

Cosmochemical: uses meteorites – 10 TW

Geochemical: uses terrestrial rocks –20 TW

Geodynamical: parameterized convection – 30 TW

TNU: geo-nυ event seen by a kiloton detector in a year



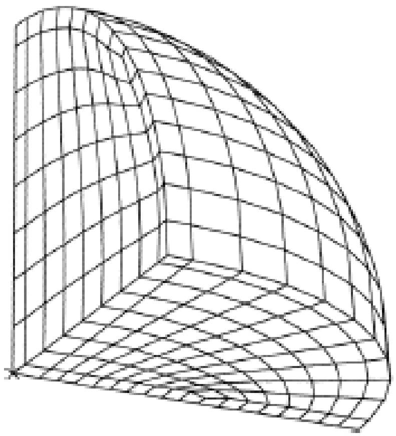
Near Field: six closest 2° × 2° crustal voxels
Far Field = bulk crust – near field crust

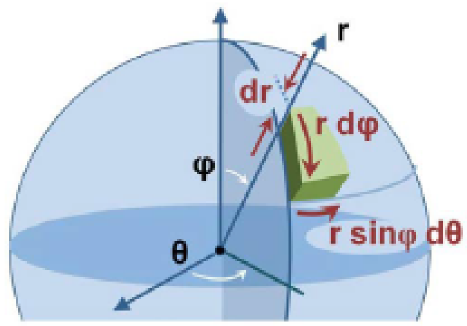
We calculated geoneutrino flux prediction at Jinping

$$\phi(\vec{r}) = \frac{X\lambda N_A}{\mu} n_\nu \langle P_{ee} \rangle \iiint \frac{A(\vec{r}')\rho(\vec{r}')}{4\pi\,|\vec{r}-\vec{r}'|^2} d\vec{r}'$$

φ … Antineutrino flux
X … Natural isotopic mole fraction
λ … Half-life
N_A … Avogadro's number
μ … Standard atomic mass
n_ν … Number of antineutrinos per decay
$\langle P_{ee} \rangle$ … Average survival probability
A … Elemental abundance
ρ … Mass density
r … position

Predicting geoneutrino flux from emitters (^{232}Th, ^{238}U) distributed spatially with mass fractions *A(r)* in the Earth with mass density *ρ(r)*



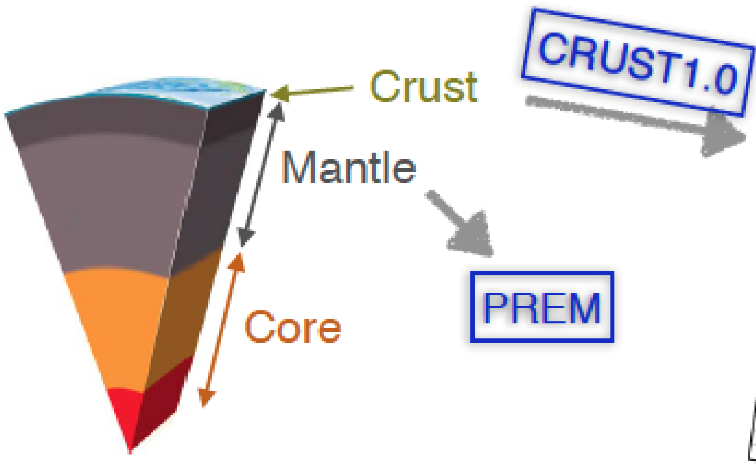


Previous geonu emission models:
(non-exhaustive list)

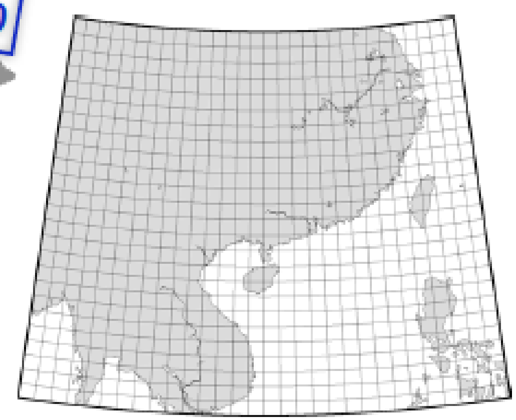
- Krauss et al. 1984
- Kobayashi & Fukao, 1991
- Mantovani et al. 2004
- Enomoto 2005 (PhD)
- Enomoto et al. 2007
- Fiorentini et al. 2007
- Huang et al. 2013
- Usman et al. 2015

Geoneutrino emission model

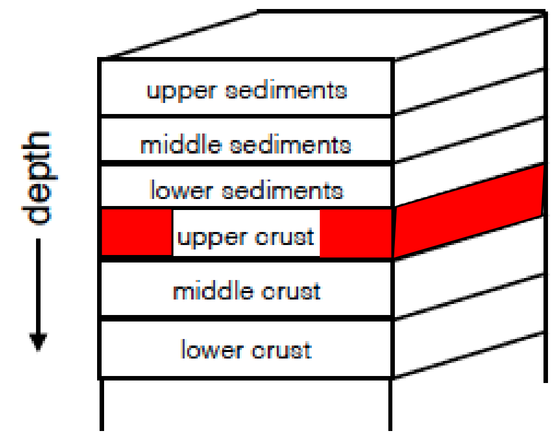
- Model of crustal geometry and material density from **CRUST1.0** model (*Laske et al.*)
- Material density in the mantle from **PREM** model (*Dziewonski & Anderson 1981*)
- Assume negligible Th, U in the core
- Total amount of Th, U in **Silicate Earth** from estimate by *Arevalo et al. 2009*, **20±4 TW** radiogenic power)



1° lat × 1° lon crustal tiles

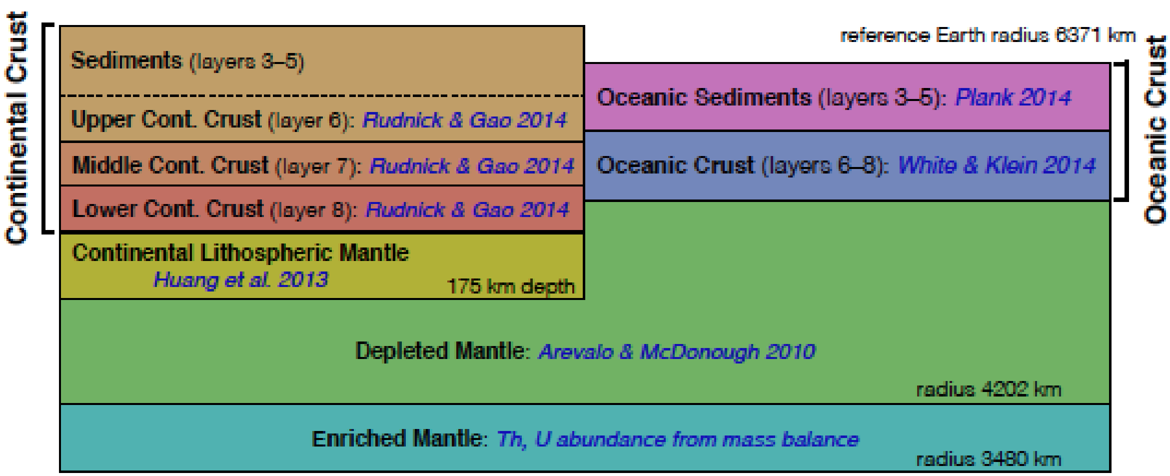


Vertical structure of a crustal tile



Continental

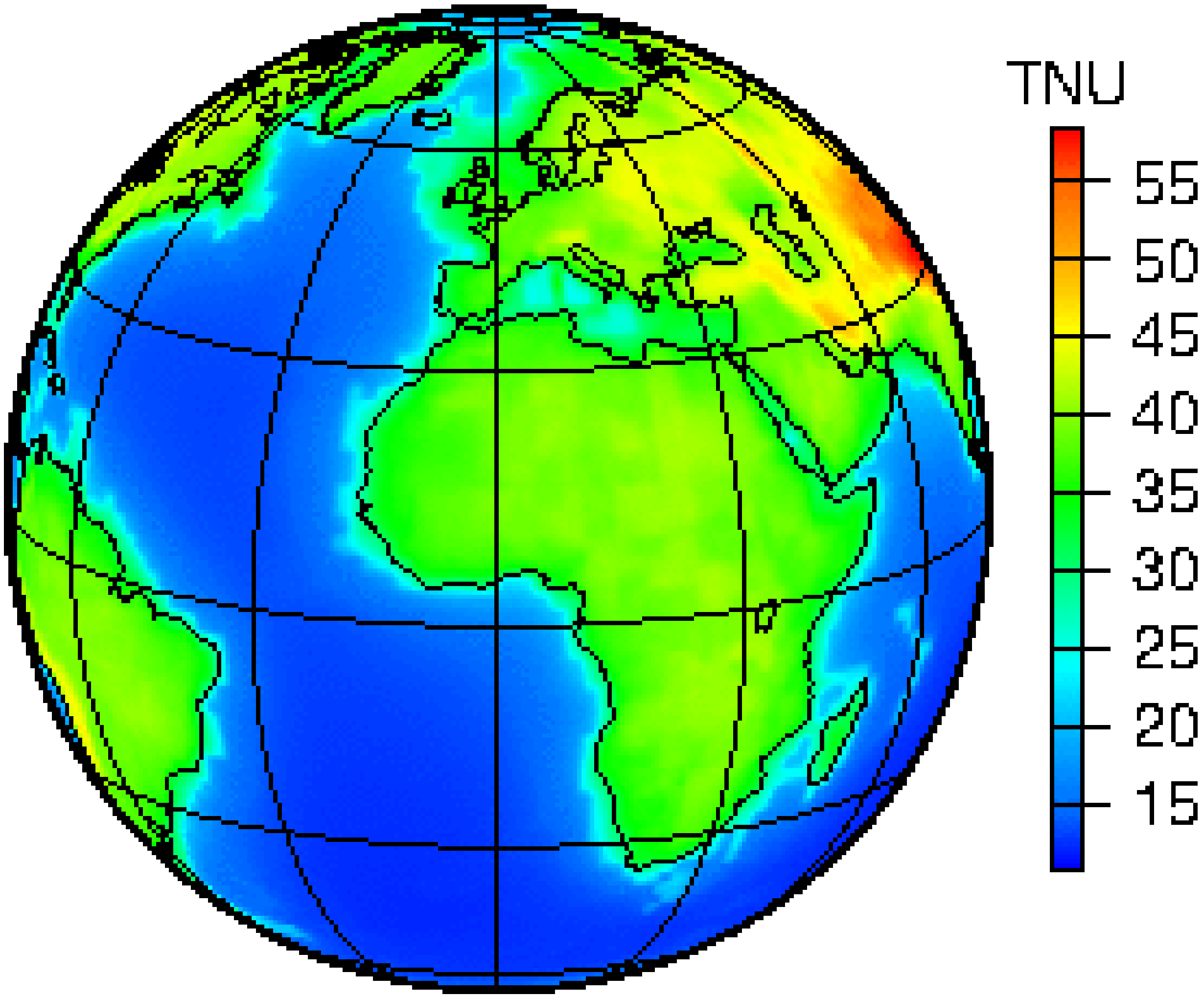
Oceanic



Mass fractions of Th and U

	Th	U
Upper CC + sediments	$(10.5 \pm 10\%) \times 10^{-6}$	$(2.7 \pm 21\%) \times 10^{-6}$
Middle CC	$(6.5 \pm 8\%) \times 10^{-6}$	$(1.3 \pm 31\%) \times 10^{-6}$
Lower CC	$(1.2 \pm 30\%) \times 10^{-6}$	$(0.2 \pm 30\%) \times 10^{-6}$
OC sediments	$(8.10 \pm 7\%) \times 10^{-6}$	$(1.73 \pm 5\%) \times 10^{-6}$
OC crust	$(0.21 \pm 30\%) \times 10^{-6}$	$(0.07 \pm 30\%) \times 10^{-6}$
CLM	$150^{+277}_{-97} \times 10^{-9}$	$33^{+49}_{-20} \times 10^{-9}$
Depleted Mantle	$(21.9 \pm 20\%) \times 10^{-9}$	$(8.0 \pm 20\%) \times 10^{-9}$
Enriched Mantle*	$147^{+74}_{-57} \times 10^{-9}$	$30^{+24}_{-18} \times 10^{-9}$
Bulk Silicate Earth	$(80 \pm 15\%) \times 10^{-9}$	$(20 \pm 20\%) \times 10^{-9}$

Predicted Global geoneutrino flux based on our new Reference Model



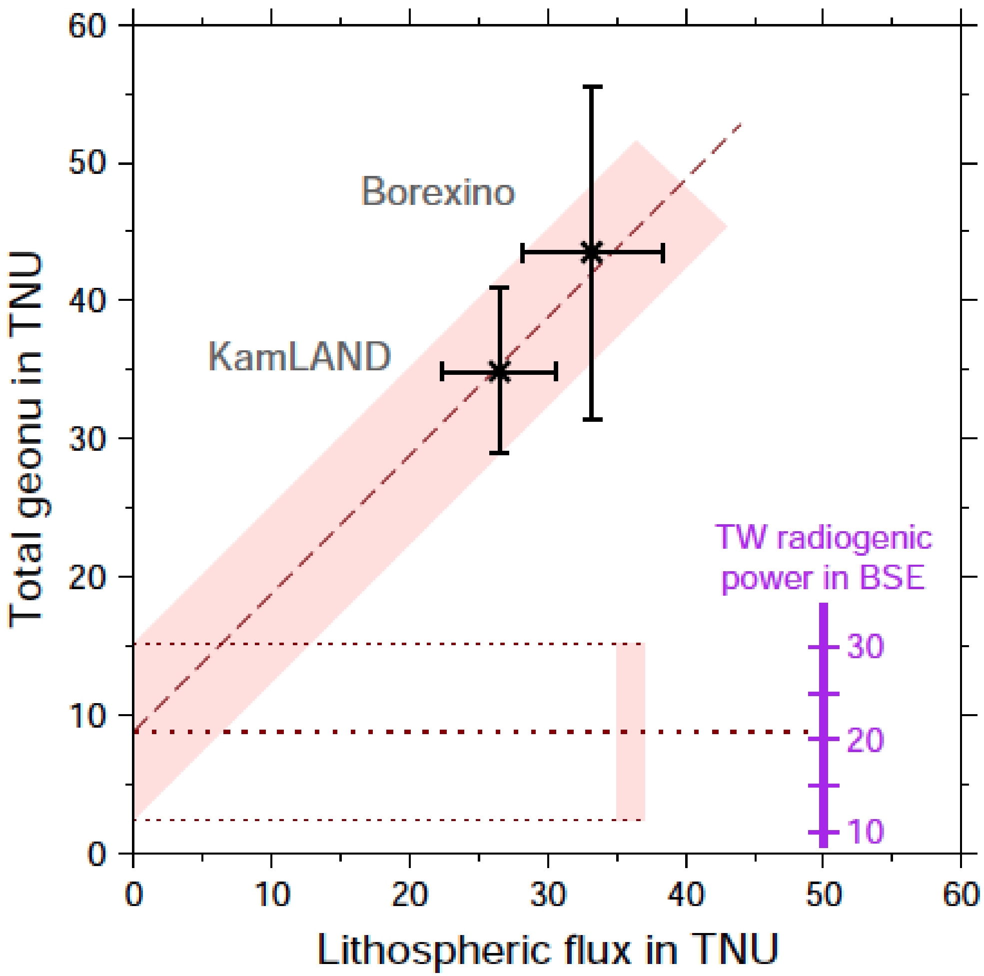
Huang et al (2013) G-cubed, 14:6, ***doi:10.1002/ggge.20129***

Latest result from KamLAND & Borexino

Measured by physics:

Total geonu

KamLAND 2016
Borexino 2015
measurements



Predicted from geology: **Lithosphere**
Emission model

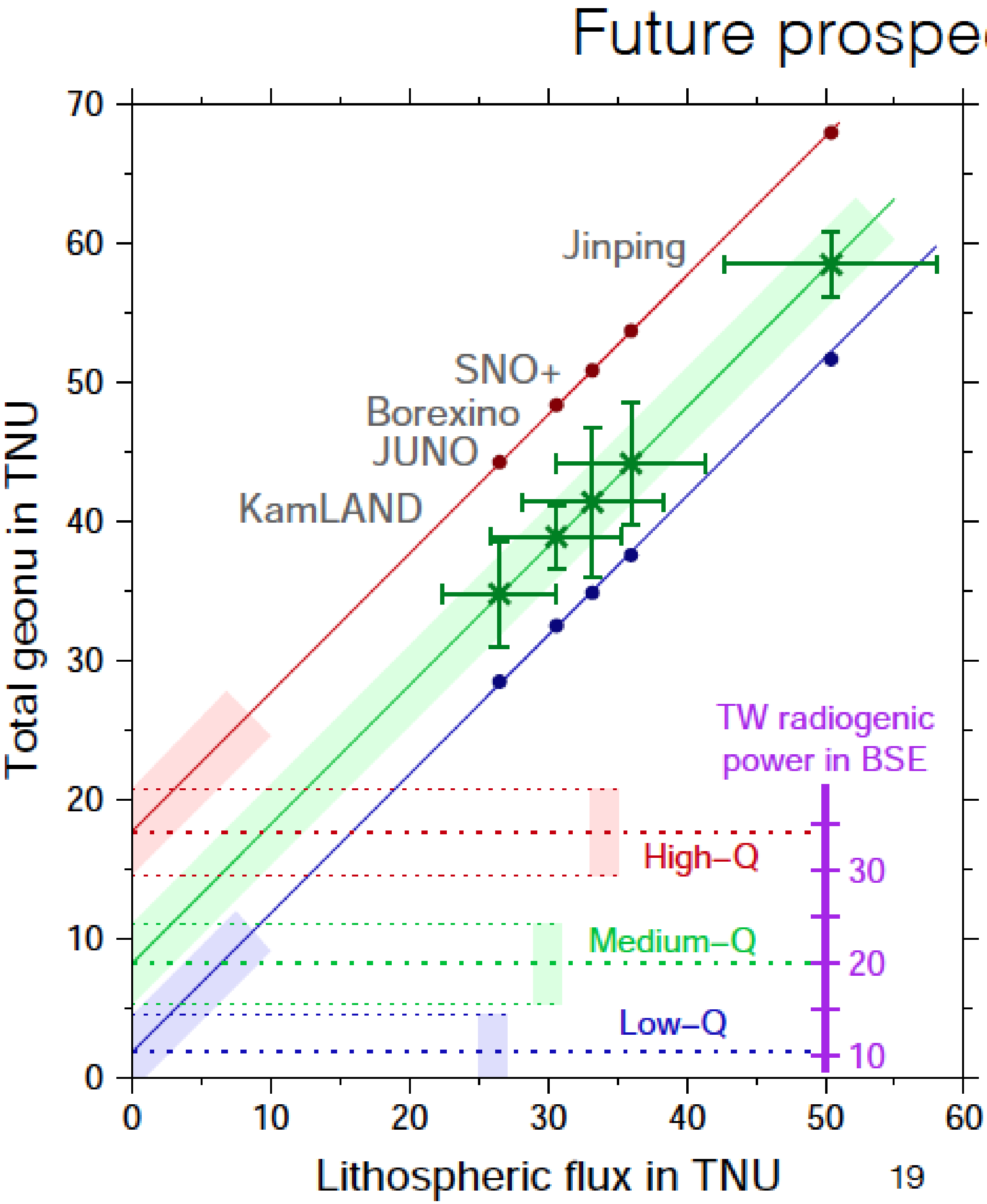
Resolving the Mantle

Result:

Mantle = 8.8 ± 6.4 TNU

(72% rel. uncertainty)

Results from detectors combined



Horizontal axis

Lithospheric flux from emission model

Vertical axis

Simulated measurement:

- Total flux from emission model
- Uncertainty est. based on previous slide

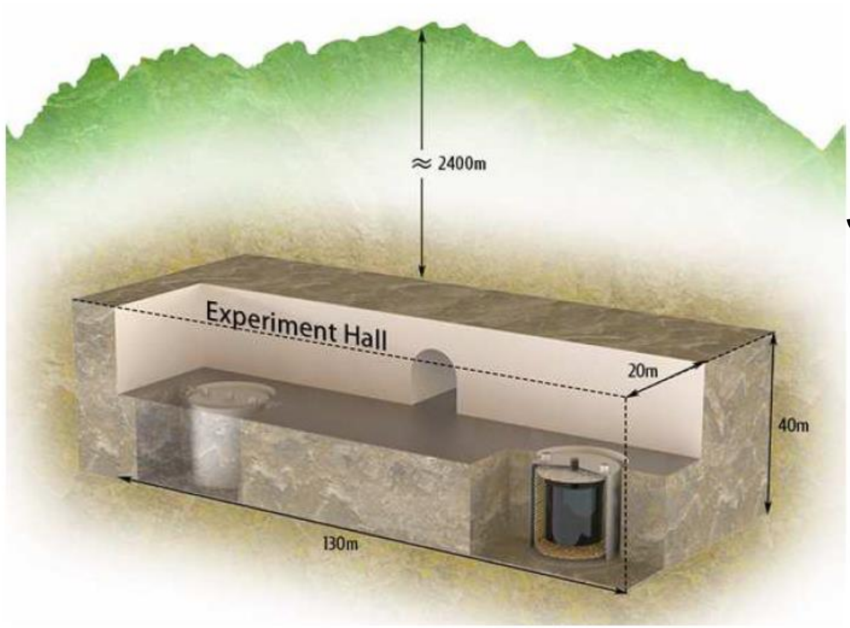
Mantle result:

High-Q: 17.7 ± 3.1 TNU

Med-Q: 8.2 ± 2.9 TNU

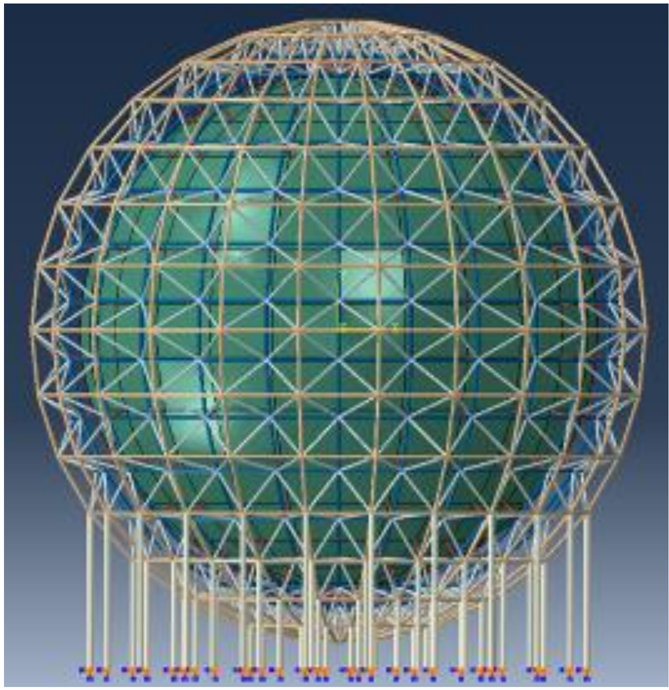
Low-Q: 1.8 ± 2.7 TNU

Future detectors

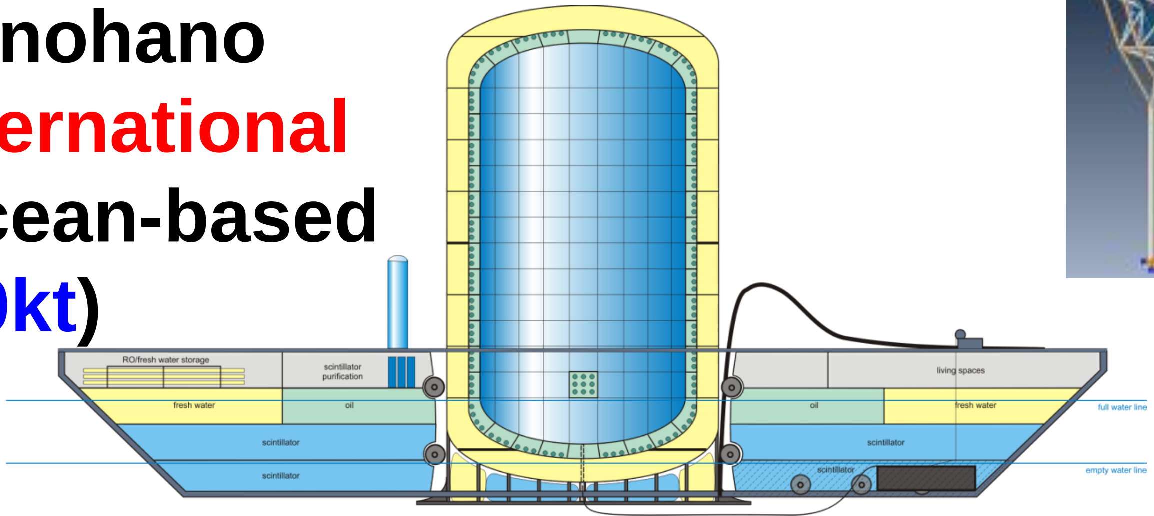


Jinping, China (4kt)

JUNO China (20kt)

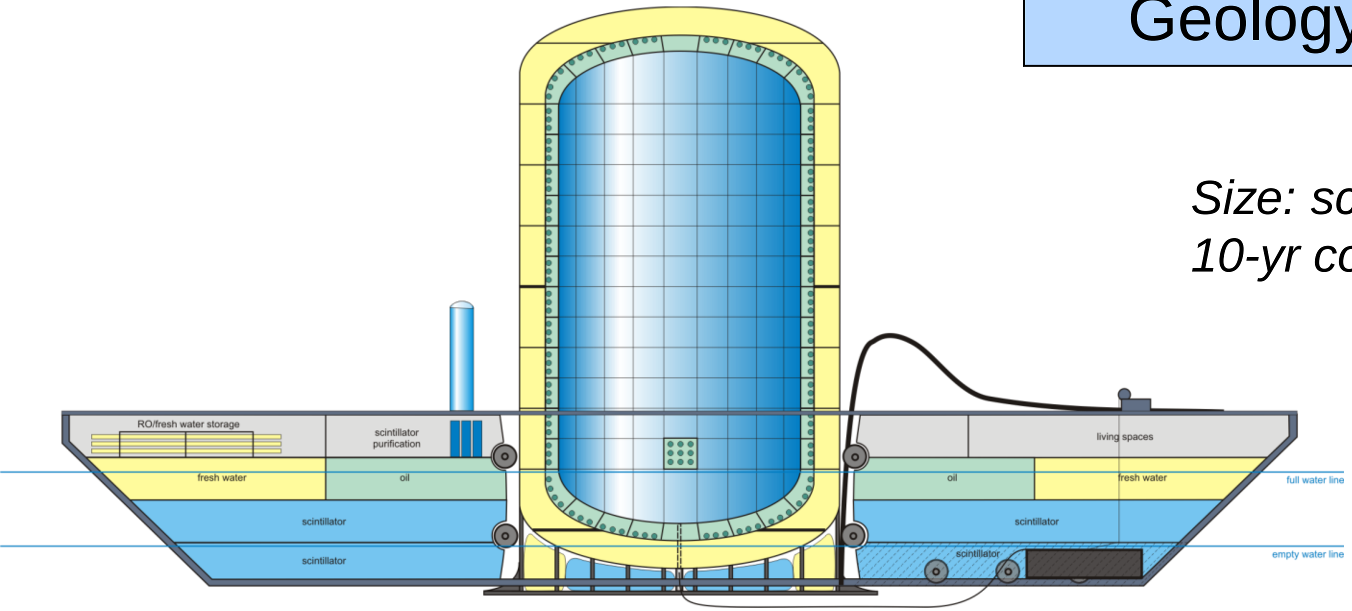


Hanohano International ocean-based (10kt)



Hanohano

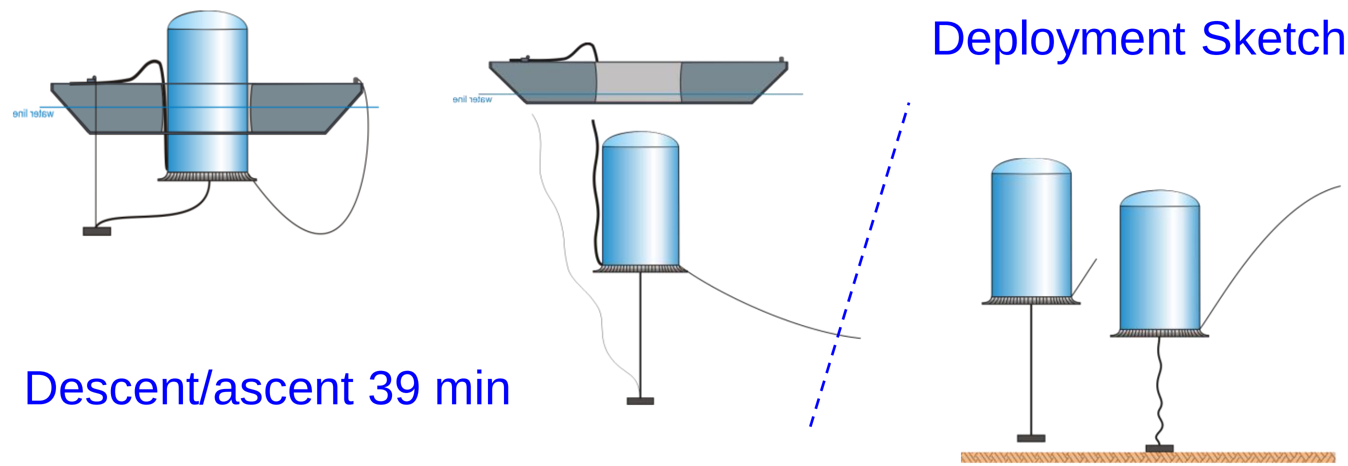
An experiment with joint interests in Physics, Geology, and Security



Size: scalable from 1 to 50 kT
10-yr cost est: $250M @ 10 kT

- multiple deployments
- deep water cosmic shield
- control-able L/E detection

A Deep Ocean
$\bar{\nu}_e$ Electron Anti-Neutrino Observatory



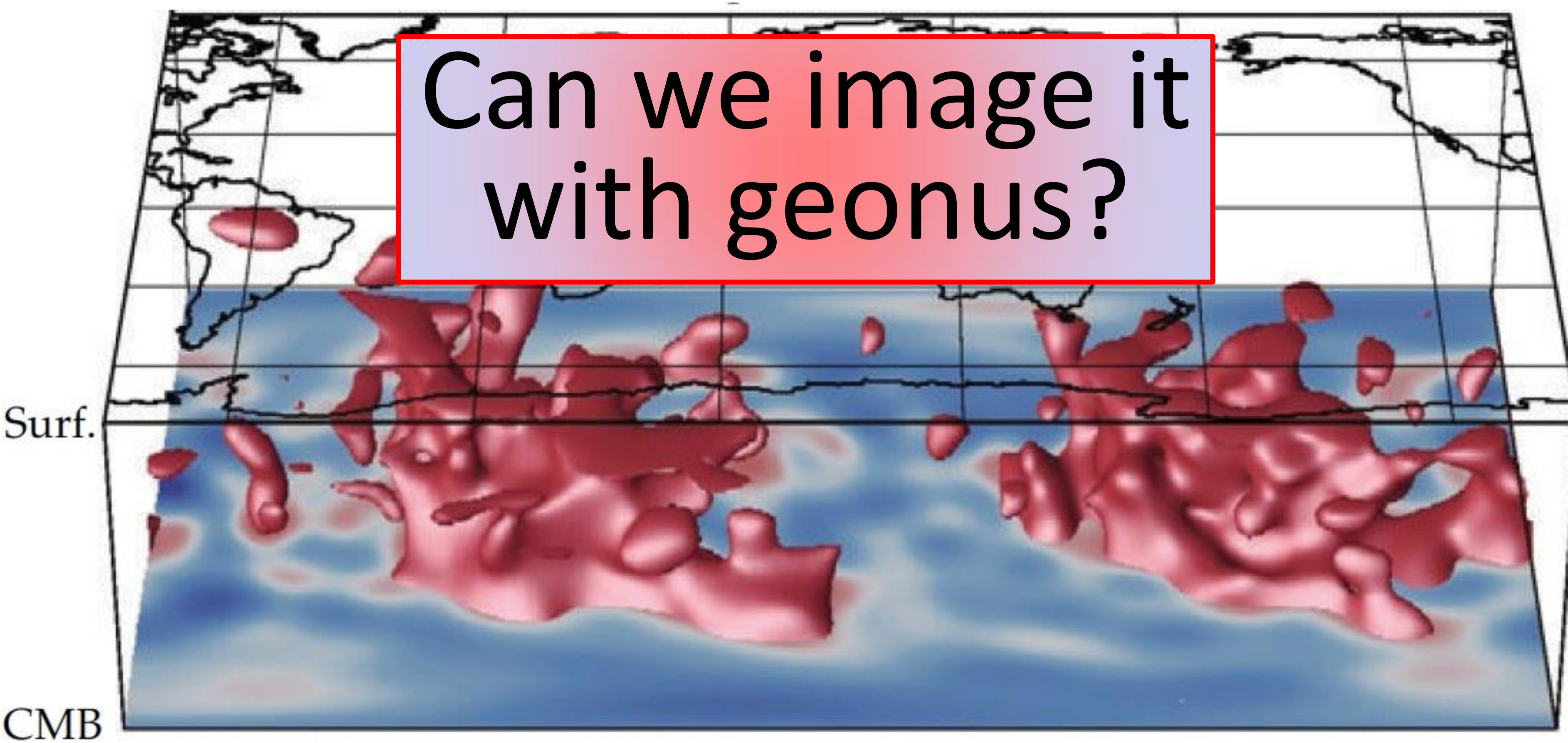
Deployment Sketch

Descent/ascent 39 min

What’s hidden in the mantle?

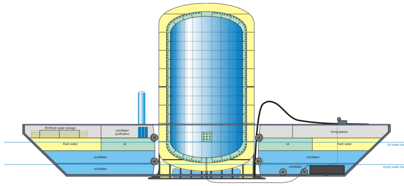
Seismically slow “red” regions in the deep mantle

Can we image it with geonus?

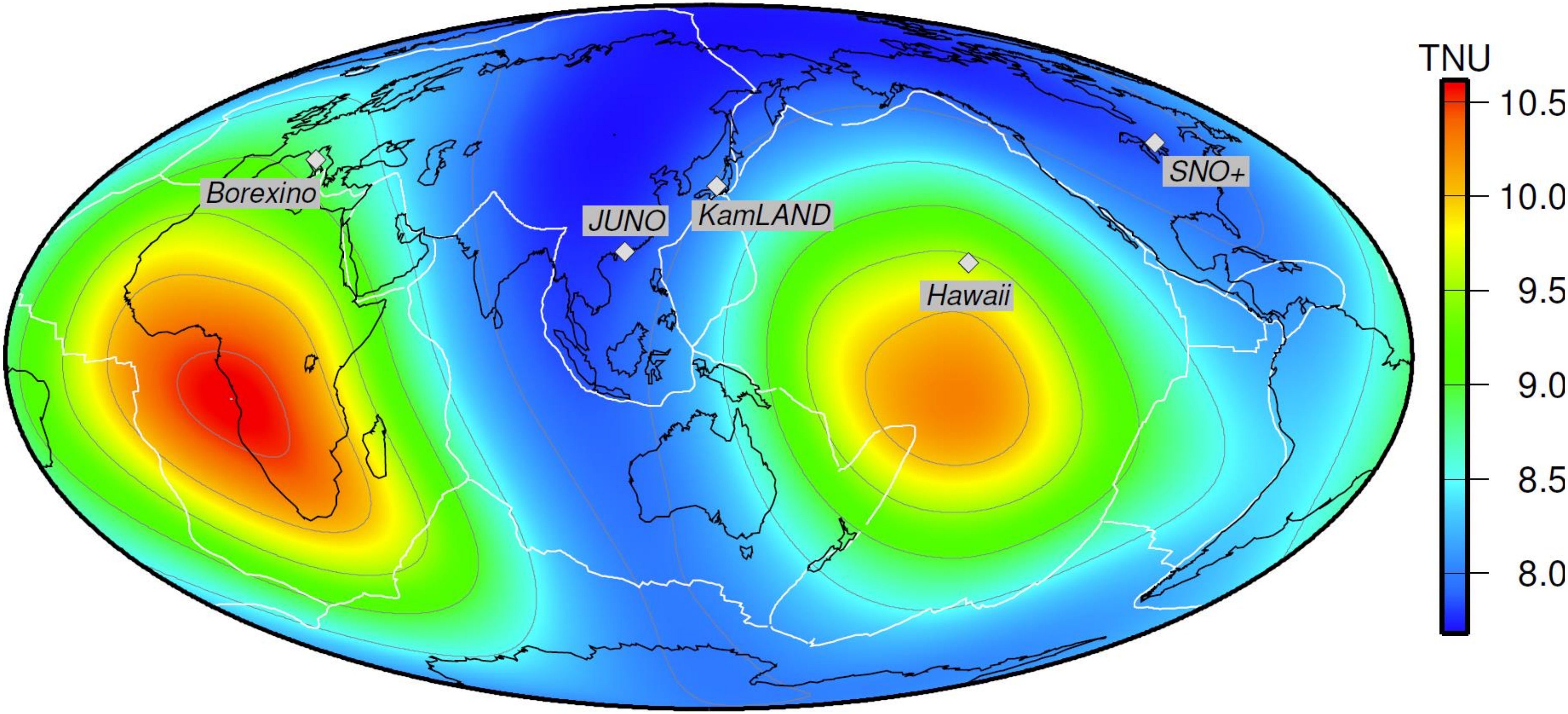


From Alan McNamara after Ritsema et al (Science, 1999)

Testing Earth Models

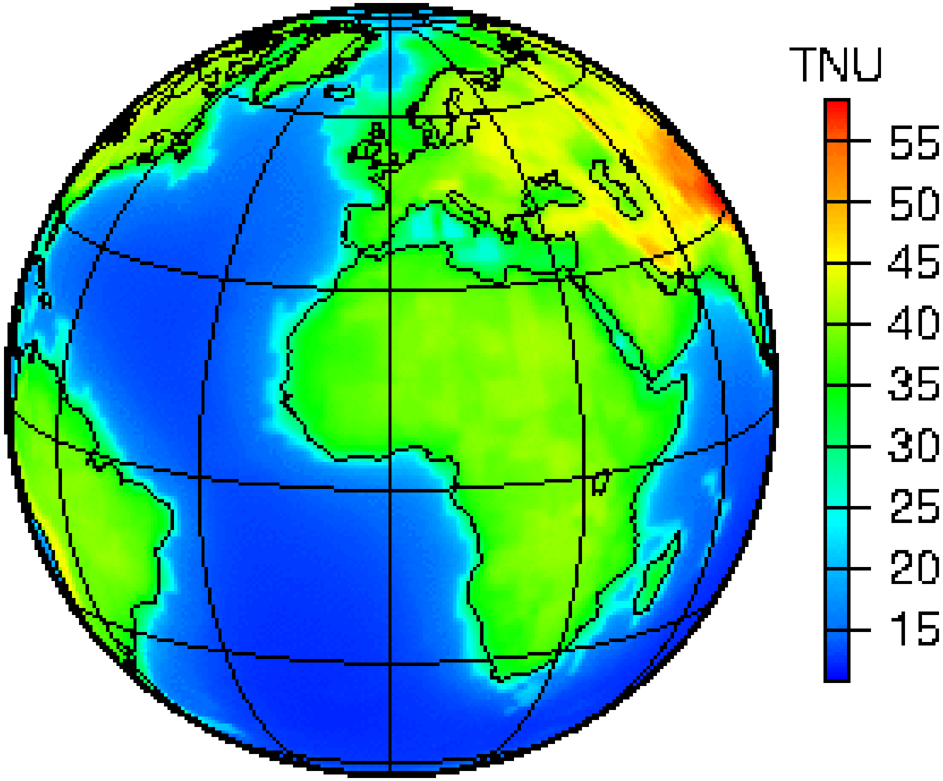


Mantle geoneutrino flux (^{238}U & ^{232}Th)



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)

Predicted geoneutrino flux



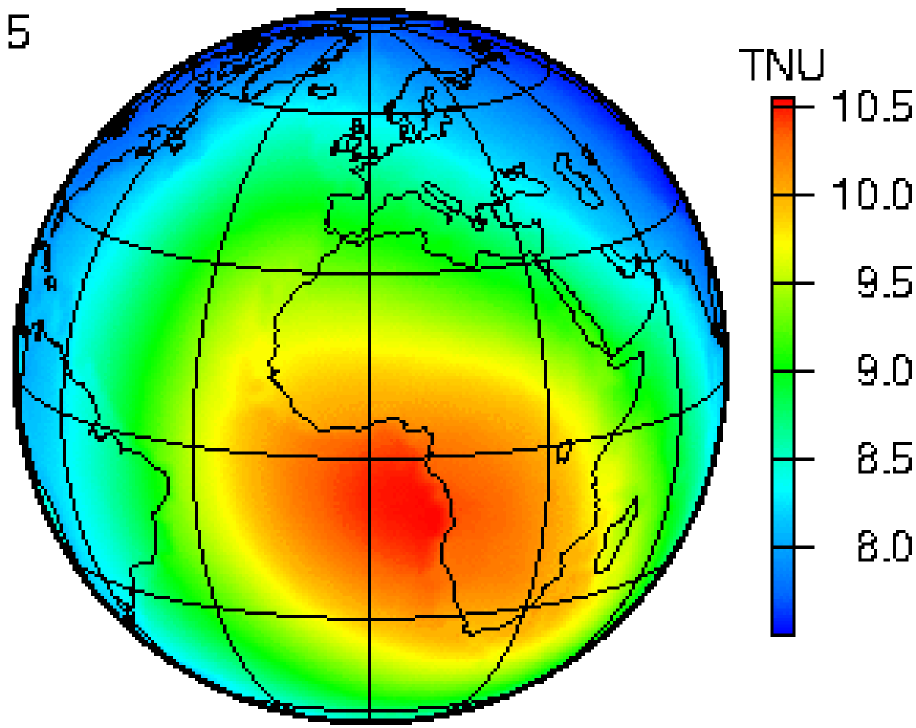
Total flux at surface

dominated by
Continental crust

Yu Huang et al (2013) G-cubed 10.1002/ggge.20129

Mantle flux at the Earth's surface

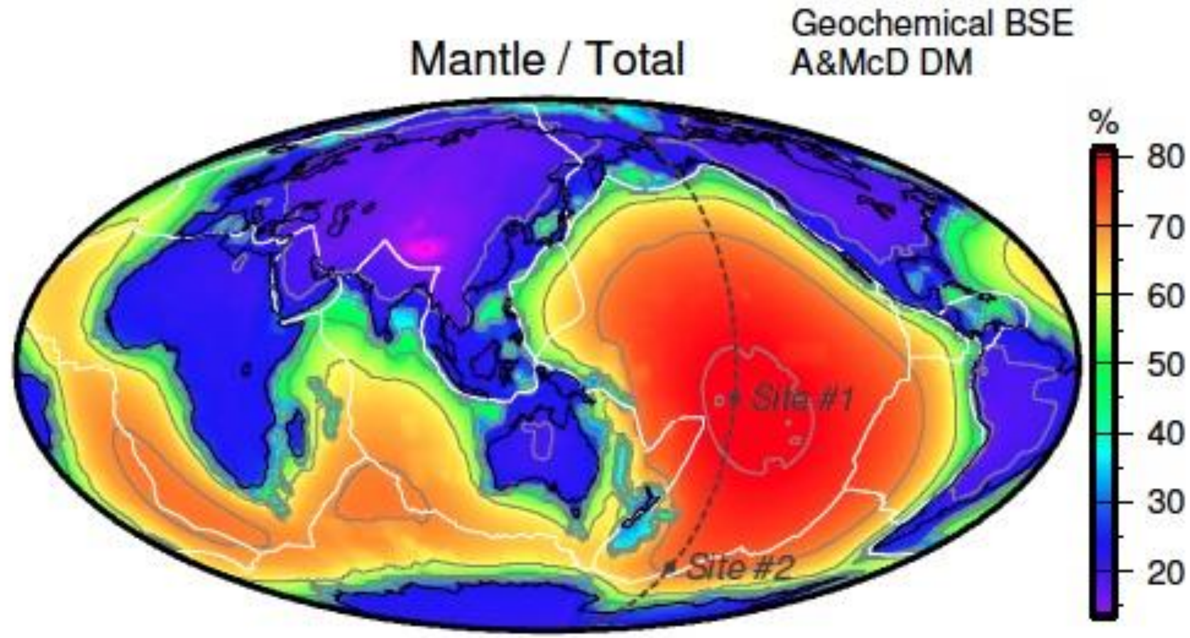
dominated by
deep mantle structures

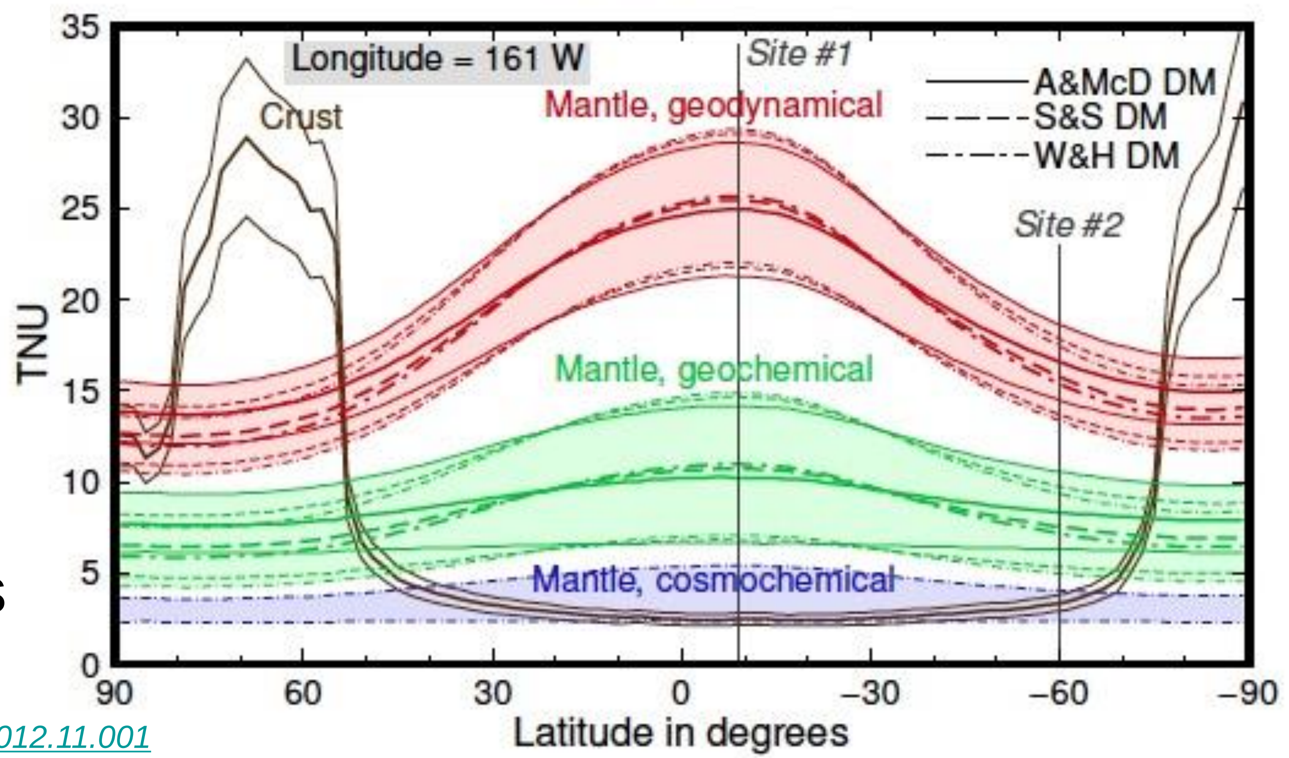


Šrámek et al (2013) EPSL 10.1016/j.epsl.2012.11.001

Ocean based experiment!

- Neutrino Imaging
- Pacific Transect
- Avoid continents
- 4 km depth deployments
- Map out the Earth's interior
- Test Earth models





Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001

SUMMARY

Earth's radiogenic (Th & U) power

28^{+24}_{-17} TW - Borexino 16^{+8}_{-5} TW – KamLAND

Prediction: models range from 8 to 28 TW (for Th & U)

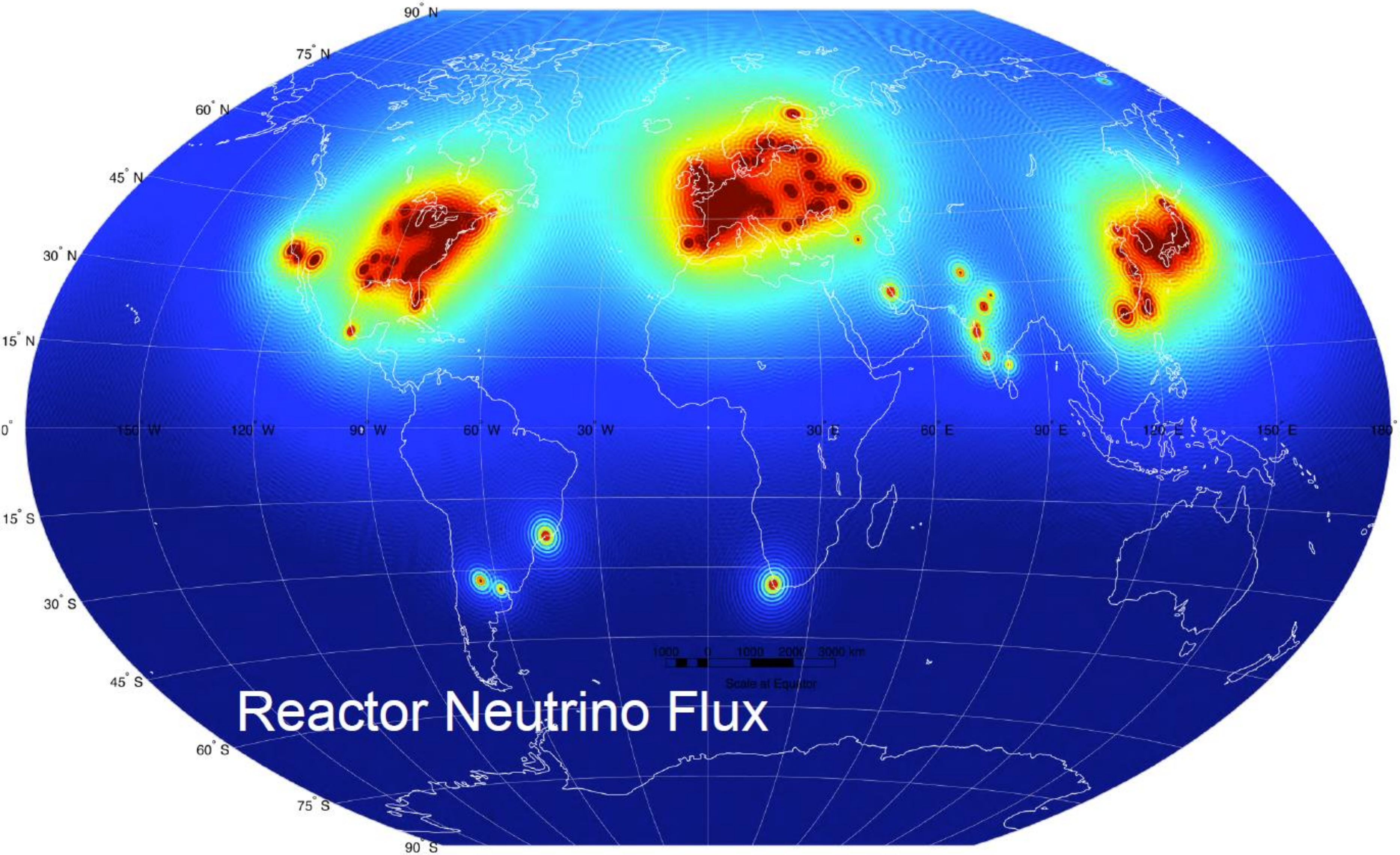
KamLAND: **MANTLE signal** 8.8 ± 6.4 TNU (~11 TW)

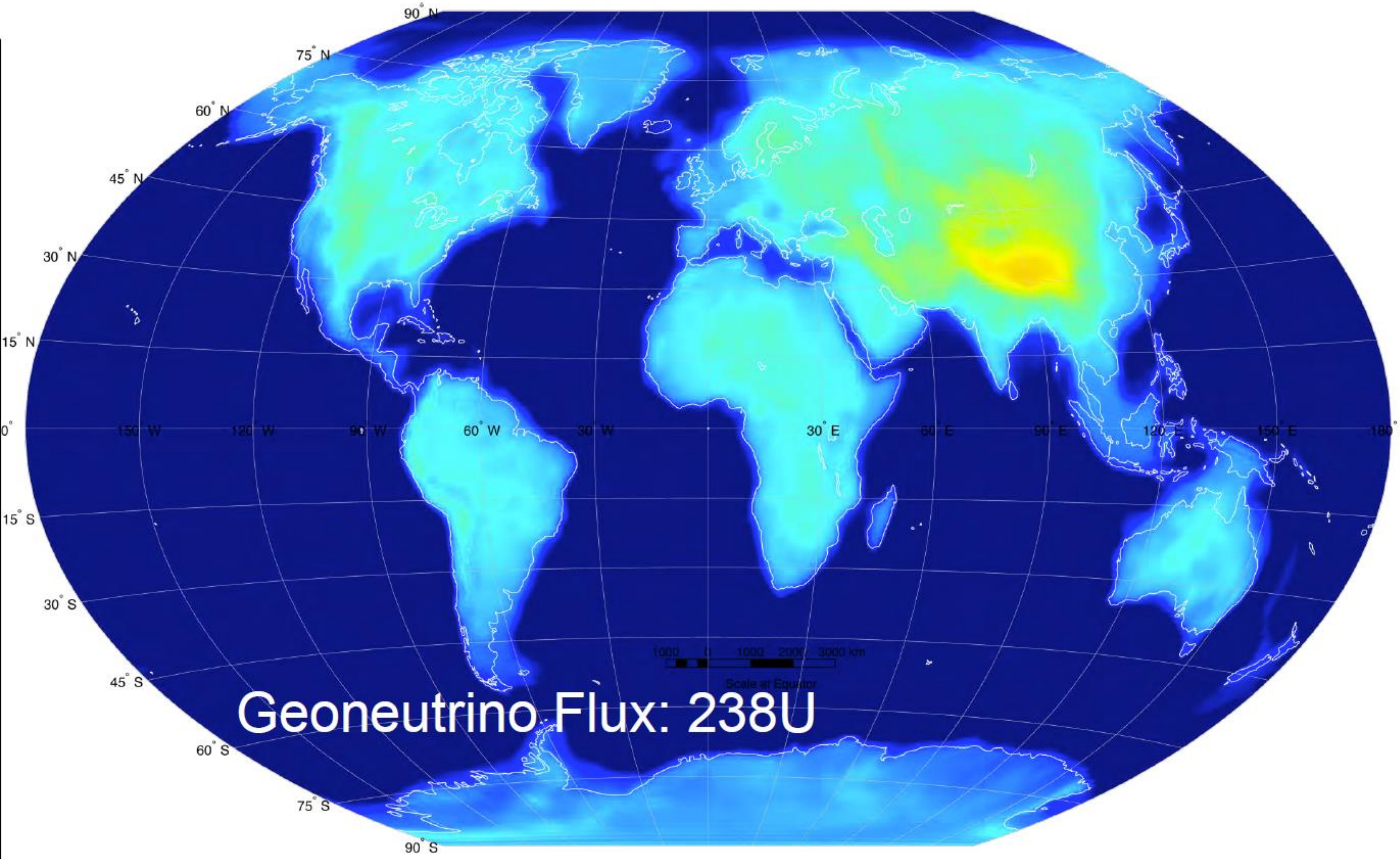
On-line and next generation GEO-NEUTRINO experiments:

- **SNO+** online 2017 ☺
- **JUNO**: 2020, enormous detector & background…
- **Jinping**: 202X, superb experiment, great for crust & mantle
- **Hanohano**: this is how to look at the mantle-only

IMPORTANT CONSIDERATIONS: **WbLS and directionality**

Backup


90° N
75° N
60° N
45° N
30° N
15° N
0°
150° W
120° W
90° W
60° W
30° W
30° E
60° E
90° E
120° E
150° E
180° E
15° S
30° S
45° S
60° S
75° S
90° S
1000 0 1000 2000 3000 km
Scale at Equator
Reactor Neutrino Flux


90° N
75° N
60° N
45° N
30° N
15° N
0°
150° W
120° W
90° W
60° W
30° W
30° E
60° E
90° E
120° E
150° E
180° E
15° S
30° S
45° S
60° S
75° S
90° S
1000 0 1000 2000 3000 km
Scale at Equator
Geoneutrino Flux: 238U