Geoneutrinos and heat production in the Earth

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Hawaii Pacific U and Physics, U Hawaii*

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*graduate student
+post-doc

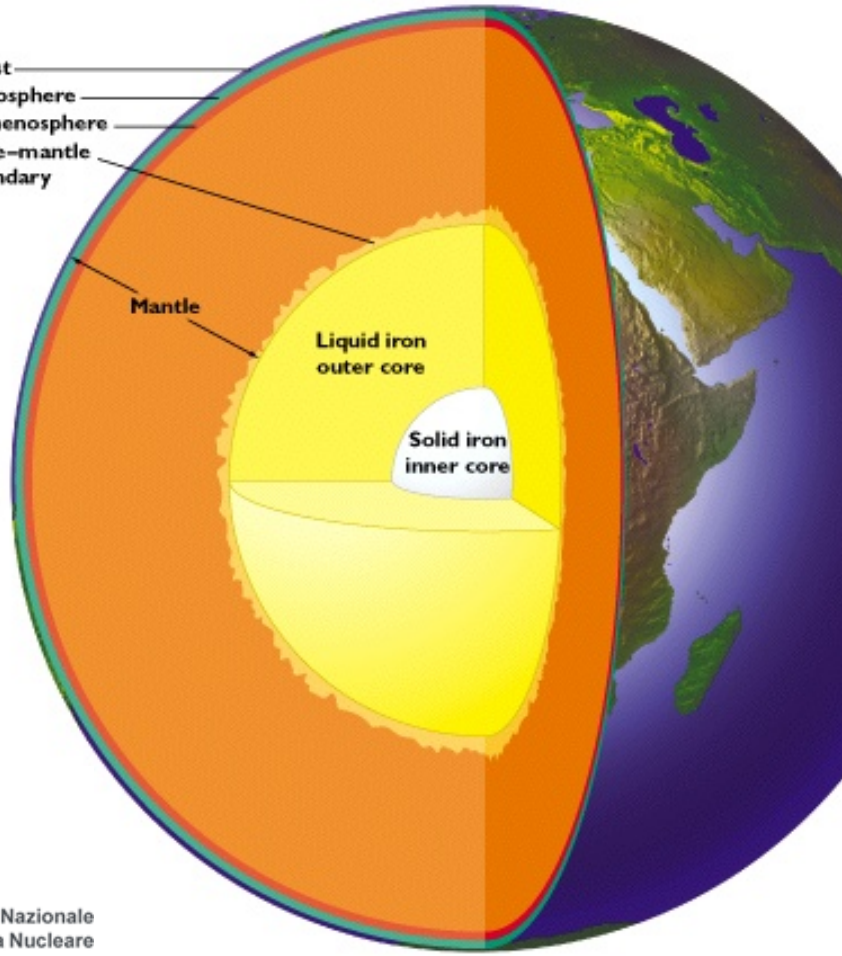
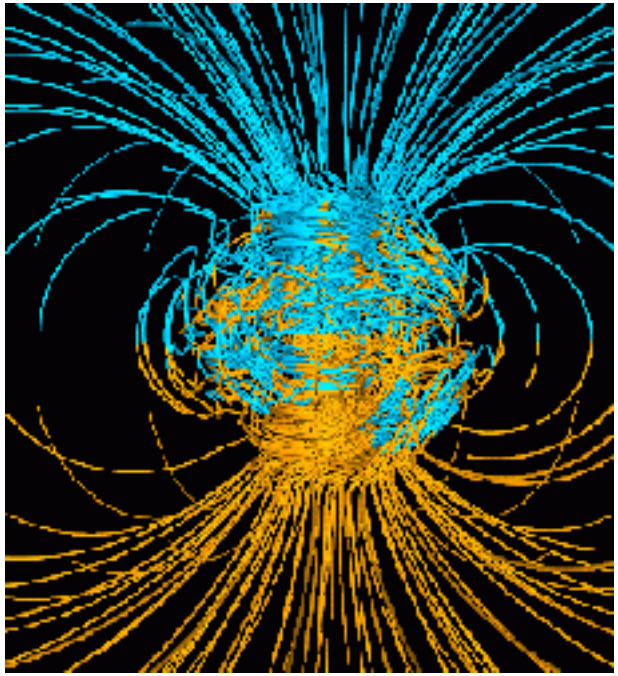
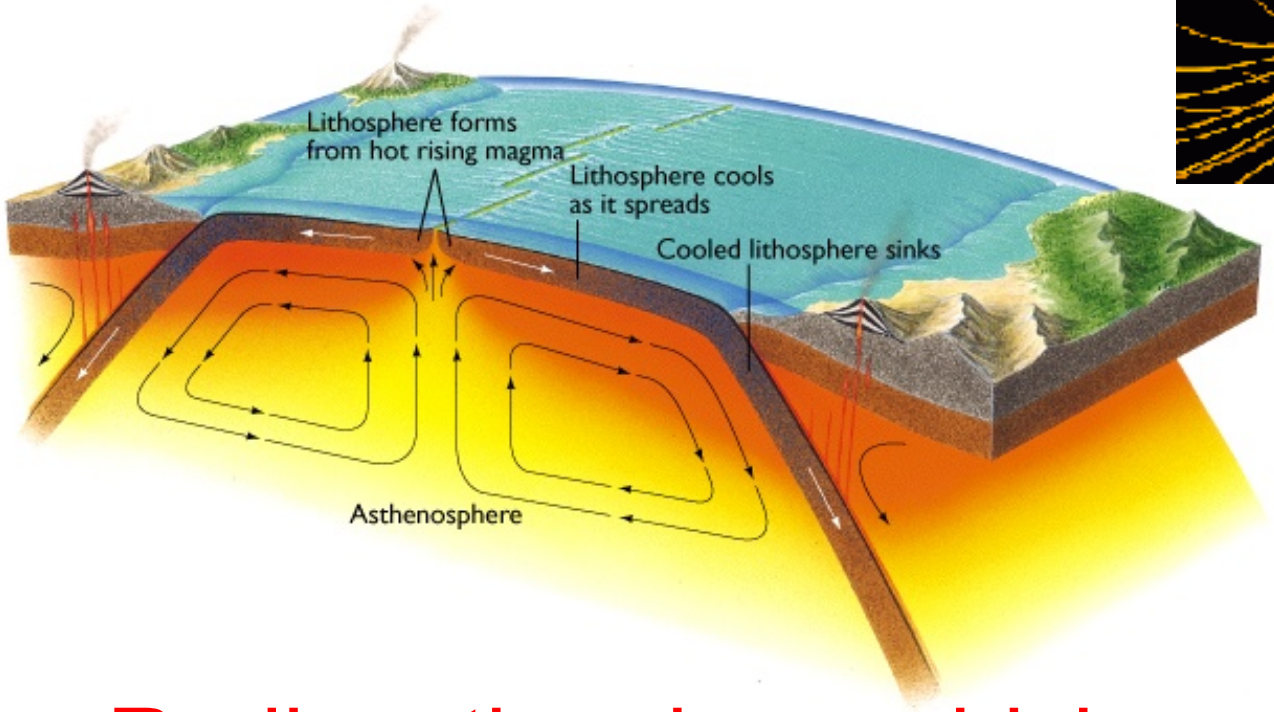
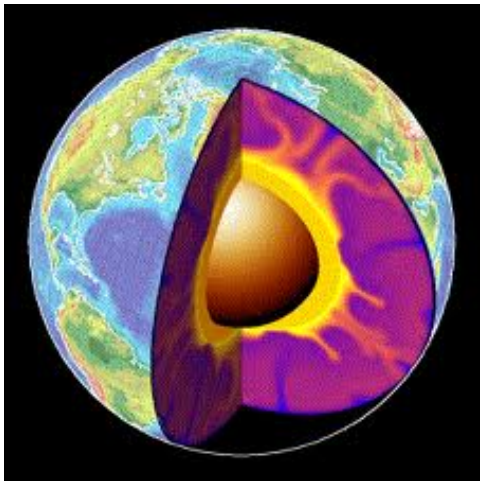


Plate Tectonics, Convection, Geodynamo







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**."

Campbell and O'Neill (March - 2012, *Nature*): "Evidence **against a chondritic Earth**"

Zhang et al (March - 2012, *Nature Geoscience*): The Ti isotopic composition of the **Earth and Moon overlaps that of enstatite chondrites**.

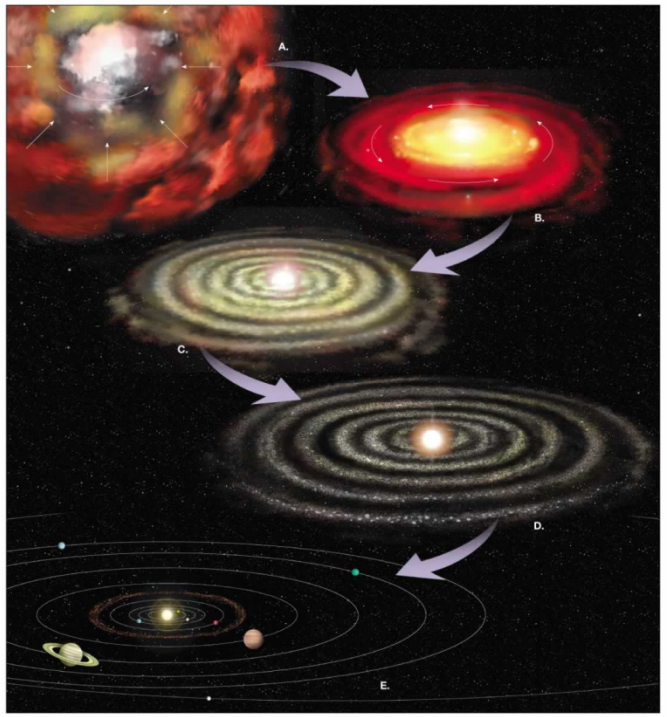
Fitoussi and Bourdon (March - 2012, *Science*): "Si isotopes support the conclusion that **Earth was not built solely from enstatite chondrites**."

Warren (Nov - 2011, *EPSL*): "Among known chondrite groups, **EH yields a relatively close fit to the stable-isotopic composition of Earth**."

- Compositional models differ widely, implying a **factor of three difference** in the U & Th abundances of the Earth

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

Nebula



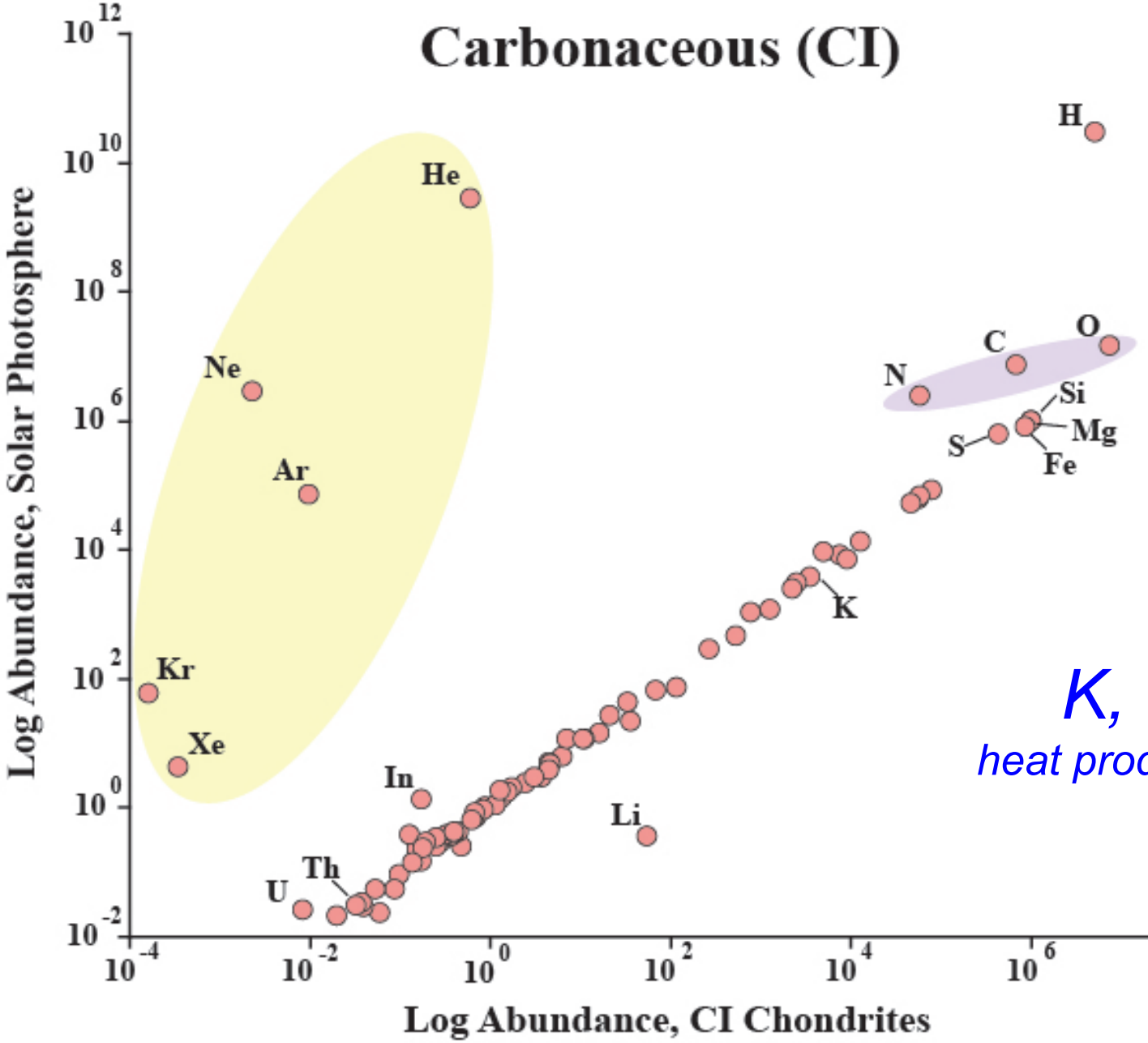
Meteorite

Heterogeneous mixtures of components with different formation temperatures and conditions

Planet:

mix of metal, silicate, volatiles

Sun and Chondrites are related

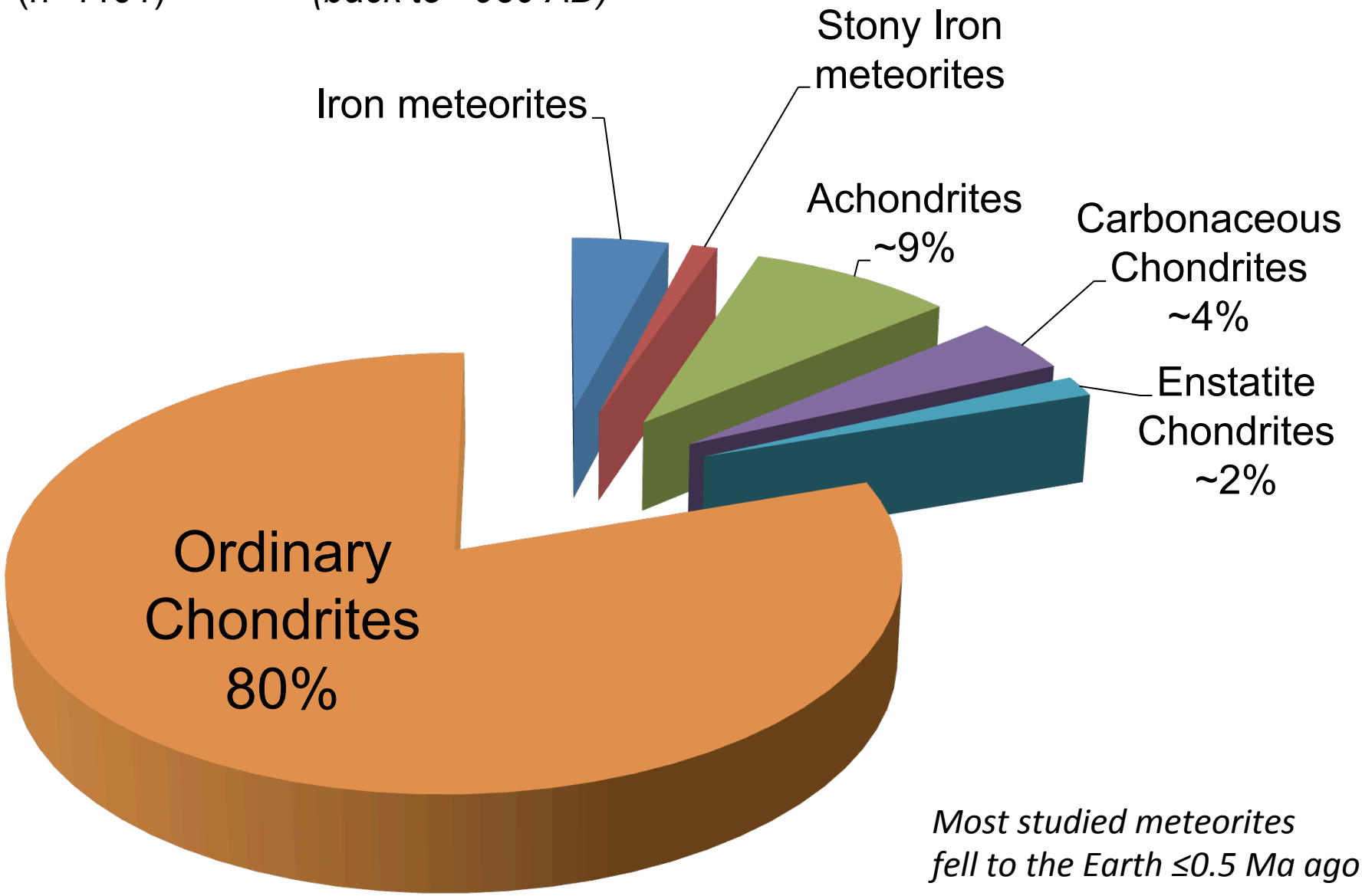


K, Th & U

heat producing elements

Meteorite: Fall statistics

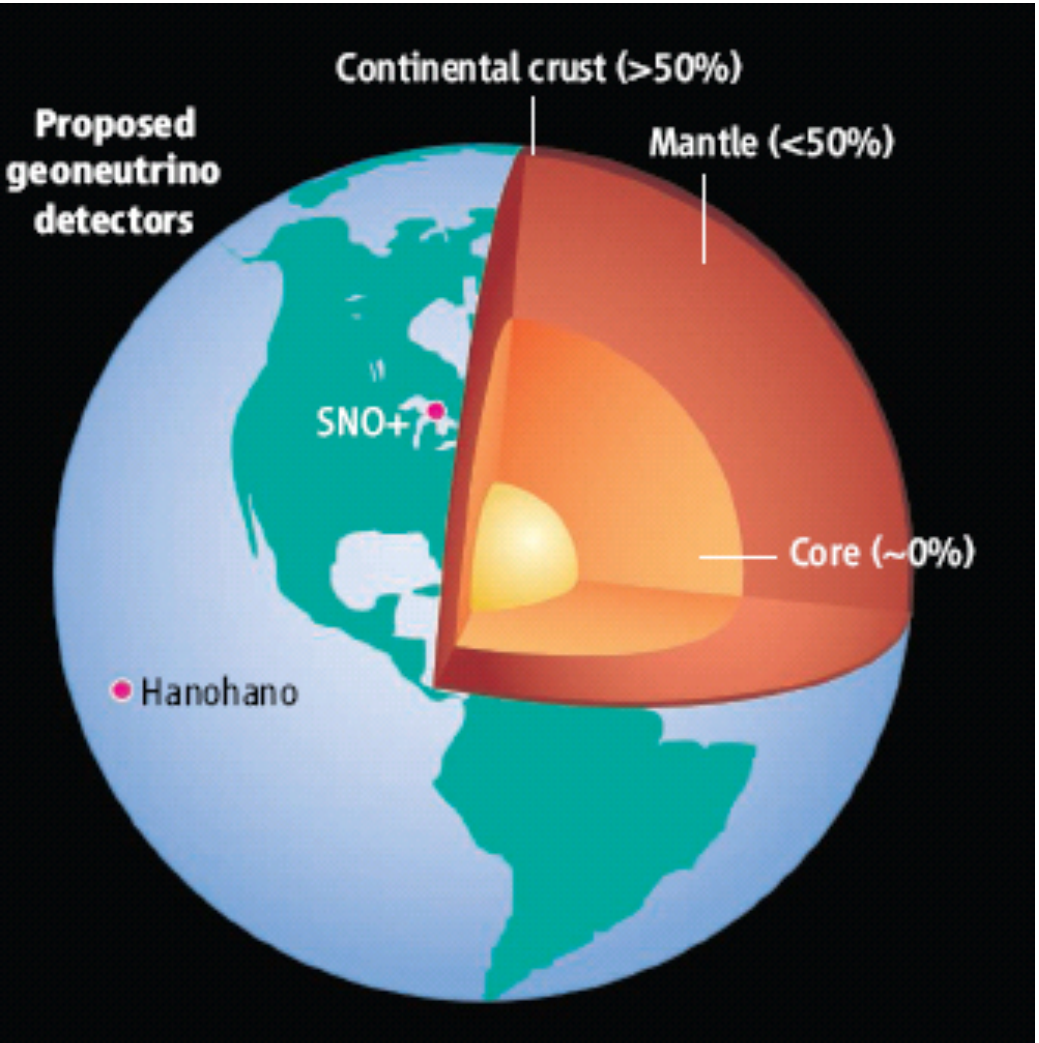
(n=1101) *(back to ~980 AD)*



Most studied meteorites fell to the Earth ≤0.5 Ma ago

U in the Earth:

"Differentiation"



~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*

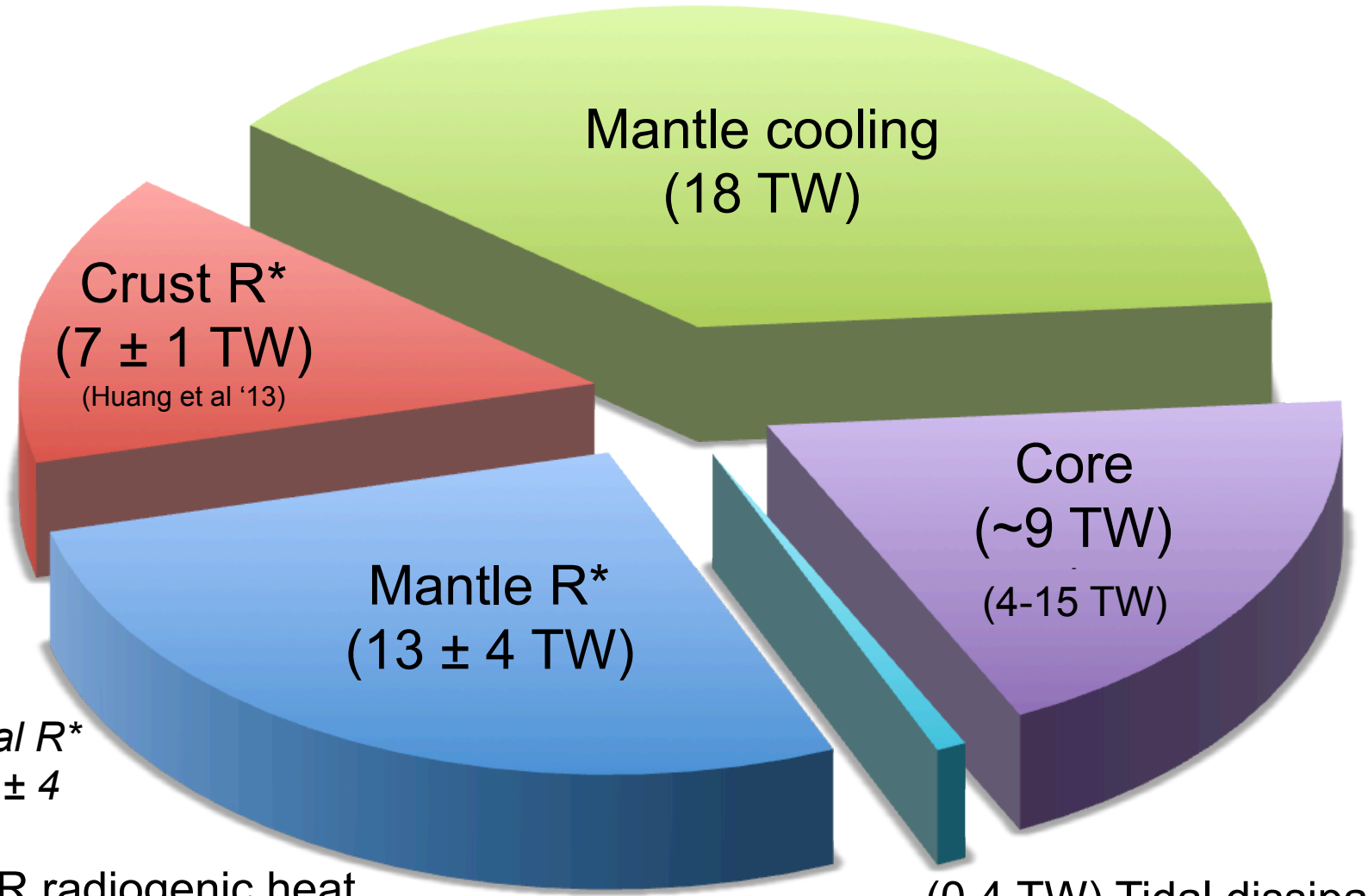
**Turcotte & Schubert (2002) 31 ng/g*

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

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

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

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



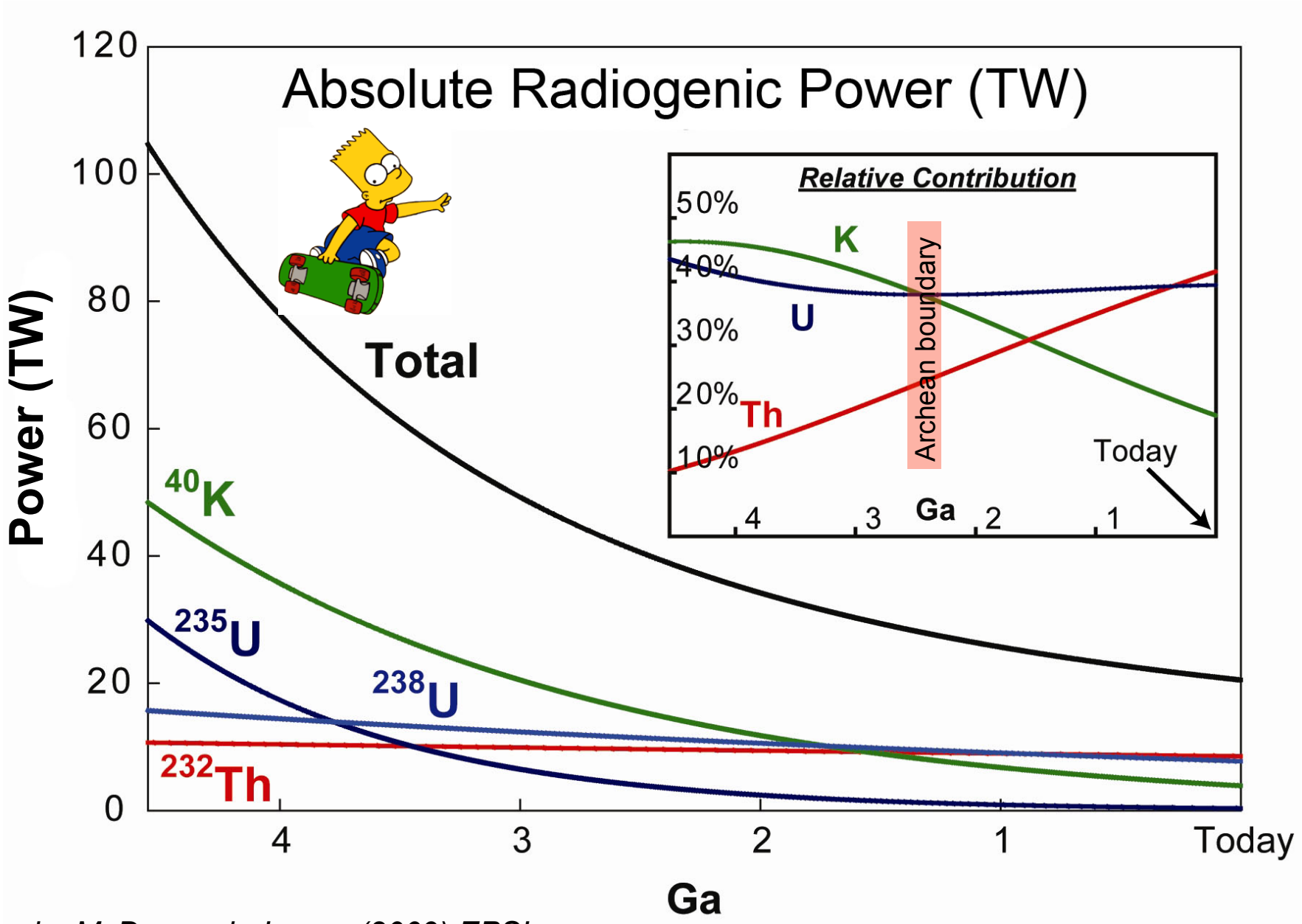
*total R**
20 ± 4

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

(0.4 TW) Tidal dissipation
Chemical differentiation

after Jaupart et al 2008 Treatise of Geophysics

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



Arevalo, McDonough, Luong (2009) EPSL

nature geoscience

2011

ARTICLES

PUBLISHED ONLINE: 17 JULY 2011 | DOI:10.

Partial radiogenic heat model for E
by geoneutrino measurement

The KamLAND Collaboration*

Latest **Borexino** results in Bellini et al 2013
http://arxiv.org/abs/1303.2571

Latest **KamLAND** results in Gando et al 2013
http://arxiv.org/abs/1303.4667

Ge **nos**
the Earth

Physics Letters B 687 (2010) 299–304

Contents lists available at ScienceDirect

2010

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

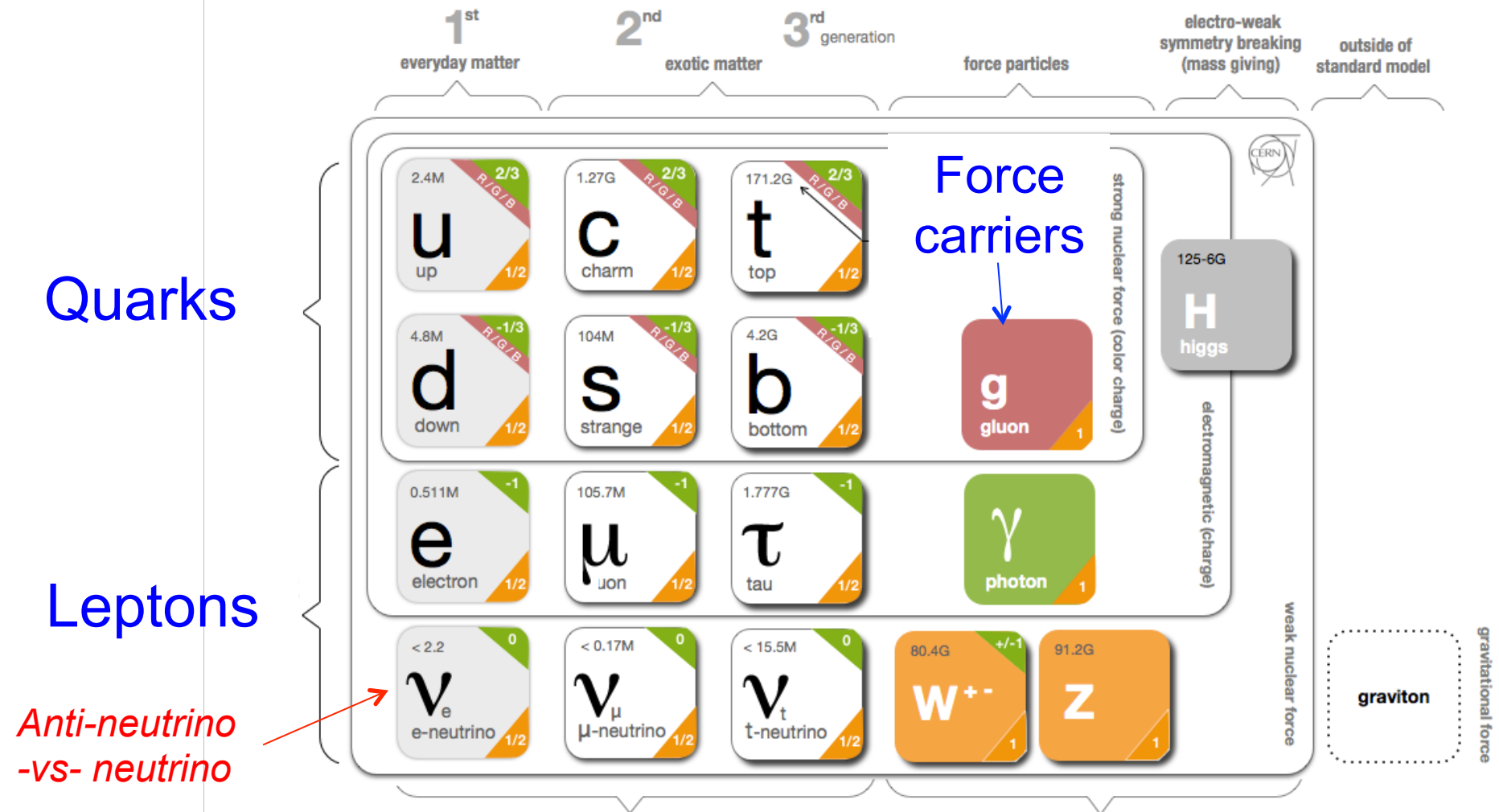
Observation of geo-neutrinos

Borexino Collaboration

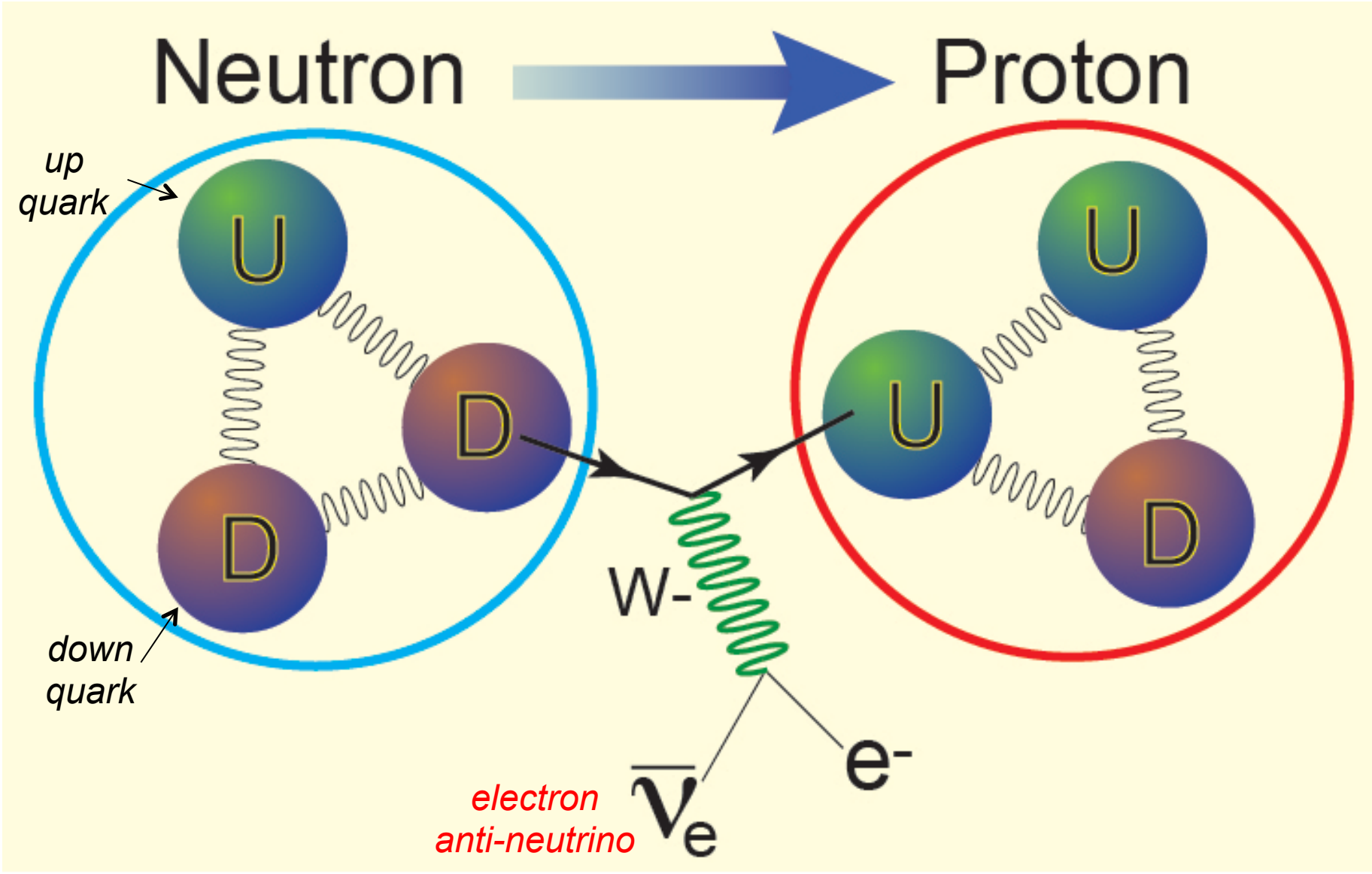
What are Geoneutrinos?

electron anti-neutrinos
from the Earth, products of
natural radioactivity

Geoneutrino flux
- typical flux $6*10^6$ cm^{-2} s^{-1}



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



Terrestrial Antineutrinos

$\bar{\nu}_e + p^+ \rightarrow n + e^+$

1.8 MeV Energy Threshold

^{238}U

1α, 1β

^{234}Pa

$\bar{\nu}_e$ 2.3 MeV 31%

5α, 2β

^{214}Bi

$\bar{\nu}_e$ 3.3 MeV 48%

2α, 3β

^{206}Pb

^{232}Th

1α, 1β

^{228}Ac

$\bar{\nu}_e$ 2.1 MeV 1%

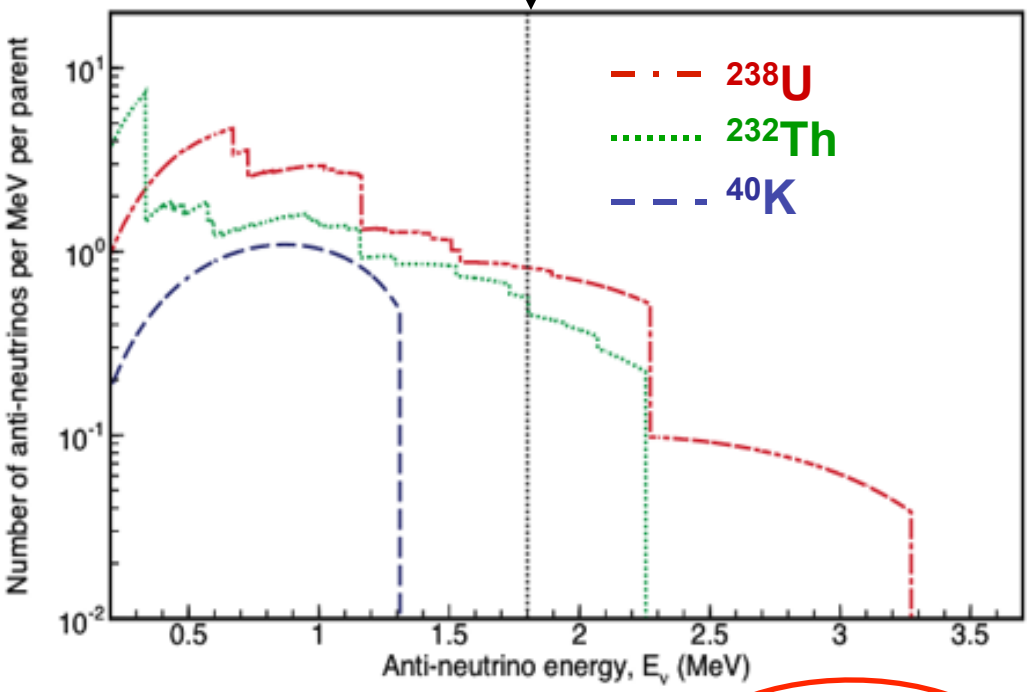
4α, 2β

^{212}Bi

$\bar{\nu}_e$ 2.3 MeV 20%

1α, 1β

^{208}Pb



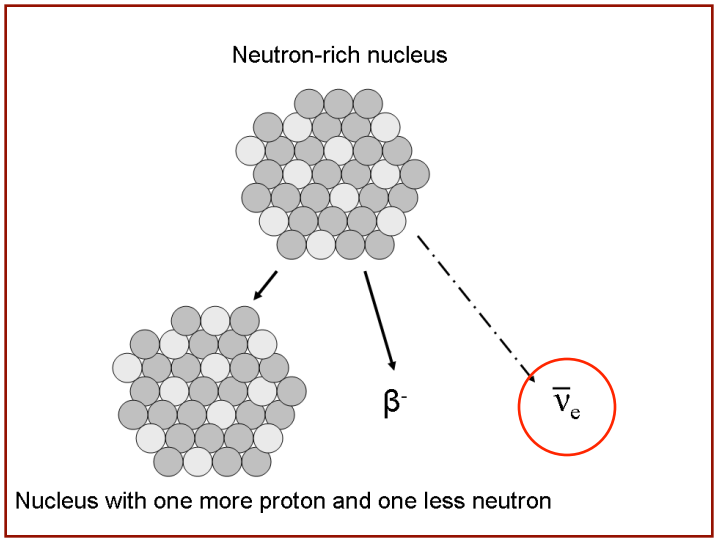
^{40}K 1β ^{40}Ca

Efforts to detect K geonus underway

Terrestrial antineutrinos from uranium and thorium are detectable

MeV-Scale Electron Anti-Neutrino Detection

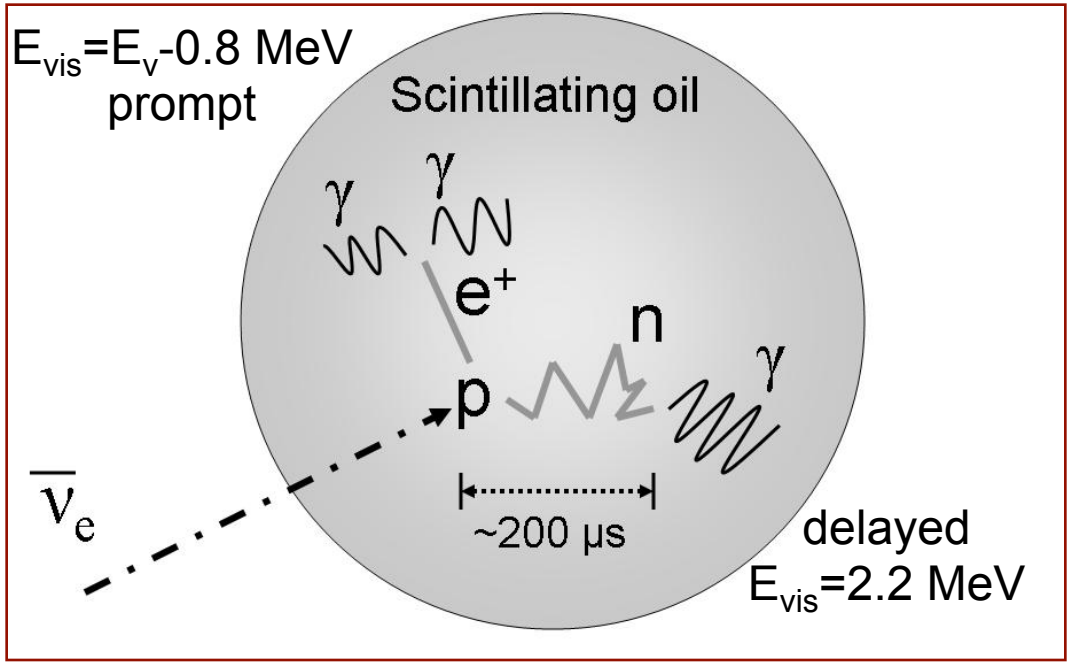
Production in reactors and natural decays



Reines & Cowan

Key: 2 flashes, close in space and time, 2nd of known energy, eliminate background

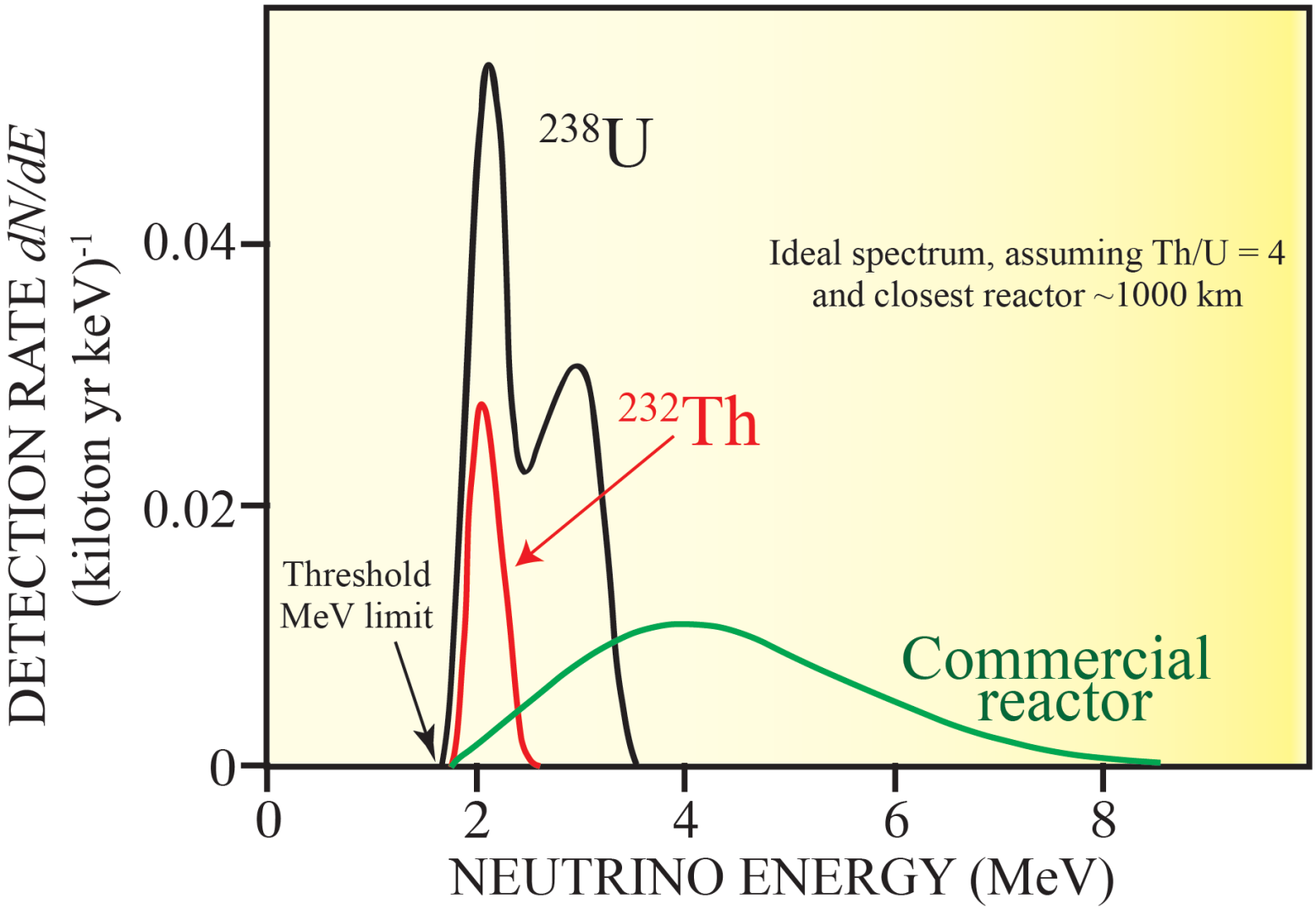
Detection



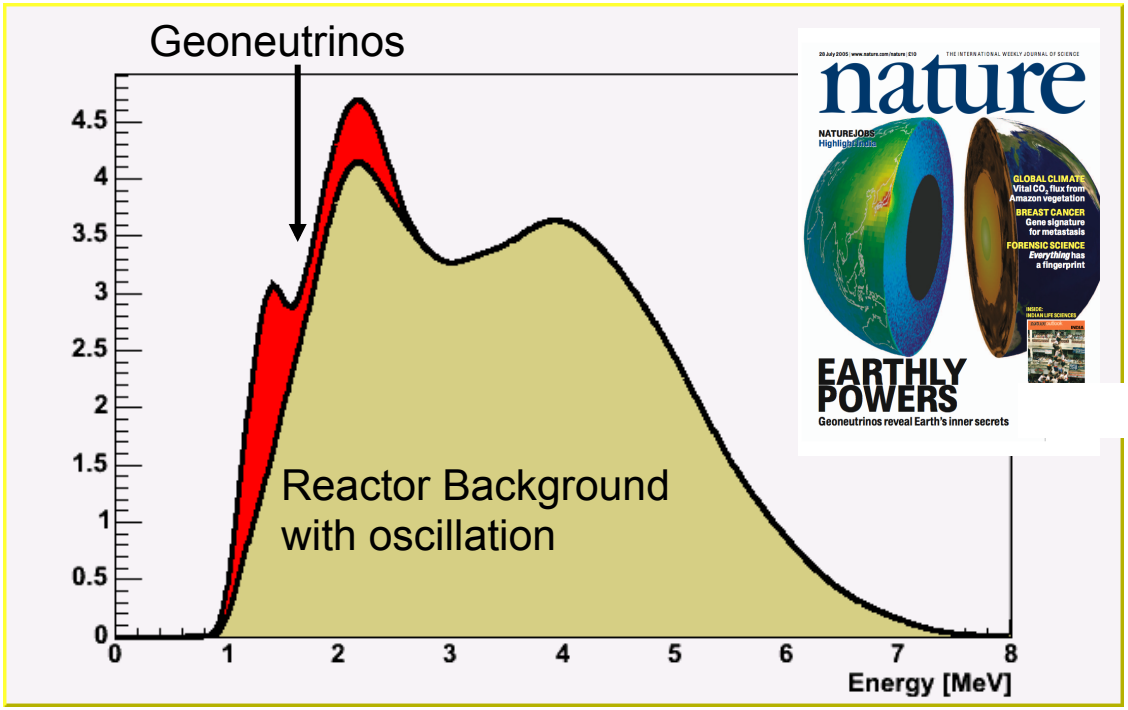
- Standard inverse β-decay coincidence
- E_ν > 1.8 MeV
- Rate and spectrum - no direction

Antineutrinos - Geoneutrinos

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



Reactor and Earth Signal

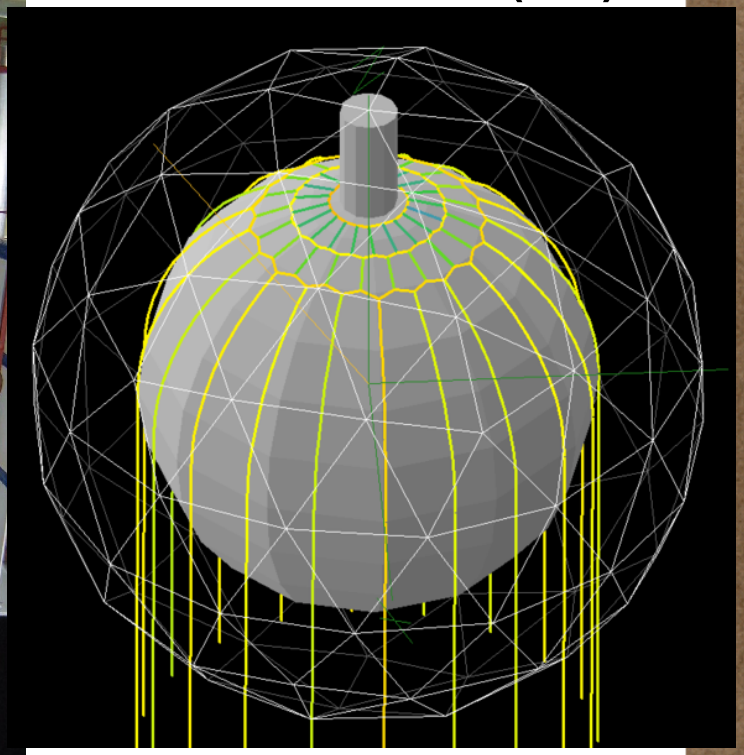


- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant contributor to the total signal.

Present LS-detectors, *data update*

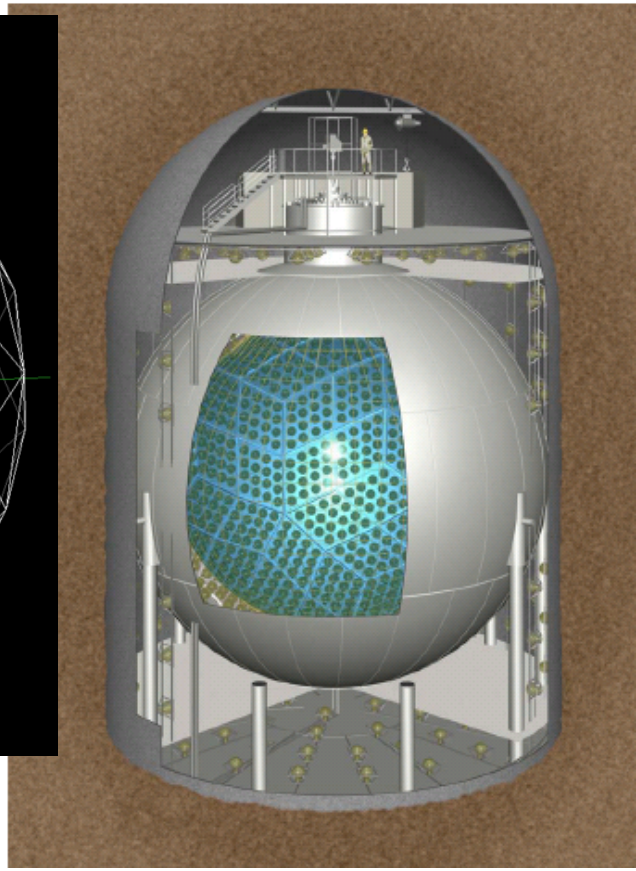
Borexino, Italy (0.3kt)

SNO+, Canada (1kt)



under construction
(online later this yr?)

KamLAND, Japan (1kt)



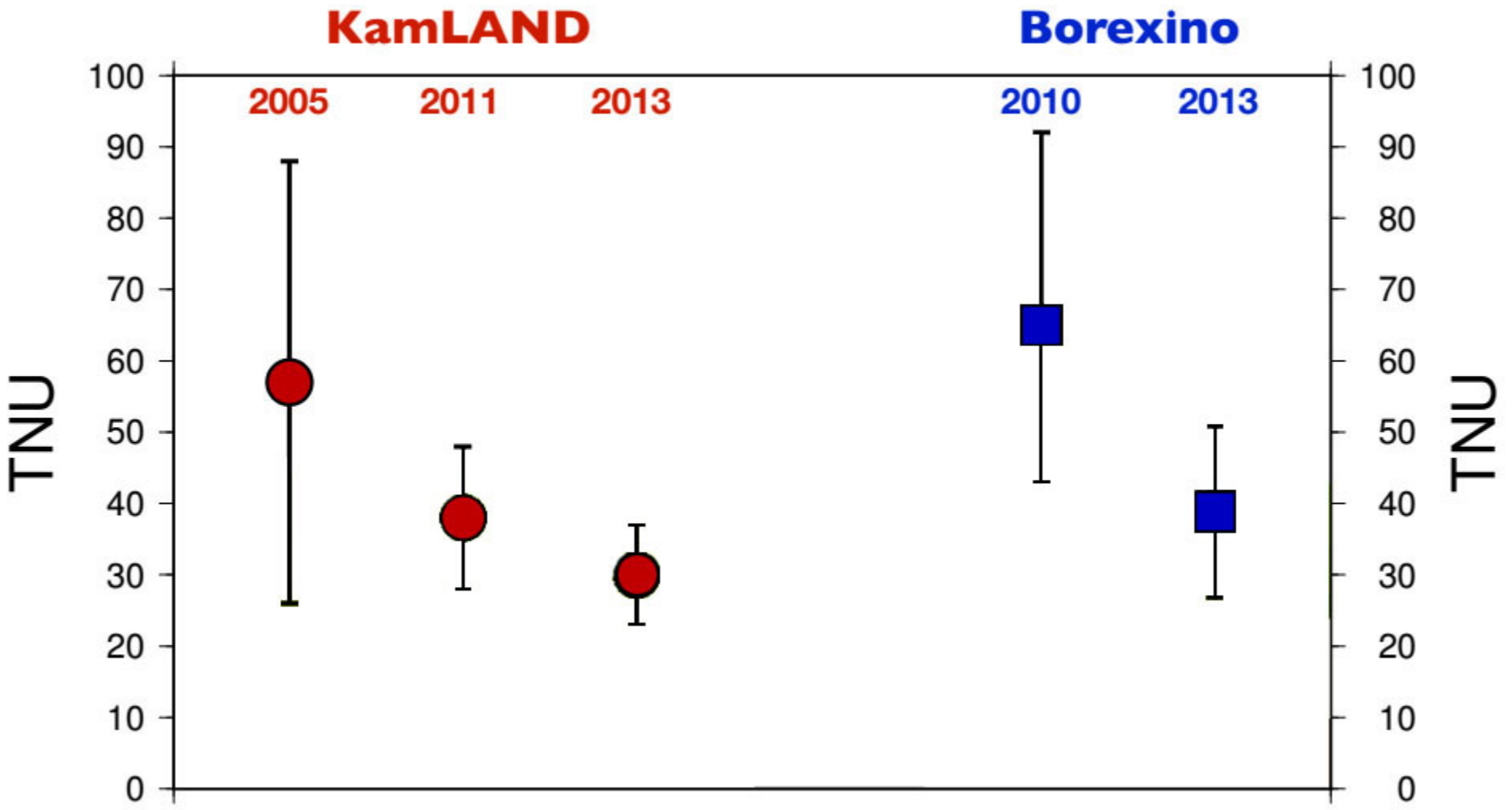
14±4 counts

from May ‘07 to Nov ‘12

116 $^{+28}_{-27}$ counts

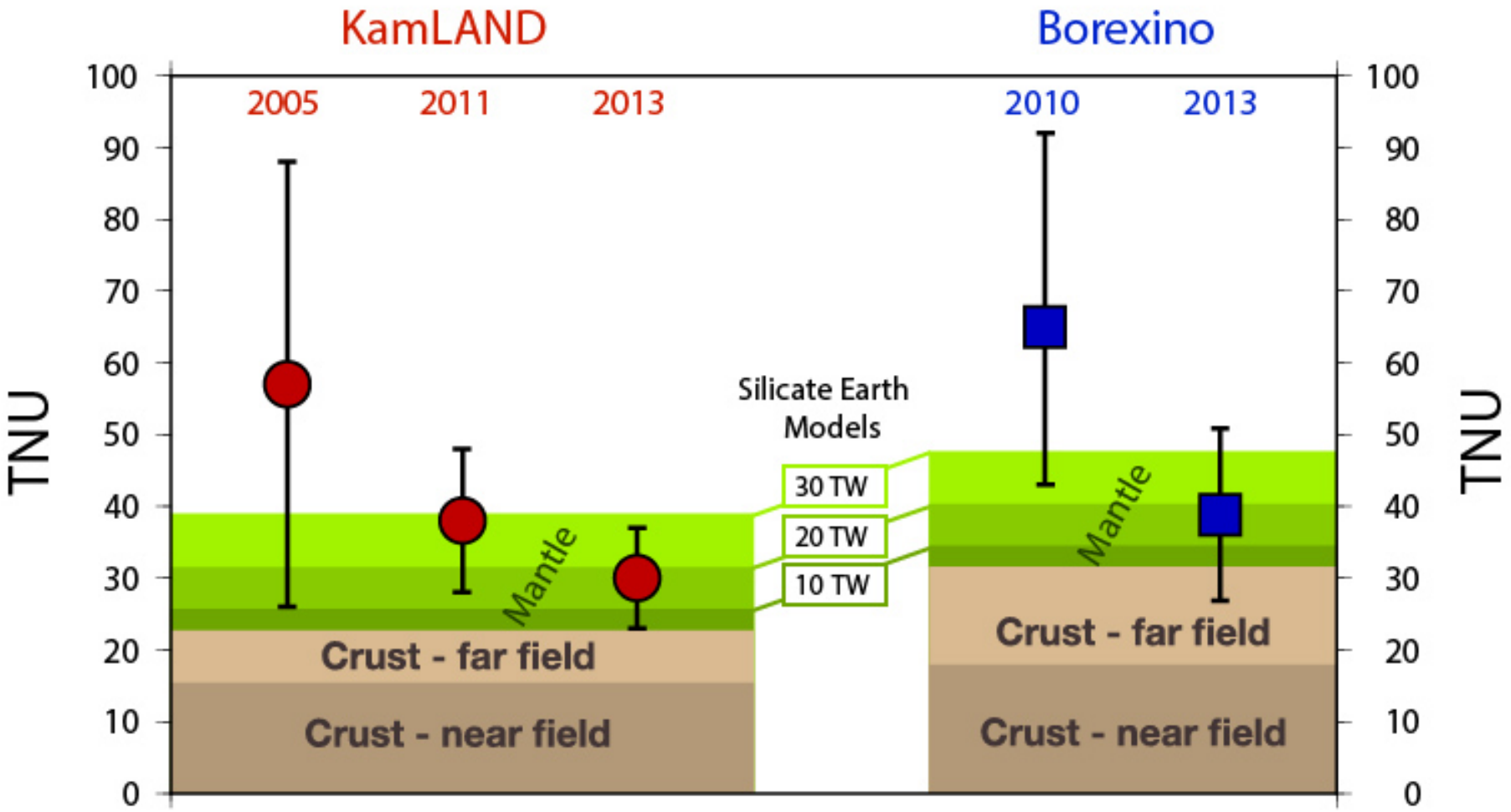
From 9 Mar ‘02 to 20 Nov ‘12

Can Physics Help Geoscience?



TNU: geo-n$\bar{\upsilon}$ event seen by a kiloton detector in a year

Summary of geoneutrino results



SILICATE EARTH MODELS

Cosmochemical: uses meteorites – 10 TW

Geochemical: uses terrestrial rocks –20 TW

Geodynamical: parameterized convection – 30 TW

Geoneutrino Flux on Earth Surface

Activity and number of produced geoneutrinos

Volume of source unit

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

Survival probability function

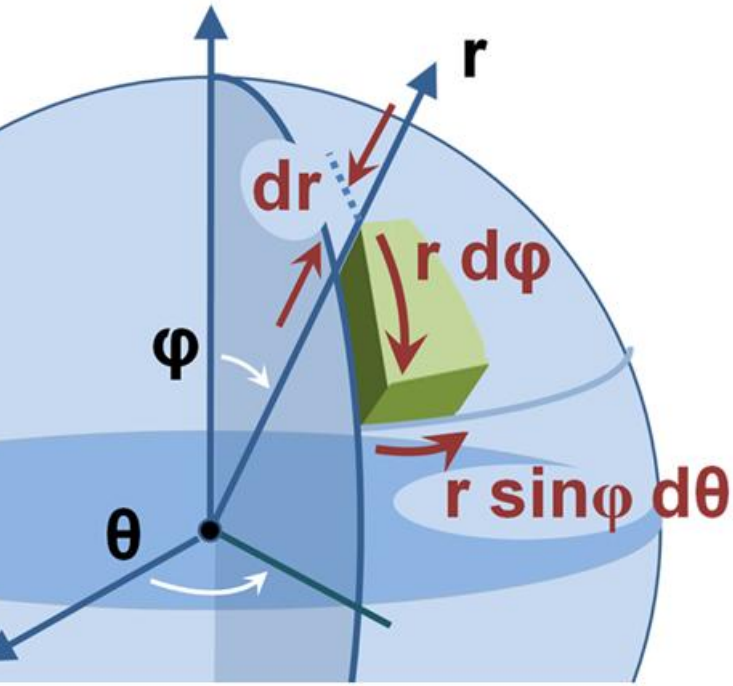
Abundance and density of the source unit

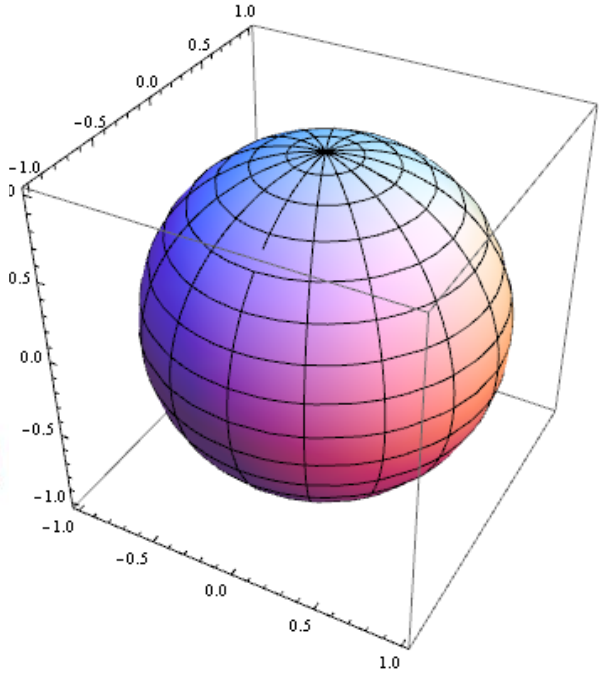
Distance between source unit and detector

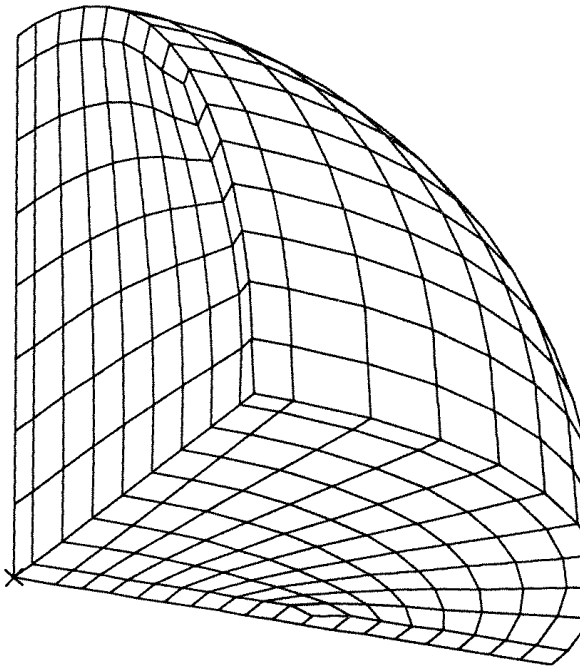
Earth structure (ρ and L) and **chemical composition** (a)

Constructing a 3-D reference model Earth

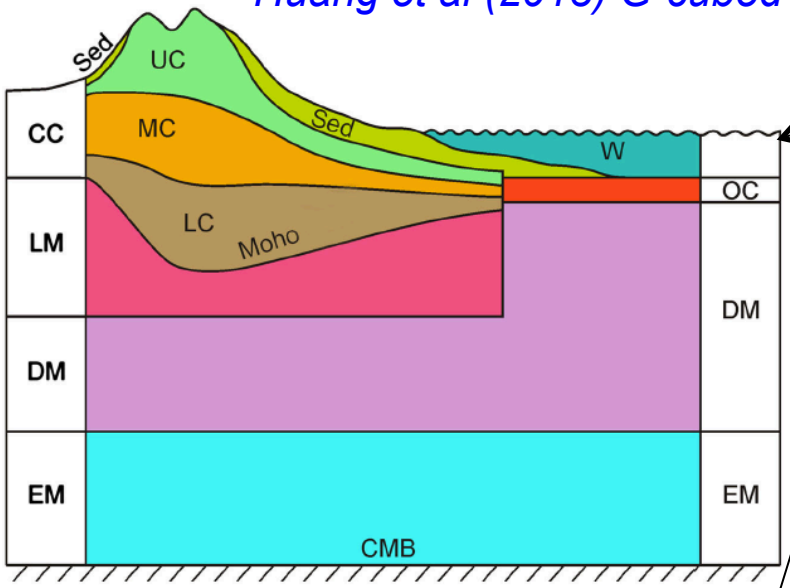
assigning chemical and physical states to Earth voxels





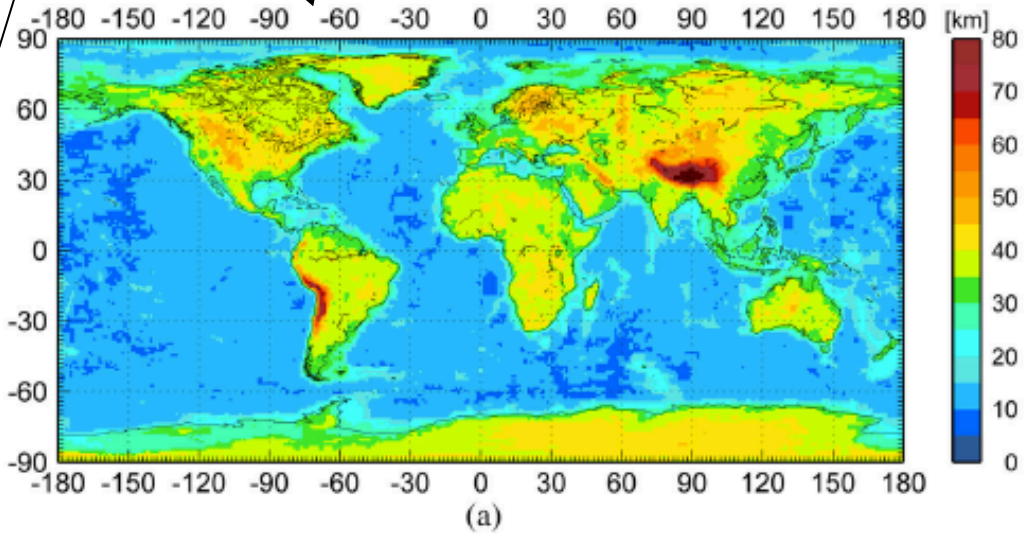


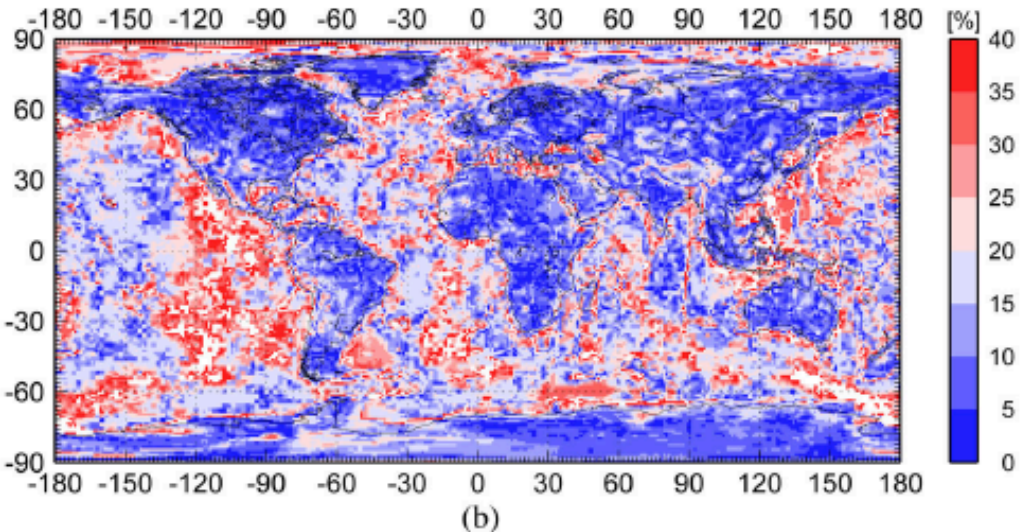
Huang et al (2013) G-cubed

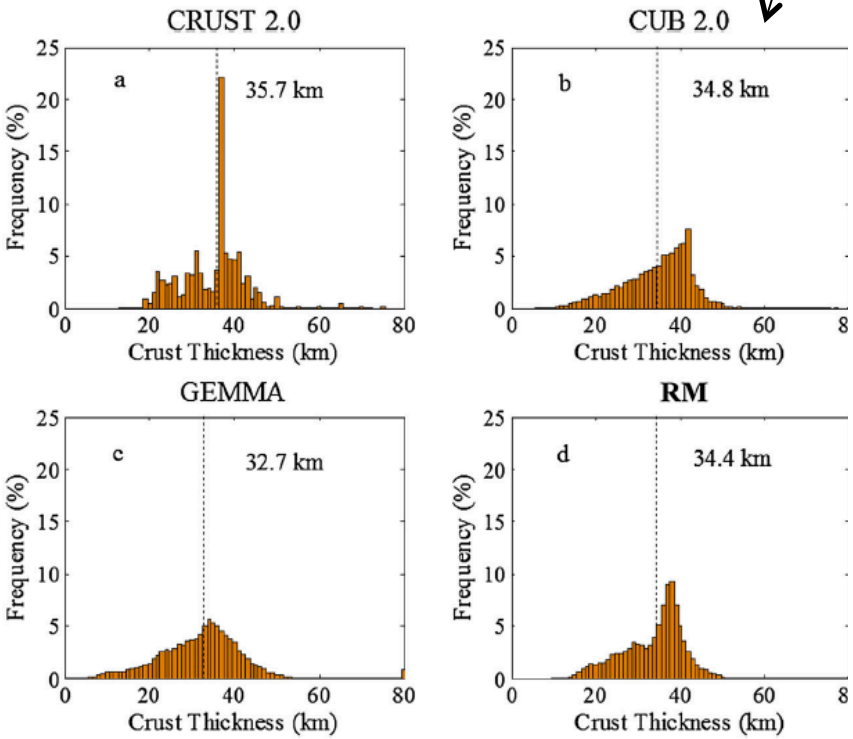


Global Earth Reference Model

- 7 layers for the top 200 km
- Integrate 3 global models for the crust
- New crust model with uncertainties

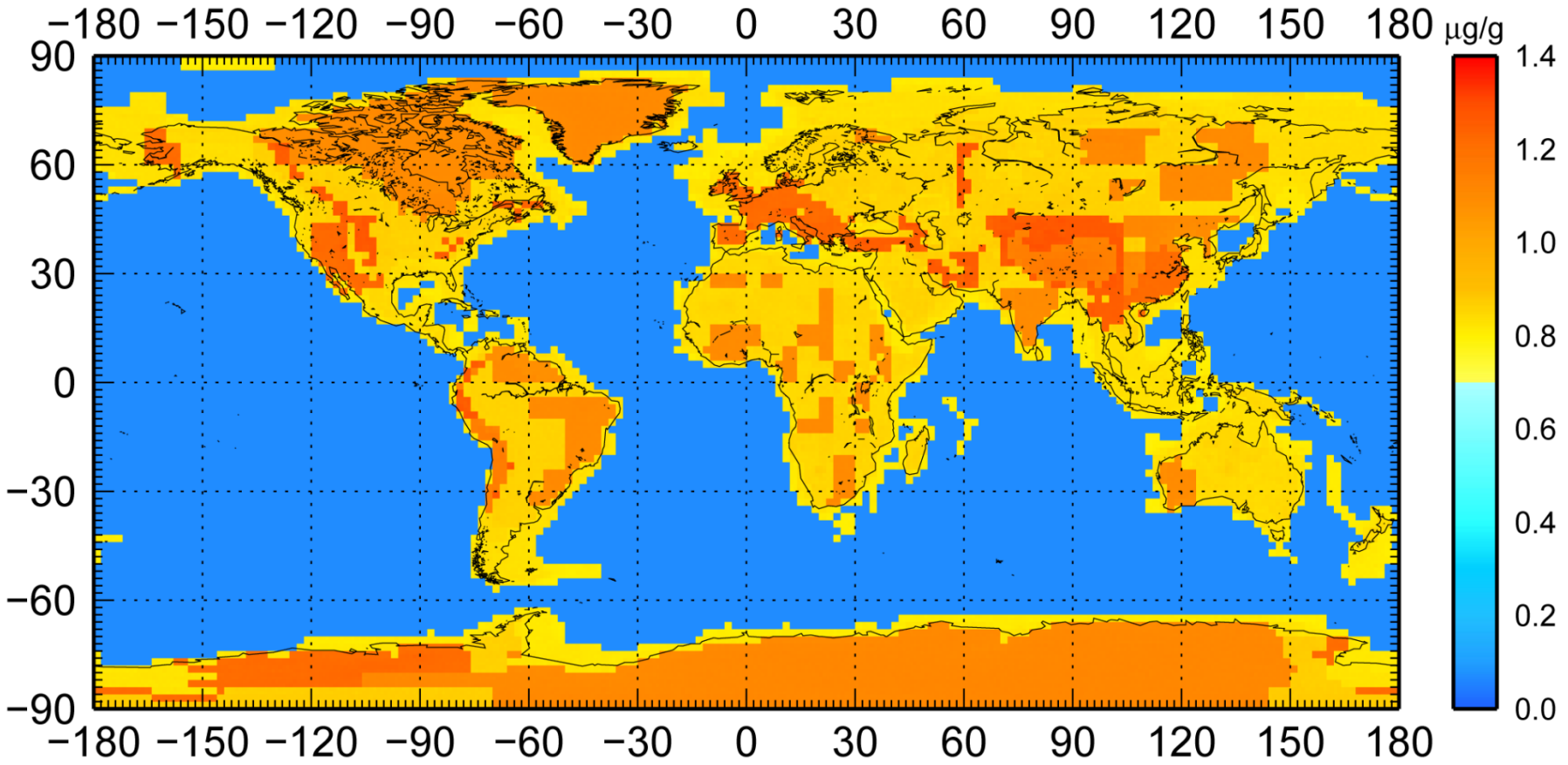






Uranium Abundance in Middle Continental Crust layer

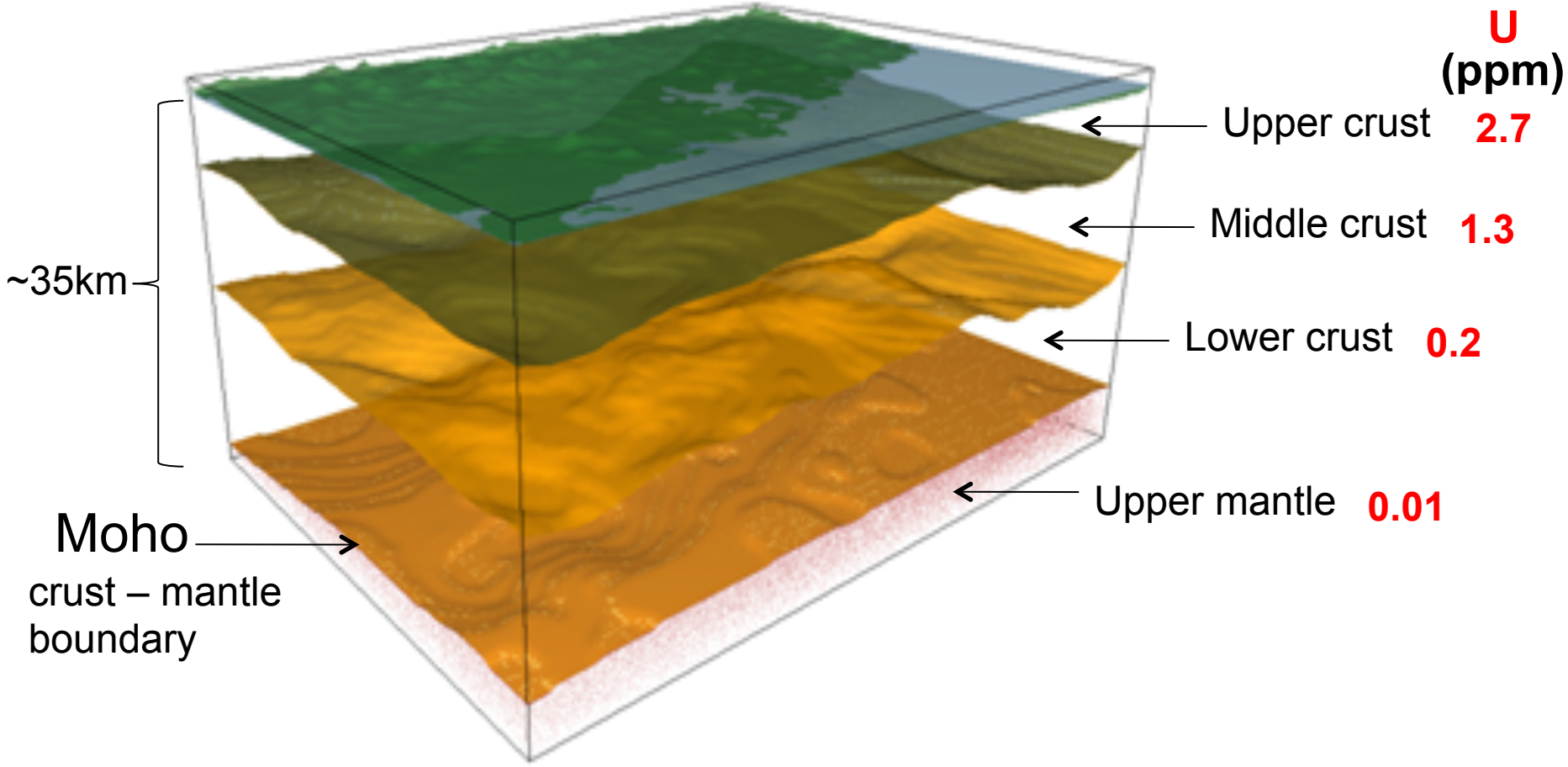
U_{MCC} (μg/g)



Average middle Cont. Crust U abundance is $0.97^{+0.58}_{-0.36}$ μg/g

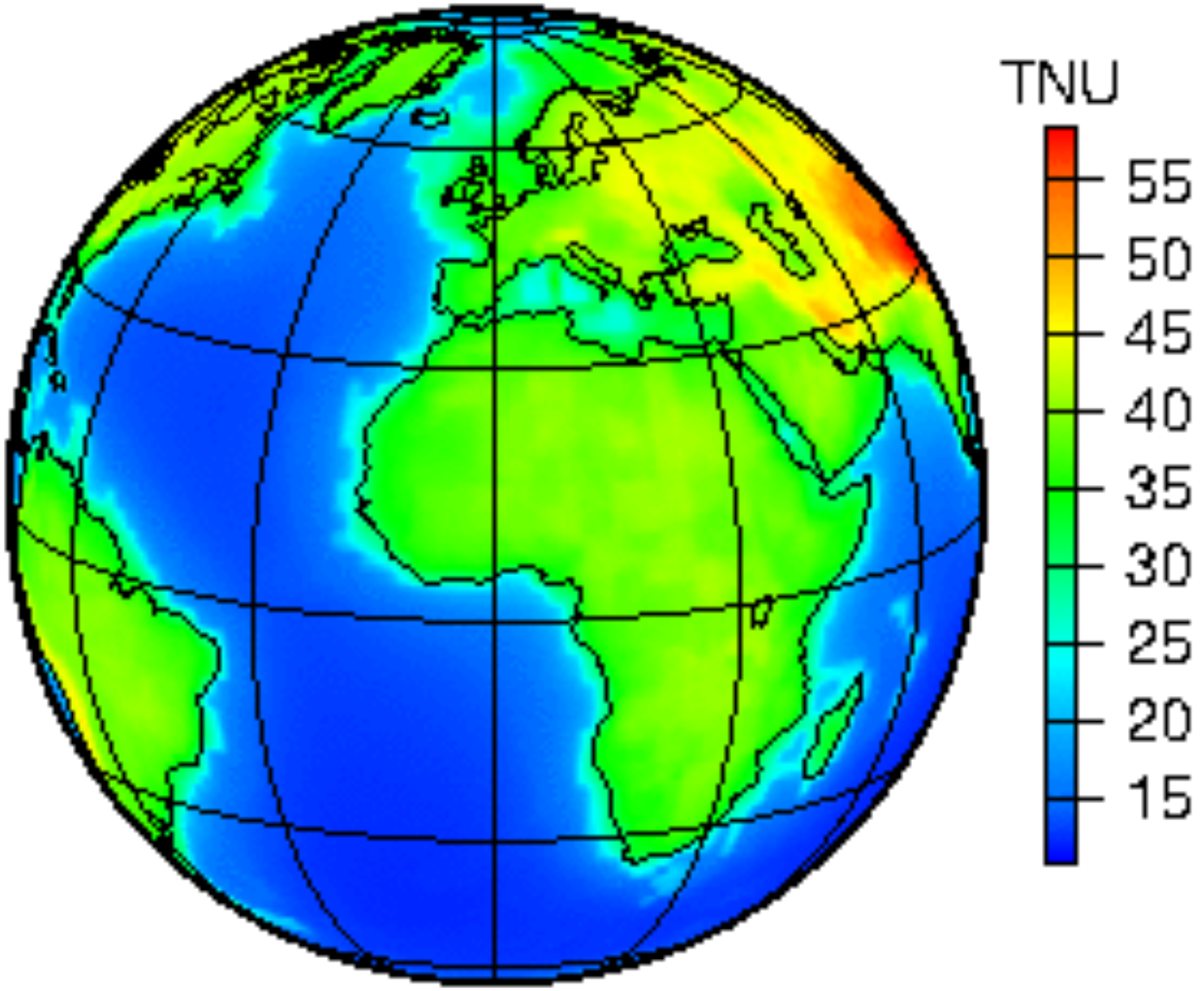
Rudnick and Gao (2003) 1.3 μg/g

Geological model – Continental Crust



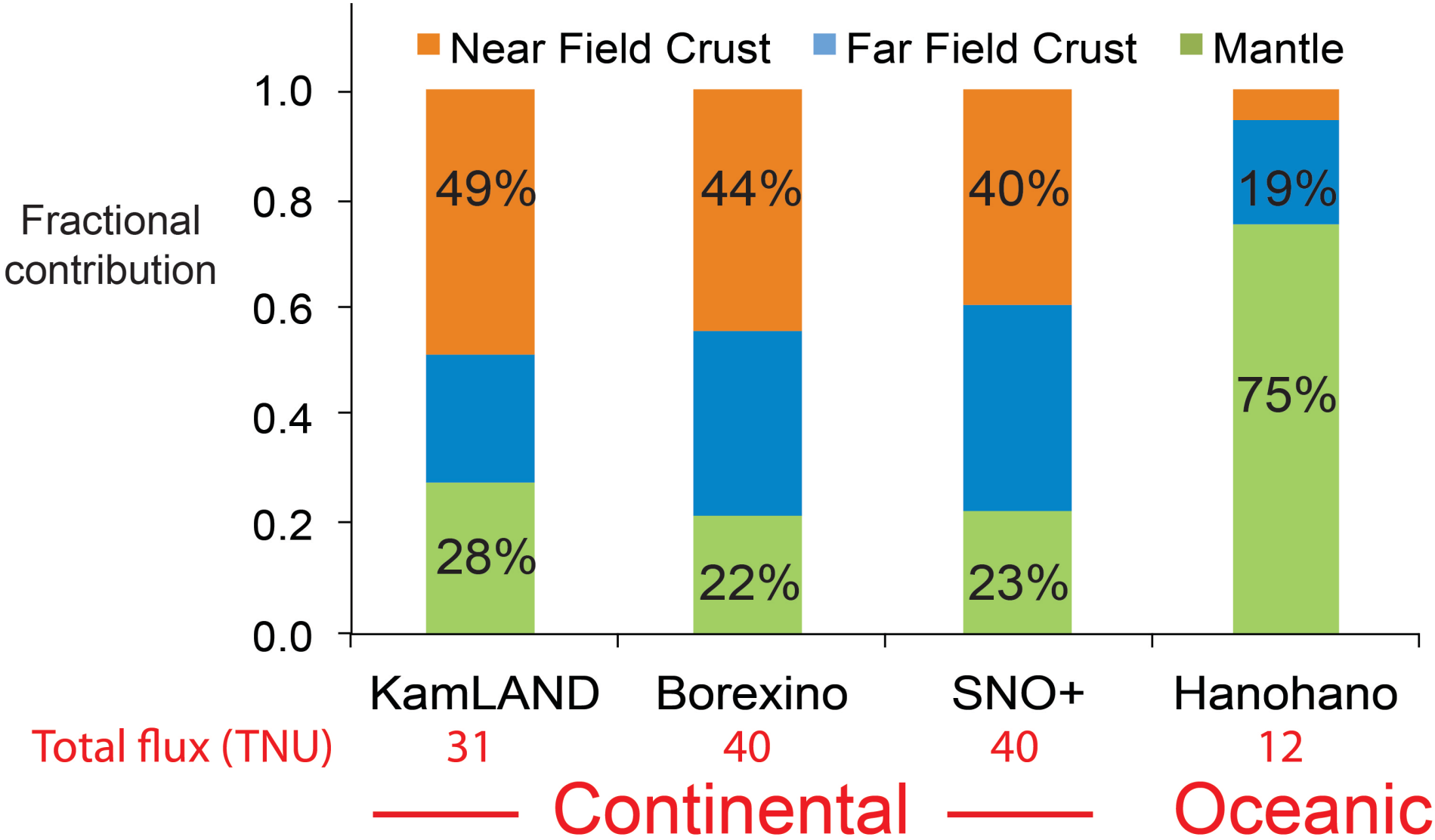
Surfaces of each layer is defined by geophysical data (i.e., gravity and seismic)

Predicted Global geoneutrino flux based on our new Reference Model



Huang et al (2013) G-cubed ***arXiv:1301.0365***

Geoneutrino contributions to detectors



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

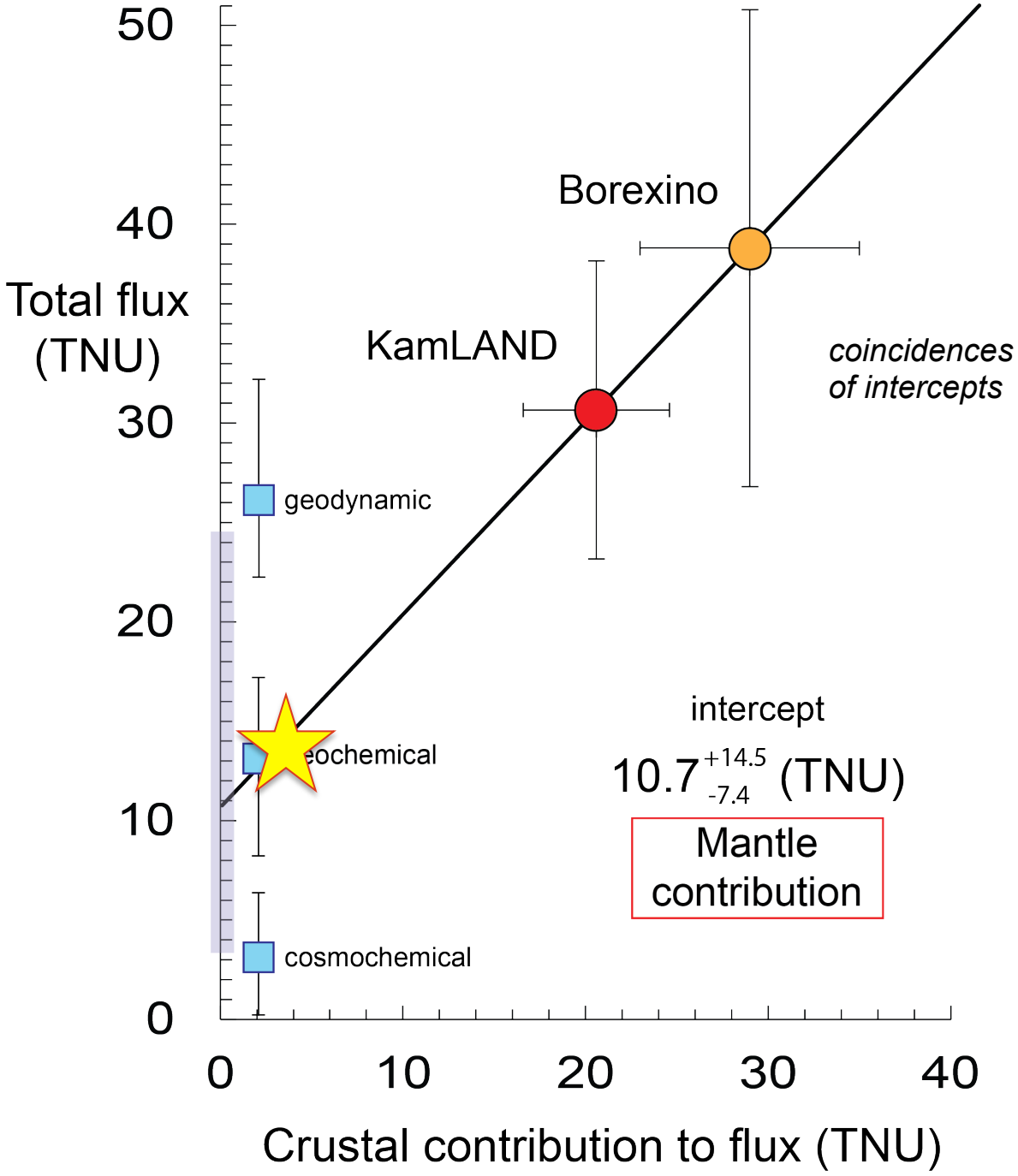
Existing data

squeezing @ limit

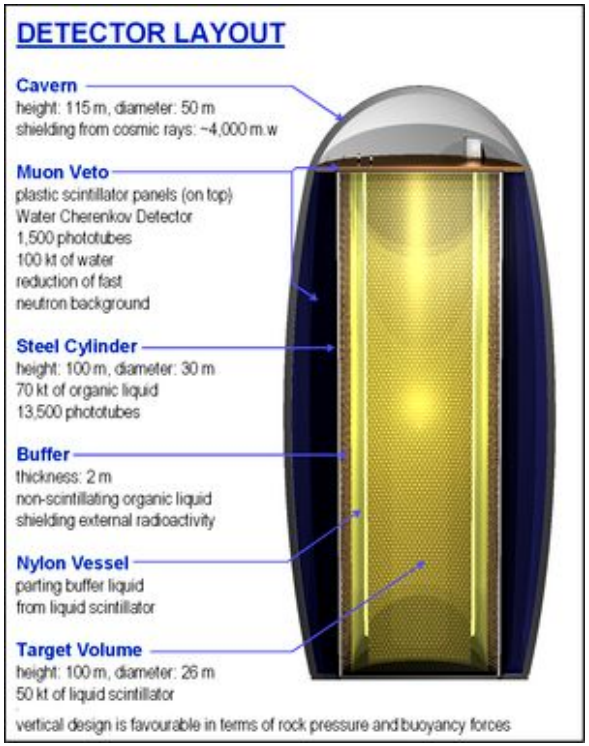
Y-axis data is strictly from physics

X-axis data is strictly from geology

Intercept is mantle contribution

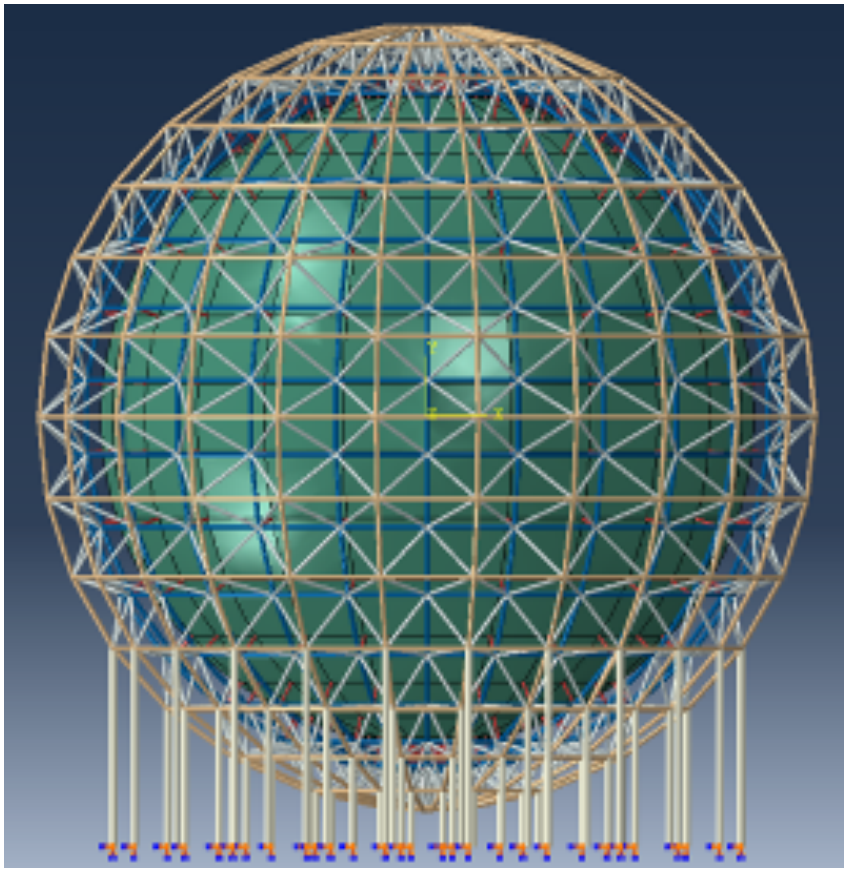


Future detectors?

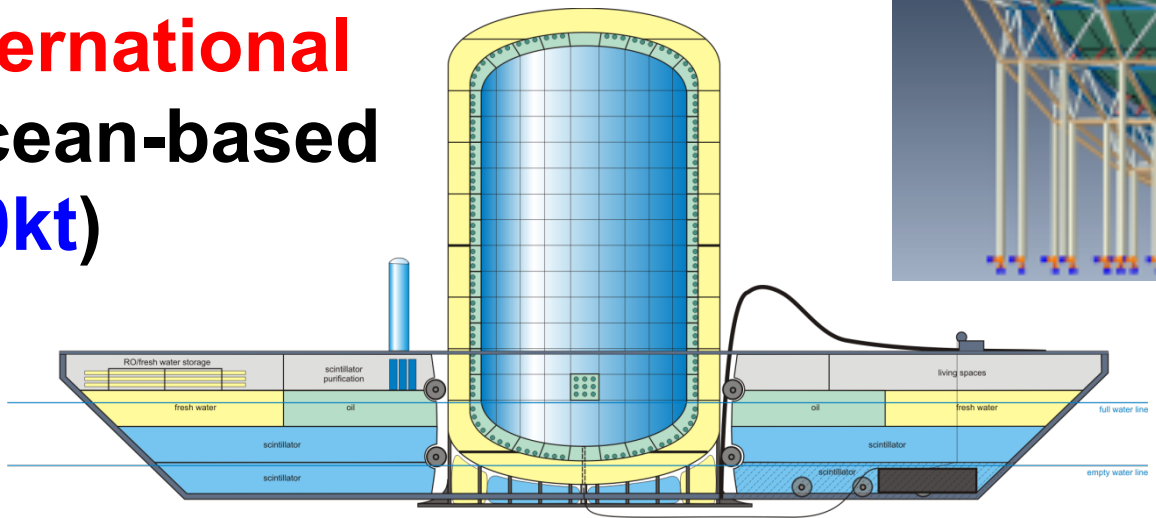


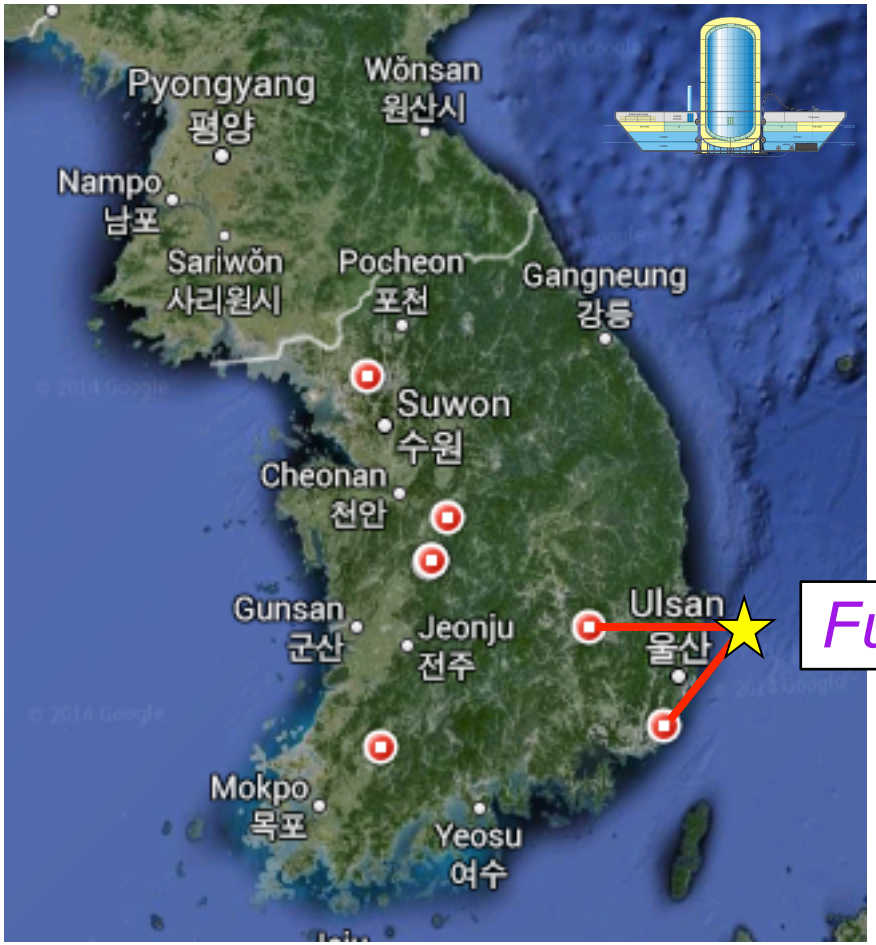
LENA, EU (50kt)

JUNO China (20kt)



Hanohano International ocean-based (10kt)





Korean Underwater Neutrino Observatory

Physic Goals

- Mass hiearchy
- Proton Decay
- Oscillation mixing

Future sight of KUNO?

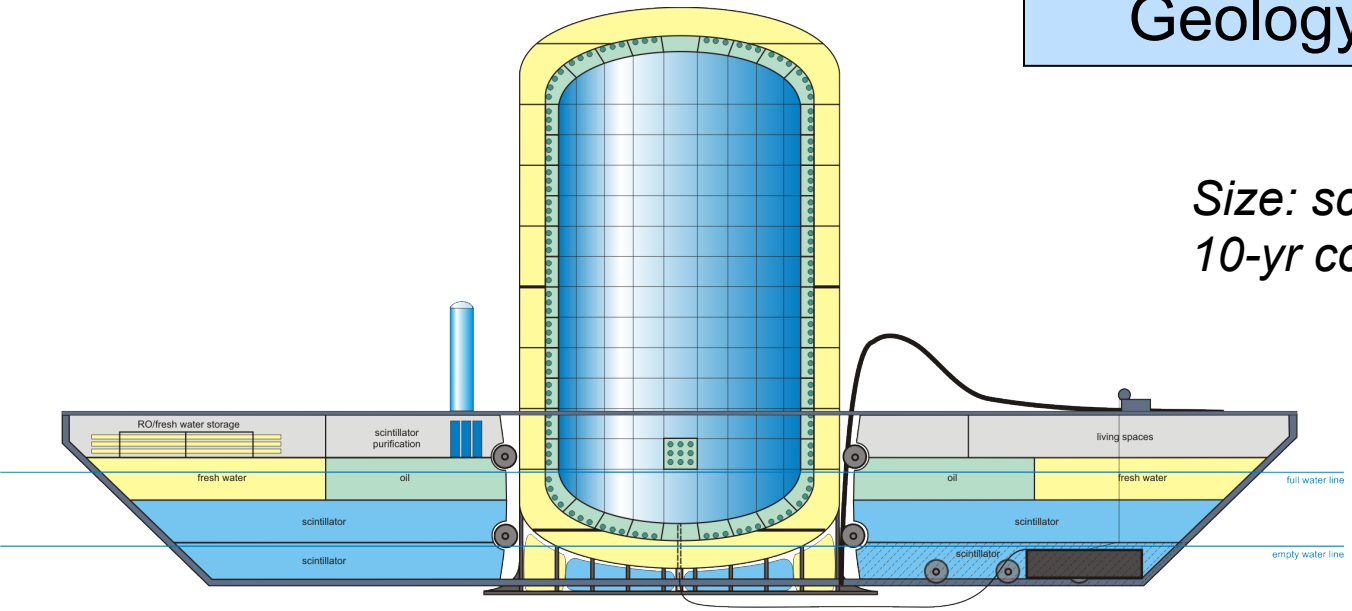
Geology Goals

- Th & U abundance
- Thermal evolution

In addition, the instrument can be used for Nuclear Monitoring Goals

Hanohano

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

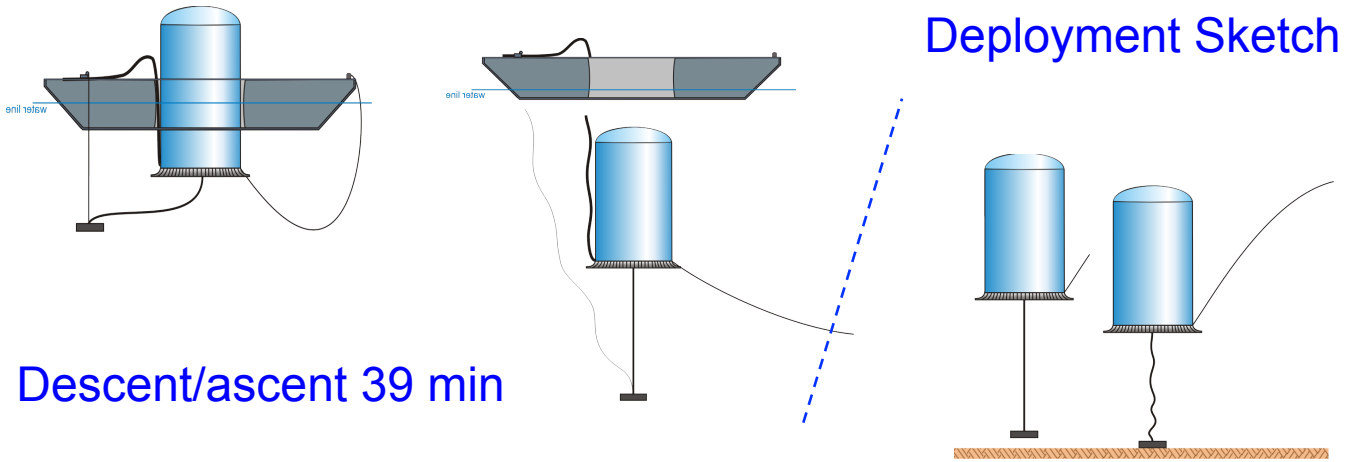


Size: scalable from 1 to 50 kT
10-yr cost est: $250M @ 10 kT

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

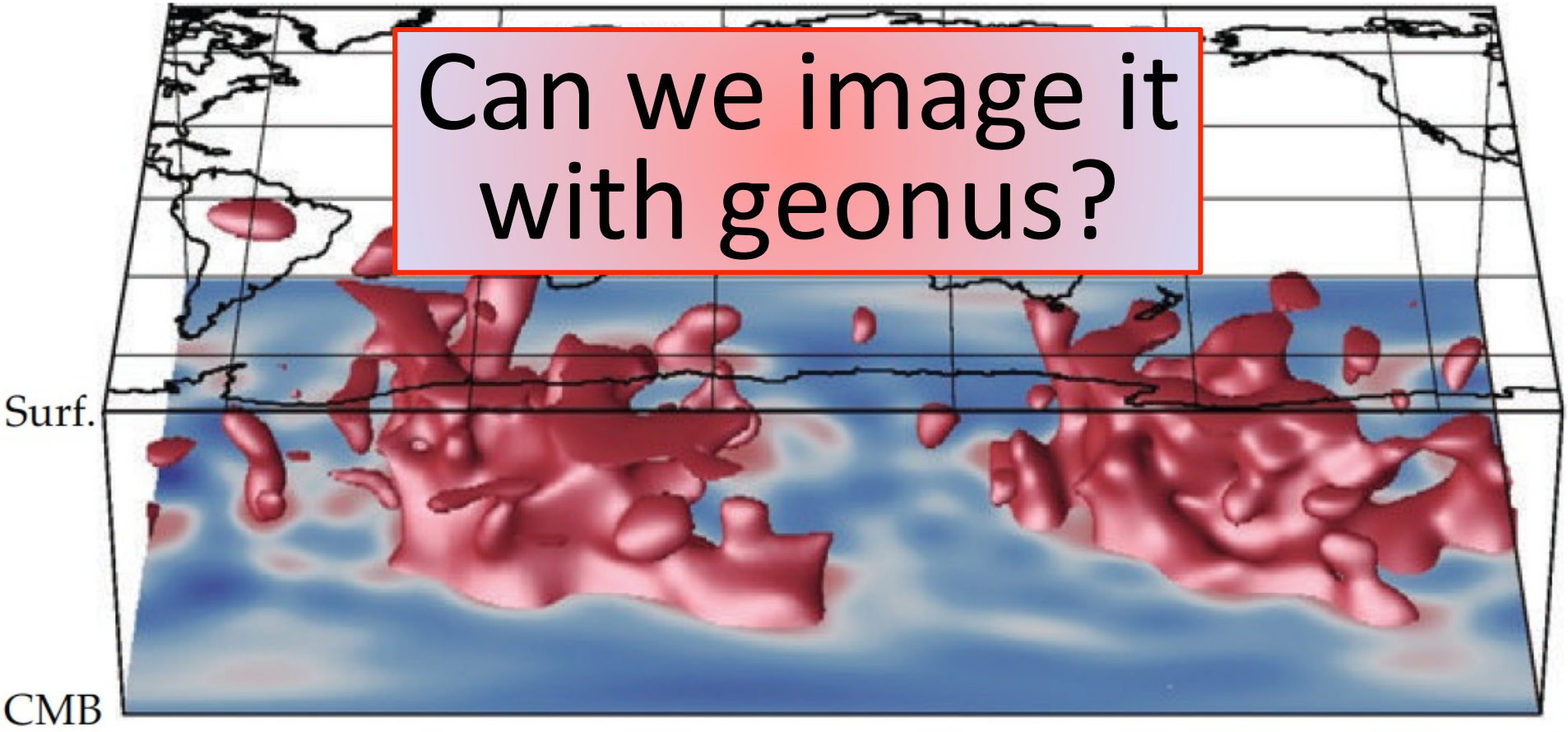
A Deep Ocean

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



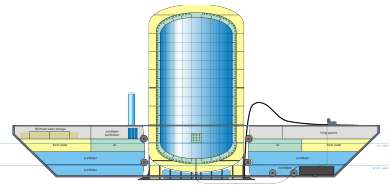
What's hidden in the mantle?

Seismically slow "red" regions in the deep mantle

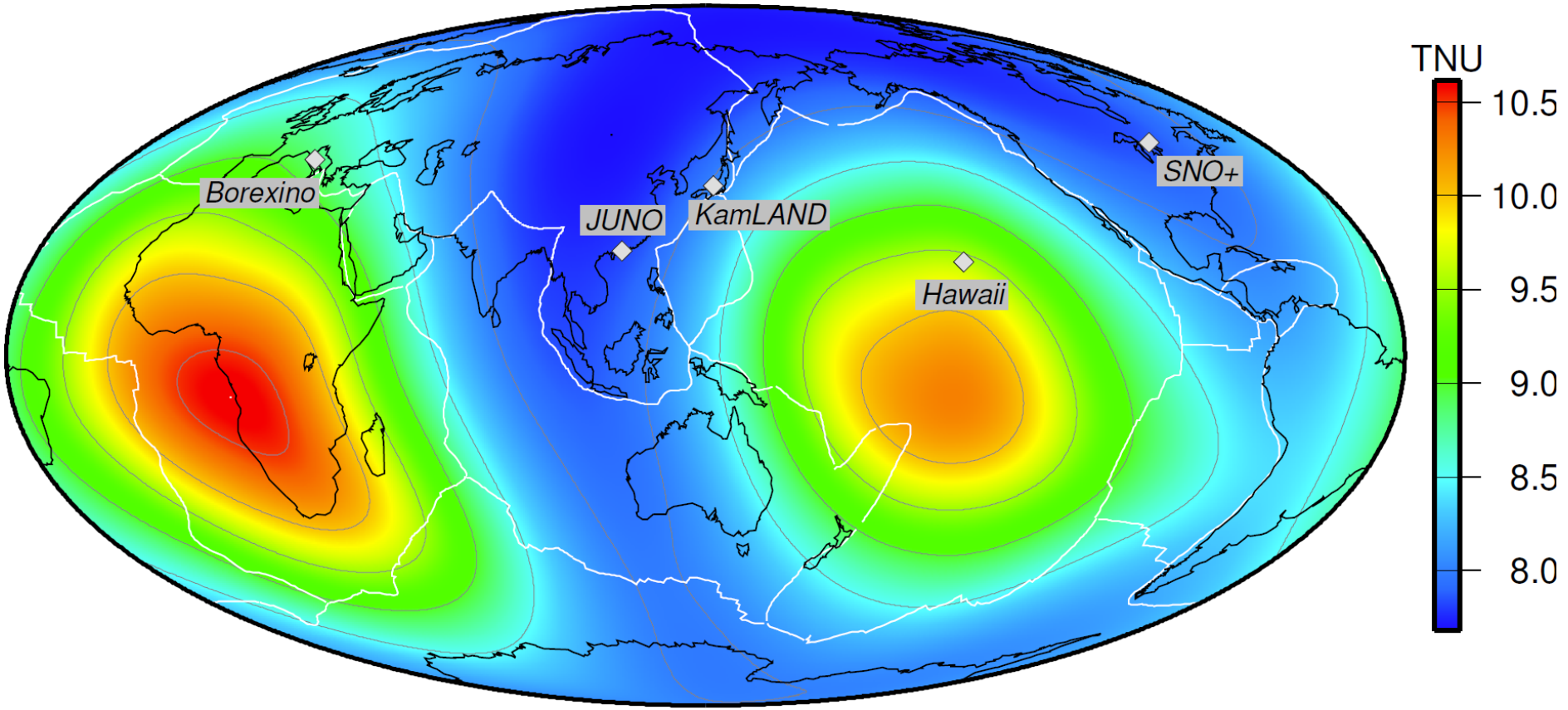


From Alan McNamara after Ritsema et al (Science, 1999)

Testing Earth Models

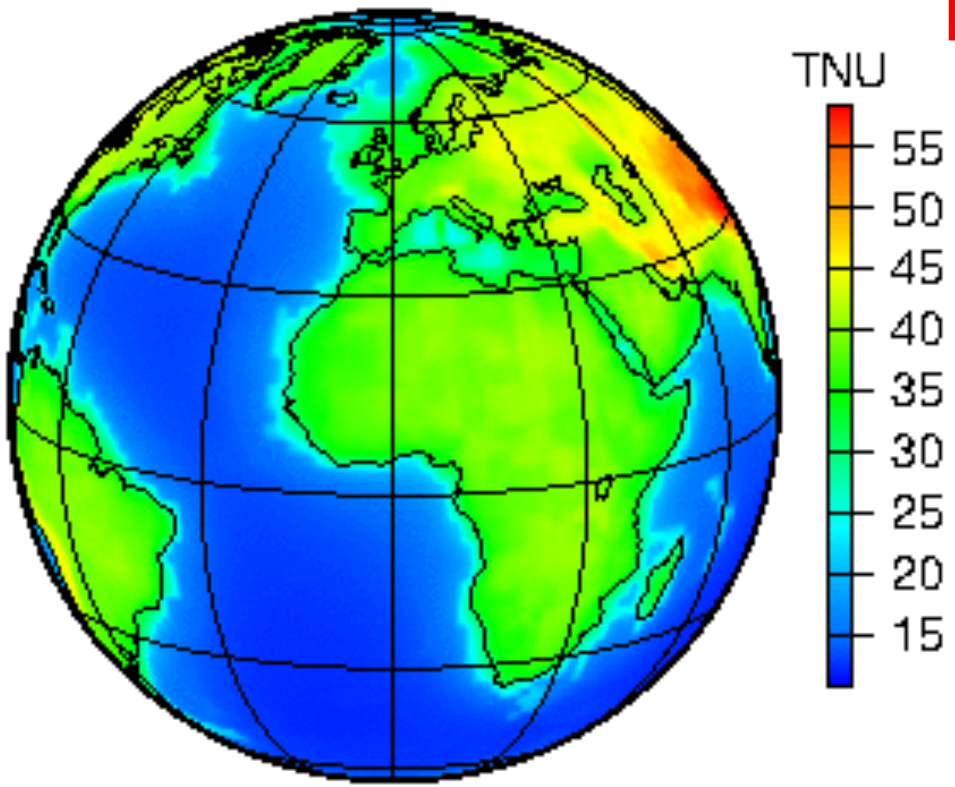


Mantle geoneutrino flux (^{238}U & ^{232}Th)



Šrámek et al (2013) EPSL [10.1016/j.epsl.2012.11.001](); [arXiv:1207.0853]()

Predicted geoneutrino flux



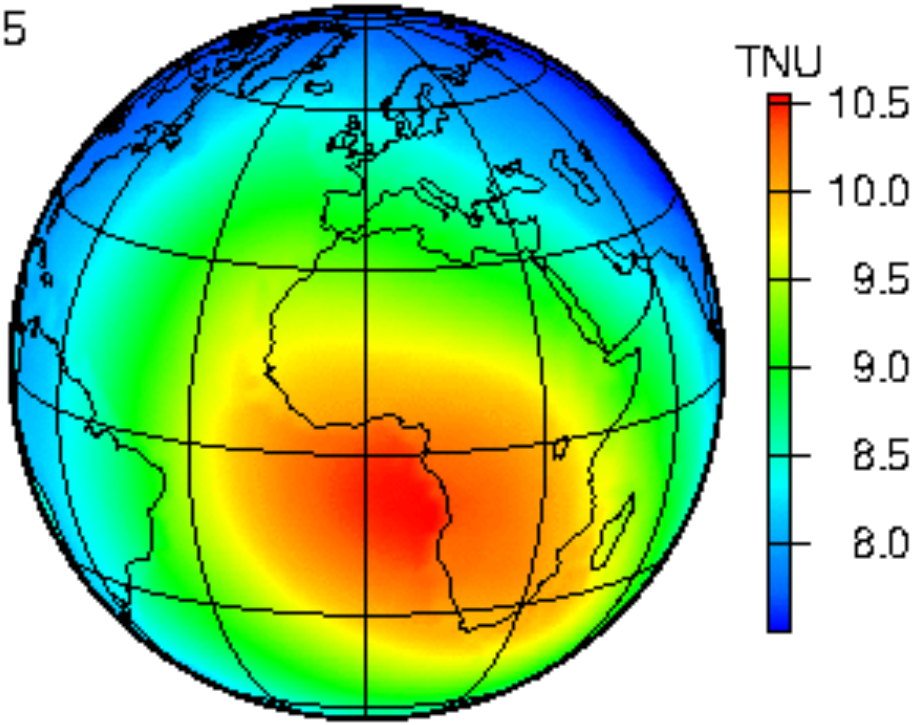
Total flux at surface

dominated by
Continental crust

Yu Huang et al (2013) G-cubed arXiv:1301.0365 10.1002/ggge.20129

Mantle flux at the Earth's surface

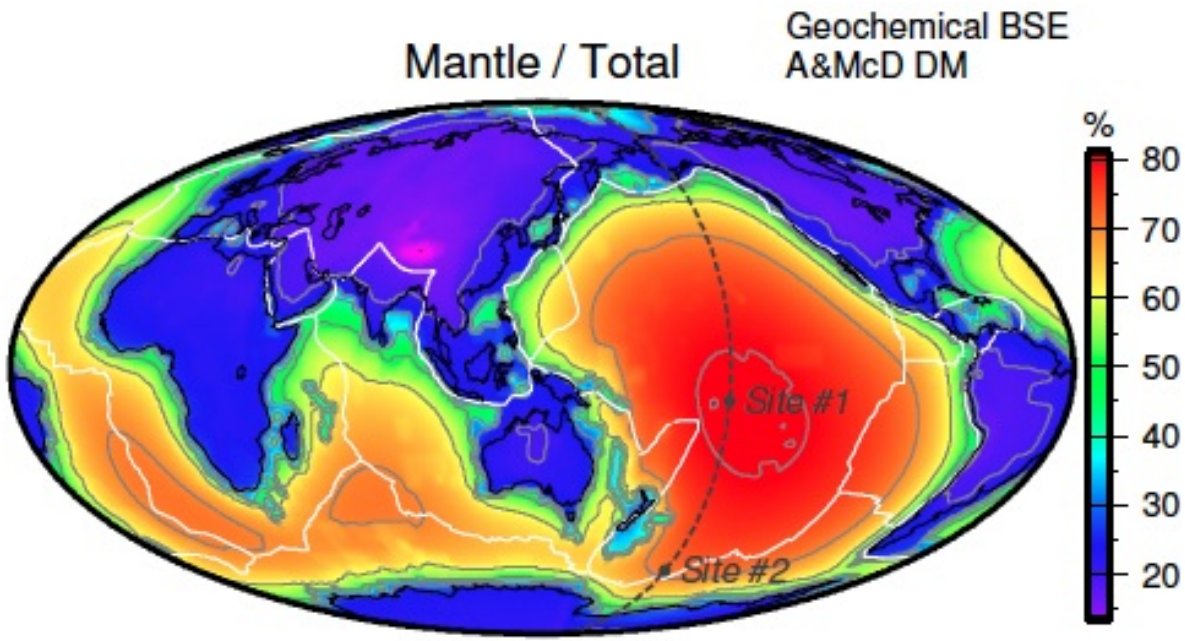
dominated by
deep mantle structures

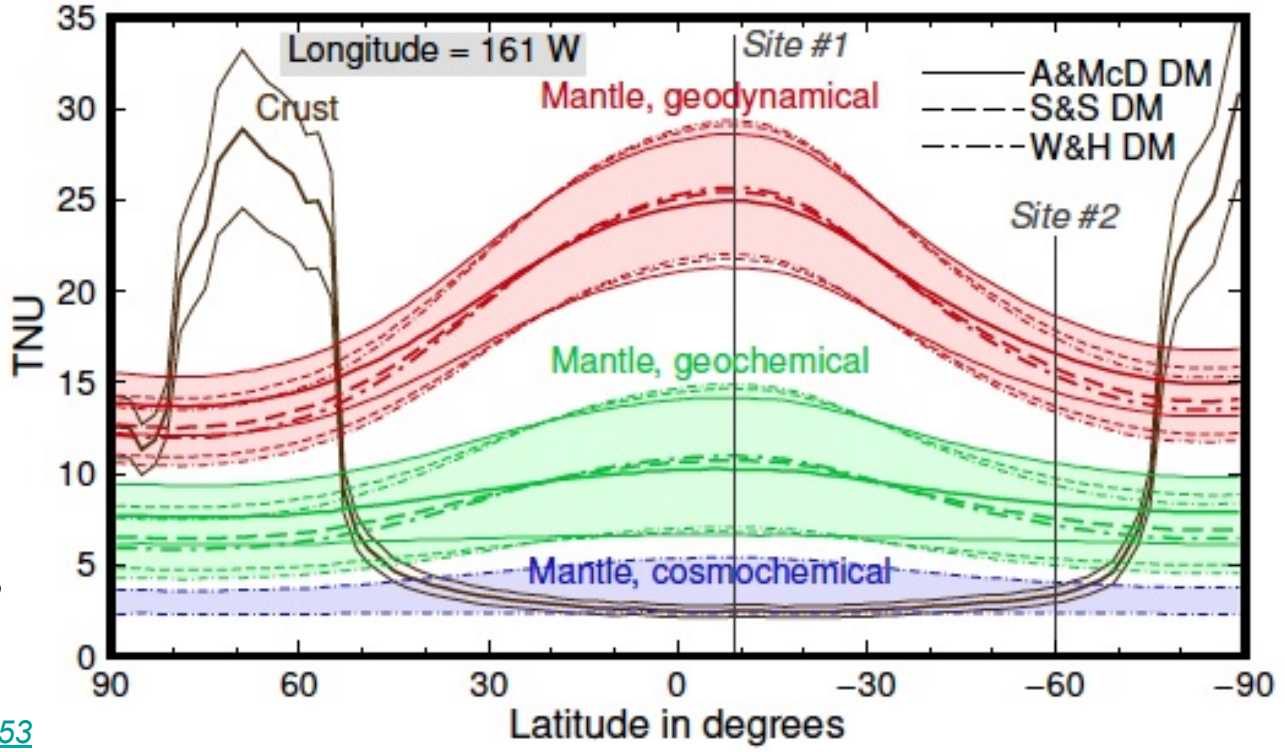


Šrámek et al (2013) EPSL 10.1016/j.epsl.2012.11.001; arXiv:1207.0853

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) EPSL arXiv:1207.0853

SUMMARY

Earth's radiogenic (Th & U) power

22 ± 12 TW - Borexino **11.2** $^{+\,7.9}_{-\,5.1}$ **TW** - KamLAND

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

On-line and next generation experiments:

- SNO+ online 2015 ☺
- **JUNO**: 2020, good experiment, big bkgd, geonu …
- Hanohano: this is **FUNDAMENTAL** for geosciences

Geology must participate & contribute to the cost

Future:

- Neutrino Imaging of Earth's deep interior ☺

Geoneutrinos: ongoing efforts and wish list

- Directionality
- ^{40}K geonus
- Detecting hidden objects in the Earth

Out-reach efforts

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Geoneutrino

From Wikipedia, the free encyclopedia

Geoneutrino is an electron antineutrino emitted in β^- decay of a radionuclide naturally occurring in the Earth. Neutrinos are the lightest of the known subatomic particles. They lack measurable electromagnetic properties and dominantly interact via the weak nuclear force. Matter is virtually transparent to neutrinos and consequently they travel, unimpeded, at near light speed through the Earth from their point of emission. Collectively geoneutrinos carry the integrated information about the abundances of their radioactive sources inside the Earth. Extracting a geologically useful information (e.g., abundances of individual geoneutrino producing elements and their spatial distribution in Earth's interior) from geoneutrino measurements is a major objective of the emerging field of ***neutrino geophysics***.

Most geoneutrinos originate from β^- decay branches of ^{40}K, ^{232}Th and ^{238}U. Together these decay chains account for more than 99% of the present day radiogenic heat generated inside the Earth. Only geoneutrinos from ^{232}Th and ^{238}U decay chains are detectable by the inverse beta decay mechanism because these have the highest energies, i.e., >1.8 MeV (megaelectronvolts), the energy needed to transform a proton into a neutron and a positron. The flashes of light generated from this interaction are recorded by large underground liquid scintillator detectors of neutrino experiments. To date, geoneutrino measurements at two sites, as reported by the KamLAND and Borexino collaborations, begin to place constraints on the

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