Imaging the Earth's interior with geo-neutrinos

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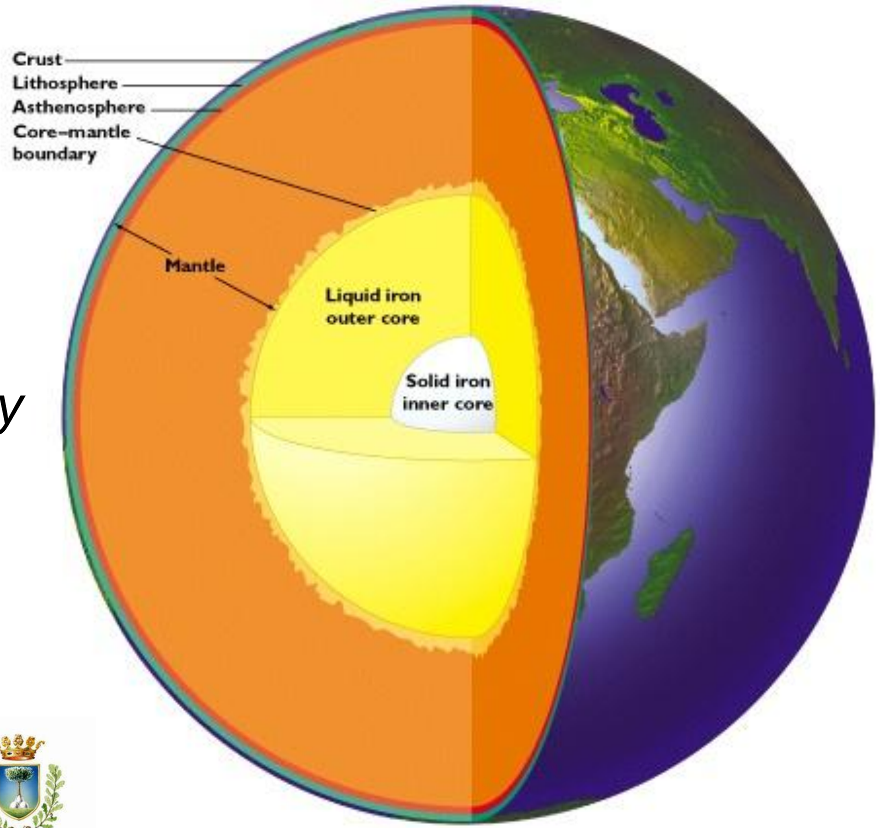

Thanks to Bill McDonough for slides

nature geoscience **2011** ARTICLES

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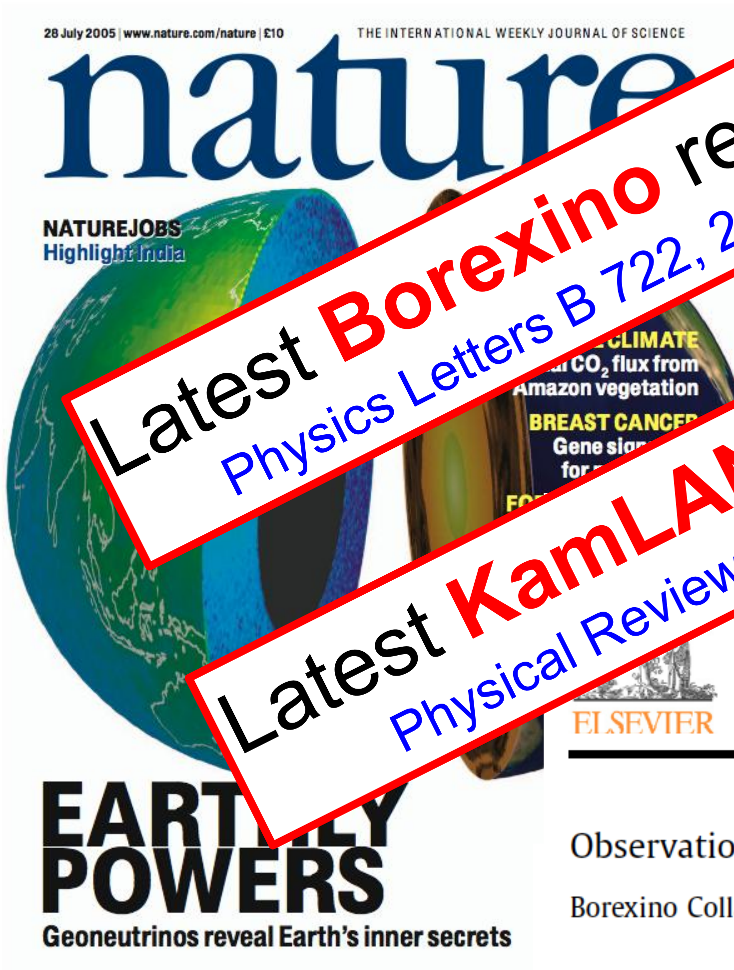
Partial radiogenic heat model for Ea
by geoneutrino measurement

The KamLAND Collaboration*



Detecti

Geo nos

the Earth

Latest Borexino results in Bellini et al 2013

Physics Letters B 722, 295–300 0.1016/j.physletb.2013.04.030

Latest KamLAND results in Gando et al 2013

Physical Review D 88, 033001 10.1103/PhysRevD.88.033001

Physics Letters B 687 (2010) 299–304

Contents lists available at ScienceDirect

2010 Physics Letters B

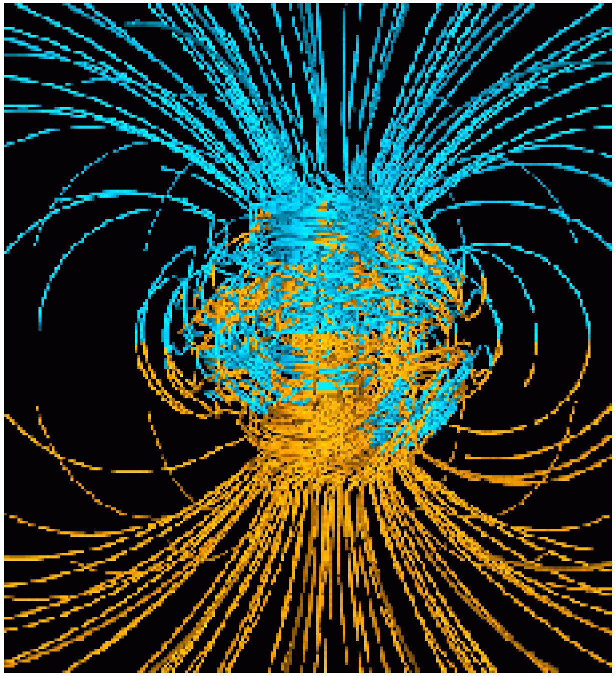
www.elsevier.com/locate/physletb

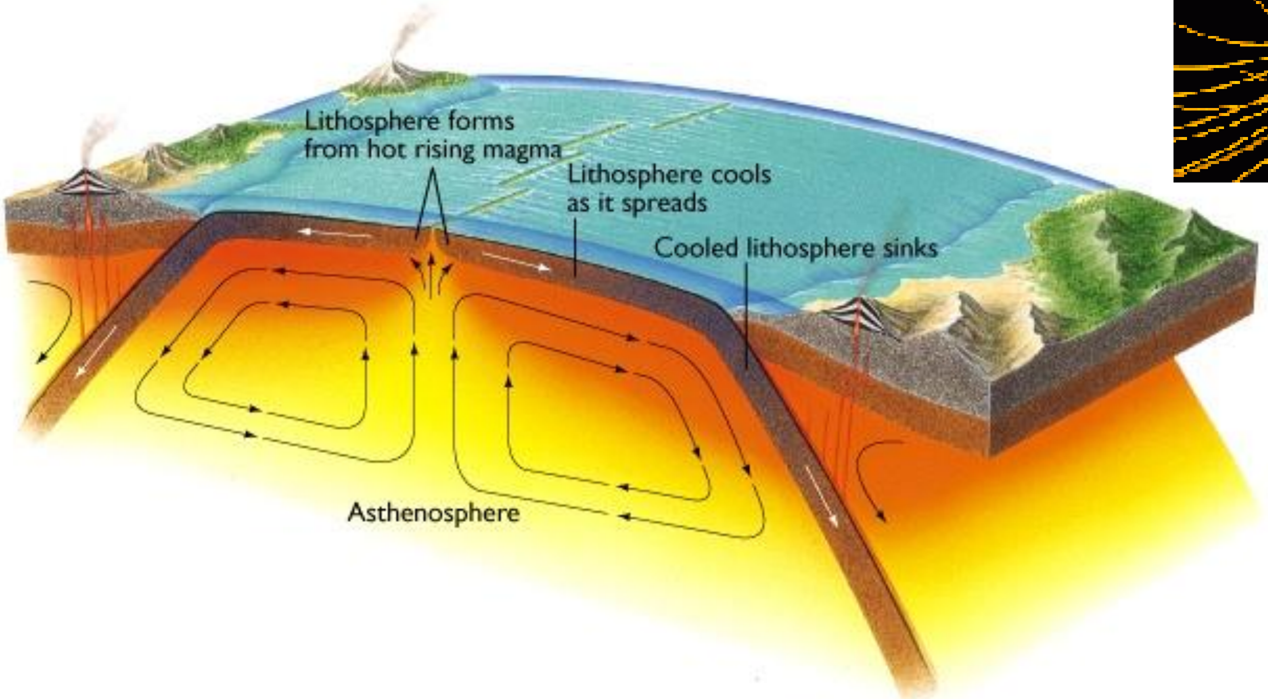
ELSEVIER

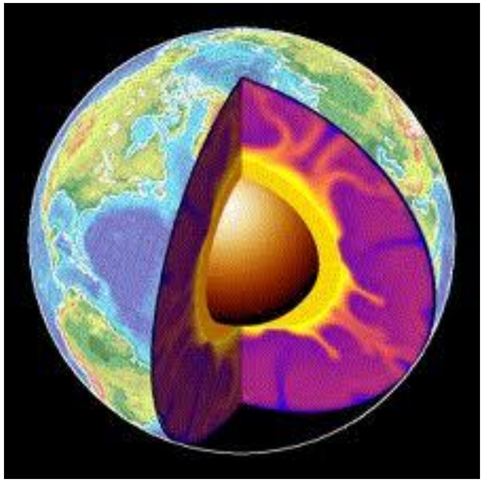
Observation of geo-neutrinos

Borexino Collaboration

Plate Tectonics, Convection, Geodynamo







Does heat from radioactive decay drive the Earth's engine?

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

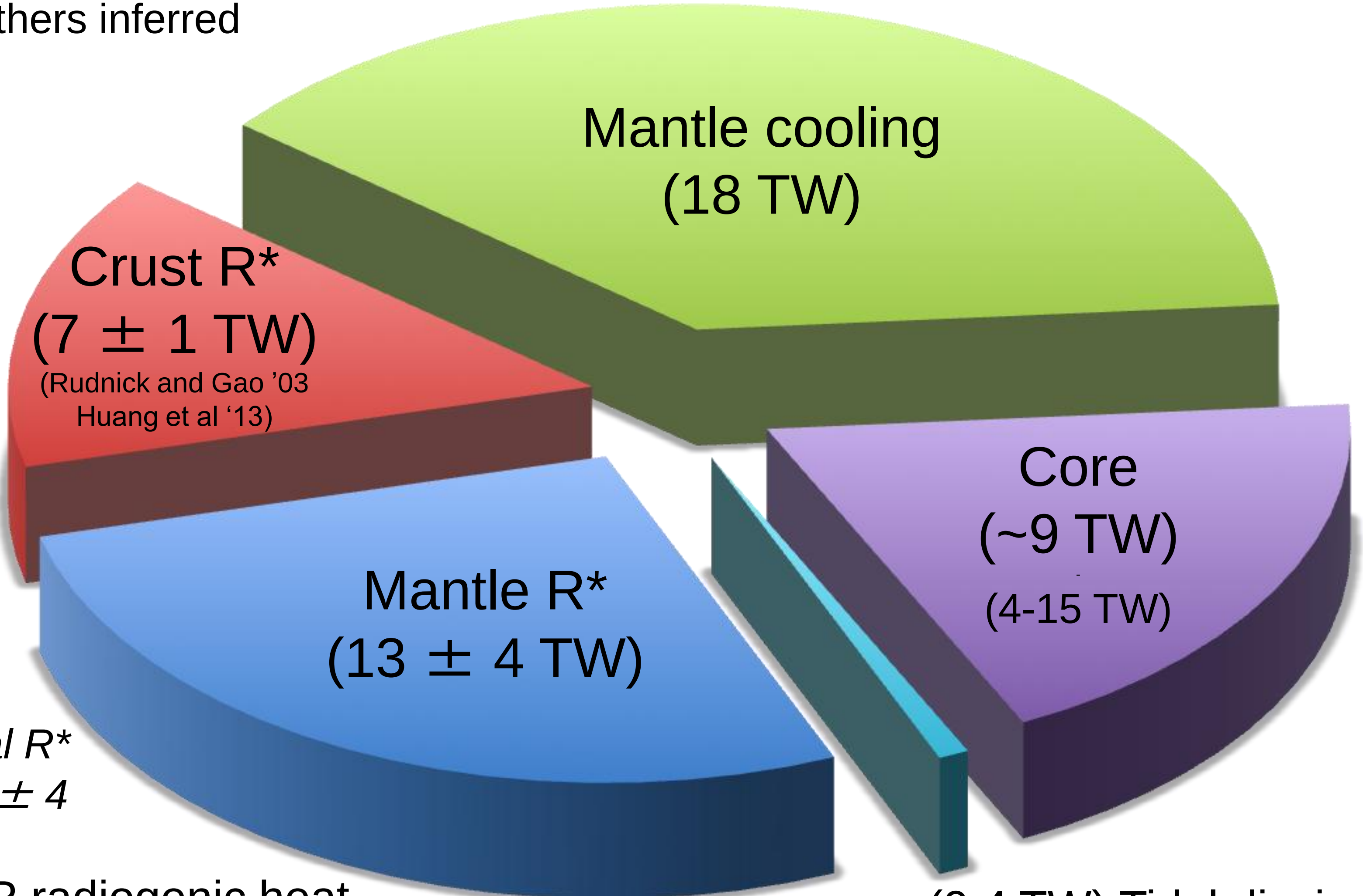
the future is… *Geoneutrino studies*

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**."

Measured Earth's surface heat flow 46 ± 3 TW

Others inferred



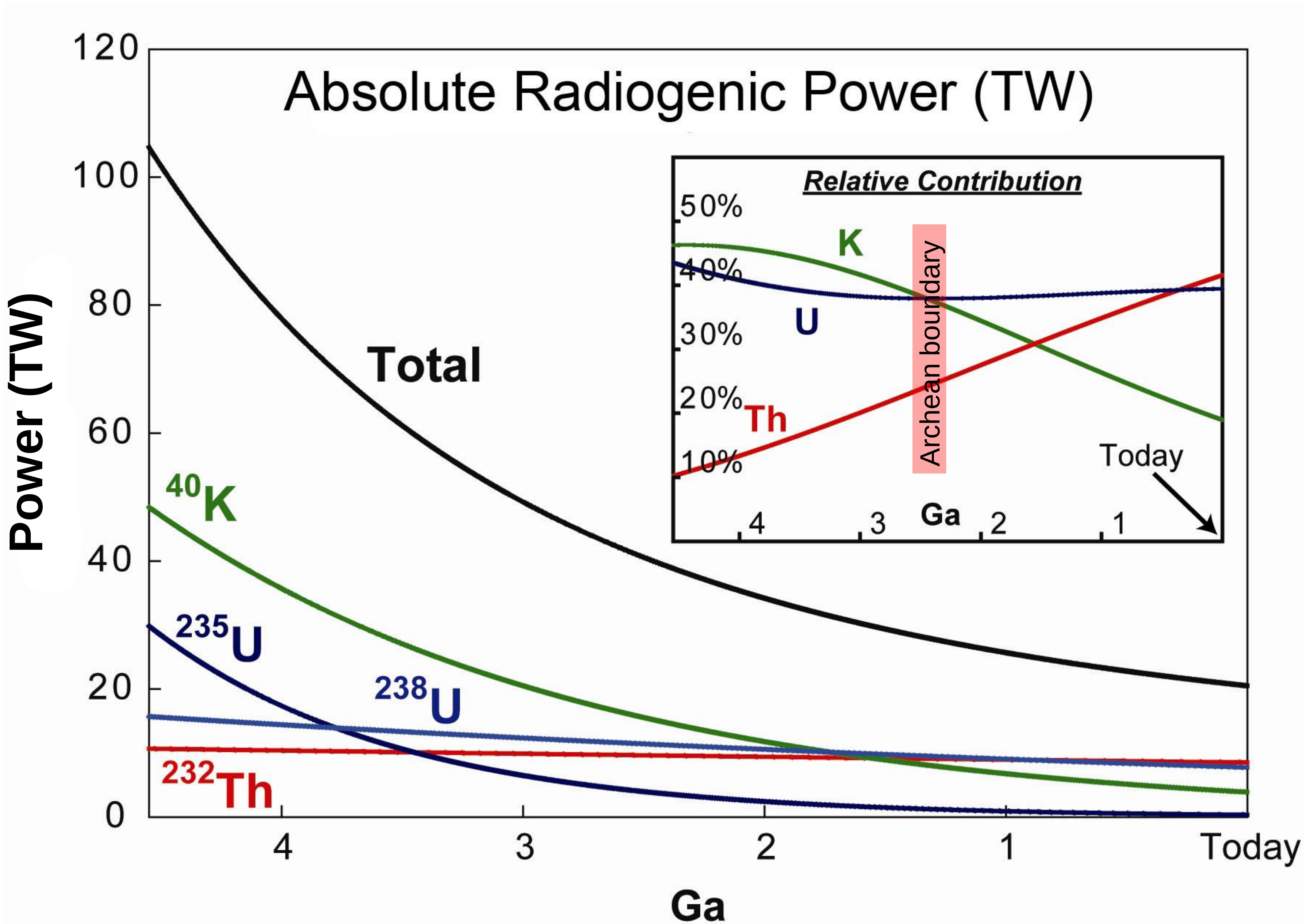
*total R**
20 ± 4

*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

U content of BSE models

- Nucelosynthesis: U/Si and Th/Si production probability
- Solar photosphere: matches C1 carbonaceous chondrites
- Estimate from Chondrites: ~11ppb planet (16 ppb in BSE)
- Heat flow: secular cooling vs radiogenic contribution… ?
- Modeling composition: which chondrite should we use?

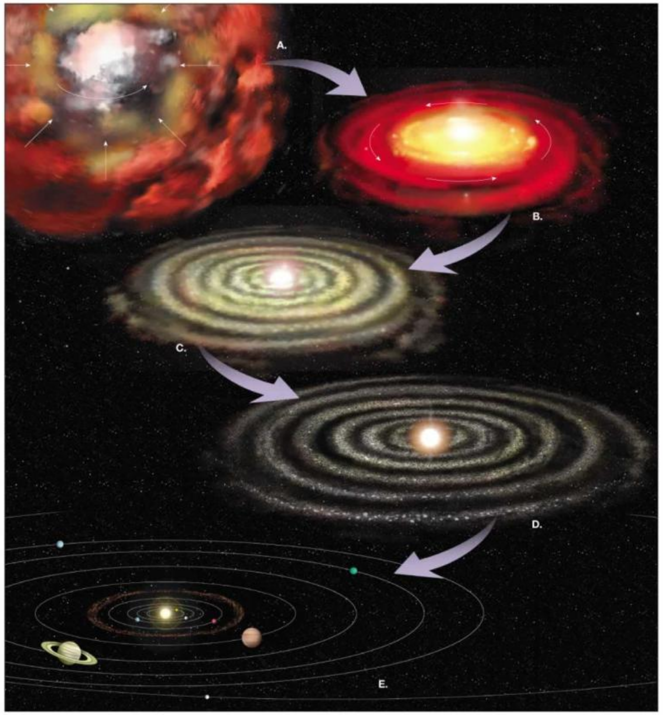
<u>A brief (albeit biased) history of U estimates in BSE:</u>

•Urey (56) 16 ppb
•Wasserburg et al (63) **33** ppb
•Ganapathy & Anders (74) 18 ppb
•Ringwood (75) 20 ppb
•Jagoutz et al (79) 26 ppb
•Schubert et al (80) **31** ppb
•Davies (80) 12-23 ppb
•Wanke (81) 21 ppb

Turcotte & Schubert (82; 03) **31** ppb
Hart & Zindler (86) 20.8 ppb
McDonough & Sun (95) 20 ppb ± 20%
Allegre et al (95) 21 ppb
Palme & O'Neill (03) 22 ppb ± 15%
Lyubetskaya & Korenaga (05) 17 ppb ± 17%
O'Neill & Palme (08) **10** ppb
Javoy et al (10) **12** ppb

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

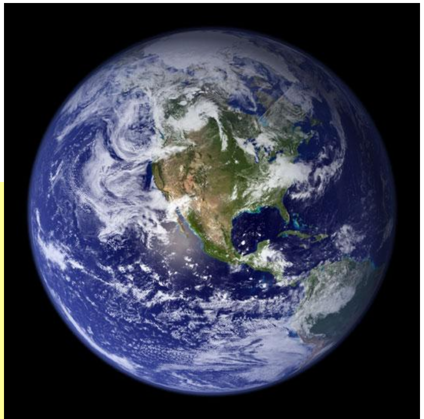
Nebula



Meteorite

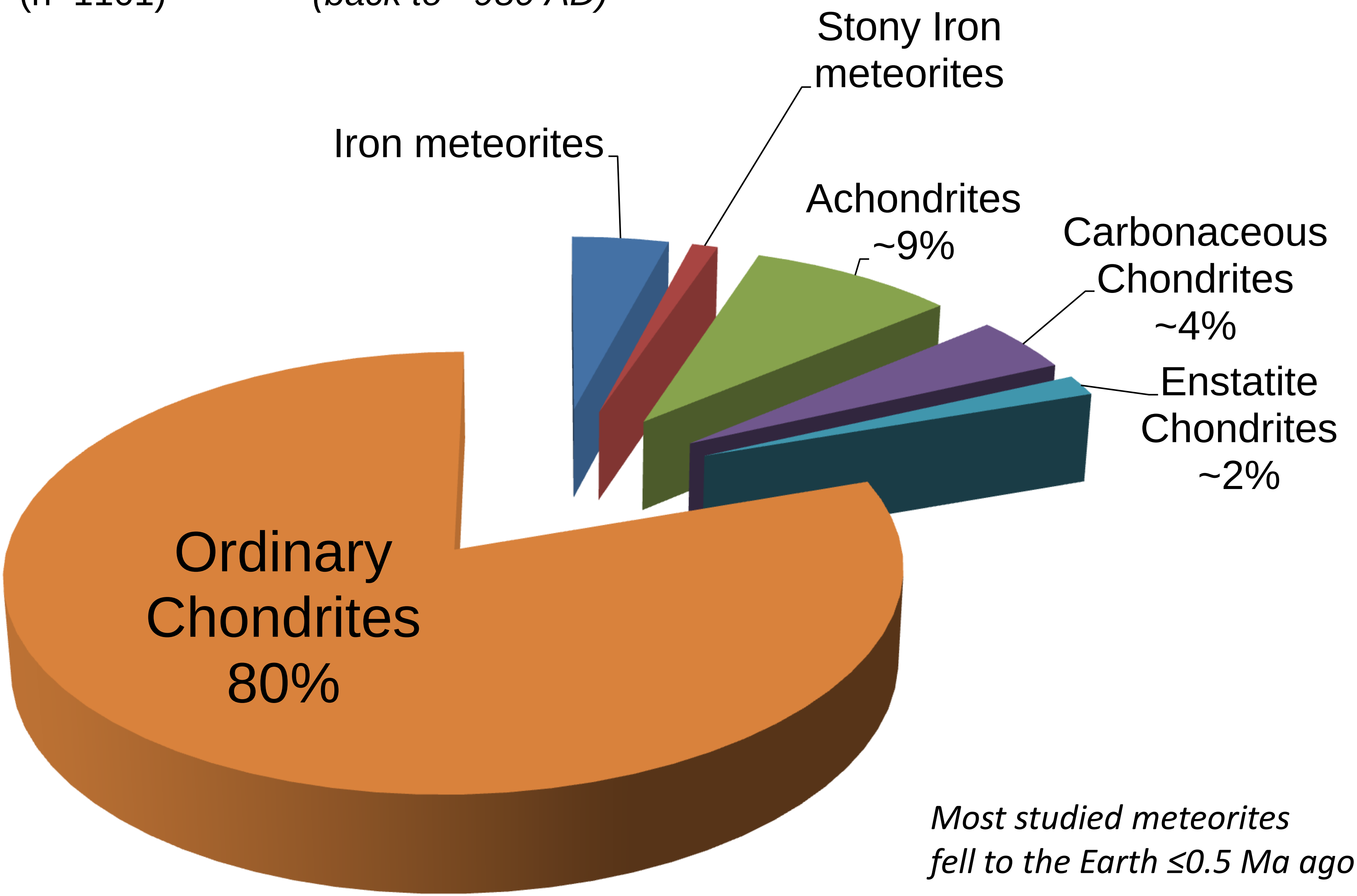
Heterogeneous mixtures of components with different formation temperatures and conditions

Planet:
mix of metal, silicate, volatiles



Meteorite: Fall statistics

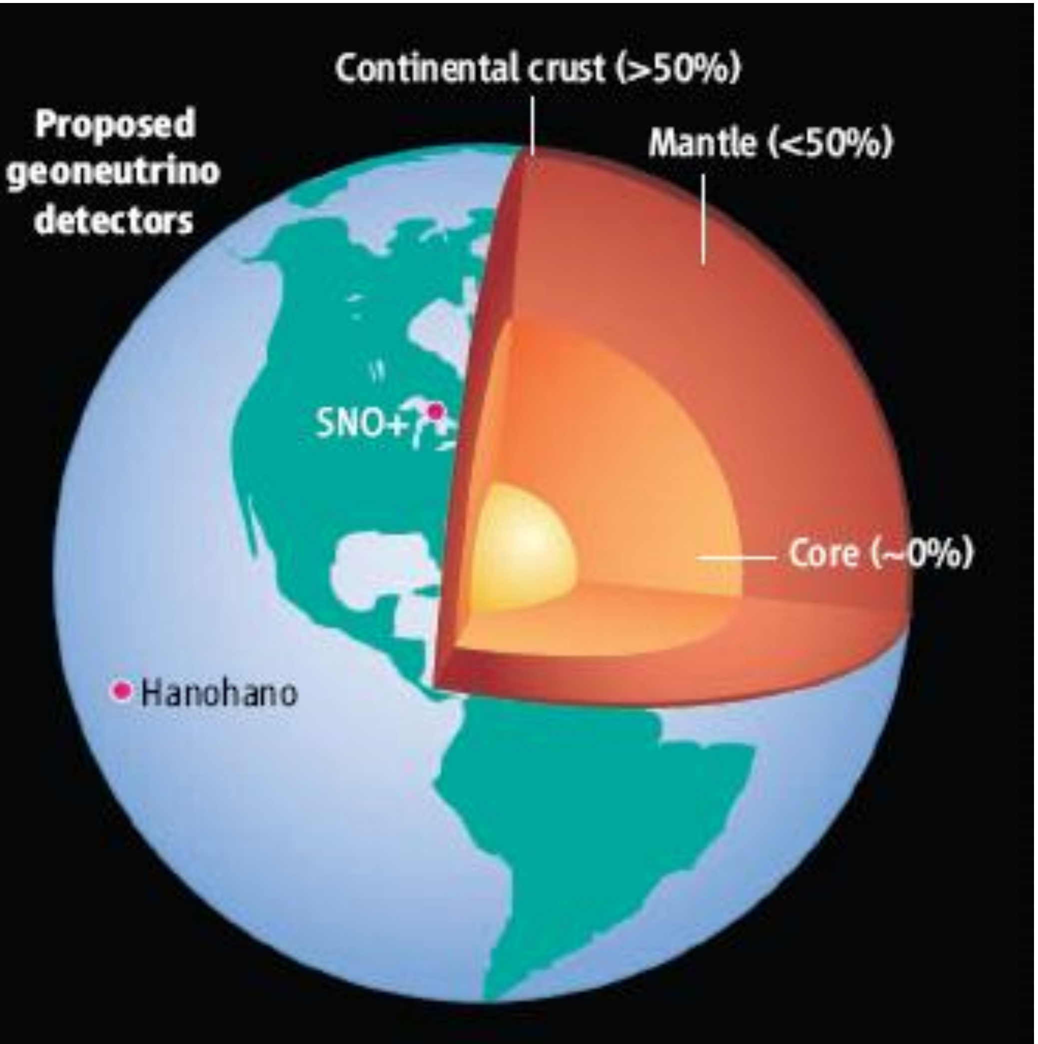
(n=1101) *(back to ~980 AD)*



Most studied meteorites fell to the Earth ≤0.5 Ma ago

U in the Earth:

"Differentiation"



~13 ppb U in the Earth
(by weight)

Metallic sphere (core)
<<<1 ppb U

Silicate sphere
20* ppb U

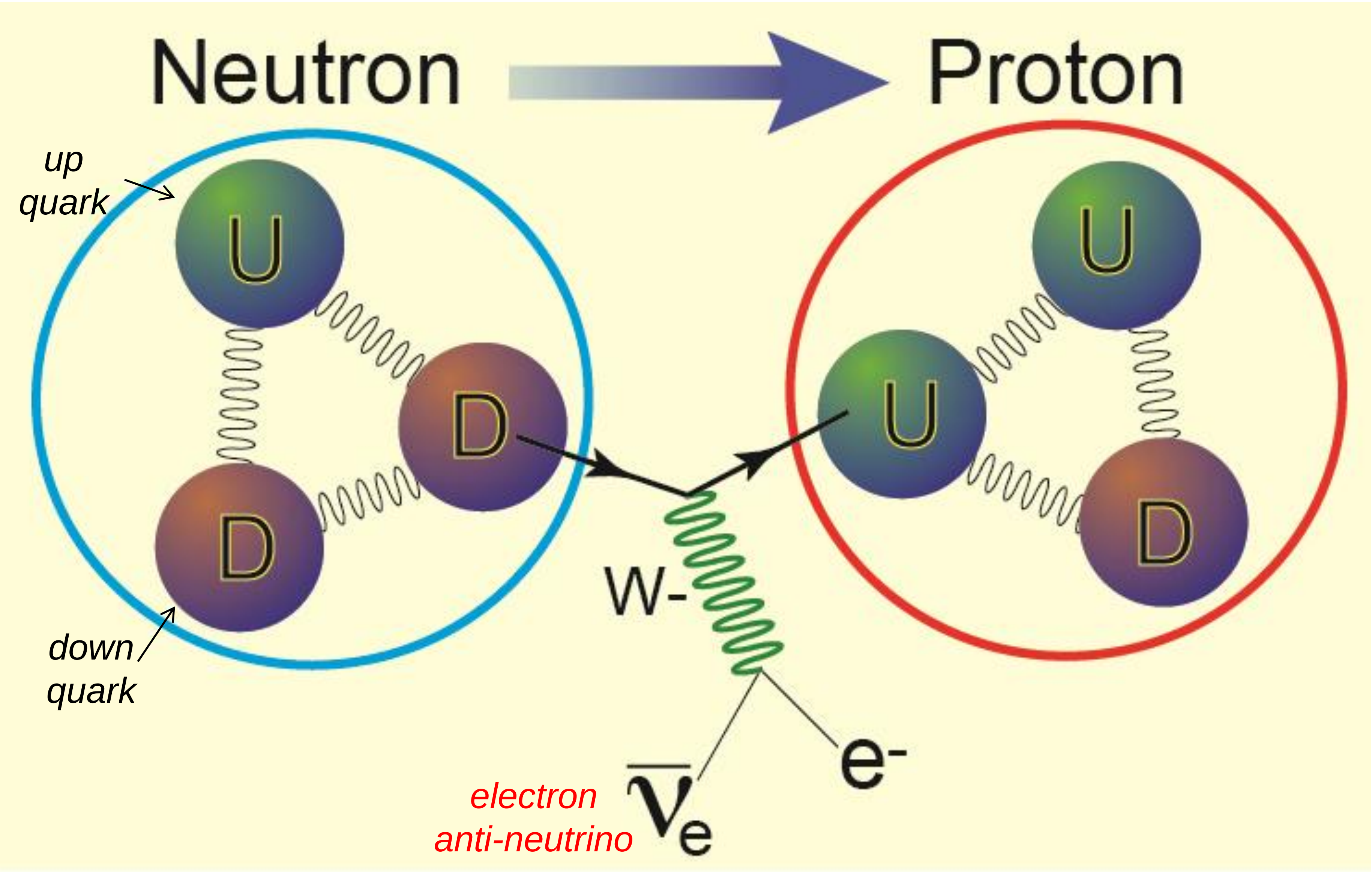
**O'Neill & Palme (2008) 10 ppb*
**Turcotte & Schubert (2002) 31 ppb*

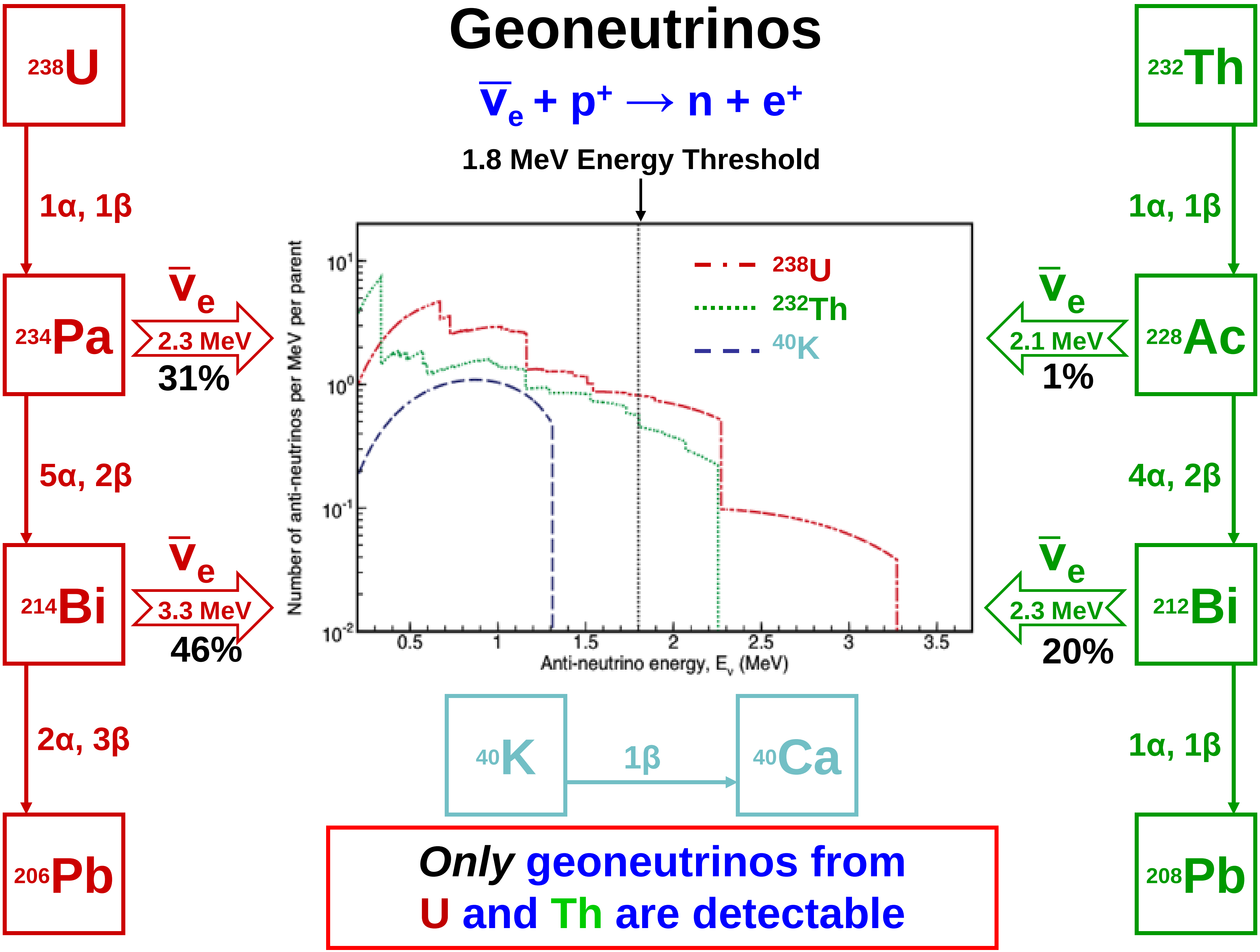
Continental Crust
1300 ppb U

Mantle
~12 ppb U

Chromatographic separation
Mantle melting & crust formation

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



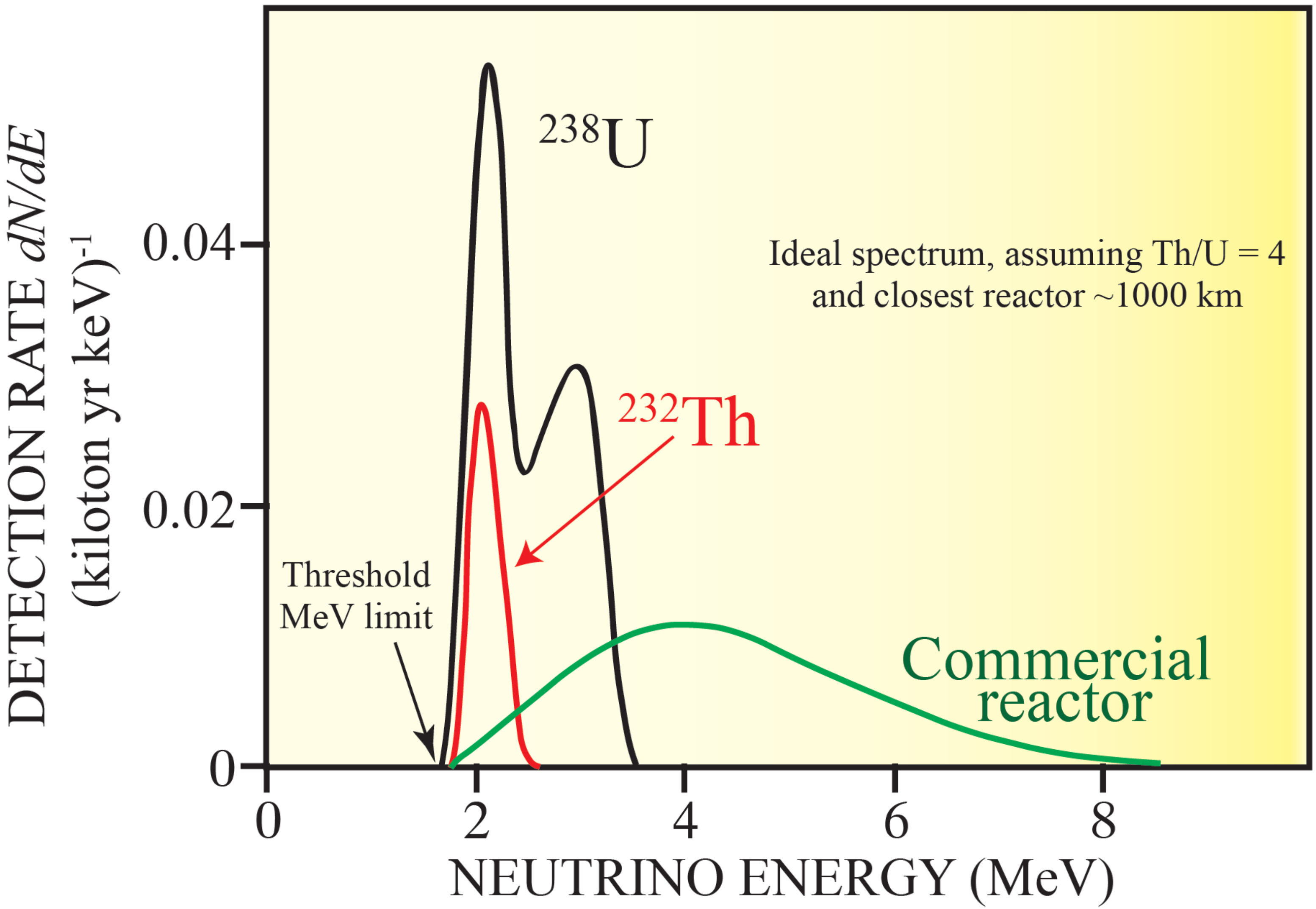

Geoneutrinos
$\bar{\nu}_e + p^+ \longrightarrow n + e^+$
1.8 MeV Energy Threshold
238U
1α, 1β
234Pa
$\bar{\nu}_e$
2.3 MeV
31%
5α, 2β
214Bi
$\bar{\nu}_e$
3.3 MeV
46%
2α, 3β
206Pb
232Th
1α, 1β
228Ac
$\bar{\nu}_e$
2.1 MeV
1%
4α, 2β
212Bi
$\bar{\nu}_e$
2.3 MeV
20%
1α, 1β
208Pb
Number of anti-neutrinos per MeV per parent
Anti-neutrino energy, E_ν (MeV)
238U
232Th
40K
40K
1β
40Ca
Only geoneutrinos from
U and Th are detectable

Earth Layer	$L^{U}_{\bar{\nu}_e}$ ($10^{23}\bar{\nu}_e\ s^{-1}$)	$L^{\mathrm{U}}_{\bar{\nu}_e}$ (TW)	$L^{\mathrm{Th}}_{\bar{\nu}_e}$ ($10^{23}\bar{\nu}_e\ s^{-1}$)	$L^{\mathrm{Th}}_{\bar{\nu}_e}$ (TW)	$L^{\mathrm{K}}_{\bar{\nu}_e}$ ($10^{23}\bar{\nu}_e\ s^{-1}$)	$L^{\mathrm{K}}_{\bar{\nu}_e}$ (TW)	$L^{\mathrm{U+Th+K}}_{\bar{\nu}_e}$ ($10^{23}\bar{\nu}_e\ s^{-1}$)	$L^{\mathrm{U+Th+K}}_{\bar{\nu}_e}$ (TW)
Crust	23	0.3	22	0.2	120	1.4	170	1.9
Mantle	32	0.4	26	0.3	160	1.9	220	2.5
Total	55	0.7	48	0.5	280	3.3	390	4.4

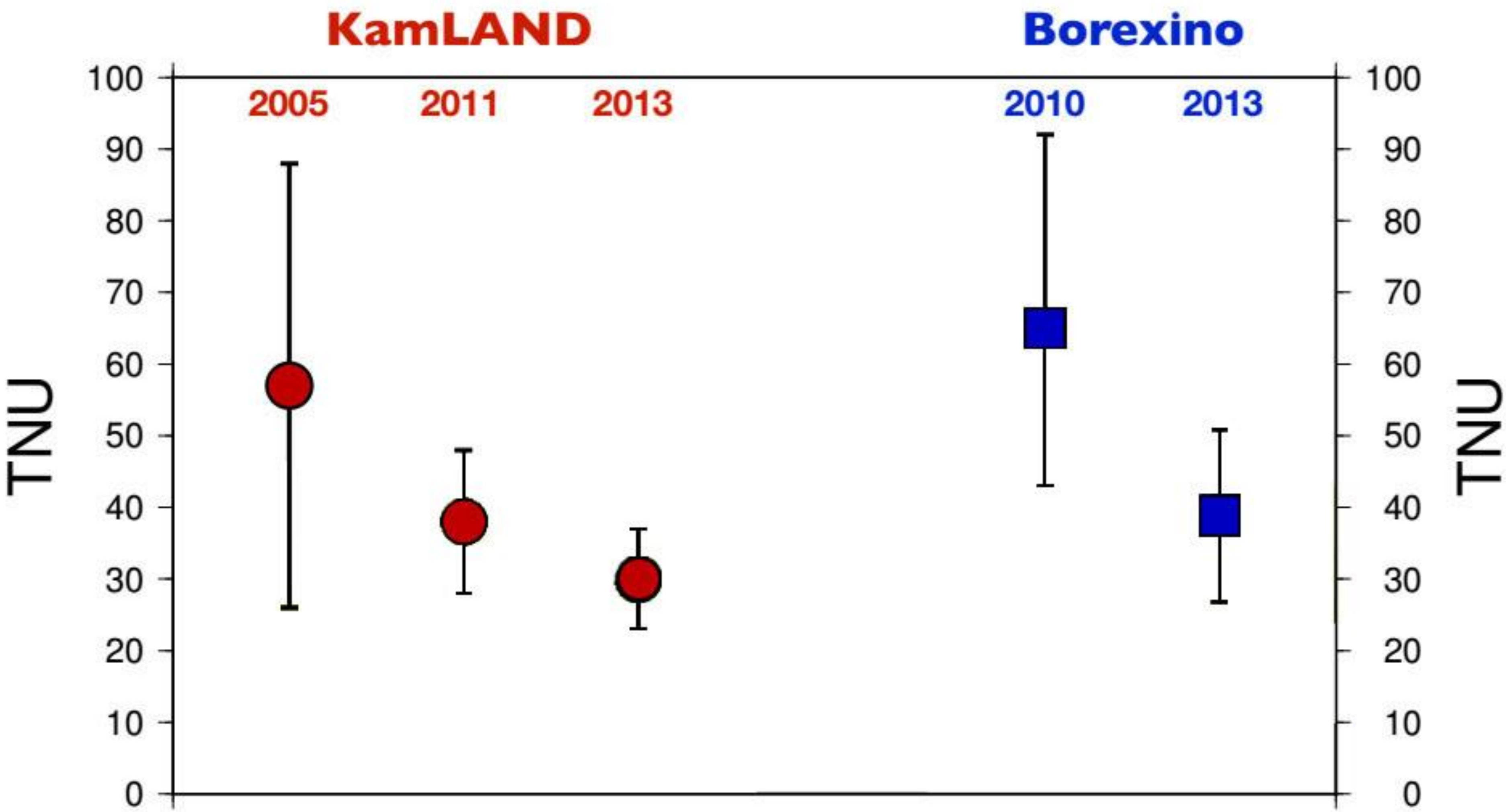
TABLE I. Contribution of geoneutrino luminosities for U, Th, and K emitted by the Earth as a function of geophysical depth. The reactor antineutrino luminosity, $L^{reactor}_{\bar{\nu}_e}$, is $1.6 \times 10^{23}\bar{\nu}_e\ s^{-1}$ and 0.04 TW.

Antineutrinos - Geoneutrinos

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

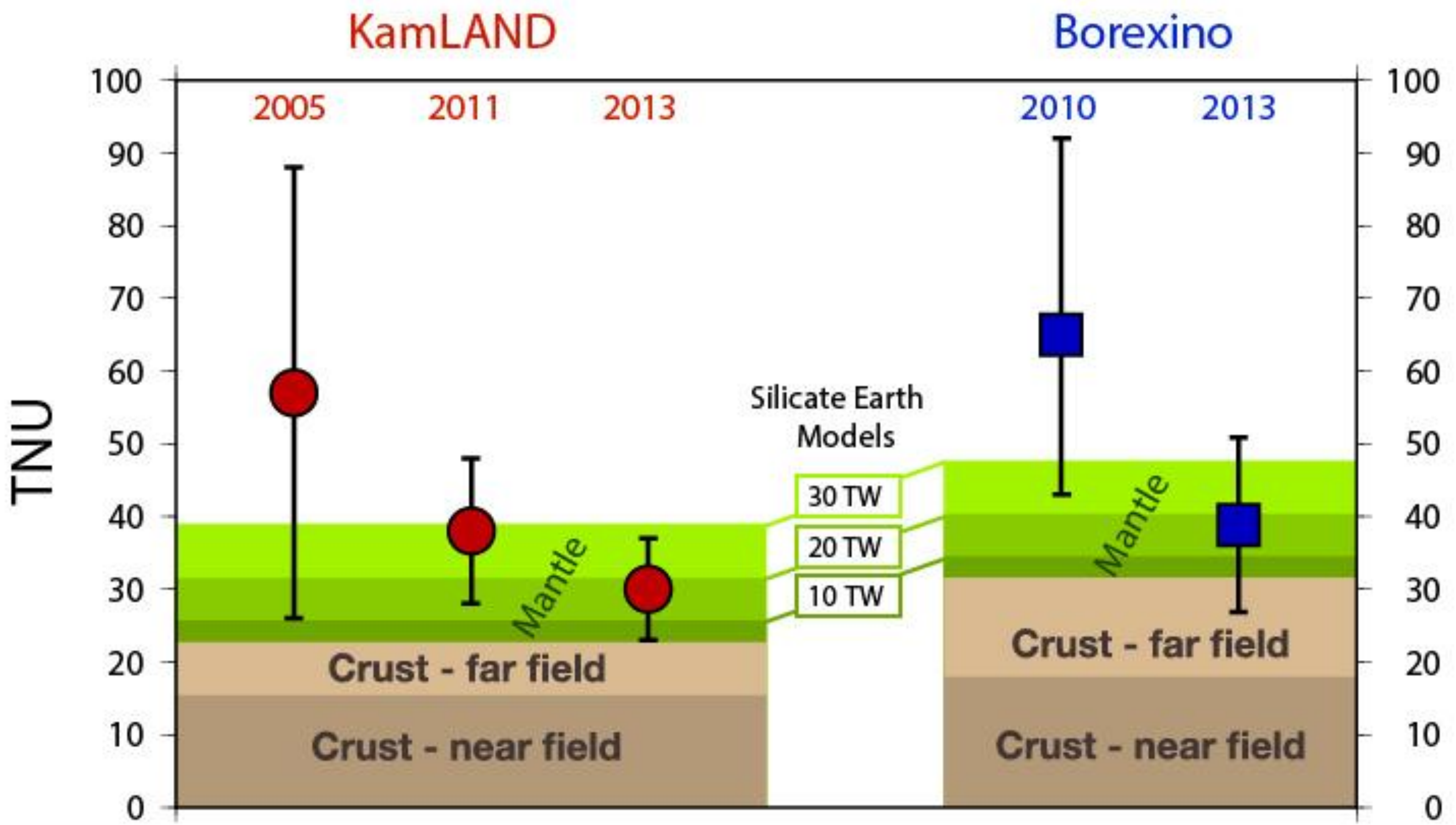


Can Physics Help Geoscience?



TNU: geo-$\overline{n\upsilon}$ 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

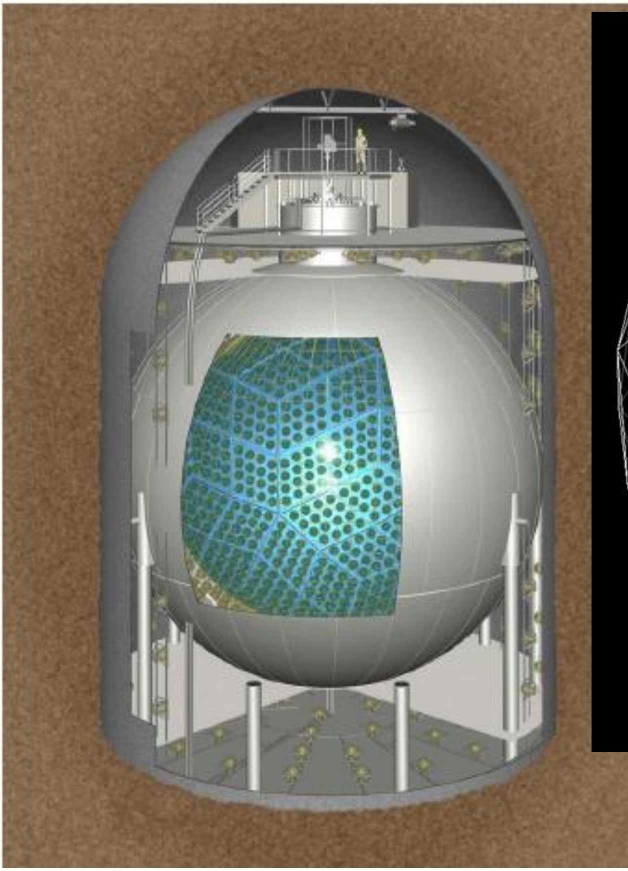
Geodynamical: parameterized convection – 30 TW

TW scales relative to U

10, 20, 30 TW ≈ 10, 20, 30 ppb

Present Liquid Scintillator Detectors

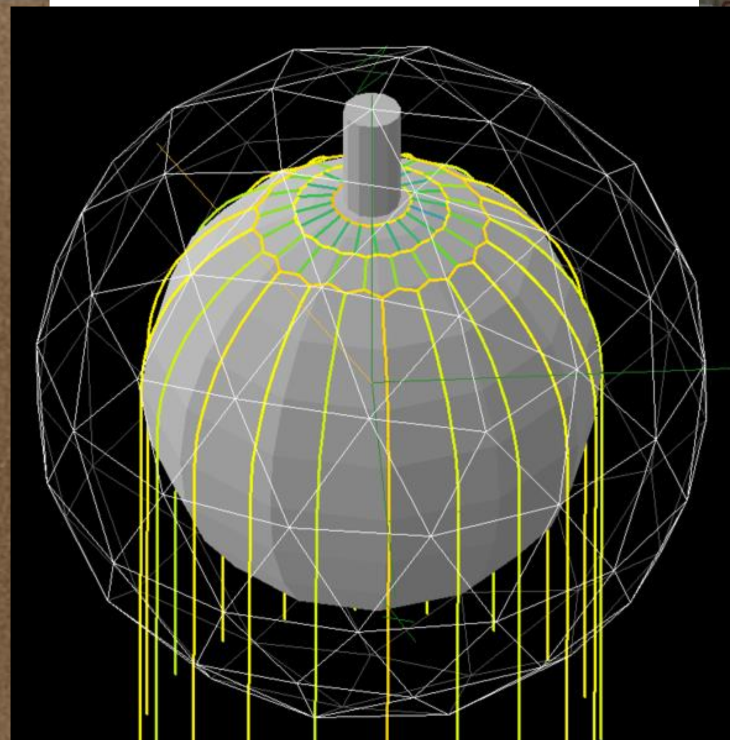
KamLAND, Japan (1kt)



116^{+28}_{-27}

from Mar ‘02 to Nov ‘12

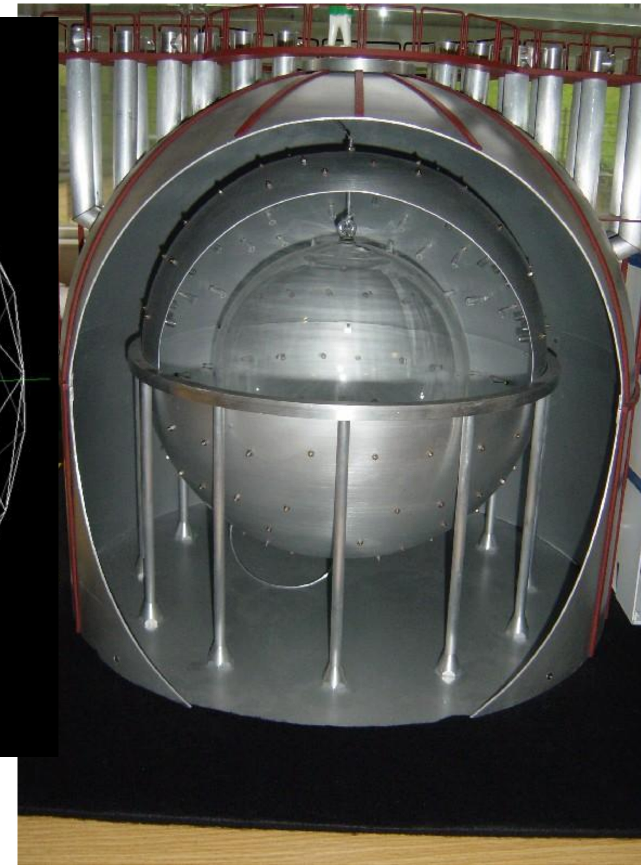
SNO+, Canada (1kt)



under construction

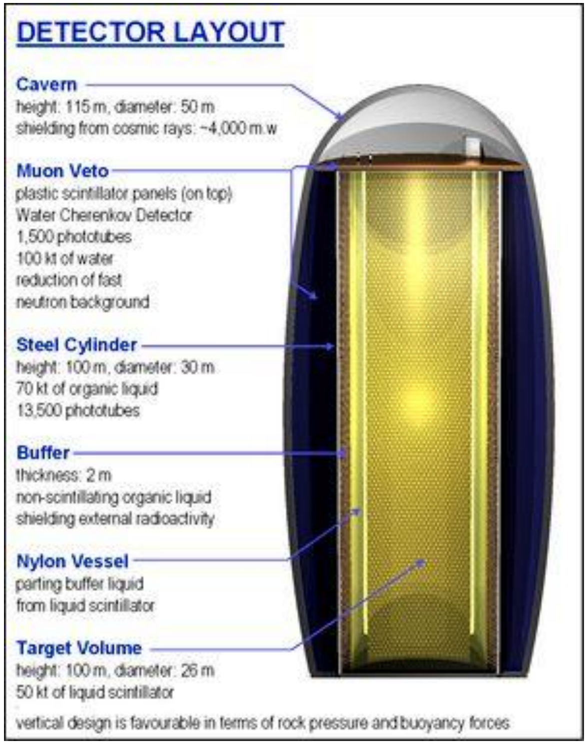
(online 2015?)

Borexino, Italy (0.3kt)



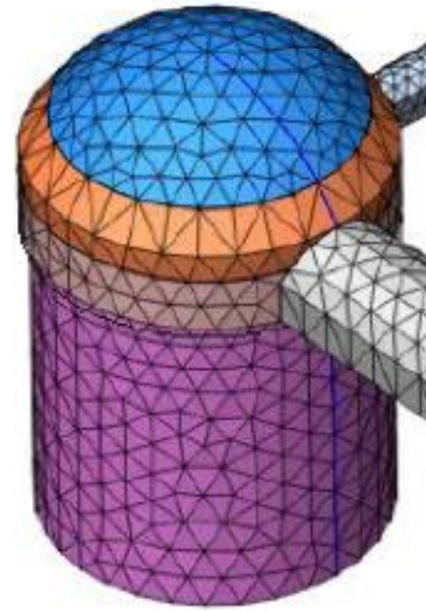
14.3 ± 4.4

from Dec ‘07 to Aug ‘12



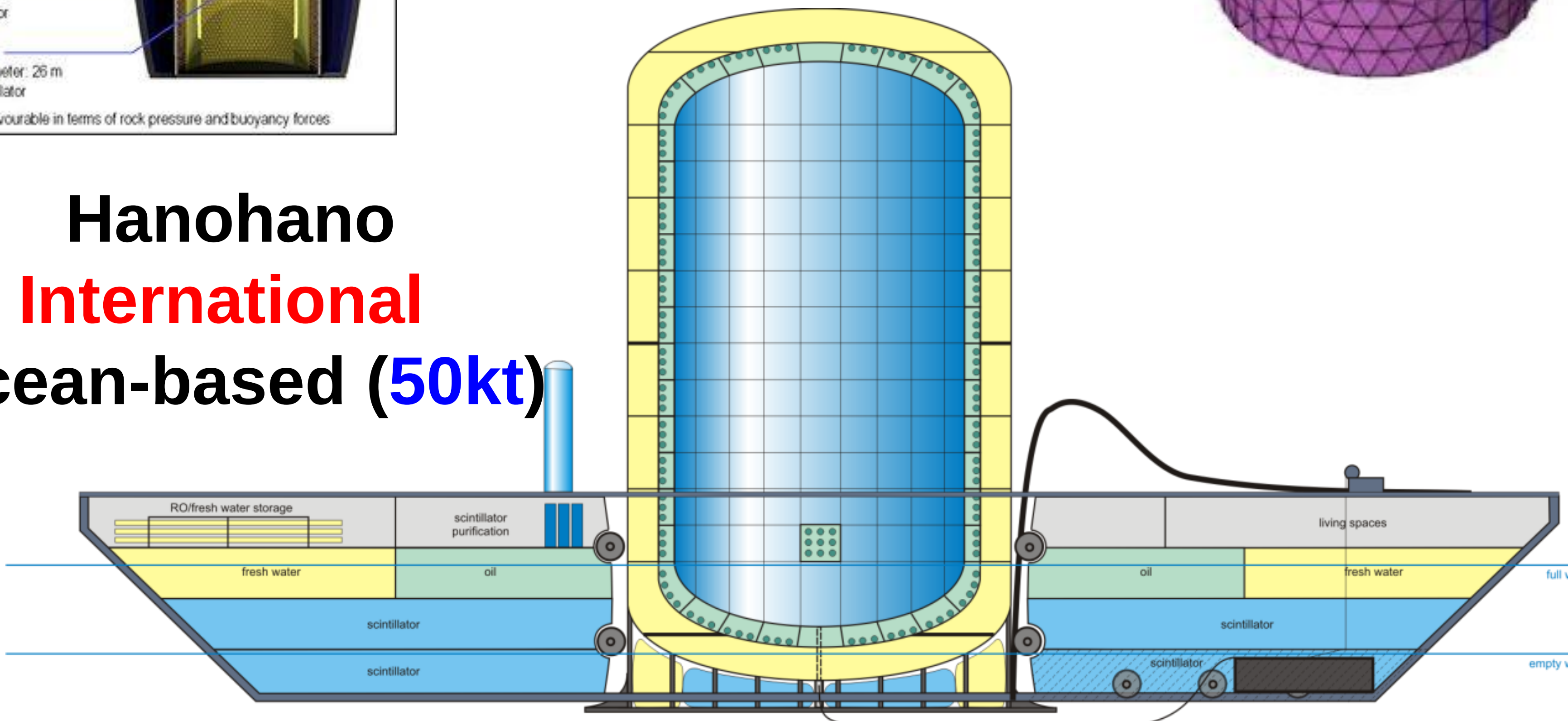
(LENA)
EU
(50kt)

JUNO
China
(20kt)



Future detectors?

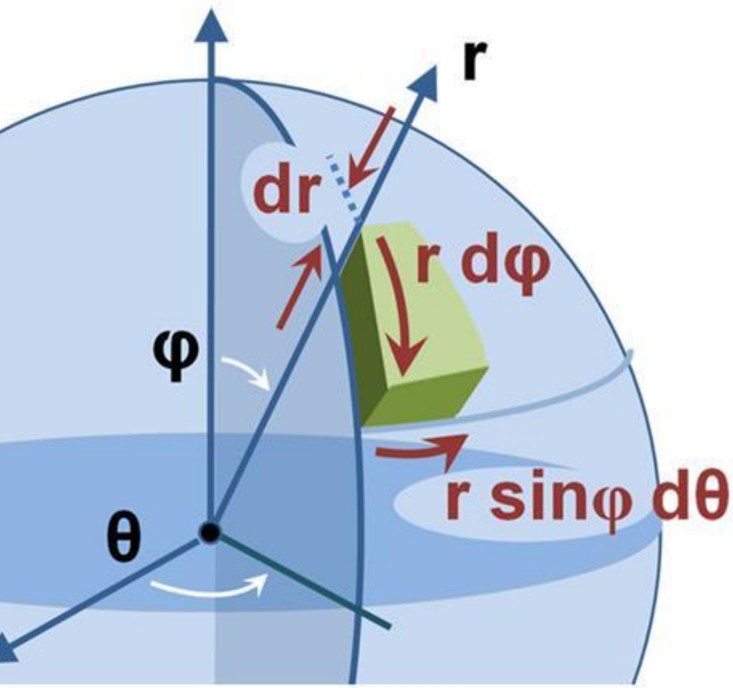
Hanohano
International
ocean-based (50kt)

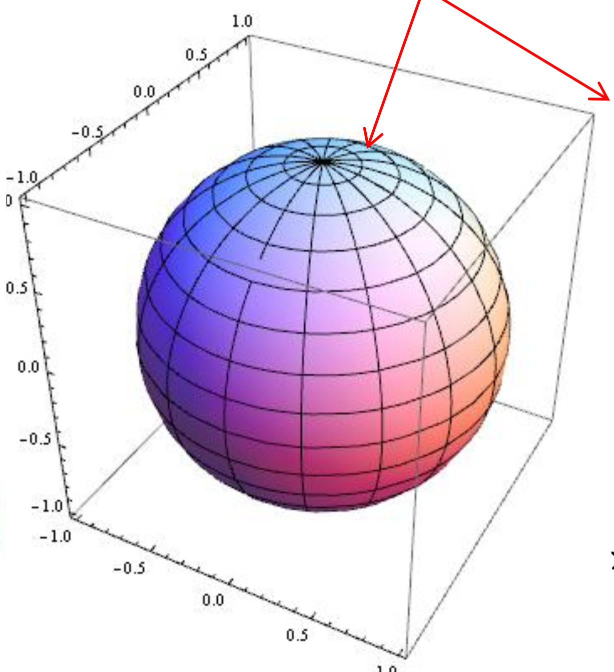


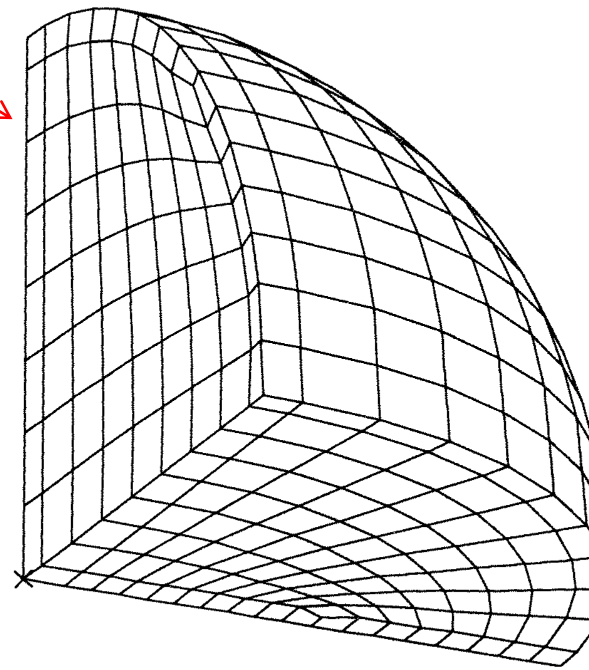
Constructing a 3-D reference model Earth

assigning chemical and physical states to Earth voxels

1^o x 1^o x "z" tile
mapping of elements







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

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

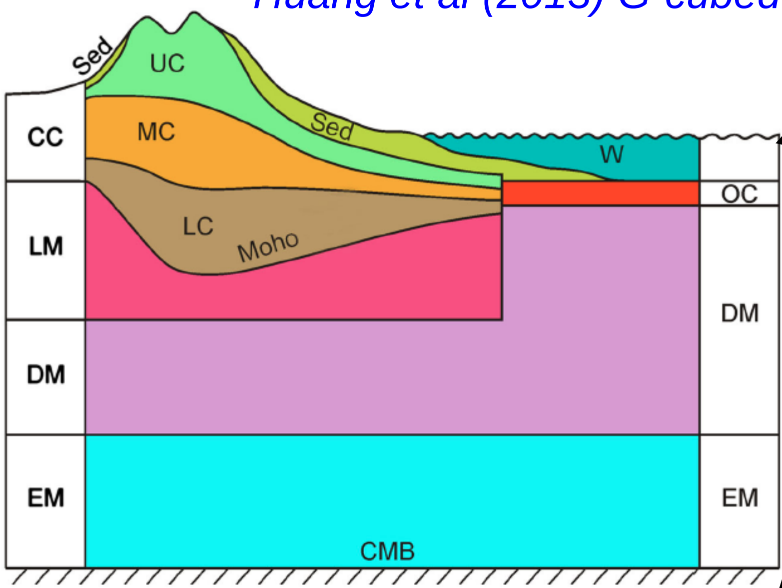
Distance between source unit and detector

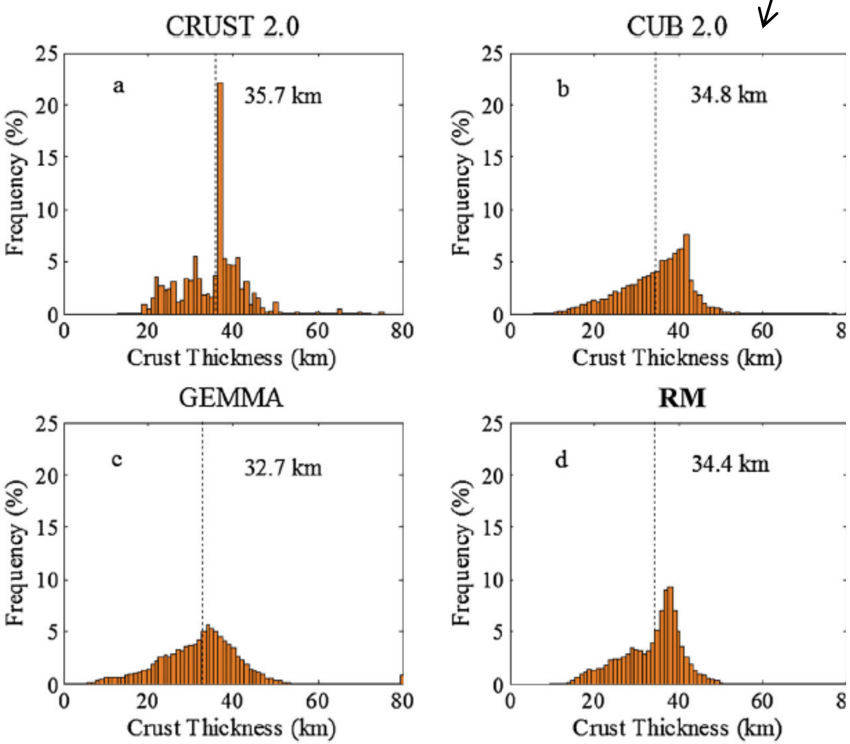
Earth structure (ρ and L) and **chemical composition** (a)

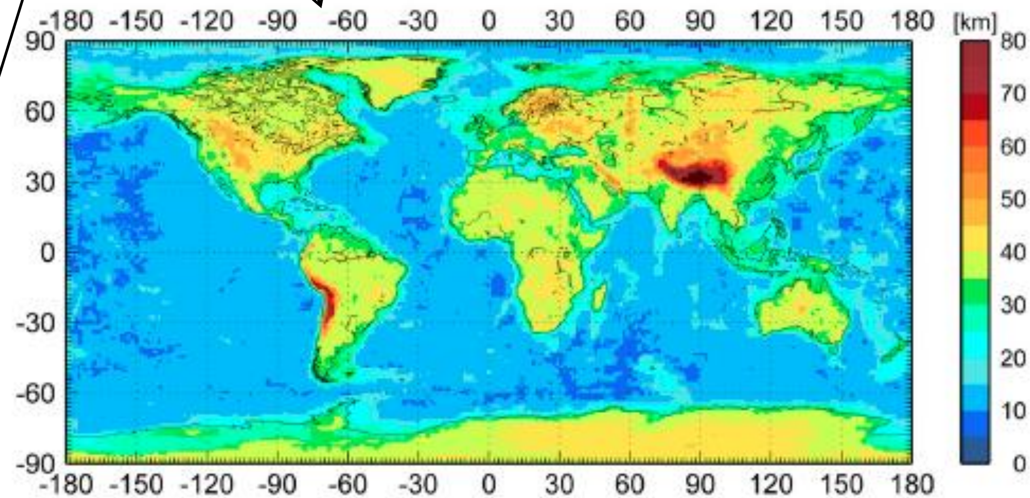
Huang et al (2013) G-cubed

Global Earth Reference Model

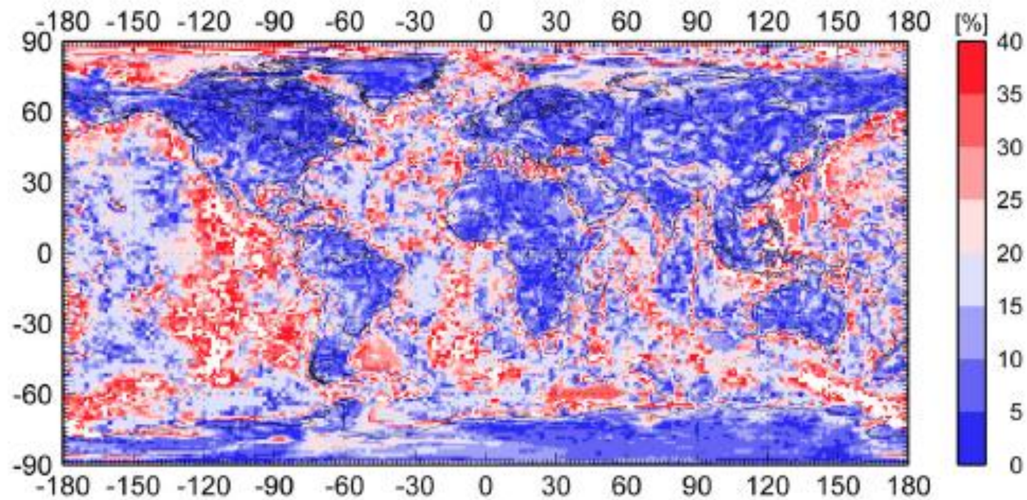
- 7 layers for the top 200 km
- Integrate 3 global models for the crust
- New crust model with uncertainties





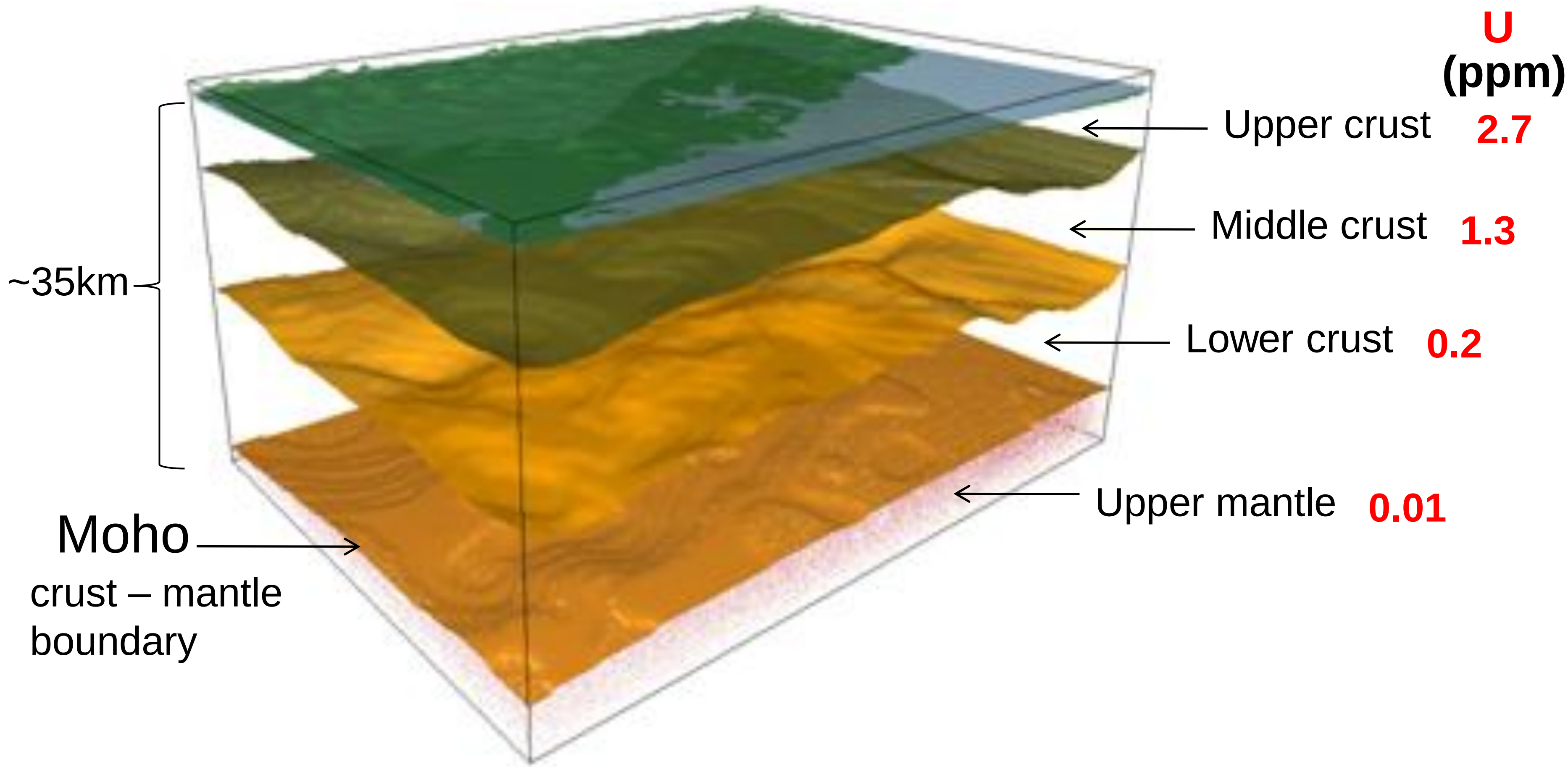


(a)



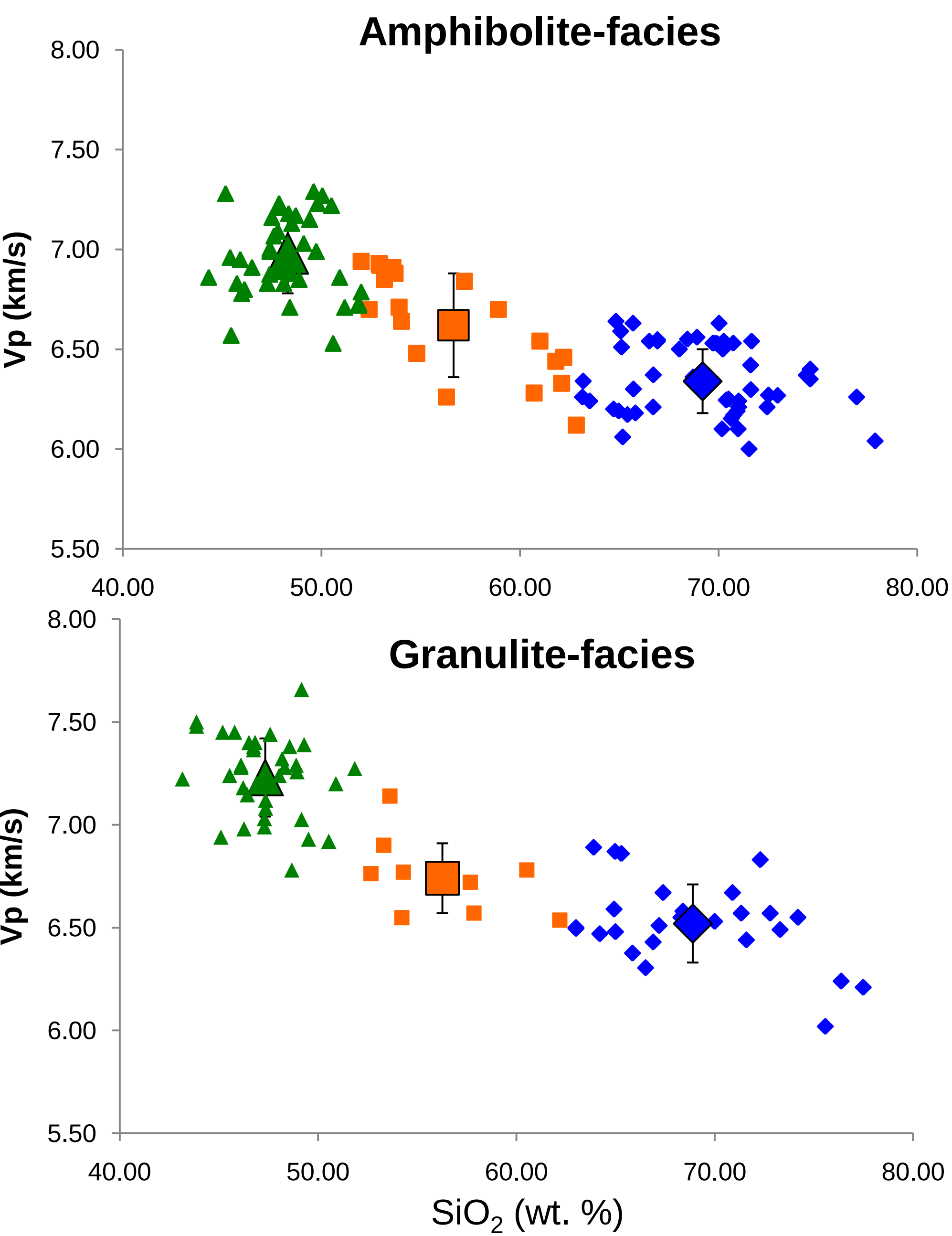
(b)

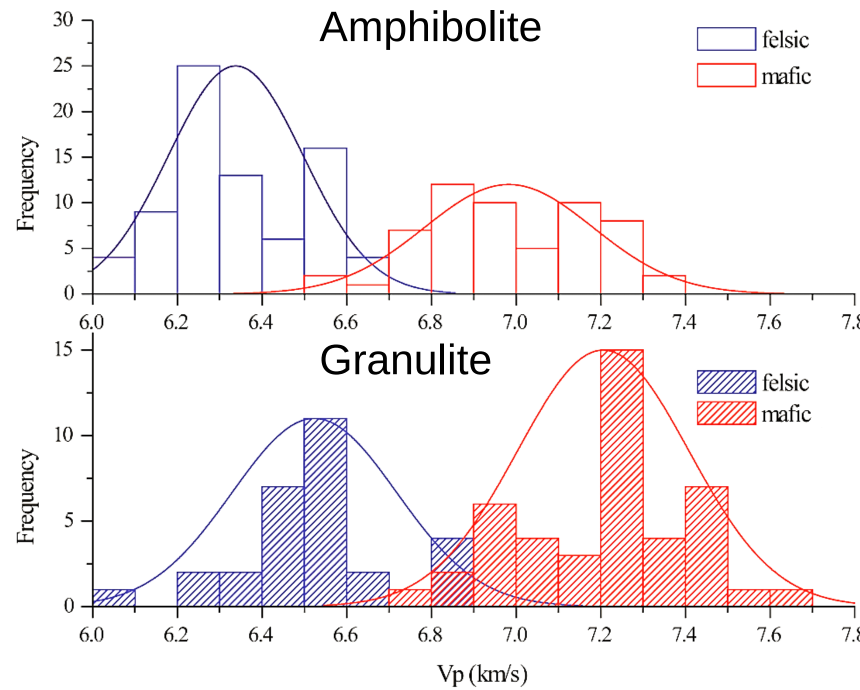
Geological model – Continental Crust



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

Seismic Velocities of Deep Crustal Rocks

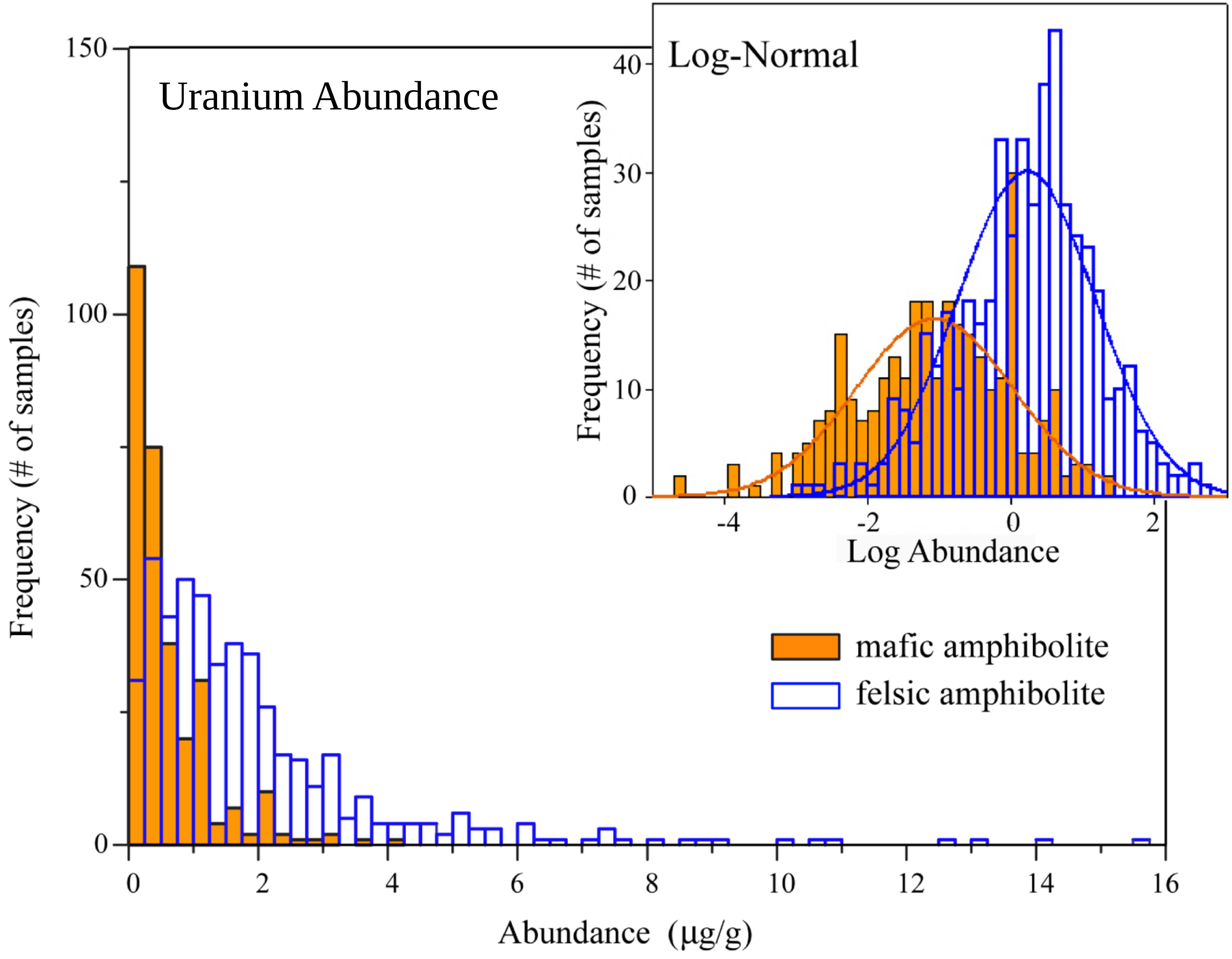




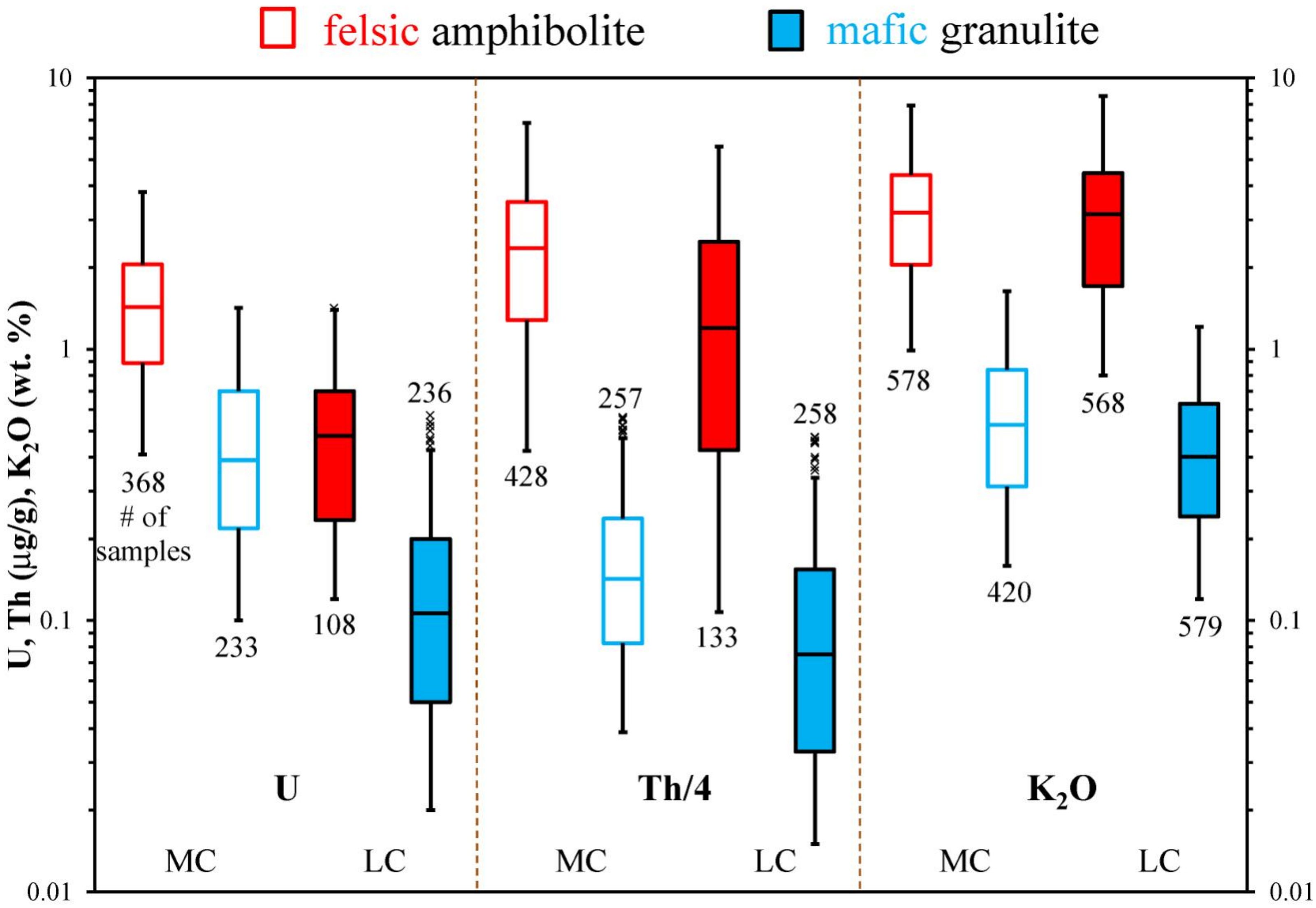
- ✓ Two components mixing in MC and LC: felsic and mafic
- ✓ Distinguishable by Vp (1-sigma)
- ✓ Close to linear relationship (Vp vs. SiO_2)

Composition of *Mafic* & *Felsic* Components

Non-Gaussian distributions



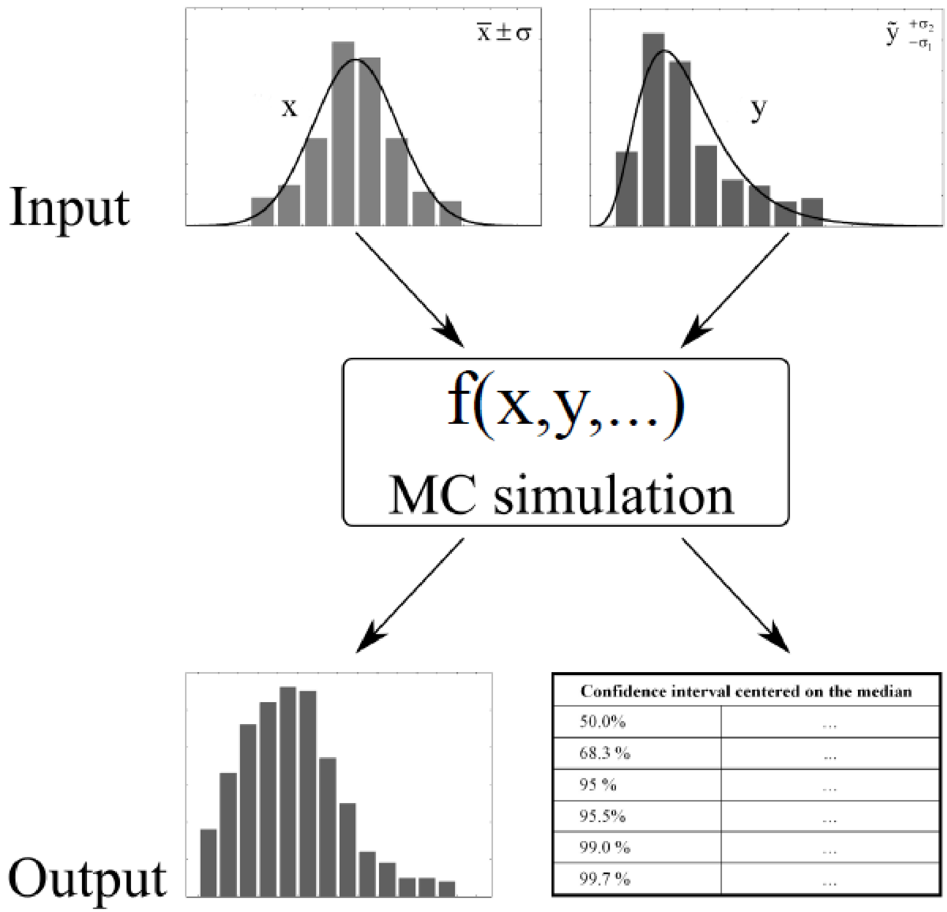
K, Th and U in the middle and lower crust



How to Track Uncertainty?

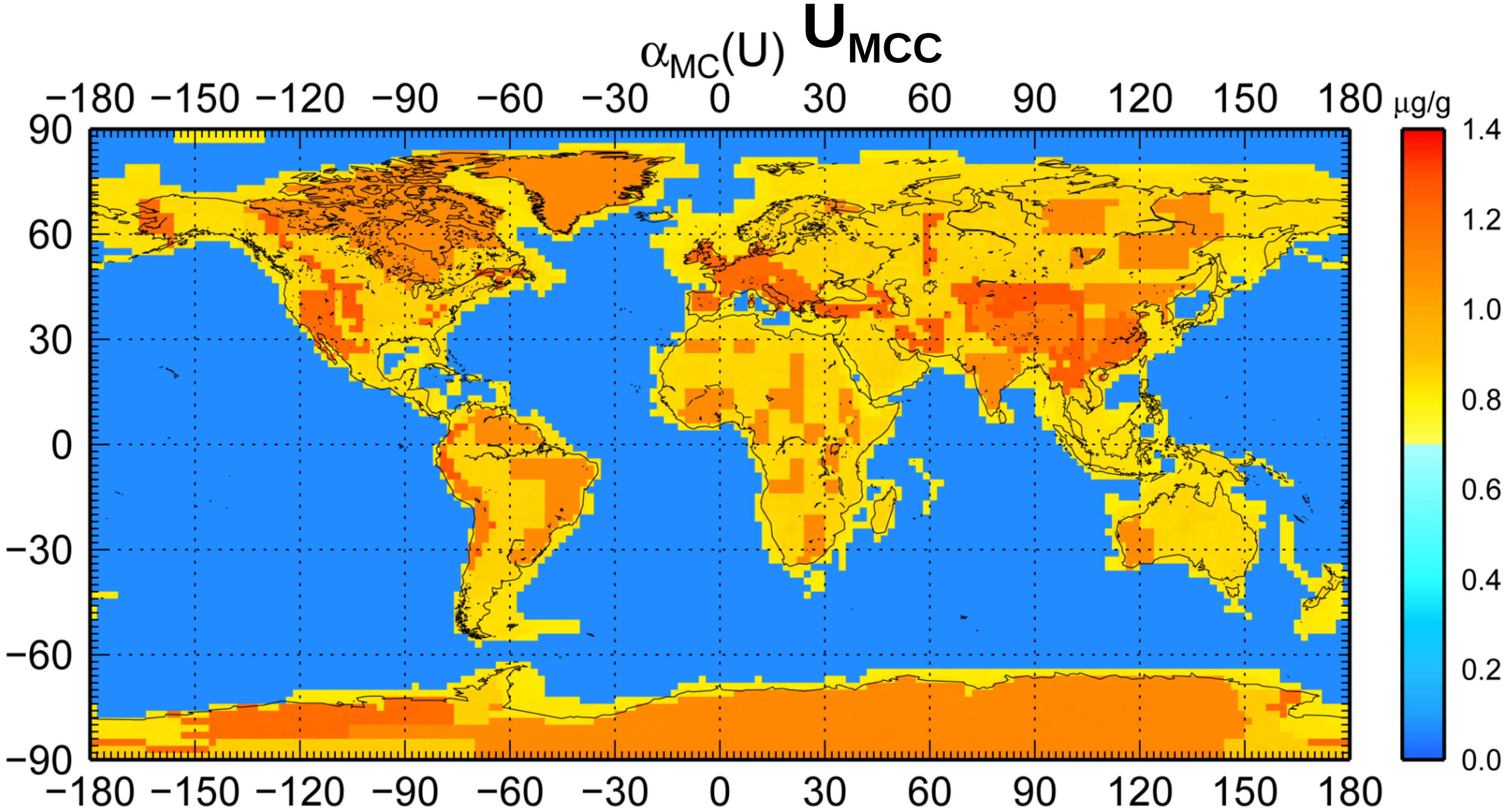
Monte Carlo simulation: highly desired for the propagation of asymmetric uncertainties

Requirement : the PDFs of all inputs are known



- ✓ Generate random samples for inputs, including correlation
- ✓ Calculate output variables
- ✓ Statistical analysis

Uranium Abundance in Middle Continental Crust layer



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

Rudnick and Gao (2003) 1.3 μg/g

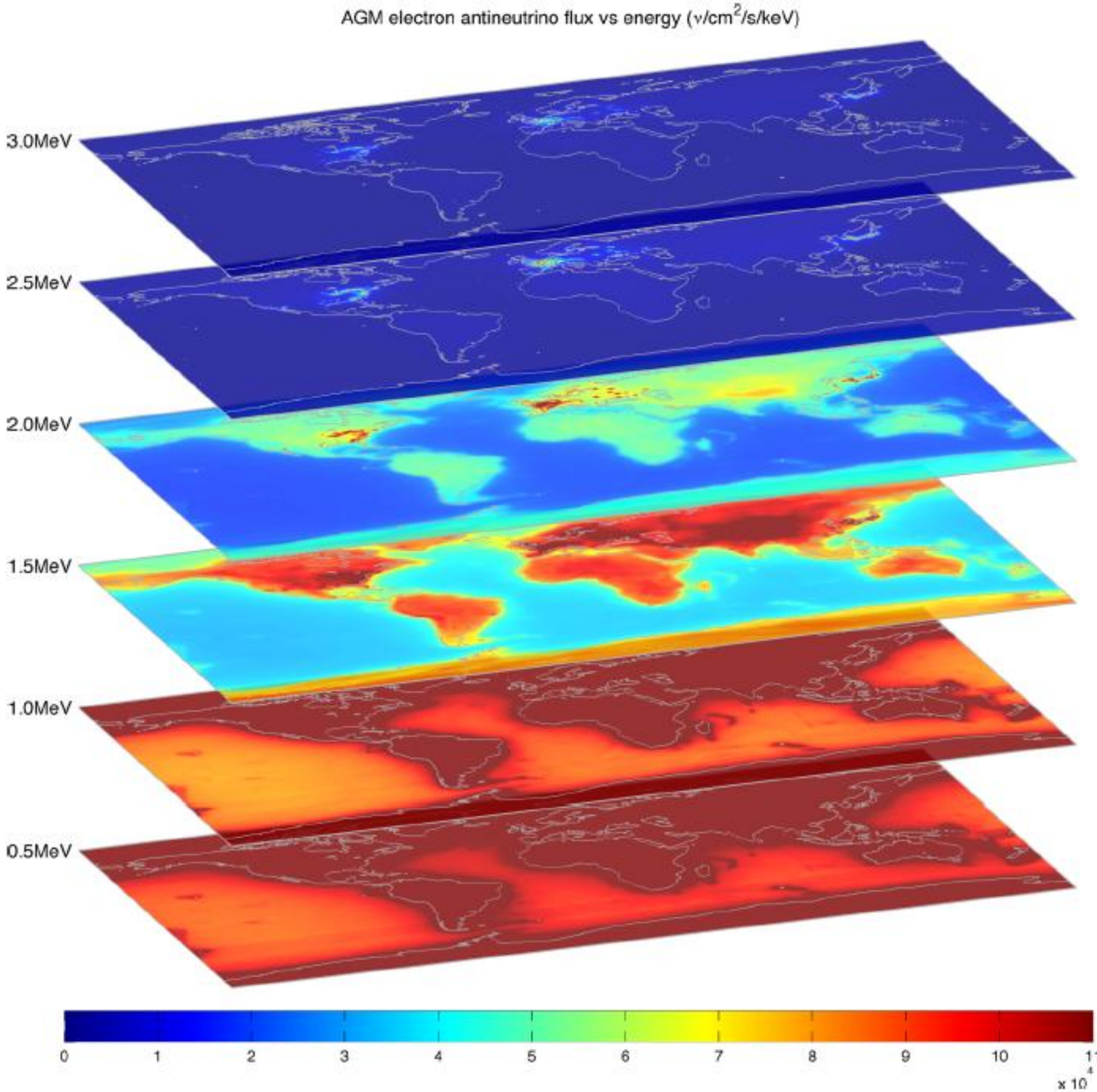
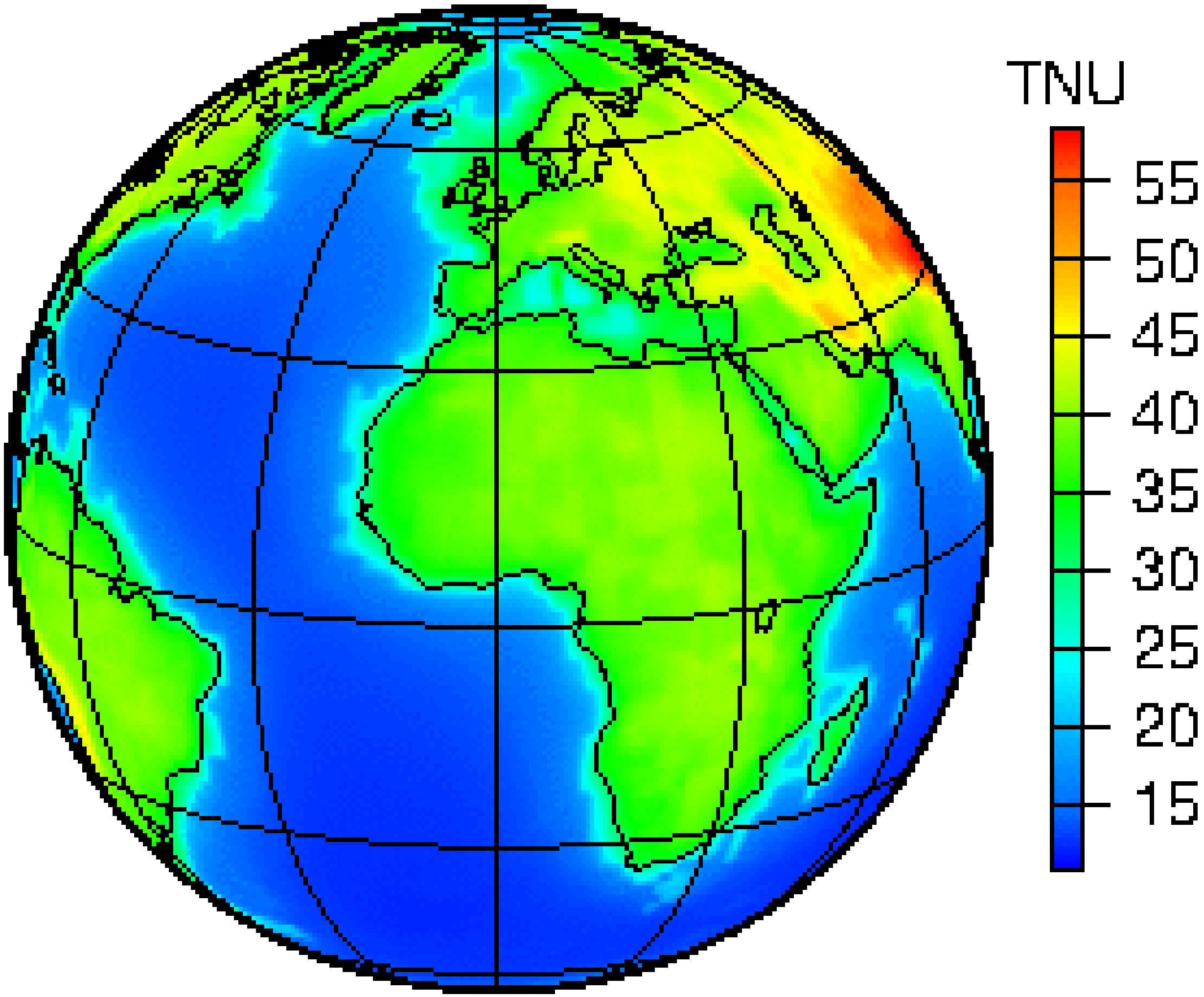


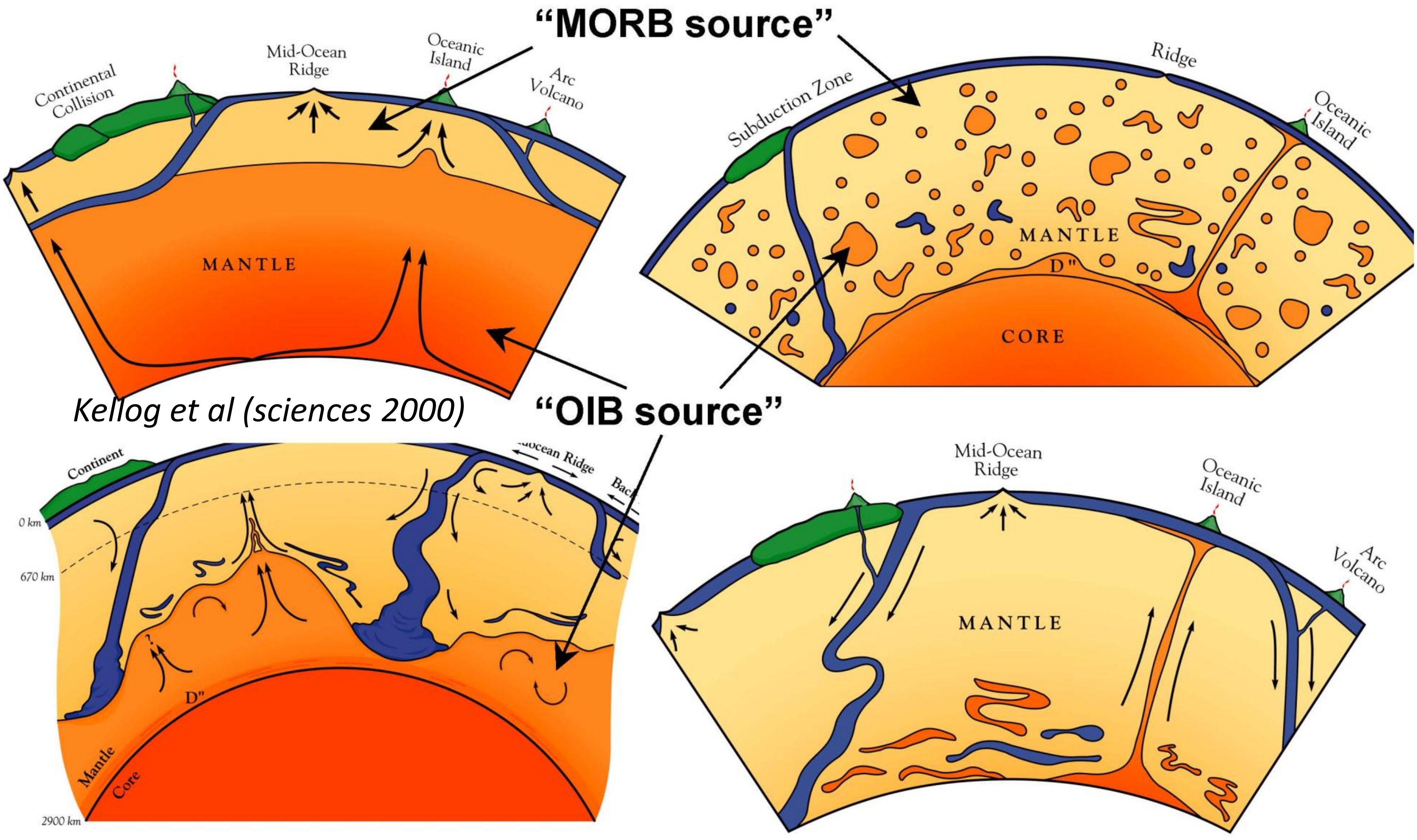
FIG. 4. AGM electron antineutrino flux displayed at select energies. The full AGM contains 1100 such energy slices from 0MeV to 11MeV. Each slice is 10keV wide. In conjunction with 720 longitude bins and 360 latitude bins, the full AGM 3-dimensional size is $360 \times 720 \times 1100$; about 285 million elements total.

Predicted Global geoneutrino flux based on our new Reference Model



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

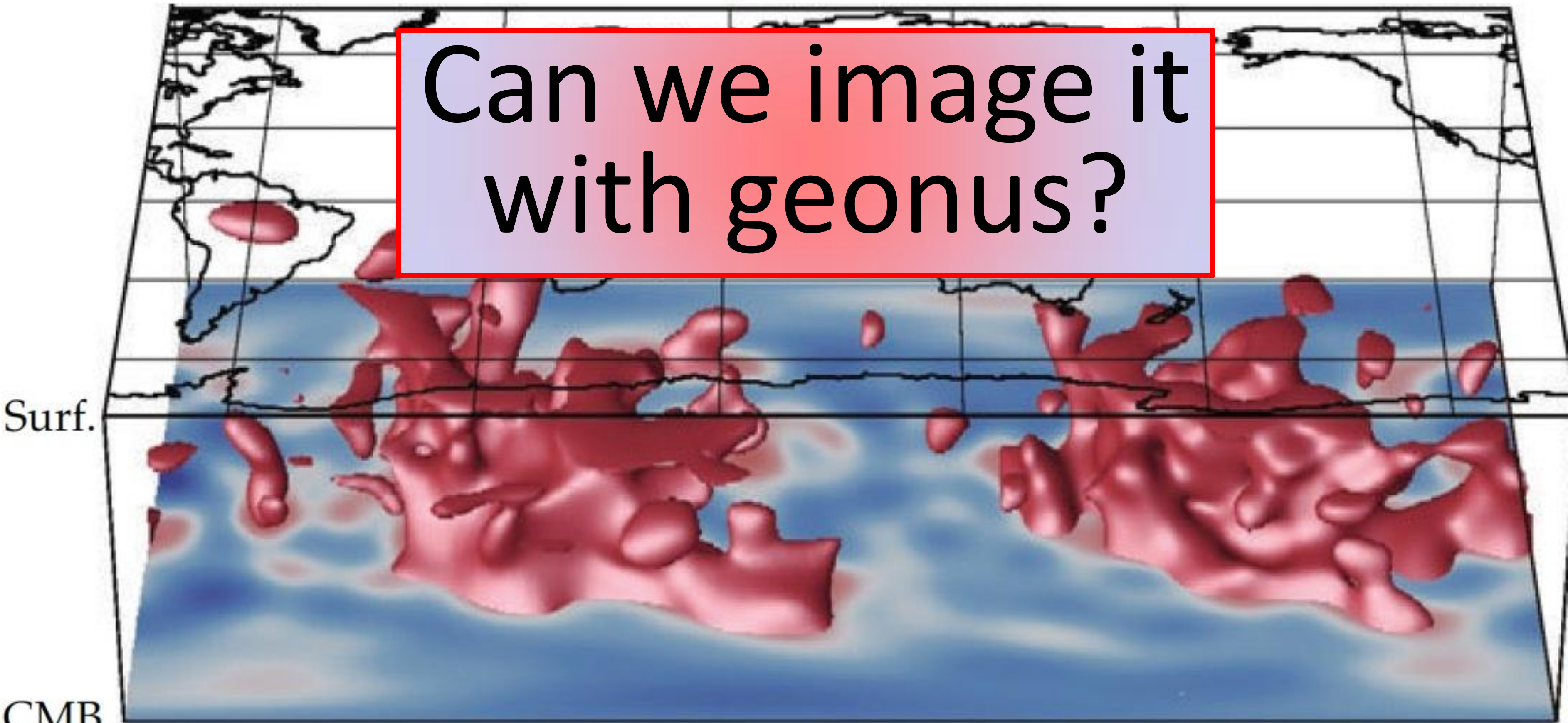
Early Earth differentiation followed by 4 billion years of plate tectonics



Kellog et al (sciences 2000)

What's hidden in the mantle?

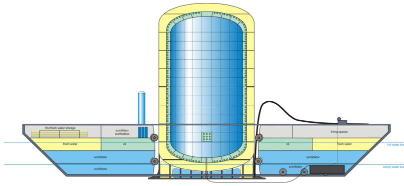
Seismically slow "red" regions in the deep mantle

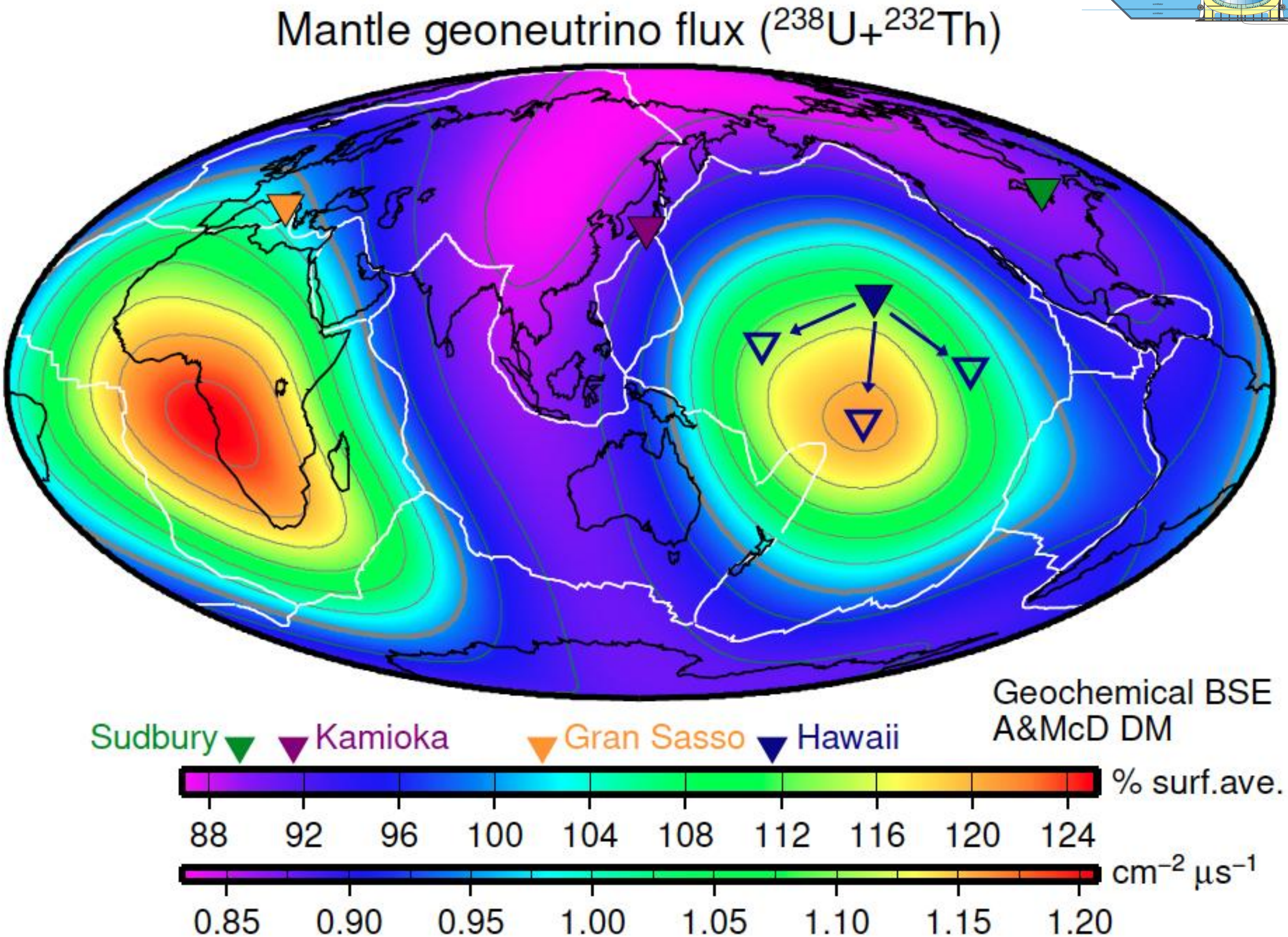


Can we image it with geonus?

Ritsema et al (Science, 1999)

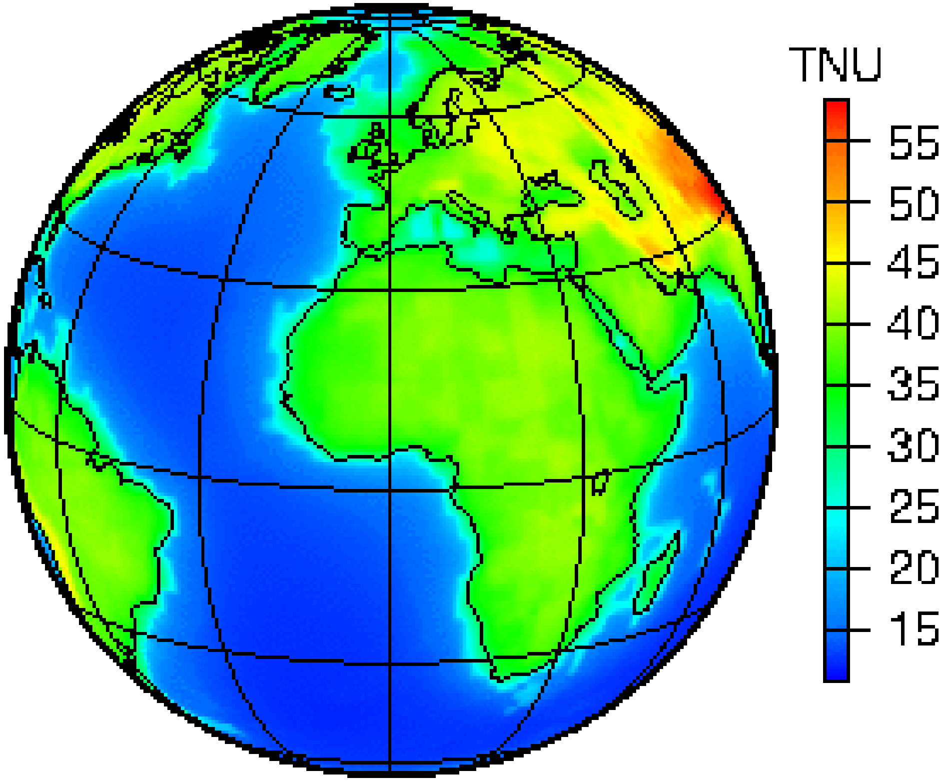
Testing Earth Models





Šrámek et al, 2013, EPSL

Predicted geoneutrino flux



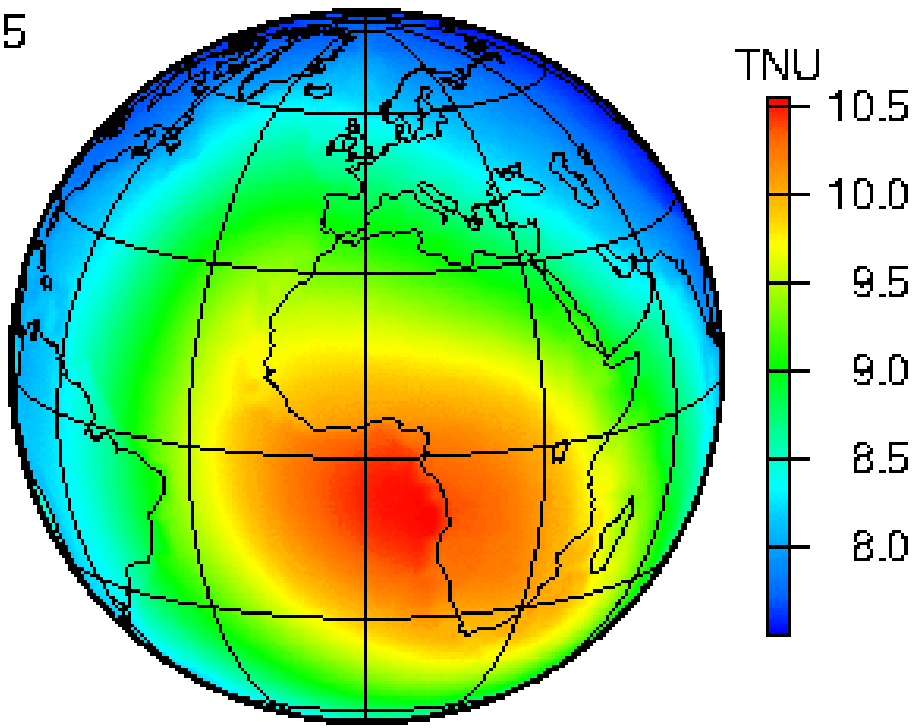
Yu Huang et al (2013) G-cubed **arXiv:1301.0365**

Total flux at surface

dominated by
Continental crust

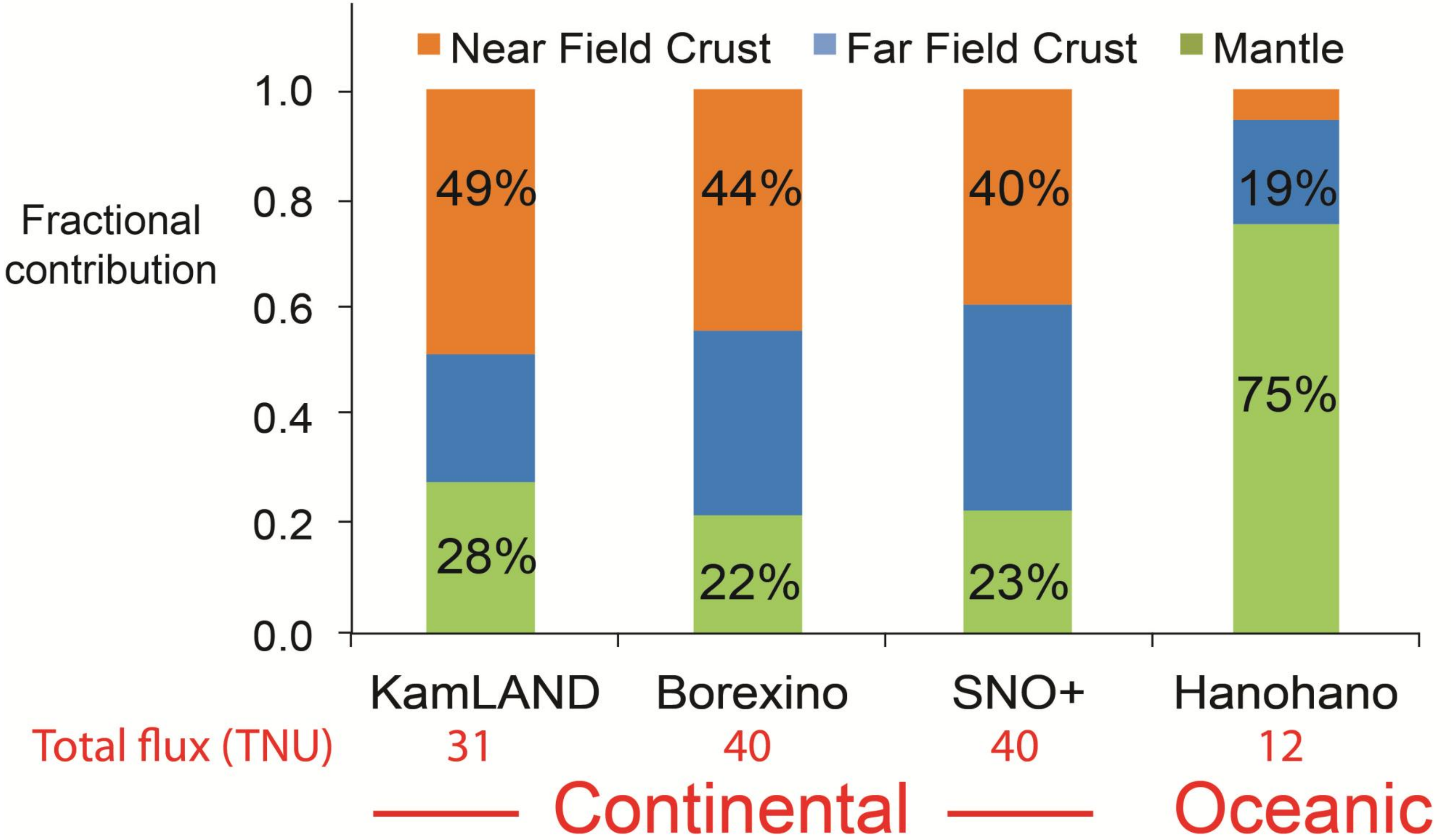
Mantle flux at the surface

dominated by
deep mantle structures



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

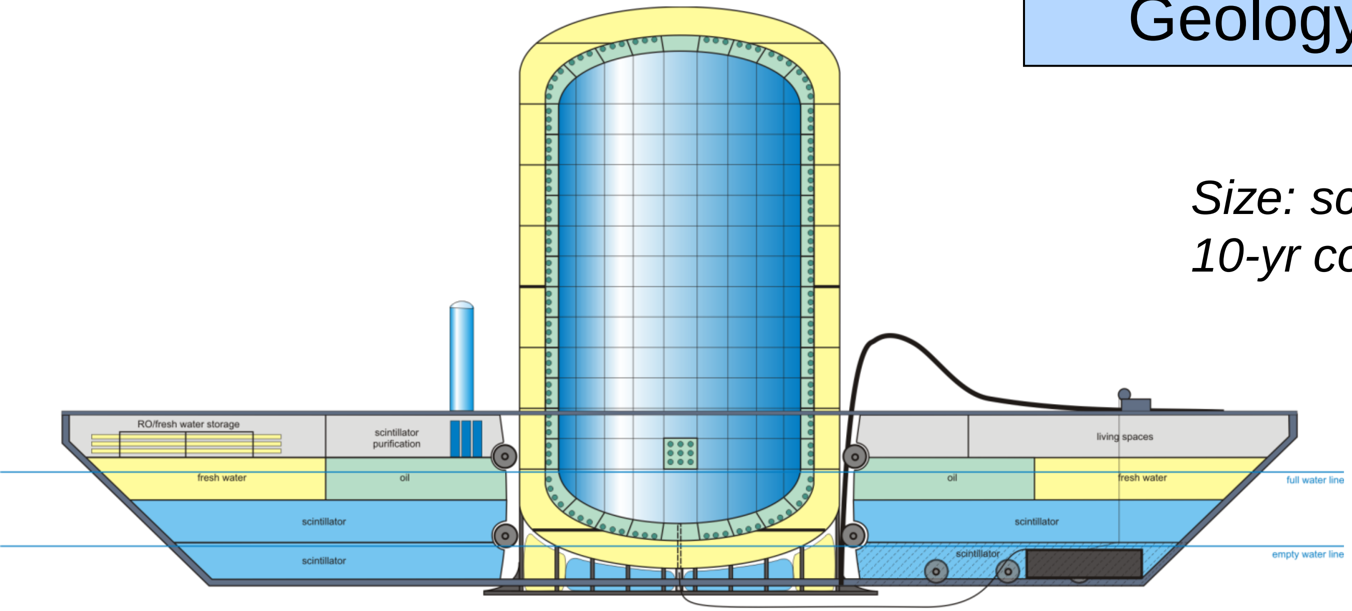
Geoneutrino contributions to detectors



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

Hanohano

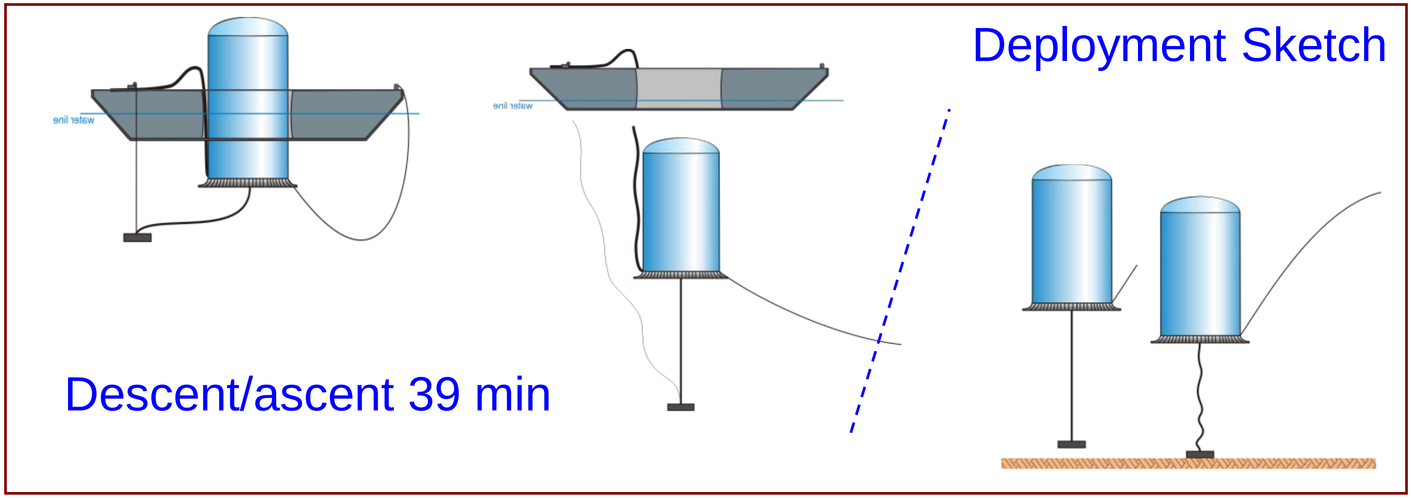
An experiment with joint interests in Physics, Geology, and Security



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

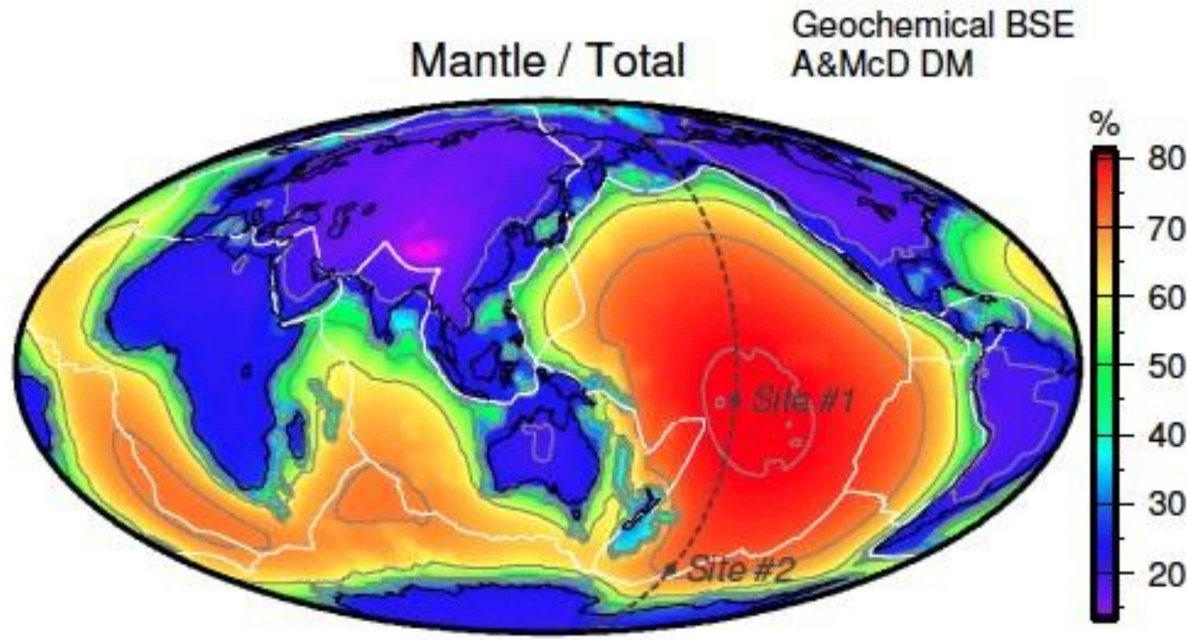
- multiple deployments
- deep water cosmic shield
- control-able L/E detection

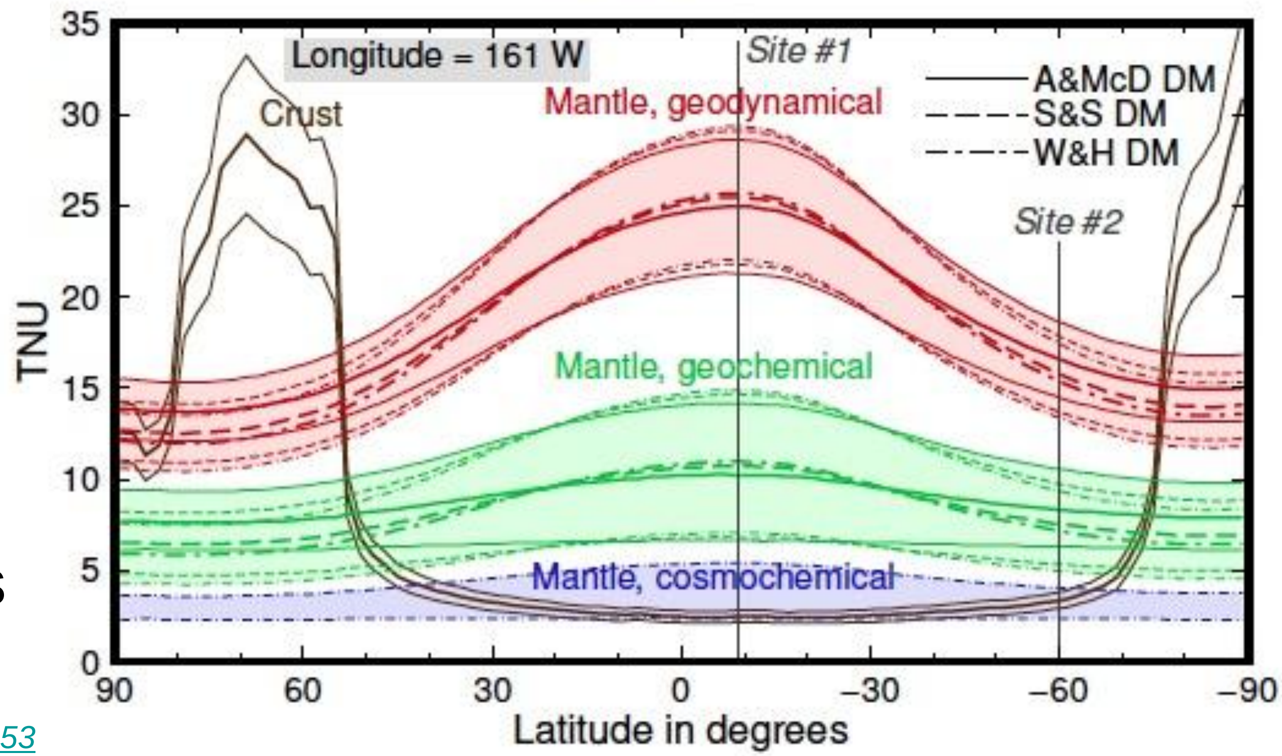
A Deep Ocean $\bar{\nu}_e$ Electron Anti-Neutrino Observatory



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

Conclusion for Physicists

- The Earth below a few kms is not well known (we know sun better)
- Seismic studies reveal velocity but little about composition
- We really do not understand the source of energy driving all of geodynamics
- Neutrinos offer unique prospect to image the earth's dominant radioactive sources of heat
- It will require a cooperation between geologists and physicists to birth this field

Geochemical BSE