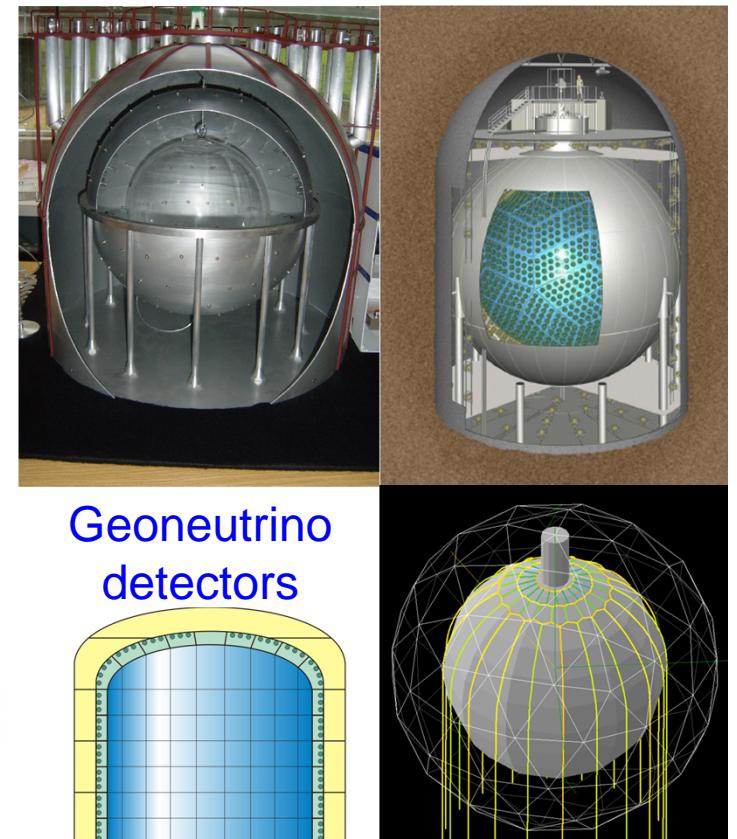
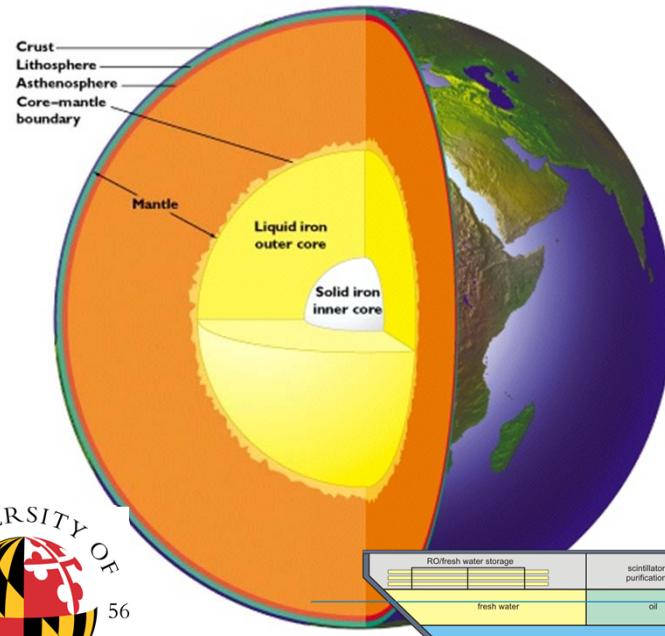


Neutrino Physics- Geoneutrinos: Particle Geophysics

IceCube -> PINGU



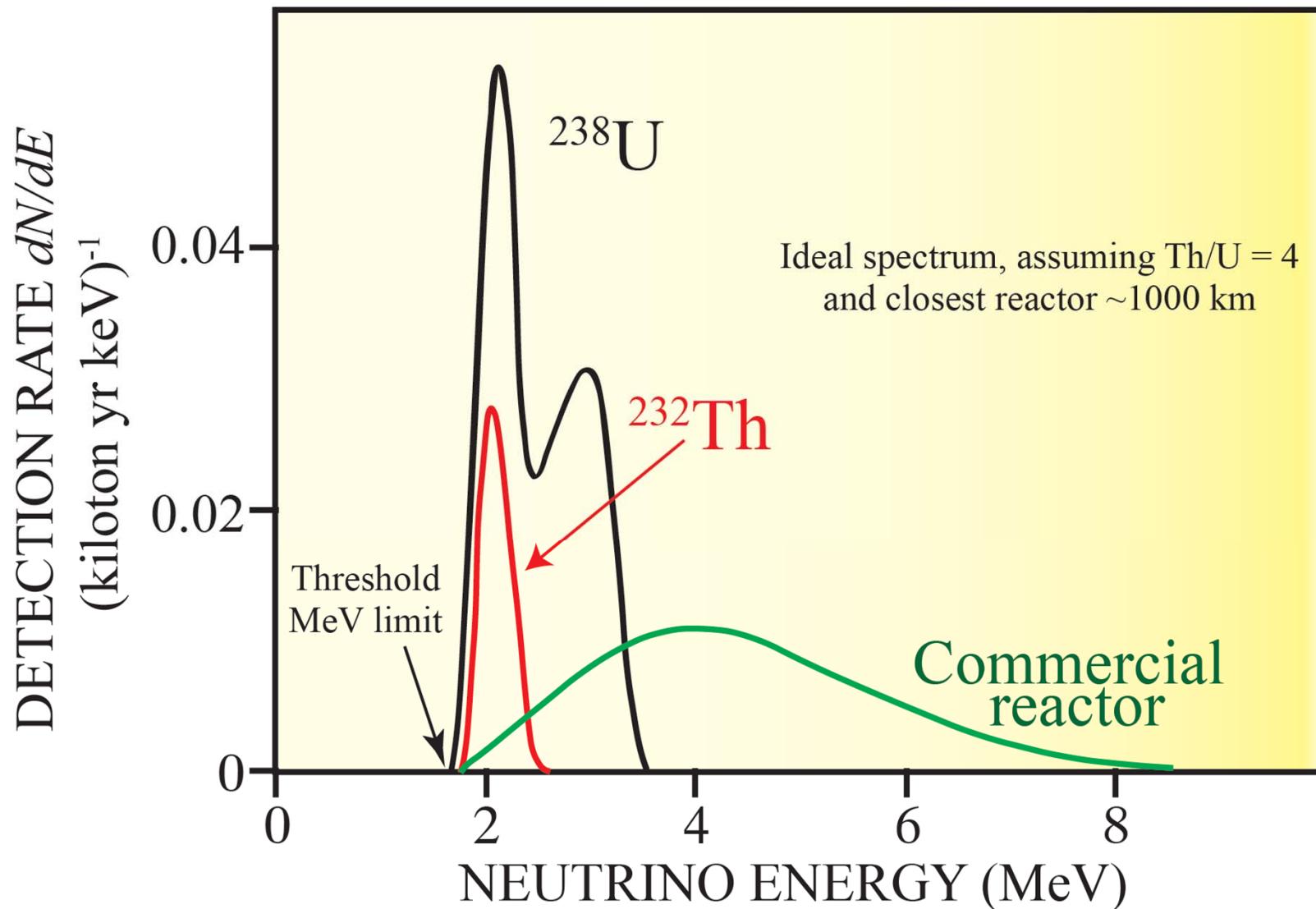
Probing Earth with neutrinos
- geoneutrinos
- neutrino oscillation
Cooling & Plate Tectonics...
Source of Earth's heat?



Bill McDonough
Geology, U Maryland



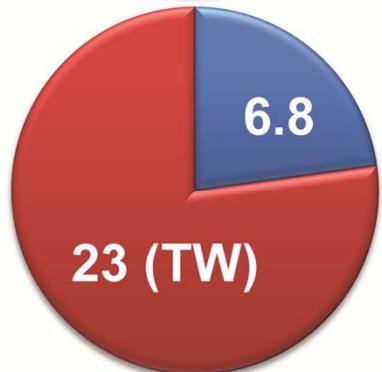
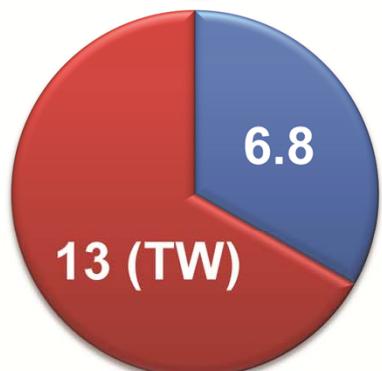
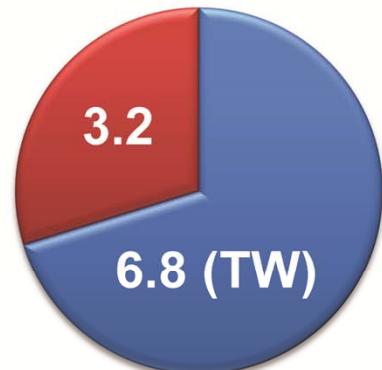
Antineutrinos - Geoneutrinos



5 Big Questions:

- What is the Planetary K/U ratio?
planetary volatility curve
- Radiogenic contribution to heat flow?
secular cooling
- Distribution of reservoirs in mantle?
whole vs layered convection
- Radiogenic elements in the core??
Earth energy budget
- Nature of the Core-Mantle Boundary?
hidden reservoirs

Bulk Silicate Earth Models



■ Cont. Crust
■ Modern Mantle

Cosmochemical
(10 TW)
(O'Neill & Palme '07)

Geochemical
(20 TW)
(McDonough & Sun '95)

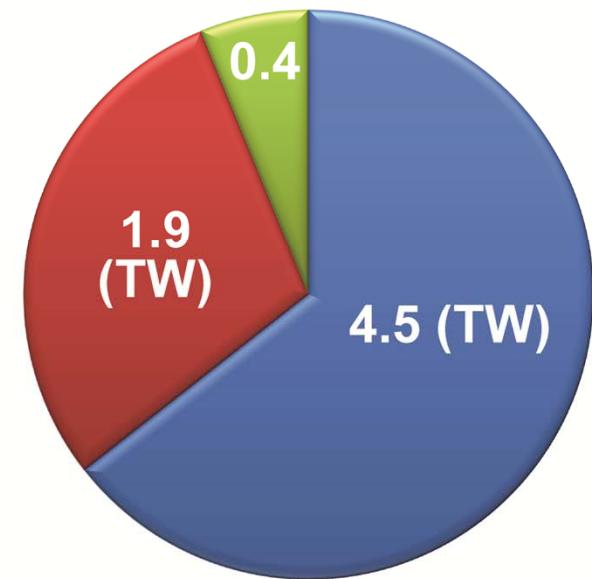
Geodynamic
(30 TW)
(Turcotte & Schubert '02)

Th/U = 4
K/U = 1.4×10^4

surface heat flow 46 ± 3 TW

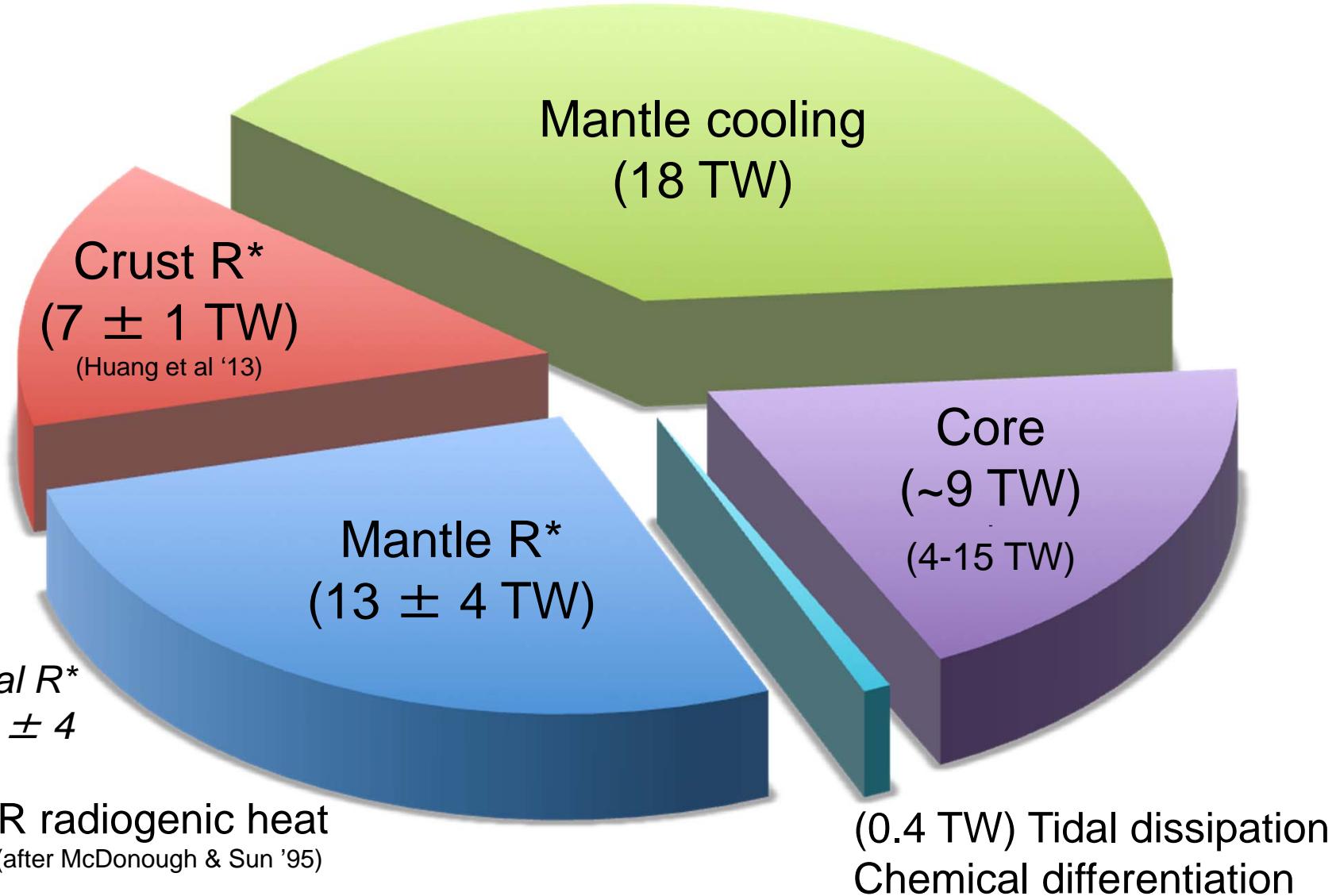
internal radiogenic heat?

Continental Crust
(Huang et al 2013)



■ Upper Crust
■ Middle Crust
■ Lower Crust

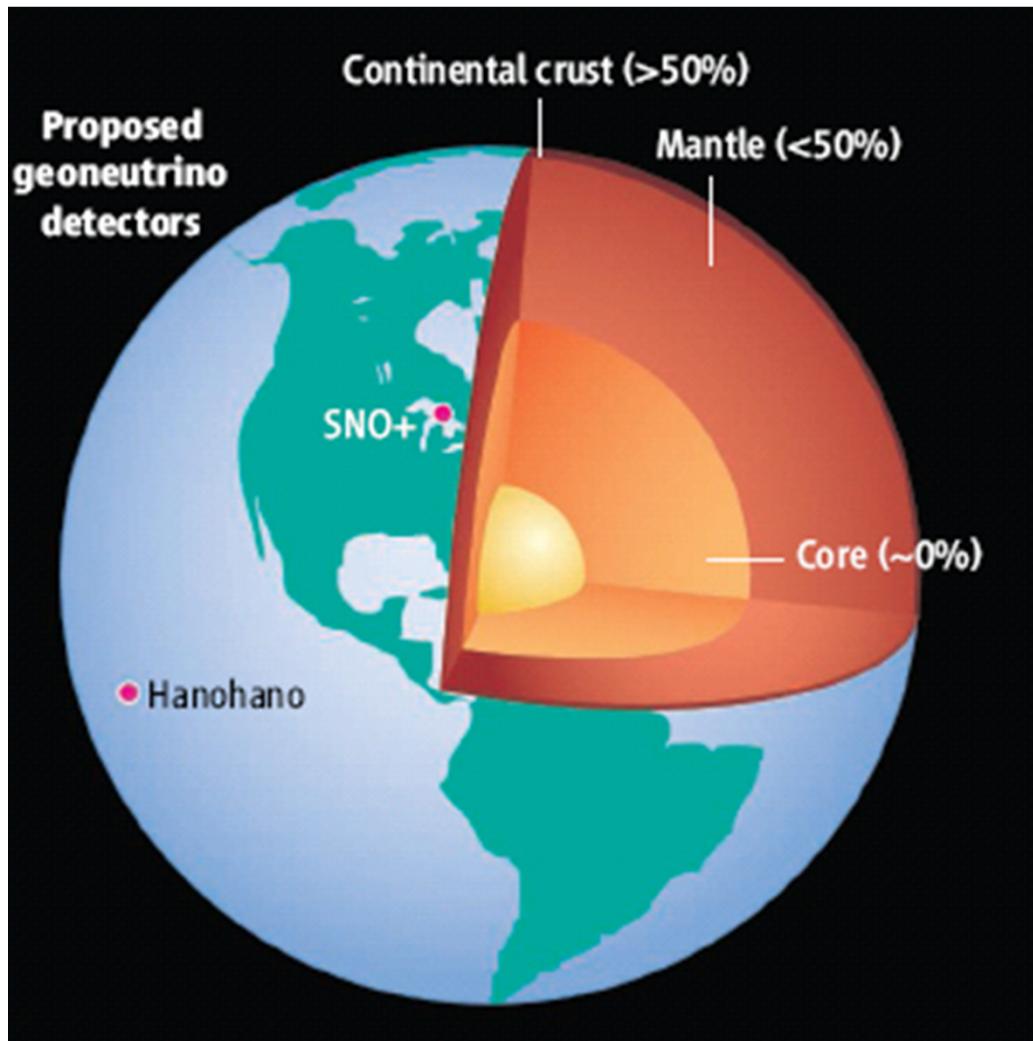
Earth's surface heat flow 46 ± 3 (47 ± 1) TW



after Jaupart et al 2008 *Treatise of Geophysics*

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

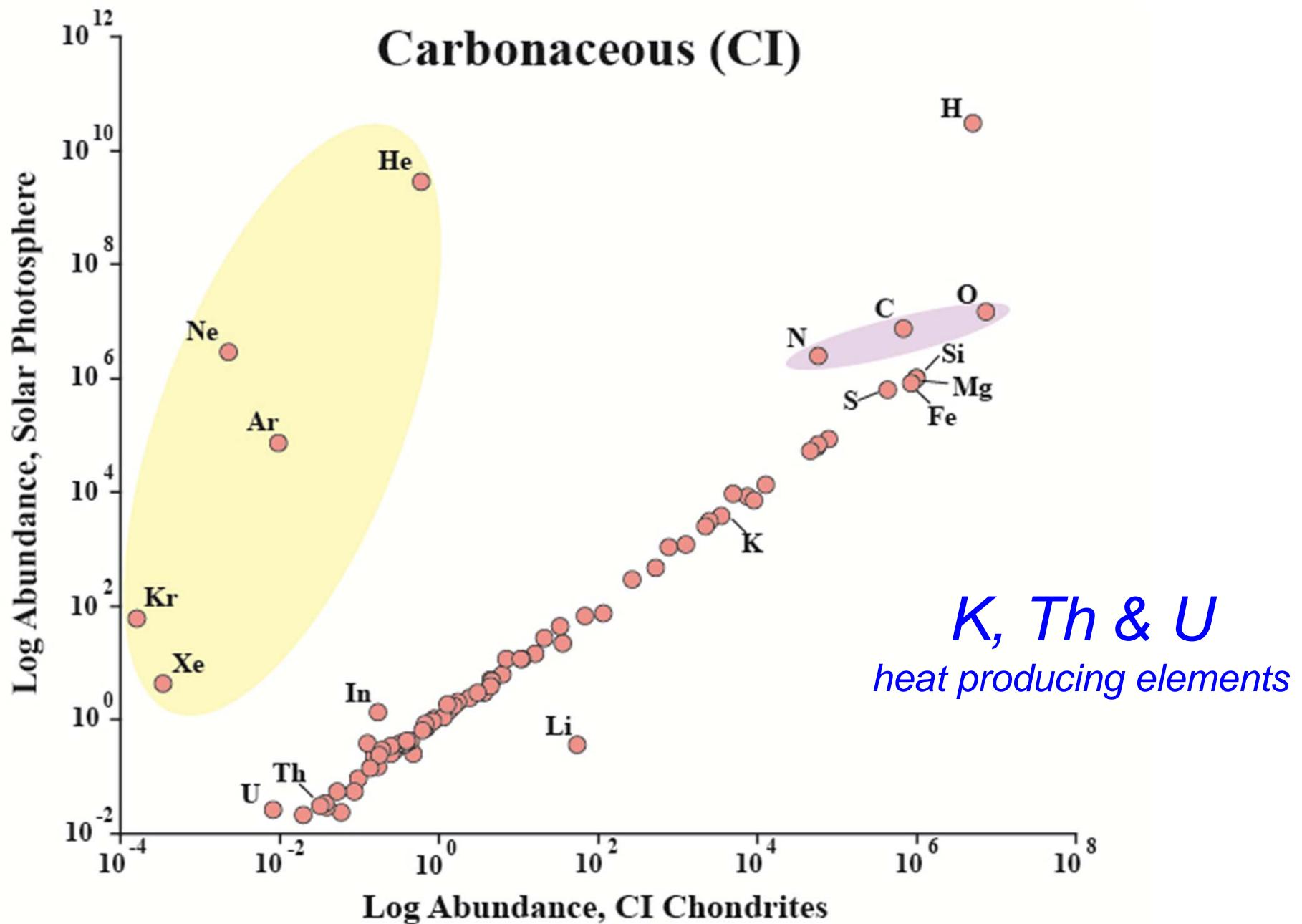
*Turcotte & Schubert (2002) 31 ng/g

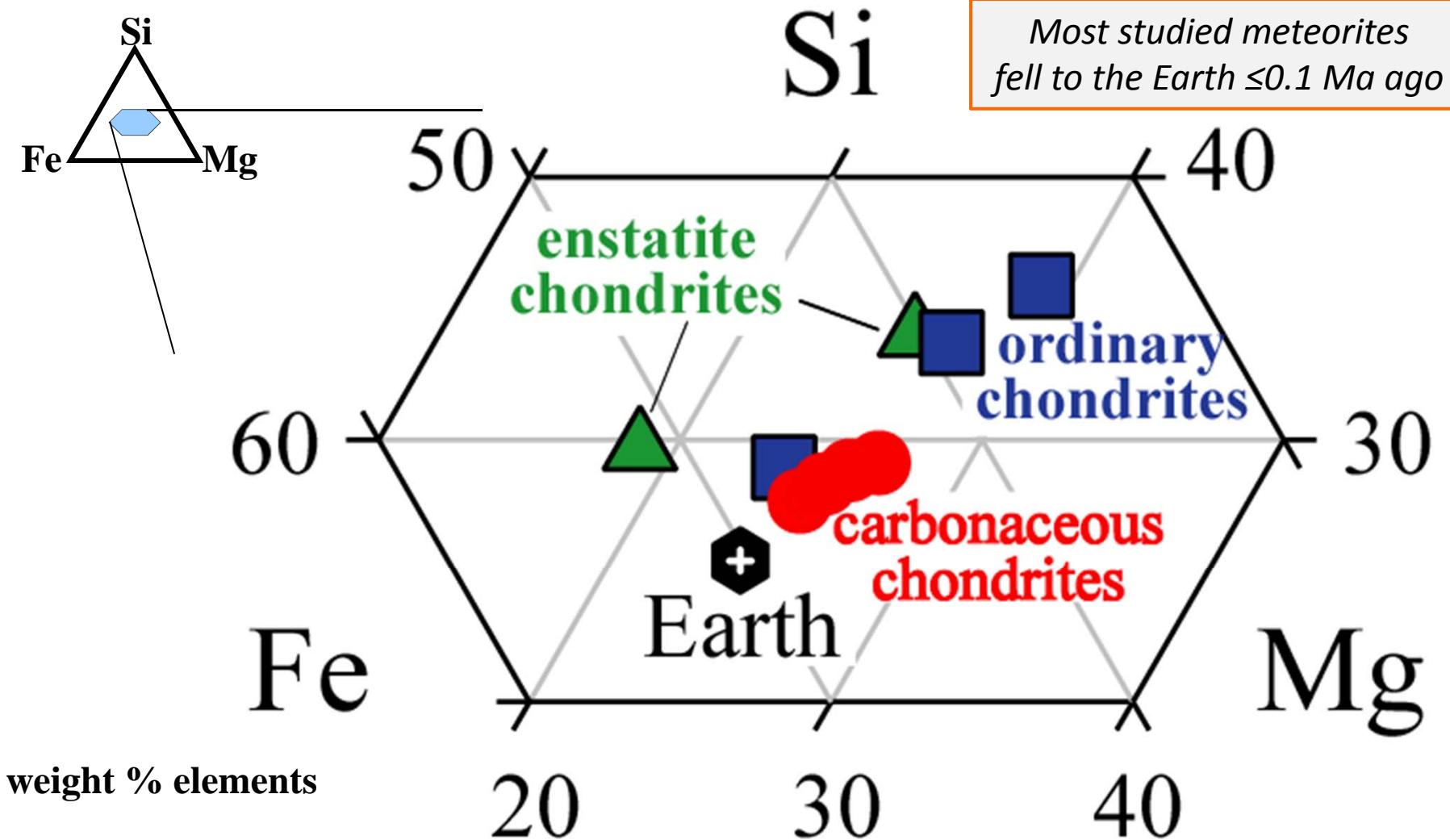
Continental Crust
1300 ng/g U

Mantle
~12 ng/g U

*Chromatographic separation
Mantle melting & crust formation*

Sun and Chondrites are related





Moles Fe + Si + Mg + O = ~93% Earth's mass
 (with Ni, Al and Ca its >98%)

Mg/Si variation in a nebula disk



Forsterite

- high temperature
- early crystallization
- high Mg/Si
- fewer volatile elements



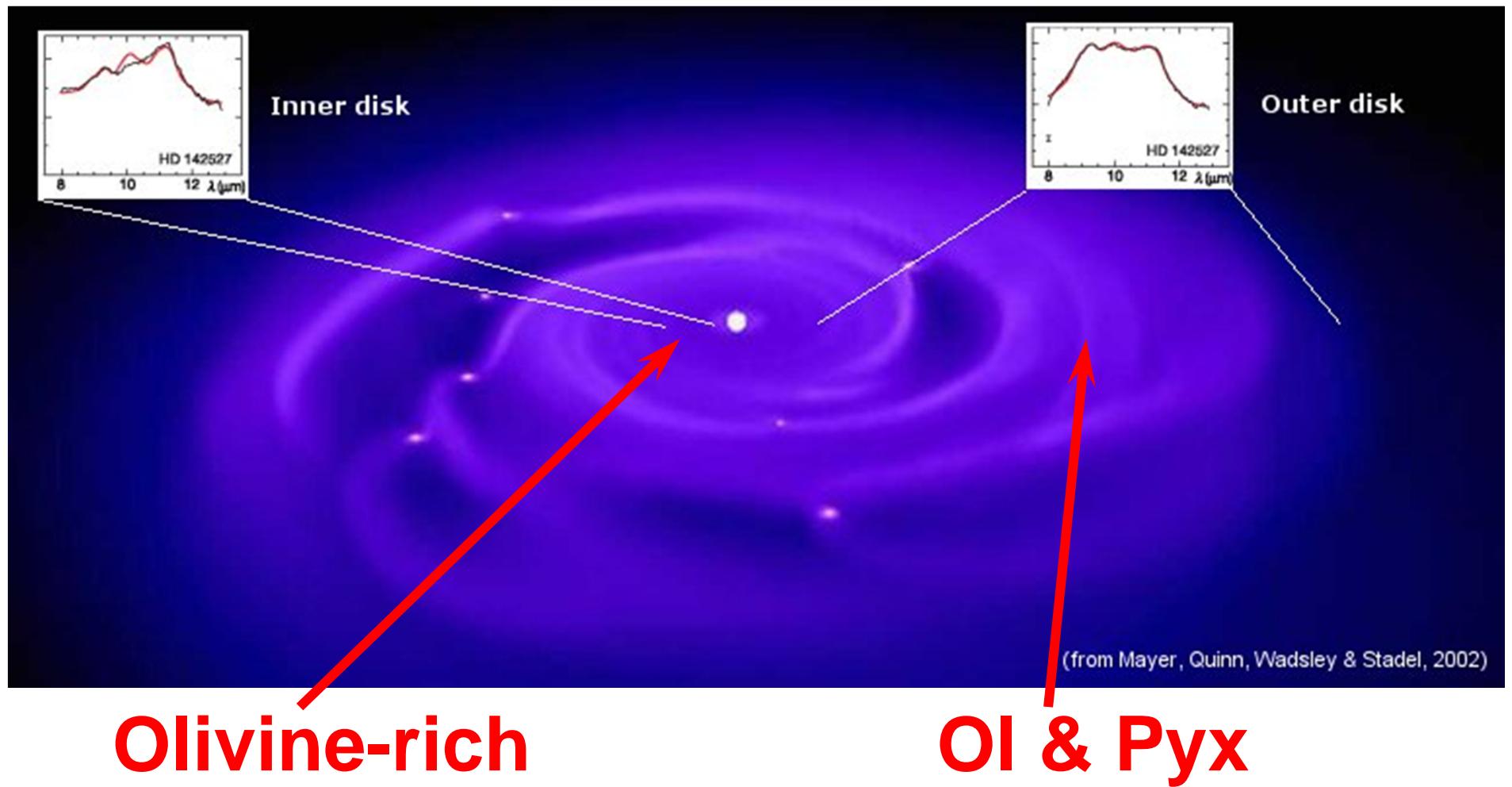
Enstatite

- lower temperature
- later crystallization
- low Mg/Si
- more volatile elements

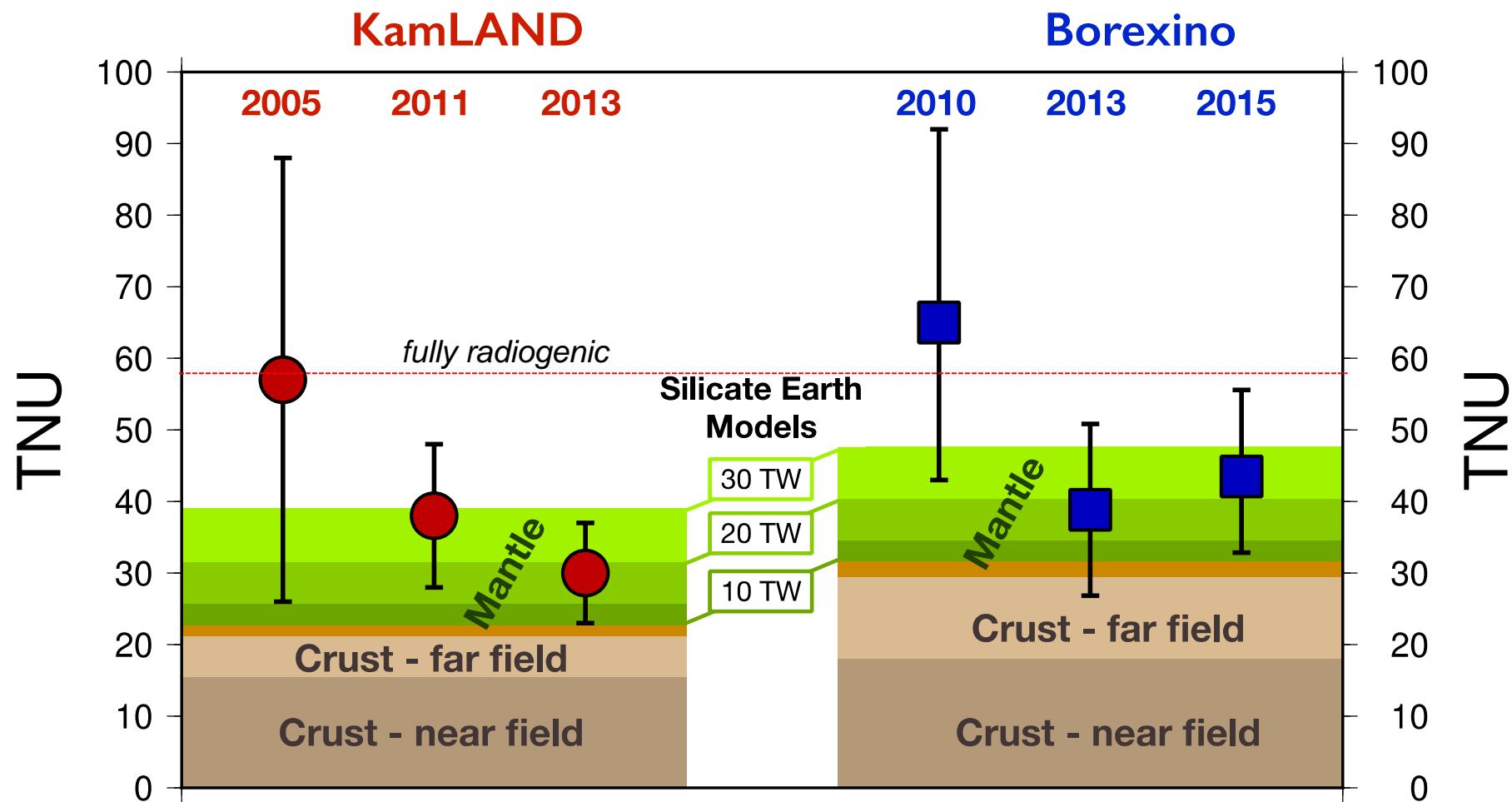
Inner nebular regions of dust to be highly crystallized,

Outer region of one star has

- equal amounts of **pyroxene** and **olivine**
- while the inner regions are dominated by **olivine**.



Summary of geoneutrino results



SILICATE EARTH MODELS

Cosmochemical: uses meteorites – 10 TW

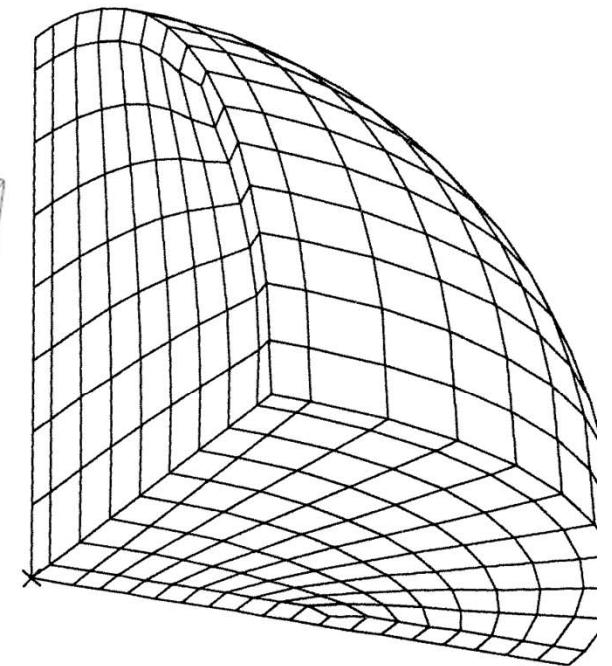
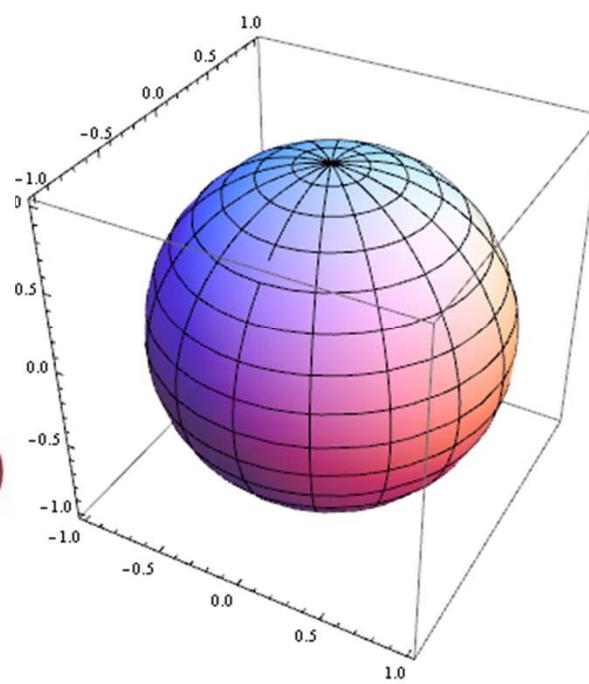
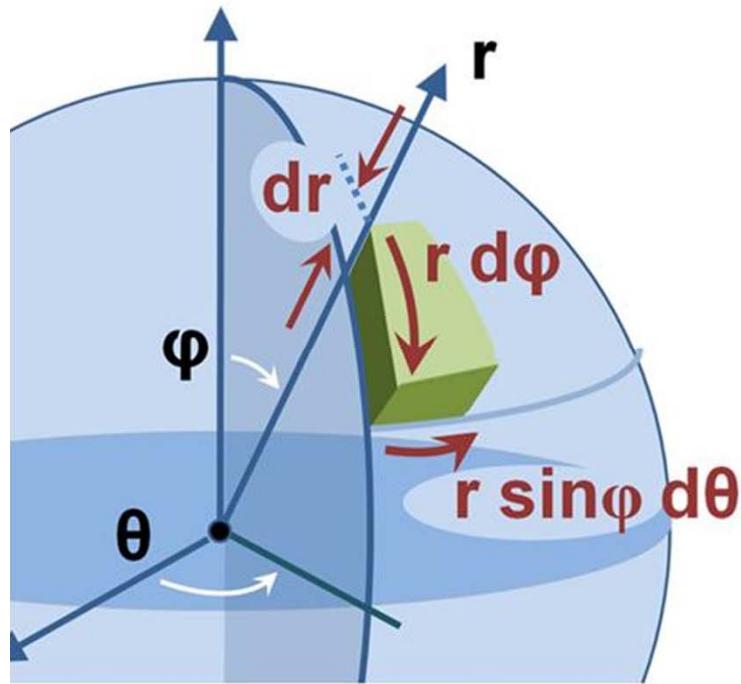
Geochemical: uses terrestrial rocks – 20 TW

Geodynamical: parameterized convection – 30 TW

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

Constructing a 3-D reference model Earth

assigning chemical
and physical states
to Earth voxels



Geoneutrino Flux on Earth Surface

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

Activity and number of produced geoneutrinos

Volume of source unit

Abundance and density of the source unit

Survival probability function

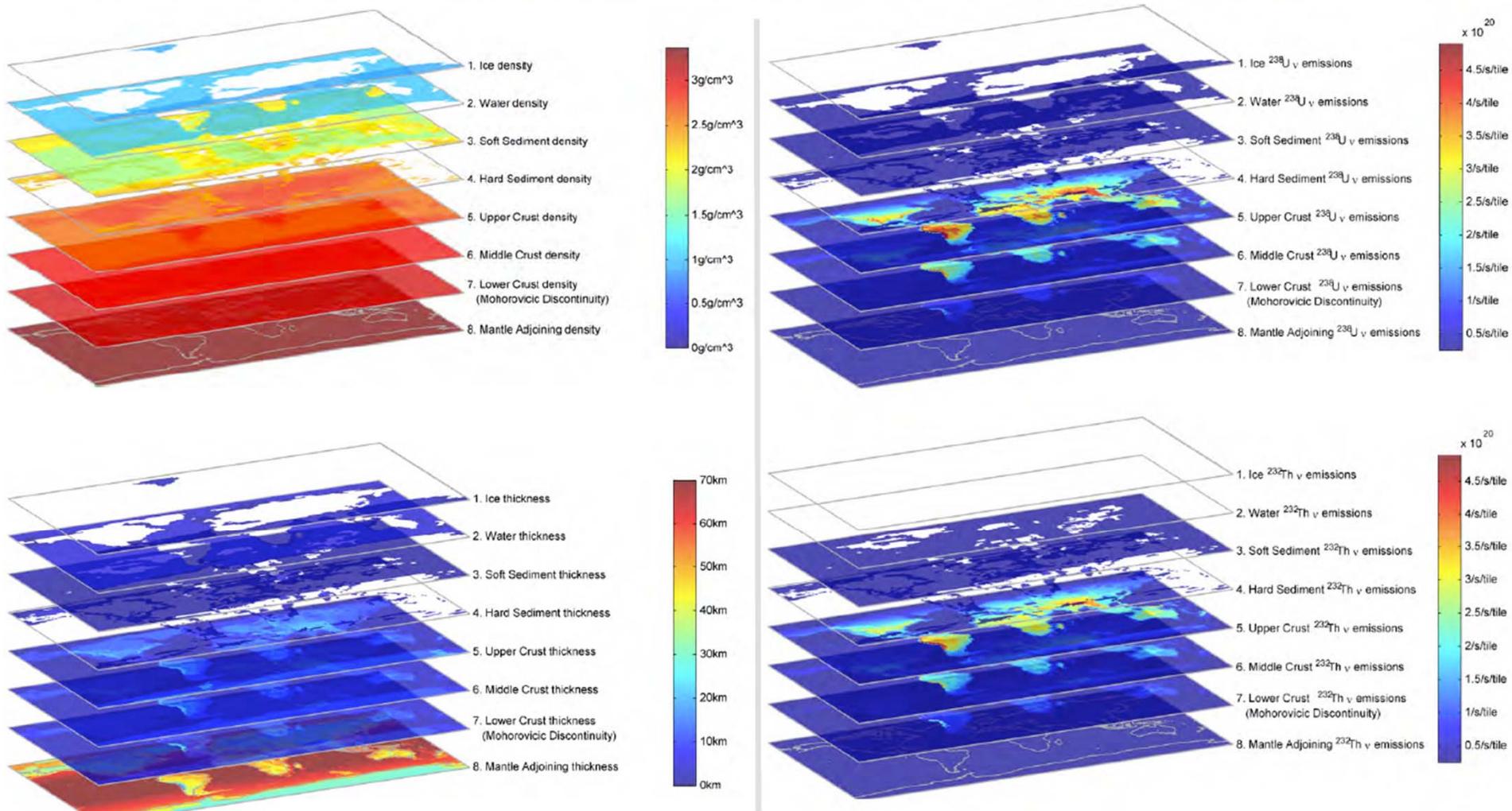
Distance between source unit and detector

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

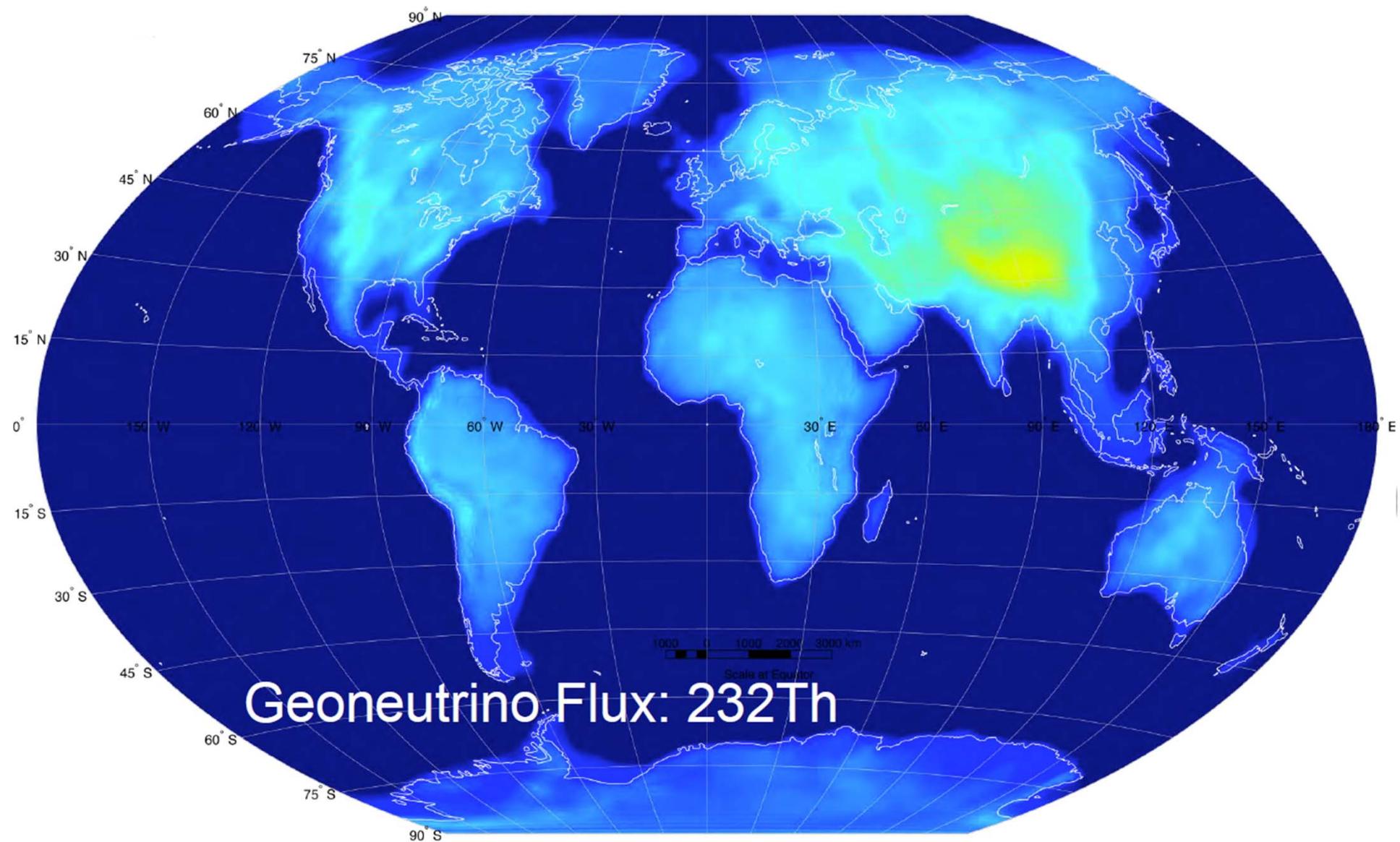
AGM2015: Antineutrino Global Map

Usman, Jocher, Dye, McDonough & Learned (2015) *Nature, Scientific Reports*, DOI: [10.1038/srep13945](https://doi.org/10.1038/srep13945)

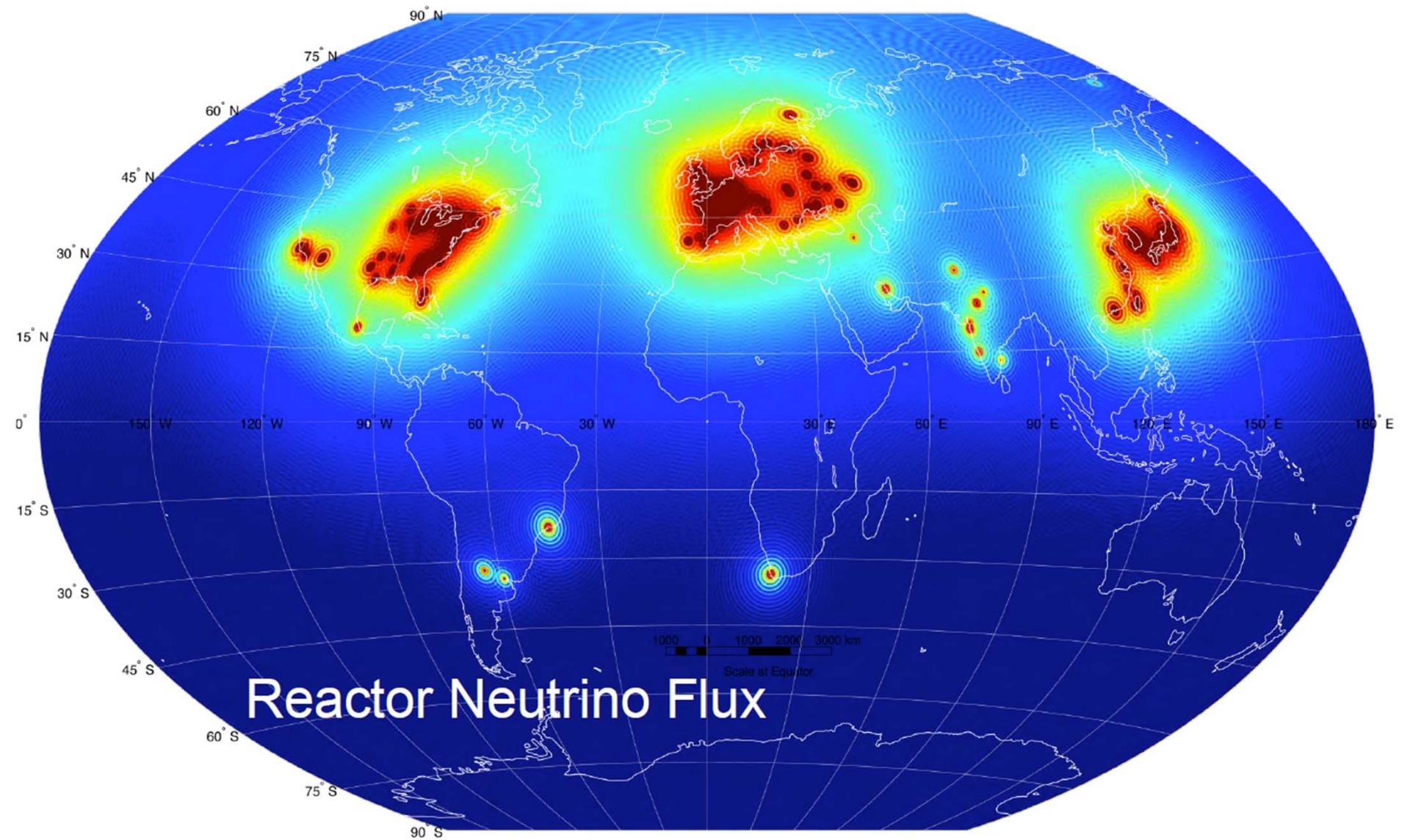
How do we model the Earth's Crust? CRUST 1.0



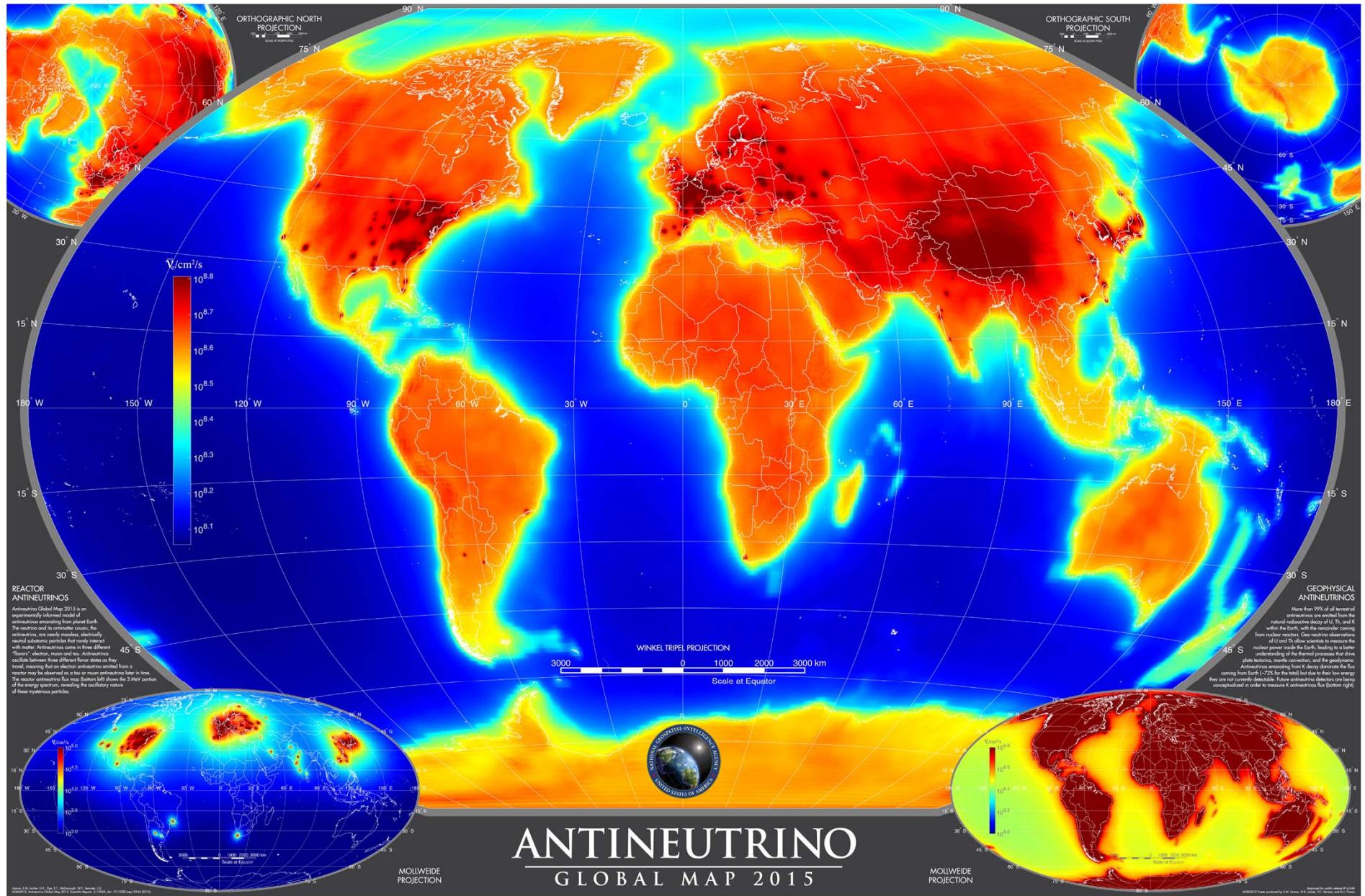
^{238}U - Geoneutrino Flux at the Earth Surface

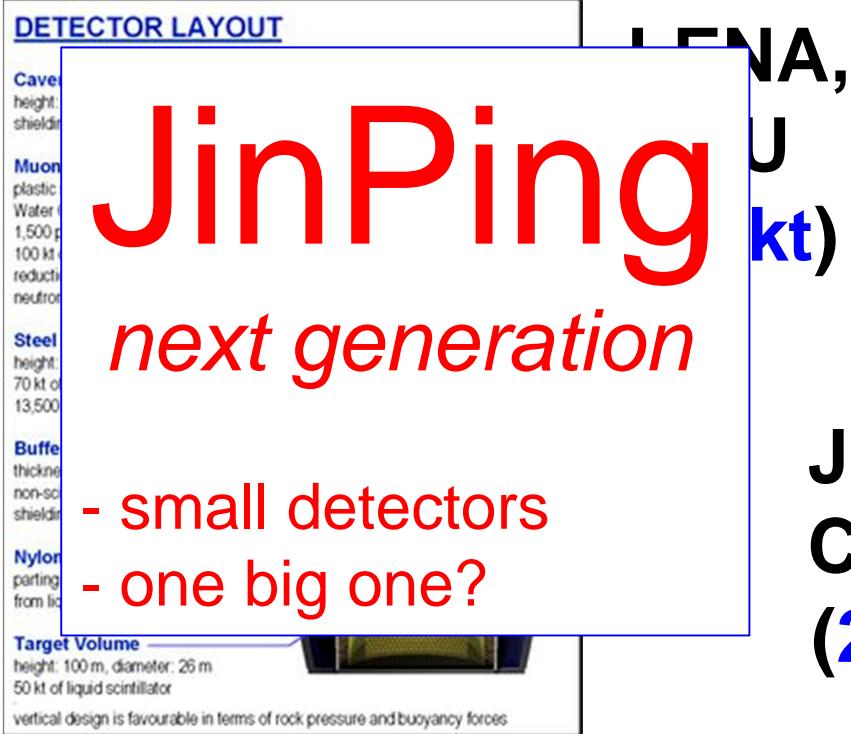


Nuclear Reactor Flux at the Earth Surface



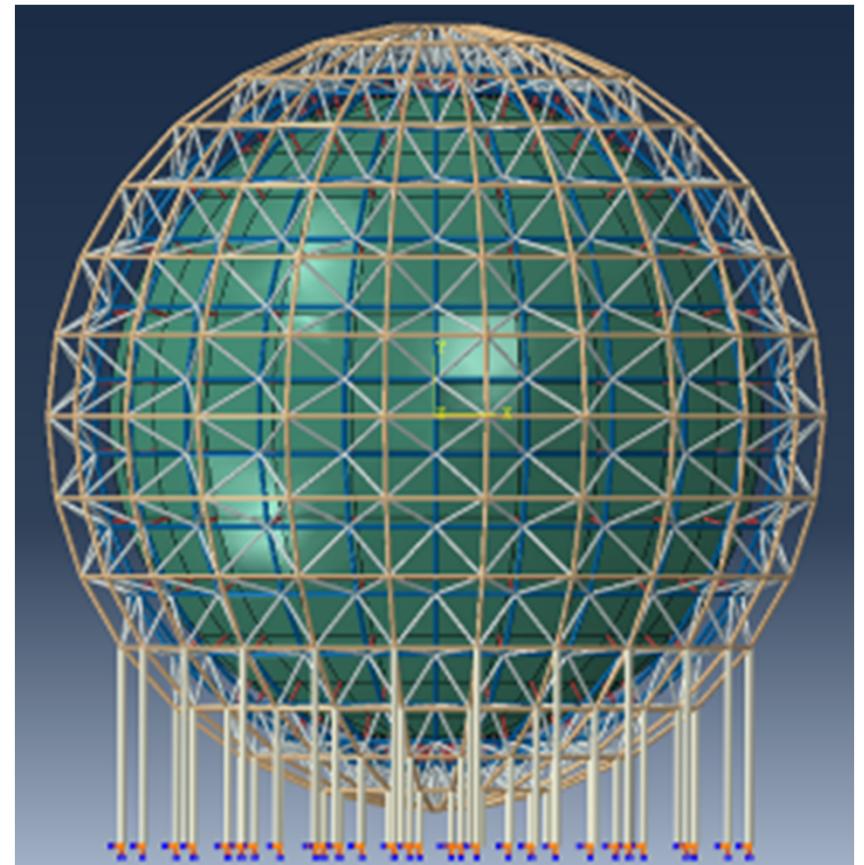
Antineutrino Map: geoneutrinos + reactor neutrinos



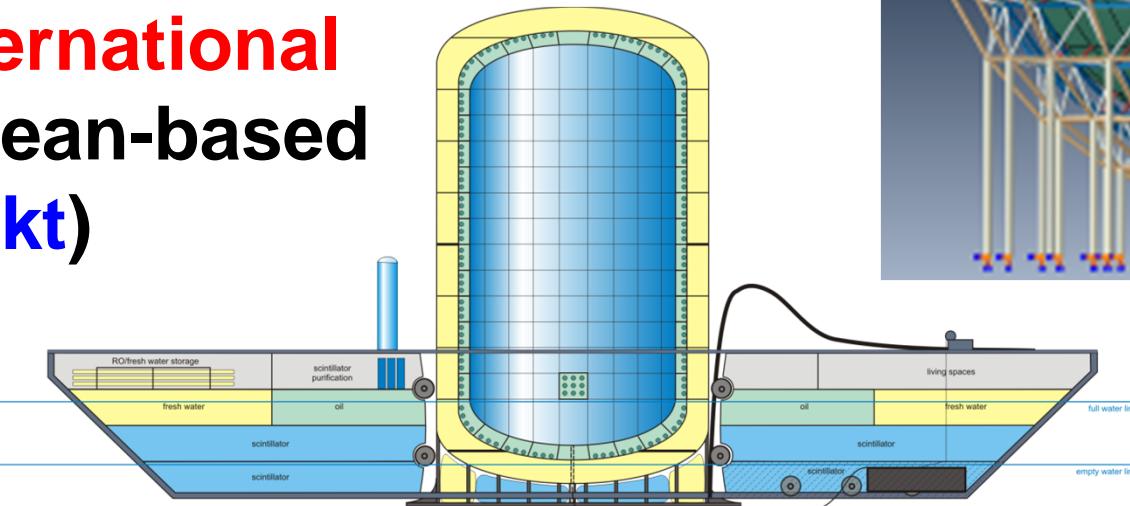


Future detectors?

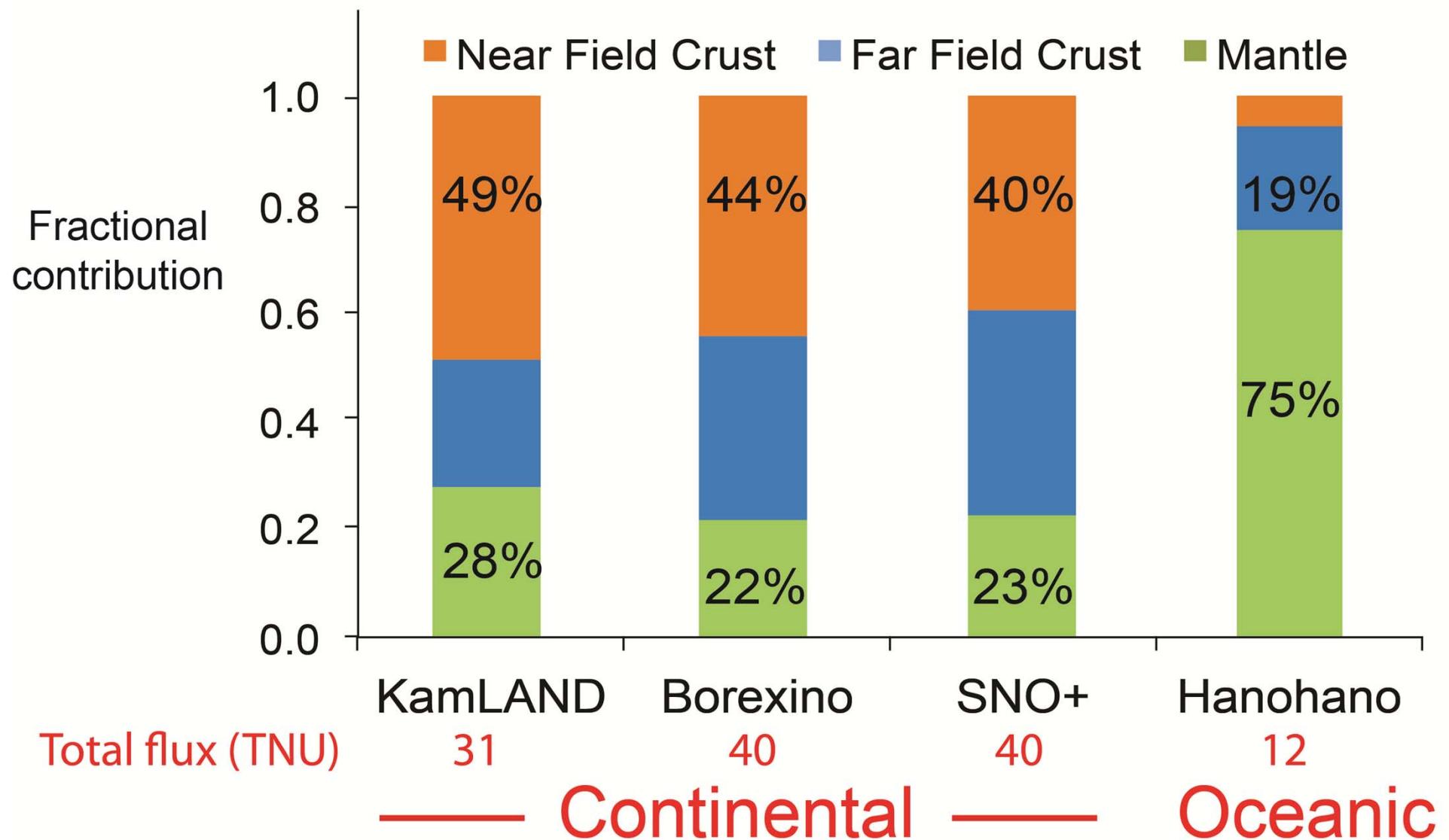
JUNO
China
(20kt)



Hanohano
International
ocean-based
(10kt)



Geoneutrino contributions to detectors

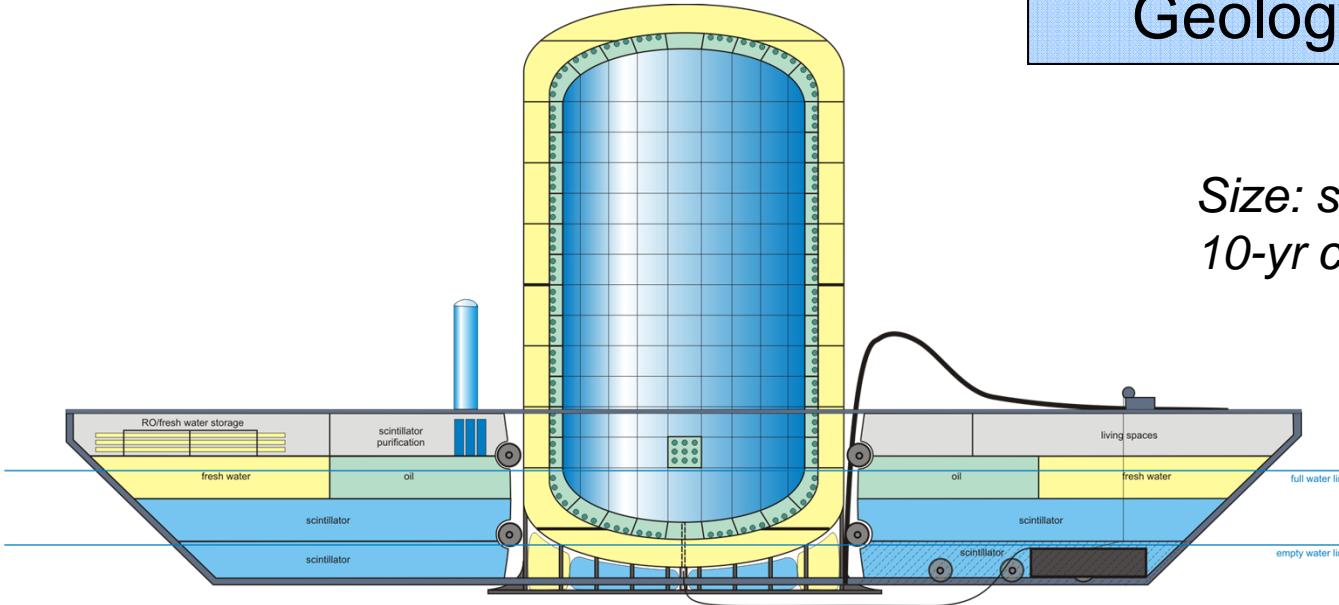


Near Field: six closest $2^\circ \times 2^\circ$ crustal voxels

Far Field = bulk crust – near field crust

Hanohano

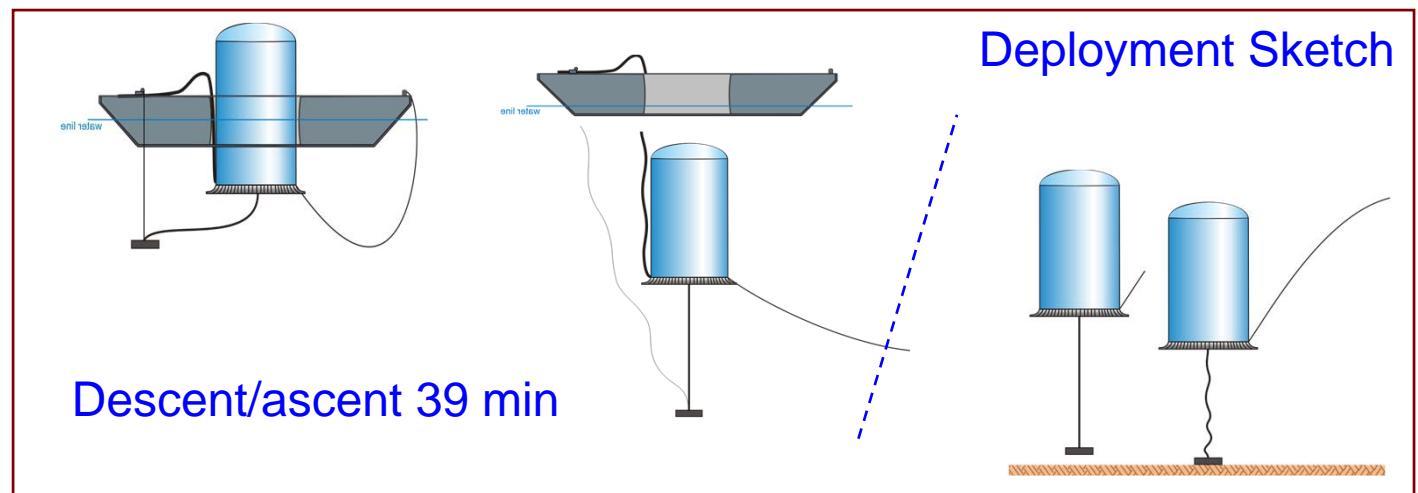
An experiment with joint
interests in Physics,
Geology, and Security



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

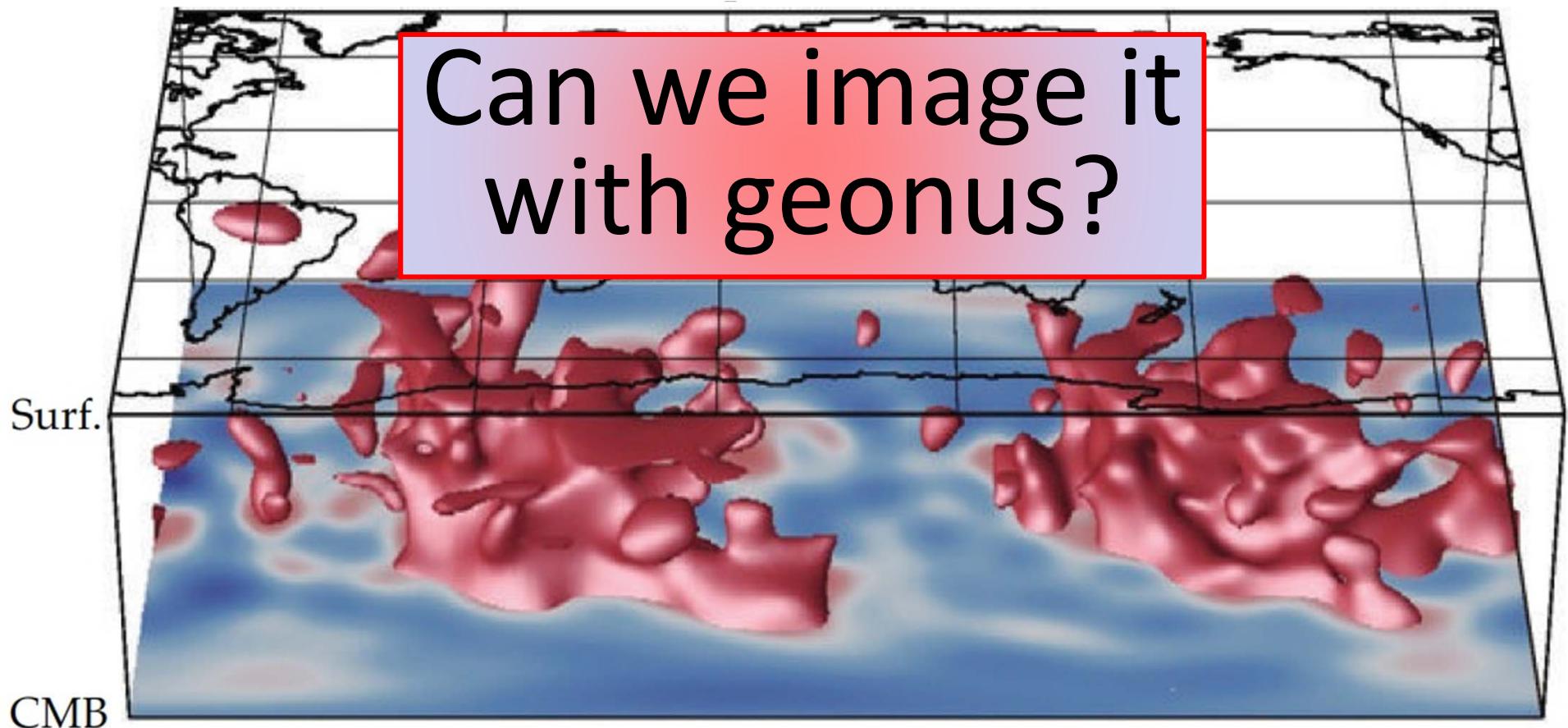
Size: scalable from 1 to 50 kT
10-yr cost est: \$250M @ 10 kT

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



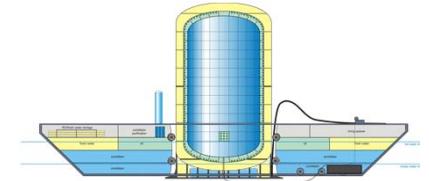
What's hidden in the mantle?

Seismically slow “red” regions in the deep mantle

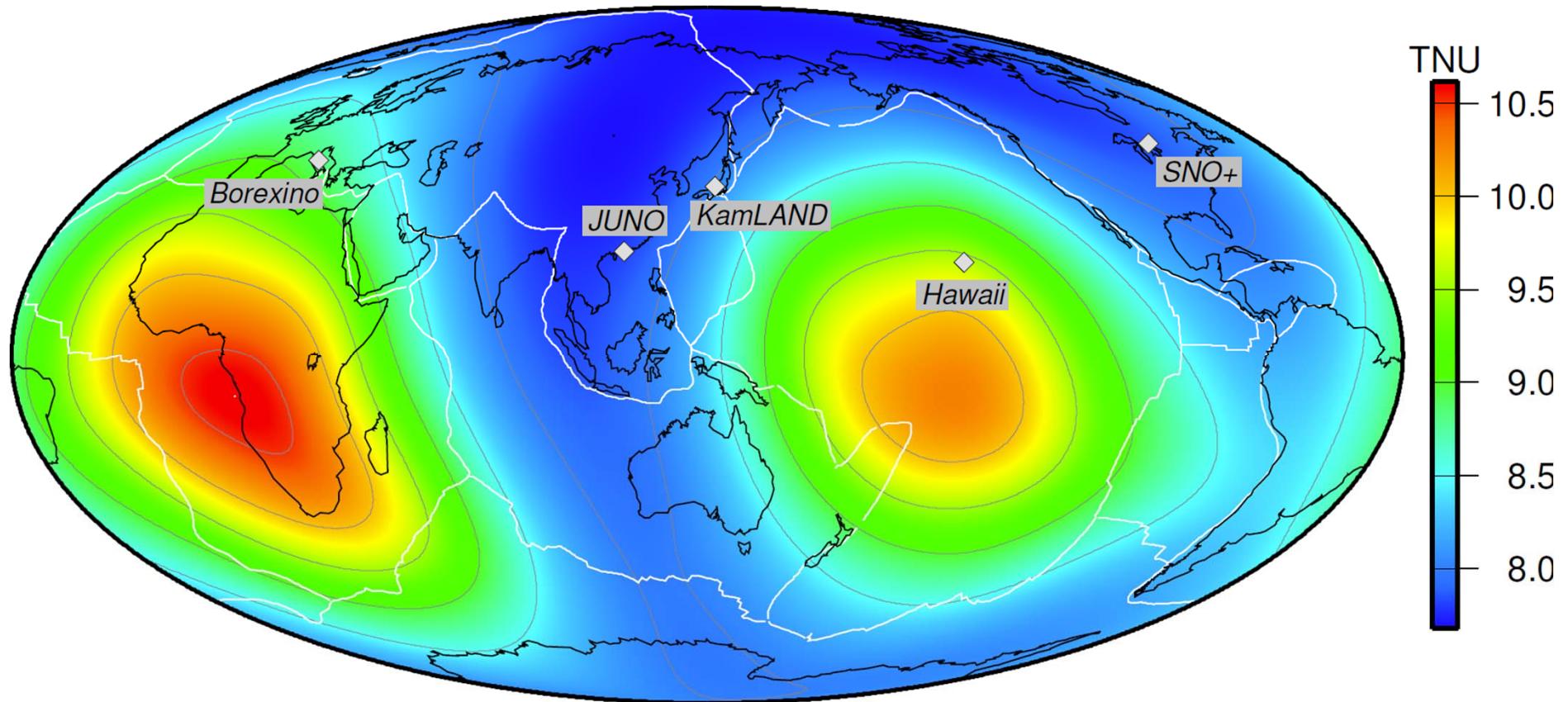


Ritsema et al (*Science*, 1999)

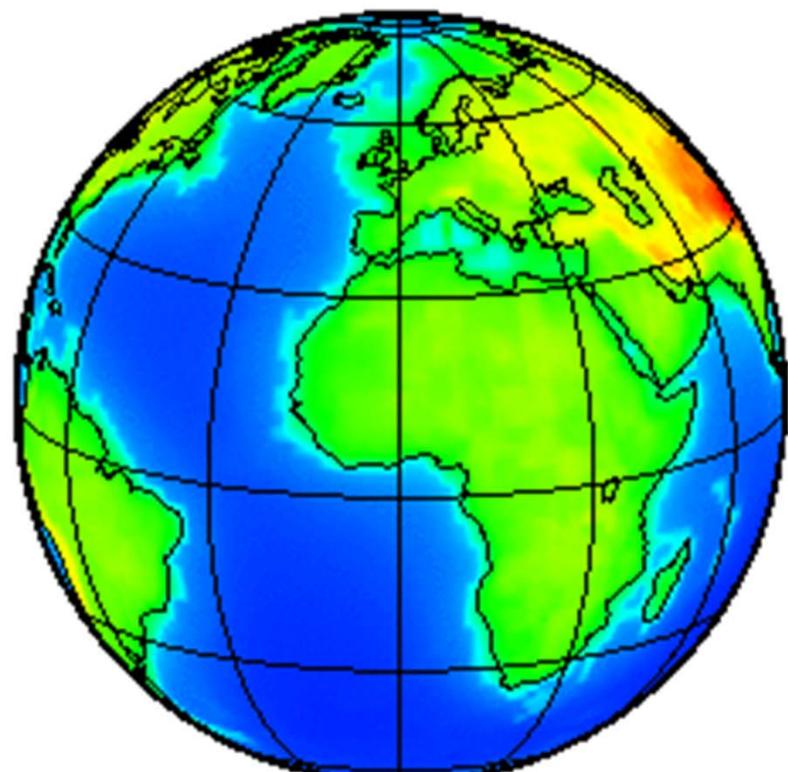
Testing Earth Models



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



Šrámek et al (2013) *EPSL* [10.1016/j.epsl.2012.11.001](https://doi.org/10.1016/j.epsl.2012.11.001); [arXiv:1207.0853](https://arxiv.org/abs/1207.0853)

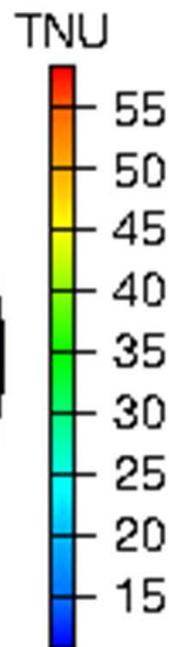


Yu Huang et al (2013) G-cubed [arXiv:1301.0365](https://arxiv.org/abs/1301.0365)
[10.1002/ggge.20129](https://doi.org/10.1002/ggge.20129)

Mantle flux at the Earth's surface

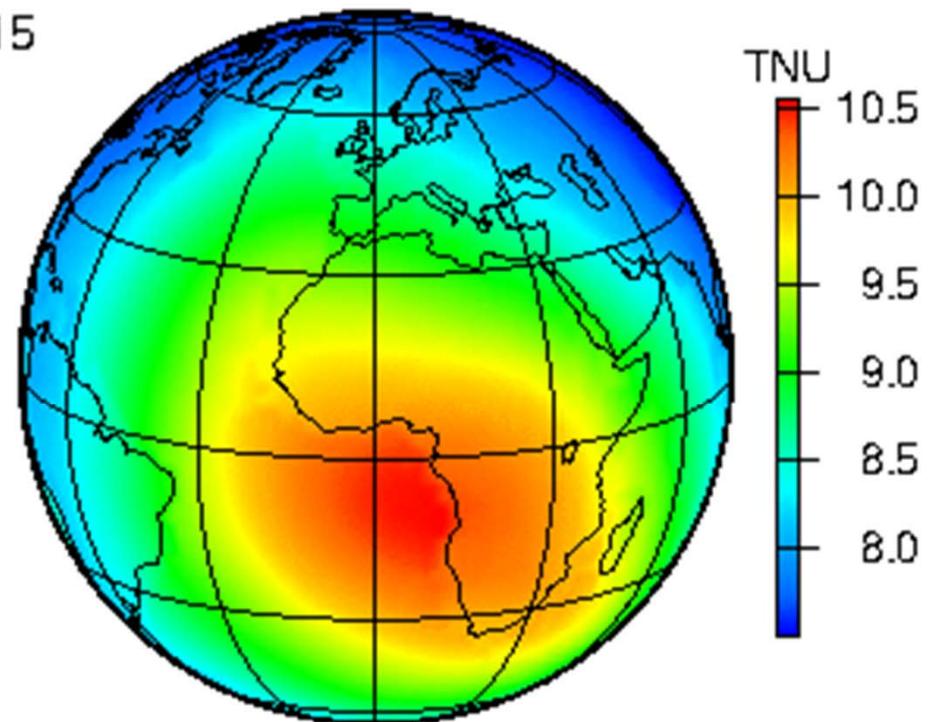
*dominated by
deep mantle structures*

Predicted geoneutrino flux



Total flux at surface

*dominated by
Continental crust*



Šrámek et al (2013) EPSL [10.1016/j.epsl.2012.11.001](https://doi.org/10.1016/j.epsl.2012.11.001); [arXiv:1207.0853](https://arxiv.org/abs/1207.0853)

SUMMARY

Earth's radiogenic (**Th & U**) power

23 - 36 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 **GEO-NEUTRINO** experiments:

- **SNO+** online 2017 ☺
- **JUNO**: 2020, good experiment, big bkgd, geonu ...
- **Hanohano**: this is how to look at the mantle-only
- **JinPing**: 20XX, excellent experiment, low bkgd, big issues

IMPORTANT CONSIDERATIONS: WbLS and directionality

Building the community - *the next generation*

Fostering future
collaboration
between Geology
and Particle Physics



ISAPP International Summer Institute

Using Particle Physics to understand and image the Earth
Geoneutrinos, Muonography, Cosmogenic Nuclides

L'Aquila – July 11-21, 2016
Gran Sasso Science Institute
Viale Francesco Crispi, 7 – 67100 L'Aquila (Italy)

Addressed to physicists and geologists
Lectures and activities
Student poster session
Pre-school for the two audiences
(physicists and geologists) to acquire
the know-how needed to follow the
school.
Participation limited to 25 students
selected on the CV basis

Organizing Committee
Matteo Agostini(GSSI)
Gianpaolo Bellini (Milan Univ. and INFN)
Stefano Davini (GSSI)
Livia Ludhova (RWTH Aachen Univ. and FZ Jülich IKP-2)
Fabio Mantovani (Ferrara Univ. and INFN)
Simone Marcocci (GSSI)
Nicola Rossi (LNGS)
Francesco Vissani (GSSI and LNGS)

Secretariat responsible
Irene Sartini (GSSI)

Website: <http://agenda.infn.it/event/SIPP2016>
Contact: isapp.summerinstitute@gssi.infn.it

Scientific committee
Gianpaolo Bellini (Milan Univ. and INFN – co-chairman)
Mark Chen (Queen Univ.)
Eugenio Coccia (GSSI) and Rome 2 Univ.)
Steven Dye (Hawaii Pacific University)
Gianni Fiorentini (Ferrara Univ. and INFN))
Antoine Kouchner (APC – Paris VII Univ.)
Aldo Ianni (Canfranc Laboratory and LNGS)
Kunio Inoue (Tohoku University)
Vedran Lekic (Maryland Univ.)
Livia Ludhova (RWTH Aachen Univ. and FZ Jülich IKP-2)
Fabio Mantovani (Ferrara Univ. and INFN)
Frank Marzano (Rome "La Sapienza" Univ.)
William McDonough (Maryland Univ. – co-chairman)
Gioacchino Ranucci (Milan INFN)
Paolo Strolin (Naples Univ. and INFN)
Taku Tsuchiya (Ehime Univ.)
Francesco Vissani (GSSI and LNGS)
Hiroko Watanabe (Tohoku Univ.)
and
the ISAPP Scientific Committee



GRAN SASSO
SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare



Fellowships for the living expenses in
L'Aquila can be assigned, if requested,
on the CV basis

