Using geoneutrinos to constrain the Earth's composition and its heat production

William F. McDonough
Research Center of Neutrino Sciences, and Earth Sciences, Tohoku University, Sendai, JAPAN
and
Geology, University of Maryland, College Park, MD, USA

Make geoneutrinos work for geosciences!

- Measuring amount of Th & U and Th/U in the Earth
- What is Th & U content of the JUNO crust
- What is happening in the lower crust

Understand the Continental Crust and its Composition

- How does JUNO help?
  - Define unknowns

Research Agenda: estimating JUNO flux

Predicting the geoneutrino flux at JUNO detectors using global geology models with LITHO1.0, & bulk crust compositions

Developing local models based on available data

Working with Chinese geoscientists to get data

Proximity: assessing added science from 3 detectors, all within a mantle depth (~3000 km) from each other

KamLAND - JUNO - Jinping

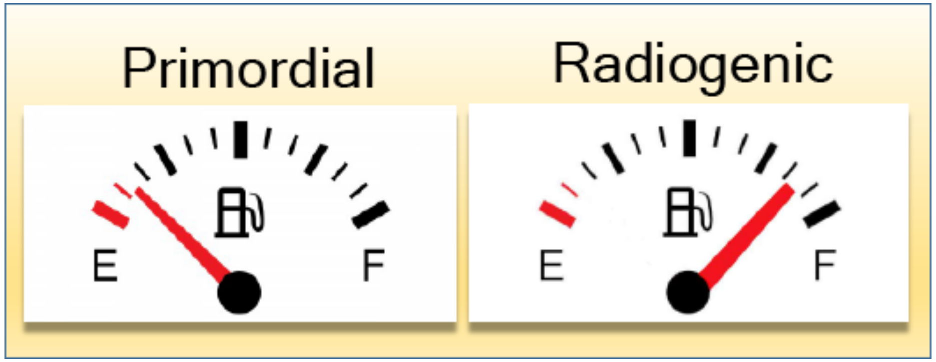
Defining the geological potential of a JUNO detector

2 variables: exposure time vs energy resolution

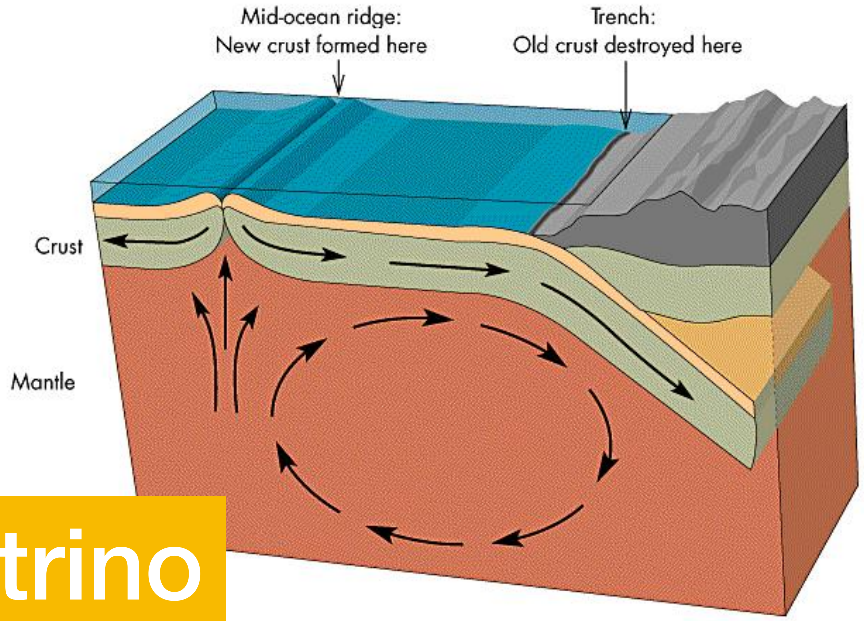
How much fuel is left to drive Plate Tectonics?

46 TW

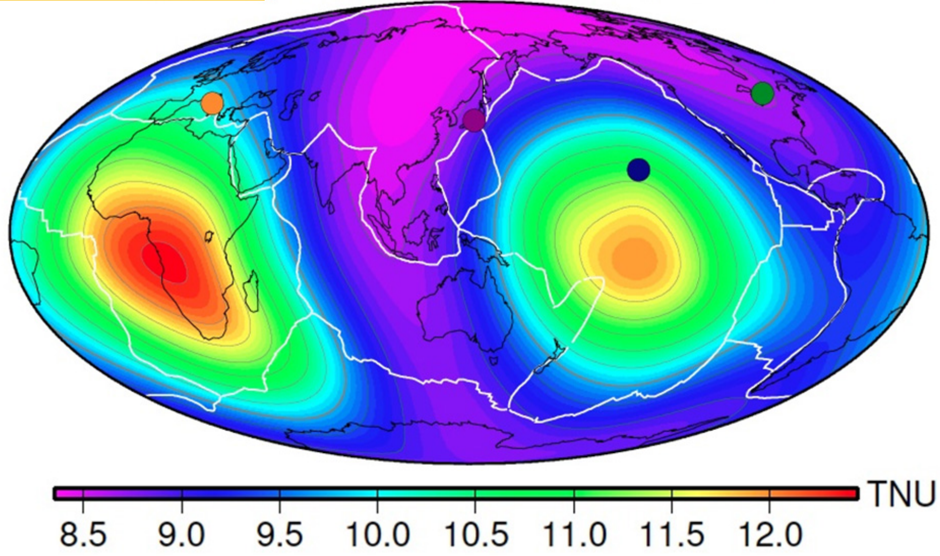
?



Geoneutrino detection



geoneutrino flux from $^{238}U + ^{232}Th$



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

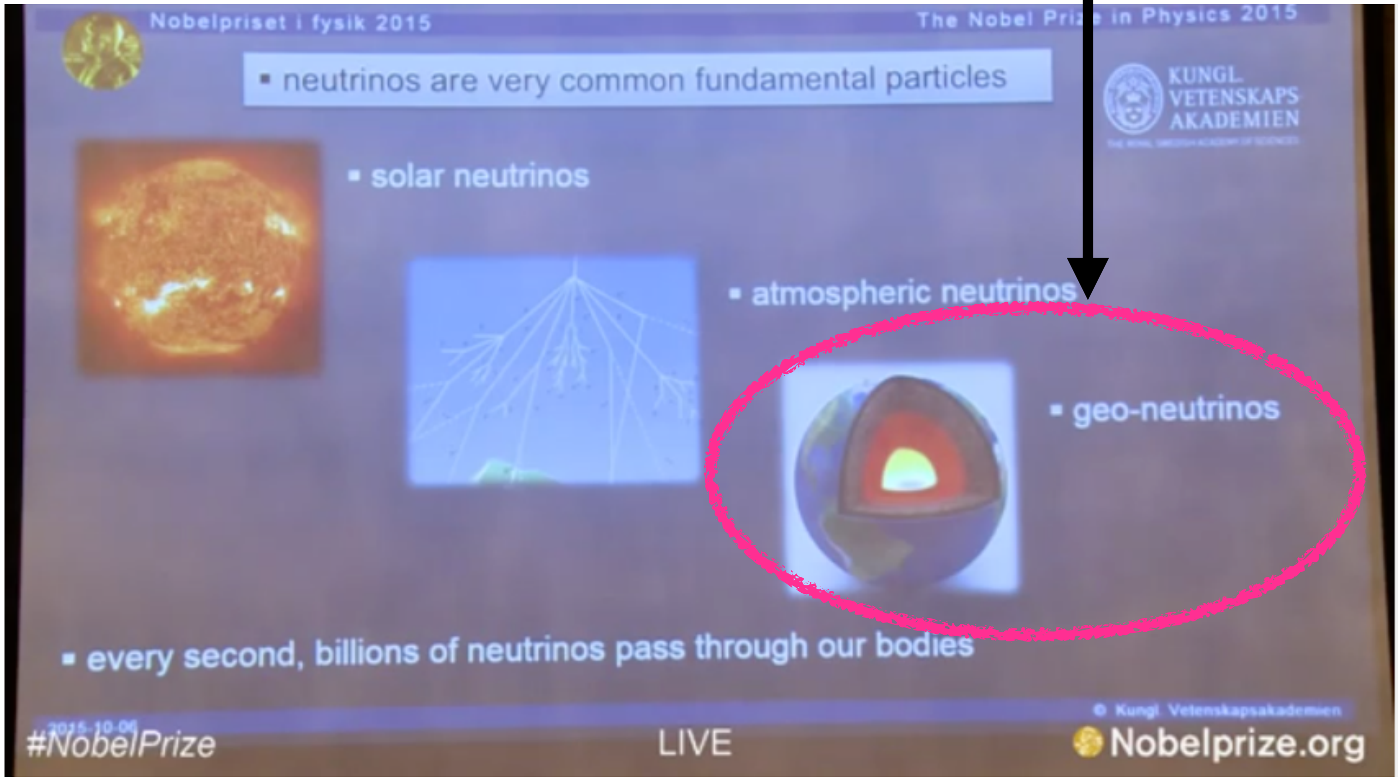
the future is… Geoneutrino studies

Importance of geo-neutrino

Nobel Prize Winners for 2015 Announced

Geoneutrinos!!!

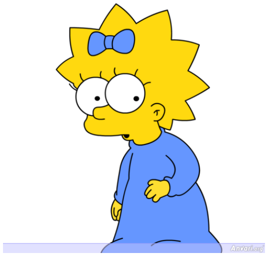
World Class Science


Nobelpriset i fysik 2015

The Nobel Prize in Physics 2015

- neutrinos are very common fundamental particles
- solar neutrinos
- atmospheric neutrinos
- geo-neutrinos
- every second, billions of neutrinos pass through our bodies

Relax

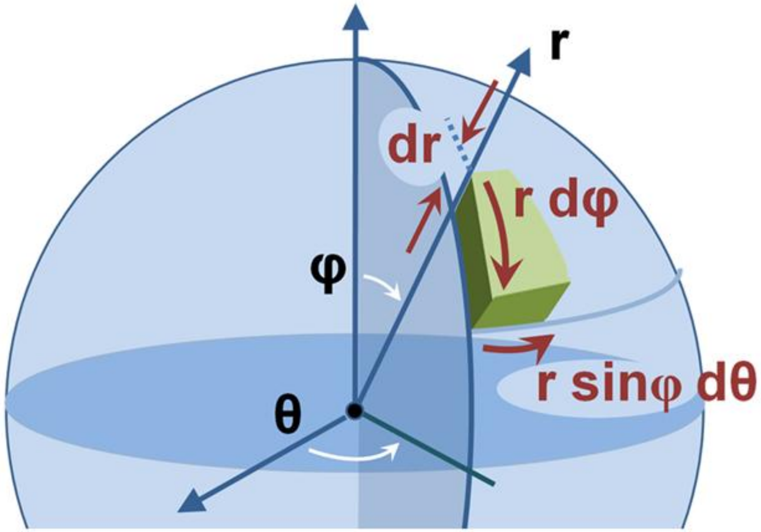


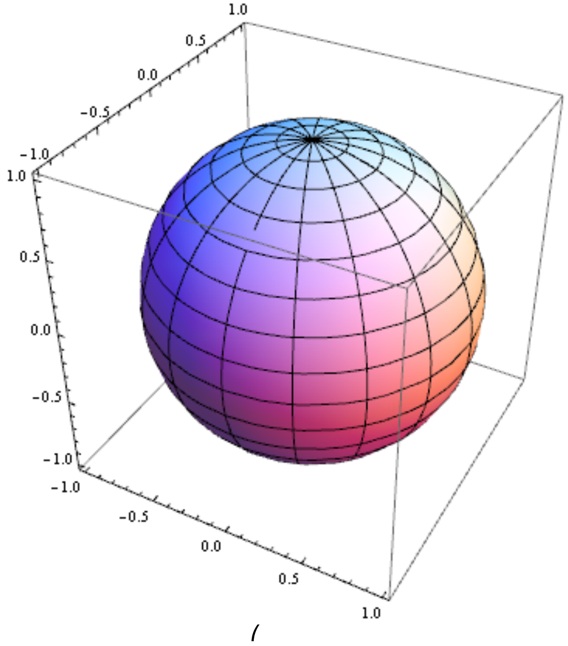
Neutrino Geoscience is holistic geology

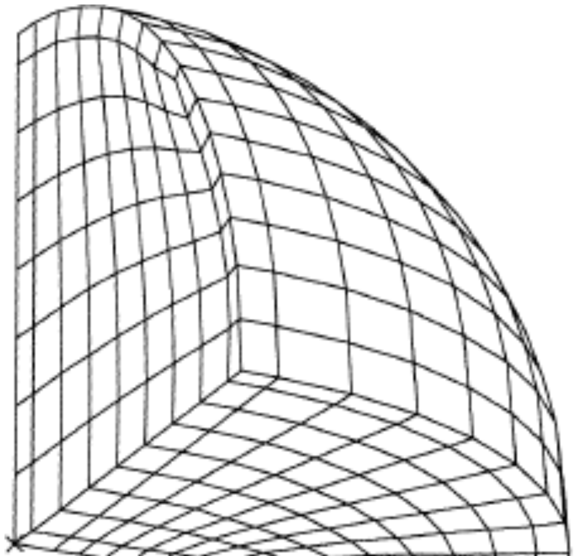
- it is not particle physics!

Constructing a 3-D reference model Earth

assigning chemical and physical states to Earth voxels





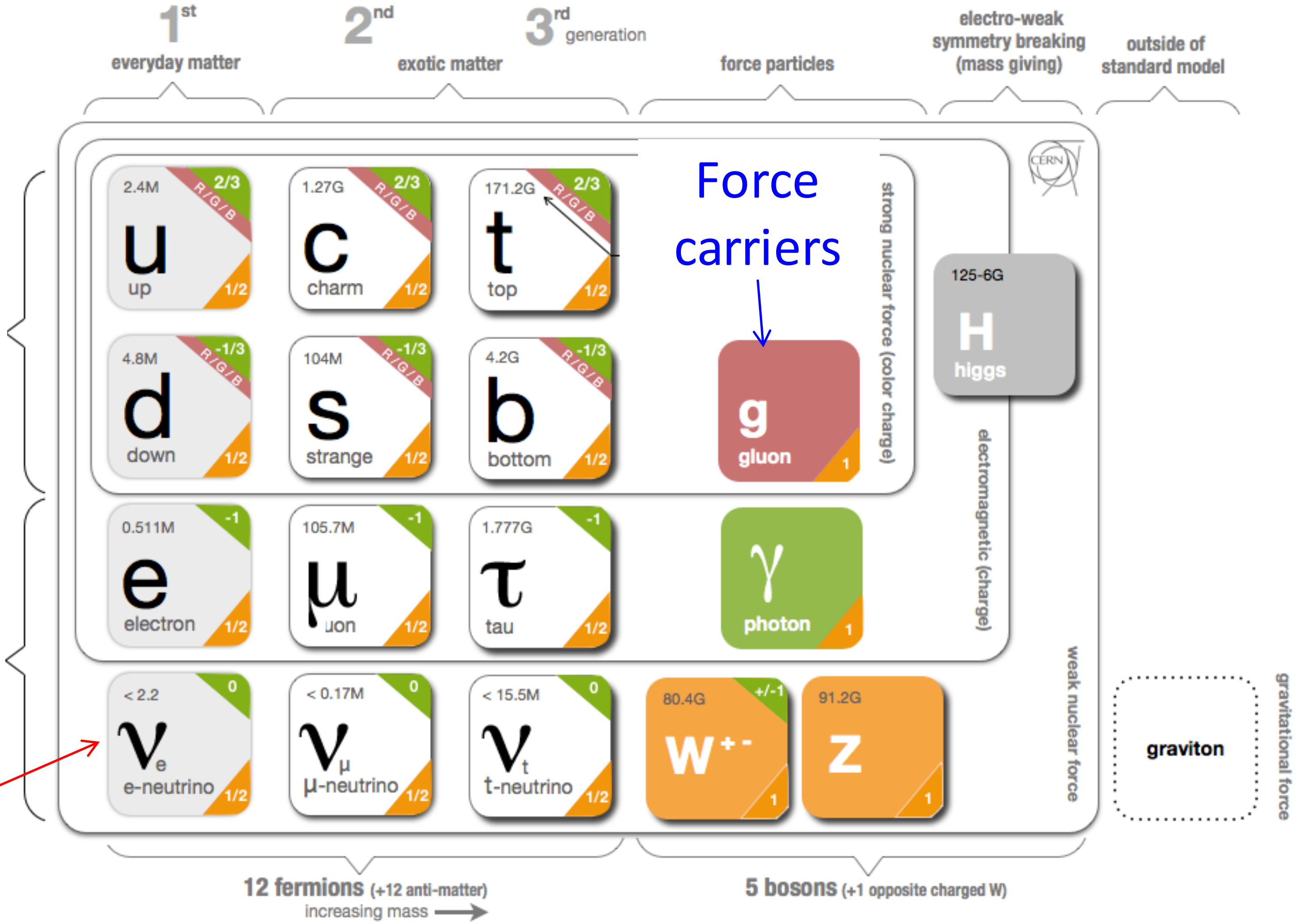


What are Geoneutrinos?

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

Geoneutrino flux

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



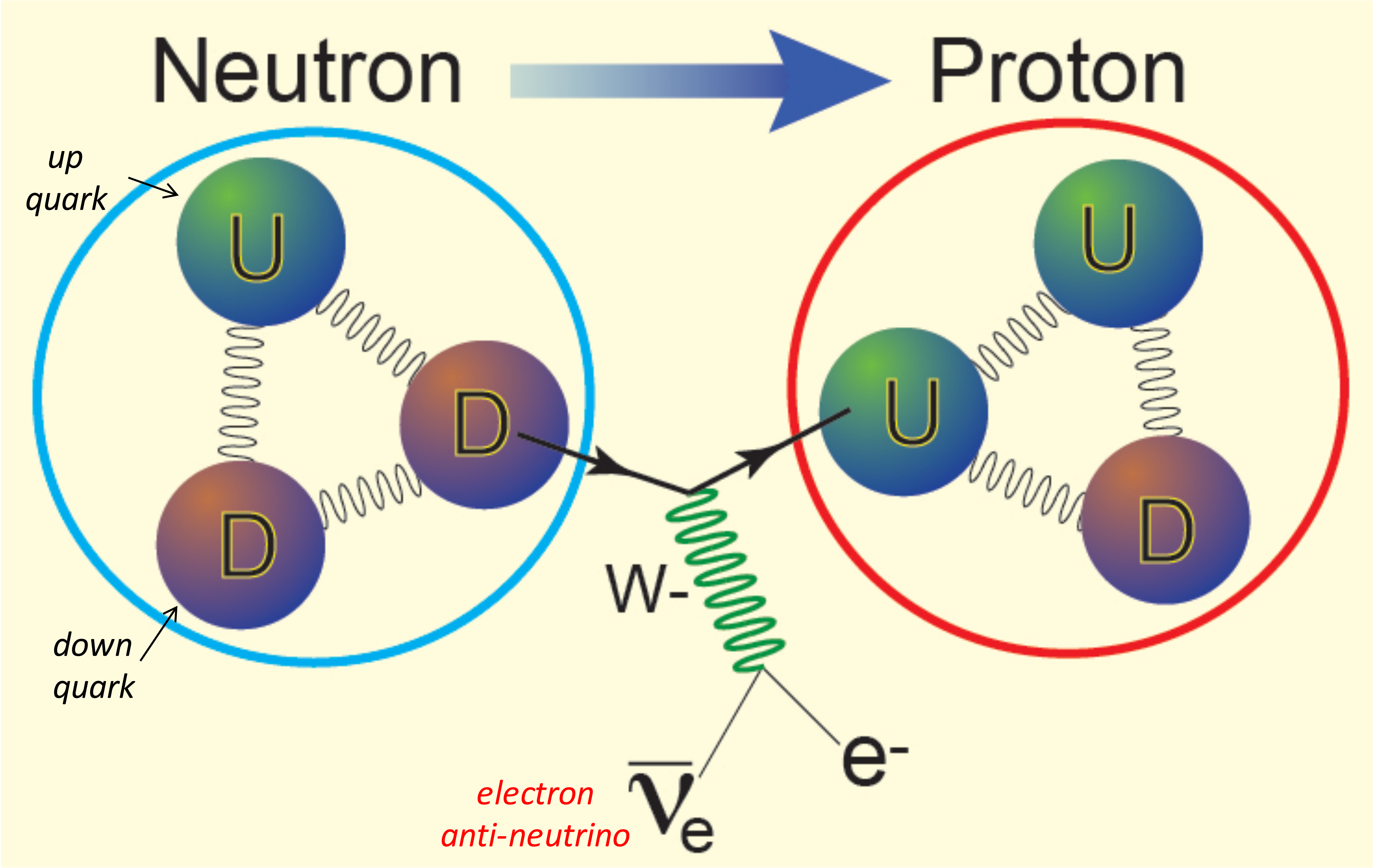
Quarks

Force
carriers

Leptons

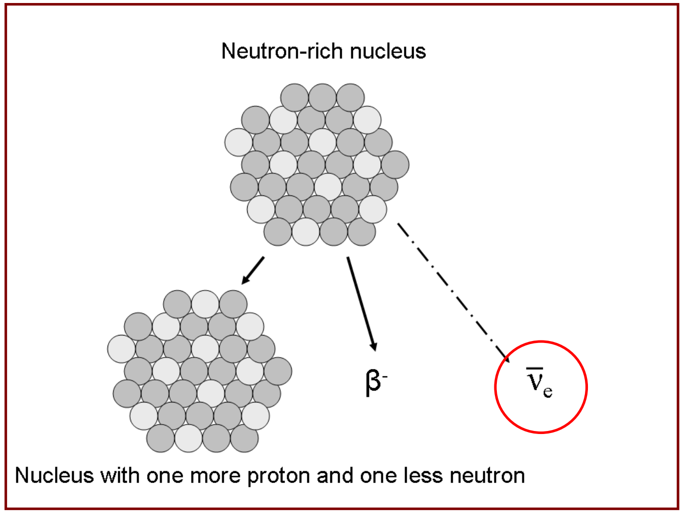
Anti-neutrino
-vs- neutrino

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



MeV-Scale Electron Anti-Neutrino Detection

Production in reactors
and natural decays


Neutron-rich nucleus

β^-

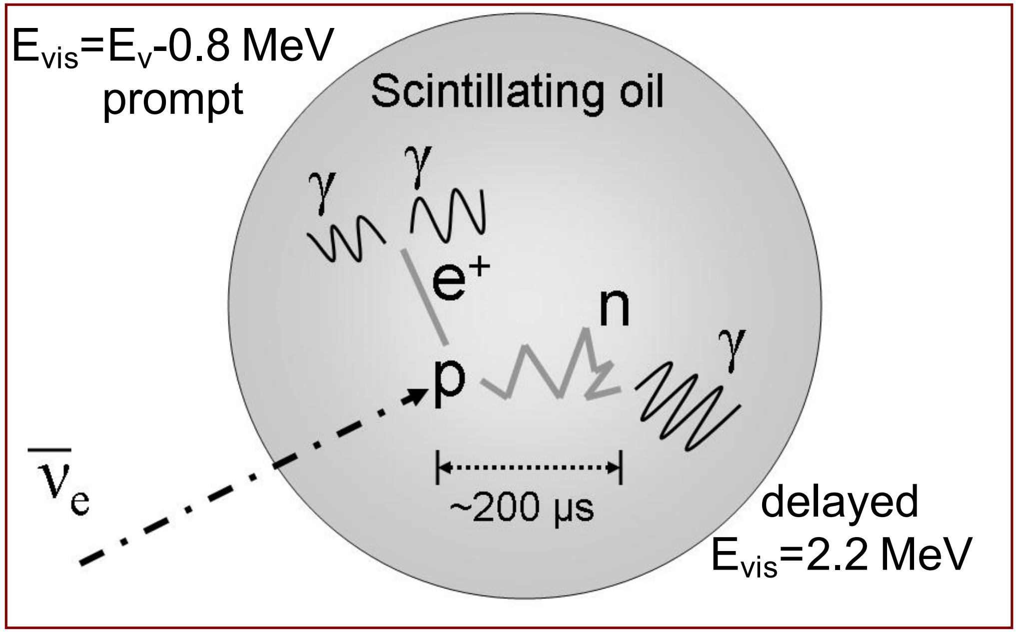
$\bar{\nu}_e$

Nucleus with one more proton and one less neutron


Reines & Cowan

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

Detection


$E_{vis}=E_\nu-0.8$ MeV
prompt

Scintillating oil

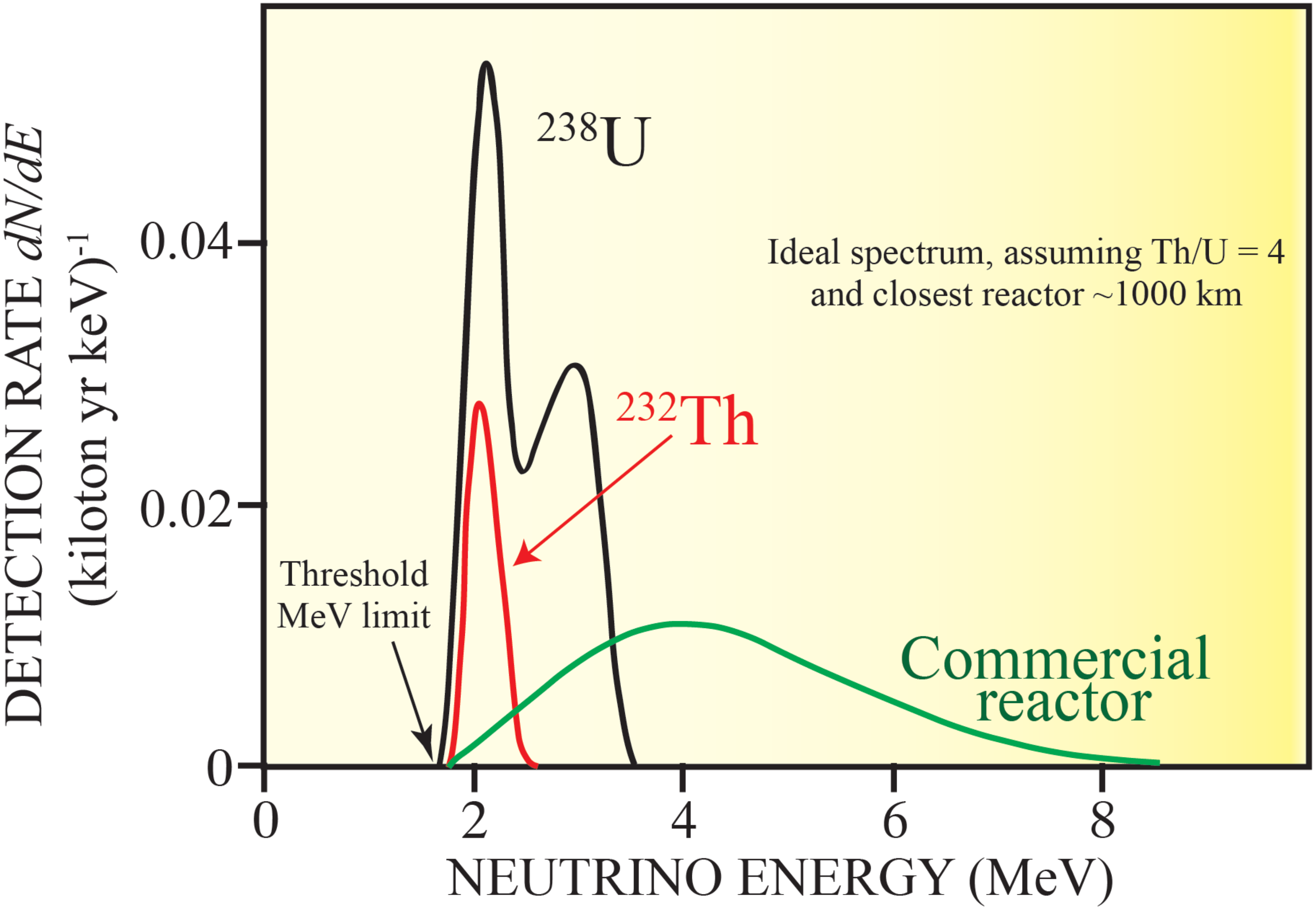
~200 μs

delayed
$E_{vis}=2.2$ MeV

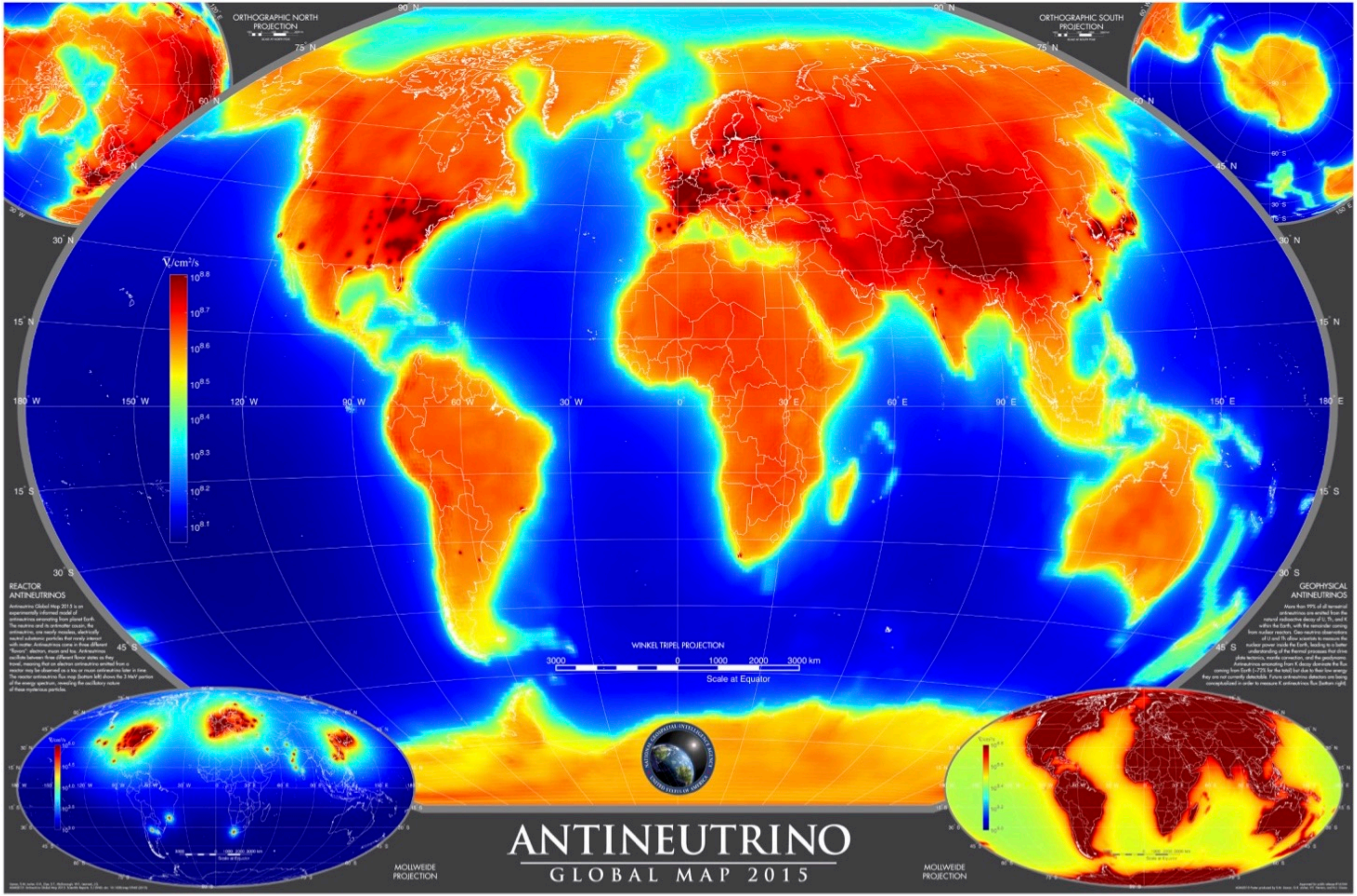
- Standard inverse β-decay coincidence
- $E_\nu > 1.8$ MeV
- Rate and spectrum - no direction

Antineutrinos - Geoneutrinos

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



Antineutrino Map: geoneutrinos + reactor neutrinos



Usman et al. 2015 doi:10.1038/

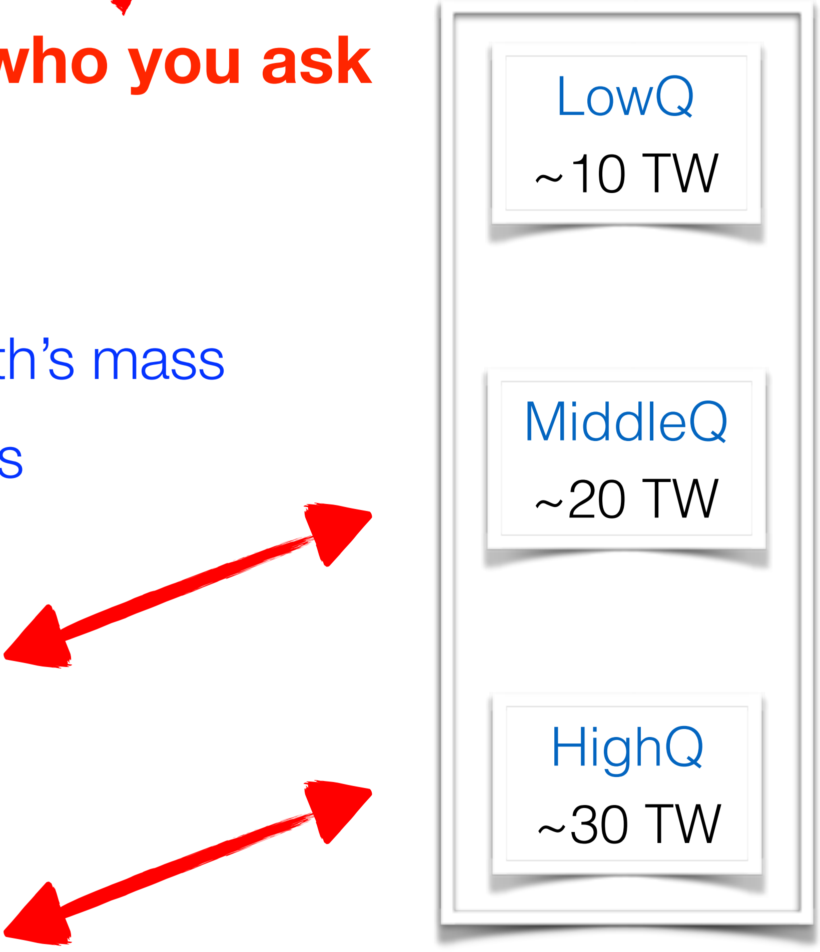
Radiogenic heat sources

- How much **U, Th, K** in the Earth ?
- … What is the Earth made of ?

Depends on who you ask

Earth's compositional models

- **O, Fe, Si, Mg** account for **~94%** of Earth's mass
- **+ Al, Ca, Ni, S** … **>99%** of Earth's mass
- Negligible **K, Th, U** in the metallic core
- 10–20–30 ppb of **U** in **Silicate Earth**
- **Th/U** ratio of ~4
- **K/U** ratio of 7000–15000
- **10–20–30 TW** of radiogenic heating



Bulk Silicate Earth (BSE) models:

LowQ
~10 TW

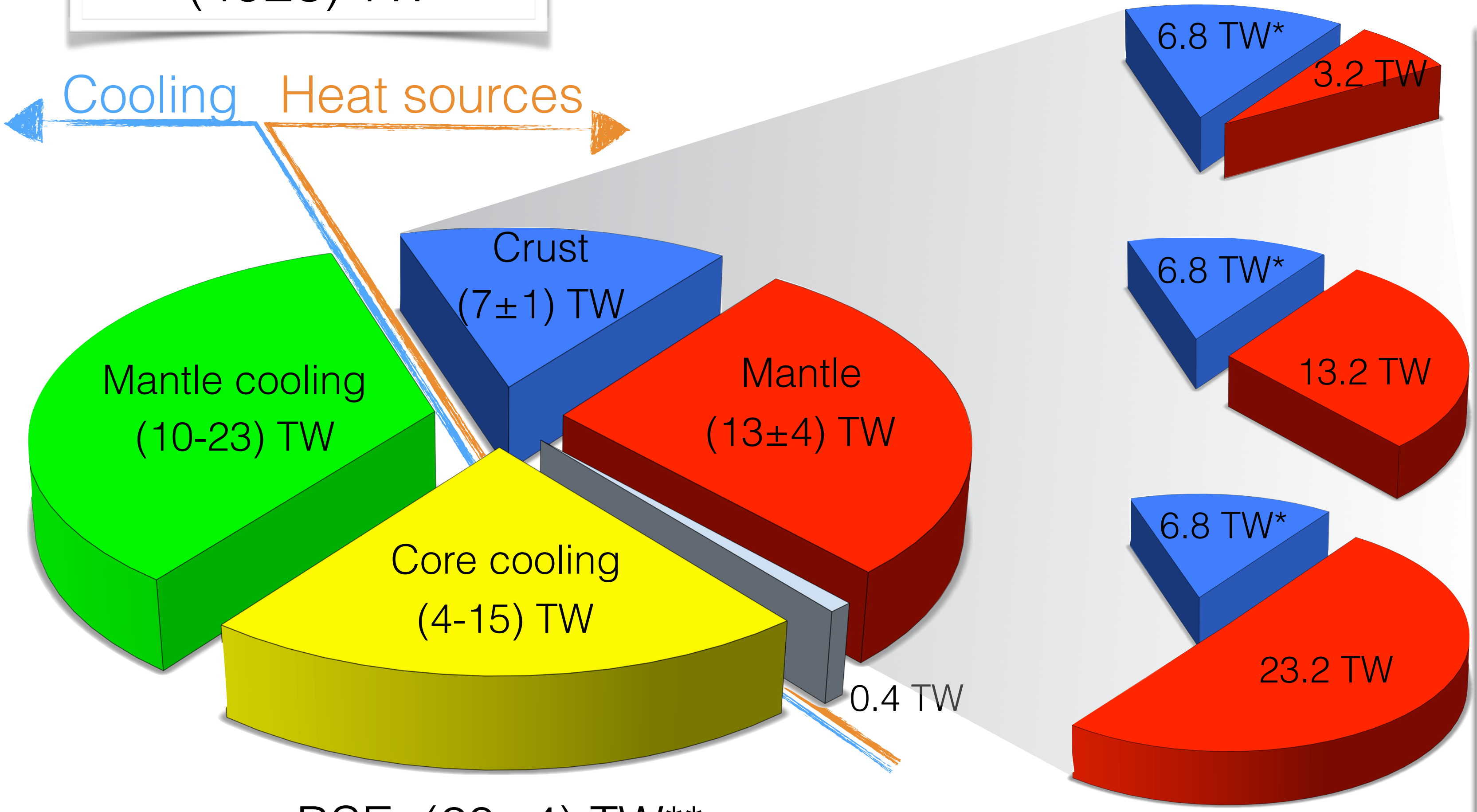
MiddleQ
~20 TW

HighQ
~30 TW

Earth’s energy balance

Surface heat flow
(46±3) TW

Bulk Silicate Earth
(BSE) models:



BSE: (20±4) TW**

LowQ
~10 TW

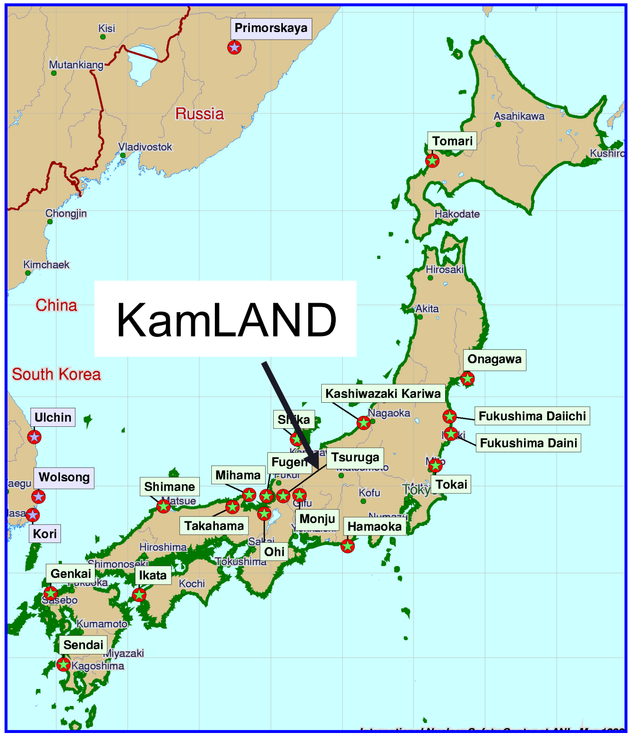
MiddleQ
~20 TW

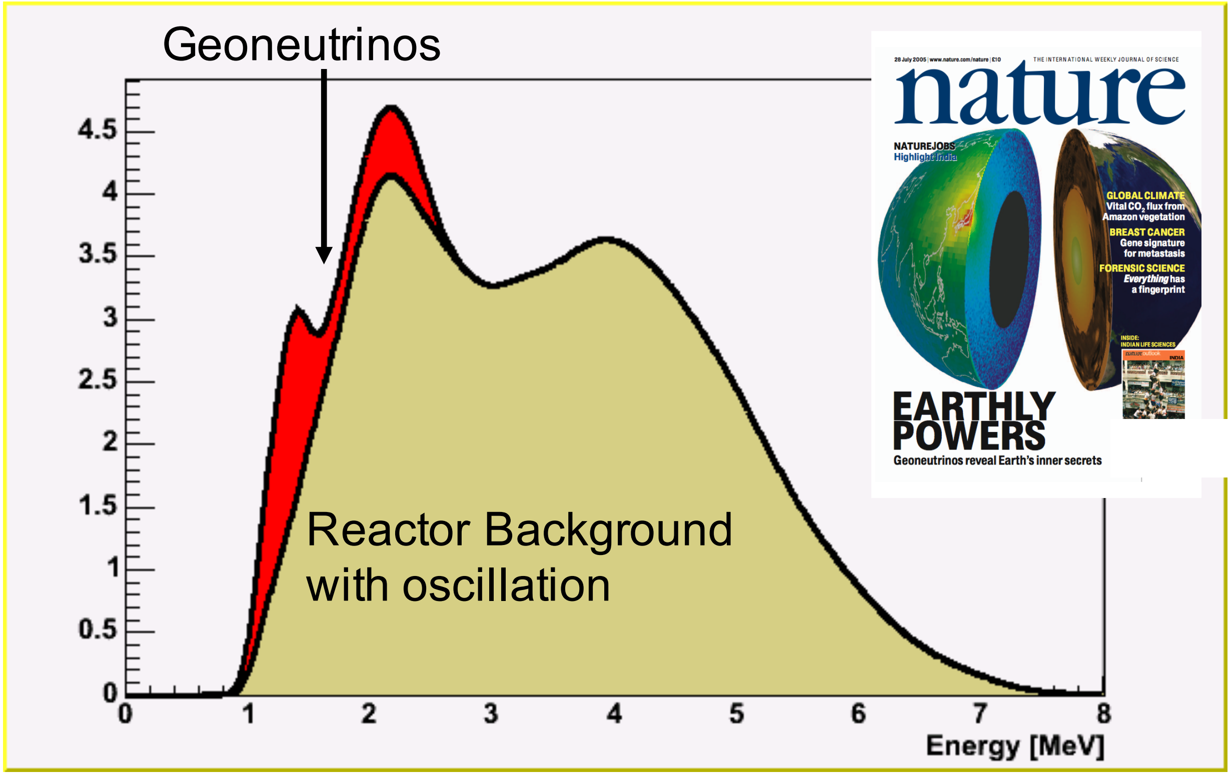
HighQ
~30 TW

Silicate Earth … models vary by a factor of 3
Mantle … models vary by a factor of 20

*Huang et al. (2013)
**McDonough & Sun (1995)

Reactor and Earth Signal


KamLAND

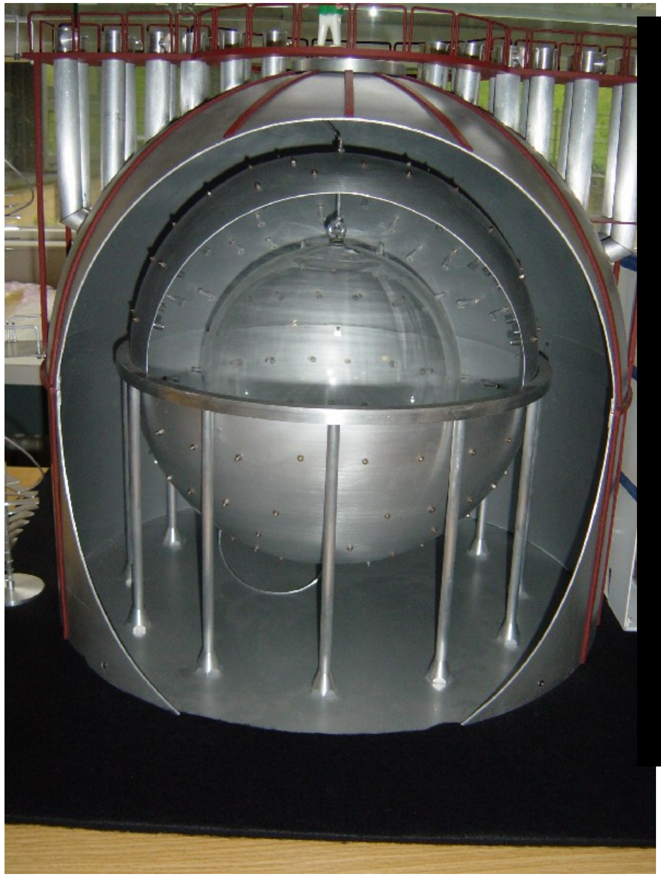

Geoneutrinos

Reactor Background with oscillation

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

Present LS-detectors, *data update*

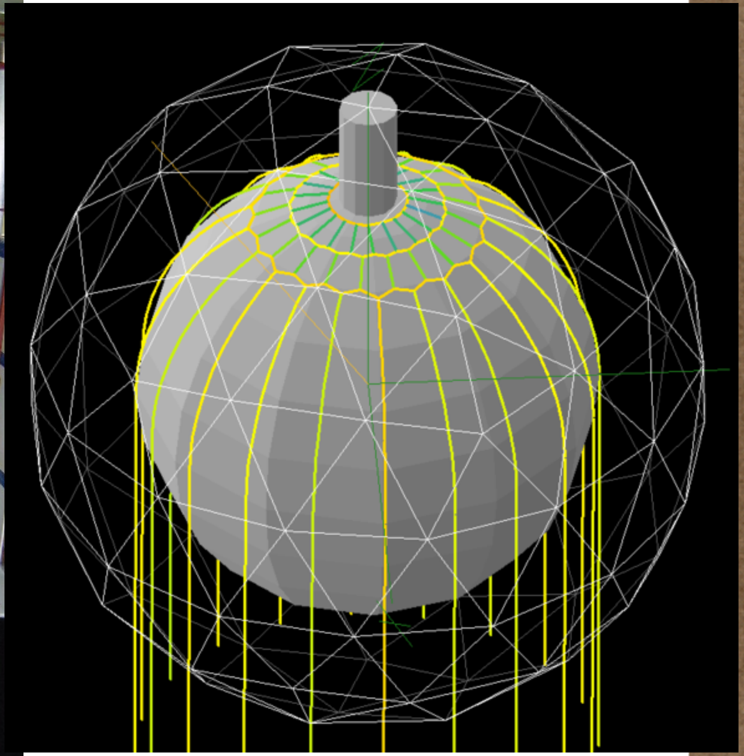
Borexino, Italy (0.3kt)



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

from May ’07 - March ‘15

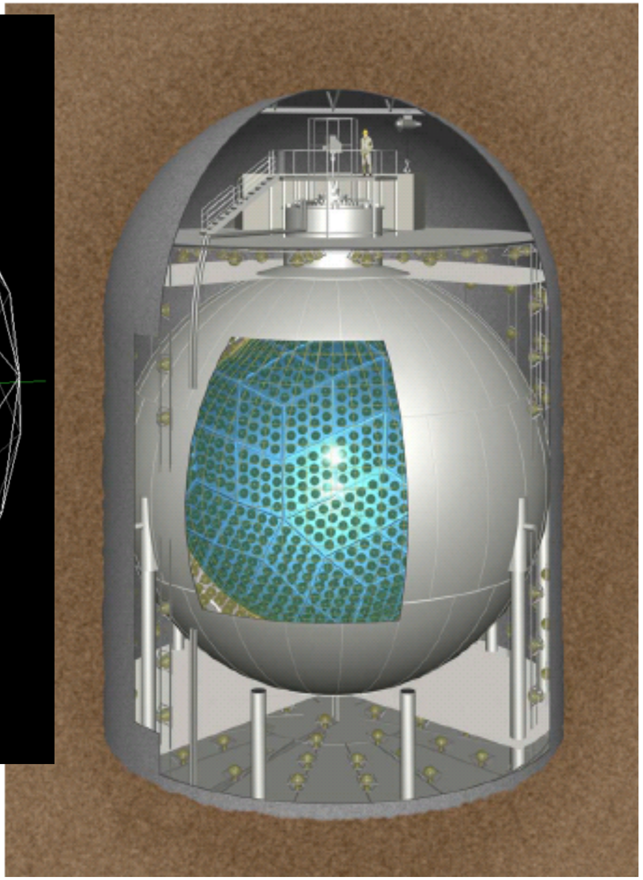
SNO+, Canada (1kt)



filled with water

(scintillator later this yr)

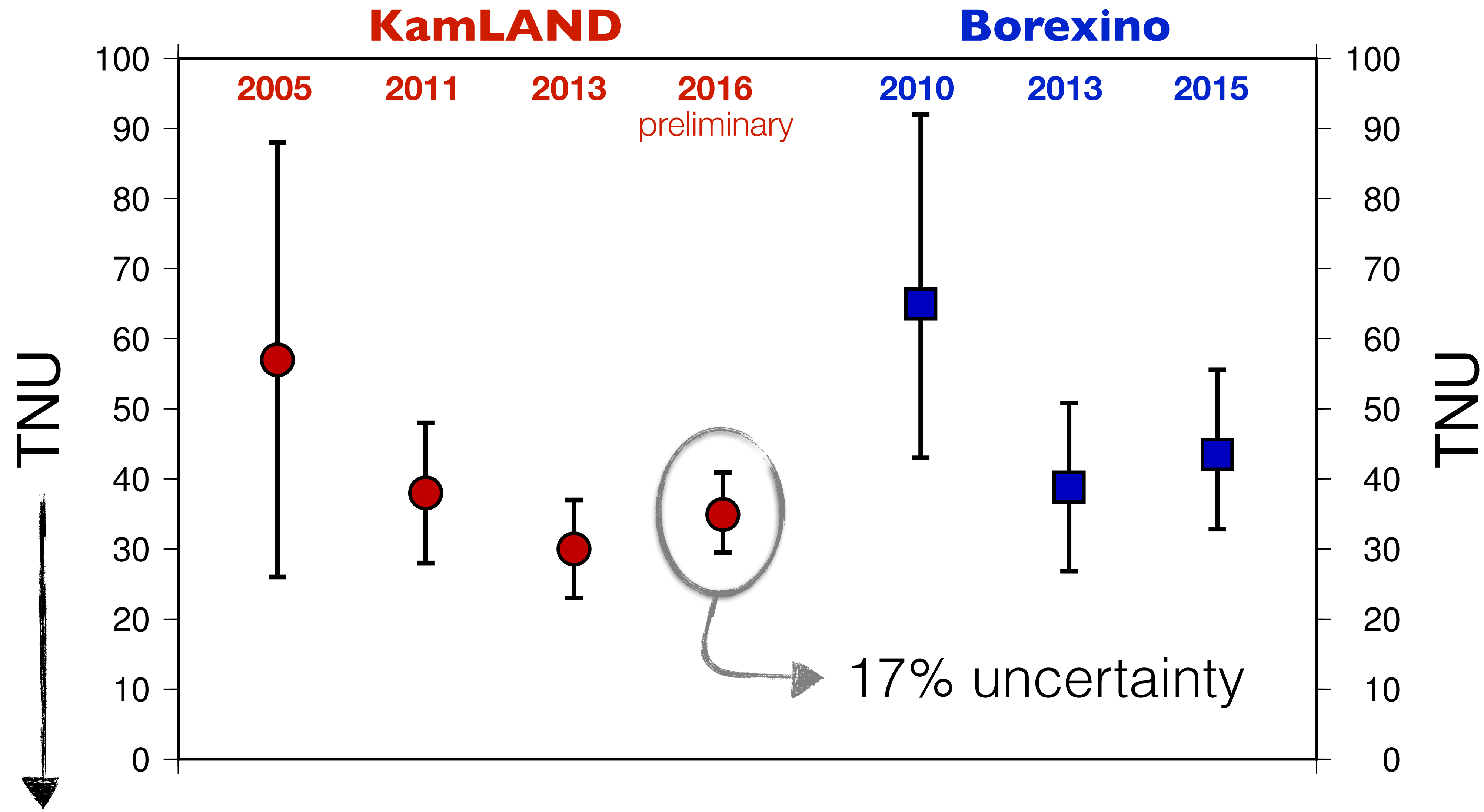
KamLAND, Japan (1kt)



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

From Mar ‘02 to Dec ‘15

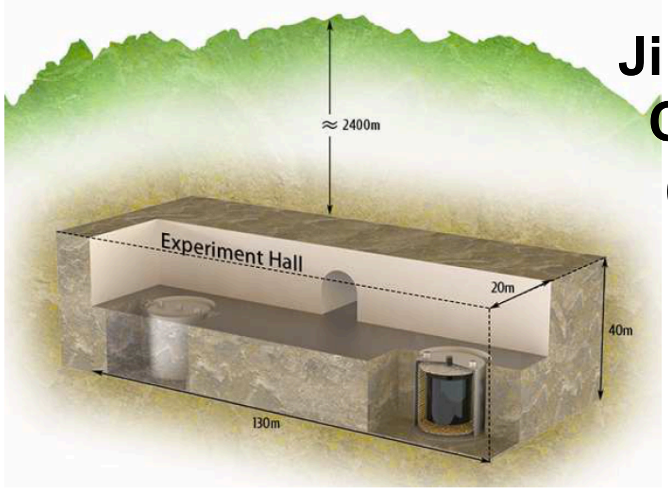
Current geoneutrino measurements



17% uncertainty

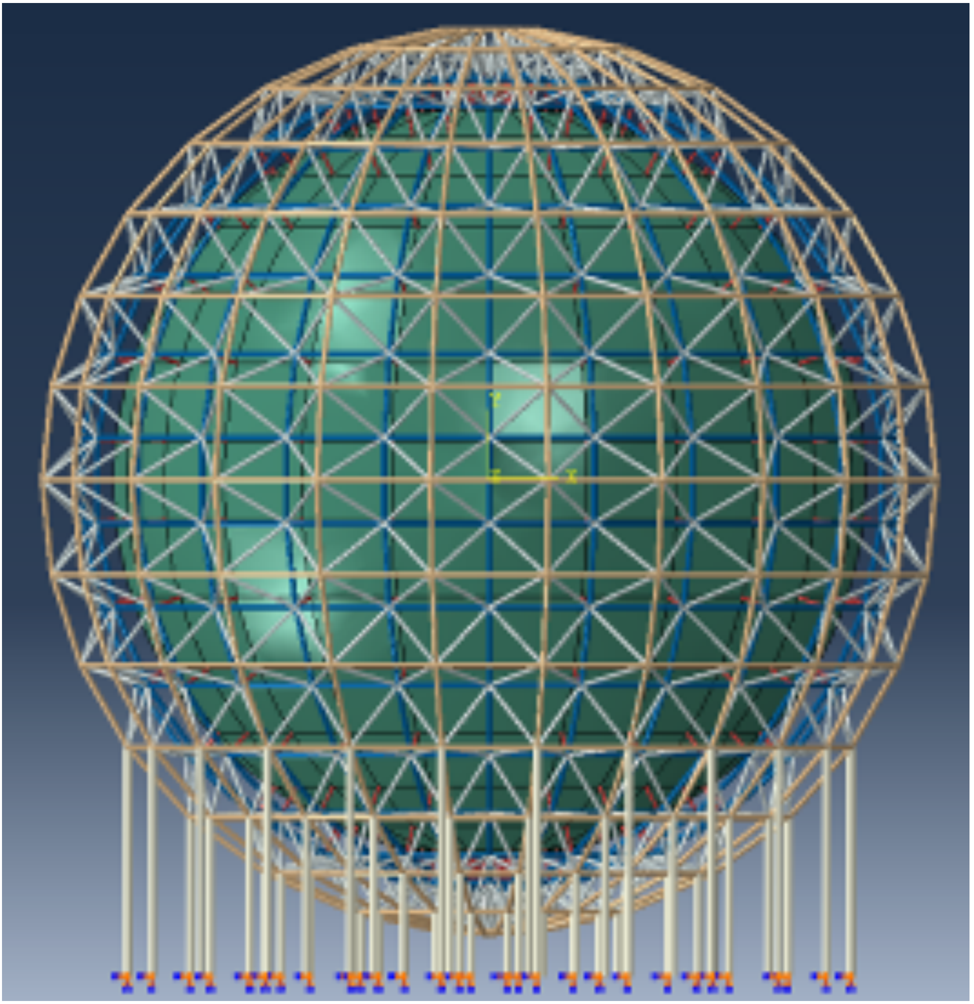
1 TNU (“Terrestrial Neutrino Unit”) = 1 event over a year-long exposure of 10^{32} protons

Future detectors

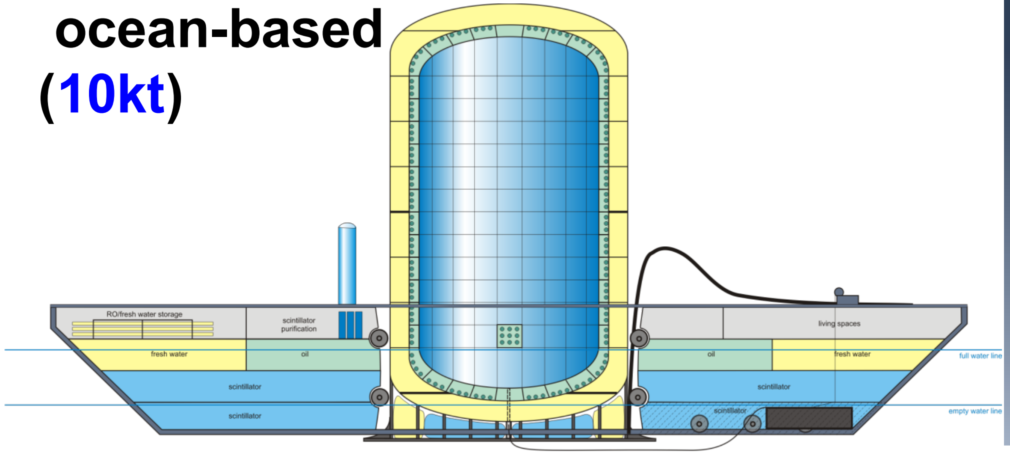


Jinping, China (**4kt**)

JUNO, China (**20kt**)

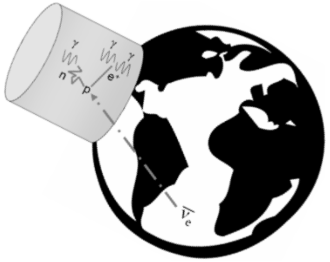


OBK (aka, Hanohano)
International
ocean-based
(**10kt**)

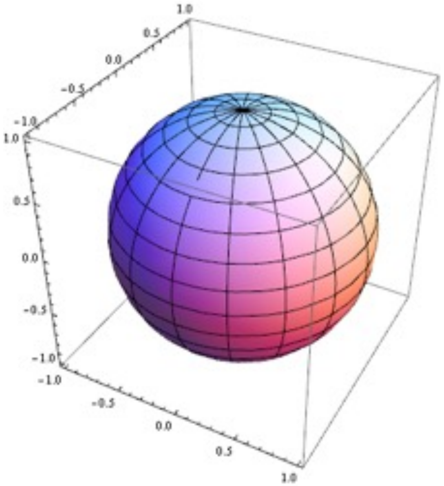


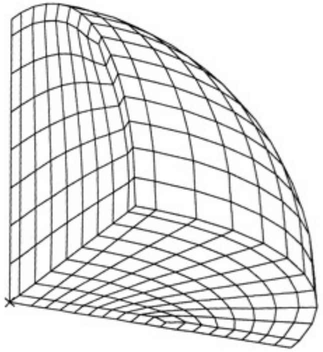
Predicting geoneutrino flux

Antineutrino flux spectrum $d\Phi/dE_\nu$ at position **r** from a given radionuclide distributed with abundance A in the Earth



$$\frac{\mathrm{d}\phi(\boldsymbol{r},E_\nu)}{\mathrm{d}E_\nu} = D\frac{\mathrm{d}n(E_\nu)}{\mathrm{d}E_\nu}\iiint\frac{\boxed{A(\boldsymbol{r}')\rho(\boldsymbol{r}')}P_{ee}(E_\nu,|\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}\mathrm{d}^3\boldsymbol{r}'$$





Inputs from geoscience:

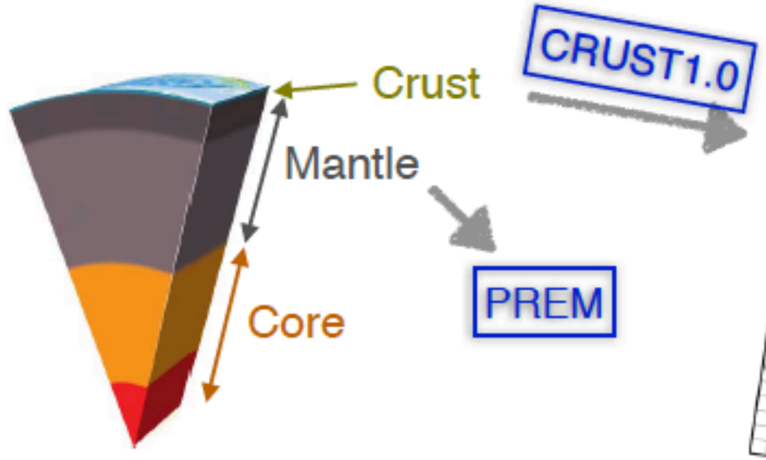
- chemical abundances A:
- density ρ

Inputs from nuclear/particle physics:

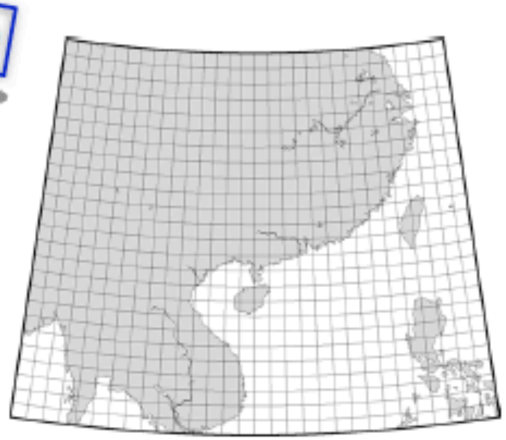
- decay rate D
- antineutrino intensity spectrum dn/dE_ν,
- antineutrino survival probability P_{ee}

Geoneutrino emission model

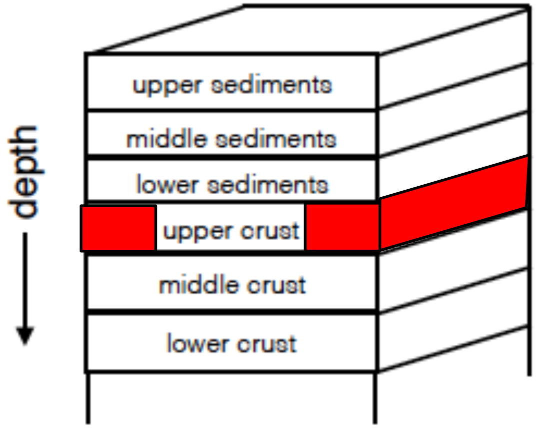
- Model of crustal geometry and material density from **CRUST1.0** model (*Laske et al.*)
- Material density in the mantle from **PREM** model (*Dziewonski & Anderson 1981*)
- Assume negligible Th, U in the core
- Total amount of Th, U in **Silicate Earth** from estimate by *Arevalo et al. 2009*, **20±4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

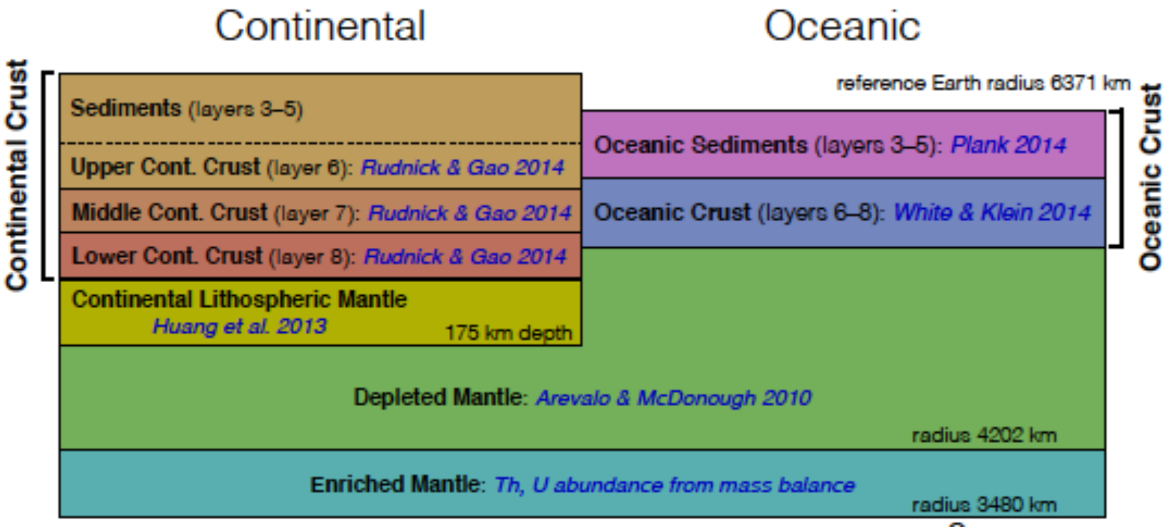


1° lat × 1° lon crustal tiles

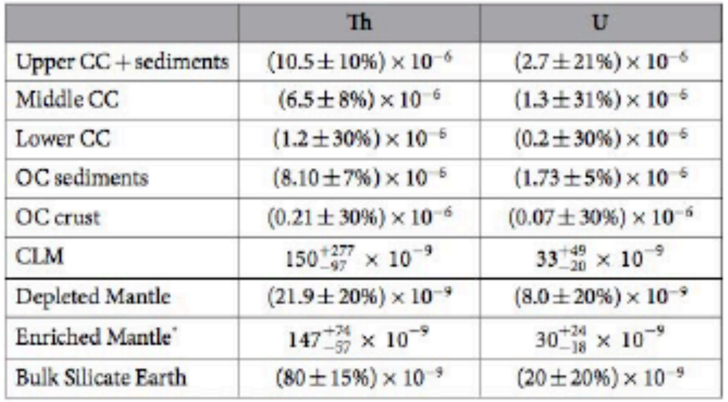


Vertical structure of a crustal tile



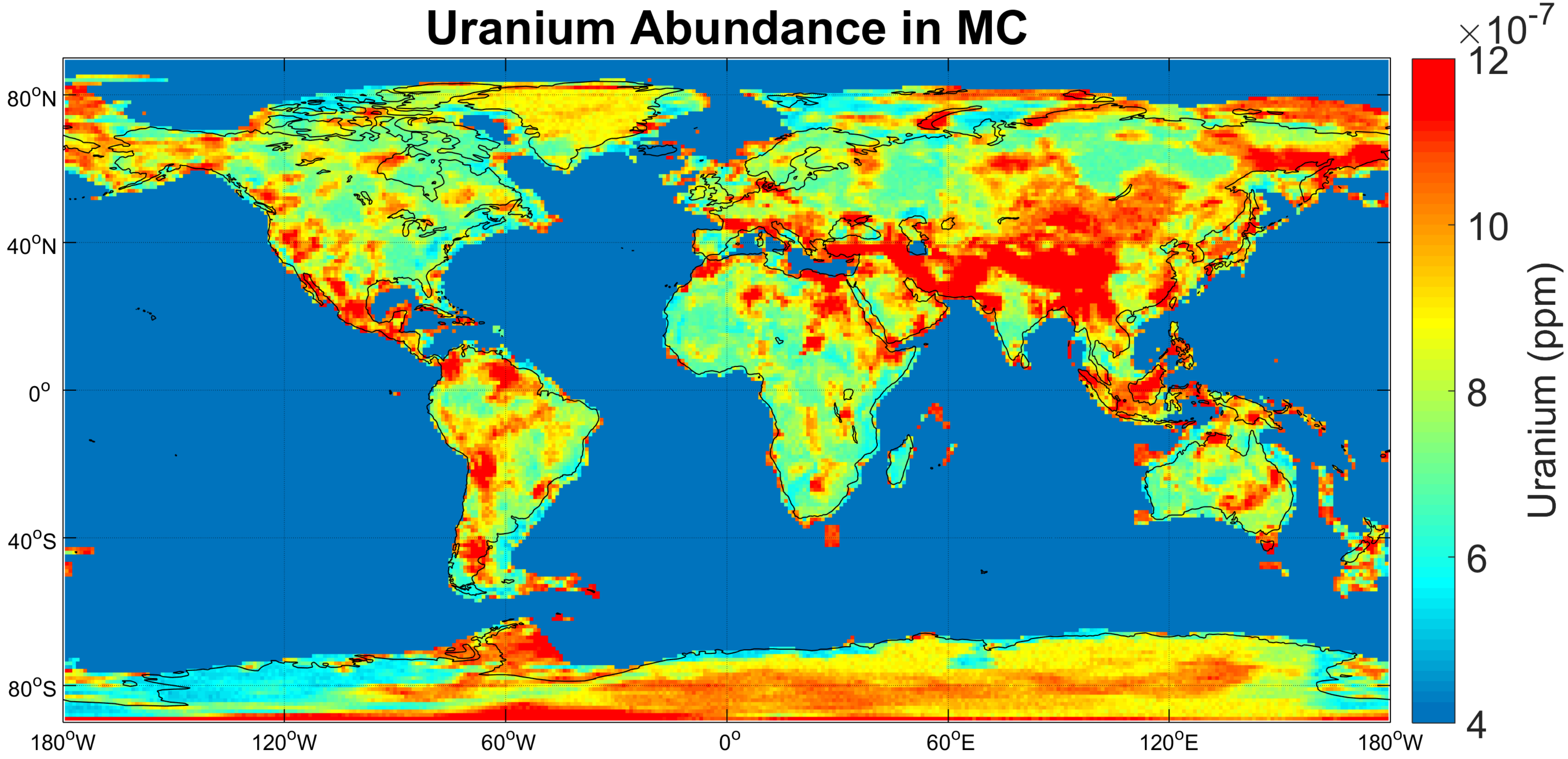


Mass fractions of Th and U



	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	$(80 \pm 15\%) \times 10^{-9}$	$(20 \pm 20\%) \times 10^{-9}$

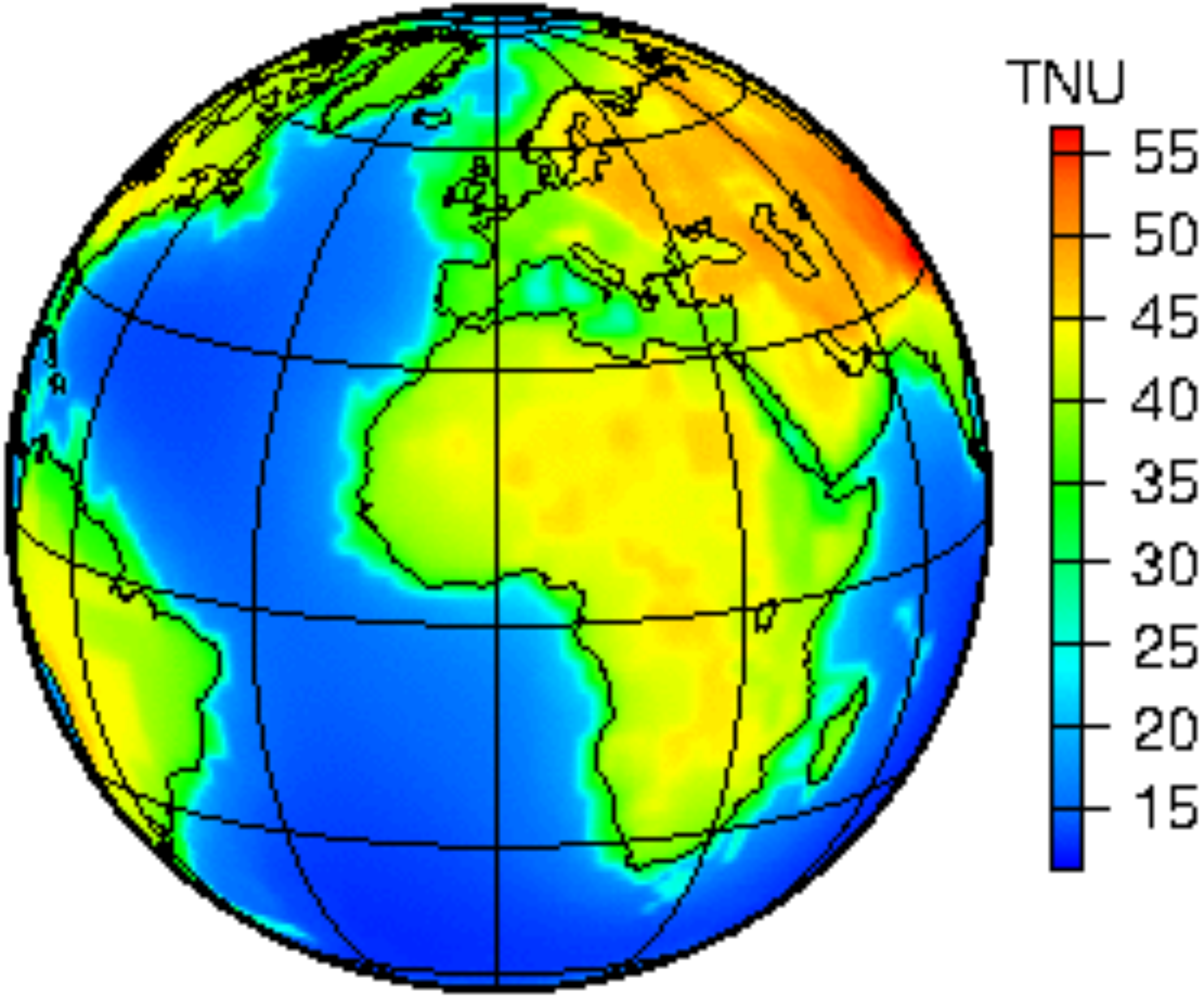
Uranium Abundance in Middle Continental Crust layer



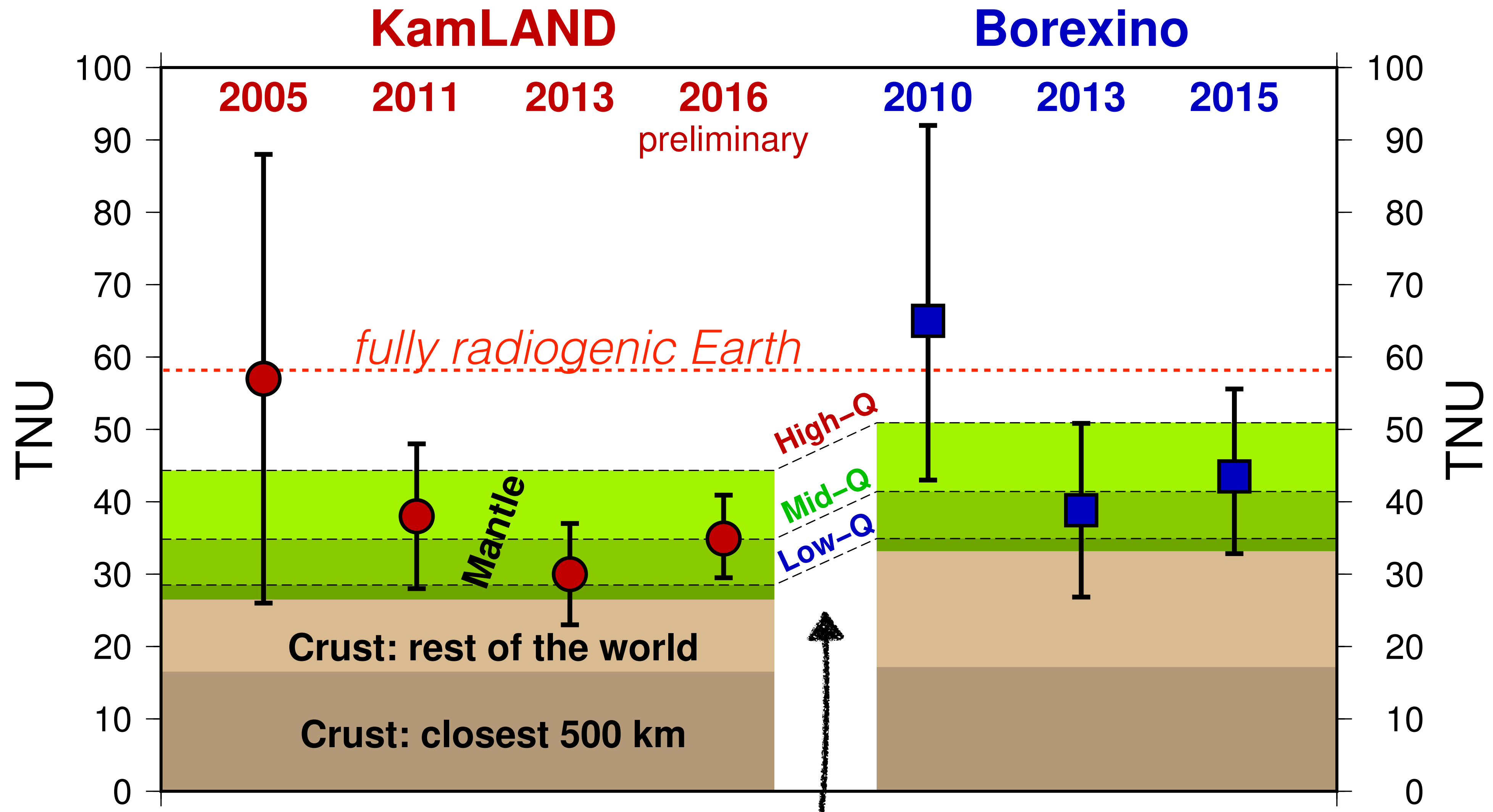
Average middle Cont. Crust U abundance is $0.97^{+0.58}_{-0.36}$ μg/g

Rudnick and Gao (2003) 1.3 μg/g

Predicted Global geoneutrino flux



Geoneutrinos measurements vs. predictions



Silicate Earth models:

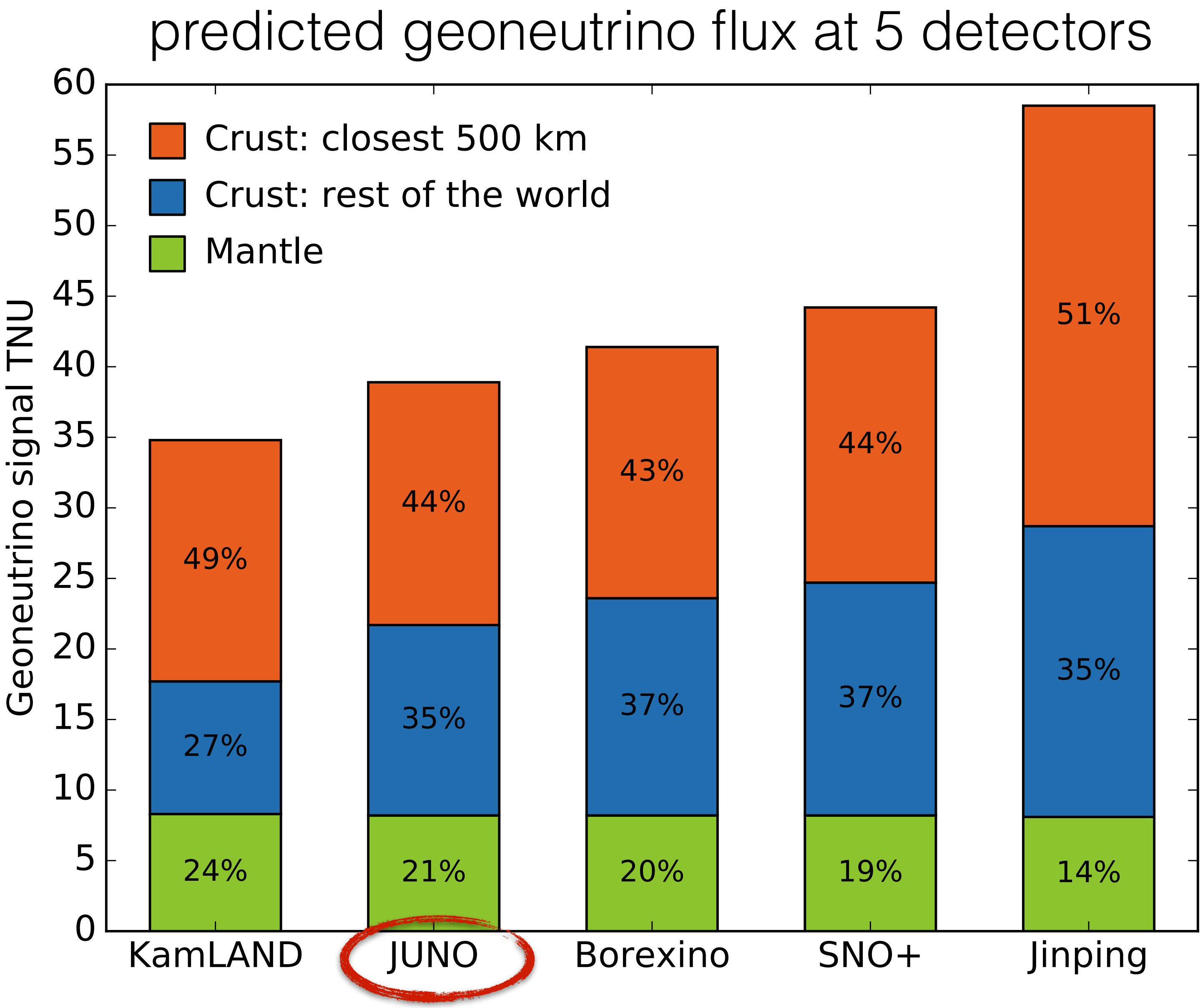
High-Q: ~33 TW radiogenic power

Middle-Q: ~20 TW

Low-Q: ~11 TW

Geoneutrino prediction from
Šrámek et al. 2016 doi:10.1038/srep33034

JUNO & its partners

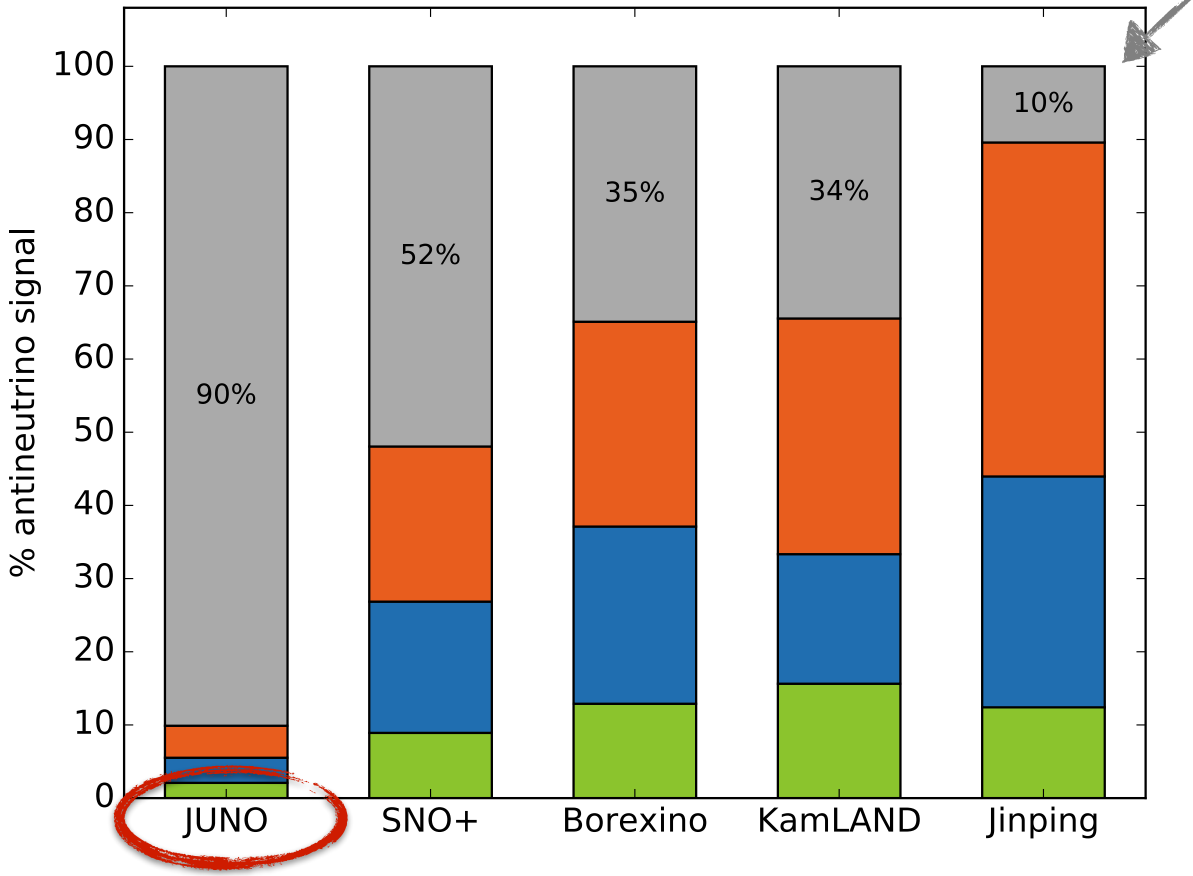


Largest geoneutrino detector

Šrámek et al 2016 doi:10.1038/

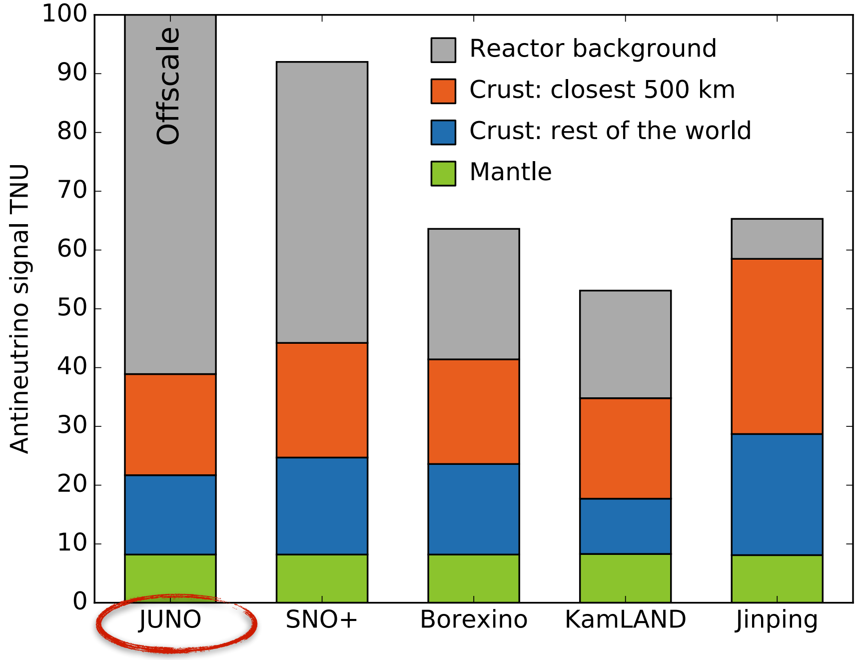
Reactor background subtraction

Relative proportions, reactor & geo-ν



- ▨ Reactor background
- 🟧 Crust: closest 500 km
- 🟦 Crust: rest of the world
- 🟩 Mantle

TNU signal

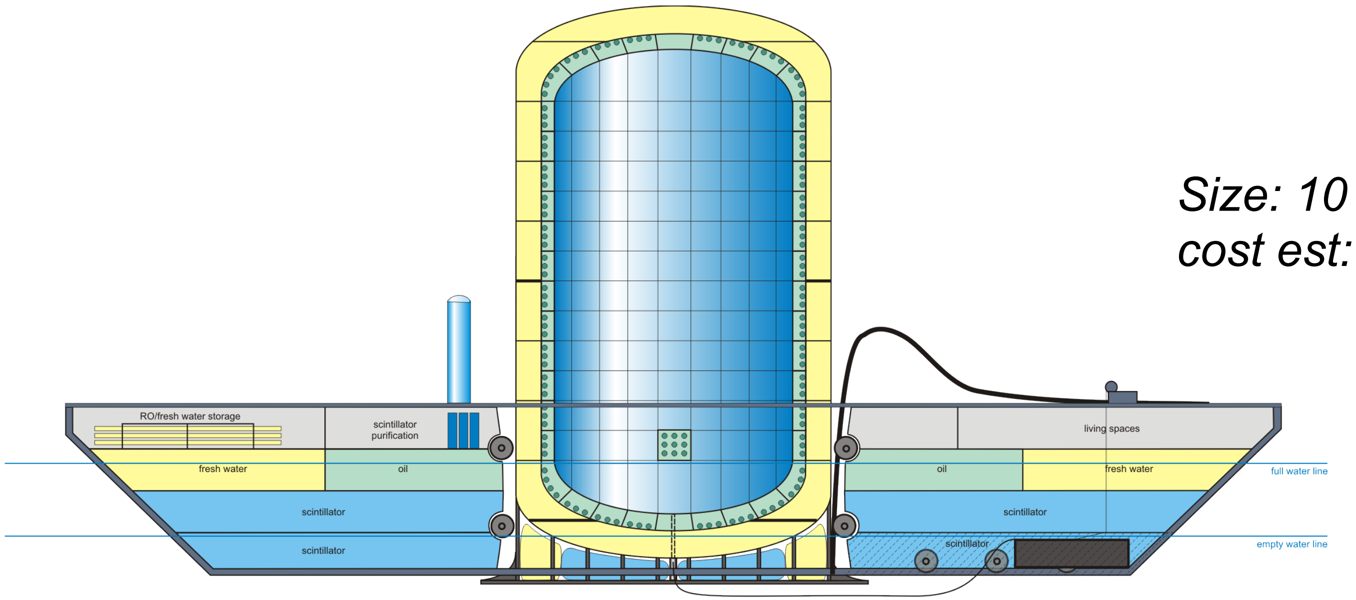


Geoneutrinos constitute 10% of signal

OBK

Ocean Bottom KamLAND

An experiment with Physics & Geology



Size: 10 to 50 kT
cost est: \$300M to \$600M

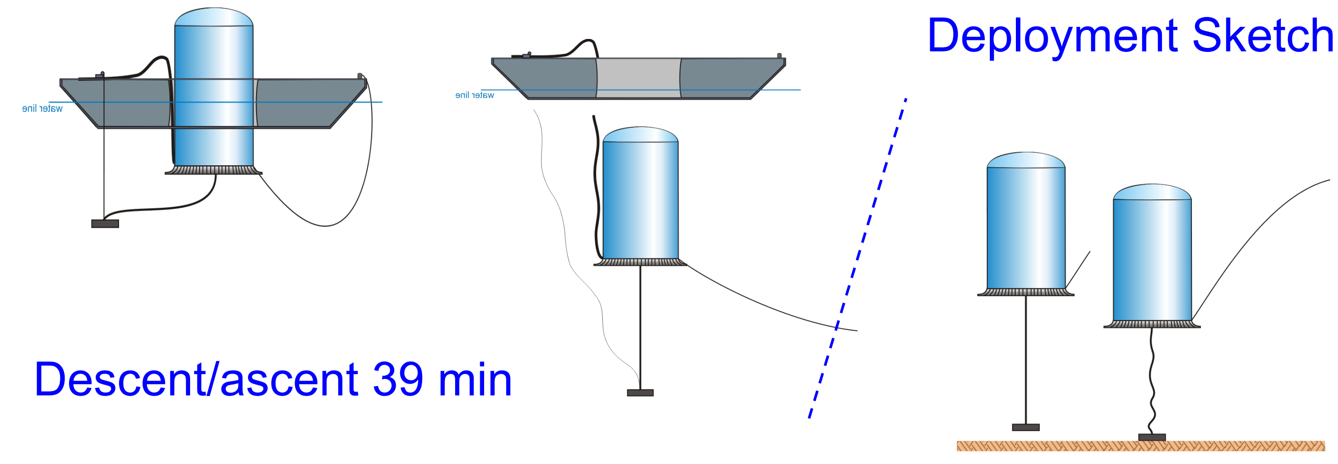
- multiple deployments
- deep water cosmic shield
- control-able L/E detection

A Deep Ocean

$\overline{\nu}_e$ Electron

Anti-Neutrino

Observatory

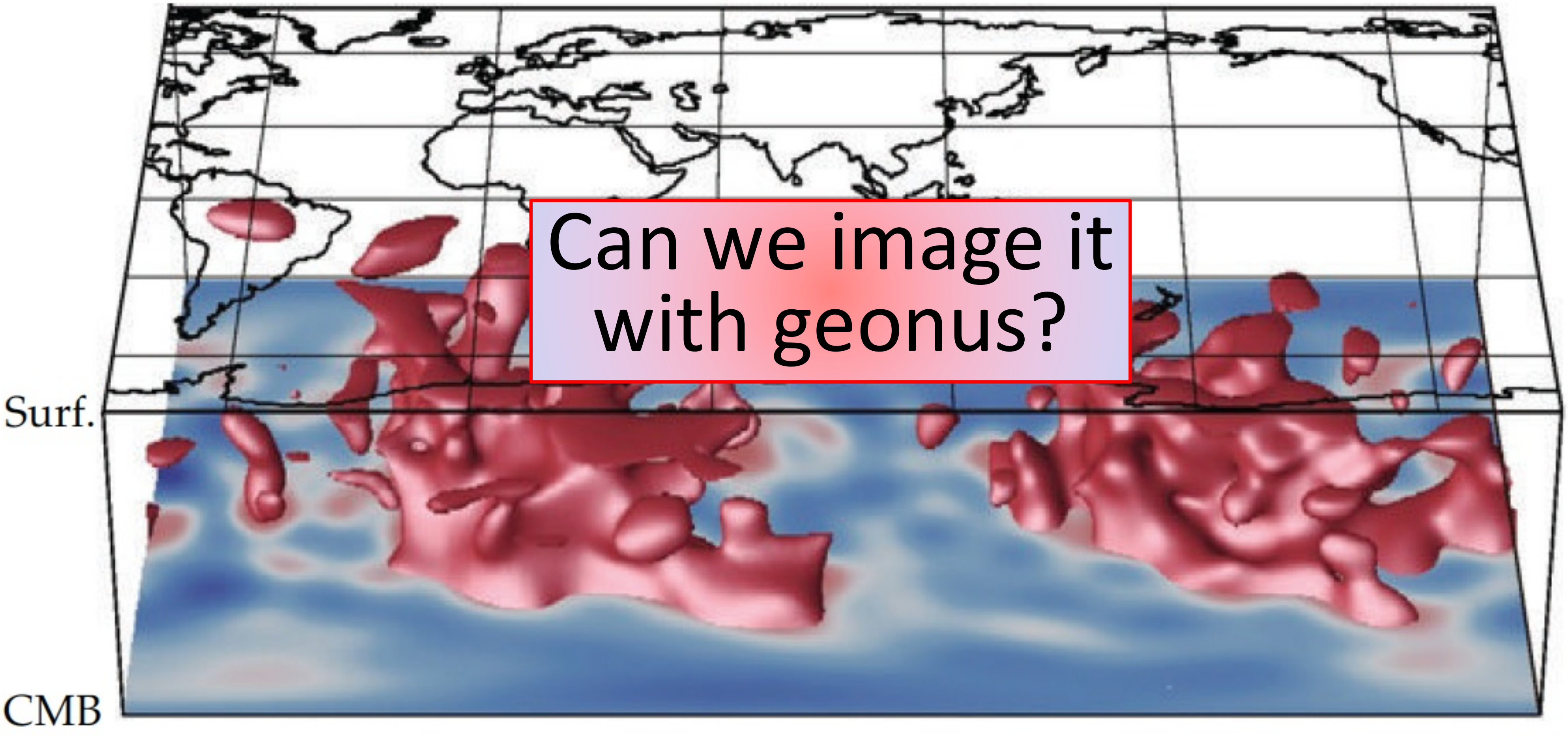


Deployment Sketch

Descent/ascent 39 min

What’s hidden in the mantle?

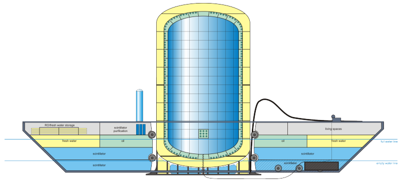
Seismically slow “red” regions in the deep mantle



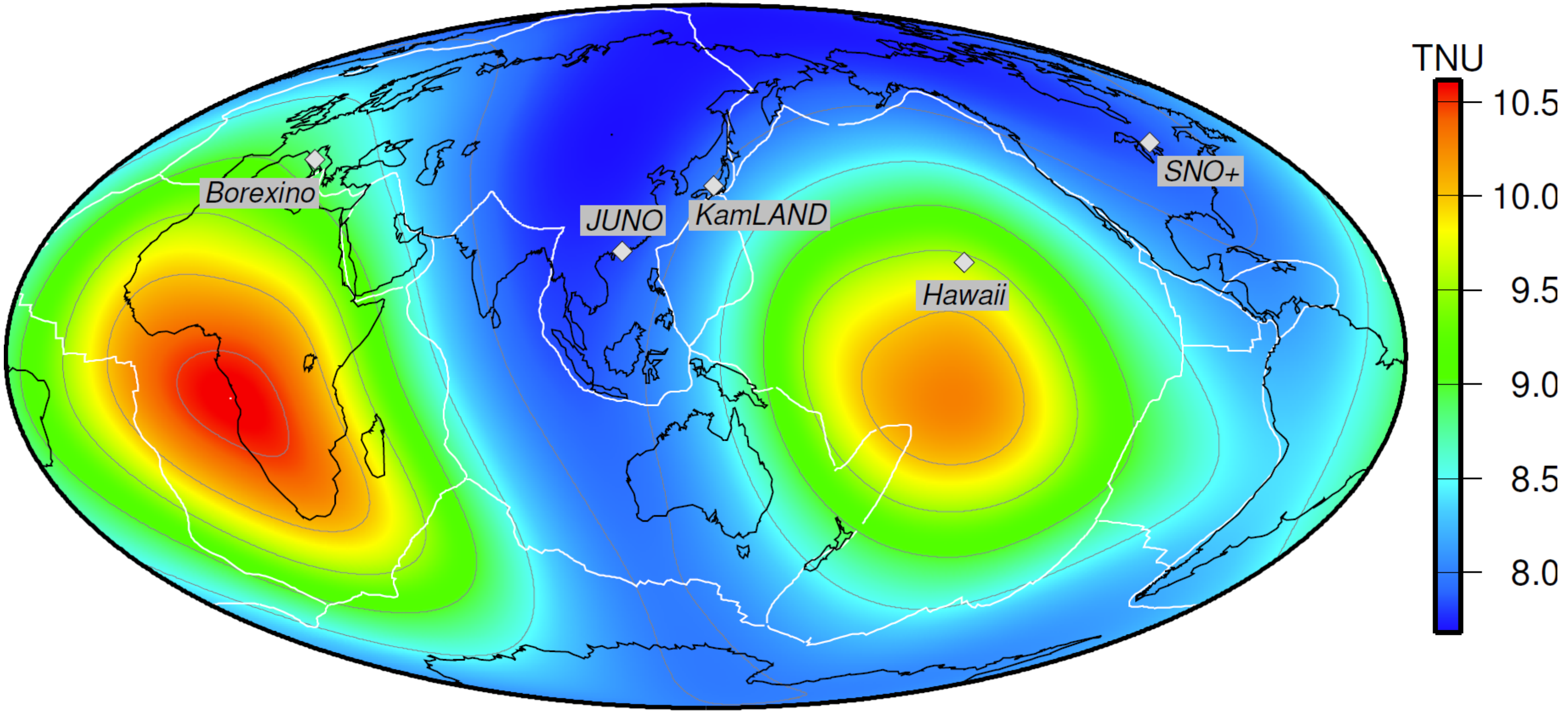
Can we image it with geonus?

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

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, 400 events/yr, but background…
- **Jinping**: 202X, deep, for Earth, Sun & Supernovae
- **OBK**: to look at the mantle-only

IMPORTANT **: Th/U, multi-detectors, and directionality**

What can Chinese Geoscientists do?

<u>Plenty left to do</u>:

-geology

-seismology

-geochemistry

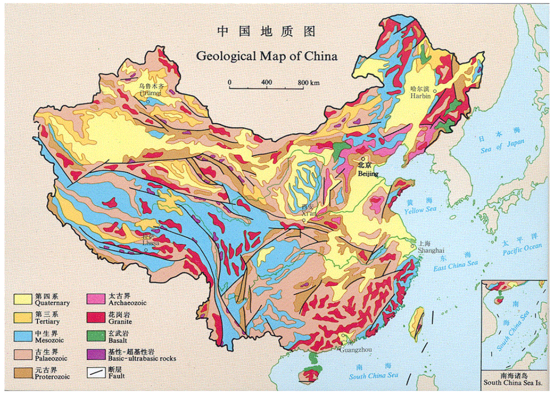
-heat flow

-gravity

-integrative modeling

- and more...

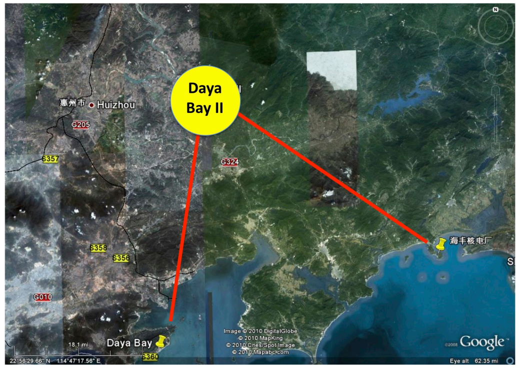
Please,
join our effort



2011

China Workshop
Neutrino Geoscience

21 April 2011   CAS, Beijing

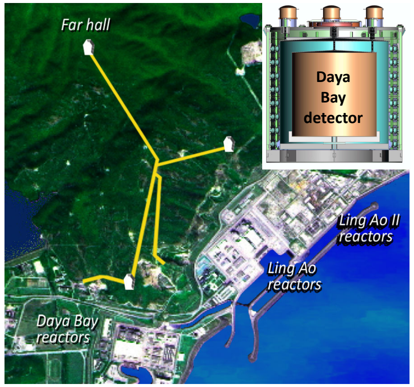


Scientific Agenda
Welcome, Introductions, Objectives
Review of Earth models and geoneutrino
Overview of Neutrinos and the Daya Bay II experiment
China's continent crust and heat producing elements

Background: Detection of geoneutrinos (electron anti-neutrino from the Earth) and the development of neutrino detectors permit measurements of Earth's nuclear power. These measurements will provide transformative insights into understanding the Earth's energy budget, specifically the abundance and distribution of U and Th in the Earth.

Workshop Agenda: The purpose of our workshop is build connections between neutrino physics and geology as Chinese scientists begin to consider a new generation of neutrino detector following the success of the Daya Bay experiment. This workshop brings together leaders in neutrino detection from IHEP and experts in geology to share the latest information and to map the path towards future measurements.

Proposed Experiment: to build an underground, 10-50 kiloton liquid scintillation detector that is site inland 60 km from the Daya Bay and Hafeng reactors. In addition to is major physics goals, this detector will measure the geoneutrino flux from continental China.



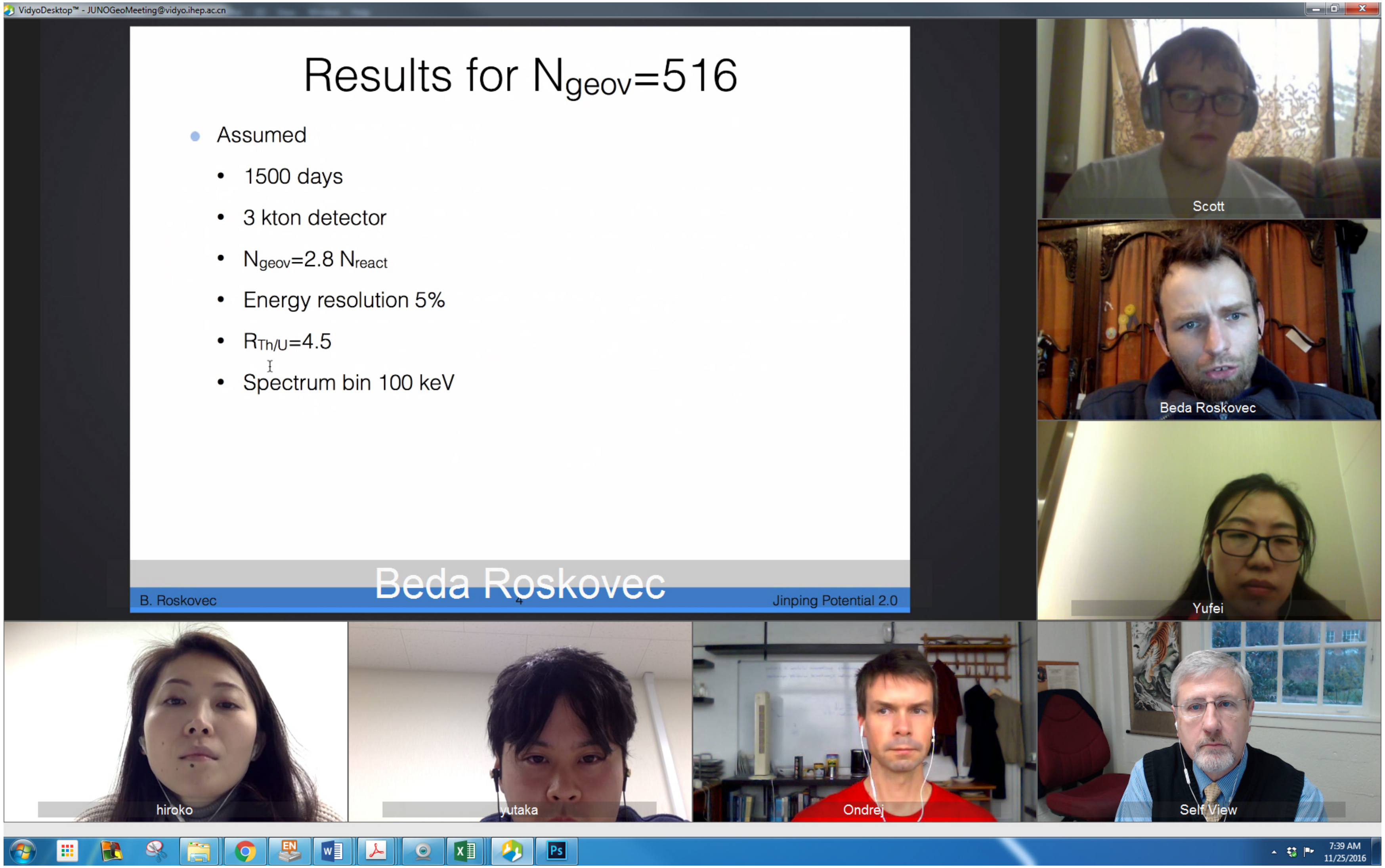
Organizing Committee
Wu, Fuyuan, Chinese Academy of Sciences
Sun, Weidong, Guangzhou Institute of Geochemistry
Wang, Yifang, Institute of High Energy Physics
McDonough, William F, University of Maryland
Rudnick, Roberta L, University of Maryland

<u>Previous Neutrino Geoscience Meetings</u>:
Gran Sasso meeting (Oct '10) http://geoscience.lngs.infn.it/Program.htm
Sudbury meeting (Oct '08) http://geonu.snolab.ca/agenda.html
Honolulu meeting (March '07) http://www.phys.hawaii.edu/~sdye/hano.html
Honolulu meeting (Dec '05) http://www.phys.hawaii.edu/~sdye/hnsc.html

Daya Bay Physics experiment http://english.ihep.cas.cn/rs/fs/dyb/

You can begin immediately!

Weekly teleconference Nodes: Beijing, Prague, Sendai, Maryland



Results for N_{geov}=516

- Assumed
  - 1500 days
  - 3 kton detector
  - N_{geov}=2.8 N_{react}
  - Energy resolution 5%
  - $R_{Th/U}$=4.5
  - Spectrum bin 100 keV

B. Roskovec 4 Jinping Potential 2.0

China

- leads the world in the next generation of detectors
- only country with/ building 2 detectors
- can lead the world in training the next generation!

How can I get involved:

-email any of us

- no knowledge of particle physics needed

-think geology!

2014

PARTICLE PHYSICS

China Builds Mammoth Detector To Probe Mysteries of Neutrino Mass

BEIJING—It isn't easy to weigh a ghost. After neutrinos were hypothesized in 1930, it took physicists 67 years to prove that these elusive particles—which zip through our bodies by the trillions each second—have mass at all. Now, a Chinese-led team is planning a mammoth neutrino detector, meant to capture enough neutrinos from nearby nuclear reactors to determine which of the three known types, or flavors, of neutrinos are heavier or lighter. That mass hierarchy could be key to explaining how neutrinos get their mass, and measuring it would be a coup for China's particle physicists.

Last month, scientists gathered in Jiangmen, in China's southern Guangdong province, to review plans for the Jiangmen Underground Neutrino Observatory (JUNO). Groundbreaking is slated for later this year on the $300 million facility, which China aims to complete by 2019. The facility, which backers say will be twice as sensitive as existing detectors, should not only pin down key properties of neutrinos themselves but also detect telltale neutrinos from nuclear reactions in the sun, Earth, and supernovas.

Other planned facilities aim to reveal the mass hierarchy (see table), but China could be the first to arrive at an ironclad result. If China can pull it off, says William McDonough, a geologist at the University of Maryland, College Park, JUNO "will not only lead to breakthroughs in neutrino physics, but revolutionize the field of geology and astrophysics." A successful project would also mark another triumph for China's neutrino research, 2 years after the Daya Bay Reactor Neutrino Experiment in Guangdong nailed a key parameter describing how different types of neutrinos morph into one another (*Science*, 16 March 2012, p. 1287).

In 1998, physicists working with the subterranean particle detector Super-Kamiokande in Japan showed that neutrinos of one flavor, muon neutrinos generated by cosmic rays in the atmosphere, can change flavor as they zip through Earth. In 2001, researchers at the Sudbury Neutrino Observatory in Canada proved that electron neutrinos from the sun do the same. Such neutrino "oscillations" prove that neutrinos have mass: Without it, the particles would move at light speed and—according to relativity—time would stand still for them, making change impossible.

Knowing a neutrino has mass isn't the same as knowing what it weighs. In the simp
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aya Bay.
They know that two of the neutrinos are close in mass and one is further off. But they don't know whether there are two lighter neutrinos and one heavier one—the so-called normal hierarchy—or an inverse hierarchy of two heavier ones and one light one.

How the masses shake out "is fundamental for a whole series of questions," says Wang Yifang, director of the Institute of High Energy Physics (IHEP) here, including whether neutrinos, like other particles, get mass from tangling with Higgs bosons or from a more exotic mechanism. The answer depends on whether the neutrino is, oddly, its own antiparticle. Physicists may be able to tell that by searching for a weird new type of radioactive decay. But, if it even exists, that decay would occur at an observable rate only if neutrinos follow an inverse hierarchy.

To explore this frontier, an international team led by Wang will build a detector 700 meters beneath a granite hill near Jiangmen, equidistant from two nuclear power plant complexes. A sphere about 38 meters in diameter will contain 20,000 tons of a material known as a liquid scintillator. About 60 times a day, one of the sextillion or so electron neutrinos spraying from the reactors every second should bump into an atomic nucleus, sparking a flash of scintillation light that the detector can measure and analyze. In the 53 kilometers that the neutrinos will traverse from reactor to detector, about 70% will change flavor, says Cao Jun, a particle physicist at IHEP. By studying the energy spectrum of the neutrinos, physicists should be able to tease out the mass hierarchy. "But it's not going to be easy because the amount of energy to be measured is minuscule," Cao says. He estimates the measurement will require 6 years of data-taking.

The key to JUNO's success will be its energy resolution. The largest liquid scintillation detector to date—KamLAND in Japan, which has 1000 tons of detector fluid—can only make out energy differences of greater than 6%. JUNO needs to double the resolution to 3%—no mean feat, especially as the larger volume of scintillator itself absorbs more light.

If it works, JUNO should also make finer measurements of the known mixing angles and mass differences. "This is particularly important for the search for a possible fourth form of neutrinos," says Lothar Oberauer

Heavy hitter. China hopes its planned JUNO detector, 38 meters across, will be the first to nail which of the three neutrino flavors is heavier or lighter.

The Race to Establish the Neutrino Mass Hierarchy

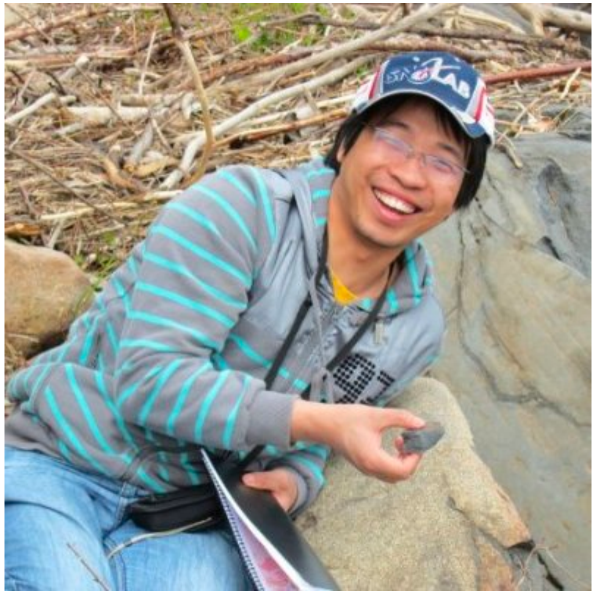
Project	Location	Source of neutrinos	Projected startup	Resolving power (in multiples of experimental uncertainty σ)
NoVA and T2K	USA and Japan	Accelerator	Running	1–3 σ
INO	India	Atmospheric	2017	2.2–2.8 σ
JUNO	China	Reactor	2019	3.2–4.4 σ
PINGU	South Pole	Atmospheric	2019	4.2–6.9 σ
LBNE	USA	Accelerator	2023	3–7 σ

CREDIT: (INSET) IHEP; (SOURCE) M. BLENNOW ET AL., ARXIV 1311.1822 (2013)

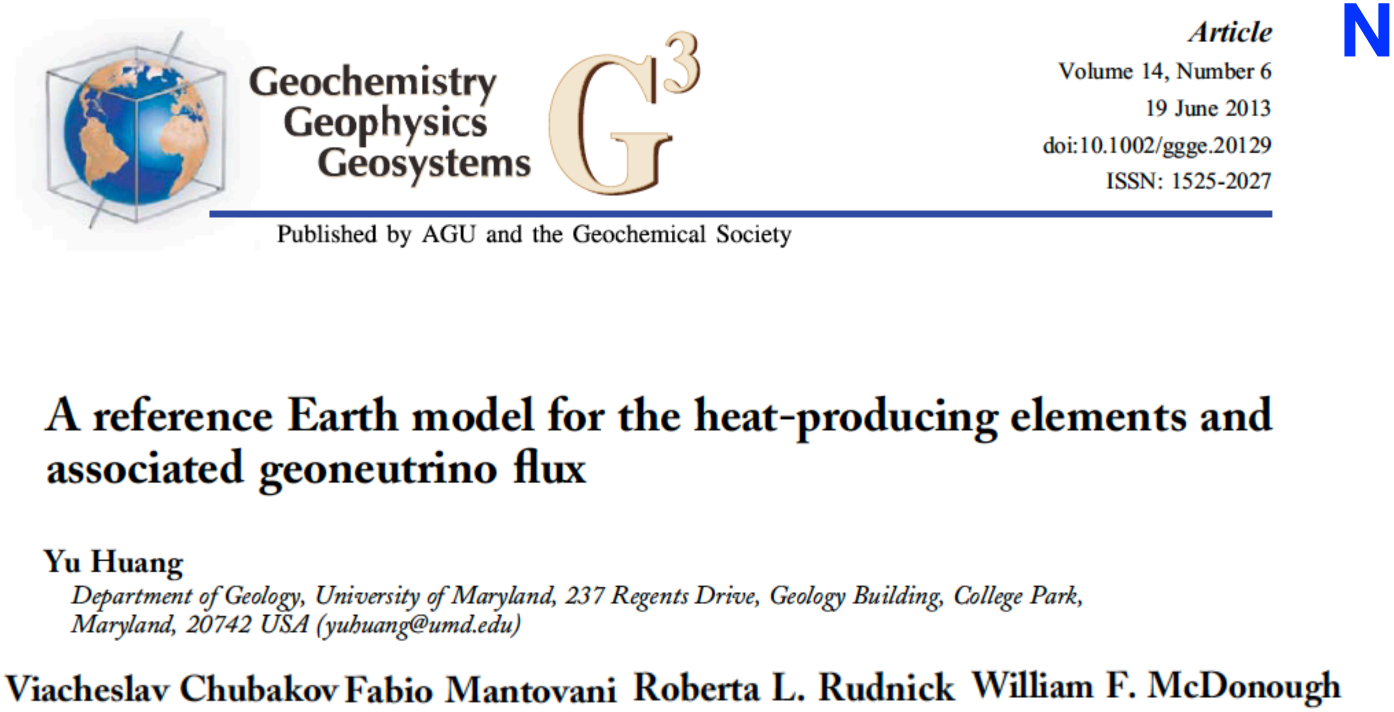
Published by AAAS

Neutrino Geoscience

- Integrating Geology, geophysics and geochemistry
- 3D quantitive modeling of the lithosphere
- Holistic geoscience



Huang Yu, 1st PhD in Neutrino Geoscience



Geochemistry
Geophysics
Geosystems

Article
Volume 14, Number 6
19 June 2013
doi:10.1002/ggge.20129
ISSN: 1525-2027

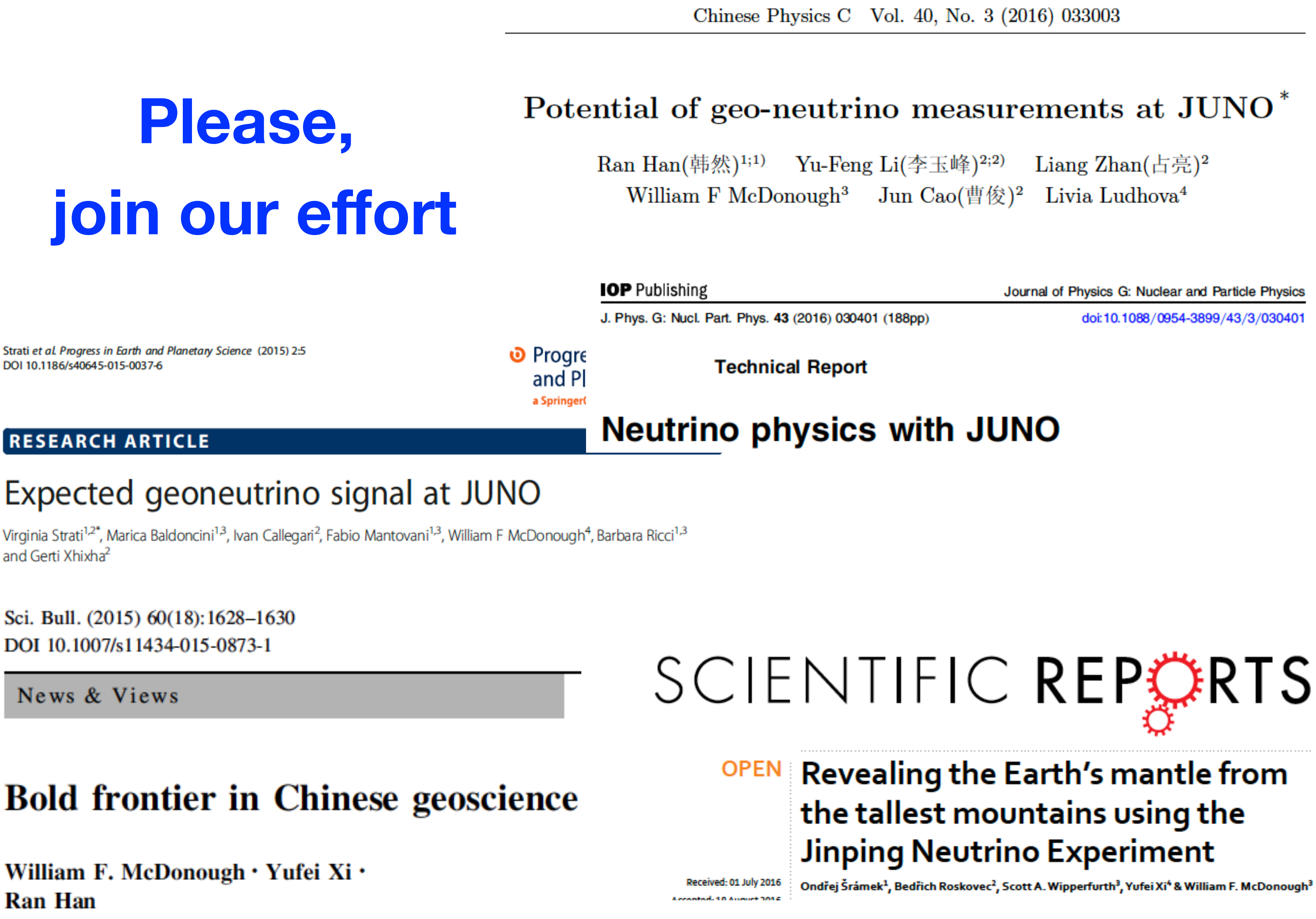
Published by AGU and the Geochemical Society

A reference Earth model for the heat-producing elements and associated geoneutrino flux

Yu Huang
Department of Geology, University of Maryland, 237 Regents Drive, Geology Building, College Park, Maryland, 20742 USA (yuhuang@umd.edu)

Viacheslav Chubakov Fabio Mantovani Roberta L. Rudnick William F. McDonough

Please, join our effort



Chinese Physics C Vol. 40, No. 3 (2016) 033003

Potential of geo-neutrino measurements at JUNO*

Ran Han(韩然)[1;1)] Yu-Feng Li(李玉峰)[2;2)] Liang Zhan(占亮)[2]
William F McDonough[3] Jun Cao(曹俊)[2] Livia Ludhova[4]

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **43** (2016) 030401 (188pp) doi:10.1088/0954-3899/43/3/030401

Technical Report

Neutrino physics with JUNO

Strati *et al. Progress in Earth and Planetary Science* (2015) 2:5
DOI 10.1186/s40645-015-0037-6

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RESEARCH ARTICLE

Expected geoneutrino signal at JUNO

Virginia Strati[1,2*], Marica Baldoncini[1,3], Ivan Callegari[2], Fabio Mantovani[1,3], William F McDonough[4], Barbara Ricci[1,3] and Gerti Xhixha[2]

Sci. Bull. (2015) 60(18):1628–1630
DOI 10.1007/s11434-015-0873-1

News & Views

Bold frontier in Chinese geoscience

William F. McDonough · Yufei Xi · Ran Han

SCIENTIFIC REPORTS

OPEN

Revealing the Earth's mantle from the tallest mountains using the Jinping Neutrino Experiment

Received: 01 July 2016

Ondřej Šrámek[1], Bedřich Roskovec[2], Scott A. Wipperfurth[3], Yufei Xi[4] & William F. McDonough[3]

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2 weeks

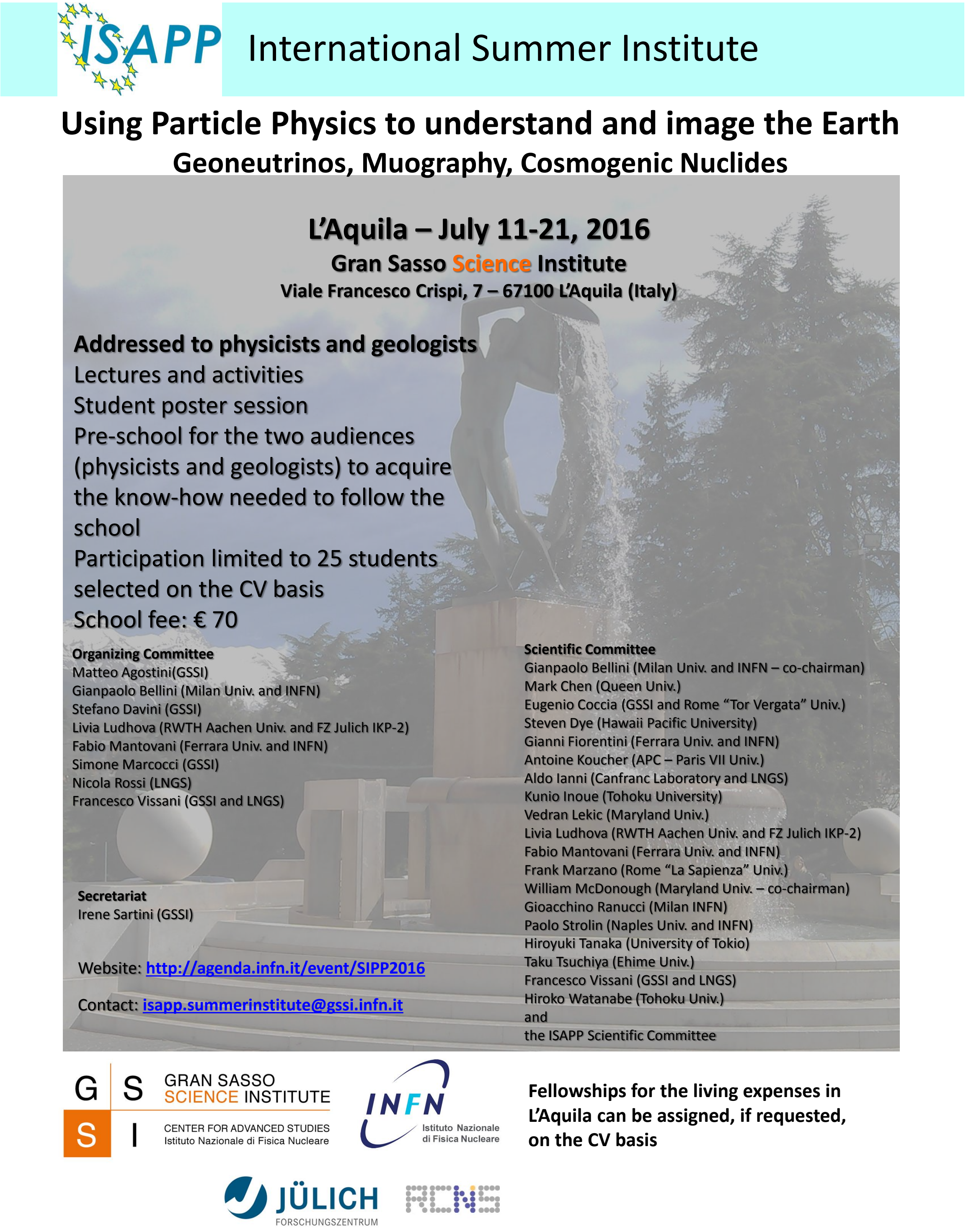
- 1st, July 2016
- L’Aquilia,Italy
- Next, July 2018
- Ferrara, Italy

Organizers:

- Fabio Mantovani
- Bill McDonough

Please come!

:)



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Website: http://agenda.infn.it/event/SIPP2016

Contact: isapp.summerinstitute@gssi.infn.it

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