USING NEUTRINOS TO STUDY THE EARTH

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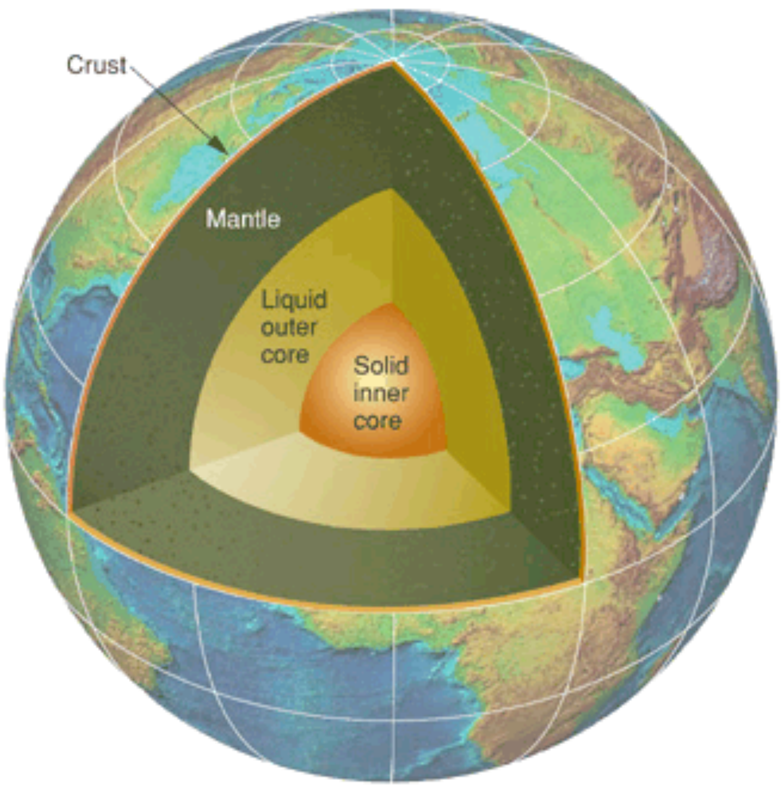
Outline

- Introduction
- Recent results
- The future

Structure of the Earth



- Seismic data splits Earth into 5 basic regions: inner core, outer core, mantle, oceanic crust, and continental crust.
- All these regions are solid except the outer core.

Convection in the Earth

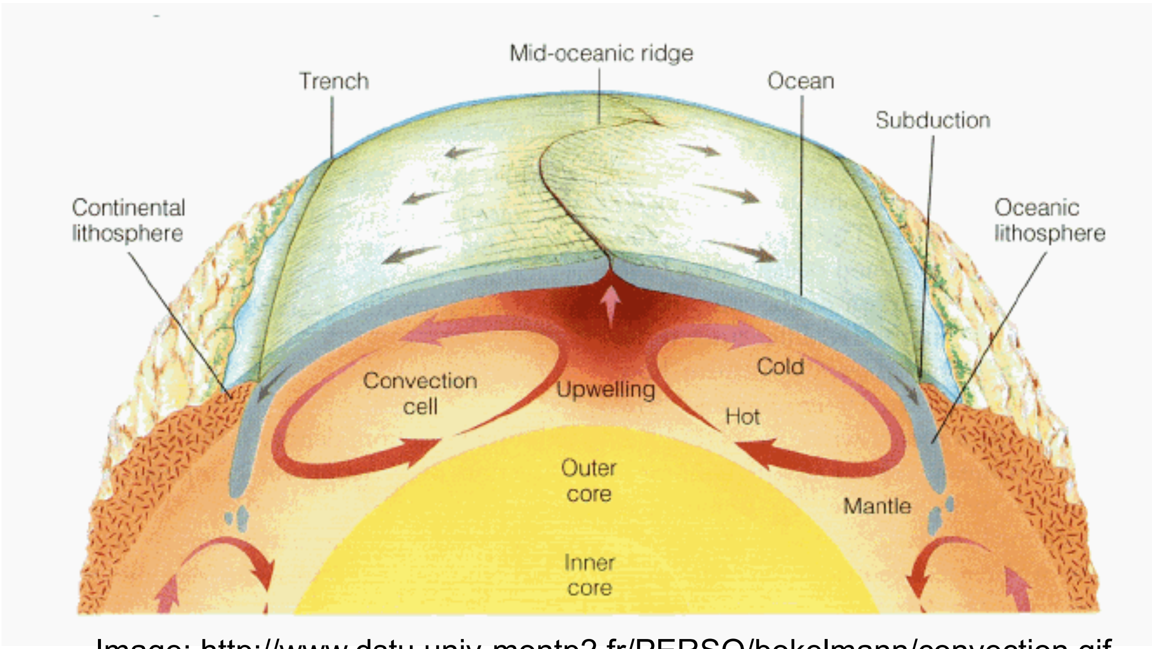


Image: http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

- The mantle convects even though it is solid.
- It is responsible for the plate tectonics and earthquakes.
- Oceanic crust is being renewed at mid-ocean ridges and recycled at trenches.

Heat flow from the Earth

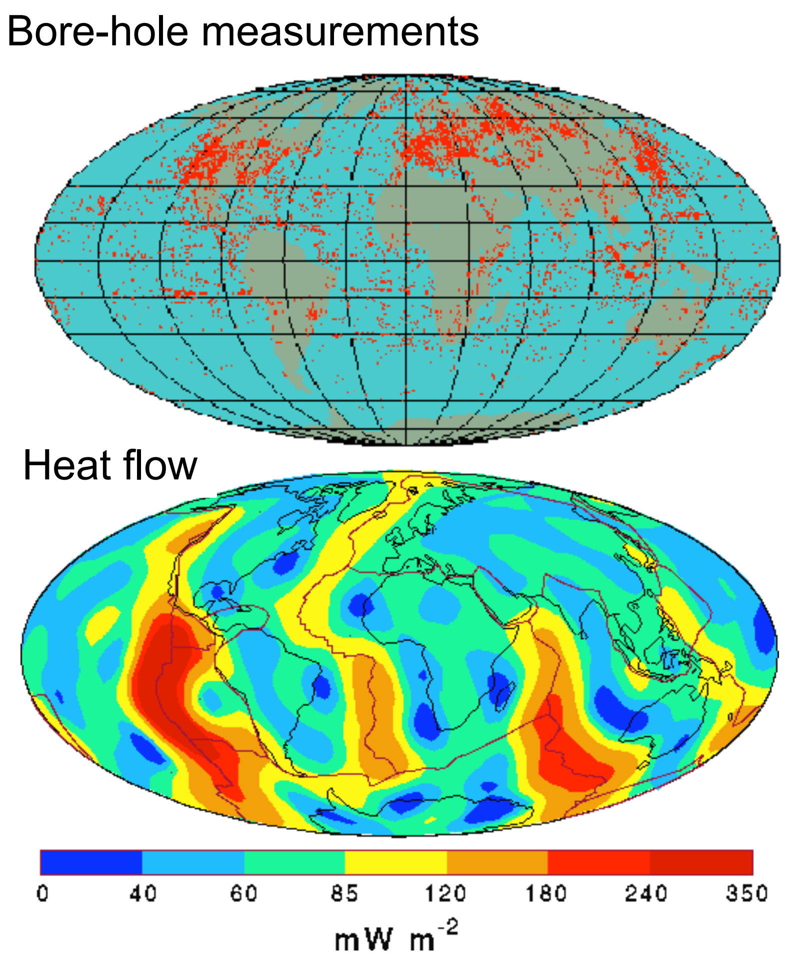
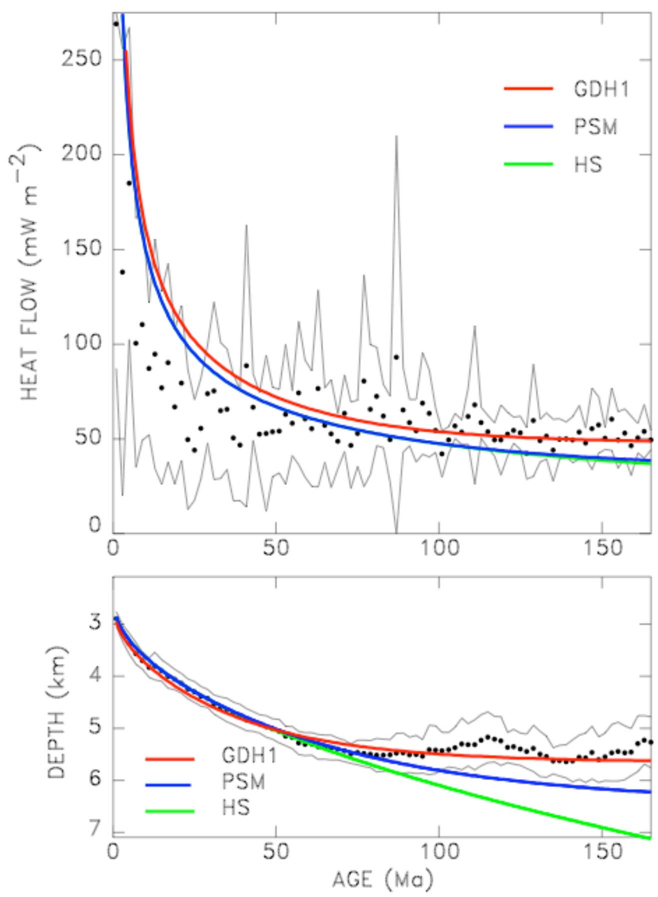


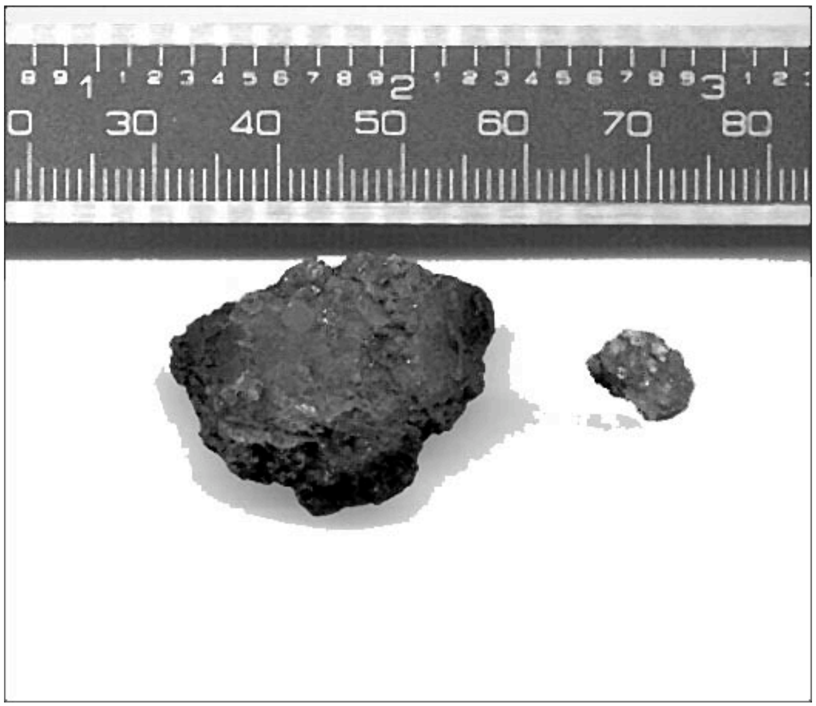
Image: Pollack *et. al*

- Conductive heat flow measured from bore-hole temperature gradient and conductivity
- Total heat flow 44.2±1.0TW (87mW/m^2), or 31±1TW (61mW/m^2) according to more recent evaluation of same data despite the small quoted errors.

Oceanic crust heat flow



Radiogenic heat

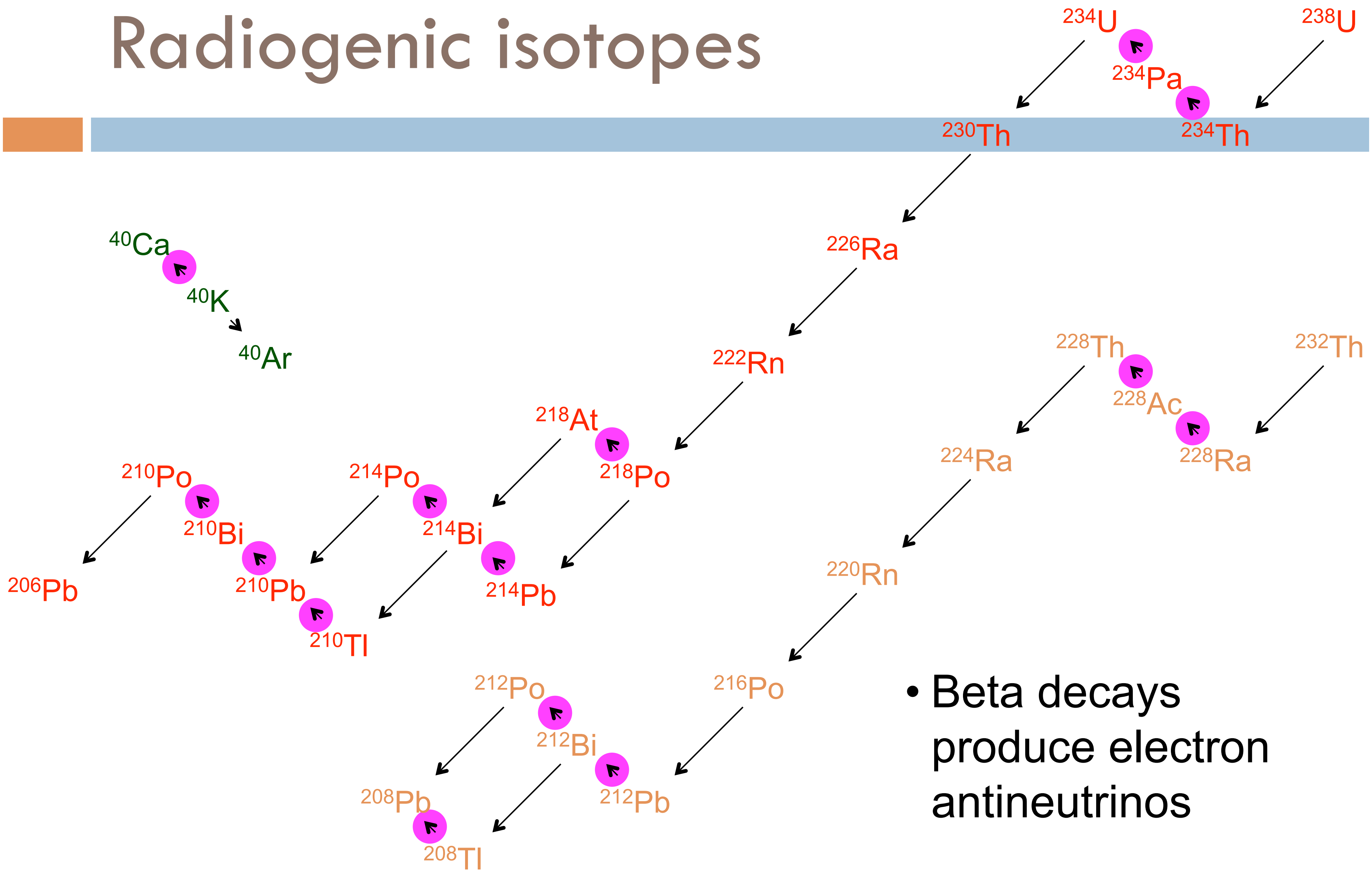


- U, Th, and K concentrations in the Earth are based on measurement of chondritic meteorites
- Chondritic meteorites consist of elements similar to those in the solar photosphere
- U, Th, and K concentrations in Bulk Silicate Earth (BSE) are 20ppb, 80ppb, and 240ppm, respectively
- This results in U, Th, and K heat production of 8TW, 8TW, and 3TW, respectively.

Discrepancy?

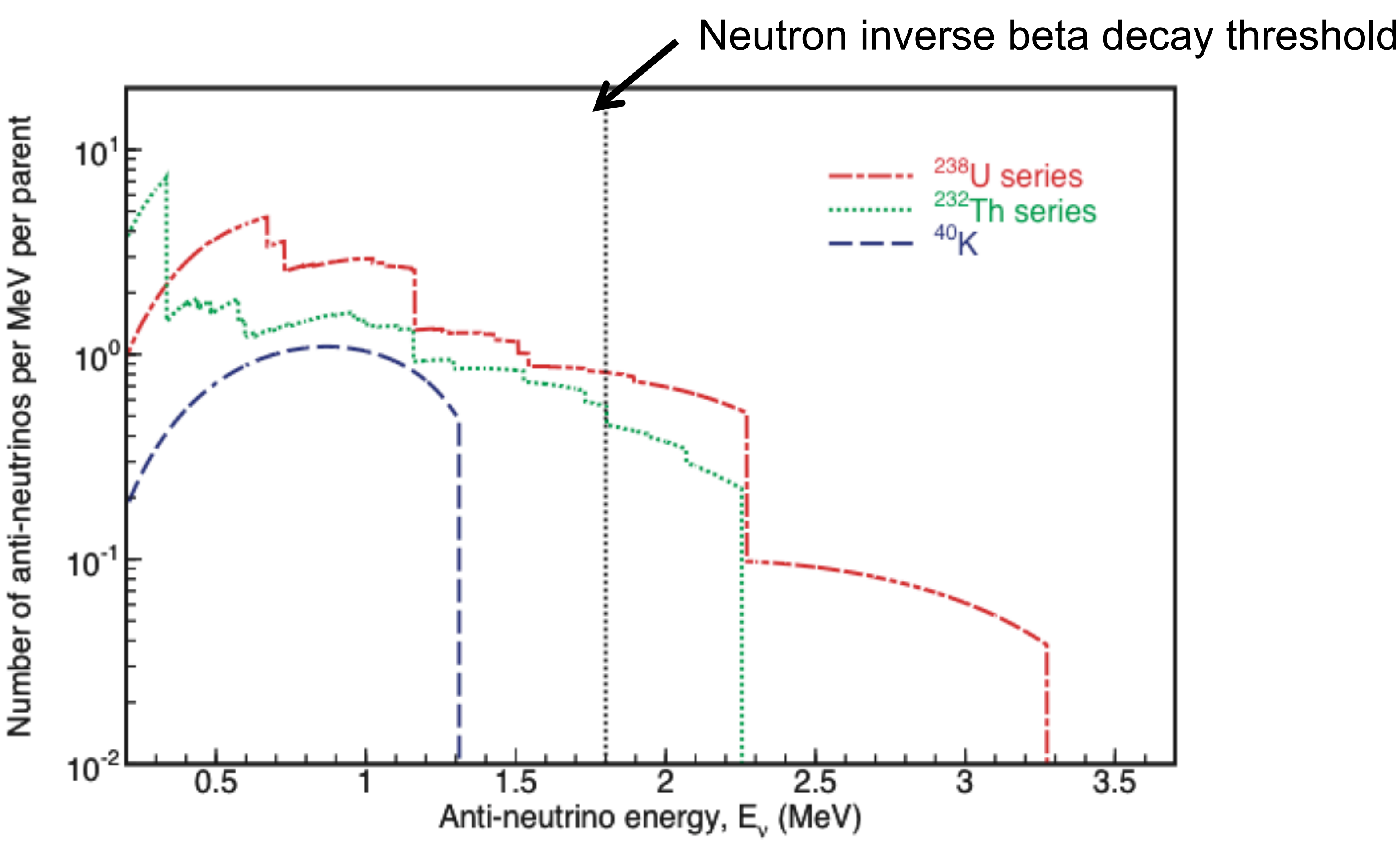
- The measured total heat flow is 44 or 31 TW.
- The estimated radiogenic heat produced is 19 TW.
- Models of mantle convection suggest that the radiogenic heat production rate should be a large fraction of the measured heat flow.
- Problem with
  - Mantle convection model?
  - Total heat flow measured?
  - Estimated amount of radiogenic heat production rate?
- Geoneutrinos can serve as a cross-check of the radiogenic heat production.

Radiogenic isotopes



- Beta decays produce electron antineutrinos

Geoneutrino signal



The expected geoneutrino flux

- The geoneutrino flux per unit energy is given by

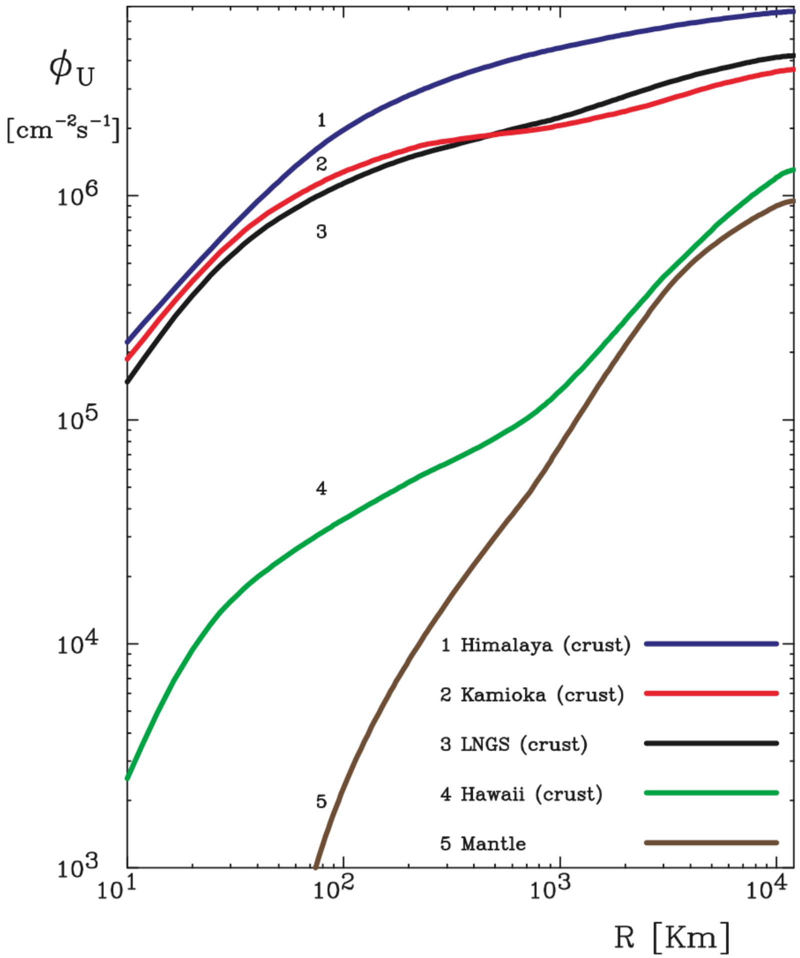
$$\frac{d\Phi}{dE_\nu}(E_\nu) \approx A \frac{dn}{dE_\nu} \int_\oplus d\mathbf{L} \frac{a(\mathbf{L})\rho(\mathbf{L})P(E_\nu, |\mathbf{r}-\mathbf{L}|)}{4\pi|\mathbf{L}|^2}$$

- A is the decay rate per unit mass
- $\frac{dn}{dE_\nu}$ is the number of antineutrinos per decay chain per unit energy
- $a(\mathbf{L})$ is the mass concentration as a function of position in the Earth
- ρ(L) is the density as a function of position in the Earth
- $P(E_\nu, |\mathbf{r}-\mathbf{L}|)$ is the survival probability due to neutrino oscillations

U and Th in the Earth

- U and Th are thought to be absent from the core and present in the mantle and crust.
  - The core is mainly Fe-Ni alloy.
  - U and Th are lithophile (rock-loving), and not siderophile (metal-loving) elements.
- U and Th concentrations are highest in the continental crust.
- Th/U ratio of 3.9 is known better than the absolute concentrations.

Local contribution



Mantovani F. *et. al* Phys Rev D **69** (2004) 013001

- On continental crust approximately 50% of the flux comes from the surrounding 500km.

Georeactor

- It has been hypothesized that a blob of uranium is located at the center of the Earth.
- This could then form a natural nuclear reactor produce up to 6TW of heat powering the Earths dynamo.
- This could explain the observed anomaly in the $^3He/^4He$ ratio.
- The only way to test this hypothesis directly is to observe the neutrinos produced by this reactor.

Have geoneutrinos been seen?

Fred Reines' neutrino detector (circa 1953)

Santa Fe
The Chief

Dear Fred,

Just accured to me that your background neutrinos my just be comming from high energy β-decaying members of U and Th families in the crust of the Earth. Do not have on the train any inform. to check it up, but it seems the order of magn. is resonable. In fact the total ~~energy~~ radioactive energy production under one square foot of surface may well be equal to the energy of sollar radiation falling on ~~Earth~~ that surface ... what do you think?

Write to me at: The Union Univ. of Mich. Ann Arbor. Mich

Yours Geo.

By Gamow in 1953

Were they geoneutrinos?

TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:

~30TW

FROM NUMBERS IN UREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/CM^{2}SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 Mev NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^5 OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS: I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRONS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

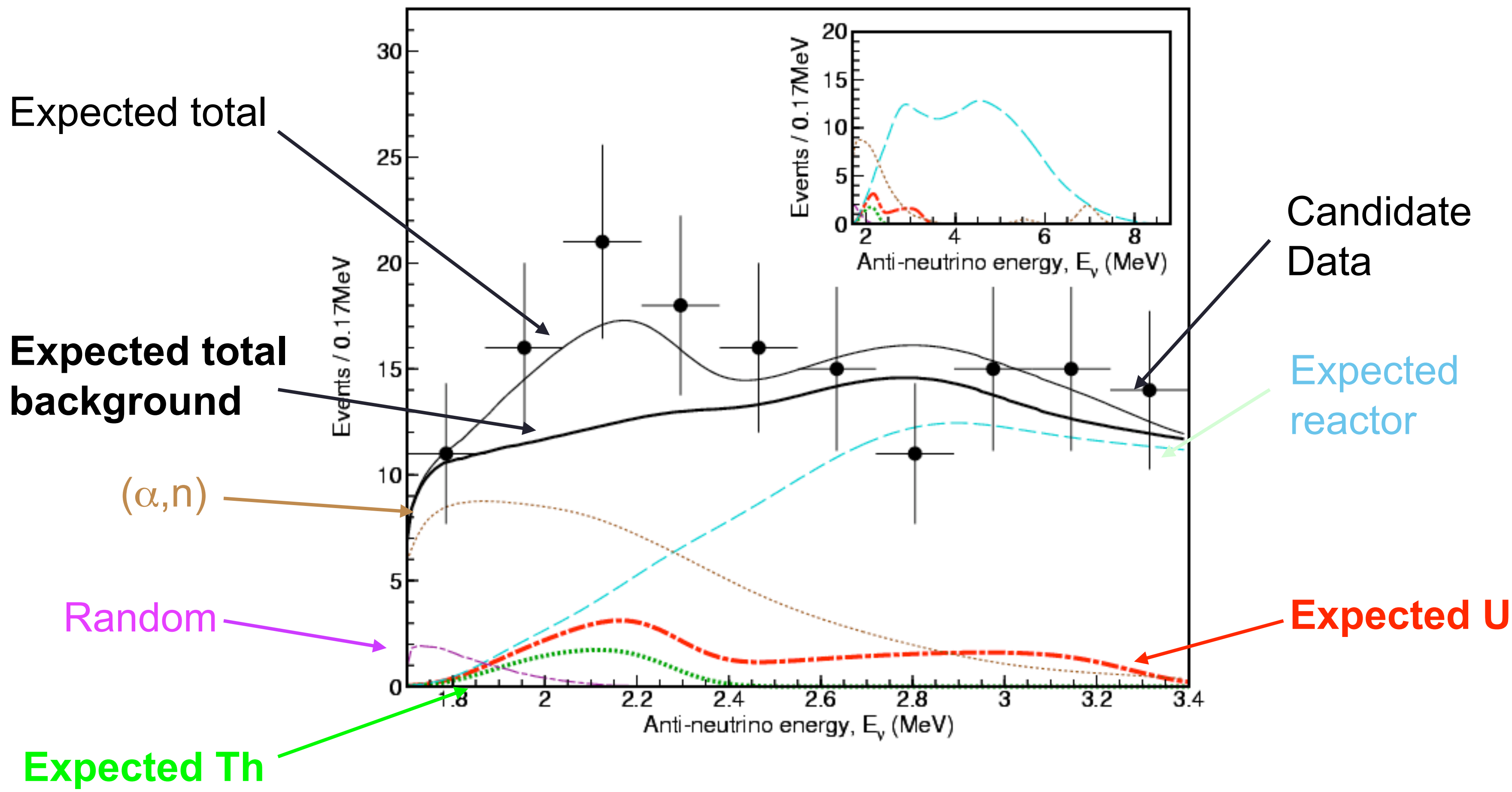
Recent geoneutrino results

First results from KamLAND

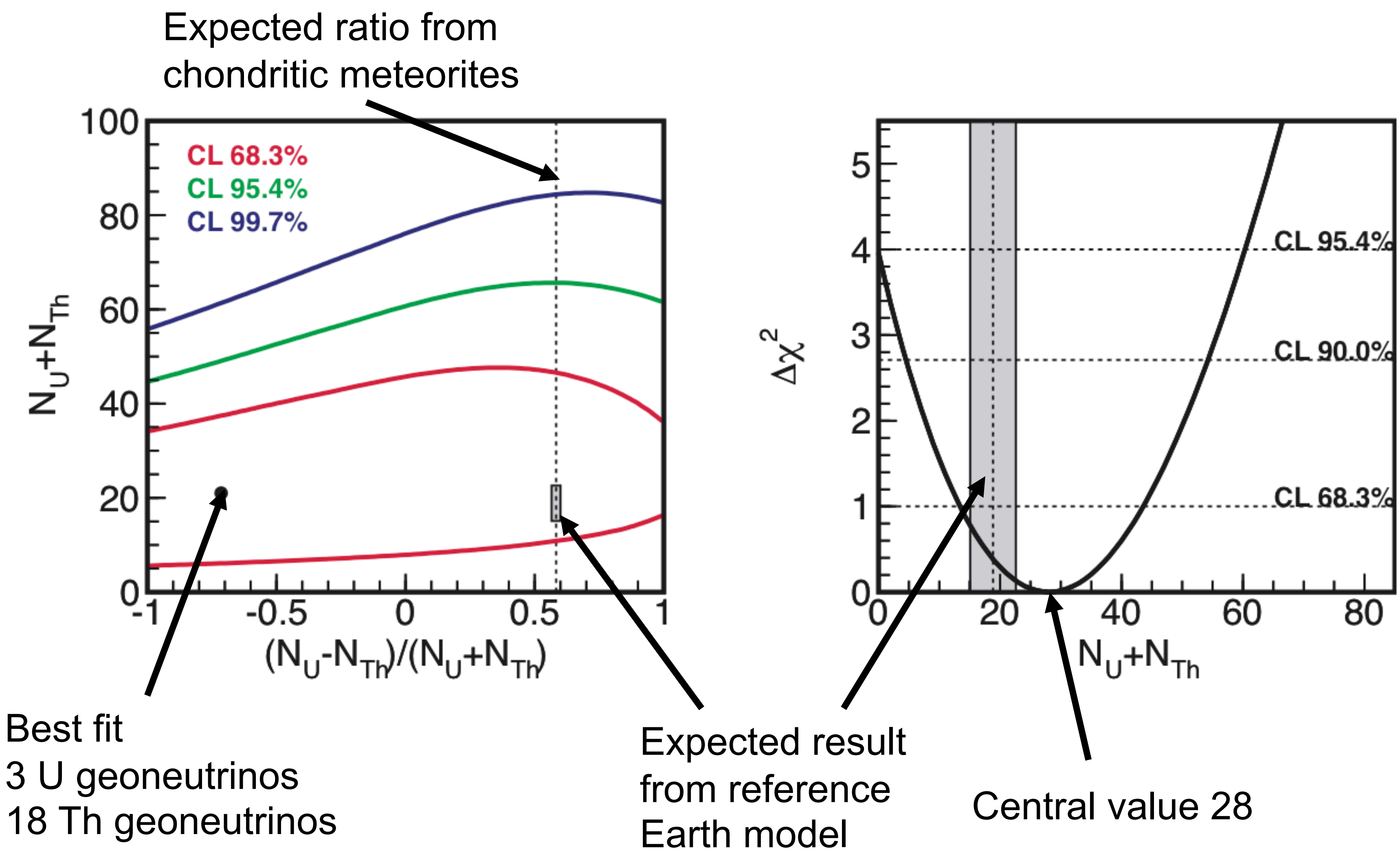
- From March, 2002 to October, 2004.
- 749.1 $\pm$ 0.5 day of total live-time.
- (3.46 $\pm$ 0.17) $\times$ 10^{31} target protons, 5m radius fiducial volume.
- 0.687 $\pm$ 0.007 of the total efficiency for geoneutrino detection.
- Expect 14.8 $\pm$ 0.7 ^{238}U geoneutrinos and 3.9 $\pm$ 0.2 ^{232}Th geoneutrinos.
- 152 candidate events
- 127 $\pm$ 13 background events.

Nature **436**, 499-503 (28 July 2005)

Candidate energy distribution

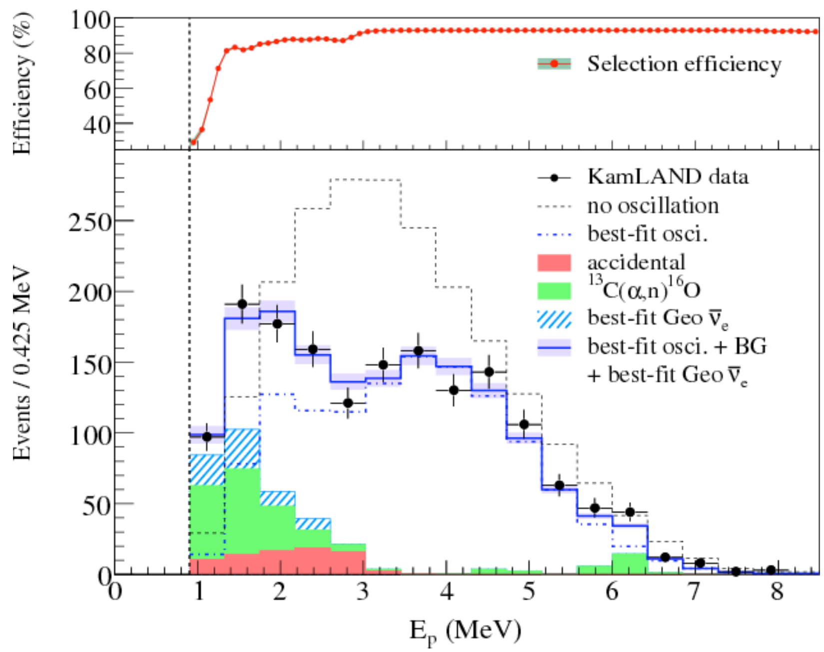


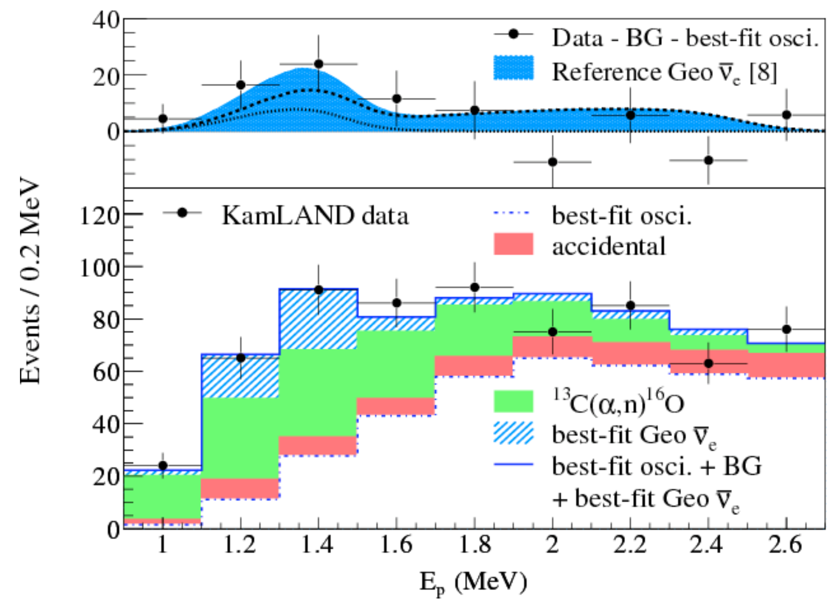
How many geoneutrinos?



Updated KamLAND results

PRL 100, 221803 (2008)





7.09×10^{32} proton･year ➔ 24.4×10^{32} proton･year

Number of Geoneutrinos : 73 ± 27

Total U and Th content

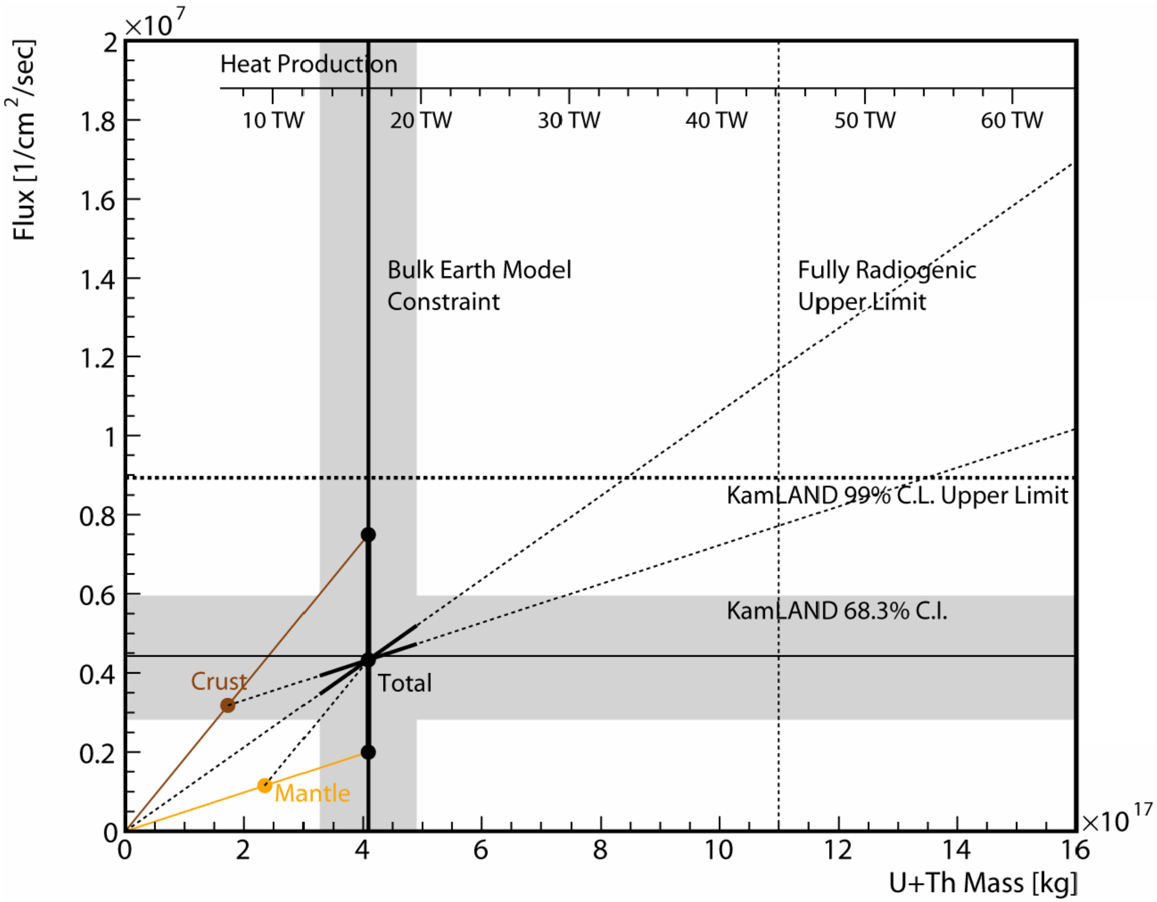
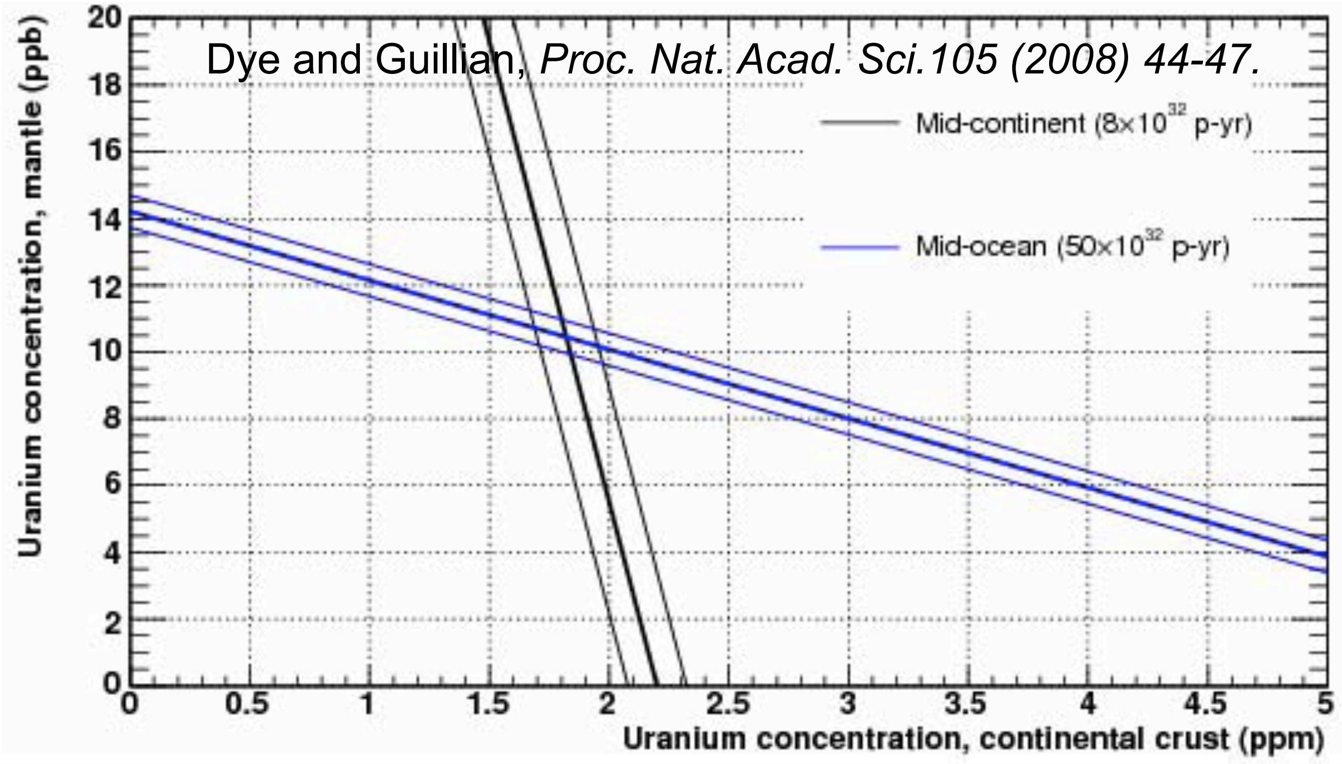


Image: S. Enomoto, Neutrino Geoscience 2008

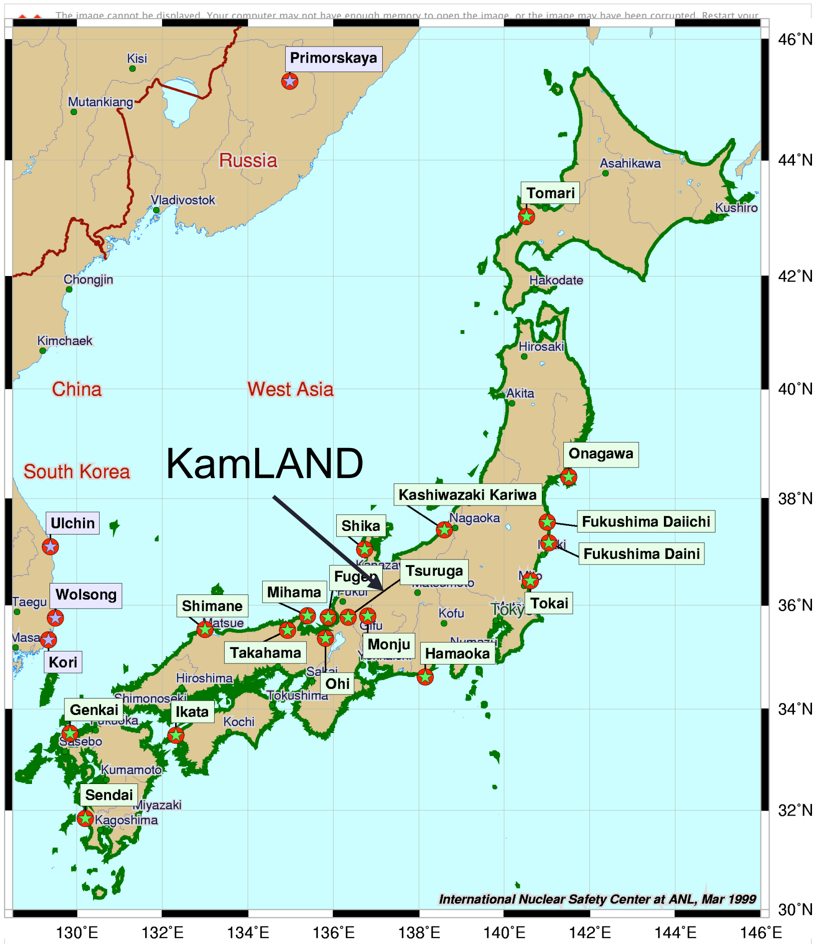
The future

Need for at least two detectors



- The heat flow in the lower and middle crust is not very well constrained and multiple measurements on different types of continental crust would also be extremely useful.

KamLAND and geoneutrinos



- KamLAND was designed to measure reactor antineutrinos, these are the most significant background and are irreducible.
- Reactor antineutrino signals are identical to geoneutrinos except for the prompt energy spectrum.
- Working on purifying the liquid scintillator, which will reduce the (α,n) background events.

Get away from reactors

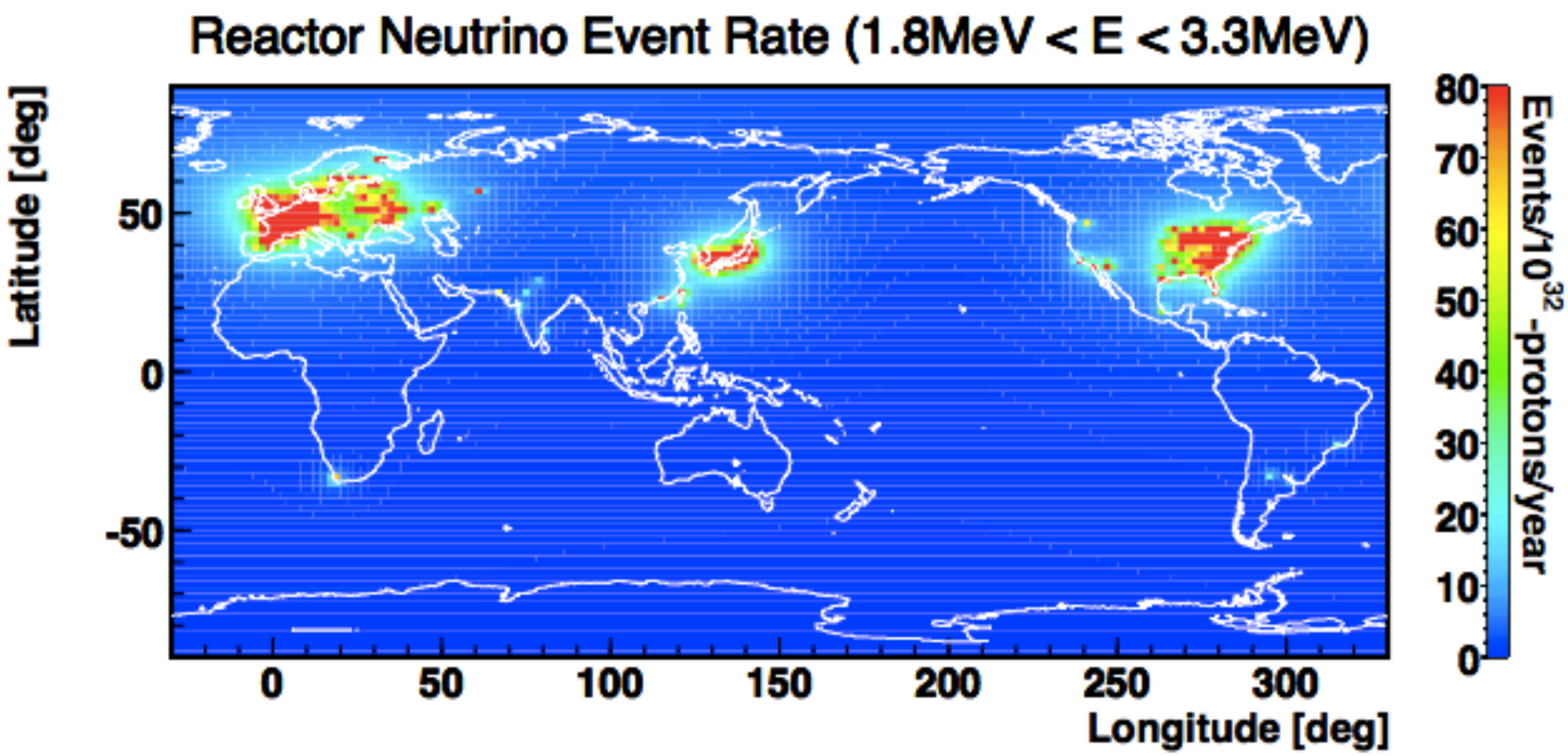


Image: S. Enomoto

Future experiments

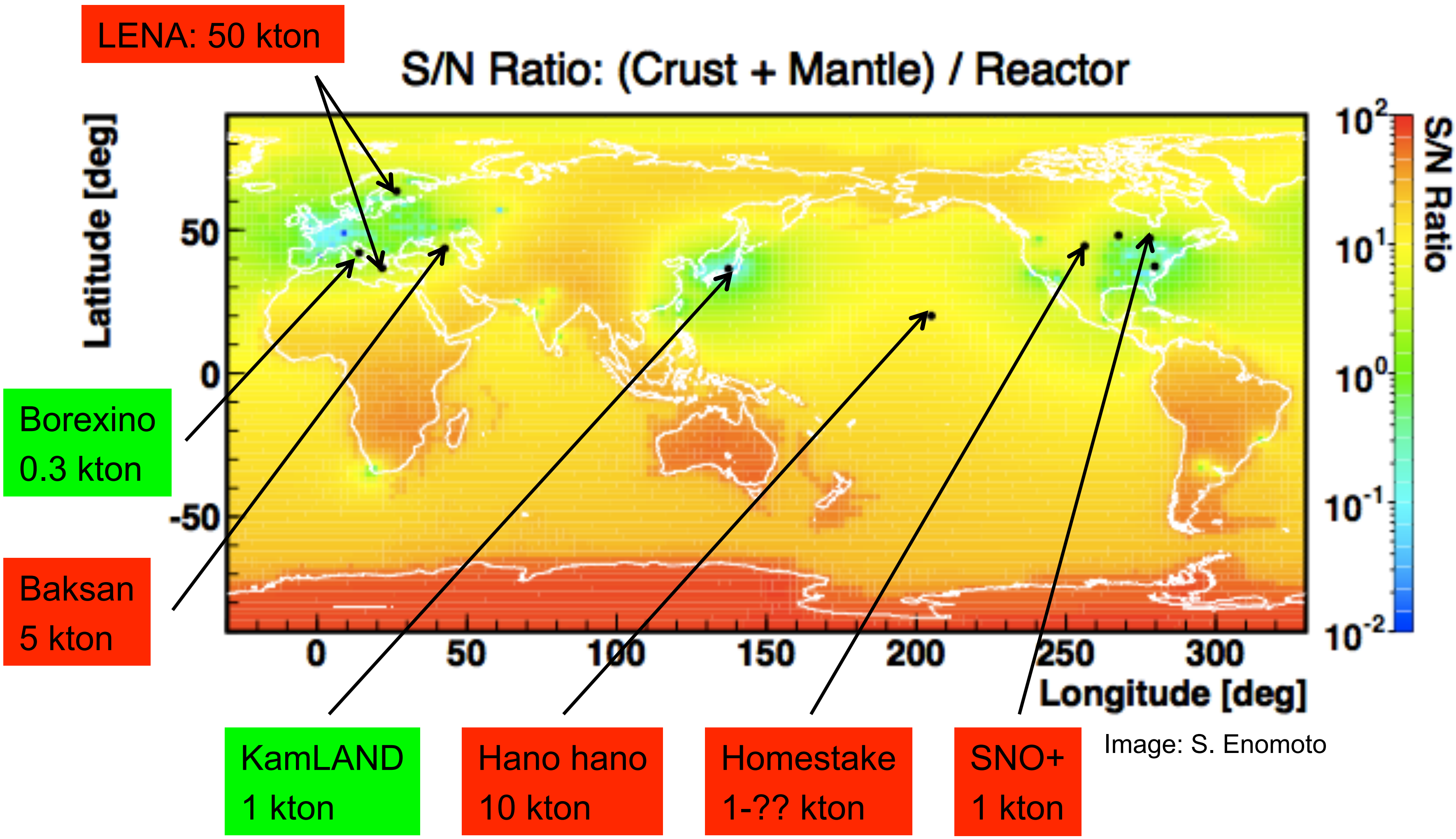


Image: S. Enomoto

Sensitivity to the mantle

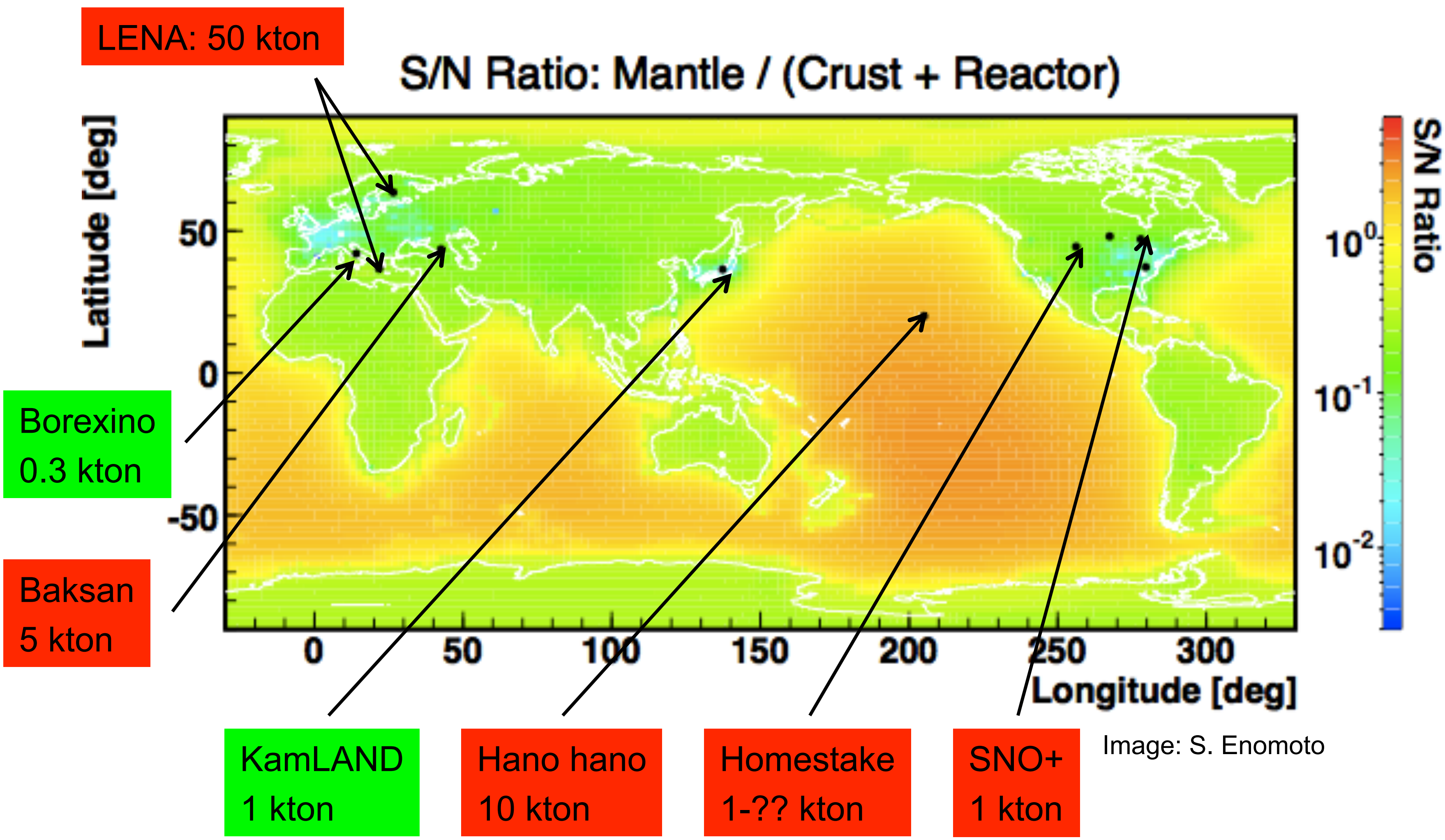
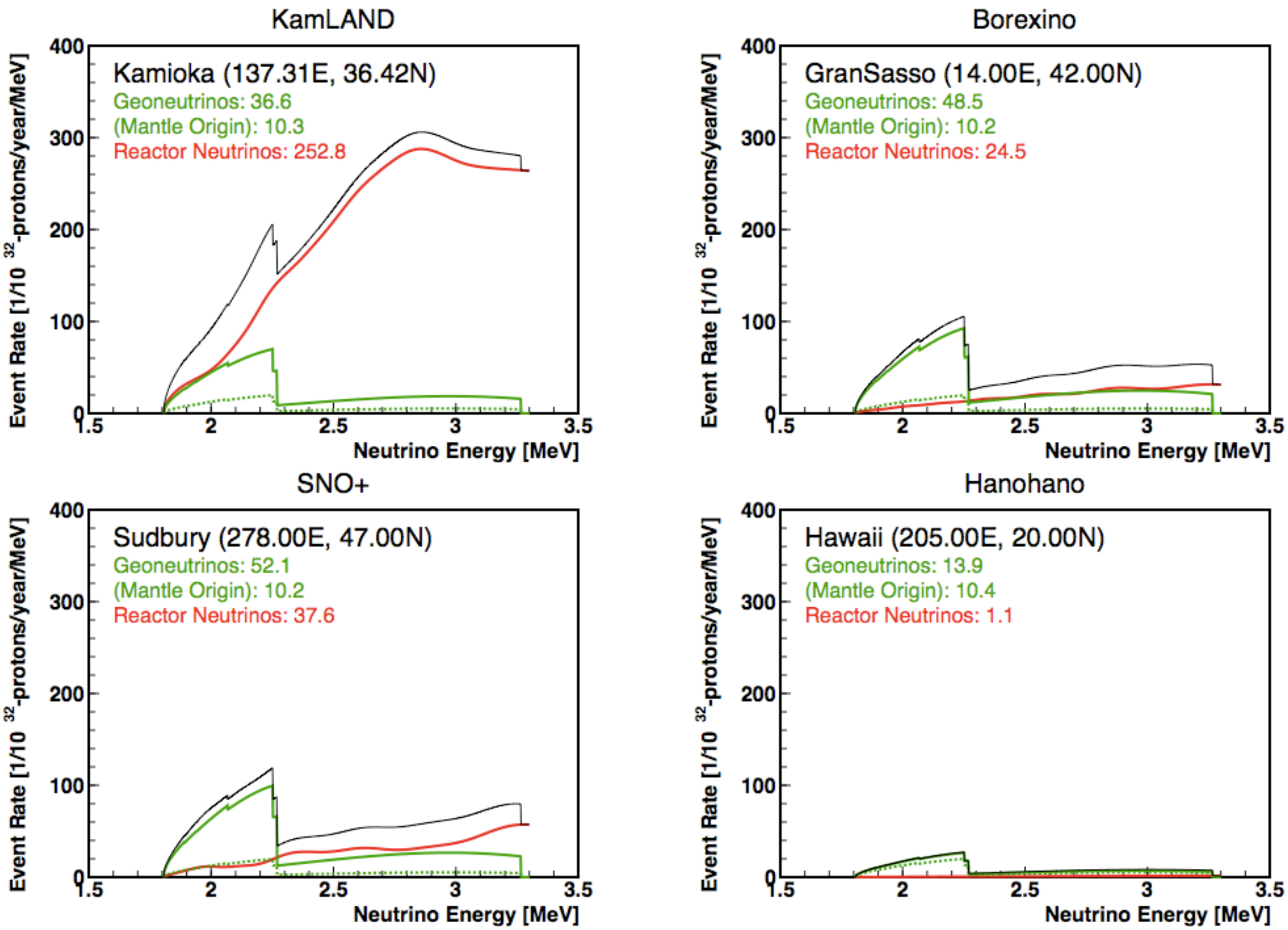


Image: S. Enomoto

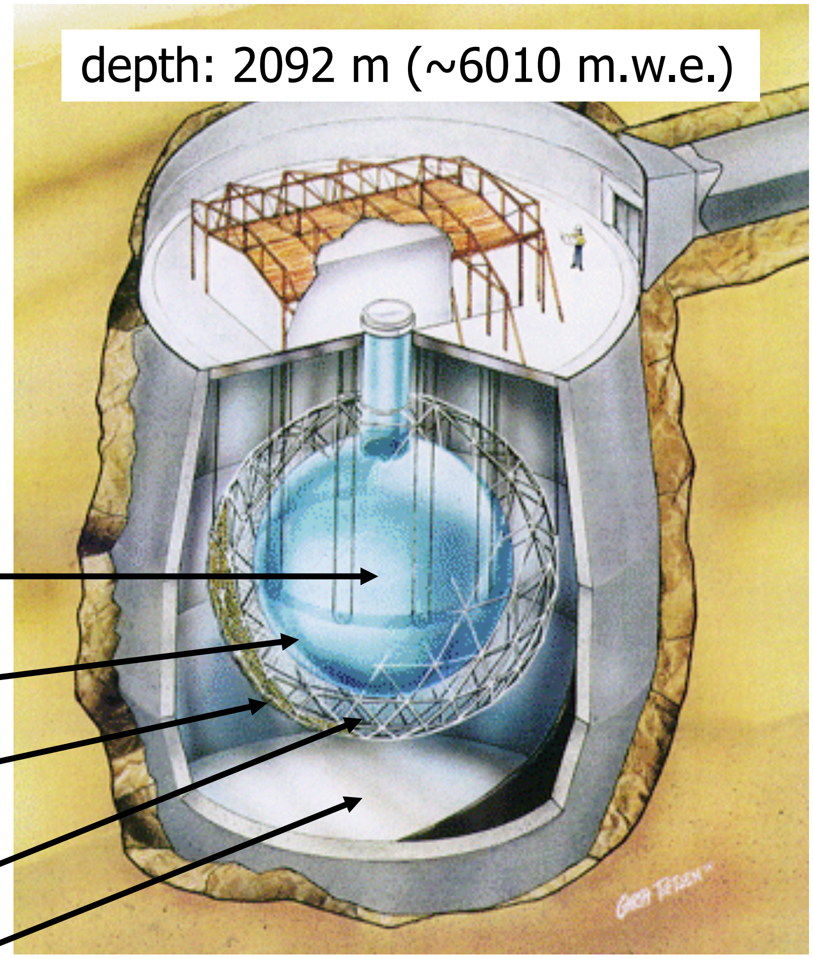
Expected signals



Images: S. Enomoto

SNO+

- Physics goals:
  - pep and CNO solar neutrinos
  - geoneutrinos
  - reactor neutrino oscillations
  - supernova neutrinos
  - double beta decay with Nd



Replace 1 kton of D_2O in SNO with liquid scintillator (2011)

12 m diameter acrylic vessel

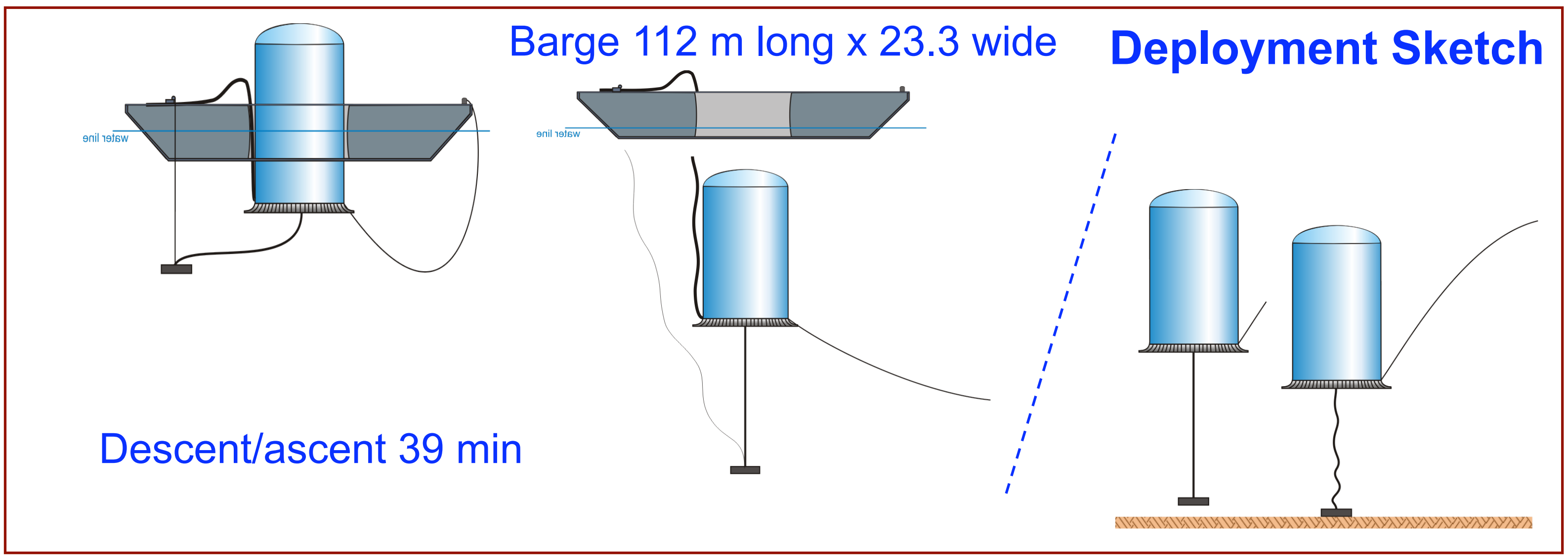
18 m diameter support structure; 9500 PMTs (~60% coverage)

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Hanohano

- Physics goals:
  - precise oscillation measurement
  - geoneutrinos
  - solar neutrinos
  - proton decay
  - supernova neutrinos
- Deploy and recover portable 10 kt scintillator
- Design study completed 2006



Far future

- The next generation of detectors can determine the total U and Th content in the mantle and the crust, but will have a hard time determining the distribution within those regions
  - Can we build a geoneutrino detector sensitive to the neutrino direction?
- ^{40}K also contributes to the total radiogenic heating of the Earth, and could play an important part in the core dynamics
  - Can we build a geoneutrino detector sensitive to neutrinos from ^{40}K decay?

Conclusions

- Geoneutrinos allow us to measure the total U and Th content of the Earth, which is believed to be the most significant heat source
- KamLAND
  - observed 73 $\pm$ 27 geoneutrinos
  - consistent with the current geological models
- Borexino
  - currently collecting data
  - because of size this will likely be statistics limited.
- SNO+
  - will principally be a double beta decay experiment
  - will likely be the next operational geoneutrino experiment
- To help break the degeneracy between geoneutrinos from the mantle and the crust we should also build a detector on the ocean floor, such as Hanohano