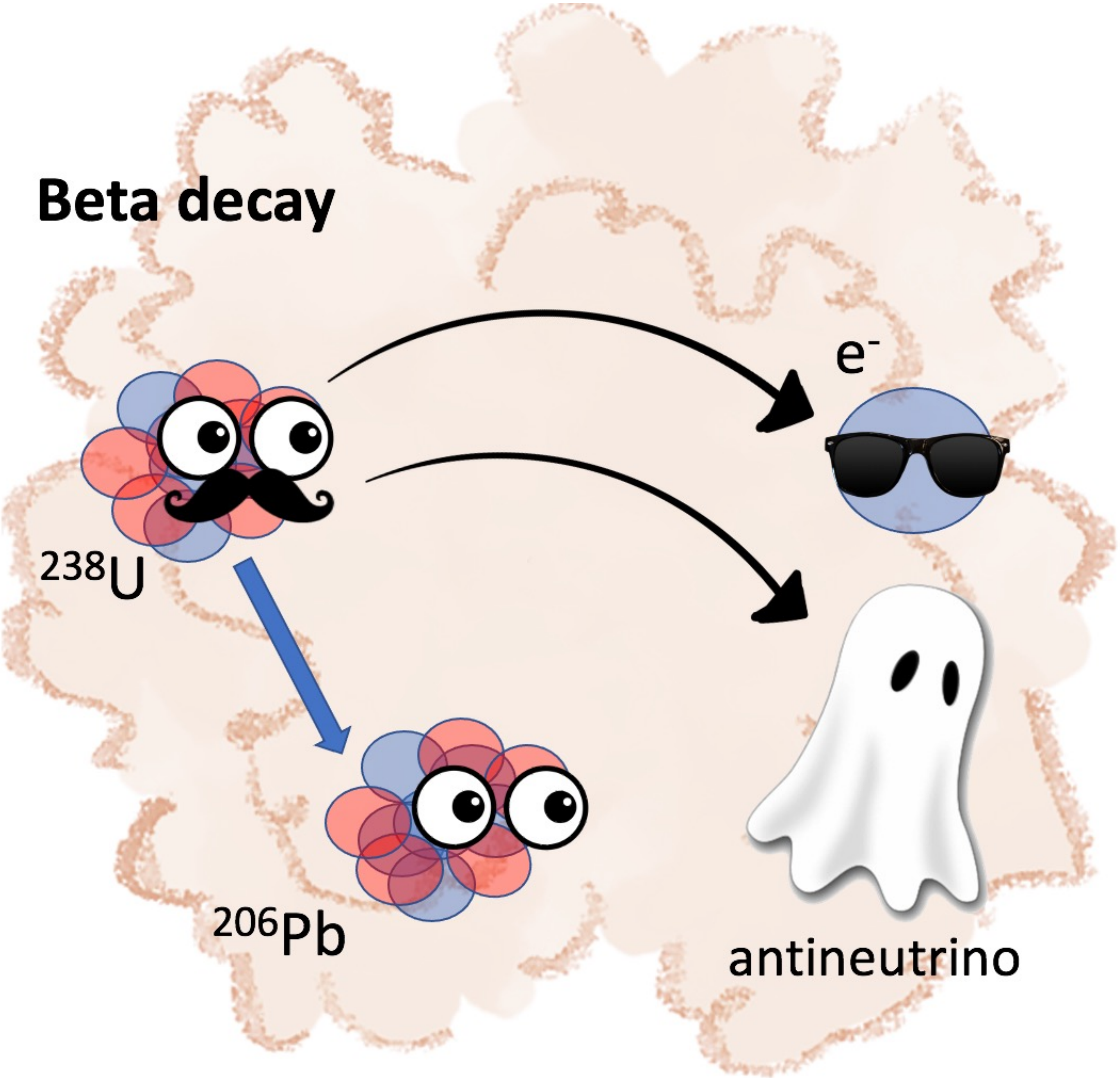
2022-08-07

What can neutrinos do for geoscience?

Ingrida Semenec (she/her)
Queen's University

What is a geoneutrino?



Electron-antineutrinos from natural radioactive decays

$^{238}_{92}U \rightarrow ^{206}_{82}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.689$ MeV (99.2739% of natural U)

$^{235}_{92}U \rightarrow ^{207}_{82}Pb + 7\alpha + 7e^- + 7\bar{\nu}_e + 46.402$ MeV (0.7205% of natural U)

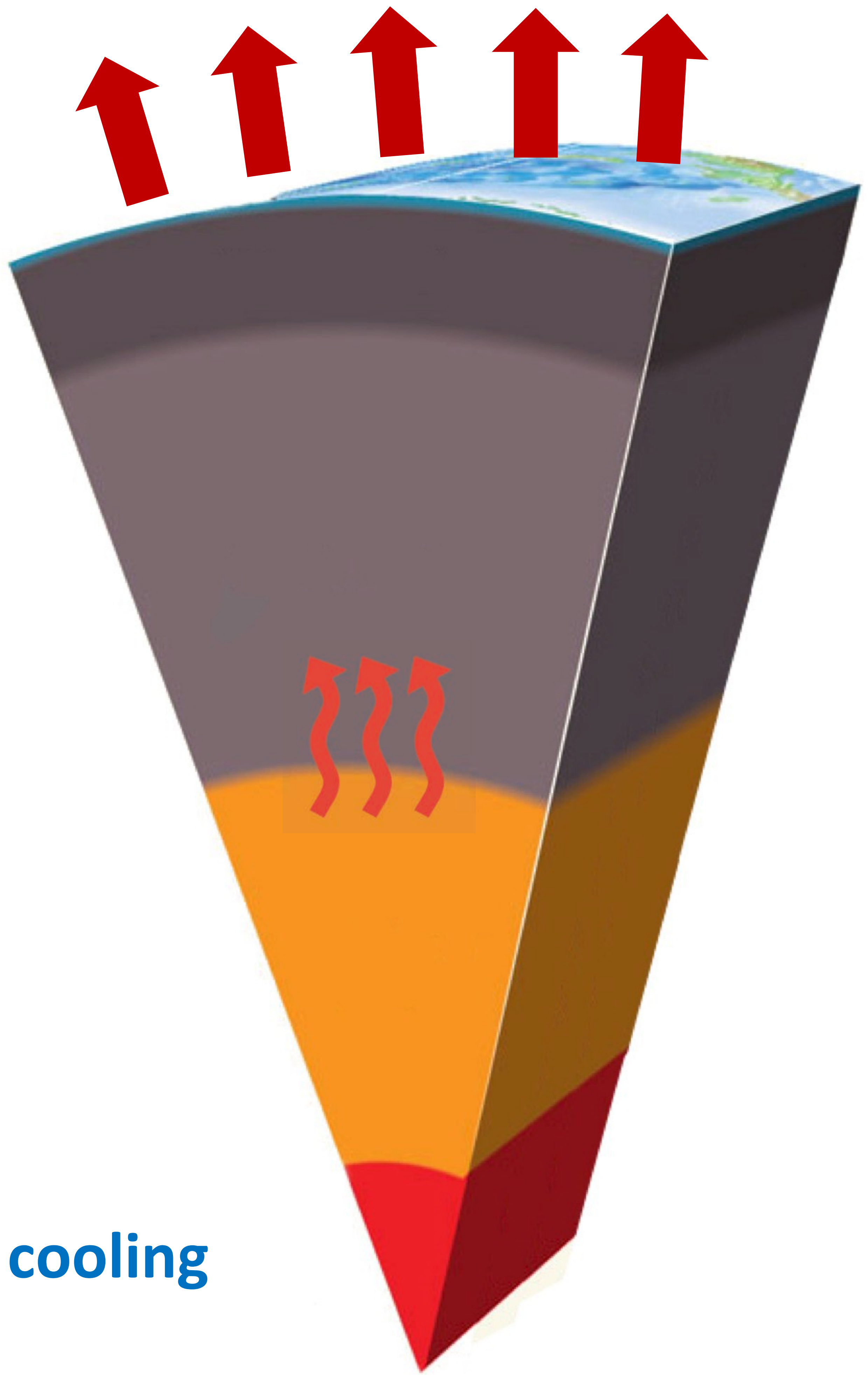
$^{232}_{90}Th \rightarrow ^{208}_{82}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652$ MeV

$^{40}_{19}K \rightarrow ^{40}_{20}Ca + e^- + \bar{\nu}_e + 1.311$ MeV (0.012% of natural K)

$^{40}_{19}K + e^- \rightarrow ^{40}_{18}Ar + \nu_e + 1.505$ MeV

Heat budget of the Earth

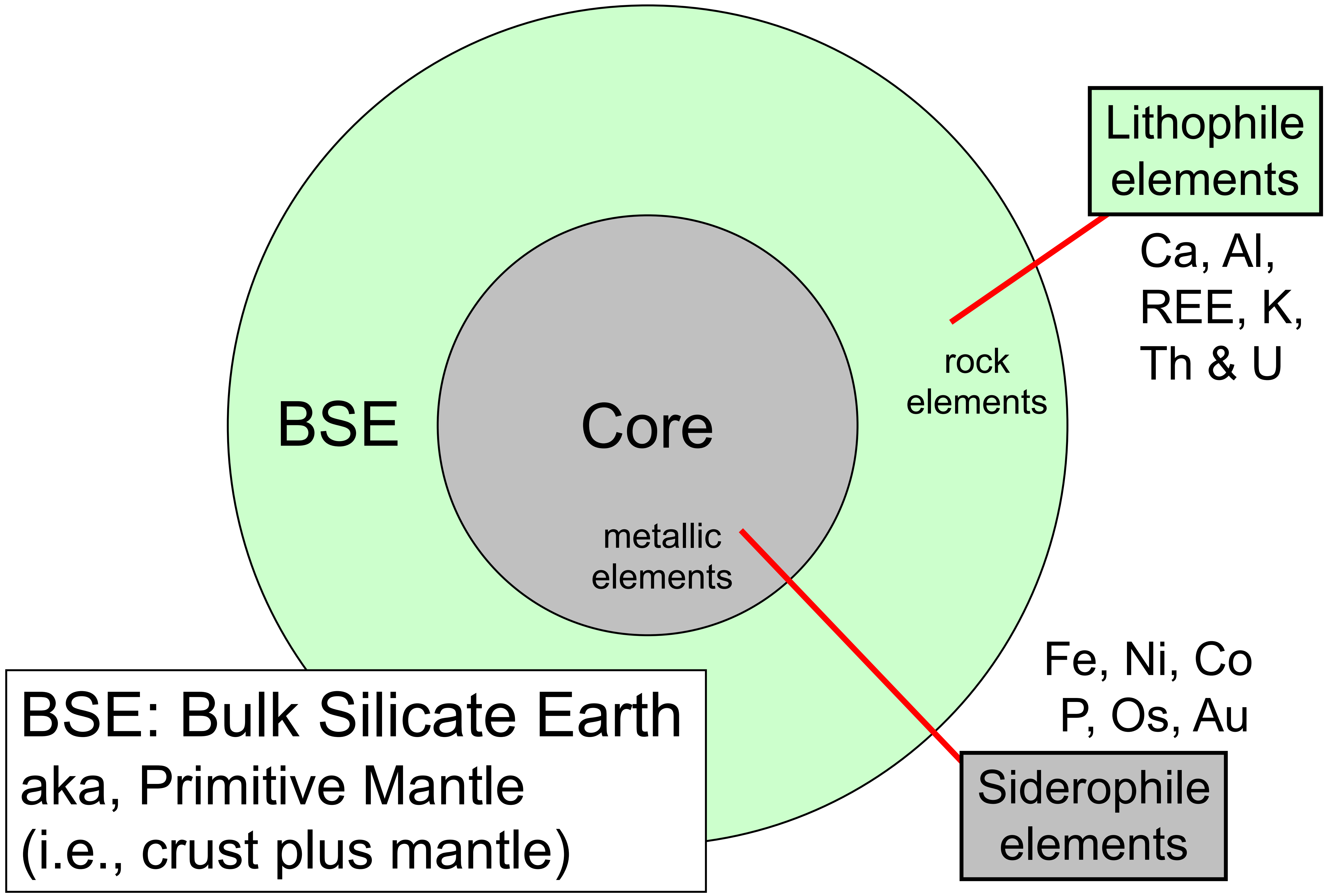
Total Amount of Surface Heat Flow = 46 ± 3 TW = Radiogenic heat + Cooling of the interior = Crustal heat production + Mantle heat production + Mantle cooling + CMB heat flow + Inner core growth + core cooling



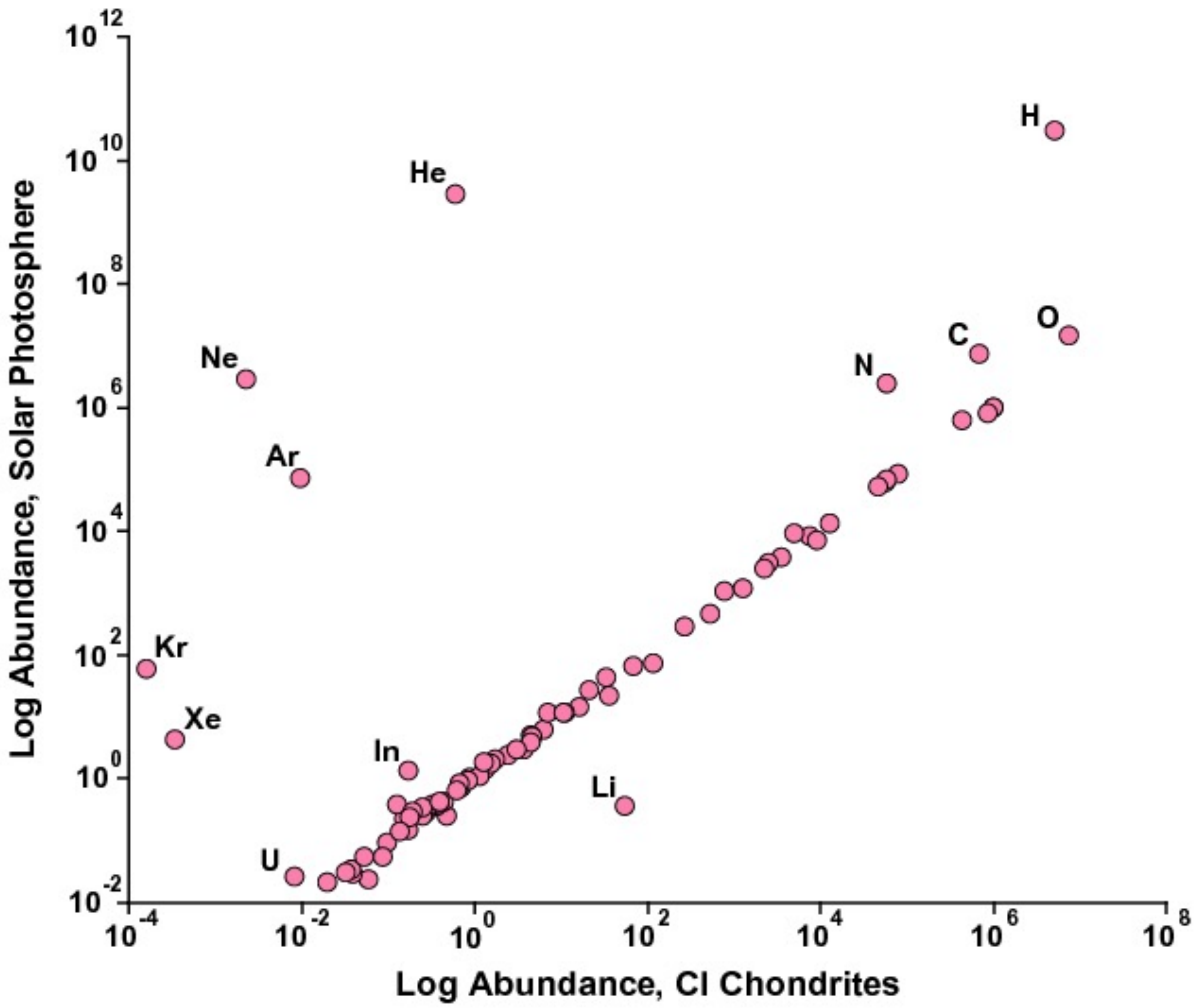
https://doi.org/10.1016/j.tecto.2012.12.001.

Bulk Silicate Earth Models

Element Distribution in the Earth

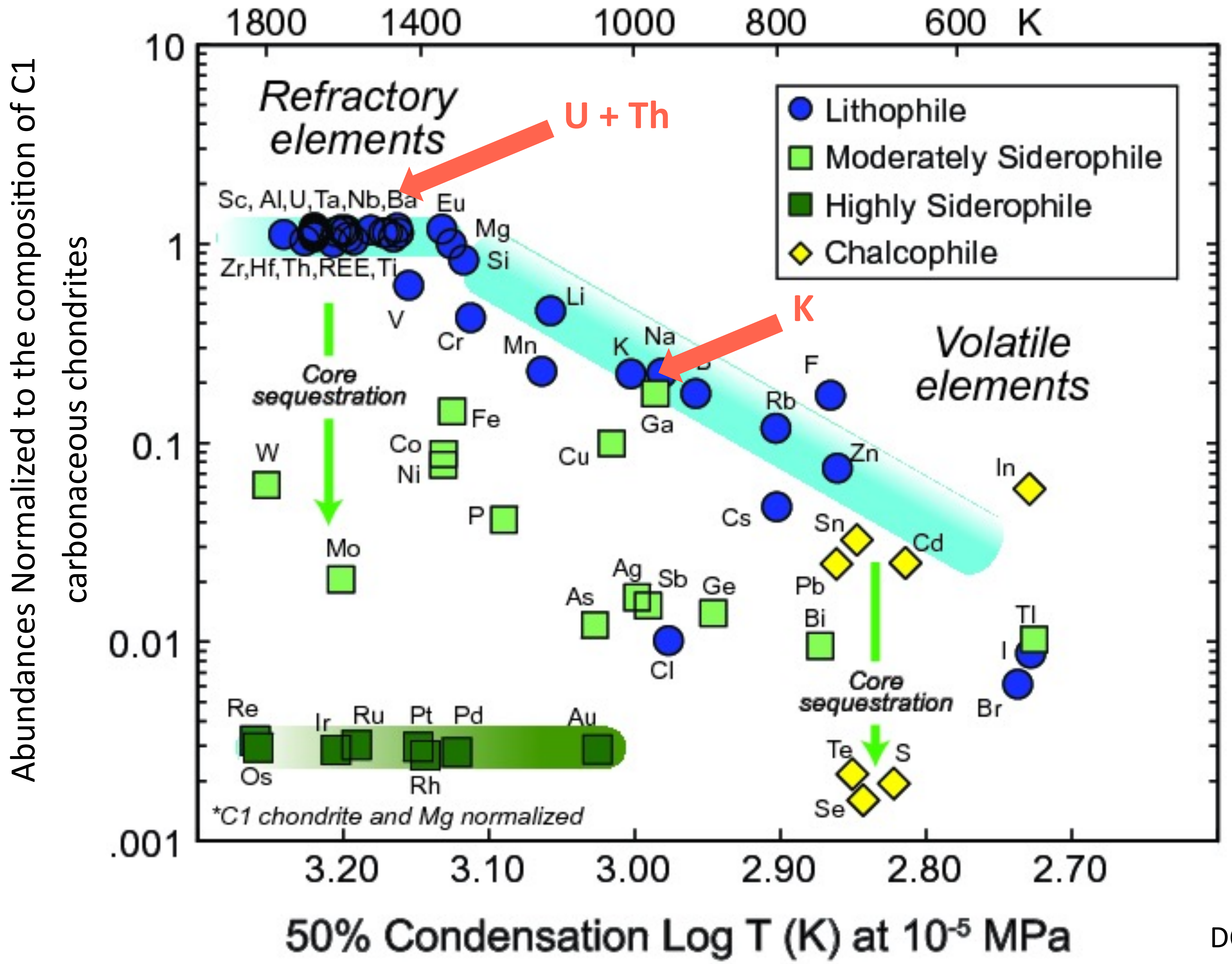


- Using meteorites to constrain ratios of some elements
- Using Earth rocks to fix absolute abundances
- Accounting for core formation and geochemical processes



DOI: 10.1016/j.ppnp.2013.07.001

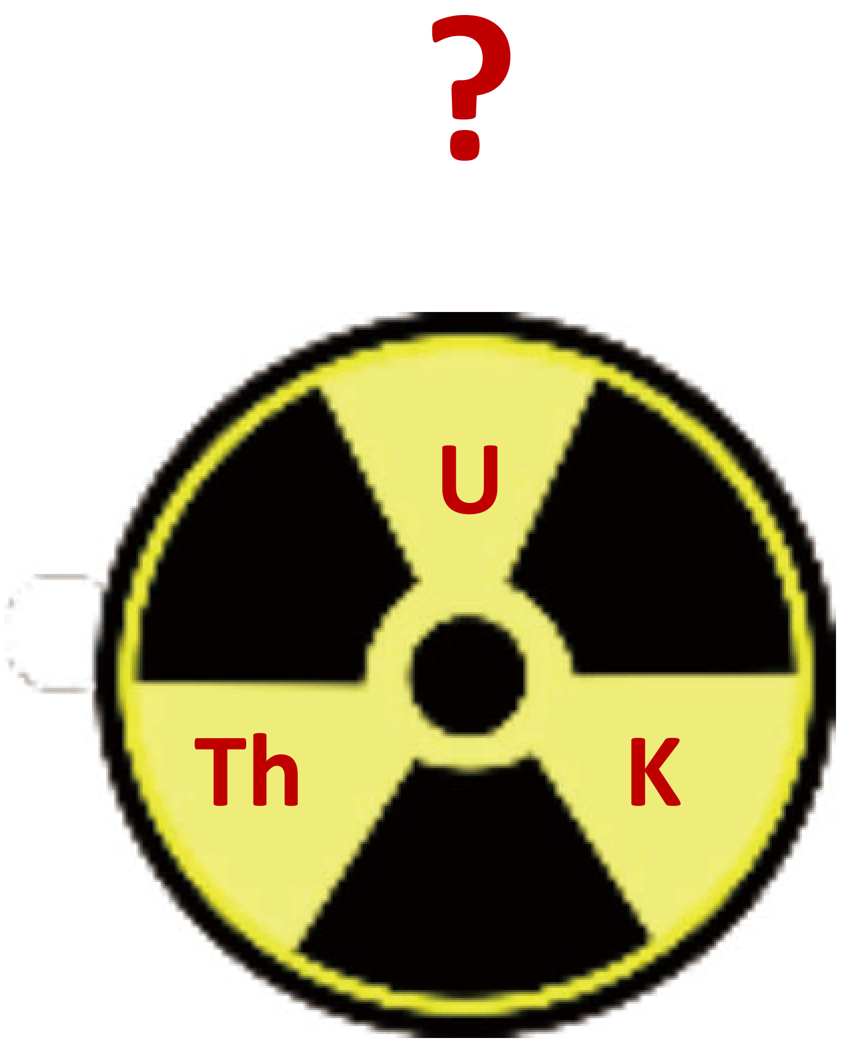
BSE abundances



DOI: 10.1016/j.ppnp.2013.07.001

Many questions that need the answers

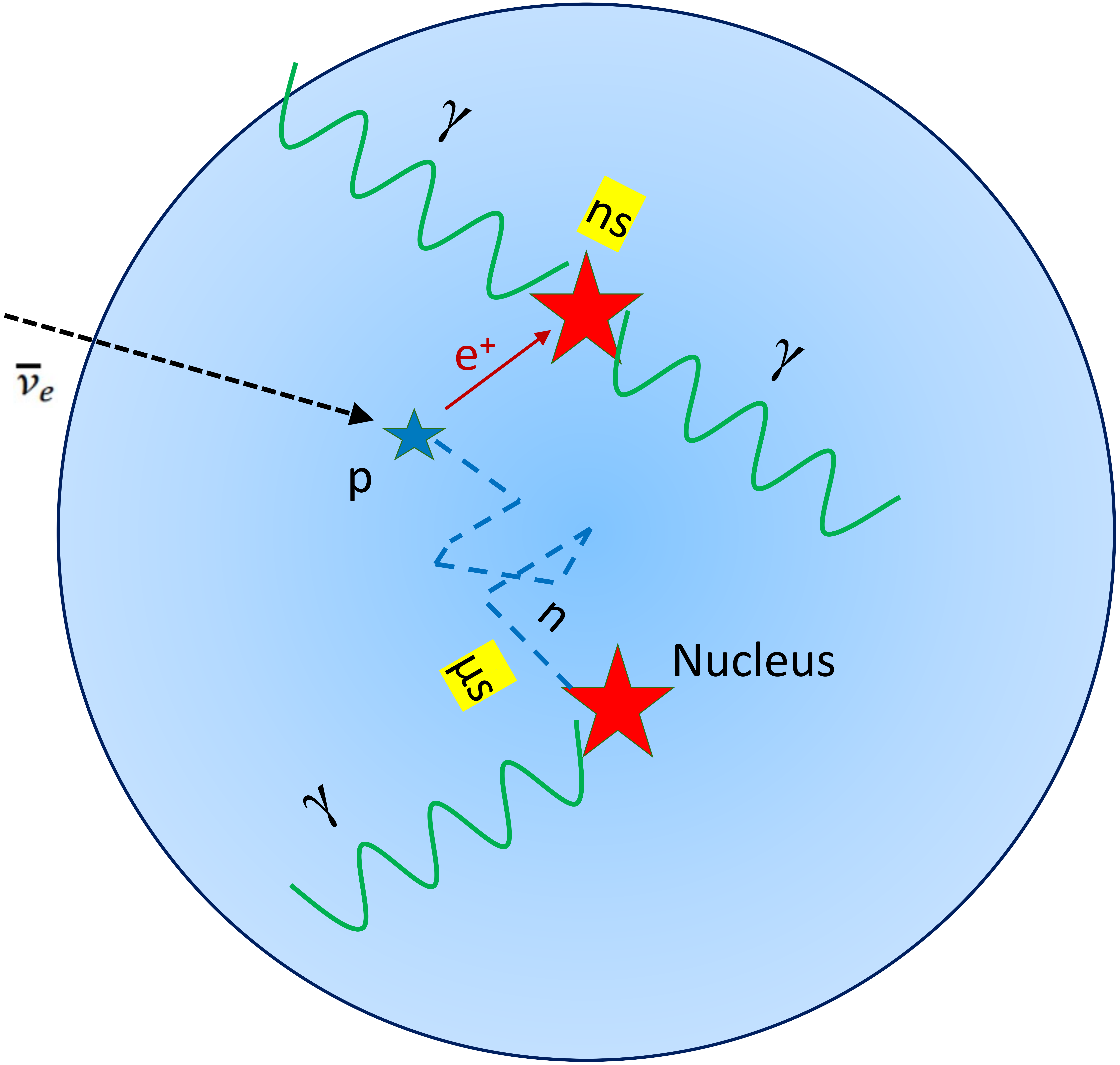
- What is the ratio of primordial cooling vs radiogenic heat?
- What is the distribution of the heat producing elements inside the Earth?
- Further constrains on U/Th mass ratio.
- ^{40}K geoneutrino detection constrain on the slope of volatile elements



How can Particle Physics help?

Liquid Scintillator Detectors

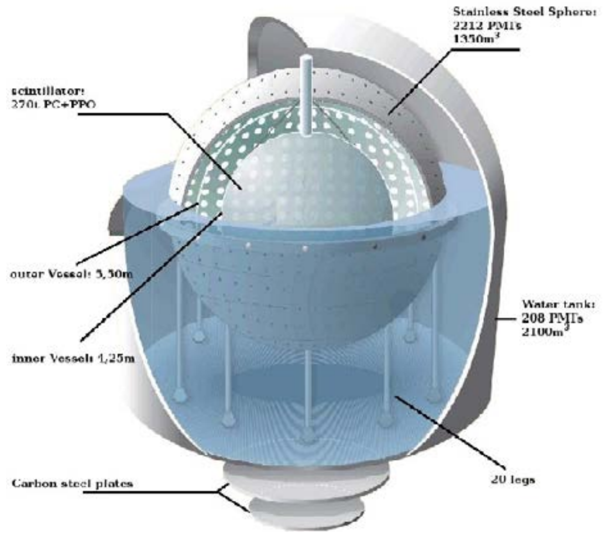
Meet all the required criteria for geoneutrino search.



How can we look for antineutrinos?

- They can interact via inverse beta decay!
- $E_{\nu} = Epr_{ompt} + E_n + 0.8\ MeV \cong E_{prompt} + 0.8\ MeV$
- Need large volume of target protons
- Low radioactive backgrounds
- Material that would be good at transferring light, which we can detect.

Geoneutrino LS Detectors



BOREXINO

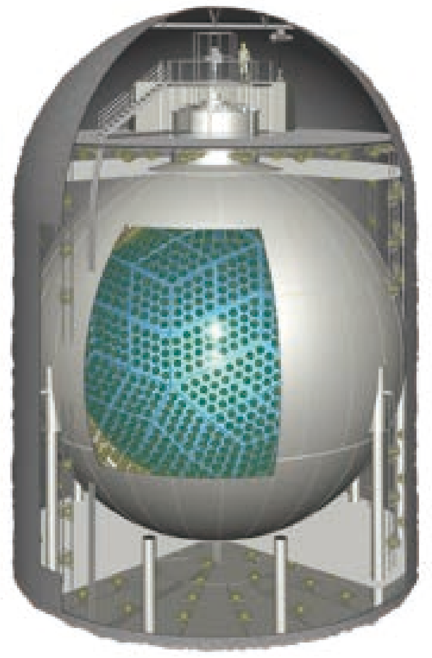
0.3 kt, LS
3.8 km.w.e.
Finished data taking

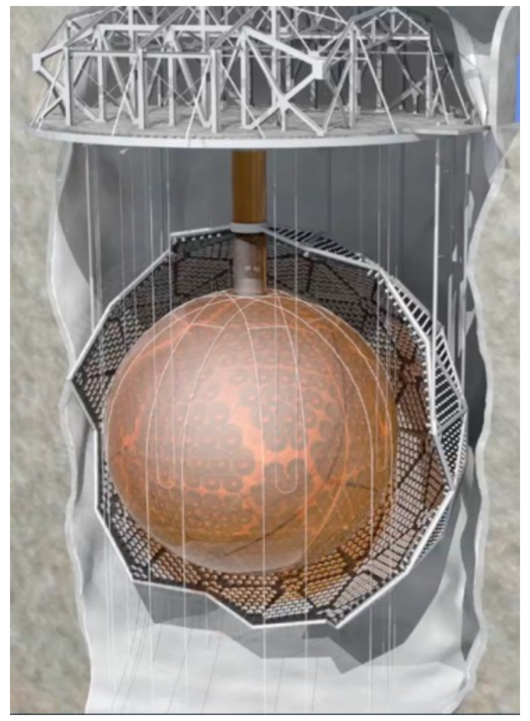
BAKSAN

~10 kt, LS
4.8 km.w.e.
R&D

KAMLAND

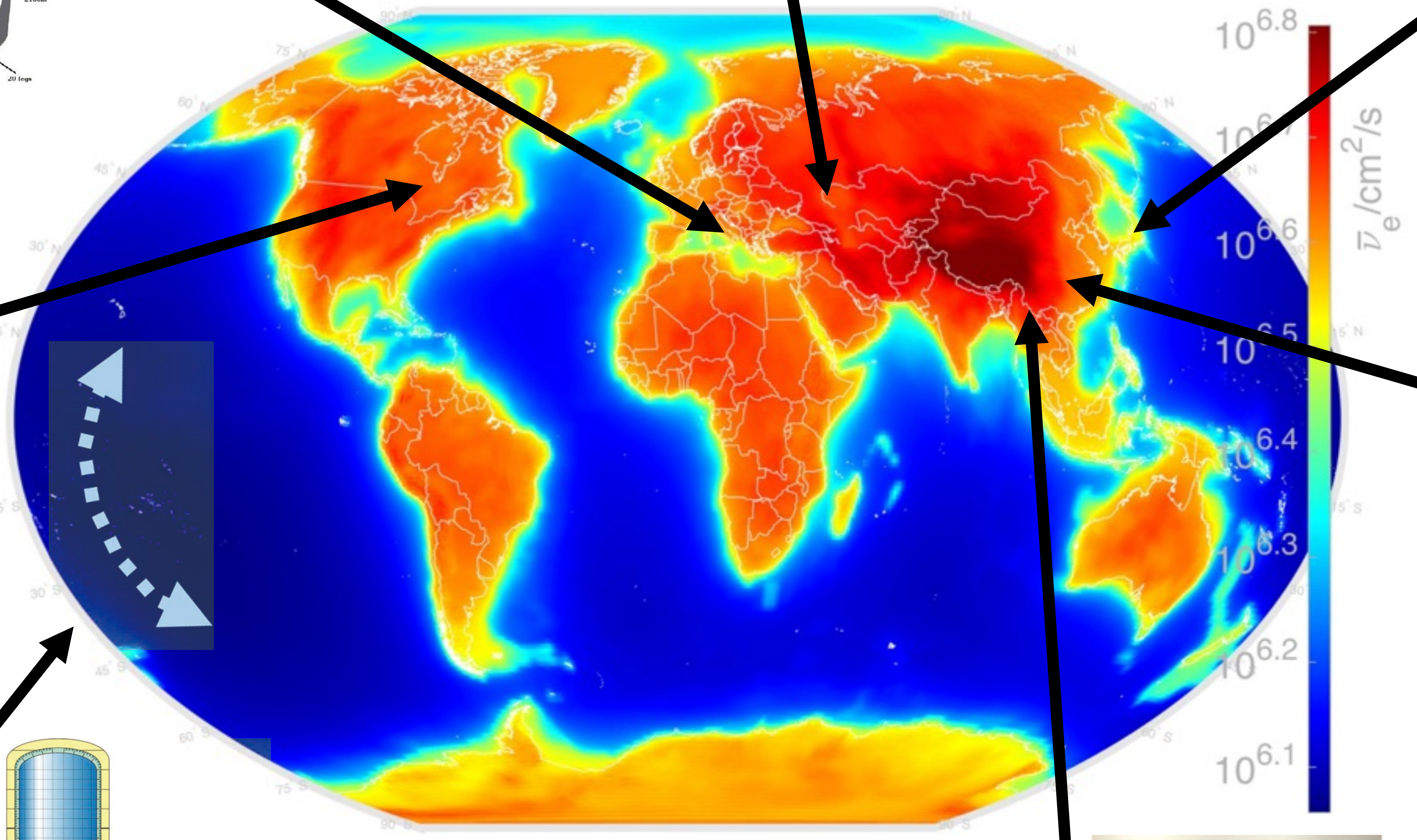
1kt, LS
2.7 km.w.e.
Running





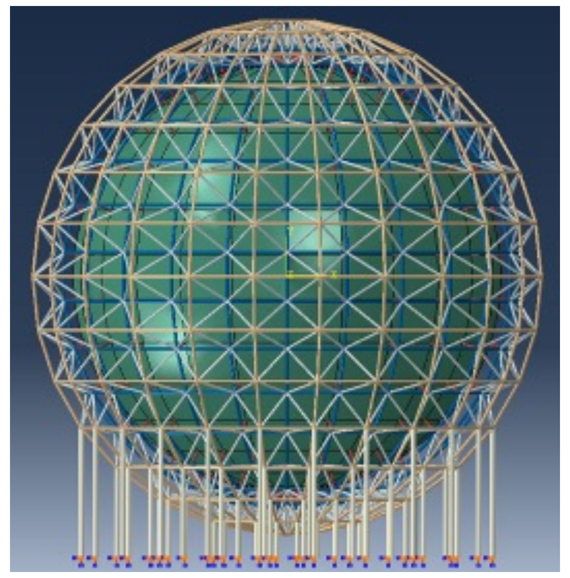
SNO+

1kt, LS
5.4 km.w.e.
Running



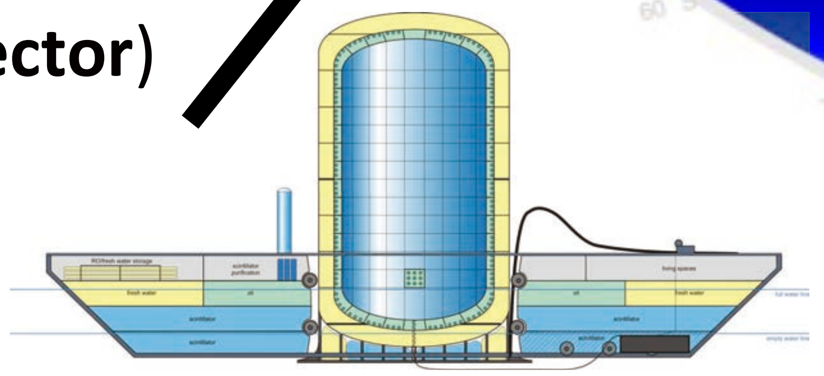
JUNO

20 kt, LS
1.5 km.w.e.
under construction
(2022~)



OBD (Ocean Bottom Detector)

10-50 kt, LS
Movable, R&D

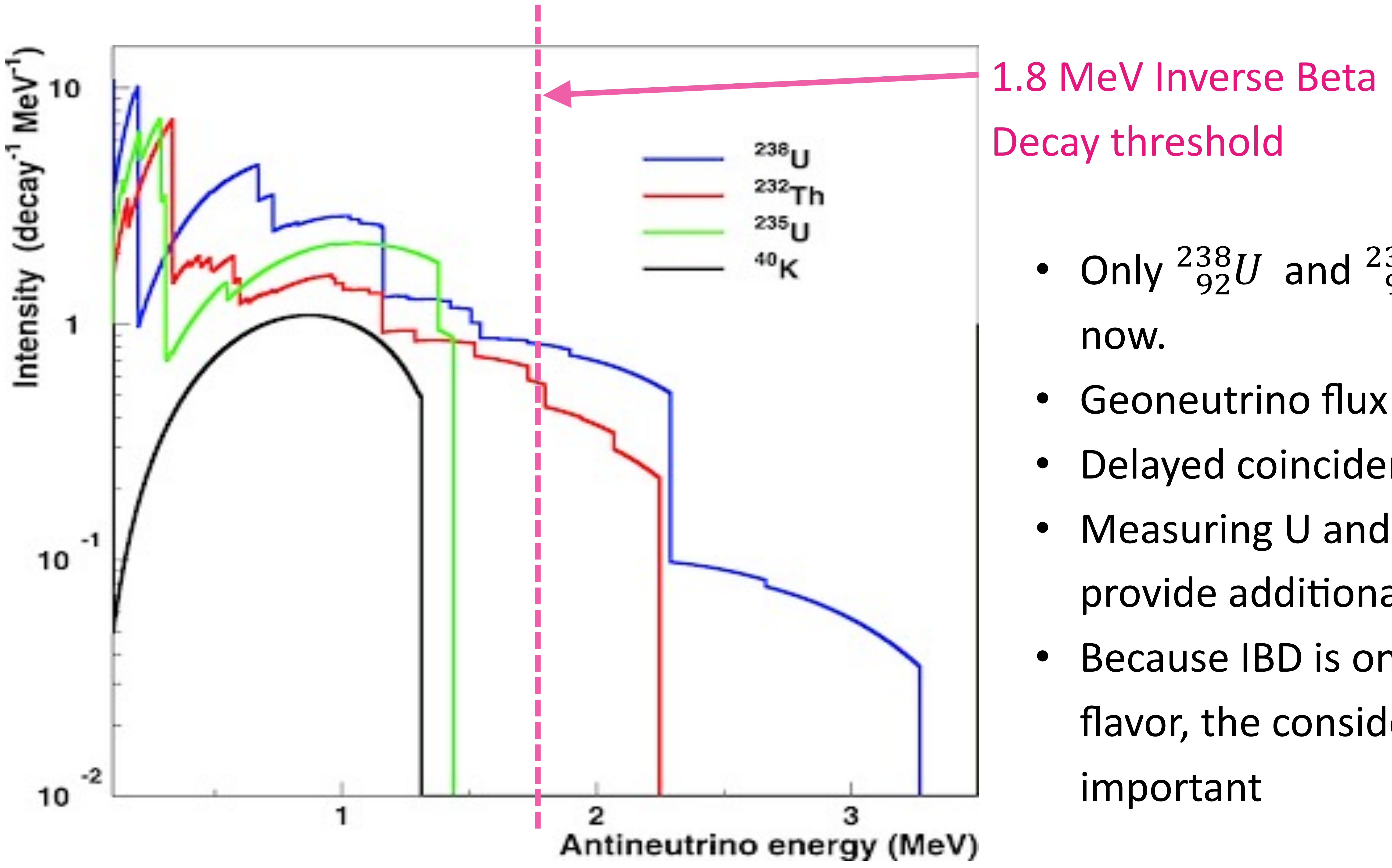


SEE THE TALK BY HIROKO!!!

JINPING

1kt, LS
7.5 km.w.e
R&D

Geoneutrino signal detection with LS



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

- Only $^{238}_{92}U$ and $^{232}_{90}Th$ geoneutrinos are detectable right now.
- Geoneutrino flux is proportional to the radiogenic heat
- Delayed coincidence tagging eliminates backgrounds
- Measuring U and Th contributions separately could also provide additional constrains on their ratio.
- Because IBD is only sensitive to electron antineutrino flavor, the consideration of oscillation probability is important

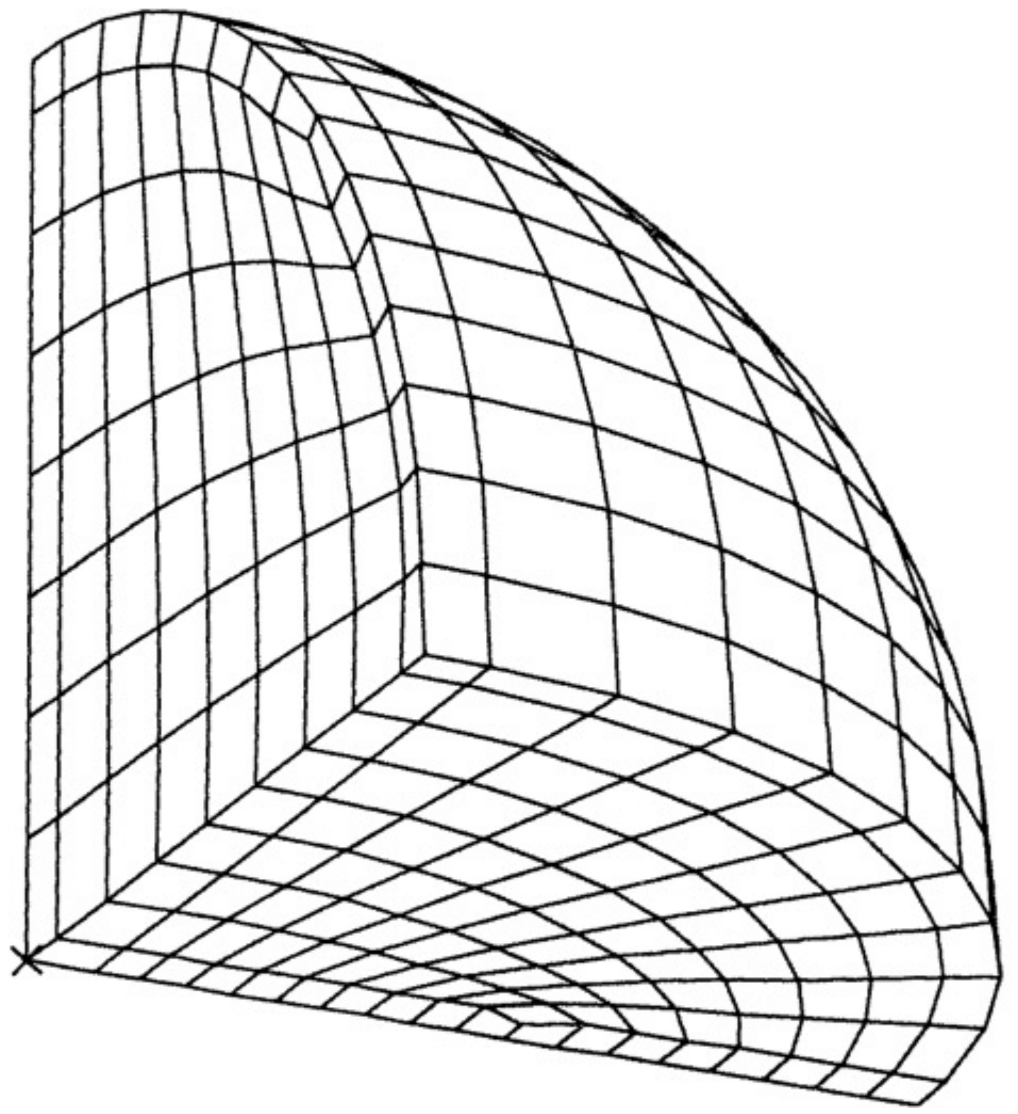
Dye, S. T. (2012), Geoneutrinos and the radioactive power of the Earth, *Rev. Geophys.*, 50, RG3007, doi:10.1029/2012RG000400.

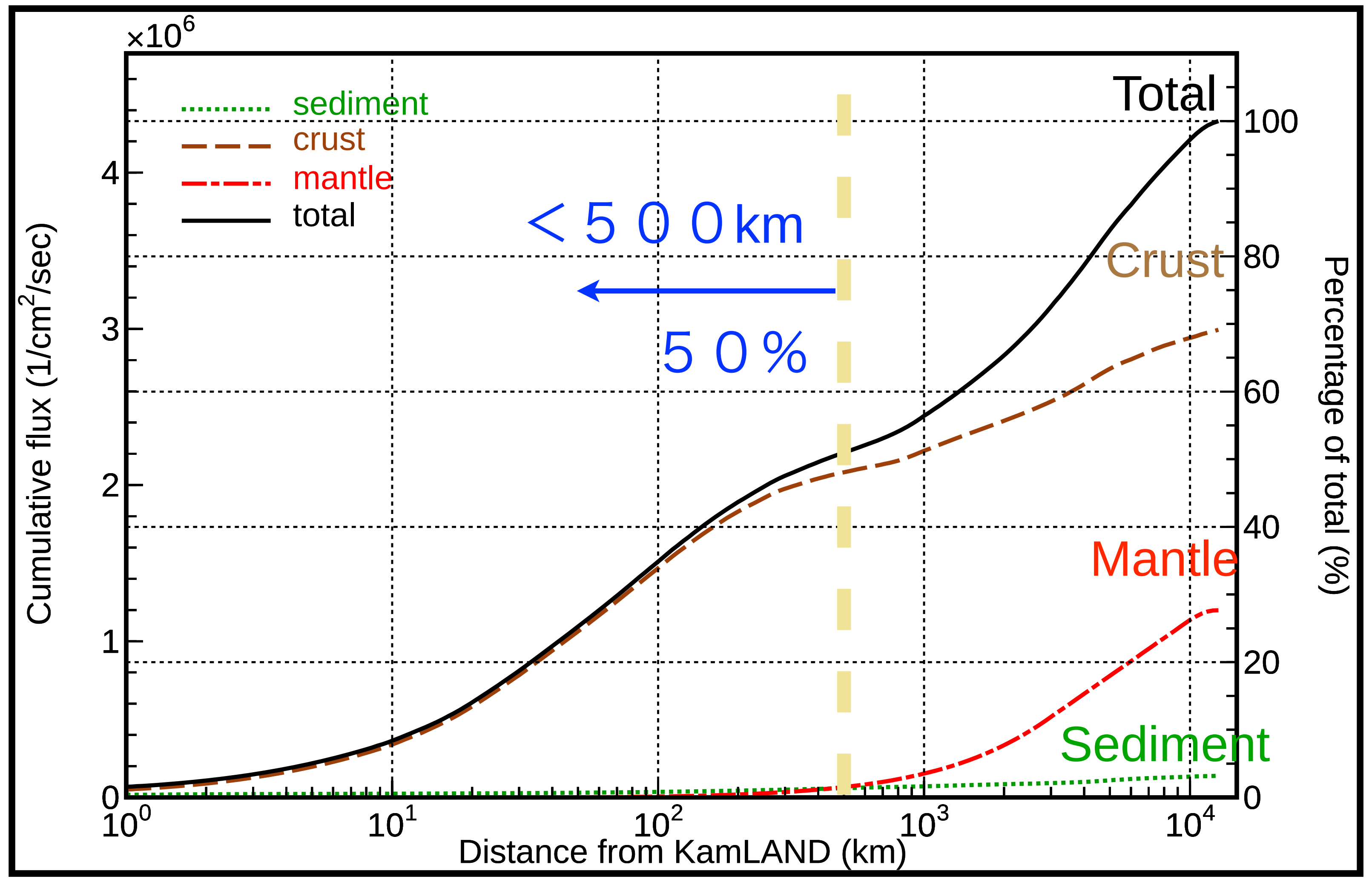
The expected signal prediction

Given a certain geological model the antineutrino spectrum at a given position r can be calculated

$$\frac{d\phi(\vec{r},E)}{dE} = \sum_i \frac{\lambda_i X_i N_A}{M_i} \left(\frac{dn_\nu}{dE}\right)_i \int_\oplus P_{ee}(E,|\vec{r}-\vec{r}'|) \frac{A(\vec{r}')\rho(\vec{r}')}{4\pi|\vec{r}-\vec{r}'|^2} d\vec{r}'$$

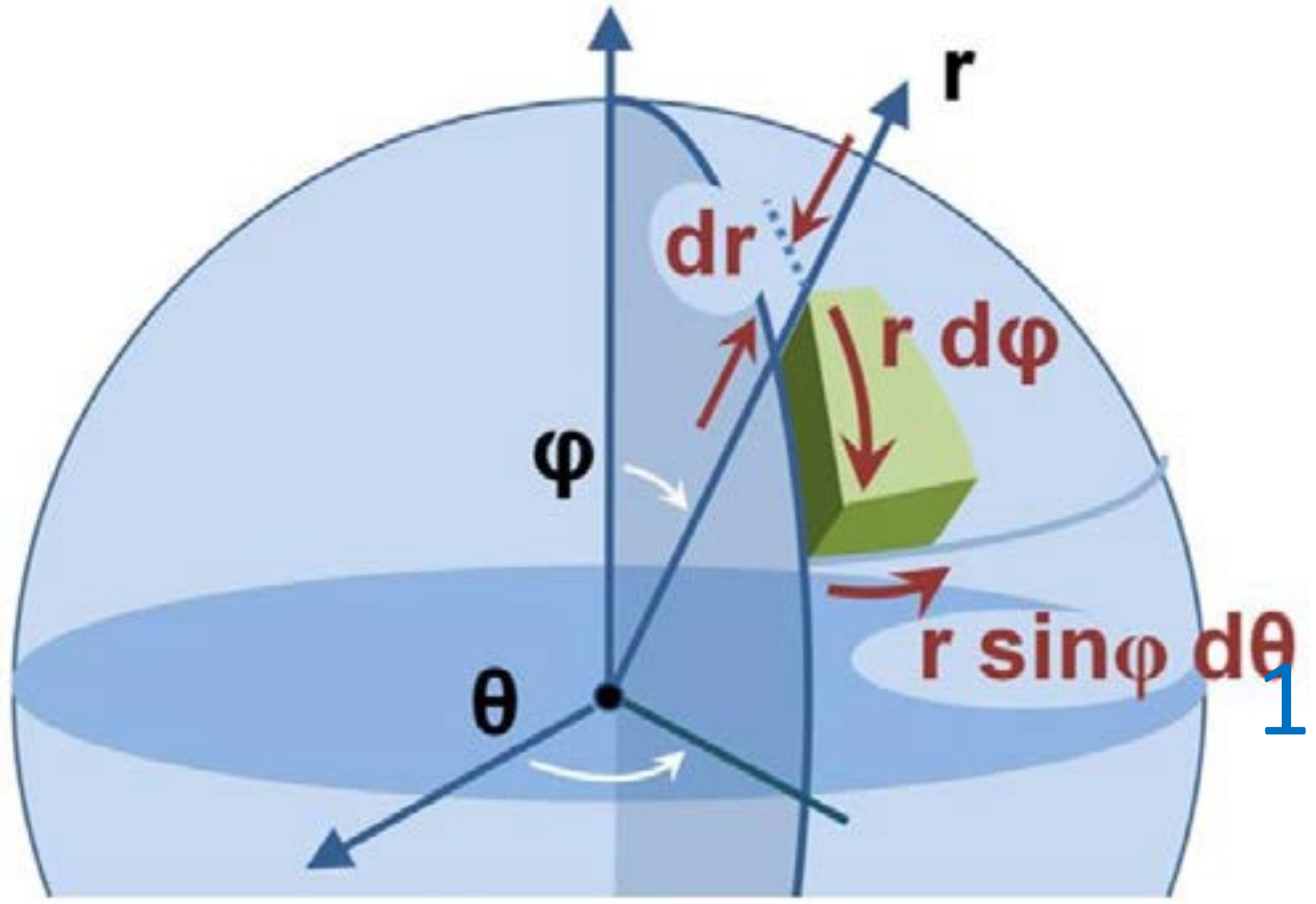
Geoneutrino flux | Decay rate | Production spectra | Survival probability | Geological factor





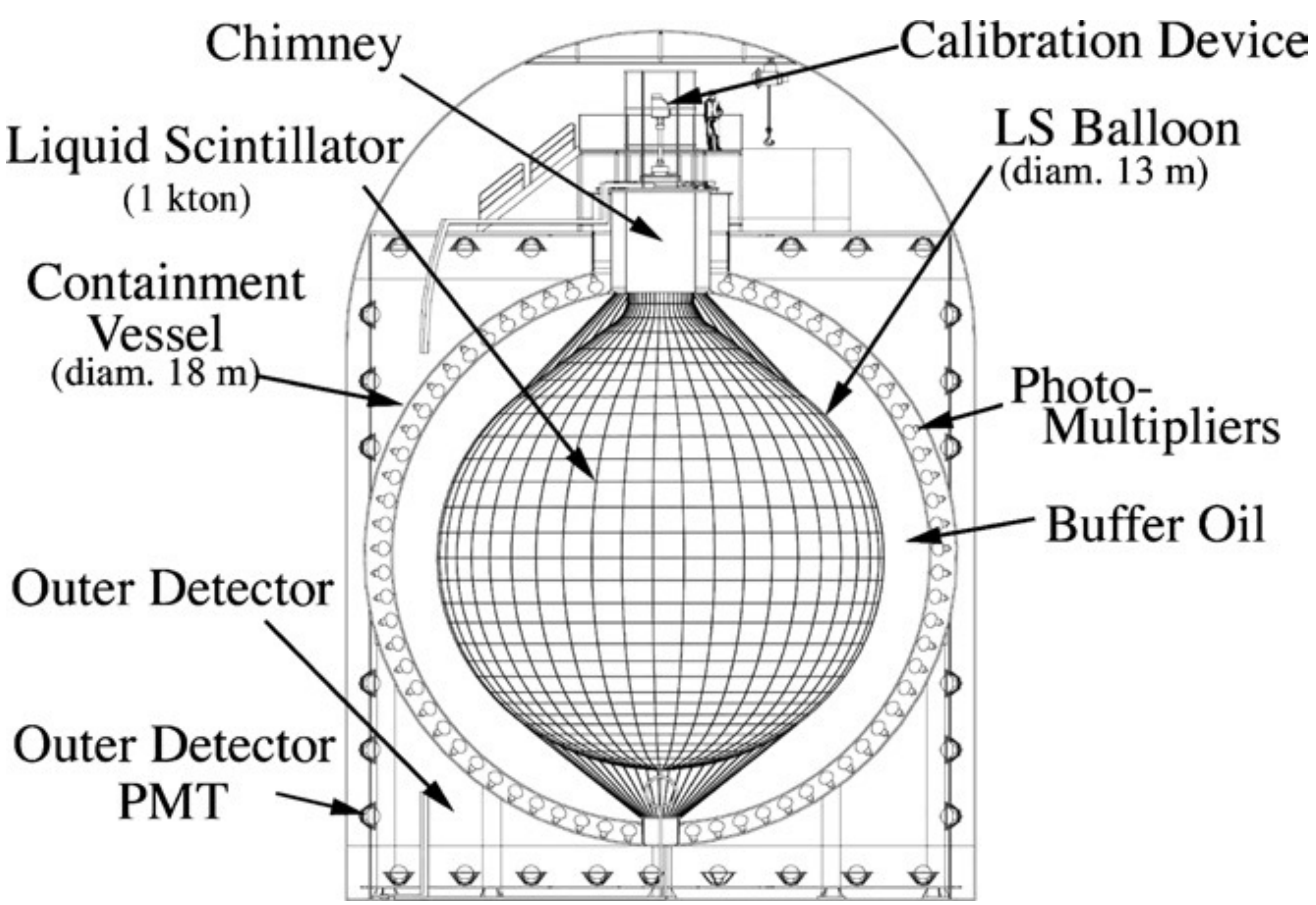
Enomoto et al. EPSL 258, 147 (2007)

About 50% of the expected geoneutrino signal comes from the crust within 500-800 km around the detector, thus local geology has to be known



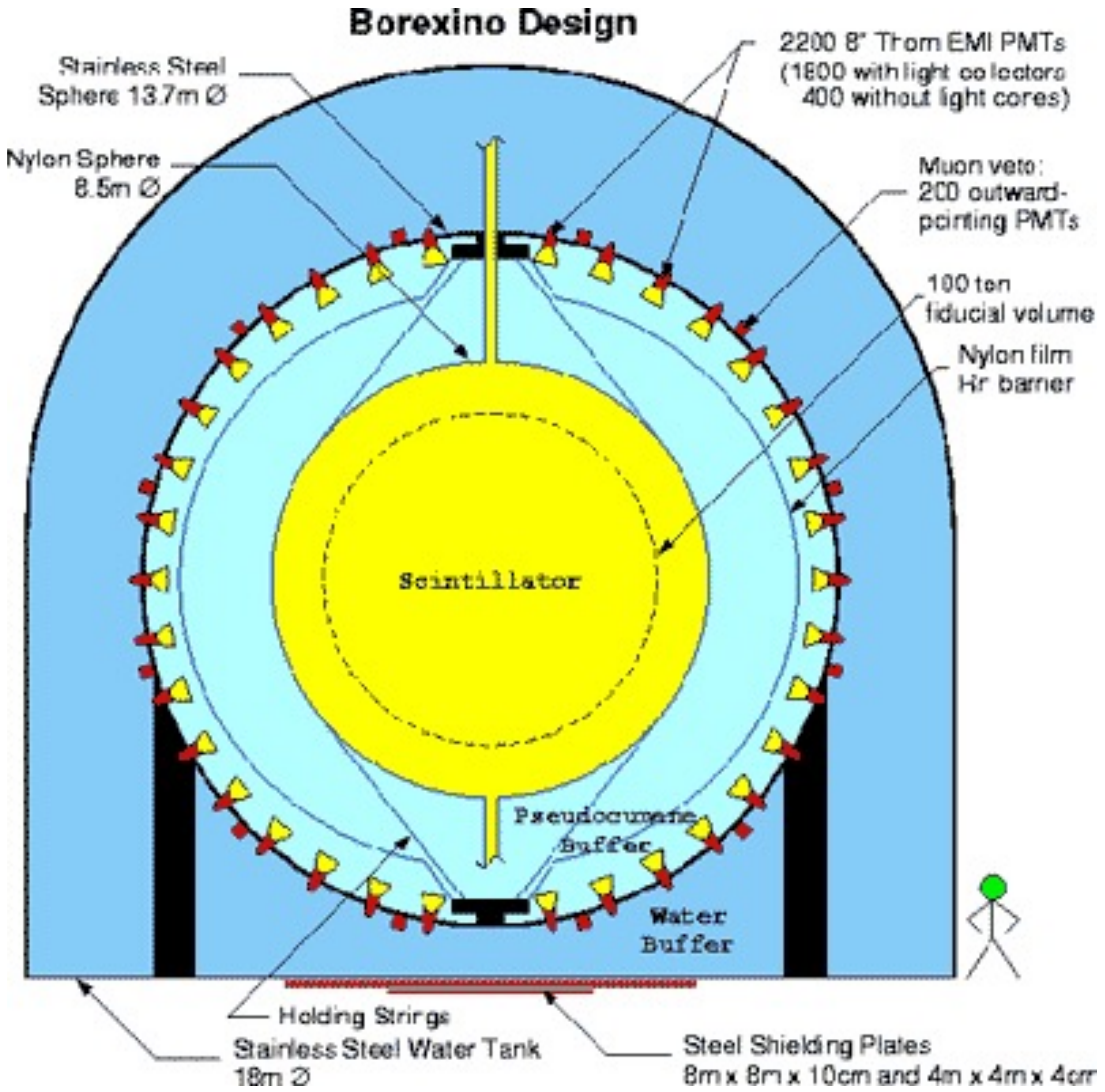
Current Experimental results

KAMLAND



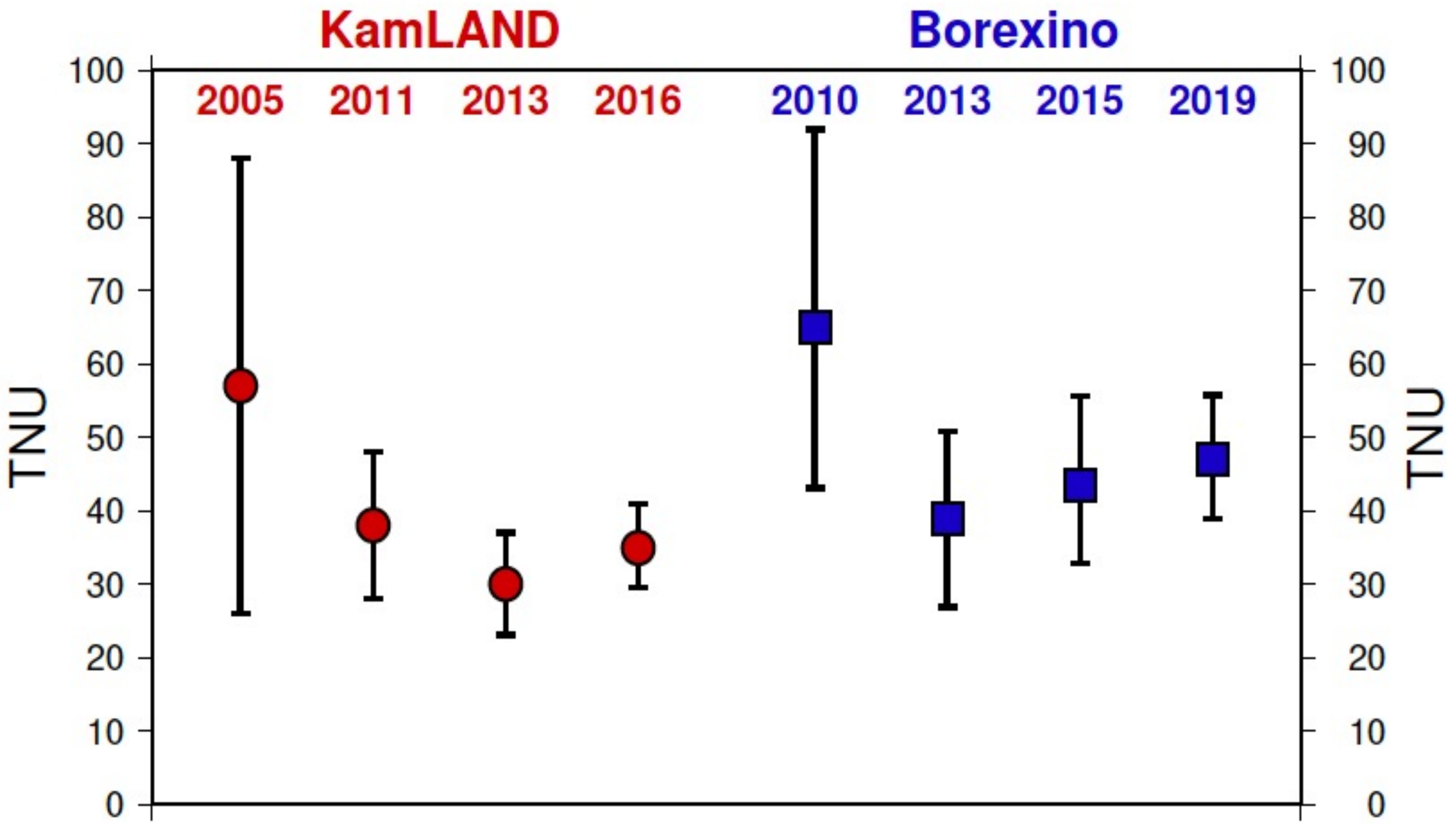
- 1000t liquid scintillator
- 2700 m.w.e depth
- Expected event ratio reactor/geo ~6.7 (~0.4 for reactor shutdown)

BOREXINO



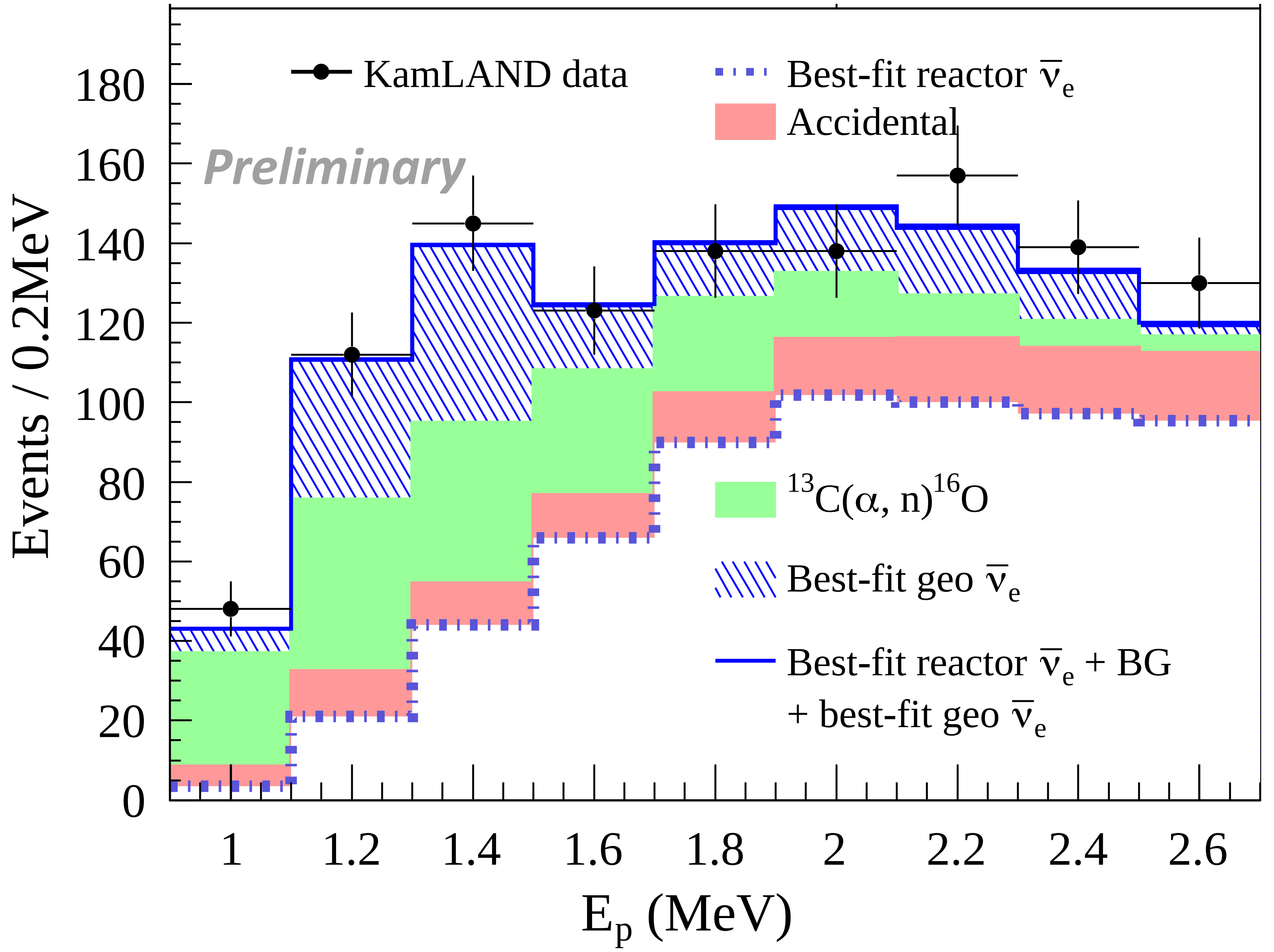
- 278 t liquid Scintillator
- 3800 m.w.e depth
- Expected event ratio reactors/geo ~ 0.3

History of geoneutrino measurements



Latest geoneutrino measurements

KAMLAND



Livetime 4397 days (Mar 9, 2002-Apr 15, 2018)

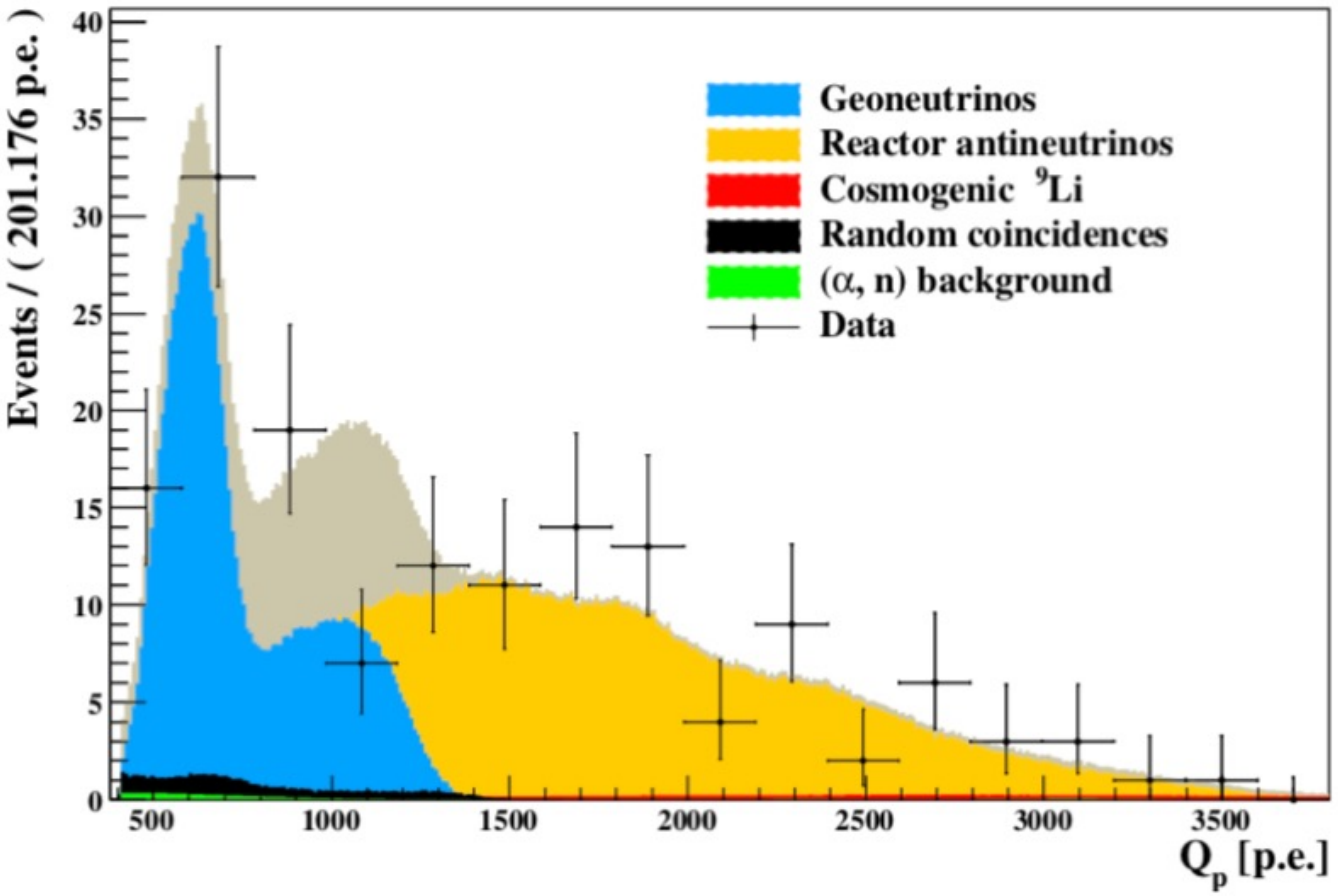
1167 candidate events

168.8 +26.3/-26.5 geoneutrino events

+15.6/-15.7% uncertainty

BOREXINO

Phys. Rev. D 101, 012009 (2020)



Livetime 3263 days (Dec 9, 2007-Apr 28, 2019)

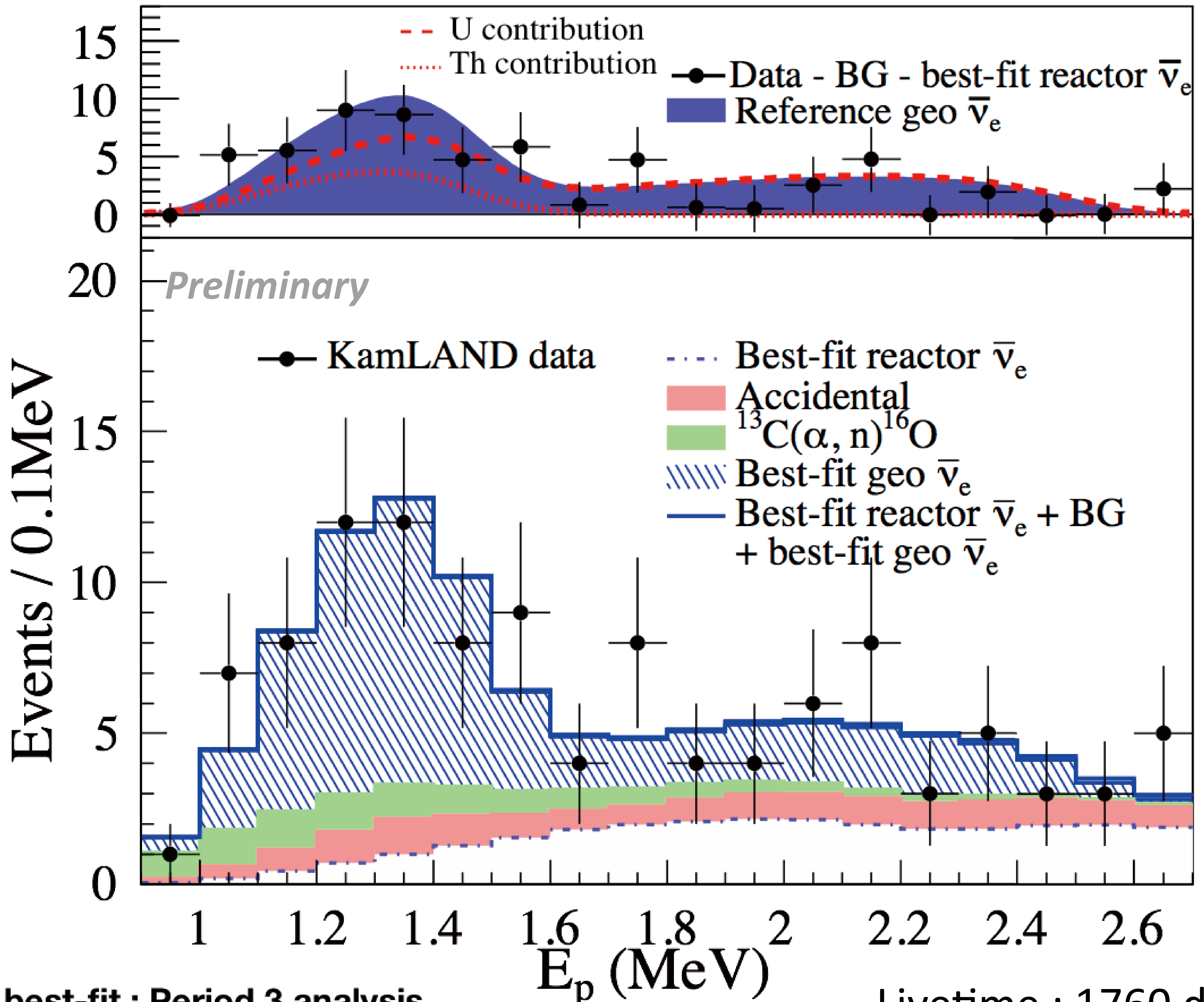
154 candidate events

52.6 +9.4/ -8.6 (stat) +2.7/-2.1 (syst) geoneutrino events

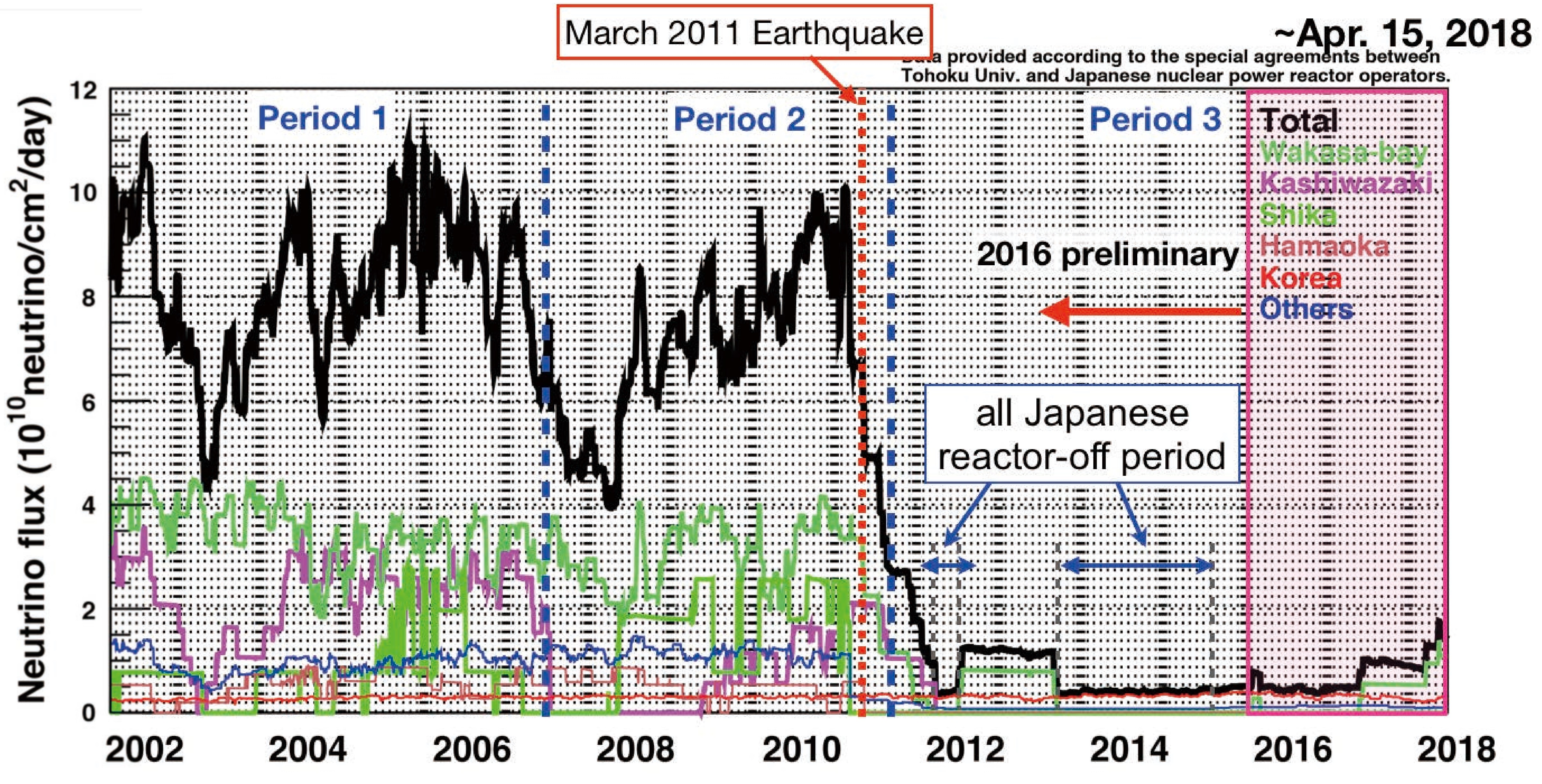
+18.3/-17.2% uncertainty

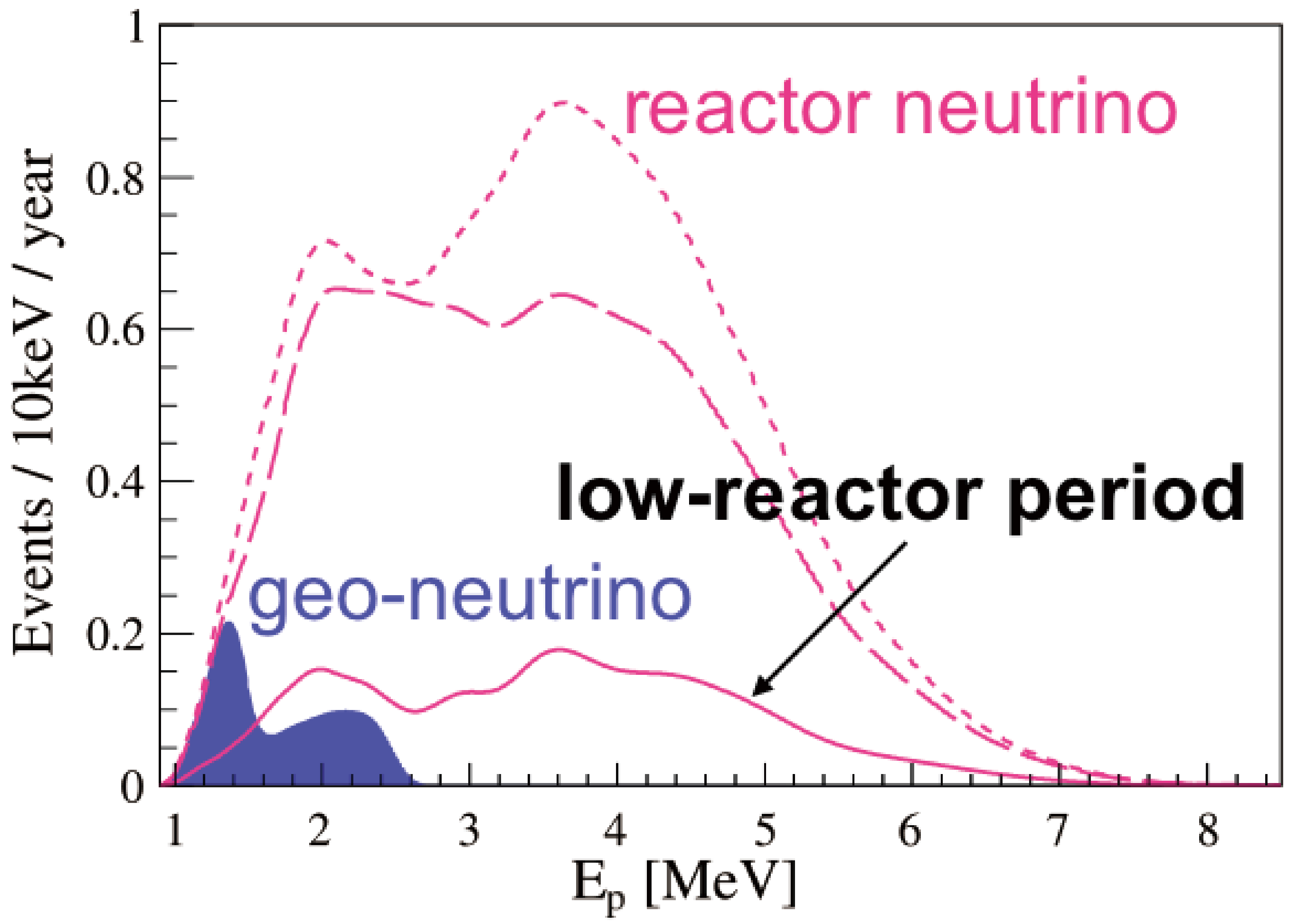
[KamLAND Information provided by: Dr. Hiroko Watanabe, Tohoku University]

KAMLAND low reactor data



best-fit : Period 3 analysis



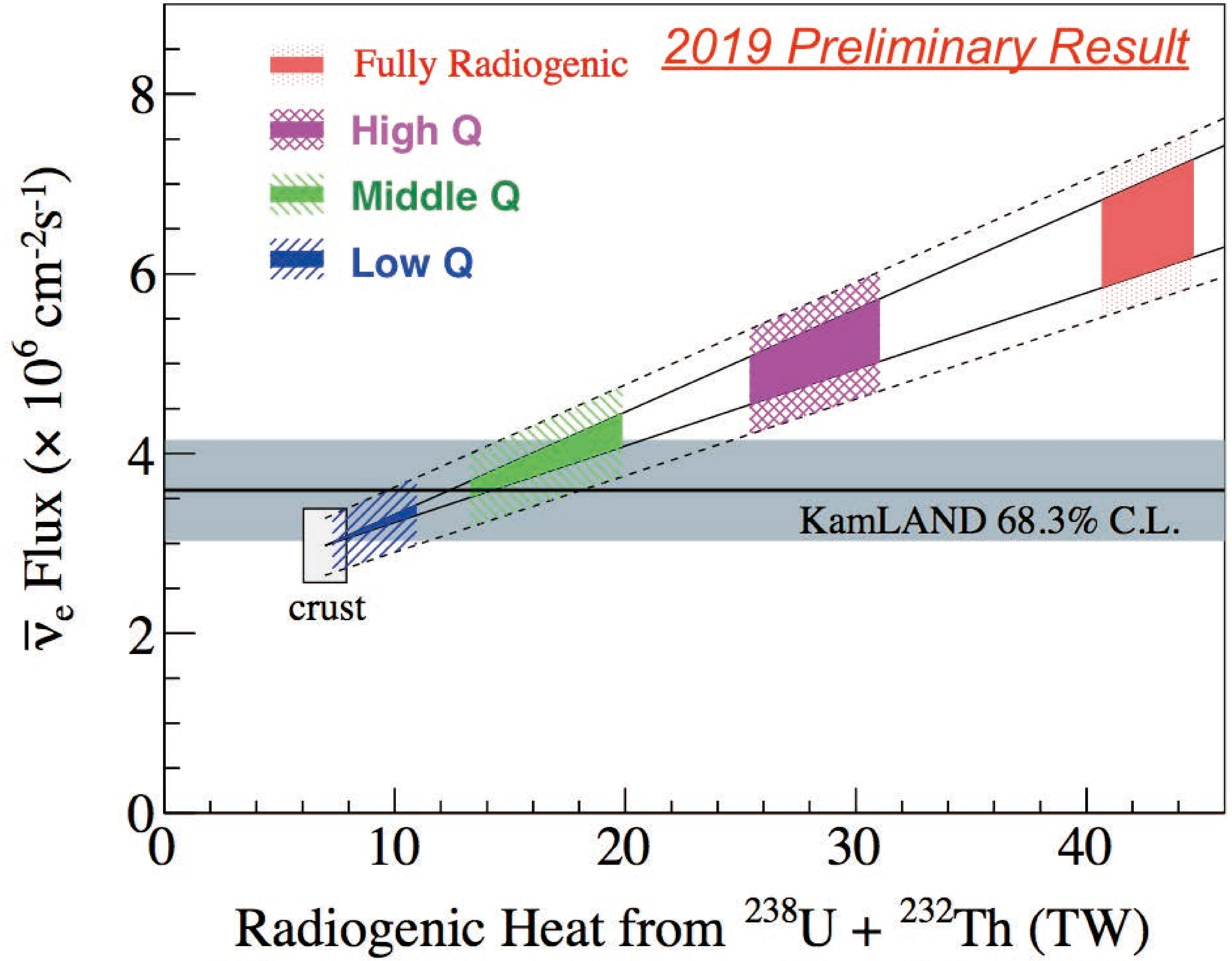


Livetime : 1760 days

Candidate : 110 ev

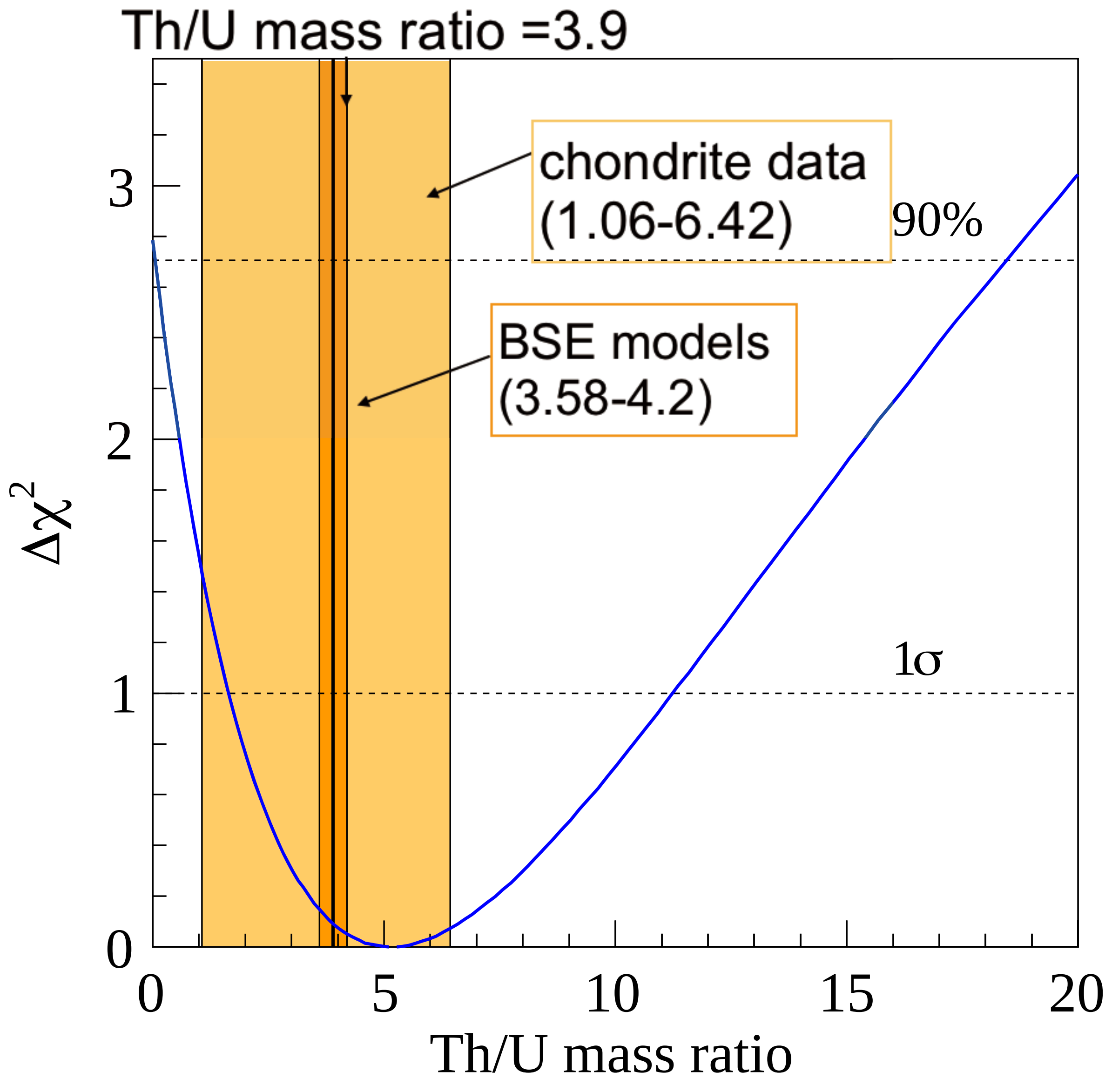
[Information provided by: Dr. Hiroko Watanabe, Tohoku University]

KAMLAND geological interpretation



Radiogenic Heat : $12.4^{+4.9}_{-4.9}$ TW
(Mantle+Crust, U+Th)

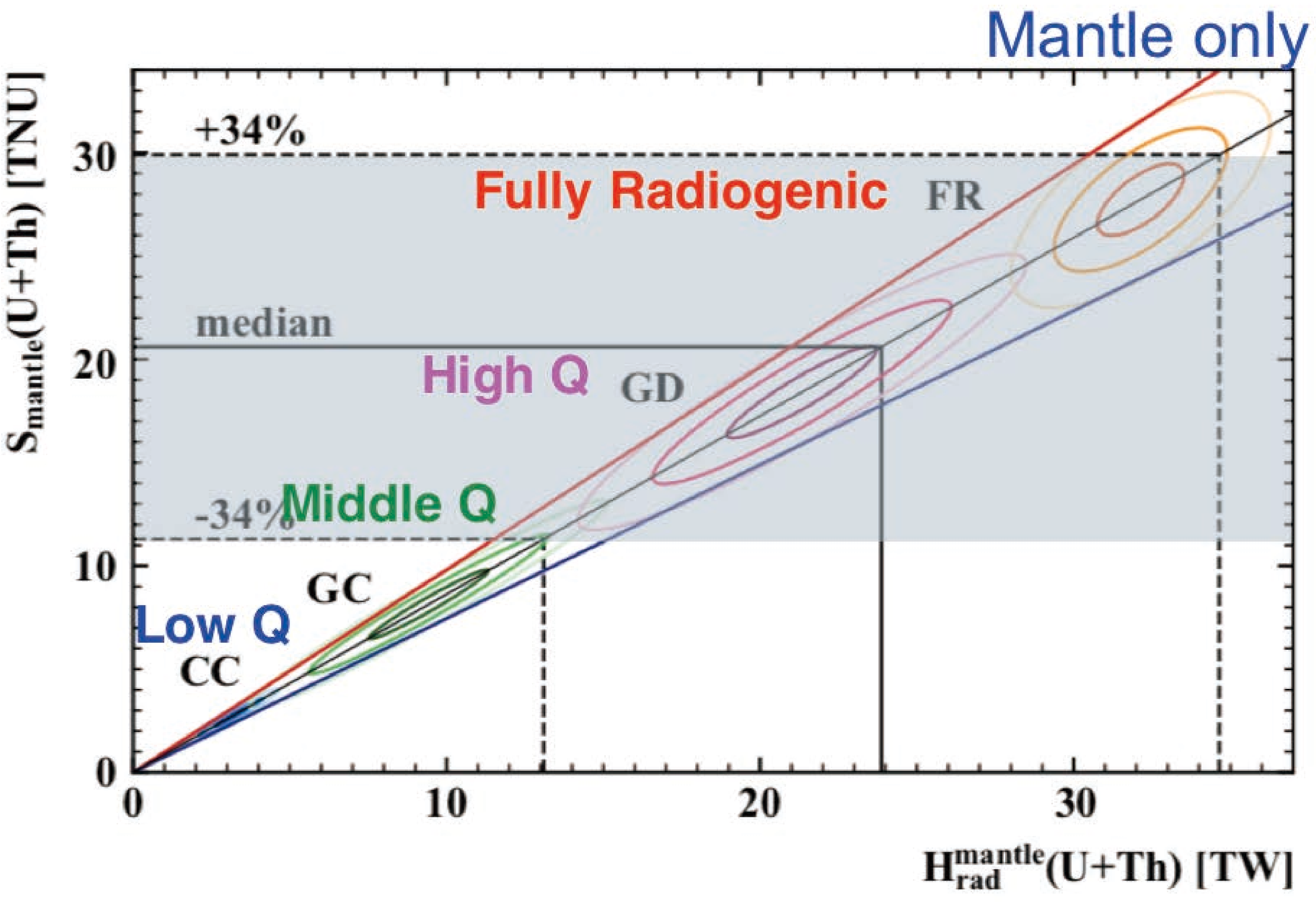
- HighQ model rejected with >2σ
- LowQ and MidQ are still within uncertainty of the measurement
- Due to low reactor dataset, U and Th contributions were able to be tested separately



Best fit
Th/U = $5.3^{+6.0}_{-3.6}$
Th/U < 18.5 (90% C.L.)
ref) 2016 preliminary
Th/U = 4.1 +5.5/-3.3, <17.0 (90% C.L.)

KamLAND best-fit is consistent with chondrite data and BSE models.

Borexino geological interpretation

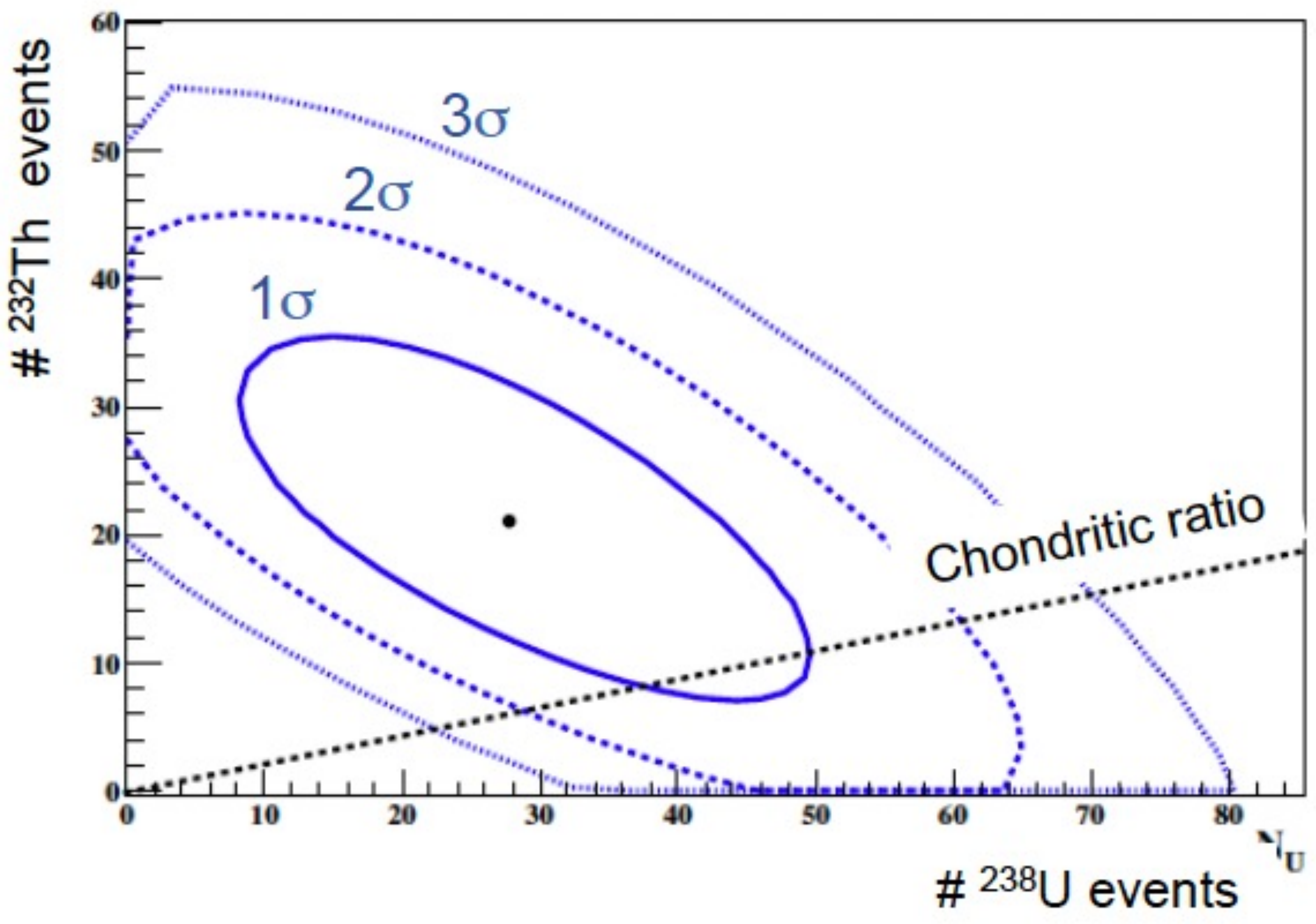


Phys. Rev. D 101, 012009 (2020)

- Mantle radiogenic heat from U+Th:

  $$24.6^{+11.1}_{-10.4}\ \text{TW}$$

- Compatible with all BSE models, but least (2.4σ) with LowQ
- No sensitivity to U/Th ratio



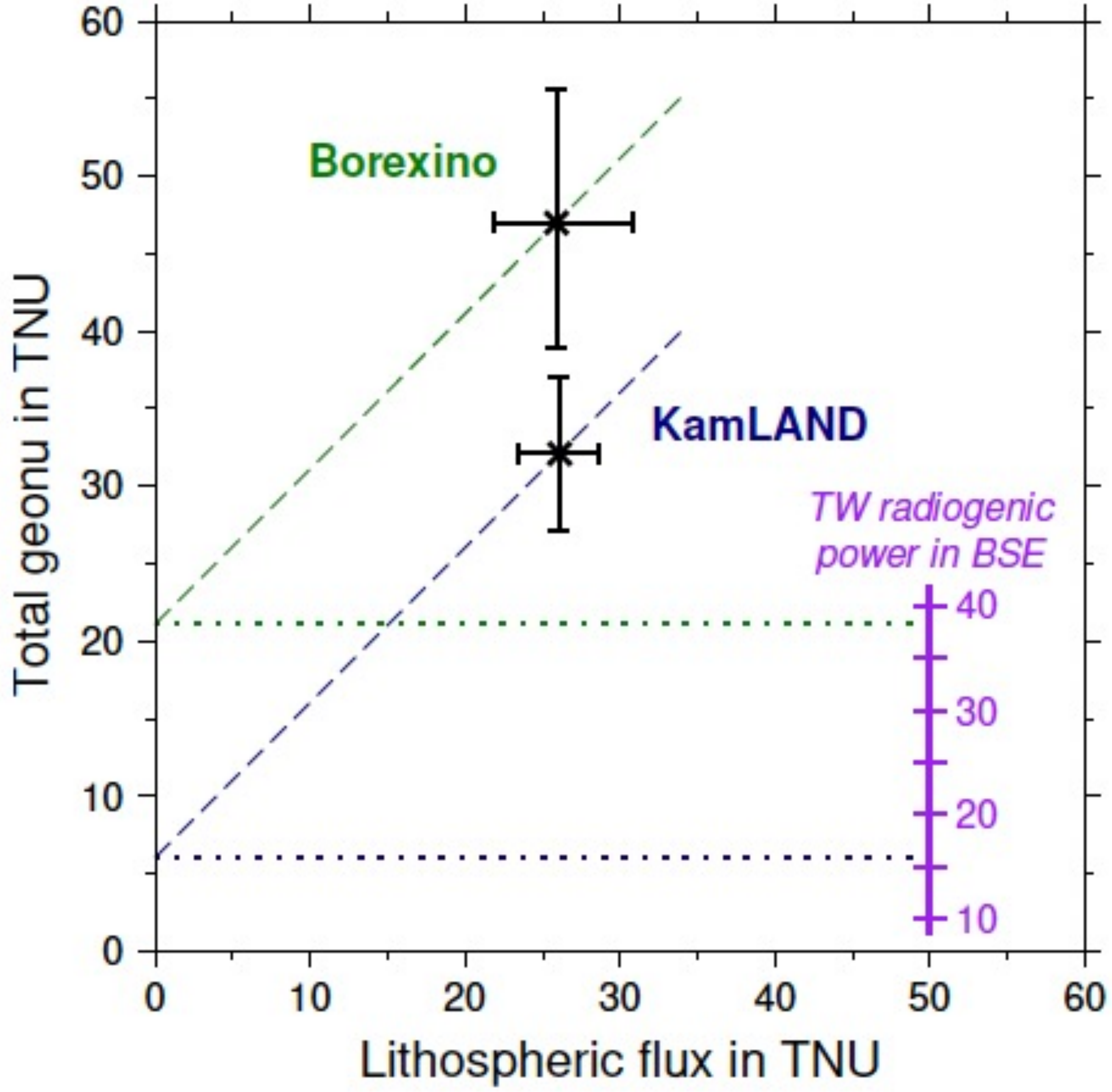
Mantle contribution (KAMLAND+BOREXINO)

Plot by: Ondřej Šrámek, Charles University, Prague, Czech Republic, ondrej.sramek@gmail.com

KAMLAND: [Watanabe 2019 at NGS Prague]
Measured signal 32.1 ± 5.0 TNU After subtracting crustal prediction: Mantle signal **6.0+5.6−5.7 TNU** Corresponds to **~15 TW** in the Earth or **~8 TW** in the mantle.

BOREXINO: [Agostini et al 2020 doi:10.1103/PhysRevD.101.012009]
Measured signal 47.0+8.6−8.1 TNU After subtracting crustal prediction: Mantle signal **21.0+9.6−9.0 TNU** Corresponds to **38.2+13.6−12.7 TW** in the Earth or **30.1+13.5−12.7 TW** in the mantle.

- Factor of 3.5 difference in mantle radiogenic power
- Ongoing effort to understand discrepancy
- Multiple groups are looking into the local crustal models



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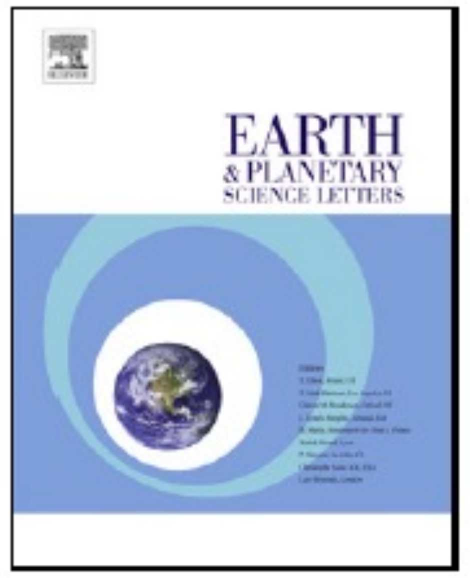

Quantifying Earth's radiogenic heat budget

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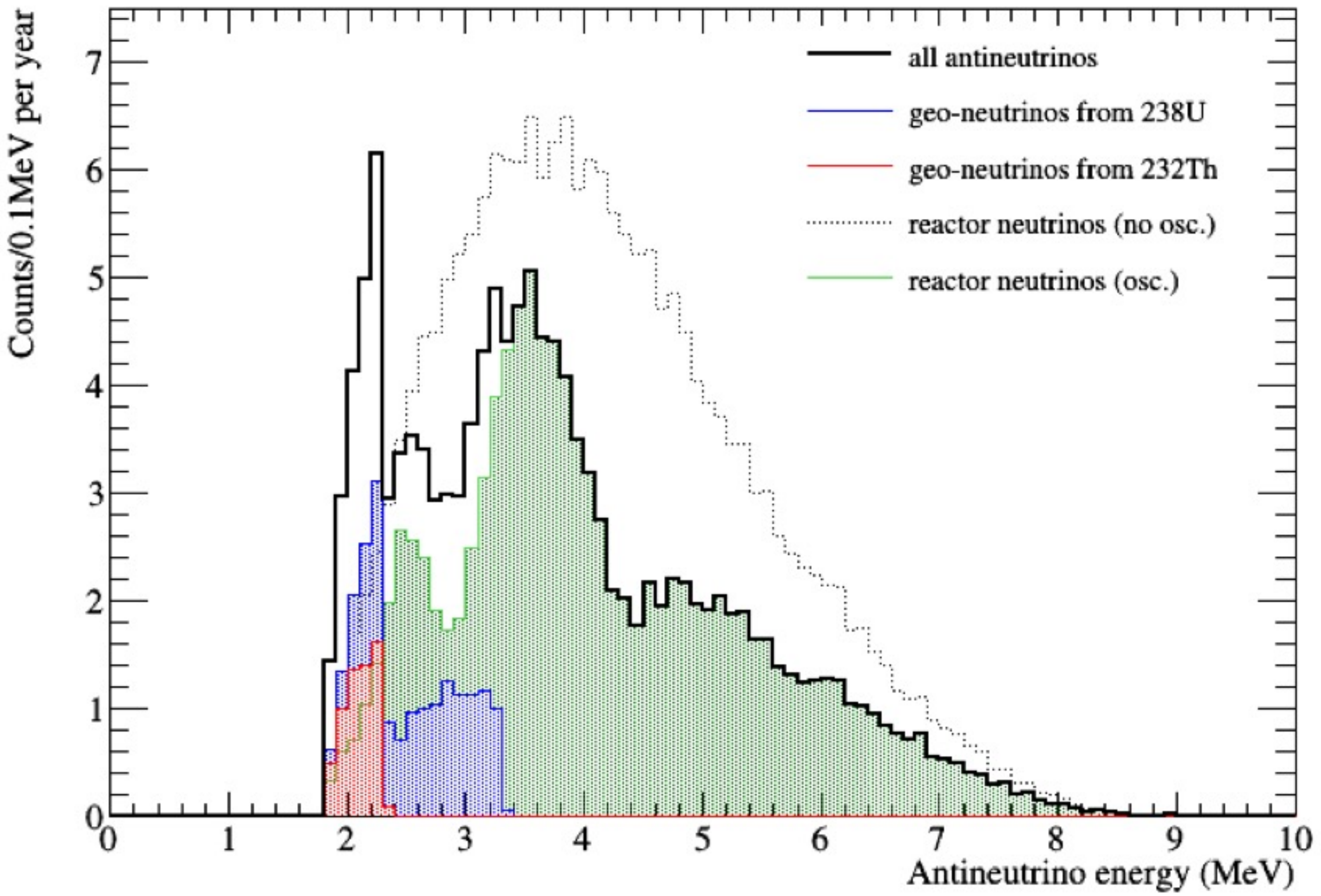
A B S T R A C T

Earth's internal heat drives its dynamic engine, causing mantle convection, plate tectonics, and the geodynamo. These renewing and protective processes, which make Earth habitable, are fueled by primordial and radiogenic heat. For the past two decades, particle physicists have measured the flux of geoneutrinos, electron antineutrinos emitted during β^- decay. These ghost-like particles provide a direct measure of the amount of heat producing elements (HPE: Th & U) in the Earth and in turn define the planet's absolute concentration of the refractory elements. The geoneutrino flux has contributions from the lithosphere and mantle. Detector sensitivity follows a $1/r^2$ (source detector separation distance) dependence. Accordingly, an accurate geologic model of the Near-Field Lithosphere (NFL, closest 500 km) surrounding each experiment is required to define the mantle's contribution. Because of its proximity to

SNO+



Expected event rate [TNU]

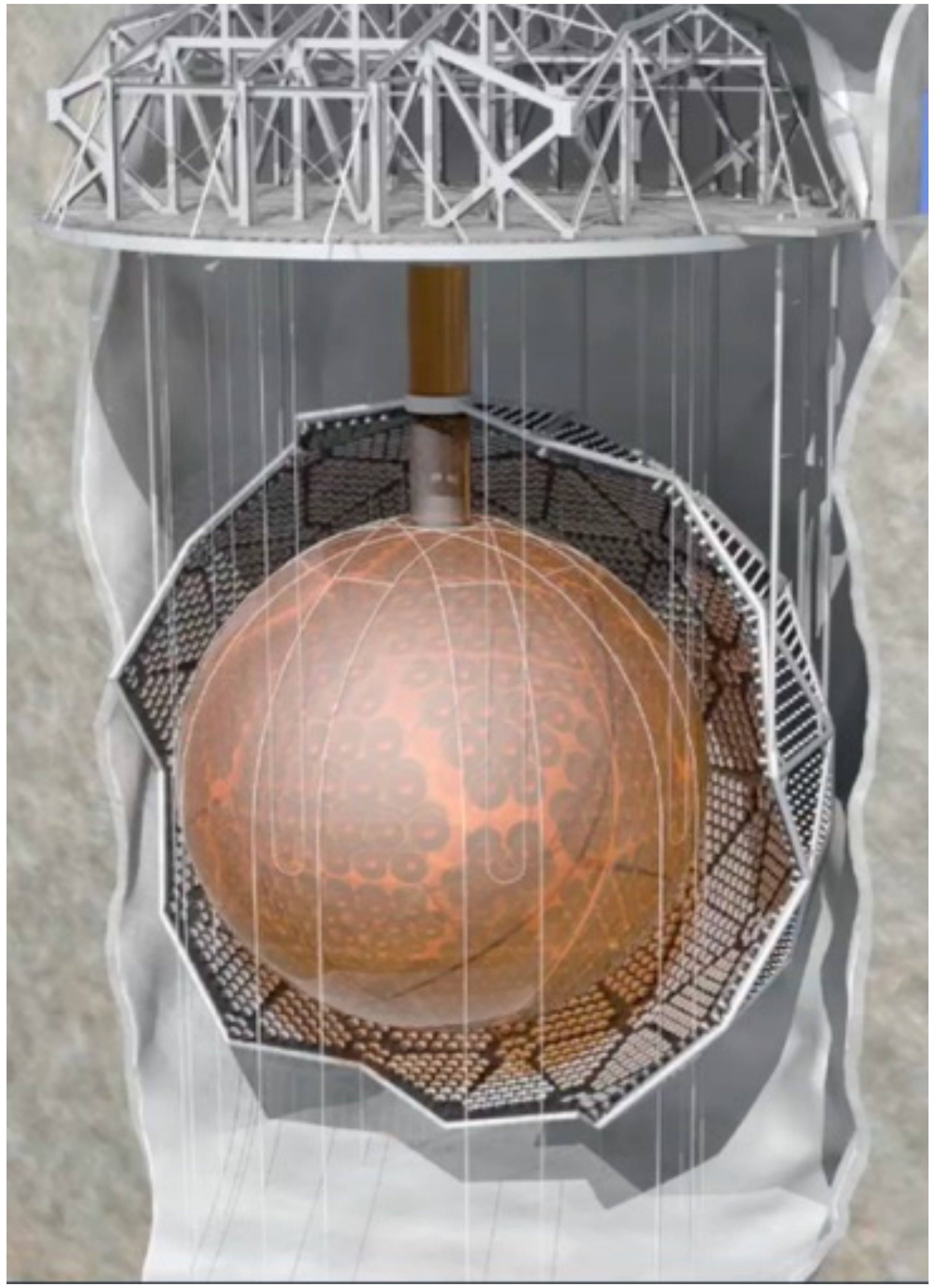
Crust 35.3±5.1

Mantle

LowQ 2.6±1.6

MidQ 8.4±2.8

HighQ 17.8±2.6

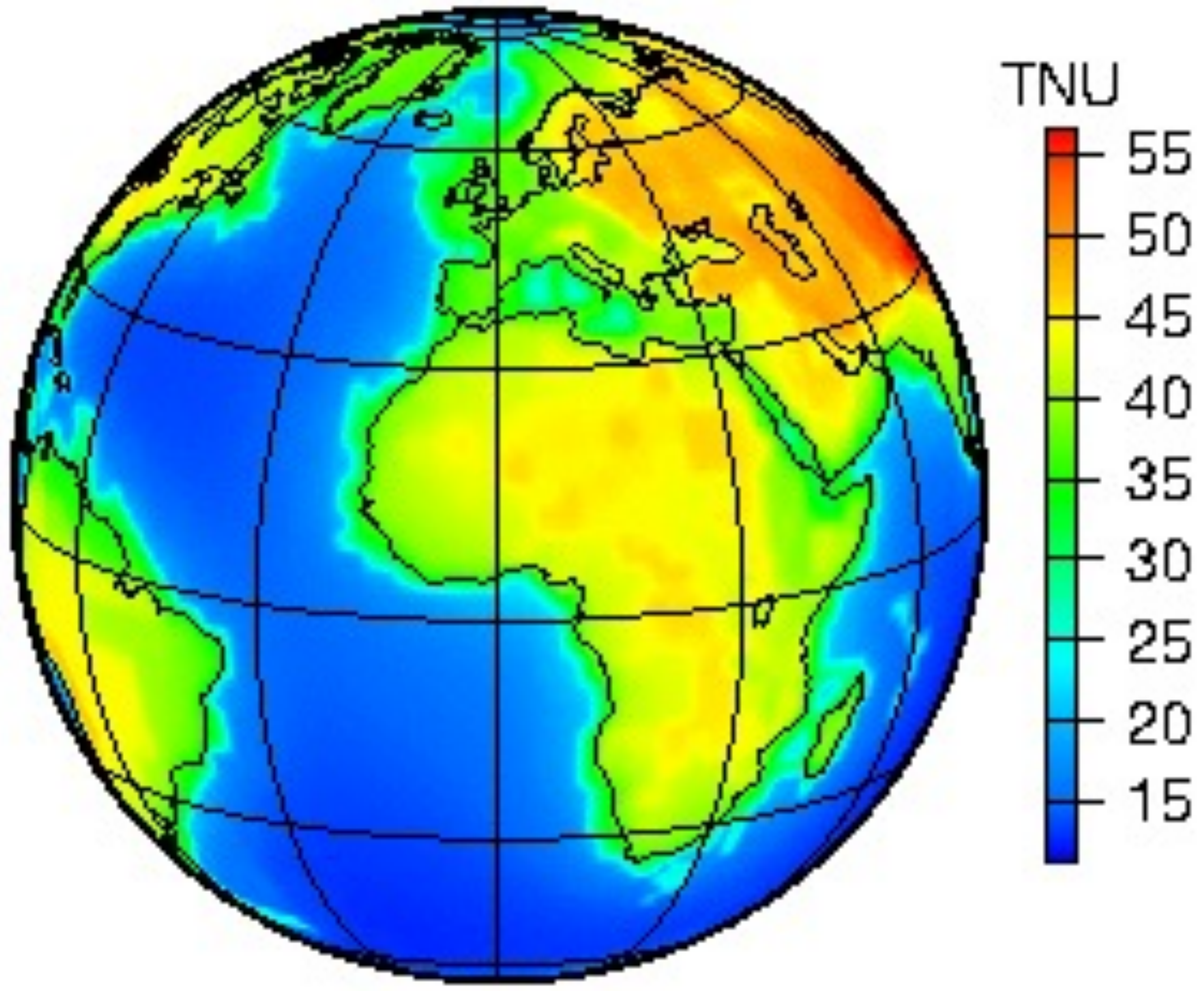


- First geoneutrino measurement in western hemisphere
- Local geology is well studied
- Currently in Scintillator phase taking data

Summary

- There still is a lot to discover about the Earth. Geoneutrinos can help us answer these questions:
  - o What is the total radiogenic heat coming from the Earths mantle?
  - o What is the distribution and concentration of the radioactive elements inside the crust and mantle?

- Borexino and KamLAND have measured the total geoneutrino signal from $^{238}_{92}U$ and $^{232}_{90}Th$ coming from the crust and the mantle.
- More statistics and measurements are needed to constrain the current BSE models.



Thank you!