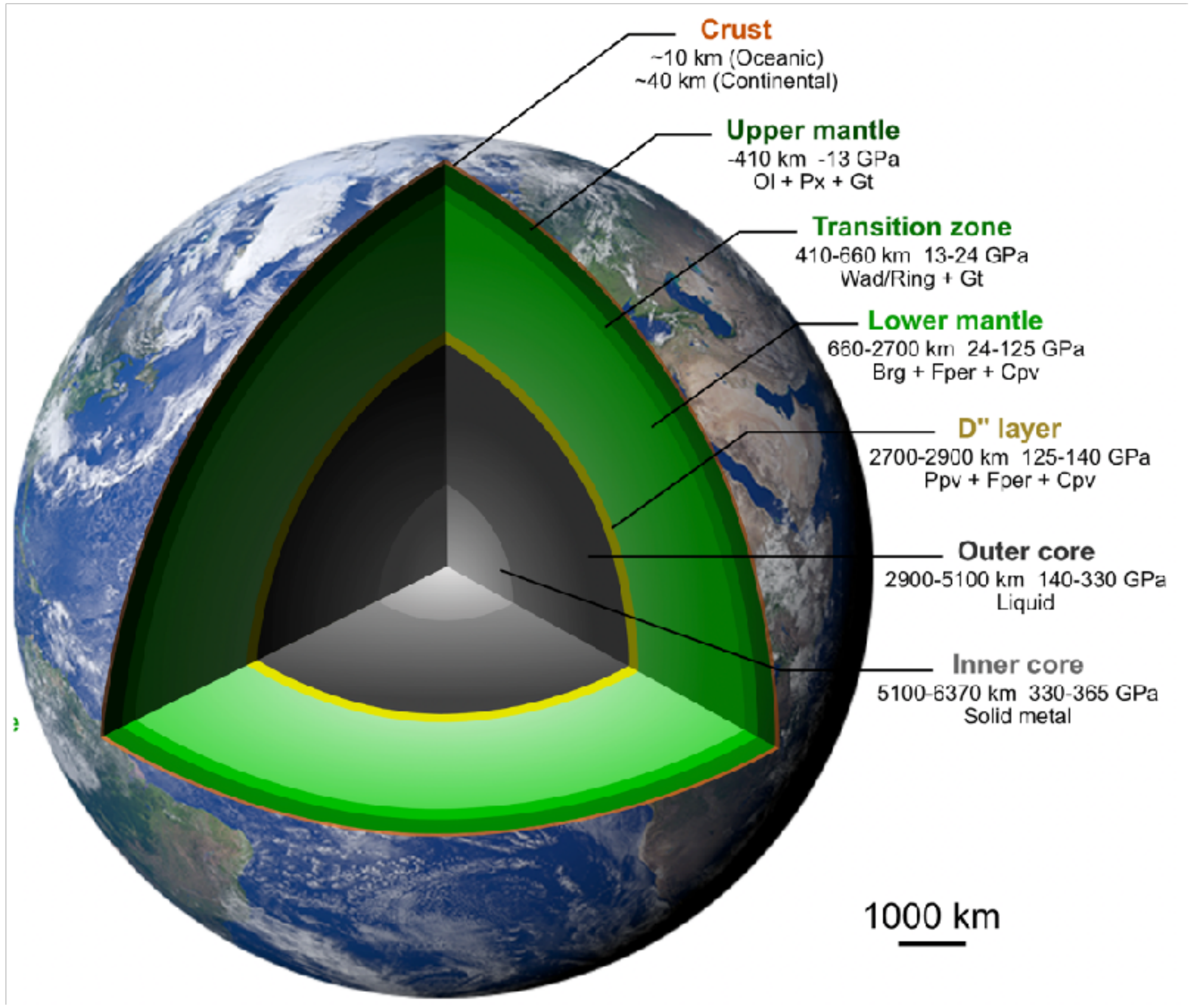
Geoneutrinos:KamLAND, Hanohano, OBD

~ Exploring the Earth's deep interior with Geoneutrinos ~



Hiroko Watanabe,
Research Center for Neutrino Science,
Tohoku University

April 28-May 2, 2025, University of Hawaii

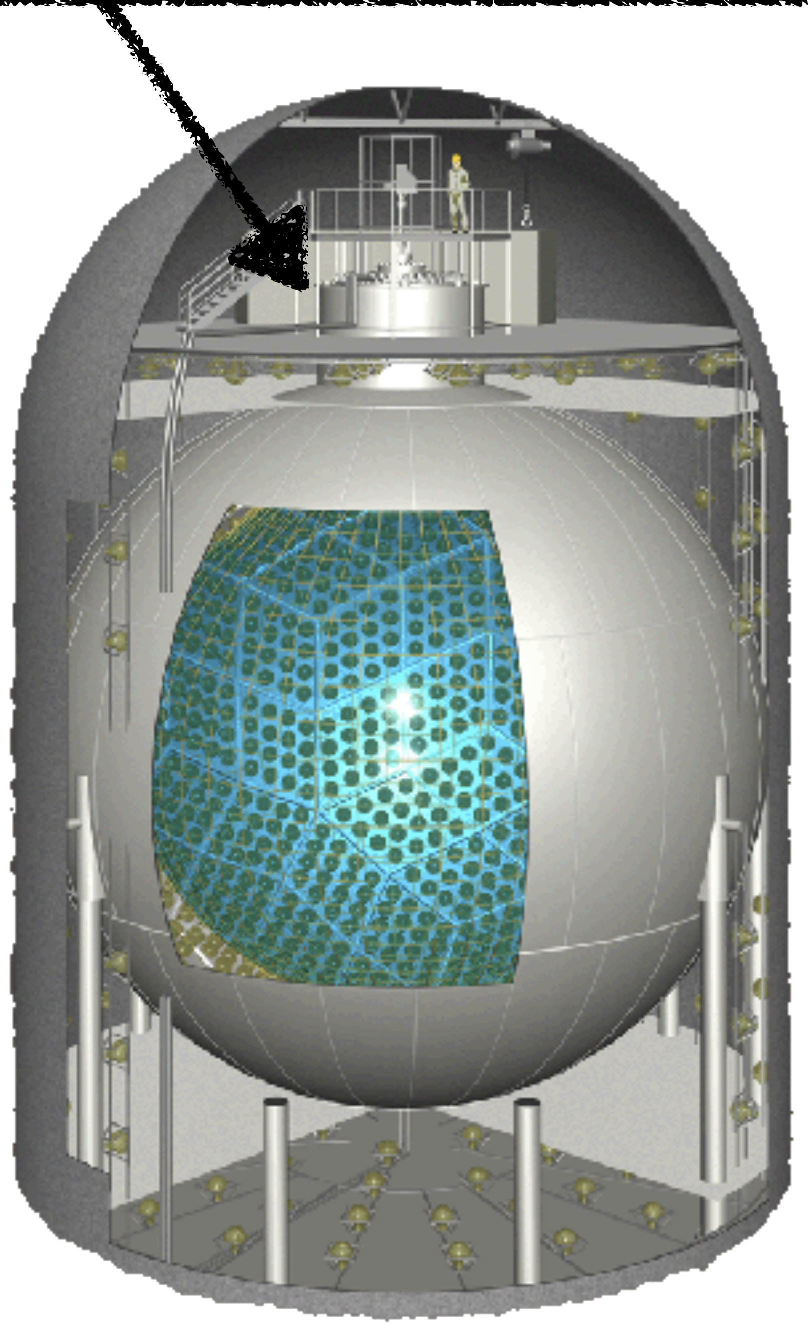
Self-introduction!

Member of KamLAND experiment since 2007

After KamLAND started in 2000

After 1st geo-neutrino paper publication in 2005

After “Hanohano” idea started to be discussed around 2005



KamLAND
@Kamioka

My research:

* Neutrino observation with KamLAND
* “Neutrino Geoscience”
  : interdisciplinary science field
  → **Ocean Bottom Detector**

with John


in 2017
Chiba


Sendai


KamLAND Collaboration Meeting 2012
2023, 2017, 2012, 2009, 2007, 2004, 2003

Earth's Structure

① Crust : Solid

- Volume : 2 %, Mass :~0.5 %
  Heat-producing elements : 40 %
- Changes of <u>seismic wave</u> and chemical composition decide boundary

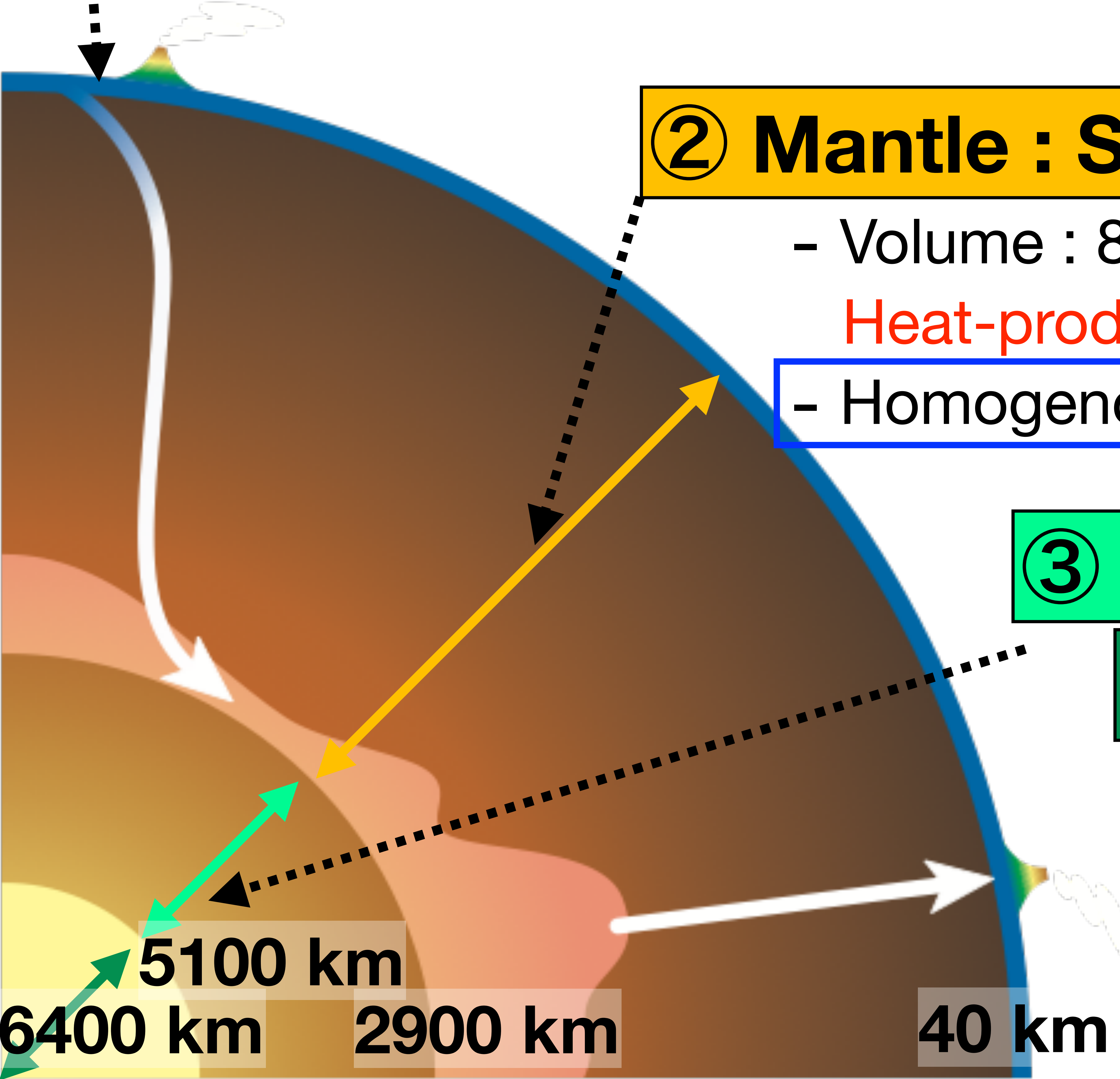
② Mantle : Solid

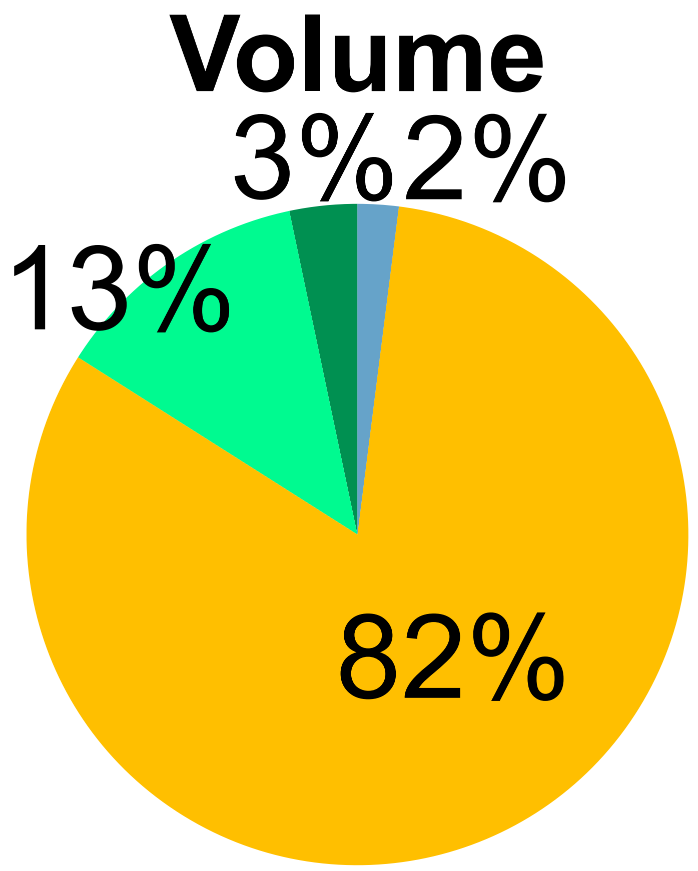
- Volume : 82 %, Mass : 68%
  Heat-producing elements : 60 %
- Homogenous or Inhomogeneous? Chemical composition?

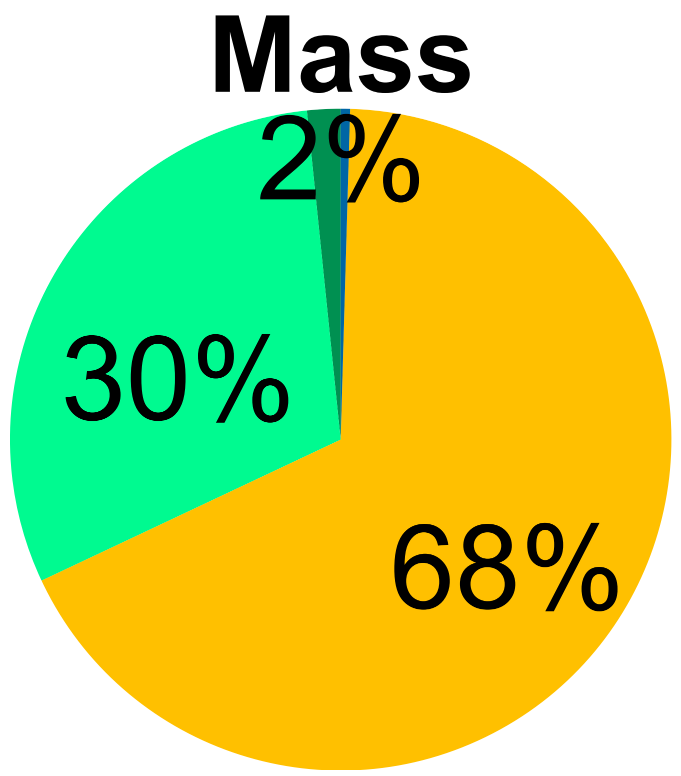
③ Outer Core : Fluid

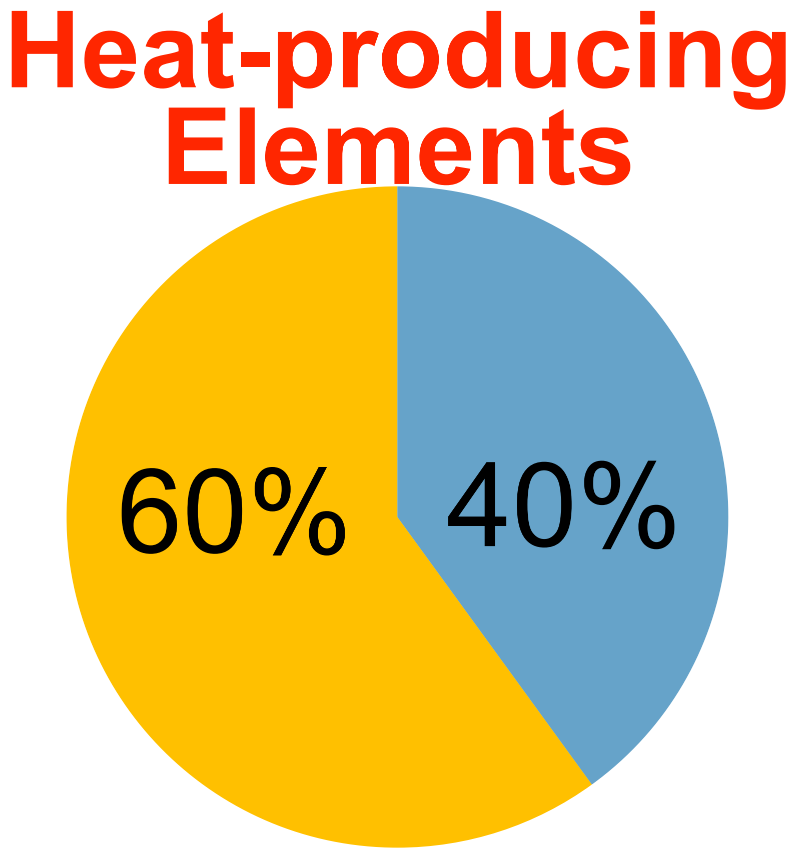
④ Inner Core : Solid

- Volume : 16%, Mass : 32%
  Heat-producing elements : negligible
- Fe (+little Ni) Density : 10% lighter than Fe
- Light elements? Amount?







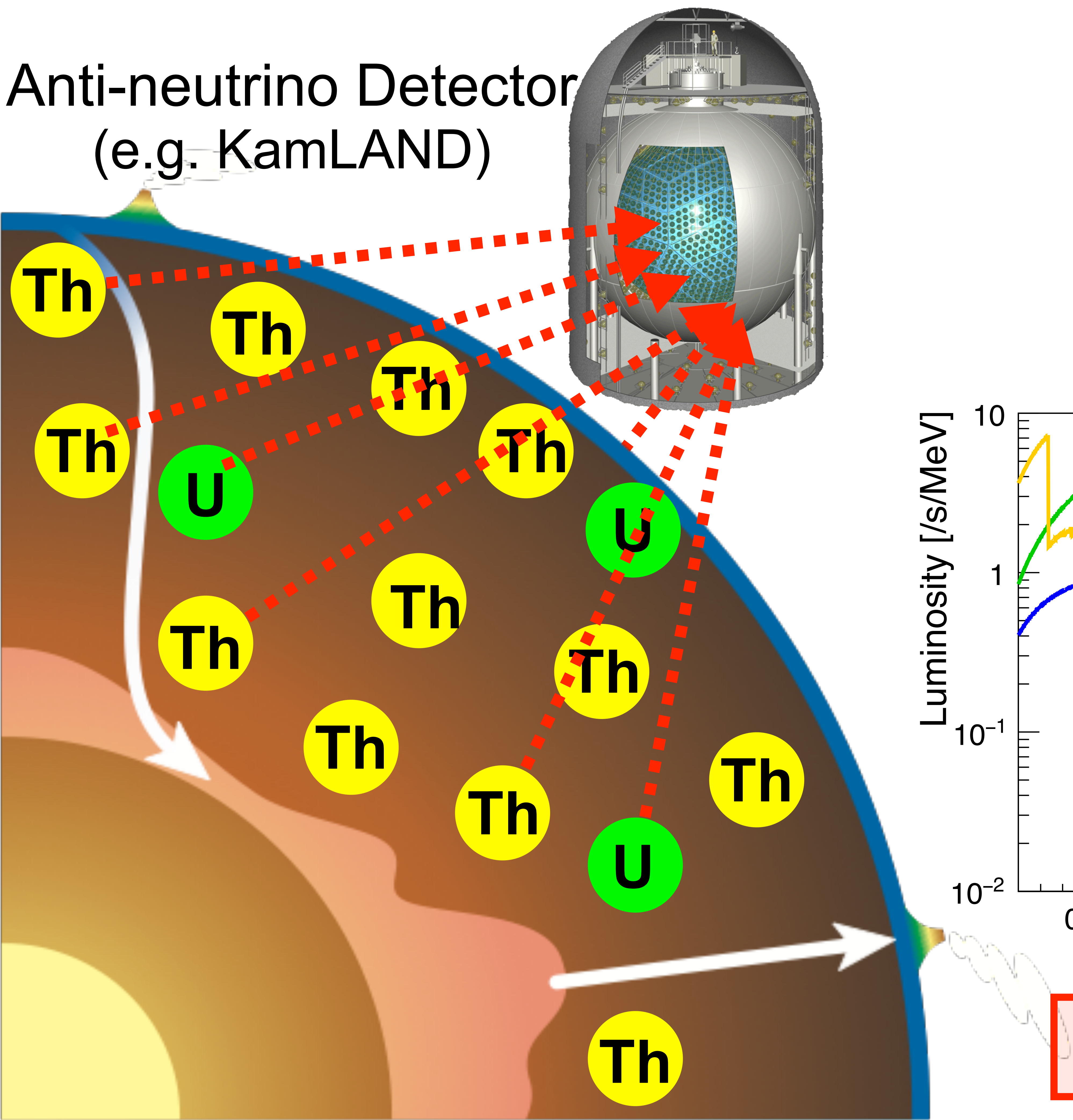


Geo-neutrinos

Electron-antineutrinos from natural radioactive decays

$\bar{\nu}_e \;\; 4.1 \times 10^6 / \mathrm{cm}^2 / \mathrm{sec}$

Anti-neutrino Detector
(e.g. KamLAND)



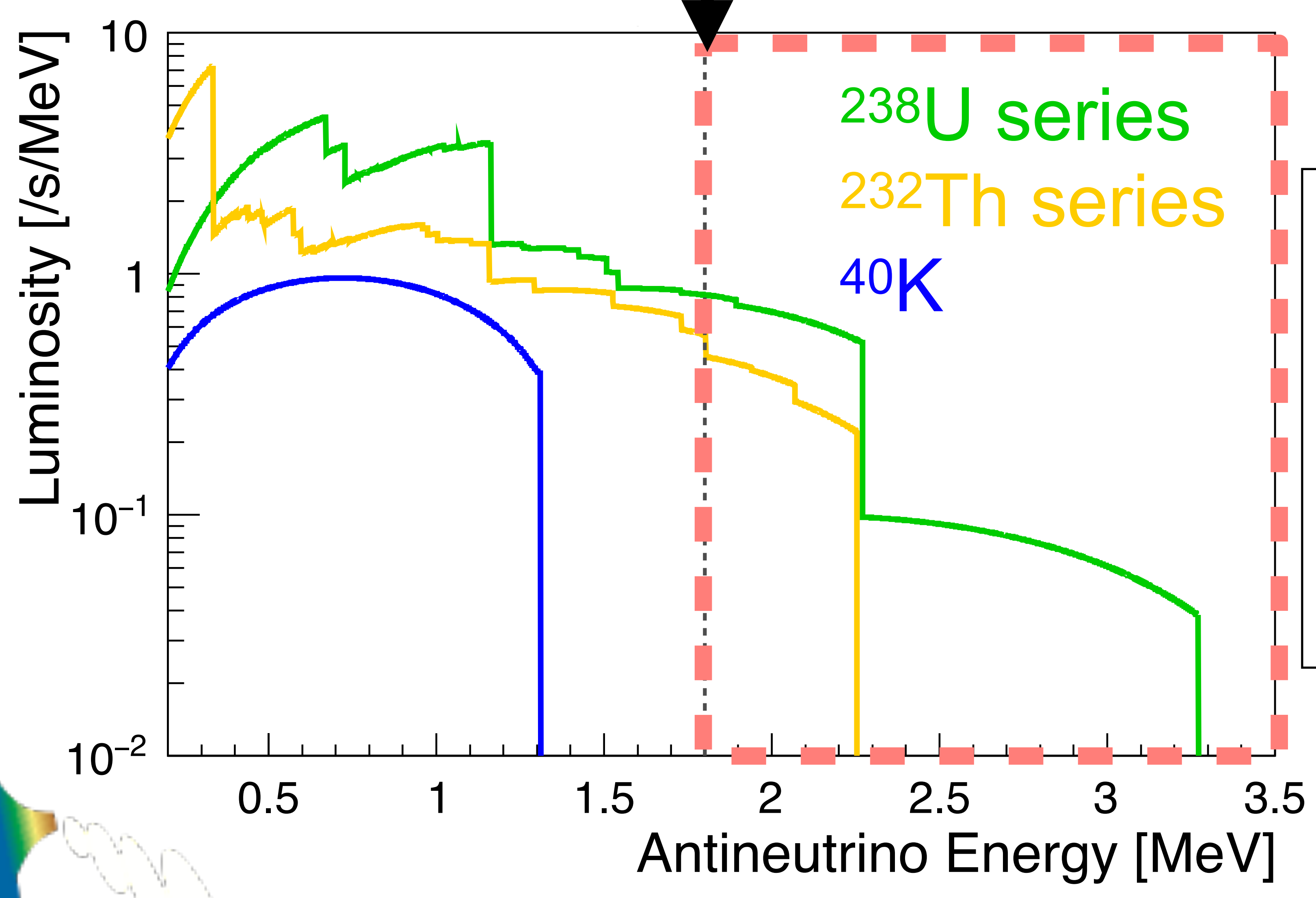
β-decay geo-neutrinos

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}\,(89.28\%)$$

Energy threshold, 1.8 MeV



inverse β-decay

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

*Only geo-neutrinos from U and Th are detectable right now

*^{40}K geo-neutrino detection needs another technology.

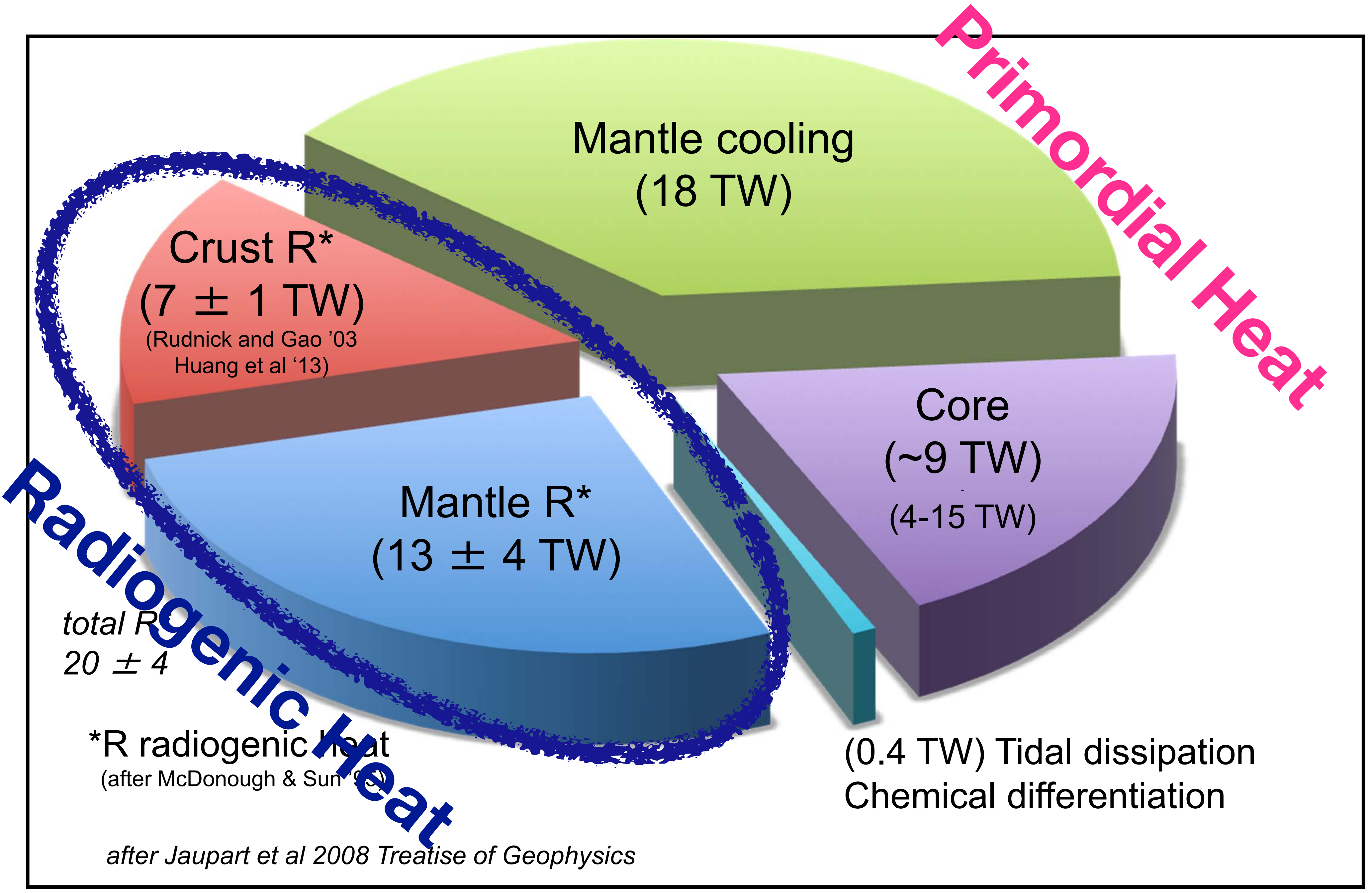
Number of geo $\bar{\nu}_e \propto$ amount of U Th, **radiogenic heat**

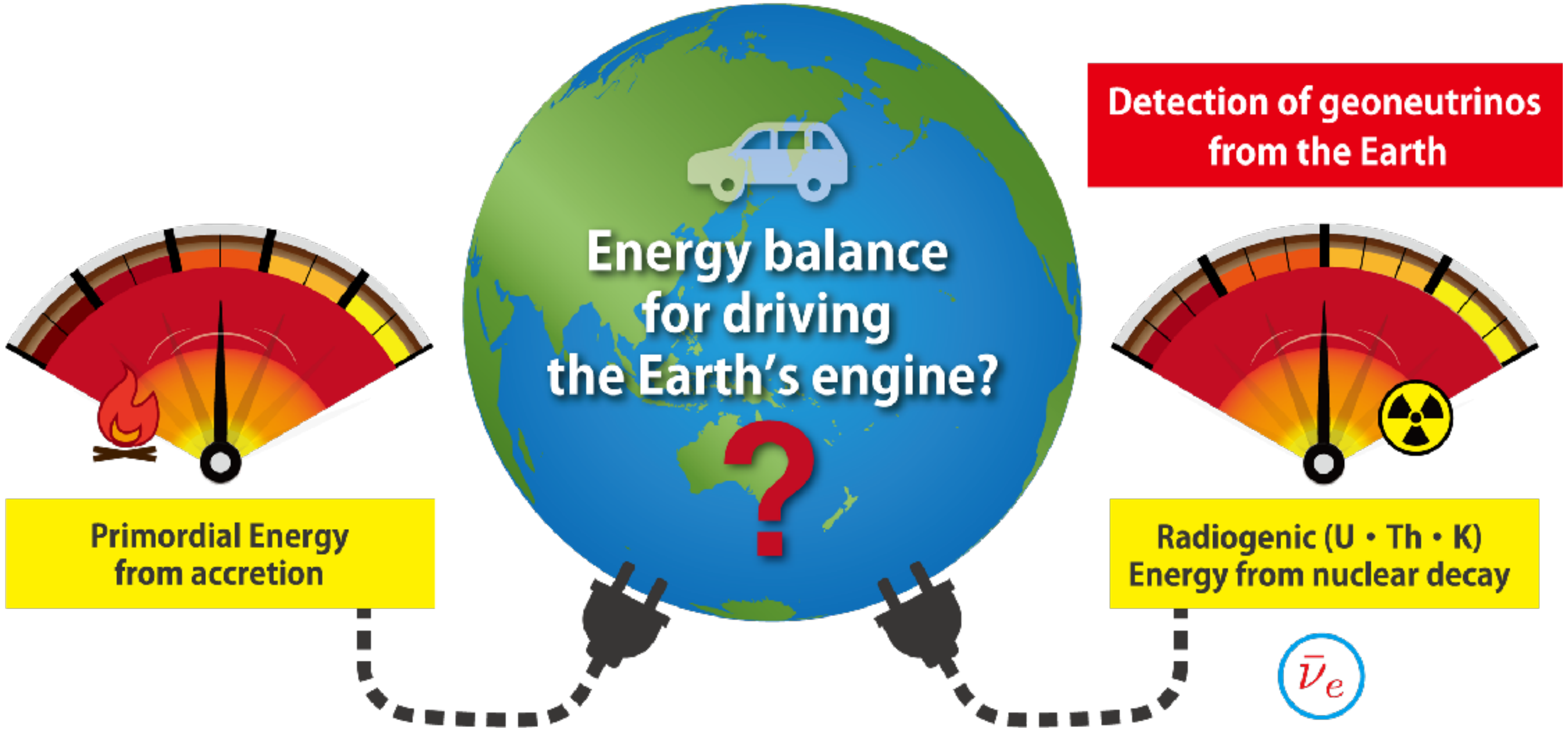
Earth's Heat Balance

Surface heat flow

46 ± 3 TW

example of Earth model





Primordial Heat

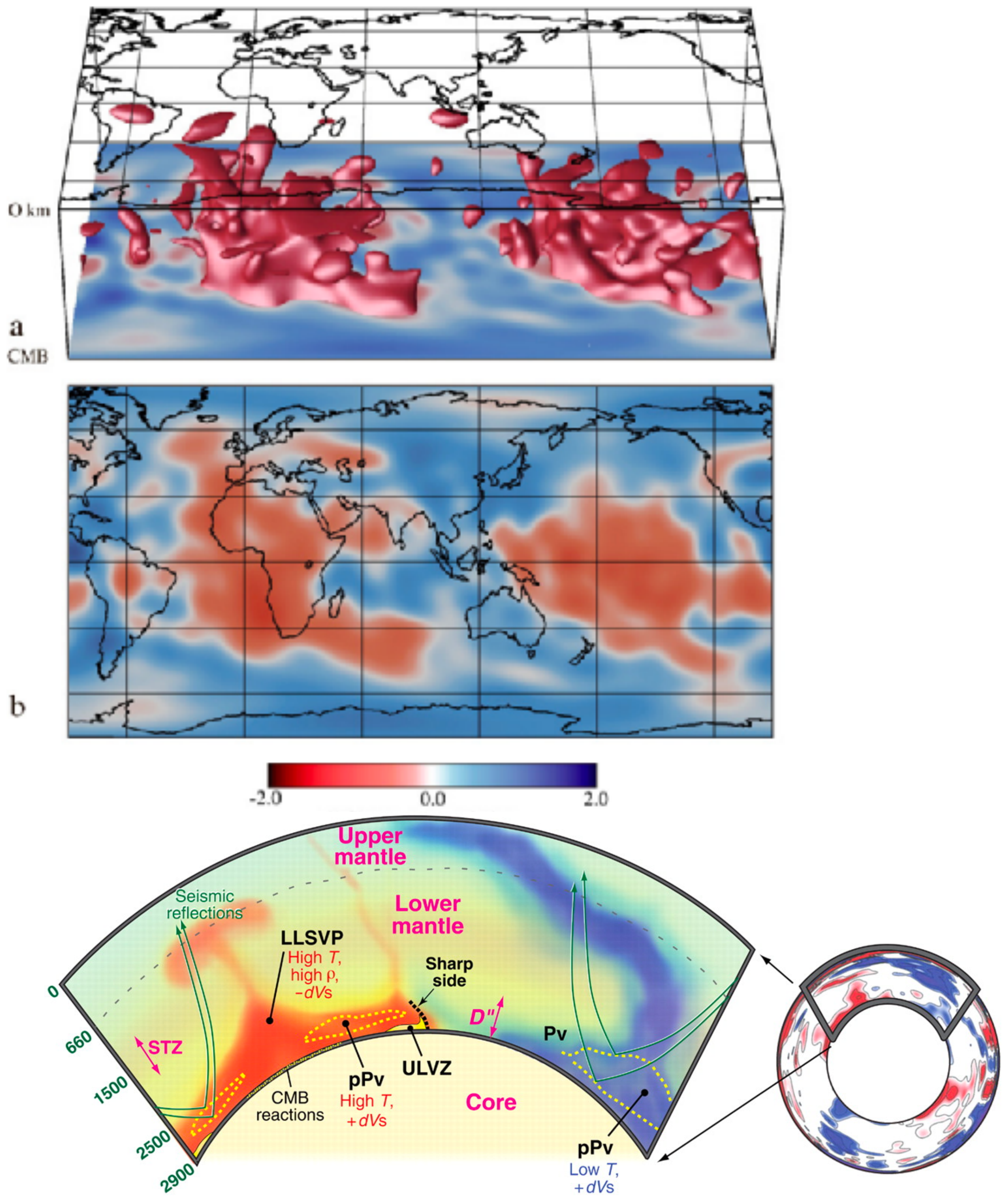
* Releases of gravitational energy through accretion or metallic core separation
* Latent heat from the growth of inner core

Q : How much radiogenic heat contributes to Earth's heat?

Why geo-neutirno?: Big questions

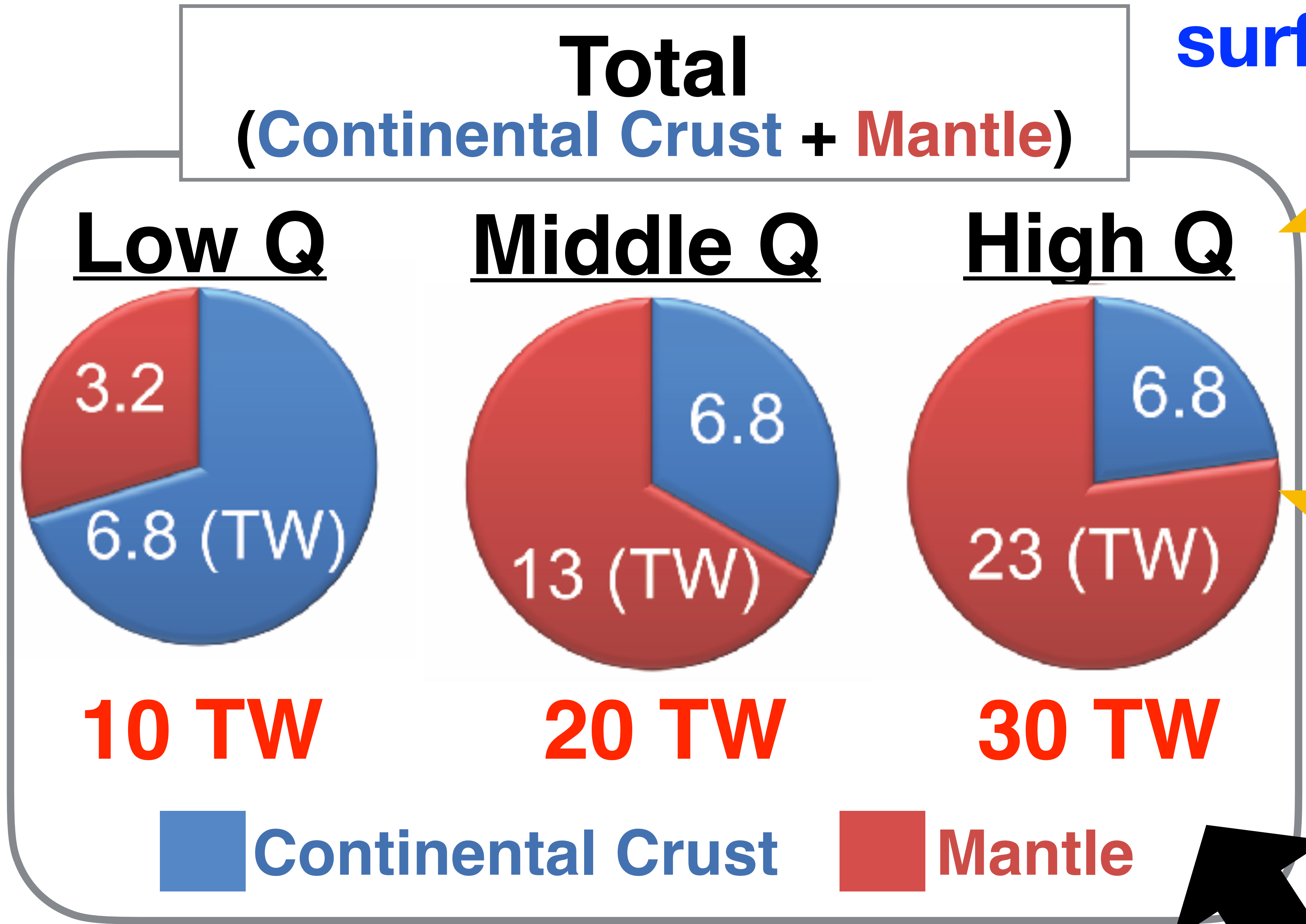
What is in the mantle?

Many seismically imaged structures and chemical heterogeneities in the mantle

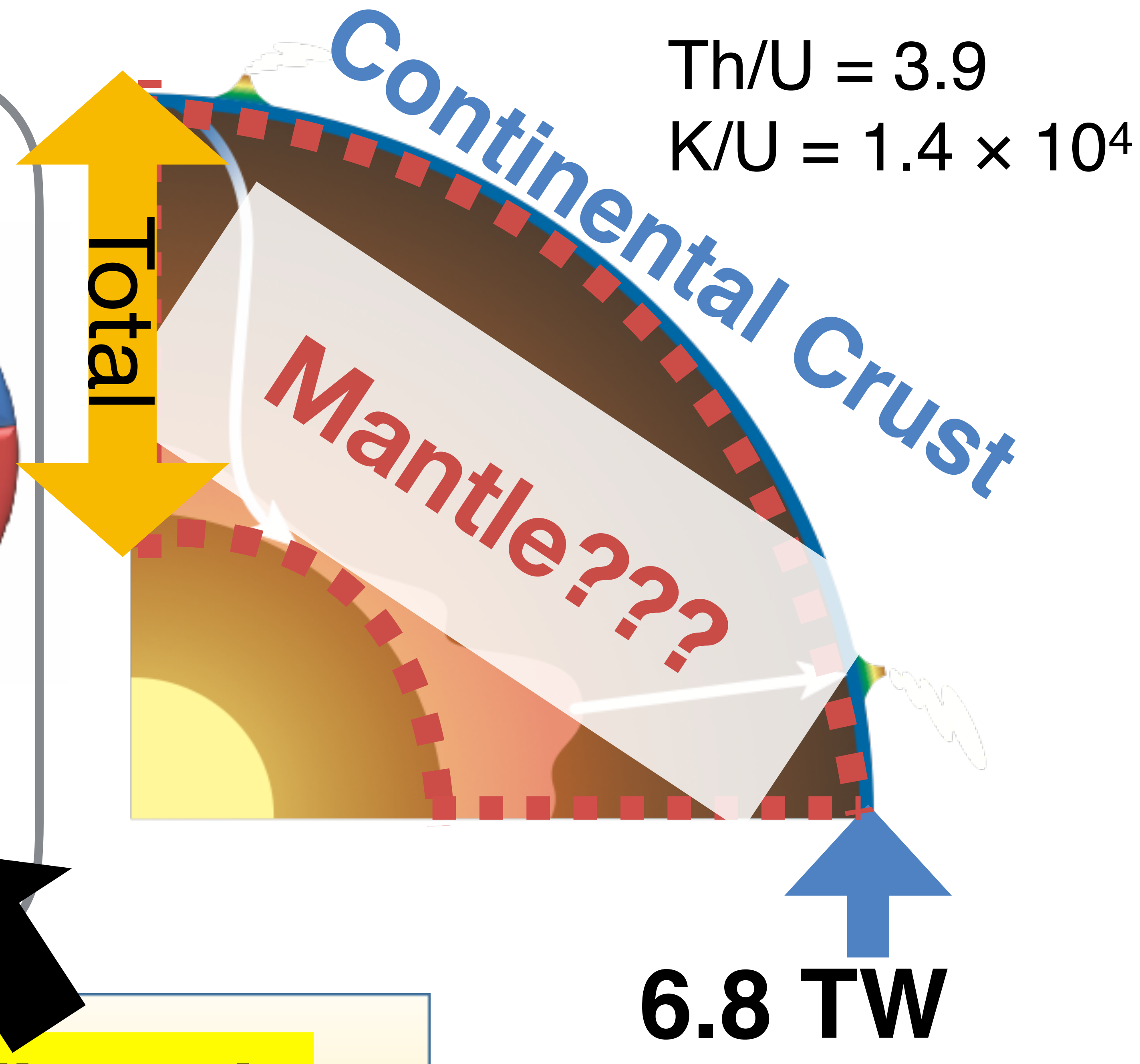


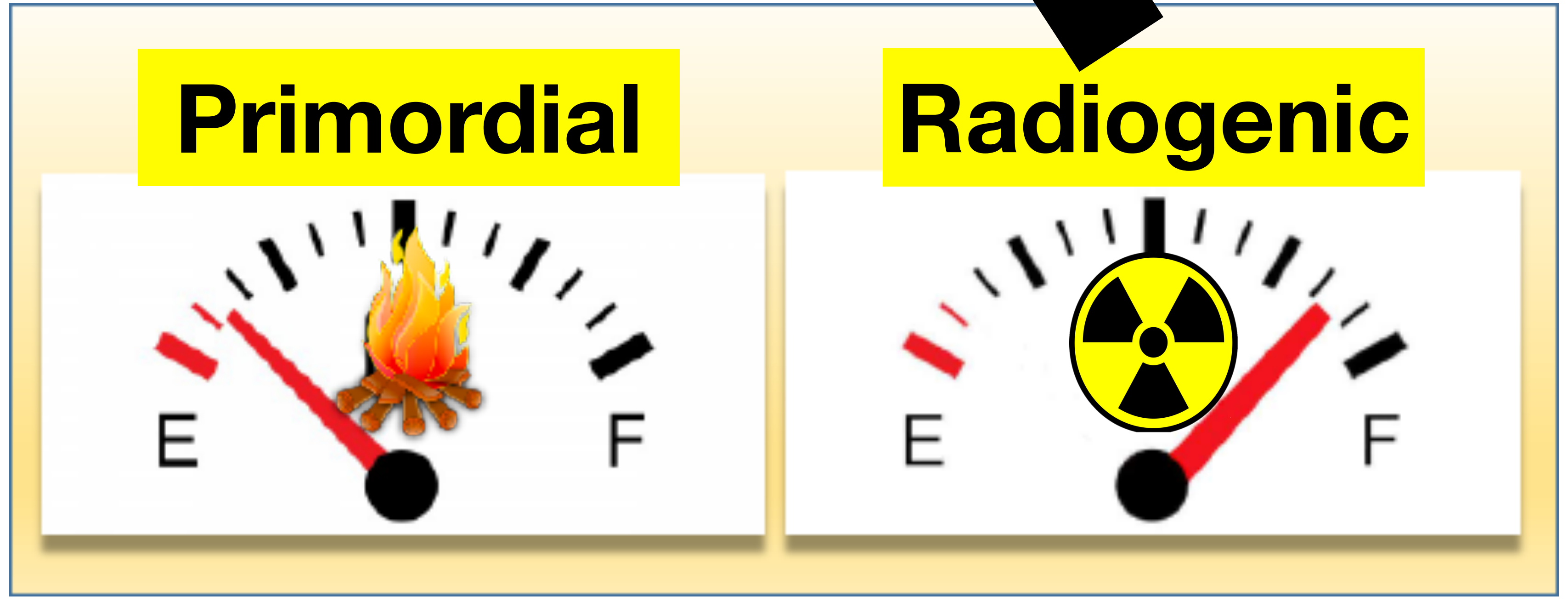
LLSVP (Large Low Shear Velocity Provinces)

How much fuel is left to drive Plate Tectonics?



surface heat flow : 46 ± 3 TW



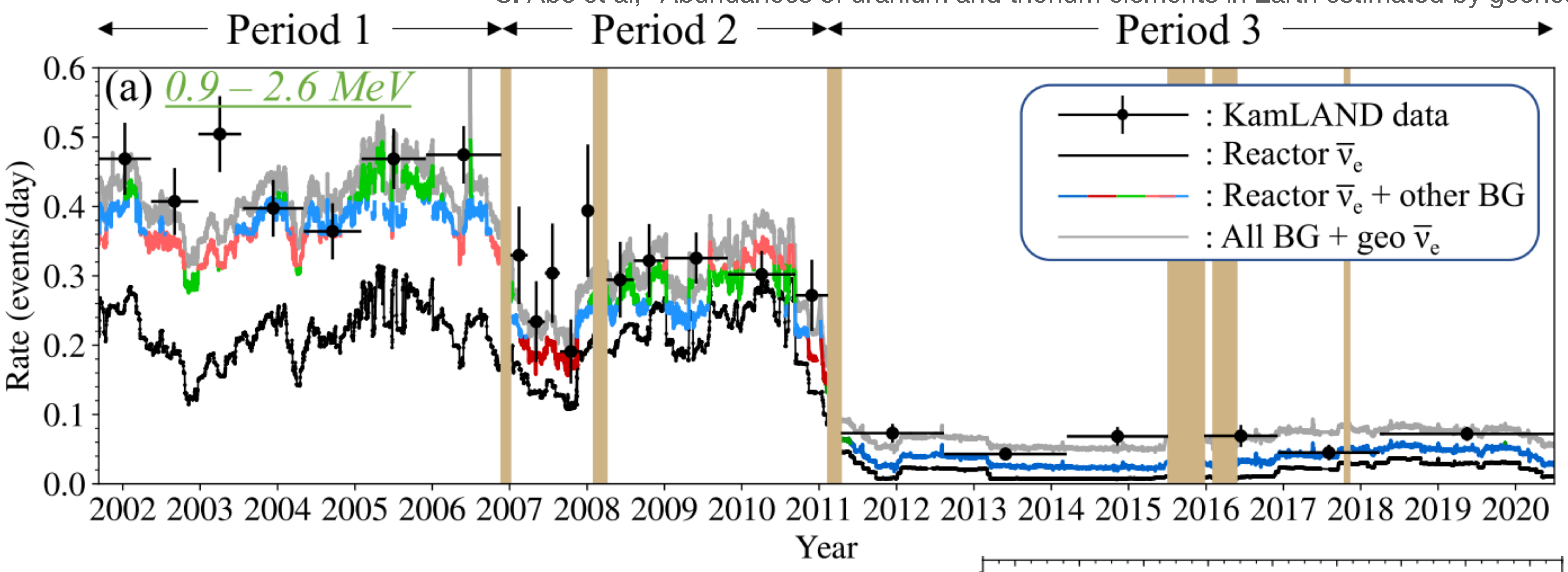


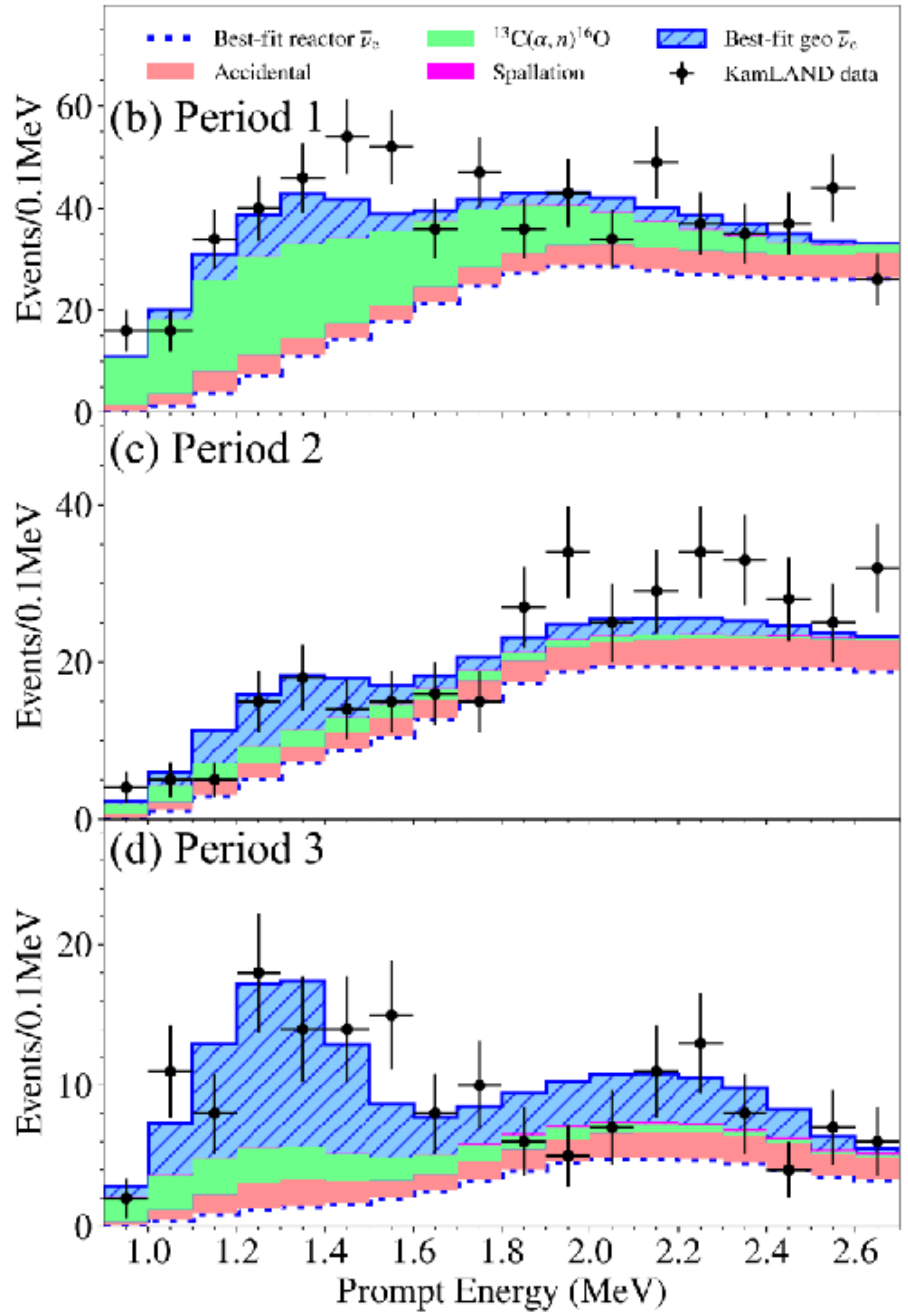
Experiments

- Two experiments have published geoneutrino measurement results so far.
- New experimental data by **SNO+** & **JUNO** will be reported soon!

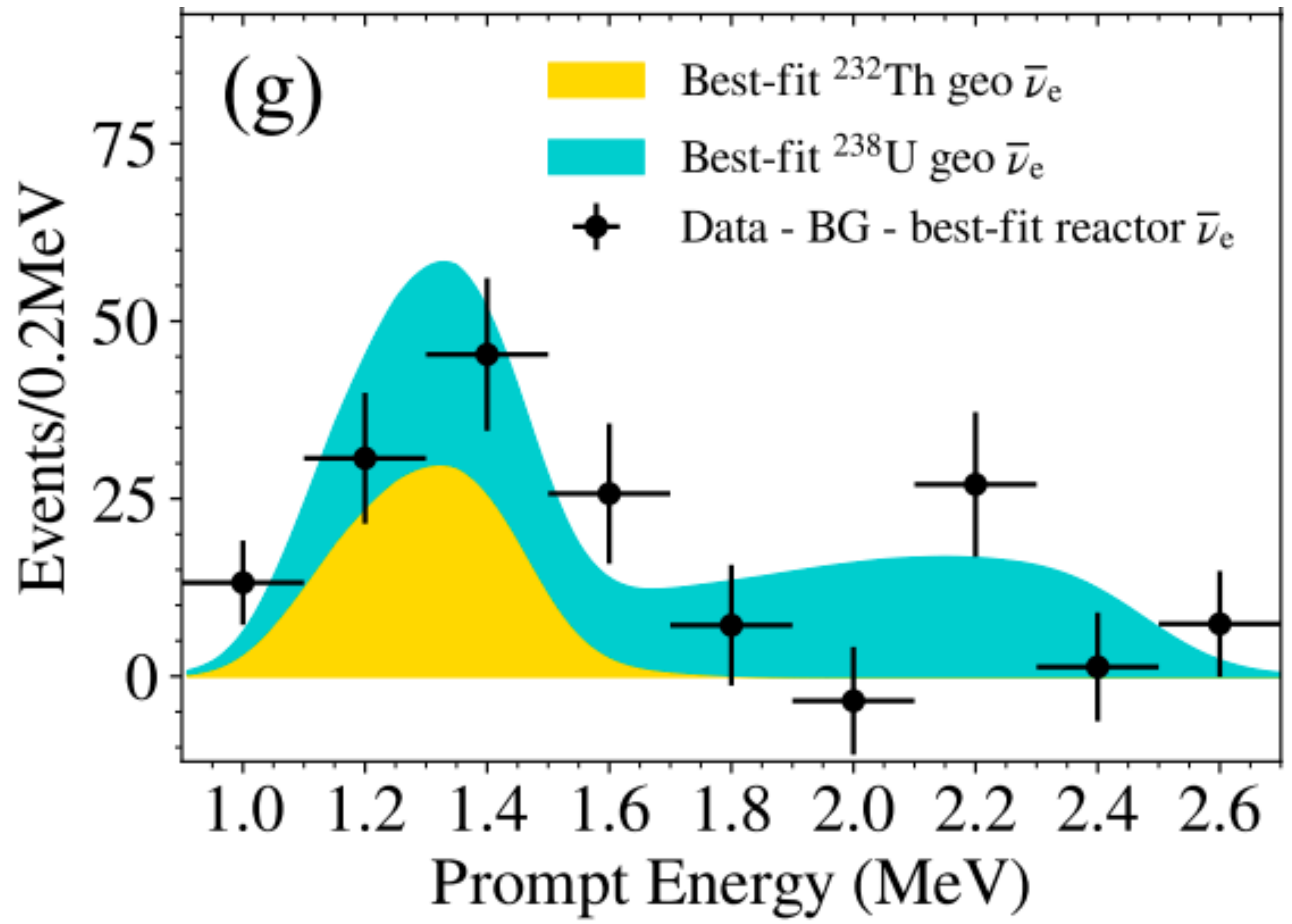
KamLAND Latest Results

S. Abe et al, “Abundances of uranium and thorium elements in Earth estimated by geoneutrino spectroscopy”, GRL, 49, e2022GL099566





Dataset : Mar, 2002-Dec, 2021
Livetime : 5227 days
(low-reactor phase : 2590 days)



- ☑ **massive dataset of low-reactor period**
  → precise measurement of U and Th contributions

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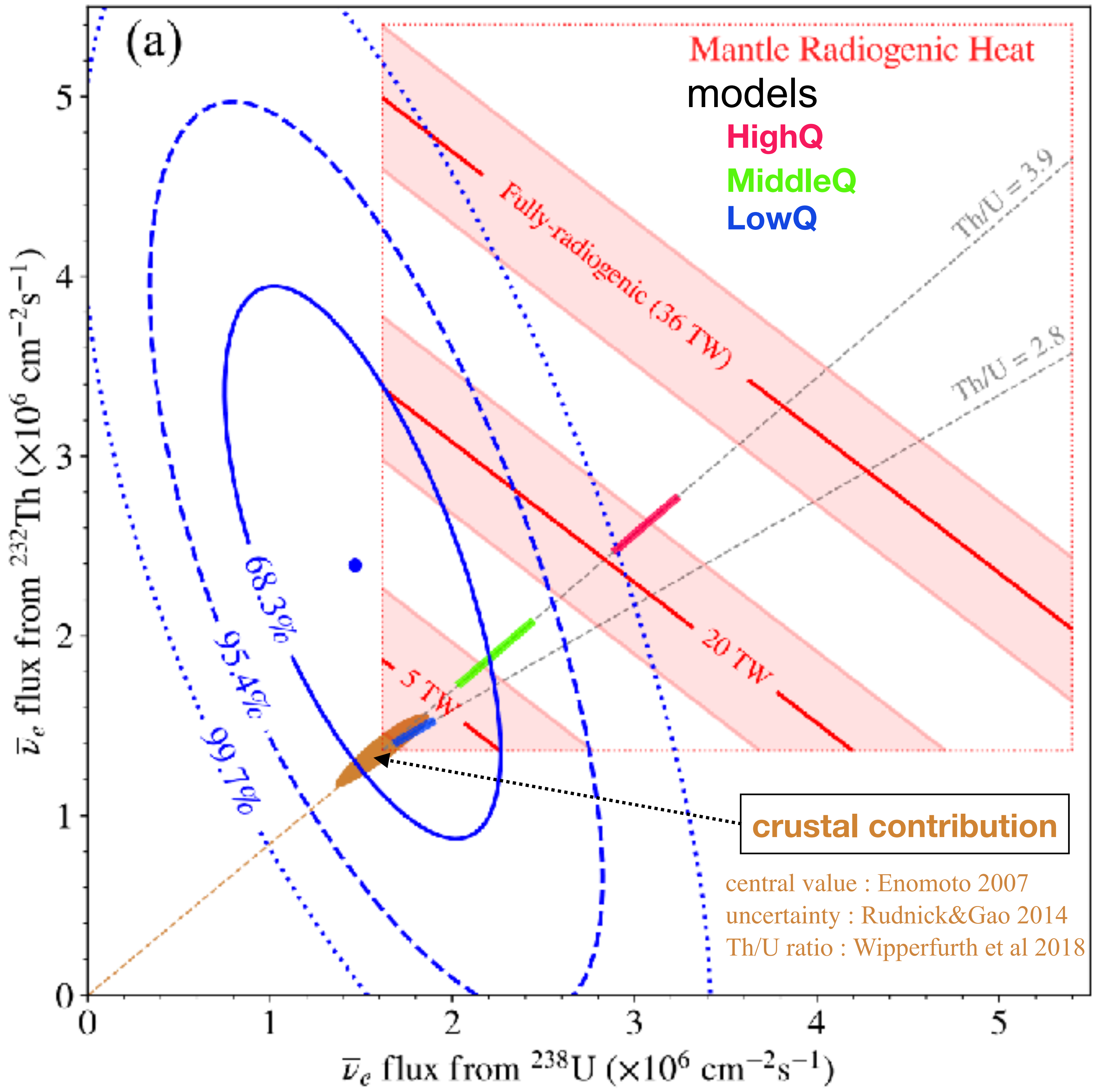
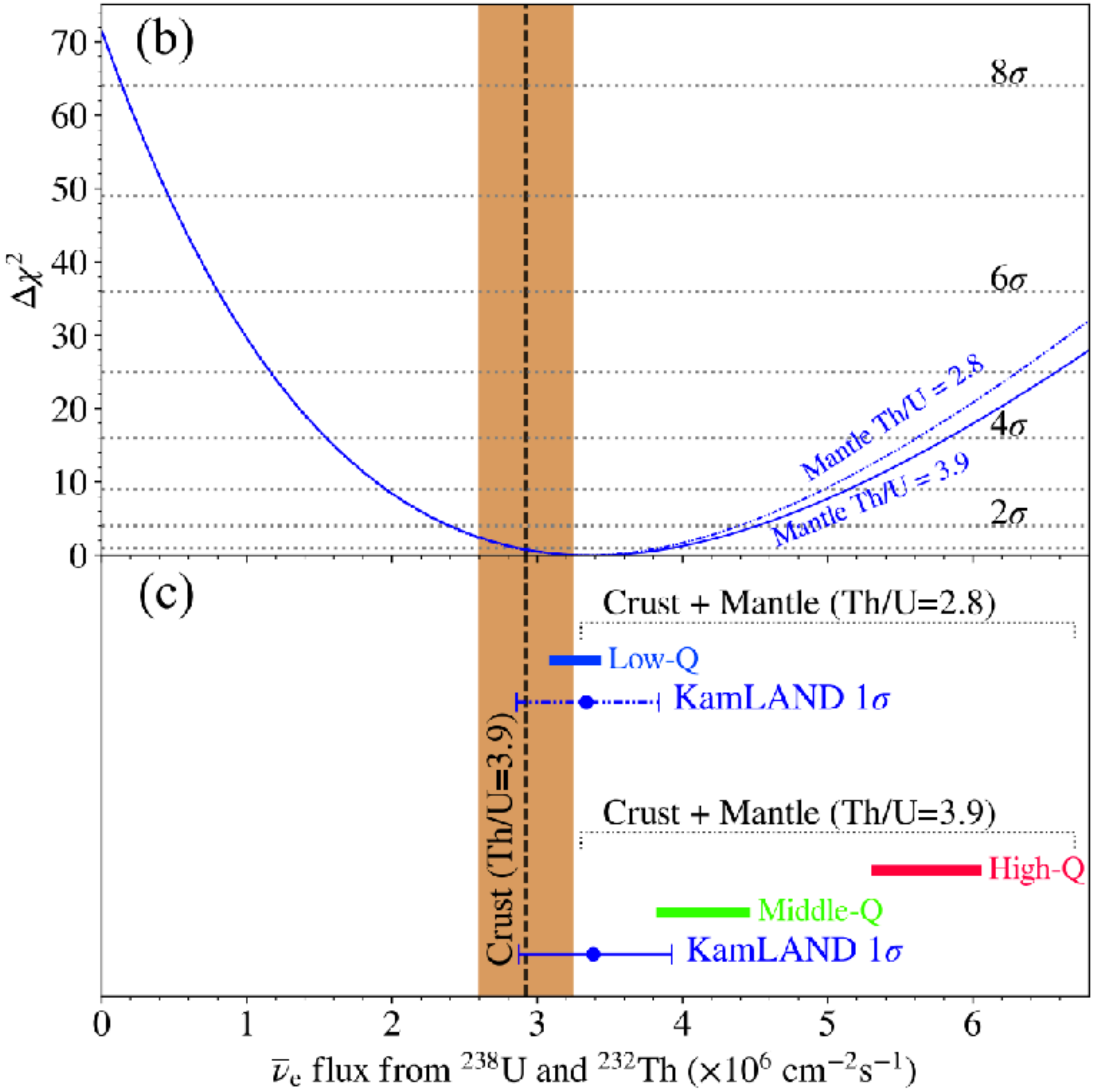




Radiogenic Heat

Th/U free

Adding heat estimate from crust,
^{238}U : 3.4 TW, ^{232}Th : 3.6 TW

$$Q^{\rm U} = 3.3^{+3.2}_{-0.8}\ \rm TW$$
$$Q^{\rm Th} = 12.1^{+8.3}_{-8.6}\ \rm TW$$
$$Q^{\rm U} + Q^{\rm Th} = 15.4^{+8.3}_{-7.9}\ \rm TW$$

Model Rejection

HighQ model is rejected at
99.76 % C.L. (homogeneous mantle)
97.9% C.L. (concentrated at CMB)

best-fit

Th/U free

	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+29}_{-28}	8.3σ

Achieved the accuracy level can further geoscientific discussion

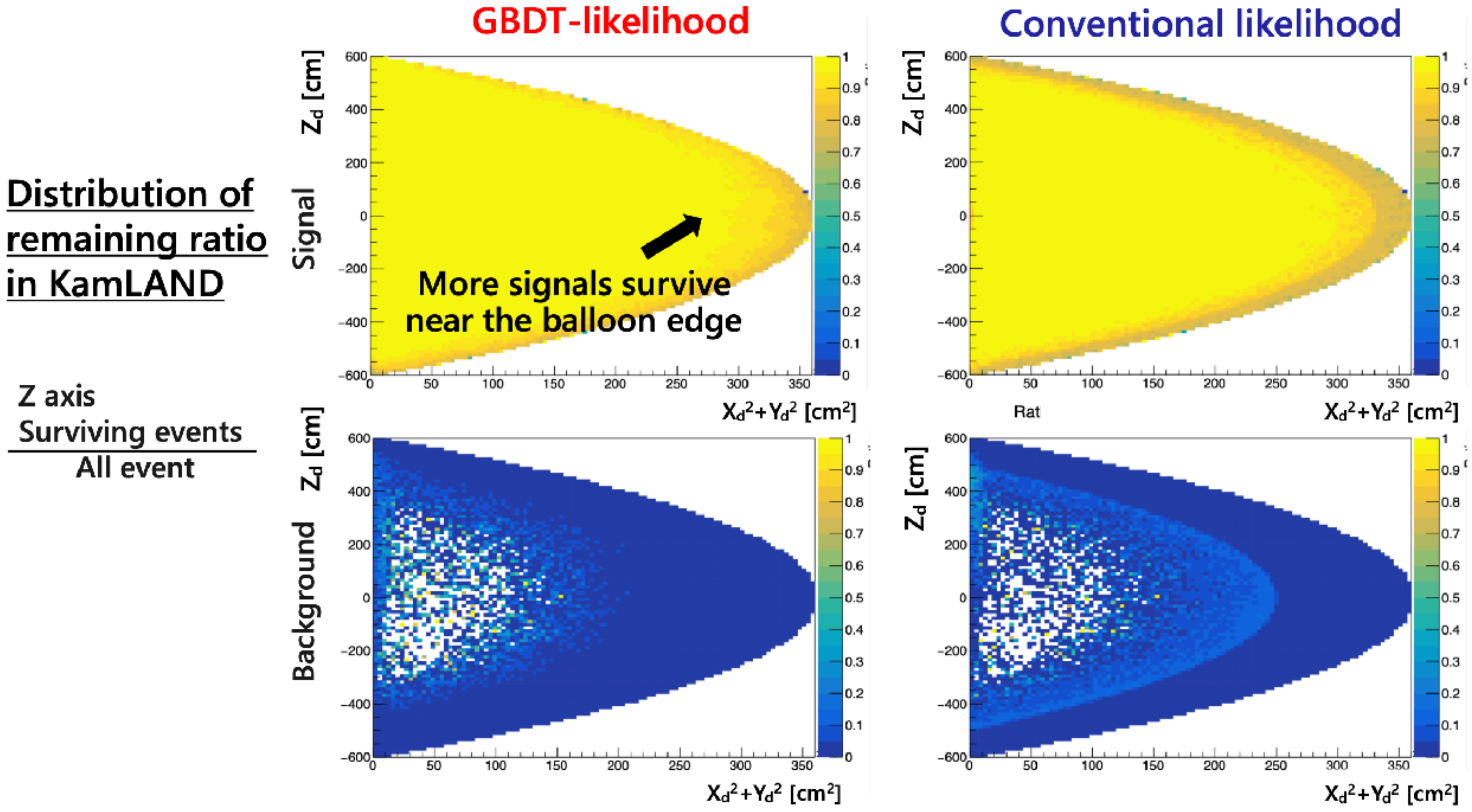
Improve the distinct spectroscopic contributions of U and Th

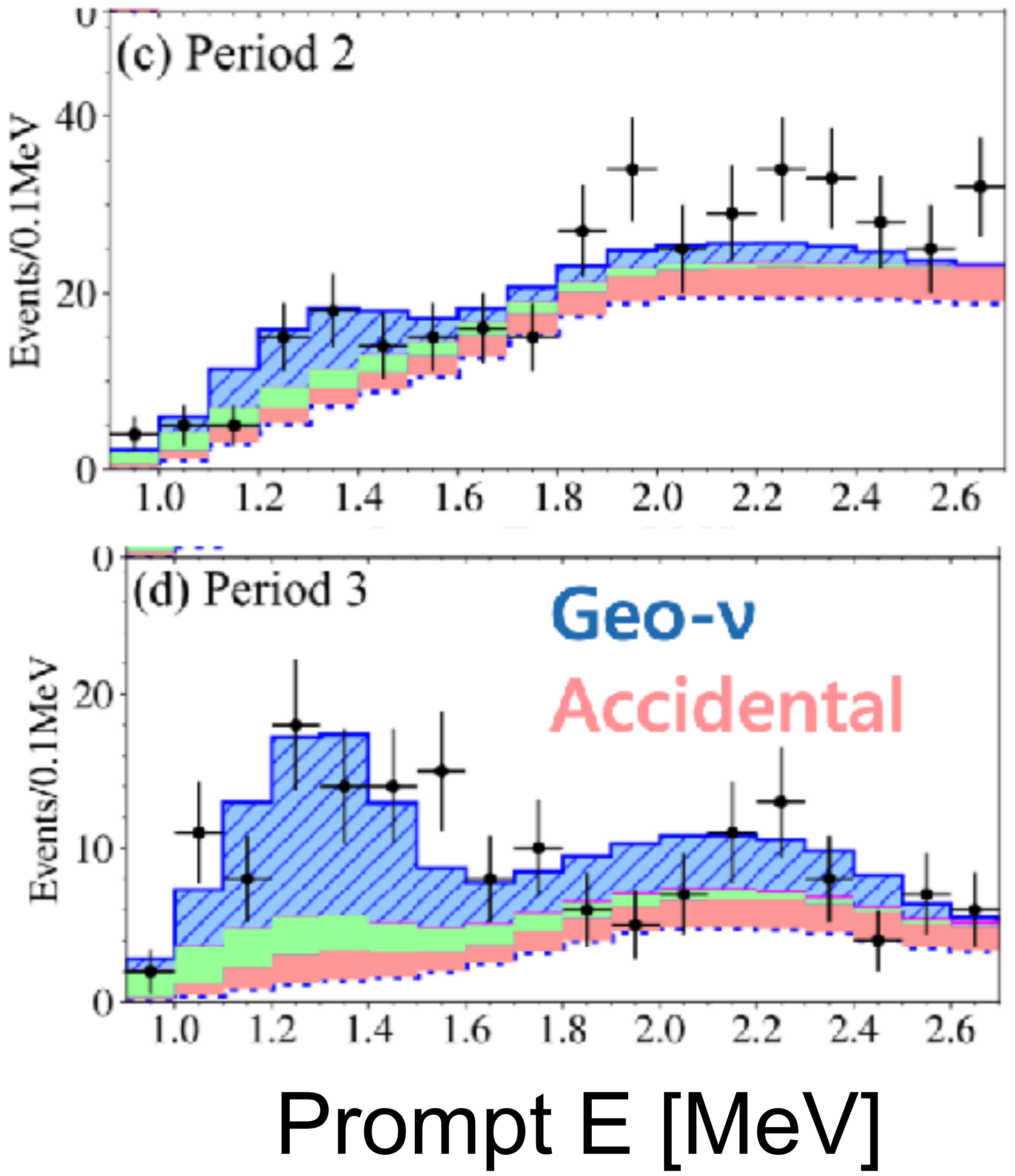
Final Result of KamLAND1

Dataset : Mar, 2002-Aug, 2024 (+2.5 years from last result)

+ BG reduction with machine learning

Gradient **b**oosting **d**ecision **t**ree is powerful algorithm for accidental BG reduction.





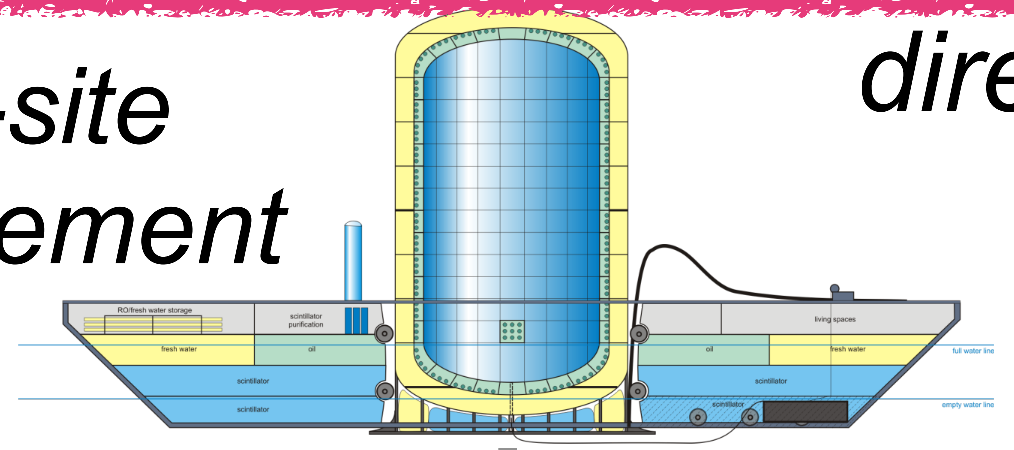
KamLAND full data analysis with GBDT is ongoing !

Neutrino Geoscience: Current and Future

what we need

improved accuracy of measurement & modelling

multi-site measurement



detector in the Ocean

directional sensitive detector

new type detector

current generation → **next** generation

total radiogenic heat in the Earth — ☑ Measuring

Th/U ratio — ☑ Measuring

Directly

distinguishing mantle contribution — ☑ Measuring

Next Target!

resolving vertical and horizontal flux differences

detecting K geo-neutrino

what we learn

first measurement in **2005**

OBD: breakthrough beyond modern land-based detector transforming our vision of deep Earth

Multisite Measurements

Observation = **Crust** + **Mantle**

(y = x + b)

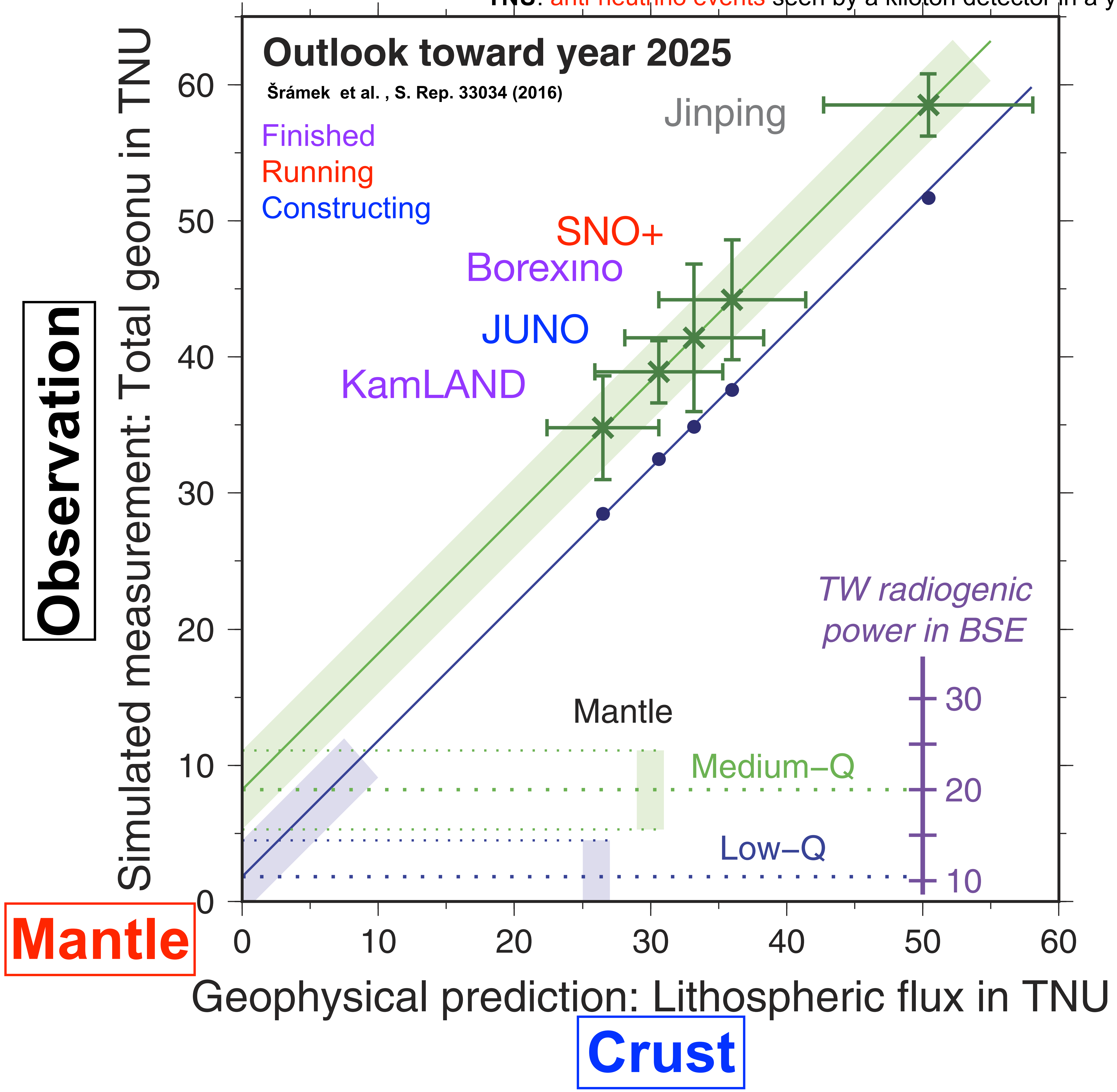
Near Future…

4 multi-site measurements can constrain mantle contribution.

* KamLAND, Borexino, SNO+, JUNO

* Crust estimation needs to be accurate.

TNU: anti-neutrino events seen by a kiloton detector in a year



Multisite Measurements+OBD

Observation = **Crust** + **Mantle**

(y = x + b)

Near Future…

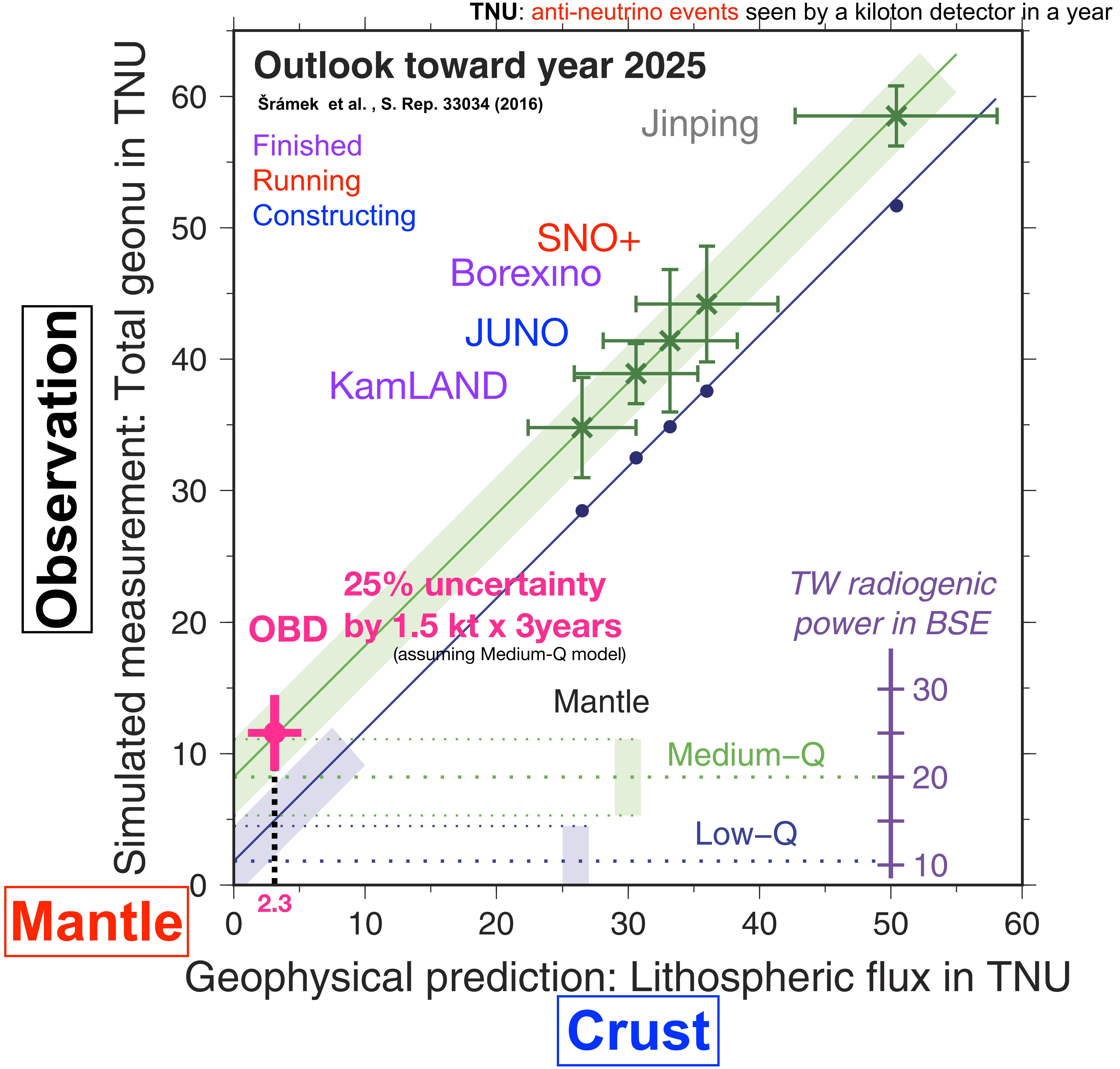
4 multi-site measurements can constrain mantle contribution.

* KamLAND, Borexino, SNO+, JUNO

* Crust estimation needs to be accurate.

+ Ocean Bottom Detector (Hanohano)

directly measure mantle contribution.



OBD/Hanohano Motivations

- **Direct Measurement of Mantle**

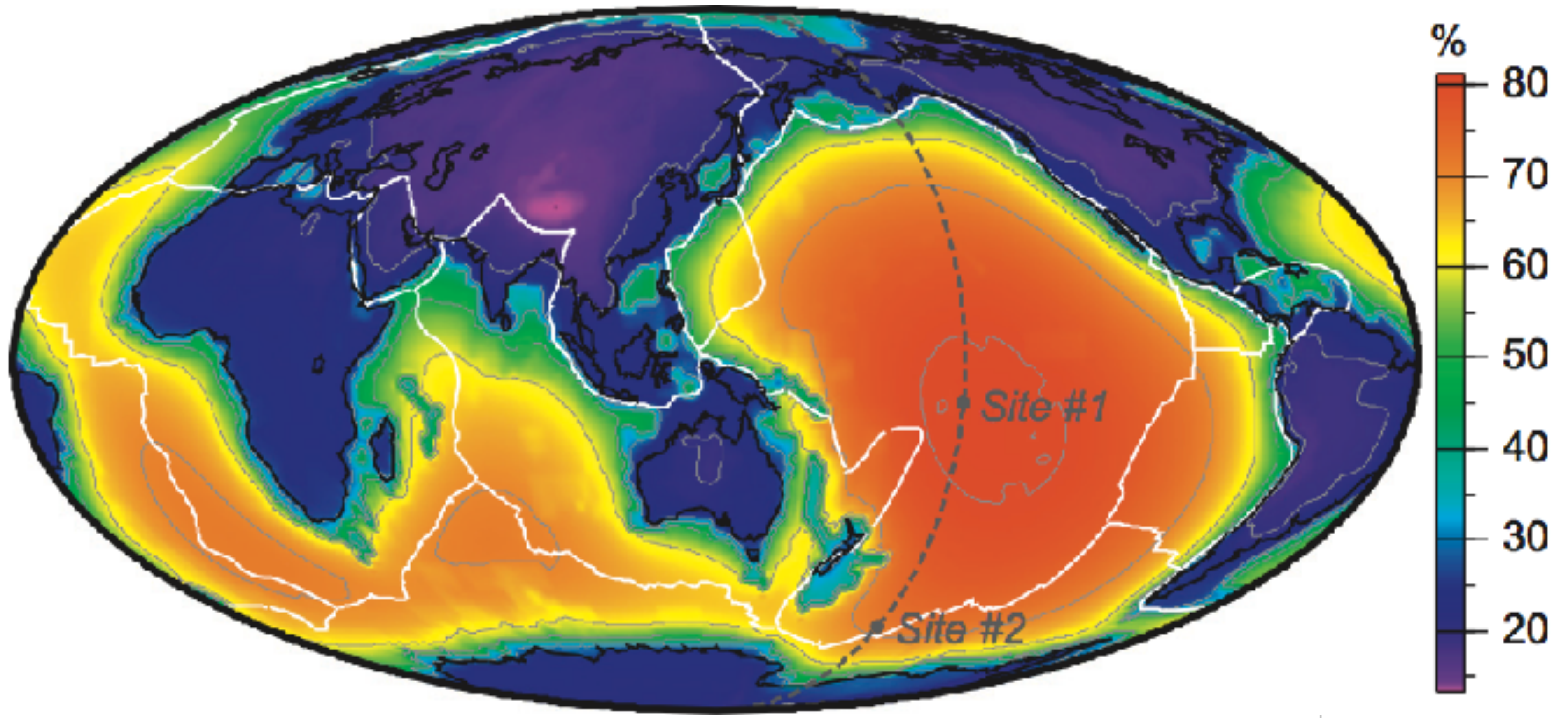
  need to be far from crust
  can be far from reactors

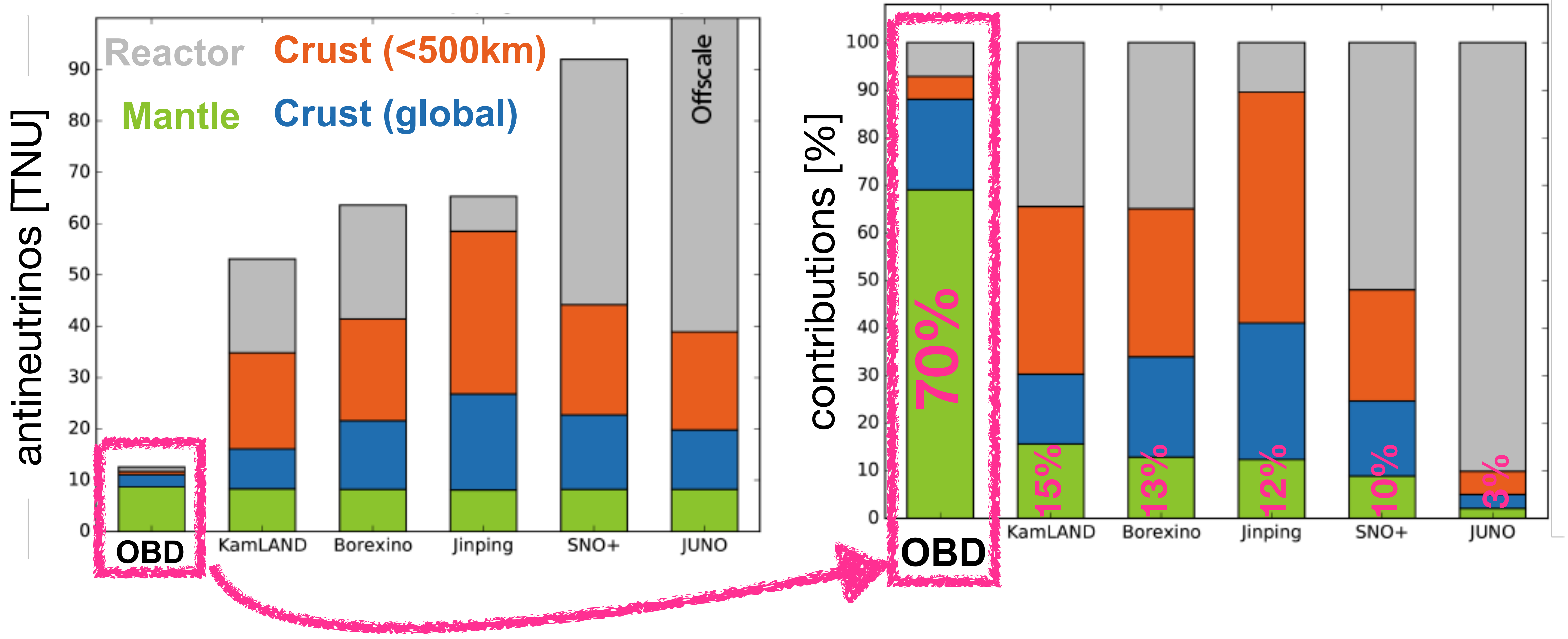
- **Multi-site Measurements**

  Solve the mystery of deep Earth!
  First detector for mapping the inhomogeneous mantle

- **Multidisciplinary Detector**

Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001





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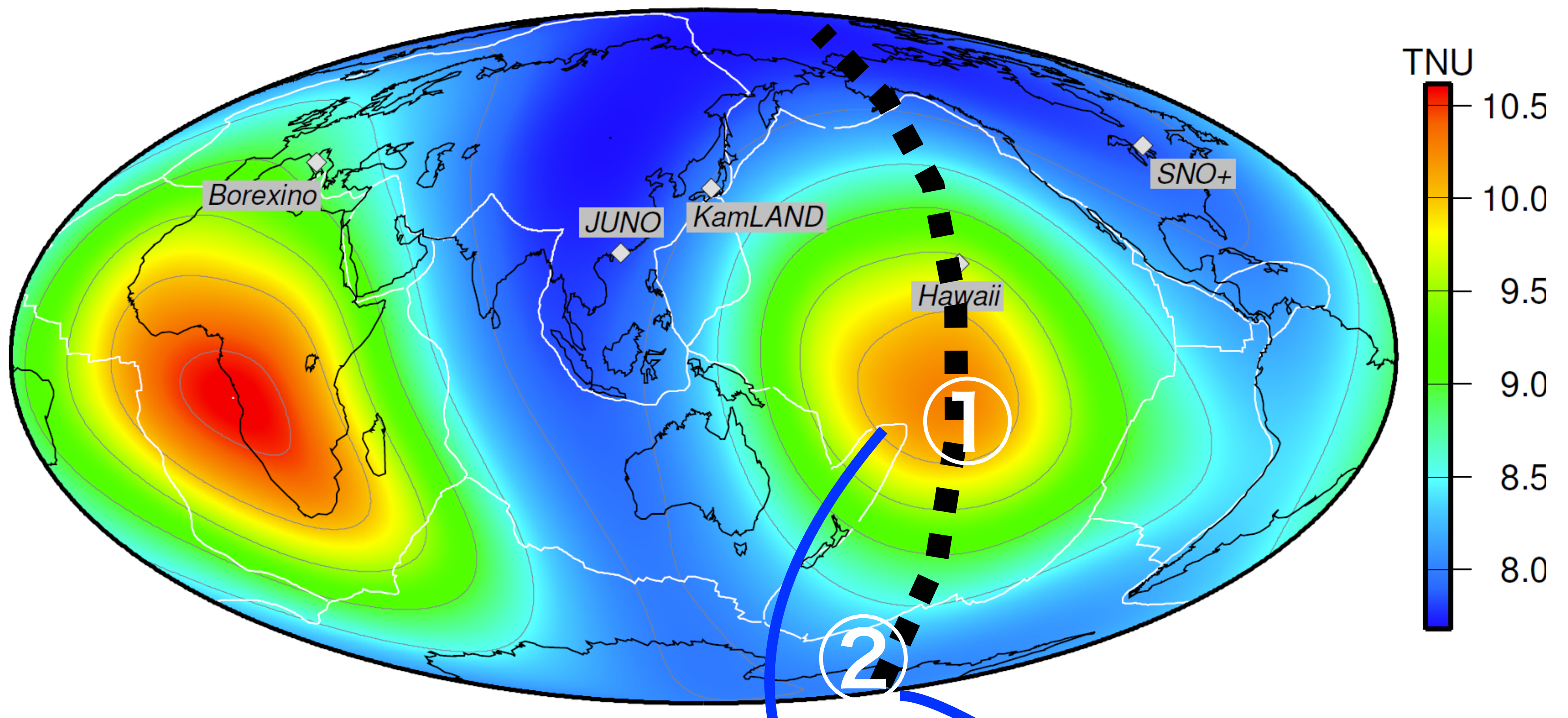
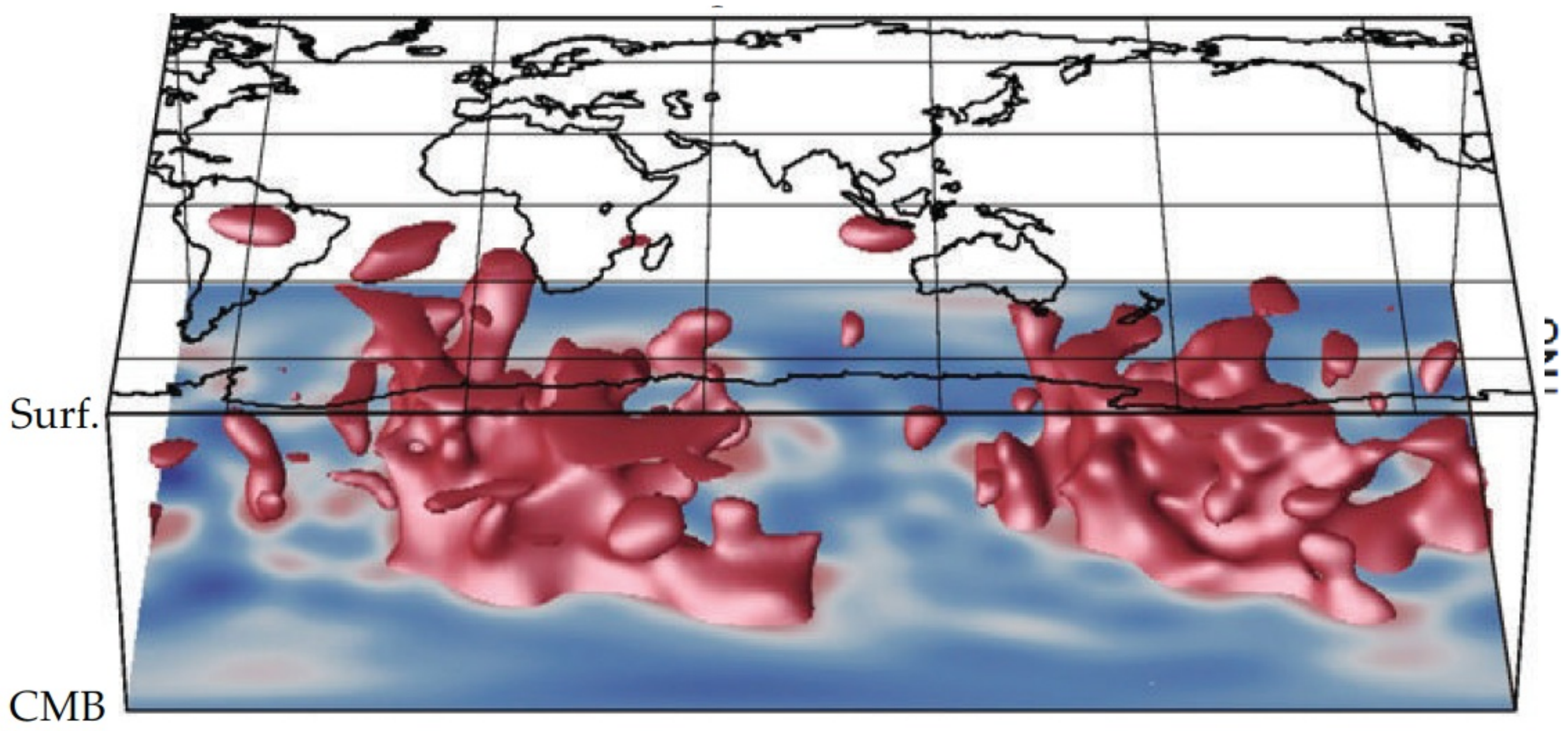
Mantle Geoneutrino Flux

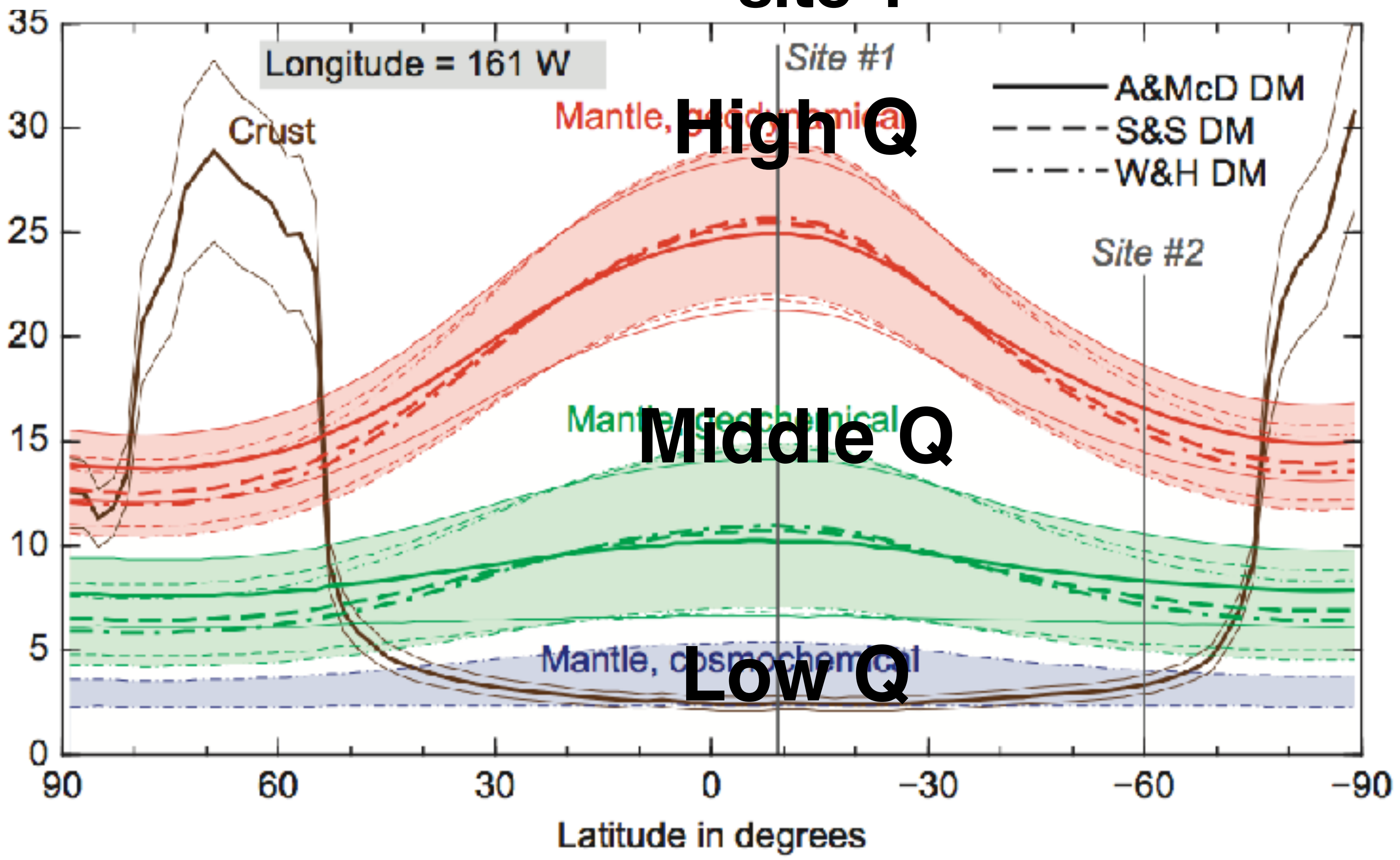


Seismically slow "red" regions in the deep mantle



From Alan McNamara after Ritsema et al (Science, 1999)

site 1
site 2



OBD/Hanohano Motivations

- **Direct Measurement of Mantle**

need to be far from crust
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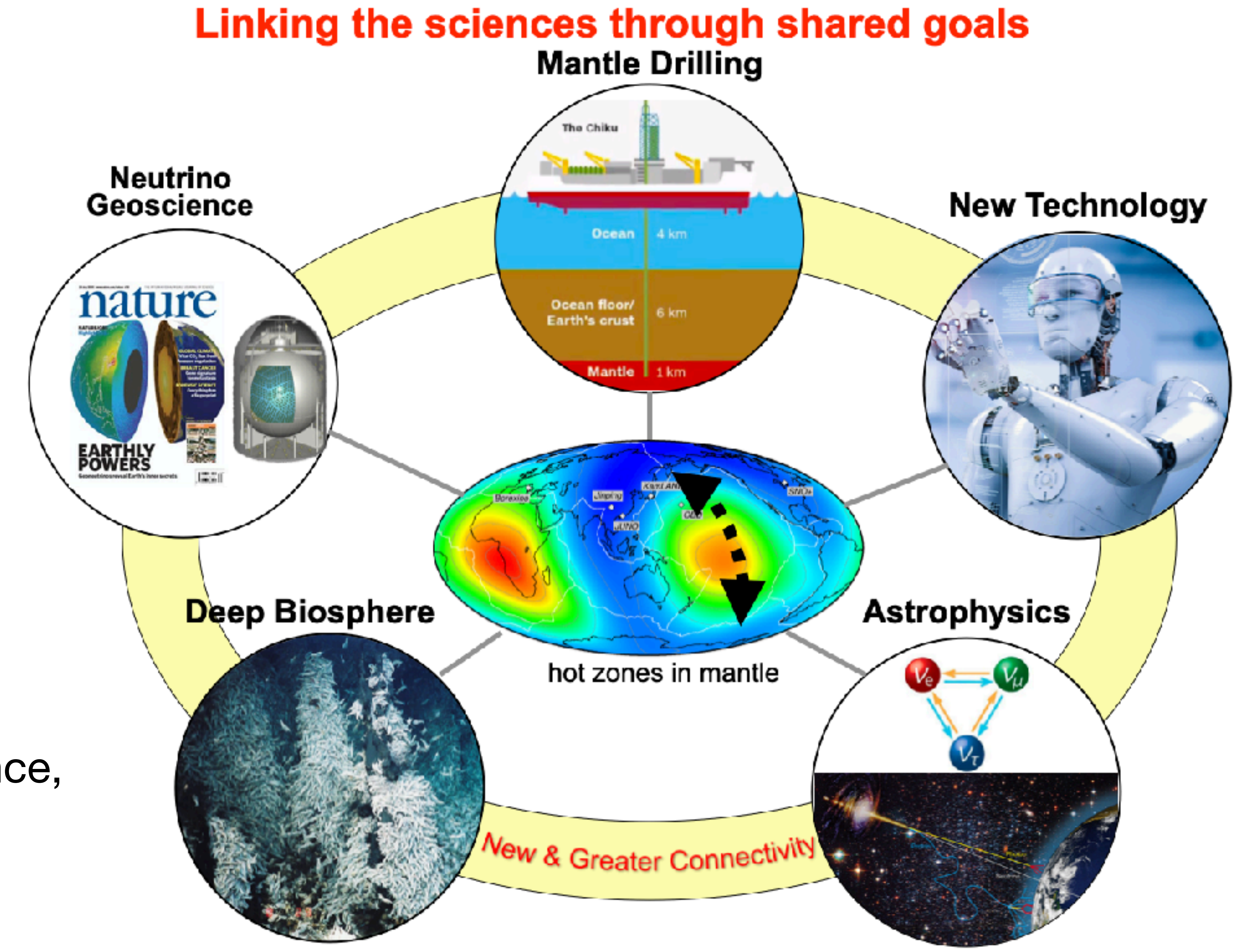
- **Multi-site Measurements**

Solve the mystery of deep Earth!
First detector for mapping the inhomogeneous mantle

- **Multidisciplinary Detector**

Physics, Geoscience, Mantle drilling, Environmental science, Biology, New technology,…



OBD Present & Future

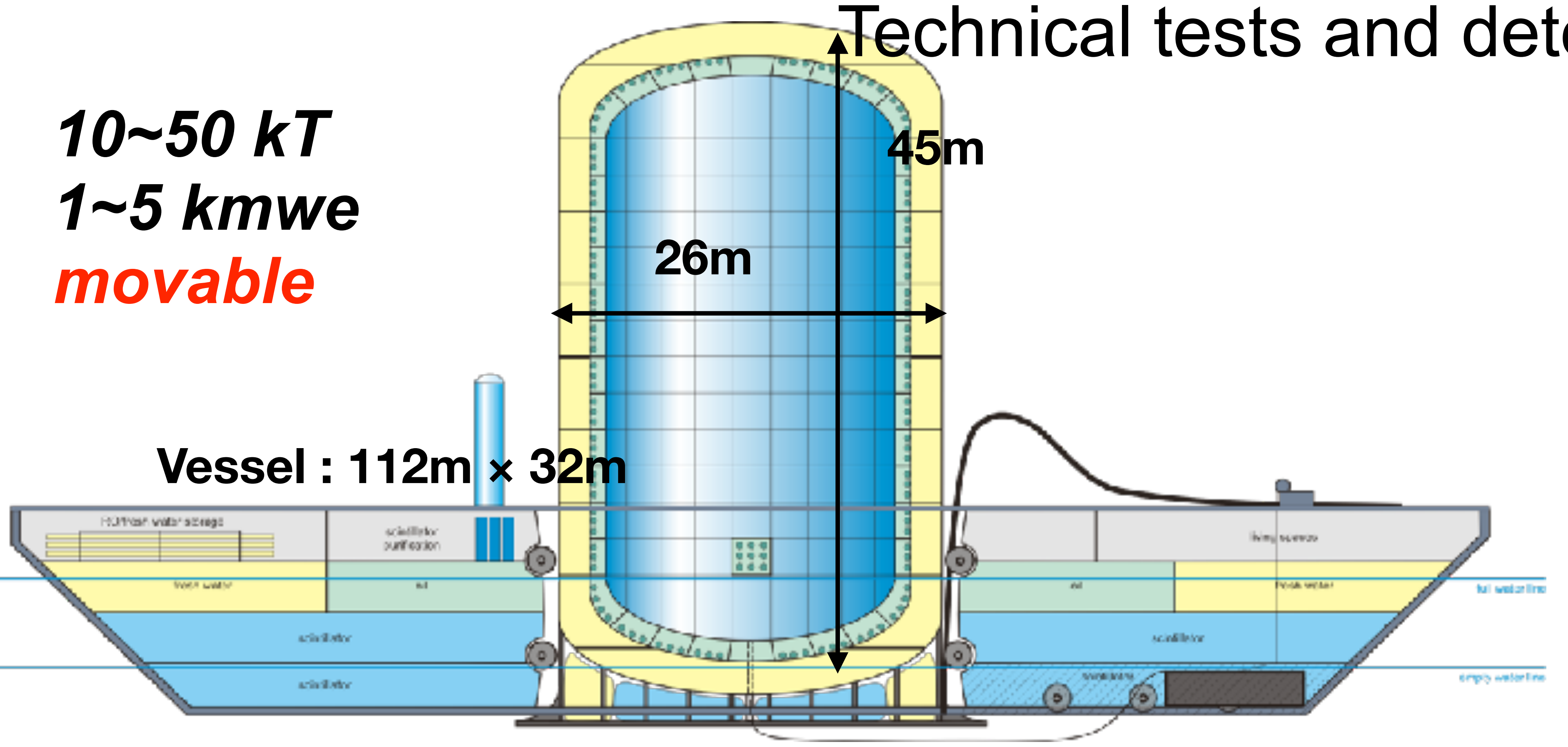
2005 not so many progress… **2019** we are here **2020-2025**

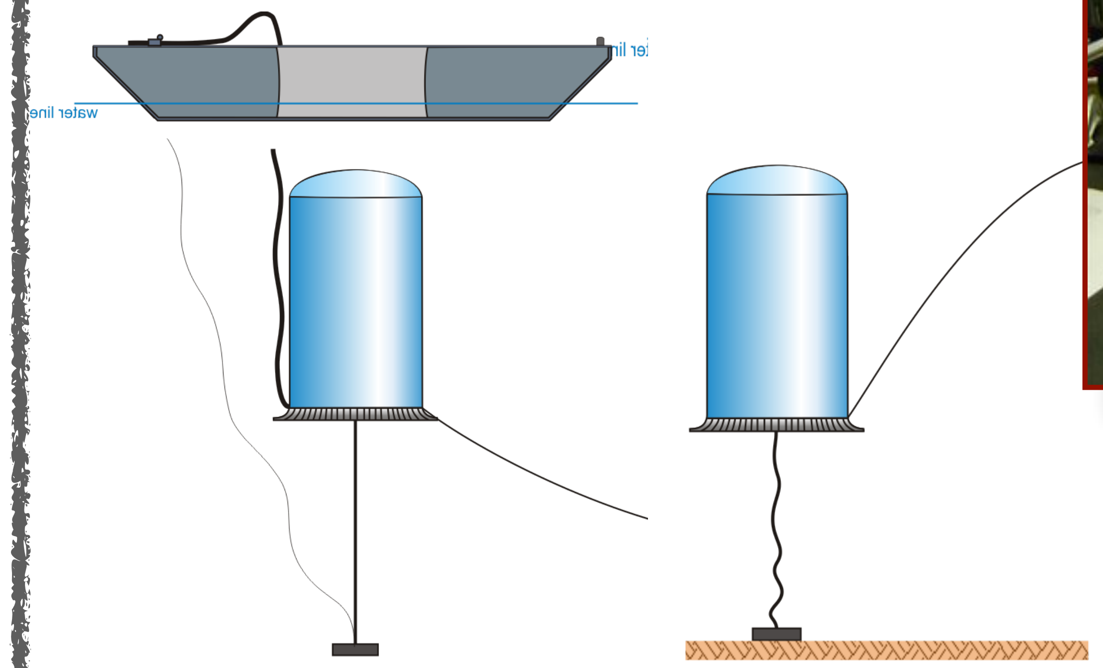
~20 kg **1-10 t** **~1.5 kt** **10-50 kt**

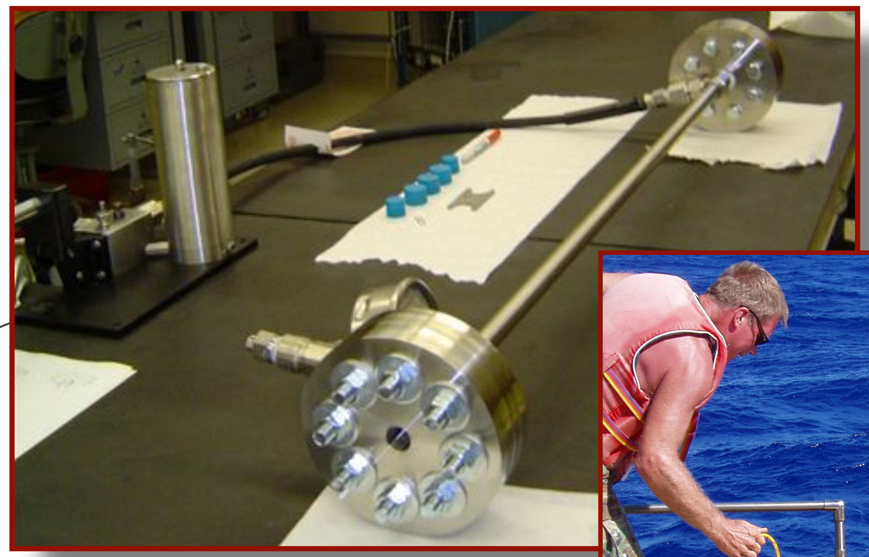
"Hanohano" 2005 U. Hawaii & Makai Ocean Engineering

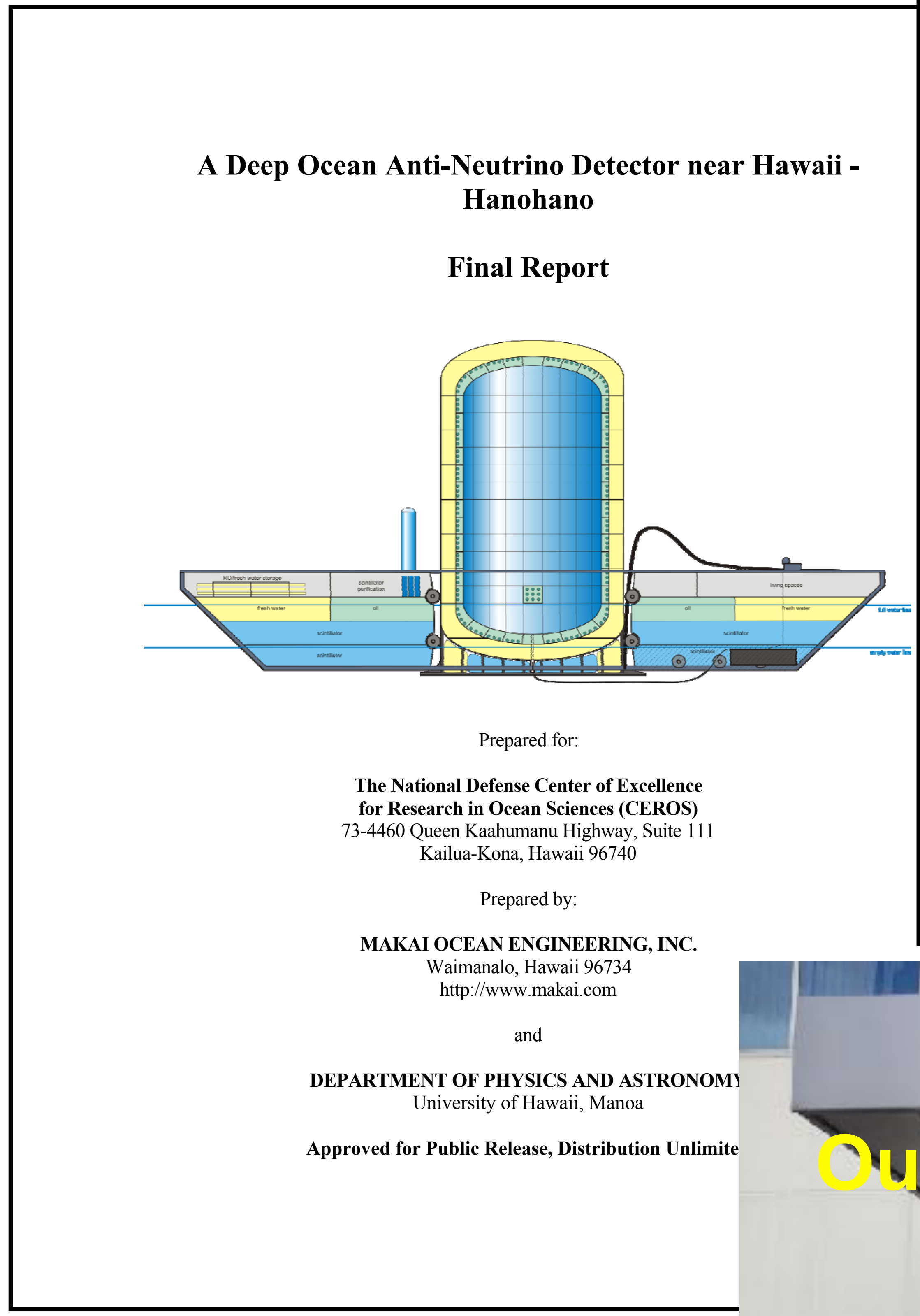
Technical tests and detector design

10~50 kT
1~5 kmwe
movable








A Deep Ocean Anti-Neutrino Detector near Hawaii - Hanohano

Final Report

Prepared for:

The National Defense Center of Excellence
for Research in Ocean Sciences (CEROS)
73-4460 Queen Kaahumanu Highway, Suite 111
Kailua-Kona, Hawaii 96740

Prepared by:

MAKAI OCEAN ENGINEERING, INC.
Waimanalo, Hawaii 96734
http://www.makai.com

and

DEPARTMENT OF PHYSICS AND ASTRONOMY
University of Hawaii, Manoa

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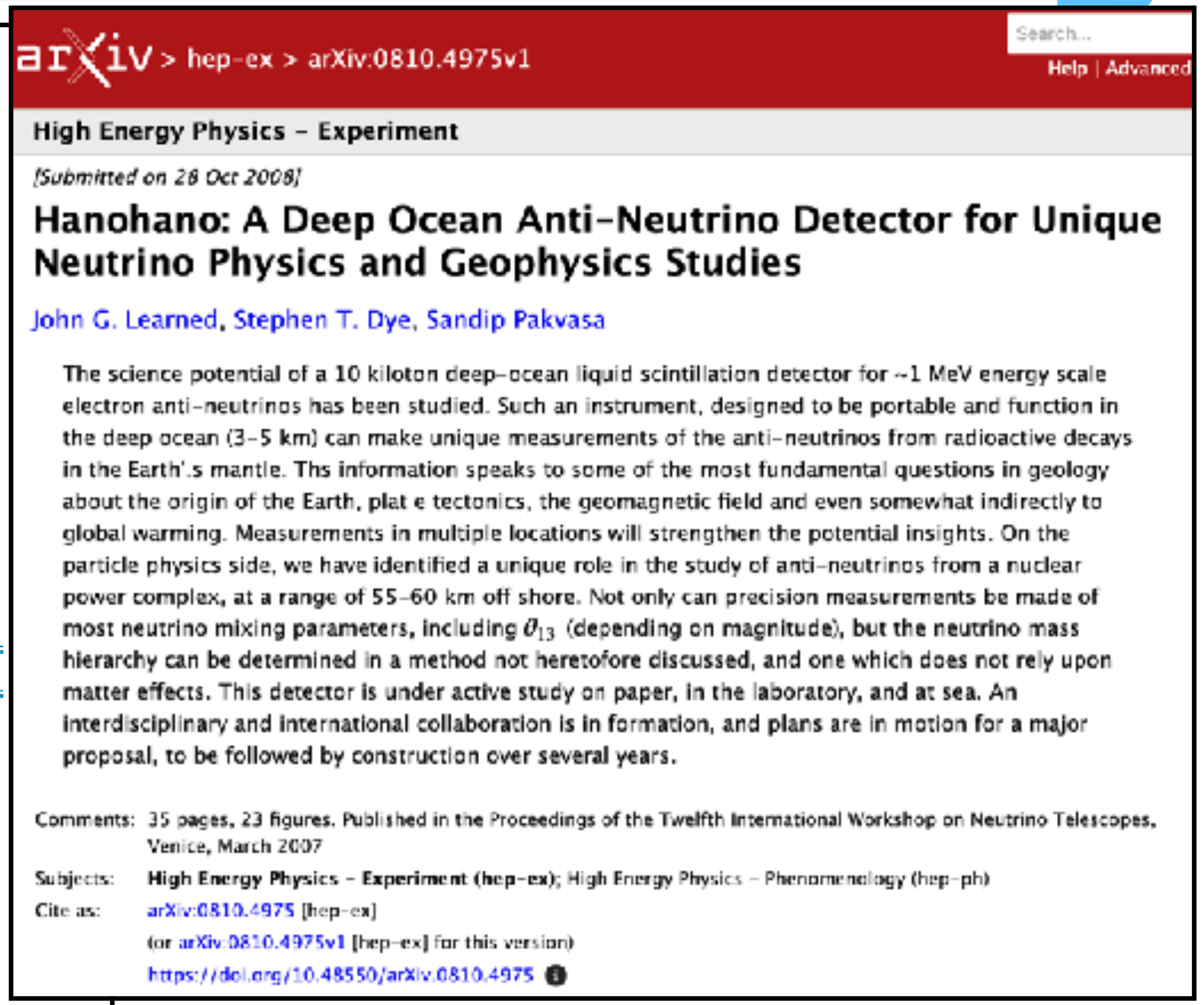

arXiv > hep-ex > arXiv:0810.4975v1

High Energy Physics – Experiment

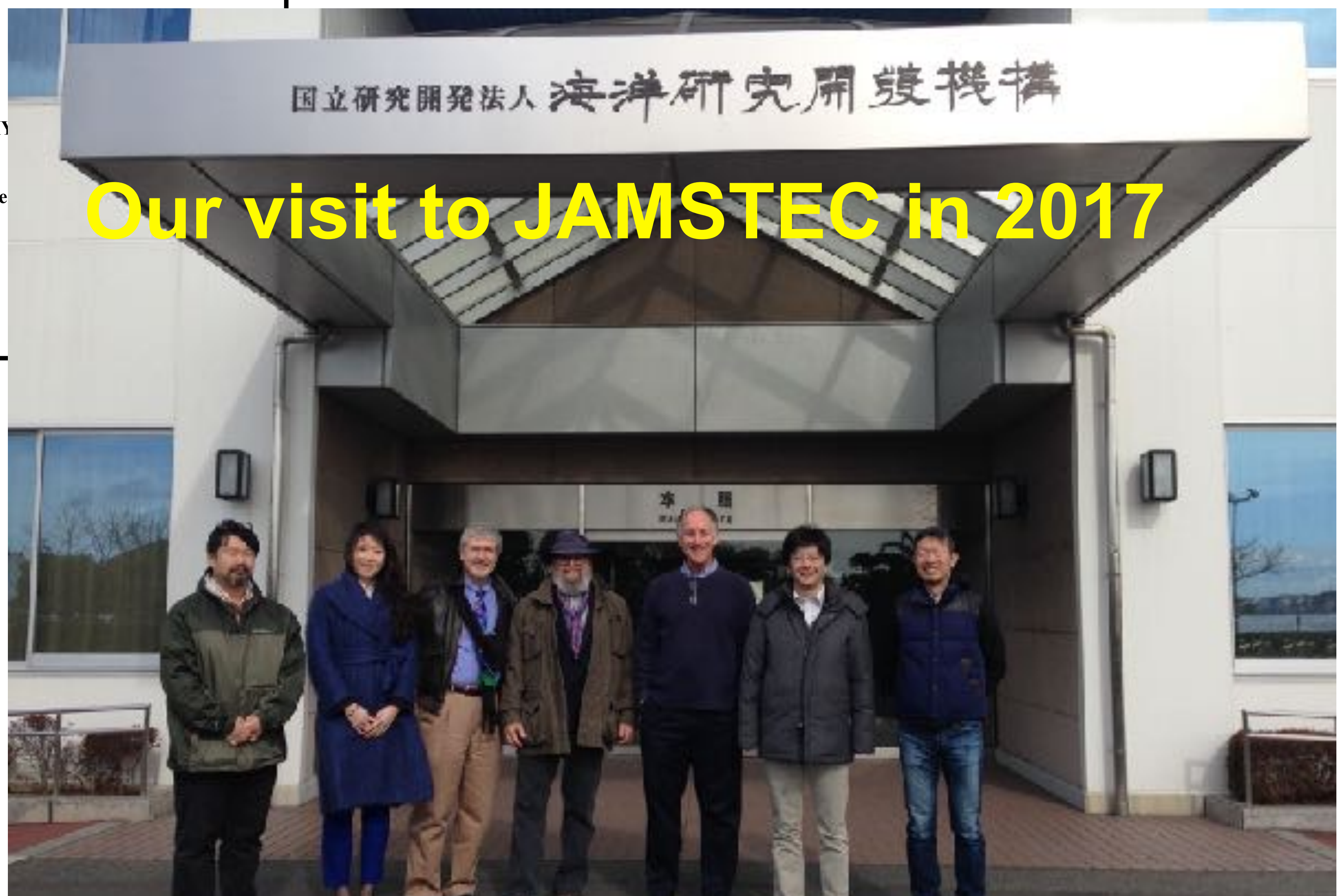
[Submitted on 28 Oct 2008]

Hanohano: A Deep Ocean Anti-Neutrino Detector for Unique Neutrino Physics and Geophysics Studies

John G. Learned, Stephen T. Dye, Sandip Pakvasa

The science potential of a 10 kiloton deep-ocean liquid scintillation detector for ~1 MeV energy scale electron anti-neutrinos has been studied. Such an instrument, designed to be portable and function in the deep ocean (3-5 km) can make unique measurements of the anti-neutrinos from radioactive decays in the Earth's mantle. This information speaks to some of the most fundamental questions in geology about the origin of the Earth, plat e tectonics, the geomagnetic field and even somewhat indirectly to global warming. Measurements in multiple locations will strengthen the potential insights. On the particle physics side, we have identified a unique role in the study of anti-neutrinos from a nuclear power complex, at a range of 55-60 km off shore. Not only can precision measurements be made of most neutrino mixing parameters, including θ_{13} (depending on magnitude), but the neutrino mass hierarchy can be determined in a method not heretofore discussed, and one which does not rely upon matter effects. This detector is under active study on paper, in the laboratory, and at sea. An interdisciplinary and international collaboration is in formation, and plans are in motion for a major proposal, to be followed by construction over several years.

Comments: 35 pages, 23 figures. Published in the Proceedings of the Twelfth International Workshop on Neutrino Telescopes, Venice, March 2007
Subjects: High Energy Physics – Experiment (hep-ex); High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:0810.4975 [hep-ex]
(or arXiv:0810.4975v1 [hep-ex] for this version)
https://doi.org/10.48550/arXiv.0810.4975



OBD Present & Future

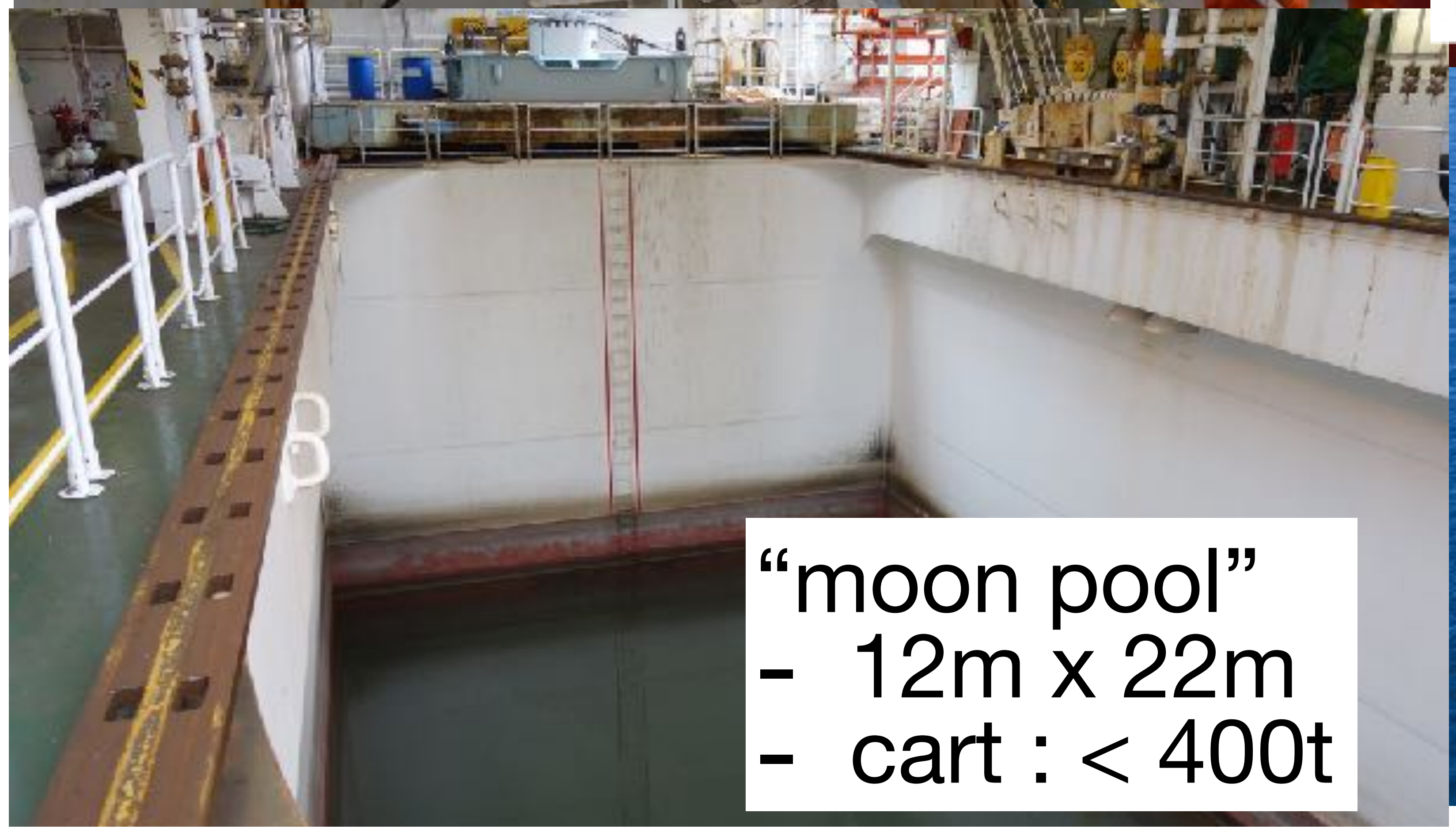
2005 not so many progress… **2019** we are here **2020-2025** funded

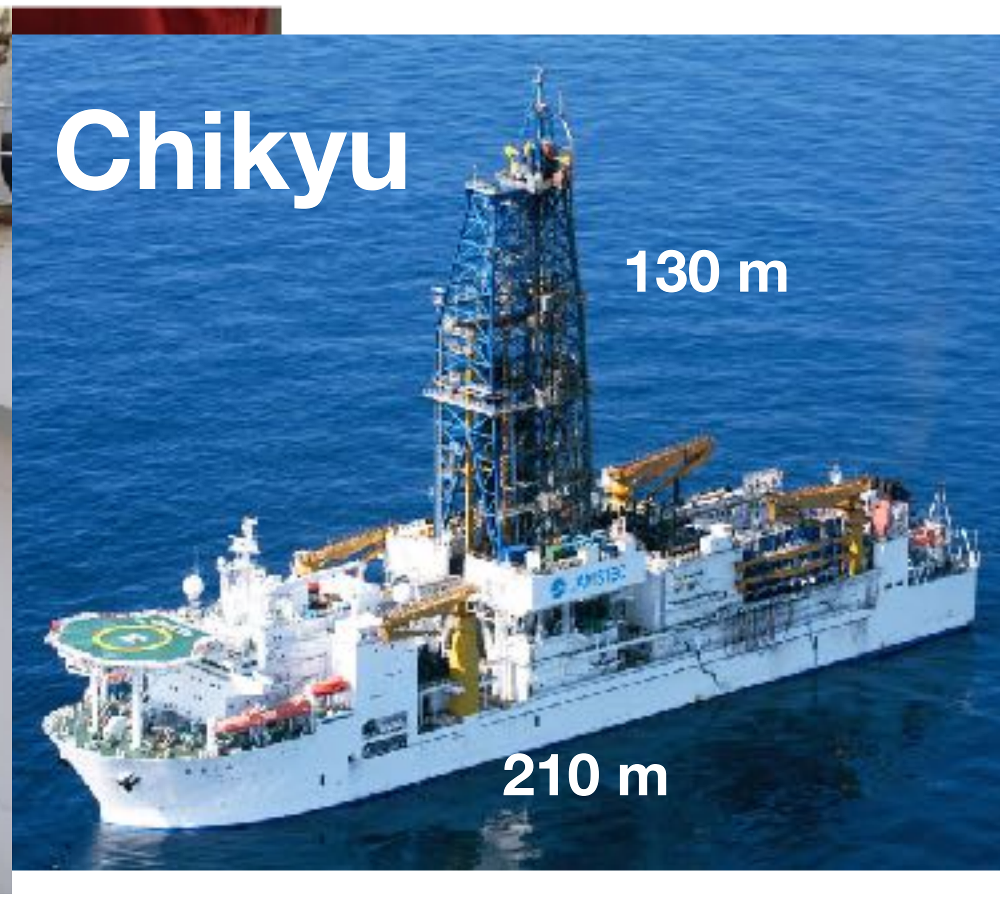
~20 kg | 1-10 t | ~1.5 kt | 10-50 kt

OBD project has started with JAMSTEC[*] & Tohoku U.

[*] Japan Agency for Marine-Earth Science and Technology

Generator
5,000kW×6 2,500kW×2
Equal to the power needed by a town of 10,000 homes (3 kW per home)





OBD Present & Future

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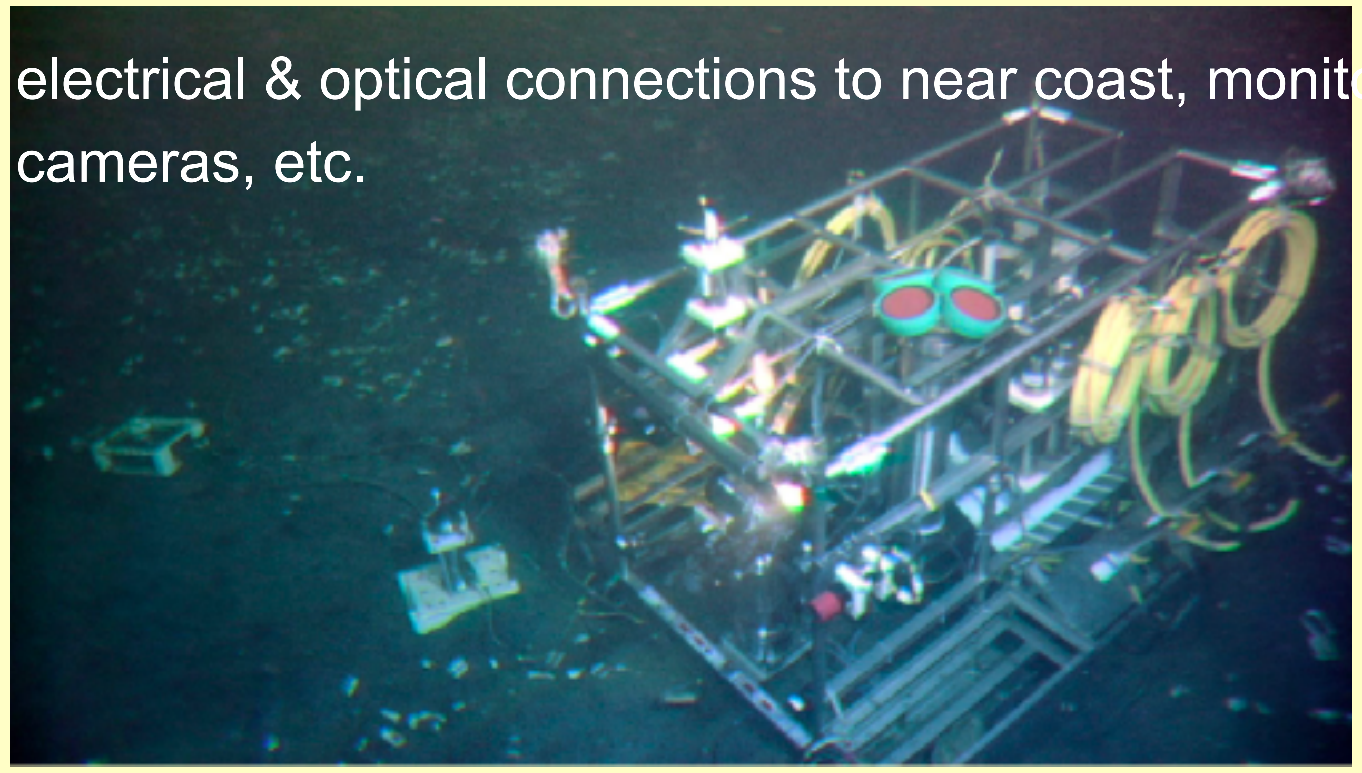
~20 kg | 1-10 t | ~1.5 kt | 10-50 kt

Technical test & world's first measurement in the ocean with LS detector

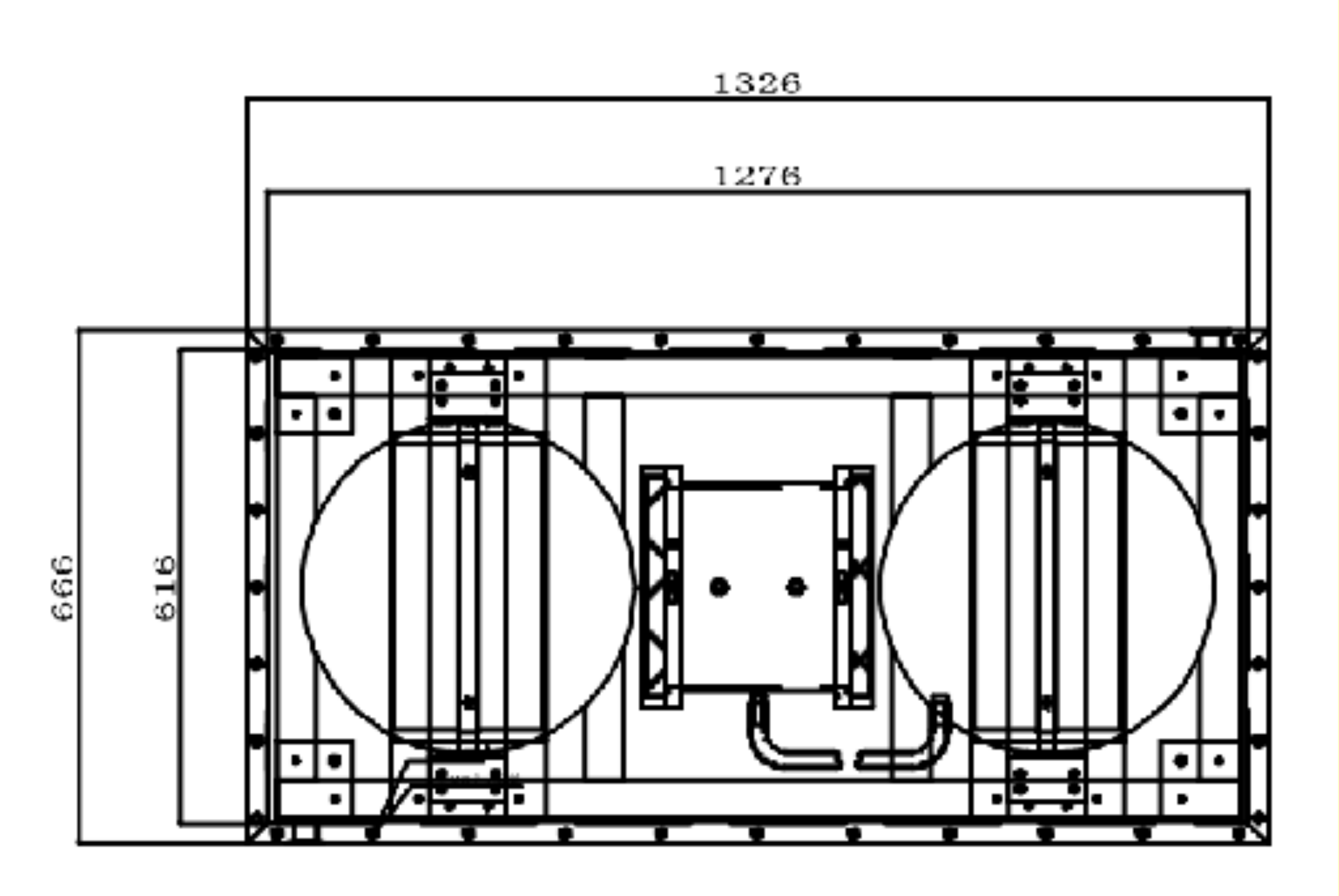
* Install detector into **~1km seafloor** (JAMSTEC's Hatsushima Observatory) take data for **several months**
  Another option: seafloor around Hawaii with battery operation
* **measure muon late in the sea → input parameter for future large detector**
* Technical developments are in progress.

* on-going: Study on glass-sheilded PMT+electronics module with IceCube team in Chiba

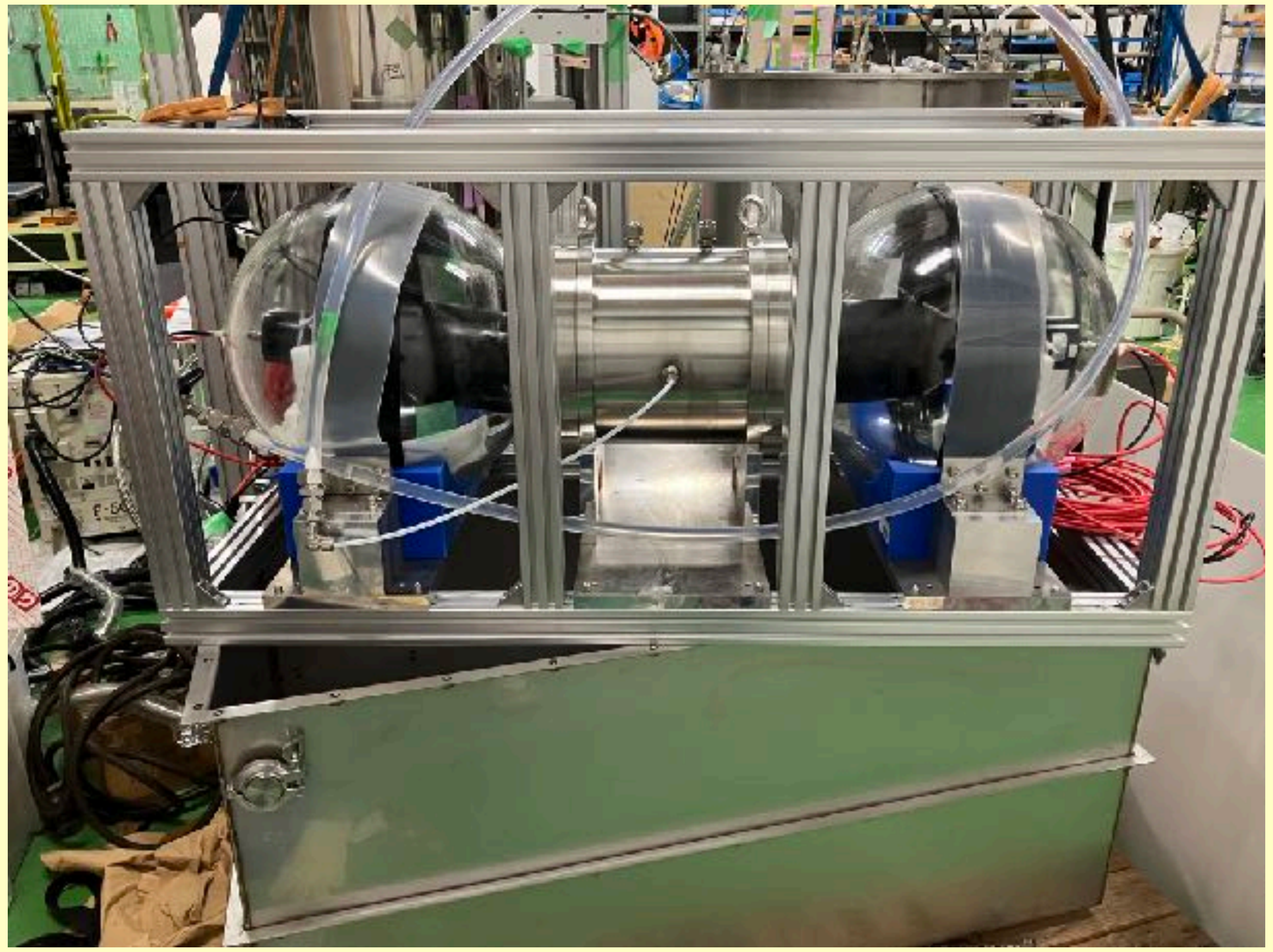
Hatsushima Observatory



detector design



Construction test at Tohoku U. with glass-sheilded PMTs



OBD Present & Future

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~20 kg | 1-10 t | ~1.5 kt | 10-50 kt

Maturity of science

Technical demonstration & environment measurement in the sea

deep sea neutrino & muon flux, ocean water density & temperature, radioactivity

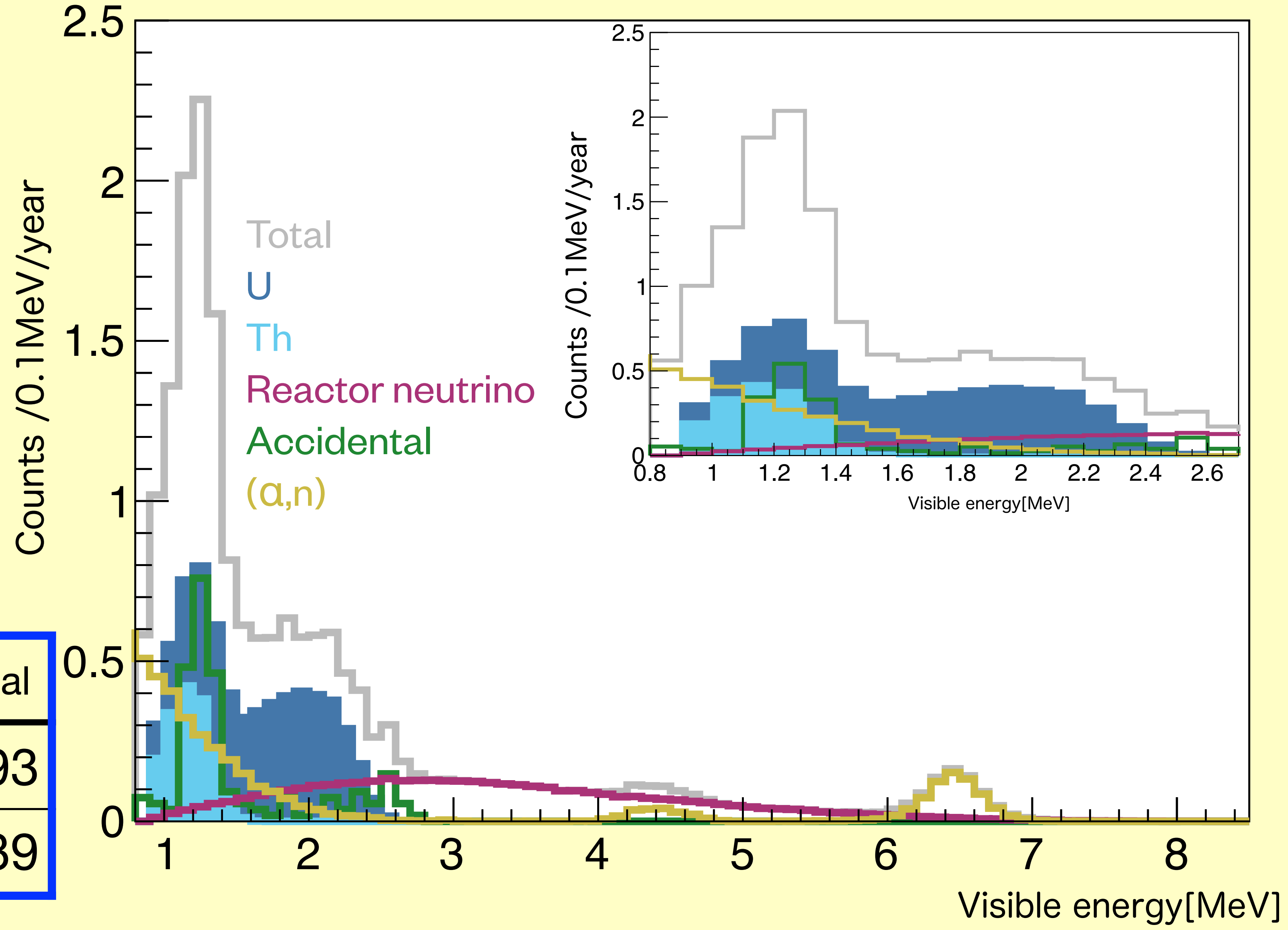
→ input parameters for ~1.5 kt detector design

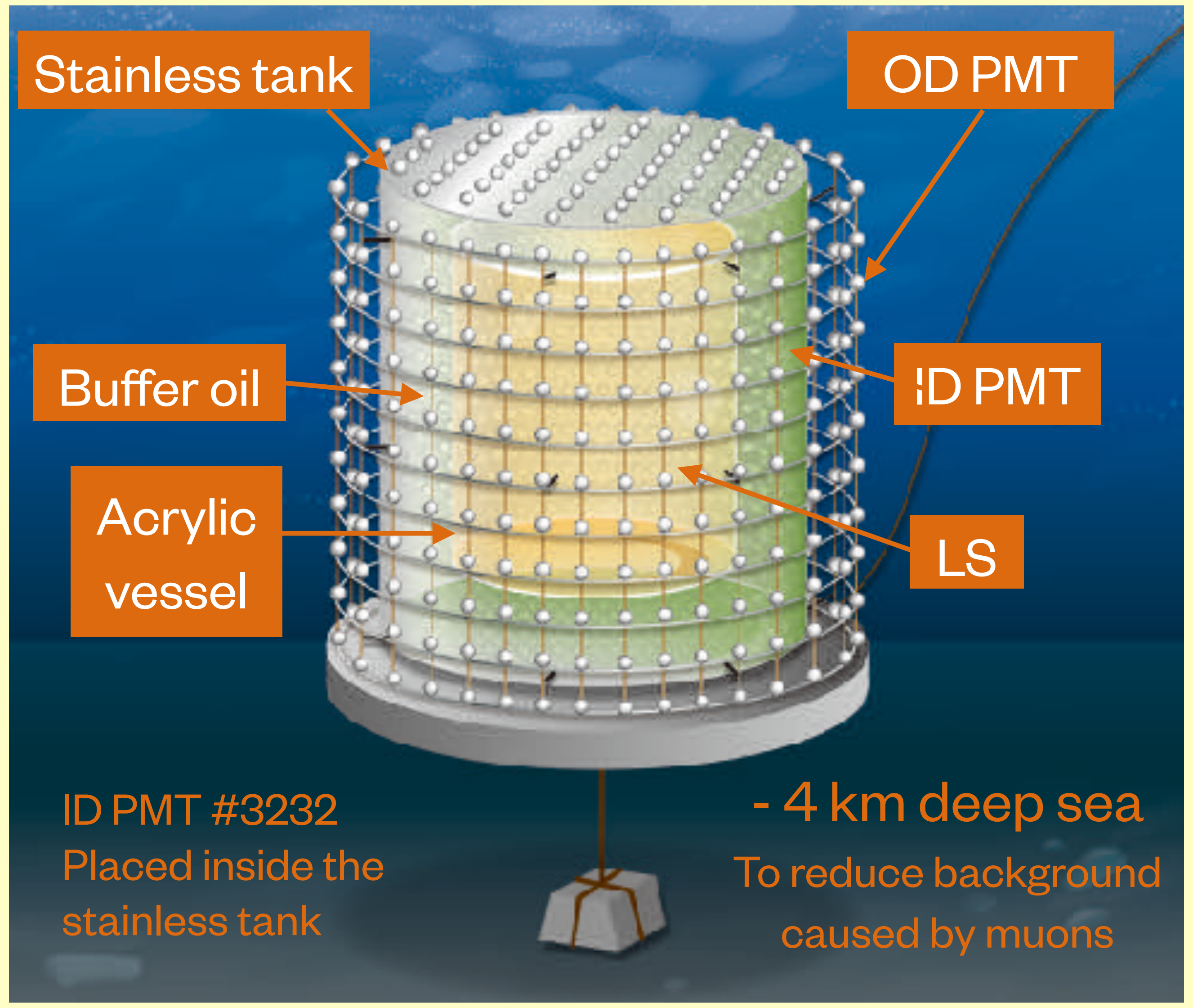
First clear mantle signal

* Detector simulation study is in progress.
* Hawaii is possible position.
* Detector should be installed at **~4km** deep sea to shield muons
  Low temperature (2-4°C)
  high pressure (40MPa)

E reagion	U (Signal)	Th (Signal)	Total (Signal)	Reactor (Backgrounds)	Acci. (Backgrounds)	(α,n) (Backgrounds)	He-Li (Backgrounds)	Fast-neutron (Backgrounds)	Total (Backgrounds)
All	6.59	1.64	8.23	4.13	1.92	3.88	0	<2.42	9.93
Geo-nu	(4.61)	(1.15)	(5.76)	1.53	1.90	2.96	0	<0.58	6.39

(mantle) [Events/year]





* **Mantle geoneutrino sensitivity**

highQ model: 1year → 3.7σ
middleQ model: 3year → 3.5σ
lowQ model: 10year → 2.5σ

* **17 kt detector case**

1month → 4.1σ
3month → 3.9σ
1year → 3.0σ

OBD Situation

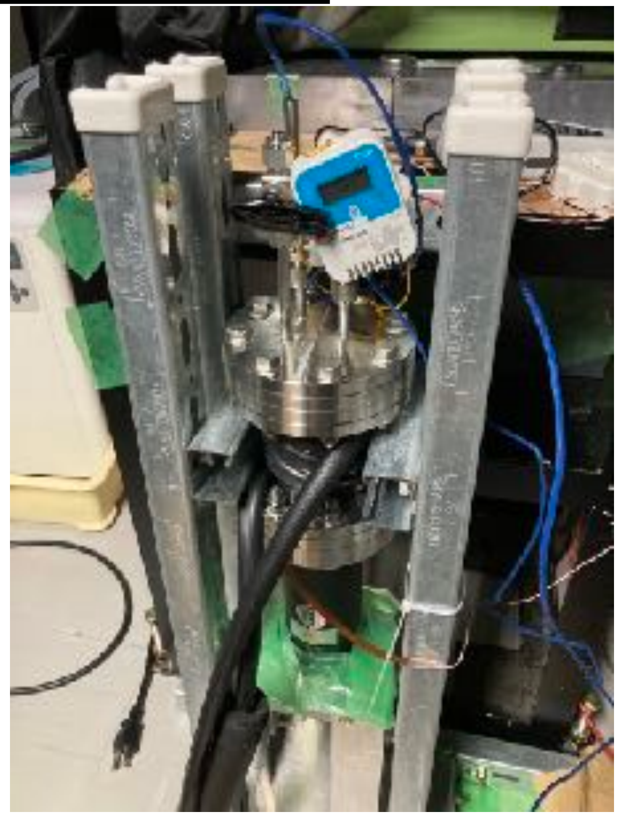
Technical Developments

✦Liquid scintillator

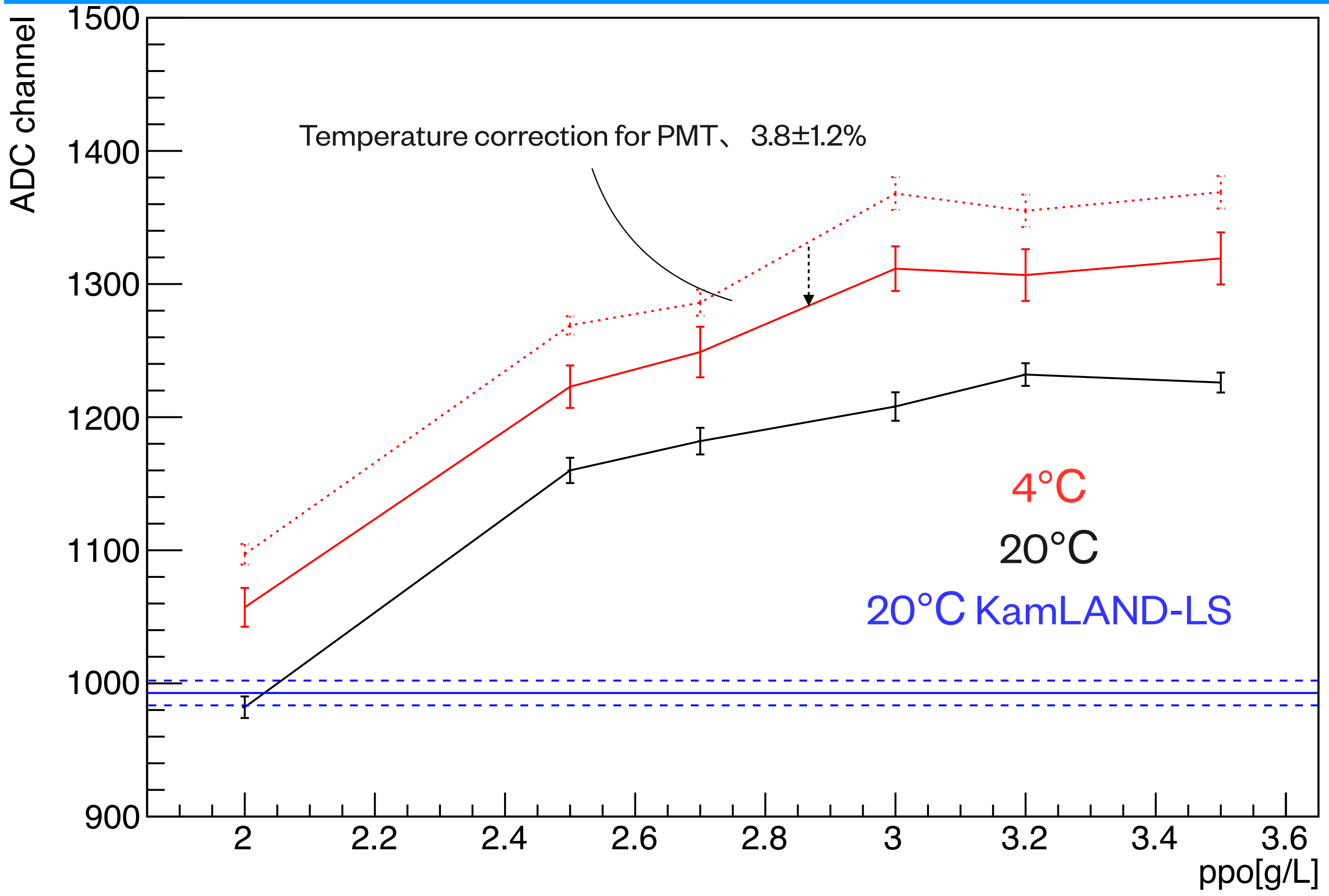
LAB(oil) + PPO(fluorescents)

Low temperature

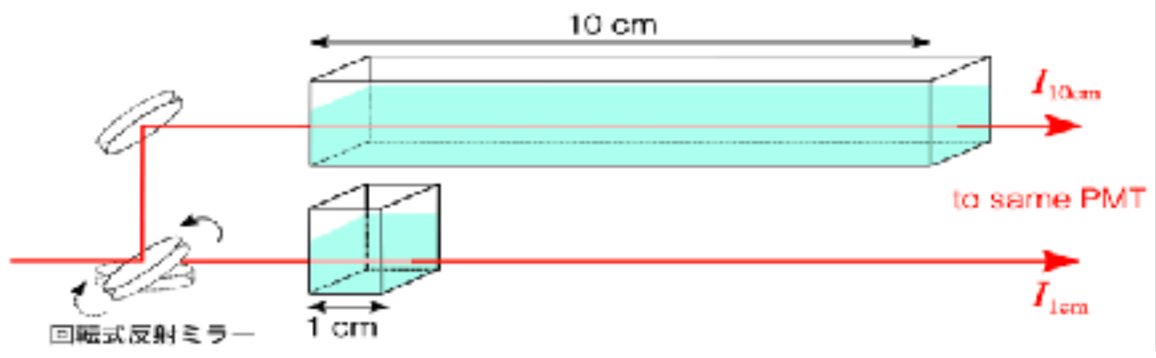
light yield



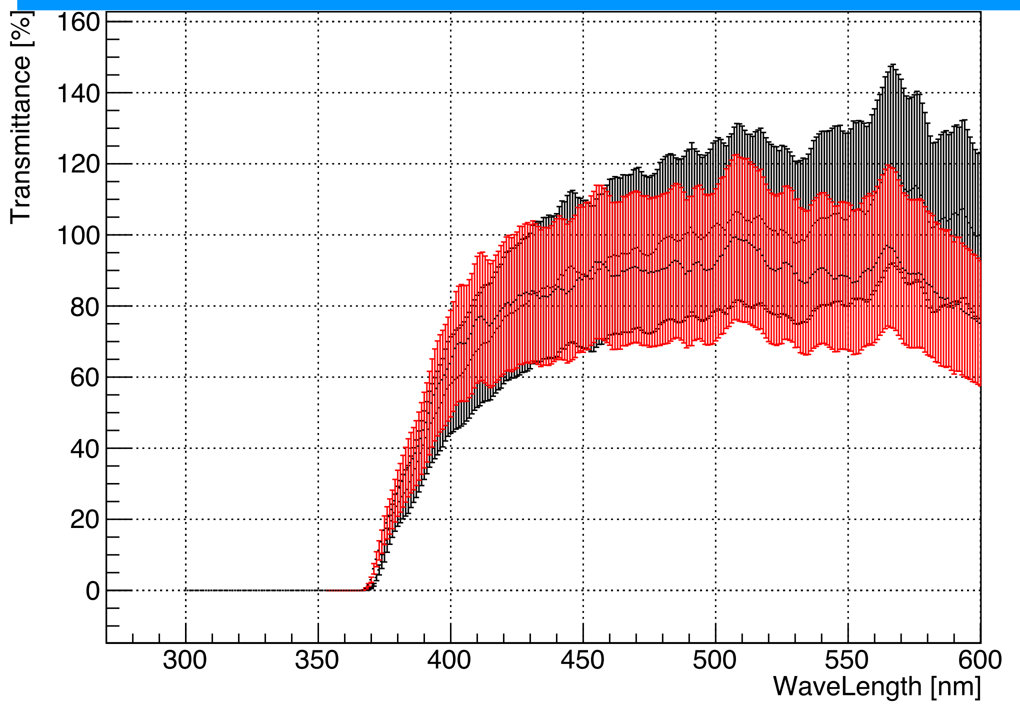
4°C is brighter than 20°C (+9%)



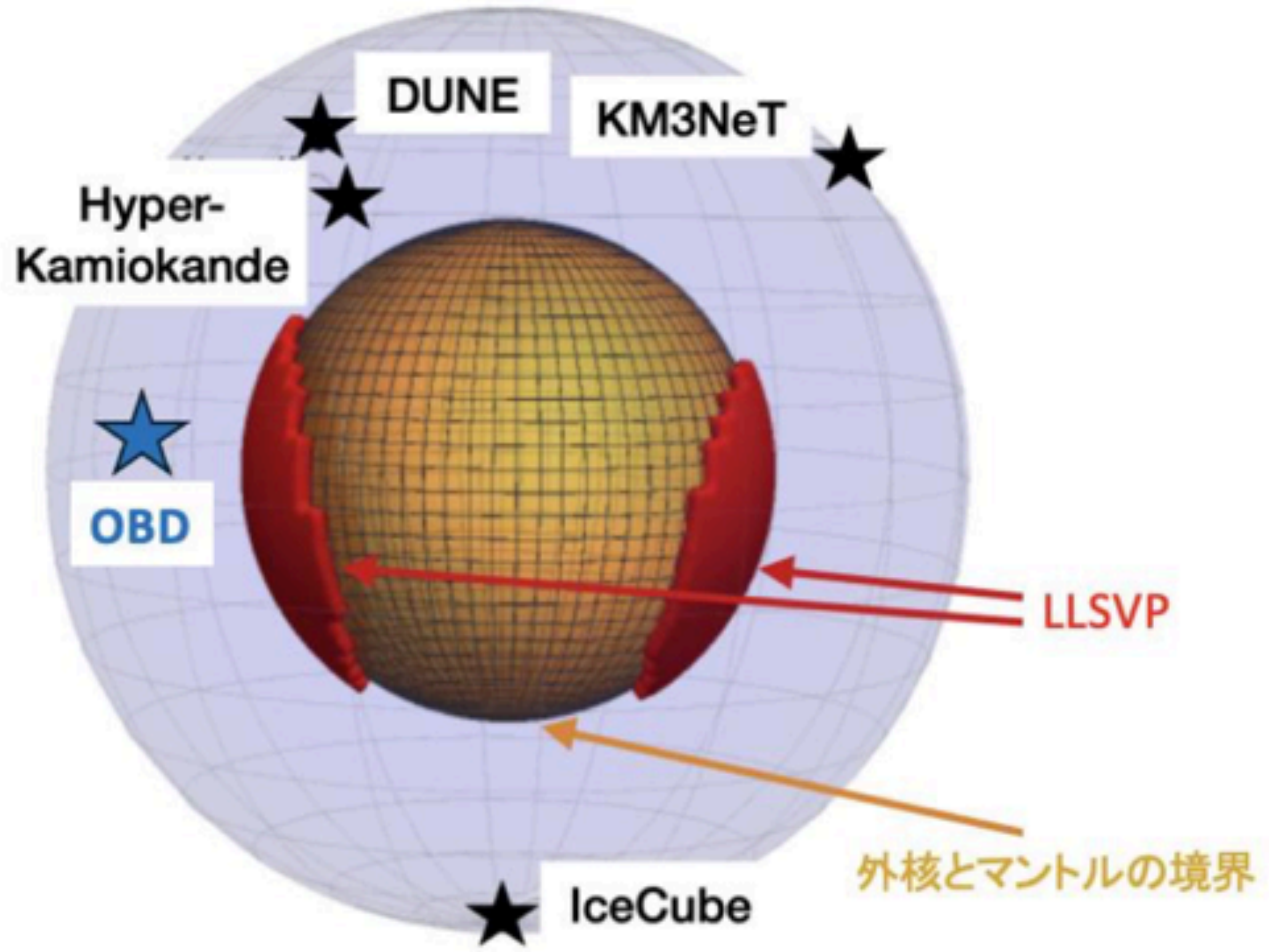
light transition



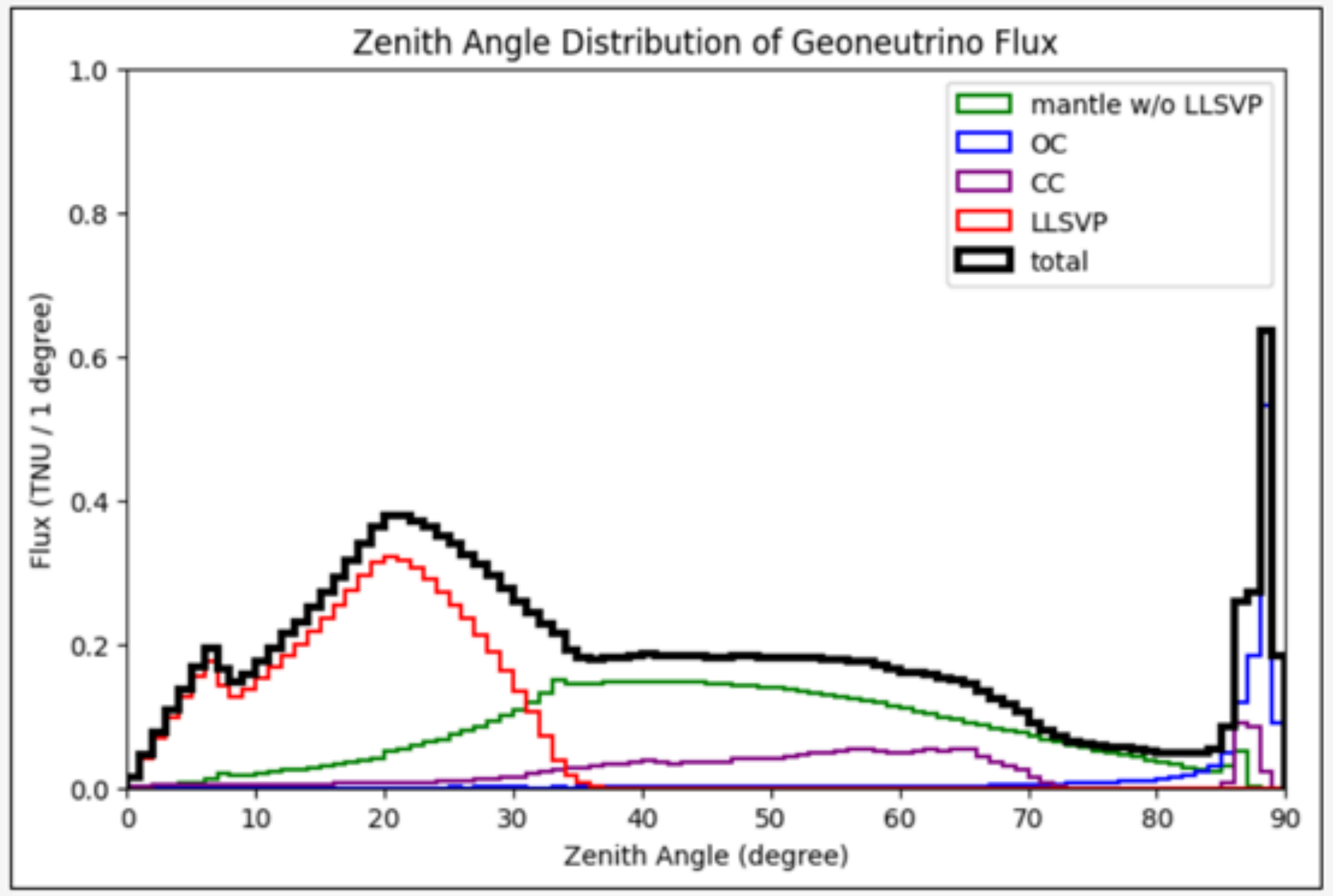
no temperature affect



Simulation Studies: LLSVP



✦Directional Sensitive Detector



✦Oscillation Tomography with high energy atmospheric-ν

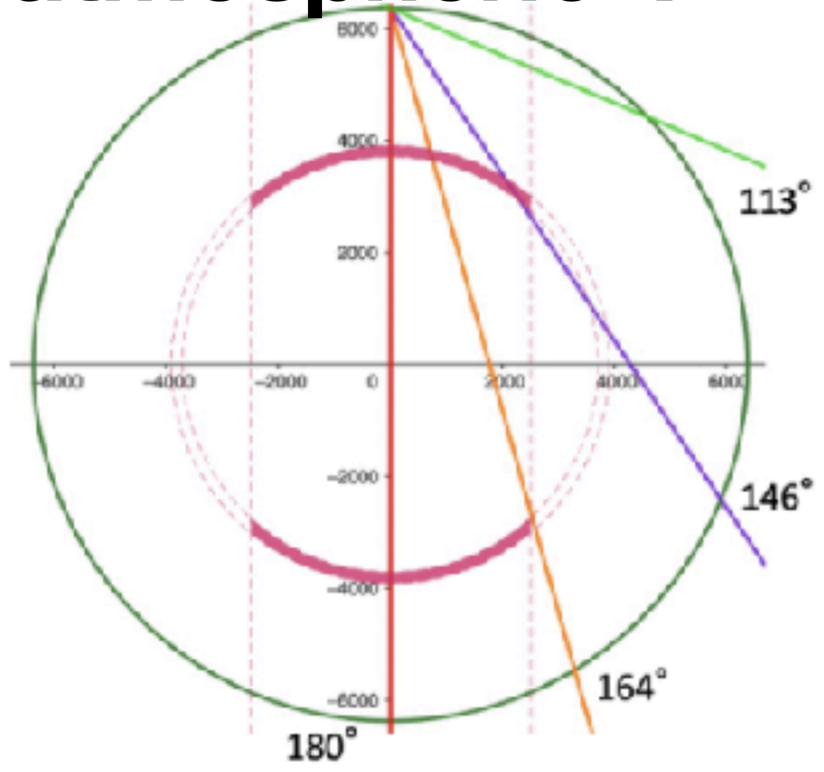
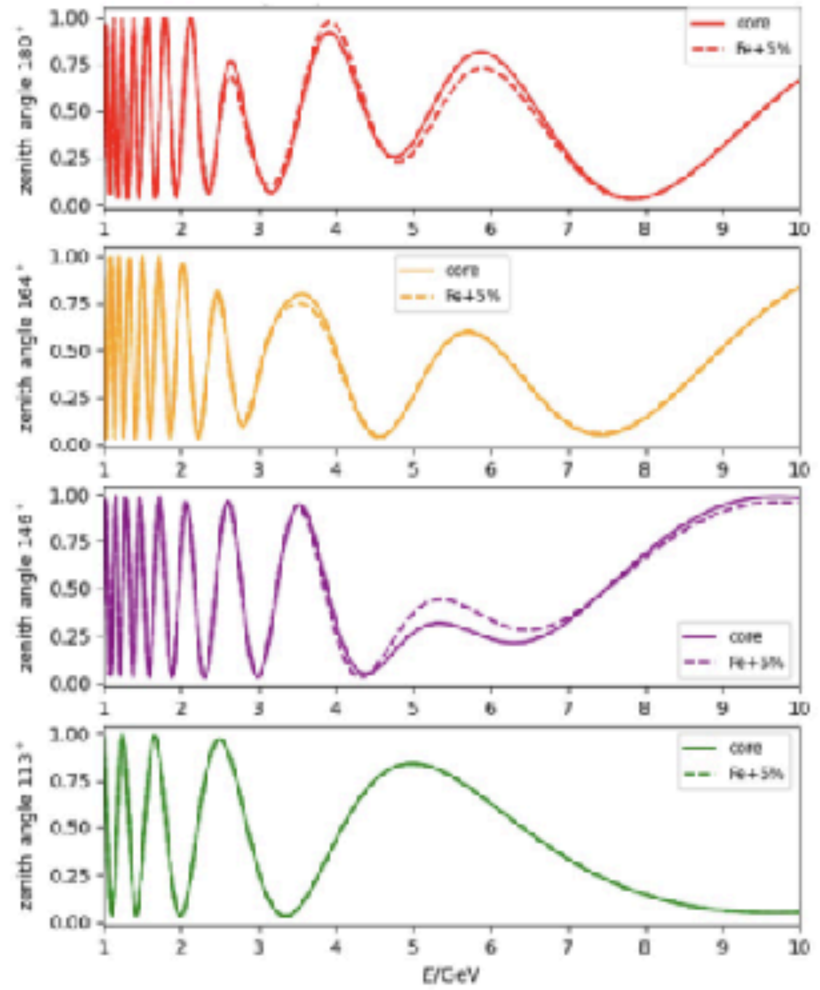


図 6.3: 大気ニュートリノの天頂角ごとの経路



OBD Situation

International Collaboration: Tohoku U., U. Hawaii, LLNL

- Started from 2024
- Writing White Paper
- Discussions on:
  - Detector design
  - Detector technology
  - Detector sensitivity
  - Expand collaborative scientific fields
  - Funding strategy etc

Summary

- Geoneutrinos are unique and new tool to measure directly the Earth's interior.
  - ▸ **Strong way to measure amount of radioactive elements in the Earth**
- To date, physics experiments have shown the usefulness of geoneutrinos.
  - ▸ **Interdisciplinary community has furthered its connection over these past 15 years.**
- **"Neutrino Geoscience" : <u>collaborations between geoscience, physics, ocean engineering and beyond</u>**
  - ▸ **Ocean Bottom Detector (OBD) = Breakthrough**

<Transformative insights>

OBD's Primary Goal : **•map the mantle**

•constrain the planet's cooling history

- **Neutrino Geoscience 2025, October 27-30, Kingston!**
  - ▸ Hawaii 2005, Hawaii 2007, Sudbury 2008, Gran Sasso 2010, Japan 2013, Czech 2019

Neutrino Geoscience 2025 – Kingston

October 27-30, 2025