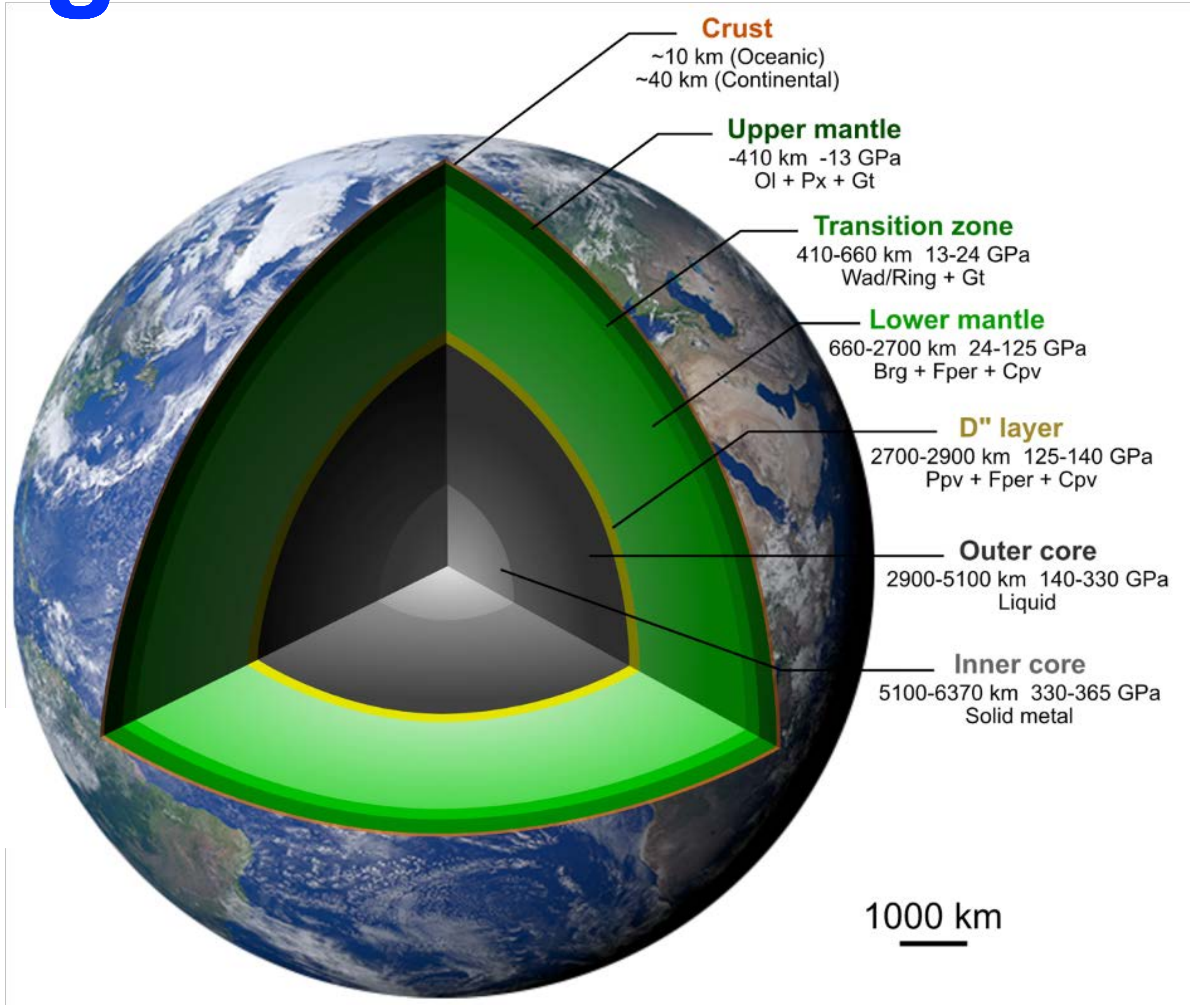
Ocean Bottom Detector: Exploring the Mantle with geo-neutrinos



Hiroko Watanabe,
Research Center for Neutrino Science,
Tohoku University

November 1, 2024

Self-introduction!

Hiroko Watanabe

Research Center for Neutrino Science

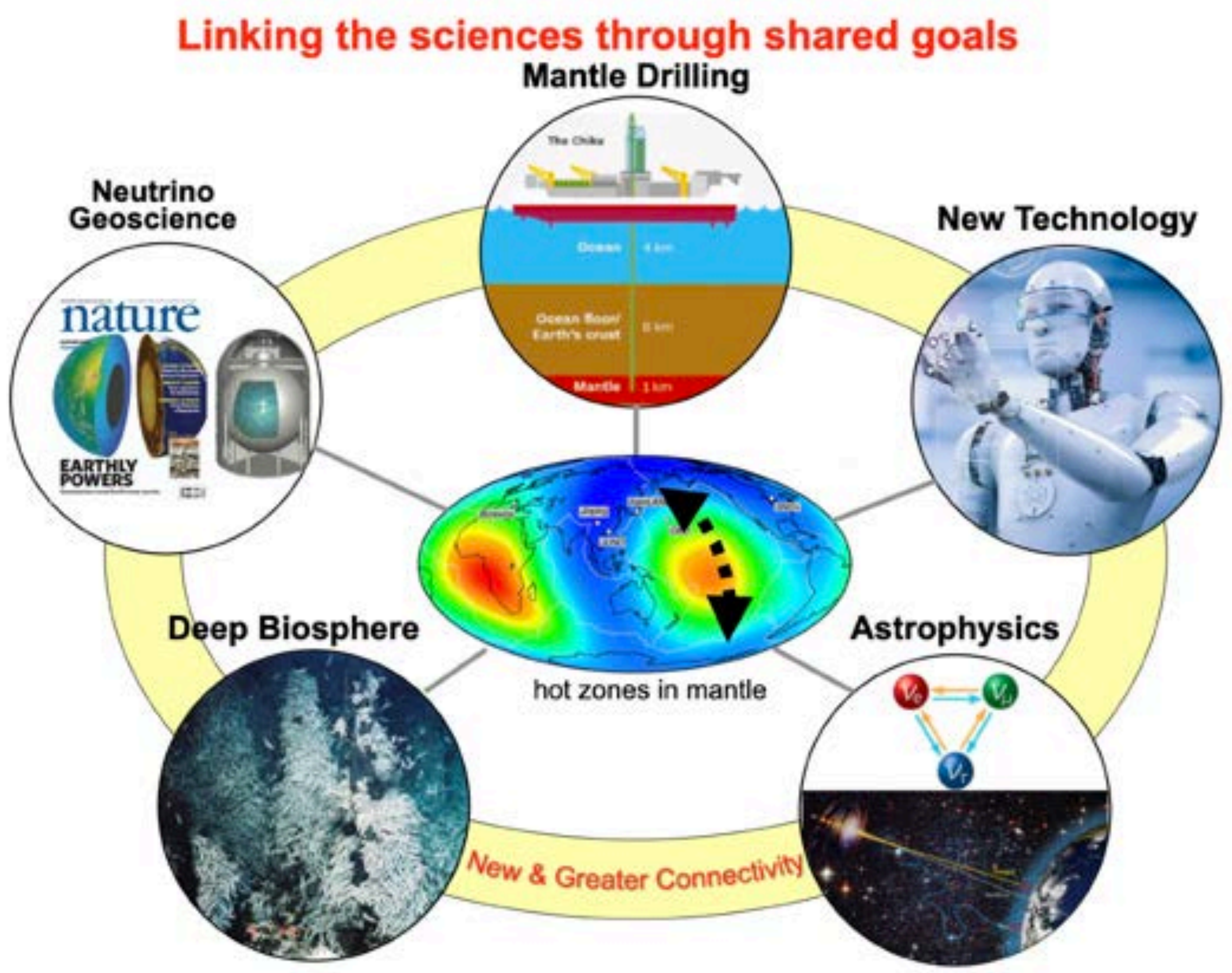
Tohoku University

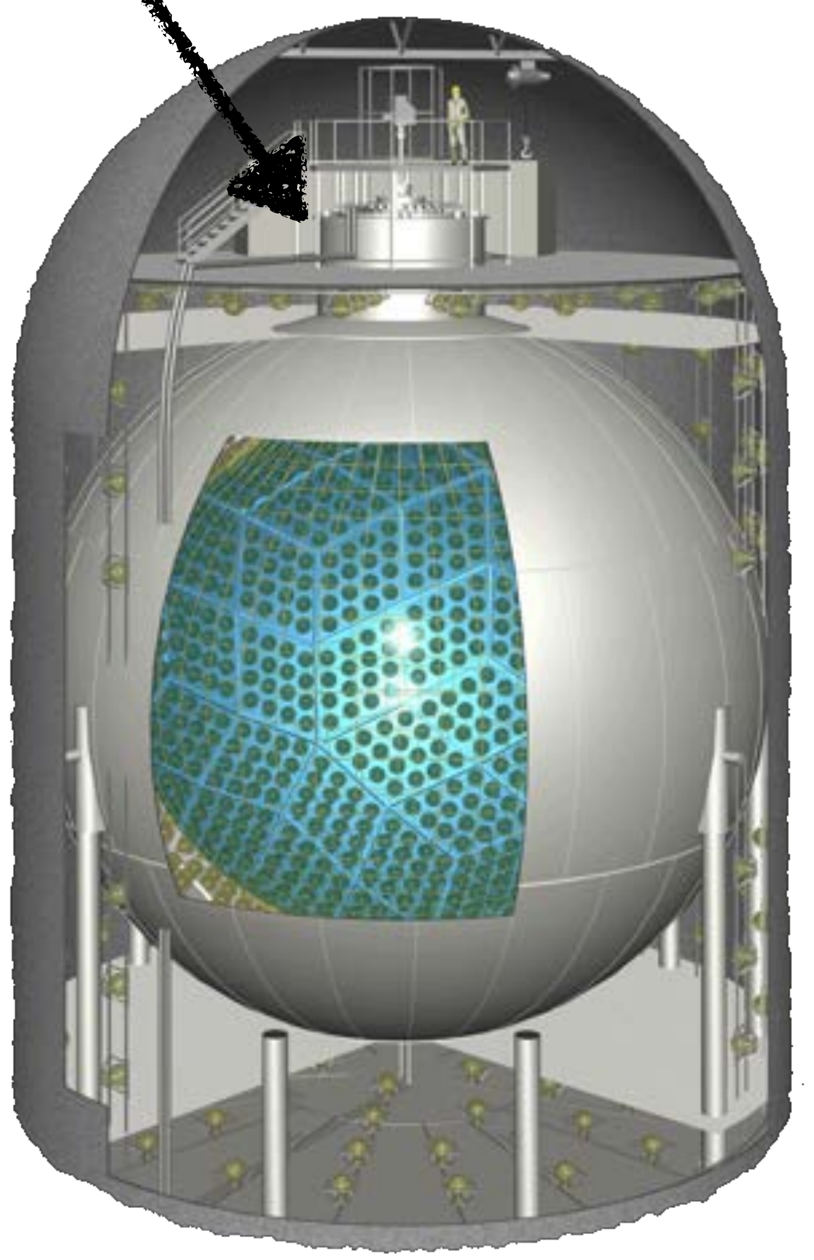
<u>My research</u>:

* Measuring neutrinos by **KamLAND**
* “Neutrino Geoscience”

  : interdisciplinary science field

  → **Ocean Bottom Detector**



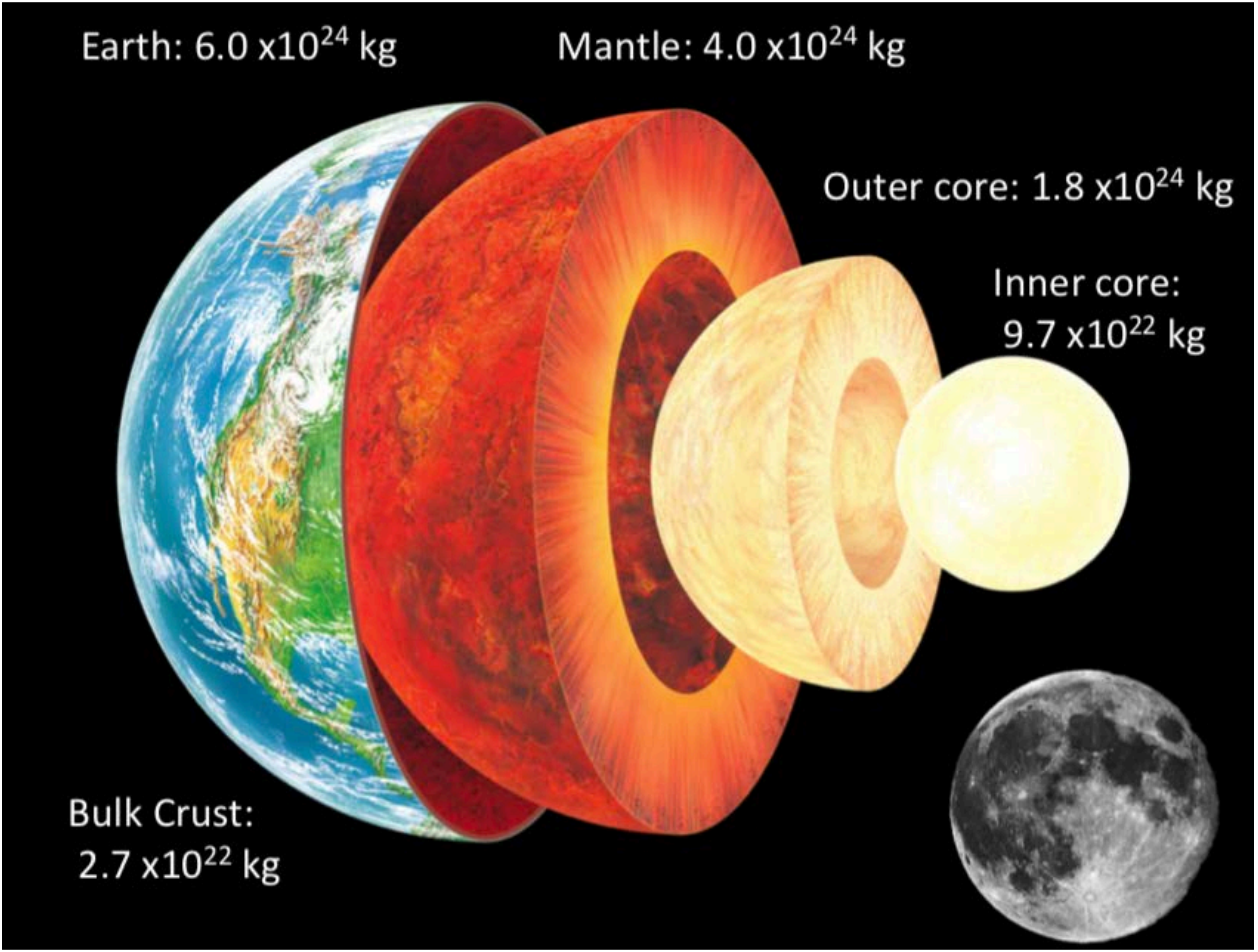


KamLAND
@Kamioka

Contents

Contents

Earth

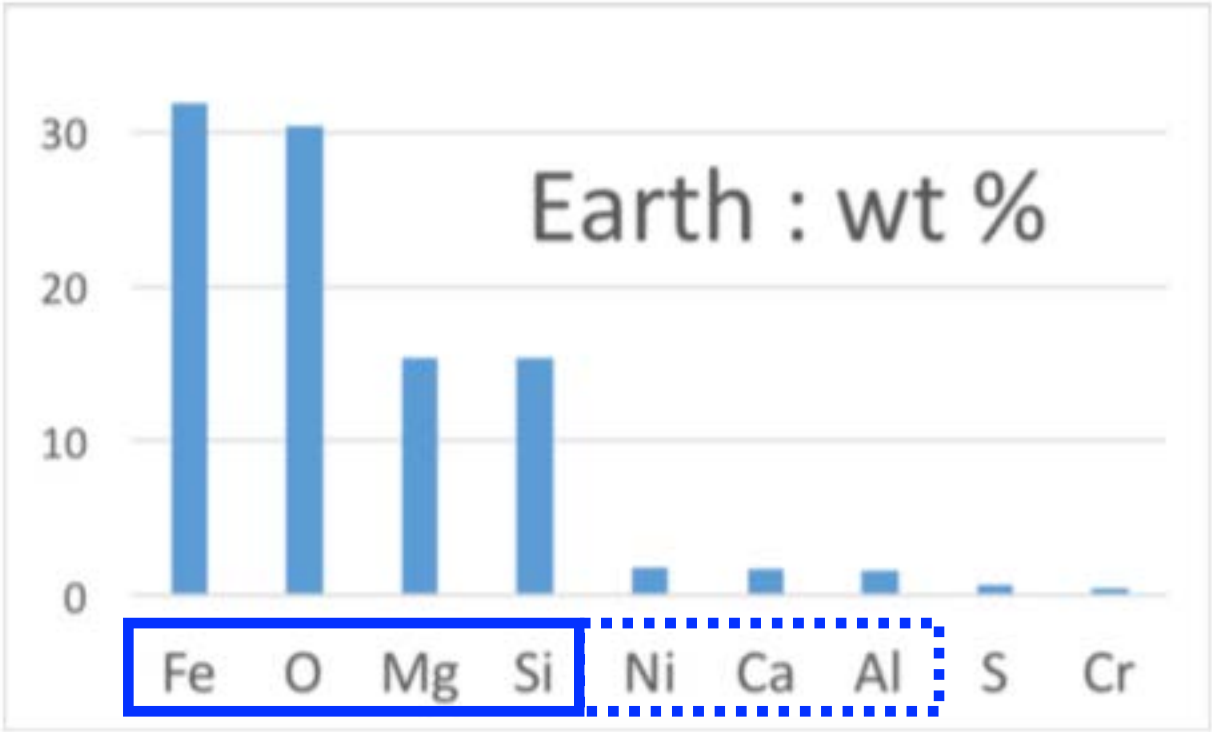


Moon scale to inner core

- **Mass** 6.0 x 10^{24} kg
- **Mean density** 5,514 kg/m^3
- **Mean radius** 6,371 km
- **Elements**

Fe, O, Mg, Si : ~94 %

+ Ni, Ca, Al : ~99 %



Earth's Structure

① Crust : Solid

※ 40K, 232Th, 235U, 238U
(~99.5% of the Earth's radiogenic heating power)

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

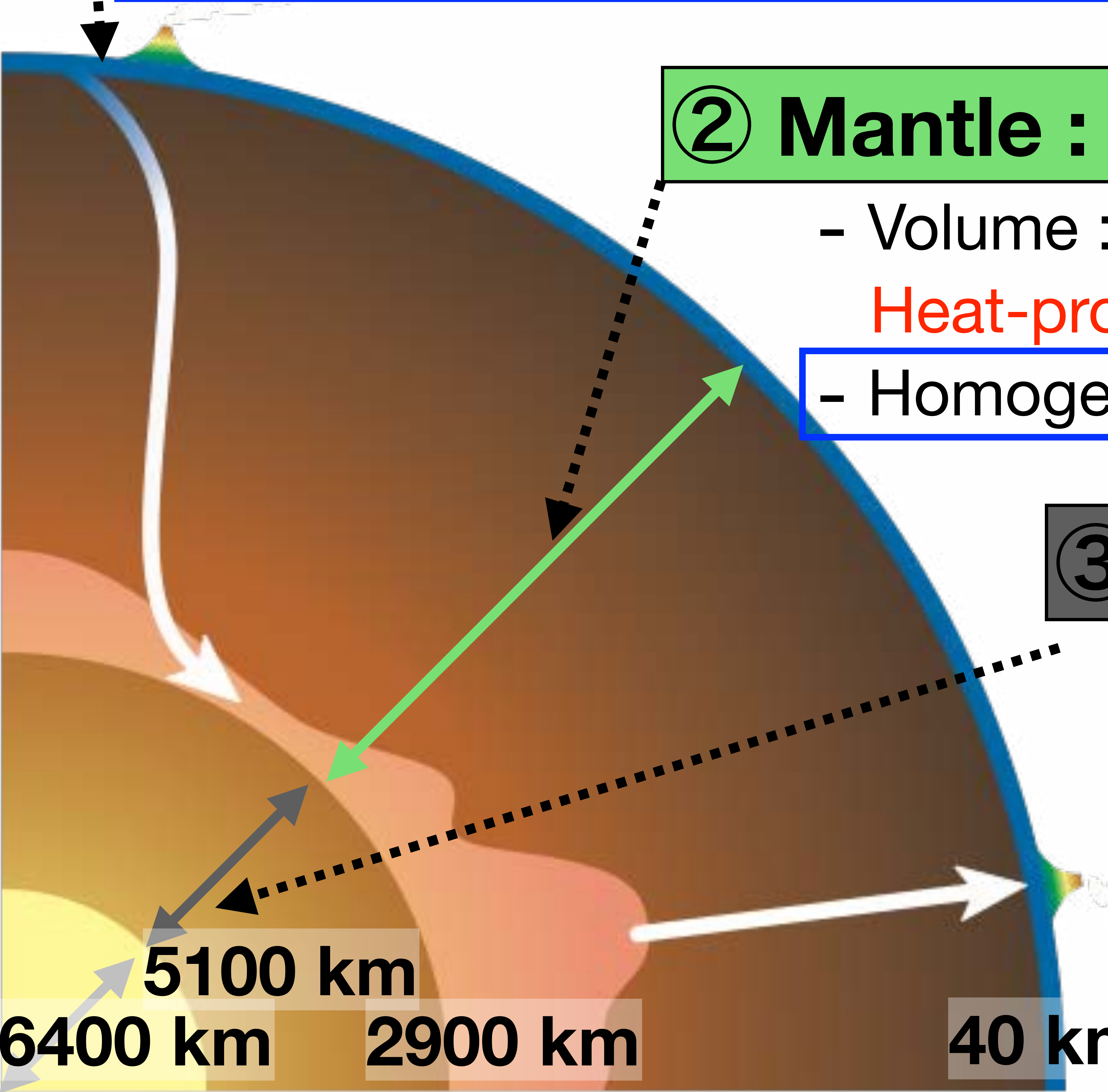
② Mantle : Solid

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

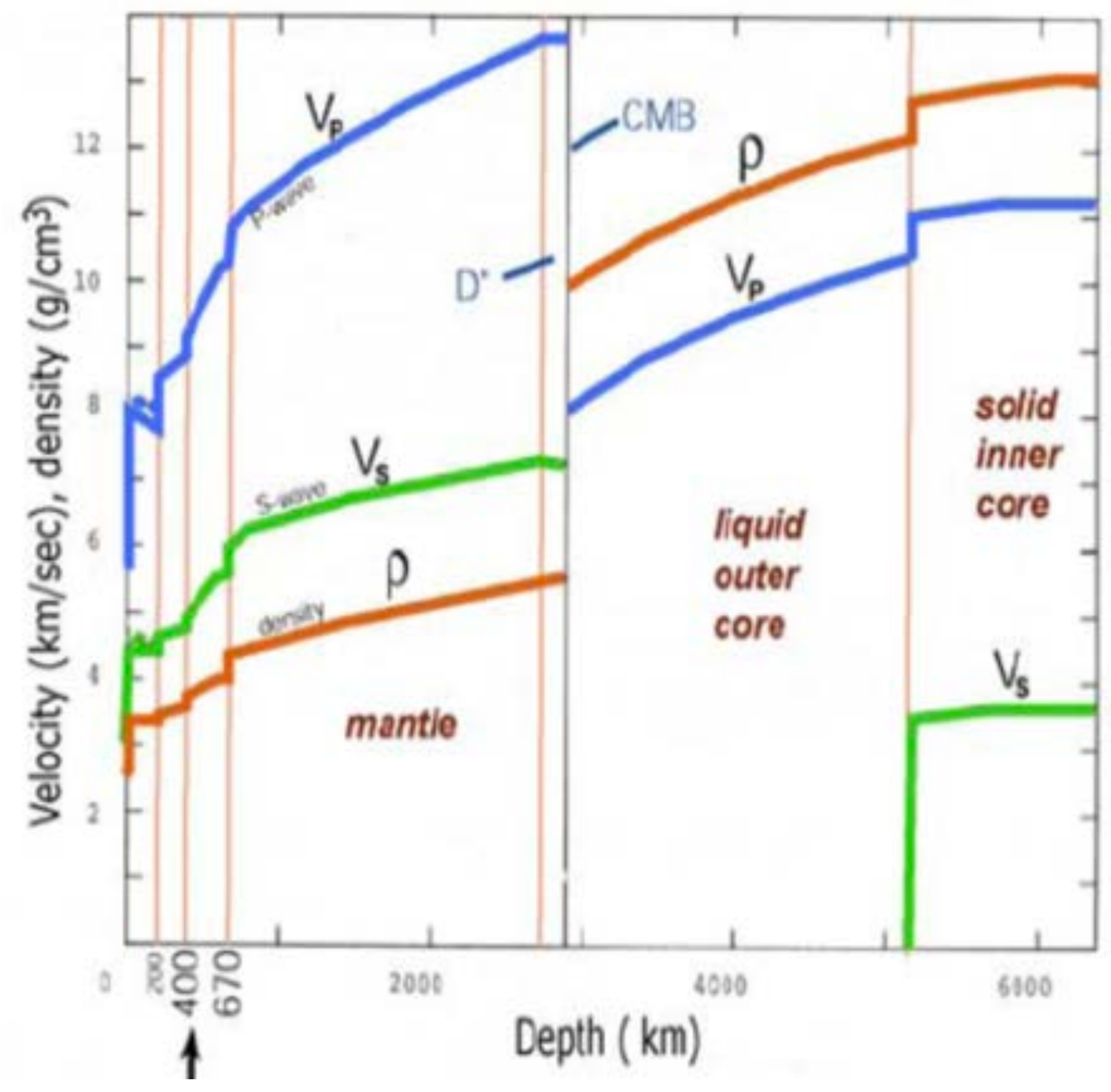
③ Outer Core : Fluid

④ Inner Core : Solid

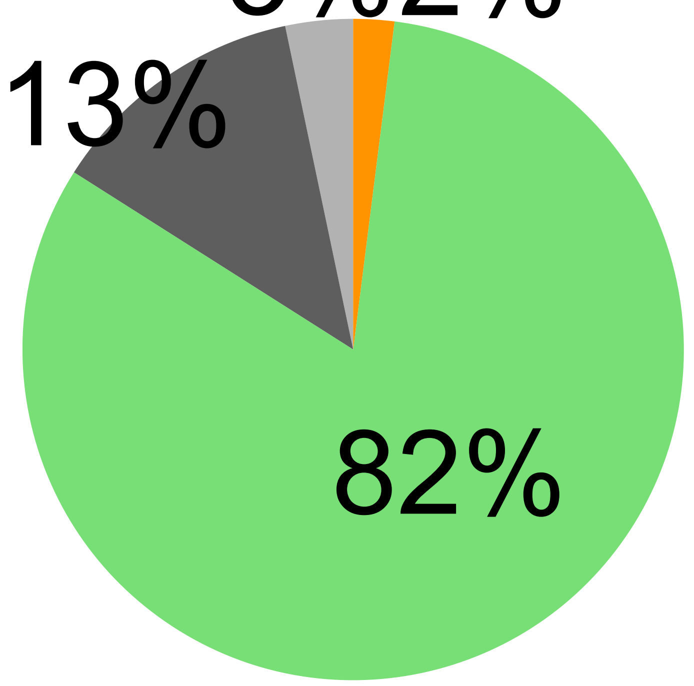
- Volume : 16%, Mass : 32%
  Heat-producing elements : negligible
- Fe (+little Ni) Density : 10% lighter than Fe
- Light elements? Amount?



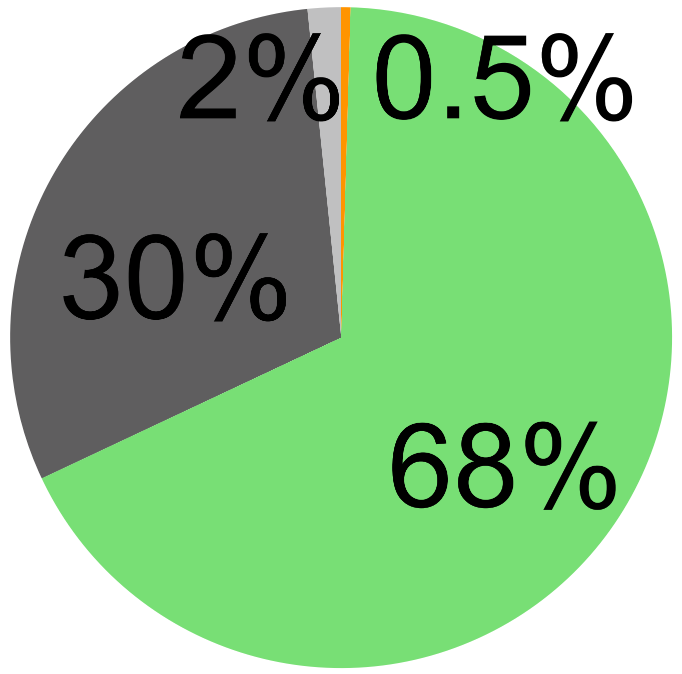
Seismic velocity structure



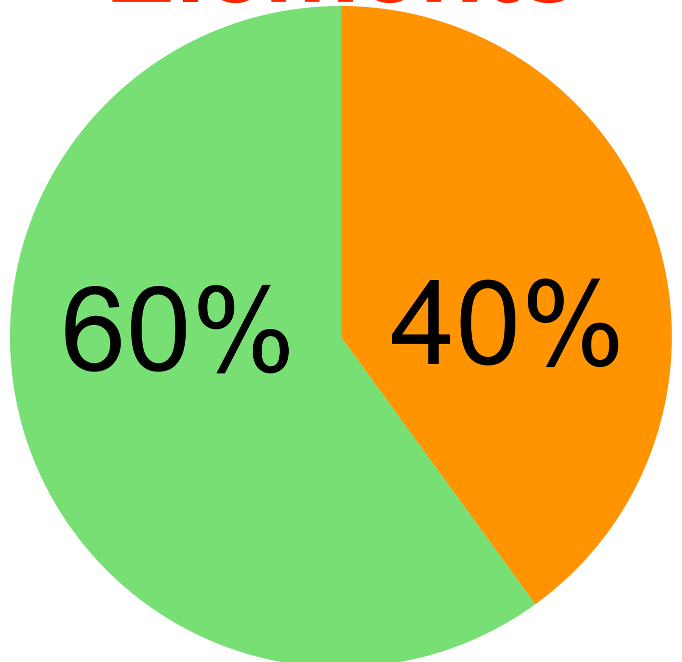
Volume



Mass



Heat-producing Elements

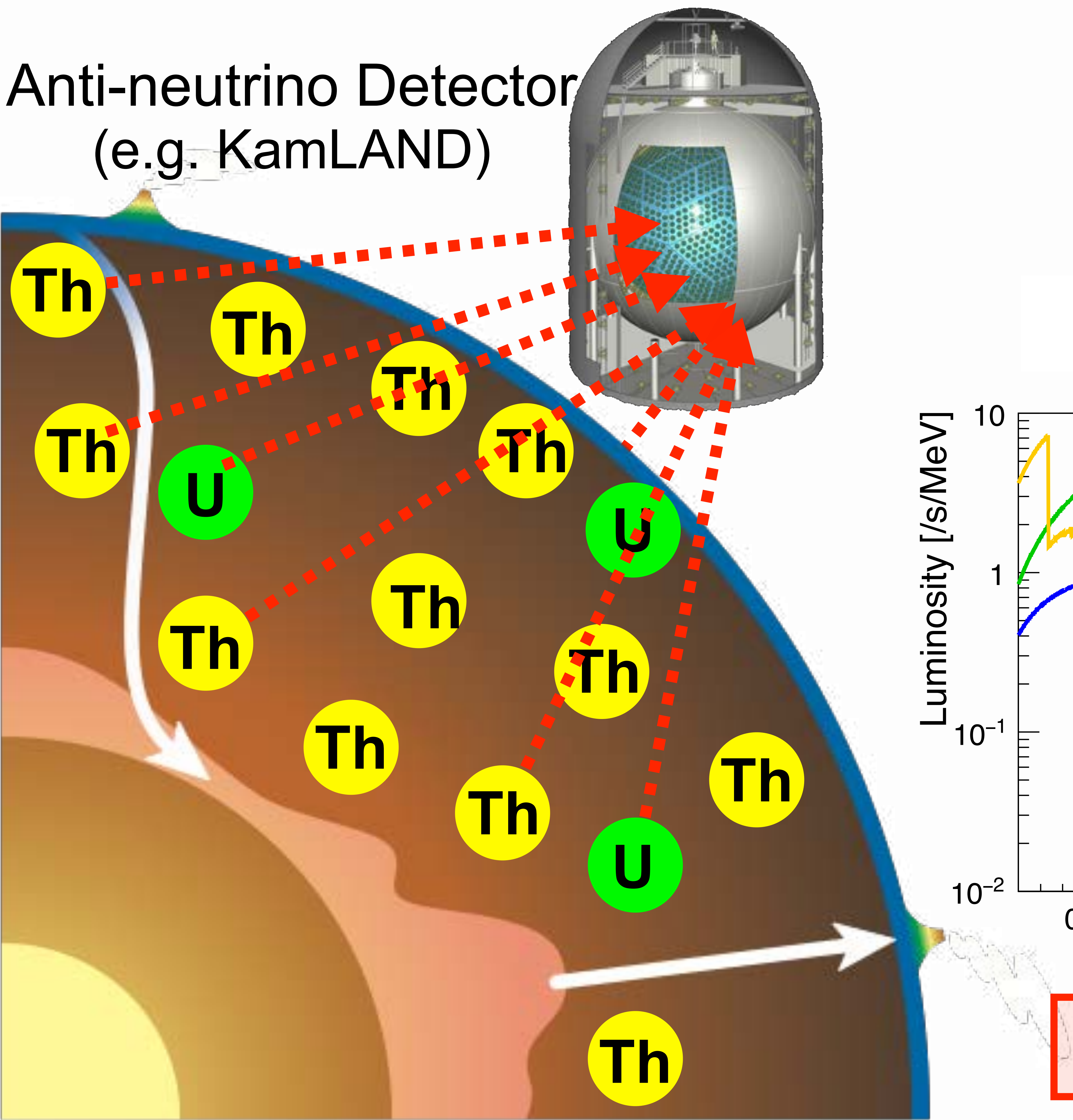


Geo-neutrinos

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)

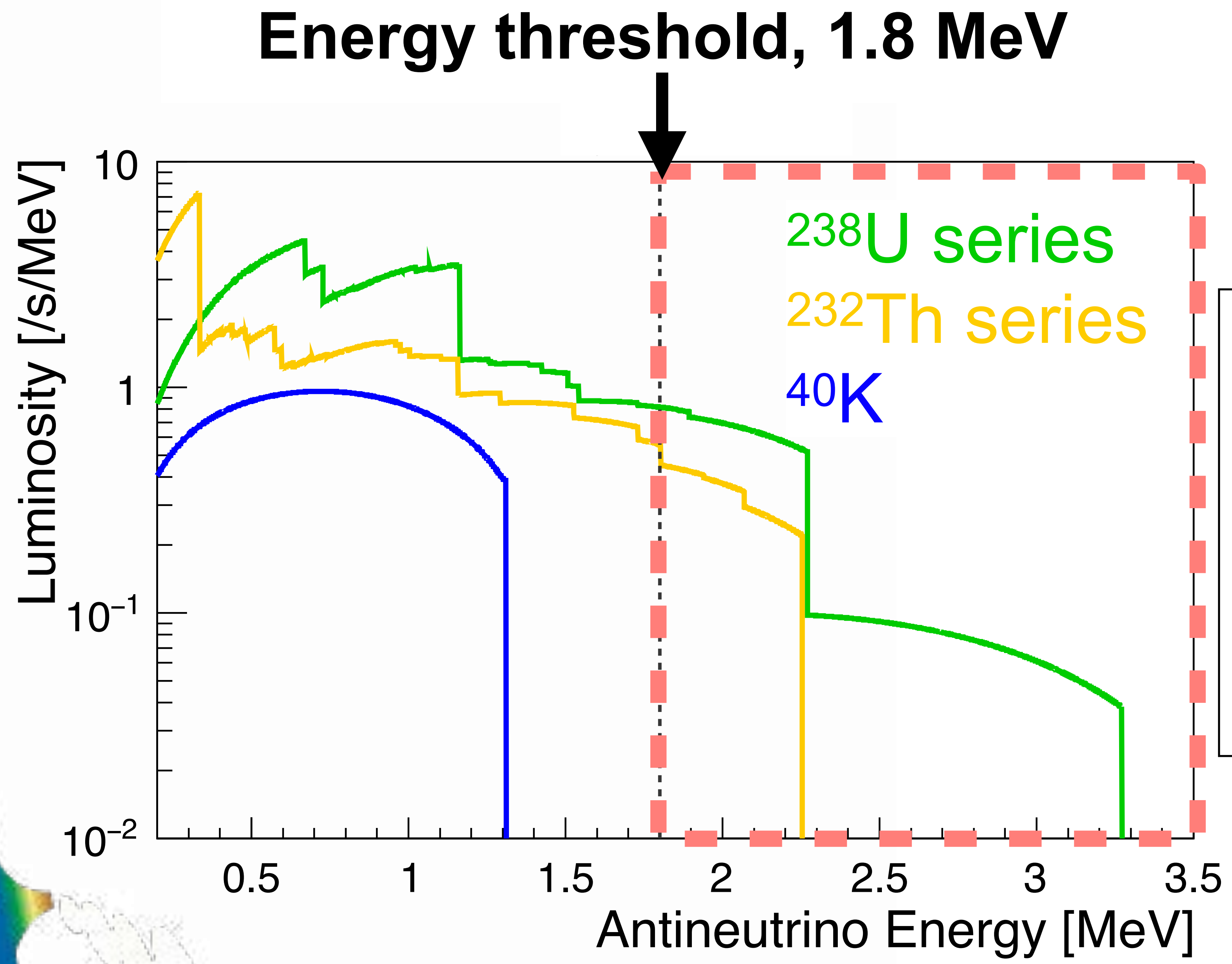


β-decay — geo-neutrinos

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

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

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



inverse β-decay

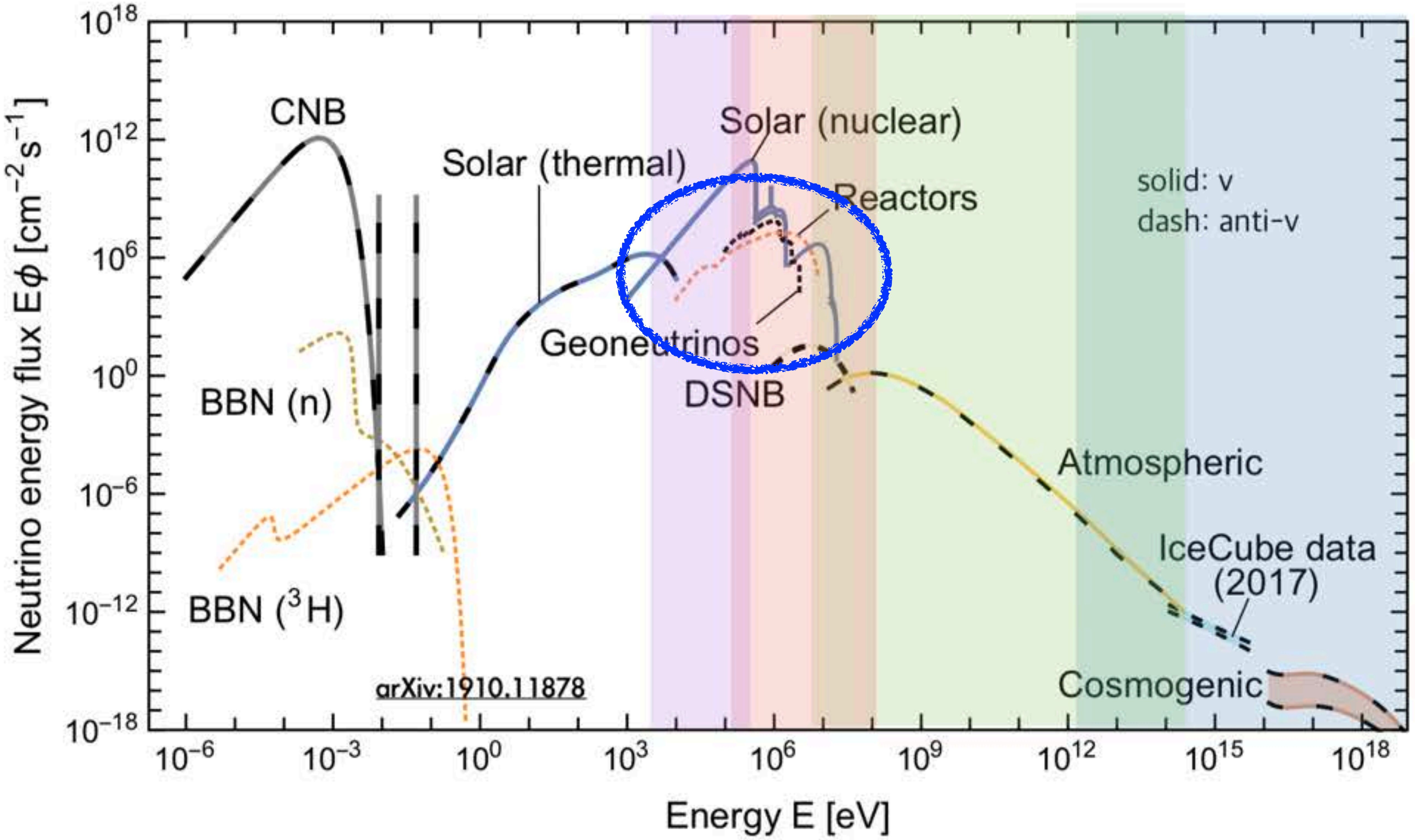
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

* 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**

Geo-neutrino Energy

a few MeV



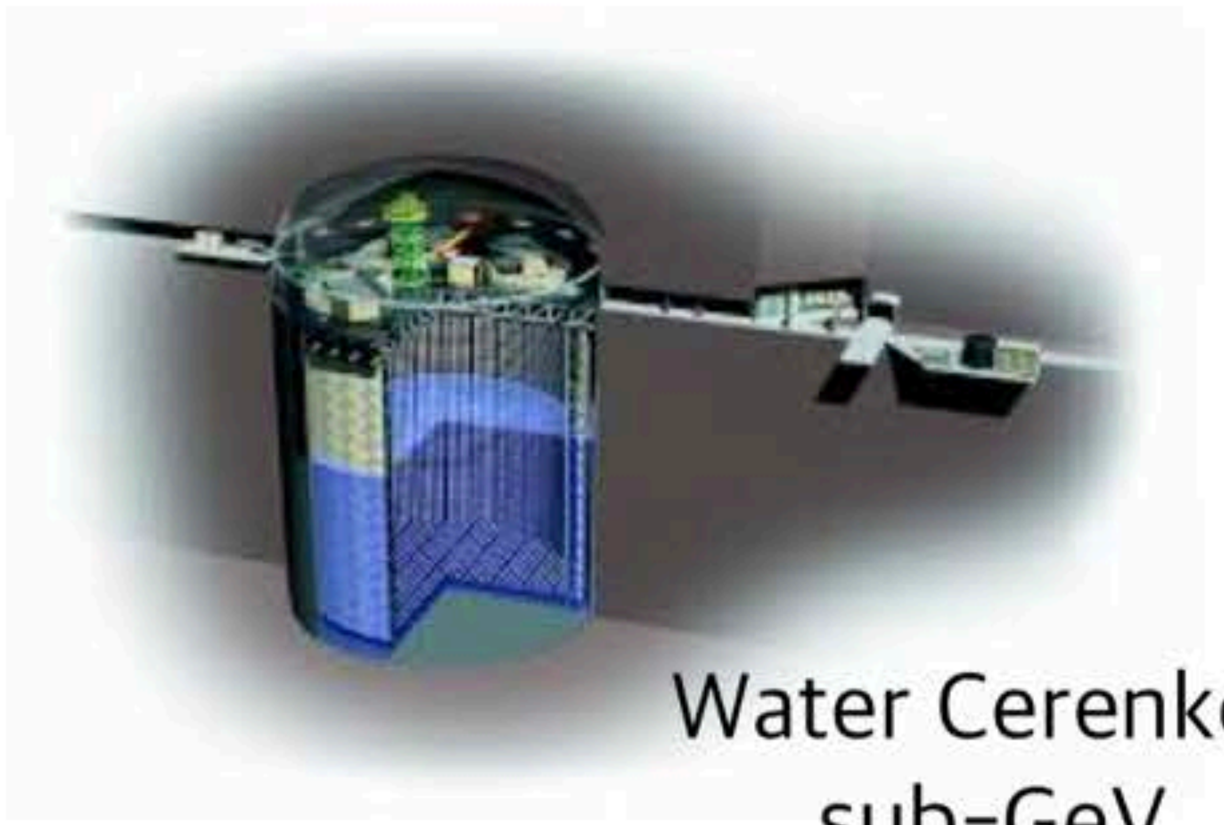
XENON

Dual-phase TPC
sub-keV

KamLAND

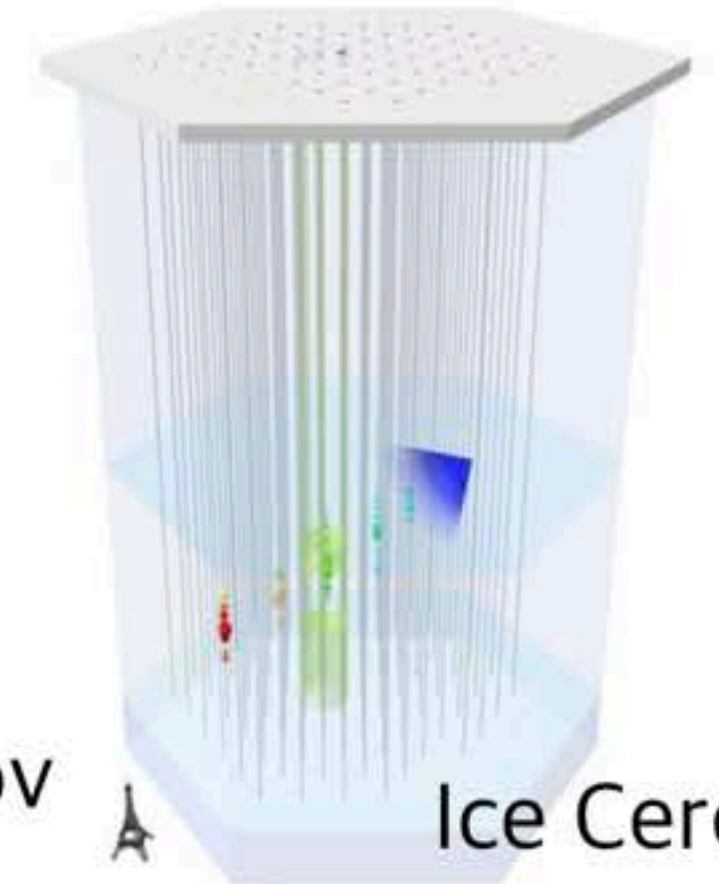
Liquid Scintillator
a few MeV

Super-Kamiokande



Water Cerenkov
sub-GeV

IceCube

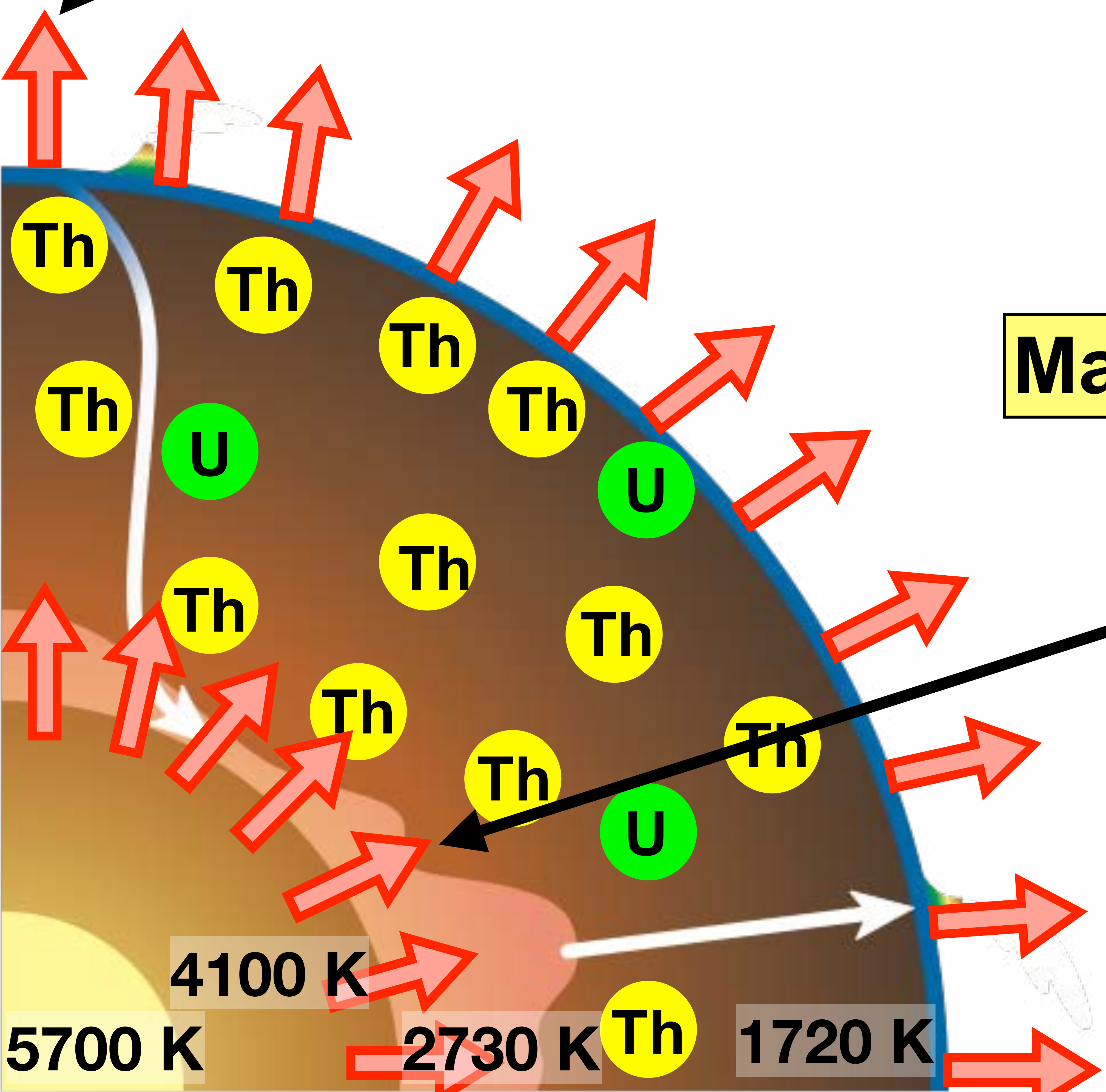


Ice Cerenkov
> TeV

Earth’s Heat Budget

		Contributions	Source
Surface heat flow (*Measured*) =	**Crust** heat production	*Model*	**Radiogenic**
	+ **Mantle** cooling	*??*	Primordial
	+ **Mantle** heat production	*??*	**Radiogenic**
	+ **CMB**※ heat flow	*??*	Primordial

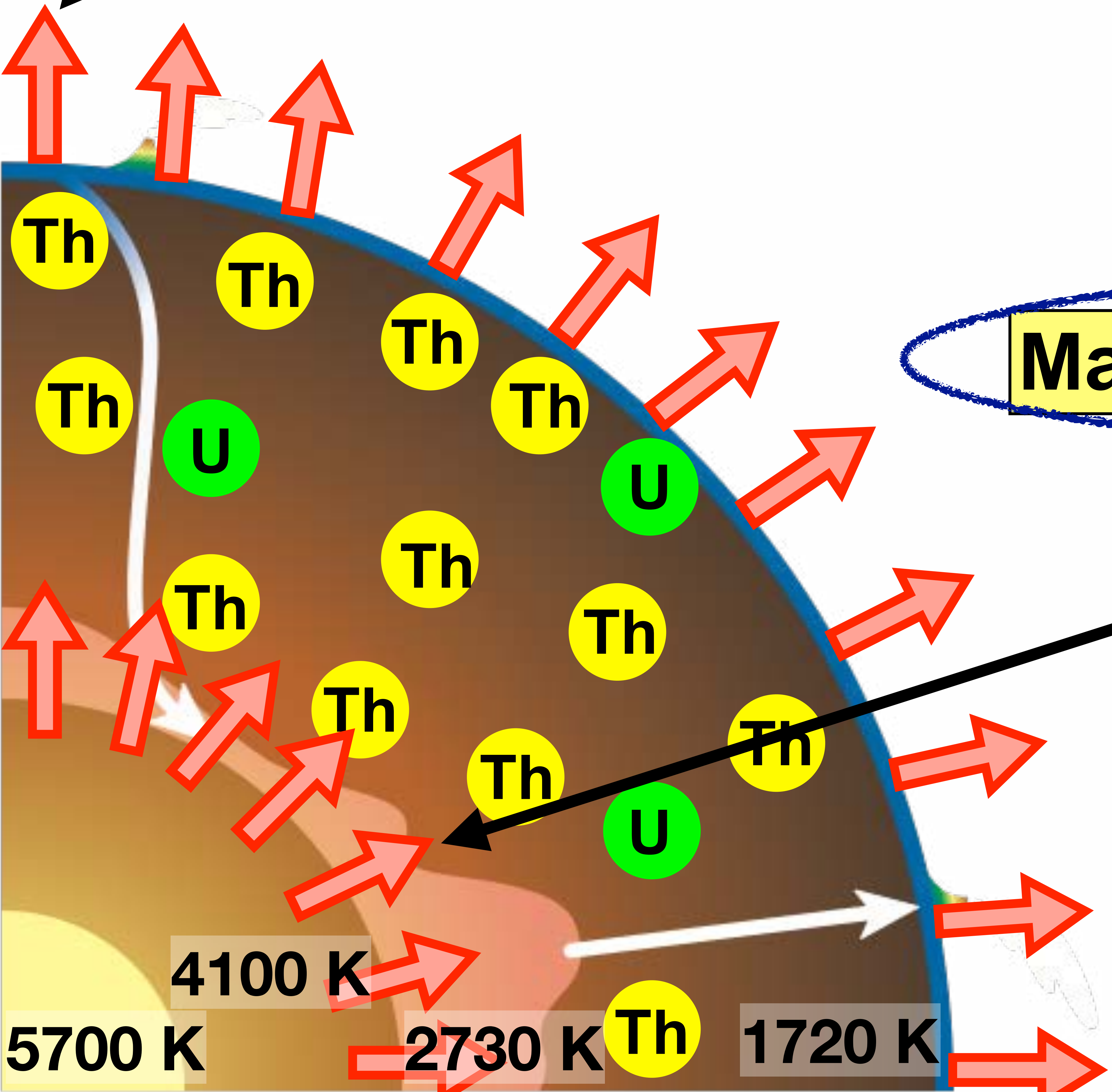
CMB※ heat flow = **Core** cooling + **Inner core** growth



※Core Mantle Boundary

Earth's Heat Budget

		Contributions	Source
Surface heat flow (*Measured*) =	**Crust** heat production	*Model*	**Radiogenic**
+	**Mantle** cooling	??	Primordial
+	**Mantle** heat production	??	**Radiogenic**
+	**CMB**※ heat flow	??	Primordial
	Core cooling + **Inner core** growth		



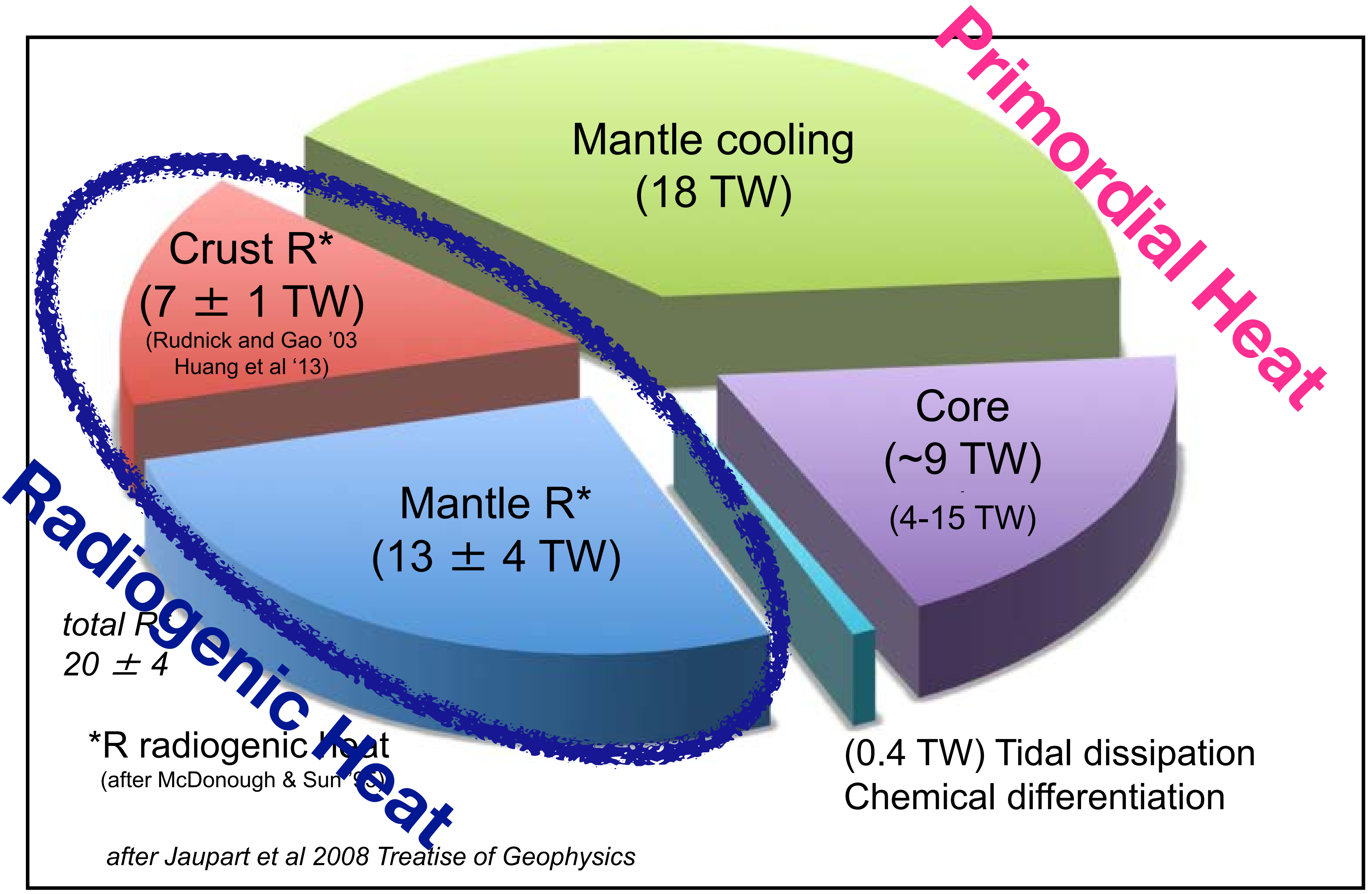
Geoneutrinos can define the amount of radiogenic heat

※Core Mantle Boundary

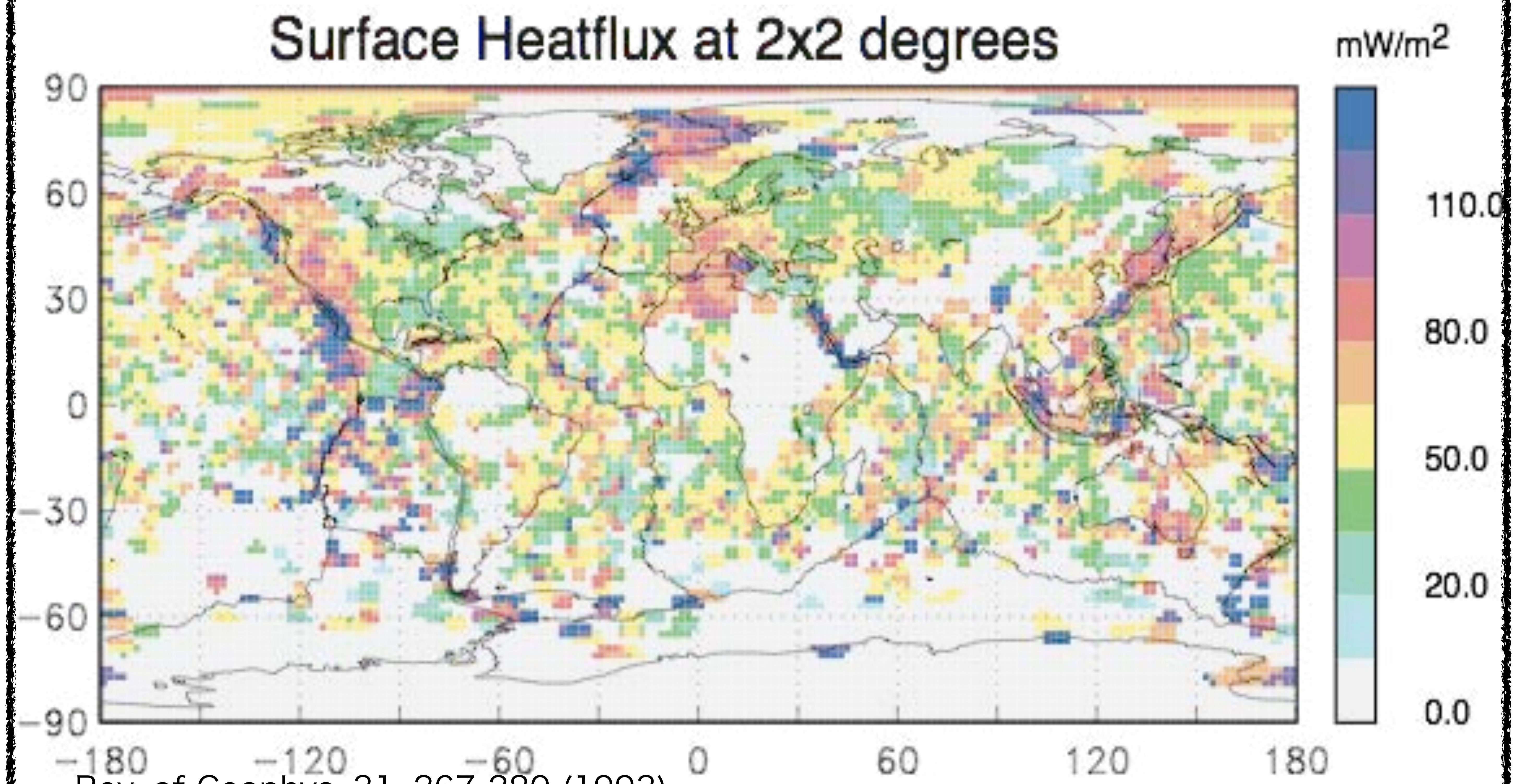
Earth's Heat Balance

☑ Surface heat flow
46 ± 3 TW

example of Earth model



crust heat flux measurement & calculation



Rev. of Geophys. 31, 267-280 (1993)

Primordial Heat

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

Earth's Heat Balance

Surface heat flow
46 ± 3 TW

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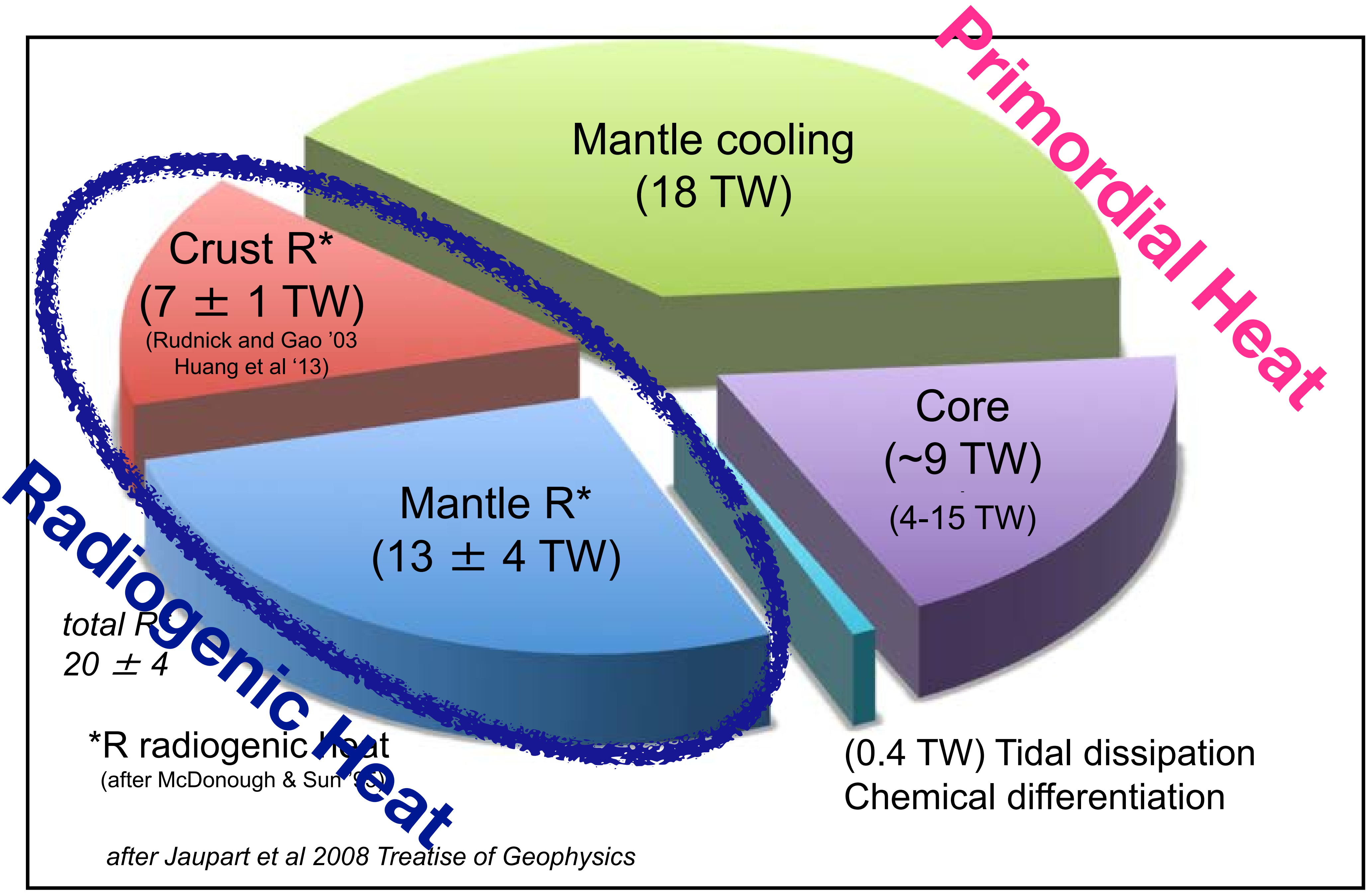

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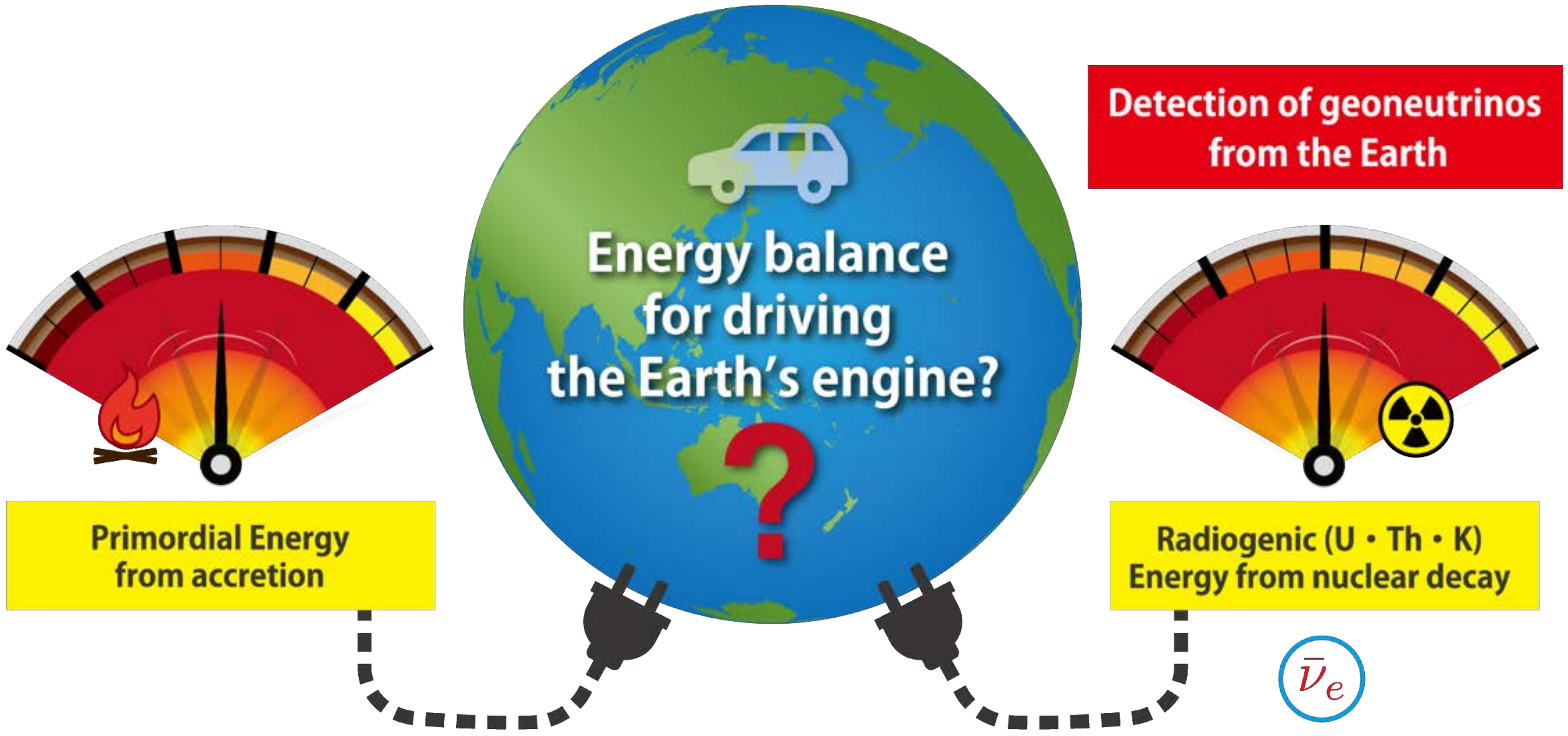
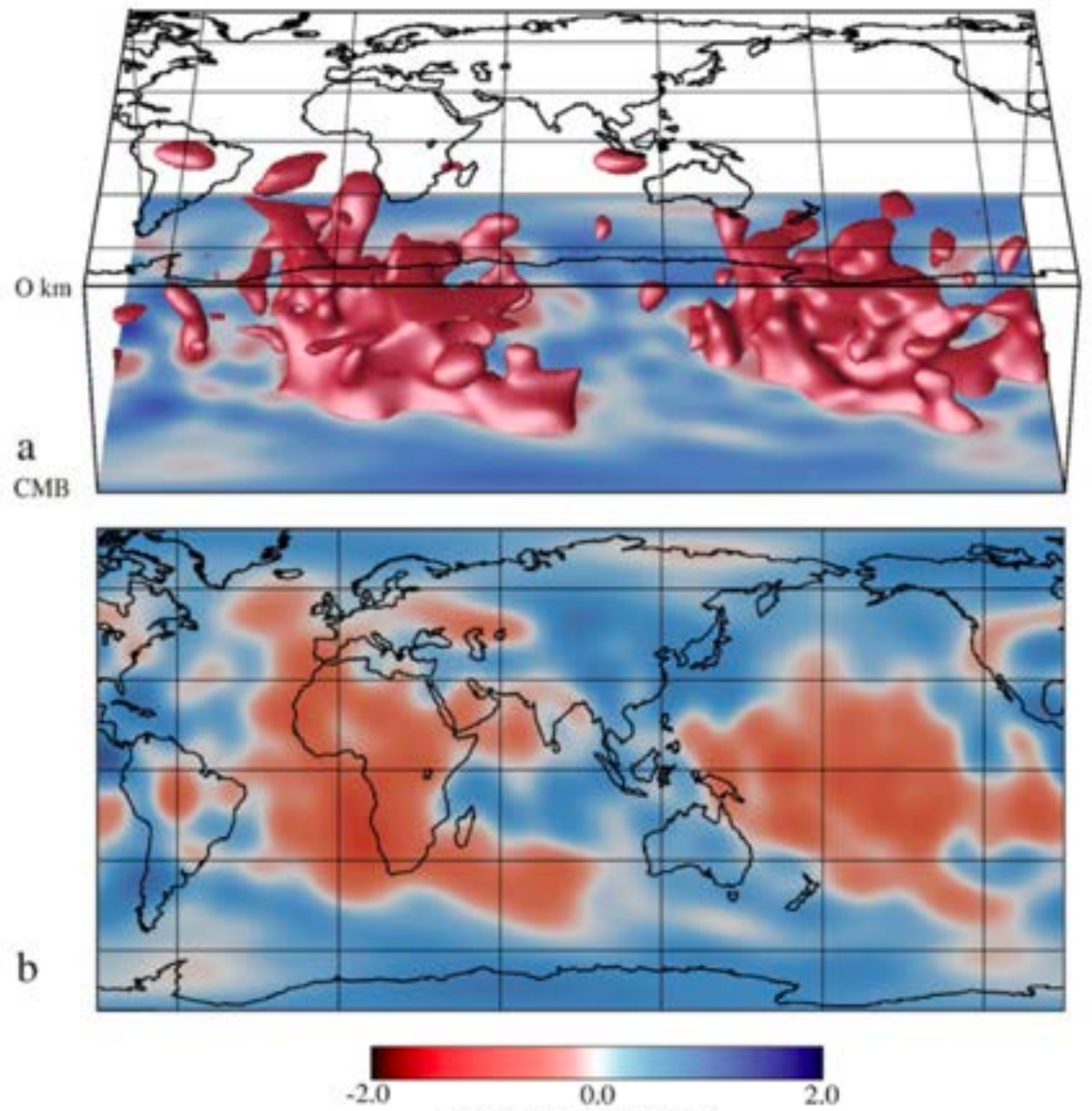


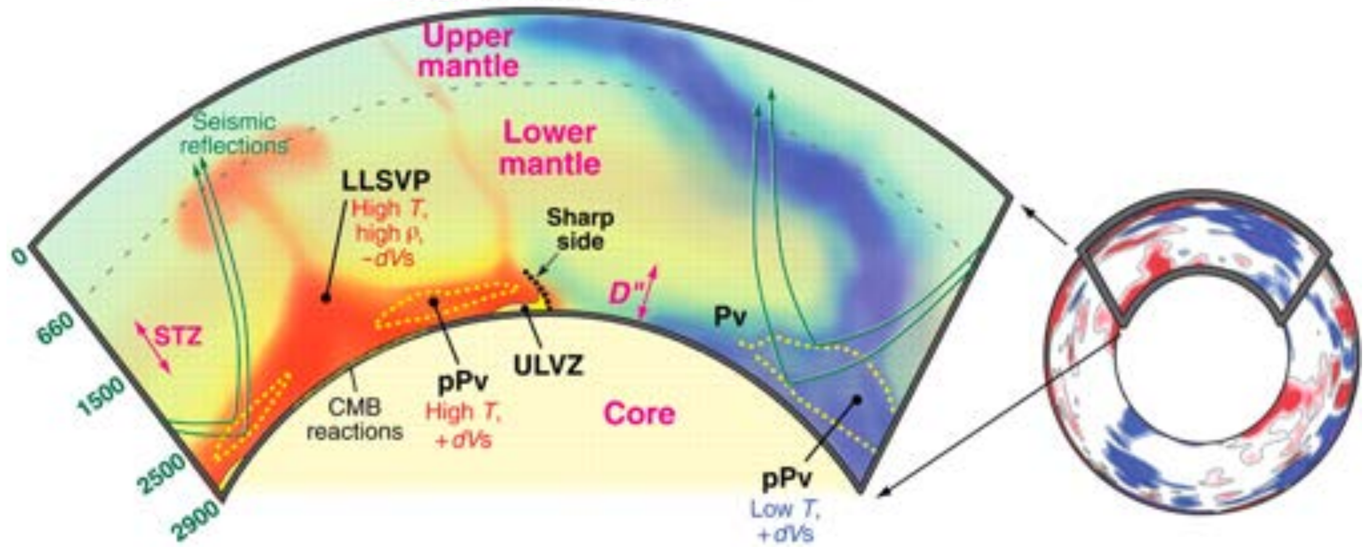
Q : How much radiogenic heat contributes to Earth's heat?

Why geo-neutirno?: Big questions

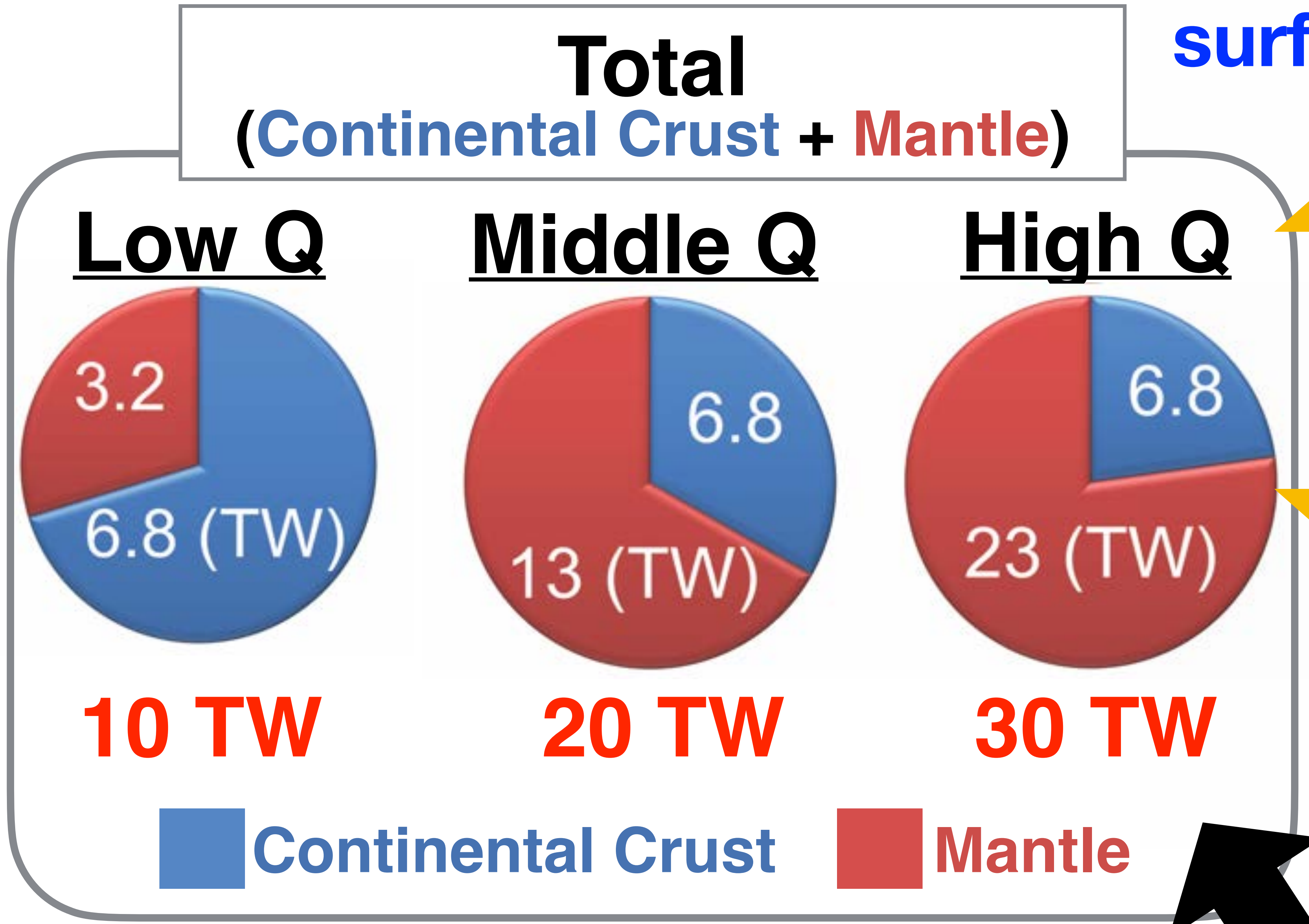
What is in the mantle?

Many seismically imaged structures and chemical heterogeneities in the mantle





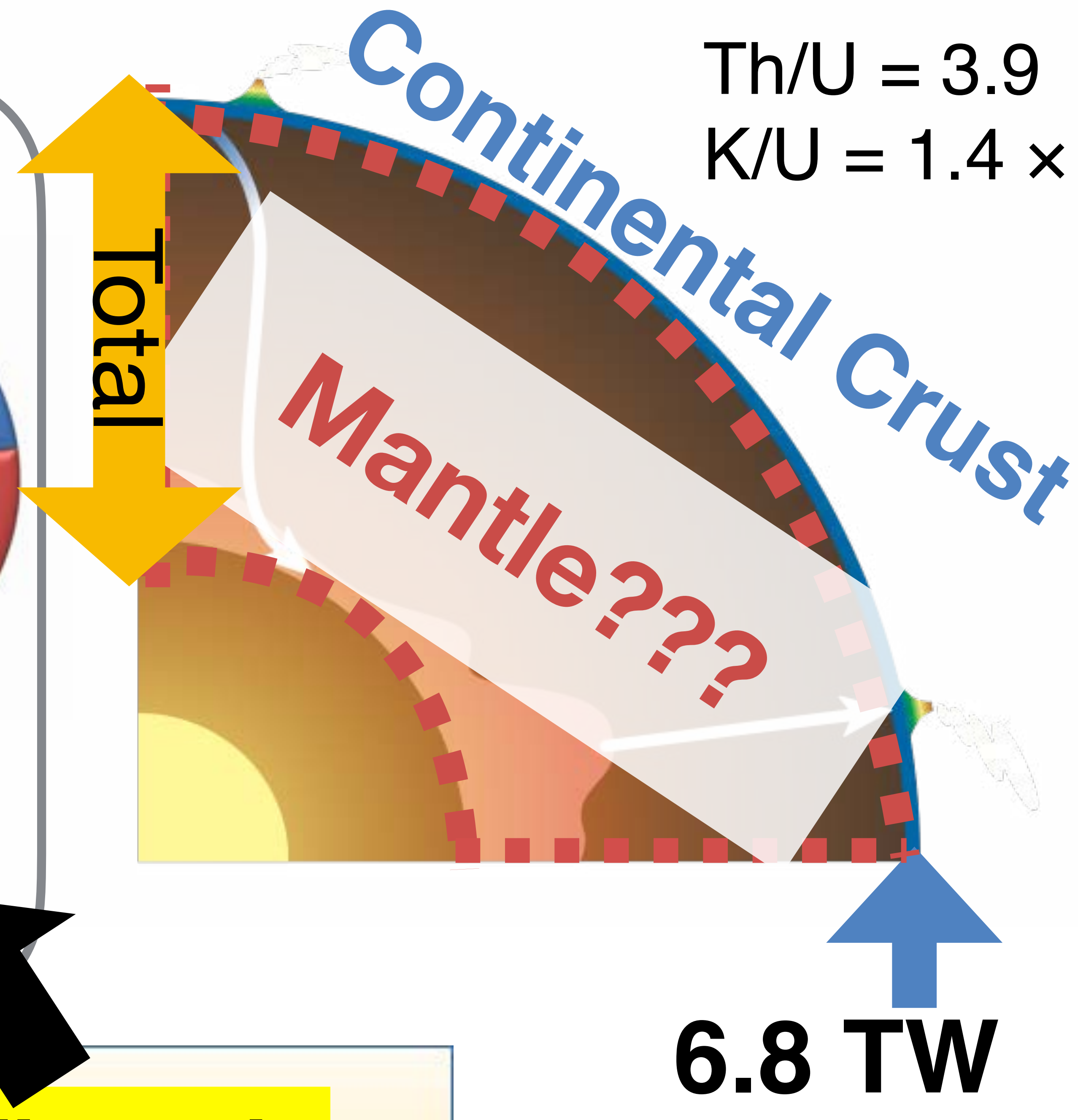
How much fuel is left to drive Plate Tectonics?

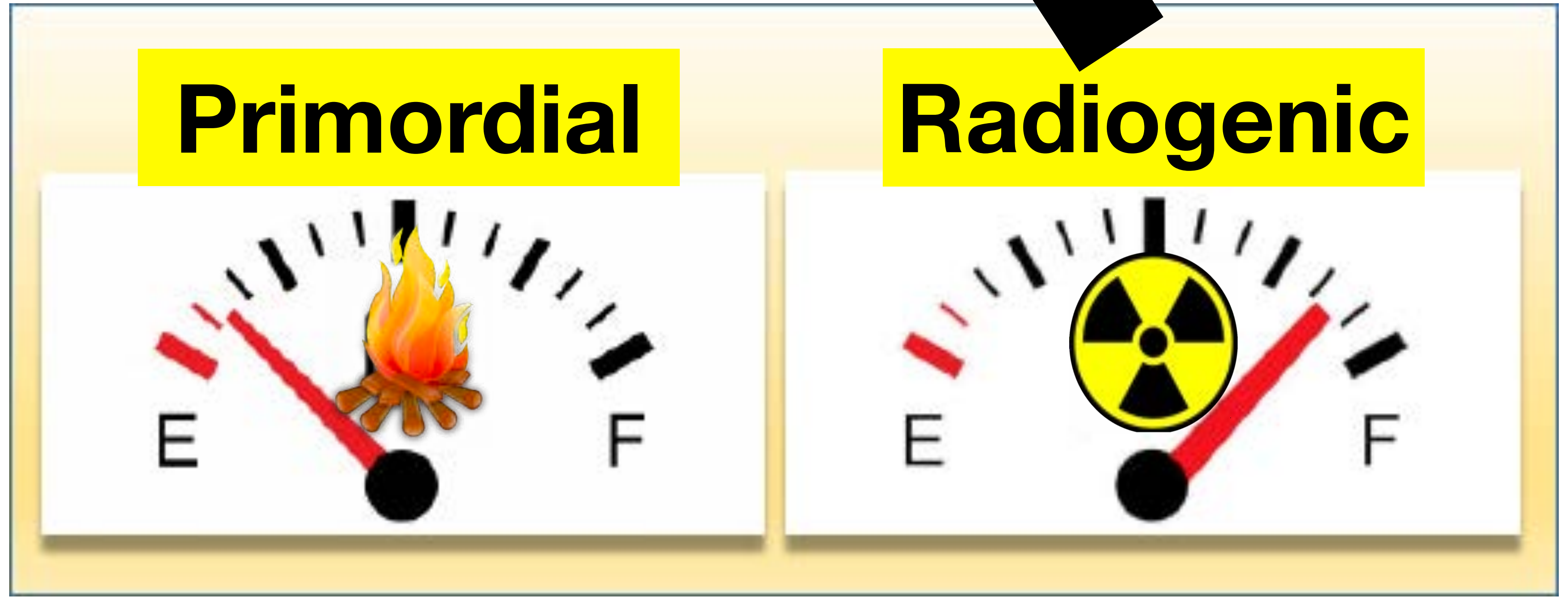


surface heat flow : 46 ± 3 TW

Th/U = 3.9

K/U = 1.4×10^4





What we can learn

Nature & amount of Earth's thermal power

1. abundance of heat producing elements (U, Th, K) in the Earth
2. clues to planet formation processes
3. amount of radiogenic power to drive mantle convection & plate tectonics
4. is the mantle compositionally layered or have large structures?

What we can learn

Nature & amount of Earth's thermal power

1. abundance of heat producing elements (U, Th, K) in the Earth
   estimates of silicate Earth 9-36 TW
2. clues to planet formation processes
   constrains chondritic Earth models
3. amount of radiogenic power to drive mantle convection & plate tectonics
   estimates of mantle 3.2-32 TW
4. is the mantle compositionally layered or have large structures?
   layers, LLSVP, super-plume piles*
   **Large-Low-Shear-Velocity Provinces*

Geo-neutrino can directly define power to drive the Earth's engine

Contents

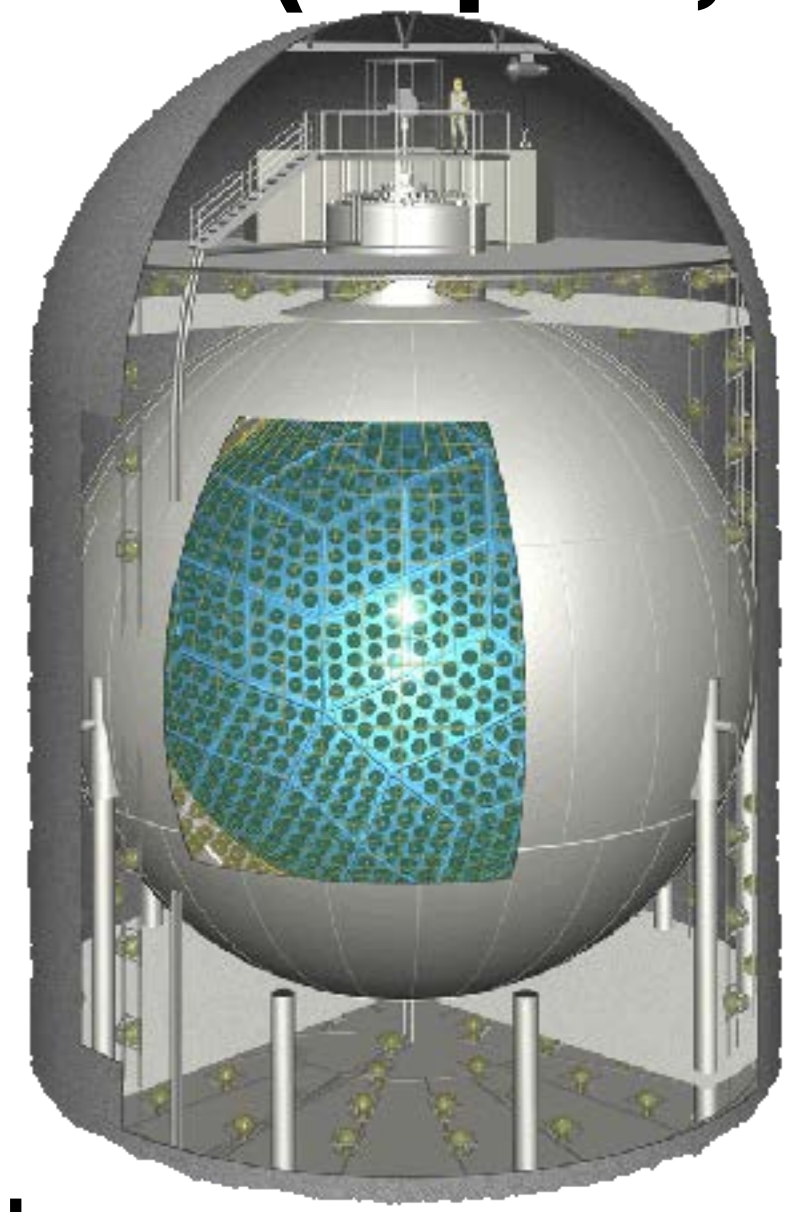
Experiments

Two experiments have published geoneutrino measurement results.

KamLAND & Borexino

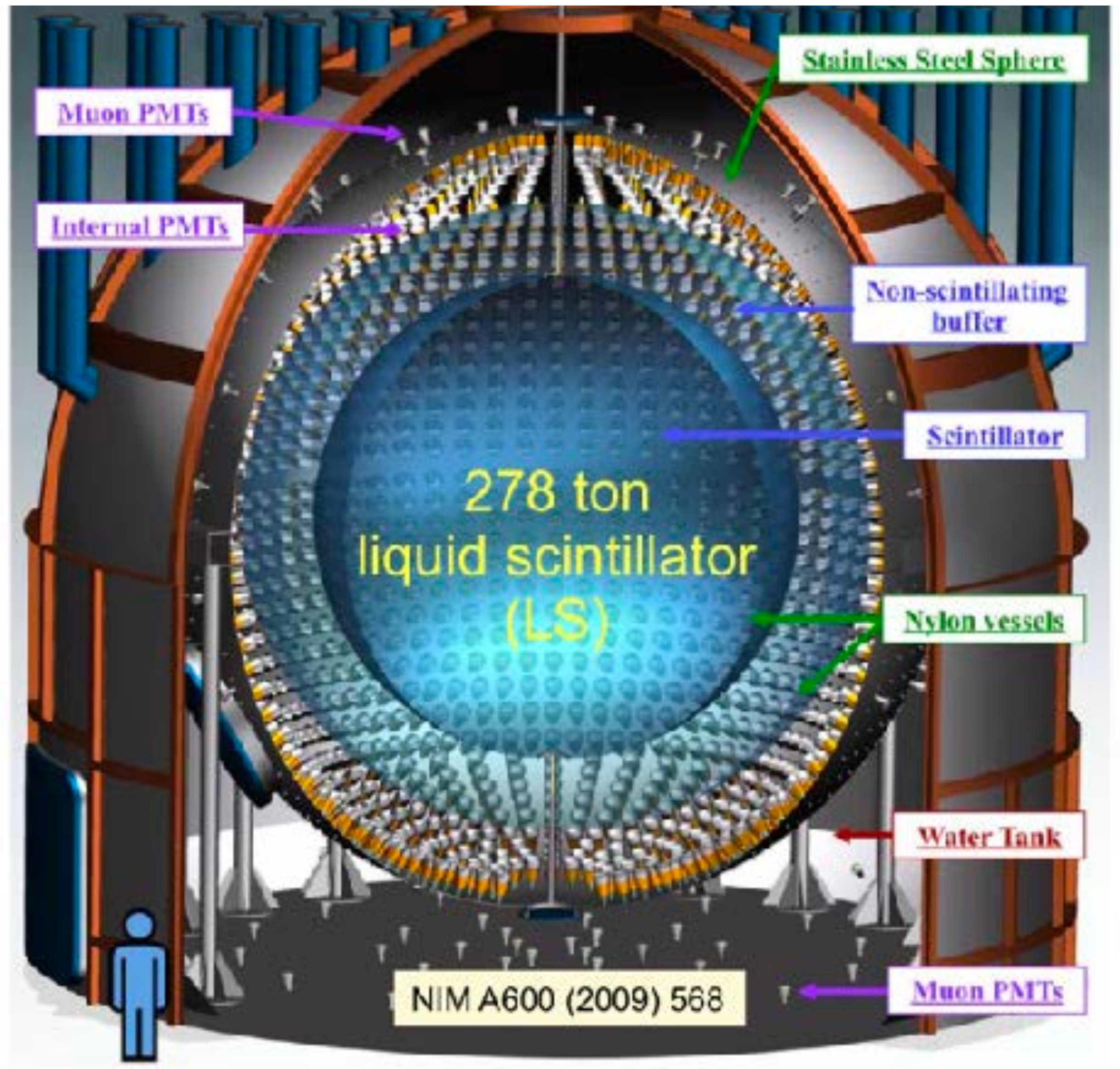
Two liquid scintillator (LS) experiments have measured geoneutrinos.

KamLAND (Japan, 2002~)



* LS : 1000 t
* Depth : 2700 m.w.e.
* expected event ratio
  reactor/geo ~**6.7** (up to 2010)
  ~**0.4** (2011~)
  w/o Japanese reactors

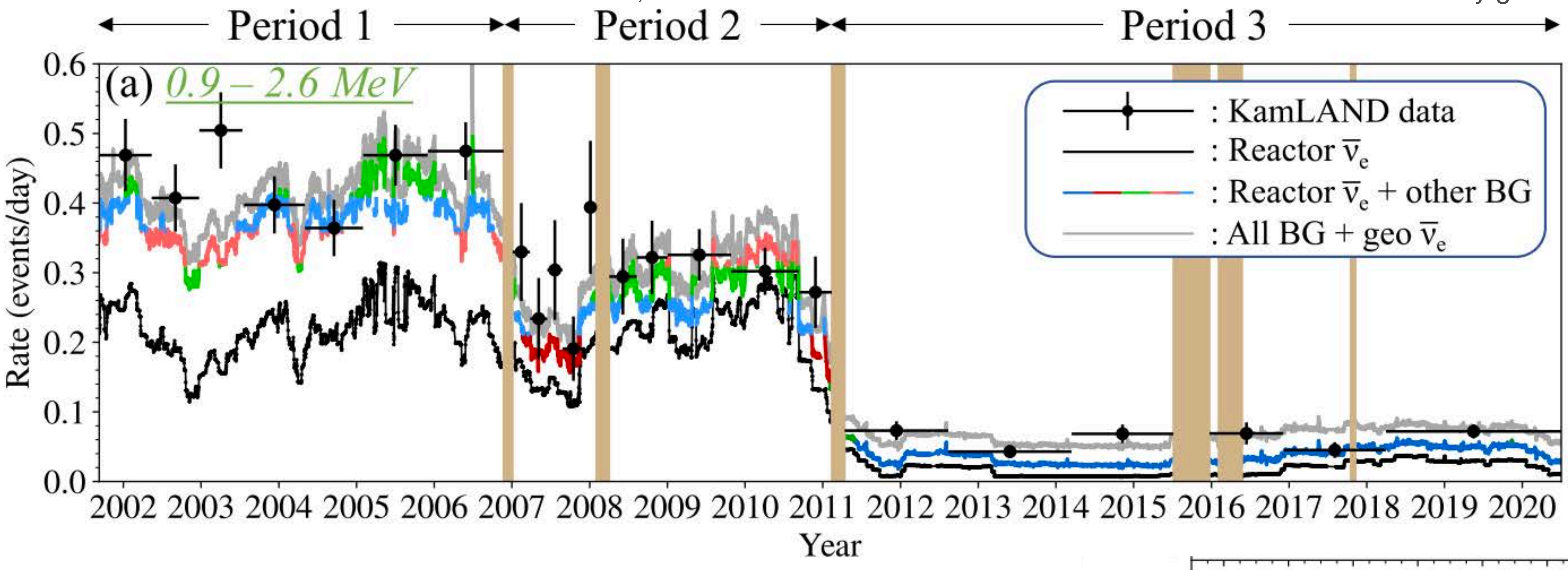
Borexino (Italy, 2007~2020)

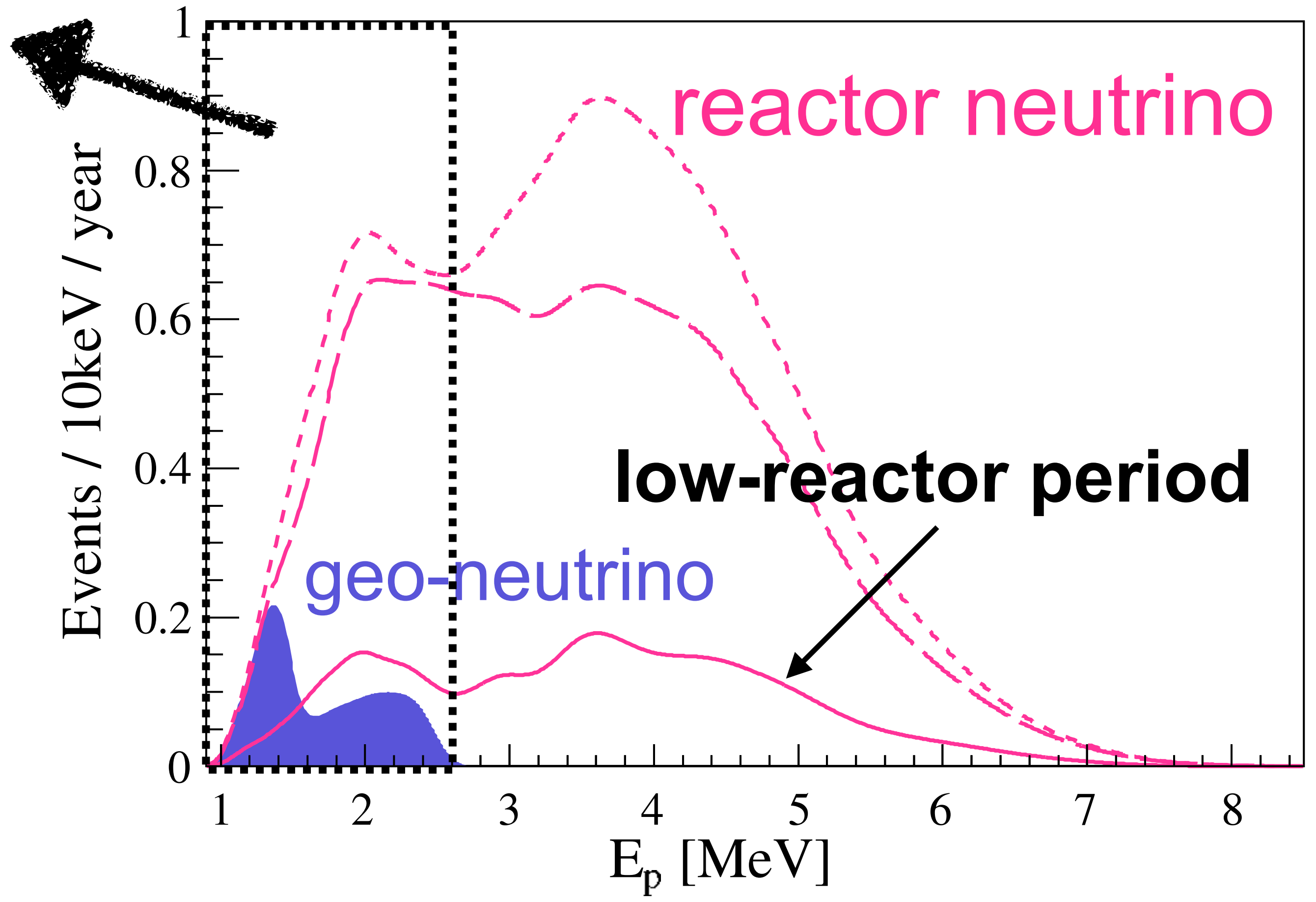


* LS : 278 t
* Depth : 3800 m.w.e.
* expected event ratio
  reactor/geo ~**0.3** (2007~)

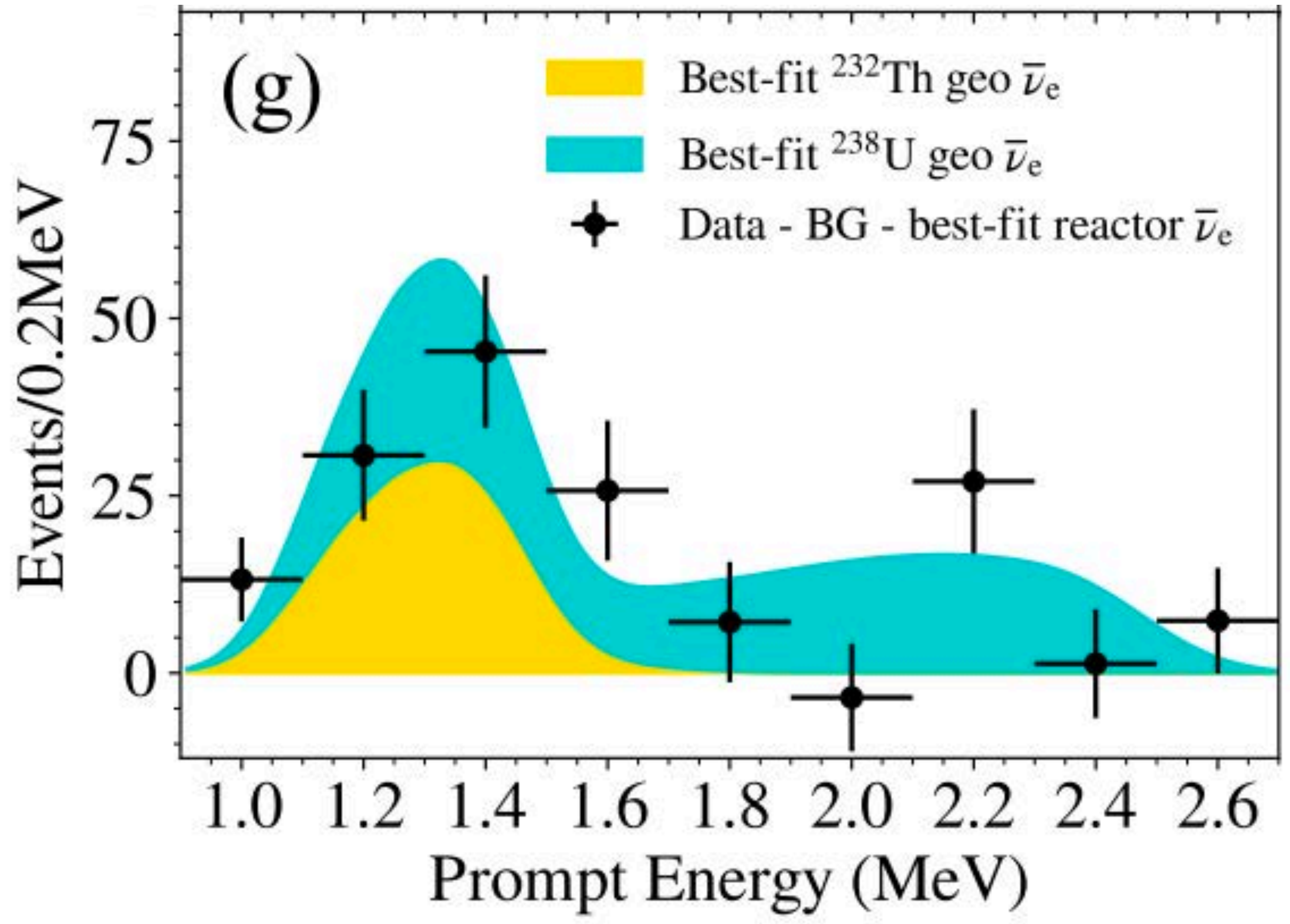
KamLAND Latest Results

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





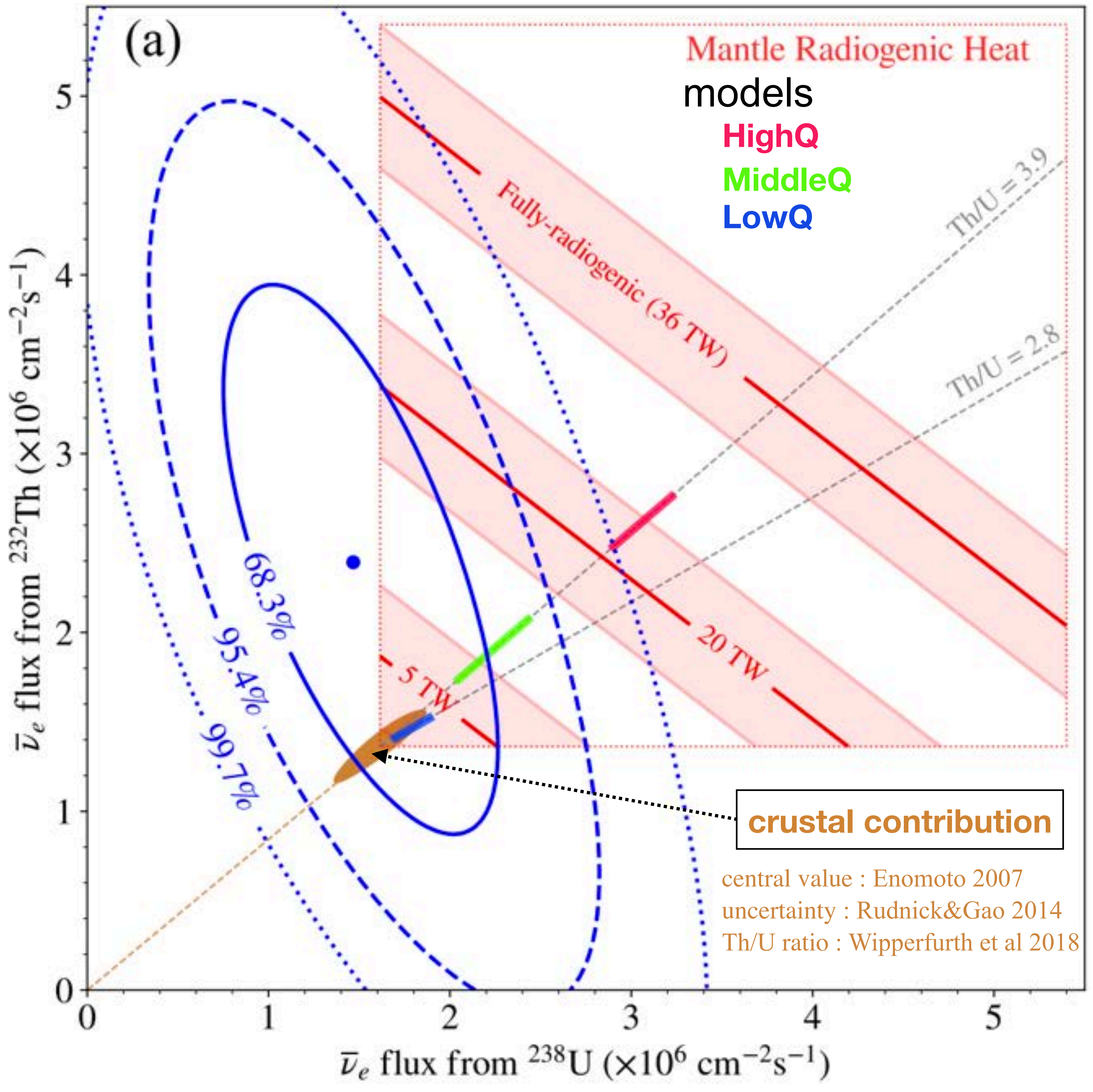
Dataset : Mar, 2002-Dec, 2021
Livetime : 5227 days
(low-reactor phase : 2590 days)

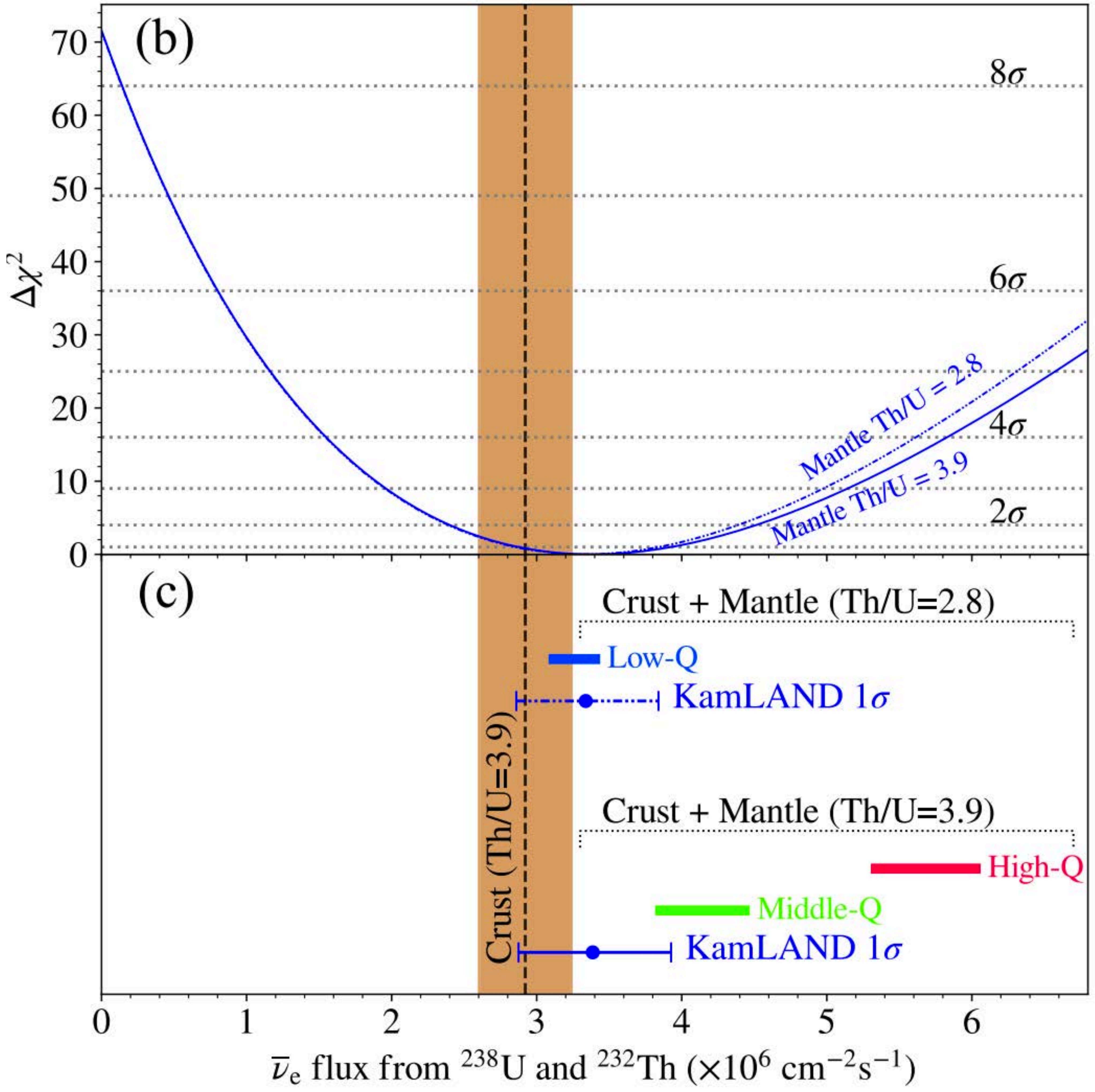


☑ **massive dataset of low-reactor period**
→ **precise measurement of U and Th contributions**

KamLAND Latest Results

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





Radiogenic Heat

Th/U free

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

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

Model Rejection

HighQ model is rejected at

99.76 % C.L. (homogeneous mantle)

97.9% C.L. (concentrated at CMB)

best-fit

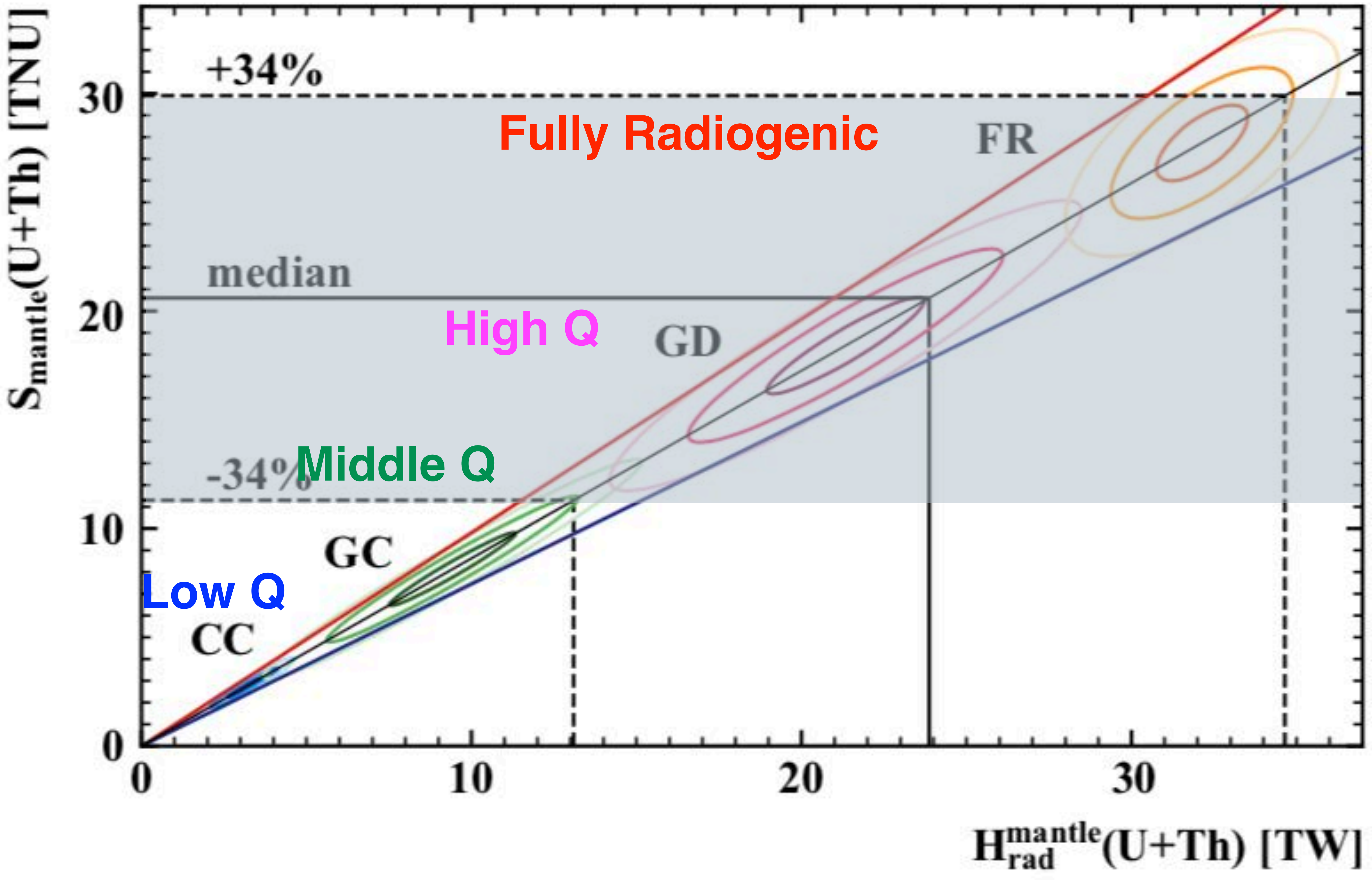
Th/U free

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

Improve the distinct spectroscopic contributions of U and Th

Mantle only

Phys. Rev. D 101, 012009 (2020)



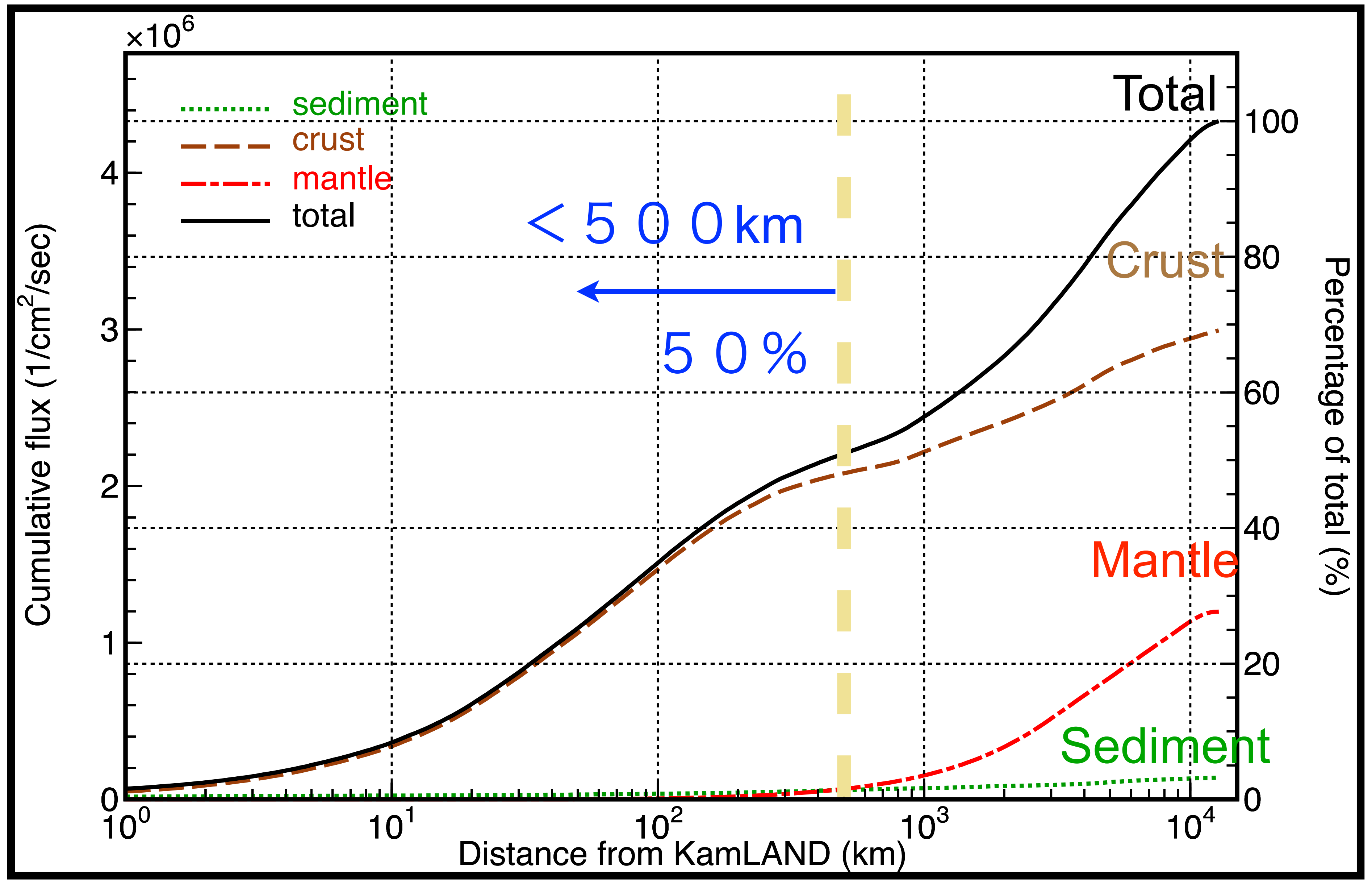
(Mantle, U+Th) 24.6 +11.1/-10.4 TW

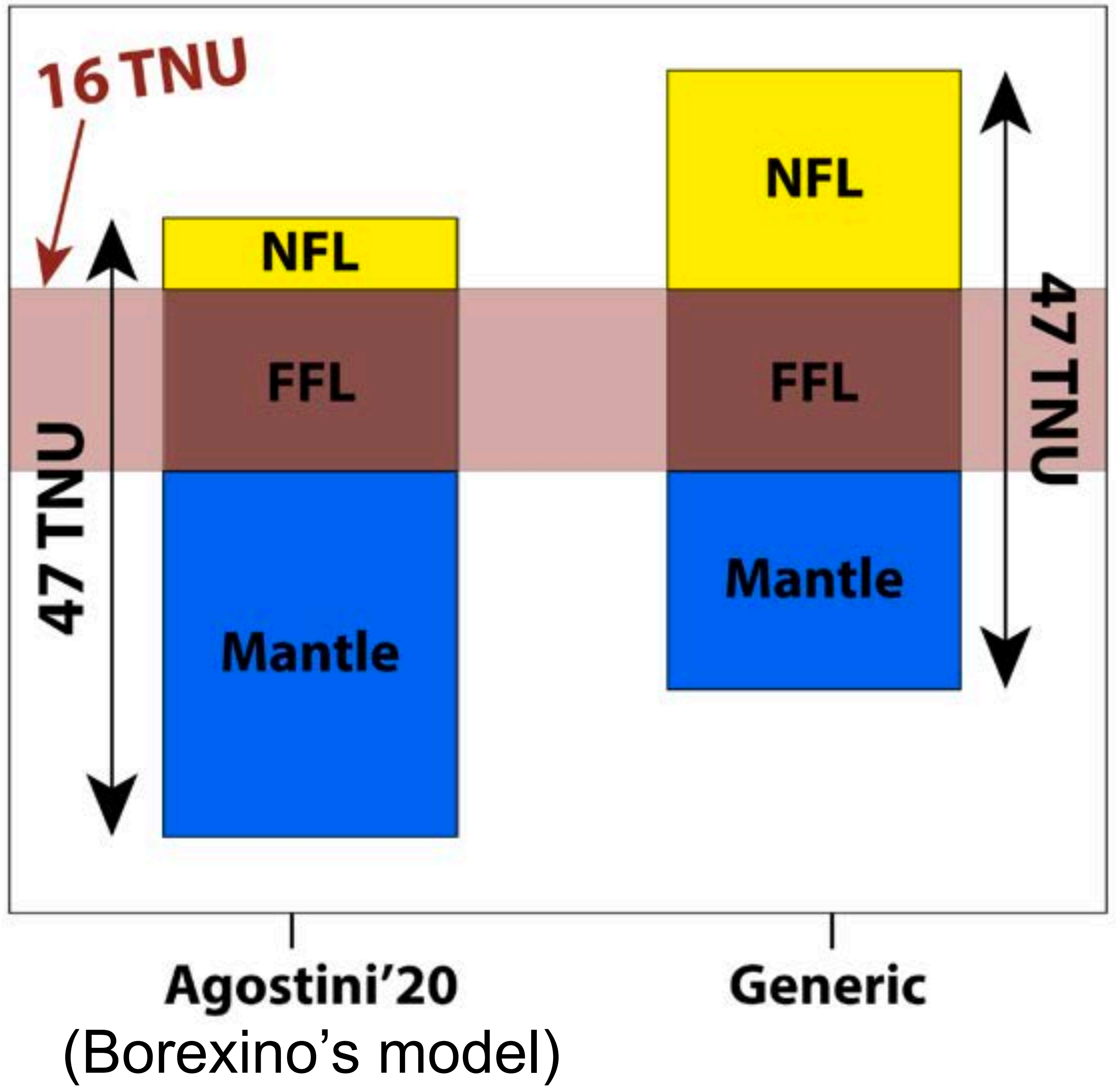
Total radiogenic heat: $38.2^{+13.6}_{-12.7}$ TW.

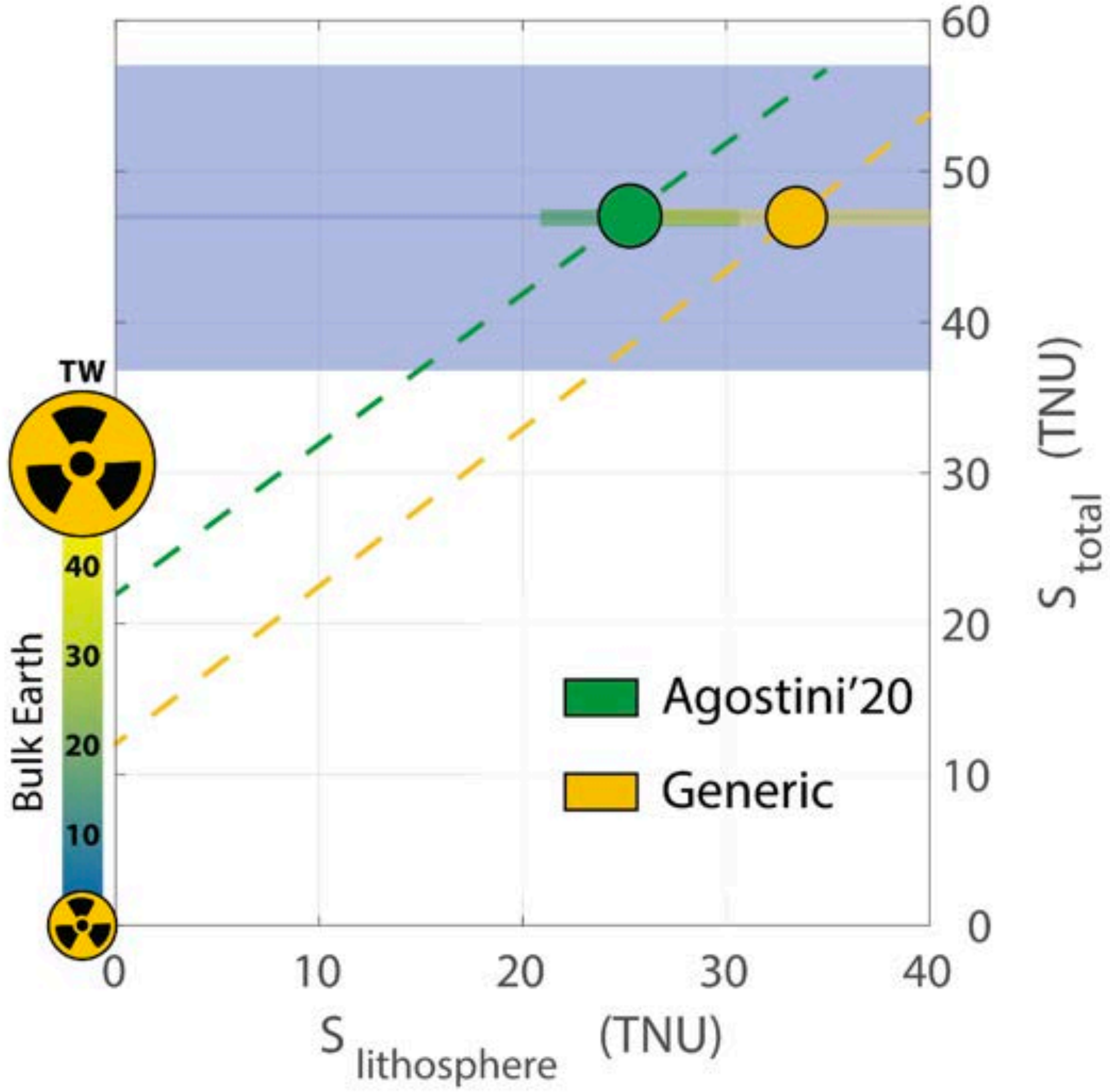
High Q (30TW radiogenic hear) model is preferred.

Lithosphere Model

Sammon, L. G. and McDonough, W. F., EPSL, 539, 117684 (2022)







$$S_{total} = S_{lithosphere} + S_{mantle} + S_{core}$$

$$S_{lithosphere} = S_{Near\ Field\ Lithosphere} + S_{Far\ Field\ Lithosphere}$$

NFL FFL

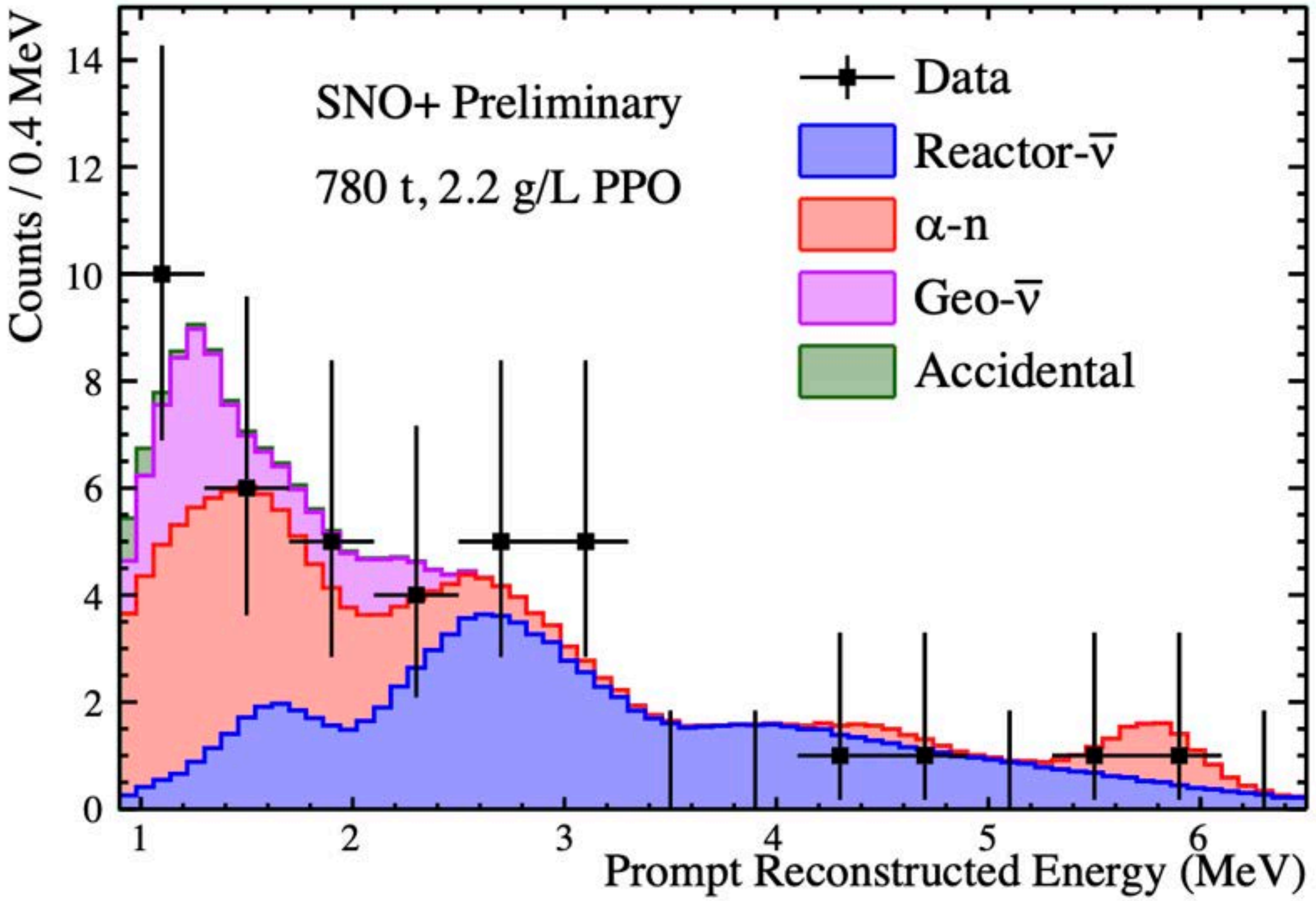
Borexino's model did not include the zero-age igneous rocks.
→ Low NFL → High mantle

Insights from geoneutrino experiments strongly depend on crustal models, especially near Lithosphere models, around the detectors.

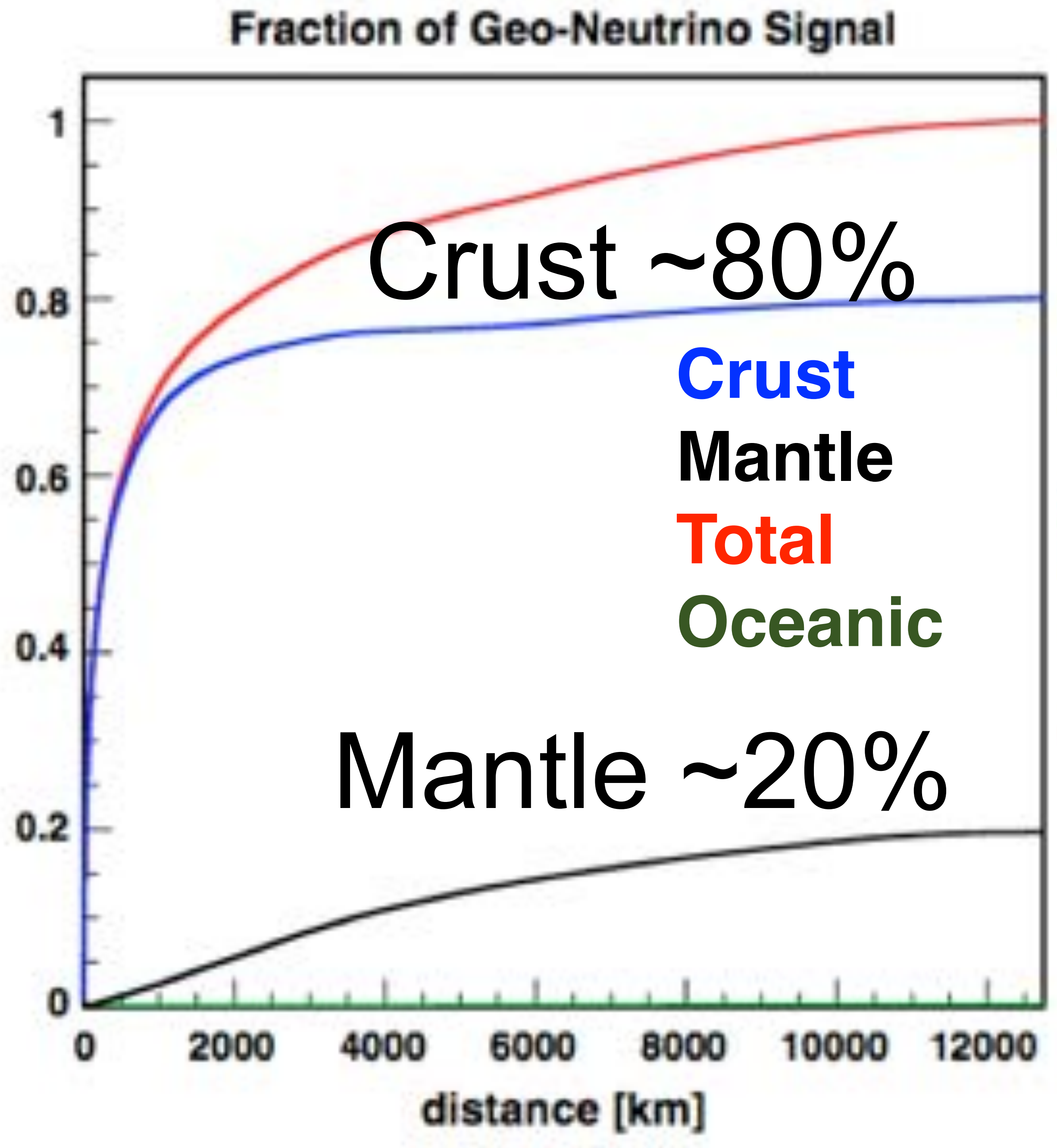
Measured anti-neutrino spectrum

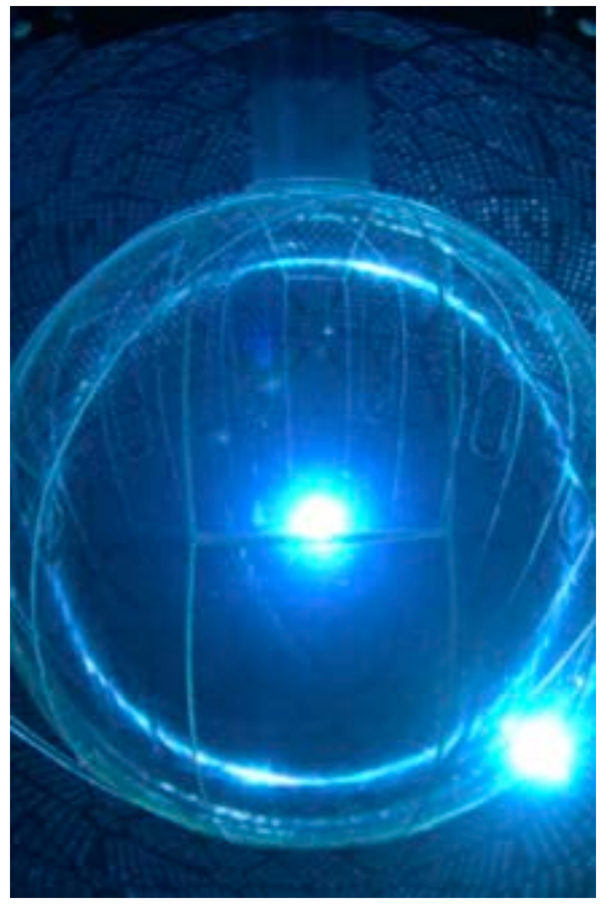
Information from I. Semenec and M. Chen

from Ana Sofia Inácio's slides presented at NeuTel2023



Expected event
[TNU]
* Crust 55.3±5.1
* Mantle
  LowQ 2.6±1.6
  MidQ 8.4±2.8
  HighQ 17.8±2.6

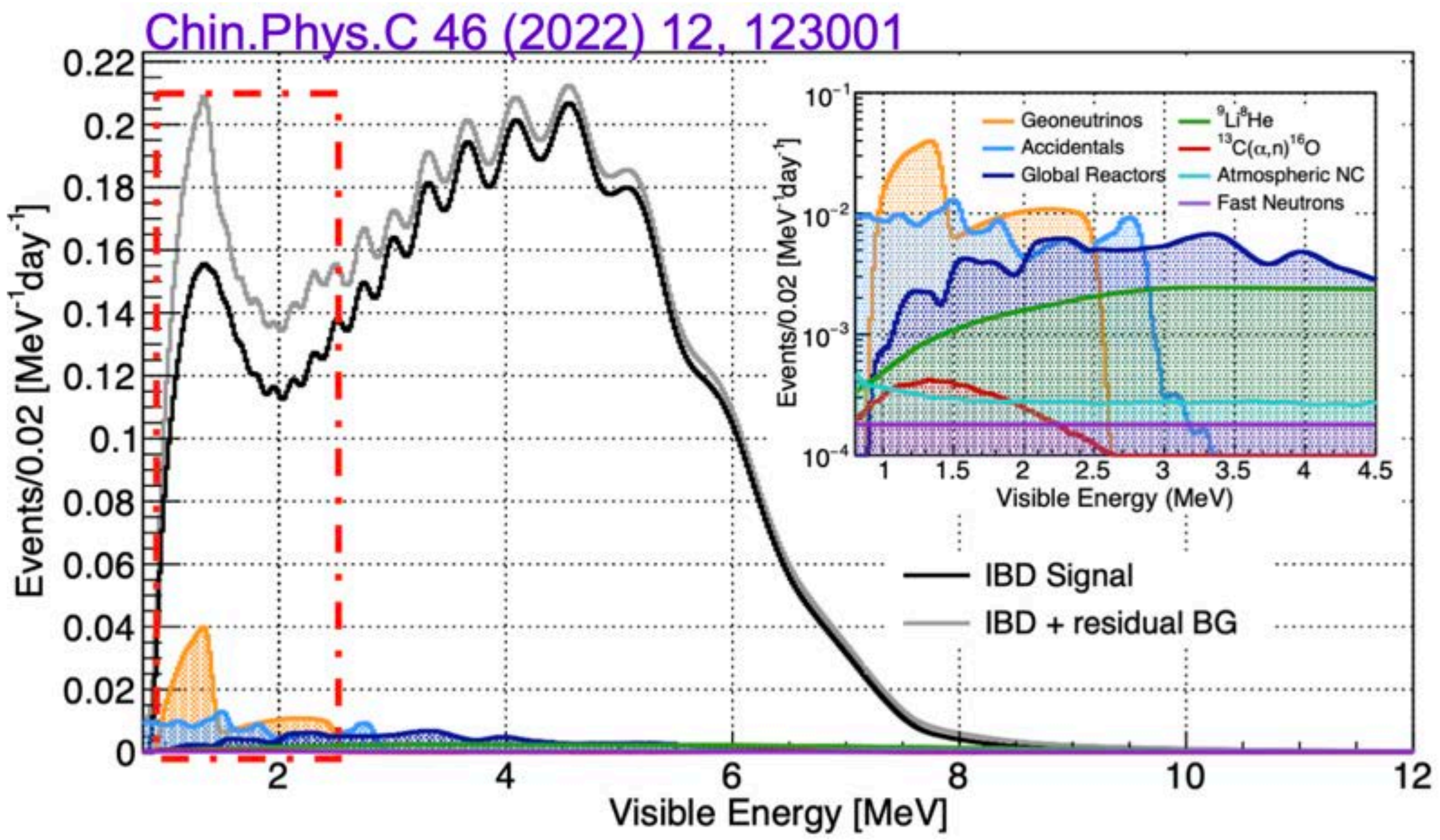




* Scintillator was filled [PPO 0.6g/L(April-July 2021), 2.2g/L (April 2022-March 2023)]
* Te will be added in 2024 for 0νββ measurement.
* <u>Geo-neutrino measurement was started, and will continue after Te addition</u>
* Local geology around SNO+ site is well studies. Very old crust area.

First measurement in North America

Expected spectrum

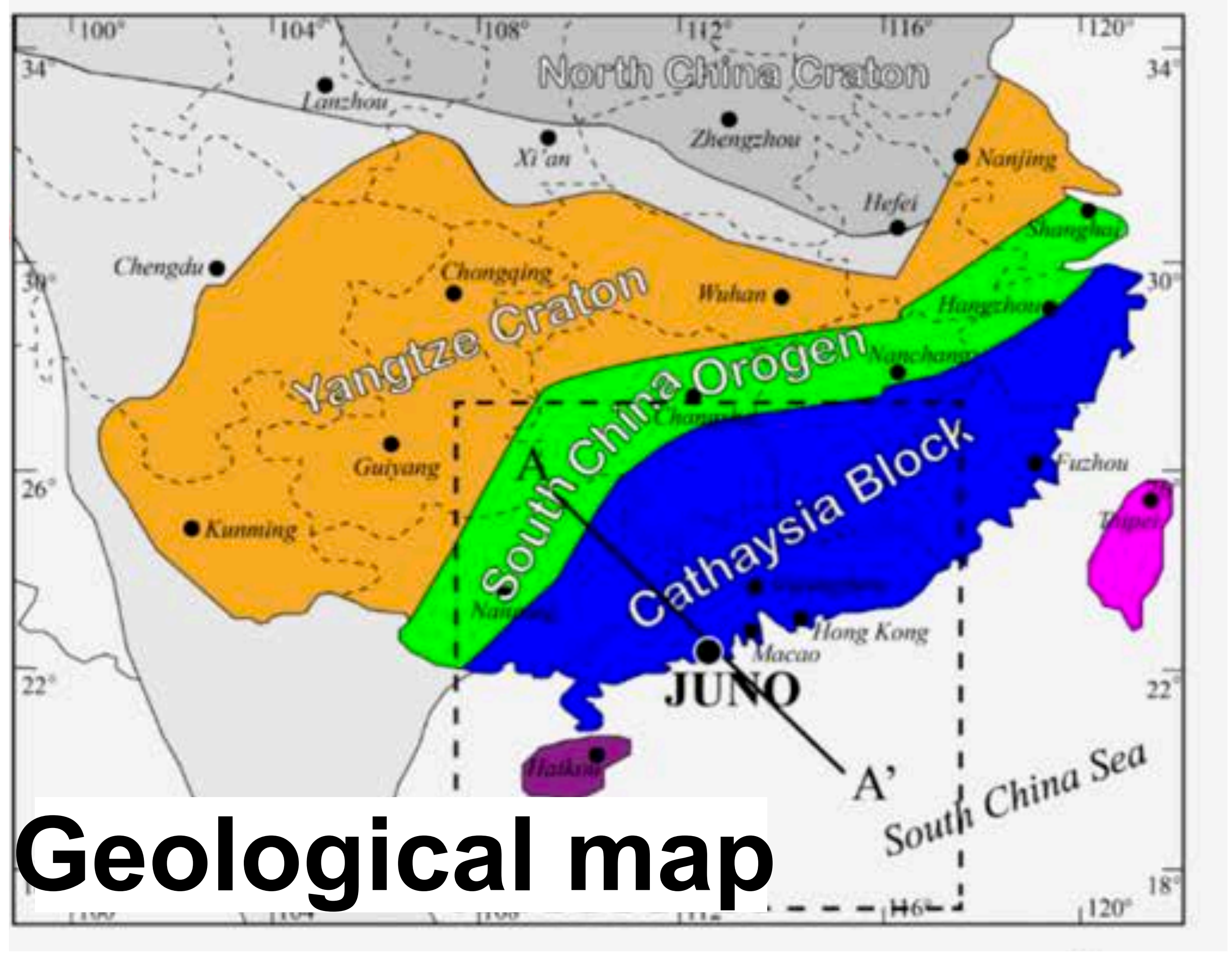


Expected event
38.7 TNU (408 events/year)

Backgrounds	Event rate/year
reactor	16100
^{9}Li-^{8}He	20
fast neutrons	100
$^{13}C(\alpha,n)^{16}O$	50
accidental events	401

Han, Li, et, al. CPC 2016

Information from J. Cao



Challenges

* Reactor neutrino background
* Refined local crustal model

Motivations

* Distinguish U/Th signals, obtain ratio
* Extract mantle component
* 2024~ data taking

➢Sensitivity: ~22% (1 year), ~8% (10 years)

Large statistics

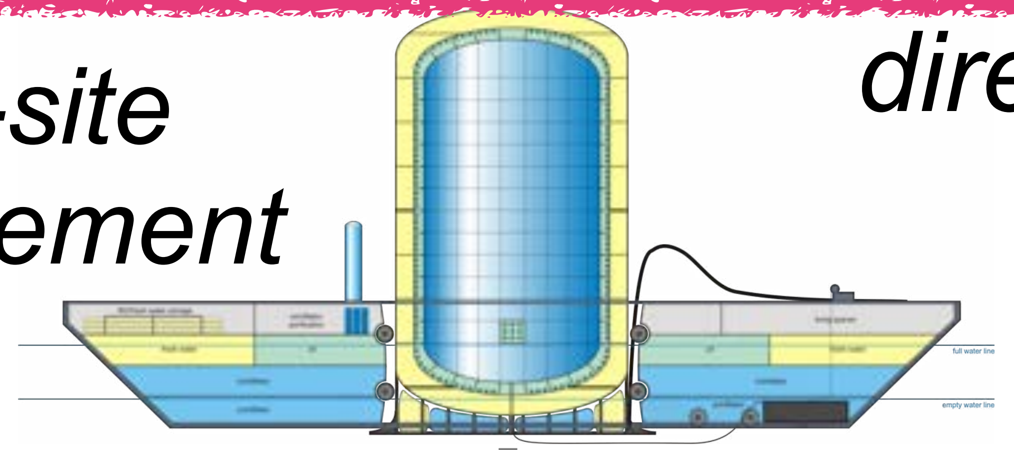
Contents

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

Multi-site Measurement + OBD

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

(y = x + b)

Near Future…

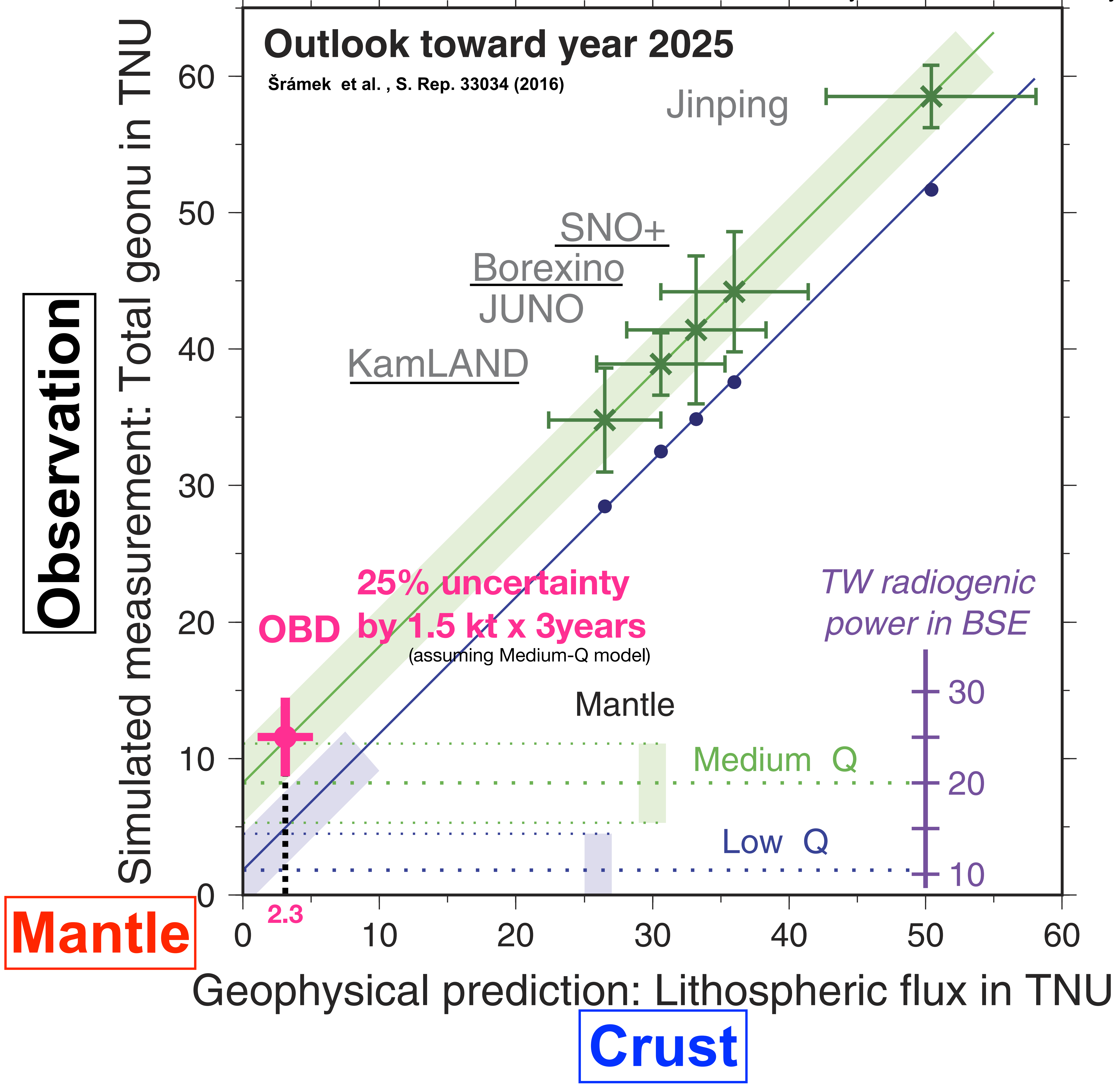
3 multi-site measurements can constrain mantle contribution.

Crust estimation needs to be accurate.

+ OBD

OBD can directly measure mantle contribution.

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



OBD Motivations

- **Direct Measurement of Mantle**

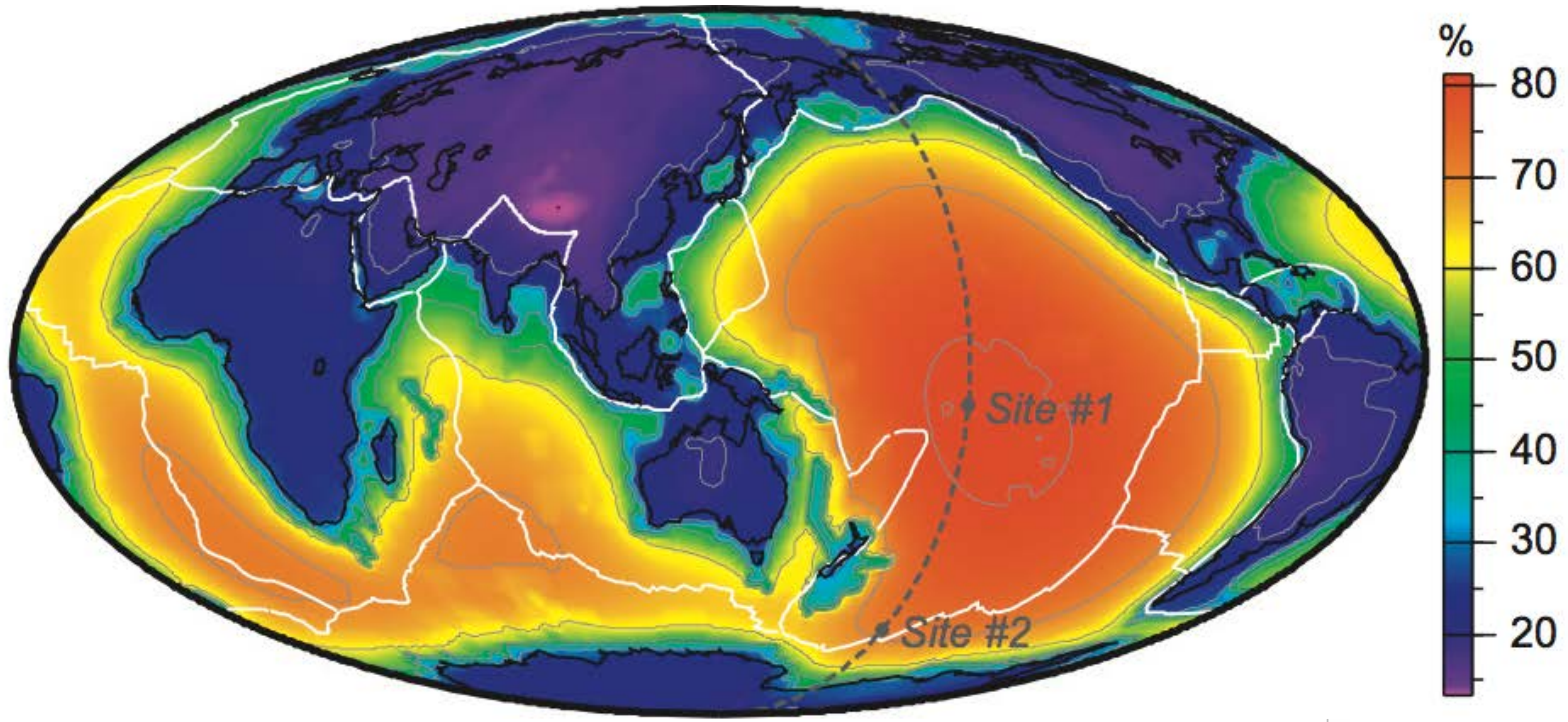
need to be far from crust
can be far from reactors

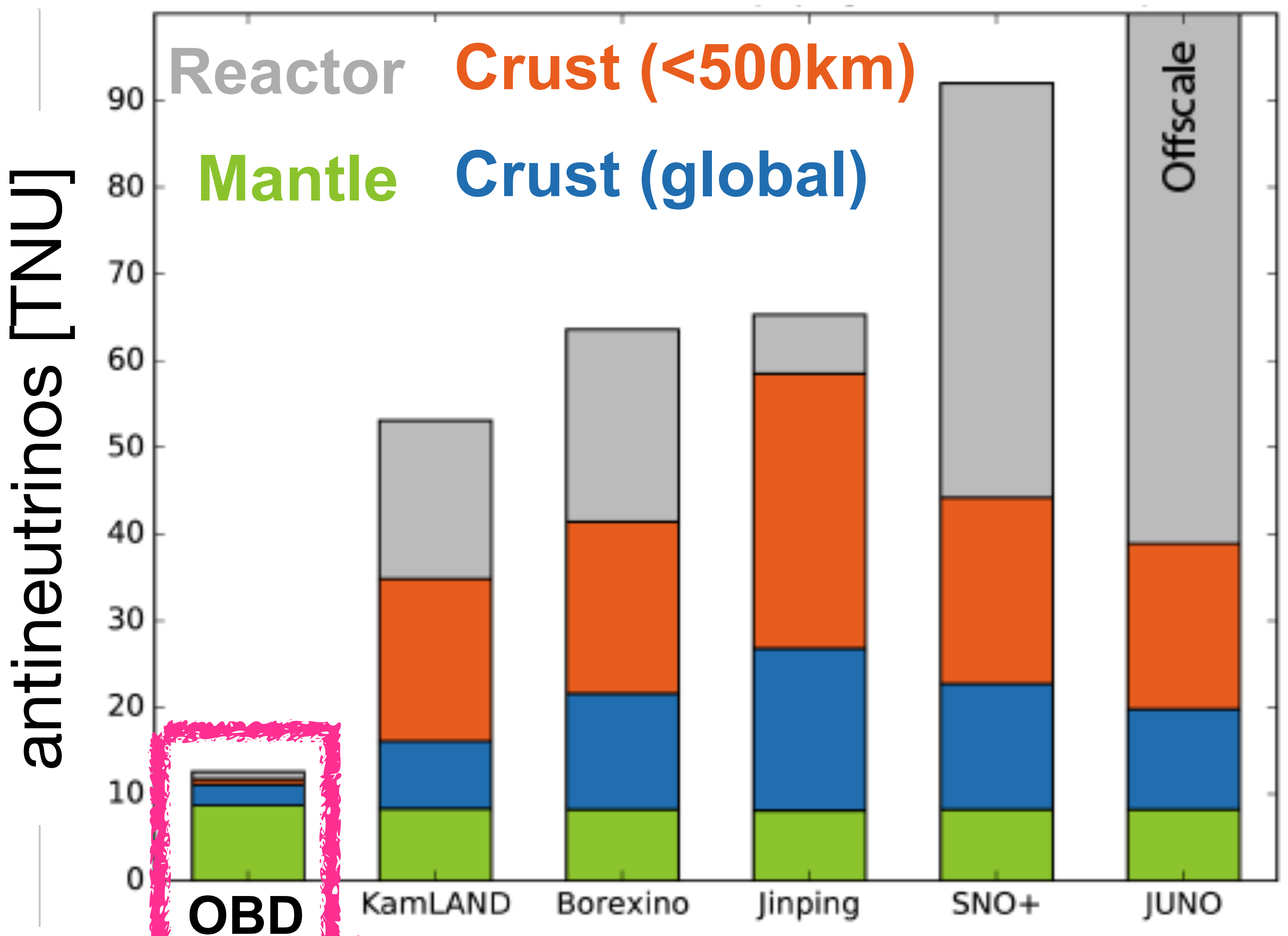
- **Multi-site Measurements**

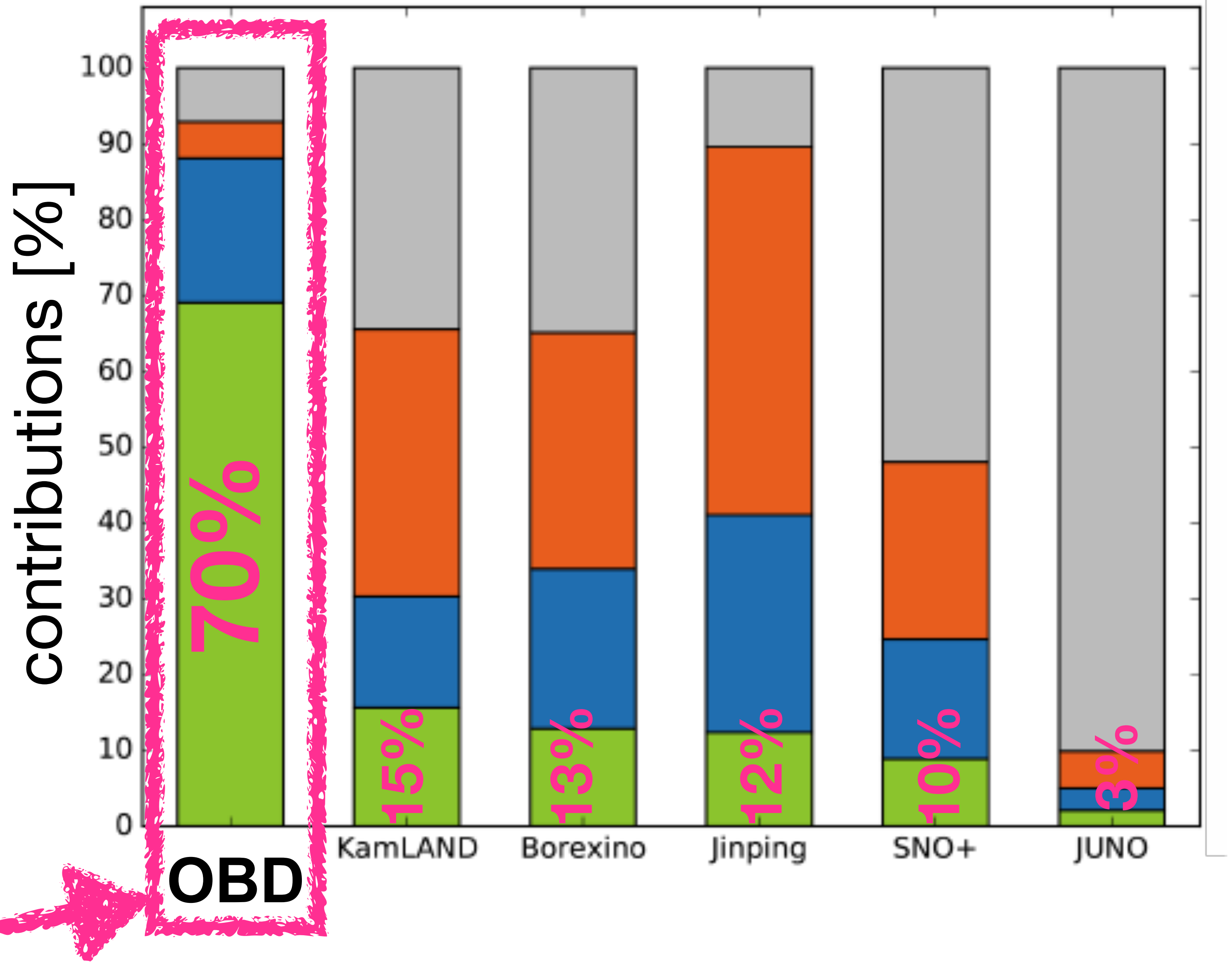
Solve the mystery of deep Earth!
First detector for mapping the inhomogeneous mantle

- **Multidisciplinary Detector**

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







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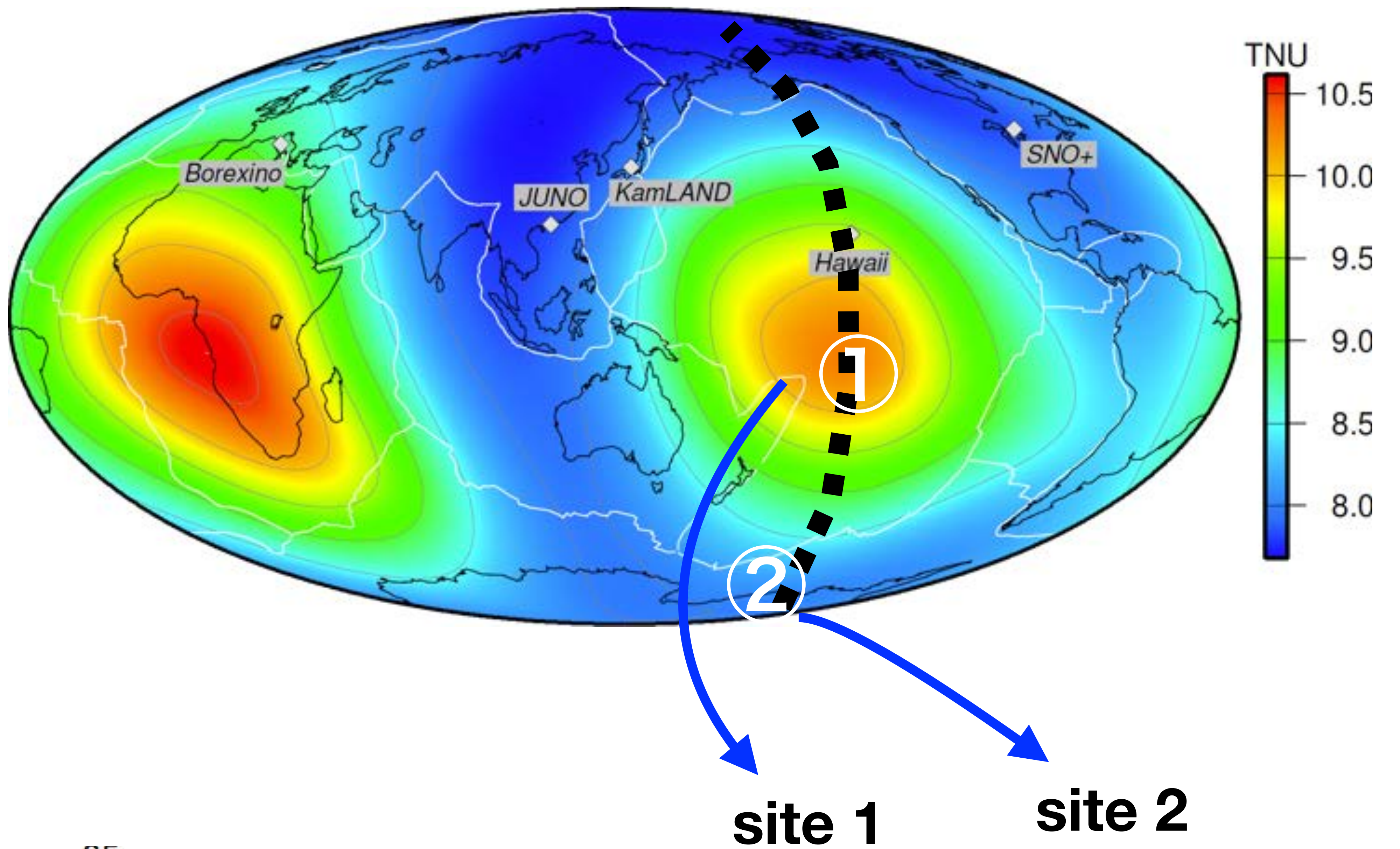
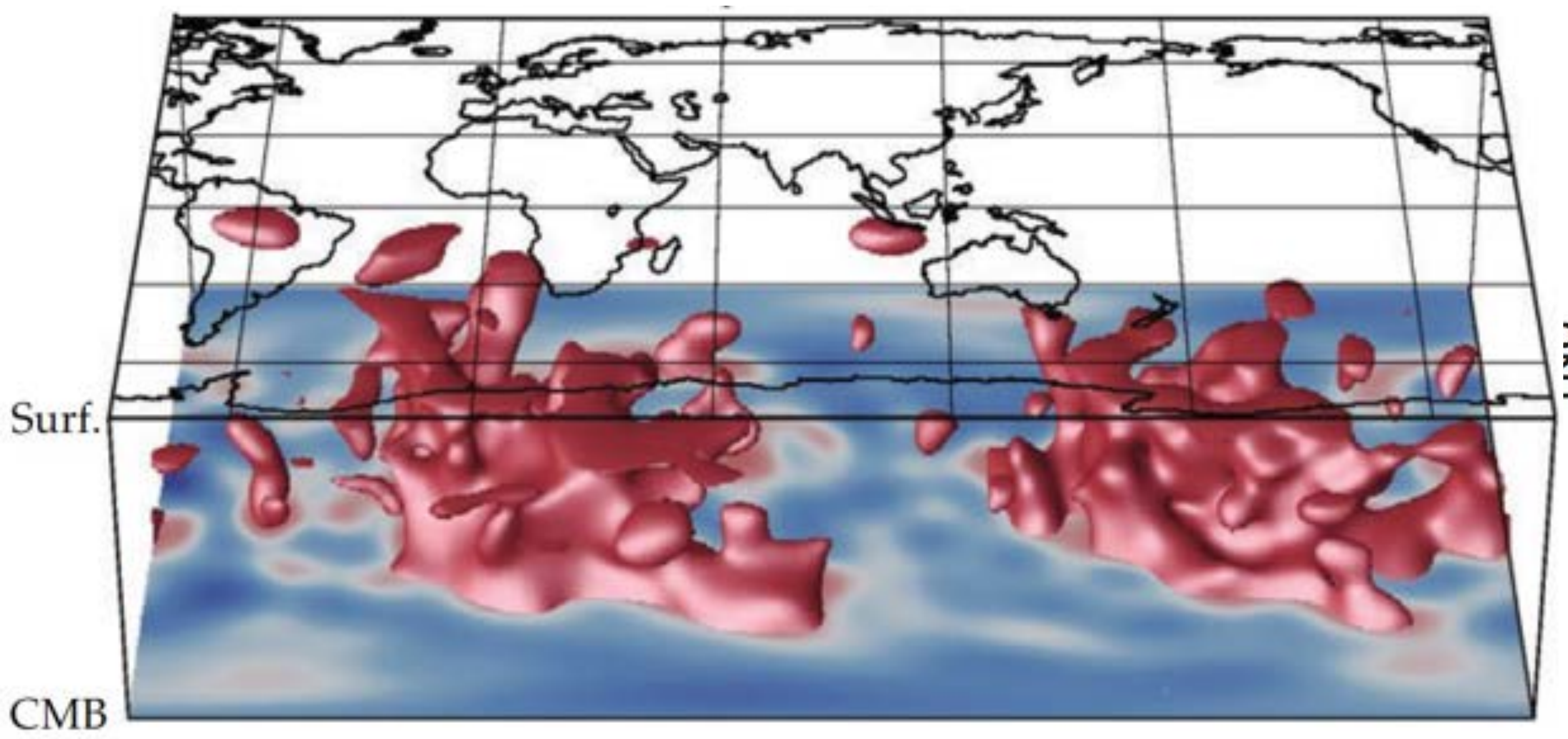
Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001

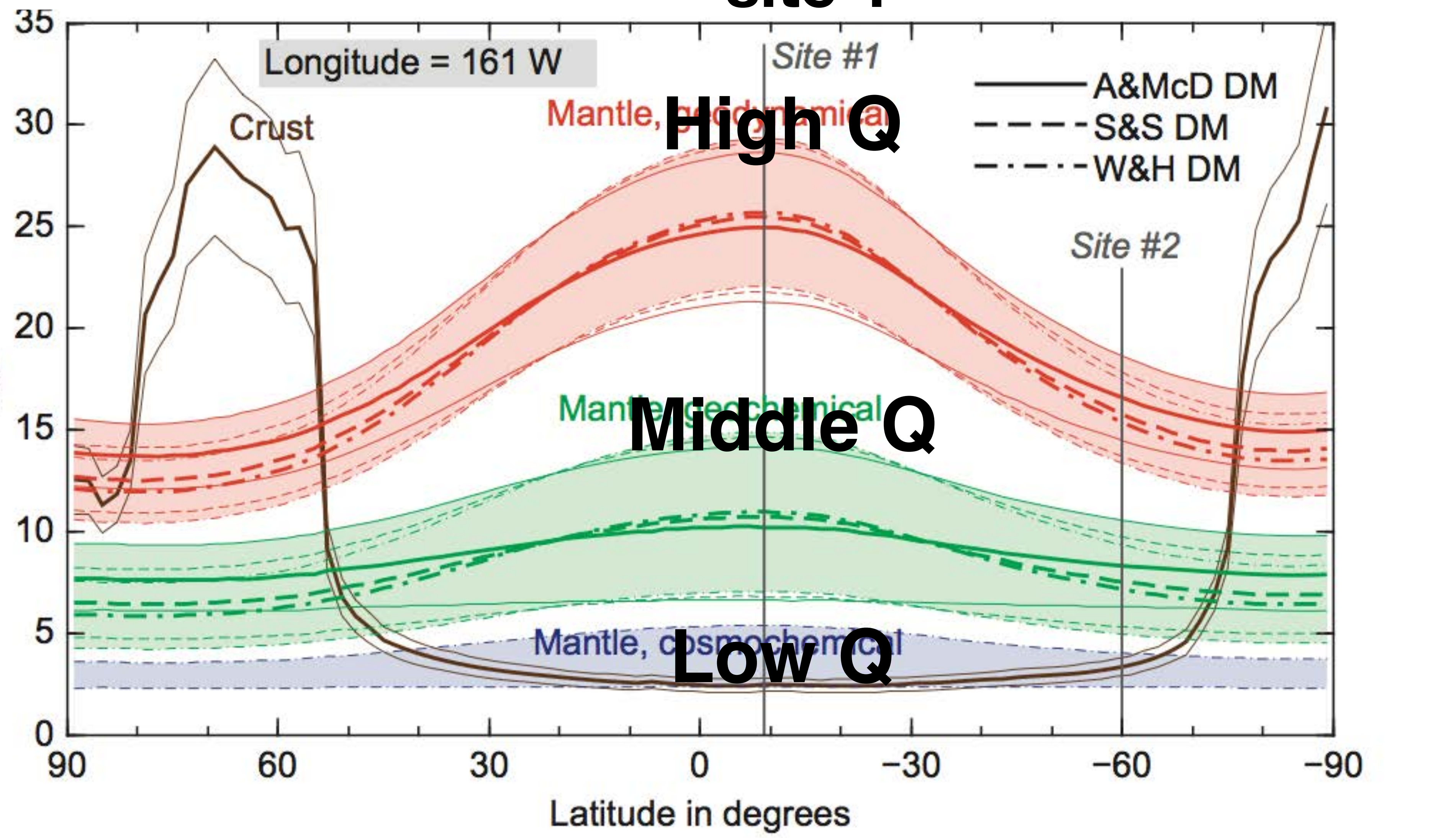
Mantle Geoneutrino Flux



Seismically slow "red" regions in the deep mantle



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



OBD Motivations

- **Direct Measurement of Mantle**

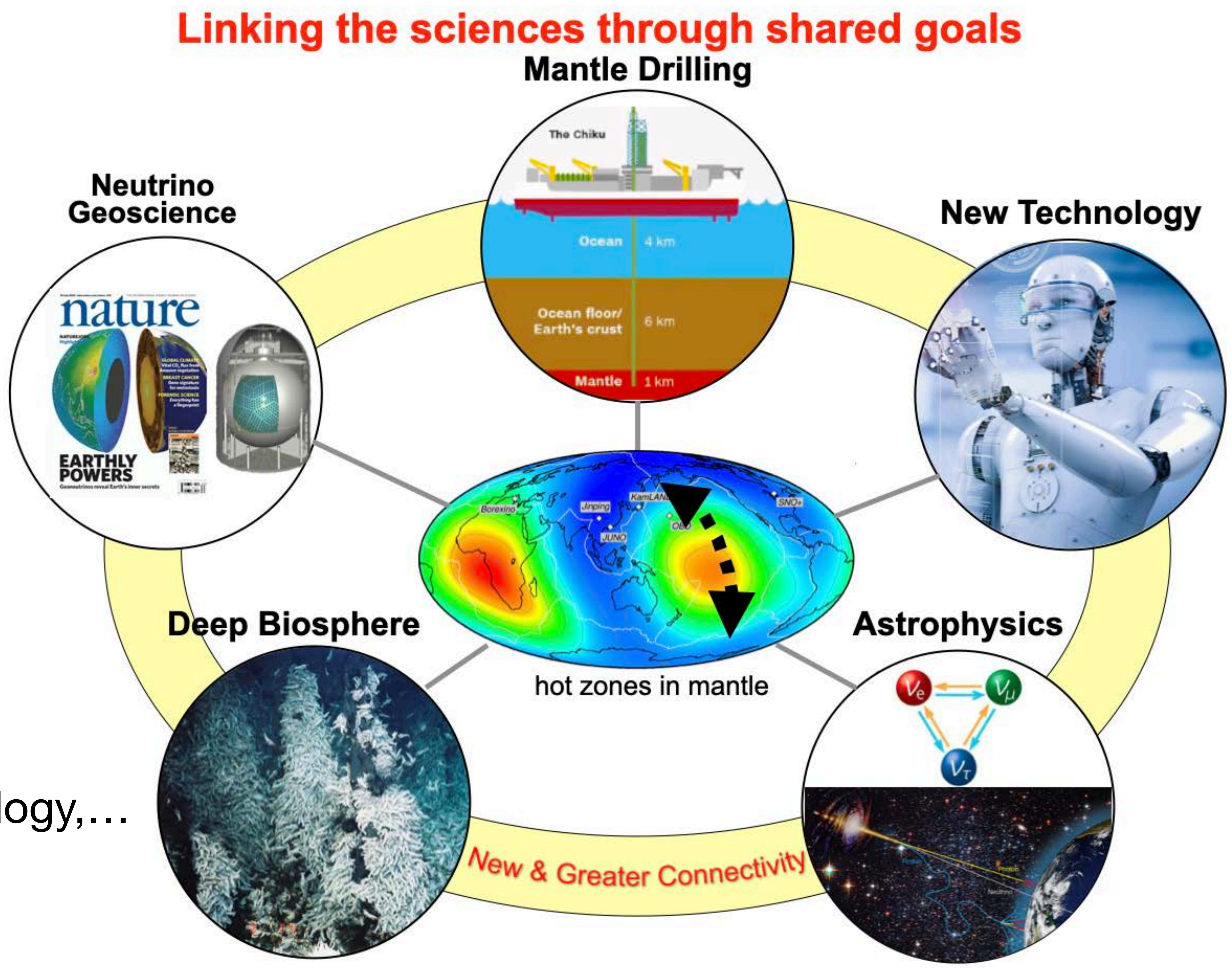
need to be far from crust
can be far from reactors

- **Multi-site Measurements**

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

- **Multidisciplinary Detector**

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



Contents

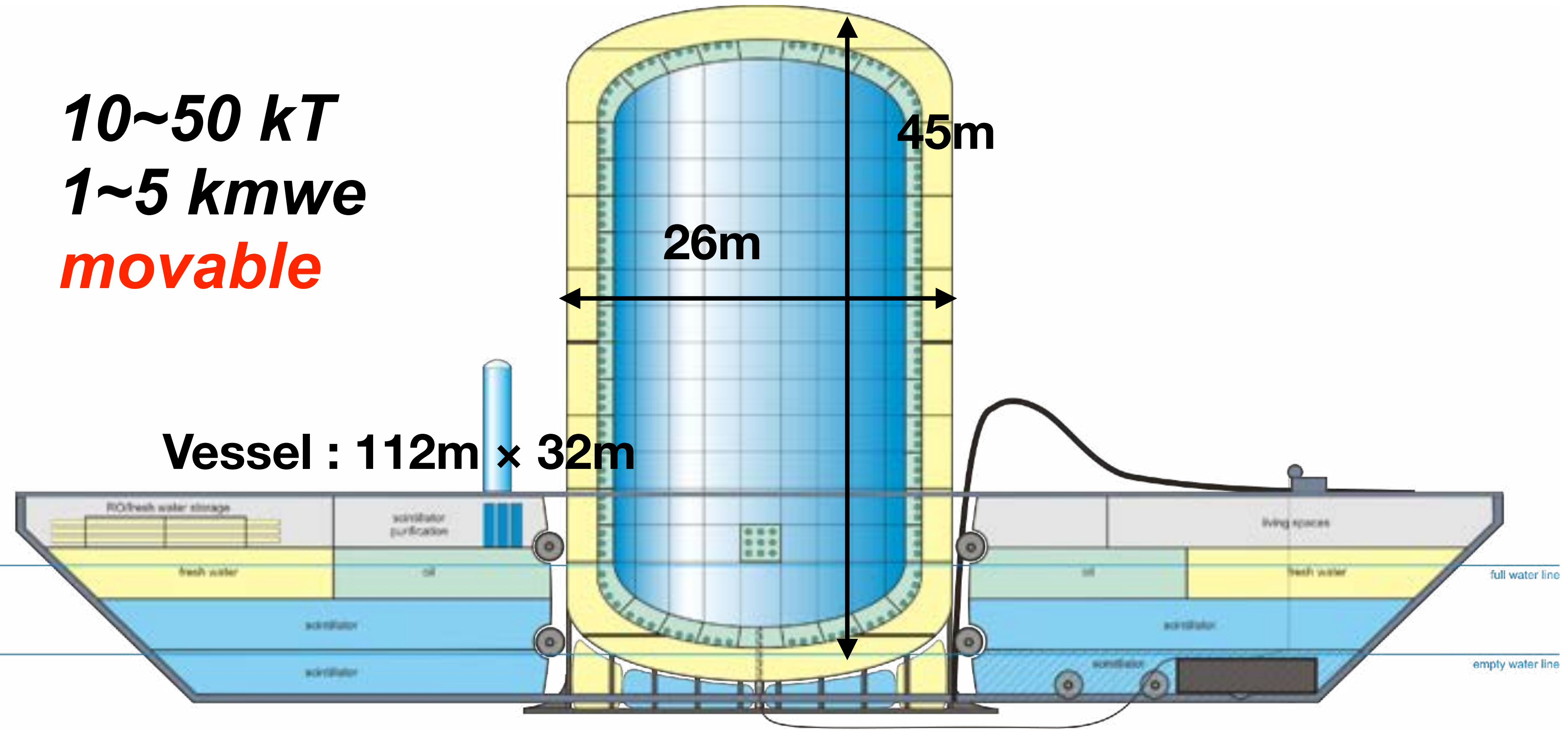
OBD Present & Future

2005 No progress… **2019** we are here **2020-2024** funded

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

"Hanohano" 2005

10~50 kT
1~5 kmwe
movable



U. Hawaii & Makai Ocean Engineering

Technical tests and detector design

OBD project has started with JAMSTEC* & Tohoku U.!

* Japan Agency for Marine-Earth Science and Technology

OBD Present & Future

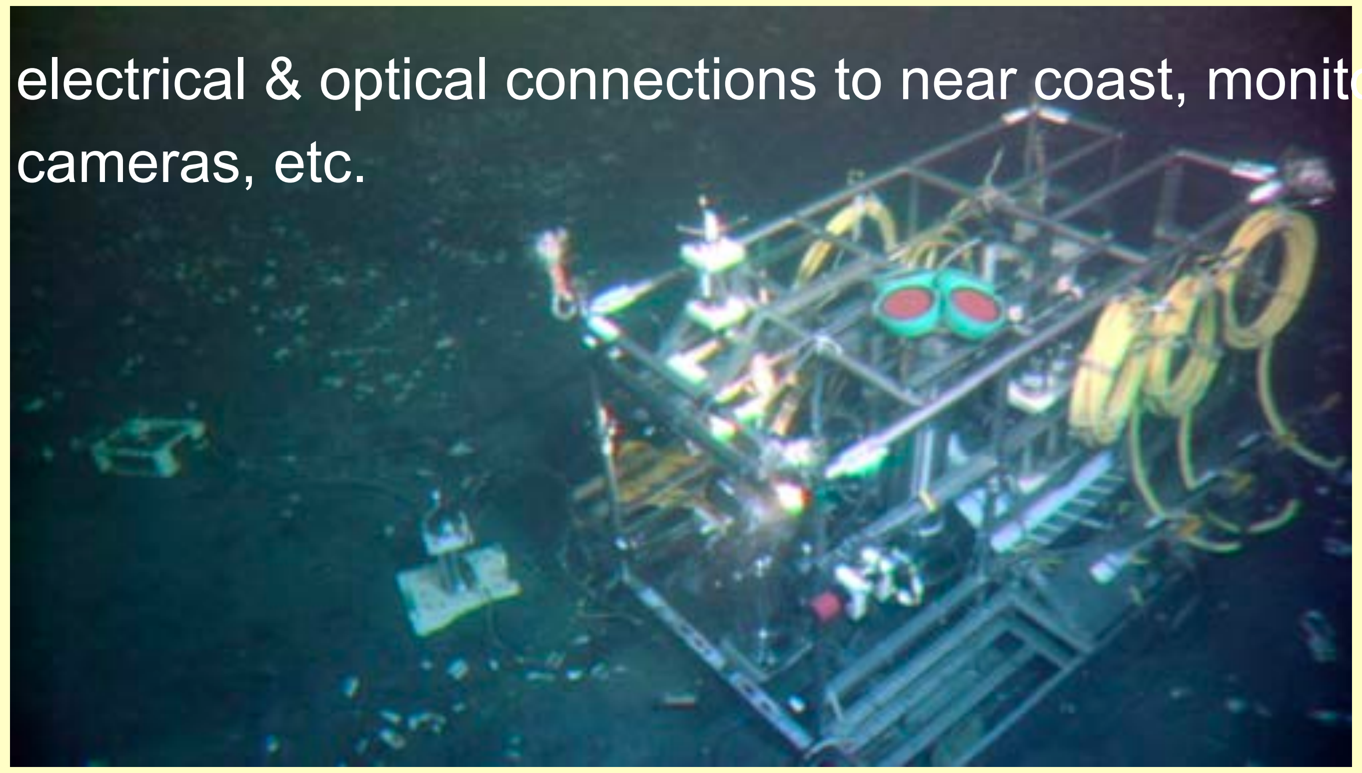
2005 No progress… 2019 we are here 2020-2024 funded

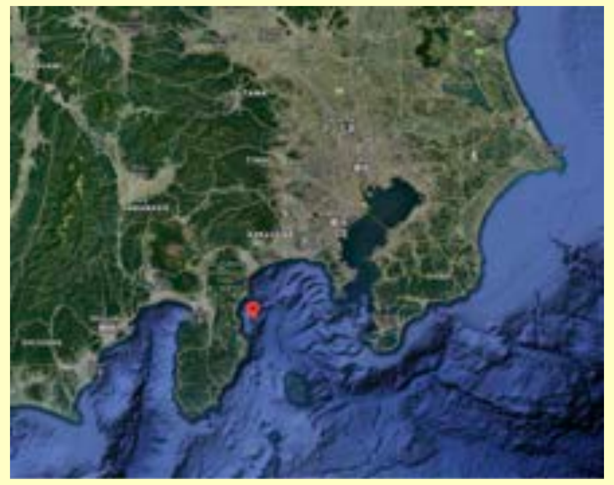
~20 kg → 1-10 t → ~1.5 kt → 10-50 kt

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

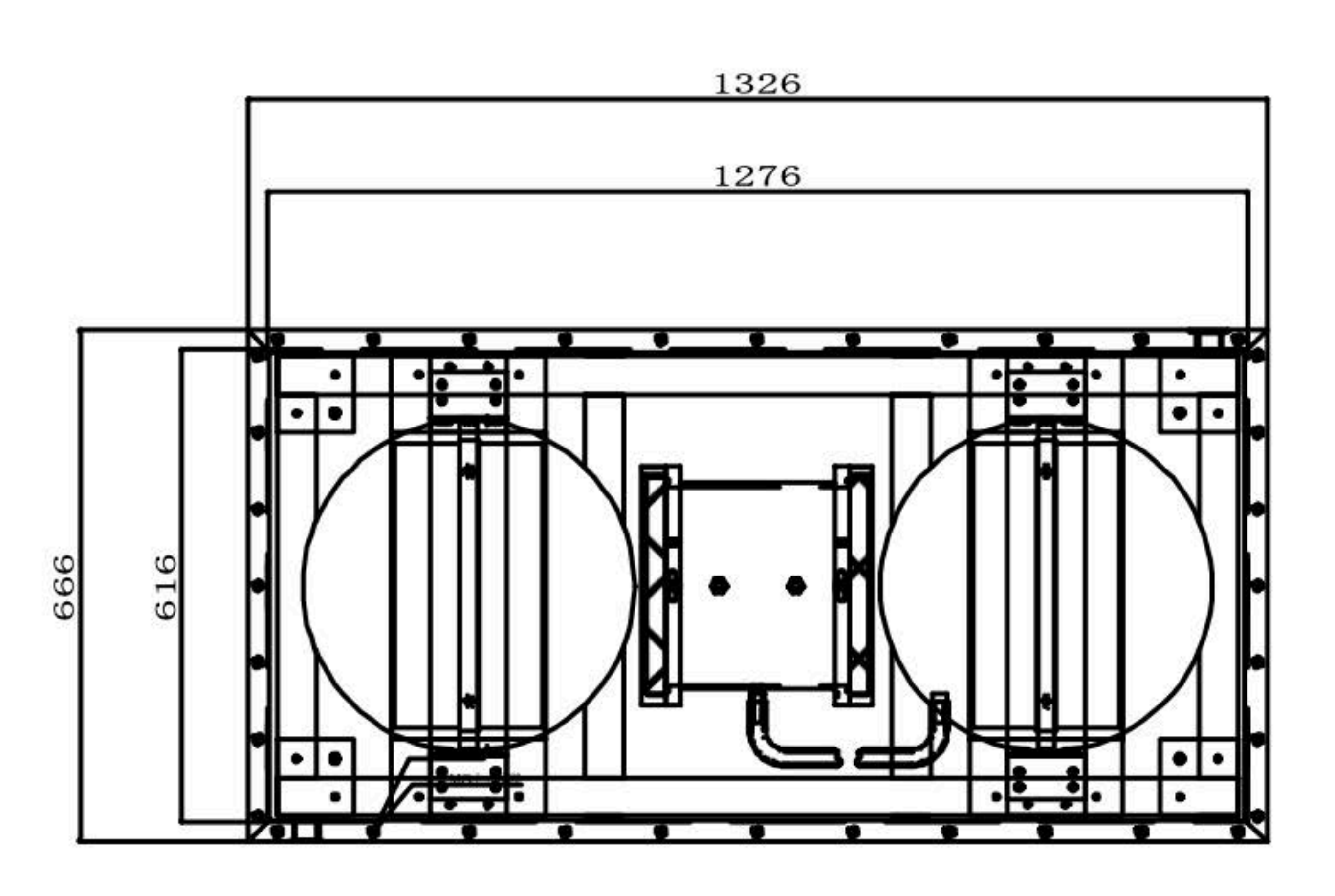
* Install detector into **~1km seafloor** (JAMSTEC's Hatsushima Observatory), take data for **several months**
* **measure muon late in the sea → input parameter for future large detector**
* Technical developments are in progress.

Hatsushima Observatory





detector design



OBD Present & Future

2005 No progress… 2019 we are here 2020-2024 funded

~20 kg → 1-10 t → ~1.5 kt → 10-50 kt

Maturity of science

Technical demonstration & environment measurement in the sea

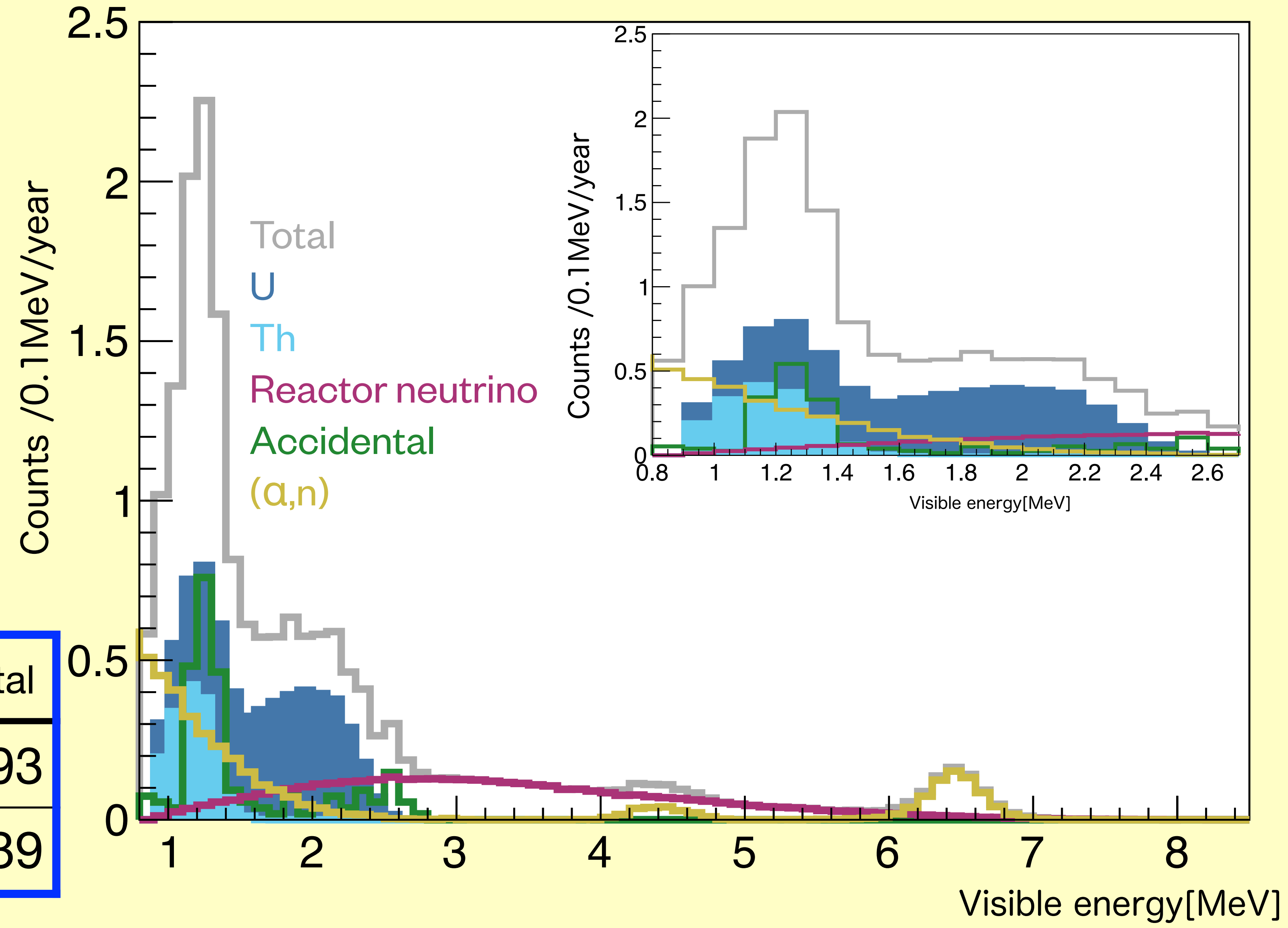
deep sea neutrino & muon flux, ocean water density & temperature, radioactivity
→ input parameters for ~1.5 kt detector design

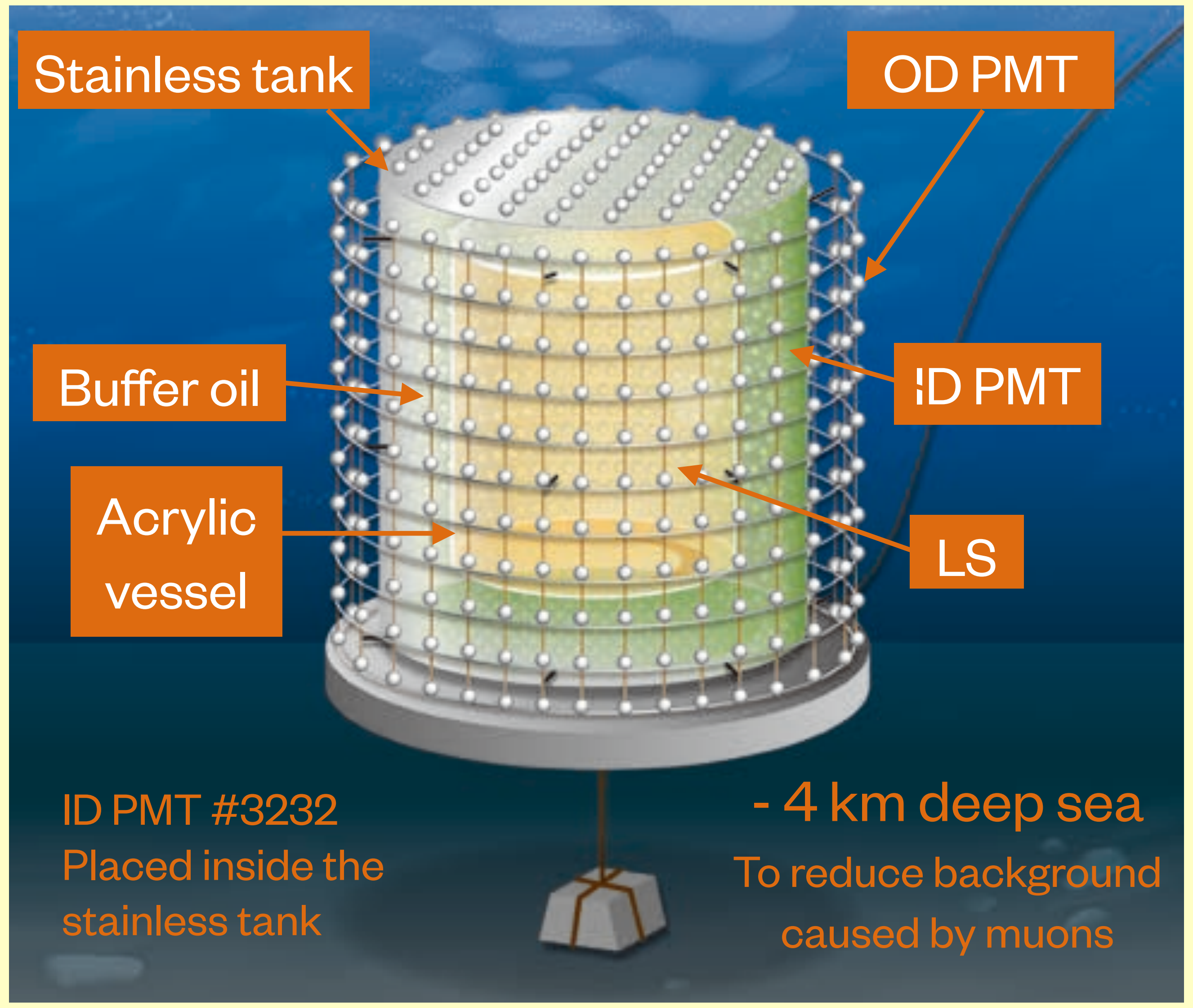
First clear mantle signal

* 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	Signal U	Signal Th	Signal Total	Backgrounds Reactor	Acci.	(α,n)	He-Li	Fast-neutron	Total
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

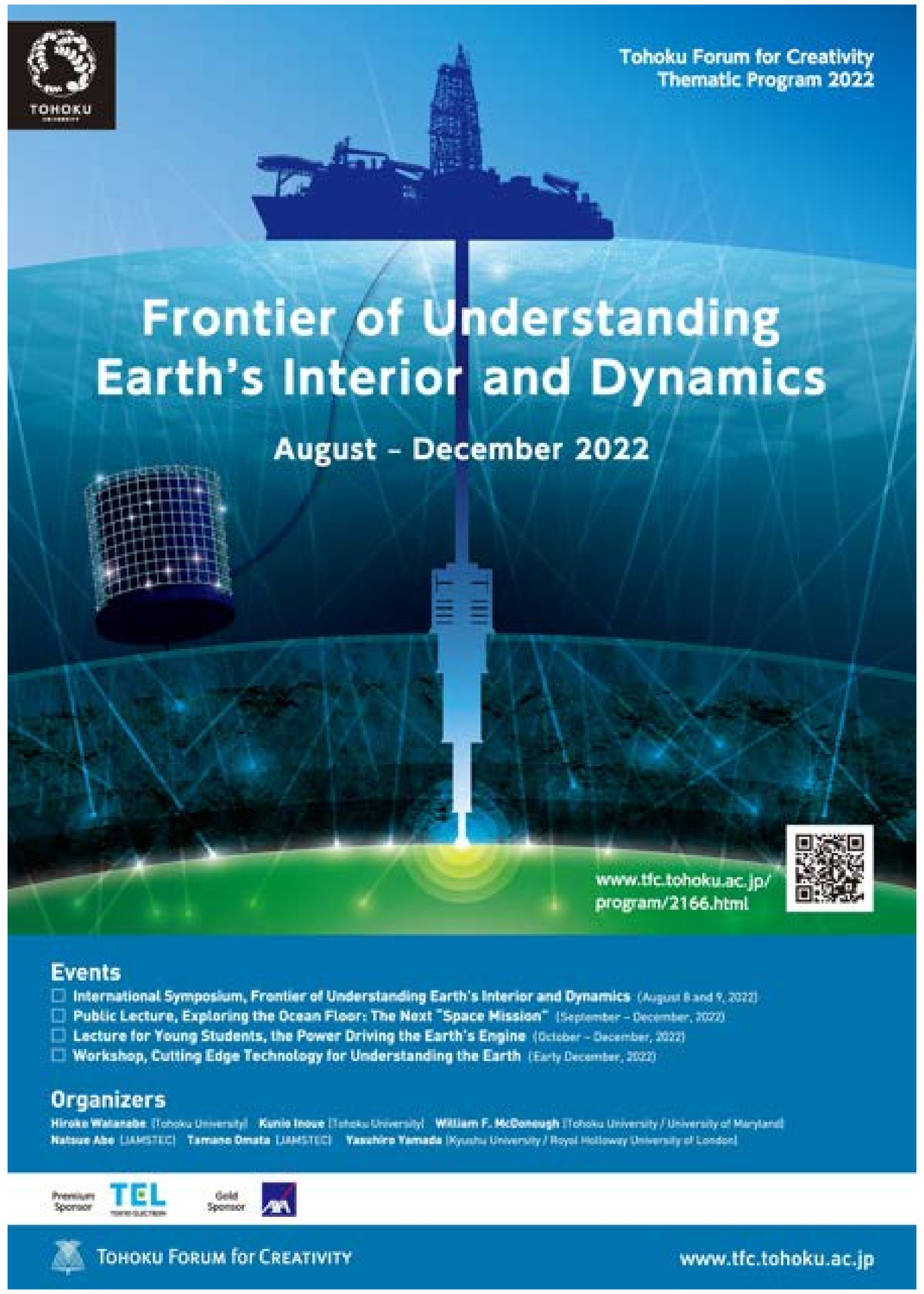
OBD Present & Future

2005 — No progress… — 2019 — we are here — 2020-2024 (funded)

~20 kg → 1-10 t → ~1.5 kt → 10-50 kt

Community Building Status

Thematic Program 2022



international symposiums

outreach @Astronomical Observatory

In total
~60 participants
from different
countries during
the program.

Corporative study with U. Hawaii

* discussing the plan for prototype detector deployment in the ocean around Hawaii island
* long-term stay at U. Hawaii for international/ interdisciplinary community building (Nov-Dec 2023)

未来の学術振興構想2023 (日本学術会議)

⑫ 観測技術革新による地球システムの理解と地球変動予測への展開

No.	学術の中長期研究戦略の名称	提案者
65	地球型惑星のデジタルツイン（再掲）	佐藤　薫（公益社団法人日本気象学会理事長・東京大学大学院理学系研究科教授、日本学術会議連携会員）
97	地球惑星科学・諸科学・社会とのミュオグラフィ連携研究基盤構築	田中　宏幸（東京大学国際ミュオグラフィ連携研究機構機構長）
98	太陽地球系結合過程の研究基盤形成	山本　衛（京都大学生存圏研究所所長・教授）
⋮		
105	深海アルゴフロートの全球展開による気候・生態系変動予測の高精度化	神田　穣太（日本海洋学会会長）
106	地球ニュートリノ観測が切り拓く新しい地球未来像	渡辺　寛子（東北大学・ニュートリノ科学研究センター助教）
107	衛星全球地球観測による気候・地球システム科学研究の推進	若林　裕之（日本リモートセンシング学会会長）

Status of Technical Developments

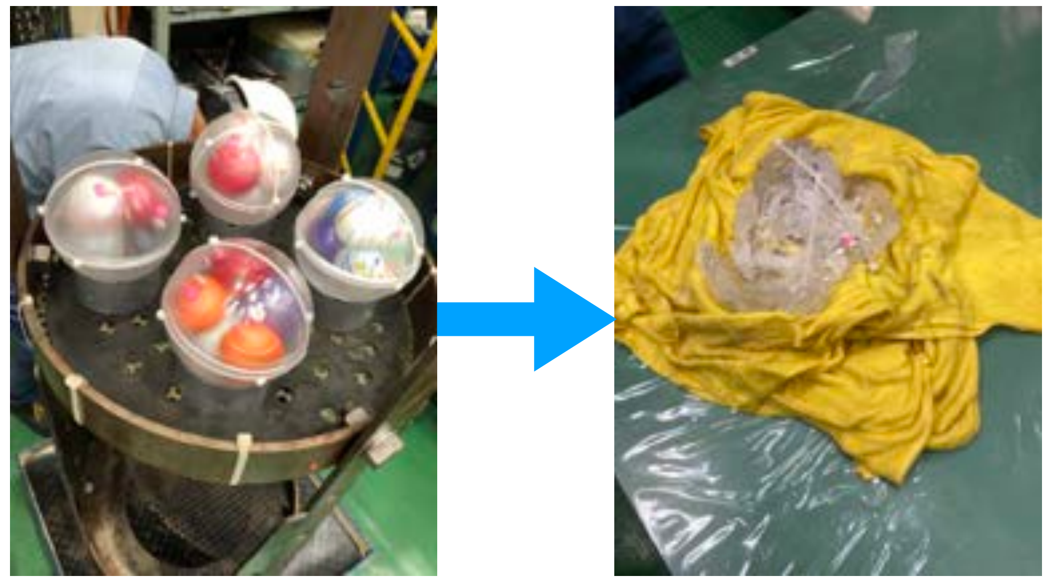
✦PMT shield

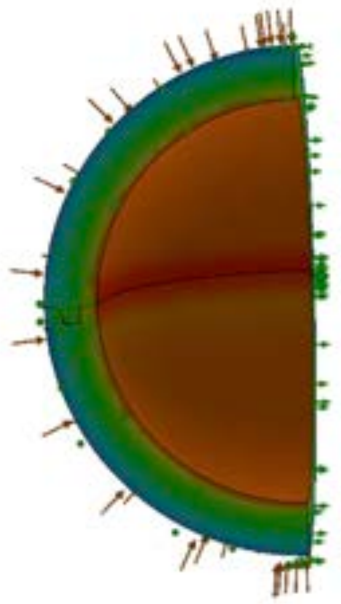
Needs : low background
pressure resistant

IceCube type PMT module is expected

Acrylic

- low background
- pressure resistant : <40MPa broken





can not be used?

Pressure test @JAMSTEC   structural calculation

Glass (OKAMOTO Glass Co.)

- pressure resistant
- very high impurities

[g/g]

	^{238}U	^{232}Th	^{40}K
target	$1x10^{-8}$	$1x10^{-8}$	$1x10^{-8}$
normal glass	$\sim 1x10^{-7}$	$\sim 1x10^{-7}$	$\sim 1x10^{-7}$
our work	$1.4x10^{-8}$	$<5.0x10^{-9}$	$3.4x10^{-9}$
reduction	1/10	1/500	1/300

* cleaner material selection
* Pt coating on the melting pot

enhance the size (20 inch)

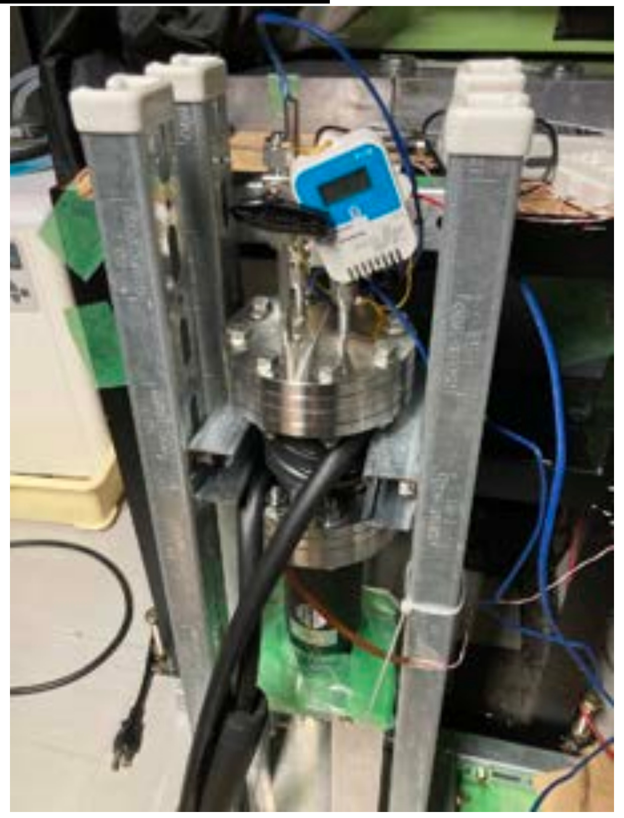
can be used

✦Liquid scintillator

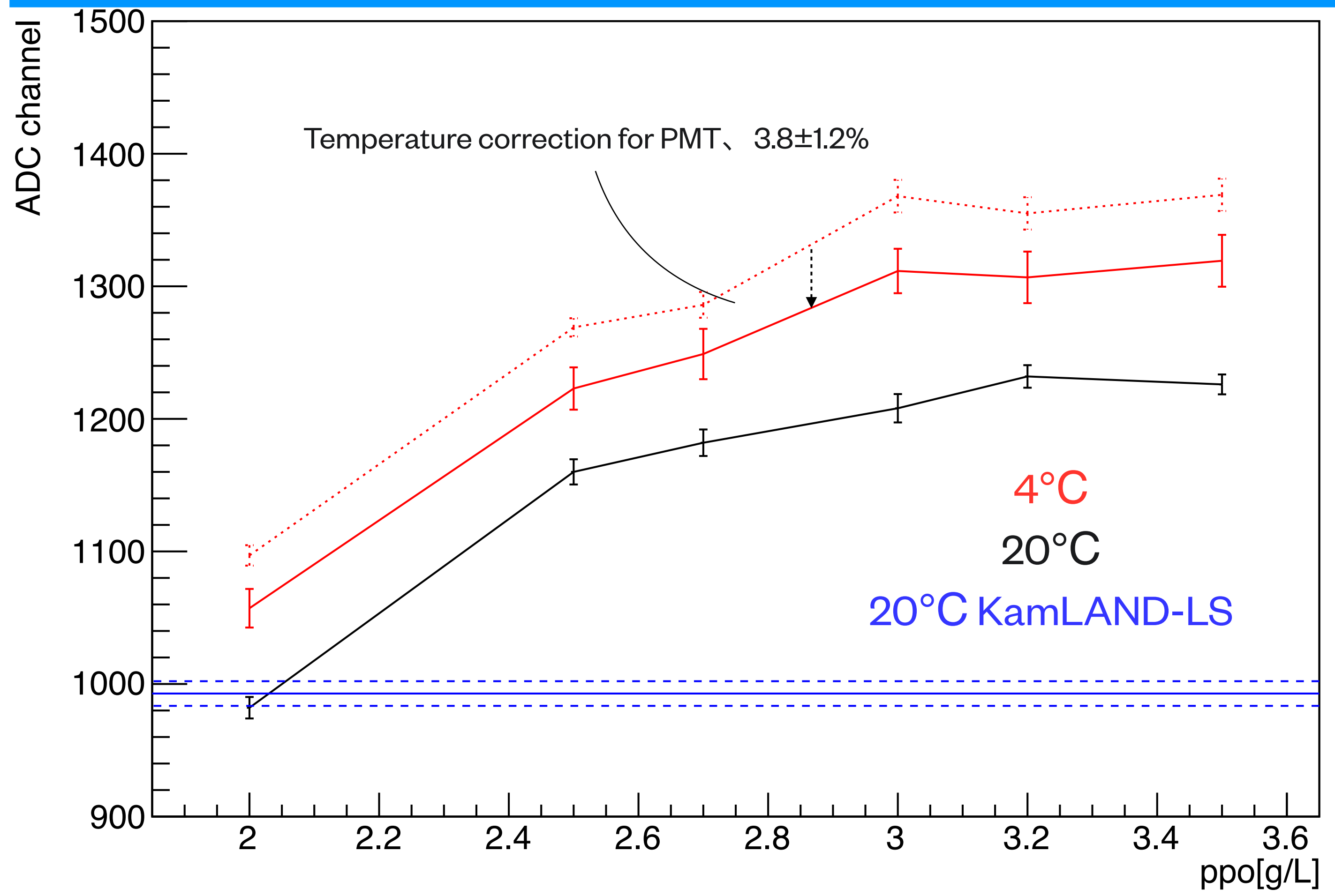
LAB(oil) + PPO(fluorescents)

Low temperature

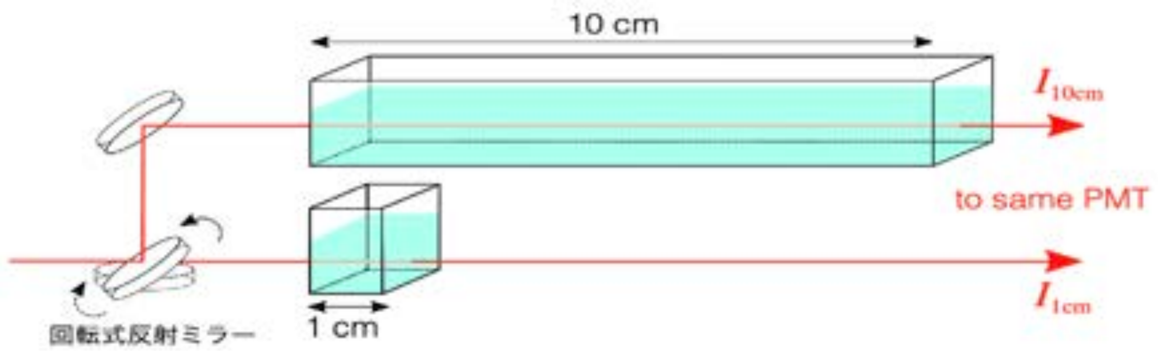
light yield



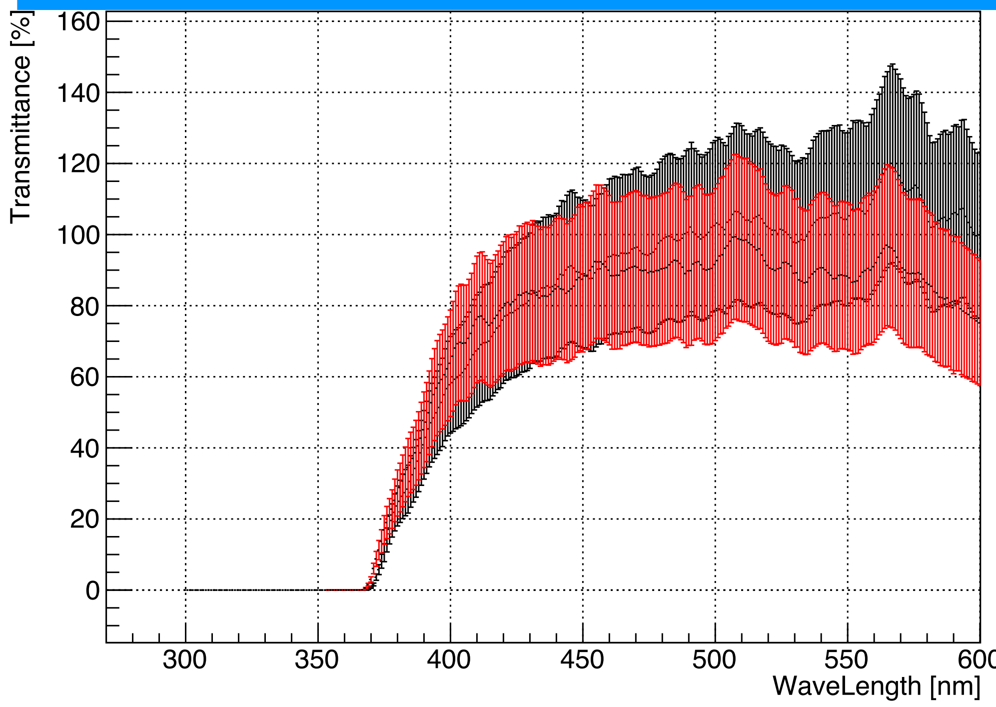
4°C is brighter than 20°C (+9%)



light transition



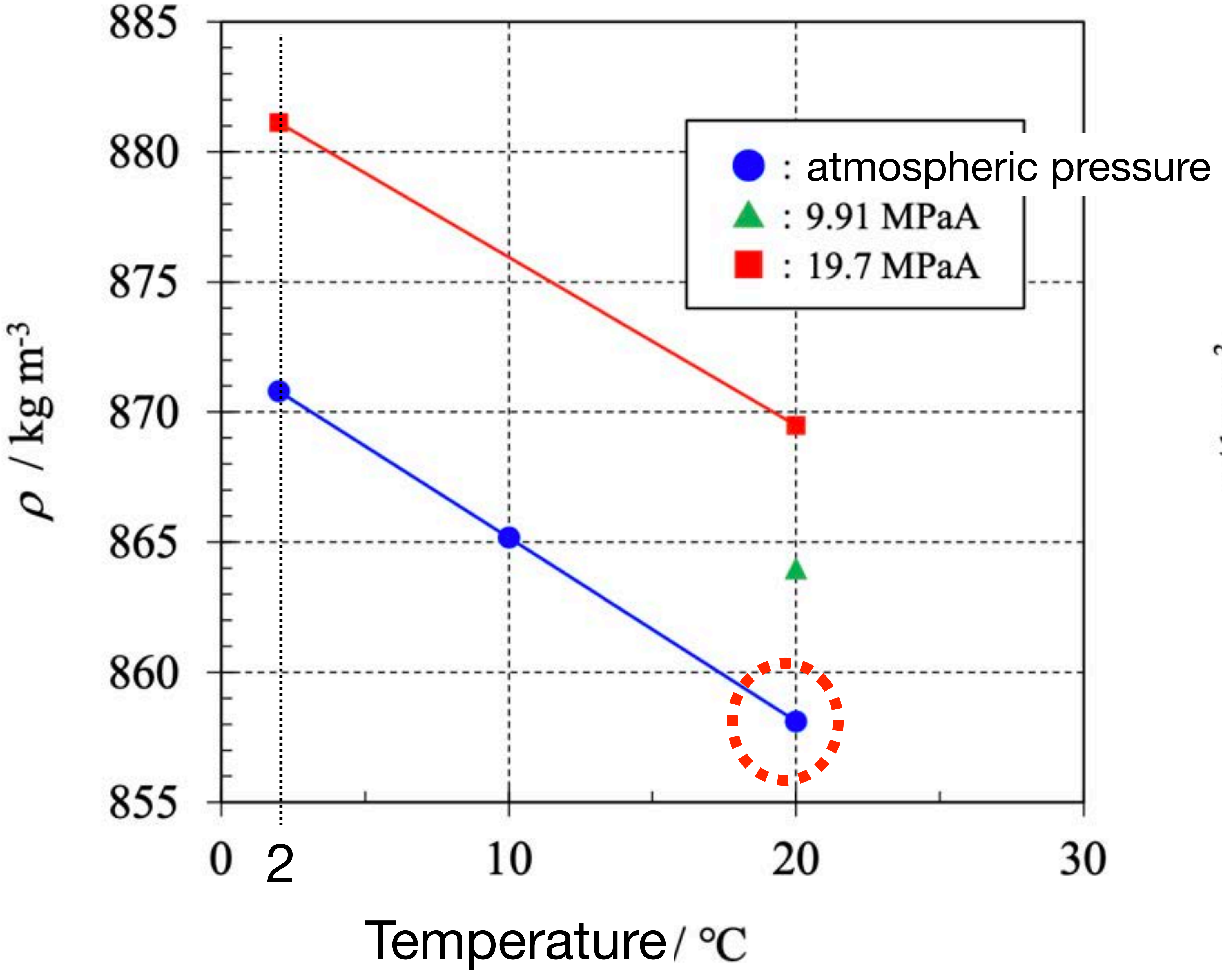
no temperature affect

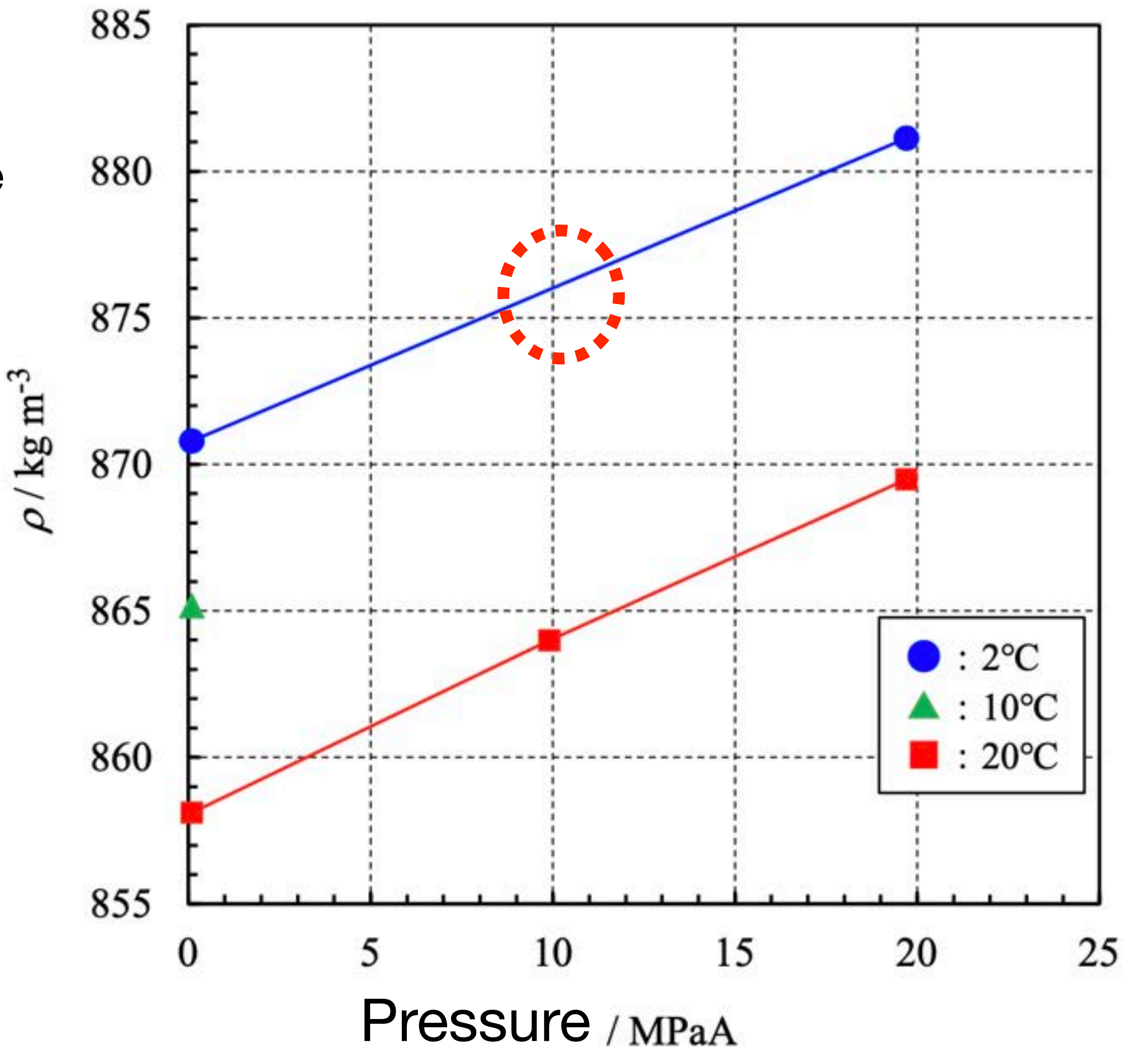


Status of Technical Developments

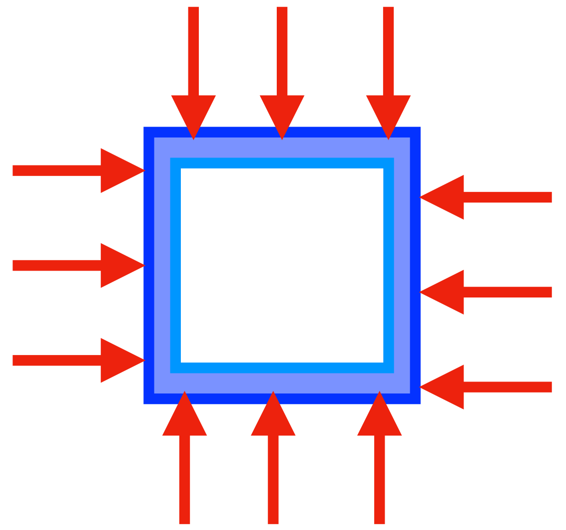
✦Liquid scintillator density under low-temperature & high pressure

Temperature & pressure dependence profiles are available.





uncertainty : 0.05%



20°C, atmospheric pressure : 858.11 kg/m³

2°C, 10 MPa (1km seafloor) : 876.02 kg/m³ (calculated) **+2.1% → 0.63 L for 30L LS**

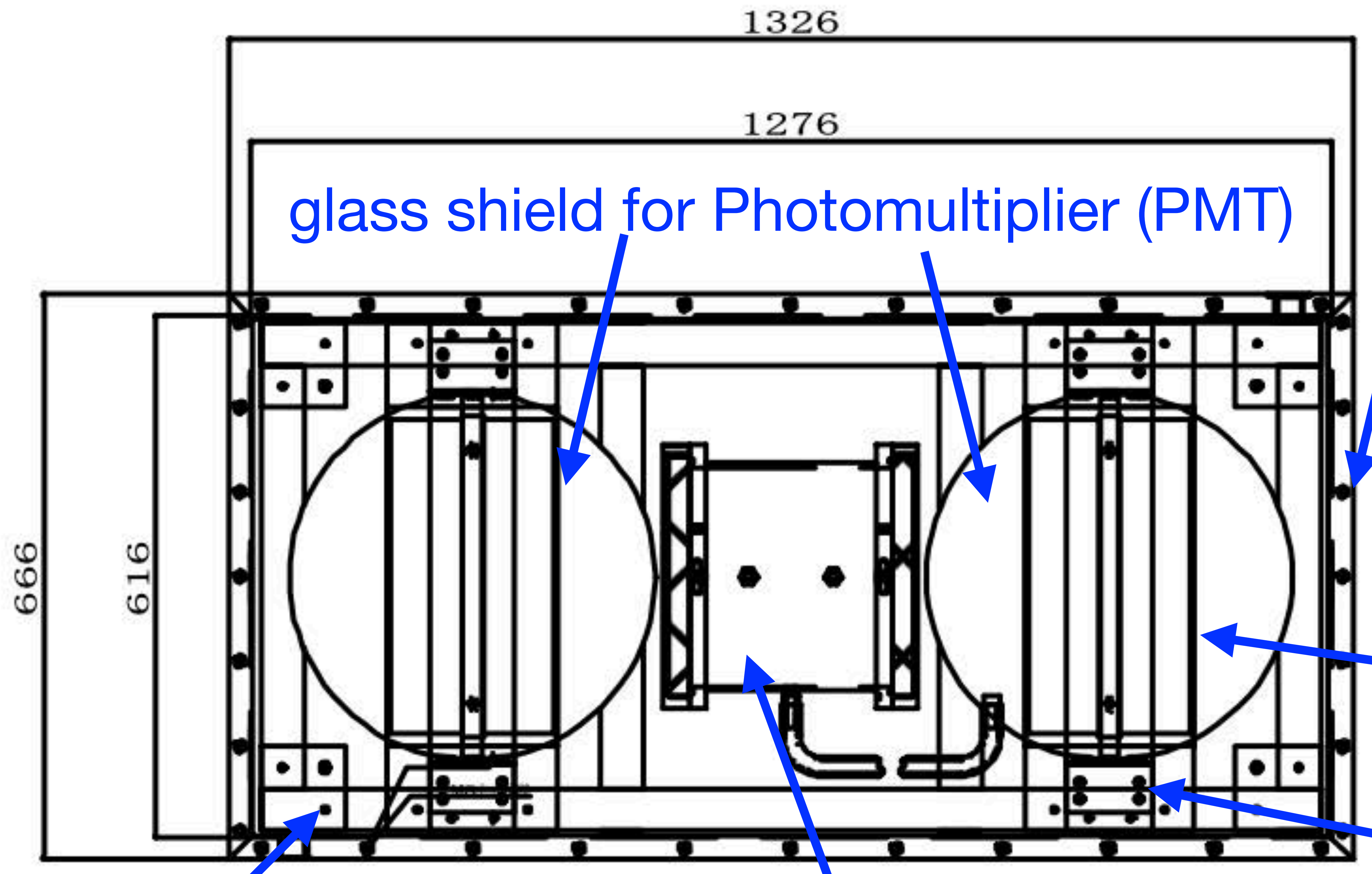
2°C, 40 MPa (4km seafloor) : 891.84 kg/m³ (calculated) **+3.9% → 68 m³ for 1.5 kt LS**

compensation volume

Status of Technical Developments

✦ Prototype detector design & construction

stainless box



glass shield for Photomultiplier (PMT)

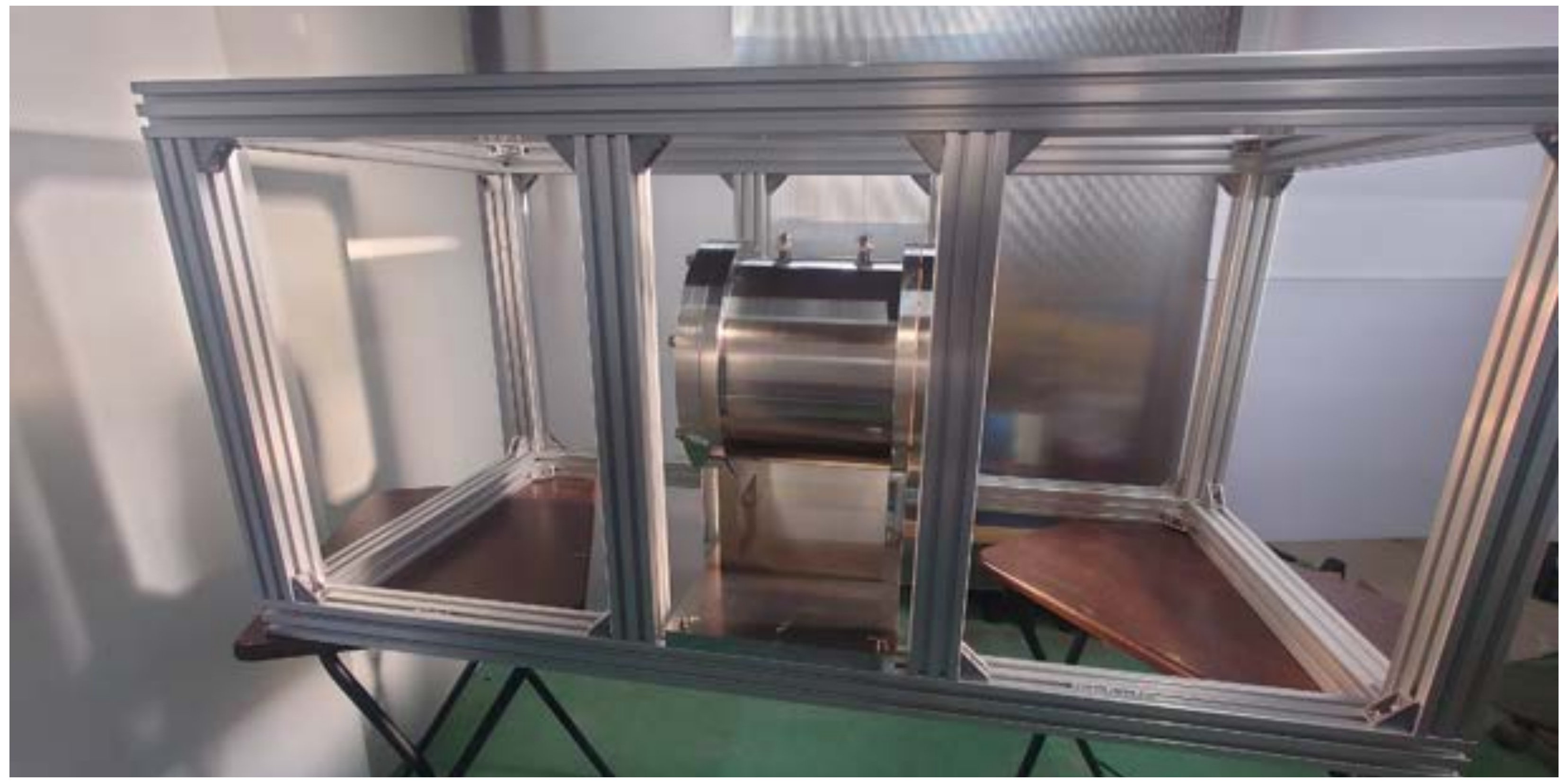
ref) IceCube experiment

PMT & electronics

flame

Liquid Scintillator tank (V=30L)

shield folder

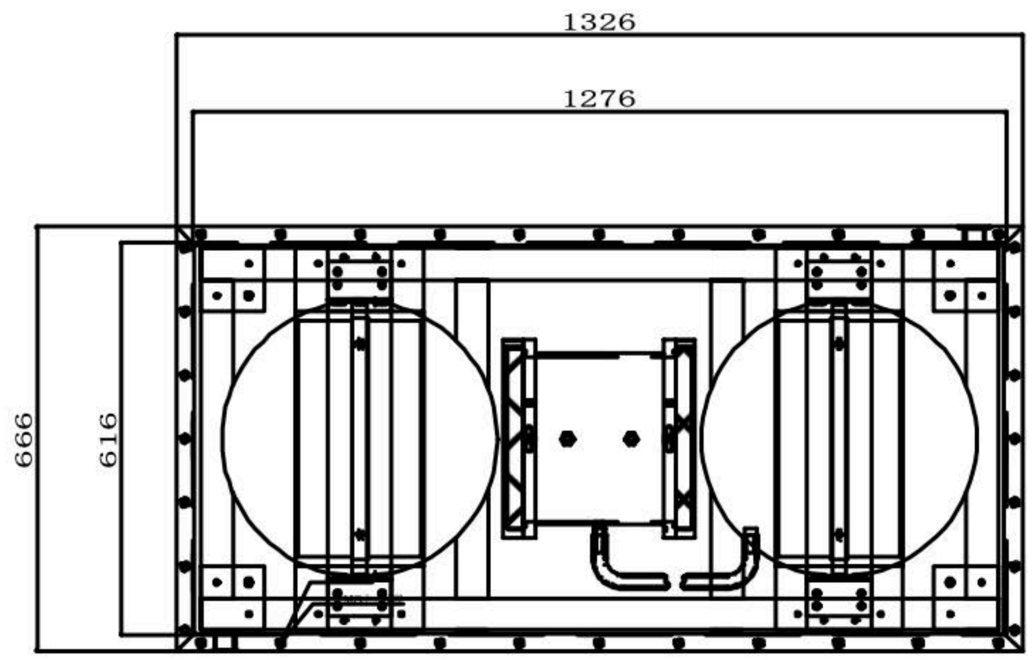


planning to deploy prototype detector into ocean in 2024

Technical and Science Coevolution

2024~

✦**Prototype detector (20kg)** : our first experience deploying LS detector into the ocean



@~1km, ~4°C, 10MPa

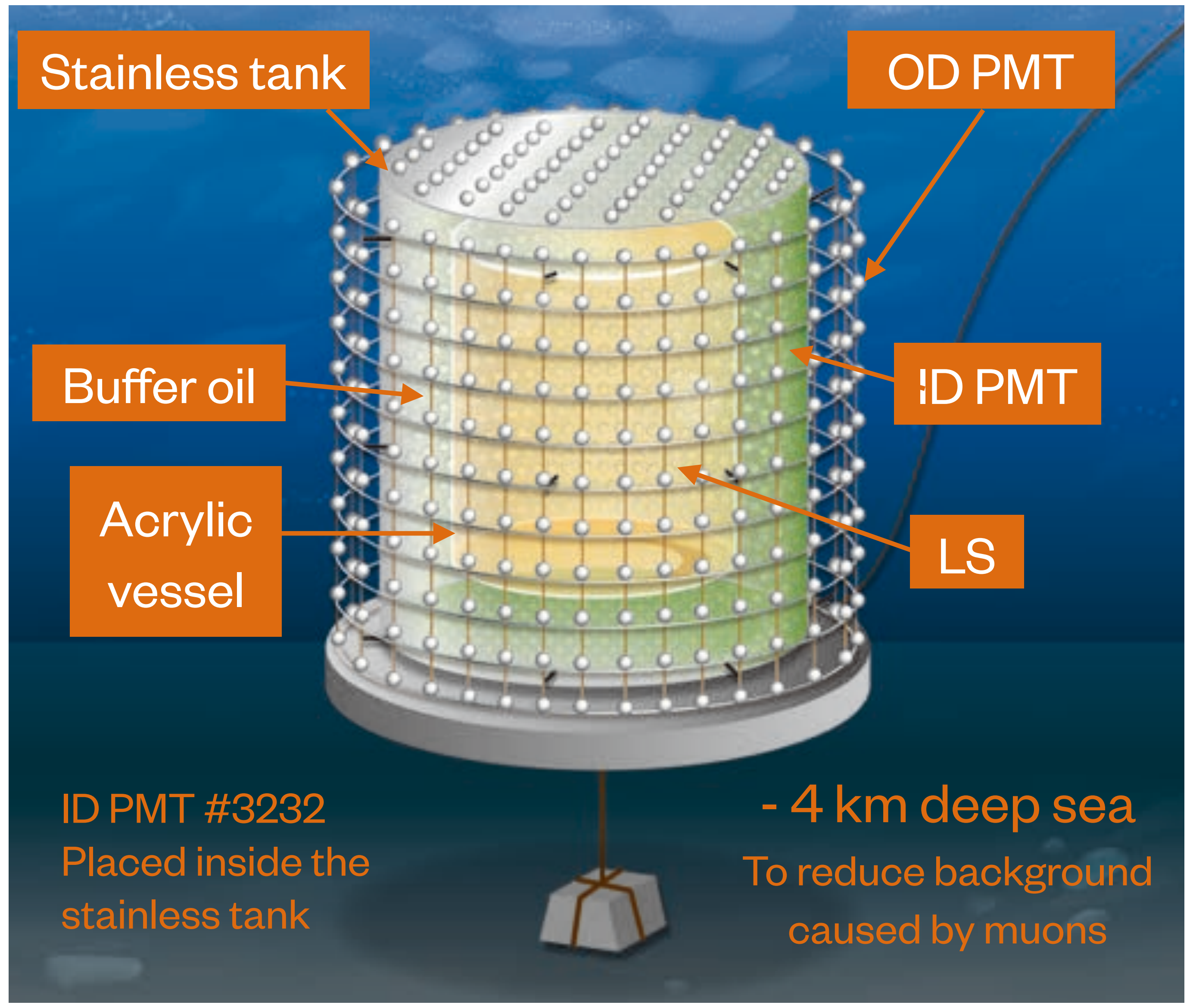
- Technical items
  - workable PMT module in the ocean
  - remote control system (monitoring, DAQ)
- Science targets: muon rate & radioactivities in the ocean → input parameters for large size detector

around 2034~

✦**Large size detector (1.5kt, 10-50kt)** : first direct measurement of mantle geo-neutrino contribution

@~4km, 2~4°C, 40MPa

- Technical items:
  - PMT modules with shield
    - for inner detector: >3000, in buffer oil region
    - for outer detector: >300, in sea water (e.g. KM3Net)
  - low-power electronics
  - data transfer system
- Science target:
  - mantle geo-neutrinos, high-energy neutrinos (OBD can use both water and LS as targets.)



Summary

- For two centuries we have asked *what is the energy that drives the Earth?*

- 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" : collaborations between geoscience, physics, ocean engineering and beyond**
  - **Ocean Bottom Detector (OBD) = Breakthrough**
  - **OBD has strong power to measure mantle contribution directly**

<Transformative insights>

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

•constrain the planet's cooling history