KamLANDにおける
地球ニュートリノ観測の最新結果

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for the KamLAND Collaboration

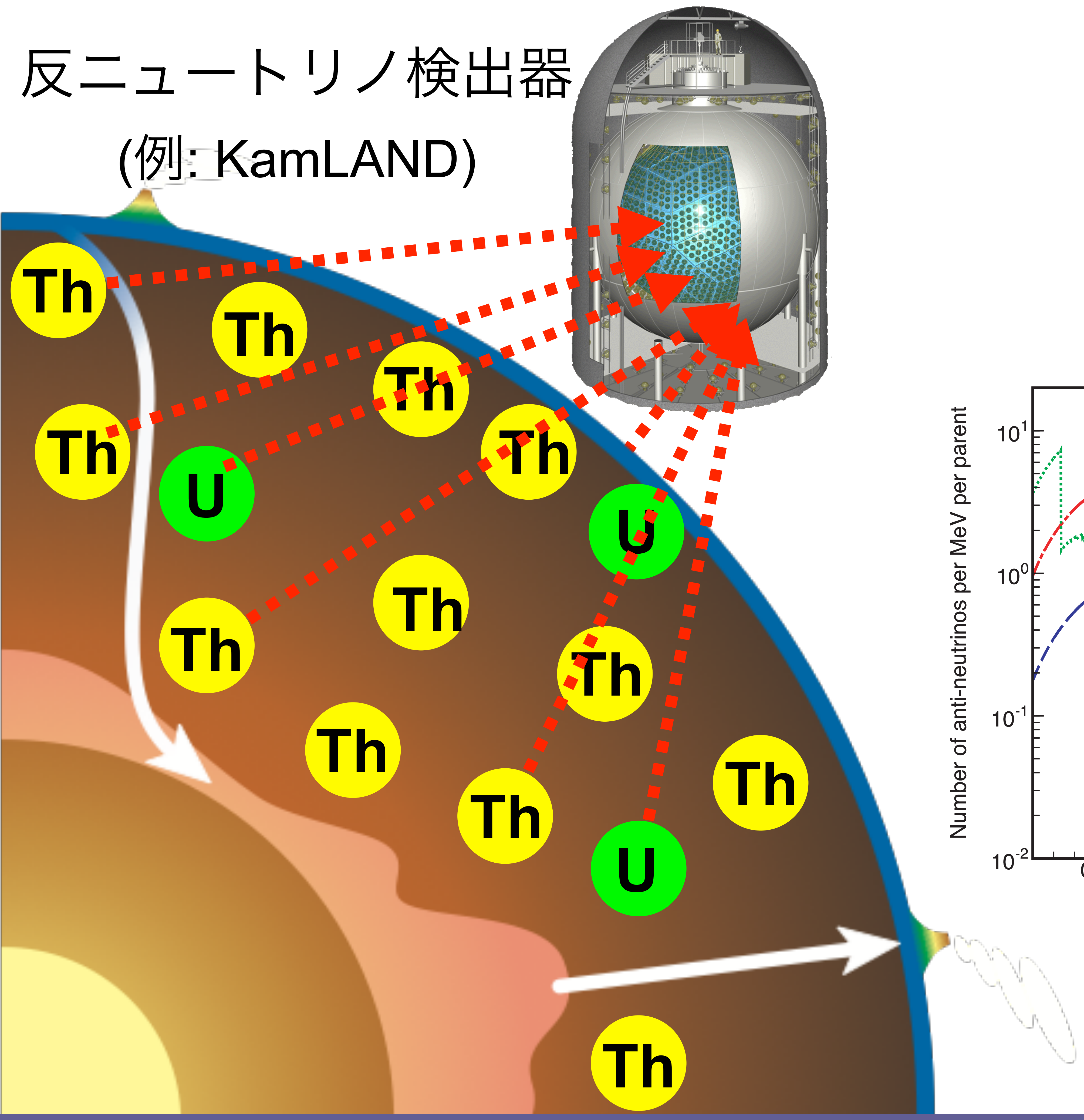
Contents

Contents

地球内放射性物質の崩壊によって放出される反ニュートリノ

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

反ニュートリノ検出器
(例: KamLAND)



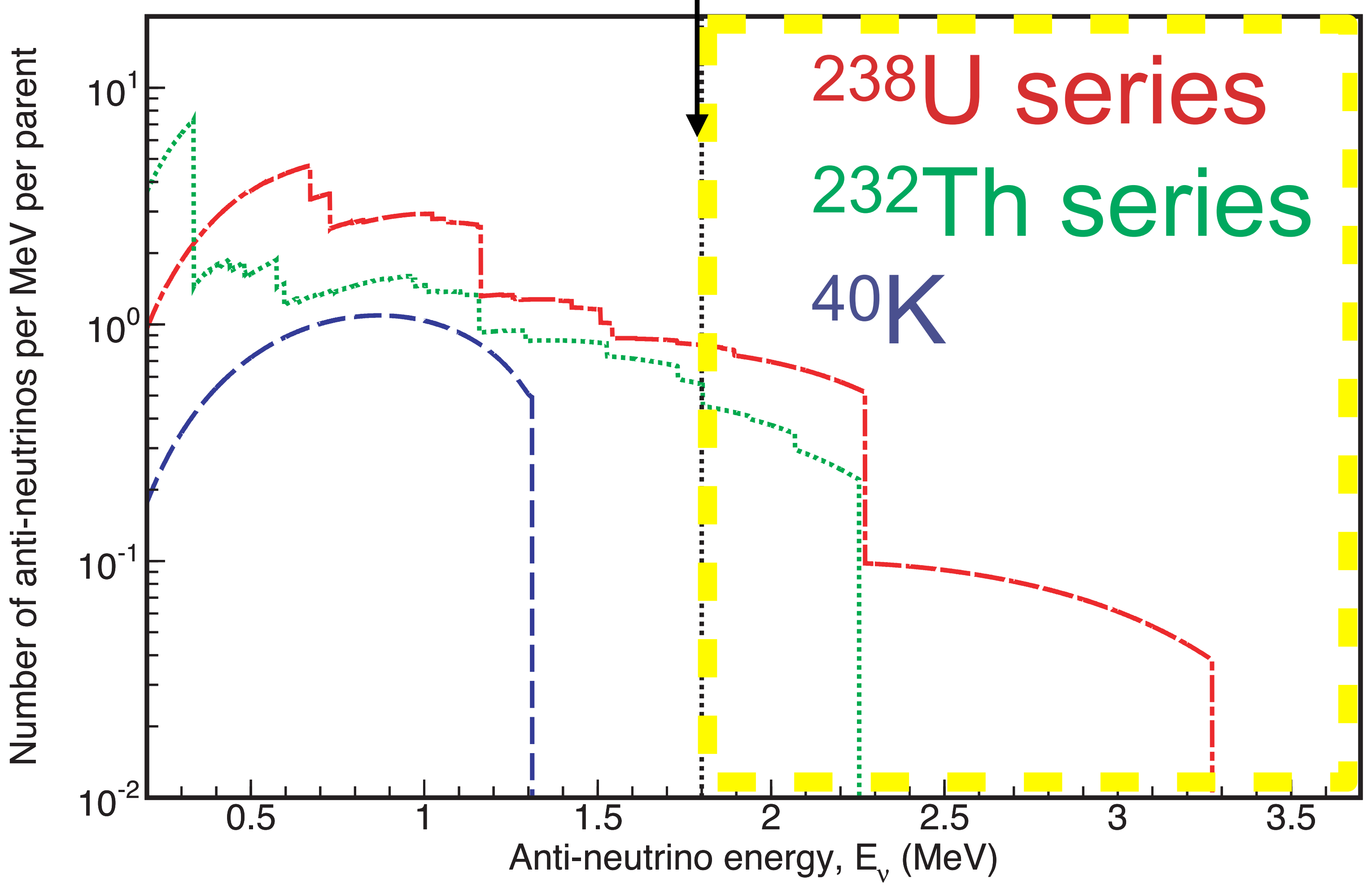
β崩壊　　地球ニュートリノ

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

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

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

エネルギー閾値 1.8 MeV



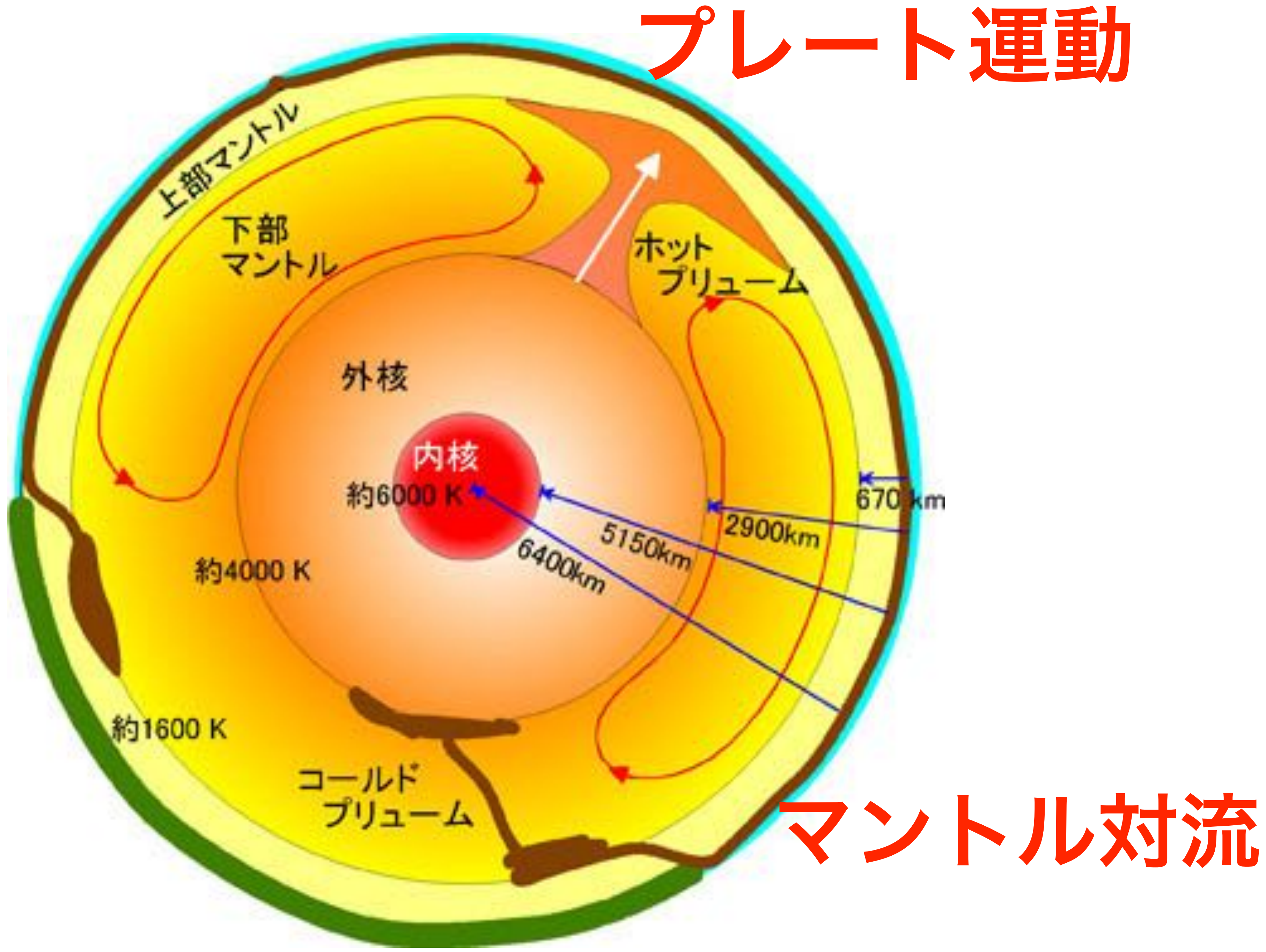
逆β崩壊

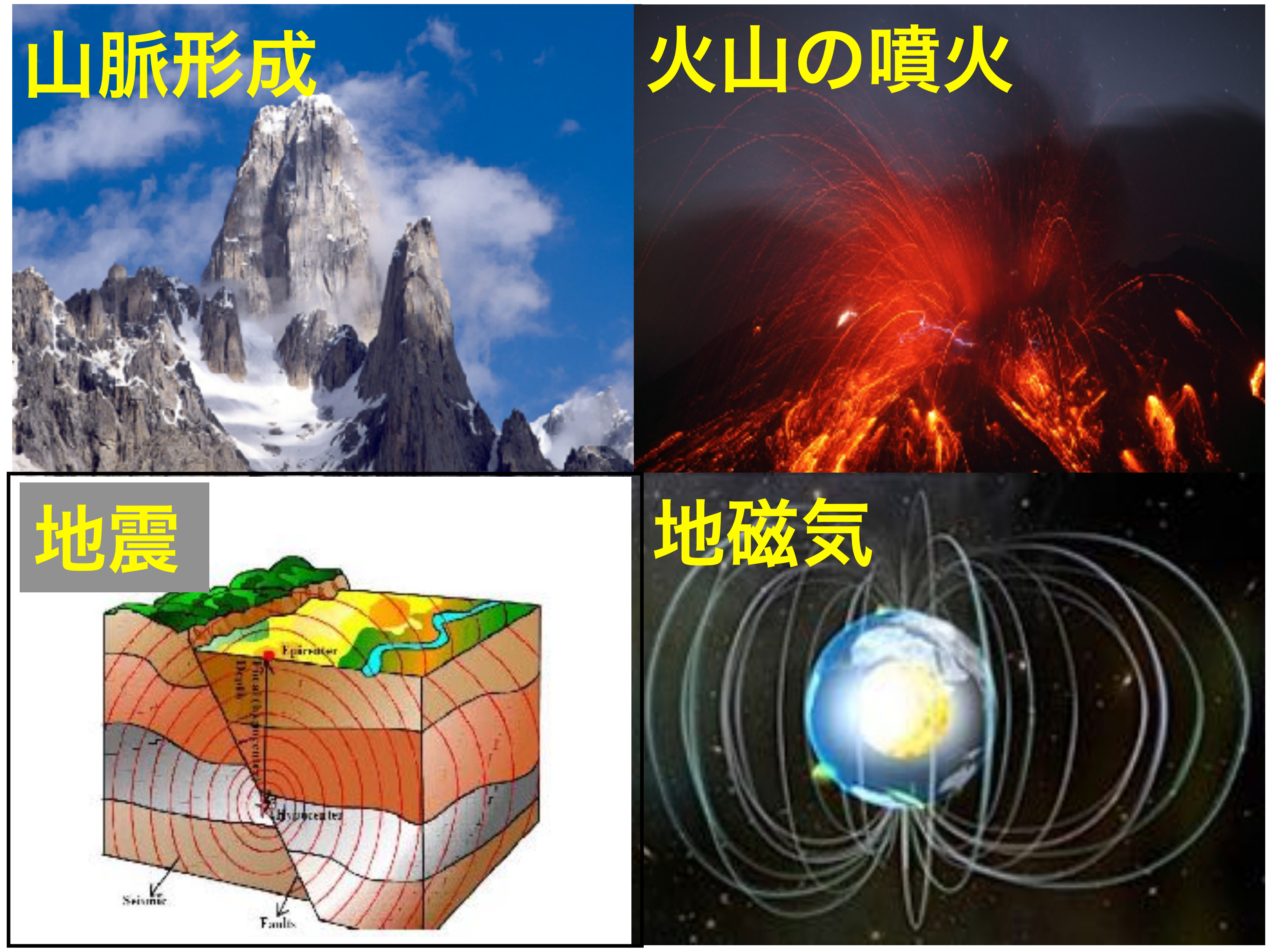
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

* 現在 U と Th 起源の地球ニュートリノのみ観測可能
* ^{40}K地球ニュートリノの観測には新技術が必要

地球ニュートリノ数∝ U Th 量, 放射化熱量

地球ニュートリノ観測目的





<u>地球活動の謎</u>

*地球活動のエネルギー源、エネルギー量は？

*マントルはどのように対流しているのか？一層 or 複数対流?

*地球磁場の生成・維持の起源は？

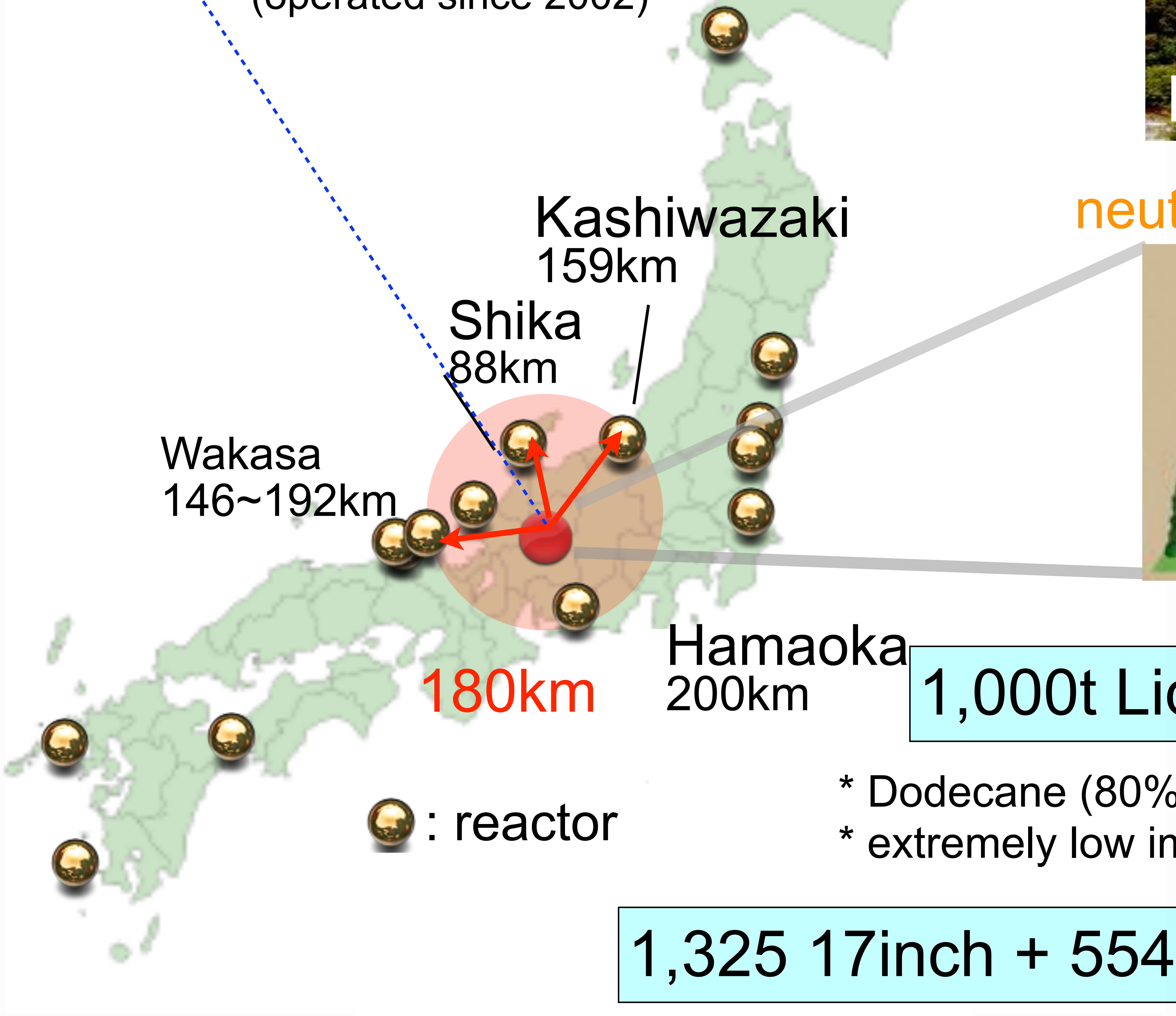
→ **地熱の理解は重要な課題**

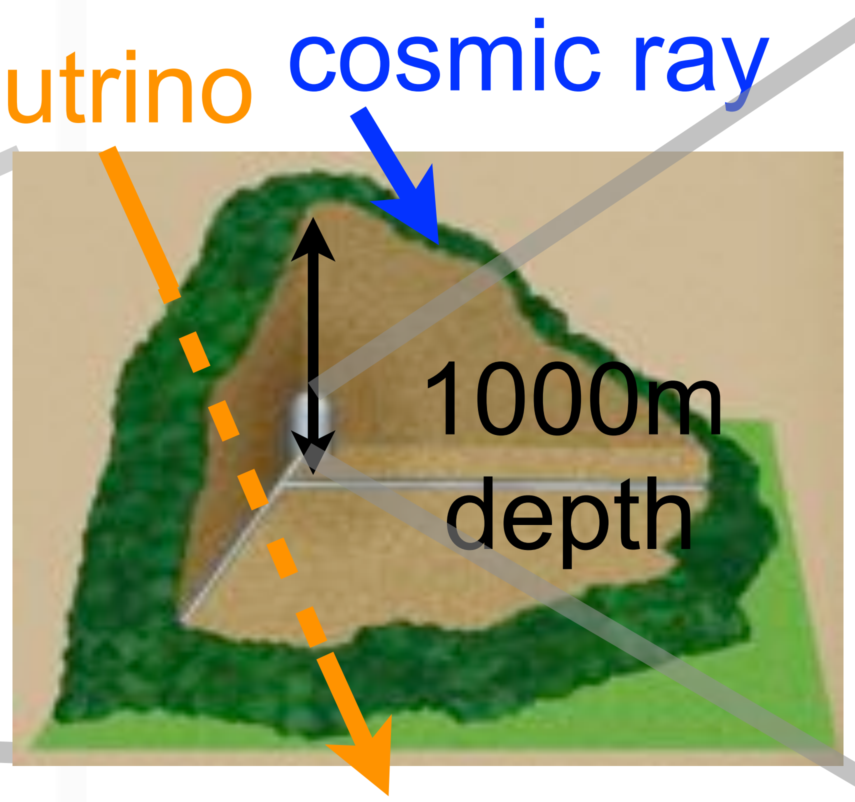
KamLAND Collaboration

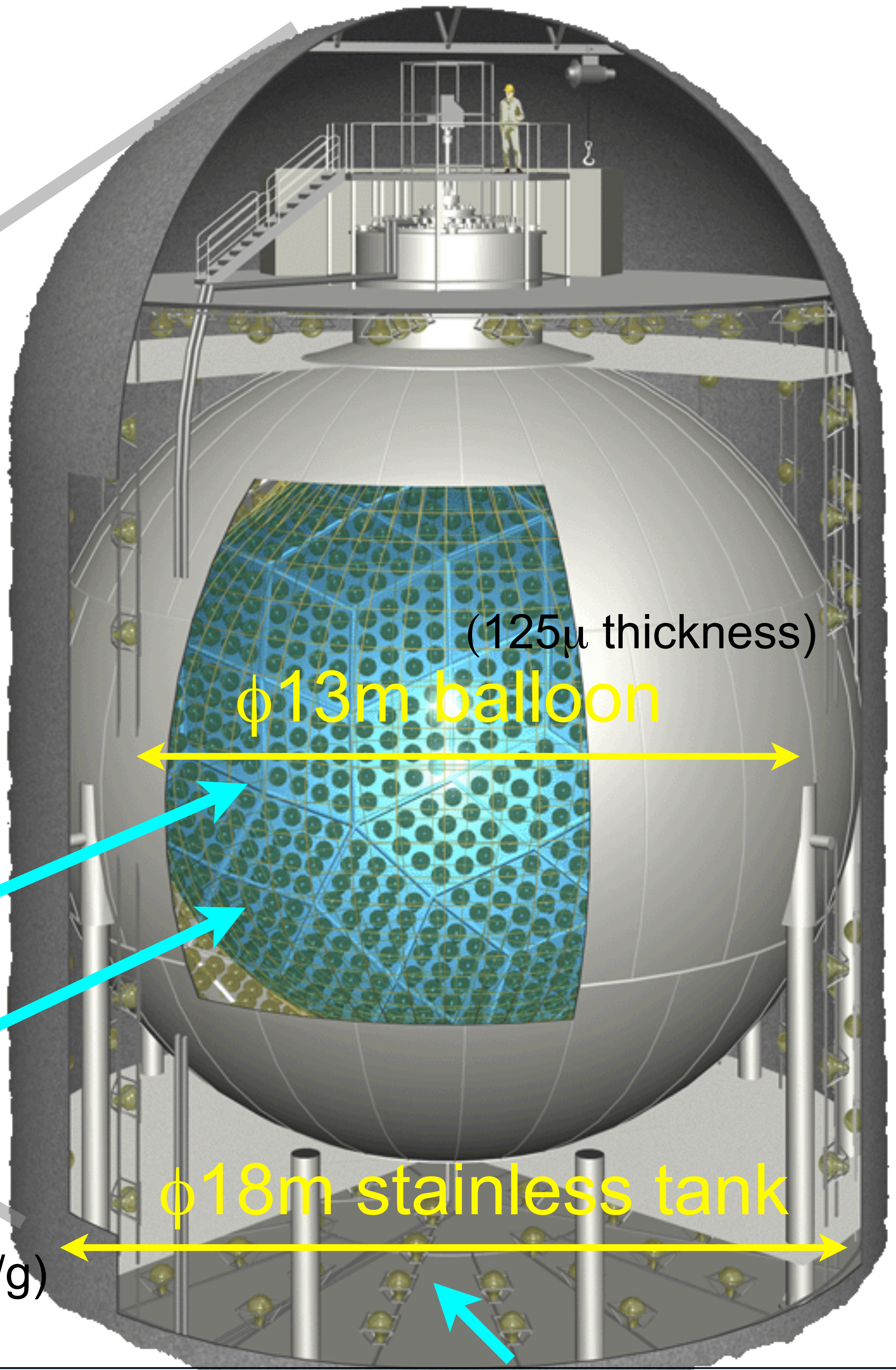
*** Institutions :**
5 from Japan
8 from US
1 from Europe
*** ~50 collaborators**

KamLAND

Kamioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector
(operated since 2002)







1,000t Liquid Scintillator

* Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)
* extremely low impurily (^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)

1,325 17inch + 554 20inch PMTs

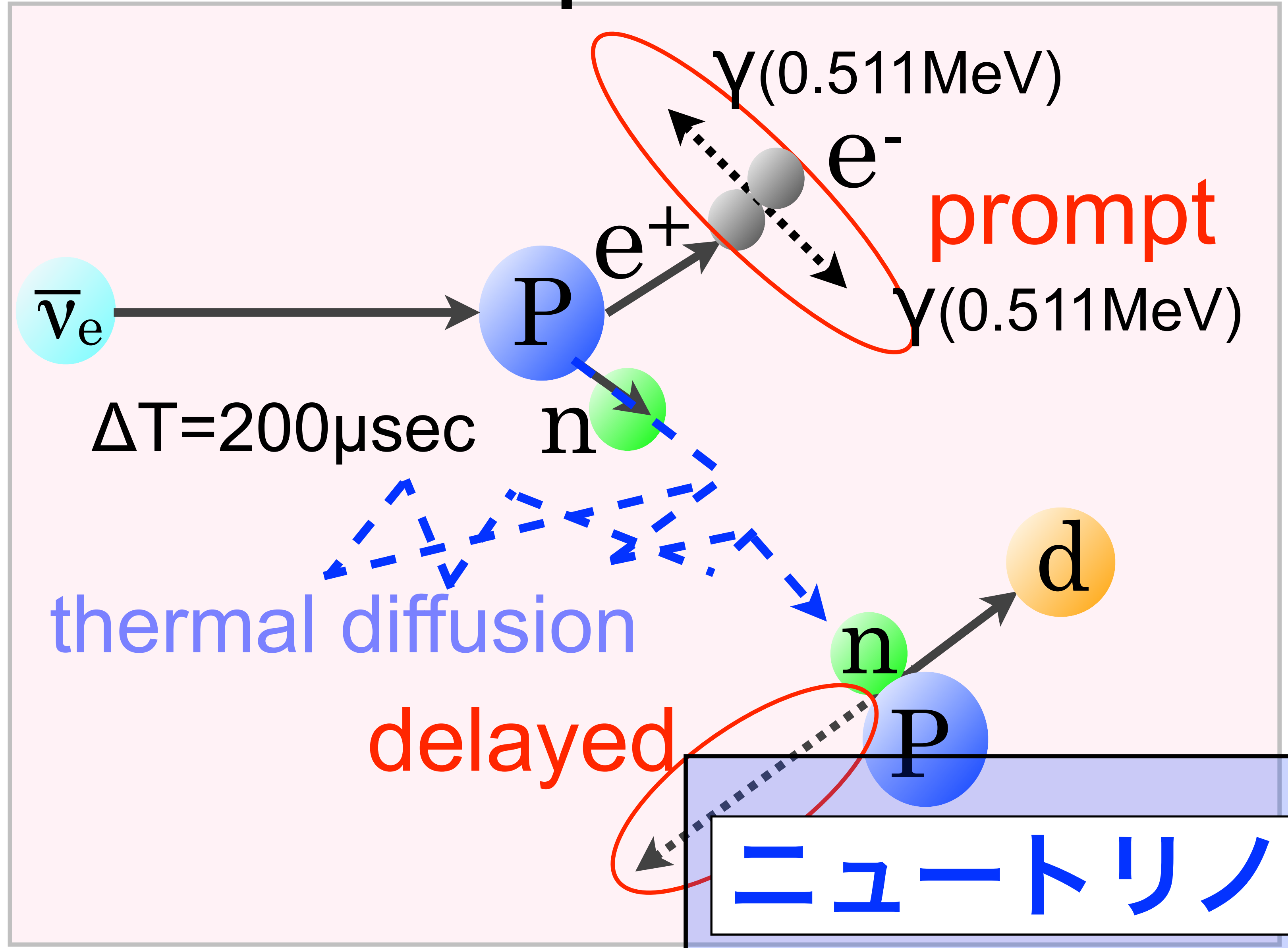
* Photo coverage 34%

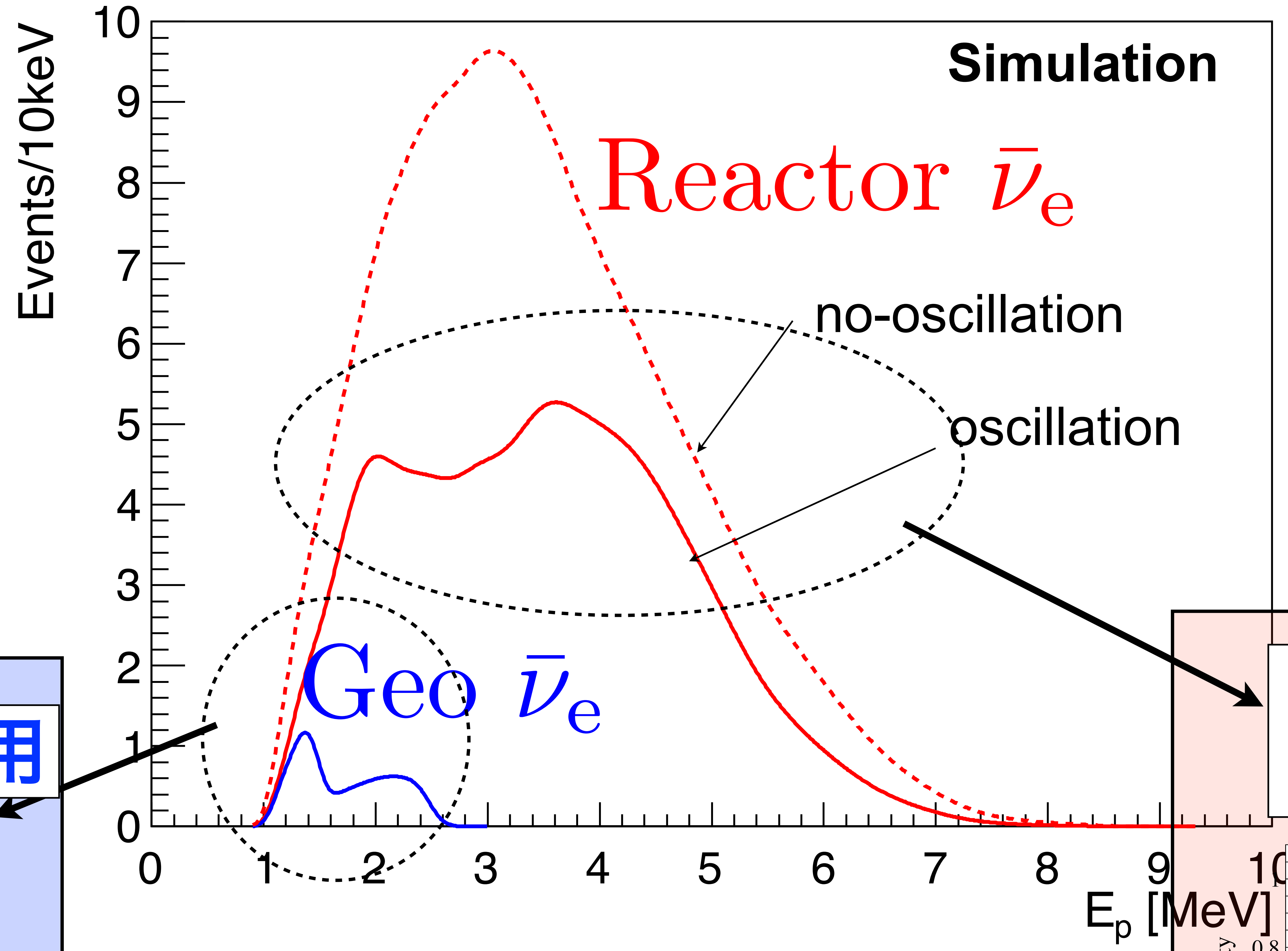
Water Cherenkov Outer Detector

* Muon veto

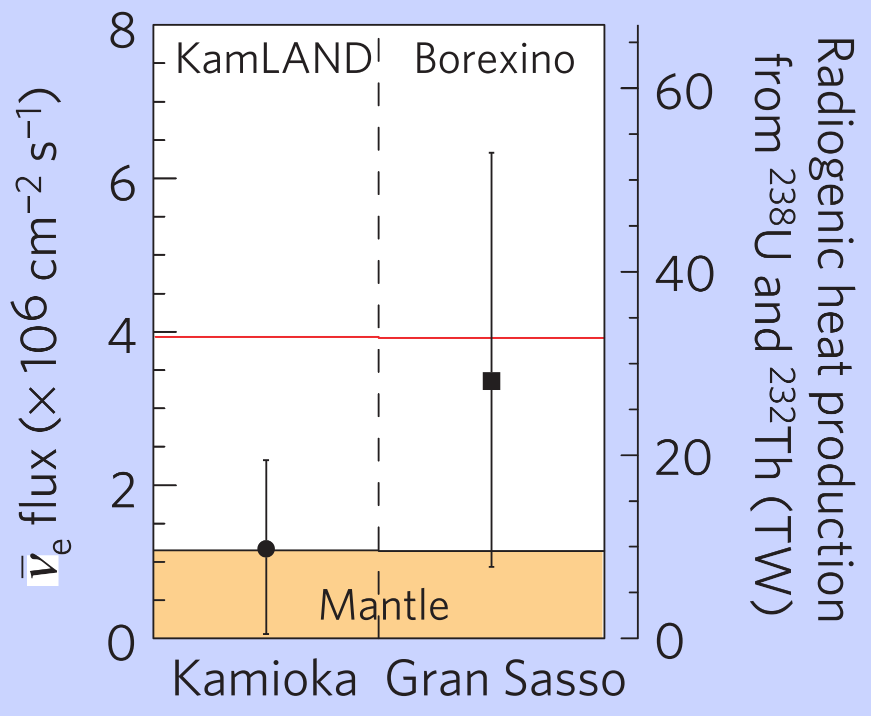
反ニュートリノ観測

逆β崩壊



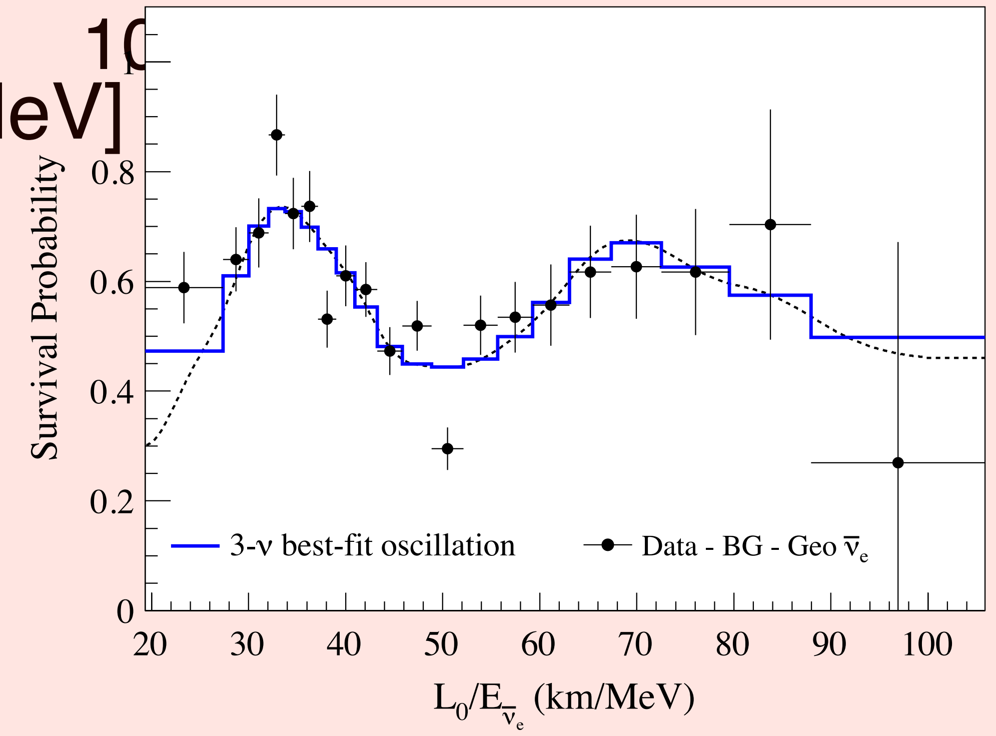


ニュートリノの応用



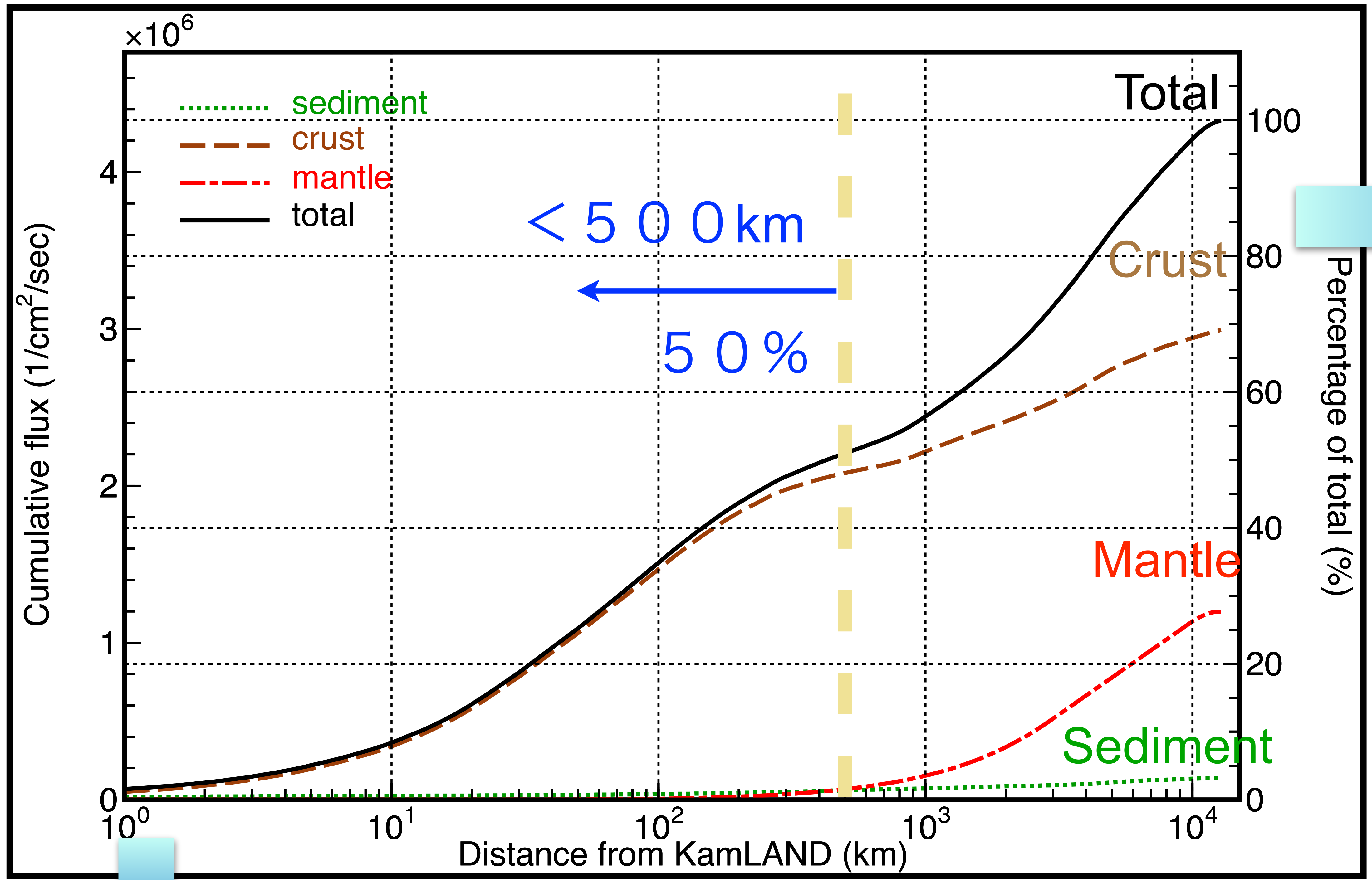
- 放射化熱の寄与の直接測定

ニュートリノの性質の理解

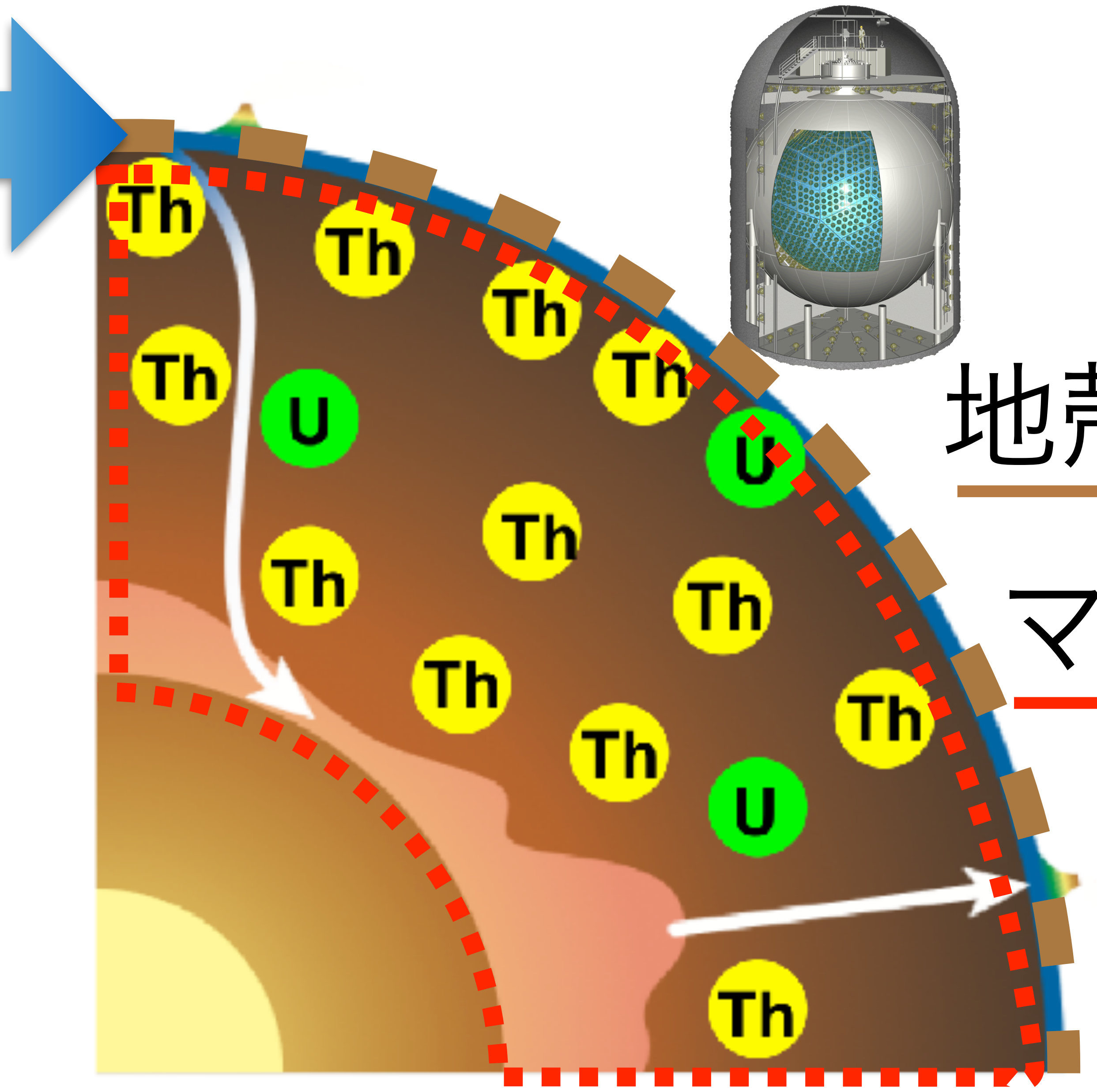


- ニュートリノ振動の形跡の観測
- 振動パラメターの精密測定

神岡における地球ニュートリノフラックス



各パートからの寄与



地殻 : 70%

マントル : 27%

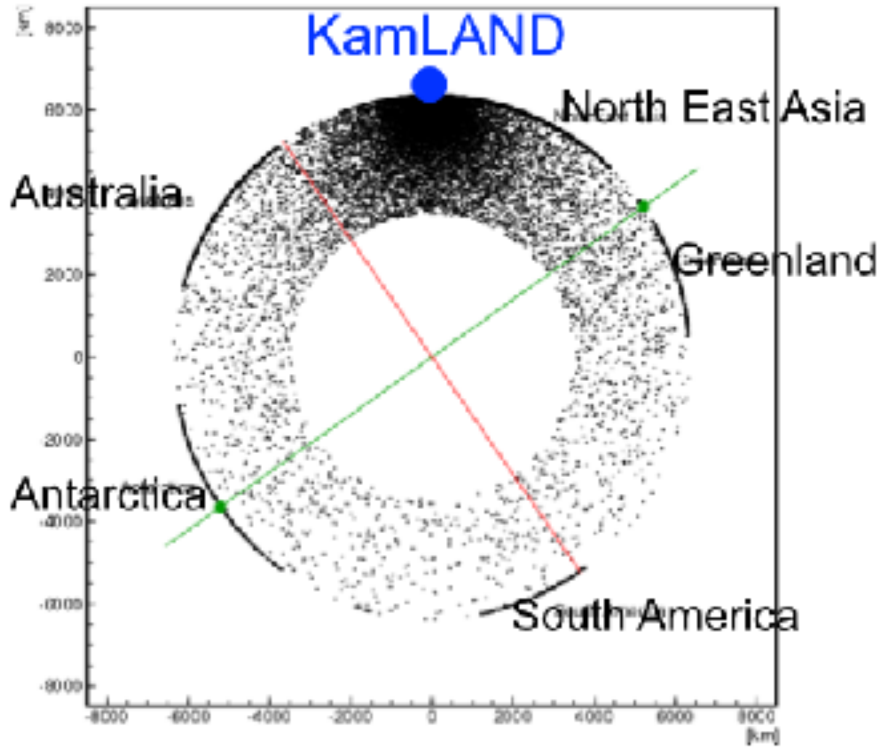
核 : 0%

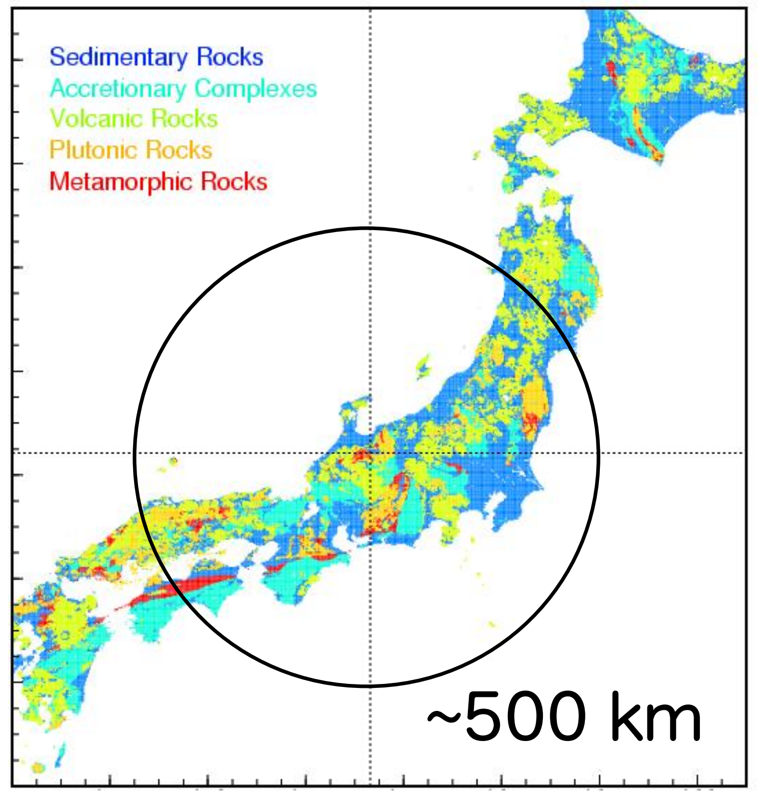
Sediment etc. : 3%

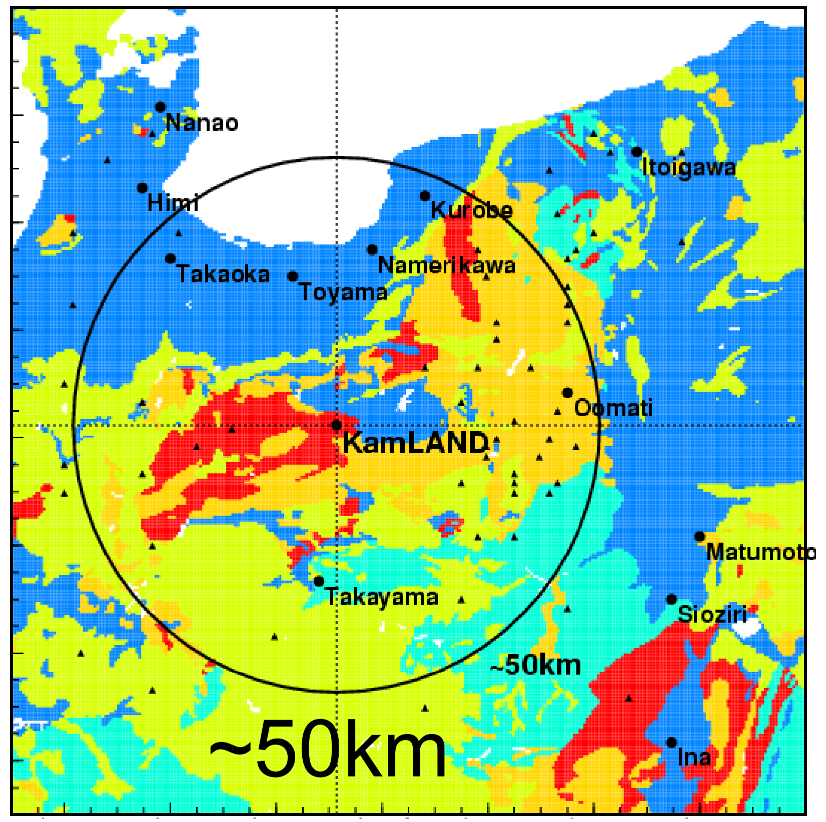
各領域からの寄与

- **50%: < 500km**
- 25%: < 50km
- 1~2%: 神岡

検出器近傍の構造の理解が重要

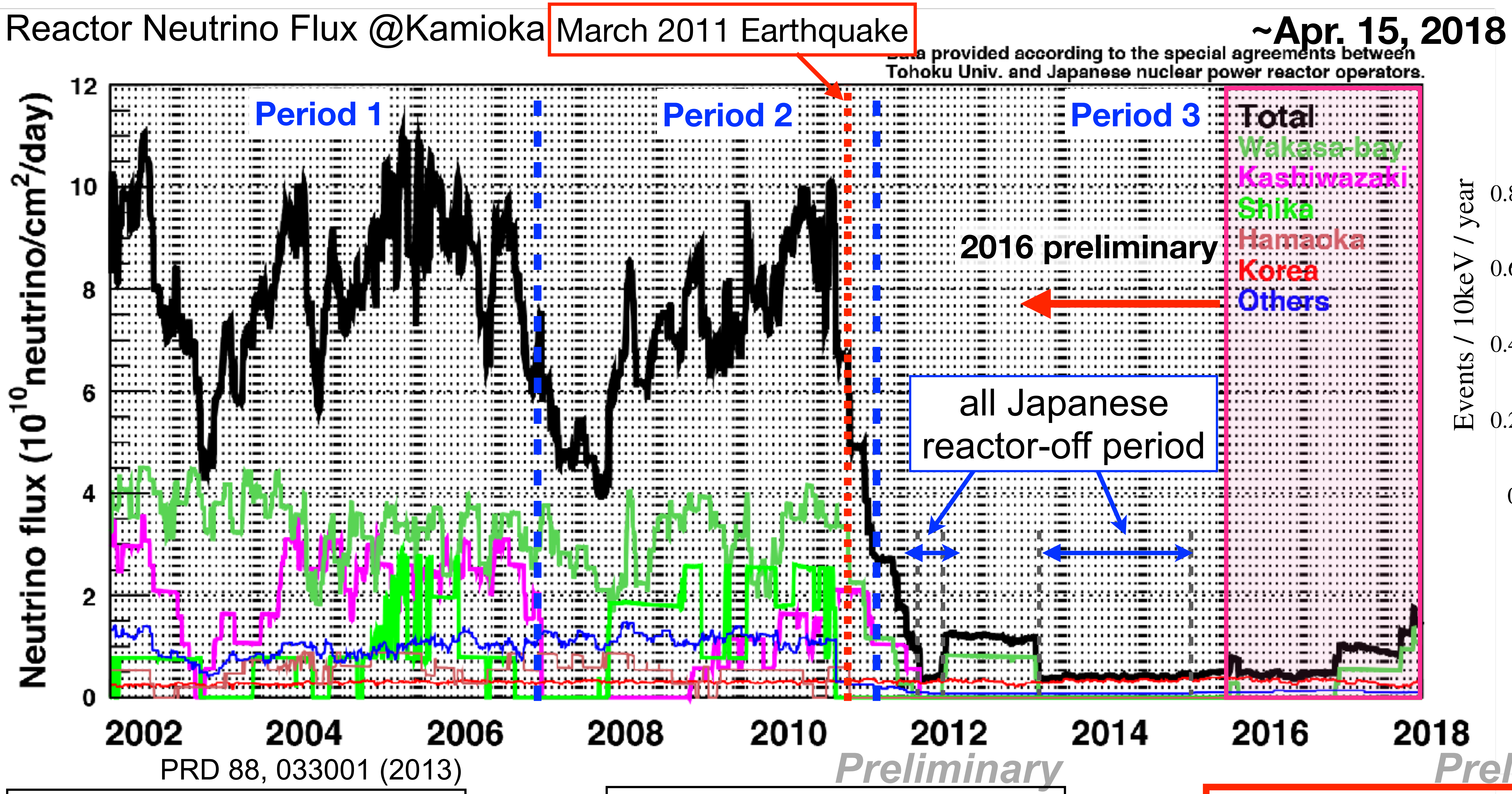


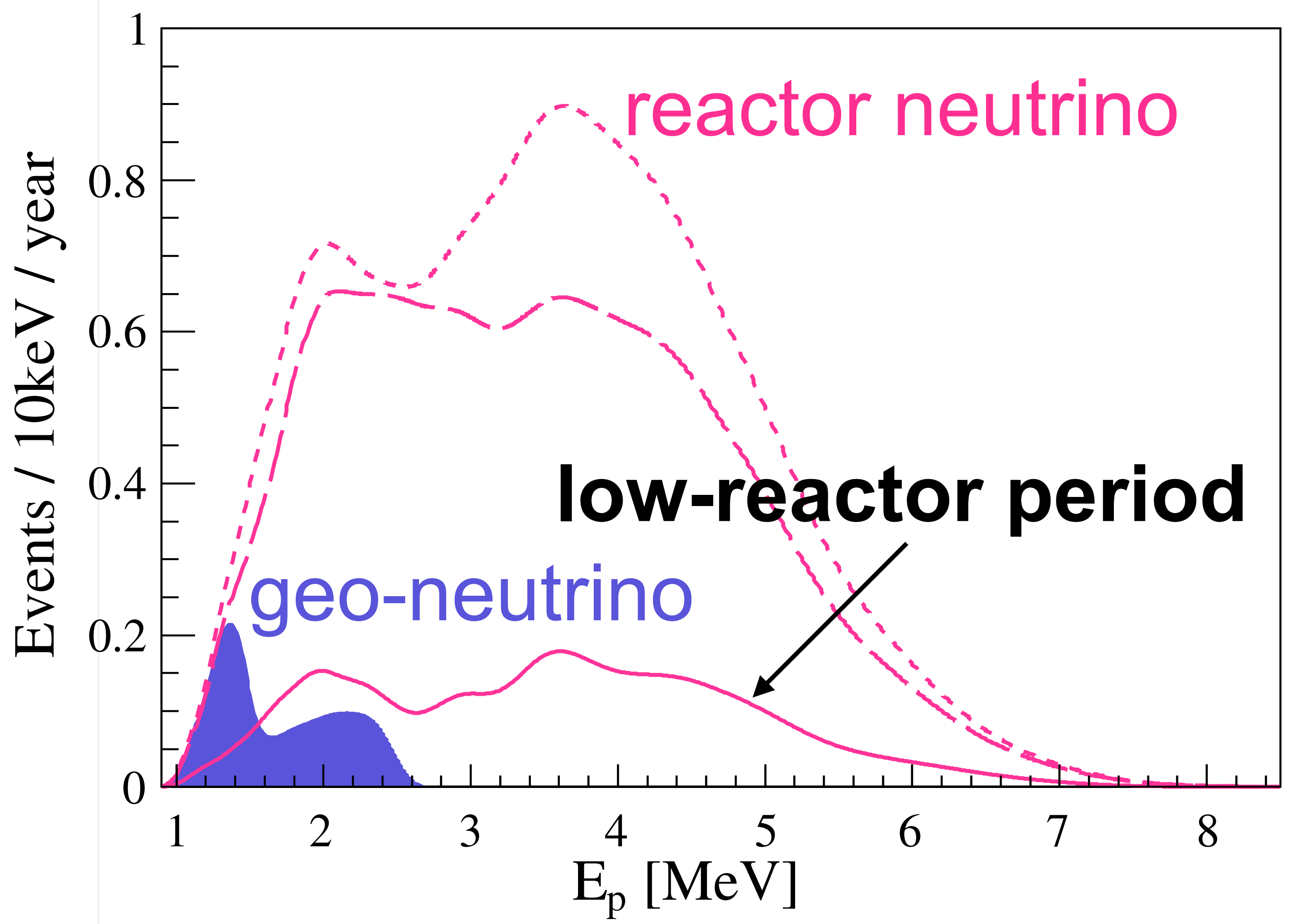




Contents

Data-set & Reactor Neutrinos





☑ +500 days of low-reactor phase from 2016 data-set

PRD 88, 033001 (2013)

Preliminary

Preliminary

2013 data-set : 2991 days
4.90×10^{32} proton-year

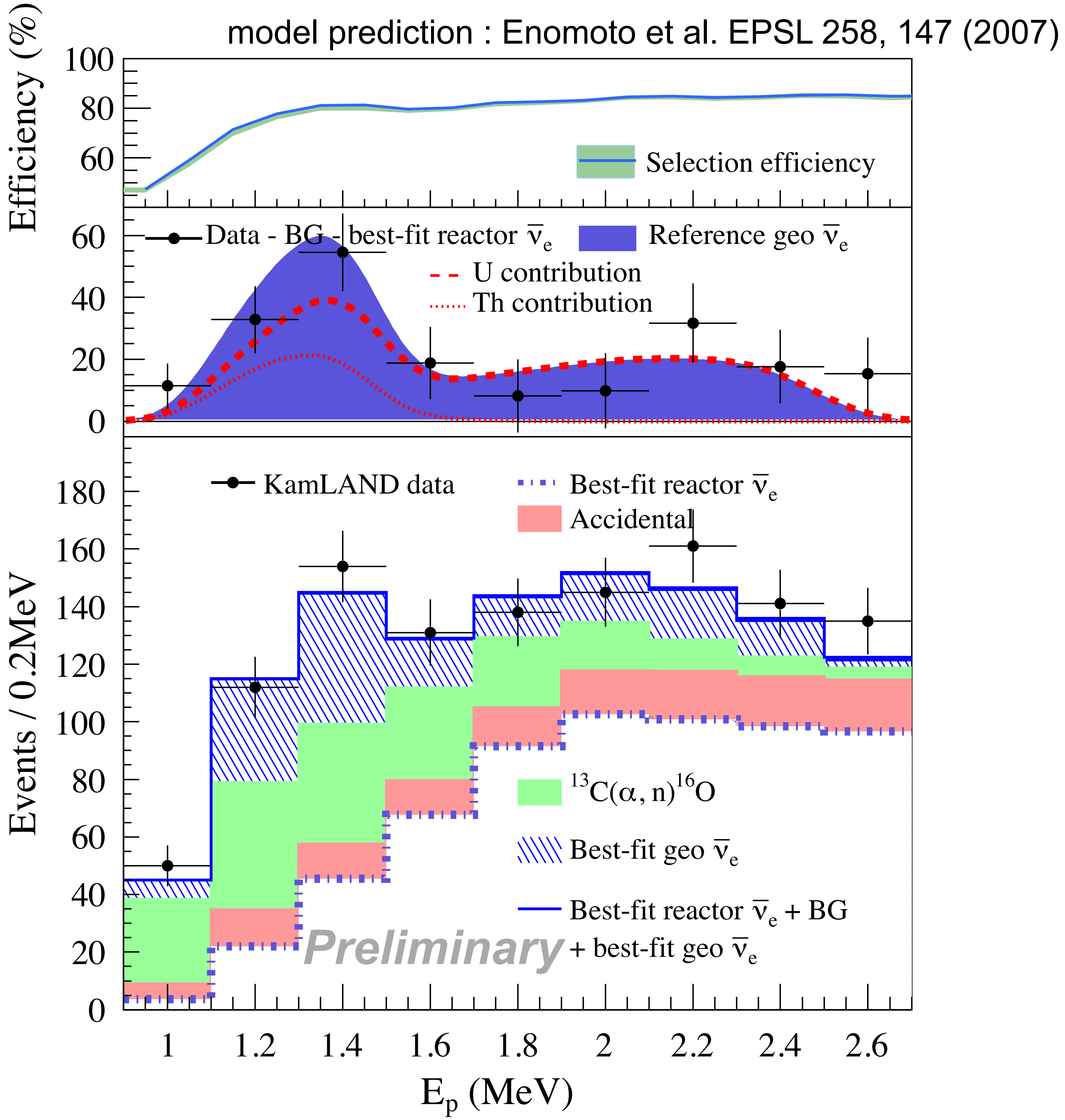
→ **2016 data-set** : 3901 days
6.39×10^{32} proton-year

→ **2019 data-set** : 4397 days
7.20×10^{32} proton-year

Period 1 : 1485.62 days
Period 2 : 1151.47 days
Period 3 : 1259.8 days → +500 days → **Period 3 : 1759.85 days**

Energy Spectrum (0.9-2.6 MeV)

2019 Preliminary Result



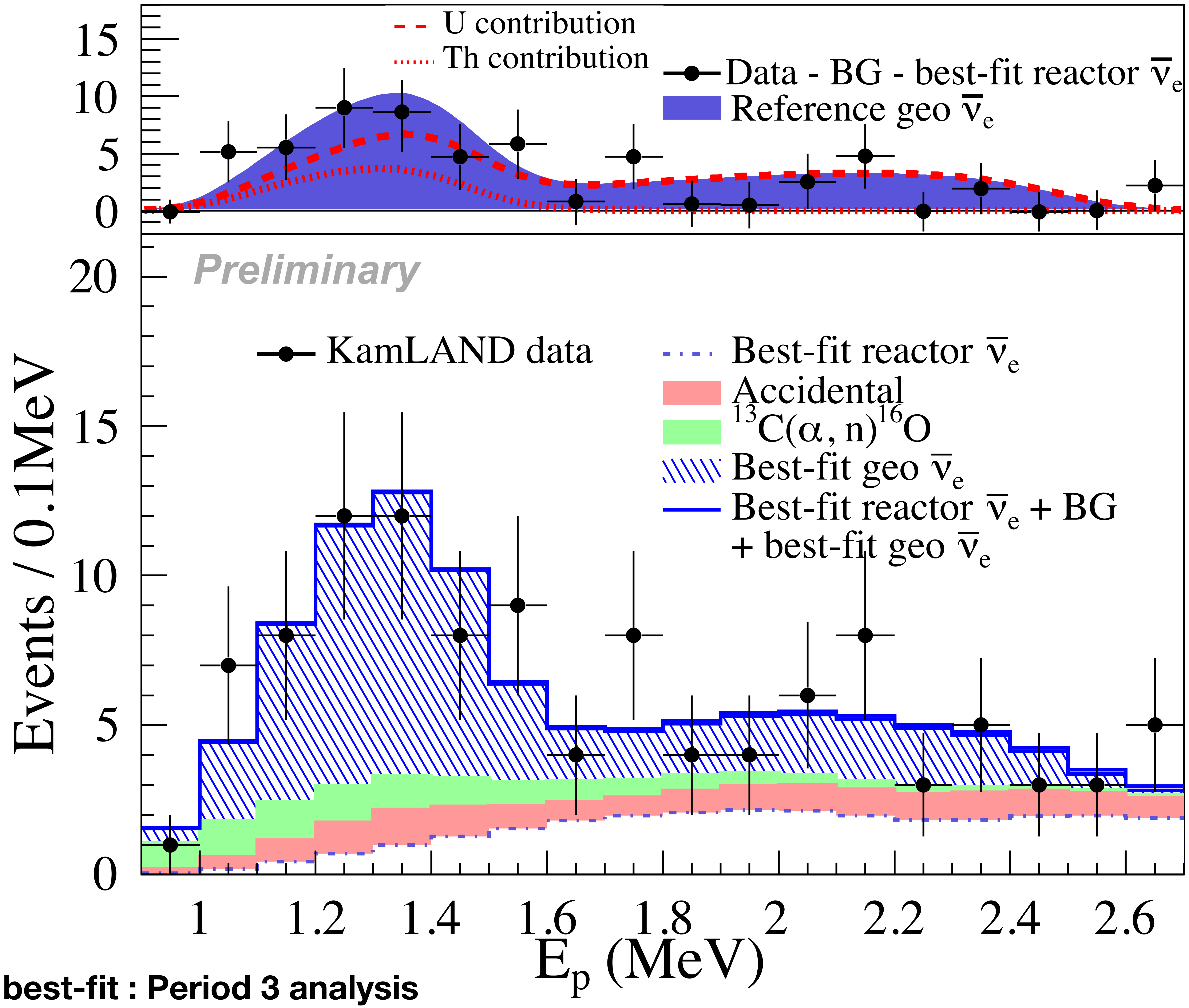
Livetime : 4397 days

Candidate : 1167 ev

Background Summary

^{9}Li	4.4 ± 0.1
Accidental	121.9 ± 0.1
Fast neutron	< 4.1
$^{13}C(\alpha, n)^{16}O$	211.6 ± 23.3
Reactor $\overline{\nu}_e$	**629.0 ± 34.4**
Total	966.9 ± 41.8

▸Energy Spectrum (0.9-2.6 MeV), Low Reactor Phase



best-fit : Period 3 analysis

Livetime : 1760 days

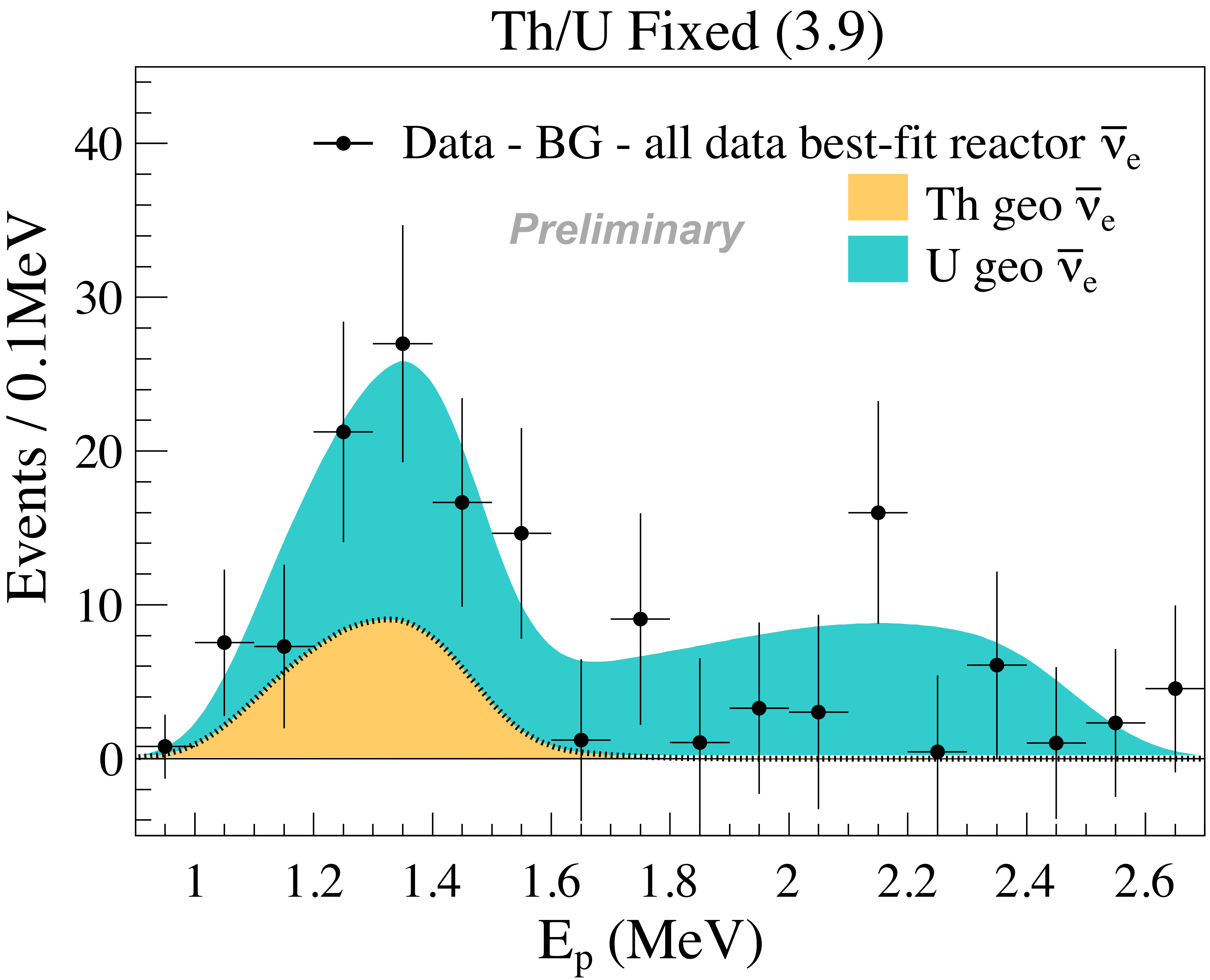
Candidate : 110 ev

☑ Geo-neutrino / Background

= 66.3 ev / 50.3 ev ~**1.3**

☑ <u>We clearly measured geo-neutrino spectrum.</u>

→ better understanding of U, Th each contribution

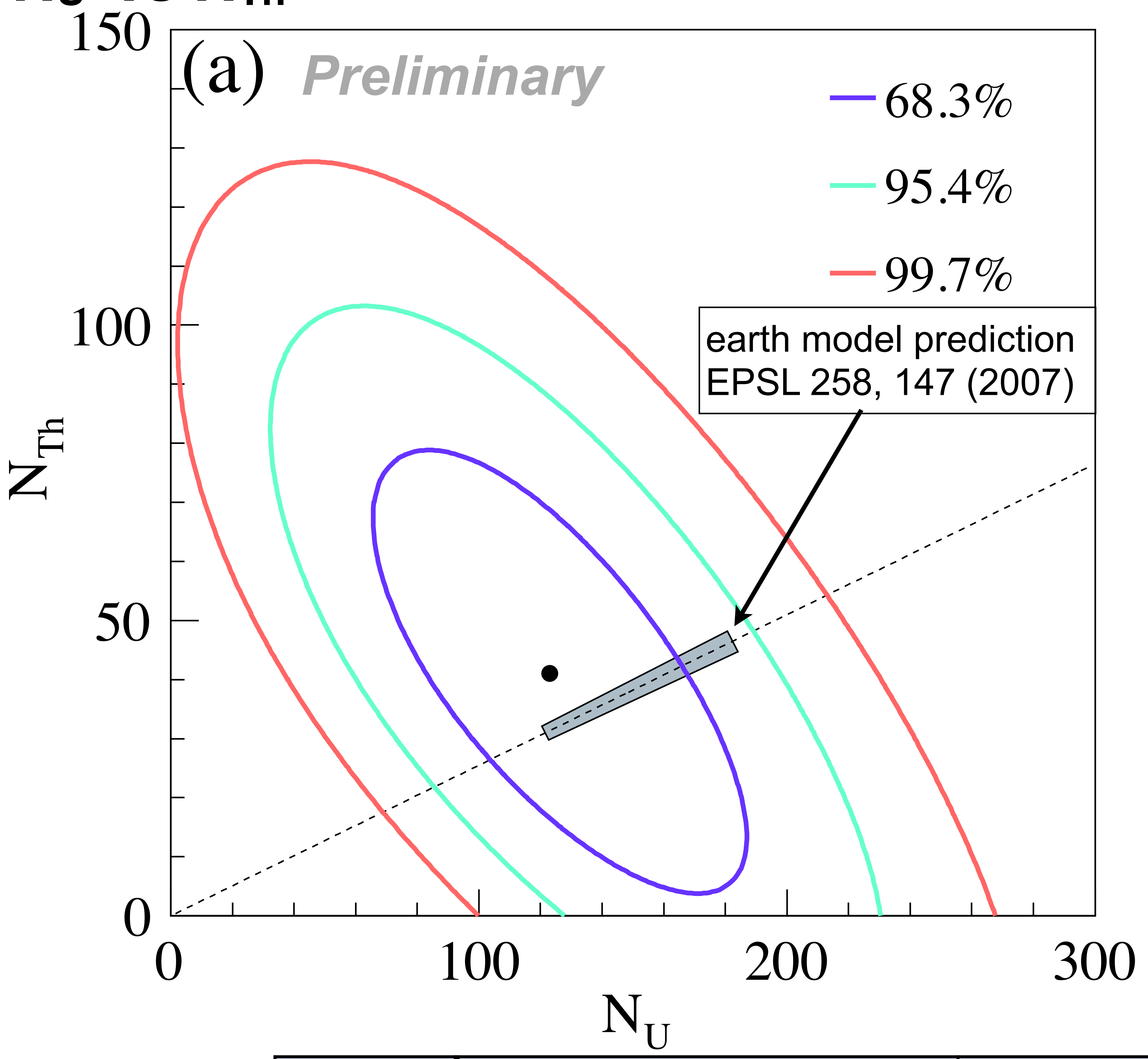


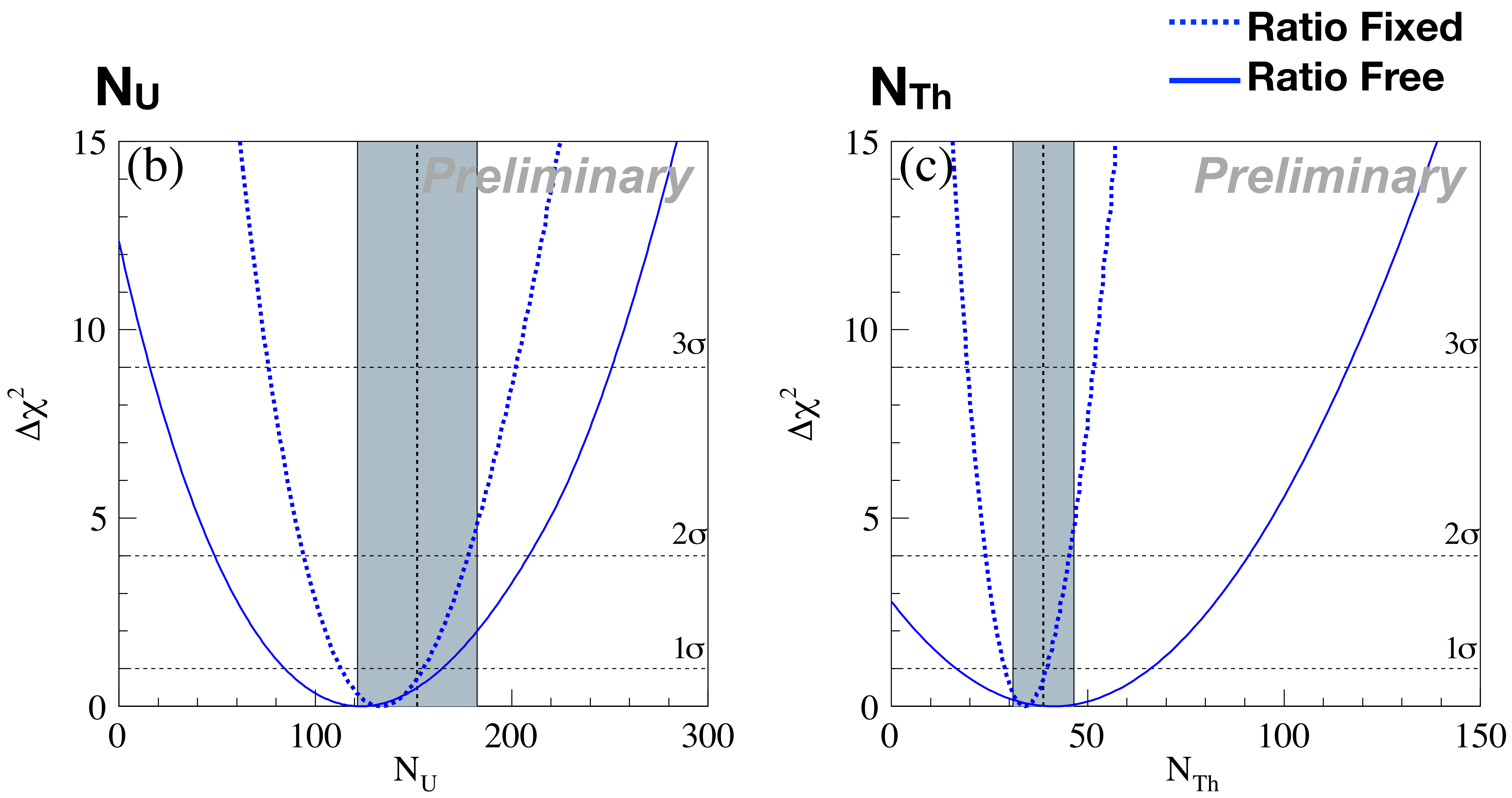
- <u>Background subtracted data</u>
  - backgrounds : all data best-fit
  - weighted average by each period's livetime
- <u>U・Th contributions</u>
  - all data best-fit with Th/U fixed analysis

☑ Good agreement

Rate + Shape + Time Analysis (1)

N_U vs N_{Th}



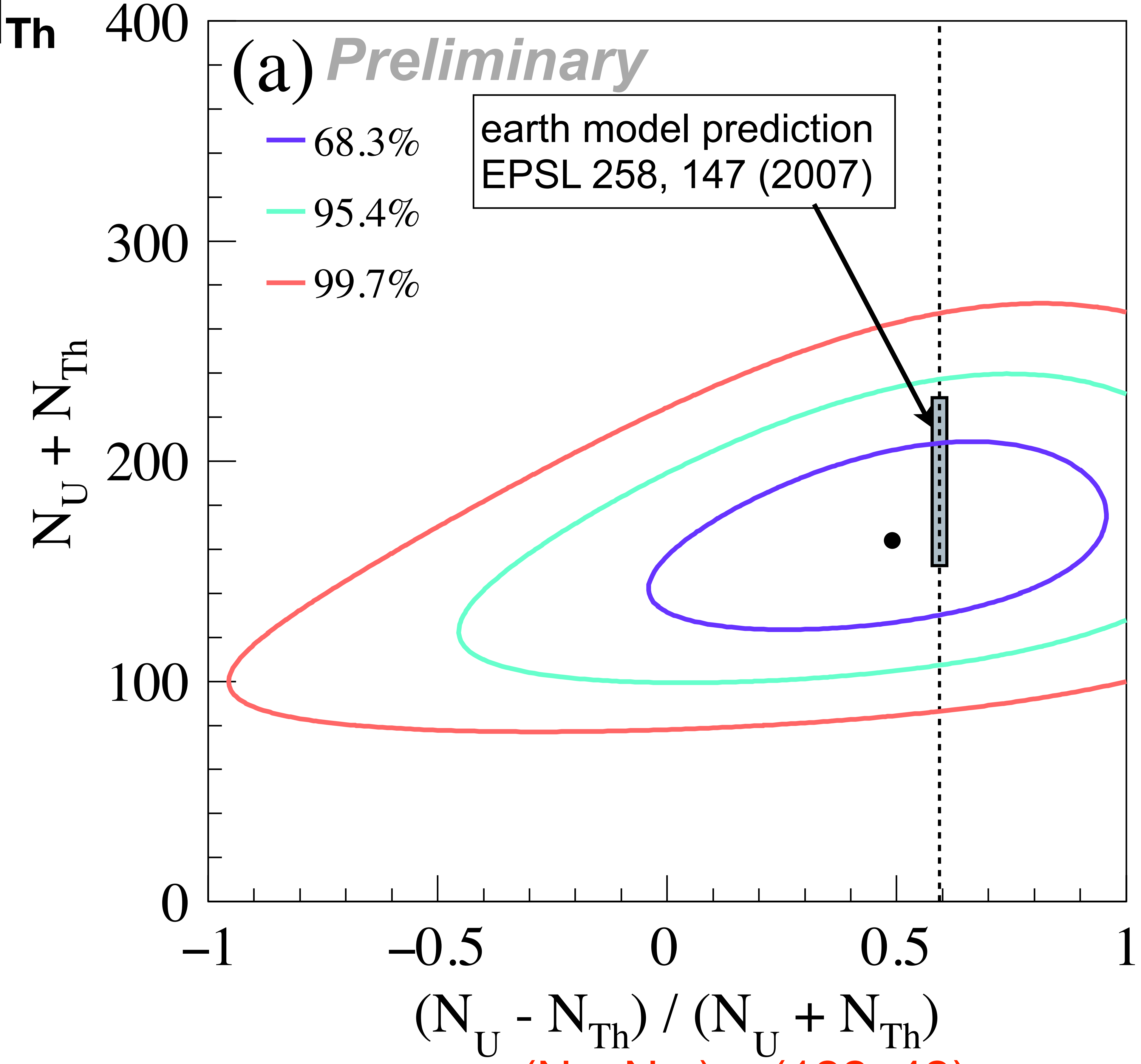


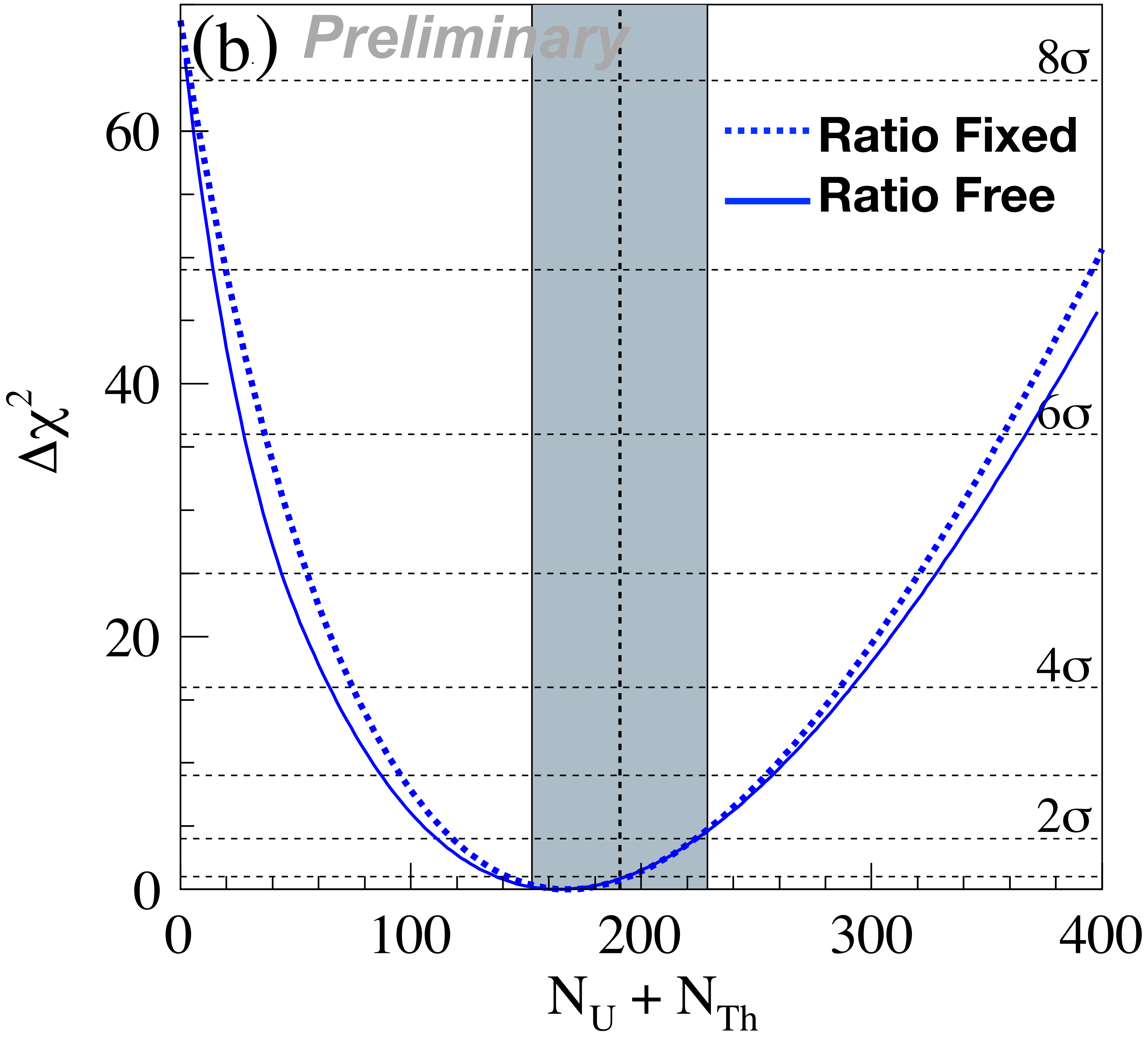
ratio free

	[event]	[TNU]	Flux [×10⁵ cm⁻²s⁻¹] best-fit	Flux [×10⁵ cm⁻²s⁻¹] model	0 signal rejection
U	**123.3 +41.2/-39.1**	23.3 +7.8/-7.4	17.9 +6.0/-5.7	22.0	**3.51σ**
Th	**41.6 +24.6/-24.7**	8.1 +4.8/-4.8	20.0 +11.9/-11.9	18.6	**1.68σ**

Rate + Shape + Time Analysis (2)

$N_U + N_{Th}$





best-fit $(N_U, N_{Th}) = (122, 42)$
$N_U + N_{Th} = 164$

ratio fixed

	[event]	[TNU]	Flux [$\times10^6$ $cm^{-2}s^{-1}$] best-fit	Flux [$\times10^6$ $cm^{-2}s^{-1}$] model	0 signal rejection
U+Th	**168.8 +26.3/-26.5 (15.6%)**	32.1 +5.0/-5.0	3.6 +0.6/-0.6	4.1	**8.14 σ**

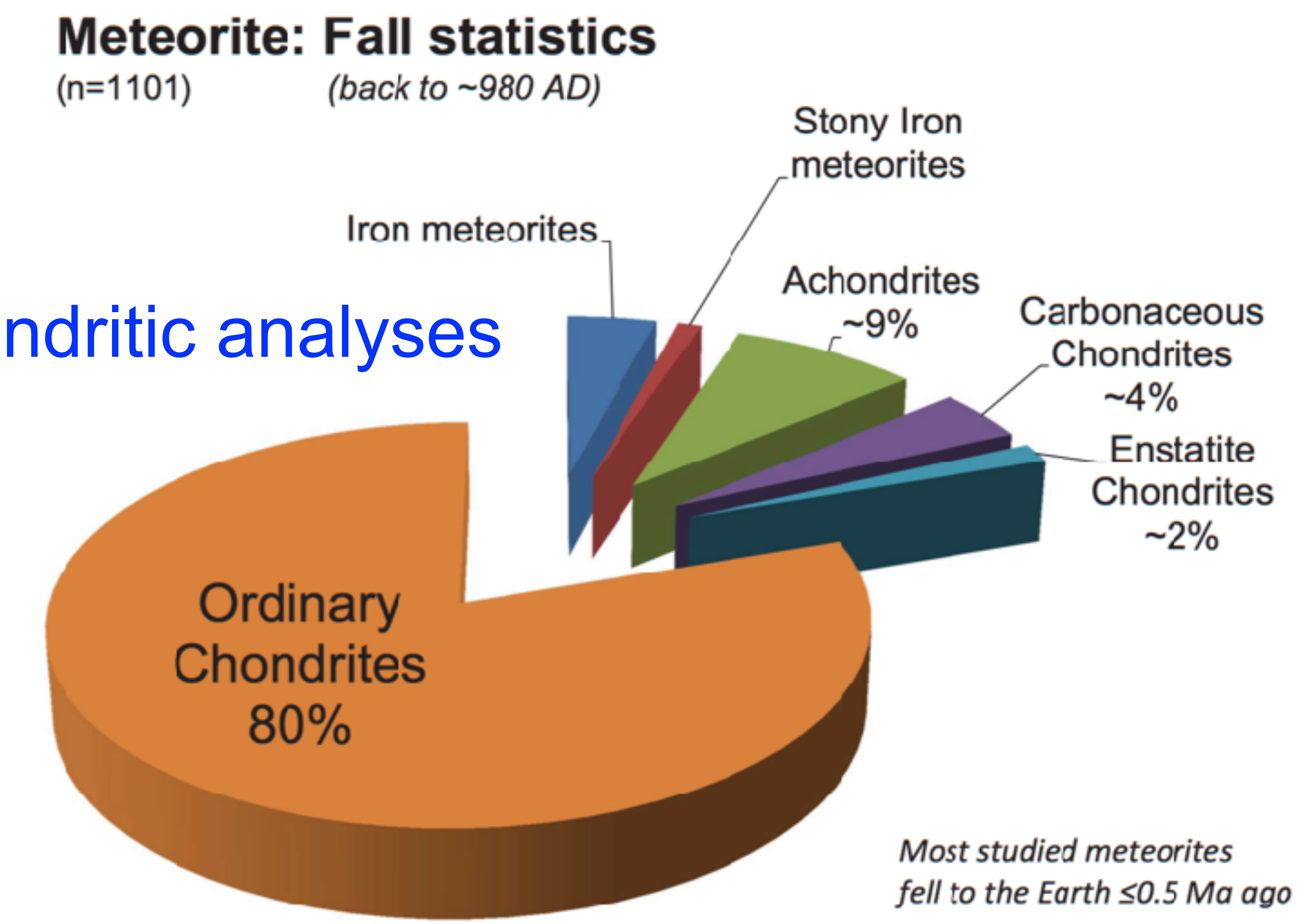
観測結果から得られる地球科学的知見

* Th/U比
* 放射化熱量
* マントルの寄与

▸Th/U 比 : Introduction

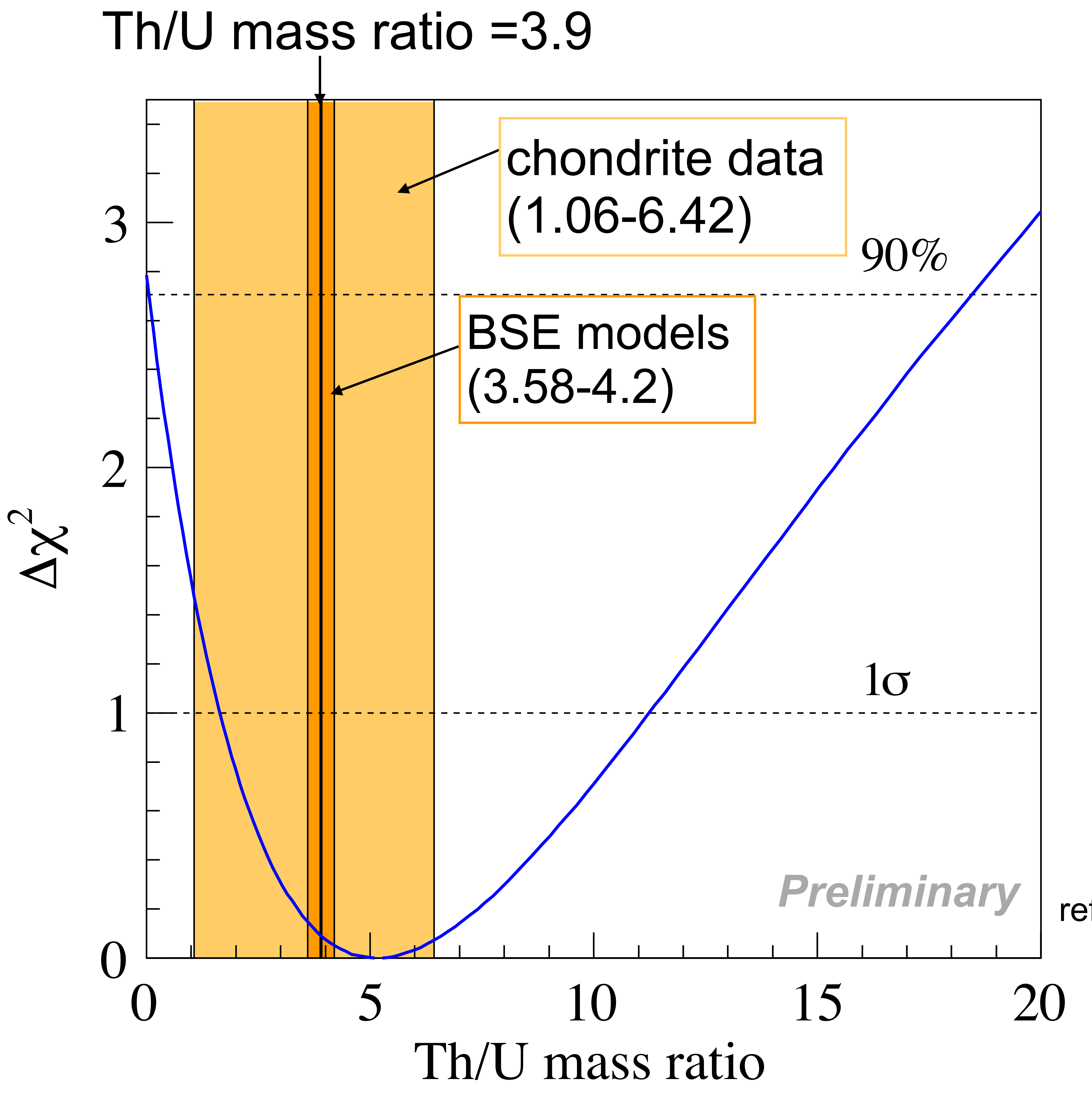
- ^{232}Th is more abundant than ^{238}U.
- Molar ratio (Th/U) in bulk silicate Earth is expected to be **3.9 ± 0.1.**

Chondritic analyses



地球ニュートリノ：**地球全体のTh/U比の独立した直接測定**

Th/U 比 : 観測結果



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.**

ref) chondrite data

Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

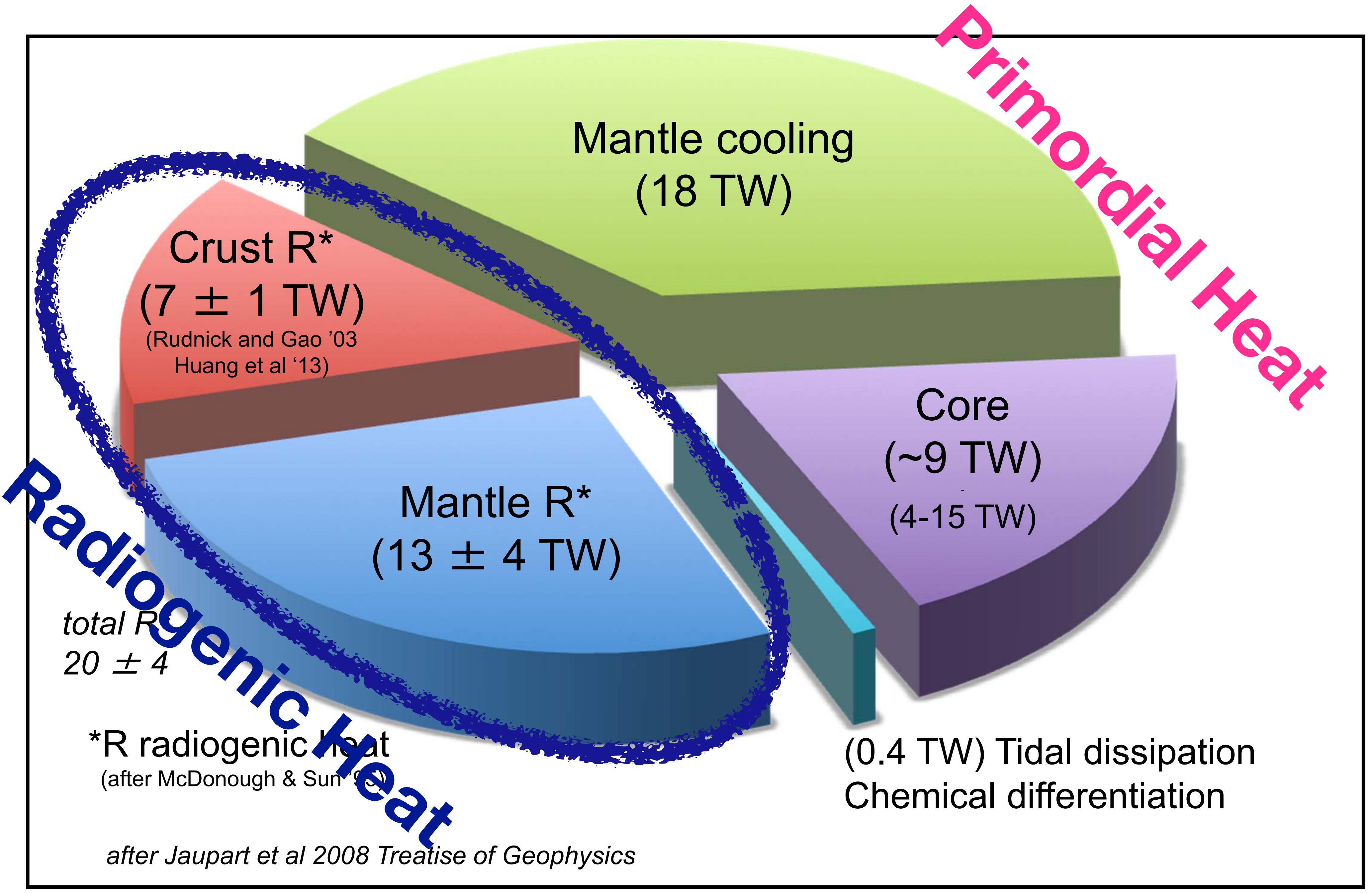
Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

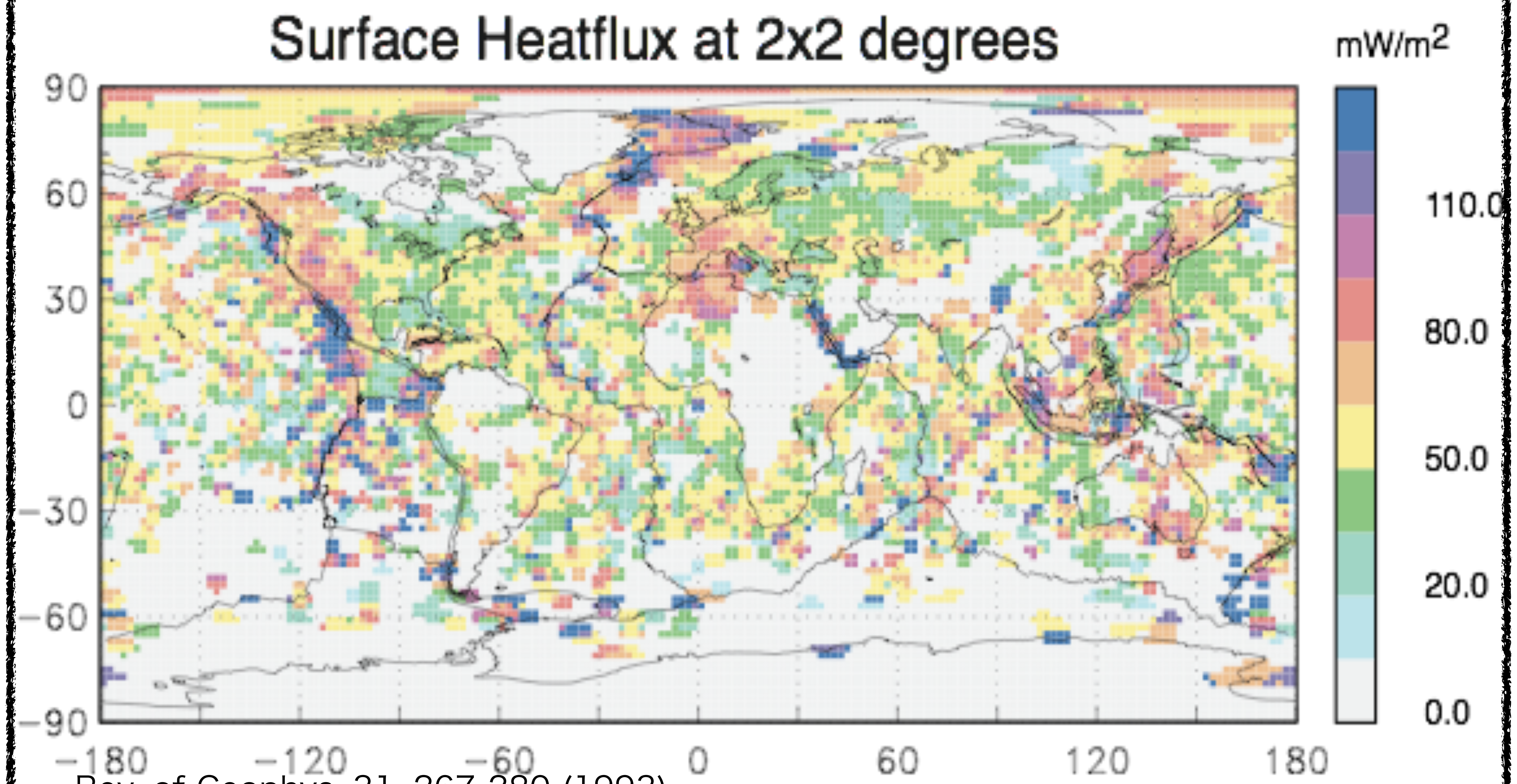
▶放射化熱量：地球の熱収支

Surface heat flow
46 ± 3 TW

example of Earth model



crust heat flux measurement & calculation



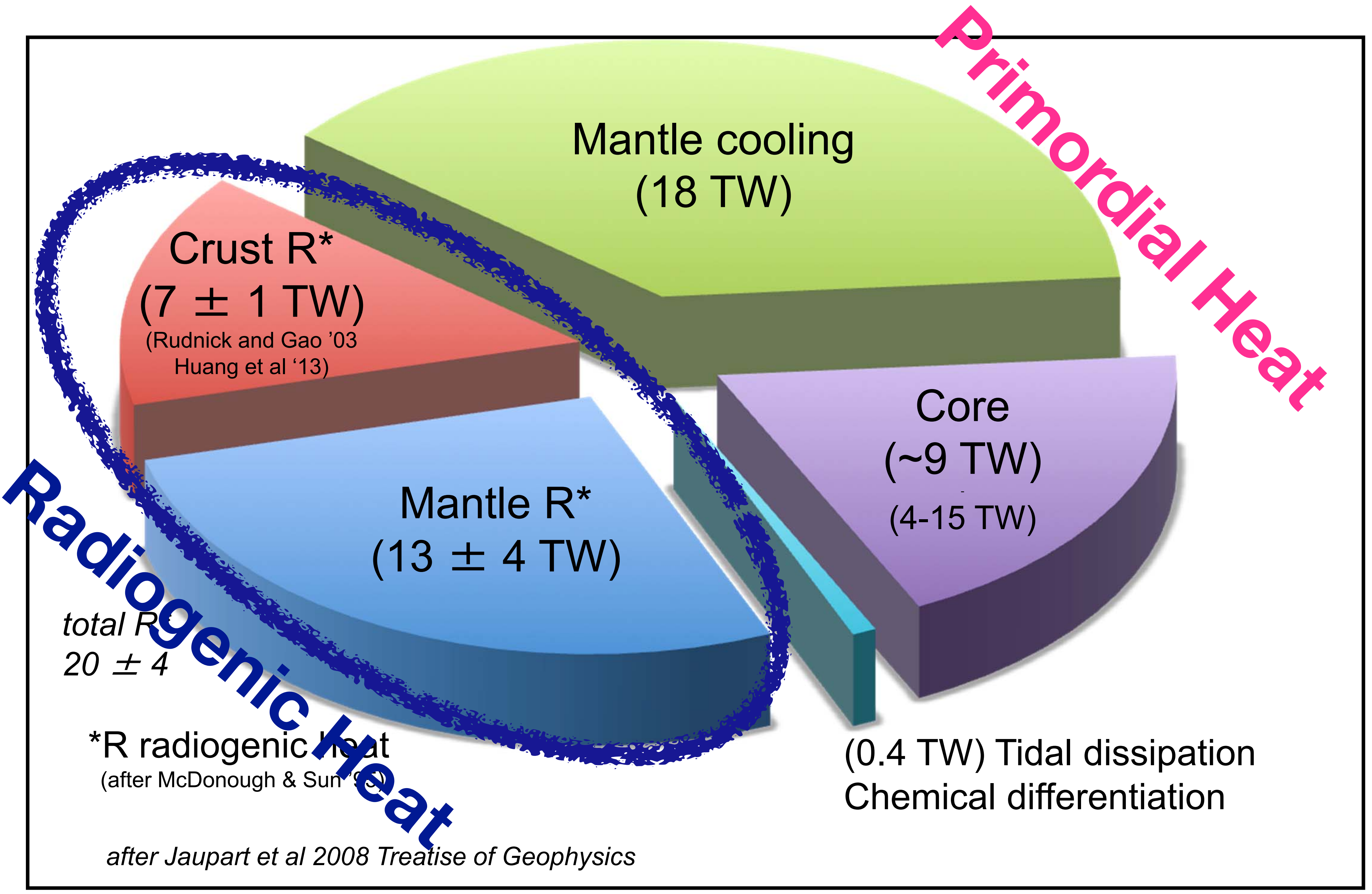
Rev. of Geophys. 31, 267-280 (1993)

Primordial Heat

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

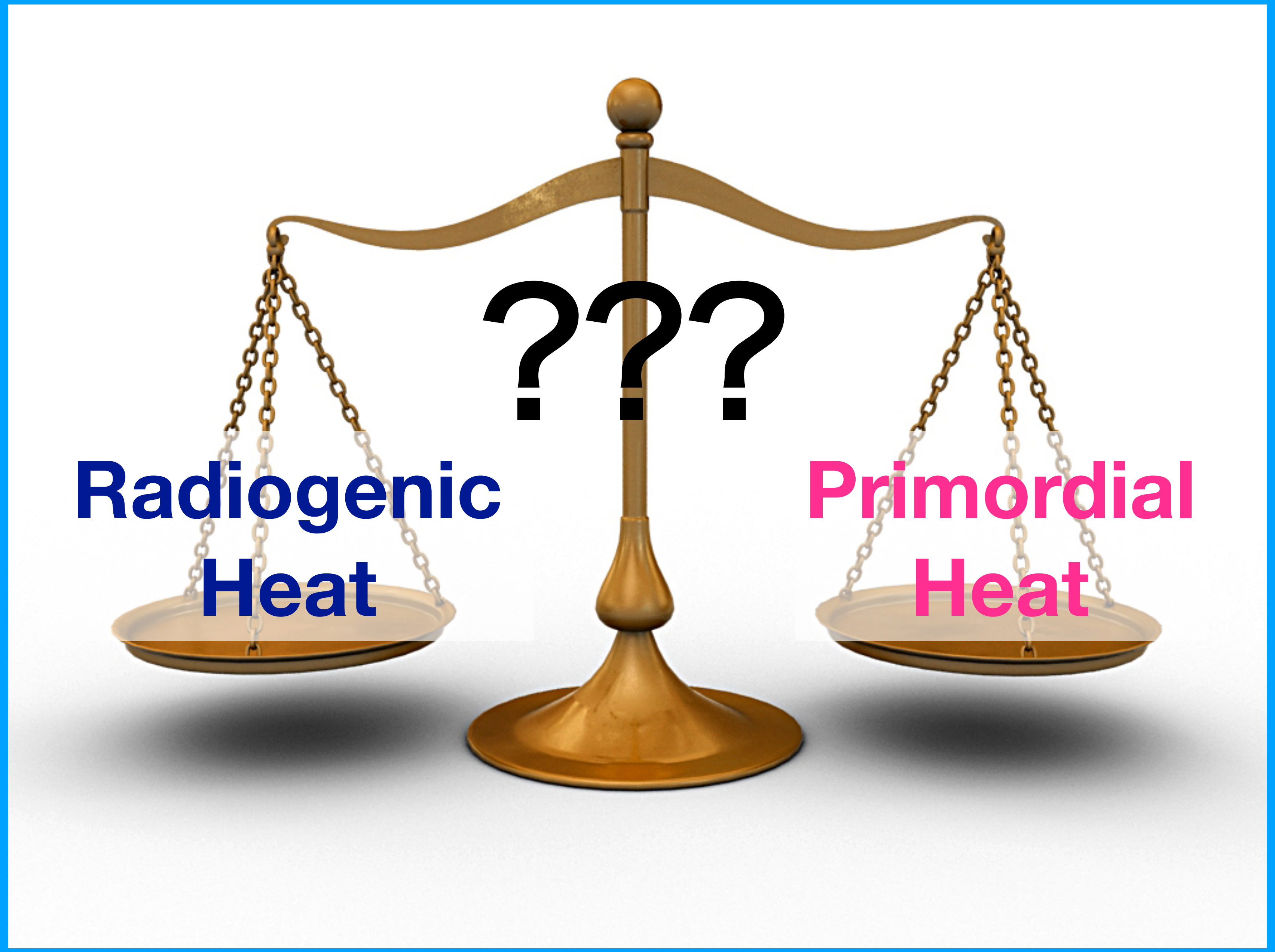
Surface heat flow
46 ± 3 TW

example of Earth model

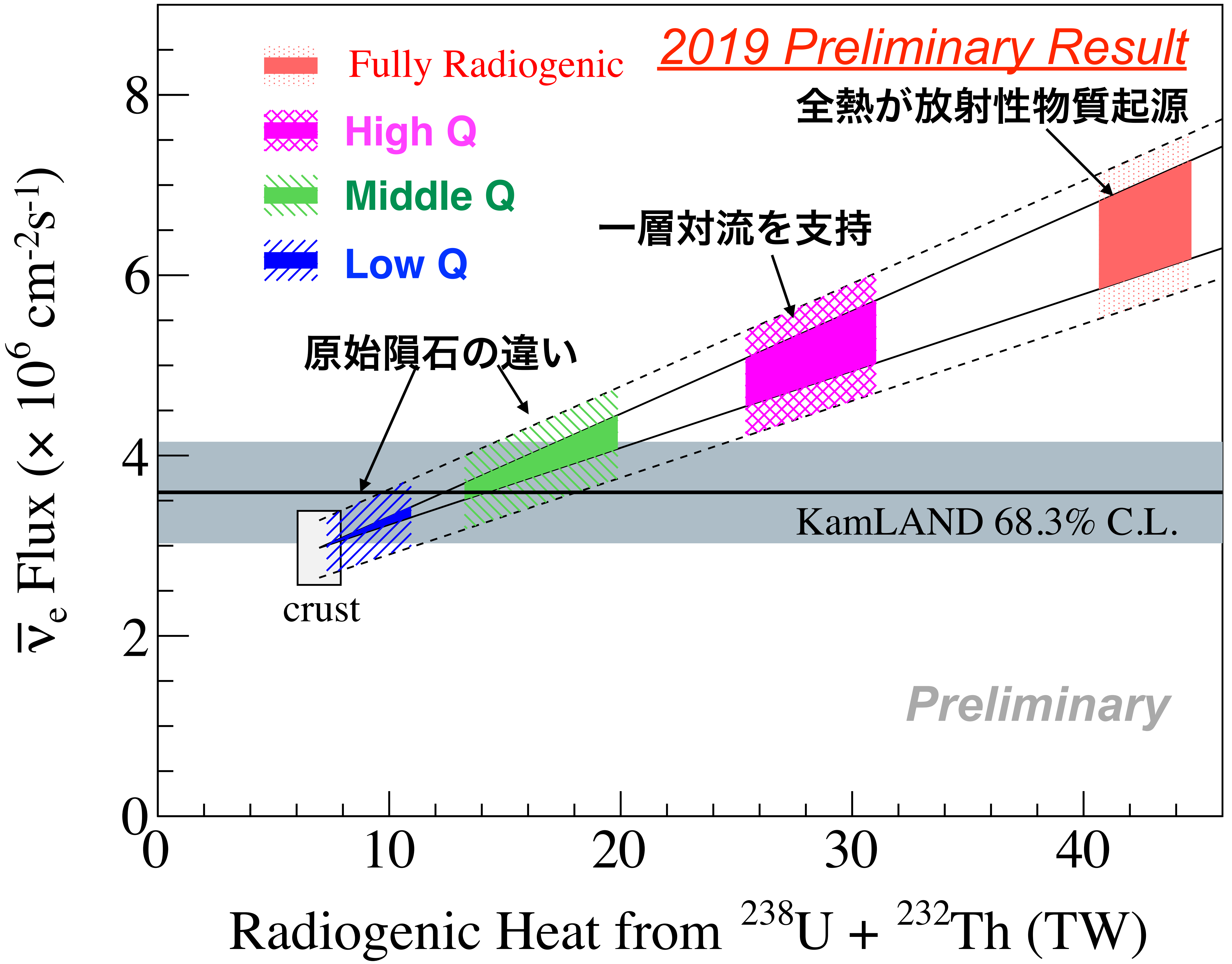


Primordial Heat
* Releases of gravitational energy through accretion or metallic core separation
* Latent heat from the growth of inner core

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



放射化熱量：観測結果

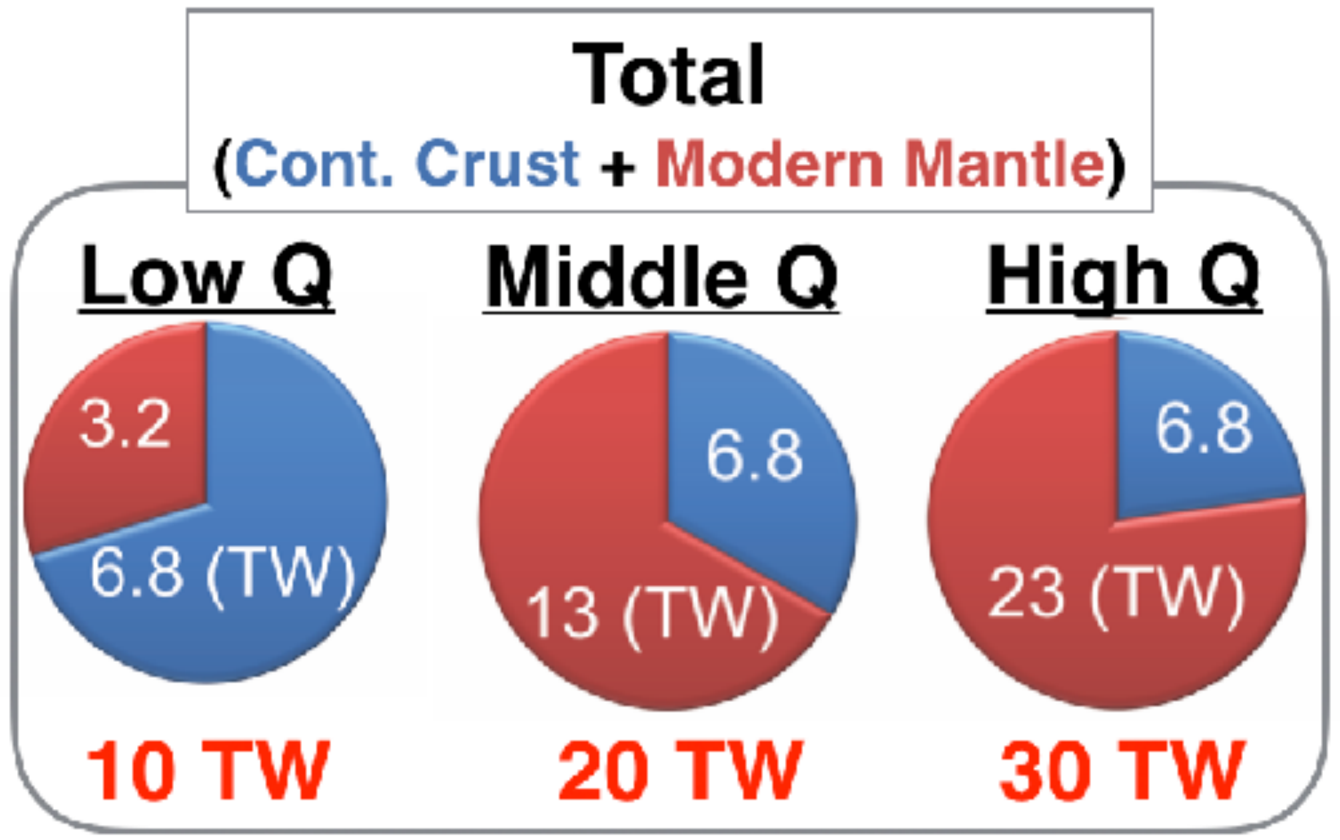


☑ Radiogenic Heat : **12.4 $^{+4.9}_{-4.9}$ TW**

(Mantle+Crust, U+Th)

Th/U = 3.9

K/U = 1.4 × 10^4



[BSE models]

High Q

based on balancing mantle viscosity and heat dissipation

Middle Q

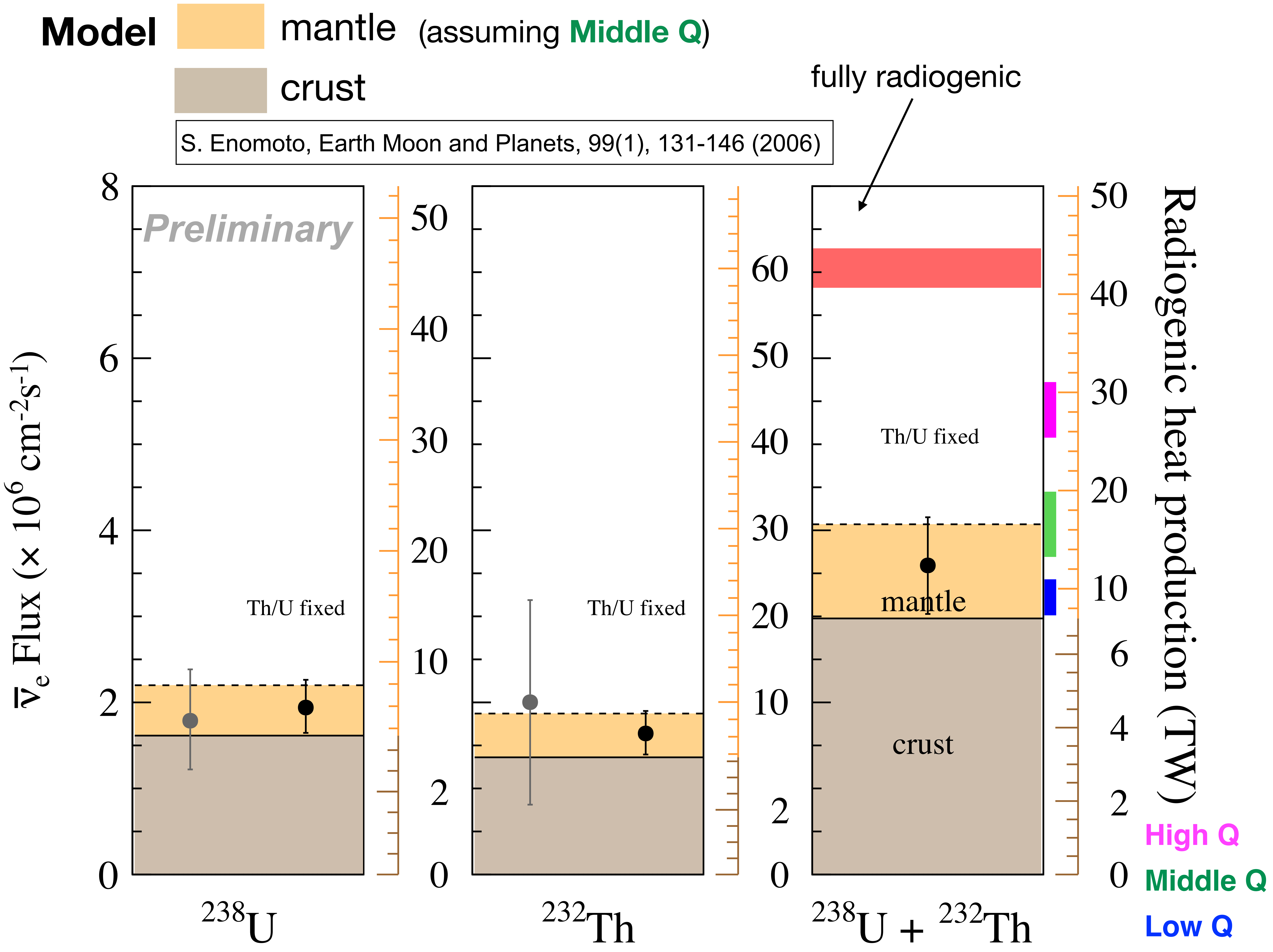
based on mantle samples compared with chondrites

Low Q

based on isotope constraints and chondritic models

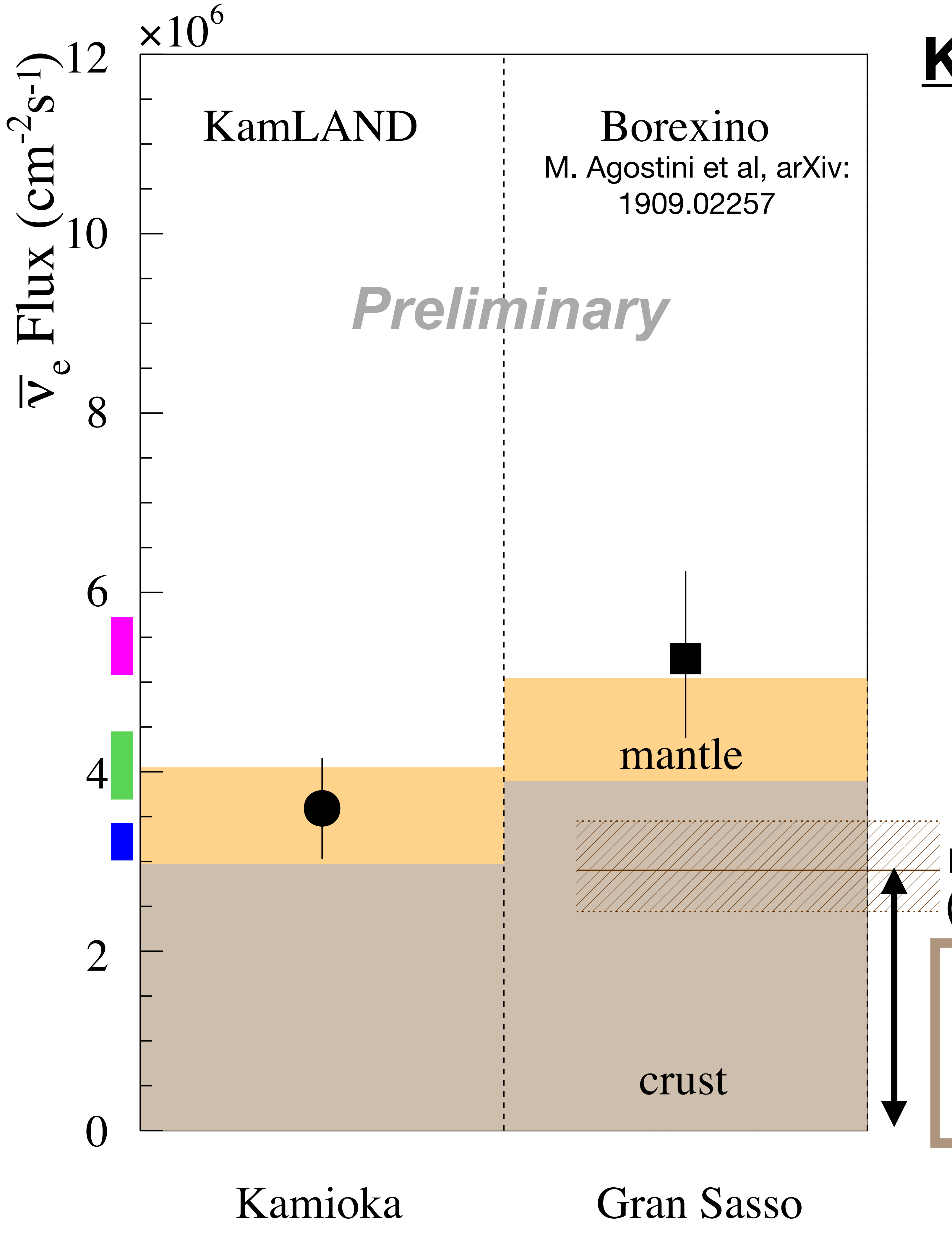
ref) Crust (U+Th) ~7 TW Enomoto et al. EPSL 258, 147 (2007) → Mantle (U+Th) ~5.4 TW

▸観測地球ニュートリノフラックスと予測モデルの比較



- ☑ ^{238}U と ^{232}Th の寄与を独立に観測
- ☑ 観測結果は地殻の寄与の予測量よりも多い
- ☑ 熱を放出する元素の現在のそれぞれの寄与を測ることで、地球のこれまでの放射化熱史を明らかにできる

▶マントルの寄与：KamLANDとBorexinoの結果



model estimation by Borexino
(~19% uncertainty)

LOC (local crust) = 9.2 ± 1.2 TNU
FFL (Far-Feild Lithosphere) = 16.3 +4.8/-3.7 TNU
(M. Agostini et al, arXiv:1909.02257, Table VI)

High Q
Middle Q
Low Q

mantle (assuming **Middle Q**)
crust

S. Enomoto, Earth Moon and Planets, 99(1), 131-146 (2006)

KamLAND

S(Mantle) = S(Observation) — S(Crust, Model)

S(Observation): $3.60^{+0.56}_{-0.57}$ $\times 10^{6}$ $cm^{-2}s^{-1}$

S(Crust, Model): $2.93^{+0.29}_{-0.29}$ $\times 10^{6}$ $cm^{-2}s^{-1}$ (10%)*

= **$0.67^{+0.63}_{-0.64}$ $\times 10^{6}$ $cm^{-2}s^{-1}$**
→ $6.0^{+5.6}_{-5.7}$ TNU

☑**High Q model is rejected with >2 σ**

>1σ tention

Borexino

M. Agostini et al, arXiv: 1909.02257

Mantle signal (median value)

$23.7^{+10.7}_{-10.1}$ *events*

$21.2^{+9.6}_{-9.1}$ *TNU*

* Recent approach of geo-neutrino flux calculation model
- indicating there is significant systematic uncertainty (60-70 %)
- trying to understand sources of uncertainties

N. Takeuchi et al. (PEPI 6222, 2019)

Summary

- 地球ニュートリノ観測は地球内部を直接観測できるユニークなツール

- **最新結果 (2019年10月)**
  - 低原子炉運転期間
    - ~4.8 年 (全livetimeの40%)
    - **地球ニュートリノの明瞭なエネルギースペクトルの観測** → **UとThのそれぞれの寄与をより良く理解**
  - 地球ニュートリノ事象観測 : **15.6 % の不定性**
  - 地球科学的知見
    - **Th/U比** : **5.3 $^{+6.0}_{-3.6}$**, 隕石分析結果・BSEモデルと無矛盾
    - **放射化熱** : **12.4 $^{+4.9}_{-4.9}$ TW** (マントル+地殻, U+Th), Middle Q・Low Qモデルを好む結果
    - **^{238}U・^{232}Th地球ニュートリノの独立した寄与の観測** → **これまでの放射化熱史を明らかにできる**
    - **マントルの寄与 : 0.67 $^{+0.63}_{-0.64}$ × 10^6 cm^{-2}s^{-2}** → *** High Qモデルは2σ以上で排除**
      *** 地殻の寄与の計算モデルへの依存が大きい**

- **将来展望:**
- KamLANDは低原子炉バックグラウンドデータの観測を継続
- 地殻モデルのより良い理解 → **マントルの寄与の見積もりをより高信頼度化**
- **多地点観測の拡大 (KamLAND, (Borexino), SNO+, JUNO, Jinping)**
- **Ocean Bottom Detector: マントル直接観測へのブレークスルー** (ポスター: 酒井君)