Results and Prospects on Geo-Neutrinos

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for KamLAND Collaboration

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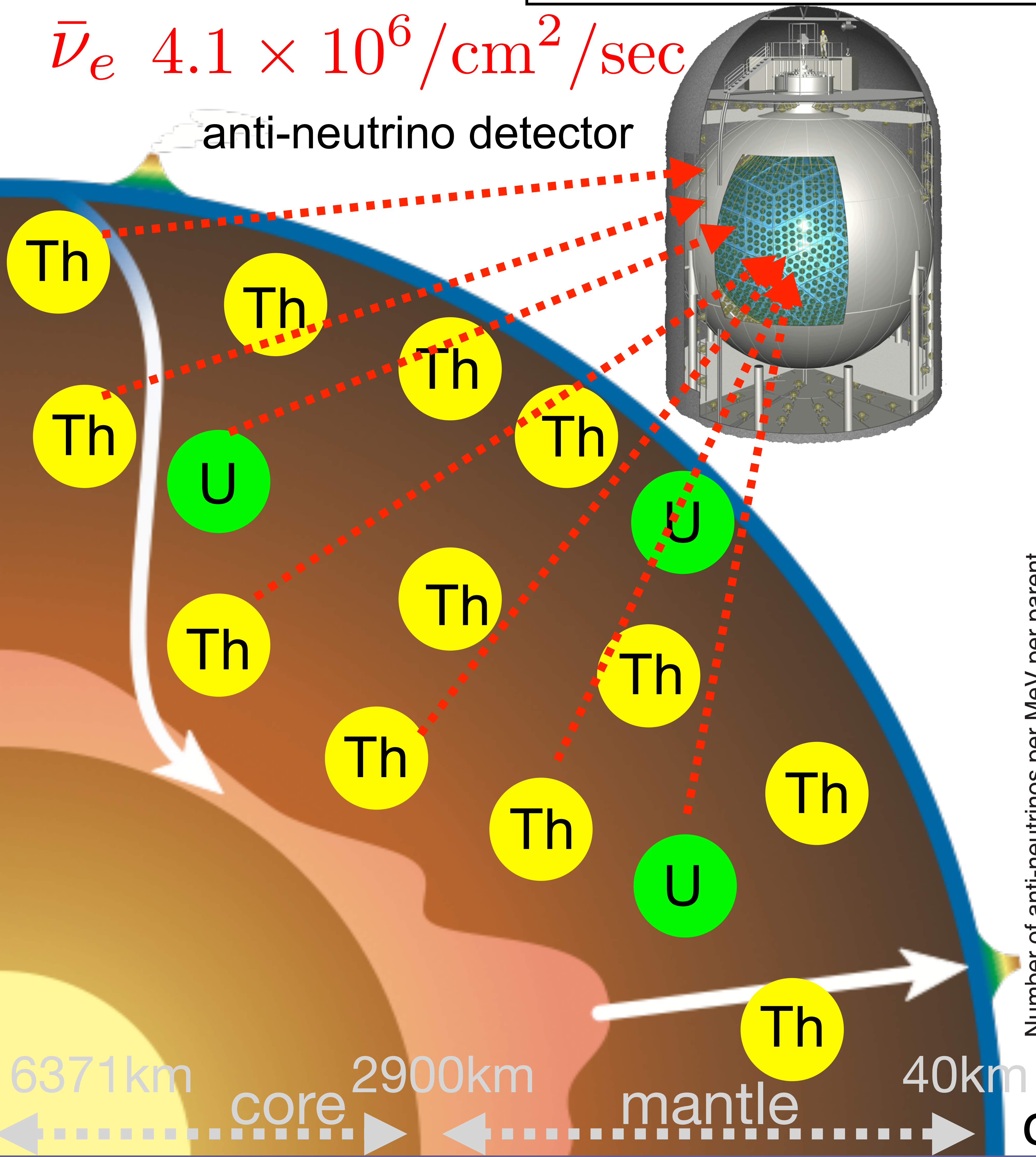
Contents

What is geo-neutrino?

Electron-antineutrino from <u>natural radioactive decay</u>

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



β-decay

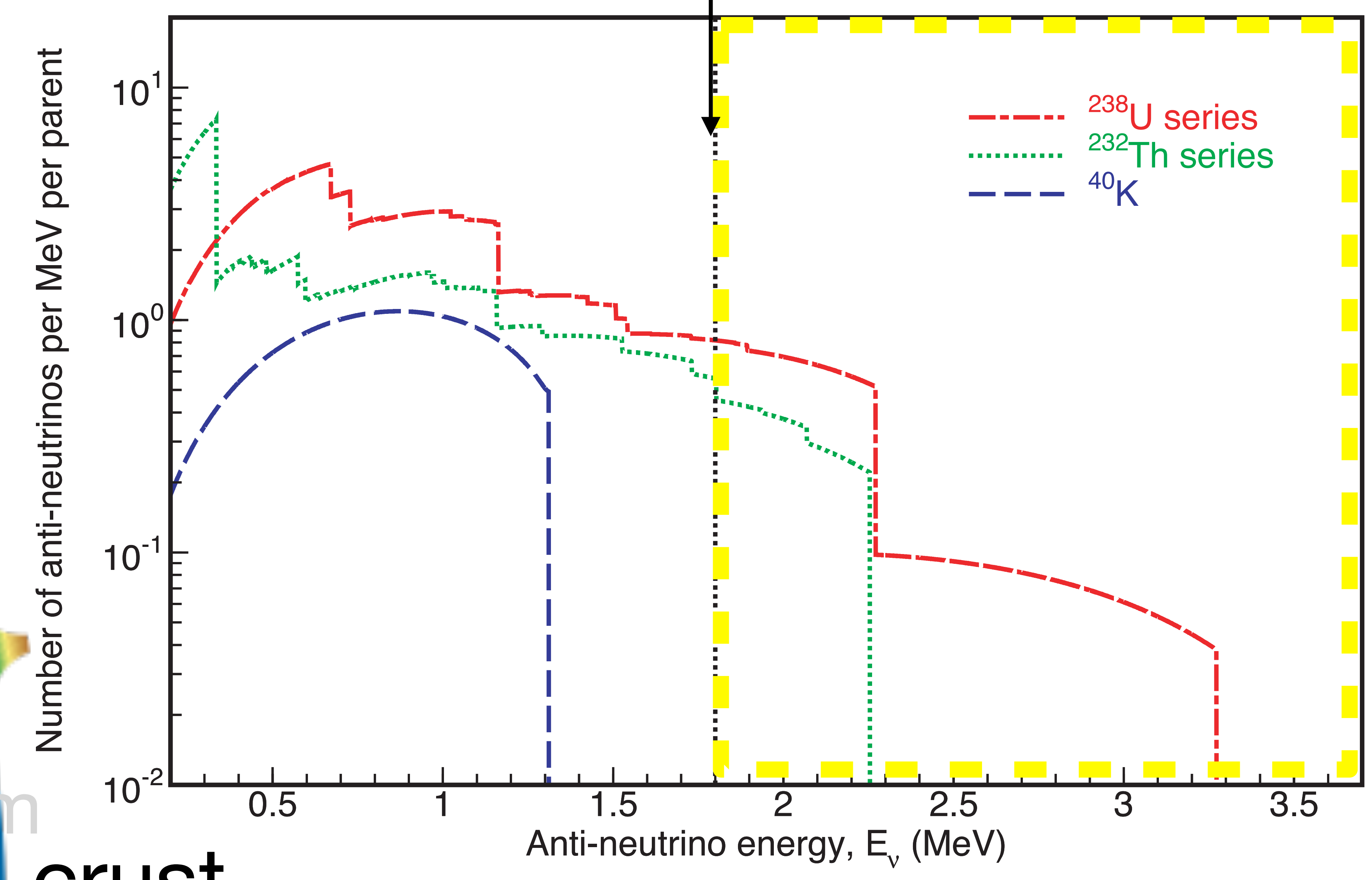
Geo-neutrinos

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

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

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

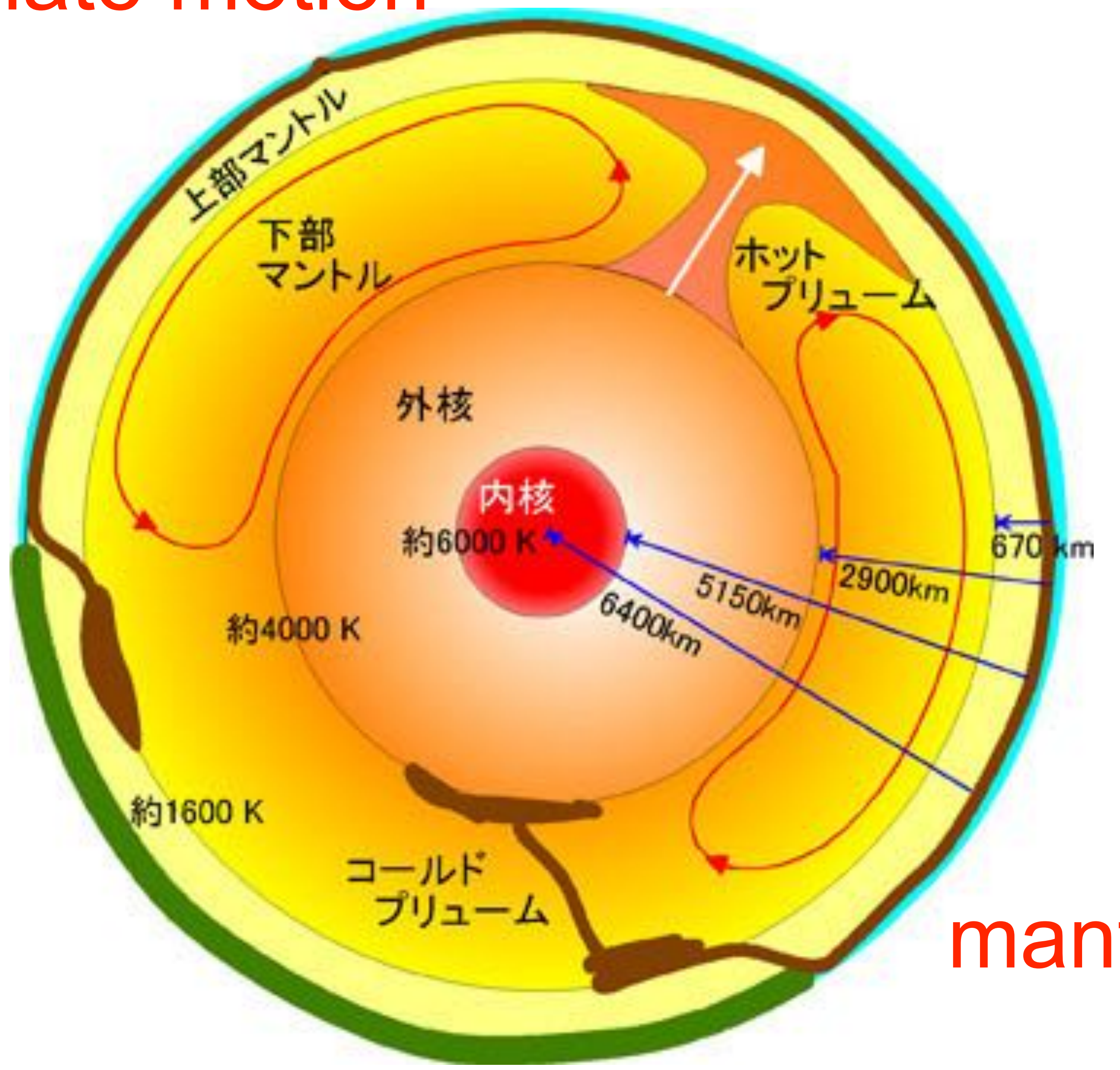
Energy threshold, 1.8 MeV

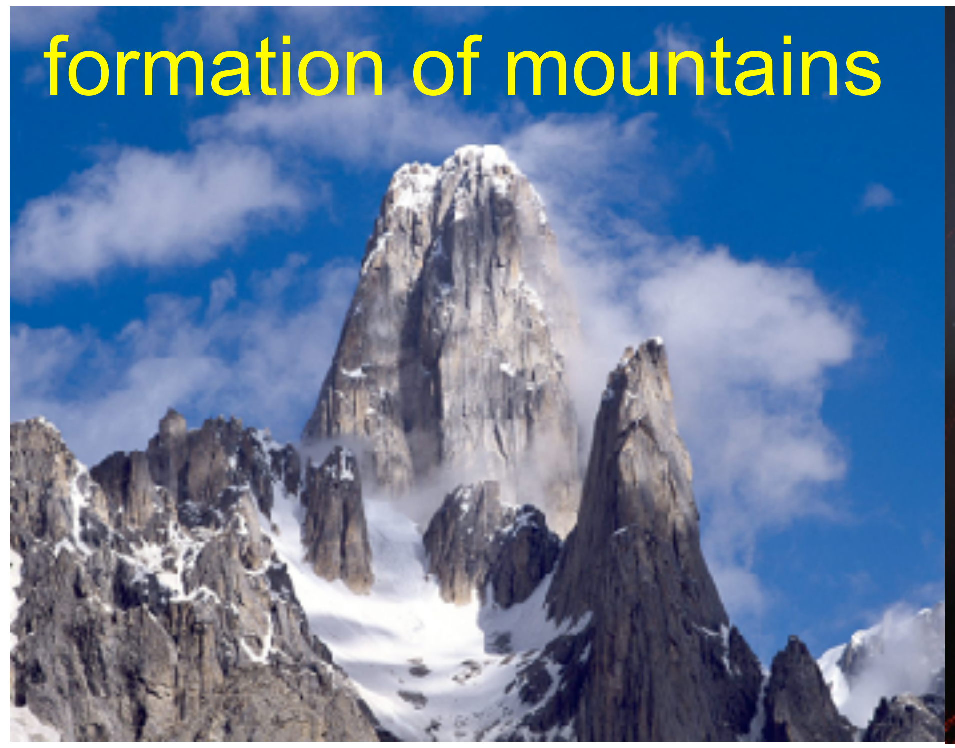


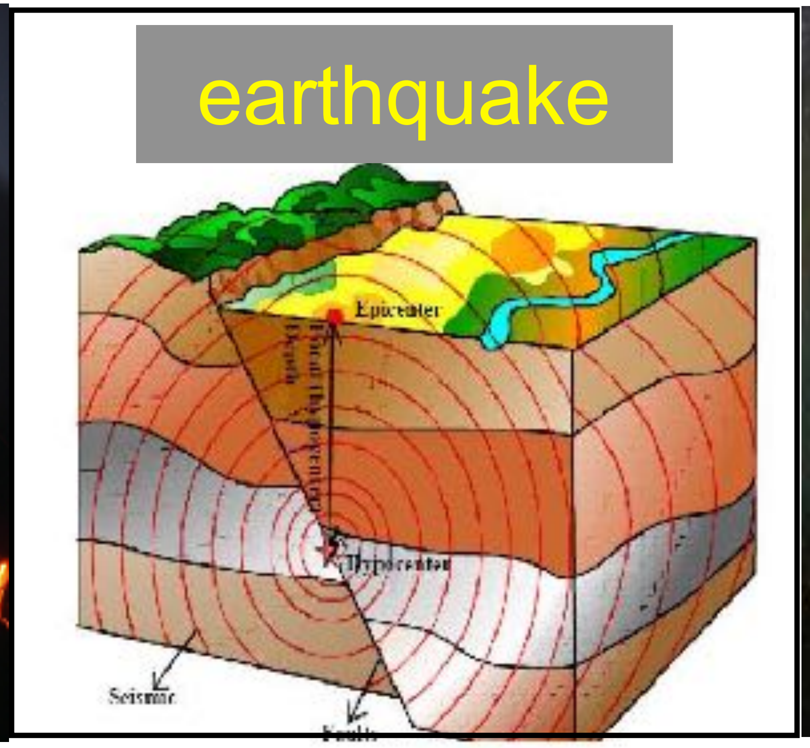
*Only geo-neutrinos from U and Th are detectable right now.

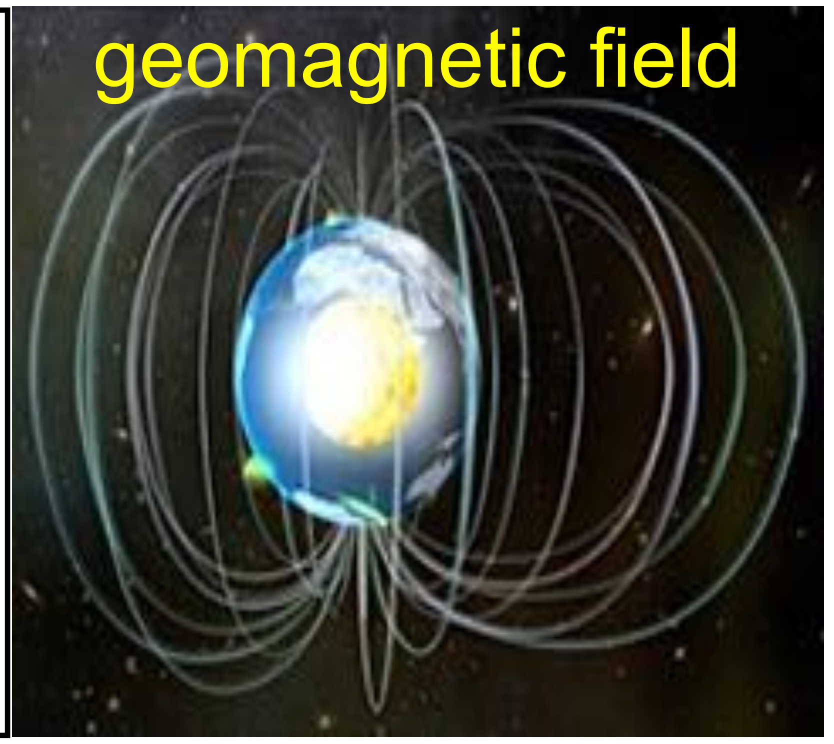
*K geo-neutrinos require new type detector

Why geo-neutrino?









Question on geophysical activity

- What are energy sources? How much energy?
- How is the mantle convecting, single or multi-layer convection?
- What is driving source of geodynamo?

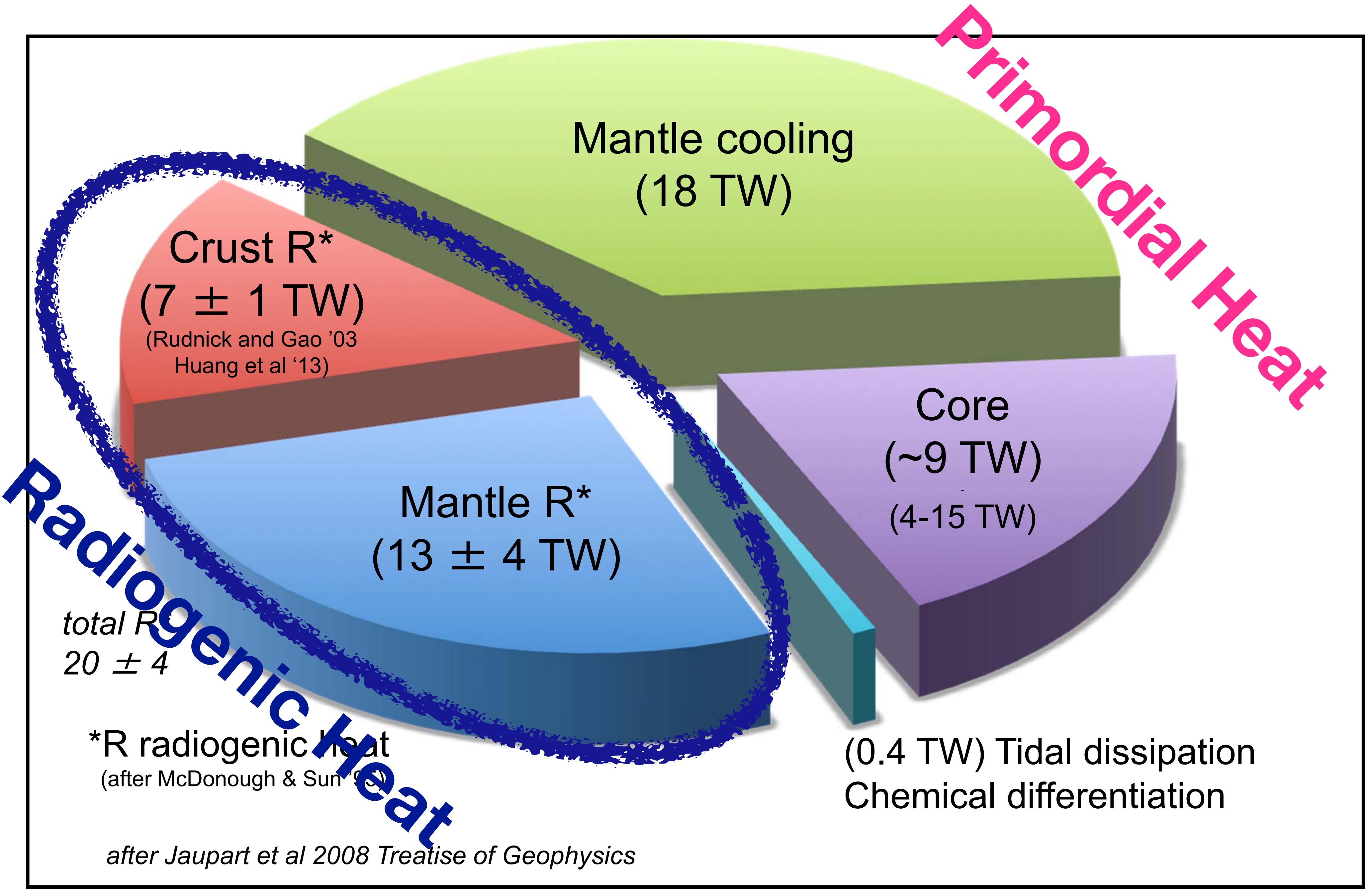
→ It is important to find out the terrestrial heat.

Earth's Heat Balance

☑ Surface heat flow

46 ± 3 TW

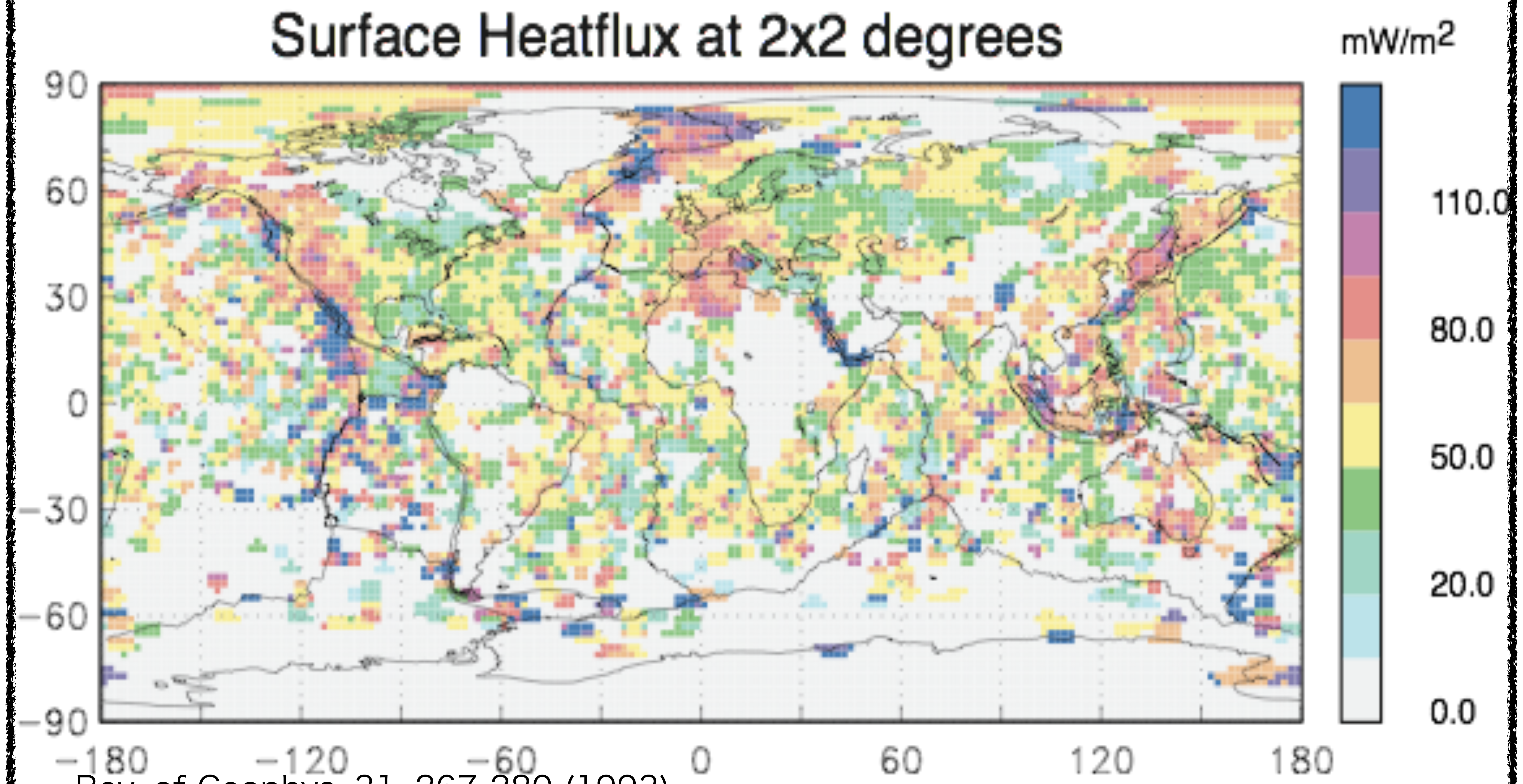
example of Earth model



Primordial Heat

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

crust heat flux measurement & calculation

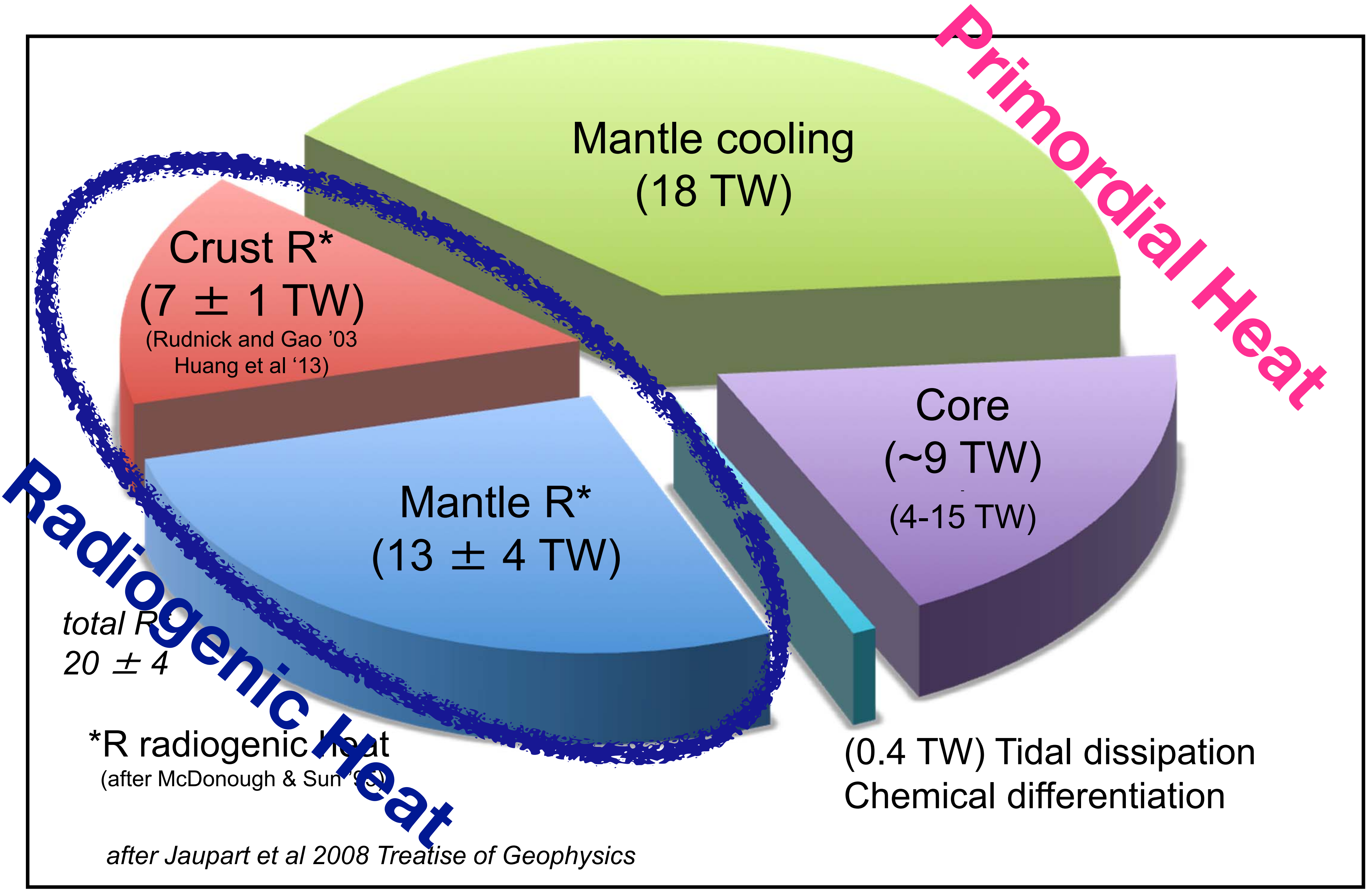


Rev. of Geophys. 31, 267-280 (1993)

Earth's Heat Balance

Surface heat flow
46 ± 3 TW

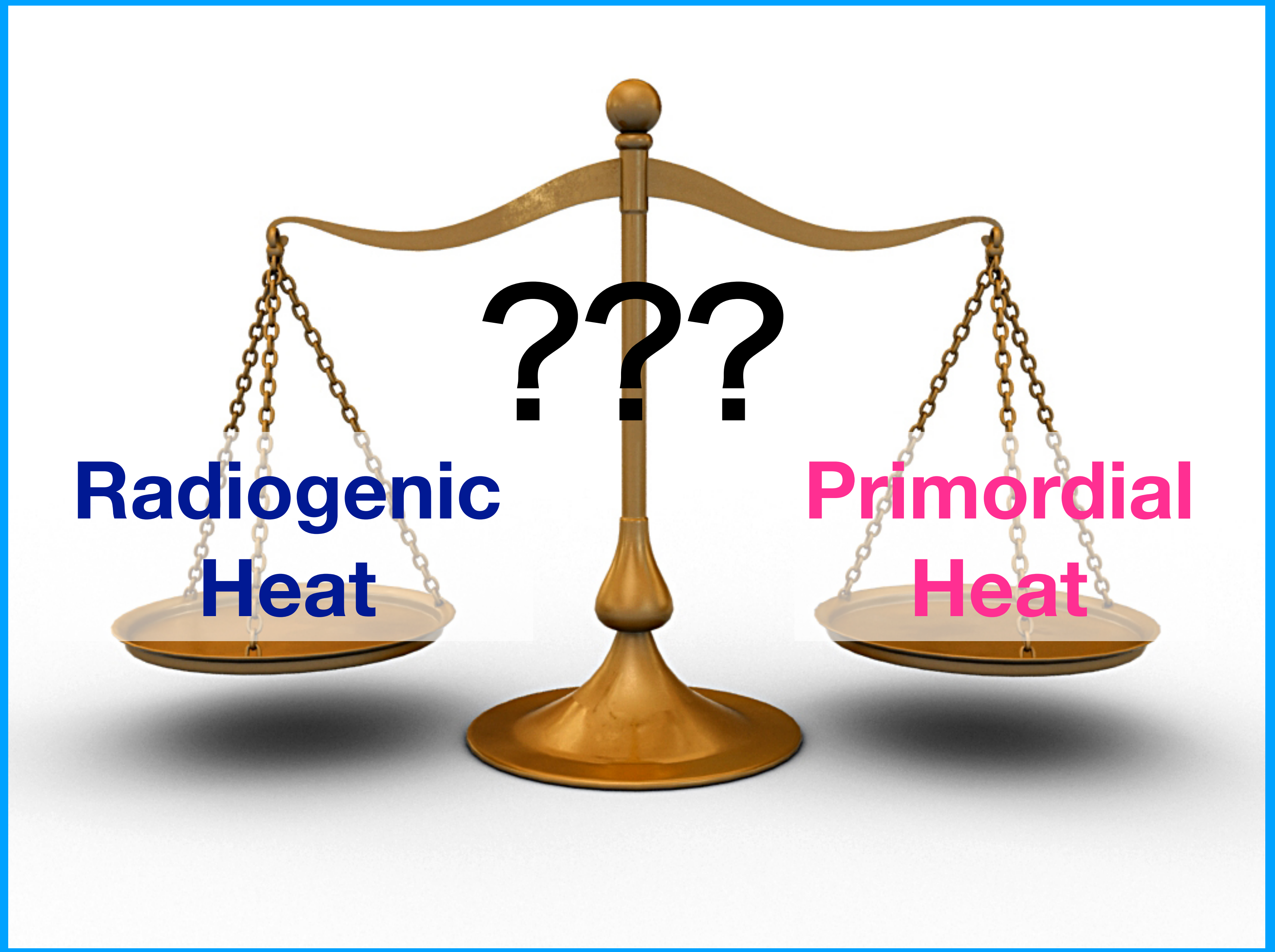
example of Earth model



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?



Earth's Heat Balance

☑ Surface heat flow
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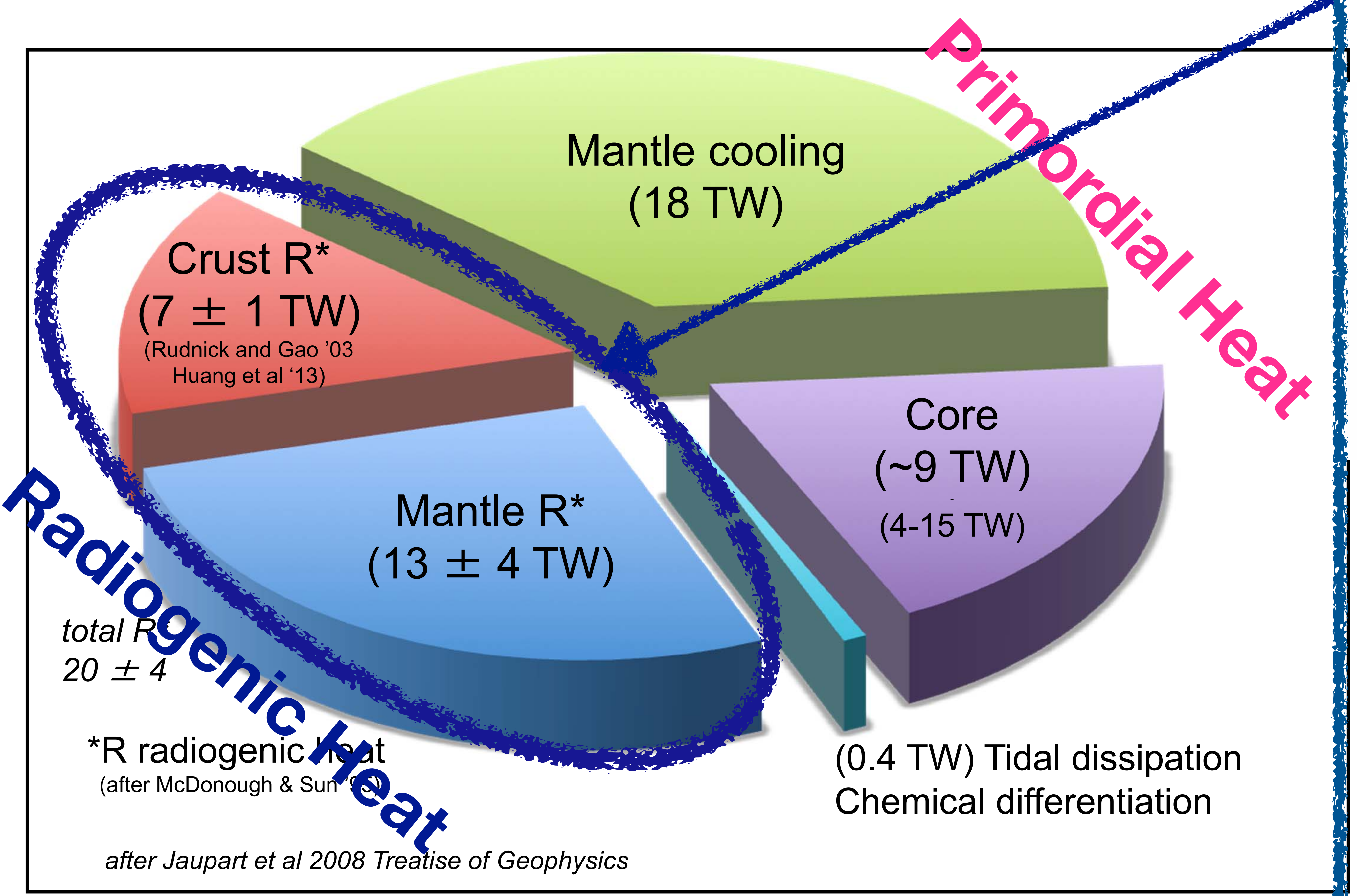


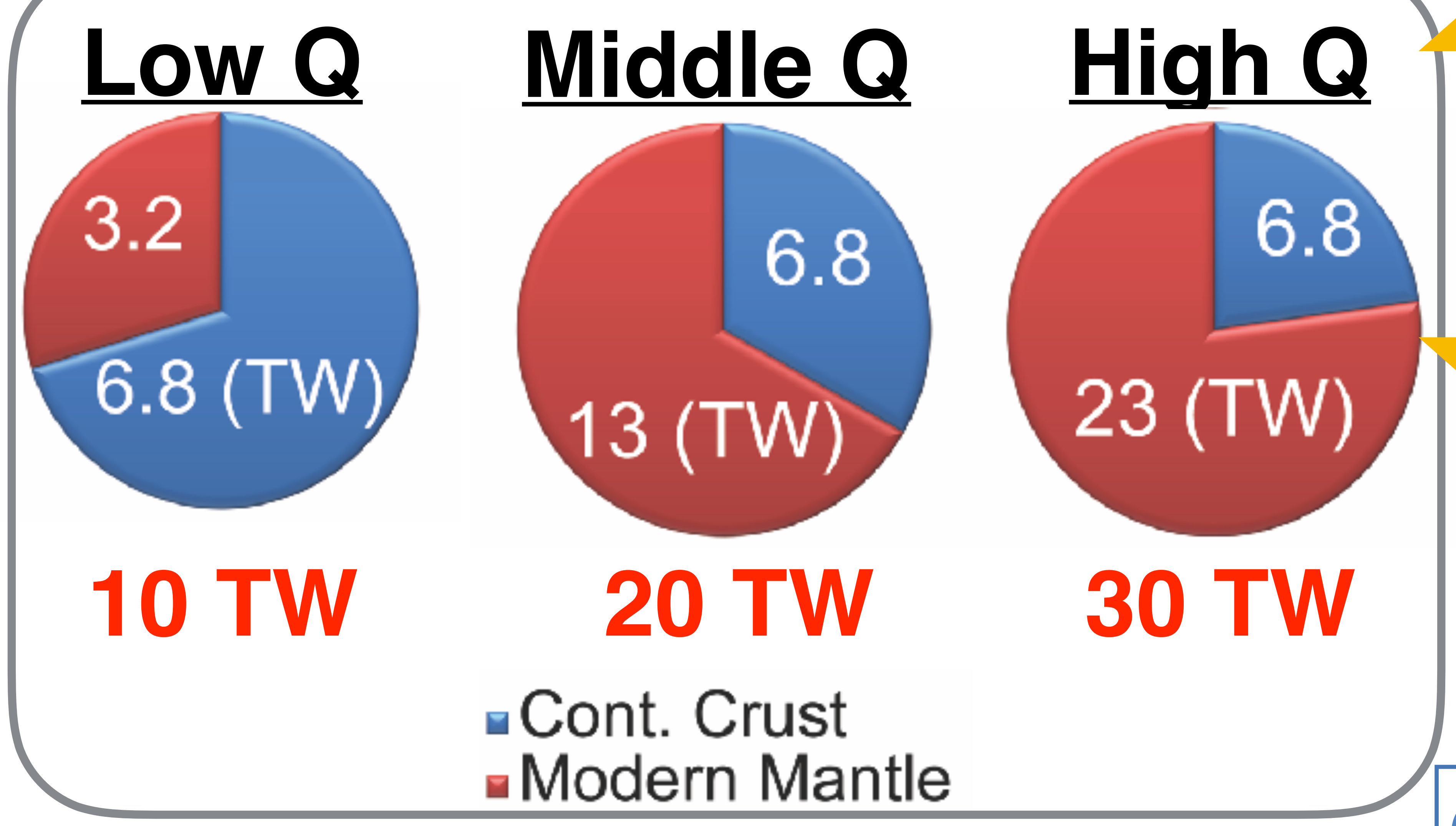
Primordial Heat

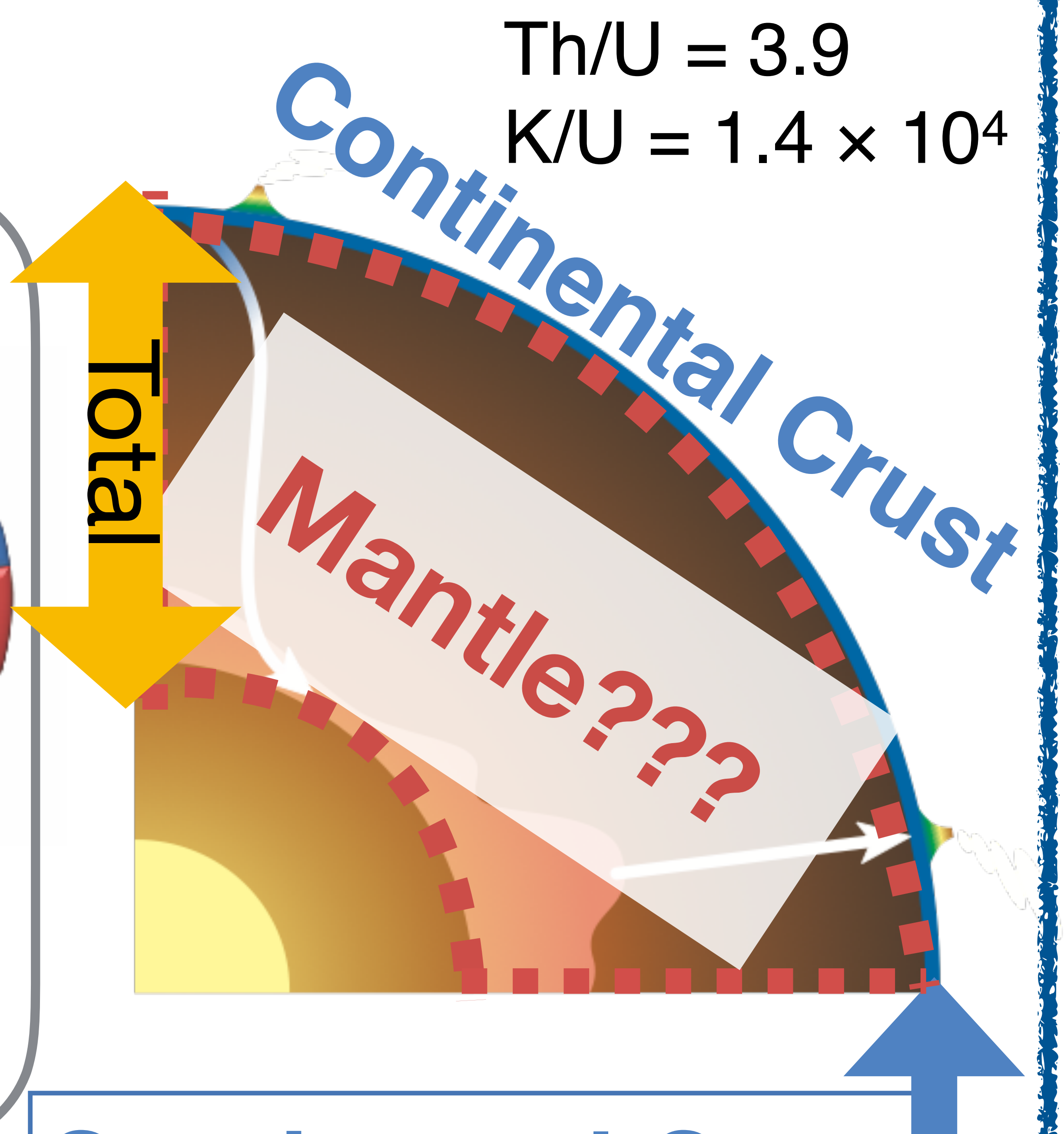
* Releases of gravitational energy through accretion or metallic core separation
* Latent heat from the growth of inner core

Bulk Silicate Earth (BSE) models

composition of chondrite meteorite

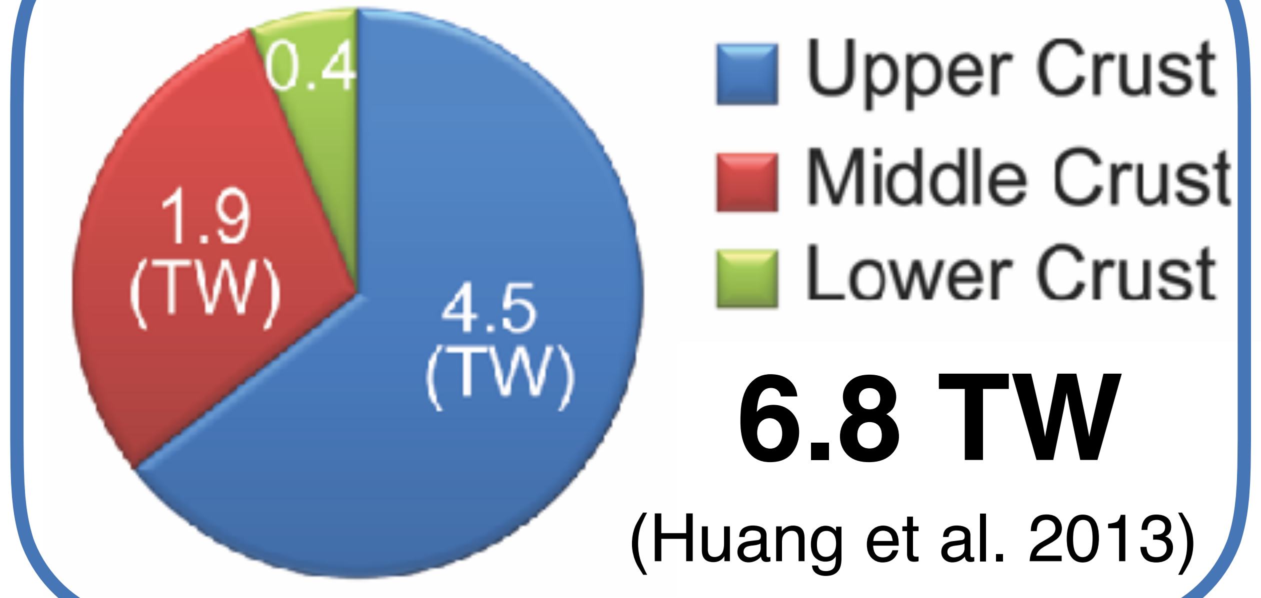
Total
(Cont. Crust + Modern Mantle)





Q : Which model can explain current Earth?

Continental Crust

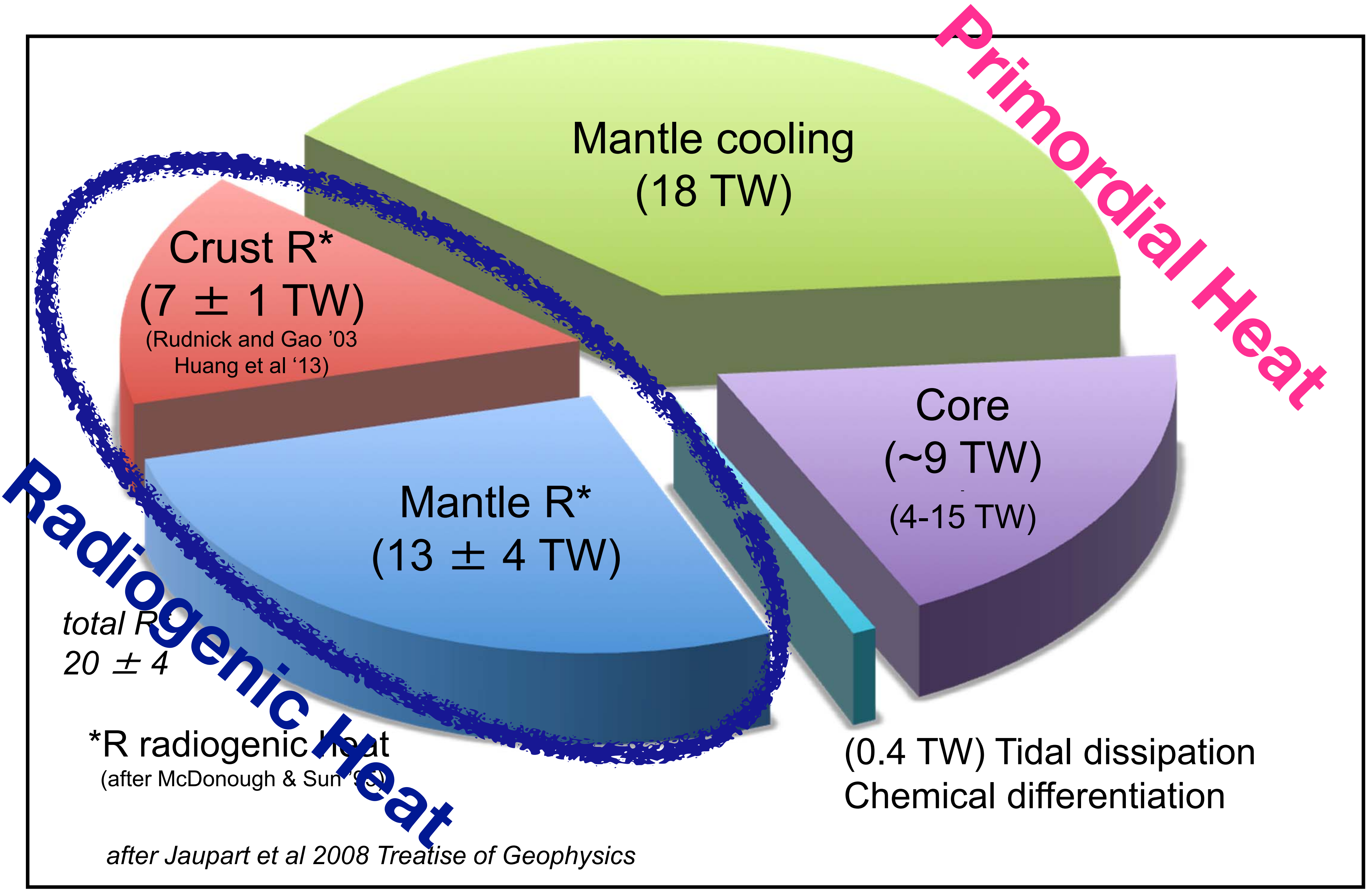


6.8 TW
(Huang et al. 2013)

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?

Q : Which model can explain current Earth?

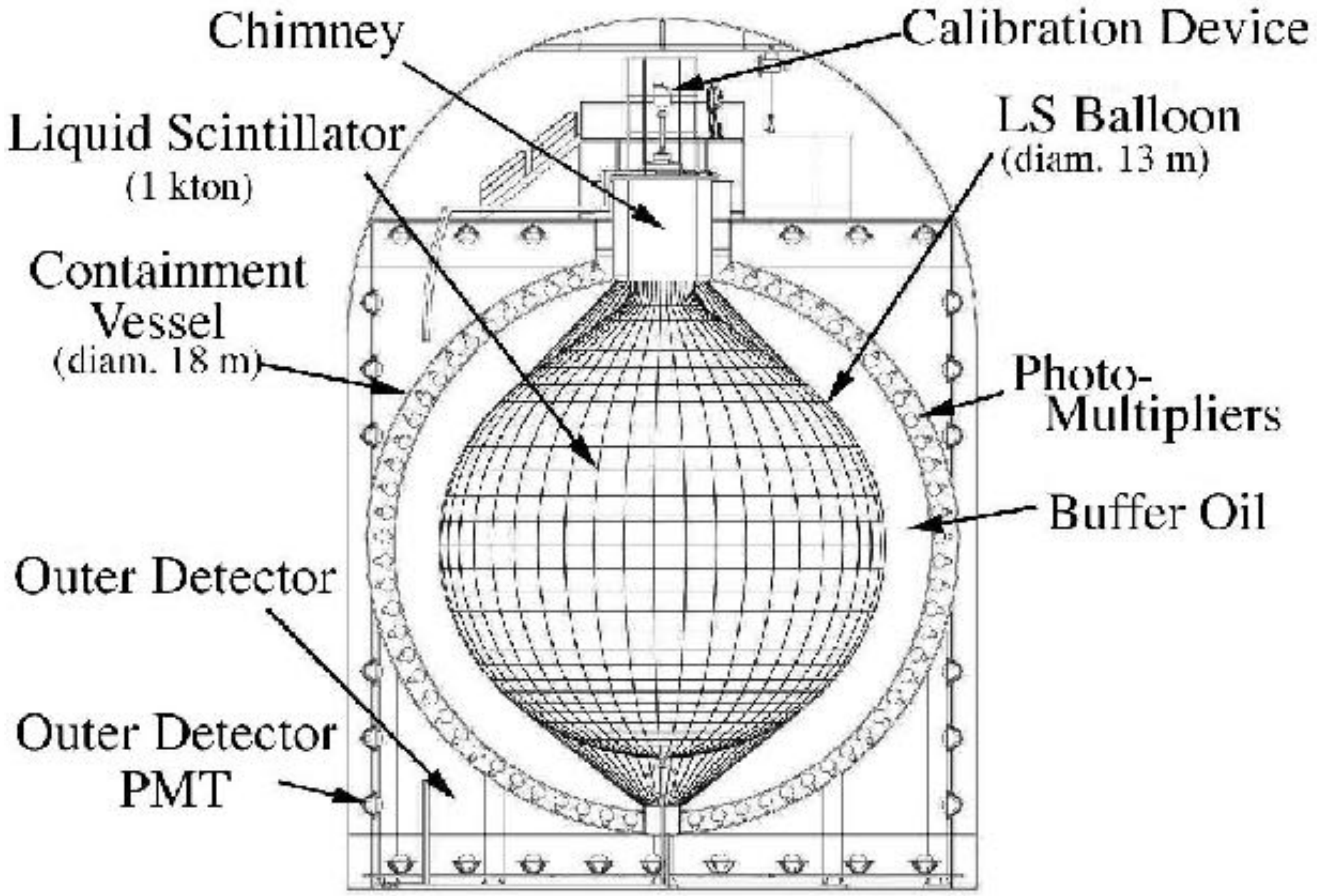
Geo-neutrino can directly define power to drive the Earth's engine

Contents

KamLAND and Borexino

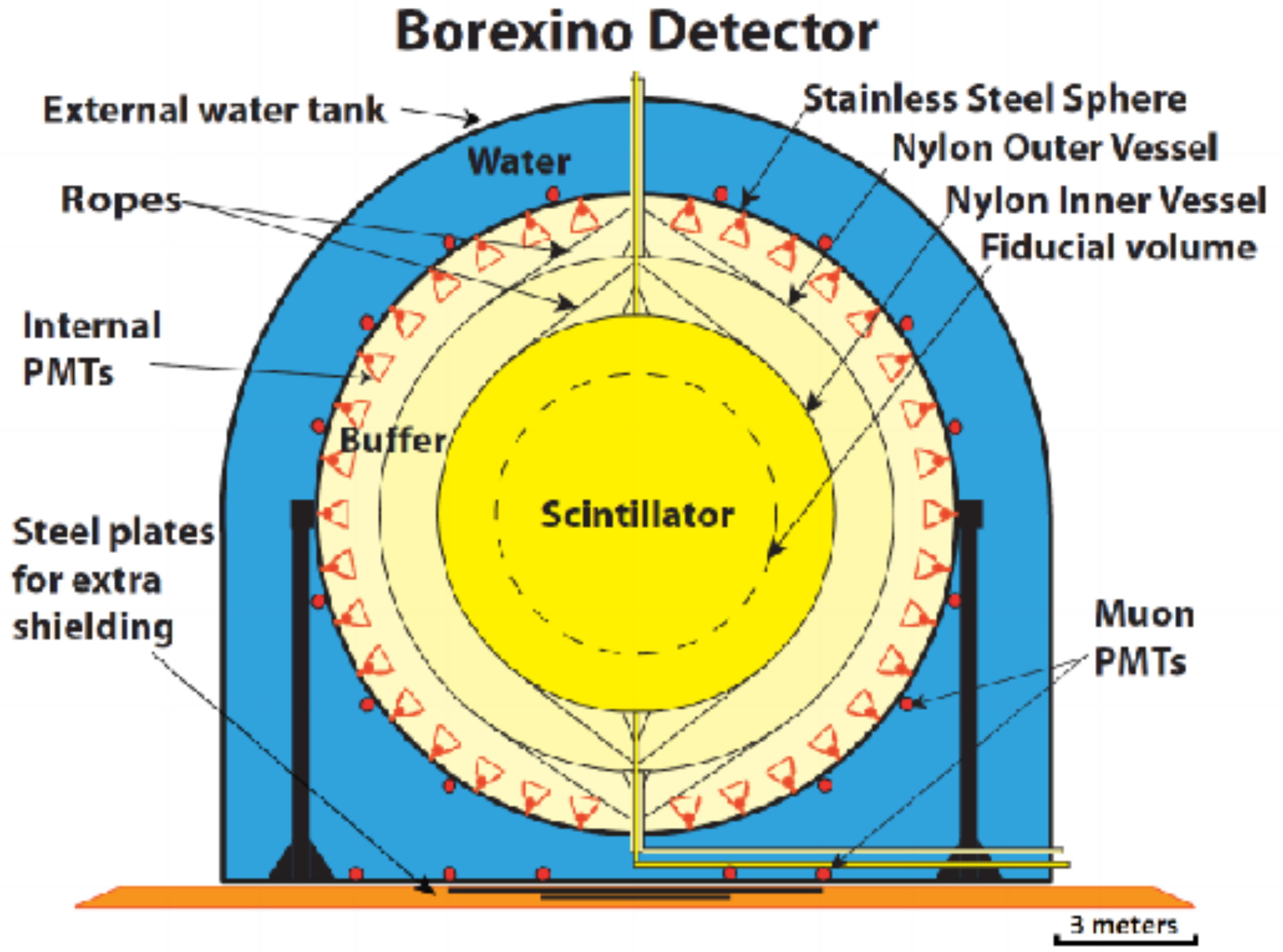
Two running liquid scintillator (LS) experiments have measured geoneutrinos.

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~)

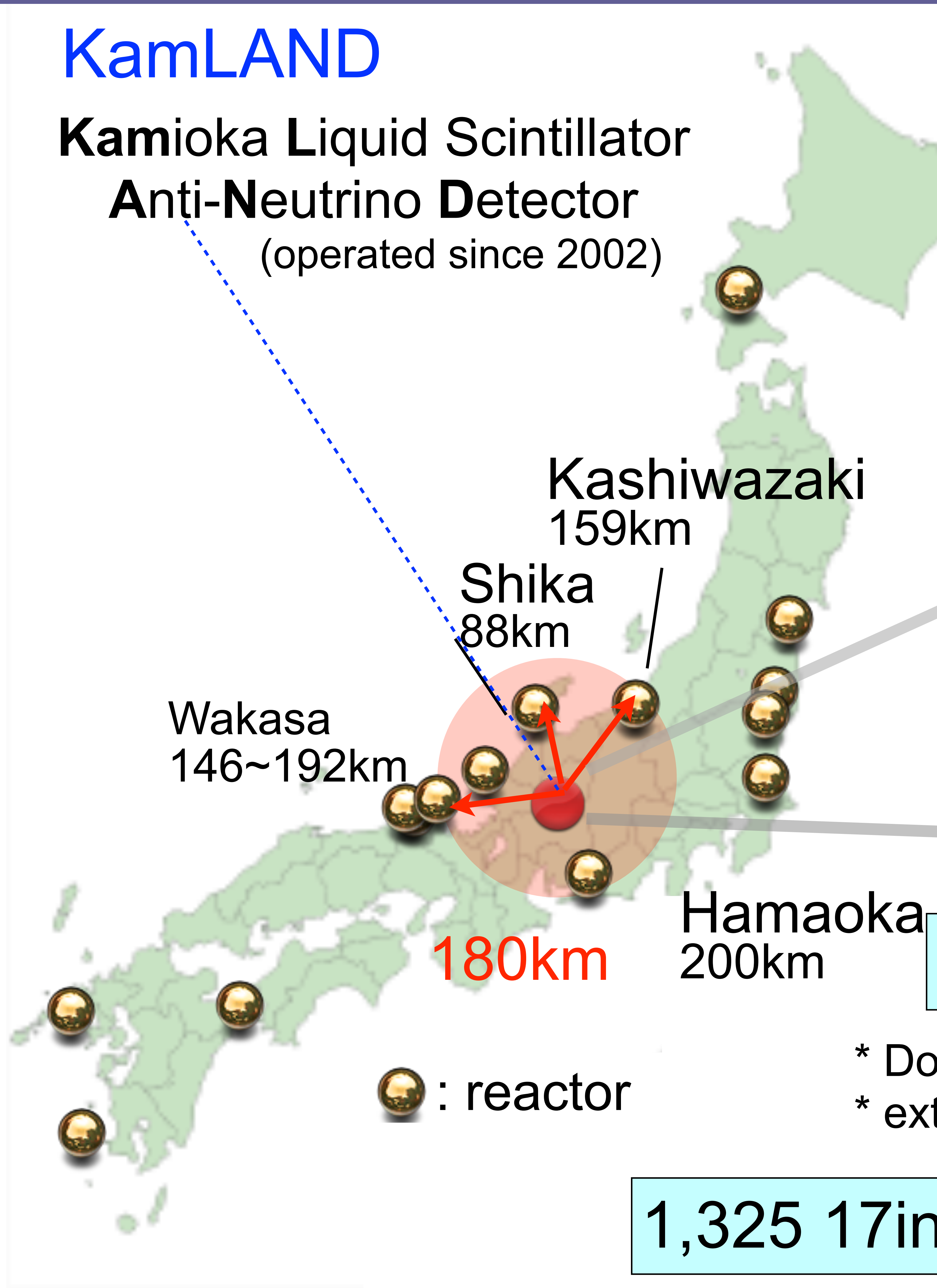


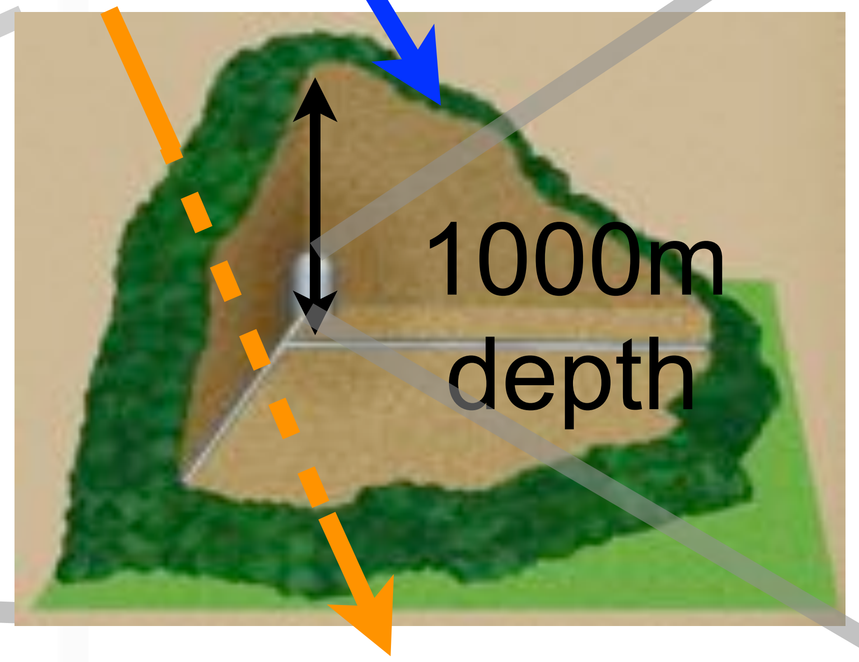
- LS : 280 t
- Depth : 3600 m.w.e.
- expected event ratio
  reactor/geo ~0.3 (up to 2010)

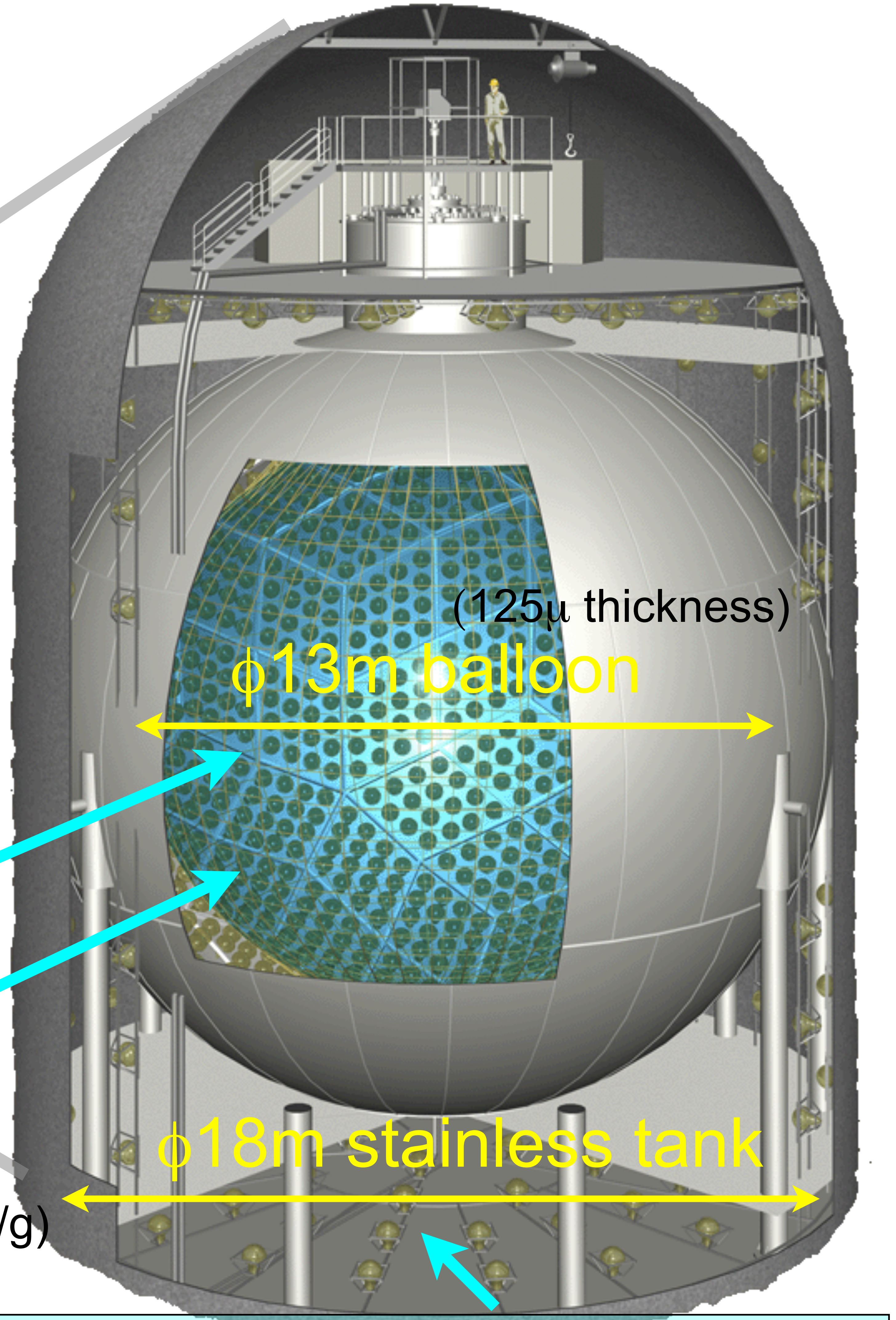
KamLAND : Site & Detector

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

KamLAND : Collaboration

Scientists : ~50

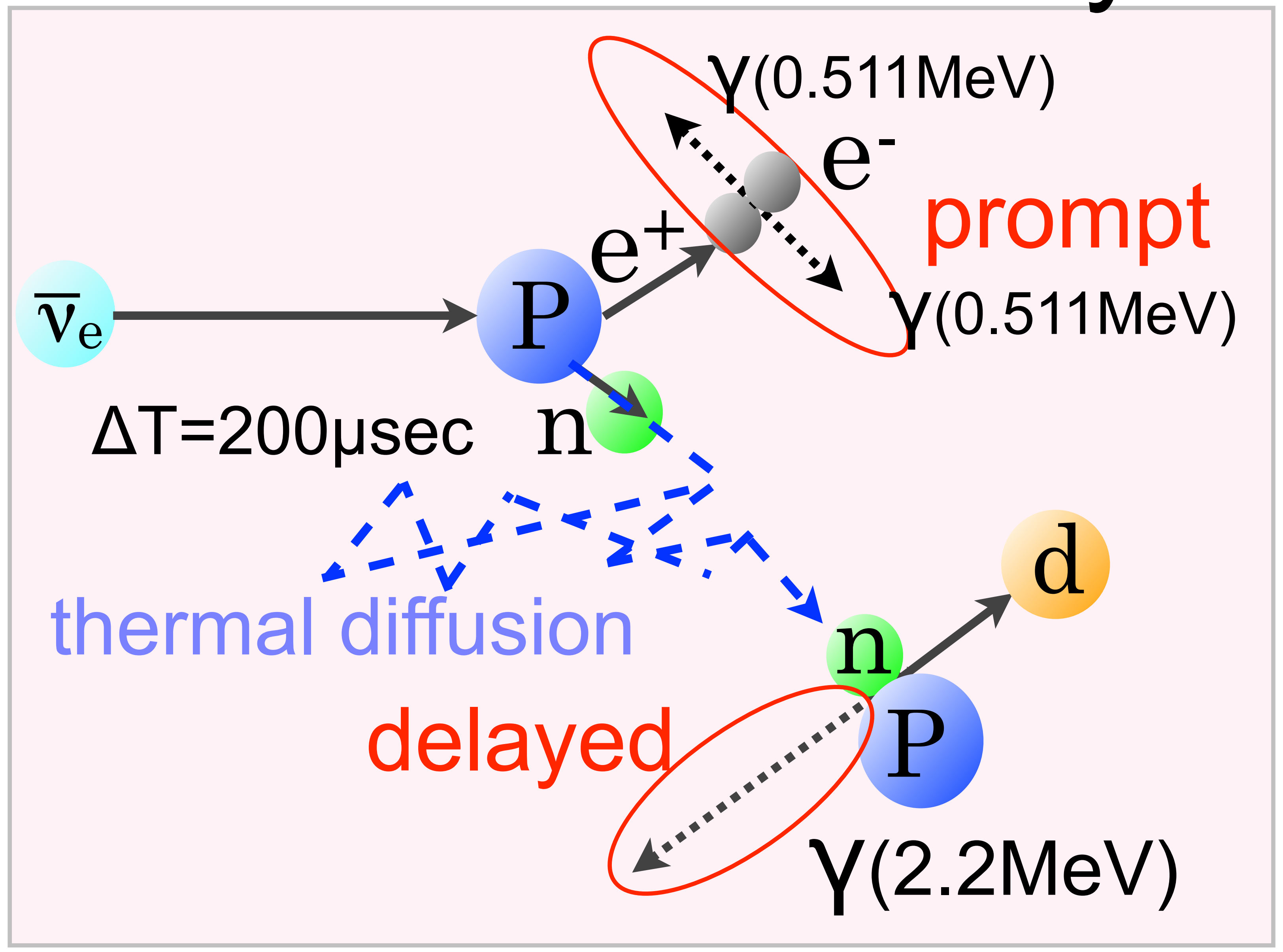
Institutes :

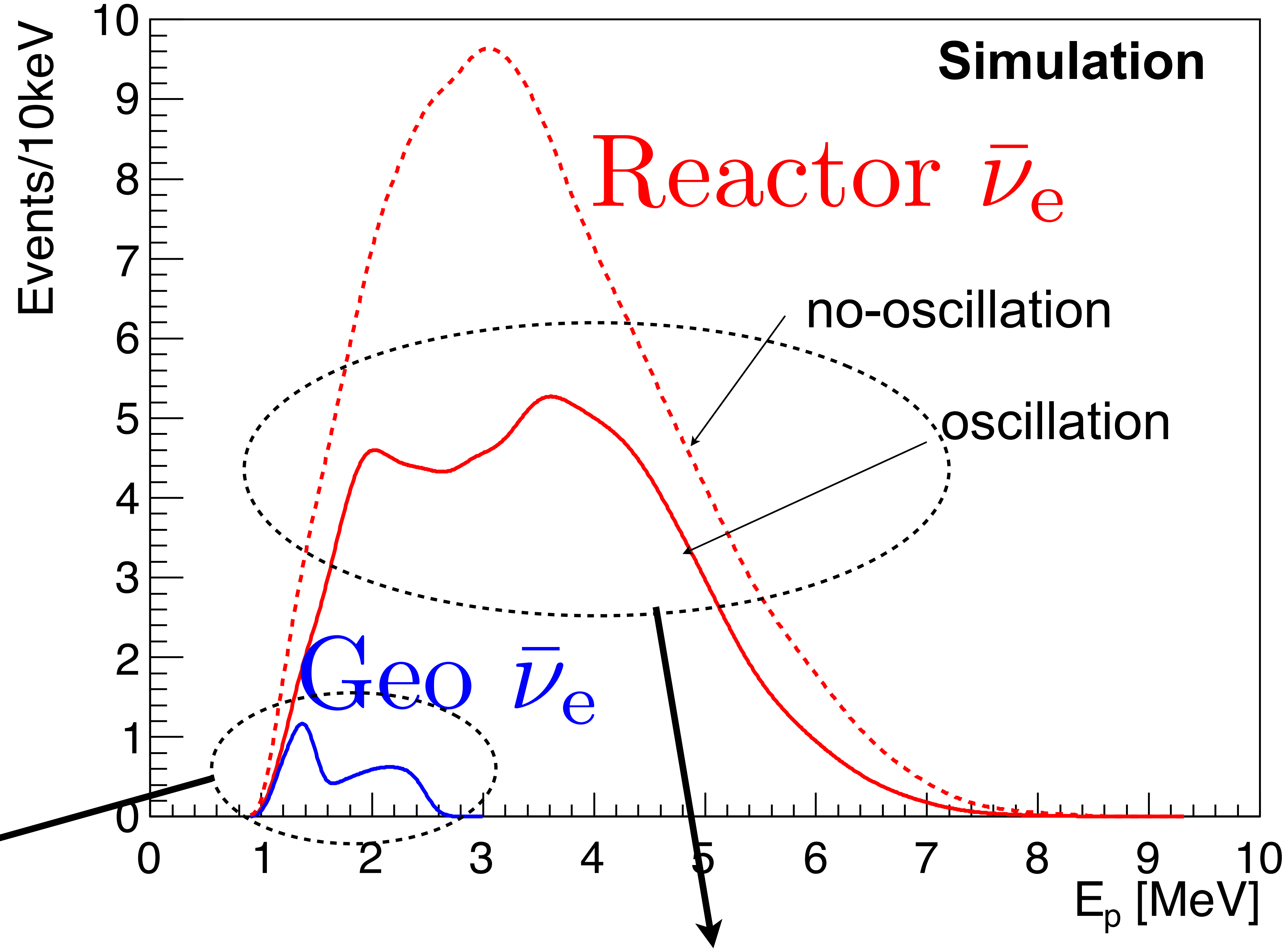
- 5 Japan
- 7 US
- 1 Europe

Sep. 2018, MIT, Boston

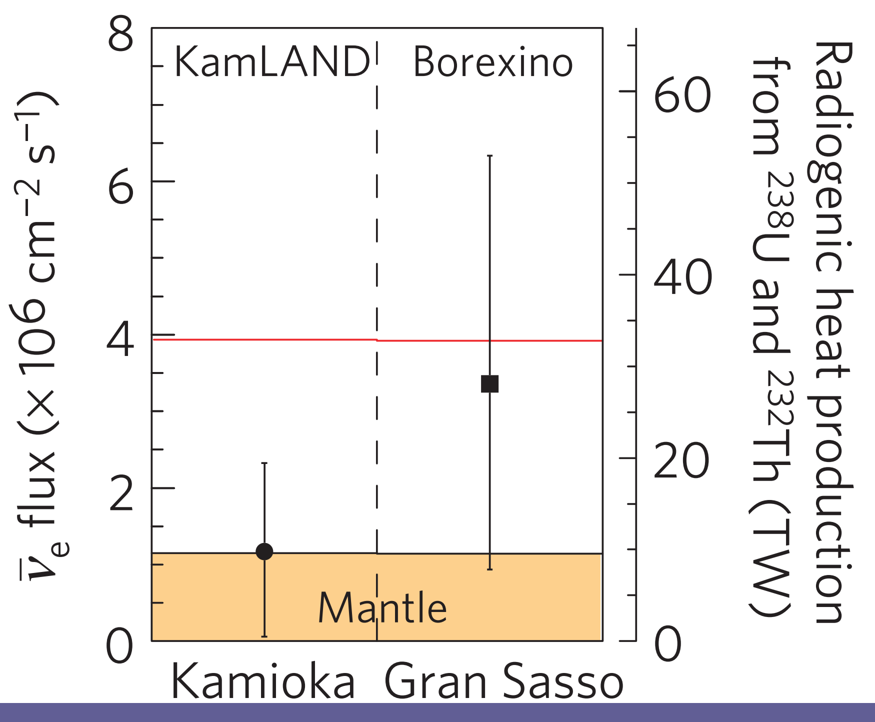
KamLAND : Anti-neutrino Studies

inverse-beta decay



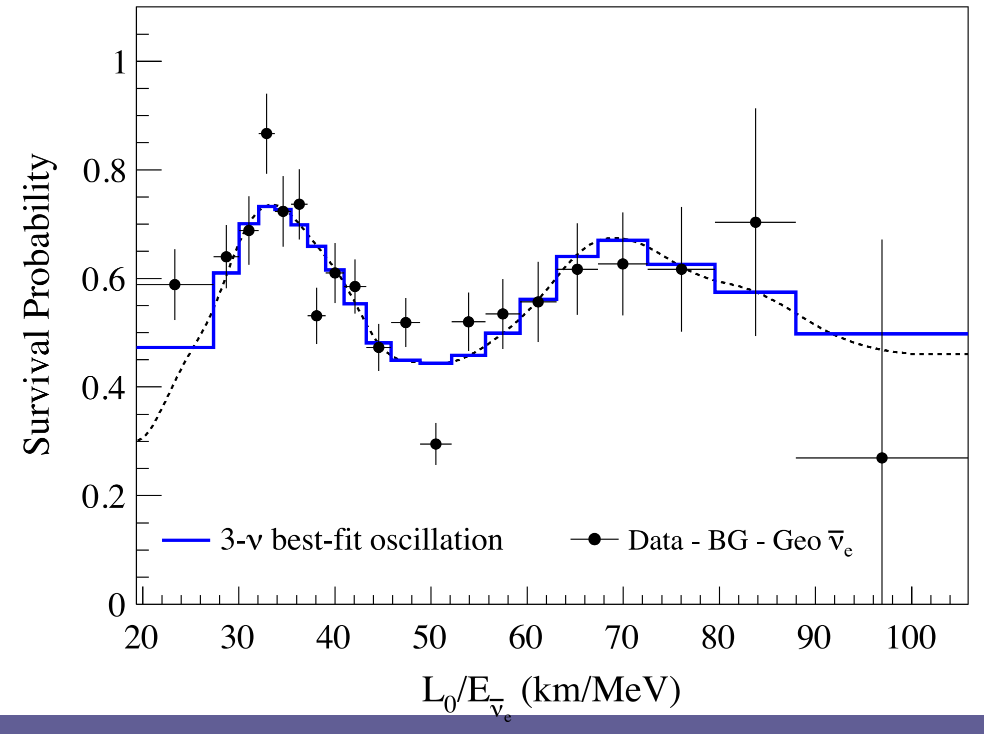


Geoneutrinos
: Neutrino Application



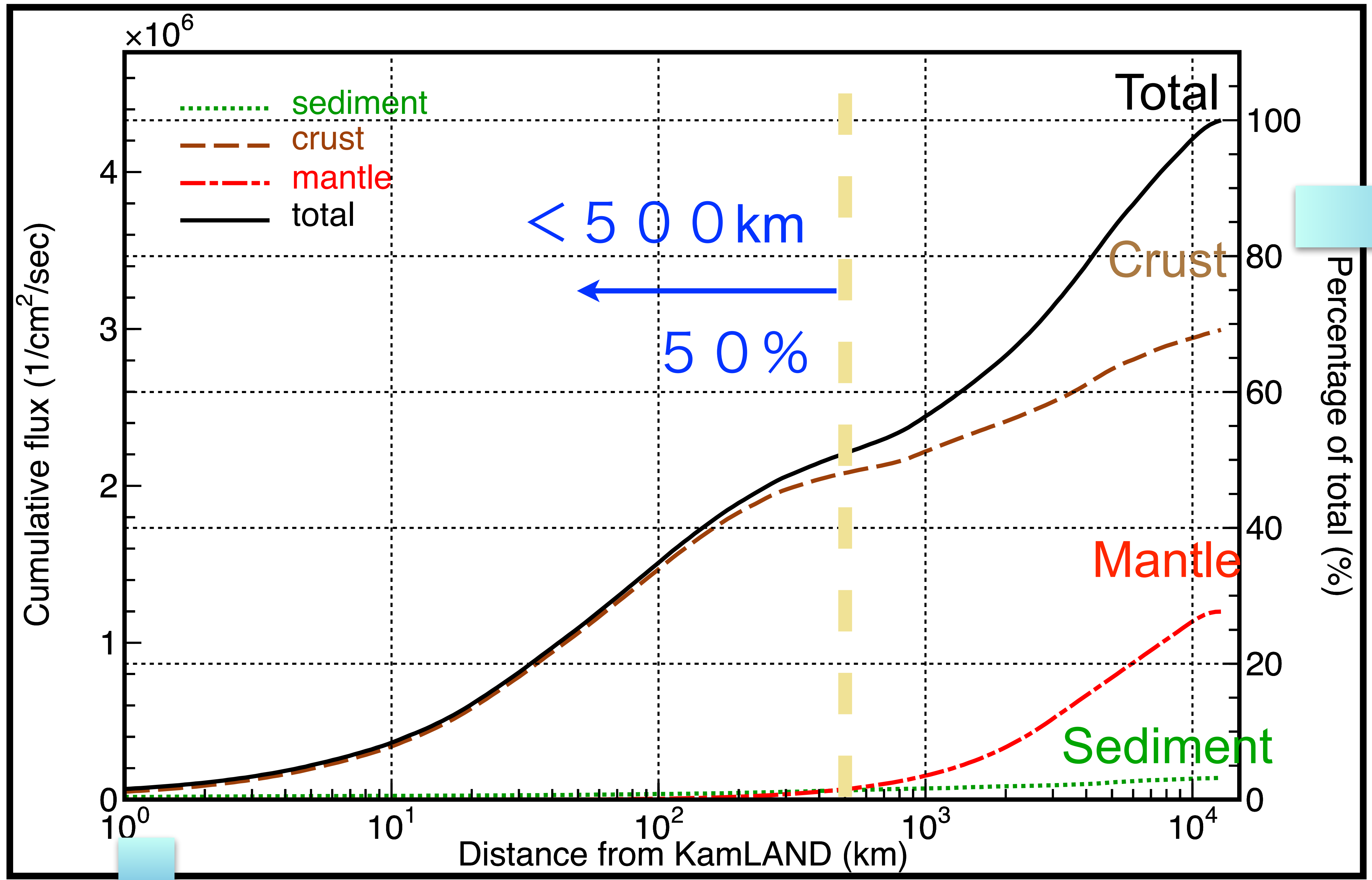
- Direct measurement of radiogenic heat contribution

Neutrino Property Study

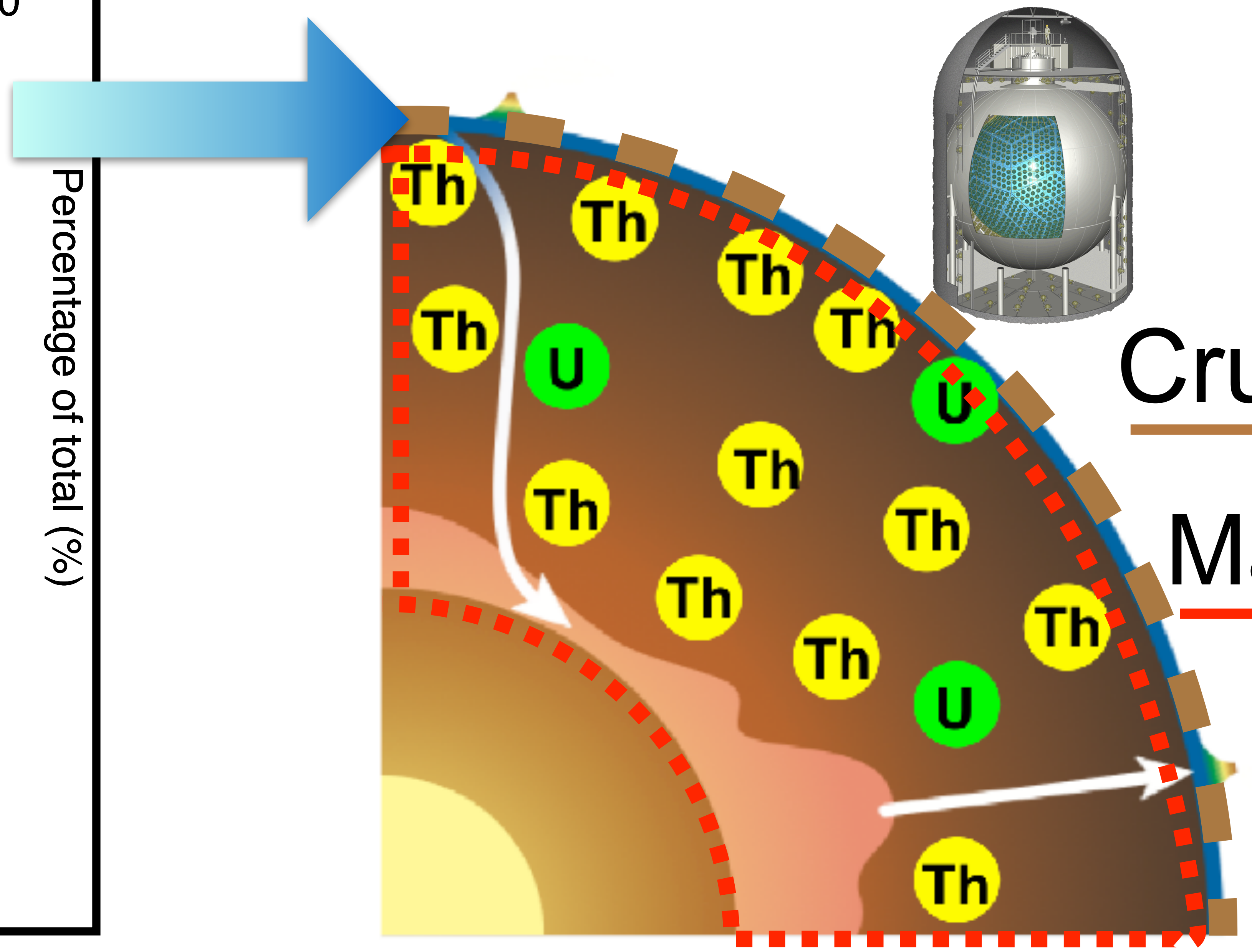


- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

KamLAND : Geo-neutrino Flux at Kamioka



Contributions from each part



Crust : 70%

Mantle : 27%

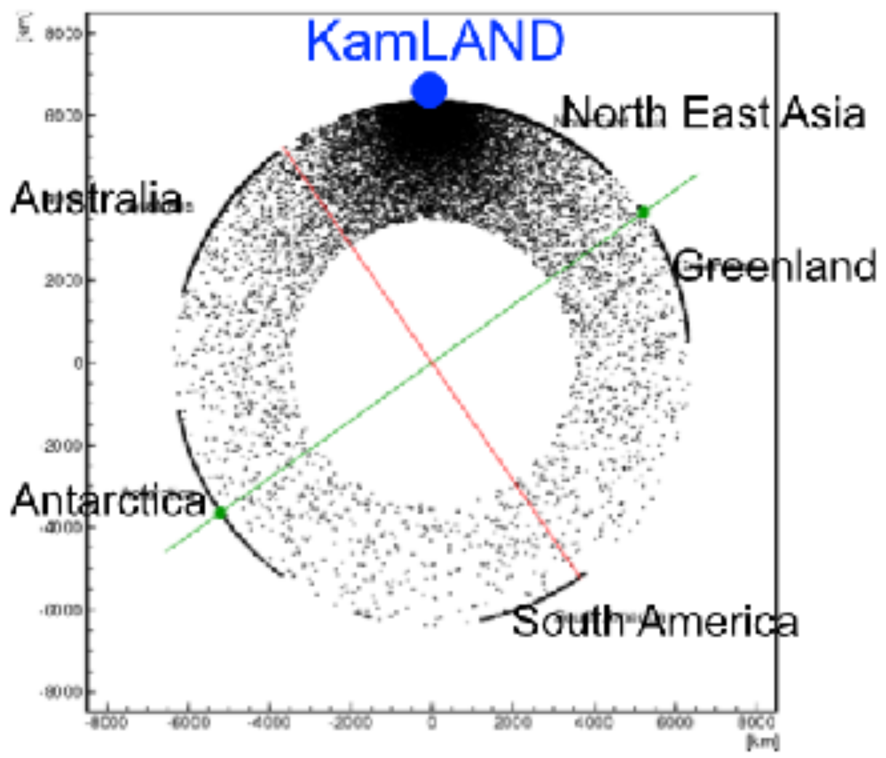
Core : 0%

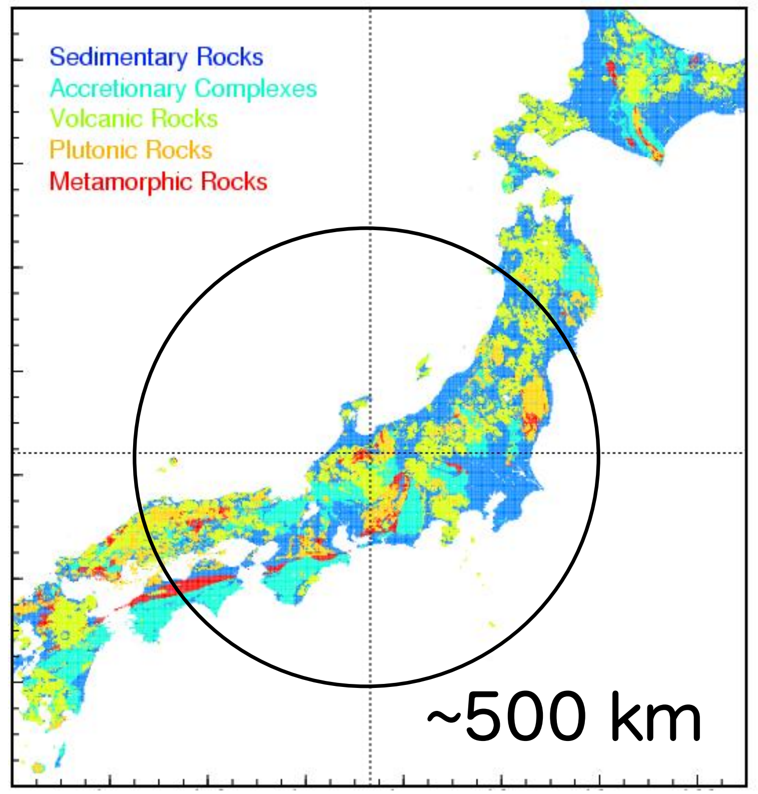
Sediment etc. : 3%

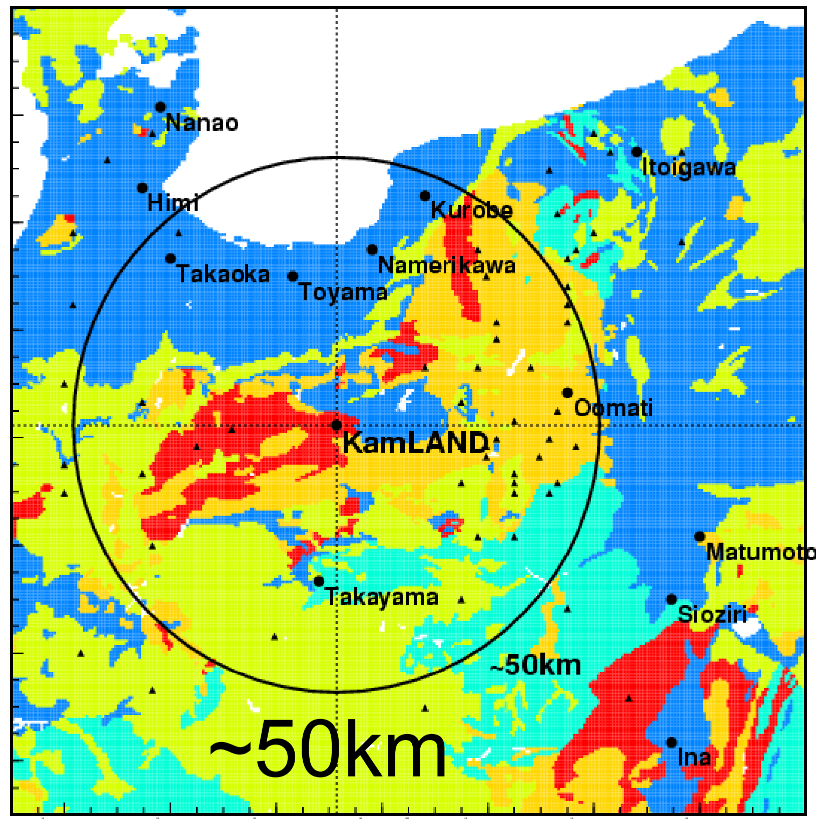
Contributions from each area

- **50%: distance < 500km**
- 25%: distance < 50km
- 1~2%: from Kamioka mine

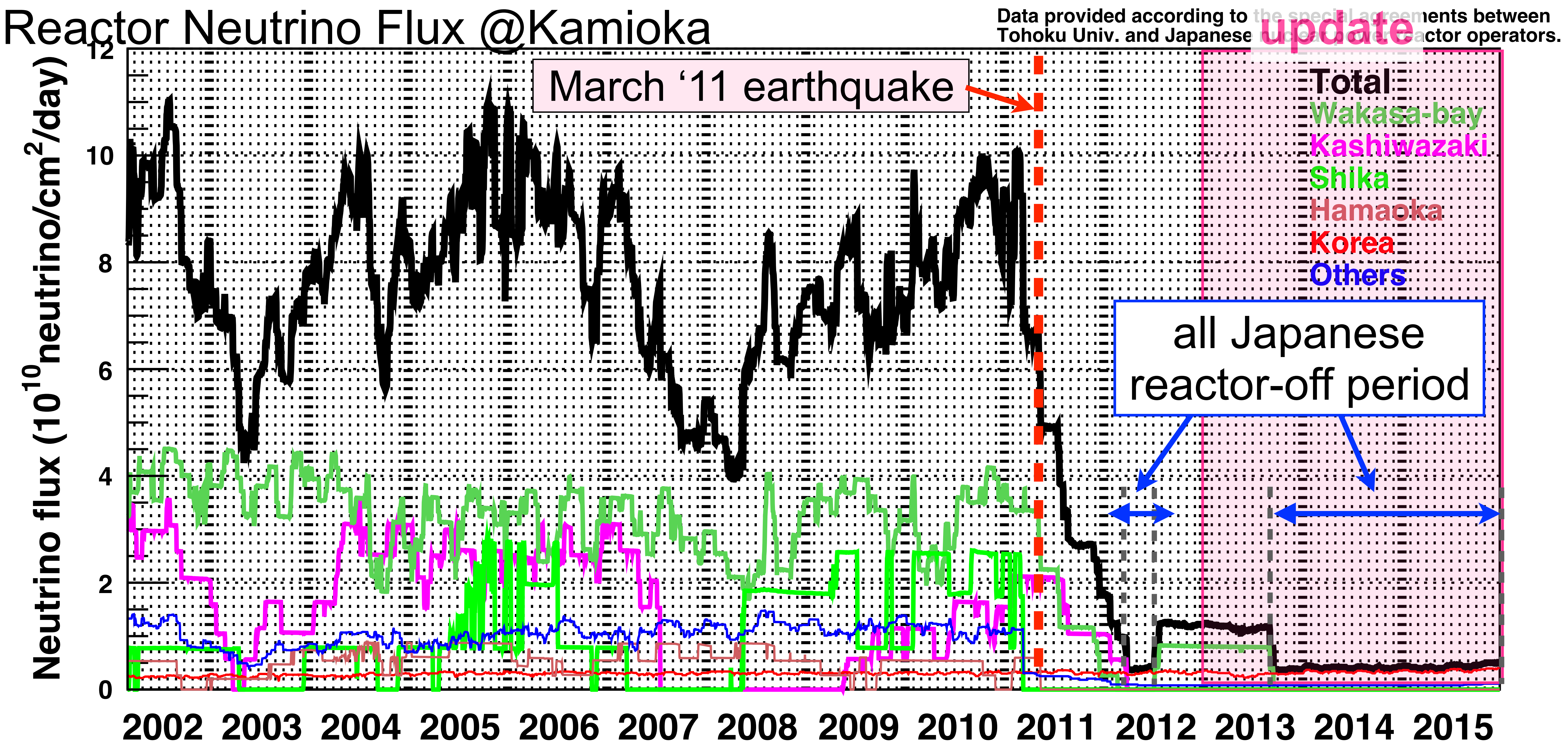
Important to understand Japanese geology

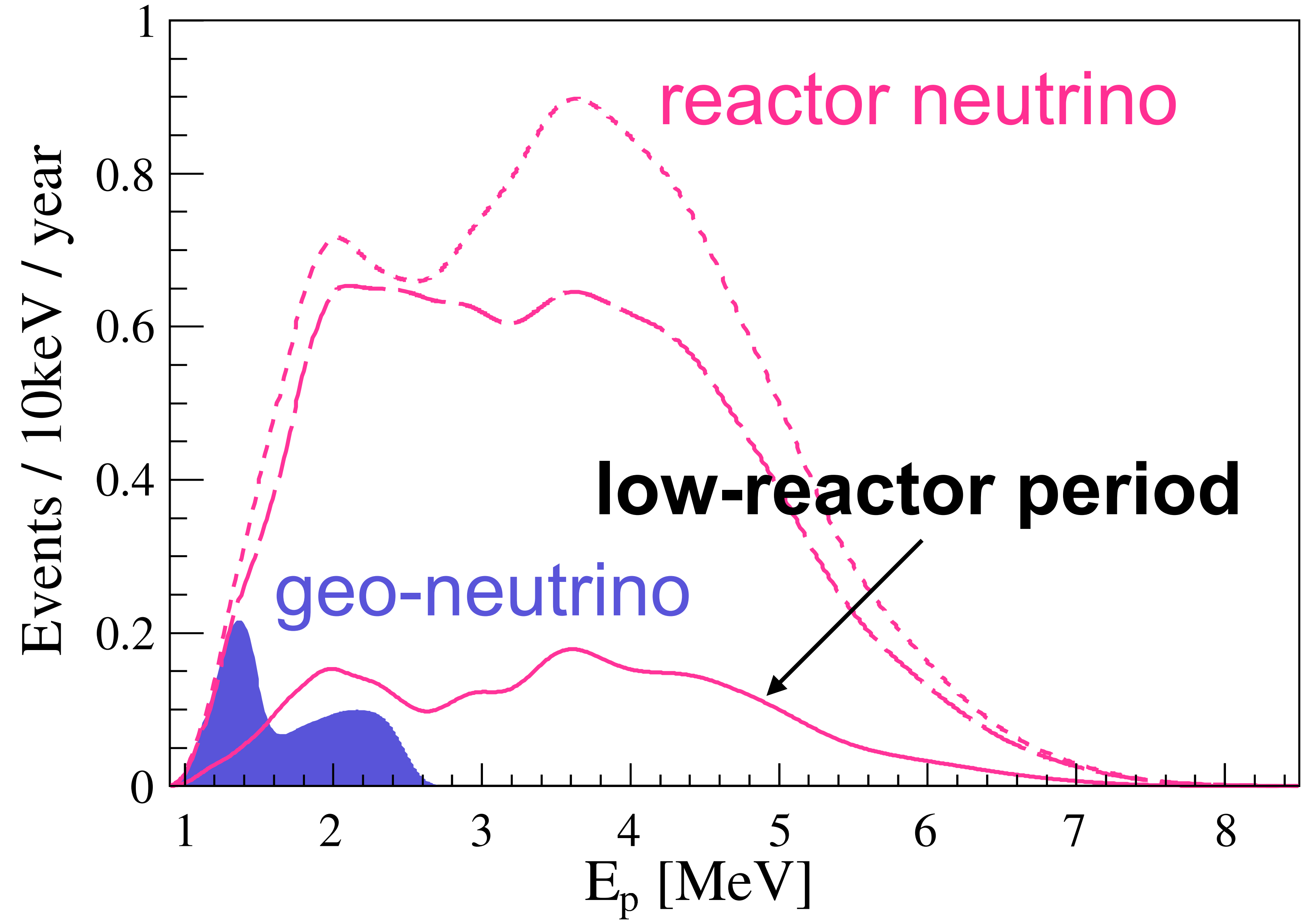






KamLAND : Data-set & Reactor Neutrinos





Reactor neutrino background is decreased significantly.

Preliminary

2013 data-set : 2991 days 4.90×10^{32} proton-year	→	**2016 data-set** : 3901 days 6.39×10^{32} proton-year

PRD 88, 033001 (2013)

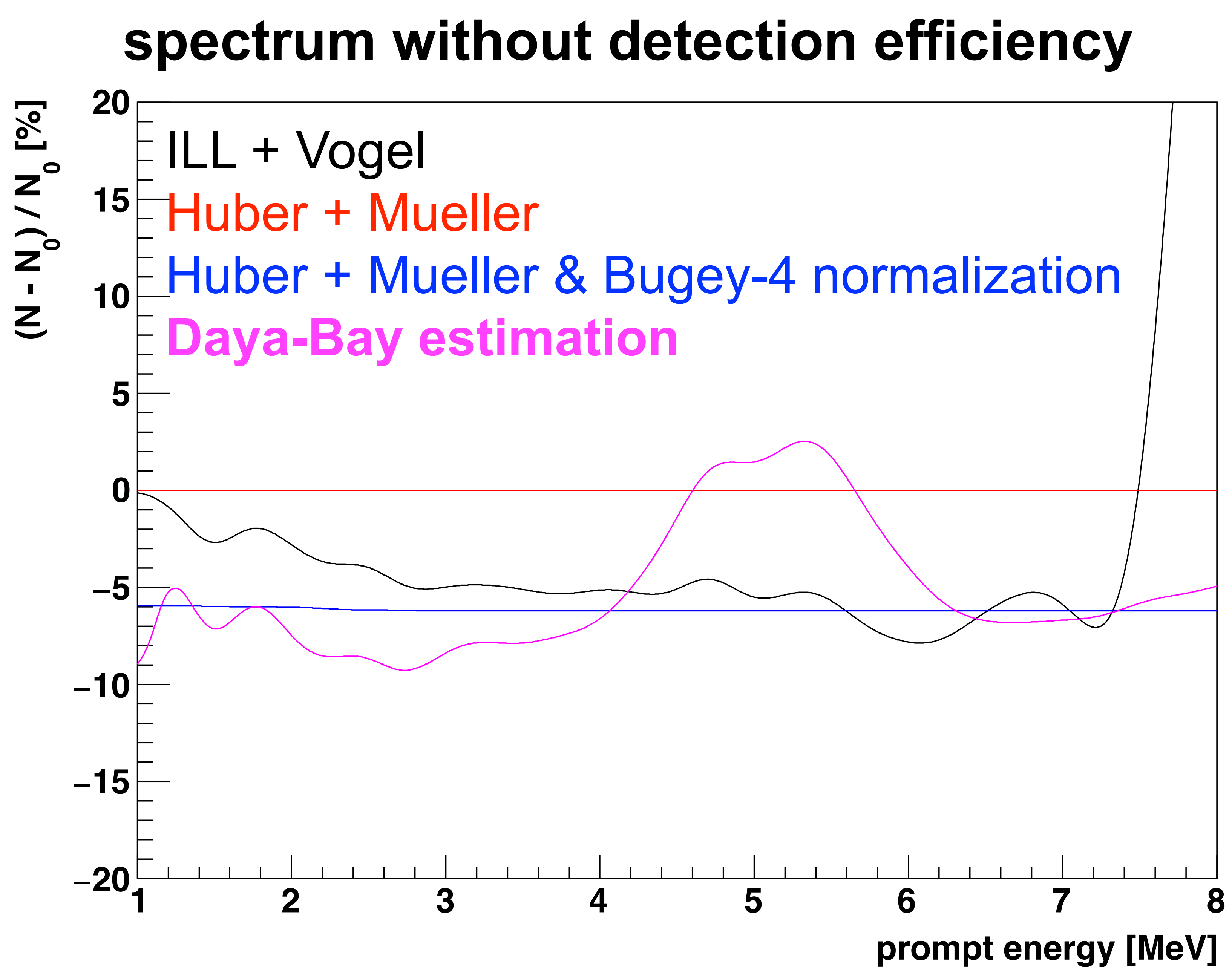
- 1.3 times of 2013 data-set

advantages {
- low-reactor operation period : **~3.5 years** livetime
- **all Japanese reactor-off period : ~2.0 years** livetime

Precise understanding of reactor neutrino spectrum enhances geo-neutrino measurement.

KamLAND : Reactor Neutrino Spectrum

2016 Preliminary Result



- Reactor neutrino spectrum for KamLAND analysis

  2013 paper : Huber + Mueller & Bugey-4 normalization

  2016 *preliminary* : **Daya Bay estimation**

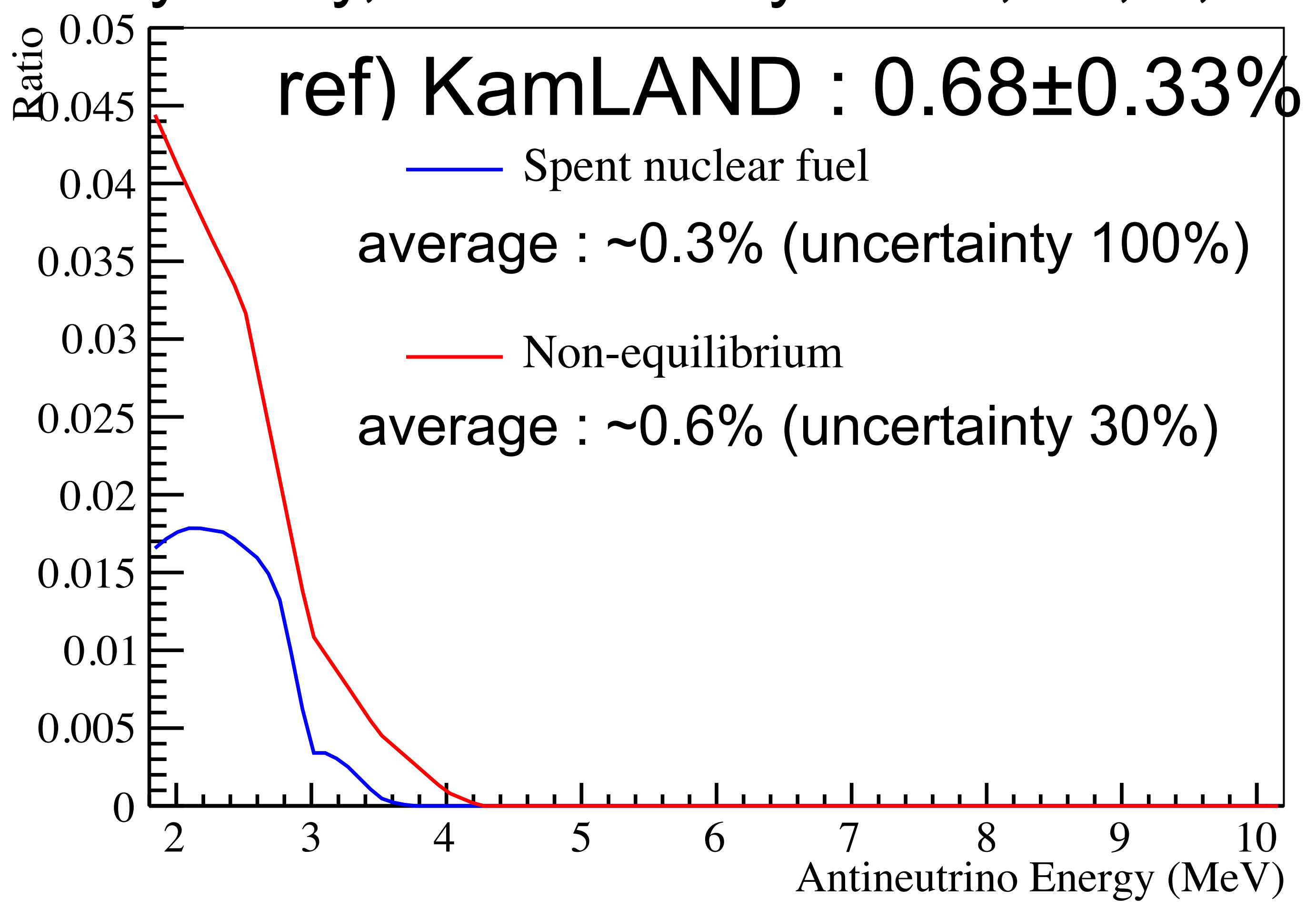
  σ_f (cm^2/fission) = $(5.92 \pm 0.12) \times 10^{-43}$ (uncertainty : 2.03%)

  * Excess at 4-6 MeV : ~+5%.

  * In the publication, Daya Bay also shows contributions from "spent nuclear fuel" and "Non-equilibrium".

  → We **subtract** these contributions from Daya-Bay spectrum, and then **add** KamLAND evaluation from history of fission rate (^{90}Sr, ^{16}Ru, ^{144}Ce, ^{97}Zr, ^{132}I, ^{93}Y)

Daya Bay, Chinese Physics C, 41, 1, 013002 (2017)



- We confirmed that :
  - ☑ 4-6 MeV excess has no impact on the geo-neutrino results.
  - ☑ effect of reactor spectrum uncertainty is much smaller than the statistical uncertainty of geo-neutrino events.

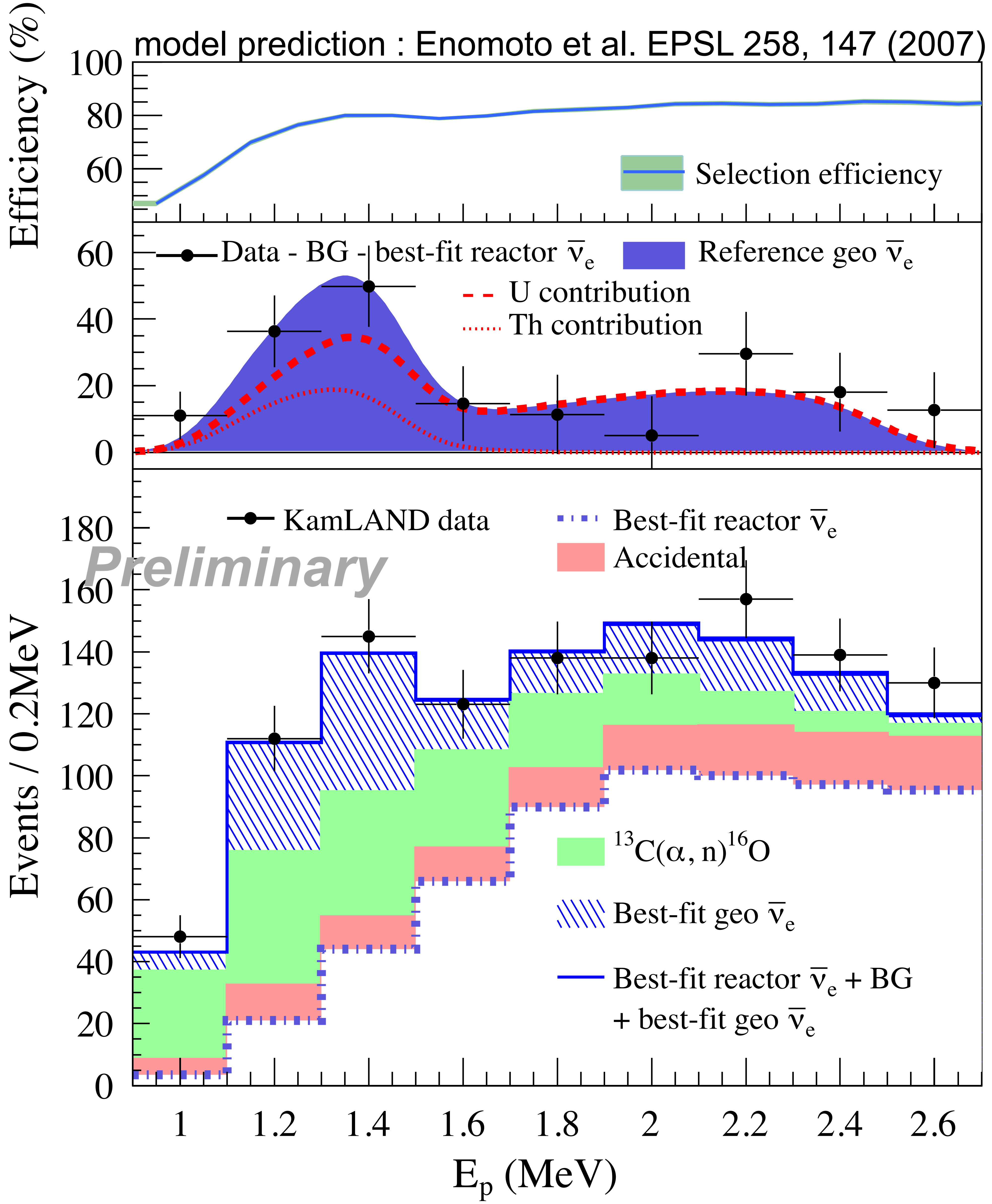
KamLAND : Event Rate Time Variation (0.9-2.6MeV)

2016 Preliminary Result

- Backgrounds :
  LS purification → non-neutrino backgrounds reduction
  Earthquake → reactor neutrino reduction
- Constant contribution of geo-neutrino
  Time information is useful to extract the geo-neutrino signal

▸KamLAND : Energy Spectrum (0.9-2.6MeV)

2016 Preliminary Result



Livetime : 3900.9 days

Candidate : 1130 ev

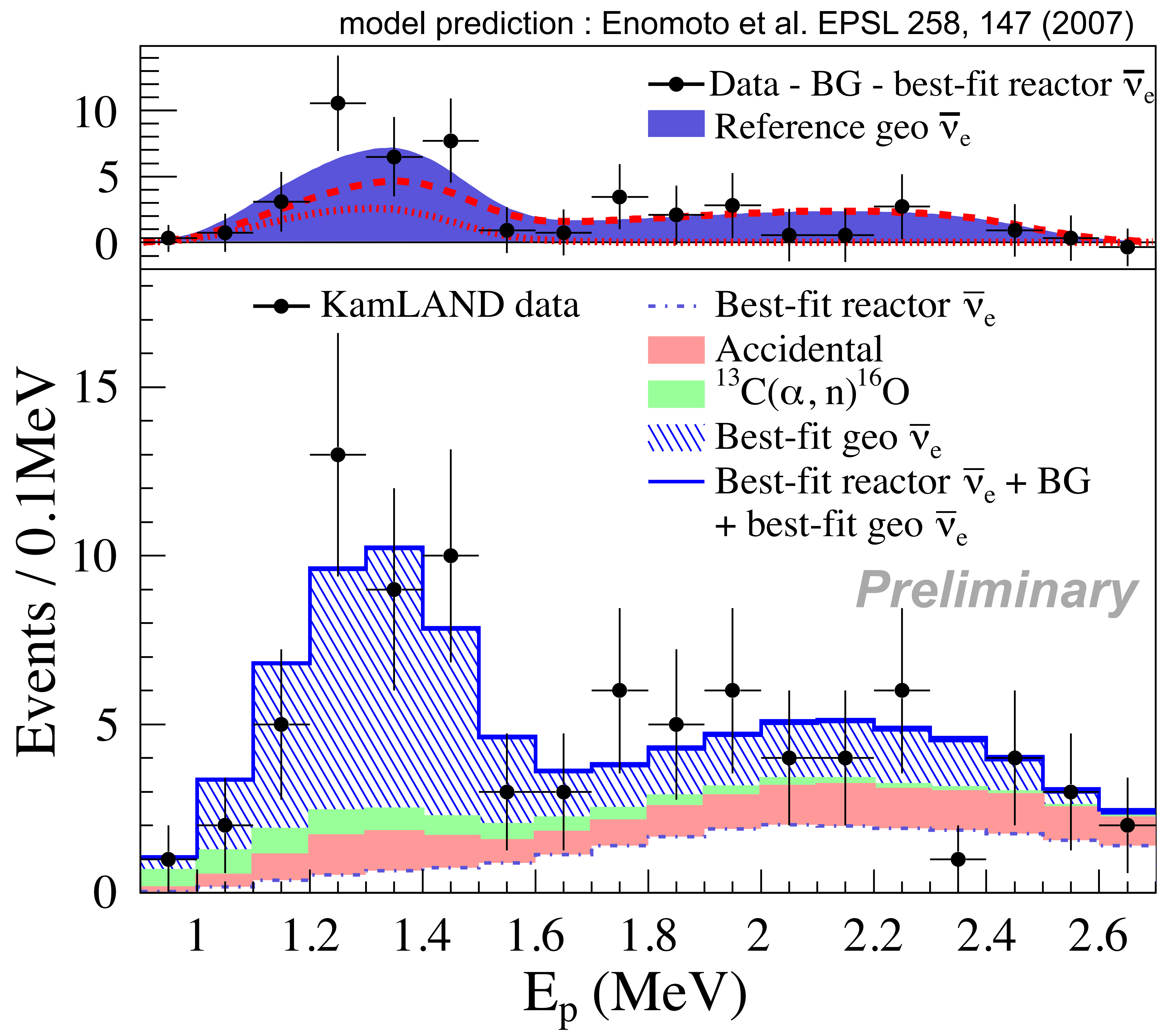
Background Summary

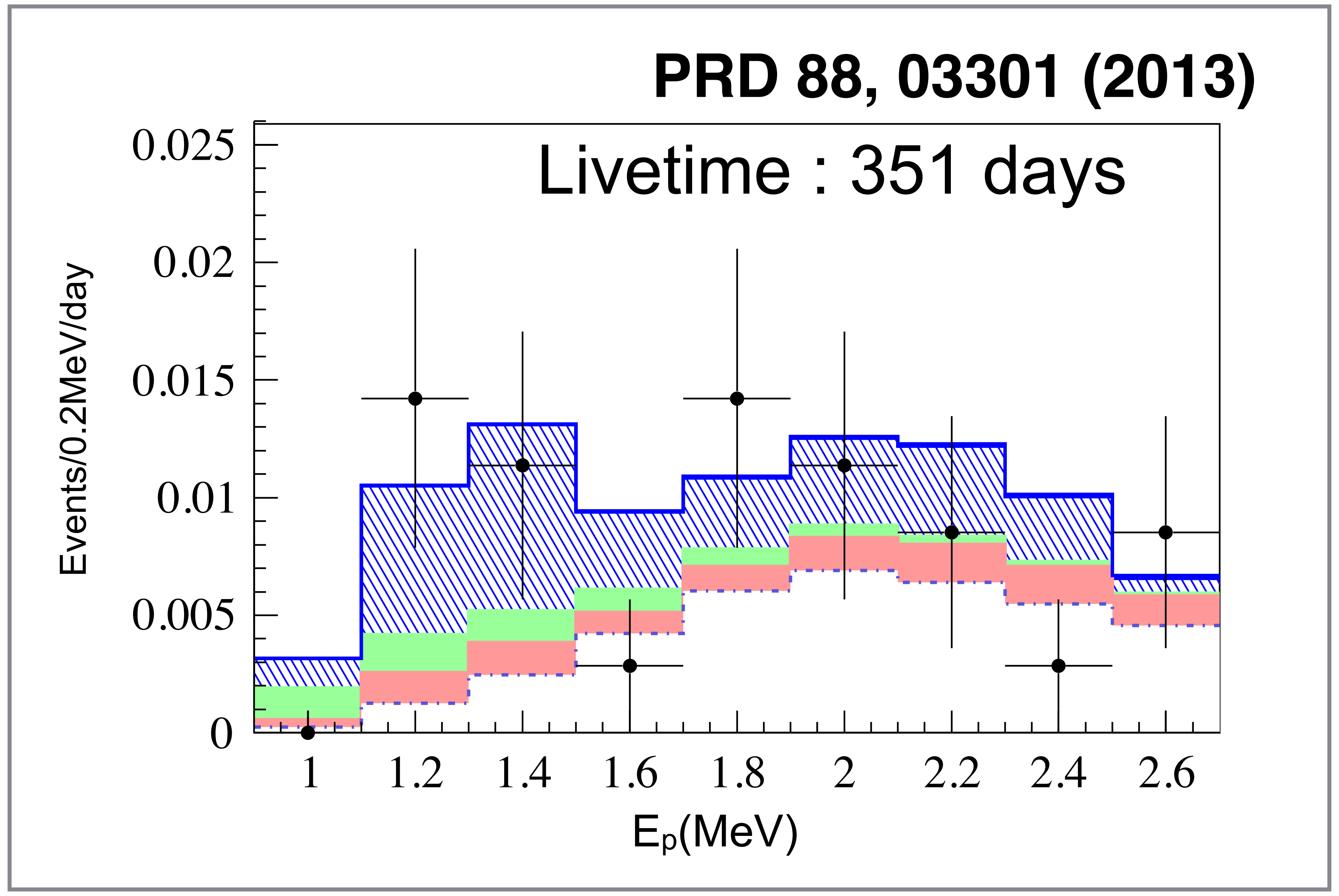
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\bar{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

KamLAND : Energy Spectrum, Low Reactor Phase

Livetime : 1259.8 days

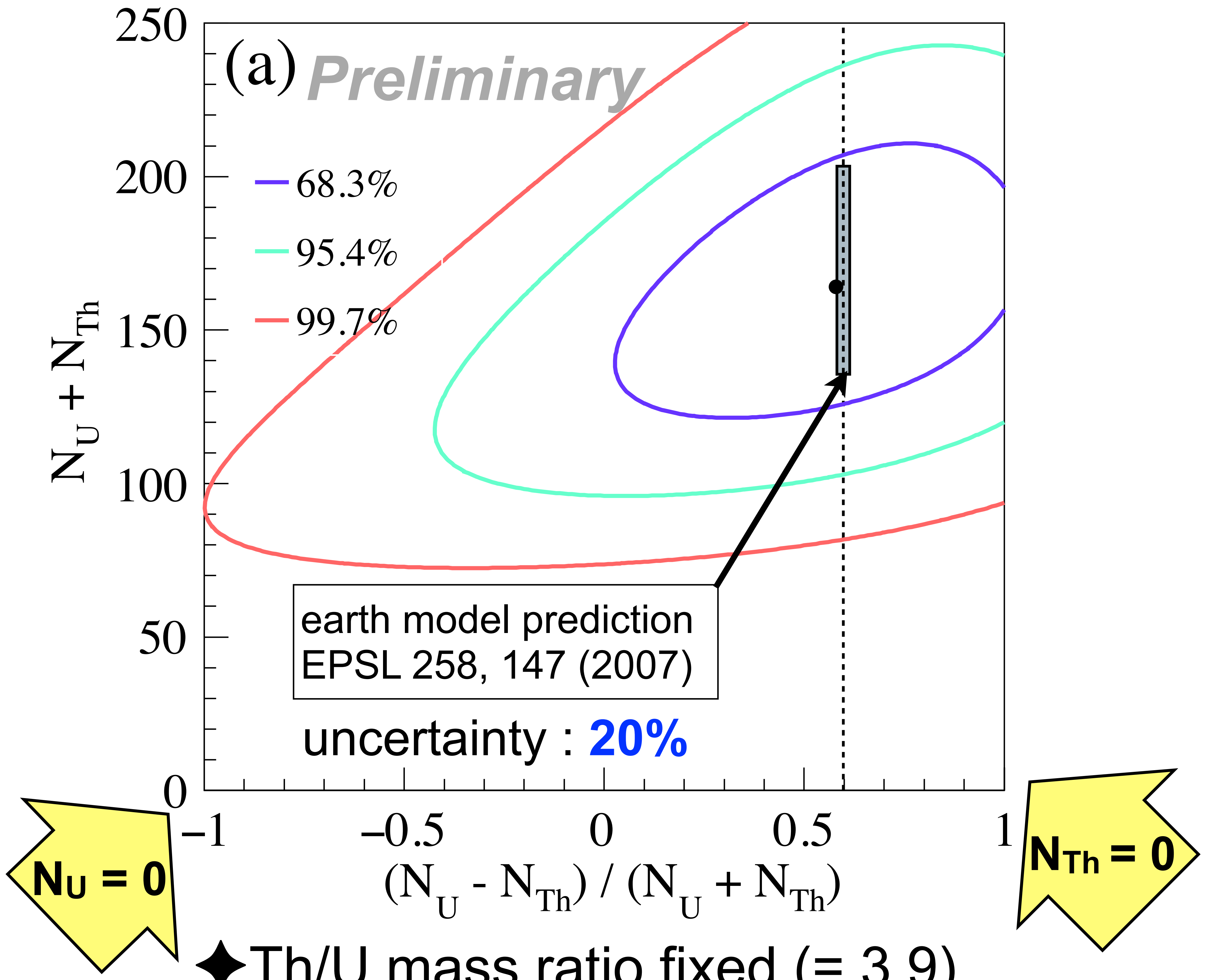
2016 Preliminary Result

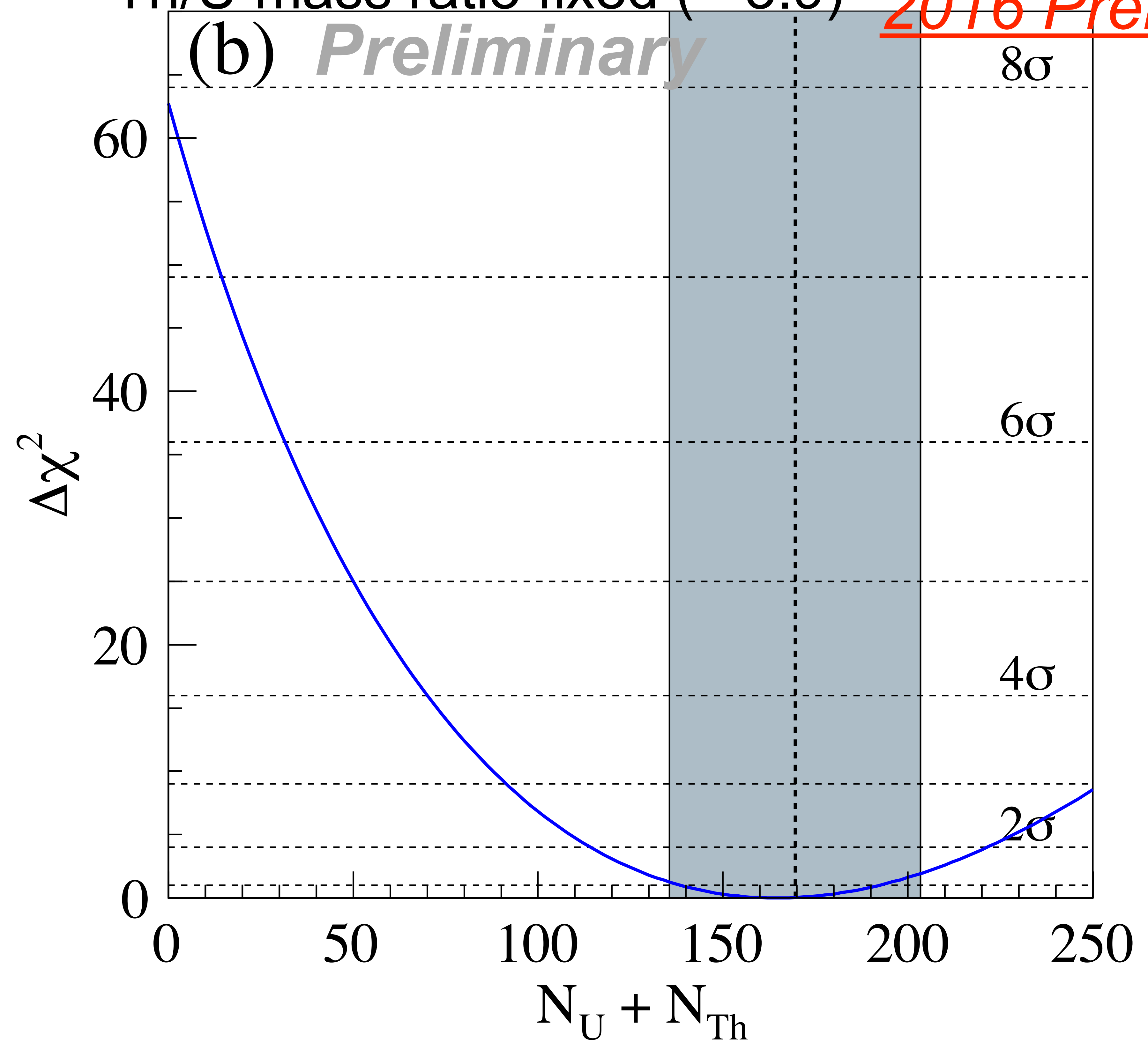




- ☑ Geo-neutrino/Background ~1.0
- ☑ We measured clear distribution of geo-neutrino events.

KamLAND : Rate + Shape + Time Analysis





2016 Preliminary Result

✦Th/U mass ratio fixed (= 3.9)

N_{geo} = 164 +28/-25 events (17%)

F_{geo} = 3.9 +0.7/-0.6 × 10^6/cm^2/sec

0 signal rejection : 7.92 σ

ref) PRD 88, 03301 (2013)

N_{geo} = 116 +28/-27 events (24%)

F_{geo} = 3.4 +0.8/-0.8 × 10^6/cm^2/sec

0 signal rejection : 4.74 σ

☑ Measurement uncertainty gets close to uncertainty of Earth model prediction.

geoscientific findings from measurement results

* Th/U Mass Ratio
* Radiogenic Heat

Th/U Mass Ratio : Introduction

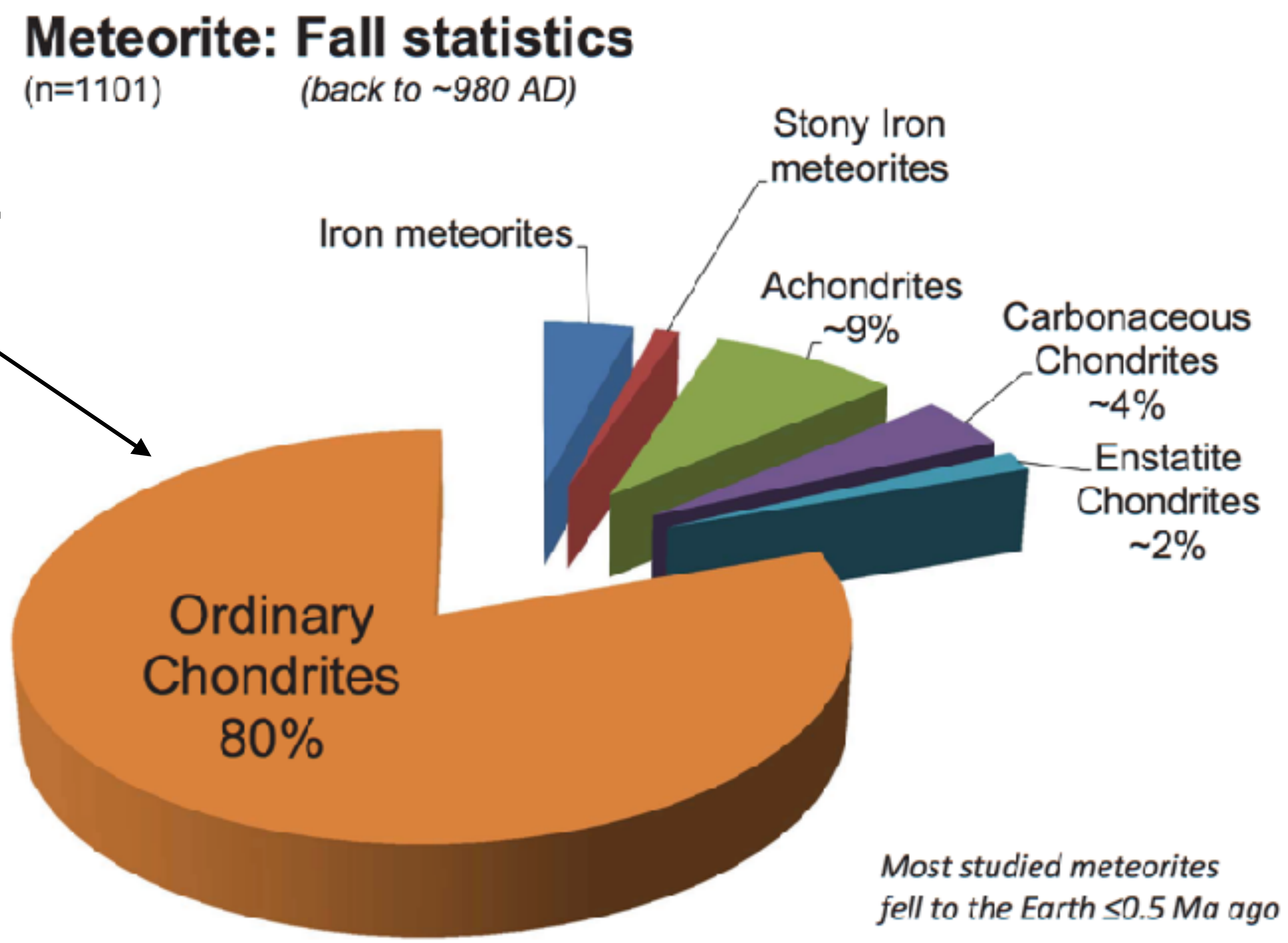
- According to geochemical studies, ^{232}Th is more abundant than ^{238}U.
  Mass ratio (Th/U) in bulk silicate Earth is expected to be **around 3.9.**

Models : 3.58-4.2

4.2 : Allegre et al. (1986)
3.92 : McDonough & Sun (1995)
3.89 : Taylor (1980)
3.85 : Anderson (2007)
3.77 : Palm & O'Neil (2003)
3.76 : Hart & Zindler (1986)
3.71 : Lyubetskaya & Korenaga (2007)
3.62 : Jagoutz et al (1979)
3.58 : Javoy et al. (2010)

- Chondrite samples analysis : **1.06-6.42**

  Fall statistics for the meteorites identified and catalogued since 980 A.D.

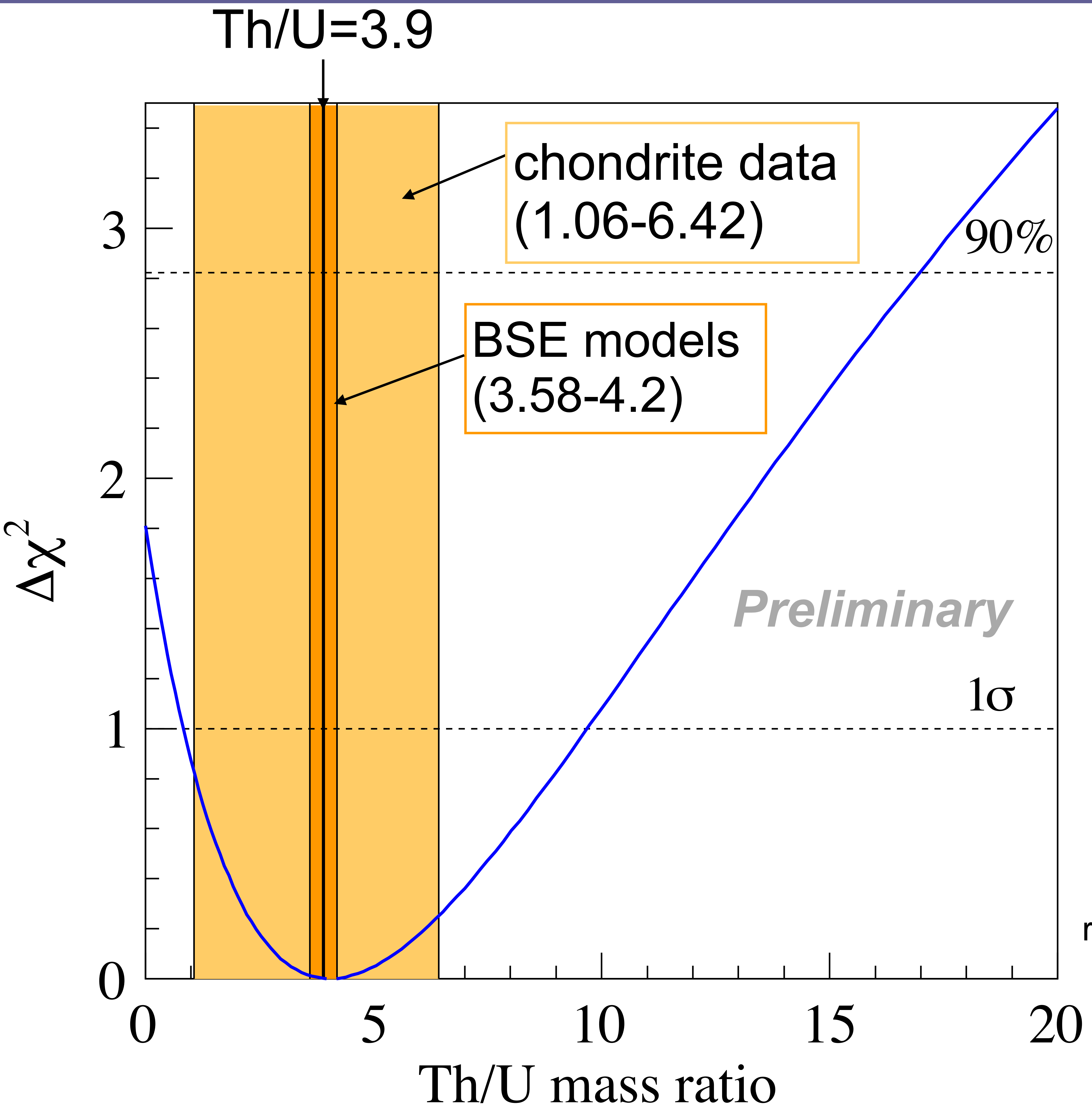


- Geo-neutrino observed rate can be converted to amount of Th & U assuming homogeneous distribution.
  Independent & direct measurement of entire Earth

slide from McDonough, 2015, in Ehime

Th/U Mass Ratio : Measurement Result

2016 Preliminary Result



Best fit

Th/U = 4.1 $^{+5.5}_{-3.3}$

Th/U < 17.0 (90% C.L.)

ref) 2013 paper Th/U < 19 (90% C.L.)

- ☑ **We have a sensitivity of Th/U mass ratio of entire Earth.**
- ☑ **KamLAND best-fit is consistent with chondrite data and BSE models.**

ref) chondrite data

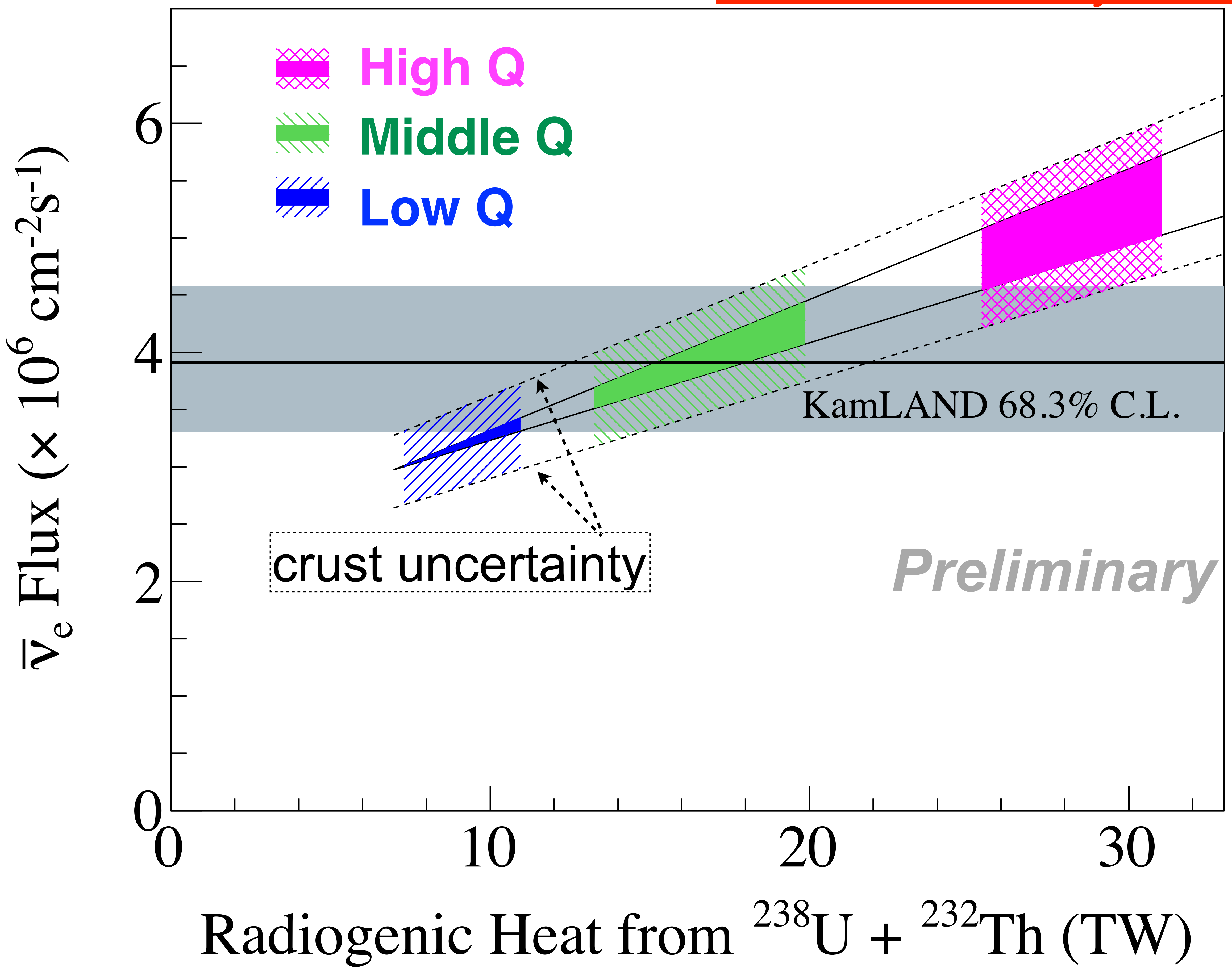
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

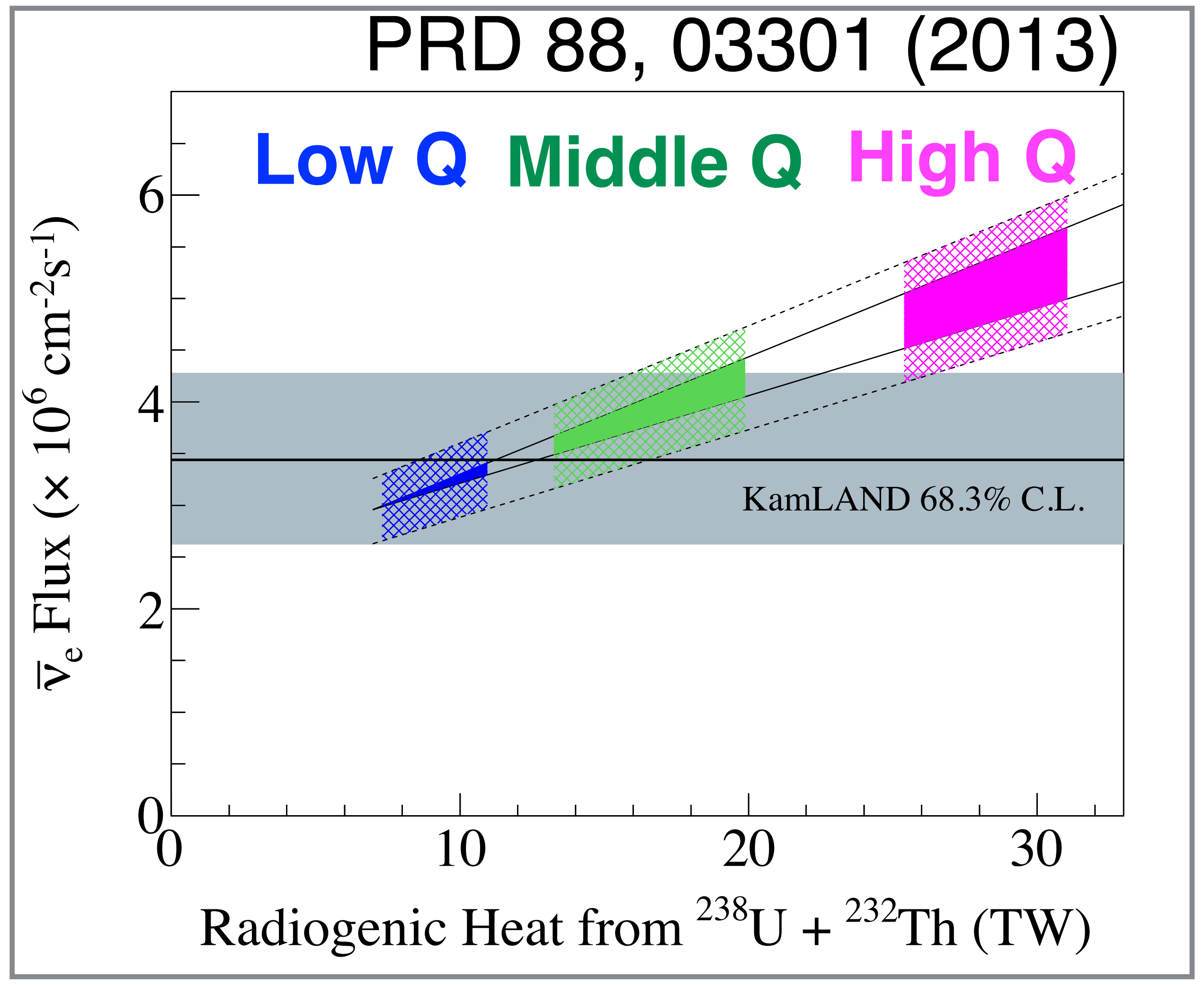
Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

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

Radiogenic Heat

2016 Preliminary Result





- ☑ Radiogenic Heat : $15.5^{+6.5}_{-6.3}$ TW
- ☑ Started to disfavor Low Q model

[BSE models]

High Q

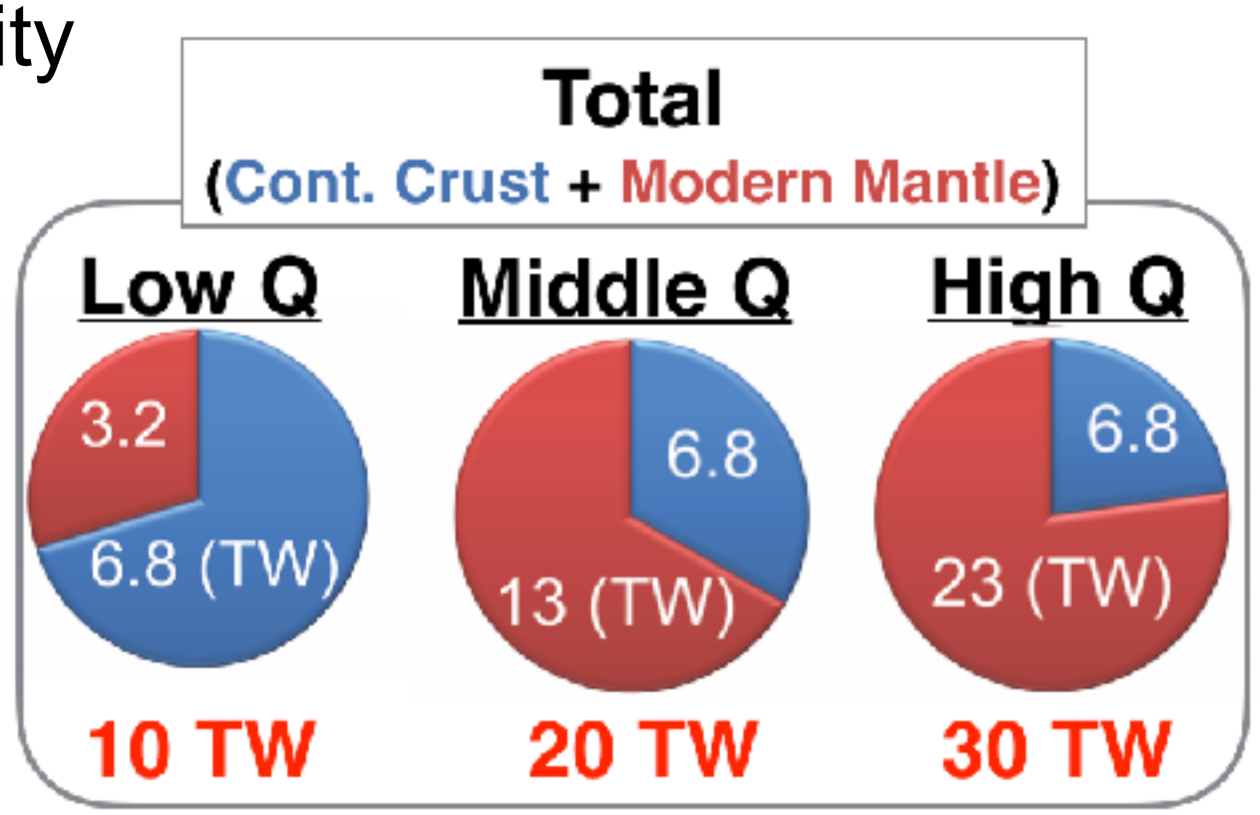
based on balancing mantle viscosity and heat dissipation

Middle Q

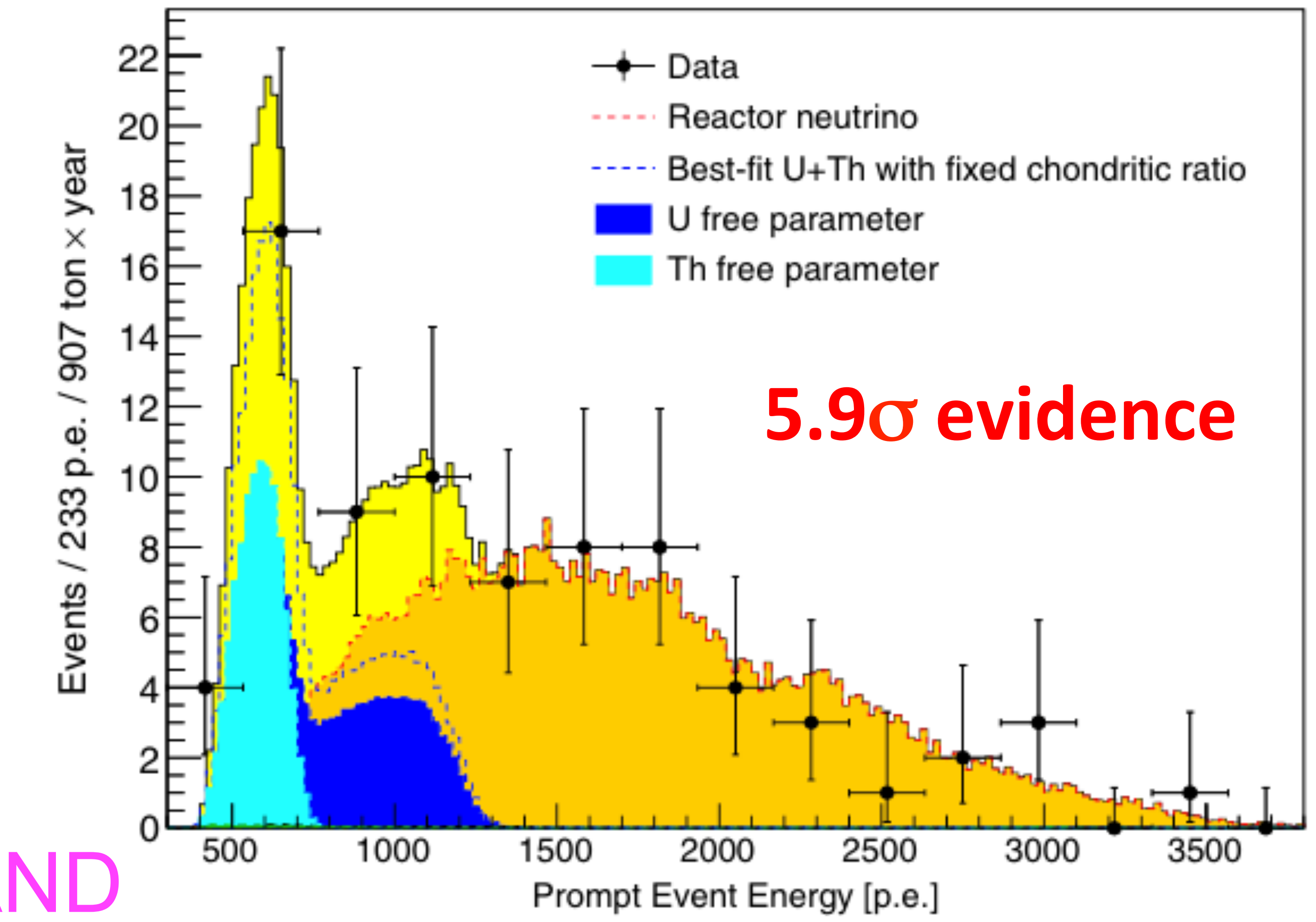
based on mantle samples compared with chondrites

Low Q

based on isotope constraints and chondritic models



Latest Borexino geoneutrino results



8.6% of KamLAND

Period	Dec.07 – Mar15 (5.5 ± 0.3) 10^{31} prot*y
Tot ev [full sp.]	77
Reactors ev.	$52.7^{+8.5}_{-7.7}$ (stat) $^{+0.7}_{-0.9}$ (sys)
Background ev.	$0.78^{+0.13}_{-0.10}$
Geo-ν ev.	$23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys))
Geo-ν signal (TNU)	$43.5^{+11,8}_{-10.4}$ (stat) $^{+2.7}_{-2.4}$ (sys)

PRD 92, 031101(2015)

Two types of fits

1) $m(^{232}Th)/m(^{238}U) = 3.9$ (CI chondrites)

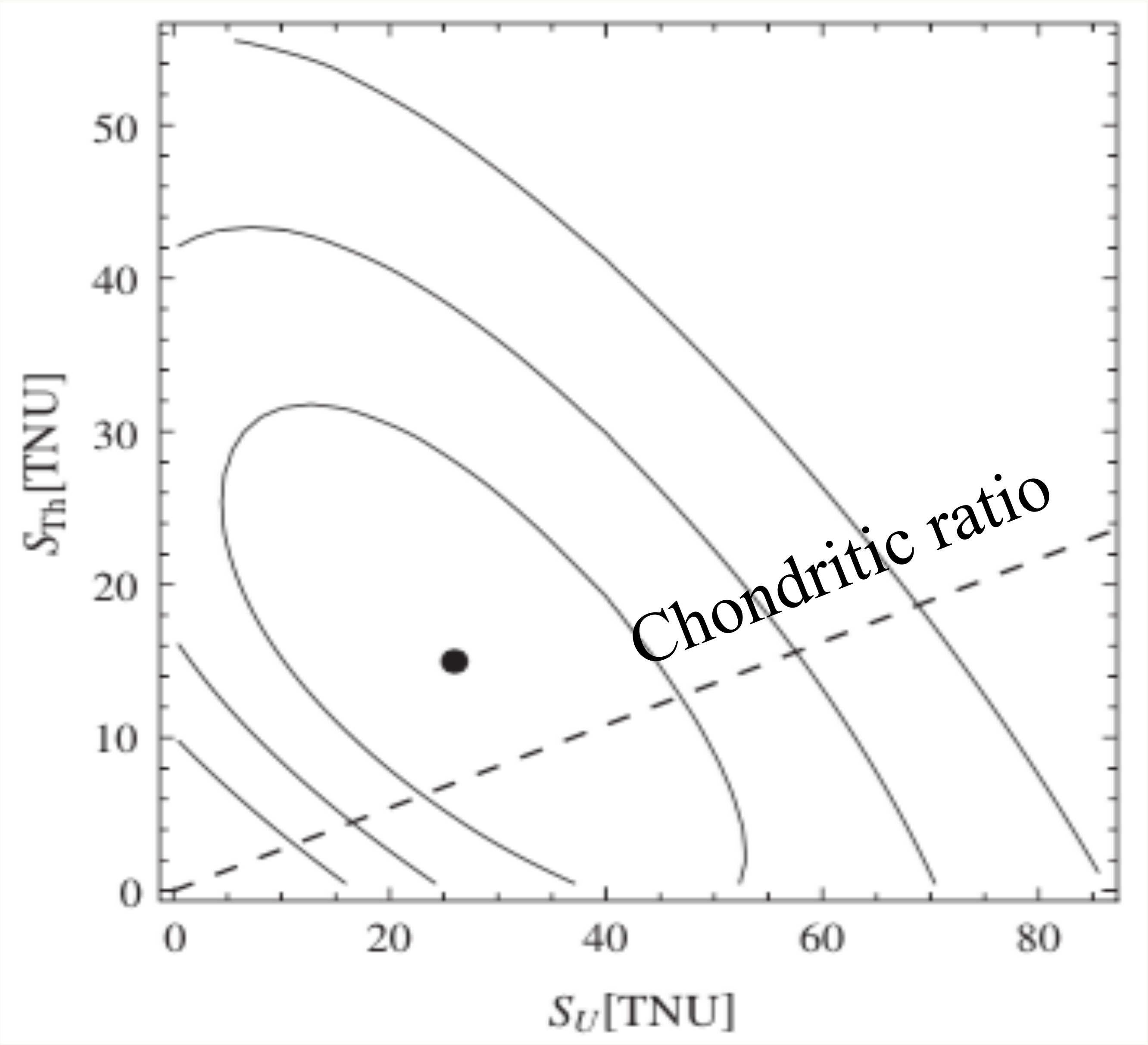
$S(^{232}Th)/S(^{238}U) = 0.27$

$S(^{238}U)/S(^{232}Th) = 3.7$ ~28% error

$N_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$ events

$S_{geo} = 43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU

2) U and Th free fit paramters

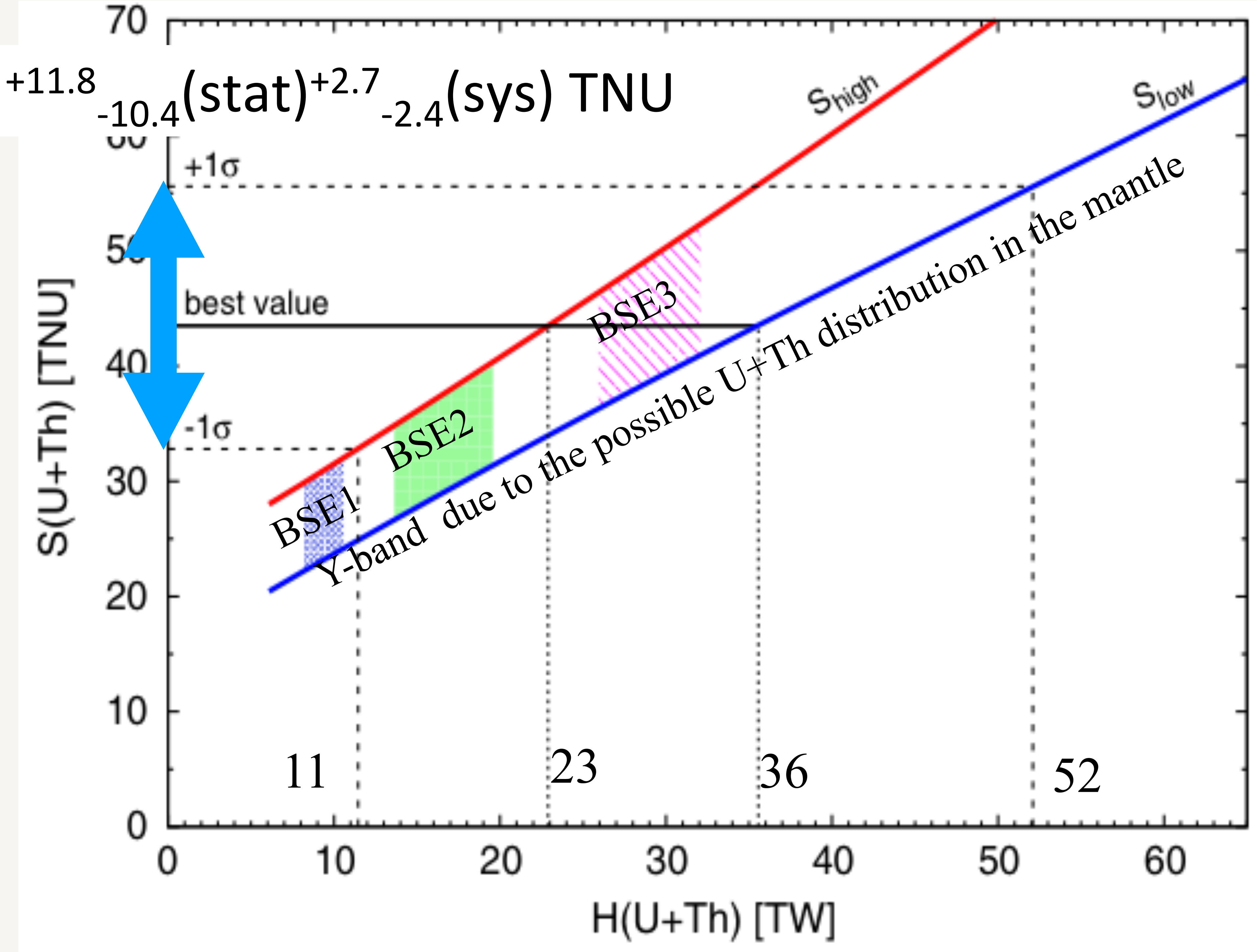


Geological implications of the new Borexino results

PRD 92, 031101(2015)

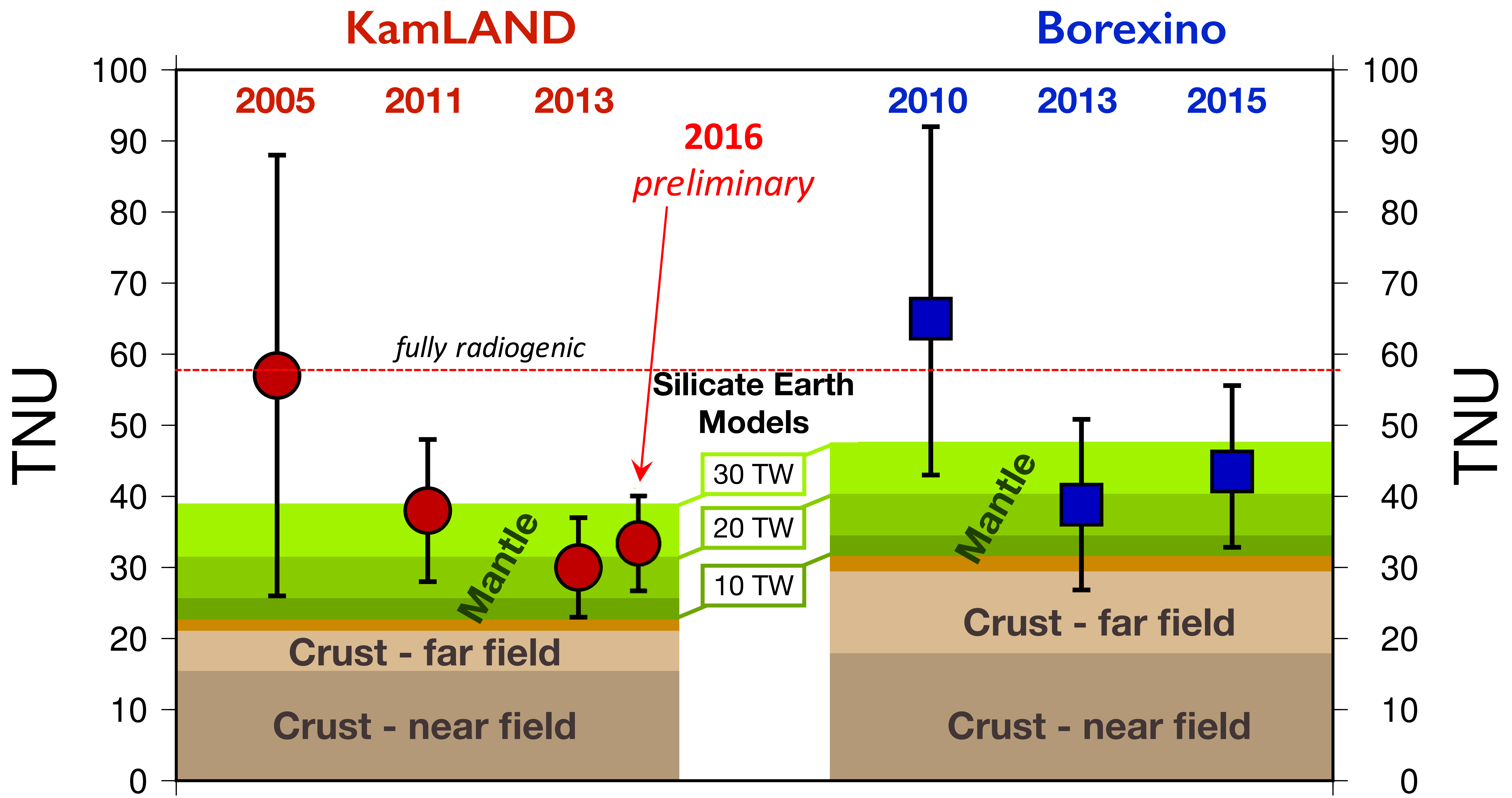
Radiogenic heat

$S_{geo} = 43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU



- Radiogenic heat (U+Th): 23-36 TW for the best fit and 11-52 TW for 1σ range
- Considering chondritic mass ratio Th/U=3.9 and K/U = 10^4 : Radiogenic heat
  (U + Th + K) = 33^{+28}_{-20}TW
  to be compared with 47 ± 2 TW of the total Earth surface heat flux (including all sources)

KamLAND & Borexino : Radiogenic Heat



Geo-neutrino Measurement

- giving **total radiogenic heat**
- testing BSE models

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

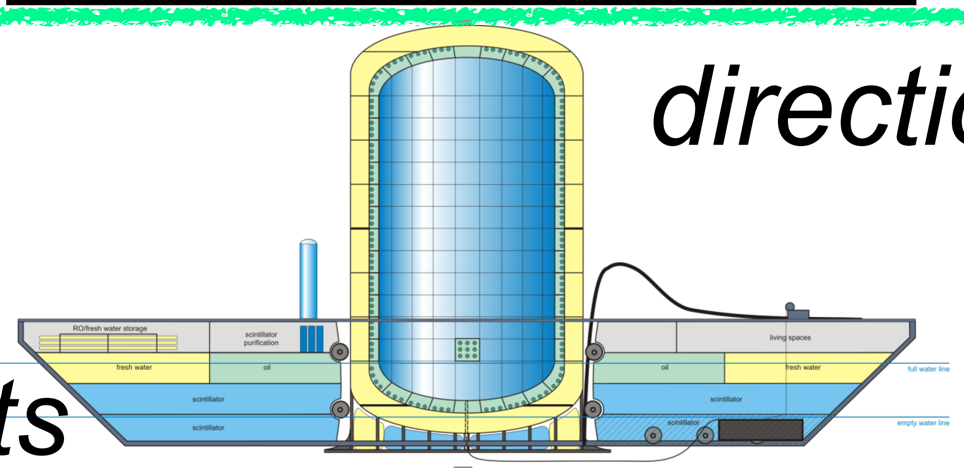
Contents

Status & Prospect of “Neutrino Geoscience”

what we need

improved accuracy of measurement & modelling

multi-site measurements



detector in the Ocean

directional sensitive detector

new type detector

current generation → **next** generation

total radiogenic heat in the Earth ☑ achieved

Th/U ratio ☑ achieved

distinguishing mantle contribution

resolving vertical and horizontal flux differences

detecting K geo-neutrino

what we learn

first measurement in **2005**

Next Target : Mantle Contribution

1. Observation - Crust (Model) = Mantle

17% error
(2016, KamLAND)

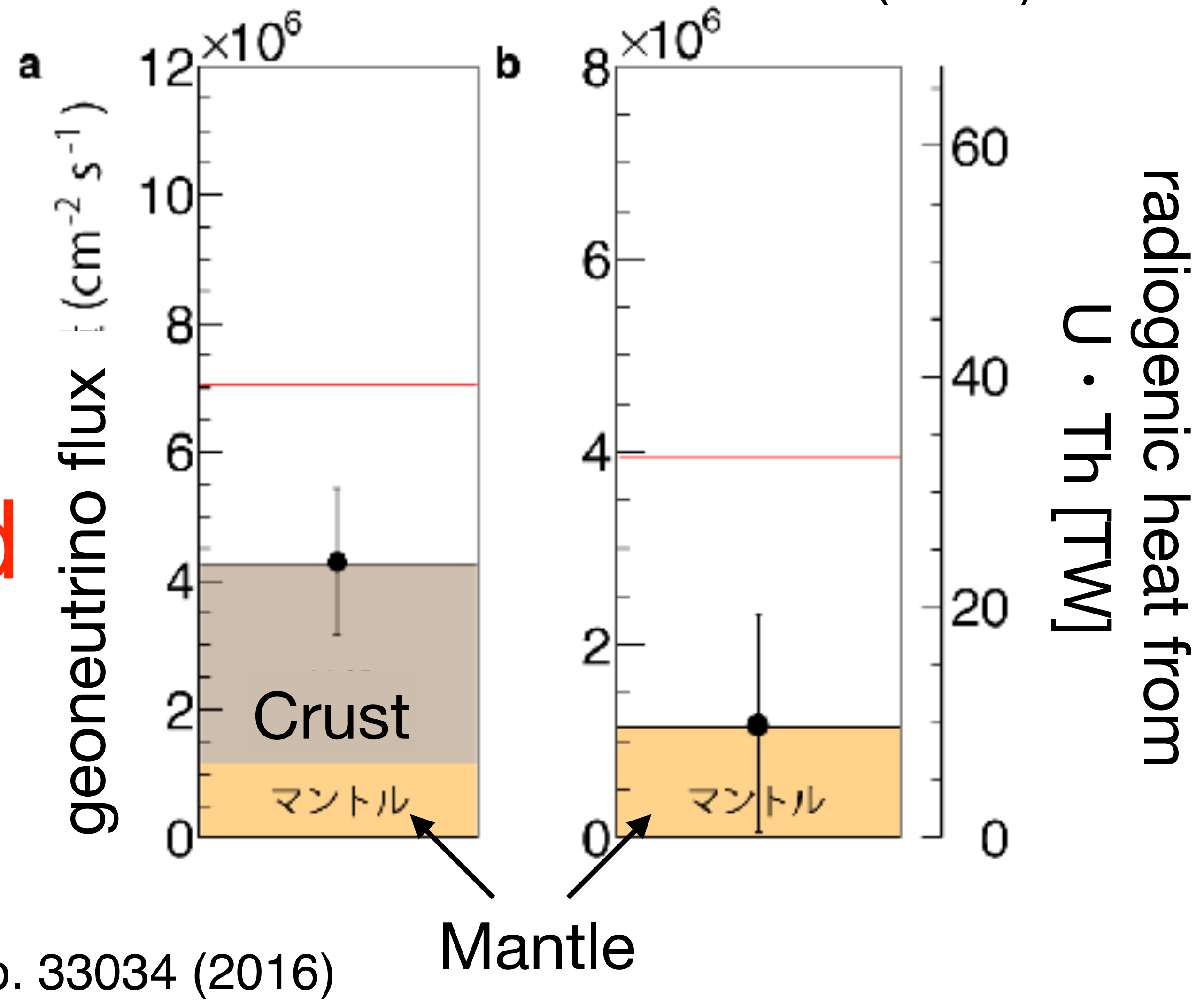
20% error

Method of uncertainty estimation is unclear

Consider geoscientific inputs
- Seismology
- Geochemistry
- Measurement result of heat flux etc

Flux model needs to be improved
(higher reliability and accuracy)

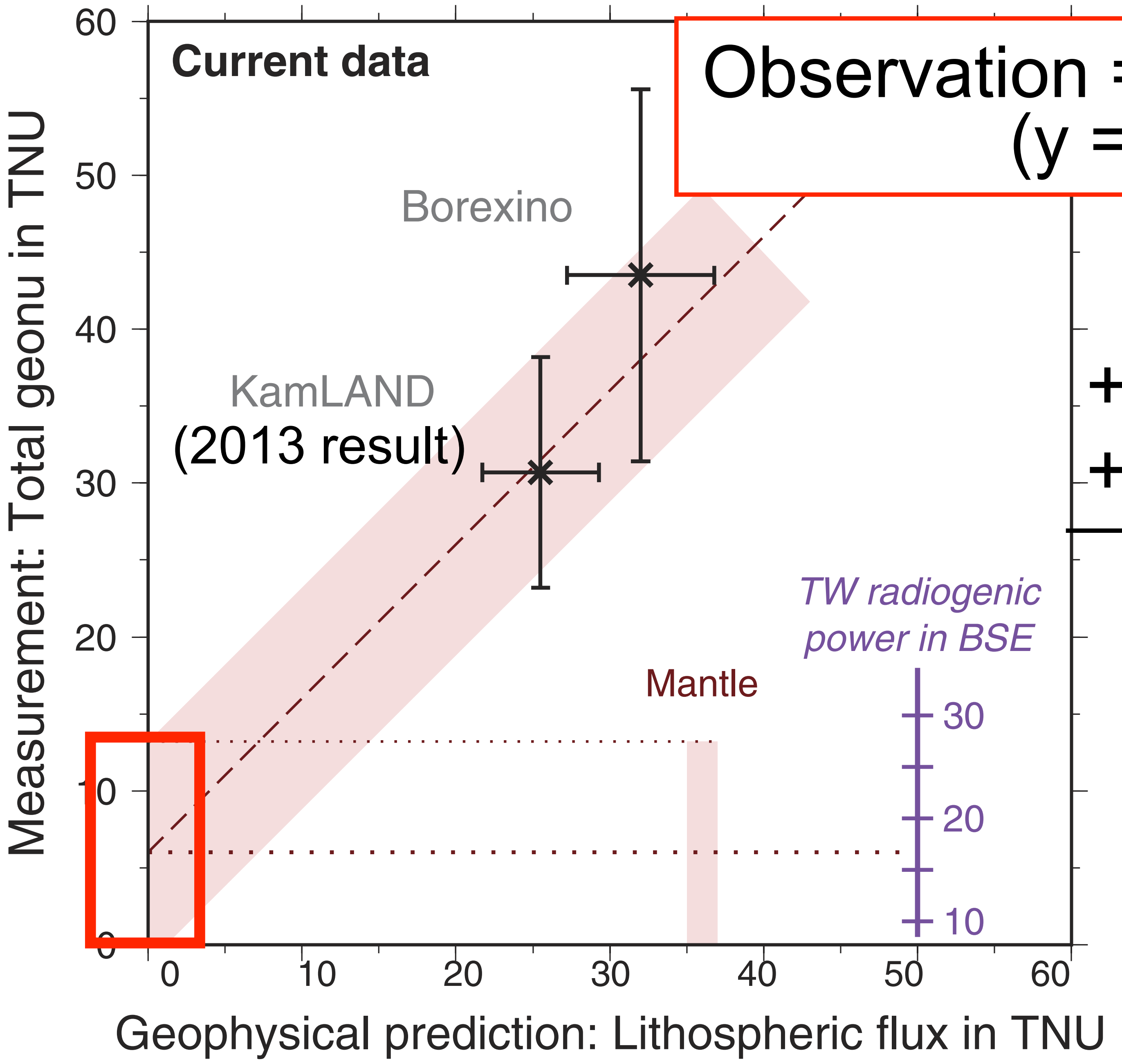
N. Geo. 1205 (2011)



2. Multi-site measurements

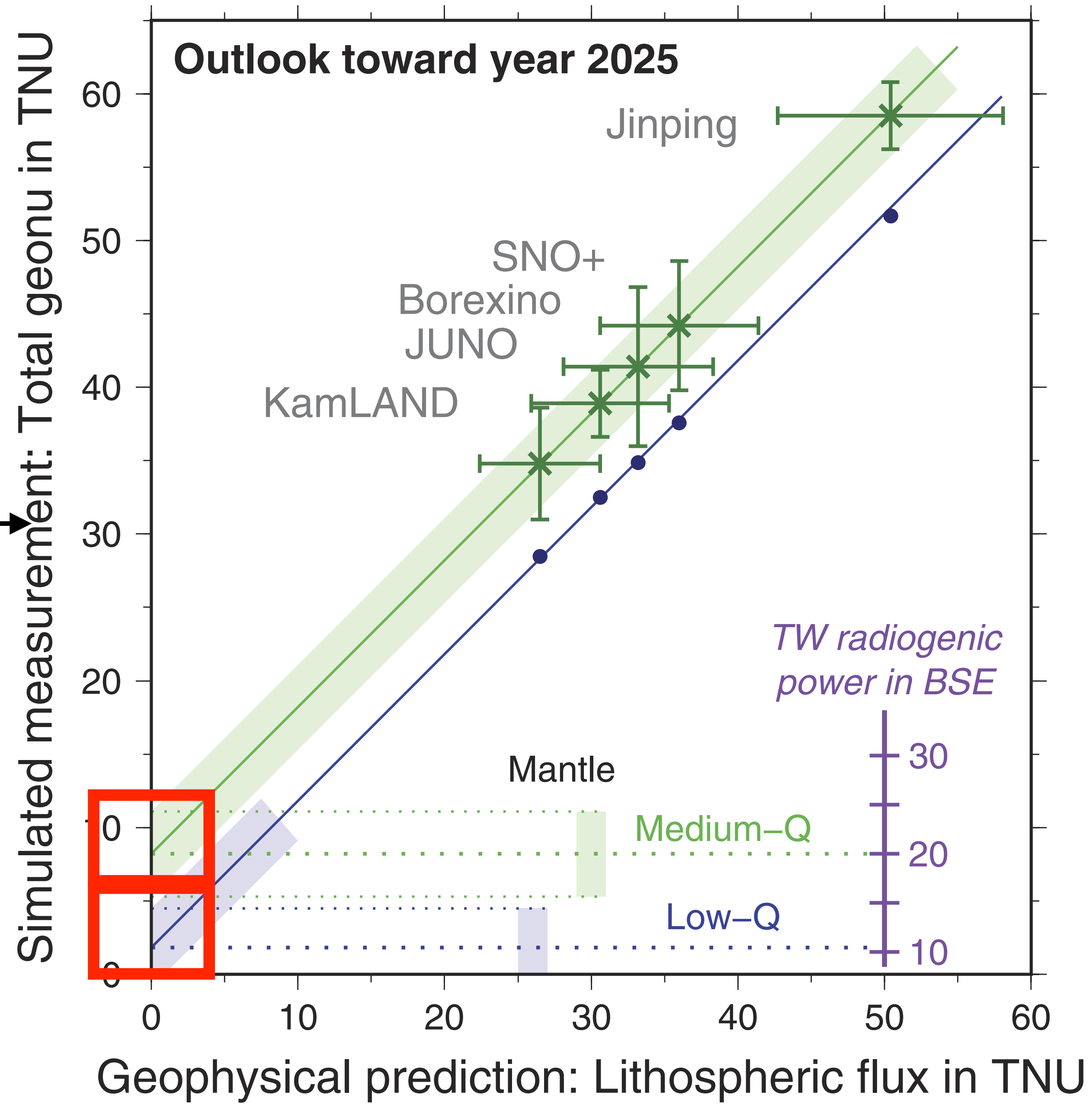
Note : Assuming homogeneous mantle

Observation = Crust + Mantle
(y = x + b)

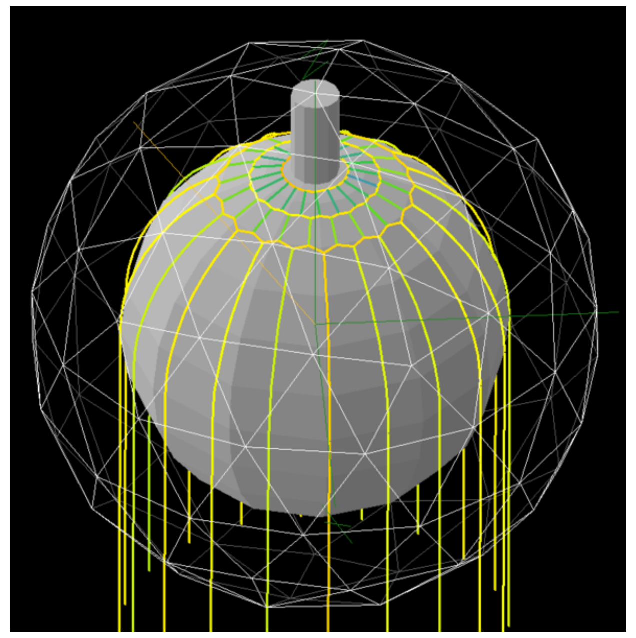


+10-year data
+New experiments

Šrámek et al. , S. Rep. 33034 (2016)

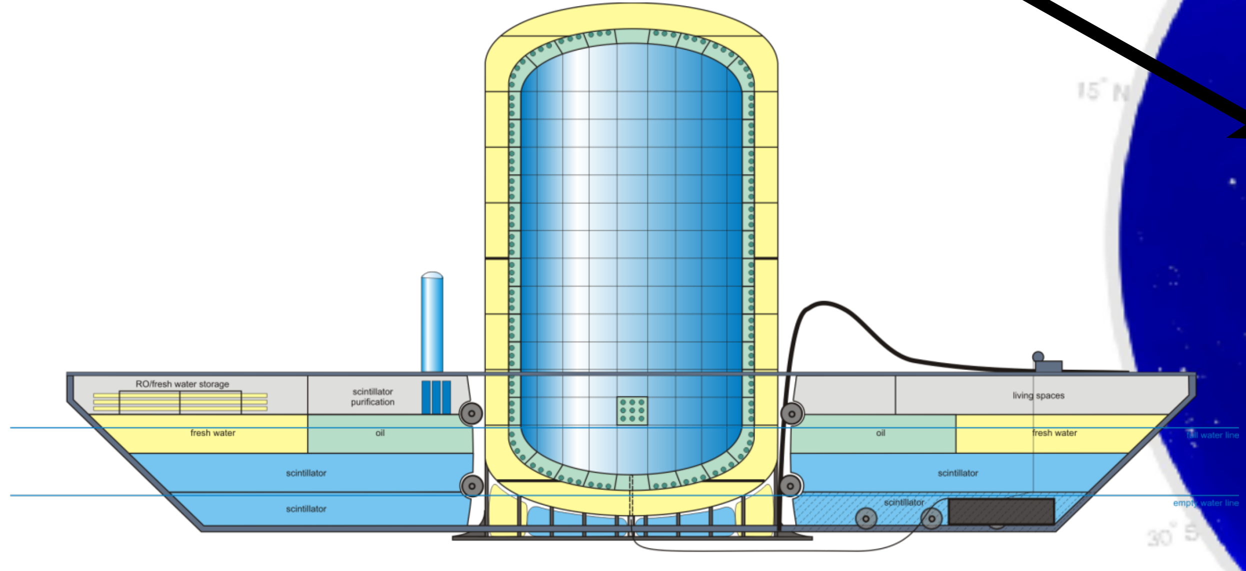


Anti-neutrino Detectors

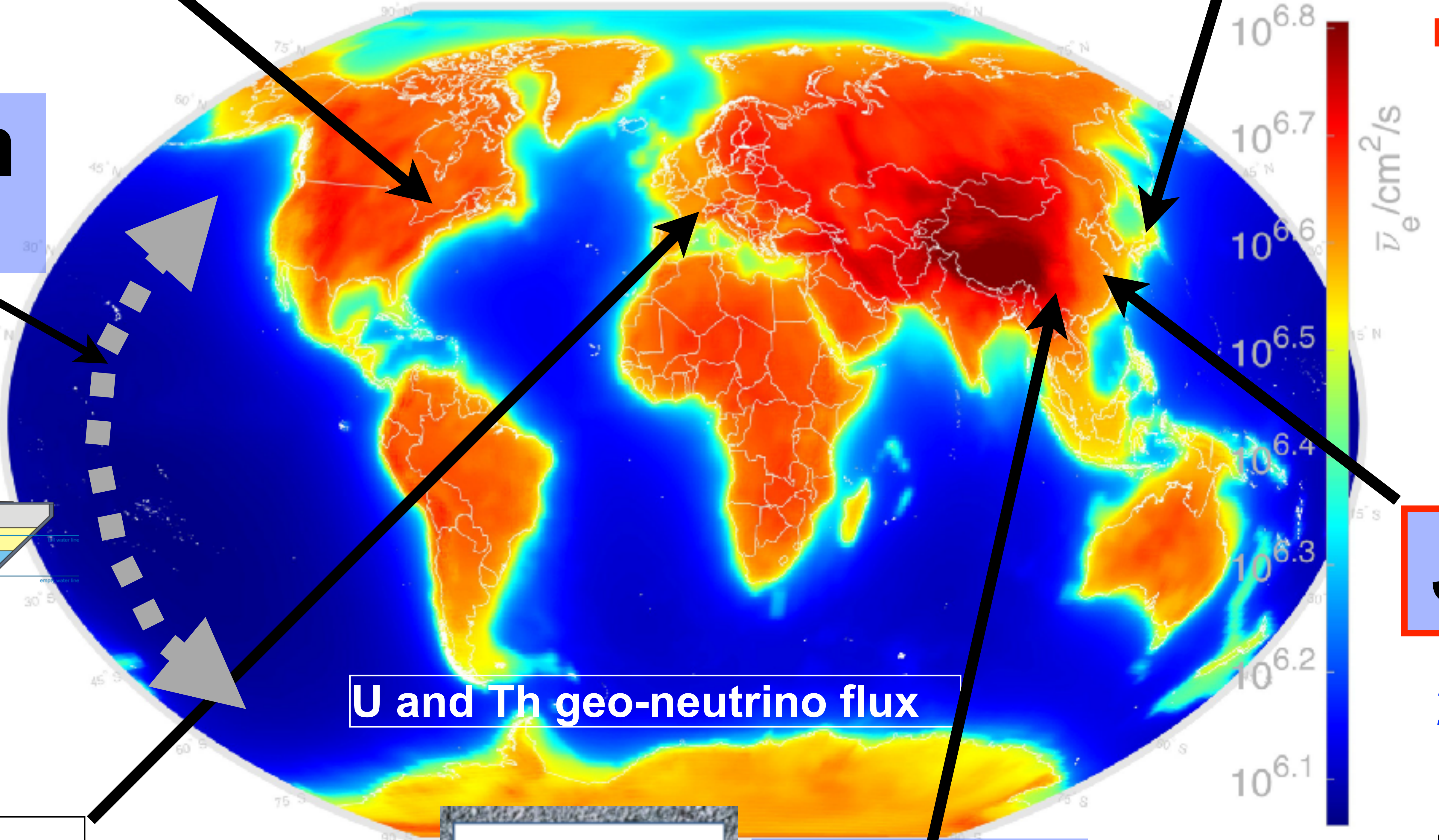


SNO+
1kt, LS+, 5.4 kmwe
Liquid scintillator filling is in progress!

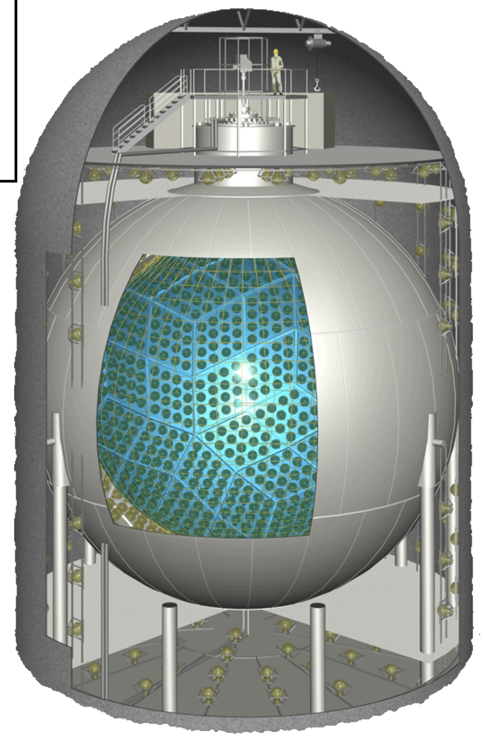
Ocean Bottom Detector



10-50kt, LS, ~5kmwe,
movable, R&D

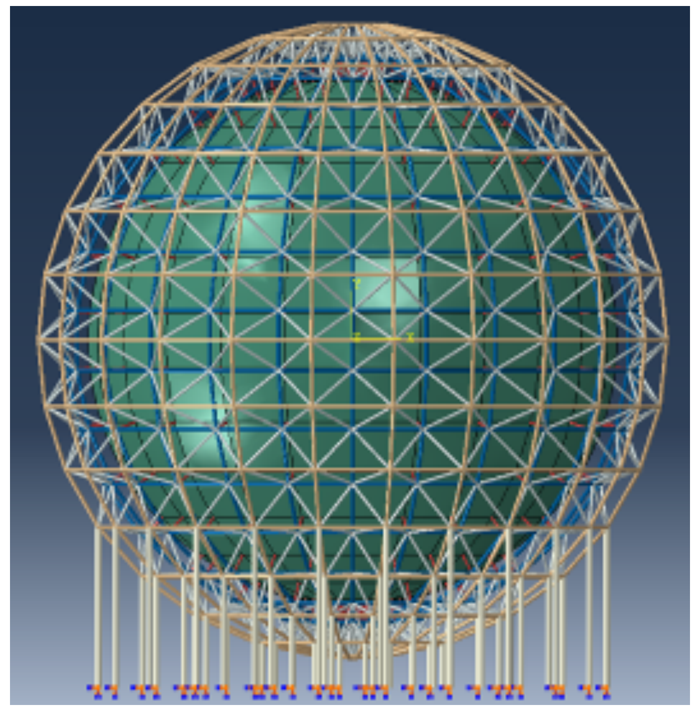


KamLAND

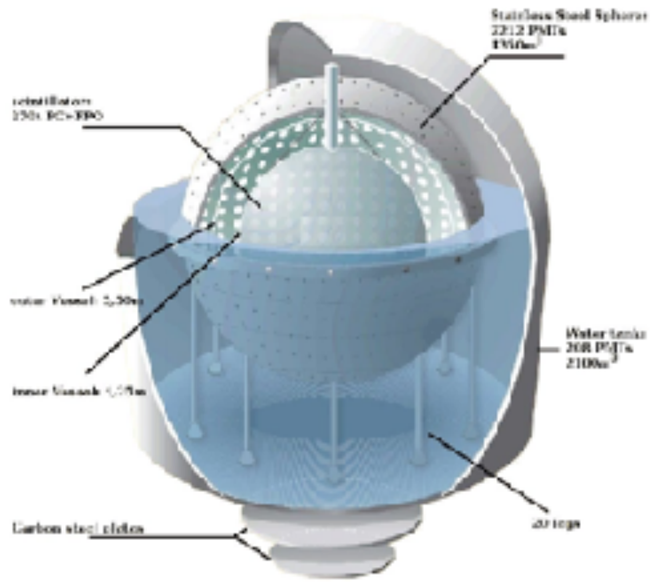


1kt, LS
2.7 kmwe
running

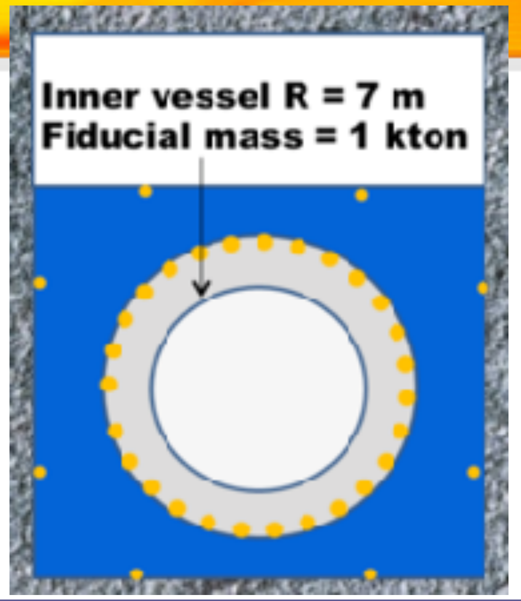
JUNO



20kt, LS
1.5 kmwe
approved
(2020~)

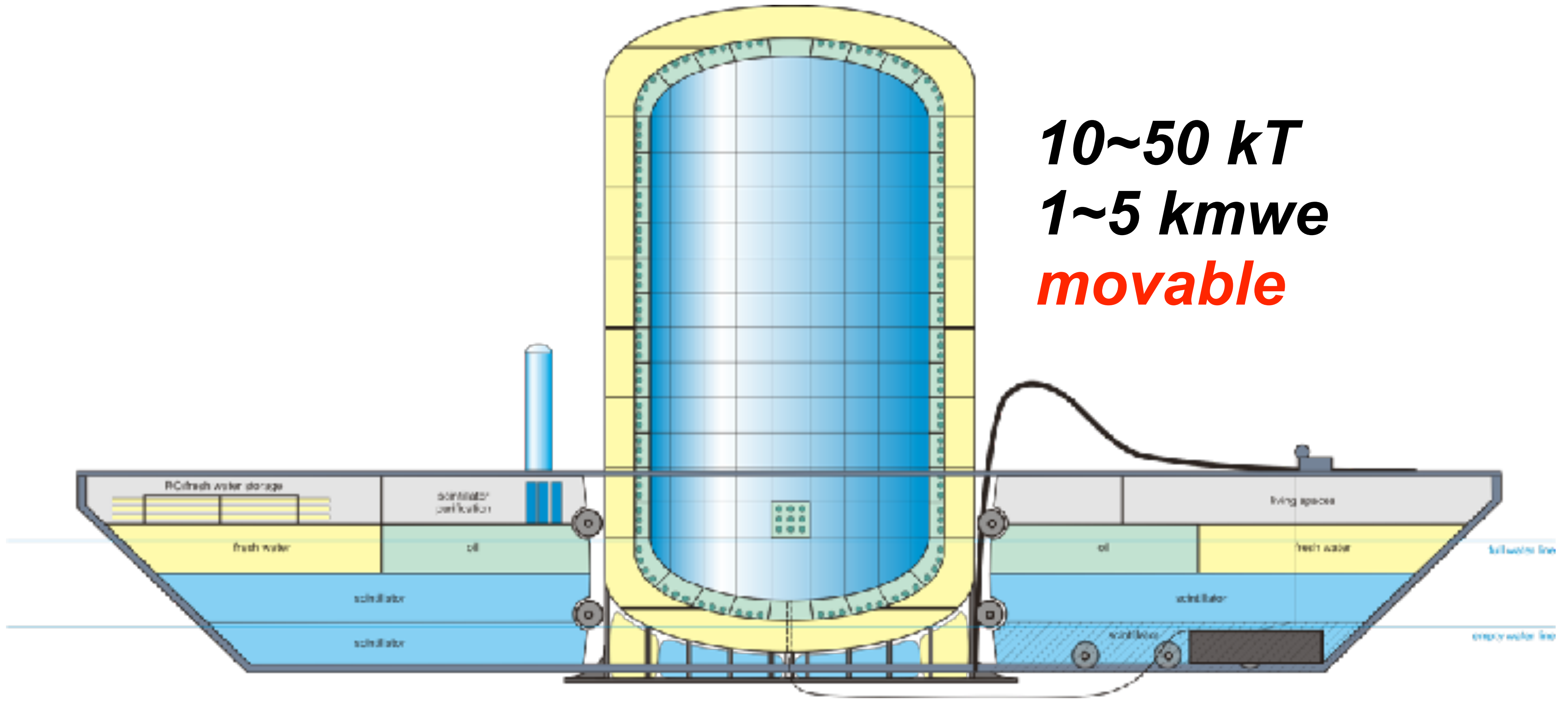


Borexino
0.3kt, LS
3.7kmwe
running

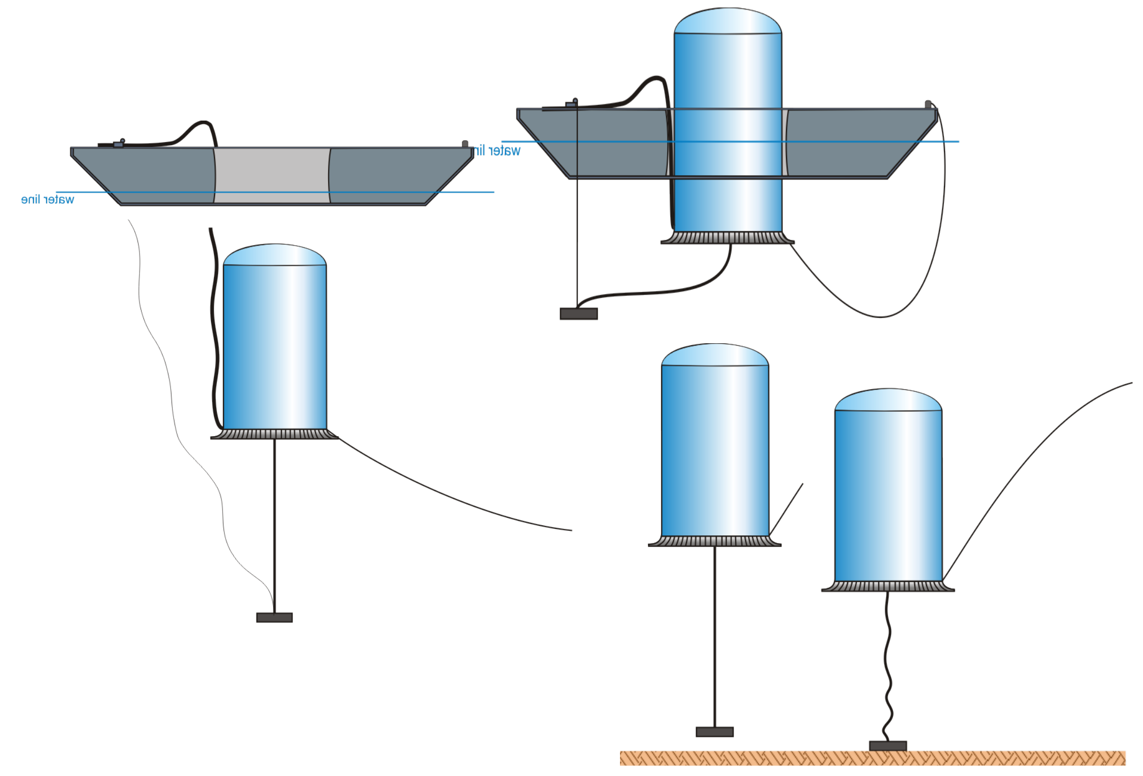


Jinping
1kt, LS
6.7 kmwe
R&D

▸Ocean Bottom Detector (OBD)

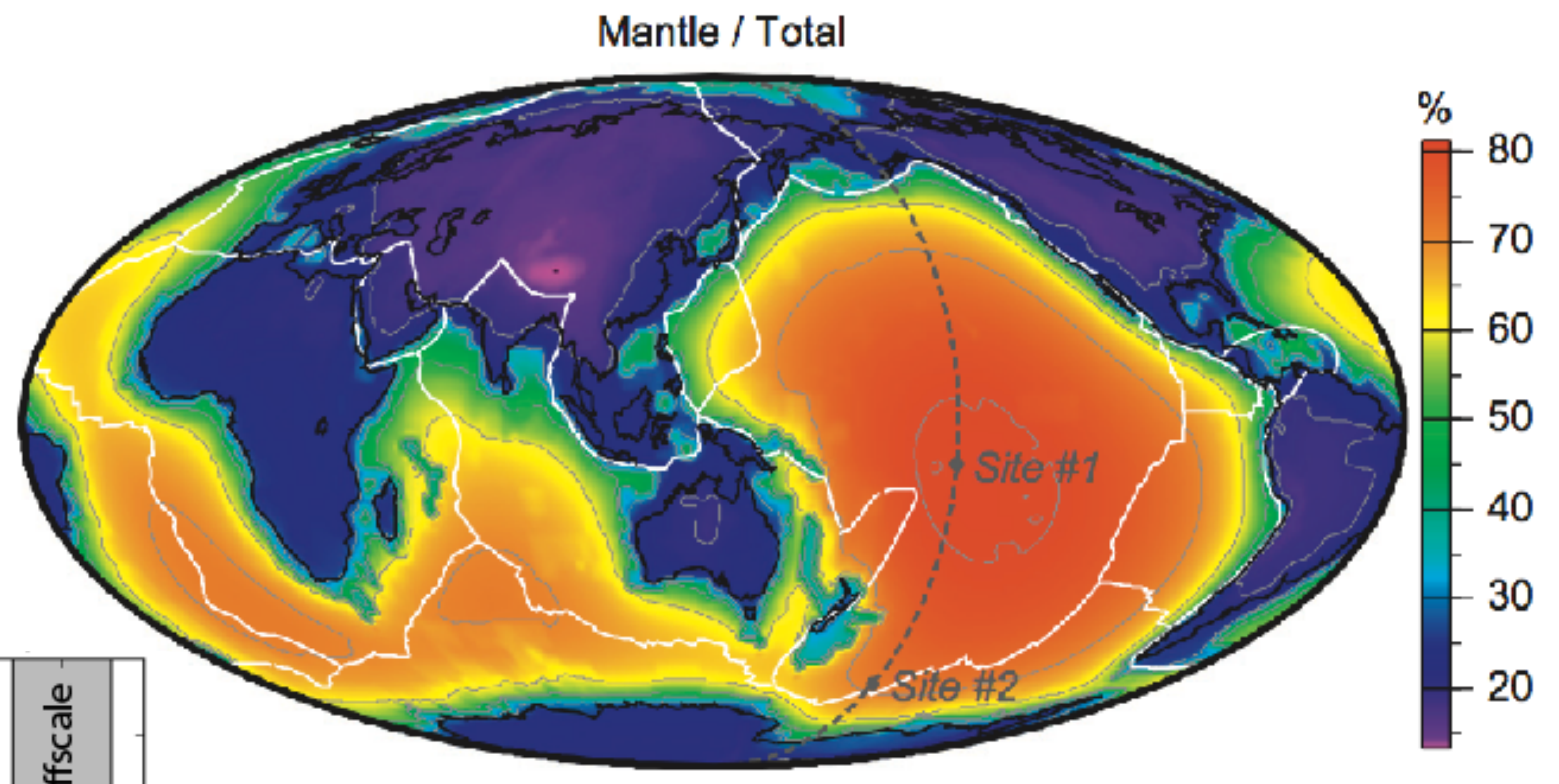


10~50 kT
1~5 kmwe
movable

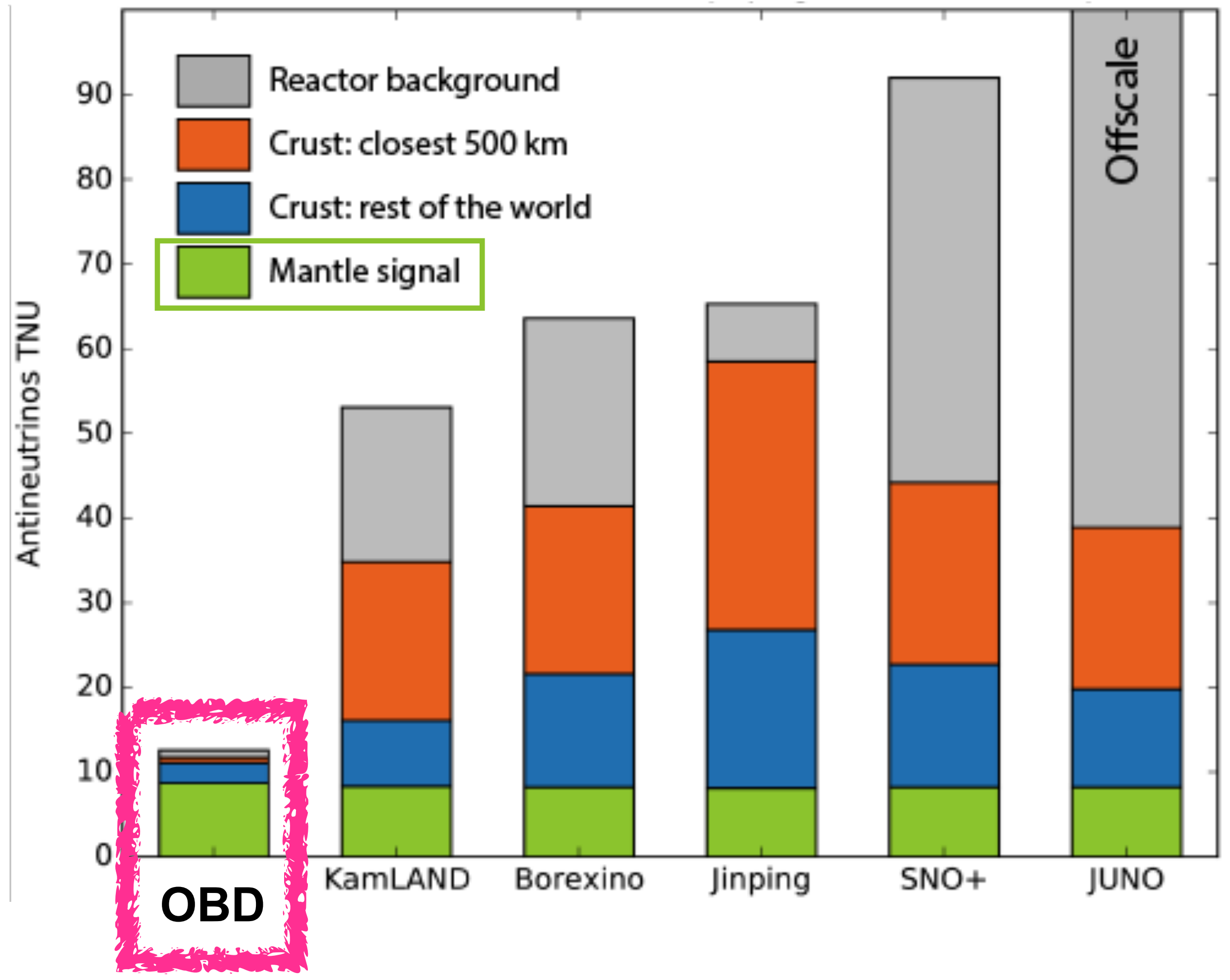


2005 : Specific engineering study was started in Hawaii.

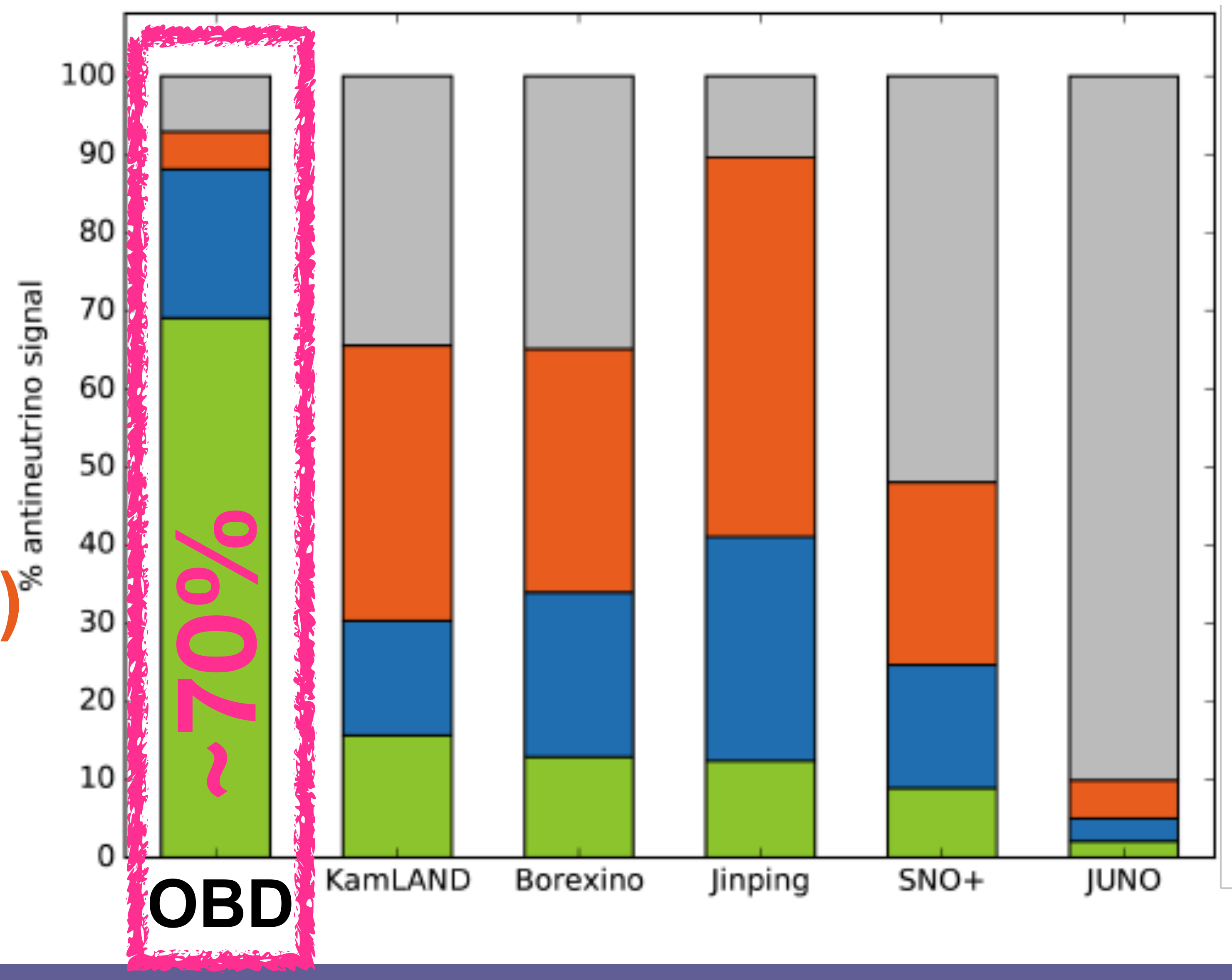
Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001



Total Flux



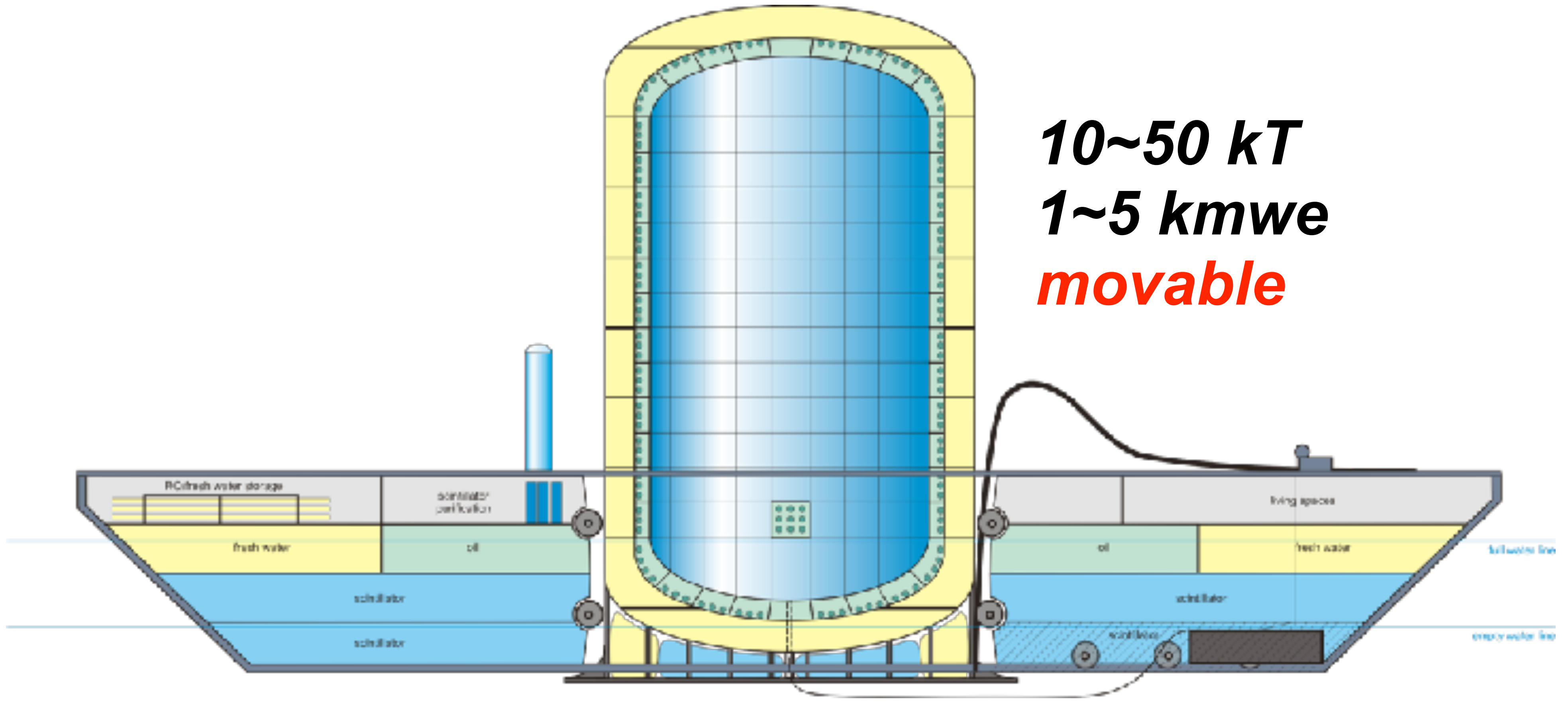
Contributions



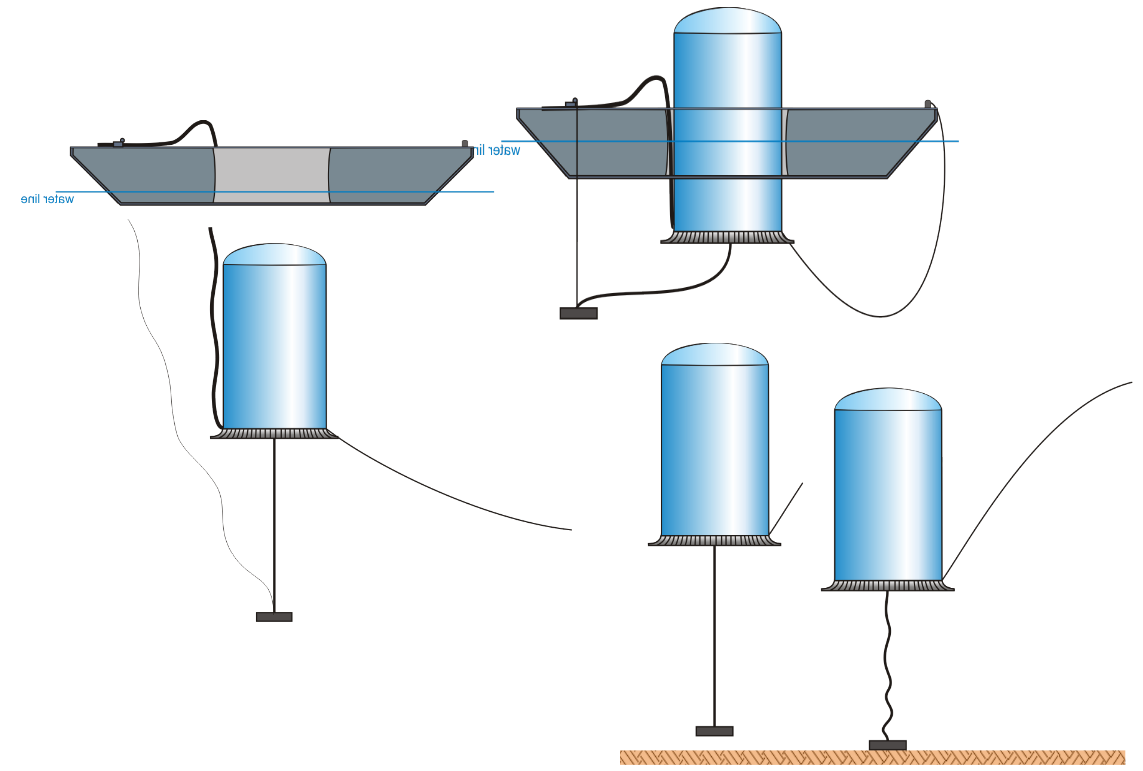
Reactor
Crust(<500km)
Crust(other)
Mantle

- **Direct measurement of mantle contribution**
- **Test of Earth models**
- **Geoneutrino has power to measure deep Earth**

▶Ocean Bottom Detector (OBD)



10~50 kT
1~5 kmwe
movable



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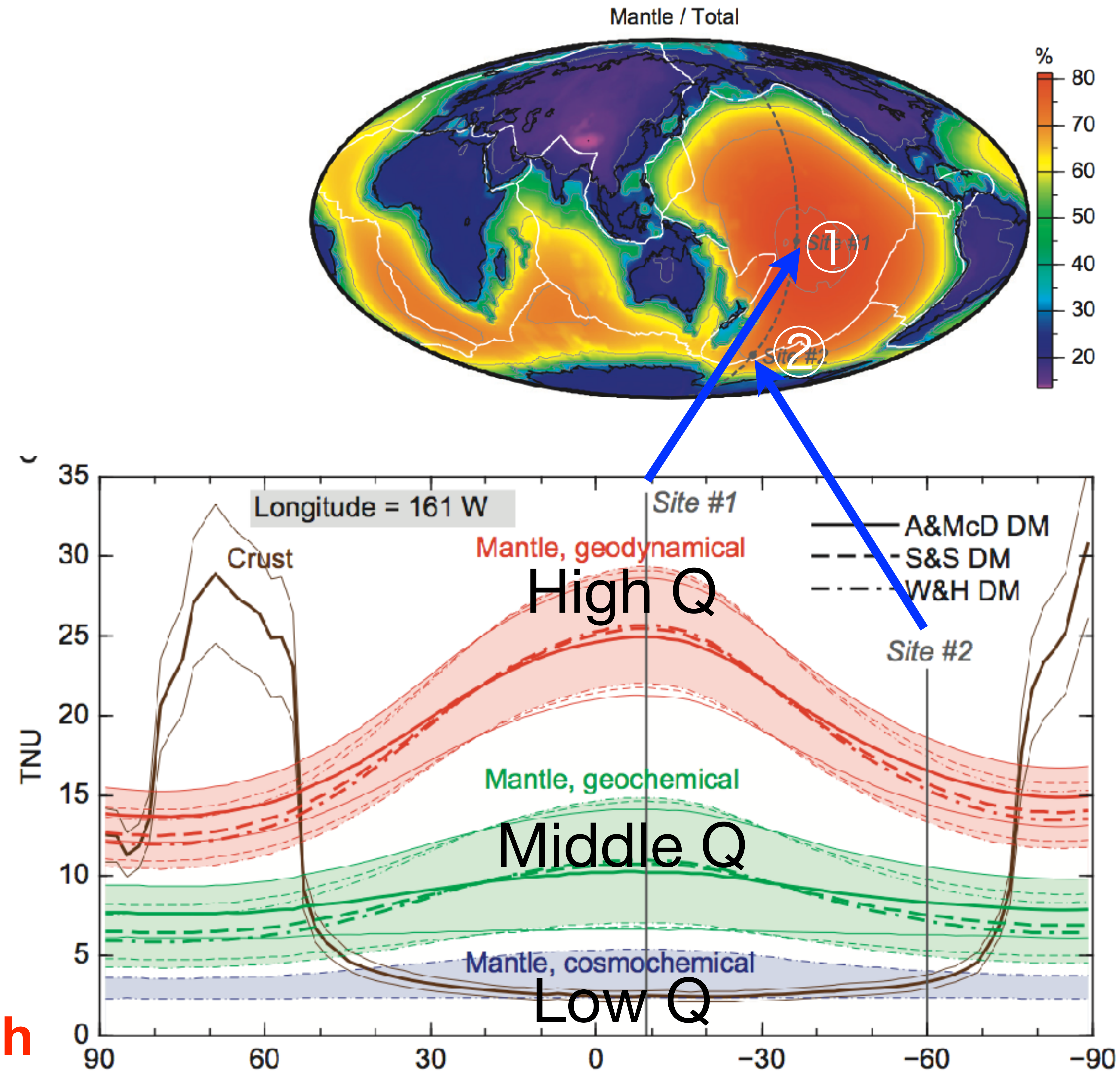


- **Direct measurement of mantle contribution**
- **Test of Earth models**
- **Geoneutrino has power to measure deep Earth**

Summary

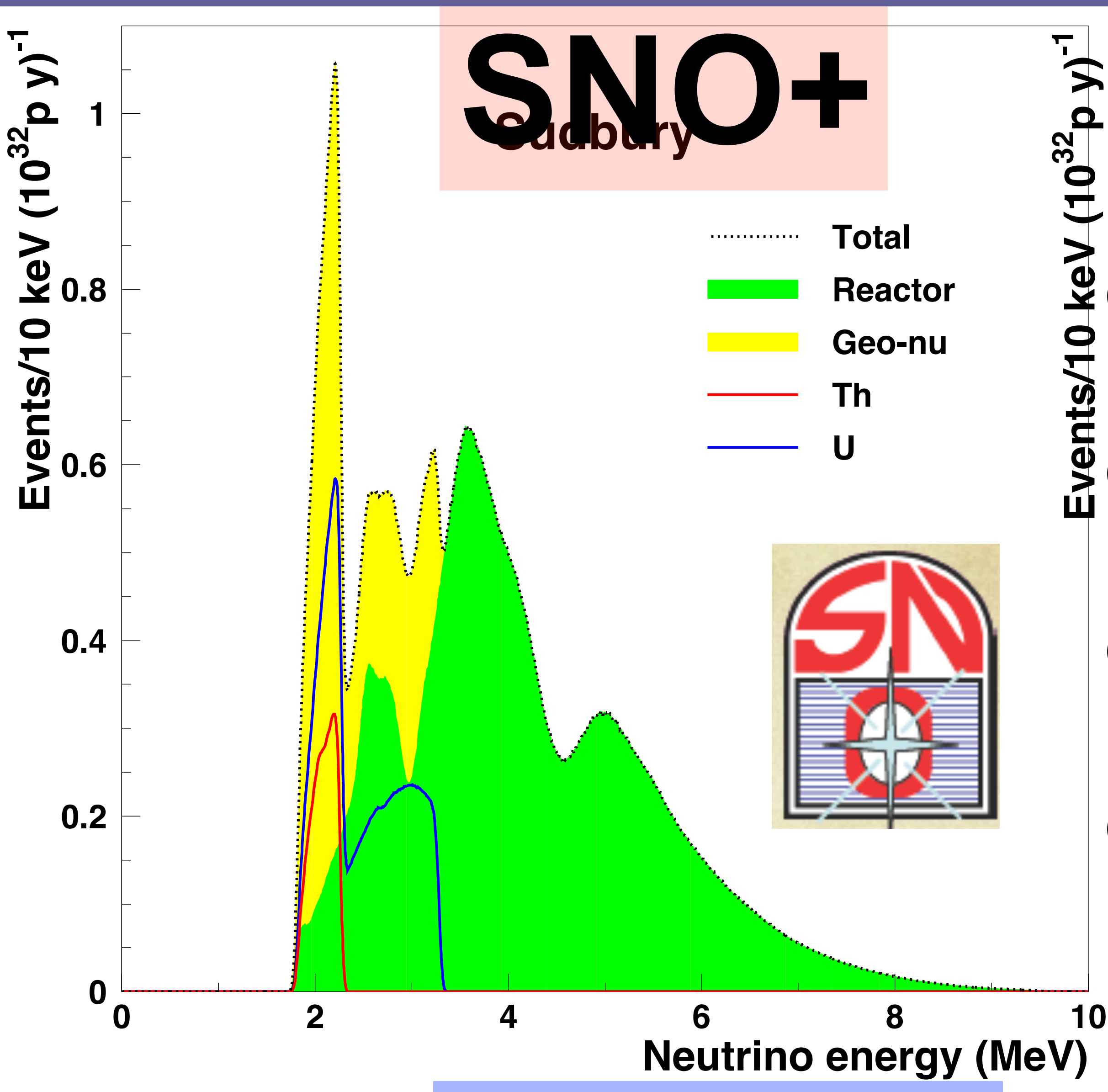
- Geoneutrinos bring unique and direct information about the Earth's interior and dynamics.

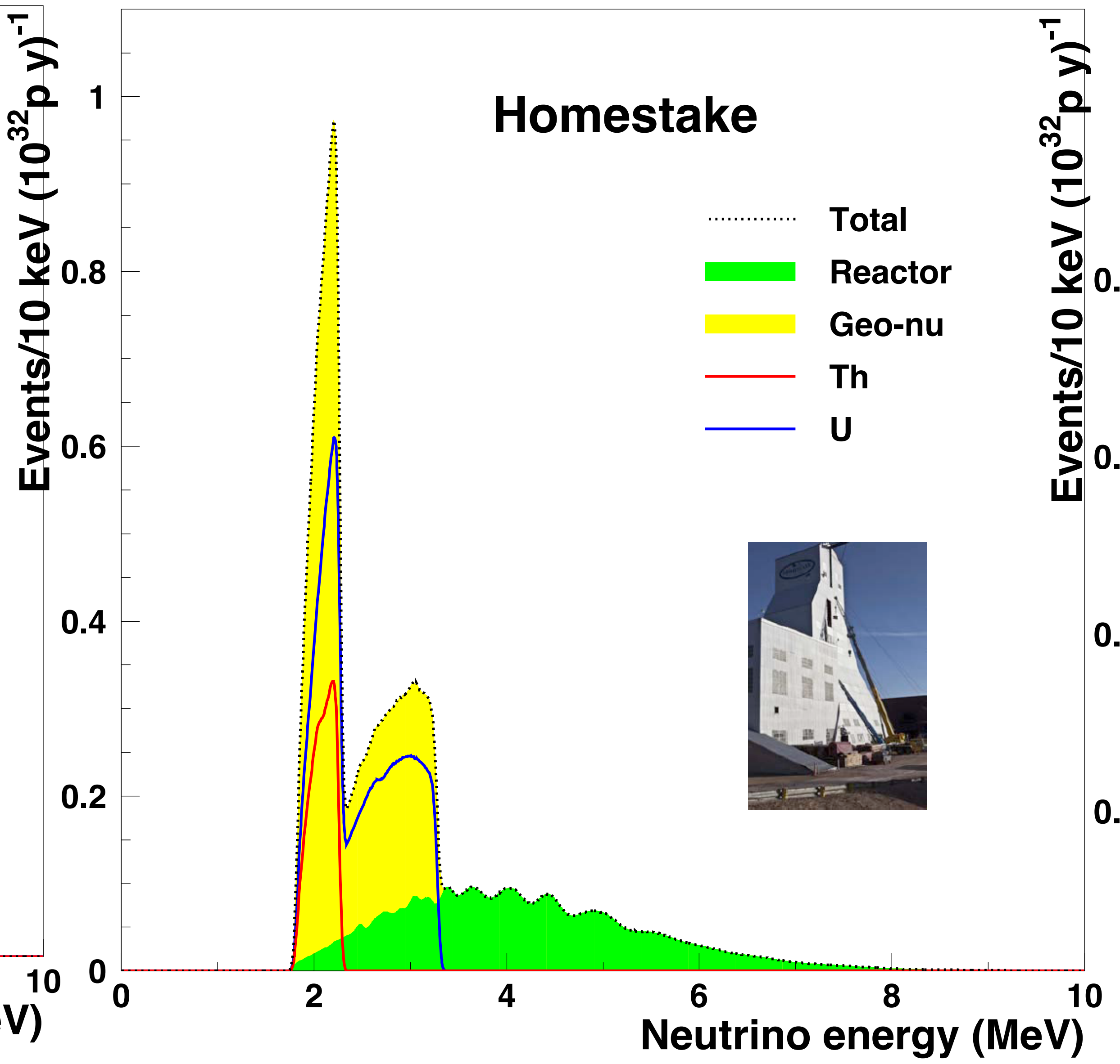
- **Results from geo-neutrino measurements**
  - Geoscientific results
    - Total radiogenic heat in the Earth
    - Th/U mass ratio
    - Test of Earth model
  - Measurement uncertainty gets close to the uncertainty of Earth model prediction.
  - KamLAND : New results with additional 500-day low reactor phase data will be published soon!

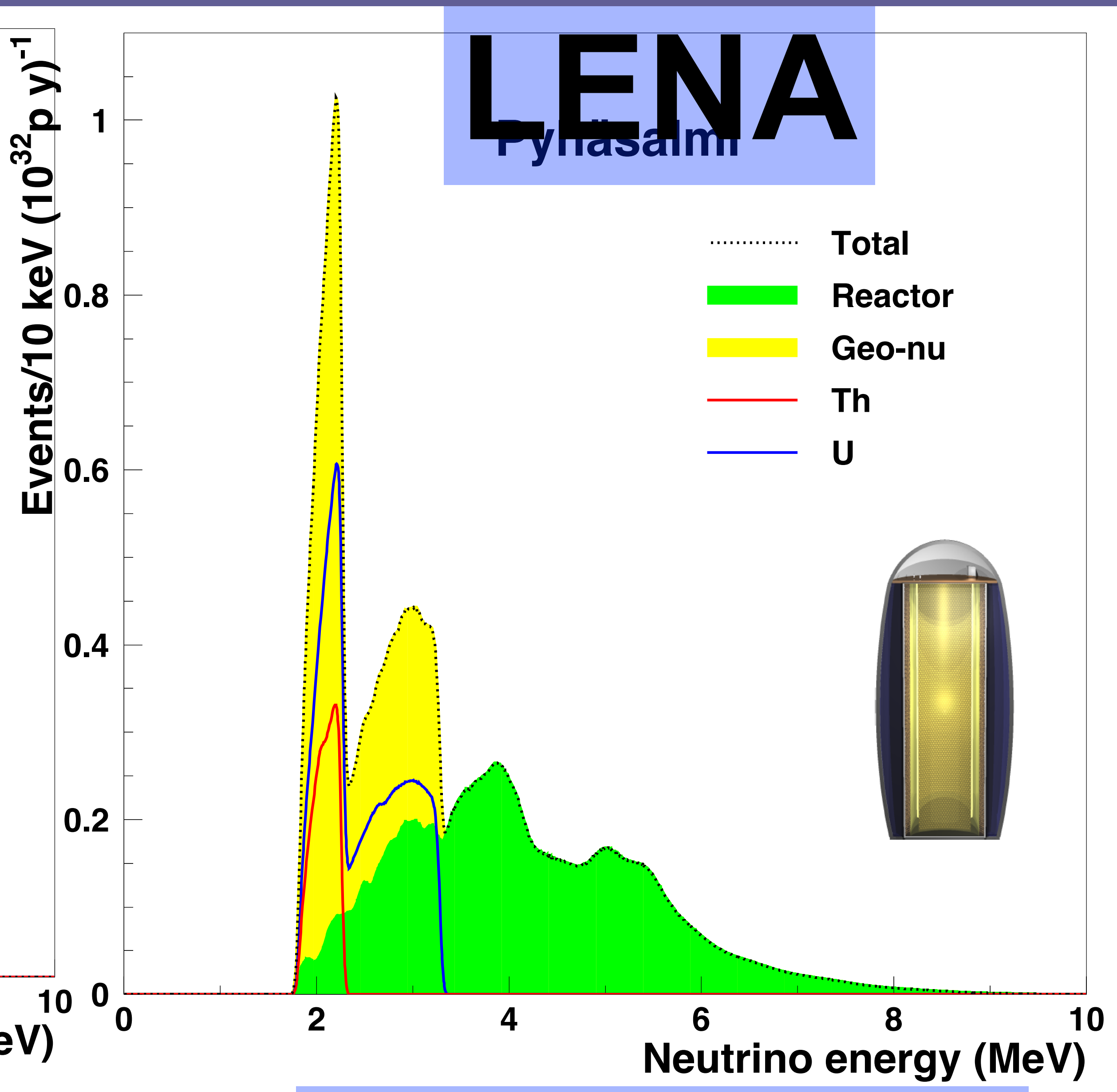
- **Future prospects of geo-neutrino measurement**
  - Nest target : Mantle contribution
    - Near future
      * Estimation of geo-neutrino contribution from mantle
      * Better understanding of crust model
      * Multi-site measurements
  - **Ocean Bottom Detector has strong power to measure mantle contribution directory.**

Backup

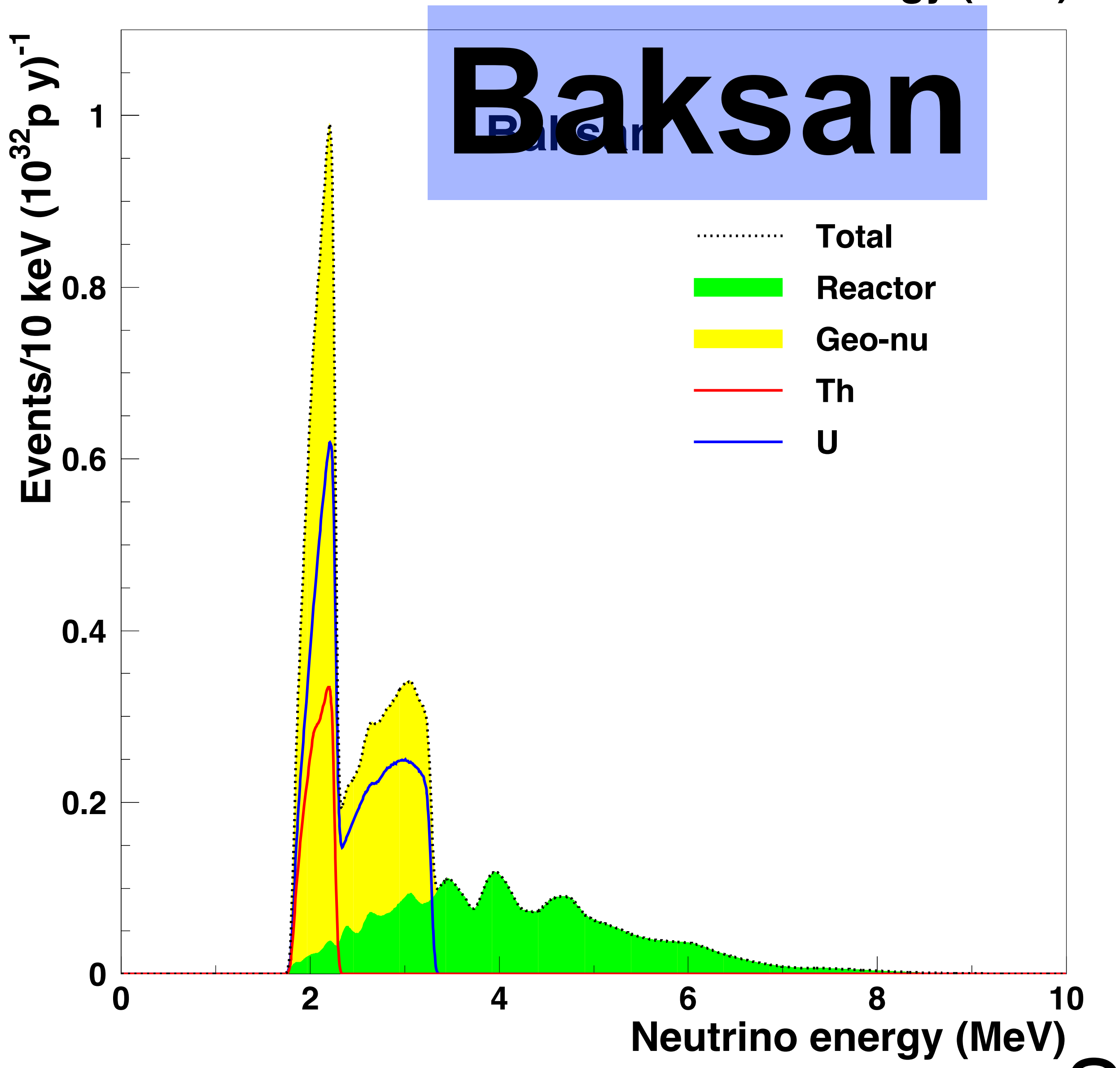
Anti-neutrino Detectors



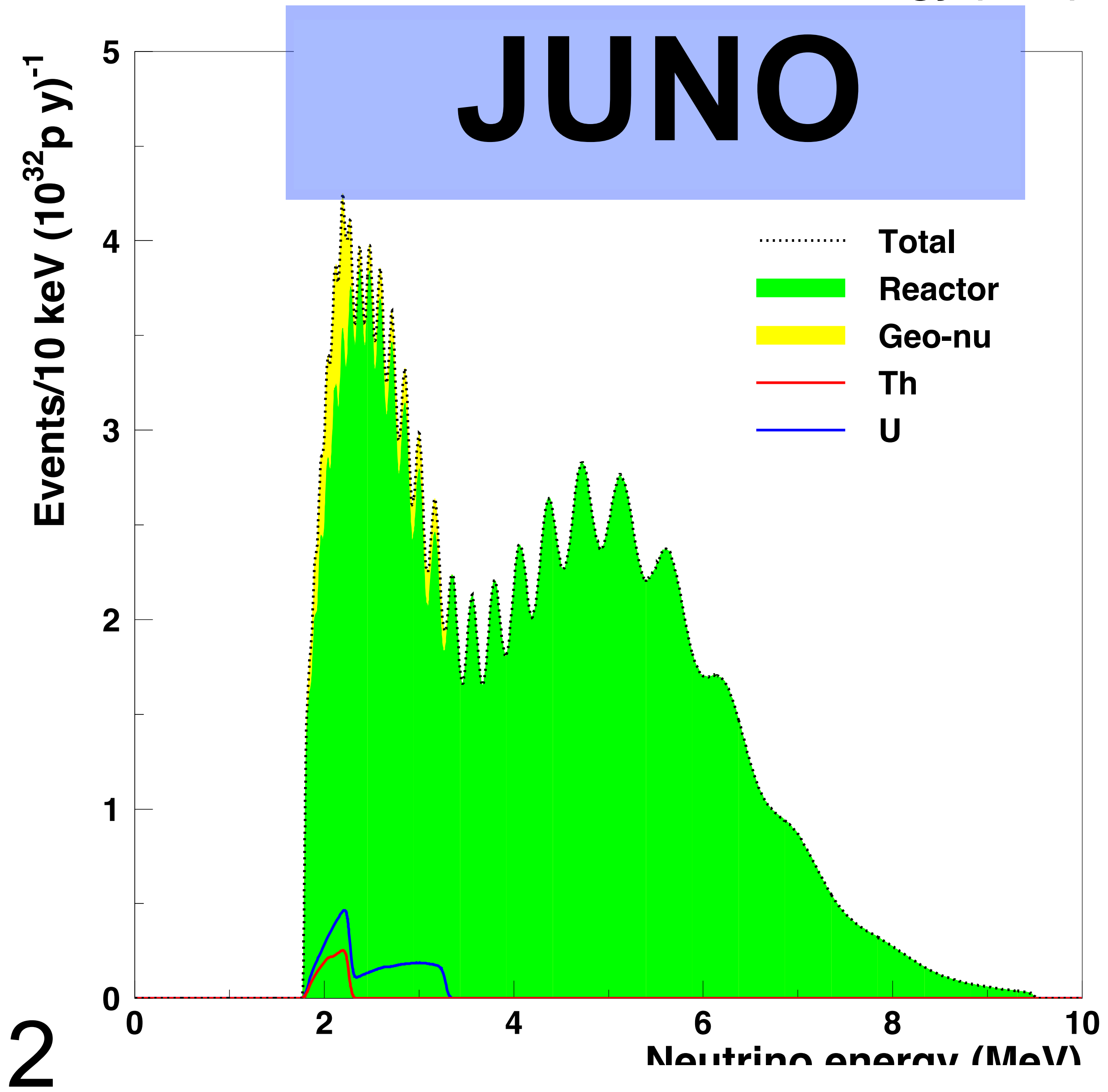




Multi-site measurements can distinguish <u>crustal differences</u>.



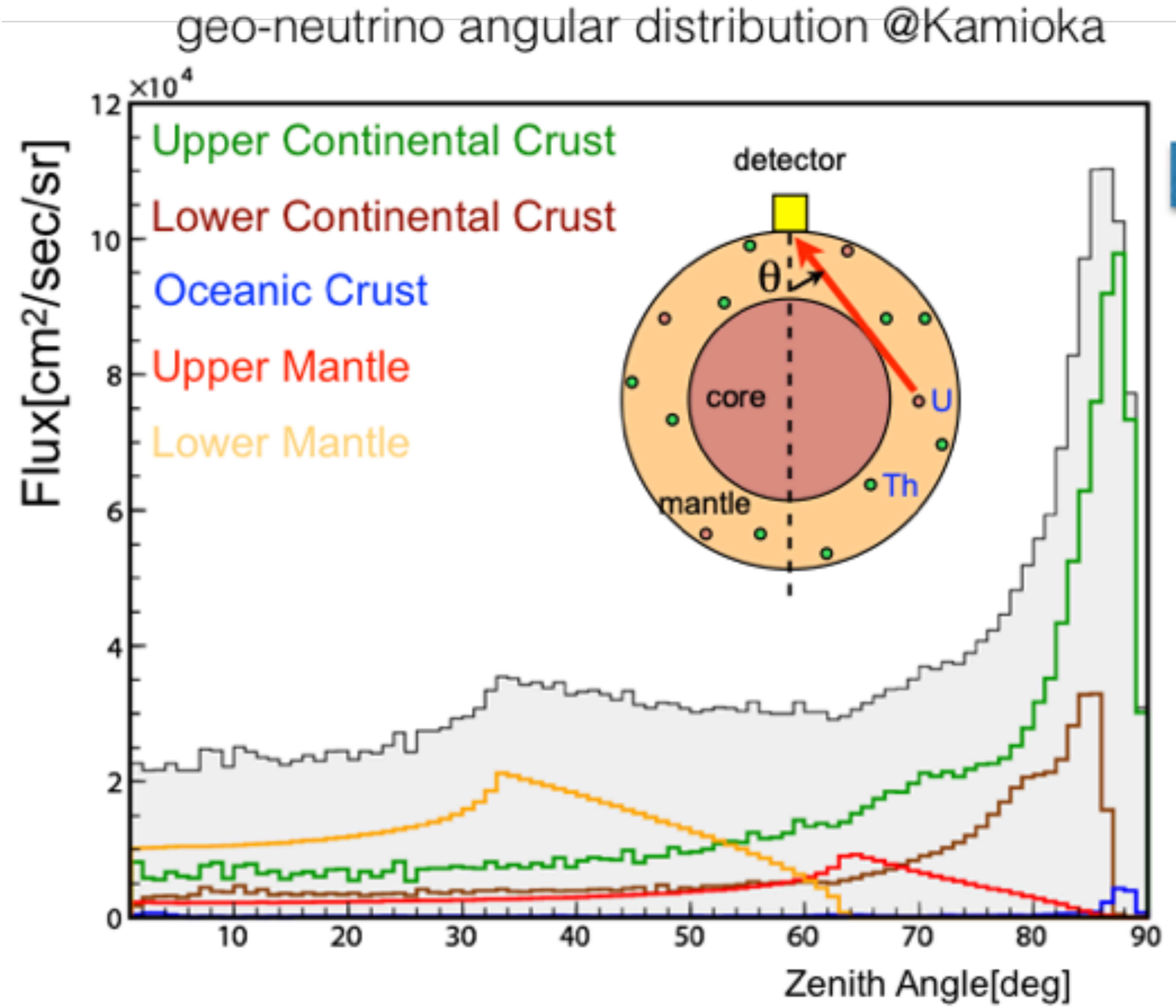
Continental Observatories

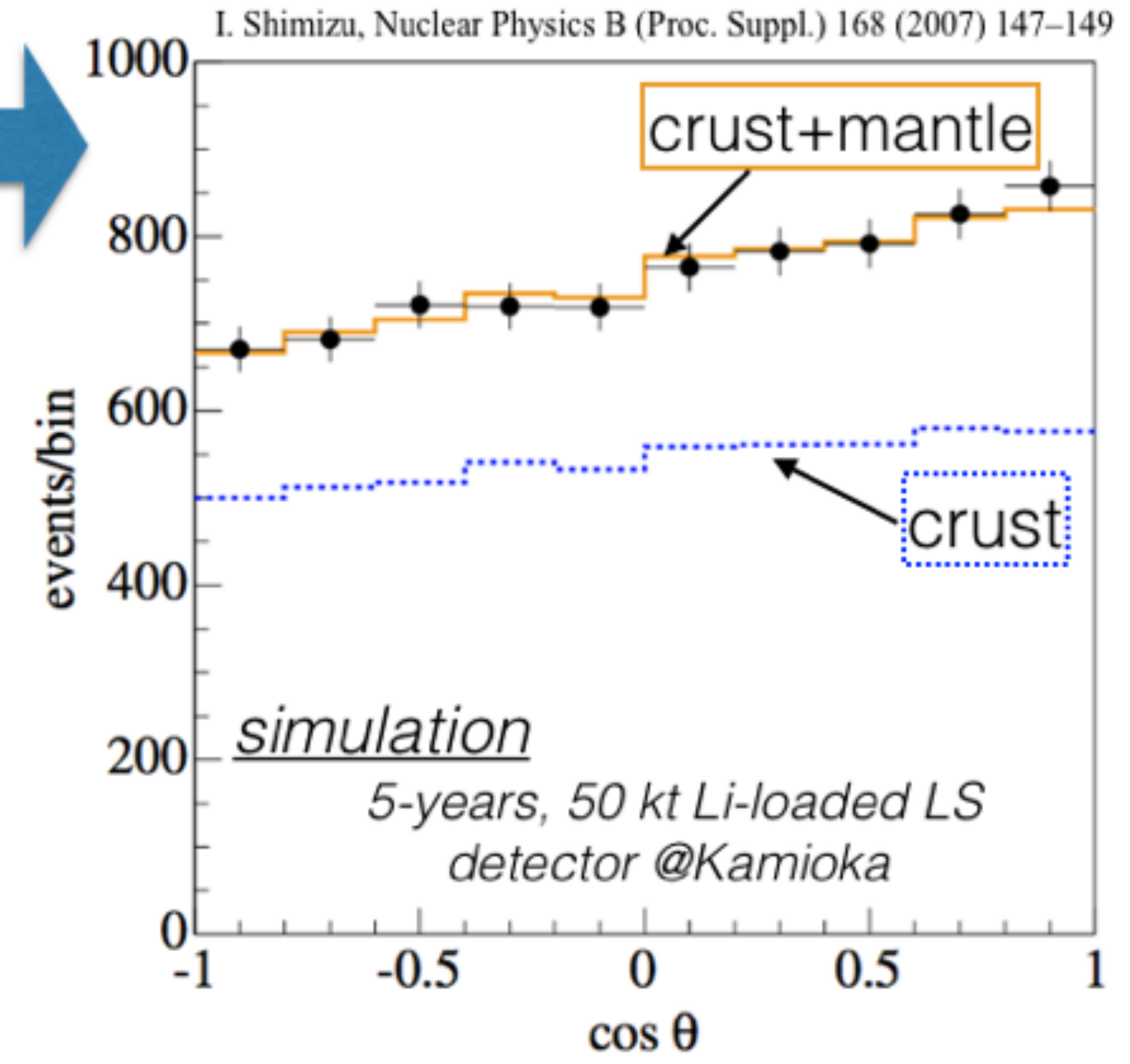


Understanding of geochemical evolution of the Earth.

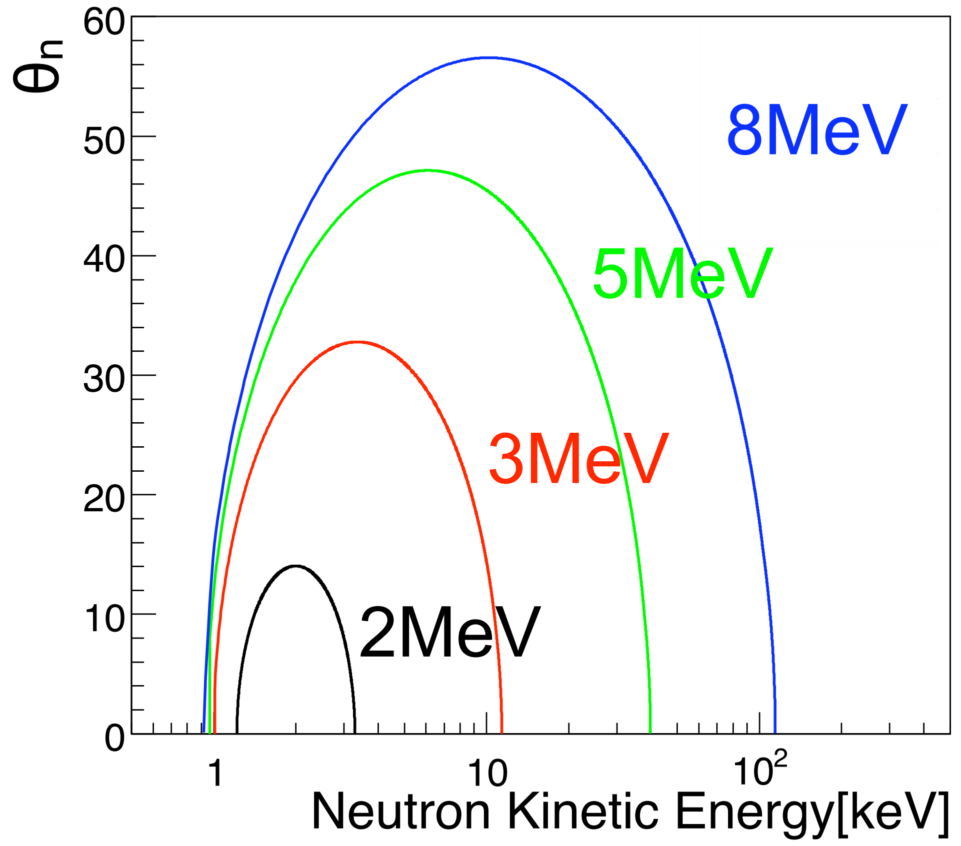
Steve Dye, Neutrino 2012

Directional Measurement



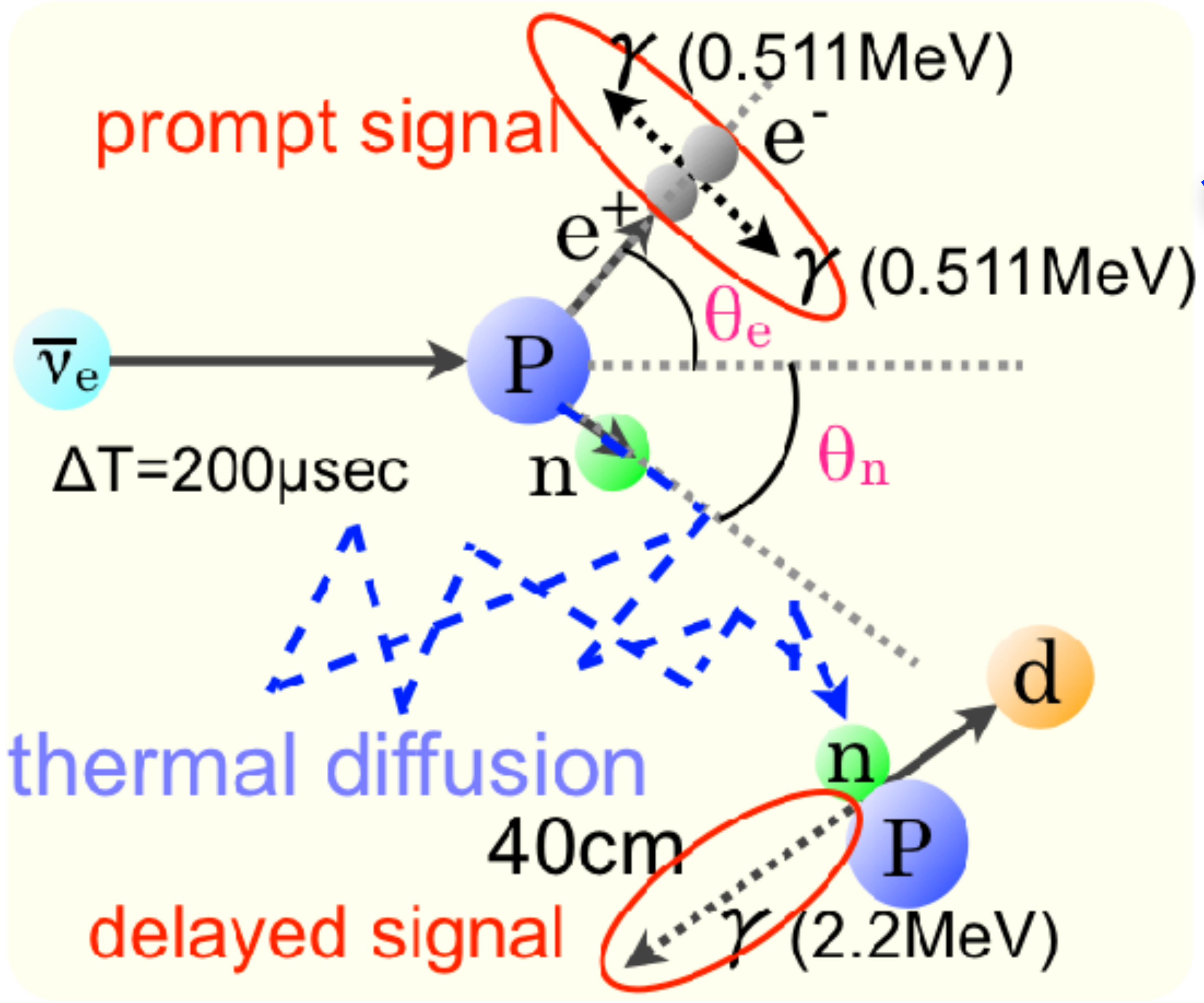


Directional Measurement with ^{6}LiLS and Imaging Detector



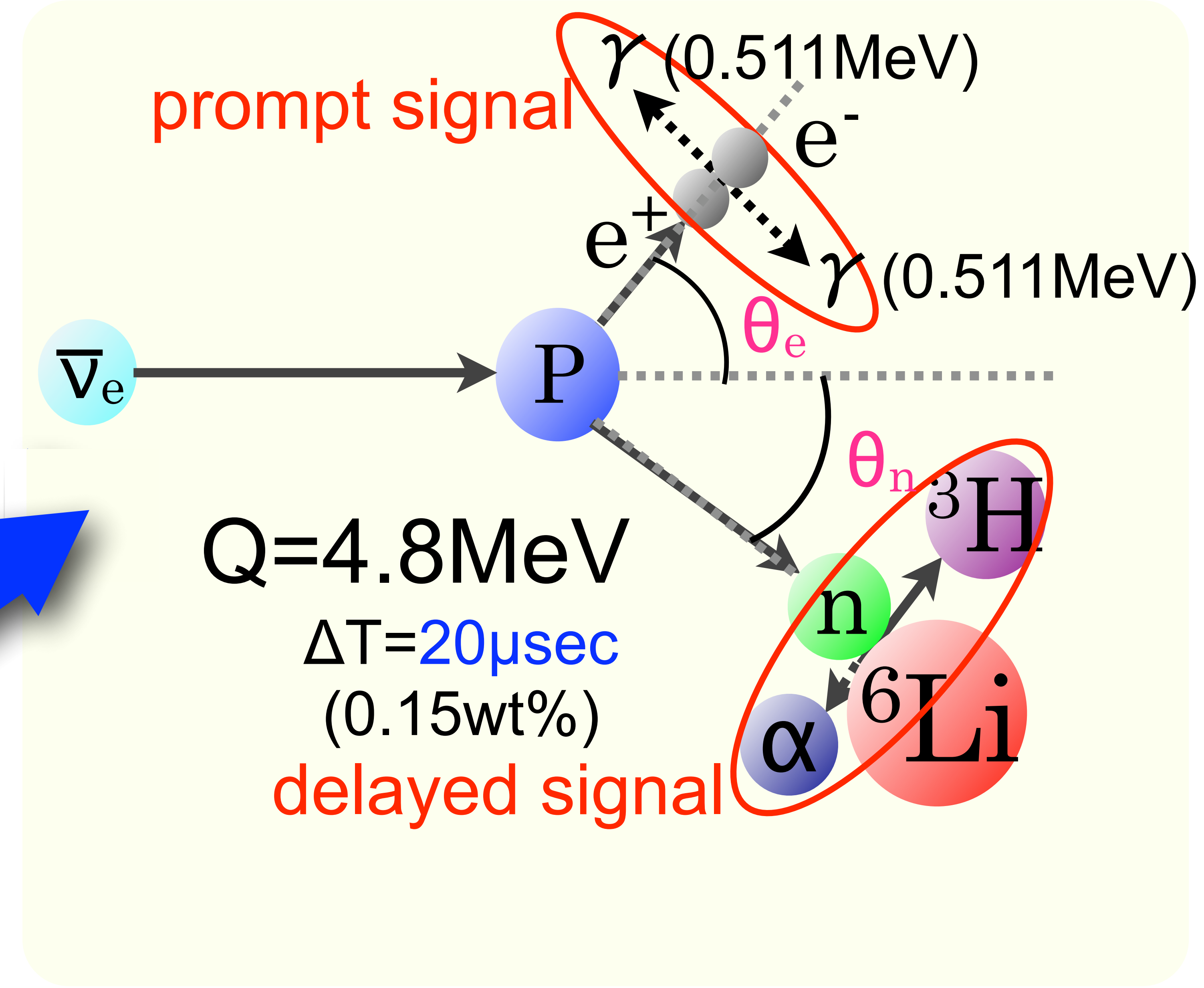
$E_{\bar{\nu}_e}$ < 3MeV → θ_n < 35°

[current liquid scintillator]



neutron has directional information of anti-neutrino

[Li loaded liquid scintillator]



- large neutron capture cross section
  (^{6}Li 940 barns vs ^{1}H 0.3 barns)
- α does't travel far

\+

high vertex resolution imaging detector

- higher than 2 cm resolution (PMT ~10cm)

▸ ^{40}K geoneutrino

Motivation

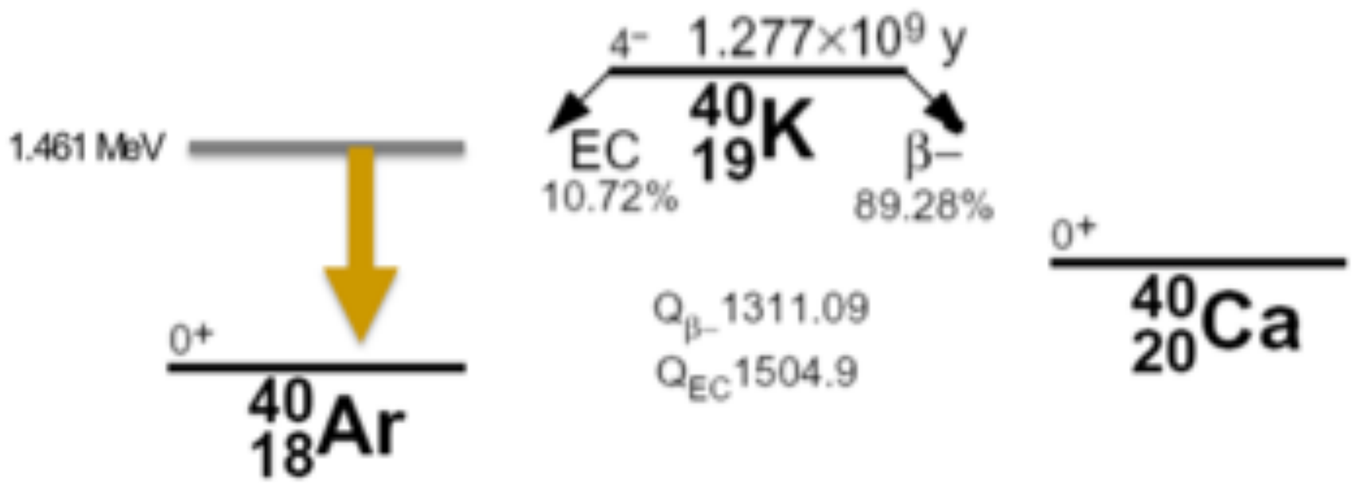
- ~16% of Earth's radiogenic heat is from ^{40}K
- K may reside in the Earth's core?

^{40}K geoeutrino measurement is useful to know amout and distribution

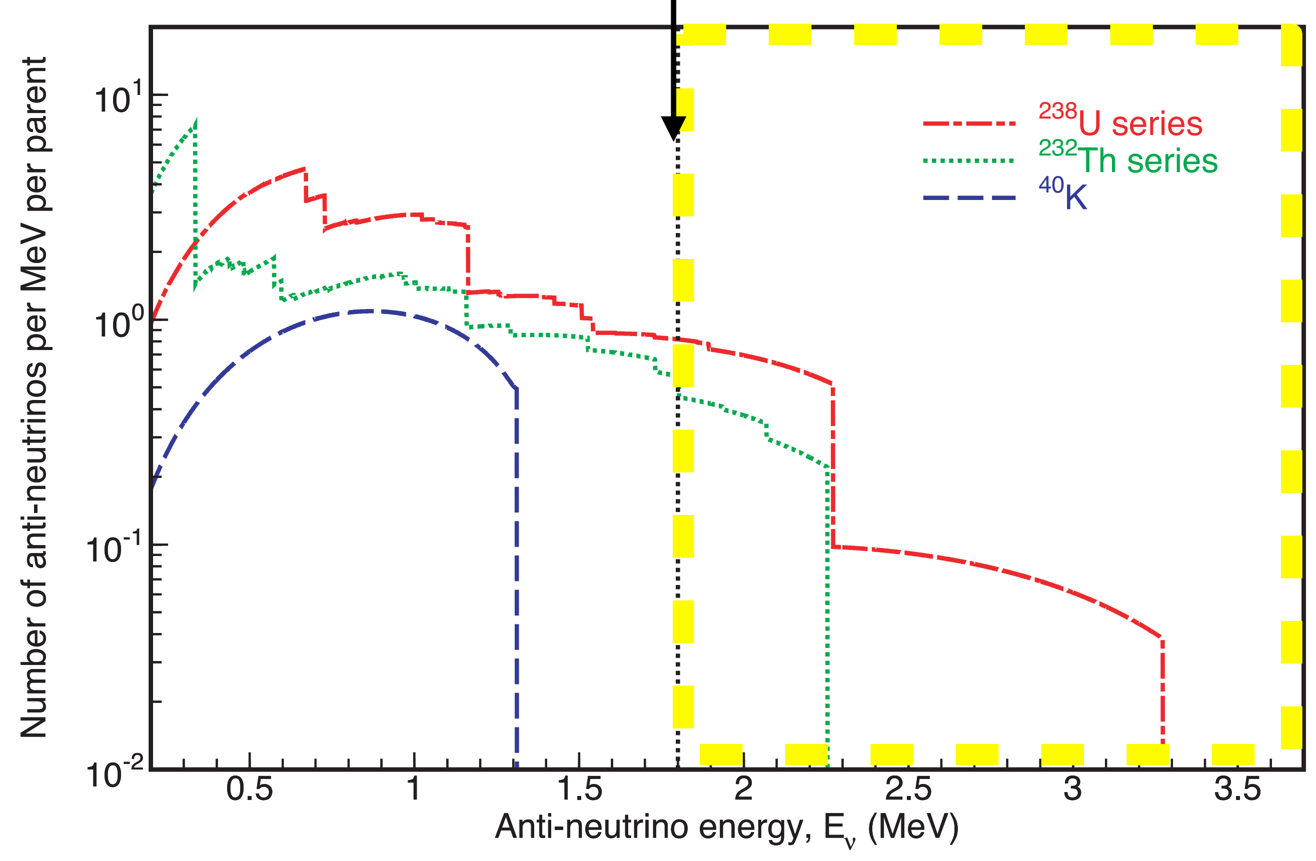
^{40}K Decay

- 89.28 % Q_β=1.311 MeV $^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ (5-15)x10^6 /cm^2/s ➡ possible?
- 10.72 % Q_{EC}=1.505 MeV $^{40}\mathrm{K} + \mathrm{e}^- \rightarrow ^{40}\mathrm{Ar} + \nu_\mathrm{e}$
  - 10.67 % to 1.461 MeV state (Eν=44 keV) (5-15)x10^5 /cm^2/s ➡ impossible…
  - 0.05 % to g.s. (Eν=1.5 MeV) (2-6)x10^3 /cm^2/s

ref)1.44 MeV pep solar ν :1.42x10^8 /cm^2/s



Energy threshold, 1.8 MeV



^{40}K Anti-neutrino

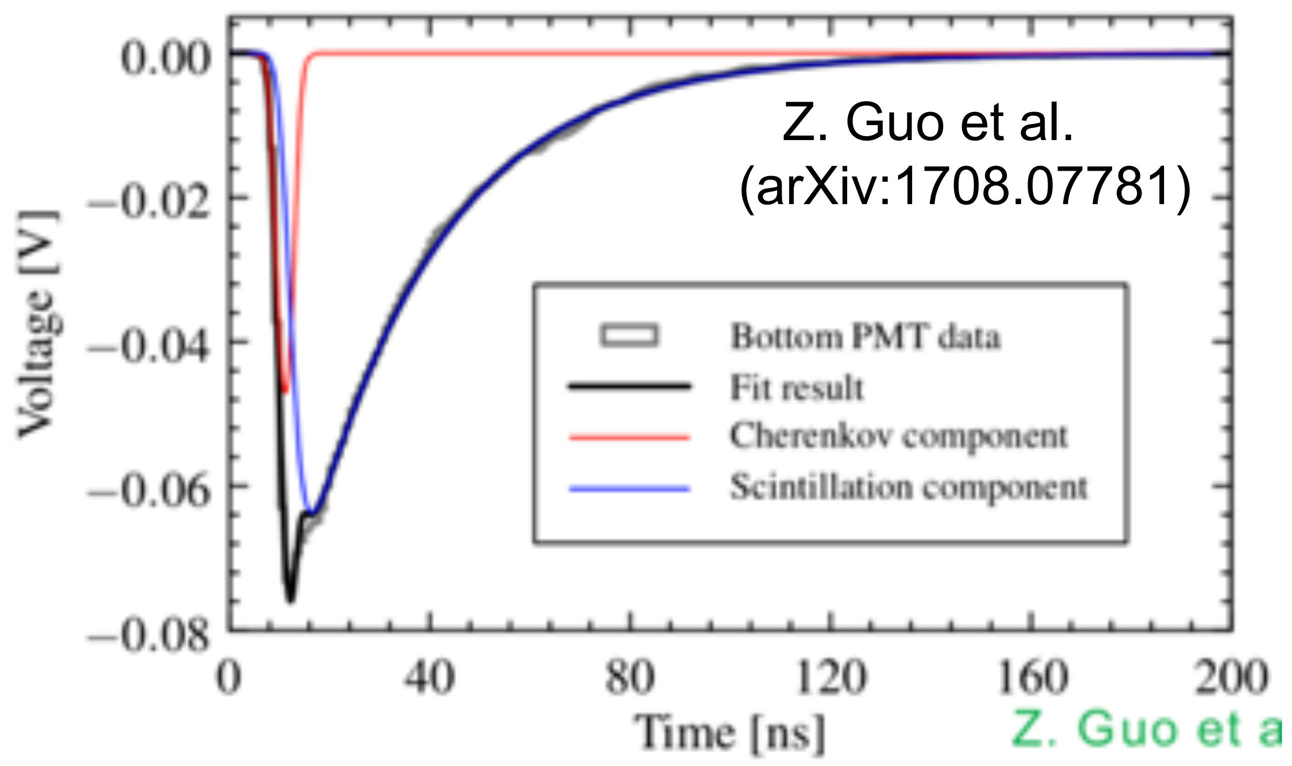
$\bar{\nu}_e - e$ scattering

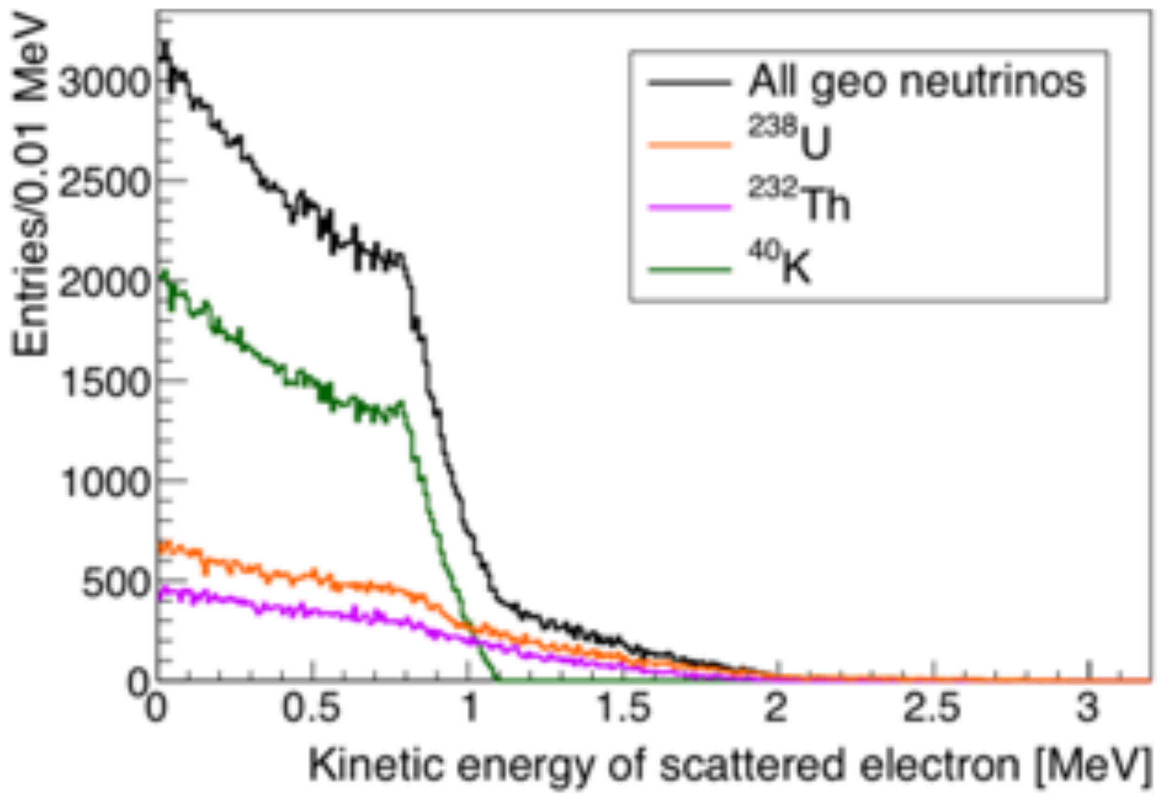
requires electron recoil directionality due to large flux of solar neutrinos

^{40}K geoneutrino

Liquid Scintillator Cherenkov Neutrino Detector

Z. Wang & S. Chen (arXiv:1709.03743)





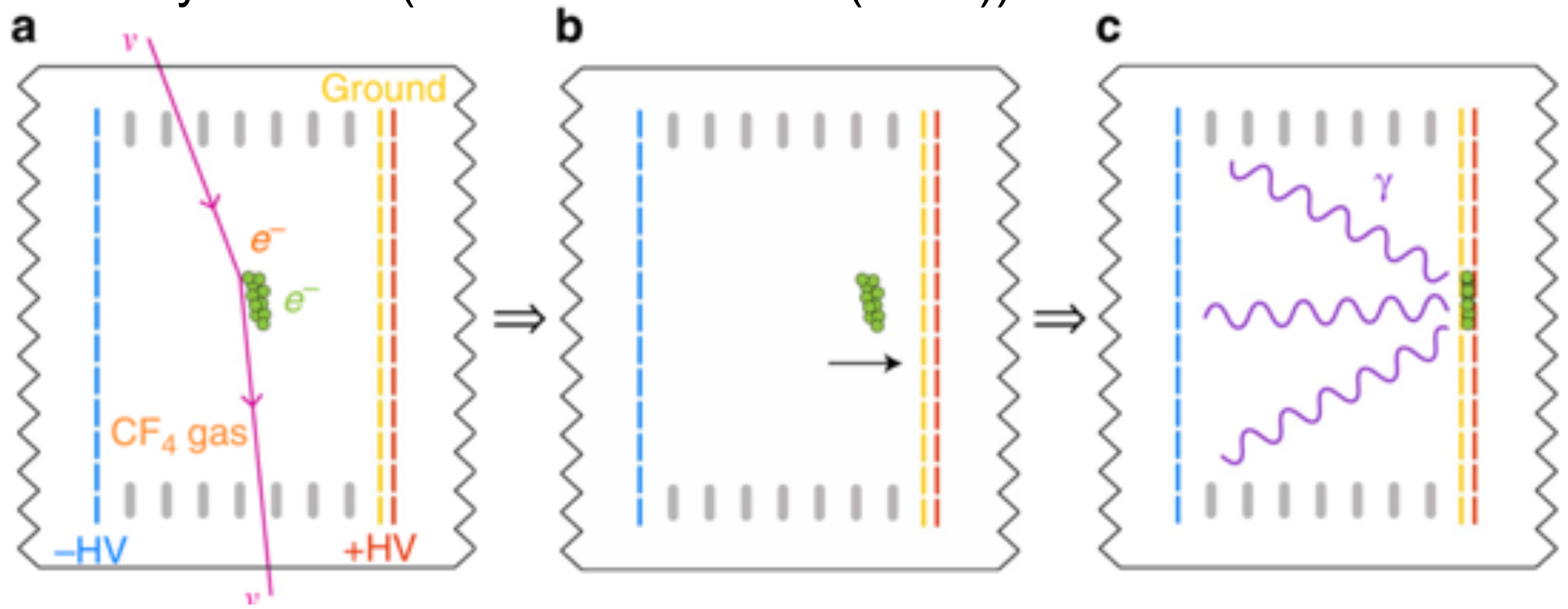
-Slow LS. Cherenkov and scintillation can be measured.

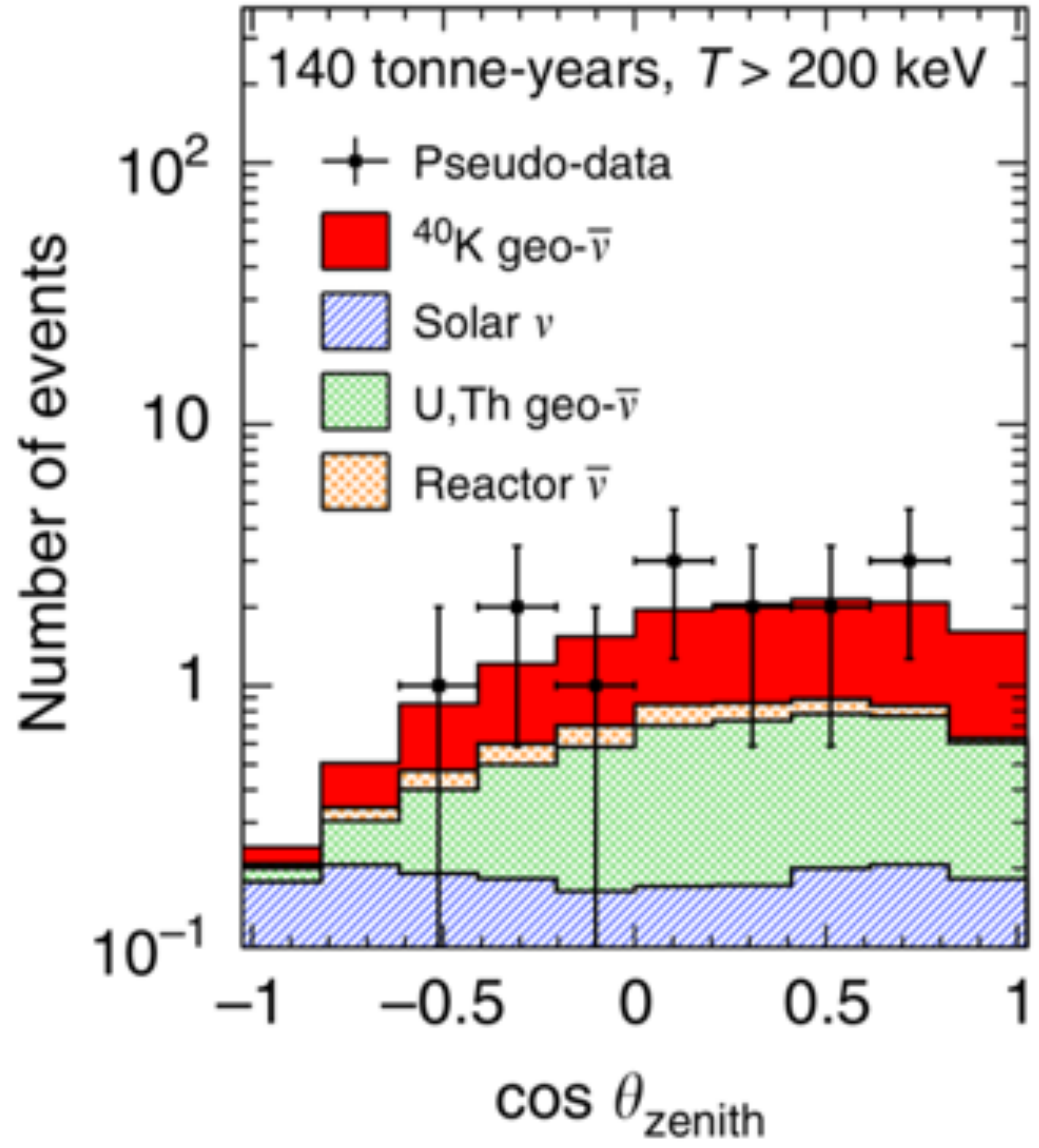
-Cherenkov → Directional information

-Serious effects from solar ν and radioactive background

Gas TPC

M. Layton et al.(Nat. Comm. 15989(2018))





-Huge gus chamber (cf. CF_4)

-Technically difficult