Geo-neutrinos to understand the Earth

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6 September 2017

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- KamLAND
- Borexino
- Future prospects
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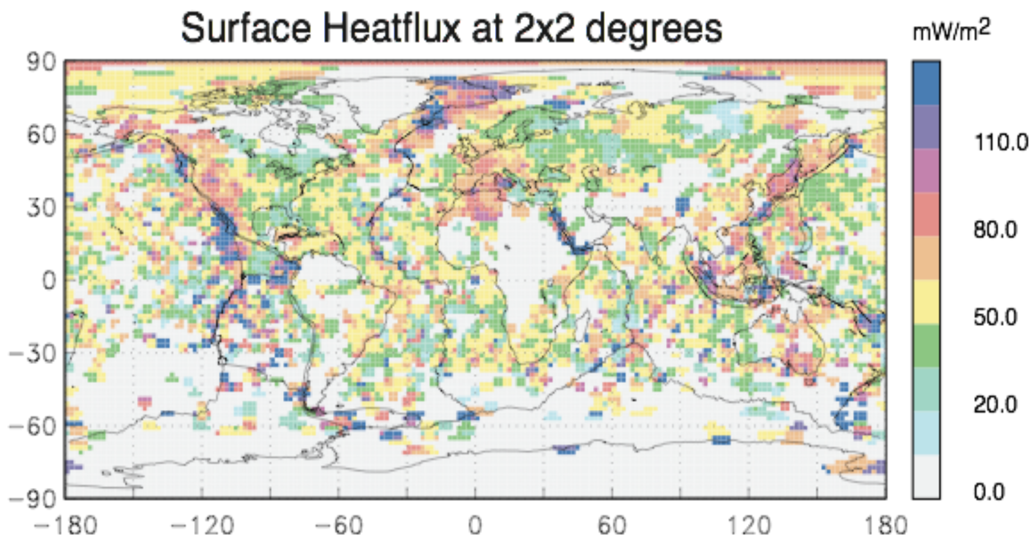
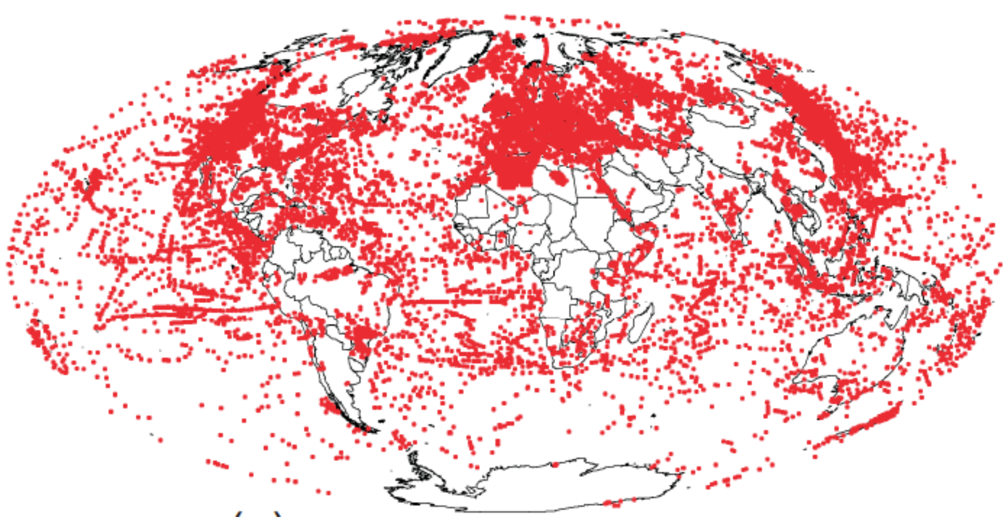
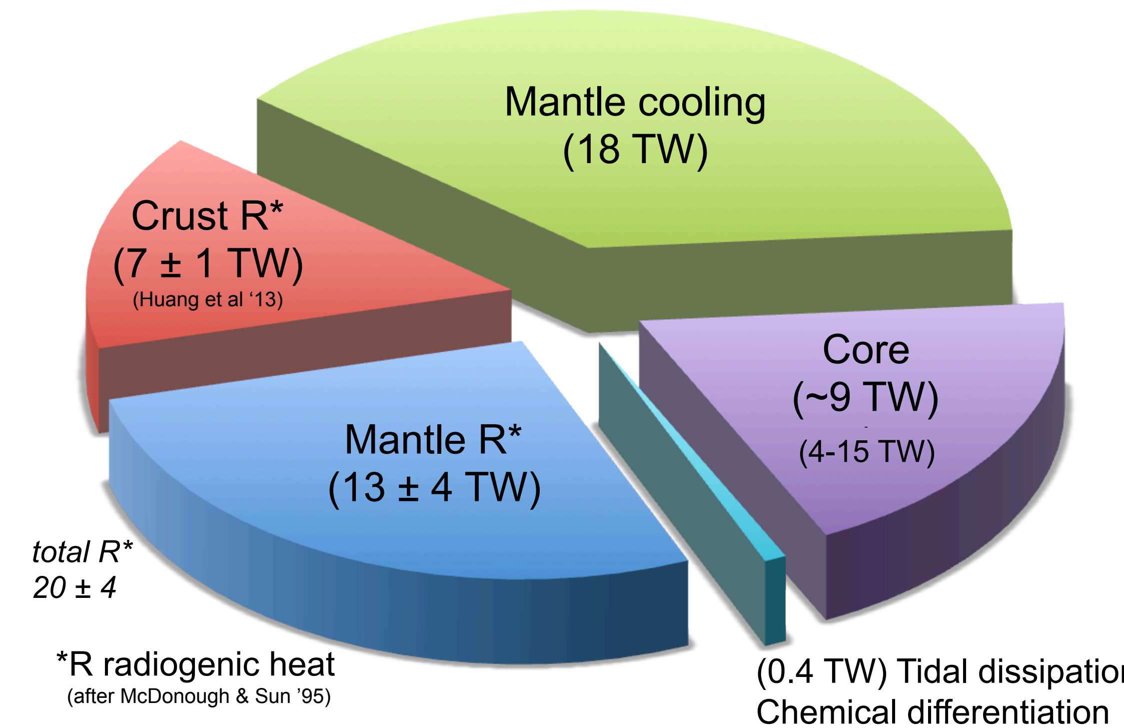
Heat Flux from the Earth's Surface



Conductive heat flow measured from
40,000 bore-hole temperature gradients



46±3 TW (Jaupart 2008)
47±1 TW (Davies 2010)



McDonough 2016

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

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

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

Geo-neutrinos

Electron-antineutrino from natural radioactive decay

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

Geo-neutrinos

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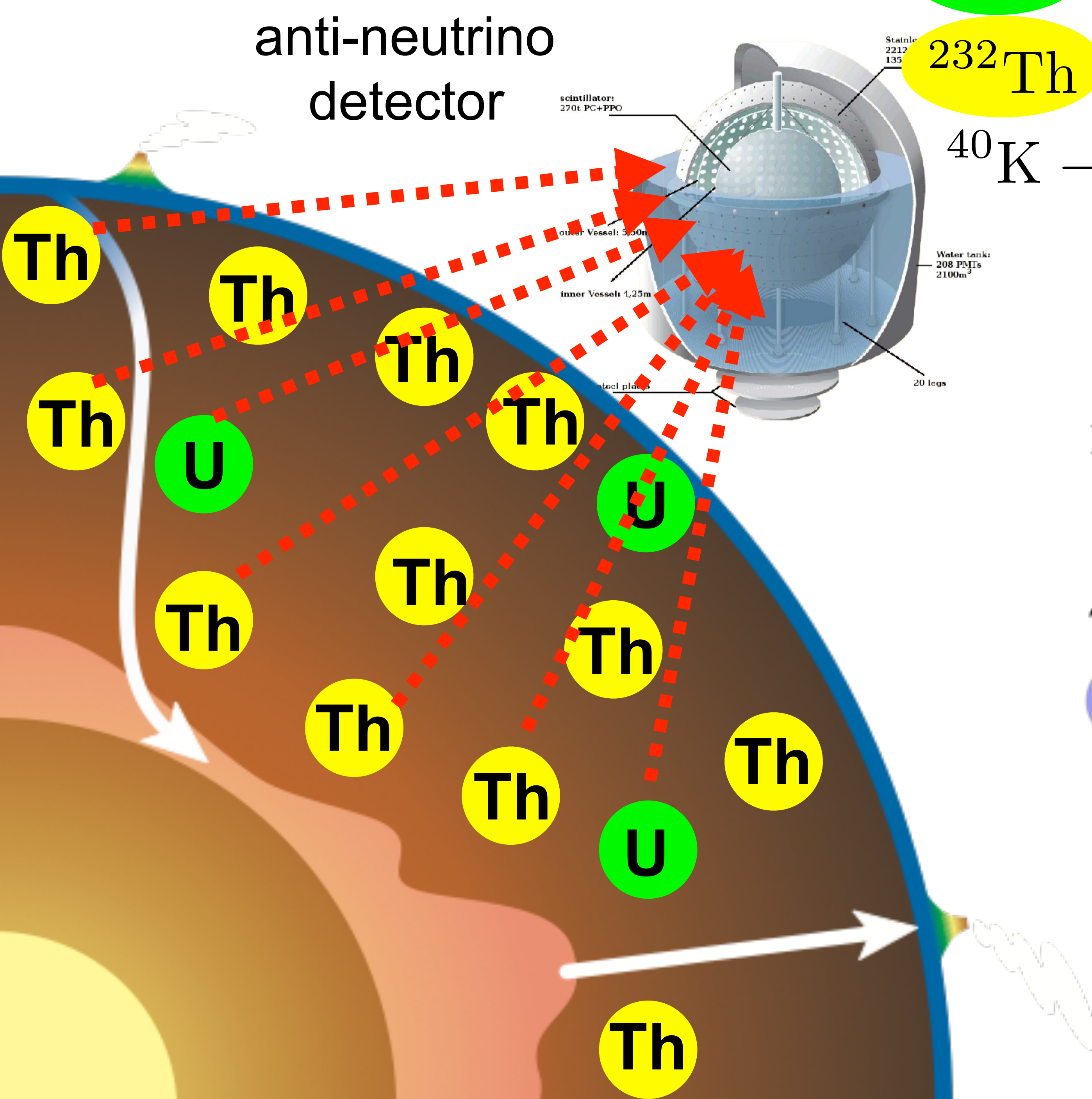
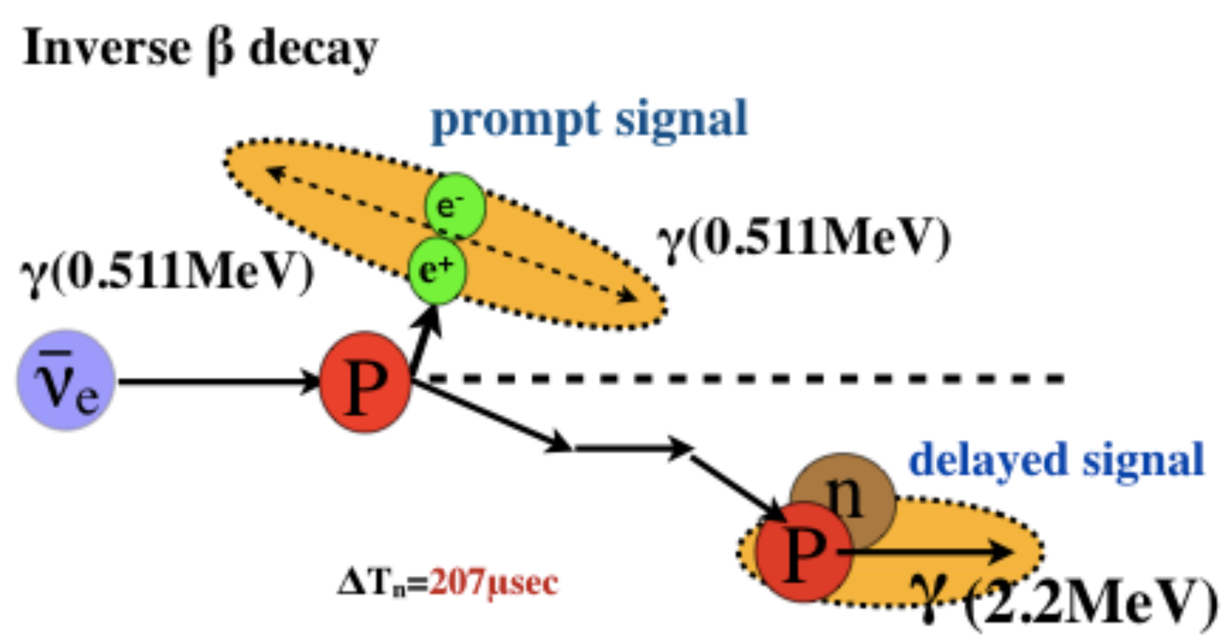


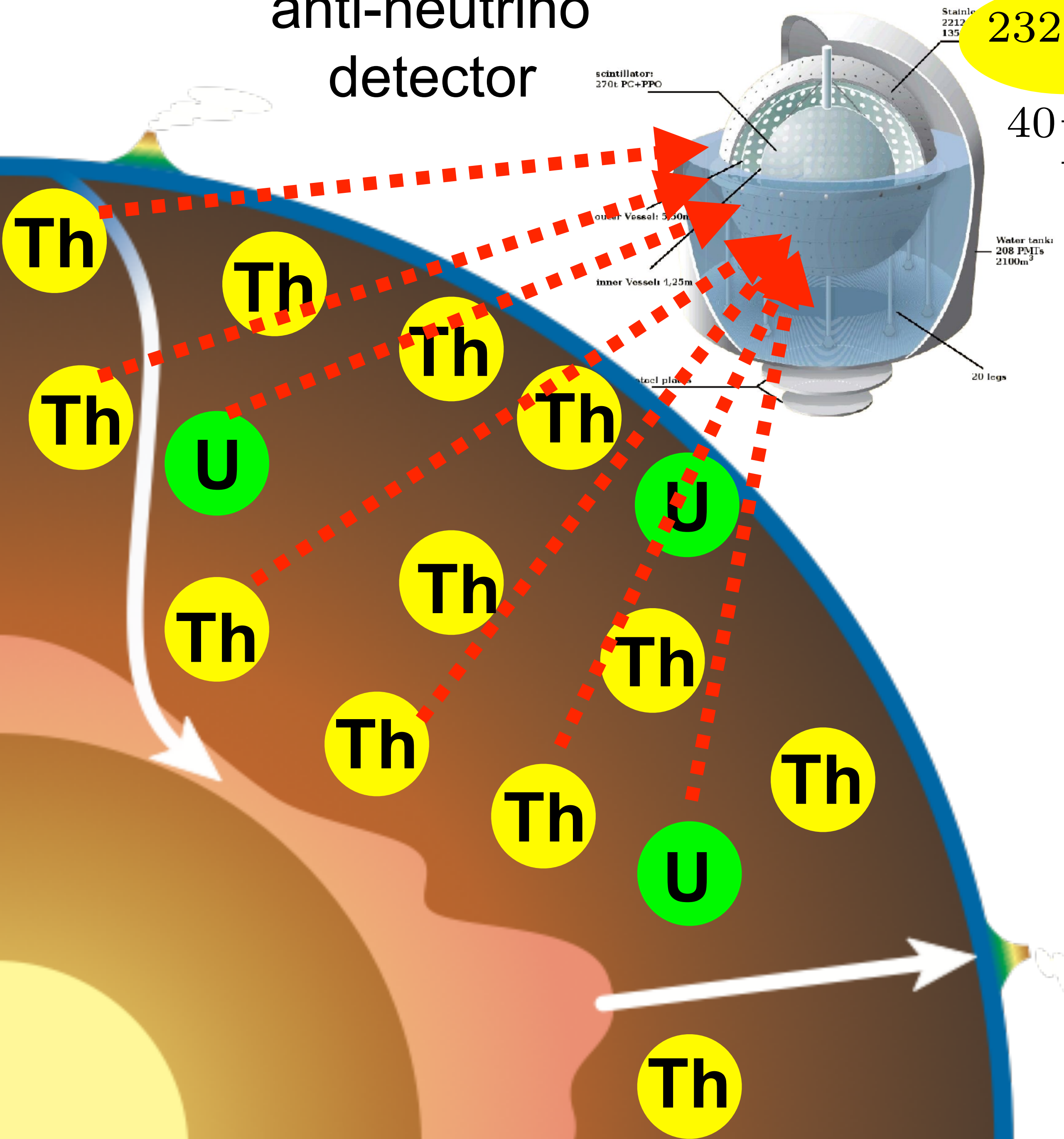


Geo-neutrinos

Electron-antineutrino from natural radioactive decay

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

anti-neutrino detector



Geo-neutrinos

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

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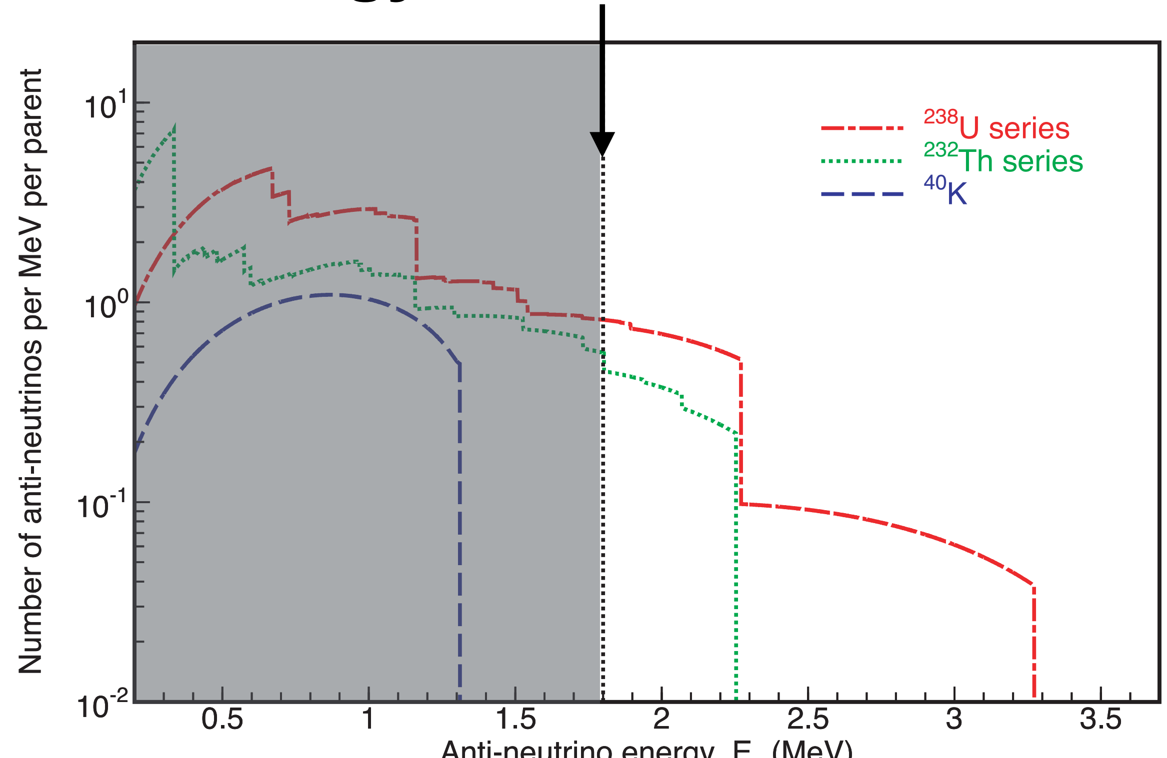
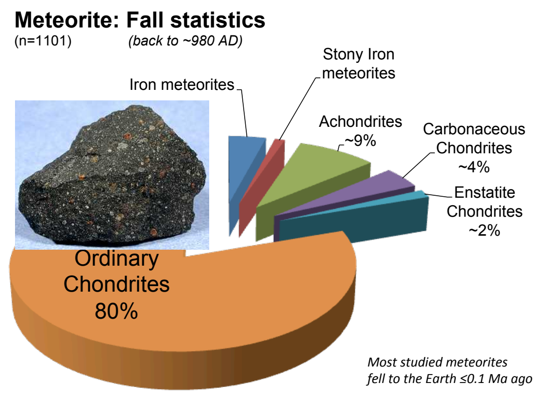
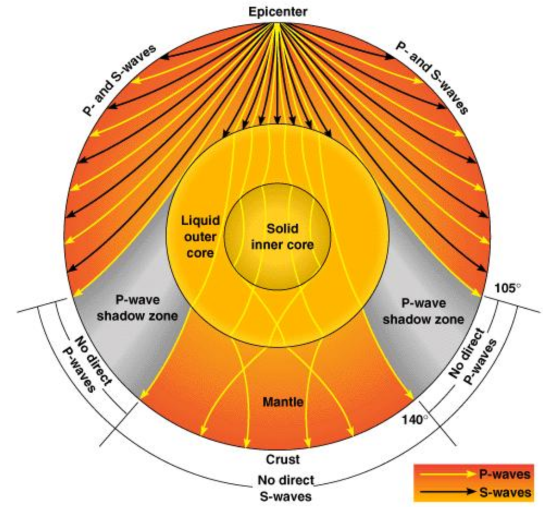
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}\,(89.28\%)$$

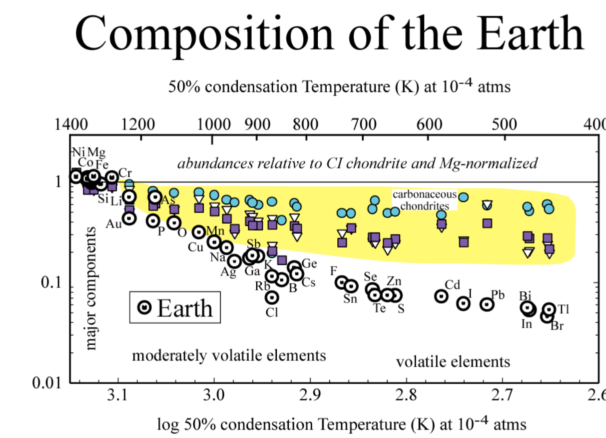
Energy threshold, 1.8 MeV

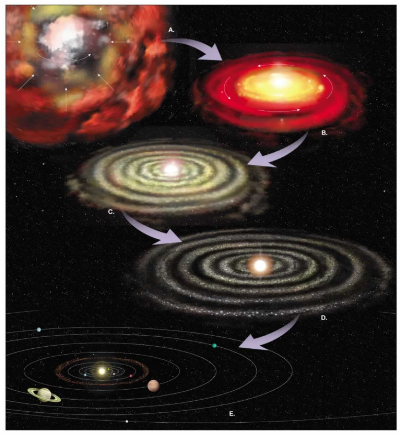


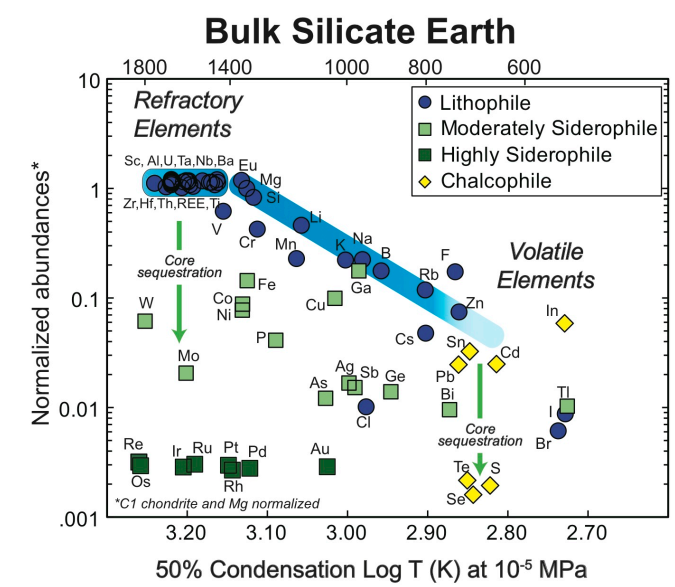
Only geo-neutrinos from U and Th are detectable











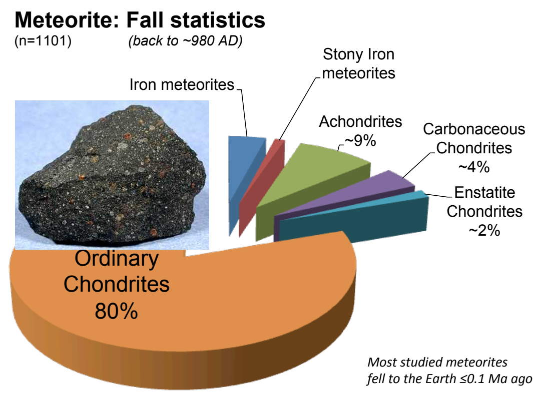
Radiogenic Total Heat

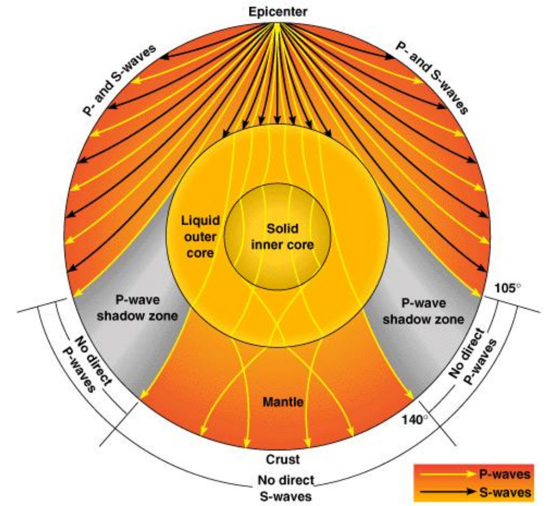
Crust

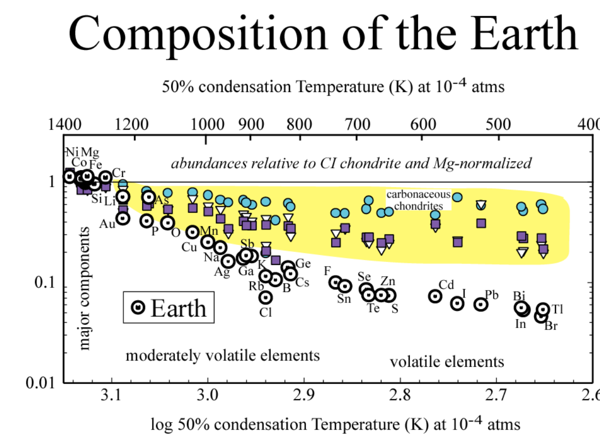
Mantle

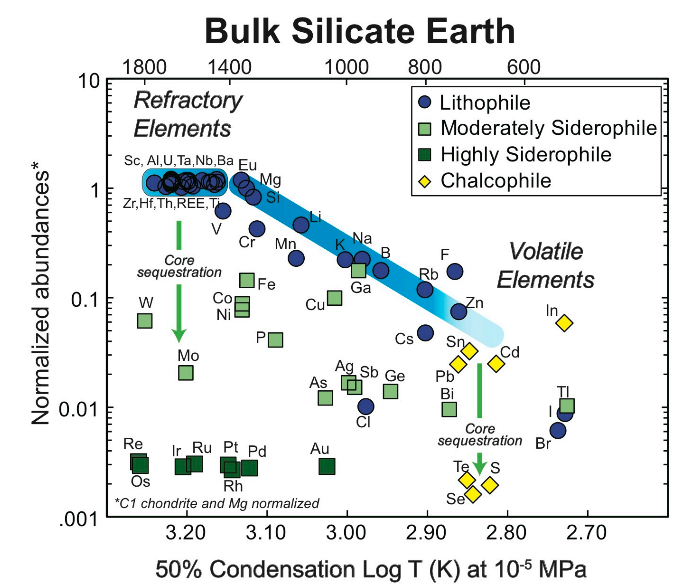
Th/U

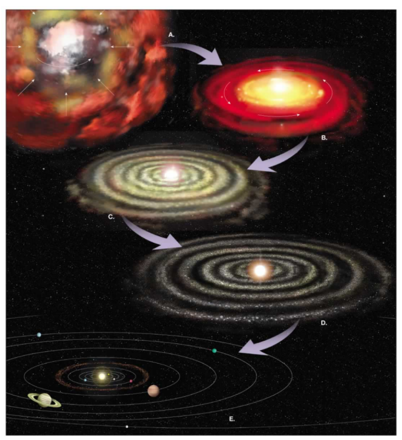
figures from McDonough 2016

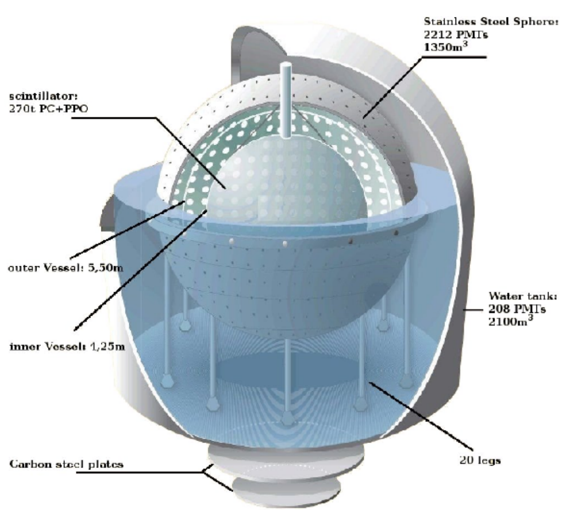




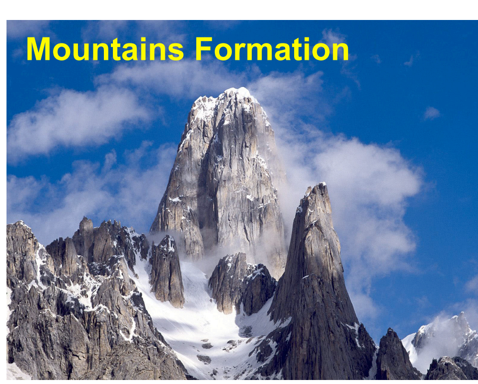


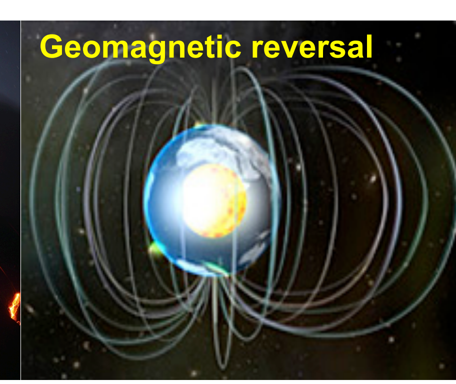


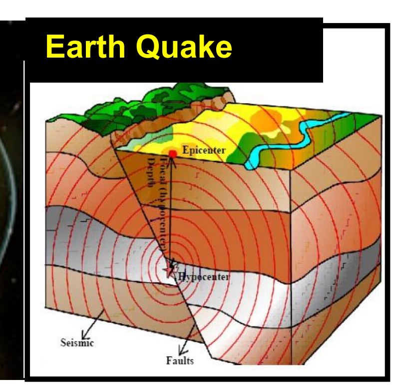




A better understanding of our planet







figures from McDonough 2016

Th/U Mass Ratio

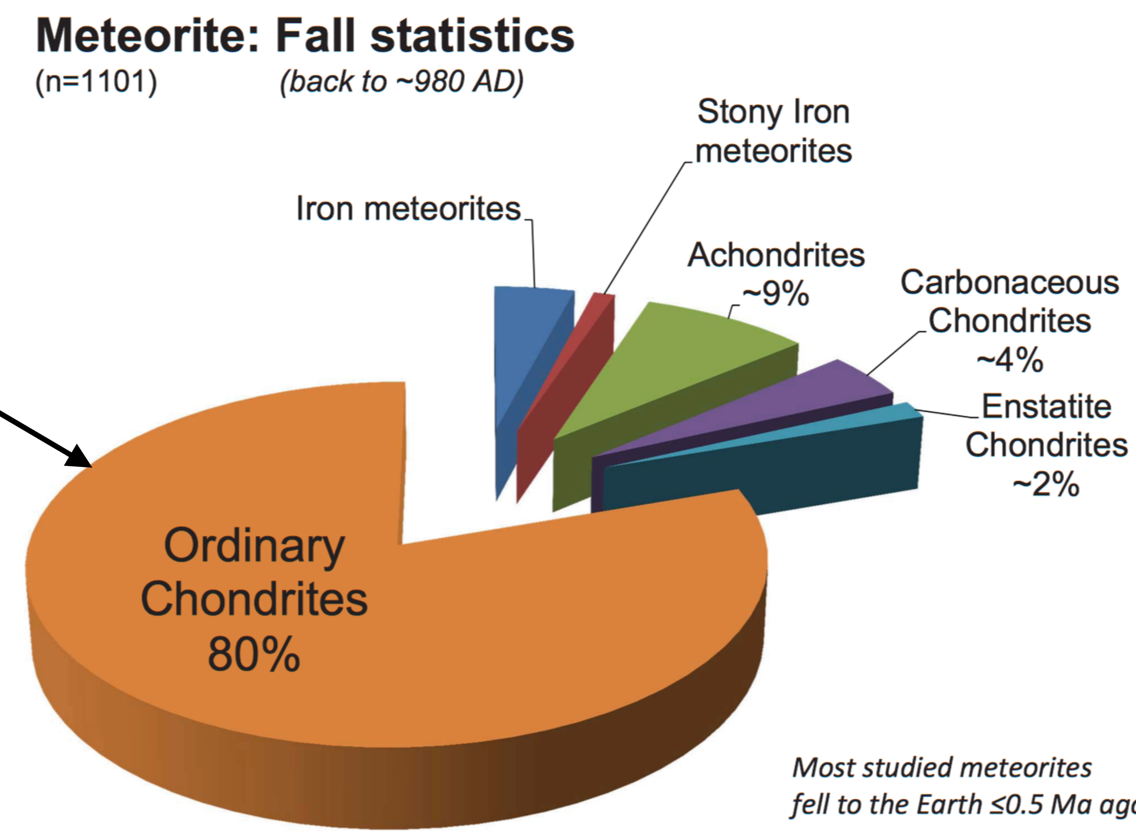
- According to geochemical studies, ^{232}Th is more abundant than ^{238}U. Mass ratio (Th/U) in bulk silicate Earth is expected to be **around 3.9.**

Models : 3.58-4.2

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

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

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

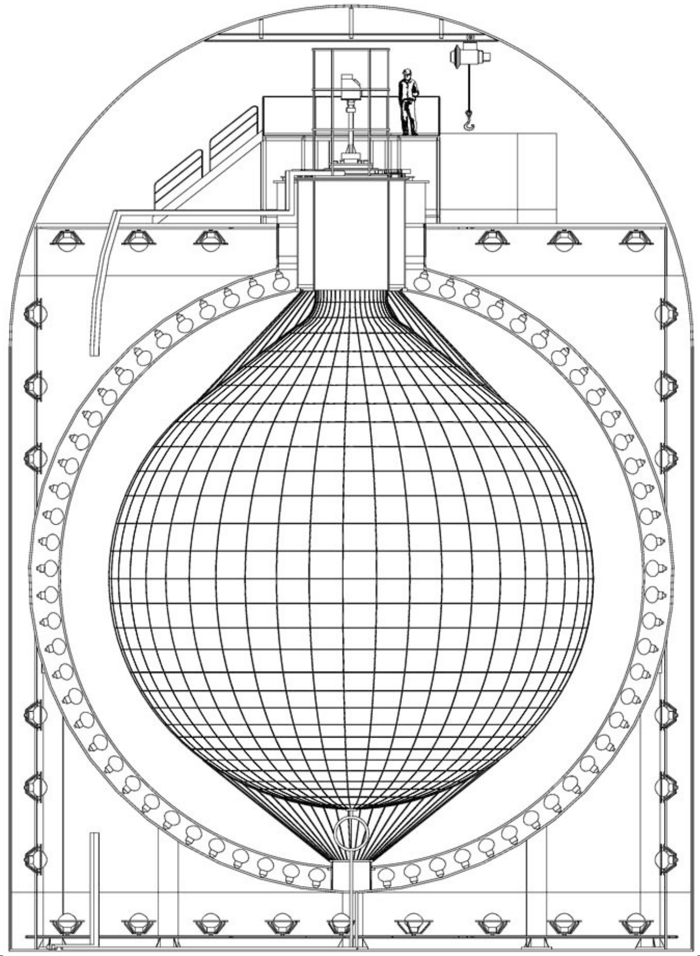


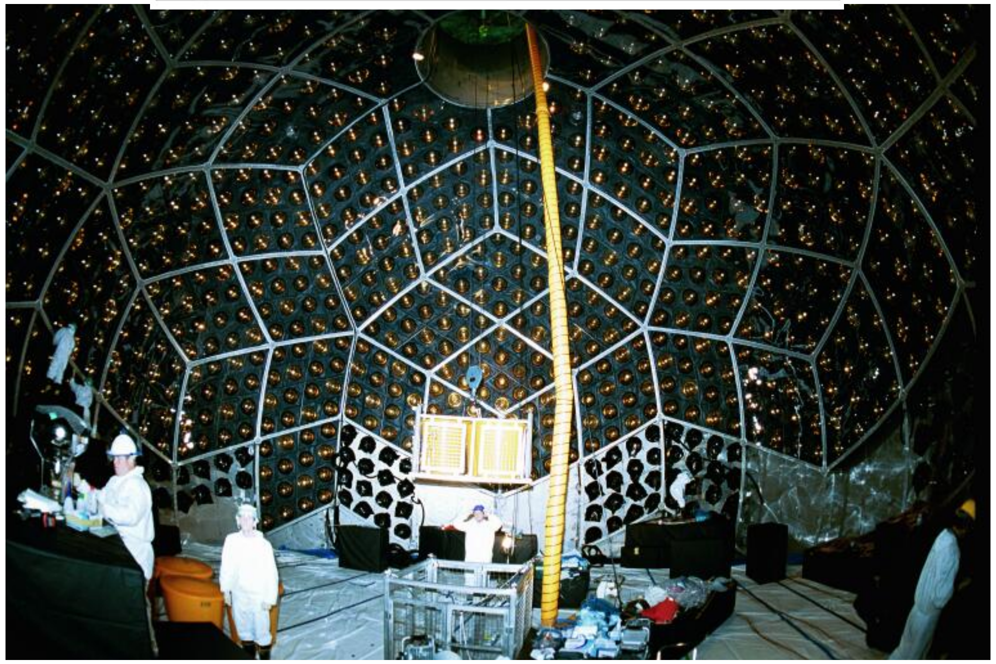
McDonough 2015

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

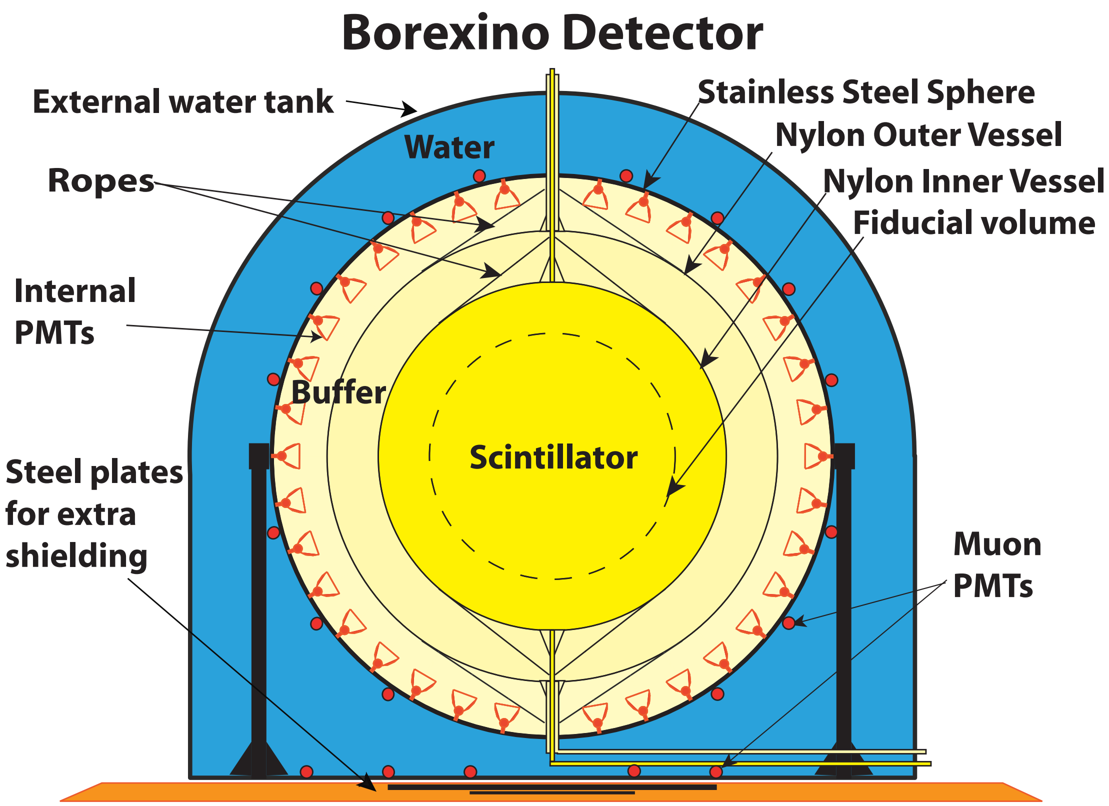
Geo-neutrino Detectors

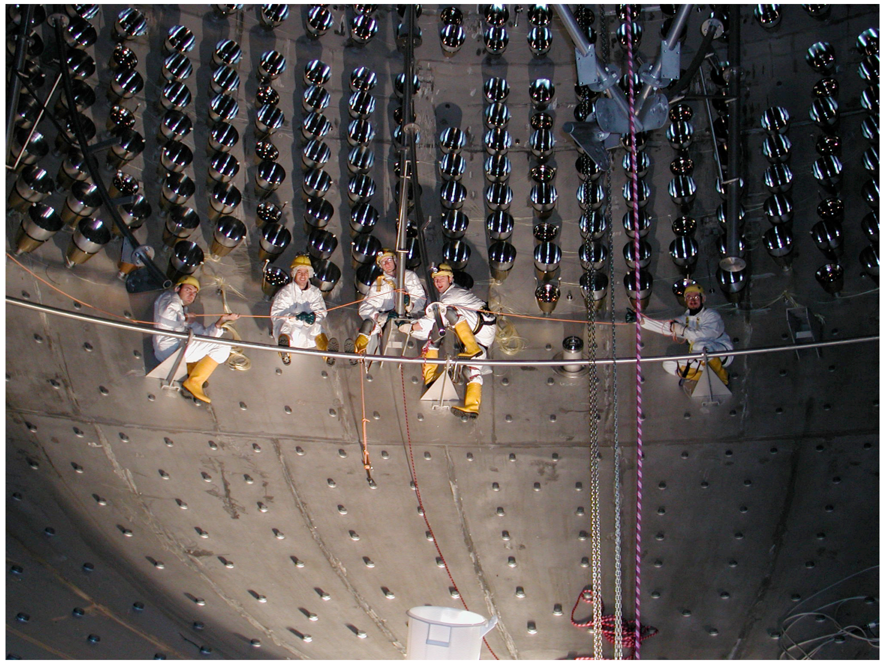
KamLAND





Borexino

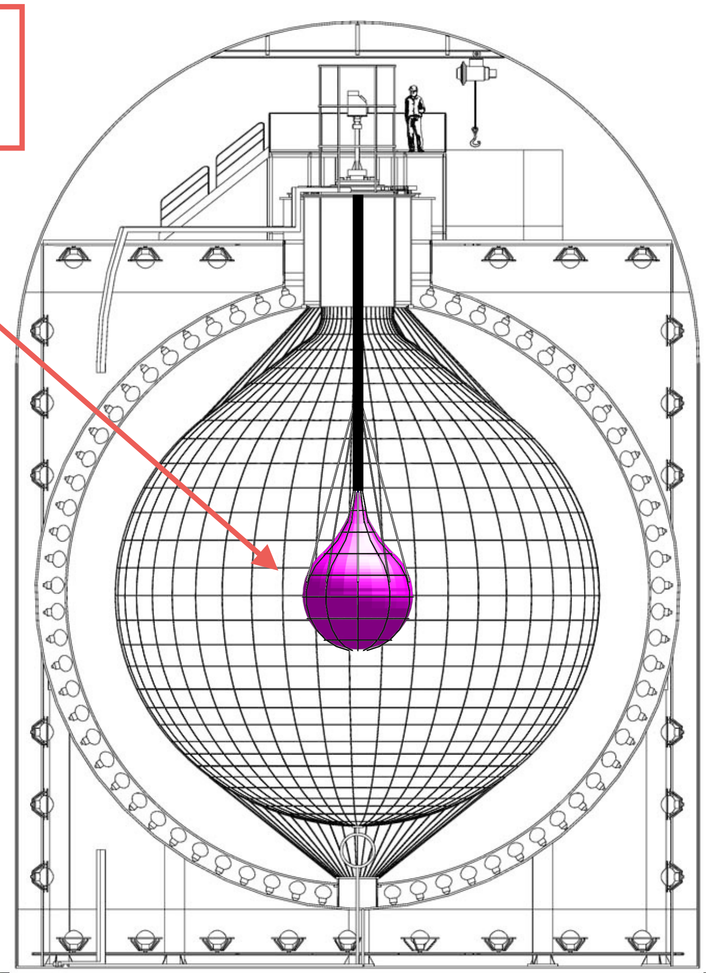


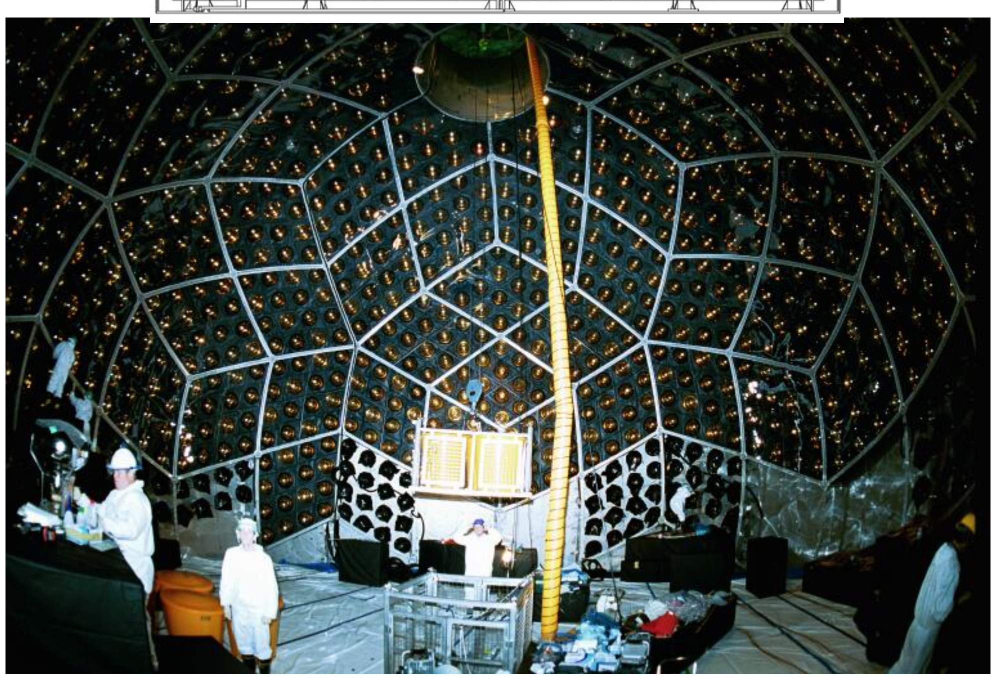


Geo-neutrino Detectors

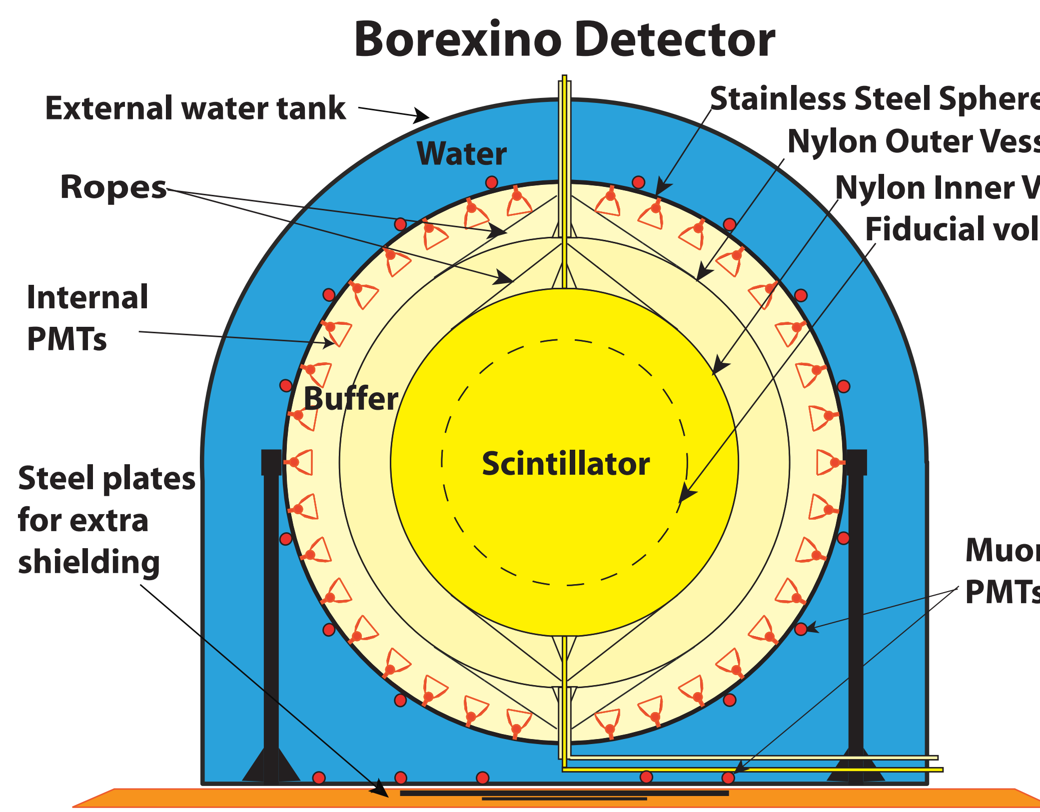
KamLAND-Zen

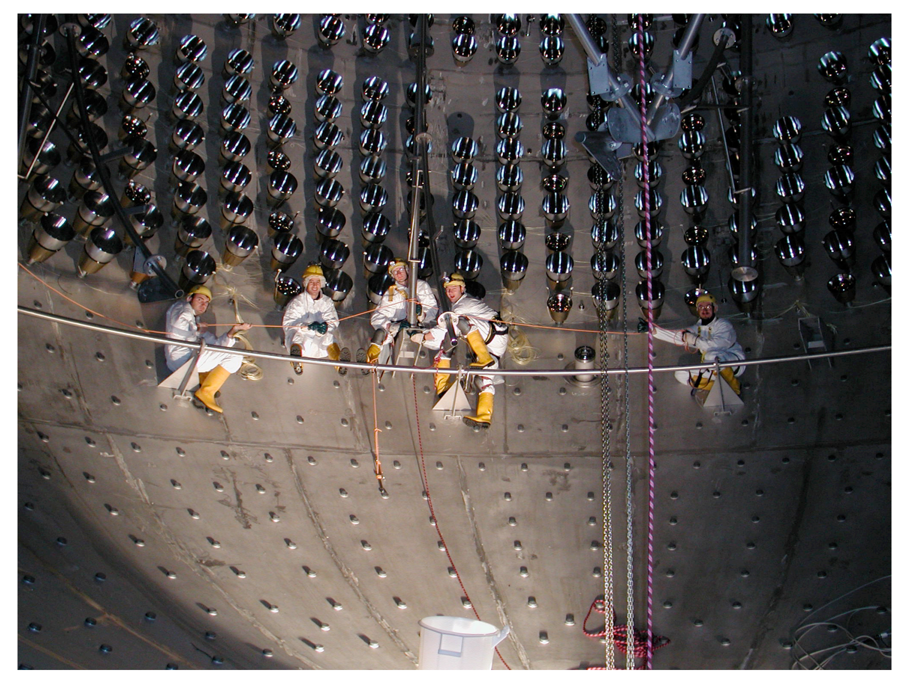
>2% vol.





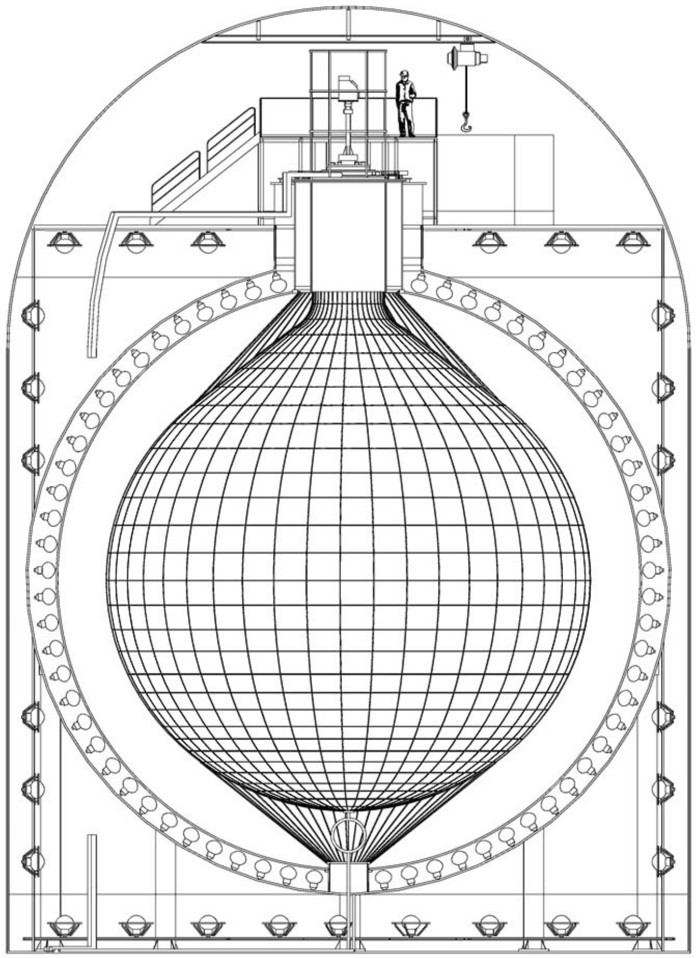
Borexino





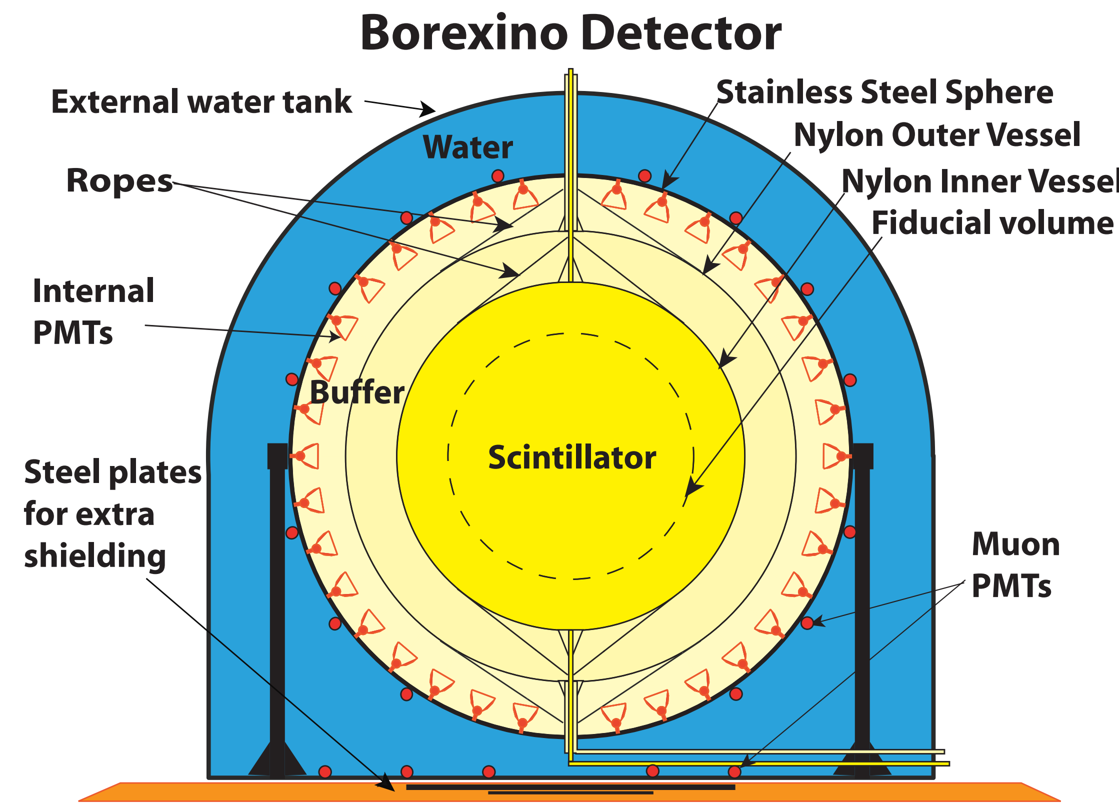
Geo-neutrino Detectors

KamLAND



- designed for long-baseline reactor $\bar{\nu}_e$ oscillations
- DAQ start 2002
- continental crust to oceanic crust transition
- liquid scintillator: ~1 kton, H/C ~1.97
- high $\bar{\nu}_e$ background from nuclear power reactors
- high initial ^{210}Po background [^{13}C(α,n)^{16}O*]

Borexino



- designed for measuring solar neutrino fluxes
- DAQ start 2007
- continental crust
- liquid scintillator: ~0.3 kton, H/C ~1.2
- lower $\bar{\nu}_e$ background from nuclear power reactors
- ultra-high radiopurity
  negligible ^{210}Po background [^{13}C(α,n)^{16}O*]

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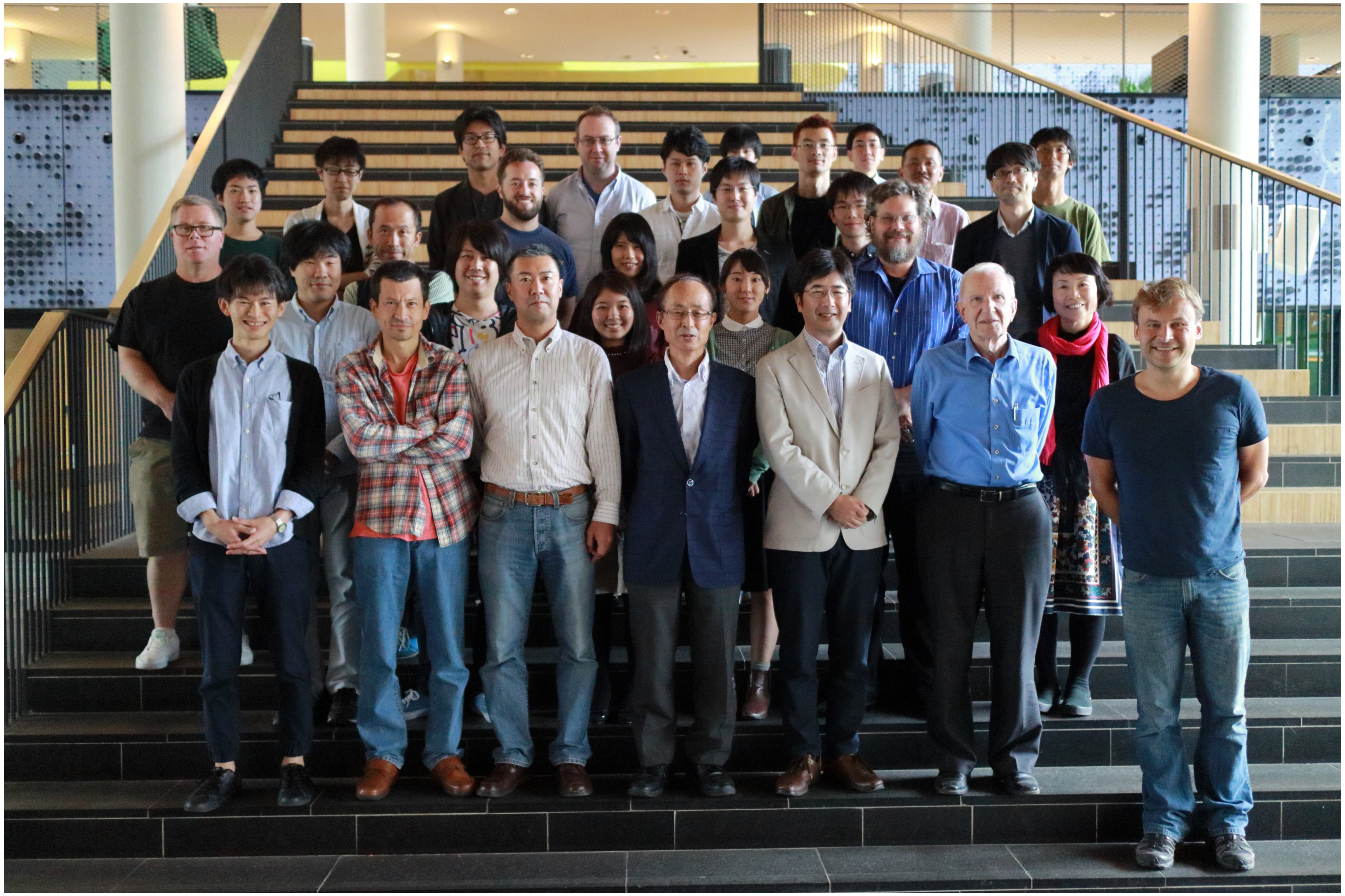
The KamLAND Collaboration

K. Asakura[1], A. Gando[1], Y. Gando[1], T. Hachiya[1], S. Hayashida[1], H. Ikeda[1], K. Inoue[1,2], K. Ishidoshiro[1], T. Ishikawa[1], S. Ishio[1], M. Koga[1,2], S. Matsuda[1], T. Mitsui[1], D. Motoki[1], K. Nakamura[1,2], S. Obara[1], T. Oura[1], I. Shimizu[1], Y. Shirahata[1], J. Shirai[1], A. Suzuki[1], H. Tachibana[1], K. Tamae[1], K. Ueshima[1], H. Watanabe[1], B. D. Xu[1,18], A. Kozlov[2], Y. Takemoto[2], S. Yoshida[3], K. Fushimi[4], A. Piepke[2,5], T. I. Banks[6,7], B. E. Berger[2,7], B. K. Fujikawa[2,7], T. O'Donnell[6,7], J. G. Learned[8], J. Maricic[8], S. Matsuno[8], M. Sakai[8], L. A. Winslow[9], Y. Efremenko[2,10,11], H. J. Karwowski[12,13], D. M. Markoff[12,14], W. Tornow[2,12,15], J. A. Detwiler[16], S. Enomoto[2,16], and M. P. Decowski[2,17]
The KamLAND Collaboration

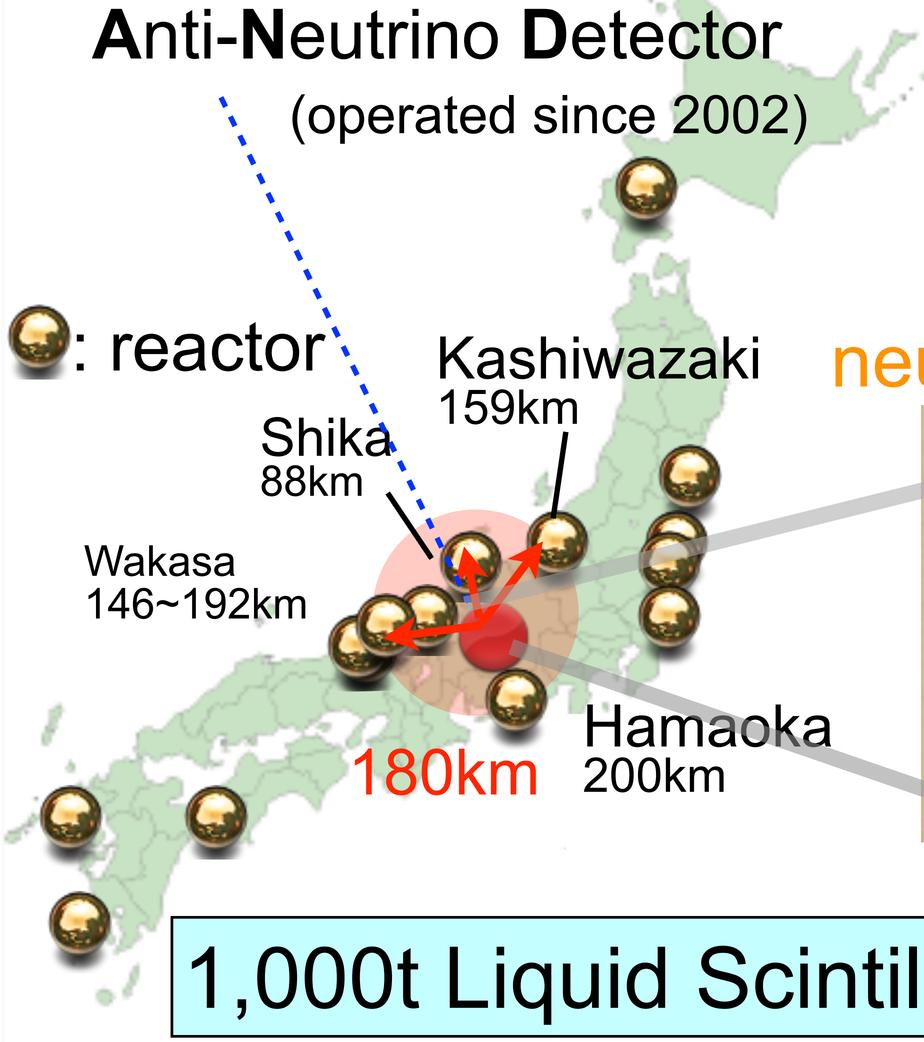
* Institutions :
  4 from Japan
  12 from US
  1 from Europe
* ~50 collaborators

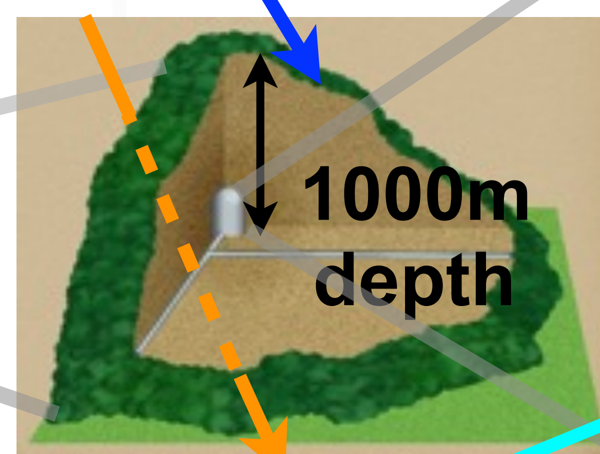


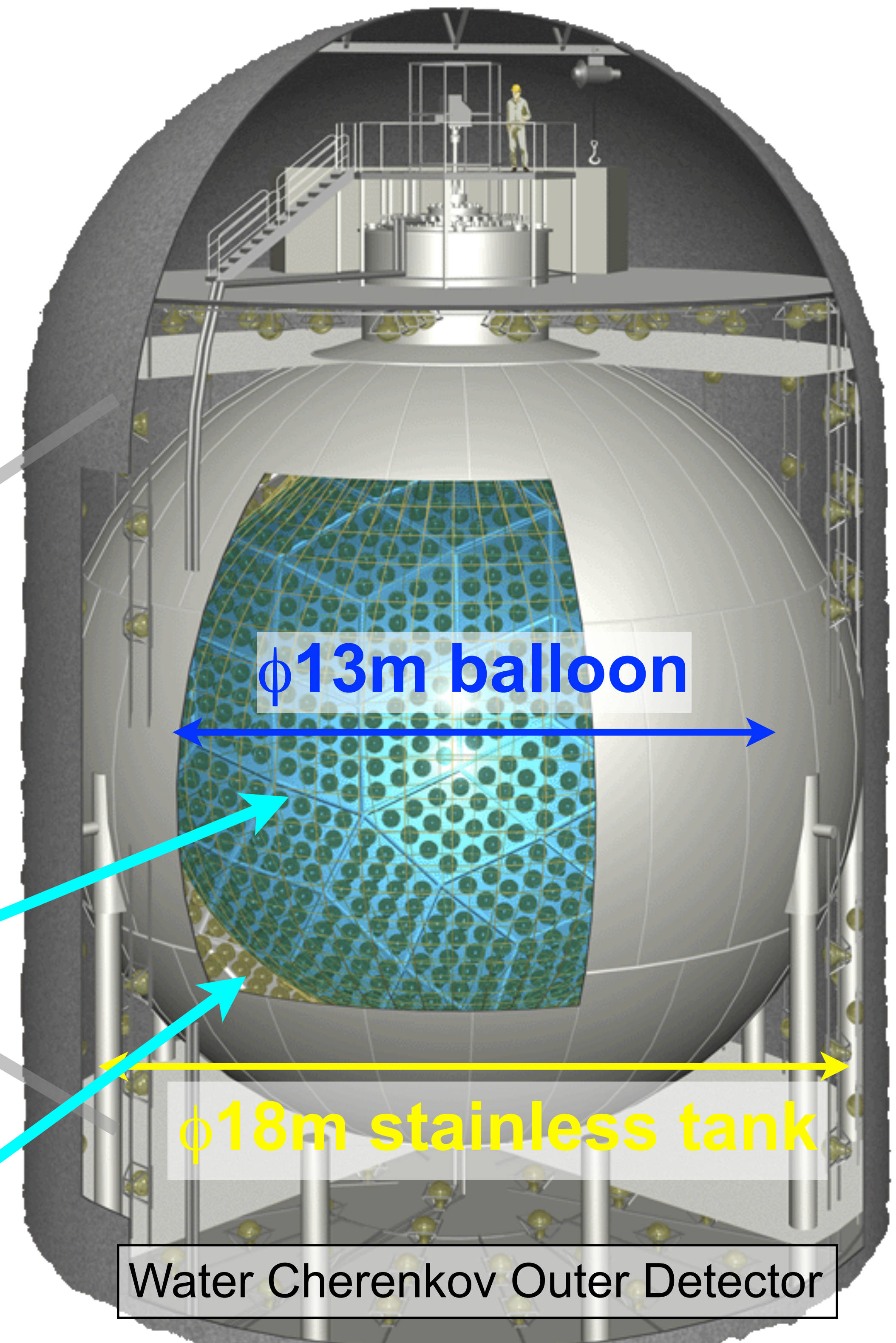
KamLAND Site and Detector

KamLAND

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







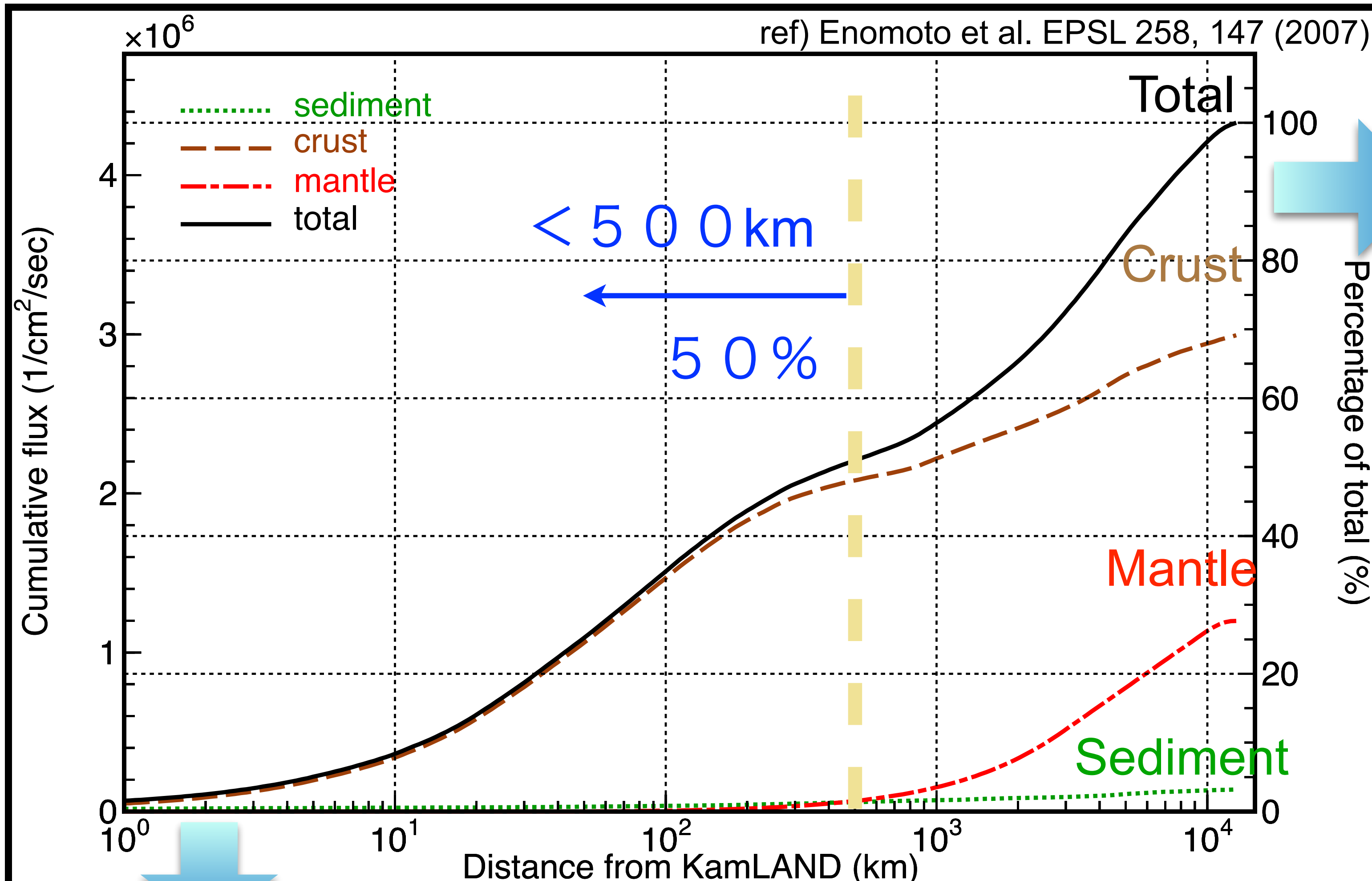
1,000t Liquid Scintillator

- extremely low impurity
(^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)
- **world's largest LS detector!**

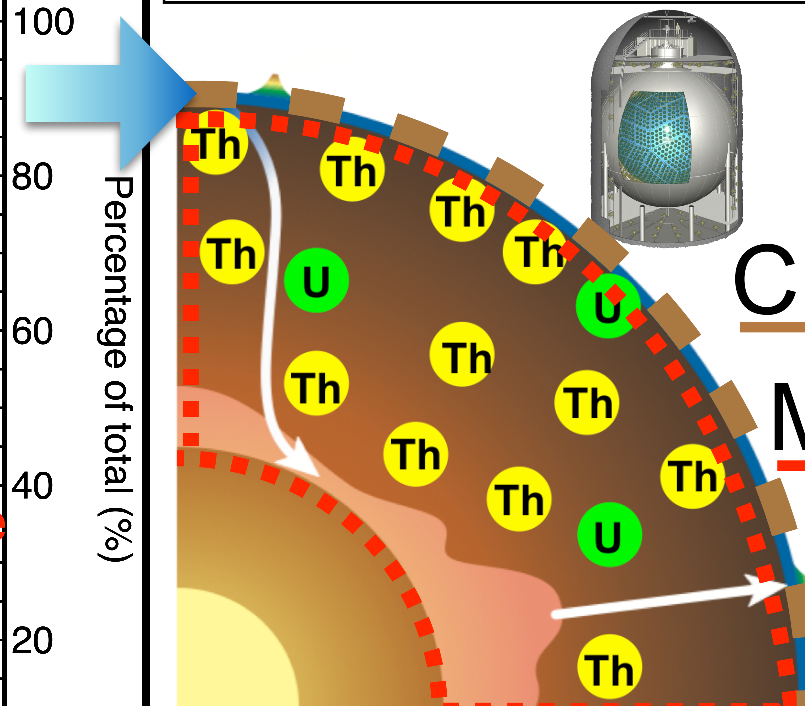
1,879 Photomultiplier Tubes

* Photo coverage 34%

Geo-neutrino Flux at Kamioka



Contributions from each part



Crust : 70%

Mantle : 27%

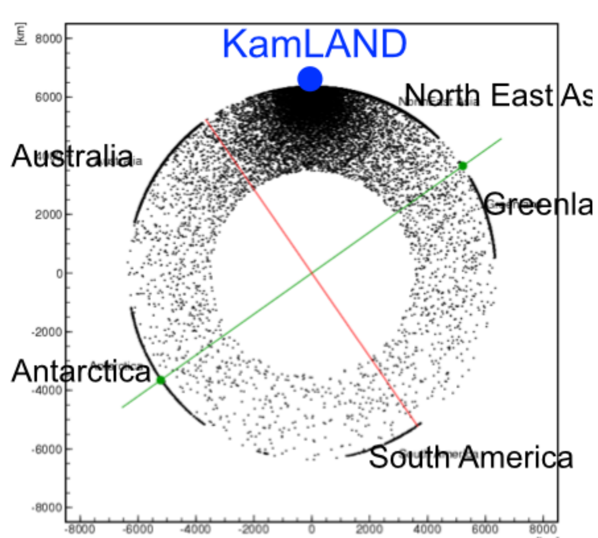
Core : 0%

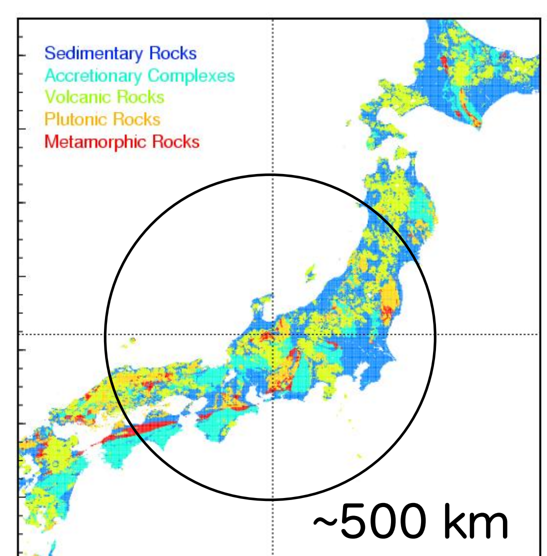
Sediment etc. : 3%

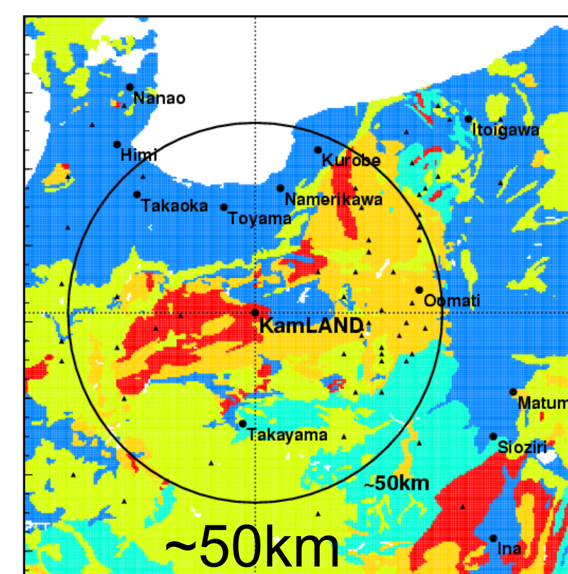
Contributions from each area

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

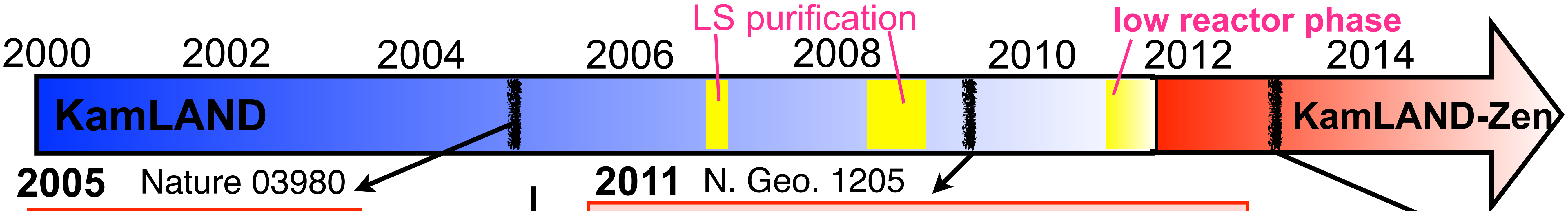
Important to understand Japanese geology





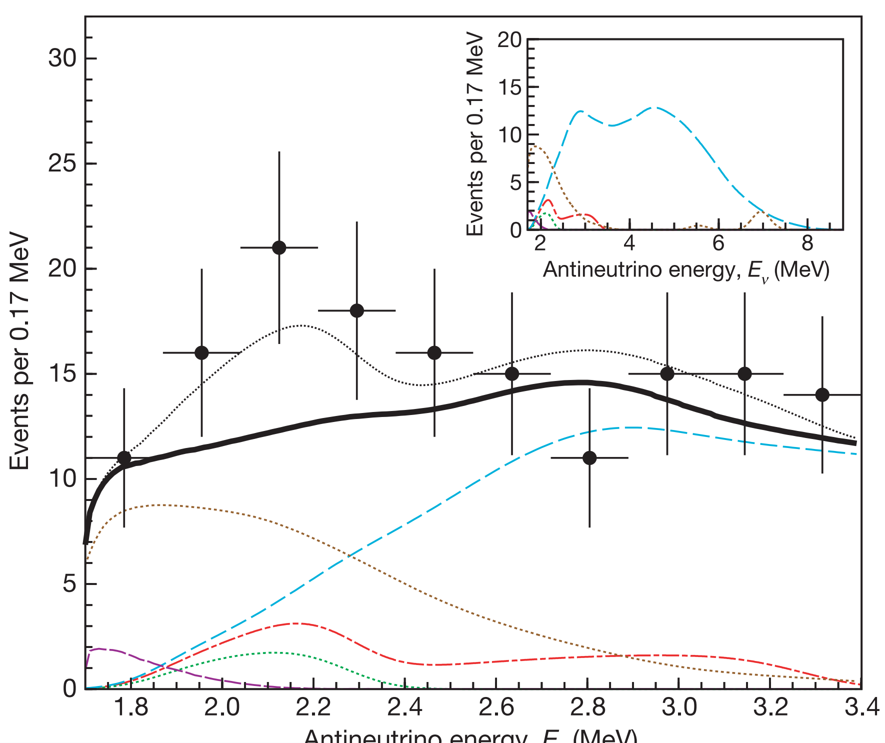


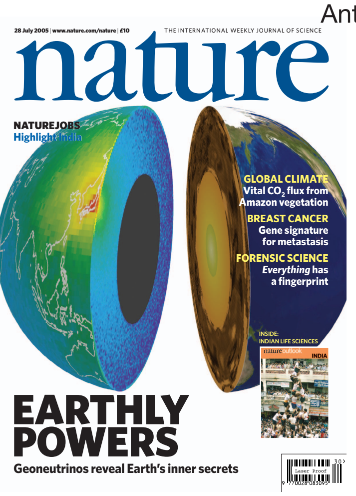
Geo-neutrino Measurements with KamLAND



2005 Nature 03980

geo-neutrino first measurement





749 days

0.71×10^{32} proton-year

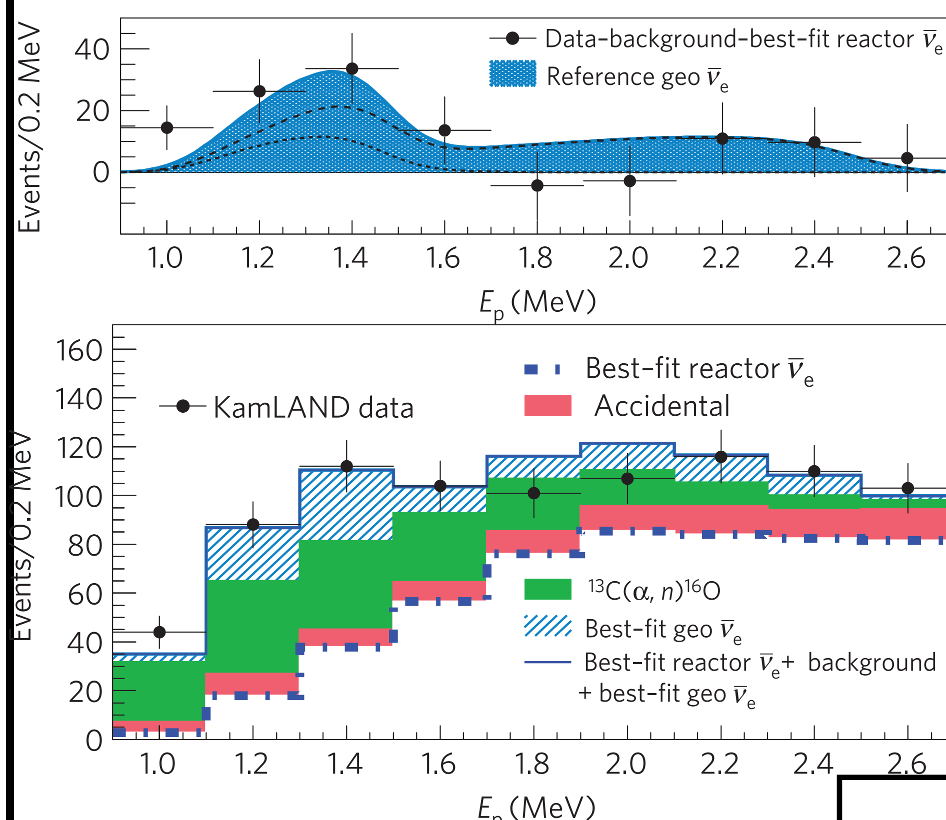
<u>geo-nu event</u>

$$28.0^{+15.6}_{-14.6}\ \text{ev}$$

(56% error)

2011 N. Geo. 1205

radiogenic heat direct measurement



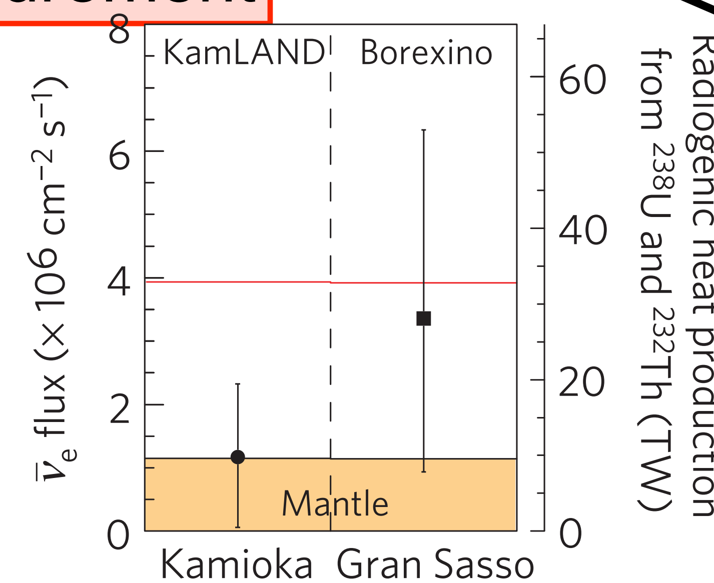
2135 days

3.49×10^{32} proton-year

<u>geo-nu event</u>

$$106^{+29}_{-28}\ \text{ev}$$

(27% error)



radiogenic heat

21±9 TW

2013 PRD 88, 03301 (2013)

include low reactor phase data

2991 days

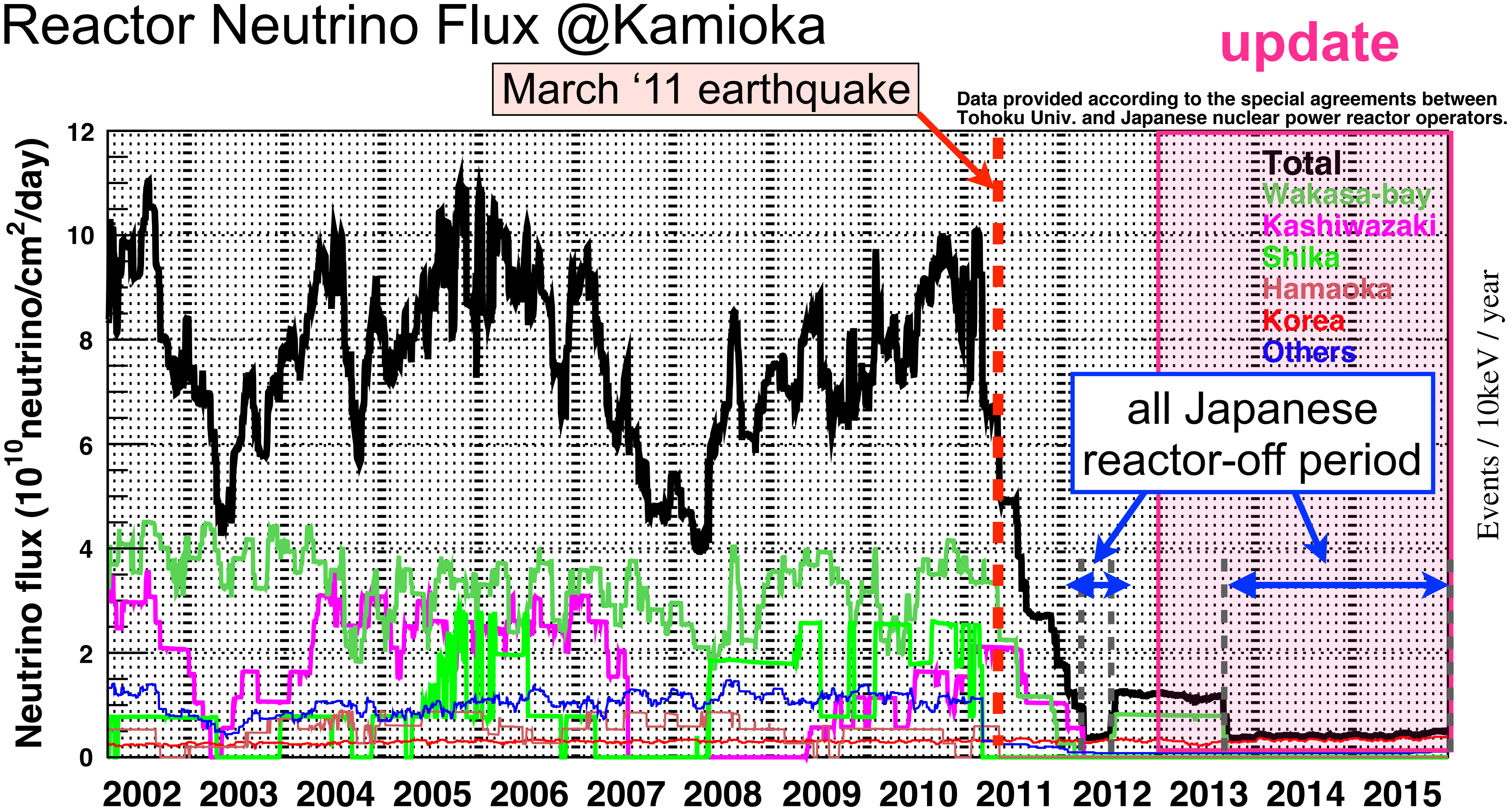
4.90×10^{32} proton-year

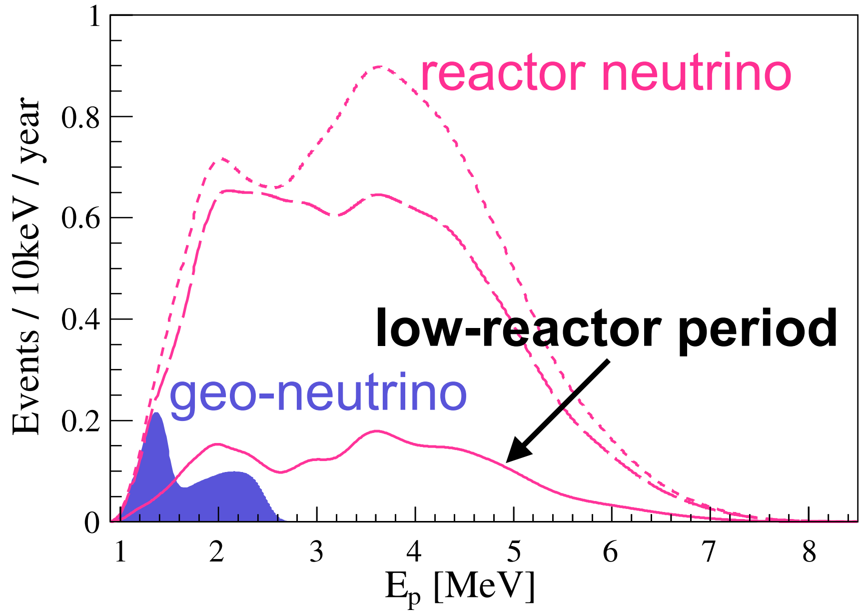
<u>geo-nu event</u>

$$116^{+28}_{-27}\ \text{ev}$$ (24% error)

2016 Update

Reactor Neutrino Flux @Kamioka





Reactor neutrino background is decreased significantly.

PRD 88, 033001 (2013)

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

Preliminary

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

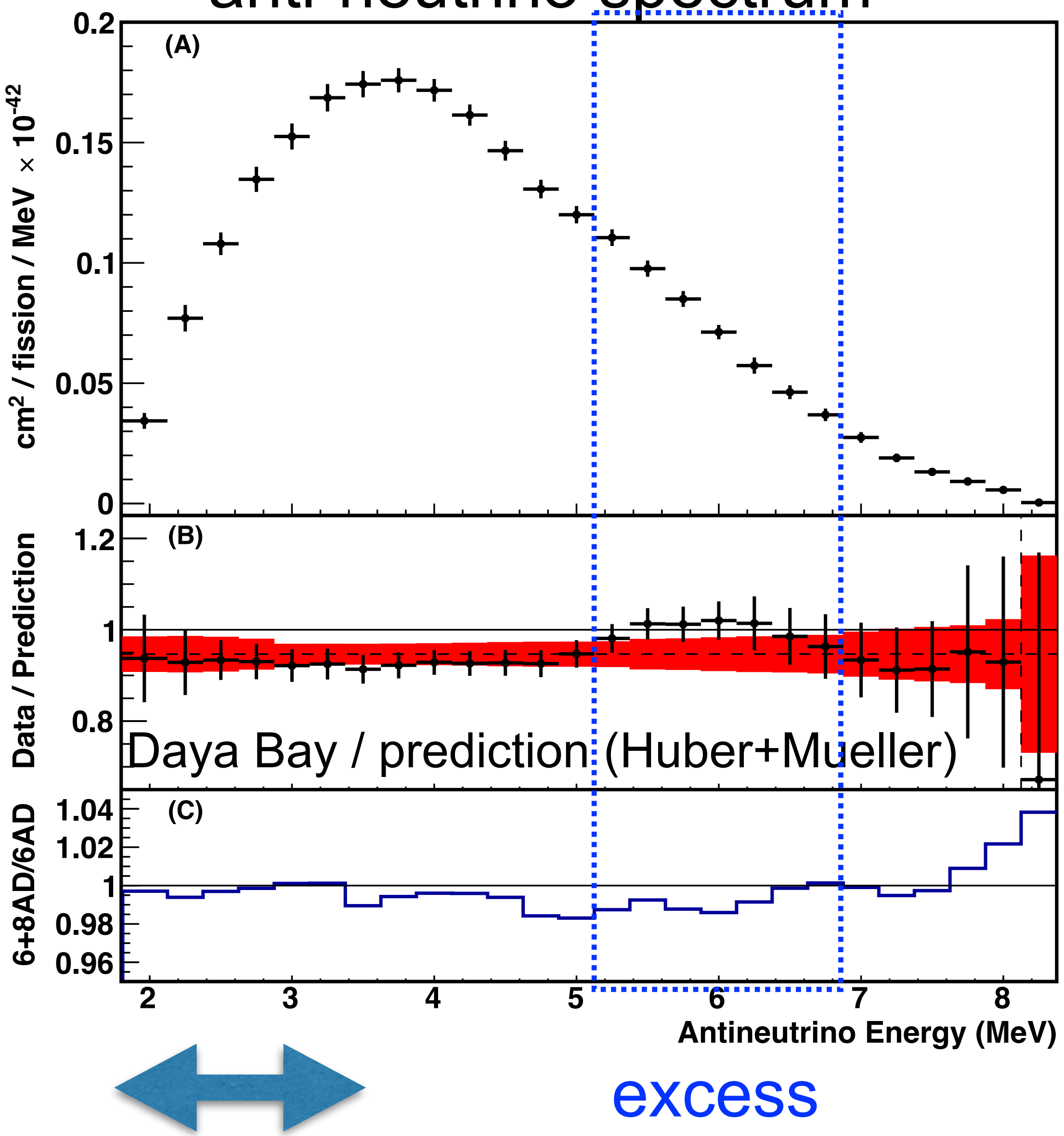
- 1.3 times of 2013 data-set

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.

Reactor Neutrino Spectrum Update

(Daya Bay, Chin. Phys. C **41**, 13002)
anti-neutrino spectrum



- Reactor neutrino experiments reported that there was an excess of events in the region of 4-6 MeV.
  - Daya Bay, RENO, Double Chooz

- Reactor neutrino spectrum for KamLAND analysis

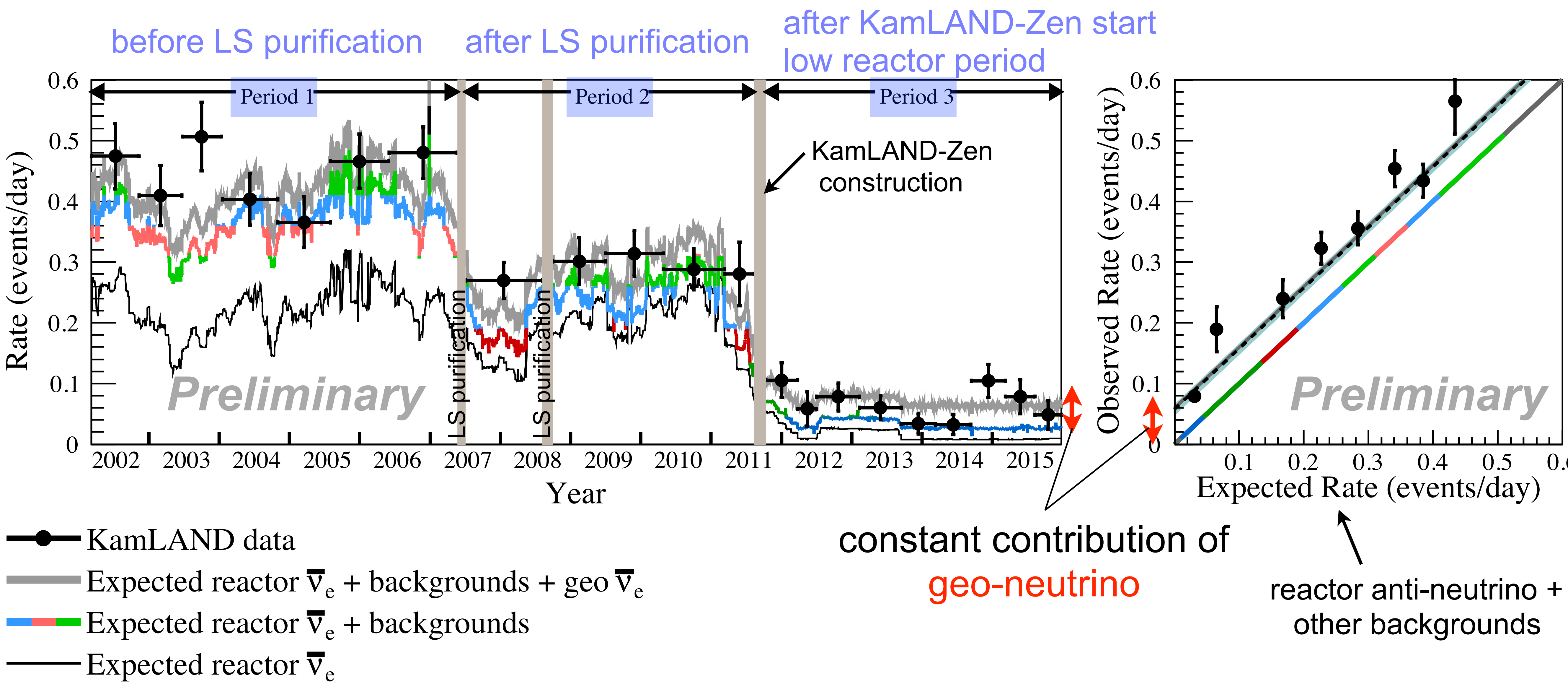
  2013 paper : Huber + Mueller & Bugey-4 normalisation

  2016 *preliminary* : **Daya Bay measurement result**

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

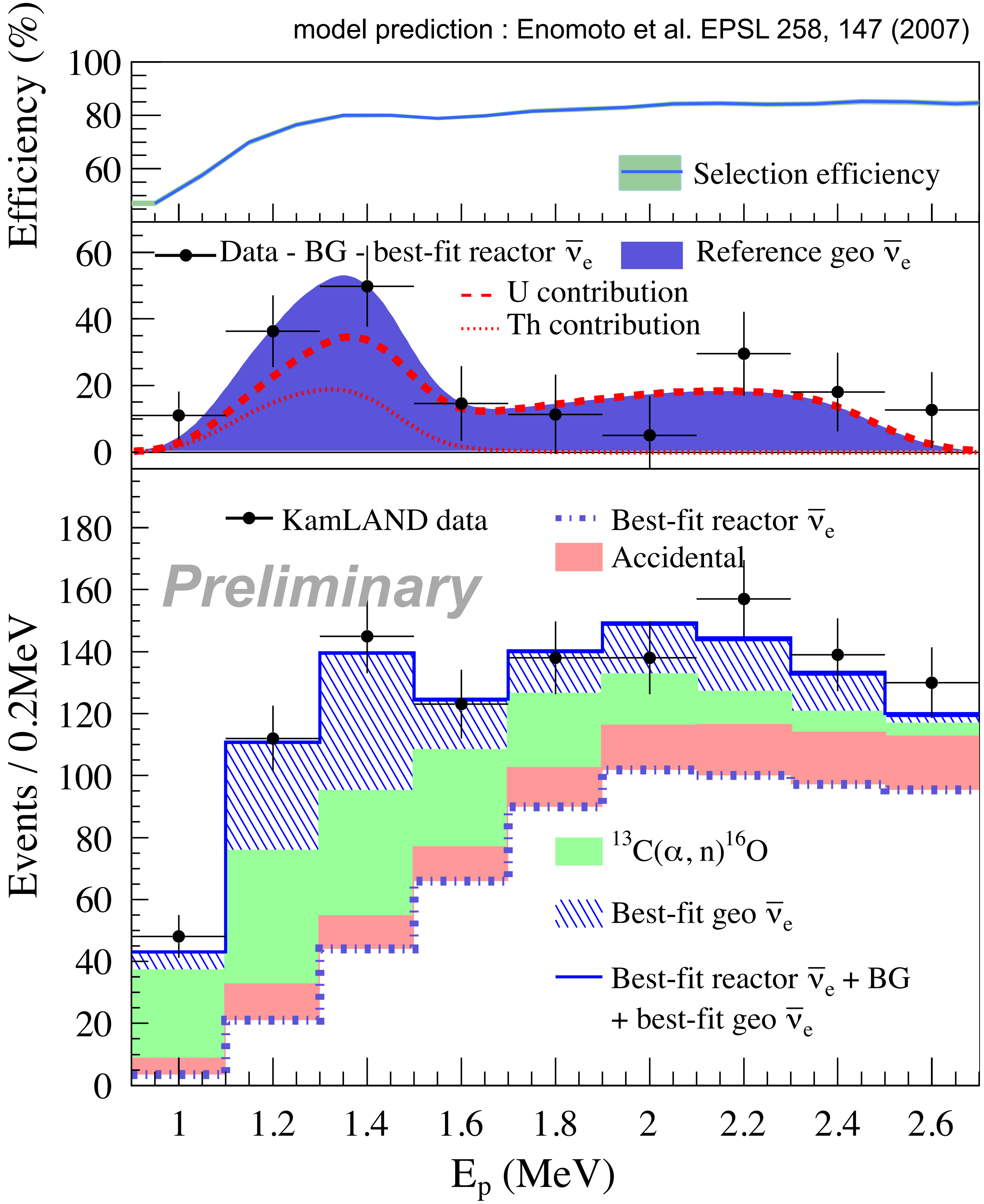
- We confirmed that :
  - ☑ 4-6 MeV excess has no impact on the geo-neutrino results.
  - ☑ effect of reactor spectrum uncertainty is much smaller than the statistical uncertainty of geo-neutrino events.

Event Rate Time Variation (0.9-2.6 MeV)



- 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

Energy Spectrum (0.9-2.6 MeV)



2016 Preliminary Result

Livetime : 3900.9 days

Candidate : 1130 ev

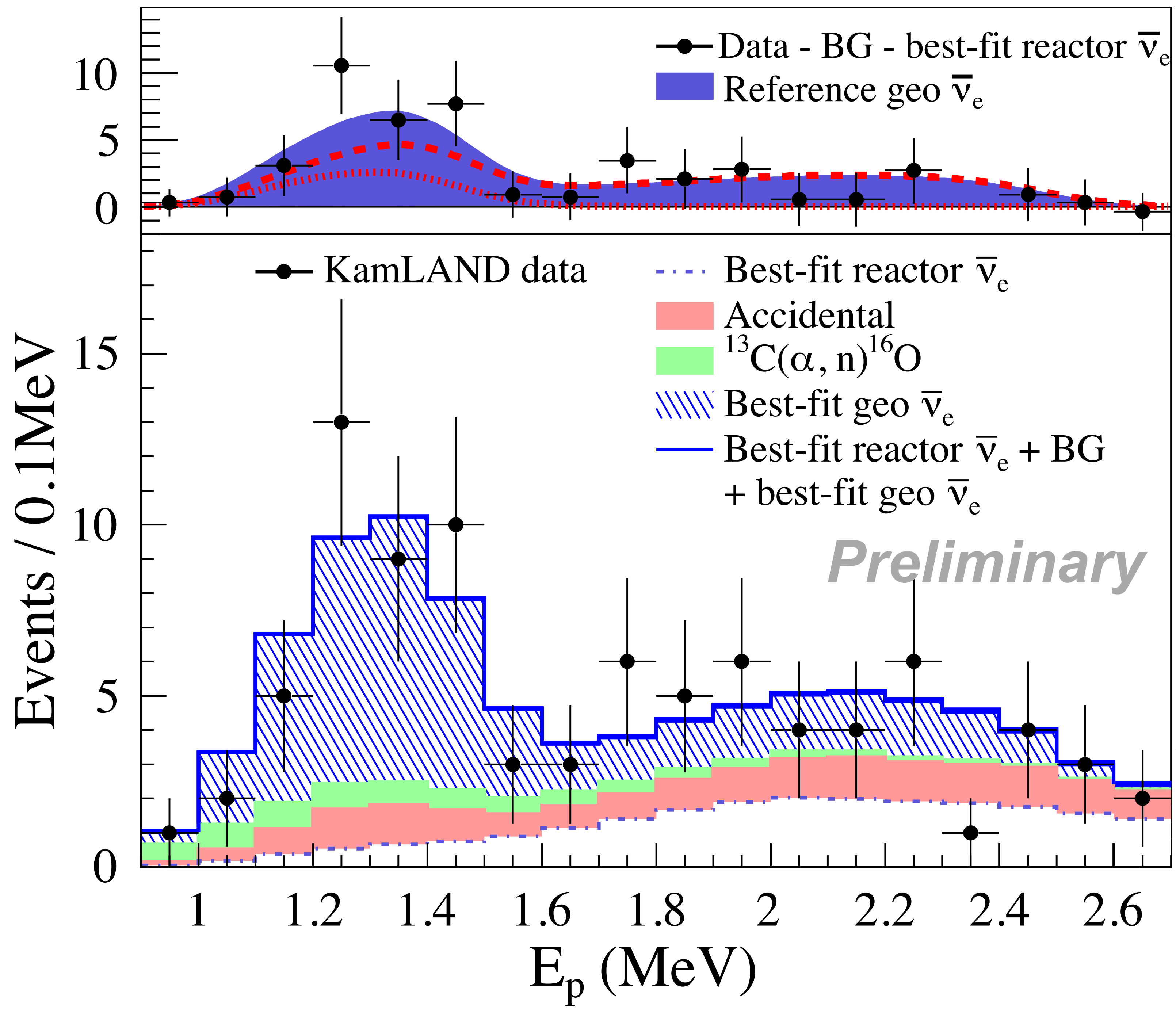
Background Summary

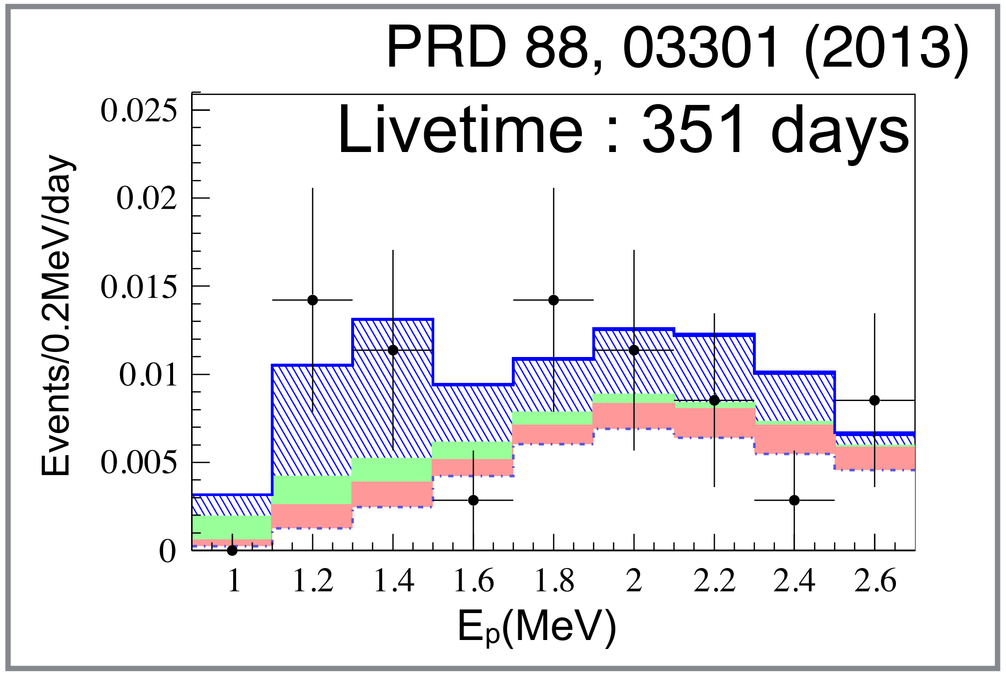
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

Energy Spectrum, Period 3 (0.9-2.6 MeV)

Livetime : 1259.8 days <u>2016 Preliminary Result</u>

model prediction : Enomoto et al. EPSL 258, 147 (2007)

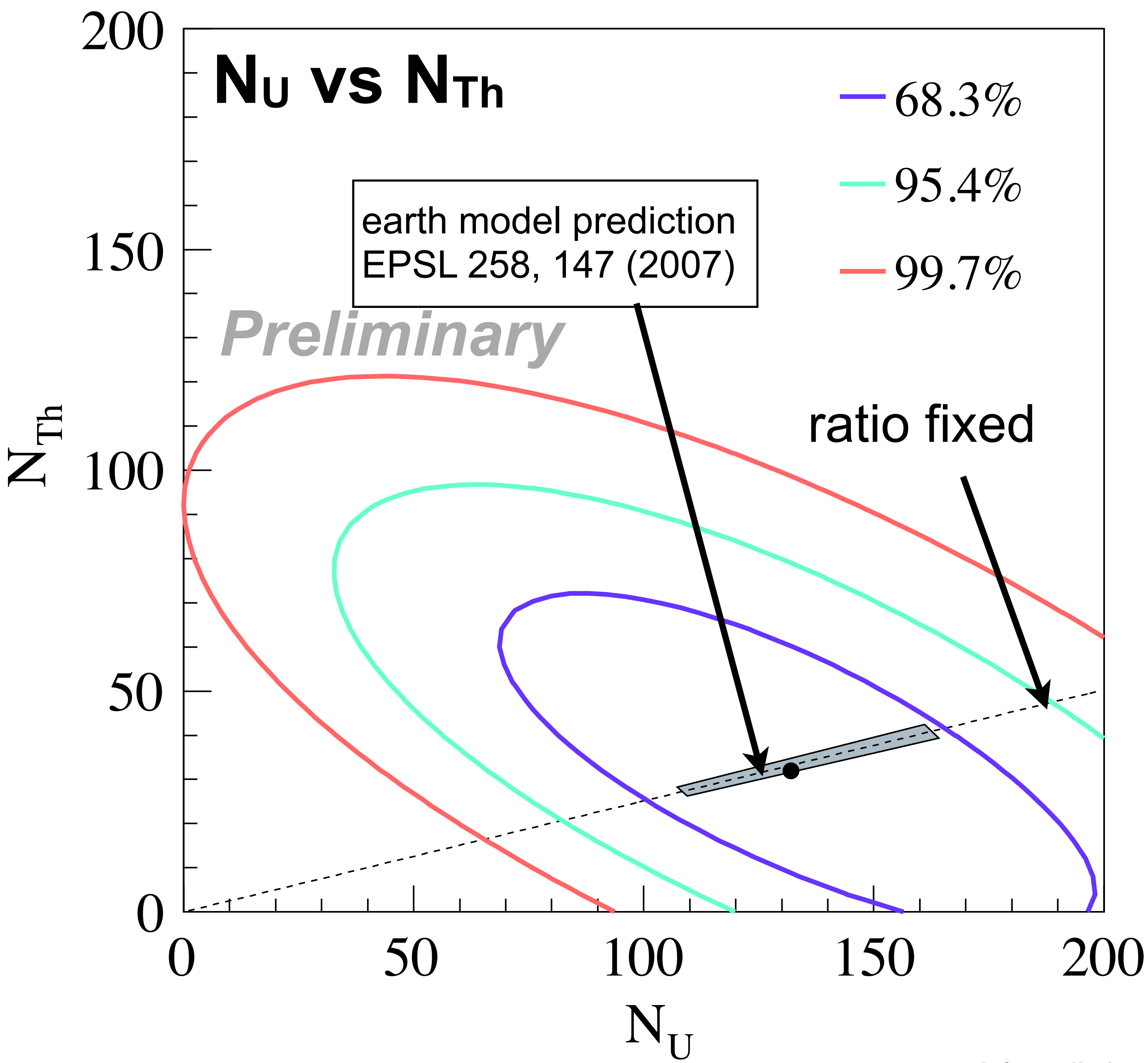




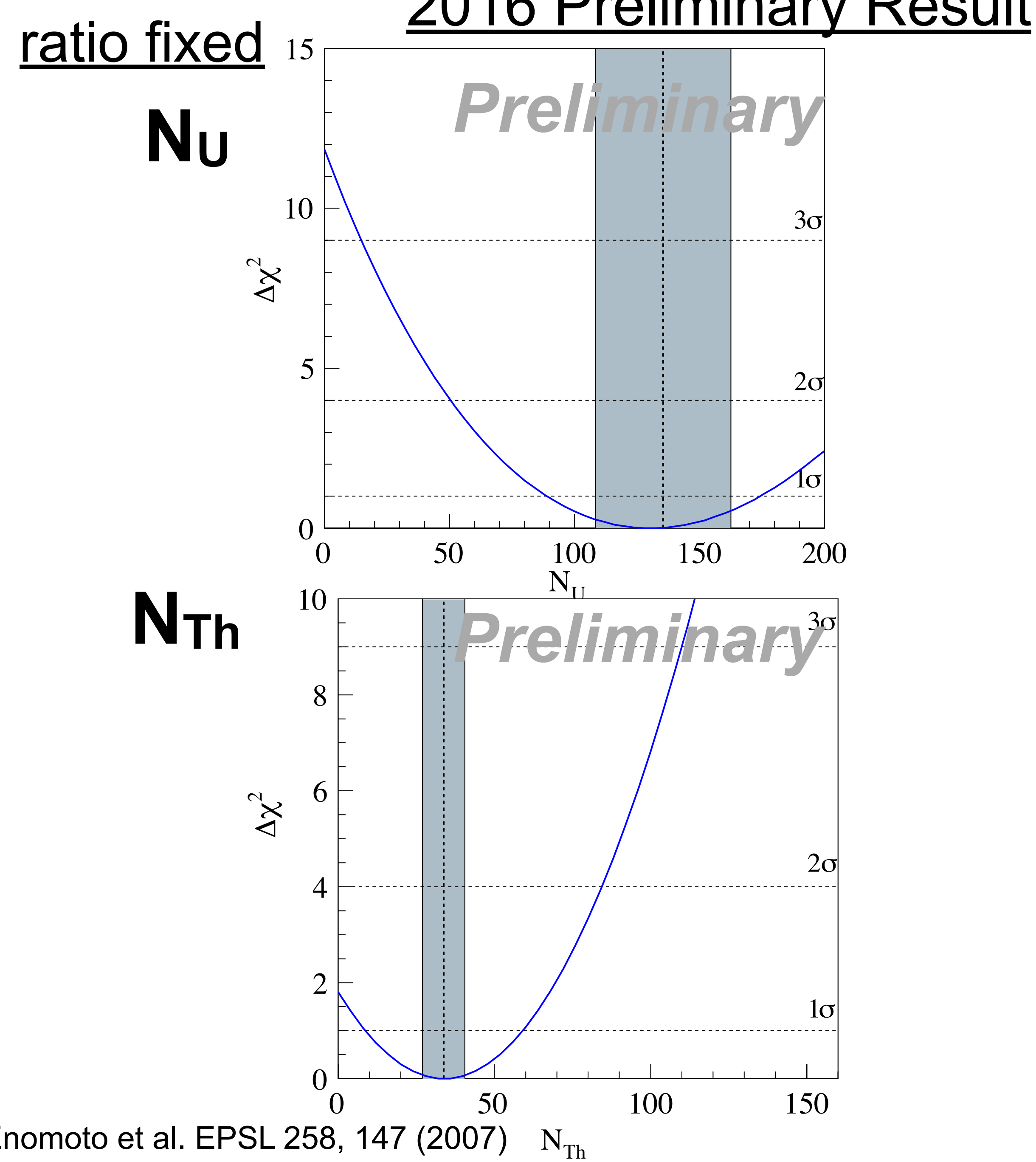
best-fit : Period 3 analysis

☑ We measured clear distribution of geo-neutrino events.

Rate + Shape + Time Analysis (1)



2016 Preliminary Result



model prediction : Enomoto et al. EPSL 258, 147 (2007)

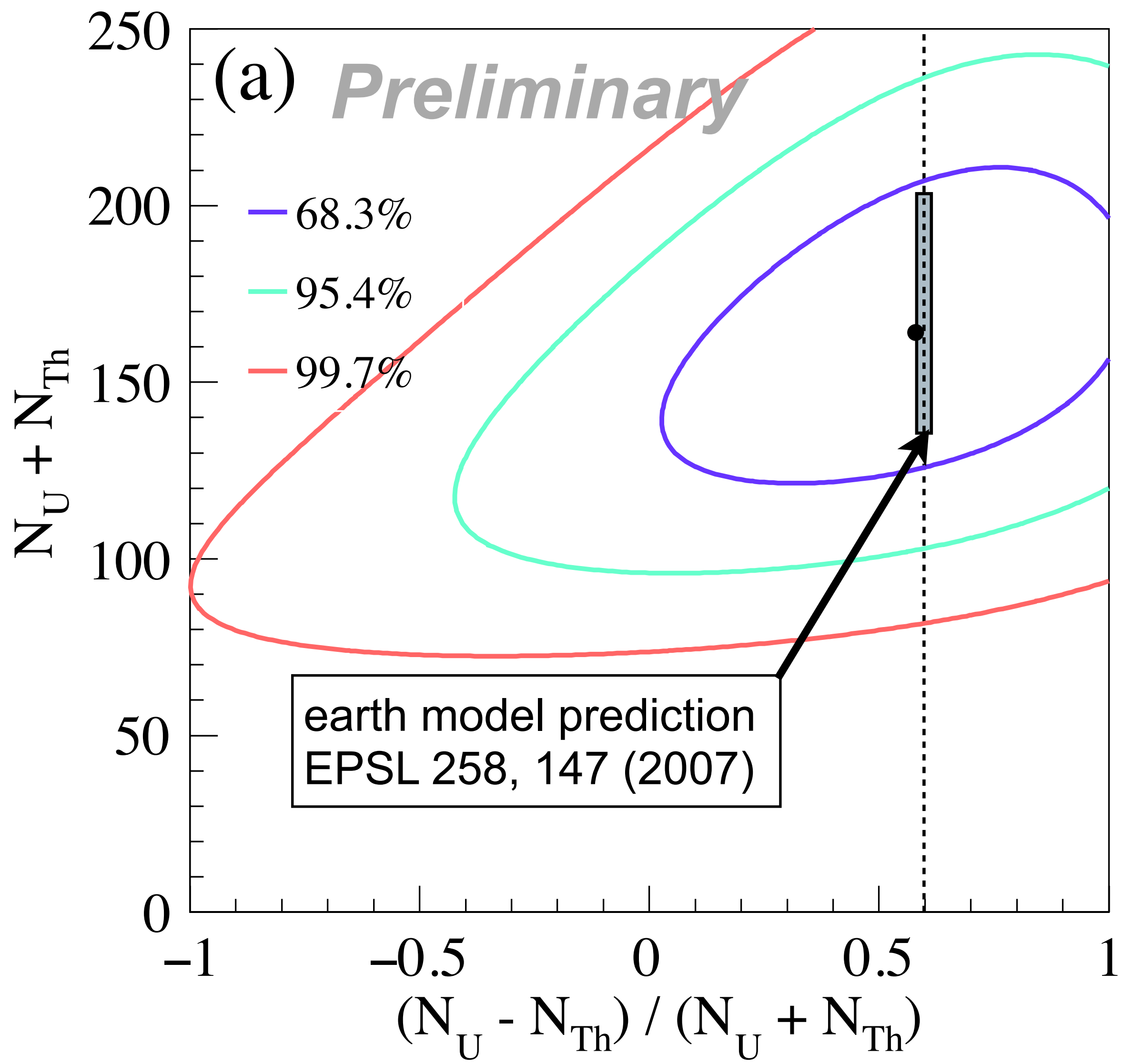
		[event]	[TNU]	Flux [$\times10^5$ cm^{-2}s^{-1}]		0 signal rejection
				best-fit	model	
ratio fixed	U	**128 +46/-39**	27.1 +9.8/-8.3	20.8 +7.5/-6.4	22.0	**3.44σ**
	Th	**32 +27/-23**	6.9 +5.9/-5.0	17.2 +14.5/-12.5	18.6	**1.34σ**

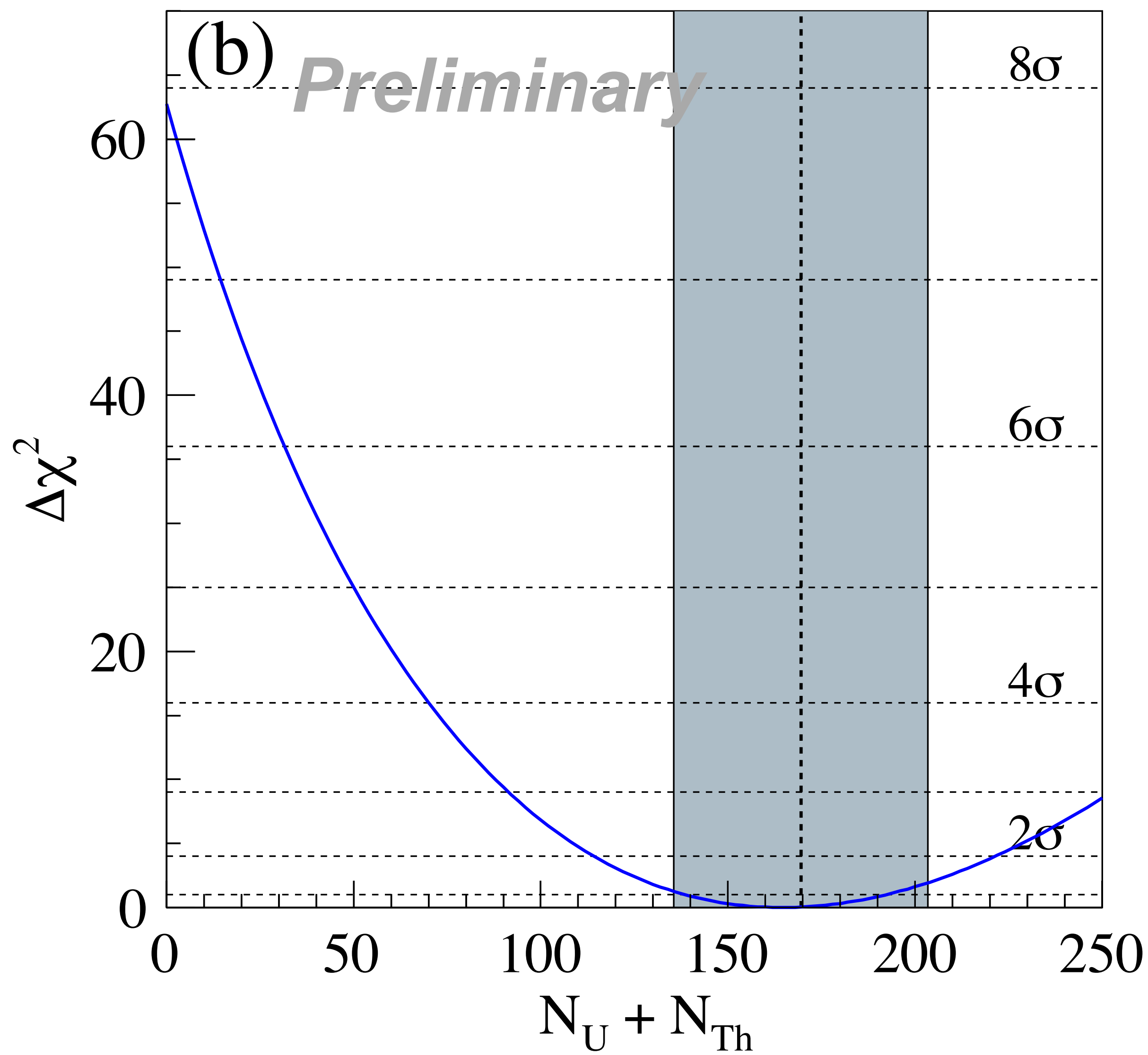
Rate + Shape + Time Analysis (2)

$N_U + N_{Th}$

ratio fixed

2016 Preliminary Result





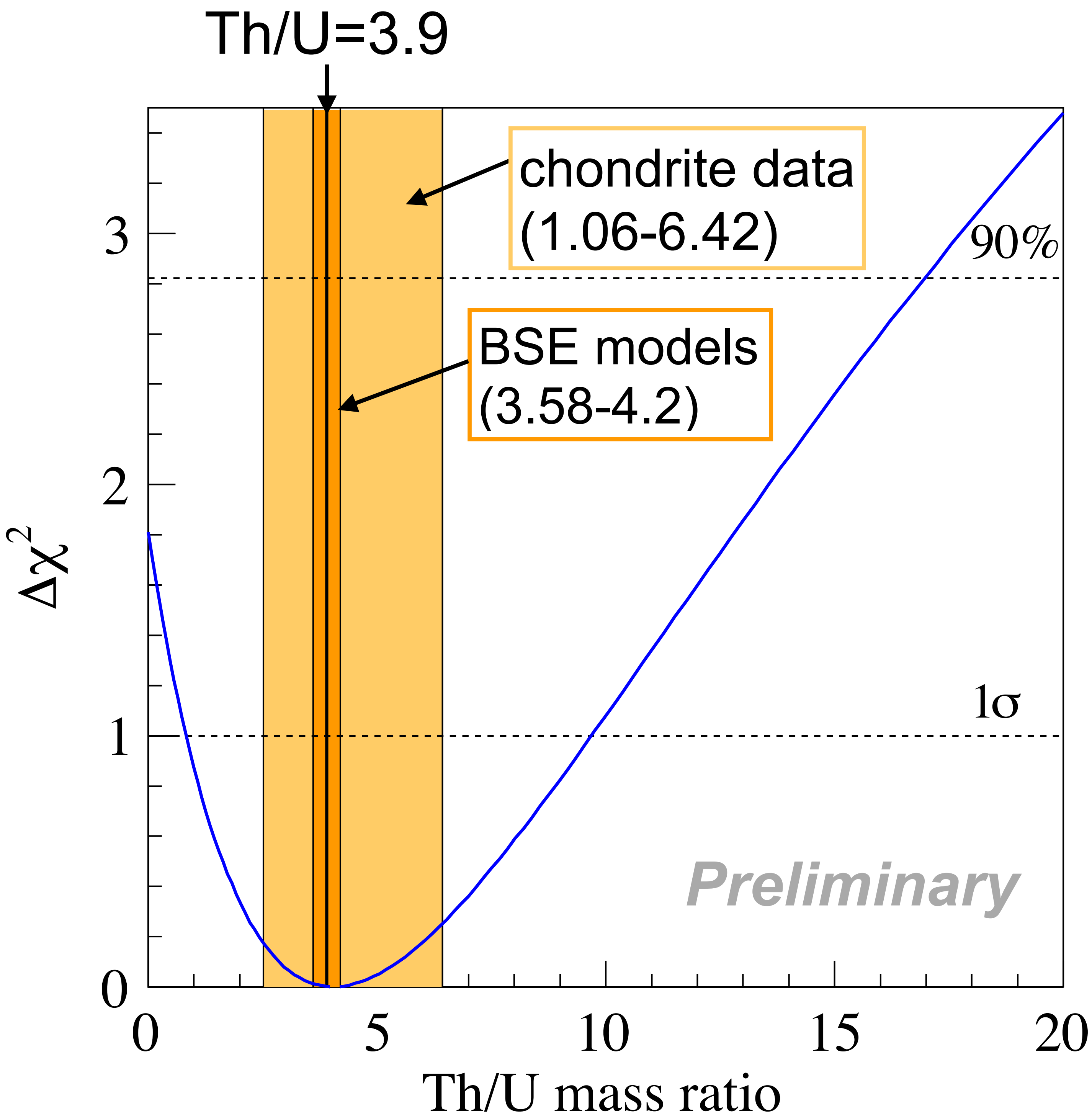
best-fit $(N_U, N_{Th}) = (130, 34)$
$N_U + N_{Th} = 164$

model prediction : Enomoto et al. EPSL 258, 147 (2007)

ratio fixed

	[event]	[TNU]	Flux [$\times 10^6$ cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U+Th	**164 +28/-25 (17%)**	34.9 +6.0/-5.4	3.9 +0.7/-0.6	4.1	**7.92σ**

Th/U Mass Ratio



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

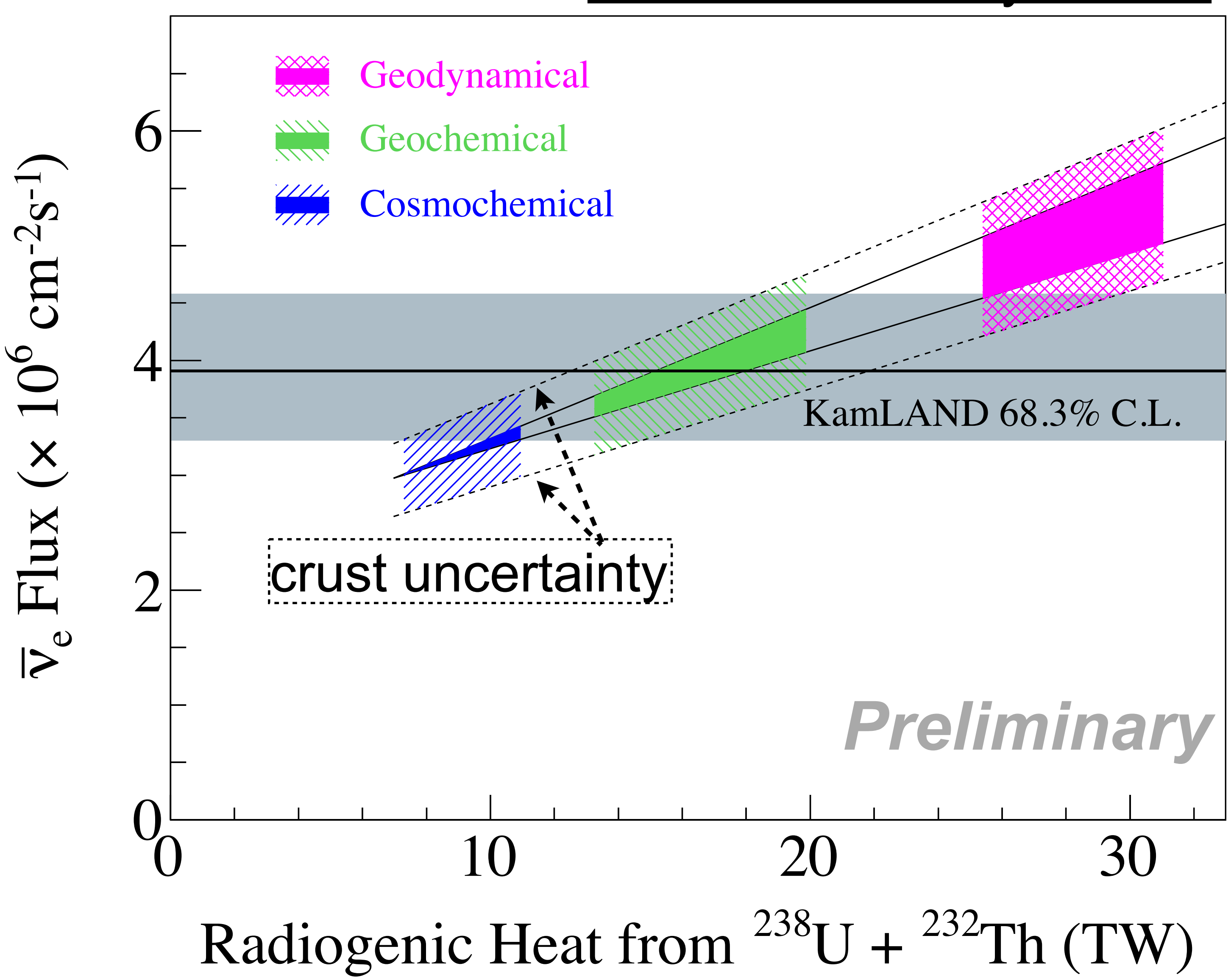
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

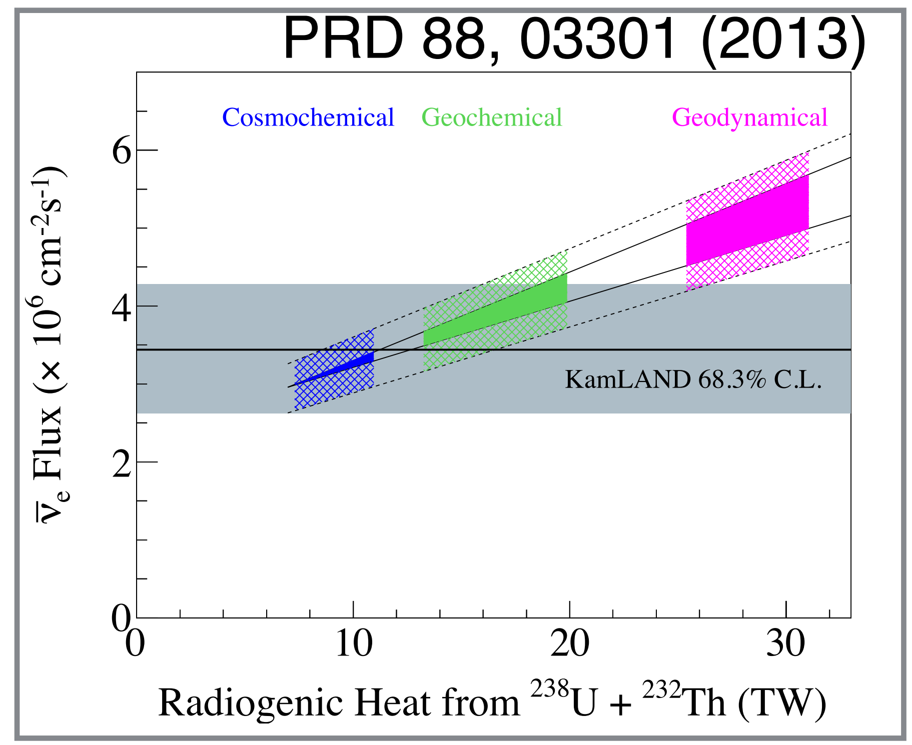
Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

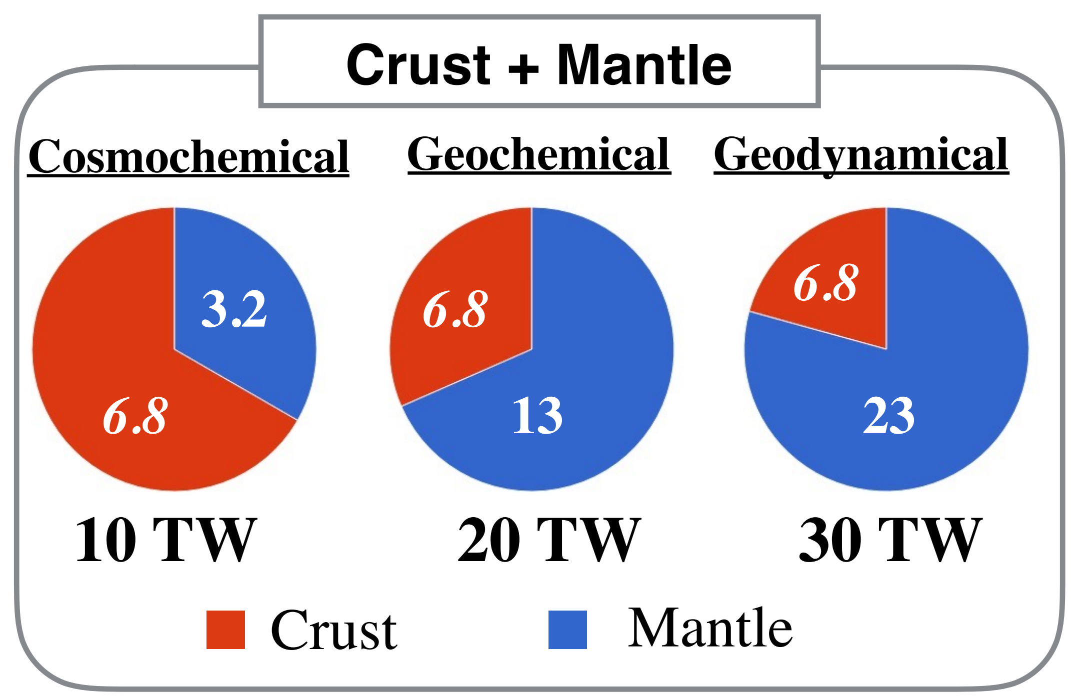
Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

Earth Model Comparison

2016 Preliminary Result







☑ Radiogenic Heat: $15.5^{+6.5}_{-6.3}$ TW

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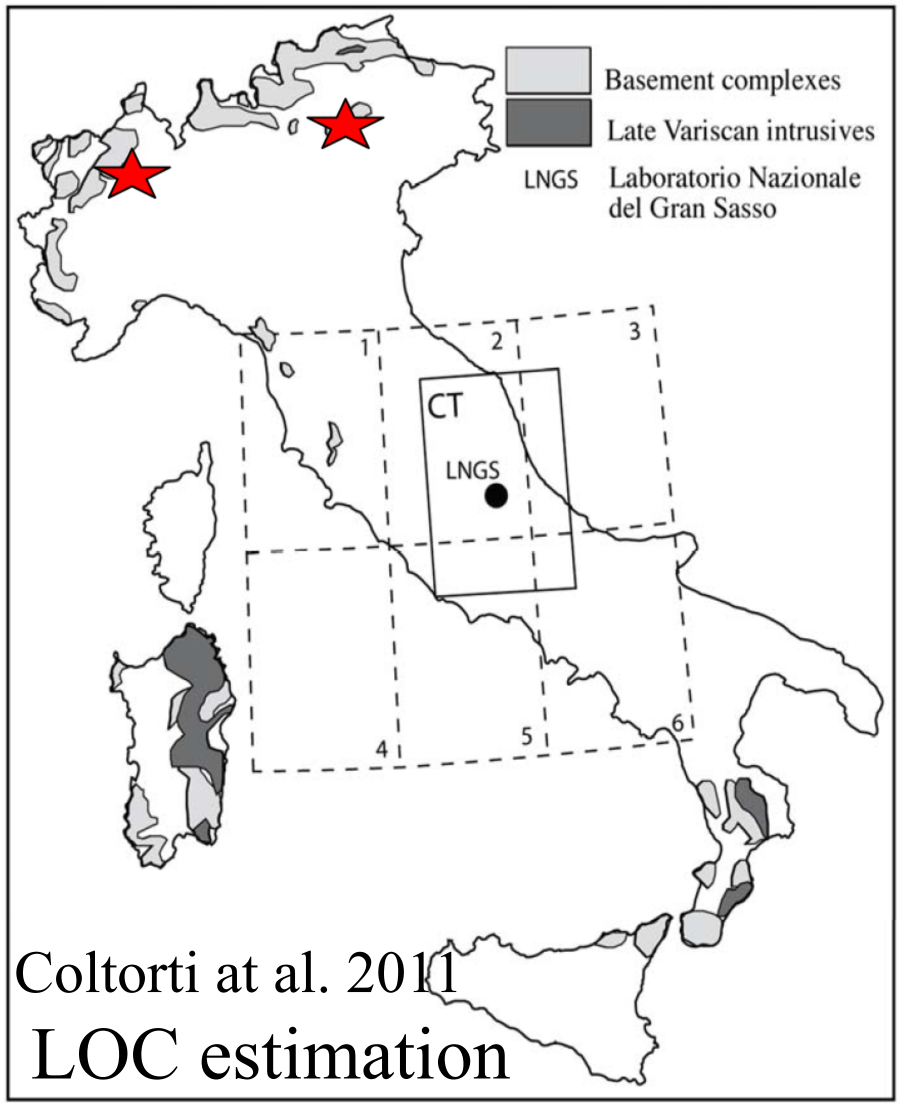
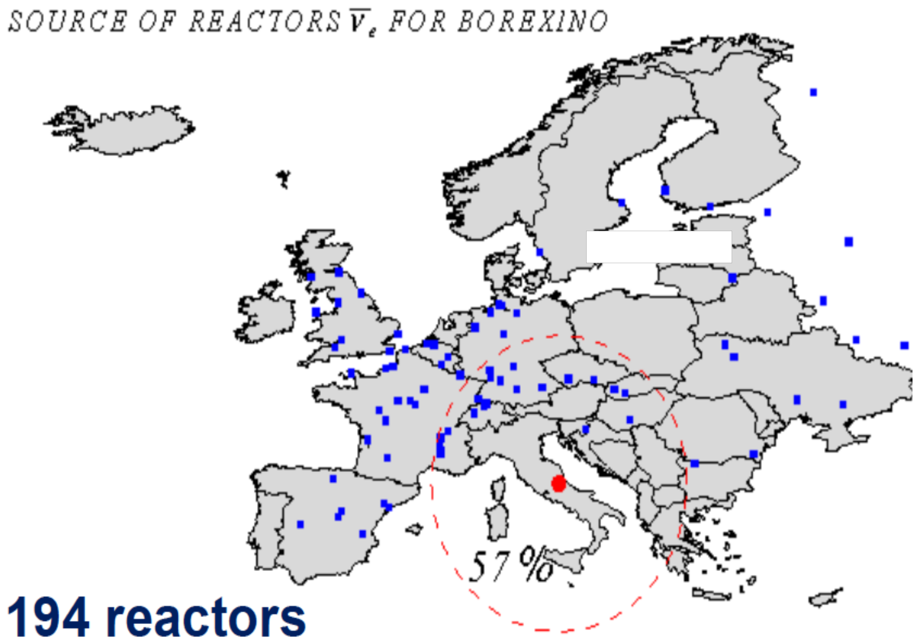
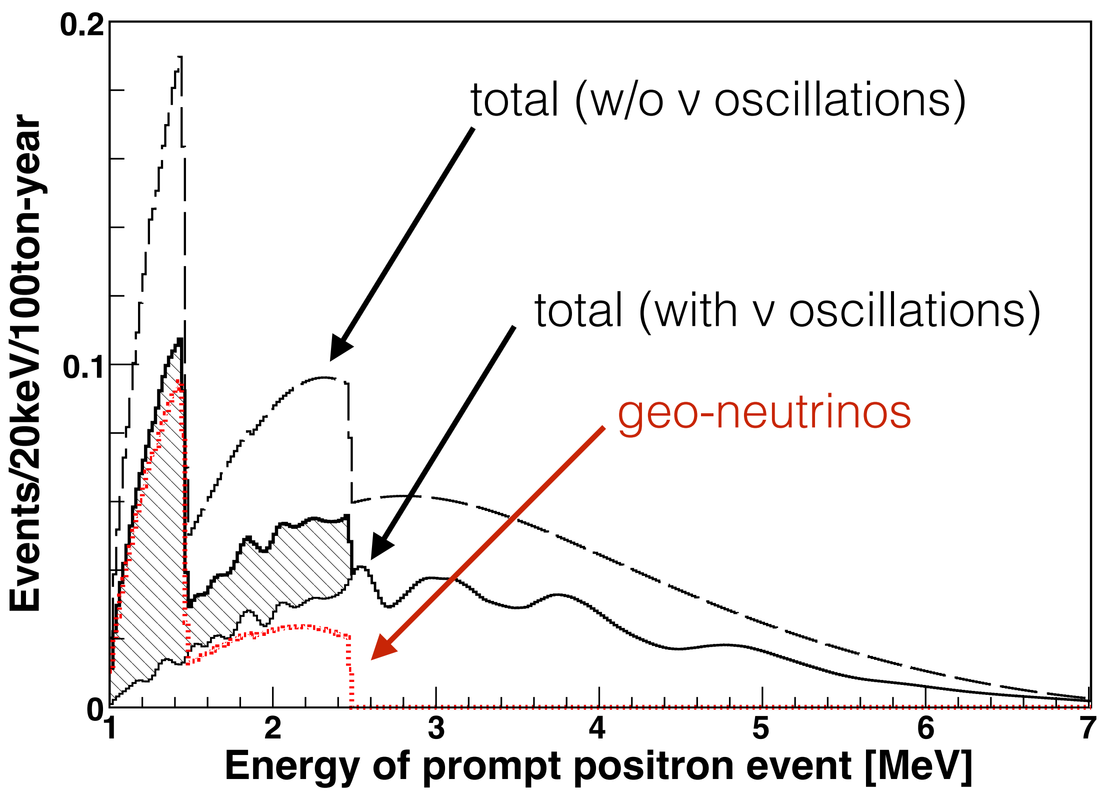
Geo-neutrino Flux at Gran Sasso



S_{crust} = 23.4±2.8 TNU*





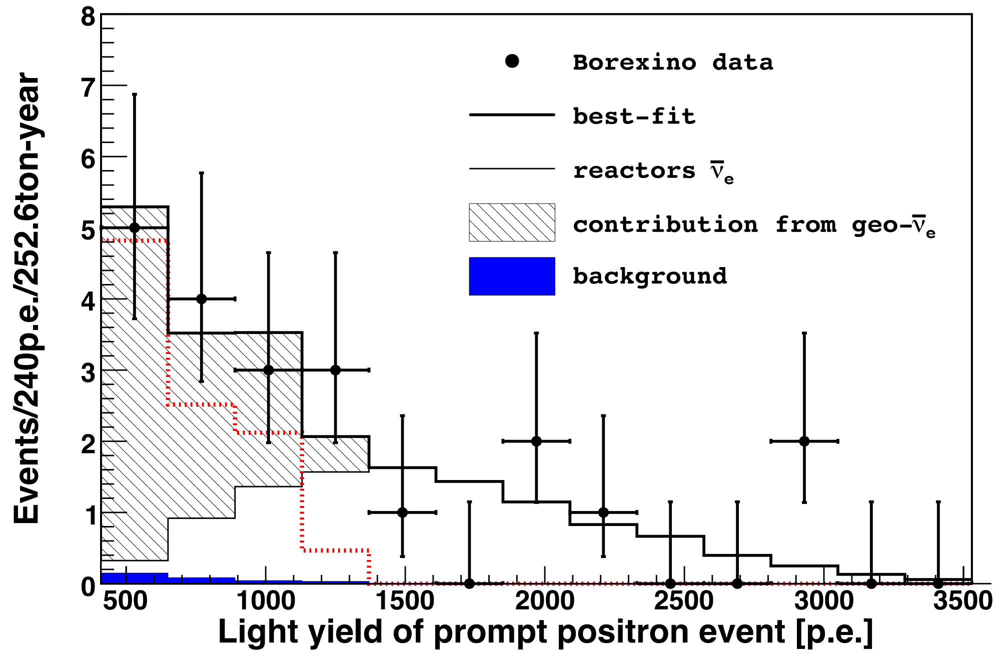
(*) 1 TNU = 1 Terrestrial Neutrino Unit = 1 event / year /10^{32} protons

Ludhova 2016

First observations of geo-neutrinos by Borexino

252.6 ton·yr exposure

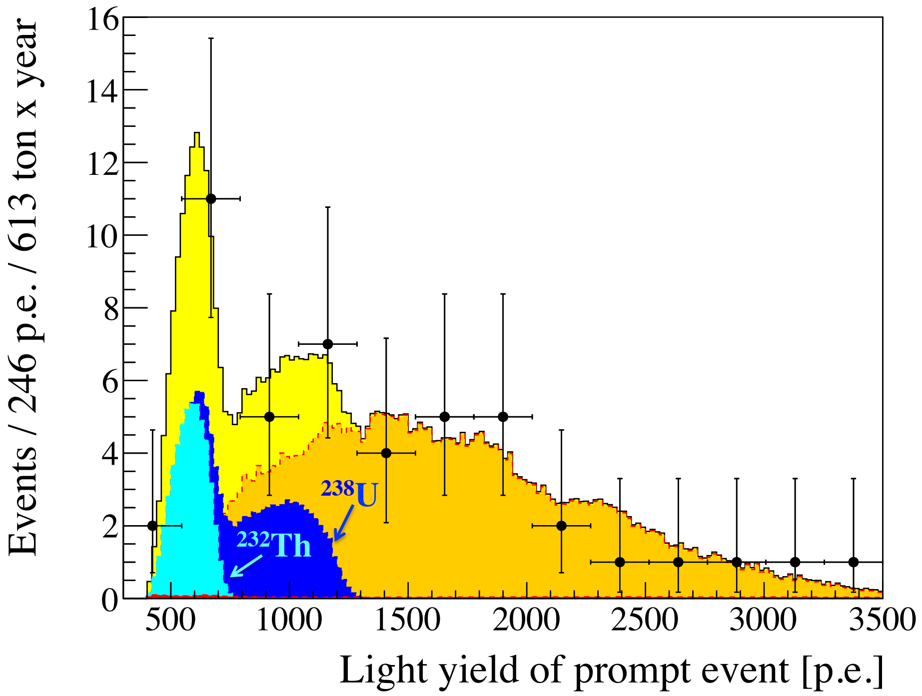
Phys. Lett. **B** 687, 299 (2010)



$3.9^{+1.6}_{-1.3}$ events / (100 ton·yr)
99.997% C.L.
first 3-σ observation

1353 days of data

Phys. Lett. **B** 722, 295 (2013)

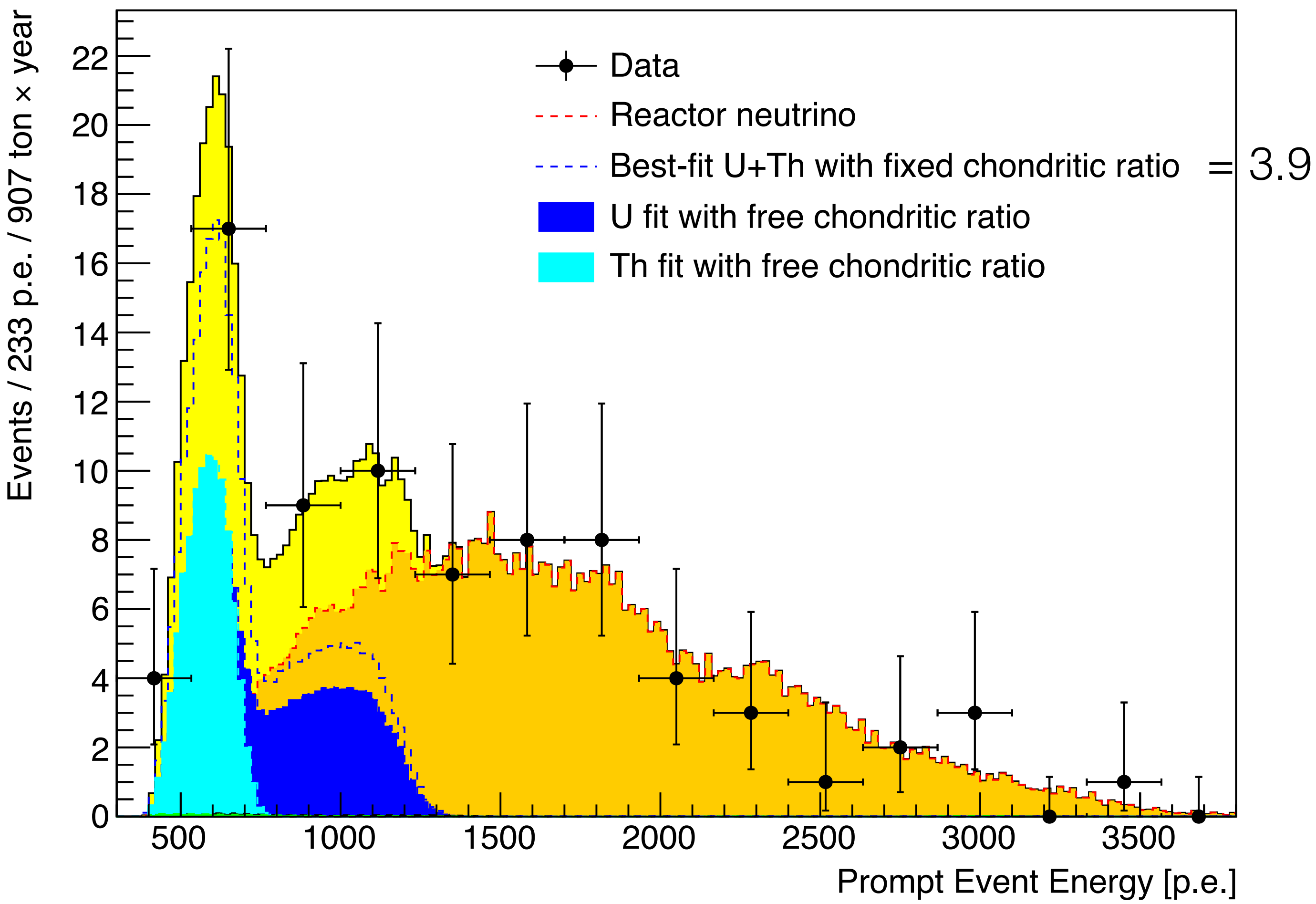


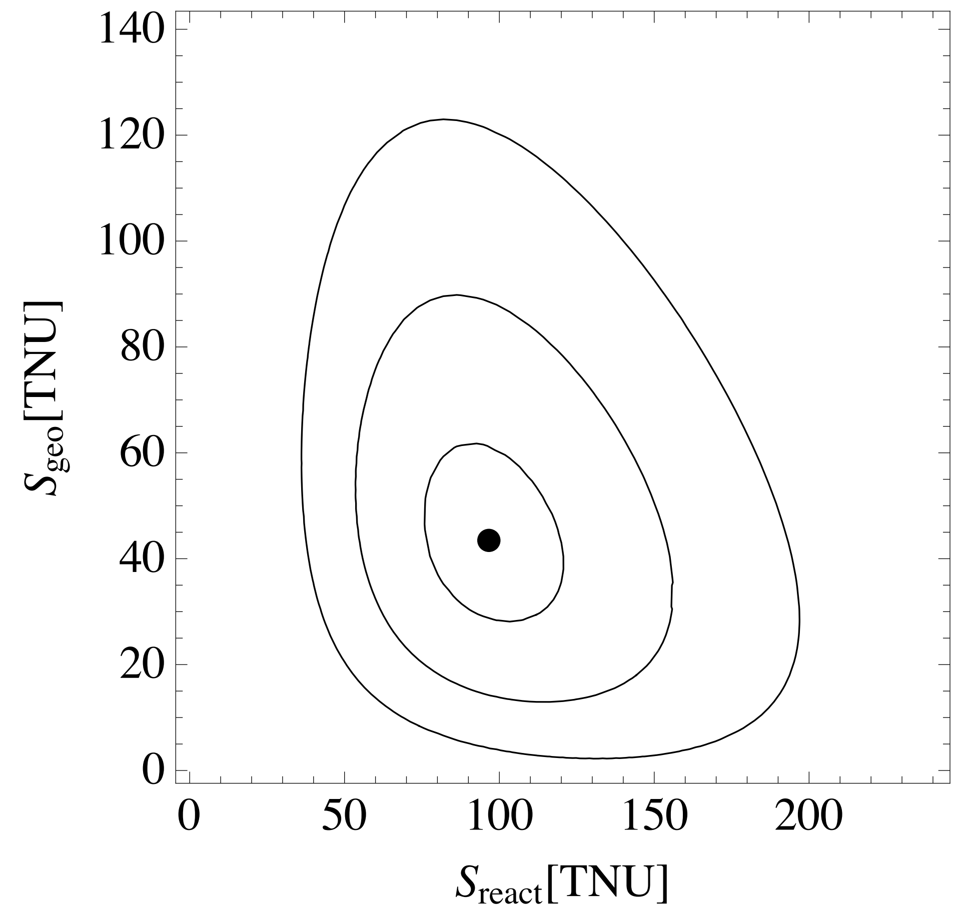
S_{geo} = 38.8 ± 12.0 TNU*
(null hypothesis 10^{-6} probability)

(*) 1 TNU = 1 Terrestrial Neutrino Unit = 1 event / year /10^{32} protons

Latest geo-neutrino results from Borexino
2056 days of data

Phys.Rev. D **92**, 031101(R) (2015)

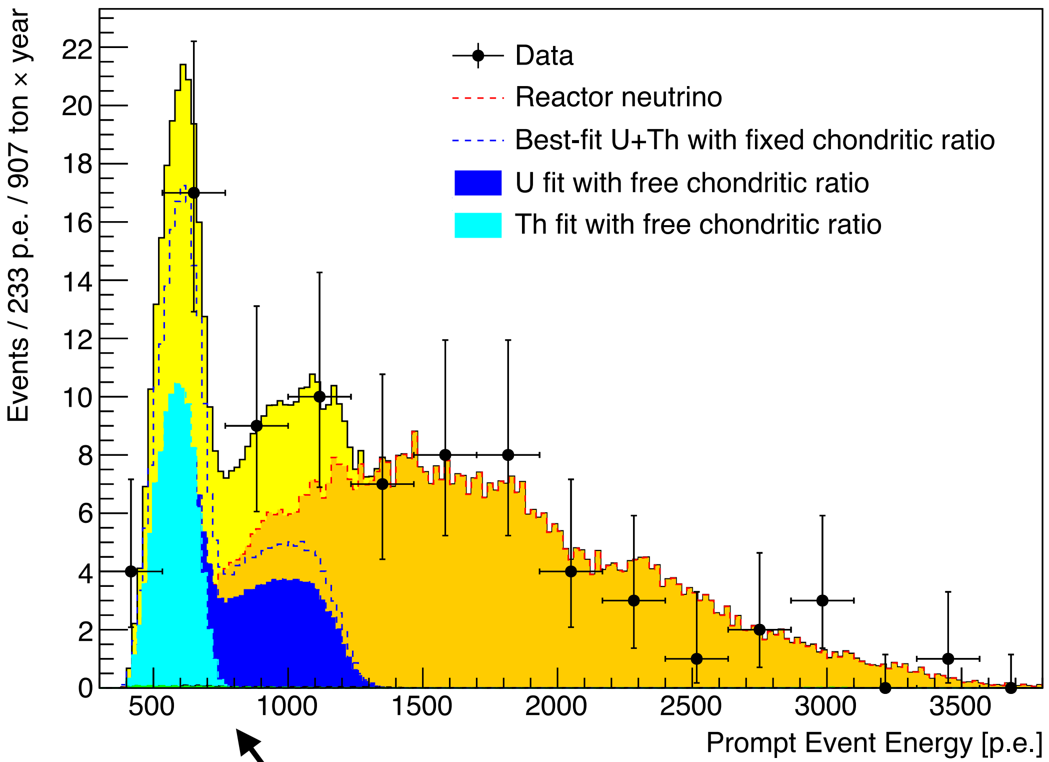




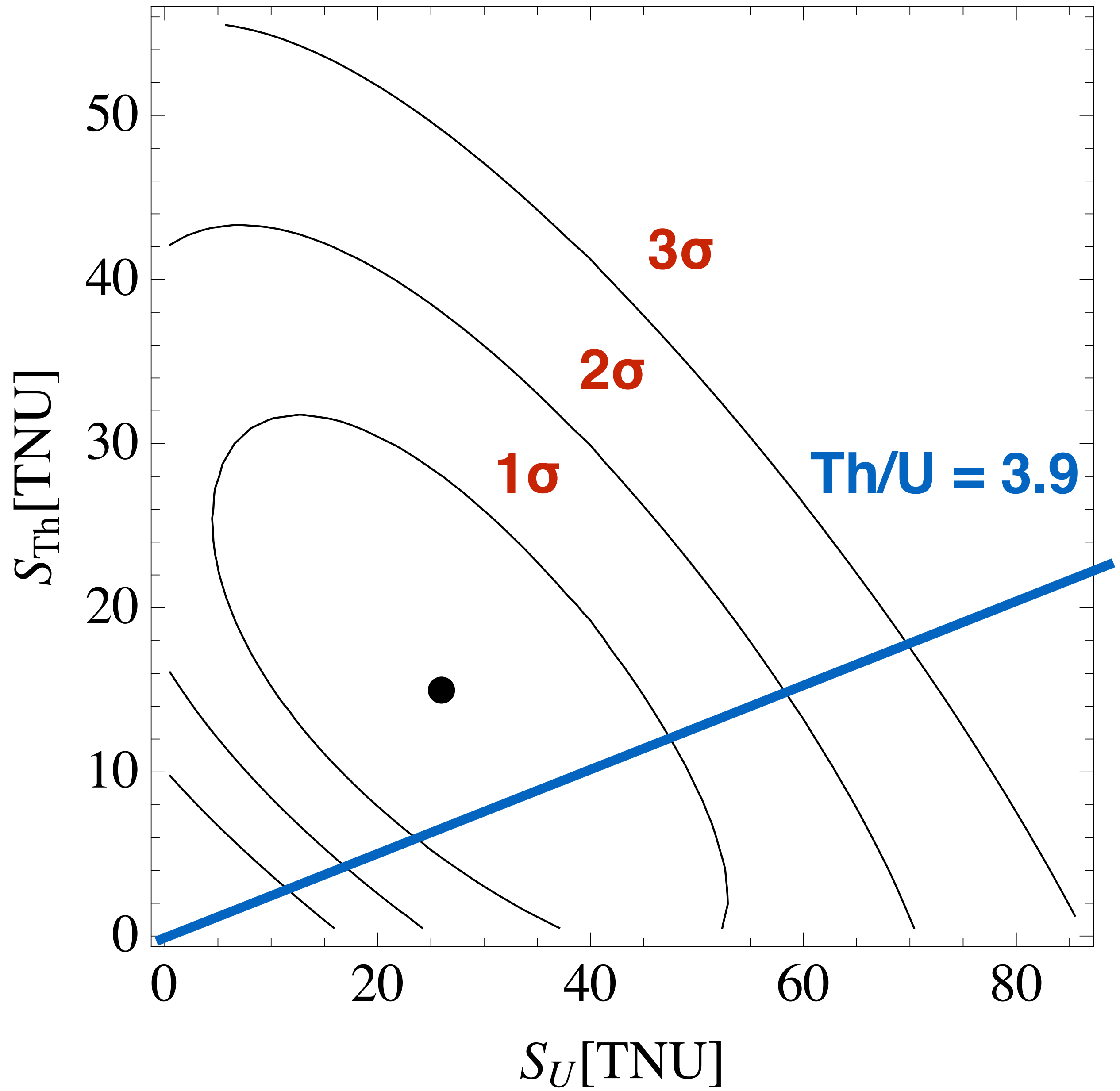
Total Events	77
Reactor	52.7 $^{-7.7}_{+8.5}$ (stat) $^{-0.9}_{+0.7}$ (syst)
Backgrounds	0.78$^{-0.10}_{+0.13}$
Geo-v Events	23.7 $^{-5.7}_{+6.5}$ (stat) $^{-0.6}_{+0.9}$ (syst)
Geo-v Rate [TNU]	43.5 $^{-10.4}_{+11.8}$ (stat) $^{-2.4}_{+2.7}$ (syst)

from Zavatarelli 2016

Th and U contributions



Th and U free parameters



from Zavatarelli 2016

Geo-neutrinos from the mantle

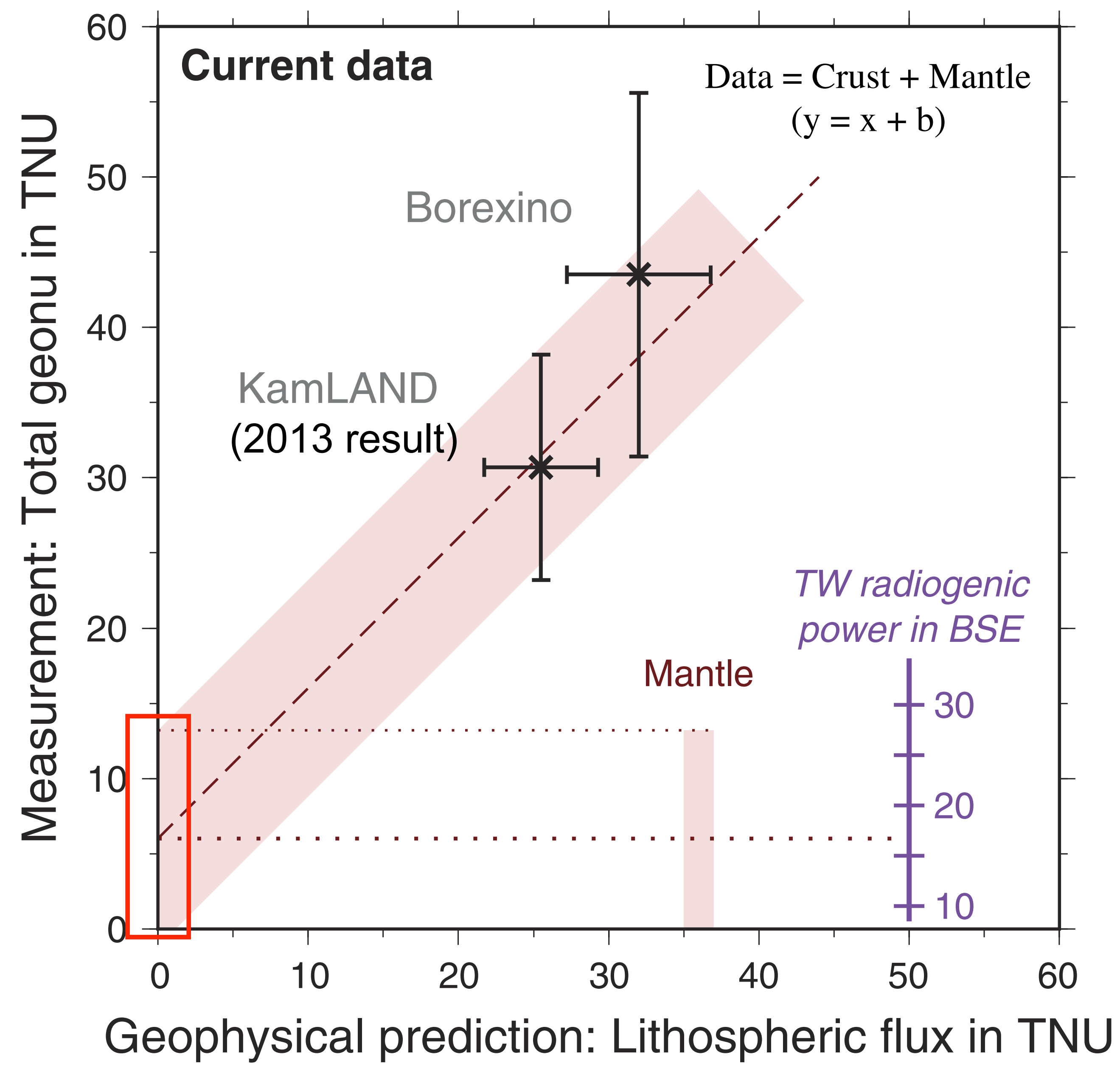
$S_{total}=43.5^{+12.1}_{-10.7}$ TNU

$S_{crust} = 23.4\pm2.8$ TNU

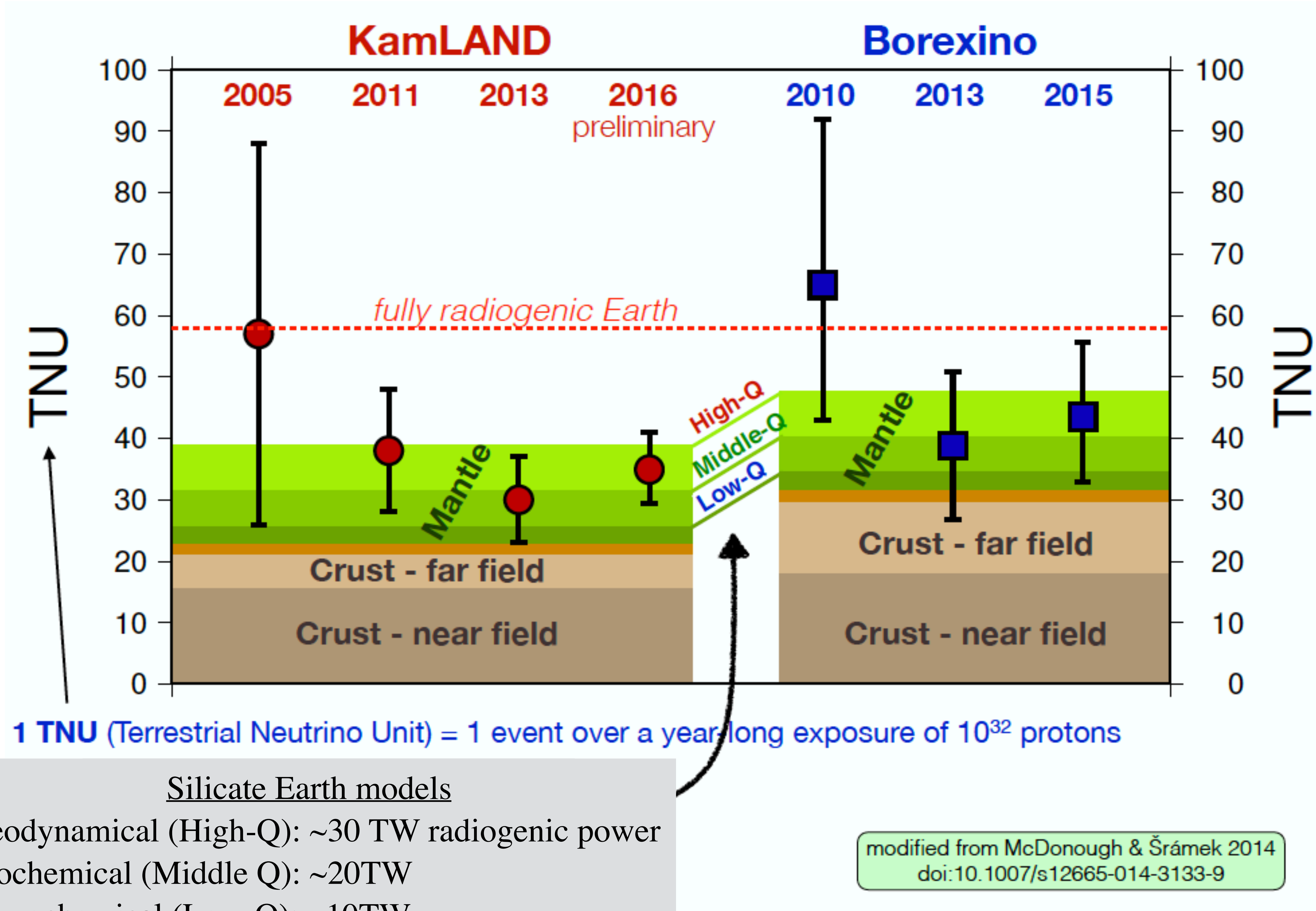
near field: Coltorti *et al.*
far field: Y. Huang *et al.*

$S_{mantle} = S_{tot} - S_{crust}$

$= 20.9^{+15.1}_{-10.3}$ TNU



KamLAND and Borexino



1 TNU (Terrestrial Neutrino Unit) = 1 event over a year-long exposure of 10^{32} protons

<u>Silicate Earth models</u>

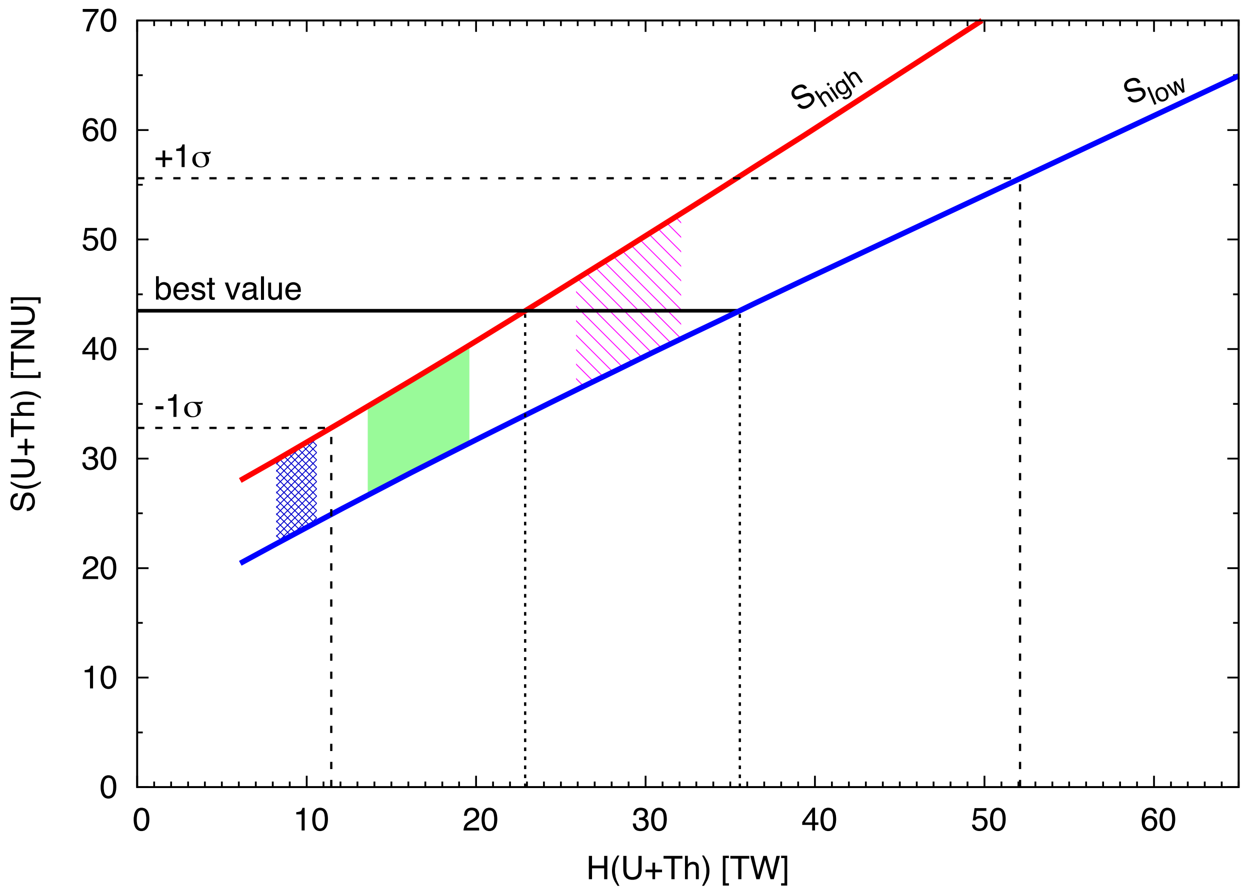
Geodynamical (High-Q): ~30 TW radiogenic power
Geochemical (Middle Q): ~20TW
Cosmochemical (Low-Q): ~10TW

Geo-neutrinos Observation

- **Sum of radiogenic heat is obtained**
- Test of BSE Model

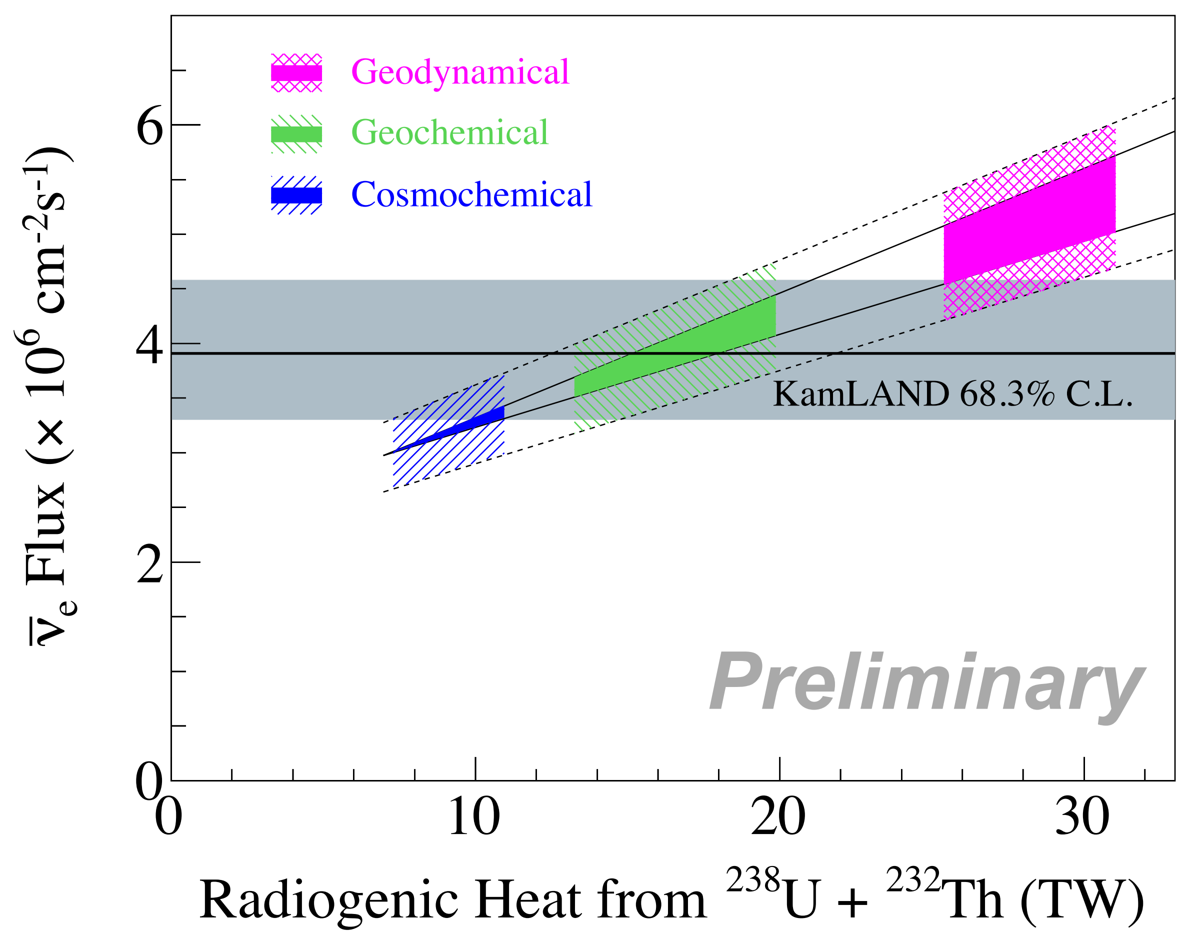
Earth Model Comparison

2015 Borexino



23–36 TW
(Model independent: 11–52 TW)

2016 KamLAND



$15.5^{+6.5}_{-6.3}$ TW

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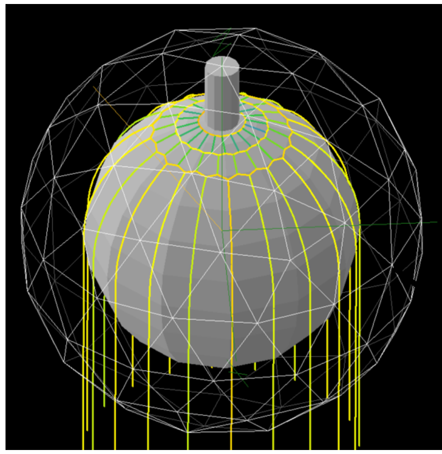
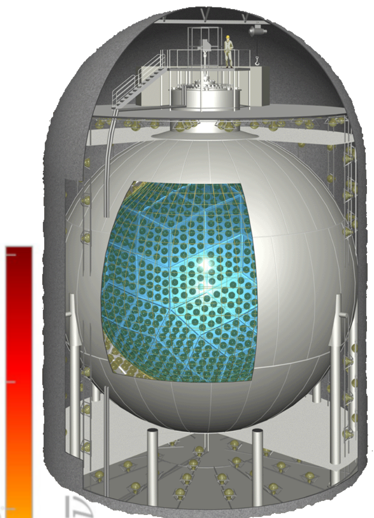
Current and Future Experiments



SNO+

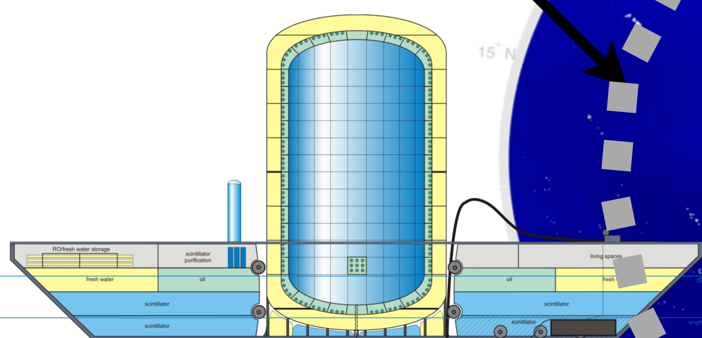
1kt, LS+, 5.4 kmwe
within 2017 online

KamLAND

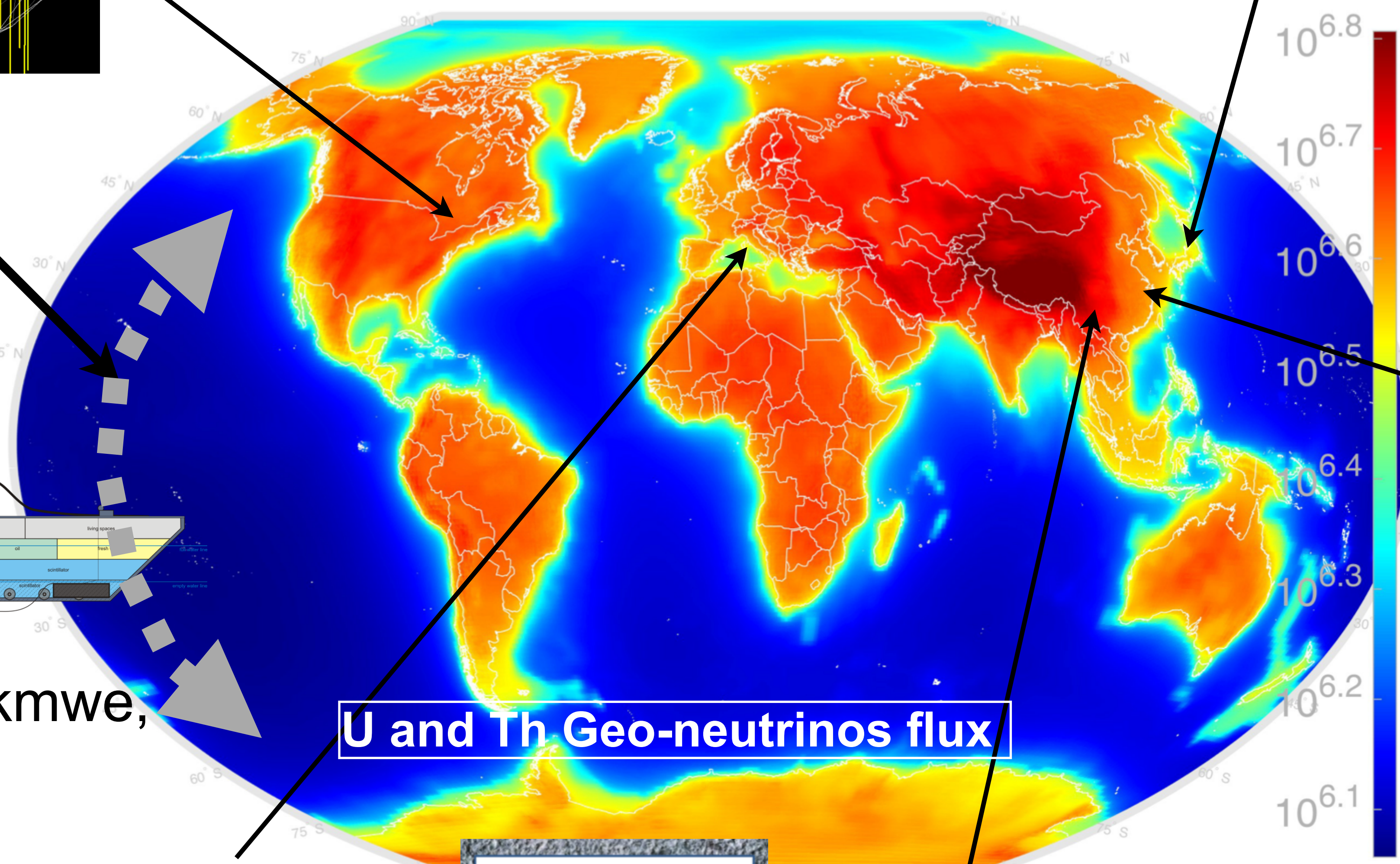


1kt, LS
2.7 kmwe
running

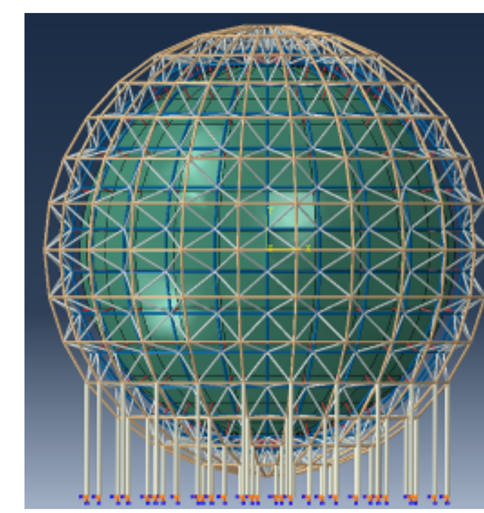
OBK



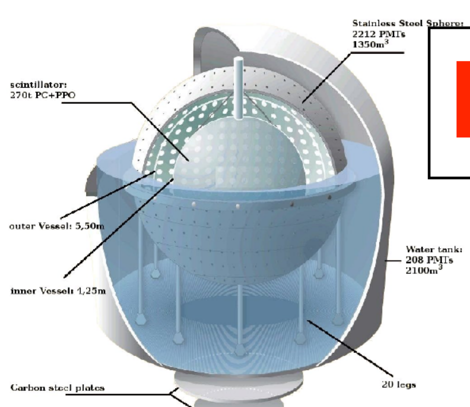
10-50kt, LS, ~5kmwe,
movable, R&D



JUNO

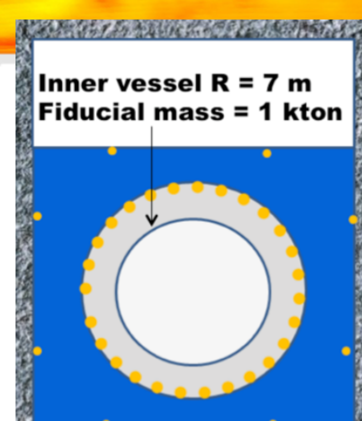


20kt, LS
1.5 kmwe
approved
(2020~)



Borexino

0.3kt, LS
3.7kmwe
running



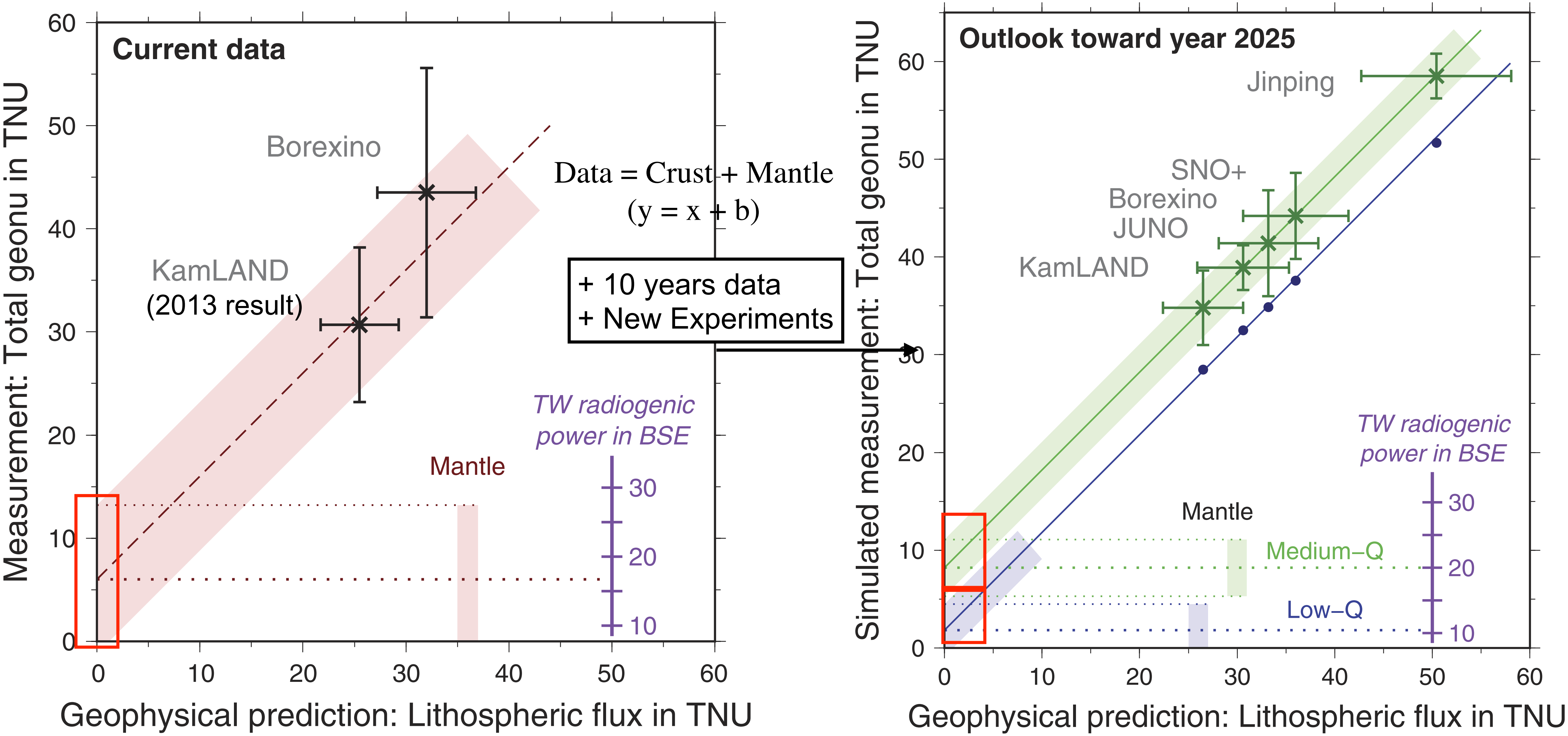
Jinping

3kt, LS
6.7 kmwe
R&D

Geo-neutrinos from the mantle

- **Observe Geo-neutrinos from mantle in the world**

Šrámek et al., S. Rep. 33034 (2016)



Summary

- KamLAND and Borexino have detected geo-neutrinos
    - Measured local radiogenic heat and Th/U ratio
- Precision will improve with additional exposure
    - Discrimination of U and Th contributions
- New experiments are expected to come online soon
    - Improved precision, multi-site measurements
    - Independent measurement of geo-neutrinos from the mantle
- R&D and investigations for experiments in the far future:
    - Directional sensitivity
    - Detection of ^{40}K geo-neutrinos?

End