KamLAND

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Research Center for Neutrino Science (Tohoku Univ.)
for the KamLAND Collaboration

Contents

Contents

KamLAND Collaboration

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The KamLAND Collaboration

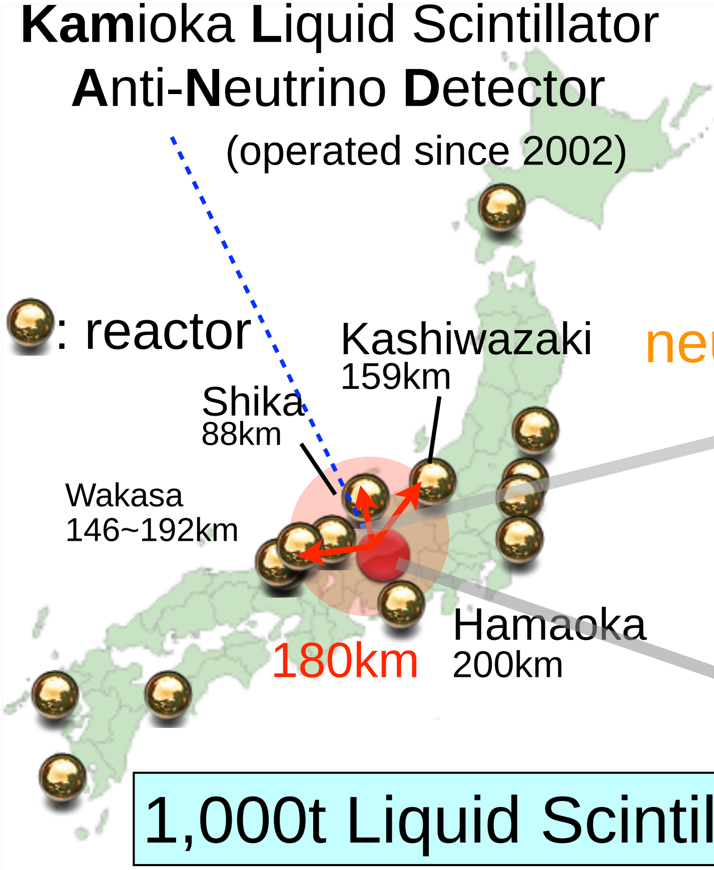
* Institutions :
  4 from Japan
  12 from US
  1 from Europe
* ~50 collaborators

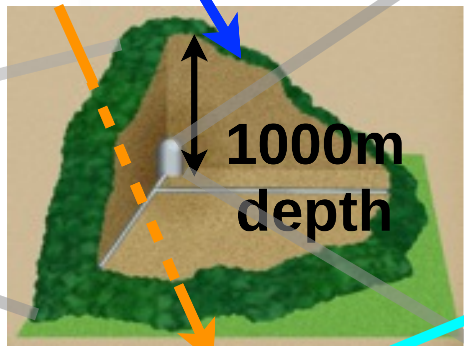
Sep. 2016 @Amsterdam

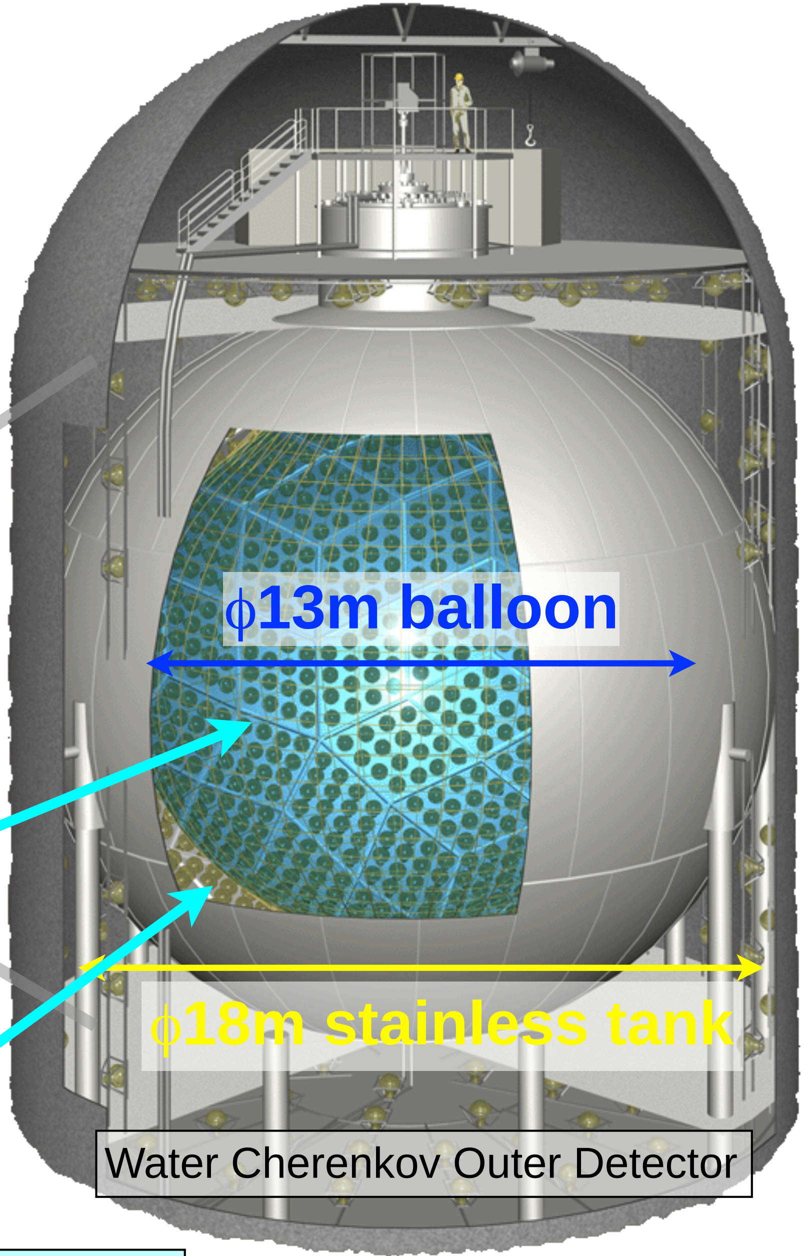
KamLAND Site and Detector

KamLAND

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







1,000t Liquid Scintillator

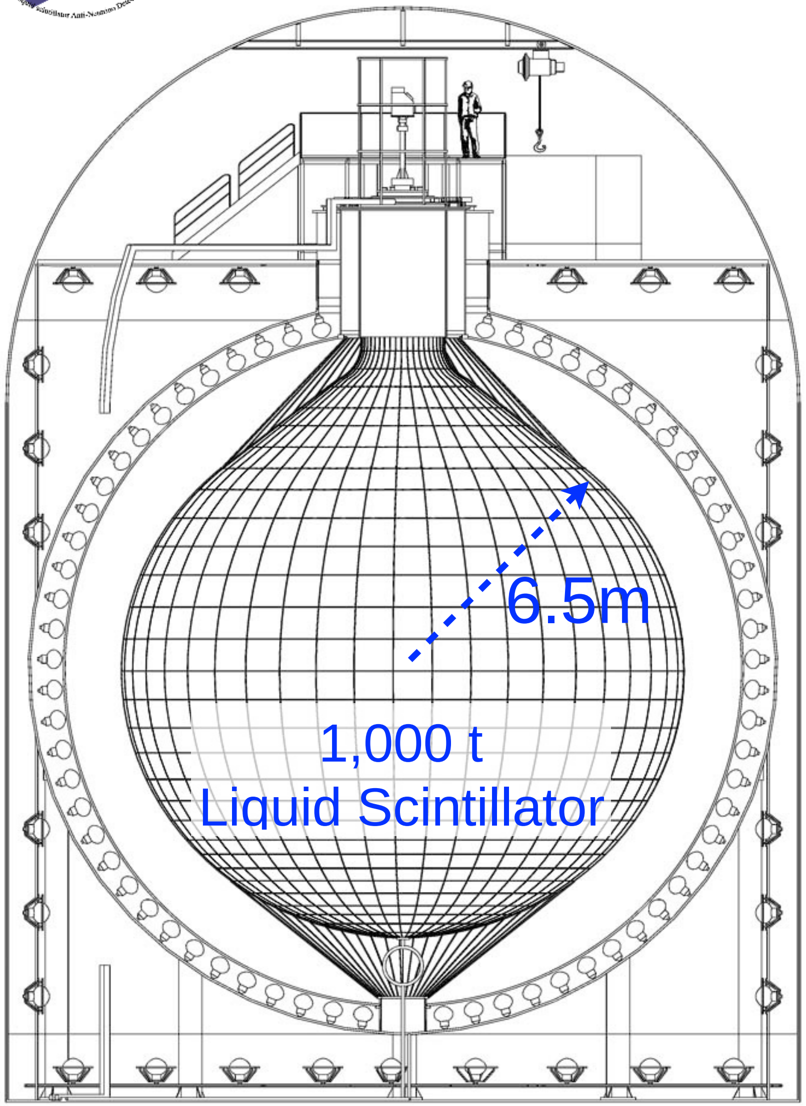
- extremely low impurity (^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)
- **world's largest LS detector!**

1,879 Photomultiplier Tubes

* Photo coverage 34%

KamLAND

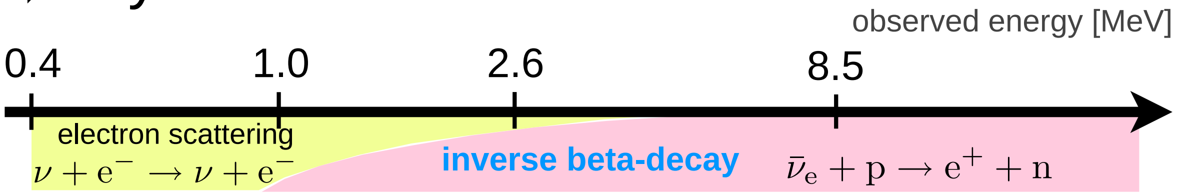
KamLAND
2000~

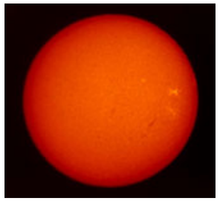


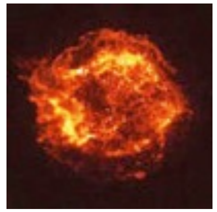
Detector Features

large volume & low backgrounds

Physics







solar neutrinos
PRC 84, 035804 (2011)
PRC 92, 055808 (2015)

geo neutrinos
Nature Vol. 436 (2005)
Nature Geoscience 4, 647-651 (2011)
PRD 88, 033001 (2013)

reactor neutrinos
PRL 100, 221803 (2008)
PRD 83, 052002 (2011)

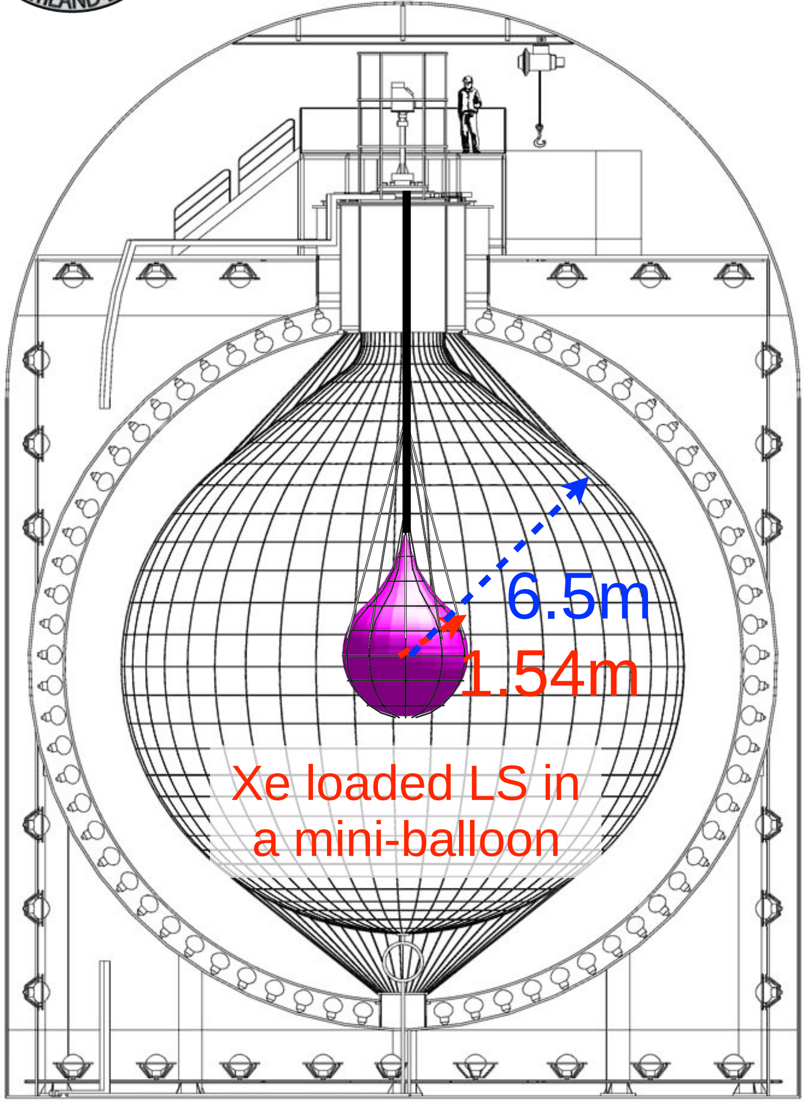
supernova neutrinos, etc.
PRL 92, 071301 (2004)
Astrophys. J. 745, 193 (2011)
Astrophys. J. 818, 91 (2016)

Different neutrino physics
in a wide energy range

KamLAND-Zen

2011~

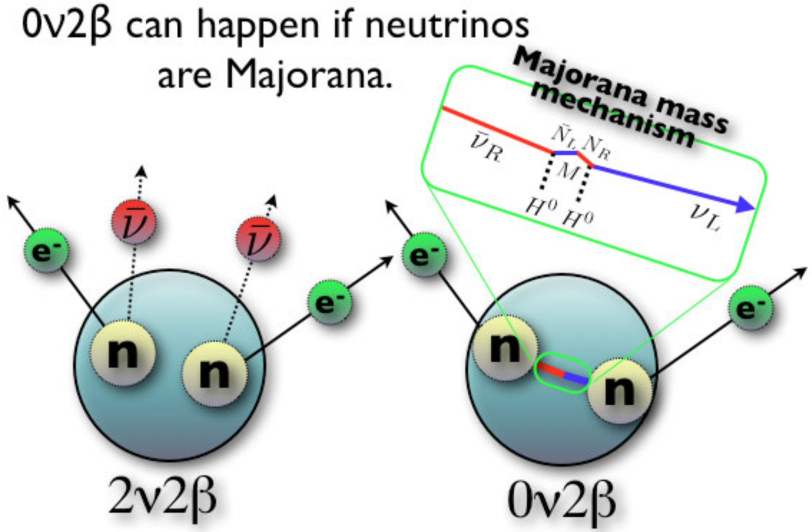
Zero Neutrino
double beta decay search



Detector Features

^{136}Xe loaded LS was installed in KamLAND
(344 kg 90% enriched ^{136}Xe installed so far)

Physics



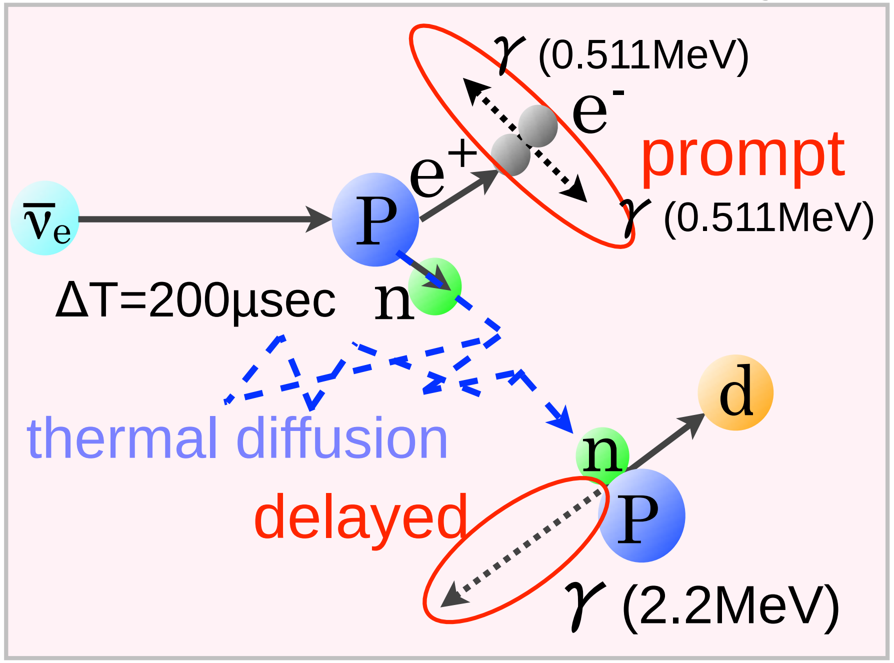
neutrino-less double beta decay

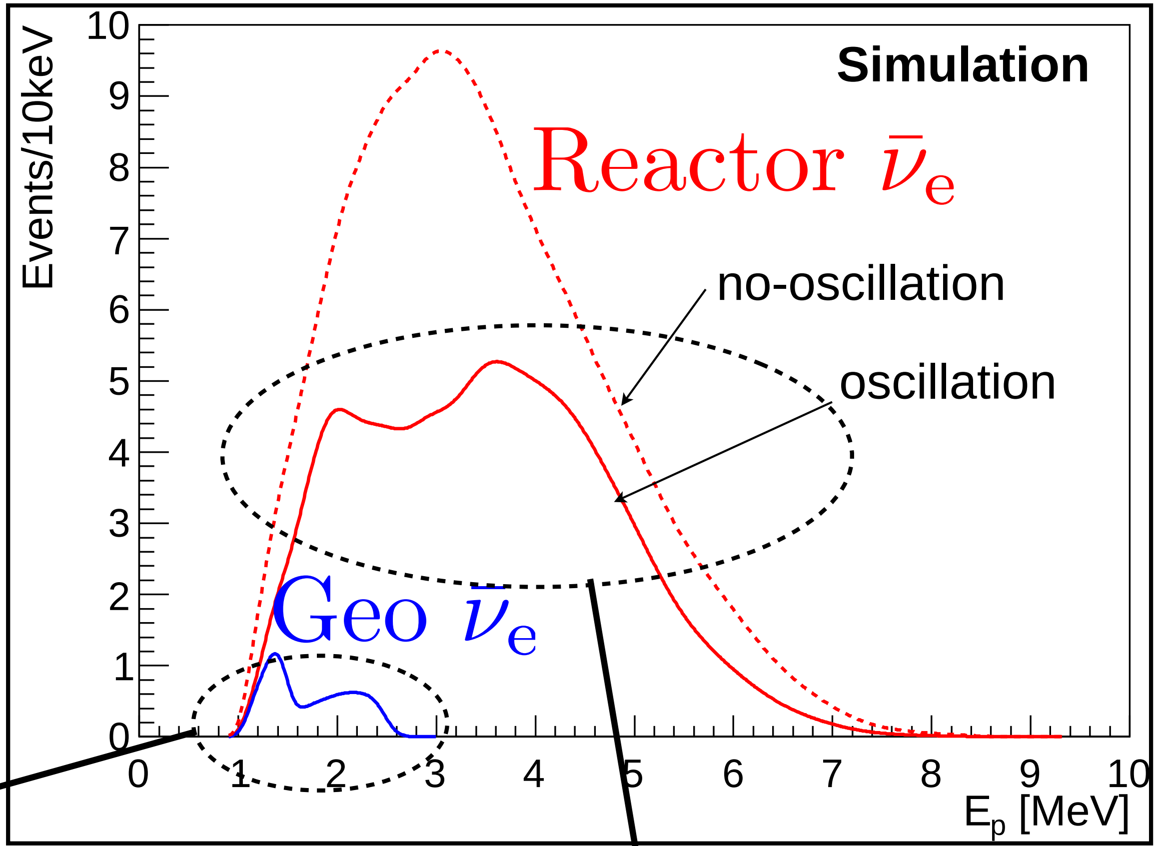
World best limit on neutrino effective mass

$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \mathrm{meV}$$ PRL 117, 082503 (2016)

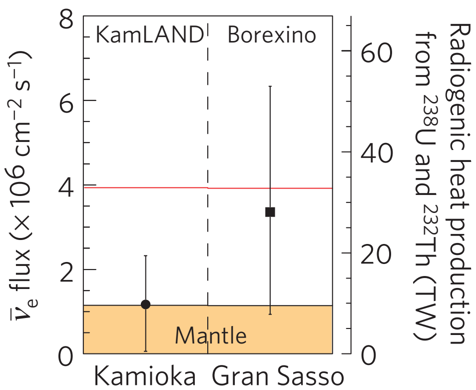
Continue to use LS volume outside of mini-balloon to measure anti-neutrino signals

inverse-beta decay



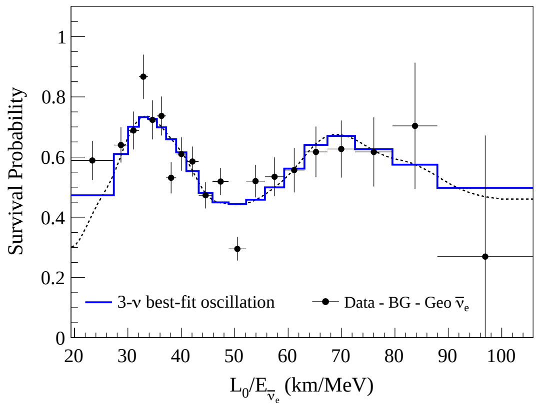


Geoneutrinos
: Neutrino Application



- Direct measurement of radiogenic heat contribution

Neutrino Property Study

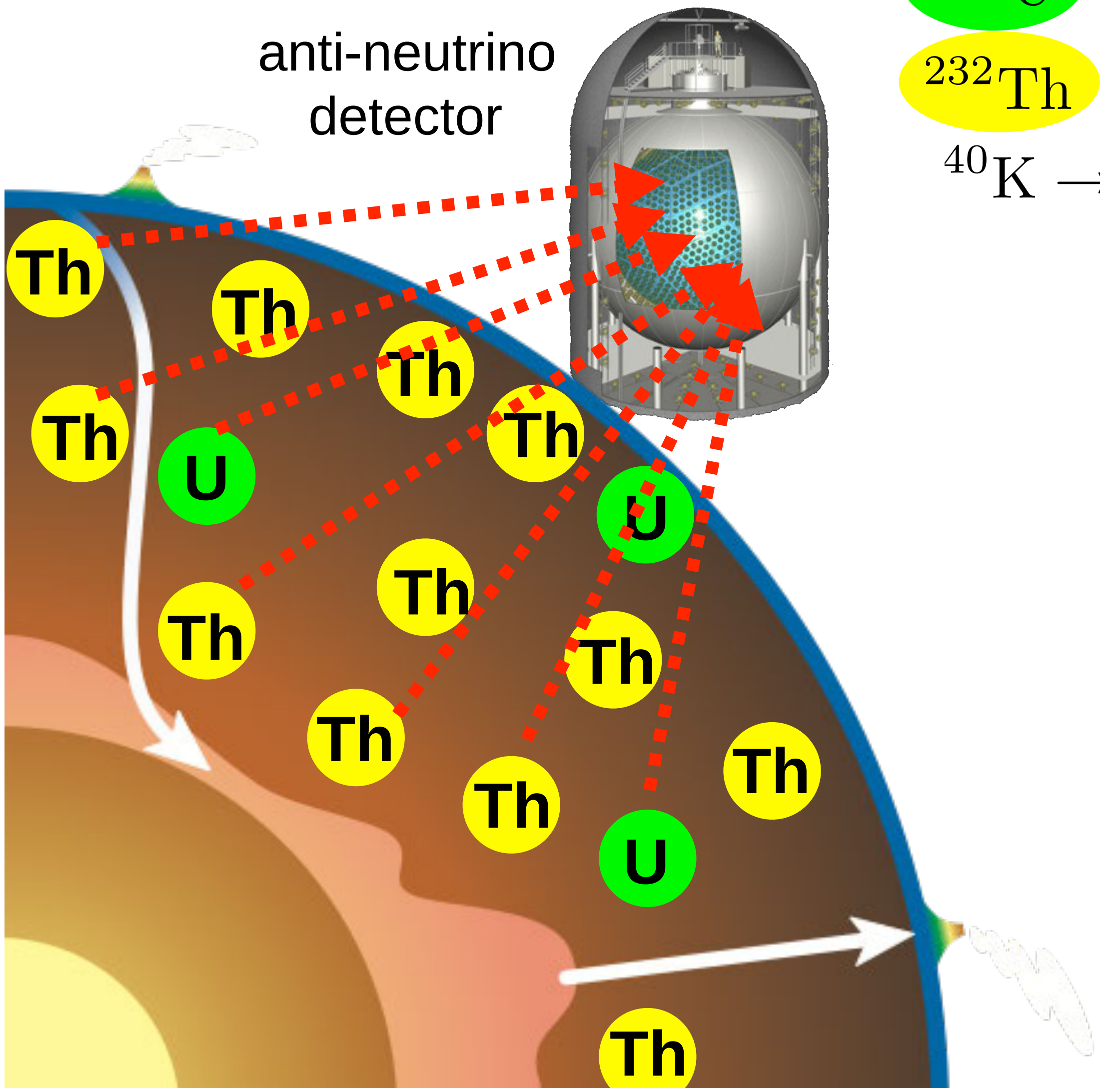


- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

Contents

Electron-antineutrino from natural radioactive decay

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



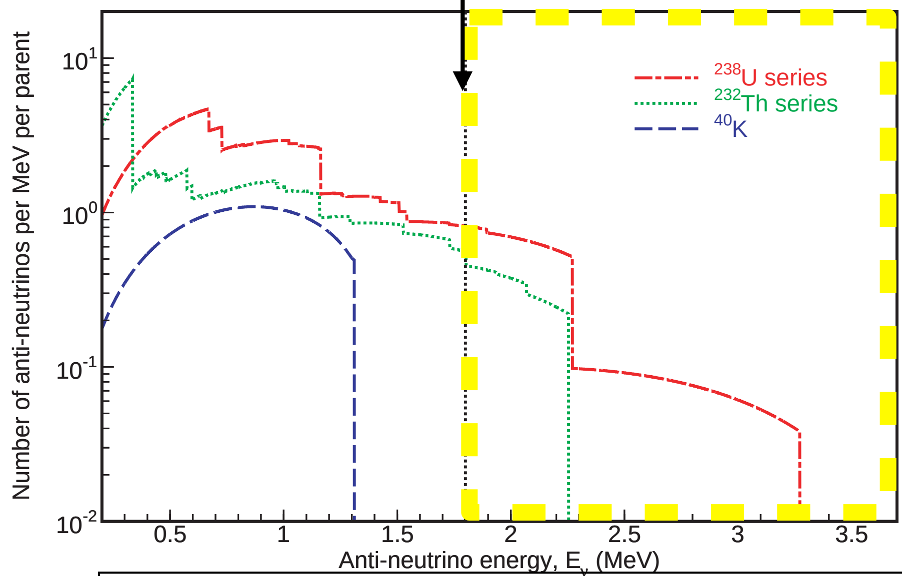
β-decay Geo-neutrinos

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

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

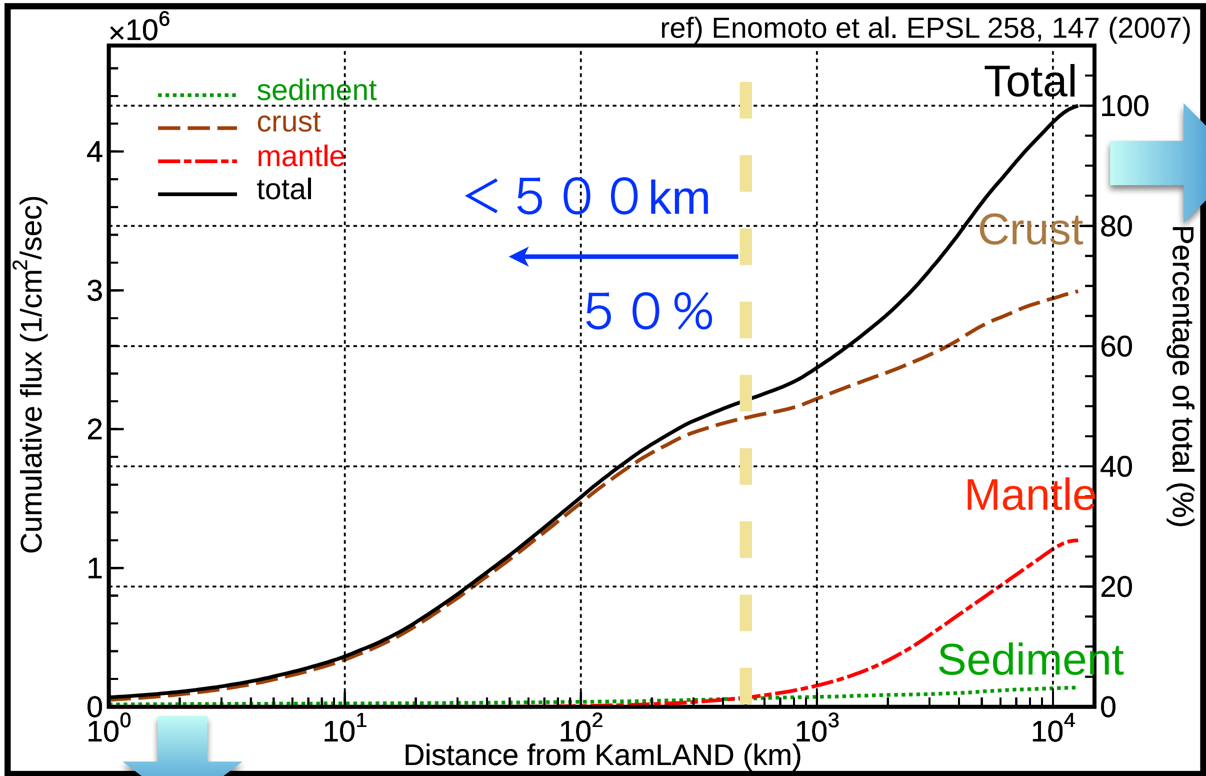
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}\ (89.28\%)$$

Energy threshold, 1.8 MeV

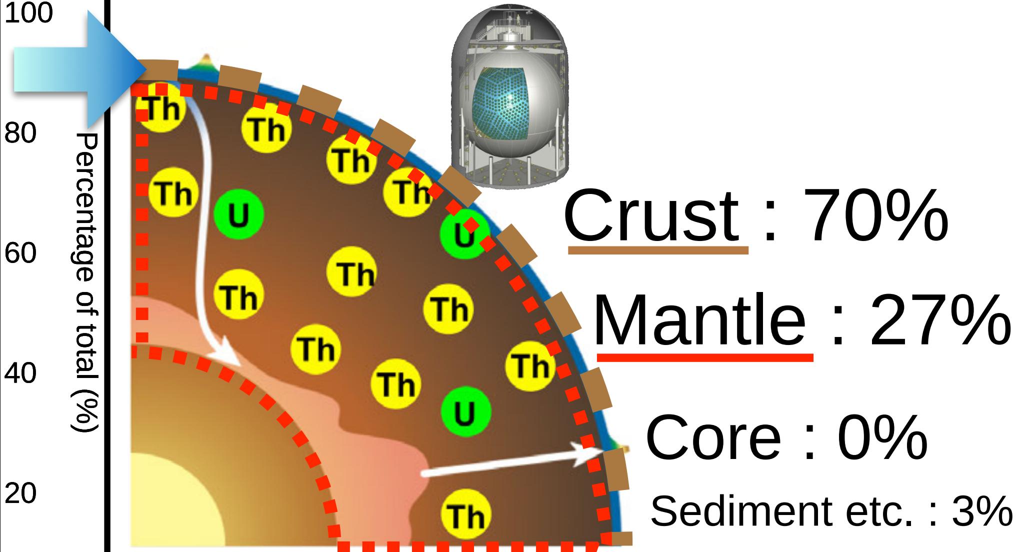


Only geo-neutrinos from U and Th are detectable

Geo-neutrino Flux at Kamioka



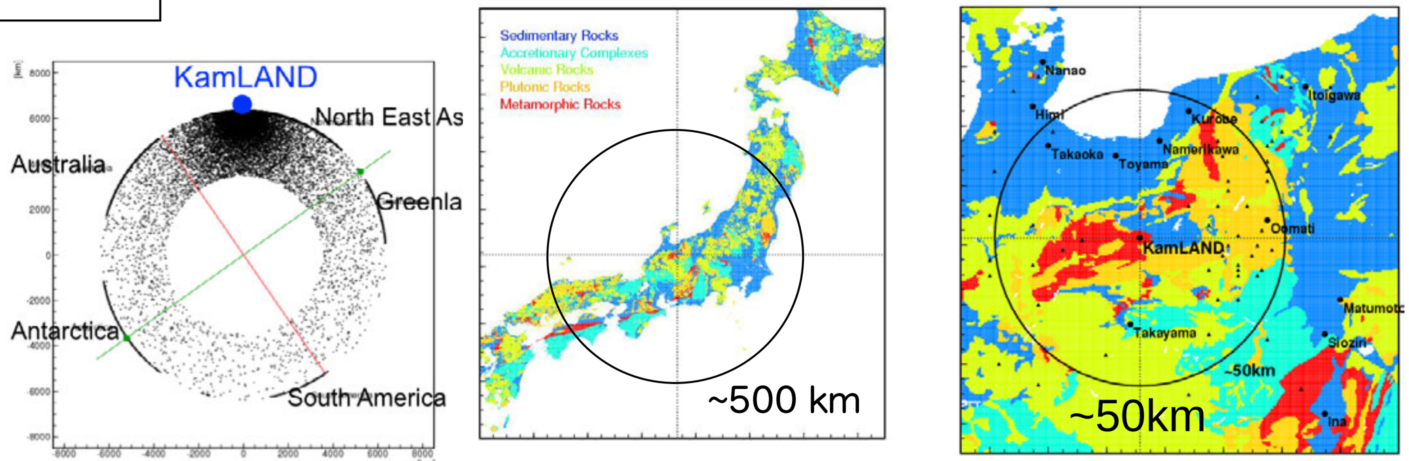
Contributions from each part



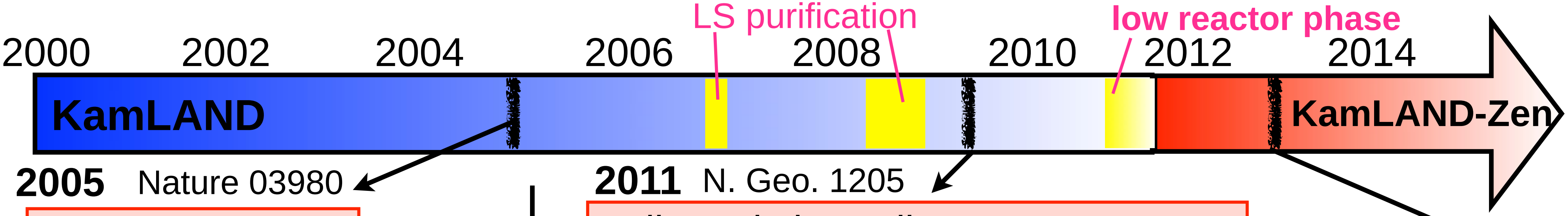
Contributions from each area

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

Important to understand Japanese geology

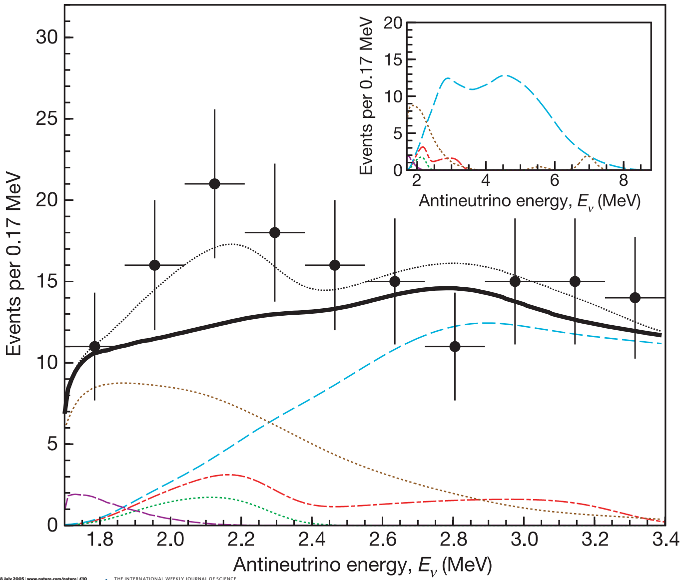


Geo-neutrino Measurements with KamLAND



2005 Nature 03980

geo-neutrino first measurement



749 days

0.71×10^{32} proton-year

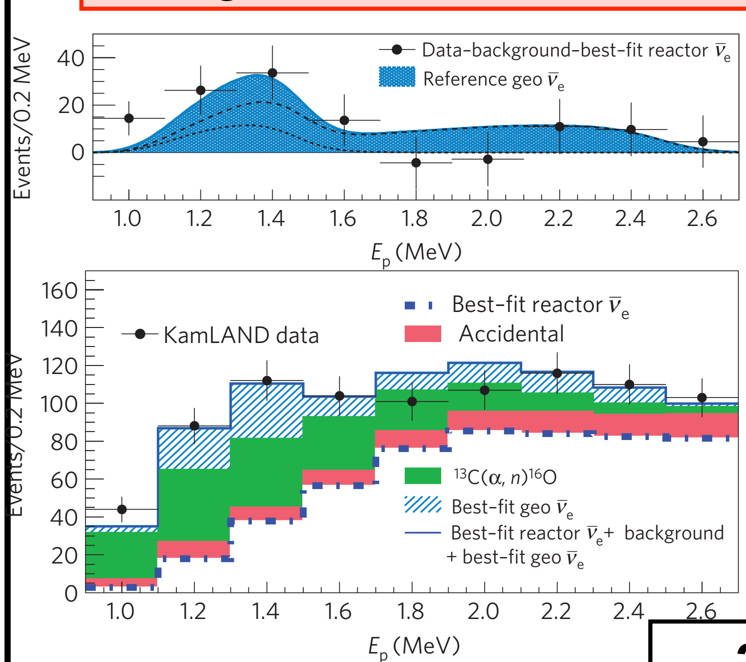
geo-nu event

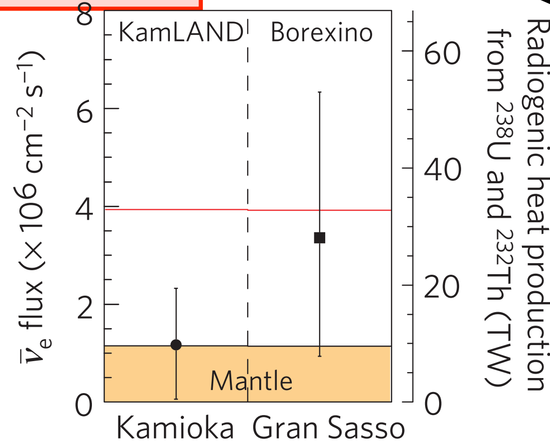
$$28.0^{+15.6}_{-14.6}\ \mathrm{ev}$$

(56% error)

2011 N. Geo. 1205

radiogenic heat direct measurement





radiogenic heat

21±9 TW

2135 days

3.49×10^{32} proton-year

geo-nu event

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

(27% error)

2013 PRD 88, 03301 (2013)

include low reactor phase data

2991 days

4.90×10^{32} proton-year

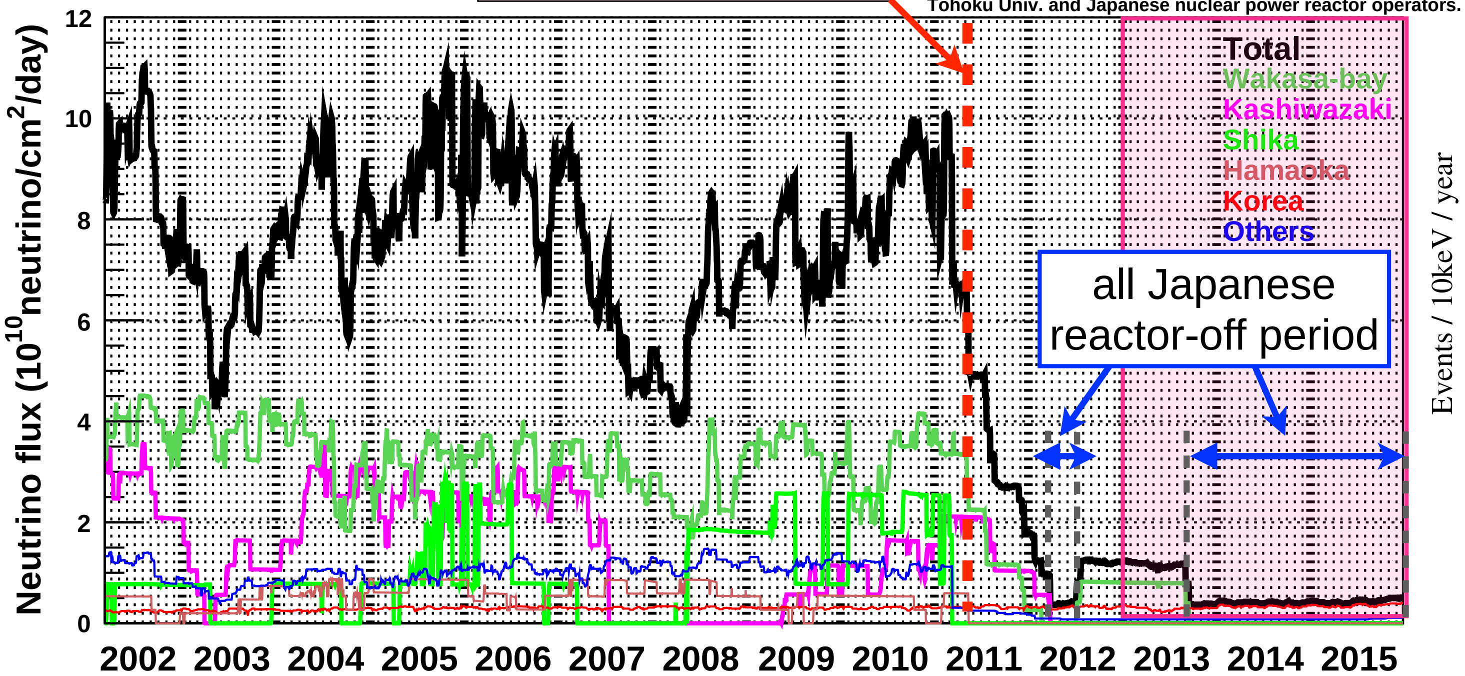
geo-nu event

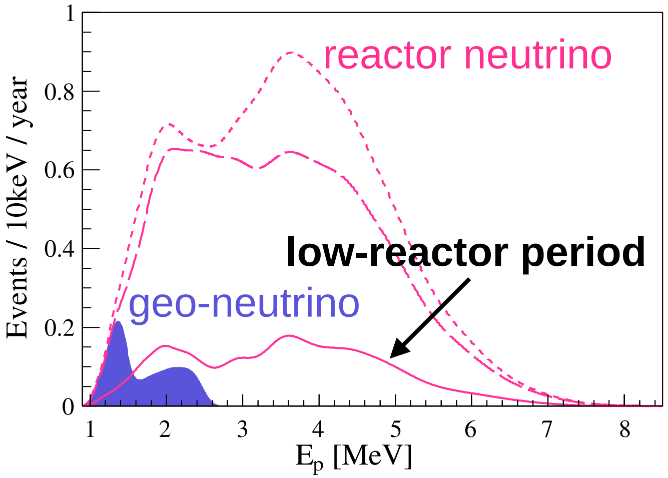
$$116^{+28}_{-27}\ \mathrm{ev}$$ (24% error)

Contents

Current Data-set

Reactor Neutrino Flux @Kamioka





Reactor neutrino background is decreased significantly.

PRD 88, 033001 (2013)

Preliminary

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

- 1.3 times of 2013 data-set

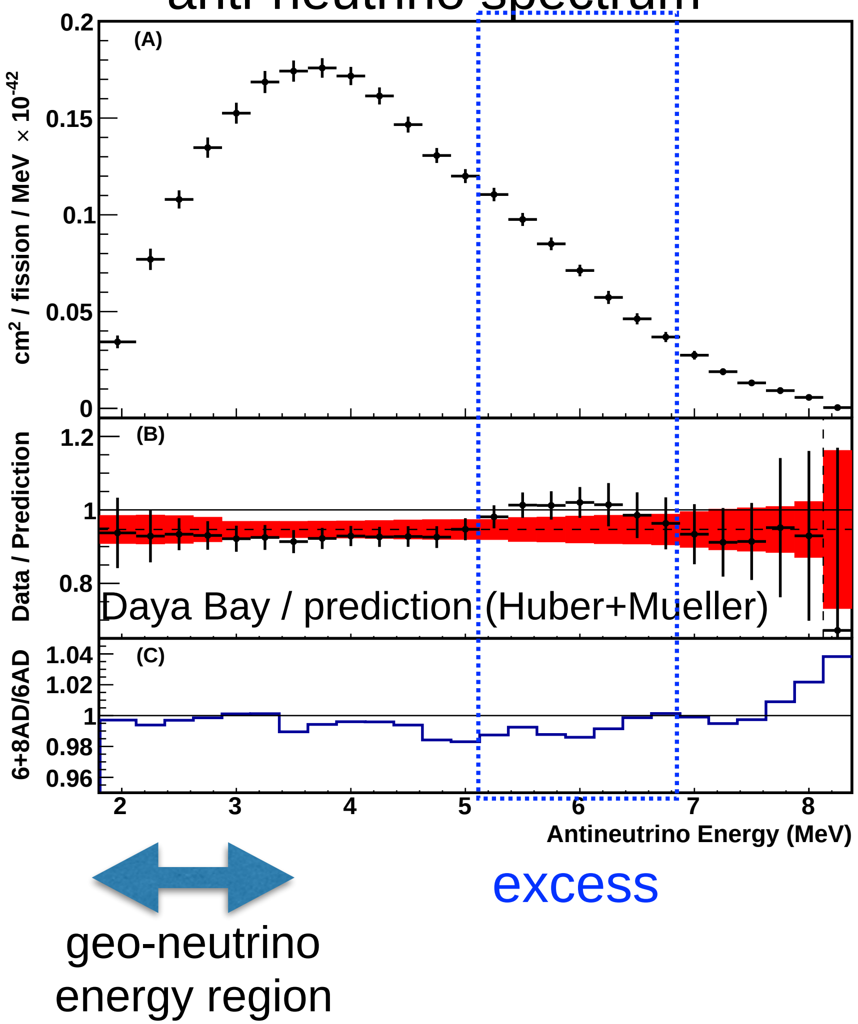
advantages {
- low-reactor operation period : **~3.5 years** livetime
- **all Japanese reactor-off period : ~2.0 years** livetime

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

Reactor Neutrino Spectrum

(Daya Bay, arXiv:1607.05378v1)

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

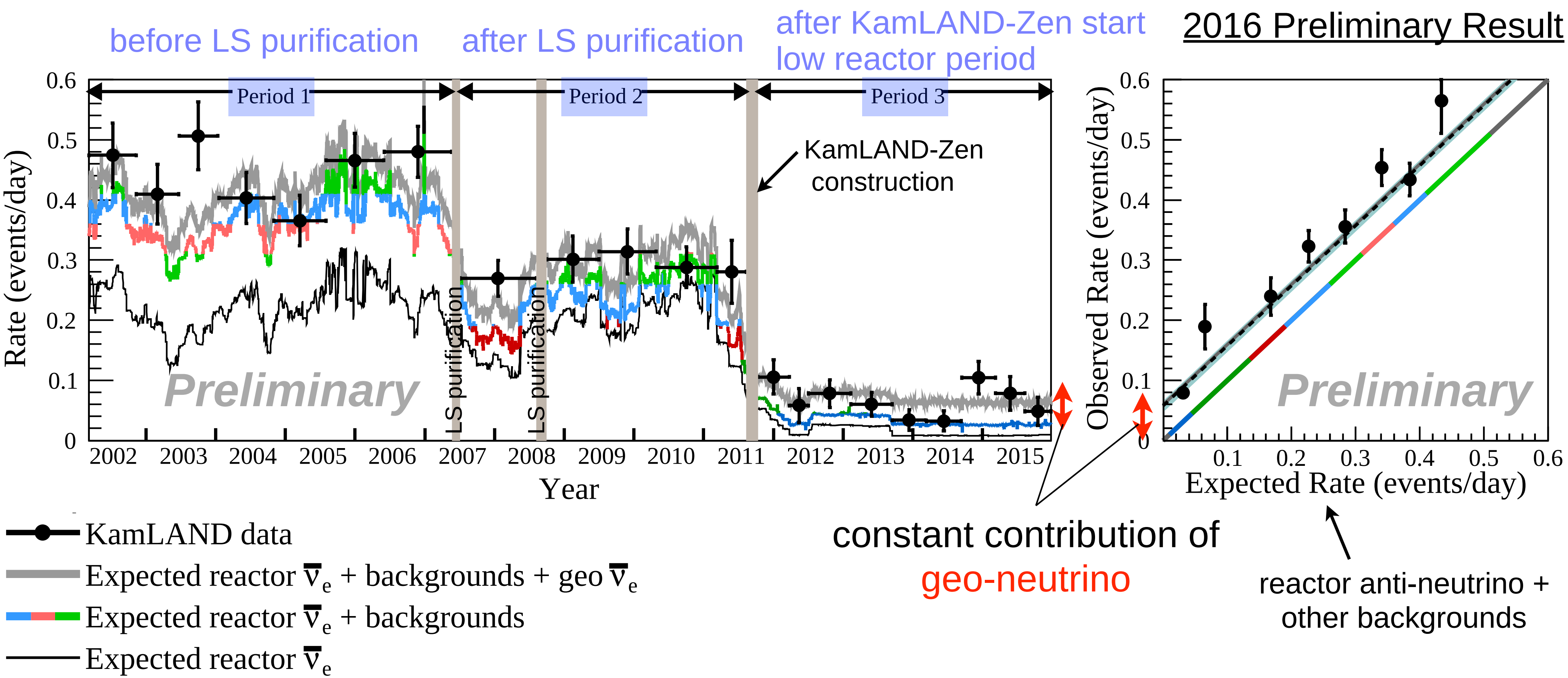
  2013 paper : Huber + Mueller & Bugey-4 normalisation

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

  σ_f (cm^2/fission) $= (5.92\pm0.12)\times10^{-43}$ (uncertainty : 2.03%)

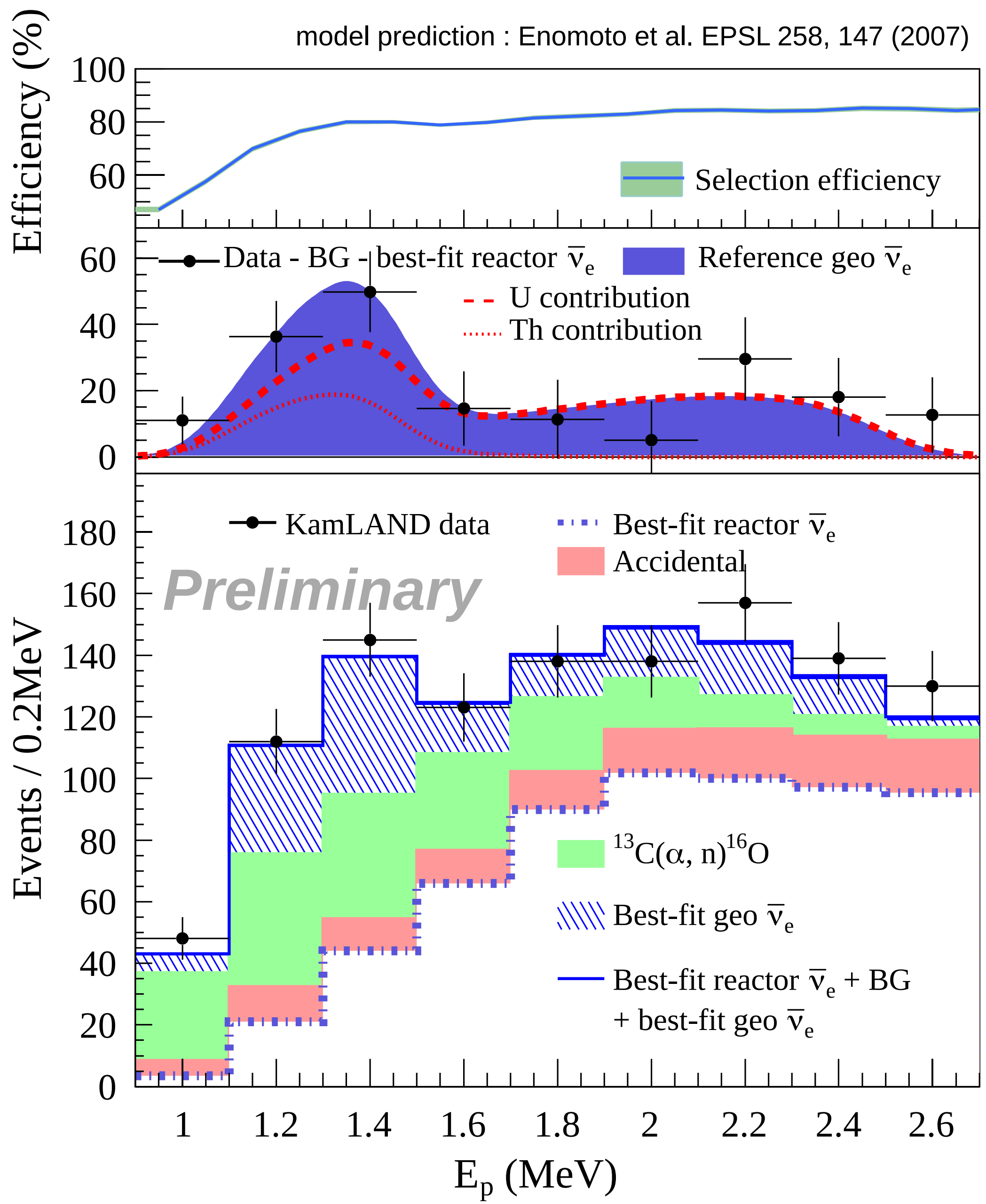
- We confirmed that :
  - ☑ 4-6 MeV excess has no impact on the geo-neutrino results.
  - ☑ effect of reactor spectrum uncertainty is much smaller than the statistical uncertainty of geo-neutrino events.

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

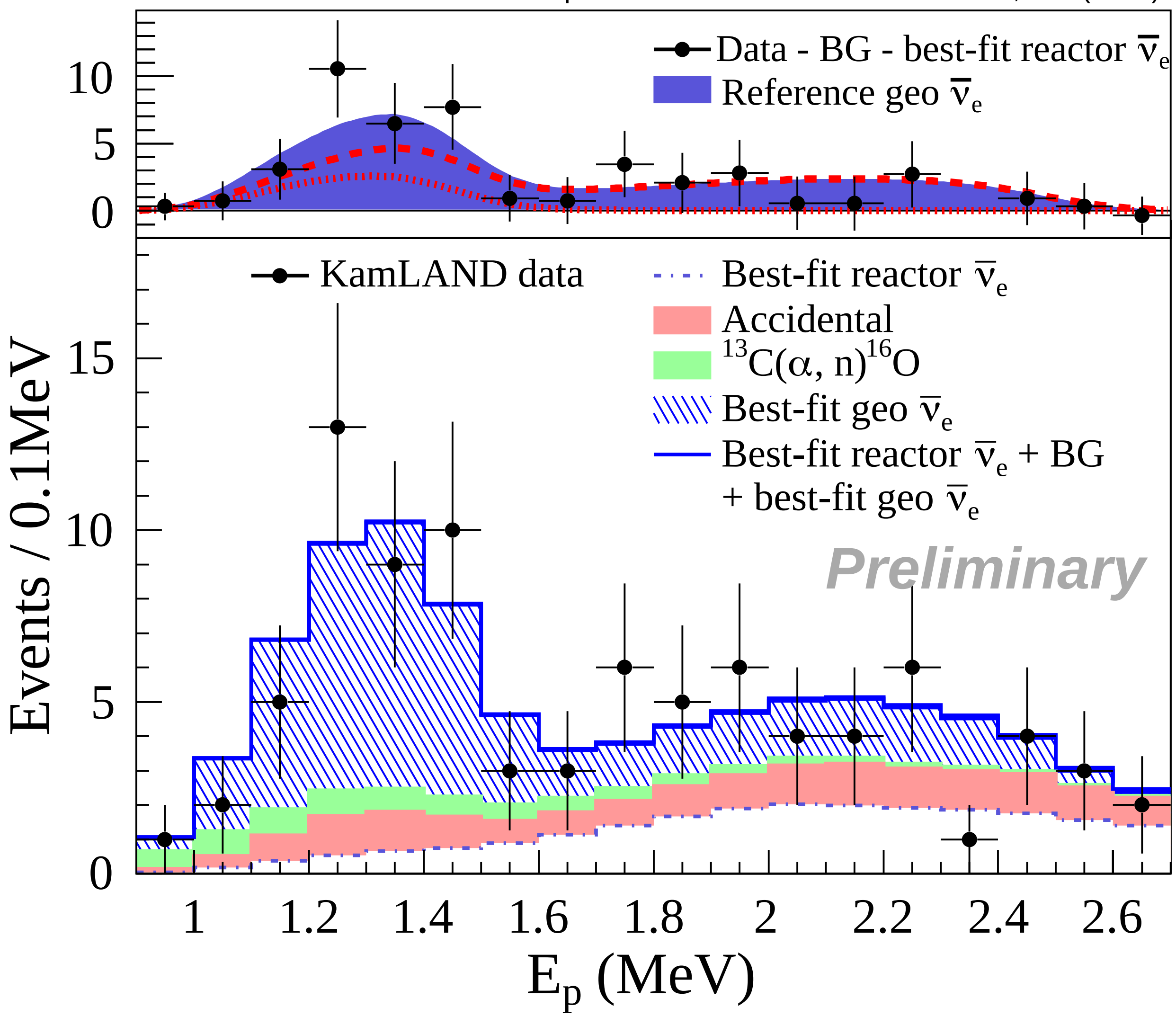
Background Summary

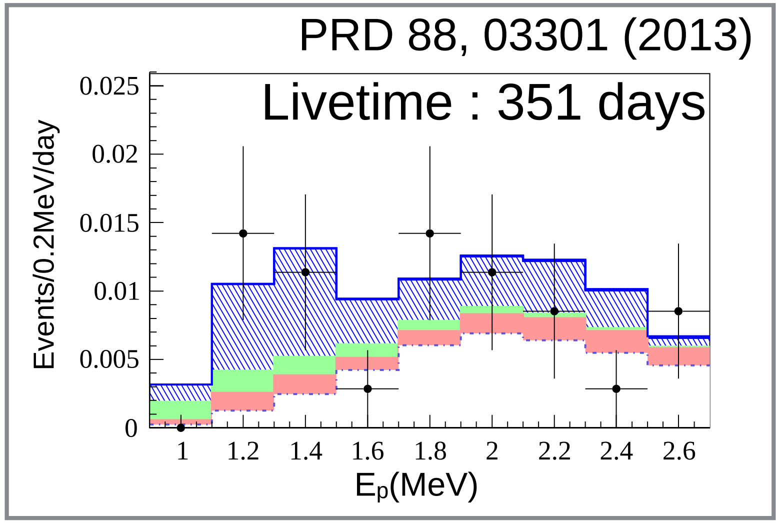
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

Energy Spectrum, Period 3 (0.9-2.6 MeV)

Livetime : 1259.8 days 2016 Preliminary Result

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



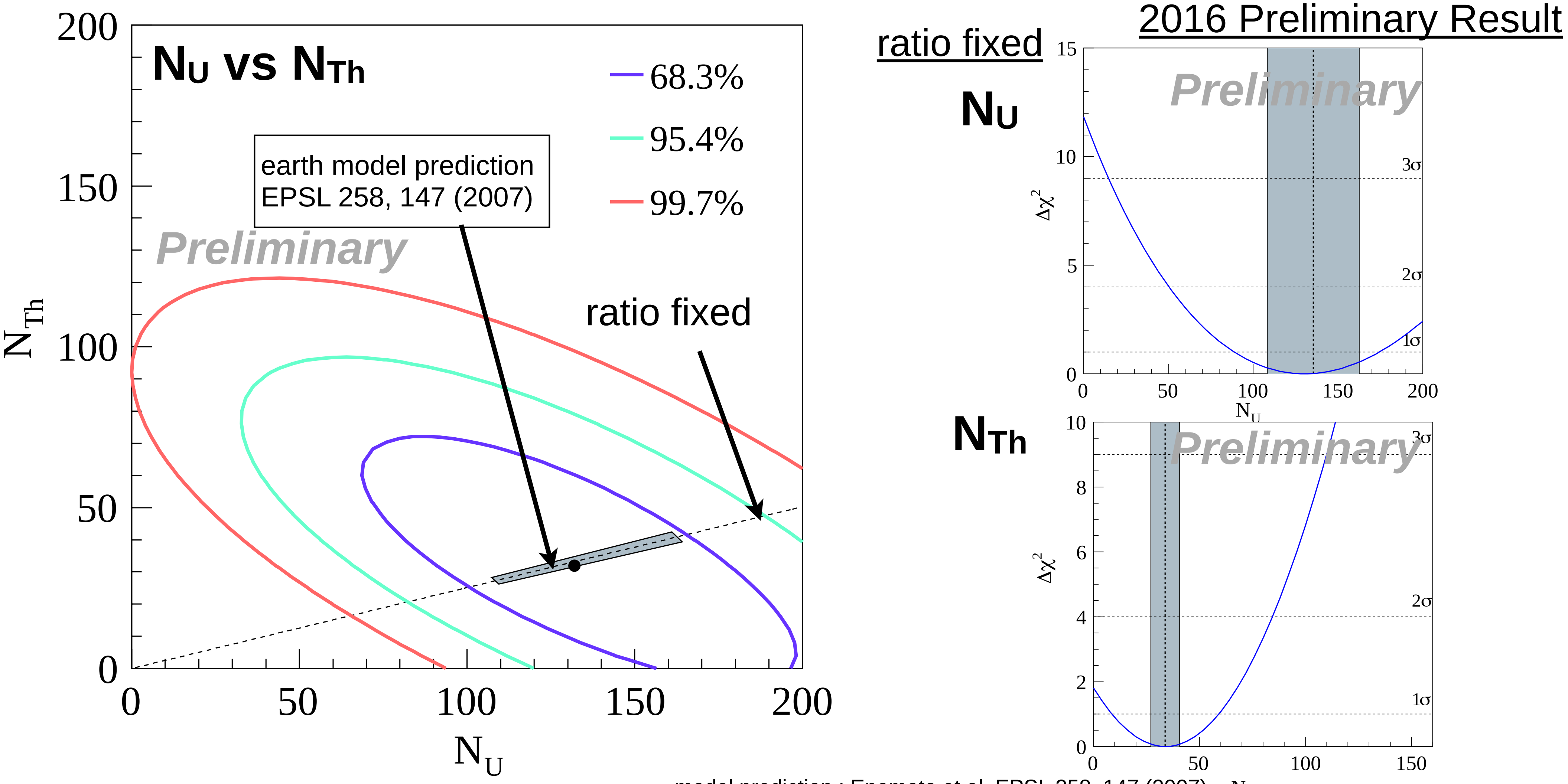


☑ We measured clear distribution of geo-neutrino events.

best-fit : Period 3 analysis

Rate + Shape + Time Analysis (1)

2016 Preliminary Result



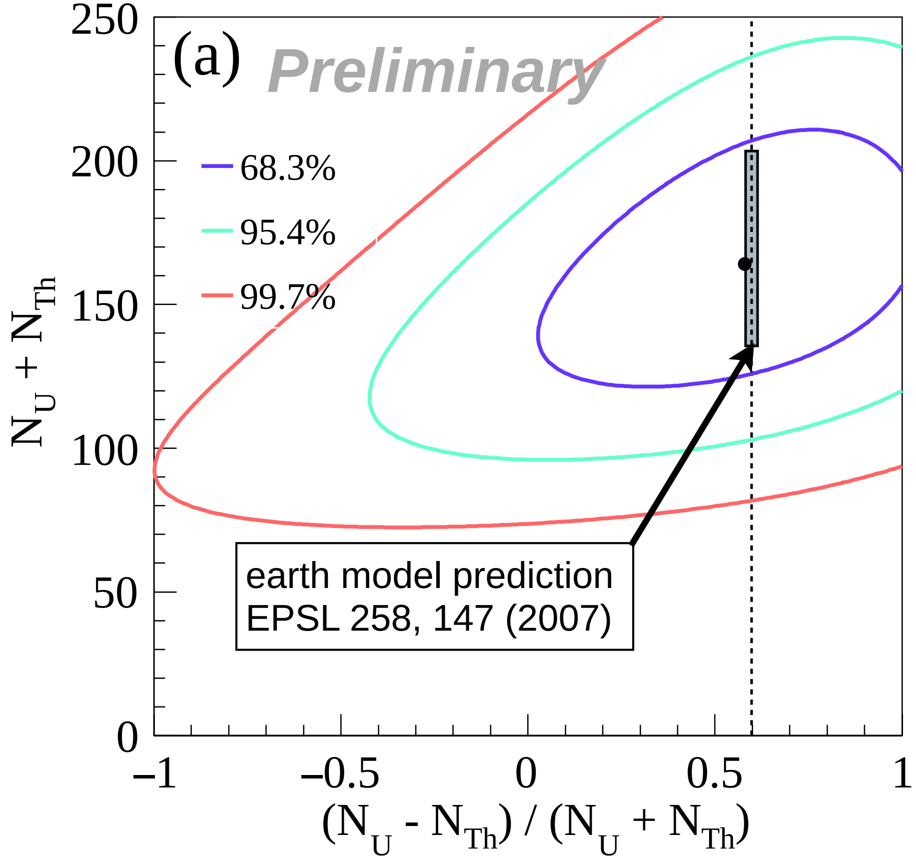
model prediction : Enomoto et al. EPSL 258, 147 (2007)

	[event]	[TNU]	Flux [$\times 10^5$ cm^{-2}s^{-1}] best-fit	Flux [$\times 10^5$ cm^{-2}s^{-1}] model	0 signal rejection
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**

ratio fixed

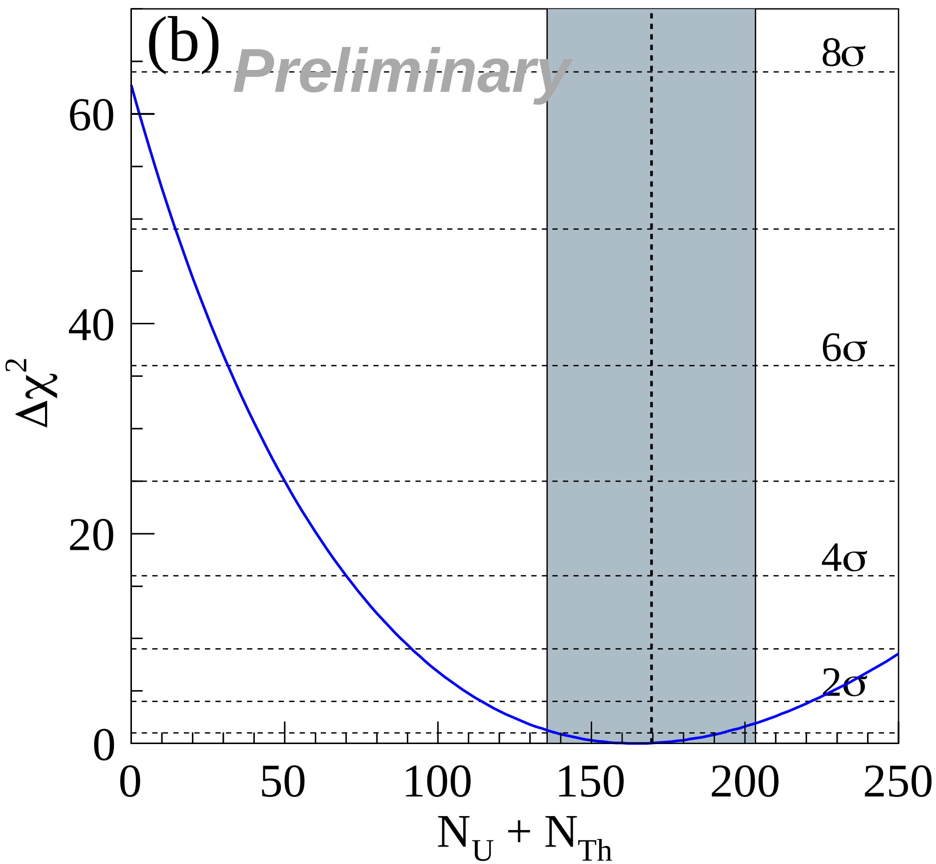
Rate + Shape + Time Analysis (2)

$N_U + N_{Th}$



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 (1)

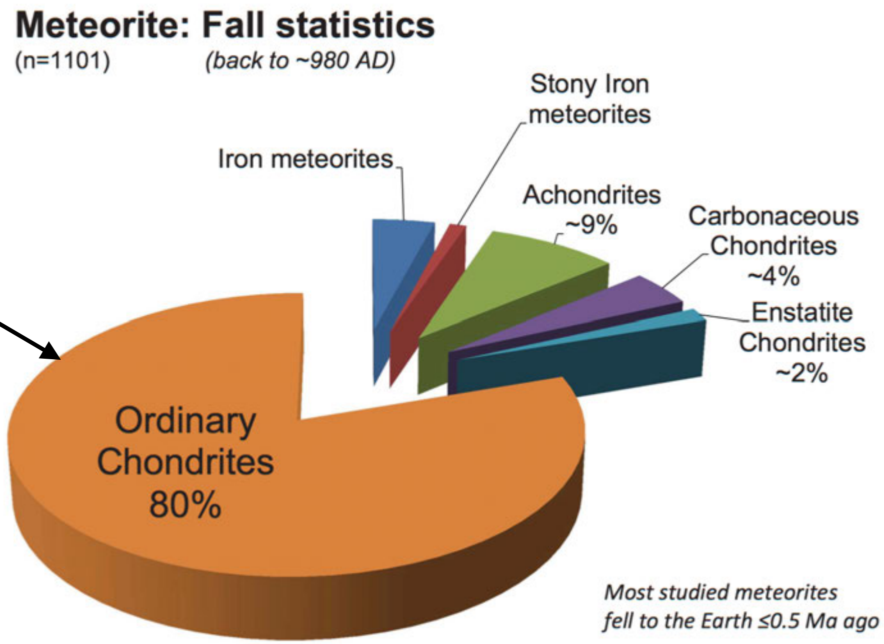
- According to geochemical studies, ^{232}Th is more abundant than ^{238}U. Mass ratio (Th/U) in bulk silicate Earth is expected to be **around 3.9.**

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.

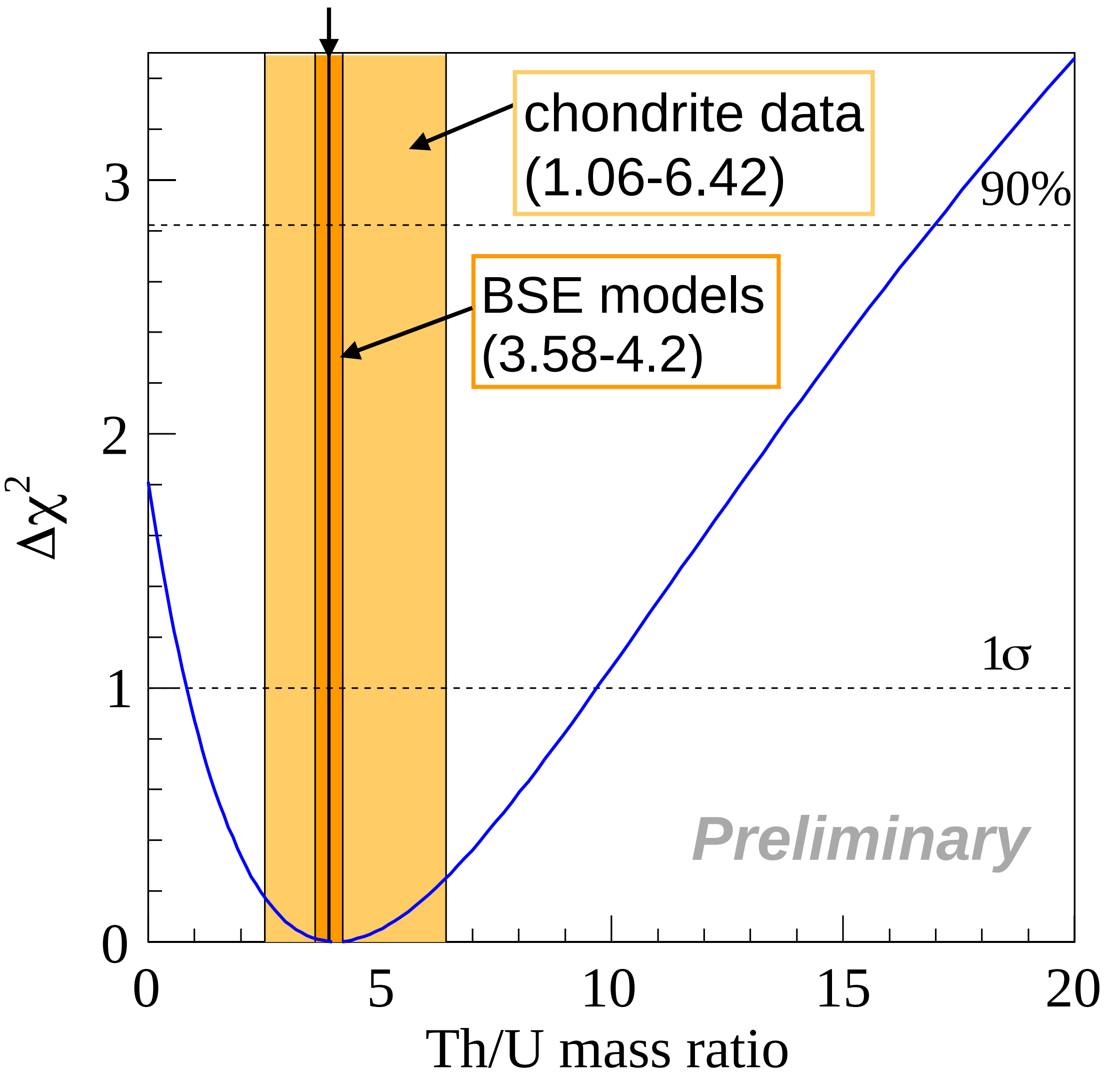


- Geo-neutrino observed rate can be converted to amount of Th & U assuming homogeneous distribution. **Independent & direct measurement of entire Earth**

slide from McDonough, 2015, in Ehime

Th/U Mass Ratio (2)

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

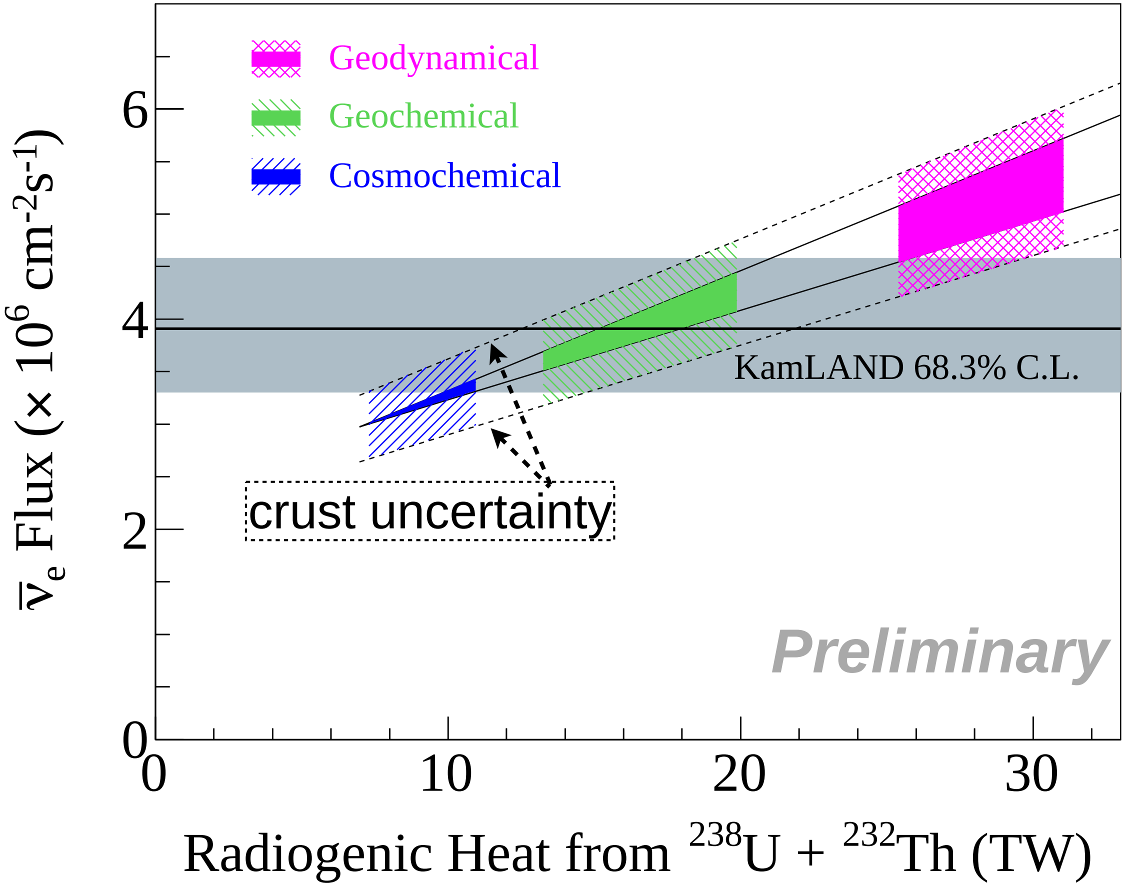
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

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

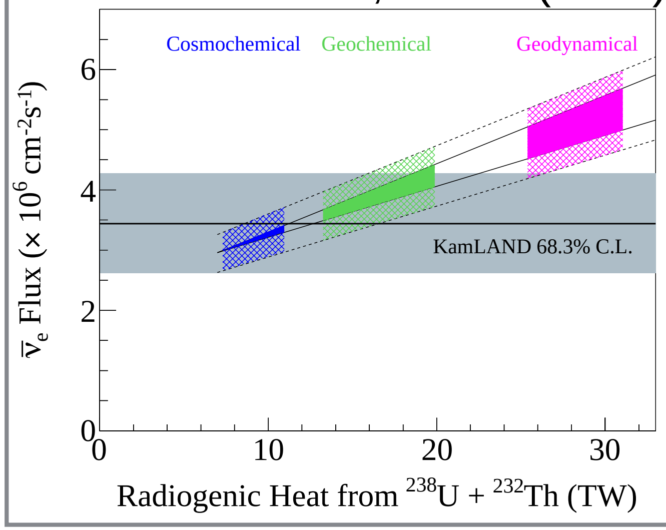
Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

Earth Model Comparison

2016 Preliminary Result



PRD 88, 03301 (2013)



[BSE composition models]

Geodynamical

based on balancing mantle viscosity and heat dissipation

Geochemical

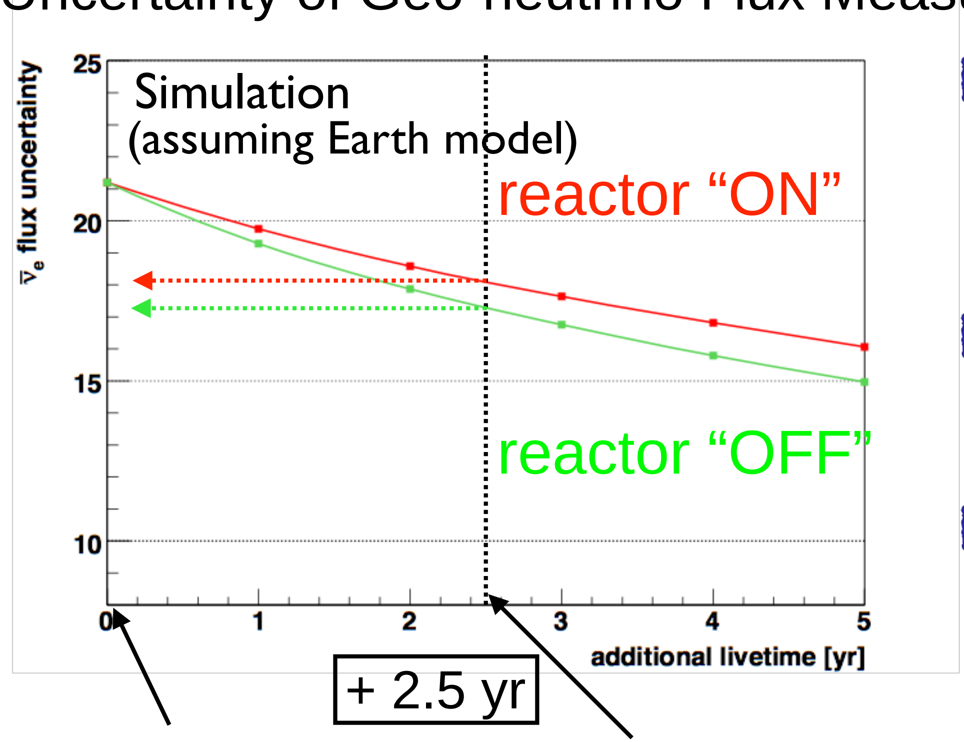
based on mantle samples compared with chondrites

Cosmochemical

based on isotope constraints and chondritic models

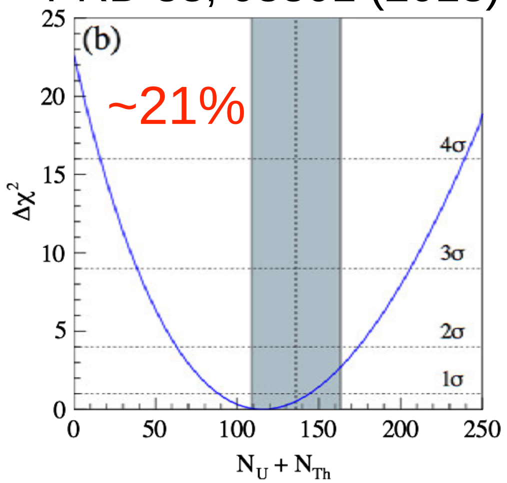
Future Prospect

Uncertainty of Geo-neutrino Flux Measurement

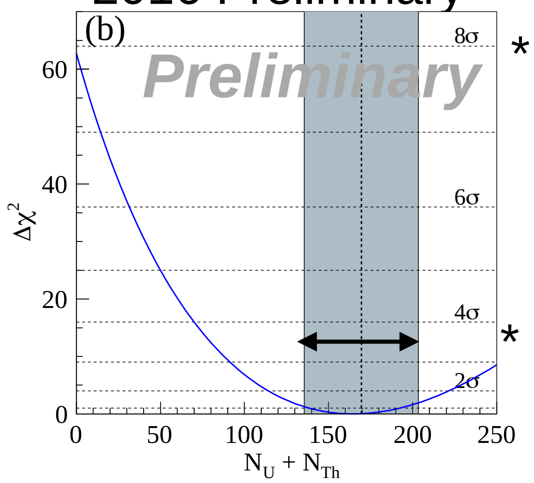


- ☑ Uncertainty of geo-neutrino flux measurement is decreased at the <u>same level of our expectation</u>.
- ☑ Measurement uncertainty gets close to uncertainty of Earth model prediction.
- ☑ It is important to improve accuracy of Earth model prediction, especially crust modelling.

PRD 88, 03301 (2013)



2016 Preliminary



* best fit with ± 1σ
$3.9^{+0.7}_{-0.6} \times 10^6$ /cm²/s : ~18%

* uncertainty of Earth model prediction : 20%

Summary

- The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.

- **Preliminary results are presented.**
  - Low-reactor operation period : ~3.5 years (33% of total livetime), **clear energy spectrum of geo-neutrino**
  - geo-neutrino event measurement with **17% uncertainty** (164^{+28}_{-25} ev). It is consistent with our expectation.
  - geoscience discussion
    - Th/U mass ratio : $\mathbf{4.1^{+5.5}_{-3.3}}$, consistent with chondrite data and BSE models
    - Observed flux : consistent with models, but started to disfavour cosmochemical model

- **Measurement uncertainty gets close to the uncertainty of Earth model prediction.**

- **Next target :**
  - Estimation of geo-neutrino contribution from mantle
  - Better understanding of crust model