KamLAND

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

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KamLAND Collaboration

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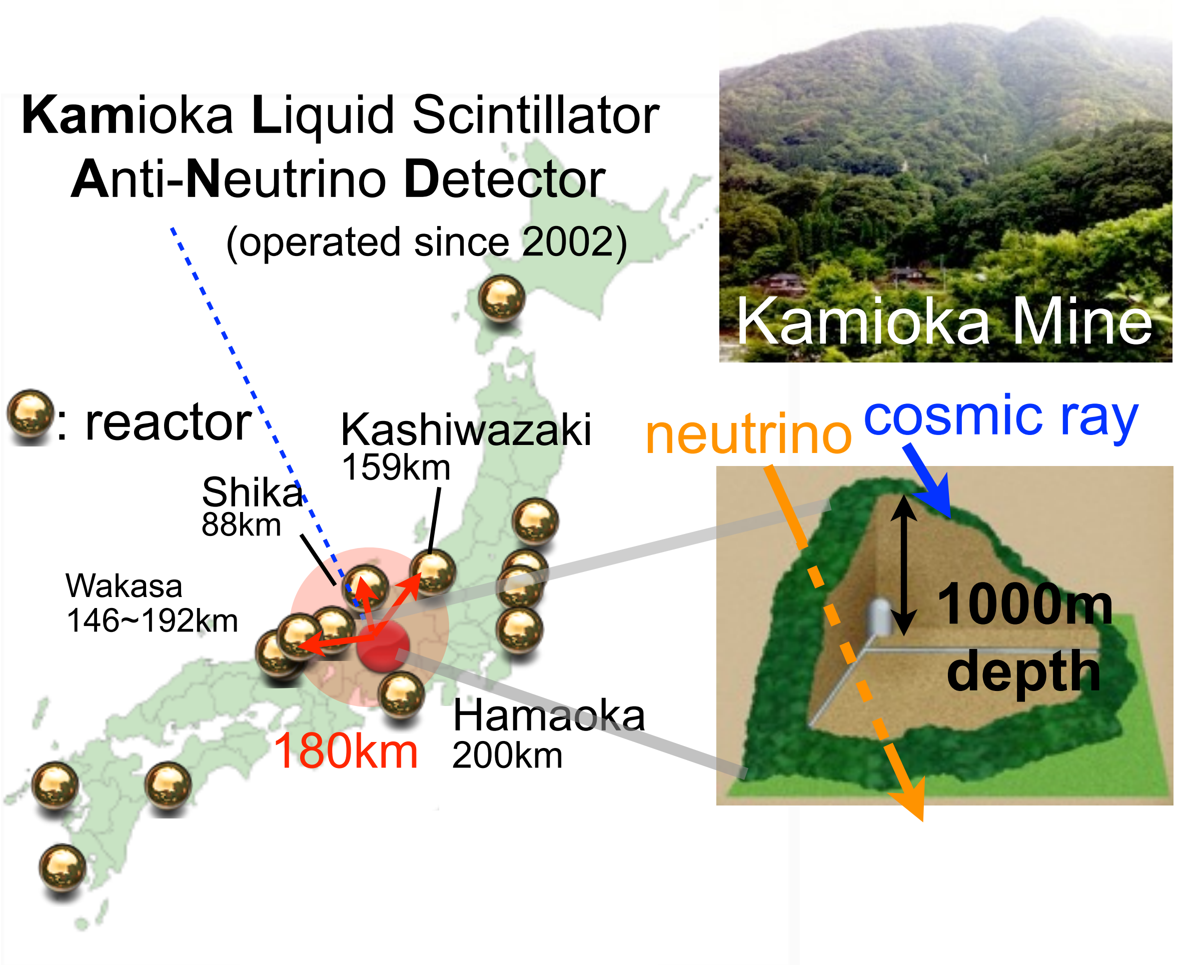
The KamLAND Collaboration

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

KamLAND

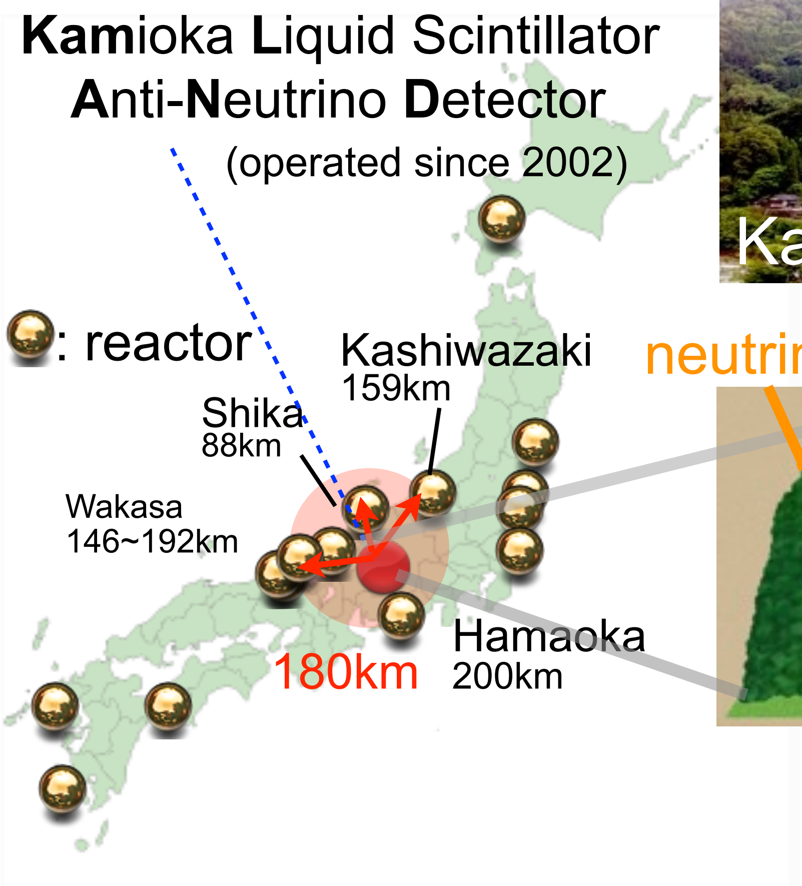
Kamioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector (operated since 2002)

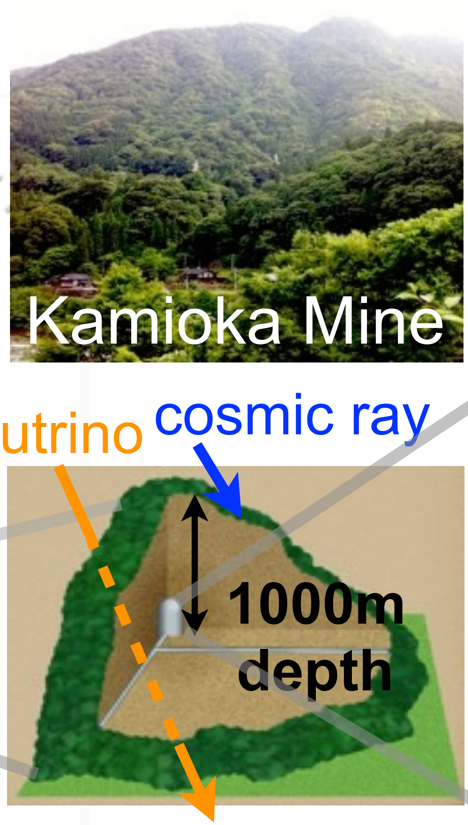


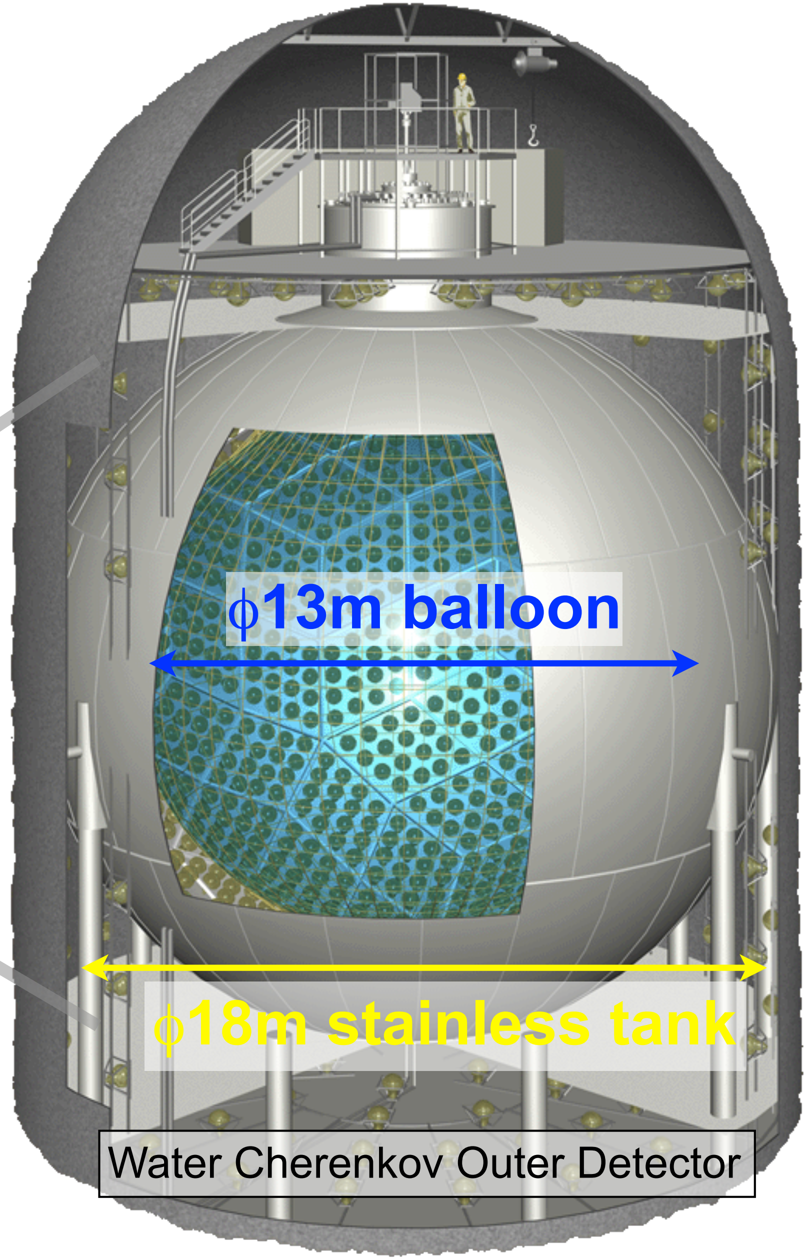
KamLAND Site and Detector

KamLAND

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







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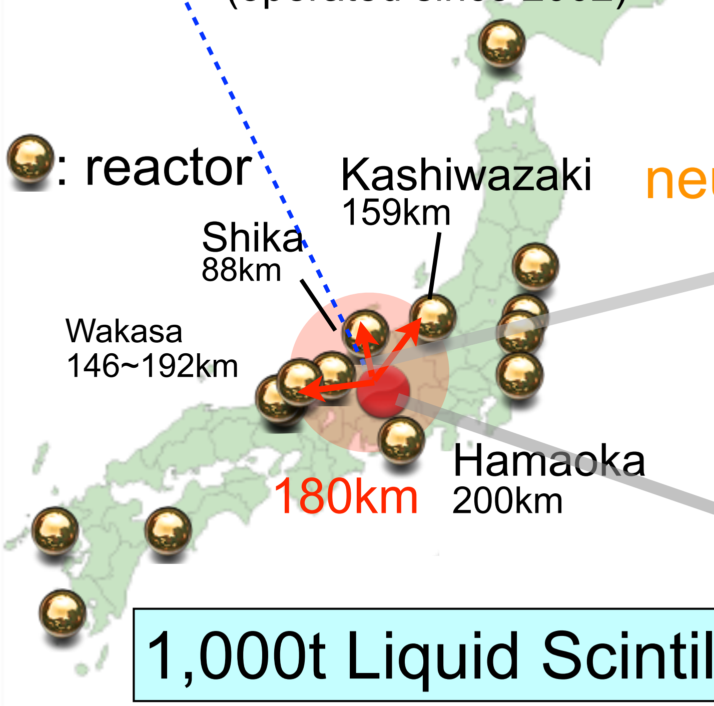

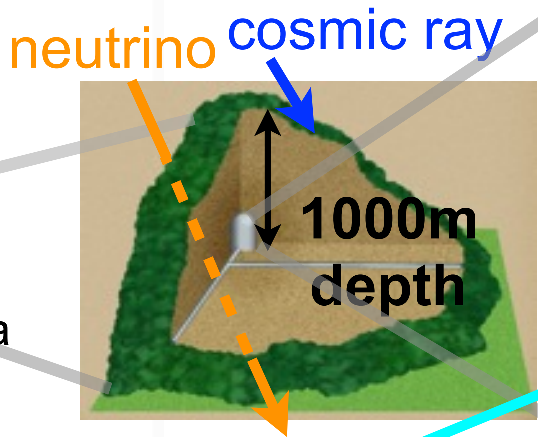

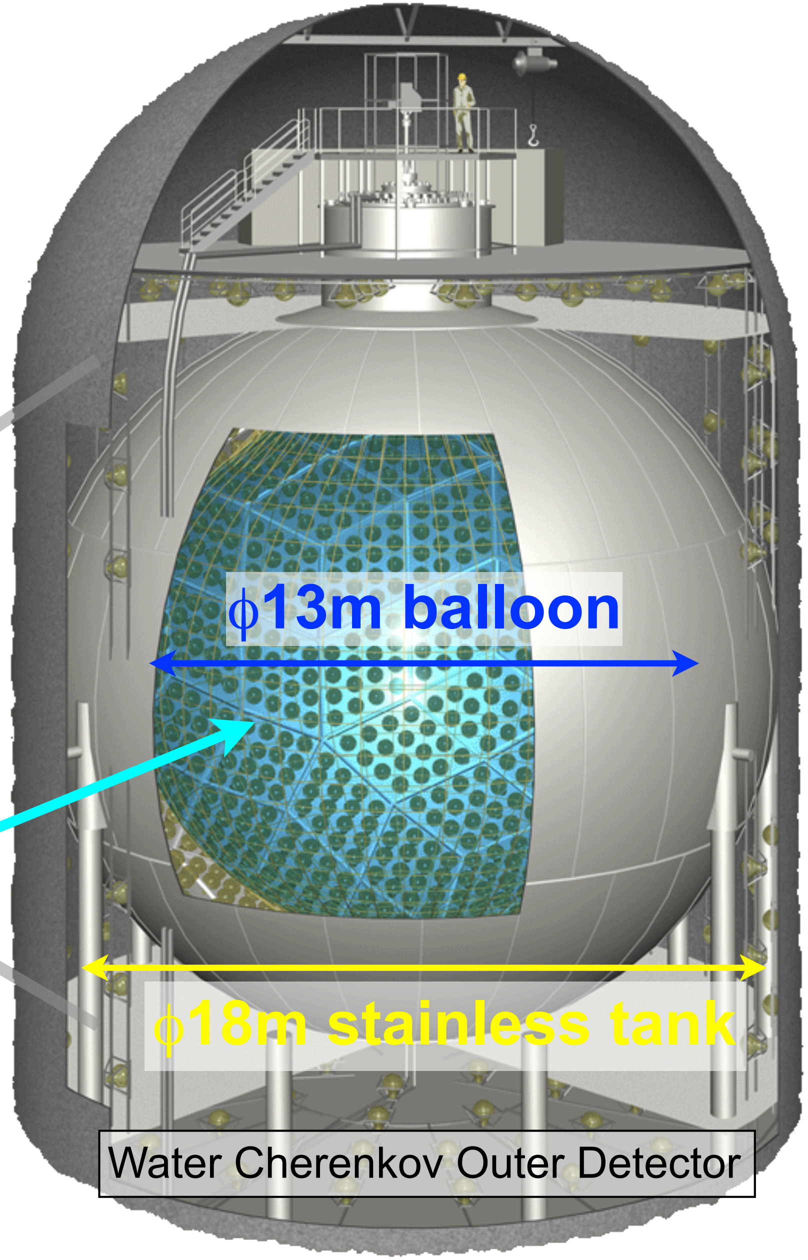

1,000t Liquid Scintillator

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

KamLAND

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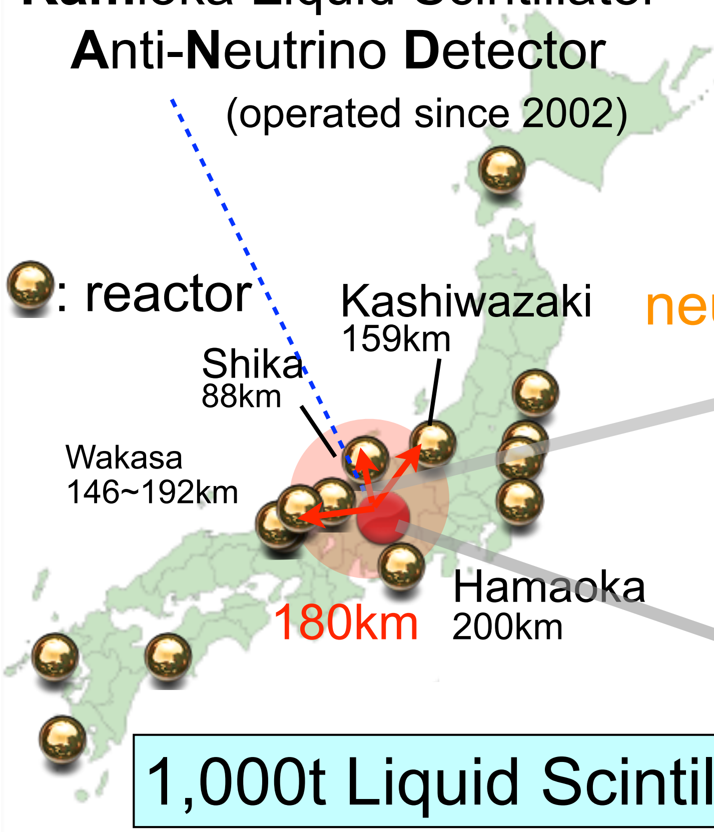
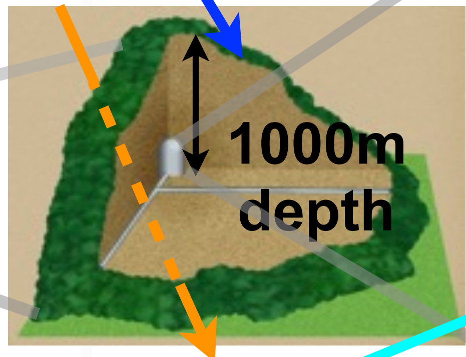
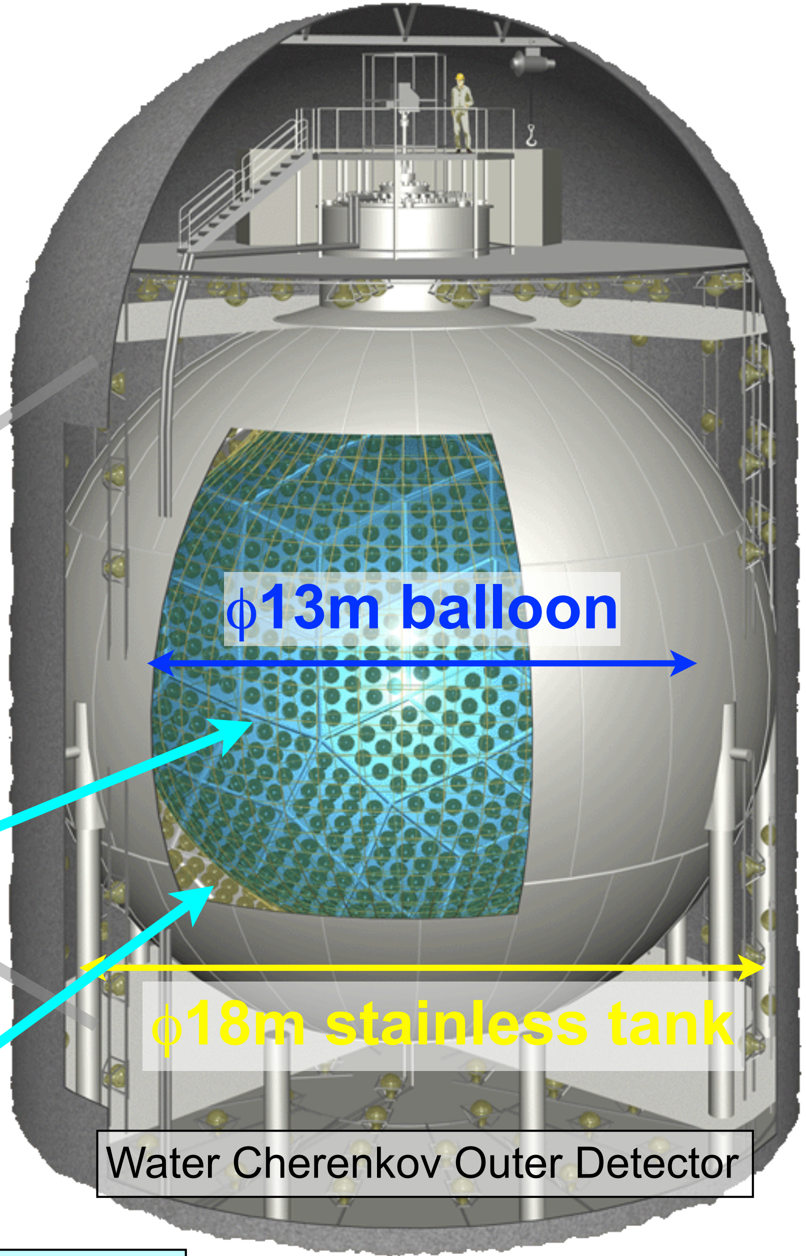
(operated since 2002)







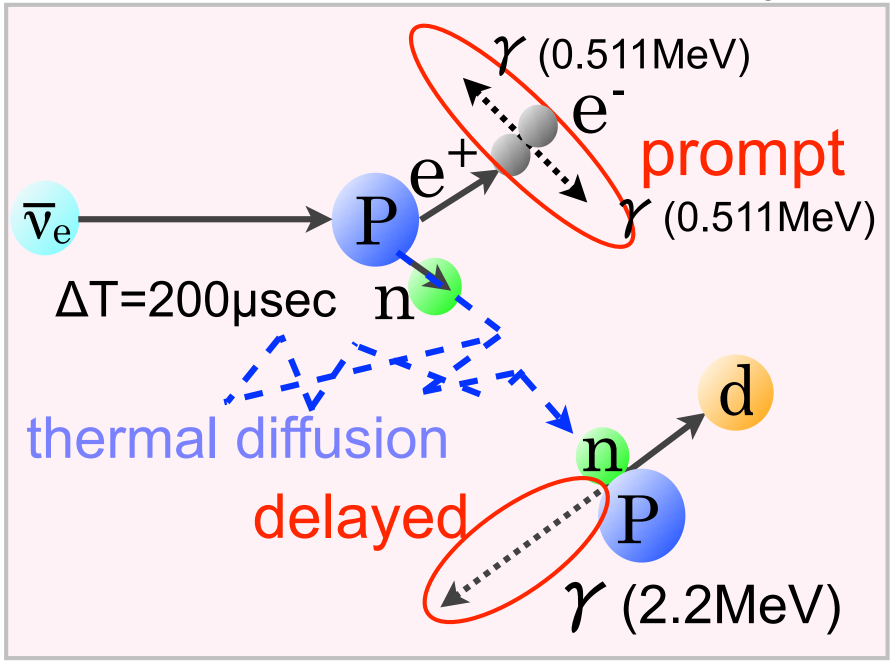
1,000t Liquid Scintillator
- extremely low impurity
(^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)
- **world's largest LS detector!**

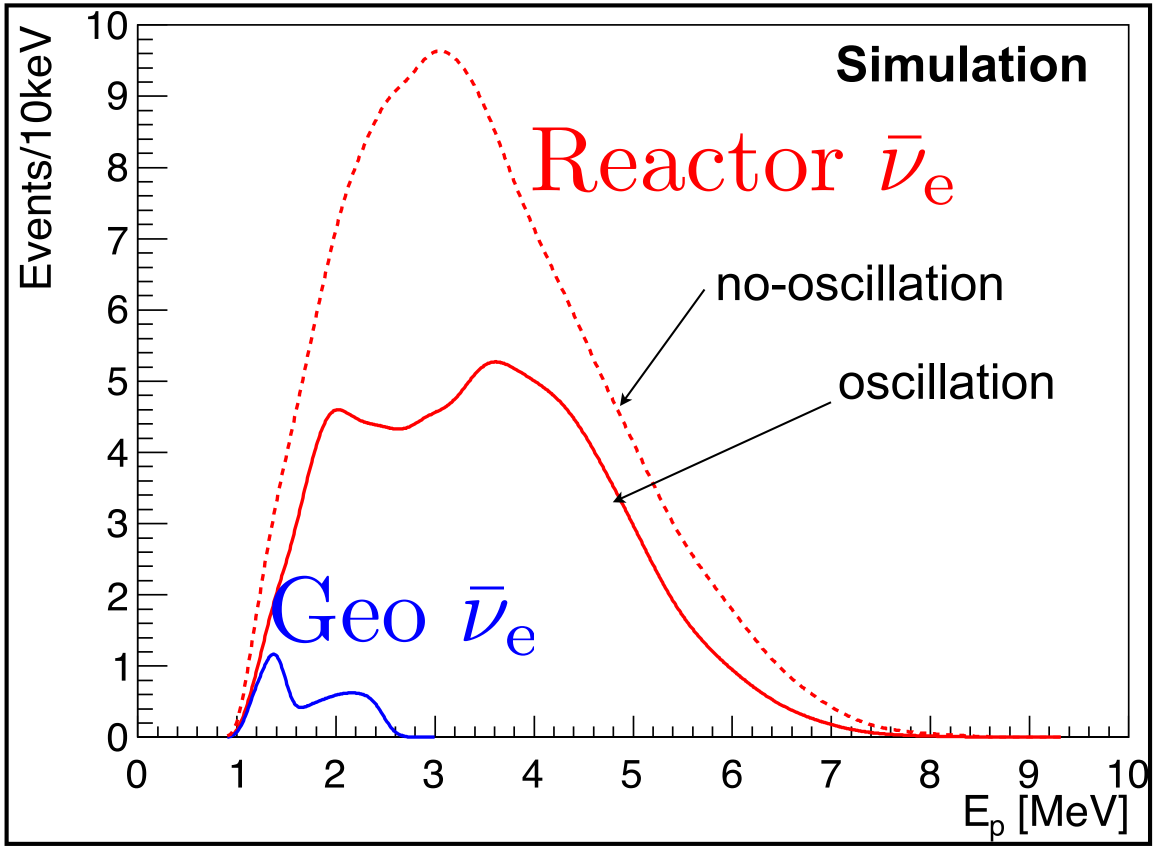
1,879 Photomultiplier Tubes

* Photo coverage 34%

Anti-neutrino Studies

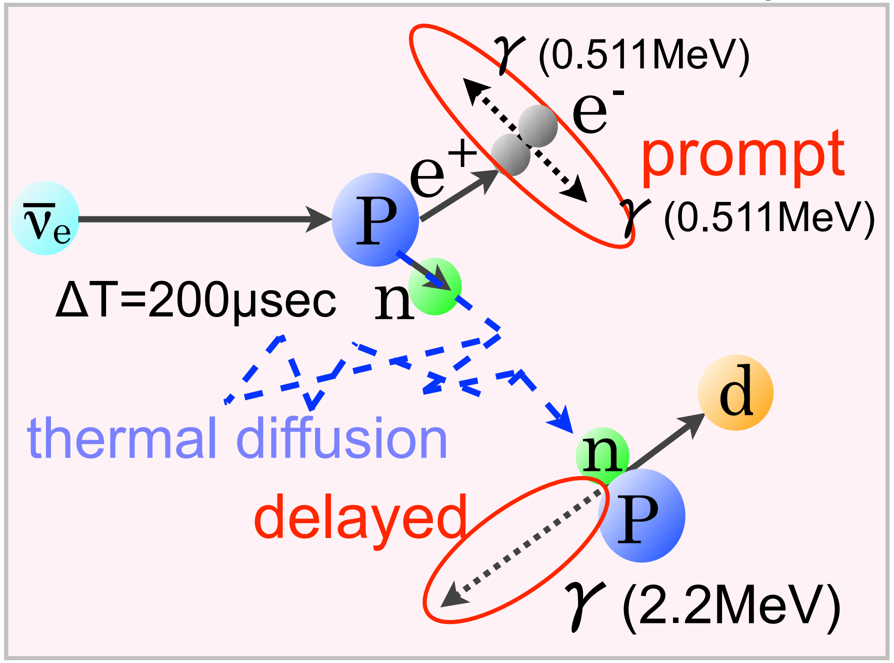
inverse-beta decay

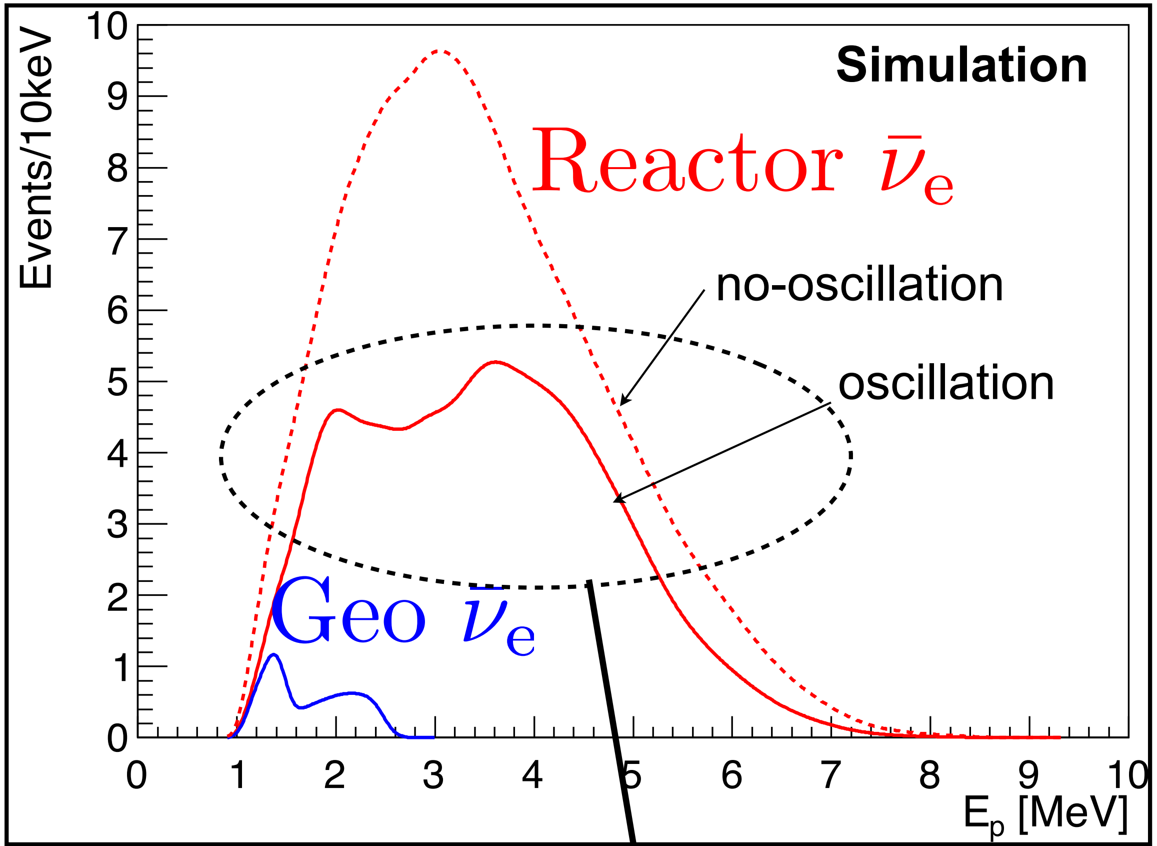




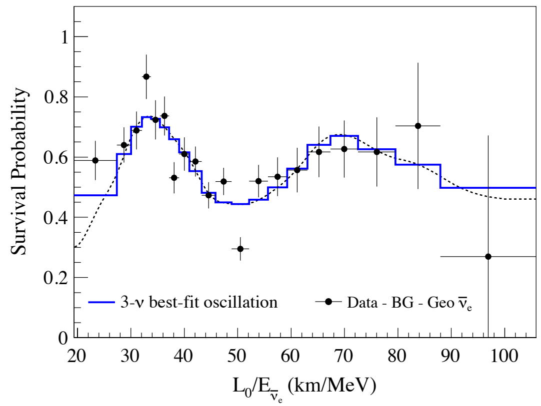
Anti-neutrino Studies

inverse-beta decay





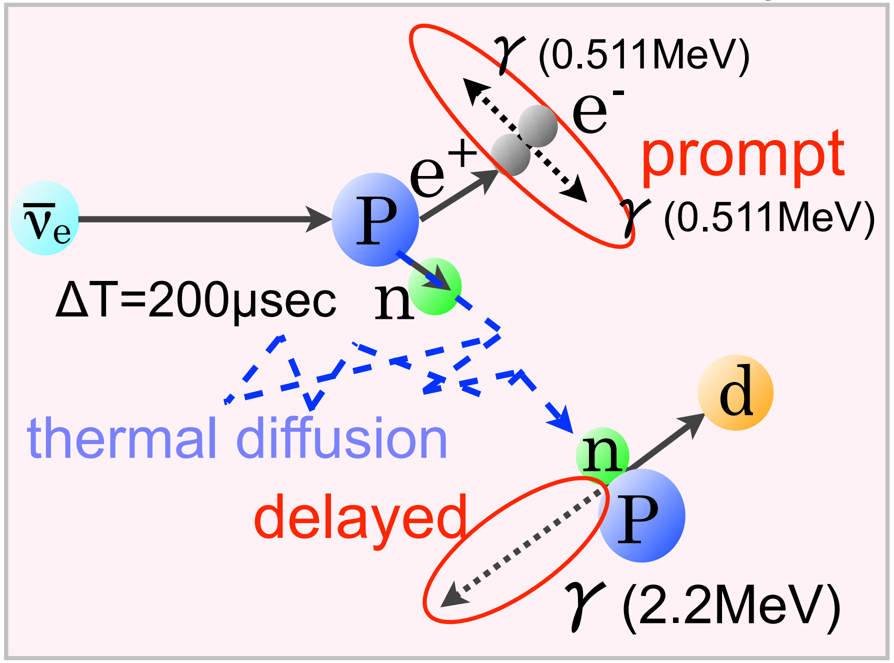
Neutrino Property Study

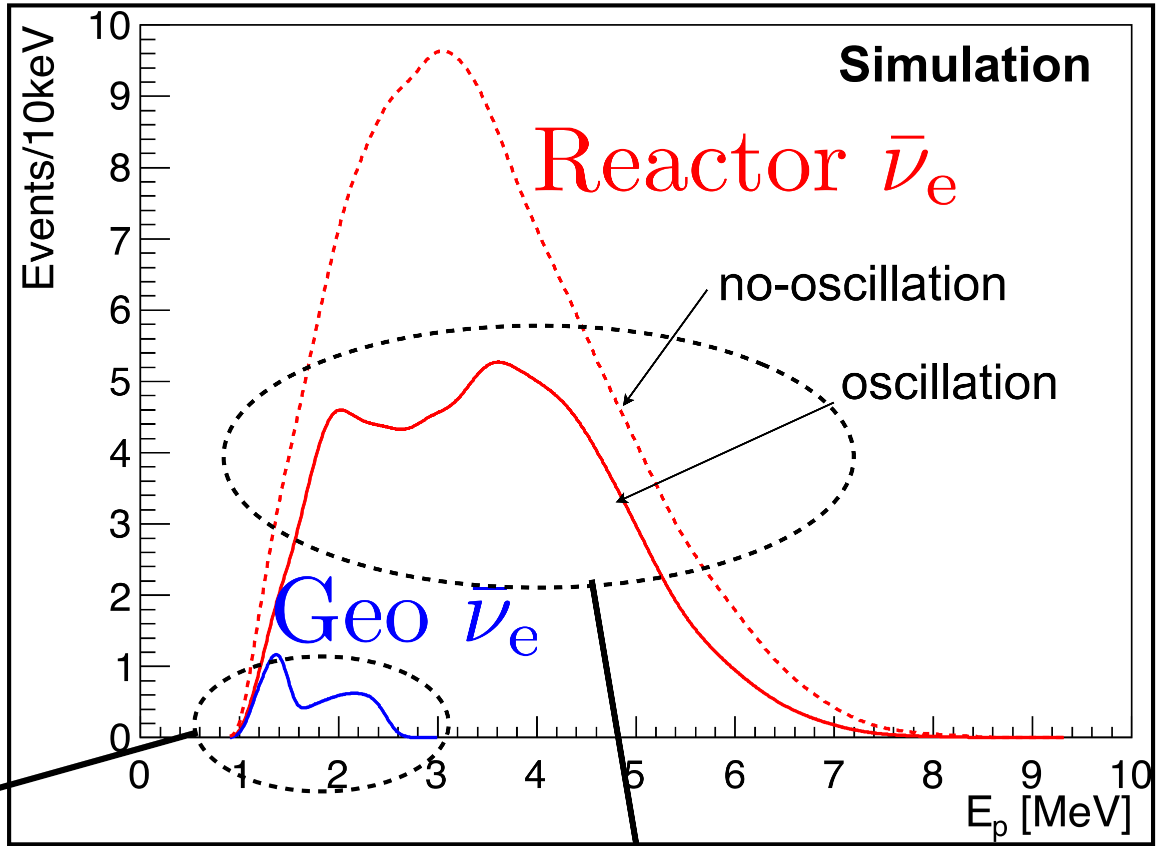


- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

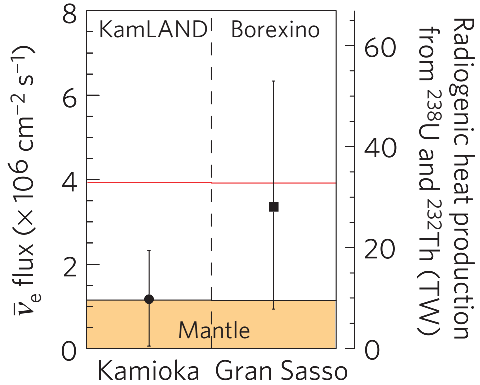
Anti-neutrino Studies

inverse-beta decay



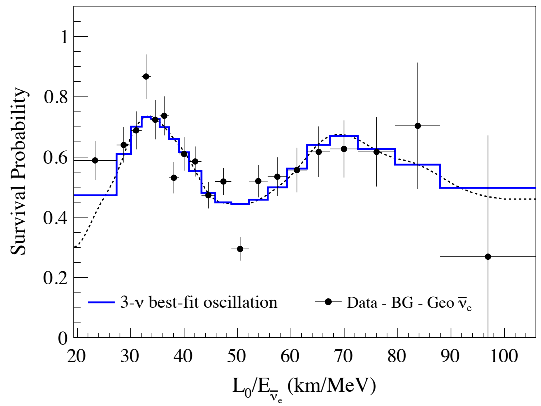


Geoneutrinos
: Neutrino Application



- Direct measurement of radiogenic heat contribution

Neutrino Property Study



- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

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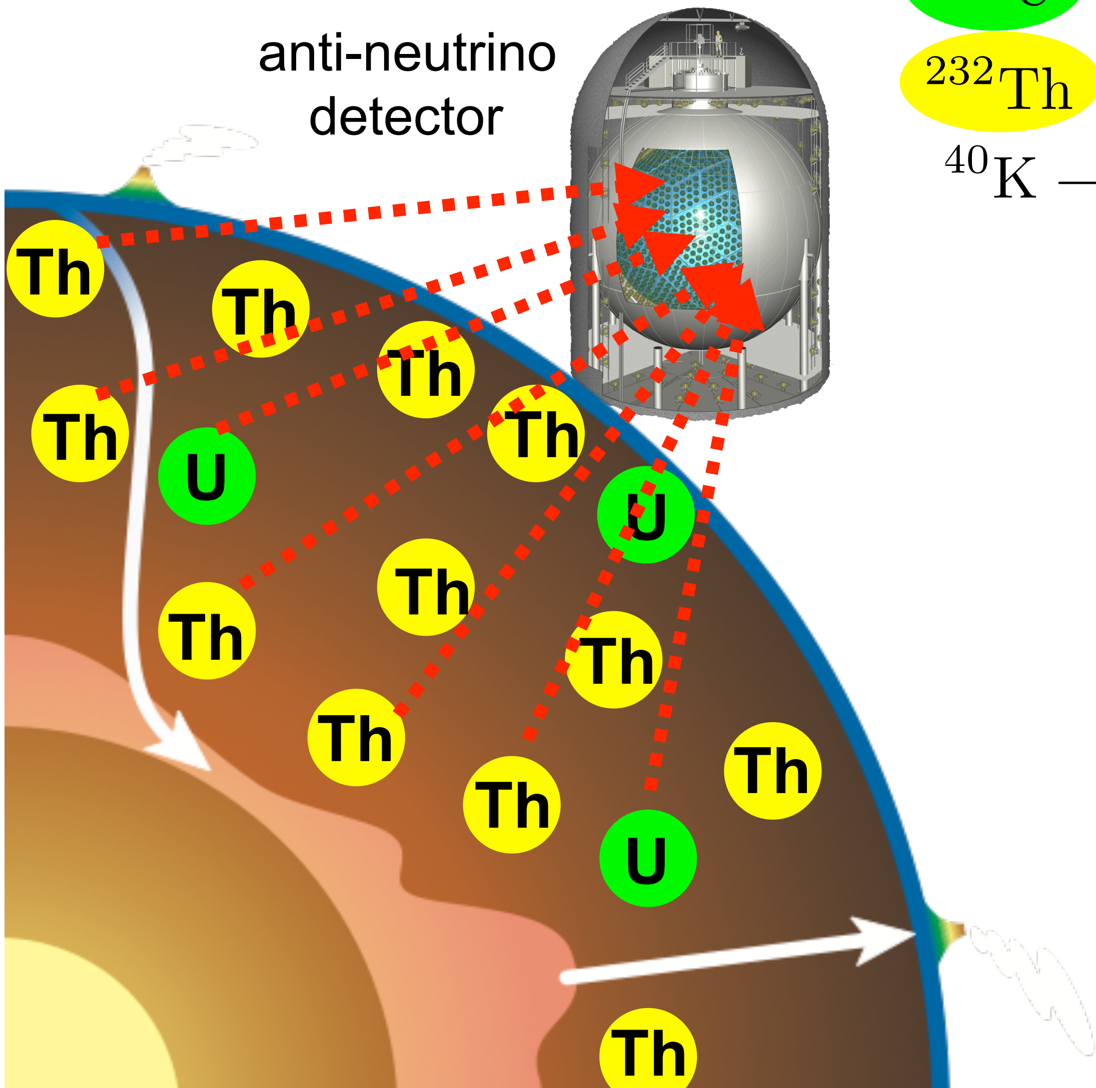
Geo-neutrinos

Electron-antineutrino from natural radioactive decay

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



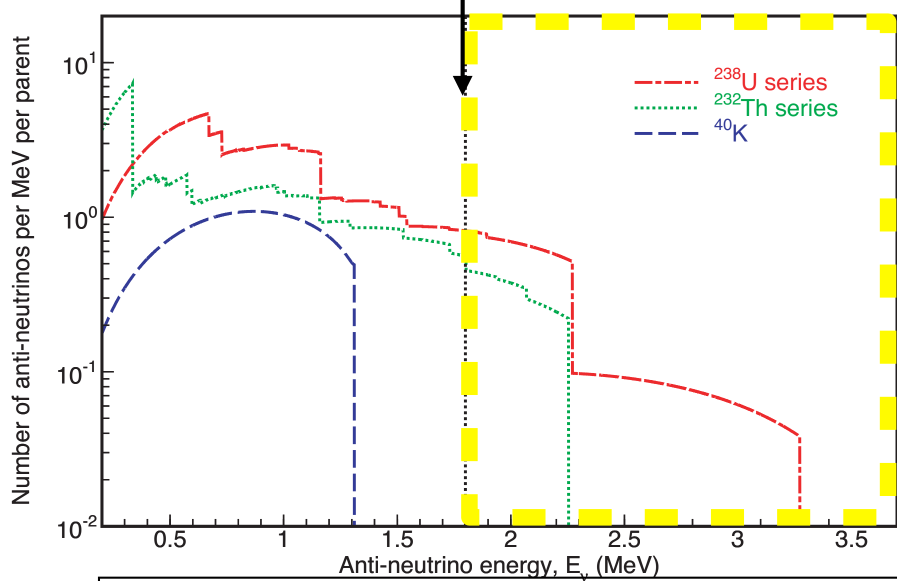
β-decay — Geo-neutrinos

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

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

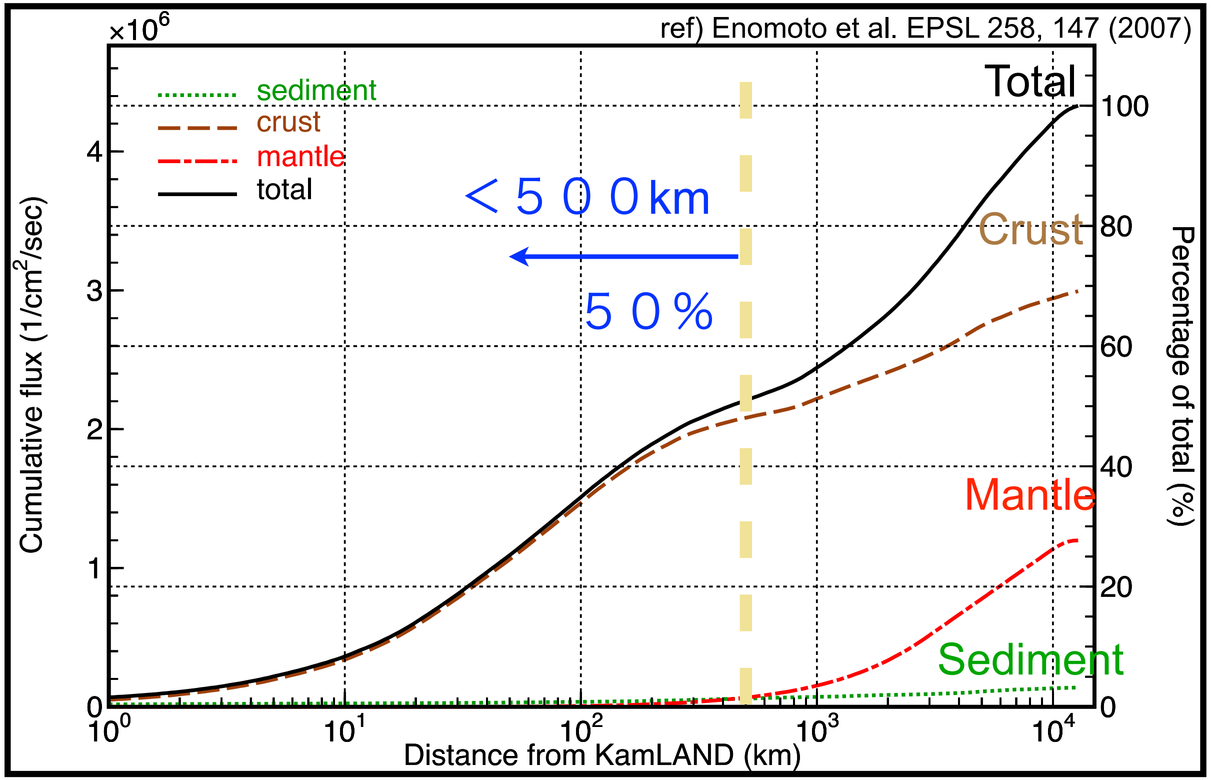
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\ (89.28\%)$$

Energy threshold, 1.8 MeV

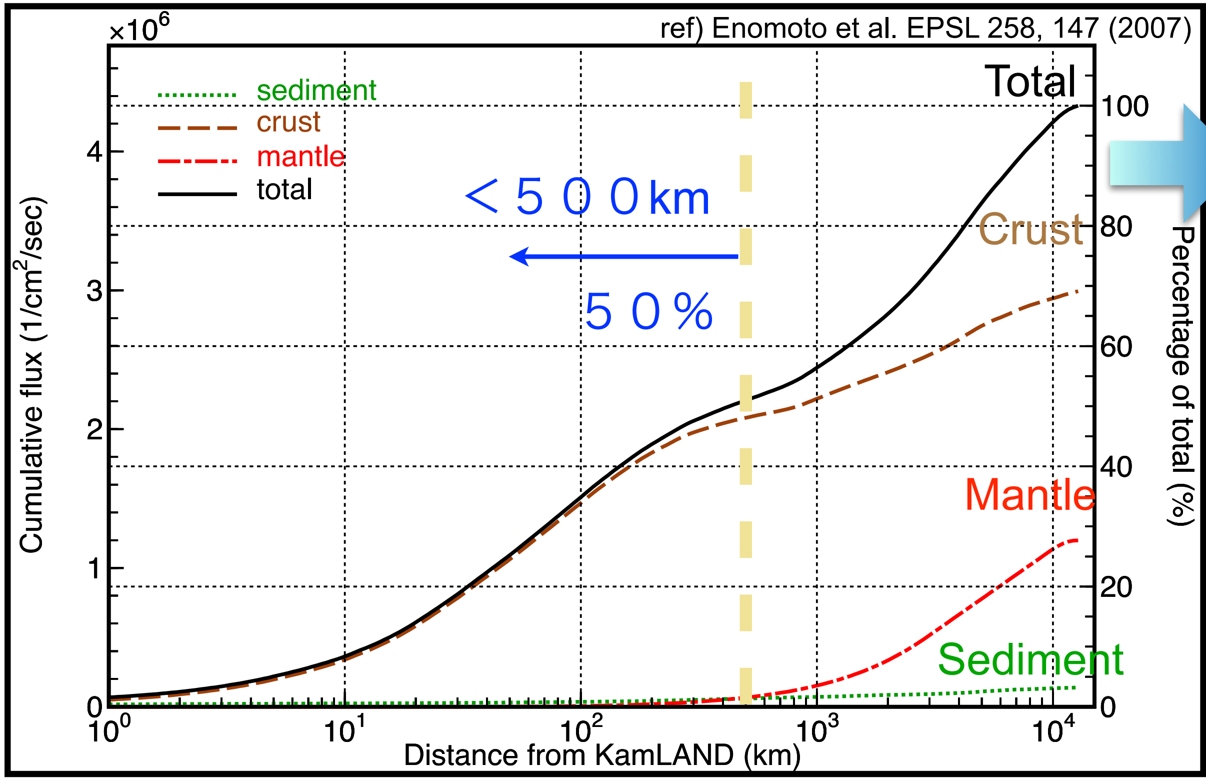


Only geo-neutrinos from U and Th are detectable

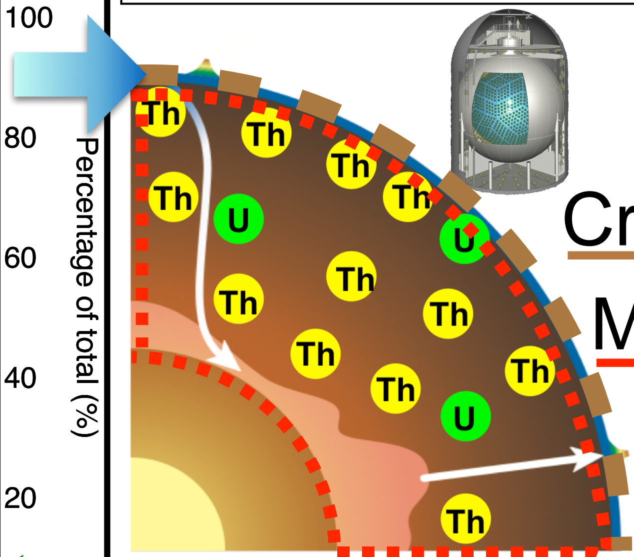
Geo-neutrino Flux at Kamioka



Geo-neutrino Flux at Kamioka



Contributions from each part



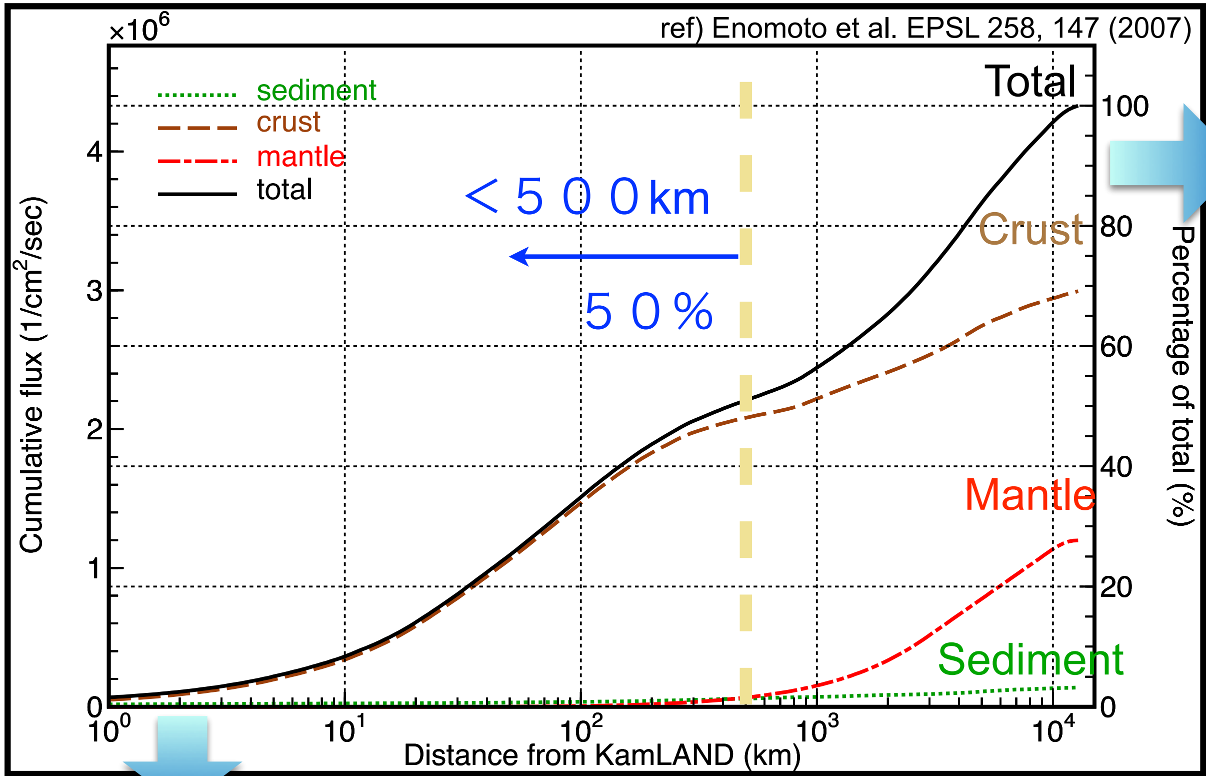
Crust : 70%

Mantle : 27%

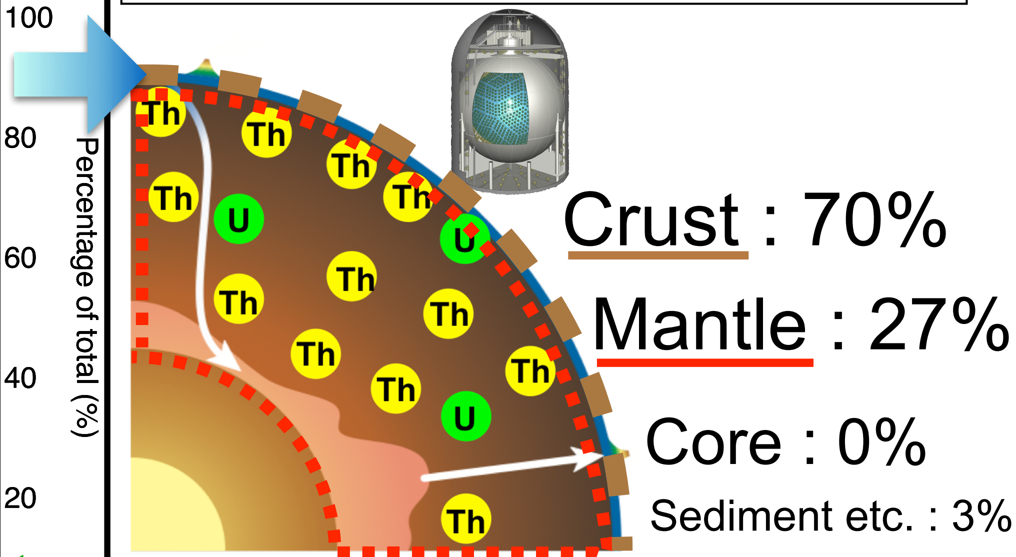
Core : 0%

Sediment etc. : 3%

Geo-neutrino Flux at Kamioka



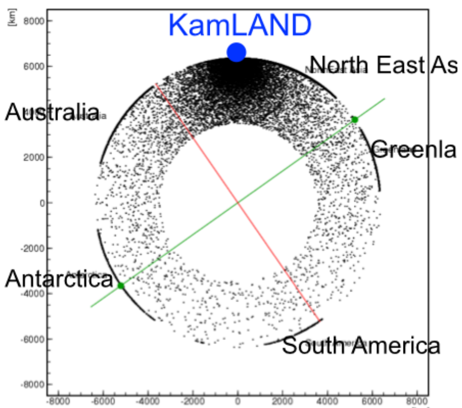
Contributions from each part

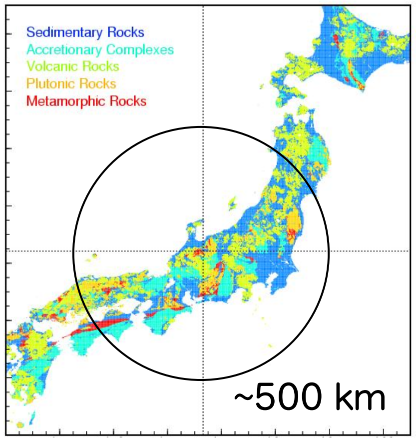


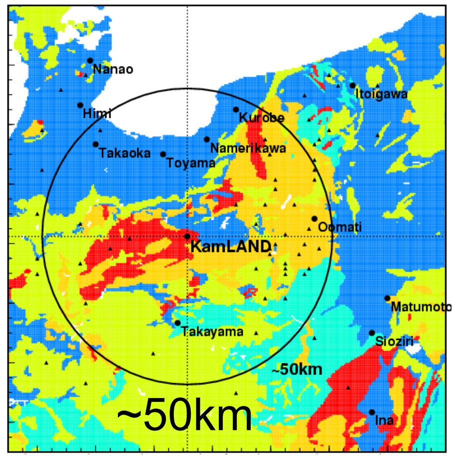
Contributions from each area

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

Important to understand Japanese geology







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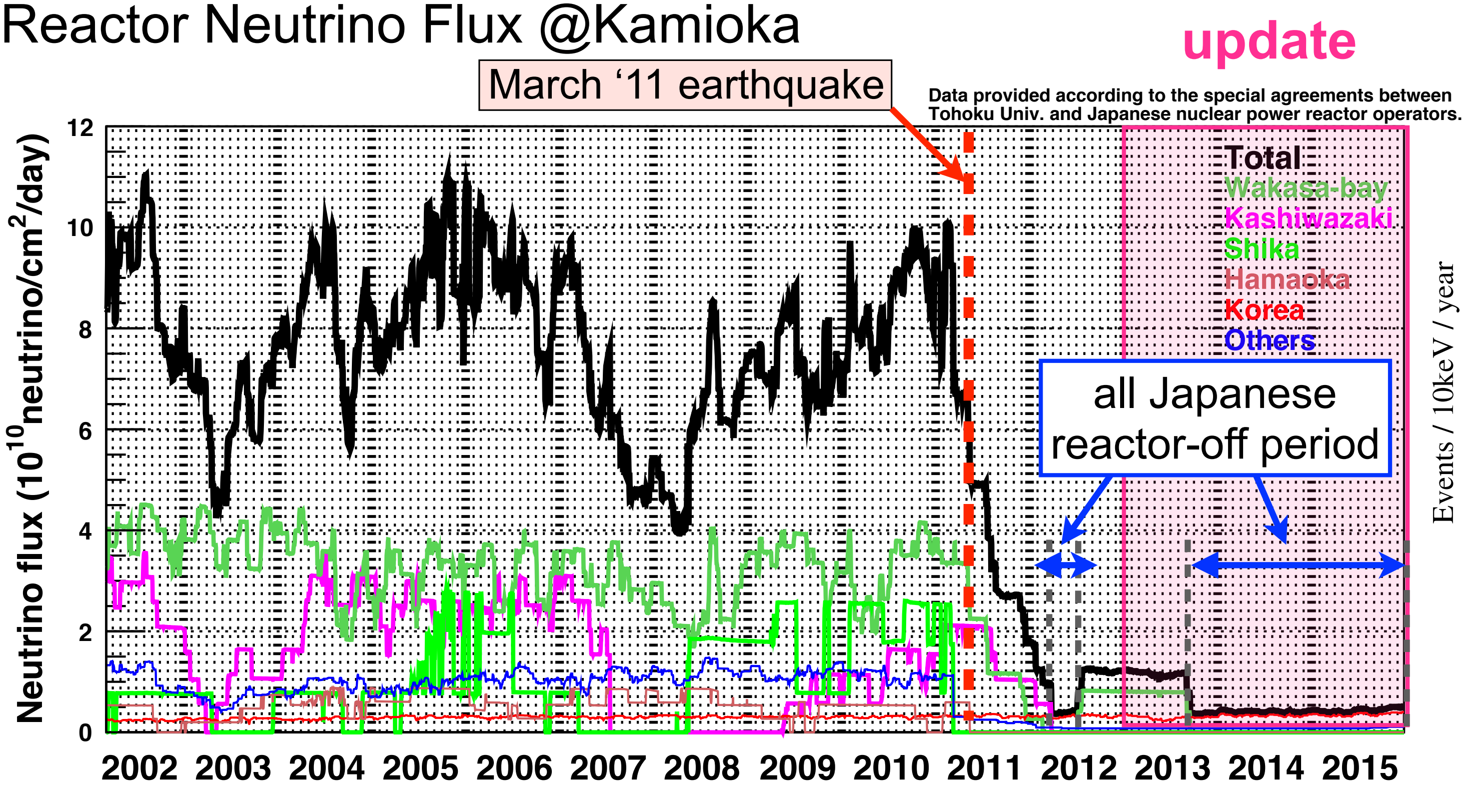
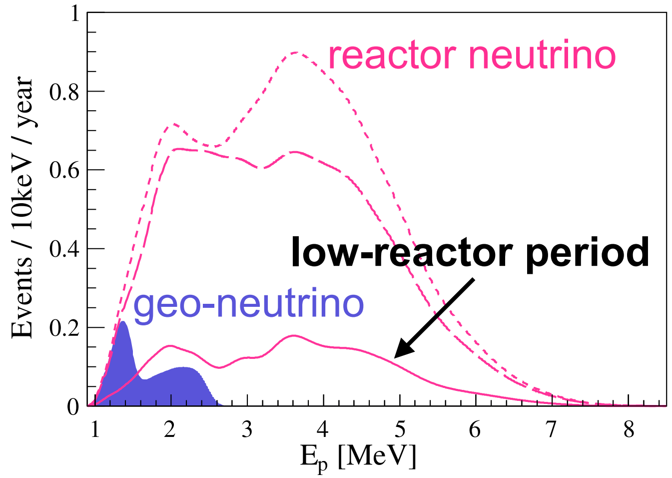
Current Data-set

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

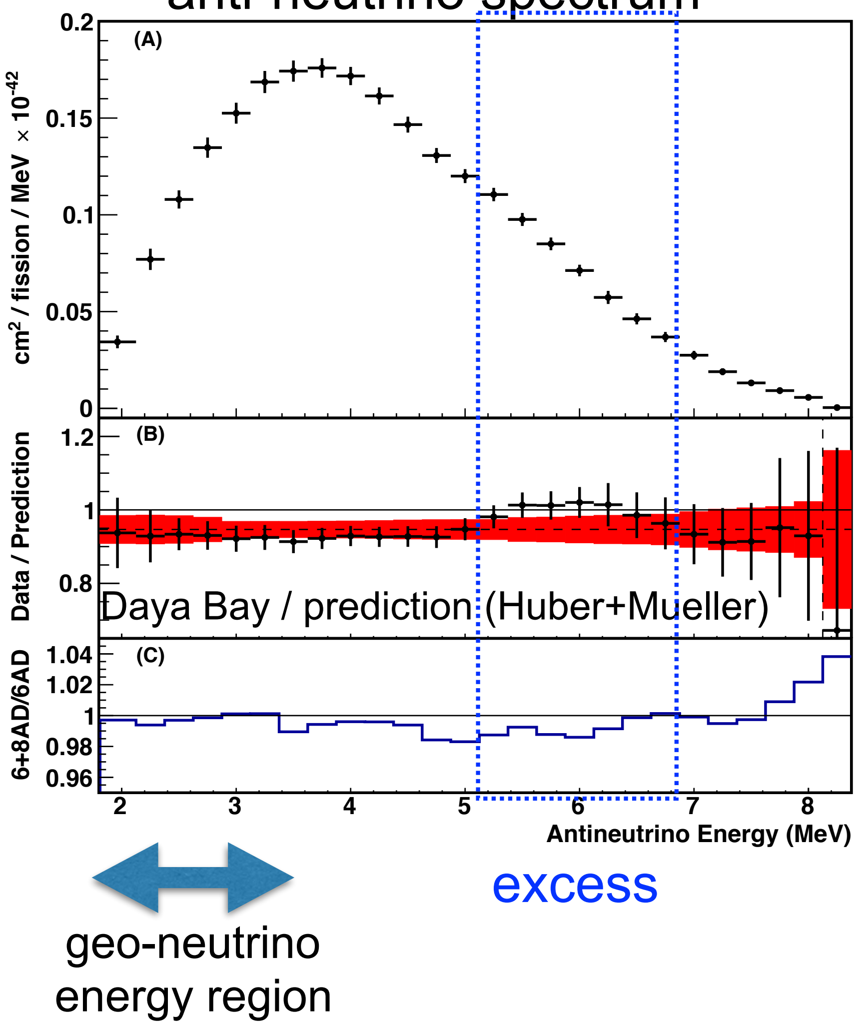
advantages {
- low-reactor operation period : **~3.5 years** livetime
- **all Japanese reactor-off period : ~2.0 years** livetime

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

Reactor Neutrino Spectrum

(Daya Bay, arXiv:1607.05378v1)

anti-neutrino spectrum



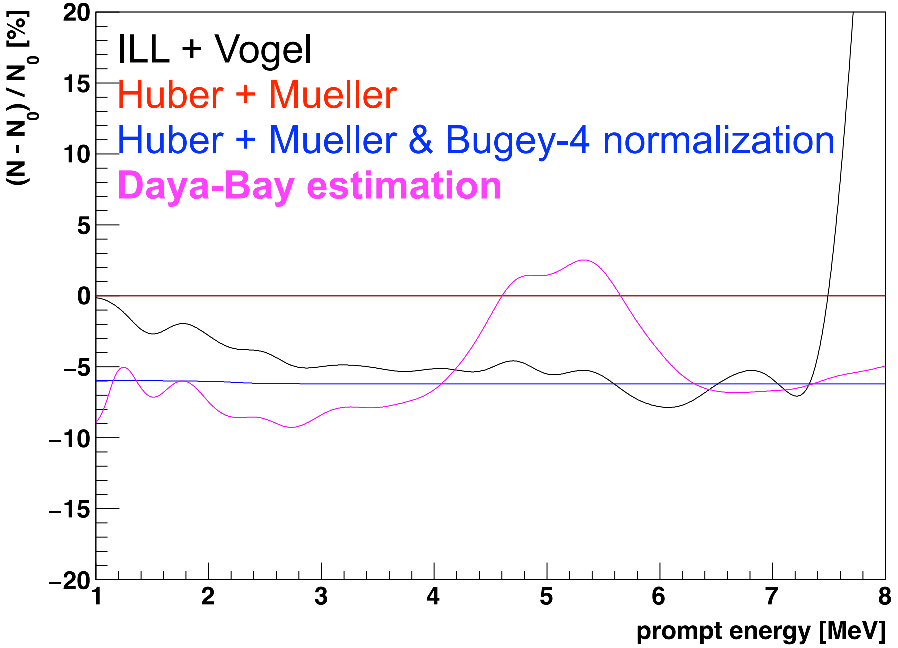
- Reactor neutrino experiments reported that there was an excess of events in the region of 4-6 MeV.
  - Daya Bay, RENO, Double Chooz

Model independent anti-neutrino spectrum is available from Daya-Bay publication (arXiv:1607.05378v1).

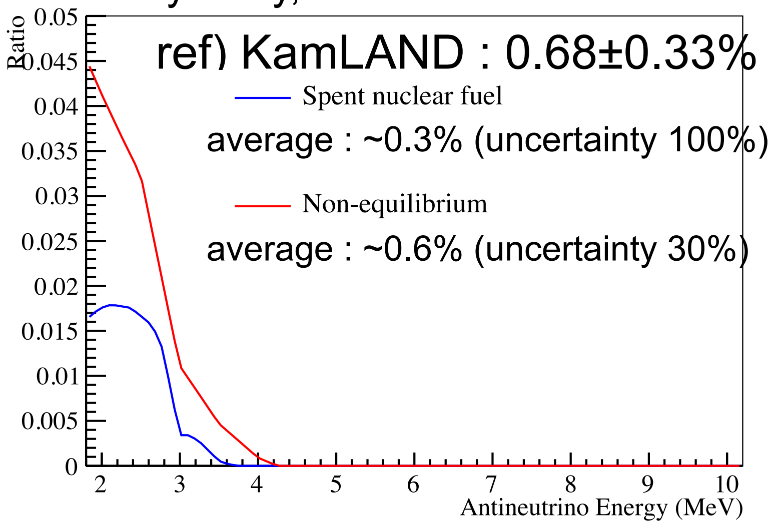
We need to consider the effect on KamLAND anti-neutrino analysis.

Reactor Neutrino Spectrum for KamLAND

spectrum without detection efficiency



Daya Bay, arXiv:1607.05378v1



2016 Preliminary Result

- Reactor neutrino spectrum for KamLAND analysis

2013 paper : Huber + Mueller & Bugey-4 normalization

2016 preliminary : **Daya Bay estimation**

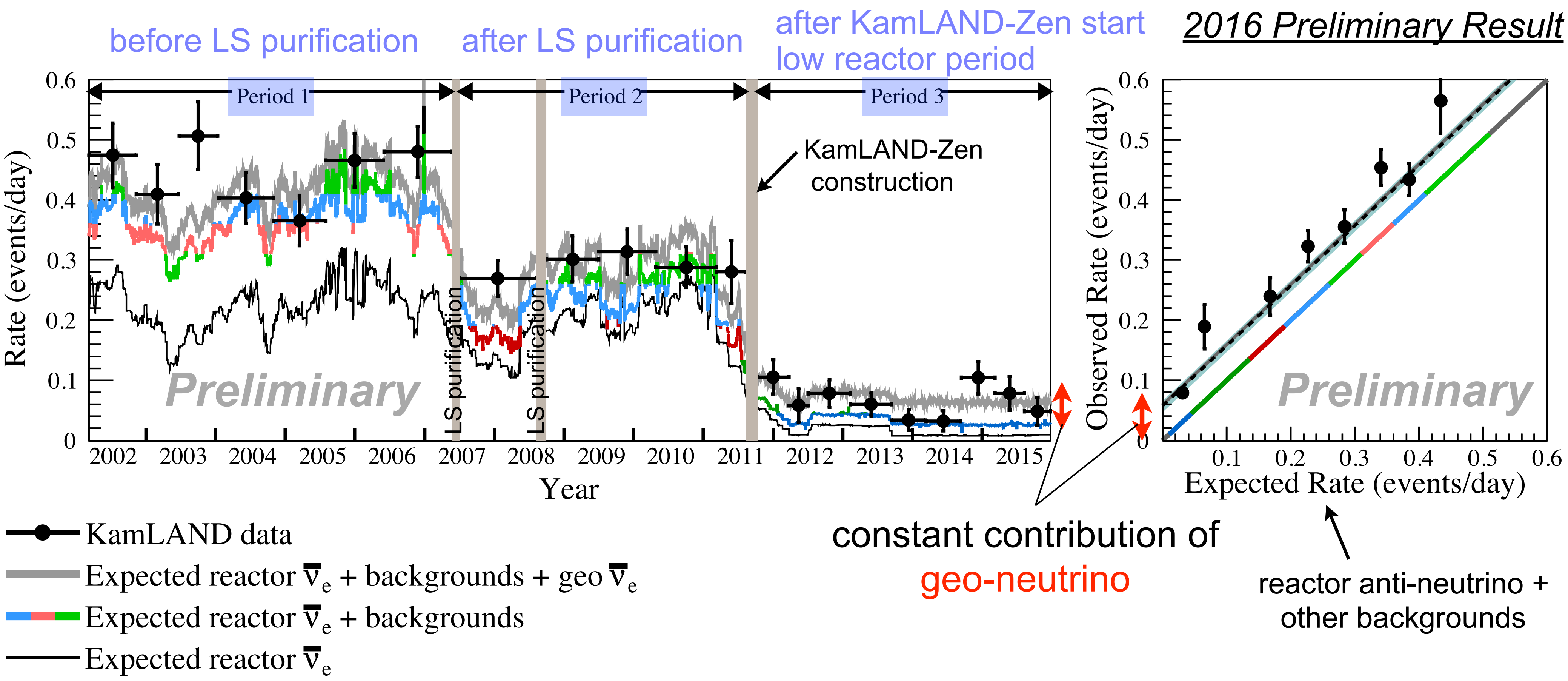
σ_f (cm^2/fission) $= (5.92\pm0.12)\times10^{-43}$ (uncertainty : 2.03%)

* Excess at 4-6 MeV : ~+5%.
* In the publication, they 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).

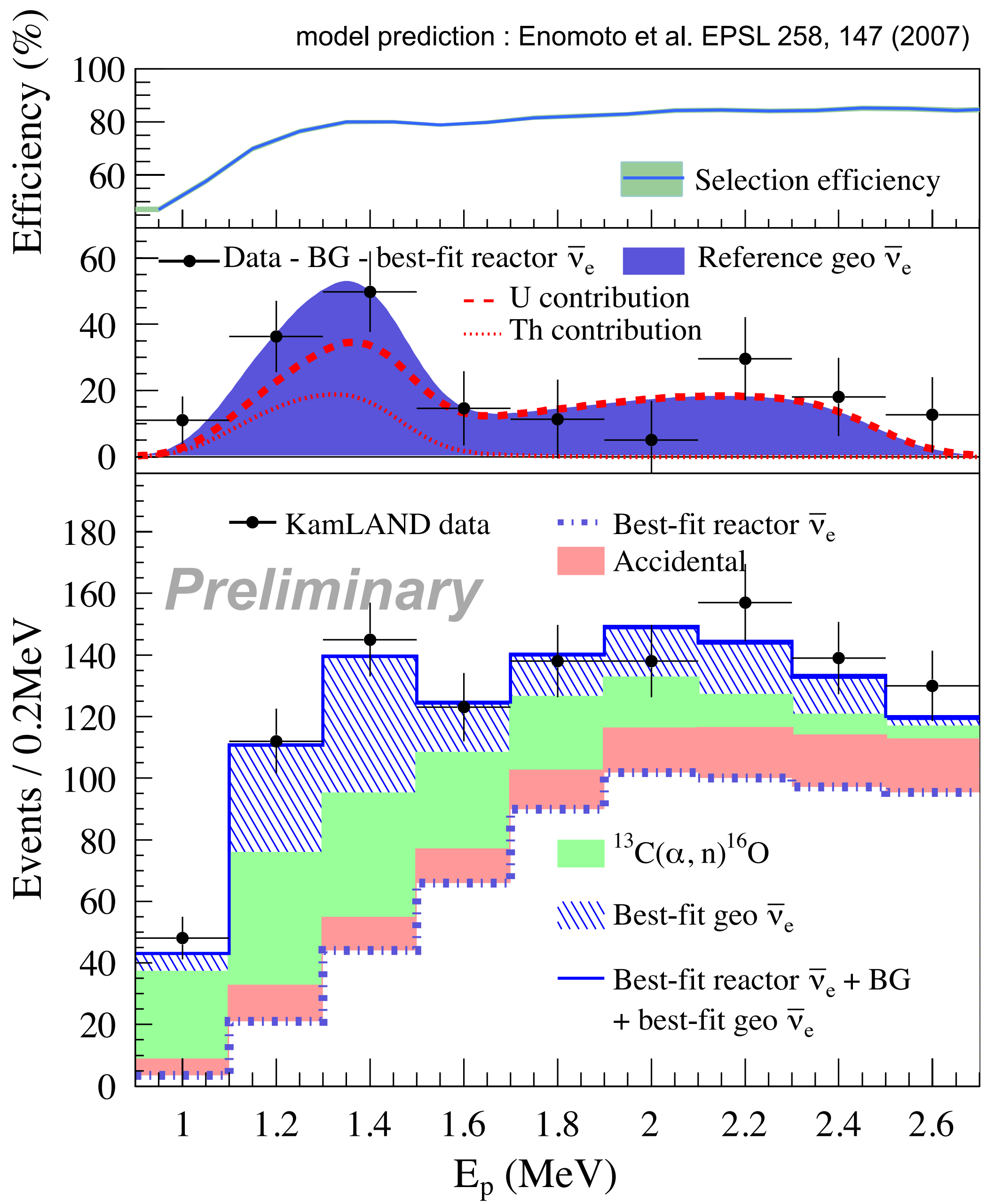
- We confirmed that :
  - ☑ 4-6 MeV excess has no impact on the geo-neutrino results.
  - ☑ effect of reactor spectrum uncertainty is much smaller than the statistical uncertainty of geo-neutrino events.

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

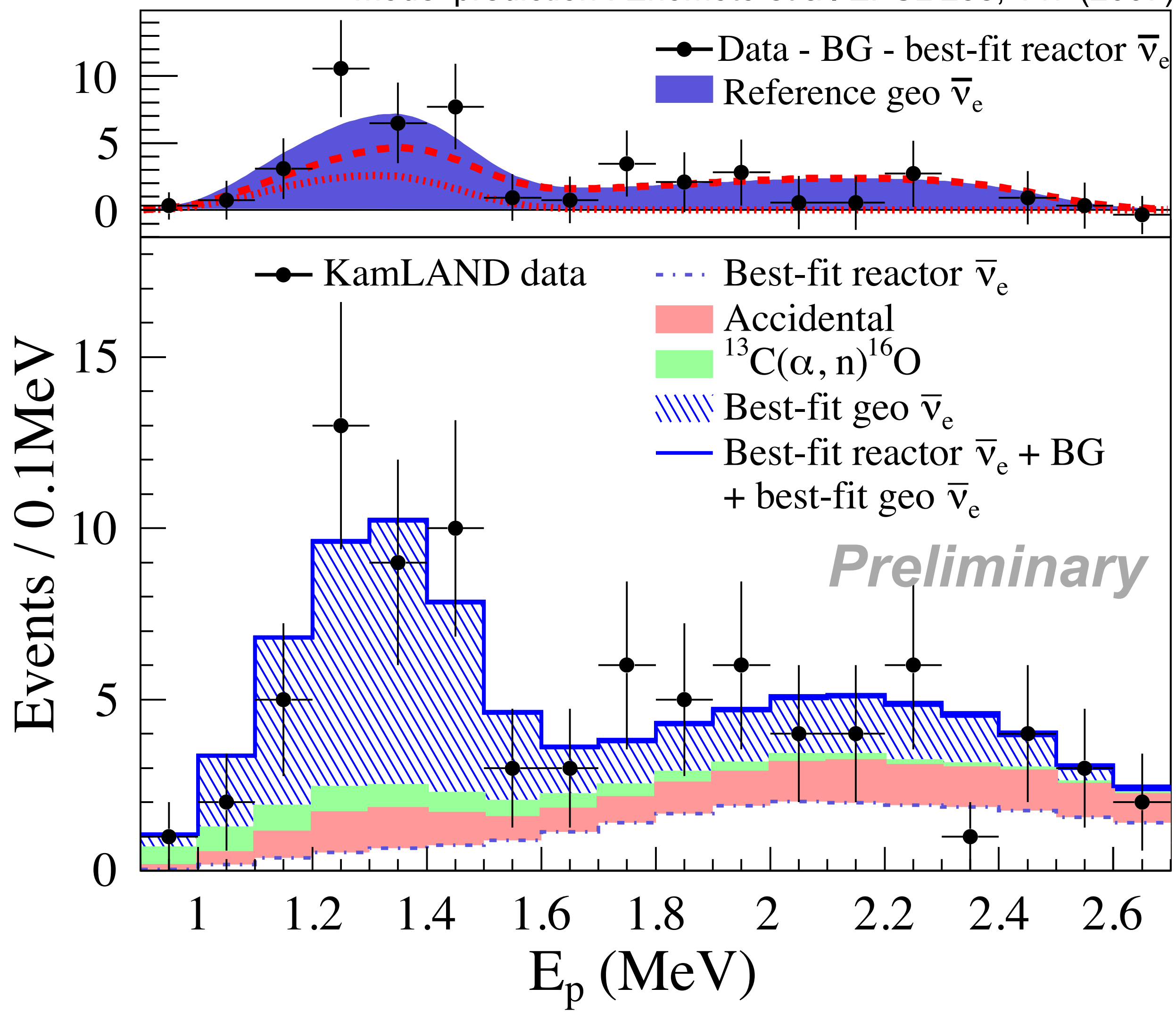
Background Summary

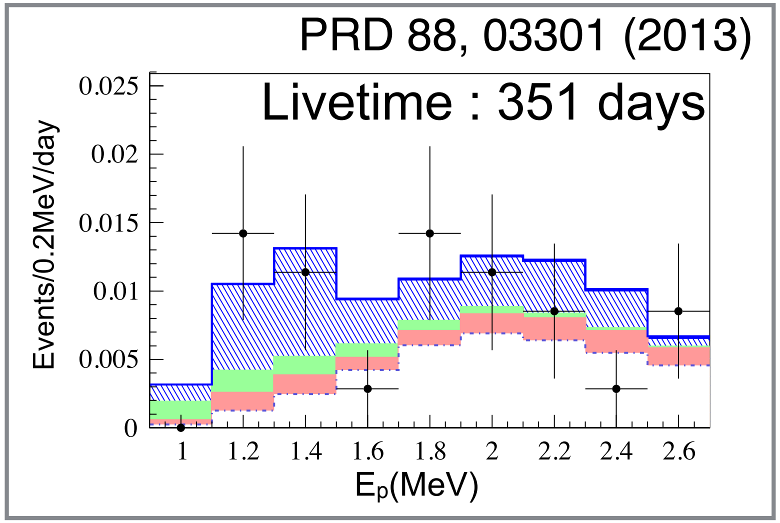
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

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)





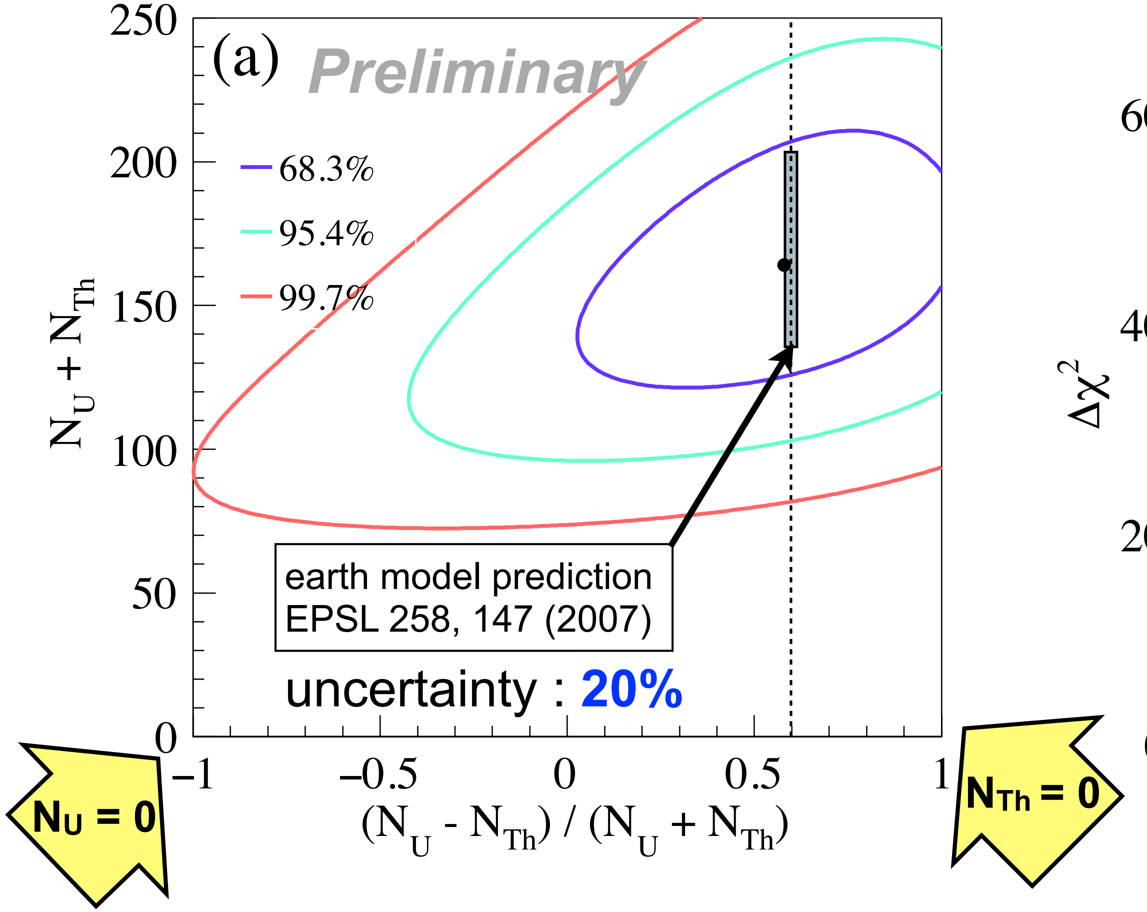
We measured clear distribution of geo-neutrino events.

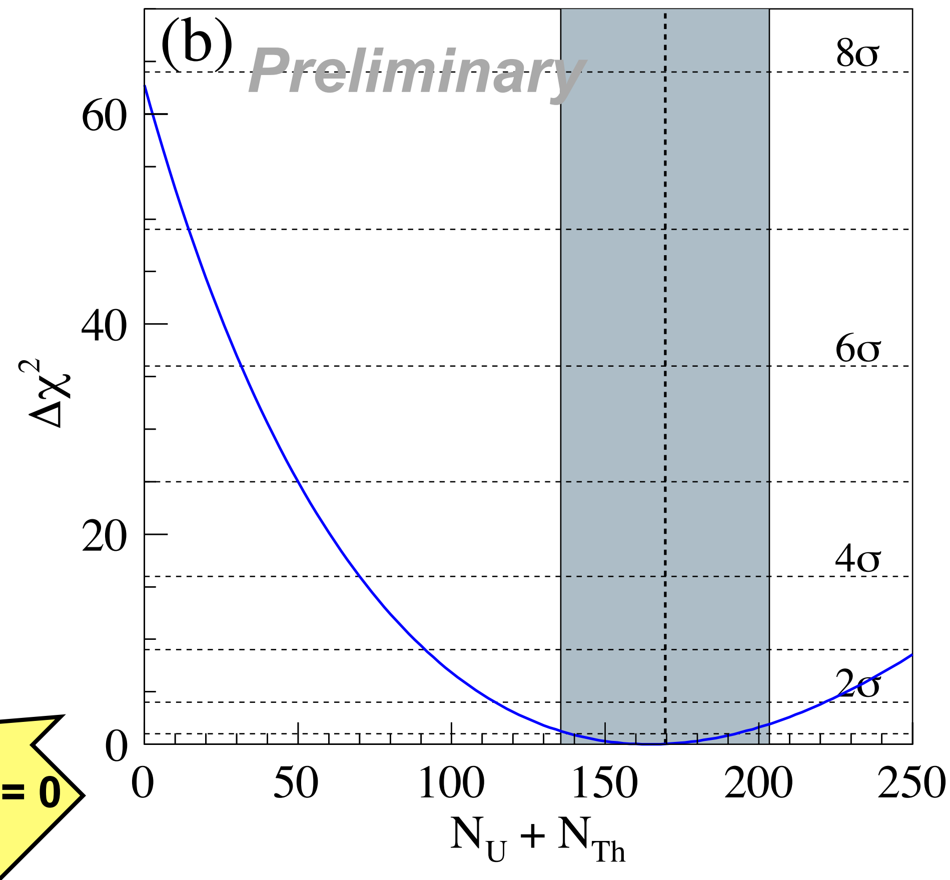
best-fit : Period 3 analysis

Rate + Shape + Time Analysis

2016 Preliminary Result

Th/U mass ratio fixed (= 3.9)





✦ 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.

▸Th/U Mass Ratio (1)

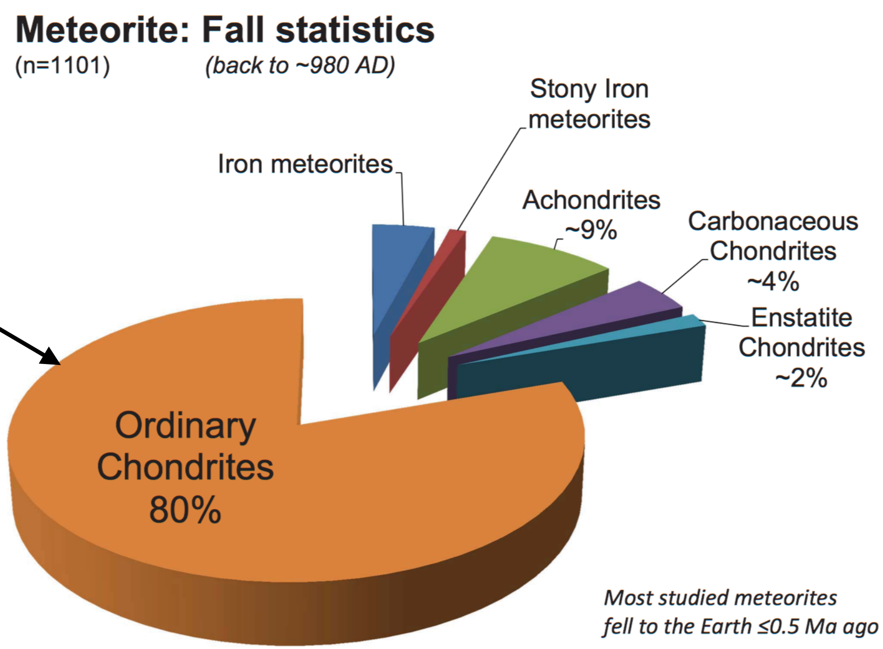
- According to geochemical studies, ^{232}Th is more abundant than ^{238}U. Mass ratio (Th/U) in bulk silicate Earth is expected to be **around 3.9.**

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.

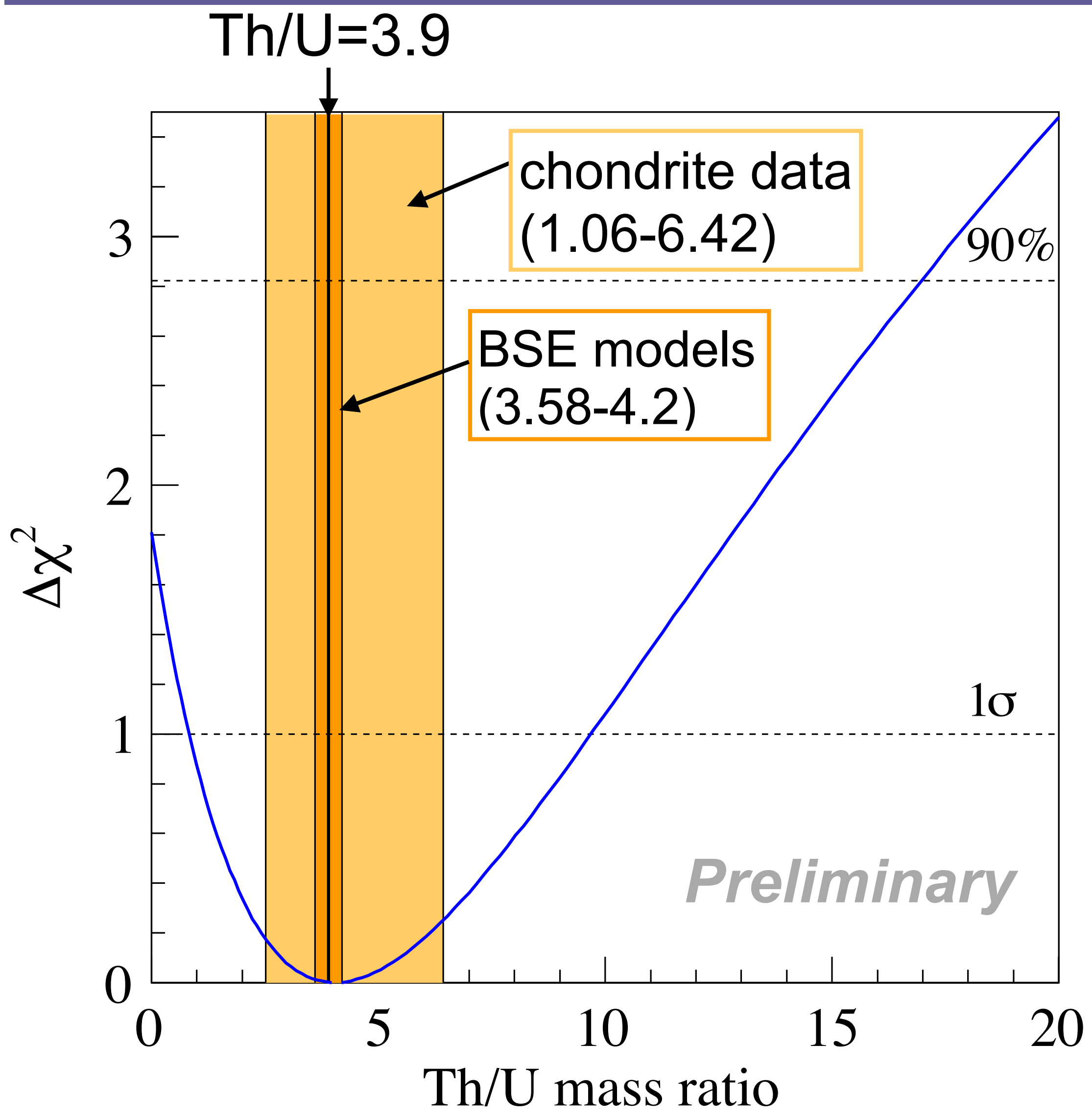


- Geo-neutrino observed rate can be converted to amount of Th & U assuming homogeneous distribution.
Independent & direct measurement of entire Earth

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) PRD 88, 03301 (2013)
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

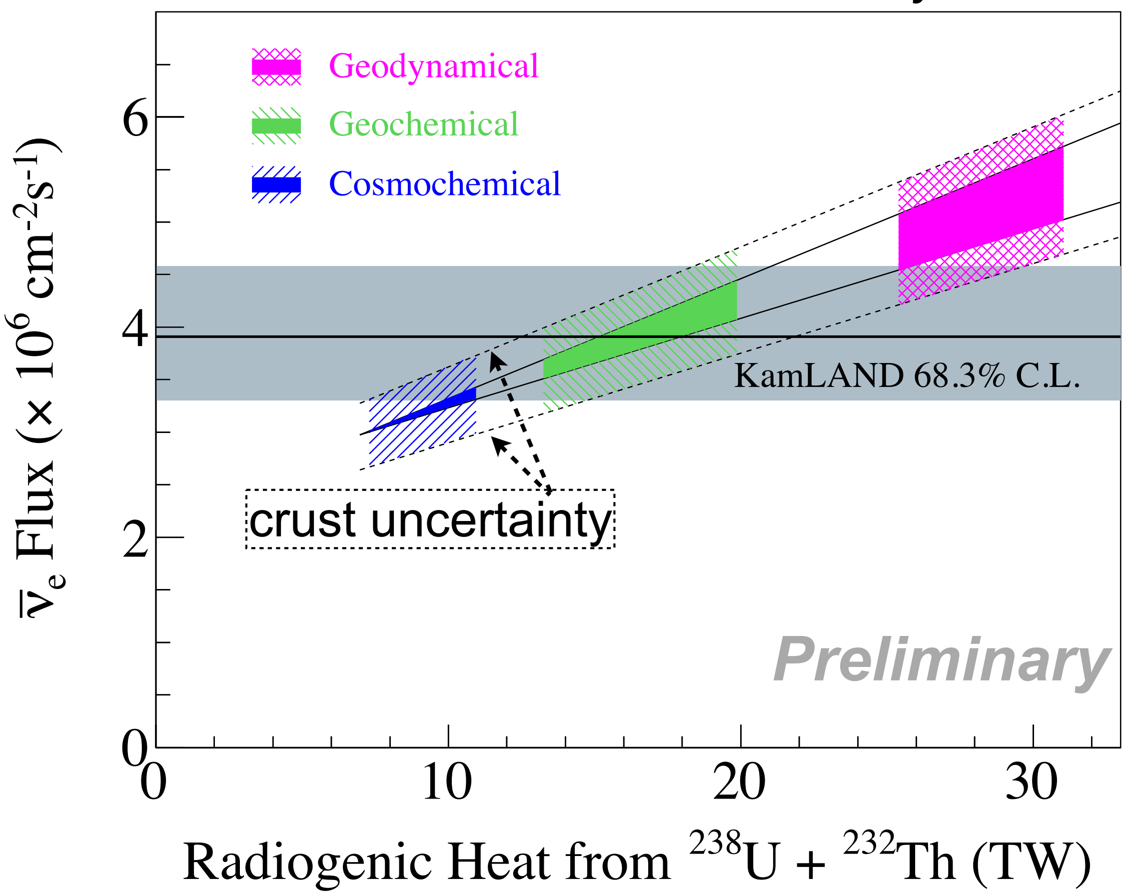
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

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

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

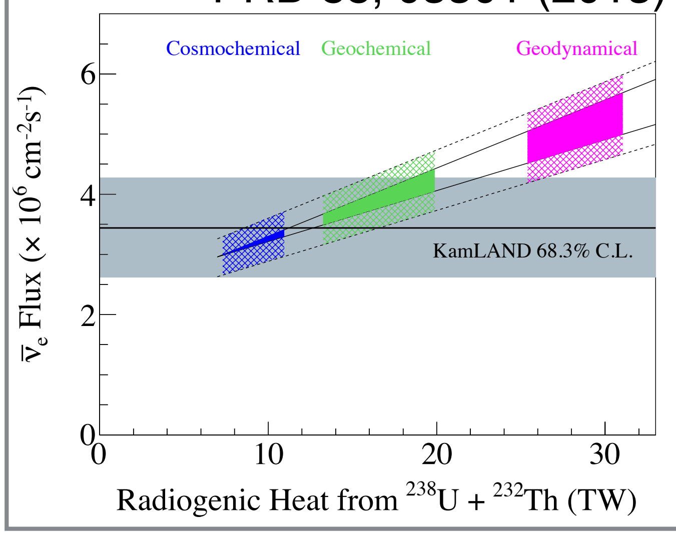
Earth Model Comparison

2016 Preliminary Result



☑ consistent with models, but started to disfavour cosmochemical model

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

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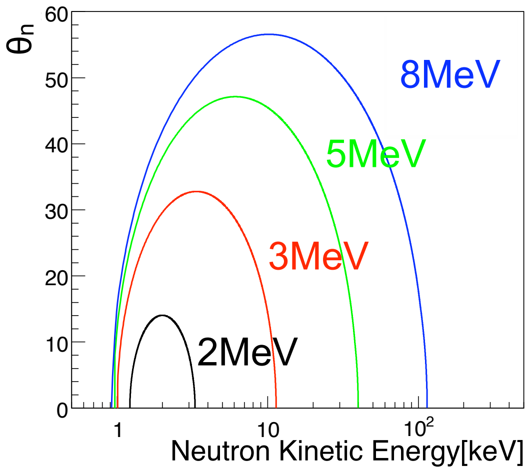
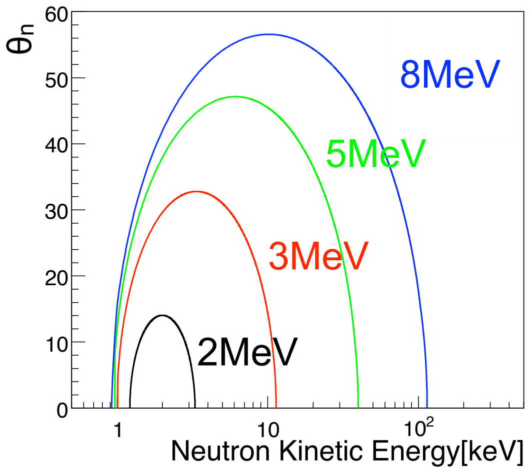
Directional Measurement with ^{6}LiLS



$E_{\bar{\nu}_e}$ < 3MeV → θ_n < 35°

neutron has directional information of anti-neutrino

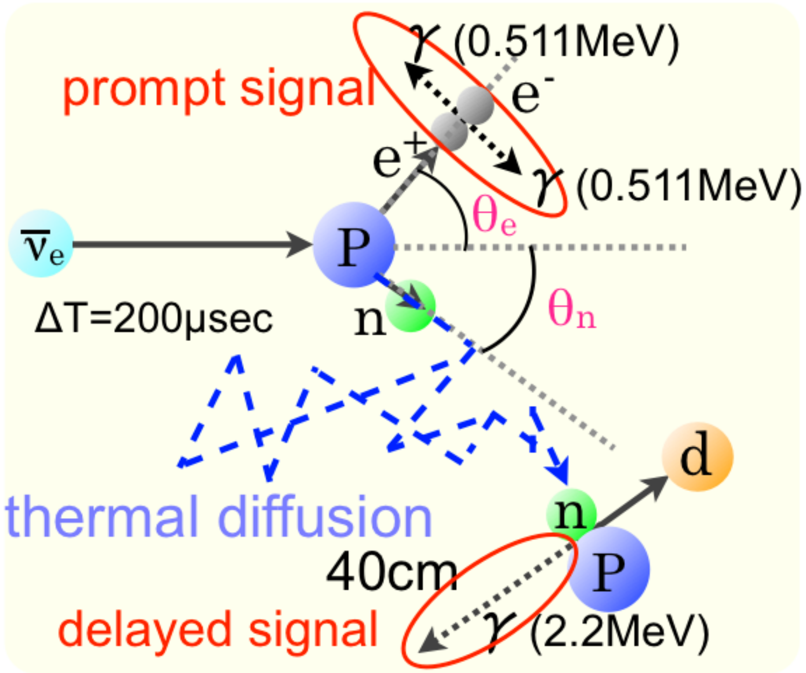
Directional Measurement with ^{6}LiLS



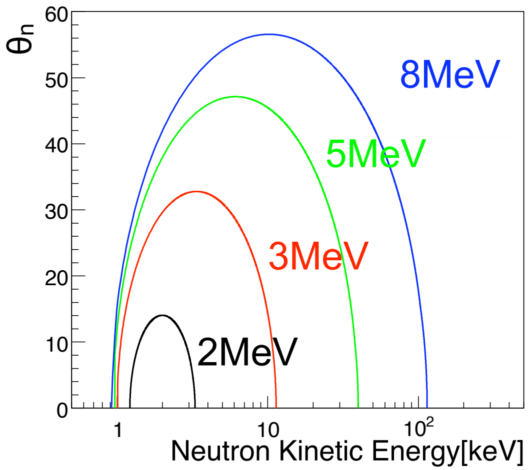
neutron has directional information of anti-neutrino

$E_{\bar{\nu}e} < 3MeV \rightarrow \theta_n < 35°$

[current liquid scintillator]



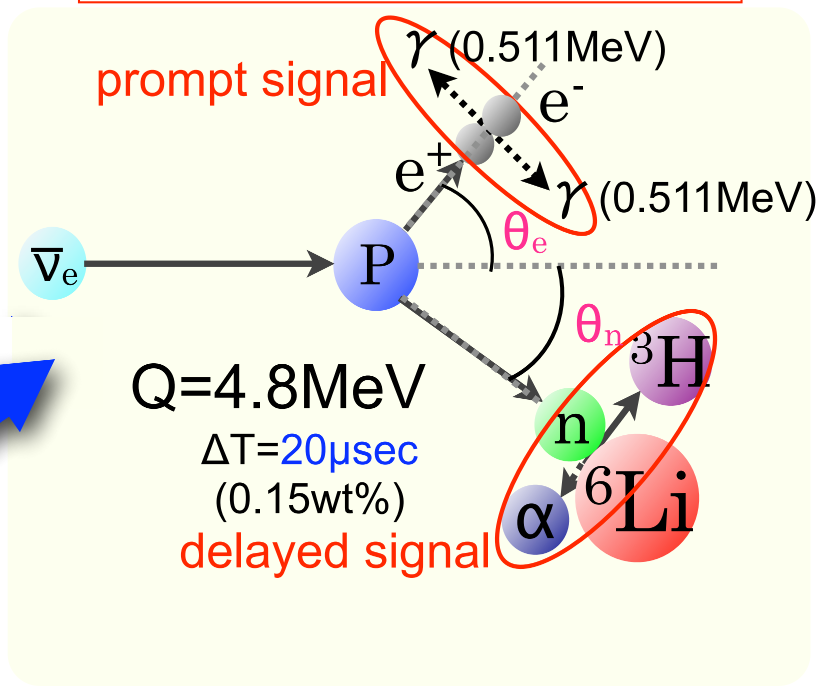
Directional Measurement with ^{6}LiLS



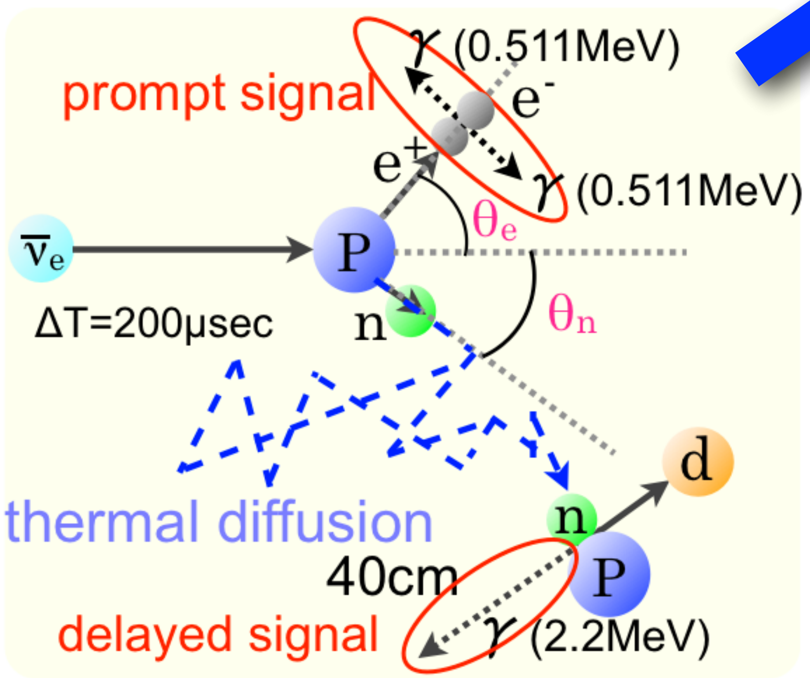
$E_{\bar{\nu}e} < 3MeV \rightarrow \theta_n < 35°$

neutron has directional information of anti-neutrino

[Li loaded liquid scintillator]

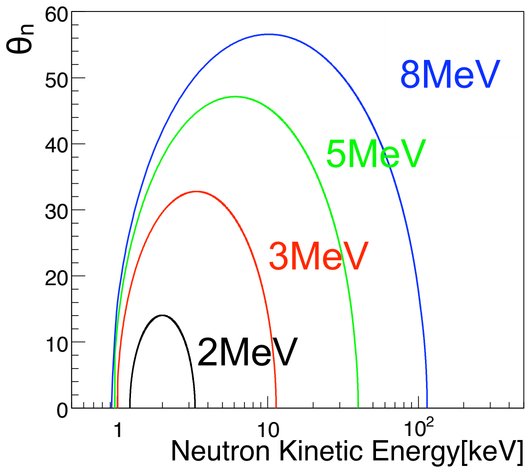


[current liquid scintillator]



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

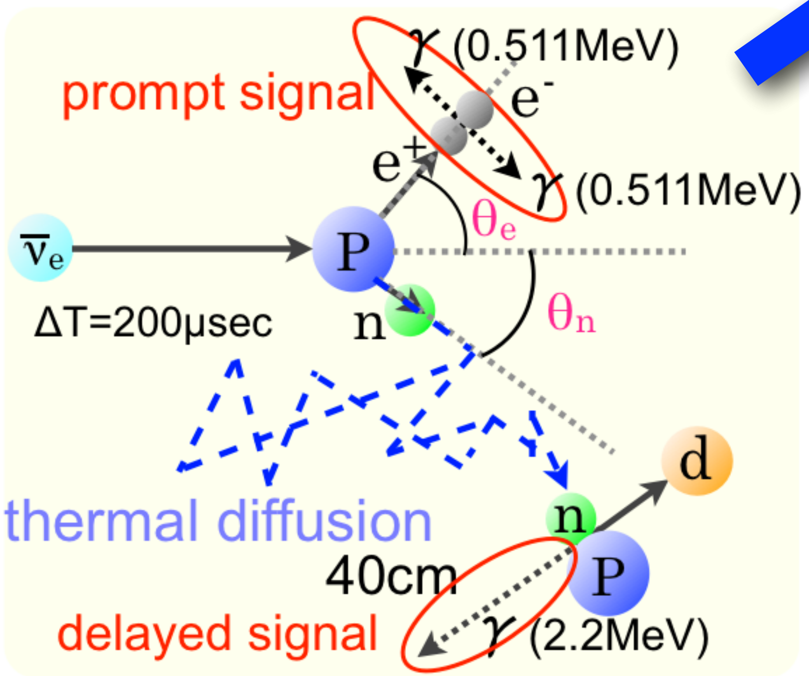
Directional Measurement with ^{6}LiLS



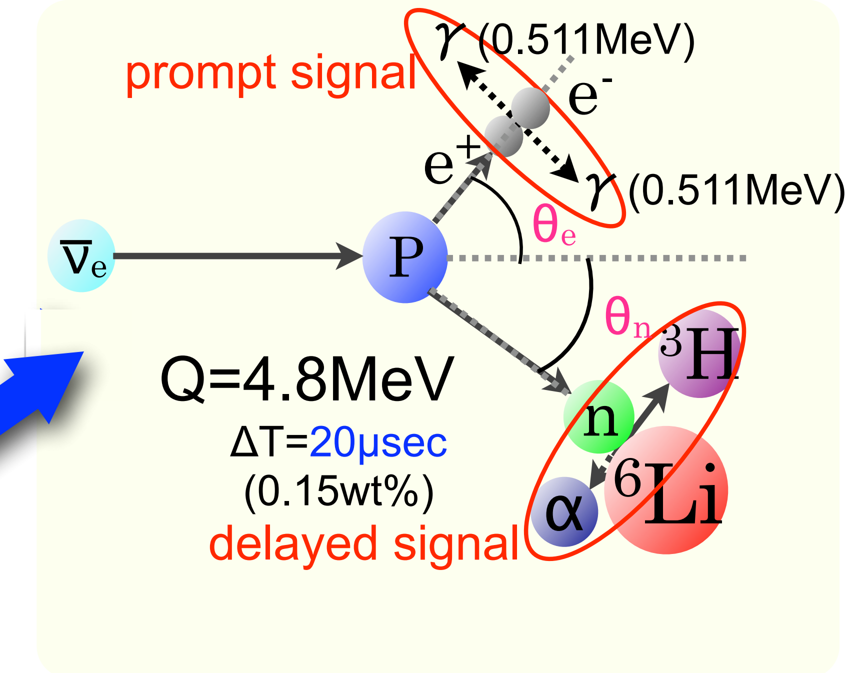
$E_{\bar{\nu}e}$ <3MeV→θ_n<35°

neutron has directional information of anti-neutrino

[current liquid scintillator]



[Li loaded liquid scintillator]



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

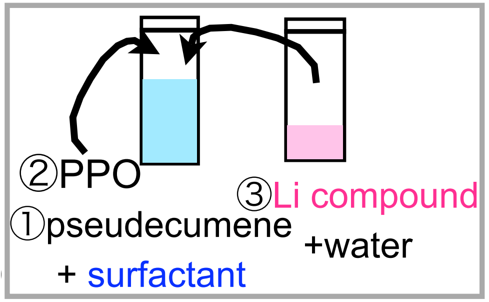
+

high vertex resolution imaging detector

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

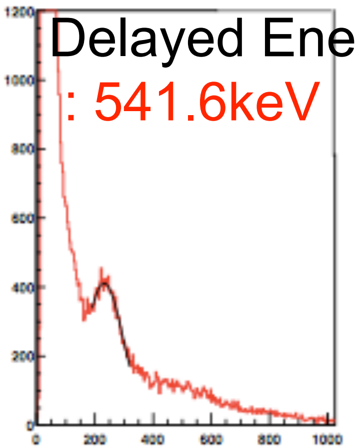
^{6}Li LS

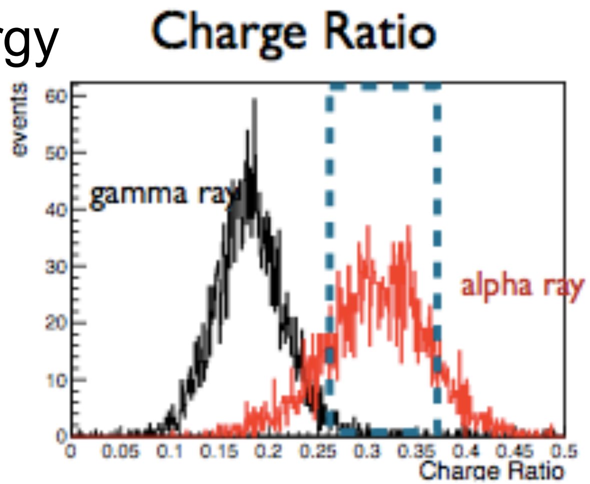
LiBr water solution
+surfactant
+PC+PPO



* We have developed ^{6}Li-LS by the original method
  * enough quality for small size detector
  * confirm > 2.5 years stability

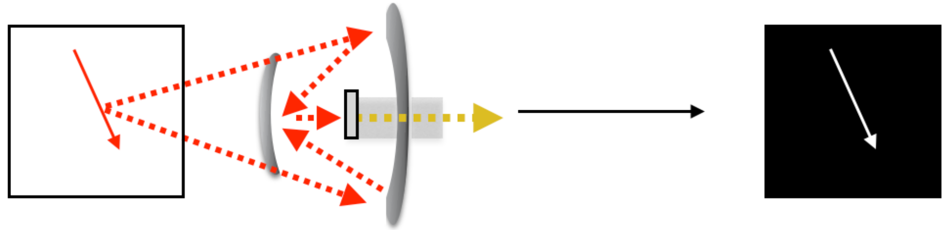
* ^{6}Li neutron capture measurement

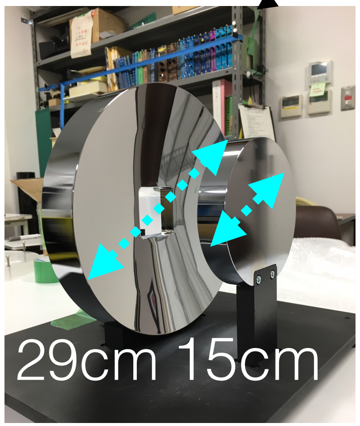




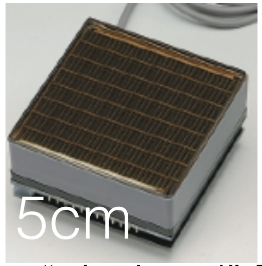
PSD quality
α acquisition efficiency:90%
γ rejection efficiency:94.27%

Imaging Detector

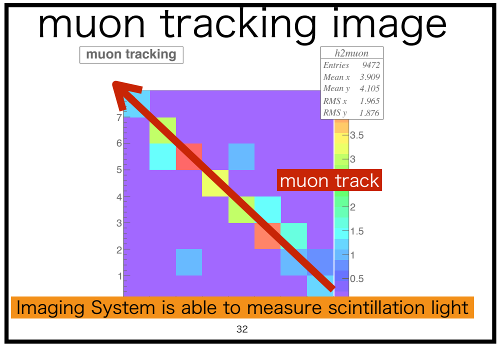




Hamamatsu H12700



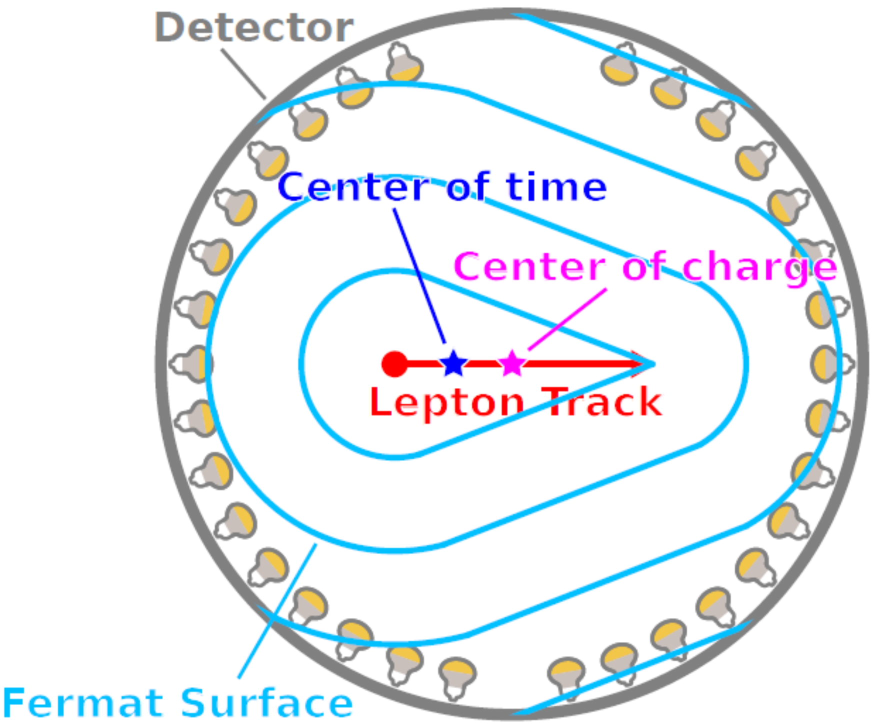
- “pixelated” PMT (64 or 256 ch)
- required to measure 1 p.e.



Ongoing Studies

* imaging test with ^{252}Cf neutron source
* 3D vertex reconstruction with 2 Imaging detectors

Idea : J. Learned (arXiv:0902.4009)



Event Reconstruction

(M. Sakai)

- Center of charge fits middle of track
- **Fermat surface**
  ≡ earliest possible photons
  ≈ Cherenkov +
  earliest scintillation
- **Center of time**
  (using Fermat surface photons)
  fits near one end of track
- **And connect dots!**

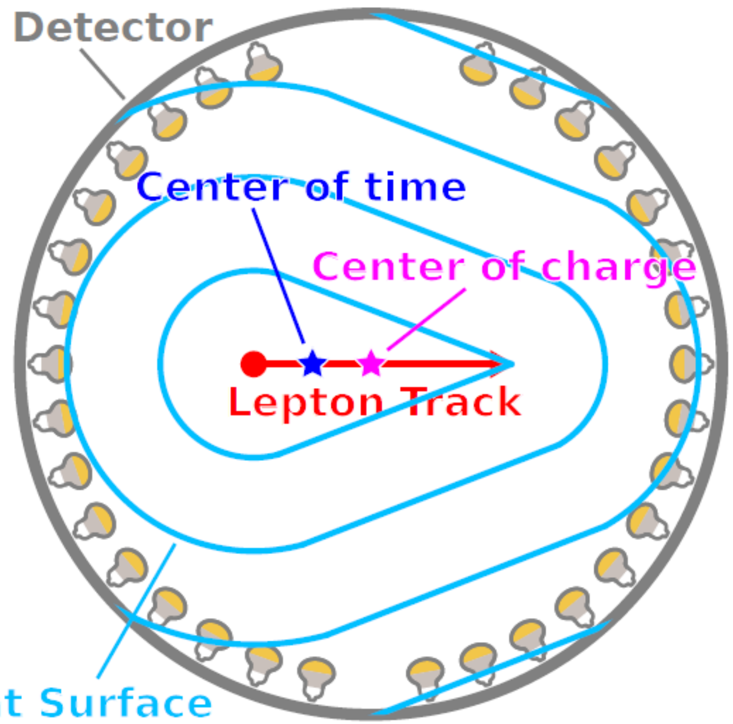
Unpublished

- Higher energy neutrino interactions
  (e.g. from cosmic ray, accelerator)
  * produce enough light to illuminate every PMT
  * scintillation light is isotopic

Directional reconstruction using "Fermat Surface"

Idea : J. Learned (arXiv:0902.4009)

Unpublished



- Higher energy neutrino interactions (e.g. from cosmic ray, accelerator)
  - * produce enough light to illuminate every PMT
  - * scintillation light is isotopic

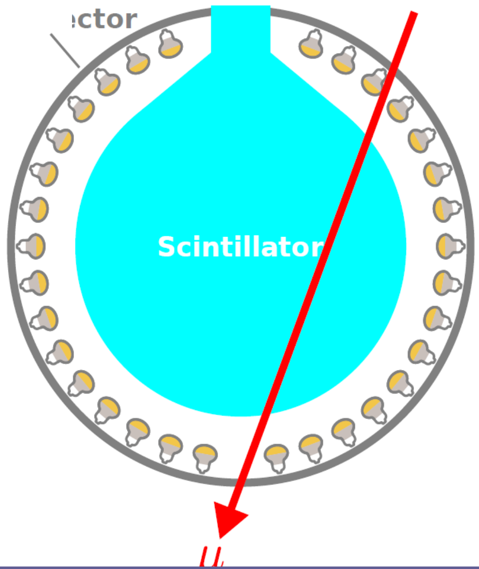
Directional reconstruction using "Fermat Surface"

Event Reconstruction (M. Sakai)

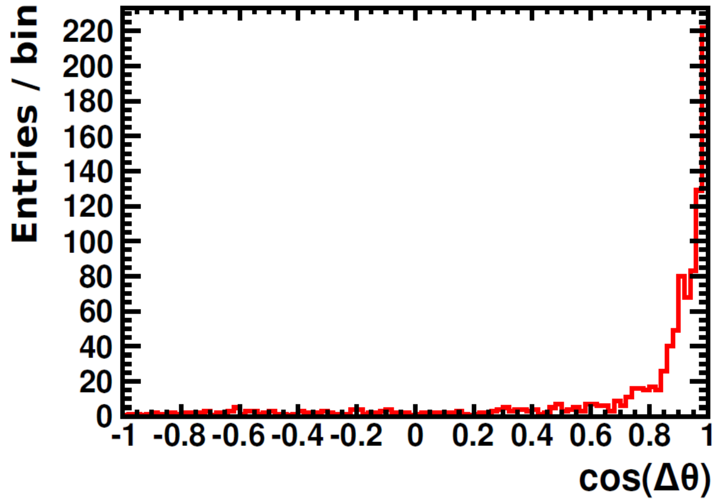
- Center of charge fits middle of track
- **Fermat surface**
  $\equiv$ earliest possible photons
  $\approx$ Cherenkov +
  earliest scintillation
- **Center of time**
  (using Fermat surface photons)
  fits near one end of track
- **And connect dots!**

Muon Event Reconstruction (M. Sakai)

μ track traversing detector

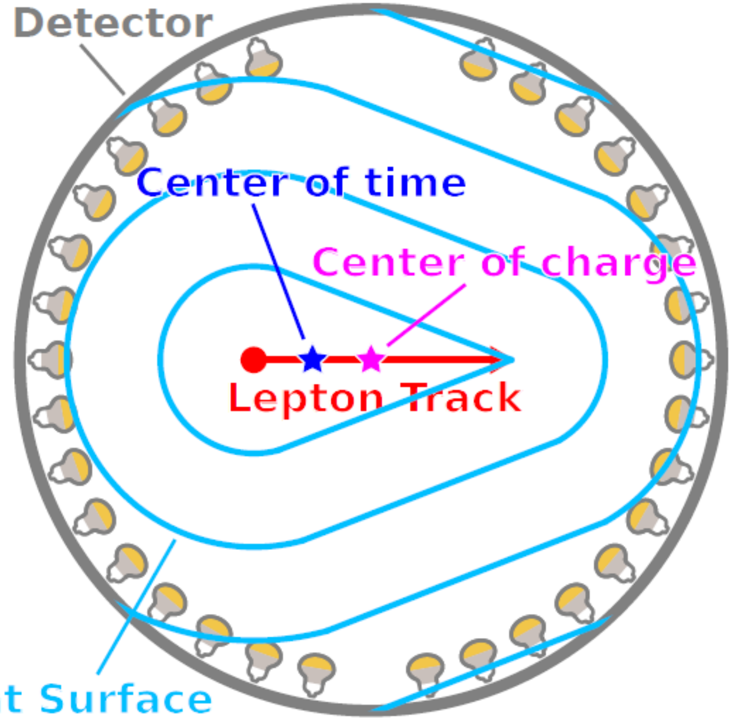


Angle deviation $\Delta\theta$ from entry-exit point μ-fitter



Directional Reconstruction in KamLAND

Idea : J. Learned (arXiv:0902.4009)



Unpublished

- Higher energy neutrino interactions (e.g. from cosmic ray, accelerator)
  * produce enough light to <u>illuminate every PMT</u>
  * scintillation light is <u>isotopic</u>

Directional reconstruction using "Fermat Surface"

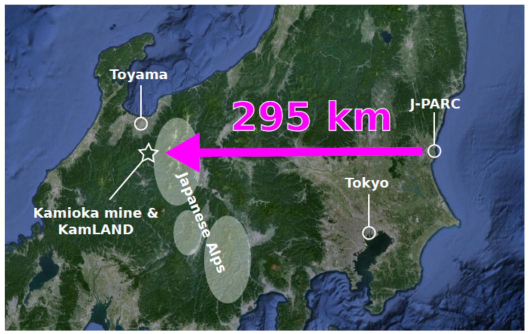
Event Reconstruction (M. Sakai)

- Center of charge fits middle of track
- **Fermat surface** ≡ earliest possible photons ≈ Cherenkov + earliest scintillation
- Center of time (using Fermat surface photons) fits near one end of track
- **And connect dots!**

<u>T2K Event Reconstruction</u> (M. Sakai)

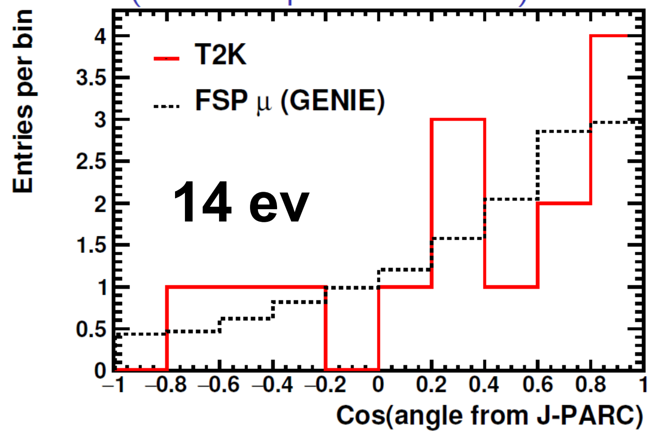
Sample is pure beam neutrinos due to having spill times

Map



Agreement with MC

(K-S test p-value = 0.65)



Summary

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

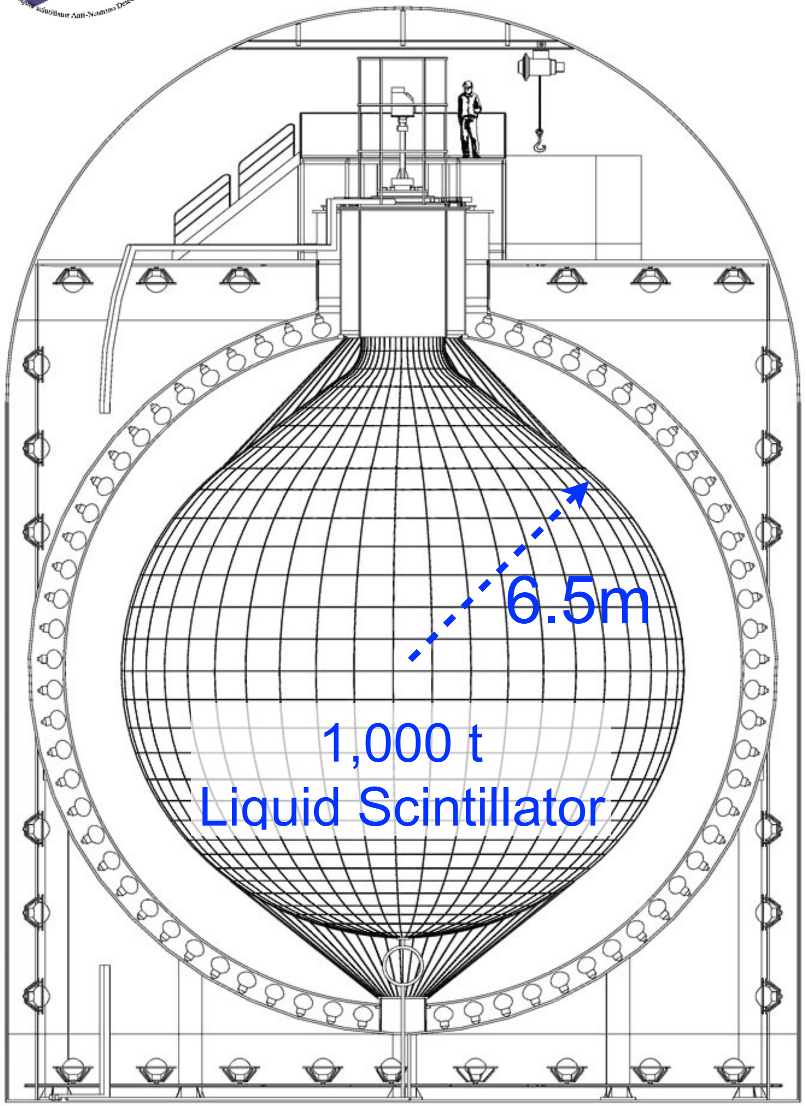
- **Preliminary results are presented.**
  - Low-reactor operation period : ~3.5 years (33% of total livetime), **clear energy spectrum of geo-neutrino**
  - geo-neutrino event measurement with **17% uncertainty** ($164\ ^{+28}_{-25}$ ev). It is consistent with our expectation.
  - geoscience discussion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

- **Studies for directional measurement are ongoing**

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

KamLAND
2000~



Detector Features

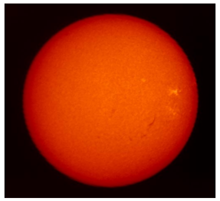
large volume & low backgrounds

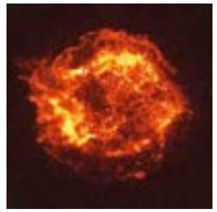
Physics

observed energy [MeV]: 0.4, 1.0, 2.6, 8.5

electron scattering $\nu + e^- \rightarrow \nu + e^-$

inverse beta-decay $\bar{\nu}_e + p \rightarrow e^+ + n$





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)

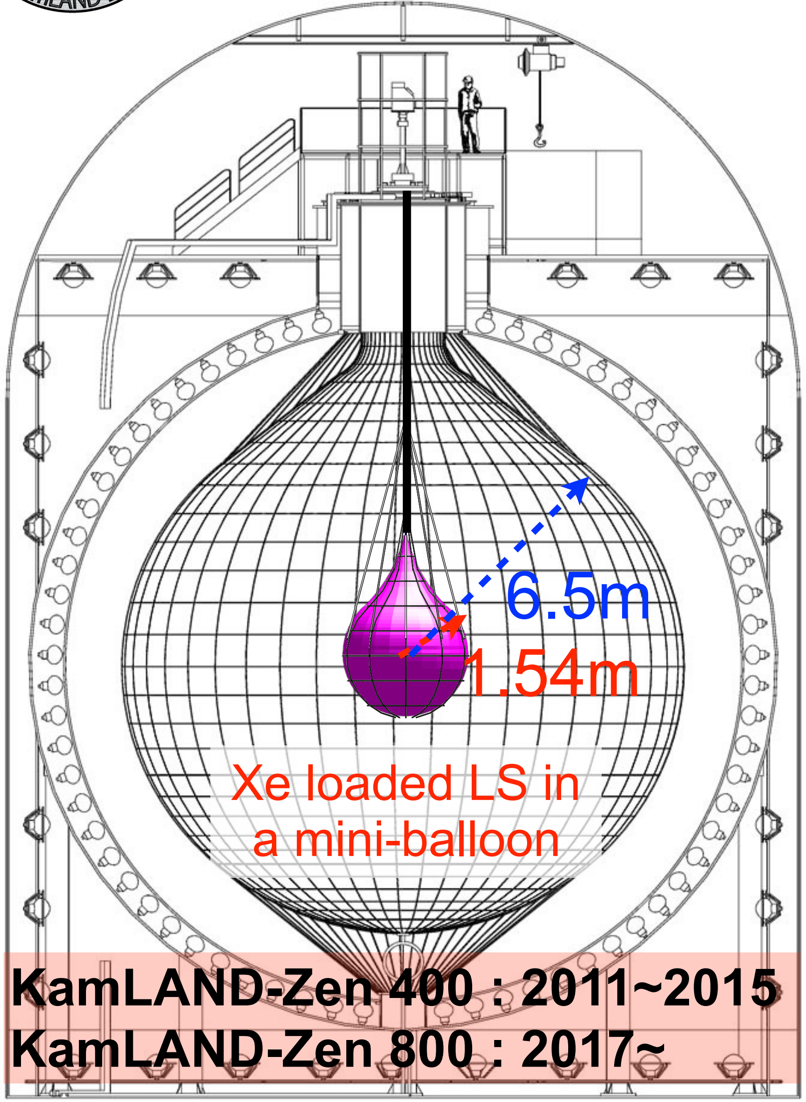
Different neutrino physics
in a wide energy range

KamLAND-Zen

KamLAND-Zen

2011~

Zero Neutrino double beta decay search

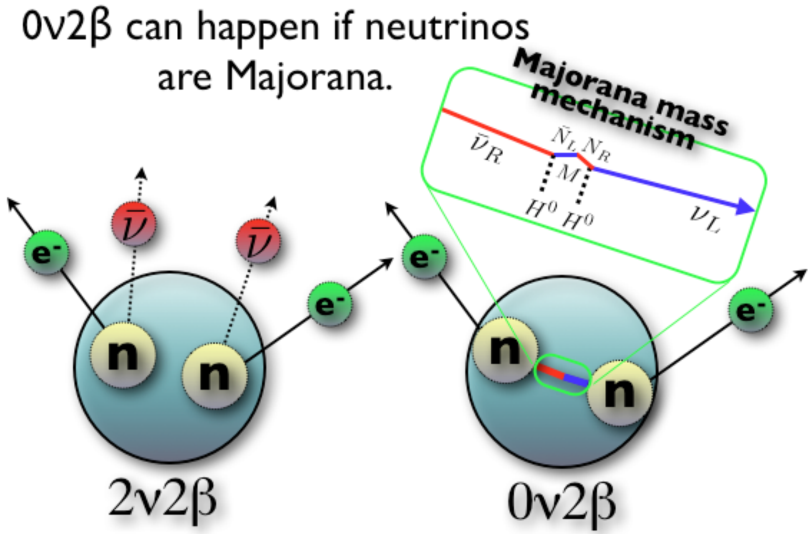


KamLAND-Zen 400 : 2011~2015
KamLAND-Zen 800 : 2017~

Detector Features

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

Physics



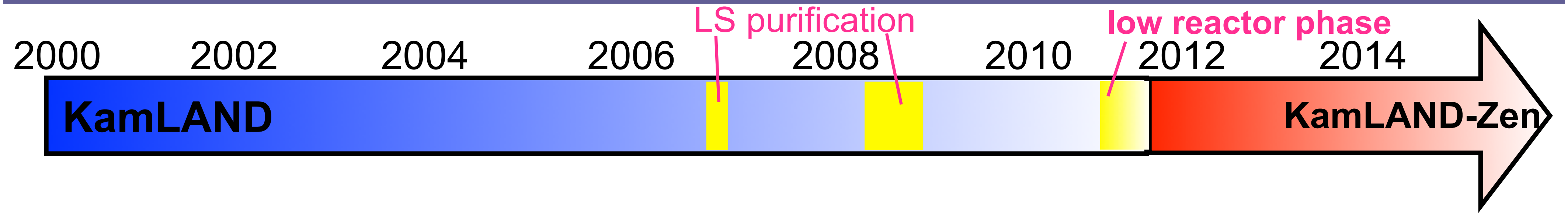
neutrino-less double beta decay

World best limit on neutrino effective mass

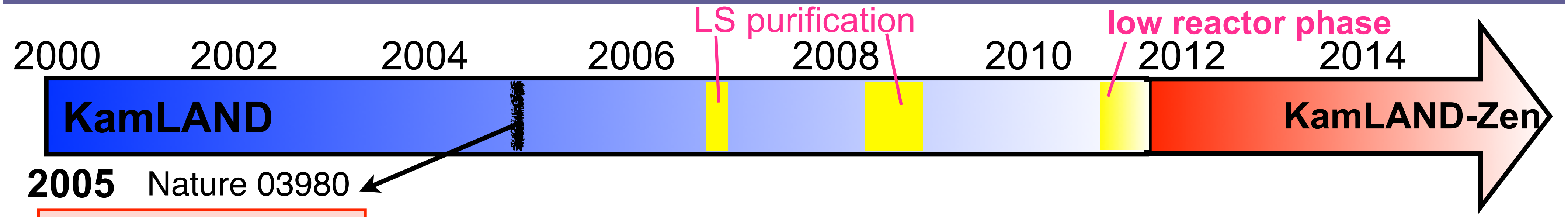
$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \mathrm{meV}$$ PRL 117, 082503 (2016)

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

Geo-neutrino Measurements with KamLAND

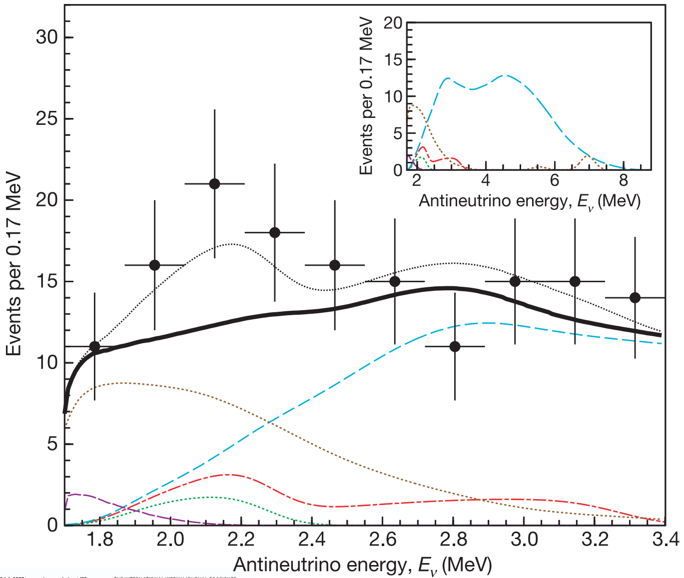


Geo-neutrino Measurements with KamLAND



2005 Nature 03980

geo-neutrino first measurement



749 days

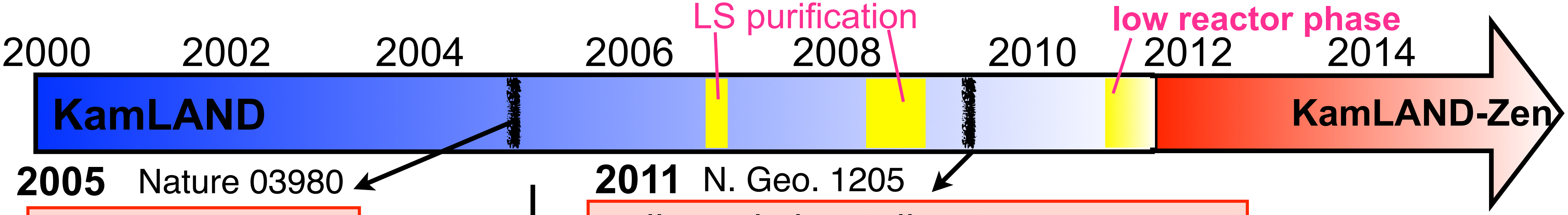
0.71×10^{32} proton-year

<u>geo-nu event</u>

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

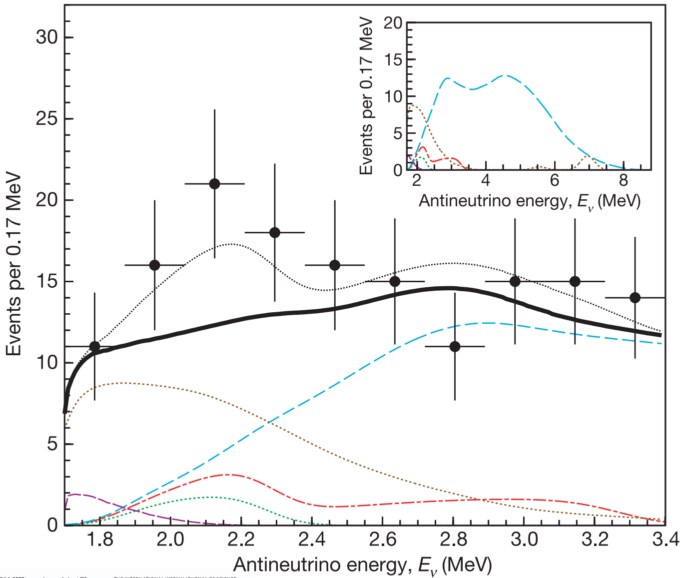
(56% error)

Geo-neutrino Measurements with KamLAND



2005 Nature 03980

geo-neutrino first measurement



749 days

0.71×10^{32} proton-year

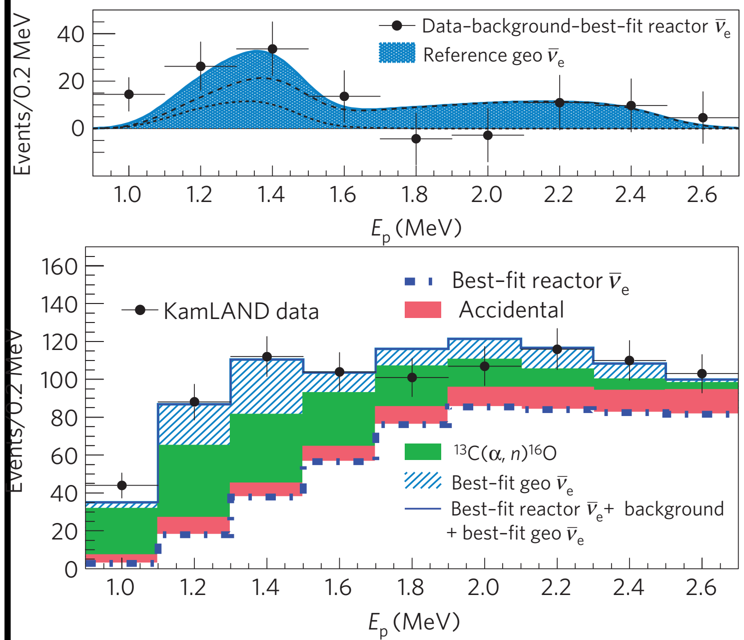
<u>geo-nu event</u>

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

(56% error)

2011 N. Geo. 1205

radiogenic heat direct measurement



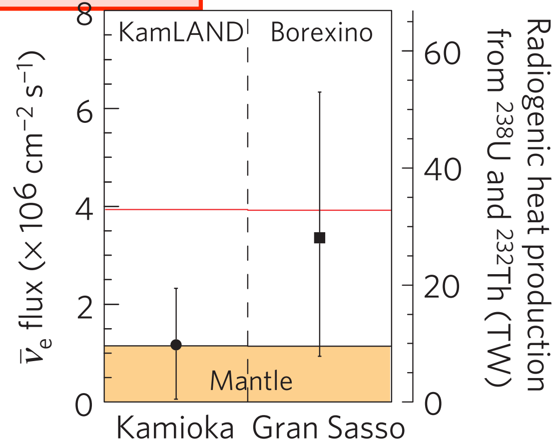
2135 days

3.49×10^{32} proton-year

<u>geo-nu event</u>

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

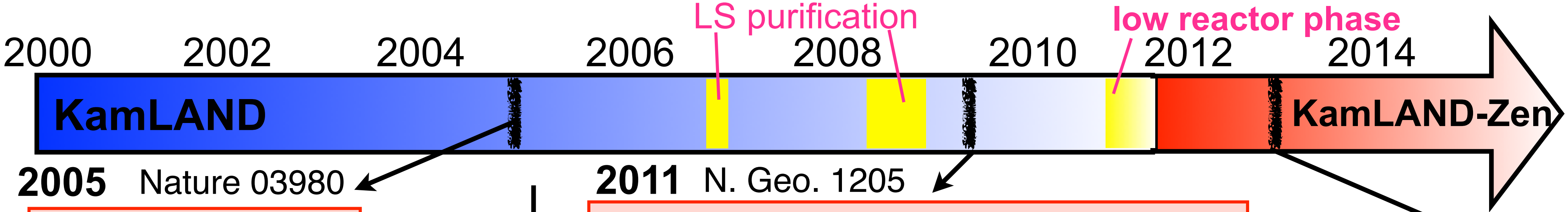
(27% error)



radiogenic heat

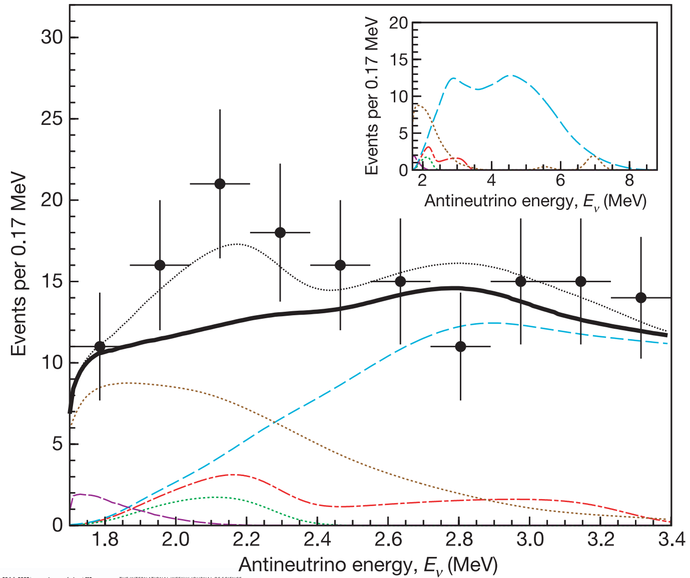
21±9 TW

Geo-neutrino Measurements with KamLAND



2005 Nature 03980

geo-neutrino first measurement



749 days

0.71×10^{32} proton-year

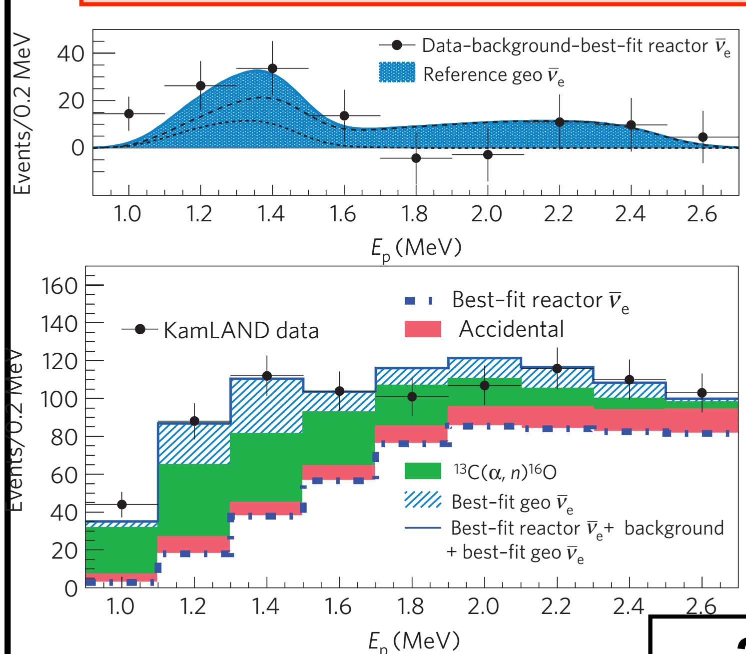
geo-nu event

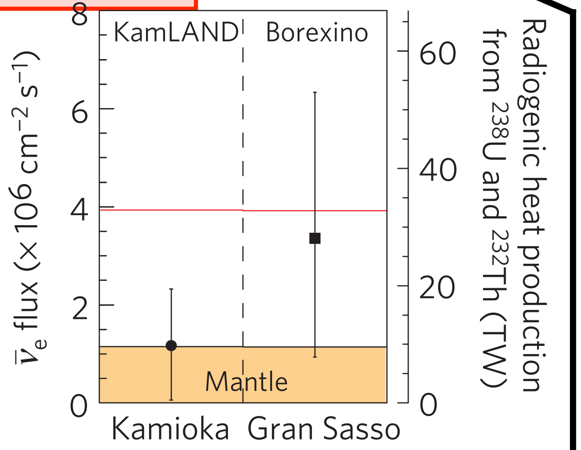
$28.0^{+15.6}_{-14.6}$ ev

(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} ev

(27% error)

2013 PRD 88, 03301 (2013)

include low reactor phase data

2991 days

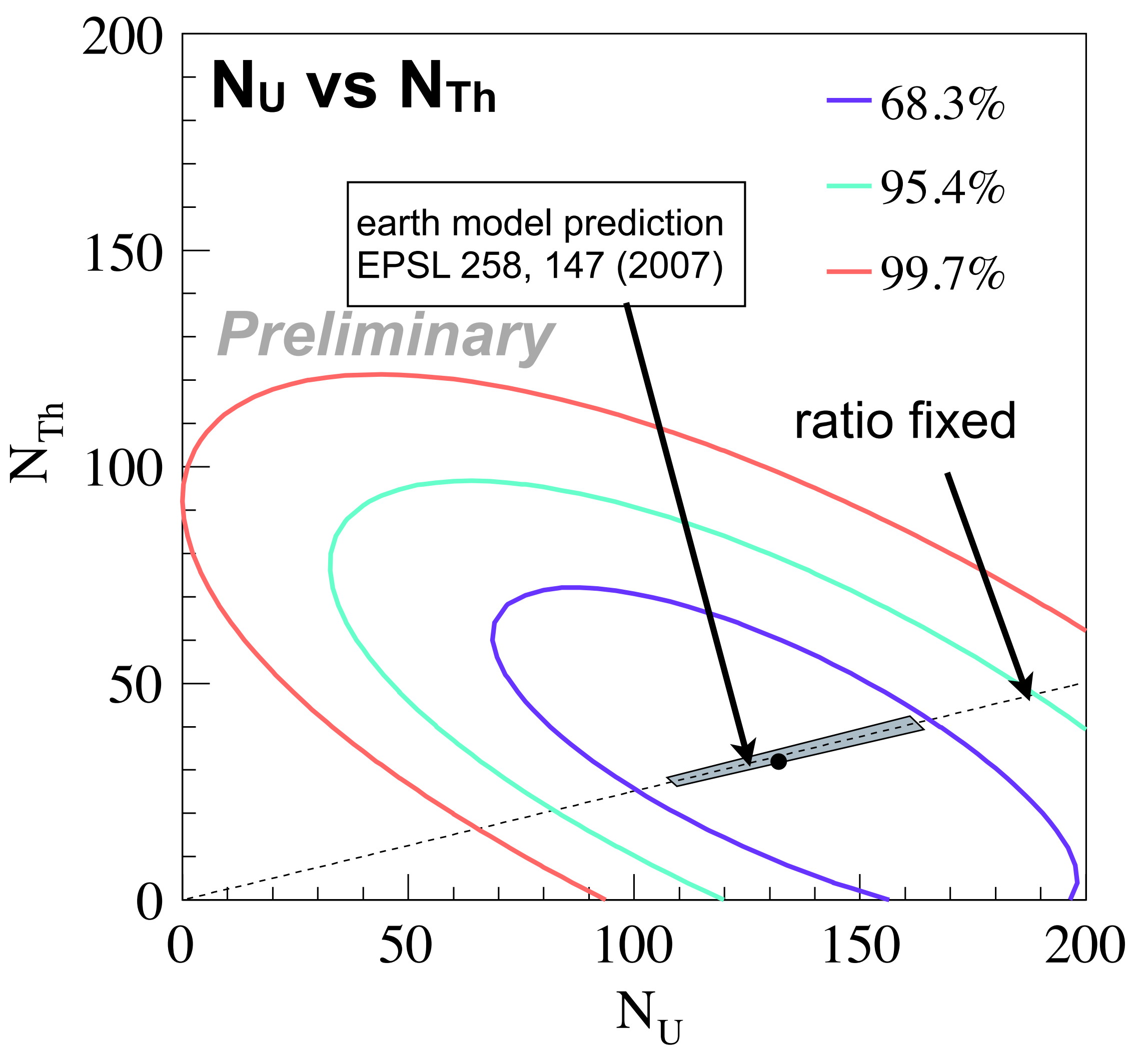
4.90×10^{32} proton-year

geo-nu event

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

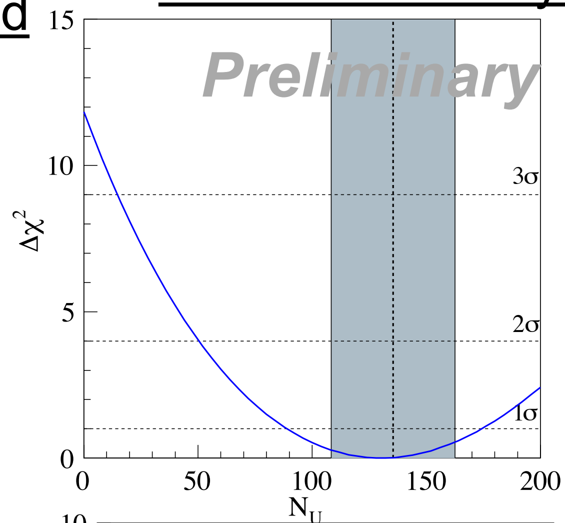
Rate + Shape + Time Analysis (1)

2016 Preliminary Result

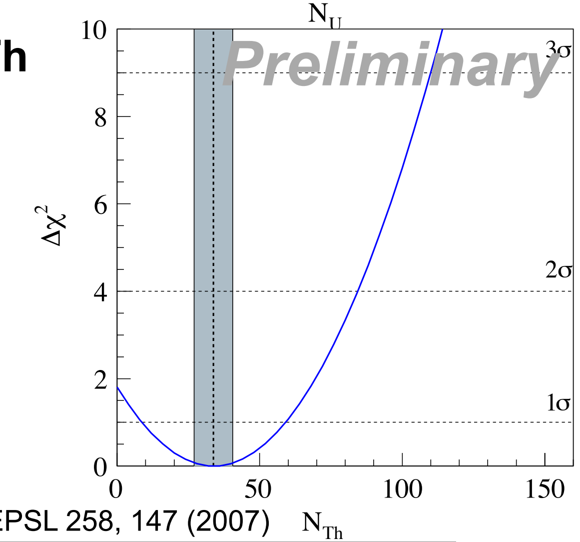


ratio fixed

N$_U$



N$_{Th}$



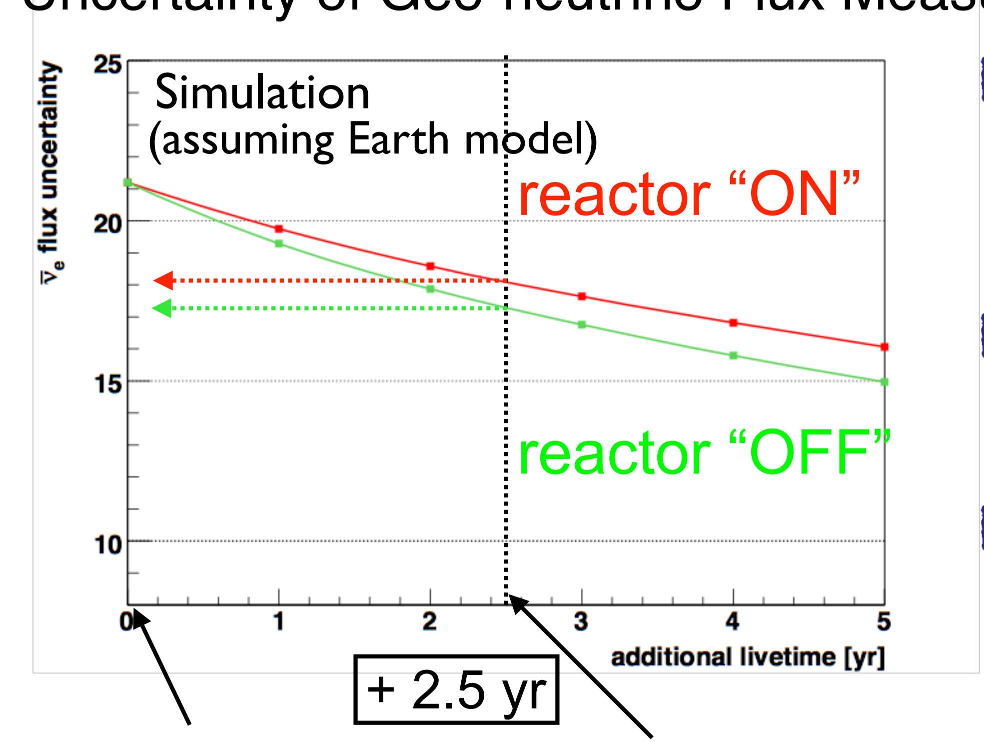
model prediction : Enomoto et al. EPSL 258, 147 (2007)

ratio fixed

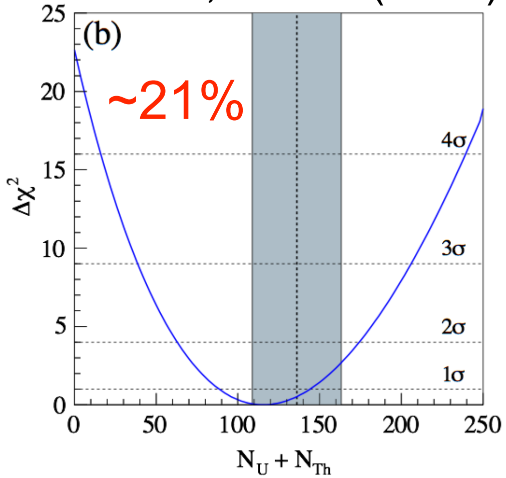
	[event]	[TNU]	Flux [×10^5 cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U	**128 +46/-39**	27.1 +9.8/-8.3	20.8 +7.5/-6.4	22.0	**3.44σ**
Th	**32 +27/-23**	6.9 +5.9/-5.0	17.2 +14.5/-12.5	18.6	**1.34σ**

Future Prospect

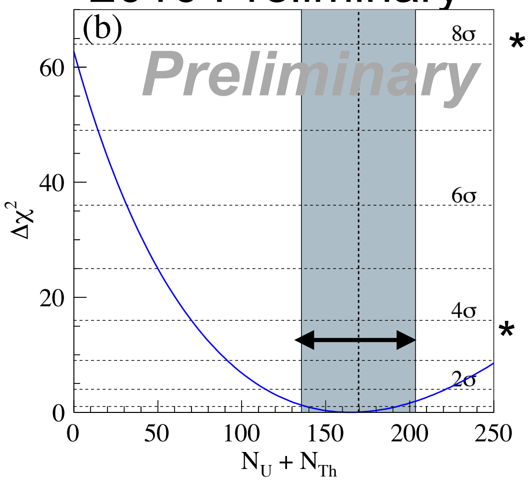
Uncertainty of Geo-neutrino Flux Measurement



PRD 88, 03301 (2013)



2016 Preliminary



- ☑ 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.

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

* uncertainty of Earth model prediction : 20%