KamLAND

status of geo-neutrino detection

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for the KamLAND Collaboration

Contents

Contents

KamLAND Collaboration

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9 Triangle Universities Nuclear Laboratory and Physics Departments at Duke University and the University of North Carolina
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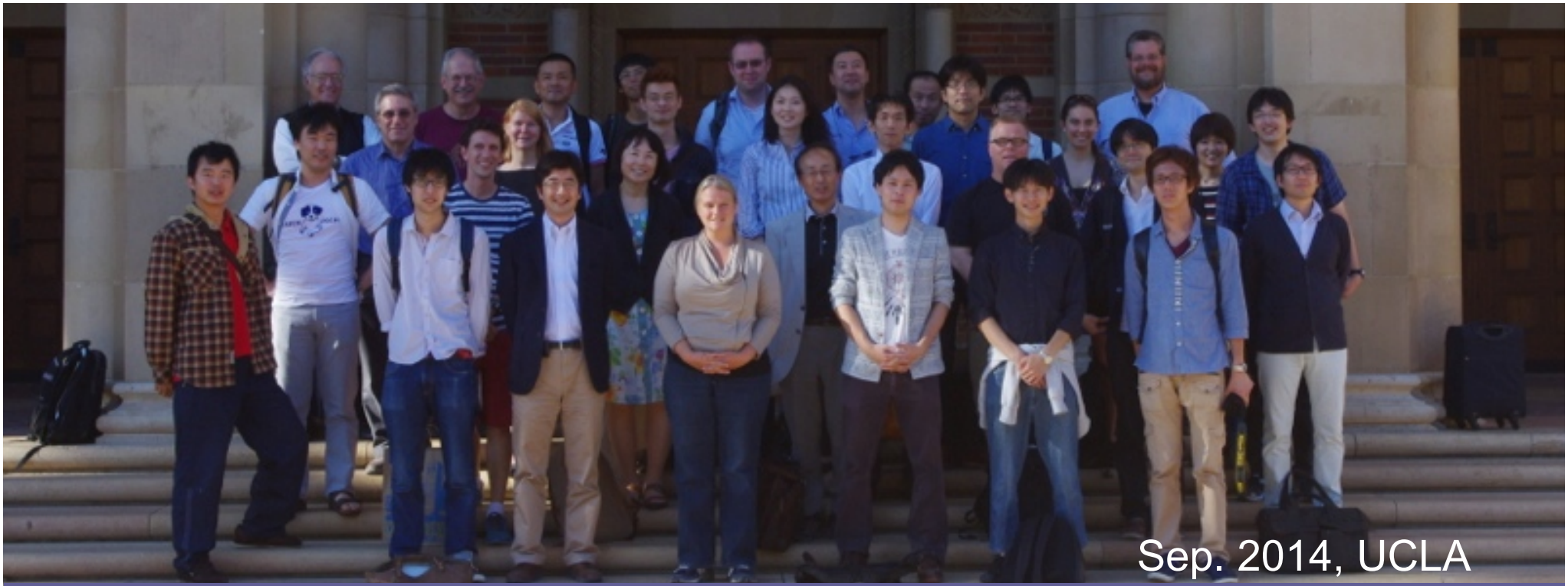
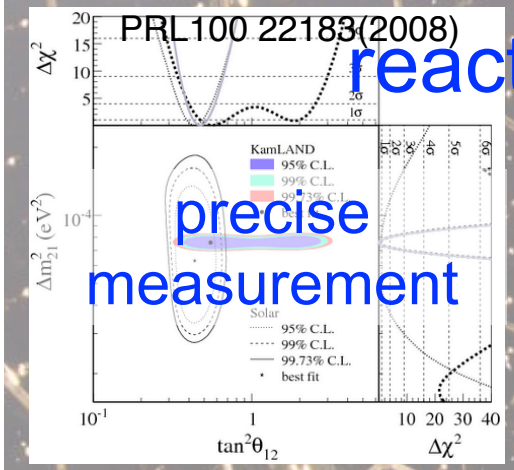
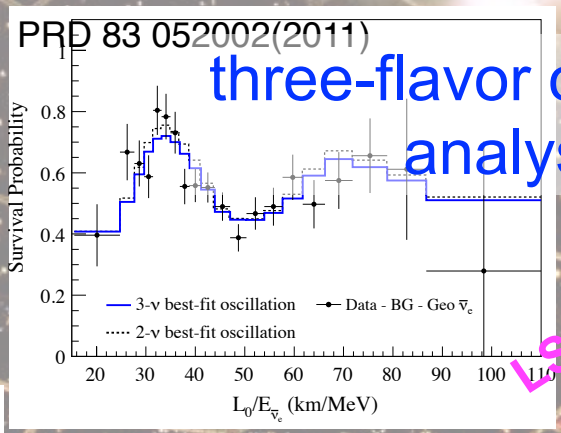


Overview of KamLAND Neutrino Physics

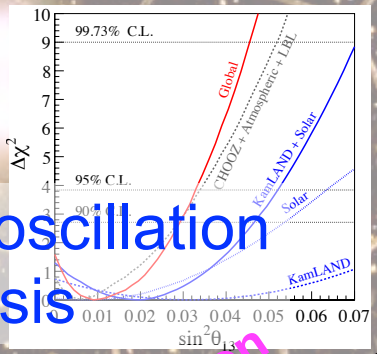


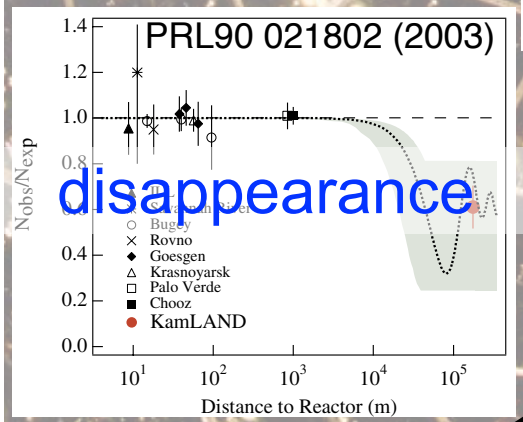
reactor neutrinos

precise measurement

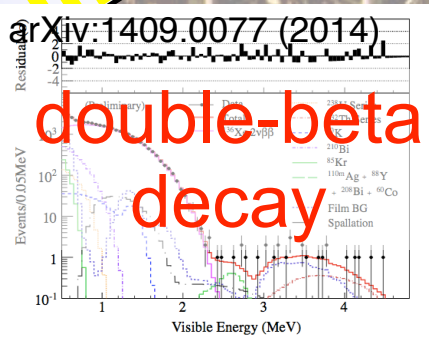


three-flavor oscillation analysis

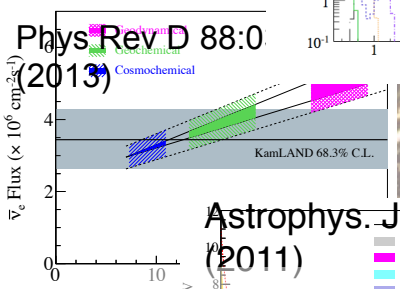


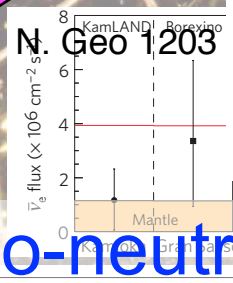


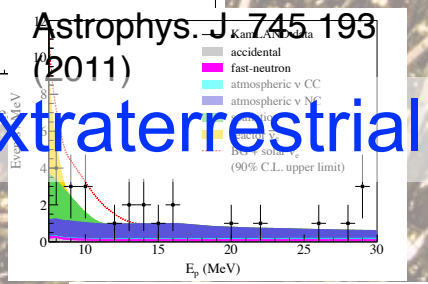
disappearance



double-beta decay

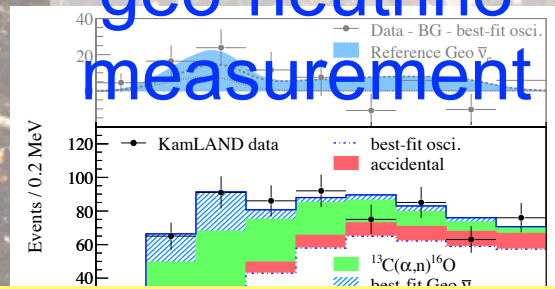


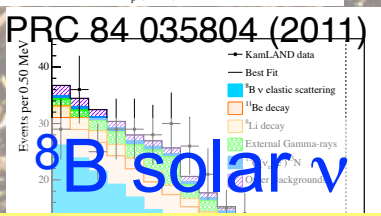




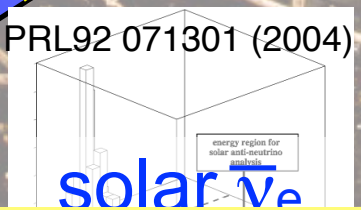
extraterrestrial $\bar{\nu}_e$

geo-neutrino measurement





^{8}B solar ν



solar $\bar{\nu}_e$

2000 2002 2004 2006 2008 2010 2011 2013

KamLAND

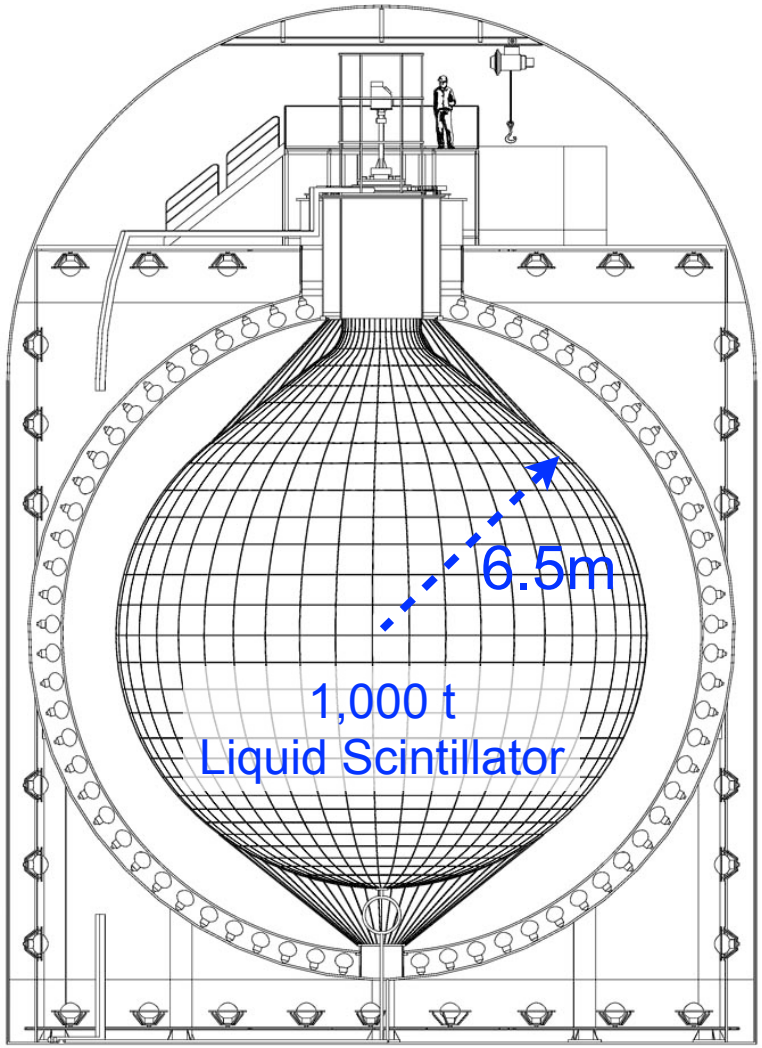
LS Purification

KamLAND-Zen

We continue to study neutrino physics with KamLAND

KamLAND

2000~

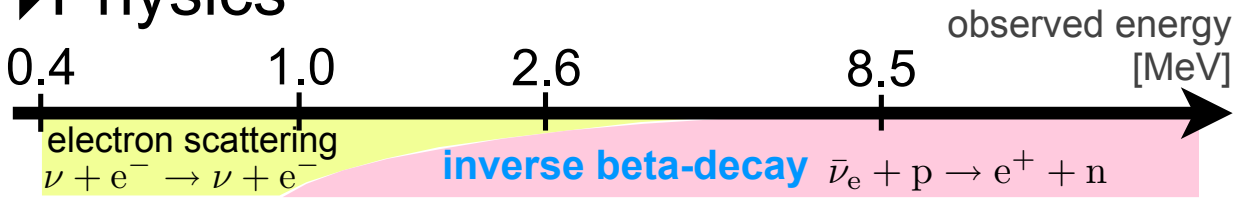


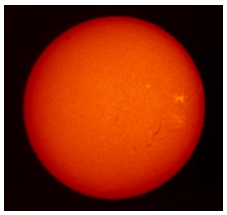
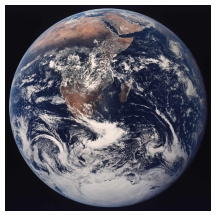
Detector Features

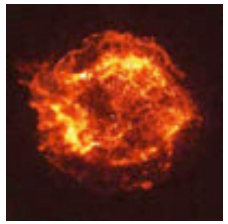
1,000t ultra-pure liquid scintillator

^{232}U: 3.5x10^{-18} g/g, ^{238}Th: 5.2x10^{-17} g/g

Physics





solar neutrinos
PRC 84, 035804 (2011)

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

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

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

Different neutrino physics in a wide energy range

KamLAND-Zen

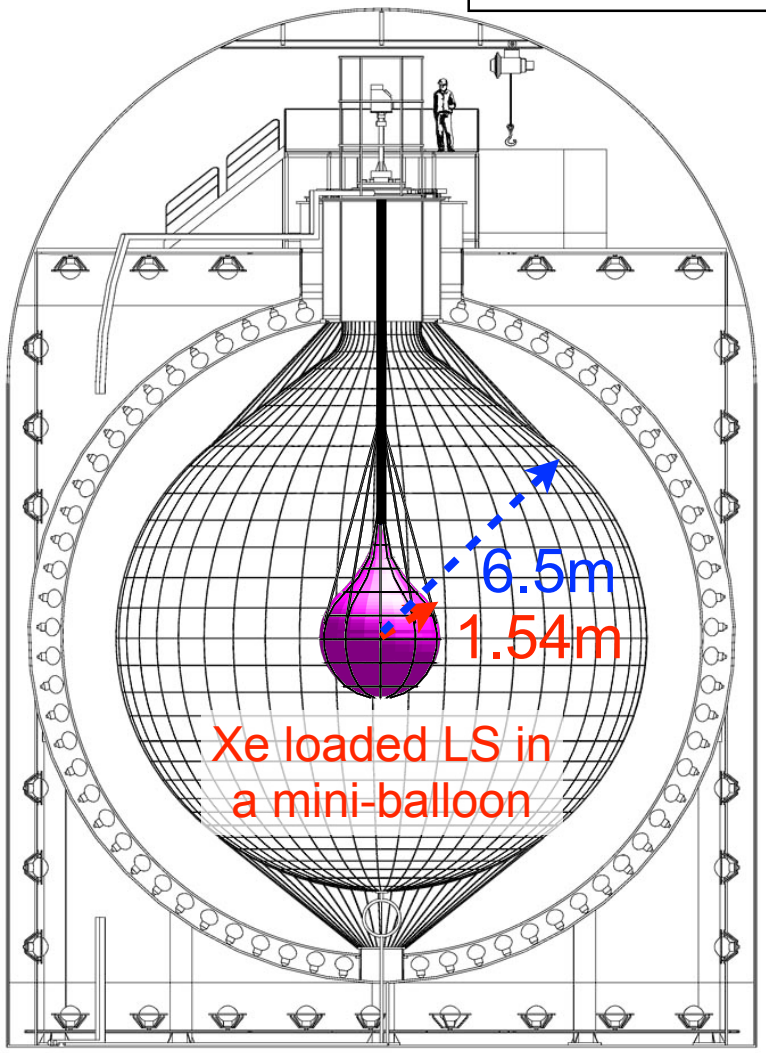
2011~

Zero Neutrino
double beta decay search

Detector Features

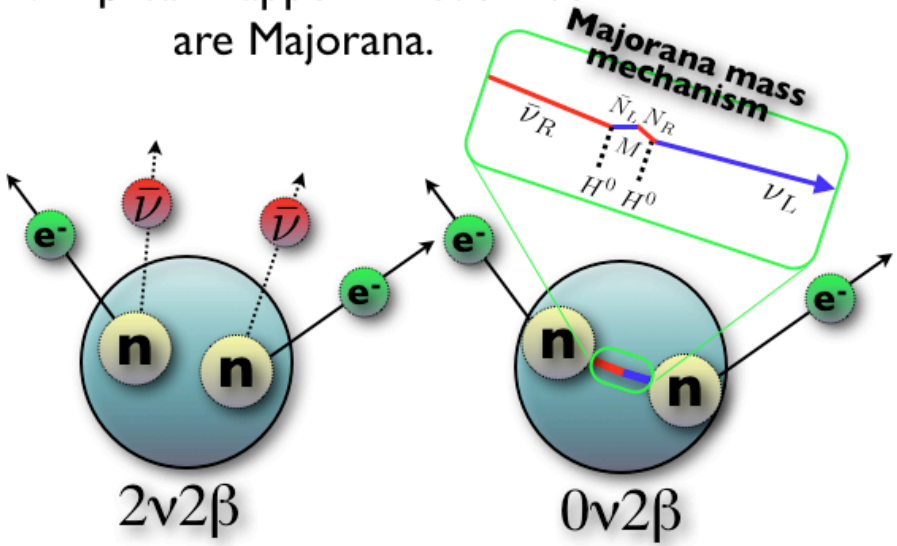
^{136}Xe loaded LS was installed in KamLAND

(383 kg of ^{136}Xe enriched Xe installed)



Physics

0ν2β can happen if neutrinos are Majorana.

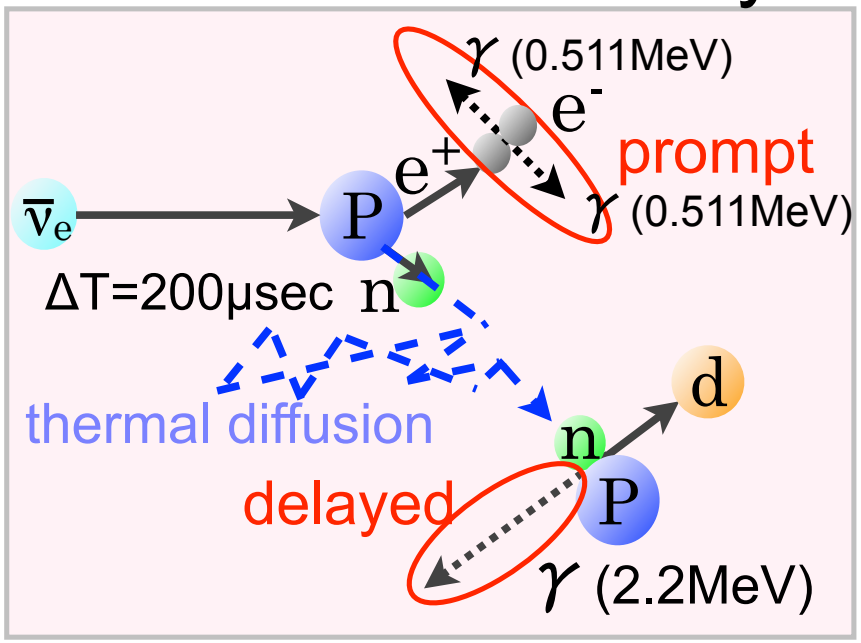


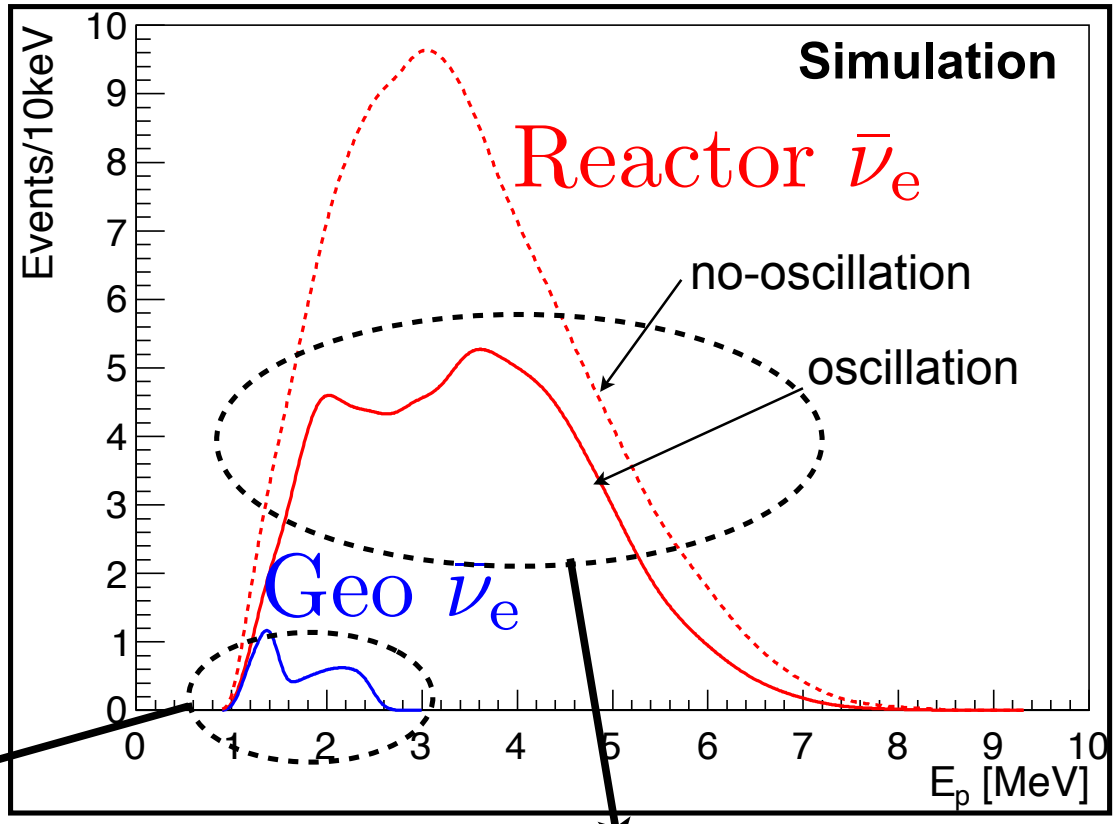
neutrino-less double beta decay

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

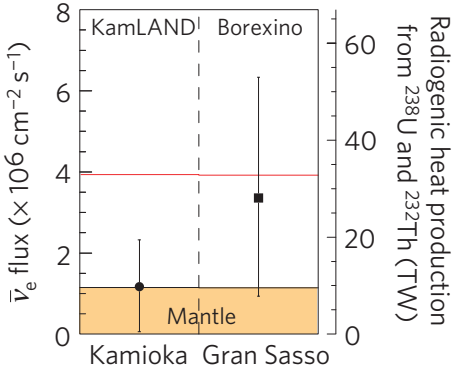
Anti-neutrino Studies

inverse-beta decay



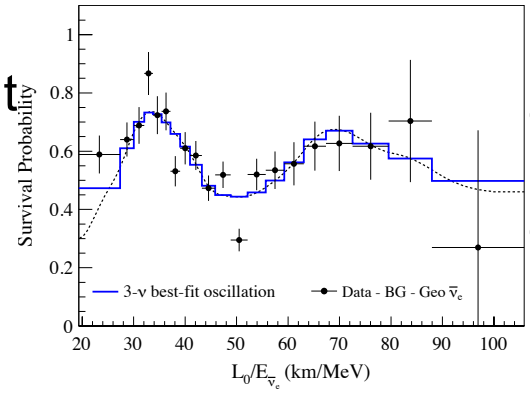


Geoneutrinos : Neutrino Application



- Direct measurement of radiogenic heat contribution

Neutrino Property Study

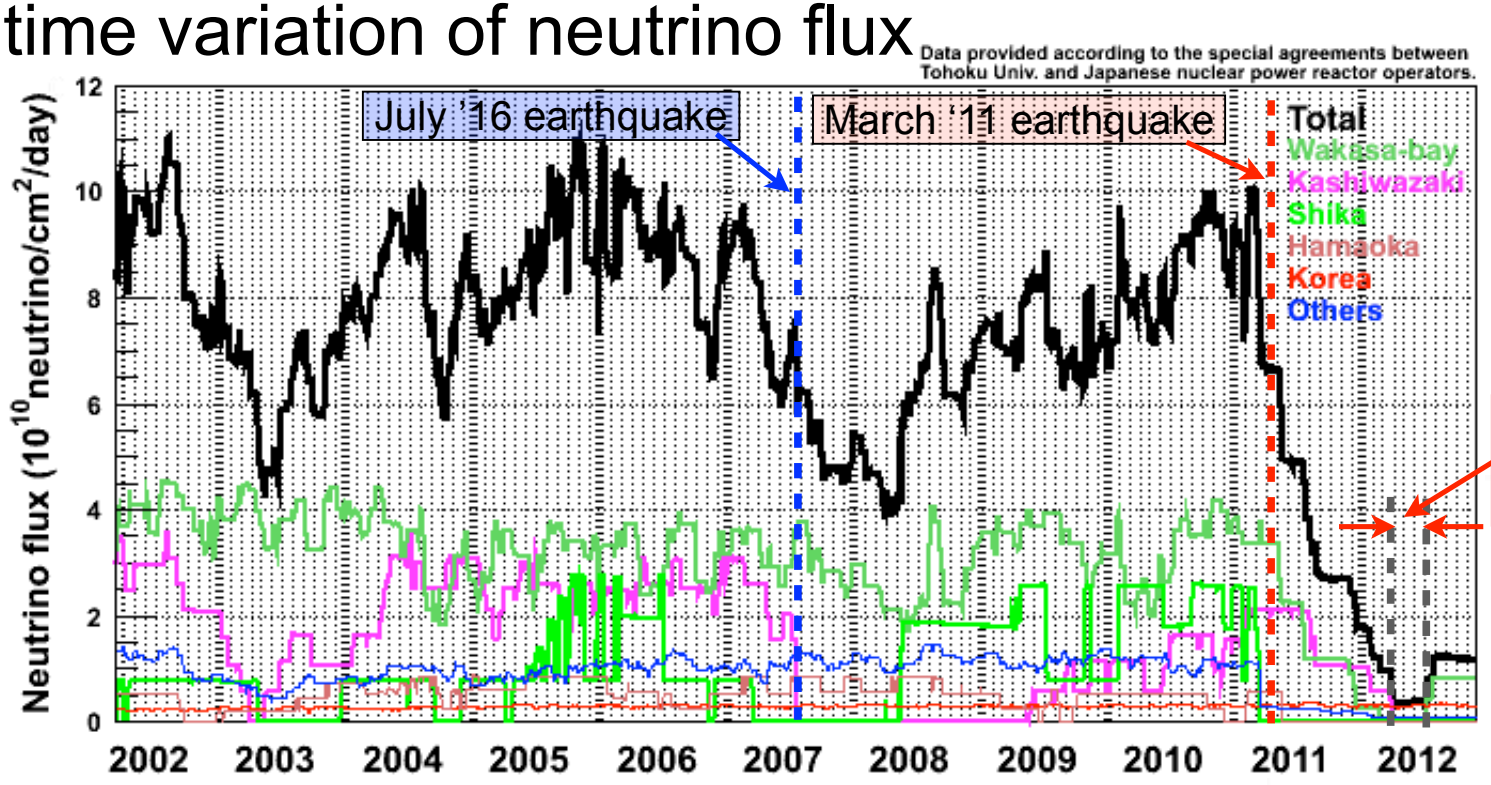


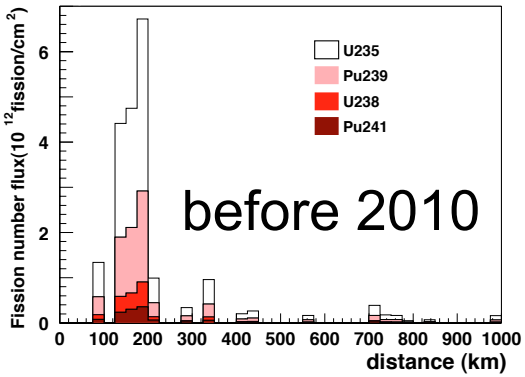
- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

Contents

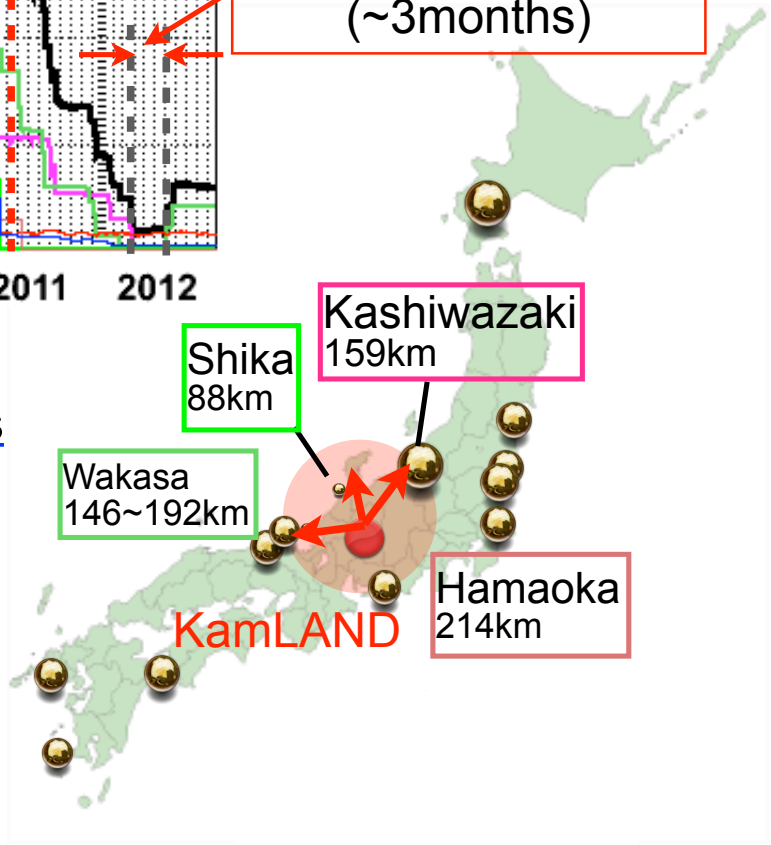
Recent Condition : reactor operation in Japan 6/23

time variation of neutrino flux





all reactor-off period (~3months)



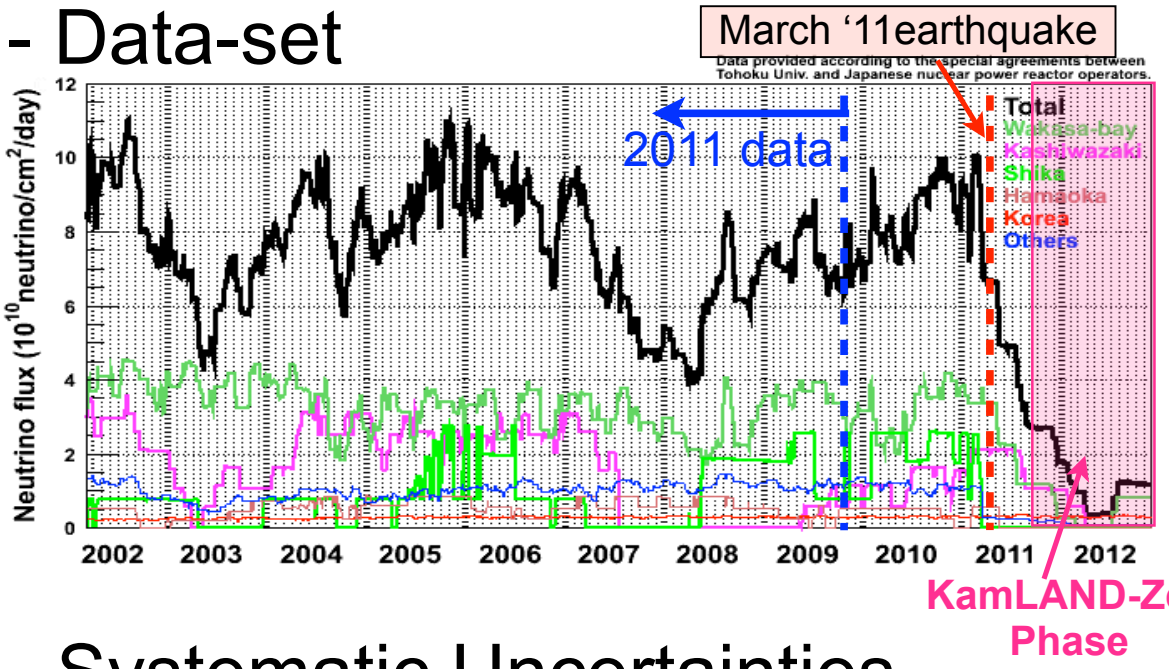
- Following the Fukushima nuclear accident in March 2011, the entire Japanese nuclear reactor industry has been subjected to protected shutdown.

- Reactor neutrino flux, which is outside the control of the experiment, was significantly reduced.

- This situation allows for a "reactor on-off" study of backgrounds for KamLAND neutrino oscillation and geoneutrino analysis.

Data-set & Systematic Uncertainties

- Data-set



PRD 88, 033001 (2013)

2013 data-set : 2991 days

4.90×10^{32} proton-year

- 1.4 times of 2011 data-set
- Includes ~1year low-reactor operation period
- Data collected after KamLAND-Zen construction is also included.

- Spectral update

235U, 239Pu, 241Pu: P. Huber
238U: Th. Mueller et al.

- Systematic Uncertainties

before/after purification

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	1.4 / 1.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_{\rm p})$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	2.7 / 2.8

- Cross section per fission was normalized by Bugey-4 result.
(same method as Double Chooz result)

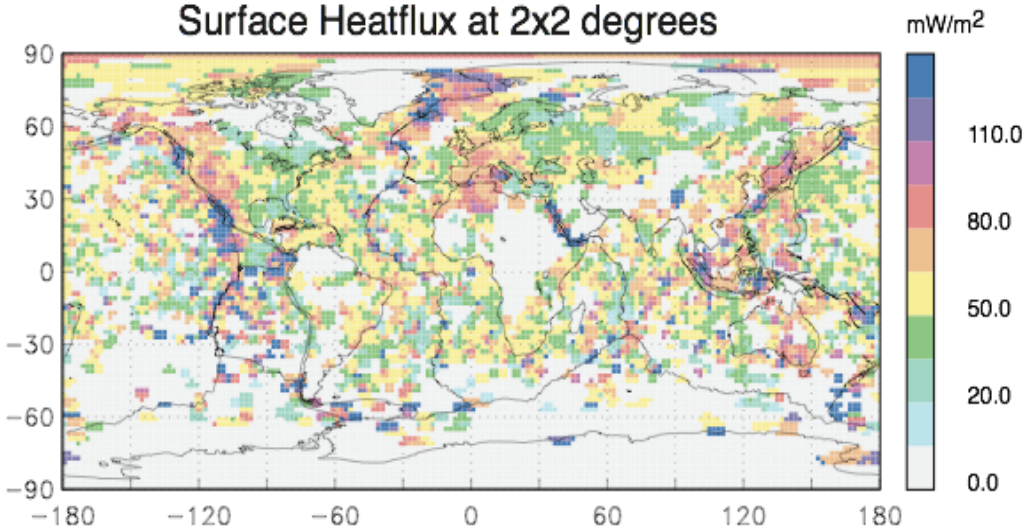
* Bugey-4 : short baseline (14m), performed most precise measurement of the neutrino inverse beta decay cross section.
* Analysis is insensitive to "Reactor Neutrino Anomaly"

Contents

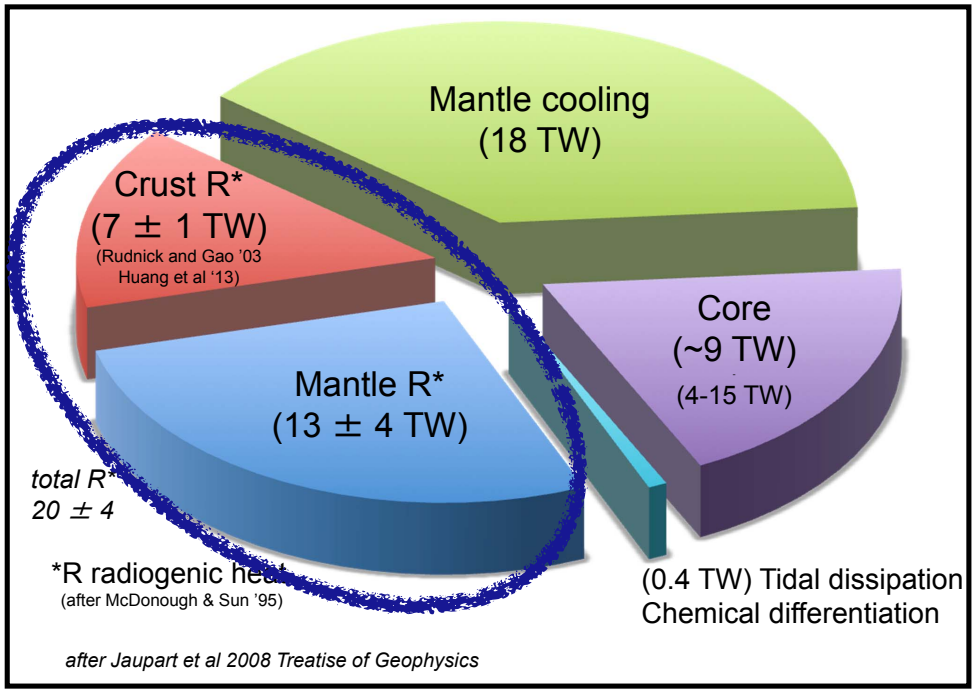
Geo-neutrino: see also
Borexino (Romain Roncin)
GeoSciences (Steve Dye)

☑ Surface heat flow
46 ± 3 TW

crust heat flux measurement & calculation



Pollack et al. 1933, Rev. of Geophys.



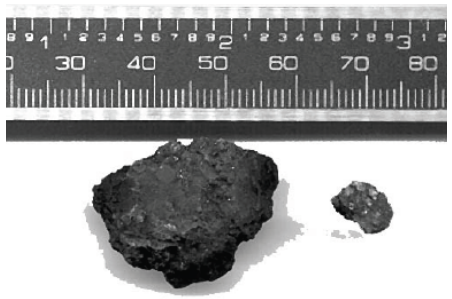
Almost half of radiogenic heat contributes to the surface heat flow.

☑ Radiogenic heat in the Earth

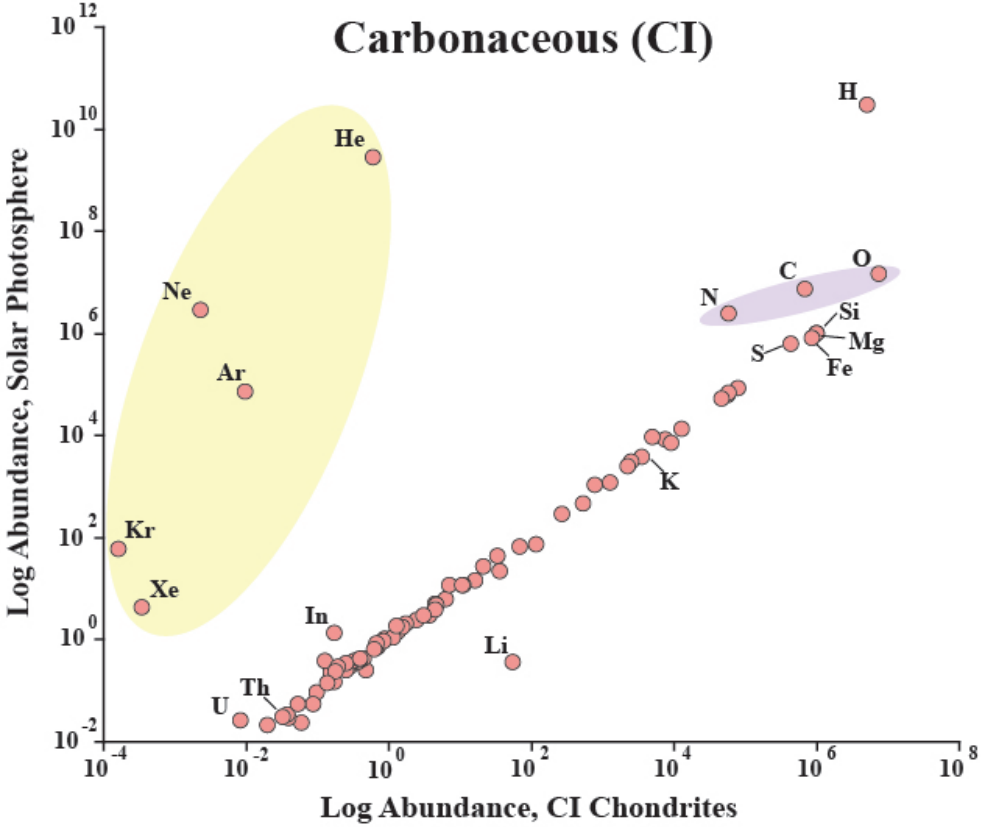
10~30 TW

Bulk Silicate Earth (BSE) model
composition of chondrite meteorite

U : 8 TW
Th : 8 TW
K : 3 TW



This is not “direct measurement”.

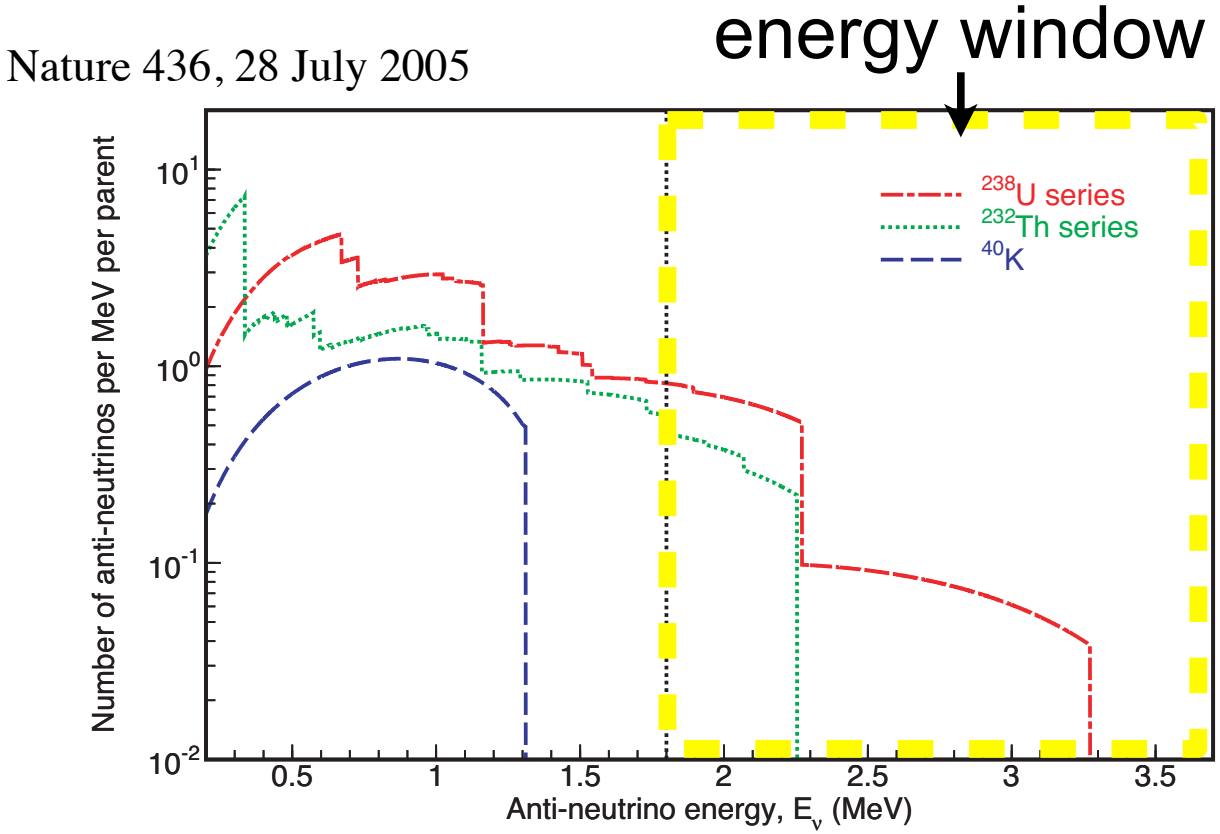


↓

Geo-neutrino can directly test radiogenic heat production.

Geo-neutrino

Geo-neutrinos are a unique, direct window into the interior of the Earth!



beta-decay

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

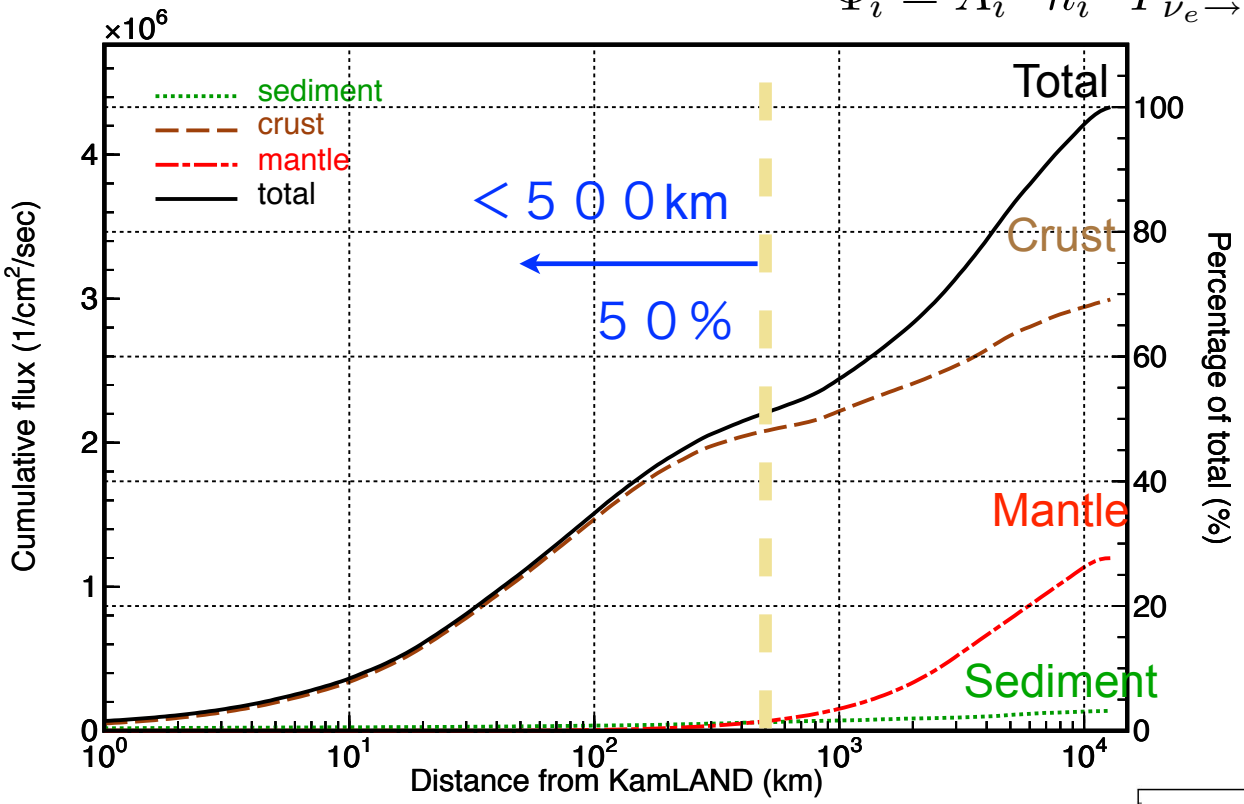
$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

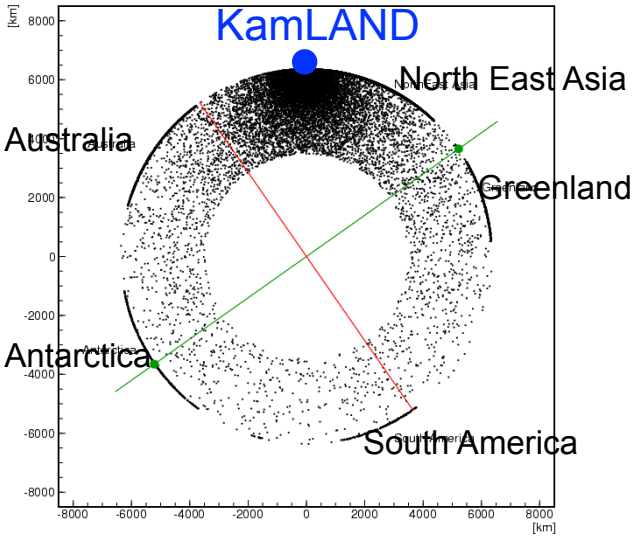
$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\,(89.28\%)$$

detectable

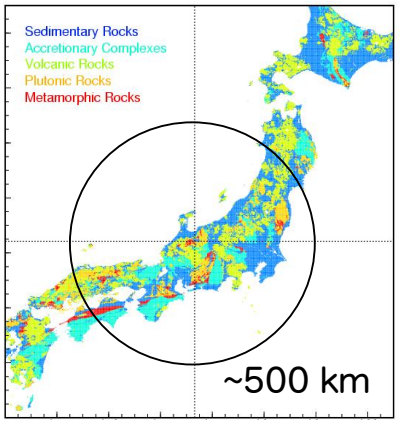
Geo-neutrino Flux at Kamioka

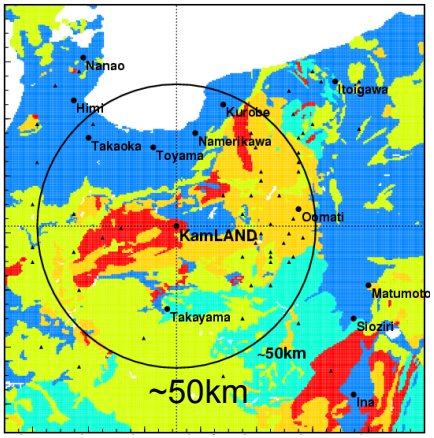
$$\Phi_i = A_i \cdot n_i \cdot P_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu, |\vec{L}|) \cdot \int_V \frac{a_i(\vec{L}) \cdot \rho_i(\vec{L})}{4\pi |\vec{L}|^2} \cdot dV$$



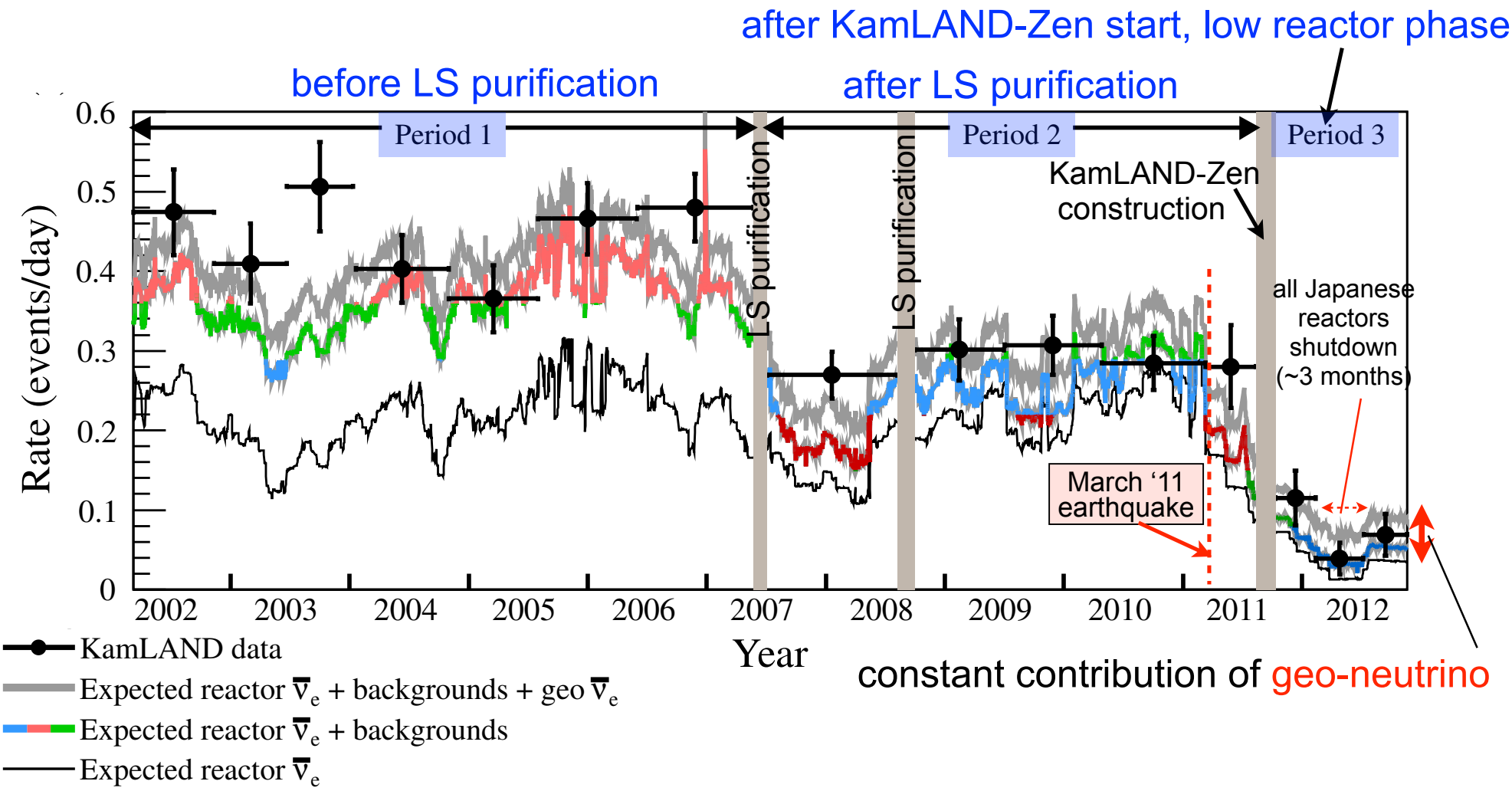


- 50%: distance < 500km
- 25%: distance < 50km
- 1~2%: from Kamioka mine





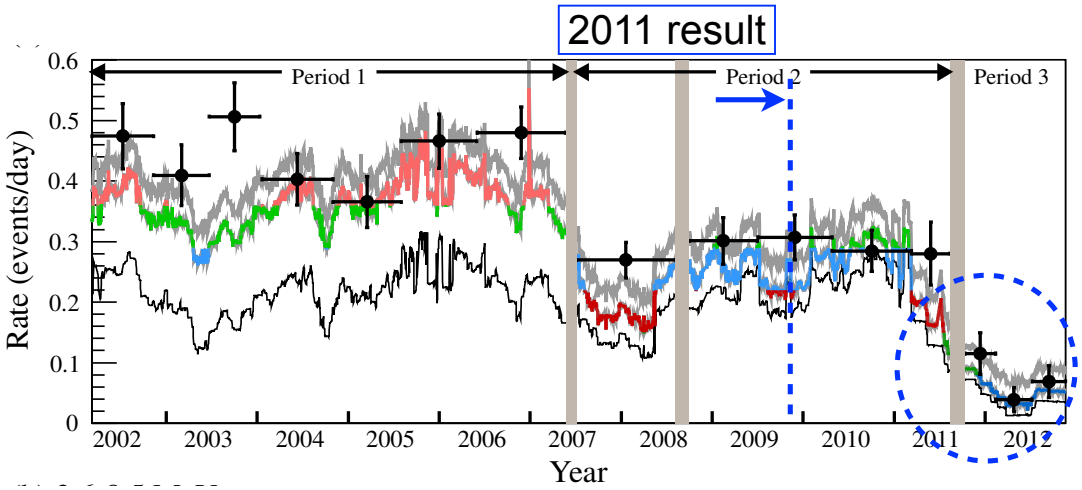
Analysis - Event rate (0.9-2.6 MeV)

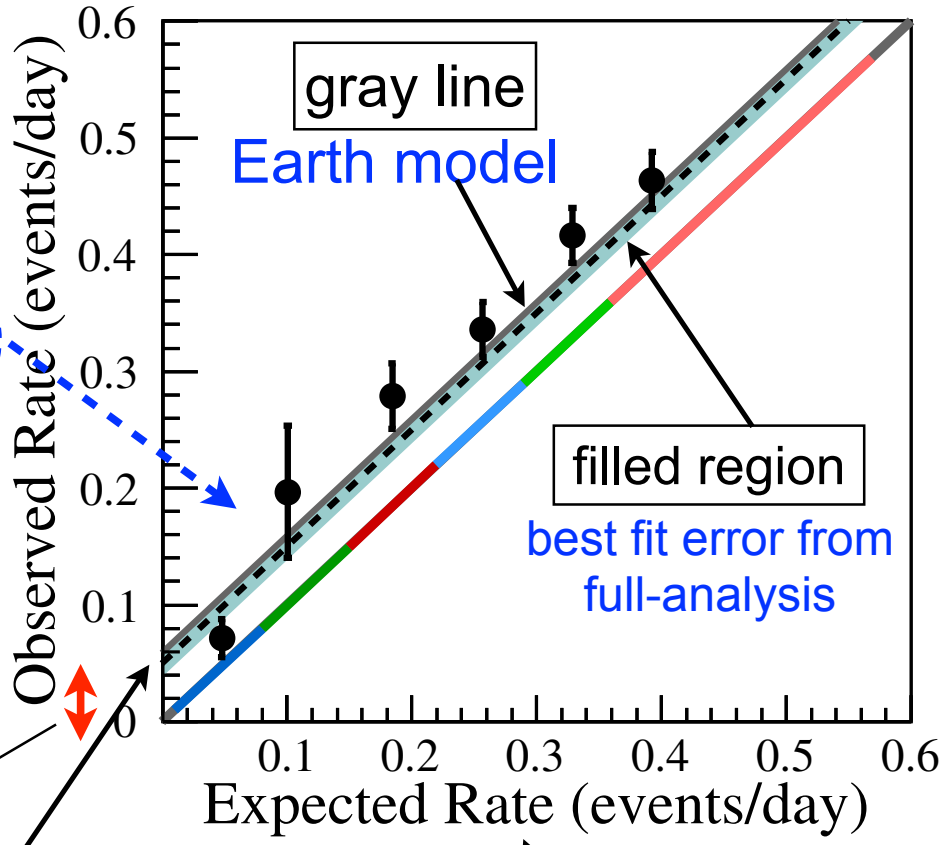


- Backgrounds :
  - LS purification → non-neutrino backgrounds reduction
  - Earthquake → reactor neutrino reduction
- Constant contribution of geo-neutrino
  - Time information is useful to extract the geo-neutrino signal

Analysis - Correlation (0.9-2.6 MeV)

- Expected Rate vs Observed Rate (0.9-2.6 MeV)





- Lower three data points added using low-reactor operation period

constant contribution of geo-neutrino

doted line's intercept

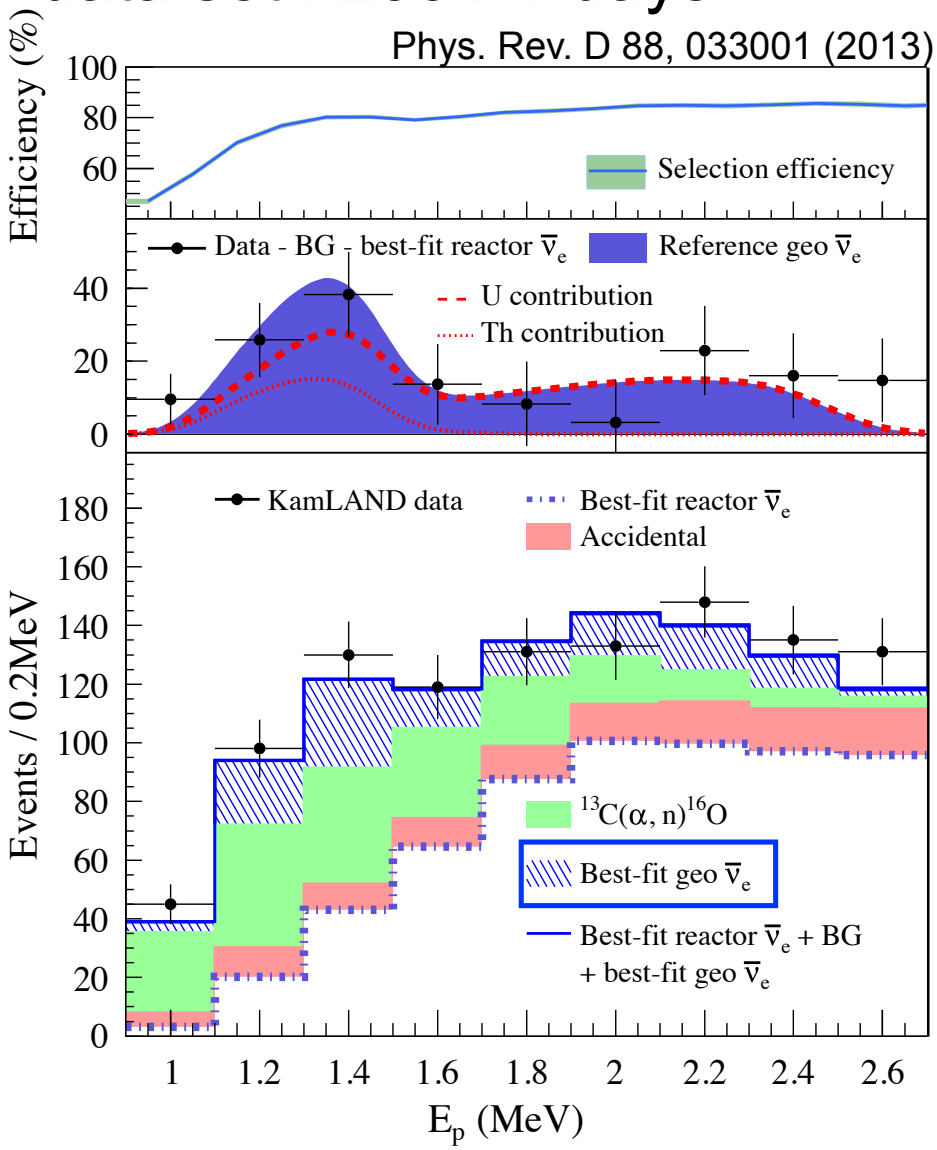
best fit from full-analysis
(Rate+Shape+Time)

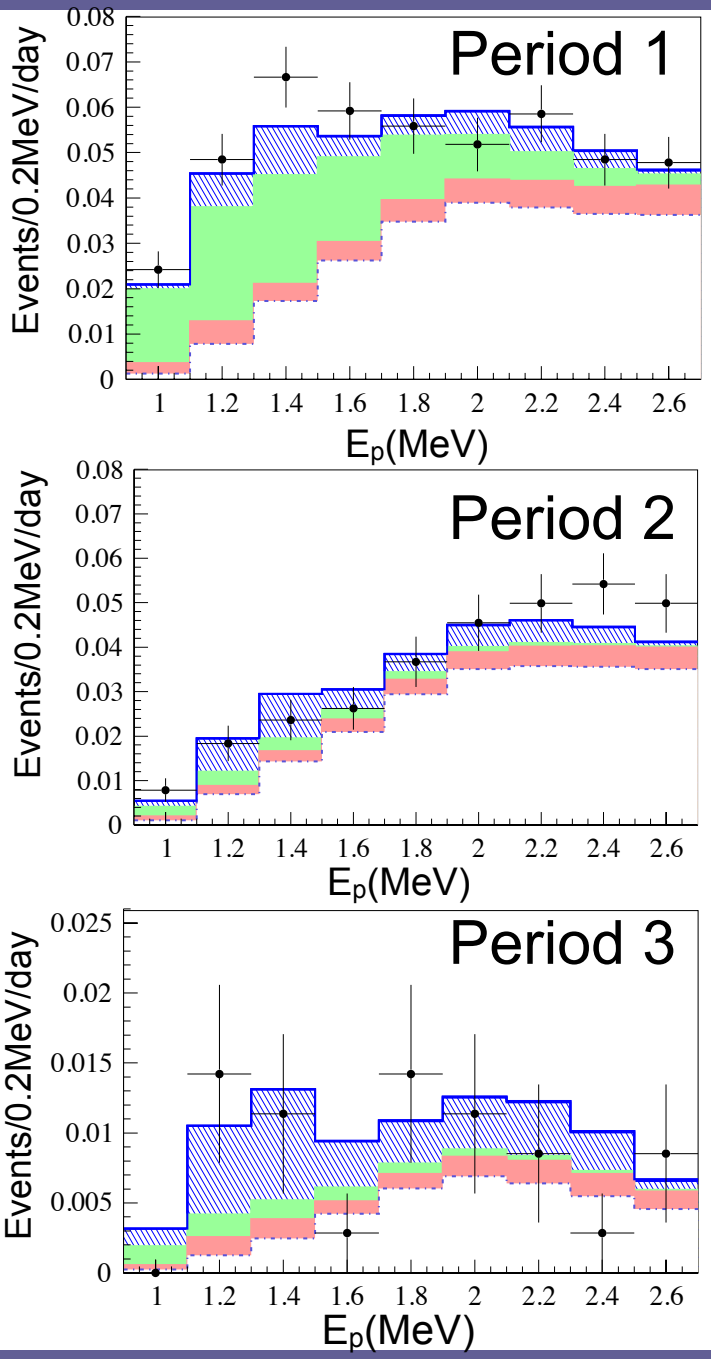
reactor anti-neutrino +
other backgrounds
(without geo-neutrino)

- Correlation between expected and observed event rate

Analysis : Energy Spectrum (0.9-2.6 MeV)

data set : 2991.1 days

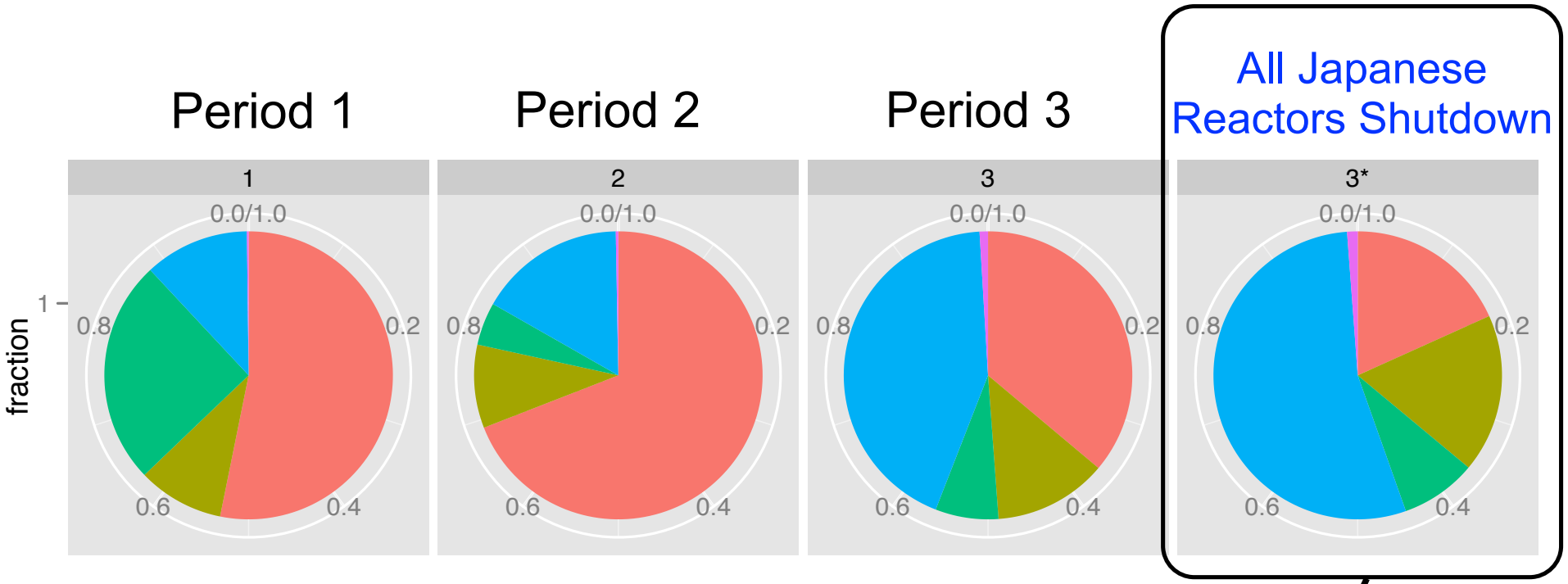




$^{13}C(\alpha, n)^{16}O$ decreased

Reactor-ν decreased

Analysis : Event Profile (0.9-2.6 MeV)



reactor neutrino
accidental background
(α,n) background
geo-neutrino
other events

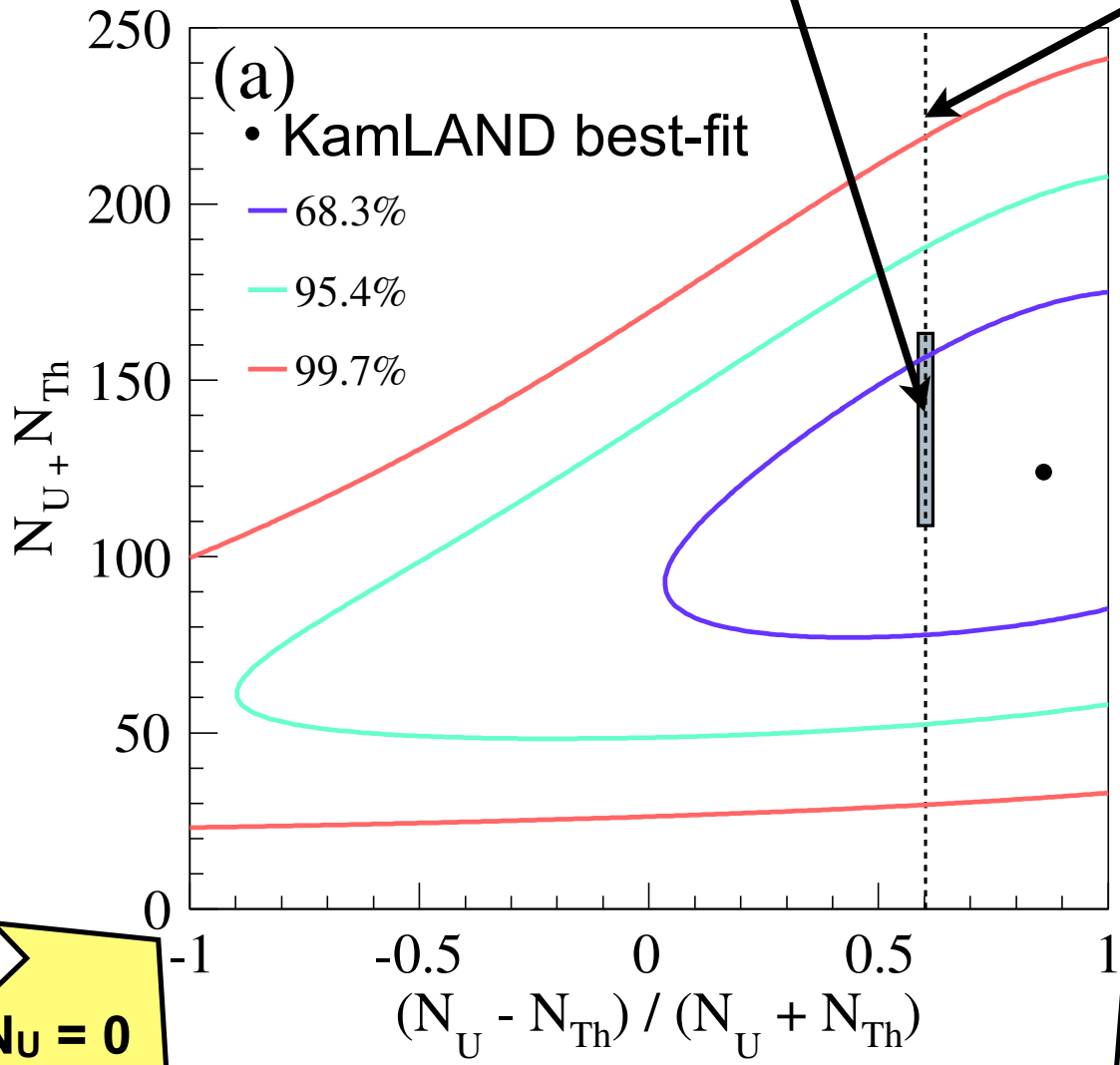
ratio between geo-neutrino signals and backgrounds is higher than 1

Analysis : Rate+Shape+Time Analysis (1)

y-axis : number of U and Th geo-neutrino

Earth model prediction
EPSL 258, 147 (2007)

Th/U = 3.9 fixed



N_U = 0

N_{Th} = 0

x-axis : ratio between U and Th geo-neutrino
→ **U, Th mass ratio**

✦limits on Th/U ratio

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

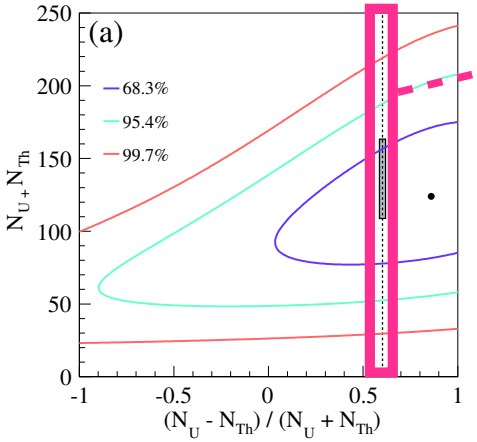
✦Th/U mass ratio
(Th/U = 3.9)

Number of geo-neutrino

$N_{geo} = 116^{+28}_{-27}$ events

$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6/cm^2/sec$

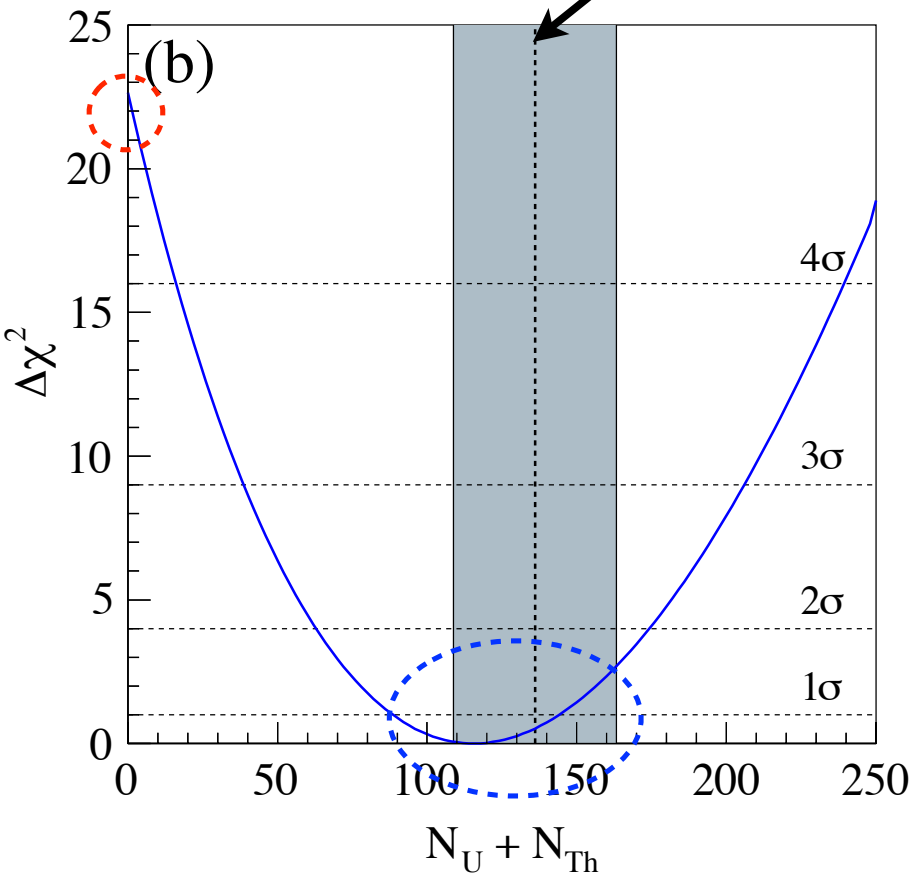
Analysis : Rate+Shape+Time Analysis (2)



Th/U=3.9

projection on N_U+N_{Th} axis

Earth model prediction
EPSL 258, 147 (2007)



✦limits on Th/U ratio

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

✦Th/U mass ratio (Th/U = 3.9)

Number of geo-neutrino

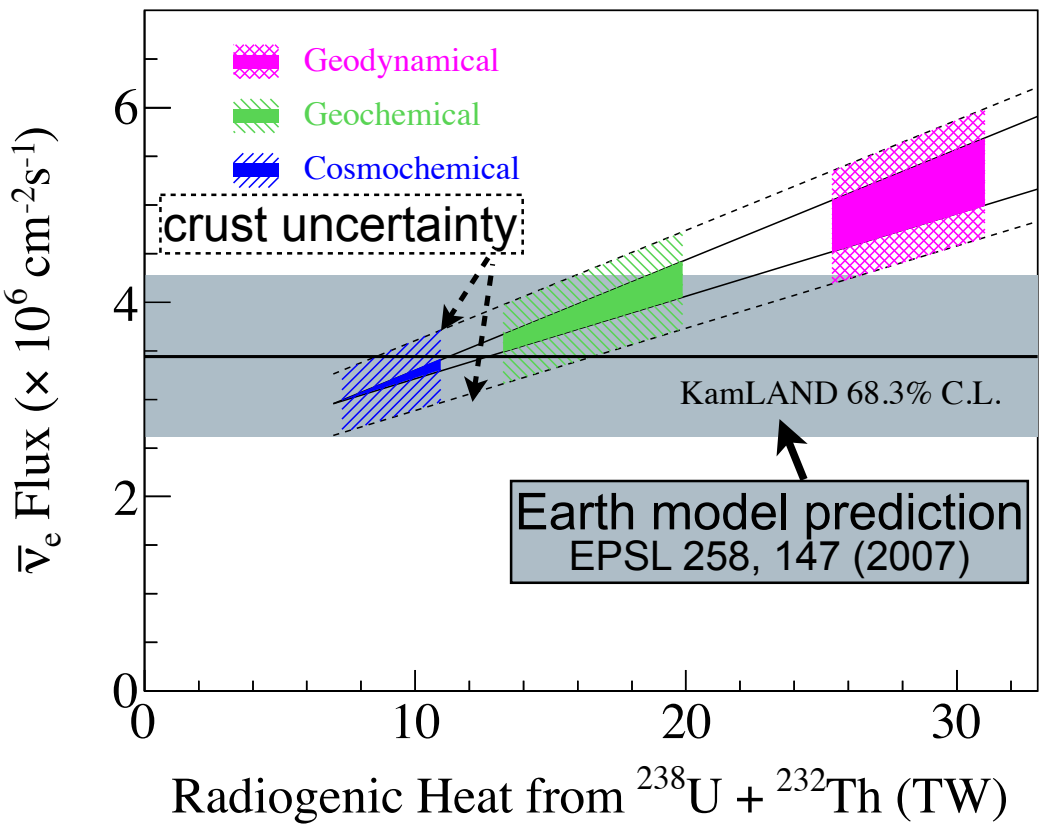
$N_{geo} = 116^{+28}_{-27}$ events

$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6/cm^2/sec$

almost same as model prediction

0signal is rejected at 99.9998% C.L.

Analysis : Comparison with Models



[BSE composition models]

Geodynamical 30TW

based on balancing mantle viscosity and heat dissipation

Geochemical 20TW

based on mantle samples compared with chondrites

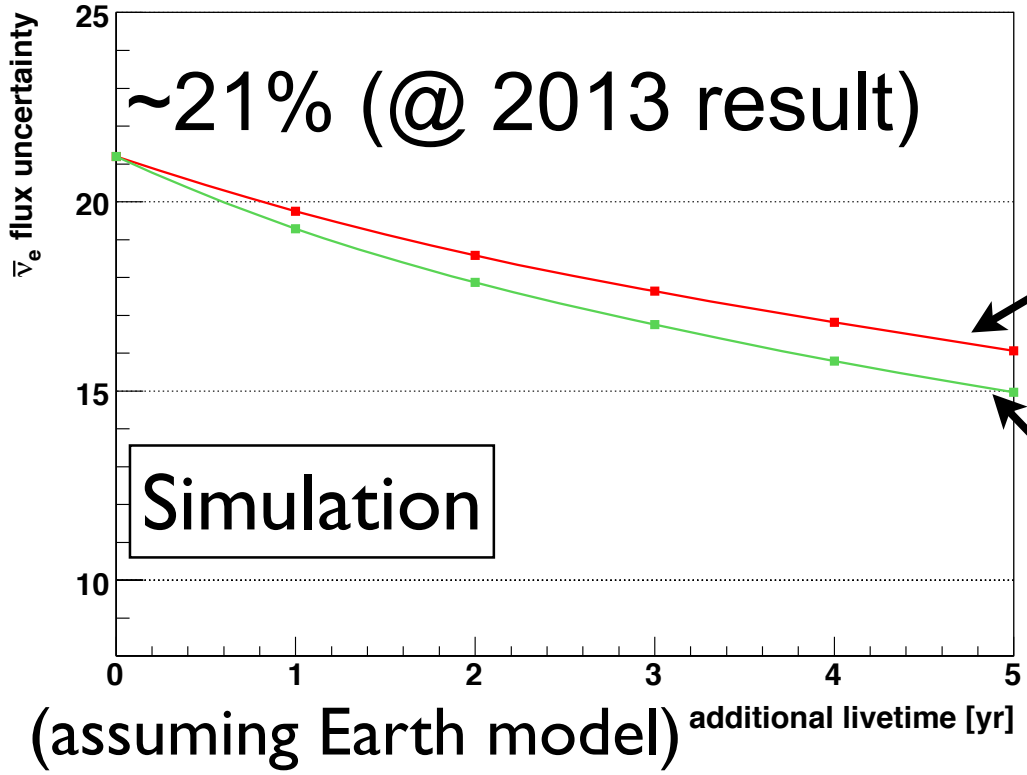
Cosmochemical 10TW

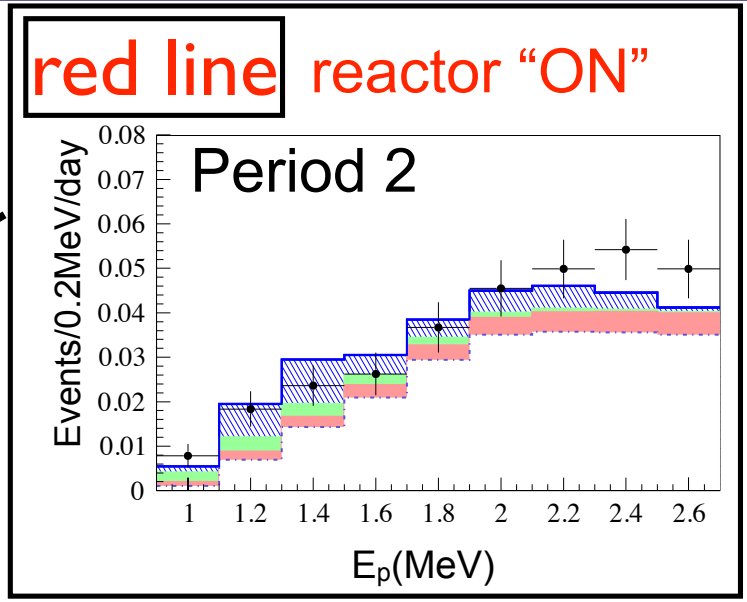
based on isotope constraints and chondritic models

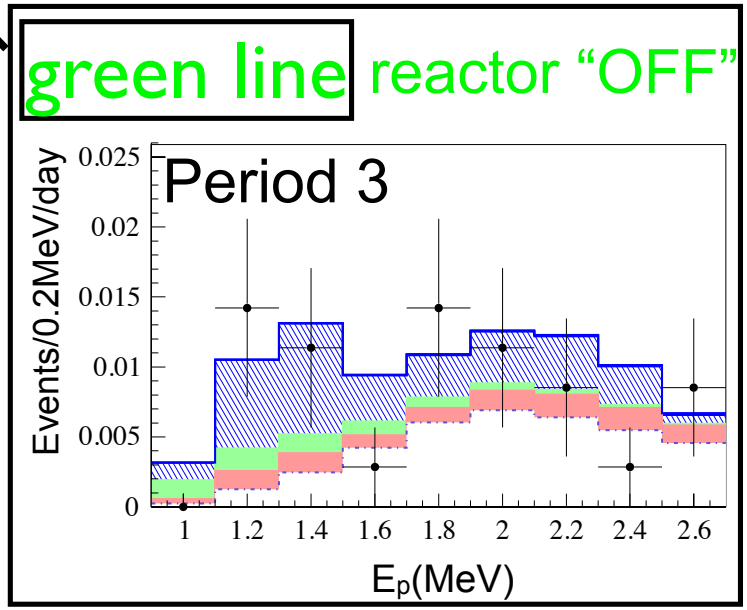
- KamLAND geo-neutrino flux translates to a total radiogenic heat production : $11.2\ ^{+7.9}_{-5.1}$ TW
- The geodynamical prediction with the homogeneous hypothesis is disfavored at 89% C.L.
- All BSE compositional models are still consistent within ~2 σ.

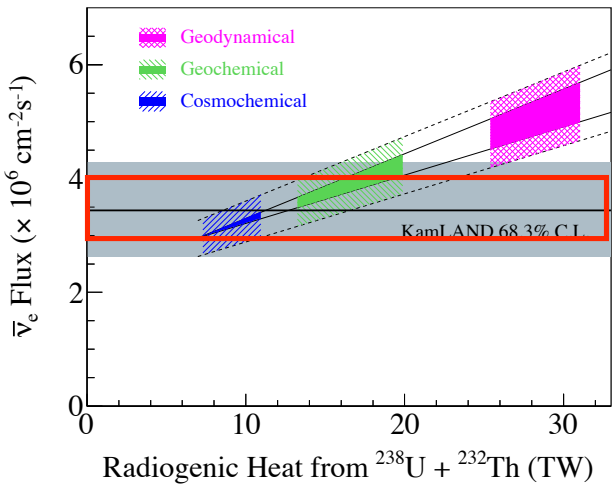
Contents

Geo-neutrino uncertainties









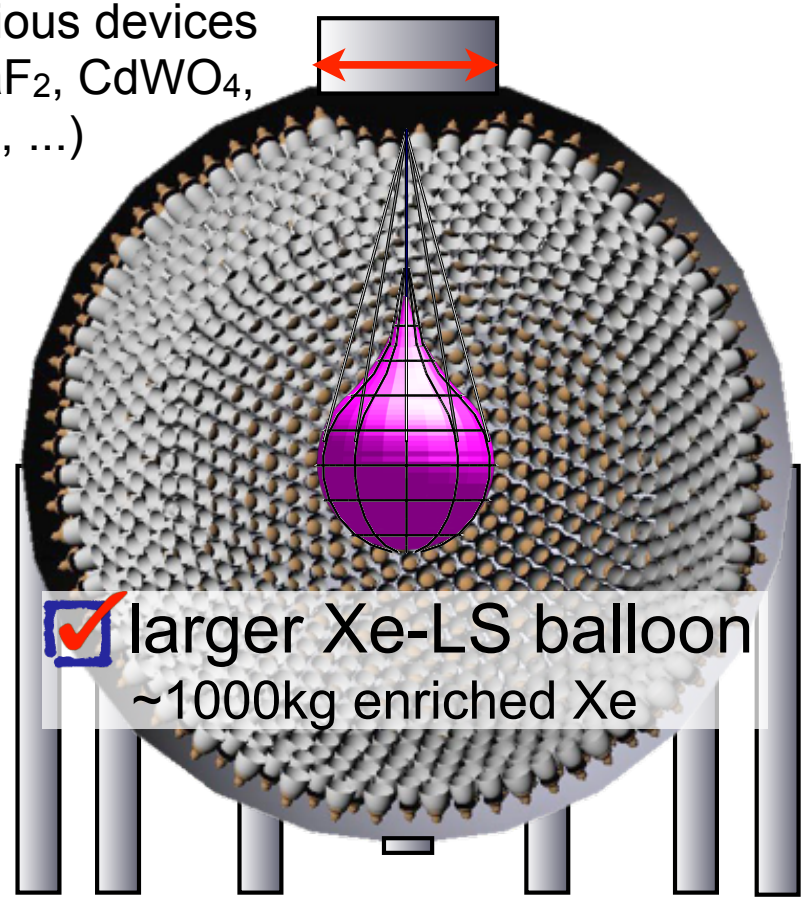
We will achieve 15~16% uncertainty with additional 5 year measurement.
(We already have another 2-year data.)

KamLAND2(-Zen) : better energy resolution

upgrade to KamLAND

☑ enlarge opening

accommodate various devices (CaF_2, $CdWO_4$, NaI, ...)

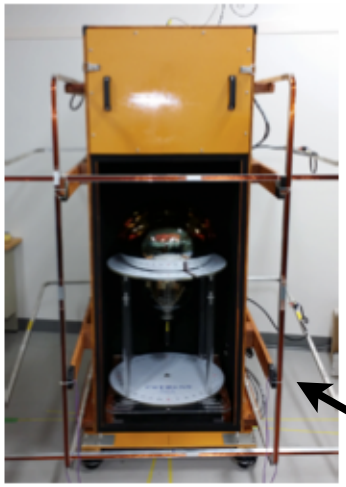


☑ larger Xe-LS balloon

~1000kg enriched Xe

☑ High performance

* High Q.E. PMT



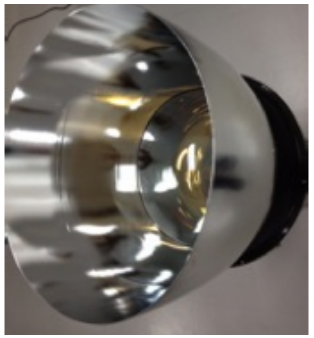
17”Φ→20”Φ,
ε=22% → 30%

Photo-coverage > **×2**

Light Collecting Eff. > **×1.8**

photon yield ×1.9

* Winstone Cone



* New Liquid Scintillator **×1.4**

LAB based LS (8,000 → 12,000 photon/MeV)

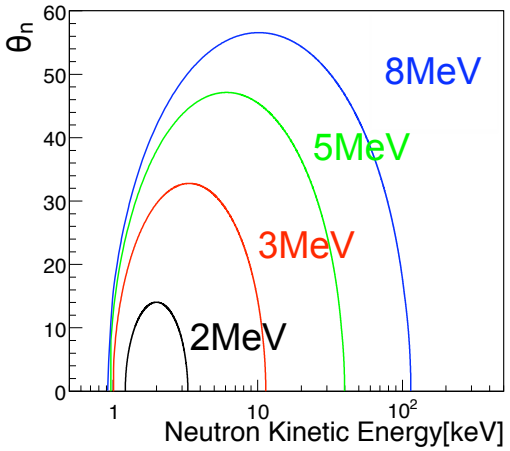
energy resolution improved

: 6.4%/√E[MeV]→**4.0%/√E[MeV]**

geo-neutrino measurement

* **improvement of U/Th ratio**
* **fiducial volume enlargement**

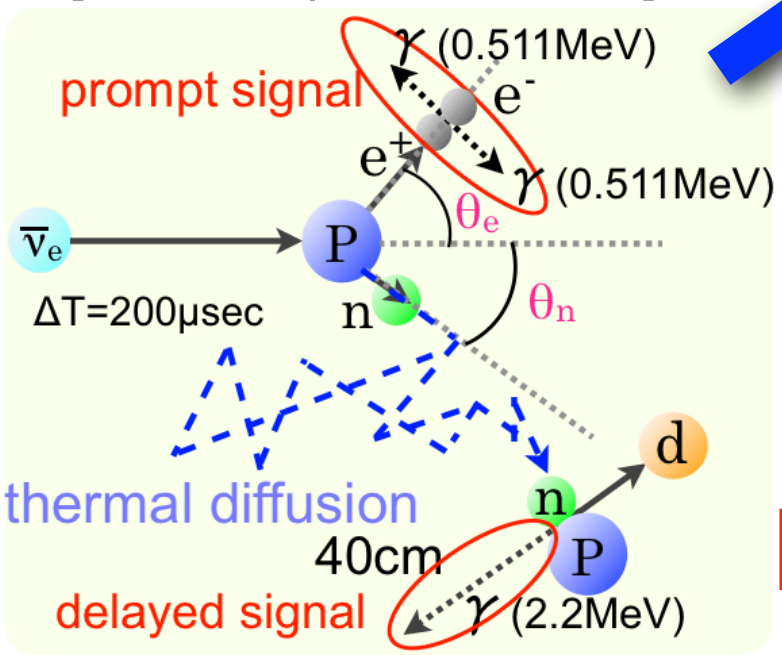
Directional measurement (1)



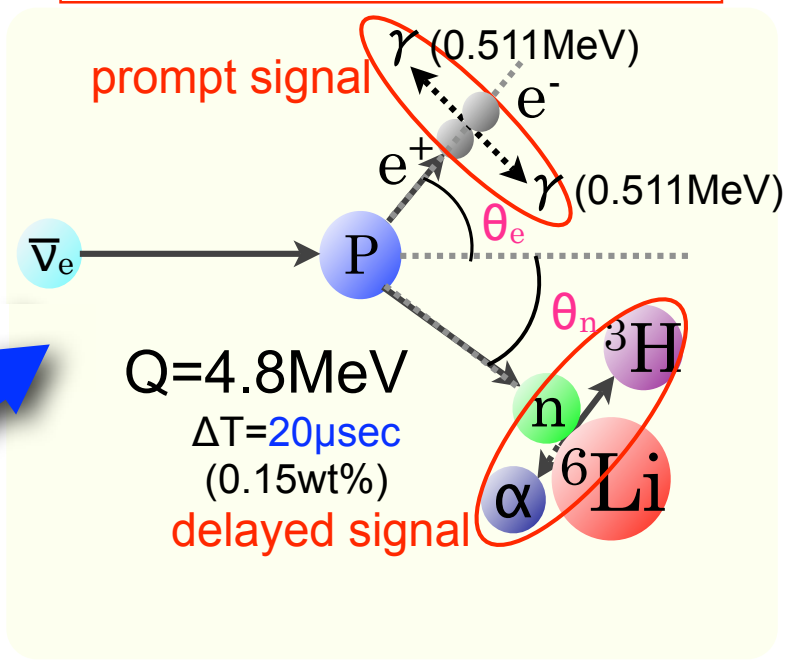
$E_{\bar{\nu}e}$ <3MeV→θ_n<35°

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

+

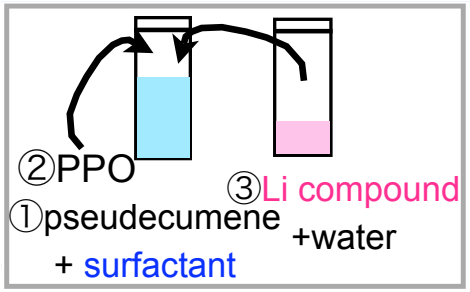
high vertex resolution imaging detector

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

Directional measurement (2)

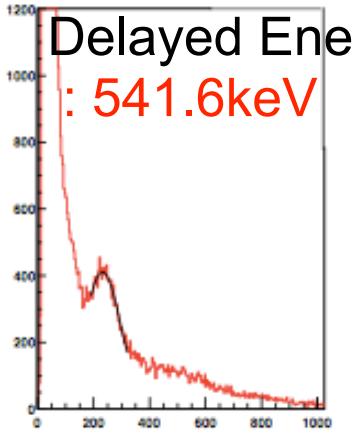
^{6}Li LS

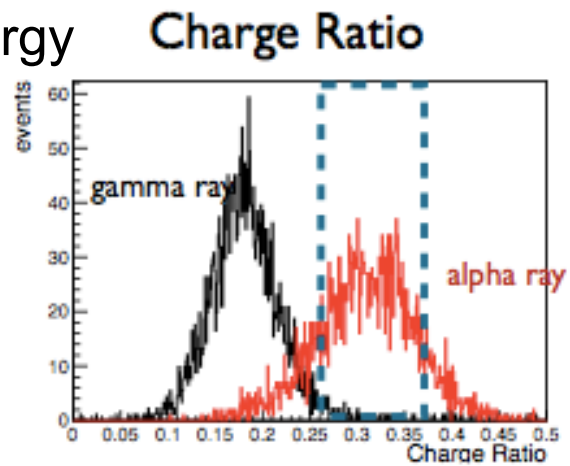
LiBr water solution
+surfactant
+PC+PPO



We have developed ^{6}Li-LS by the original method

* ^{6}Li neutron capture measurement

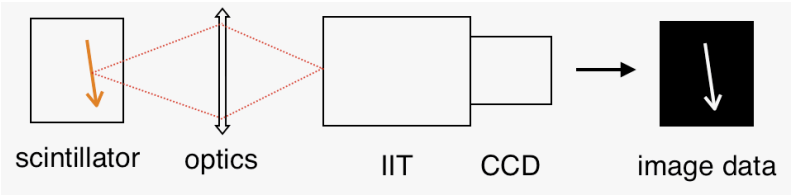




PSD quality

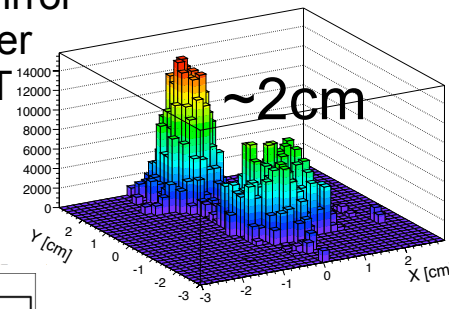
α acquisition efficiency:90%
γ rejection efficiency:94.27%

Imaging Detector



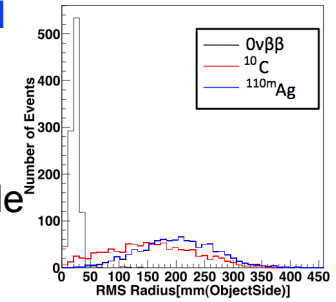
- light collection by lens array or mirror
- image capture by Image intensifier
+CCD camera or multi-anode PMT

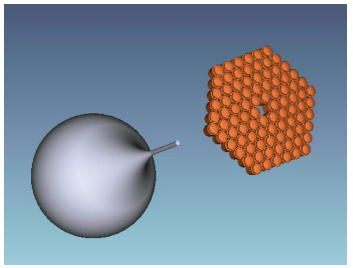
[^{60}Co source bright spot separation]
(LS size : 6cm×6cm×3cm)



※ planning to install in KamLAND detector

background reduction by particle ID

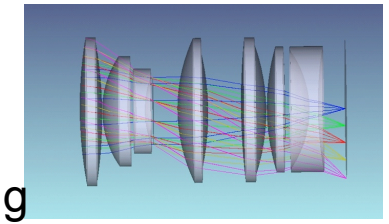




[1st step]
Small size detector (~200L)

- LiLS : done
- lens array, electronics : studying

Detector design is under way.



achieved 1cm vertex resolution

Contents

Summary

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

- **Geo-neutrino**

- Observed flux is fully consistent with Earth models

- Results for low reactor background:
  Geo-neutrino observation is very sensitive

- Now we enter the era of conducting critical tests of Earth models