



Review of KamLAND and Geo-neutrinos

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for the KamLAND Collaboration

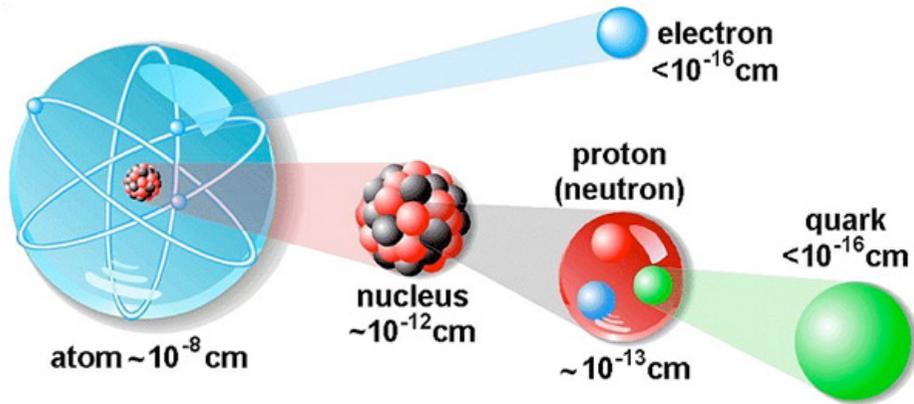
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1. Neutrinos
2. KamLAND
3. Recent Results
4. Summary

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▶ Neutrinos

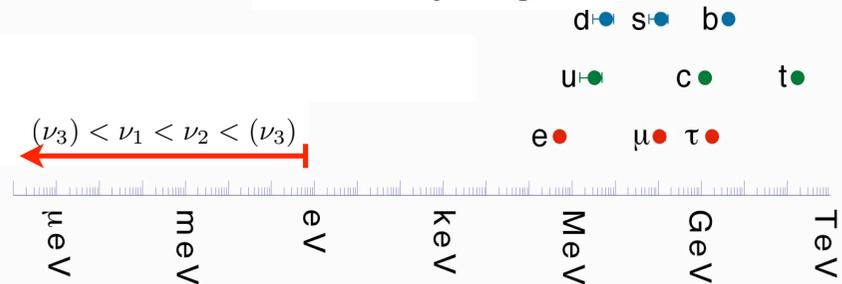


elementary particles

	mass →	charge →	spin →																									
	2.4 MeV/c ²	2/3	1/2	u	up	1.27 GeV/c ²	2/3	1/2	c	charm	171.2 GeV/c ²	2/3	1/2	t	top	0	0	1	γ	photon	≈126 GeV/c ²	0	0	0	H	Higgs boson		
QUARKS	4.8 MeV/c ²	-1/3	1/2	d	down	104 MeV/c ²	-1/3	1/2	s	strange	4.2 GeV/c ²	-1/3	1/2	b	bottom	0	0	1	g	gluon								
	0.511 MeV/c ²	-1	1/2	e	electron	105.7 MeV/c ²	-1	1/2	μ	muon	1.777 GeV/c ²	-1	1/2	τ	tau	0	0	1	Z	Z boson								
LEPTONS	<2.2 eV/c ²	0	1/2	ν_e	electron neutrino	<0.17 MeV/c ²	0	1/2	ν_μ	muon neutrino	<15.5 MeV/c ²	0	1/2	ν_τ	tau neutrino	80.4 GeV/c ²	±1	1	W	W boson								

Neutrino is an elusive particle.
Typical properties

- extraordinary light particle



- electrically neutral

- most abundant matter-particle in the universe
other particles: $10^{-8}/\text{cm}^3$

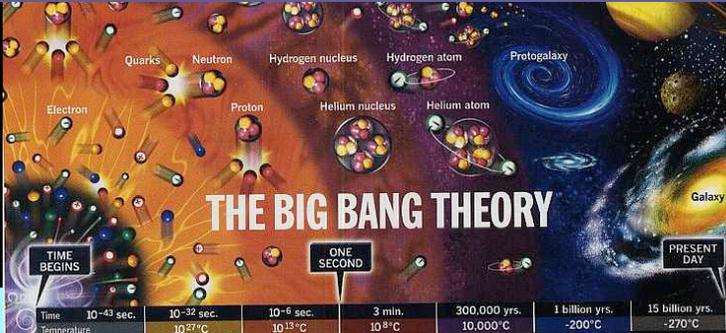
$$\nu : 300/\text{cm}^3$$

- easily penetrate even astronomical objects

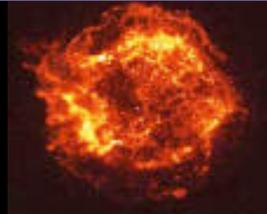
▶ Neutrinos Sources & Fluxes

Big Bang

$$300 \nu / \text{cm}^3$$



Sun



Supernova

Cosmic Ray



$$66 \text{ billion } \nu_e / \text{cm}^2 / \text{sec}$$

Human Body

300 million /day



Reactor

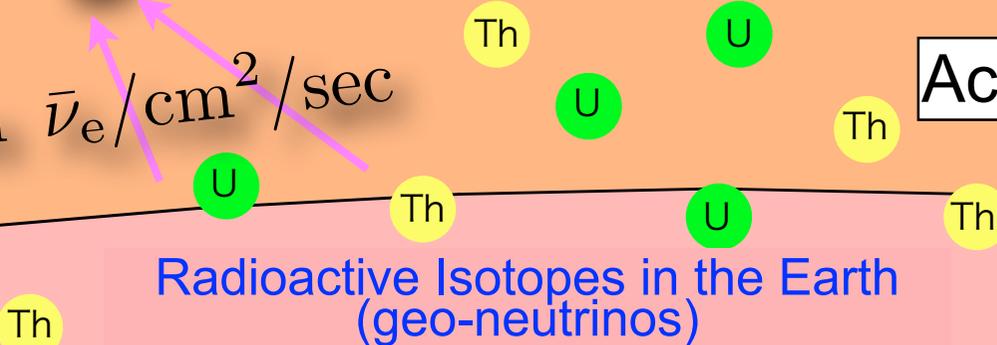
$$6 \text{ million } \bar{\nu}_e / \text{cm}^2 / \text{sec}$$

(神岡)



Accelerator

Radioactive Isotopes in the Earth
(geo-neutrinos)



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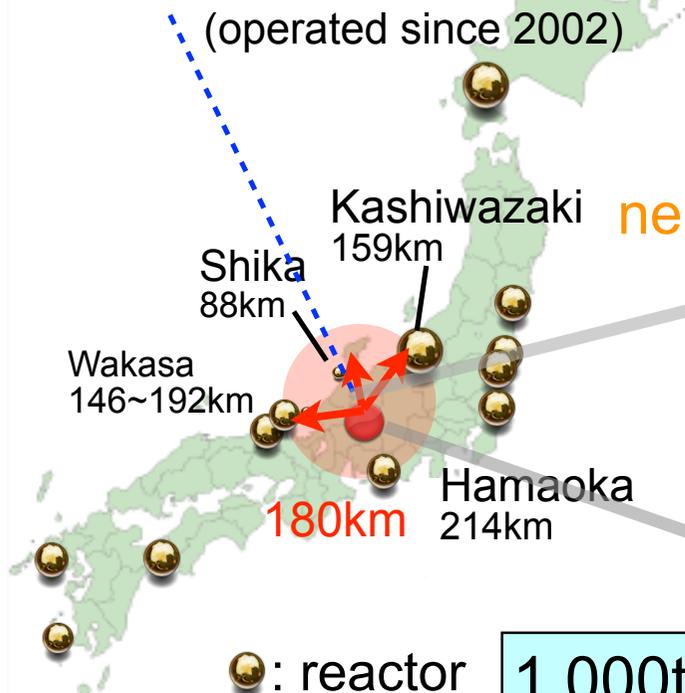
▶ KamLAND Site & Detector

KamLAND

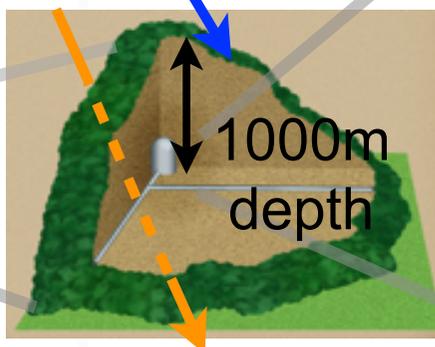
**Kamioka Liquid Scintillator
Anti-Neutrino Detector**
(operated since 2002)



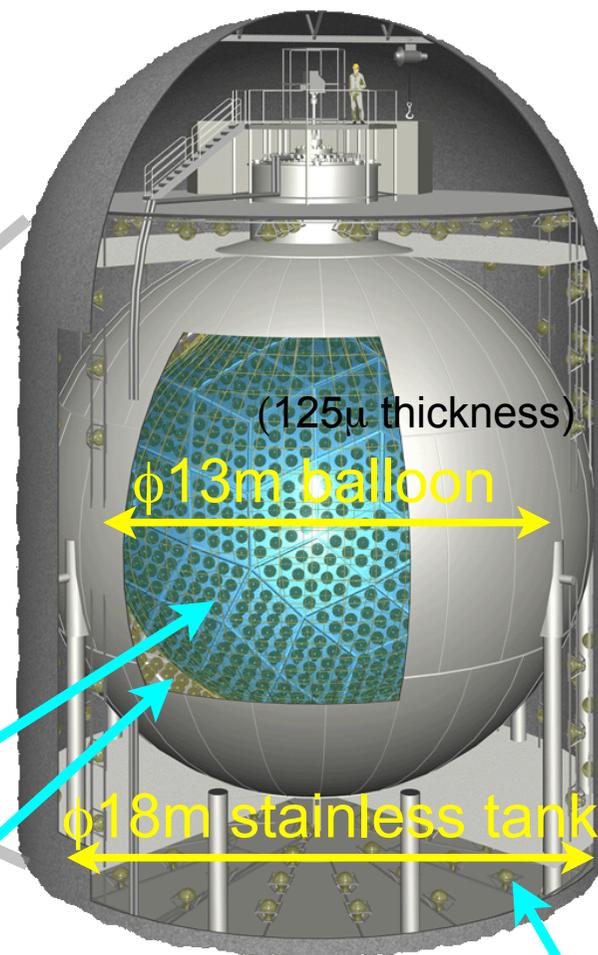
Kamioka Mine



neutrino cosmic ray



1000m
depth



1,000t Liquid Scintillator

- * Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)
- * extremely low impurity ($^{238}\text{U}:3.5 \times 10^{-18}\text{g/g}$, $^{232}\text{Th}:5.2 \times 10^{-17}\text{g/g}$)

1,325 17inch + 554 20inch PMTs

* Photo coverage 34%

Water Cherenkov Outer Detector

* Muon veto

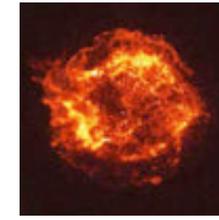
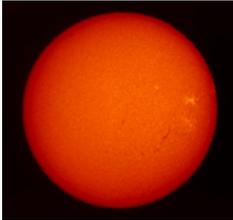
► Physics Target in KamLAND



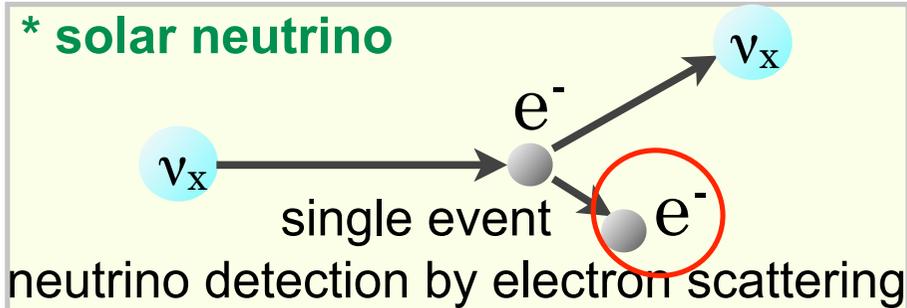
electron scattering
 $\nu + e^- \rightarrow \nu + e^-$

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

solar neutrino **geo neutrino** **reactor neutrino** **supernova neutrino, etc.**



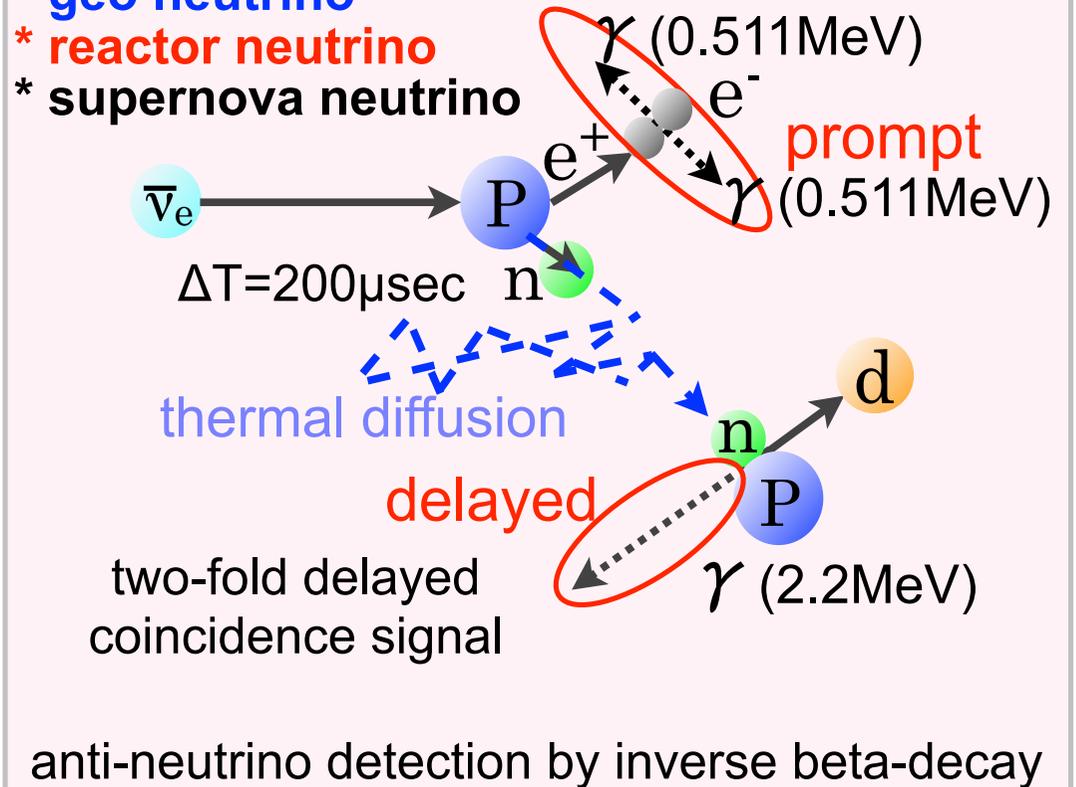
* solar neutrino



* geo neutrino

* reactor neutrino

* supernova neutrino



recent results

* solar neutrino

Phys. Rev. C 84, 035804 (2011)

* geo neutrino

Nature Geoscience 4, 647-651 (2011)

arXiv:1303.4667 (2013) *today's topics*

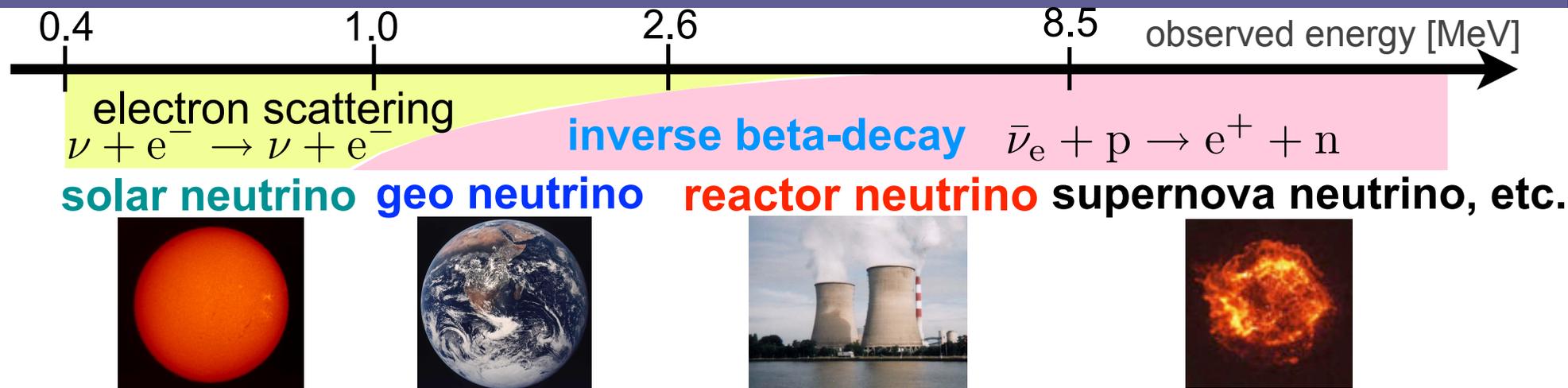
* reactor neutrino

arXiv:1303.4667 (2013)

* extraterrestrial neutrino

Astrophys. J. 745, 193 (2011)

► Physics Target in KamLAND



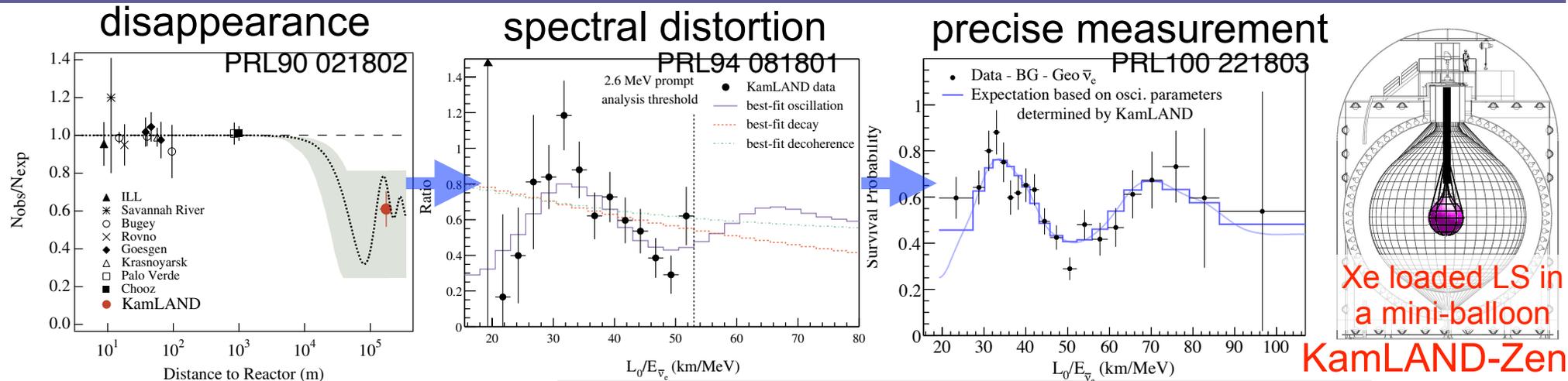
Other Experiments



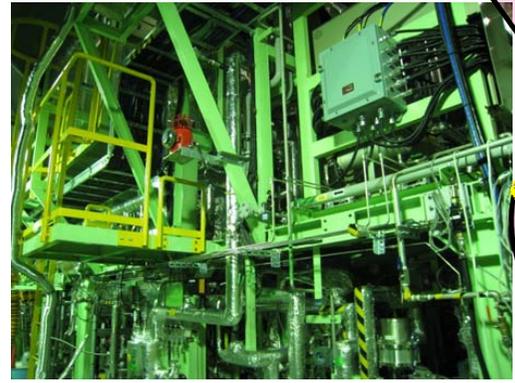
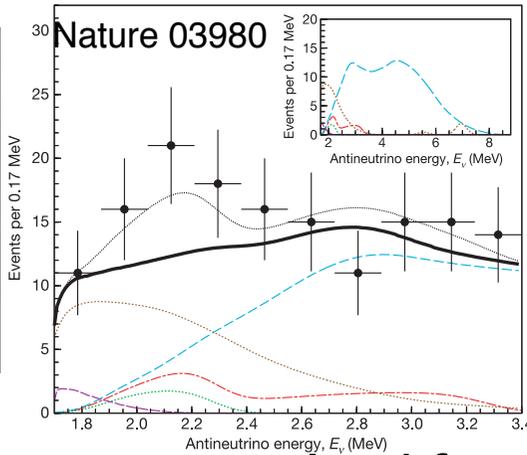
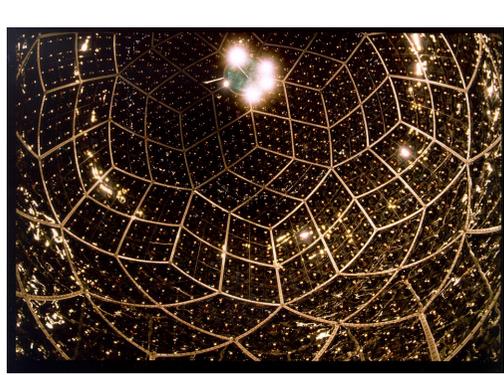
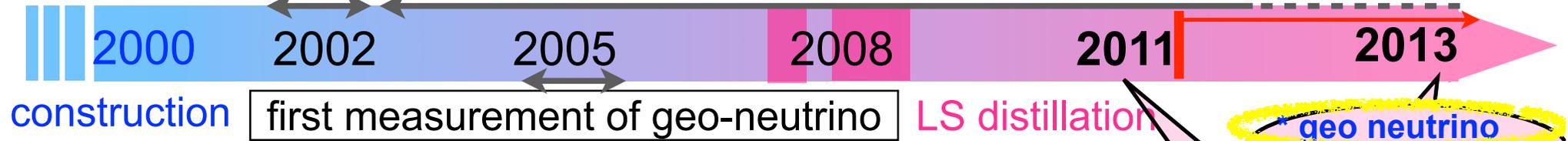
KamLAND Physics Target

We study neutrino physics in the wide range of energy comprehensively.

▶ History of KamLAND and Neutrino Physics



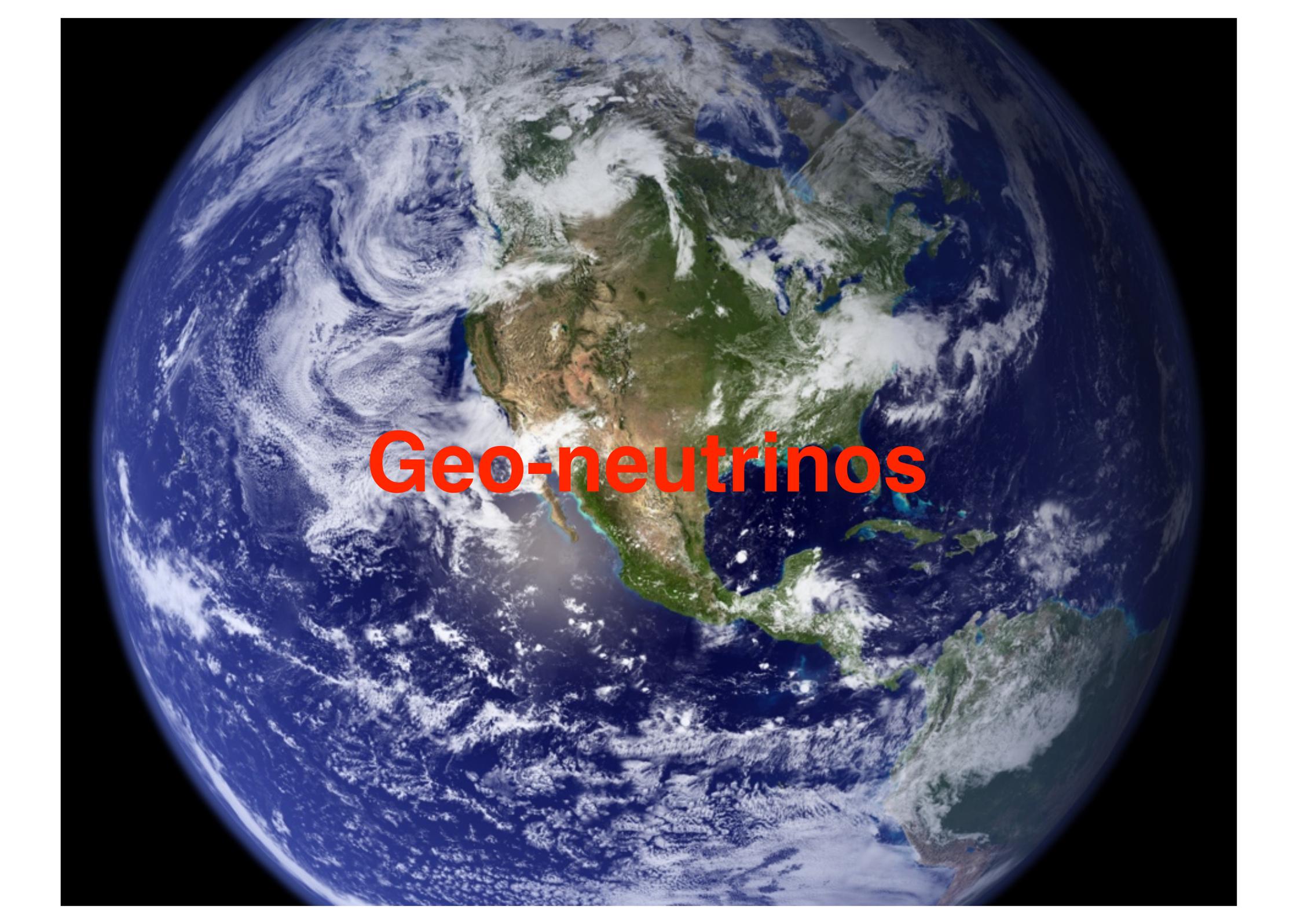
solve "solar neutrino problem" precise measurement of neutrino oscillation



✓ Neutrino measurement evolved from understanding of neutrino properties to utilization of neutrino as a "probe".

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A satellite image of Earth showing the Americas, with the text "Geo-neutrinos" overlaid in red. The image shows the Western Hemisphere, including North and South America, with swirling cloud patterns over the oceans. The text is centered over the continent of North America.

Geo-neutrinos

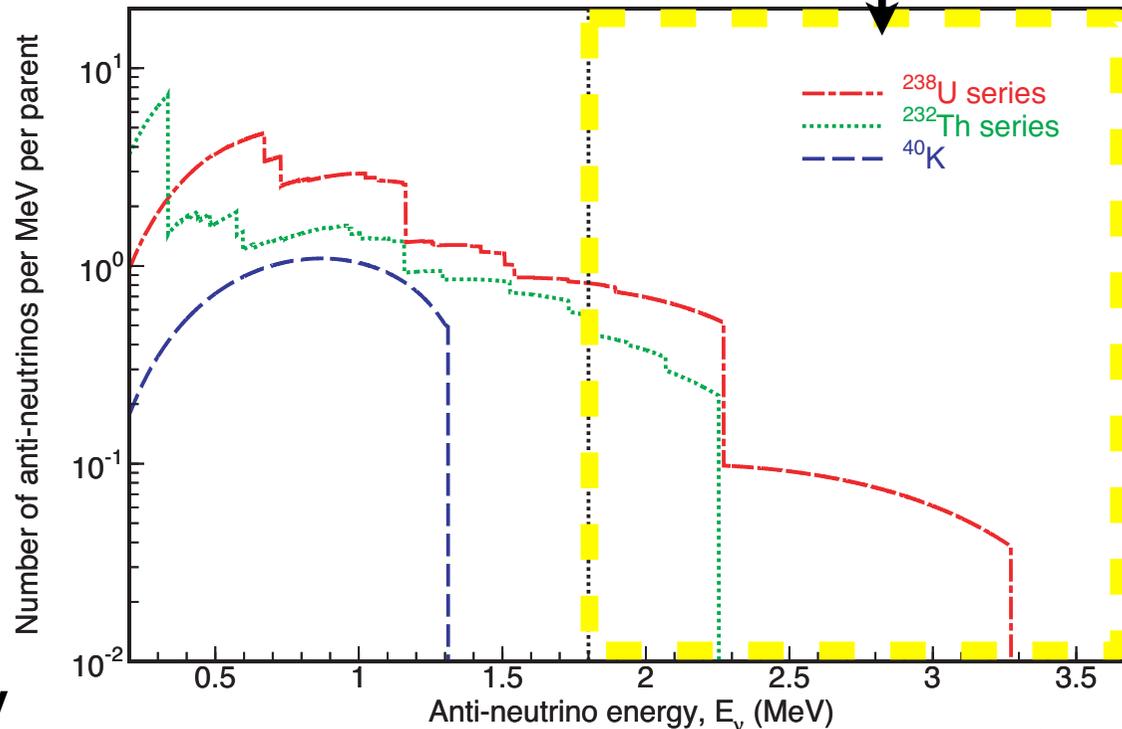
▶ Geo Neutrino at KamLAND

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

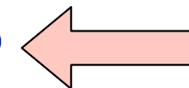
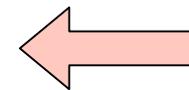
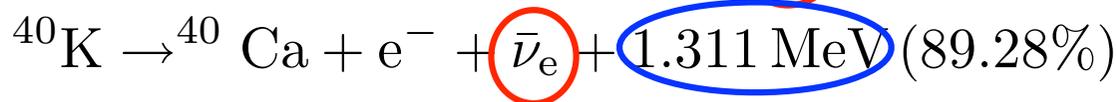
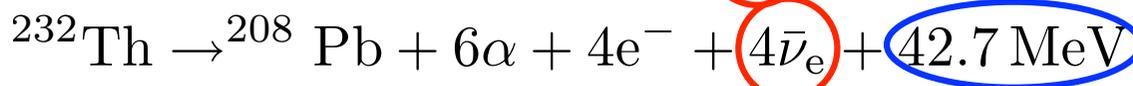
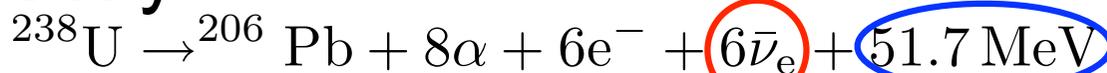
- calculation of geo antineutrino energy spectrum

Nature 436, 28 July 2005

KamLAND energy window



beta-decay



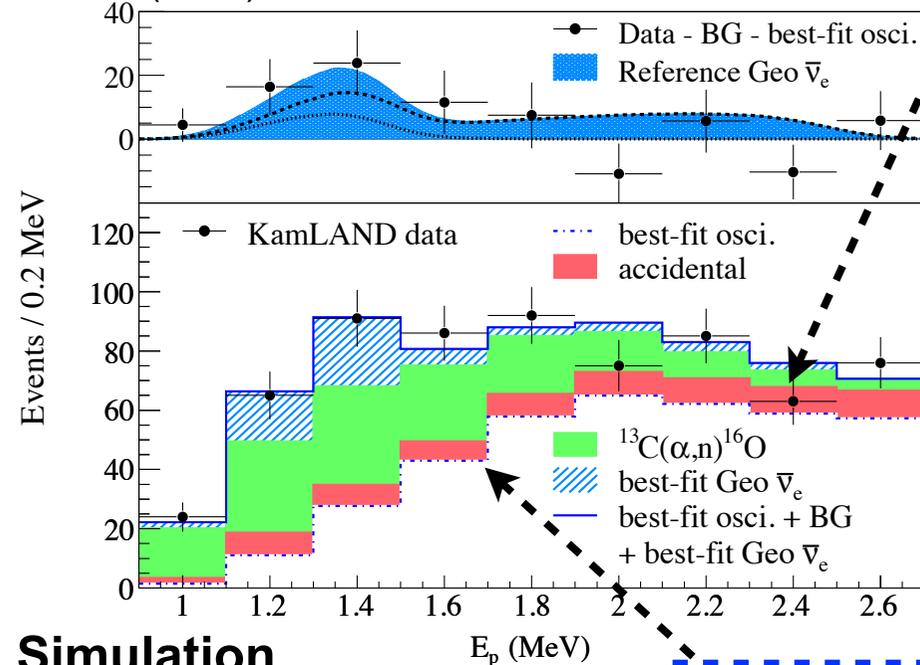
KamLAND
can detect !

► Backgrounds for Geo-neutrino

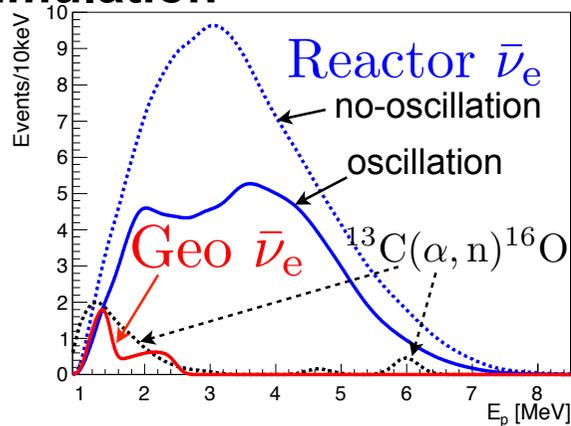
In our past publications, major backgrounds were

Non- ν : ^{13}C (^{210}Po α , n) ^{16}O , accidental **Reactor- ν** .

PRL 100(2008)221803

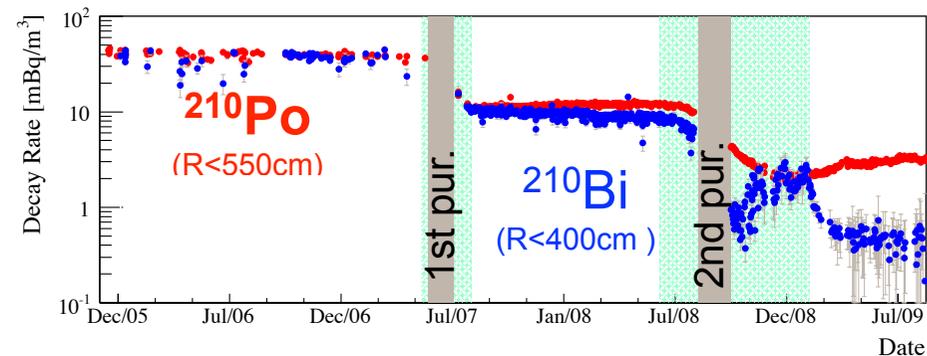


Simulation



^{13}C (^{210}Po α , n) ^{16}O

(1) Dominant BG source (α , n) was reduced by factor ~ 20 (2 times distillation)



(2) Determination of the cross section is improved by in-situ calibration uncertainty : **11%** for ground state

Reactor- ν

(3) Operational issues at the power reactor and serious earthquakes **reduced the reactor neutrino flux.**

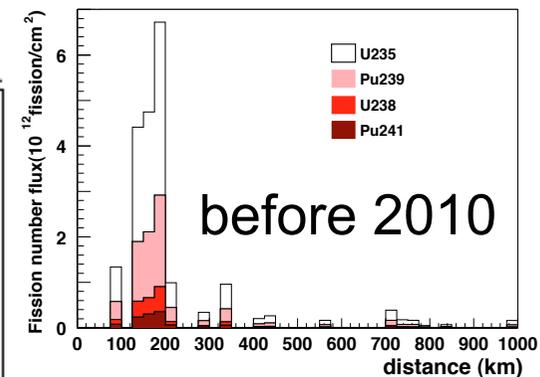
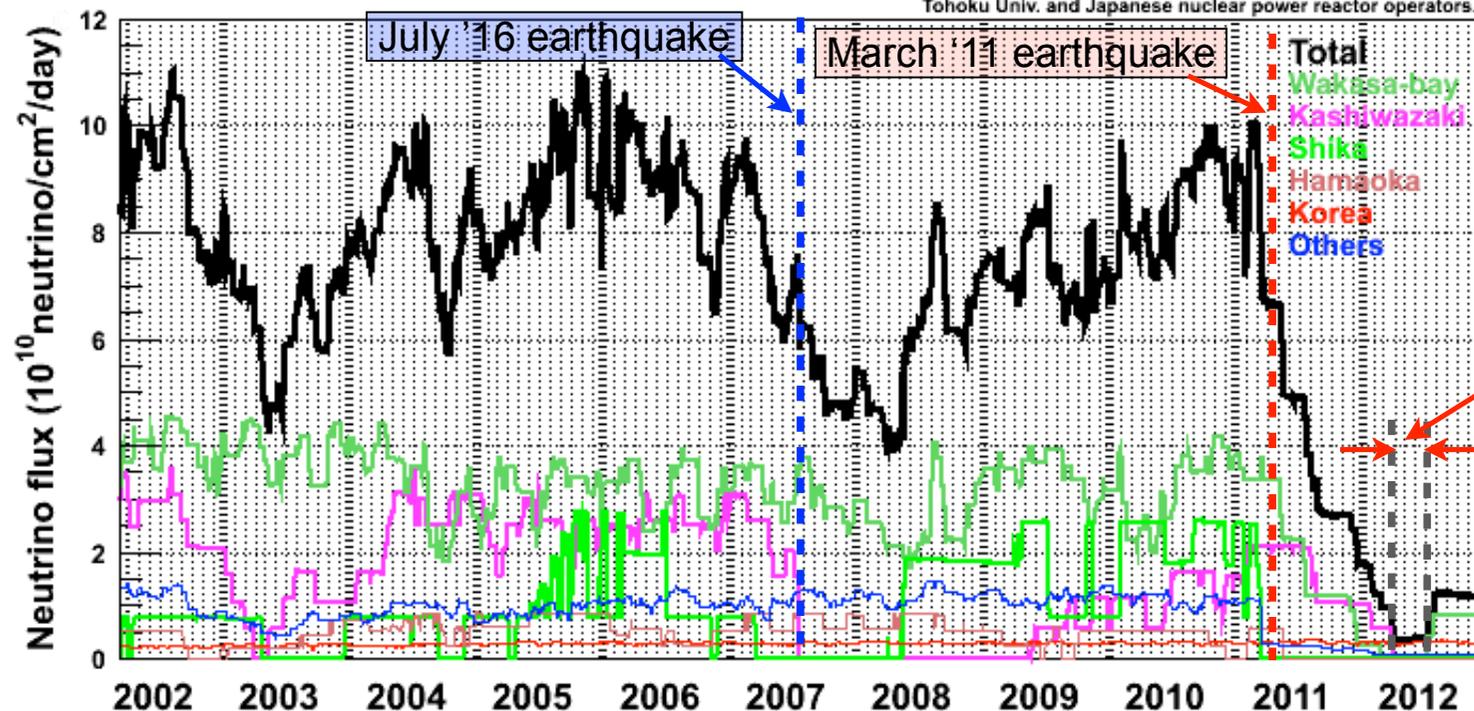
① **July 2007~**, extended shutdown of Kashiwazaki-Kariwa nuclear power station \rightarrow **$\sim 60\%$** of normal operation

② **March 2011~**, shutdown of entire Japanese nuclear reactor industry \rightarrow **$\sim 5\%$** of normal operation

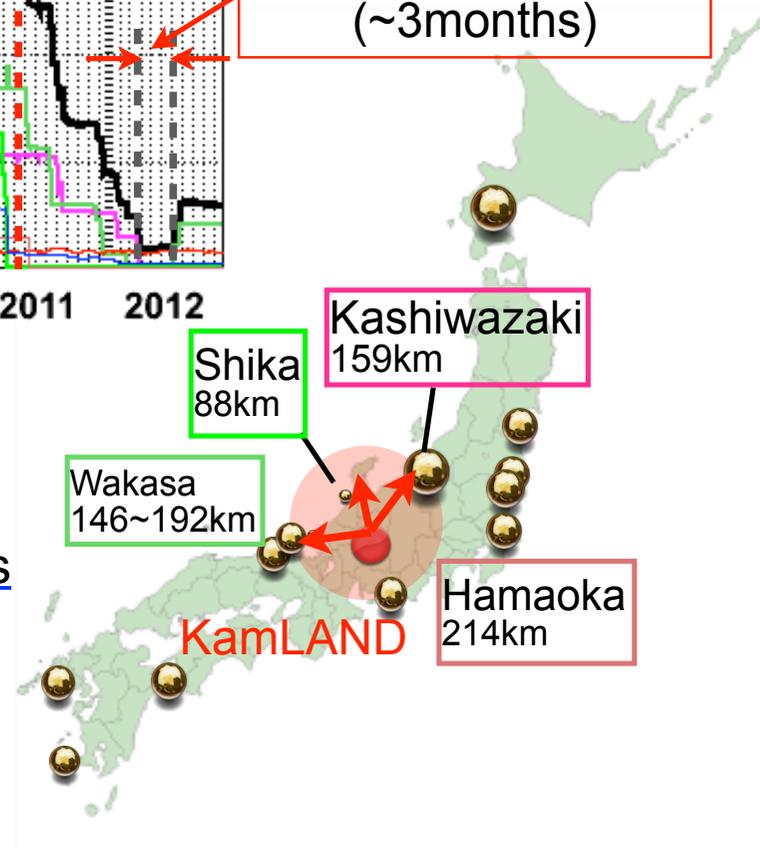
▶ Recent Condition : reactor operation in Japan

time variation of neutrino flux

Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.



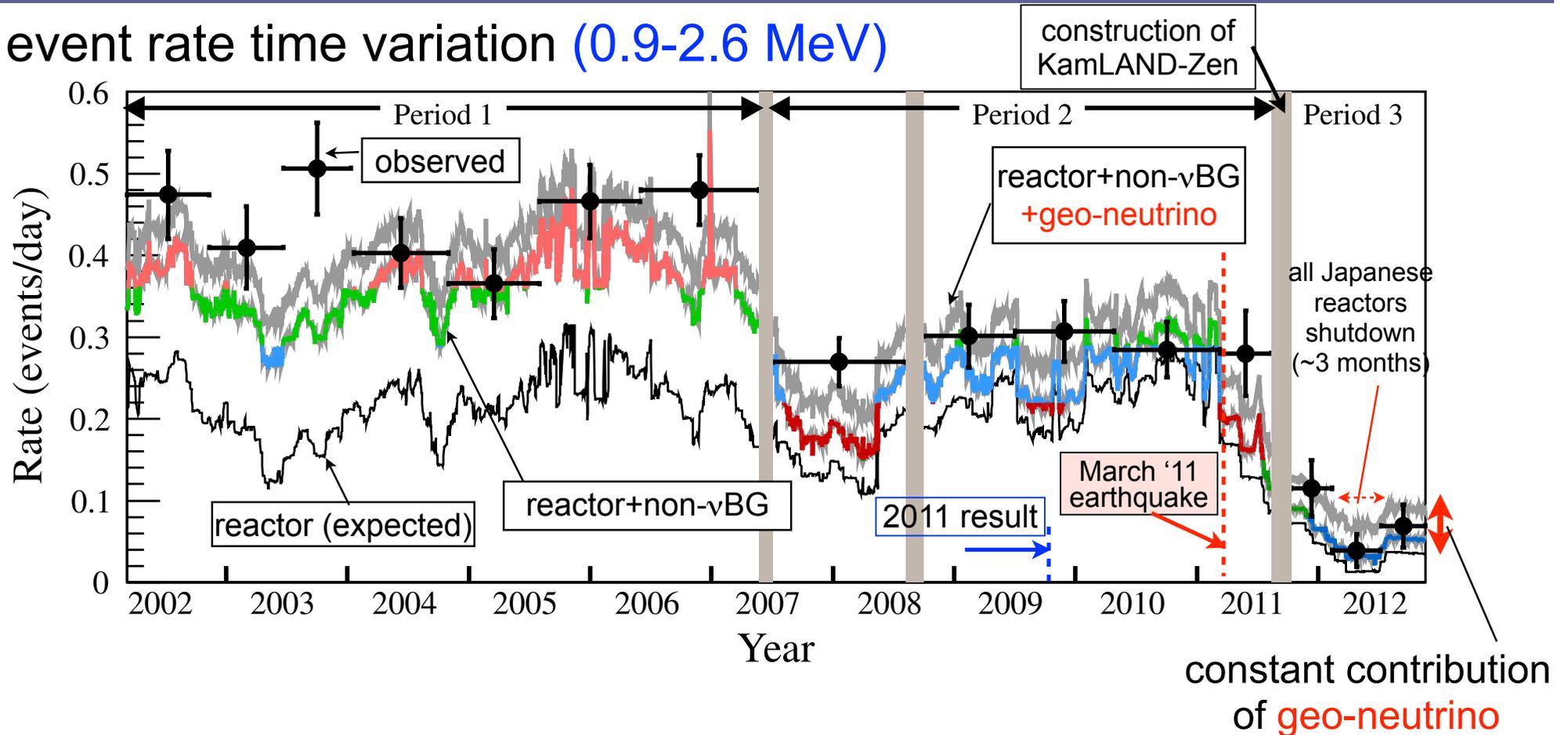
all reactor-off period
(~3months)



- Reactor neutrino flux, which is outside the control of the experiment, was significantly reduced.
- Following the Fukushima nuclear accident in March 2011, the entire Japanese nuclear reactor industry has been subjected to protected shutdown.
- This situation allows for a “reactor on-off” study of backgrounds for KamLAND neutrino oscillation and geoneutrino analysis.

► Analysis - Event rate (0.9-2.6 MeV)

- event rate time variation (0.9-2.6 MeV)



- Backgrounds

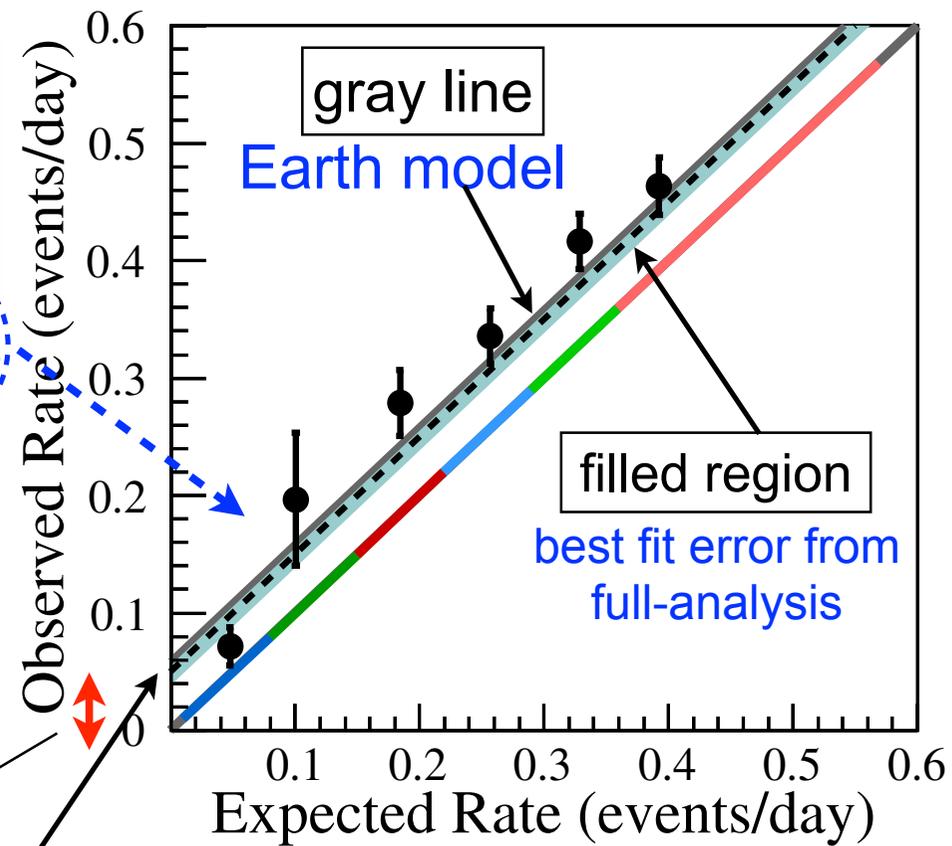
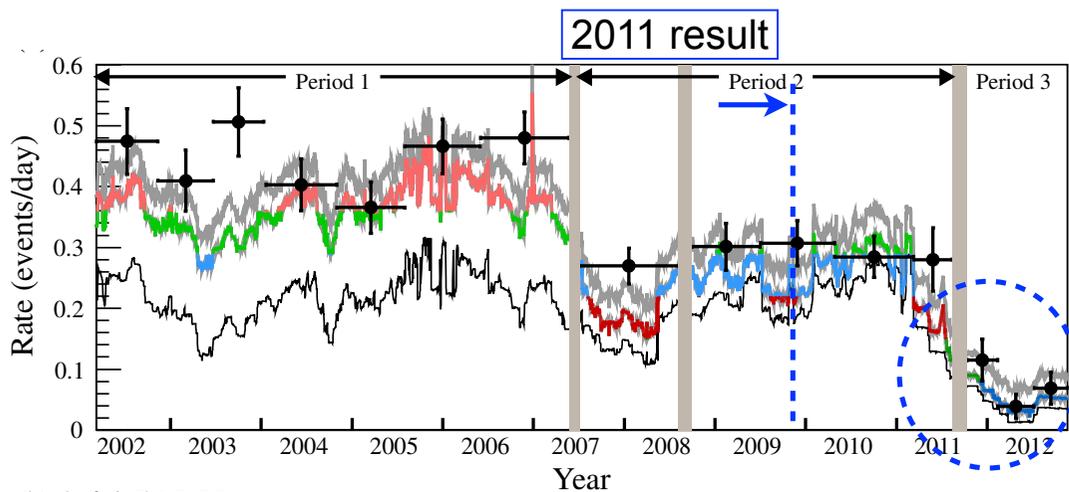
- * The non-nu background for geo-neutrino was decreased by half from what it was before 2007.
- * Reactor neutrino background was significantly decreased by two times earthquakes.

- Constant contribution of geo-neutrino is seen above the estimated reactor neutrino + non-neutrino background in the energy range 0.9 - 2.6 MeV.

→ 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 can be added by using low-reactor operation period.

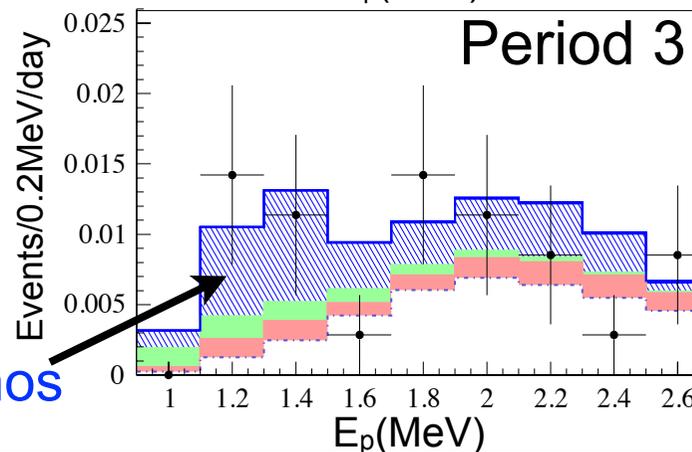
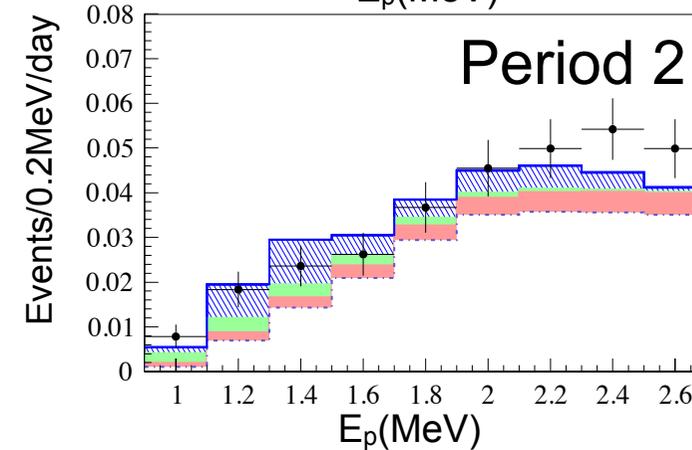
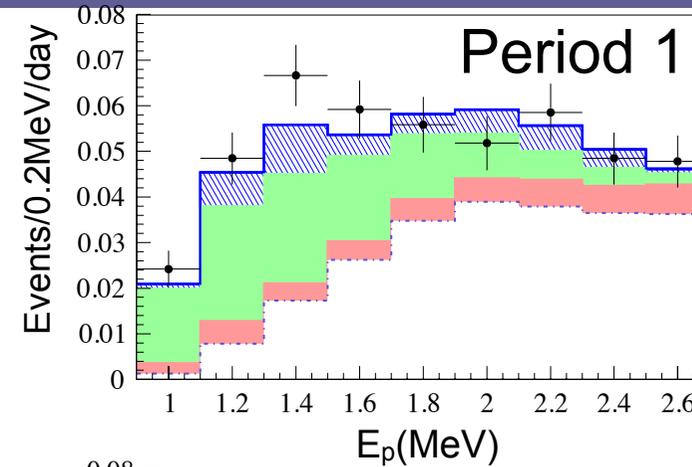
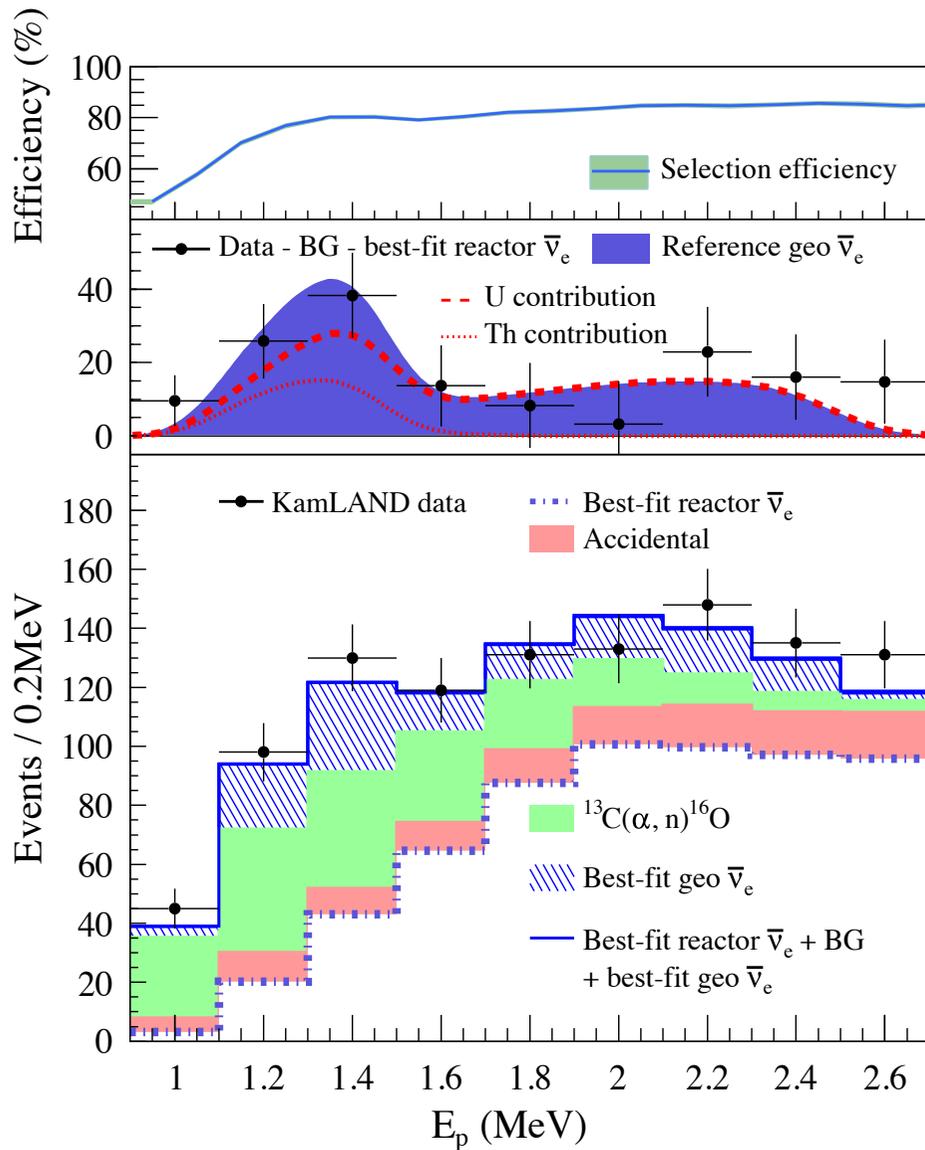
- Strong correlation between expected and observed event rate.

constant contribution of **geo-neutrino**

dotted line's intercept
best fit from full-analysis
(Rate+Shape+Time)
116 +28/-27 events

reactor anti-neutrino + other backgrounds

► Analysis : Energy Spectrum (0.9-2.6 MeV)



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

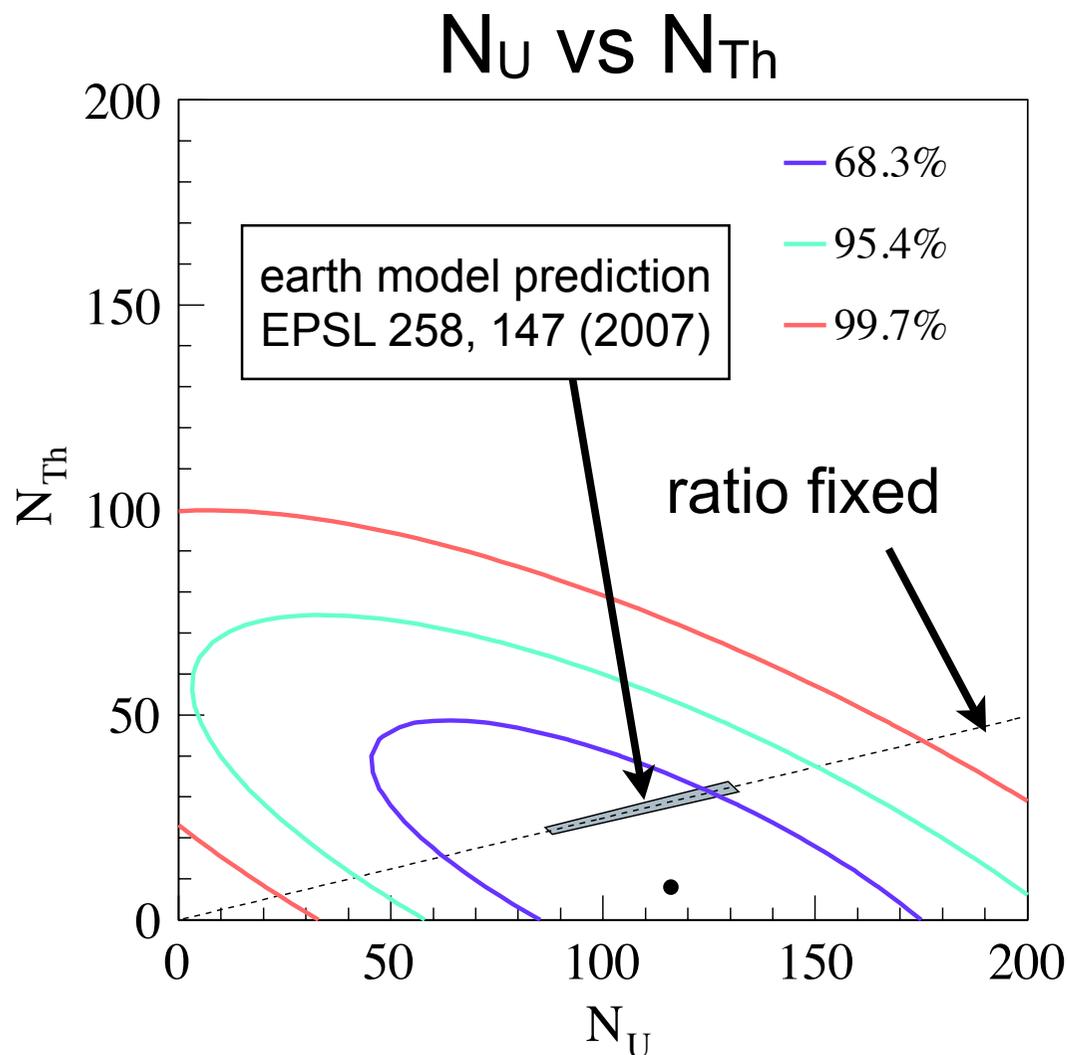
↓ decreased

Reactor- ν

↓ decreased

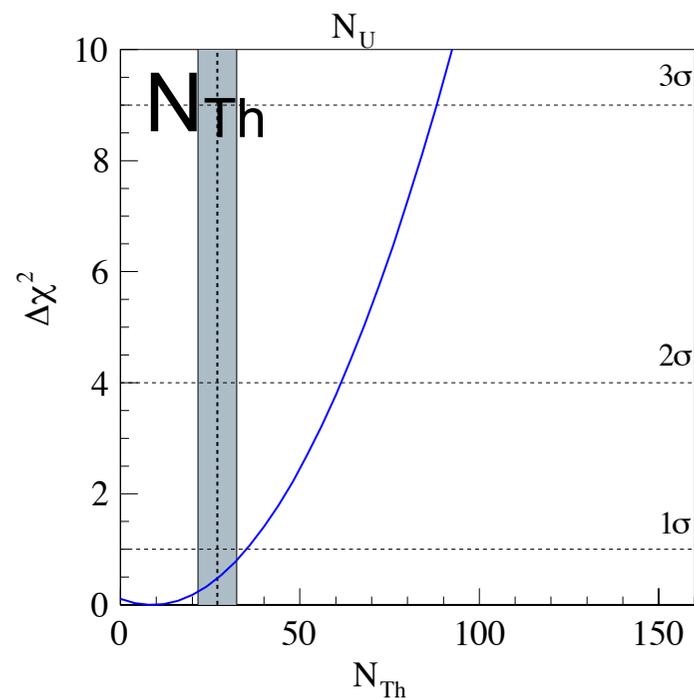
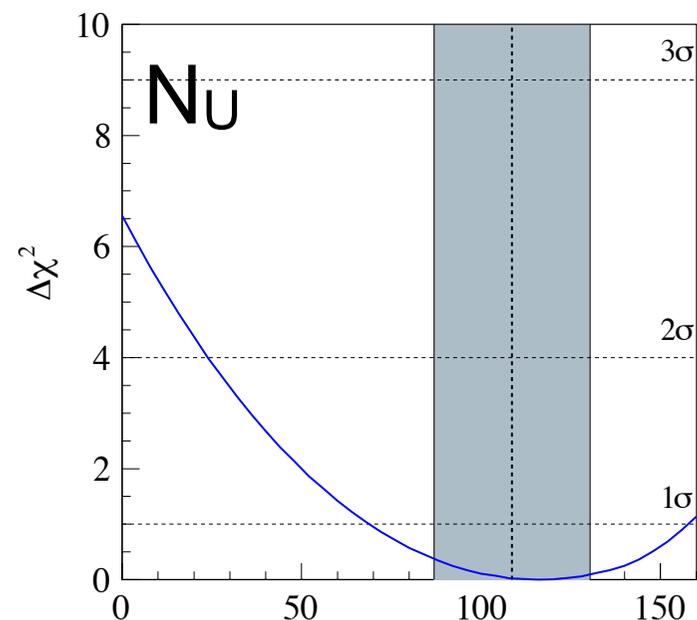
geo-neutrinos

► Analysis - Rate+Shape+Time Analysis (1)



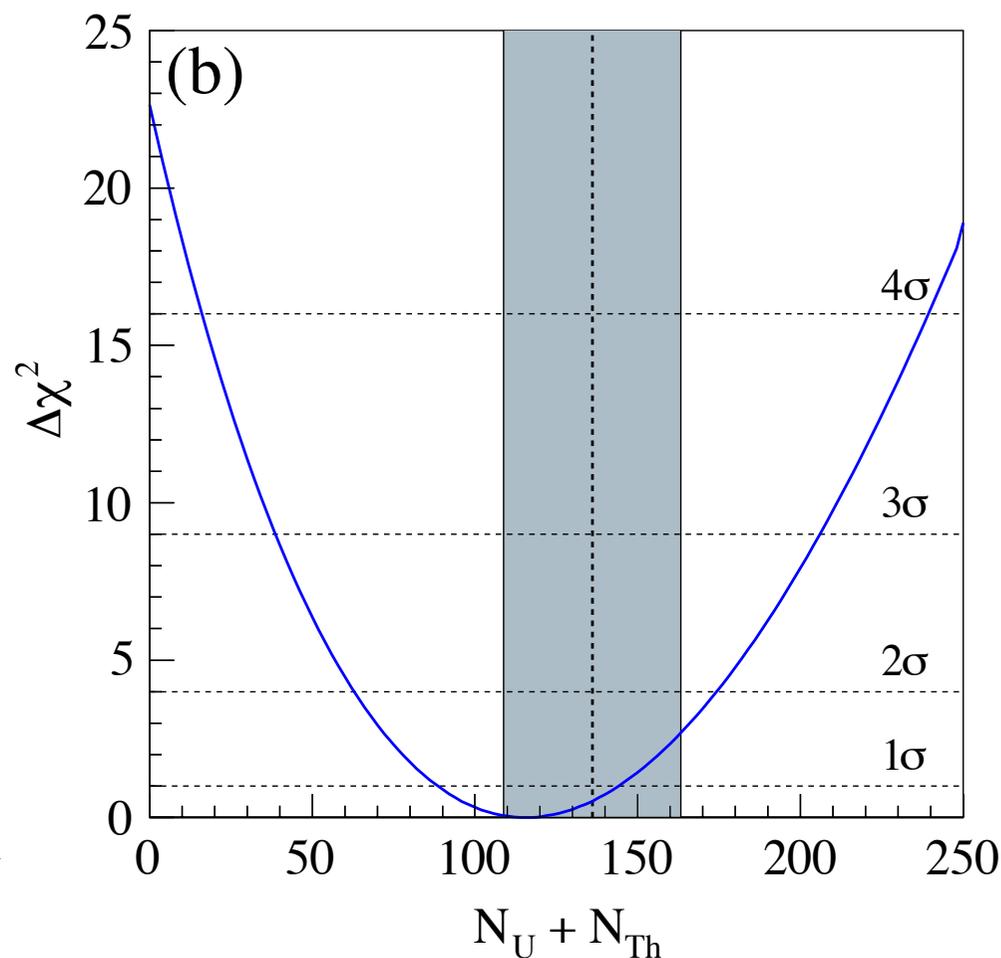
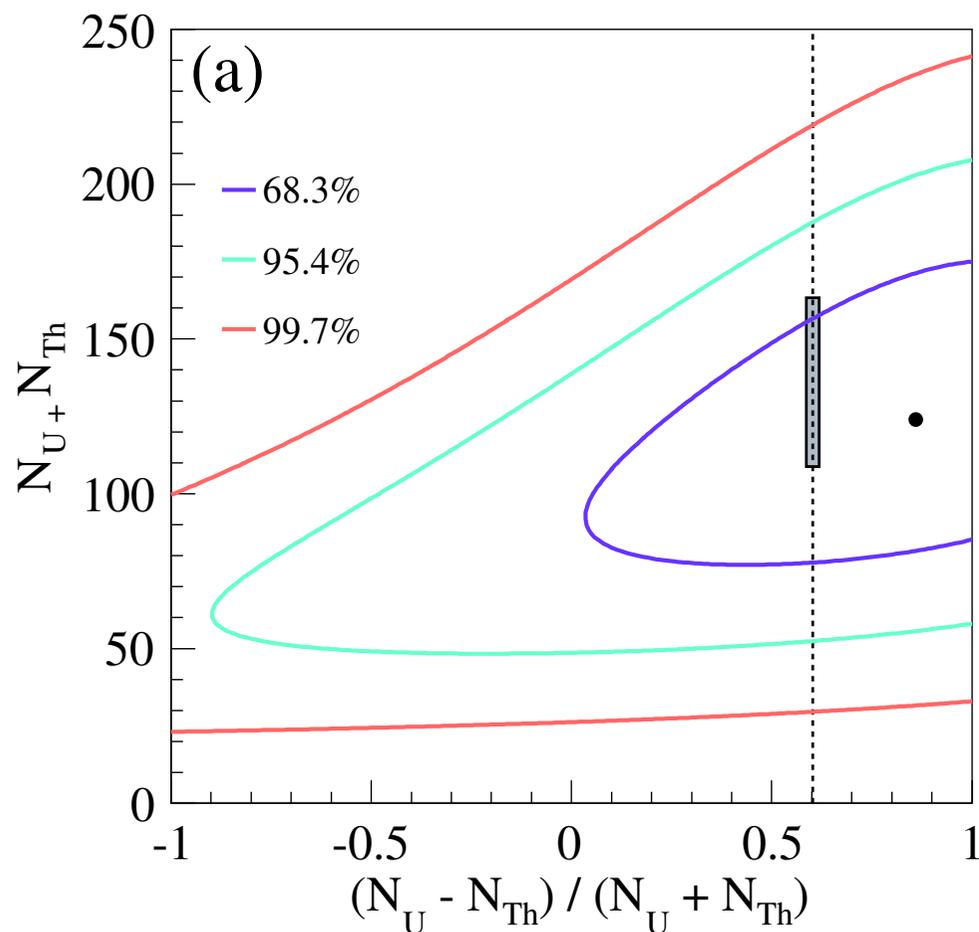
best-fit $(N_U, N_{Th}) = (116, 8)$

N_U 0 signal : rejected at 2.6σ (99.0%)



► Analysis - Rate+Shape+Time Analysis (2)

$N_U + N_{Th}$

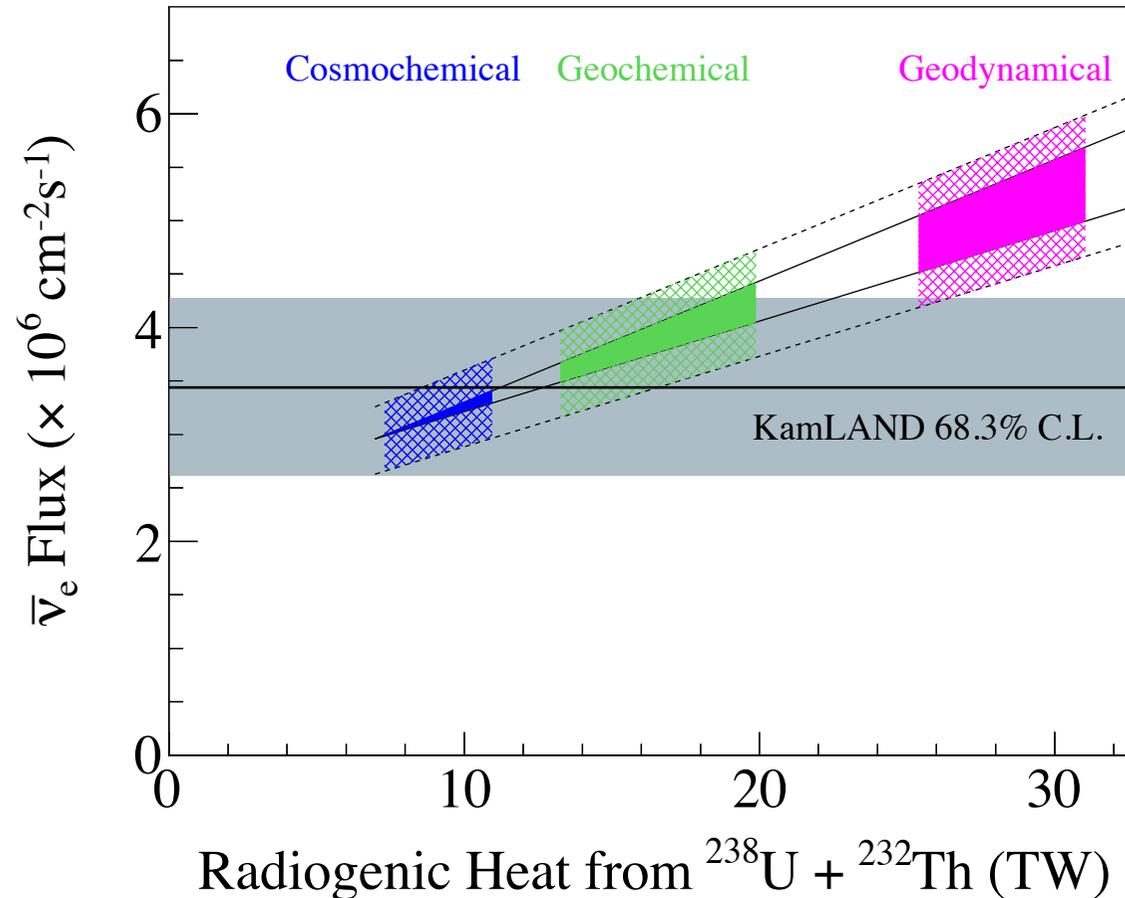


best-fit $N_U + N_{Th} = 116^{+28}_{-27}$

Flux : $3.4^{+0.8}_{-0.8} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$

0 signal rejected at 99.9998% C.L. (2×10^{-6})

► Analysis - Comparison with Models



- The measured 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.
- The BSE composition models are still consistent within $\sim 2 \sigma$.

▶ Summary

- ▶ Neutrino observation applies to two different interests, studying neutrino properties and investigating optically invisible deep interior of the astronomical objects utilizing its elusiveness.
- ▶ The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.
- ▶ **Recent analysis results are presented.** ([available at arXiv:1303.4667](https://arxiv.org/abs/1303.4667))
 - **Geo-neutrino**
 - Observed flux is fully consistent with Earth model.
 - [We presented the analysis results with very few running reactors. Geo-neutrino observation is very efficient.](#)
 - Now, we enter the era of obtaining geophysical formation from geo-neutrino measurements.