KamLAND and KamLAND-Zen Results

"RENO-50" toward Neutrino Mass Hierarchy

June 13–14th 2013

K.Ueshima (RCNS Japan)
for KamLAND and KamLAND-Zen collaboration

Collaboration

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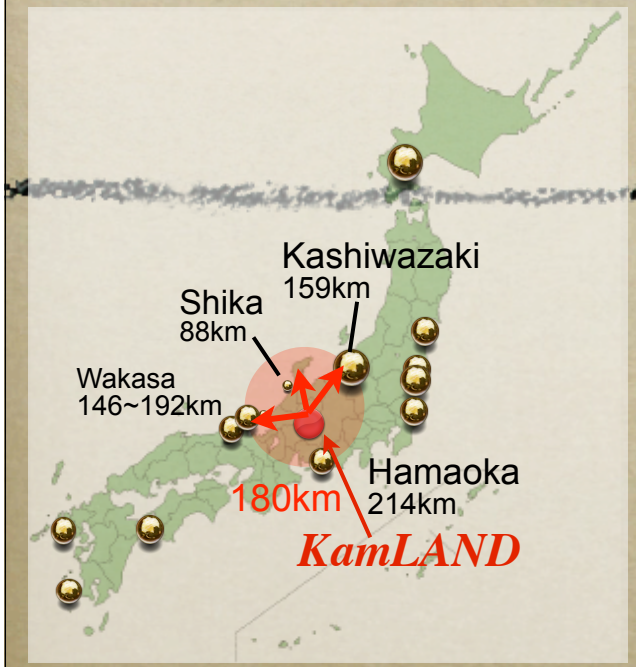
11 institutes
46 scientists

Hida Japan
March 2013

Contents

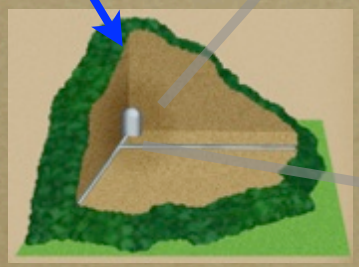
KamLAND



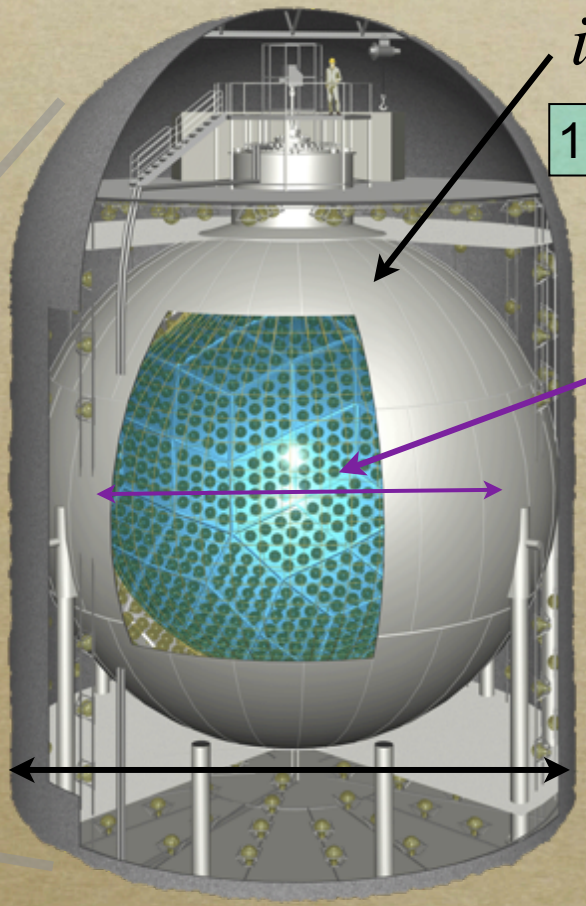
KamLAND

***Kam**ioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector*

cosmic ray



1000m
depth



inner detector

1,325 17inch + 554 20inch PMTs

* Photo coverage 34%

balloon
ϕ13m,135μm thick.

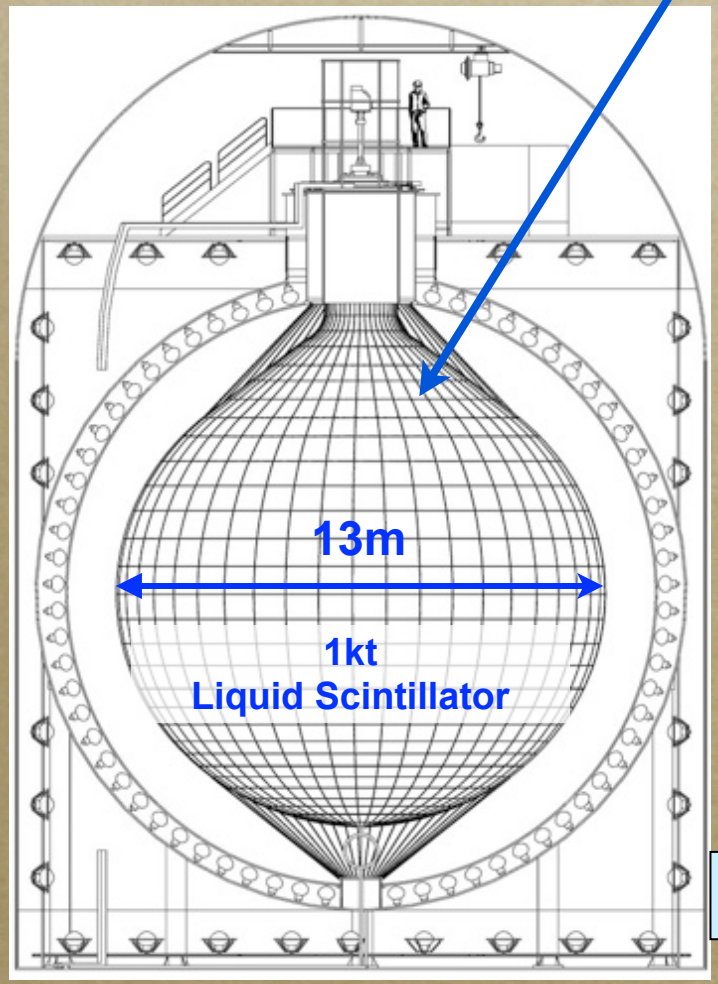
Water Cherenkov outer detector
ϕ18m, 3.2 kton pure water

225 20inch PMTs
* Muon veto

Physics

KamLAND

DAQ was started from 2002



Balloon
ϕ13m,135μm thick.

1kton Liquid Scintillator

* Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)

σ_v: 12cm$/\sqrt{E(MeV)}$ σ_E: 6.4%$/\sqrt{E(MeV)}$

observed energy [MeV]

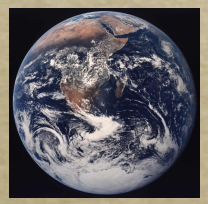
0.4 1.0 2.6 8.5

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

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

solar neutrinos

PRC 84, 035804 (2011)

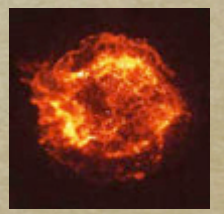


geo neutrinos

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

reactor neutrinos

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



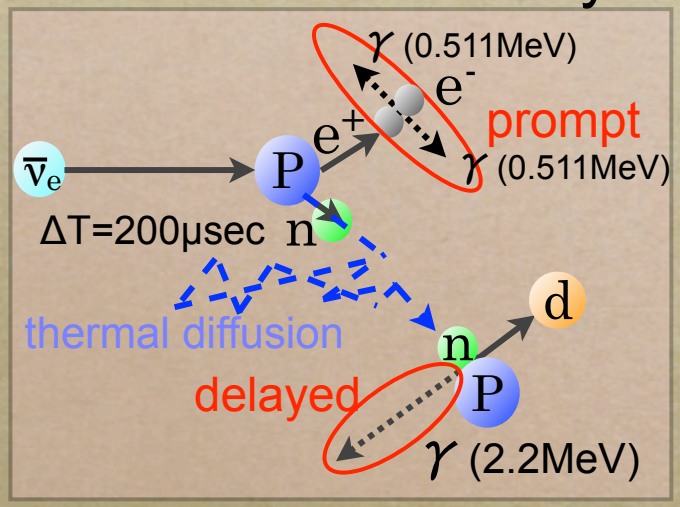
supernova neutrinos, etc.

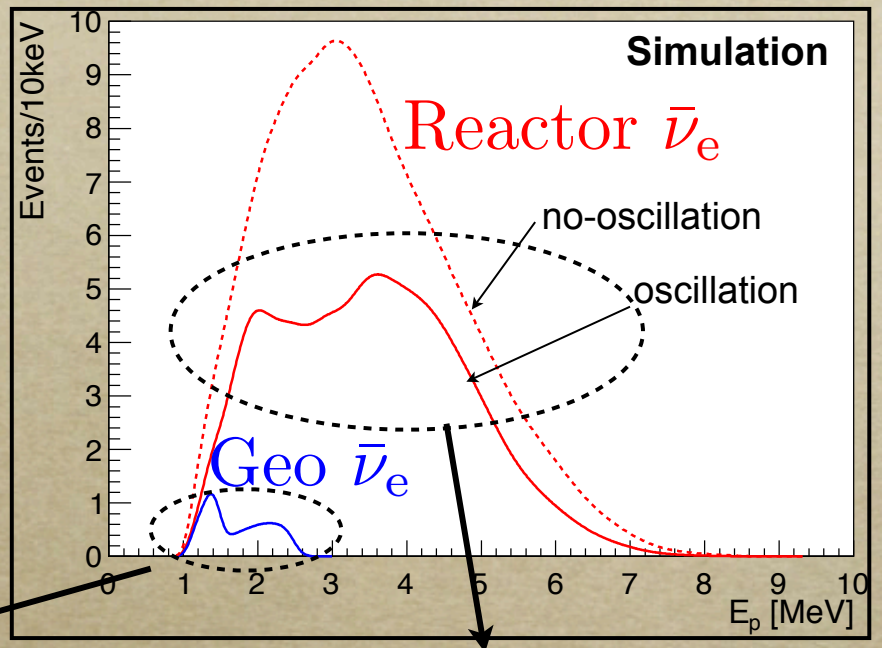
PRL 92, 071301 (2004)
Astrophys. J. 745, 193 (2011)

Different neutrino physics in the wide energy range

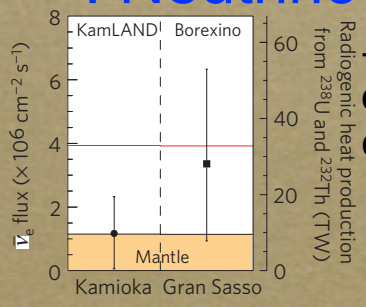
anti-neutrino detection

inverse-beta decay



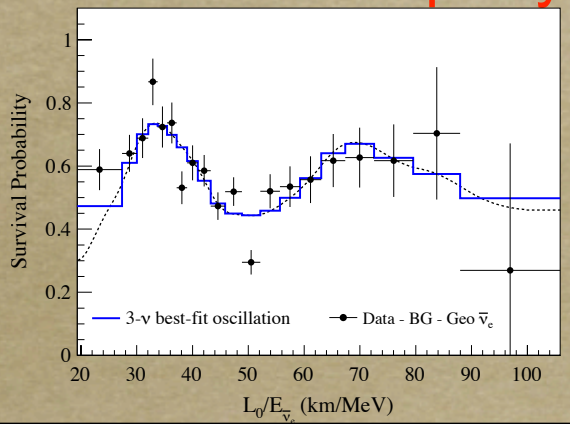


Geoneutrinos : Neutrino Application



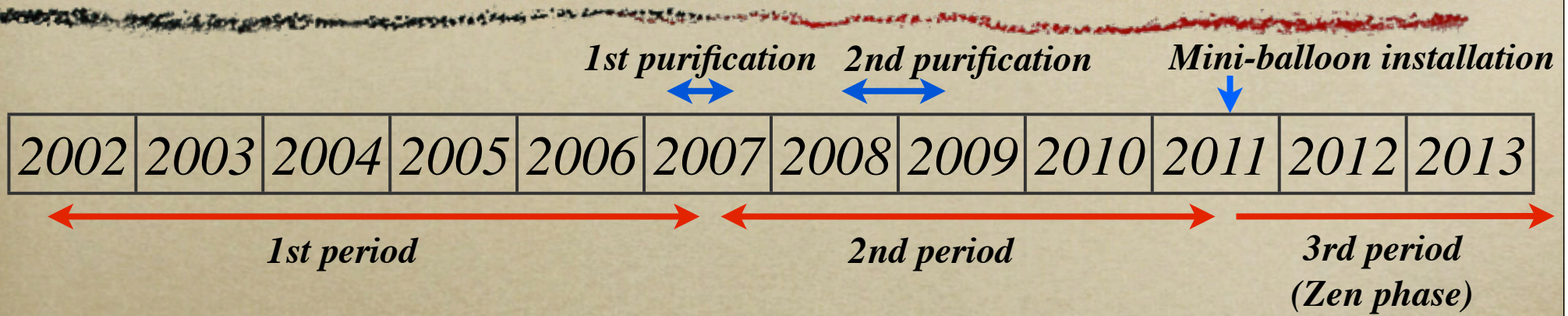
- Direct measurement of radiogenic heat contribution

Neutrino Property Study



- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

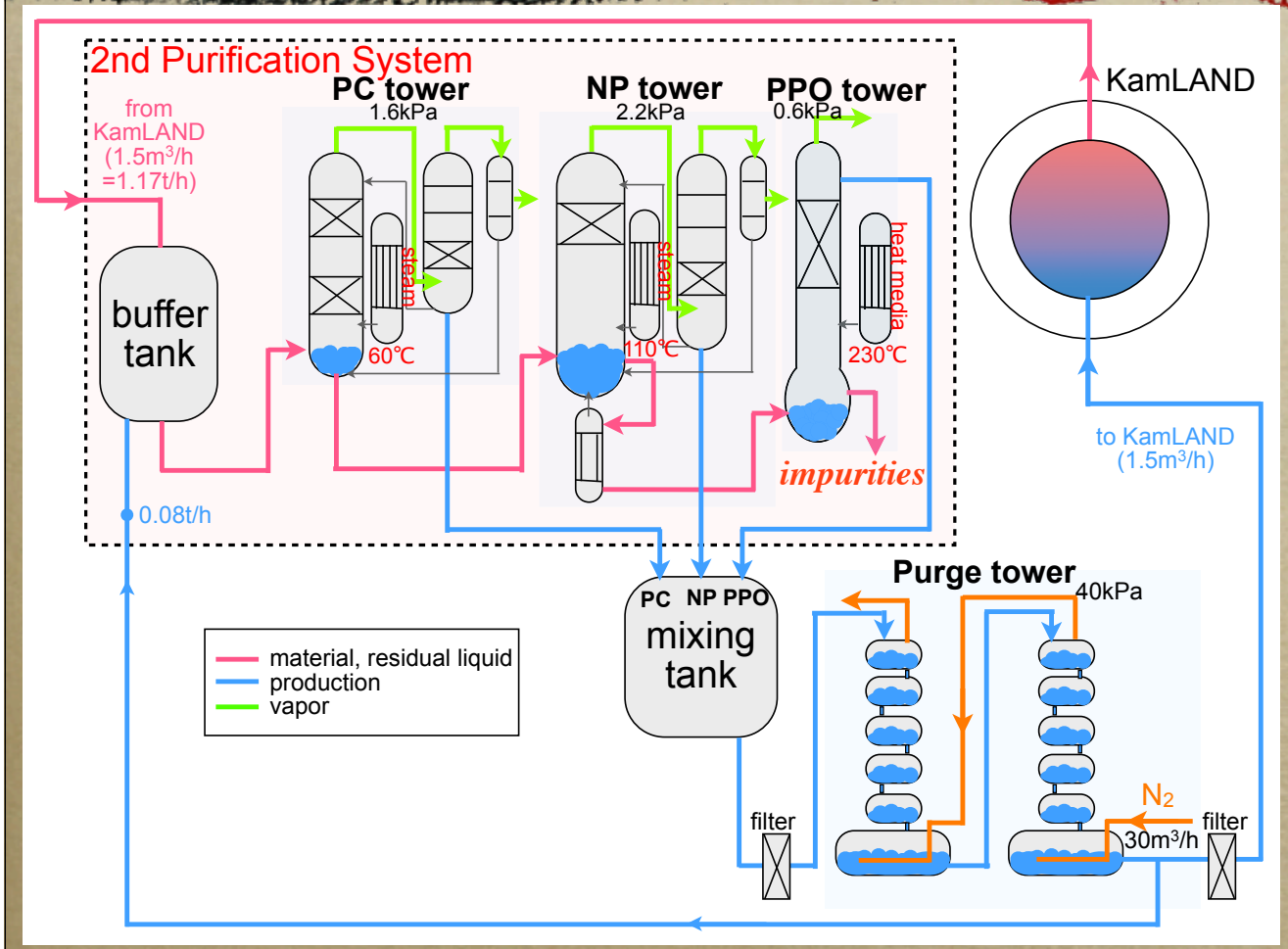
History

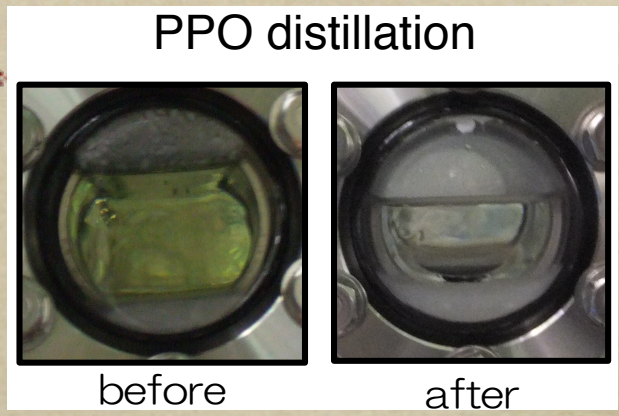


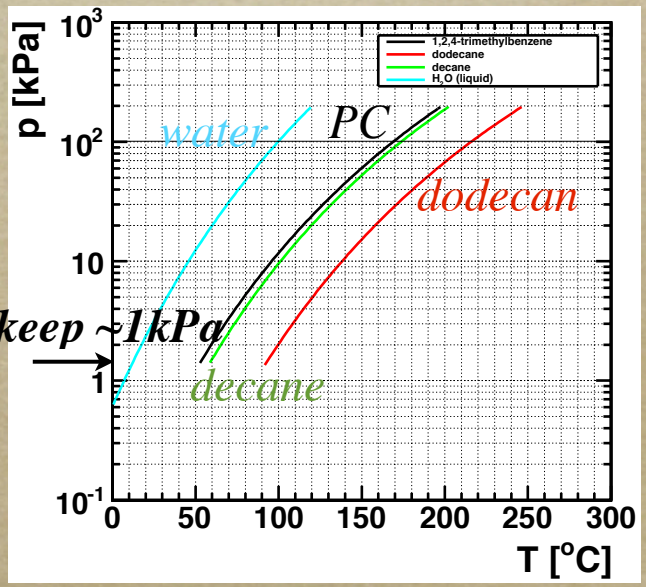
- *1st period (2002-2007): Water extraction and N2 purge were performed in 2002.*
- *2nd period(2007-2011): LS distillation and N2 purge were performed from Mar. to Aug. in 2007 and from Jun. in 2008 to Feb. 2009.* ***Nitrogen purity was also improved by the pure nitrogen generation system.***
- *3rd period(2011–)：Mini-balloon was installed for KL-Zen.*

The anti-neutrino study can be continued using outside Mini -balloon. *FV was decreased only about 17% for anti-neutrino analysis.*

Distillation system

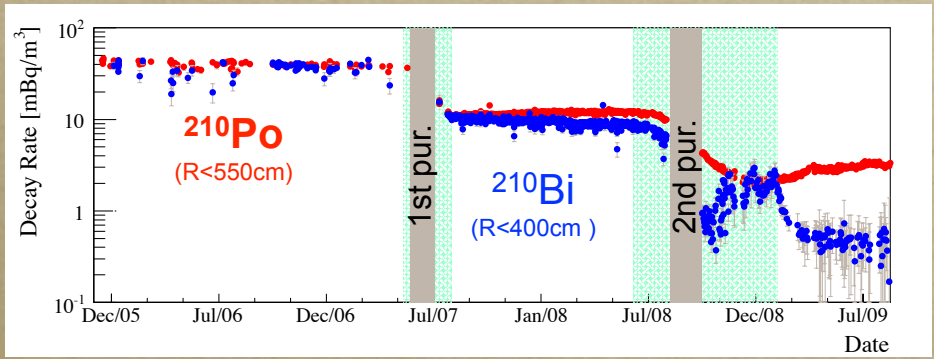




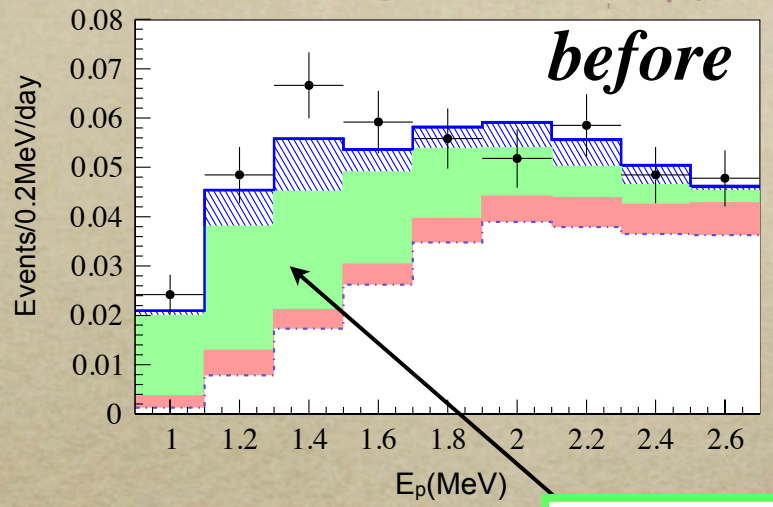


Achieved ultra low impurity (^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)

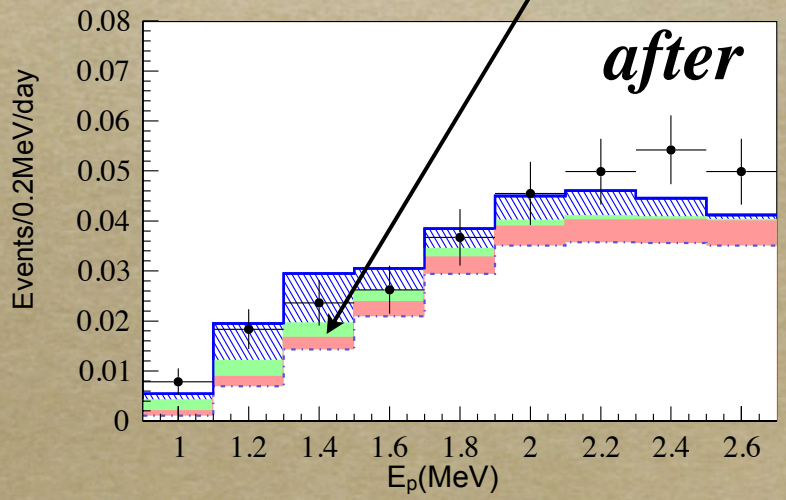
BG reduction



Dominant BG source (α, n) was reduced to **1/20** by 2 times distillation.



^{13}C (^{210}**Po** α, n)^{16}O



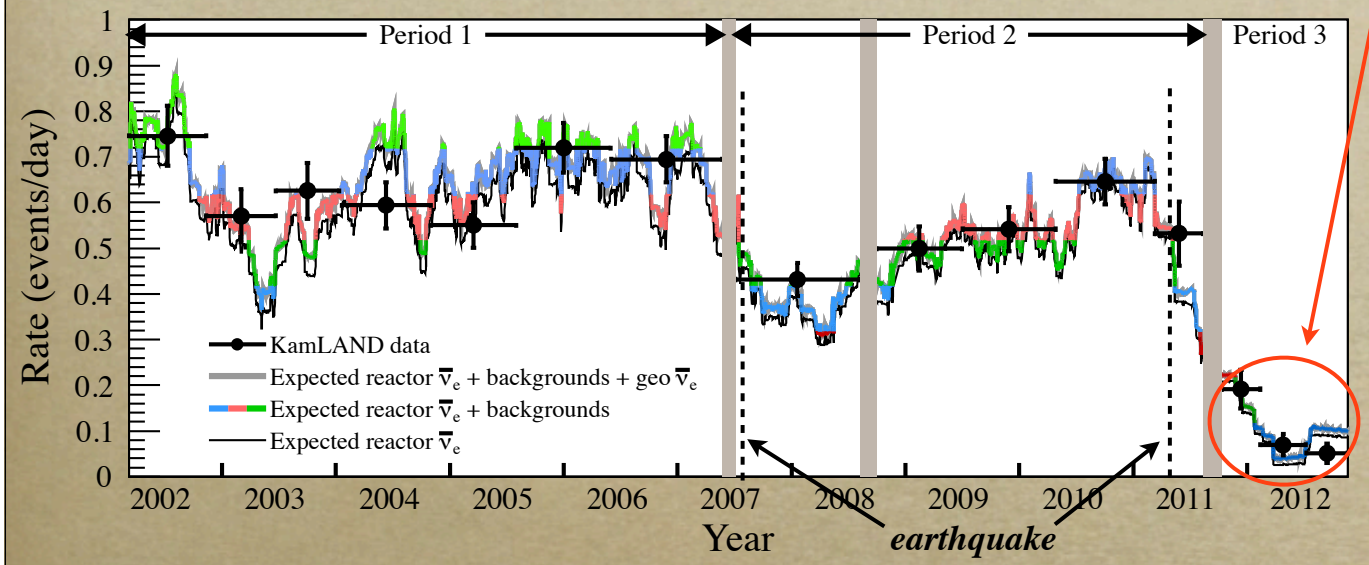
Reactor neutrino result

arXiv:1303.4667
“Reactor On-Off
Antineutrino Measurement
with KamLAND”

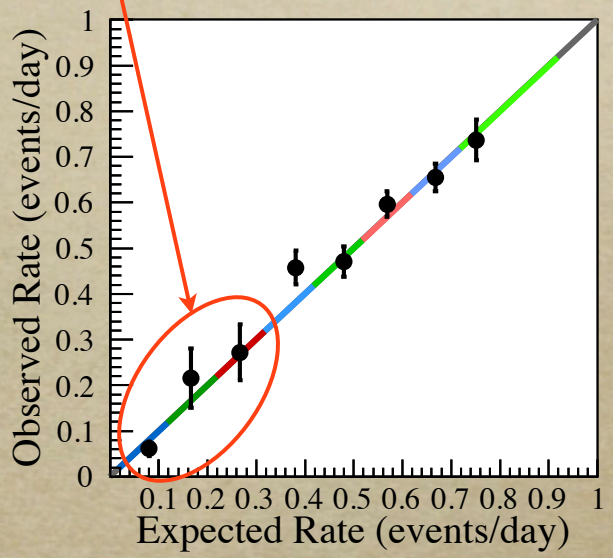
Reactor neutrino

2.6-8.5MeV

event rate time variation



low reactor phase

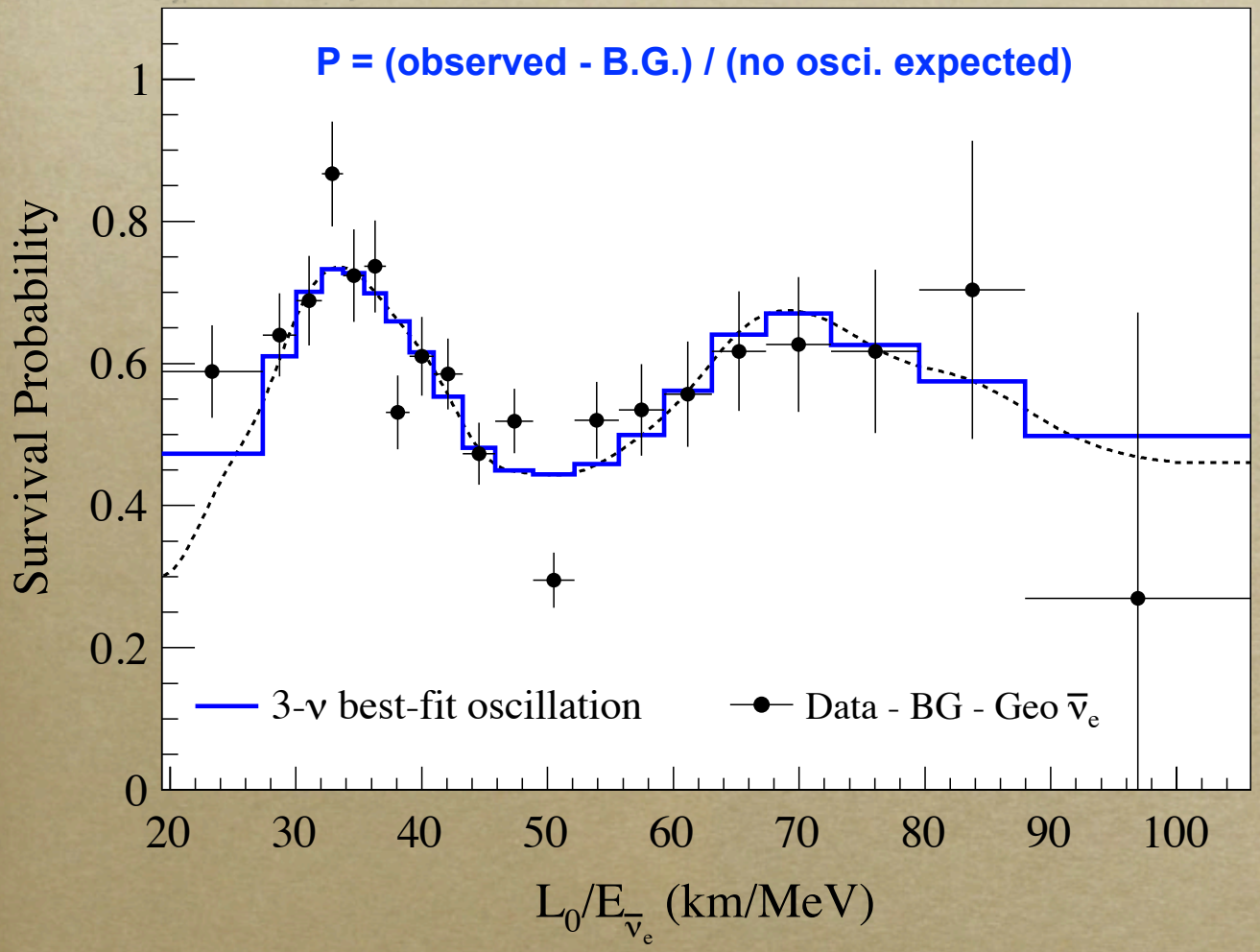


All Japanese reactors were shut down for 3 month due to the big earth quake in period 3.

Recent condition provides a unique opportunity to confirm and constrain backgrounds for the reactor anti-neutrino oscillation analysis.

Strong correlation between expected and observed event rate.

L/E plot



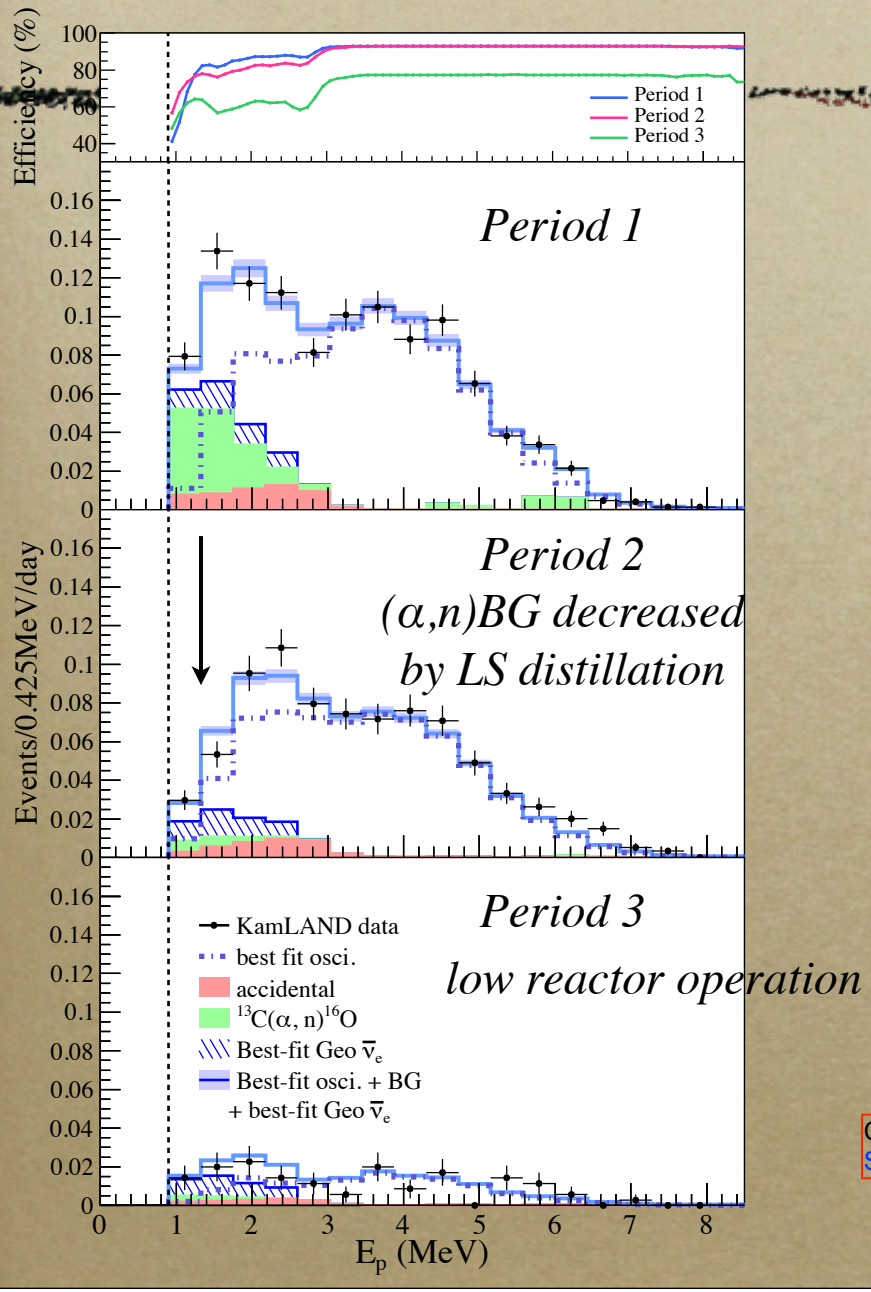
※L_0=180km fixed
(flux-weighted average)

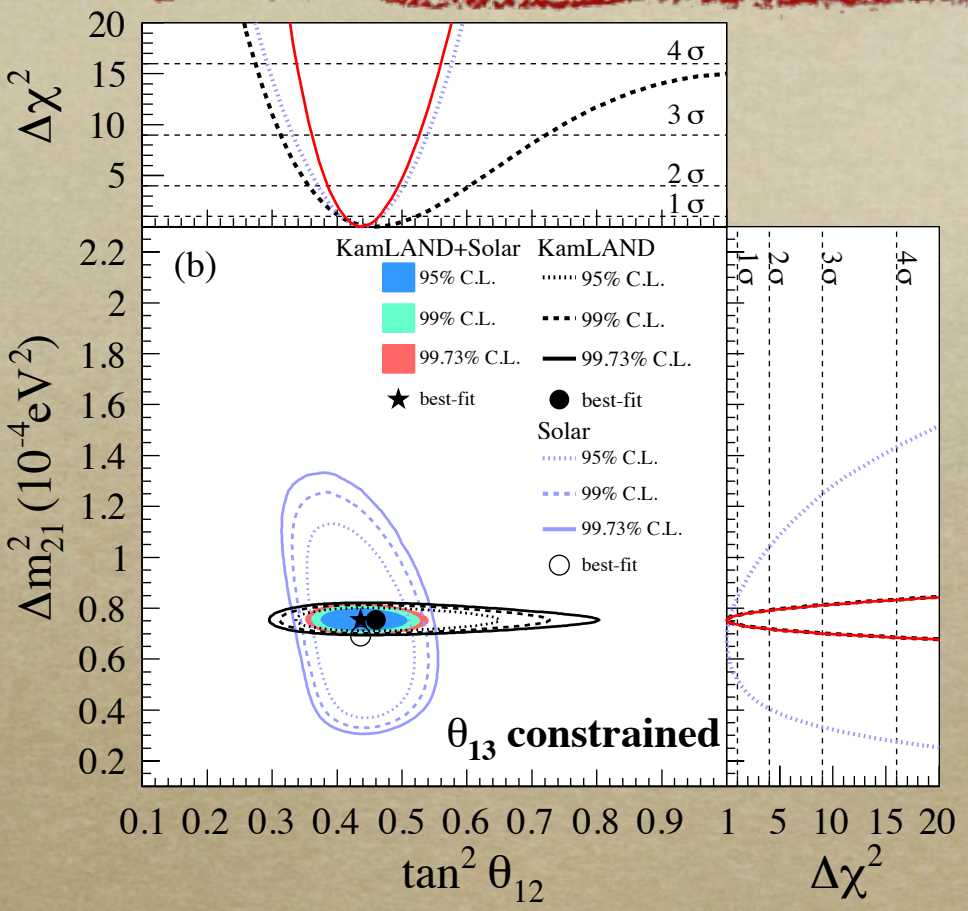
best-fit parameters
(KamLAND only)

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

2 cycles of oscillation was measured precisely

Oscillation parameter





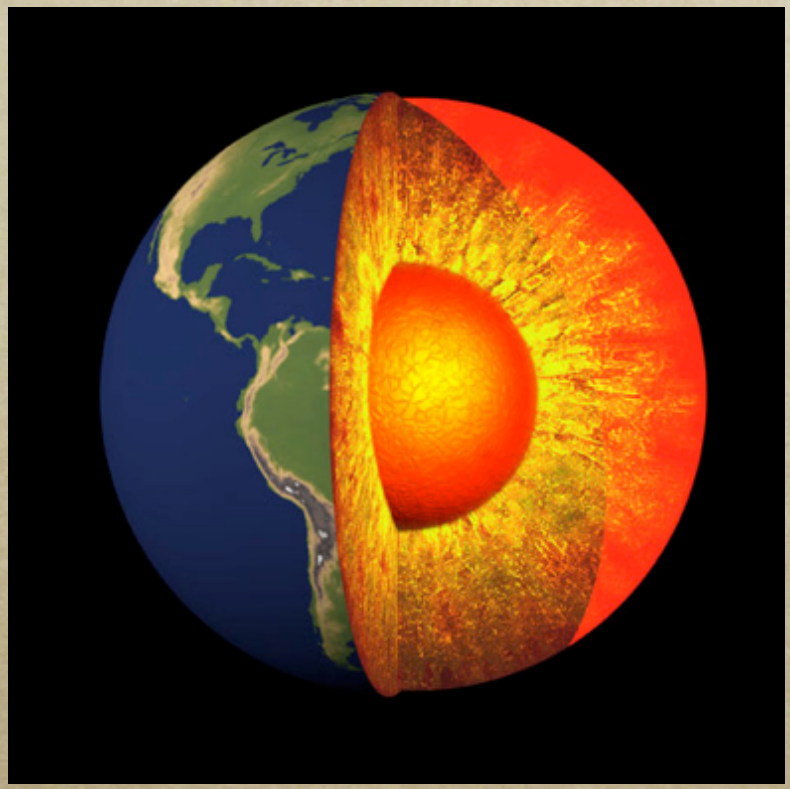
solar + KamLAND + θ_{13} experiments

Cl, Ga, Borexino, SK, SNO I + II + III (All)

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\text{eV}^2$$
$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$
$$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$$

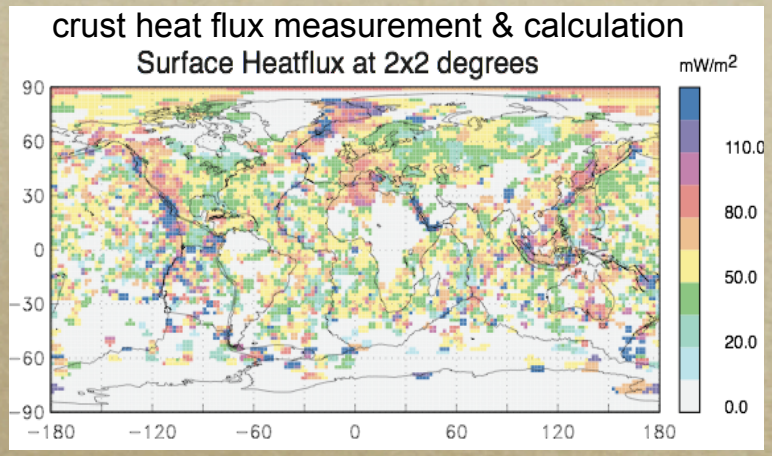
accelerator (T2K, MINOS) + short baseline reactor neutrinos (Double Chooz, Daya Bay, RENO)

Geo neutrino result



arXiv:1303.4667
“Reactor On-Off
Antineutrino Measurement
with KamLAND”

What's the heat source in the Earth ?



47± 2 TW

Solid Earth 1, 5 (2010)

Bulk Silicate Earth (BSE) model
chondrite meteorite analysis
(same meteorite of Earth's origin)

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

This is not "direct measurement".

20 TW

Only half of radiogenic heat contribute to the surface heat flow.

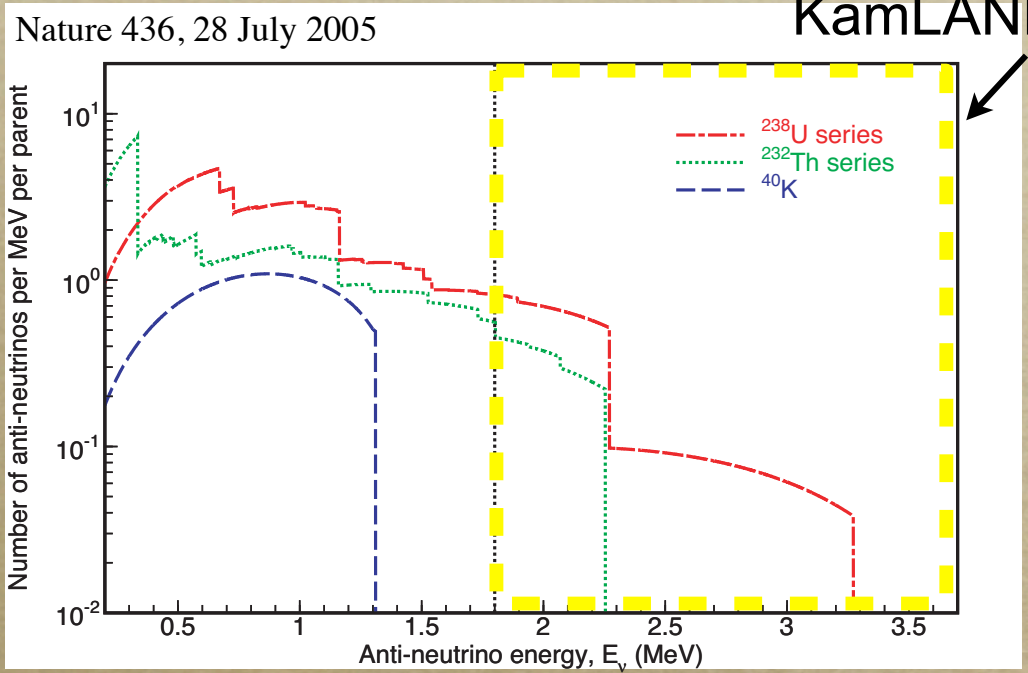
Using analysis result of Geo-neutrino flux,
we can measure the radiogenic heat directly.

Geo-neutrino

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

- calculation of geo antineutrino energy spectrum

KamLAND energy window



beta-decay

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

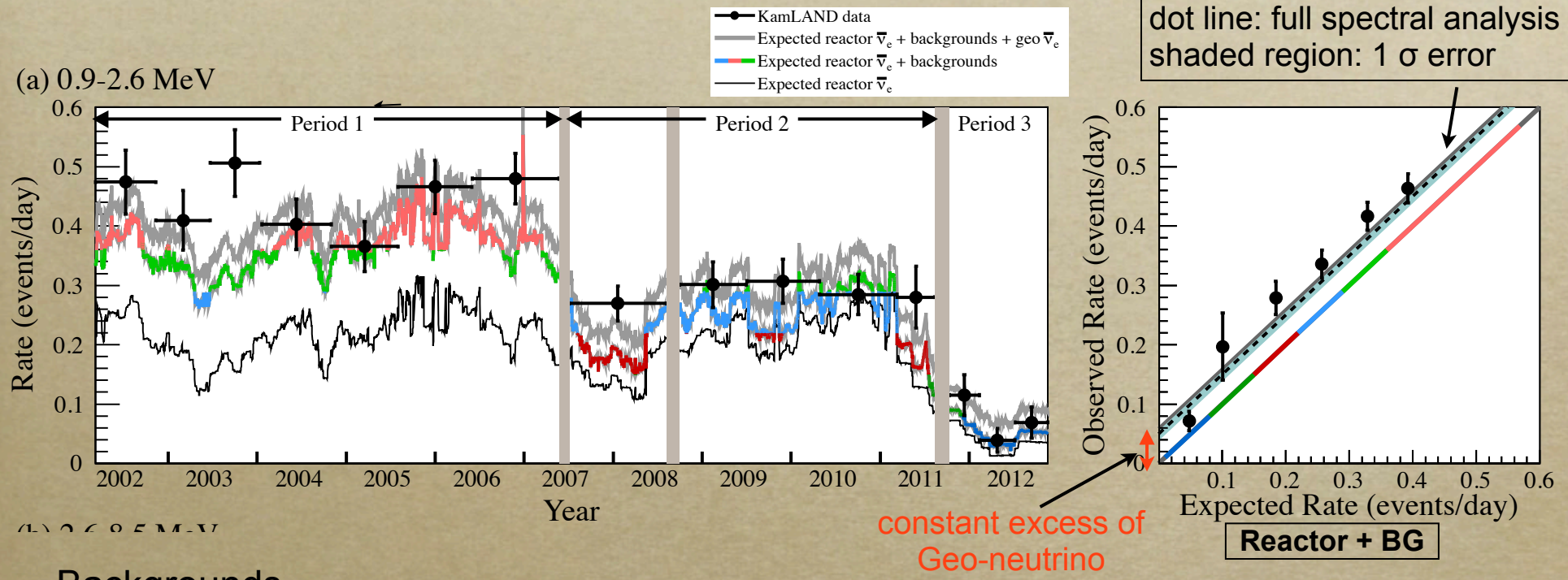
$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

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

KamLAND can detect !

Geo neutrino analysis

- event rate time variation (0.9-2.6 MeV)



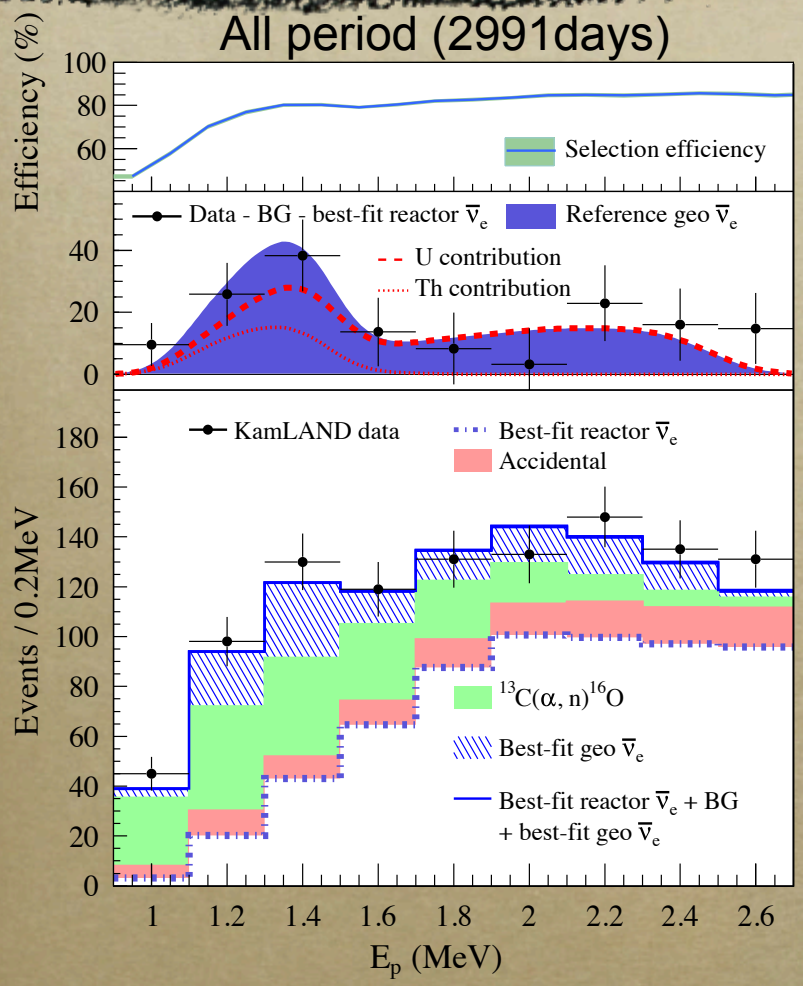
Backgrounds

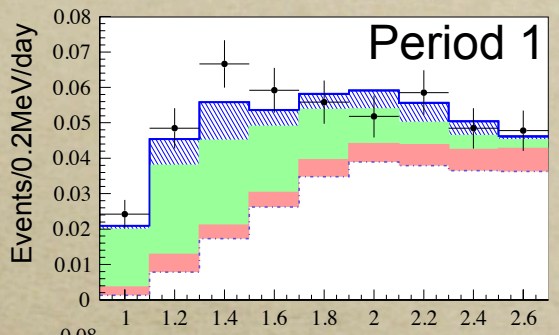
* The non-nu background for geo-neutrino was decreased by LS distillation.
* Reactor neutrino background was significantly decreased by the earthquake.

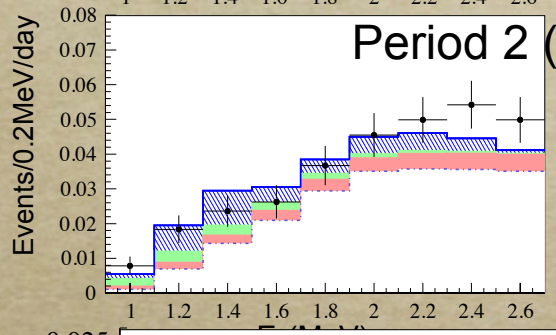
* Constant excess of Geo-neutrino is seen above the estimated reactor neutrino + non-neutrino background in the energy range 0.9 - 2.6 MeV.

→ Time information is useful to extract the geo-neutrino signal

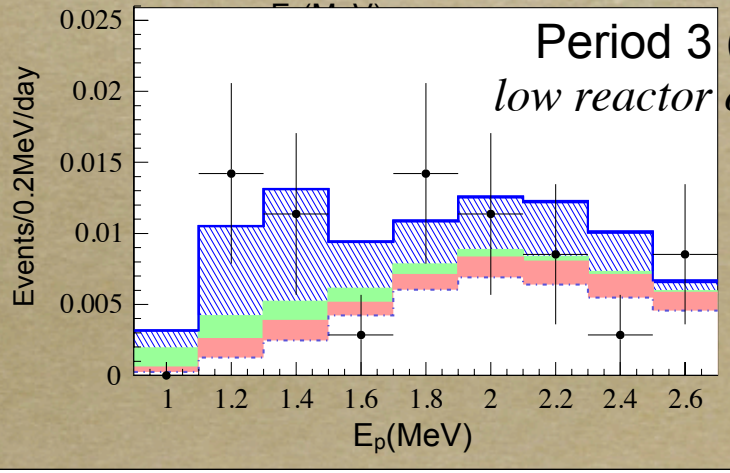
Energy spectrum (Geo-ν region)





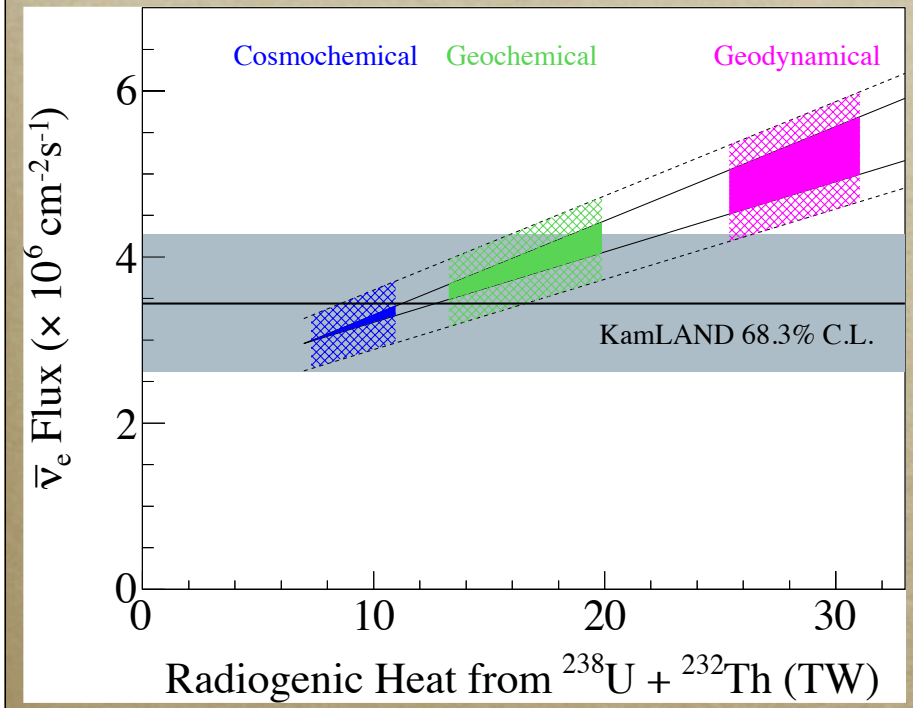


(α,n)BG decreased by LS distillation



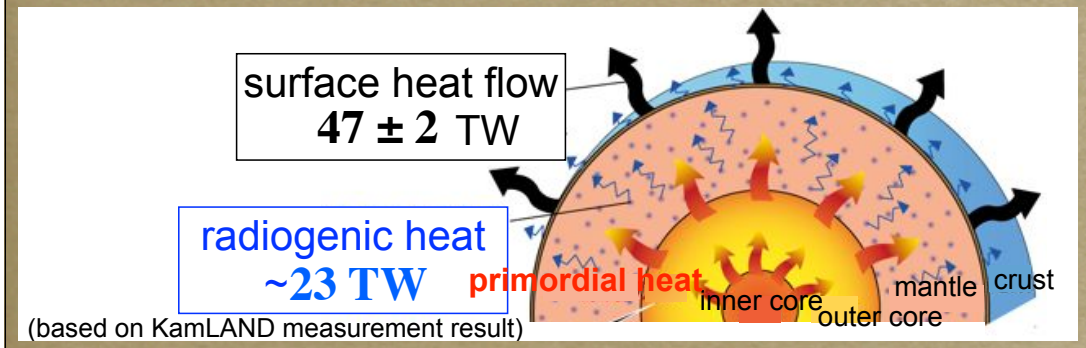
Geo-ν 116^{+28}_{-27} events

Geo neutrino result



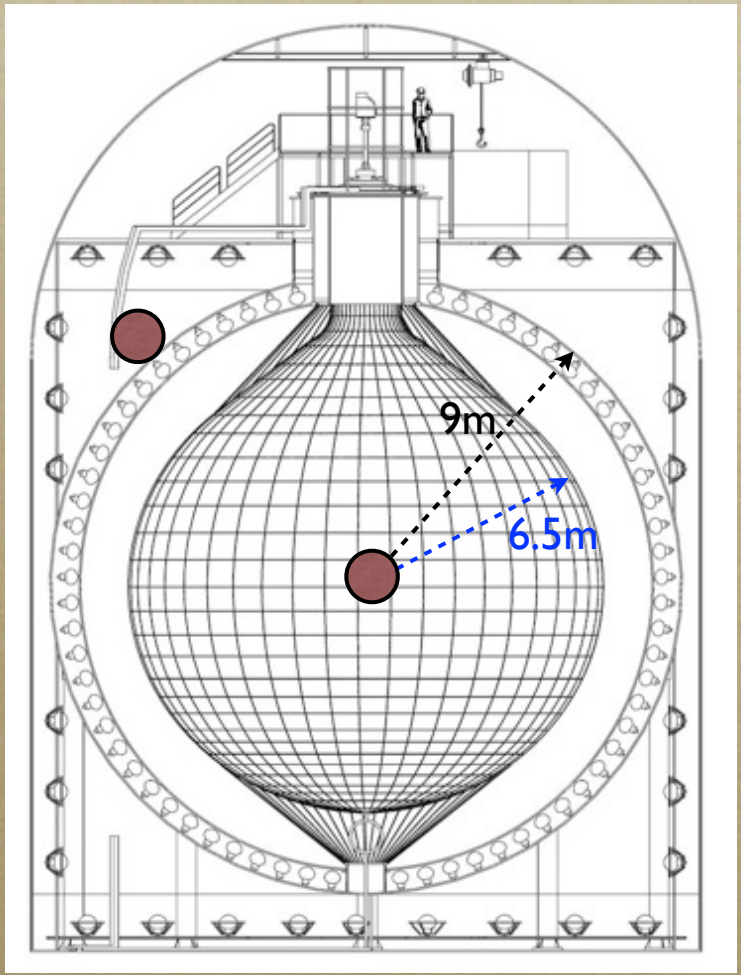
- The measured KamLAND geo-neutrino flux ($3.4\pm0.8\times10^6$ /cm^2/sec) translates to a total radiogenic heat production : $11.2\ ^{+7.9}_{-5.1}$ TW
- The geodynamical prediction with the homogeneous hypothesis is disfavored at 89% C.L.
- The BSE composition models are consistent within ~2 σ.

Total radiogenic heat (~23TW) contribute to the ~half of surface heat flow (47TW) taking into account the contribution of the crust (7.0 TW) and other isotopes (4.3TW).



Earth's primordial heat is remaining !!

Future project



CeLAND

4th neutrino search

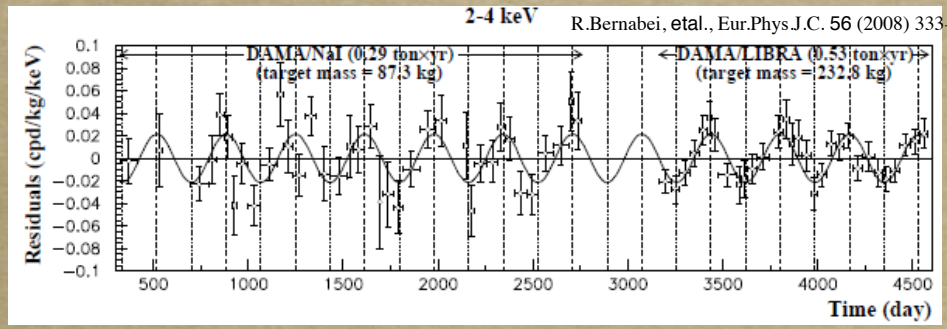
Ce source in KamLAND

KamLAND-Pico

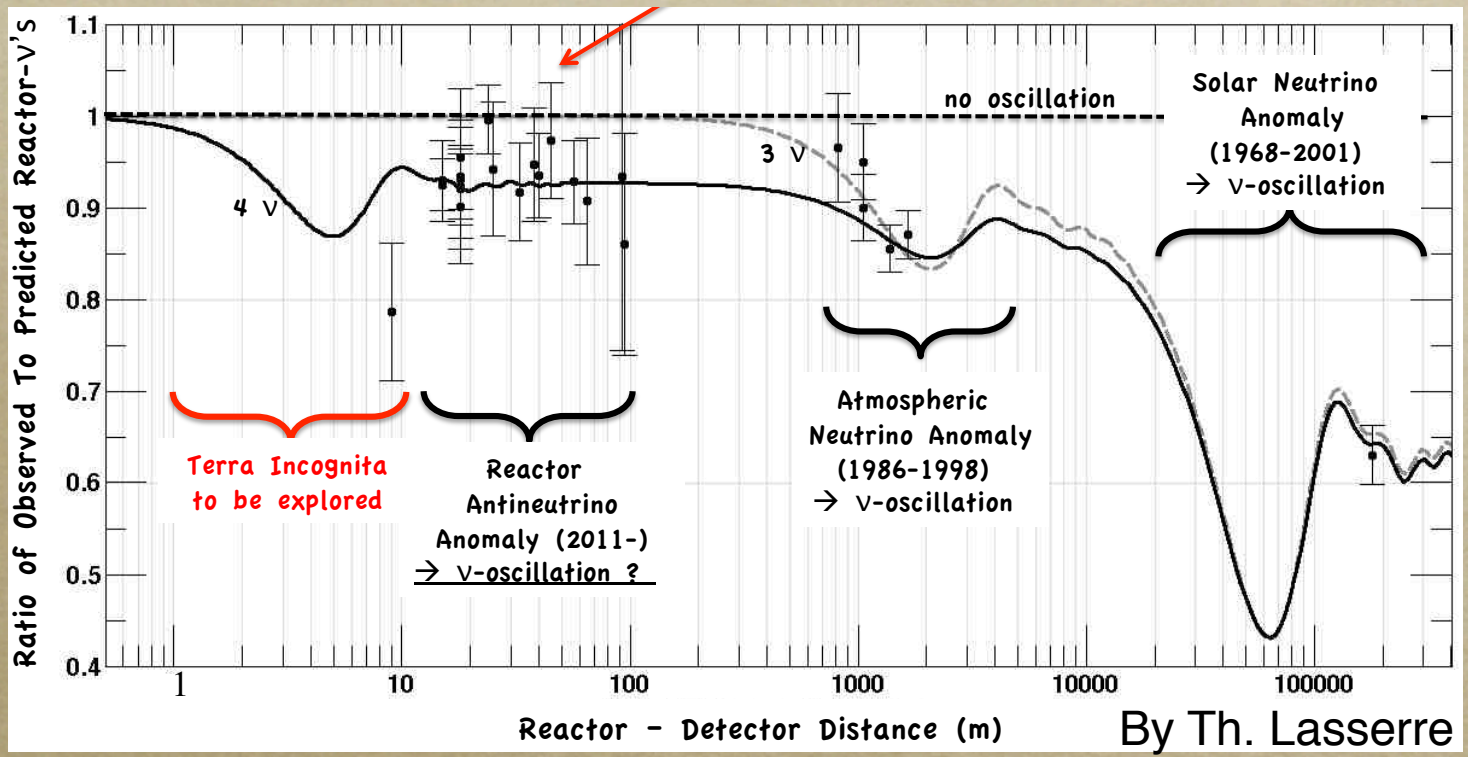
Dark matter search

NaI in KamLAND

Check DAMA annual modulation

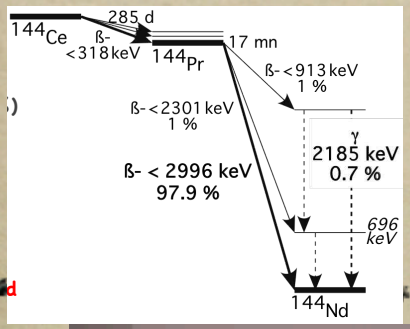


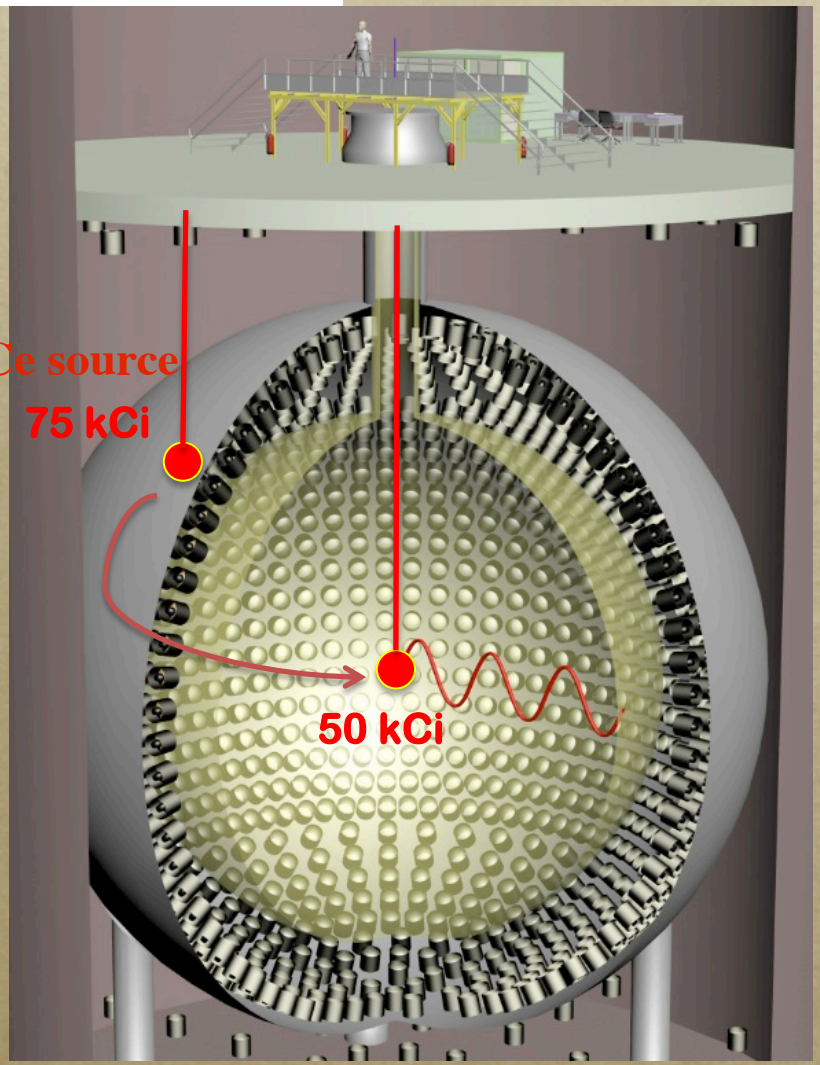
Reactor ν Anomaly

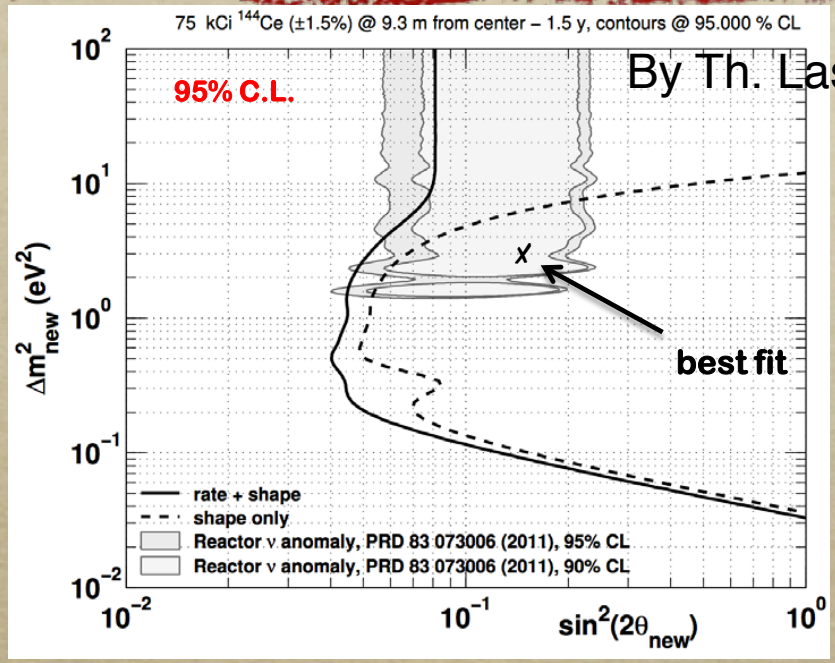


Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

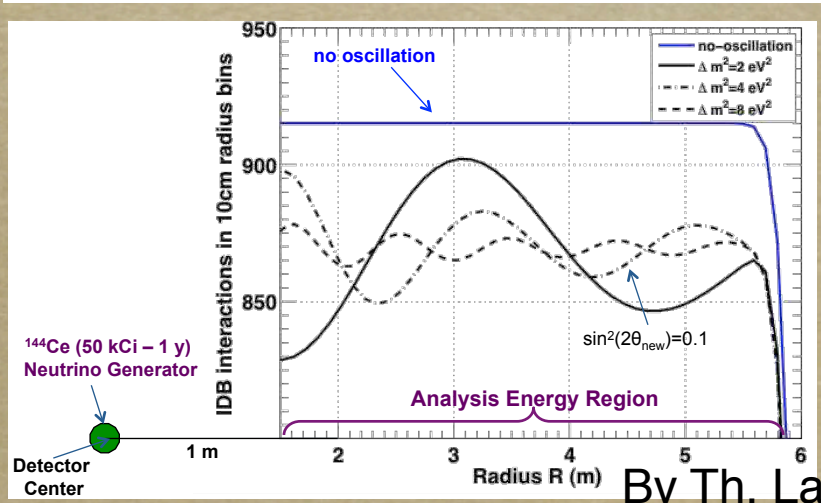
4th neutrino search (CeLAND)







By Th. Lasserre

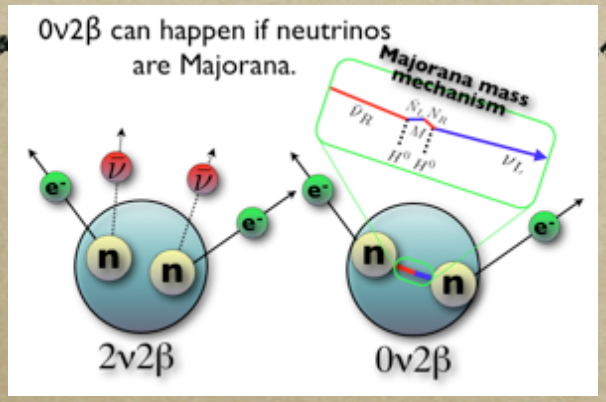


By Th. Lasserre

◦ *KamLAND-Zen result*

Zero neutrino double beta decay search

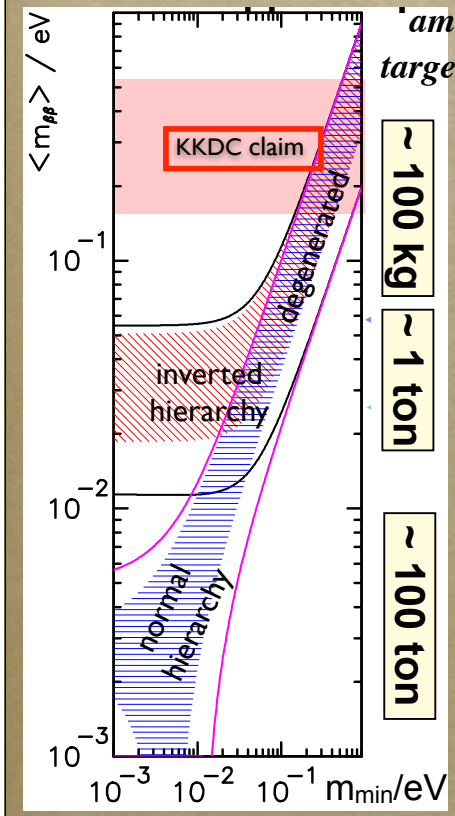
Neutrino less double beta decay



If neutrinos are Majorana particle, 0ν2β can happen.

- *effective neutrino mass
- *mass hierarchy
- * lepton number violation
- * evidence of Majorana particle

Big impact for particle physics!!



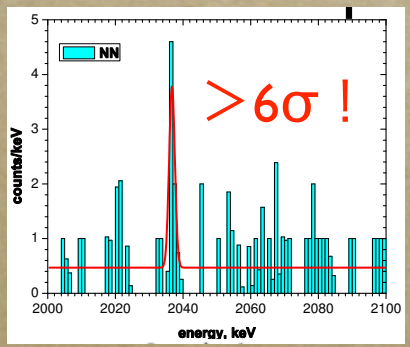
amount of target nucleus

~ 100 kg

~ 1 ton

~ 100 ton

KK claim *^{76}Ge 11kg*



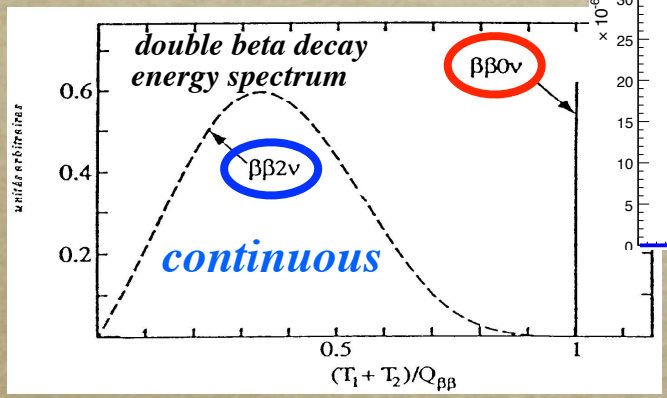
exposure 71 kg・yr

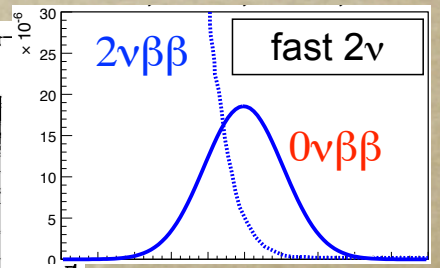
$T_{1/2}=2.23^{+0.44}_{-0.31}\times10^{25}$ yr

$m_{\beta\beta}$ = *0.18-0.43 eV at 2σ*

Klapdor et al. Mod.Phys.Lett.A21(2006)1547

monochromatic



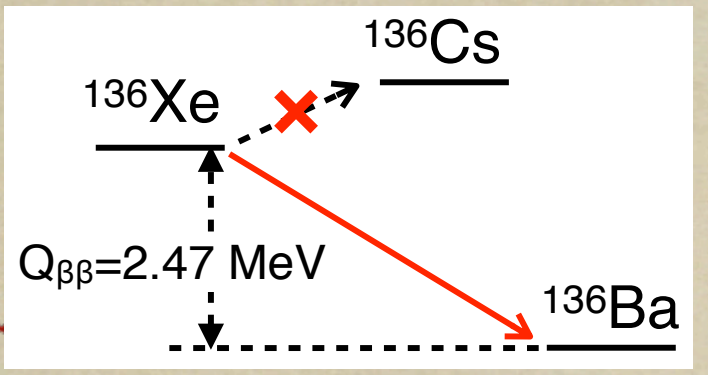


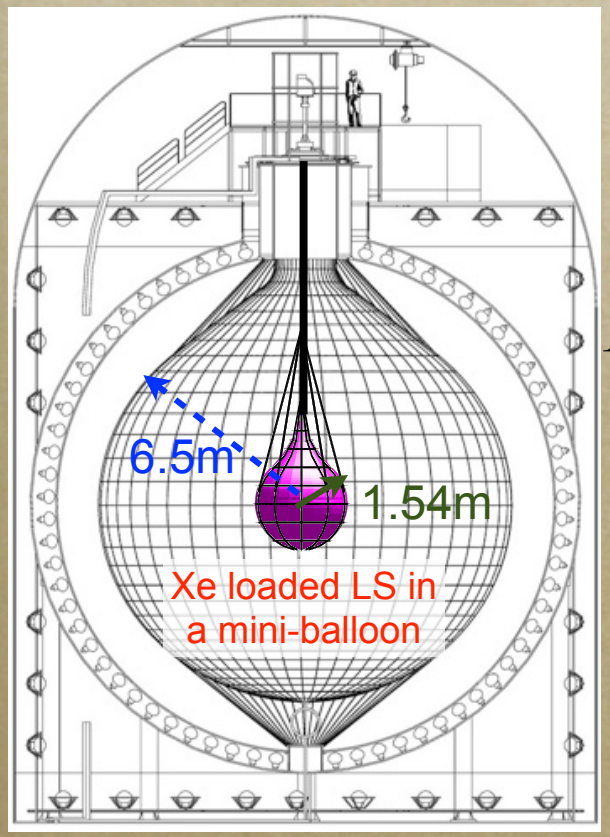
2ν tail events

0ν2β is very rare event.

Required ultra low BG detector with high energy resolution

KamLAND-Zen





- Detector Features

Xe loaded LS was installed in Sep.2011.

↳ *320kg 91% enriched ^{136}Xe*

DAQ was started form Sep. 2011.
(The project was started from 2009)

^{136}Xe merit

enrichment is available ~91%

Xe is dissolved in LS 3wt% at 1 atm.

collect Xe from Xe loaded LS by degassing

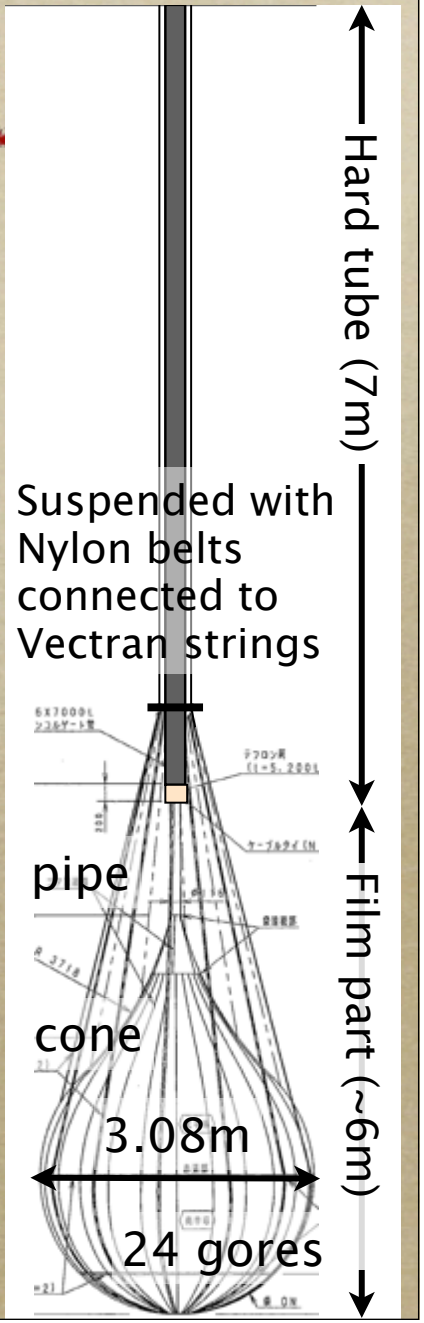
purification method is established

High scalability: replace to big balloon and dissolve ~ton ^{136}Xe.

If 0ν2β signal was observed, we can check without ^{136}Xe data using same detector.

Mini-balloon production

at Sendai in June 2011



Mini-balloon installation

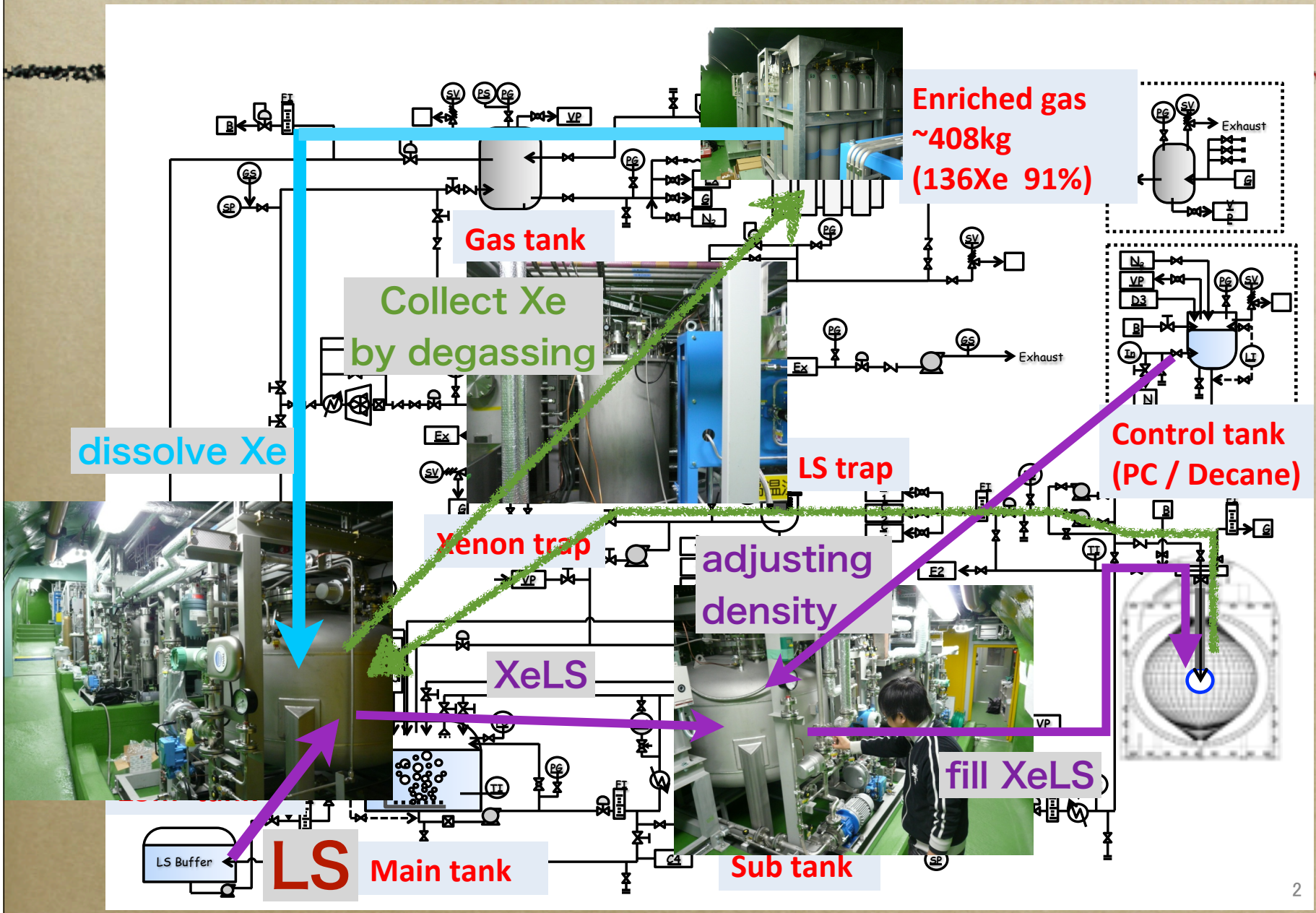

deflated
Mini-balloon


clean room
class ~100
Deployment of balloon and tube

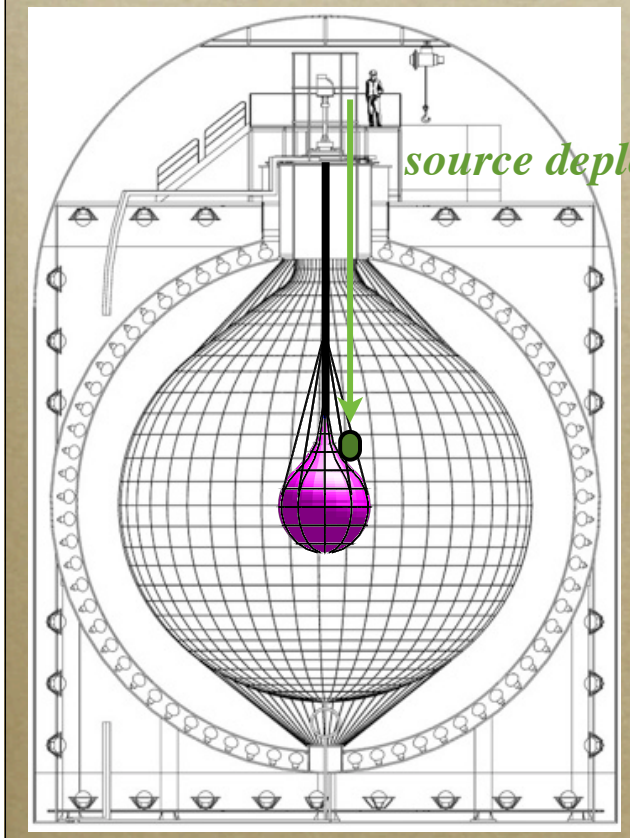

balloon going through light shield

Deflated Mini-balloon was delivered to Kamioka. After the Mini-balloon was installed in KamLAND, the Mini-balloon was inflated using normal LS. Finally the normal LS was replace to the Xe loaded LS.

Xenon system



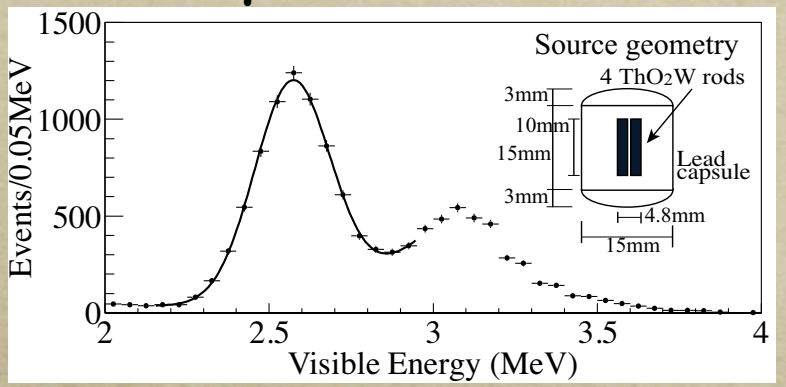
Calibration



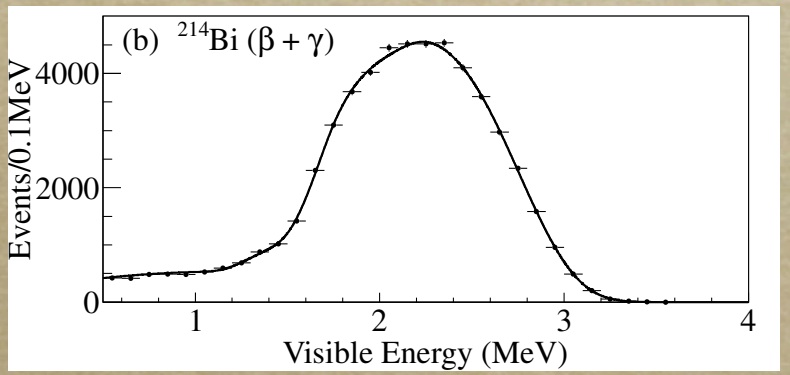
Vertex resolution : 15cm$/\sqrt{E(MeV)}$

Energy resolution: 6.6%$/\sqrt{E(MeV)}$

(a) ^{208}Tl: 2.6MeV γ



(b) ^{214}Bi: β+γ decay



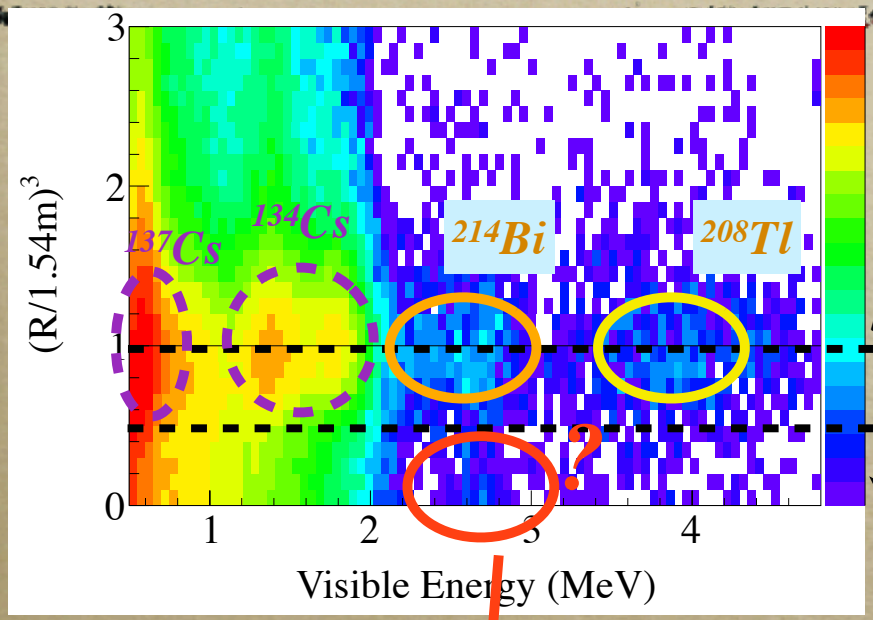
^{222}Rn $^{214}\mathrm{Bi} \xrightarrow[Q_\beta=3.272\ \mathrm{MeV},99.989\ \%]{T_{1/2}=19.9\ \mathrm{min}} {}^{214}\mathrm{Po} \xrightarrow[Q_\alpha=7.687\ \mathrm{MeV}]{T_{1/2}=164.3\ \mu\mathrm{sec}} {}^{210}\mathrm{Pb}.$

β+γ decay

(c) 2.2MeV γ from spallation neutrons capture on protons

1st result

exposure: 27.4 kg*yr

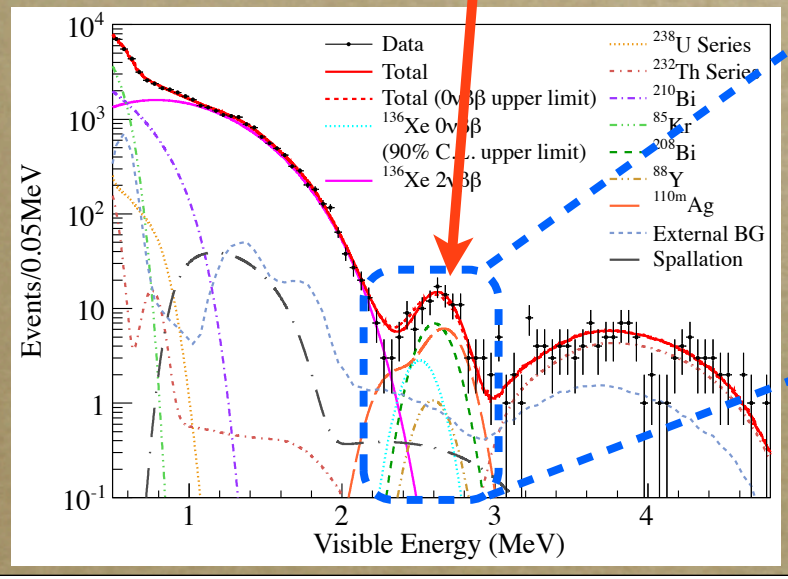


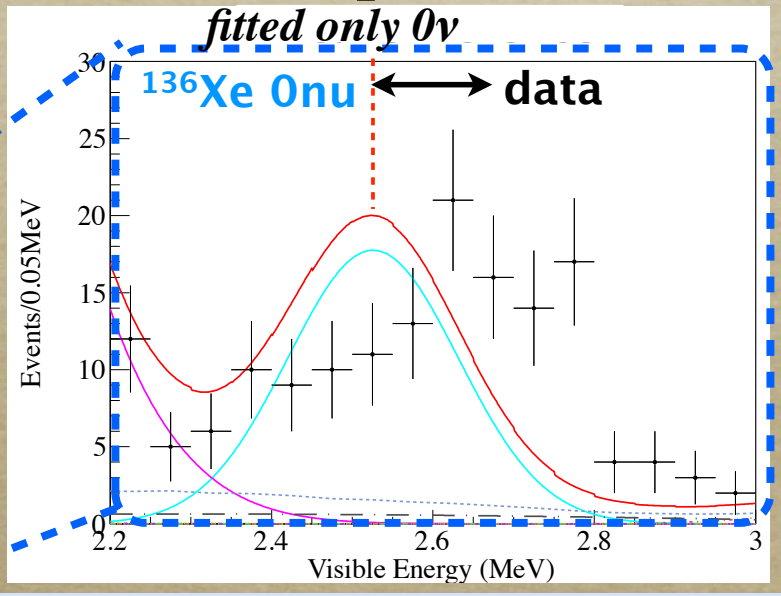
FV is set to 1.2m radius for 2ν2β analysis.

$$T^{2\nu2\beta}_{1/2} = 2.38 \pm 0.02(stat) \pm 0.14(sys) \times 10^{21} yr$$

Phys.Rev.C85,045504(2012)

Is this peak 0ν.....?

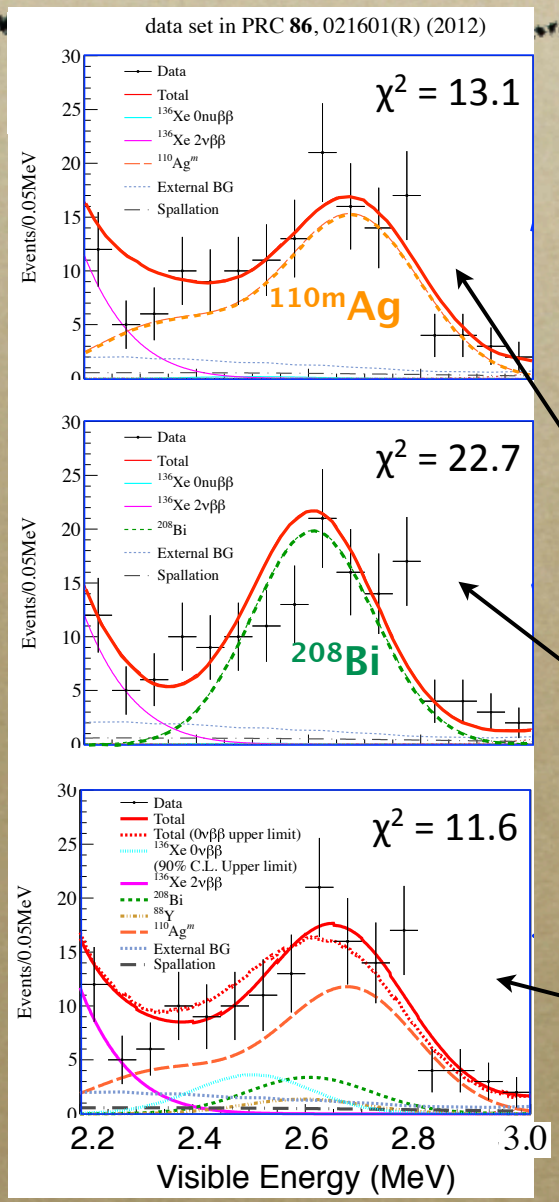




3% difference between data and 0ν

event rate was ~0.25/ton/day

BG study



survey <u>all decay path</u> of <u>all nucleus</u> in ENSDF

~millions *~thousands*

http://ie.lbl.gov/databases/ensdfserve.html

Only four candidates ($T_{1/2}$ > 30 days)with peak in 0ν region remained.

Candidates ($T_{1/2}$)	χ^2 (2.2-3.0 MeV)
[1] 0ν+^{110m}Ag (250 d)	13.1 *most favored*
[2] 0ν+^{208}Bi (3.6×10^5 y)	22.7
[3] 0ν+^{88}Y (107 d)	22.2
[4] 0ν+^{60}Co (5.3 y)	82.9
simultaneous fit	11.6
0ν only	85.0

BG origin

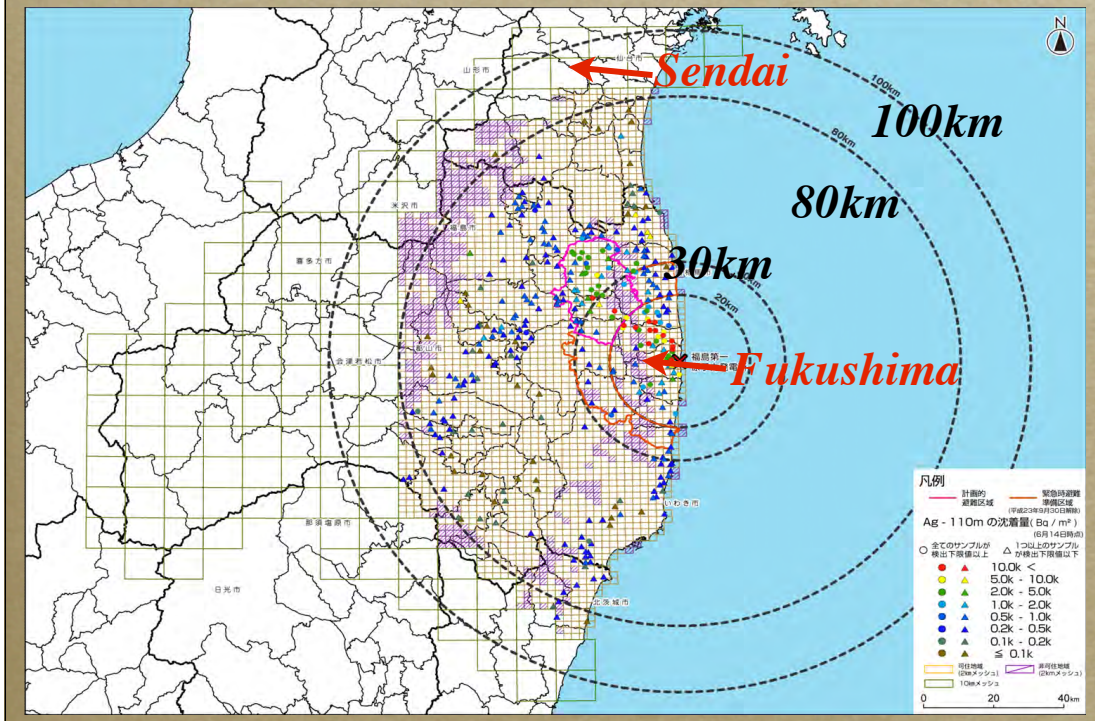
1, fall out from Fukushima.

^{134}Cs and ^{137}Cs were observed at KamLAND.

The ratio (^{134}Cs/^{137}Cs) is also same with soil samples.

^{110m}Ag also fall out of Fukushima.

^{110m}Ag Concentration map in soil sample



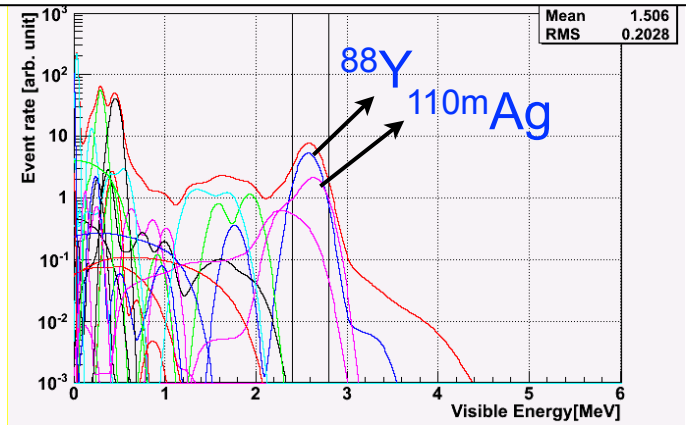
http://radioactivity.nsr.go.jp/ja/contents/6000/5050/24/5600_103120.pdf

2, Spallation products from ^{136}Xe

^{110m}Ag is also produced from ^{136}Xe by cosmic ray.

^{136}Xe was imported by air from Russia.

100 days on surface, 300 days in the mine



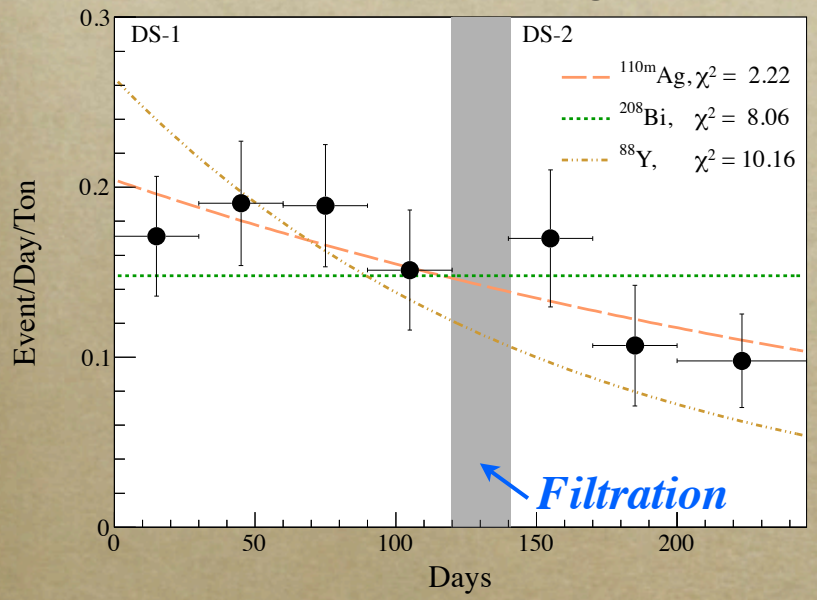
^{110m}Ag production :
accelerated ^{136}Xe on hydrogen target

Phys.Rev.C76,064609(2007)

Latest result

PRL **110**, 062502 (2013)

time variation at 0ν region



^{110m}Ag is most favored.

FV is increased to 1.35m radius for 0ν2β analysis.
livetime 213.4 days
exposure: 89.5 kg*yr

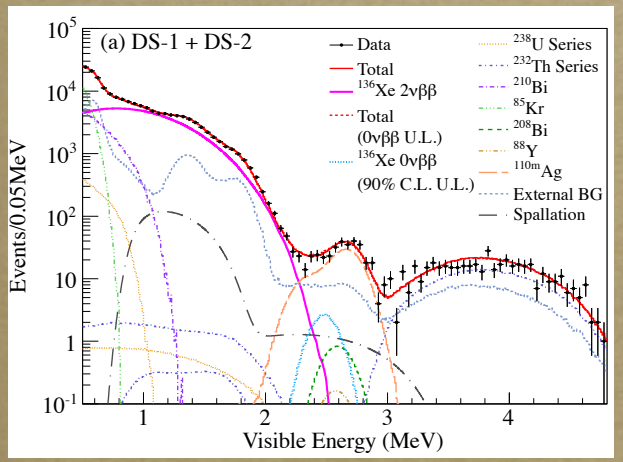
0ν2β result

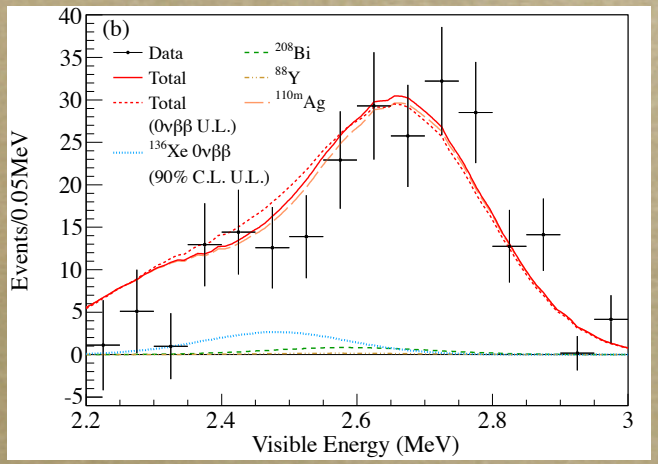
$$T^{0\nu2\beta}_{1/2} > 1.9\times10^{25}\,\text{yr}\ (90\%\ \text{C.L.})$$

best upper limit

$$\langle m_{\beta\beta}\rangle < 0.16 - 0.33\ \text{eV}$$

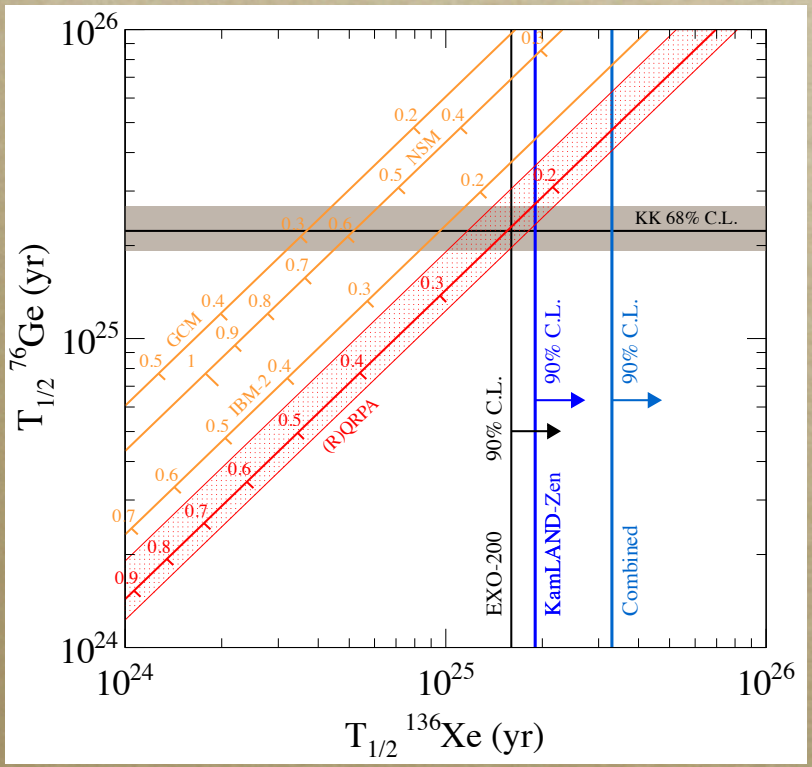
(90% C.L.)





Comparison with other Exp.

correlation between ^{76}Ge and ^{136}Xe



$T^{0\nu2\beta}_{1/2}(^{136}Xe) \rightarrow \langle m_{\beta\beta}\rangle \rightarrow T^{0\nu2\beta}_{1/2}(^{76}Ge)$

NME uncertainty ***NME uncertainty***

using same NME model

KamLAND-Zen result

$T^{0\nu2\beta}_{1/2} > 1.9\times10^{25}$yr *(90% C.L.)*

EXO-200 result PRL **109**, 032505 (2012)

$T^{0\nu2\beta}_{1/2} > 1.6\times10^{25}$yr *(90% C.L.)*

combined (KL-Zen + EXO-200)

$T^{0\nu2\beta}_{1/2} > 3.3\times10^{25}$yr *(90% C.L.)*

$\langle m_{\beta\beta}\rangle < 0.12 - 0.25$ eV *(90% C.L.)*

K.K. claim is rejected more than 97.5% C.L.

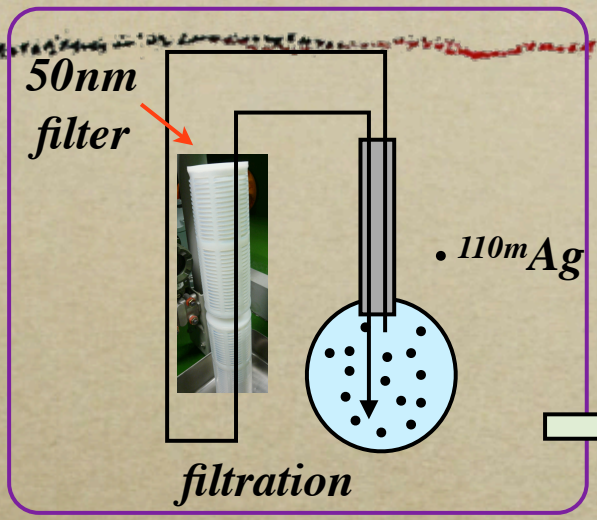
(considering various QRPA model)

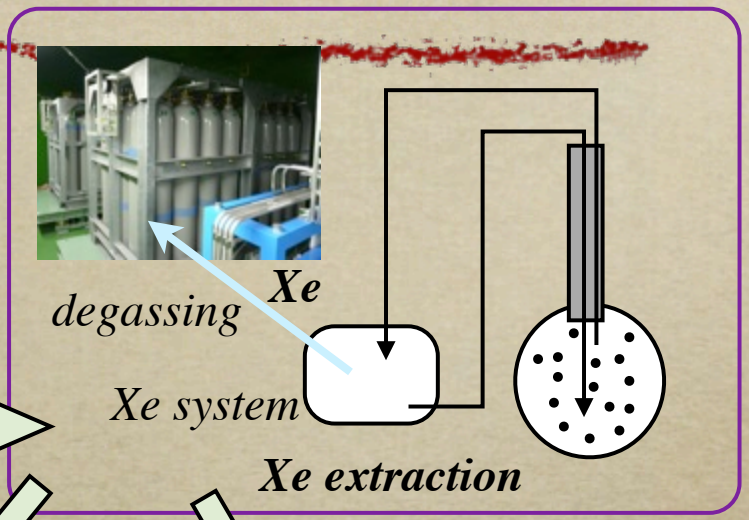
Purification activity

Sep. 2011 *DAQ start*

1st phase

Feb. 2012 filtration
2.3 MIB volume



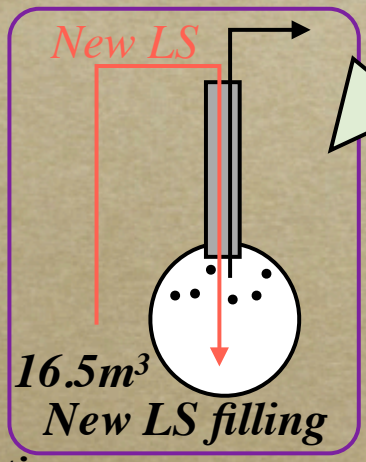


Jun. 2012 Xe extraction
~290kg Xe (90%) was collected.

Aug. 2012 New LS filling

Sep. 2012 Xe gas distillation (400kg)

Nov. 2012 Distilled LS circulation
fire accident in the KL area



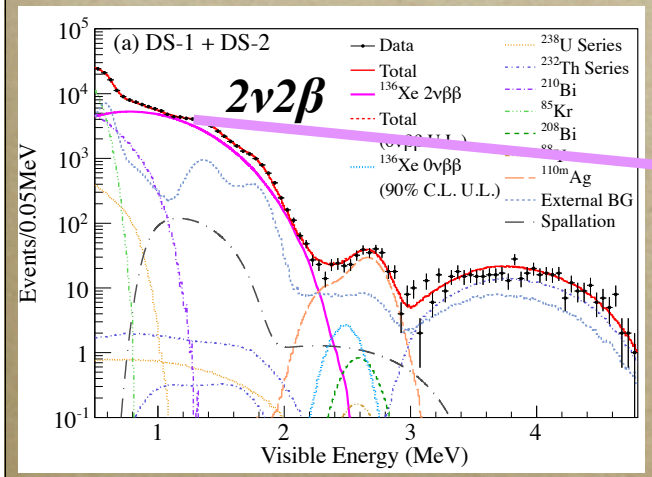
Jul. 2013 restart Distilled LS circulation

Aug. 2013 Xe-LS filling

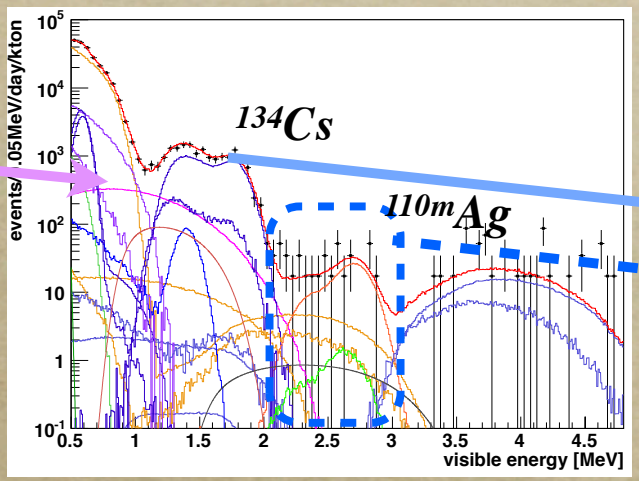
start phase2 DAQ

BG reduction

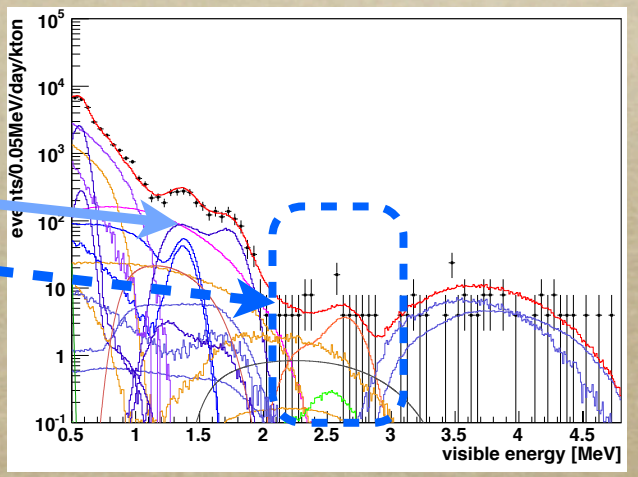
1st phase result



After Xe extraction



After New LS filling

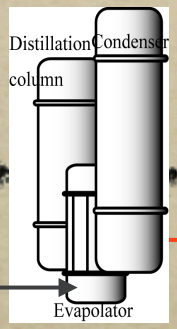


90% Xe was collected by degassing.
2ν2β events was decreased.
^{110m}Ag was still remaining in MIB.

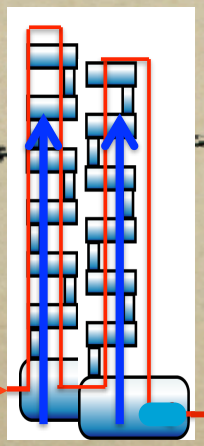
^{110m}Ag was still remaining in MIB.
The reduction rate was 1/3~1/4.
Including ^{110m}Ag decay, the event rate of ^{110m}Ag decreased to 1/9~1/12.
^{134}Cs was also decreased.

On going purification activity

Distilled-LS circulation

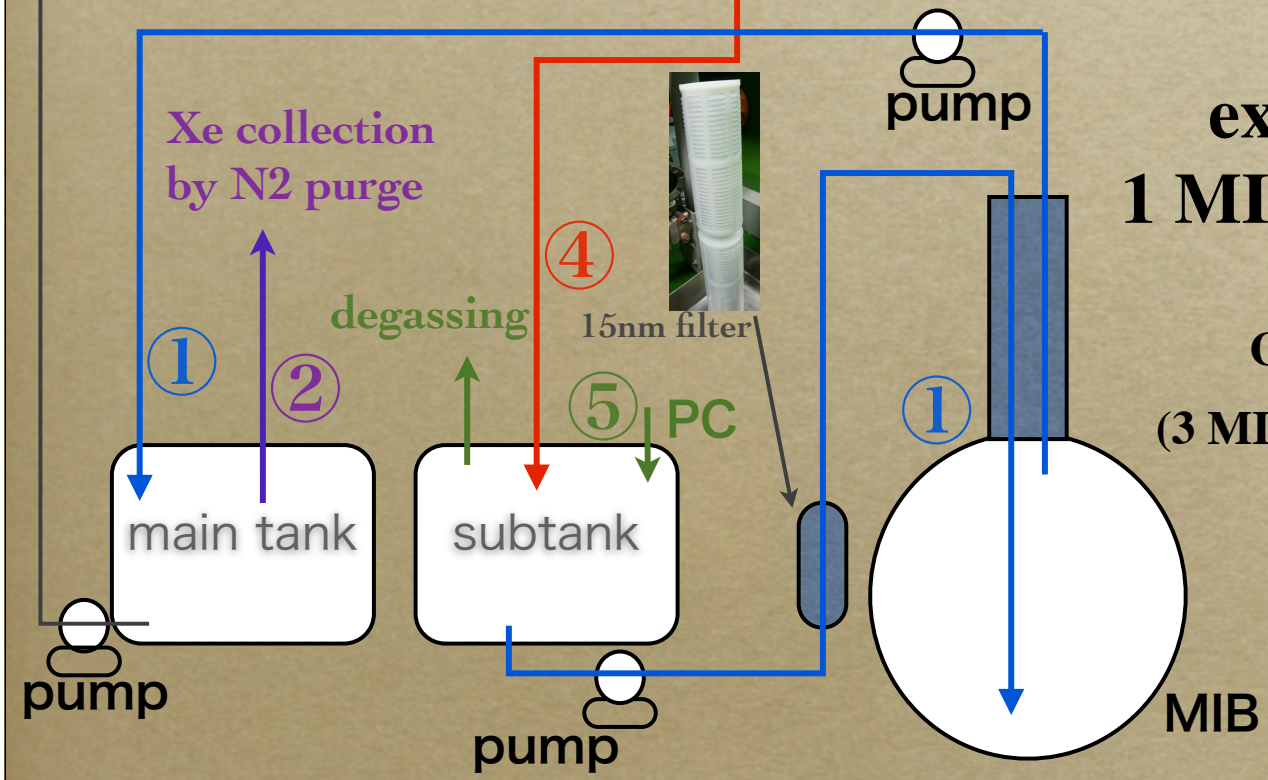


③ LS distillation



N_2 purge tower

1, filling LS from sub-tank and draining LS from MIB.
2, Xe collection by N2 purge. (GC measurement)
3, LS distillation (every 3 batches).
4, LS without PPO is transferred to sub-tank passing through N2 purge tower
5, degassing and adjusting LS density using PC.



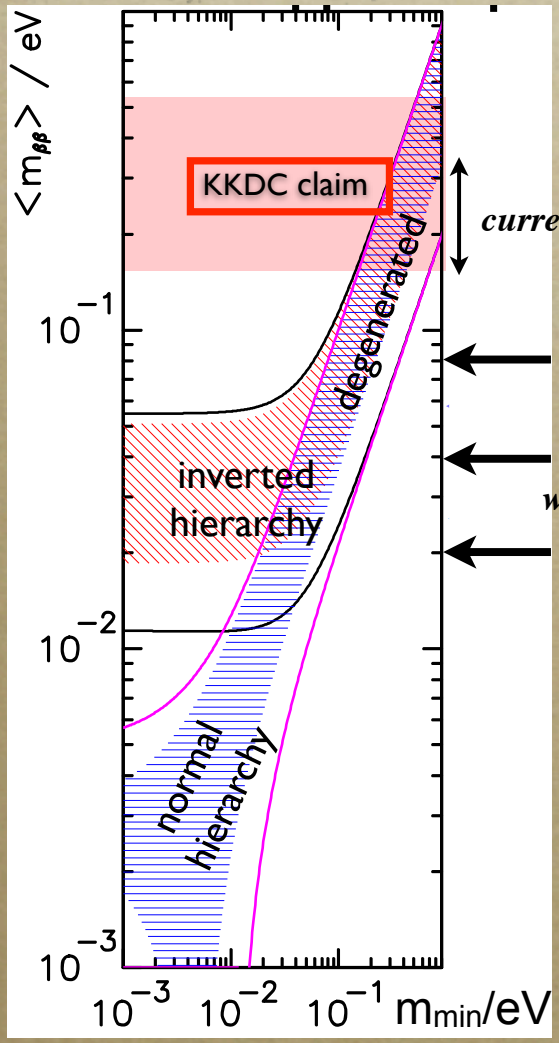
expected reduction rate
1 MIB volume (16.5m³) ~ 1/3

Goal: 100 times ^{110m}Ag reduction

(3 MIB volume LS circulation is required)

→ $\langle m_{\beta\beta} \rangle$ ~ 80 meV

Future prospects



current limit KL-Zen

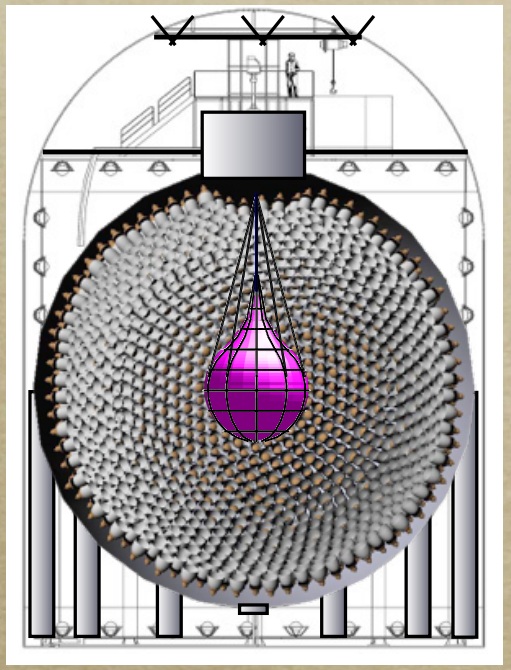
KL-Zen 2nd phase
1/100 ^{110m}Ag reduction

KL-Zen >600kg phase
with ultra clean new MIB

KamLAND2-Zen

KamLAND2-Zen

1000kg ^{136}Xe



1. Winston cone
light yield ×1.8

2. High Q.E. PMT or HPD
QE~22% → >30%
light yield ×1.9

3. High Light yield LS
KL LS 8000ph/MeV
Standard 12000ph/MeV
→ light yield ×1.4

E resolution at 2.6MeV 4% → < 2.5%
(simple calculation < 2%)

sensitivity ~20meV / 5 yr

cover all inverted hierarchy region

Summary

- ***Recent condition provides a unique opportunity to confirm and constrain backgrounds for the reactor anti-neutrino oscillation analysis.***
- ***Geo-neutrino is measured efficiently at low reactor phase. Observed flux is fully consistent with Earth model.***
- ***The 0ν2β half life was limited more than $1.9*10^{25}$ yr (KL-Zen only 90%C.L.) As the result of the combined analysis using EXO-200 and KamLAND-Zen, the K.K. Claim is rejected at 97.5% C.L.*** $\langle m_{\beta\beta} \rangle$ *<120-250 meV (90%C.L.)*
- ***The purification activity is on-going to reduce ^{110m}Ag. The 2nd phase DAQ will be started from August 2013.***