New Developments at KamLAND

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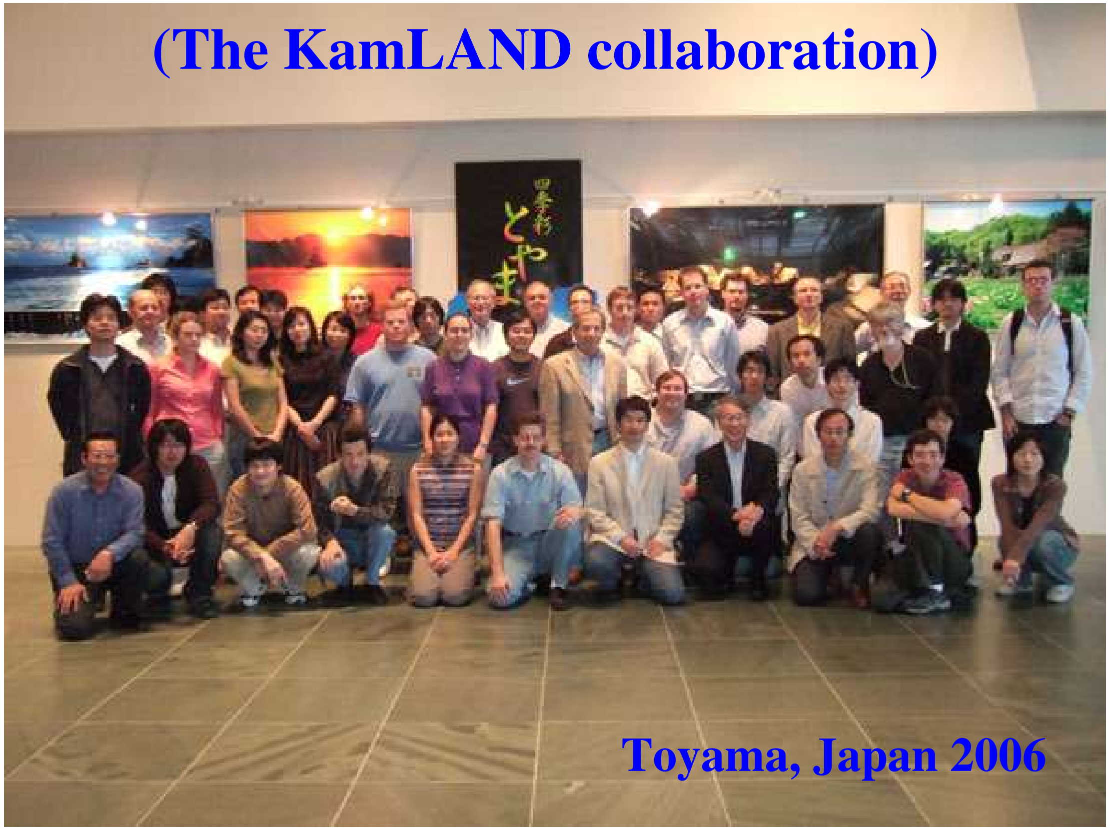


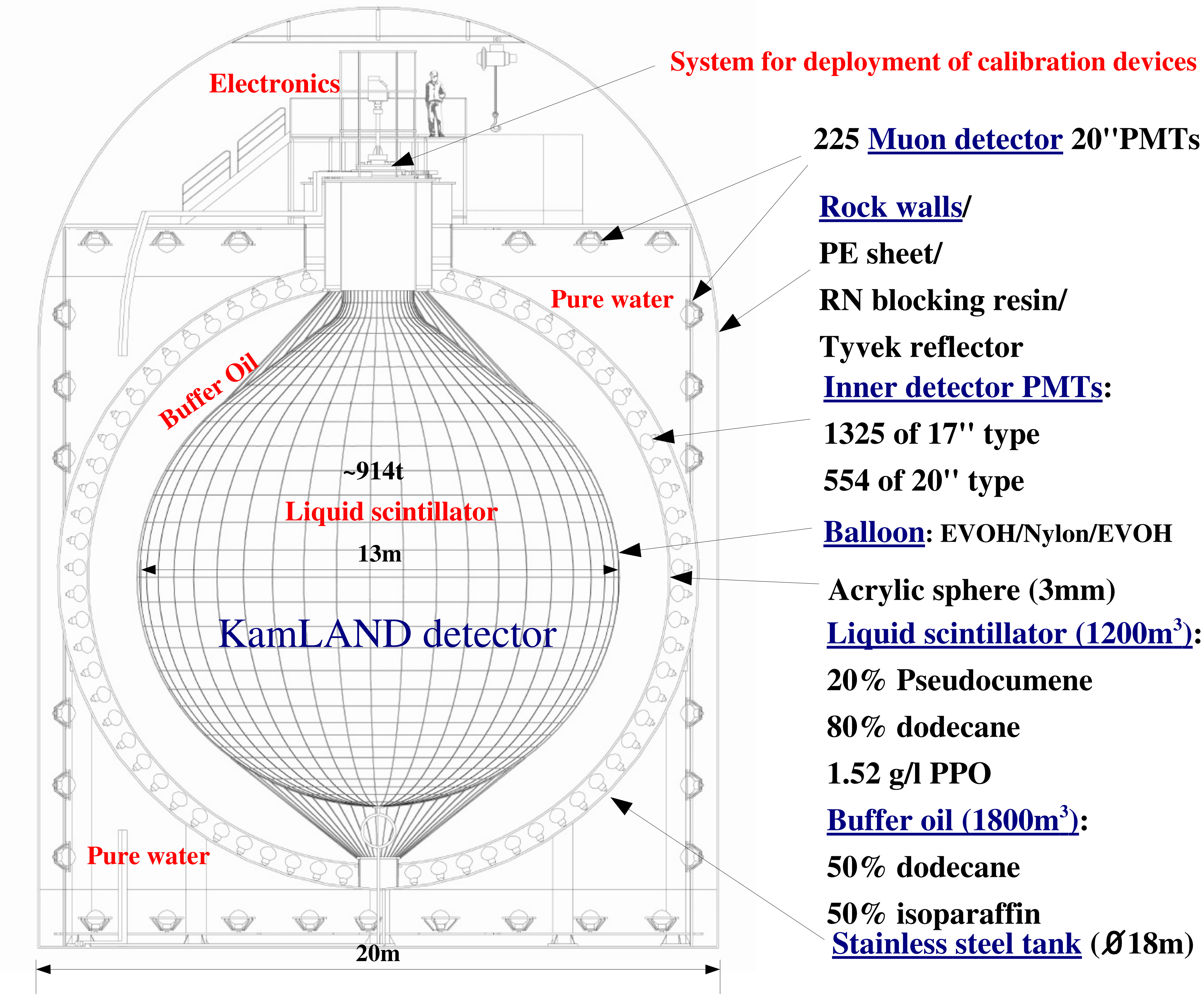
International Workshop on Neutrino Masses and Mixings

Shizuoka U., Japan December 17-19 (2006)

The KamLAND project

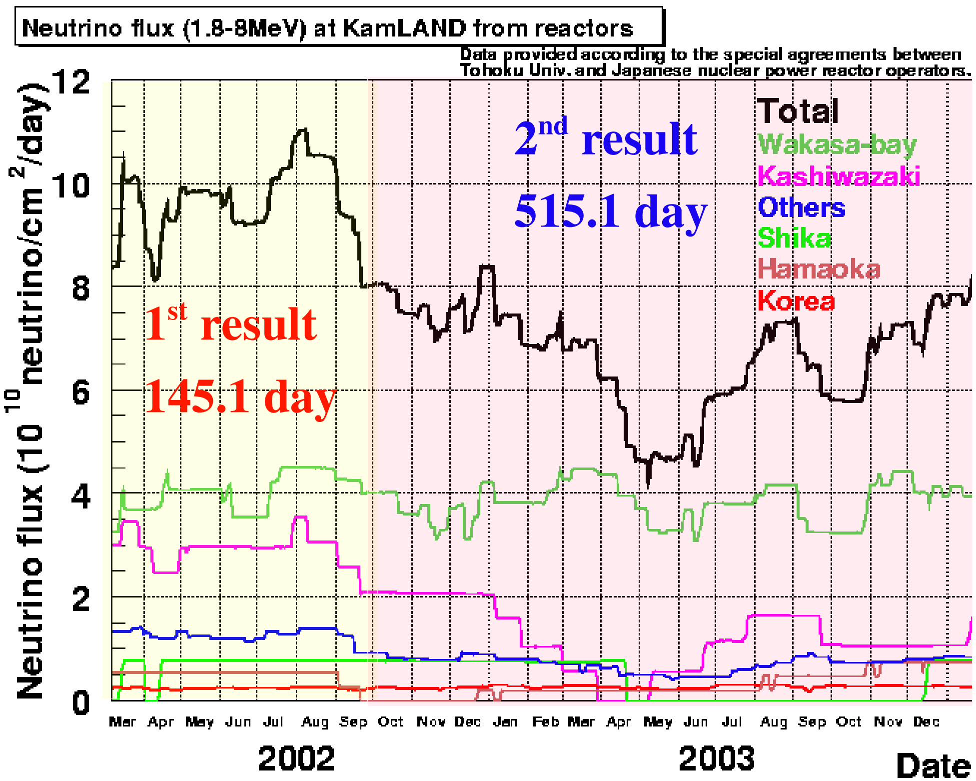
The KamLAND detector is located in a cylindrical cavern of 20-meter diameter and 36-meter deep in the Kamioka Mine near Kamioka Town. This cavern was used before by Kamiokande water Cherenkov detector operated by Tokyo University until 1997.

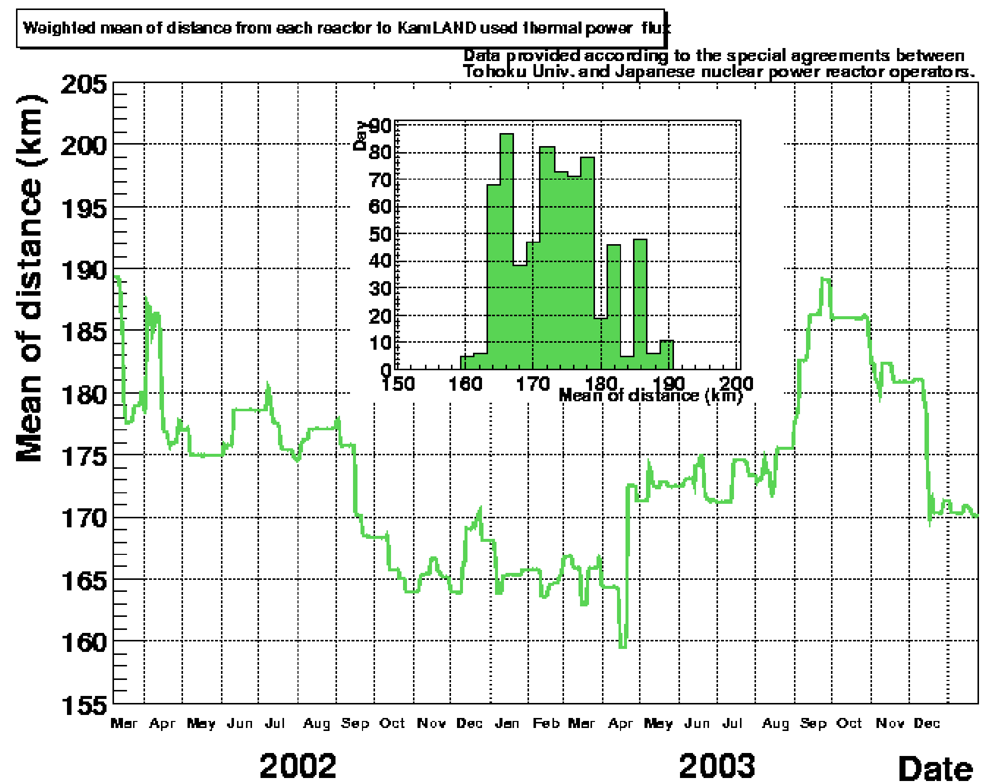
KamLAND is surrounded by a large number of high power nuclear reactors located at distance ≥ 100km which makes it well suitable for high precision measurement of the Δm^2.


System for deployment of calibration devices
Electronics
225 Muon detector 20''PMTs
Rock walls/
PE sheet/
RN blocking resin/
Tyvek reflector
Pure water
Inner detector PMTs:
1325 of 17'' type
554 of 20'' type
Buffer Oil
~914t
Liquid scintillator
13m
Balloon: EVOH/Nylon/EVOH
Acrylic sphere (3mm)
KamLAND detector
Liquid scintillator (1200m3):
20% Pseudocumene
80% dodecane
1.52 g/l PPO
Buffer oil (1800m3):
50% dodecane
50% isoparaffin
Pure water
Stainless steel tank (Ø18m)
20m

Reactor anti-neutrino flux at the KamLAND location

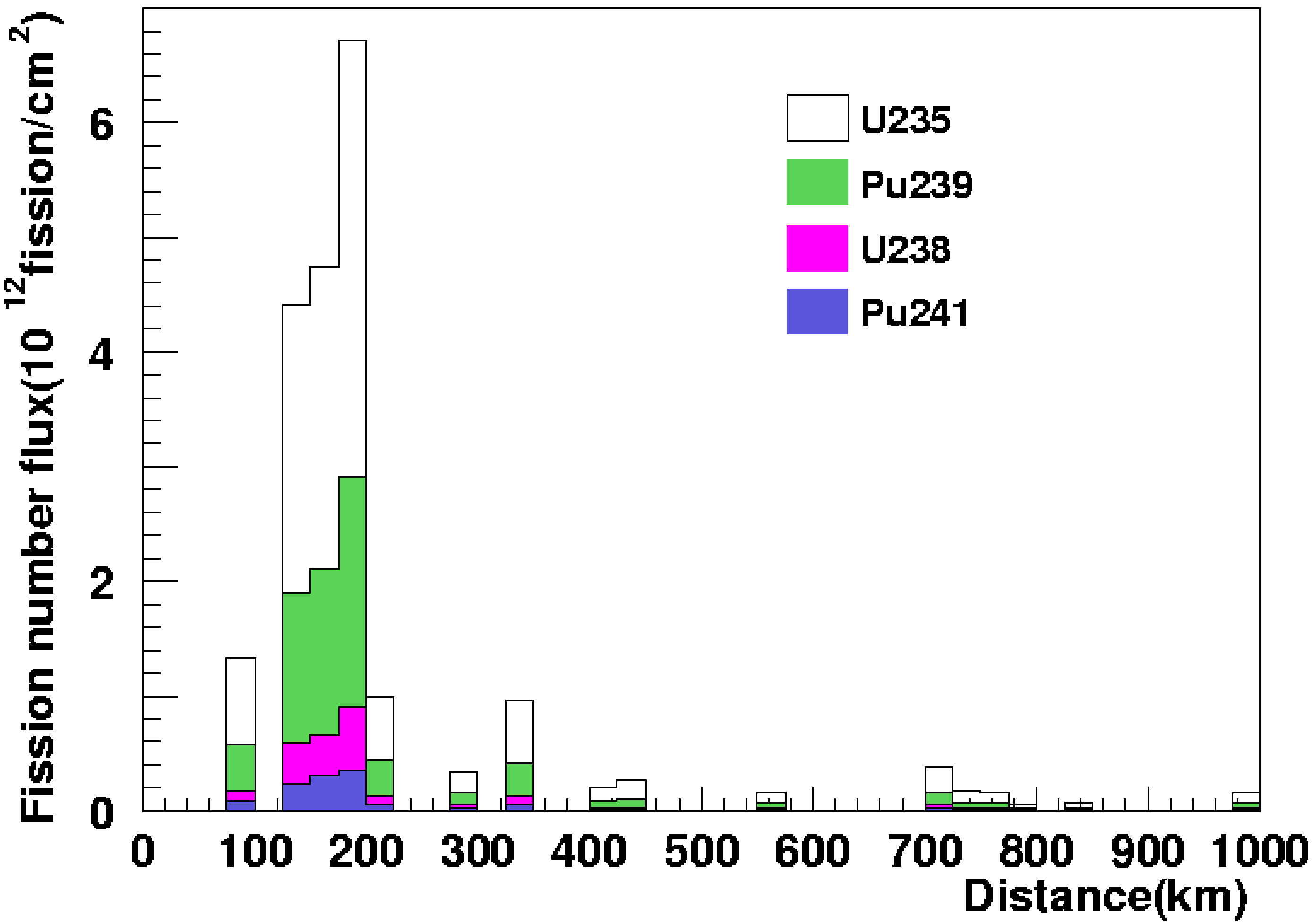
(1st and 2nd results)





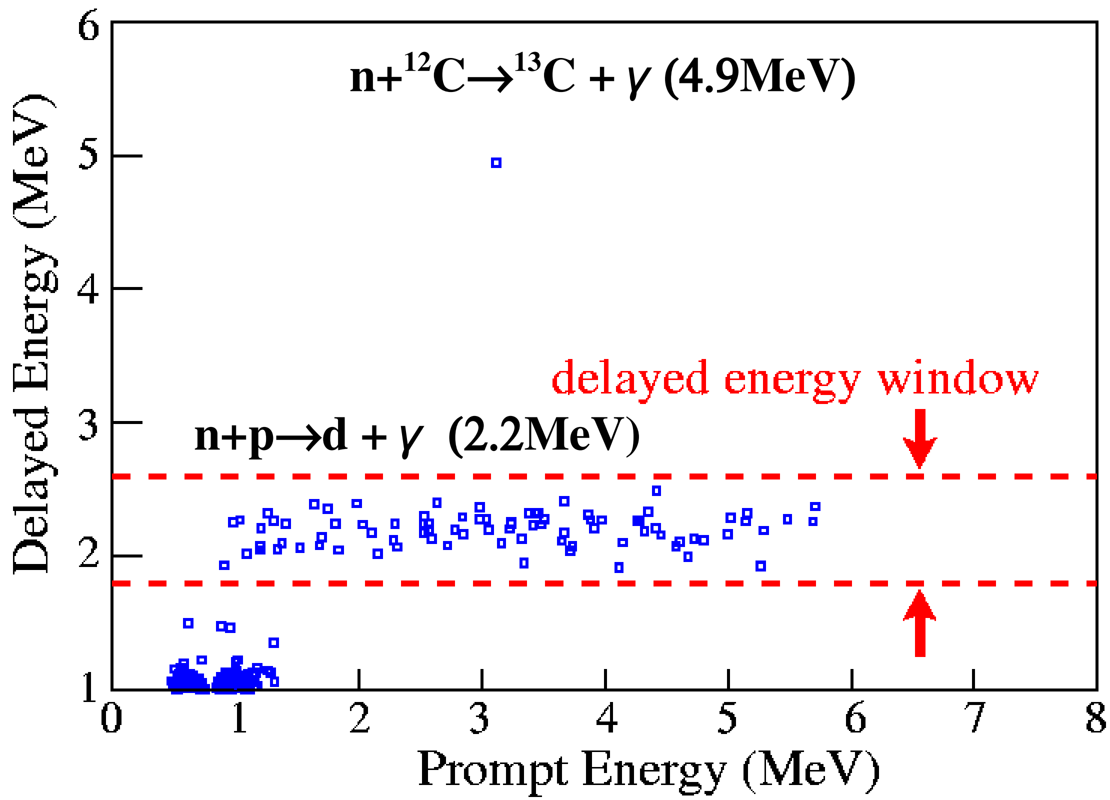
Two KamLAND publications dedicated to the reactor anti-neutrino detection covered a period from the year 2002 to 2004. The anti-neutrino flux, and mean distance (~180km) to reactors change all the time depending on which reactors were ON/OFF. Several reactors located close to KamLAND give the major contribution to the total flux.

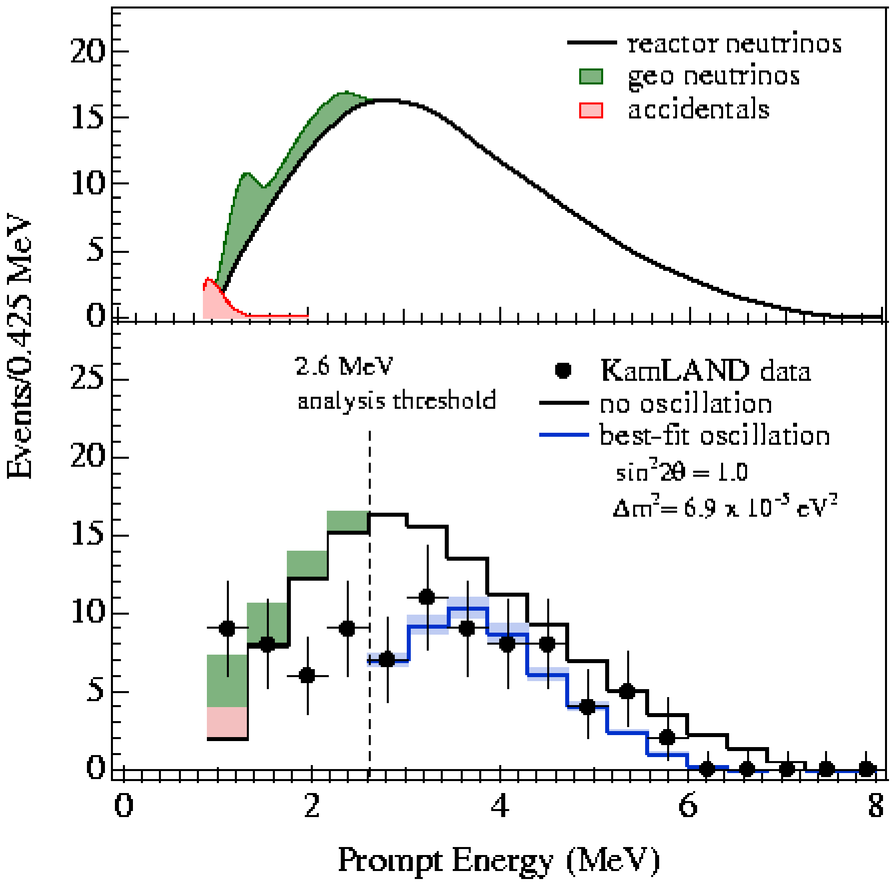
The reactor anti-neutrino flux at KamLAND location



Japanese electric power companies provide detailed thermal power, fuel enrichment, burn up, exchange or reshuffling information for each reactor. Using model of reactor core the fission rates of each fuel are obtained at each reactor. The averaged relative fission yields are: ^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu = 0.563 : 0.079 : 0.301 : 0.057

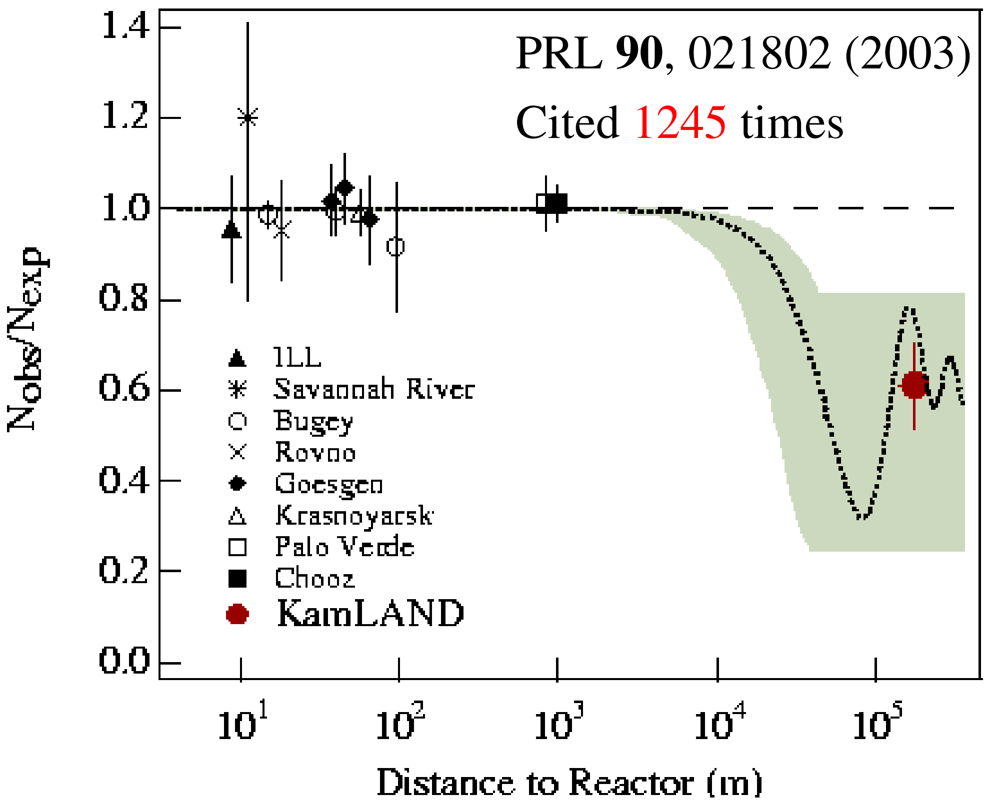
Neutrino candidates energy spectrum (1st result)

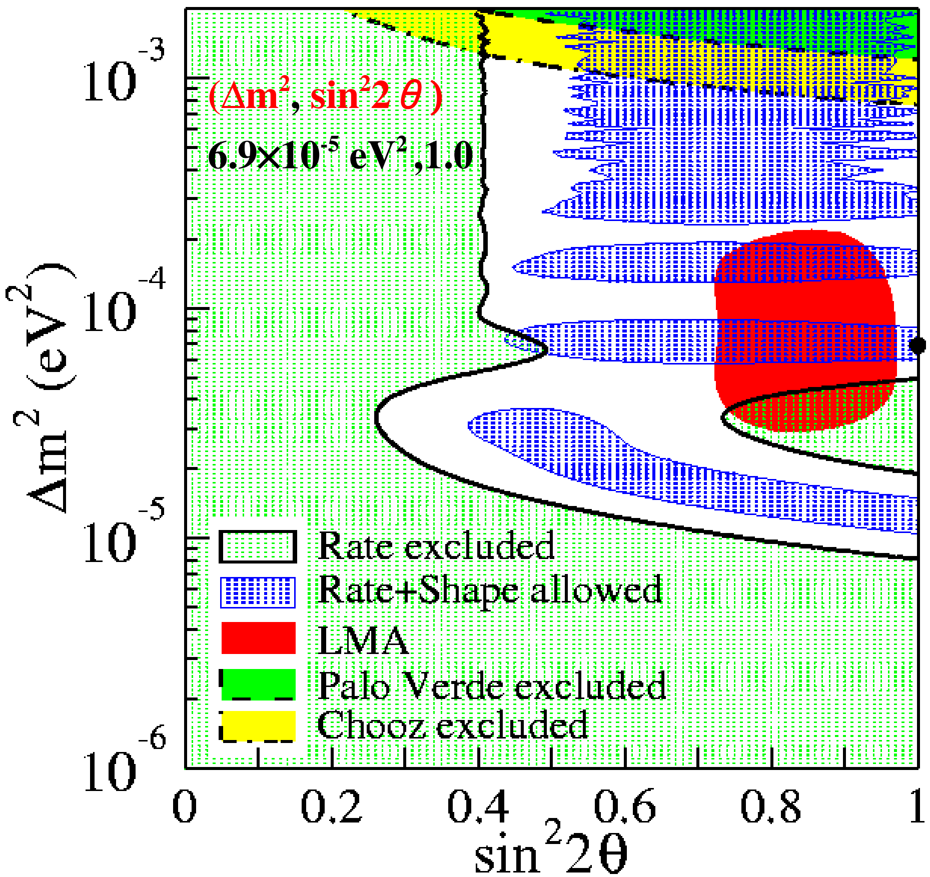




Prompt (positron) and Delayed (γ-ray from n+p) events form space-and-time correlated pairs with average lifetime τ~210μs. The 1st result corresponds to the 162 (ton year) exposure.

Evidence for reactor anti-neutrino disappearance (1^{st} result)

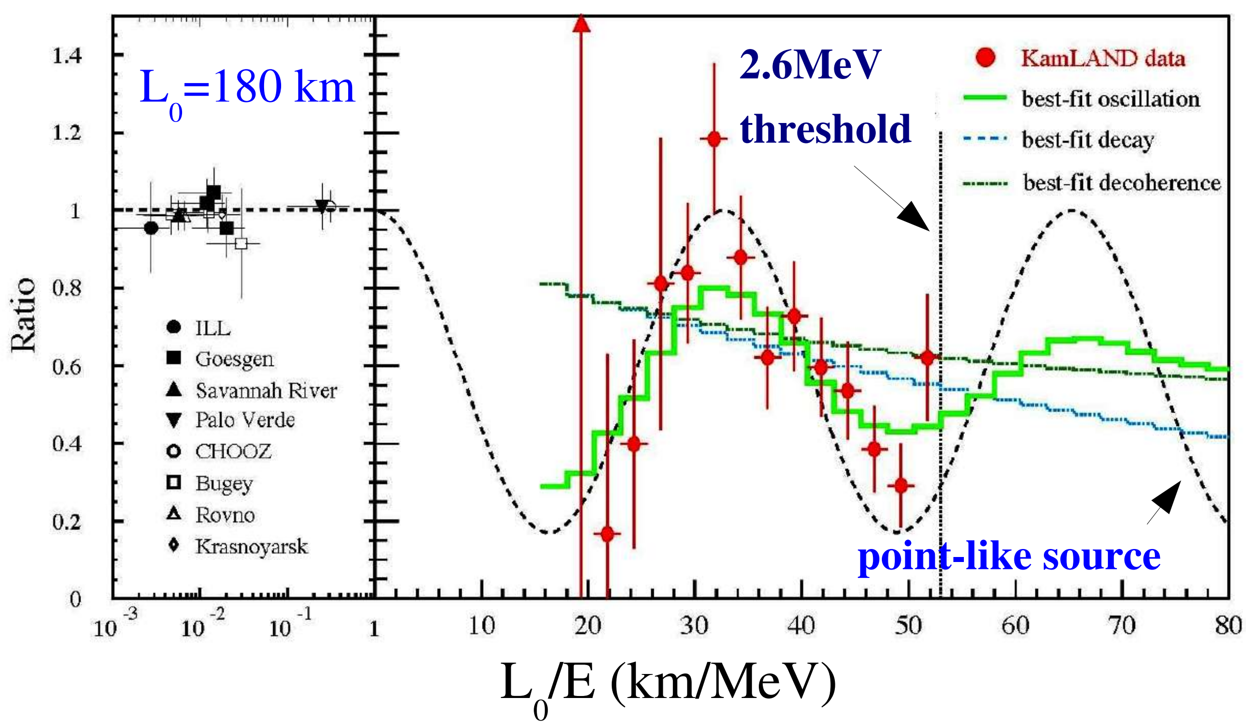


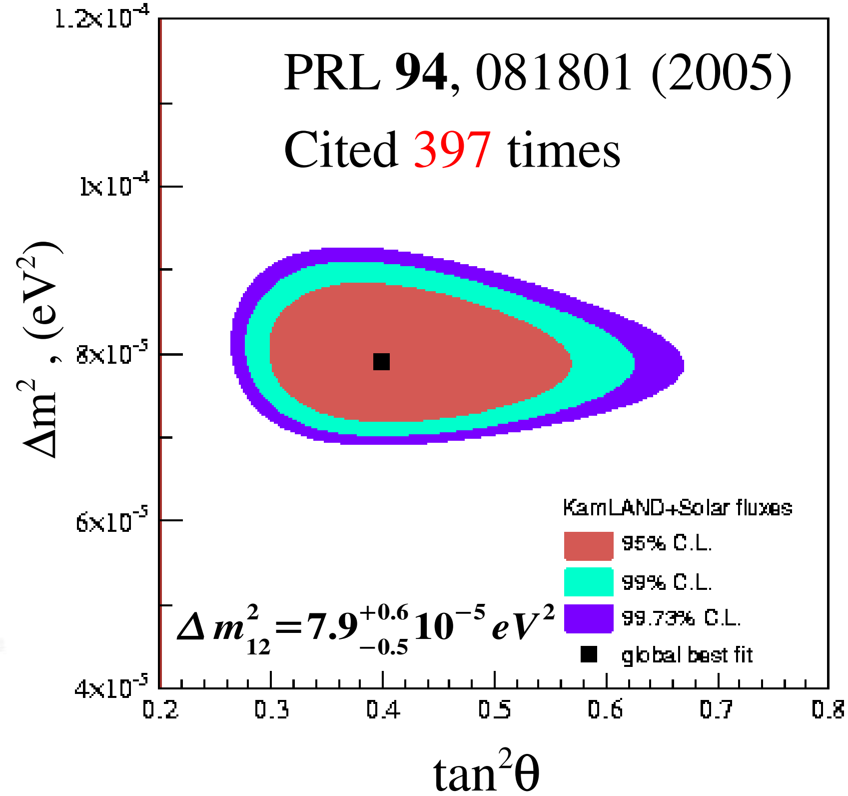


$$P(E_\nu, L) \simeq 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{1.27\,\Delta m_{12}^2 [eV]^2 L[m]}{E_\nu [MeV]}\right)$$

The number of expected for no oscillation case was 86.8 ± 5.6 events. The number of observed was 54 events. The reactor anti-neutrino disappearance was confirmed at 99.95% CL and the "Solar neutrino problem" was finally resolved.

The 2nd result: spectral distortion was observed

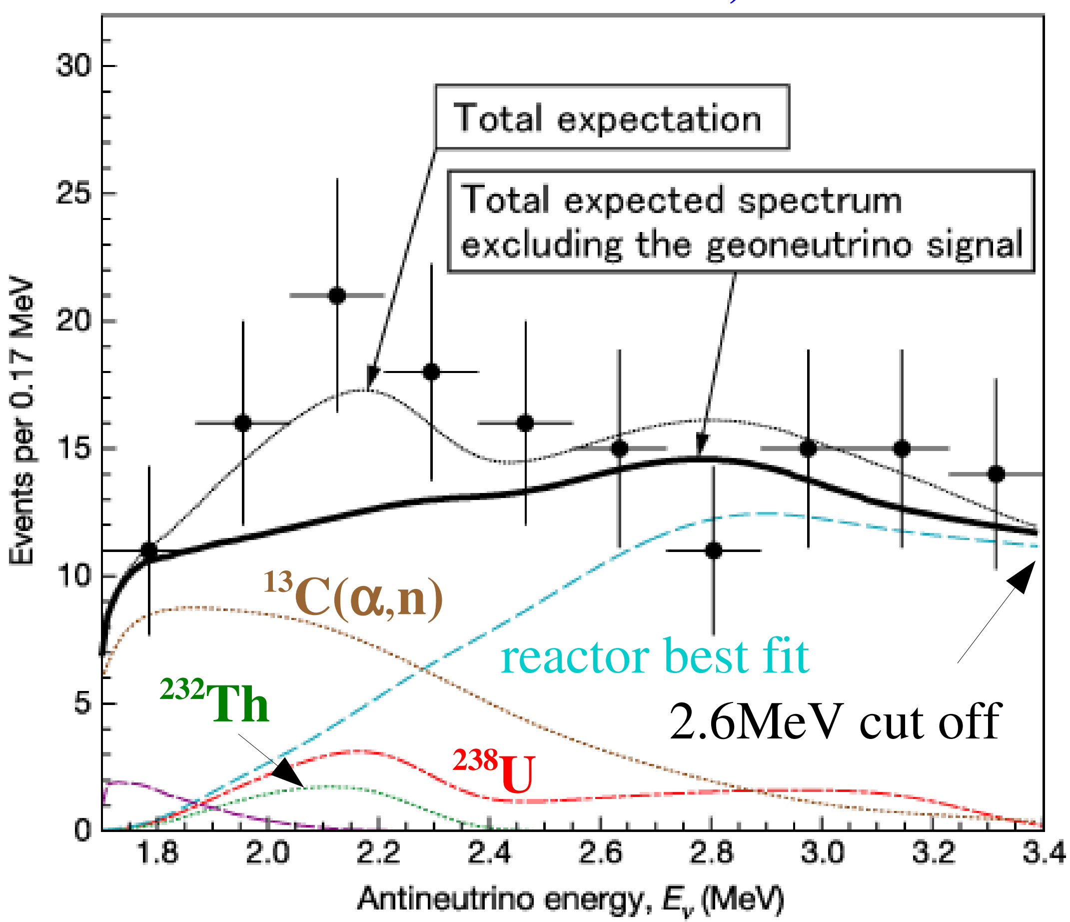


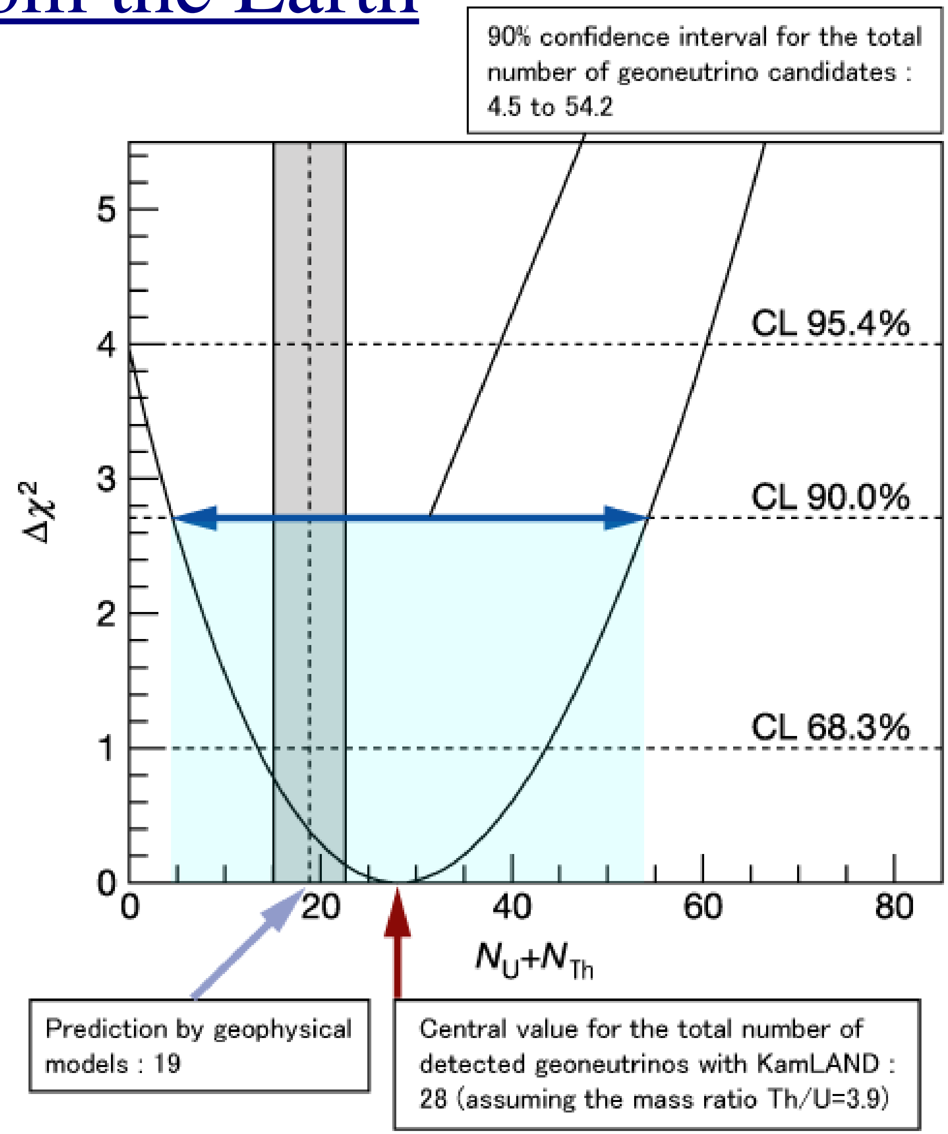


Exposure was increased to 766.3 ton-year, the number of expected events for the non-oscillation case was 365.2±23.7 and number of background events 17.8±7.3, while number of observed events was 258. The reactor anti-neutrino disappearance was confirmed at 99.998%CL. Observed spectrum was inconsistent with no oscillation case at 99.6% CL. Neutrino deficit and spectral distortion combined together excluded no oscillation scenario at 99.999995%CL. The Δm^2 value was precisely determined.

Anti-neutrinos from the Earth

Nature 436:499-503,2005





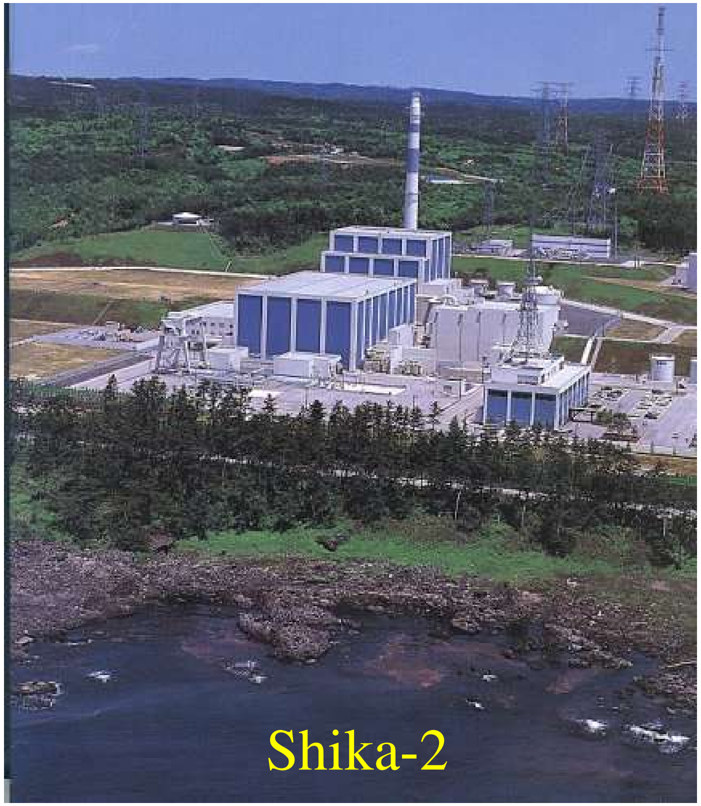
^{238}U ($T_{1/2}$= 4.47×10^9y) → $^{206}Pb + 8\,^4He + 6e^- +$ **6** $\bar{\nu}_e$ + 51.7MeV (100%)

^{232}Th ($T_{1/2}$= 14×10^9y) → $^{208}Pb + 6\,^4He + 4e^- +$ **4** $\bar{\nu}_e$ + 42.7MeV (100%)

Developments after the 2nd result and future plans

- New nuclear reactors started operation near the KamLAND
- Collaboration efforts to improve data analysis procedures, and reduce systematic errors continued
- New full detector volume calibration system commissioned in Fall 2006
- With more data the new KamLAND publication on the reactor anti-neutrino disappearance is expected to be ready next year
- New level of detector radiopurity for solar neutrino detection. Detector purification work is in progress right now

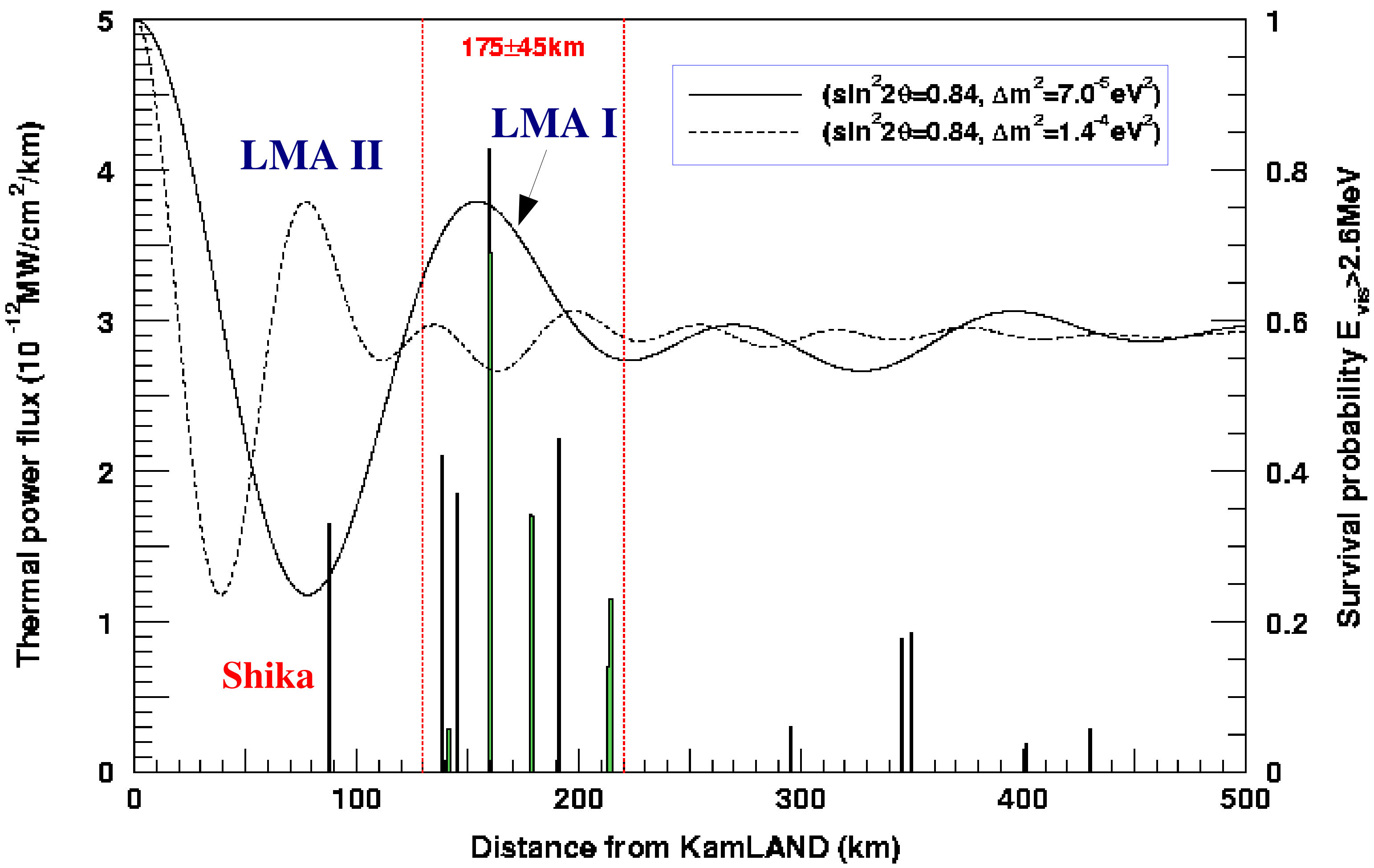
New reactor units near KamLAND



Shika-2 is located 87.7km from KamLAND. This **A**dvanced **B**oiling **W**ater **R**eactor has nominal thermal power ~3.93GW and contributes about 14.4% of the total anti-neutrino flux at KamLAND. Unit started test operation in June 2005, then reached full power in October 2005 and continued operation until July 2006.

Hamaoka-5 unit is located 214.5km from KamLAND. This reactor also ABWR with the nominal thermal power ~3.93GW. It contributes ~2.4% of the total anti-neutrino flux at KamLAND location. Test operation started in April 2004, reached full power in December 2004 and continued until June 2006.

Possible effect from Shika-2

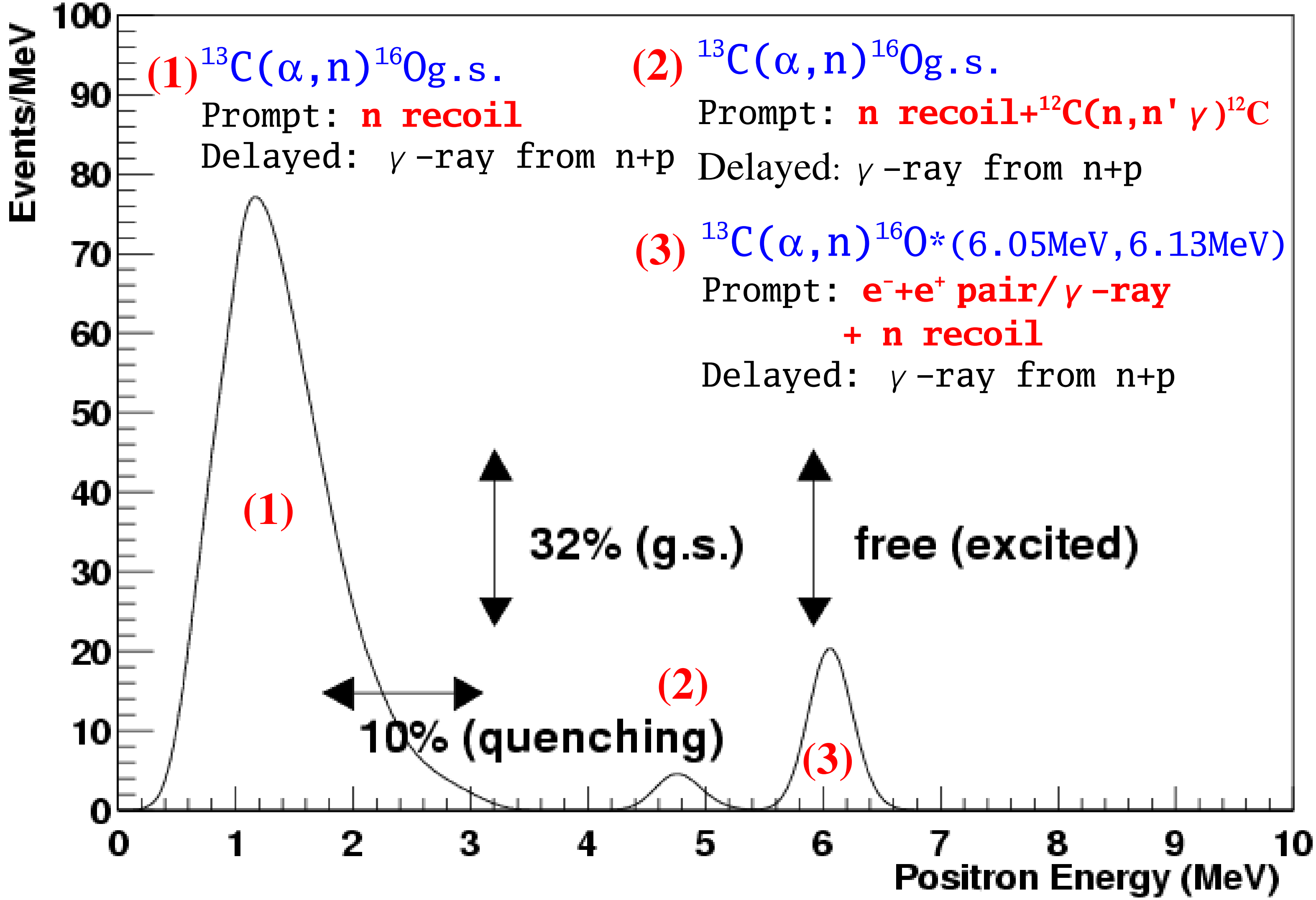


Survival probability is more sensitive to LMA I and LMA II parameters at distance where Shika-2 unit is located compared to distances >140km where all other reactors are located.

Efforts to improve data analysis procedures

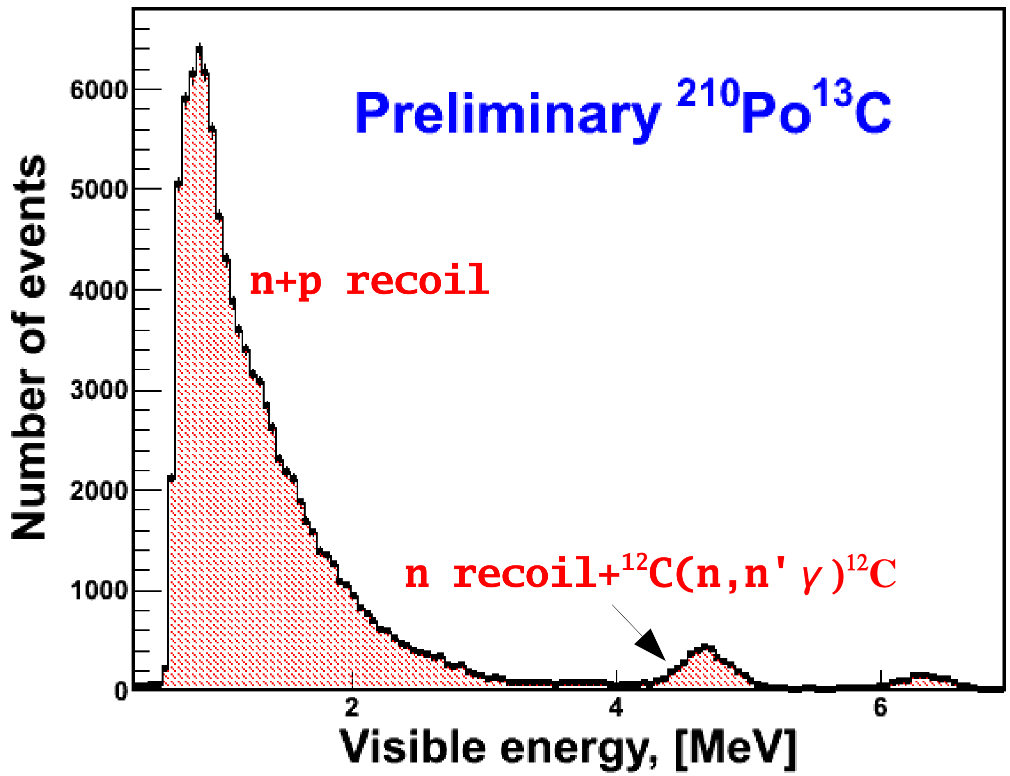
- The 1st KamLAND result was mostly Rate analysis, while 2nd result is based mostly on spectrum Shape distortion information
- With more statistics and with time-variation of reactor anti-neutrino flux the Rate+Shape analysis may cause some reduction of resolution providing less improvements than was expected from a longer exposure. Rate+Shape+Time analysis becoming more important and such procedures are being developed in collaboration
- The optimum choice of fiducial volume is also studied
- In KamLAND published papers Δm^2 result was obtained using 2.6MeV threshold for Prompt events to exclude uncertainty from the geo-neutrino spectrum. At the same time, spectrum shape below 2.6MeV has sensitivity for separation of LMA 0, I, II regions as well as sensitivity within LMA I itself. Combined analysis of geo-neutrino and reactor data are also being developed.

Correlated background: $^{13}C(\alpha,n)^{16}O$



5.3MeV α-particles from the ^{222}Rn daughter ^{210}Po initiate reactions on ^{13}C (1.1%) producing neutrons with energy 0-7.5MeV able to mimic correlated signals from reactor anti-neutrinos. Energy scale for the proton recoil part and cross-sections were known with large uncertainties.

Improved understanding of the $^{13}C(\alpha,n)^{16}O$ background



The $^{13}C(\alpha,n)^{16}O$ cross-section was measured in a dedicated experiment with a primary goal to reduce uncertainty for the number of background events in KamLAND geo-neutrino analysis. New cross section data allowed to reduce error from 30% to 4% (published in the Physical Review C 72, 062801 (2005)).

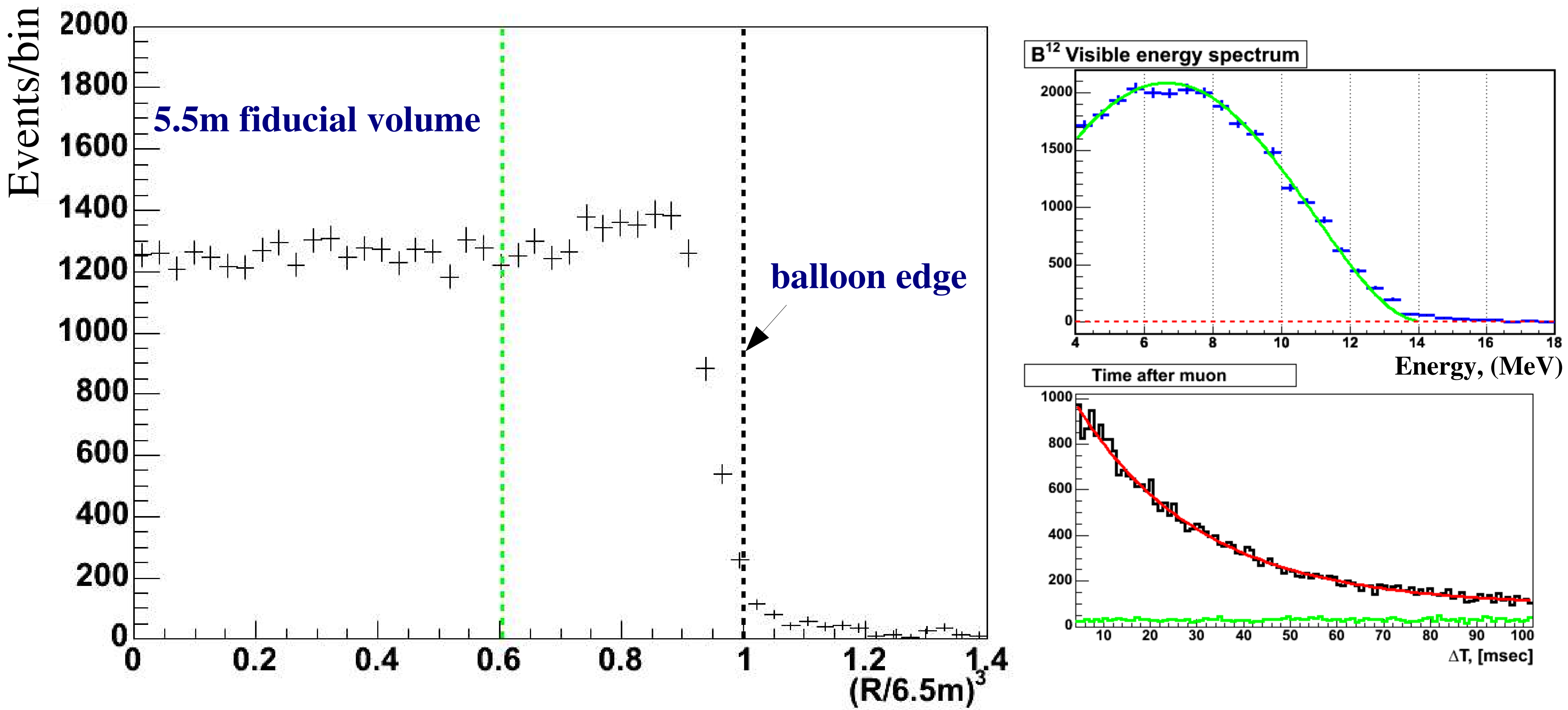
Energy spectrum from the $^{13}C(\alpha,n)$ reaction previously was simulated using GEANT Monte-Carlo. Recently acquired calibration data using the $^{210}Po^{13}C$ radioactive source allow to reduce also the energy scale systematic error.

Systematic uncertainty in the number of expected anti-neutrino events (2nd result)

Systematic uncertainty	%
Fiducial volume	4.7
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.06
Reactor thermal power	2.1
Fuel composition	1
Antineutrino spectra	2.5
Cross section	0.2
Total error	6.5

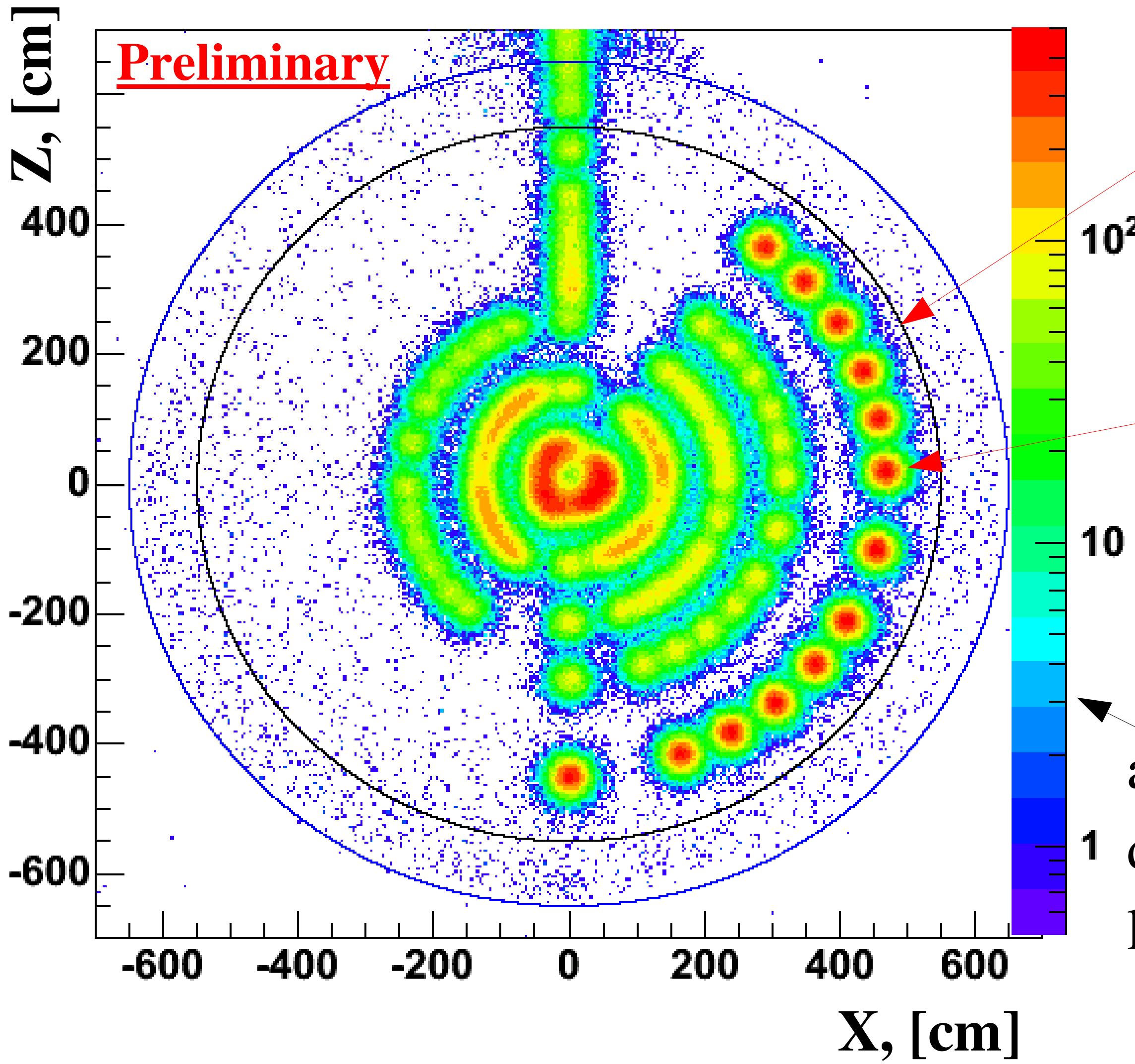
The Total error could be reduced only if the fiducial volume uncertainty would become smaller. It was estimated to be 4.7% for the second KamLAND publication.

The fiducial volume systematic error calculation with ^{12}B events



^{12}B events produced by muon spallation and therefore distributed uniformly in the detector volume. The number of ^{12}B events reconstructed inside the fiducial volume compared to the total number in the detector is used to estimate the systematic uncertainty of the fiducial volume value.

The KamLAND detector full volume calibrations



5.5m fiducial volume

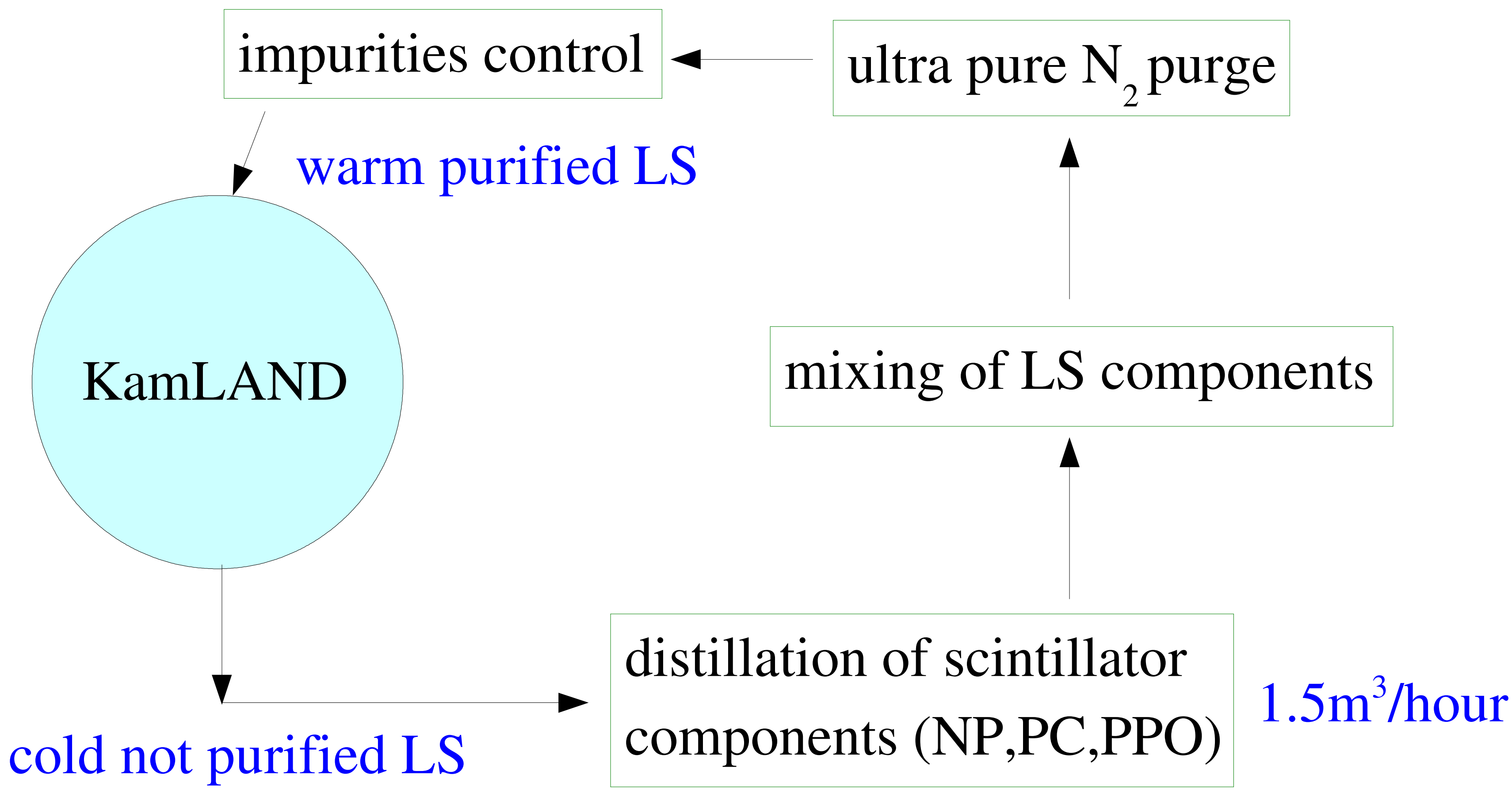
calibration sources

a fraction of calibration data taken at various locations in the detector

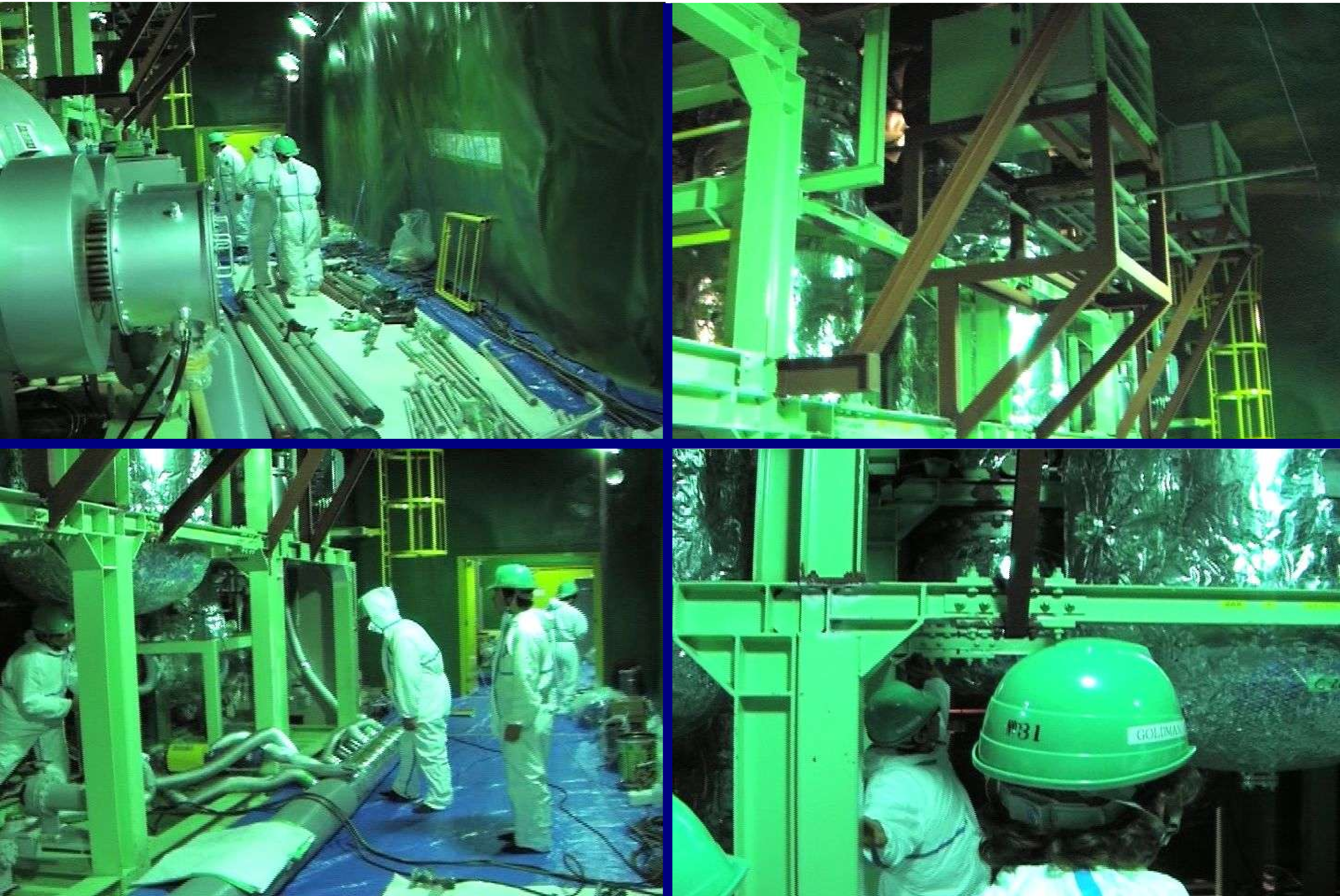
Detector survey using various radioactive sources (^{60}Co, ^{68}Ge, Am-Be, ^{210}Po^{13}C) was done to confirm our understanding of the detector which is based on calibration sources deployments along the vertical axis only and the ^{12}B, n capture, ^{9}Li data.

Purification of the KamLAND detector

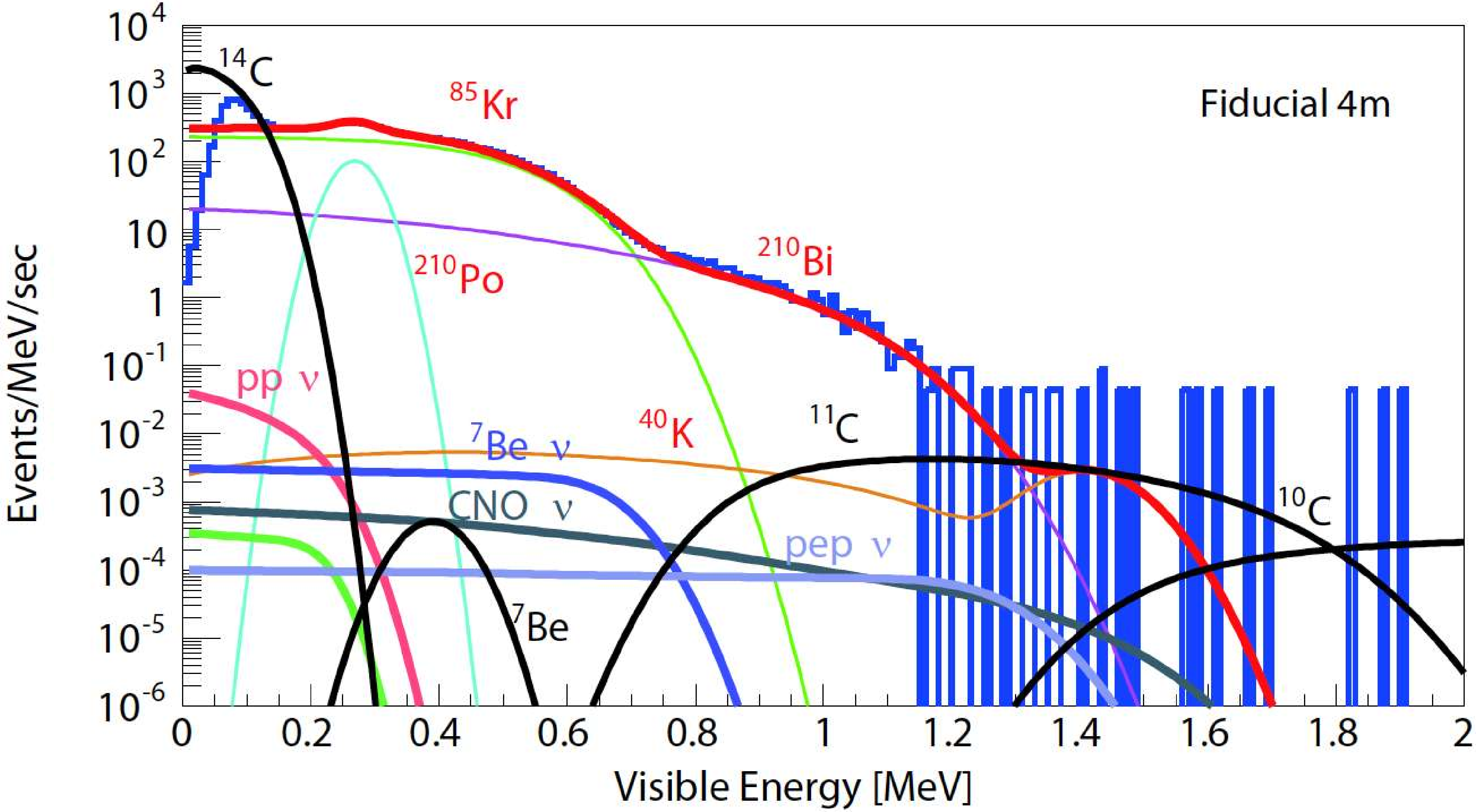
Next stage of the KamLAND experiment will be started after detector purification which is planed to be completed in April 2007.



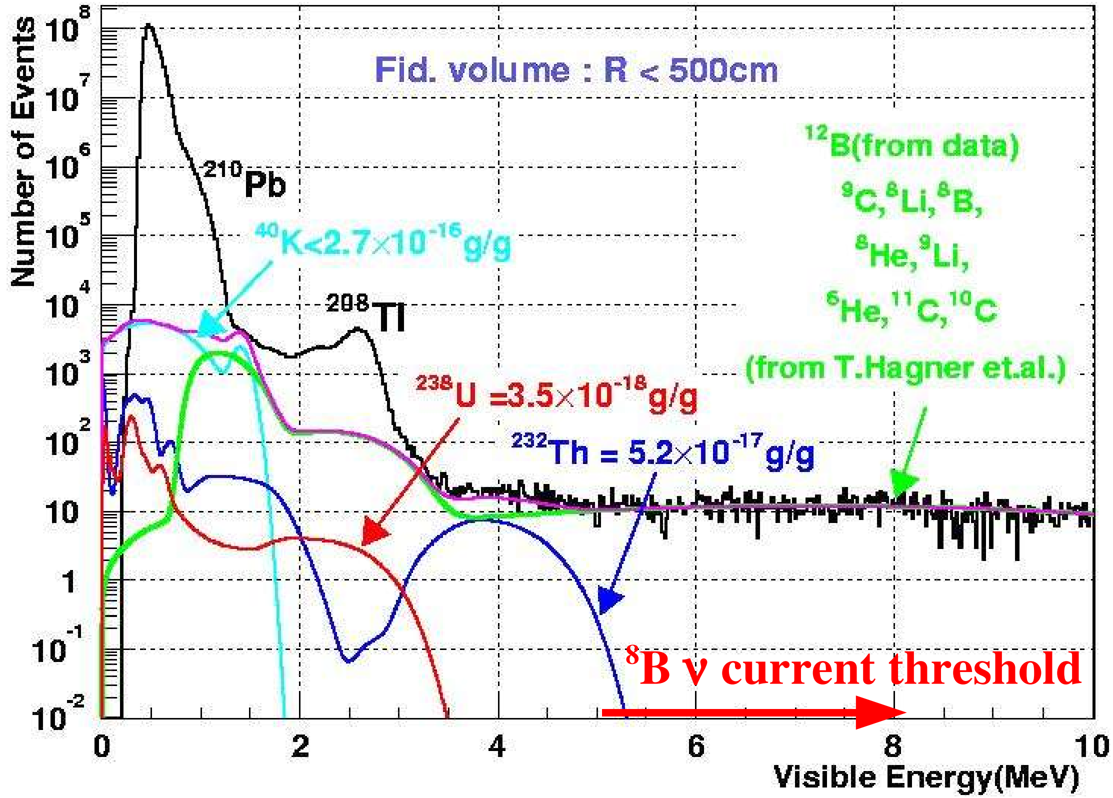
Distillation system in pictures

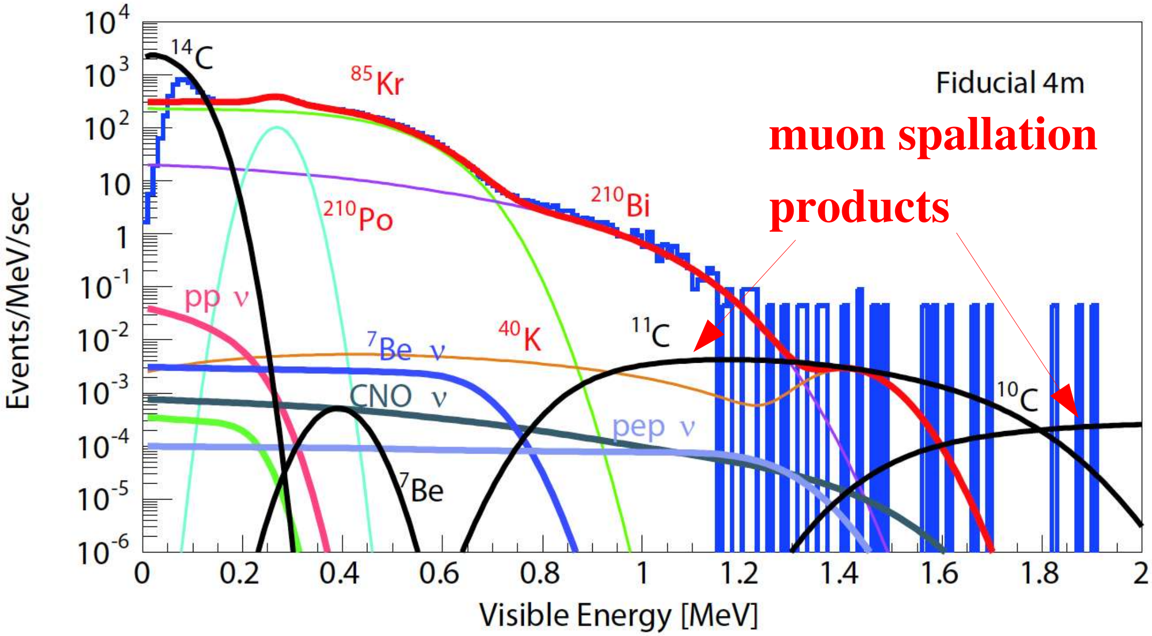


^{7}Be solar neutrino detection at KamLAND



At present, we observe high background rates from ^{85}Kr (β -emitter, $T_{1/2}$=10.8y, Q = 687keV) which is present in the air as a product of nuclear fission reactors, and from daughter products of ^{222}Rn: ^{210}Pb (22.3y)→^{210}Bi (β -emitter)→^{210}Po (α-emitter). Observation of the ^{7}Be solar neutrinos is possible after 10^{-5} reduction of the ^{85}Kr and ^{210}Pb concentration in the liquid scintillator.



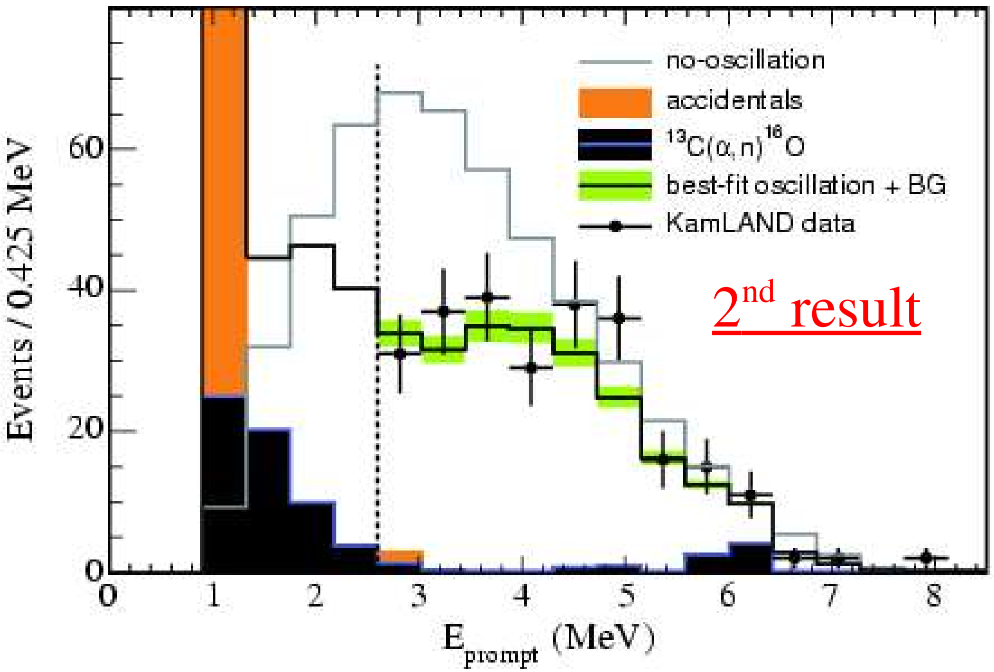


^{8}B, pep and CNO solar neutrino detection

For ^{40}K and ^{232}Th **10^2** reduction factor is expected after purification. ^{232}Th decays (^{208}Tl β-decays) are currently limiting ^{8}B solar neutrino detection threshold by ~5MeV. ^{40}K removal is needed for pep and CNO ν detection.

The pep and CNO ν detection also requires suppression of ^{11}C (^{10}C) background. 95% of ^{11}C nuclei produced together with a neutron, which can be detected and used to apply veto cut to a certain part of the detector volume. After 3 years of data taking CNO+pep may be measured with ~3% precision.

Reactor anti-neutrino and geo-neutrino background after purification



Removal of ^{210}Pb means absence of the $^{13}C(\alpha, n)^{16}O$ correlated events in the anti-neutrino sample which makes the reactor data almost background free. Geo-neutrino detection conditions will be also improved but below 2.6MeV reactor anti-neutrinos will be still a major background for geo-neutrinos.

- Accidental coincidences: 2.69±0.02 events
- $^{8}He/^{9}Li$ (correlated background) after muon cuts: 4.8±0.9 events
- μ-induced fast neutrons from rocks and OD:< 0.89 events
- $^{13}C(\alpha, n)^{16}O$ initiated by ^{210}Po α-particles: 10.3±7.1 events
- Total number of background events: 17.8±7.3

New publication of the 2002-2006 data set is expected next year

The second result included data from March 9 2002 until January 11, 2004. Next publication will include data until the end of December of 2006 which is the time when purification of the KamLAND scintillator will be started. Purification process will be causing changes of the liquid scintillator properties, and therefore physics data taken during the actual purification stage is most likely to be used for the SuperNova detection only, and control of the detector status.

The 3^{rd} result will increase the total detector live time by a factor of ~2.5 compared to the 2^{nd} result.

Summary

- KamLAND experiment is in good shape, purification stage began in December 2006
- Purification of the detector will improve detection conditions for the reactor anti-neutrinos and anti-neutrinos from Earth, and ^{8}B solar neutrinos. It will allow to measure previously unaccessible solar νs: ^{7}Be, pep, and CNO
- Efforts continue to reduce systematic uncertainties and improve analysis methods
- New publication on reactor anti-neutrino disappearance is expected next year with 2.5 time more data size and reduced errors on Δm^2 by factor ~2