KamLAND results & prospects

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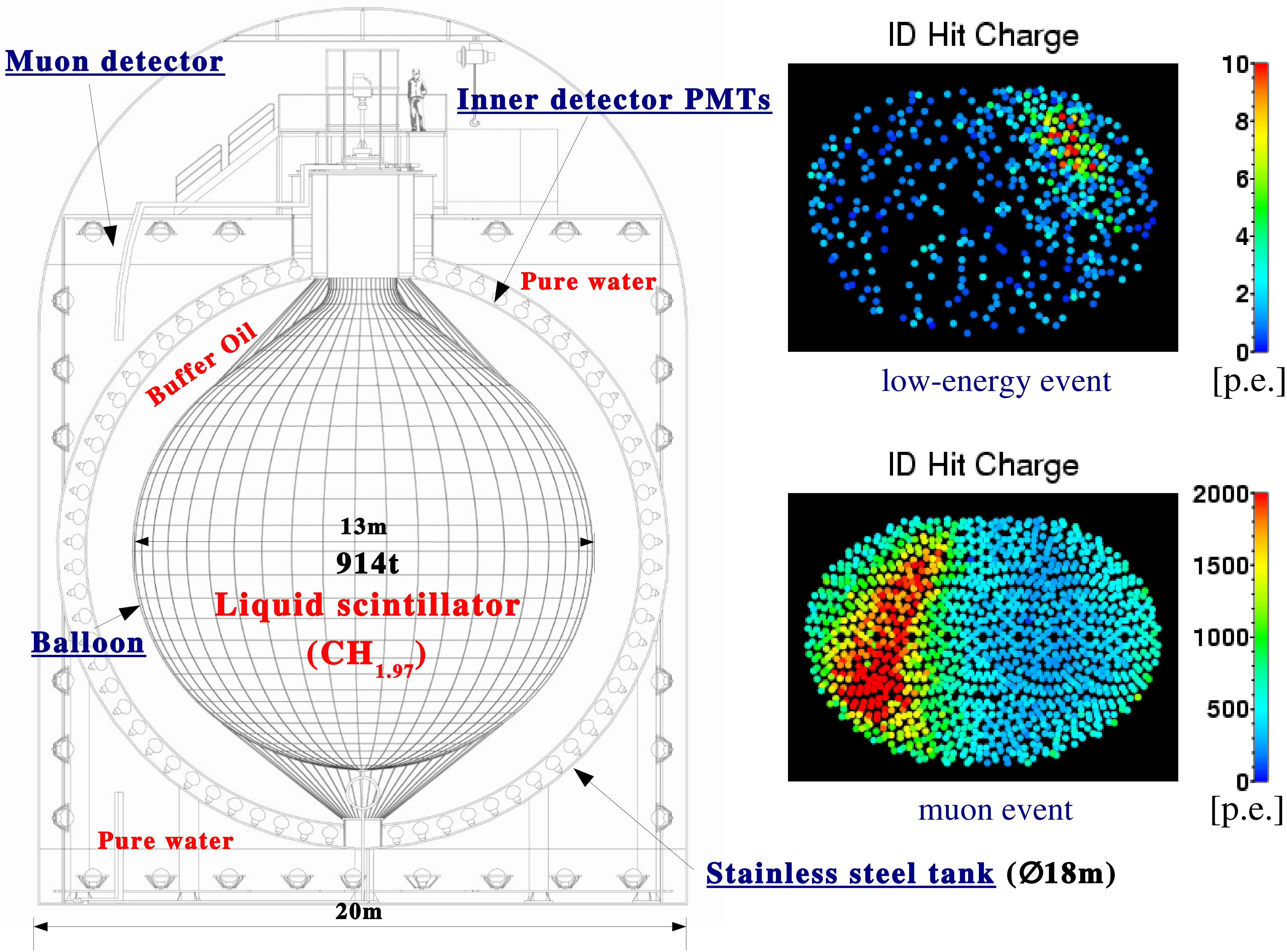
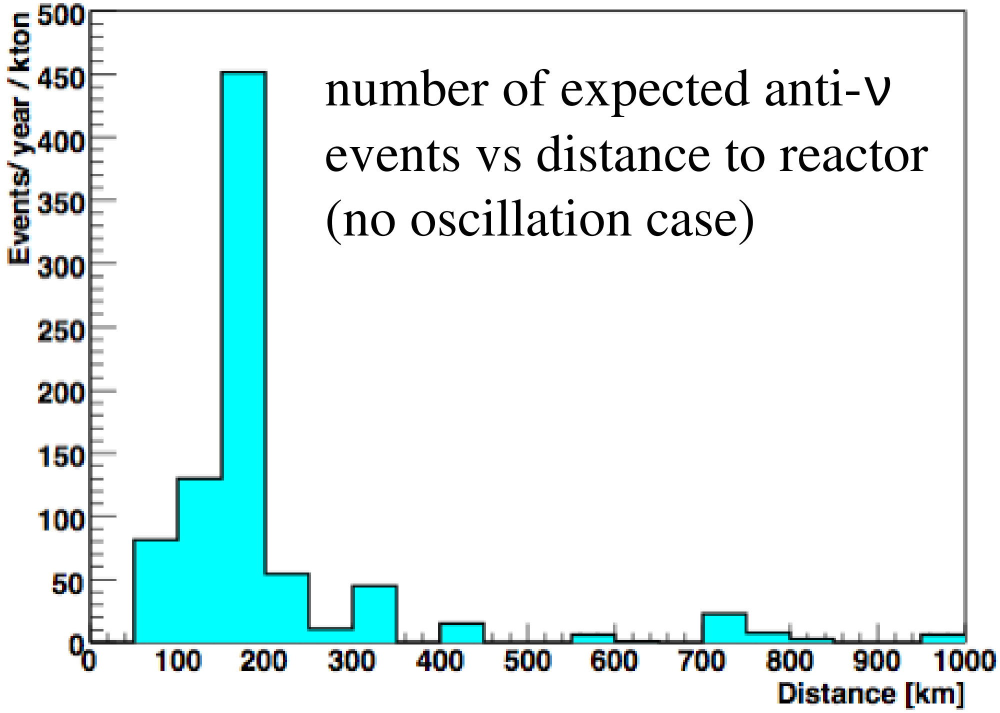


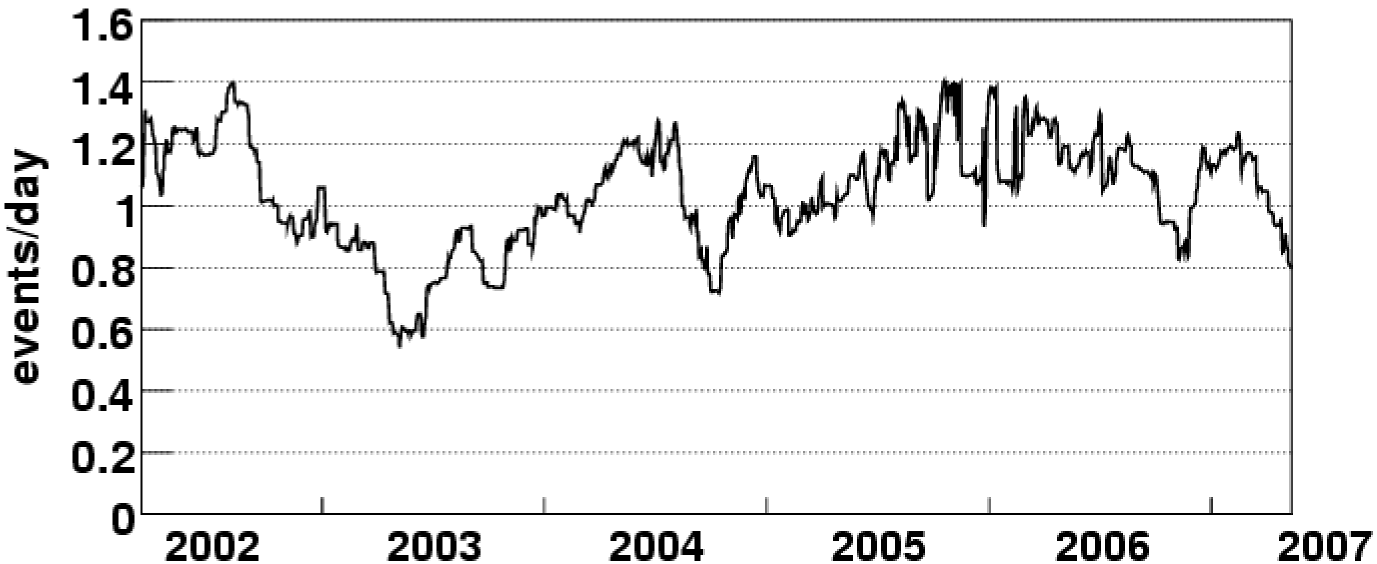
Muon detector
Inner detector PMTs
Pure water
Buffer Oil
13m
914t
Liquid scintillator
(CH1.97)
Balloon
Pure water
Stainless steel tank (Ø18m)
20m
ID Hit Charge
10
8
6
4
2
0
low-energy event
[p.e.]
ID Hit Charge
2000
1500
1000
500
0
muon event
[p.e.]

Reactor anti-neutrino signal at KamLAND



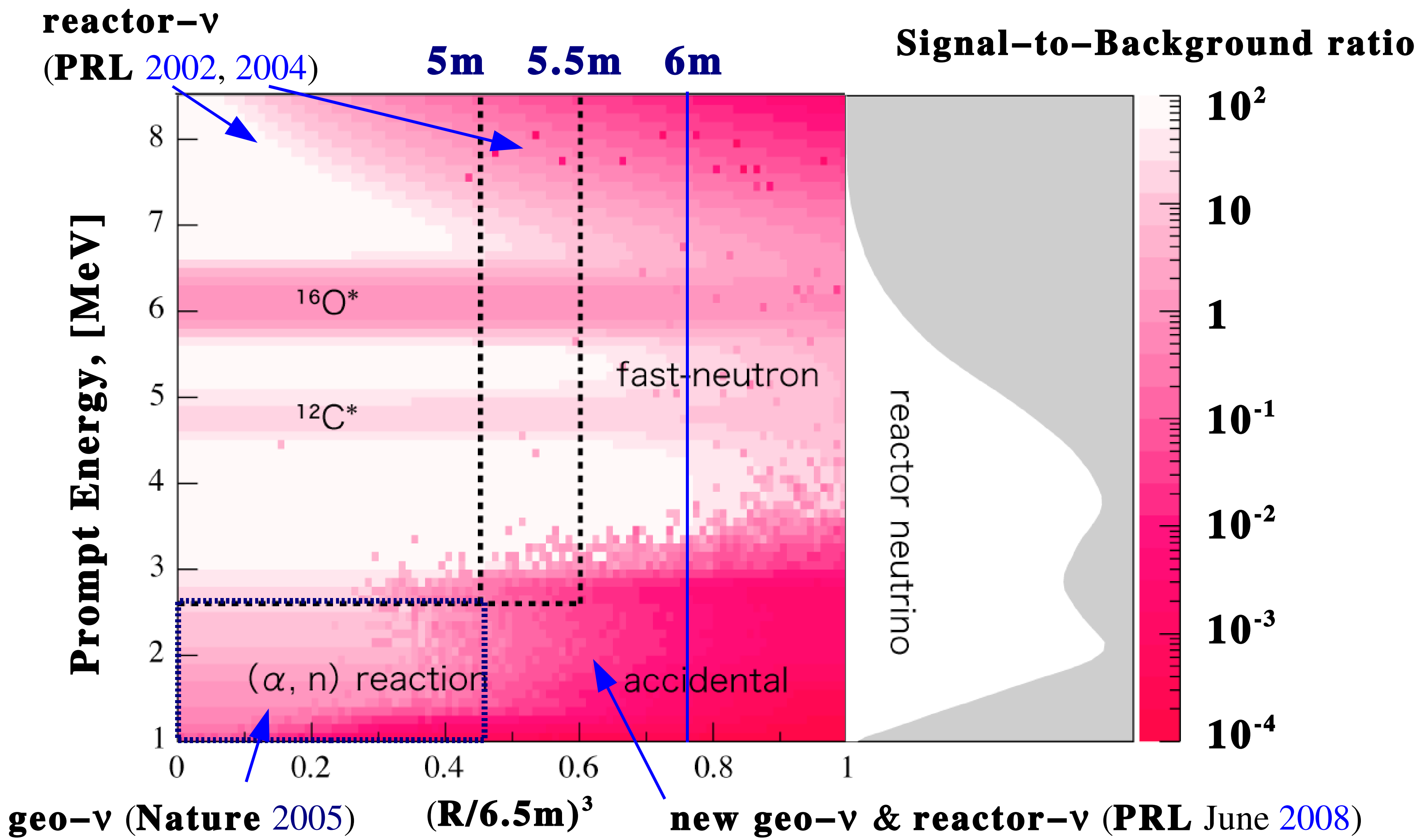
For 55 Japanese nuclear power reactor units thermal power output, details of fuel manipulation are provided by a consortium of Japanese electric companies.

Averaged fision yields
^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570**:**0.078**:**0.295**:**0.057



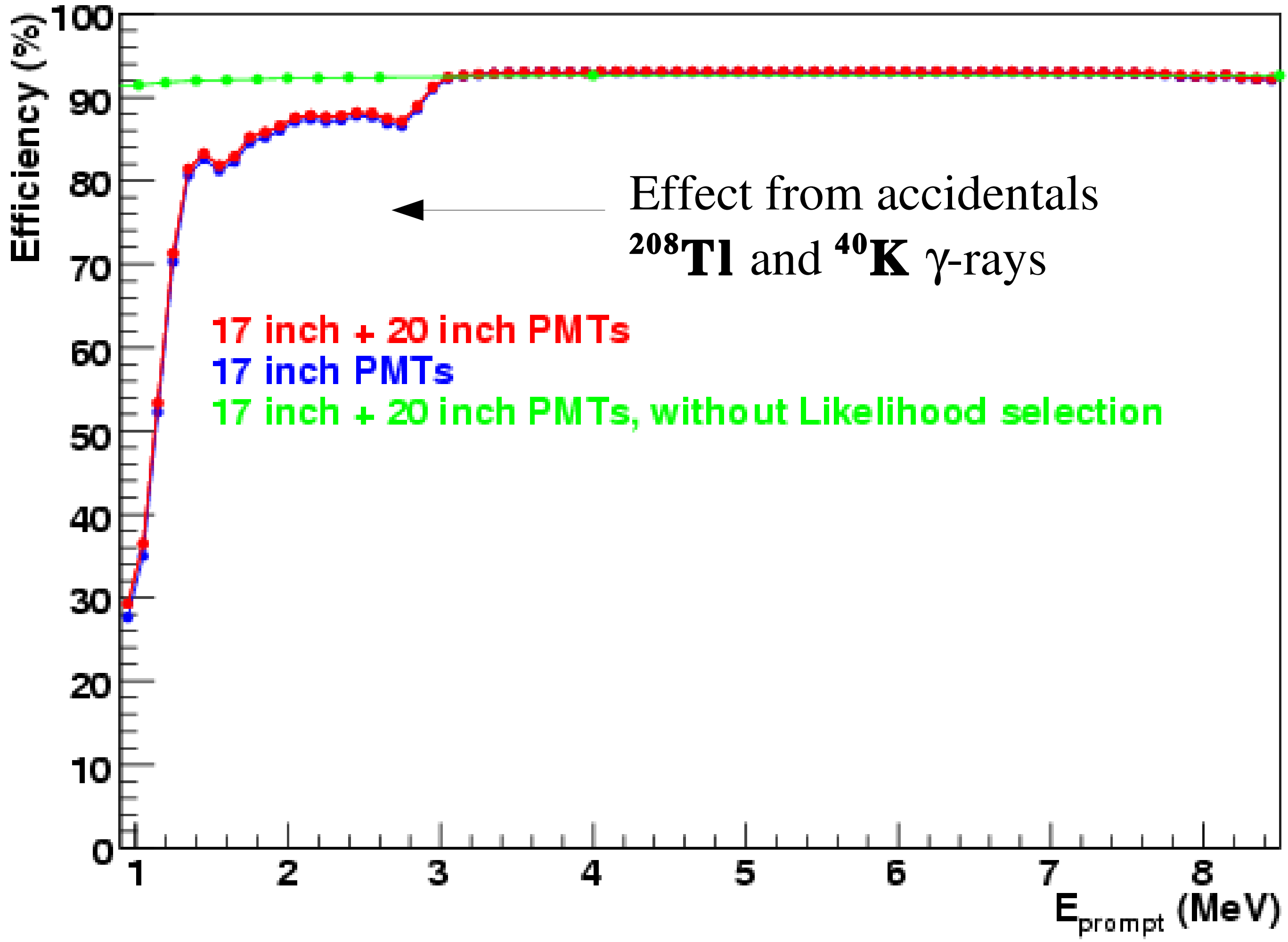
Time variation of the number of expected anti-ν events assuming no oscillation

The anti-neutrino data analysis



The Prompt-Delayed pairs (from **ν+p ⟶ n+e$^+$** and backgrounds) separated by **ΔT<1ms**, and **ΔR<2m** are shown. Variable selection criteria suppress *accidentals* making combined analysis using a full **0.9-8.5MeV** energy range and enlarged **6m** fiducial volume possible.

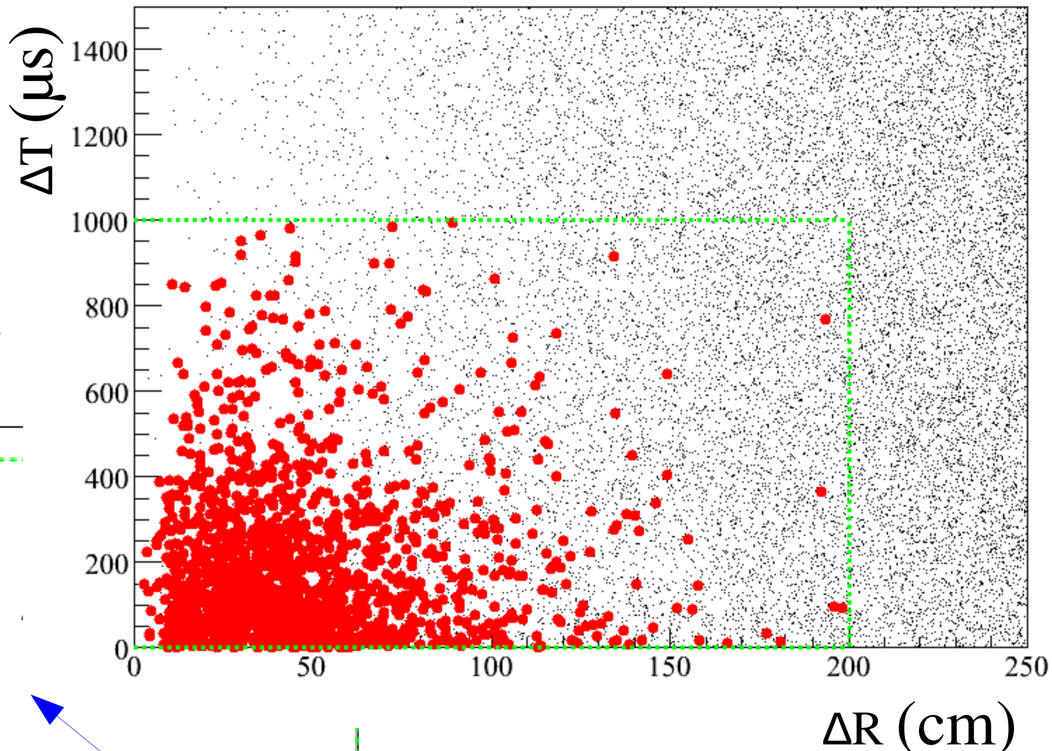
Selection of anti-neutrino events



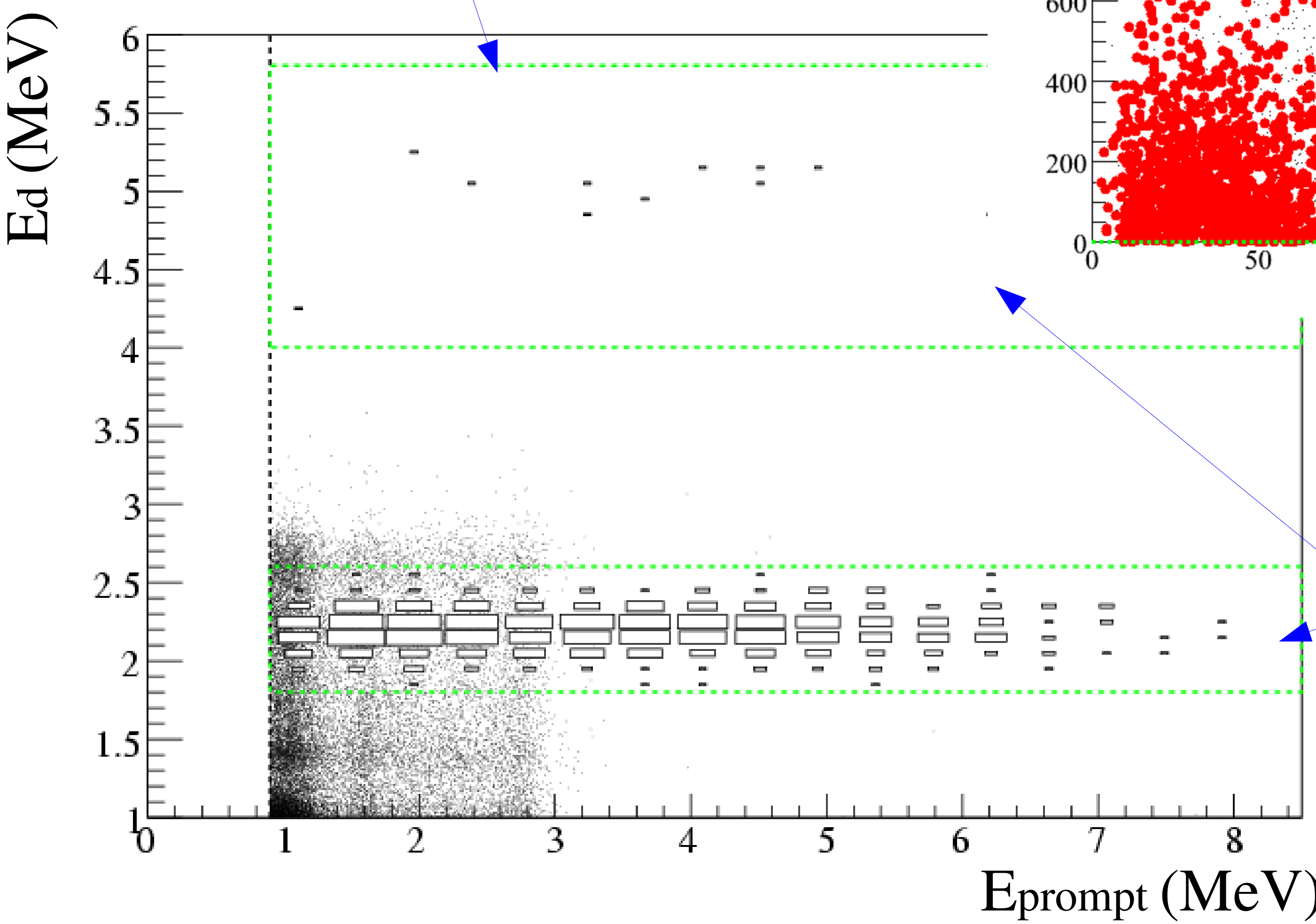
PDF for **accidental coincidence** events is constructed using off-time window (10ms-20s) as **facc**(R_p, R_d, E_d, ΔT, ΔR). PDF for **anti-ν signal (fs)** is created using Monte-Carlo simulation. For each candidate pair ratio = fs/(facc+fs) is calculated and used to select signal-like events. As a result, detection efficiency below 3MeV is getting lower than for box cuts.

Selection of anti-neutrino events

The **red** and **black** points show events with and without likelihood selection cut

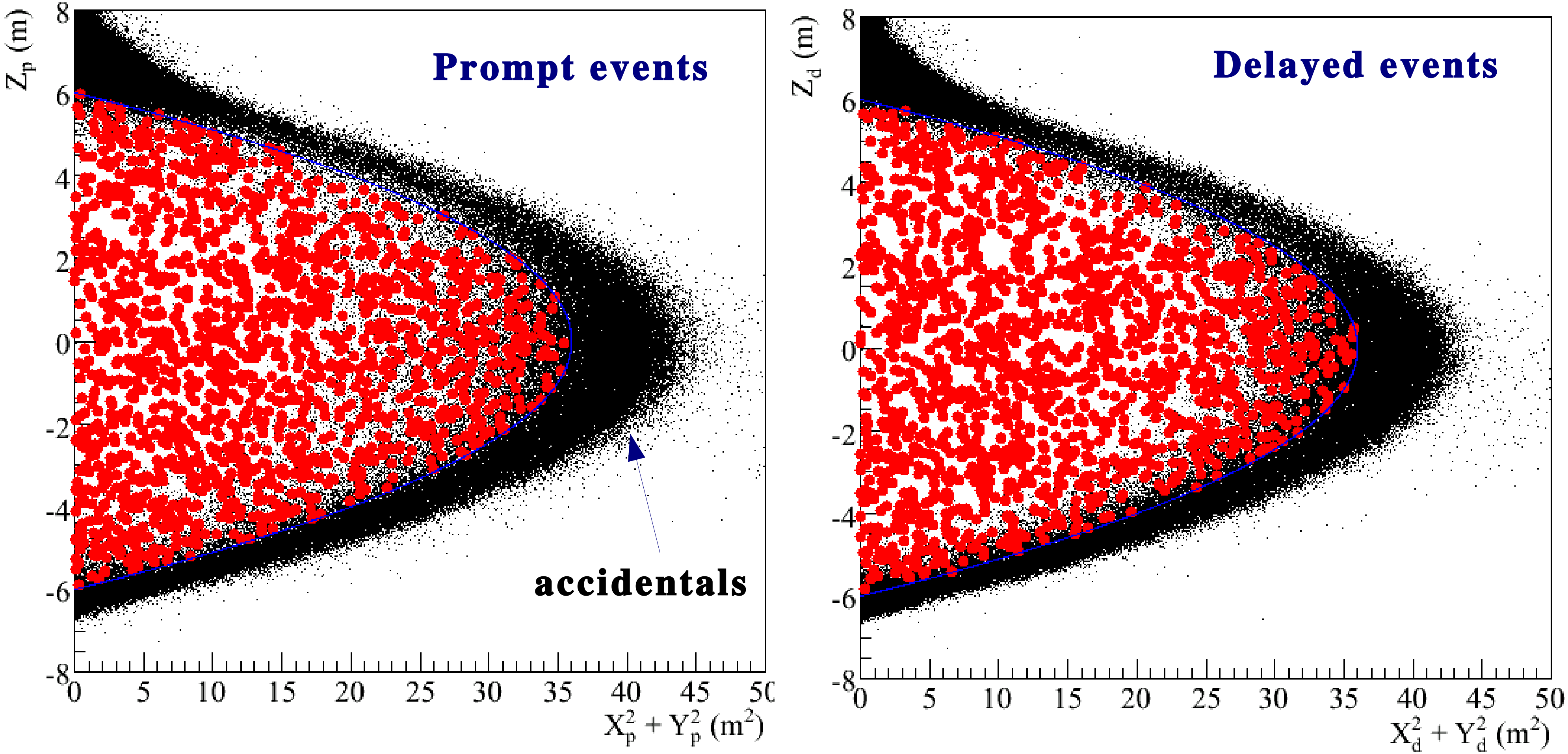


The **box** histogram and **black** points show events with and without likelihood selection cut



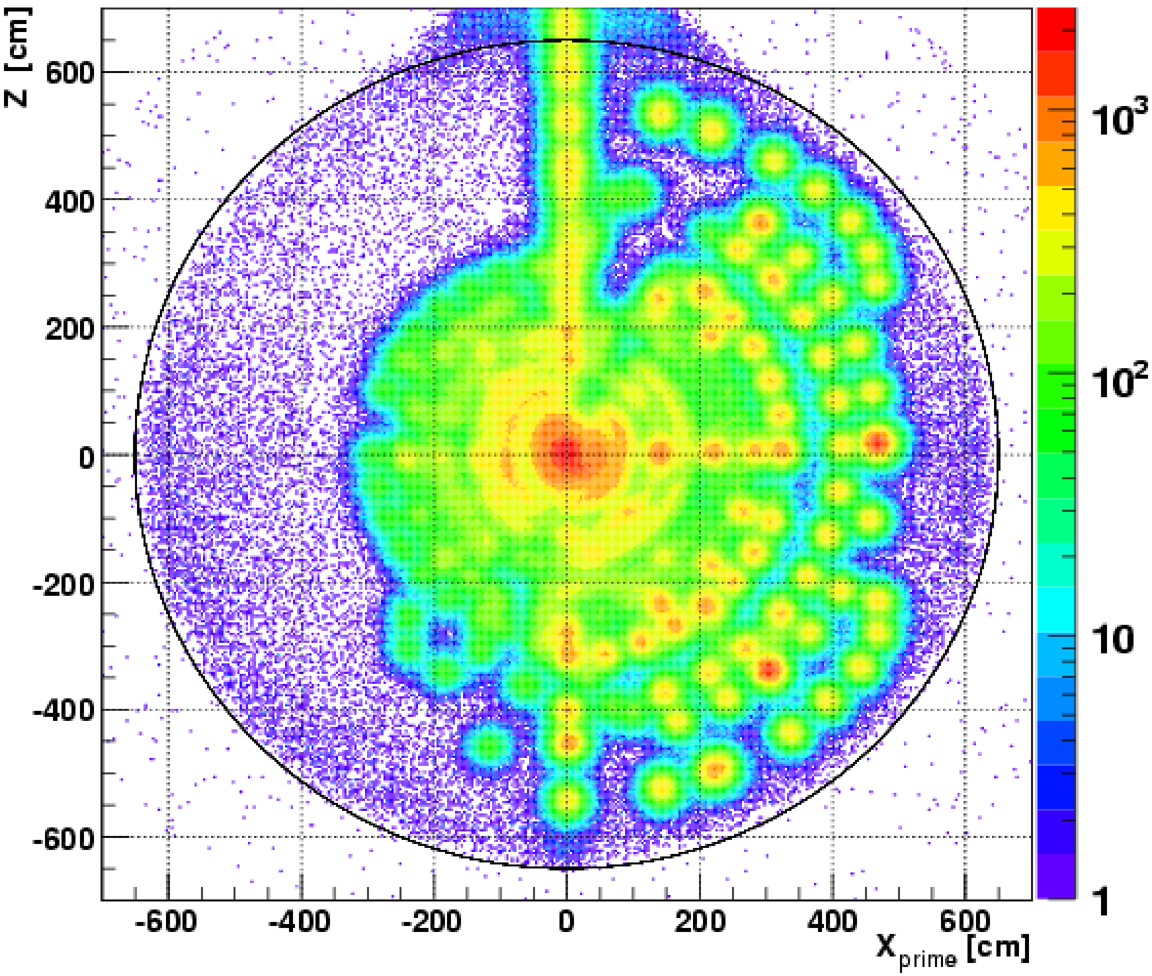
The **Delayed energy** range corresponding to **n** capture on **H** and ^{12}**C**

Distribution of anti-neutrino events in KamLAND



The **red** **(black)** points show vertex location of Prompt (left) & Delayed (right) events **with** and **without** the likelihood selection cut. **Anti−ν** events are distributed *uniformly*, while majority of accidentals are located *near the balloon edge*.

Estimation of the fiducial volume uncertainty



Off-axis calibration system was used to deploy $^{241}Am^{9}Be$, $^{210}Po^{13}C$, ^{60}C, ^{68}Ge, and ^{203}Hg sources into KamLAND and study vertex reconstruction biases at distances up to 5.5m away from the detector center. We found that the event vertex fitter reconstructs event's position with a bias < 3cm within the 5.5m volume which corresponds to 1.6% systematic error.

The 6m fiducial volume (FV) uncertainty, 1.8%, was determined by using the off-axis calibration data and uniformly distributed μ-induced β-emitter ^{12}B events. For comparison, the 4.7% FV uncertainty was used for the 2^{nd} KamLAND result.

Estimation of the expected (α,n) background

^{210}Po 5.3MeV α-particle interaction on ^{13}C:

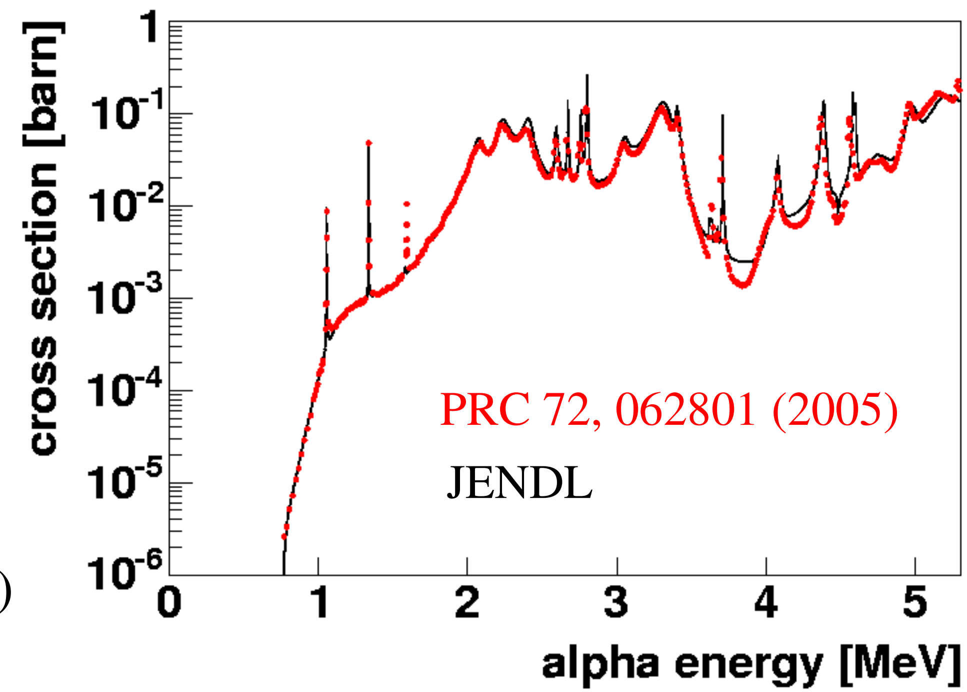
(g.s.) $\alpha + {}^{13}C \rightarrow {}^{16}O + n$ (3-7MeV)

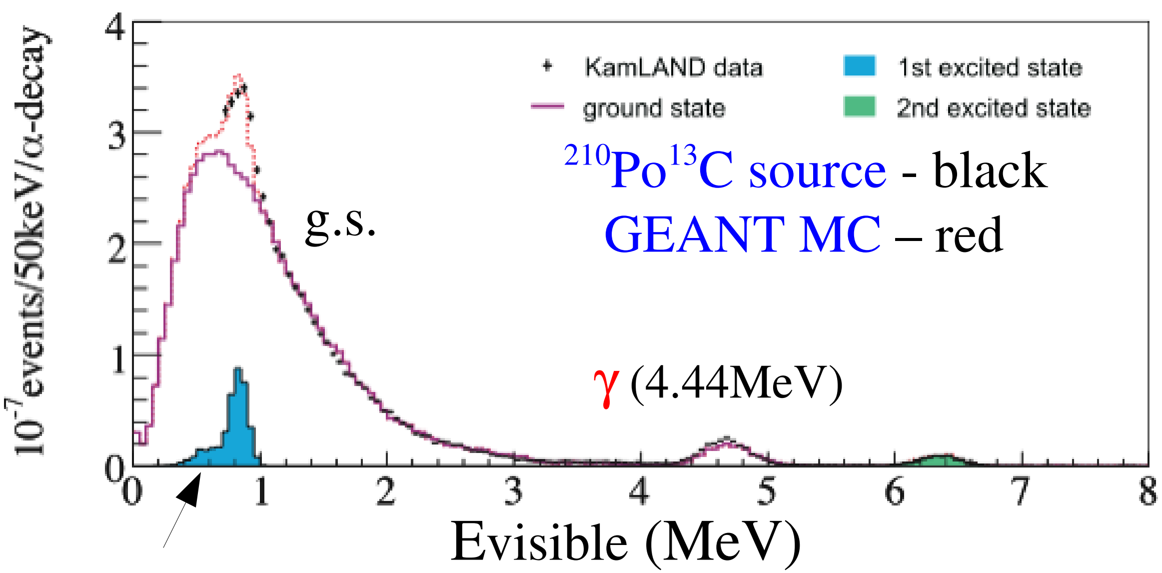
$n + {}^{12}C \rightarrow {}^{12}C + n + \gamma$ (4.44MeV)

(1st) $\alpha + {}^{13}C \rightarrow {}^{16}O^*$ (6.05MeV) + n (0-0.5MeV)

(2nd) $\alpha + {}^{13}C \rightarrow {}^{16}O^*$ (6.13MeV) + n (0-0.5MeV)

1st (2nd) excited states of ^{16}O decay to **e^-e^+** (**γ**-ray)





e^-e^+ from 1st exc. st. are absorbed in the source material

Expected number of (α, n) events:

ground state 163.3 ± 18.0

excited states 18.7 ± 3.7

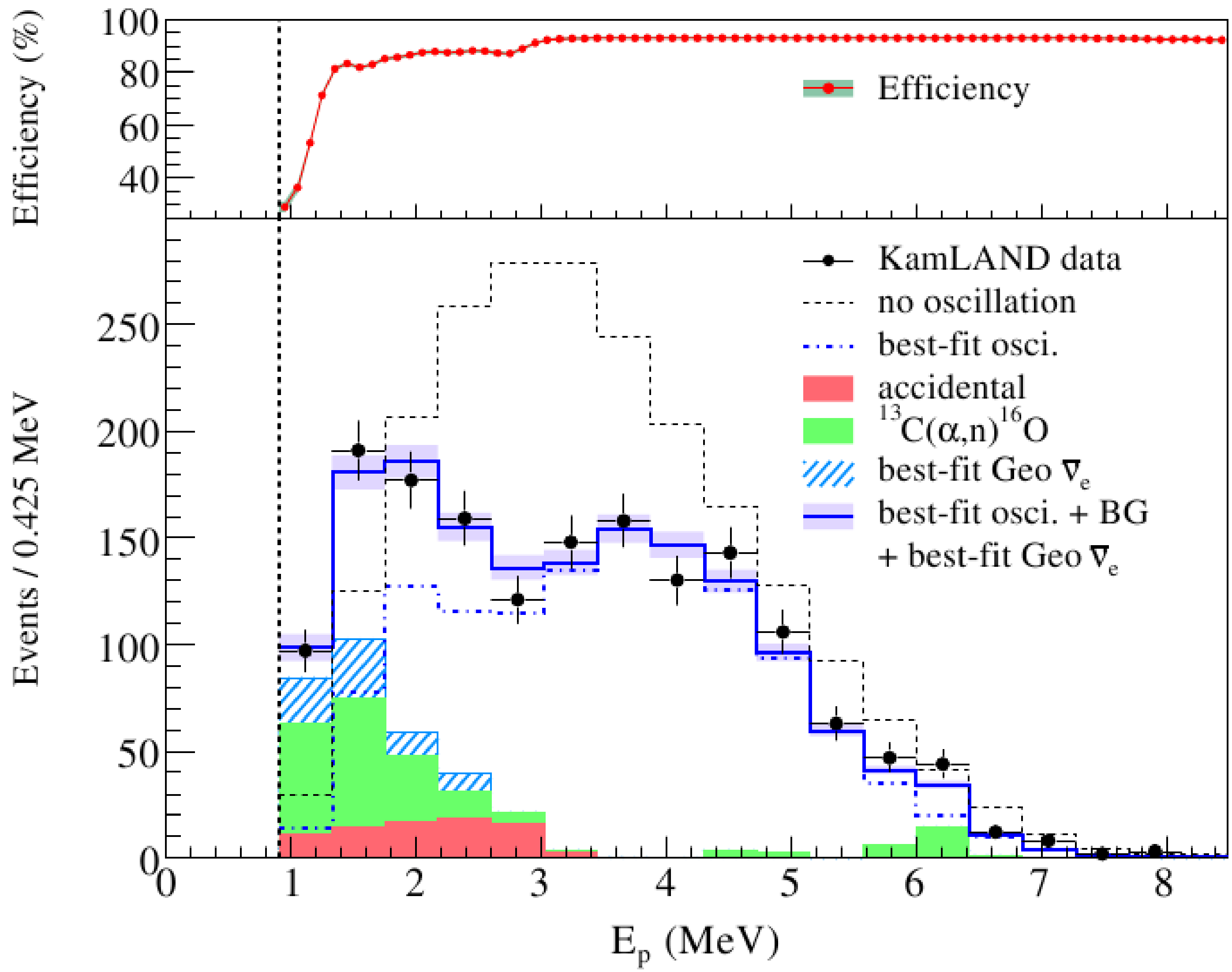
Compared to the 2nd KamLAND result:

Error for g.s. reduced: 32%→11%

Error for exc. st. reduced: 100%→20%

10% energy scale error was removed by calibration of the **recoil-proton Visible energy** using a neutron generator.

The anti-neutrino energy spectrum



Plot shows the Prompt event energy (e^+ kinetic energy + $2m_e$) which can be converted to

$$\mathbf{E_\nu \approx E_{prompt} + 0.8MeV}$$

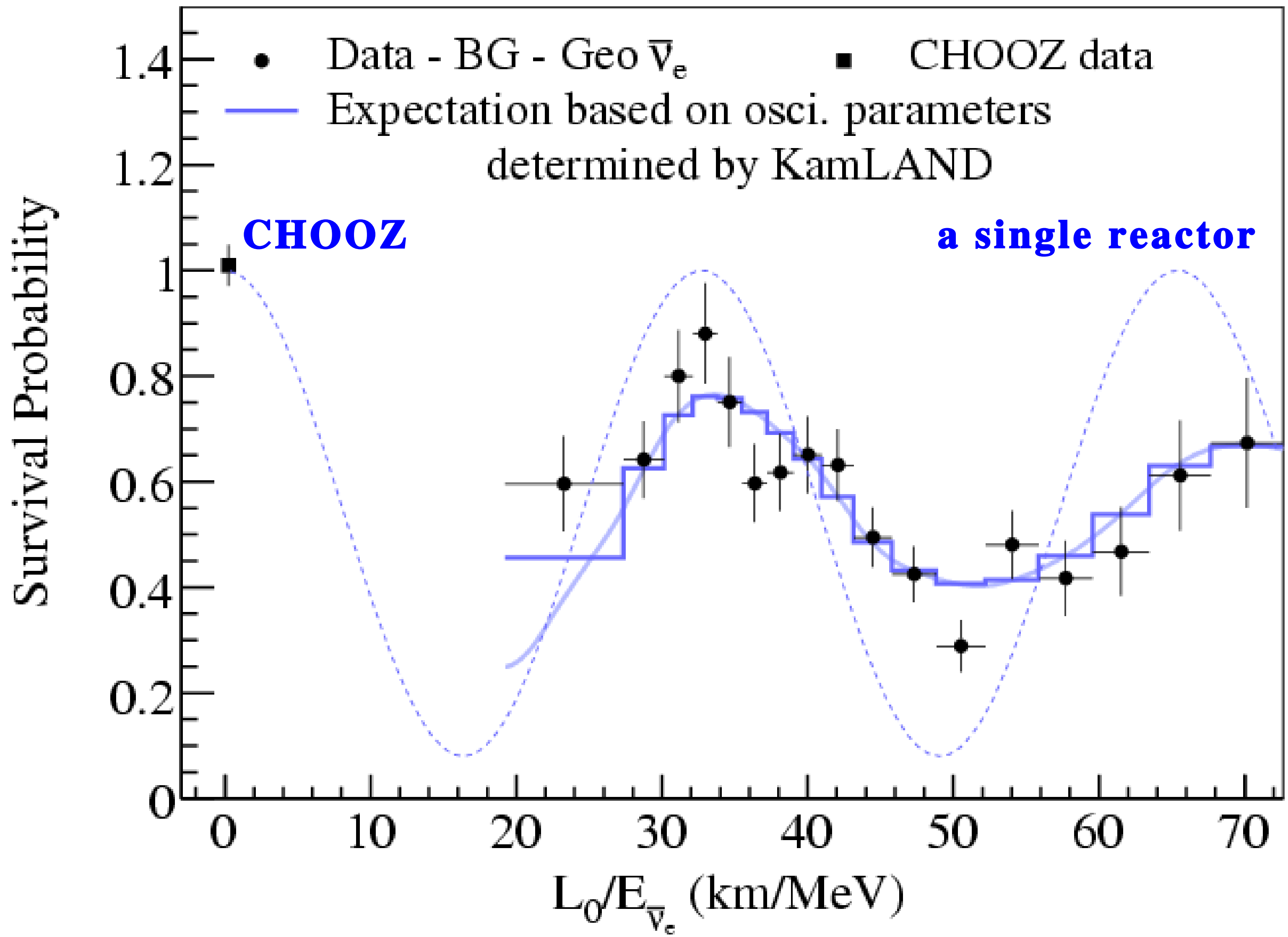
The best fit values:

$\Delta m_{21}^2 = 7.58 \times 10^{-5} (eV^2)$

$\tan^2\theta_{12} = 0.56$

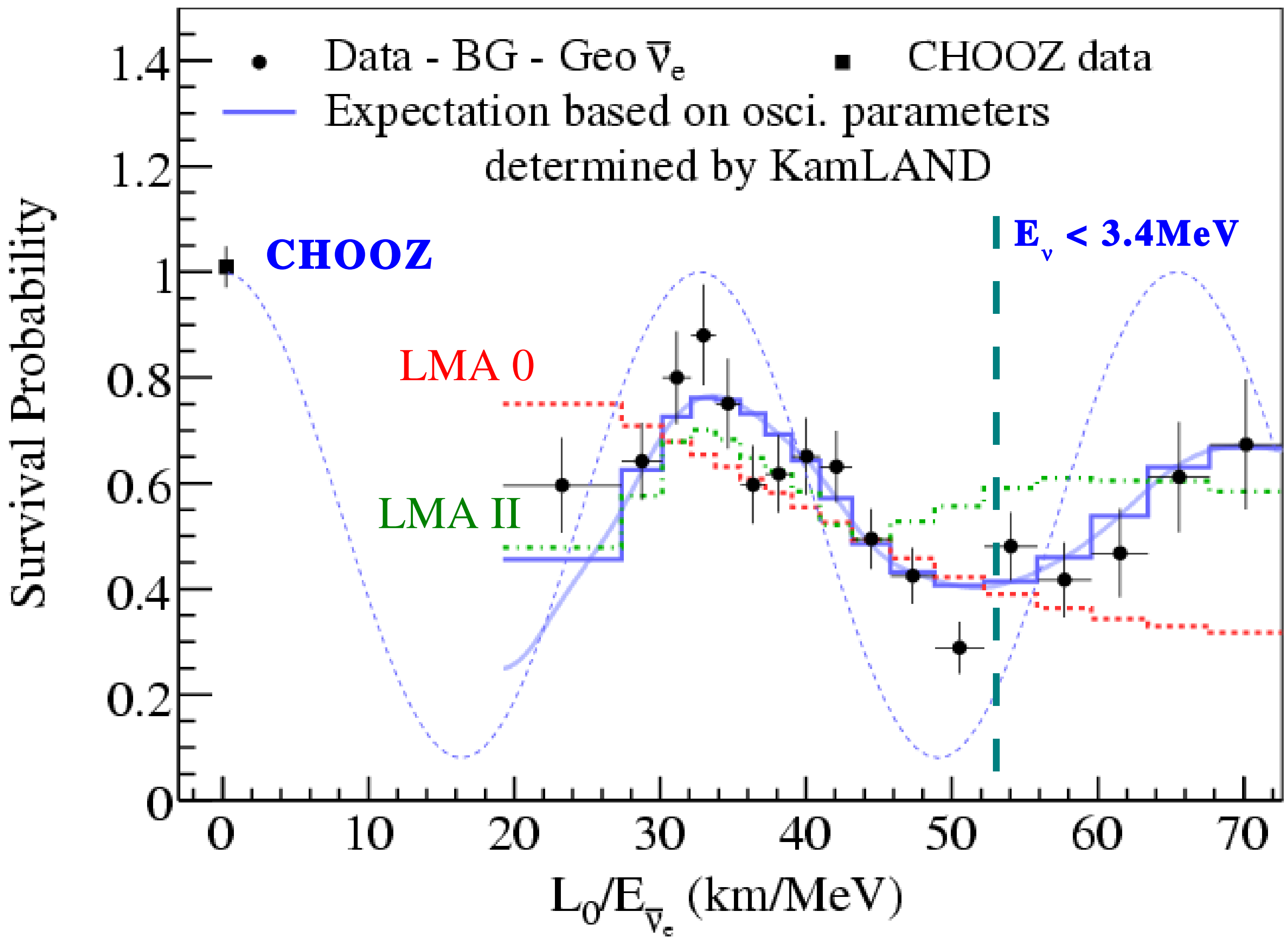
Data taken between March 9, 2002 and May12, 2007, the 2.44×10^{32} proton-year exposure is used. This is KamLAND only result (using $\theta_{13}=0$ and taking into account reactor flux time variation). Scaled reactor spectrum with no oscillations included is excluded at a 5.1σ level.

The L_0/E_ν oscillation plot (L_0 =180km)



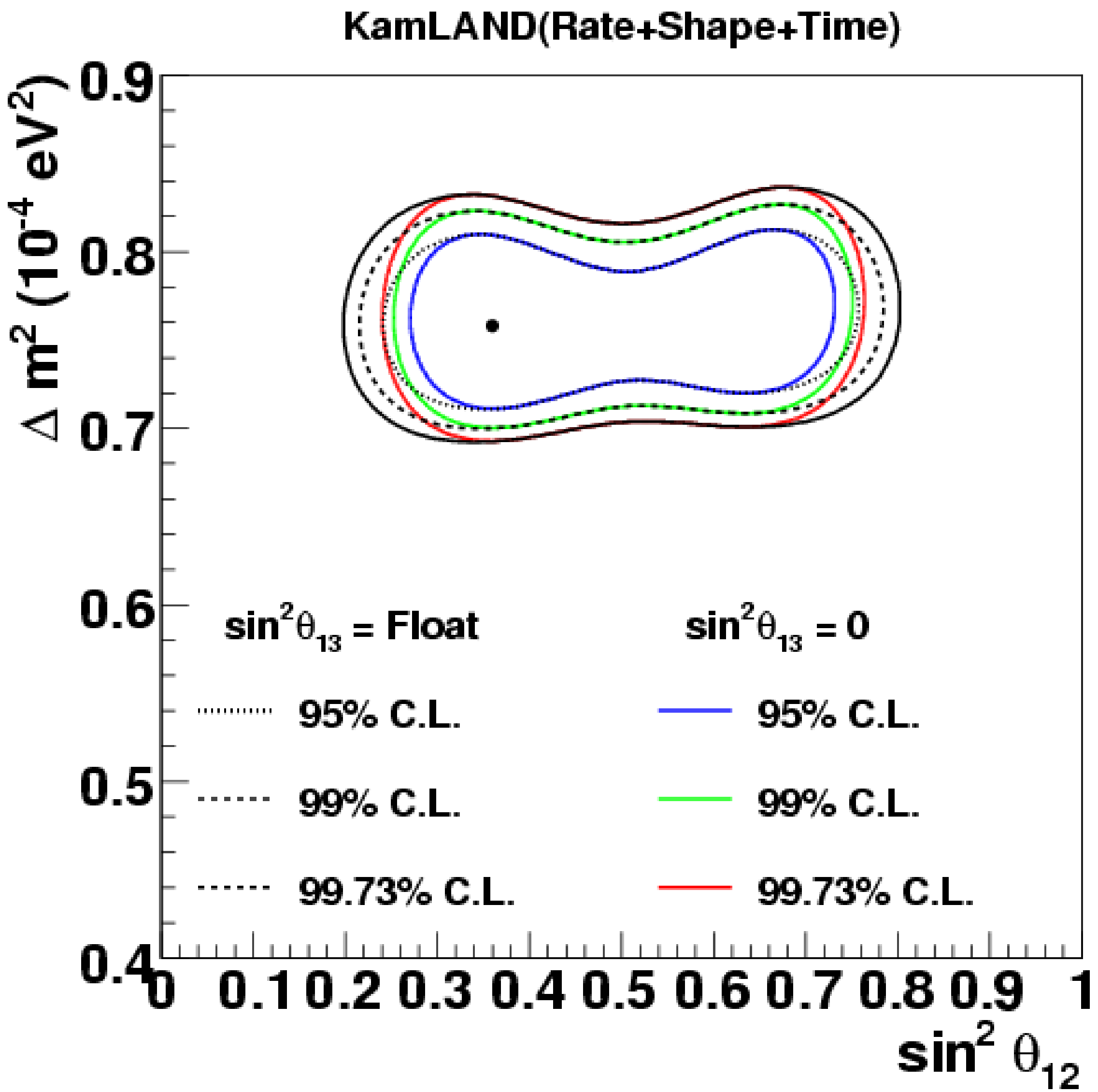
The KamLAND and CHOOZ data plotted as **(Data - BG)/(Exp)** , where **Data** is number of observed events, **Exp** is number of expected in **no oscillation** case, **BG** is number of expected background events including geo-neutrinos.

The L_0/E_ν oscillation plot: LMA I, 0, II vs data



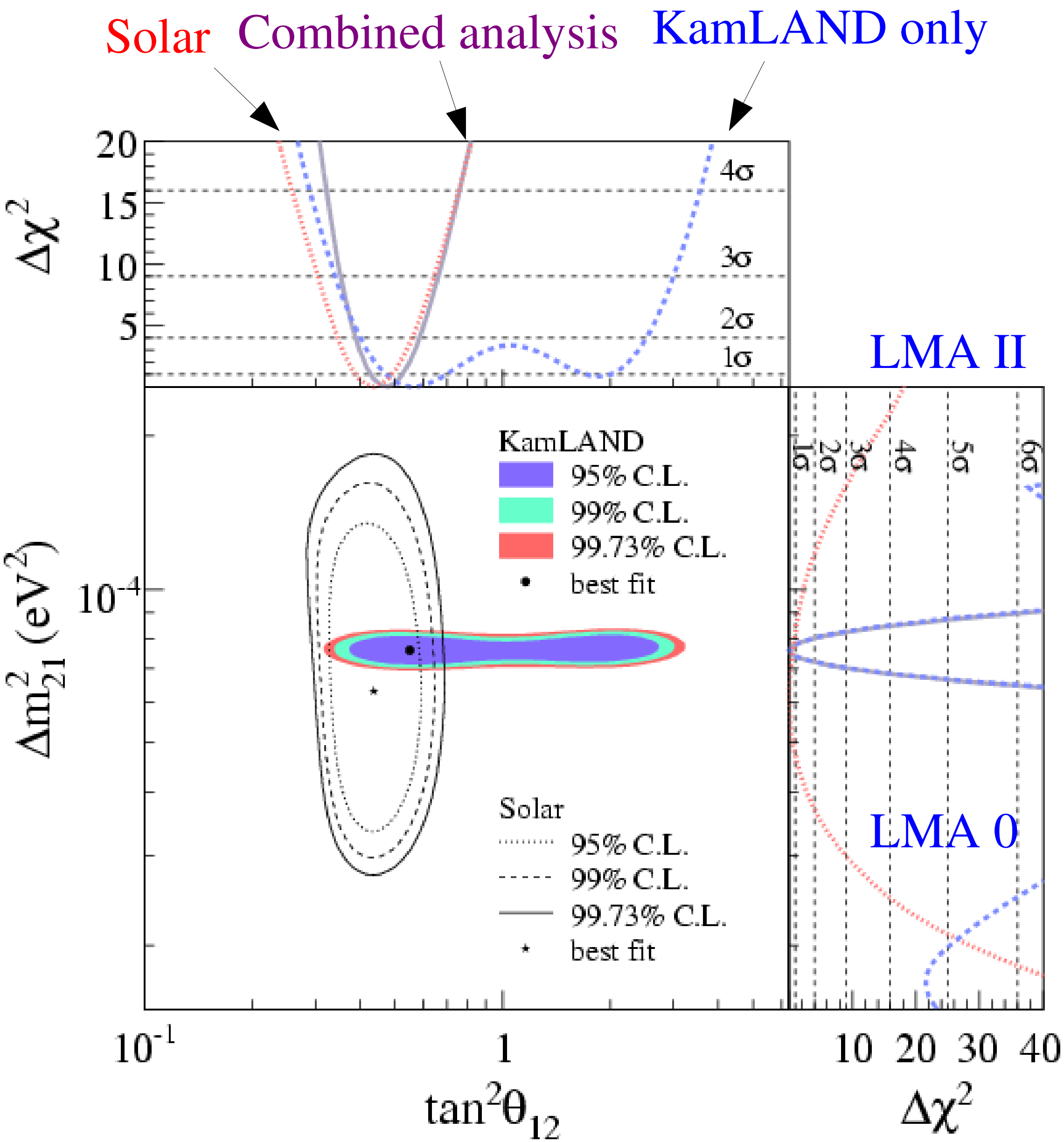
The 2nd KamLAND result was obtained for the E_ν >3.4MeV to avoid the geo-ν background, while data below 3.4MeV has a power to distinguish between different LMA regions. New analysis excluded alternative solutions (LMA 0, LMA II) by more than 4σ.

Effect of non-zero θ_{13}



The Δm^2 result remains the same if three neutrino oscillation is considered, while uncertainty for θ_{12} is getting slightly larger

KamLAND + Solar oscillation analysis



KamLAND only:

$\Delta m^2 = 7.58^{+0.14}_{-0.13}(st) \pm 0.15(syst) \cdot 10^{-5}$ (eV^2)

$\tan^2\theta = 0.56^{+0.10}_{-0.07}(st)^{+0.1}_{-0.06}(syst)$

KamLAND+solar:

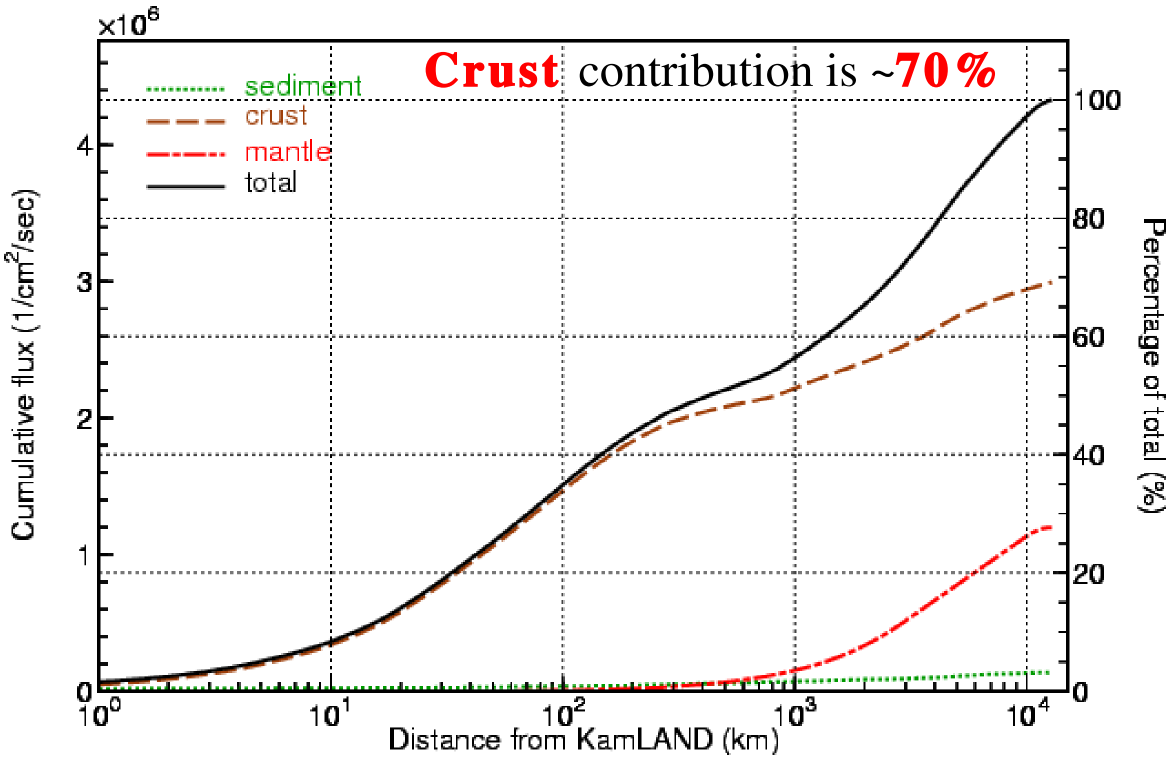
$\Delta m^2 = 7.59 \pm 0.21 \cdot 10^{-5}$(eV^2)

$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

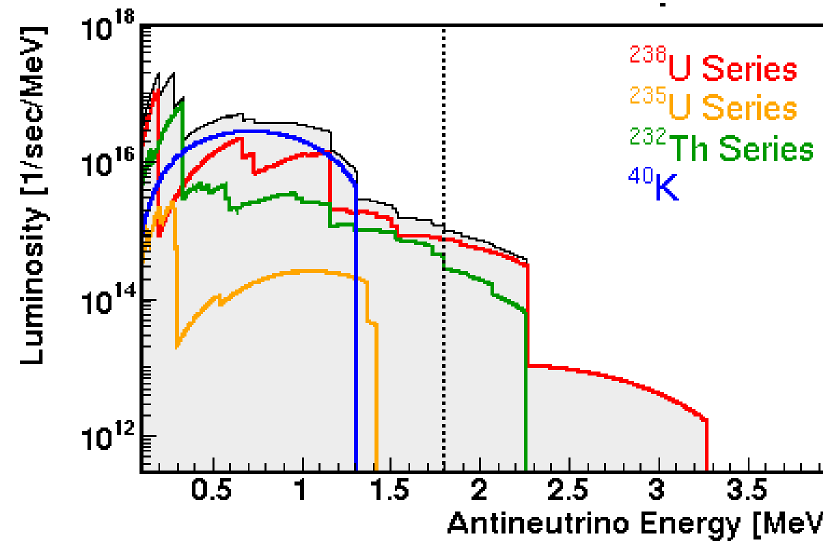
Only LMA I remains

KamLAND improved result for mixing angle and Δm^2. Solar data have no effect on the Δm^2 measurement.

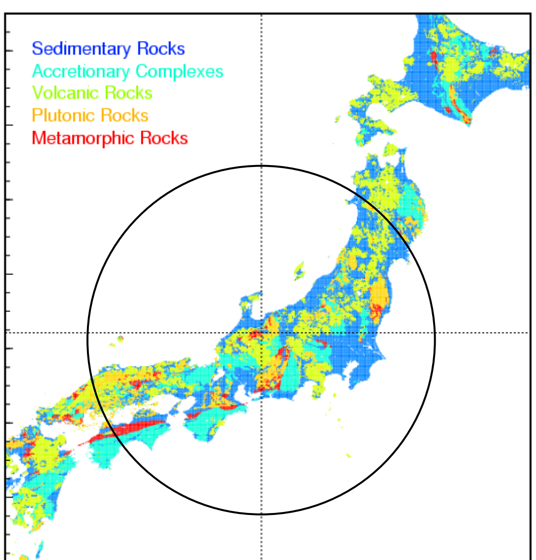
Expected geo-neutrino signal at KamLAND



$$\bar{\nu}_e + p \rightarrow e^+ + n$$



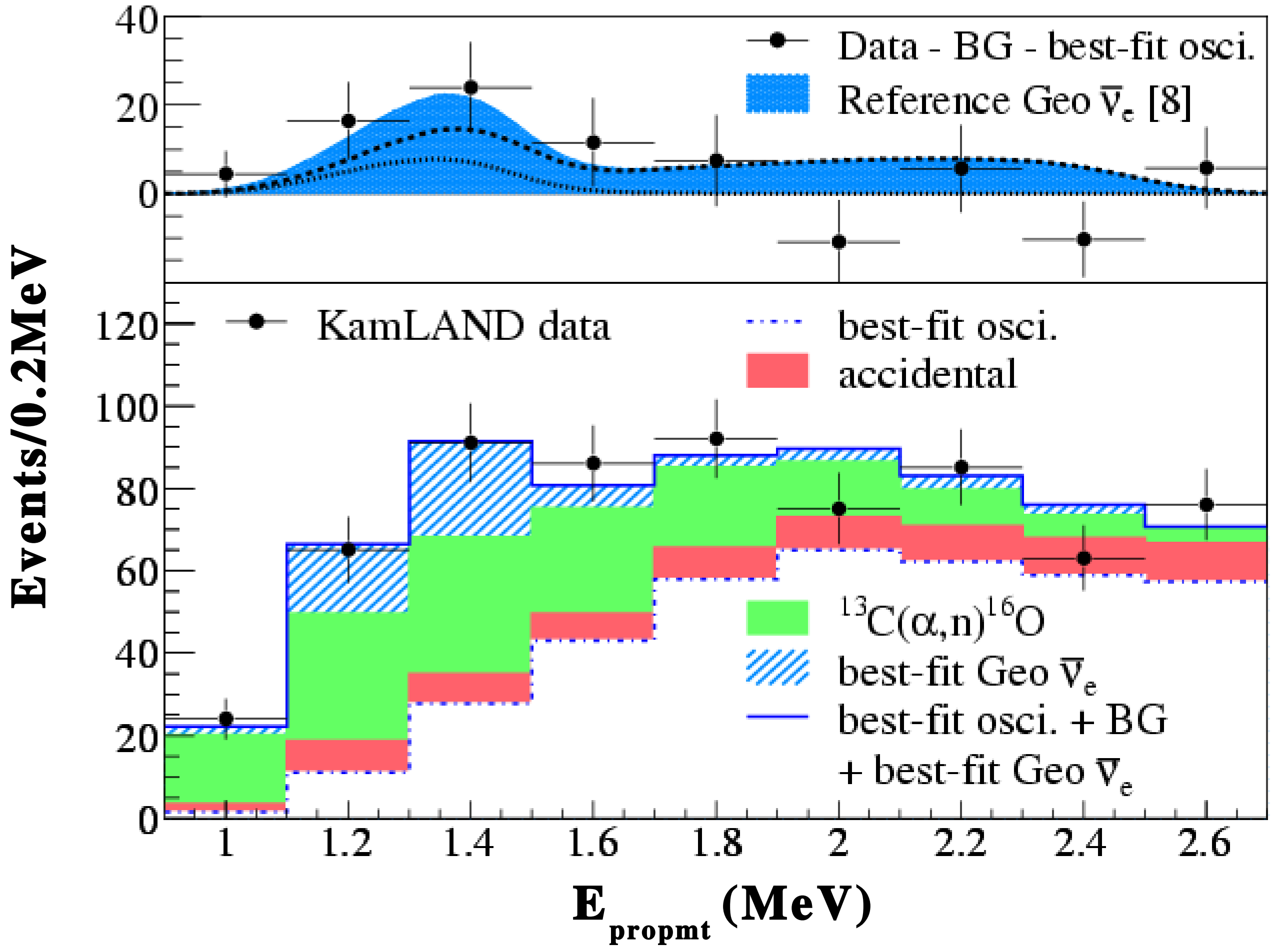
Threshold:1.8MeV



Area within 500km gives ½ of the total expected geo ν flux at the KamLAND location.

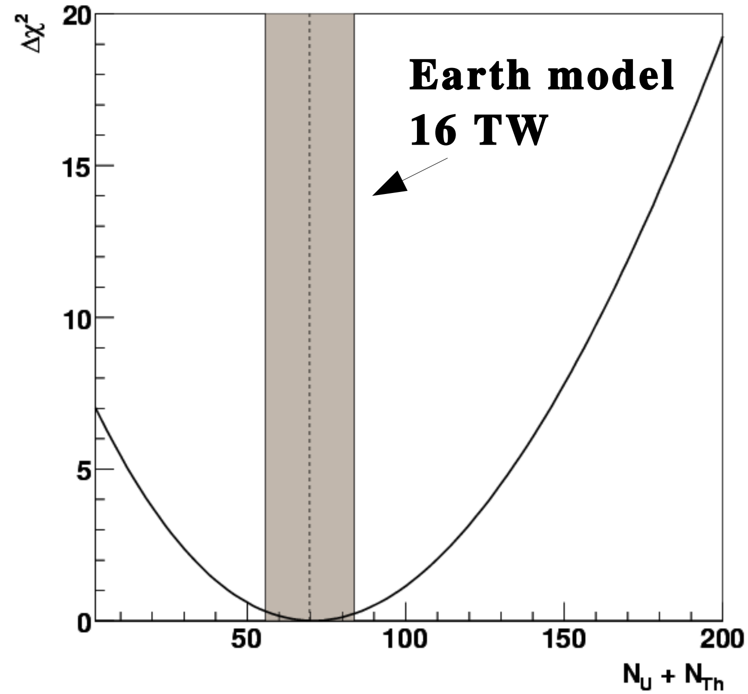
Geo-neutrinos carry information about the absolute amount and distribution of the U/Th/K in the crust, mantle and core. This information may help to understand mechanisms of Earth formation, and its dynamics.

The second geo-neutrino result



Rate + Shape + Time analysis results

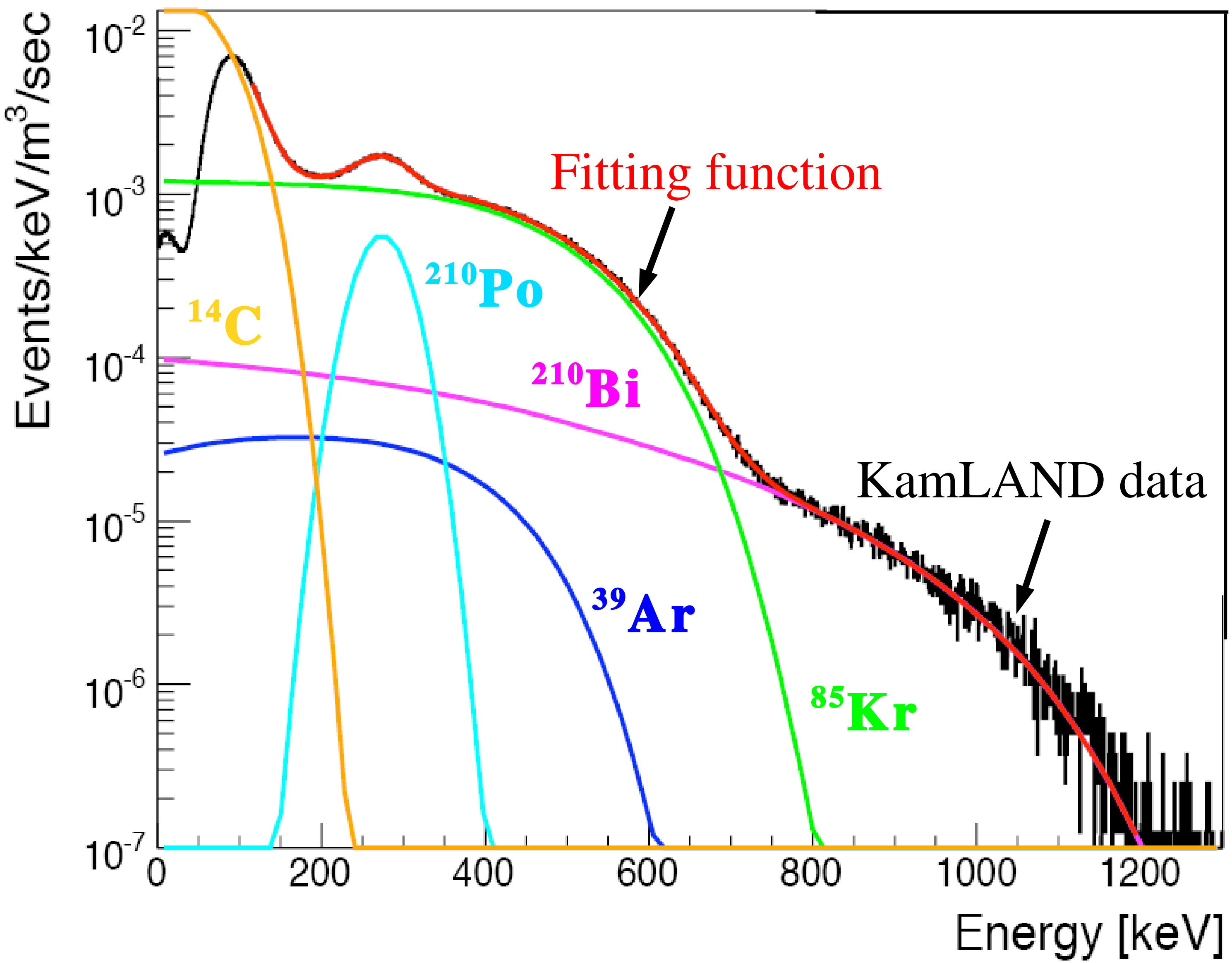
with SNO oscillation constraint



The Th/U mass ratio was fixed at 3.9. Number of geo-neutrinos, **73 ± 27**, corresponds to flux (4.4 ±1.6) x 10^6 (cm^{-2} s^{-1}). This result is consistent with the reference Earth model which predicts flux 2.24 x 10^6 (cm^{-2} s^{-1}) for **U** (56.6 events) and 1.9 x 10^6 (cm^{-2} s^{-1}) for **Th** (13.1 events) assuming **16 TW** of the radiogenic heat.

Reference Earth model: S. Enomoto *et al*, Earth Planet Sci Lett. **258**,147 (2007)

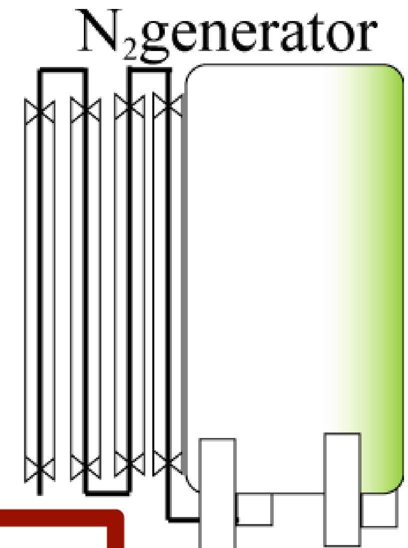
Solar neutrino background before start of distillation

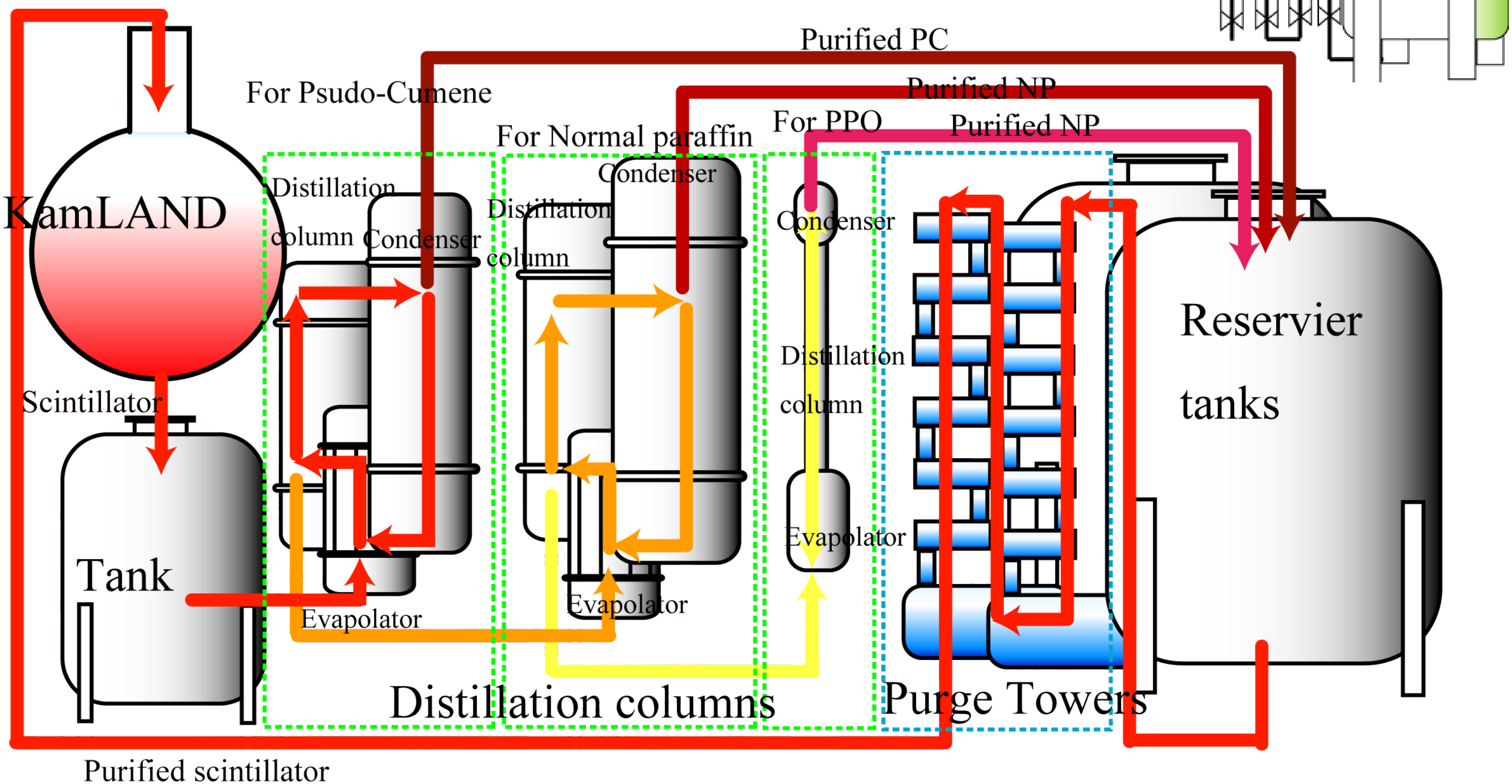


Observation of low energy solar neutrinos requires removal of ^{85}Kr and ^{222}Rn decay products: ^{210}Pb → ^{210}Bi → ^{210}Po.

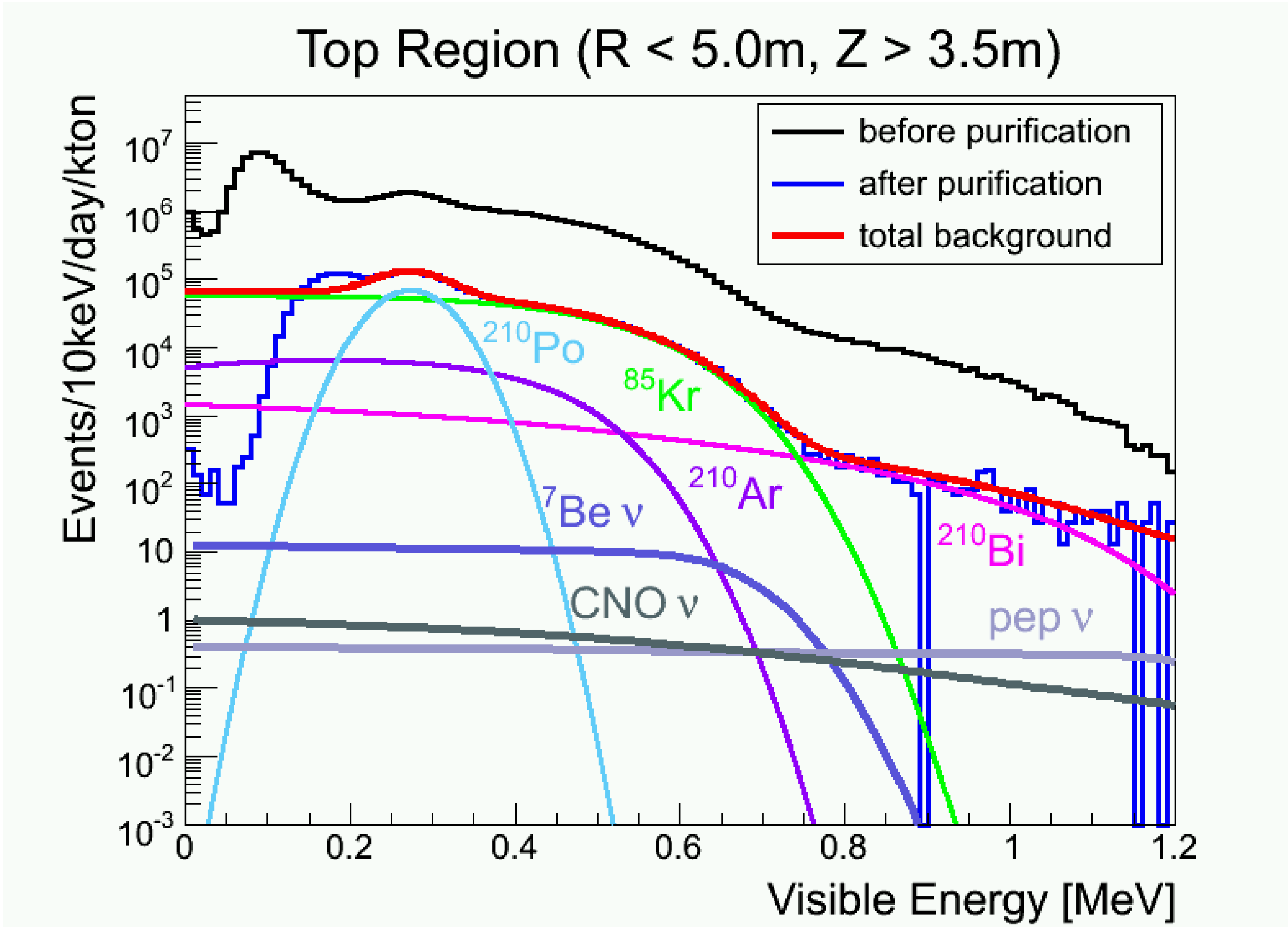
KamLAND Purification System

- Distillation goal is to remove ^{210}Pb, ^{40}K, and Th/U
- pure N_2 purge goal is to remove ^{85}Kr, ^{39}Ar, and ^{222}Rn



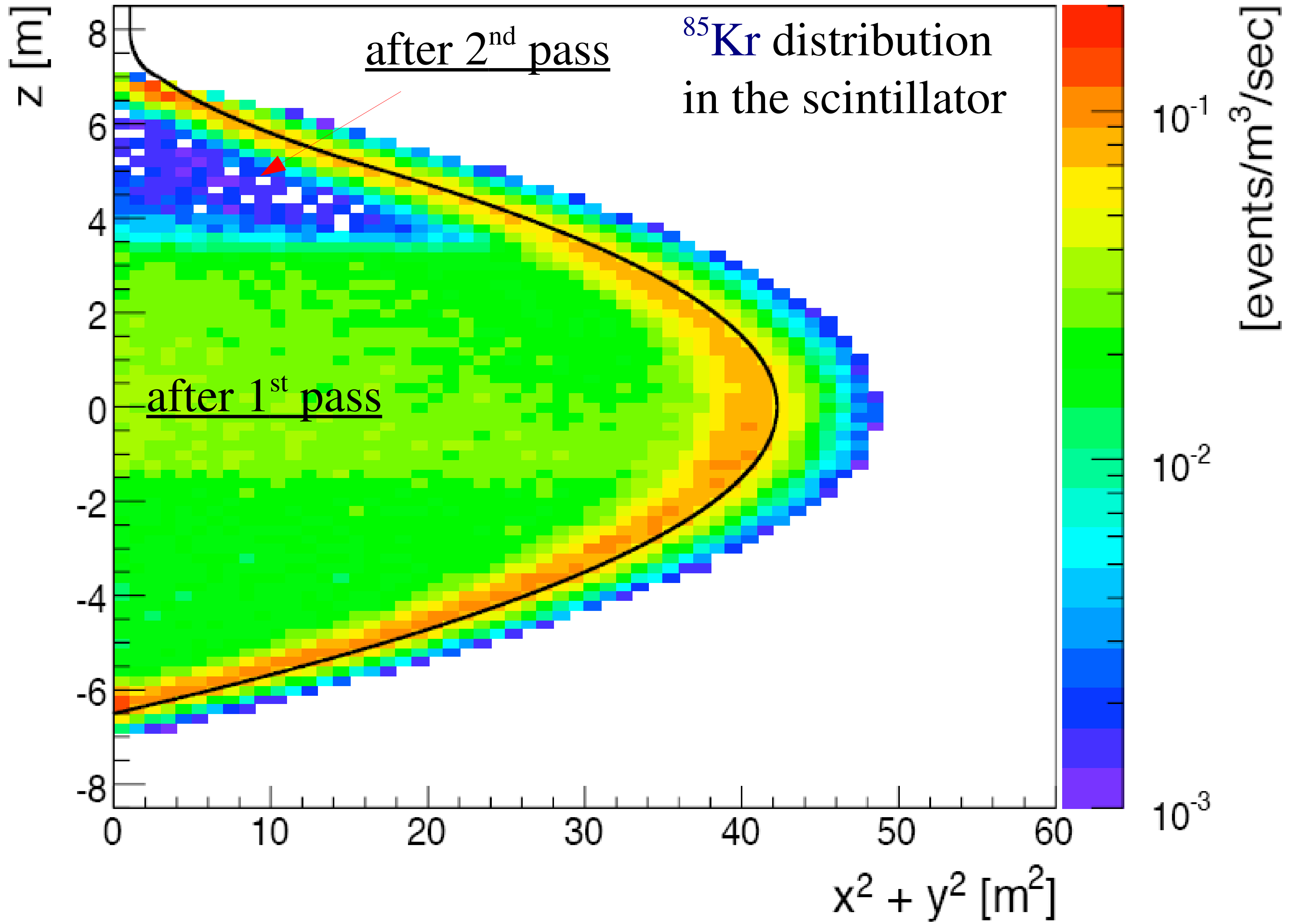


Background reduction after the 1st stage of purification

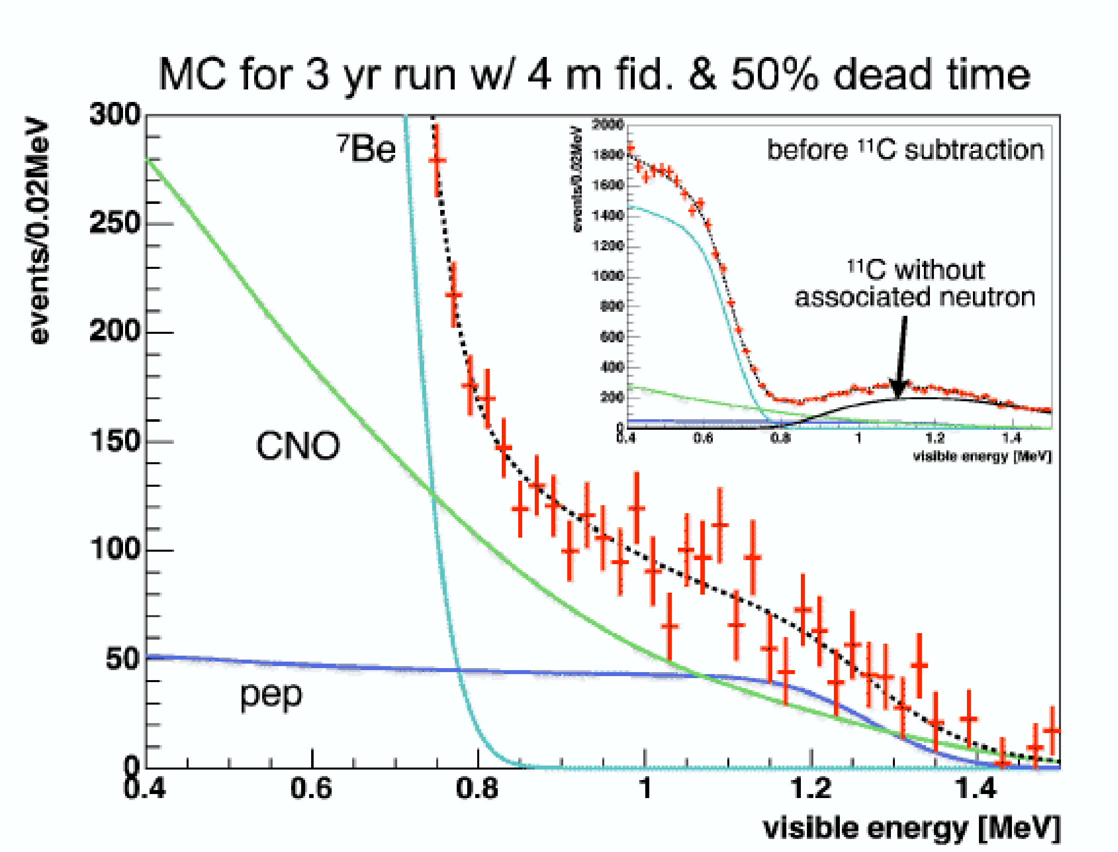


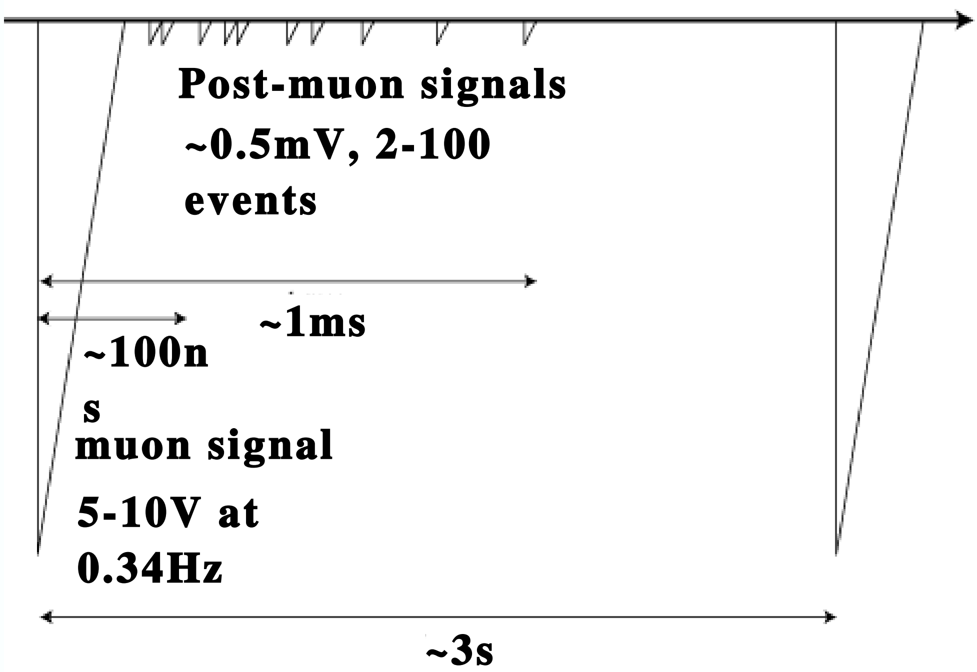
About 1700m^3 of the KamLAND scintillator were purified last year. Due to mixing between purified and non-purified scintillator purification effect is smaller than needed for the ^{7}Be observation. The upper part of the detector is filled with scintillator after a 2nd pass through the system. The 2nd purification campaign started 2 weeks ago and will continue for 6 month.

The current status of KamLAND



Detector upgrade towards the solar neutrino detection

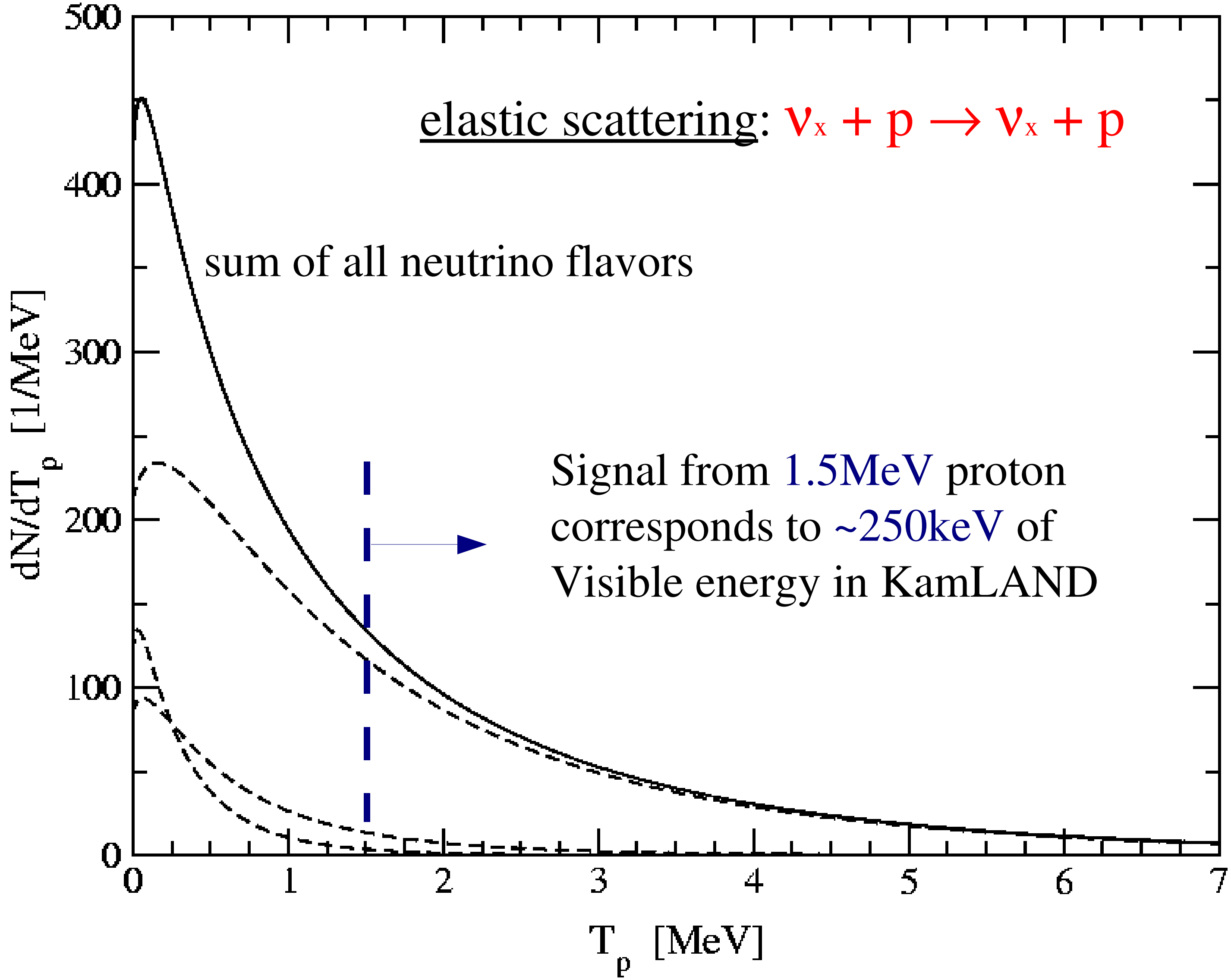




95% of the ^{11}C nuclei are produced in $^{12}C+\mu \rightarrow ^{11}C+n$ reaction. Detection of the neutron after muon should allow to veto a small part of the detector volume until ^{11}C decays and reduce background for measurement of the pep and CNO solar neutrinos. Technique was successfully tested in KamLAND but new electronics is needed to improve veto efficiency.

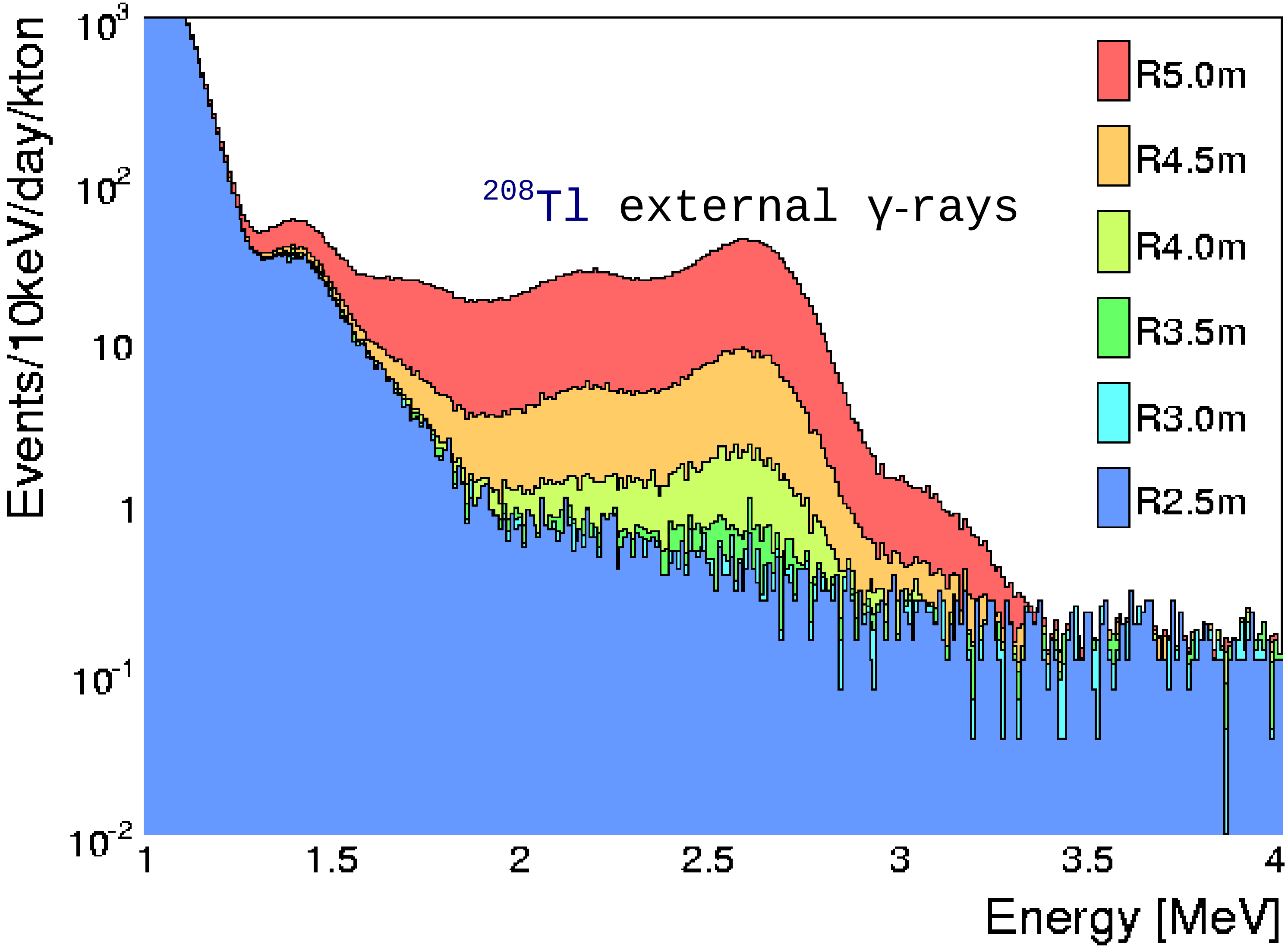
A new deadtime-free data acquisition electronics was developed for the solar pep/CNO neutrino observation with KamLAND. It aims to detect all neutrons produced by muons. The number of neutrons after a muon can reach 60~100, and therefore capability of collecting multiple signals is crucial.

Sensitivity to the SN neutrinos after purification



The proton-recoil energy spectrum in KamLAND from SN (3×10^{53}ergs) at 10kpc from PRD **66**, 033001 (2002). Background reduction at the low energy region, a large detector mass, and high H/C ratio makes KamLAND a unique tool for the SN neutrino detection.

KamLAND as 0νββ detector



The central region of KamLAND provides very clean environment free from the external γ-ray background. It can be used to accommodate a large scale ^{136}Xe 0ββν experiment which is going to be the next physics goal of KamLAND. As a first stage we plan to load 200kg of enriched isotope, and then ≥1000kg as a second stage.

Conclusion

- The "reactor-ν" phase has been completed with 4.1 years of the detector livetime. The new PRL paper was accepted for publication on May 19 2008.
- KamLAND measured $\Delta m^2 = 7.59 \pm 0.21\times10^{-5}(eV^2)$
- KamLAND improved precision of the measurement of $\theta_{12} \approx 35$ degrees
- The 2nd purification campaign has been started. Distillation system was improved, measures to avoid mixing between purified and non-purified scintillator were taken.
- Main physics goals after the purification: ^{7}Be, CNO+*pep* solar neutrinos, continuation of geo-ν detection, new window for the SN neutrinos detection (via the proton recoil)
- After the solar neutrino phase search for the neutrinoless double β-decay will be started in 2 stages: first 200kg as a prototype, and then ≥1000kg of enriched isotope ^{136}Xe.