Results and Future of the KamLAND Experiment

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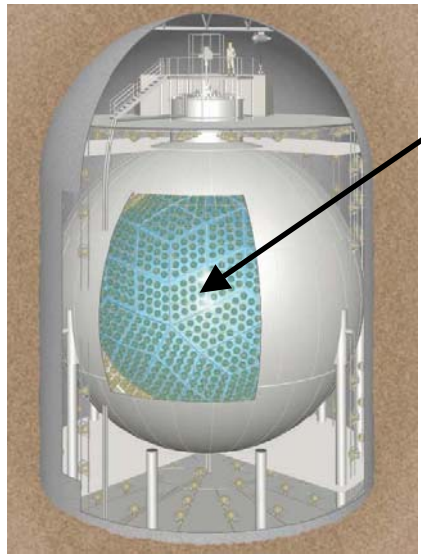
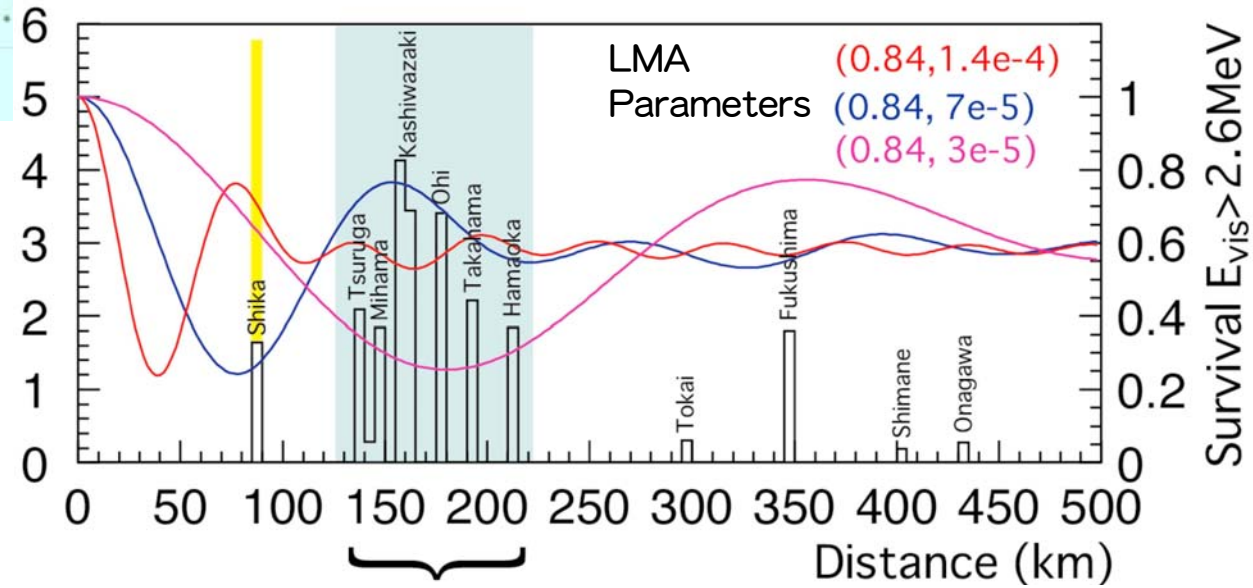
for the KamLAND Collaboration

WIN05 @ Delphi, Greece, 6-11 June 2005

The KamLAND Experiment

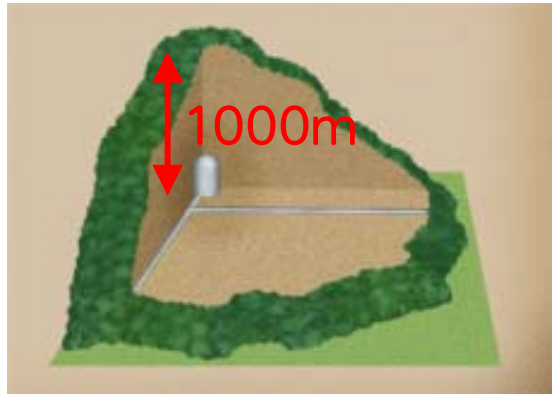


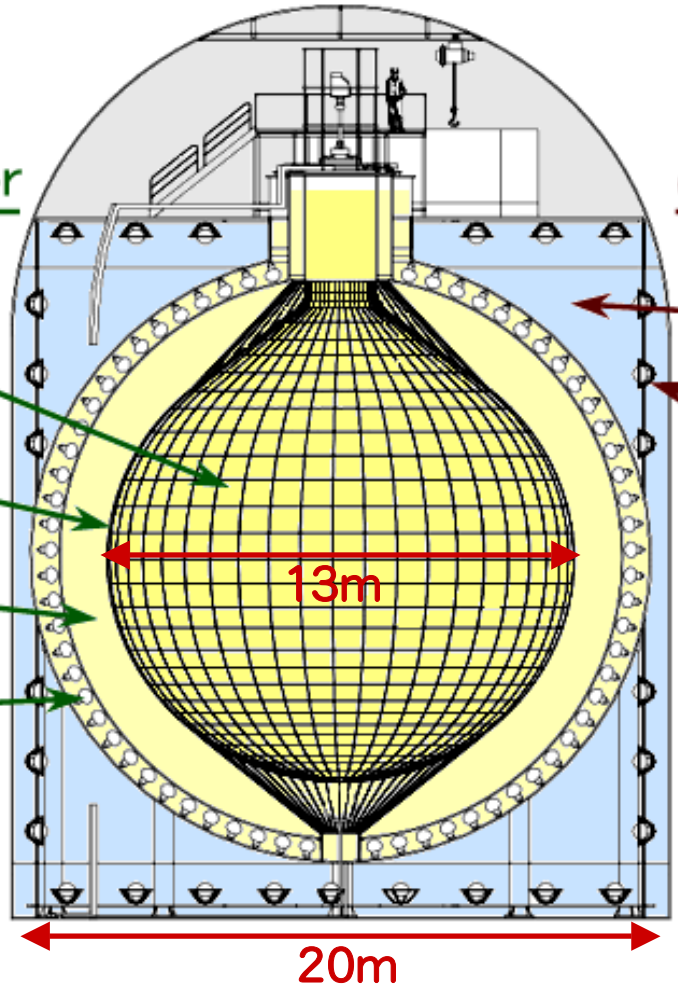
1000ton LS
1879 PMT's



80% of total contribution comes from 130~220km distance

The KamLAND Detector





Inner Detector

Liquid Scintilaltor
1000ton

Plastic Balloon
13m diameter

Mineral Oil
1.75m thickness

PMT
1325 17-inch
554 20-inch

Outer Detector

Water

PMT
225 20-inch

photo-coverage: 34%
~ 500 p.e. / MeV

LS: 80%: dodecane
20%: pseudocumene
1.5g/l: PPO

~ 8000 photons/MeV
λ ~ 10m

MO: 50%: dodecane
50%: isoparafin

$\rho_{LS}/\rho_{MO} = 1.0004$

Detection Method

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

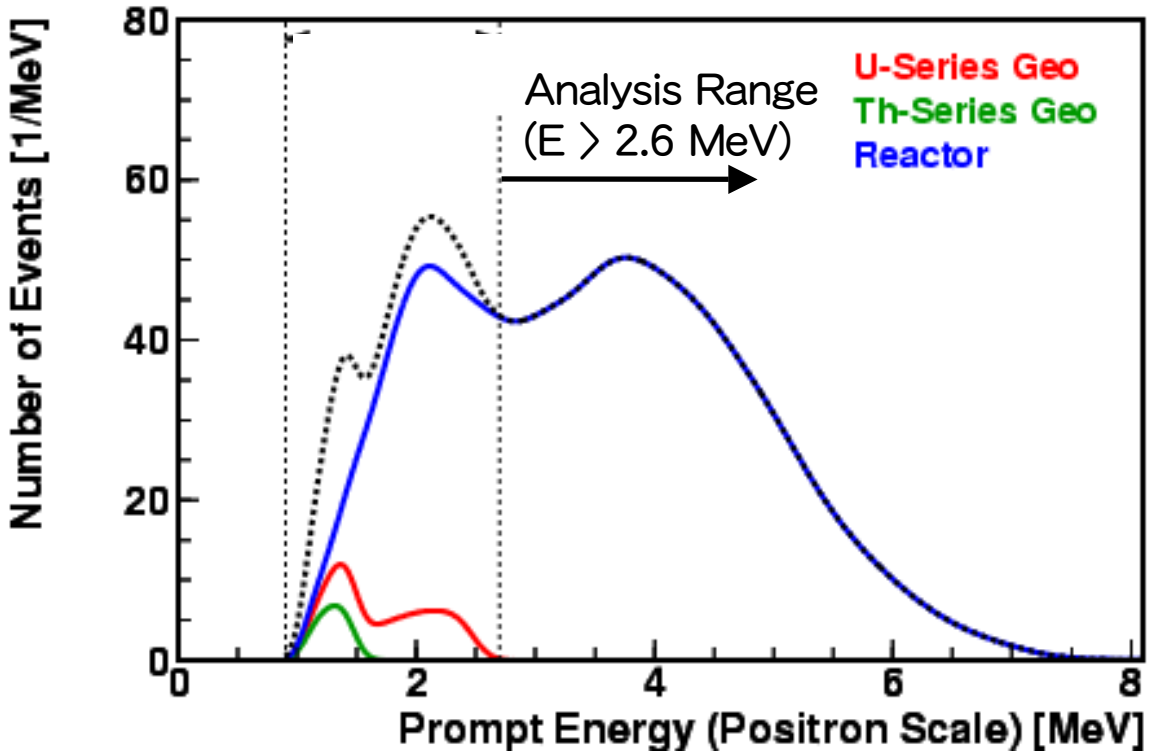
$\tau \sim 210\ \mu\text{sec}$

$$n + p \rightarrow d + \gamma(2.2\text{MeV})$$

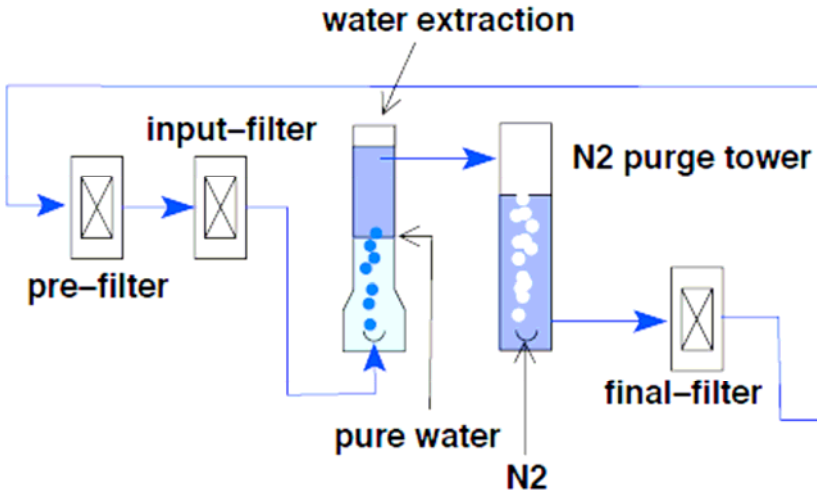
$$E_{\text{threshold}} = 1.8\ \text{MeV}$$

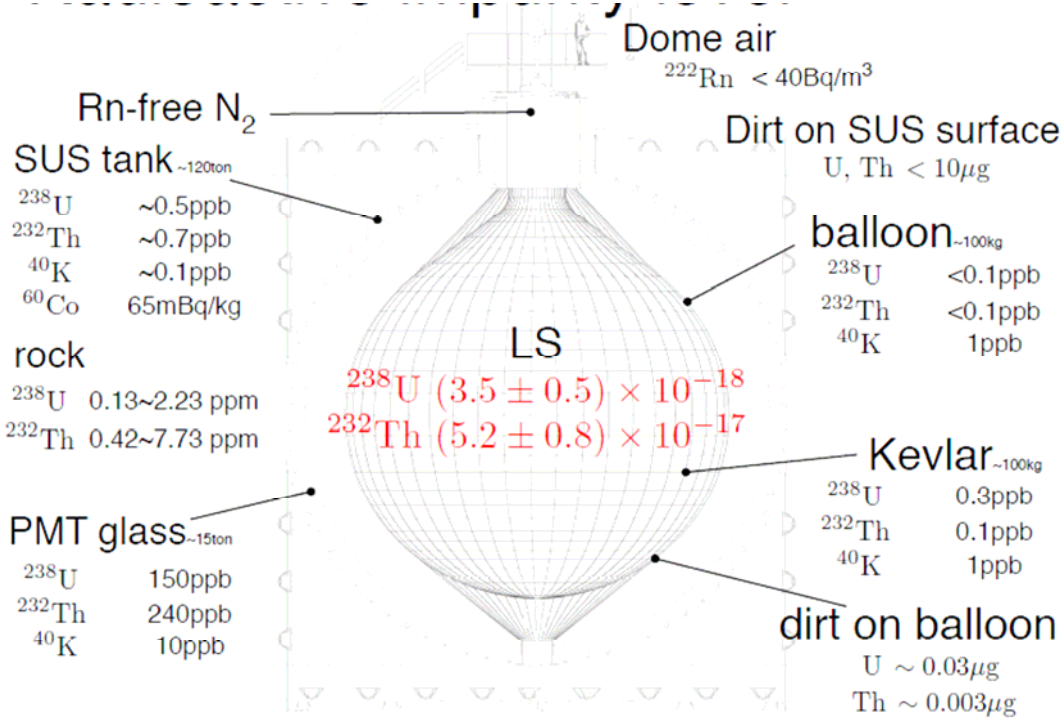
$$E_{\text{prompt}} = E_{\nu_e} - 0.78\ \text{MeV}$$

$$E_{\text{delayed}} = 2.2\ \text{MeV}$$



LS Purification and Radioactive Impurity





before

U: ~10^{-10} g/g, Th: <10^{-12} g/g, K: 7×10^{-11} g/g

⇩

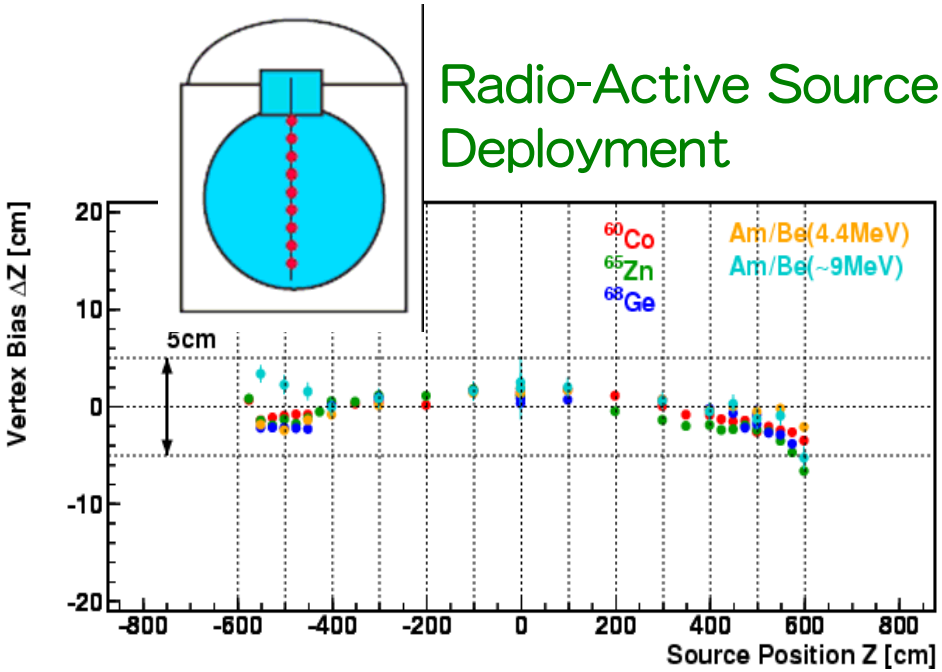
after

U: 3.5×10^{-18} g/g, Th: 5.2×10^{-17} g/g, K: 2.7×10^{-16} g/g

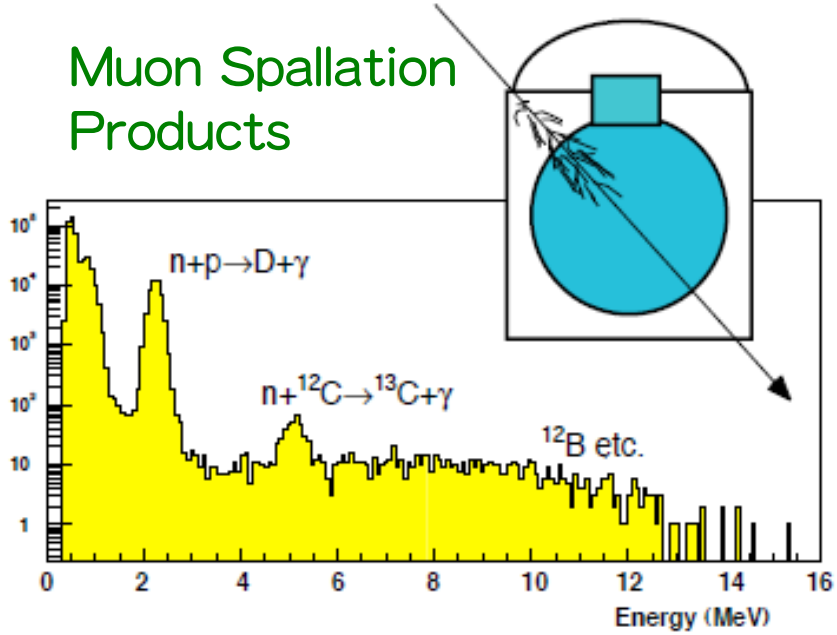
measurable only by KamLAND itself !

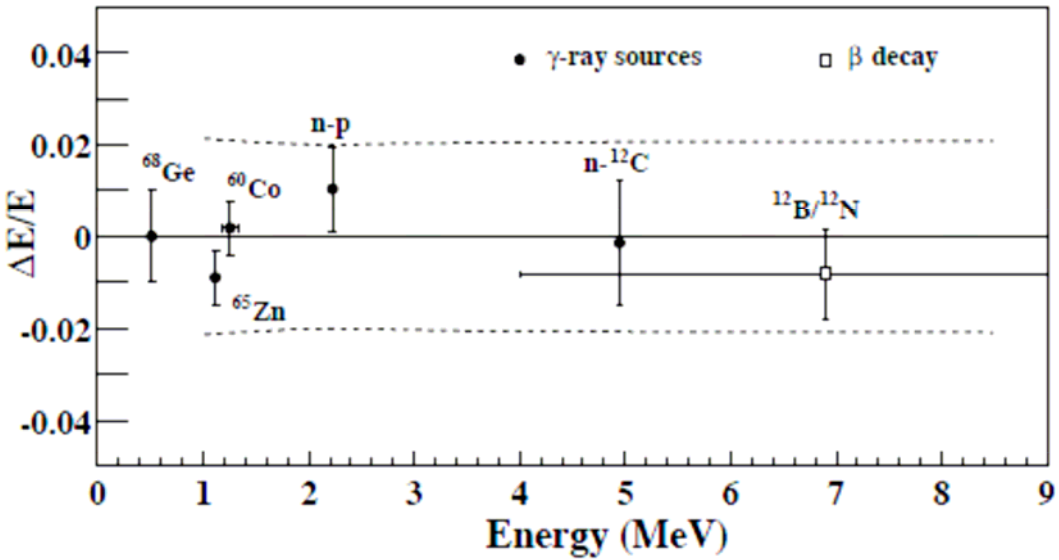
Detector Calibration

Radio-Active Source Deployment



Muon Spallation Products





Vertex Resolution

$$20.6\,\mathrm{cm}/\sqrt{\mathrm{E\,(MeV)}}$$

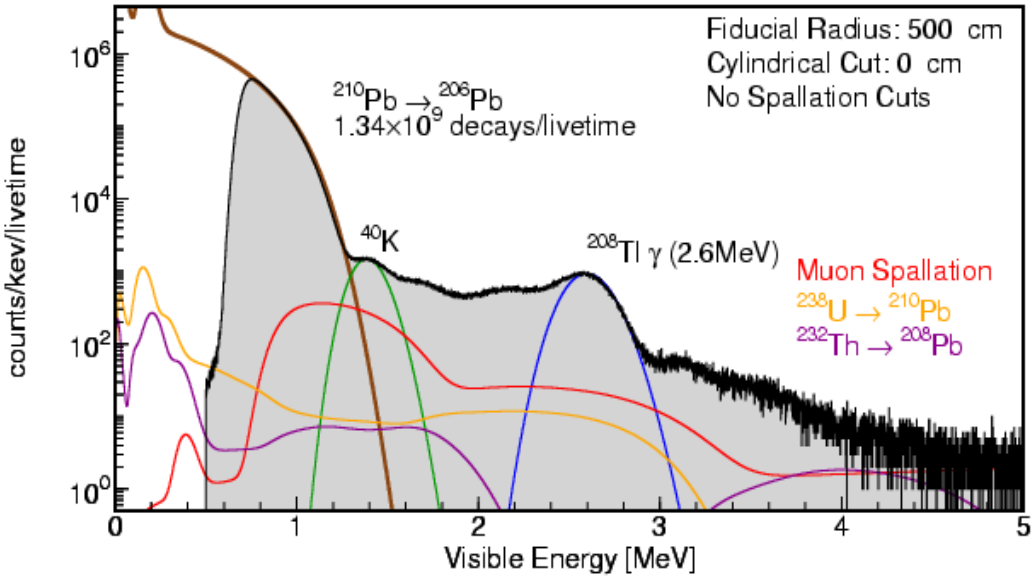
Energy Resolution

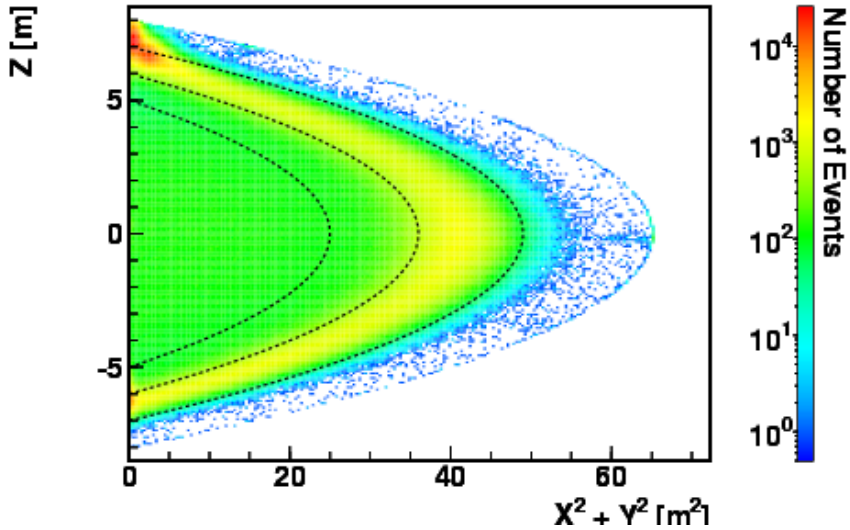
$$6.2\,\%/\sqrt{\mathrm{E(MeV)}}$$

Fiducial Volume Error: 4.7%

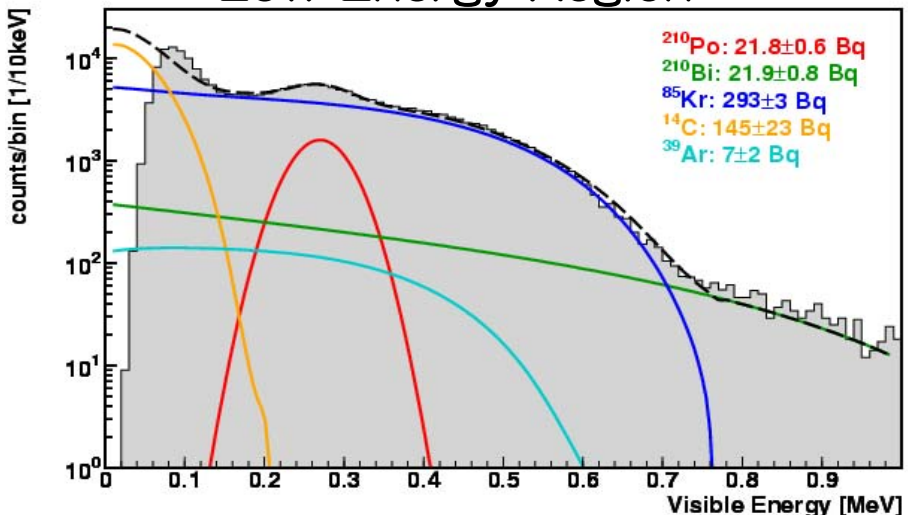
Detector Activity (Singles Spectrum)

Normal Trigger Range





Low Energy Region



Major Background Sources:

LS impurity (^{210}Pb, ^{85}Kr, ^{39}Ar)
extrinsic gamma (^{40}K, ^{208}Tl)
muon spallation (^{10}C, ^{11}C, ^{12}B, ...)

Event Selection

Delayed Coincidence:

$0.5 < \Delta T < 1000\,\mu\text{sec}$

$\Delta R < 200$ cm

$1.8 < E_{delayed} < 2.6$ MeV

Fiducial Volume:

$R_{prompt} < 550$ cm

$R_{delayed} < 550$ cm

Spallation Cuts:

$\Delta T_{\mu} > 2$ msec

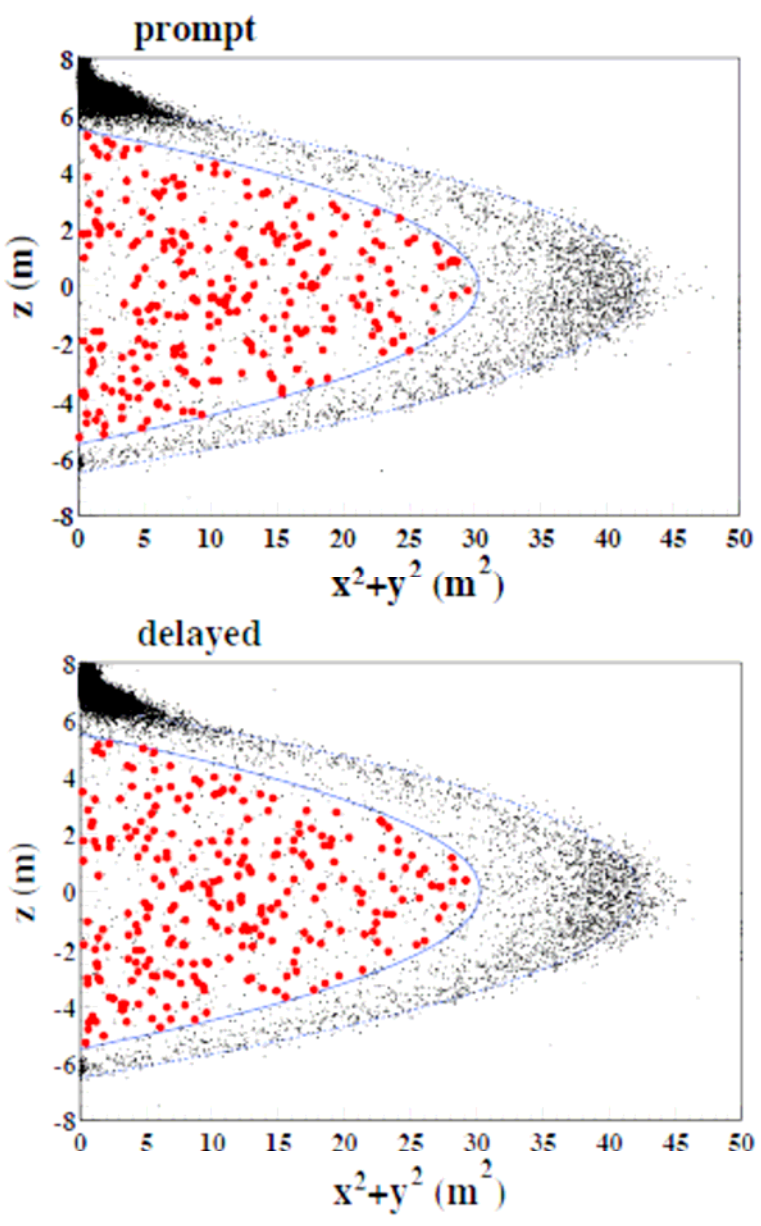
$\Delta T_{\mu} > 2$ sec (showering muons)

or

$\Delta L > 300$ cm (non-showering)

Energy Window:

$2.6 < E_{prompt} < 8.5$ MeV



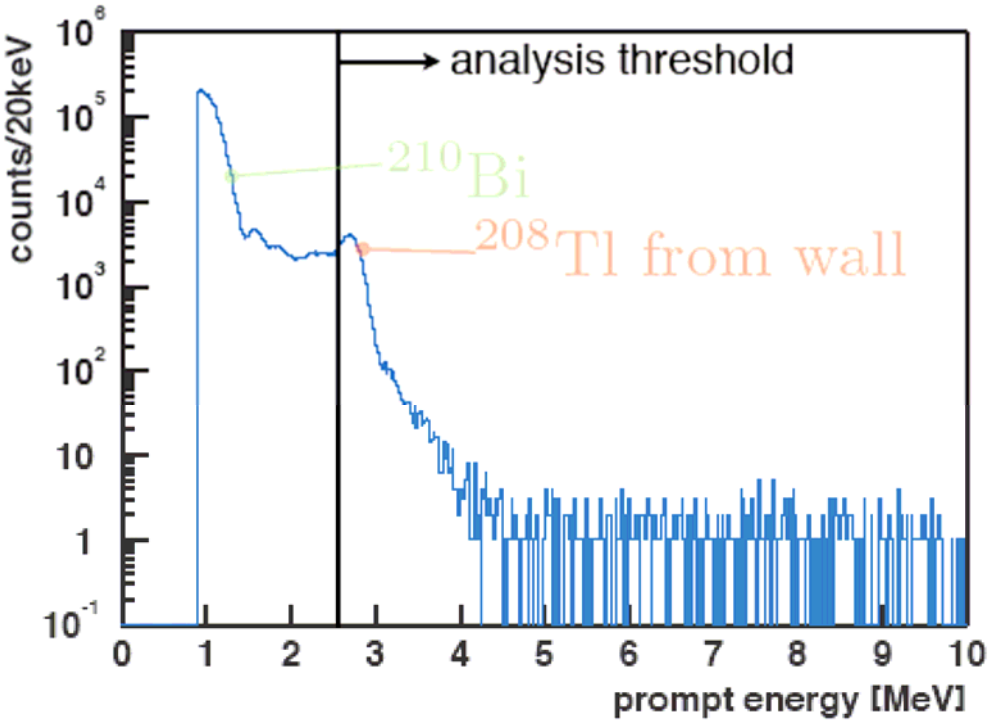
Backgrounds Summary

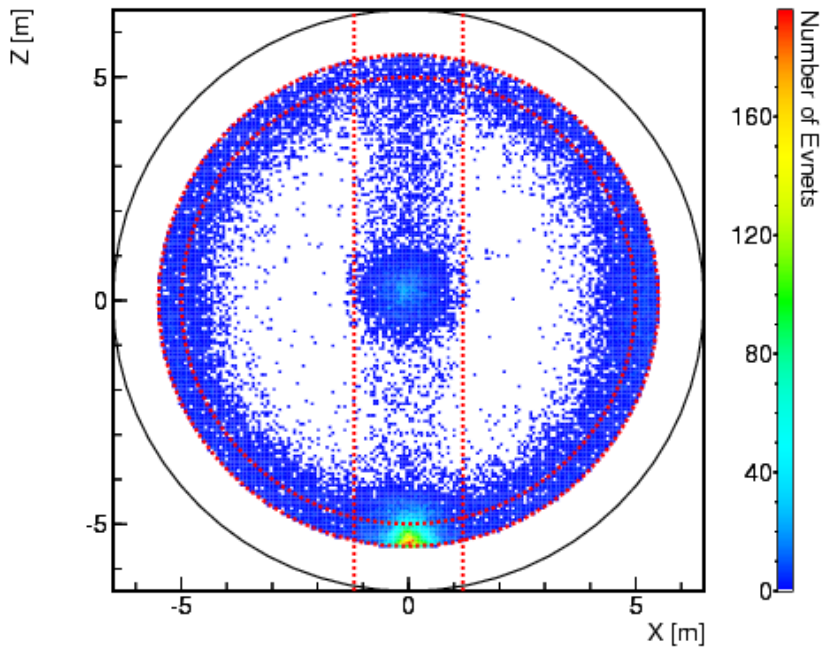
515.1 days, >2.6MeV, 5.5m fiducial

Accidental Coincidence	2.69 ± 0.02
Spallation events	4.8 ± 0.9
Fast neutron	< 0.9
$^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$	10.3 ± 7.1
Total	17.8 ± 7.3

Accidental Coincidence Background

off-time coincidence spectrum





⇒ 2.69 ± 0.02 events

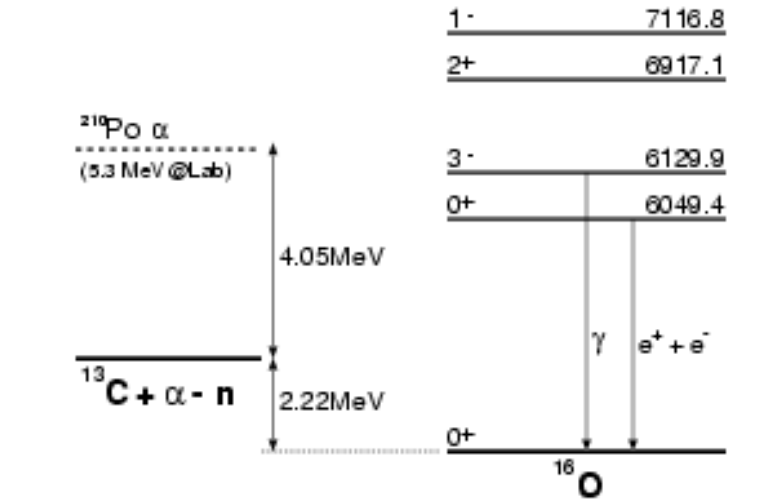
(α, n) Background

^{232}Rn ⋯⋯▶ ^{210}Pb

3.8 d　　22.3 y

→ ^{210}Bi → ^{210}Po → ^{206}Pb

5.013 d　138.4 d　stable



α (5.3 MeV)

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

$^{13}C\,(\alpha,n)\,^{16}O^*$ → $^{16}O^*(6.13) \rightarrow {}^{16}O + \gamma$

$^{16}O^*(6.05) \rightarrow {}^{16}O + e^+ + e^-$

$^{14}N\,(\alpha,n)\,^{17}F$

$^{15}N\,(\alpha,n)\,^{18}F$

$^{17}O\,(\alpha,n)\,^{20}Ne$

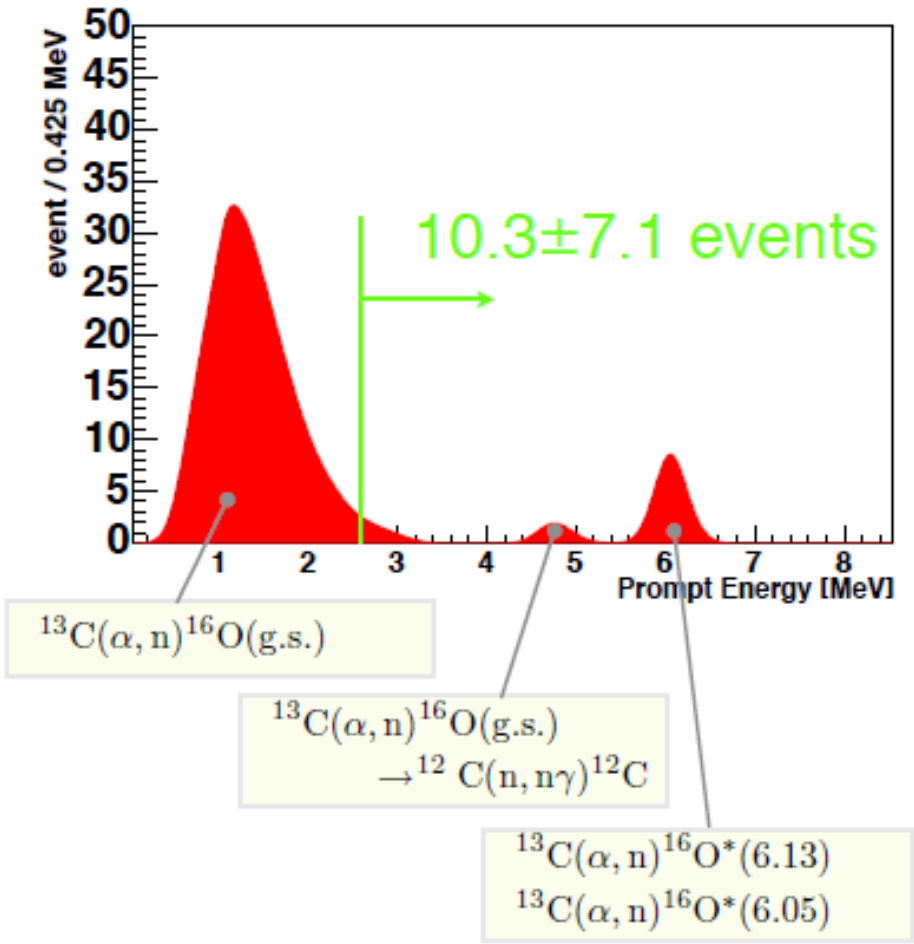
$^{18}O\,(\alpha,n)\,^{21}Ne$

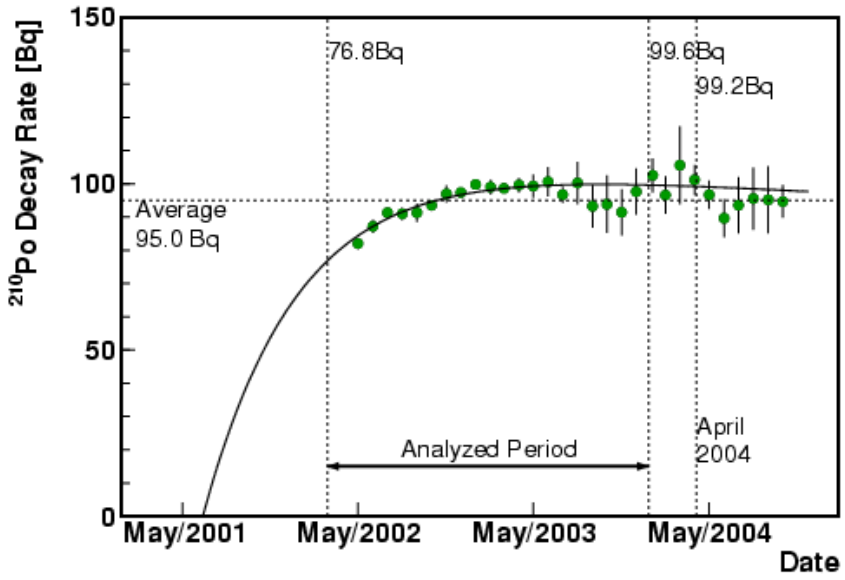
n → $n + p \rightarrow n + p$

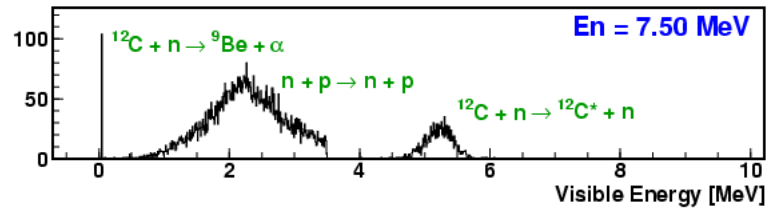
$n + {}^{12}C \rightarrow n + {}^{12}C^*$

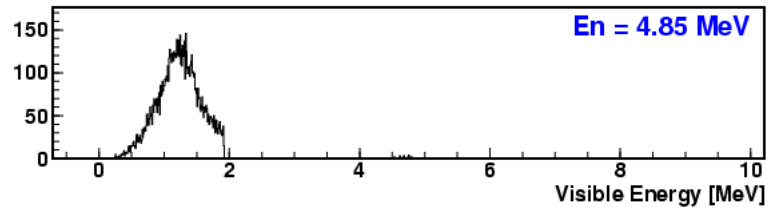
↳ $^{12}C + \gamma$ (4.4MeV)

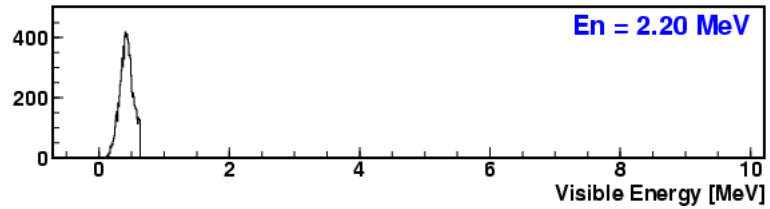
(α, n) Background









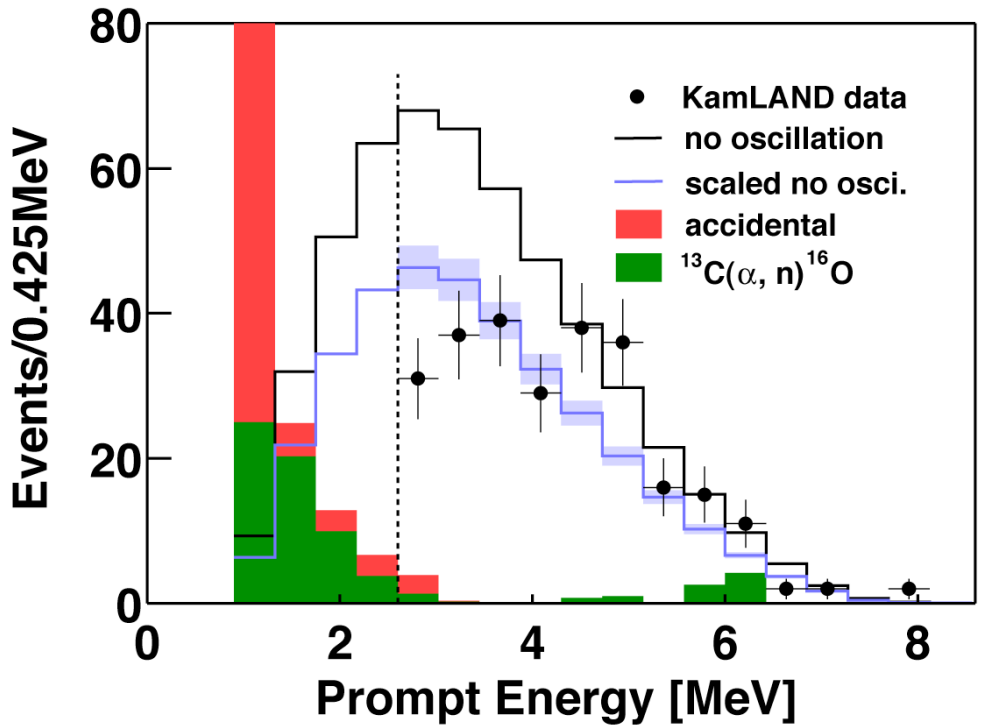


Analysis

Data Summary

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure

expected signal	365.2 ± 23.7
BG	17.8 ± 7.3
observed	258



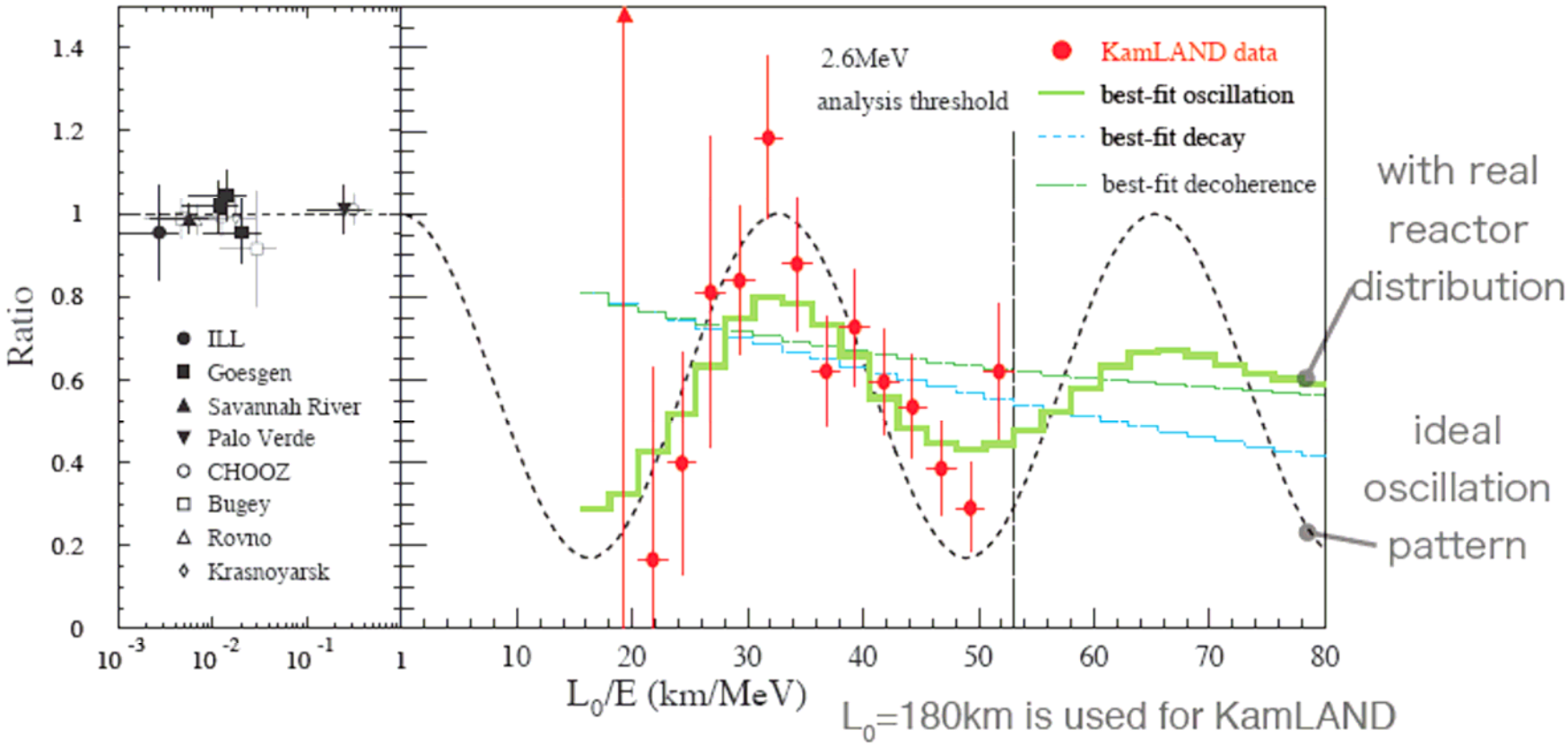
- Observed/Expected: R = 0.658 $\pm$0.044(stat) $\pm$ 0.042(syst)
  $\Rightarrow$ neutrino disappearance at 99.998% C.L.

- Hypothesis test of scaled no-oscillation: χ^2/ndf = 37.3/19
  $\Rightarrow$ spectral distortion at $>$ 99.6% C.L.

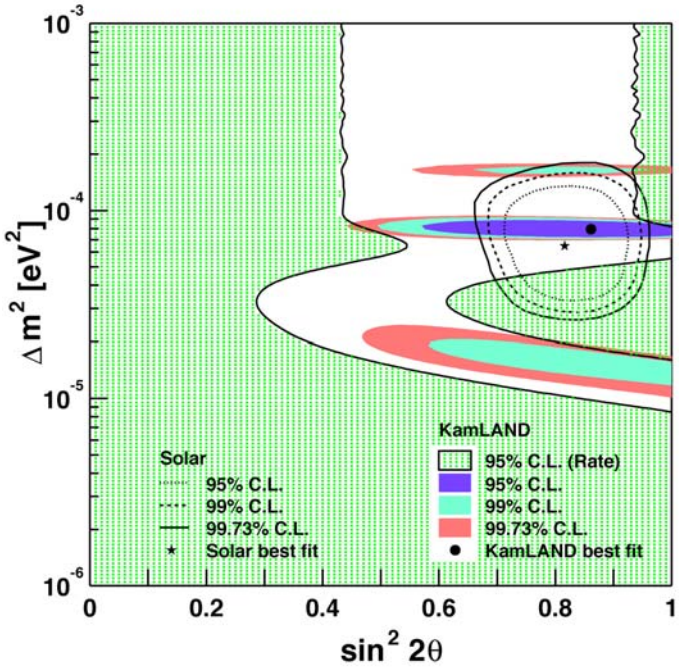
- Rate + Shape: 99.999995% C.L.

L/E Analysis

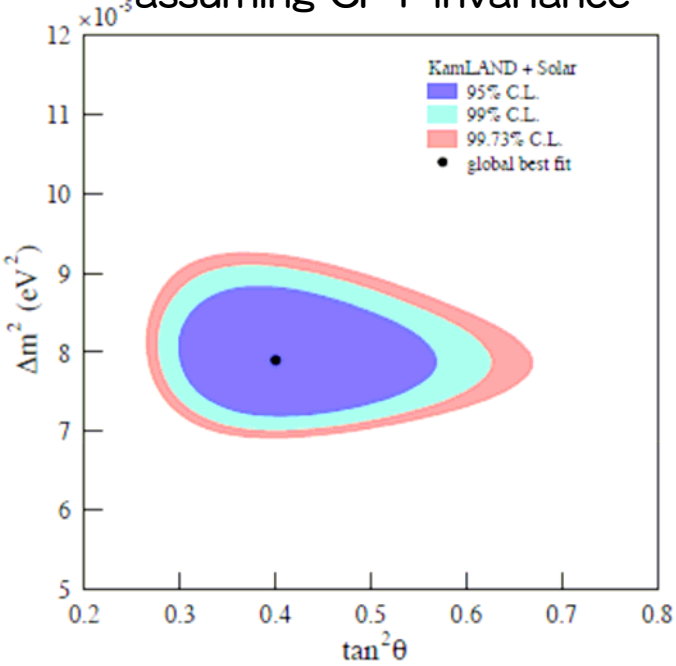
		spectrum shape test χ^2/ndf	GOF
oscillation	$P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$	24.2/17	11.1%
decay	$P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$	35.8/17	0.7%
decoherence	$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$	32.2/17	1.8%

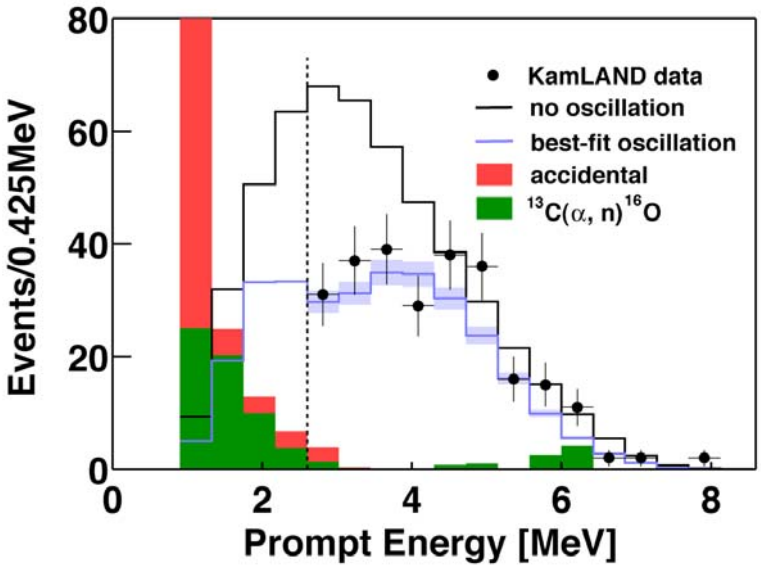


Oscillation Analysis



KamLAND + Solar
assuming CPT invariance





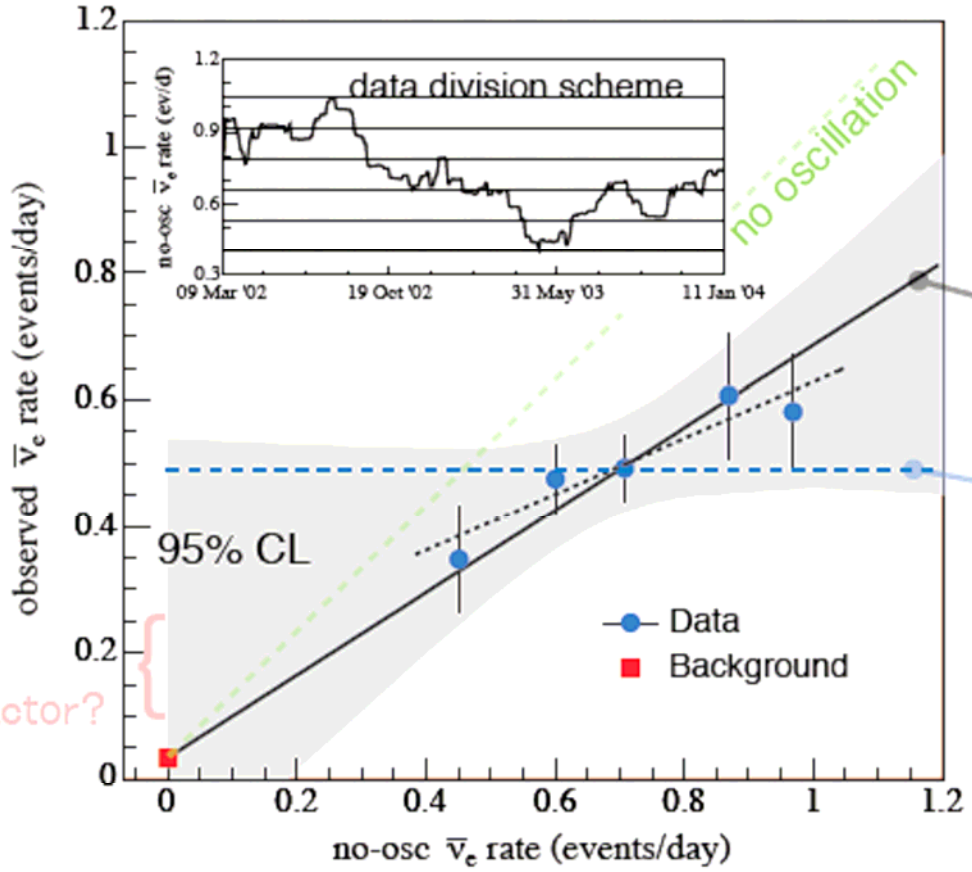
KamLAND best-fit (rate + shape)

$$\Delta m^2 = 7.9\times10^{-5}\ \mathrm{eV}^2,\quad \tan^2\theta = 0.46$$

KamLAND + Solar

$$\Delta m^2 = 7.9^{+0.6}_{-0.5}\times10^{-5}\ \mathrm{eV}^2,\quad \tan^2\theta = 0.40^{+0.10}_{-0.07}$$

Correlation with Reactor Power



constrained to expected BG

$\chi^2 = 2.4/4$

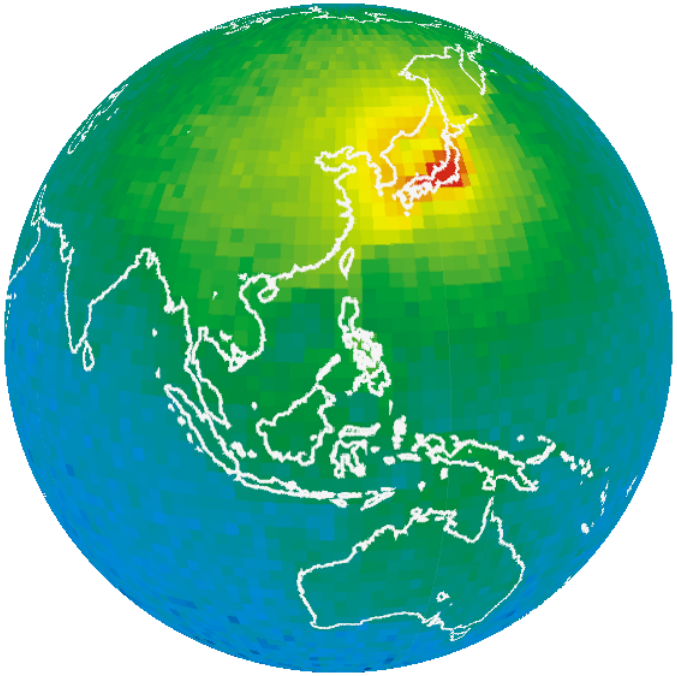
$\chi^2_{\rm flat} = 5.4$

at present statistics is not enough to state something

Future of the KamLAND Experiment

- ✓ Geo-Neutrino Detection
  (~ few weeks)
- ✓ Improvements in Reactor Analysis
  (~ few months)
- ✓ Solar Neutrino Detection
  (~ few years)

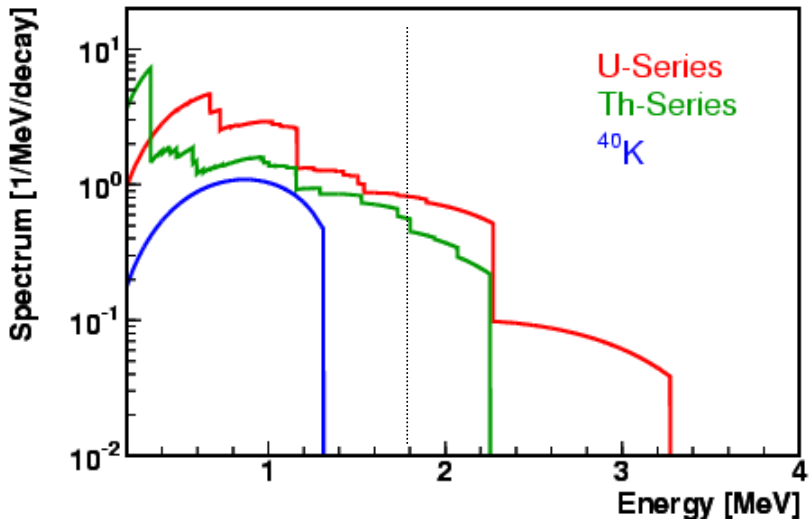
Geo-Neutrino Detection at KamLAND



$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6\,\mathrm{e}^{-} + 6\,\bar{\nu}_{\mathrm{e}} + 51.7\ [\mathrm{MeV}]$$

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

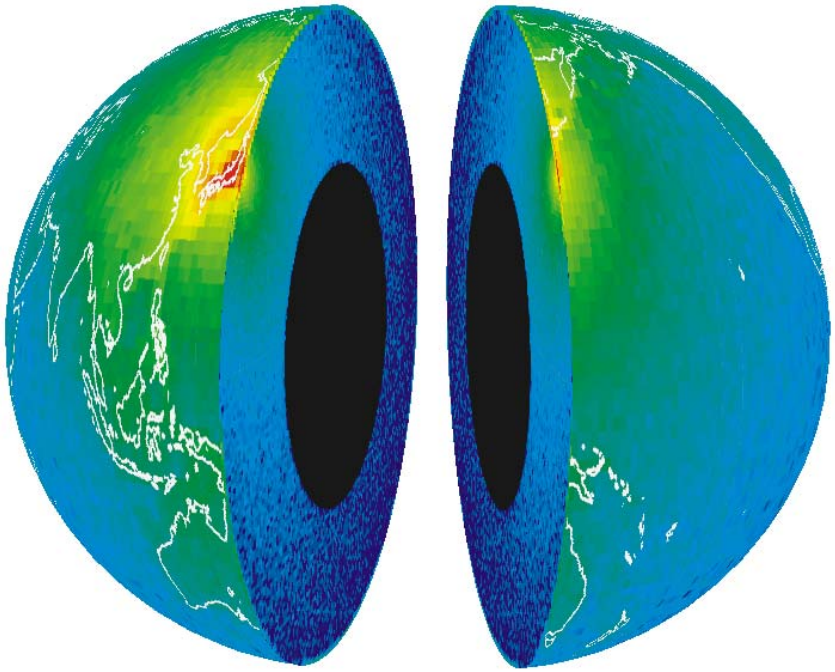
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}} + 1.31\ [\mathrm{MeV}]$$



Radiogenic Heat ~ 20 TW
Observed Surface Heat Flow: ~ 40TW

⇒ provides important constraints in Earth's energetics

Geo-Neutrino Detection at KamLAND



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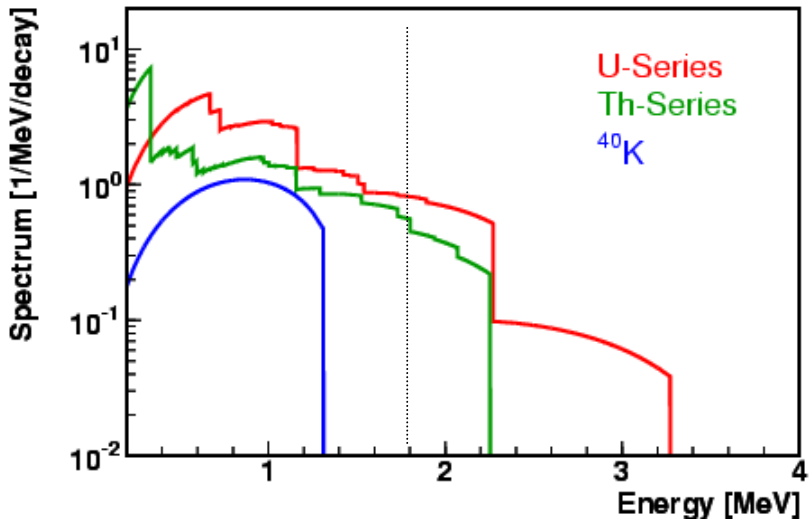


Radiogenic Heat ~ 20 TW
Observed Surface Heat Flow: ~ 40TW

⇒ provides important constraints in Earth's energetics
⇒ provides unique knowledge in composition of Earth's interior

Geo-Neutrino Detection At KamLAND

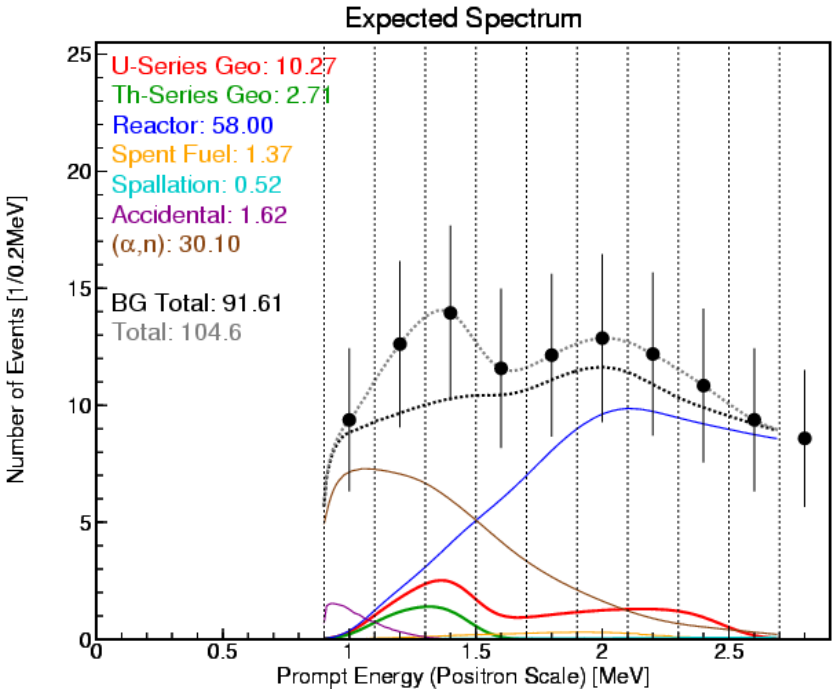
Expected Flux:

- U-Series:
  - 2.3×10^6 [1/cm^2/sec]
  - 30.1 [events/10^{32}-protons/year]
- Th-Series:
  - 2.0×10^6 [1/cm^2/sec]
  - 6.7 [events/10^{32}-protons/year]

Expected Events:

(5 m fiducial, 515 day exposure)

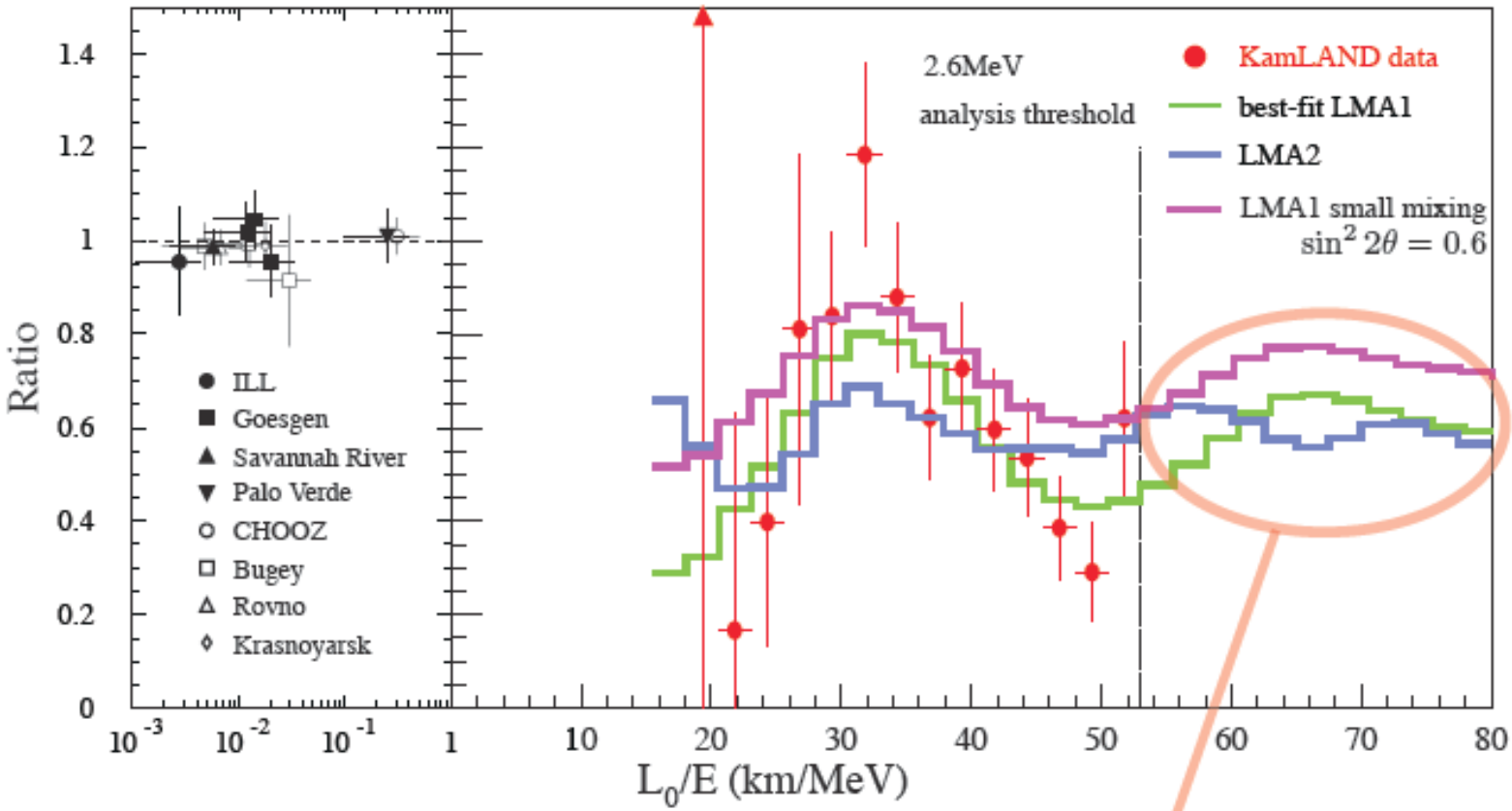
- U-Series: 10.3
- Th-Series: 2.7
- Reactor BG: 58
- (α,n) BG: 30



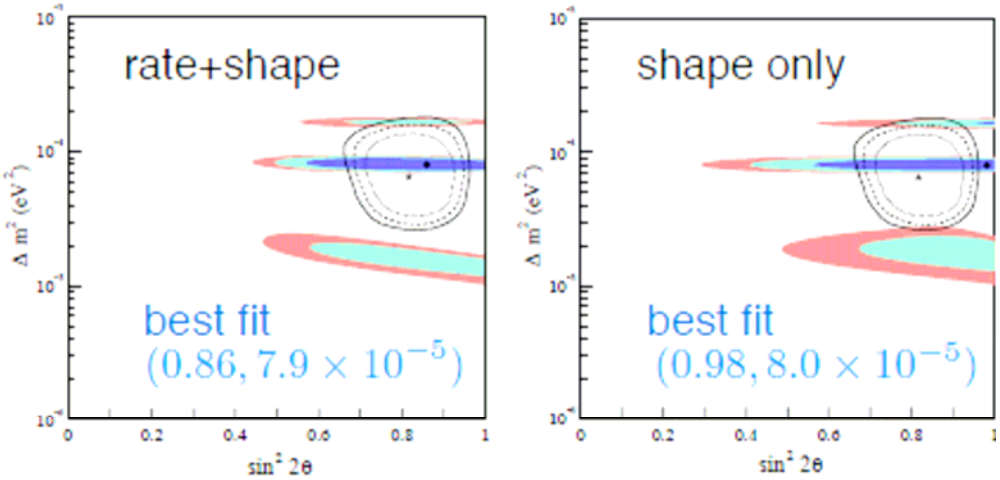
data will be published in few weeks !

Geo-Neutrino Detection and Extended Analysis Window

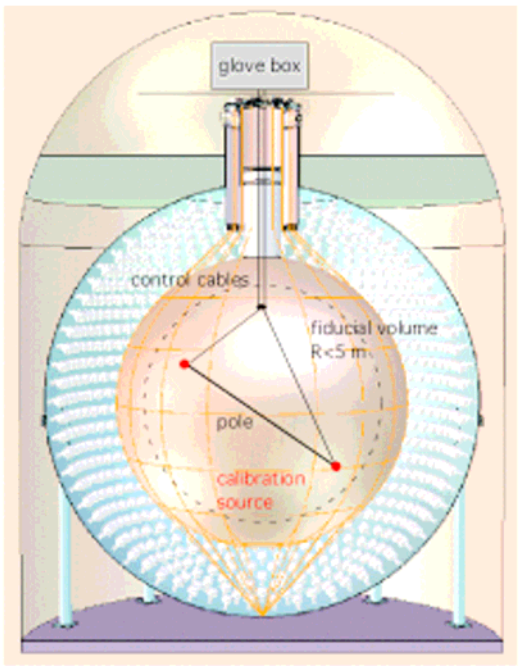
Analysis of low-energy region also benefits reactor analysis

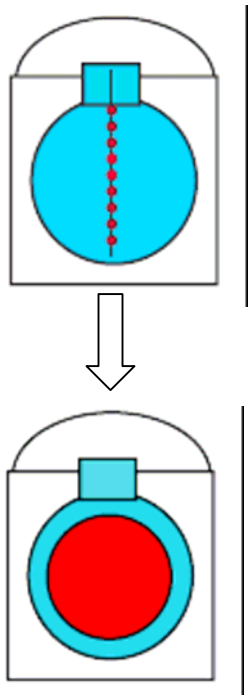


Further Improvements of Systematic Errors

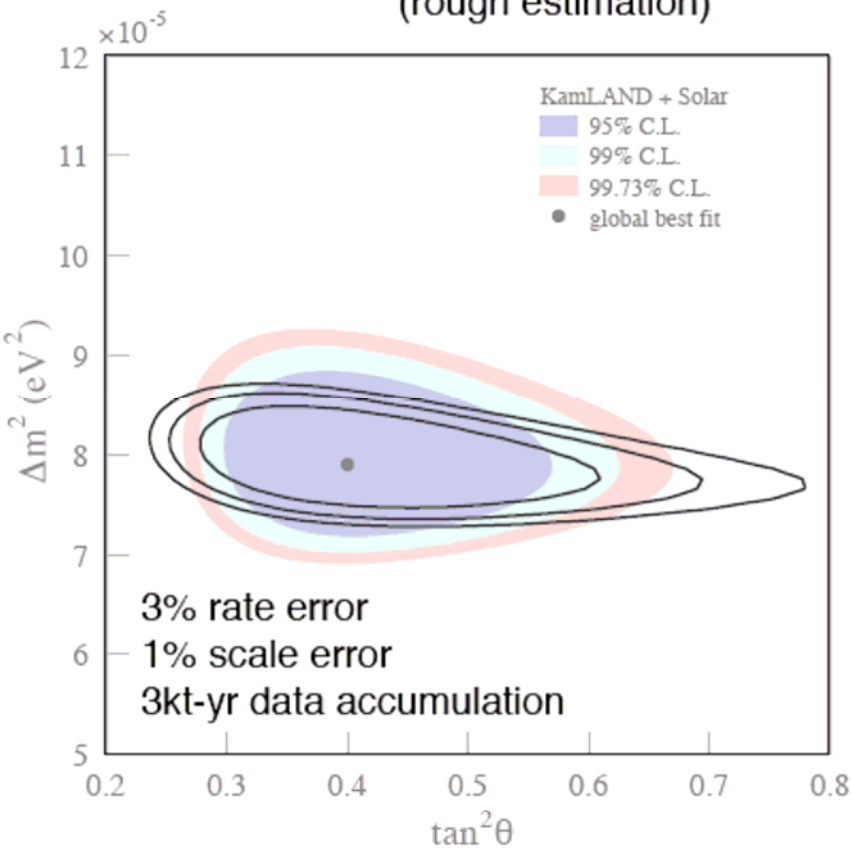


results are mostly obtained from shape information, due to large systematic errors on rate

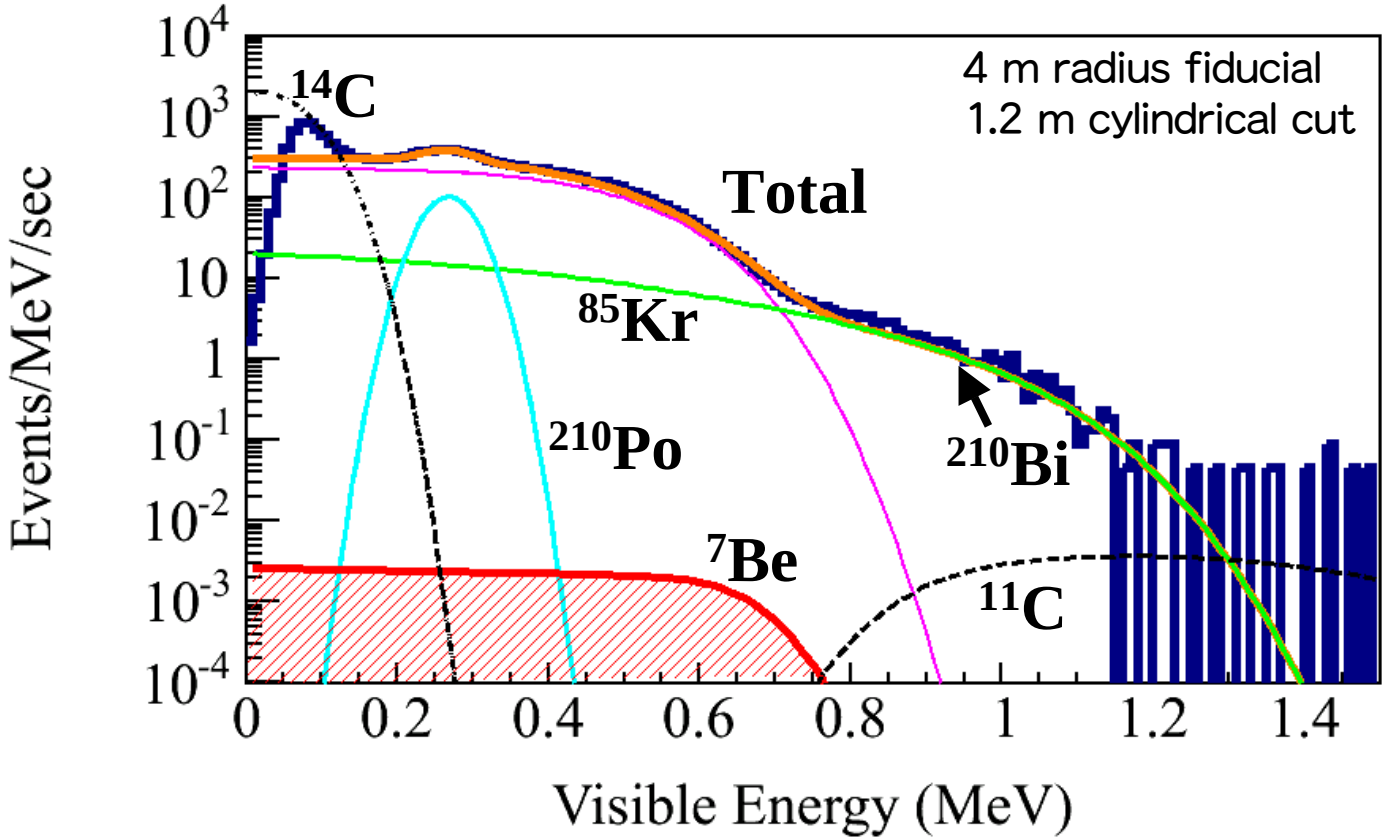




(rough estimation)



Towards Solar Neutrino Detection



Required Improvements:

^{210}Pb: 10^{-4}~10^{-5}

^{85}Kr, ^{39}Ar: ~10^{-6}

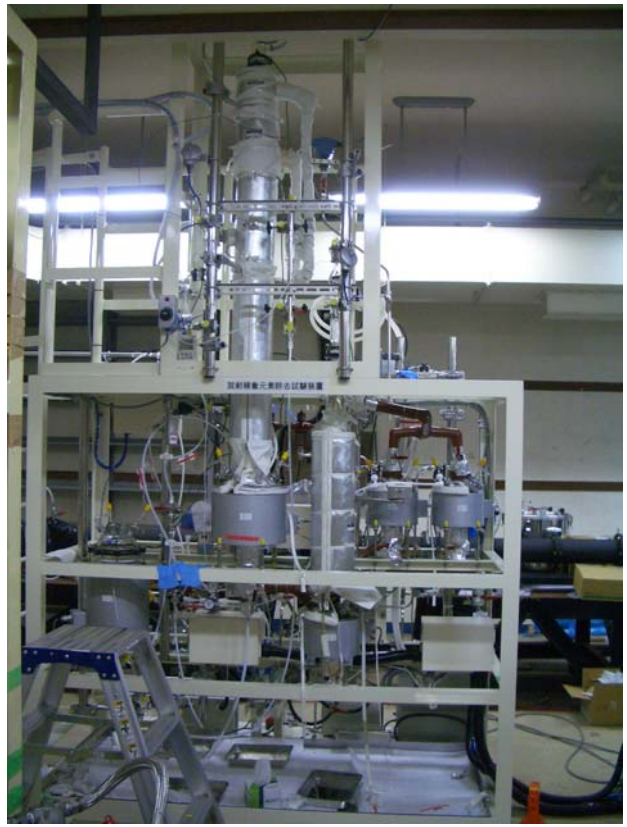
LS Purification

- N_2 gas purge (N_2/LS = 25)
  - Rn: ~1/10
  - Kr: ~1/100

- Fractional Distillation (164 ℃, 300 hPa)
  - Pb: 3×10^{-5}
  - Rn: 1×10^{-5}
  - Kr: $< 2 \times 10^{-6}$

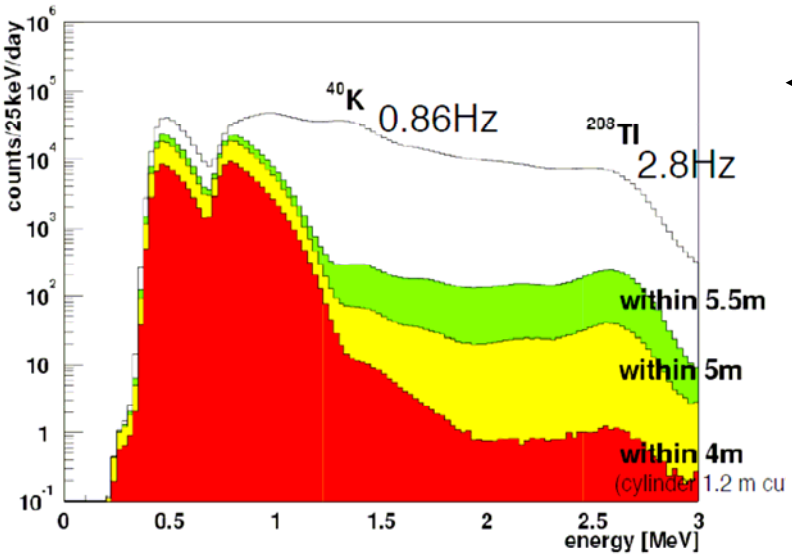
residual Pb might be organic lead
(disintegrate at ~ 200℃)

Distillation System
Test Bench



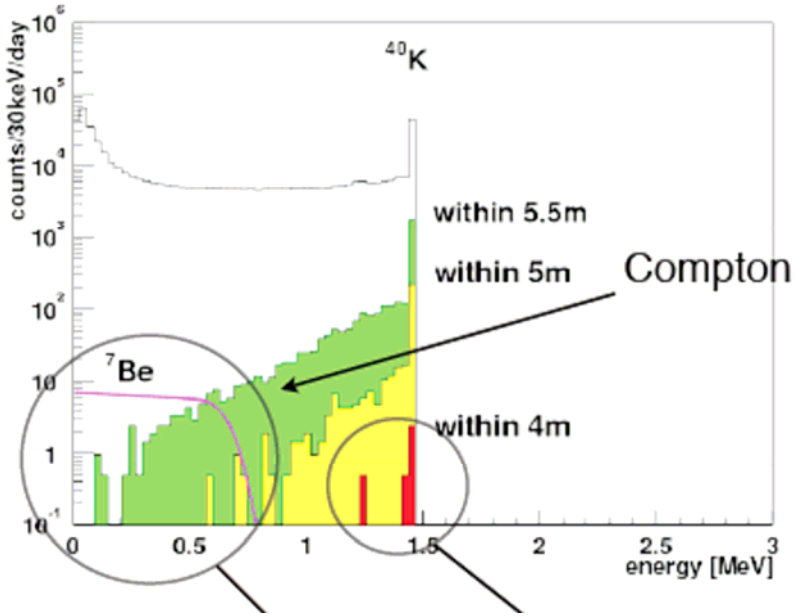
Required performance is almost achieved

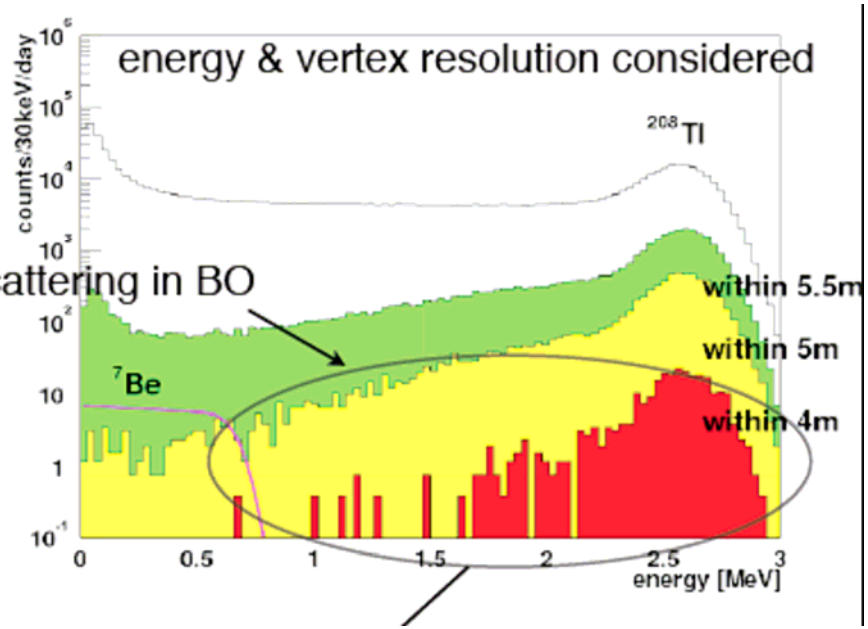
Extrinsic Gammas Screening



← Current KamLAND Rate

MC of extrinsic gammas (^{40}K, ^{208}Tl)



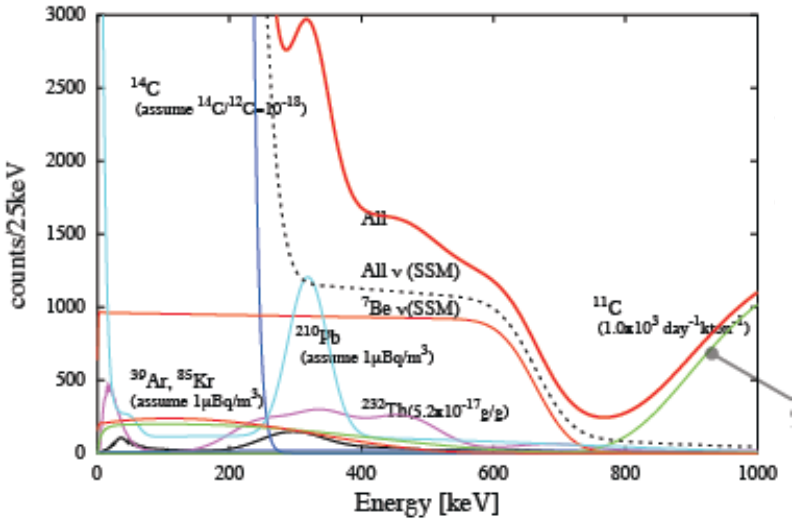


^{7}Be ν : ~1 μHz

^{40}K: < 3.4 μHz

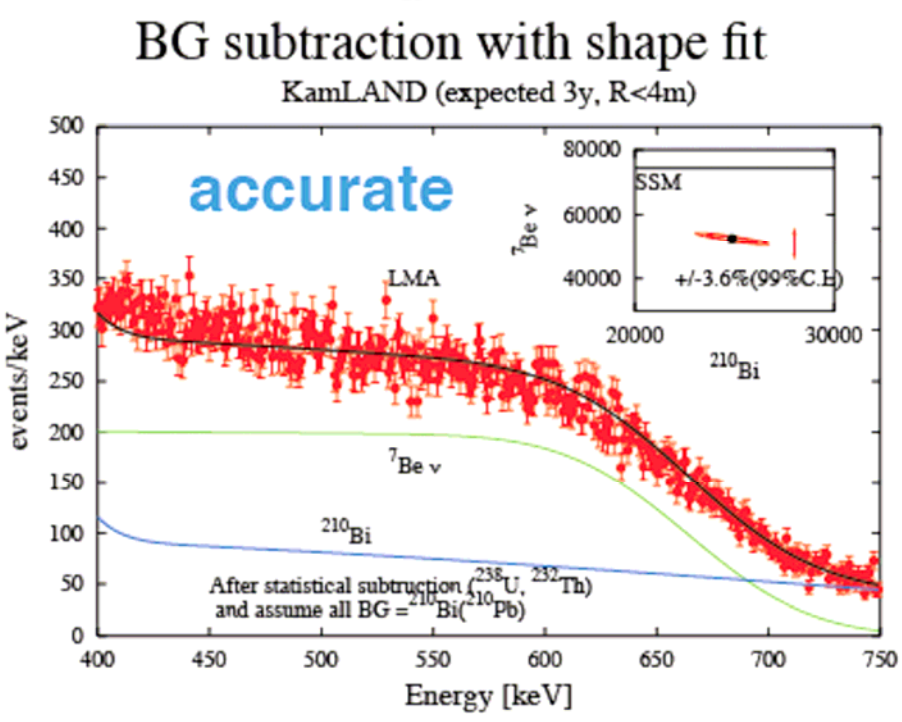
^{208}Tl: < 5.6 μHz

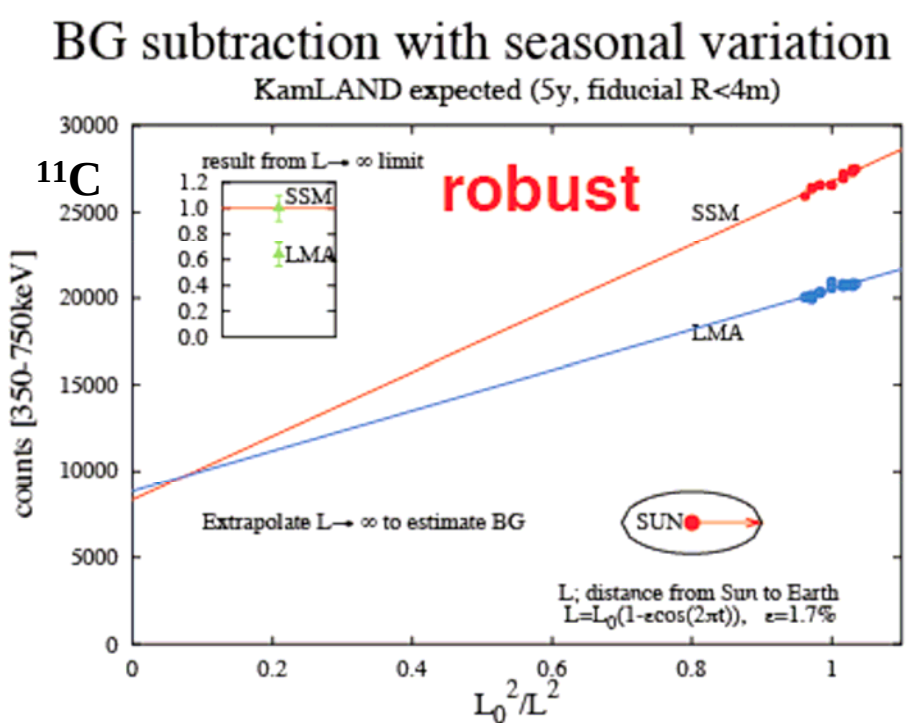
Solar Neutrino Prospects



^{7}Be neutrinos will be seen between ^{14}C and ^{11}C background

^{11}C can be reduced with neutron tagging
(pep and CNO neutrinos extractable???)





Summary

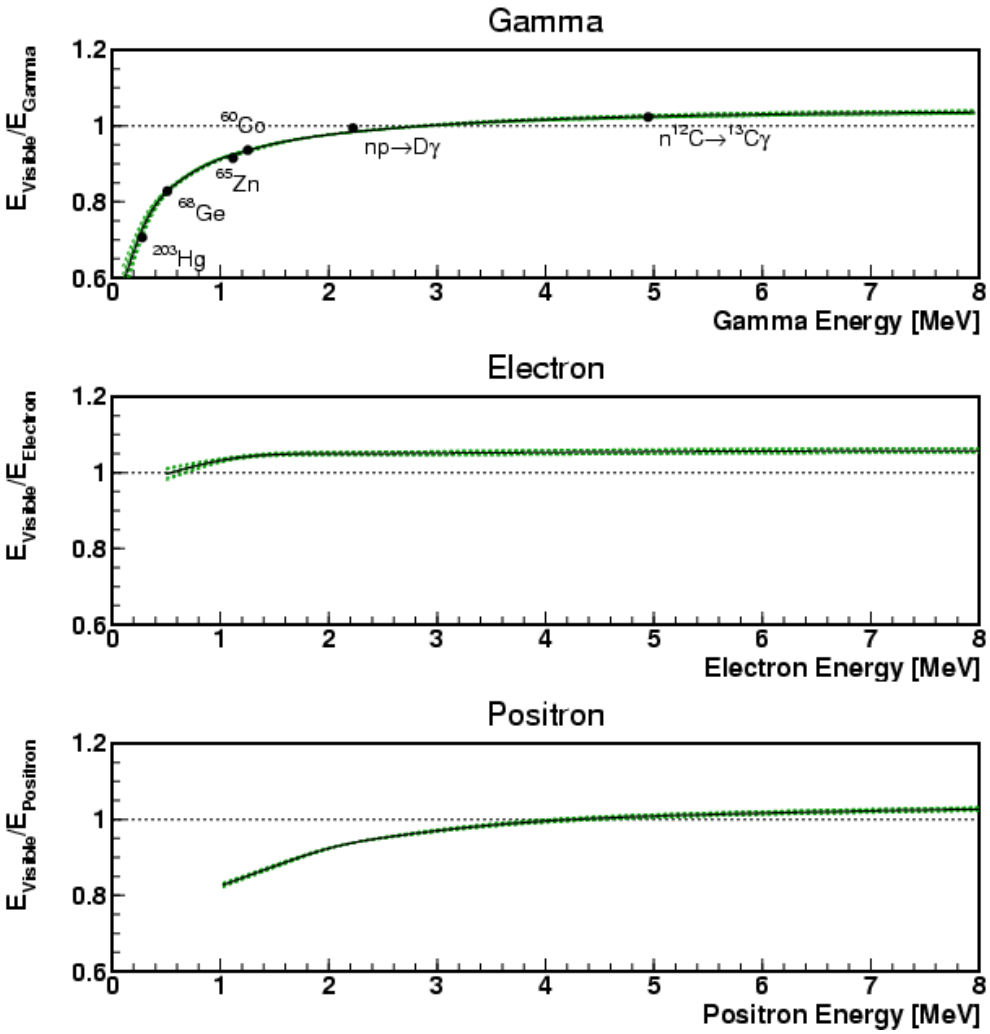
- Rate+Shape analysis excluded no-oscillation at 99.999995%.
- Spectrum distortion (L/E) shows oscillatory behavior.
- Oscillation parameters are precisely measured:

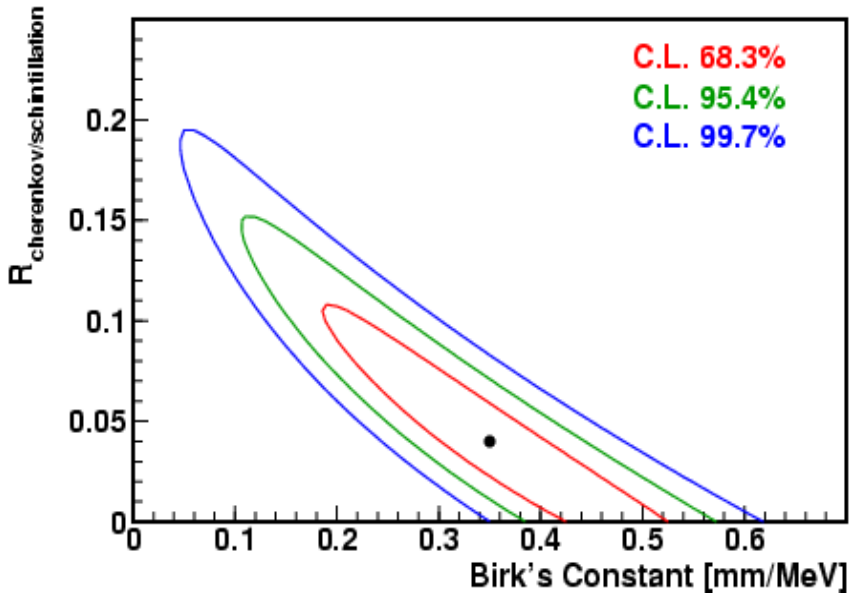
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ \mathrm{eV}^2, \quad \tan^2\theta = 0.40^{+0.10}_{-0.07}$$

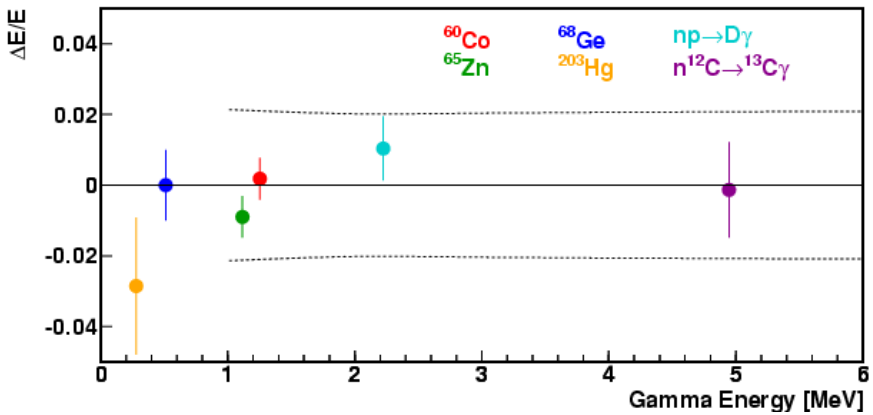
- Geo-Neutrino detection result will be published very soon.
- Full-volume calibration will improve $\sin^2 2\theta$ measurement.
- Purification goal for ^{7}Be neutrino measurement is almost achieved.

Energy Scale Determination

$$\Delta E_{\mathrm{vis}} = A\left\{\frac{1}{1+R}\cdot\frac{1}{1+k_b\frac{dE}{dx}}+\frac{R}{1+R}\cdot\frac{dN_{\mathrm{ch}}}{dE}\right\}\Delta E$$

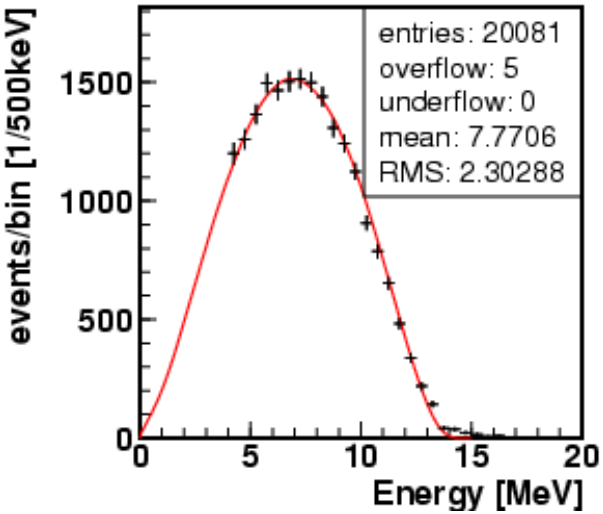


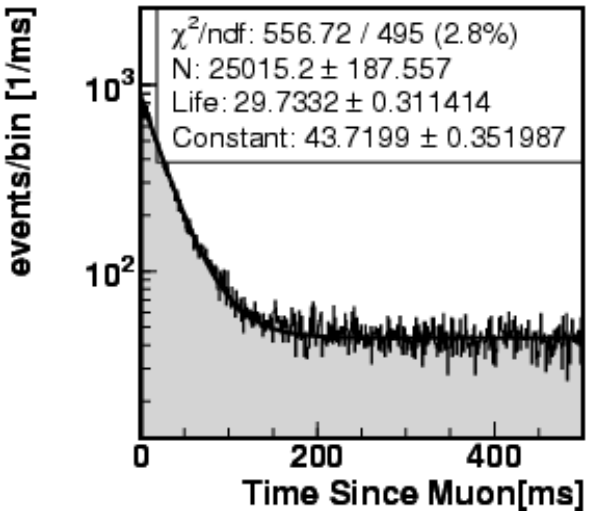


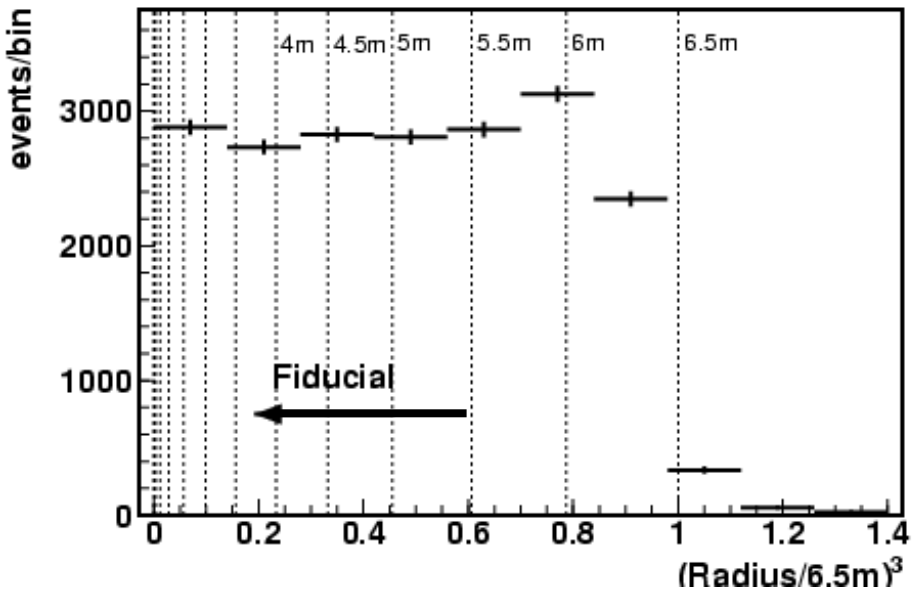


Fiducial Volume Calibration

With Muon Spallation (^{12}B)







Fiducial/Total Volume Ratios

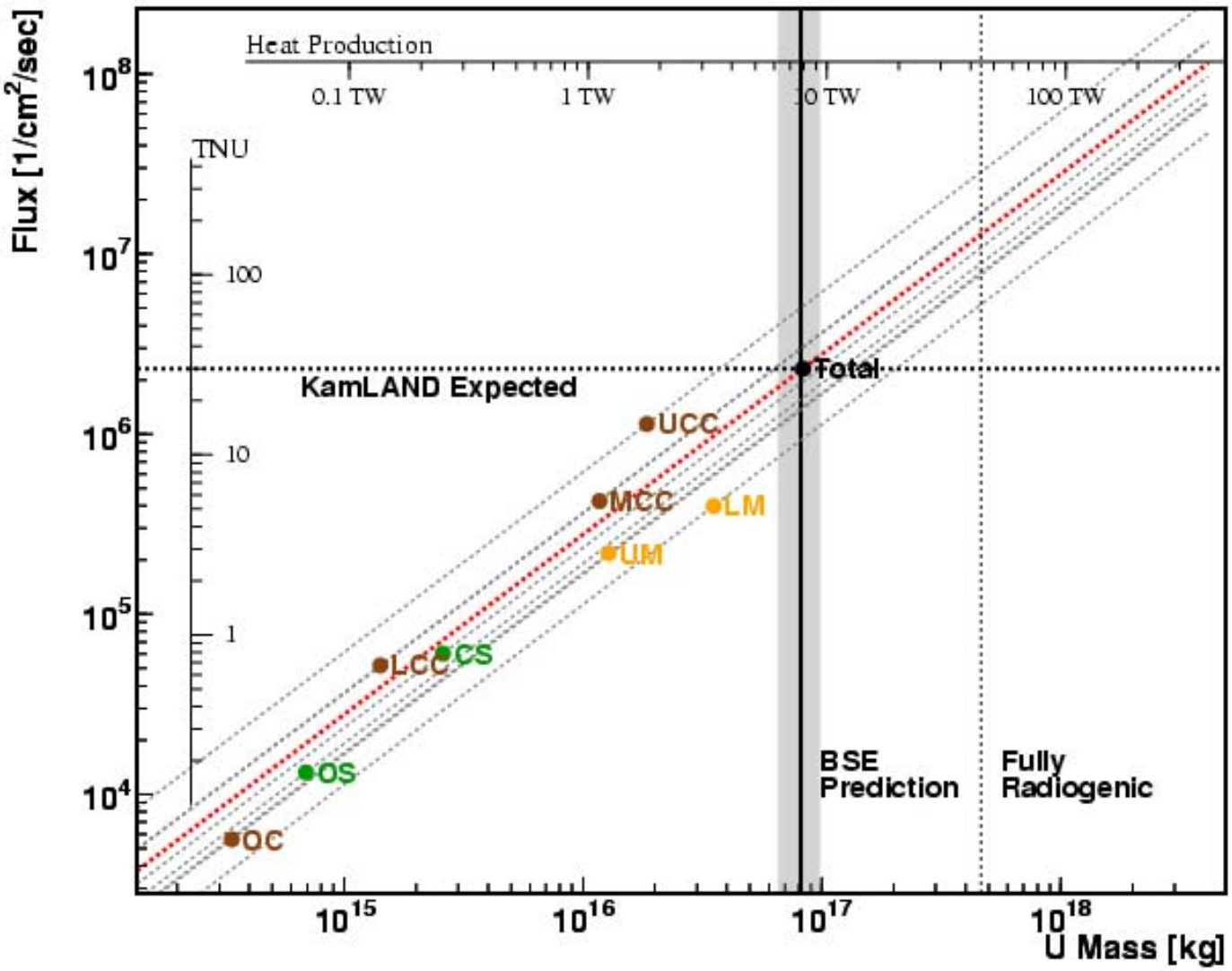
geometrical	$0.595 \pm 0.013 \quad \left(= \frac{696.9\,\mathrm{m}^3}{1171 \pm 25\,\mathrm{m}^3}\right)$
^{12}B	$0.607 \pm 0.006 \pm 0.006$
$\mathrm{p}(\mathrm{n},\gamma)\mathrm{d}$	0.587 ± 0.013
^{9}Li relative	$< 2.7\%$

conservative volume error 4.7%

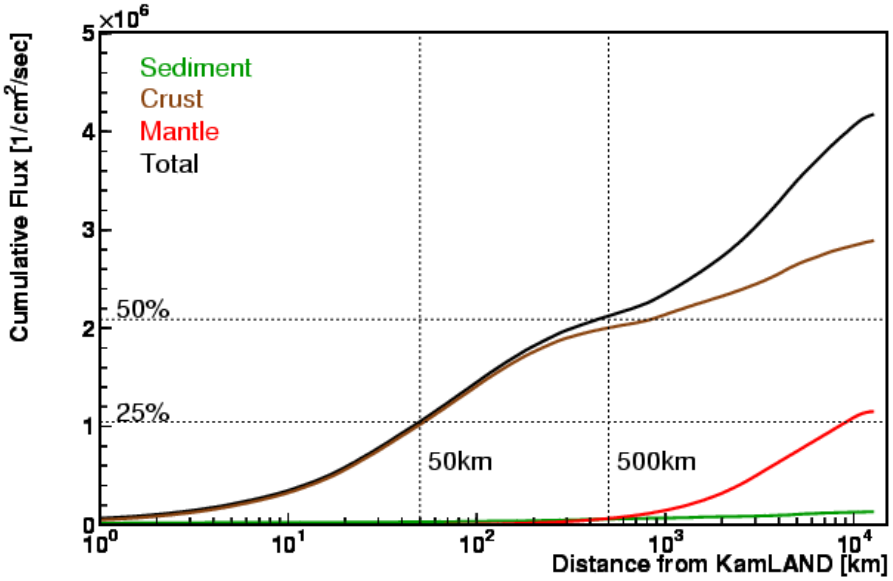
Systematic Errors Summary

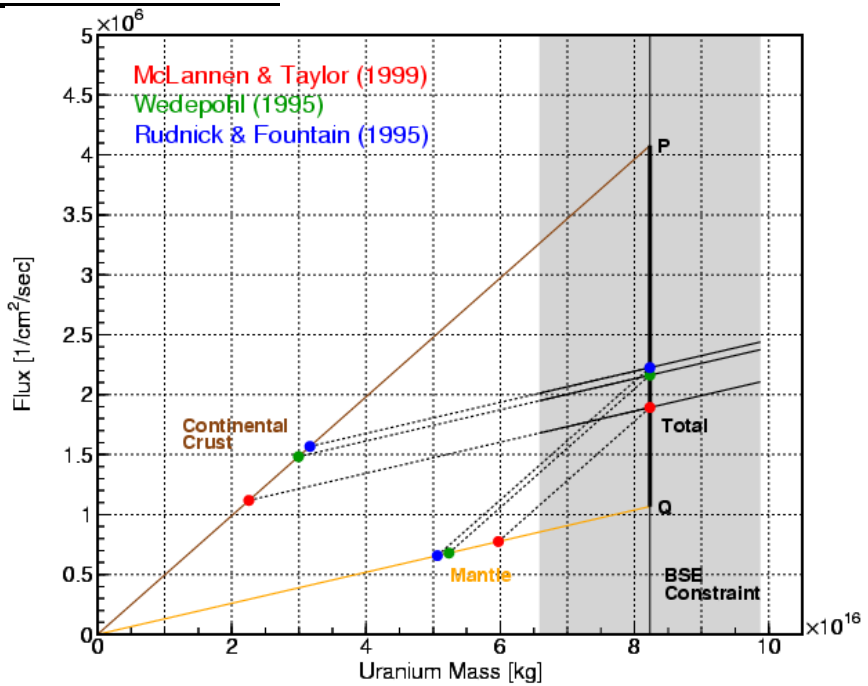
Systematic	%
Fiducial volume	4.7
Energy threshold	2.3
Efficiency of cuts	1.6
Livetime	0.06
Reactor power	2.1
Fuel composition	1.0
$\overline{\nu}_e$ spectra	2.5
Cross section	0.2
Total	6.5

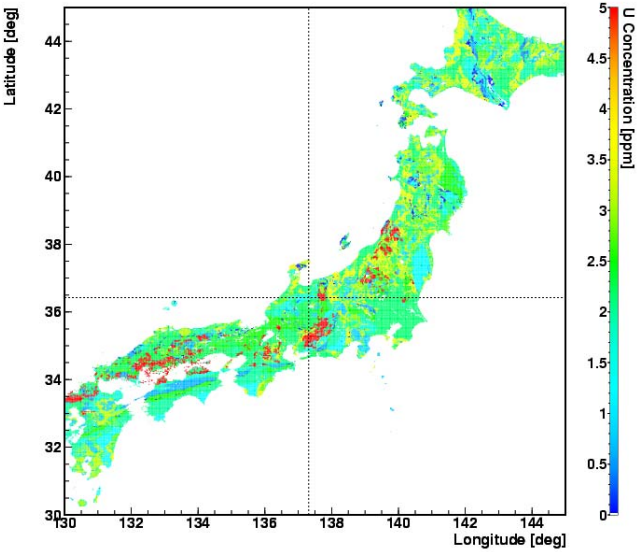
Geo-Neutrino Flux and Earth Models

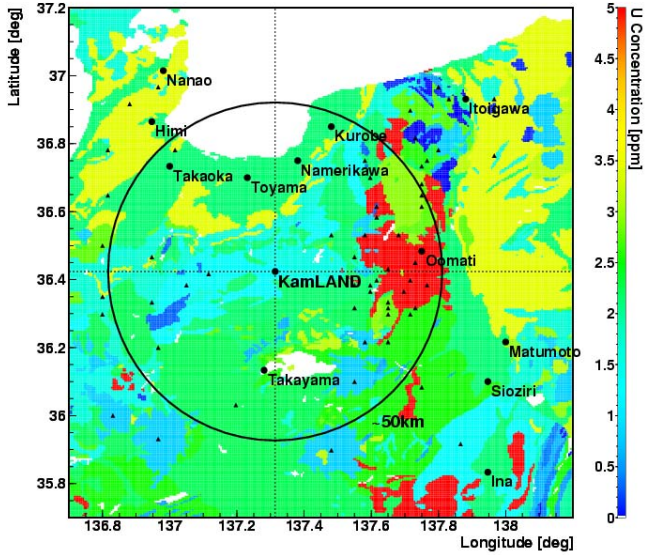


Geo-Neutrino Flux Uncertainties

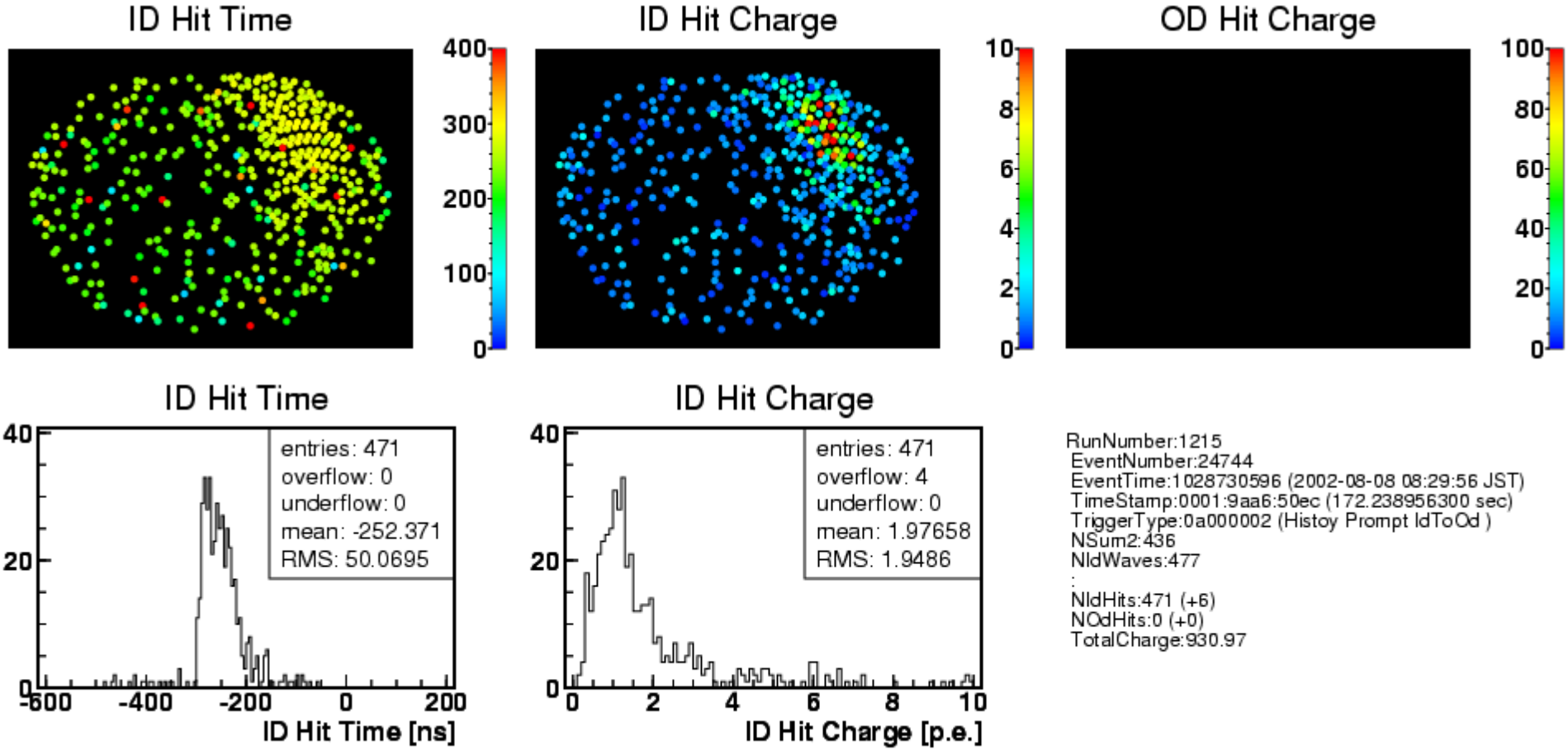








Event Display: Low Energy Event



RunNumber:1215
EventNumber:24744
EventTime:1028730596 (2002-08-08 08:29:56 JST)
TimeStamp:0001:9aa6:50ec (172.238956300 sec)
TriggerType:0a000002 (Histoy Prompt IdToOd)
NSum2:436
NIdWaves:477
:
NIdHits:471 (+6)
NOdHits:0 (+0)
TotalCharge:930.97

Powered by KiNOKO

Event Display: Muon Event