Experimental Study of Geoneutrinos with KamLAND

1. Geoneutrino Physics with KamLAND
2. The KamLAND Detector and Data Analysis
3. KamLAND Result and Discussion

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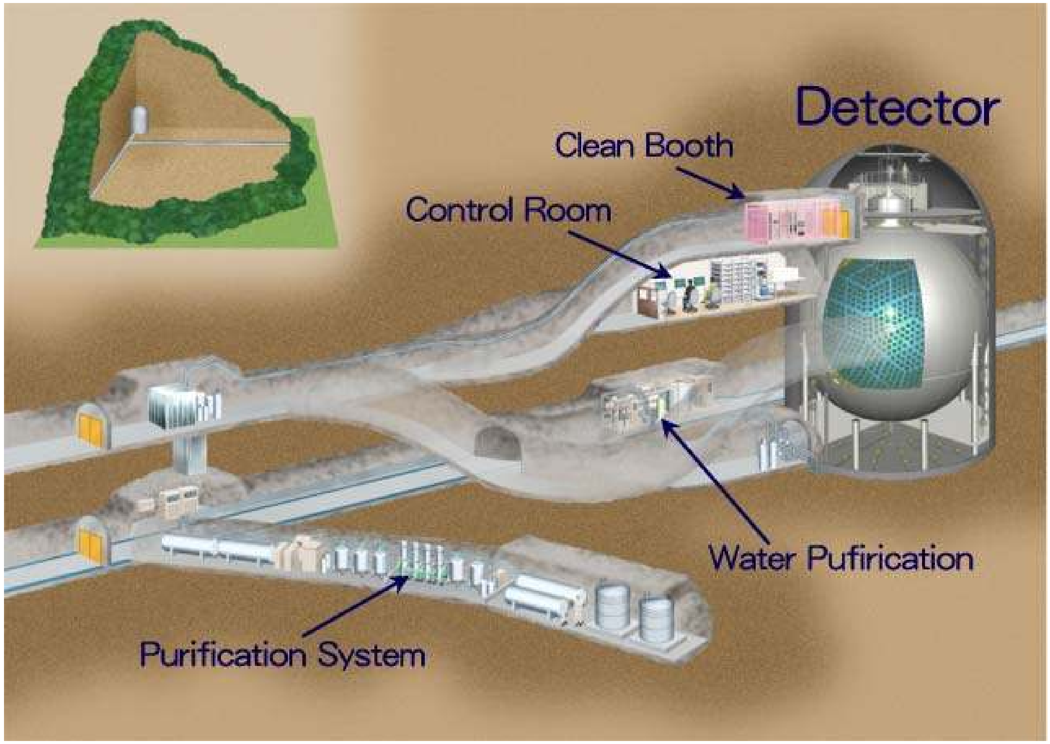
KamLAND Experiment

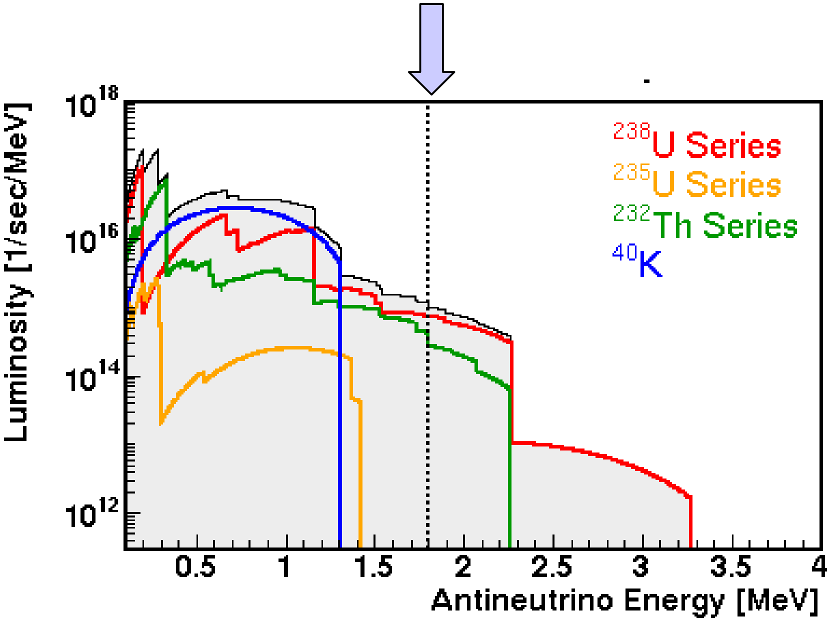
- observes low energy anti-neutrinos at the Kamioka Mine, Hida, Japan
- consists of 1000ton Liquid Scintillator, surrounded by 1845 PMT's



Reaction:

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

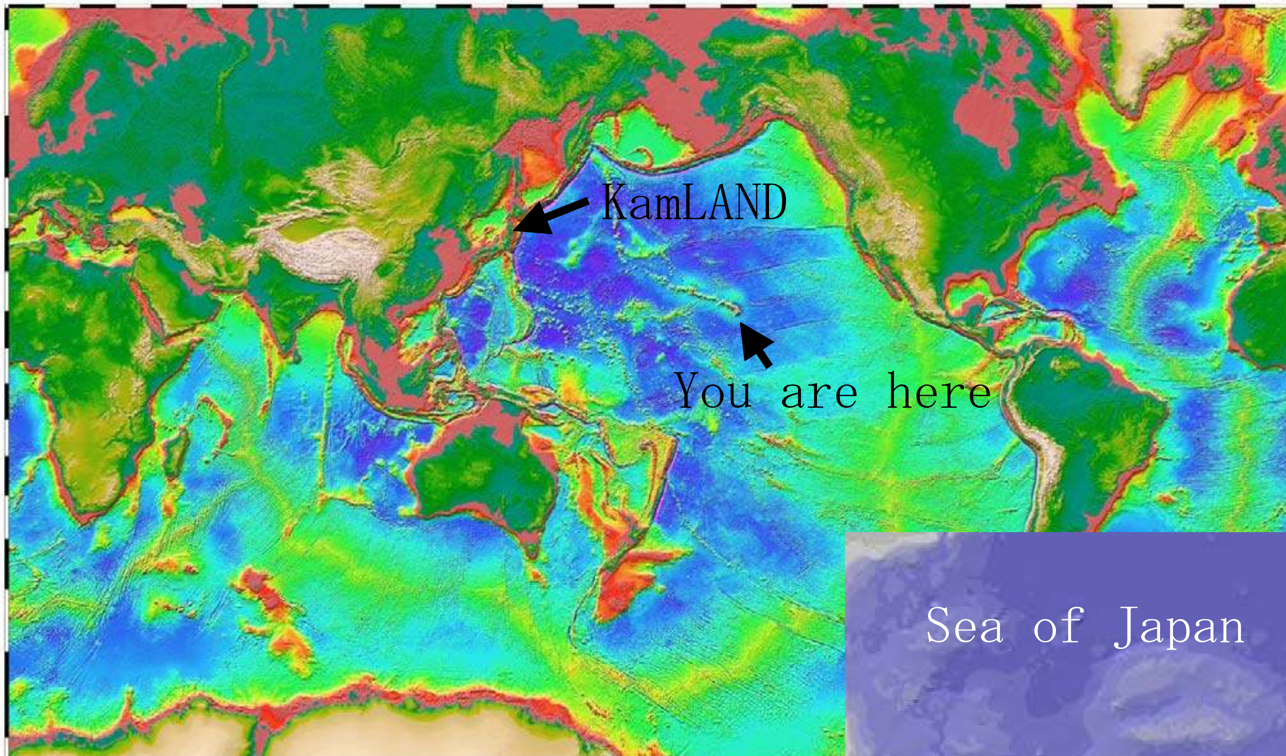
Threshold: 1.8 MeV

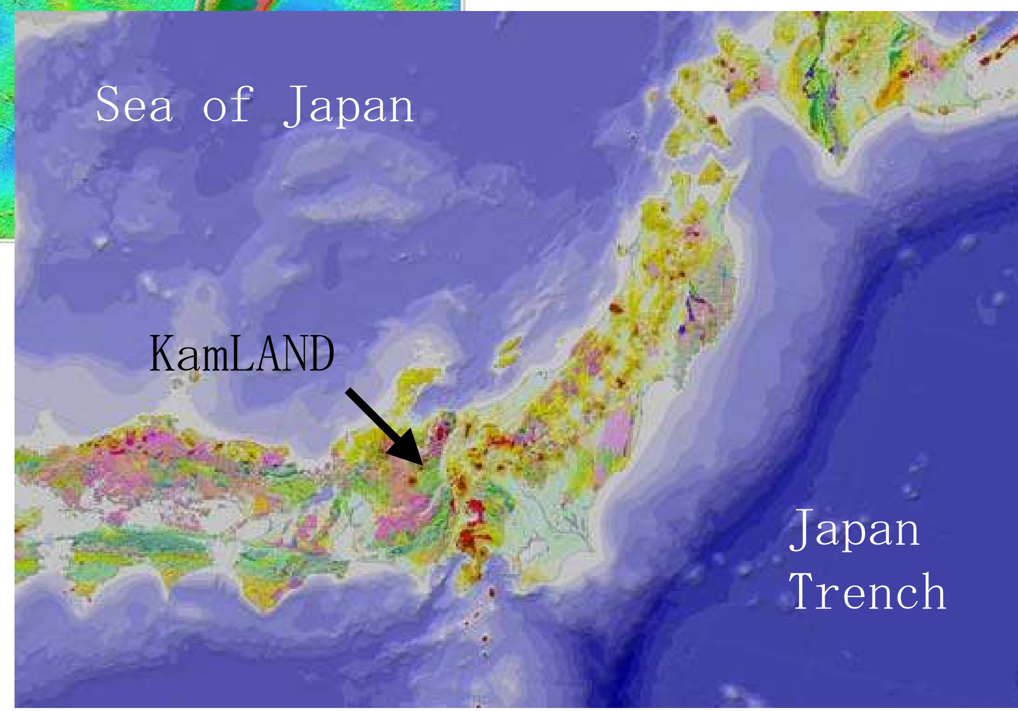


discriminative sensitivity to antineutrinos

→avoids overwhelming solar neutrino background

KamLAND Location





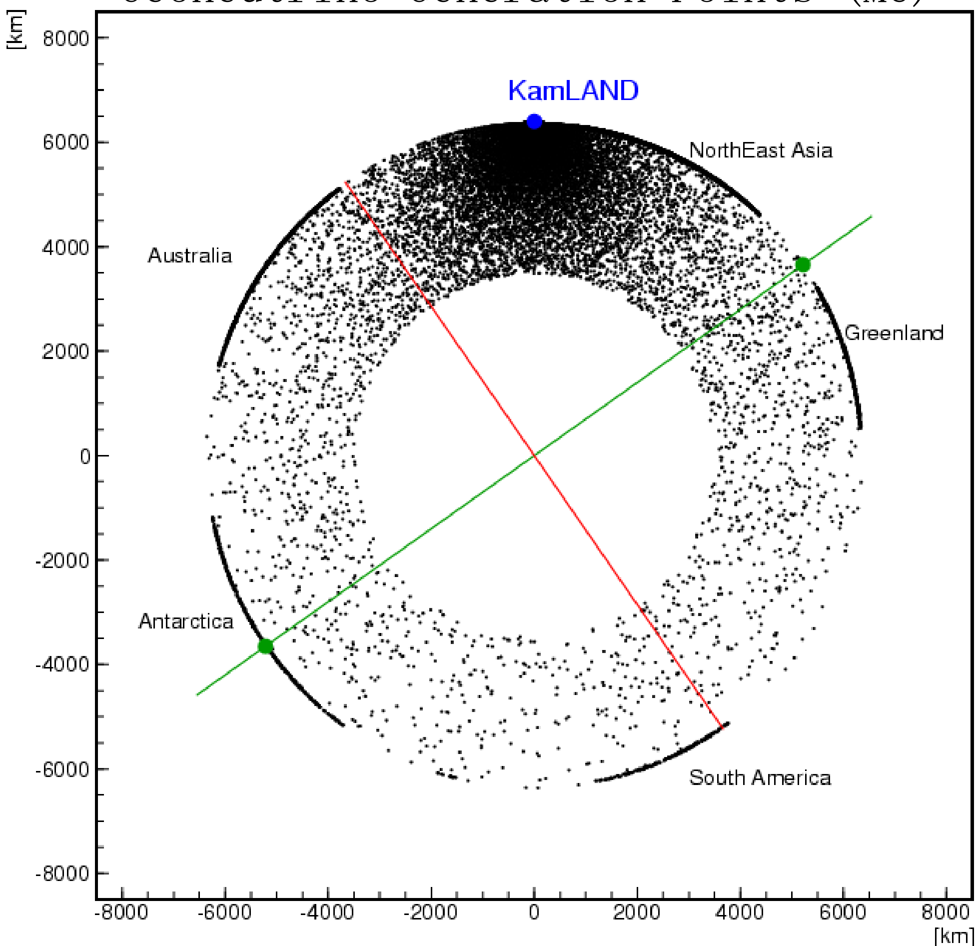
Geological Setting

- Boundary of Continent and Ocean
- Island Arc (Orogenic)
- '*Hida*' Metamorphic Zone
- Zn, Pb, limestone mine (skarn)
- Surrounded by Gneiss Rocks

Geoneutrino Flux Integration

$$F_{U/Th} = A \cdot \int_{Earth} \frac{\rho_{U/Th}(\vec{r})}{4\pi \,|\, \vec{r} - \vec{r}_{KamLAND} \,|^2} P(\overline{\nu}_e \to \overline{\nu}_e)\, dV$$

Geoneutrino Generation Points (MC)



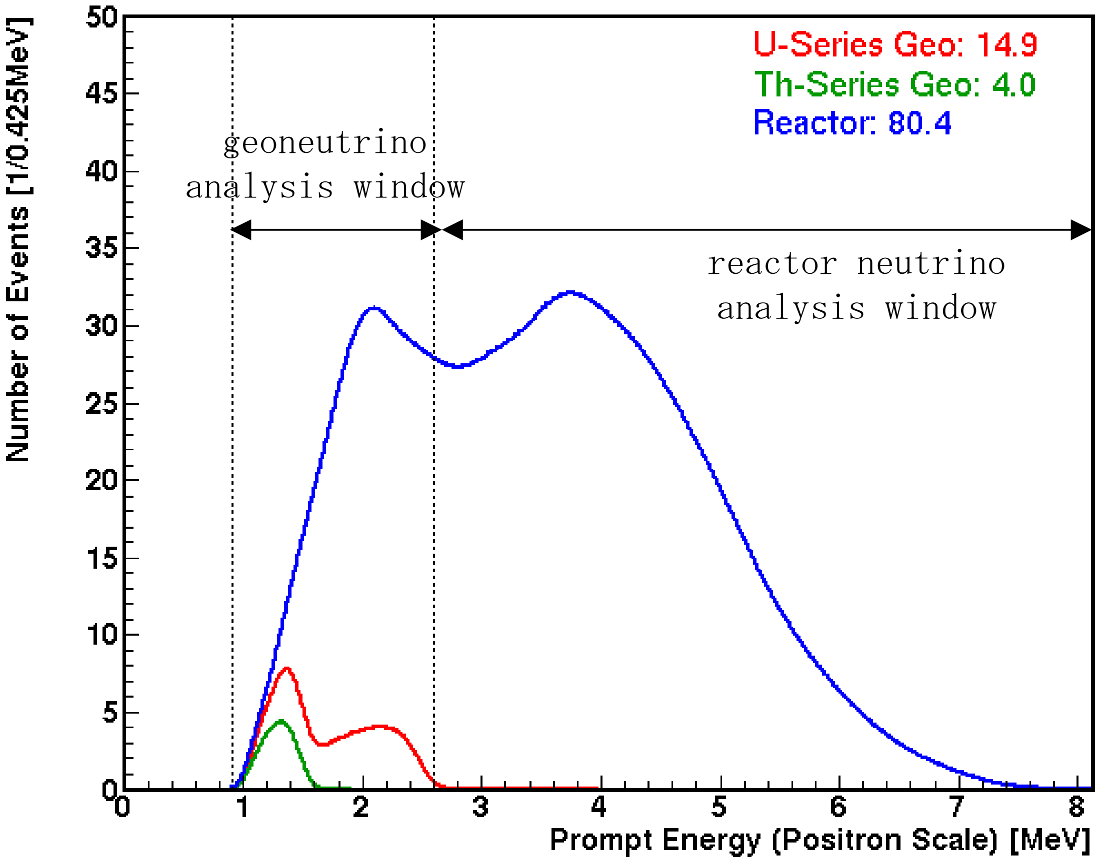
Geoneutrino Flux at KamLAND

- U-series
  - 2.3×10^6 [1/cm^2/sec]
  - 30.5 [events/10^{32}protons/year]
- Th-series
  - 2.0×10^6 [1/cm^2/sec]
  - 8.0 [events/10^{32}protons/year]

10^{32}protons ~1.2kton CH_2

Expected Neutrino Spectrum at KamLAND

- 408ton CH_2 (5m radius volume), 714 days, 69% efficiency
- Oscillation parameters from KamLAND 2nd Result



expected event rate:

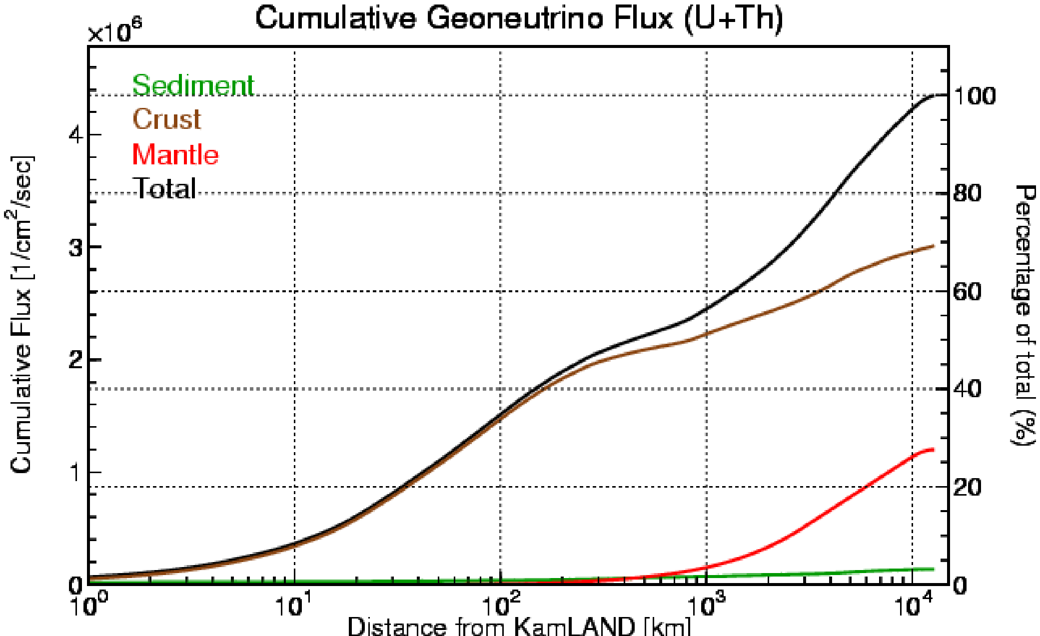
U series: 14.9

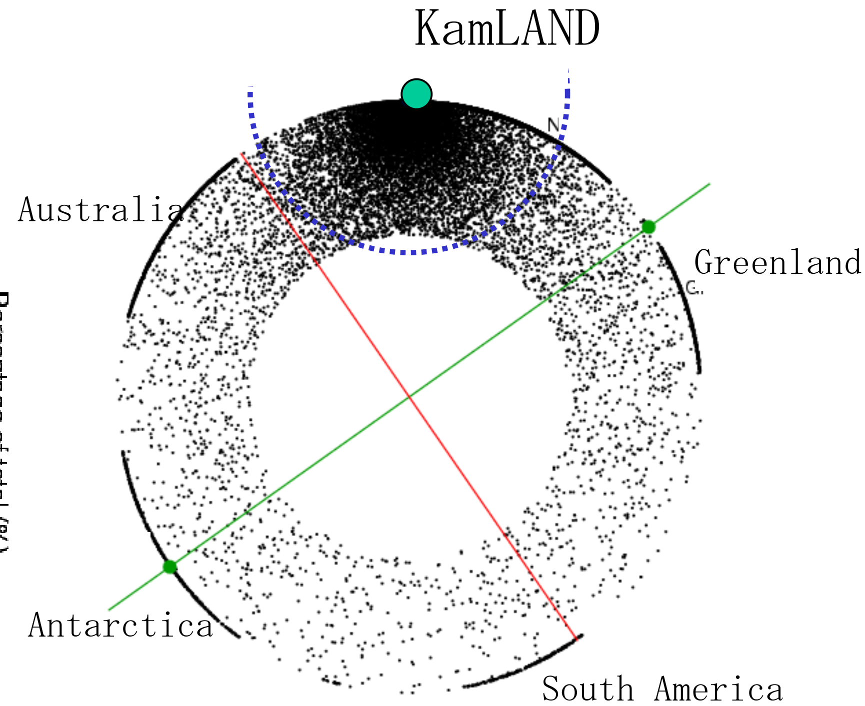
Th series: 4.0

Reactor (E<3.4MeV): 80.4

Where Neutrinos Come From?

Assuming uniform crustal composition (no local variation),





'*Earth around Japan*'

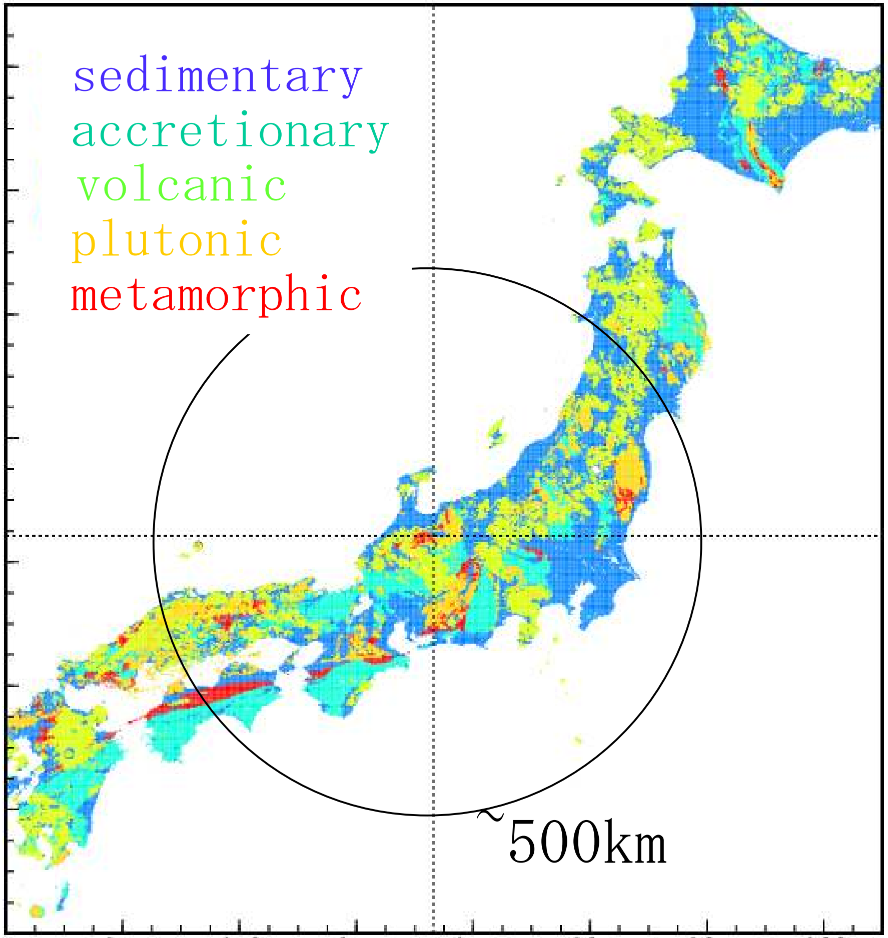
Japan Island Arc

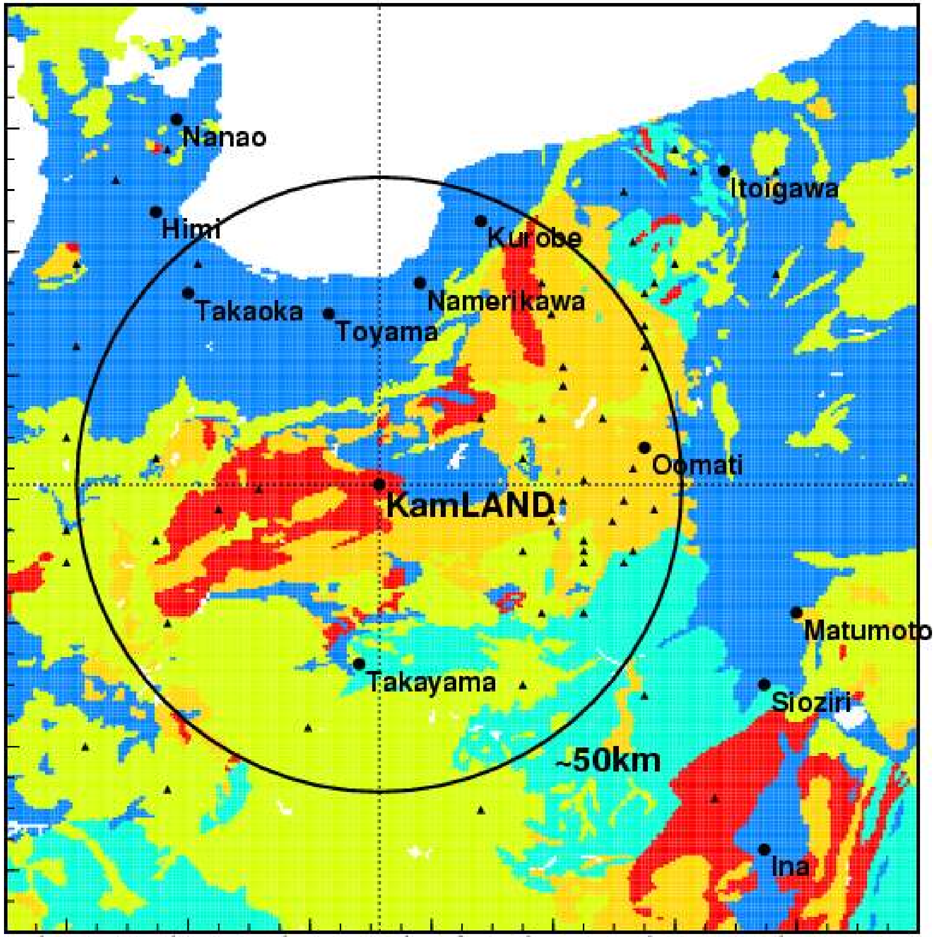
Hida Metamorphic Zone

Kamioka Mine

KamLAND is looking at
'*Earth around Japan*',
if local variation is averaged enc

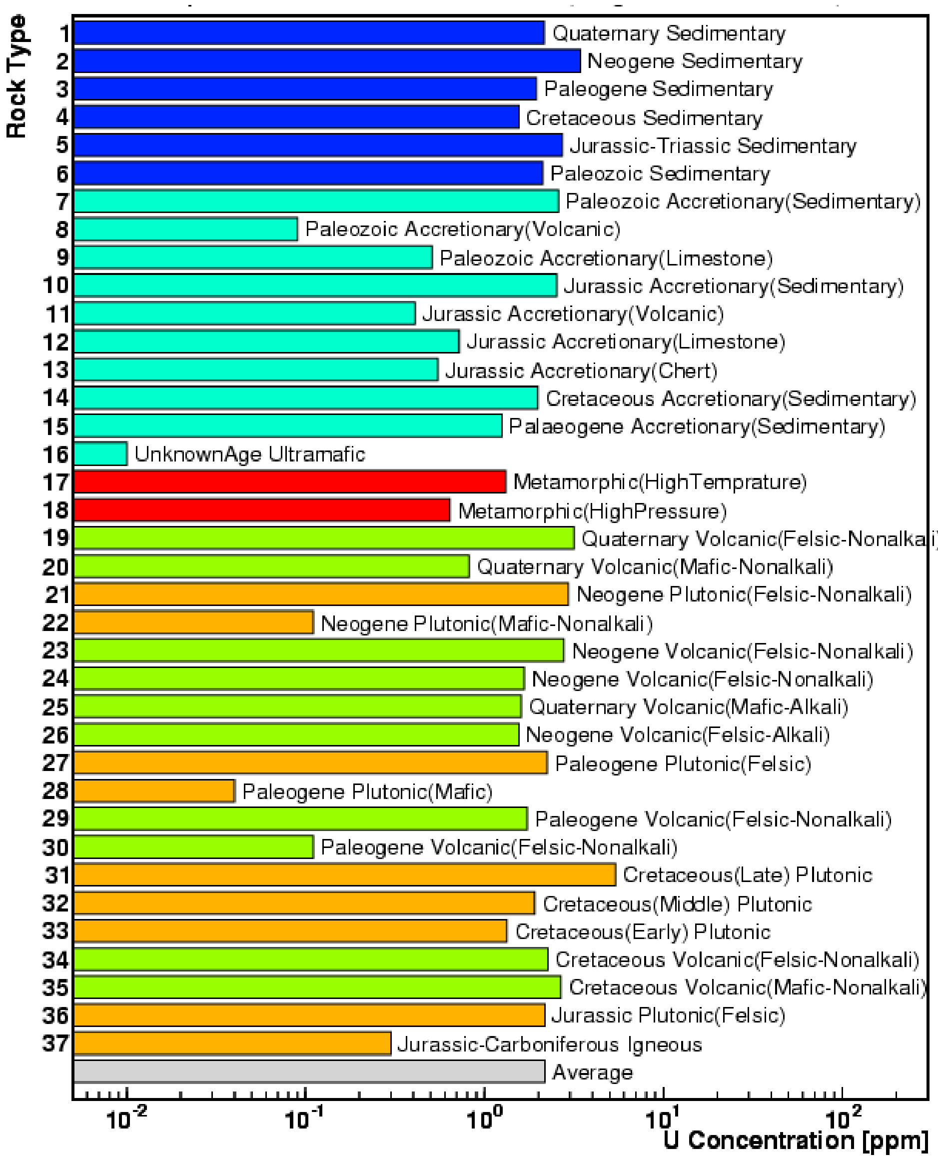
Local Geology Study 1 - Geological Map





- Japan Geological Map, published from Geological Survey of Japan (199
- classifies the surface geology into 165 geologic groups.

Local Geology Study 2 - Geochemical Analysis

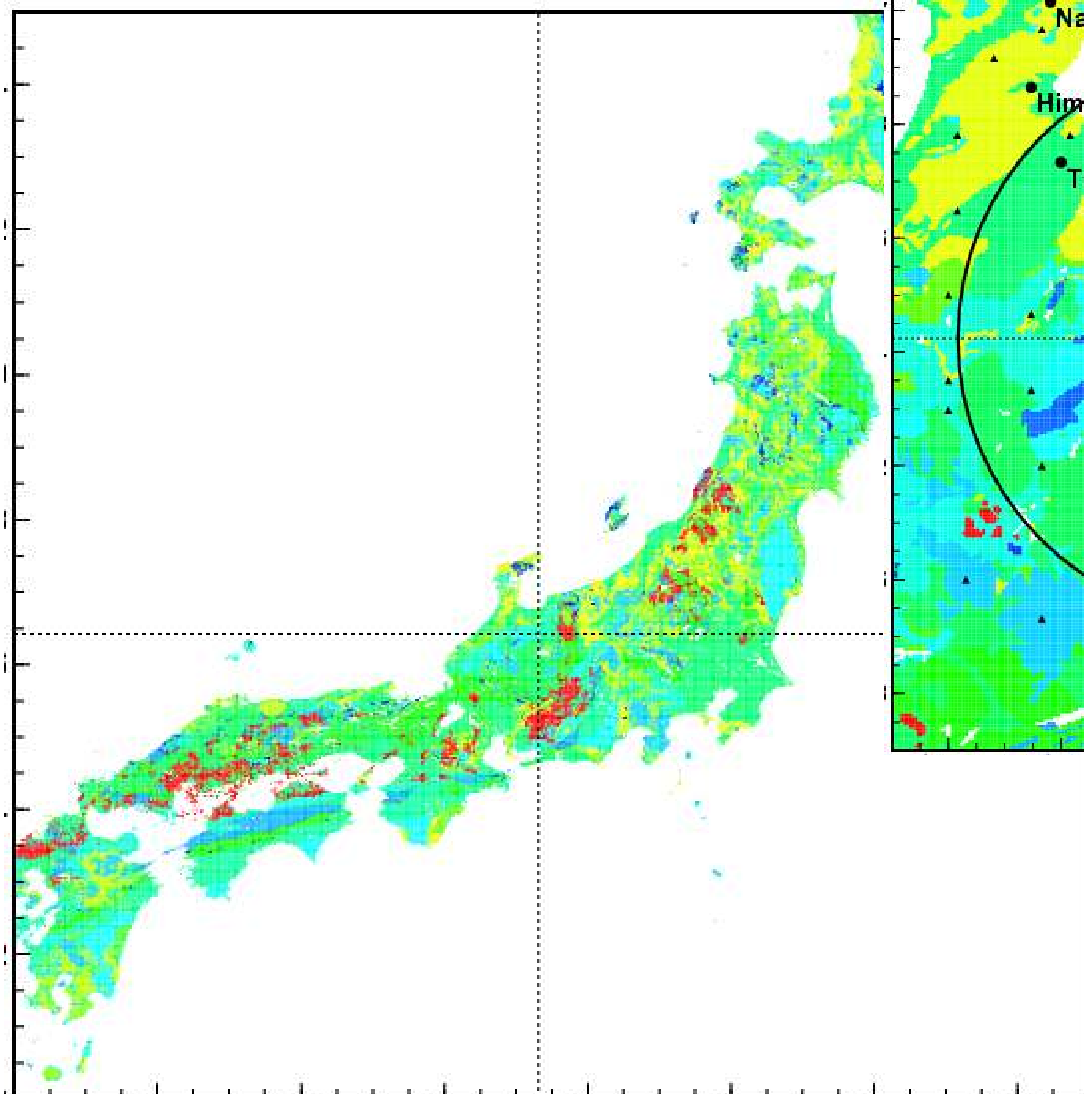


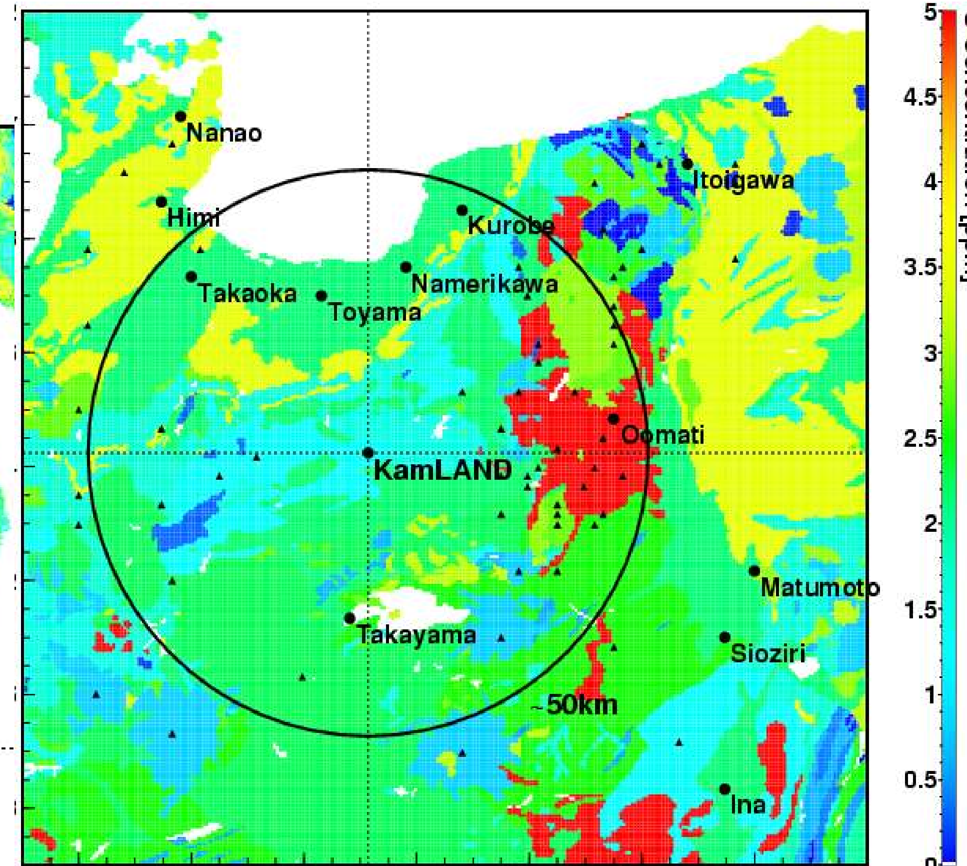
Togashi et.al. (2000)

(Geochemistry Geophysics Geosystems, volume 1 number 27)

- classifies surface geology into 37 groups
- collects 166 rock samples to cover rock varieties and abundances

Surface U/Th Distribution Models





- This is just a model
- This is just for surface
- This is everything we have

Effect of Local Geology

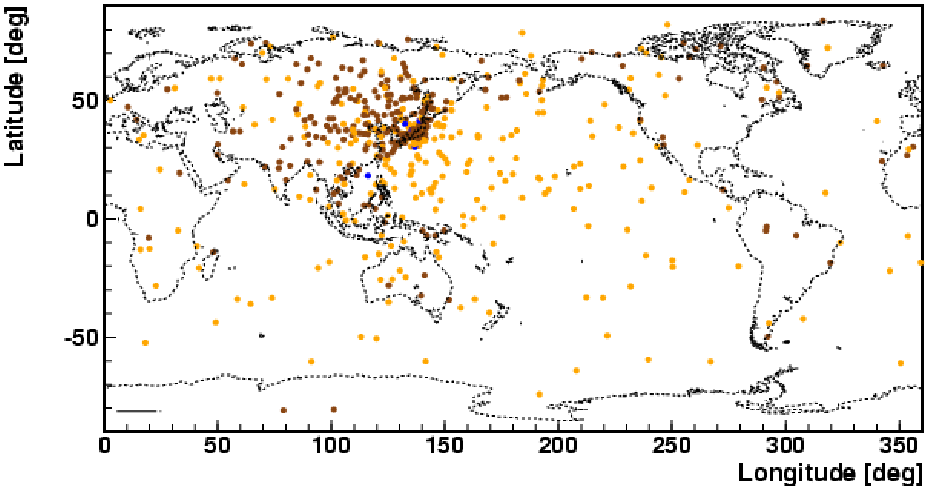
- Assuming surface exposed geology extends to 5km depth,
- Calculates possible variation in geoneutrino flux

Composition Model of Each Geological Group	U-series [$1/10^{32}$H/yr]	Th-series [$1/10^{32}$H/yr]
Global Average Represented Composition	4.8	0.96
Group Average Represented Composition	3.8	0.97
Neighbor-Sample Represented Composition	4.6	0.83
Whole Earth	30.1	6.7

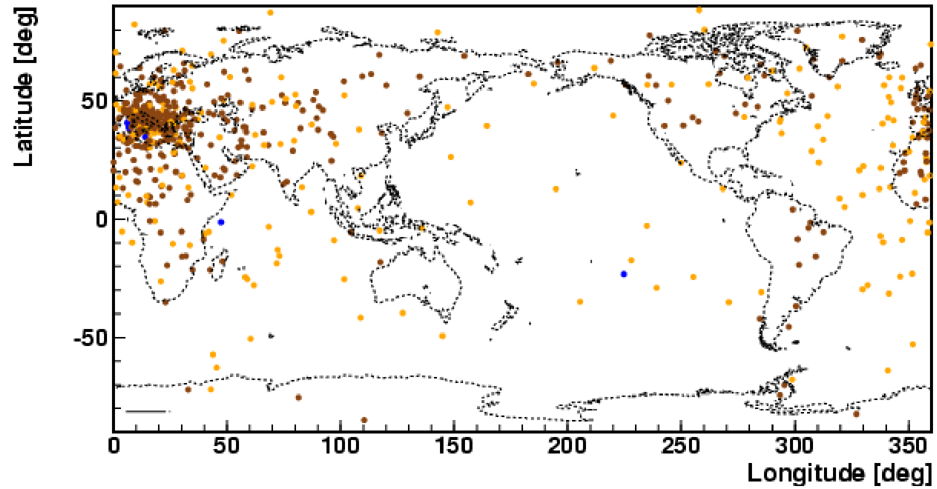
- Range of variation is about 4%
- If 'surface' is simply extended to whole upper crust, we get ~
- vertical information is crucial

Comparison with Other Sites

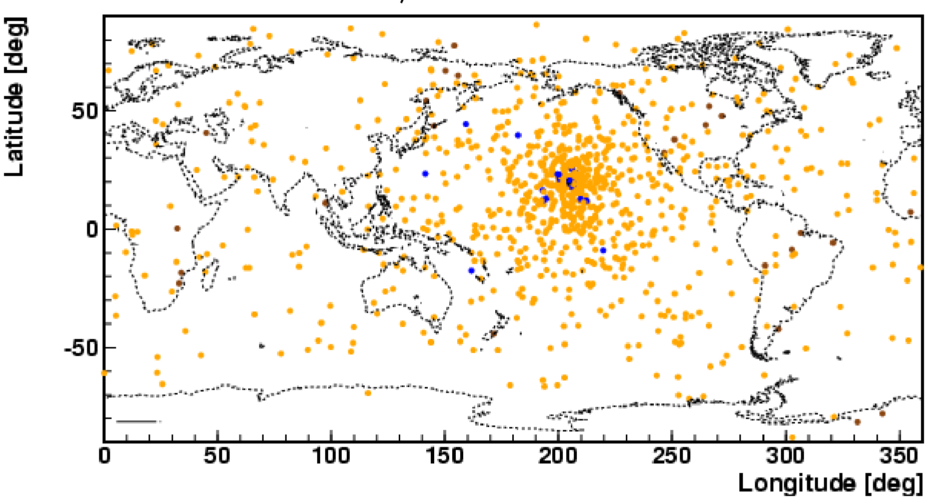
Kamioka / Island Arc



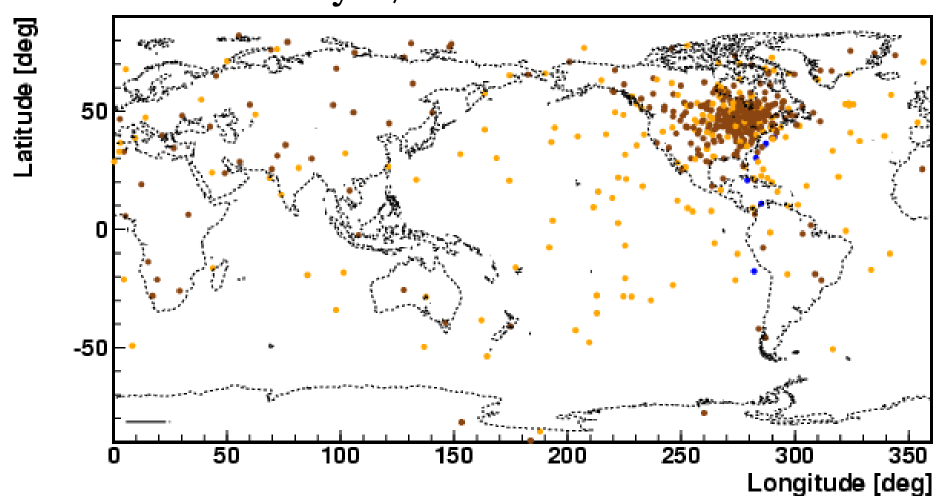
Gran Sasso / Mesozoic Crust



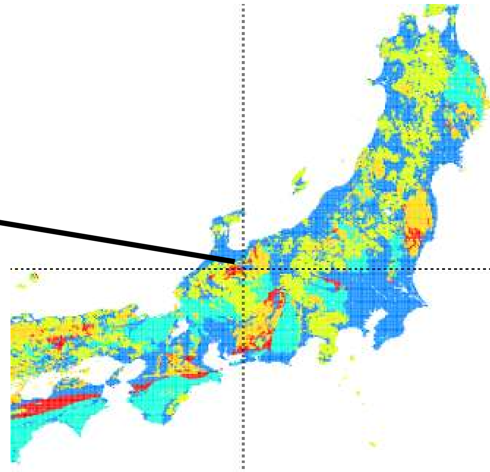
Hawaii / Oceanic Island

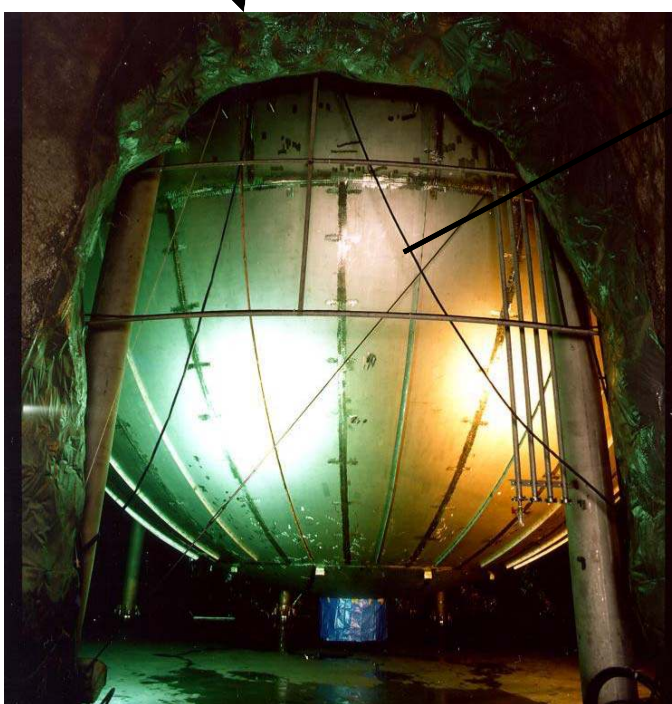


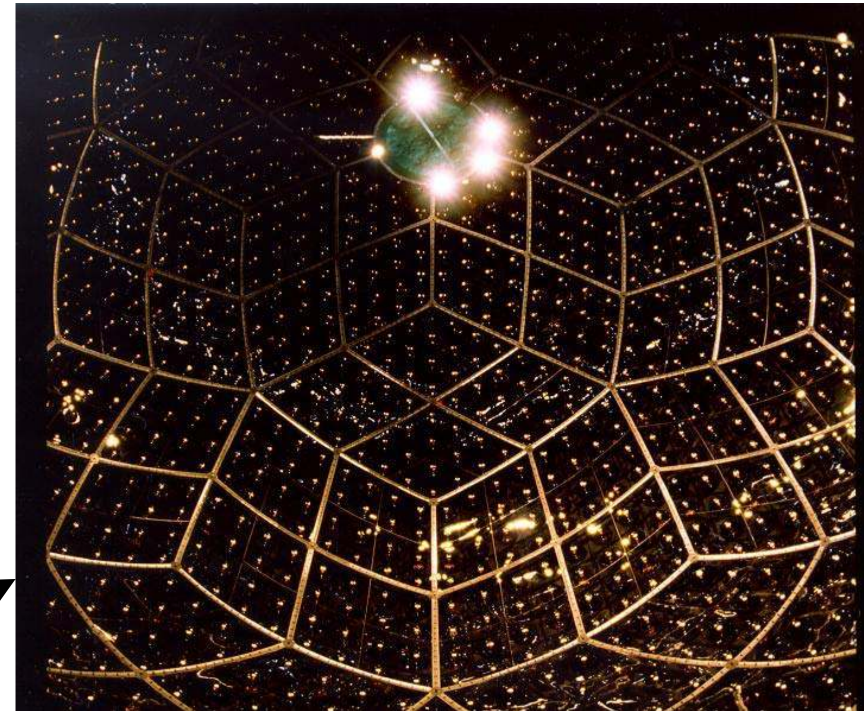
Sudbury / Archean Crust



KamLAND Detector







Neutrino Detection Method

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

$$e^+ + e^- \rightarrow 2\gamma\ (0.511\text{MeV})$$

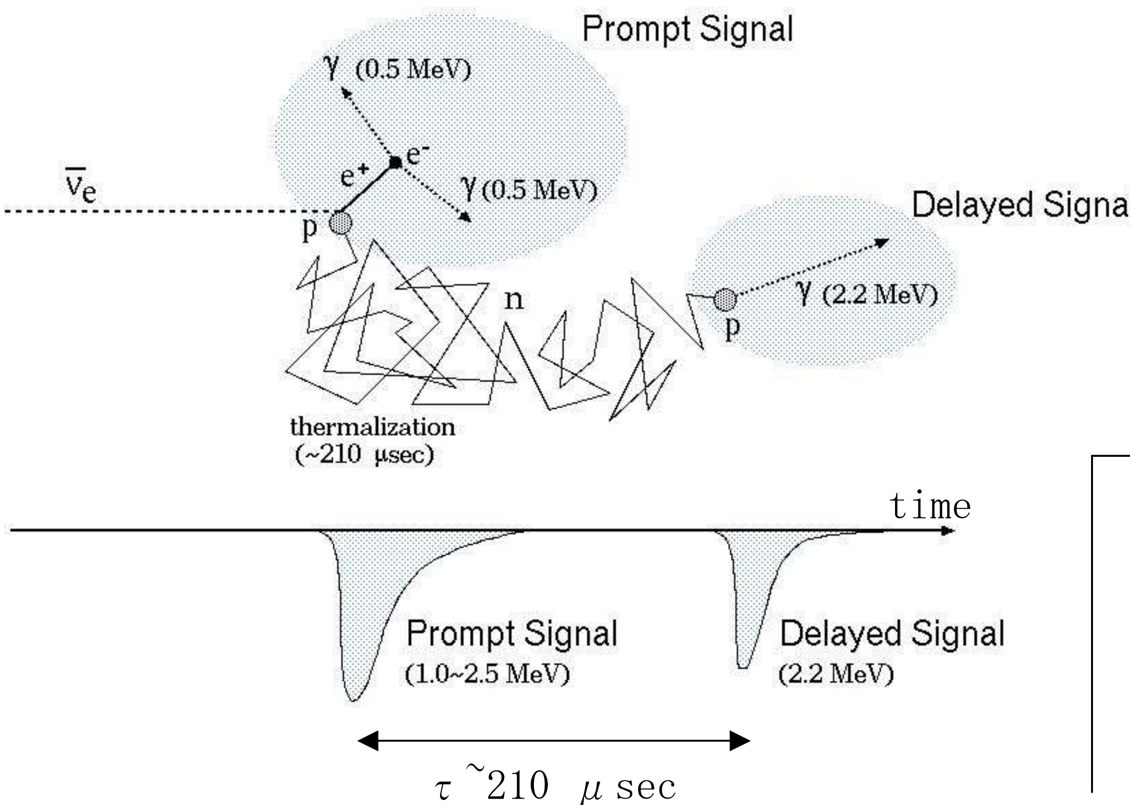
$$n + p \rightarrow d + \gamma\ (2.2\text{MeV})$$

τ ~210 μ sec

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

$$E_{\text{prompt}} = E_{\nu_e} - 0.8 \text{ MeV}$$

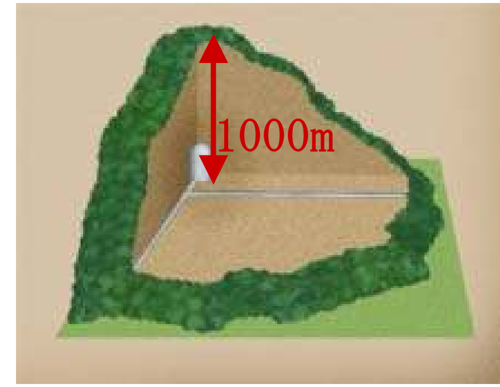
$$E_{\text{delayed}} = 2.2 \text{ MeV}$$

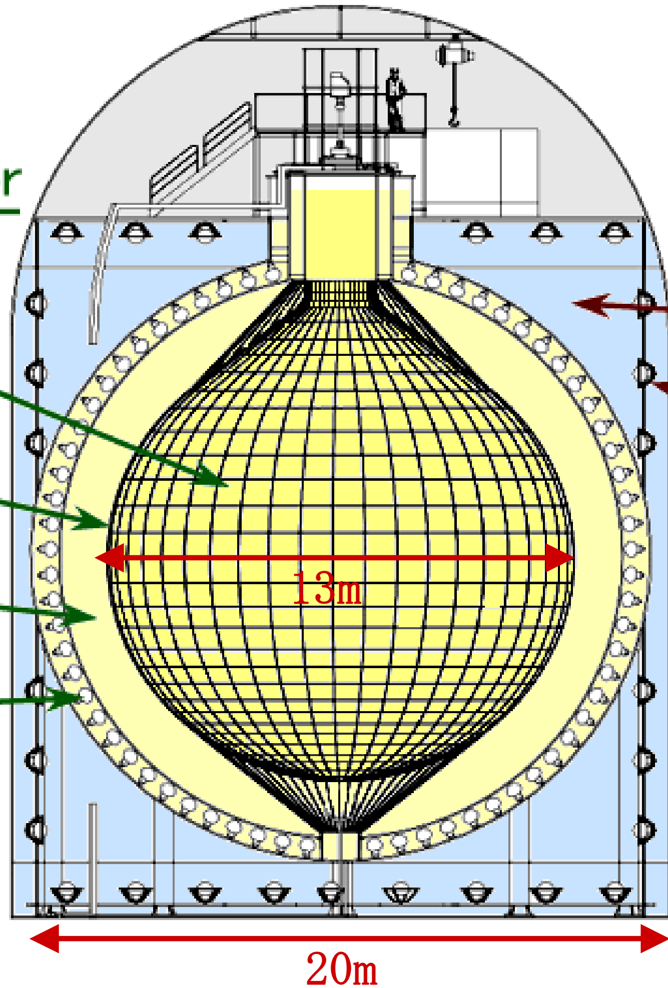


$$E_{\text{geo-}\nu_e} : 0 \text{ MeV} \sim 3.3 \text{ MeV}$$

$$E_{\text{prompt}} : 1.0 \text{ MeV} \sim 2.5 \text{ MeV}$$

KamLAND Detector Design





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

~ 8000 photons/MeV

λ ~ 10m

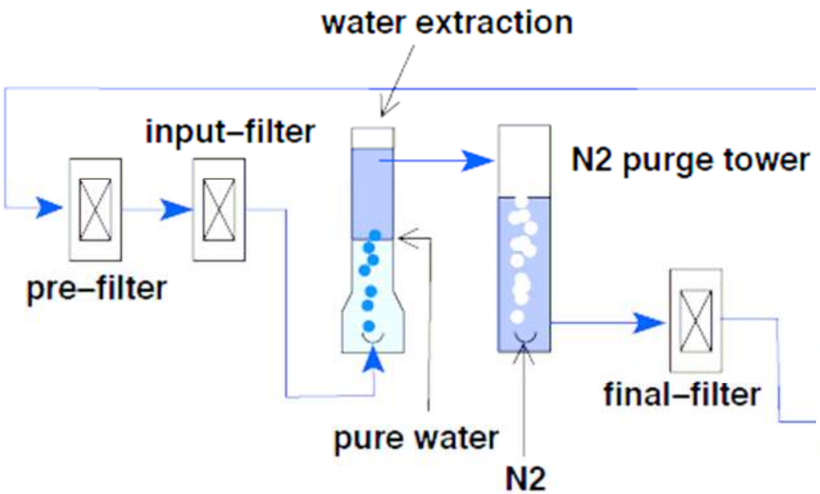
MO: 50%: dodecane
50%: isoparafin

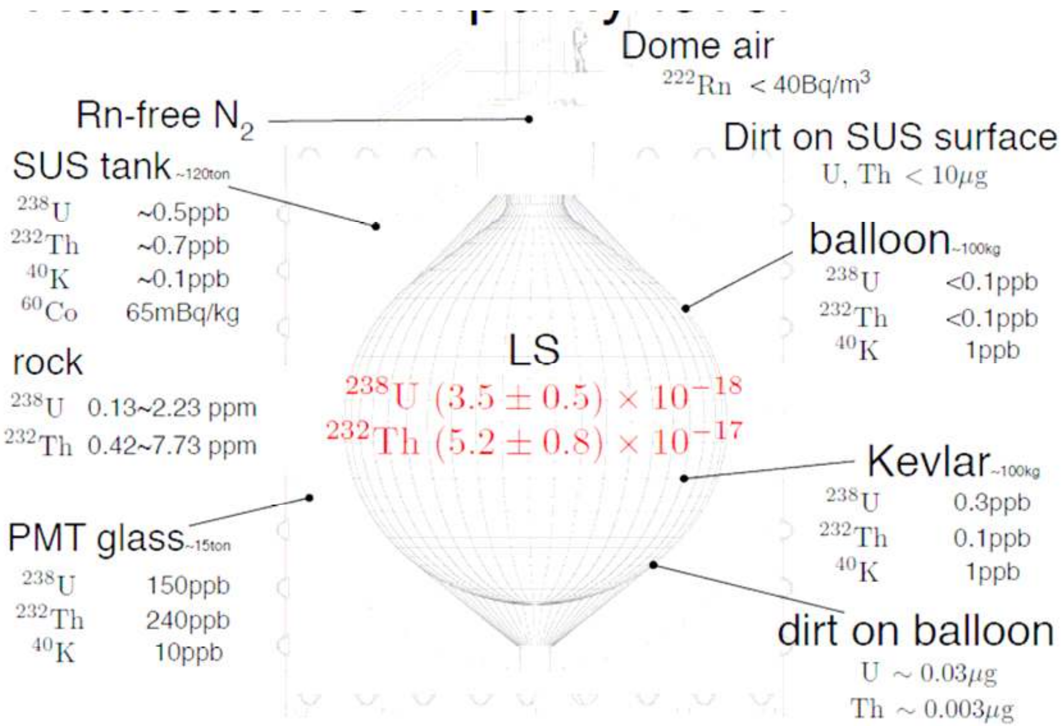
$\rho_{LS}/\rho_{MO} = 1.0004$

photo-coverage: 34%

~ 500 p.e. / MeV

LS Purification and Radioactive Impurity





before

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

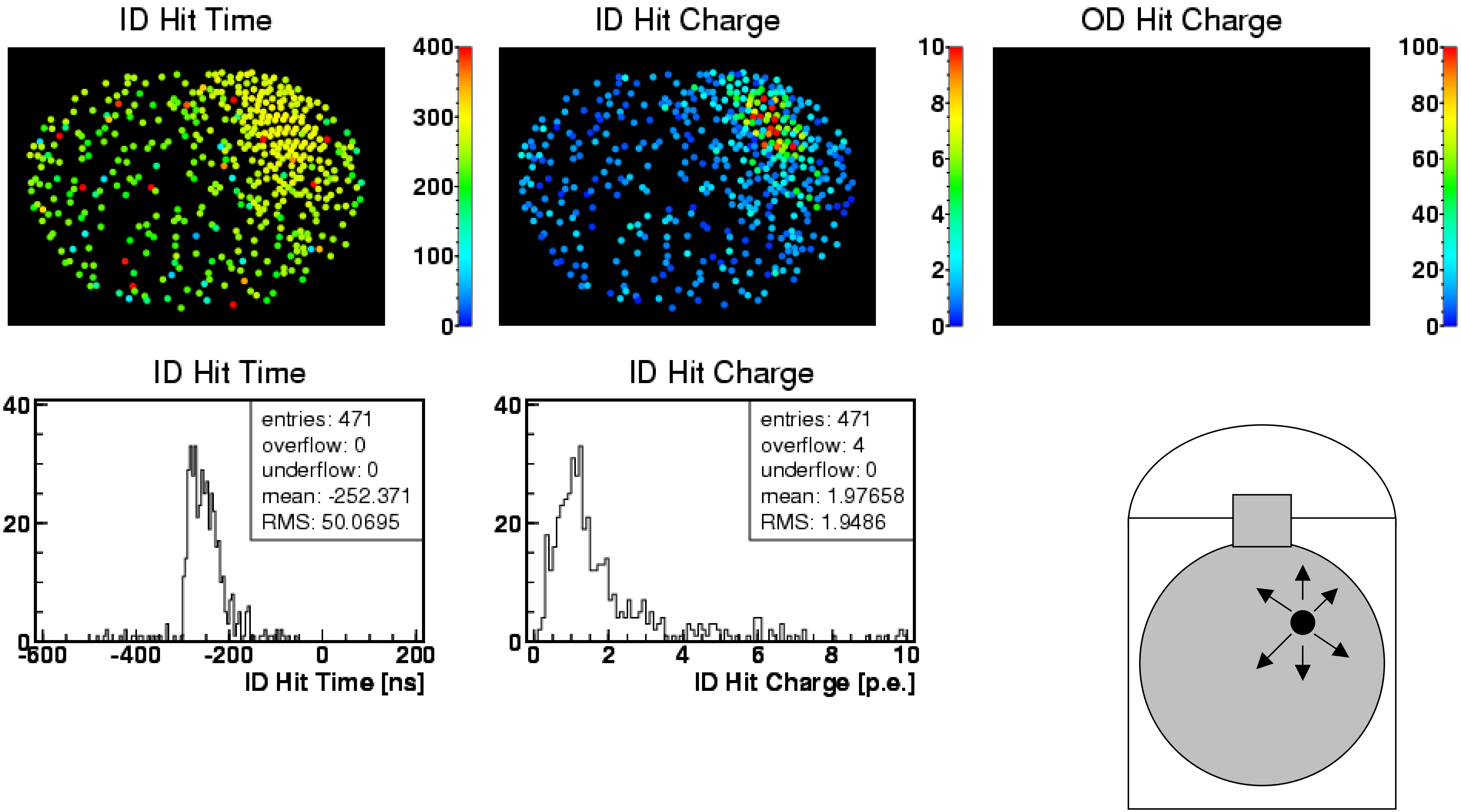
⇩

after

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

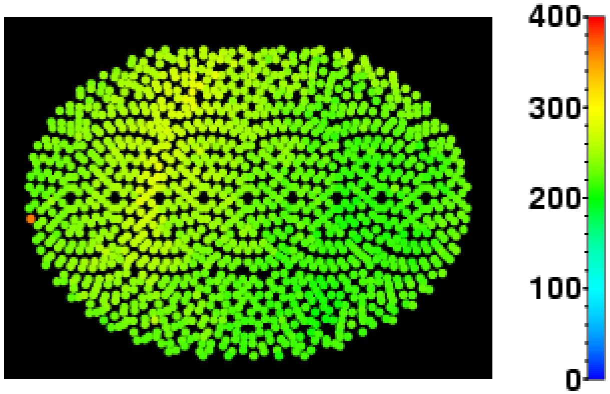
measurable only by KamLAND itself !

KamLAND Event: Low Energy Event

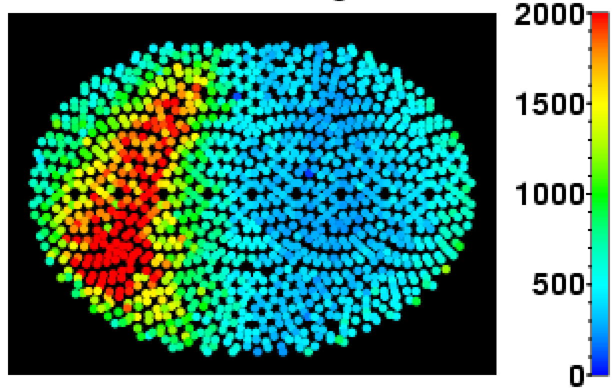


KamLAND Event: Cosmic Muon Event

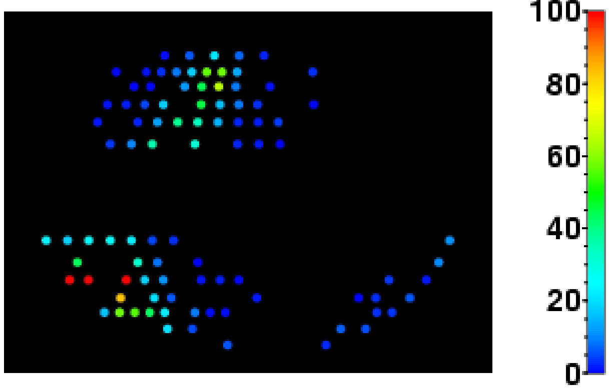
ID Hit Time



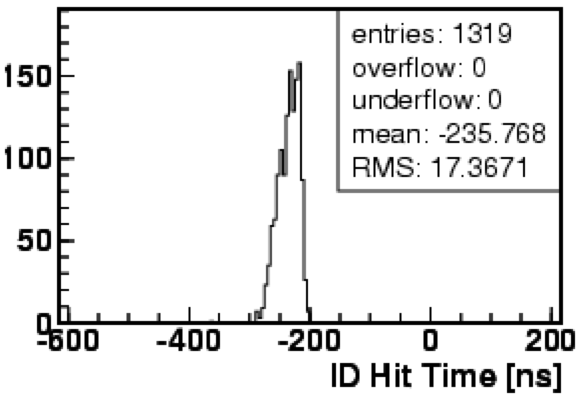
ID Hit Charge



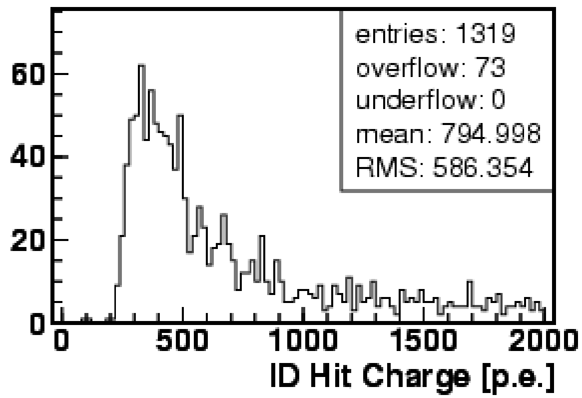
OD Hit Charge

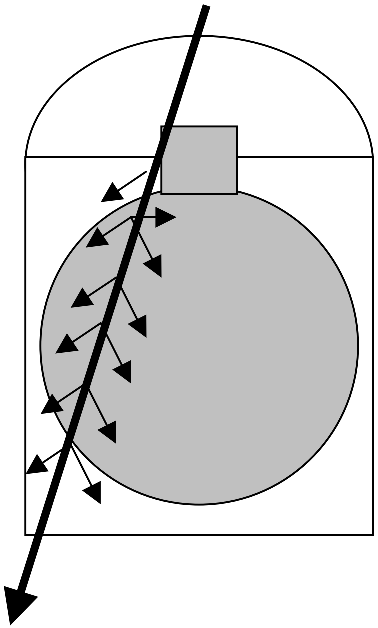


ID Hit Time



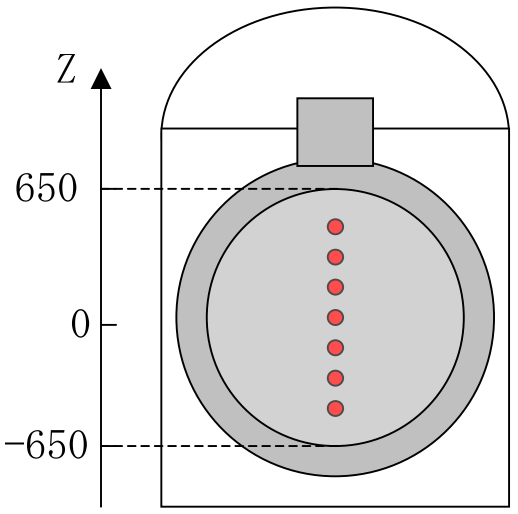
ID Hit Charge

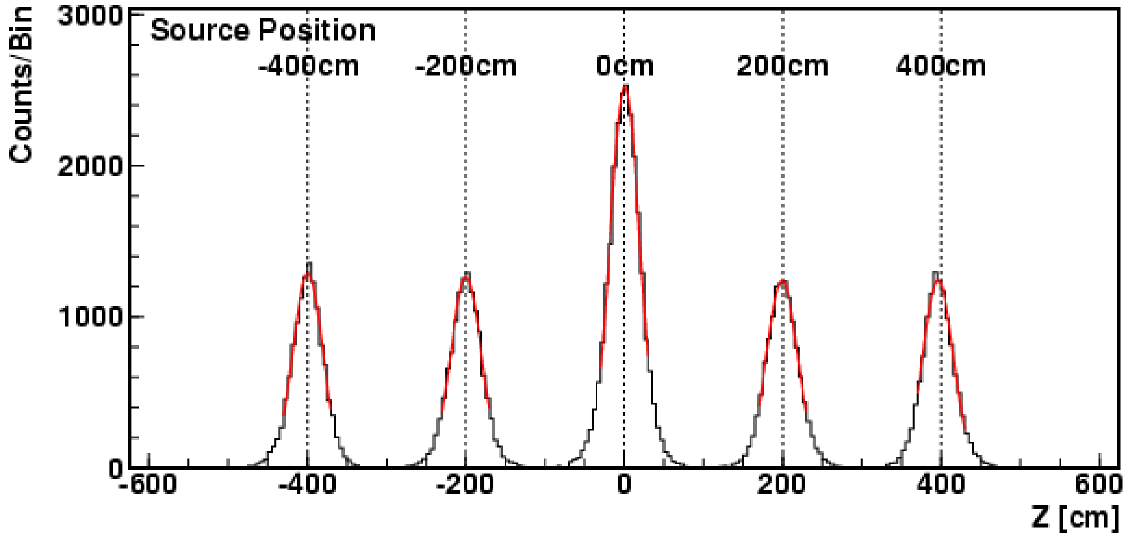


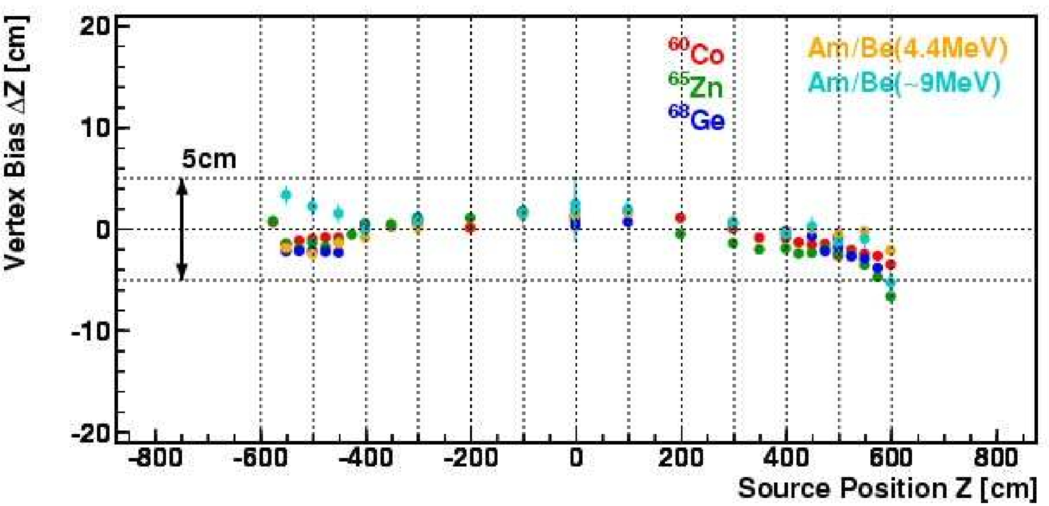


Vertex Reconstruction

Determined from PMT hit timing







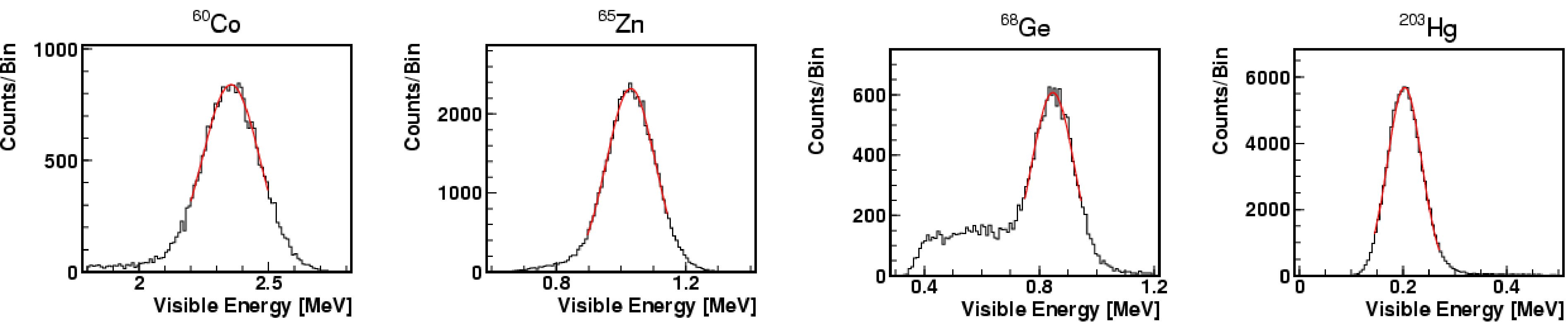
$$\sigma = 20.6\mathrm{cm}/\sqrt{E_{\mathrm{vis}}(\mathrm{MeV})}$$

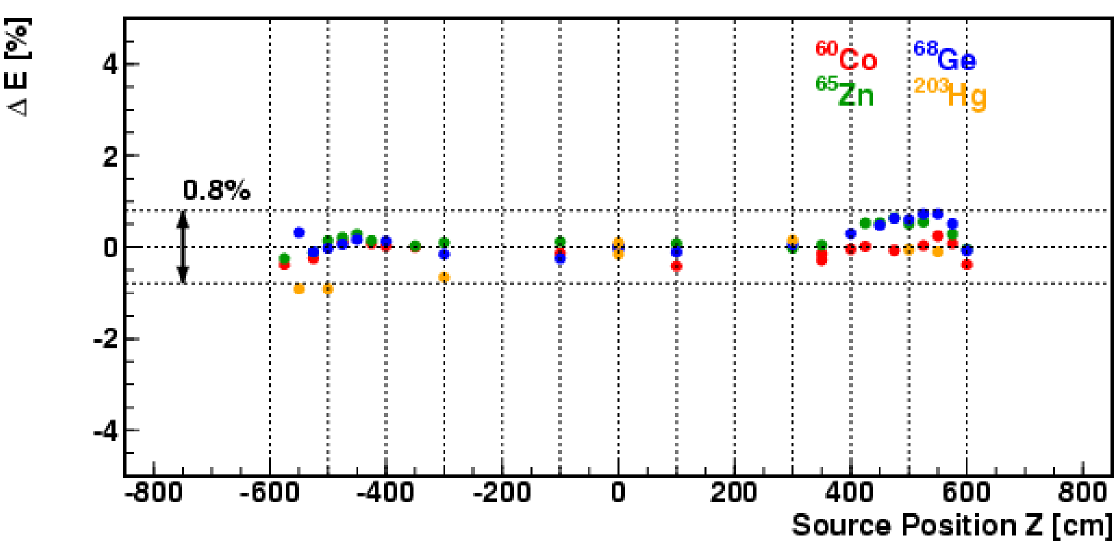
< 5 cm vertex bias
in −550cm < Z < 550cm

Visible Energy (light yield) Estimation

Determined from total PMT hit charge, with corrections of

- light attenuation, balloon / rope shadowing
- PMT angle, quantum efficiency, discriminator threshold





Visible Energy

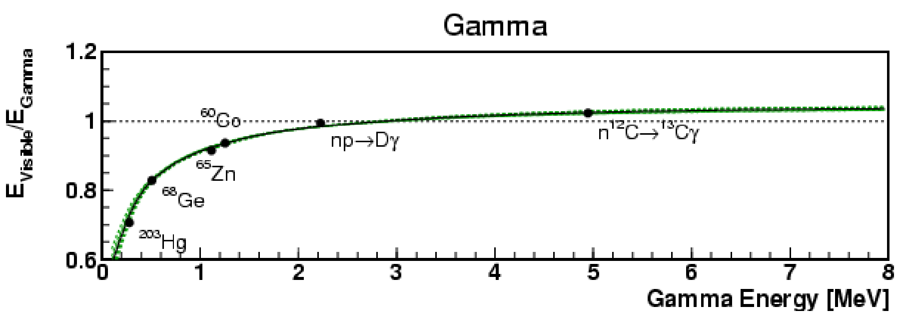
(photon yield)

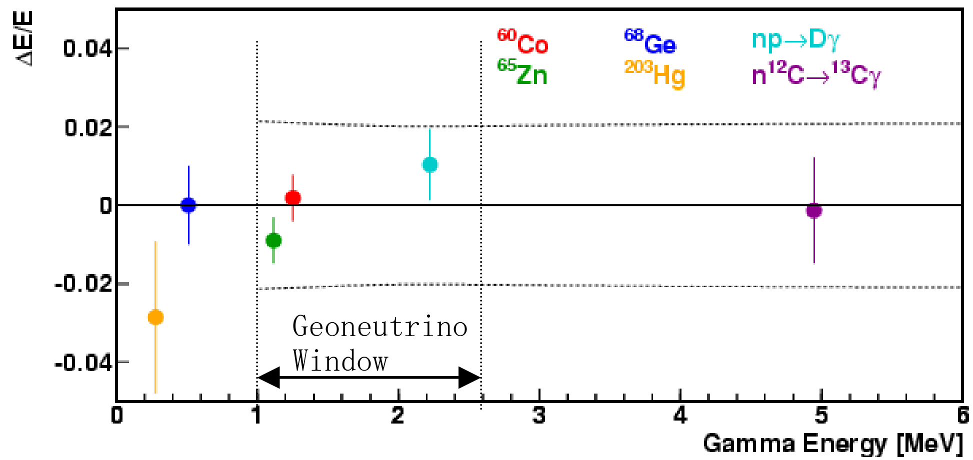
$$\sigma = 6.2\% / \sqrt{E_{vis}(\mathrm{MeV})}$$

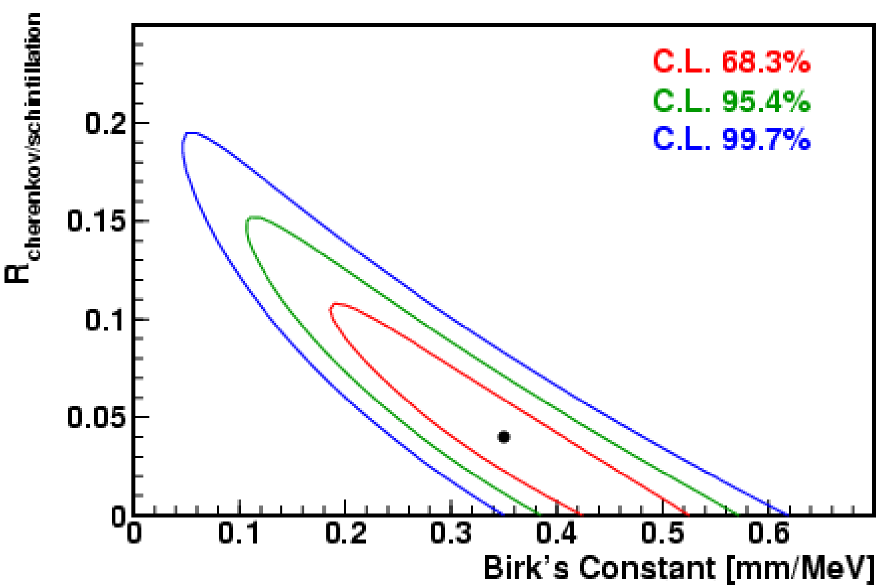
< 0.8% position dependence in −550cm < Z < 550cm

Energy Scale Study

$$\Delta E_{\text{vis}} = A\left\{\frac{1}{1+R}\cdot\underbrace{\frac{1}{1+k_b\frac{dE}{dx}}}_{\text{Quenching}} + \frac{R}{1+R}\cdot\underbrace{\frac{dN_{\text{ch}}}{dE}}_{\text{Cherenkov Light}}\right\}\Delta E$$



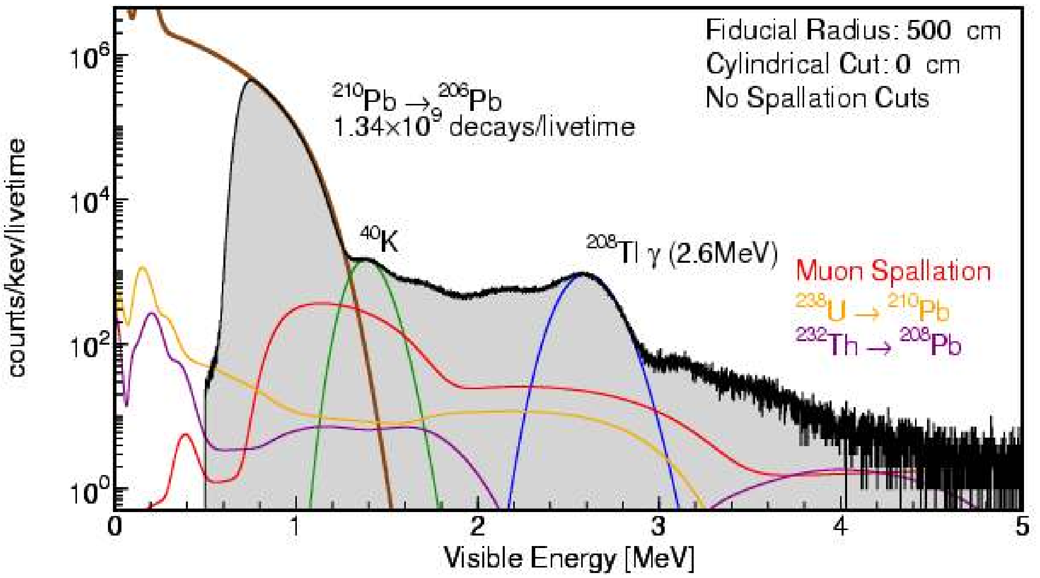




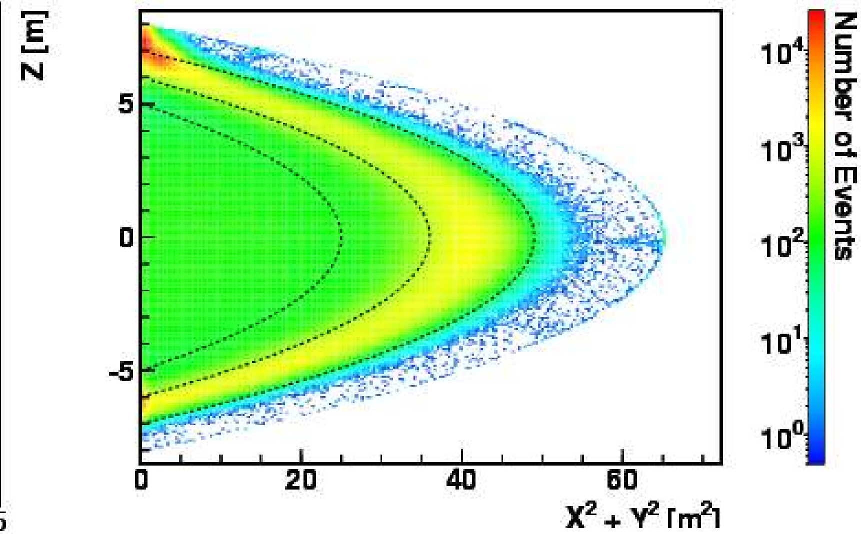
Energy reconstructed within 2% error

Detector Activity (Singles Spectrum)

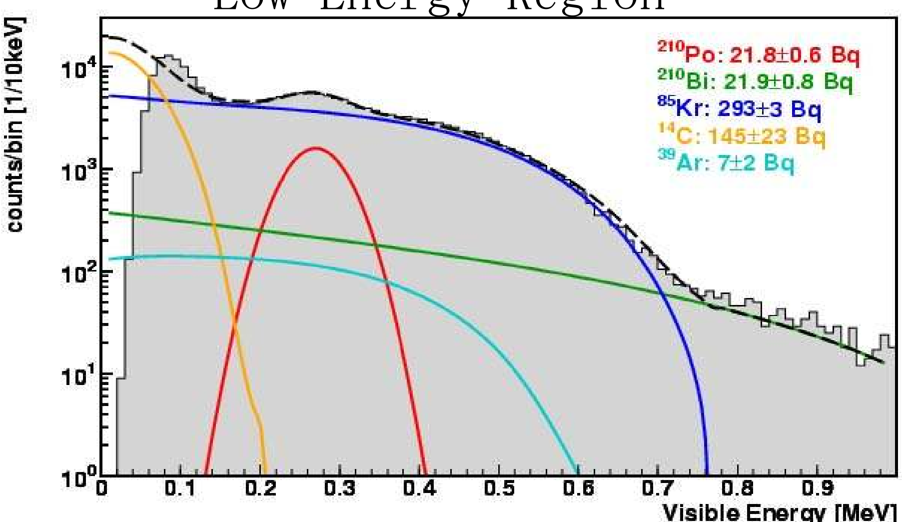
Normal Trigger Range



Event Vertices



Low Energy Region



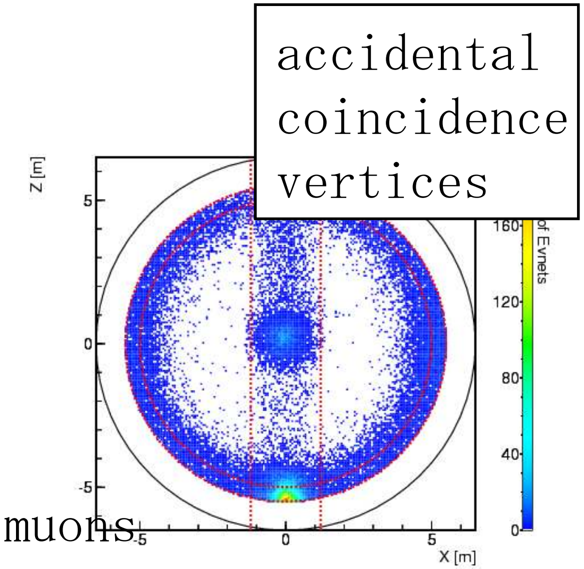
Major Background Sources:

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

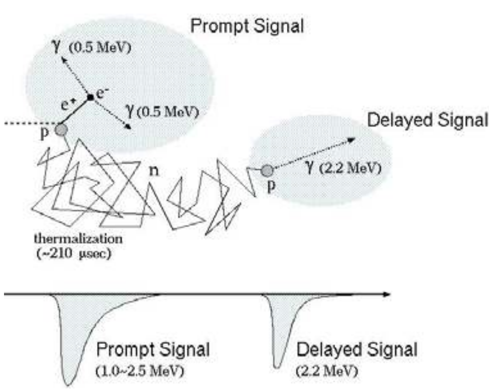
Measured LS impurity:

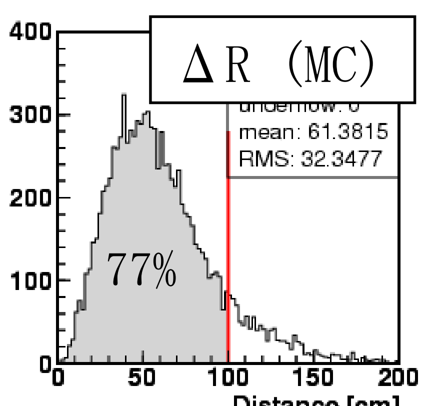
- U: 3.5×10^{-18} g/g
- Th: 5.2×10^{-17} g/g

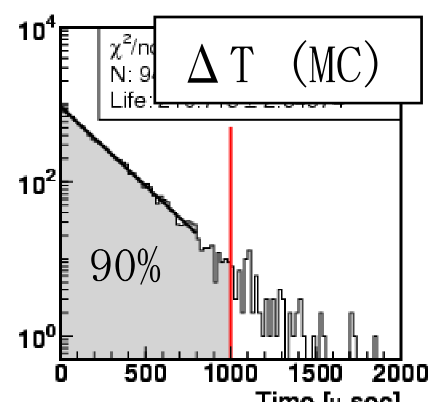
Event Selection

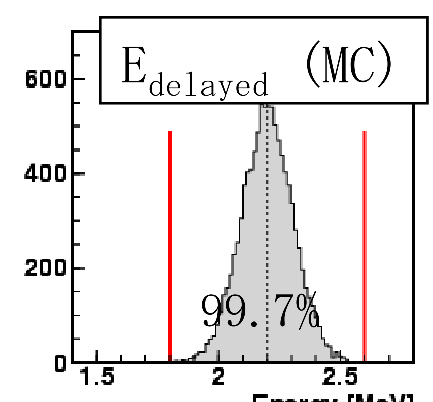


- Fiducial Volume
  - selects 500 cm radius from center
  - removes 120 cm radius from vertical axis
- Muon Spallation Cut (^{9}Li etc)
  - 2sec full volume veto following showering muons
  - 2sec 3m-cylindrical veto following non-showering muons
- Coincidence Event Selection
  - Distance： 0 < ΔR < 100cm
  - Interval： 0.5 μsec < ΔT < 1000 μsec
  - Delayed Signal Energy： 1.8 MeV < $E_{delayed}$ < 2.6 MeV





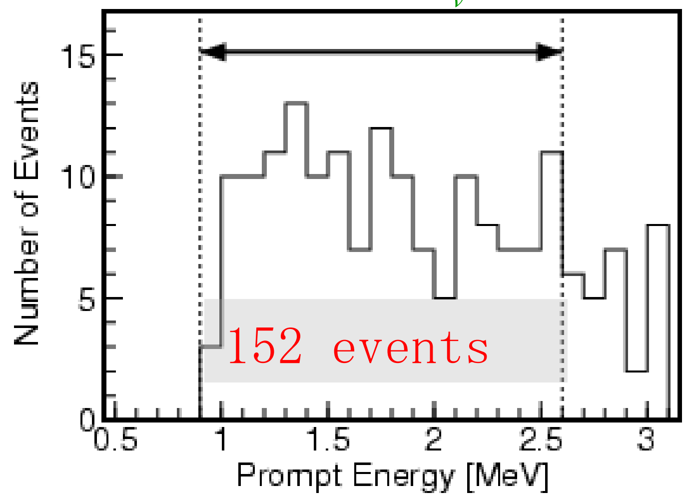




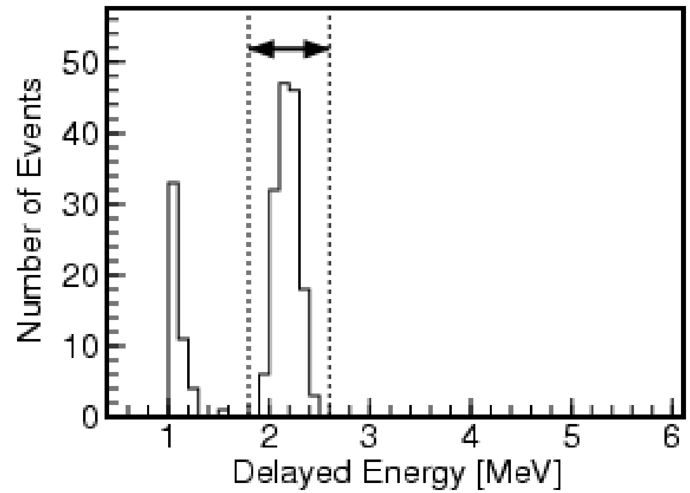
Selected Candidates Summary

- Livetime: 749.14 days
- # of protons: 3.459×10^{31}

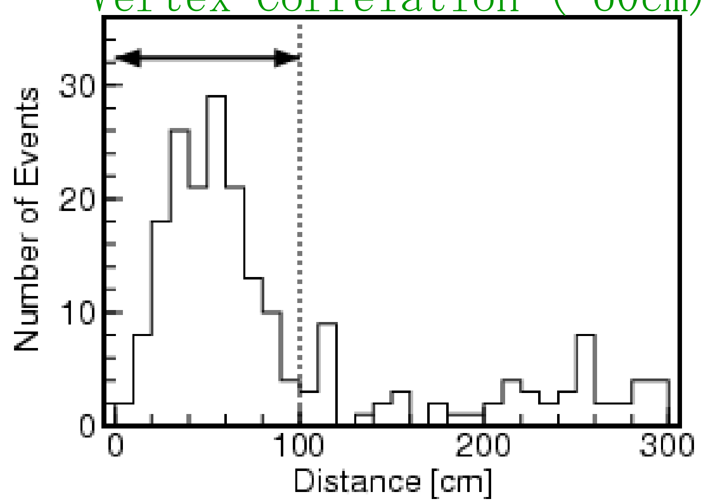
Prompt Signal ($E_{\nu} - 0.8$MeV)



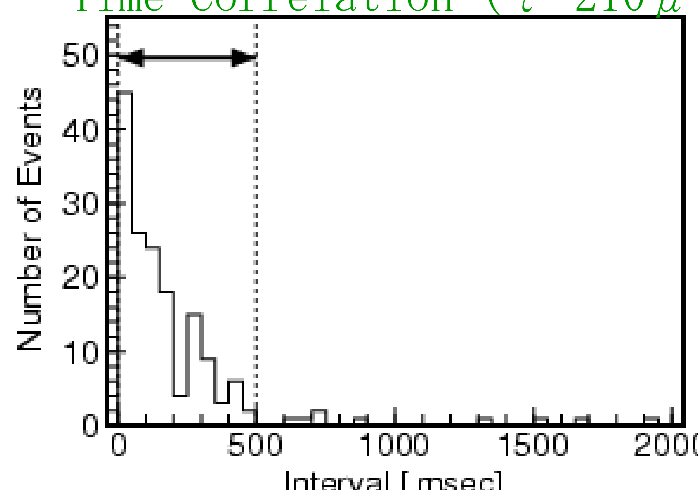
Delayed Signal(2.2MeV)



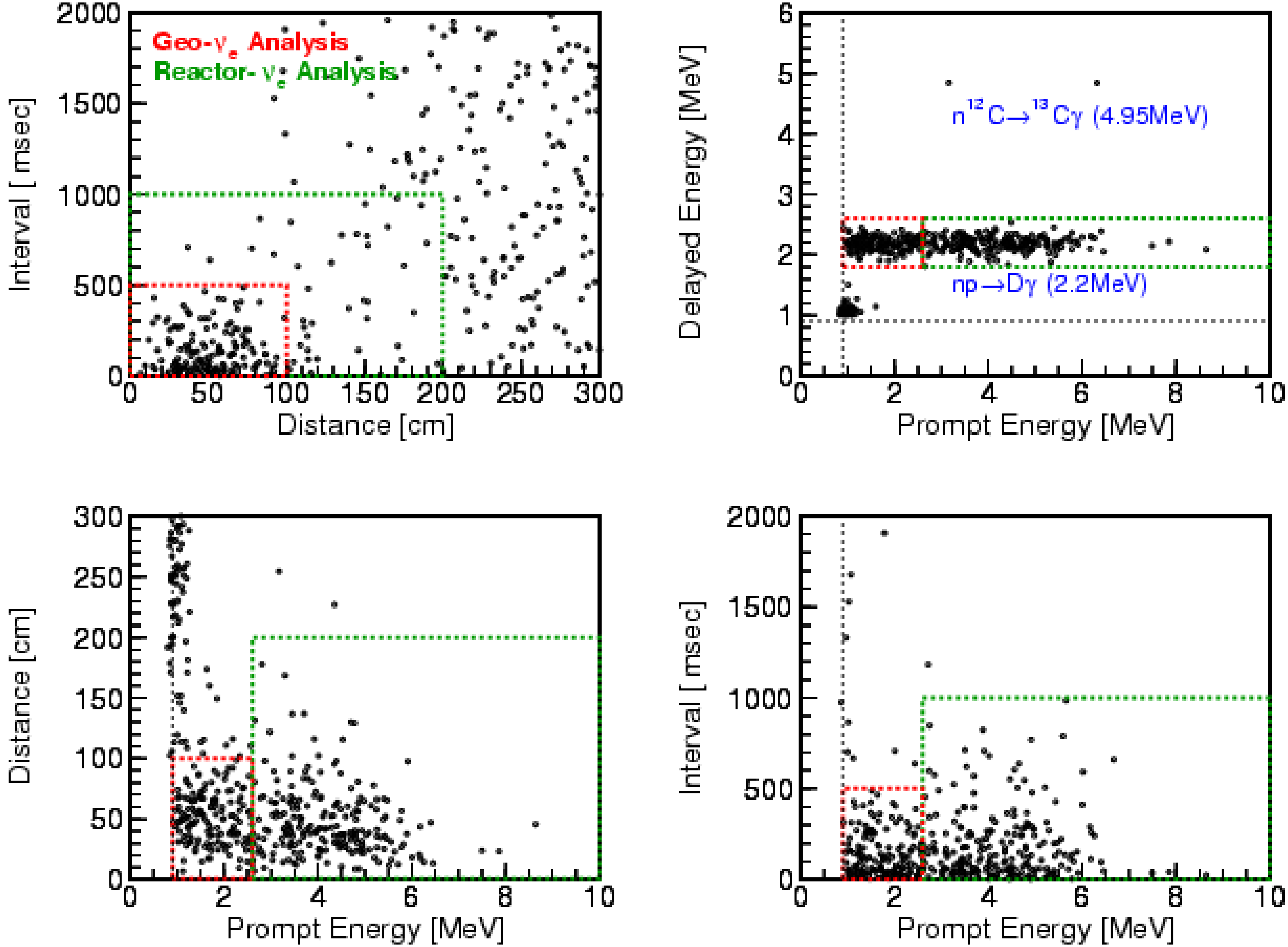
Vertex Correlation (~60cm)



Time Correlation (τ=210μs)



Selected Candidates Summary (N-2 plot)



Backgrounds Overview

- Neutrinos
  - Reactor : 80.4±7.2
  - Spent Fuel (Ru, Ce, St) : 1.9±0.2

- Accidental Coincidence : 2.4±0.0077

- Correlated Signals
  - Muon spallation products (^{9}Li, ...): 0.30±0.047
  - Fast neutron (from outside): < 0.1

  - Cascade decay (Bi-Po, ...)
  - Spontaneous Fission (^{238}U, ...)
  - Neutron Emitter (^{210}Tl, ...)
  - (α, n) Reaction, (γ, n) Reaction
  - Deuteron disintegration by solar neutrinos
  - Atmospheric neutrino interaction with ^{12}C

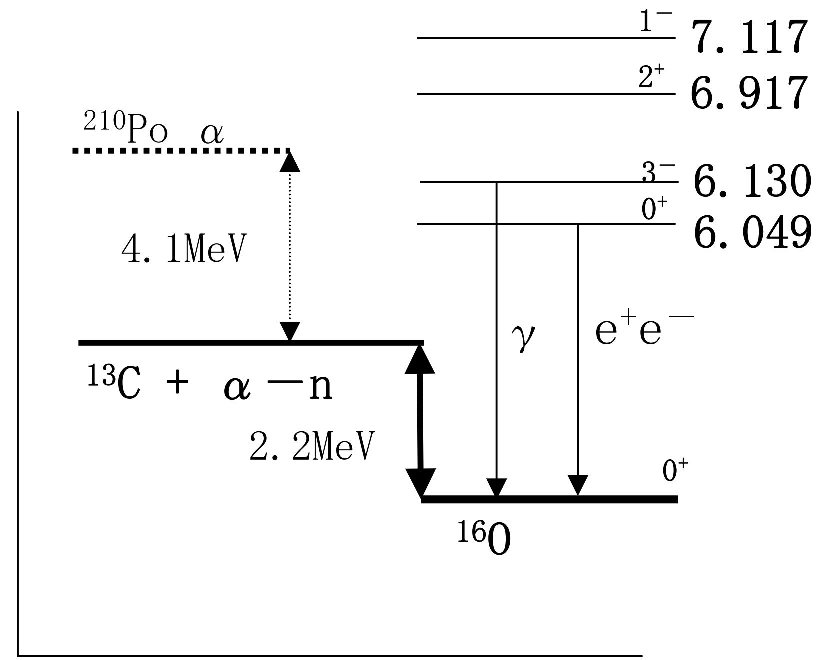
(α, n) Reaction Background Overview

α-decays of LS impurity

^{210}Pb → ^{210}Bi → ^{210}Po → ^{206}Pb

^{210}Pb	^{210}Bi	^{210}Po	^{206}Pb
22.3 y	5.013 d	138.4 d	stable

⇓ α



- $^{13}C(\alpha, n)^{16}O$
- $^{13}C(\alpha, n)^{16}O^*$
- $^{14}N(\alpha, n)^{17}F$
- $^{15}N(\alpha, n)^{18}F$
- $^{17}O(\alpha, n)^{20}Ne$
- $^{18}O(\alpha, n)^{21}Ne$

$^{16}O^*(6.13) \rightarrow {}^{16}O + \gamma$

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

⇒ n

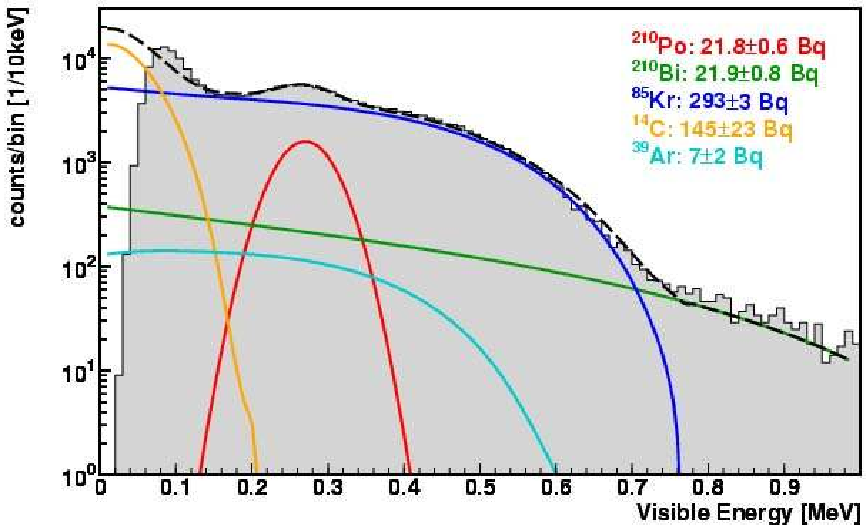
$n + p \rightarrow n + p$

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

↳ $^{12}C + \gamma$ (4.4M

prompt signals

(α, n) Reaction Backgrounds : ^{210}Po Decay Rate



^{210}Po decay rate:

21.1 Bq

1.50×10^{9} decays/livetime

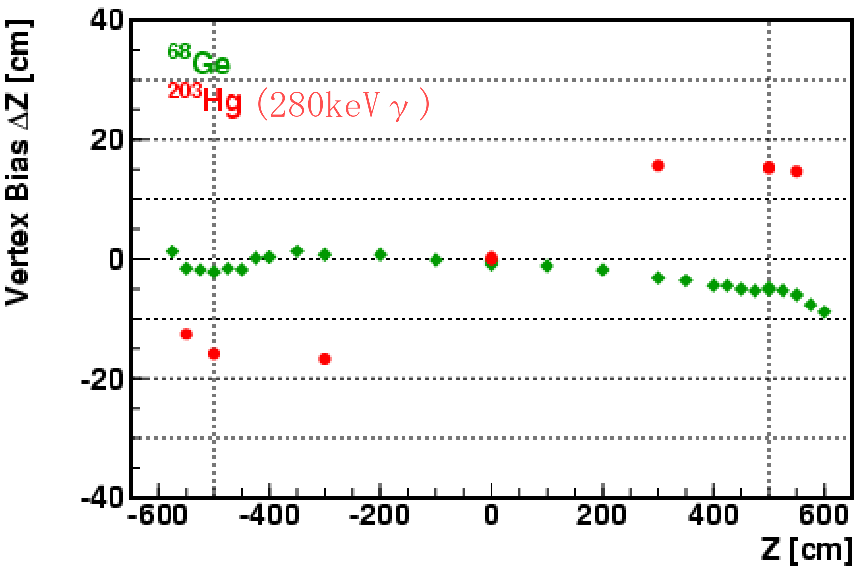
Uncertainties:

Energy scale uncertainty

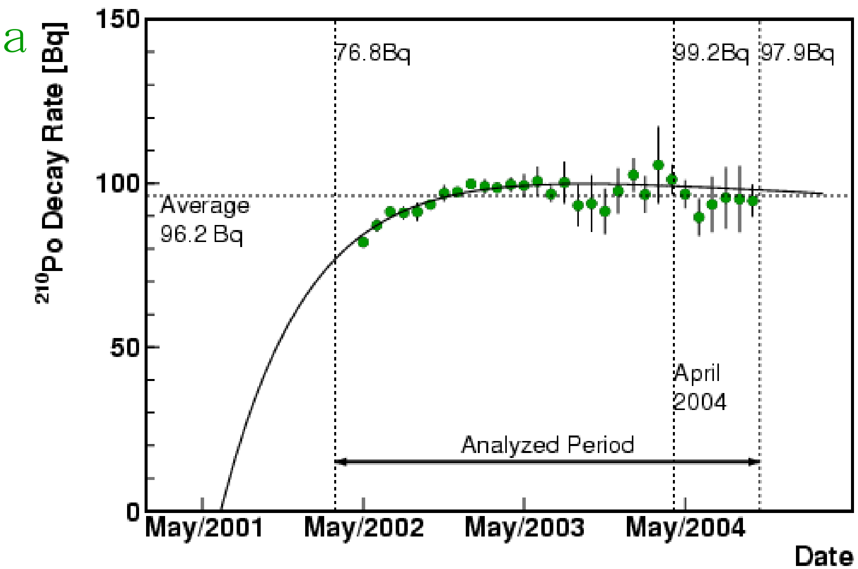
Vertex bias at low-energy region

^{210}Po decay rate non-equibrilum

⇒ 14% systematic error

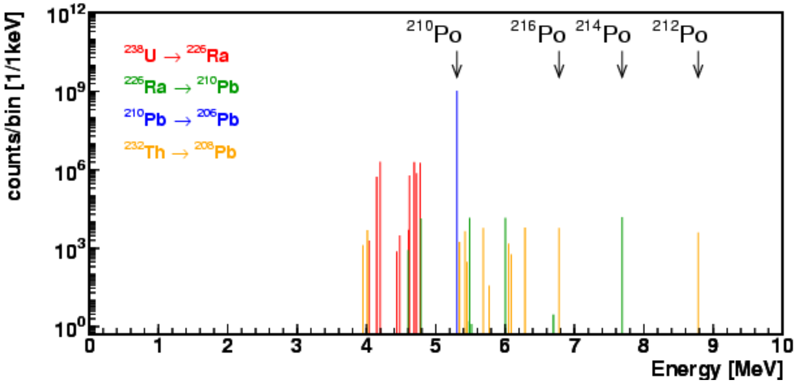


a

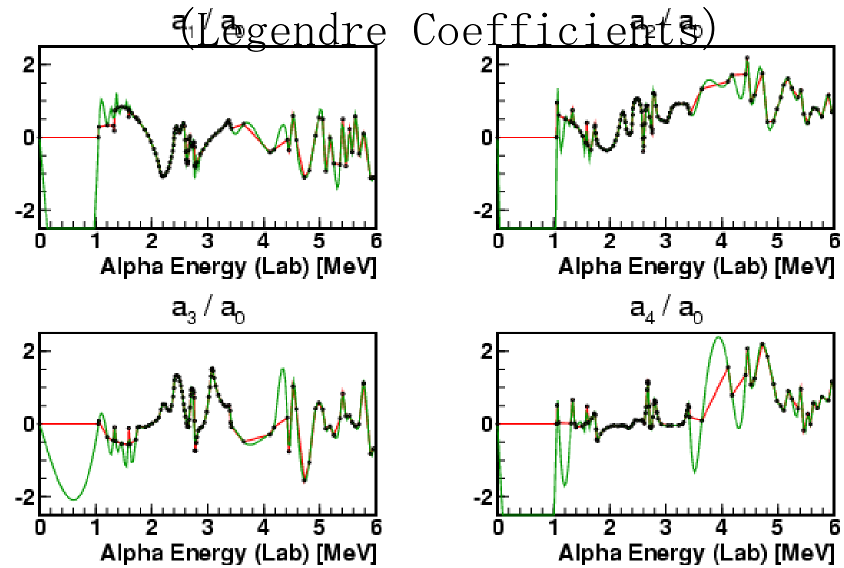


(α, n) Reaction Background : Neutron Generation

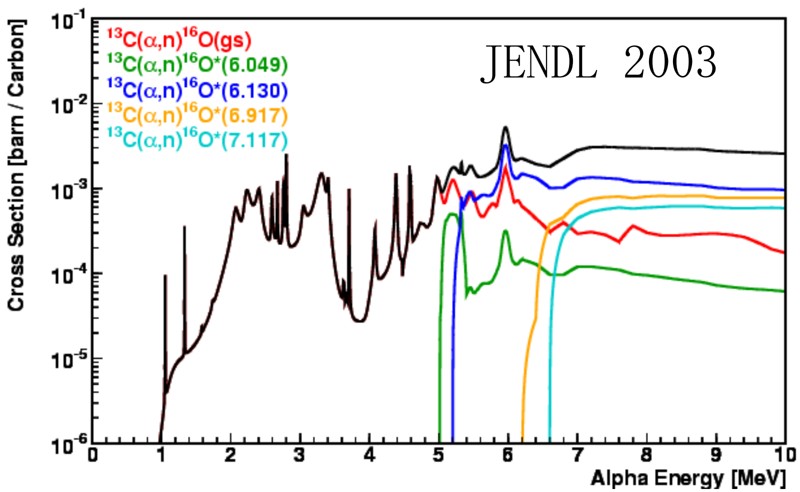
α Spectrum in LS



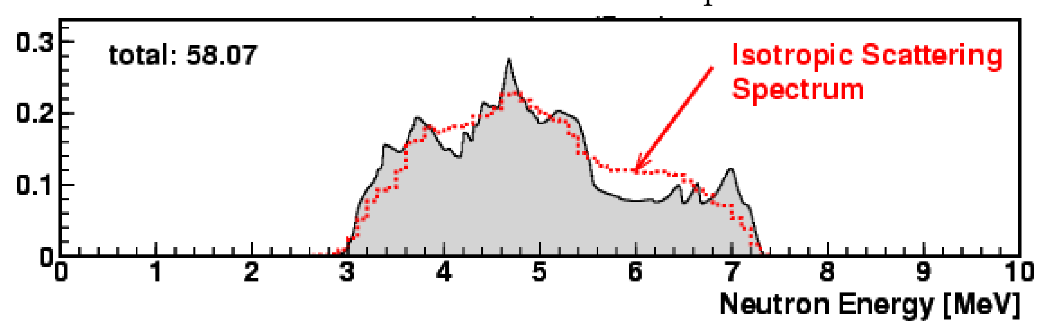
$^{13}C(\alpha, n)$ angular distribution (Legendre Coefficients)



$^{13}C(\alpha, n)$ Cross Section



Calculated Neutron Spectrum



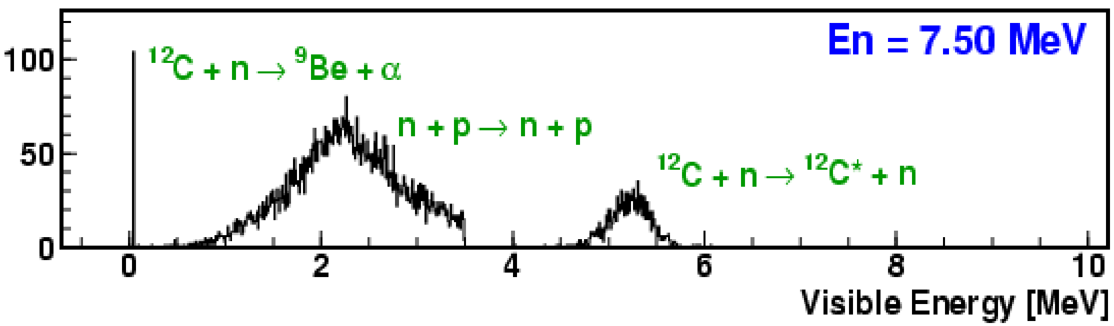
Uncertainties:

(α, n) cross section, branching ratios, angular distribution

$\Rightarrow$ 20% error

(α,n) Reaction: Proton Scattering and Visible Energy

Neutron Visible Energy Calculation (MC)

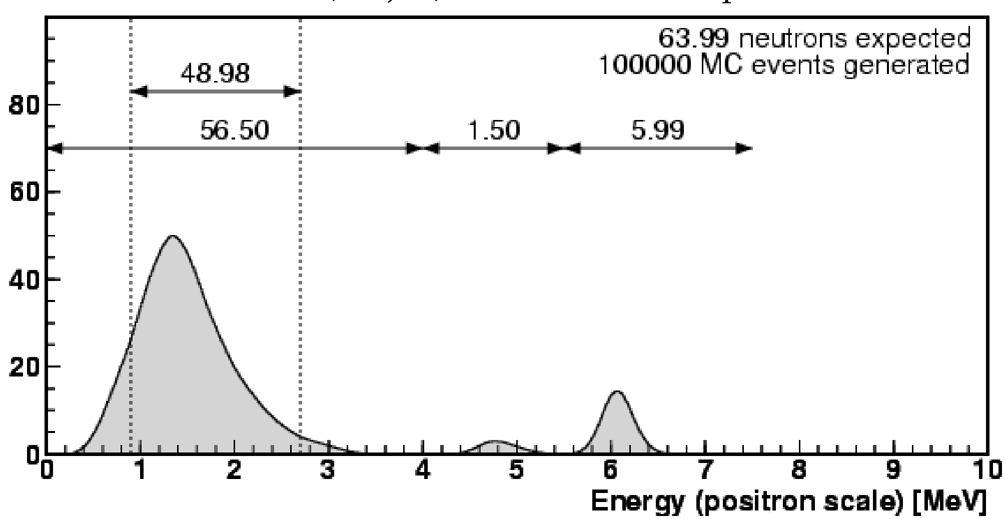


- n-p scattering (MC)
- proton energy loss (numerical)
- scintillation light production

$$dN = \frac{1}{1 + k_b \frac{1}{\rho}\frac{dE}{dx} + C\left(\frac{1}{\rho}\frac{dE}{dx}\right)^2 + \ldots} dE$$

- no direct measurement available for proton quenching factor
- Birks constant uncertainty (calculation requires lots of details)

Calculated (α,n) Reaction Spectrum



Uncertainties:

proton quenching factor

(α,n) angular distribution

$\Rightarrow$ 10% horizontal error

Summary of Backgrounds

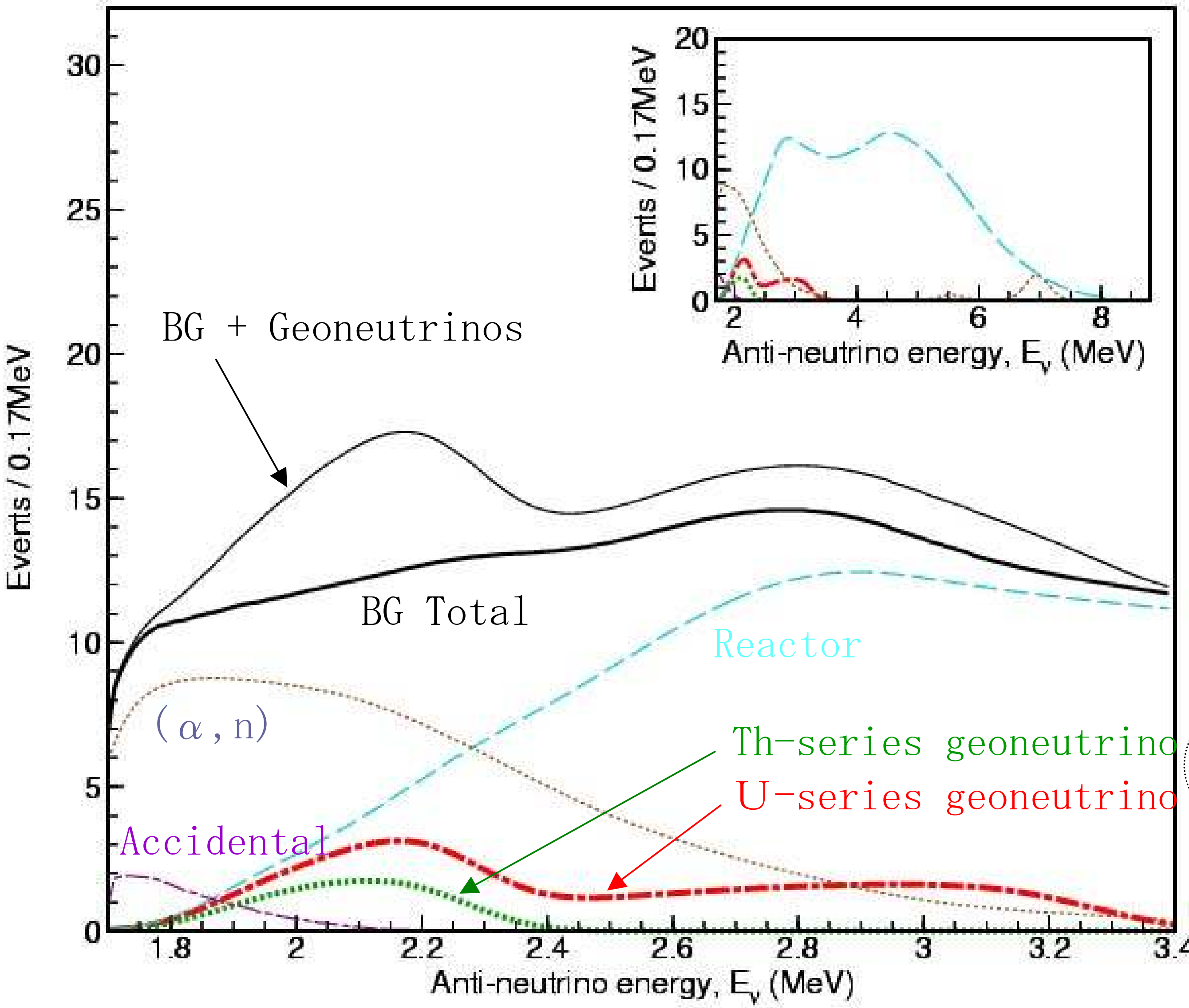
- Neutrinos
  - Reactor: 80.4±7.2
  - Spent Fuel : 1.9±0.2
- Cosmic Muon Induced
  - Fast neutron (from outside): < 0.1
  - Spallation products (^{9}Li): 0.30±0.047
- Radioactive Impurity
  - Accidental coincidence 2.38±0.0077
  - Cascade decay negligible
  - Spontaneous fission < 0.1
  - (α,n) reaction 42.4±11.1
  - (γ,n) reaction negligible

152 events observed

total: 127.4 ± 13.3

(syst.)

Expected Spectrum

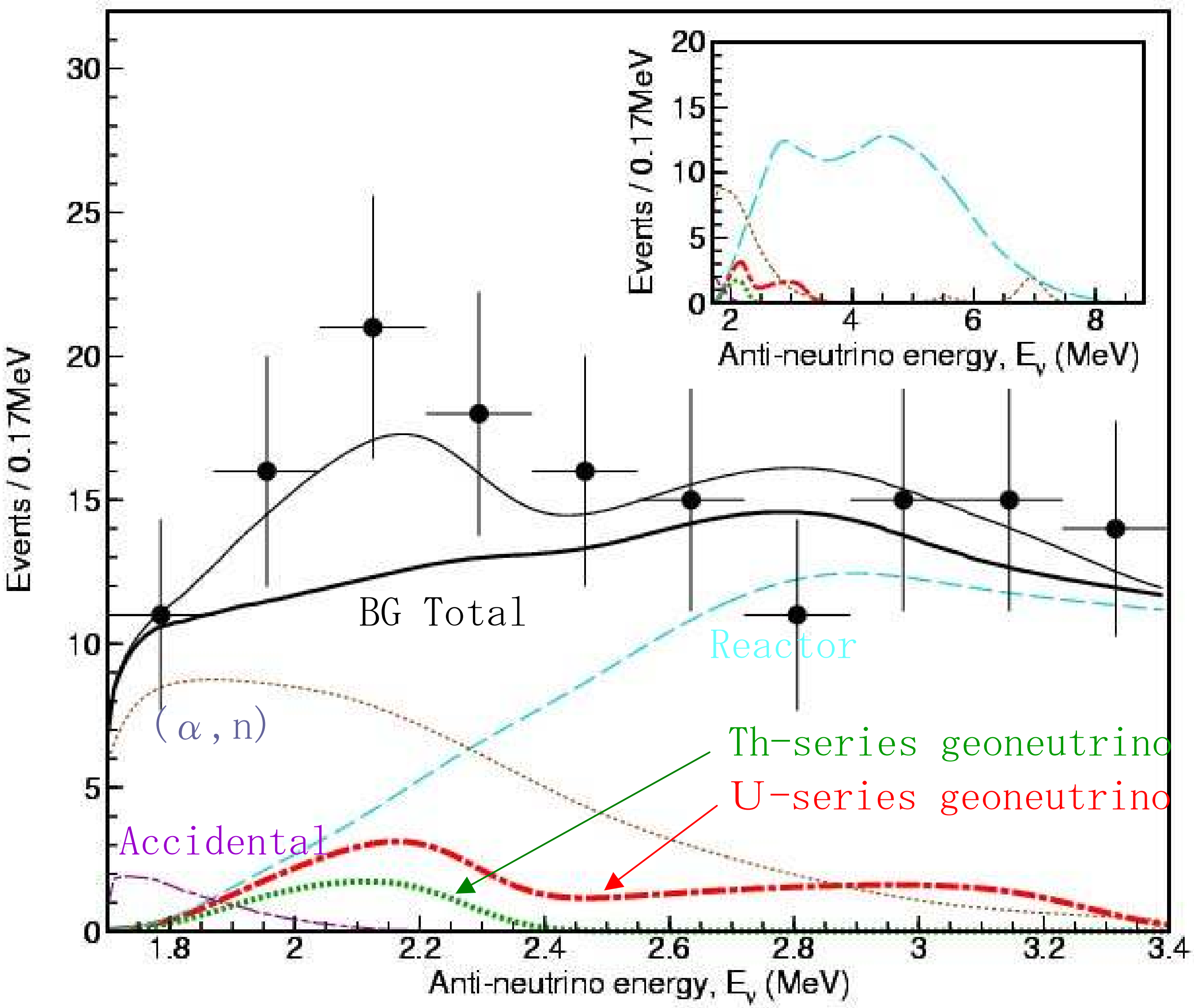


Predicted number by our Earth model

(4.0 events)

(14.9 events)

KamLAND Observation

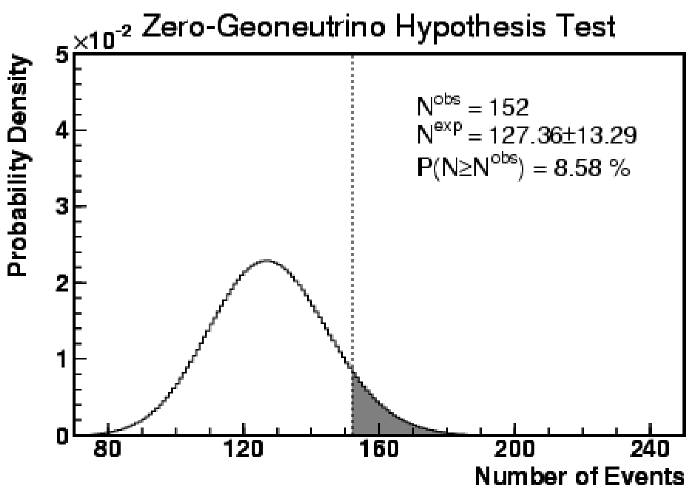


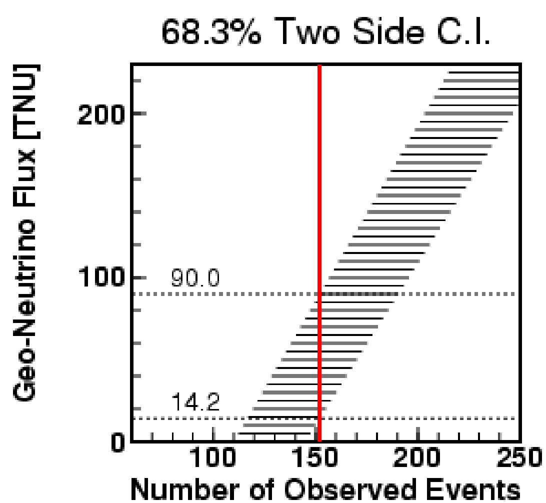
Event Rate Analysis

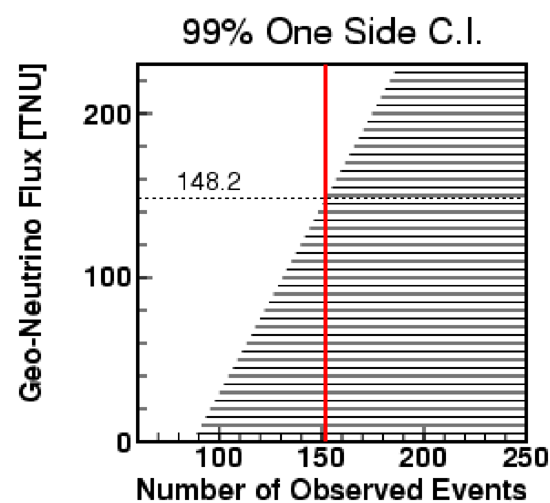
- observed: 152
- backgrounds: 127.4 ±13.3 (syst.)
- excess: 24.6±17.9
- systematic error: 5.0% (mainly FV; large correlation with backgroun

$$P(N;F_{\mathrm{geo}})=\int_{\nu} d\nu\left(\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(\nu-N^{\mathrm{expexted}})^2}{2\sigma^2}}\times\frac{\nu^N e^{-\nu}}{N!}\right)$$

Probability of observing N-events under given neutrino flux F_{geo}



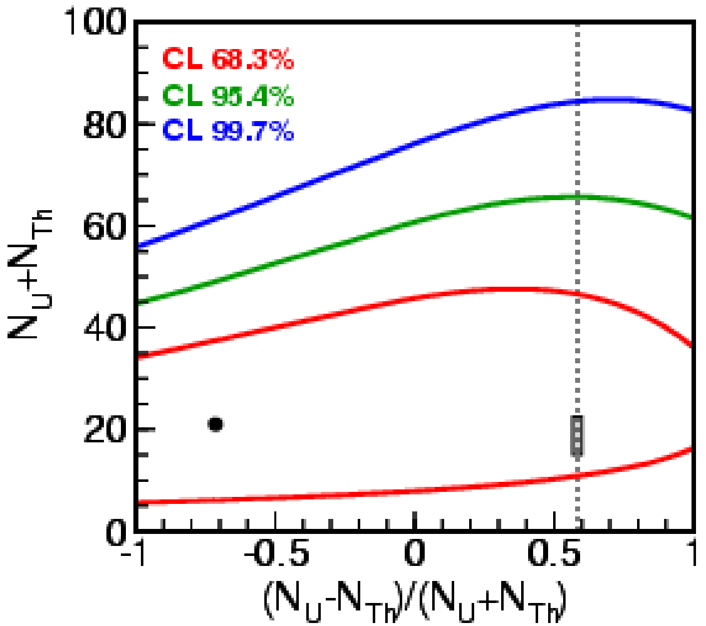




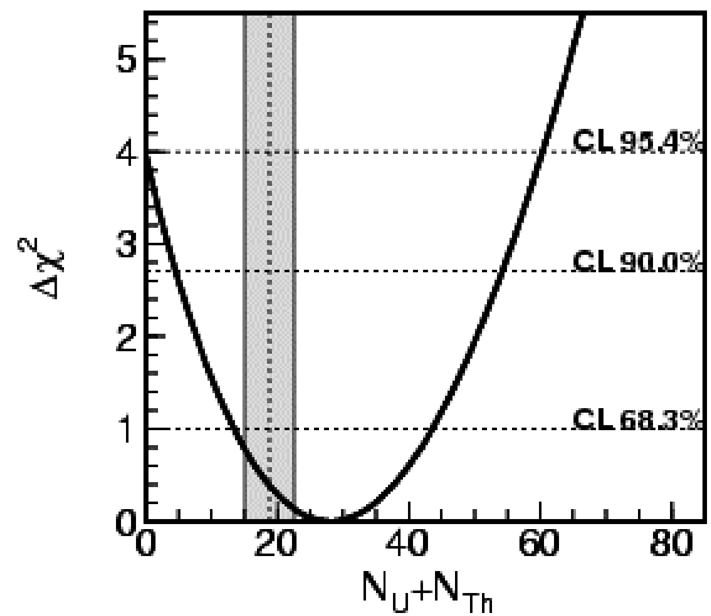
- significance: 91.4%
- geoneutrino events: 25^{+19}_{-18} (19 predicted by Earth models)
- 99% C.L. upper limit: 72 events

Unbinned Spectrum Shape Analysis

$$\chi^2_{\rm shape} = -2\log\prod_k \frac{dP(E_k; N_U, N_{Th}, {\rm BG-parameters})}{dE} + \chi^2_{\rm BG-parameters}$$

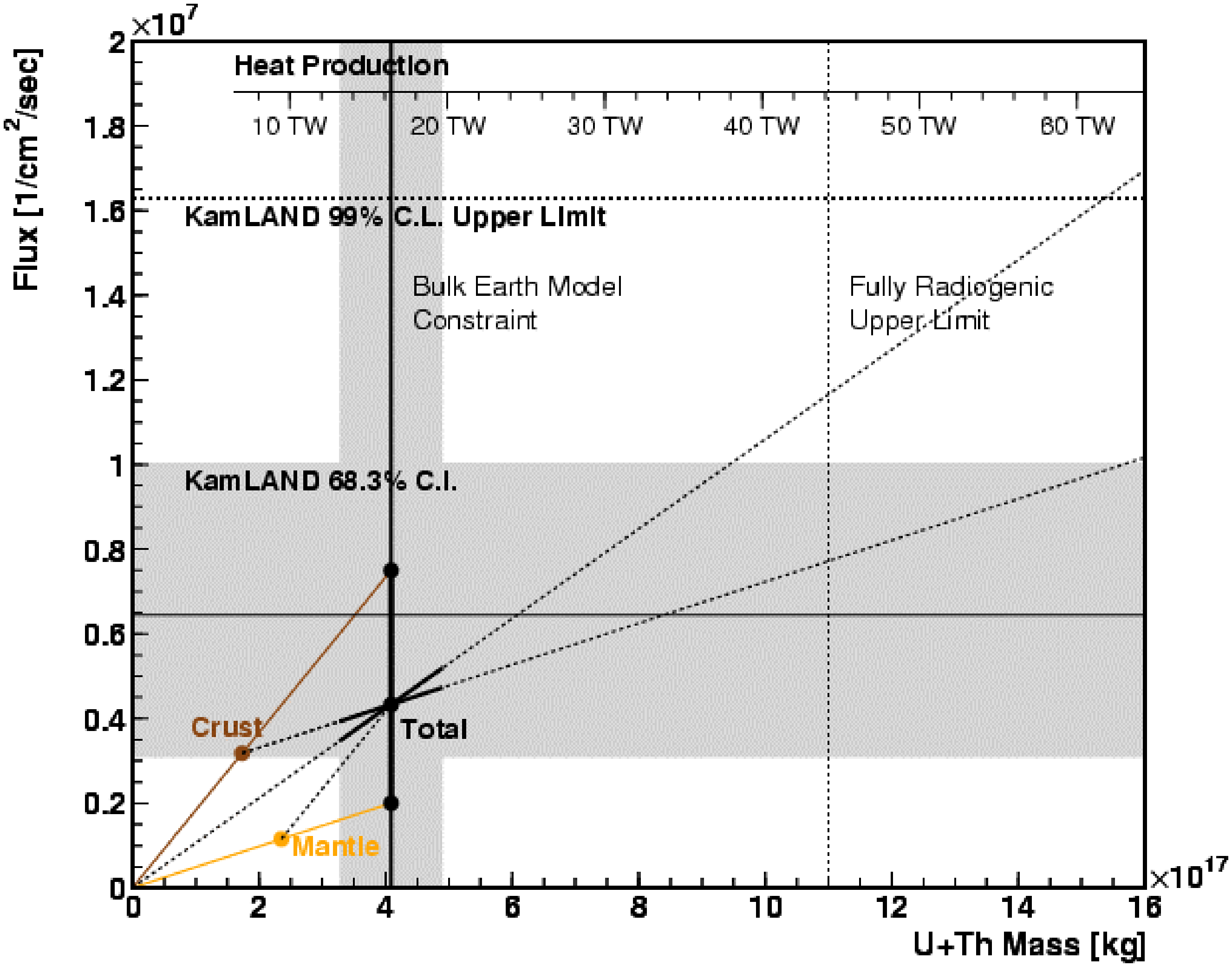


Incorporates Th/U = 3.9 constraint



- 90% confidence interval: 4.5 to 54.2
- 99% C.L. upper limit：70.7
- N_{geo}=0 excluded at 95.3%(1.99σ)

Comparison with Earth Model Prediction



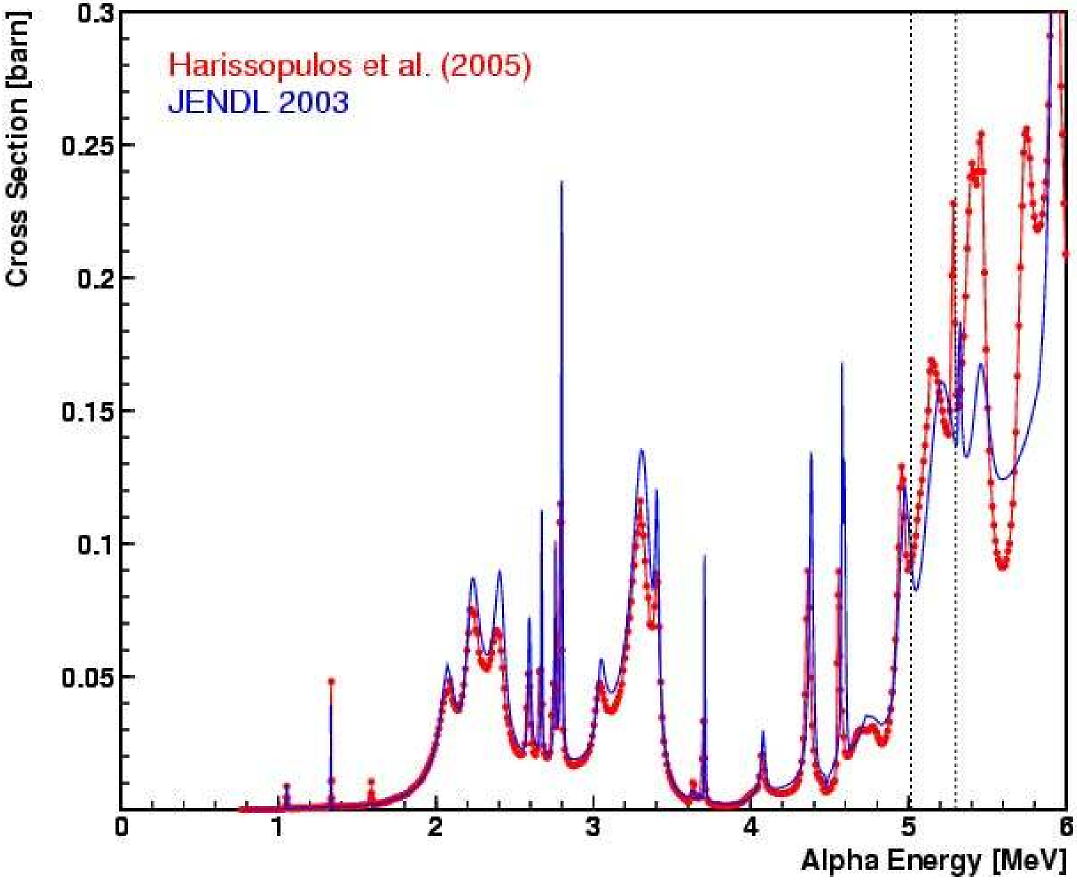
- KamLAND result is consistent with Earth model predictions
- 99%C.L. limit is outside of Earth model constraints

KamLAND Future Prospects

- (α, n) background study improvements
  - Better cross section data now available
  - Proton quenching will be measured
  - Alpha-source calibration being considered
- Further LS purification
  - Removes radioactive impurities at 10^4~10^6
  - Reduces backgrounds, increases efficiency

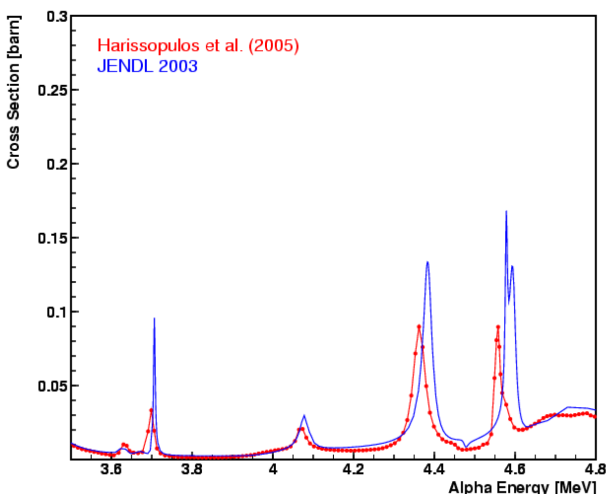
New (α, n) Cross Section Data

New measurement by Harissopulos et al. (2005)
22 μg/cm² Carbon target with 99±2% ^{13}C enrichment



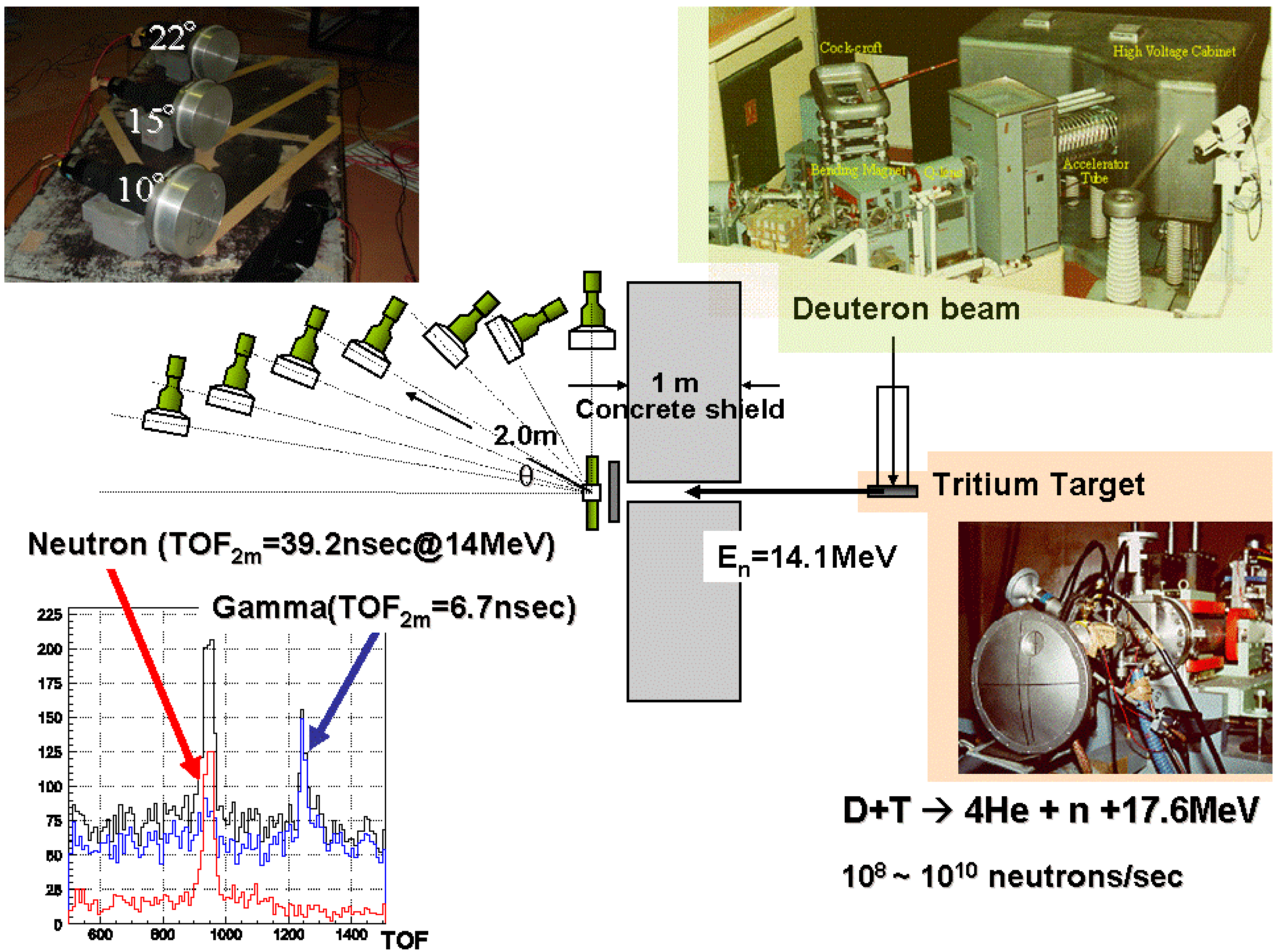
- Reduces systematic error from 20% to 4%
- Lowers neutron yield (5%) ?

- Some data still missing:
  - branching to excitation
  - angular distribution



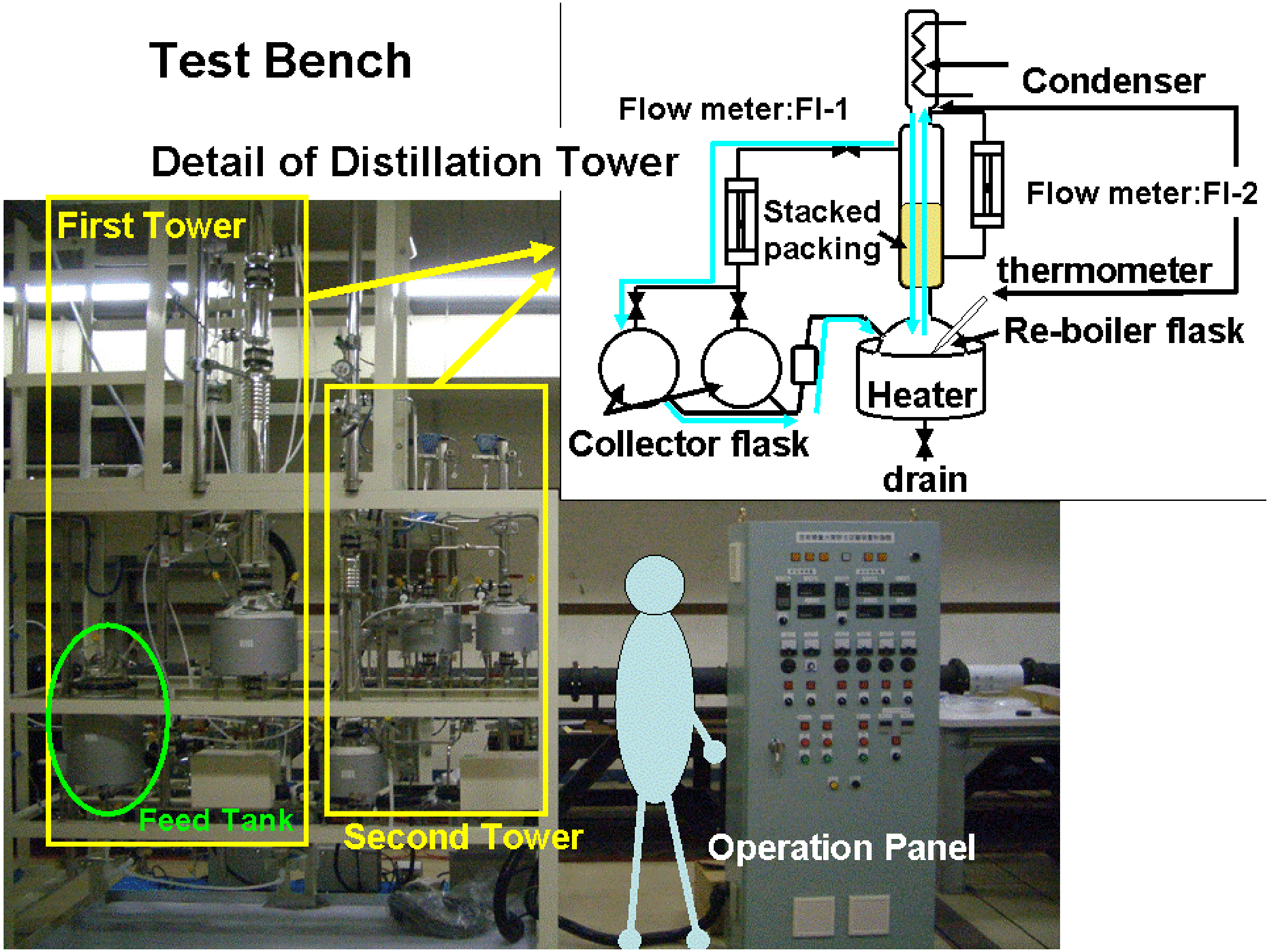
Proton Quenching Factor Measurement

Mono-energetic neutron beam from OKTAVIAN at Osaka University

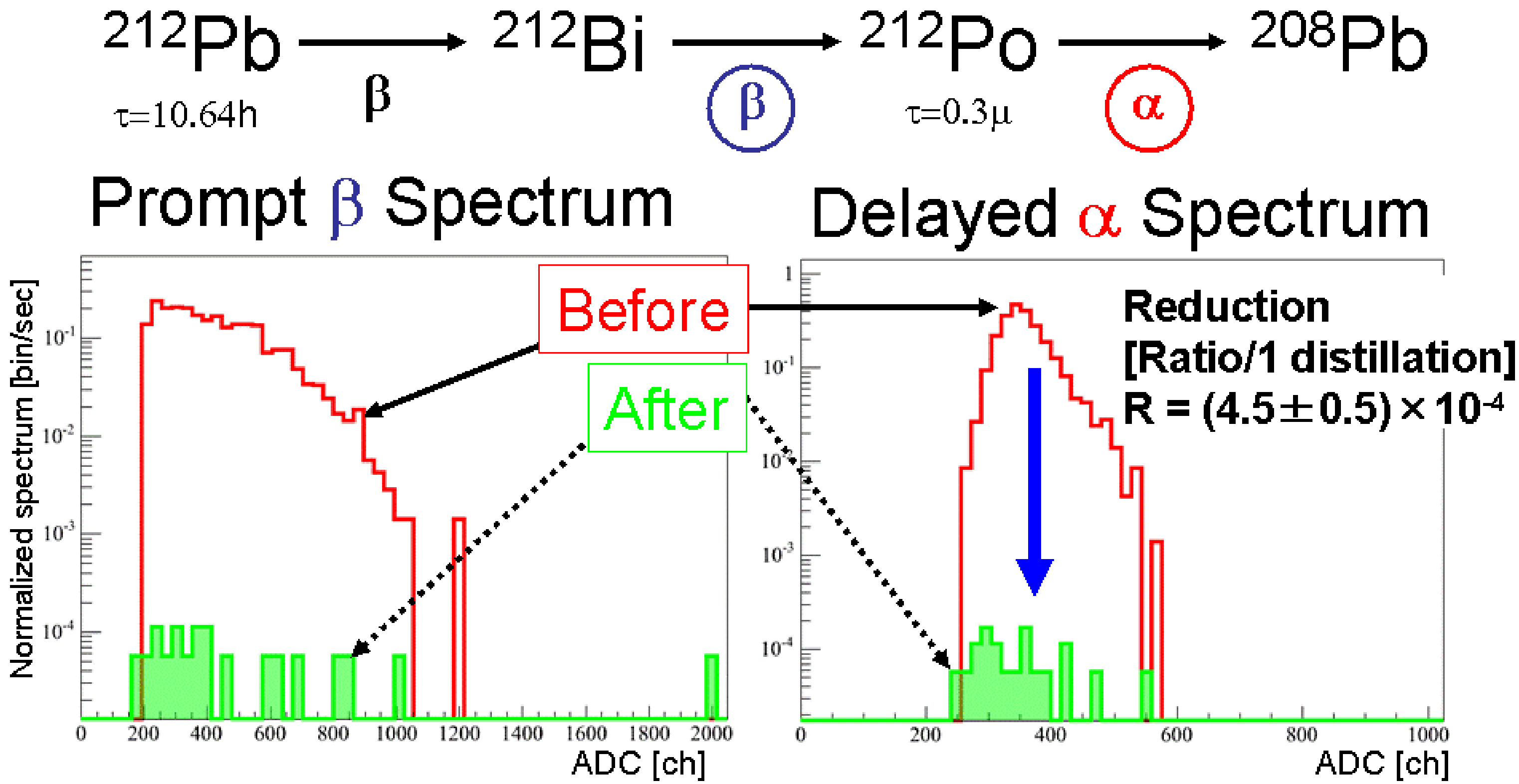


LS distillation for the KamLAND solar phase

Removes radioactive impurities at 10^4~10^6

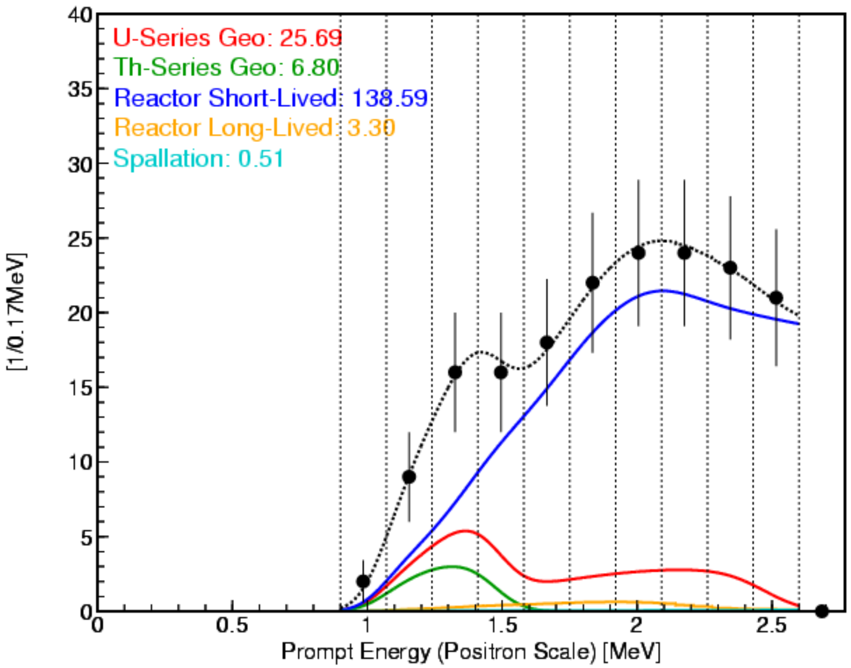


Current Achievement

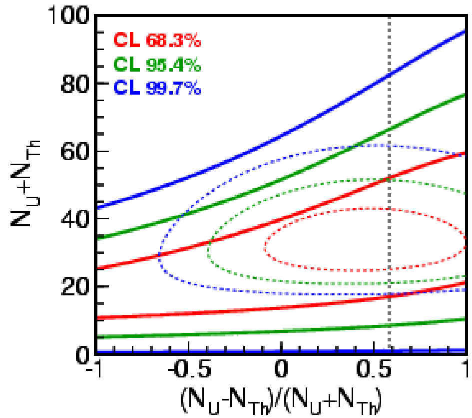


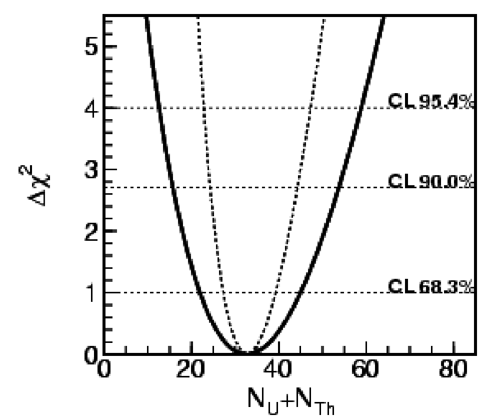
$(4.5 \pm 0.5) \times 10^{-4}$ Reduction of Pb

KamLAND Prospect After Purification



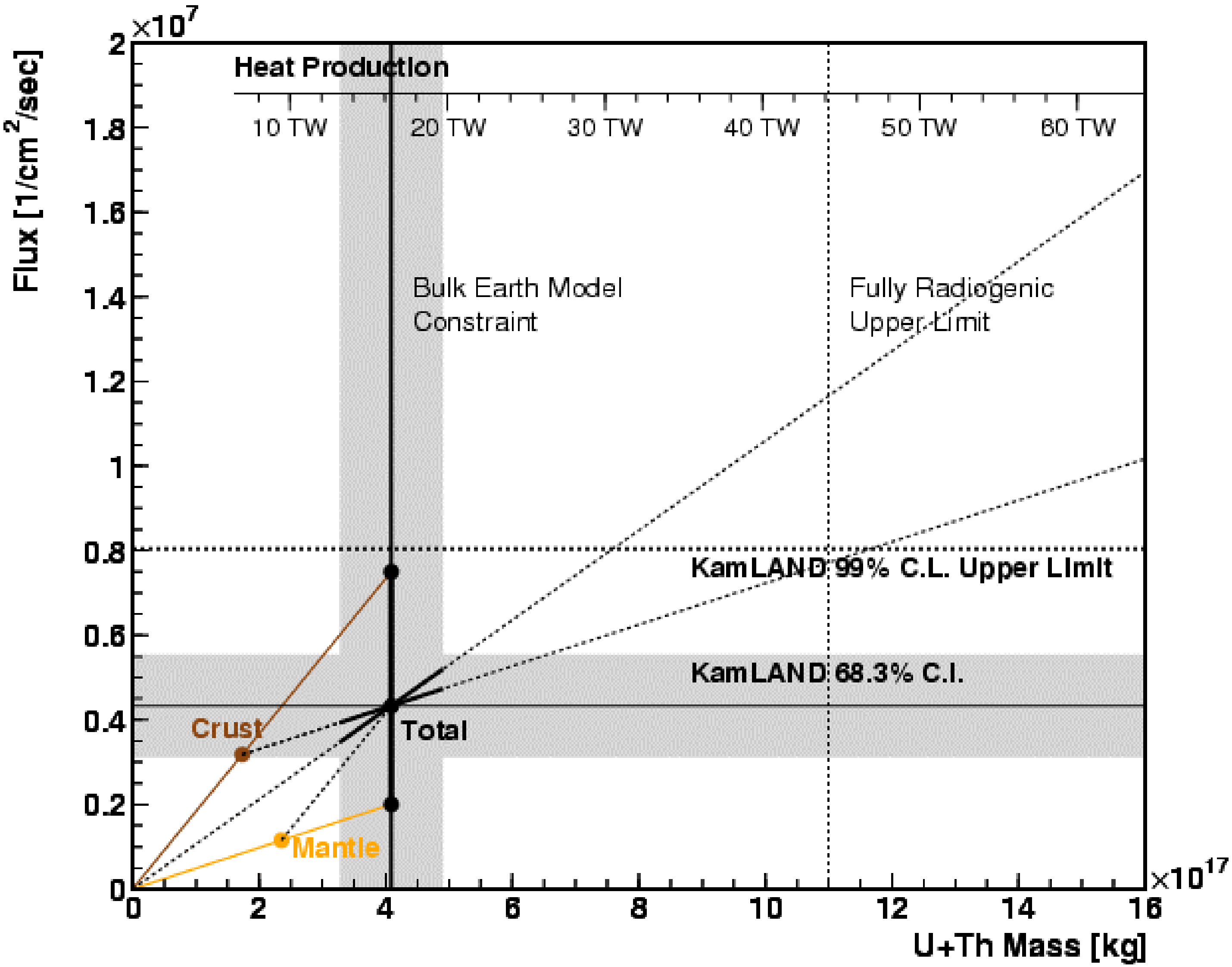
Assuming
- 10^{-5} background reduction
- 749 days exposure
- Increased Fiducial Volume (5.5m)
- Improved Efficiency (90%)





- Error is reduced from 54% to 28%
- Significance : 99.96%
- Error is dominated by reactor neutrino statistics

KamLAND Future Prospect



Summary

- KamLAND achieved the first experimental study of neutrinos

- 749 days exposure of KamLAND results
  - ✓ 90% Confidence Interval: 4.5 to 54.2
  - ✓ 99% C.L. upper limit: 70.7
  - ✓ Consistent with predictions by Earth models

- A number of improvements are in progress