Precision Measurement of Neutrino Oscillation Parameters with KamLAND

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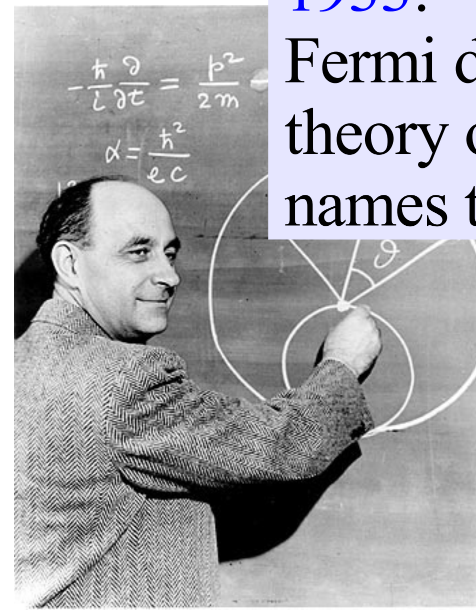
Nov. 29, 2007

Overview

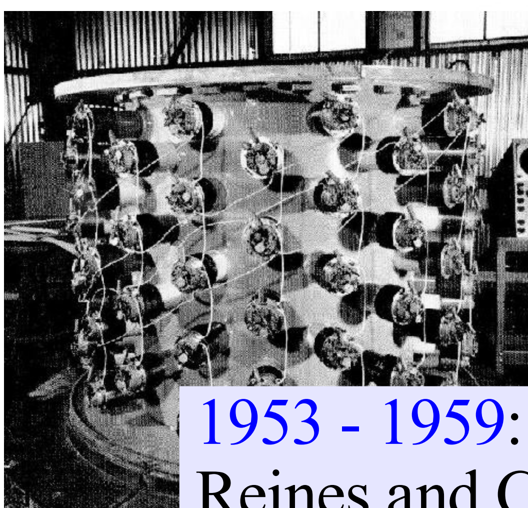
- **History:**
  - Neutrinos and the Solar Neutrino Problem
- **KamLAND:**
  - Previous Results
  - Recent Improvements
  - Future Prospects

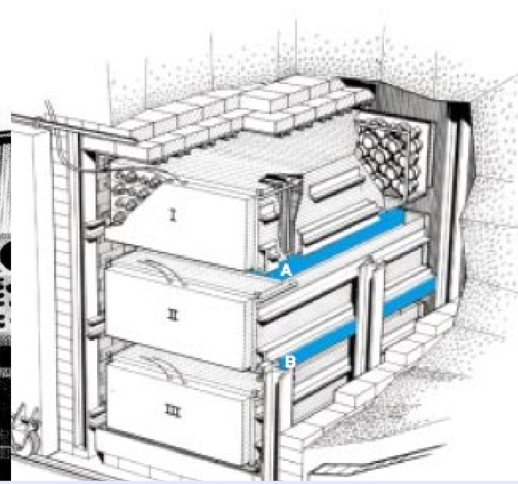
History of Missing Neutrinos

1930:
Pauli proposes neutral fermion.

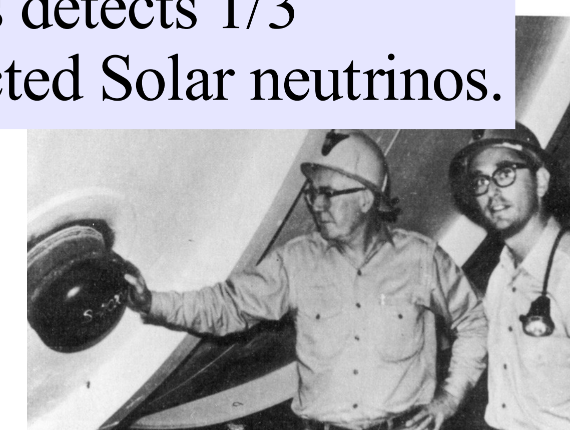


1933:
Fermi develops theory of beta-decay, names the '*neutrino*'.





1953 - 1959:
Reines and Cowan detect neutrinos from nuclear reactors.



1968:
Davis detects 1/3 expected Solar neutrinos.

What's wrong with the Sun?

Solar experiments continue to show deficit.

<u>Chlorine:</u>
- Homestake

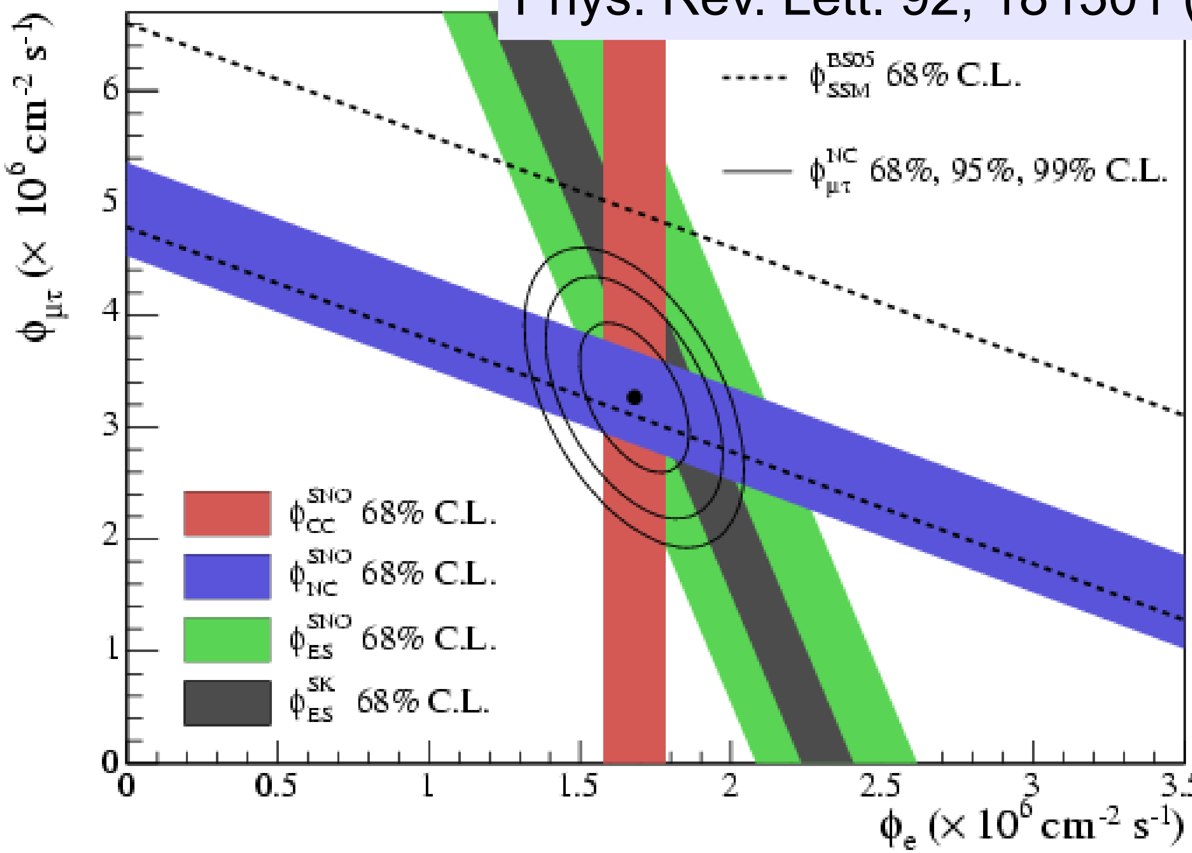
<u>Gallium:</u>
- Sage
- Gallex/GNO

<u>Water-Cherenkov:</u>
- Kamiokande
- Super-K: 0.41 ± 0.04

SNO shows evidence for flavor-change!

Phys. Rev. Lett. 89, 011301 (2002).

Phys. Rev. Lett. 92, 181301 (2004).



Neutrino Oscillation

Neutrinos change character based on perspective!

Interaction eigenstates
≠ Mass eigenstates

$$|\nu_e\rangle = \sum_{m_i} U^*_{ei} \; |\nu_i\rangle$$

Pontecorvo (1957):
ν / anti-ν oscillation

Maki, Nakagawa, and Sakata (1962):
Flavor oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

$\Delta m^2_{12} = m^2_1 - m^2_2$

θ_{12} mixing angle

L is distance from source
E is neutrino energy

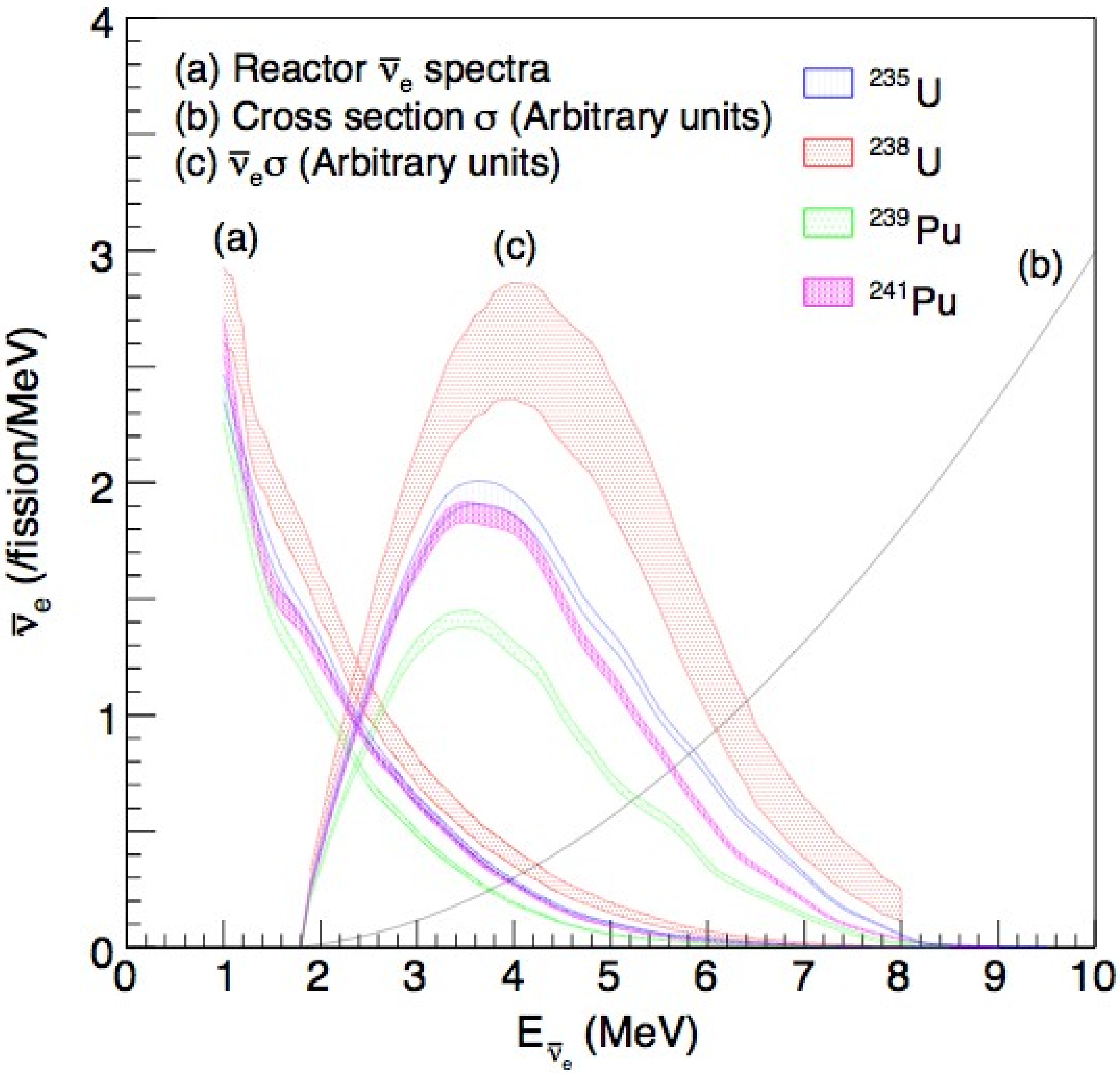
What about Reactor neutrinos?

- Probe the Solar Neutrino Oscillation with Reactor Neutrinos
  - Need long baseline:

$$L \sim L_{osc} \sim \frac{E(MeV)}{\Delta m^2_{solar}(eV^2)} \sim 100\,km$$

Solar experiments	**Reactor experiments**
Neutrinos: ν_e	Anti-neutrinos: $\overline{\nu}_e$
Distance: 1.5 x 10^8 km	Up to 100s km
Propagation: ν's travel through dense matter	Very little matter
Model prediction: Solar model	Reactor model

Reactor Neutrinos



Reaction Process: inverse β-decay

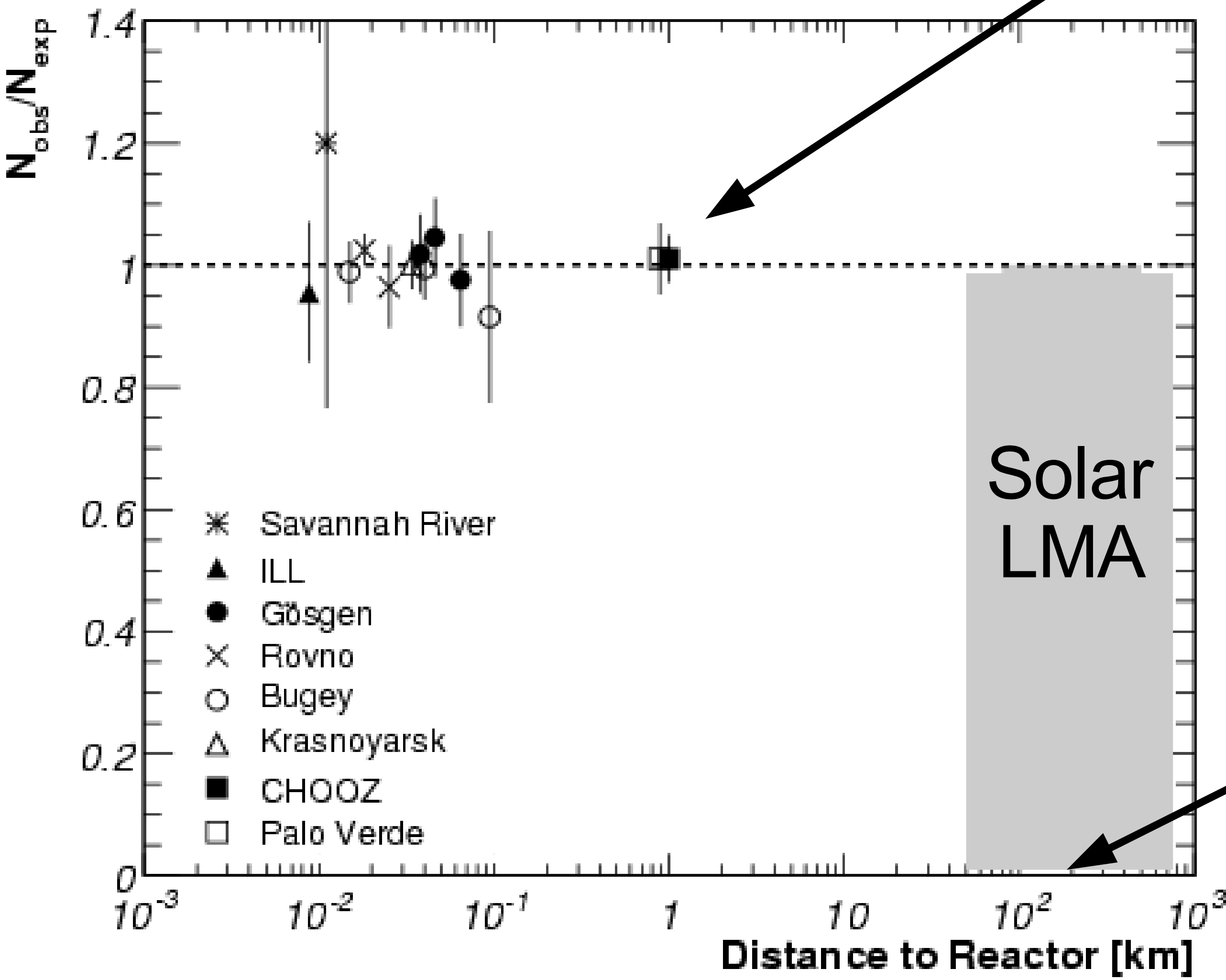
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Threshold: 1.8 MeV

$$E_{e^+} \approx E_\nu - 0.8\ MeV$$

Oscillation Searches at Reactors

$E \approx 1\, MeV, \quad L_{max} \approx 1\, km, \quad Sensitivity\ \Delta m^2 \Rightarrow 10^{-3}\, eV^2$

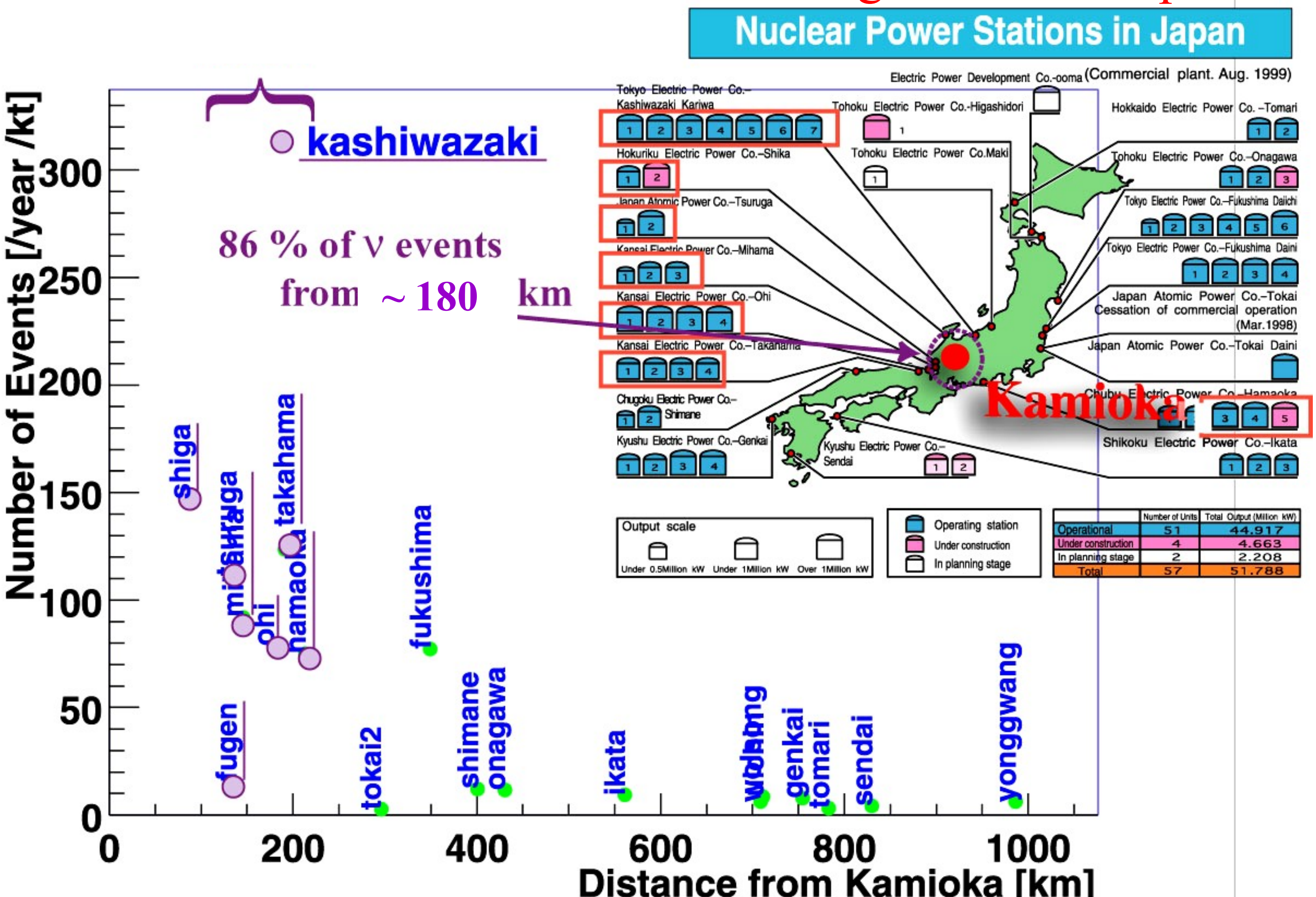


Measured spectra within ~2% of expected

Signal rate falls $1/L^2$

Surrounded by Reactors

~12% of global nuclear power



KamLAND Collaboration

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- **Lawrence Berkeley National Laboratory / University of California, Berkeley**: M.P.Decowski, J.A. Detwiler, S.J.Freedman, B.K.Fujikawa, F.Gray, K.M.Heeger, L.Hsu, R.Kadel, K.-B.Luk, H.Murayama, T.O'Donnell, H.M.Steiner, L.A.Winslow
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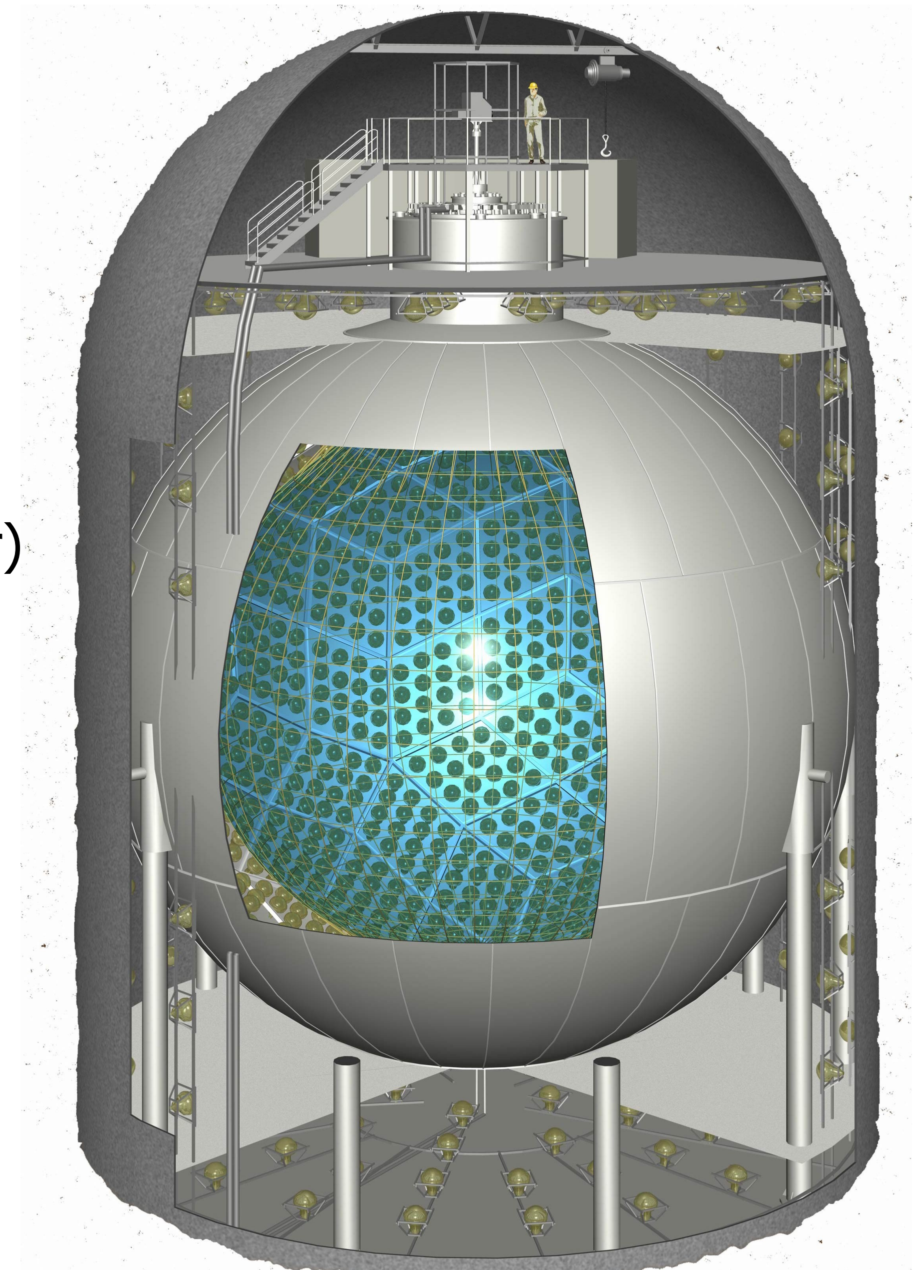
- **CEN Bordeaux-Gradignan:** F.Piquemal, J.-S.Ricol

KamLAND Detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% pseudocumene (scint)
    - 80% dodecane (oil)
    - 1.5 g/L PPO (wavelength shifter)
  - 2.5m buffer region filled with oil
- 34% PMT coverage
  - 1325 17” fast PMTs
  - 554 20” large PMTs
- Water Cherenkov veto counter

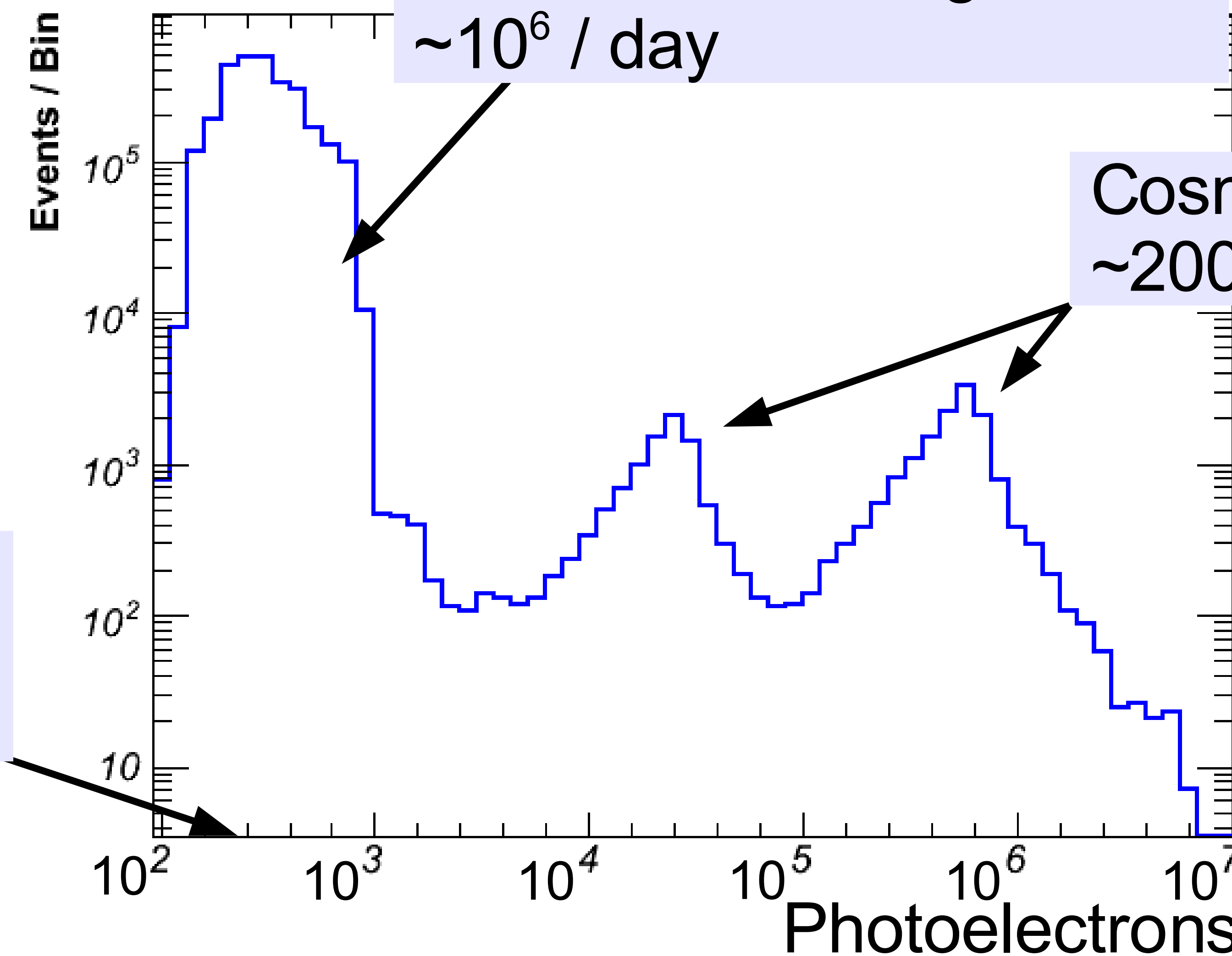


Detector Construction

A View from the Inside

Needle in the Haystack

Trigger Rate: ~50 Hz



Radioactive Backgrounds: ~10^6 / day

Cosmic Rays: ~20000 / day

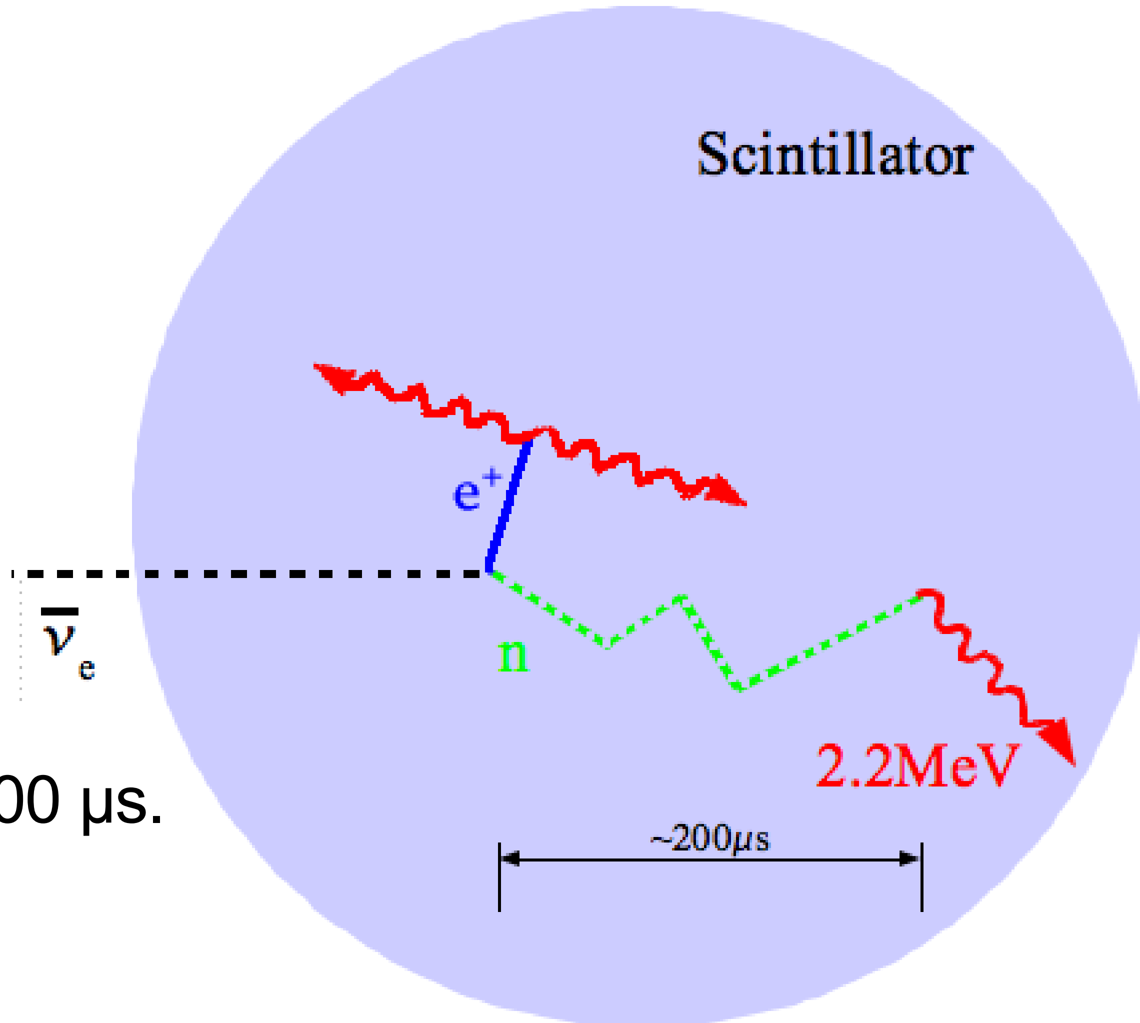
Reactor Neutrinos: ~1 / day

Anti-neutrino Detection Method

Reaction Process: inverse β-decay

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

$$n + p \rightarrow d + \gamma$$



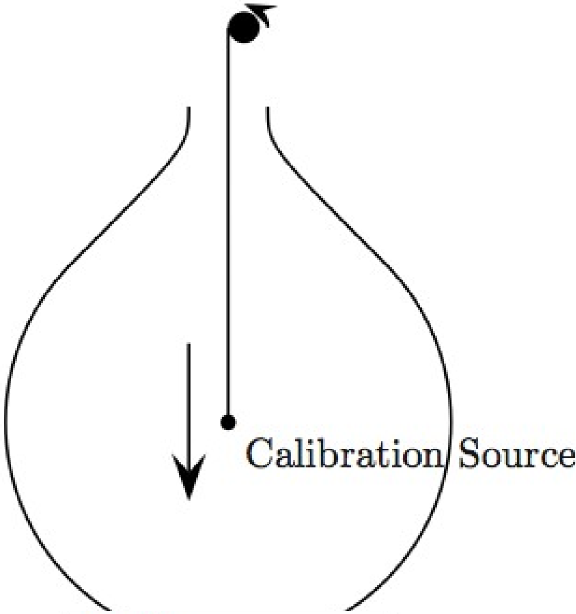
Look for the neutron!

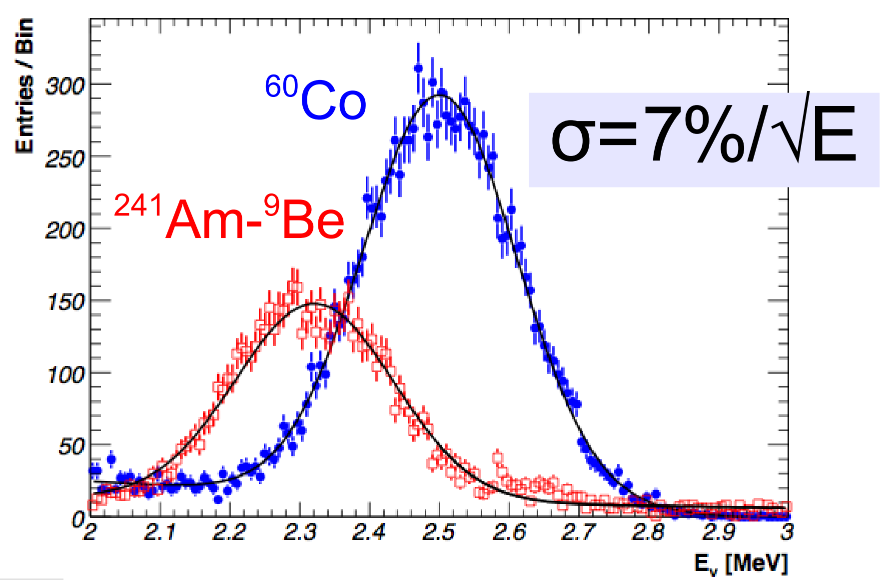
Second event delayed by ~200 μs.

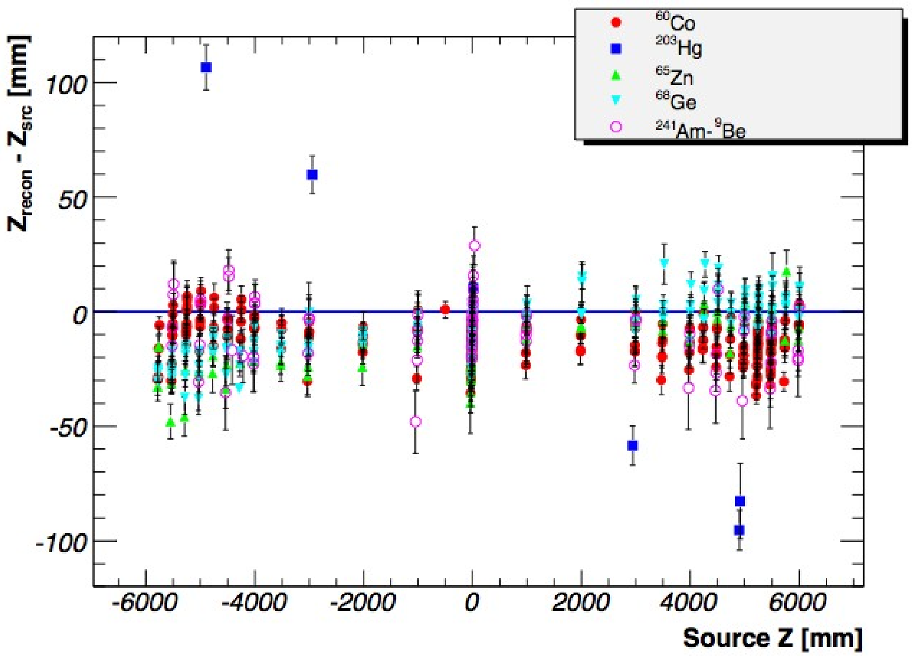
Delayed coincidence: good background rejection

Calibration / Reconstruction

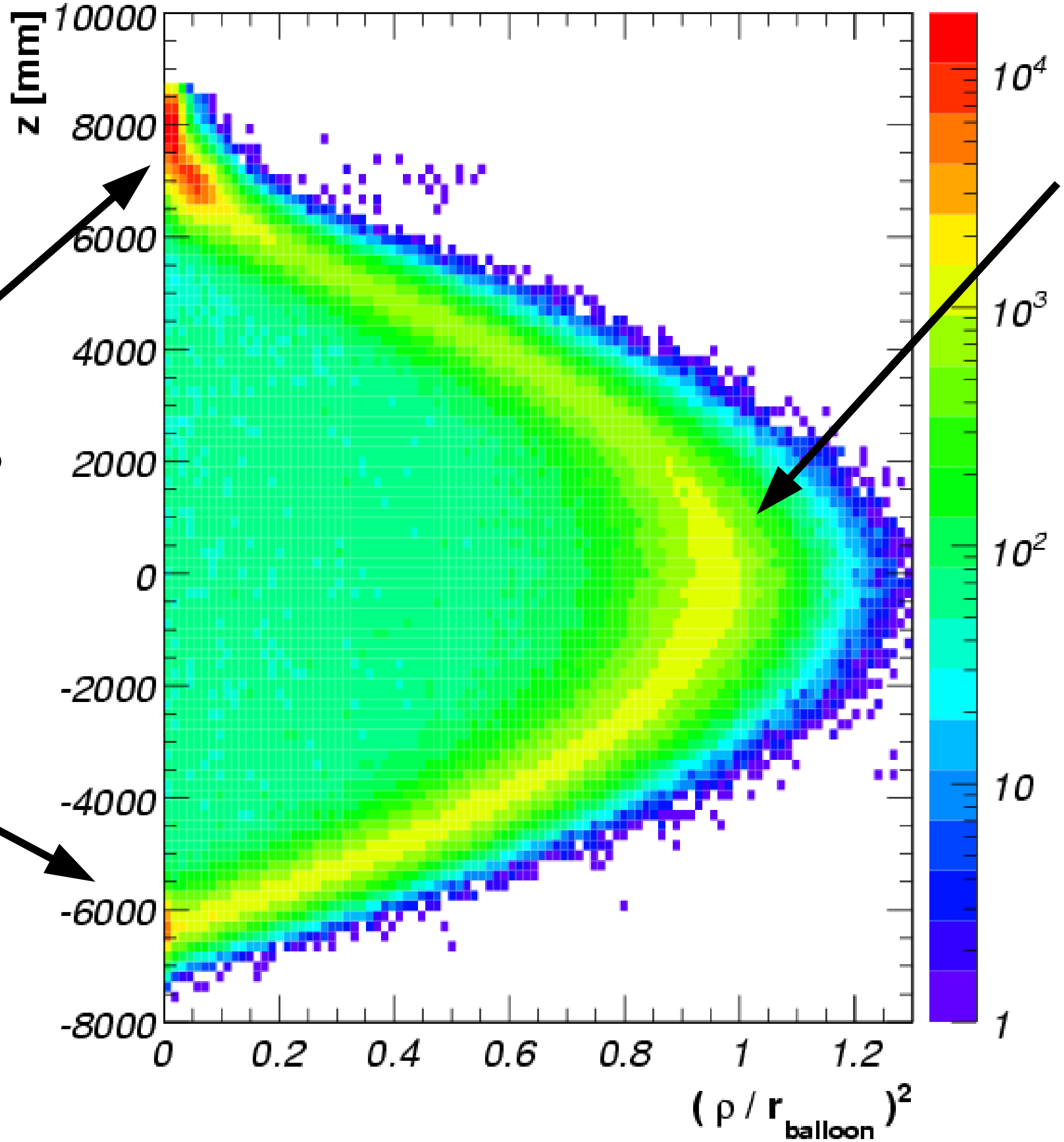
- Not Just a Calorimeter!
- Event Reconstruction
  - Position -> Use Relative PMT Firing Times
  - Energy -> Use PMT Charges, corrected for position
  - Verify with calibration sources







Imaging the Detector

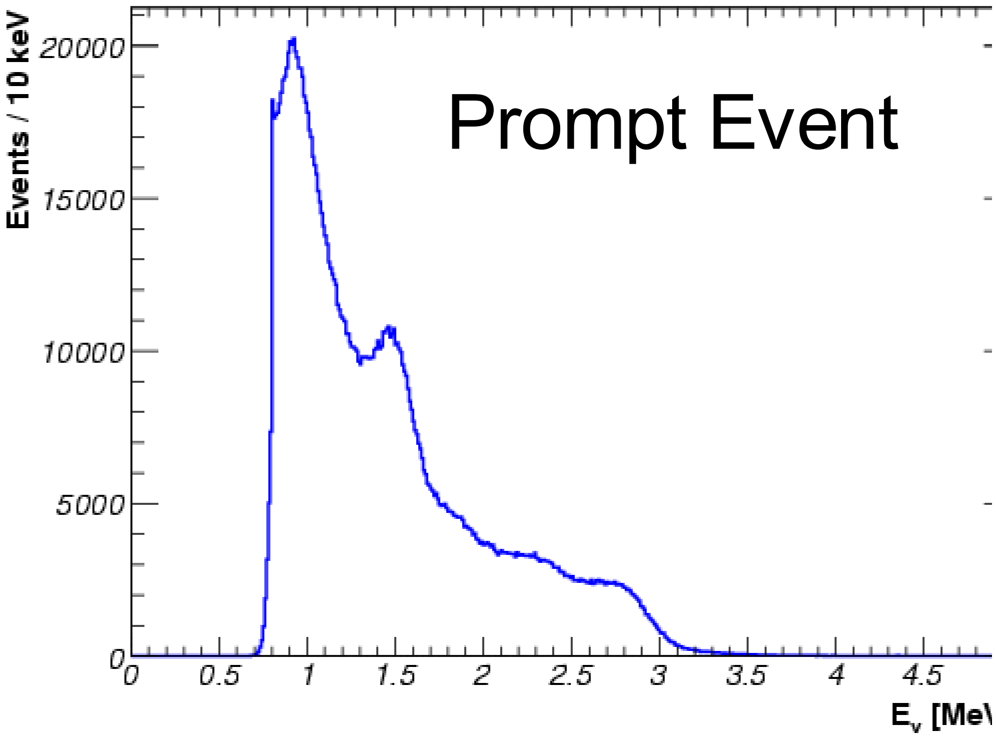


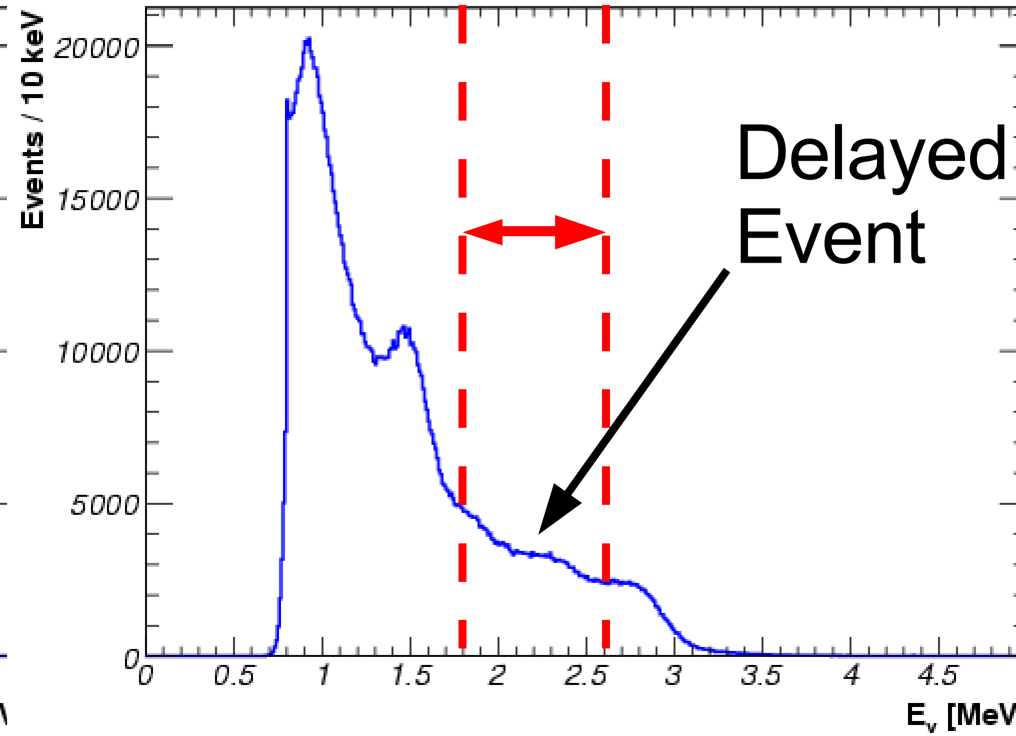
Singles mostly at balloon boundary (Radioactive backgrounds and external gammas)

High singles rate at neck and bottom (stainless steel)

Backgrounds: Accidentals

Two singles accidentally mimic delayed-coincidence





Reduce accidental rate:

R_p, R_d < 5.5 m ΔR < 2 m ΔT < 1 ms

2.6 < E_p < 8.5 MeV 1.8 < E_d < 2.6 MeV

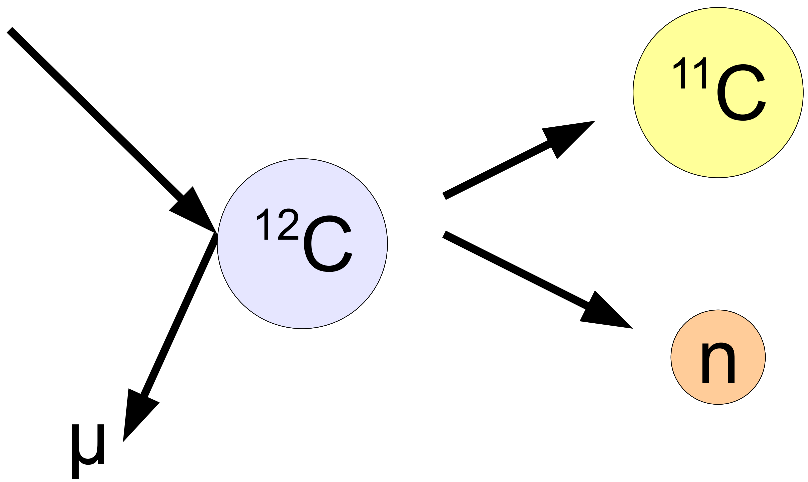
Cosmic Rays

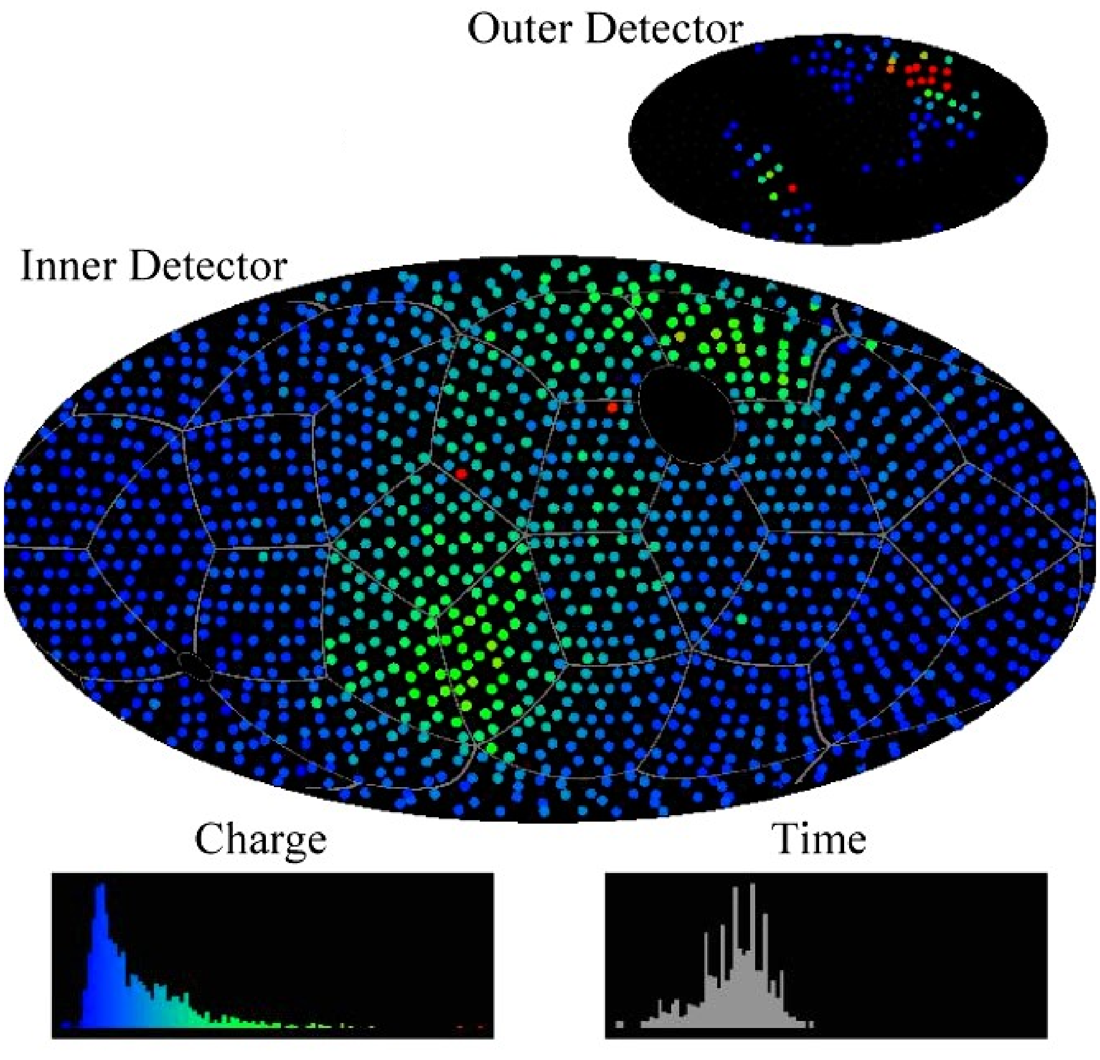
Cosmic ray events:
- easy to veto

But...

Muon Spallation

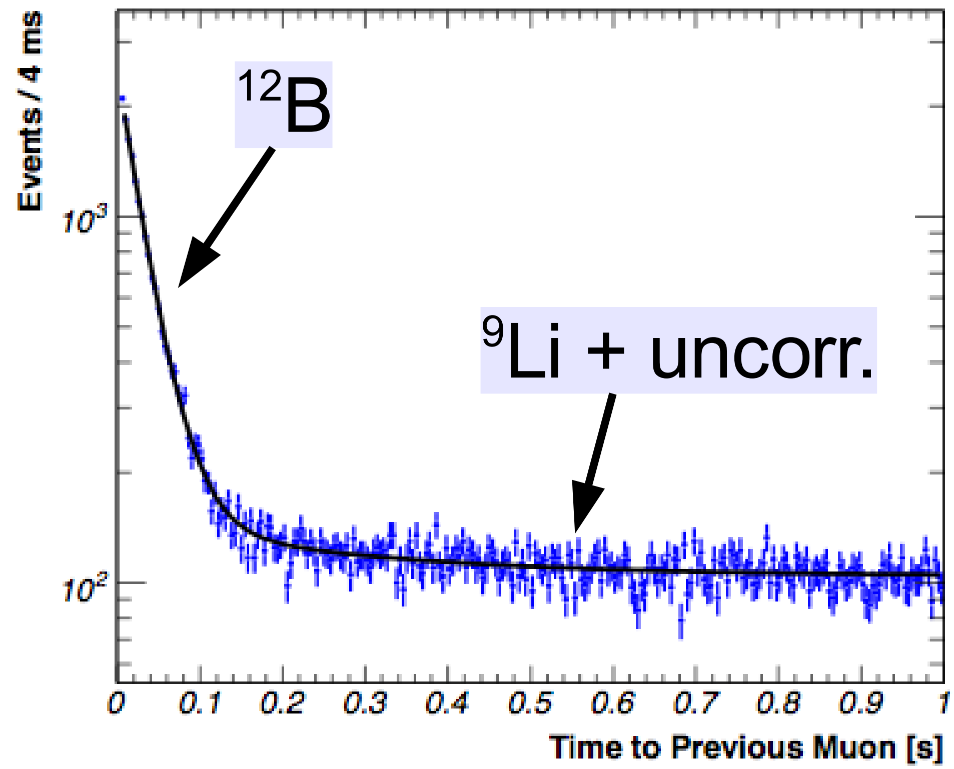
-Creates radioactivity throughout detector!

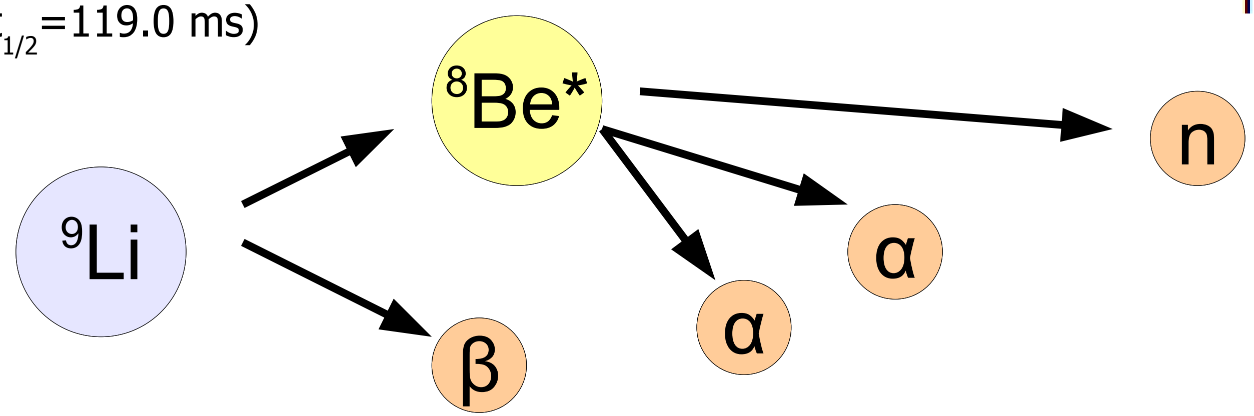




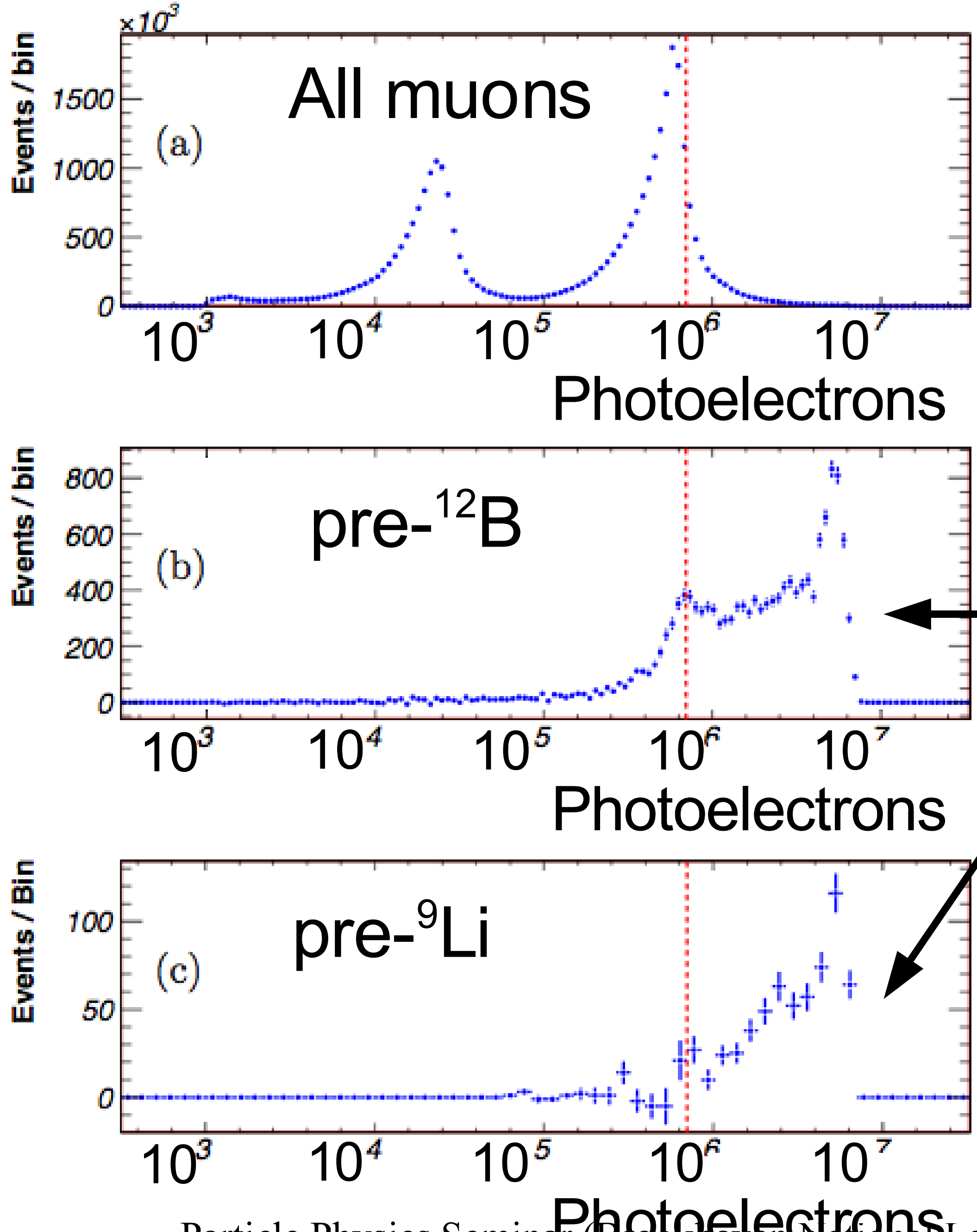
Spallation

- Muon Rate: ~0.32 Hz
- High Rate / Short Lifetime:
  - Free n (t_c=209 us)
  - ^{12}B ($t_{1/2}$=20.2 ms), ^{12}N ($t_{1/2}$=11.0 ms)
- β-n decay: Also emits neutron!
  - ^{9}Li ($t_{1/2}$=178.3 ms)
  - ^{8}He ($t_{1/2}$=119.0 ms)





Spallation Light

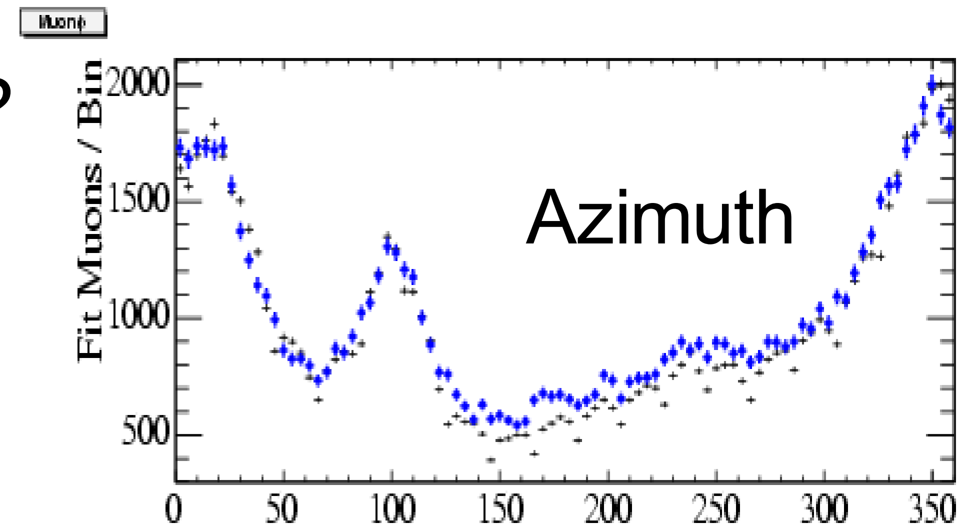


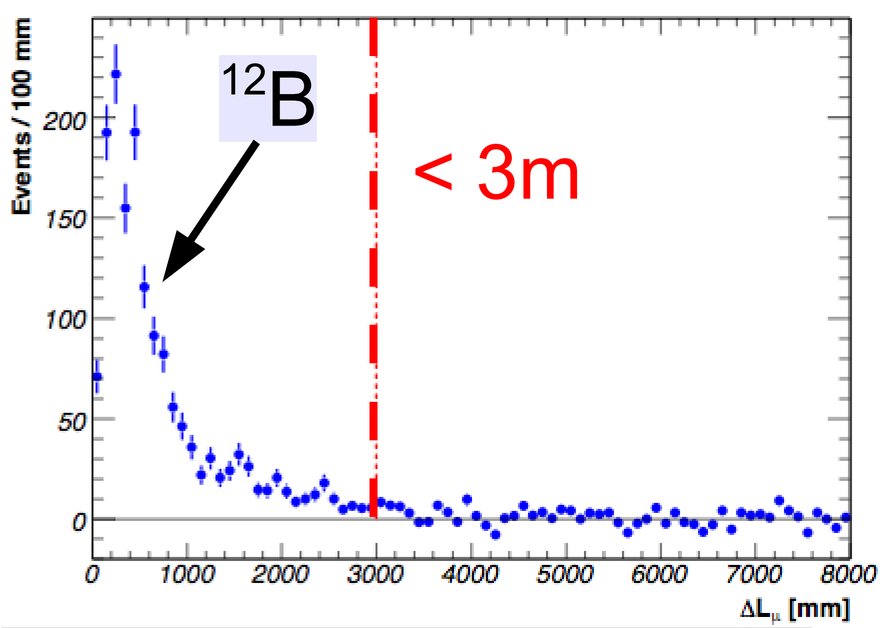
Extra light from spallation is visible.

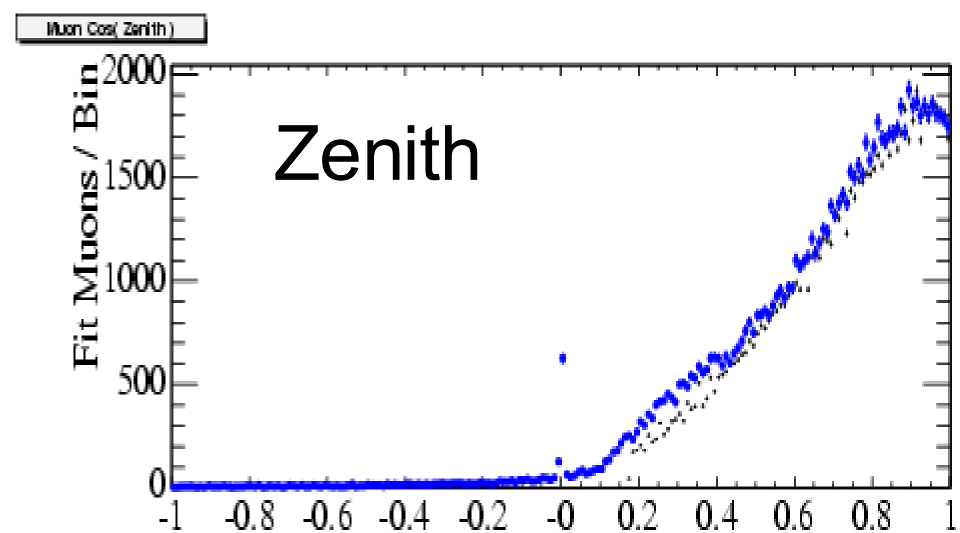
Veto detector for 2s after 'spallation muon'

Muon Reconstruction

- **Problem**: Check Muon Fitter?
- **Tests**:
  - Use MUSIC simulation
  - Compare with spallation







Backgrounds: $^{13}C(\alpha,n)$

High energy α can produce a delayed-coincidence.

$^{210}Po \rightarrow {}^{206}Pb + \alpha(5.3\ MeV)$

~1 in 10^7! ↳ $\alpha + {}^{13}C \rightarrow n + {}^{16}O$ (1)

↳ n,p scatters

↳ $^{12}C(n,n)^{12}C^*(4.4MeV)$

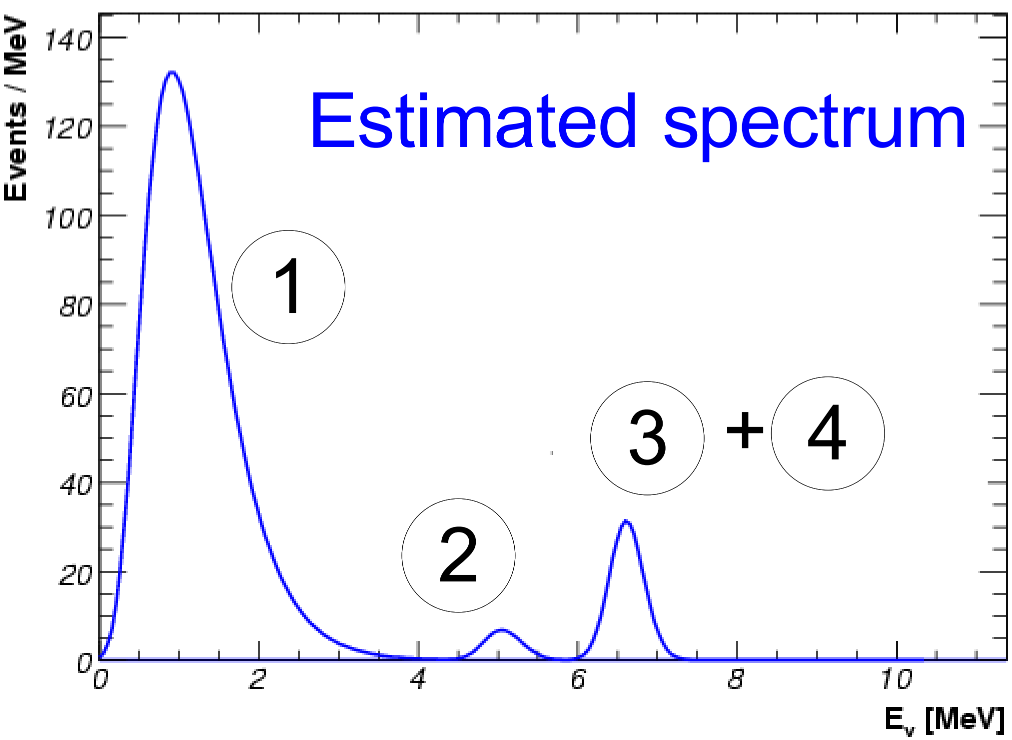
↳ γ (2)

→ $n + {}^{16}O^*(6.0\ MeV)$

↳ $e^+ + e^-$ (3)

→ $n + {}^{16}O^*(6.1\ MeV)$

↳ γ (4)



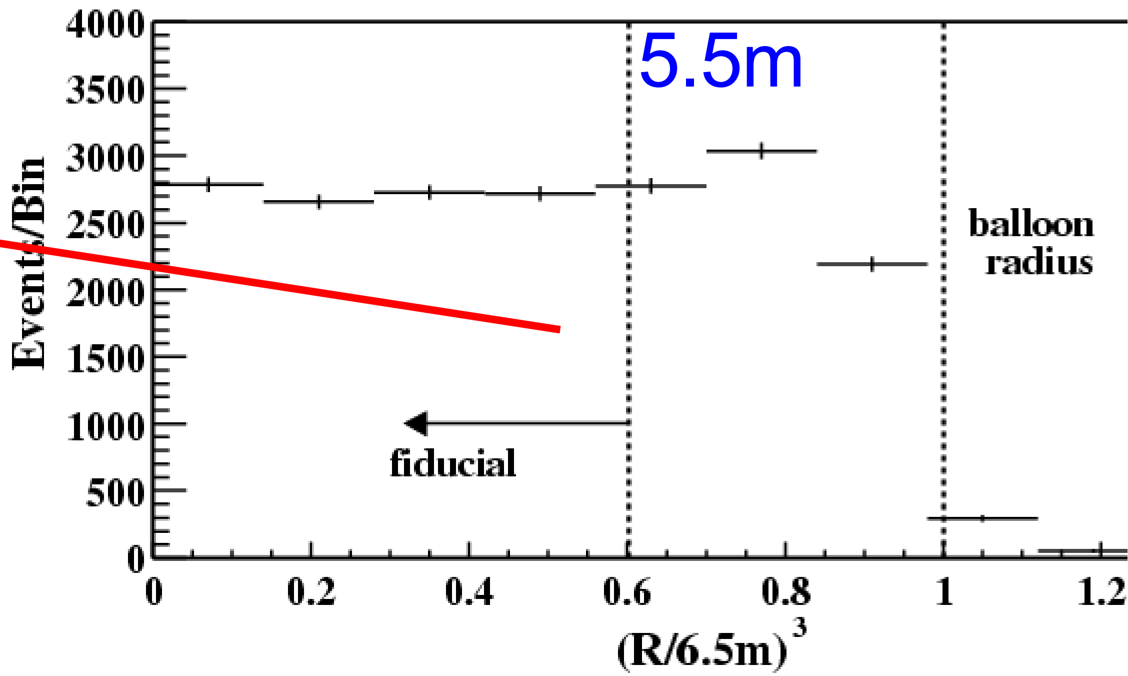
Systematics and Efficiency

Efficiency:

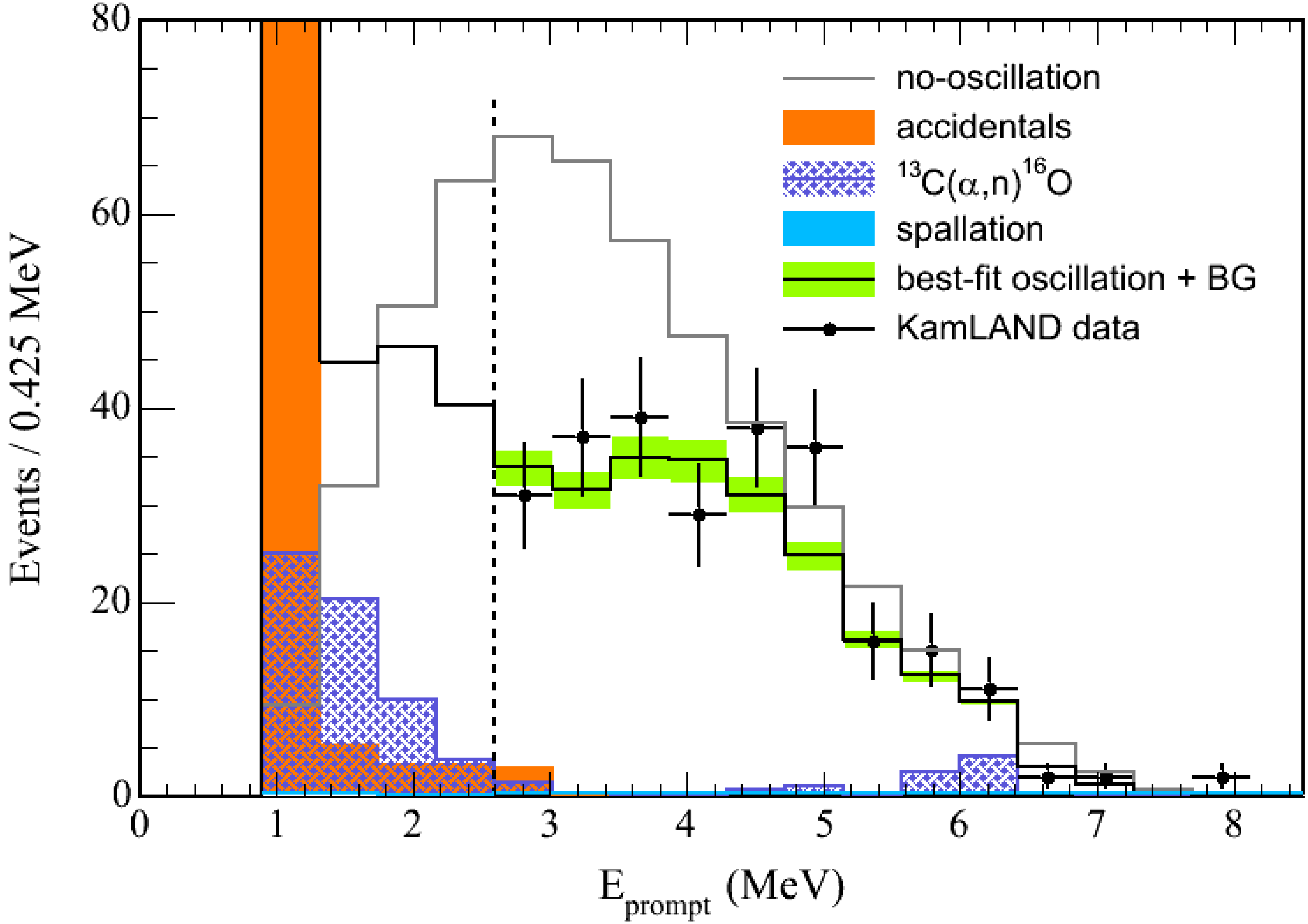
- Delayed-Coincidence: 0.90
- Muon Veto: 0.90

Systematics:

Fiducial Volume	4.7	Reactor power	2.1
Energy threshold	2.3	Fuel composition	1.0
Efficiency of cuts	1.6	$\overline{\nu}_e$ spectra [5]	2.5
Livetime	0.06	Cross section [7]	0.2
Total systematic error			6.5



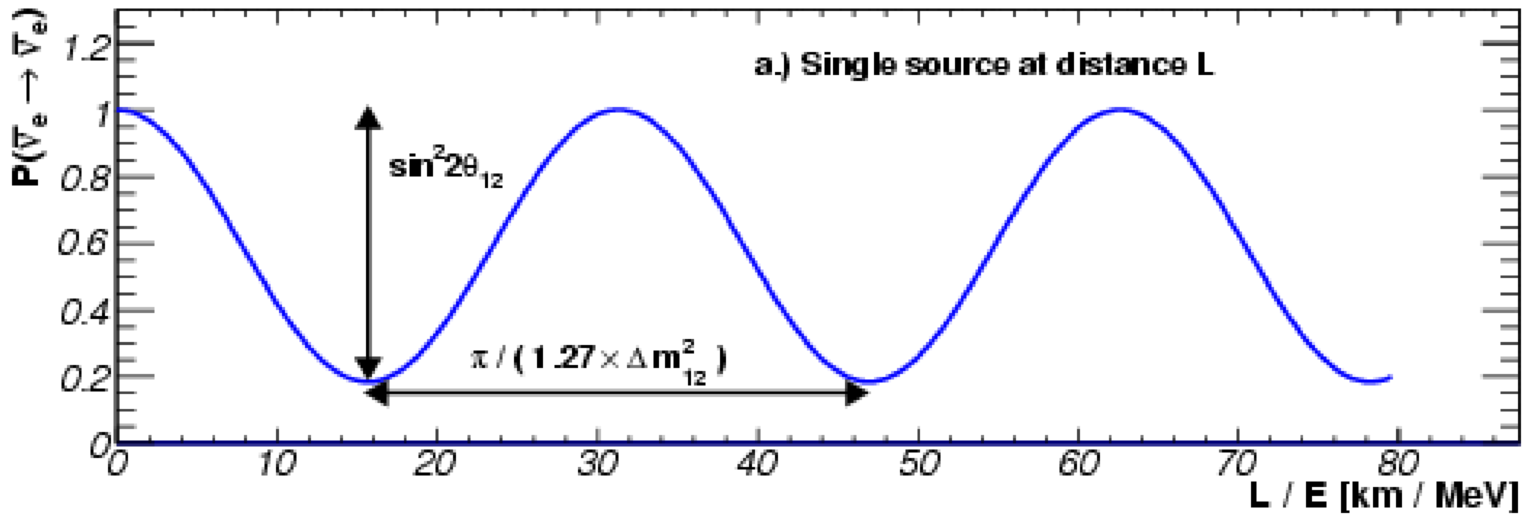
Past Results



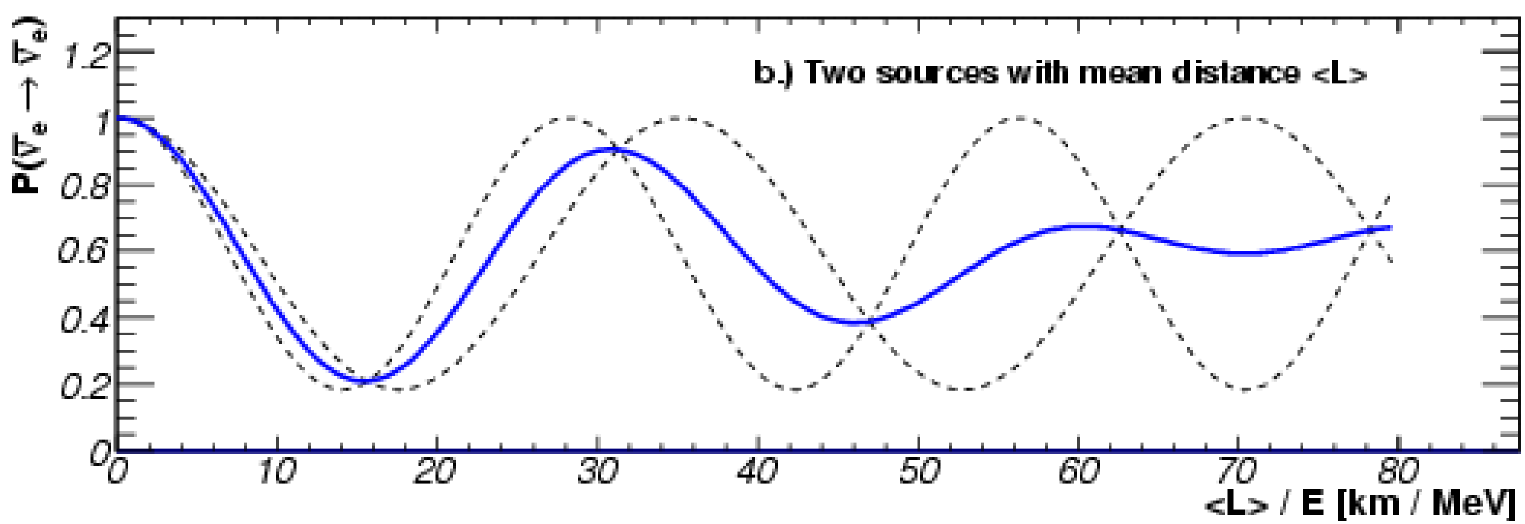
Oscillation Signature

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

Single source oscillation in L/E

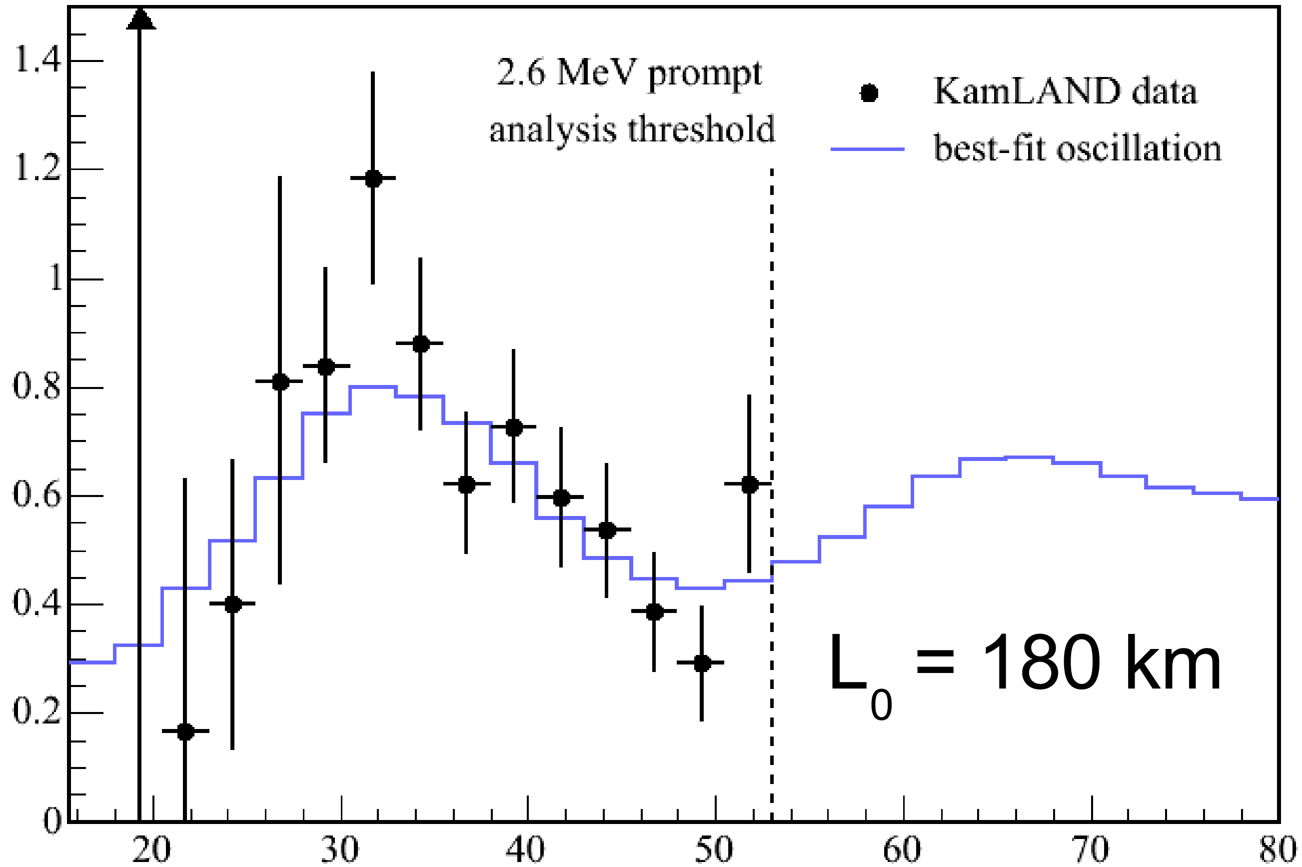


Distortion from multiple sources



KamLAND Results

(Events – BG) / No Osc. Exp.

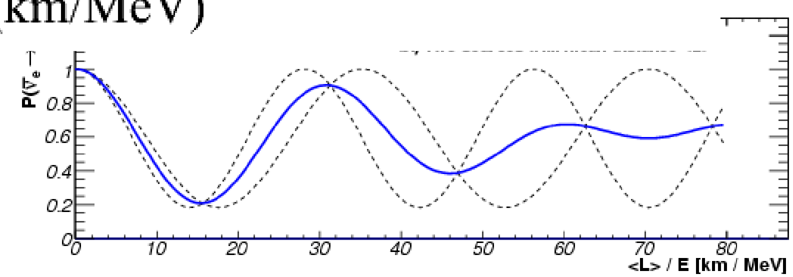


$L_0/E_{\bar{\nu}_e}$ (km/MeV)

Signature of Neutrino Oscillation

Phys.Rev.Lett. 94, 081801 (2005)

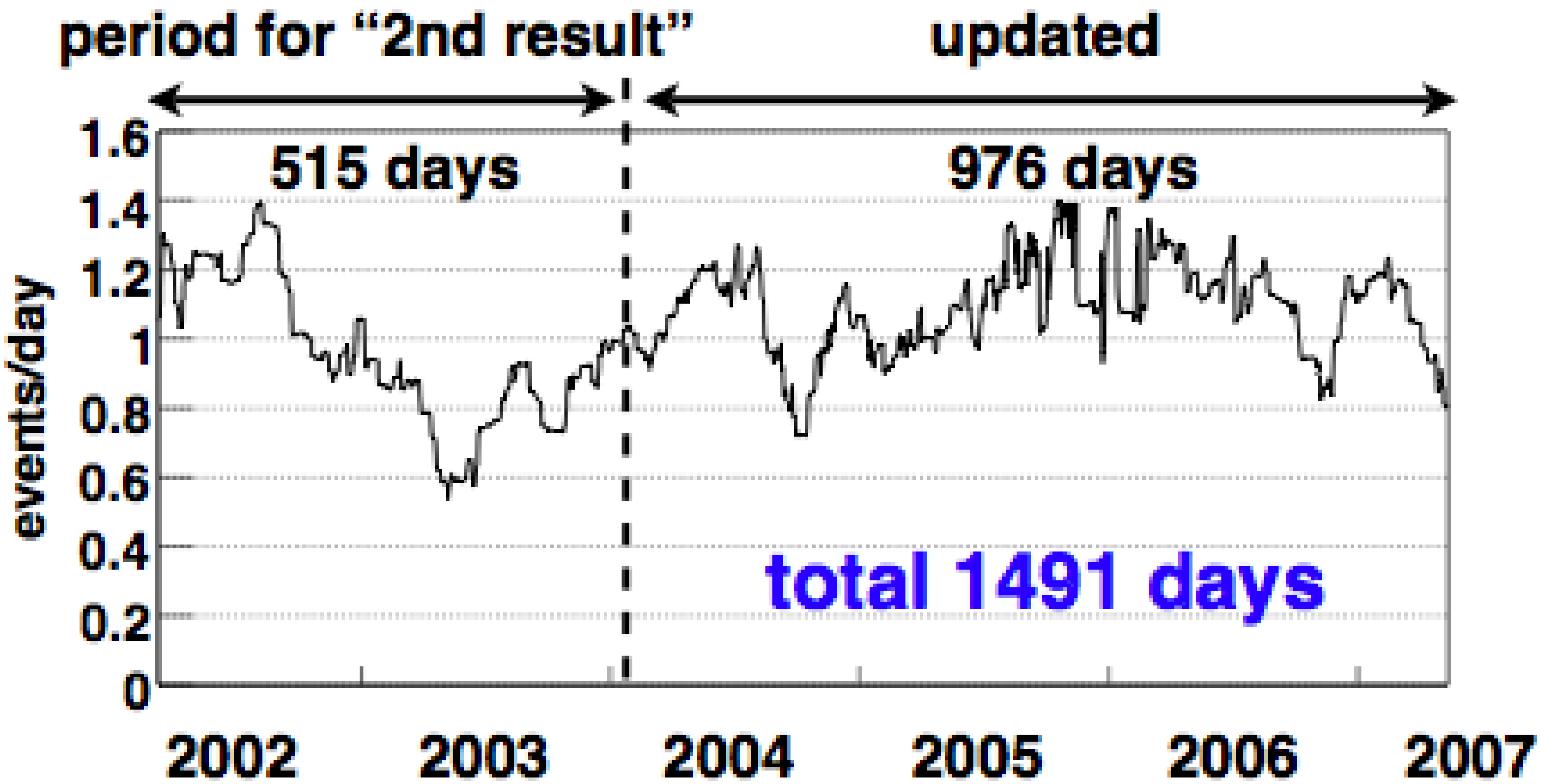
$$\Delta m^2 = 8.3\times10^{-5}\,\mathrm{eV}^2 \text{ and } \tan^2\theta = 0.41$$



Recent Improvements

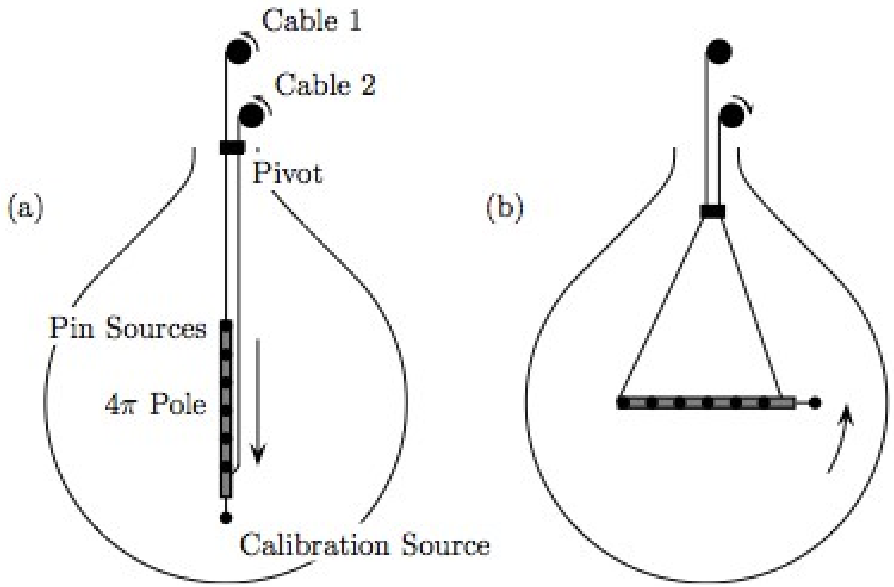
- Increase statistics
- Reduce Volume Uncertainty
- Characterize (α,n) Background
- Reduce Energy Threshold / Optimize Cuts

Improvement: Statistics

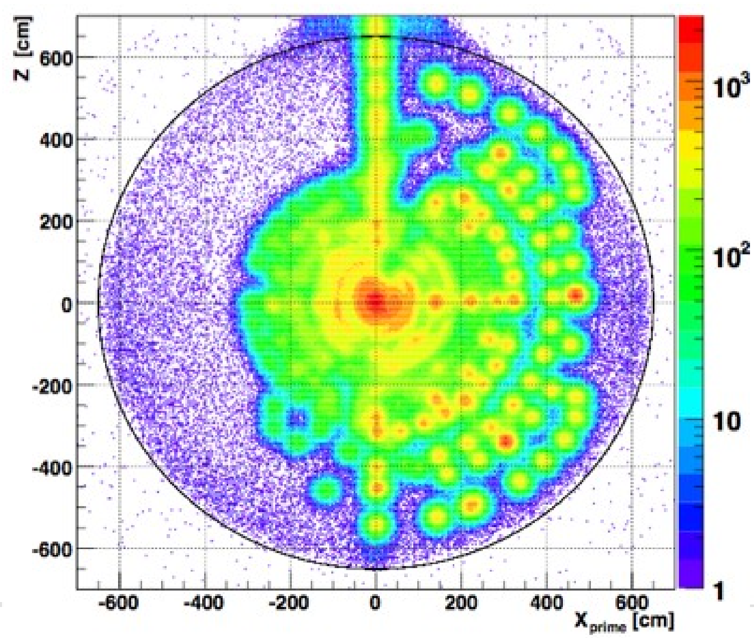


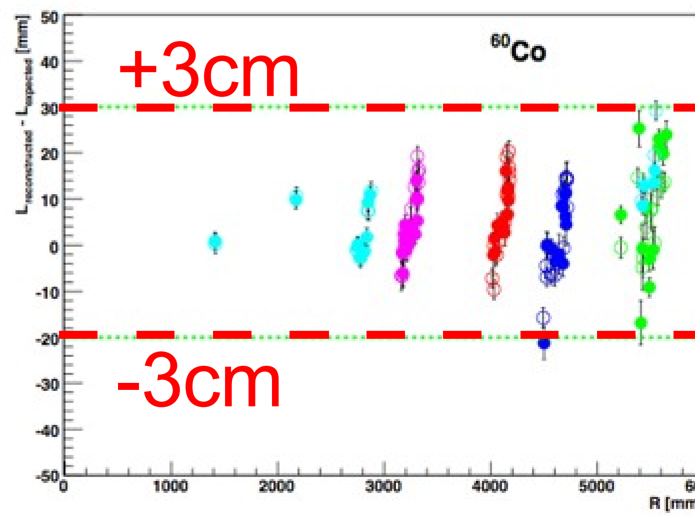
3x previous runtime

Improvement: 4π Calibration



Full-volume calibration



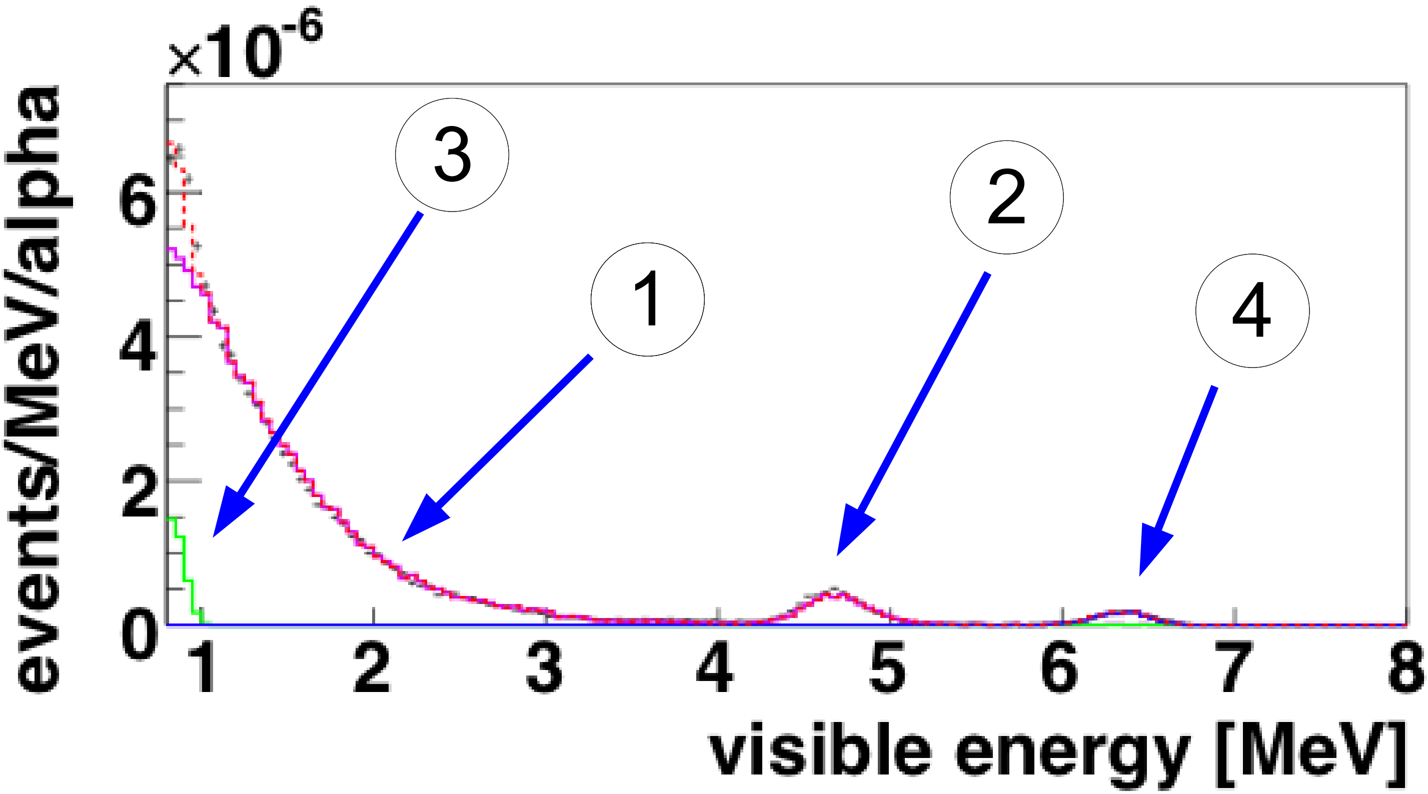


3cm radial bias:
~2% volume uncertainty

Improvement: $^{13}C(\alpha,n)$

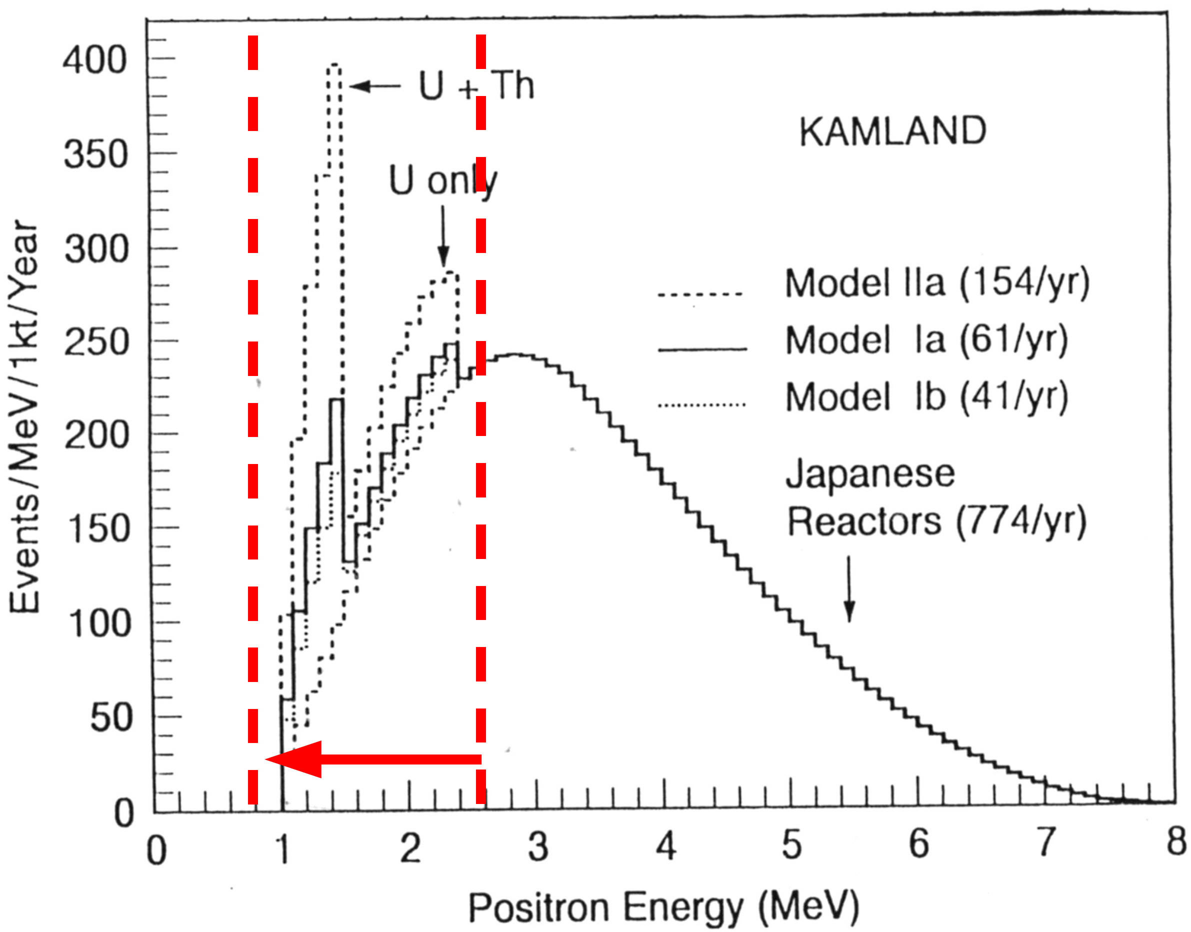
Calibration using ^{210}Po-^{13}C source

- Improved understanding of largest background
- Reduce energy threshold below 2.6 MeV



Backgrounds: Geo-neutrino

Anti-neutrinos produced in the earth's crust from U/Th decays



$E_{\bar{\nu}\,(geo)} < 2.49$ MeV

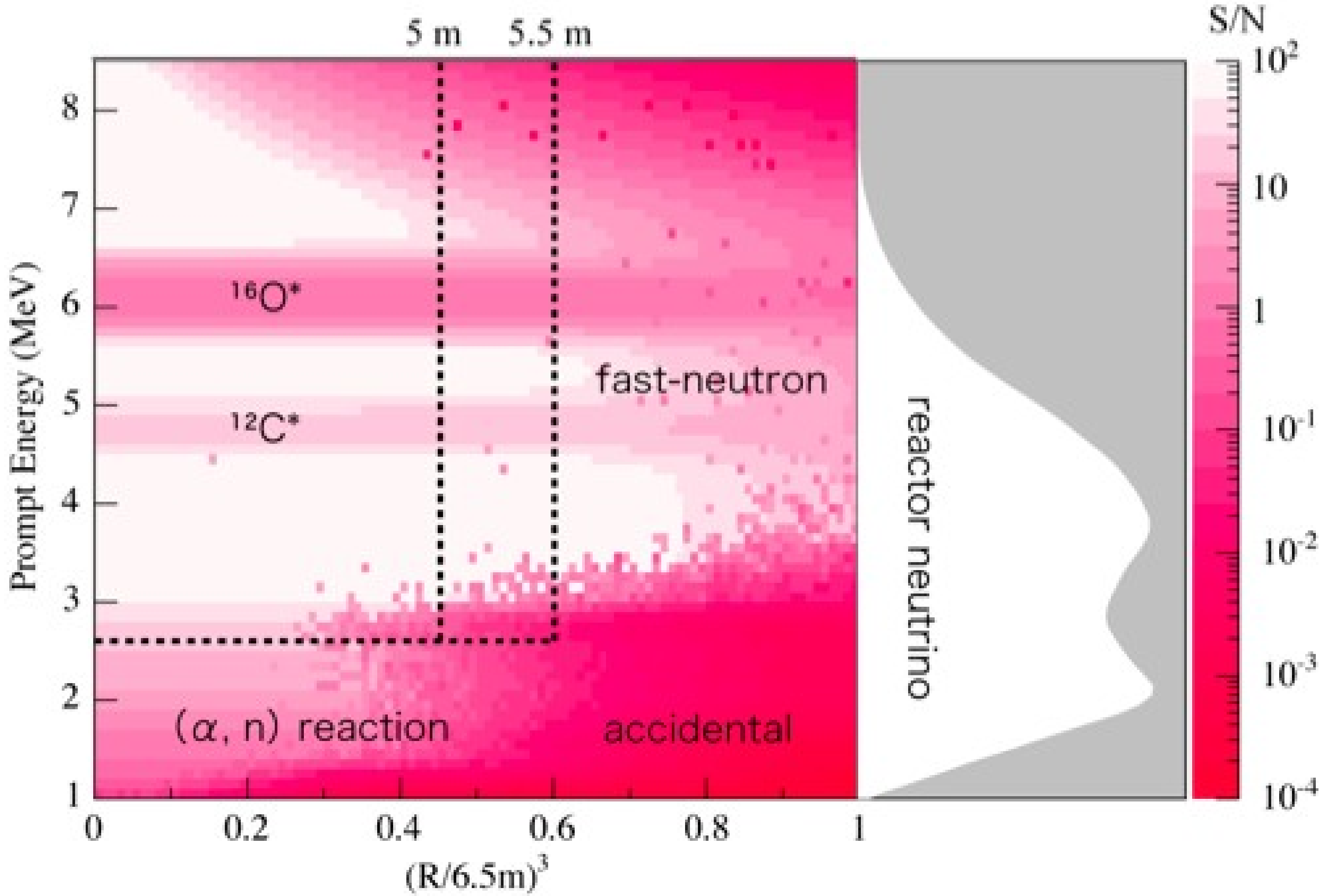
Improvement: L-cut

Problem: Accidentals dominate signal at low energies

Solution: Vary cuts based on prompt event energy

Bin candidates:
- Radius
- ΔR
- Δt
- Energy

Reject bins with low S/N ratio



Improvement: Energy Threshold

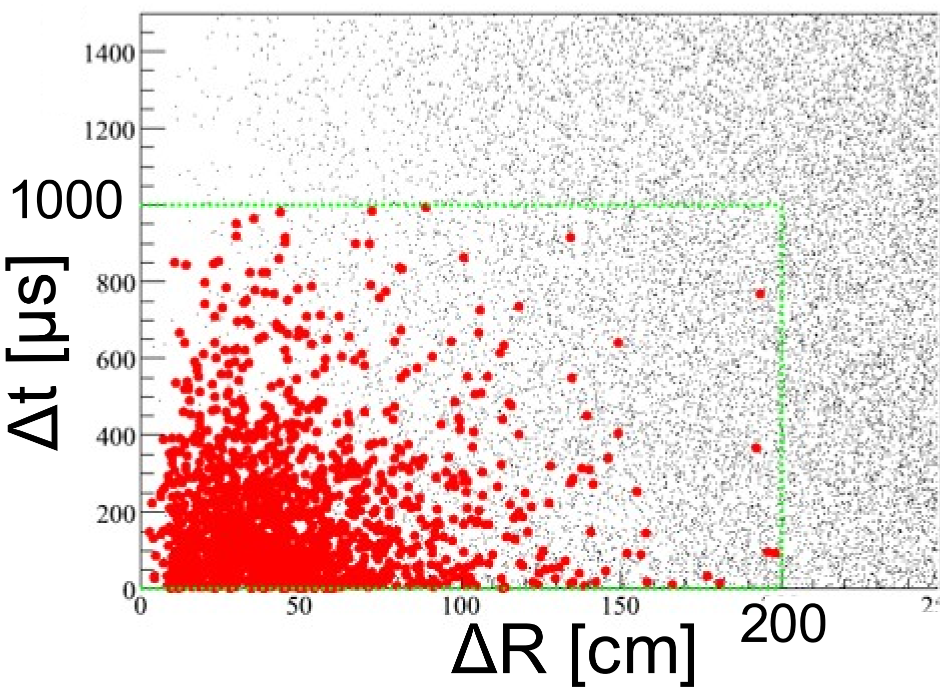
Likelihood Ratio:

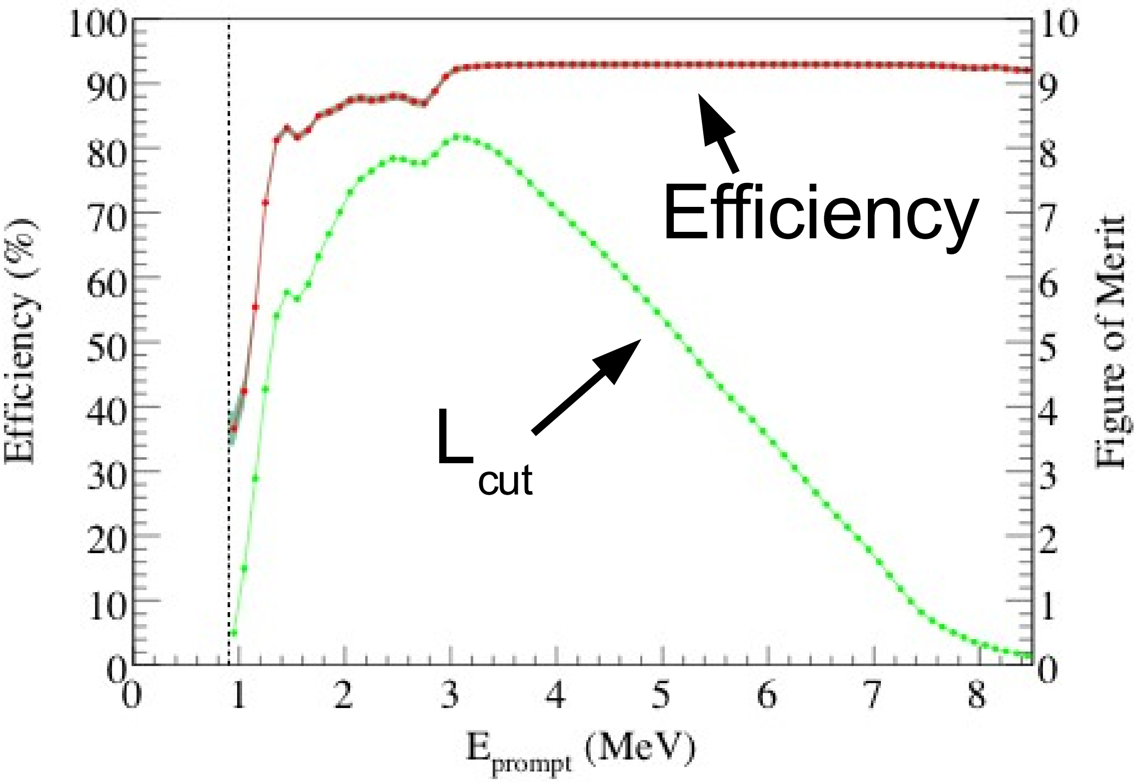
$L = P_{\nu} / (P_{\nu} + P_{acc})$

$L_{cut}(E_p)$ chosen at maximum $S/\sqrt{(S+B_{acc})}$

-All Candidates

-Candidates After L-selection





Systematic Uncertainties

Detector Related [%]		Reactor Related [%]	
Fiducial Volume	1.8	Spectrum	2.4
Energy Scale	1.5	Reactor Power	2.1
L-cut	0.6	Fuel Composition	1
Cross section	0.2	Long-lived nuclei	0.3

Total Systematic Uncertainty: 4.1%

Background Summary

Background	Contribution
Accidentals	80.5 ± 0.1
$^{9}Li/^{8}He$	13.6 ± 1.0
Fast neutron & Atmosperic ν	<9.0
$^{13}C(\alpha,n)^{16}O$ G.S.	157.2 ± 17.3
$^{13}C(\alpha,n)^{16}O$ $^{12}C(n,n\gamma)^{12}C$ (4.4 MeV γ)	6.1 ± 0.7
$^{13}C(\alpha,n)^{16}O$ 1st exc. state (6.05 MeV $e^{+}e^{-}$)	15.2 ± 3.5
$^{13}C(\alpha,n)^{16}O$ 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total excluding geo-neutrinos	276.1 ± 23.5
Geo-neutrino decays U+Th [8]	56.8+13.3

Combined Spectral Analysis

Best Fit:

$\Delta m^2 = 7.58 \times 10^{-5}\ eV^2$

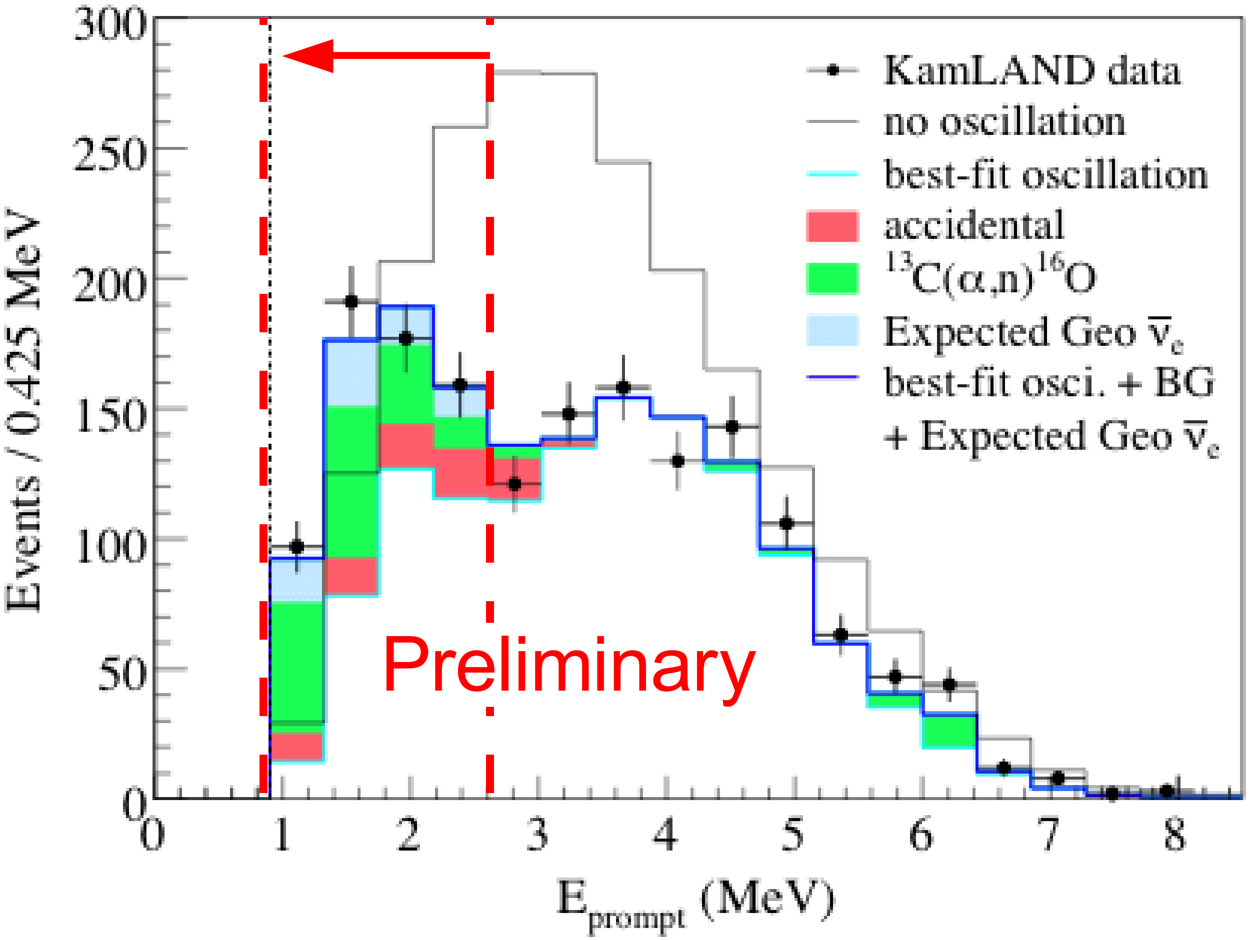
$\tan^2\theta = 0.56$

Geo-neutrino events:

39.3 U

29.4 Th

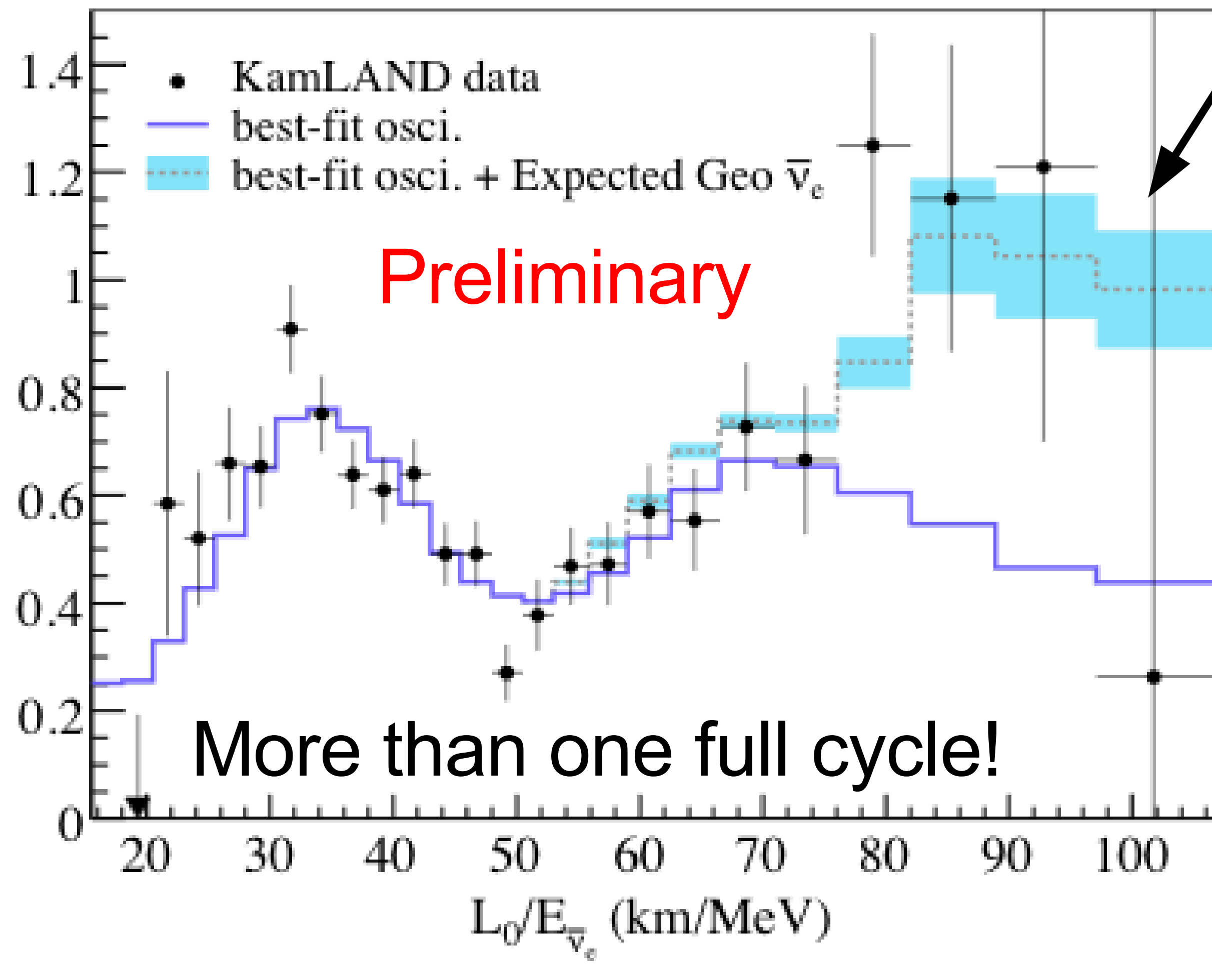
Threshold moved to 0.9 MeV



Neutrino Oscillation

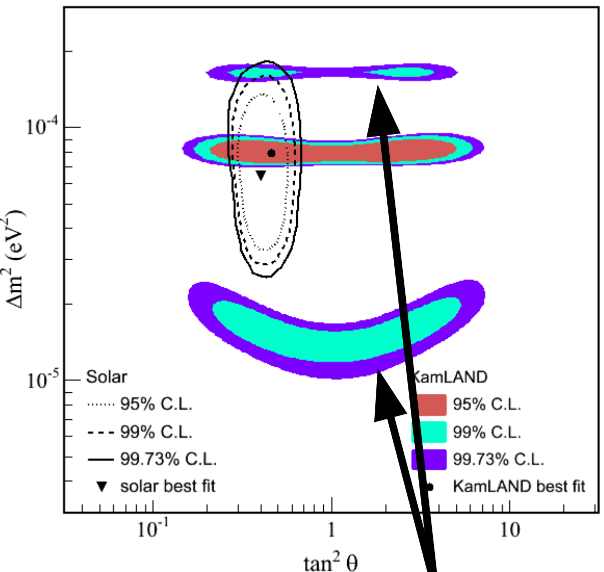
Geo-neutrino
from Earth model

(Events – BG)
No Osc. Exp.

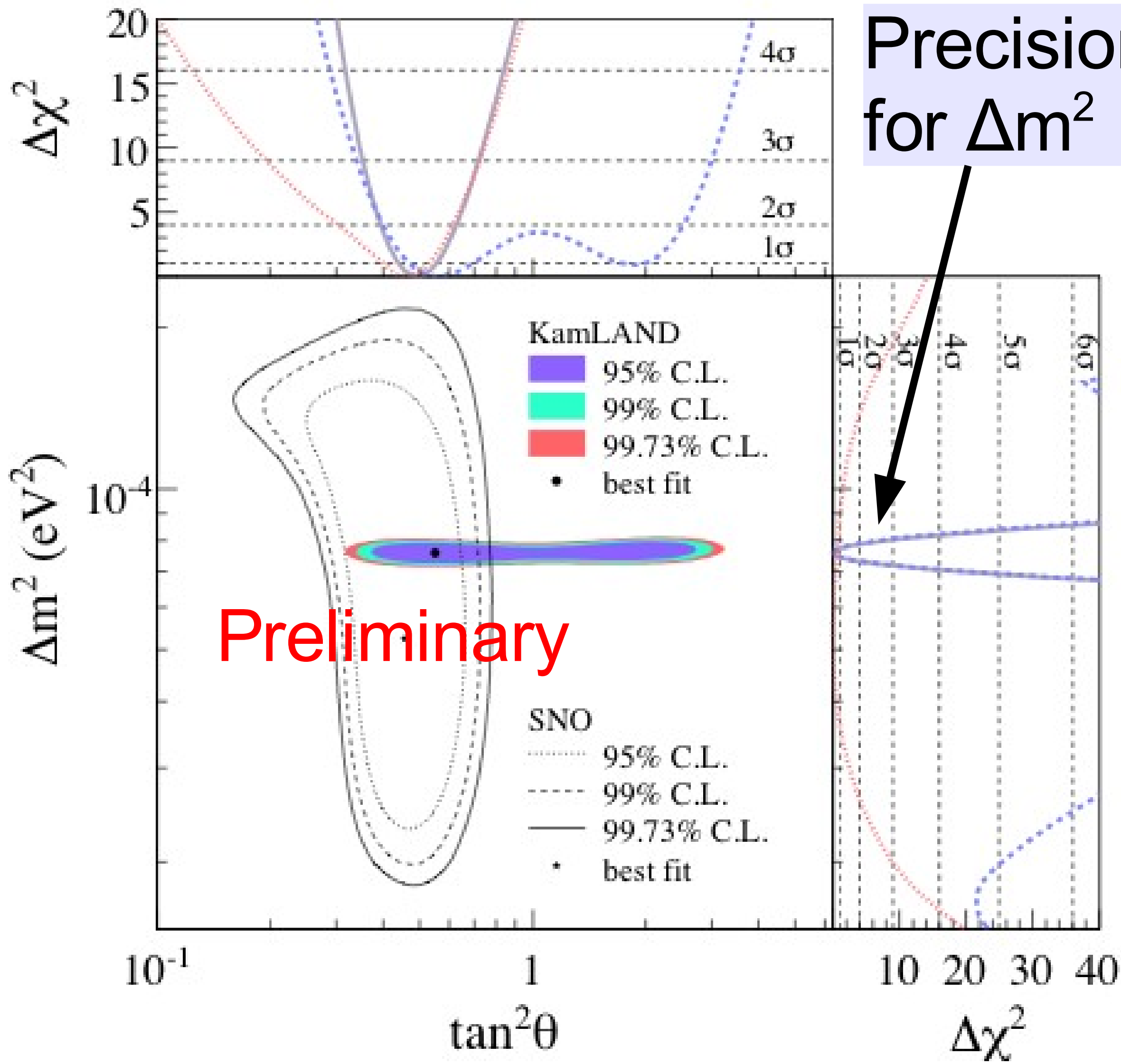


Reference Baseline: L_0 = 180 km

Oscillation Parameters



Previous regions now excluded



Precision value for Δm^2

KamLAND only $\tan^2\theta = 0.56^{+0.14}_{-0.09}$ $\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$

KamLAND Future

Purification: reduce radioactive backgrounds

- Improve Reactor and Geo-neutrino measurements
- If reduction reaches 10^{-6}: ^{7}Be Solar Neutrinos

High-Energy Anti-neutrinos

Spallation physics