# Results from KamLAND

and future prospects

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# Introduction

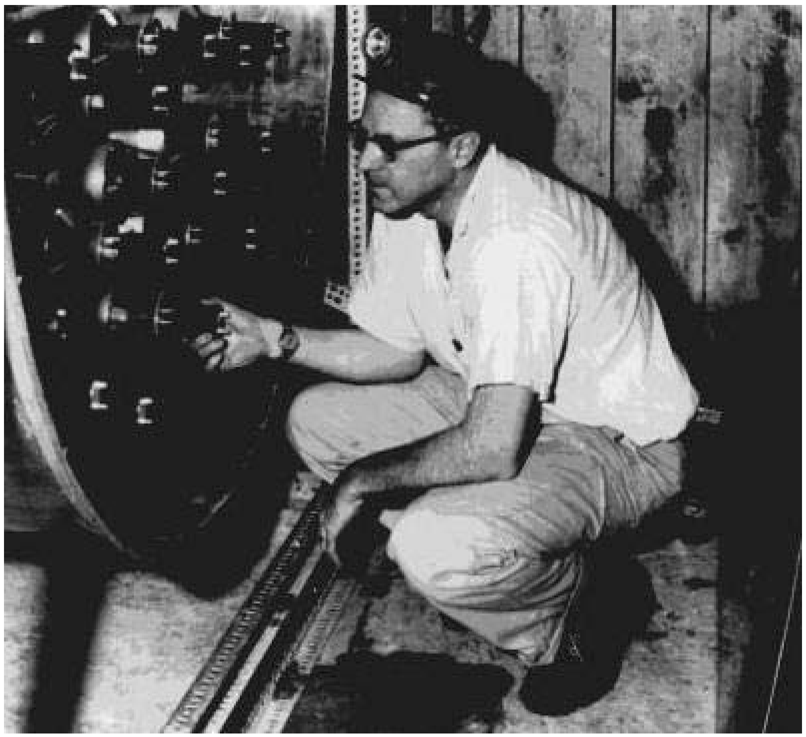
- A little neutrino history
- The Solar Neutrino Problem
- The KamLAND concept
- 1999-2002 Construction
- Backgrounds – almost none!
- Signals – reactor event sample
- Neutrino oscillations
- Conclusions and Deep Thoughts


# The Heroic Age

In 1930 Pauli proposed the existence of a neutral fermion with very small mass to explain beta decay electron energy spectra

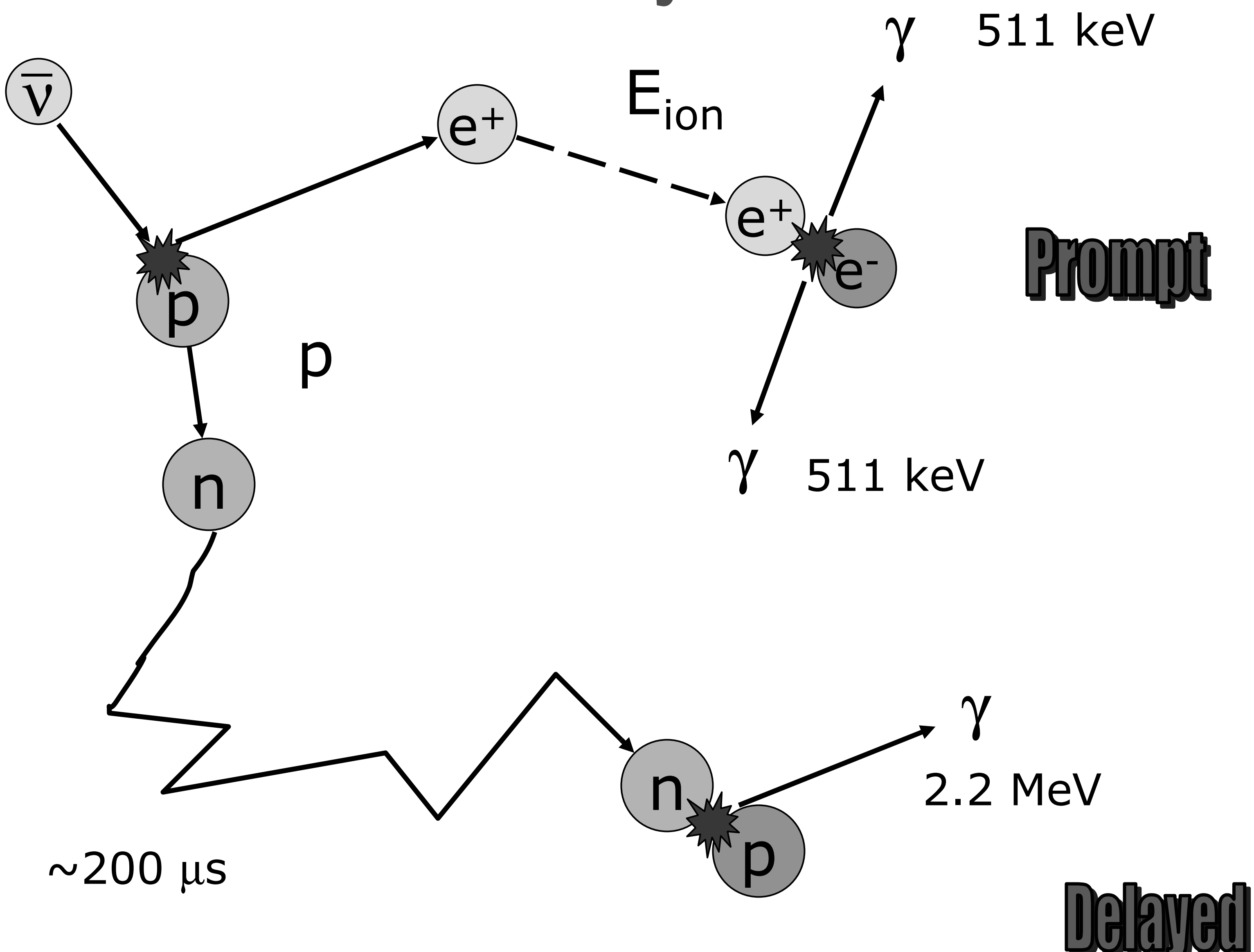
He feared such a particle might never be detected due to its elusive nature

# 1956 – Neutrinos Really Exist!



- Reines and Cowan detect neutrinos coming from the core of a nuclear reactor
- Photomultiplier tubes
- Liquid scintillator
- “high speed” coincidence circuits

# Inverse Beta Decay



# A Mirror of the Neutrino Spectrum

**$E_{prompt} = E_{\nu} - 0.78$ MeV – $E_n$**

**$E_n$: neutron recoil energy (small)**

**0.78 MeV: neutron – proton $\Delta mc^2$**

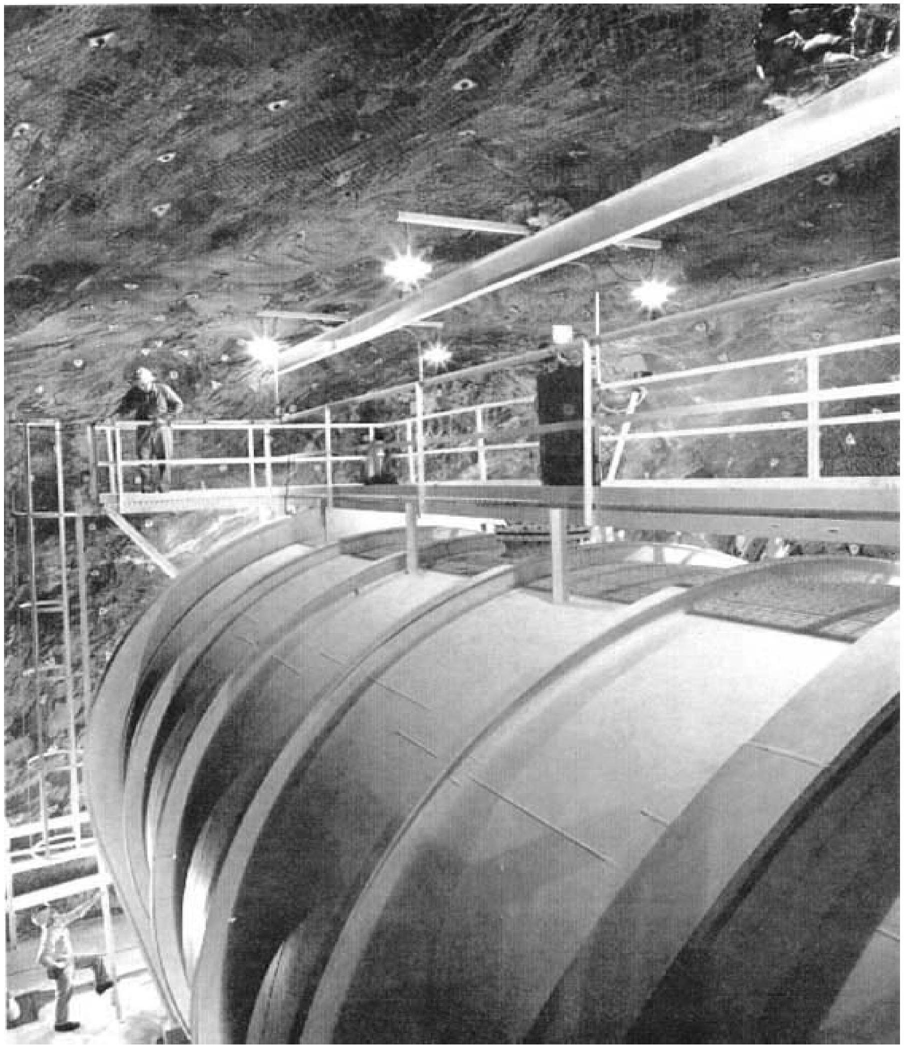
**Prompt energy spectrum is close to being original neutrino spectrum convoluted with the cross section!**

This double coincidence technique was the key to reducing the background to a low enough level to finally make the neutrino detectable

big people

small detector

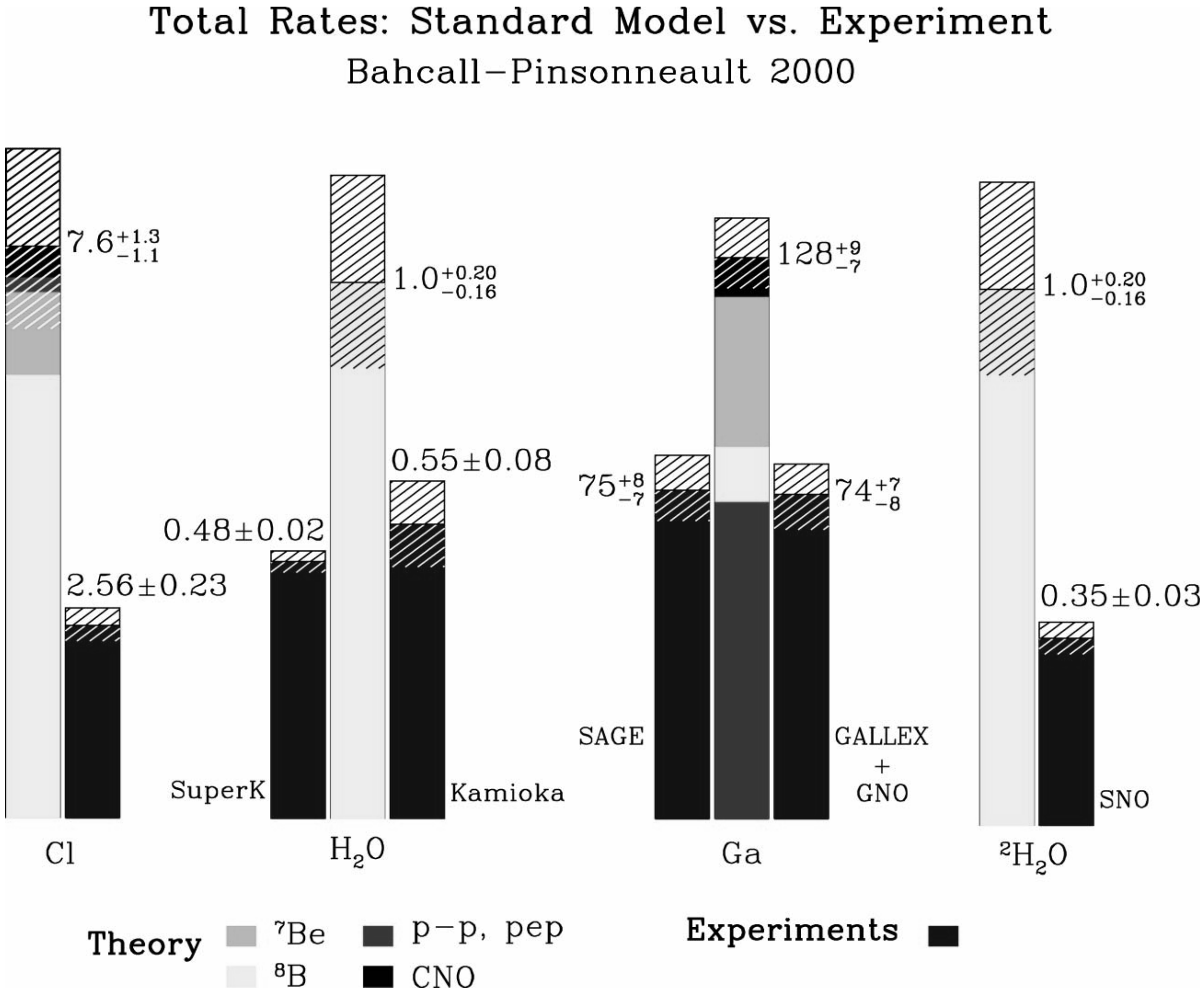
# Physics where the Sun Doesn't Shine…



- after a failed attempt to detect the neutrino in 1954 Davis looks for solar neutrinos
- in 1968 he reported that there is a problem…
- there are less than 1/3 of the expected number of $\nu_e$'s

# Fast Forward 40 years…

# Too Few Solar ν's



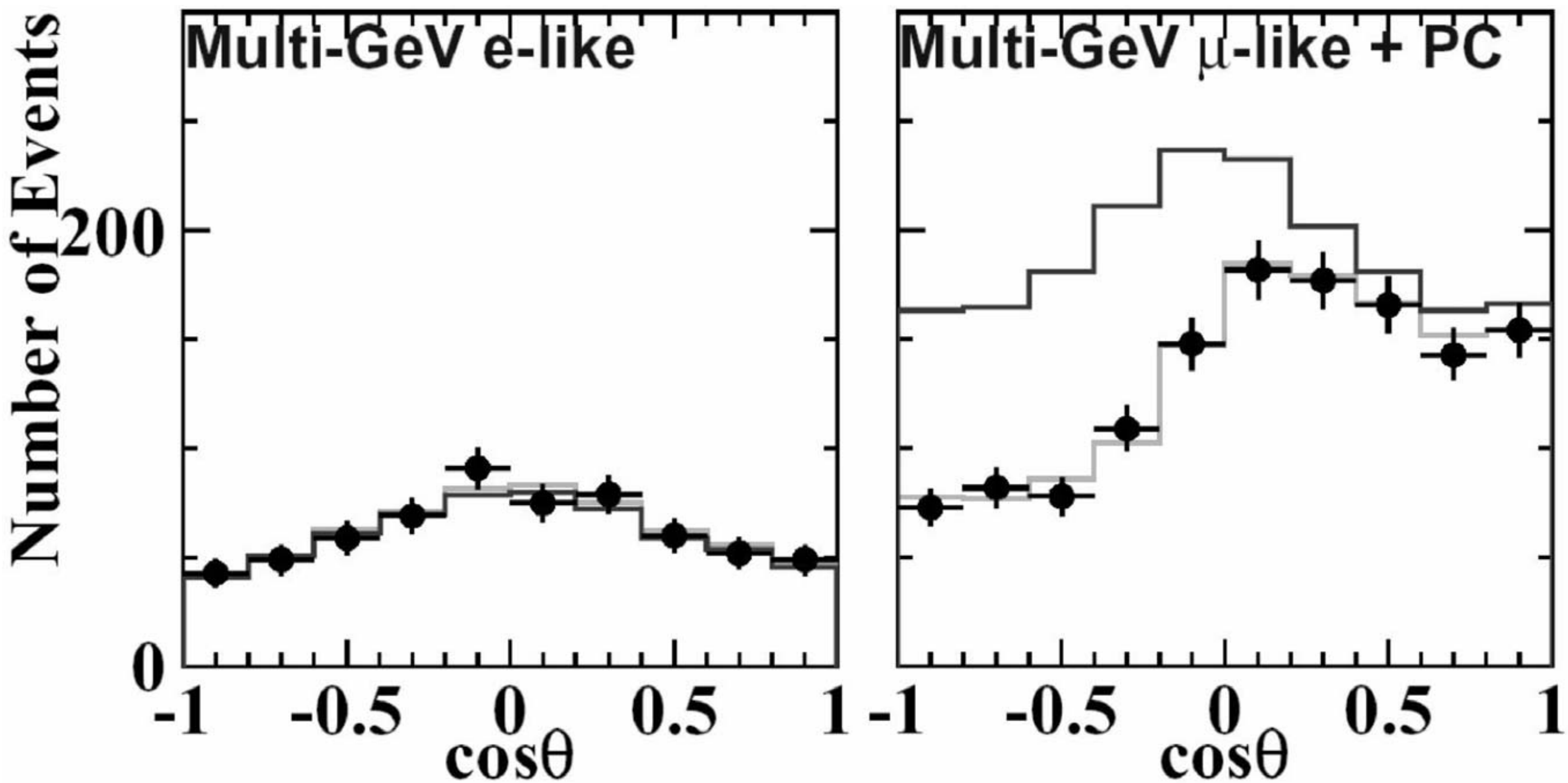
# Neutrino Oscillations

$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta\, e^{-im_1^2 t/4p} + |2\rangle \sin\theta\, e^{-im_2^2 t/4p}$$

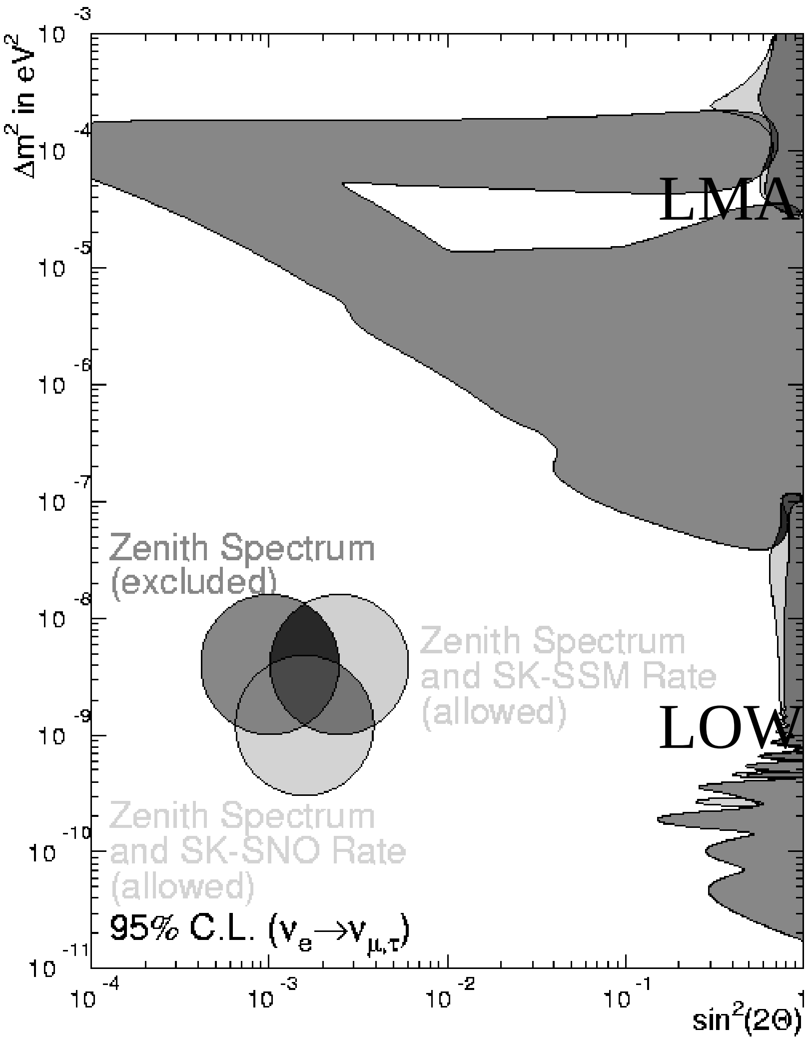
- "survival probability" for two components
- $|\langle\nu_\mu|\nu_\mu\rangle|^2 = 1 - \sin^2 2\theta \sin^2[1.27\delta m^2 (L/E)]$

a very sensitive way to look for neutrino mass

# 1998: Super-Kamiokande Neutrino Oscillation Measurements Survive Longer than the “New Economy”



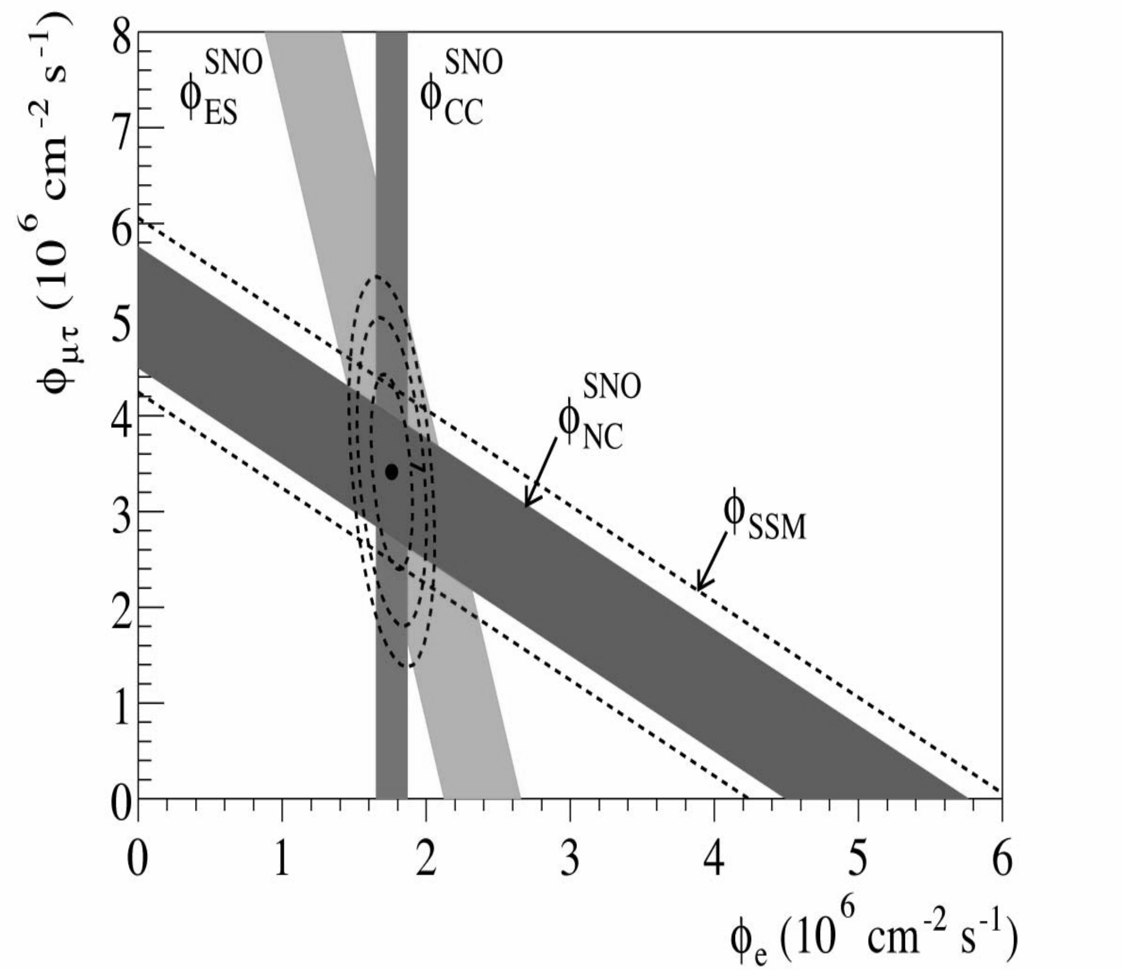
# Super-K Solar ν's




No spectral distortion or "matter effects" seen in propagation through the earth

- Two major solutions left:
  - LMA
  - LOW

# SNO measures total neutrino flux via NC capabilities



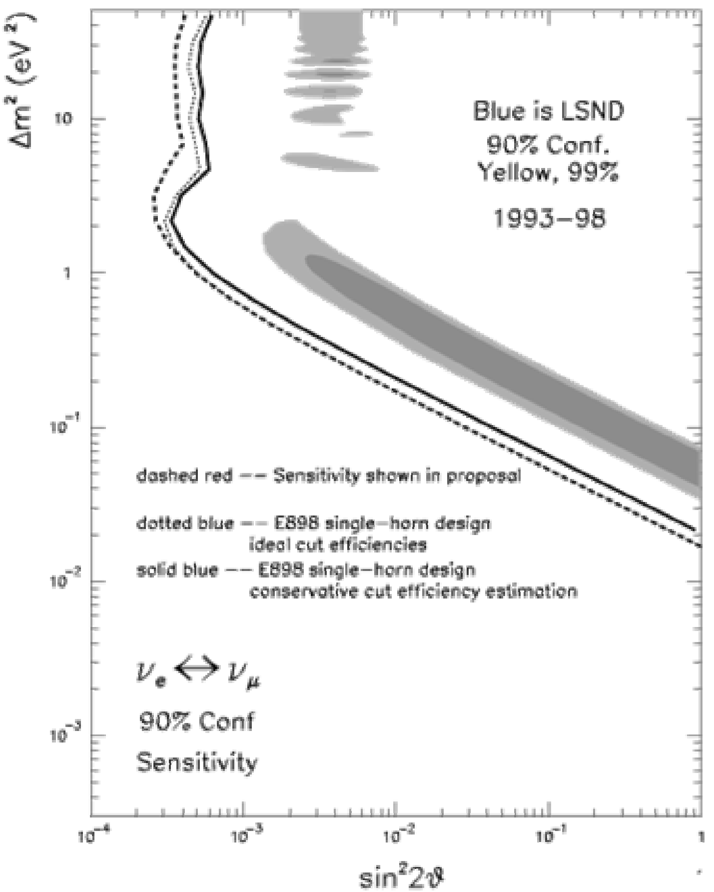

total flux matches expectations!

combining all experiments now leaves only one oscillation region left

**LMA**

# Unanswered Questions

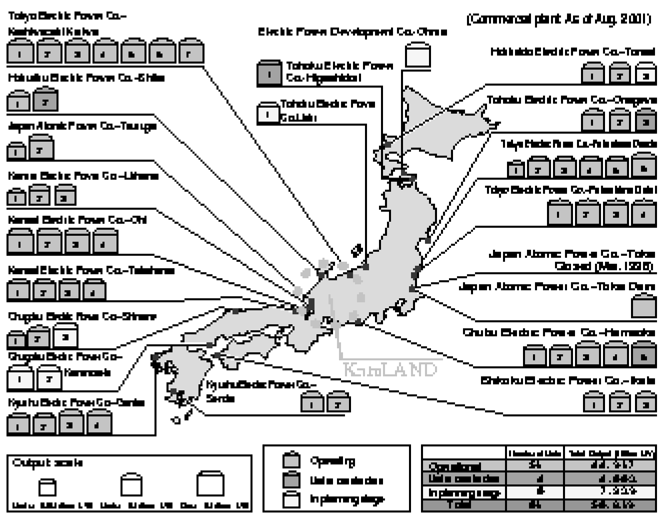
- Is LMA the solution to the Solar Neutrino Problem? (excluding other solutions not a very satisfying way to say LMA is correct)
- If so, what are the exact mixing parameters?
- Could $\sin^2 2\theta$ be very close to, or exactly 1?
- LSND? CPT violation? Do anti-neutrinos have the same mass hierarchy as neutrinos?



# The KamLAND Concept

- re-do the Reines-Cowan experiment but with a BIG detector and MANY reactors at distances ~100 km or more
- this would allow testing the LMA solution to the Solar Neutrino Problem with a well-understood neutrino source
- JAPAN is a good place to do this

# Japan is an excellent location



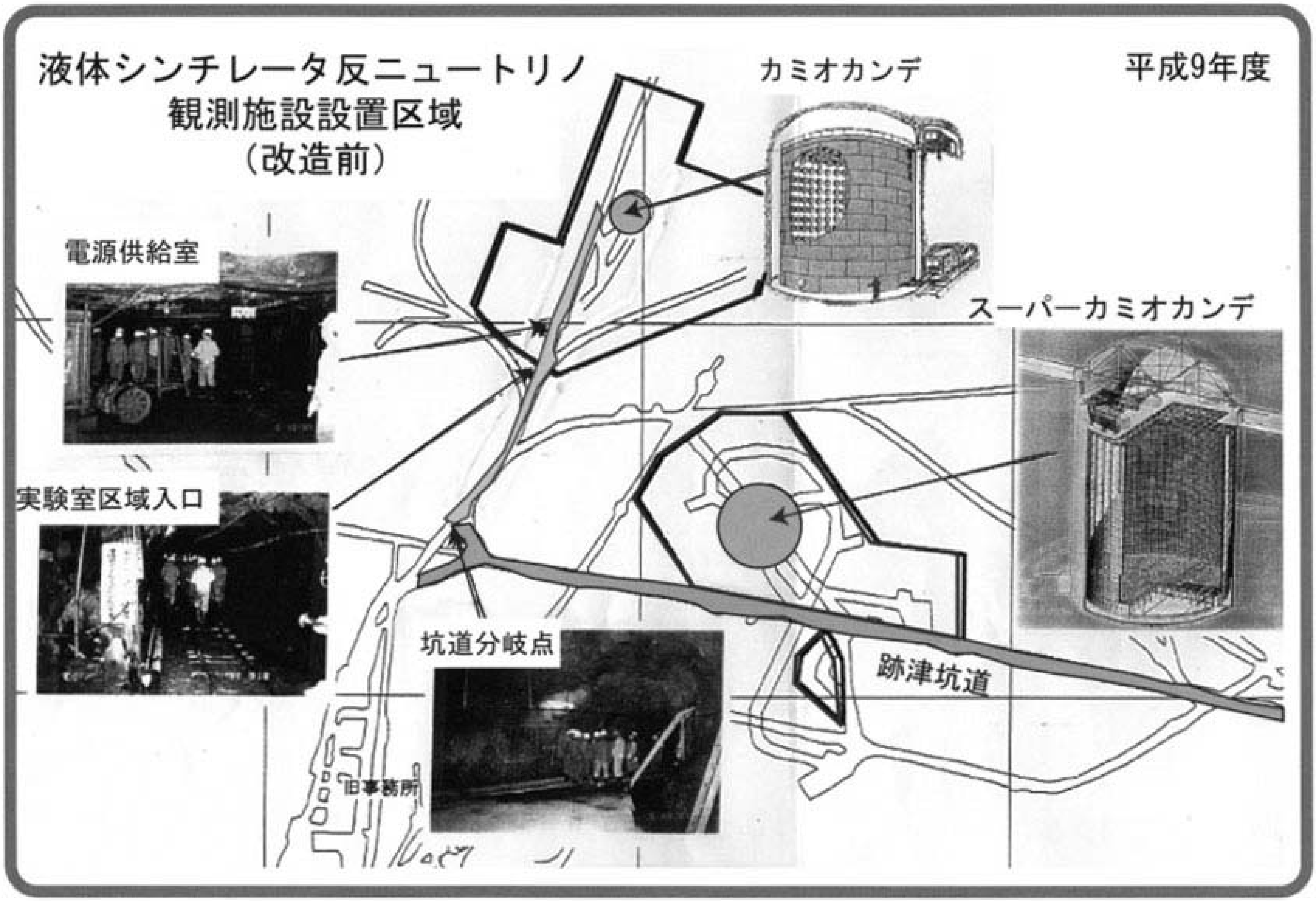
1 km deep in
Kamioka Mine
1

water-filled
active veto

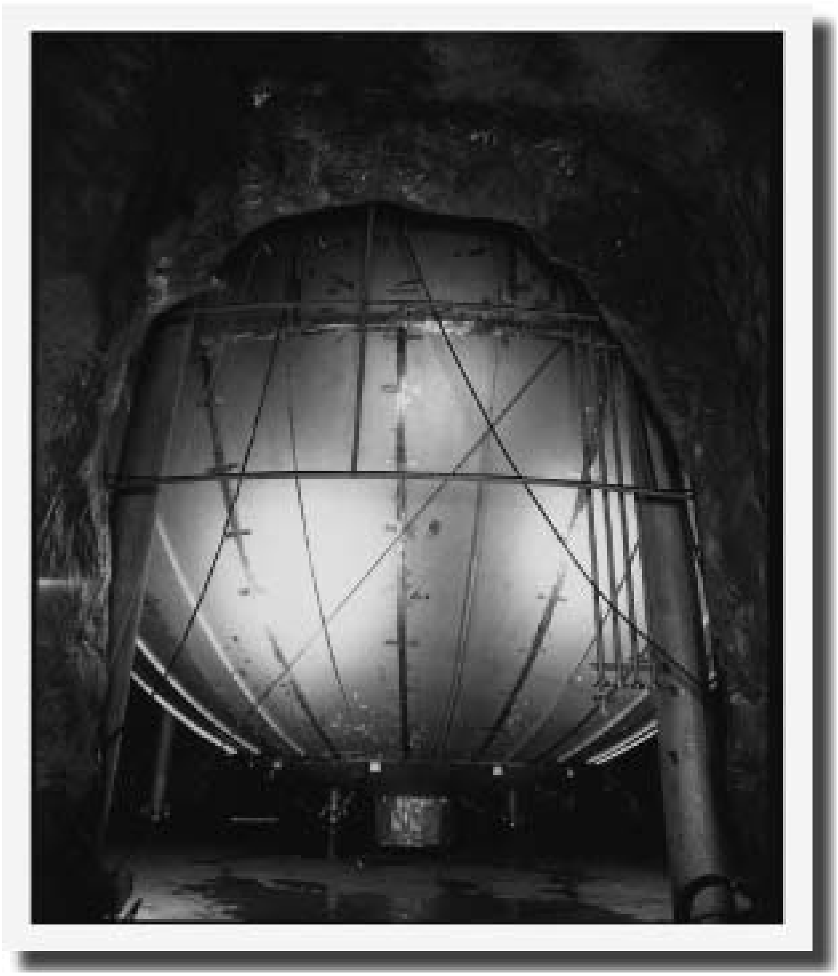
buffer oil
region

1325 17”
554 20” PMT’s

scintillator
filled balloon
6.5 m radius
1000 tons


液体シンチレータ反ニュートリノ
観測施設設置区域
（改造前）
平成9年度
カミオカンデ
スーパーカミオカンデ
電源供給室
実験室区域入口
坑道分岐点
跡津坑道
旧事務所

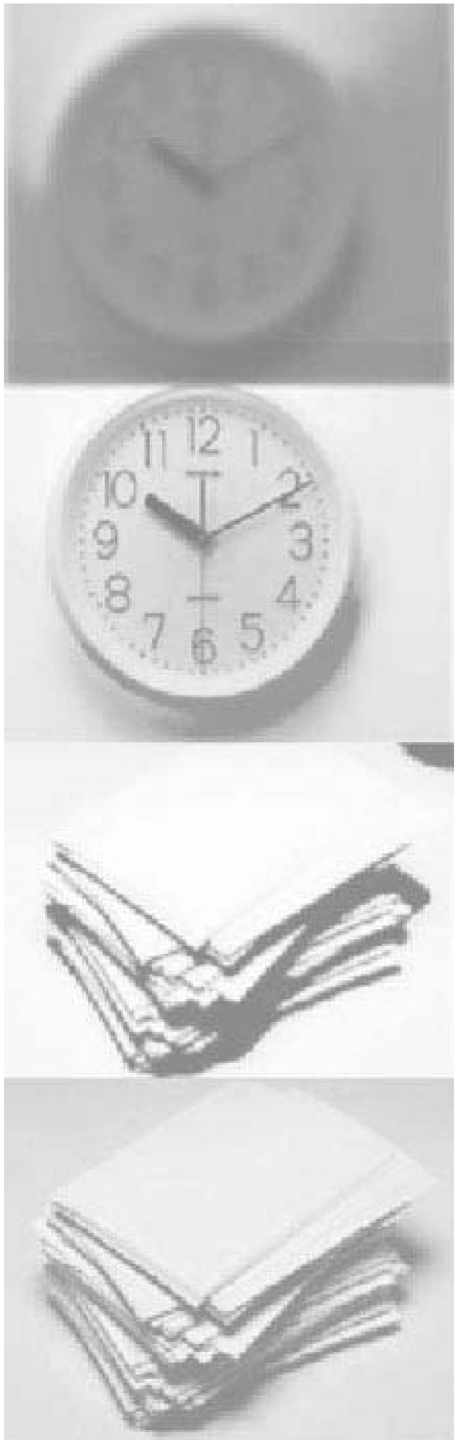
# KamLAND Construction



- use Kamiokande site
- cavity renovation started in 1998
- PMT installation 2000
- Oil filling 2001
- taking data January, 2002
- whew!

# Expected Signal

- Reactor anti-neutrino flux as a function of time and distance
- energy threshold and calibration
- fiducial volume resolution
- efficiency of event selection cuts
- live time



# Livetime

- March 4, 2002 to October 6, 2002
- 145.1 live days
- uncertainty 0.07%

# Trigger Efficiency

- 200 hits ~0.7 MeV (prompt)
- 120 hits ~0.4 MeV (delayed)
- electronics deadtime <<0.1%
- For reactor neutrinos, we use a data reduction threshold of 0.9 MeV and an analysis threshold of 2.6 MeV
- for this analysis the efficiency is essentially 100% for both prompt and delayed triggers

# Energy Calibration

- $^{60}$Co, $^{65}$Zn, $^{68}$Ge, and AmBe sources provide $\gamma$ lines in the range 0.5 to 7.6 MeV
- these are deployed along the z-axis on a regular basis
- about 300 p.e./MeV are observed, giving an energy resolution of 7.5% at 1 MeV.
- off the z-axis the energy reconstruction is confirmed using muon spallation products and contaminents in the detector

# Energy Reconstruction

- “Standard” corrections for absorption, PMT acceptance, PMT wall density, scattering from detector walls, ropes, etc are all made
- In addition to sources we have UV lasers and LED’s to do these
- …but KamLAND is more complicated than the “typical” water Cherenkov detector

# Living in the Material World

- liquid scintillator has a non-linear response in energy due to saturation effects. This is on the order of a few percent for $\gamma$'s to factors of 10-15 for highly-ionizing $\alpha$'s
- Cherenkov light production is a significant contribution to the visible energy due to the PPO waveshifter in the scintillator
- We measure these effects *in situ* using calibration sources and “tagged” $\alpha$'s from U/Th/Rn contaminants $^{212}$Po and $^{214}$Po

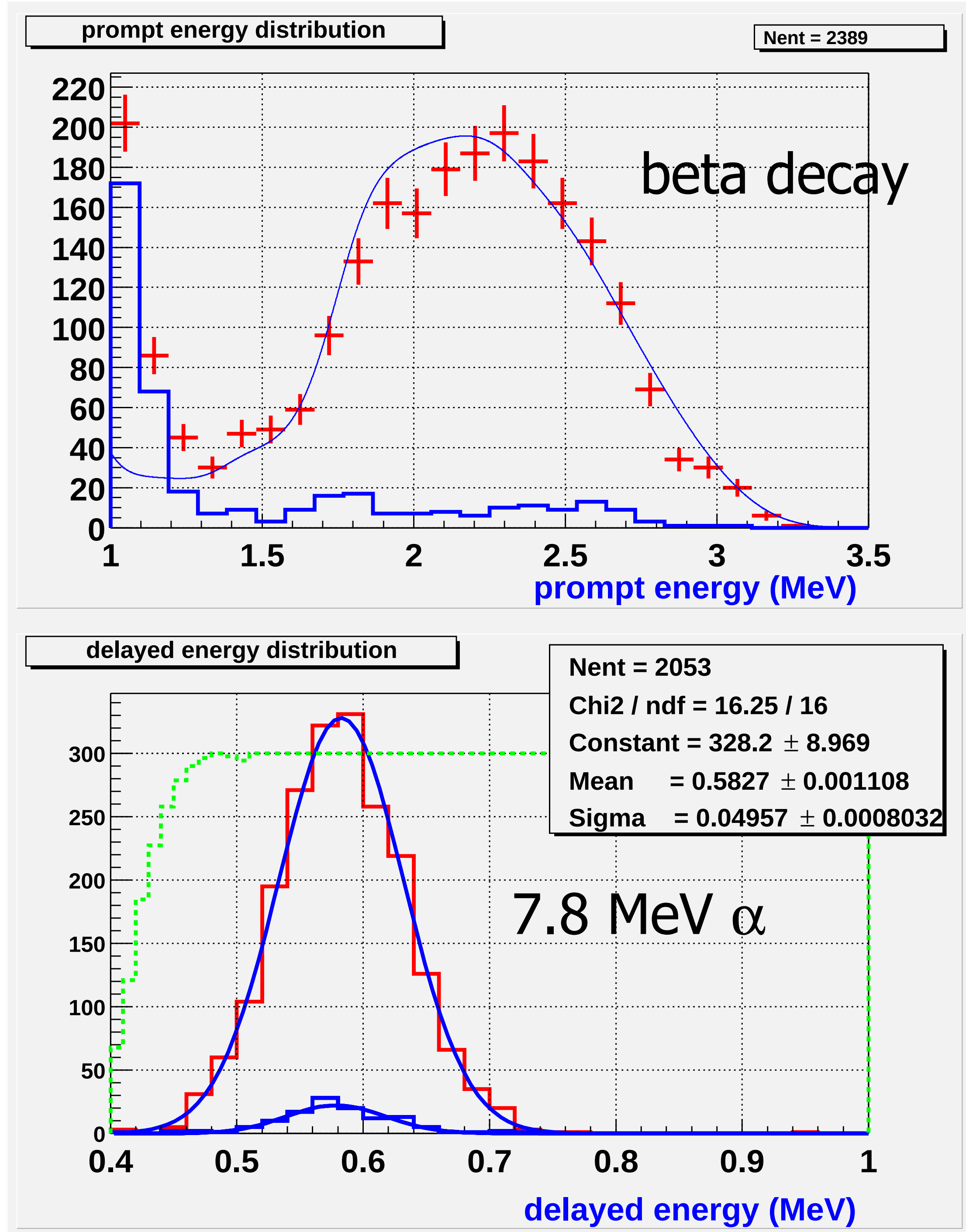
$^{214}Bi \Rightarrow {}^{214}Po + \beta^{-}$

Q=3.27 MeV

$^{214}Po \Rightarrow {}^{210}Pb + \alpha$

Q=7.83 MeV

$t_{1/2}$= 164 μs

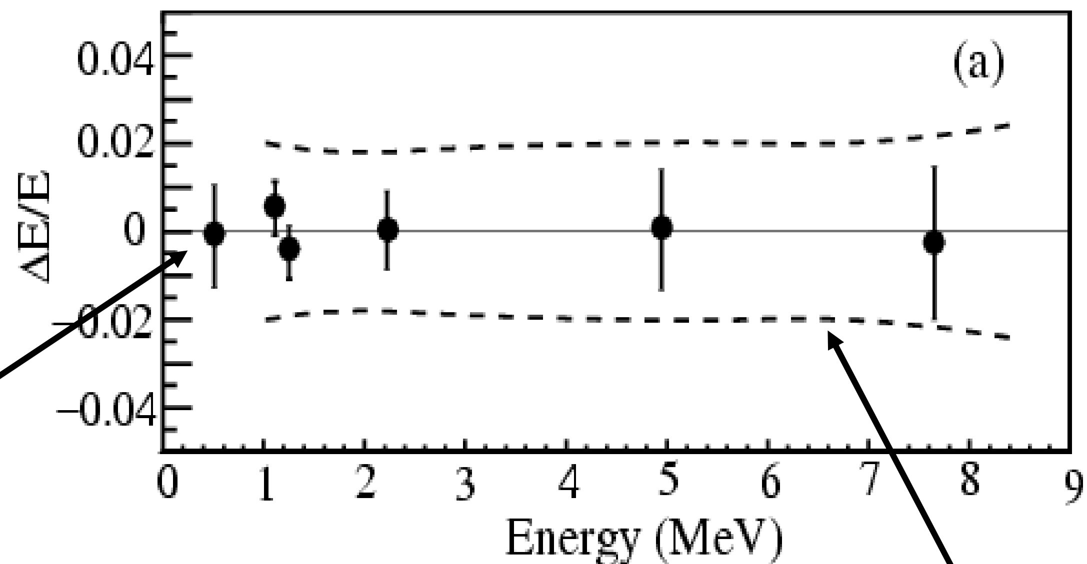


# Energy Reconstruction Uncertainty

- also use $^{40}K$, $^{208}Tl$, $^{12}N$, $^{12}B$, and thermal neutron capture from muon spallation to test off-axis reconstruction
- variation within the fiducial volume less than 0.5%
- energy scale time variation is less than 0.6%
- total energy scale systematic uncertainty at 2.6 MeV is 1.91%
- uncertainty in rate above 2.6 MeV due to energy calibration uncertainty:

  2.13%

# Results of Energy Calibration




individual
sources

energy correlated
systematic uncertainty

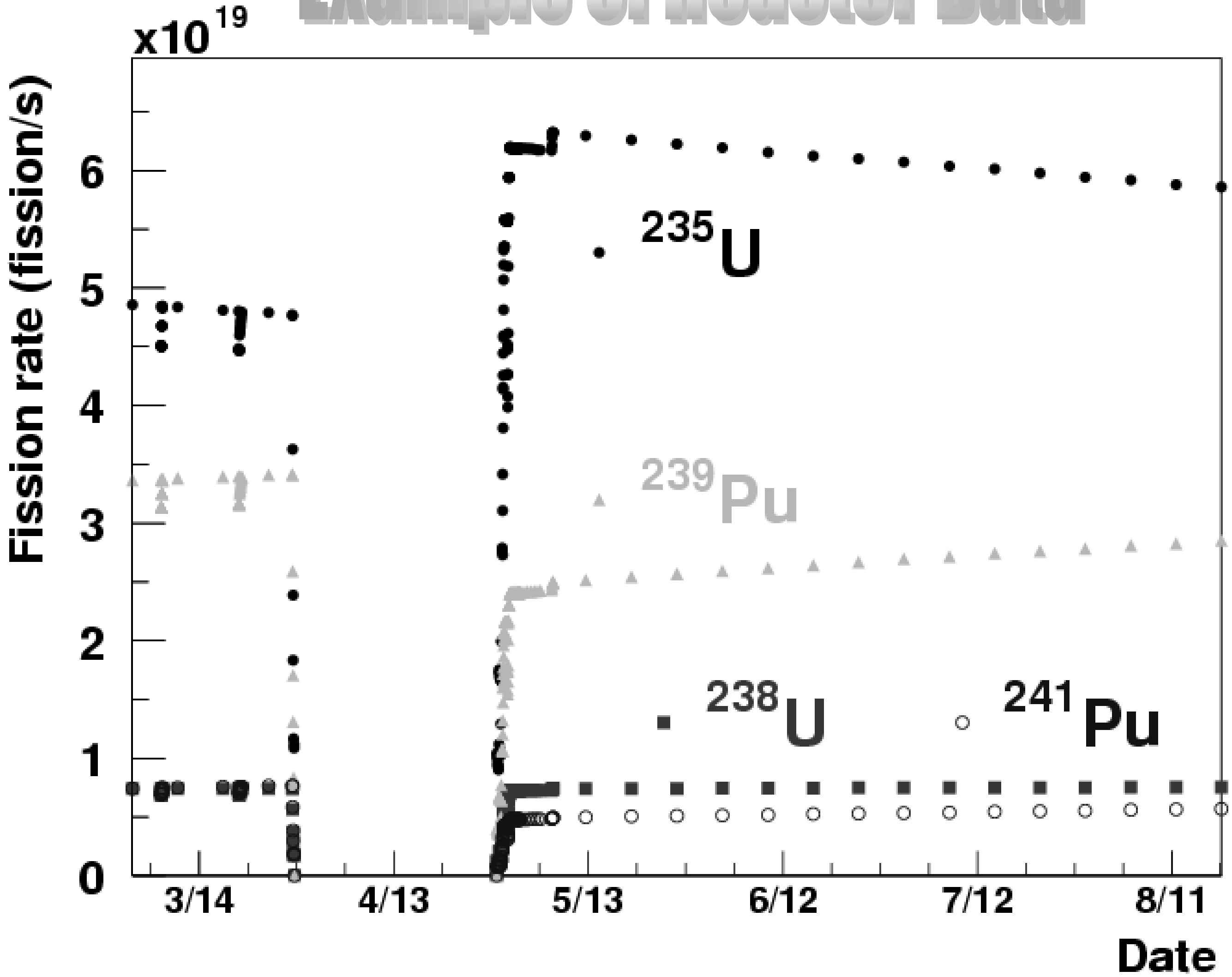
# Reactor Thermal Power

- Thermal power history provided for all Japanese reactors. By law, this is required to be known to better than 2%.
- While all reactors considered, 79% of the flux comes from 26 reactors in the distance range 138-214 km
- Another 6.7% from one reactor at 88 km
- All other reactors more than 295 km away
- Korean reactors 2.5% (estimated to 10%)
- Rest of the world is 0.7% (estimated to 50%)

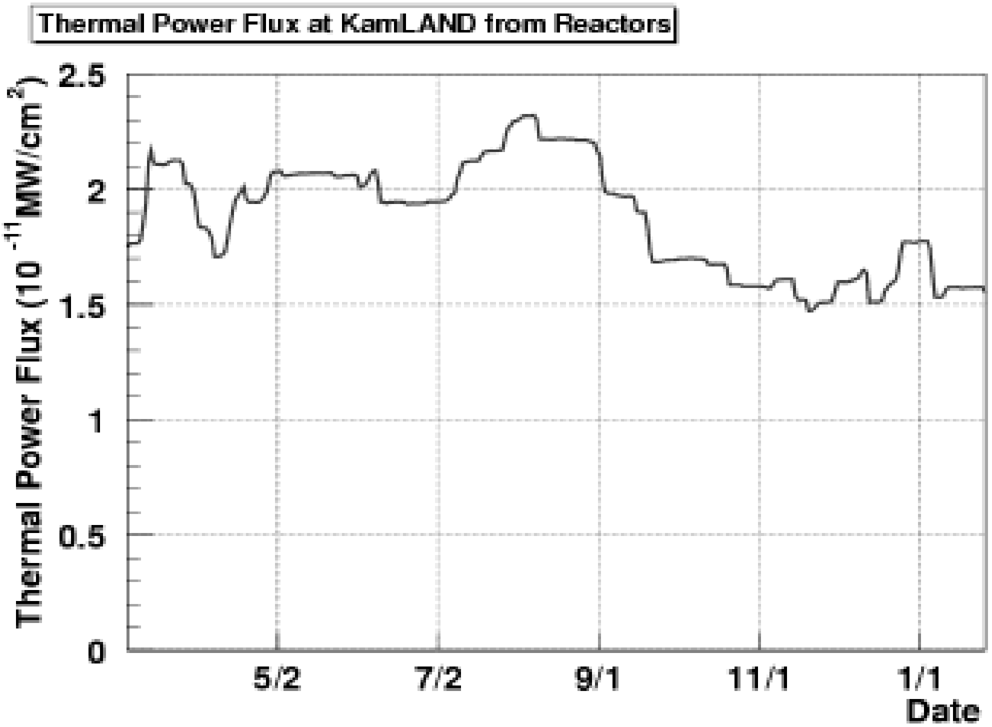
# Reactor Fuel Loading and History

- ✓ Average fuel loading: $^{235}U$:$^{238}U$:$^{239}Pu$:$^{241}Pu$ is 0.568: 0.078: 0.297: 0.057
- ✓ error in anti-neutrino flux from uncertainty in fuel loading is less than 1%
- ✓ uncertainty in flux per fission is 2.5% based on estimates from several calculations
- ✓ power history uncertainty folded into the contribution of delayed beta emitters adds another 0.3% uncertainty

# Example of Reactor Data



# Time Variation of Summed Flux



# Uncertainty in the Interaction Rate

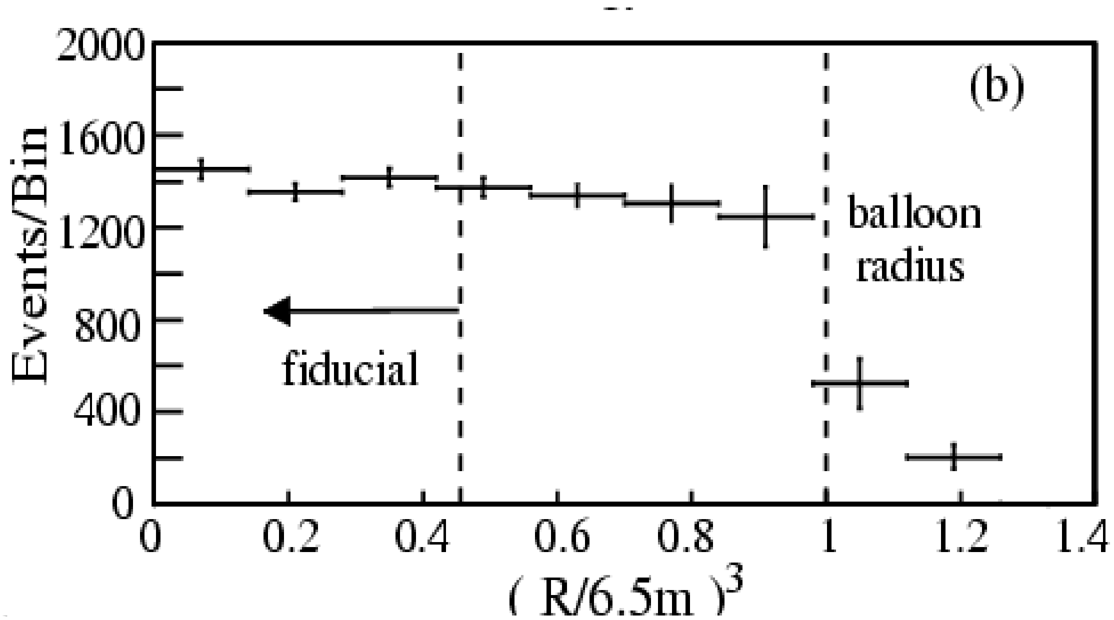
| | |
|---|---|
| Reactor Power: | 2.05% |
| Fuel Loading: | 1.00% |
| History: | 0.28% |
| Spectrum: | 2.48% |
| Cross Section: | 0.20% |
| | 3.39% |

# Fiducial Volume Resolution

- The total mass of scintillator added to the detector is uncertain to 2.13%
- the ratio of fiducial to total volume is checked using neutron capture from muon spallation.
- comparison of the capture rate inside the fiducial and total volume agrees to within 4.06% of the expected volume ratio.

# Vertex Distribution of neutron capture from muon spallation events

agrees to within 4.06% of expectation




total uncertainty in target mass: 4.58%

# Event Selection

- Energy and fiducial volume cut
- muon spallation cut (loss of 11.4% in live time)
- time between prompt and delayed event ($0.5 < \Delta T < 660\ \mu s$)
- distance between prompt and delayed vertex cut ($\Delta L < 1.6m$)
- distance from central axis thermometer array > 1.2 m
- total selection efficiency: 78.3(1.6)%

- the total efficiency of these cuts was verified using the absolute source strengths of the $^{60}Co$ and $^{65}Zn$ sources
- the total efficiency of the distance and time cuts was verified with AmBe source to within 1% using the 4.4 MeV gamma as a tag for the neutron de-excitation of $^{13}C^*$

# Expected Event Rate

- Total systematic uncertainty in the expected rate is 6.42%
- expected rate: 86.8$\pm$5.6 events above 2.6 MeV
- Background?

# Accidental Coincidences

- Singles rate of 30 Hz with time and distance cuts
- expected number of accidentals is very small
- 0.0086 events

# $^{8}Li$ and $^{8}He$

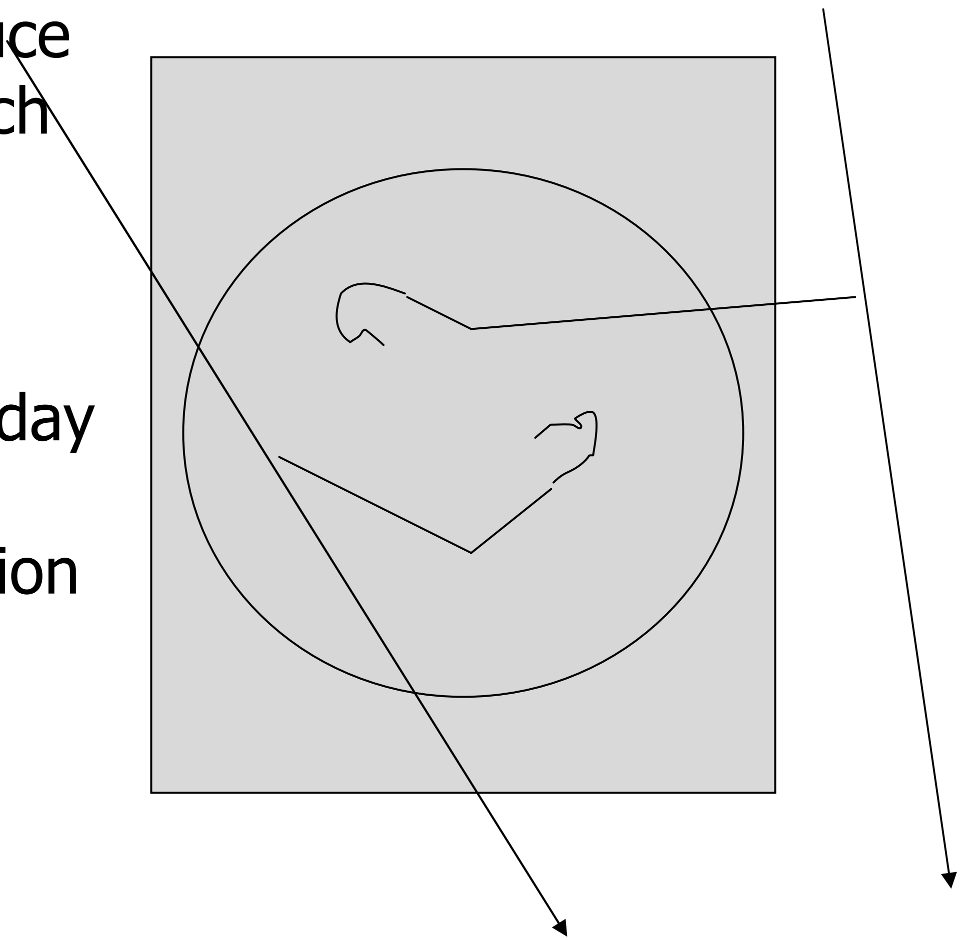
- These spallation products (produced by the passage of muons through the detector) can mimic reactor neutrino events in that they can neutron de-excite to a beta unstable daughter
- such backgrounds can be almost eliminated by applying a time and distance cut around muon induced events
- estimated background in sample $0.94 \pm 0.85$

# Fast Neutrons

muons may produce fast neutrons which can mimic reactor events

~3,000 neutrons/day

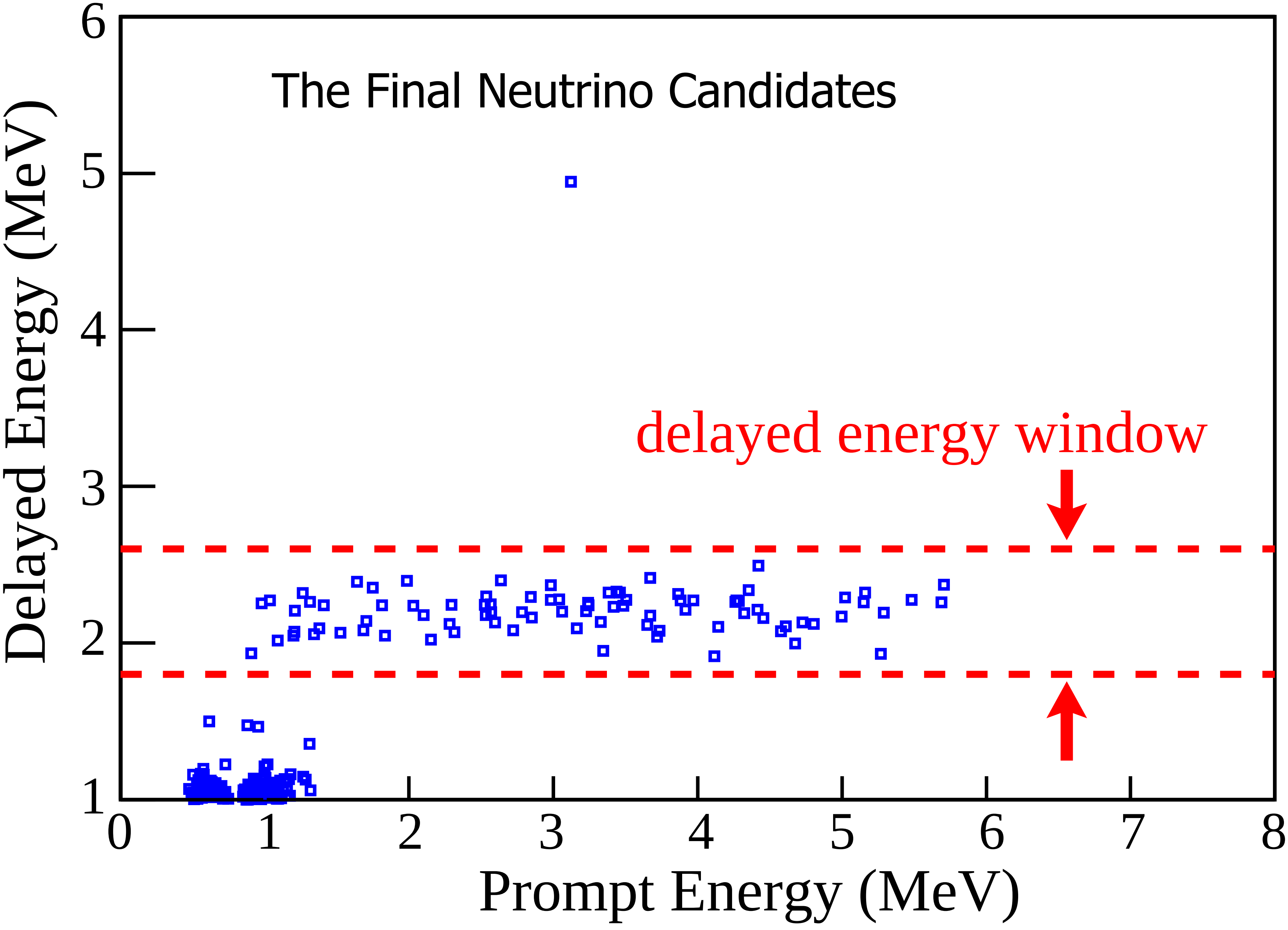
important calibration source



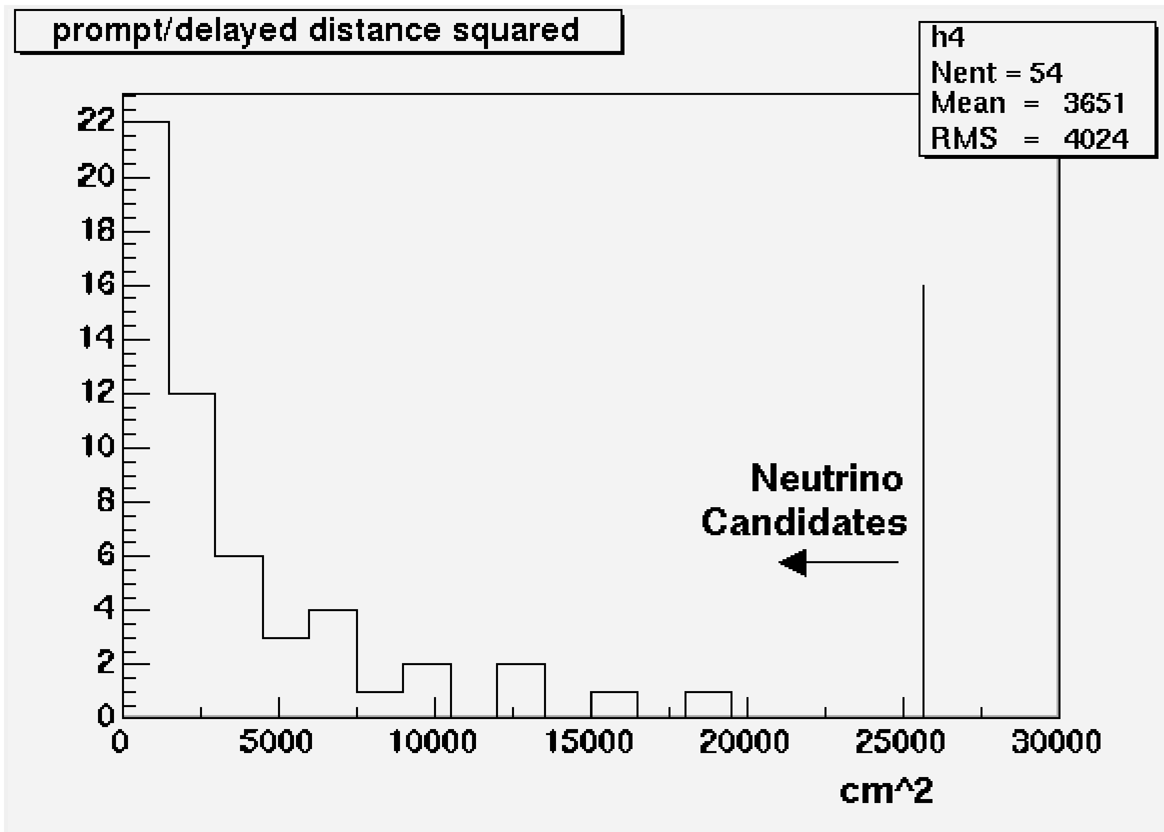
# Fast Neutrons

- almost all neutrons are tagged by precursor muons in the detector or water veto
- we can measure the distance from the track of the capture to let us calculate the rate of missed captures from muons in the rock
- OD-only muons with a fast neutron let us measure the energy distribution of the recoil protons
- we estimate backround above 2.6 MeV

  <0.5 events


The Final Neutrino Candidates
delayed energy window
Delayed Energy (MeV)
Prompt Energy (MeV)
0
1
2
3
4
5
6
7
8
1
2
3
4
5
6

# ΔL Distribution of neutrino events




not sensitive to cut value

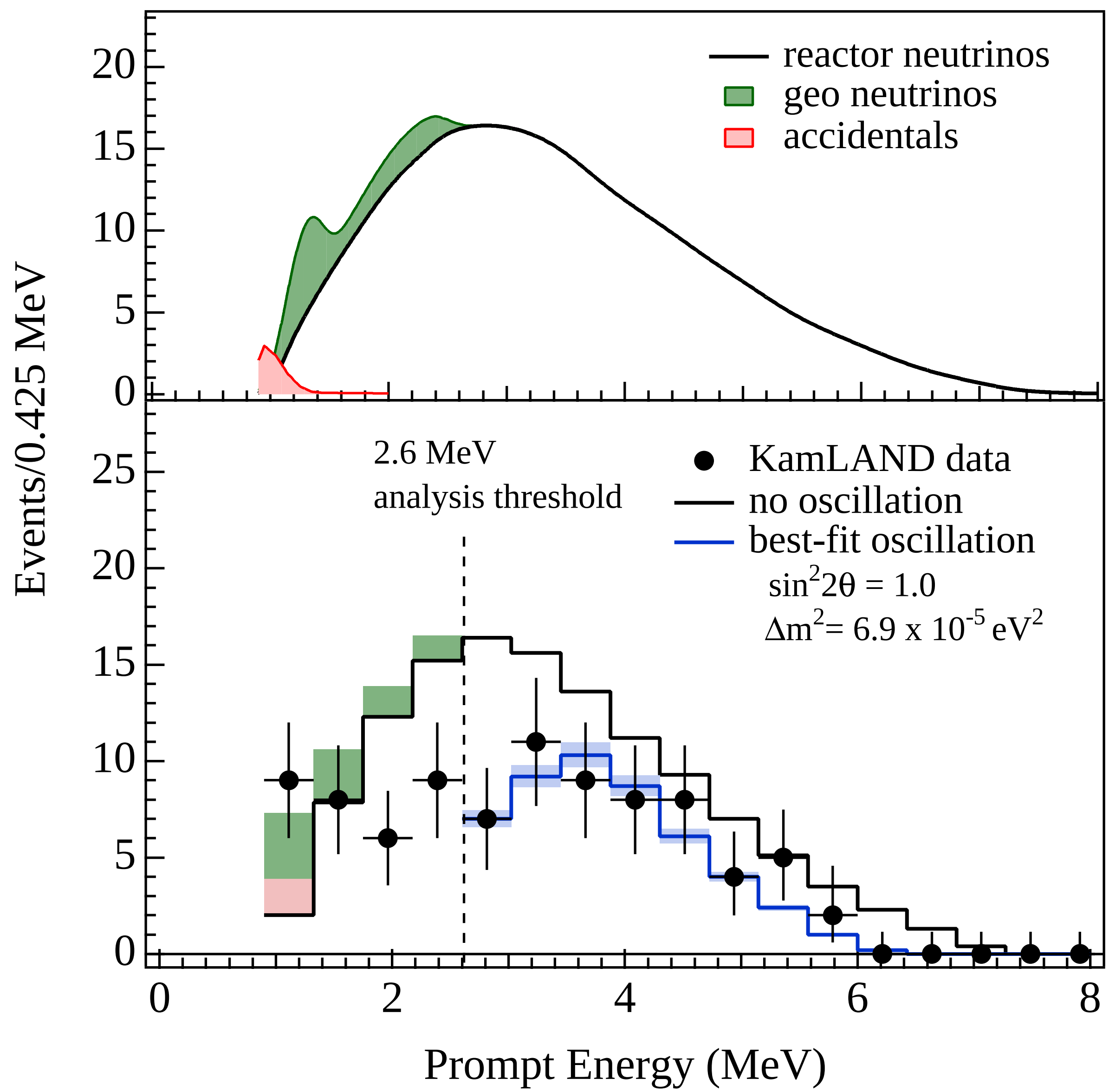
# Measured Event Rate

- To avoid ambiguities associated with geo-neutrinos we make a cut at 2.6 MeV
- 54 events survive these cuts
- measured/expected ratio:

$0.611 \pm 0.085(\text{stat.}) \pm 0.041(\text{syst.})$

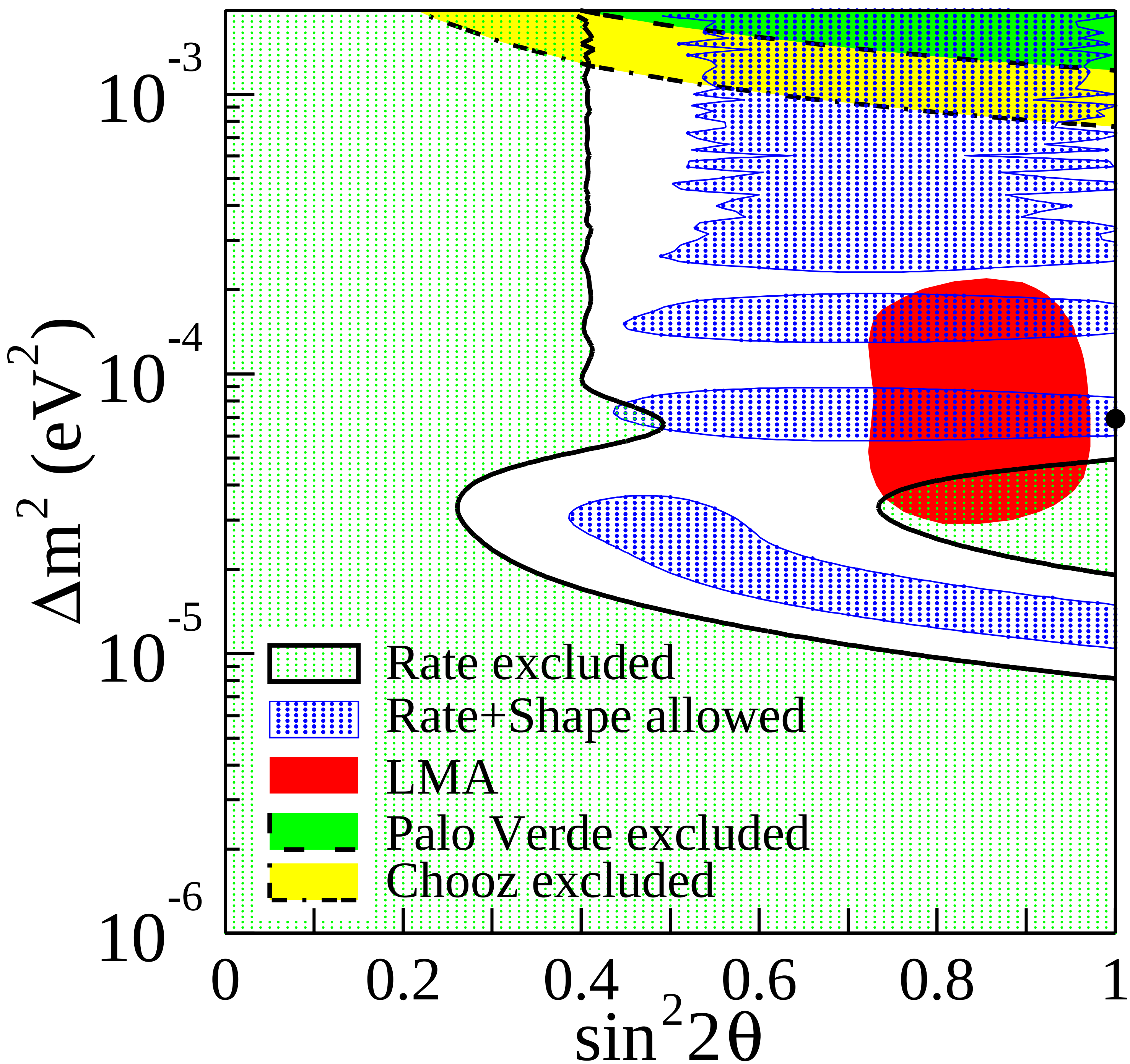
probability of no disappearance <0.05%

# Measured Spectrum



# Neutrino Oscillations

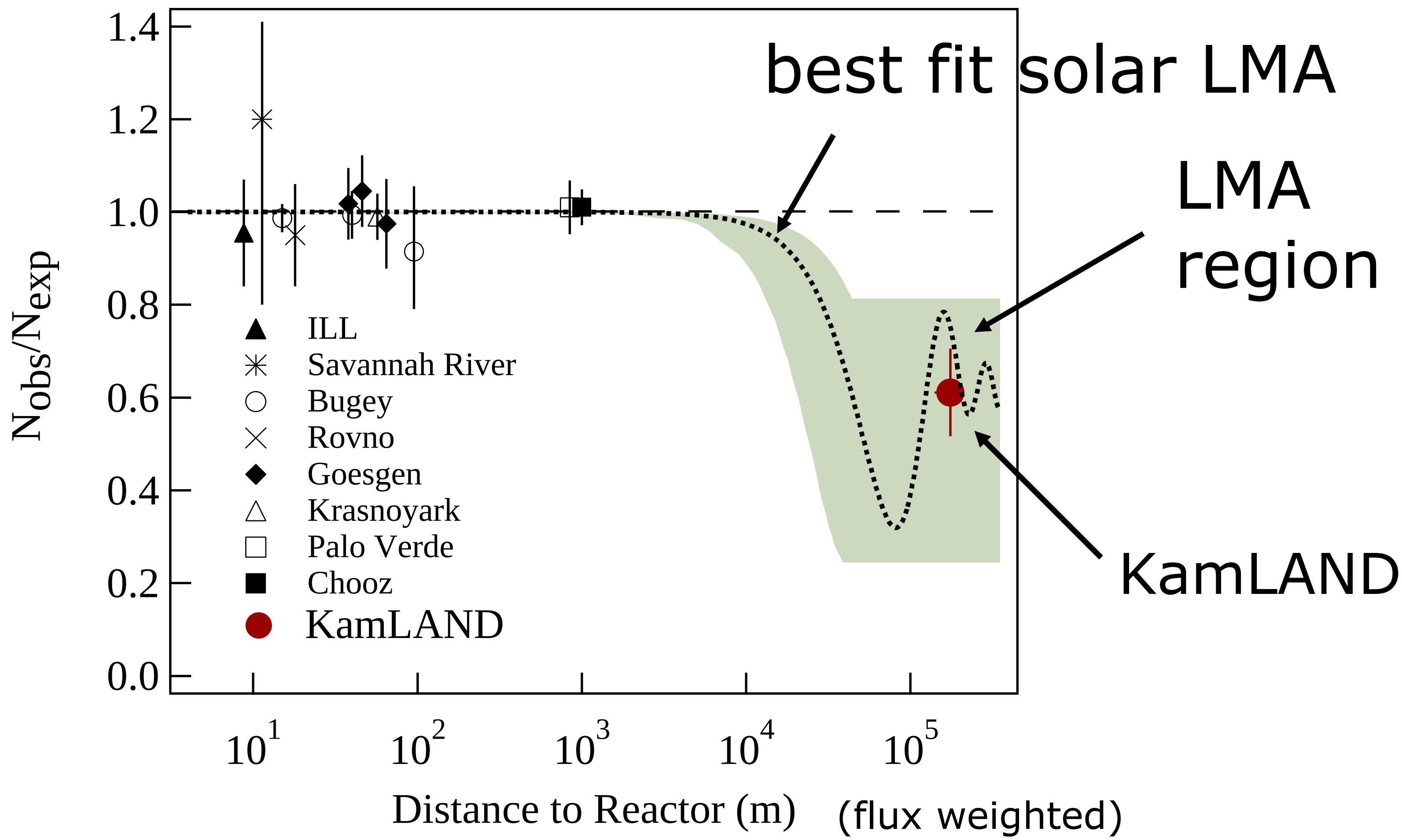
- Fit using a two-component mixing model
- Simple $\chi^2$ fit to the rate as a hypothesis test
- Maximum likelihood test using spectral shape and taking into account correlated uncertainties



$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$\Delta m^2\ (eV^2)$
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$
Rate excluded
Rate+Shape allowed
LMA
Palo Verde excluded
Chooz excluded

- best fit: $\sin^2 2\theta = 1.0$  $\Delta m^2 = 6.9 \times 10^{-5}$ eV$^2$
- global minimum at $\sin^2 2\theta = 1.01$
- distorted spectrum consistent at the 93% confidence
- but renormalized undistorted spectrum also consistent at 53%

# Comparison with Other Experiments



# Conclusions

- A deficit of reactor neutrinos is seen at a $4.1\sigma$ level
- backgrounds are very low
- Combining spectral information with the simple rate measurement gives a two-component best fit of $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 6.9 \times 10^{-5}$ eV$^2$
- best fit may (will?) likely change with additional spectral data

# Deep Thoughts*: The Future*

- 3 live years: statistical error 13.9% to 5.0%
- improve energy calibration
- improve fiducial volume resolution (new calibration arm)
- improve energy resolution (increase light collection by 40%)
- systematic error 6.4% to ~4.7% or less
- error in rate goes from 15.3% to 6.9%

# $\sin^2 2\theta$

- suppression factor $f \sim 1-\sin^2 2\theta(1/2)$ gives $\sin^2 2\theta=0.78(0.19)$
- a  24% measurement using rate only
- note that spectrum mostly improves $\delta m^2$ resolution
- estimated improvements give ~10% measurement
- *Veritas filia temporis*   (Francis Bacon)
- $^8B$ solar neutrinos, geo-neutrinos, nucleon decay results on the way
- $^7Be$ neutrinos will take some time
- thanks!