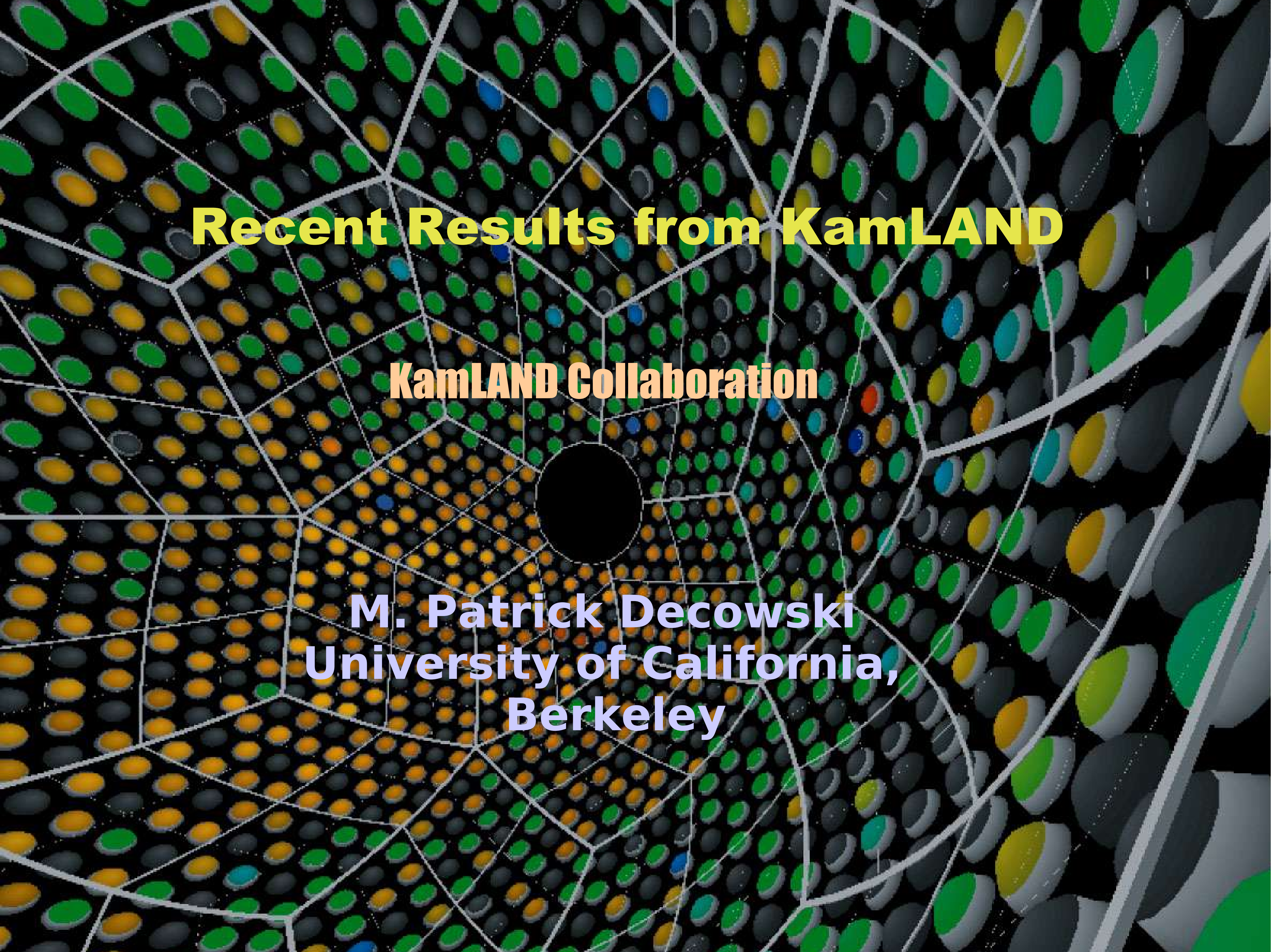
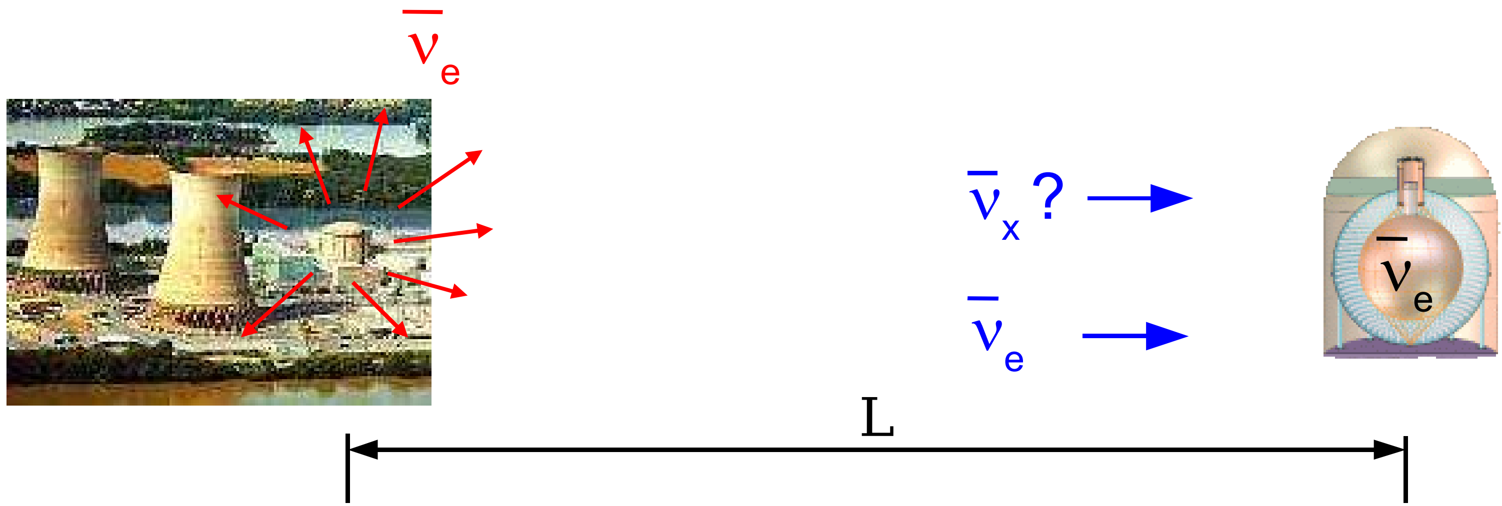


Recent Results from KamLAND

KamLAND Collaboration

M. Patrick Decowski
University of California, Berkeley

Reactor Neutrino Experiments

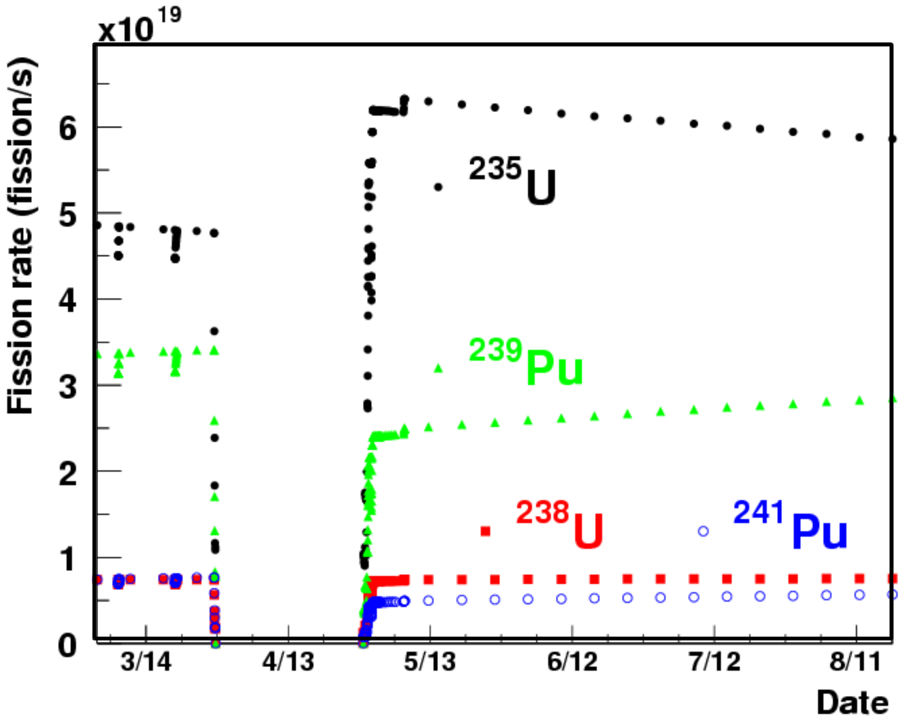


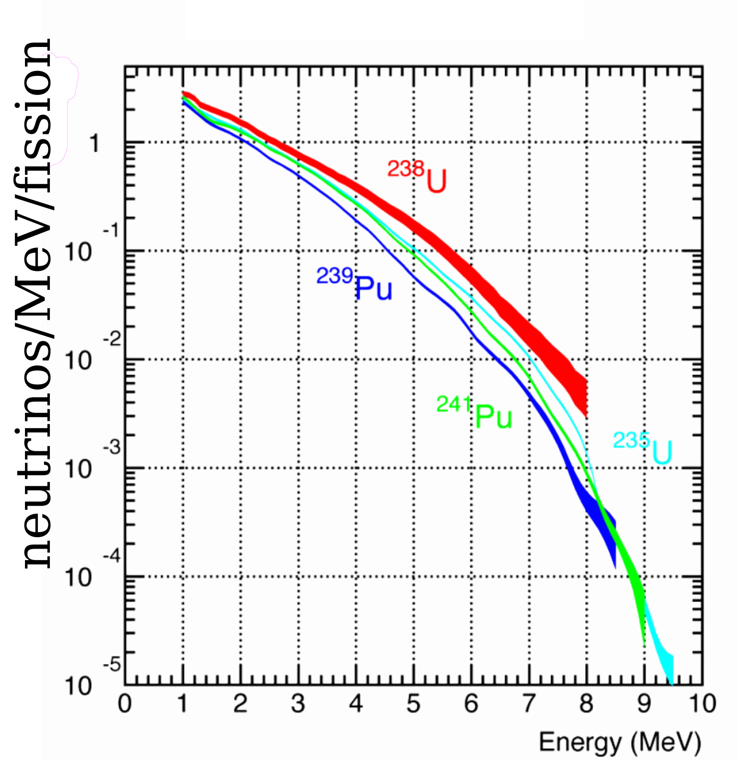
Reactors produce few MeV anti-neutrinos:
Energy too low to produce μ or τ

$\rightarrow$ disappearance experiments

Calculating Neutrino Spectra

99.9% of $\overline{\nu}_e$ produced by just 4 fission elements



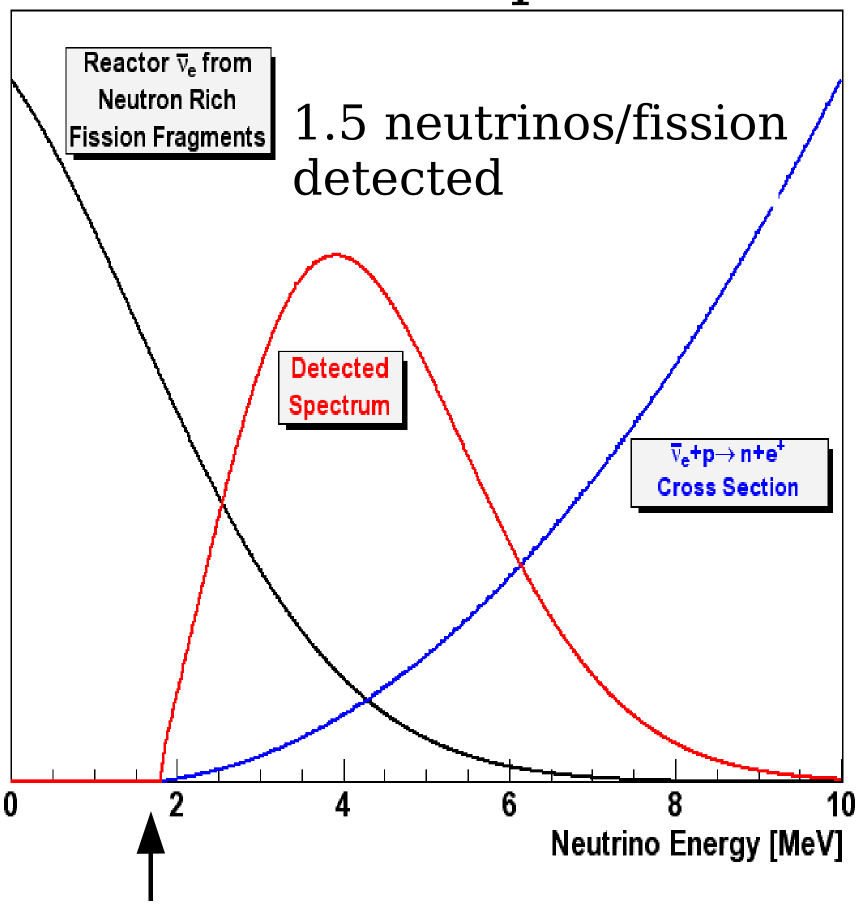


- Fission rates provided by Reactor companies
  - Chiefly function of thermal power
  - Weak function of water inlet T: 10% error → ~0.15% rate change

2.5% uncertainty in anti-neutrino spectrum

Detected Reactor Spectrum

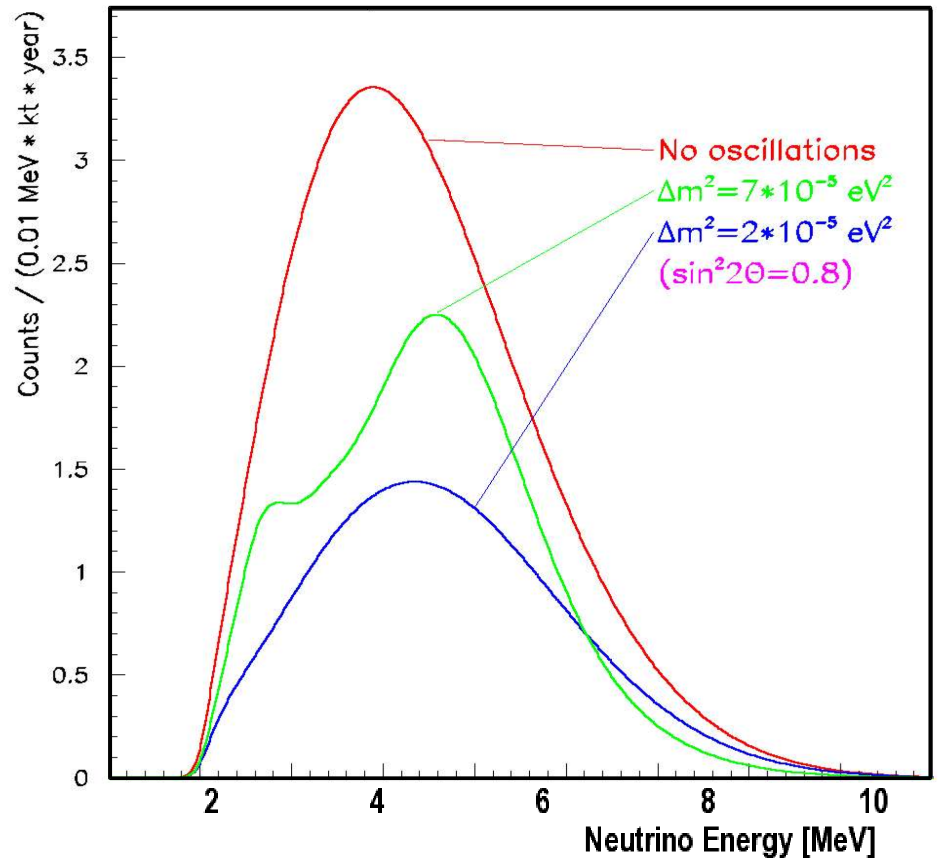
Un-oscillated spectrum



1.5 neutrinos/fission detected

1.8MeV threshold in inverse beta decay

Oscillated spectrum



Neutrino oscillations change both overall normalization ('rate') and introduce shape distortions

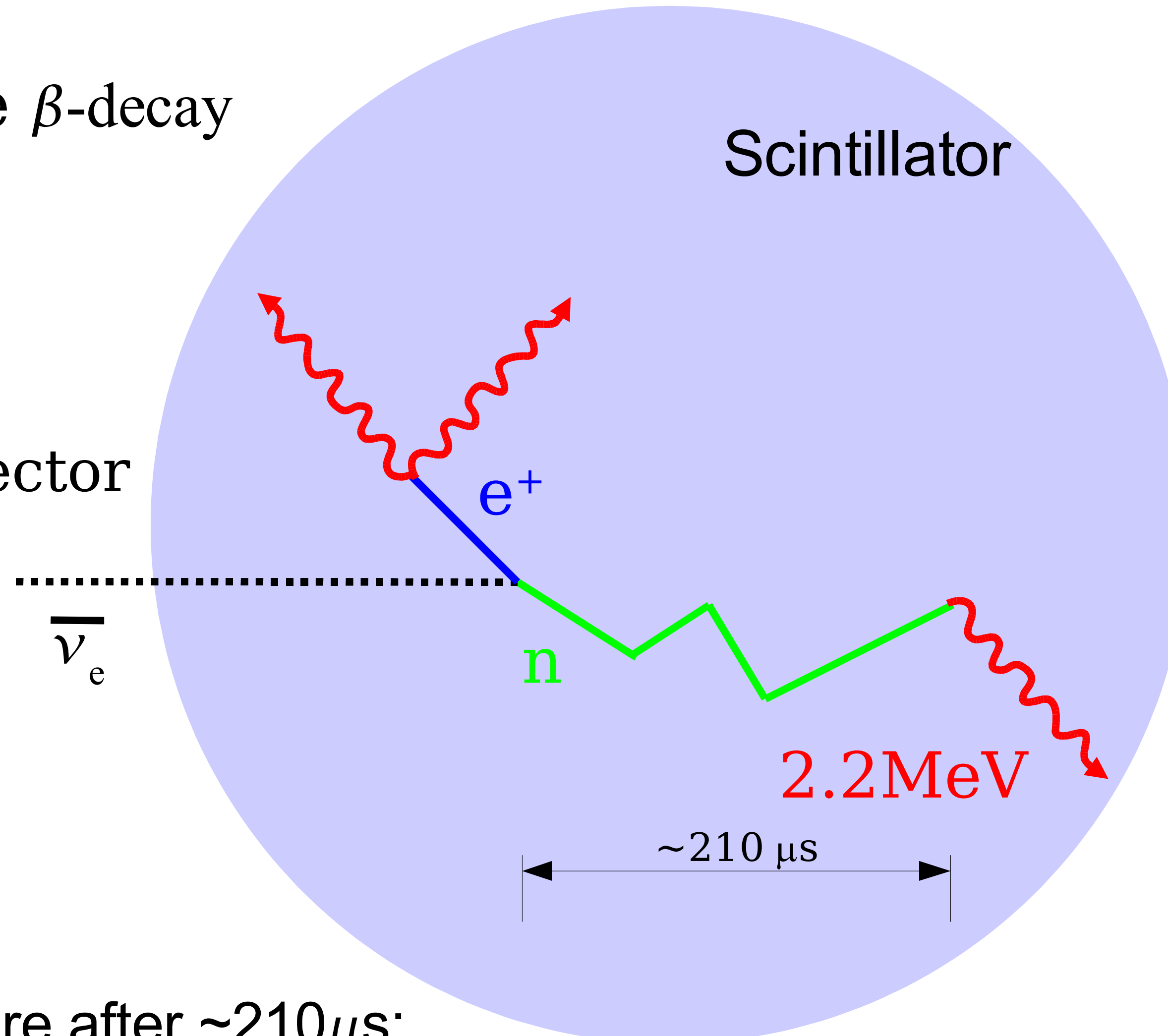
Anti-Neutrino Detection Method

Reaction Process: inverse β-decay

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

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

Scintillator is target and detector



- Distinct two-step signature:
  - prompt event: positron

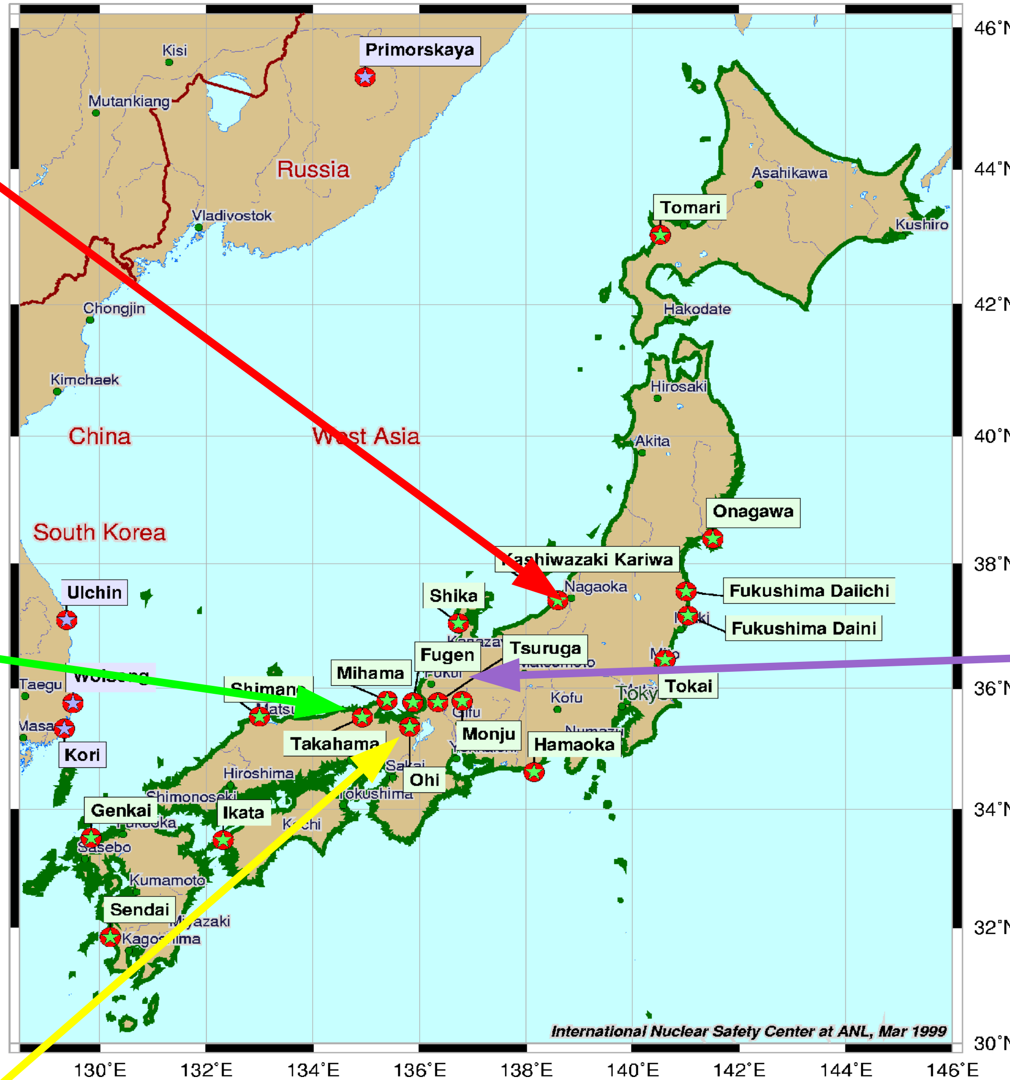
    $$E_\nu \approx E_{e^+} + \bar{E}_n + 0.8\,MeV$$

  - delayed event: neutron capture after ~210μs:

    2.2 MeV gamma

Delayed coincidence: good background rejection

KamLAND Reactors



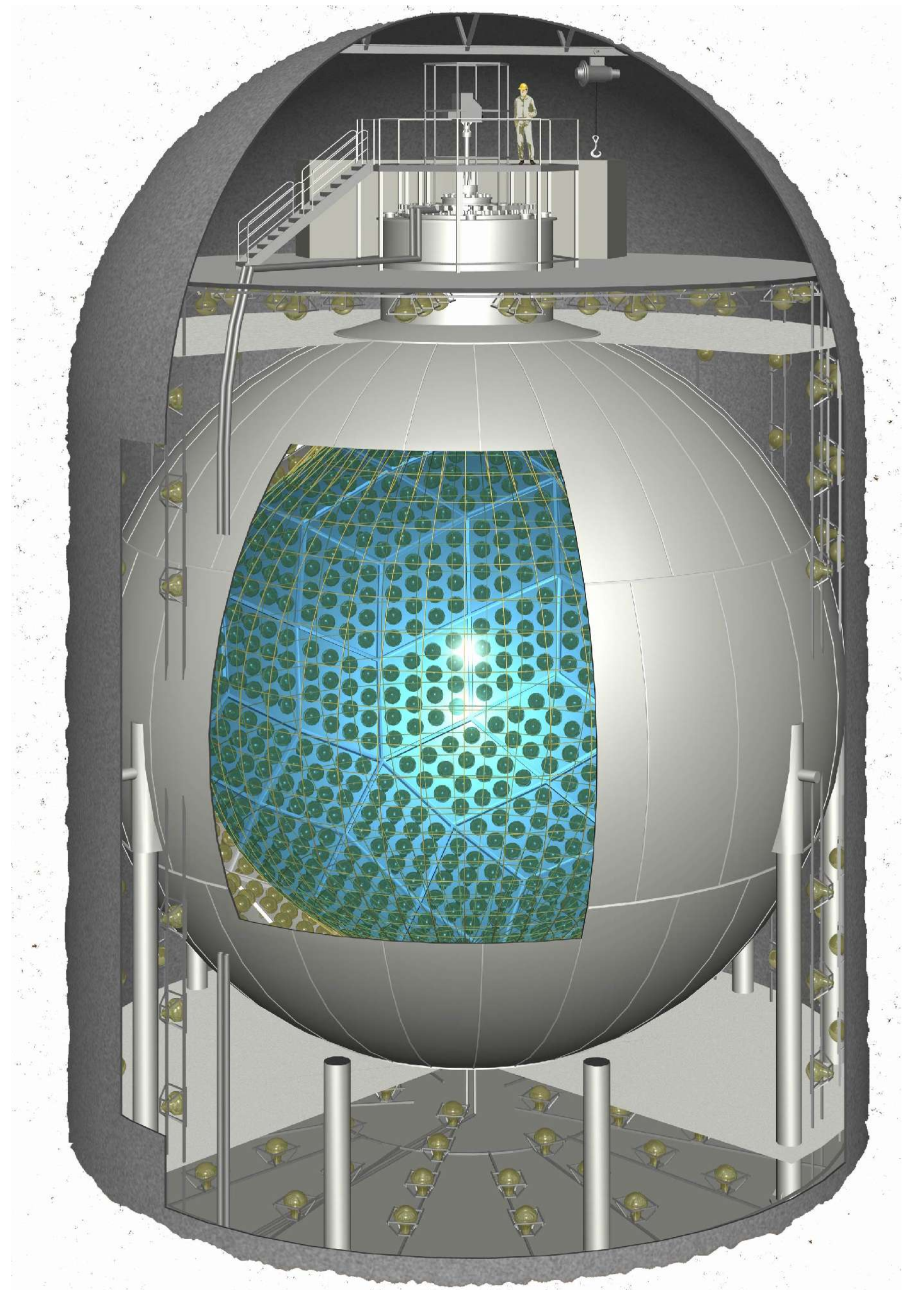
KamLAND uses the entire Japanese nuclear power industry as a long-baseline source: **53** reactors

2700 mwe overburden

80% of flux from baselines 140-210 km

KamLAND Detector

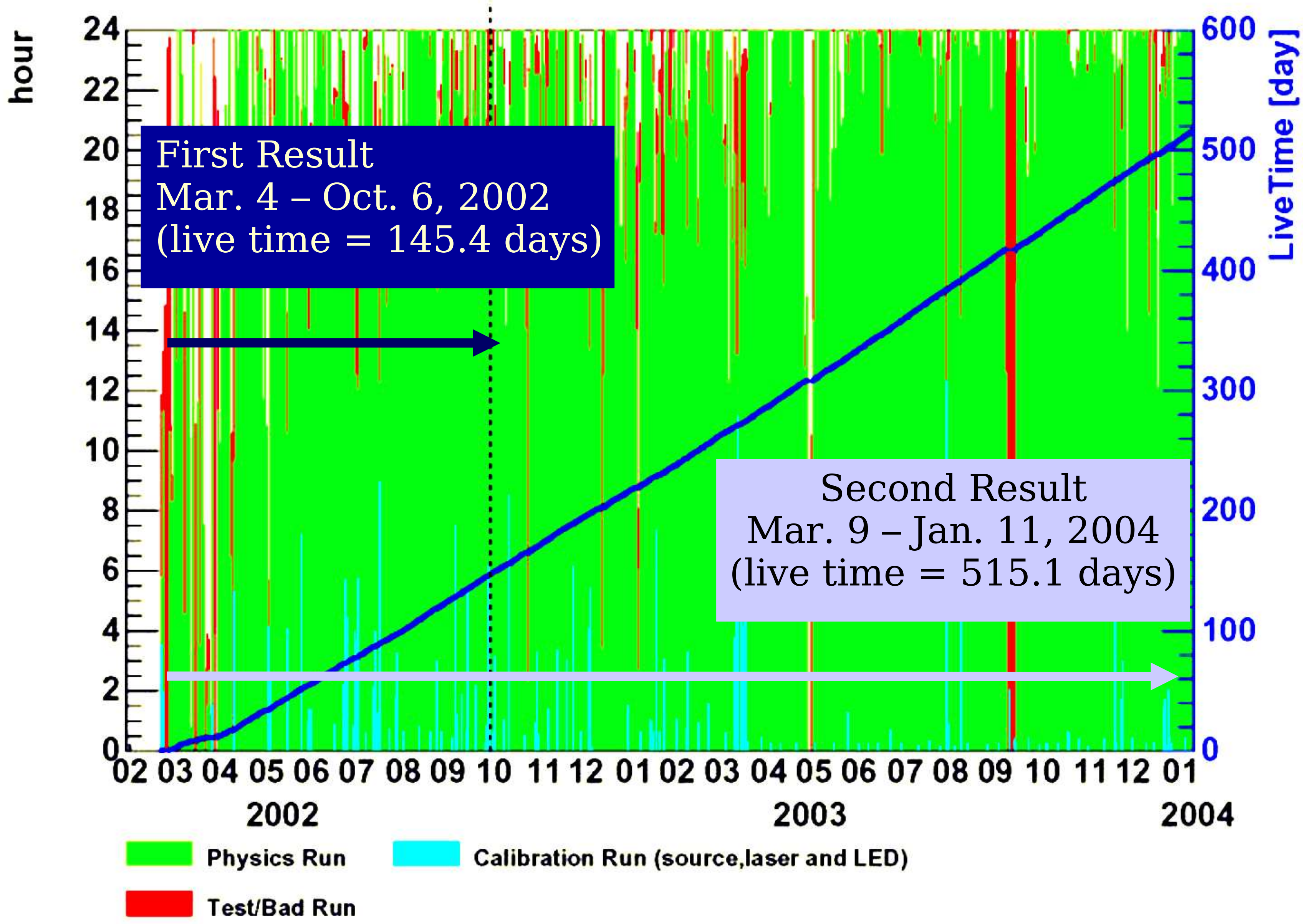
- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% pseudocumene (scint)
    - 80% dodecane (oil)
  - 2.5m buffer region filled with oil
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Multi-hit,
  deadtime-less electronics
- Water Cerenkov veto counter



Energy resolution:

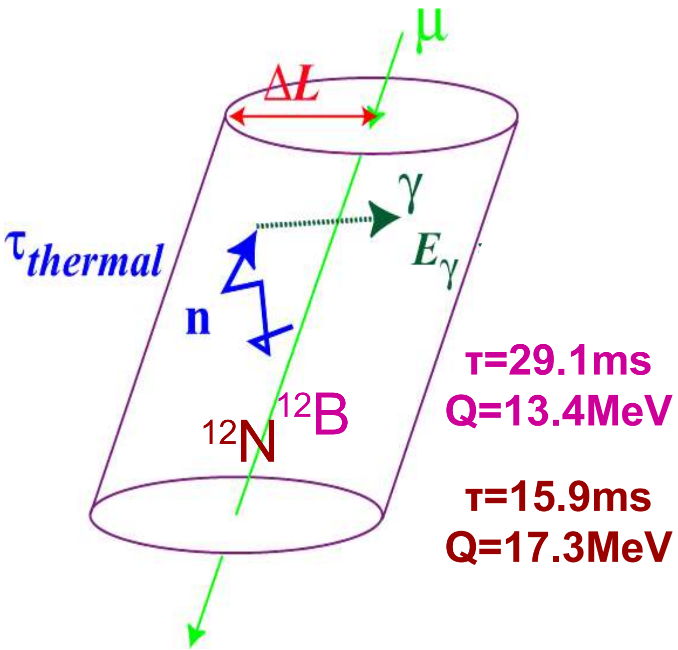
$\sigma/E = 6.2\%/\sqrt{E(\text{MeV})}$

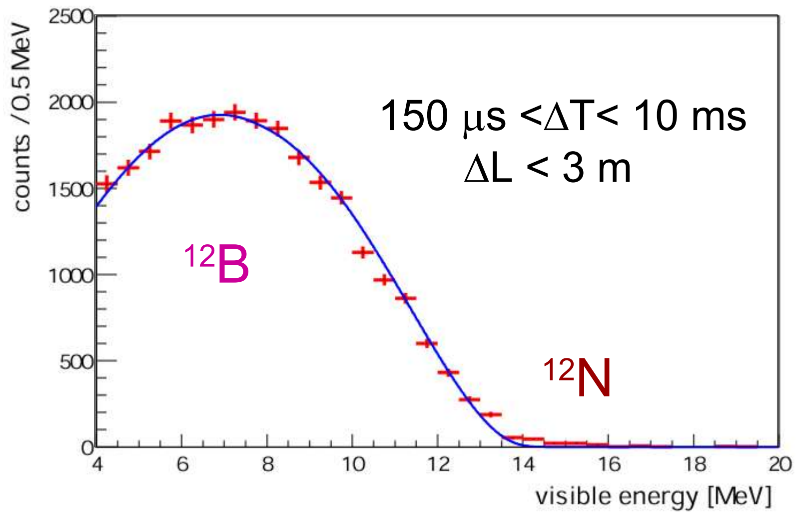
Live Time


hour
LiveTime [day]
First Result
Mar. 4 – Oct. 6, 2002
(live time = 145.4 days)
Second Result
Mar. 9 – Jan. 11, 2004
(live time = 515.1 days)
24 22 20 18 16 14 12 10 8 6 4 2 0
600 500 400 300 200 100 0
02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01
2002
2003
2004
Physics Run
Calibration Run (source,laser and LED)
Test/Bad Run

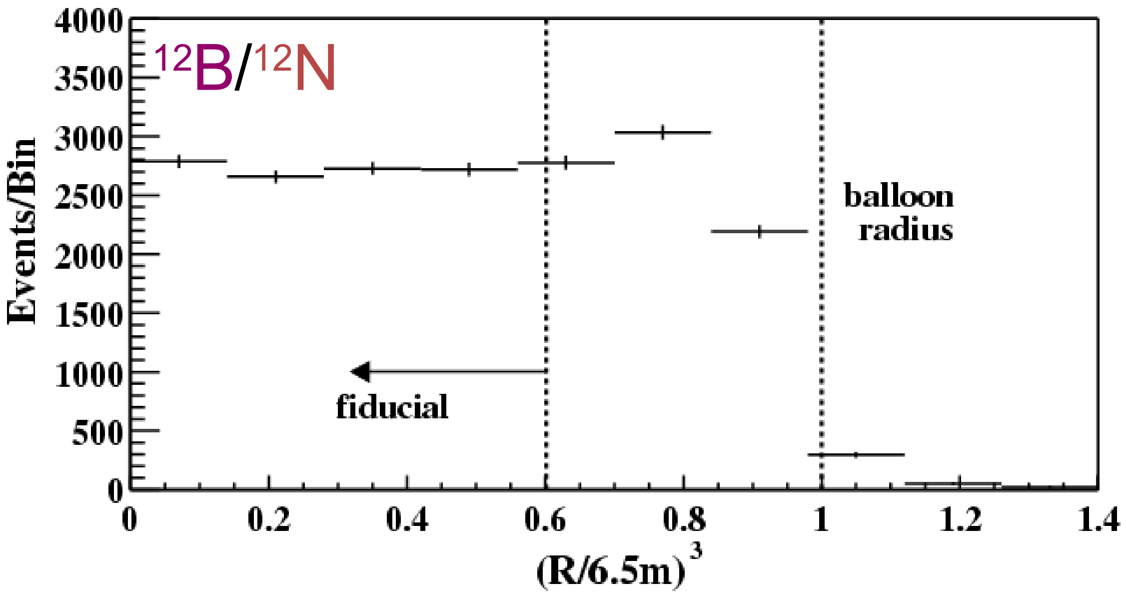
Spallation Products

Muons induce spallation products in rock and scintillator





Can also be used for detector studies:



Anti-neutrino Event Selection

Inverse beta-decay selection:

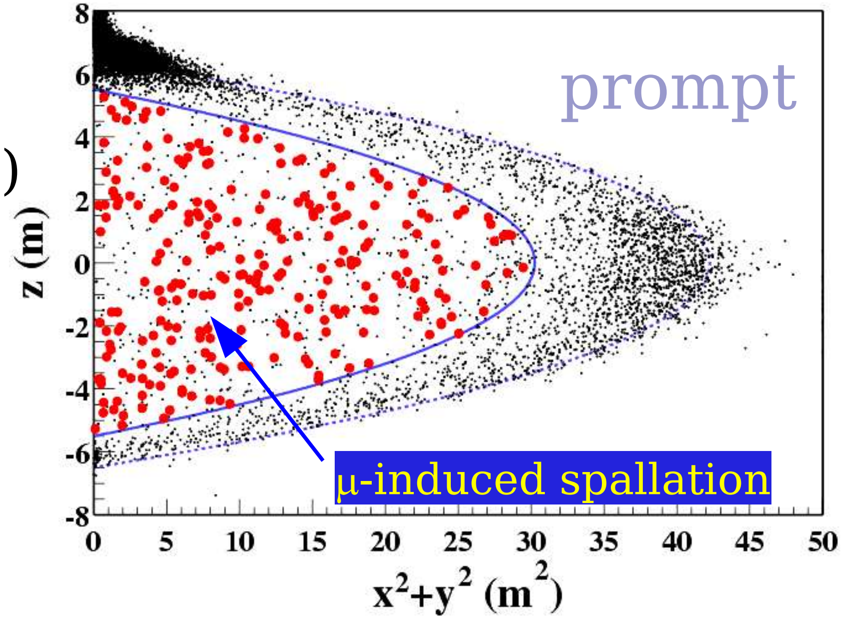
- $R_{prompt,\ delayed}$ < 5.5 m (543.7 tons, 33% inc)
- ΔR < 2 m
- 0.5 μs < ΔT < 1000 μs
- 1.8 MeV < $E_{delayed}$ < 2.6 MeV
- 2.6 MeV < E_{prompt} < 8.5 MeV

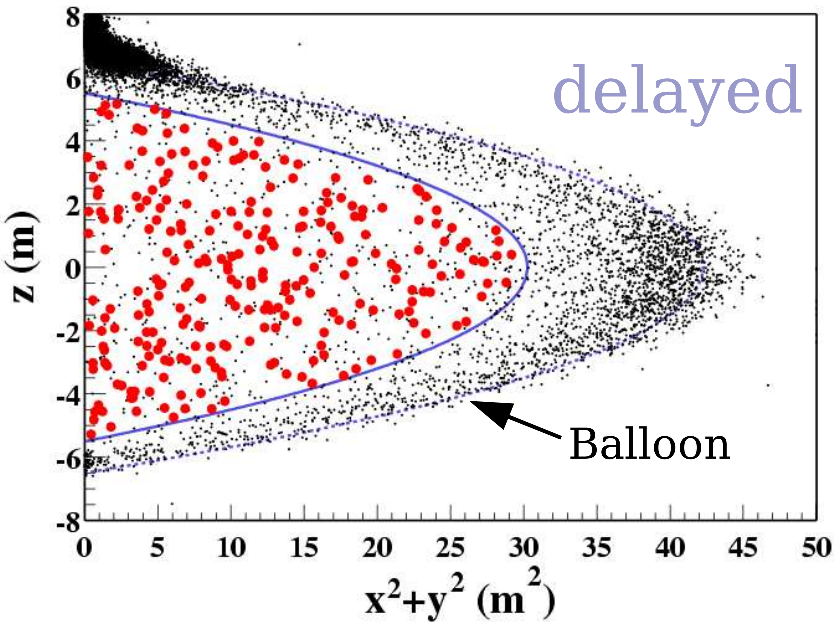
Tagging efficiency 89.8%

Muon-induced spallation event cuts:

- 2 ms veto after every μ
- 2 s veto for showering/bad μ
- 2 s veto in a R = 3m tube along track

Dead time 9.7%





Systematic Uncertainty

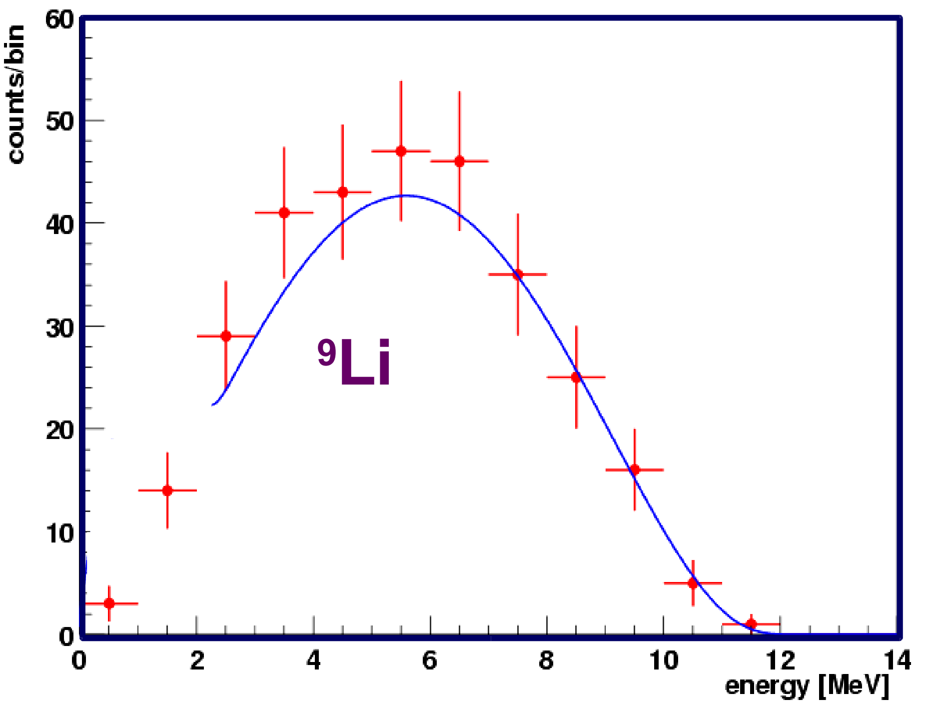
Uncertainty	%
Fiducial Volume	4.7
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.1
Reactor thermal power	2.1
Fuel Composition	1.0
Antineutrino spectra	2.5
Cross section	0.2
Total uncertainty	6.5

Backgrounds*

^{9}Li is a beta delayed-neutron emitter: mimics anti-neutrino

Background	# Events
9Li/8He	4.8 ± 0.9
Accidental	2.6 ± 0.02
Fast Neutron	<0.89
Total	**7.5 ± 1.3**

$Q_{deposit} > 10^6$ p.e., $\Delta T_\mu < 0.5$ s, $0.5 < \Delta T < 1$ms, $\Delta R < 2$m



* at ν2004

Observed Number of Events

(766.3 ton-yr, ~4.7x the statistics of the first paper)

Observed:	258
Expected, in absence of oscillations:	365.7 ± 23.7
Background*:	7.5 ± 1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

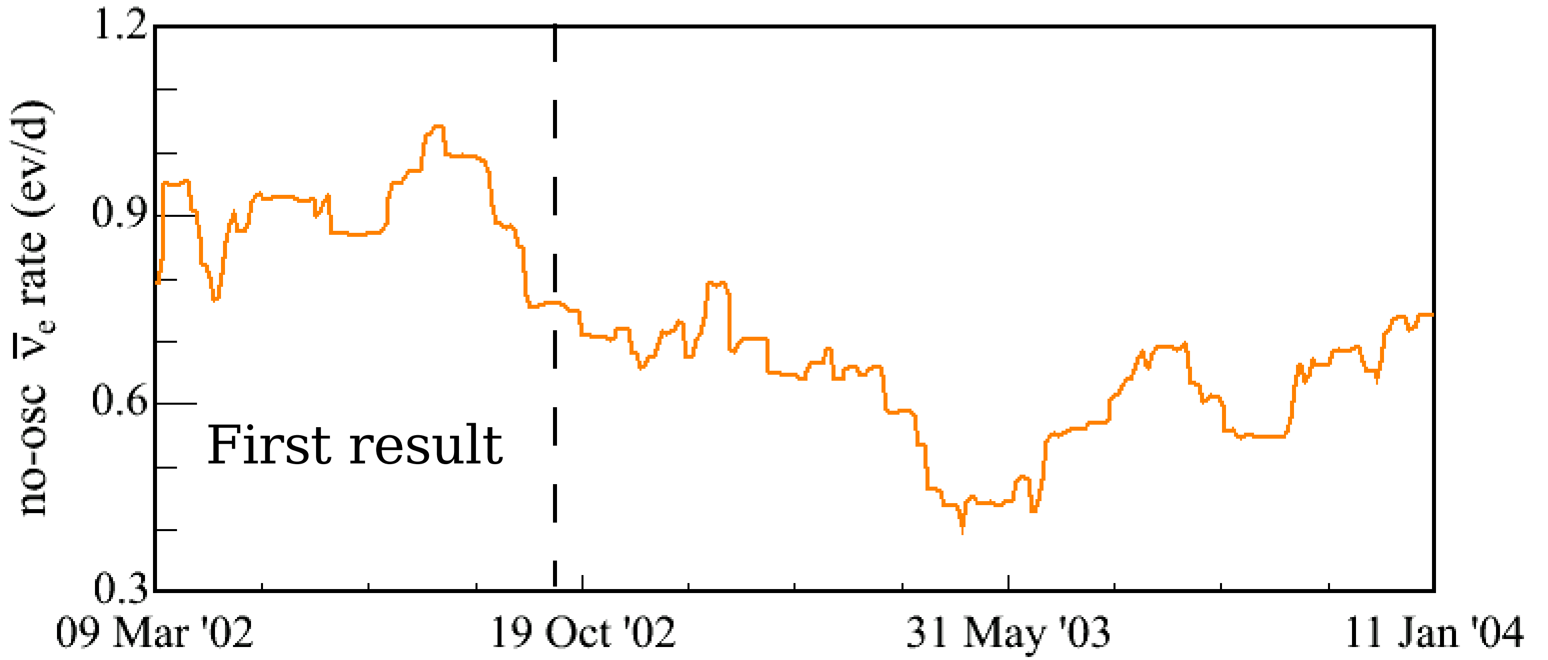
$$\frac{N_{obs} - N_{BG}}{N_{no\text{-}osc}} = 0.686 \pm 0.044(\text{stat}) \pm 0.045\ (\text{syst})$$

Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

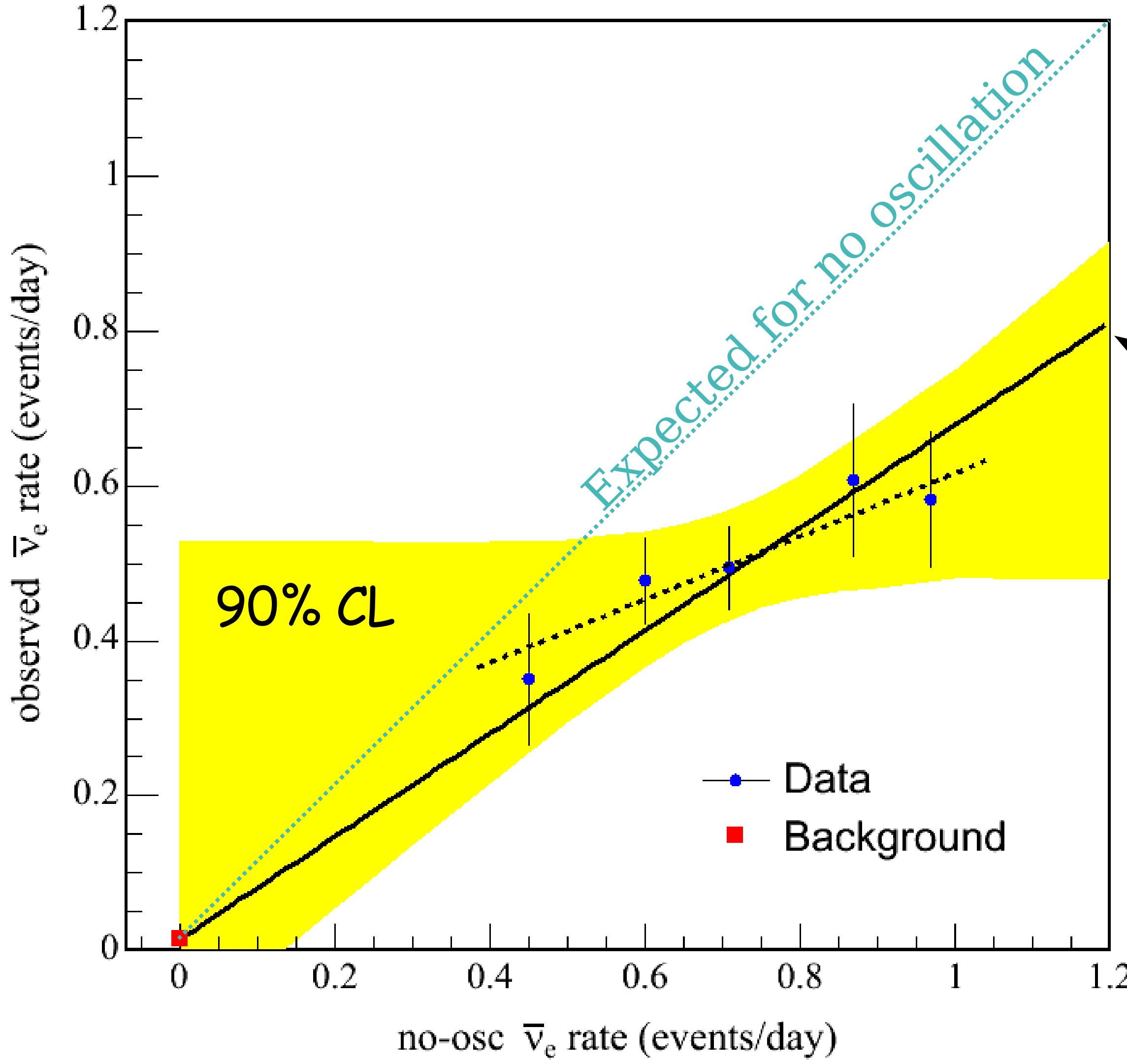
* at ν2004

Reactor Flux variations

2003 had large reactor flux variations,
various reactors were shutdown for inspection



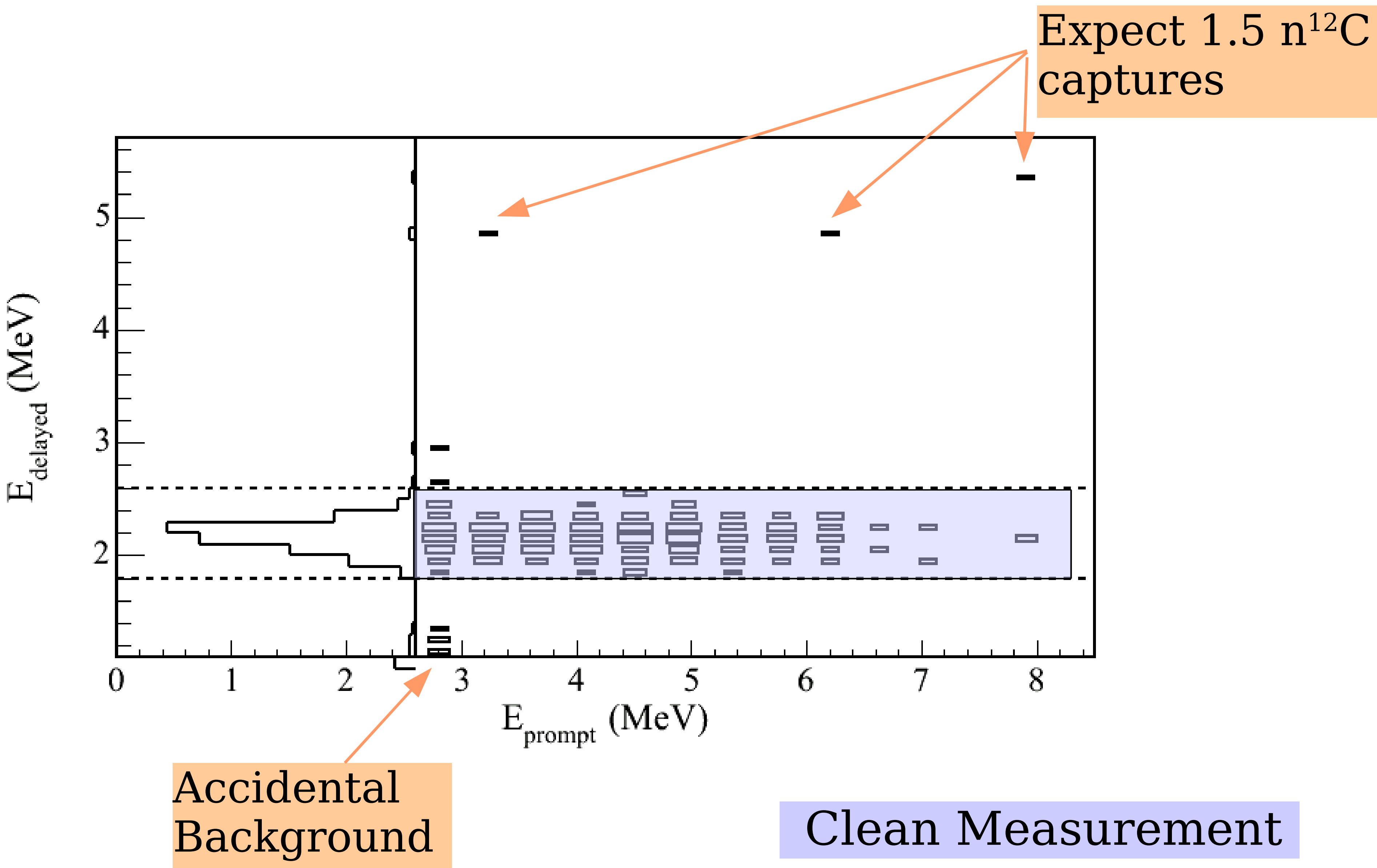
Correlation of Expected and Observed Event Rates



Fit constrained through known background
χ^2=2.1/4

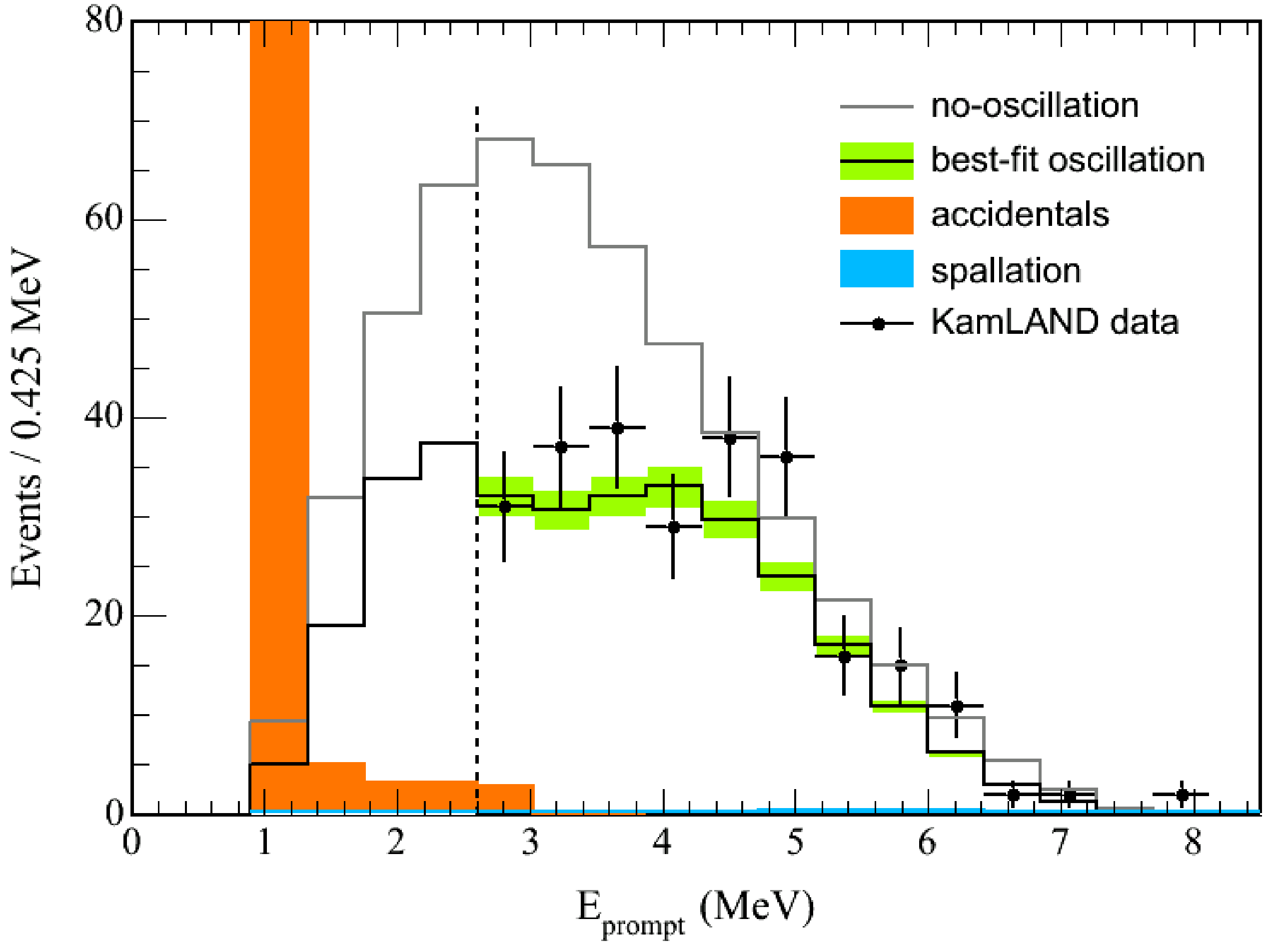
(But a horizontal line still gives a decent fit with χ^2=5.4/4)

Correlation $E_{delayed}$ vs E_{prompt}



Clean Measurement

Energy Spectrum



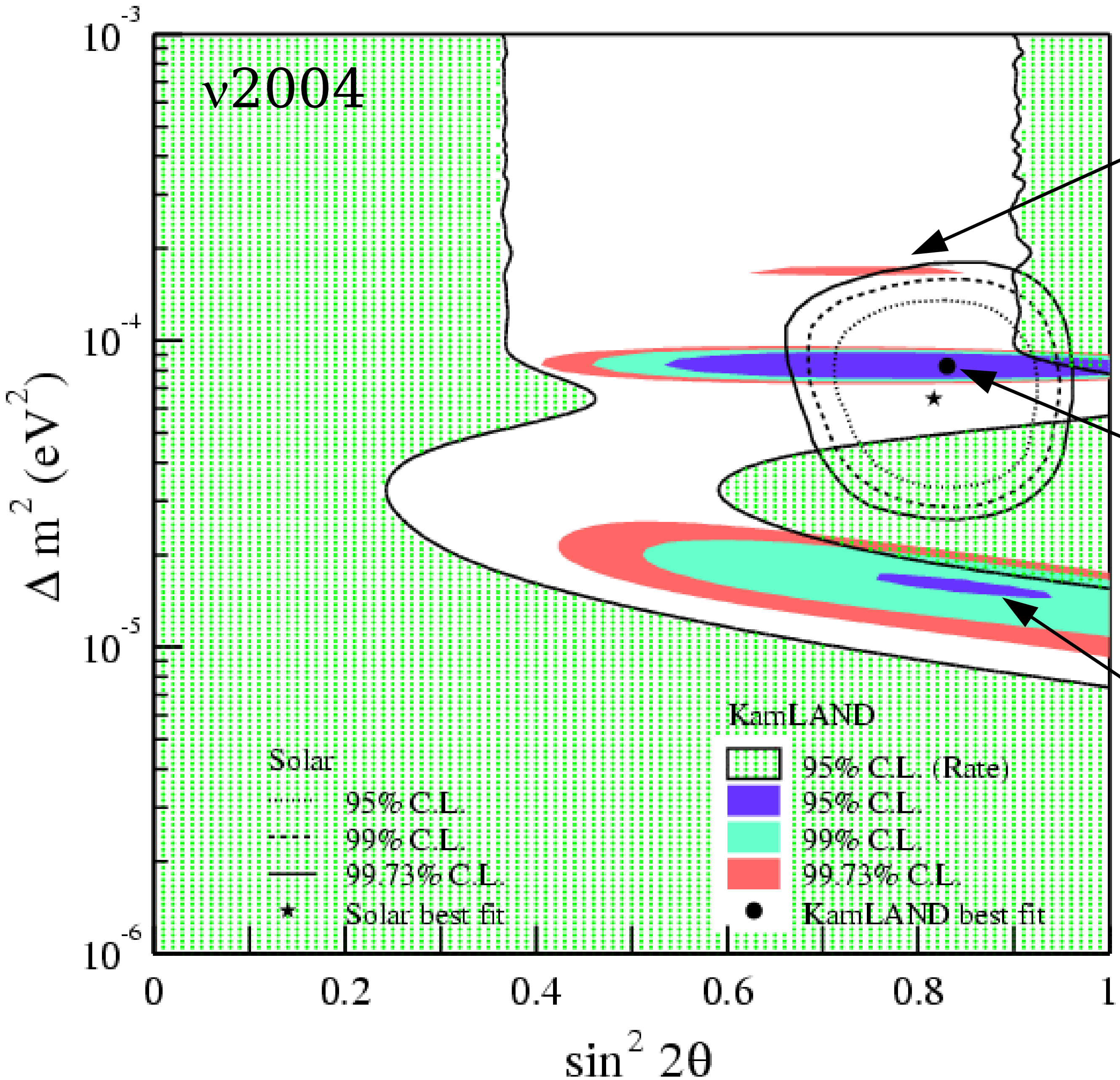
best fit
(rate + shape)

$\Delta m^2 = 8.3 \times 10^{-5}\ eV^2$
$\sin^2 2\theta = 0.83$

un-binned likelihood fit:
$\chi^2/dof = 18.3/18$
(goodness of fit is 42%)

A fit to a simple **rescaled reactor spectrum** is excluded at 99.89% CL (χ^2=43.4/19)

Unbinned Likelihood: 2-flavor

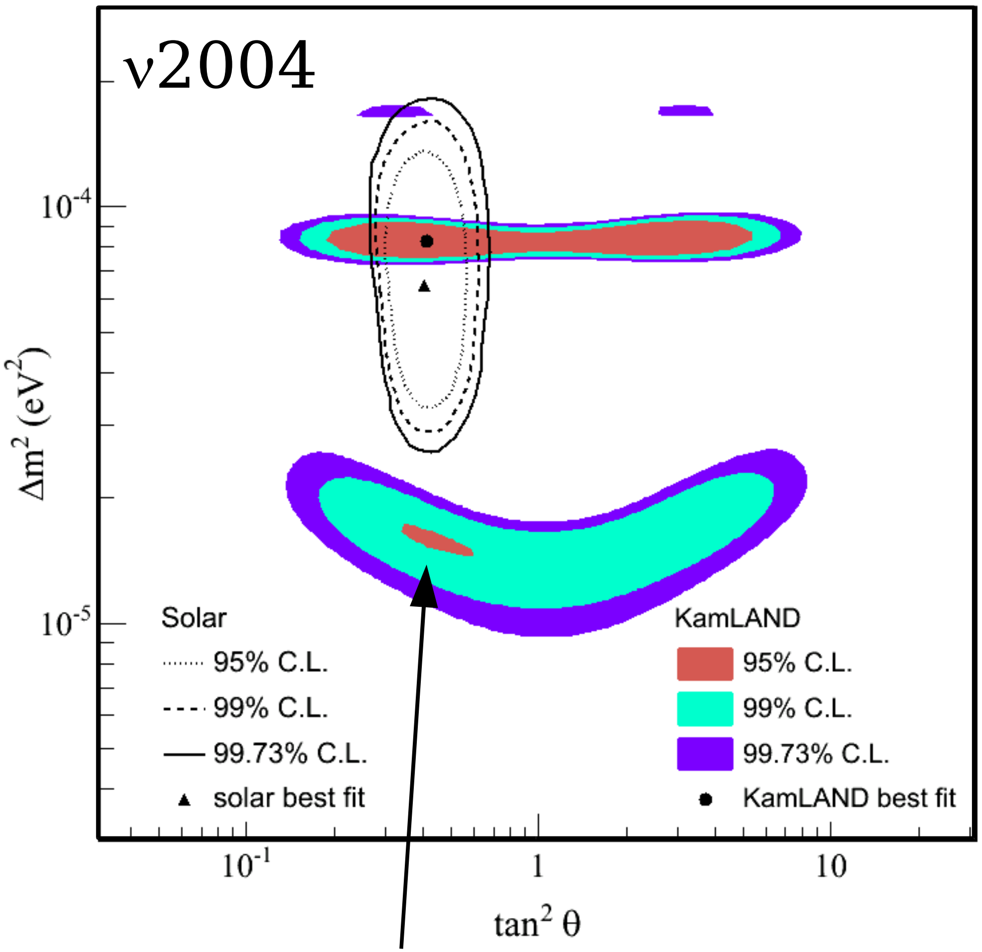


LMA2 excluded at 99.6% CL

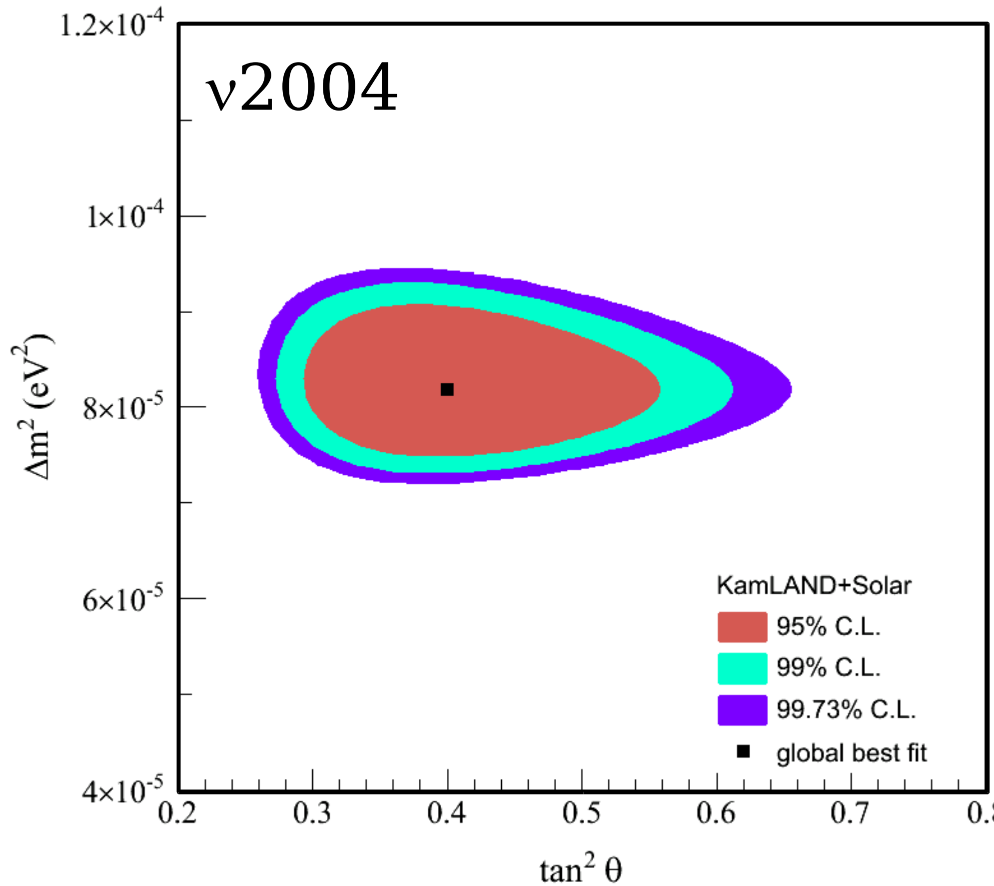
$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2
$\sin^2 2\vartheta = 0.83$

LMA0 disfavored at 94% CL

KamLAND 2-flavor and Global



matter effect



$\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.40^{+0.09}_{-0.07}$

Background Addendum

- During a recent review of all backgrounds it was realized that there is an additional, non-negligible background:

in Rn-chain:

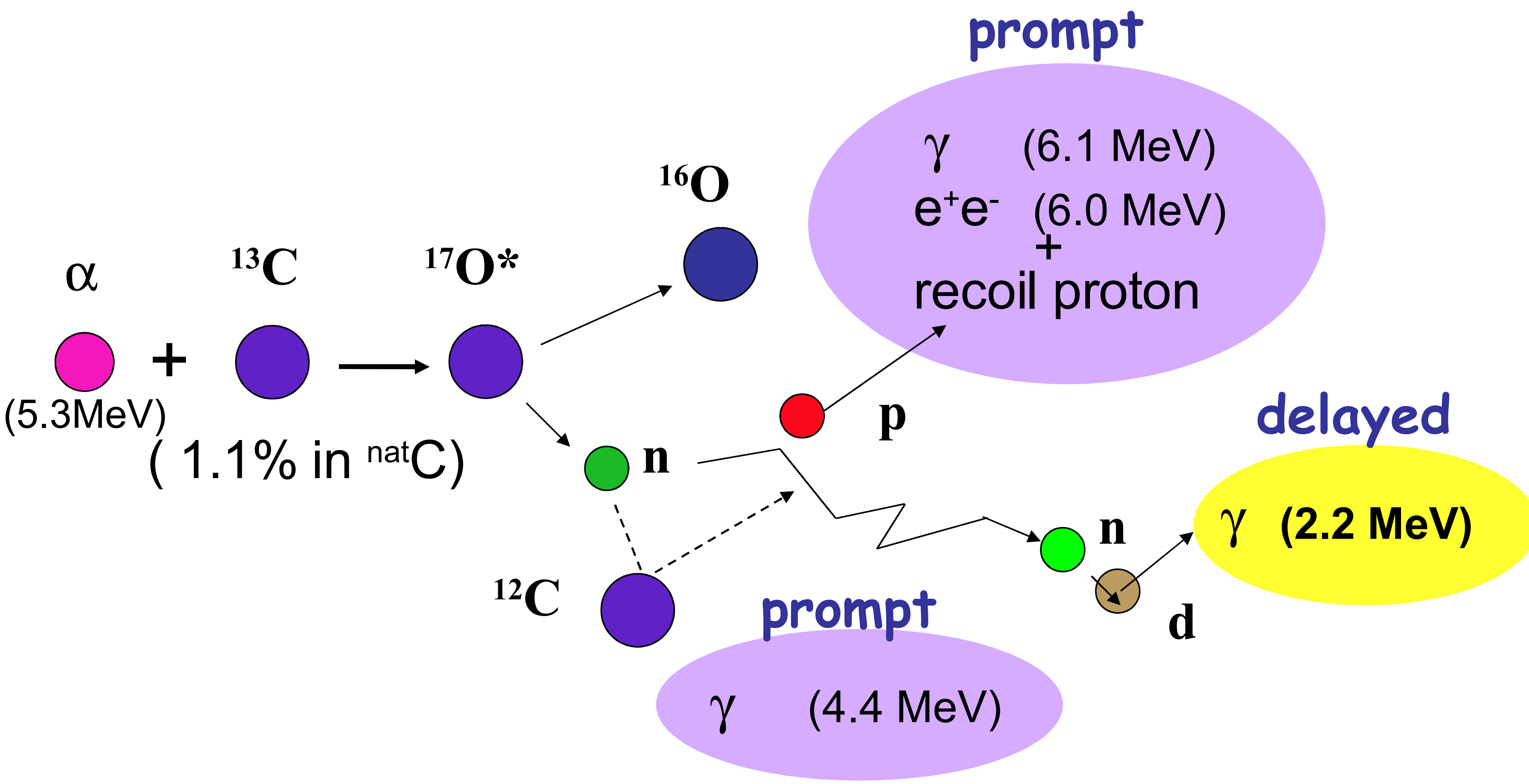
$$\ldots\ {}^{210}\mathrm{Pb} \xrightarrow{22.3\ \mathrm{yr},\ \beta^-} {}^{210}\mathrm{Bi} \xrightarrow{5\mathrm{d},\ \beta^-} {}^{210}\mathrm{Po} \xrightarrow{138\mathrm{d},\ \alpha} {}^{206}\mathrm{Pb}$$

5.3MeV α

Can react with ^{13}C in scintillator (1.1% in nat. C):
$^{13}C(\alpha,n)^{16}O$

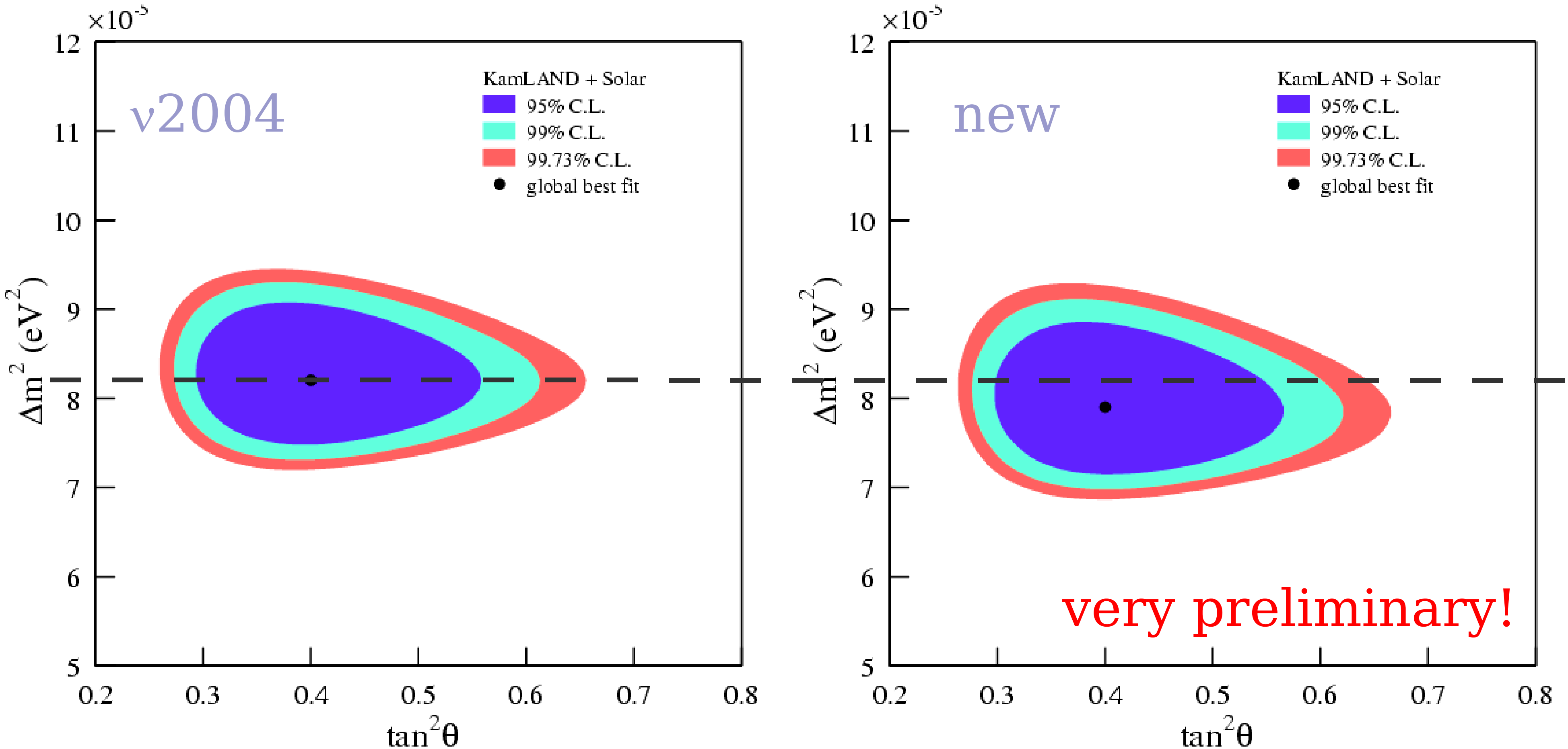
Reaction probability is $O(10^{-8})$

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



Preliminary estimation: ~10 events (E_{prompt} > 2.6MeV)

Effect of new Background



$\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.40^{+0.09}_{-0.07}$

Impact on just presented results is small

Conclusions

- KamLAND reactor exposure of 733 ton-yr, a 470% increase over previous result
- Data consistent with large flux swings in 2003
- Spectrum distortion significant
- The ν2004 KamLAND+Solar result:

  $\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$; $\tan^2\theta = 0.40^{+0.09}_{-0.07}$
- Expect small update of results due to new background
- Don't stop looking for backgrounds...!

(The KamLAND Collaboration)

[1]*Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan*
[2]*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*
[3]*Physics Department, University of California at Berkeley and*
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[4]*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[5]*Physics Department, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[6]*Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA*
[7]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[8]*Physics Department, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[9]*Physics Department, Stanford University, Stanford, California 94305, USA*
[10]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[11]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA and*
Physics Departments at Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill
[12]*Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[13]*CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I, F-33175 Gradignan Cedex, France*