

Reactor $\bar{\nu}_e$ Disappearance at KamLAND



The KamLAND Collaboration



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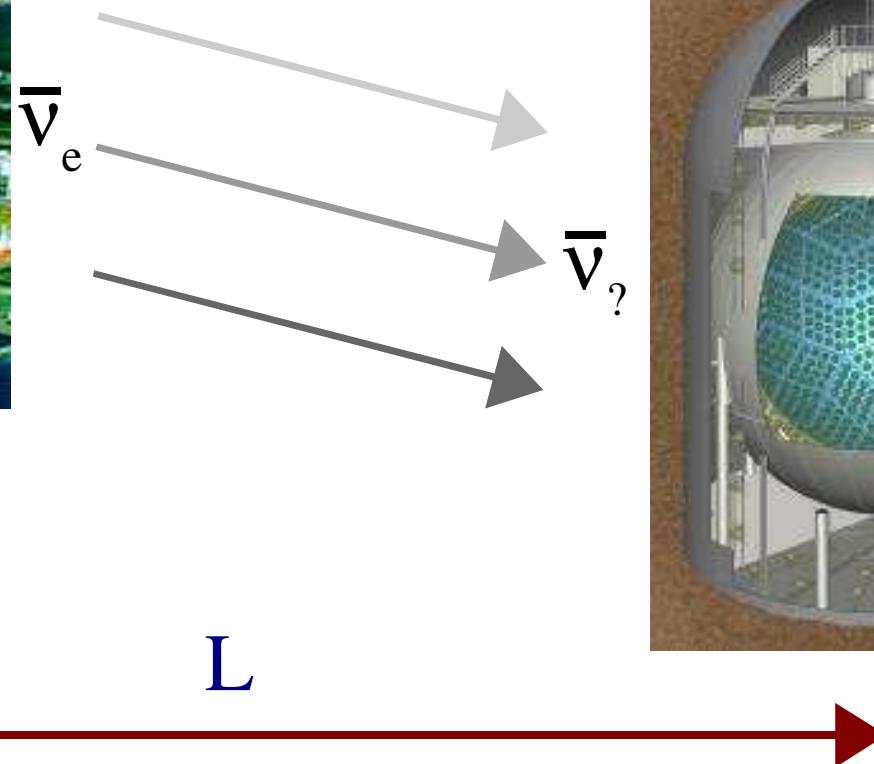


Introduction

Reactor antineutrino experiments:
look for a flux deficit at a distance L



Nuclear reactor





Neutrino Oscillations

- Write the weak states ν_l as a linear combination of mass eigenstates ν_j :

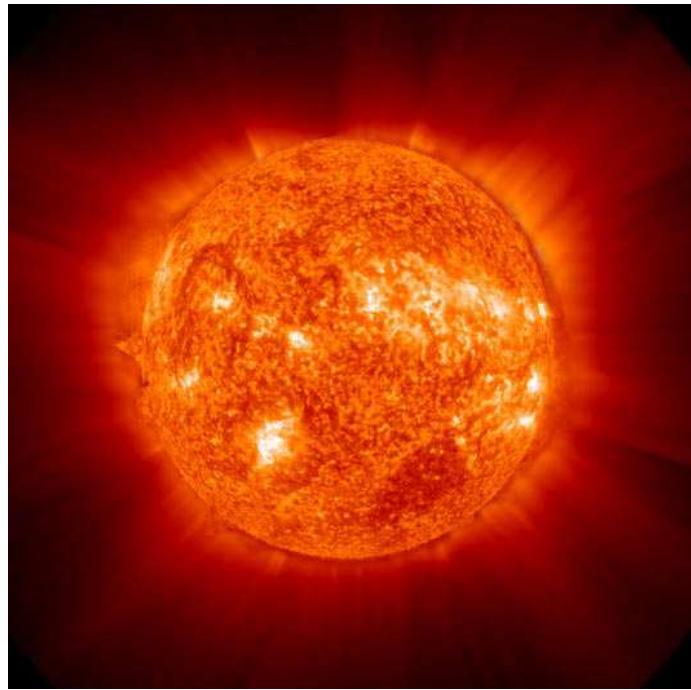
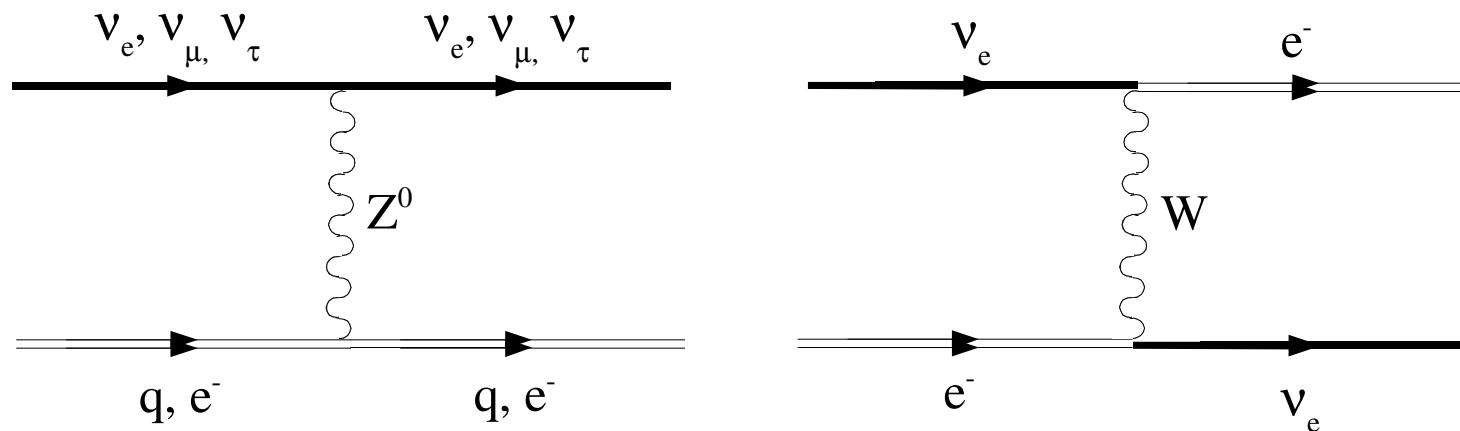
$$\nu_l = \sum_j U_{lj} \nu_j$$

- Oscillation probability for 2 flavors (e.g. ν_e , ν_μ):

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{\pi L}{L_{osc}}; \quad L_{osc} \equiv \frac{\pi E}{1.27 \Delta m^2}$$



MSW Effect*



$$n = 1 + \frac{2\pi N}{p^2} f_l(0) \quad L_0 = \frac{2\pi}{\sqrt{2} G_F N_e}$$

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta_m \sin^2 \frac{\pi L}{L_m}$$

$$\tan 2\theta_m \equiv \tan 2\theta \left(1 + \frac{L_{osc}}{L_0} \sec 2\theta \right)$$

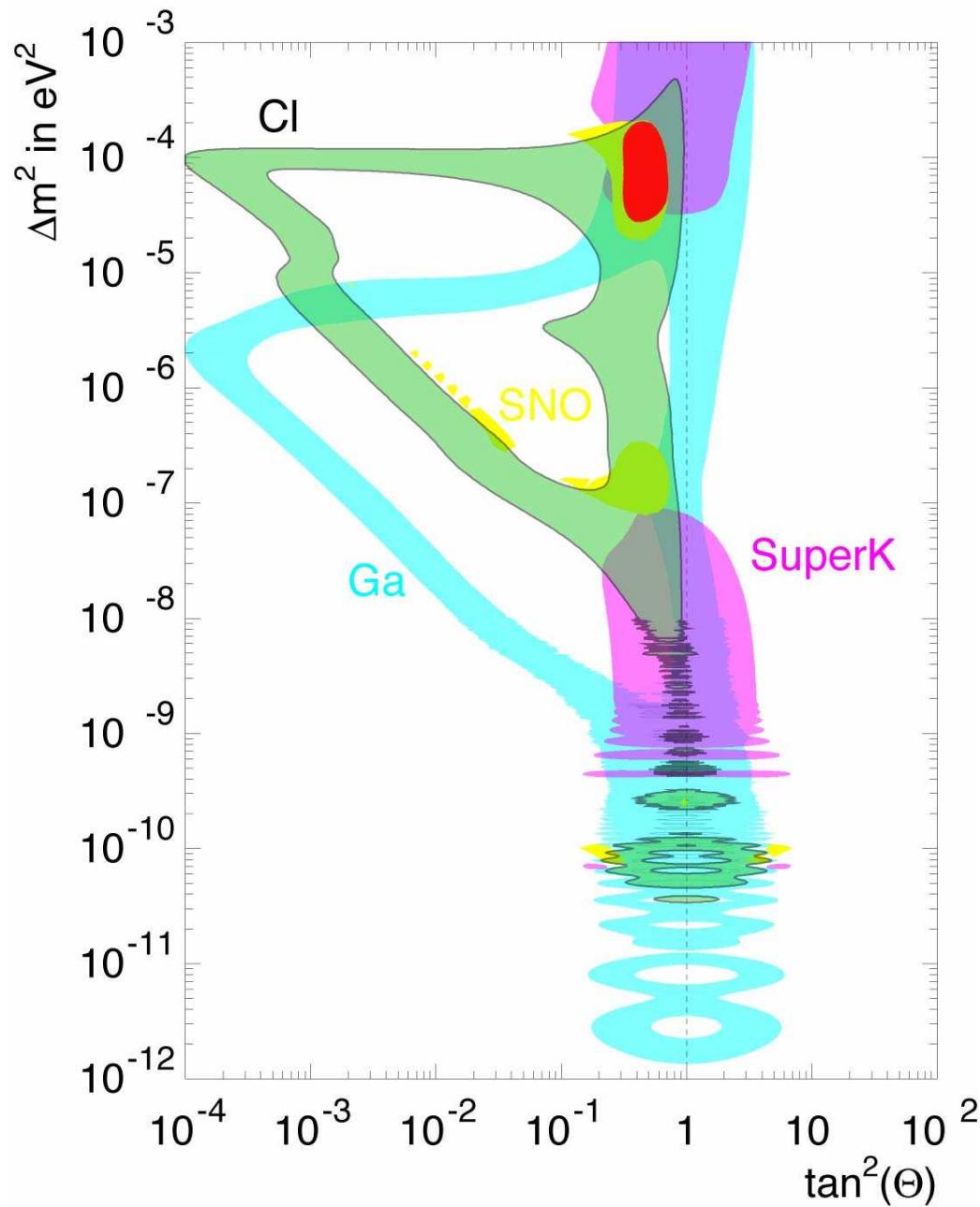
$$L_m \equiv L_{osc} \left[1 + \left(\frac{L_{osc}}{L_0} \right)^2 + \frac{2 L_{osc}}{L_0} \cos 2\theta \right]^{-1/2}$$

* L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978)

S.P. Mikheev and A. Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985)



Solar Neutrino Mixing Parameters



Neutrinos On Earth



- Control source and detector
- Sun: $L_0 \sim 200 \text{ km} \ll R_{\text{sun}}$; Rock: $L_0 \sim 10^4 \text{ km} > R_{\text{earth}}$
→ Matter effects much less significant

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

Neutrino beams

- sensitivity to small Δm^2 requires very large L
- appearance possible
- collimated source

Reactors

- sensitive to very small Δm^2
- disappearance only
→ limited $\sin^2 2\theta$ sensitivity
- 4π source



Reactors In Japan

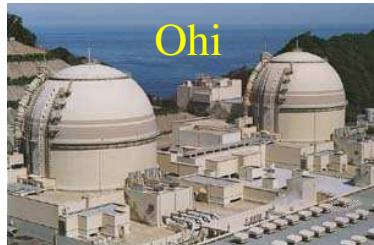
55% of total
flux from:



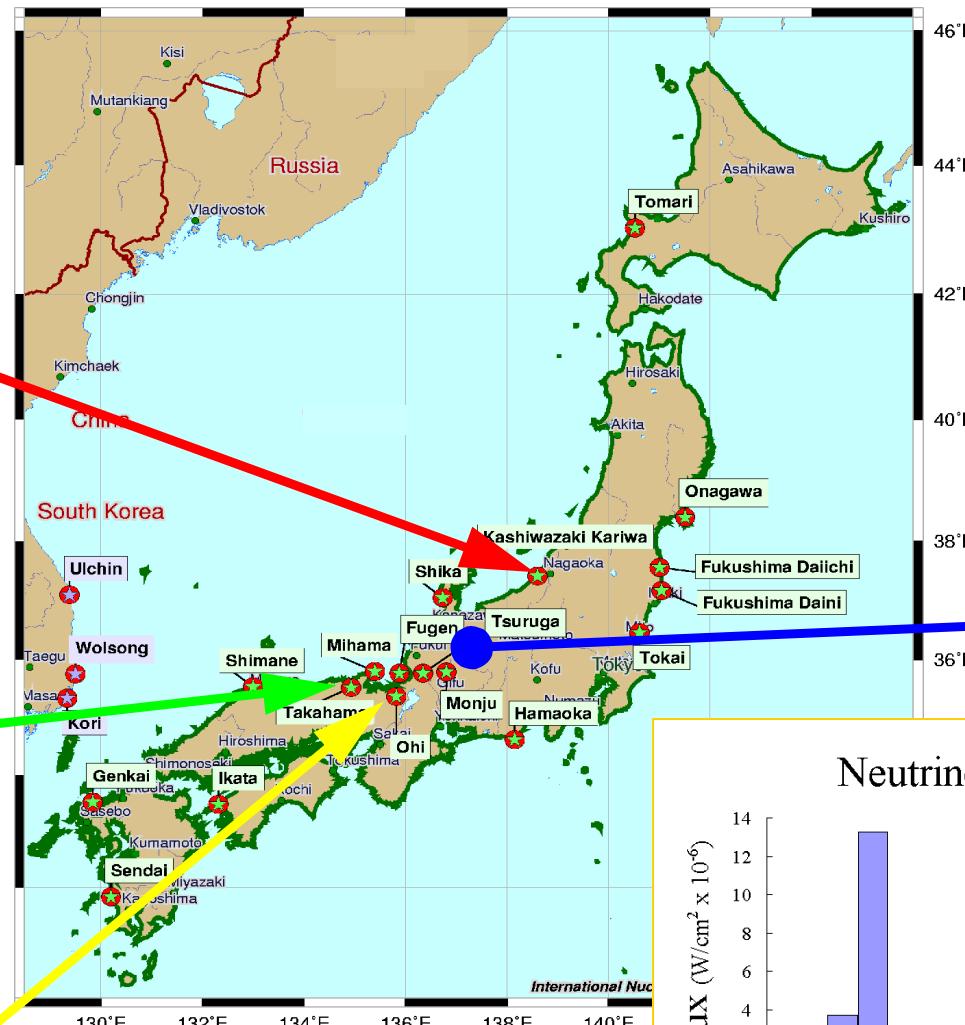
Kashiwazaki



Takahama



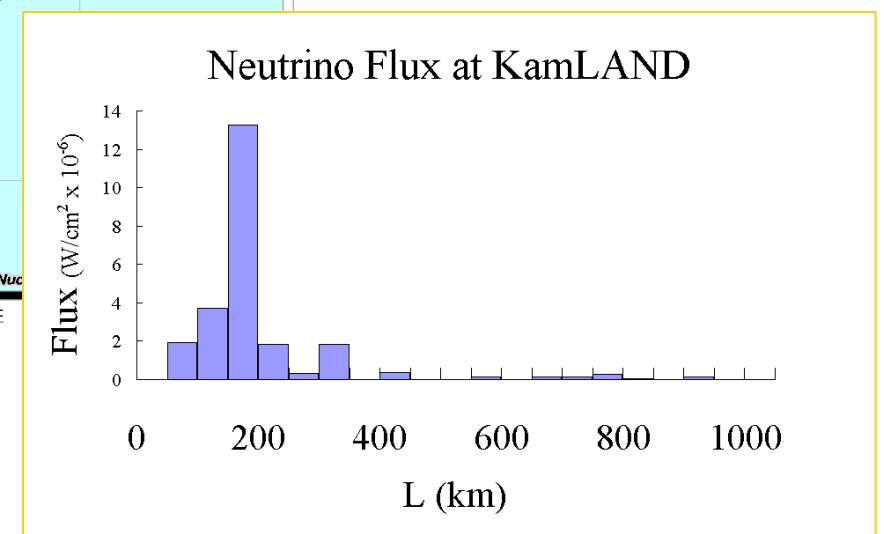
Ohi



80% of total flux from
baselines 140-210 km

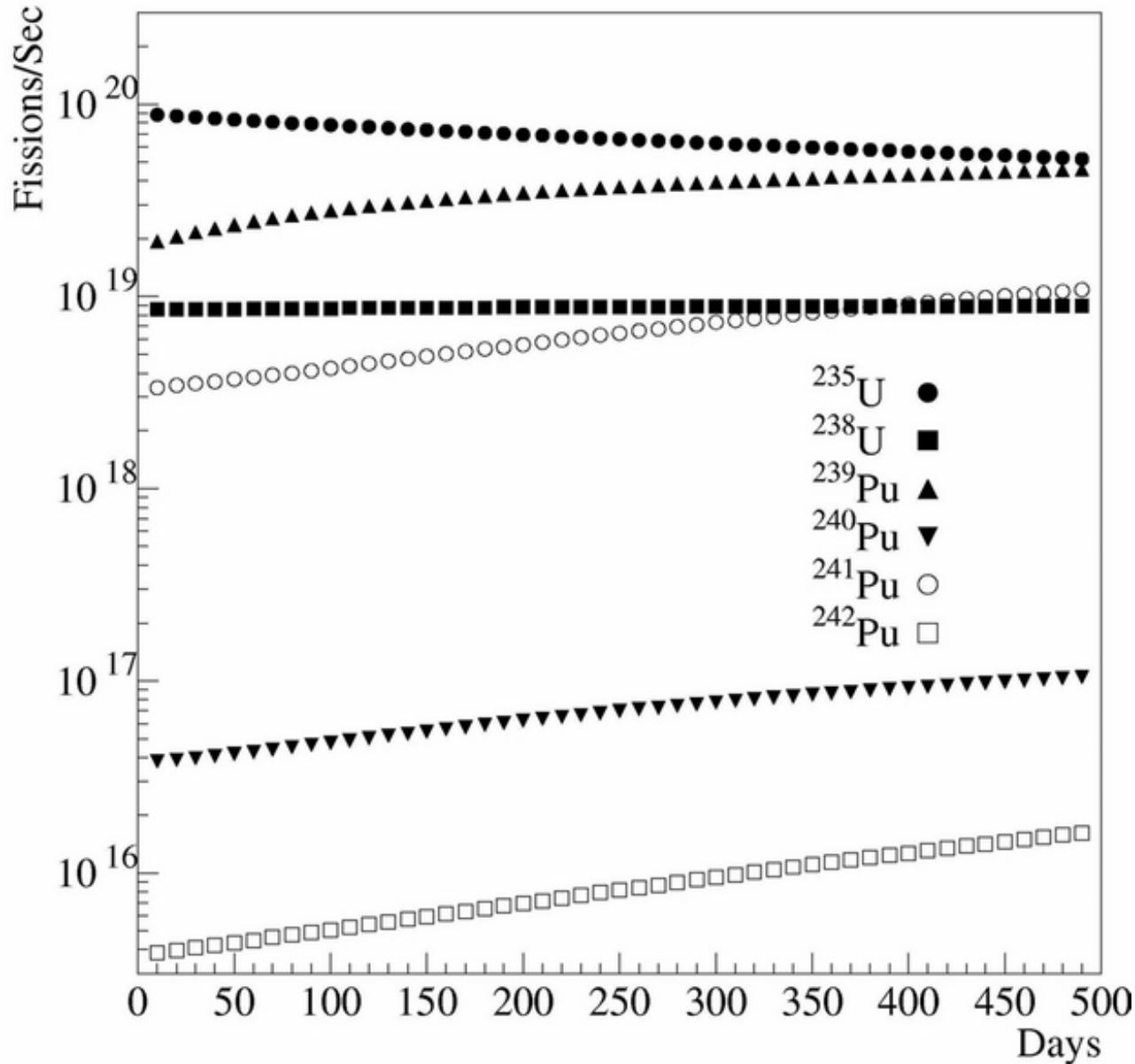
KamLAND uses
the entire Japanese
nuclear power
industry as a **180 GW_{th}**
long-baseline source!

KamLAND





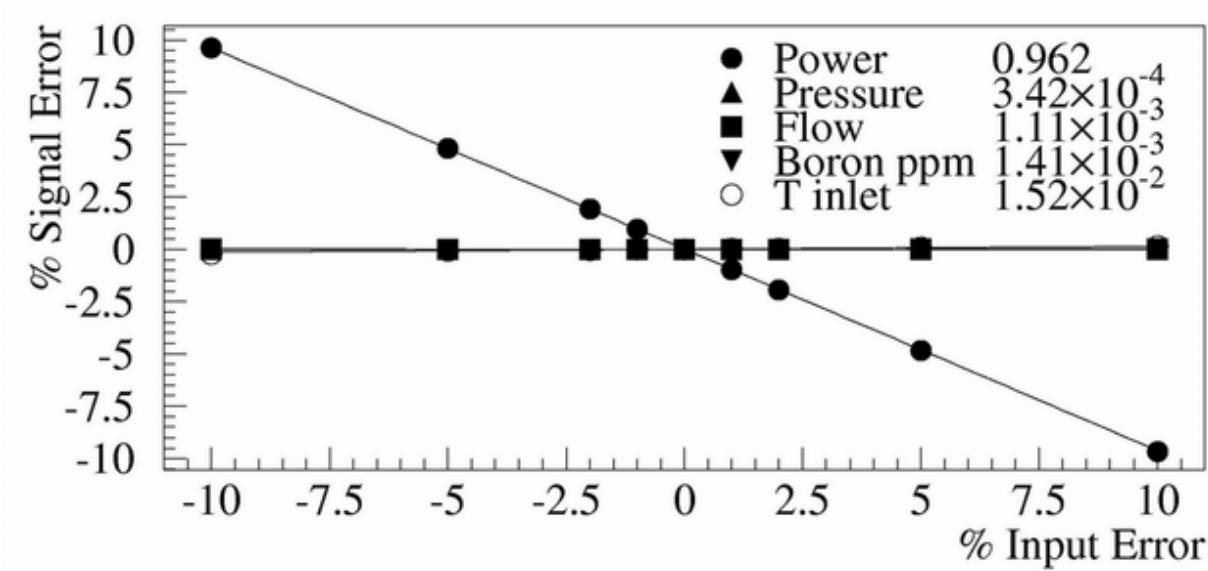
Reactor Fuel Cycle



$> 99.9\%$ of ν are produced by fissions of ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu



Simulation Inputs



Economics pushes the uncertainty on the power to < 1%



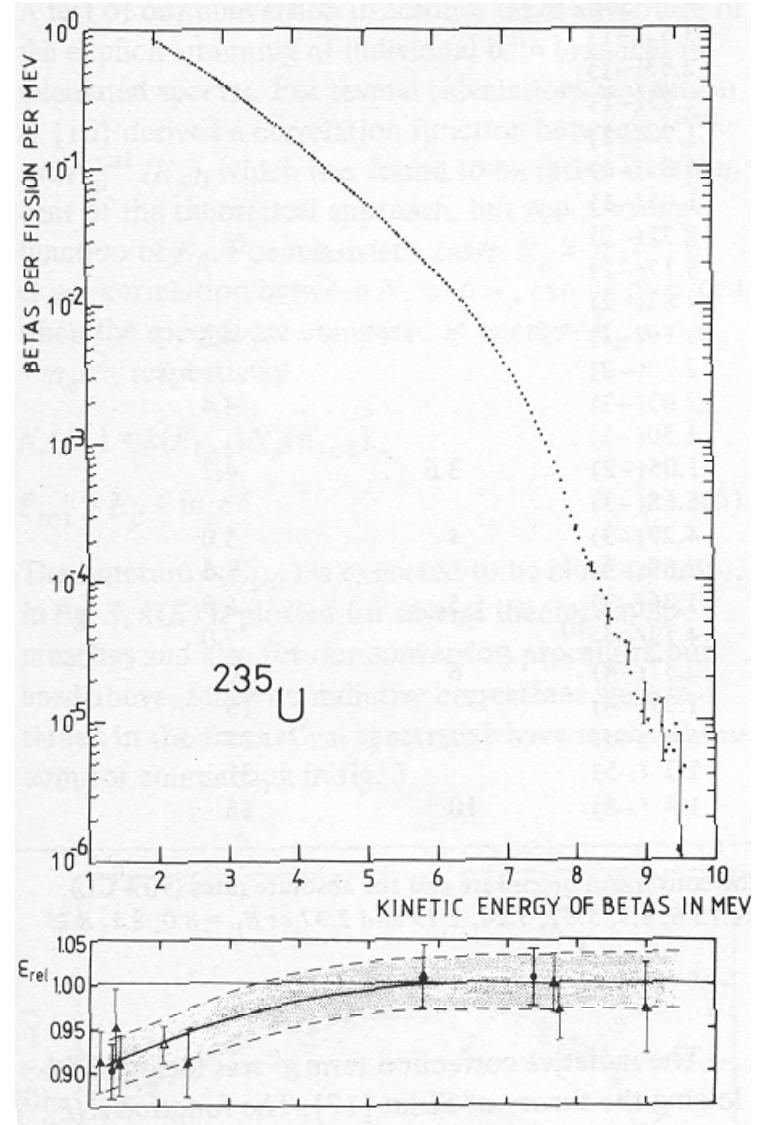
$\bar{\nu}_e$ Spectra

- ^{235}U , ^{239}Pu , and ^{241}Pu : $\bar{\nu}_e$ spectra are derived from β -spectra measurements

A. A. Hahn *et al.*, Phys. Lett. **B218**, 365 (1989)
K. Schreckenbach *et al.*, Phys. Lett. **B160**, 325 (1985)

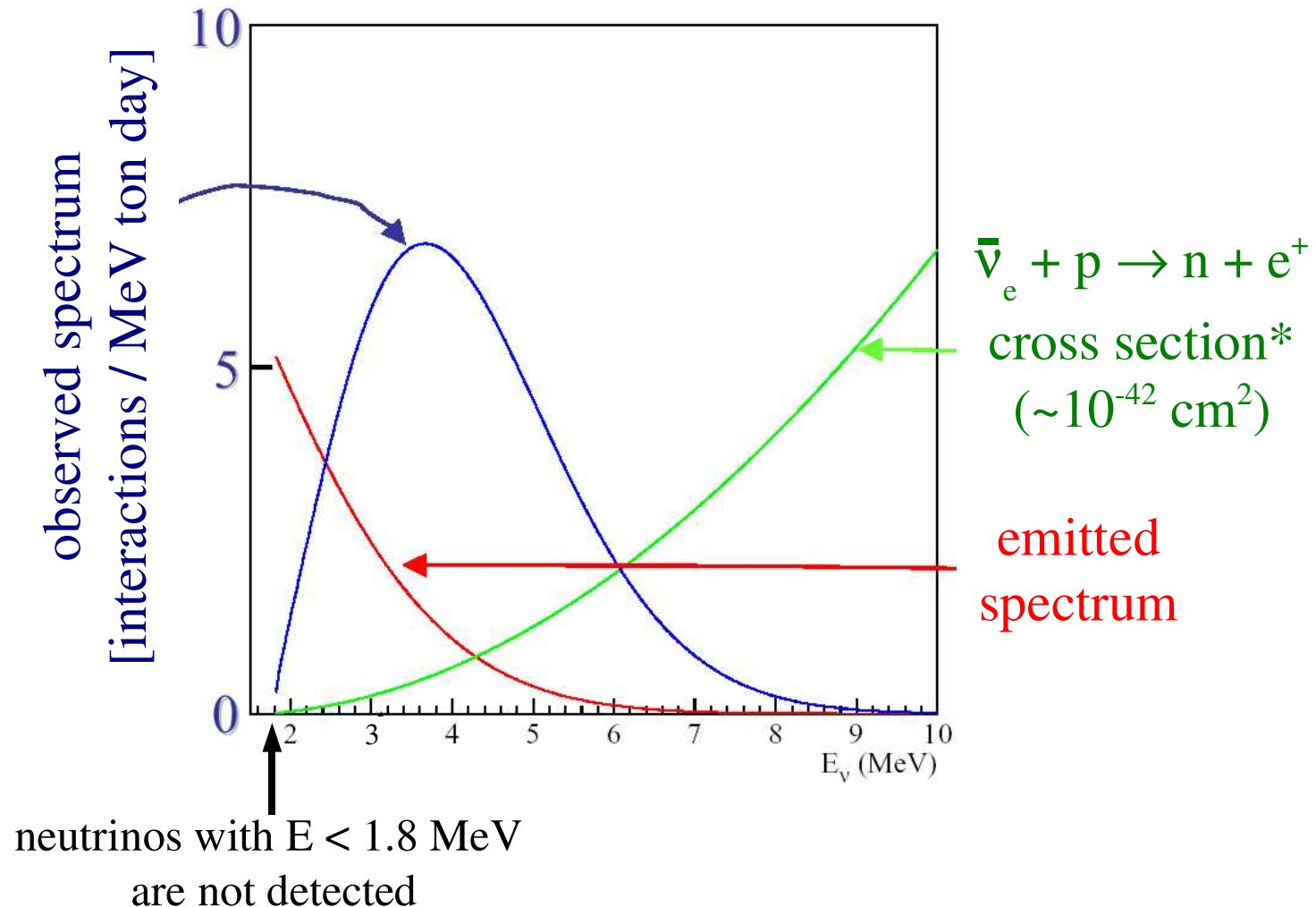
- ^{238}U : no measurements are available, so we must rely on calculations

P. Vogel *et al.*, Phys. Rev. **C52** (2498)





The Detected $\bar{\nu}_e$ Spectrum

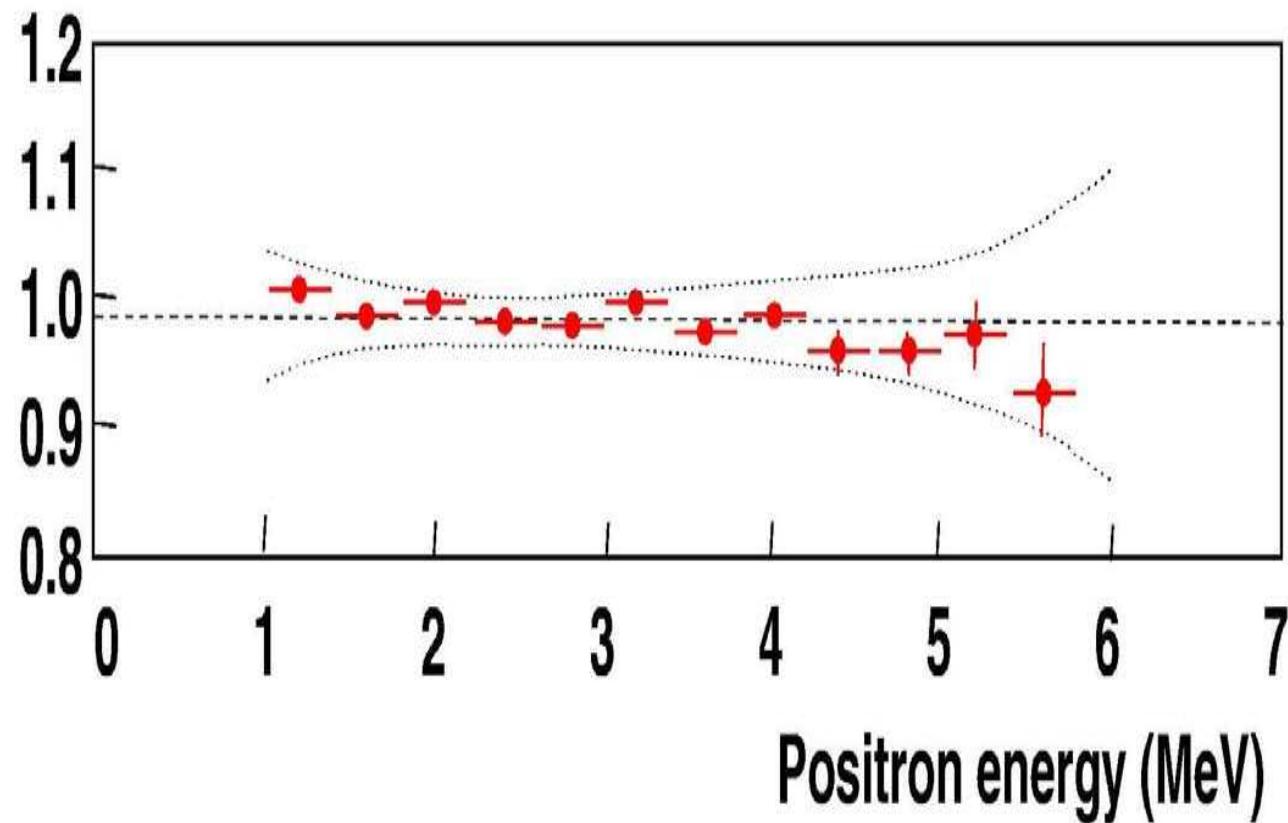


* P. Vogel and J. F. Beacom, Phys. Rev. D60, 053003 (1999)

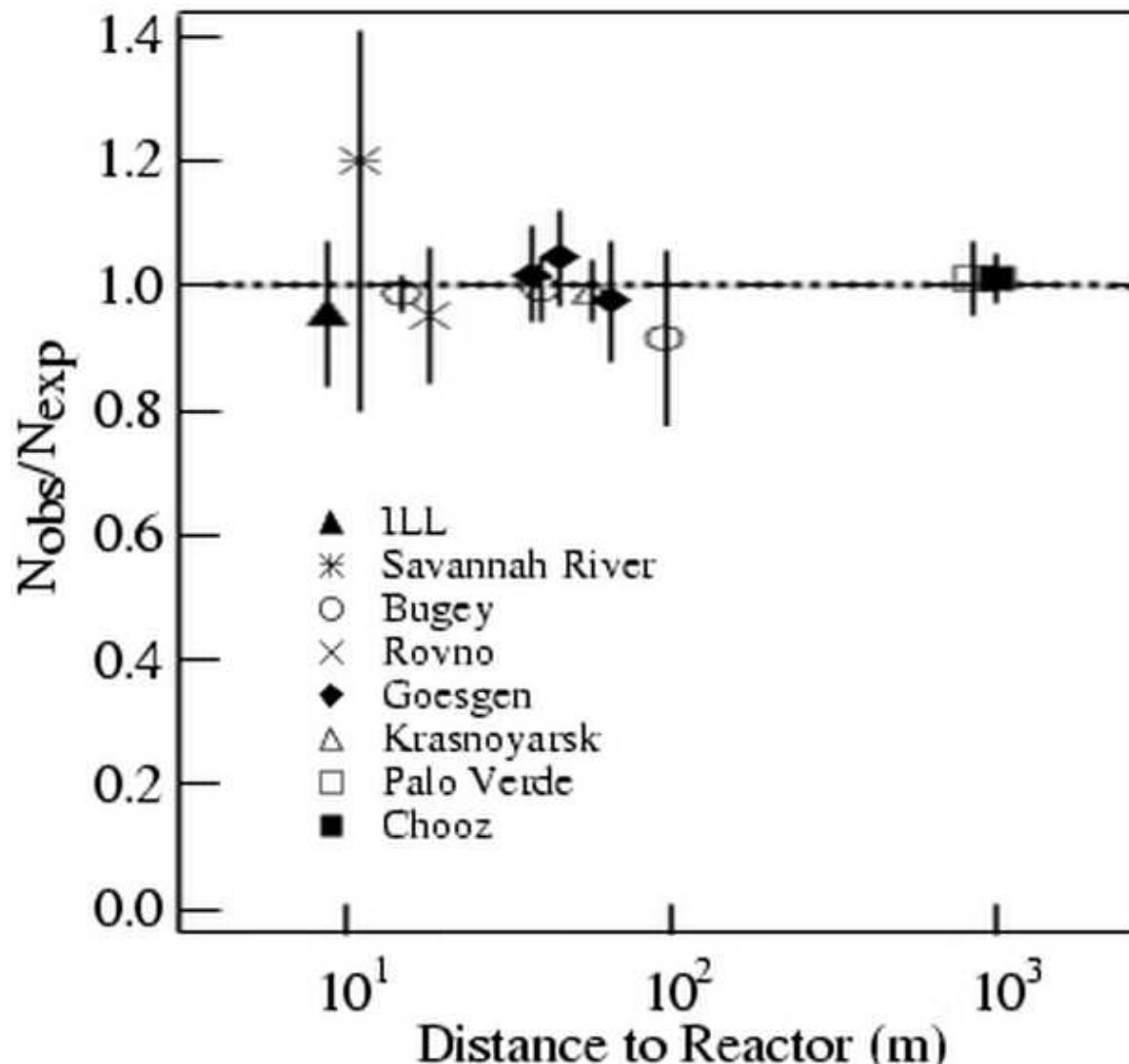


Previous Results

From Bugey 3: short baseline ($L = 15$ m, 40 m), 1.5×10^5 events

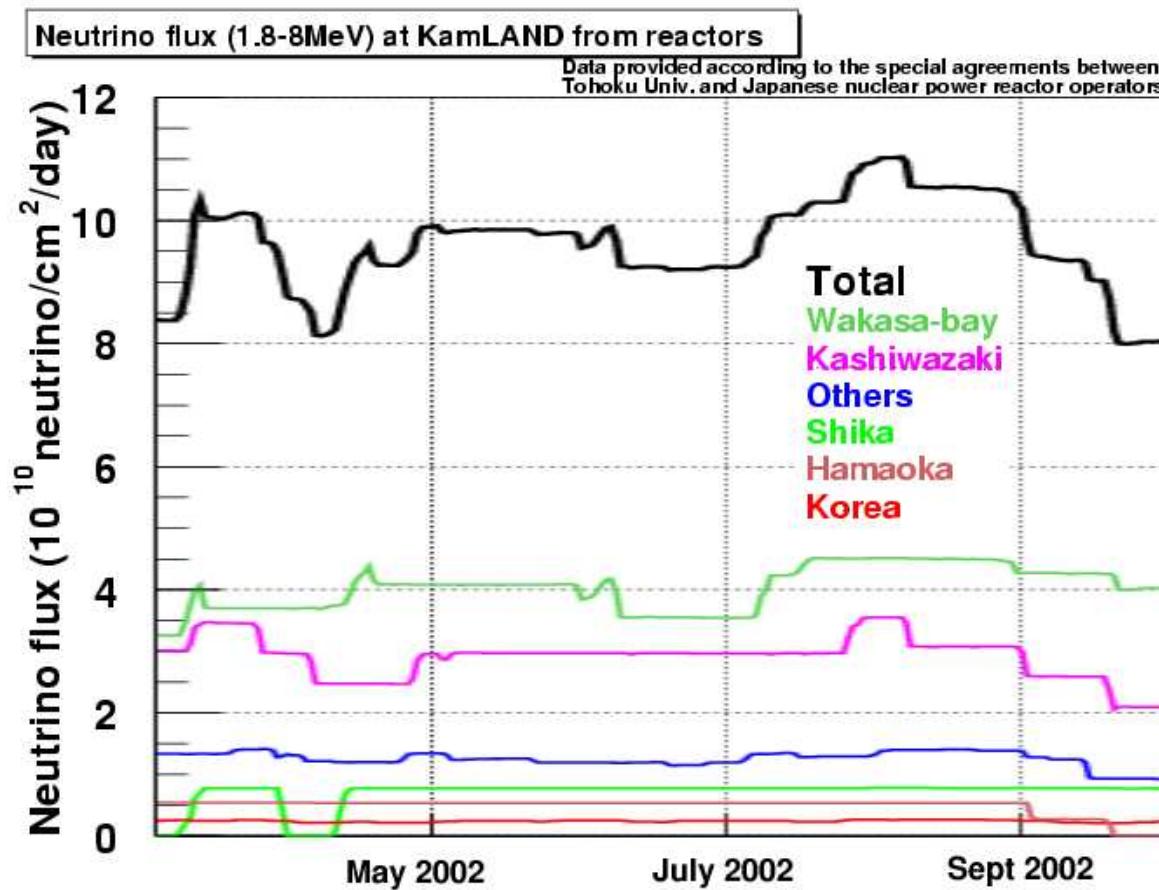


Previous Results





Antineutrino Flux at KamLAND

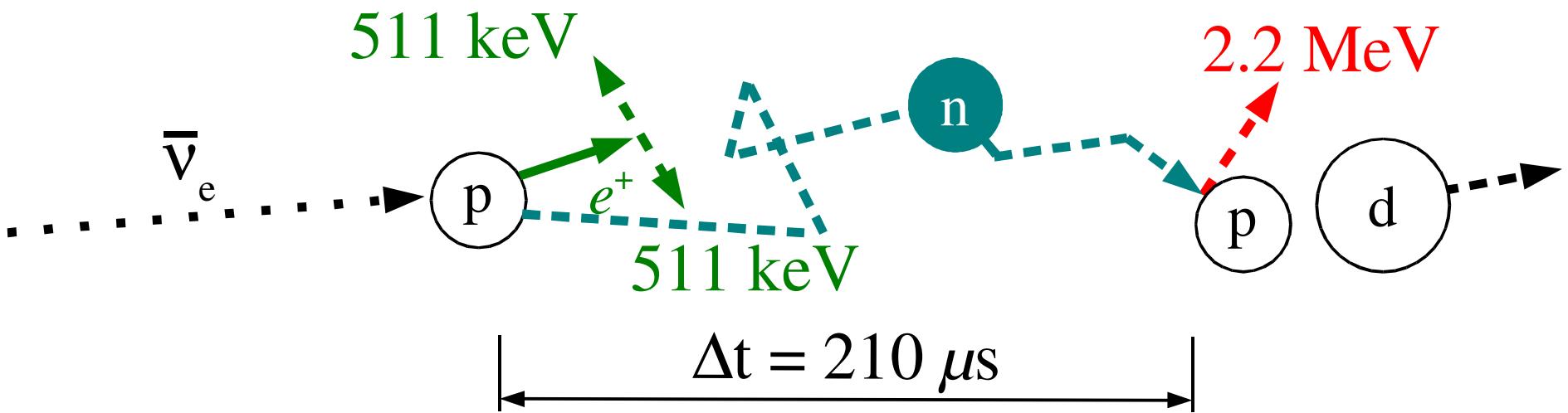
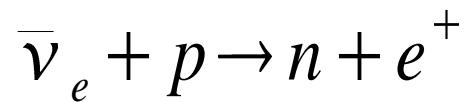


Signal Systematics (%)

Live time	0.07	Time lag	0.28
Reactor power	2.0	$\bar{\nu}_e$ spectra	2.5
Fuel composition	1.0	$\bar{\nu}_e$ - p cross section	0.2



Event Signature

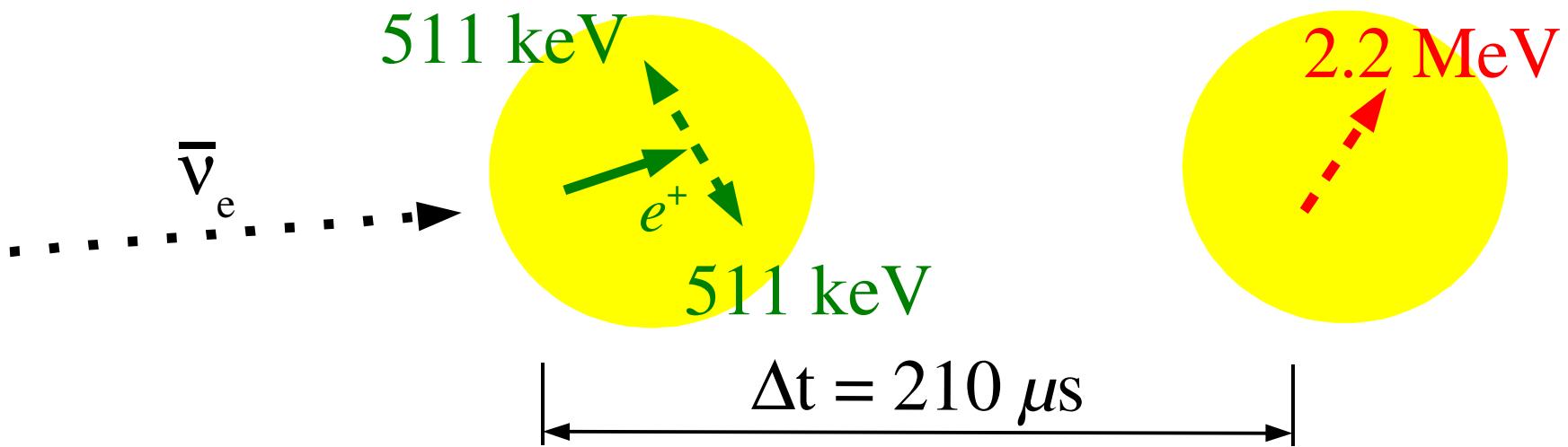
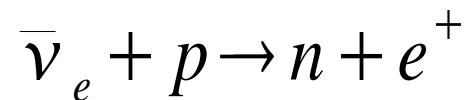


Coincidence signal: detect

- Prompt: e^+ energy + annihilation γ
- Delayed: n -capture γ



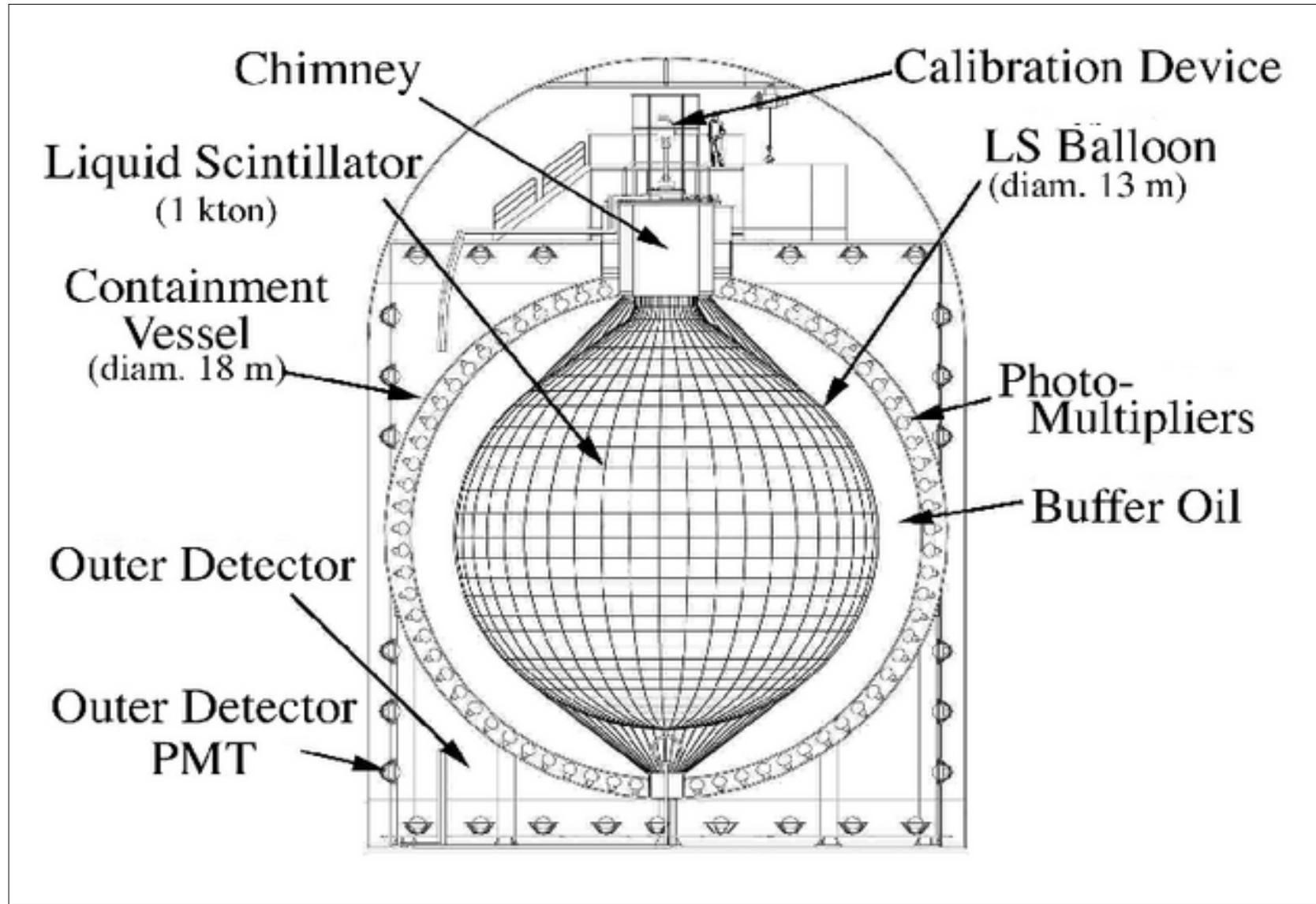
Event Signature



Coincidence signal: detect

- Prompt: e^+ energy + annihilation γ
- Delayed: n -capture γ

The KamLAND Detector





KamLAND Trigger

Coincidence, prescale threshold:

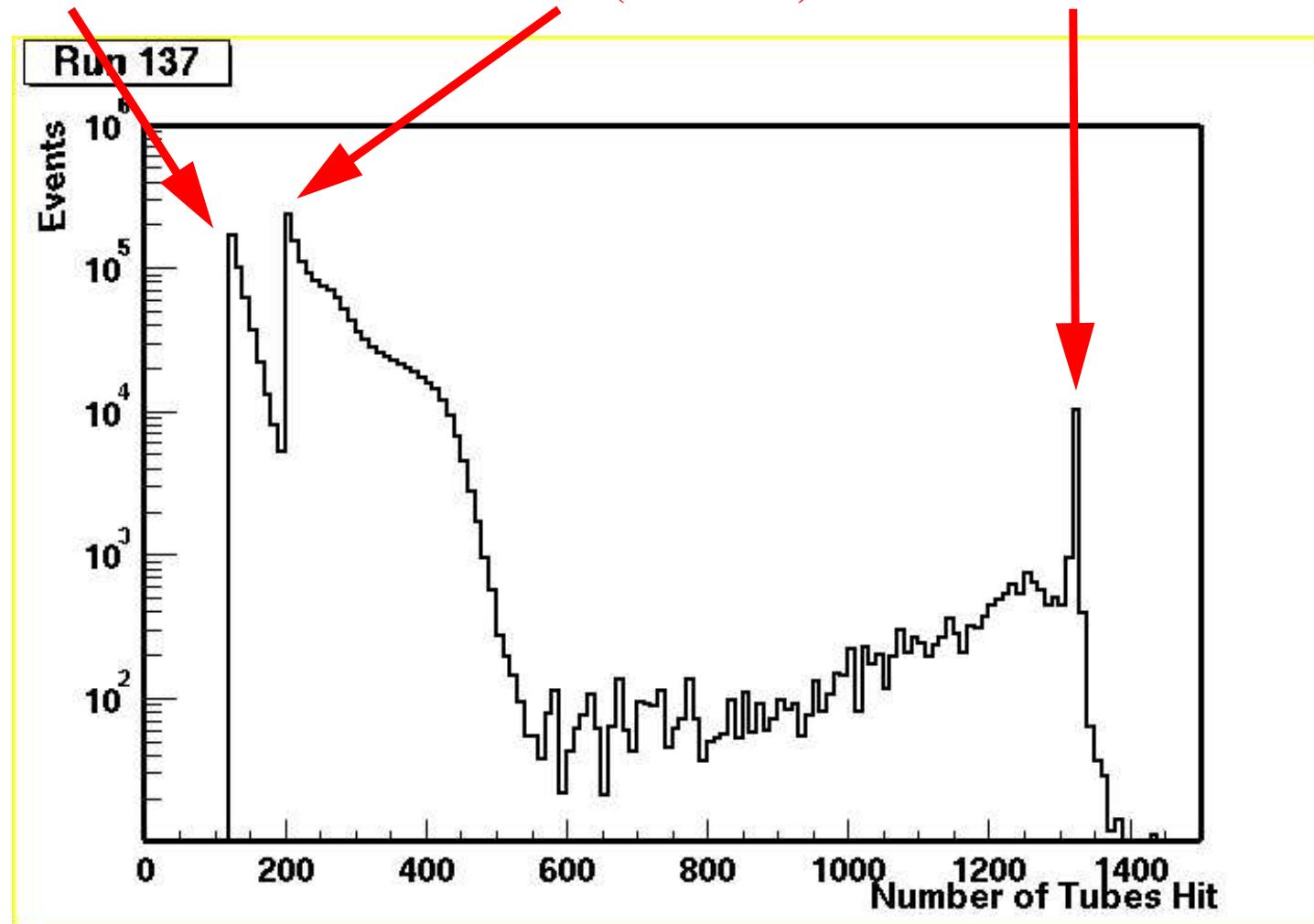
120 PMT's hit

Singles threshold:

200 PMT's hit (~0.7 MeV)

Muons:

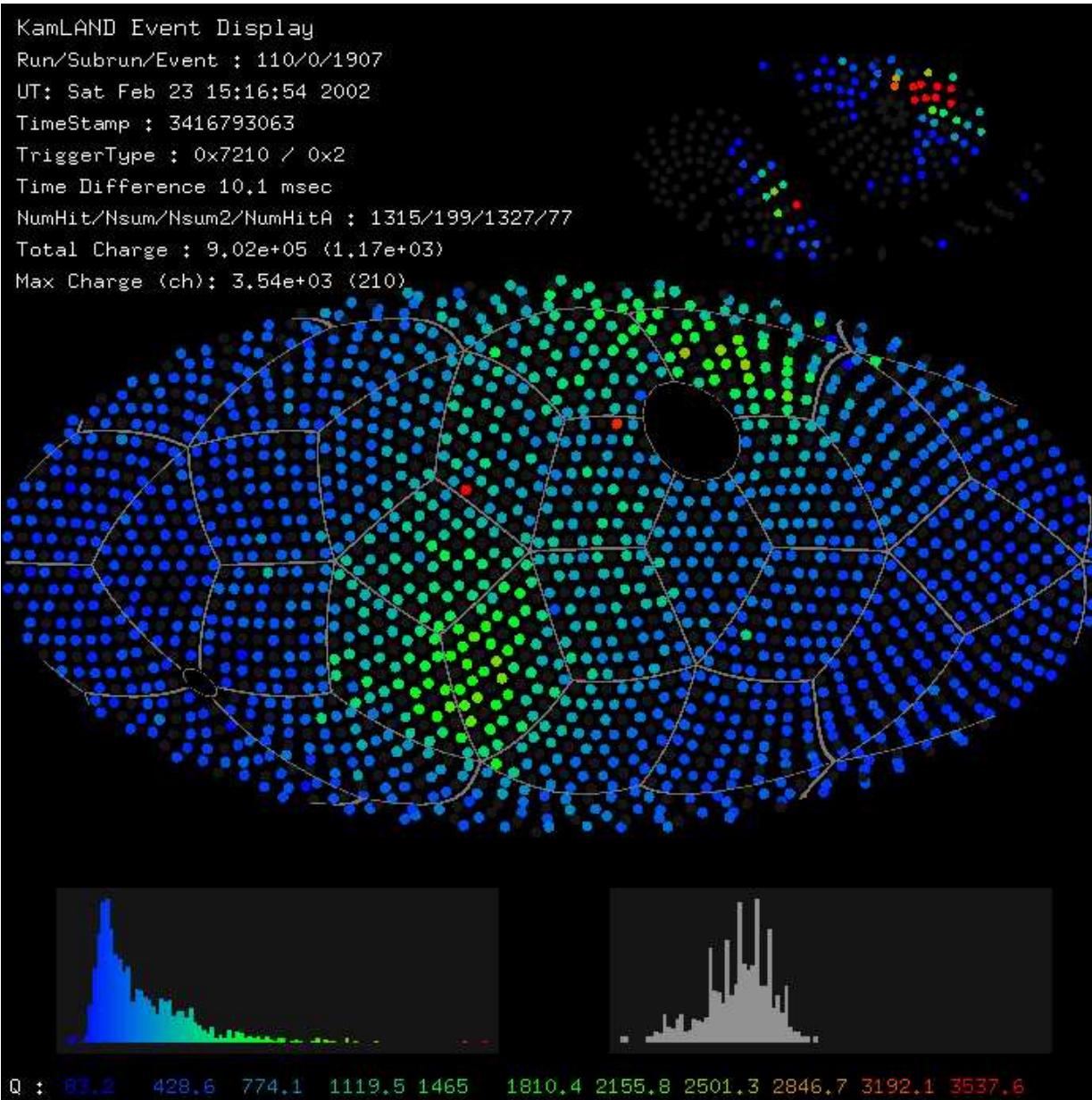
all tubes hit





KamLAND Data

KamLAND Event Display
Run/Subrun/Event : 110/0/1907
UT: Sat Feb 23 15:16:54 2002
TimeStamp : 3416793063
TriggerType : 0x7210 / 0x2
Time Difference 10.1 msec
NumHit/Nsum/Nsum2/NumHitA : 1315/199/1327/77
Total Charge : 9.02e+05 (1.17e+03)
Max Charge (ch): 3.54e+03 (210)



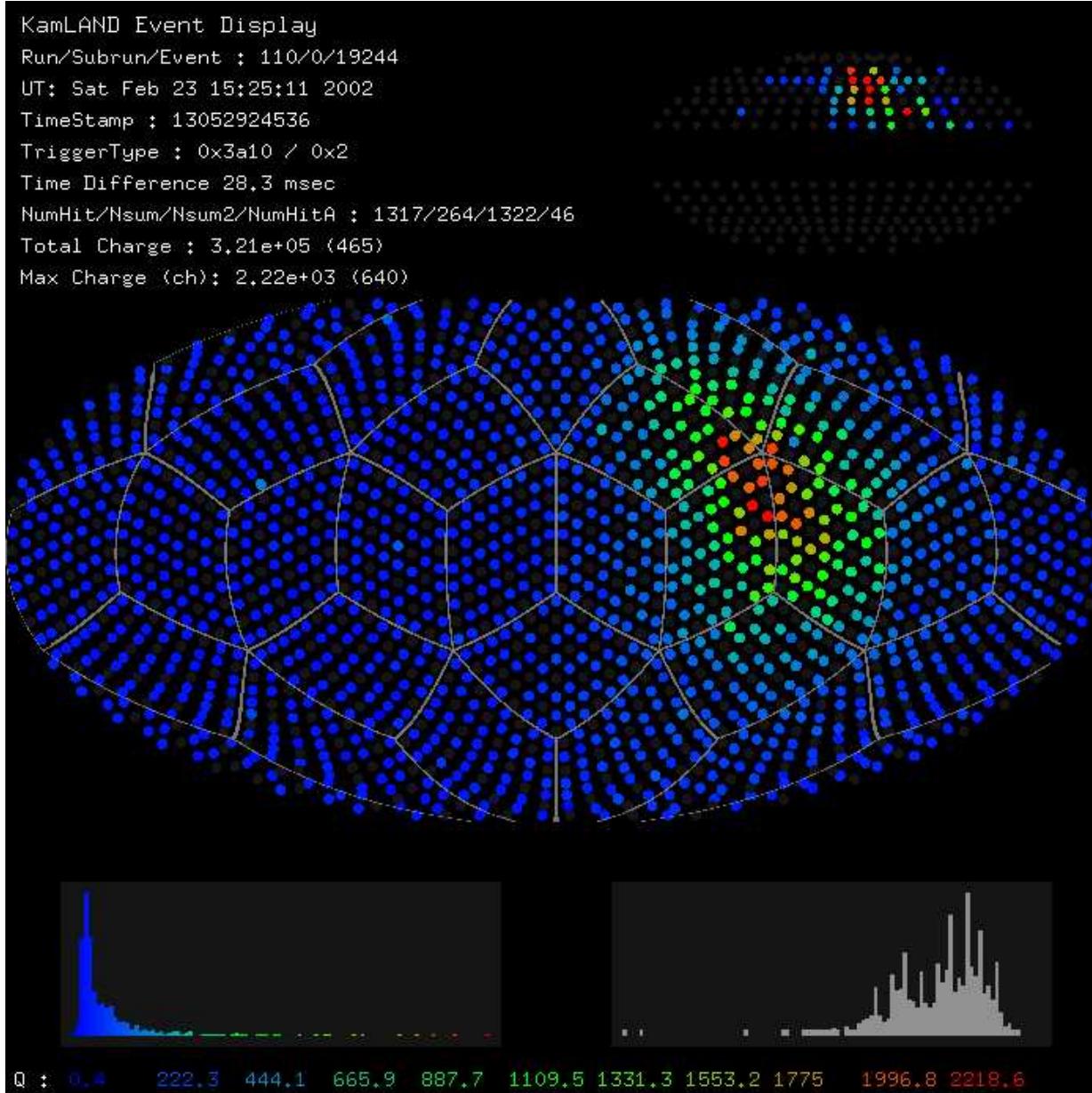
Event Display:
through-going muon

color is pulseheight

all tubes illuminated



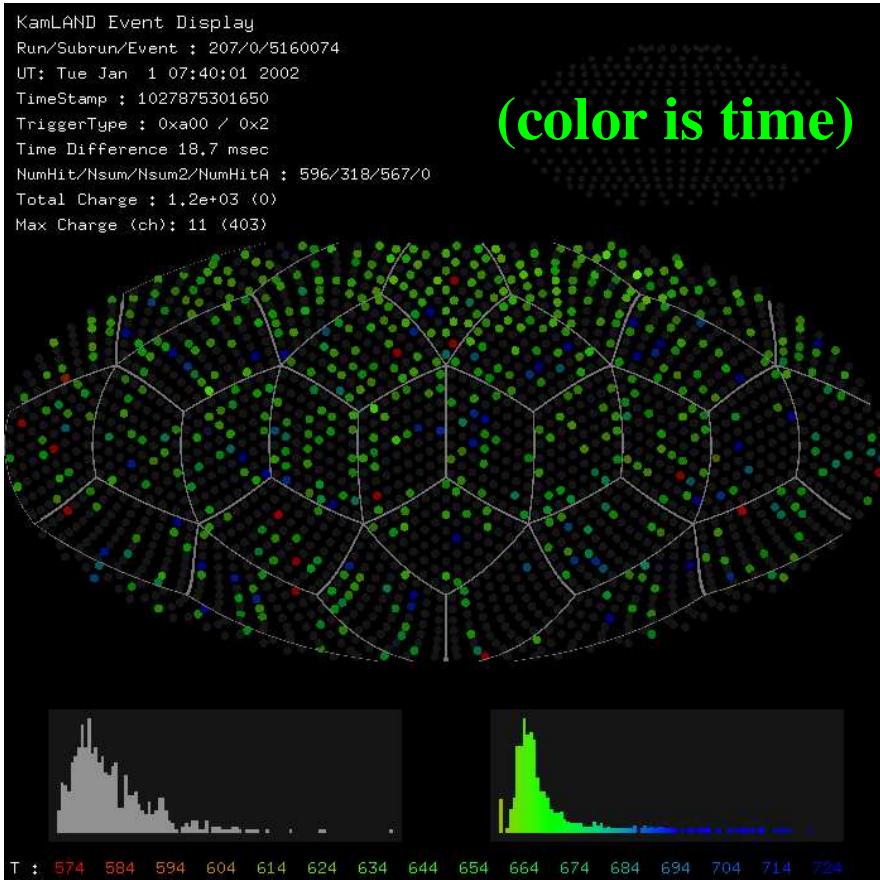
KamLAND Data



Stopped muon

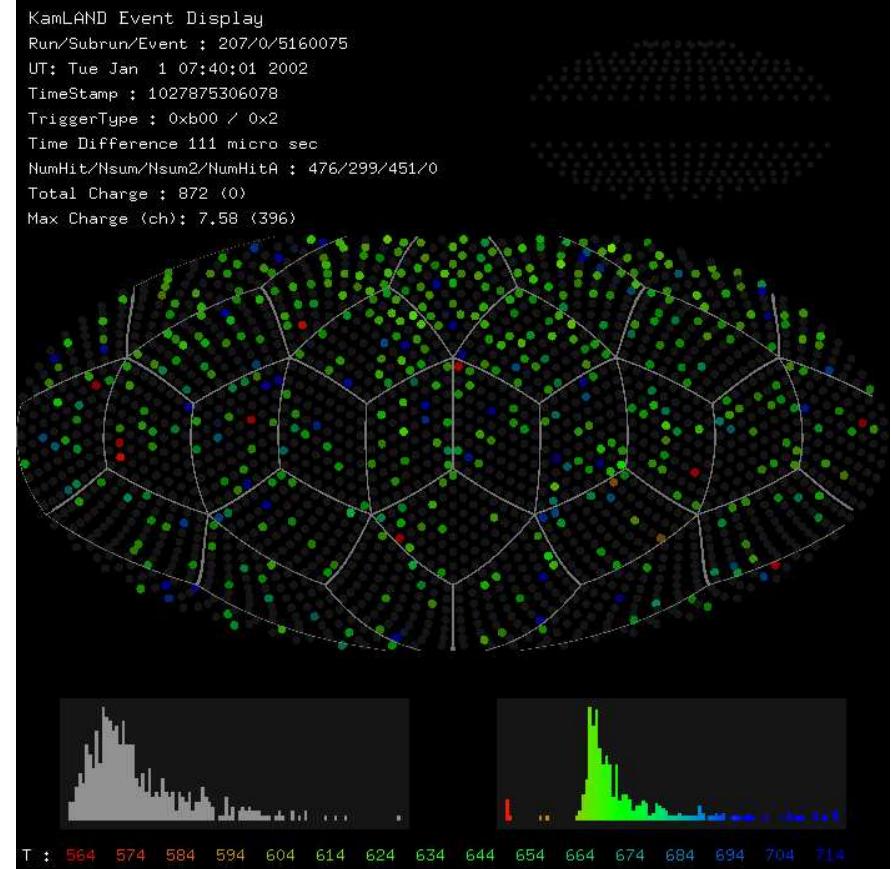


Antineutrino Candidate



Prompt Signal
 $E = 3.20 \text{ MeV}$

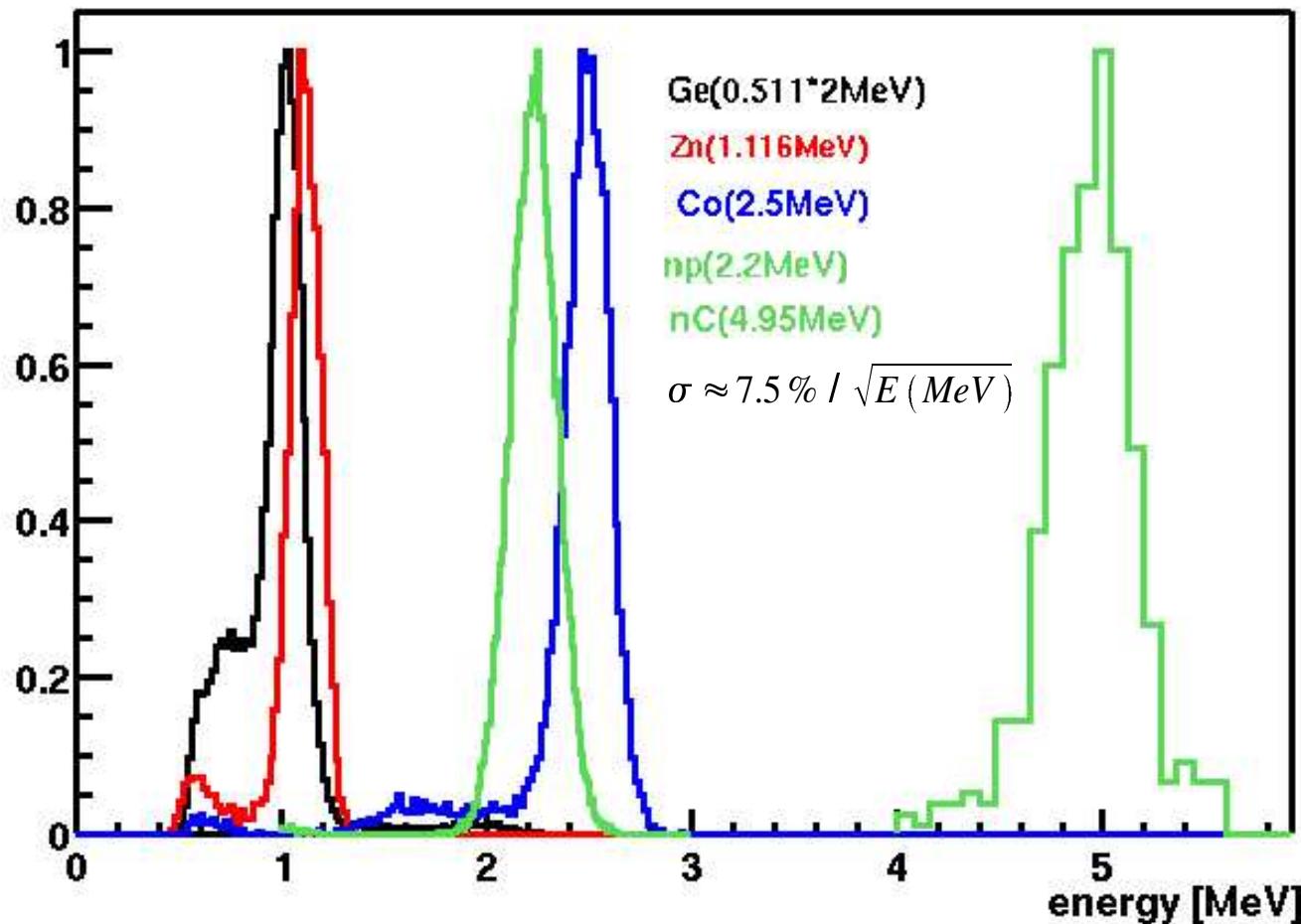
$$\Delta t = 111 \mu\text{s}$$
$$\Delta R = 34 \text{ cm}$$



Delayed Signal
 $E = 2.22 \text{ MeV}$

Calibrations

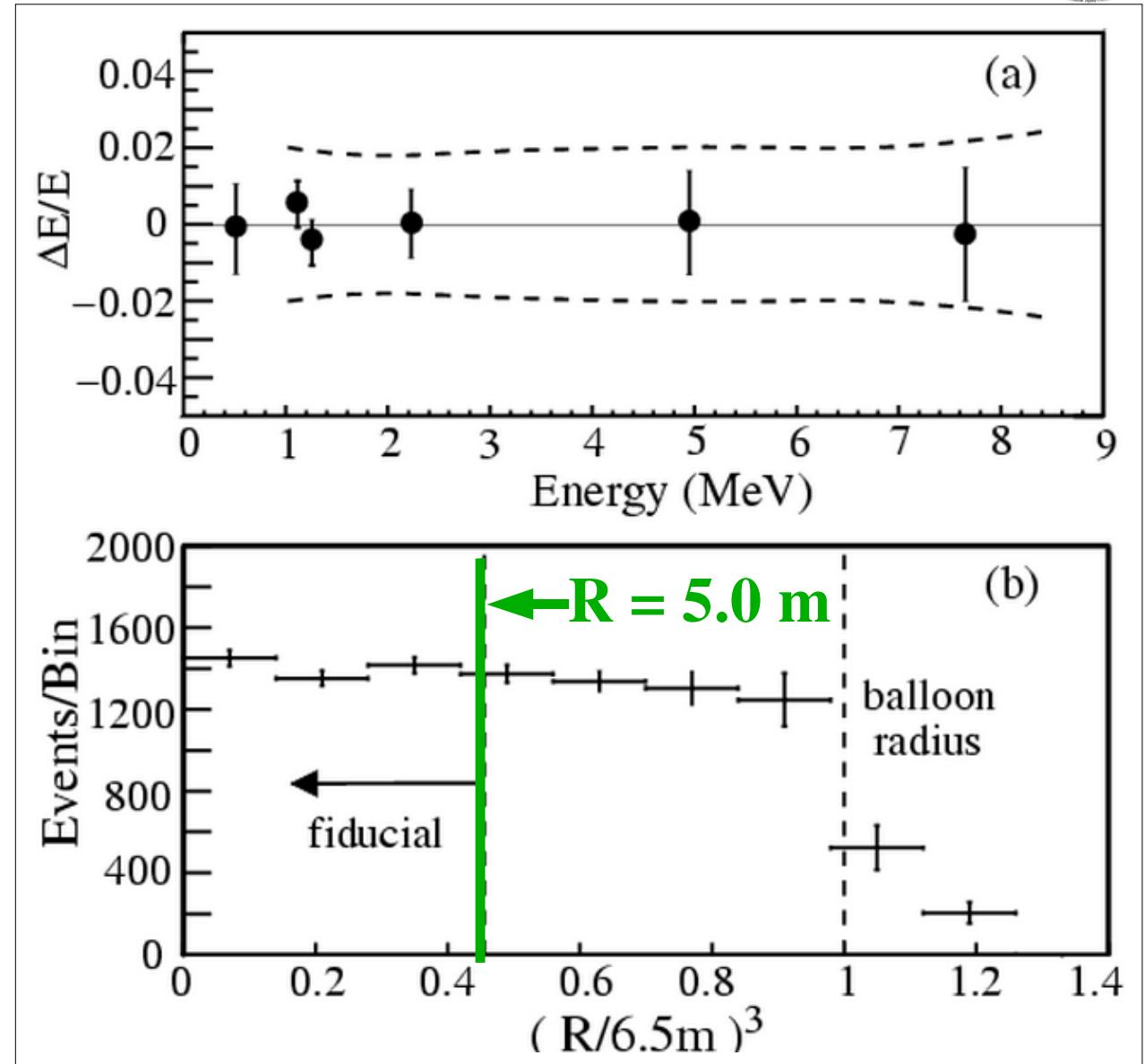
Radioactive gamma sources inserted in detector to calibrate energy and position reconstruction



Reconstruction Performance

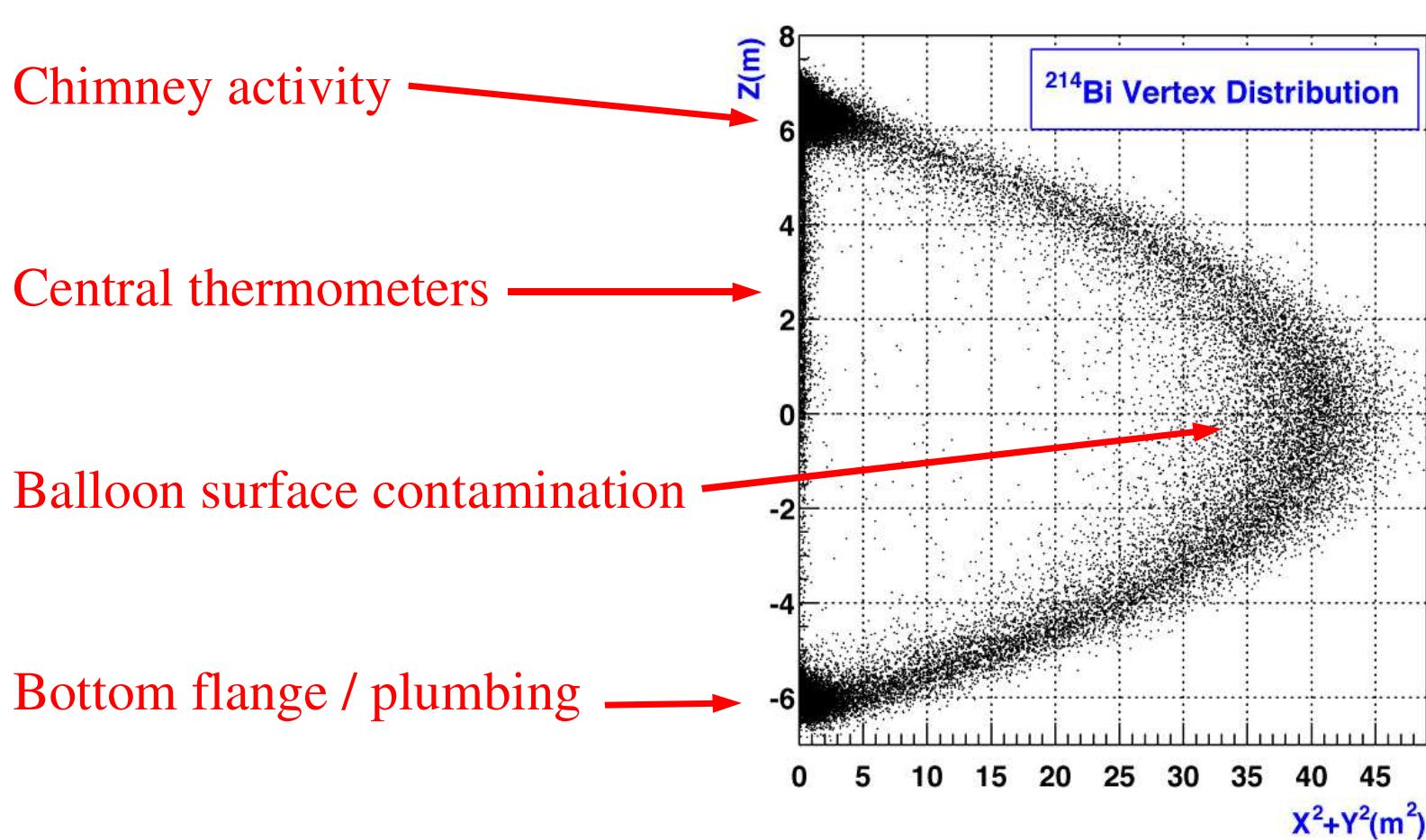
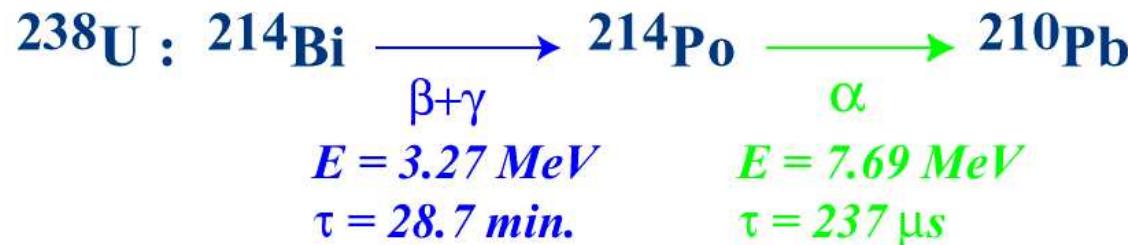
Energy scale
determined from
radioactive source
calibrations

$R = 5.0$ m radius
fiducial volume
estimation from
spallation neutron
uniformity



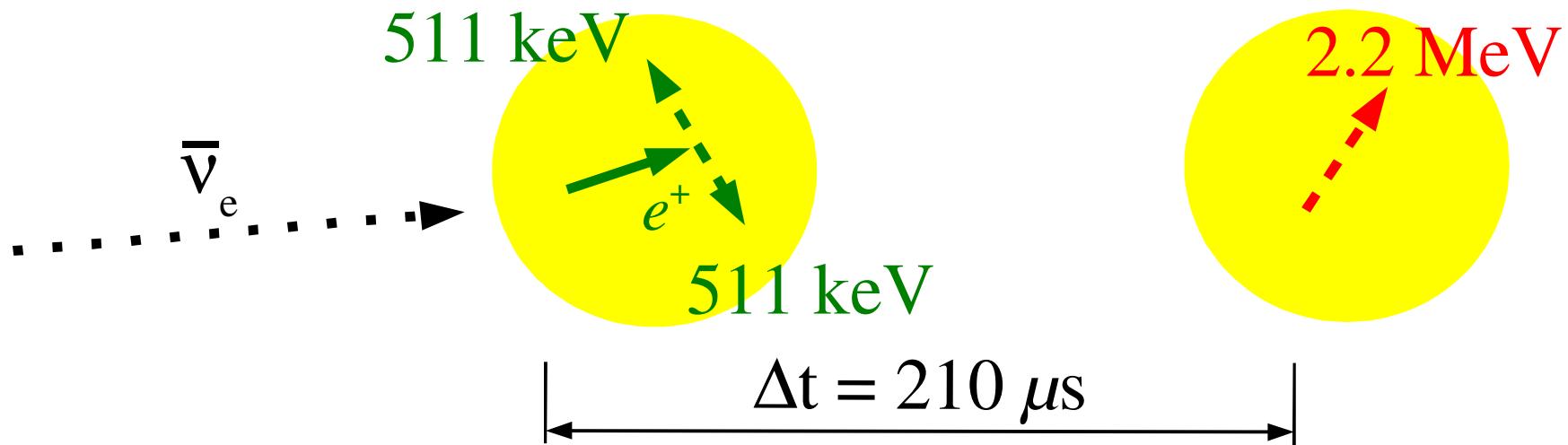


Autoradiography of KamLAND





Event Selection



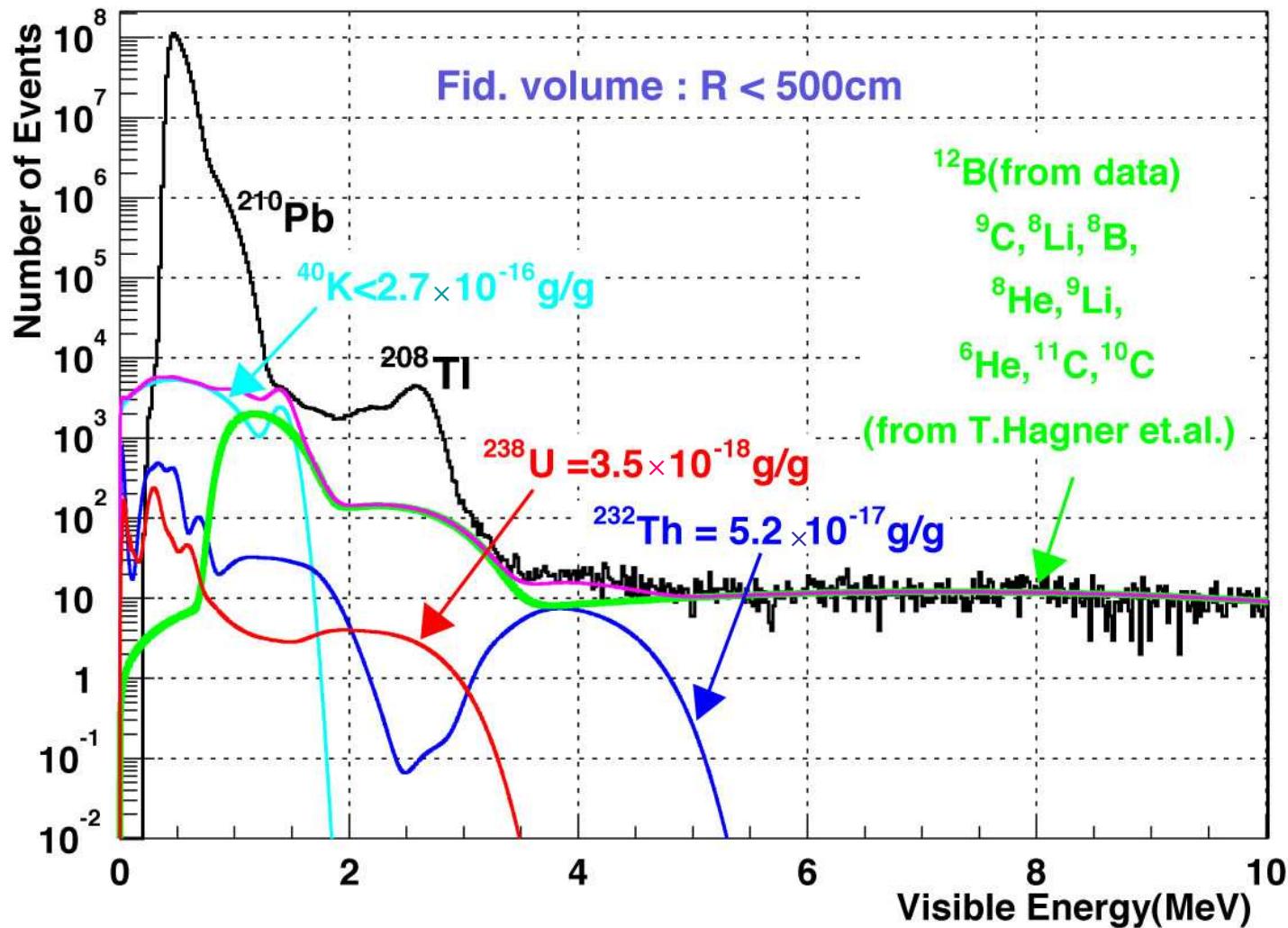
- Time correlation: $0.5 \mu\text{s} < \Delta t < 660 \mu\text{s}$
- Vertex correlation: $\Delta R < 1.6 \text{ m}$
- Delayed event energy: $1.8 \text{ MeV} < E_{\text{del}} < 2.6 \text{ MeV}$
- Spherical fiducial volume: $R < 5 \text{ m}$
- Z-axis: $\rho > 1.2 \text{ m}$

Total efficiency: $78.3 \pm 1.6 \%$

Residual accidental background: $< 10^{-5} / \text{day}$



Backgrounds



Accidental bg estimated from different time window 0.020-20 seconds
 0.0086 ± 0.0005 events



Cosmogenic Backgrounds

2700 m.w.e. overburden cuts muon rate to ~0.3Hz

Muons leave neutrons which can fake the signal

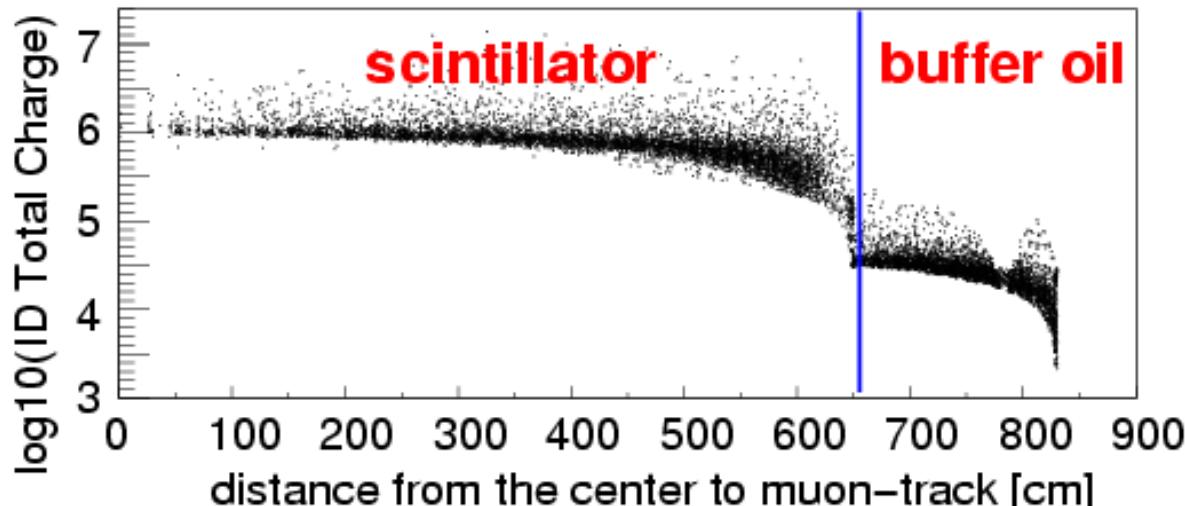
- Veto detector for 2 ms after muons

Muons also create longer lived (> 100 ms) neutron emitters

- Veto 3m cylinder around muon track for 2 s
- For high energy muons (> 3 GeV), veto entire detector for 2 s

Correction to livetime: 11.4%

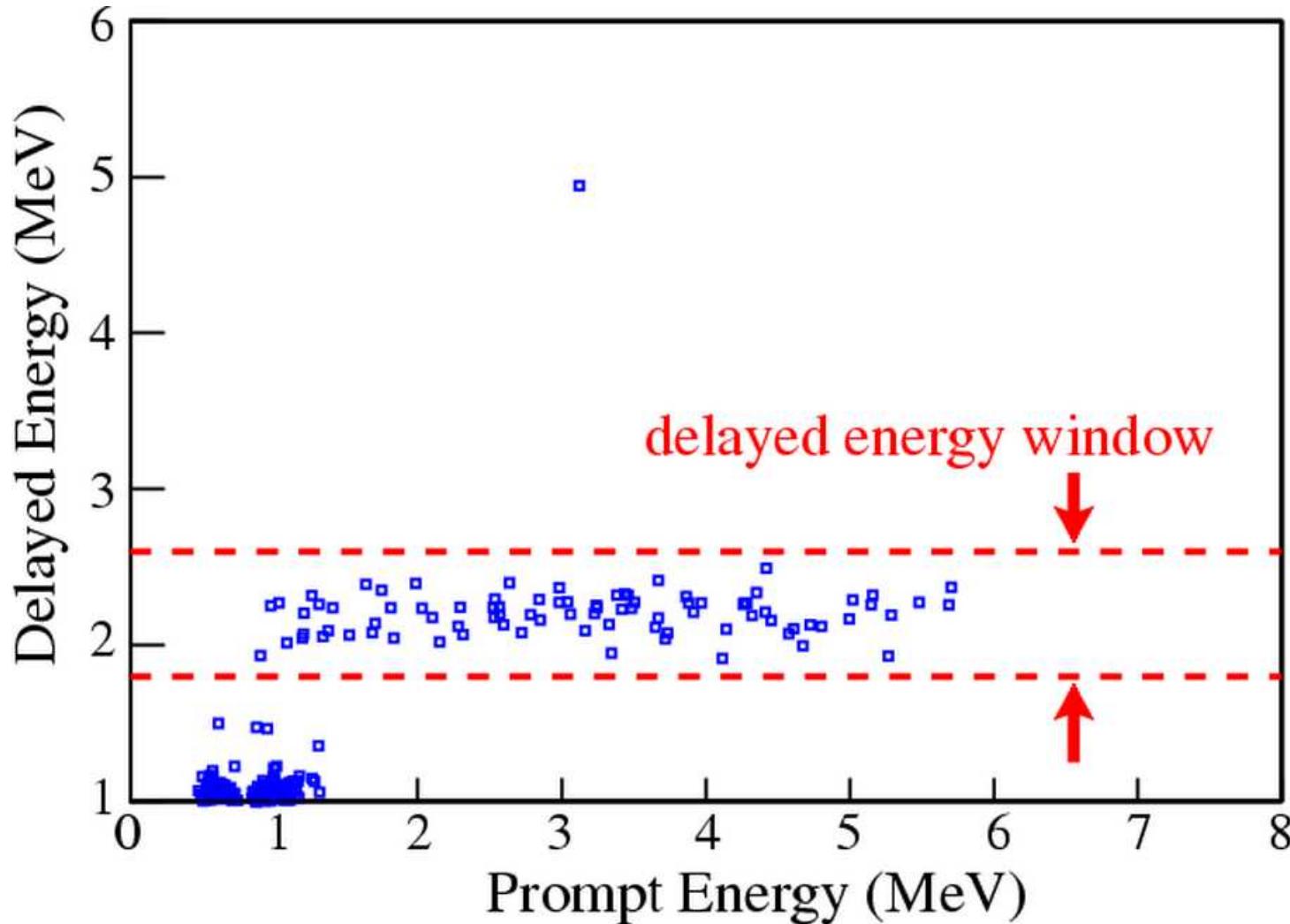
Residual correlated background: 1 ± 1 event



Muon track reconstruction reveals the balloon boundary



Prompt/Delayed Event Energies





Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

Total Scintillator Mass	2.1
Fiducial mass ratio	4.1
Energy threshold	2.1
Efficiency of cuts	2.1
Live time	0.07
Reactor power	2.0
Fuel composition	1.0
Time lag	0.28
Antineutrino spectra	2.5
$\bar{\nu}_e$ - p cross section	0.2
Total systematic error	6.4%



Measured Event Rate

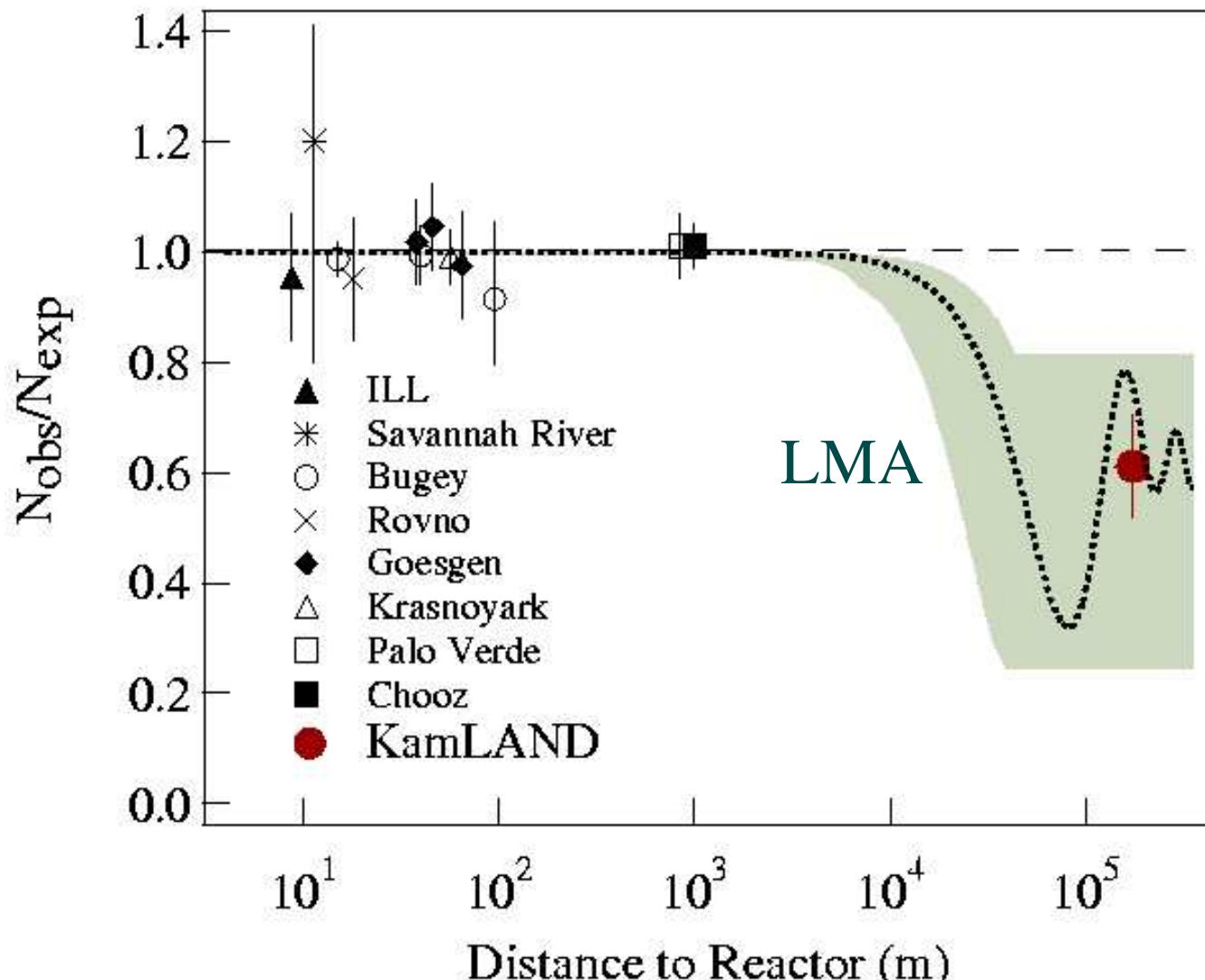
For no oscillations, in 145.1 live-days we expect
 86.8 ± 5.6 events (1 ± 1 bg)

We observe...

54

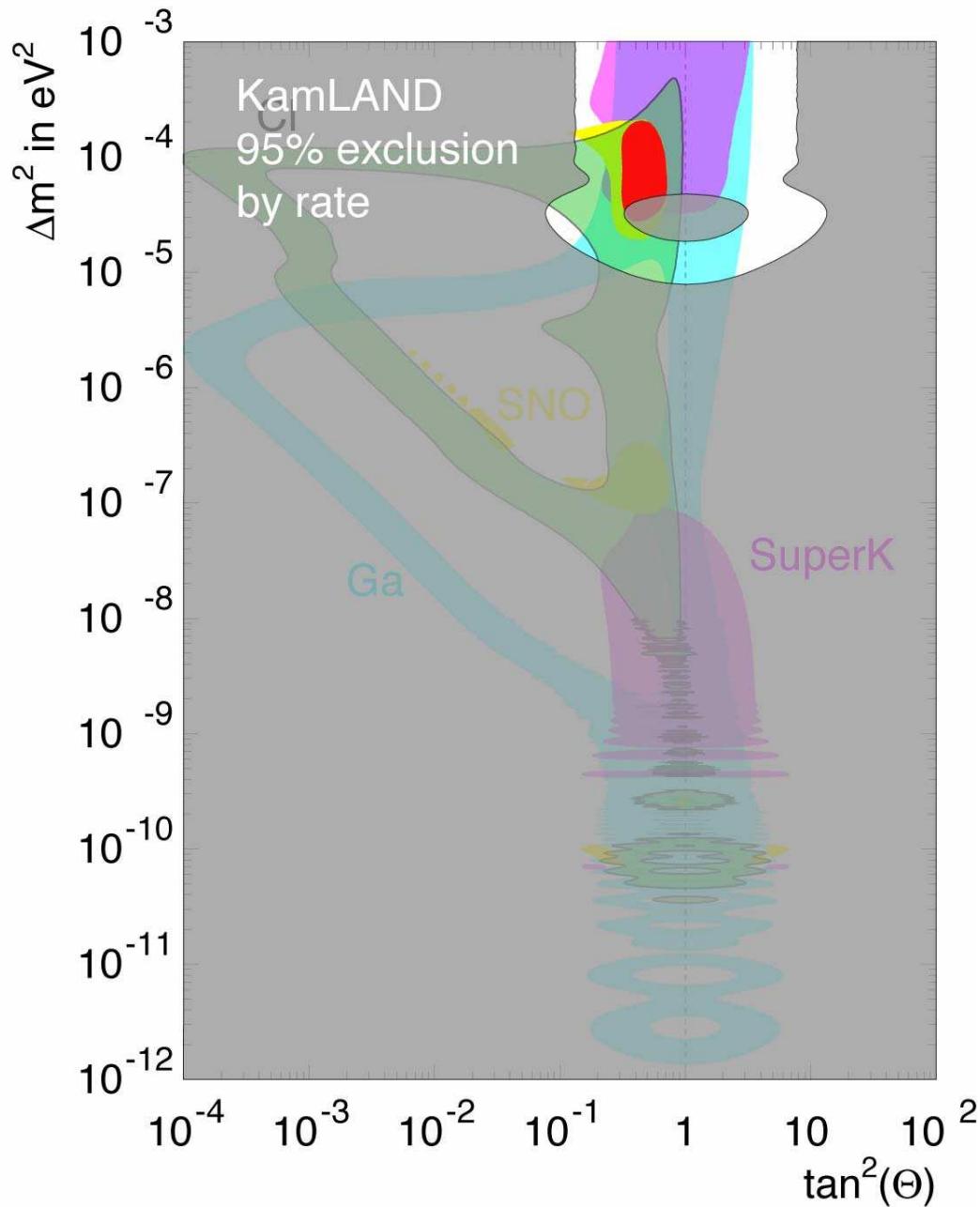


Measured Event Rate

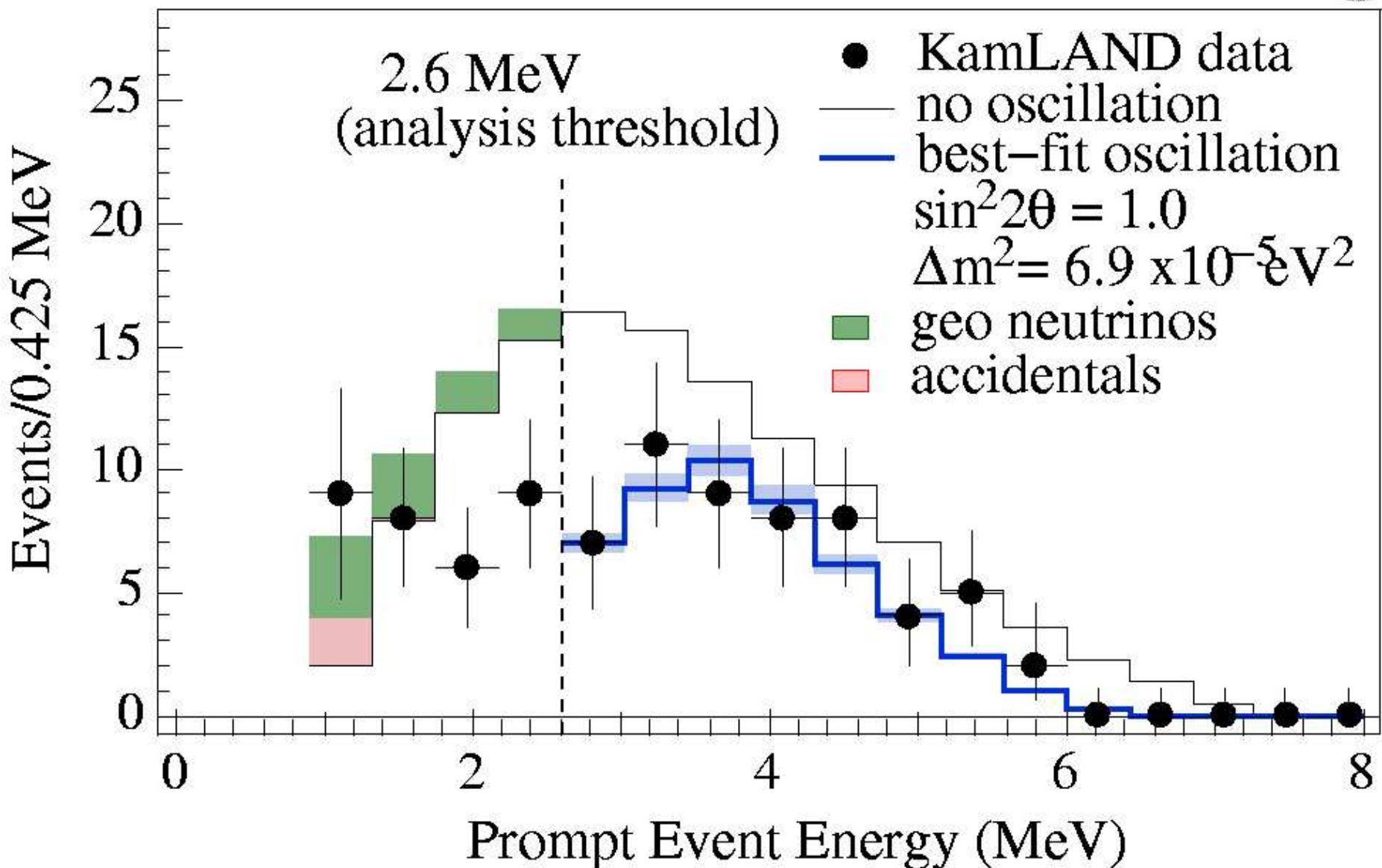




Solar Neutrino Mixing Parameters



Event Spectrum



Fit to Oscillation Parameters

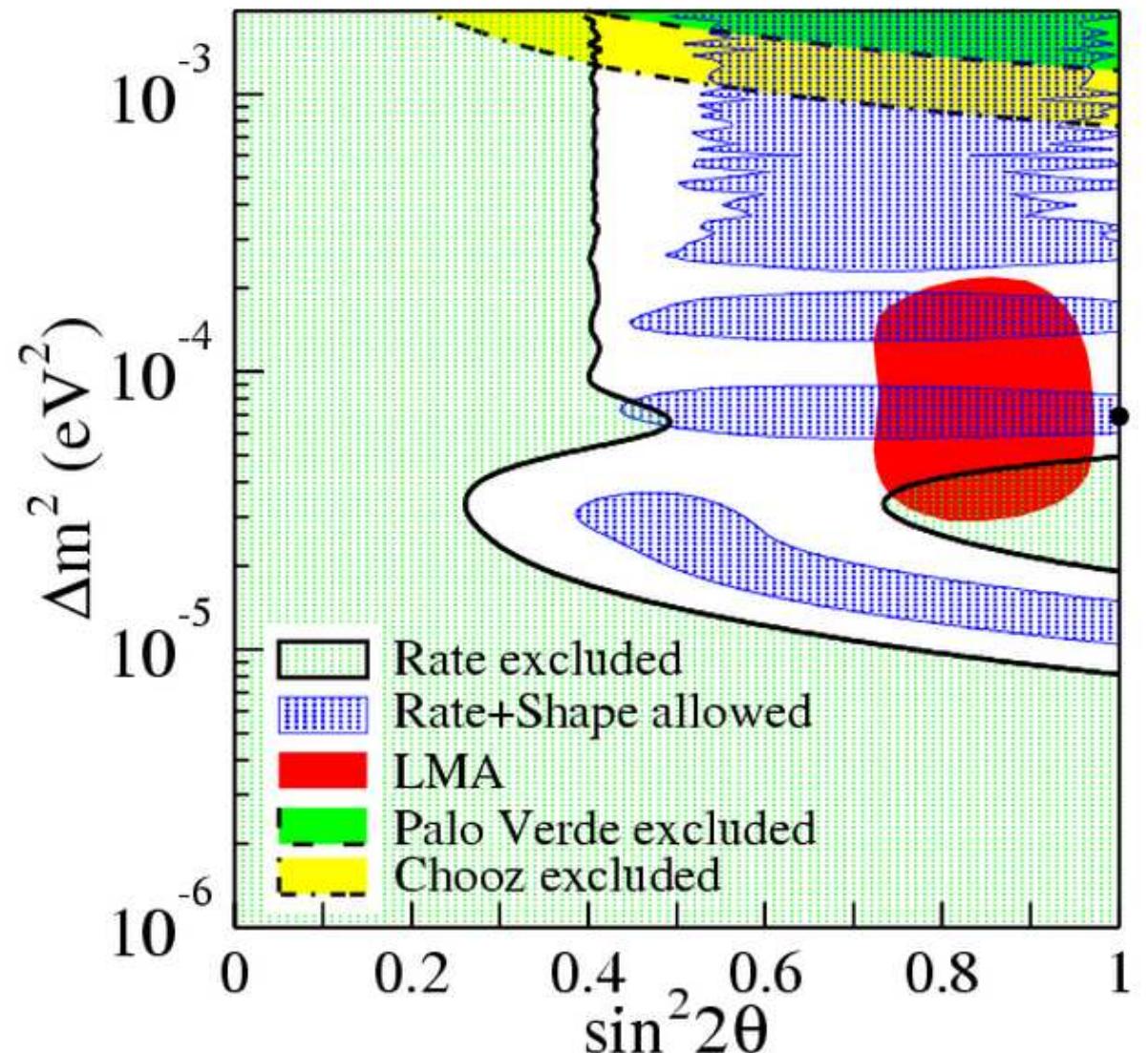


Best fit parameters:

$$\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$$

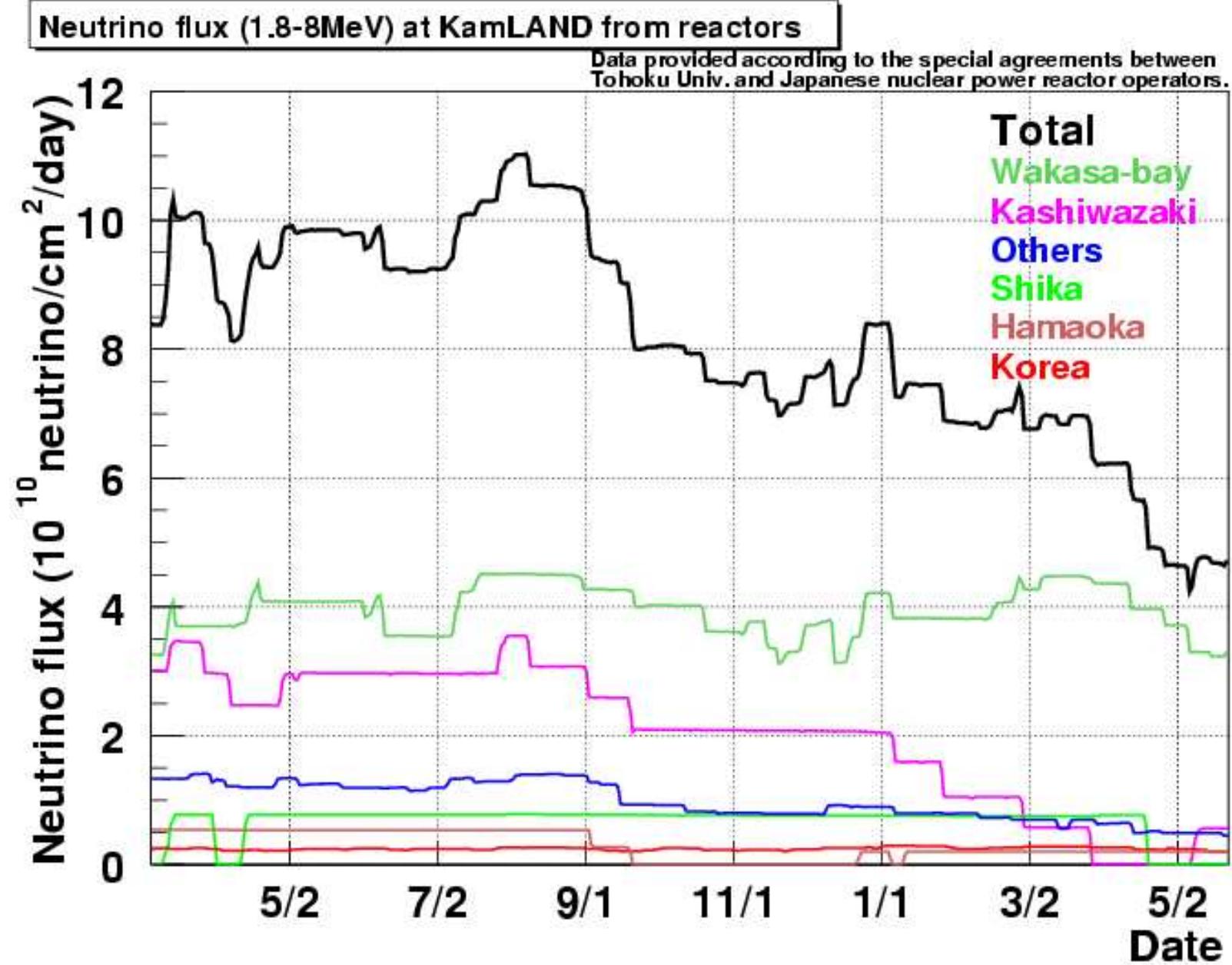
$$\sin^2 2\theta = 1.0$$

All contours at 95% CL



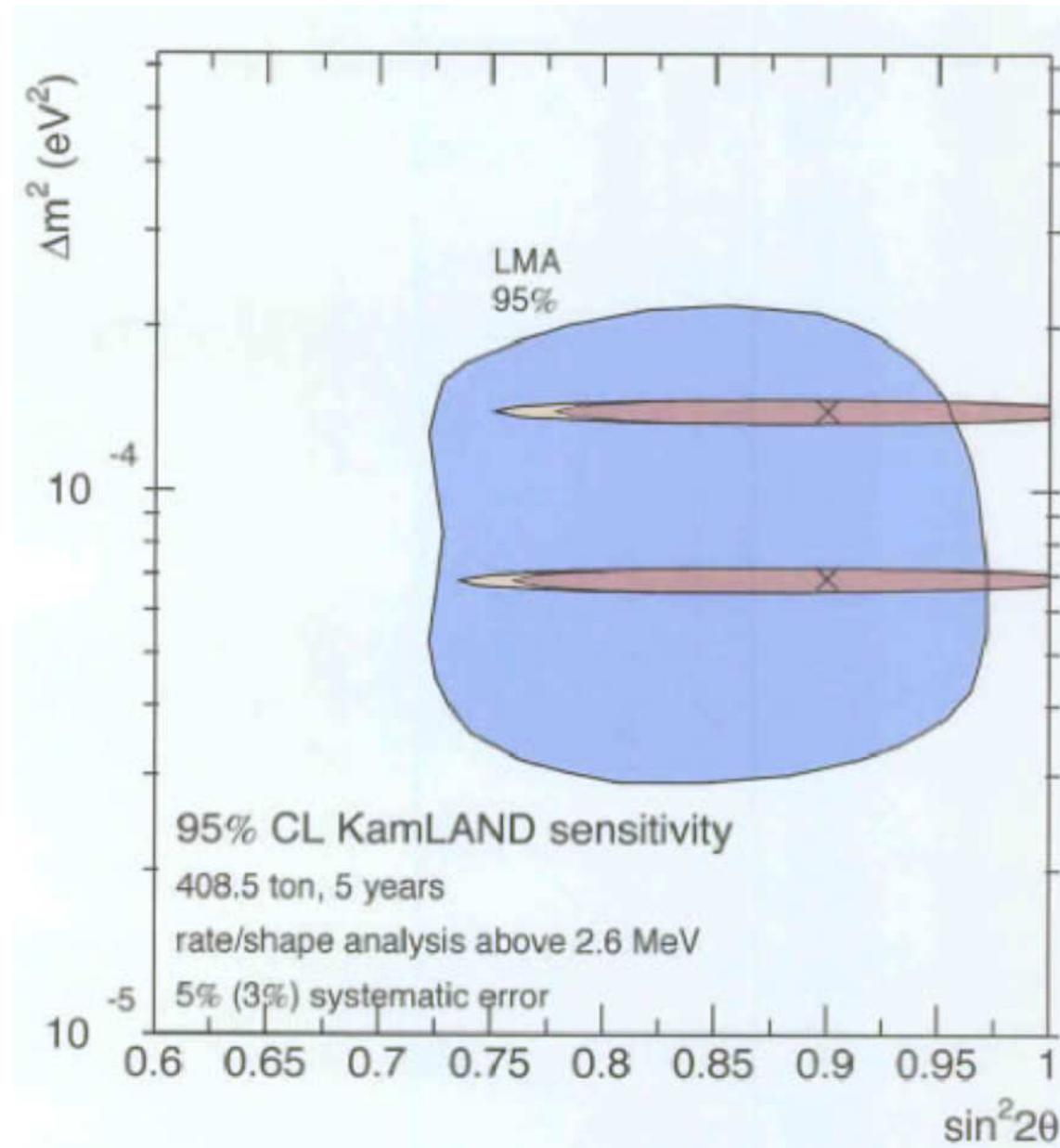


Time Variation of Flux





Expected Sensitivity





3-Flavor Mixing

$$m_1, m_2, m_3$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i \delta_{cp}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i \delta_{cp}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i \alpha/2} & 0 \\ 0 & 0 & e^{-i \alpha/2 + i \beta} \end{pmatrix}$$

solar + **KamLAND**:

$$\theta_{12} \sim 30^\circ$$

$$\Delta m^2_{12} \sim 10^{-4} \text{ eV}^2$$

atmospheric ν:

$$\theta_{23} \sim 45^\circ$$

$$\Delta m^2_{23} \sim 3 \times 10^{-3} \text{ eV}^2$$

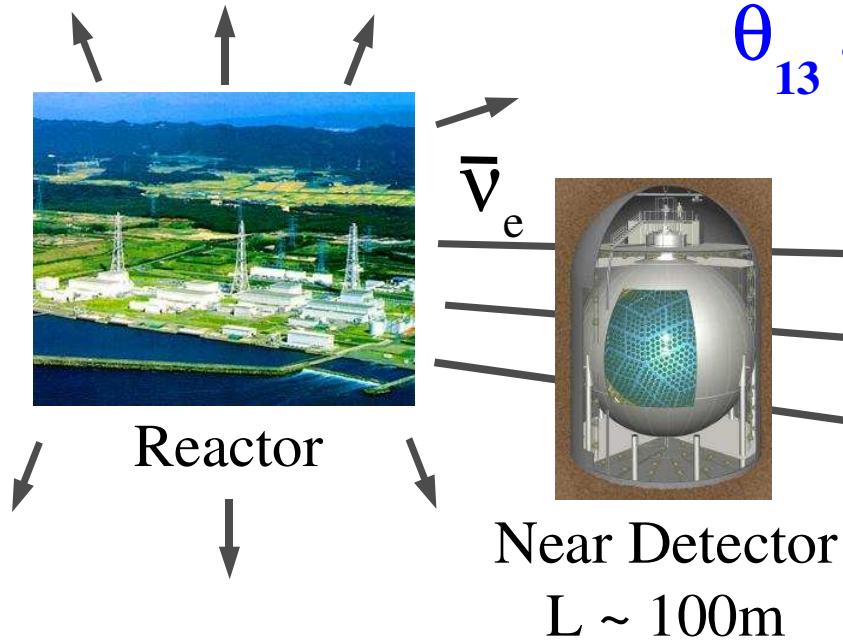
$$\theta_{13} < 10^\circ$$

$$\Delta m^2_{13} \sim \pm 3 \times 10^{-3} \text{ eV}^2$$

future accelerator/reactor

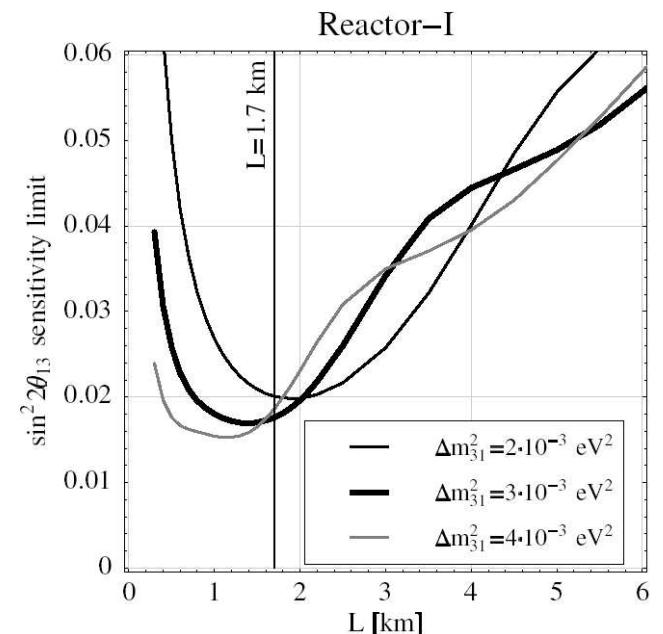
neutrinoless
double beta decay

θ_{13} at Reactors



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.27 \Delta m_{13}^2 L}{E} + O(\alpha^2)$$

- First discussed by L.A.Mikaelyan and V.V.Sinev, Phys. Atom. Nucl. **63**, 1002 (2001)
- Also see P. Huber et al., arXiv:hep-ph/0303232 and the more comprehensive list at <http://kmheeger.lbl.gov/theta13/references.html>



from Huber et al.



Conclusions

- KamLAND observed, for the first time, disappearance of electron **antineutrinos** in a laboratory-style experiment
- Assuming CPT invariance, this result **excludes** solar neutrino oscillation solutions except LMA at > **99.95% CL**
- Many other physics results coming soon! (updated reactor results, geo-neutrinos, solar antineutrinos, neutron production...)