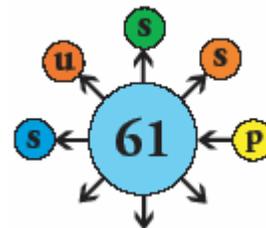


Neutrino Experiments with Reactors

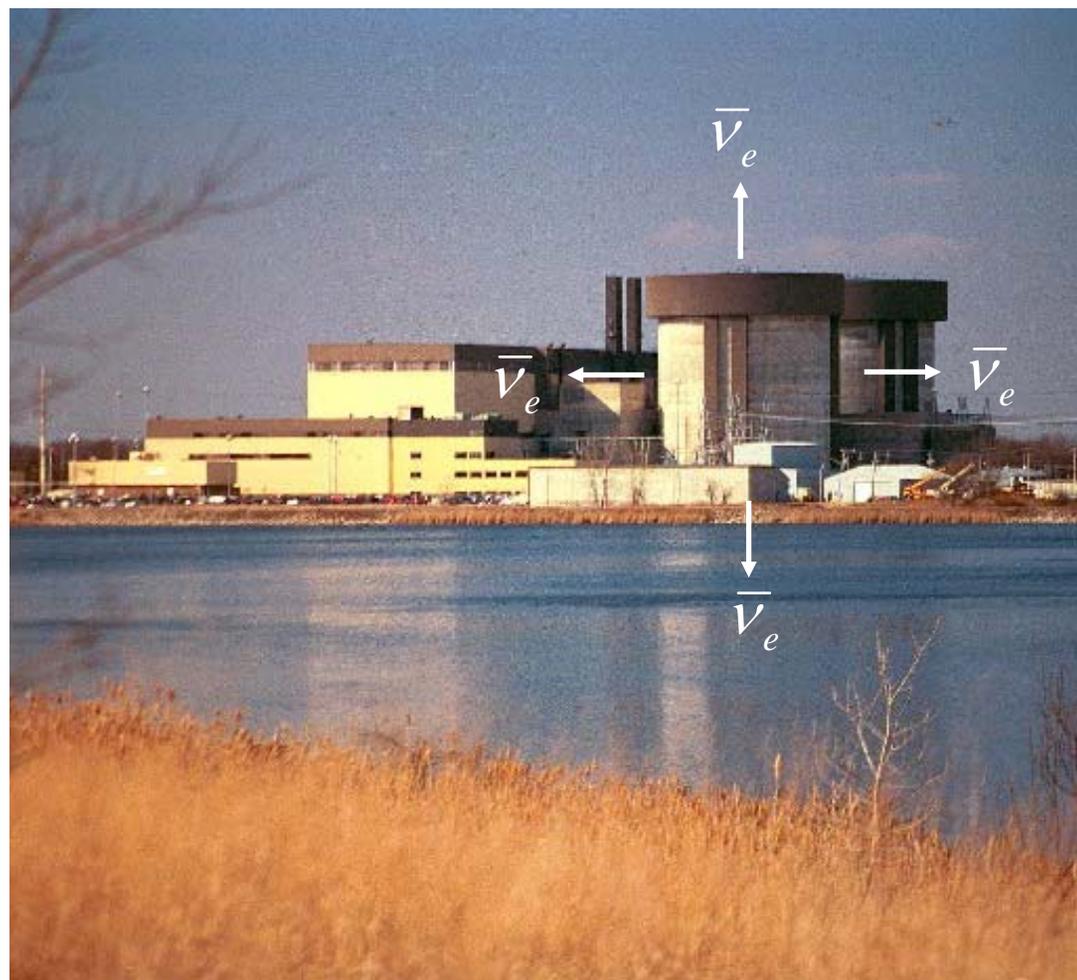
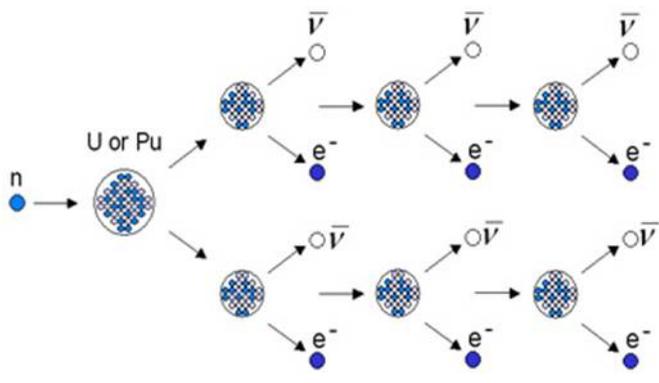
Ed Blucher, Chicago

- Reactors as antineutrino sources
 - Antineutrino detection
 - Reines-Cowan experiment
 - Oscillation Experiments
 - Solar Δm^2 (KAMLAND)
 - Atmospheric Δm^2 -- θ_{13} (CHOOZ, Double-CHOOZ, Daya Bay, Braidwood)
 - Conclusions
- } Lecture 1



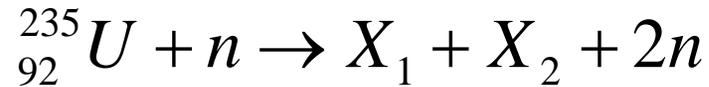
Reactors as Antineutrino Sources

Reactors are copious, isotropic sources of $\bar{\nu}_e$.



β^- decay of neutron rich fission fragments and U and Pu fission

Example: ^{235}U fission



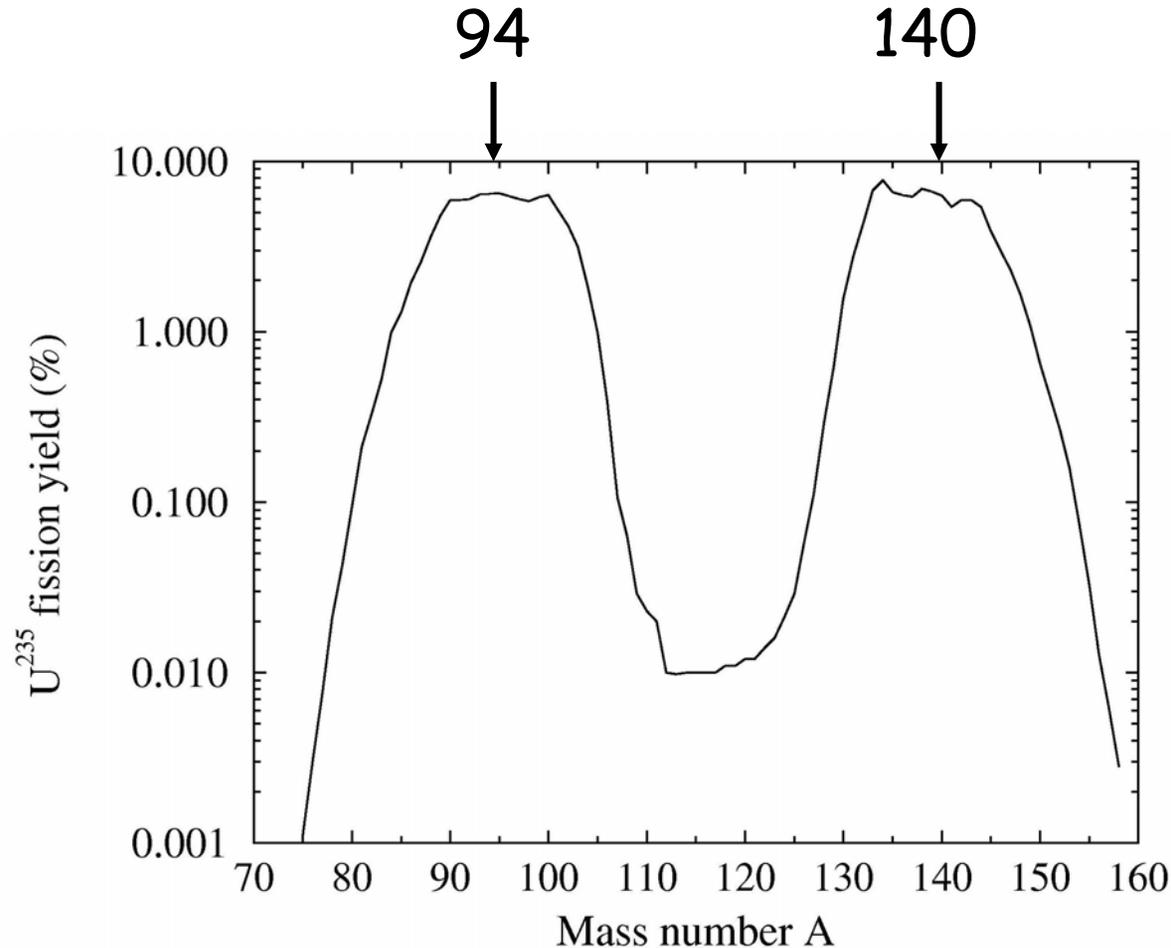
Stable nuclei with most likely A from ^{235}U fission:



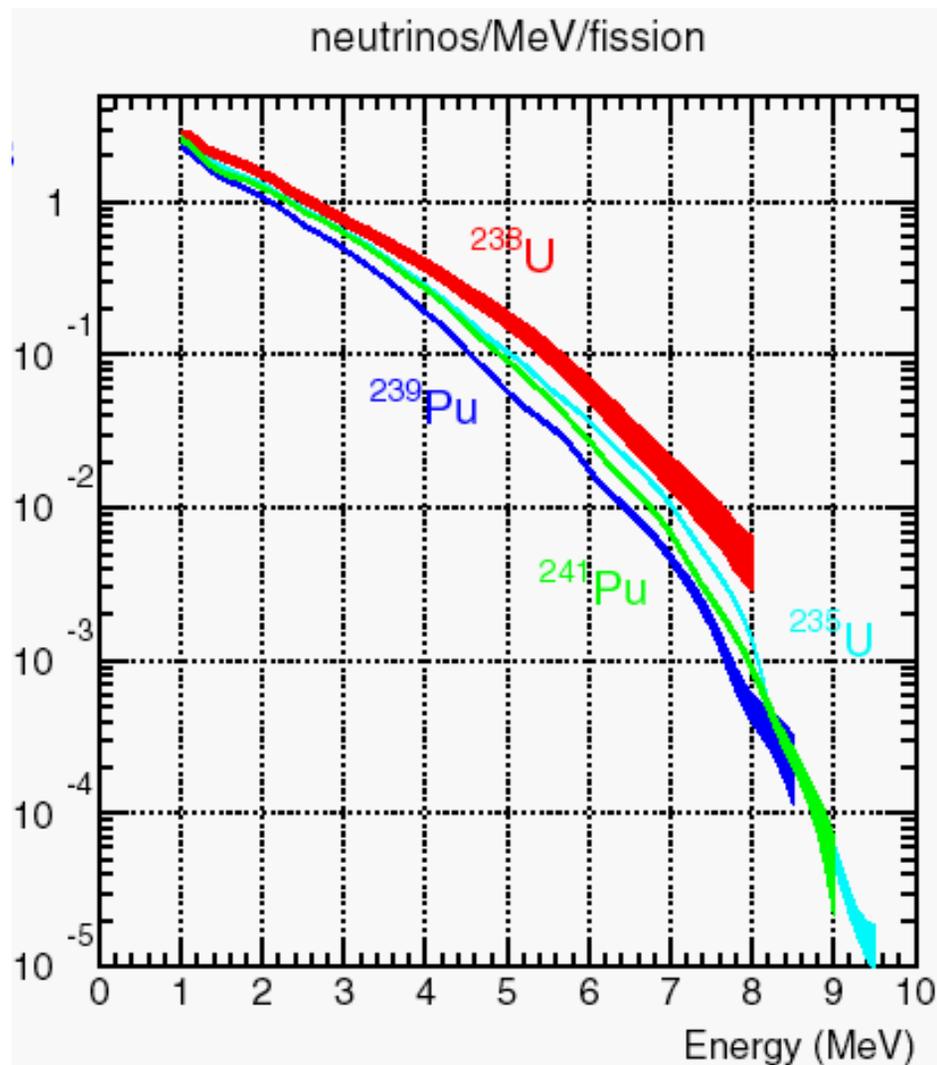
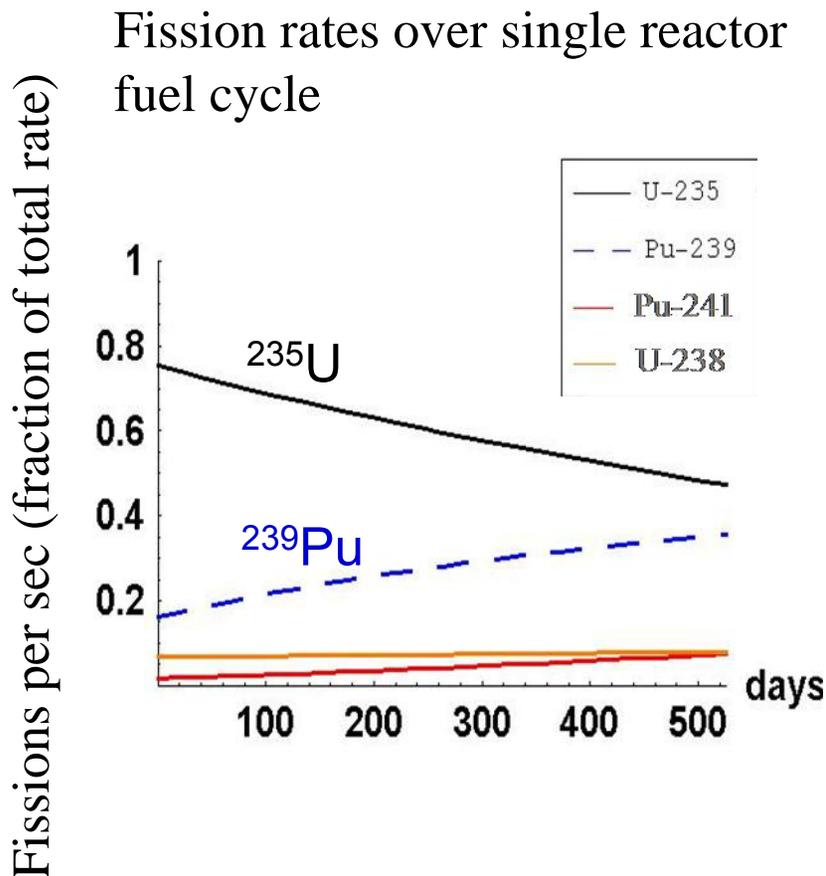
Together, these have 98 p and 136 n, while fission fragments (X_1+X_2) have 92 p and 144 n

On average, 6 n have to decay to 6 p to reach stable matter

➡ ~ 200 MeV/fission and $\sim 6 \bar{\nu}_e$ / fission implies that 3GW_{th} reactor produces $\sim 6 \times 10^{20} \bar{\nu}_e$ / sec.

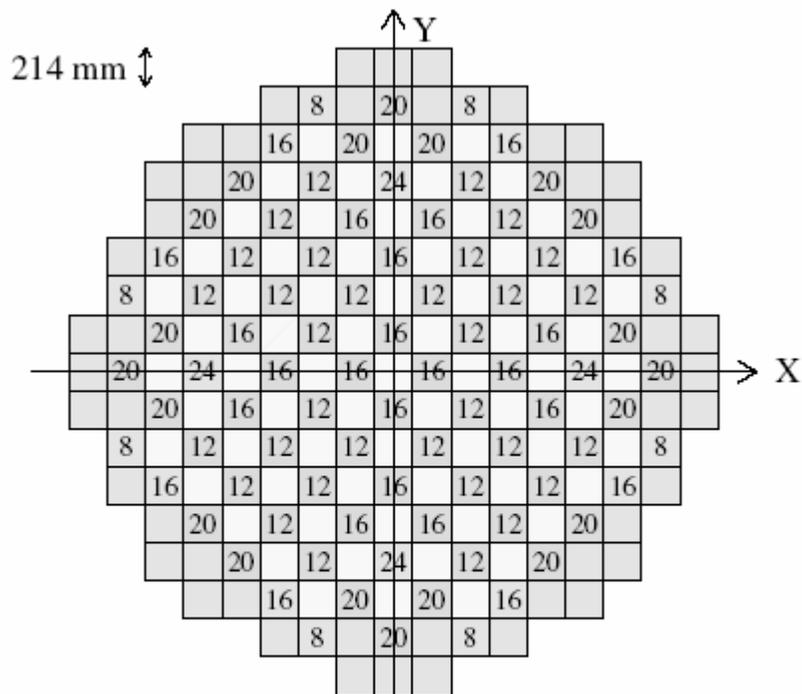


> 99.9% of $\bar{\nu}$ are produced by fissions in ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu

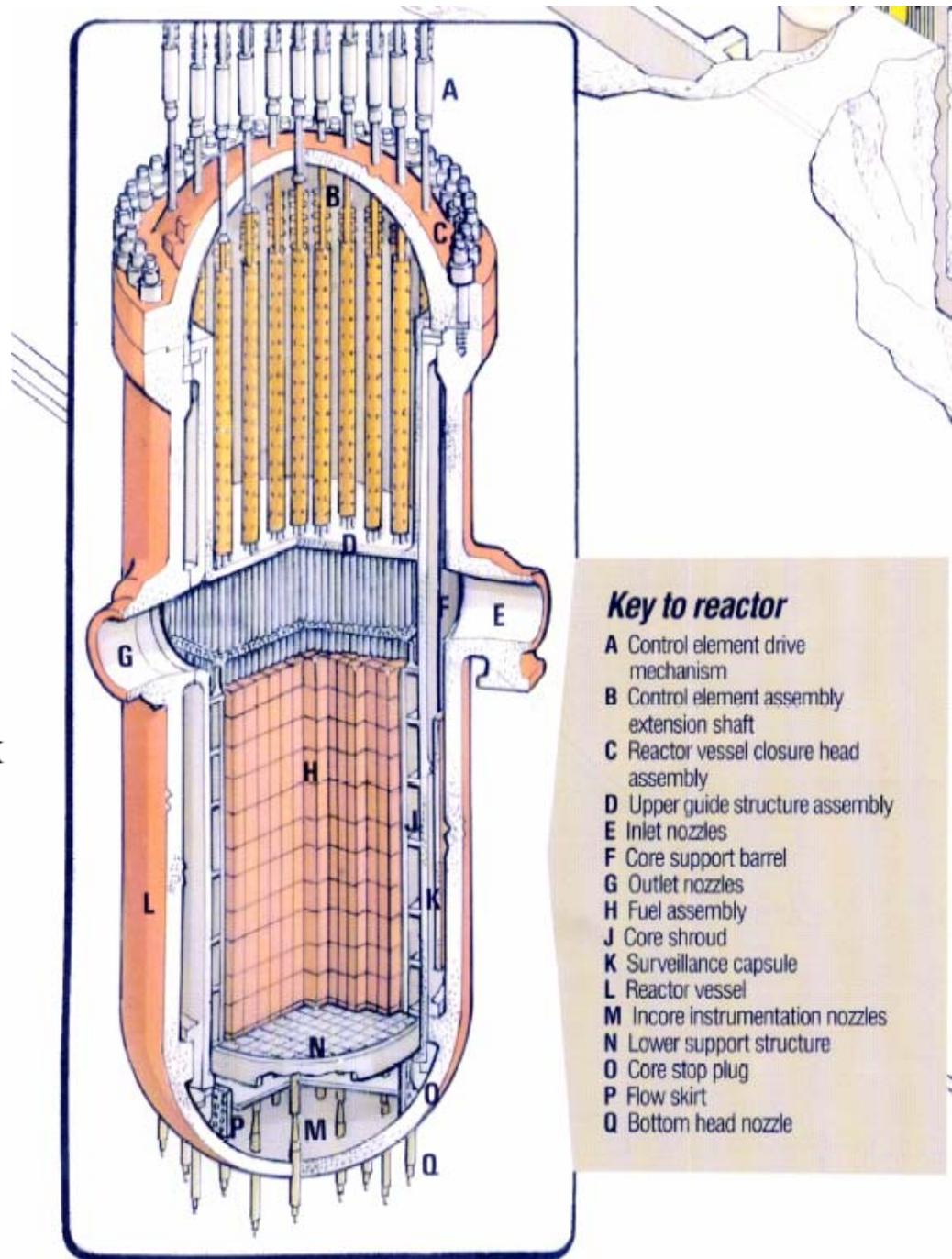


Plutonium breeding over fuel cycle (~250 kg over fuel cycle) changes antineutrino rate (by 5-10%) and energy spectrum

Each reactor core is an extended antineutrino source:
 ~ 3 m in diameter and 4 m high.



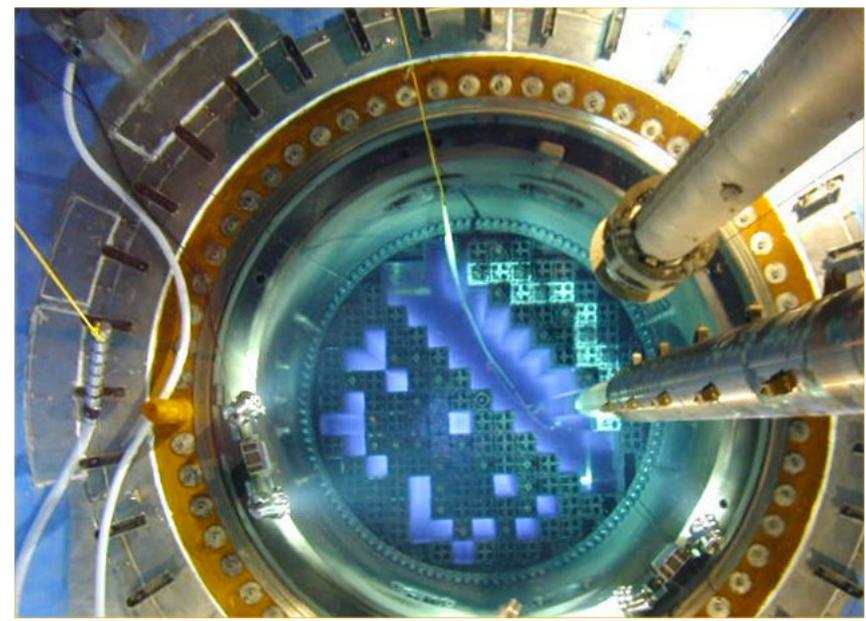
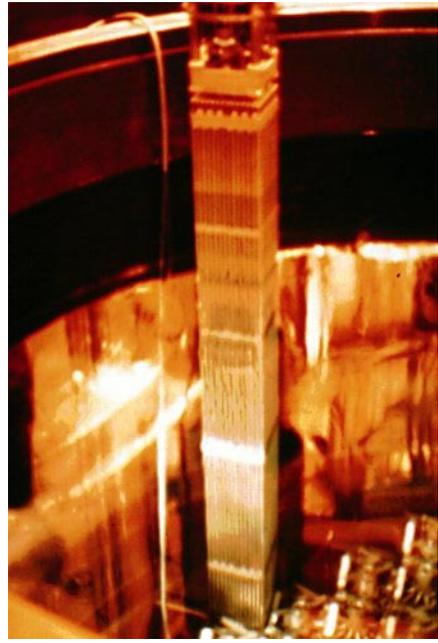
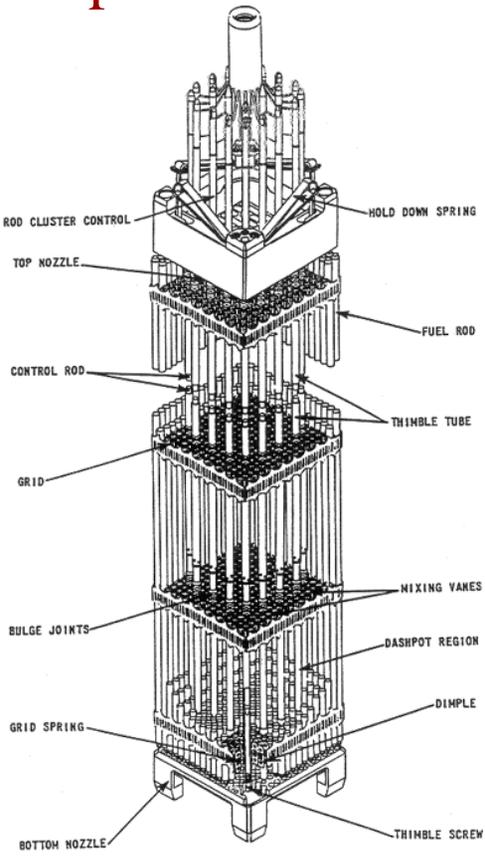
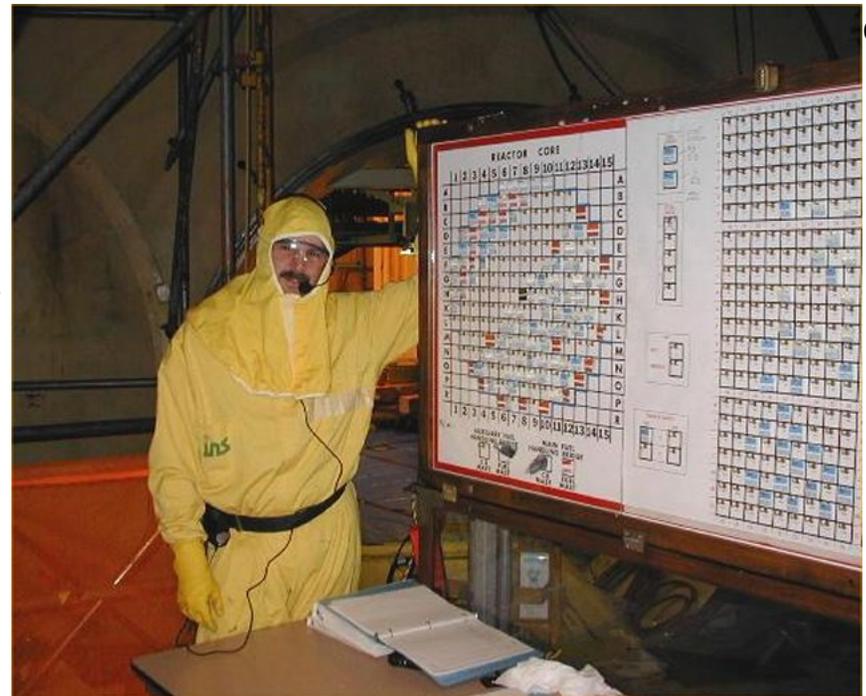
- Region 1: 1.8 % enrichment
- Region 2: 2.4 % enrichment
- Region 3: 3.1 % enrichment



- Key to reactor**
- A Control element drive mechanism
 - B Control element assembly extension shaft
 - C Reactor vessel closure head assembly
 - D Upper guide structure assembly
 - E Inlet nozzles
 - F Core support barrel
 - G Outlet nozzles
 - H Fuel assembly
 - J Core shroud
 - K Surveillance capsule
 - L Reactor vessel
 - M Incore instrumentation nozzles
 - N Lower support structure
 - O Core stop plug
 - P Flow skirt
 - Q Bottom head nozzle

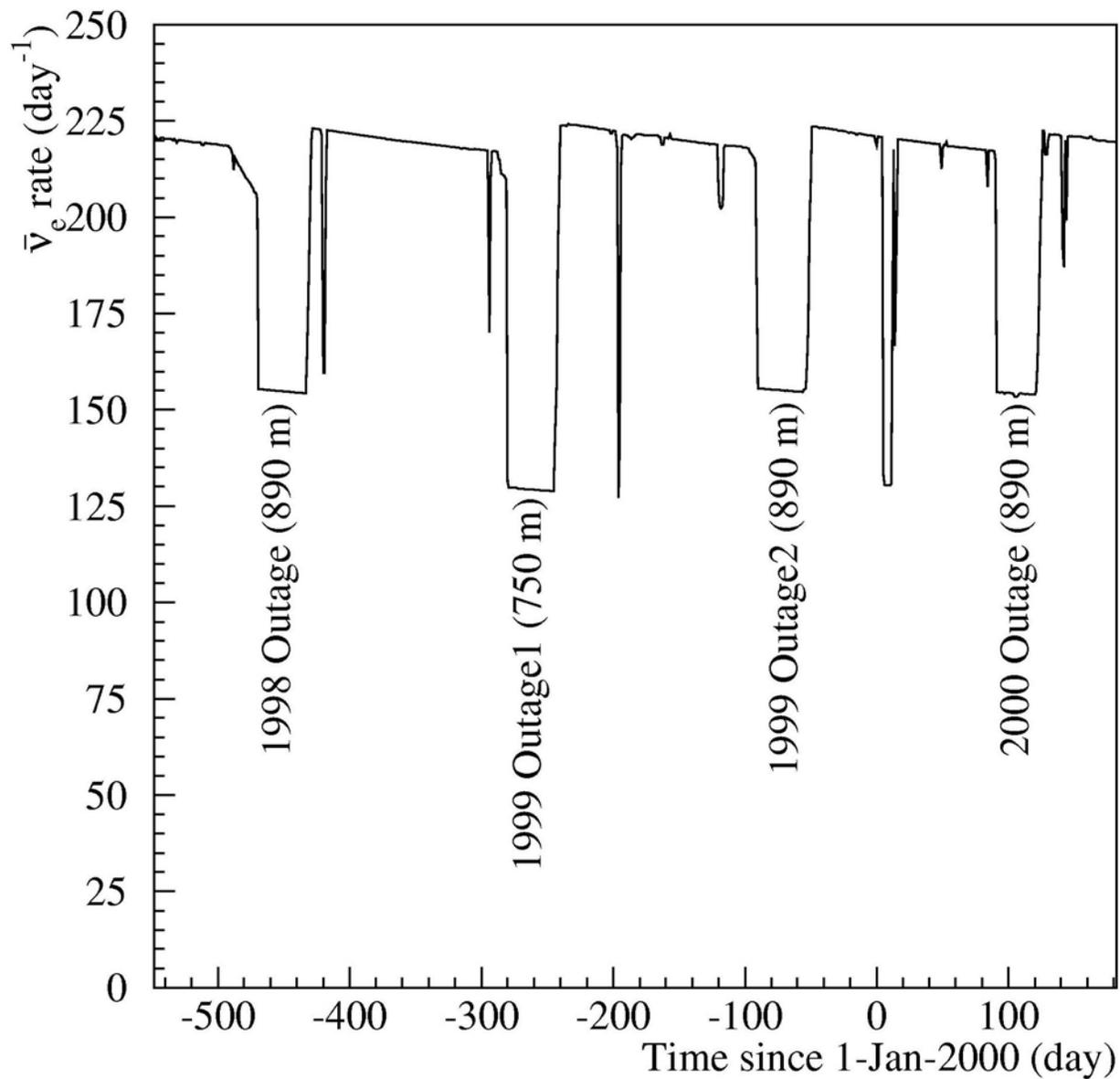
Reactor refueling

- 1 month shutdown every 12-18 months
- 1/3 of fuel assemblies are replaced and remaining fuel assemblies repositioned



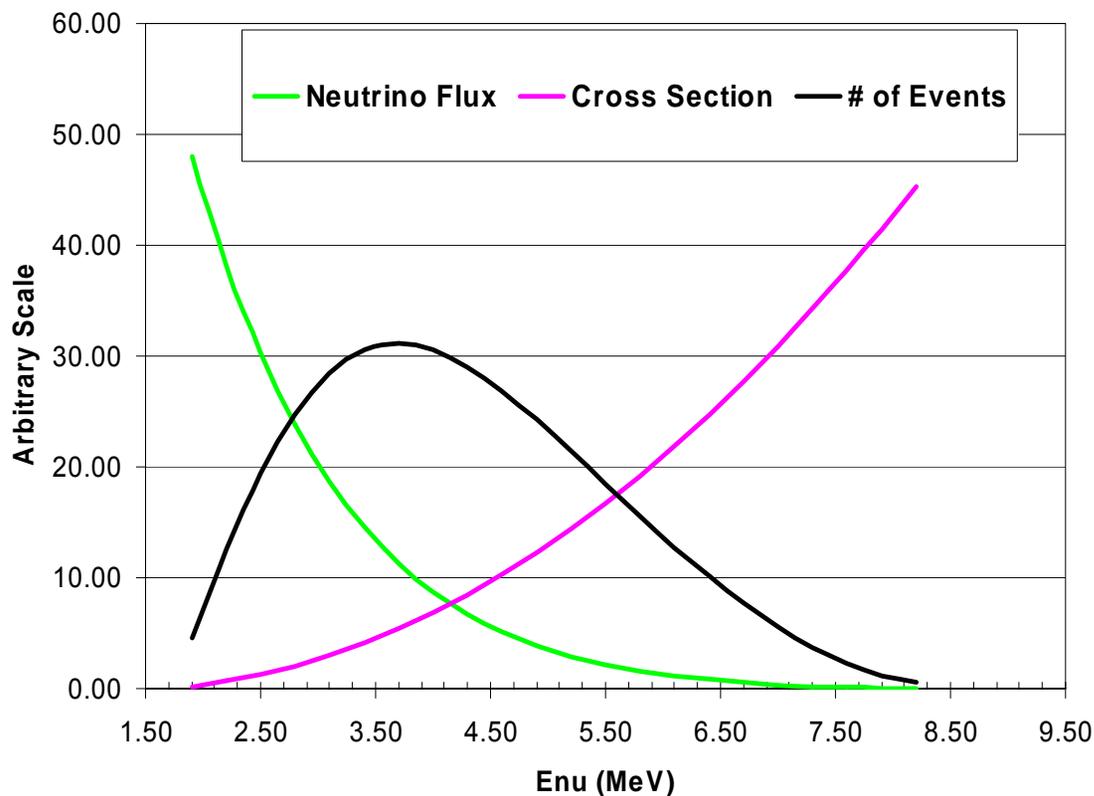
Reactor Fuel Assembly

$\bar{\nu}$ Rate for 3-Core Palo Verde Plant



Detection of $\bar{\nu}_e$

Inverse β Decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



Also possible:

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

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2/m_e^5}{\int_{p.s.}^R \tau_n} E_e^{(0)} P_e^{(0)}$$

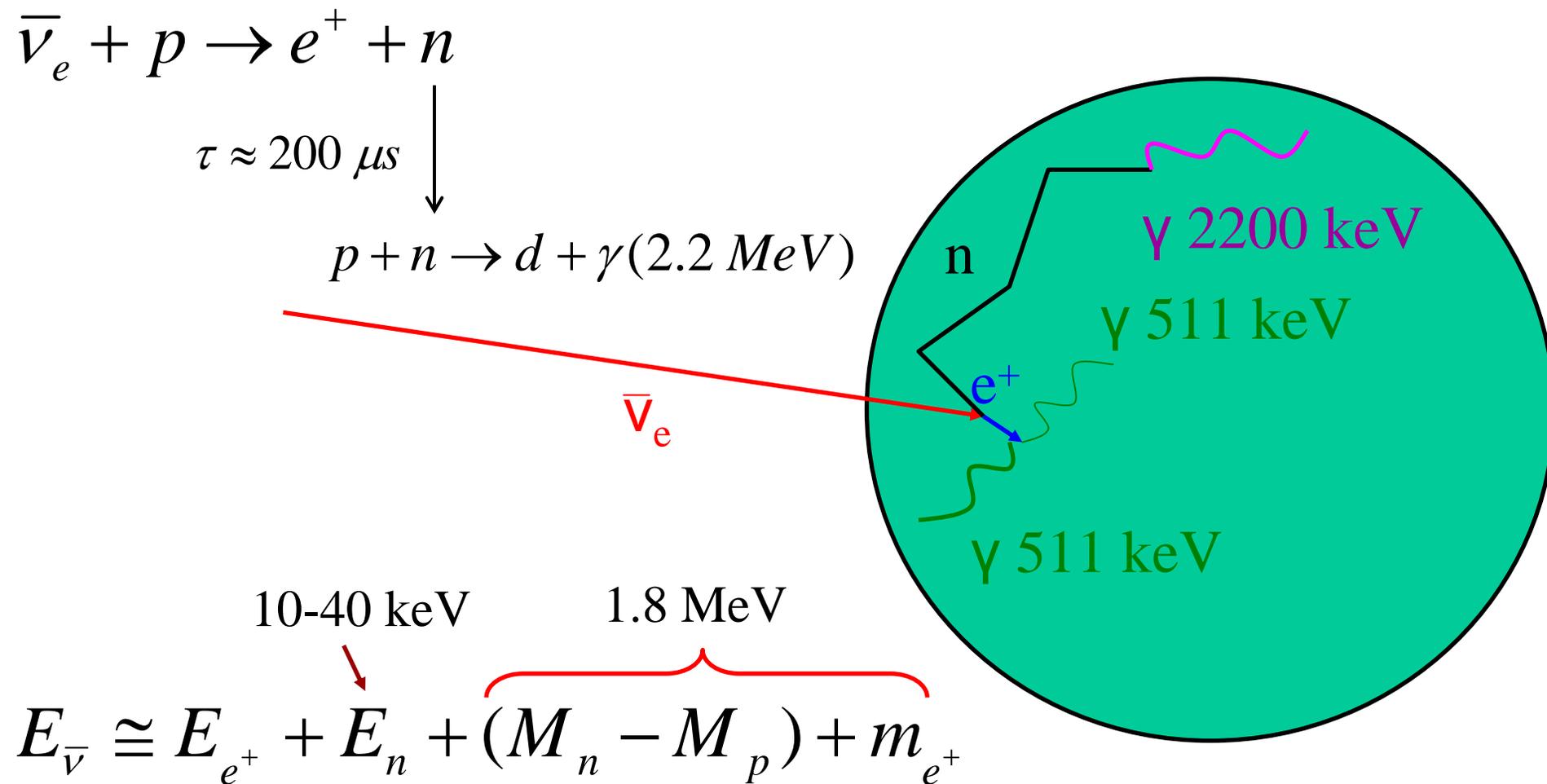
$$E_{th} \sim M_n + m_{e^+} - M_p$$

$$= 1.804 \text{ MeV,}$$

so only $\sim 1.5 \bar{\nu}_e$ / fission
can be detected.

~ 1 event per day per ton of LS per GW thermal at 1 km

Experiments detect coincidence between prompt e^+ and delayed neutron capture on hydrogen (or Cd, Gd, etc.)



Including E from e^+ annihilation, $E_{\text{prompt}} = E_{\bar{\nu}} - 0.8 \text{ MeV}$

The First Detection of the Neutrino
Reines and Cowan, 1956



Clyde Cowan Jr.

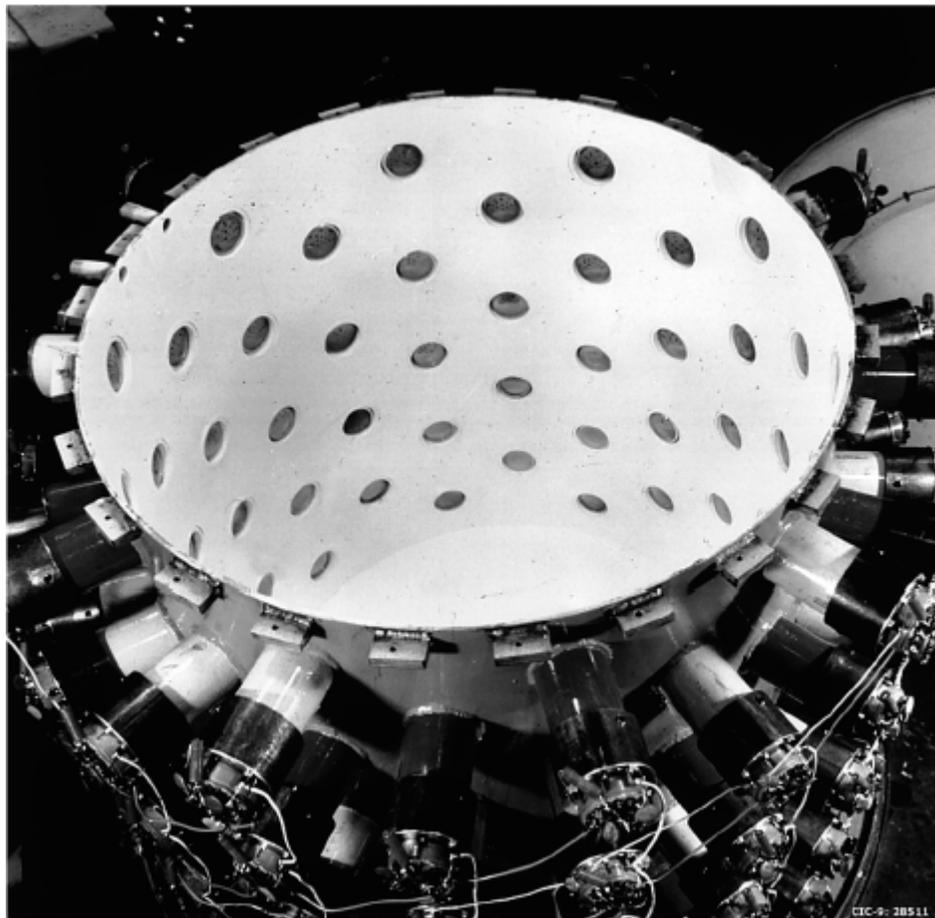


Frederick Reines

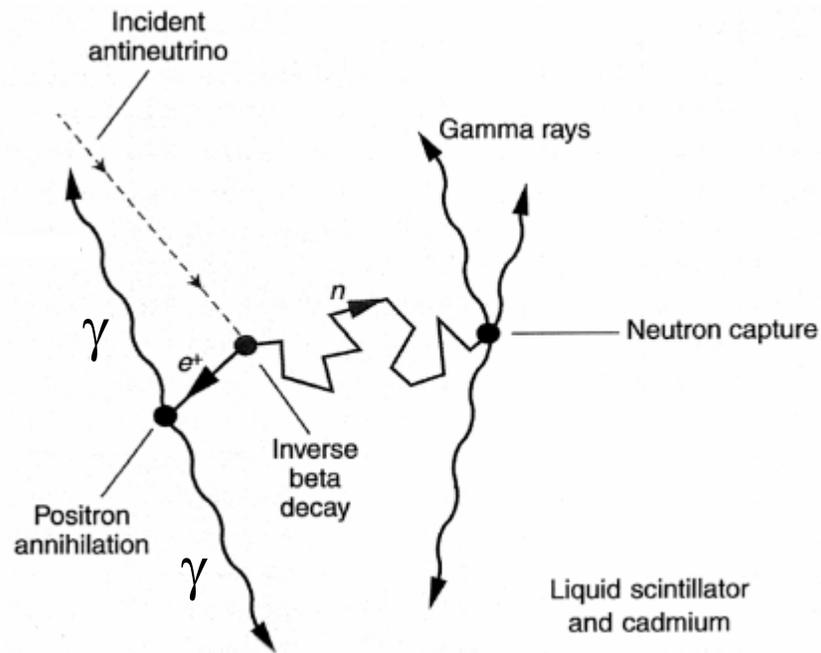
1953 Experiment at Hanford



Detector from Hanford Experiment



300 liters of liquid scintillator
loaded with cadmium



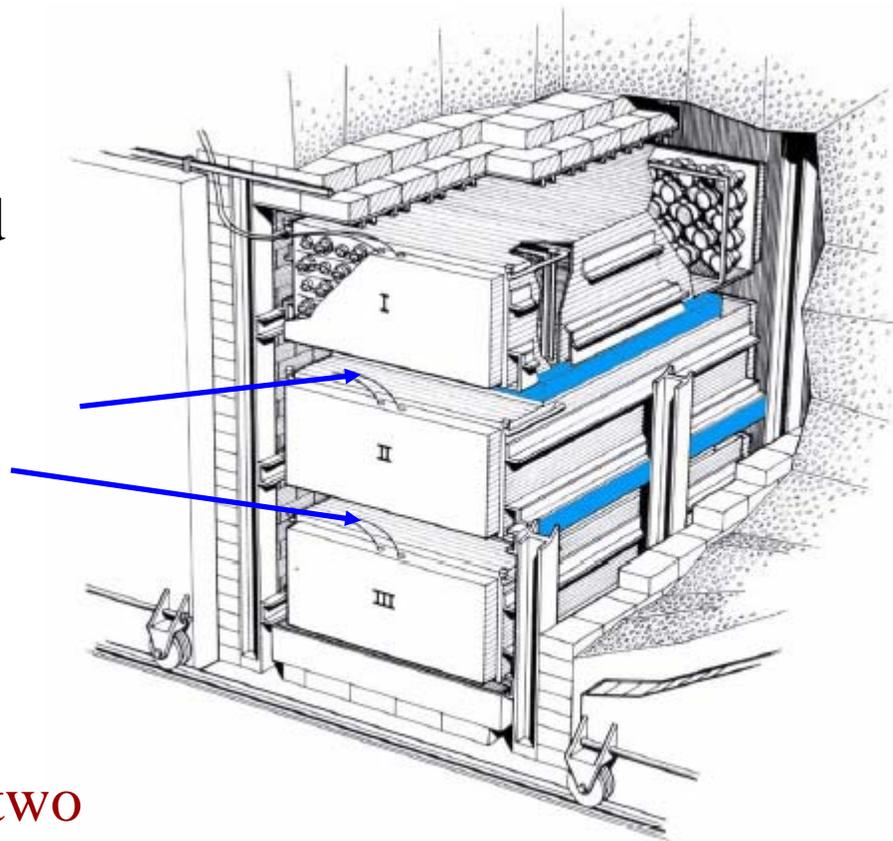
Signal was delayed coincidence
between positron (2-5 MeV) and
neutron capture on cadmium
(2-7 MeV)

High background (S/N~1/20)
made the experiment inconclusive:
 0.41 ± 0.20 events / minute

1956: Savannah River Experiment

Tanks I, II, and III were filled with liquid scintillator and instrumented with 5" PMTs.

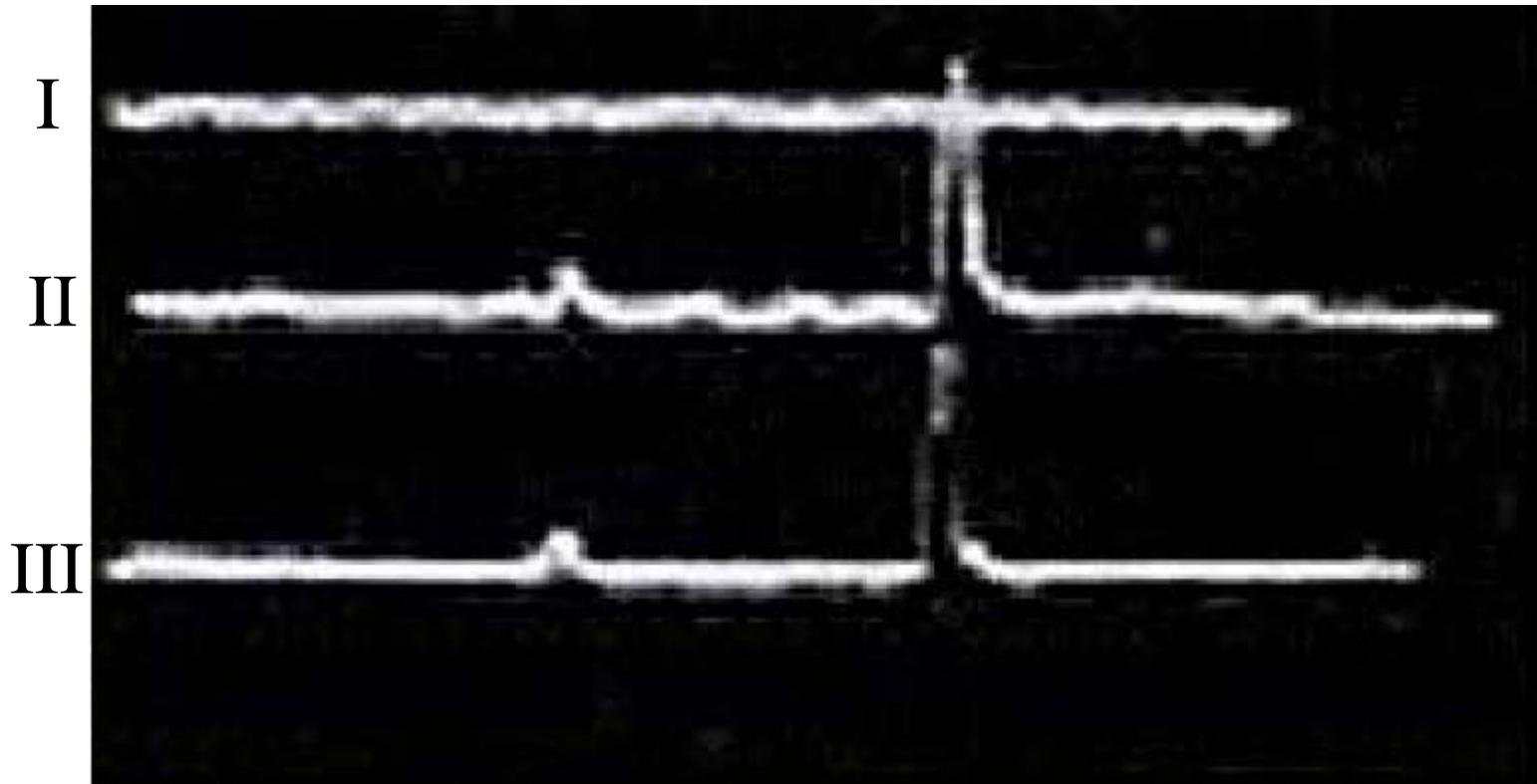
Target tanks (blue) were filled with water+cadmium chloride.

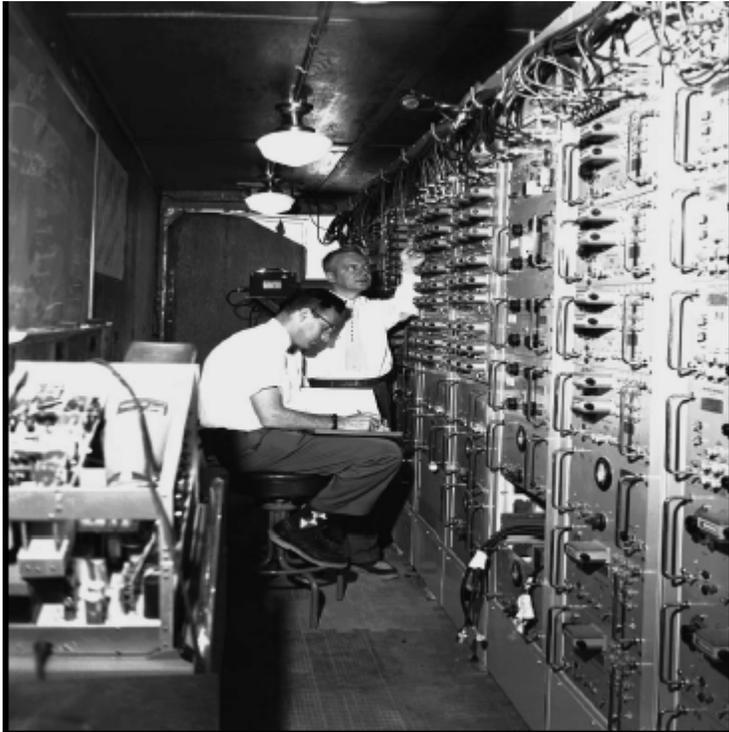


Inverse β decay would produce two signals in neighboring tanks (I,II or II,III):

- prompt signal from e^+ annihilation producing two 0.511 MeV γ s
- delayed signal from n capture on cadmium producing 9 MeV in γ s

Data were recorded photographically from
oscilloscope traces





Electronics trailer

Shielding: 4 ft of soaked sawdust



By April 1956, a reactor-dependent signal had been observed.

Signal / reactor independent background $\sim 3:1$

In June of 1956, they sent a telegram to Pauli:

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.²²

- A Science article reported that the observed cross section was within 5% of the $6.3 \times 10^{-44} \text{ cm}^2$ expected (although the predicted cross section has a 25% uncertainty).
- In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by $\times 2$ to $(10 \pm 1.7) \times 10^{-44} \text{ cm}^2$
- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma = (12^{+7}_{-4}) \times 10^{-44} \text{ cm}^2$

Excellent account of Reines and Cowan experiments:

R. G. Arms, “Detecting the Neutrino”, *Physics in Perspective*, 3, 314 (2001).

Oscillation Experiments with Reactors

Antineutrinos from reactors can be used to study neutrino oscillations with “solar” $\Delta m_{12}^2 \sim 8 \times 10^{-5} \text{ eV}^2$ and “atmospheric” $\Delta m_{13}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2$

➔ Mean antineutrino energy is 3.6 MeV. Therefore, only disappearance experiments are possible.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E},$$

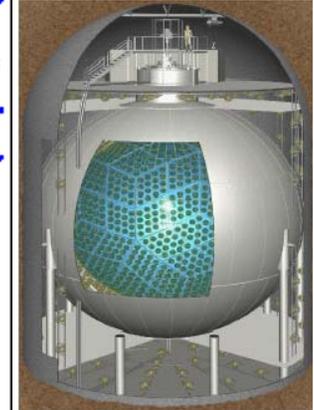
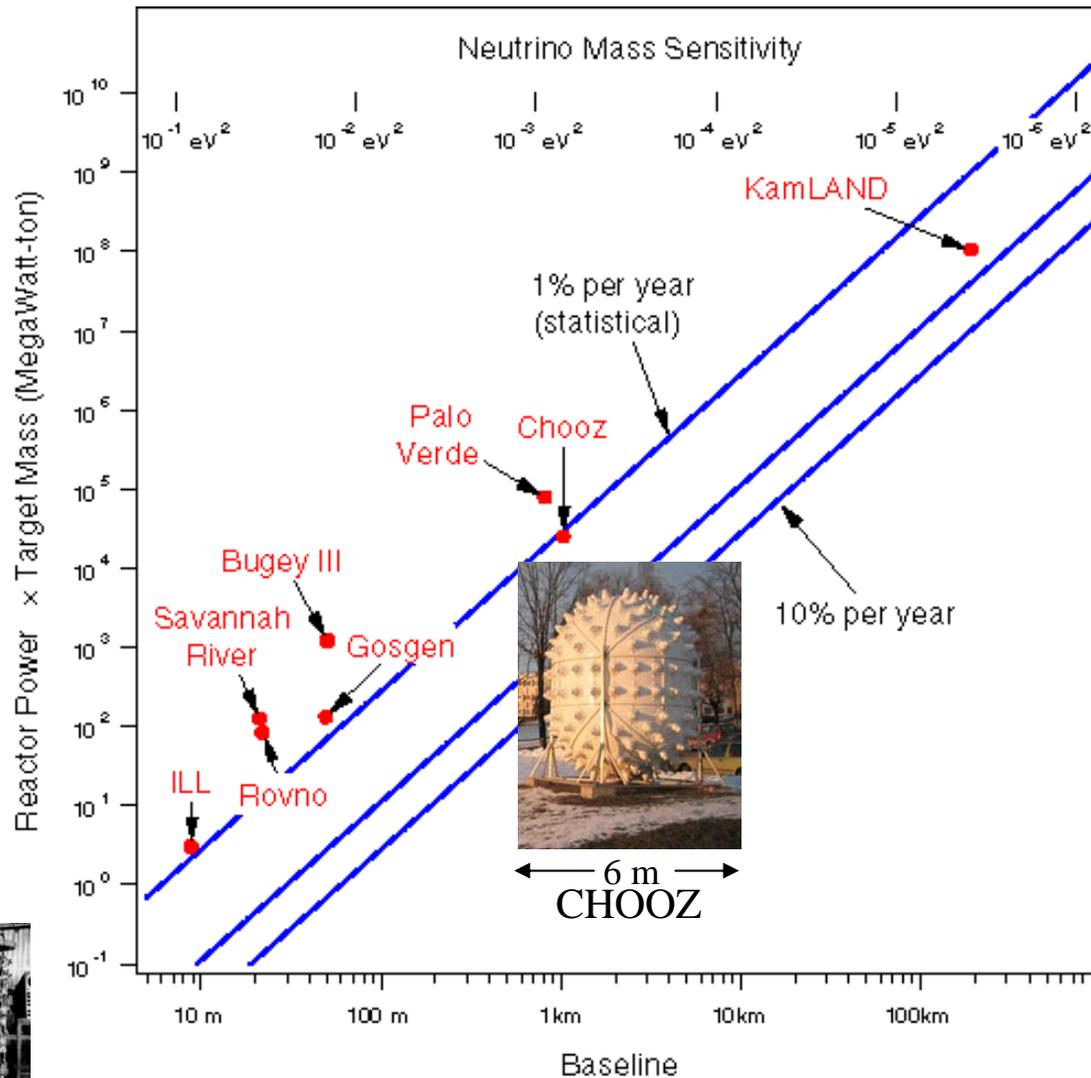
where $\Delta m_{ij}^2 = m_i^2 - m_j^2$.

Experiments look for non- $1/r^2$ behavior of antineutrino rate.

Oscillation maxima for $E_\nu = 3.6 \text{ MeV}$:

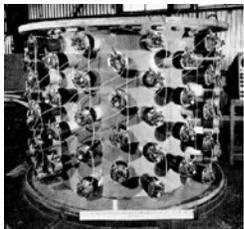
$$\begin{array}{ll} \Delta m_{12}^2 \sim 8 \times 10^{-5} \text{ eV}^2 & \text{➔} \quad L \sim 1.8 \text{ km} \\ \Delta m_{13}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2 & \text{➔} \quad L \sim 60 \text{ km} \end{array}$$

Long history of neutrino experiments at reactors



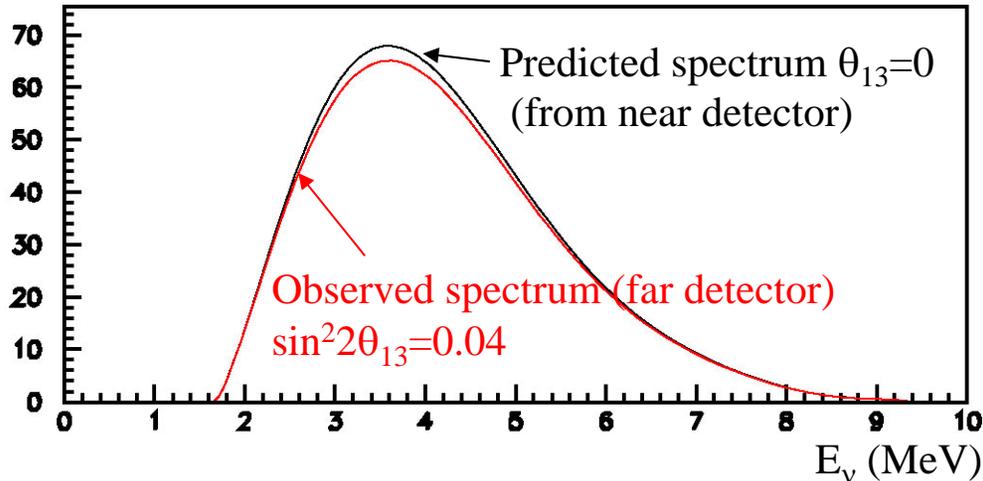
20 m

KamLAND



1 m
Poltergeist

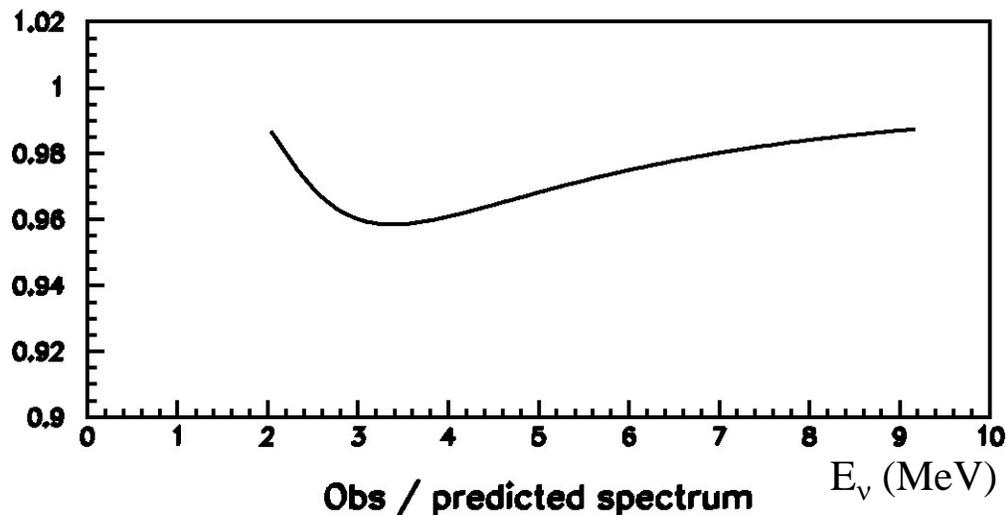
Normalization and spectral information



Counting analysis: Compare number of events in near and far detector

Systematic uncertainties:

- relative normalization of near and far detectors
- relatively insensitive to energy calibration



Energy spectrum analysis: Compare energy distribution in near and far detectors

Systematic uncertainties:

- energy scale and linearity
- insensitive to relative efficiency of detectors

Issues affecting oscillation experiments

- Knowledge of antineutrino flux and spectrum
- Detector acceptance
- Backgrounds:
 - Uncorrelated backgrounds from random coincidences
 - Reduced by limiting radioactive materials
 - Directly measured from rates and random trigger setups
 - Correlated backgrounds
 - Neutrons that mimic the coincidence signal
 - Cosmogenically produced isotopes that decay to a beta and neutron: ${}^9\text{Li}$ ($\tau_{1/2}=178$ ms) and ${}^8\text{He}$ ($\tau_{1/2}=119$ ms); associated with showering muons.
 - Reduced by shielding and veto systems

In absence of a direct measurement, how well can antineutrino rate and flux be determined from reactor power?

Recall that $> 99.9\%$ of $\bar{\nu}$ are produced by fissions in ^{235}U , ^{239}Pu , ^{238}U , ^{241}Pu (90% from first two).

Use direct measurements of electron spectrum from a thin layer of fissile material in a beam of thermal neutrons

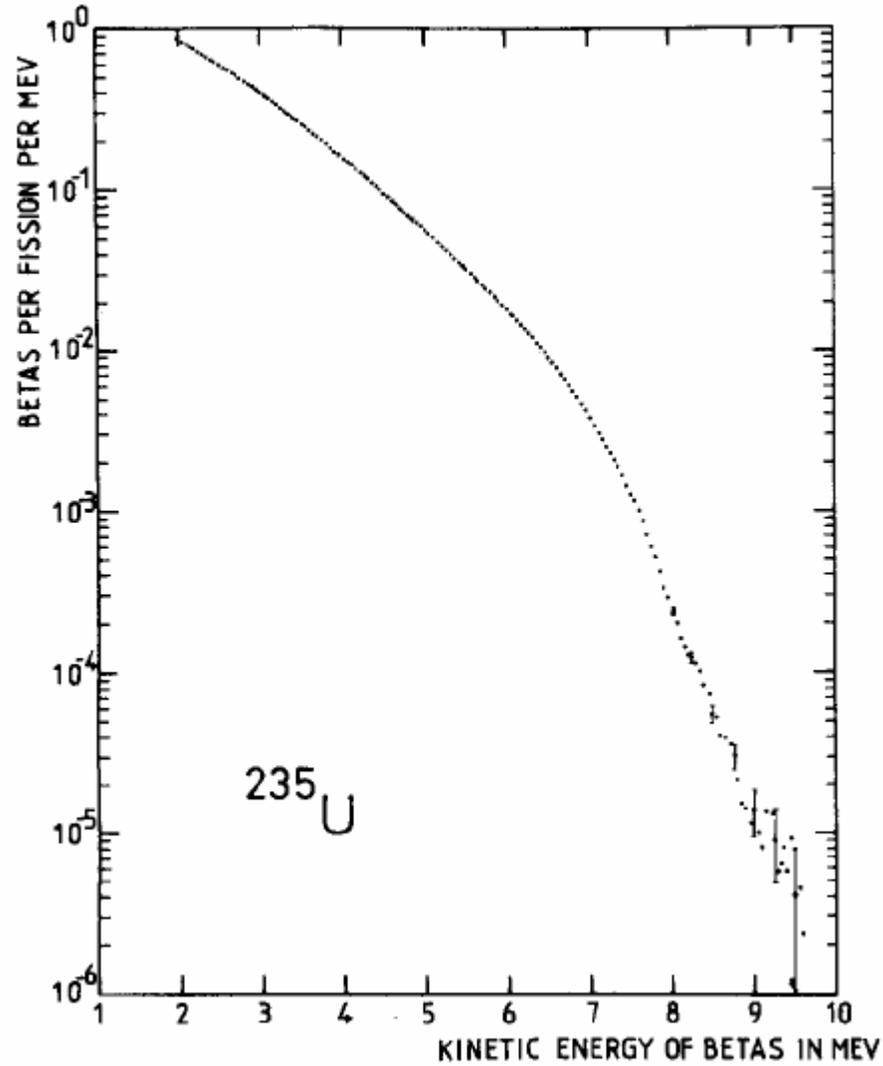
A. Schreckenbach et al. Phys. Lett B 160, **325** (1985); A. Hahn et al., Phys. Lett. B **218**, 365 (1989).

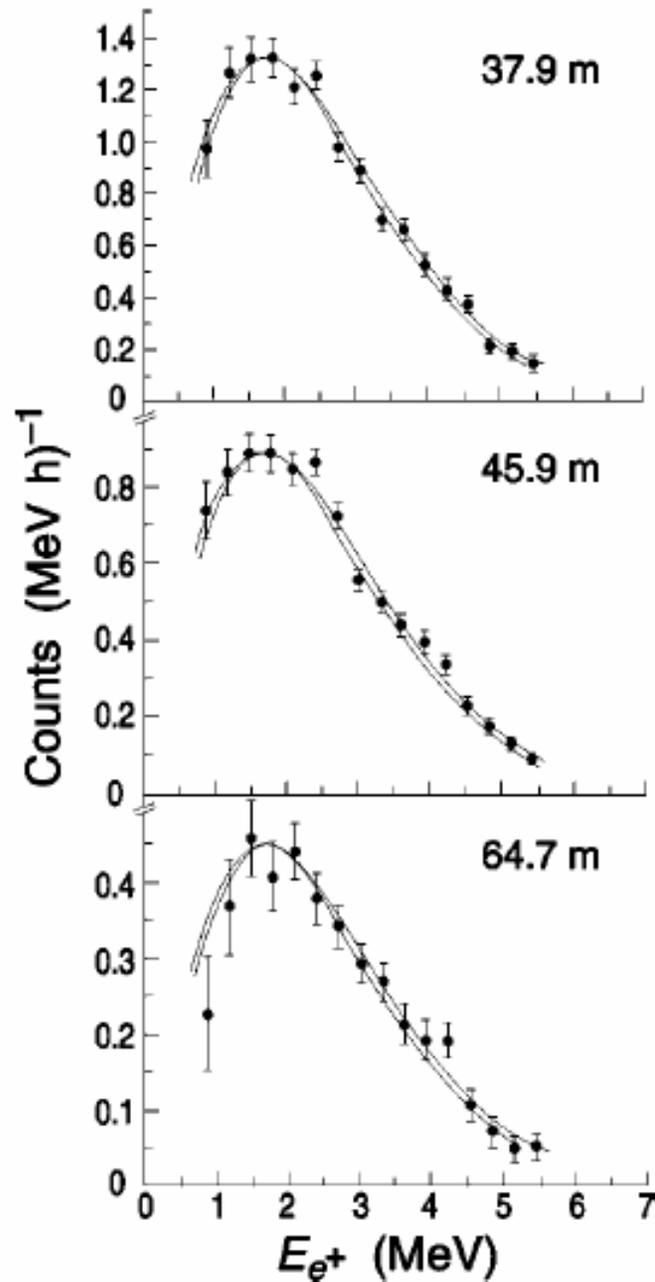
Must rely on calculation for ^{238}U .

→ Total flux uncertainty is about 2-3%.

Uncertainty can be checked with short-baseline experiments (Gösgen, Bugey)

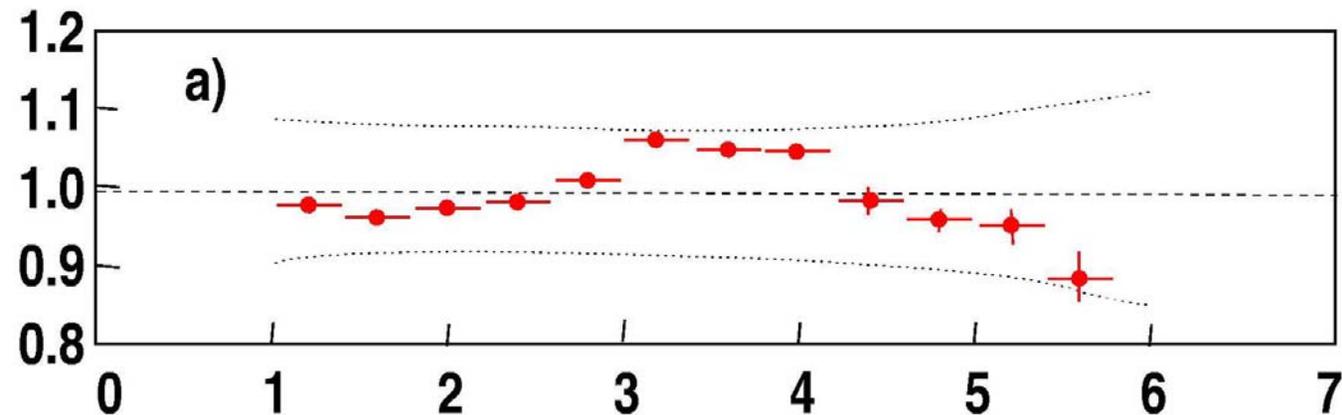
β Spectrum for ^{235}U Fission Products



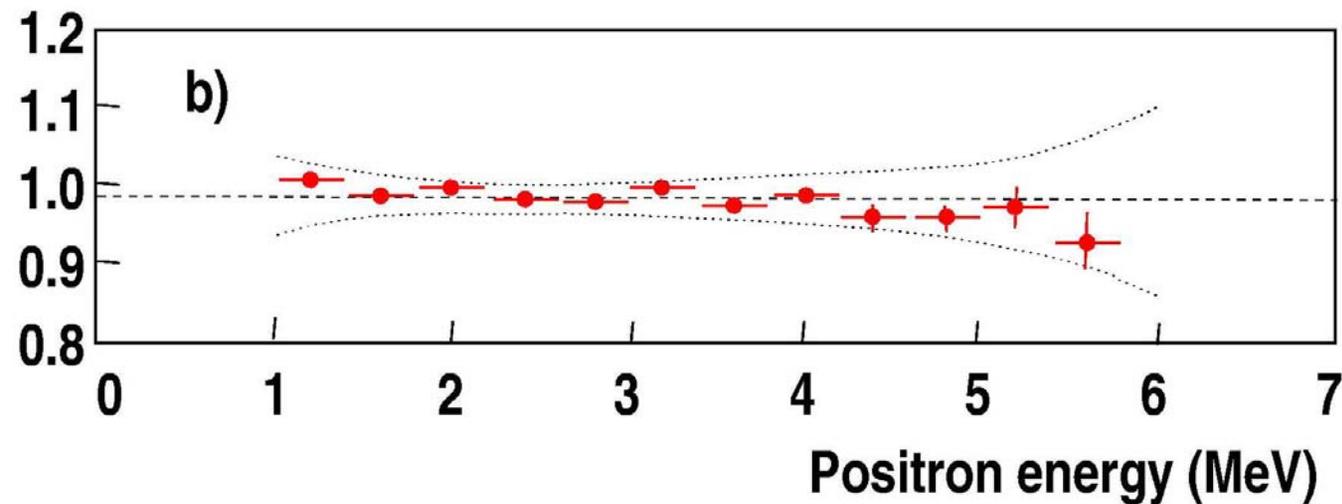


Positron Spectra from Gösgen Experiment

The two curves are from fits to data and from predictions based on *Schreckenbach et al.*



Bugey3/"first
principle calculation"

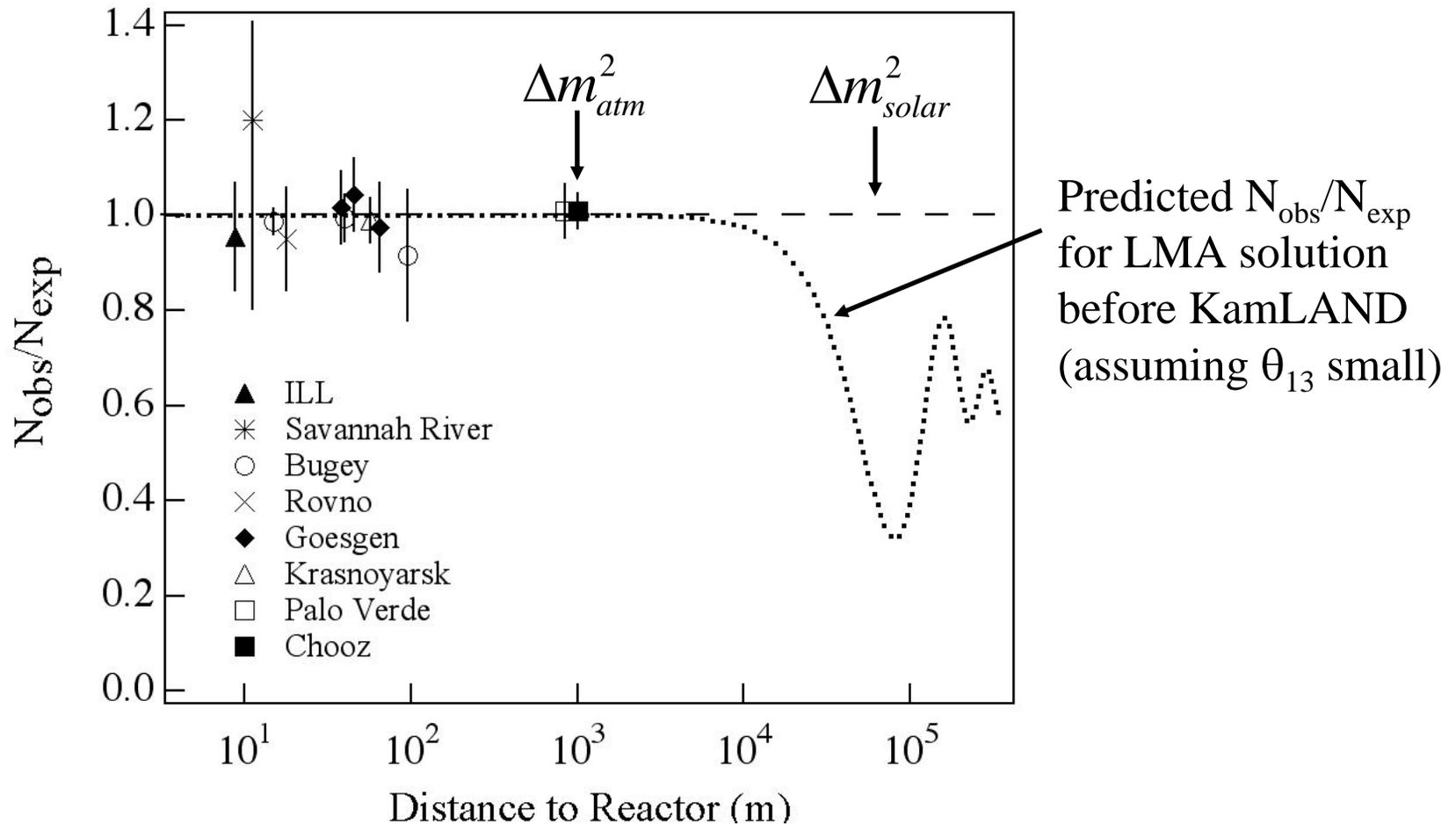


Bugey3/"best
prediction" (*uses
 β^- spectra where
possible and
calculation for ^{238}U*)

Solar Δm^2 : The KamLAND Experiment

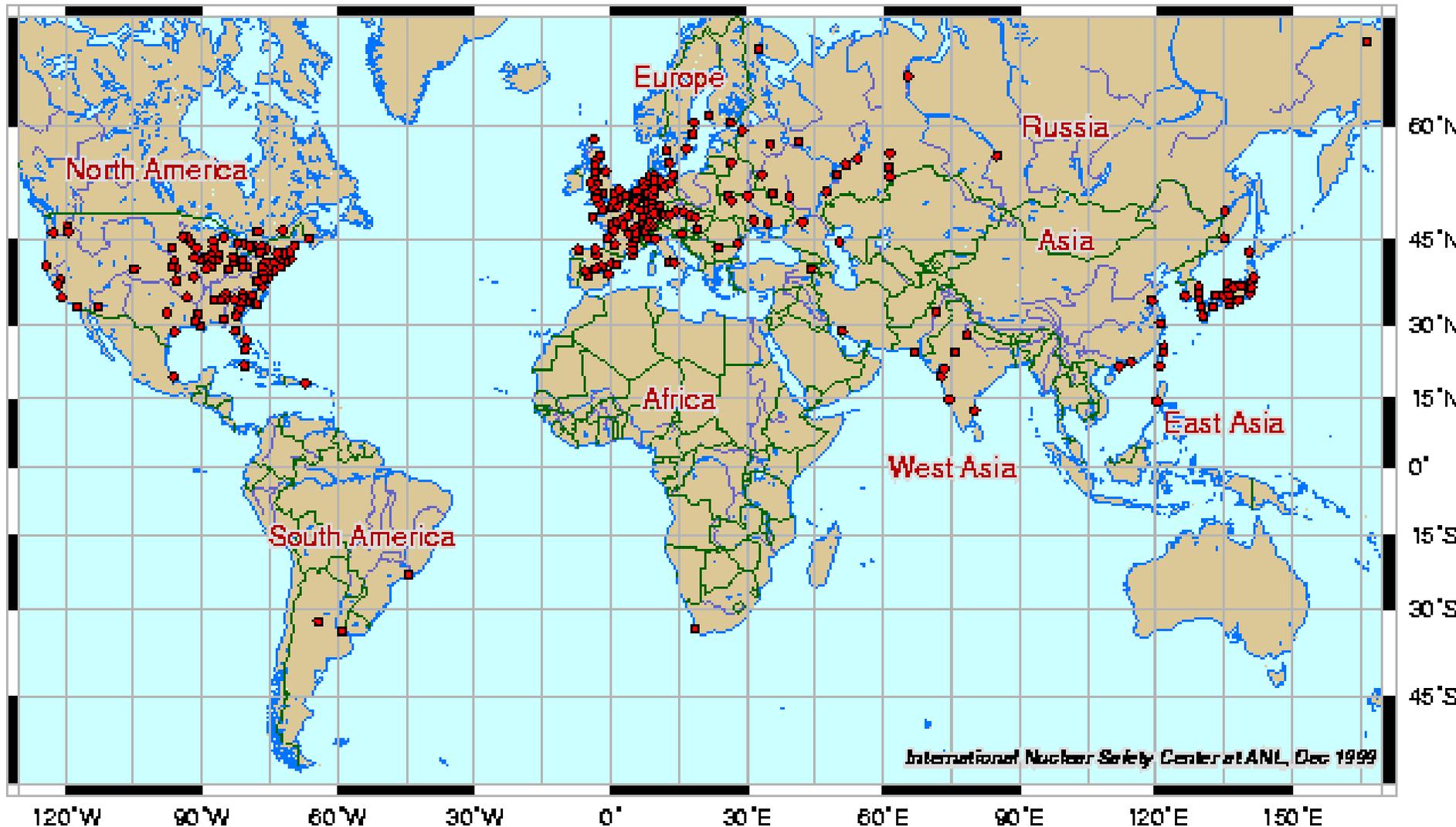
Goal: Study oscillations at $\Delta m^2_{\text{solar}} \sim 8 \times 10^{-5} \text{ eV}^2$ using nuclear reactors.

Observed / expected flux for reactor experiments

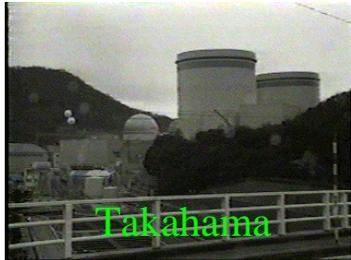


~100 km baseline requires very large detector and very large ν source (and very deep experimental site).

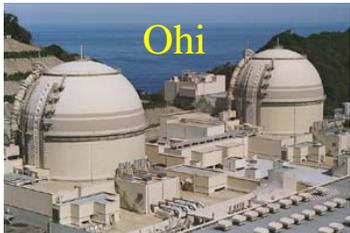
Large concentrations of reactors in U.S., Europe, and Japan.



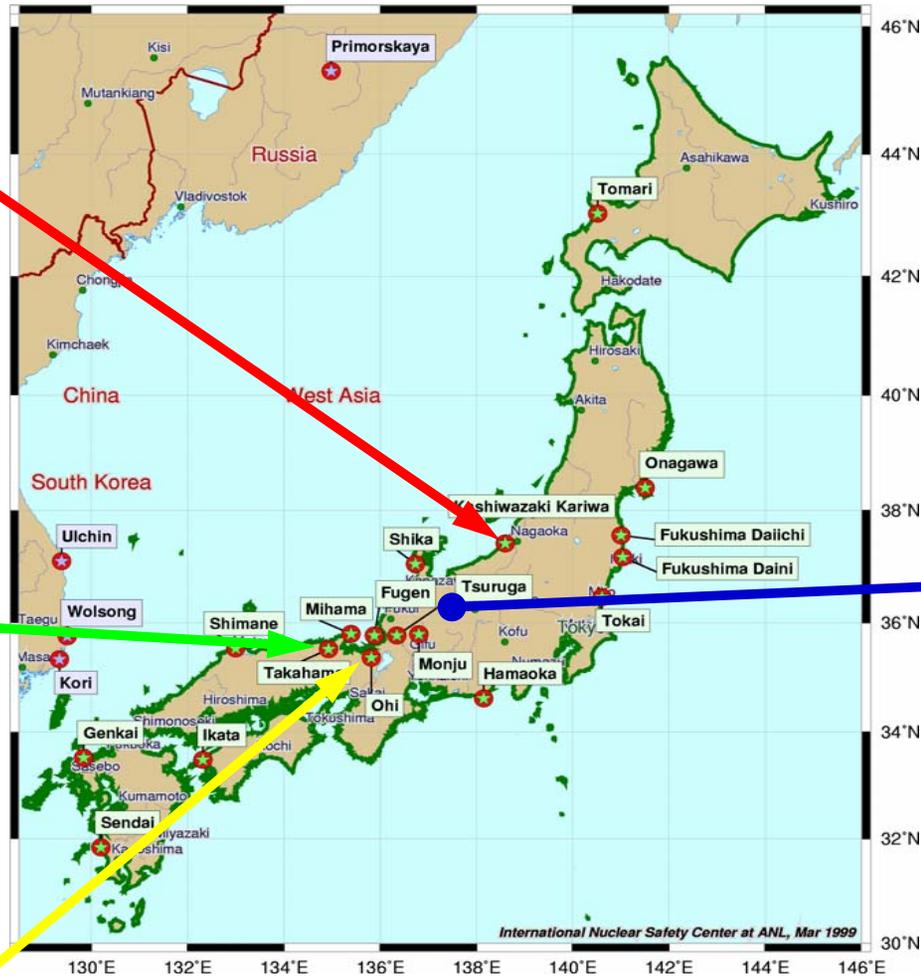
Kashiwazaki



Takahama



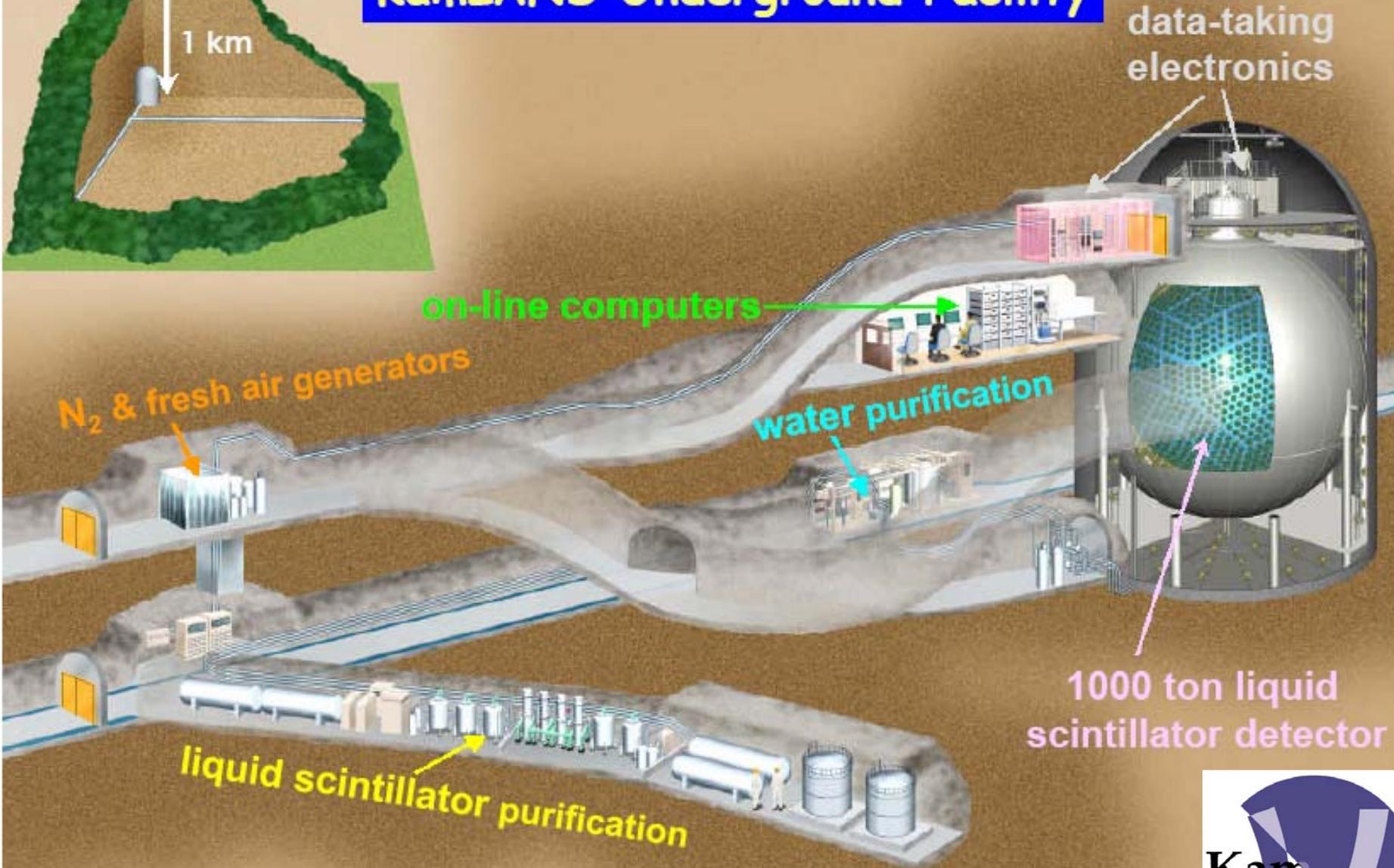
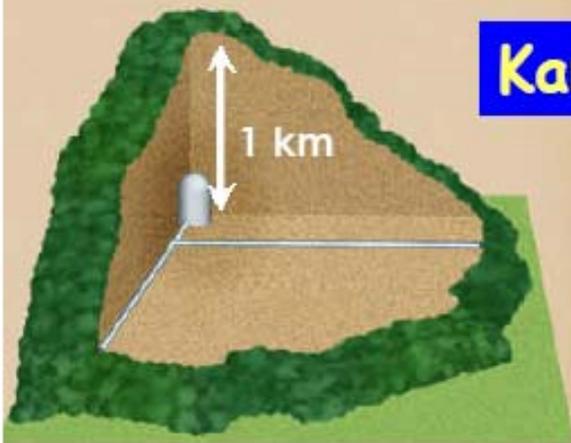
Ohi



KamLAND uses the entire Japanese nuclear power industry as a long-baseline source

KamLAND

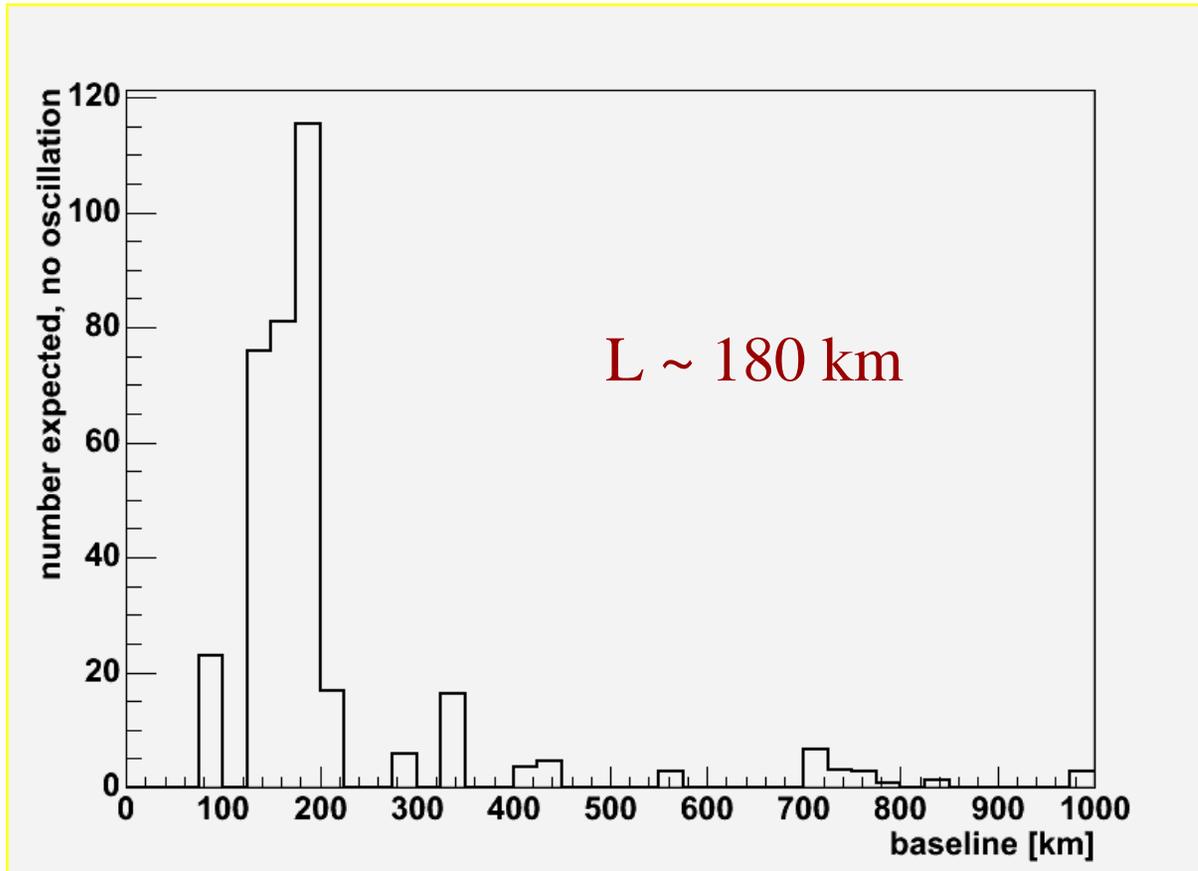
KamLAND Underground Facility



Reactors contributing to antineutrino flux at KAMLAND

	Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($\text{cm}^{-2} \text{s}^{-1}$)	Rate noosc* ($\text{yr}^{-1} \text{kt}^{-1}$)
Japan	Kashiwazaki	160	7	24.3	$4.1 \cdot 10^5$	254.0
	Ohi	179	4	13.7	$1.9 \cdot 10^5$	114.3
	Takahama	191	4	10.2	$1.2 \cdot 10^5$	74.3
	Tsuruga	138	2	4.5	$1.0 \cdot 10^5$	62.5
	Hamaoka	214	4	10.6	$1.0 \cdot 10^5$	62.0
	Mihama	146	3	4.9	$1.0 \cdot 10^5$	62.0
	Sika	88	1	1.6	$9.0 \cdot 10^4$	55.2
	Fukushima1	349	6	14.2	$5.1 \cdot 10^4$	31.1
	Fukushima2	345	4	13.2	$4.8 \cdot 10^4$	29.5
	Tokai2	295	1	3.3	$1.6 \cdot 10^4$	10.1
	Onagawa	431	3	6.5	$1.5 \cdot 10^4$	9.3
	Simane	401	2	3.8	$1.0 \cdot 10^4$	6.3
	Ikata	561	3	6.0	$8.3 \cdot 10^3$	5.1
	Genkai	755	4	10.1	$7.8 \cdot 10^3$	4.8
Sendai	830	2	5.3	$3.4 \cdot 10^3$	2.1	
Tomari	783	2	3.3	$2.3 \cdot 10^3$	1.4	
South Korea	Ulchin	712	4	11.5	$9.9 \cdot 10^3$	6.1
	Yonggwang	986	6	17.4	$7.8 \cdot 10^3$	4.8
	Kori	735	4	9.2	$7.5 \cdot 10^3$	4.6
	Wolsong	709	4	8.2	$7.1 \cdot 10^3$	4.3
Total Nominal		-	70	181.7	$1.3 \cdot 10^6$	803.8

A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka

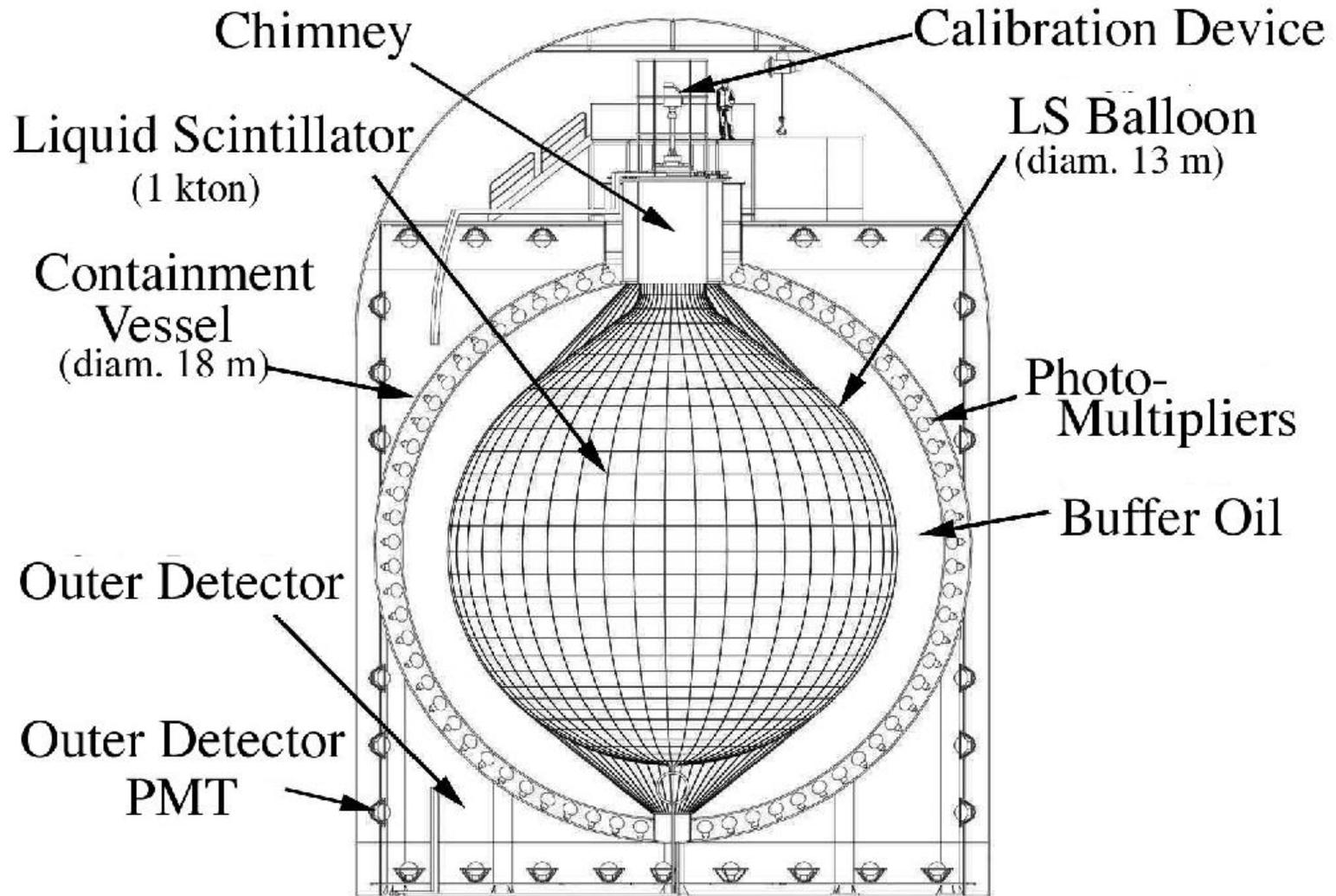


Korean reactors:
 $3.4 \pm 0.3\%$

Rest of the world
+JP research reactors:
 $1.1 \pm 0.5\%$

Japanese spent fuel:
 $0.04 \pm 0.02\%$

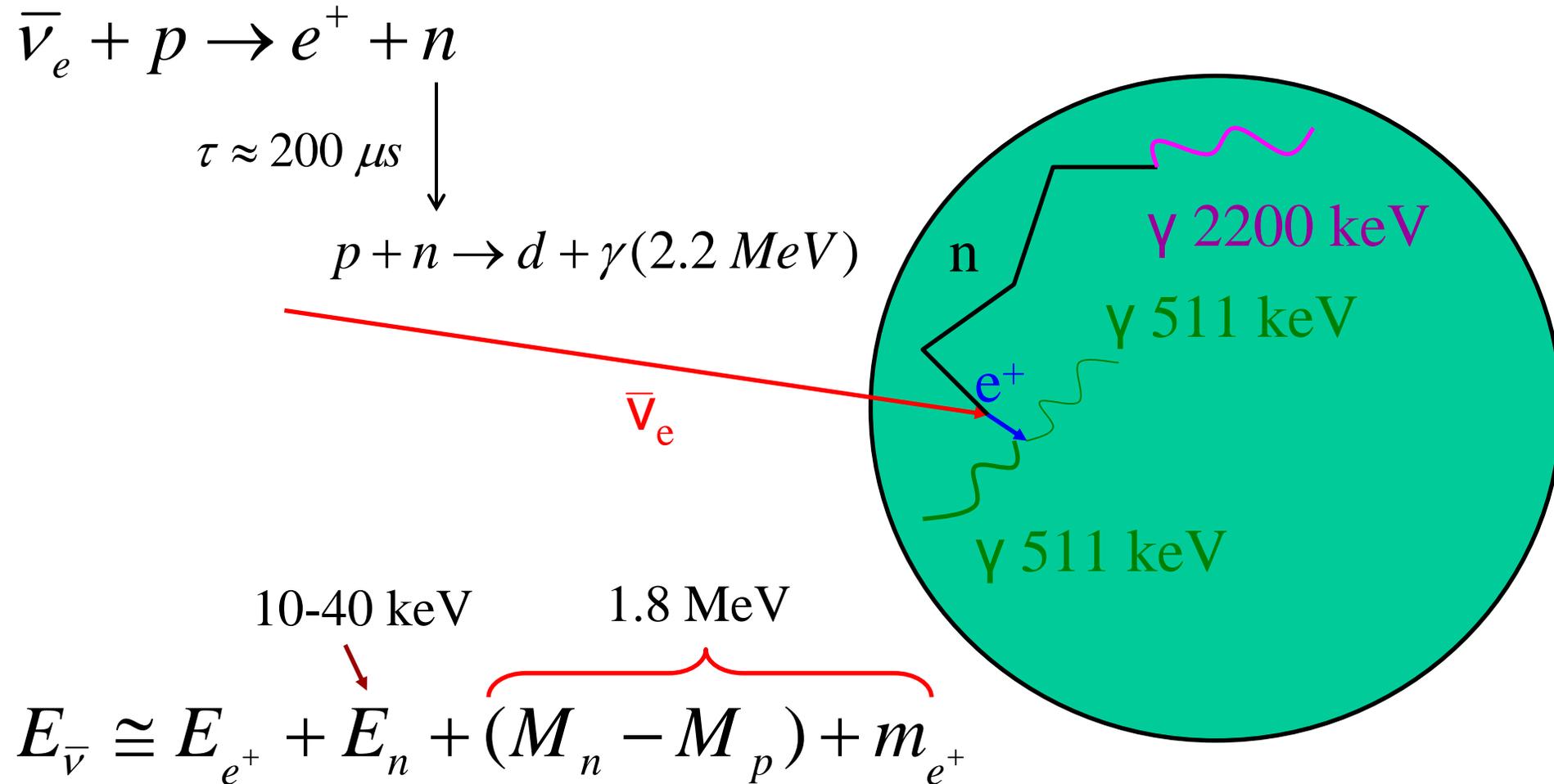
KAMLAND Detector



Looking up at containment vessel

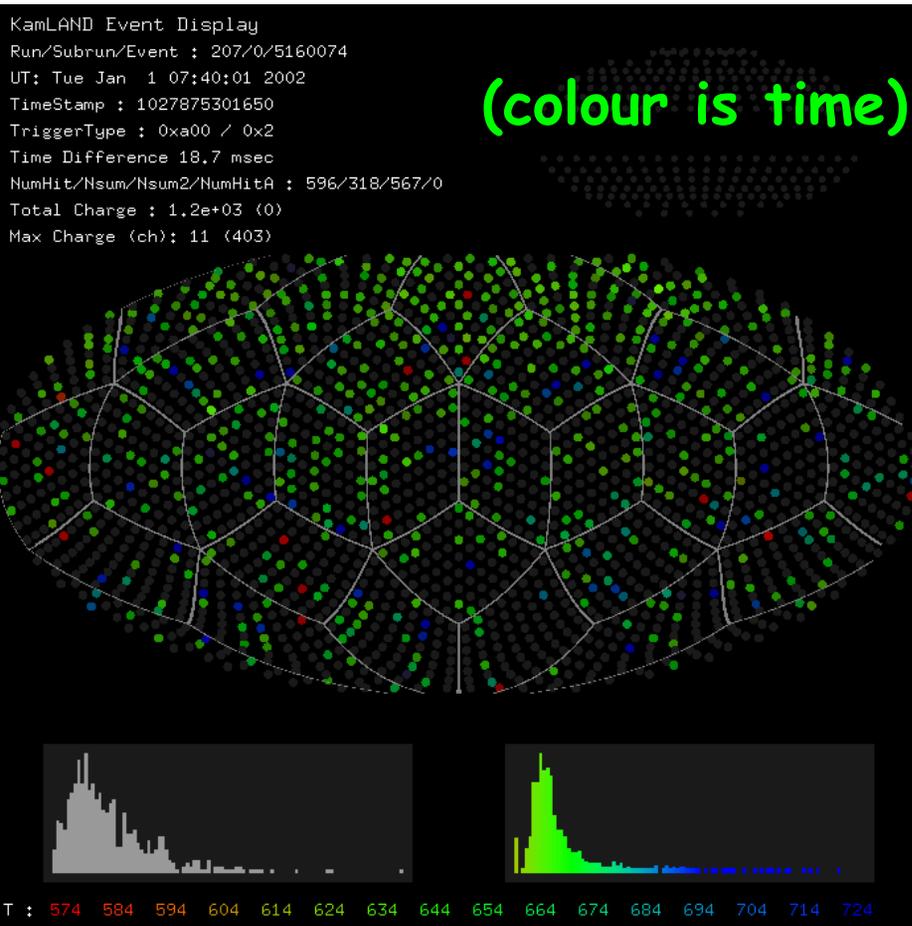


Antineutrino signature: coincidence between prompt e^+ and delayed neutron capture on hydrogen



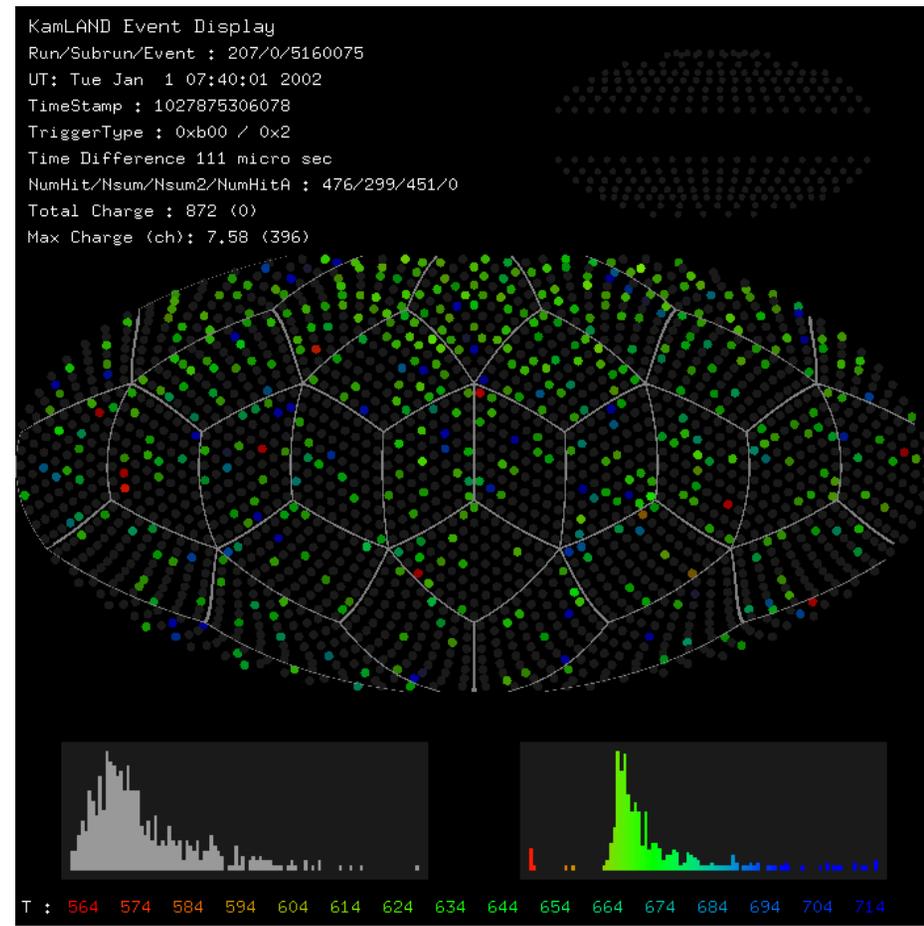
Including E from e^+ annihilation, $E_{\text{prompt}} = E_{\bar{\nu}} - 0.8 \text{ MeV}$

Anti-Neutrino Candidate



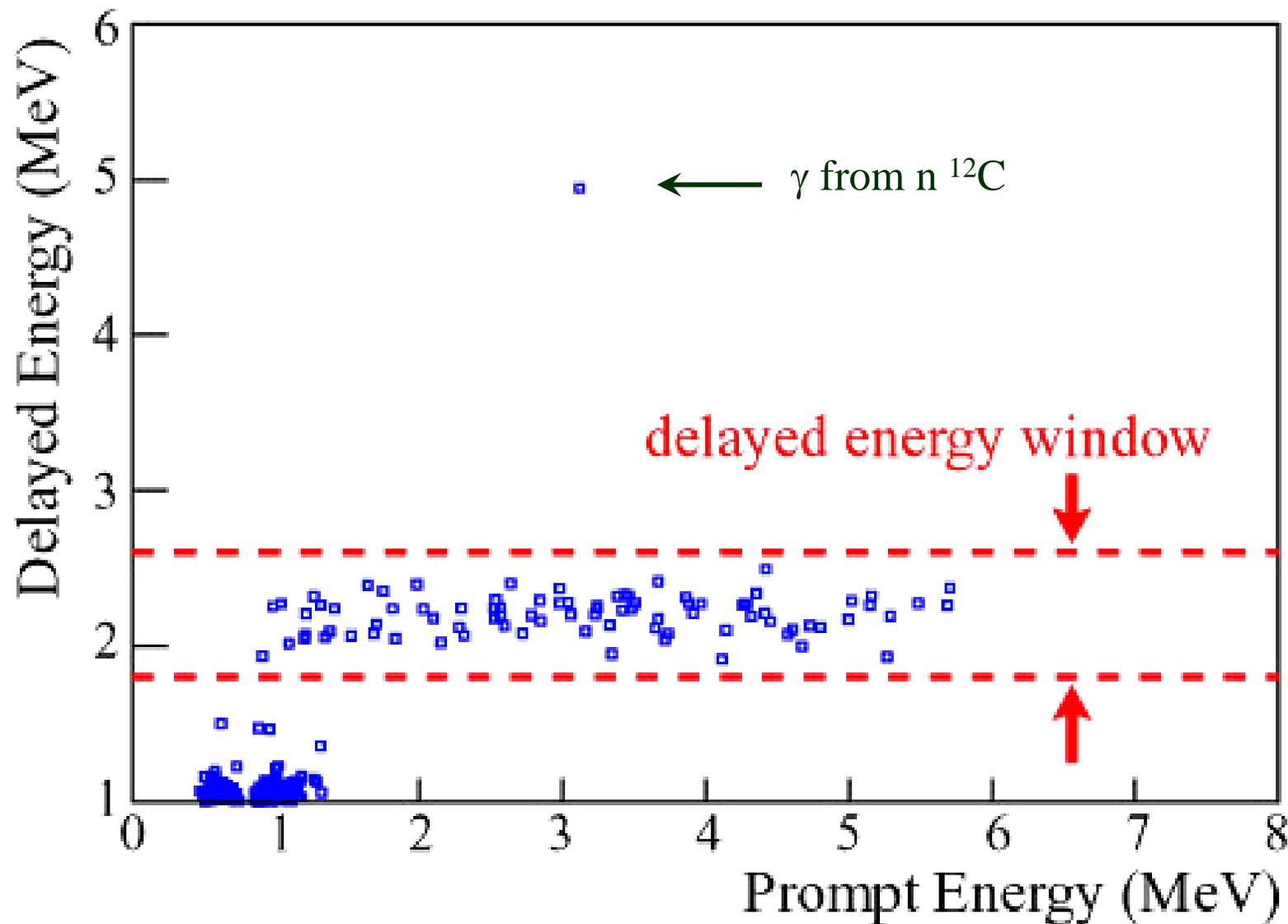
Prompt Signal
 $E = 3.20 \text{ MeV}$

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

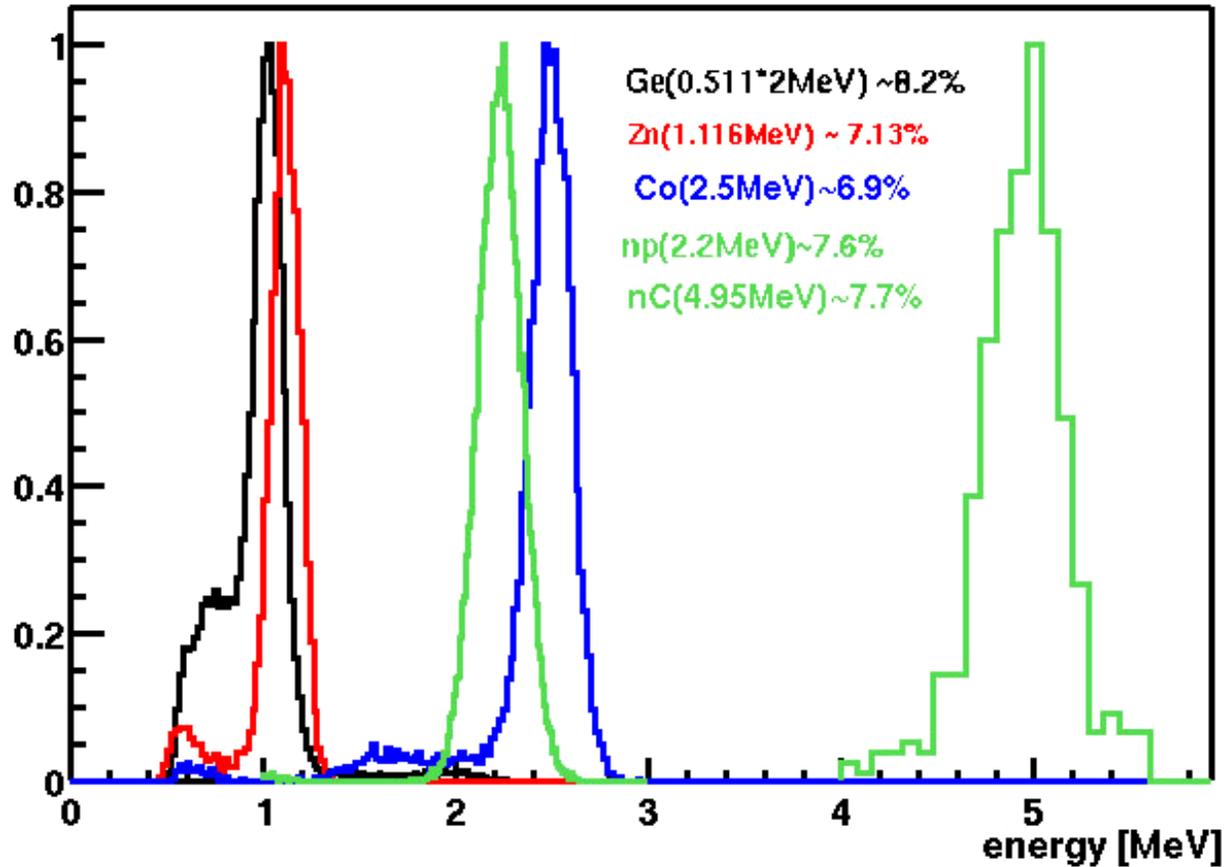


Delayed Signal
 $E = 2.22 \text{ MeV}$

Delayed vs. Prompt Energy for $\bar{\nu}_e$ Candidates

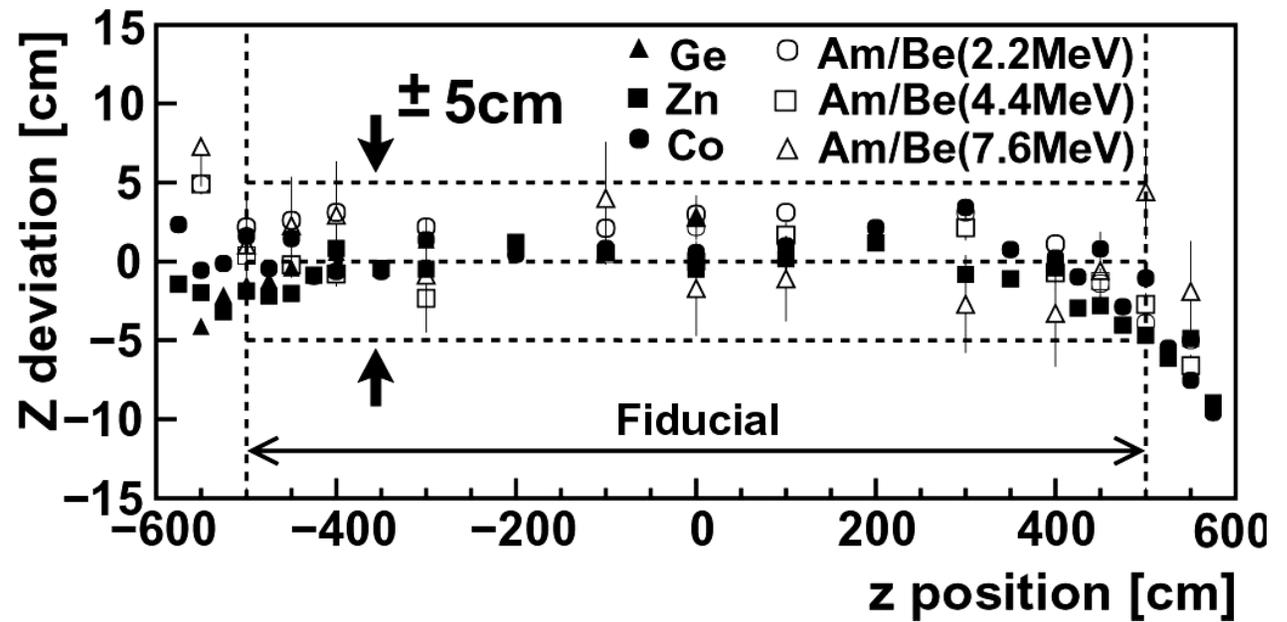
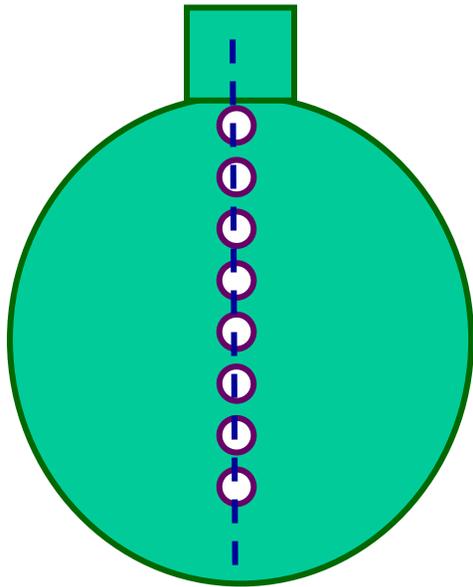


Energy Calibration with Sources

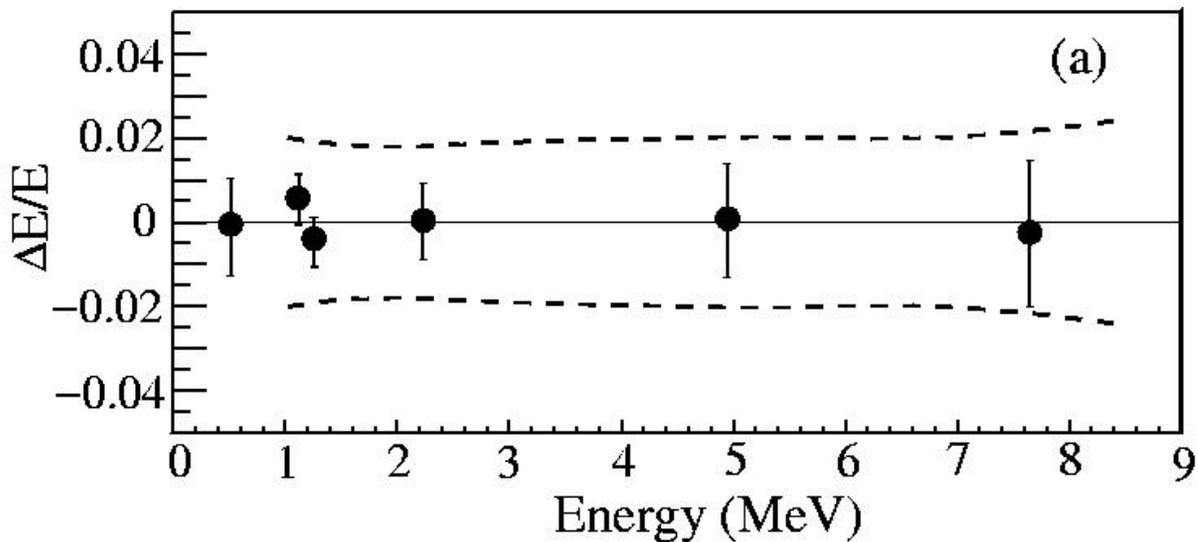


$\Delta E/E \sim 7.5\% / \sqrt{E}$, Light Yield: 260 p.e./MeV

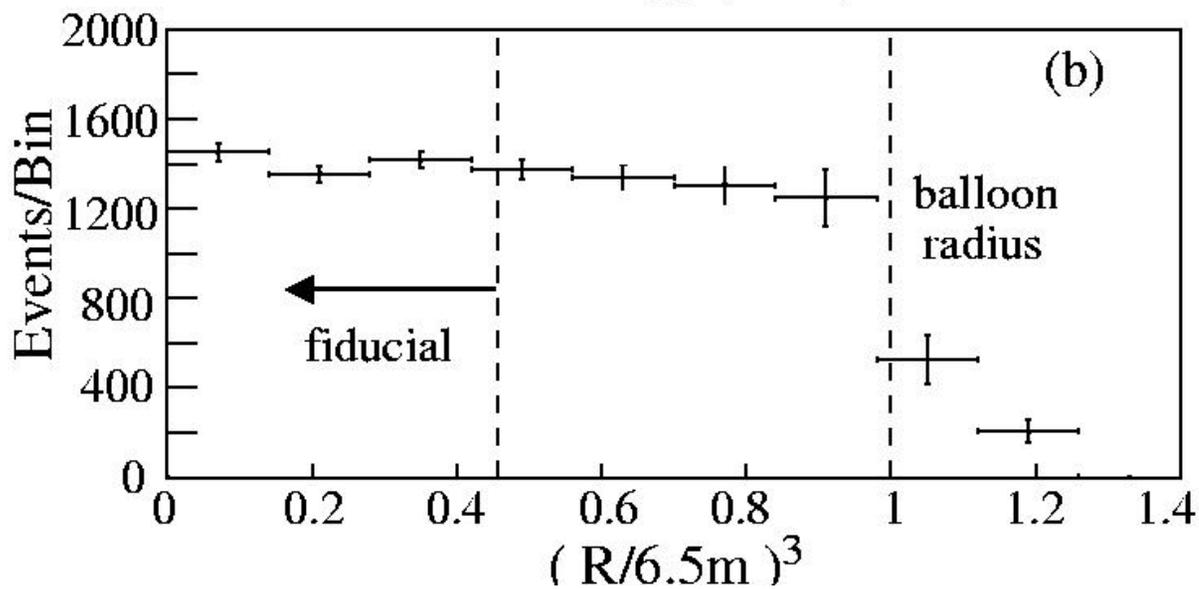
Test of Position Reconstruction Along Vertical Axis



Detector Performance



$$\sigma_E \sim 7.5\% / \sqrt{E(\text{MeV})}$$



$$\sigma_R \sim 20 \text{ cm}$$

Event Selection Requirements

- Fiducial volume: $R < 5$ m
- Time correlation: $0.5 \mu\text{sec} < \Delta t < 660 \mu\text{sec}$
- Vertex correlation: $\Delta R < 1.6$ m
- Delayed energy: $1.8 \text{ MeV} < E_{\text{delay}} < 2.6 \text{ MeV}$
- Prompt energy: $E_{\text{prompt}} > 2.6 \text{ MeV}$
- Muon veto: 2 msec veto after any muon
 - + 2-sec veto following a showering muon
 - + reject events within 2 sec and 3 m of muon tracks

Estimated Systematic Uncertainties

	%
Total LS mass	2.1
Fiducial mass ratio	4.1
Energy threshold	2.1
Selection cuts	2.1
Live time	0.07
Reactor power	2.0
Fuel composition	1.0
Time lag	0.28
$\bar{\nu}_e$ spectra	2.5
Cross section	0.2

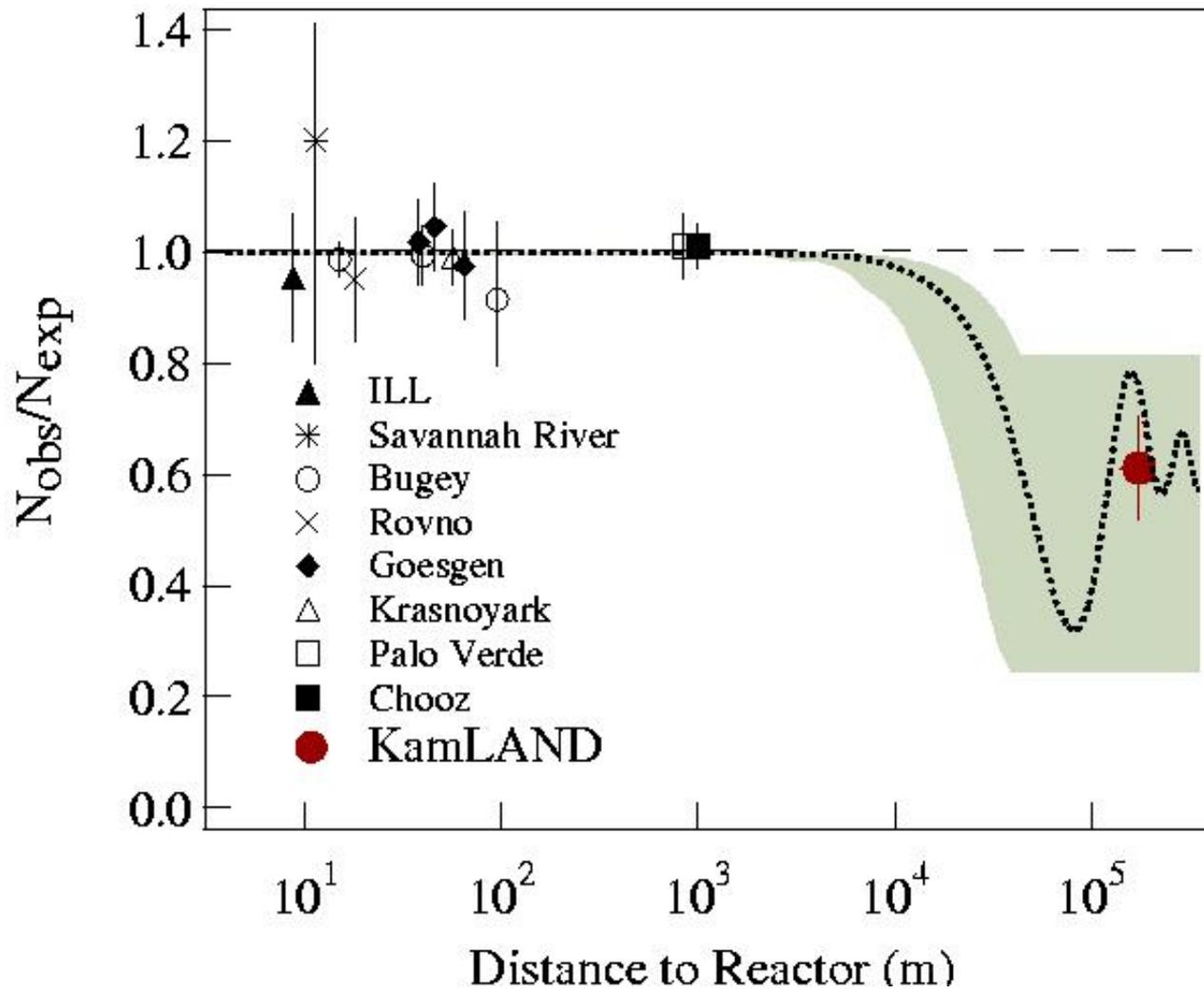
Total systematic error	6.4 %
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Observed Event Rates with $E_{prompt} > 2.6 \text{ MeV}$
 (Data collected from March--October 2002)

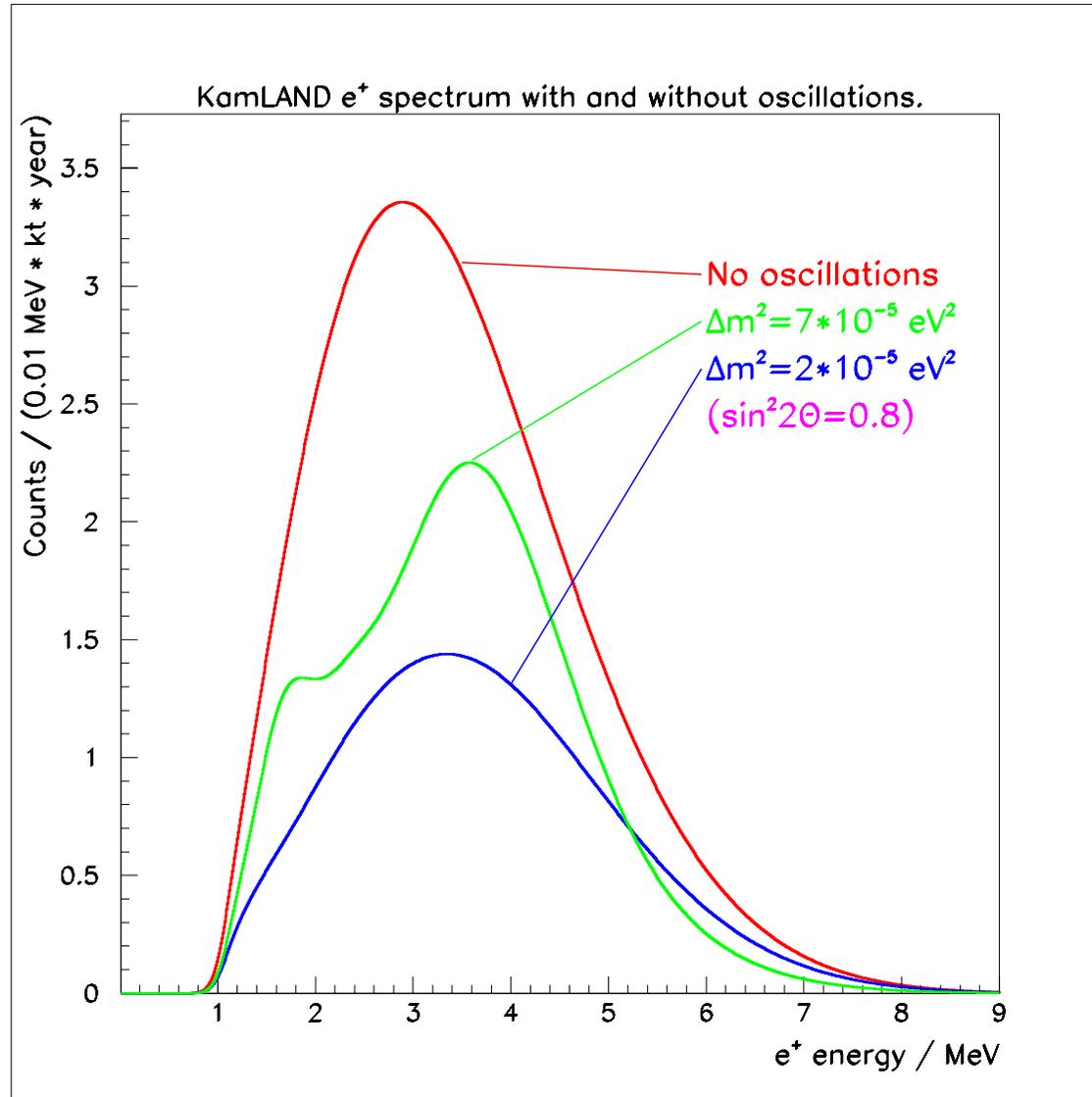
Observed	54 events
Expected	86.8 ± 5.6 events
Total Background	1 ± 1 events
<hr/>	
<i>accidental</i>	0.0086 ± 0.0005
${}^9\text{Li}/{}^8\text{He}$	0.94 ± 0.85
<i>fast neutron</i>	< 0.5
<hr/>	

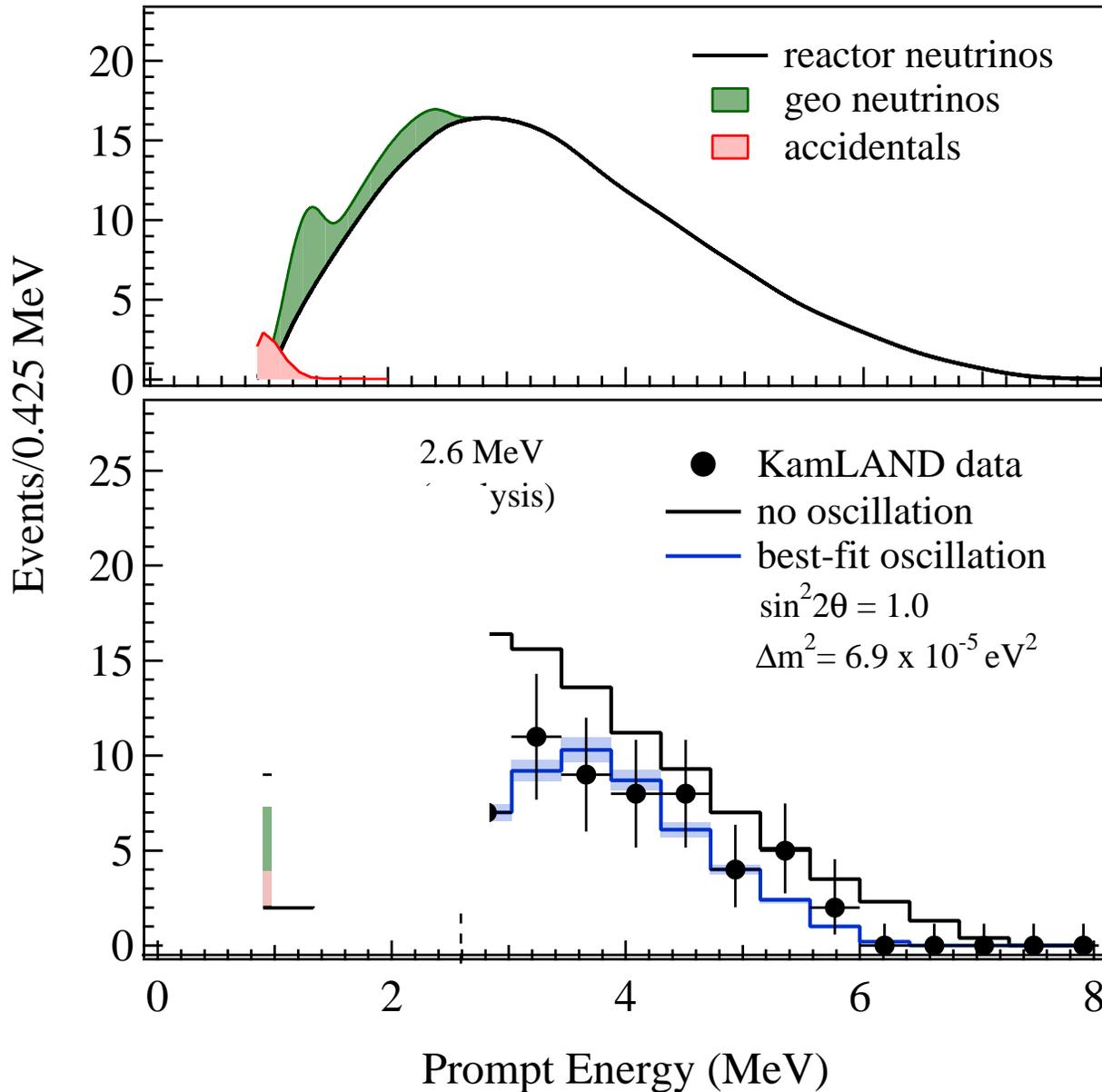
➡ Inconsistent with $1/R^2$ flux dependence at 99.95 % c.l.

$$\frac{N_{obs} - N_{bckg}}{N_{expected}} = 0.611 \pm 0.085(stat) \pm 0.041(syst)$$



Oscillation Effect in Rate and Energy Spectrum





Energy spectrum consistent with oscillations at 93% c.l., but also consistent with no oscillation shape at 53% c.l.

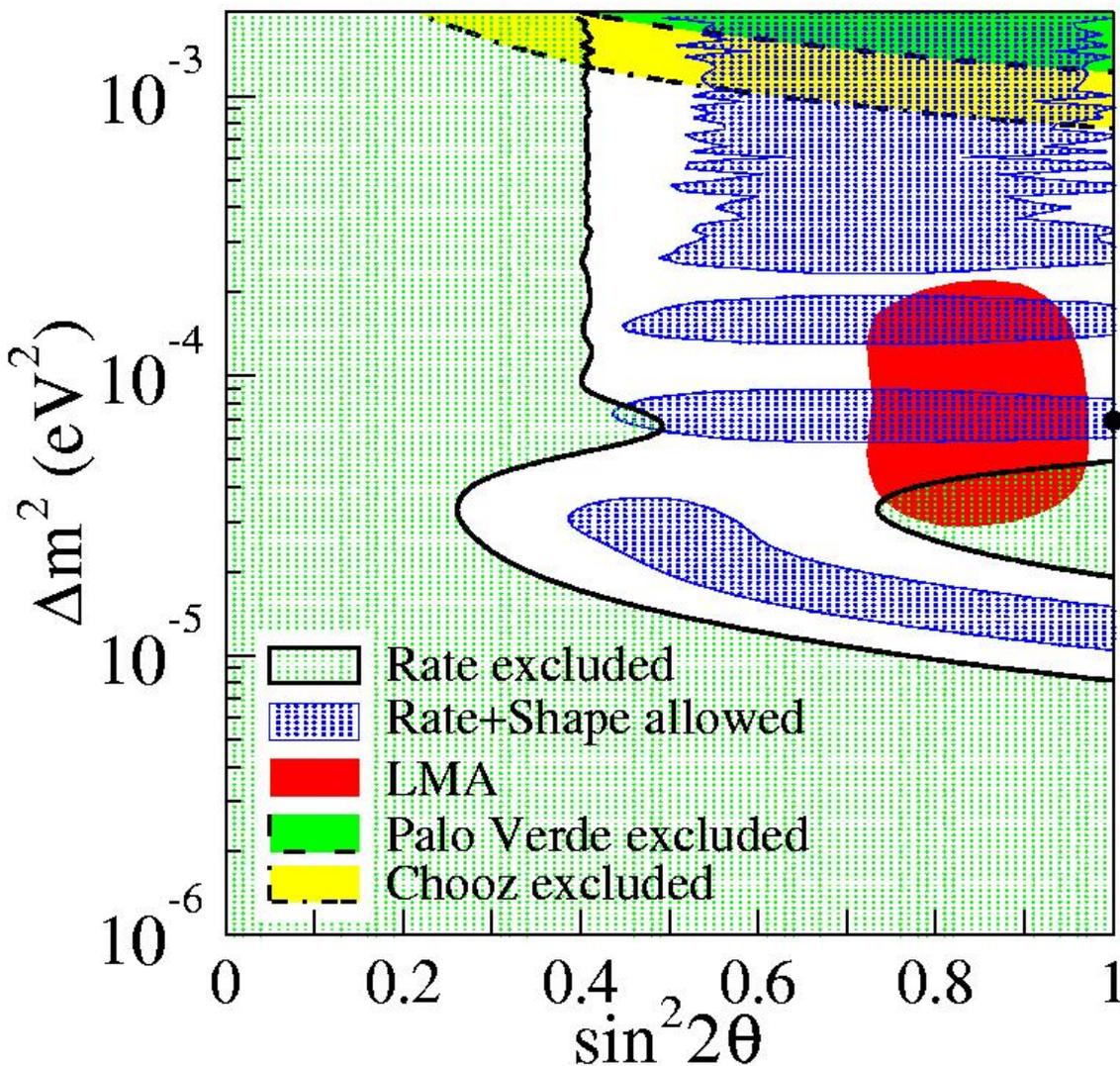
Need more data.

Allowed Values of Δm^2 and $\sin^2 2\theta$

Best fit :

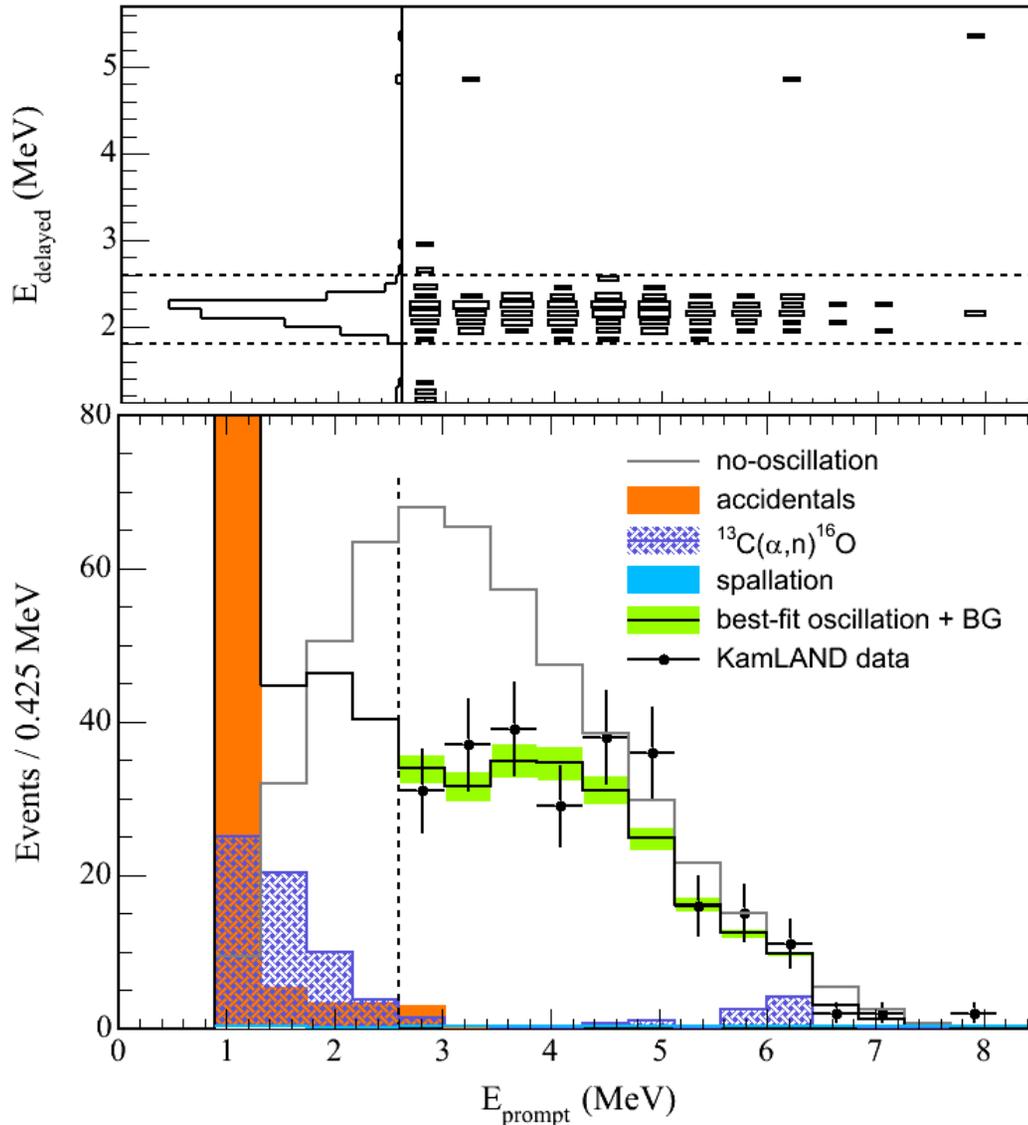
$$\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$$

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



In 2005, with more data, clear evidence for spectral distortion

(Data collected from March 2002 to January 2004)

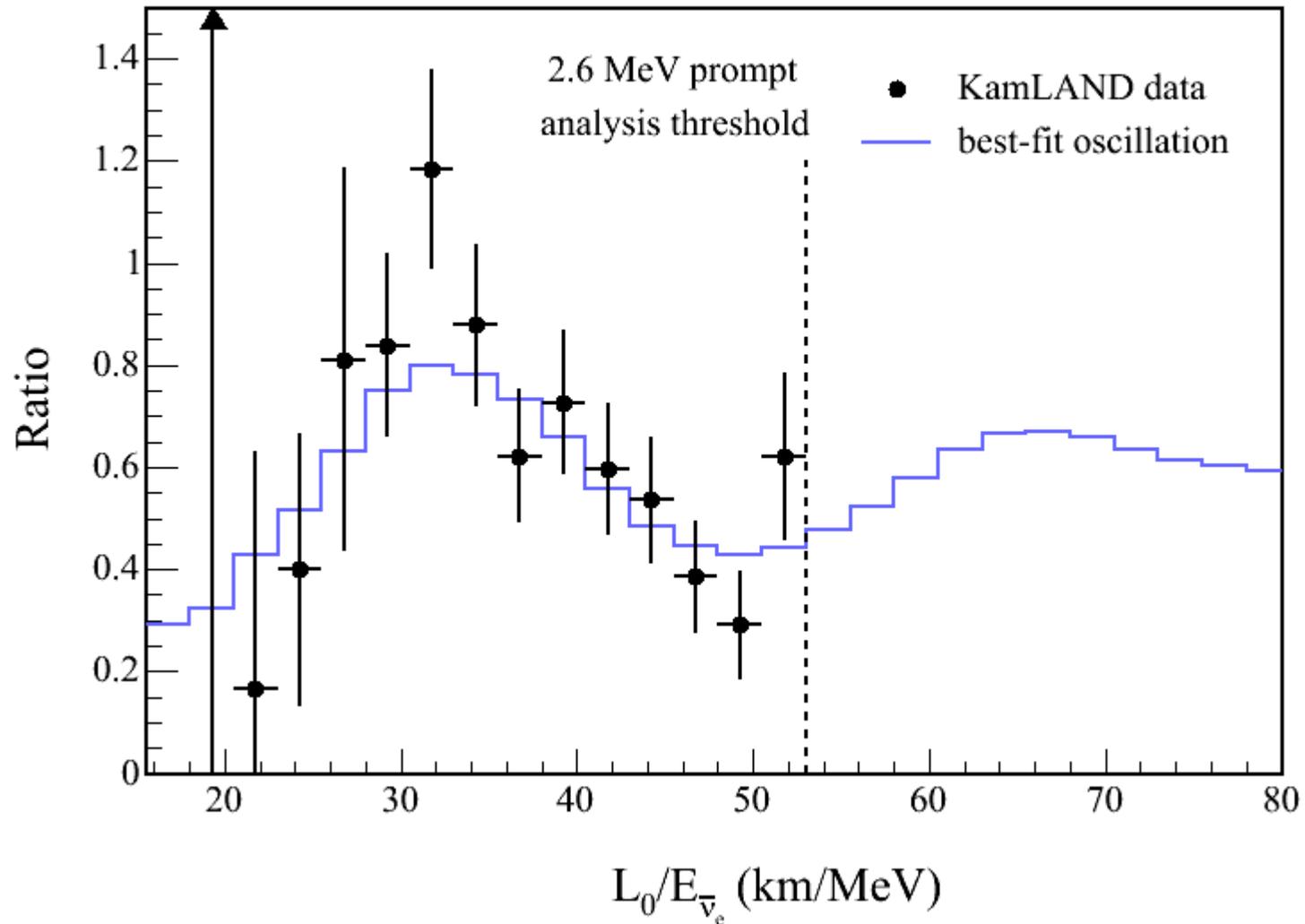


Expected w/o oscillations:
 365 ± 24 (syst) events

Observed:
 258 events

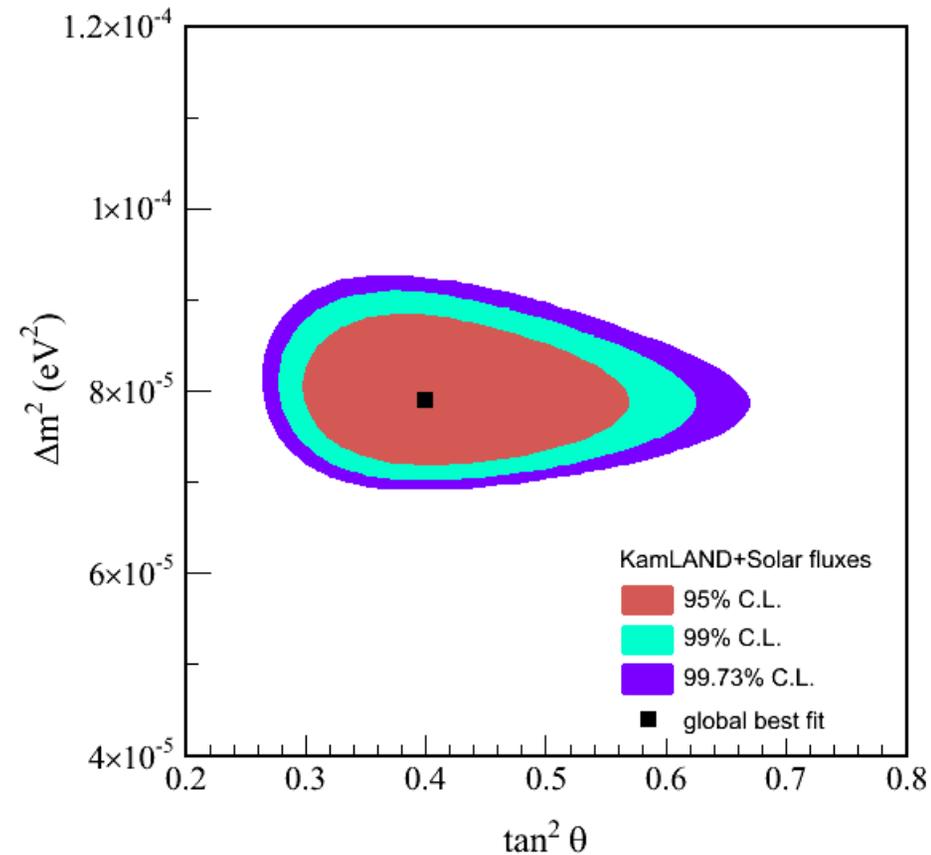
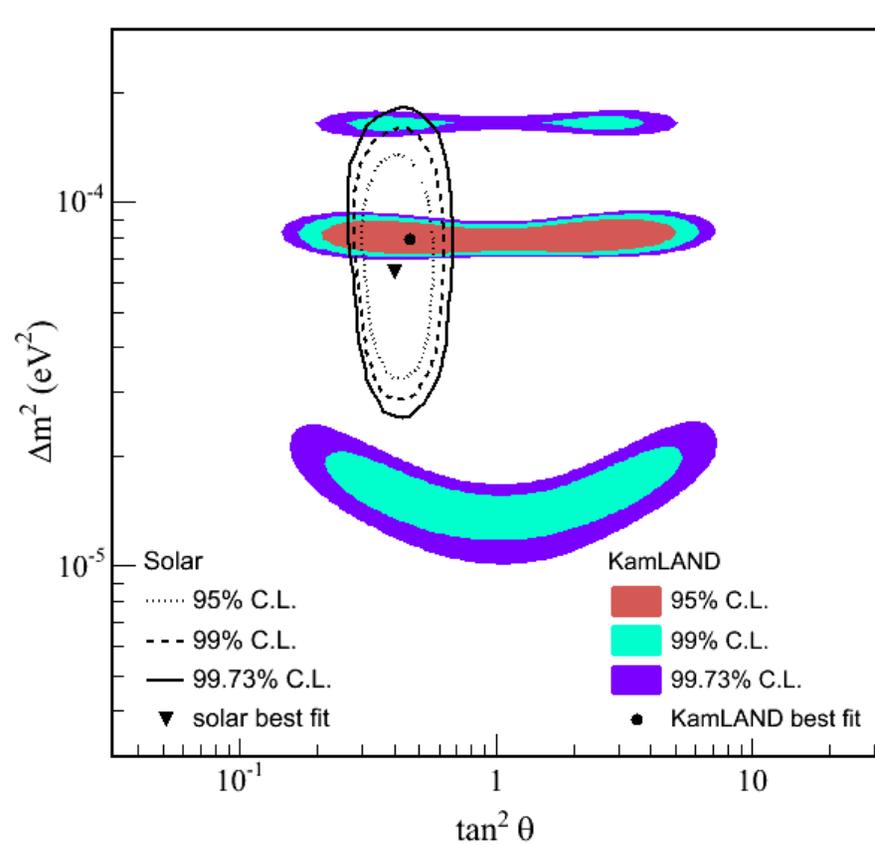
No oscillation shape only
 consistent with observed
 spectrum at 0.5% level.

Observed ν spectrum / expectation with no oscillations



Shape-only analysis gives: $\Delta m^2 = (8.0 \pm 0.5) \times 10^{-5} \text{ eV}^2$

Allowed Values for Δm_{12}^2 and θ_{12}



Best fit (assuming CPT):

$$\Delta m^2 = (7.9^{+0.6}_{-0.5}) \times 10^{-5} \text{ eV}^2 \text{ and } \tan^2 \theta = 0.40^{+0.10}_{-0.07}$$