Neutrino Experiments with Reactors

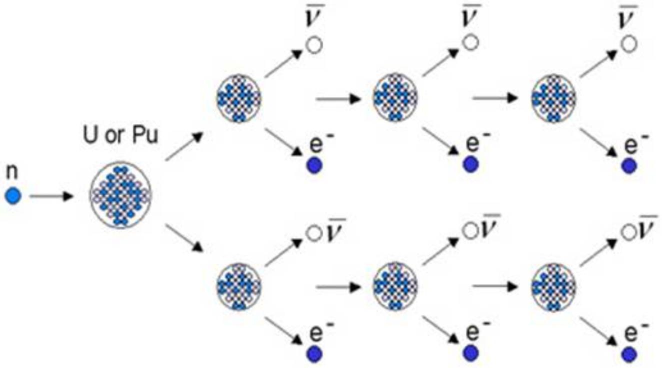
Ed Blucher, Chicago

- 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)
- Conclusions

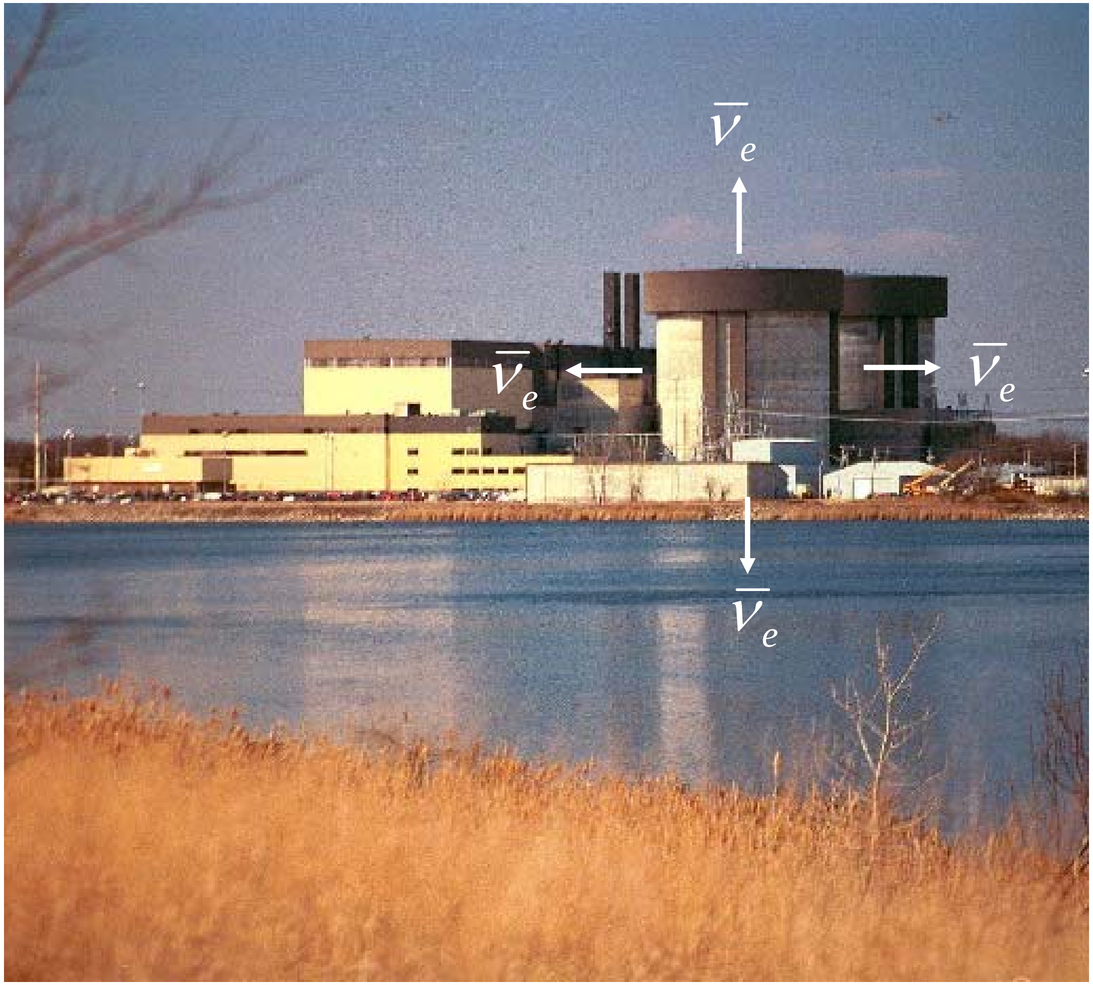
Lecture 1

Reactors as Antineutrino Sources

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

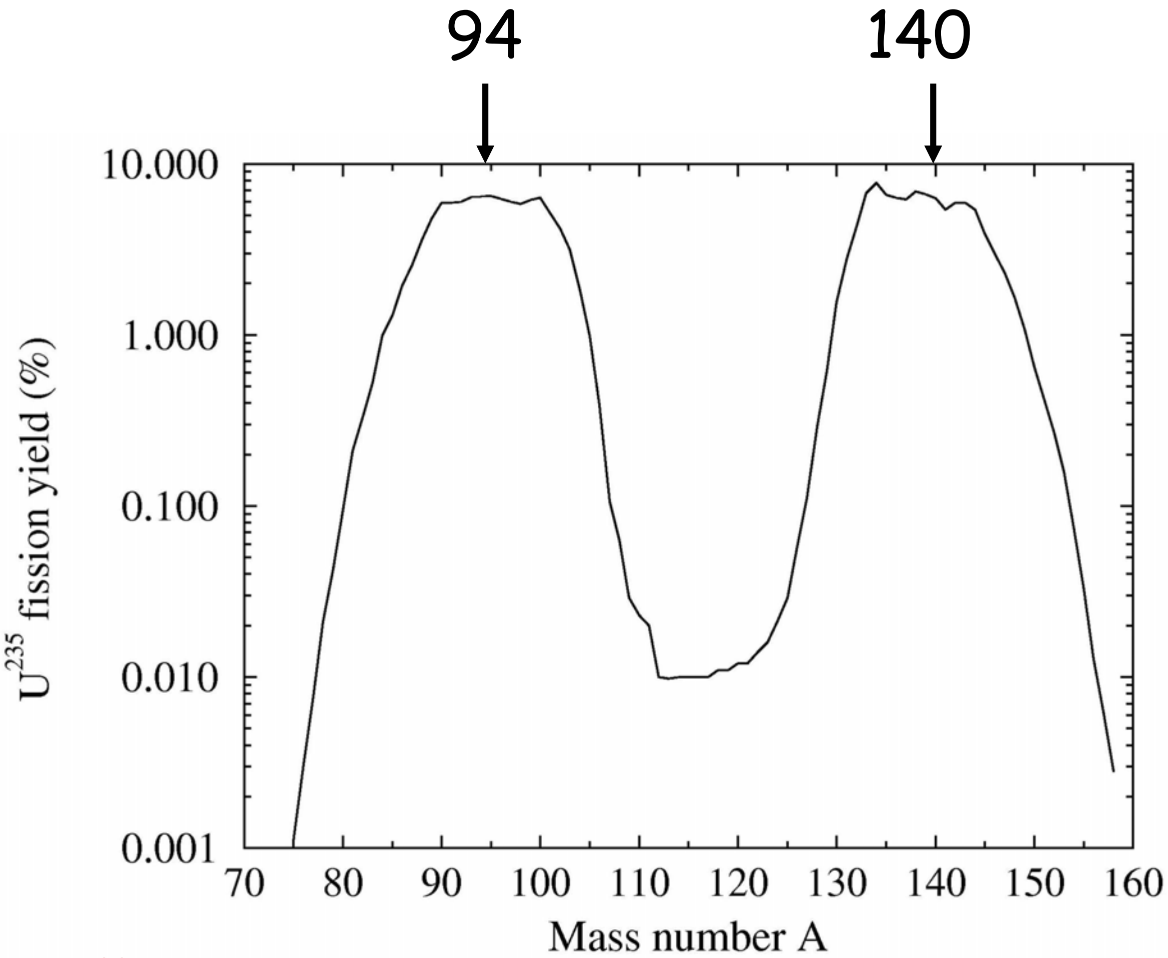


β^- decay of neutron rich fission fragments and U and Pu fission



Example: ^{235}U fission

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



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

$^{94}_{40}Zr$ $\quad$ $^{140}_{58}Ce$

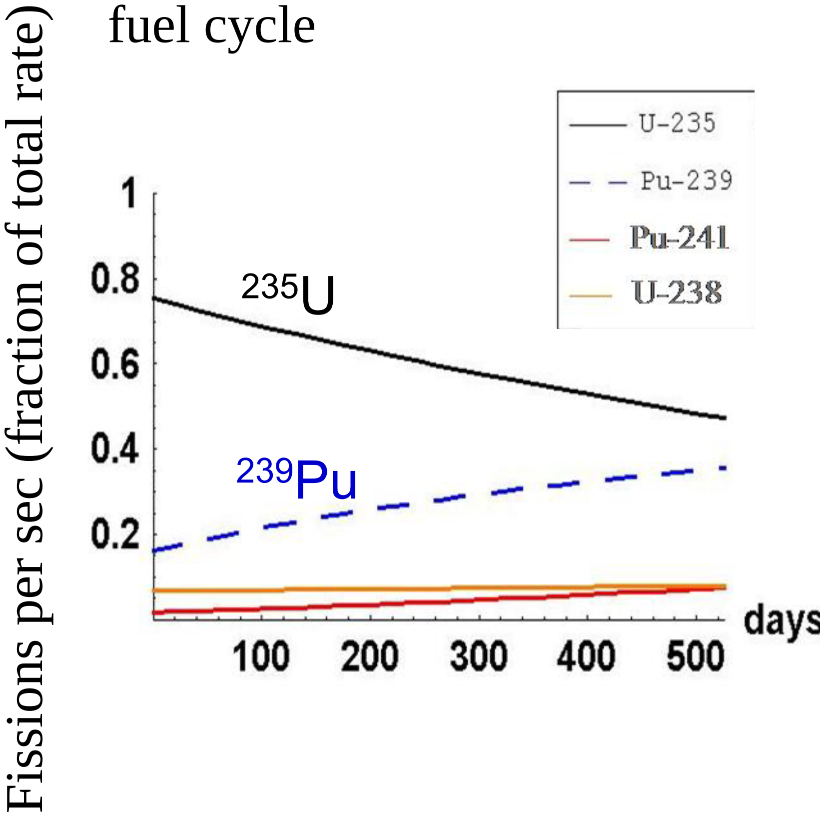
Together, these have 98 p and 136 n, while fission fragments (X_1+X_2) have 92 p and 142 n

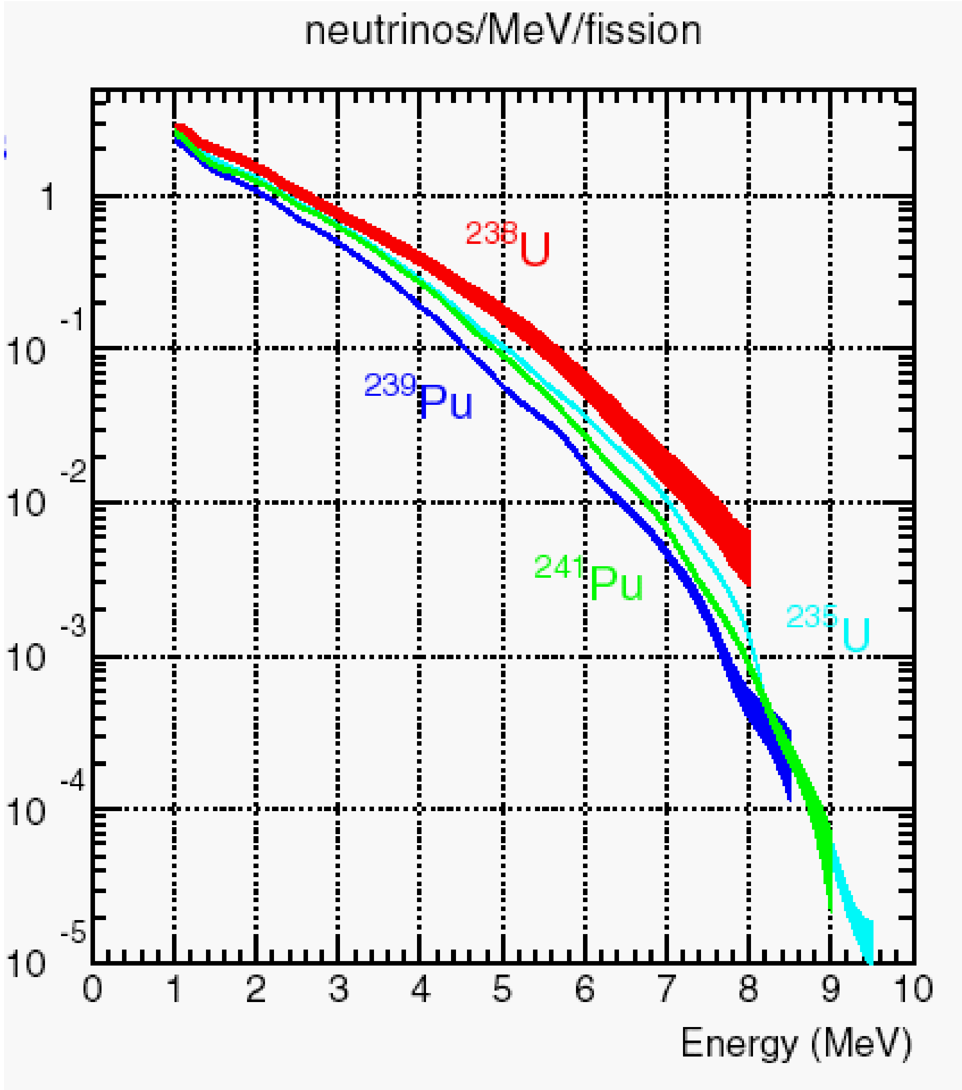
On average, 6 n have to decay to 6 p to reach stable matter

~ 200 MeV/fission and ~6 $\bar{\nu}_e$ / fission implies that 3GW$_{th}$ reactor produces $\sim 6\times10^{20}\ \bar{\nu}_e/\mathrm{sec}$.

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

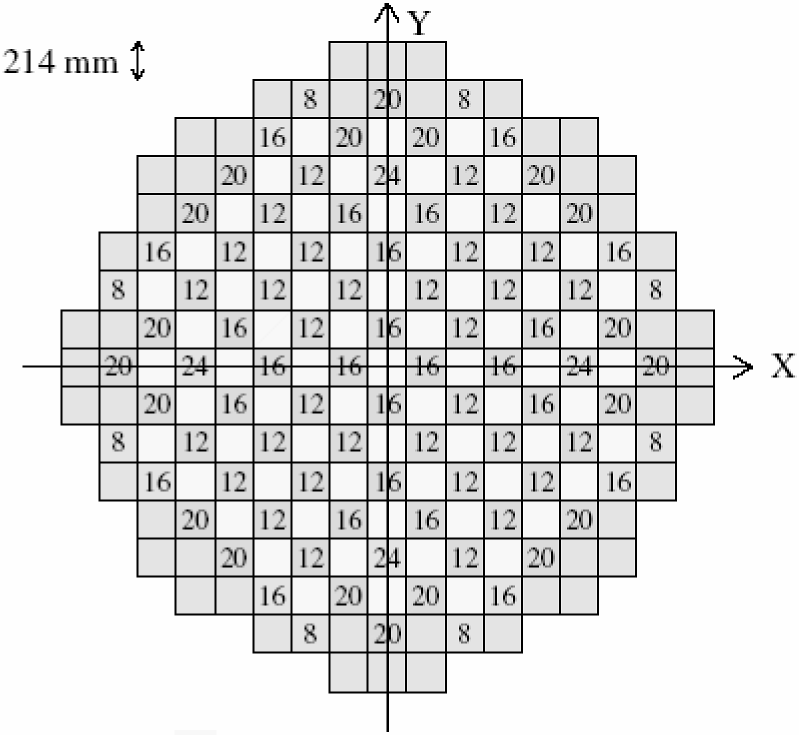
Fission rates over single reactor fuel cycle





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.



						8		20		8						
					16		20		20		16					
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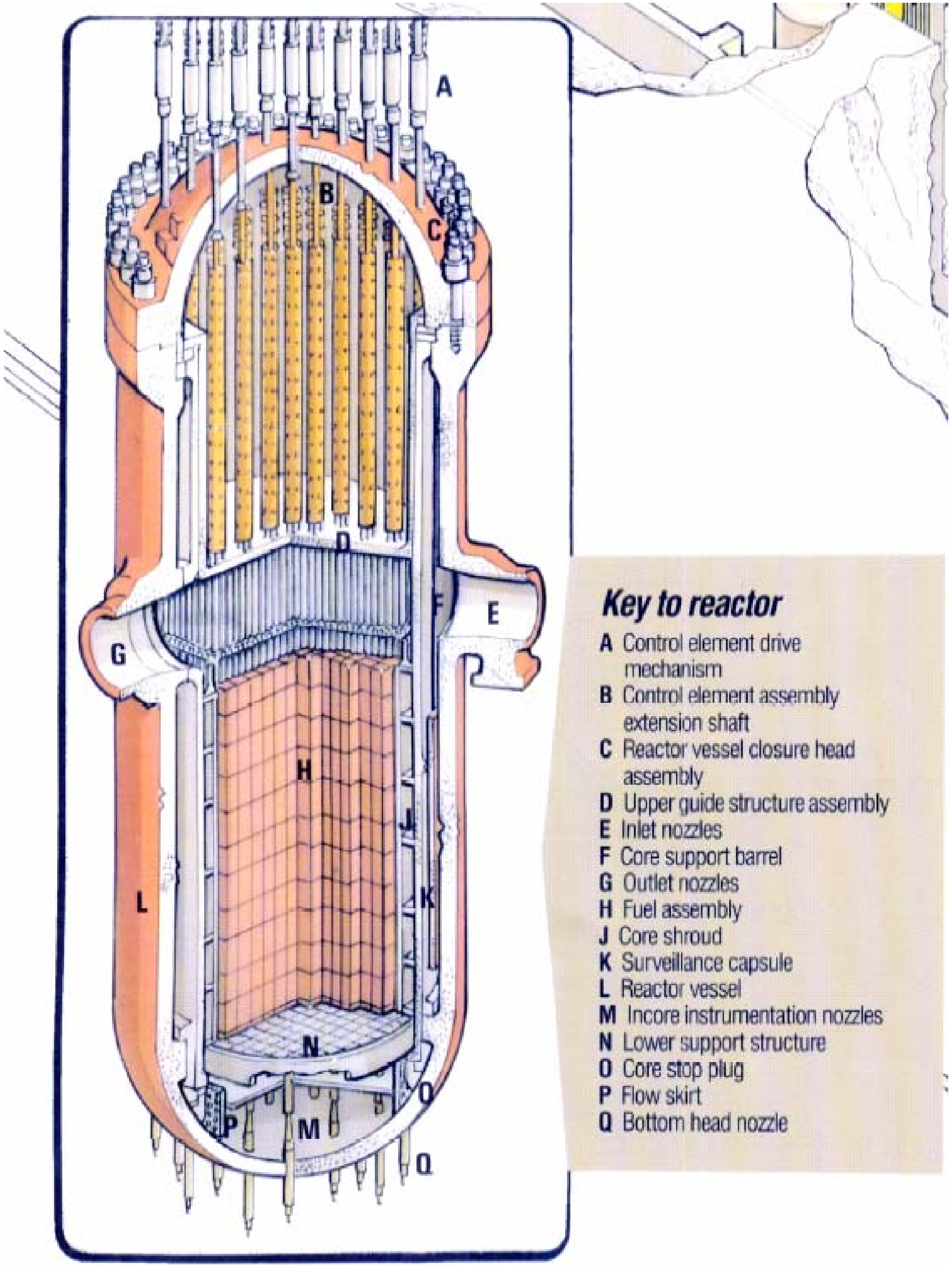
		16		12		12		16		12		12		16		
	8		12		12		12		12		12		12		8	
		20		16		12		16		12		16		20		
	20		24		16		16		16		16		24		20	
		20		16		12		16		12		16		20		
	8		12		12		12		12		12		12		8	
		16		12		12		16		12		12		16		
			20		12		16		16		12		20			
				20		12		24		12		20				
					16		20		20		16					
						8		20		8						

□ Region 1: 1.8 % enrichment

▨ Region 2: 2.4 % enrichment

▨ Region 3: 3.1 % enrichment

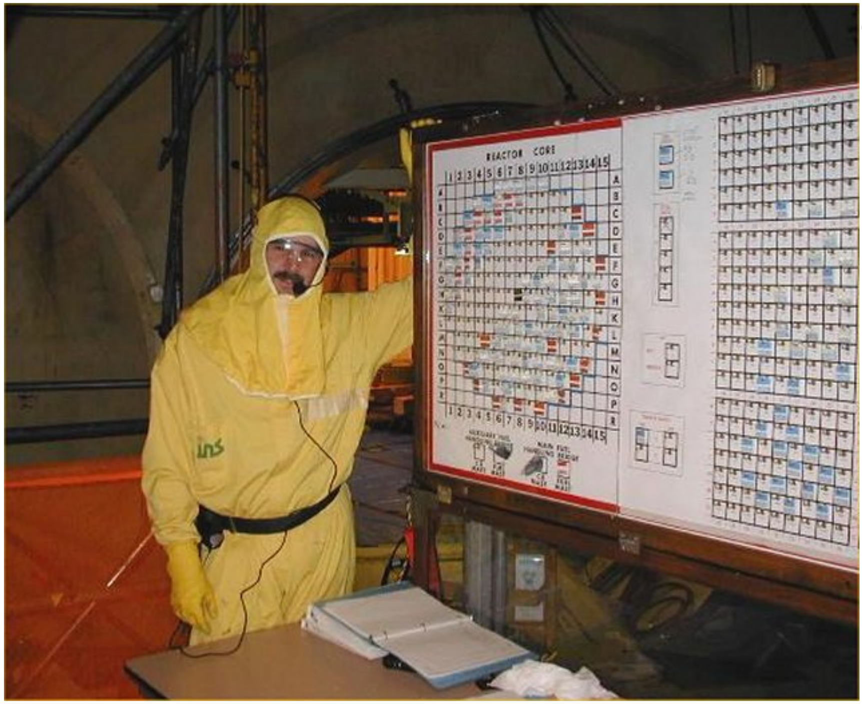


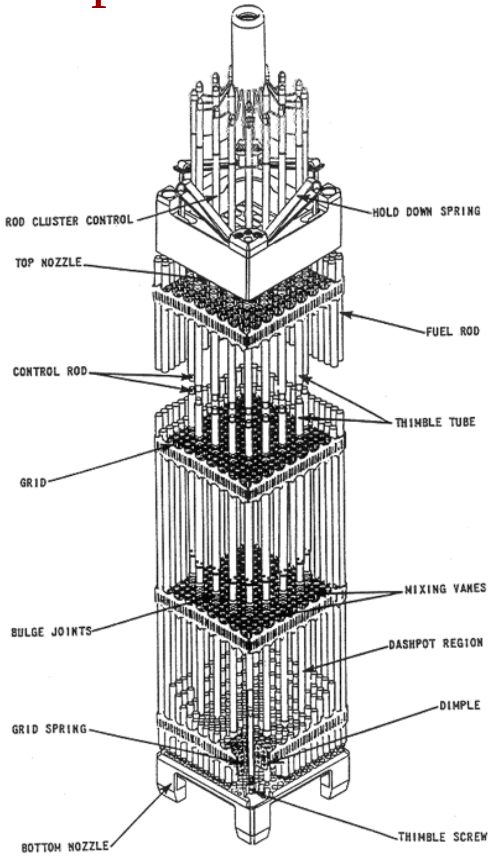
Key to reactor

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

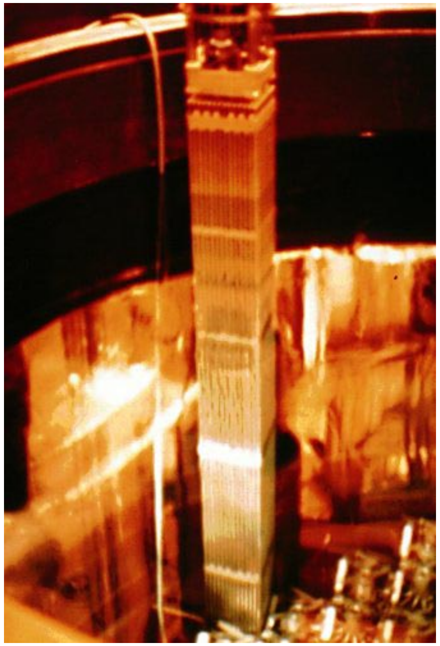
Reactor refueling

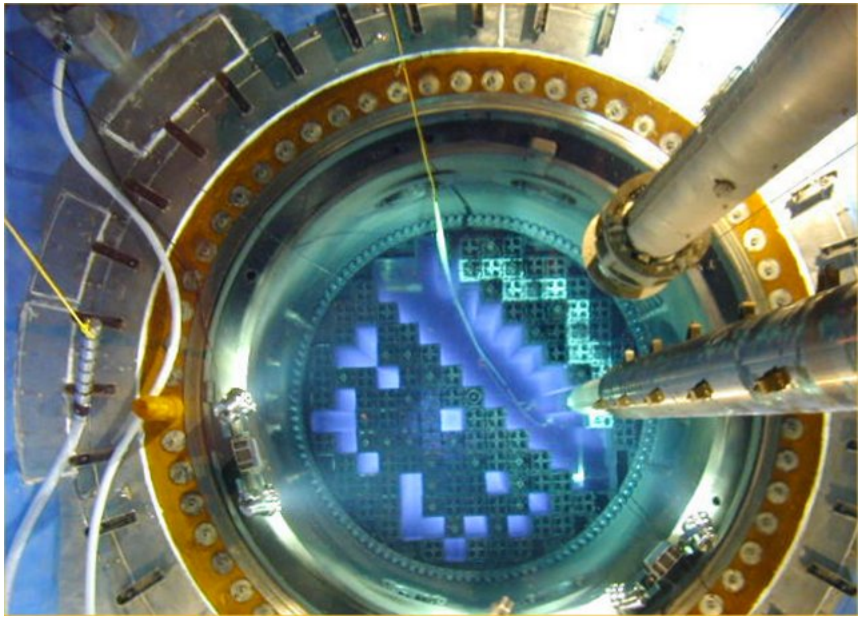
- 1 month shutdown every 12-18 months
- 1/3 of fuel assemblies are replaced and remaining fuel assemblies repositioned



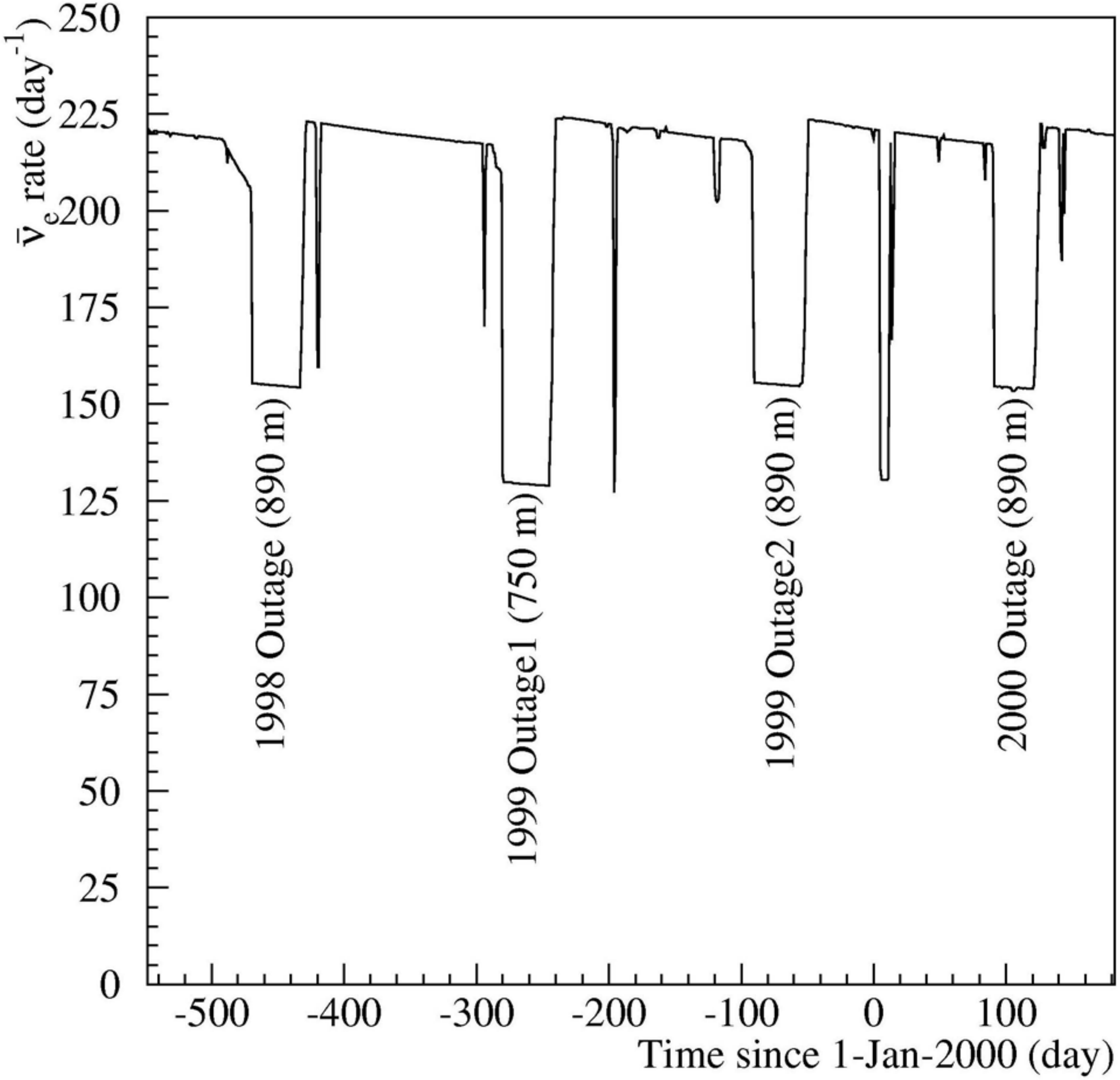


Reactor Fuel Assembly





ν Rate for 3-Core Palo Verde Plant



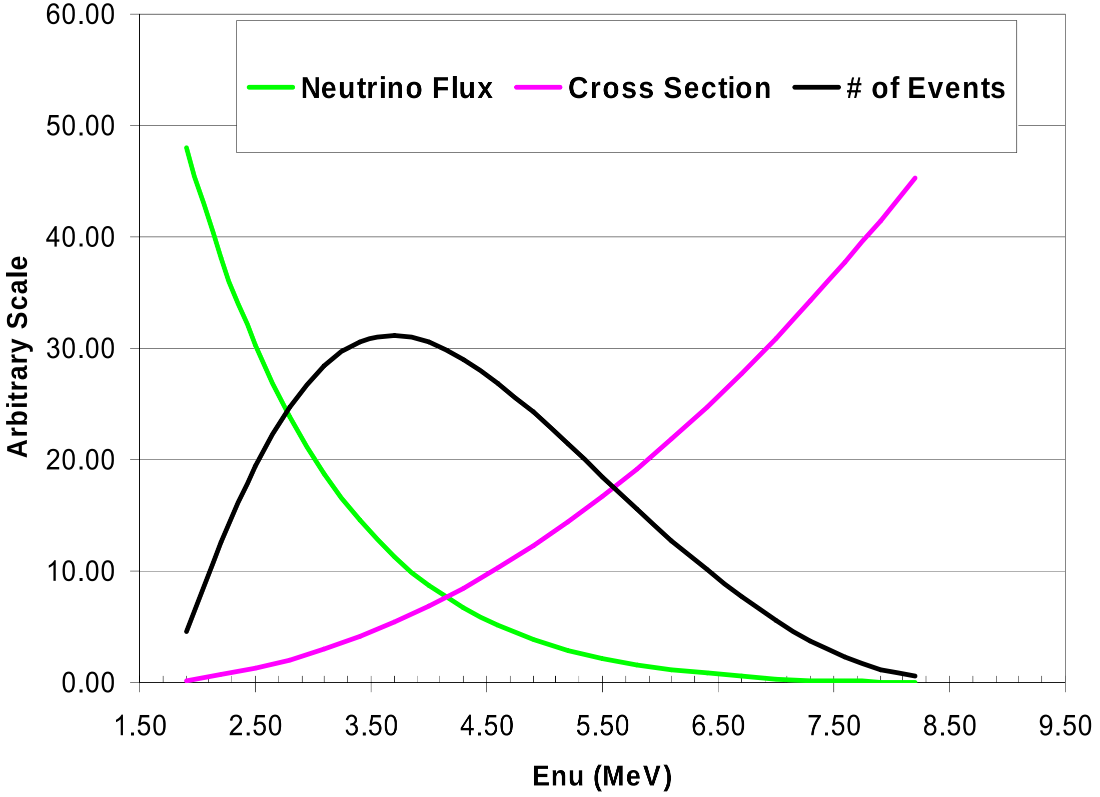
Detection of $\bar{\nu}_e$

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

Also possible:

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

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



$$\sigma^{(0)}_{\text{tot}} = \frac{2\pi^2/m_e^5}{f^R_{p.s.}\tau_n} E_e^{(0)} p_e^{(0)}$$

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

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

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

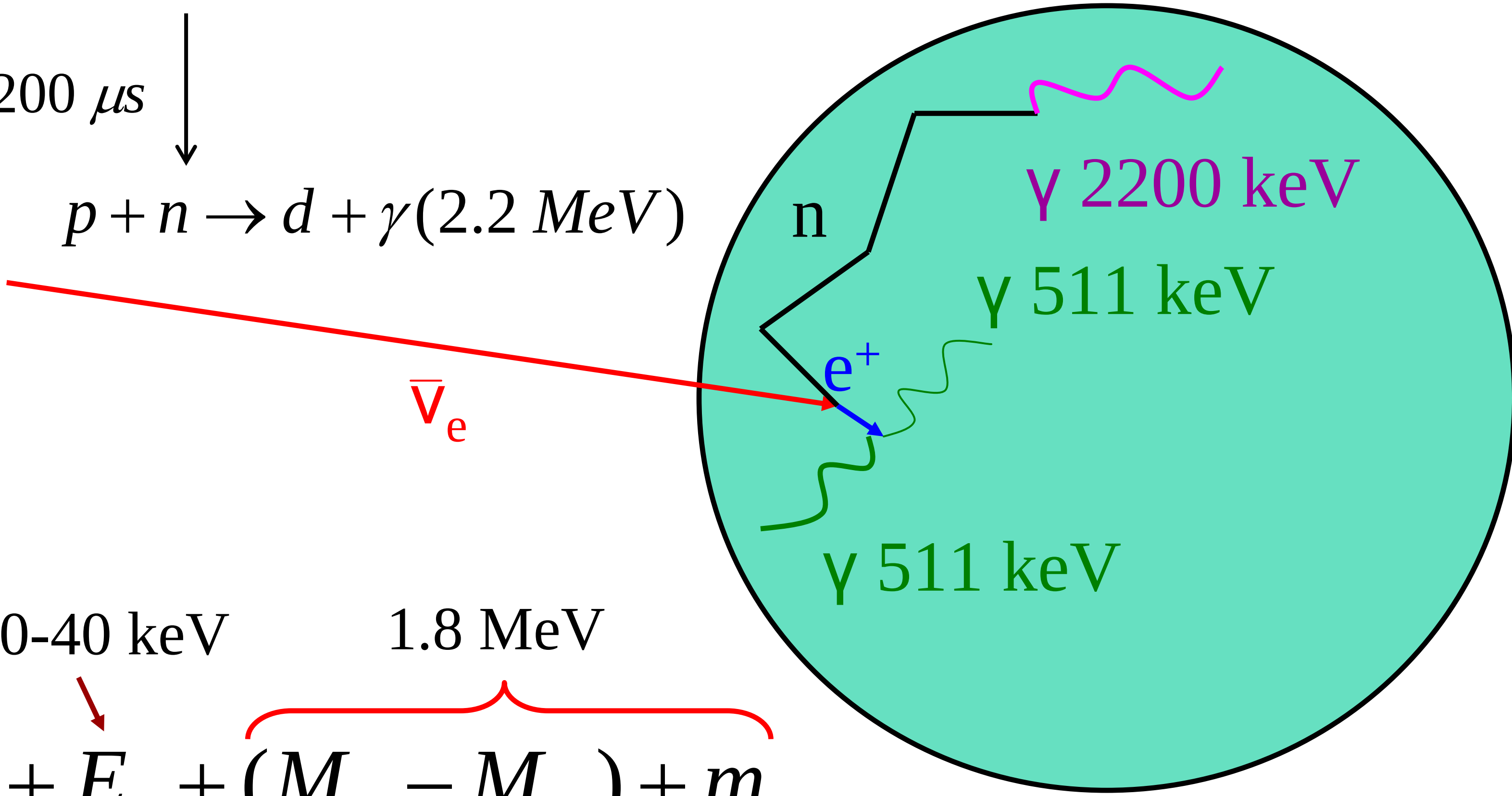
~1 event per day per ton of LS per GW thermal at 1 km

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

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

$$\tau \approx 200\ \mu s$$

$$p + n \to d + \gamma(2.2\ MeV)$$



$$E_{\bar{\nu}} \cong E_{e^+} + \overset{\text{10-40 keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{\text{1.8 MeV}}$$

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

The First Detection of the Neutrino

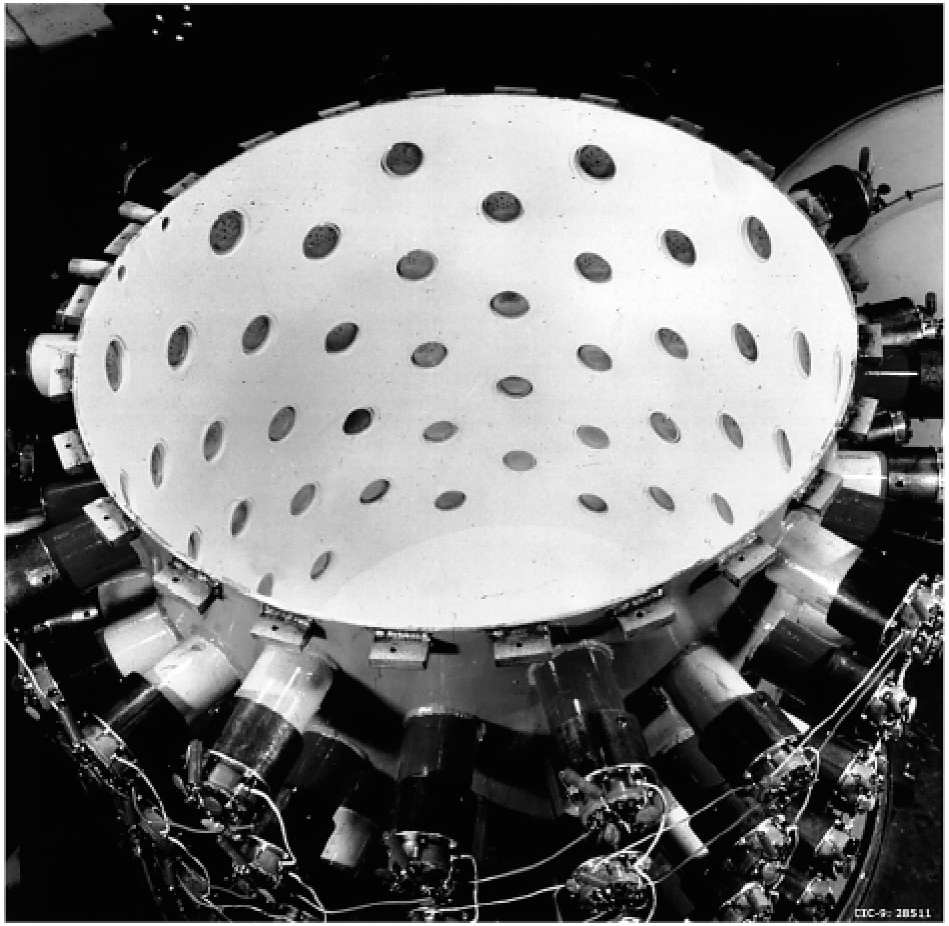
Reines and Cowan, 1956

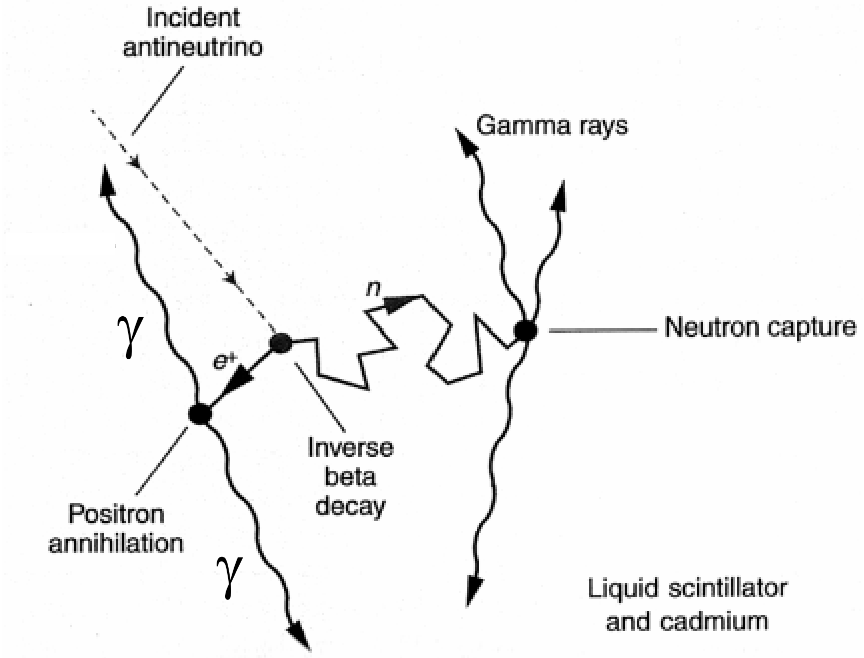
Clyde Cowan Jr.

Frederick Reines

1953 Experiment at Hanford

Detector from Hanford Experiment





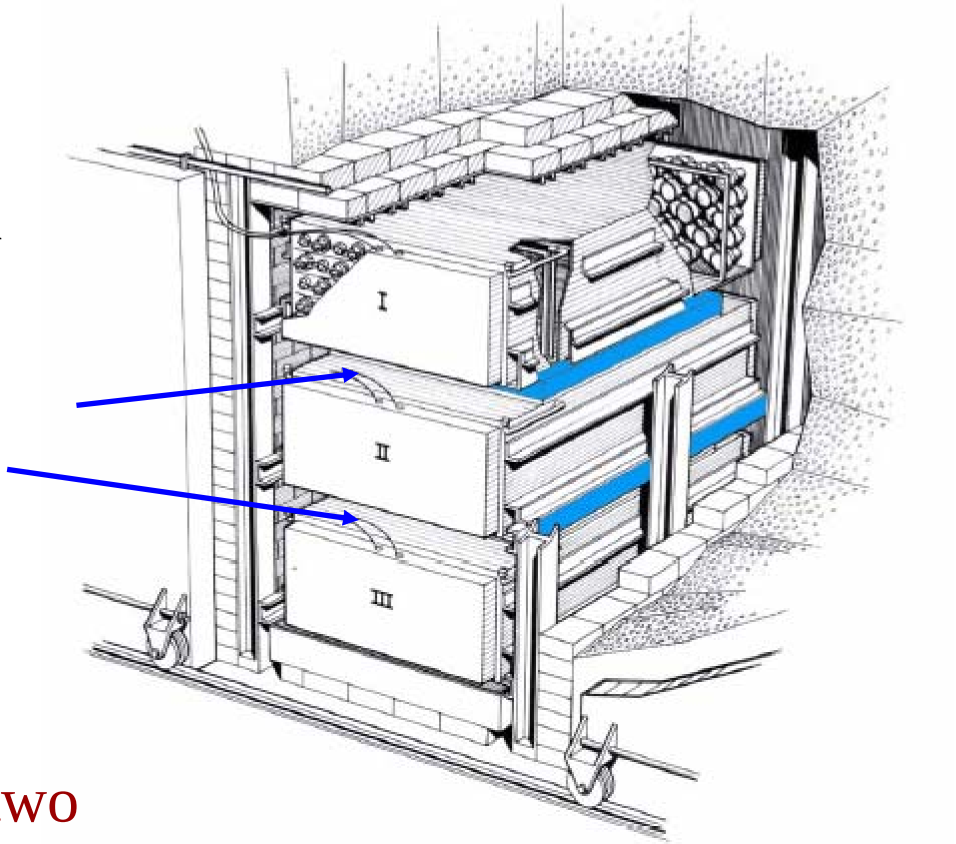
Signal was delayed coincidence between positron (2-5 MeV) and neutron capture on cadmium (2-7 MeV)

300 liters of liquid scintillator loaded with cadmium

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.

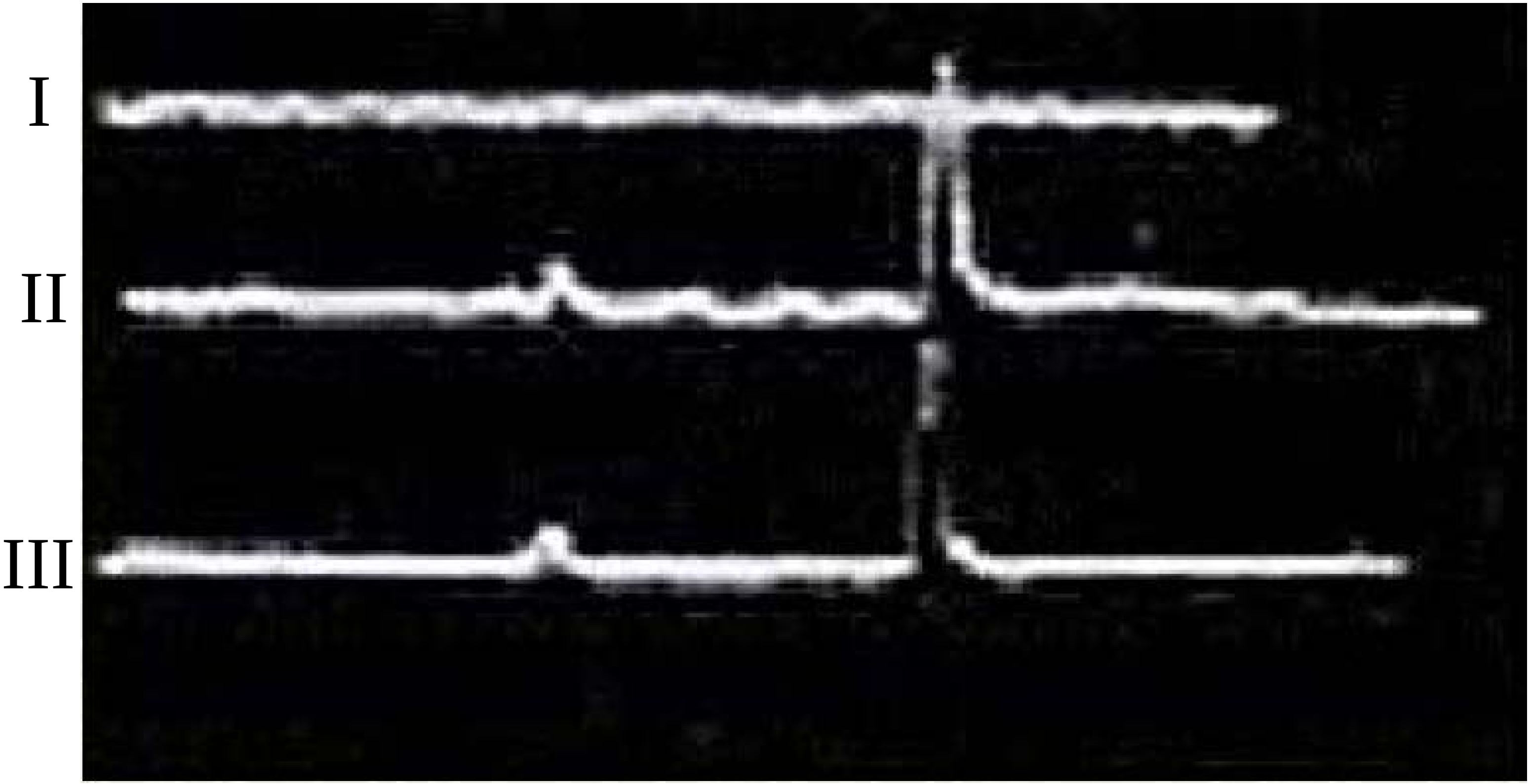


Target tanks (blue) were filled
with water+cadmium chloride.

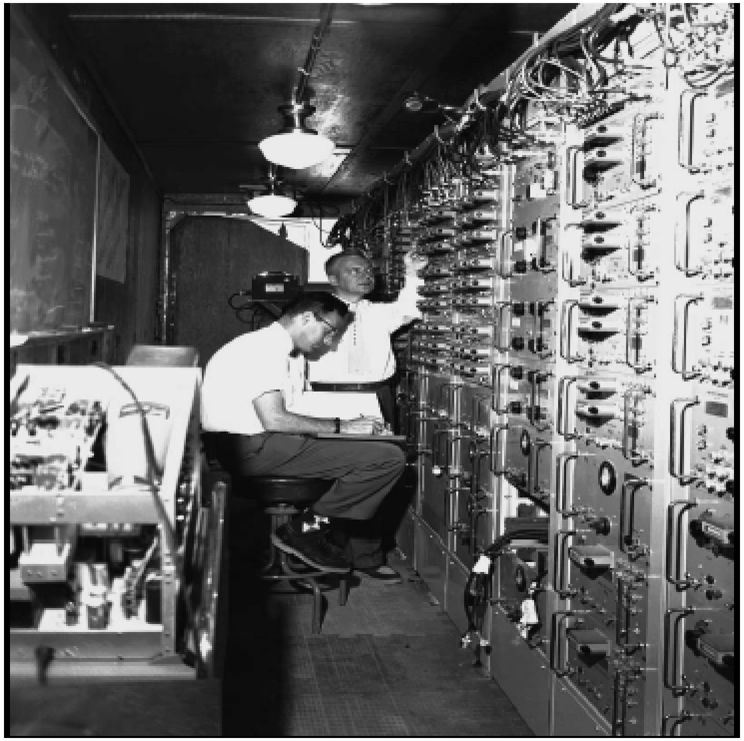
Inverse β decay would produce two
signals in neighboring tanks (I,II or II,III):

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

Data were recorded photographically from oscilloscope traces



Savannah River Experiment



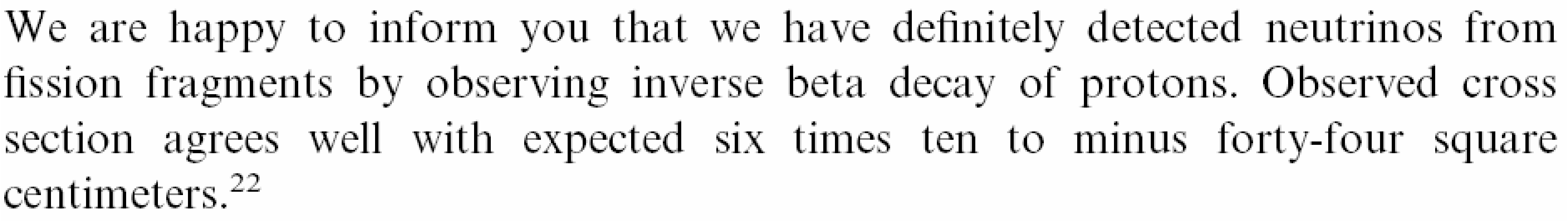
Electronics trailer

Shielding: 4 ft of soaked sawdust

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

Signal / reactor independent background ~ 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 6.3×10^{-44} cm^2 expected (although the predicted cross section had a 25% uncertainty).

- In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by ×2 to $(10\pm1.7)\times10^{-44}$ cm^2

- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma=(12^{+7}_{-4})\times10^{-44}\ \mathrm{cm}^2$

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" $\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 and "atmospheric" $\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2

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

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

where $\Delta m^2_{ij} = m^2_i - m^2_j$.

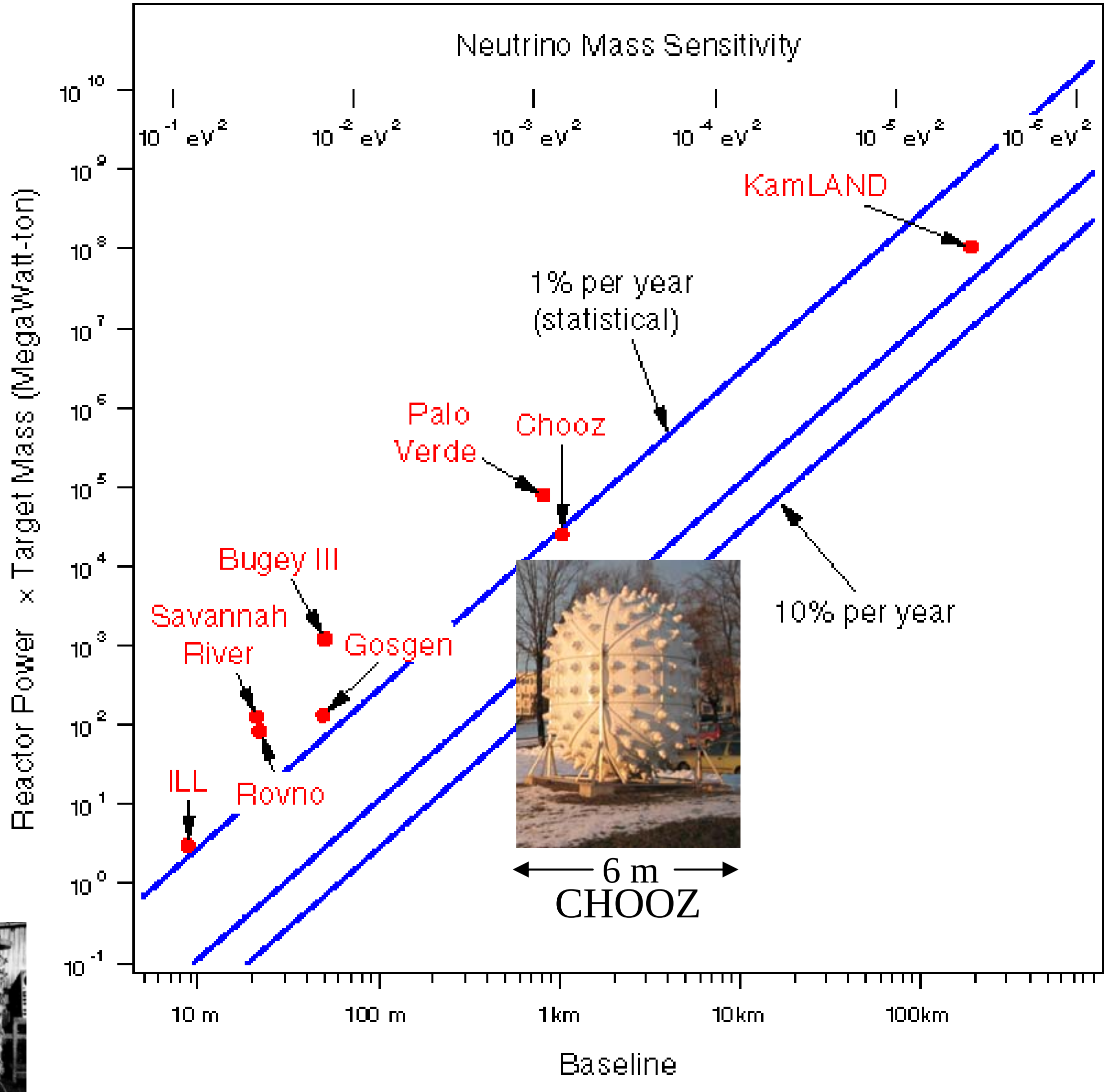
Experiments look for non-1/r^2 behavior of antineutrino rate.

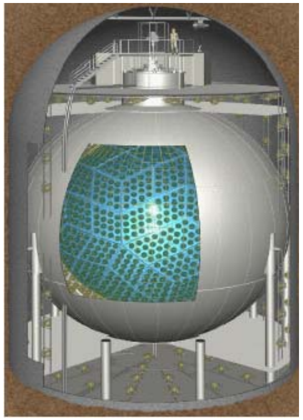
Oscillation maxima for E_ν=3.6 MeV:

$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 ➡ L ~ 60 km

$\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2 ➡ L ~ 1.8 km

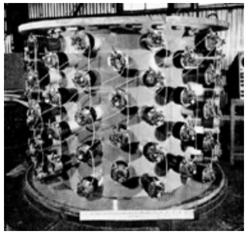
Long history of neutrino experiments at reactors





20 m

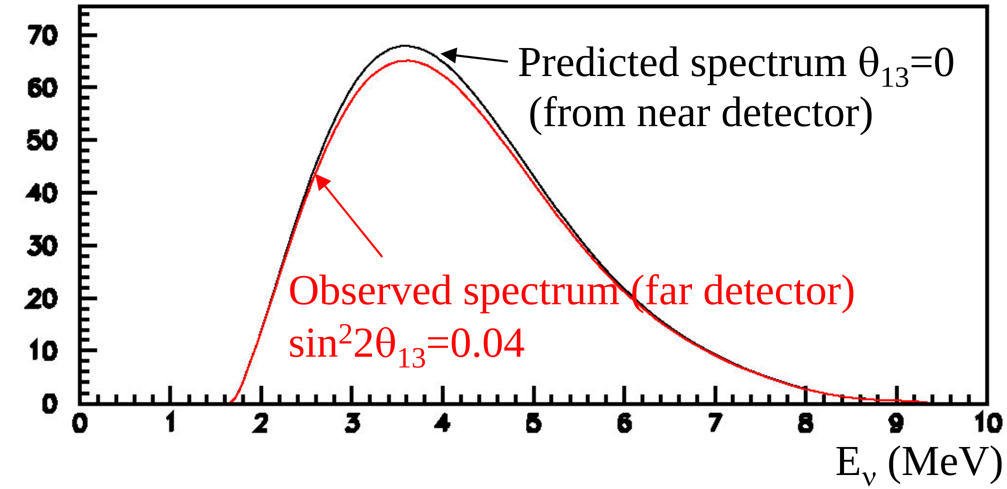
KamLAND



1m

Poltergeist

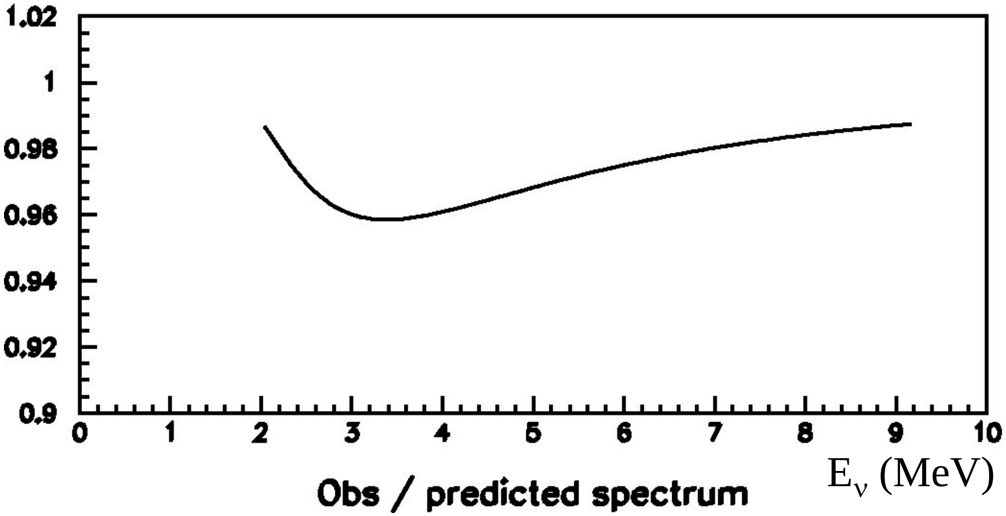
Normalization and spectral information



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



Obs / predicted spectrum

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}Li ($\tau_{1/2}$=178 ms) and ^{8}He ($\tau_{1/2}$=119 ms); associated with showering muons.
    - Reduced by shielding (depth) and veto systems

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

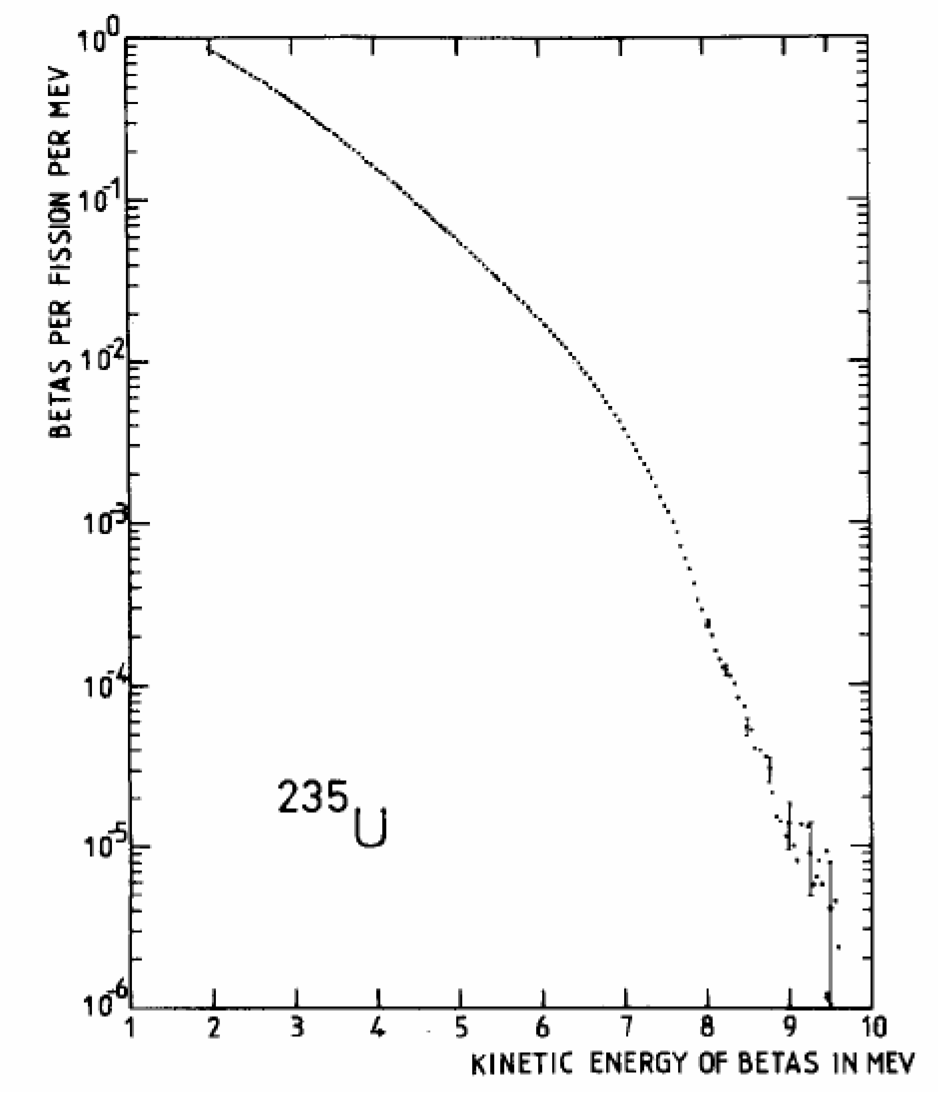
Recall that > 99.9% of ν are produced by fissions in ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu (90% from first two).

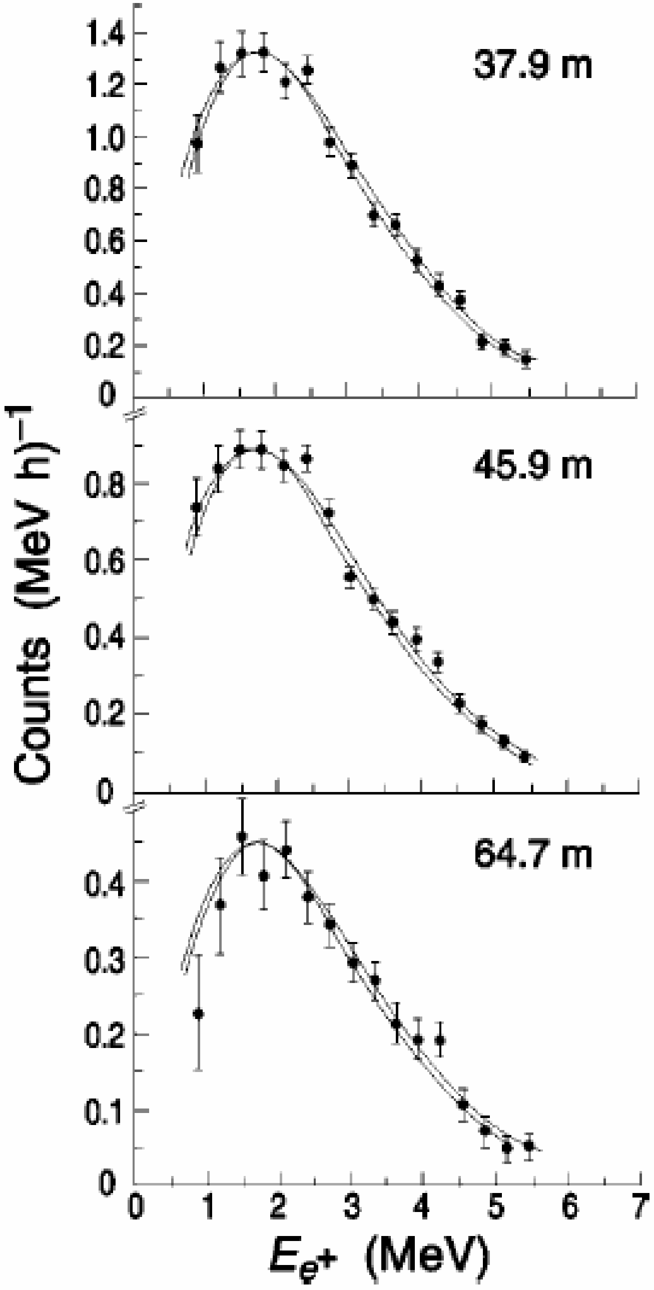
Use direct measurements of electron spectrum from a thin layer of fissile material in a beam of thermal neutrons
A. Schreckenbach et al. Phys. Lett B 160, **325** (1985); A. Hahn et al., Phys. Lett. B **218**, 365 (1989).
Must rely on calculation for ^{238}U.

→ Total flux uncertainty is about 2-3%.

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

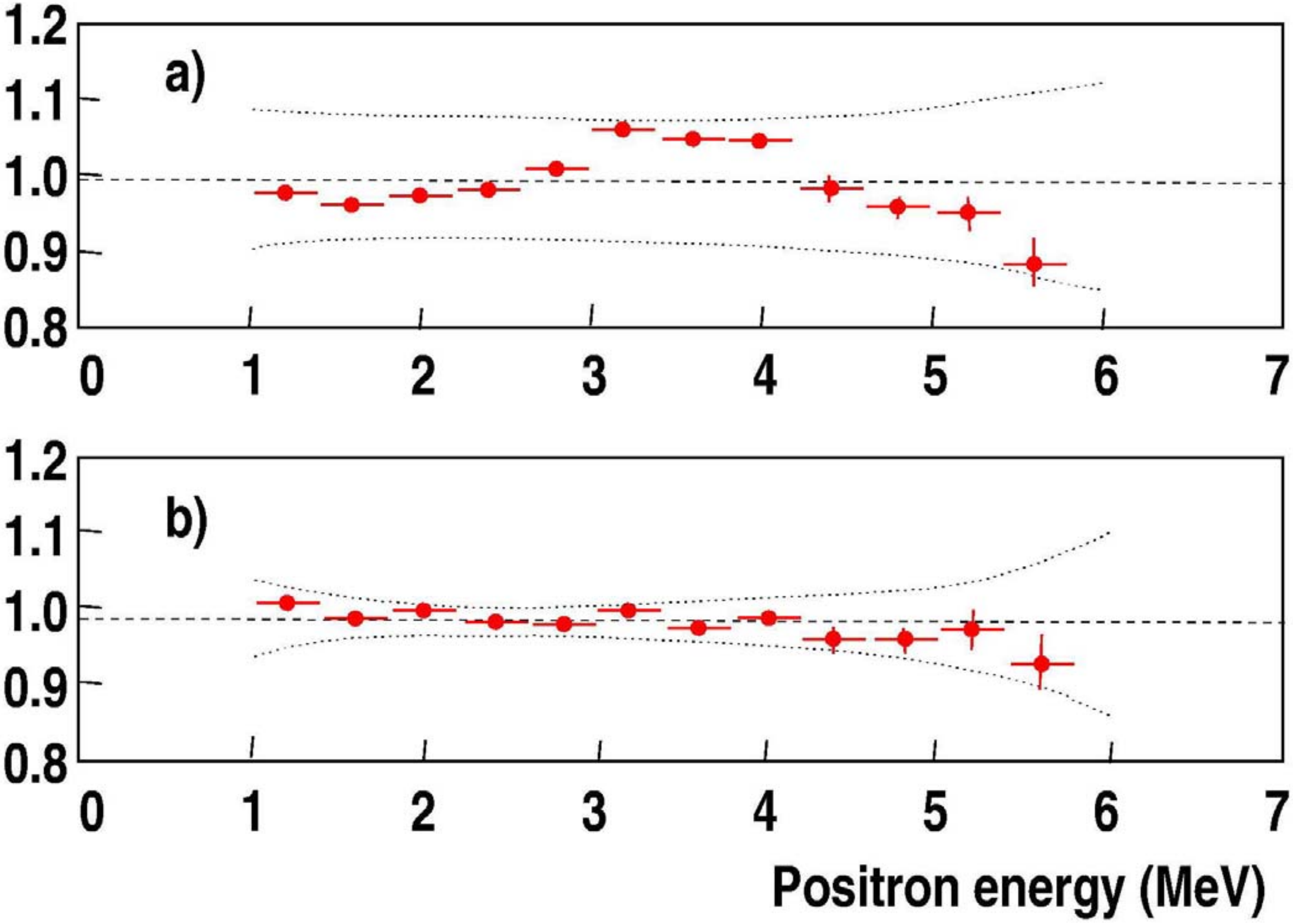
β Spectrum for ^{235}U Fission Products





Positron Spectra from Gösgen Experiment

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



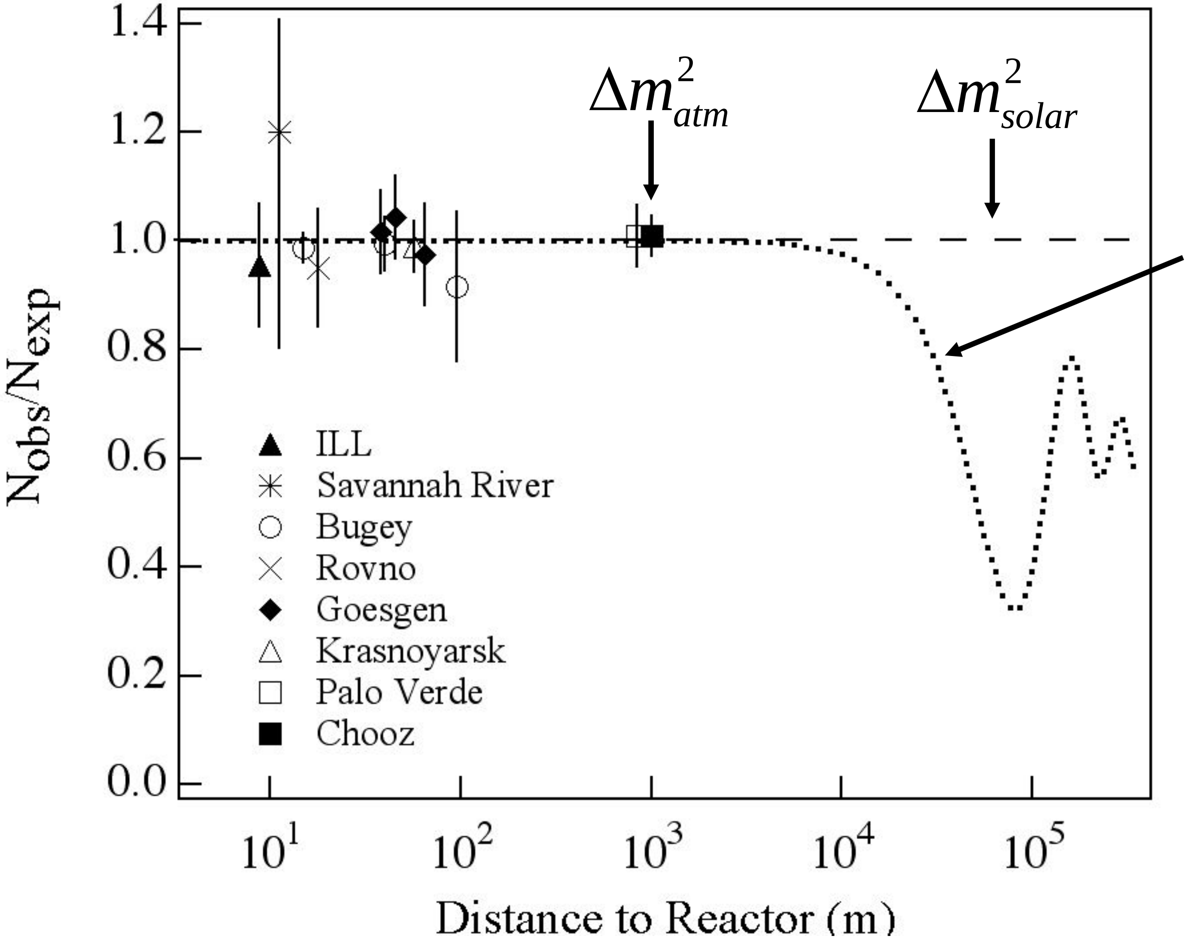
Bugey3/”first principle calculation”

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

Solar Δm^2: The KamLAND Experiment

Goal: Study oscillations at $\Delta m^2_{solar} \sim 8\times10^{-5}$ eV^2 using nuclear reactors.

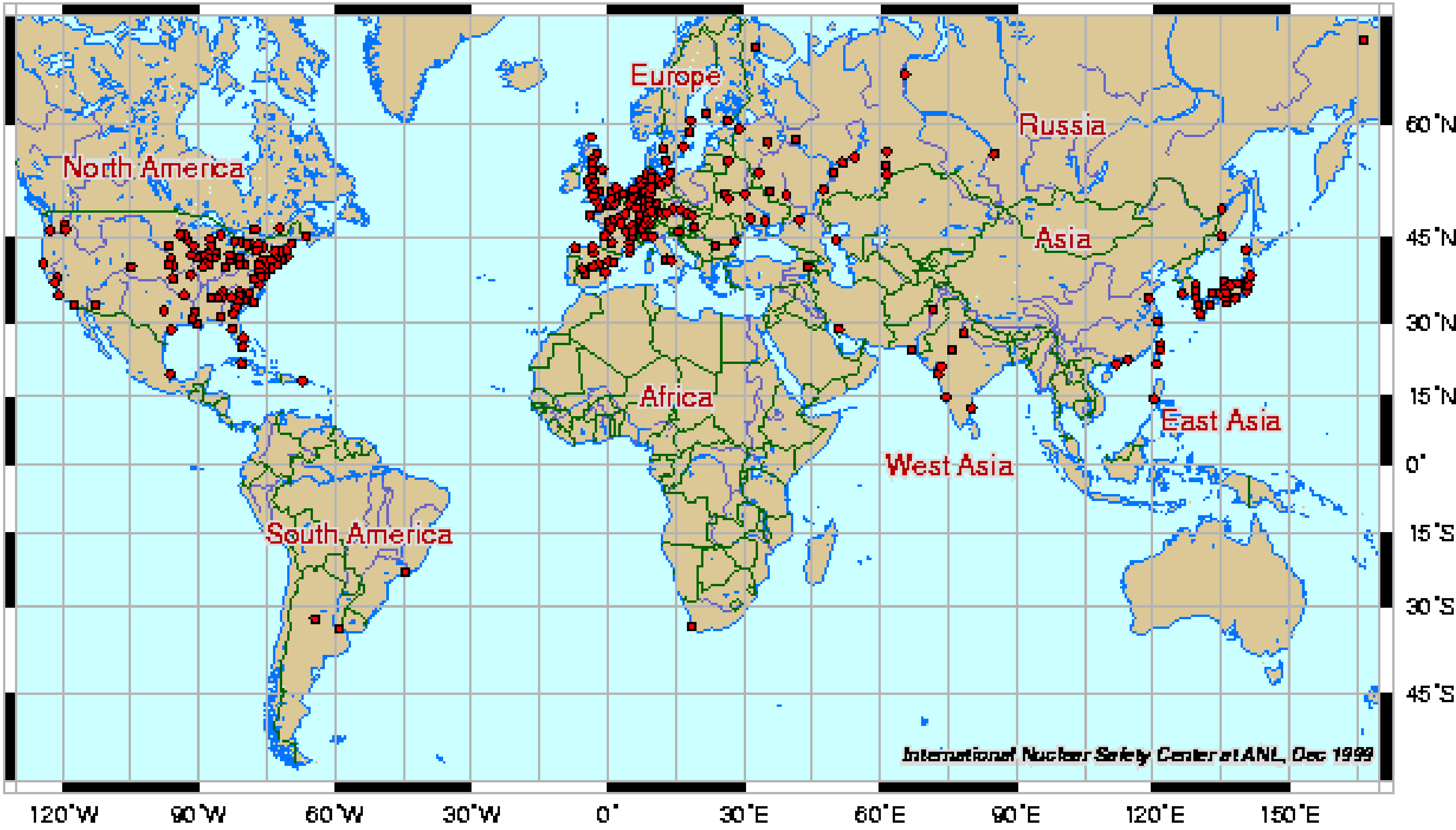
Observed / expected flux for reactor experiments



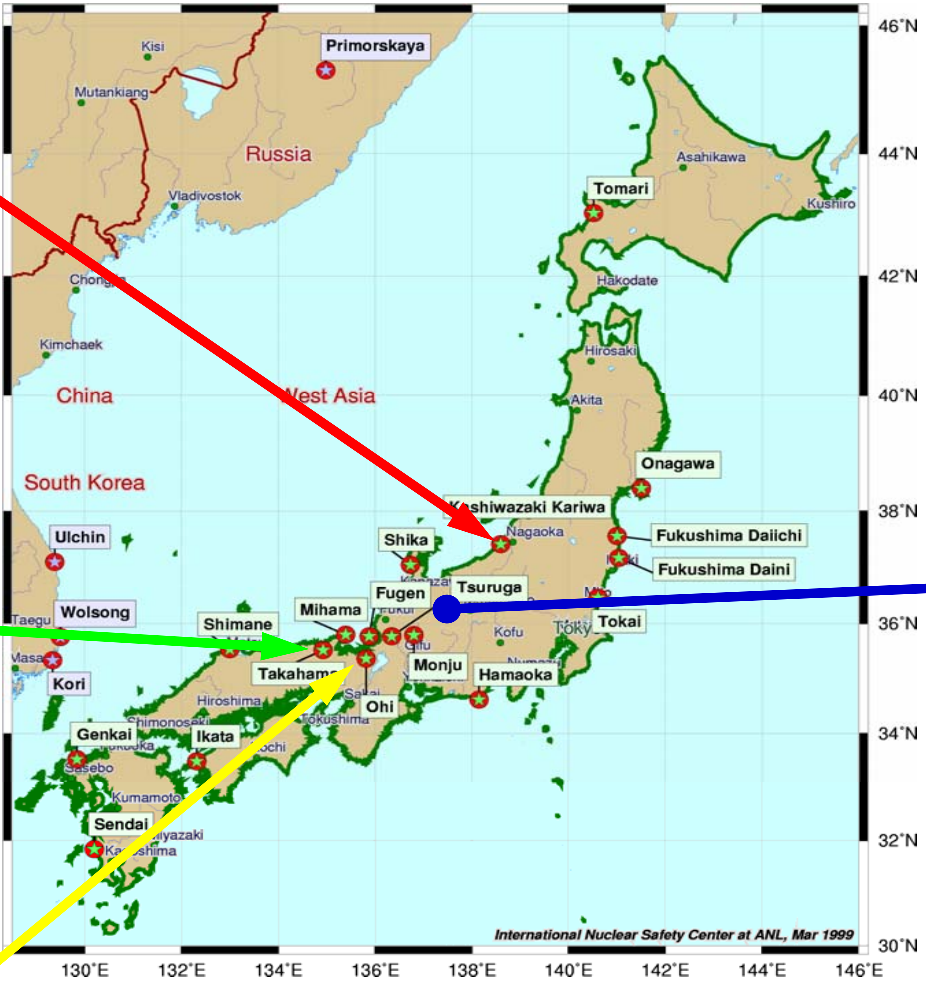
Predicted N_{obs}/N_{exp} for LMA solution before KamLAND (assuming θ_{13} small)

~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.



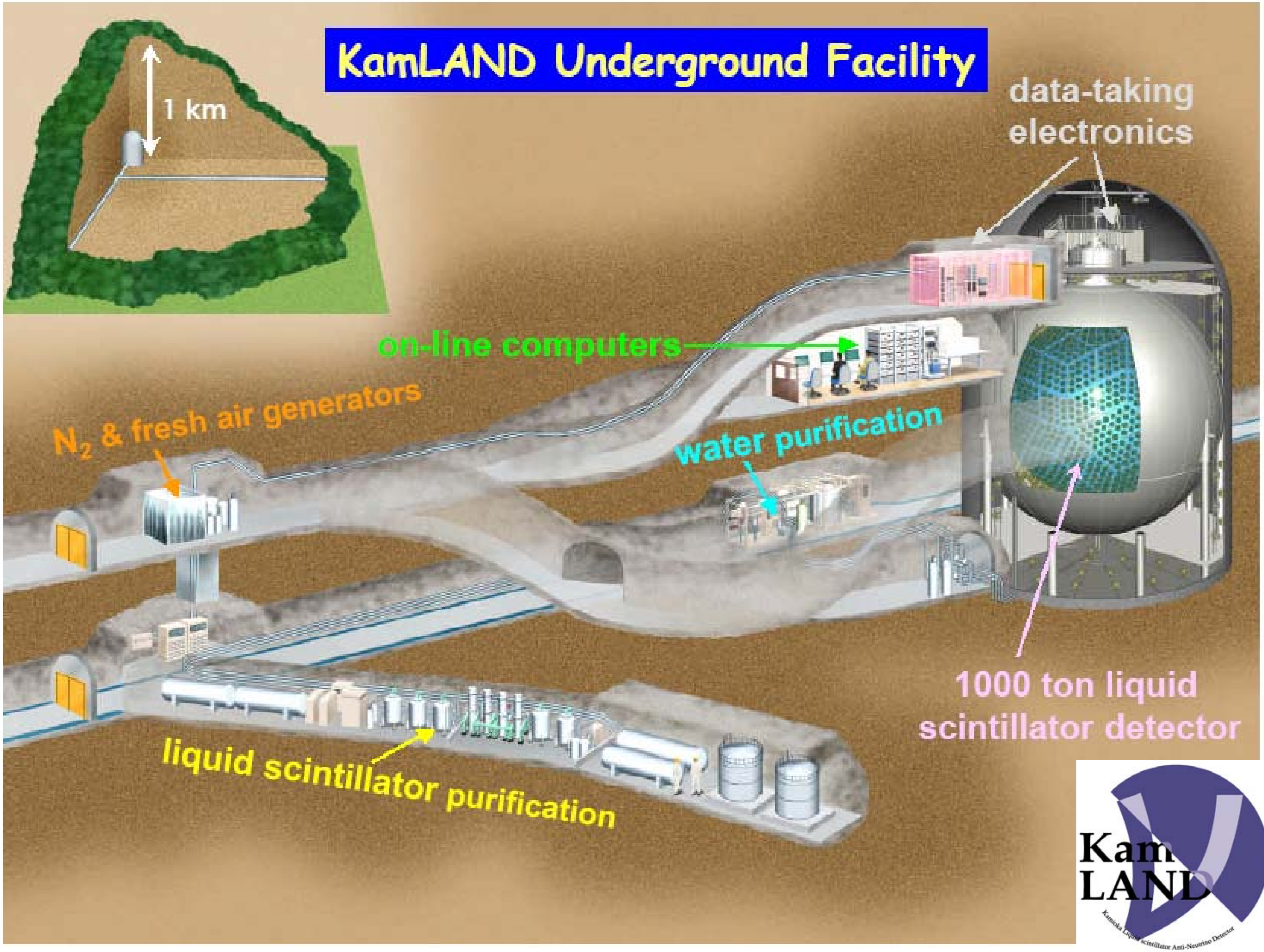
International Nuclear Safety Center at ANL, Dec 1999



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

KamLAND

KamLAND Underground Facility



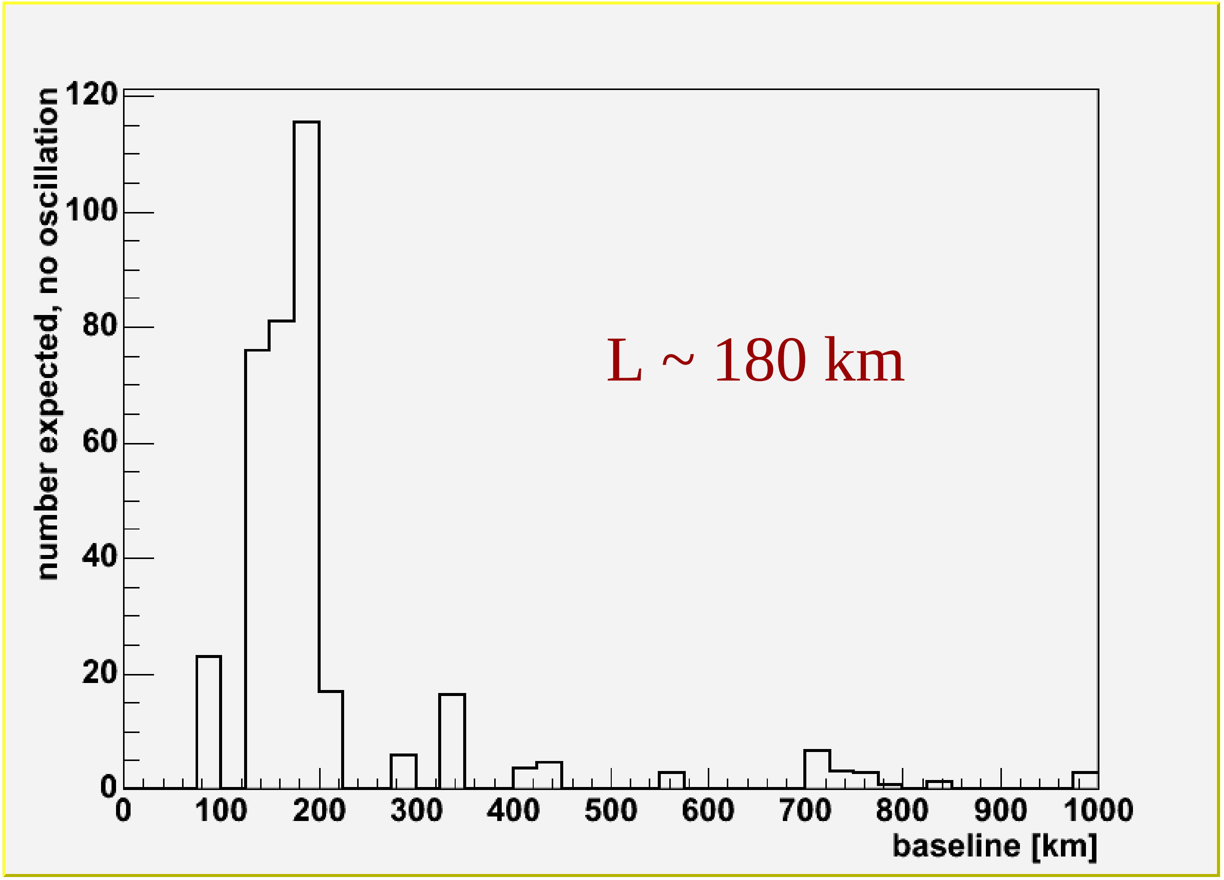
KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

Reactors contributing to antineutrino flux at KAMLAND

Site		Dist (km)	Cores (#)	P_{therm} (GW)	Flux $(cm^{-2}\,s^{-1})$	Rate noosc* $(yr^{-1}\,kt^{-1})$
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



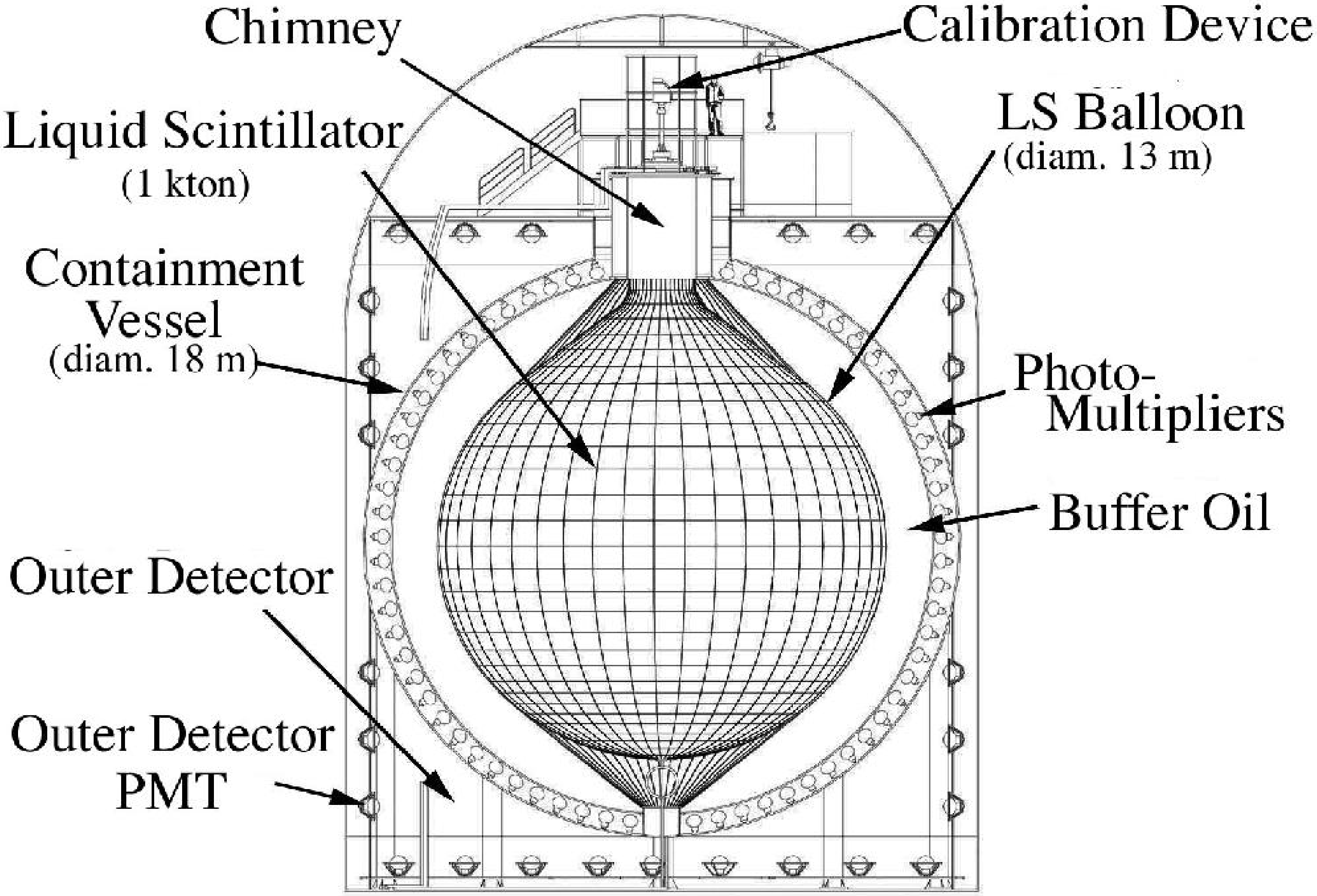
L ~ 180 km

Korean reactors:
3.4±0.3%

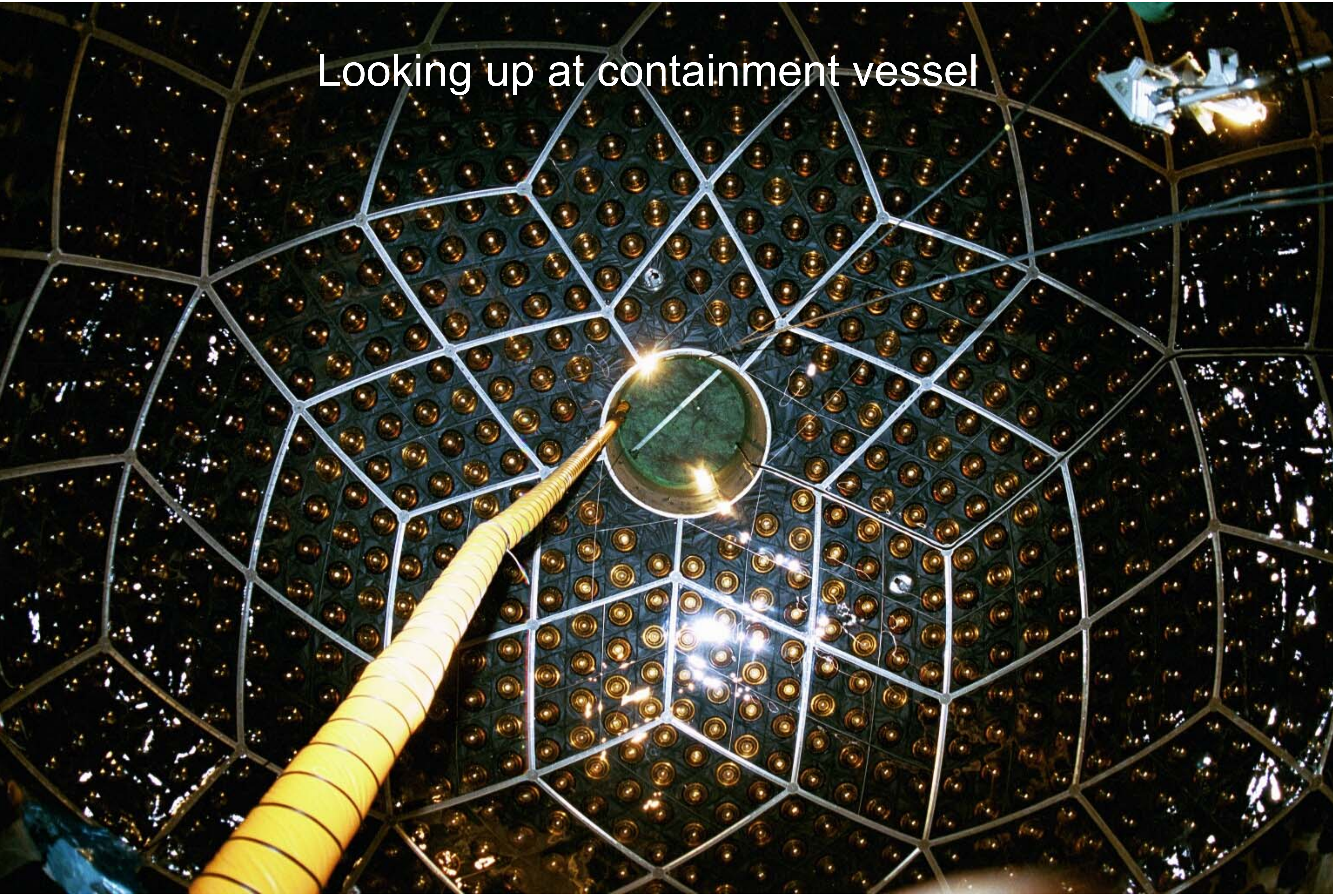
Rest of the world
+JP research reactors:
1.1±0.5%

Japanese spent fuel:
0.04±0.02%

KAMLAND Detector



Looking up at containment vessel

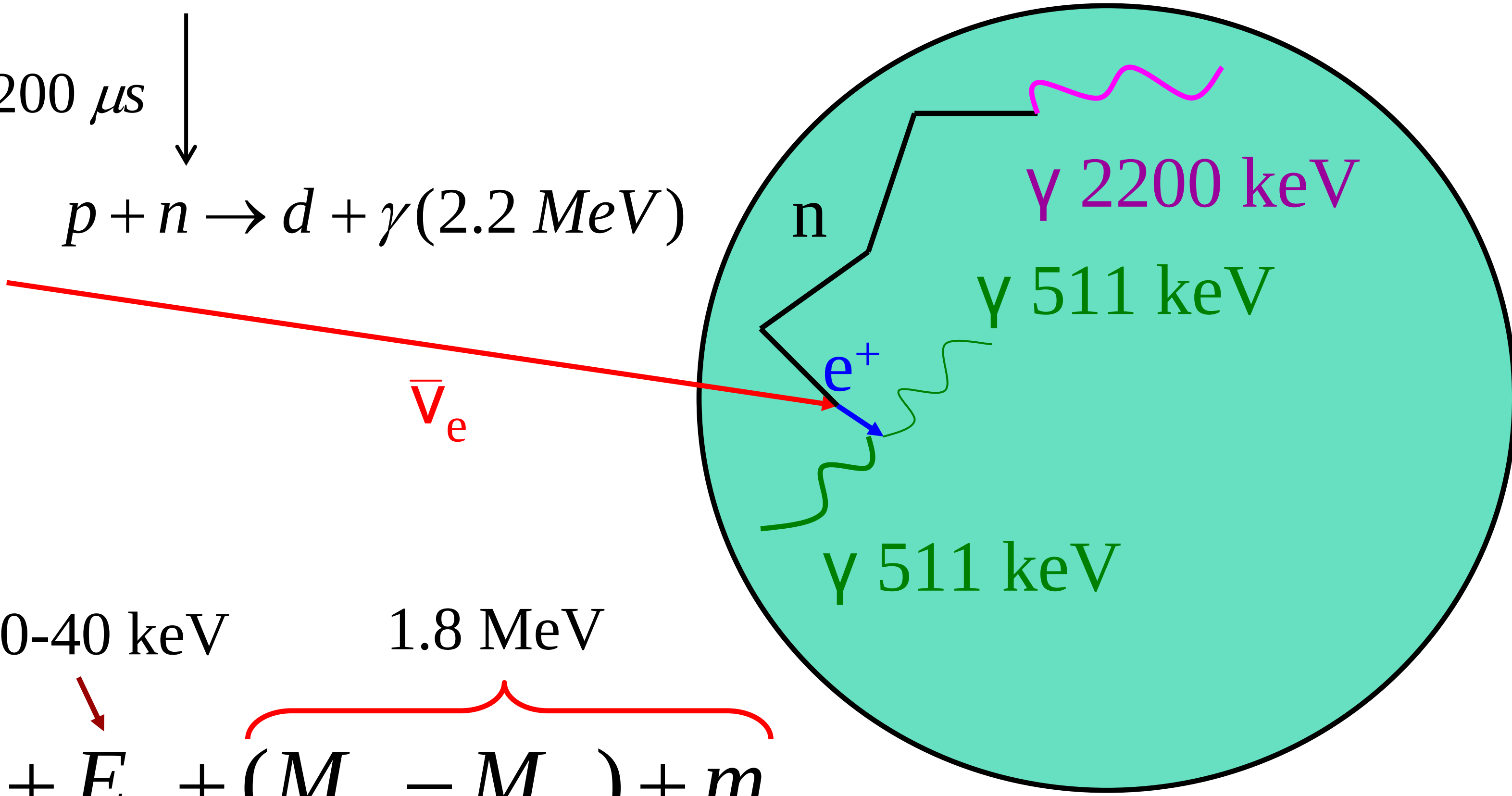


Antineutrino signature: coincidence between prompt e$^+$ and delayed neutron capture on hydrogen

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

$$\tau \approx 200\ \mu s \quad \downarrow$$

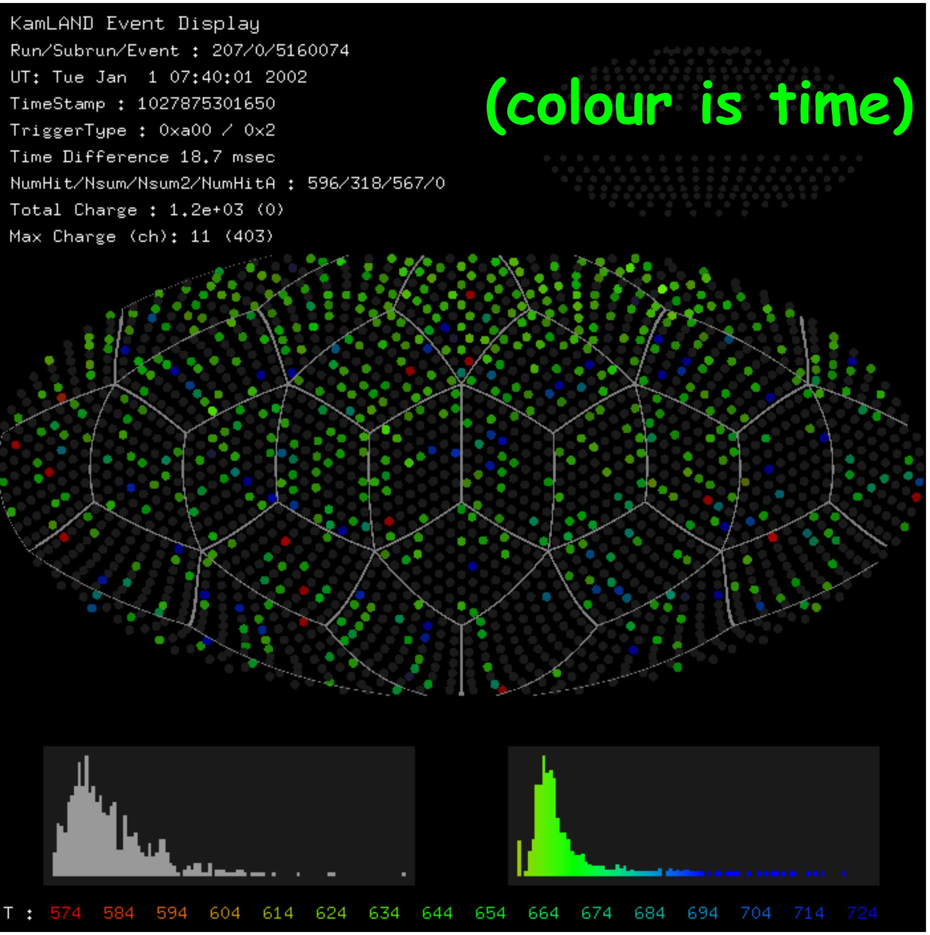
$$p + n \rightarrow d + \gamma(2.2\ MeV)$$



$$E_{\bar{\nu}} \cong E_{e^+} + \overset{\text{10-40 keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{\text{1.8 MeV}}$$

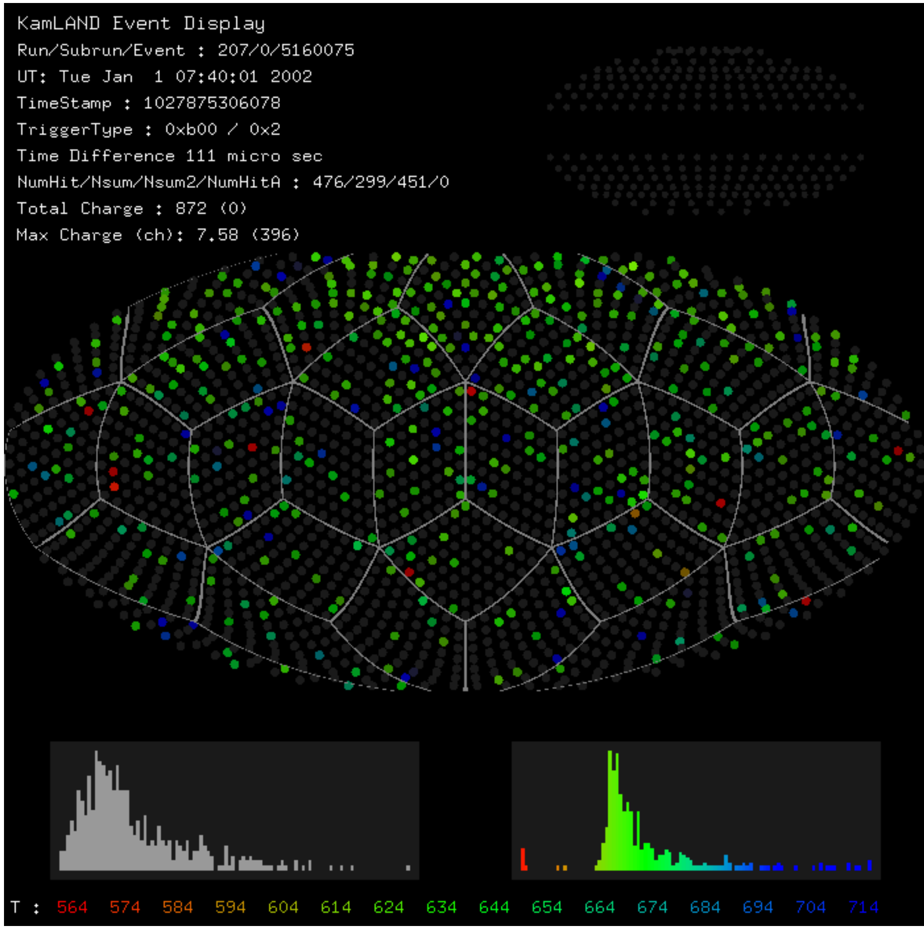
Including E from e$^+$ annihilation, $E_{prompt} = E_{\nu} - 0.8$ MeV

Anti-Neutrino Candidate



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)
```

(colour is time)



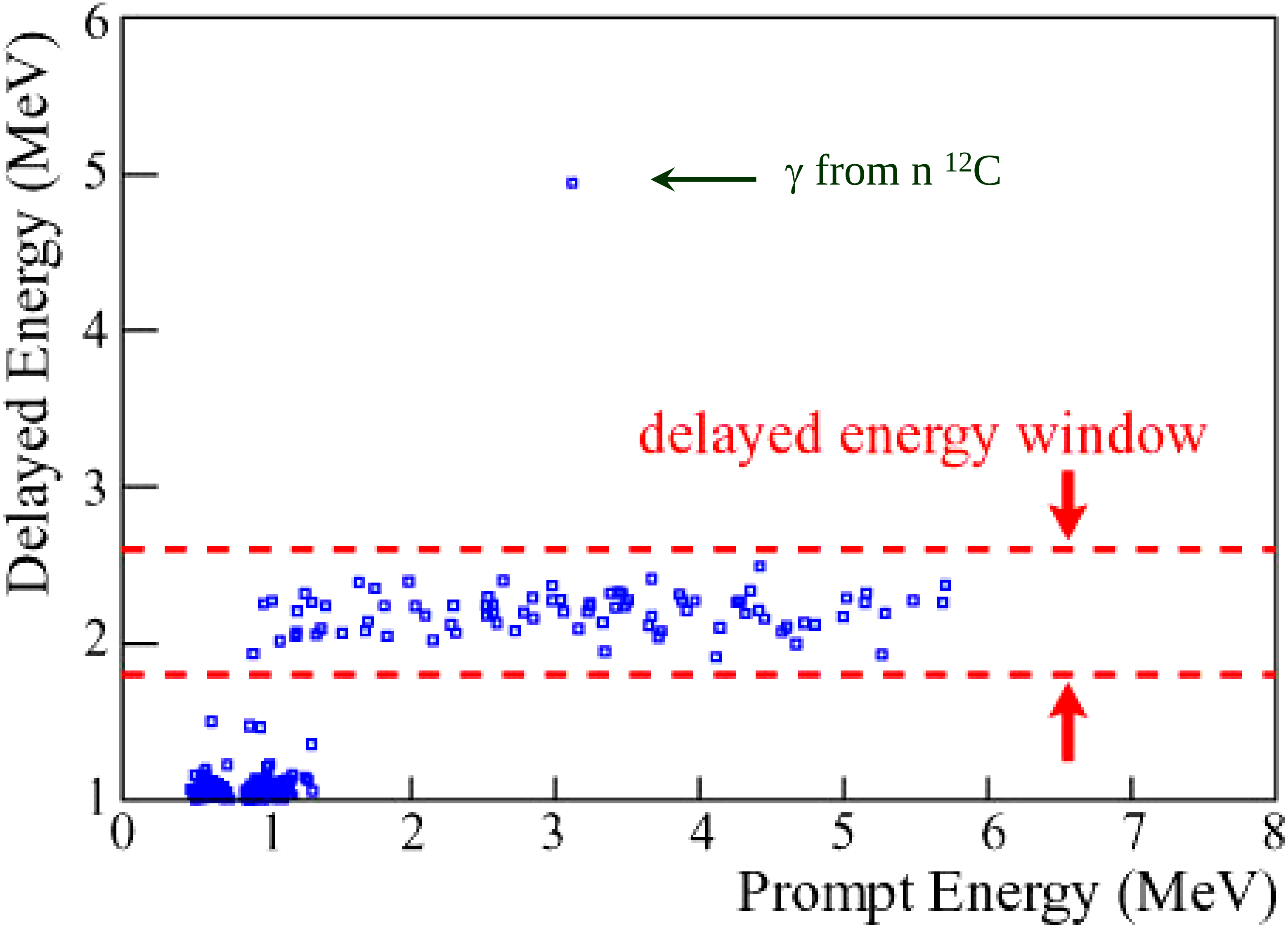
```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.58 (396)
```

Prompt Signal
E = 3.20 MeV

Δt = 111 ms
ΔR = 34 cm

Delayed Signal
E = 2.22 MeV

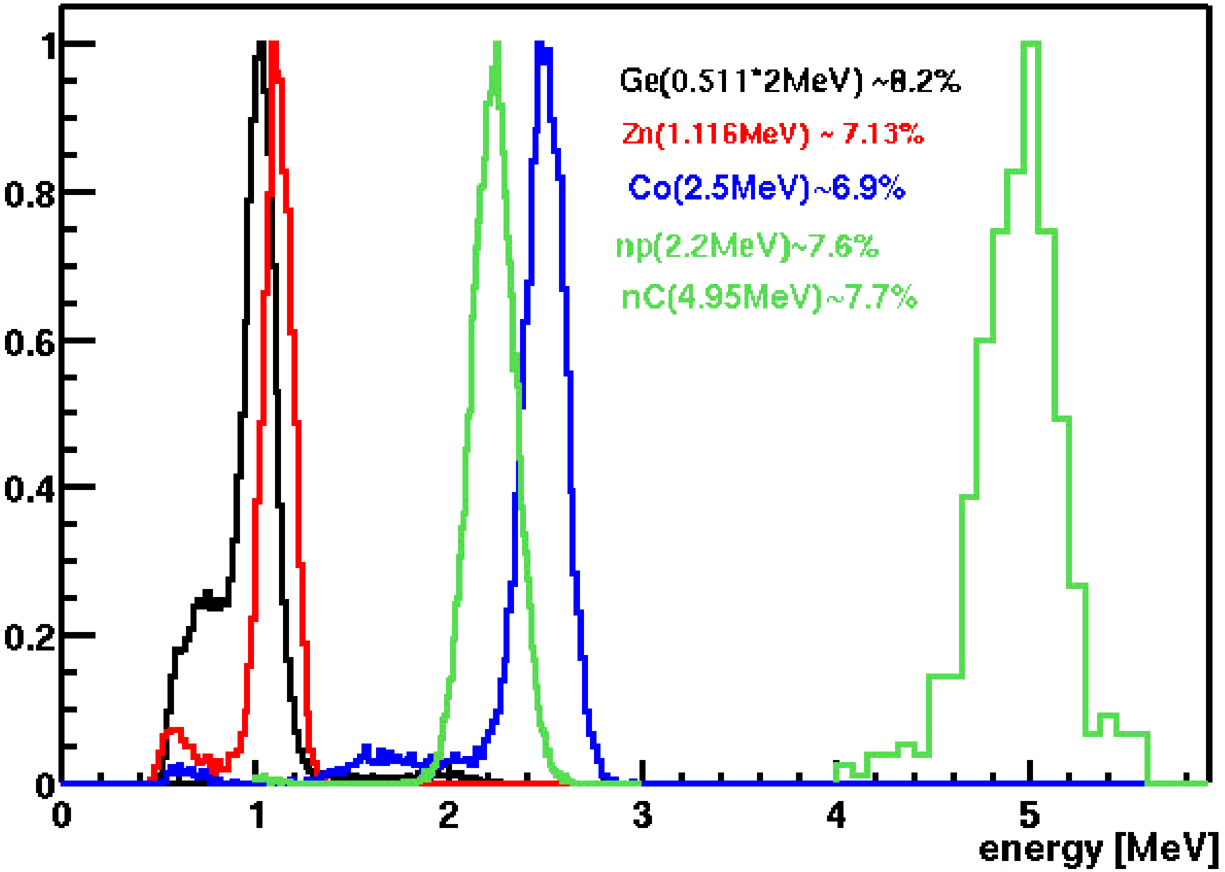
Delayed vs. Prompt Energy for $\bar{\nu}_e$ Candidates



γ from n ^{12}C

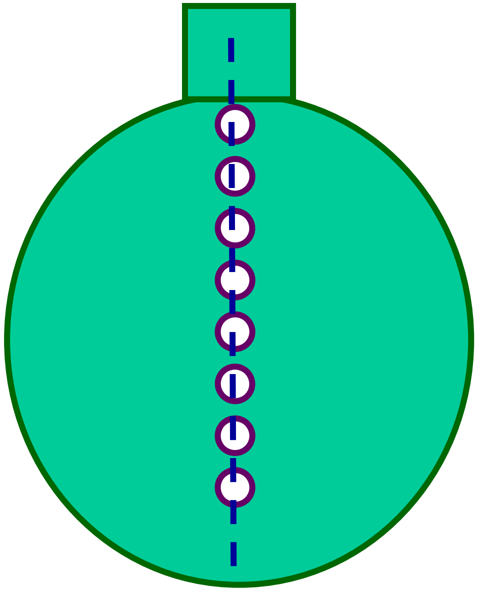
delayed energy window

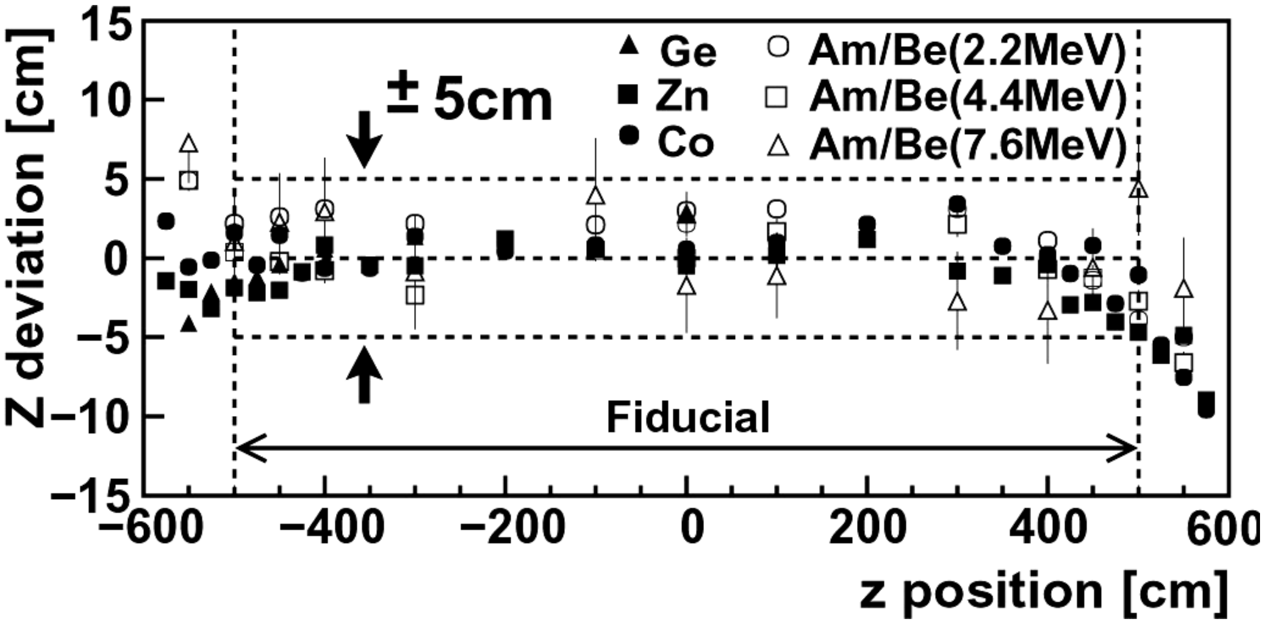
Energy Calibration with Sources



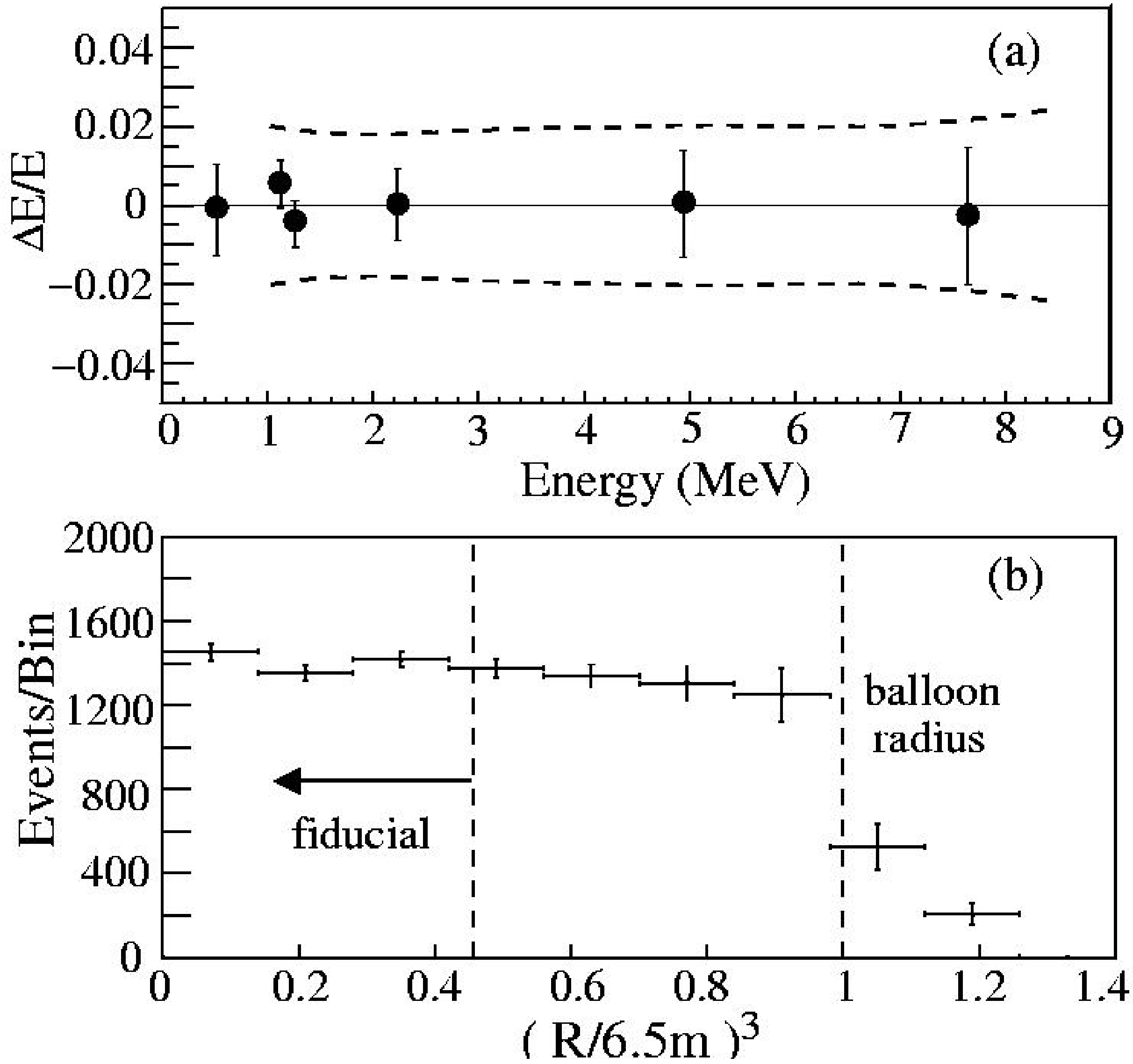
ΔE/E ~ 7.5% /√E , Light Yield: 260 p.e./MeV

Test of Position Reconstruction Along Vertical Axis





Detector Performance



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

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

Event Selection Requirements

- Fiducial volume: $R < 5$ m
- Time correlation: 0.5 μsec $< \Delta t <$ 660 μsec
- Vertex correlation: $\Delta R < 1.6$ m
- Delayed energy: 1.8 MeV $< E_{delay} <$ 2.6 MeV
- Prompt energy: $E_{prompt} >$ 2.6 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 %

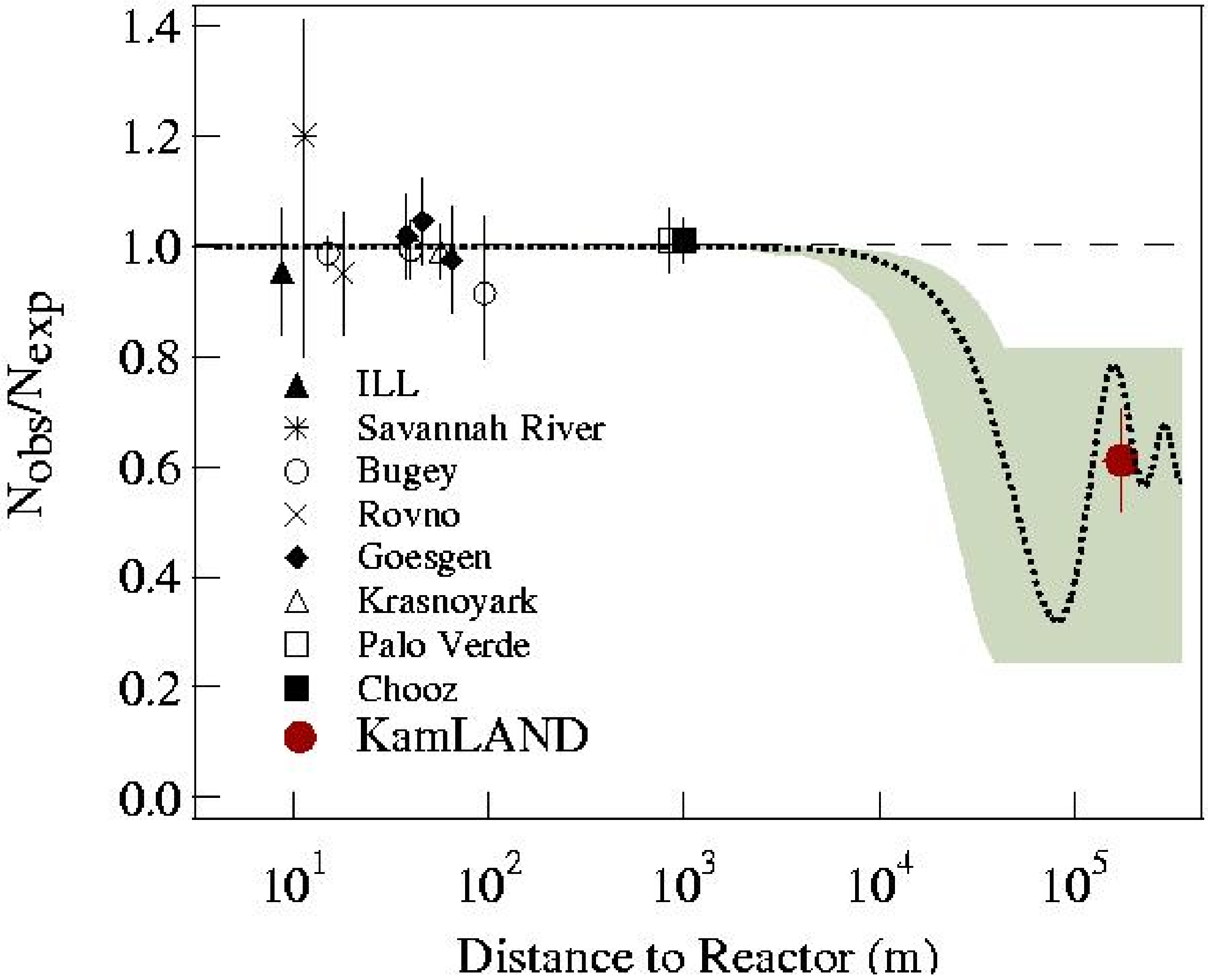
Observed Event Rates with $E_{prompt} > 2.6$ *MeV*
(Data collected from March--October 2002)

Observed	54 events
Expected	86.8 ± 5.6 events
Total Background	1 ± 1 events

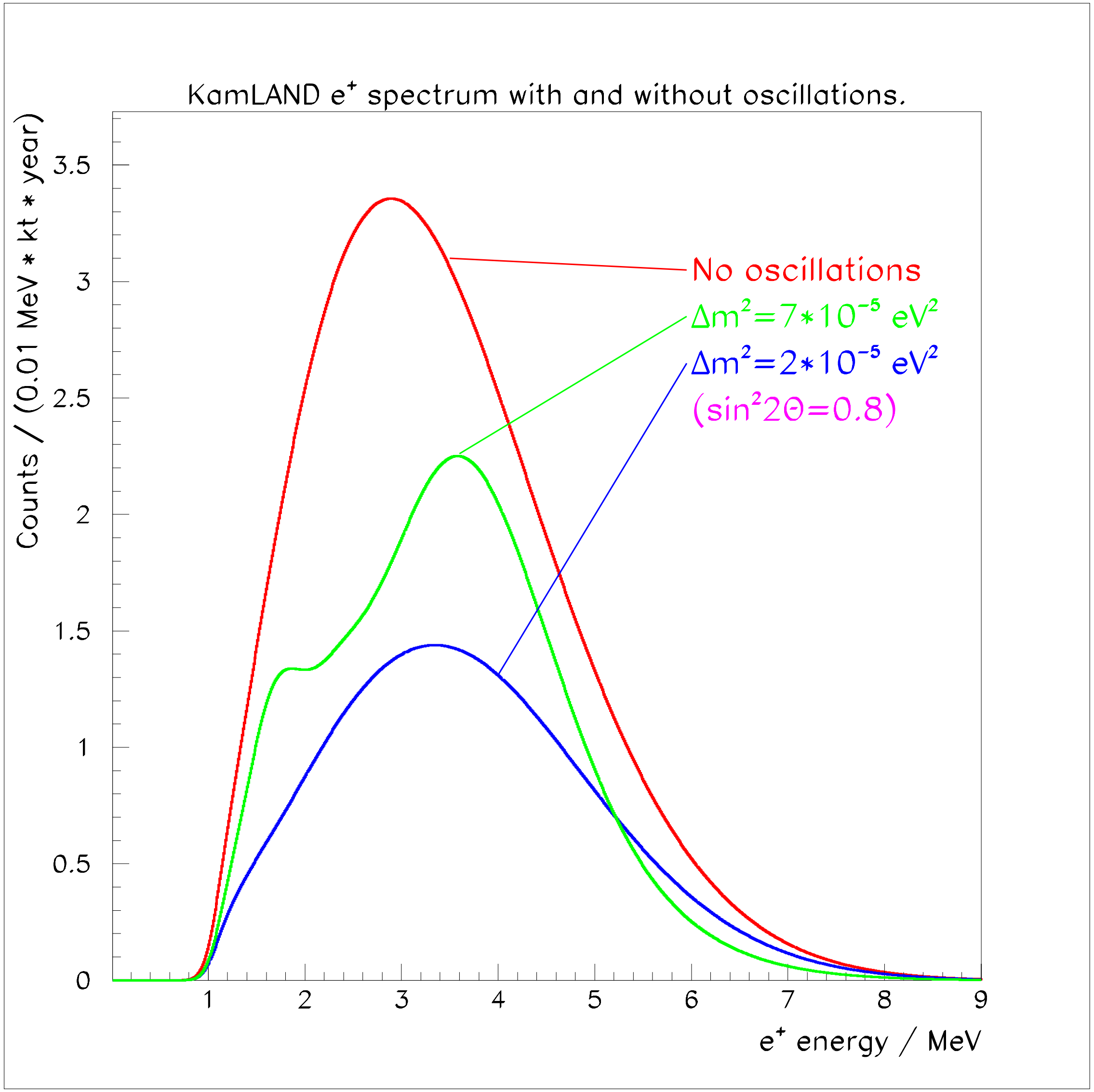
accidental	0.0086 ± 0.0005
$^{9}Li/^{8}He$	0.94 ± 0.85
fast neutron	< 0.5

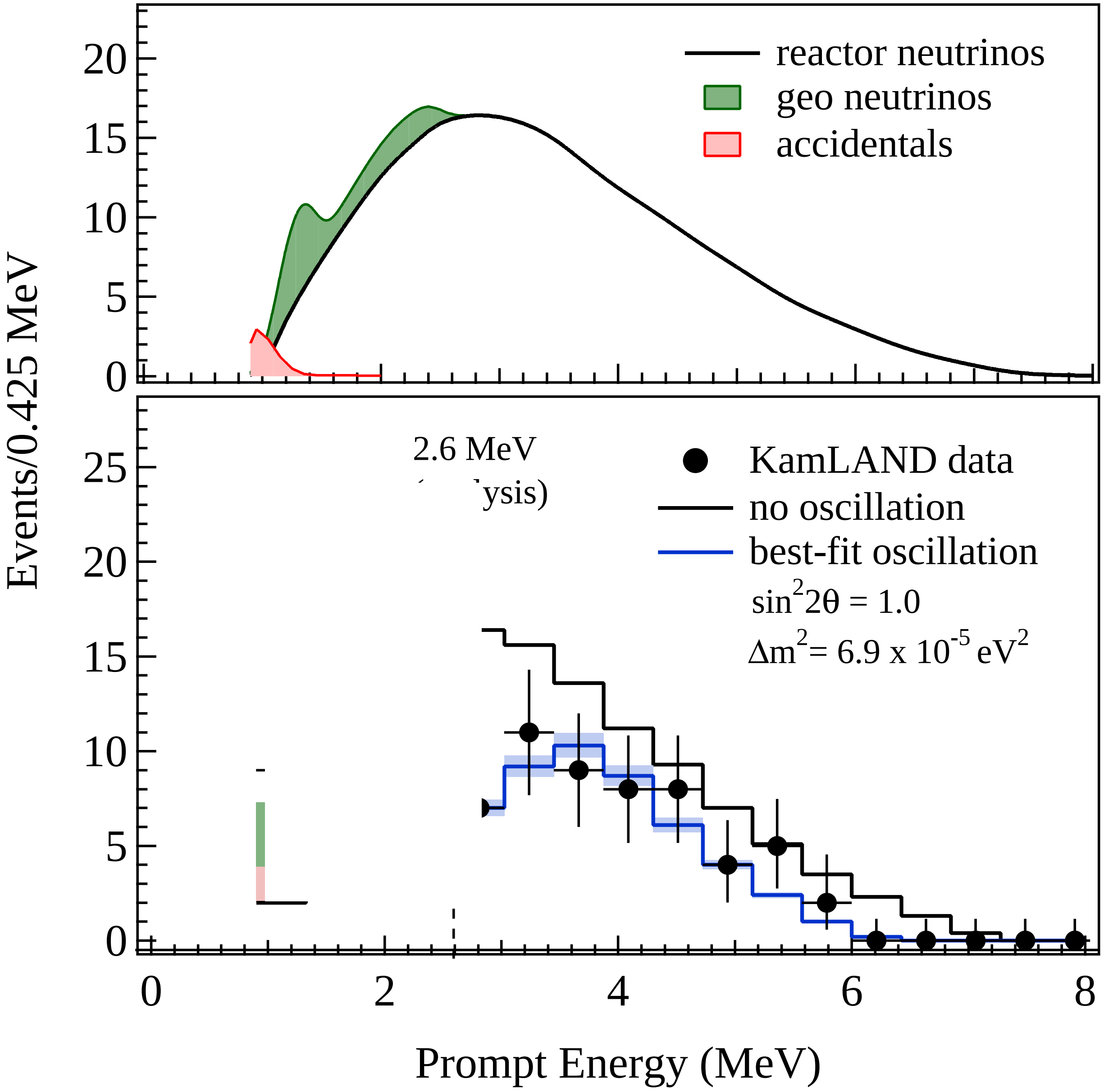
→ Inconsistent with $1/R^2$ flux dependence at 99.95 % c.l.

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



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.

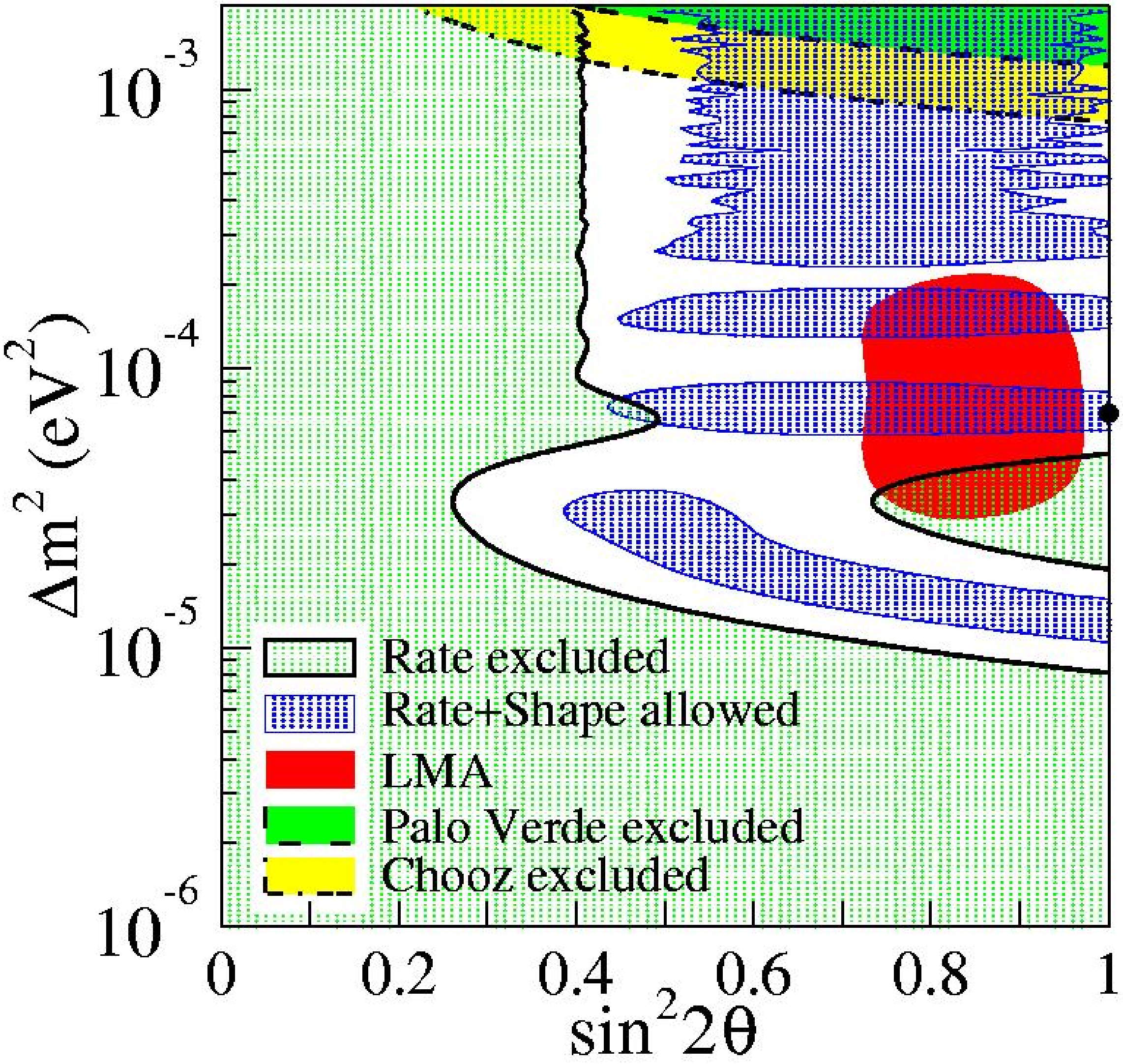
Need more data.

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

Best fit :

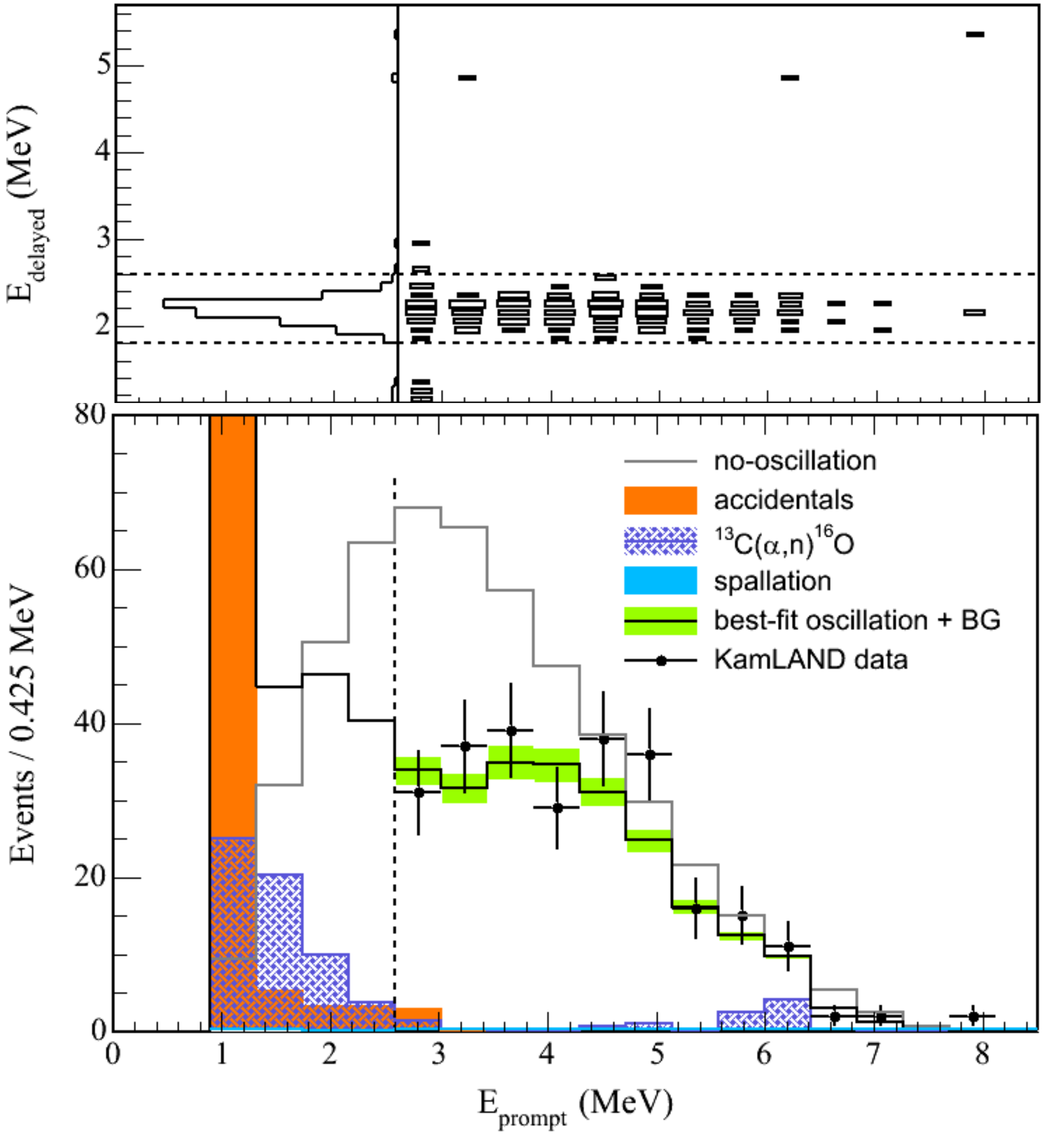
$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$

$\sin^2 2\theta = 1.0$



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

(Data collected from March 2002 to January 2004)

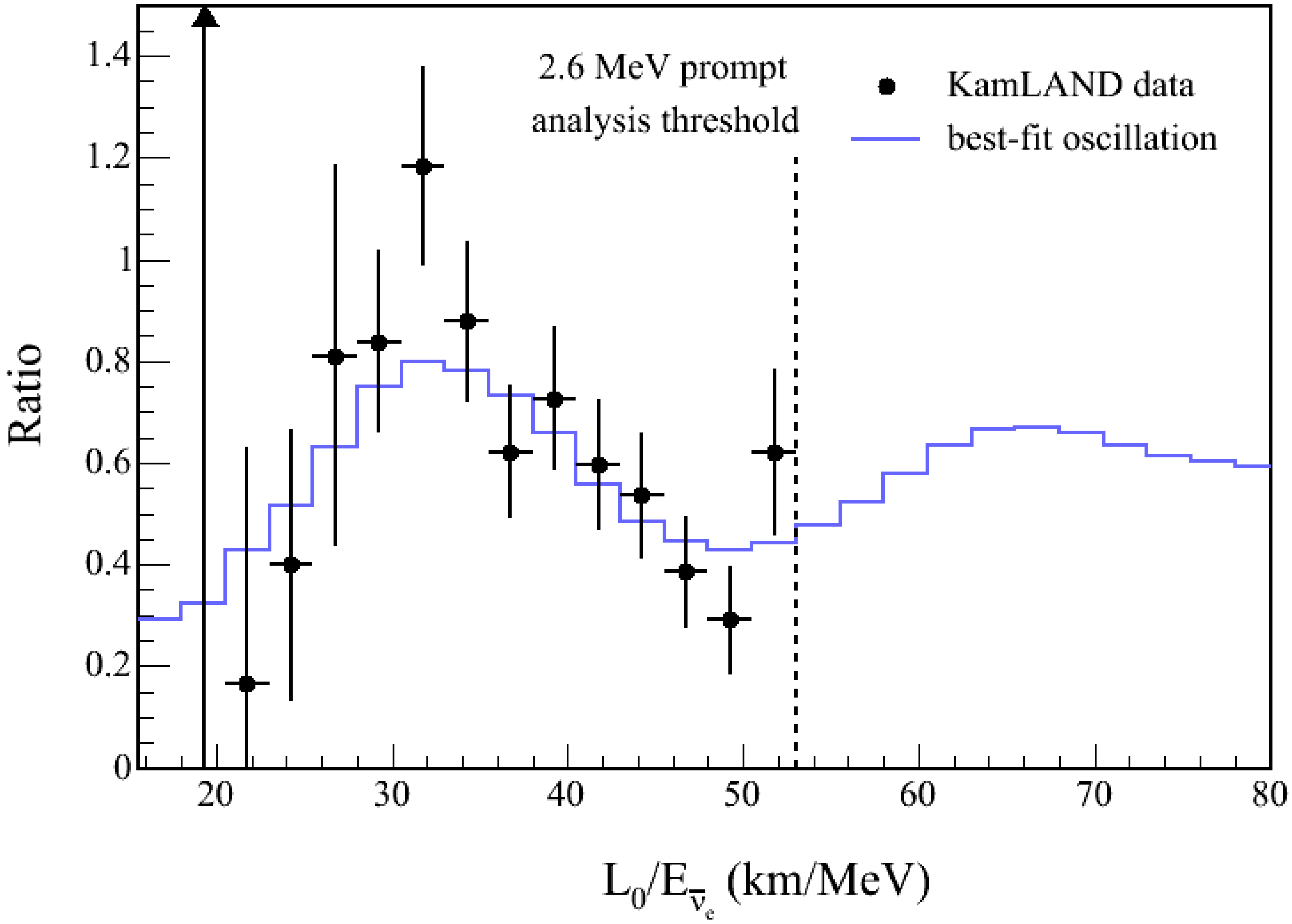


Expected w/o oscillations:
365 ± 24 (syst) events

Observed:
258 events

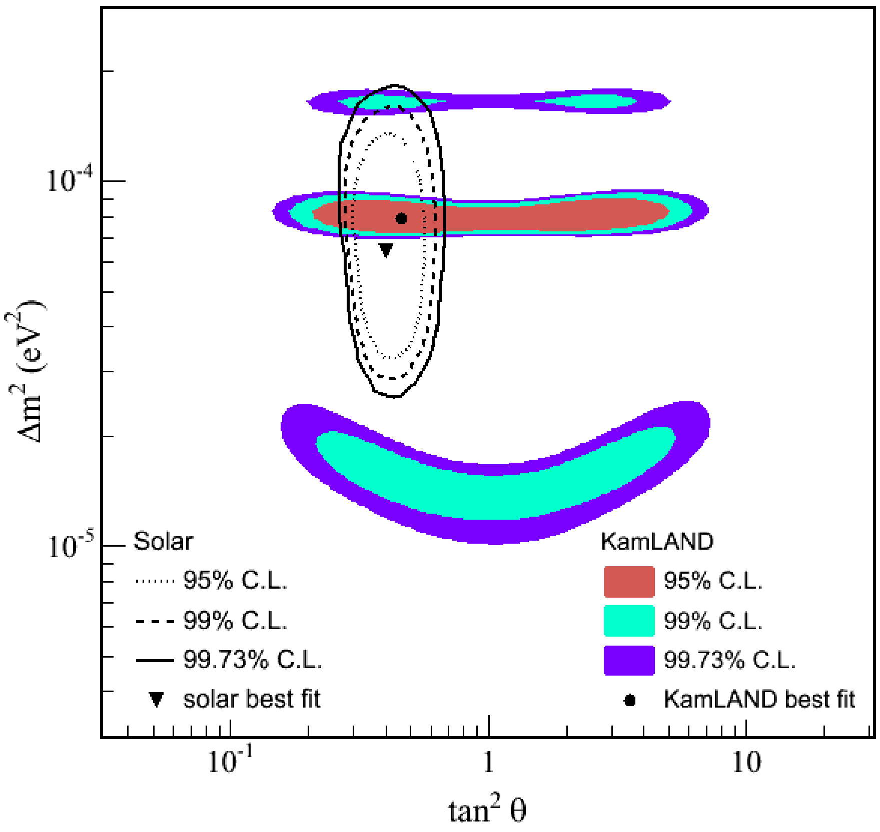
No oscillation shape only consistent with observed spectrum at 0.5% level.

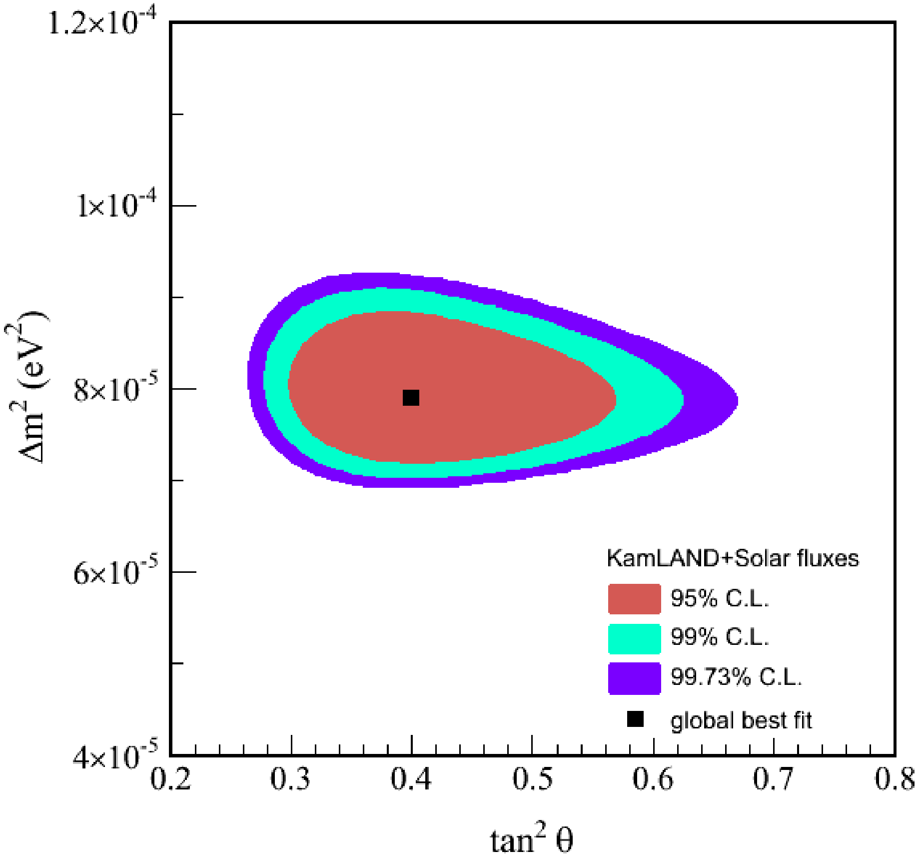
Observed ν spectrum / expectation with no oscillations



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

Allowed Values for Δm^2_{12} and θ_{12}





Best fit (assuming CPT):

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