KamLAND
update

KamLAND: Kamioka Liquid-Scintillator Anti-Neutrino Detector

Stuart Freedman
University of California at Berkeley
and
Lawrence Berkeley National Laboratory

NSAC
Bethesda
July 21, 2006

Essentials of Neutrino Oscillations

m_2c^2

m_1c^2

$$|\nu_e\rangle = |\psi_{\nu_e}(0)\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\psi_{\nu_e}(t)\rangle = \cos\theta\, e^{-\frac{i m_1 c^2 t}{\hbar}}\,|\nu_1\rangle + \sin\theta\, e^{-\frac{i m_2 c^2 t}{\hbar}}\,|\nu_2\rangle$$

$$P_{ee}(t) = \left|\langle\psi_{\nu_e}(0)|\psi_{\nu_e}(t)\rangle\right|^2 = \left|\cos^2\theta\, e^{-\frac{i m_1 c^2 t}{\hbar}} + \sin^2\theta\, e^{-\frac{i m_2 c^2 t}{\hbar}}\right|^2$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar} t\right)$$

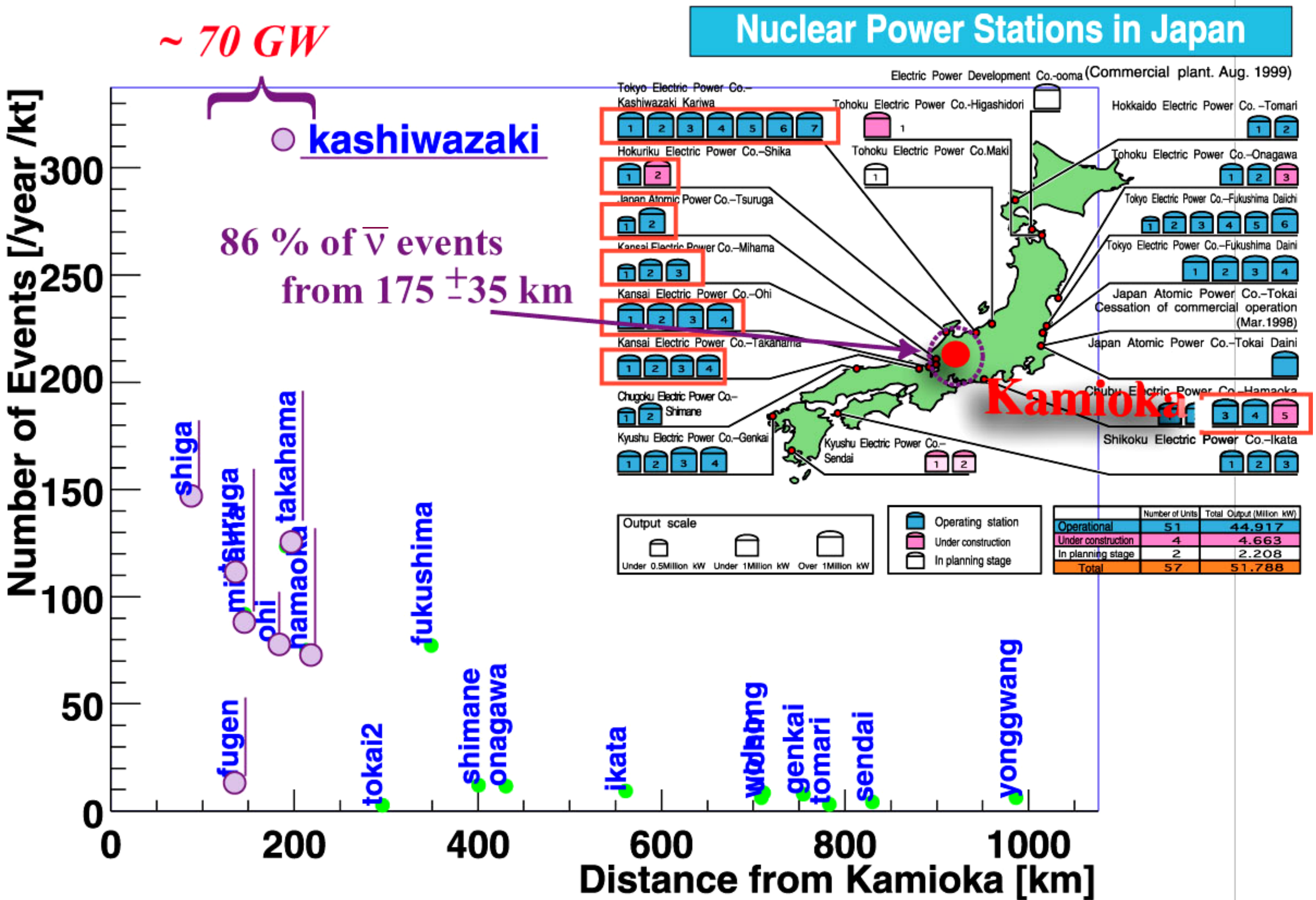
$$t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \qquad \gamma = \frac{E}{mc^2} \qquad m = \frac{m_1 + m_2}{2}$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)c^4}{4\hbar c} \frac{L}{E}\right)$$

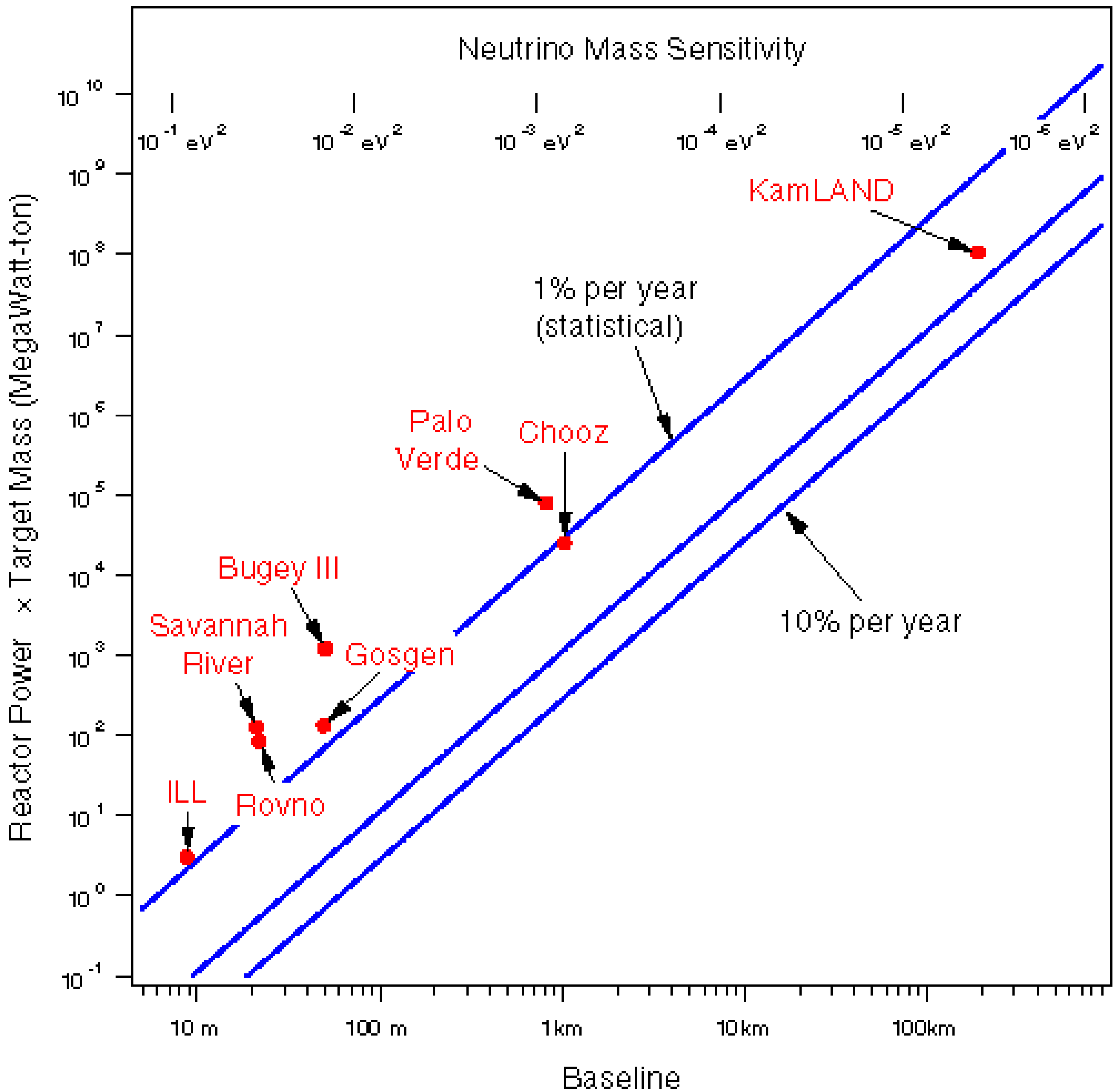
$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

20 % of world nuclear power

~ 70 GW



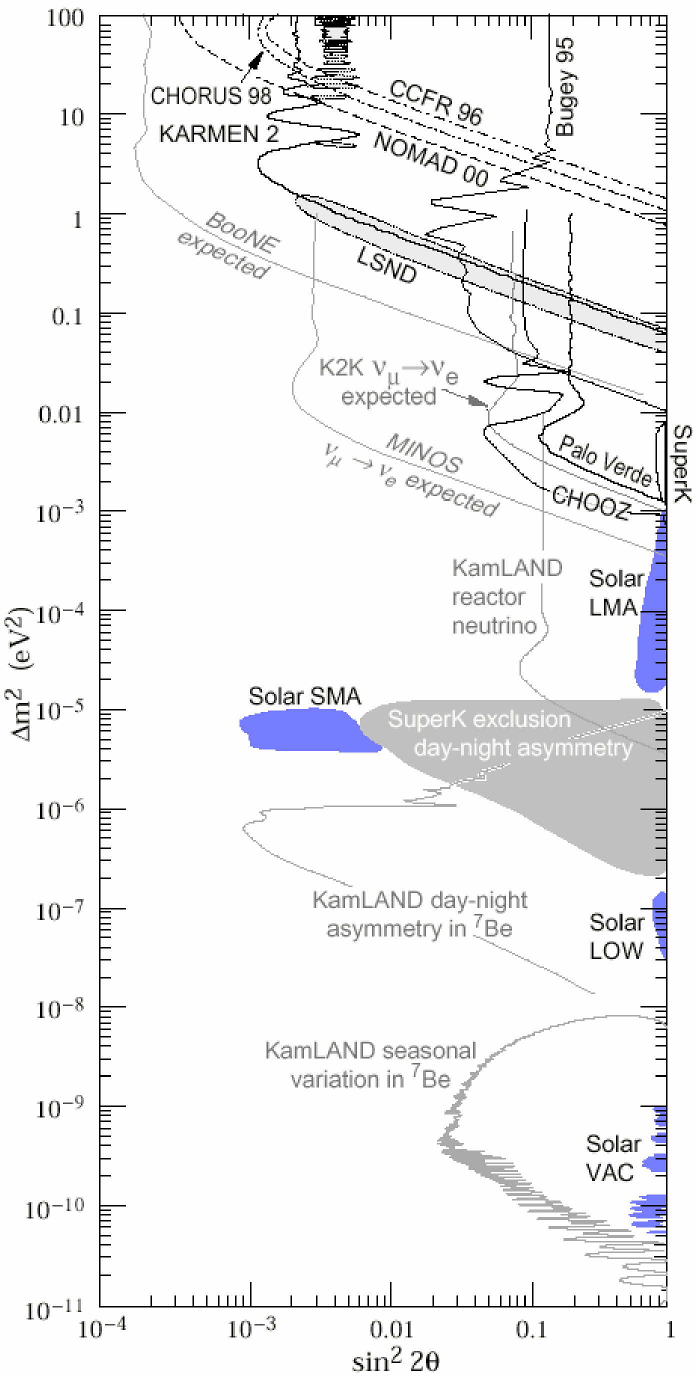
	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788



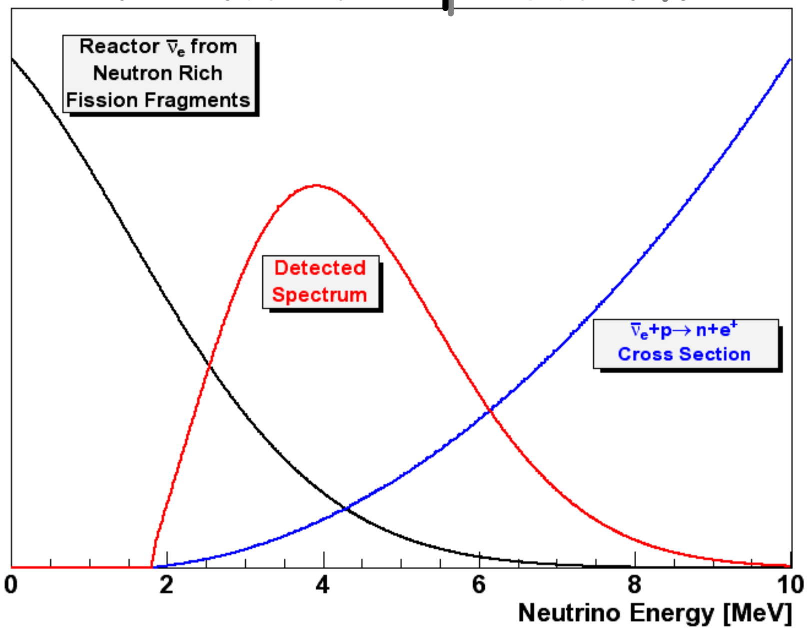
Long-Baseline Reactor-Anti-Neutrino Experiments

At the time the LRP was being drafted

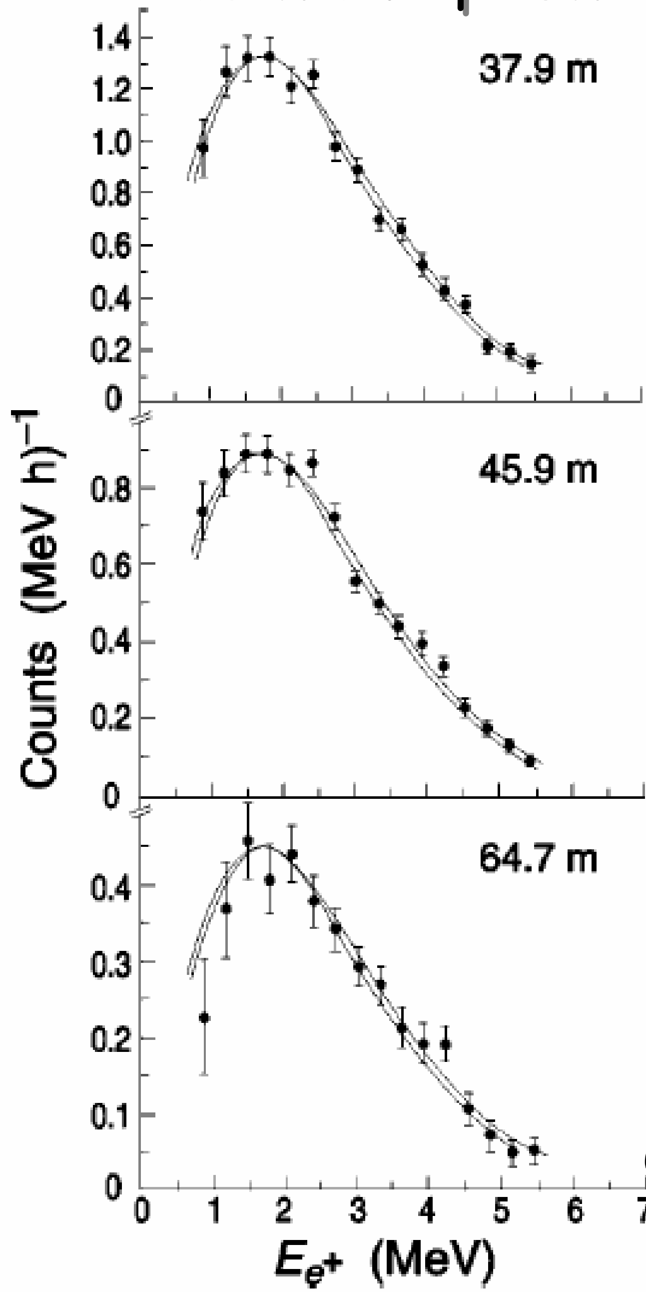
- The case for neutrino flavor change was compelling
- The case for neutrino oscillations was growing stronger
- Evidence of large mixing angles was mounting



Neutrino Spectrum



Positron Spectrum



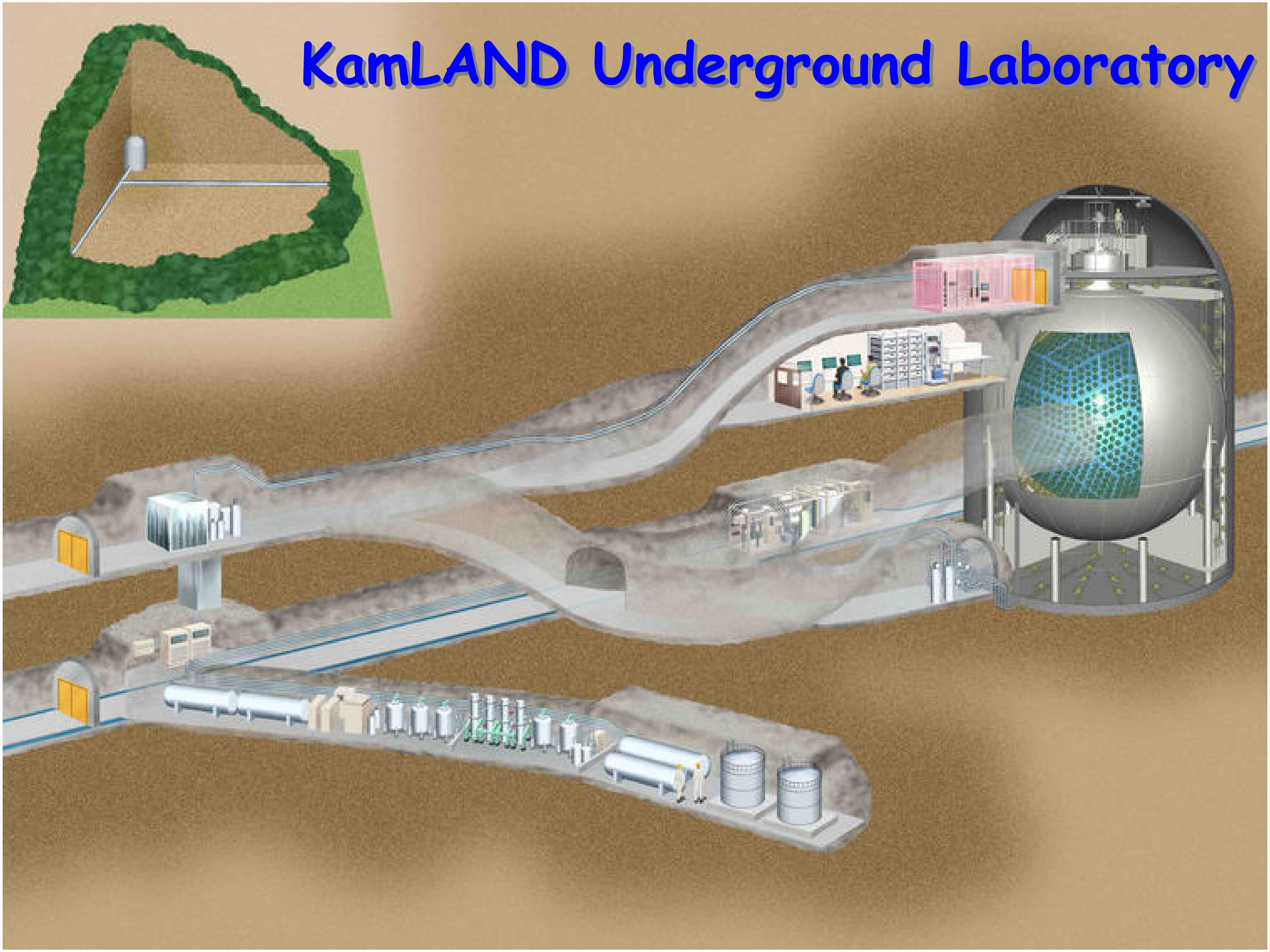
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

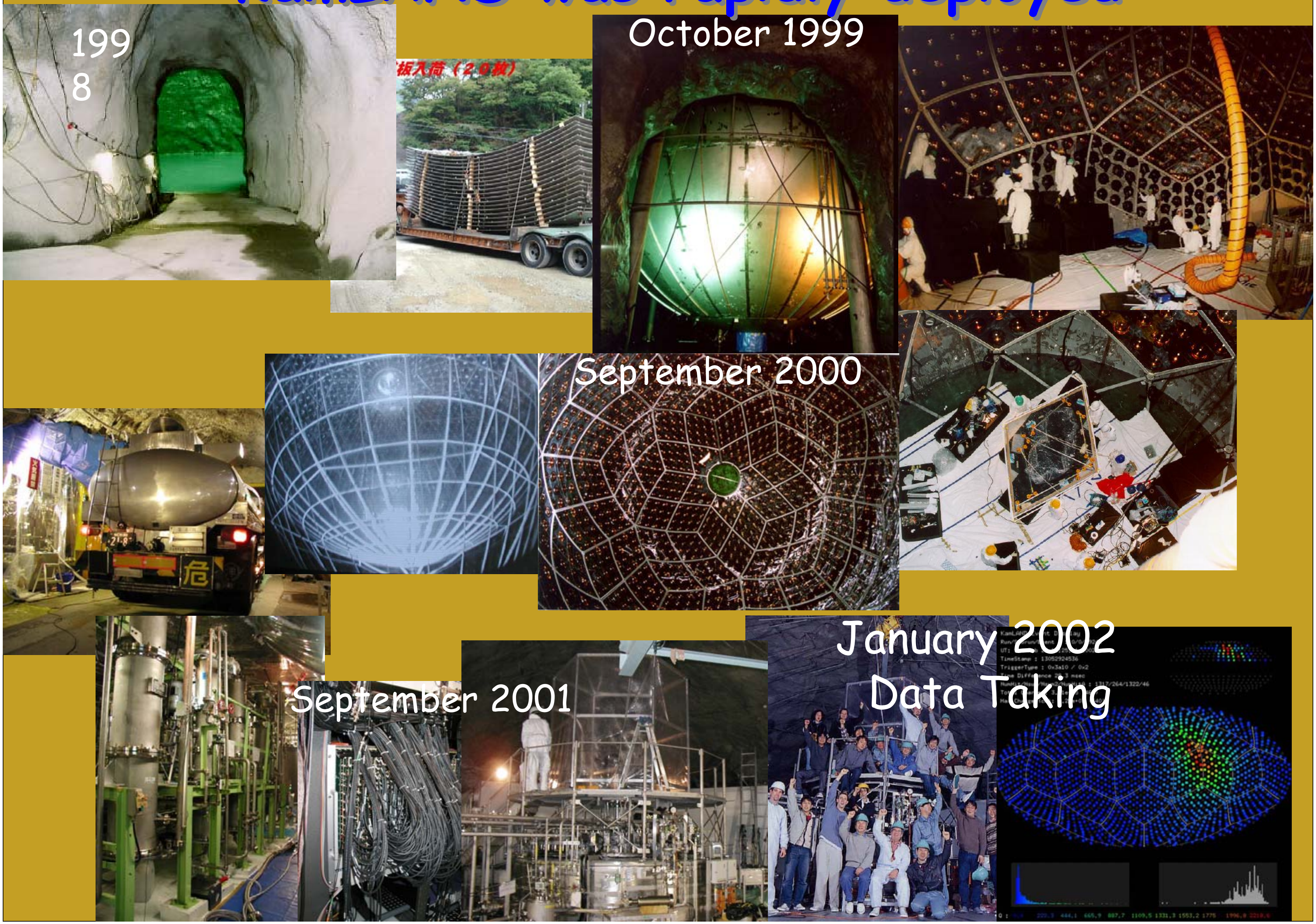
$$n + p \rightarrow d + \gamma (2.2\ MeV)$$

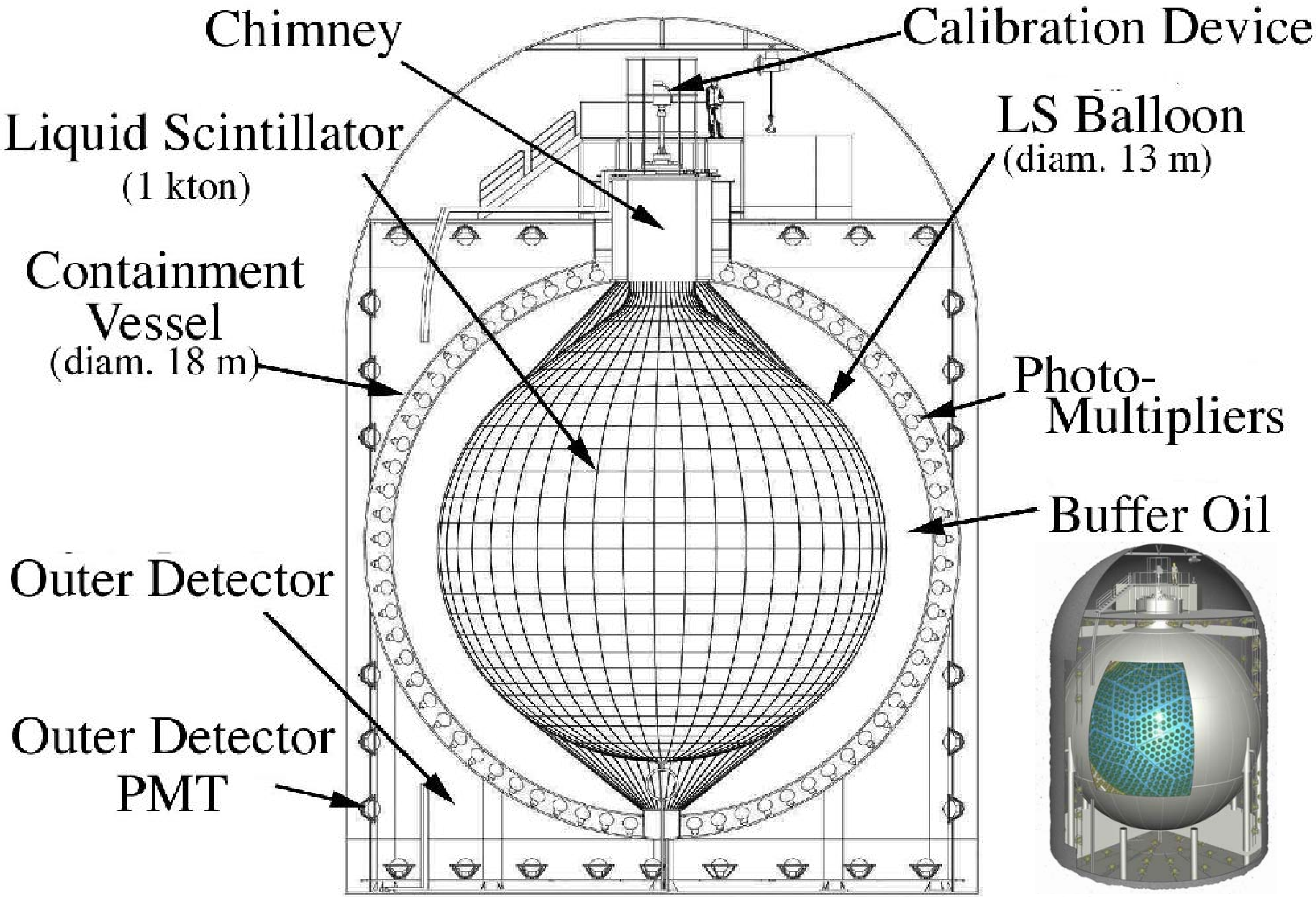
Goesgen

KamLAND Underground Laboratory

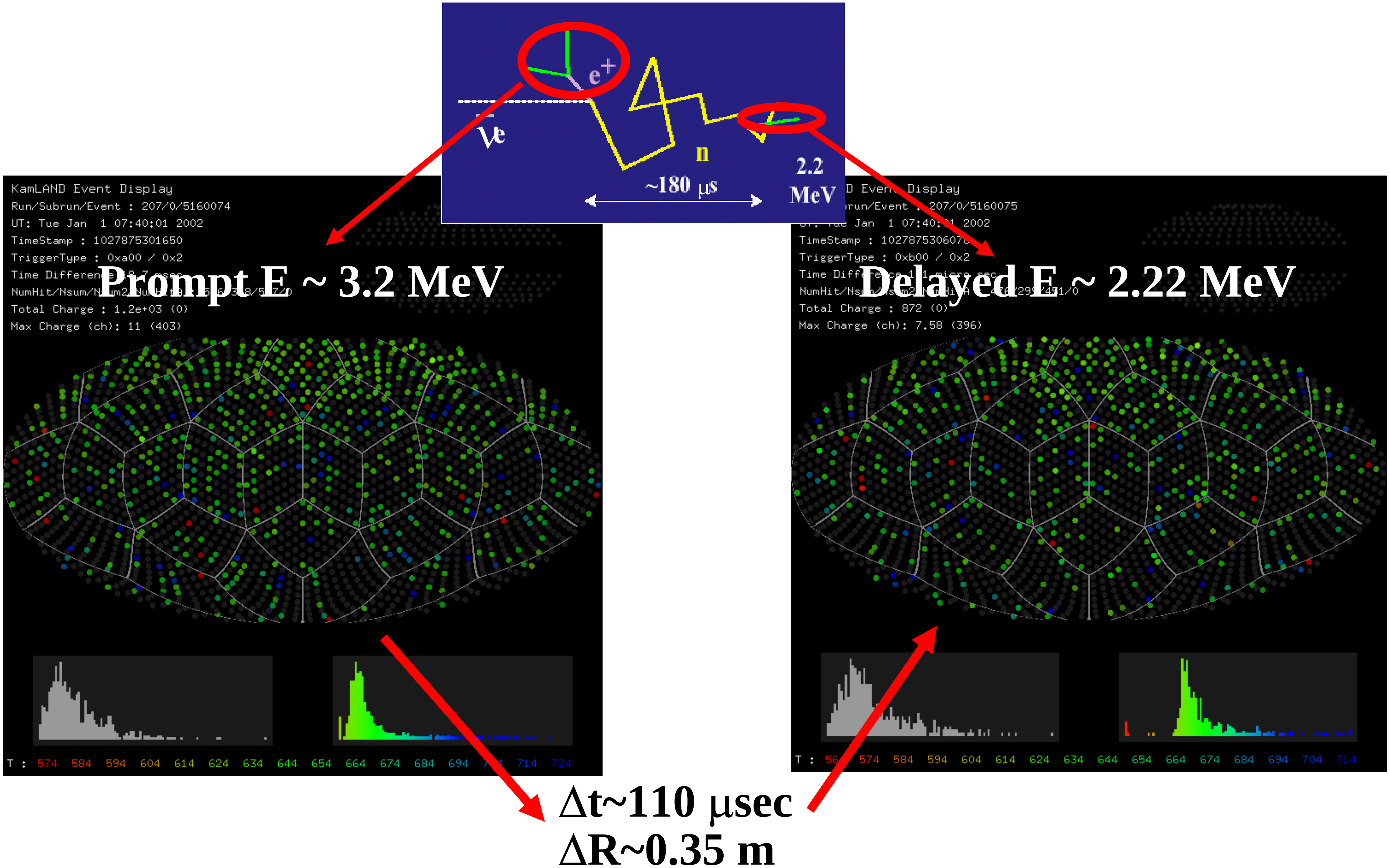


KamLAND was rapidly deployed





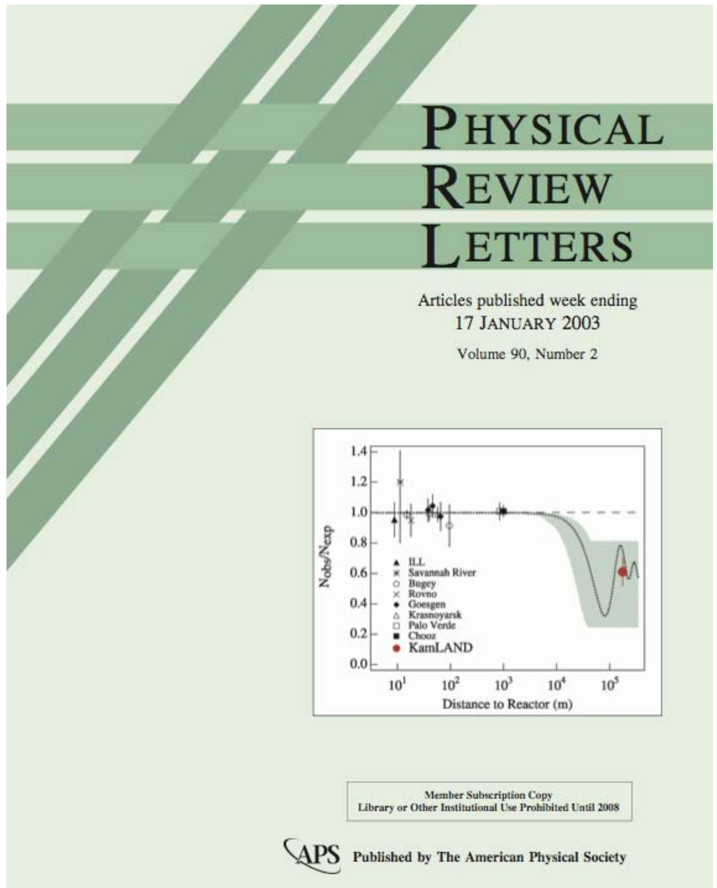
3.2 ton water veto



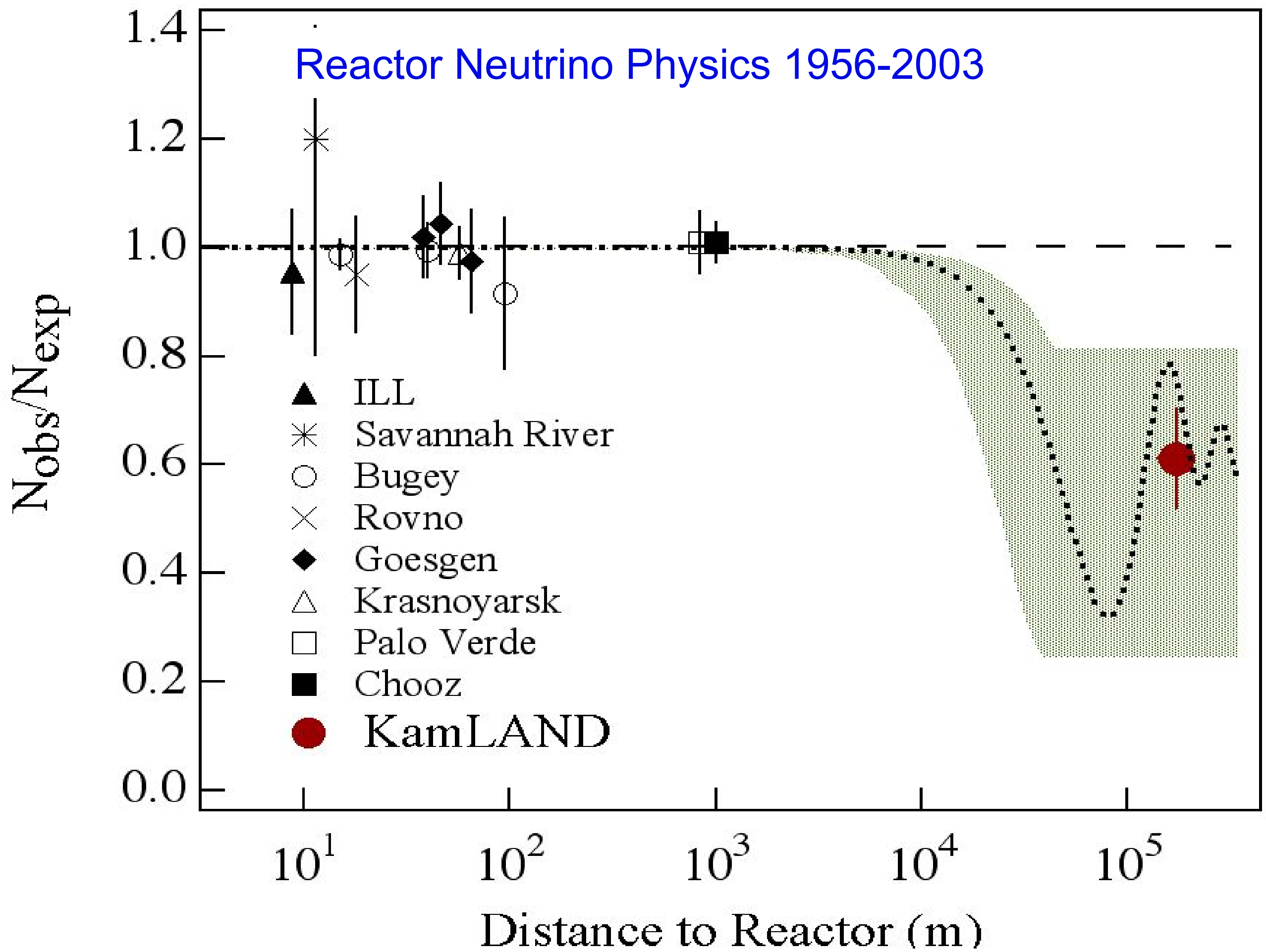
Candidate Neutrino Event

KamLAND's first reactor result

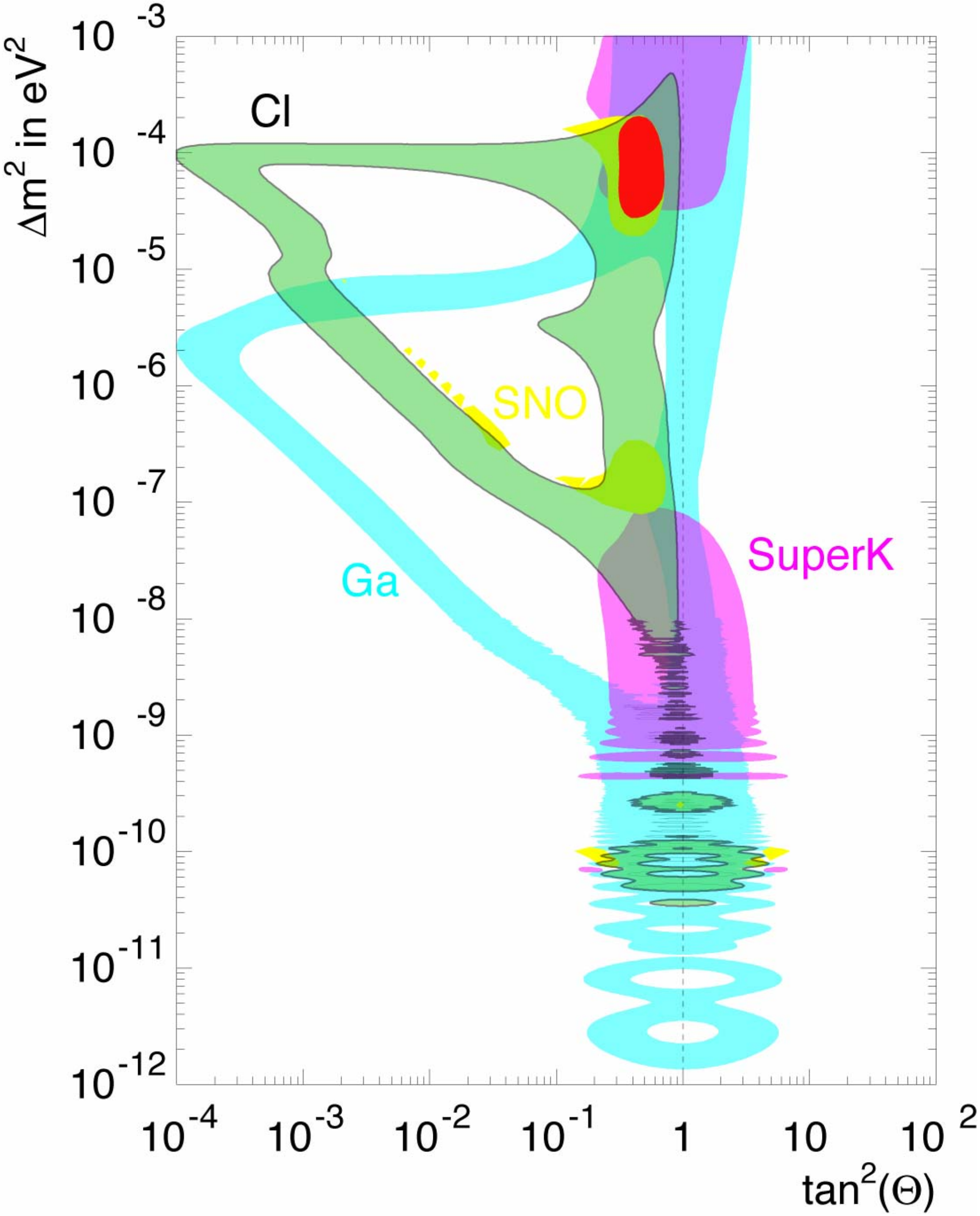
Phys. Rev. Lett. 90, 021802 (2003)
First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance



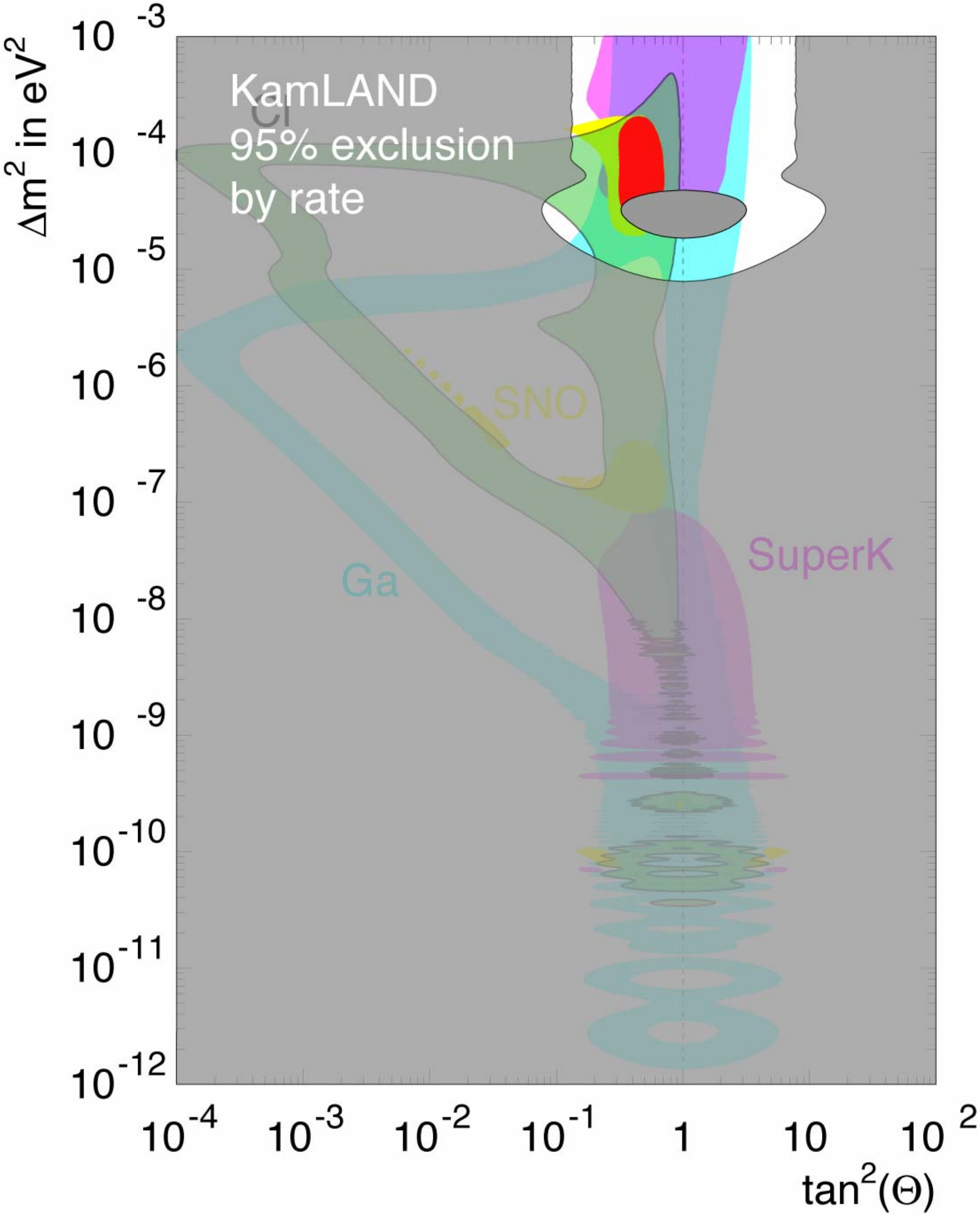
(most cited paper in physics, 2003)



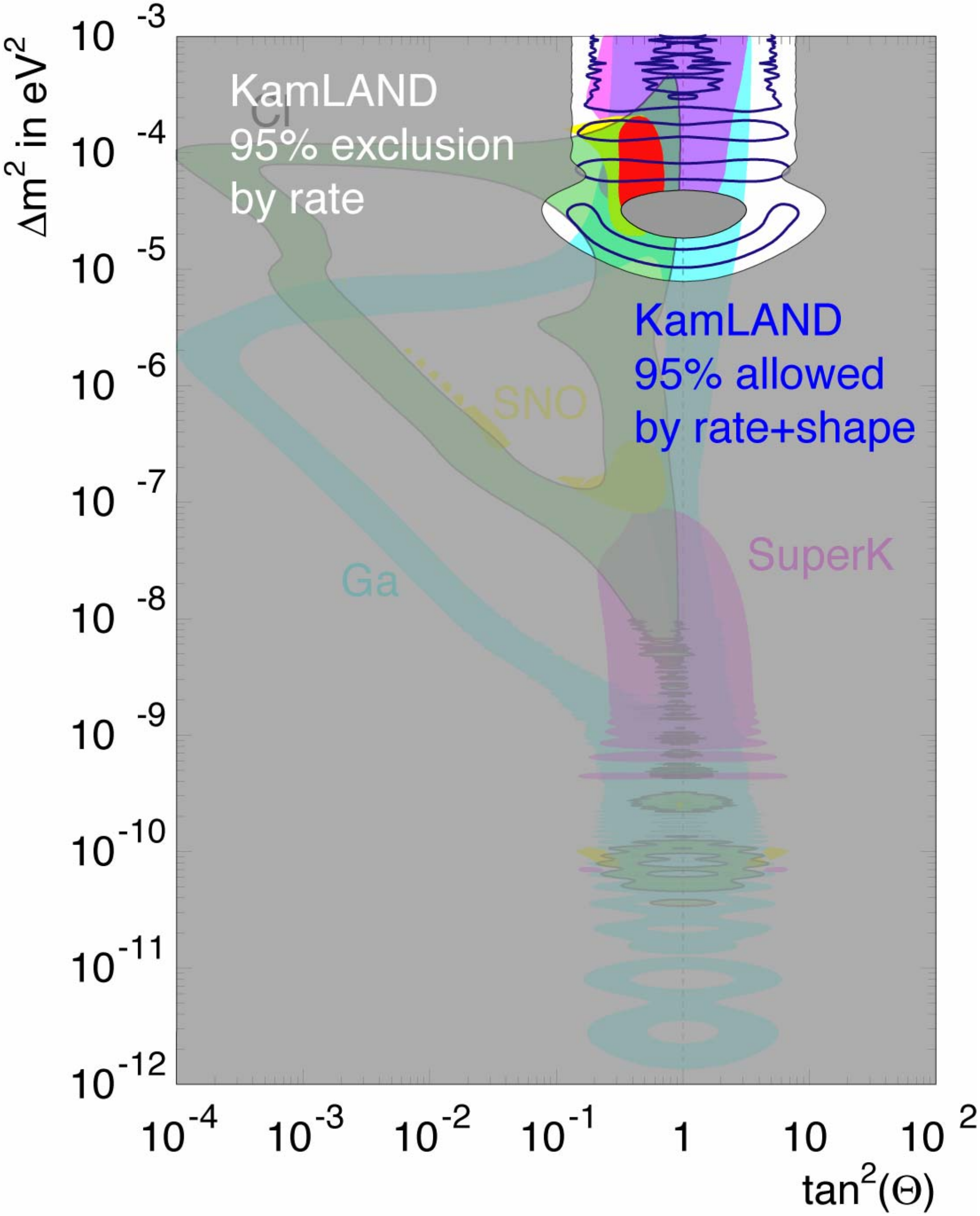
Reactor Neutrino Physics 1956-2003
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)



Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Cl
SNO
SuperK
Ga
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$



KamLAND
95% exclusion
by rate
Cl
SNO
SuperK
Ga
Δm^2 in eV^2
$\tan^2(\Theta)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}



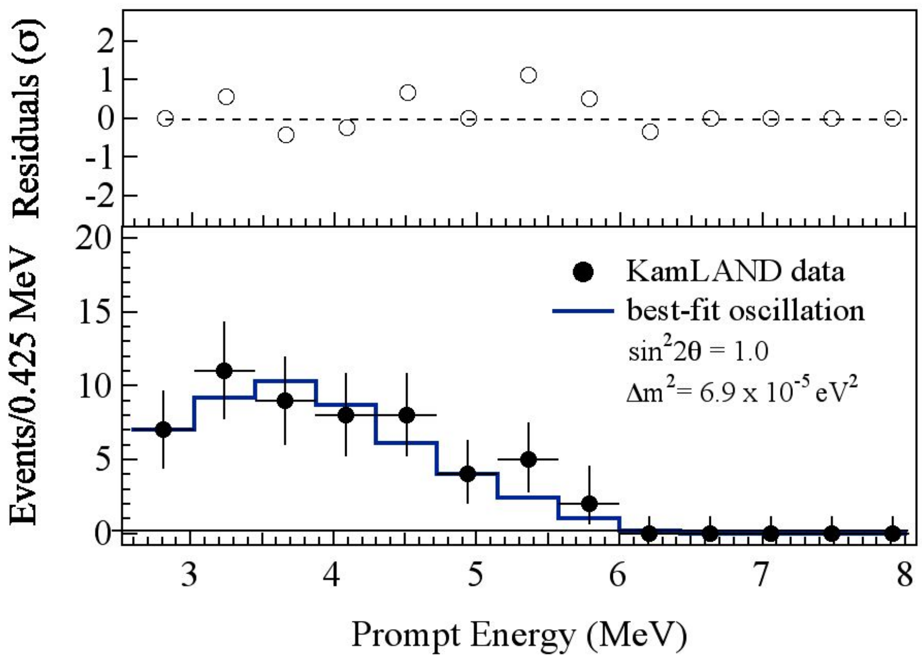
KamLAND
95% exclusion
by rate
Cl
KamLAND
95% allowed
by rate+shape
SNO
SuperK
Ga
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

From 2002 Data Set

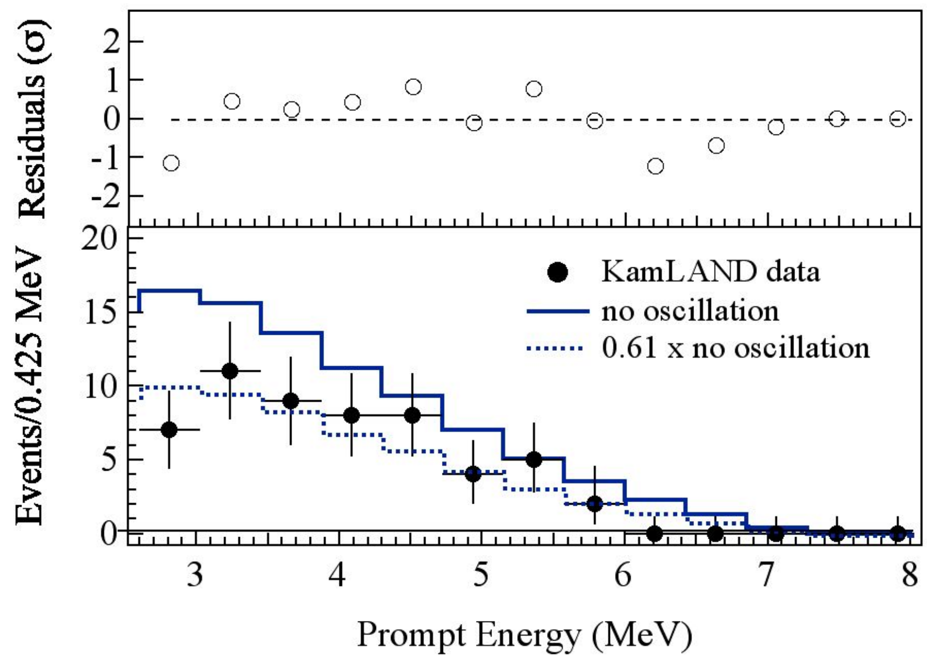
166 ton-years

Is the Neutrino Spectrum Distorted?

2-ν oscillation: best-fit



No oscillation, flux suppression



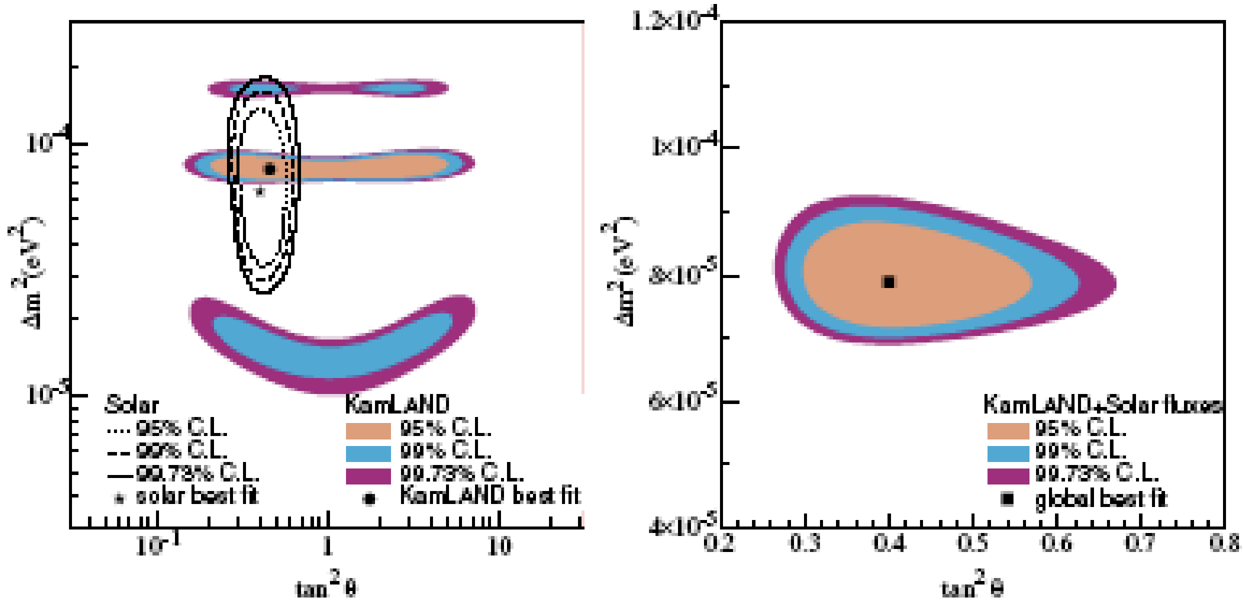
$\chi^2_{/ 8\ d.o.f} = 0.31$

Data and best oscillation fit consistent at 93% C.L.

Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo

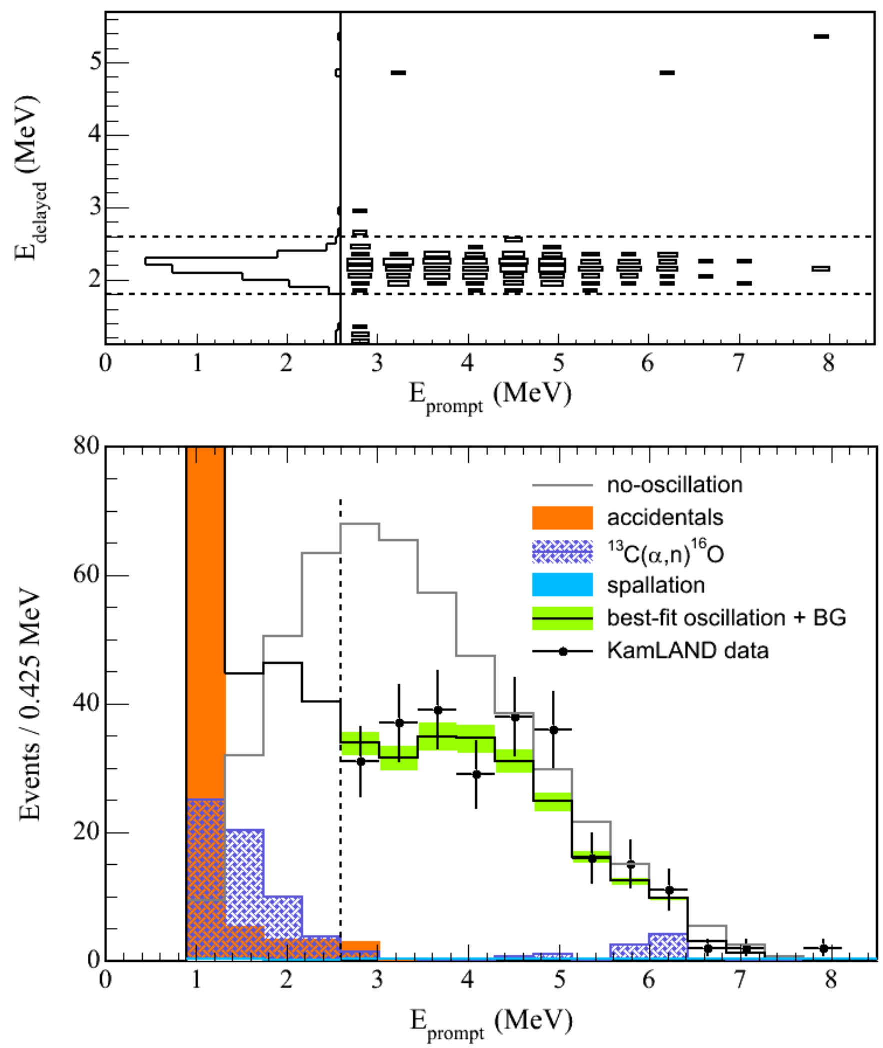
KamLAND's second reactor result

Phys. Rev. Lett. 94, 081801 (2005)
Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion



2004 Data Set

Is the Neutrino Spectrum Distorted?



11.1% χ^2_p/DOF = 24.2/17.

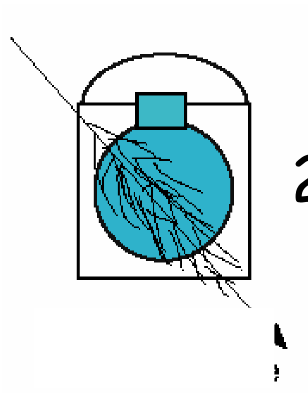
0.4% (χ^2_p/DOF = 37.3/18).

χ^2 / 11 d.o.f = 13

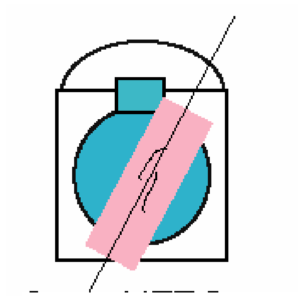
Backgrounds

1. Random coincidences 2.69 ± 0.02 events

2. Spallation Backgrounds from neutrons and delayed beta emitters ^{9}Li and ^{8}He 4.8 ± 0.9 (dead time 9.7%)



2 sec



2 *msec* + 2 sec in 6 *mϕ* cylinder

3. ^{210}Po $\alpha \longrightarrow$ $^{13}C(\alpha,n)^{16}O^*$(~6 *MeV*) and

$^{13}C(\alpha,n)^{16}O \longrightarrow {}^{12}C(n, n')^{12}C^*$(4.4 *MeV*) 10.3 ± 7.1 events

Total: 17.8 ± 7.3

Systematic Uncertainties

E > 2.6 MeV

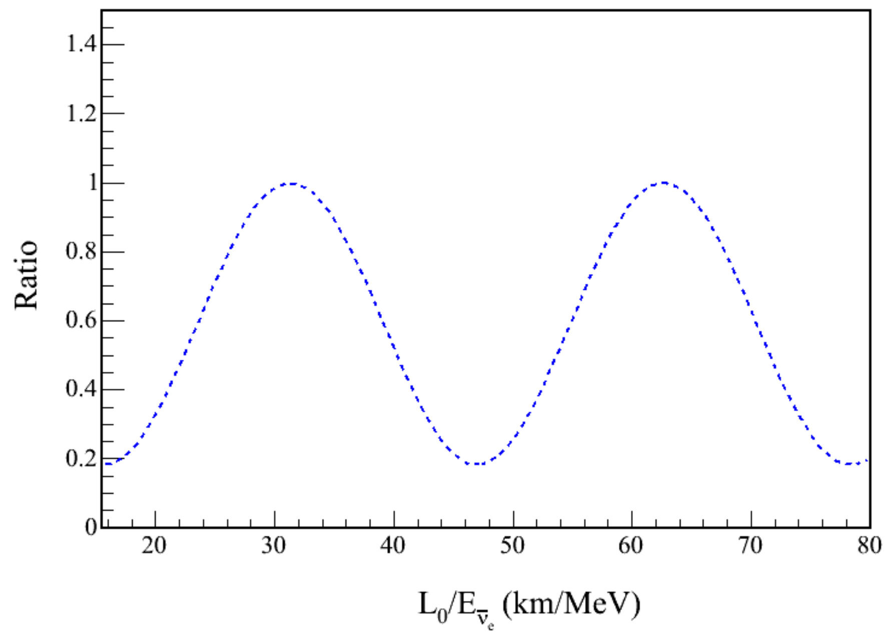
	%
Fiducial mass ratio	4.7
Energy threshold	2.3
Efficiency of cuts	1.6
Live time	0.06
Reactor power	2.1
Fuel composition	1.0
$\bar{\nu}_e$ cross section	0.2
Total uncertainty	**6.5 %**

Looking for the oscillation effect

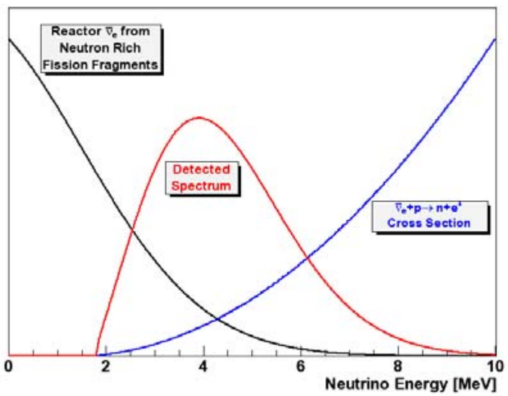
$$\left|\left\langle \psi_{\nu_e}(t) \middle| \psi_{\nu_e}(0)\right\rangle\right|^2 = 1 - \sin^2(2\theta)\sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar}t\right)$$

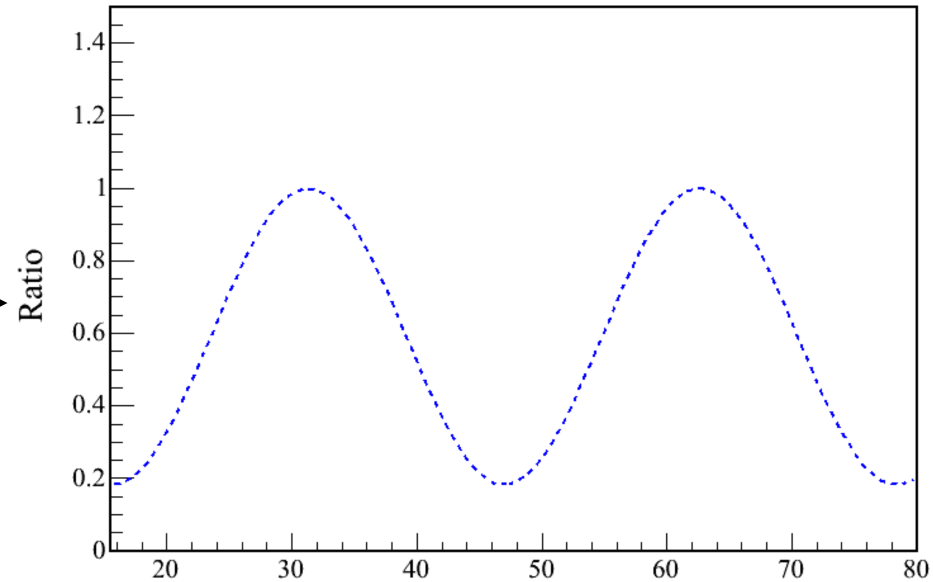
$$P_{ee} = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{(m_2^2 - m_1^2)L}{E}\right)$$

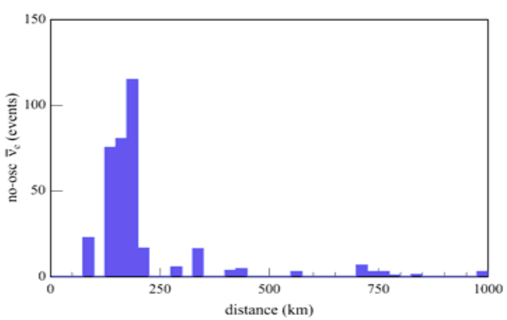
$$L = c \bullet t_{lab} \qquad t_{restframe} = \frac{t_{lab}}{\gamma} = \frac{m}{E}t_{lab}$$

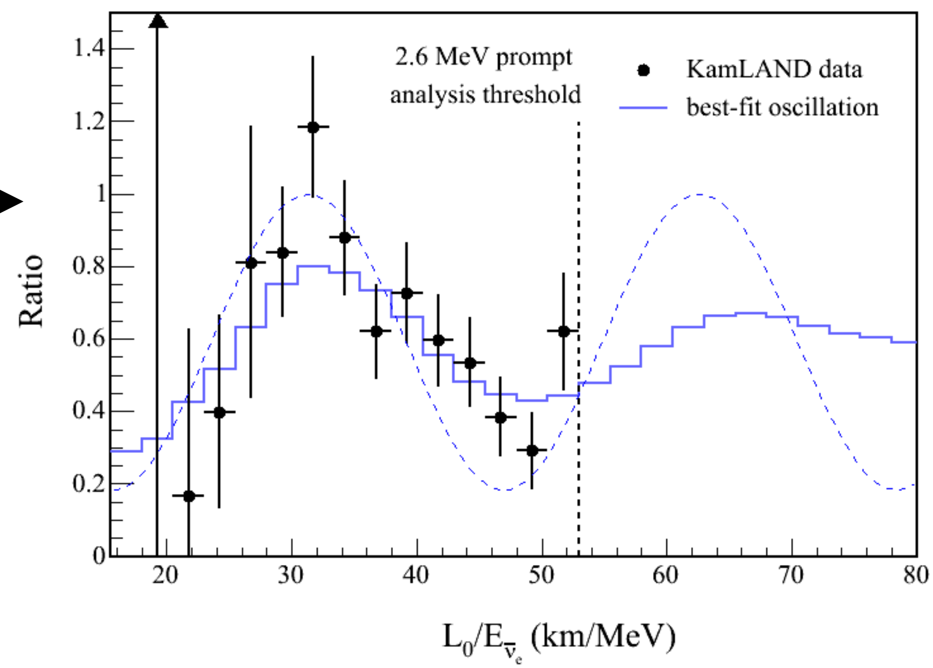


Observing the oscillations in the neutrino rest frame

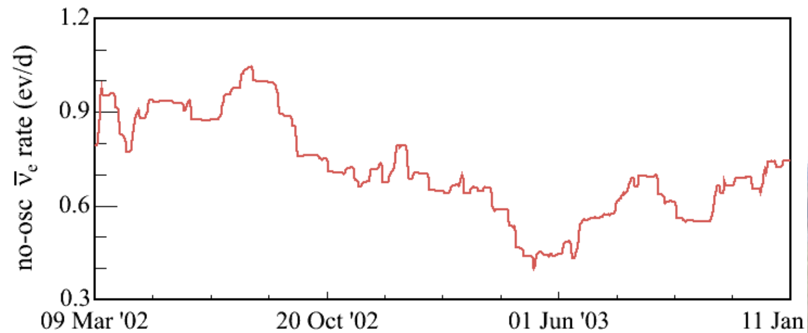






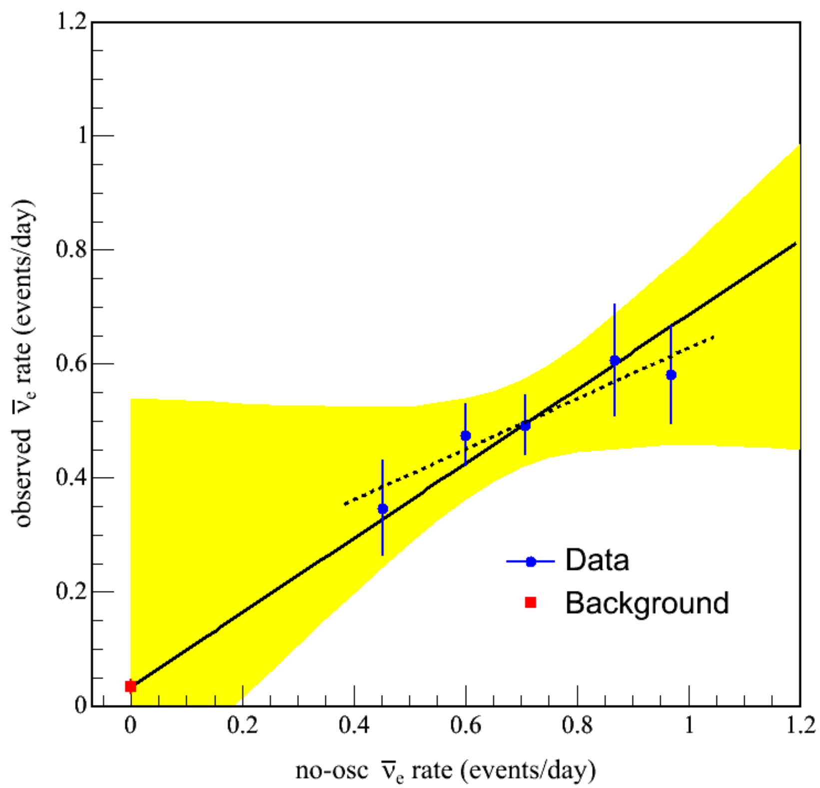


KamLAND Correlation of Count Rate and Reactor Power



Kashiwazaki shutdown

Reactor at the core of the earth?



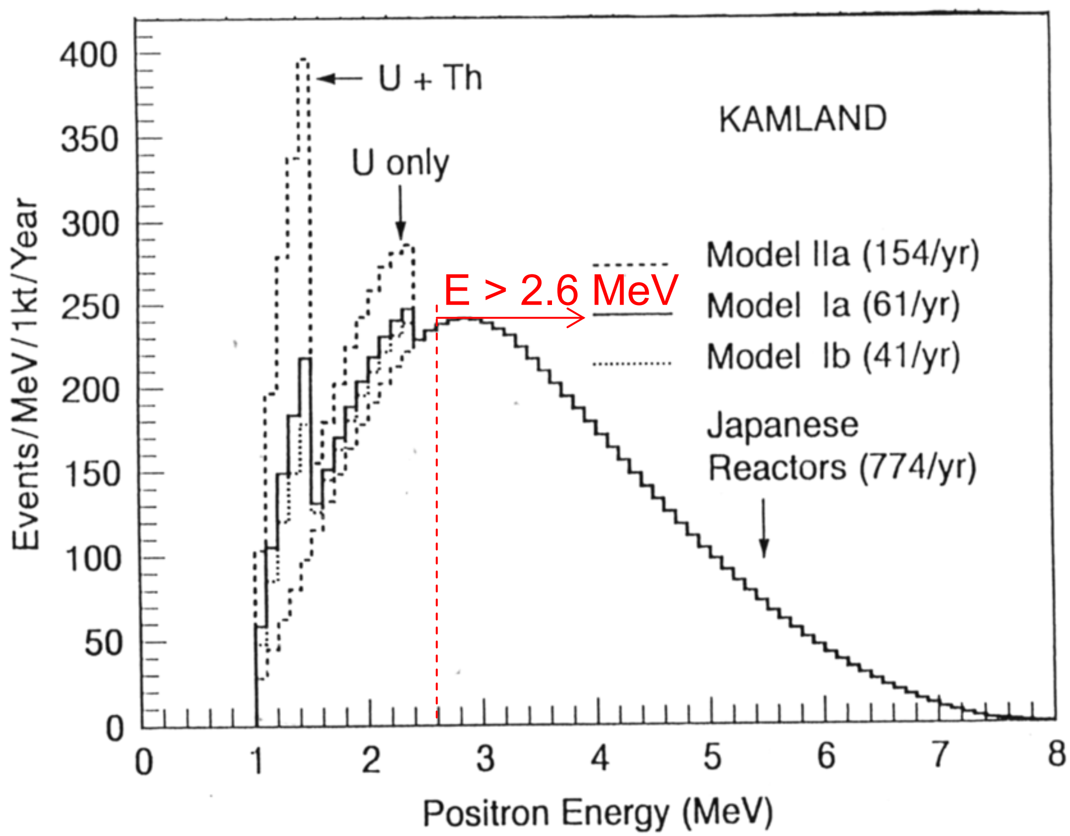
Observation of Geoneutrinos

Nature Vol 436|28 July 2005|doi:1-38/nature03980
Experimental Investigation of Geologically Produced Antineutrinos with KamLAND

Geo-Neutrino Signal

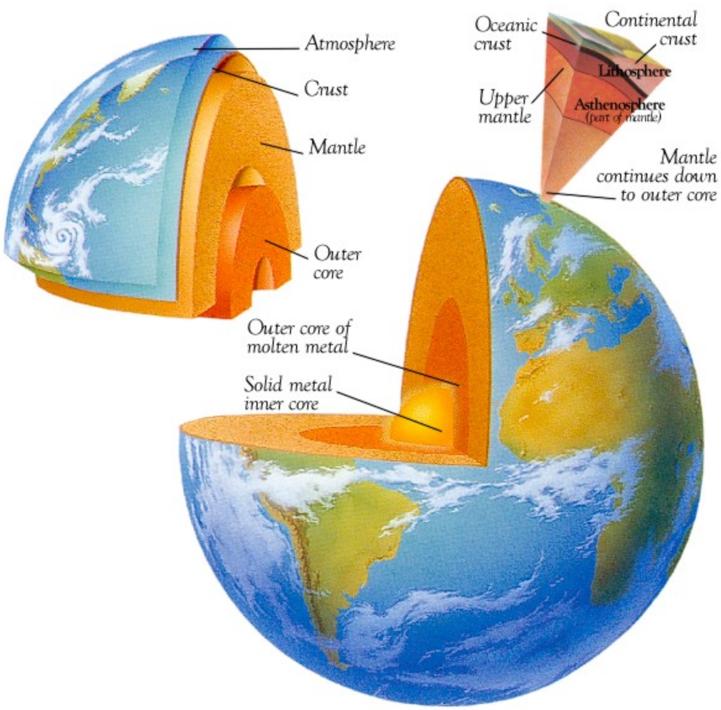
U/Th decays in the Earth produce radiogenic heat (40-60% of 40TW)

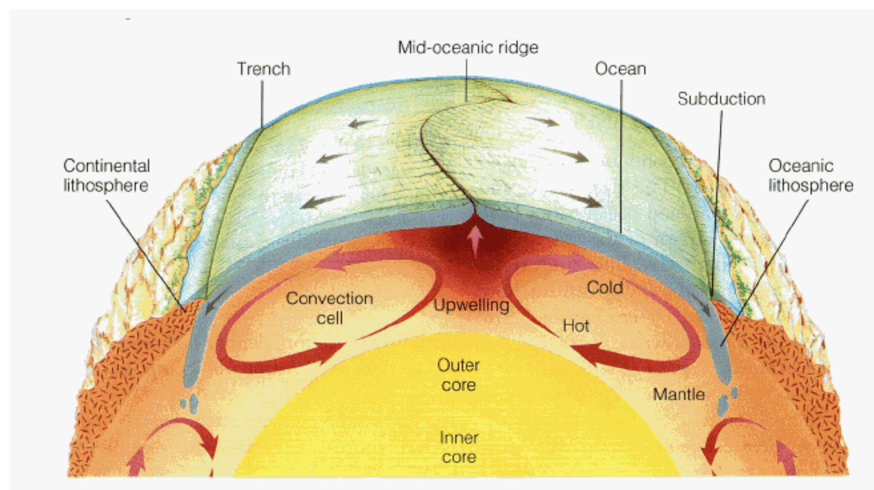
$E_{\nu(geo)} < 2.49$ MeV

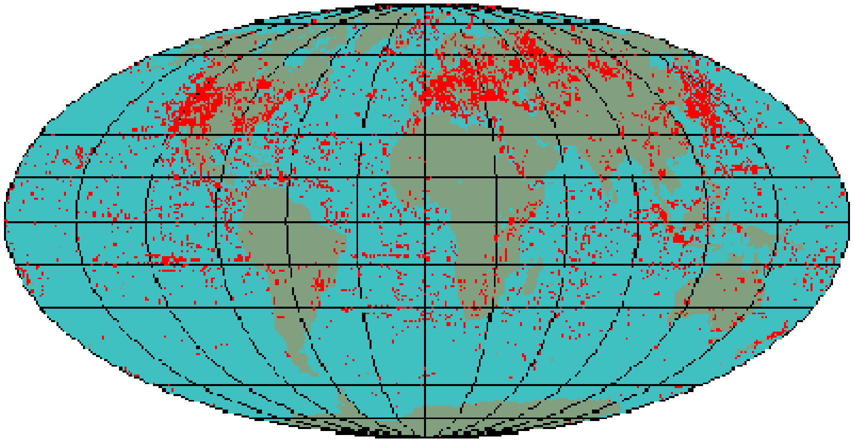


Raghavan et al. PRL 80 (1998)

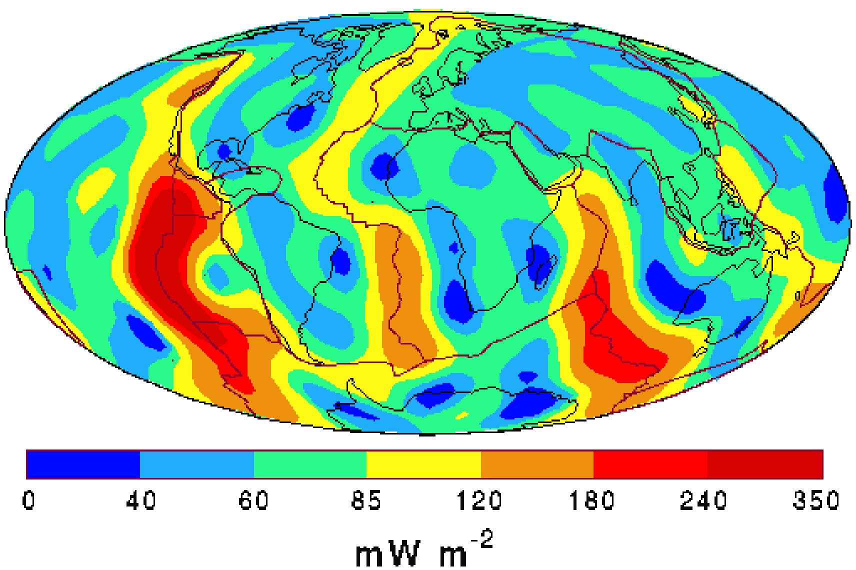
The Earth is made up of five basic regions: Core, Mantle, Oceanic crust, and Sediment







Bore Holes



Heat Flow

Heat flow from the earth determined from bore-hole temperature gradients.

44.2 ± 1.0 TW or

31 ± 1 TW (same data)

Radiogenic heat should contribute. Using the composition of chondritic meteorites expect

U/Th/K

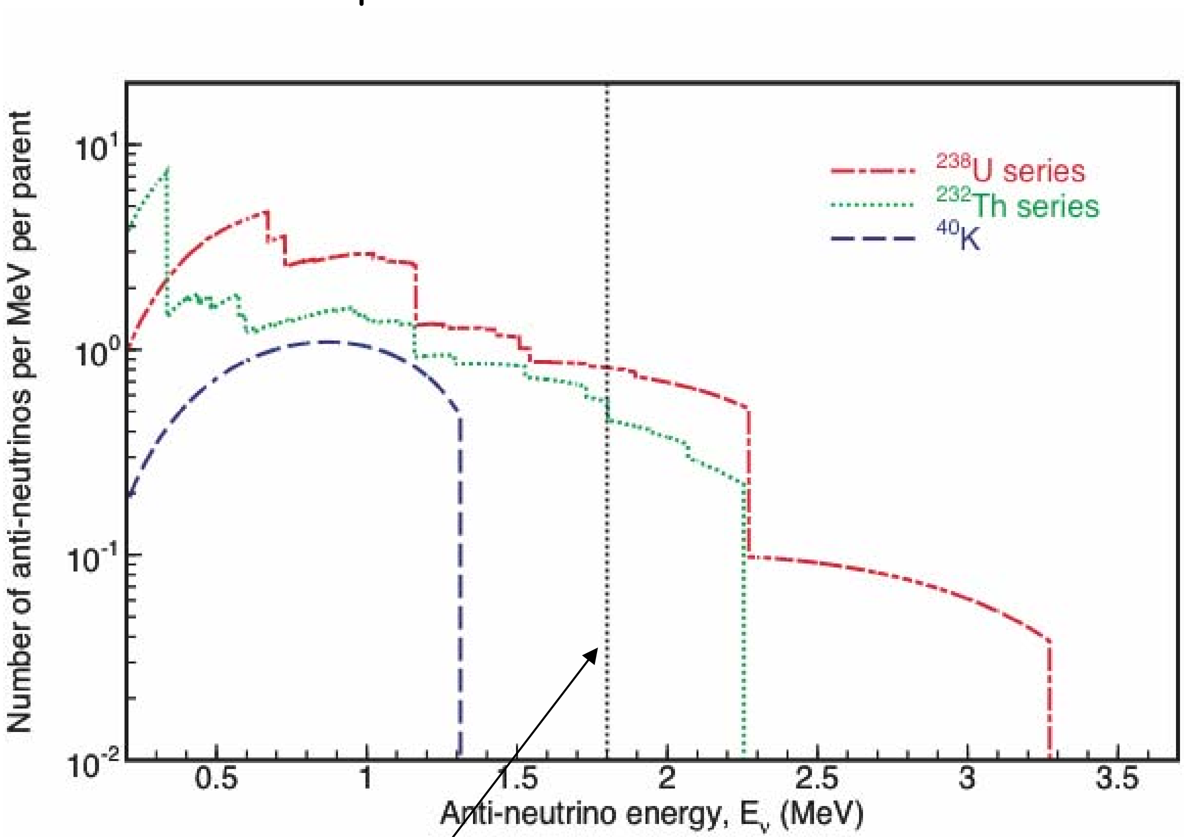
20ppb/80ppb/240ppm

8 TW/8 TW/3 TW

Puzzle:

19 TW ≠ 44.2 TW or 31 TW

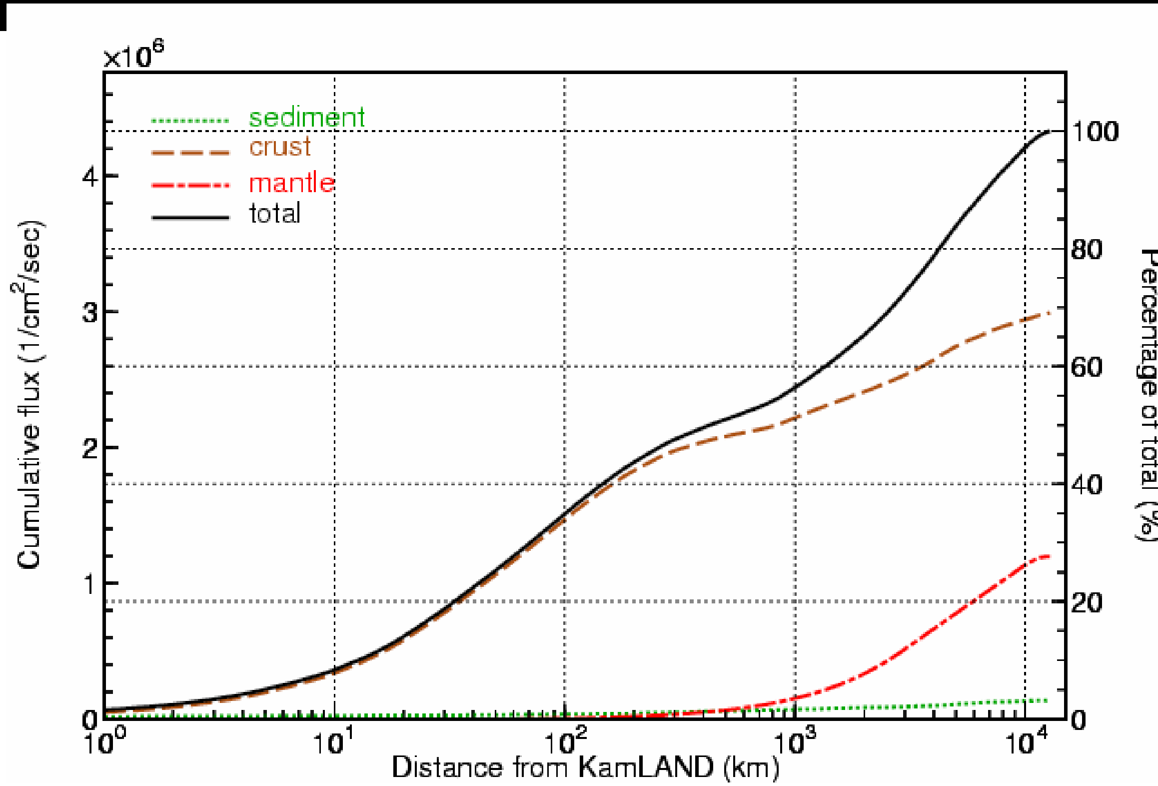
Neutrino Spectrum from K and the U and Th chains



KamLAND Threshold

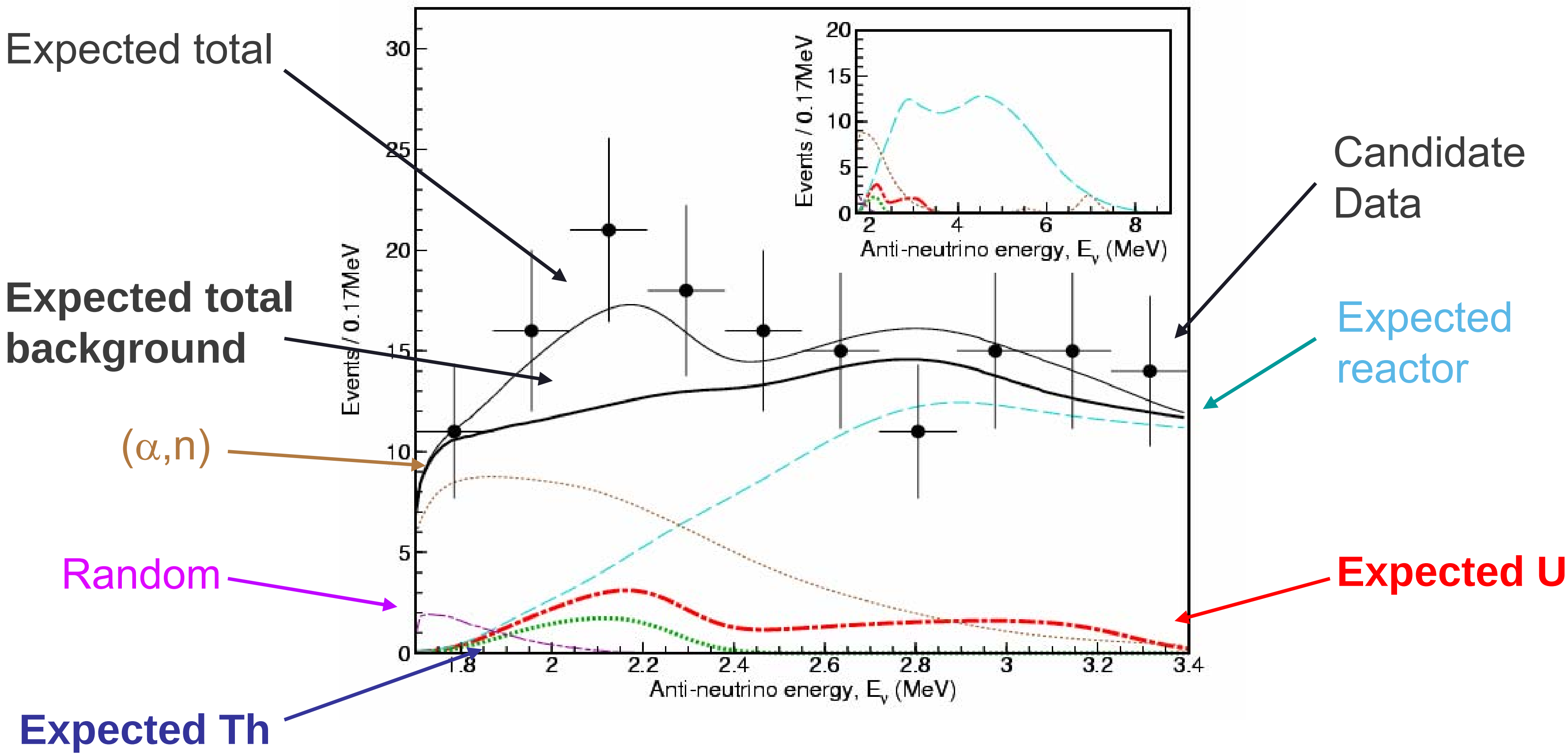
Reference Model

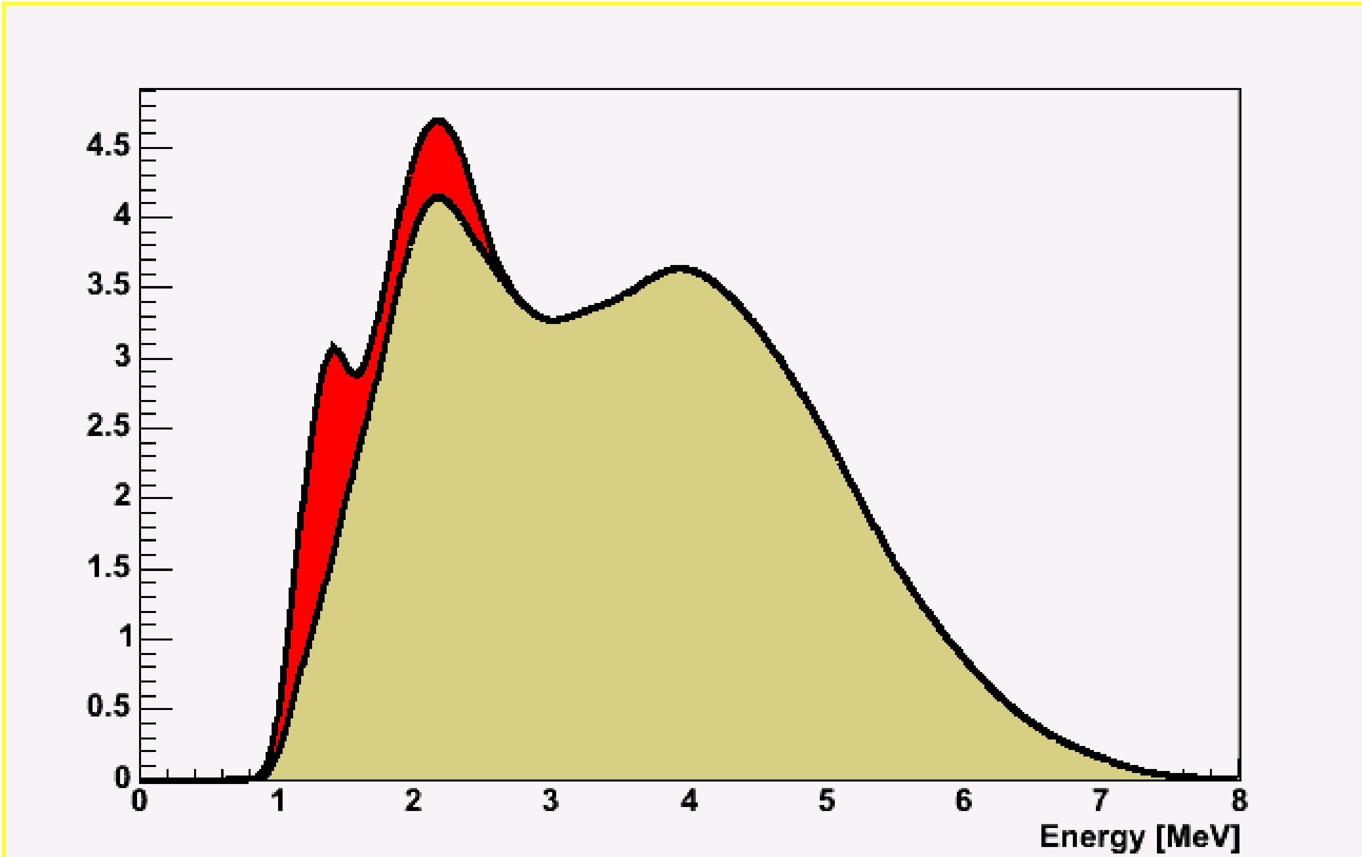
		U [ppm]	Th [ppm]
Sediment	Continental	2.8	10.7
	Oceanic	1.68	6.91
Continental Crust	Upper	2.8	10.7
	Middle	1.6	6.1
	Lower	0.2	1.2
Oceanic Crust		0.1	0.22
Mantle		0.012	0.048
Core		0	0



Geoneutrino Signal

4.5 to 54.2 geoneutrinos 90%CL
60 TW (99%) upper limit for U and Th

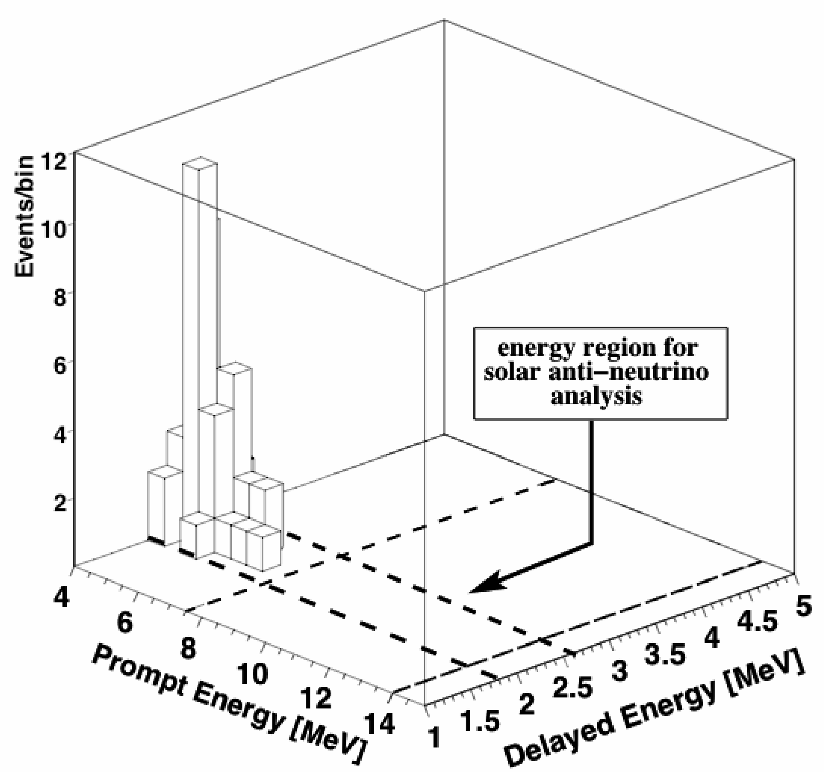


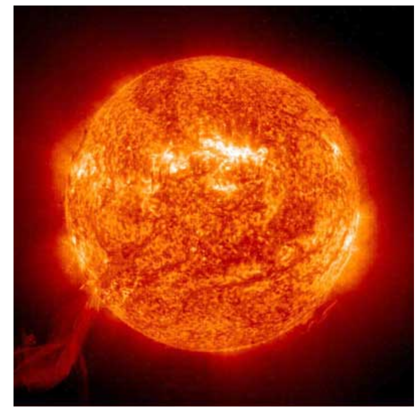


KamLAND is in the wrong place for geophysics, the biggest background for geo-neutrinos is reactor neutrinos

KamLAND provides best limits on energetic $\overline{\nu}_e$

High Sensitivity Search for nu-bar's from the Sun and Other Sources at KamLAND Phys. Rev. Lett. 92, 071301 (2004)





(best limits by a factor of 30)

Other applications of KamLAND

Search for the invisible decay of neutrons with KamLAND. Phys.Rev.Lett.96:101802 (2006)

<u>n -> $\nu\nu\nu$:</u>

$^{11}C^* \rightarrow {}^{10}C_{GS} + n$

$^{11}C^* \rightarrow {}^{10}C^* + n \rightarrow {}^{10}C_{GS} + n + \gamma$ (3.5 MeV)

$\tau > 5.8 \times 10^{29}$ yr (90% C.L.)

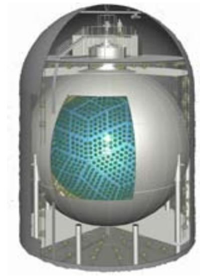
<u>n -> $\nu\nu$:</u>

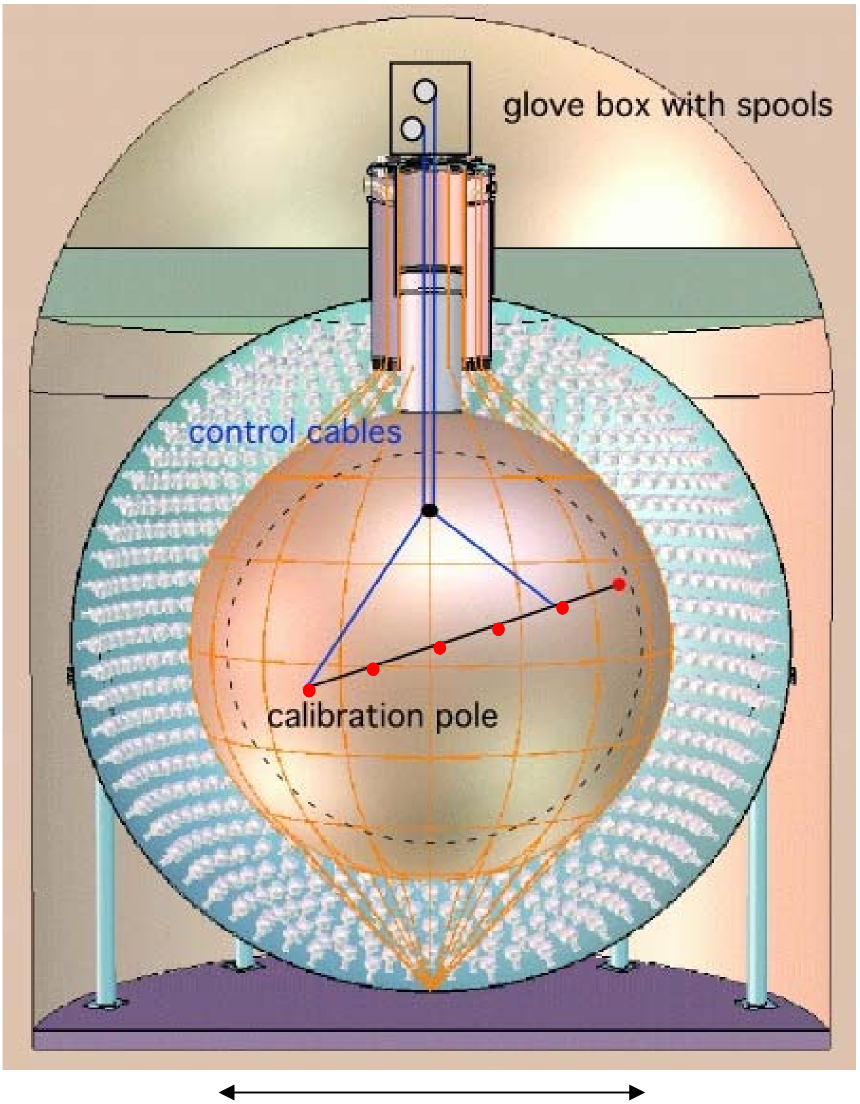
$^{10}C^* \rightarrow {}^{9}C_{GS} + n$

$^{10}C^* \rightarrow {}^{9}C^* + n \rightarrow {}^{8}B_{GS} + p + n$

$\tau > 1.4 \times 10^{30}$ yr (90% C.L.)

KamLAND 4π Calibration

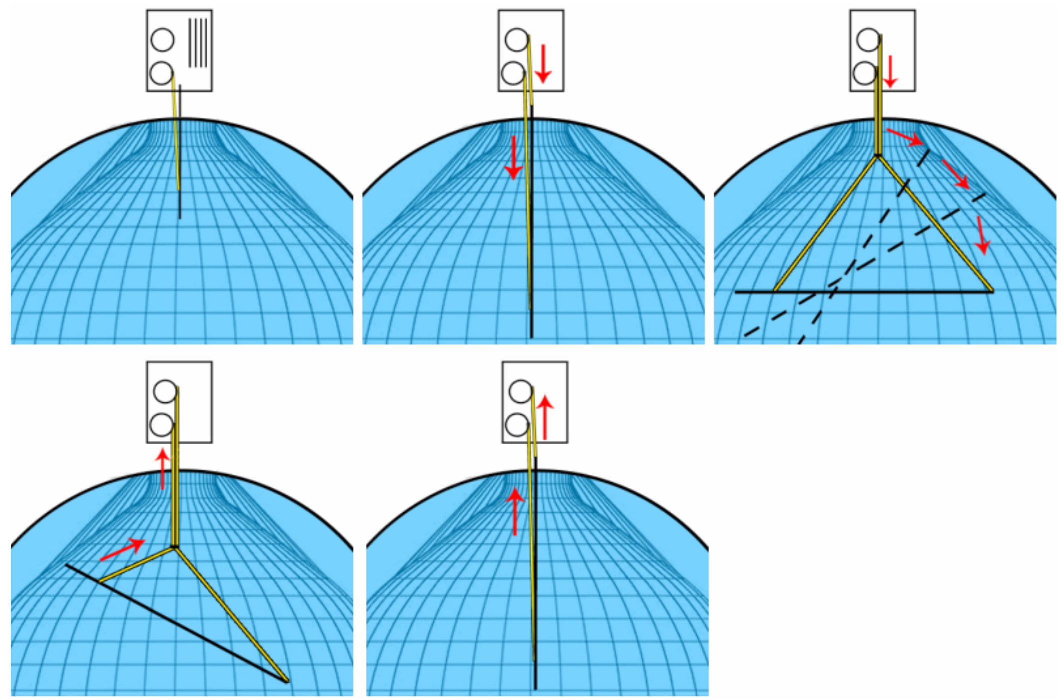




Understanding the Detector Response

Event energy $E(r,\theta,\phi)$

Vertex reconstruction $R_{fit}(r,\theta,\phi)$

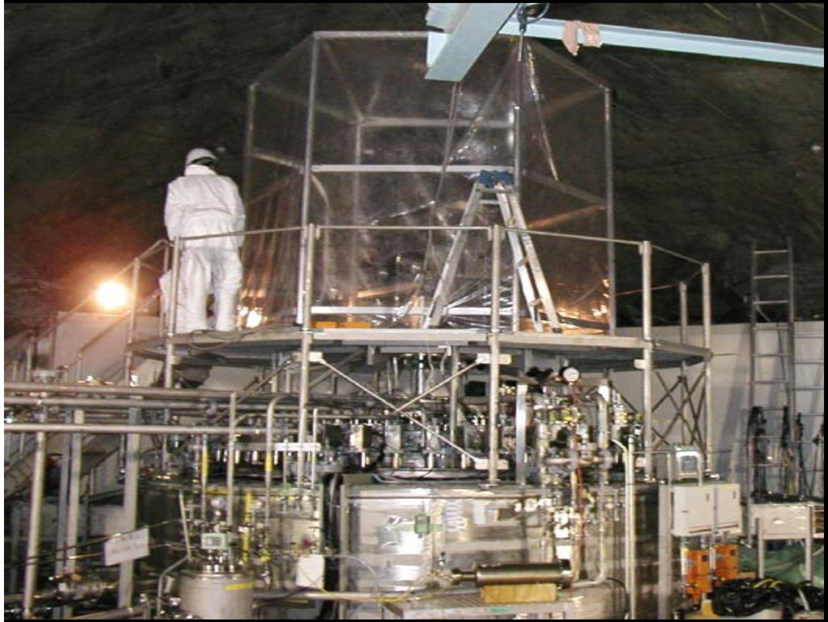


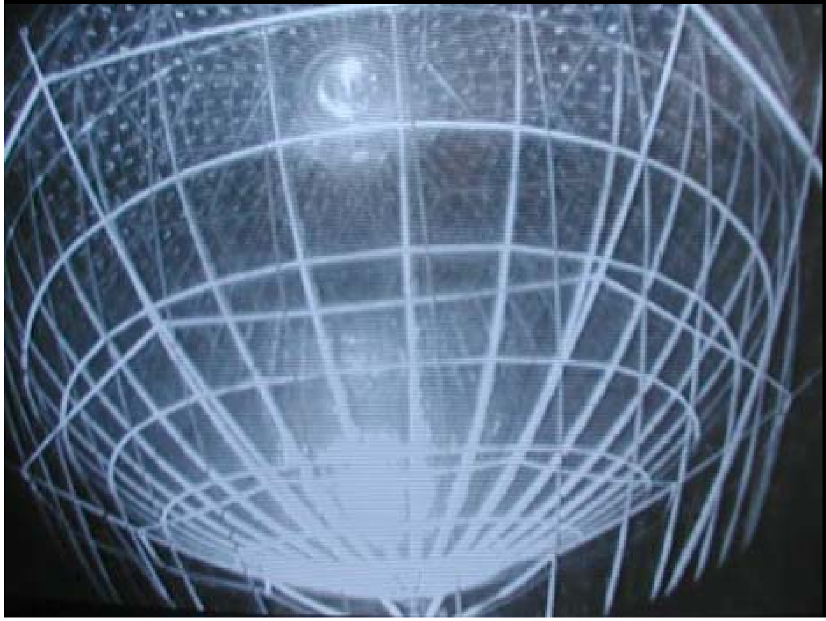
Fiducial volume: R < 5.5 m

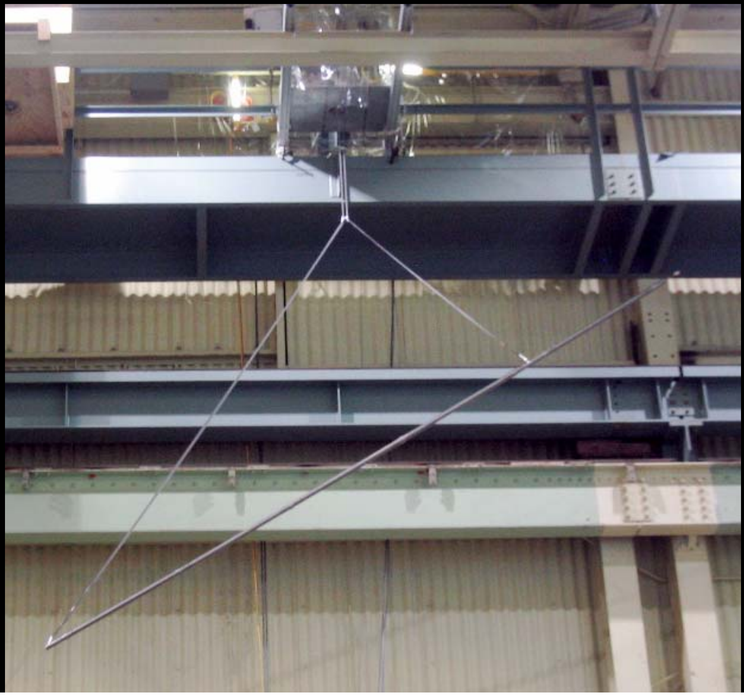
ΔR_{FV} = 5 cm $\rightarrow$ ΔV= 2.7%

ΔR_{FV} = 2 cm $\rightarrow$ ΔV= 1.1%

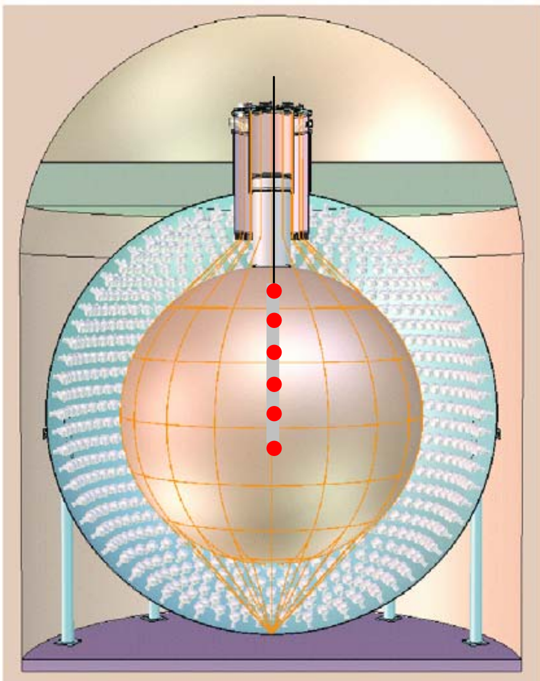
KamLAND 4π Calibration System







July 10, 2006: First 4π Calibration Data

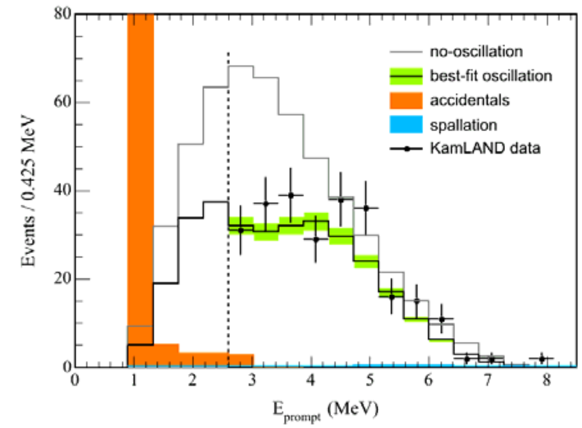


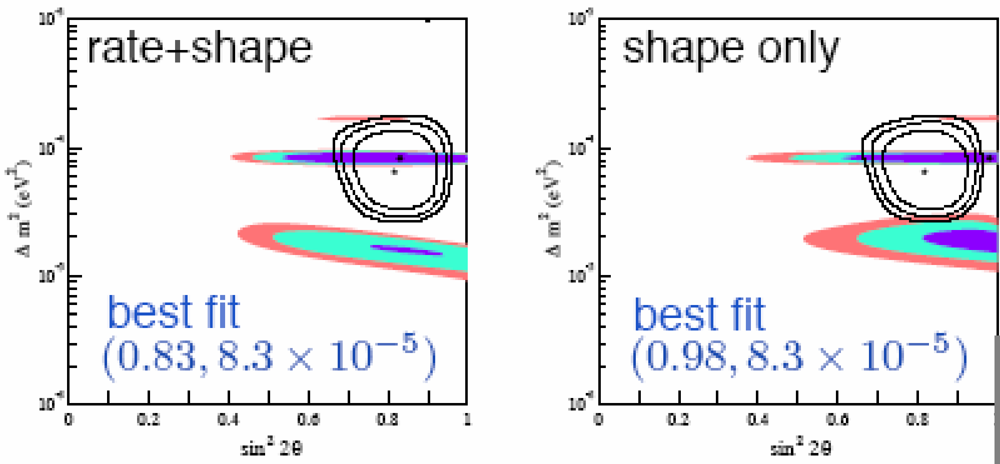
Calibration with multiple equal-distant ^{60}Co sources.

→ Allows study of radial dependence of fitter bias

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Reduction of Systematic Errors





Current Parameters

Most constraints from $\overline{\nu}_e$ spectrum due to systematic error on ν_e rate

Future

Reduce systematic errors for precision measurement of oscillation parameters

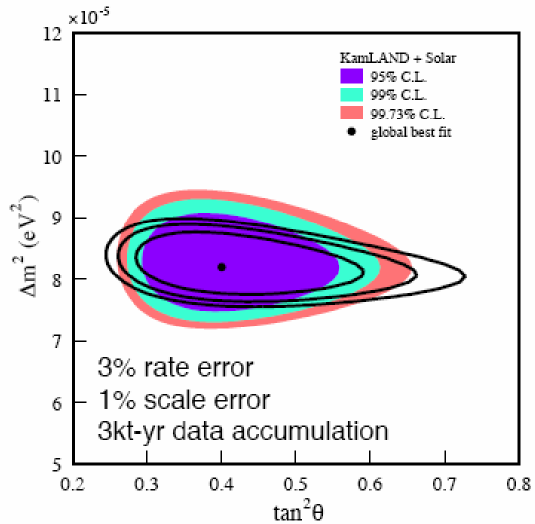
→ most precise determination of Δm_{12}^2

→ improve on θ_{12} from $\overline{\nu}_e$

KamLAND only
rate+shape sensitivity

(rough estimation)

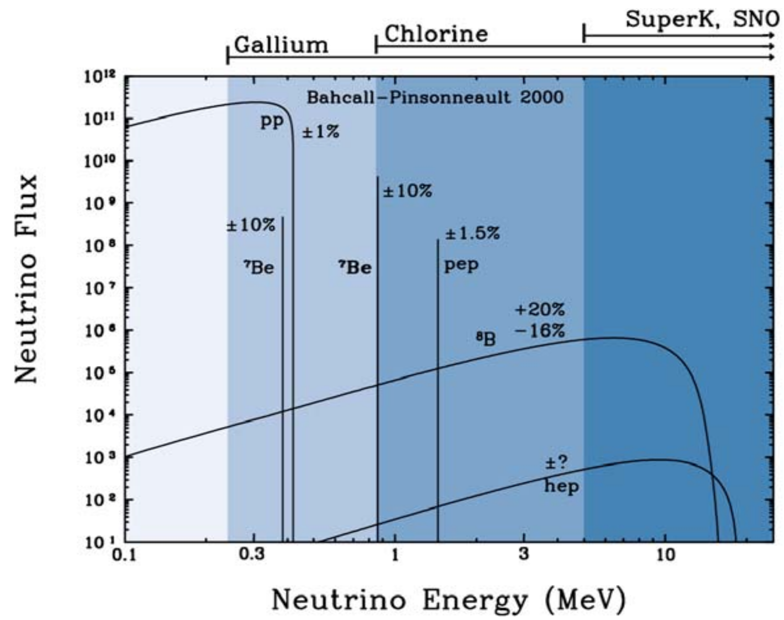
factor ~2 improvement?

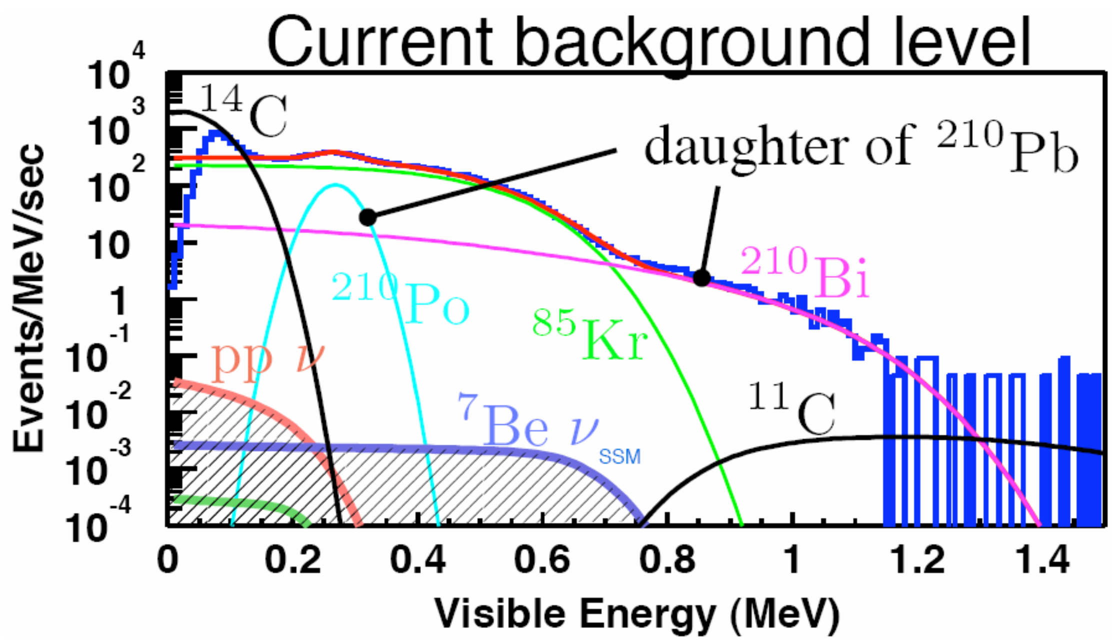


capability to reject full mixing

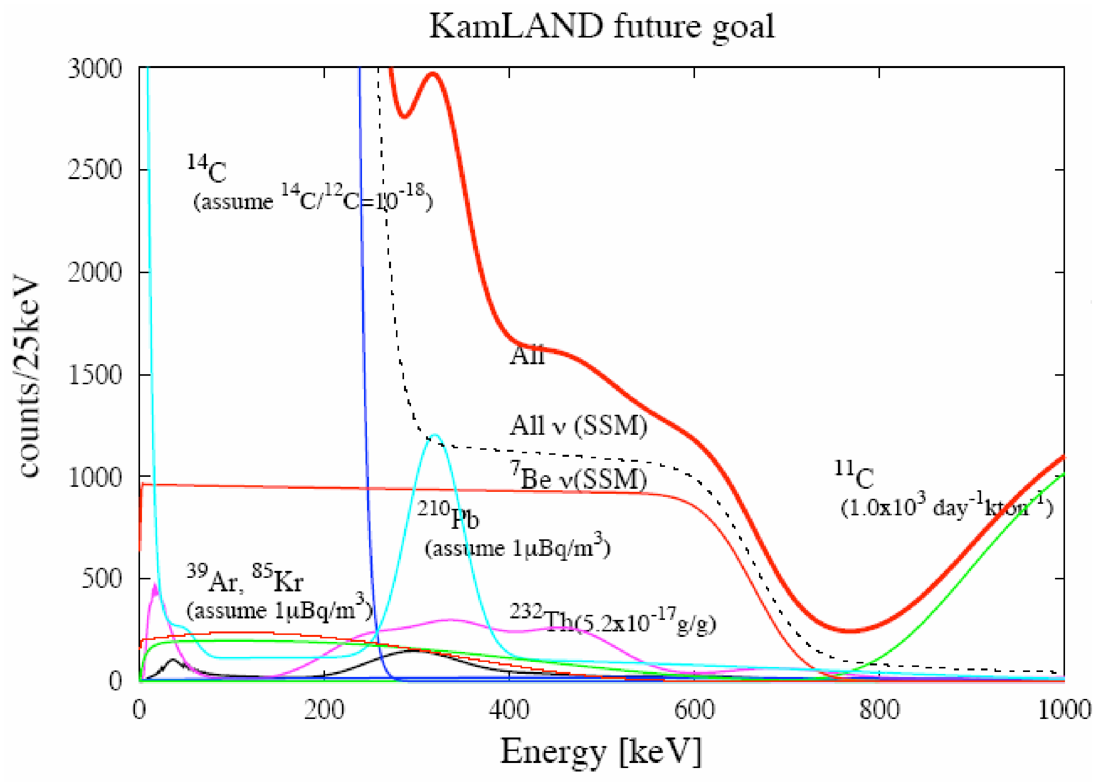
mixing angle determination comparable with current solar data

The next step for KamLAND: Solar Neutrinos





- Signal and backgrounds:
  - ^{7}Be signal now ~10^5-10^6 below backgrounds:
  - ^{85}Kr, ^{210}Bi β, ^{210}Po α



Control room for purification facility

Purification to begin in fall 2006

KamLand Collaboration