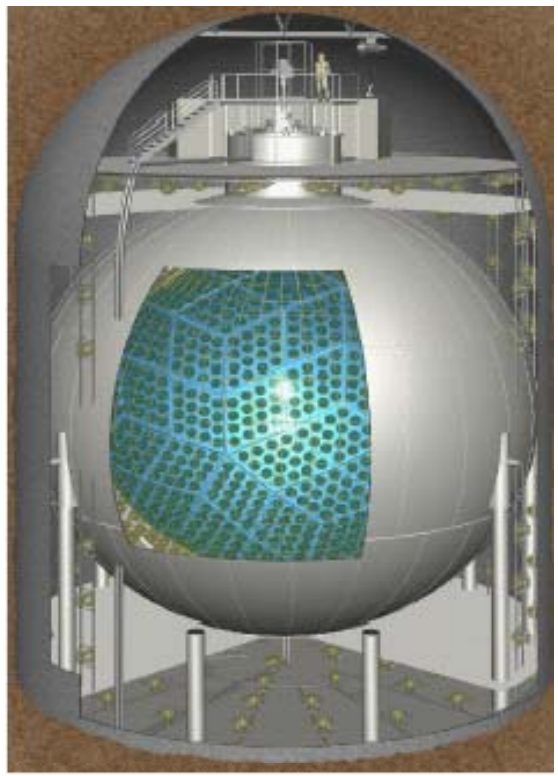
First Results from KamLAND

Kamioka **L**iquid-Scintillator **A**nti-**N**eutrino **D**etector

Stuart Freedman

HEPAP meeting at LBNL

March 6, 2003



KamLAND Collaboration

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Berkeley KamLAND Group

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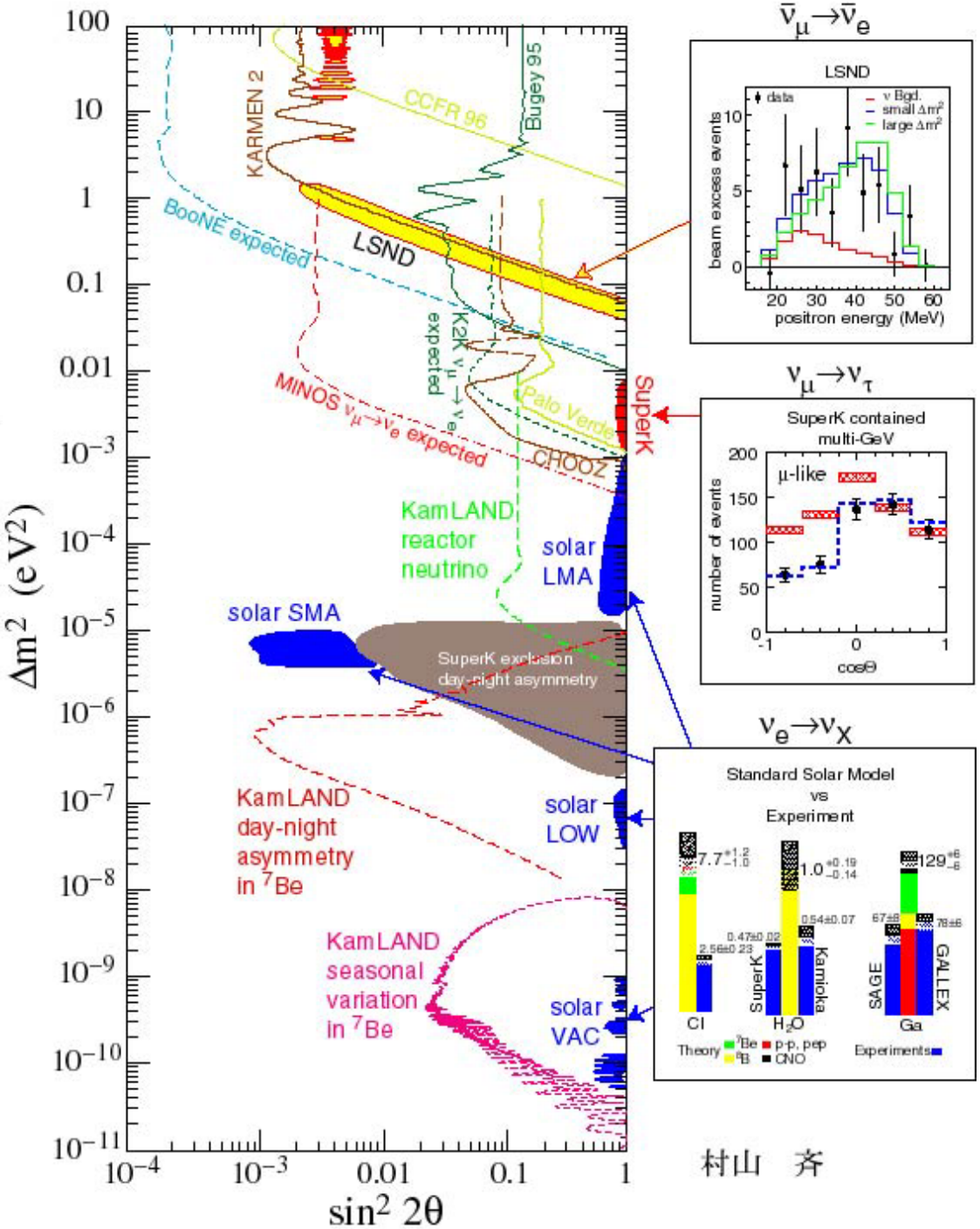
Neutrino Physics at LBNL

Early 90's SNO (NSD)

Late 90's KamLAND

New initiatives under discussion - NWG

Бруно Понтекорво



村山 斉

SNO

Fluxes

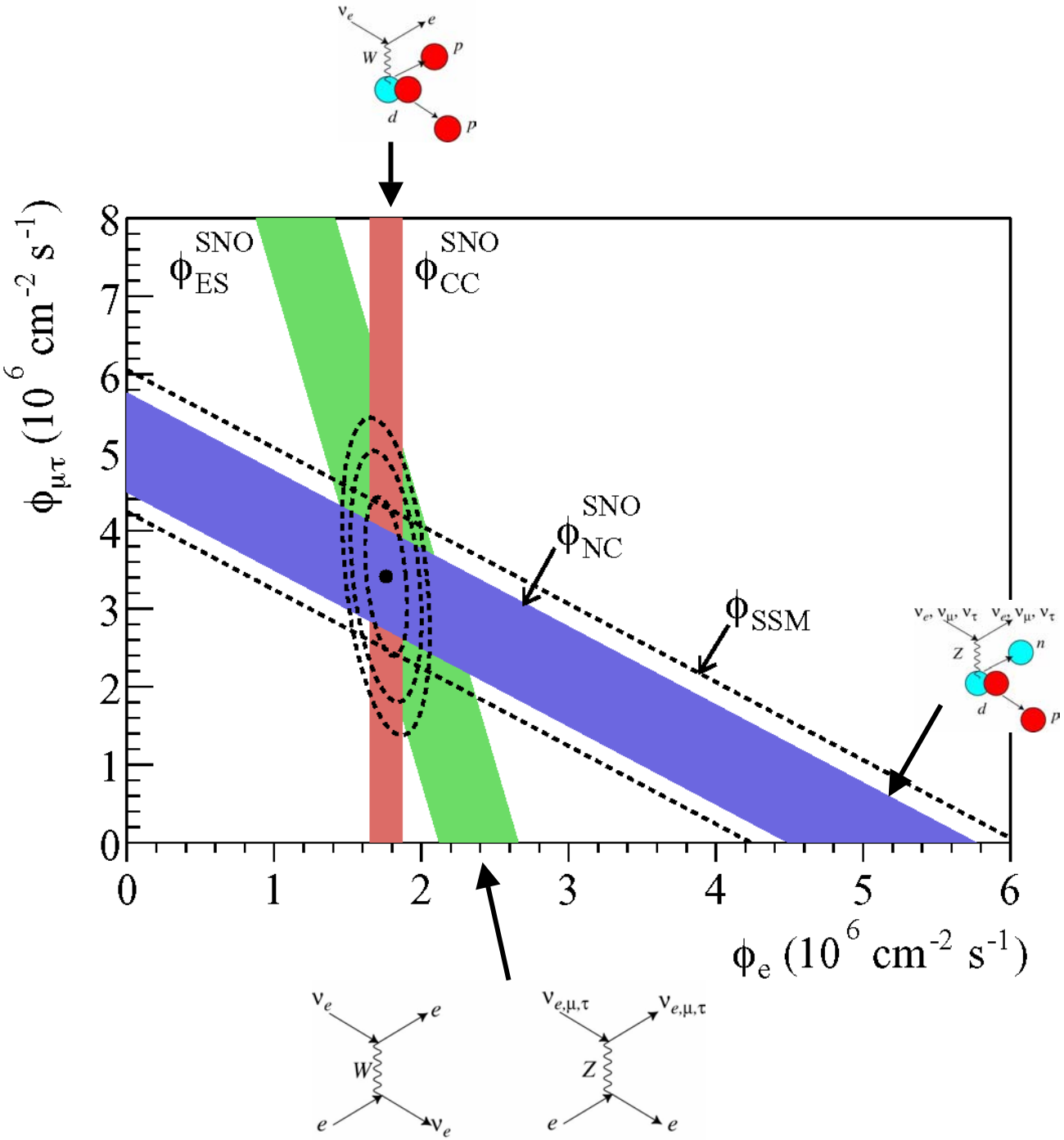
(10^6 cm^{-2} s^{-1})

ν_e: 1.76(11)

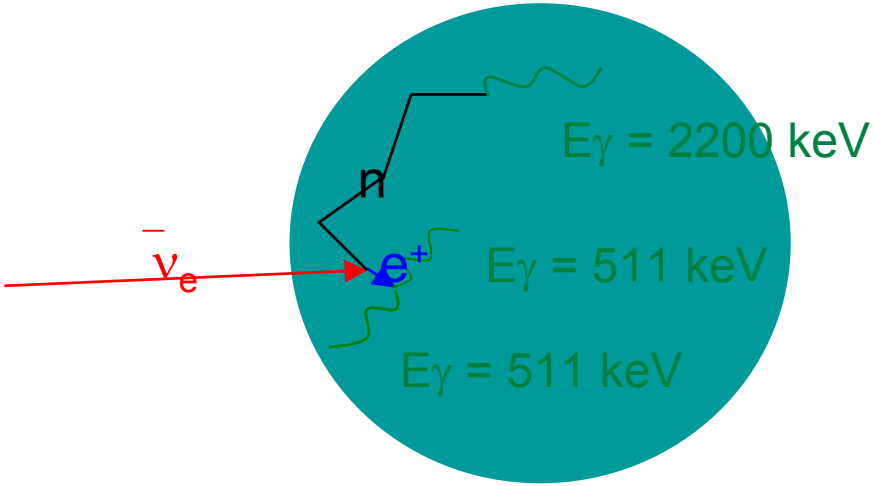
$\nu_{\mu\tau}$: 3.41(66)

ν_{total}: 5.09(64)

ν_{SSM}: 5.05



First Direct Detection of the Neutrino

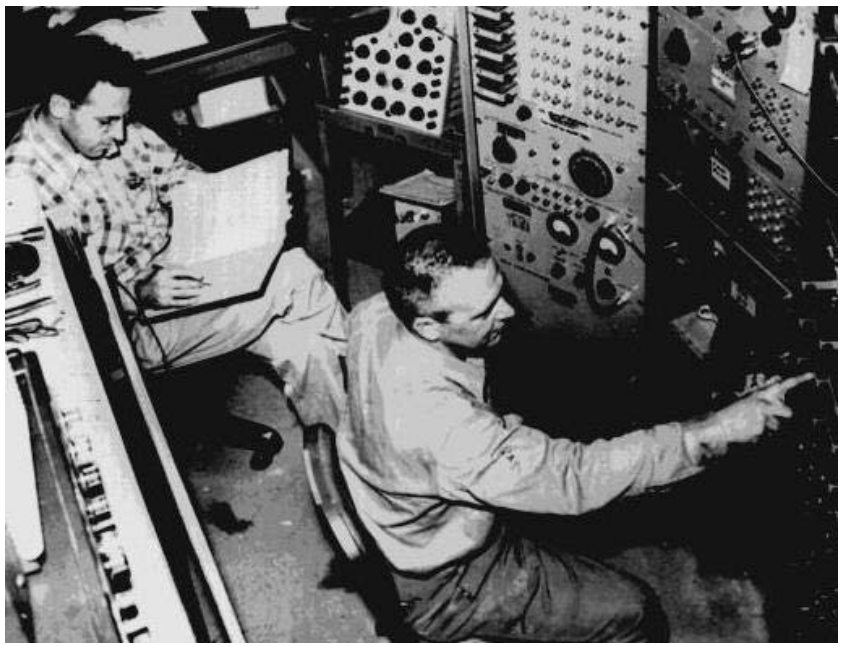


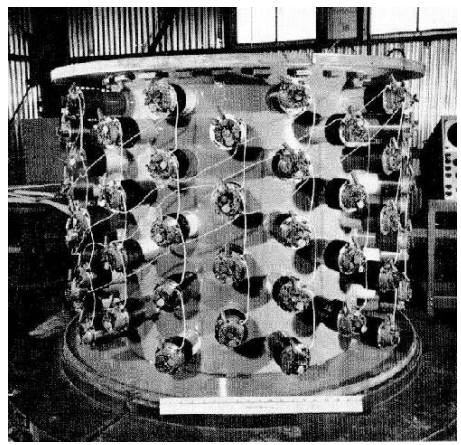
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\tau \approx 210\ \mu s$$

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

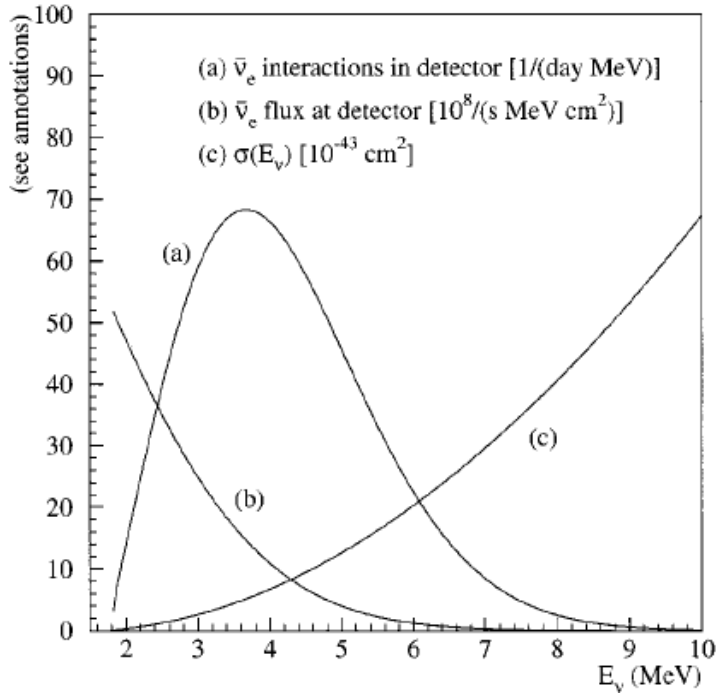
$$E_{prompt} \cong E_\nu - \overline{E_n} - 0.8\ MeV$$





Reines and Cowan 1956

Inverse Beta Decay Cross Section and Spectrum

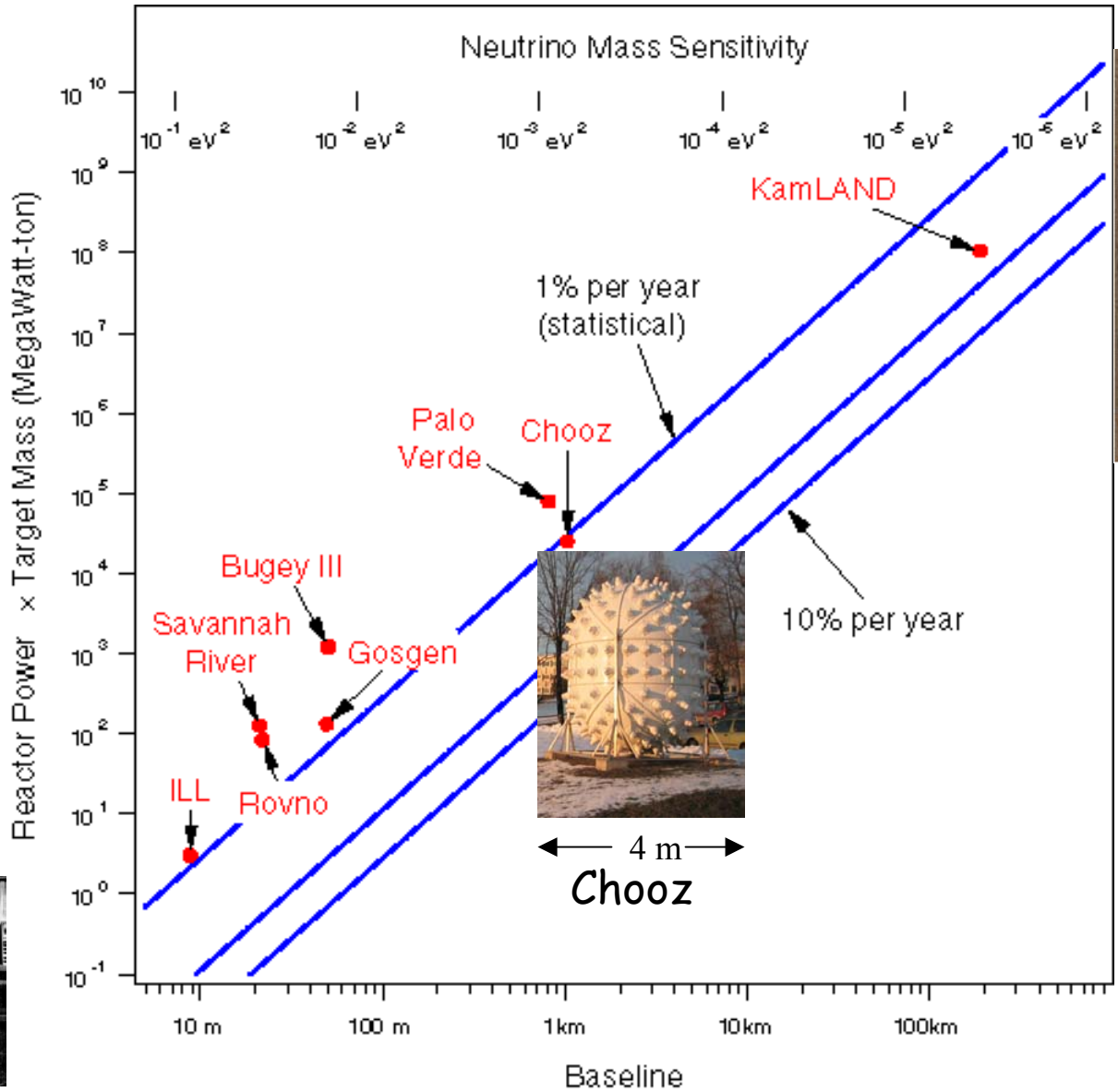


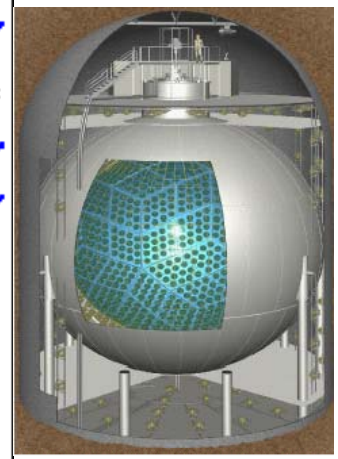
$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \text{MeV}^2} \right) \times 10^{-42}\ \text{cm}^2$$

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R)$$

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



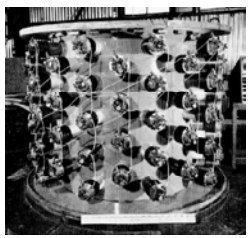


20 m

KamLAND

4 m

Chooz

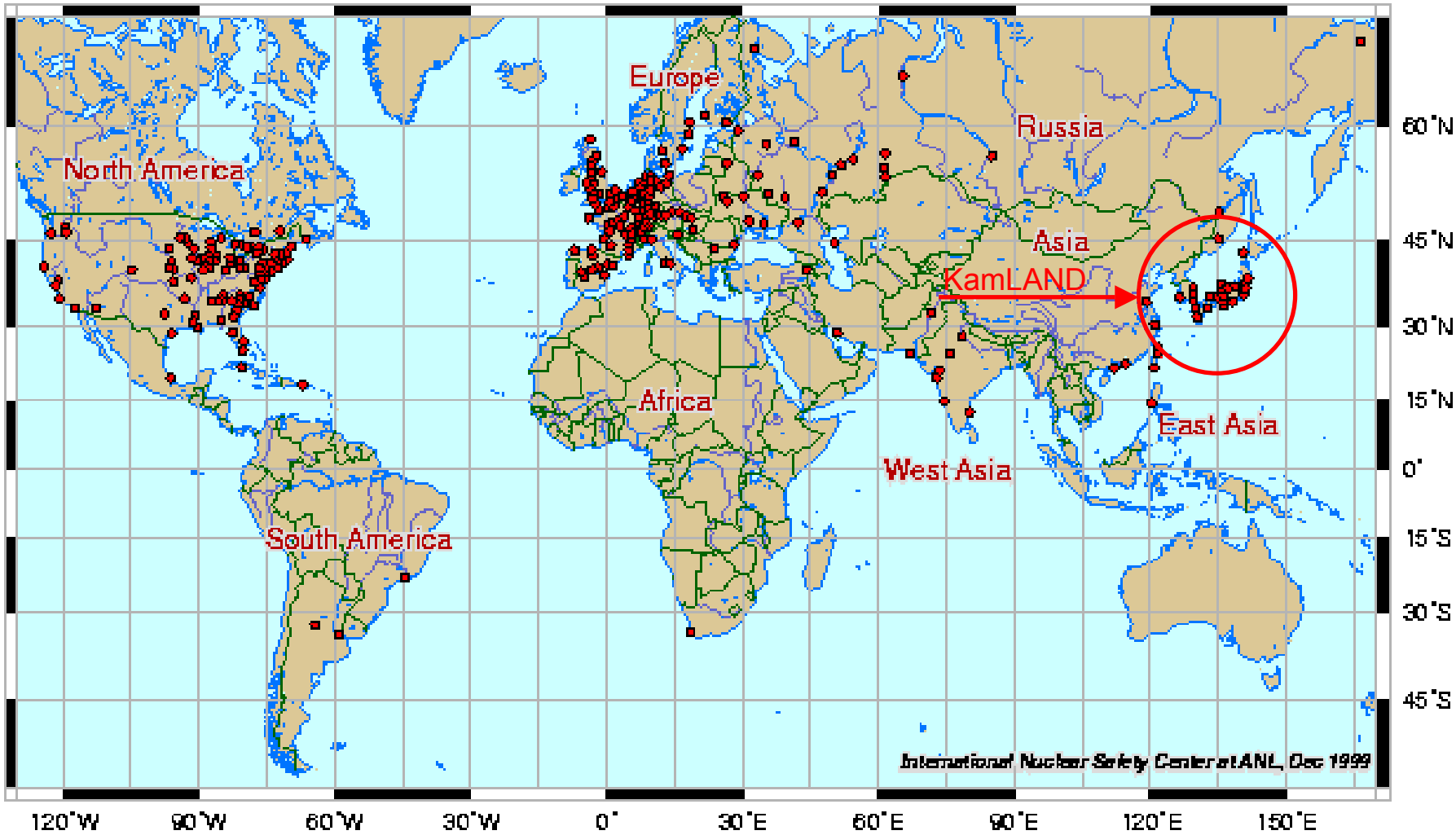


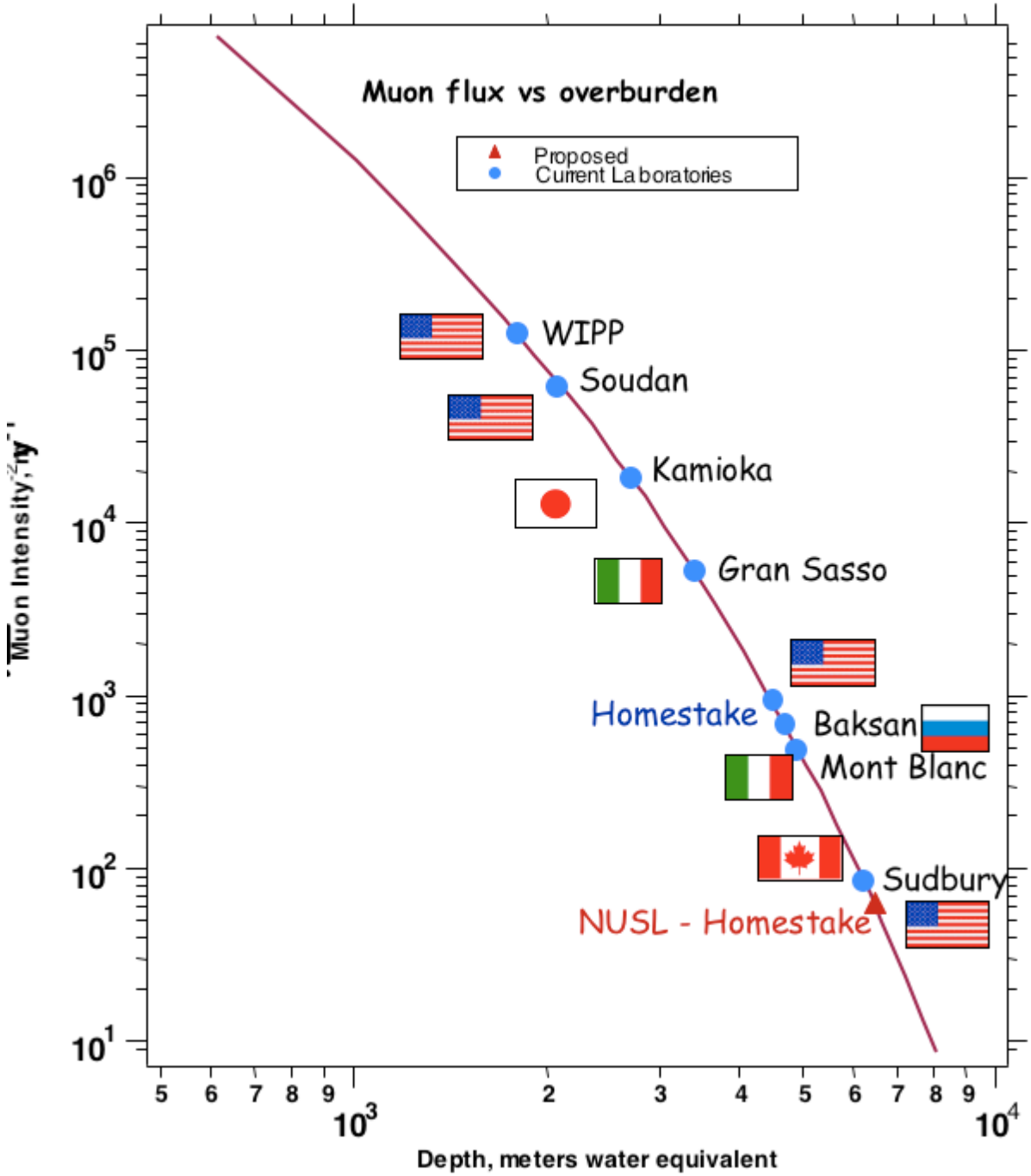
1m

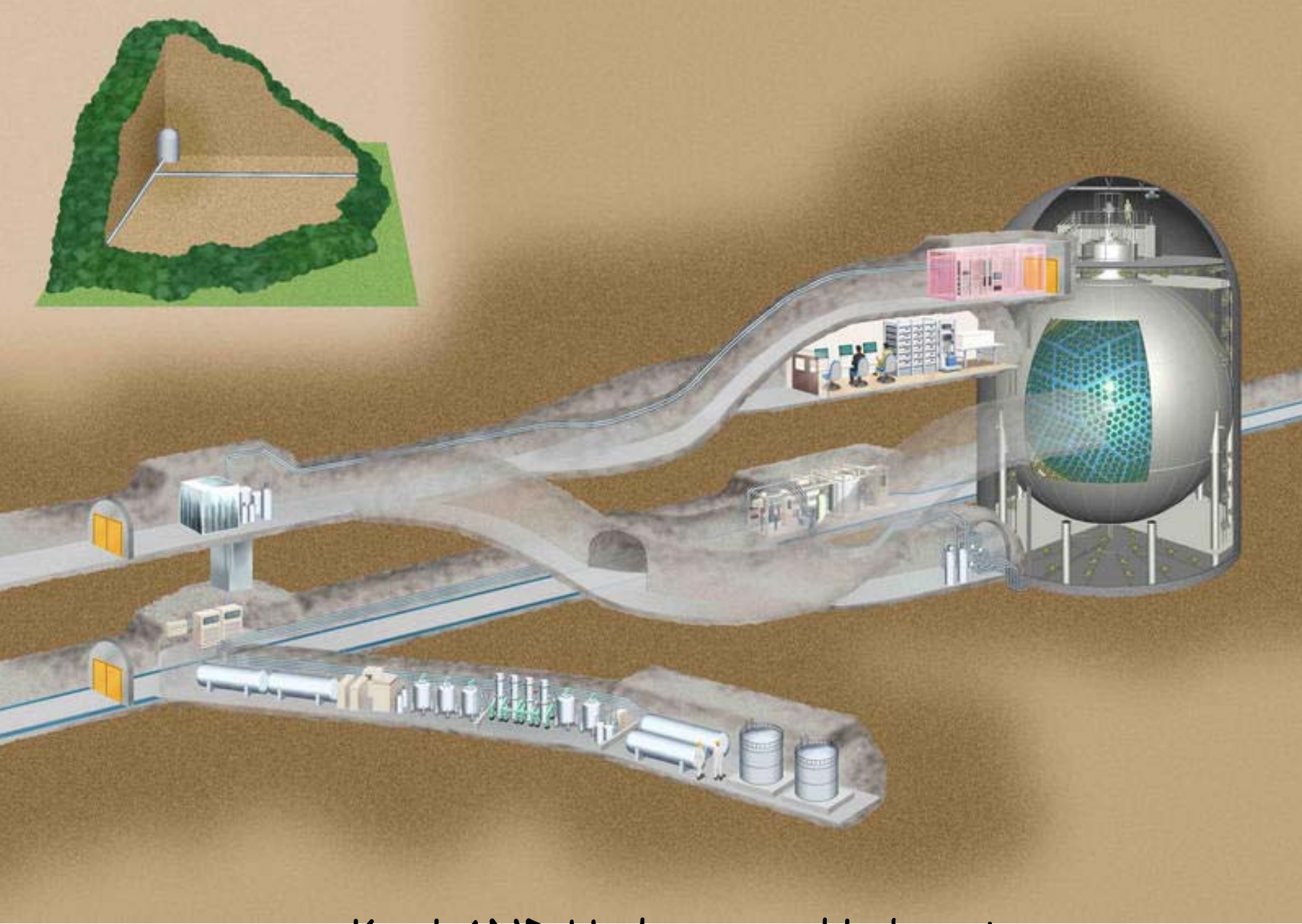
Poltergeist

Long Baseline Reactor Neutrino Experiments

Potential Reactor Neutrino Sources

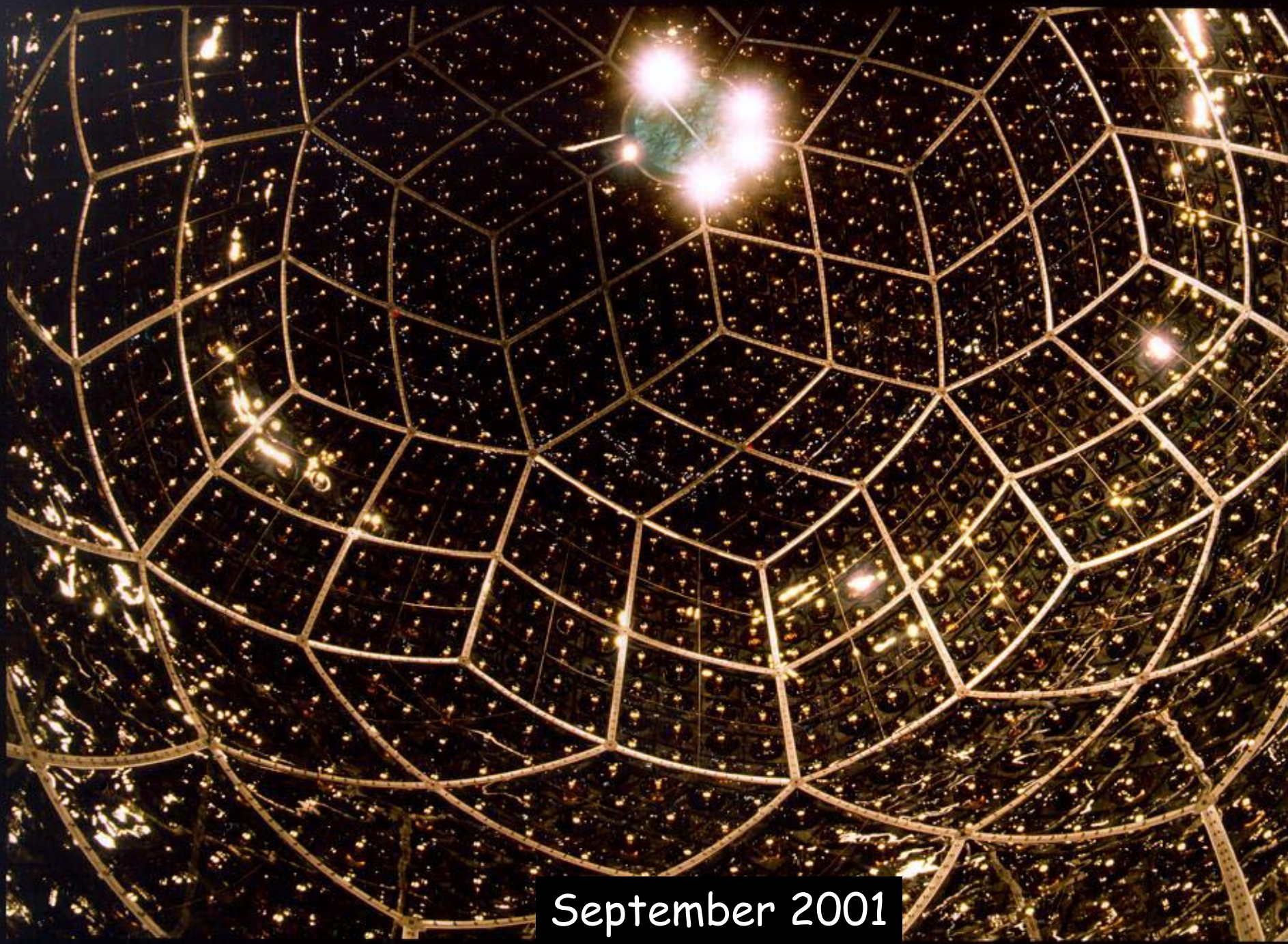



Muon flux vs overburden
Proposed
Current Laboratories
WIPP
Soudan
Kamioka
Gran Sasso
Homestake
Baksan
Mont Blanc
Sudbury
NUSL - Homestake
Muon Intensity, yr⁻¹
Depth, meters water equivalent
10⁶
10⁵
10⁴
10³
10²
10¹
5 6 7 8 9
10³
2 3 4 5 6 7 8 9
10⁴



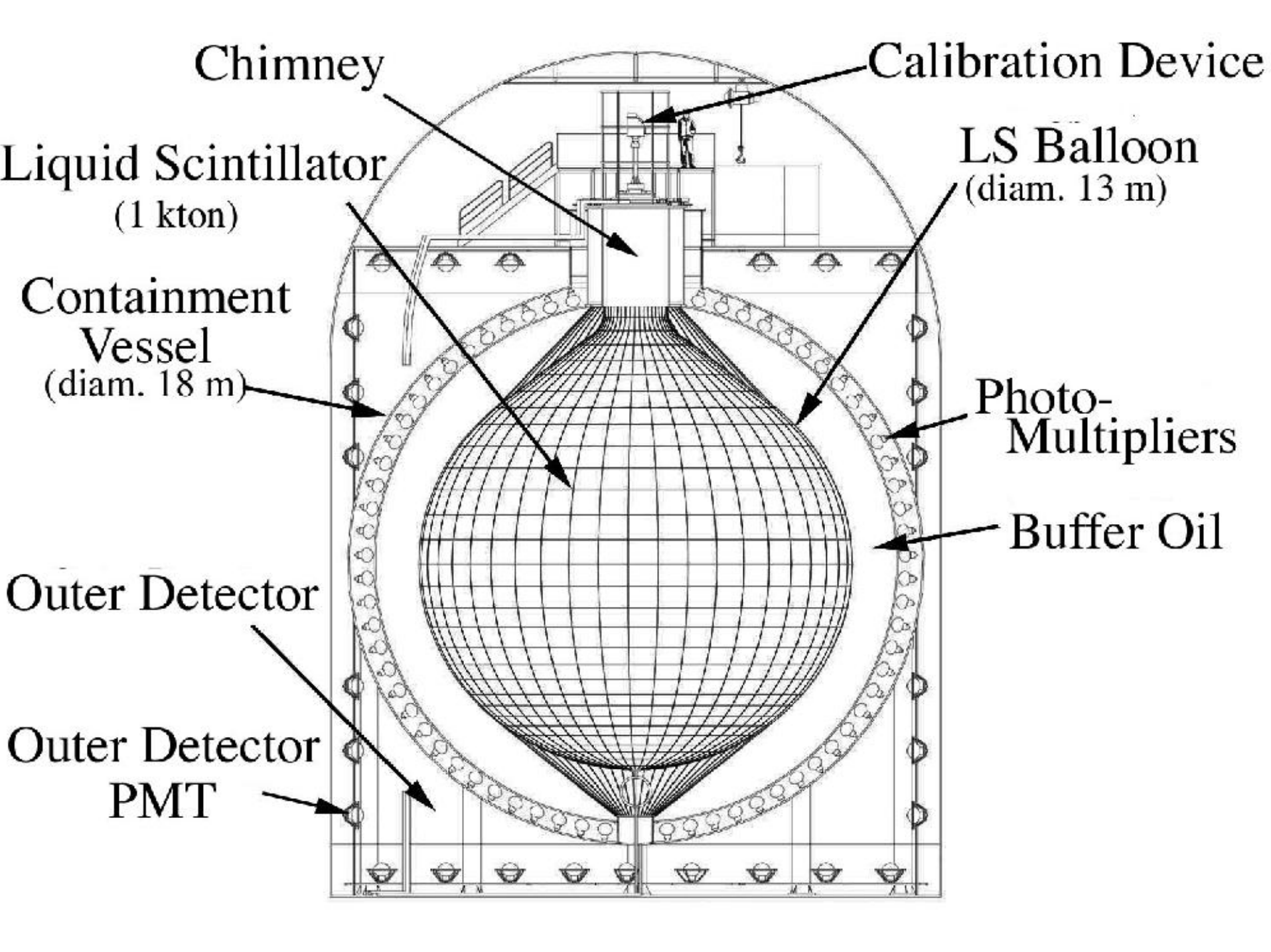
KamLAND Underground Laboratory

September 1999

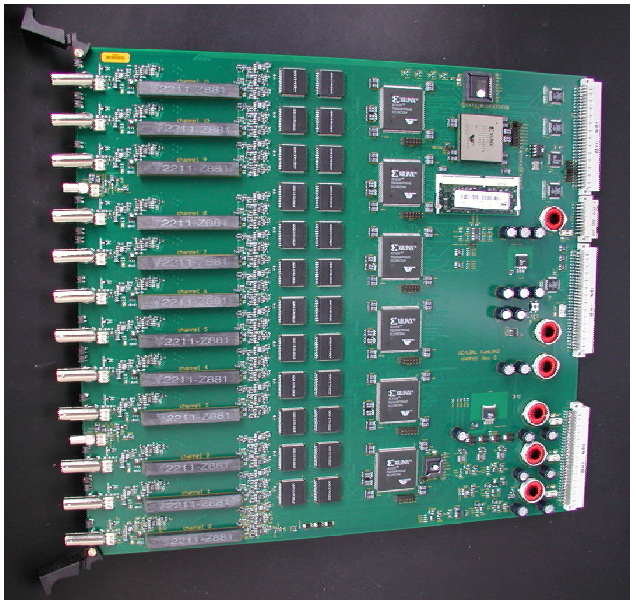

September 2001

January 22, 2002

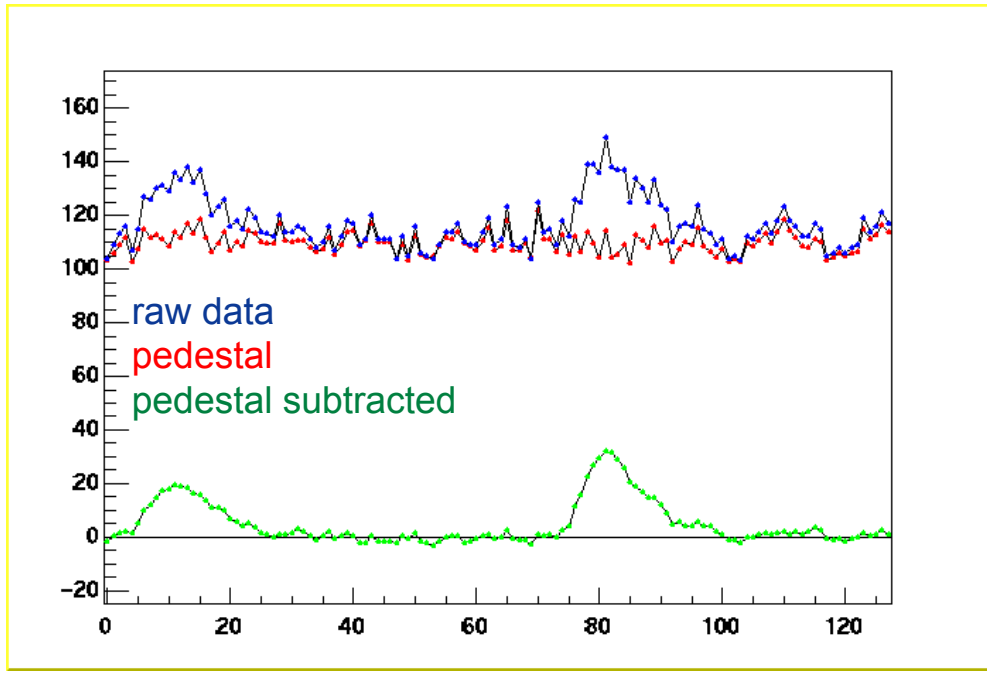
Data taking begins


Chimney
Calibration Device
Liquid Scintillator
(1 kton)
LS Balloon
(diam. 13 m)
Containment
Vessel
(diam. 18 m)
Photo-
Multipliers
Buffer Oil
Outer Detector
Outer Detector
PMT

Front End Electronics



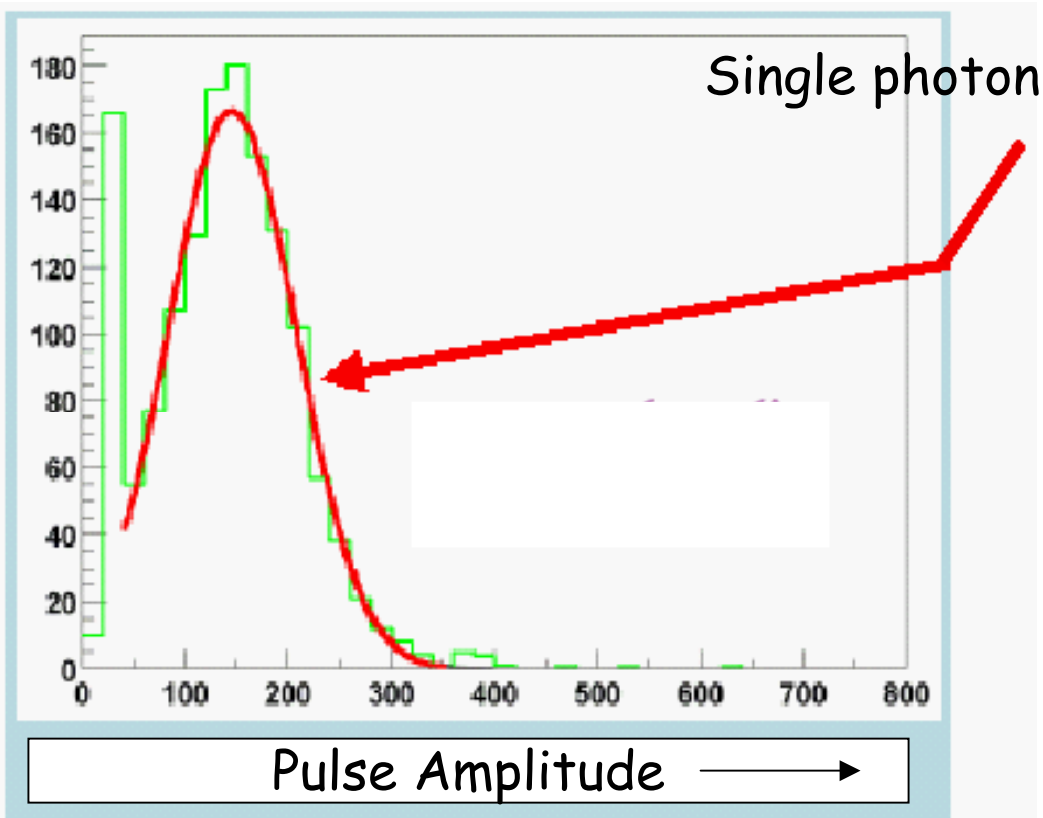
Waveforms are recorded using Analogue Transient Waveform Digitizers (ATWDs), allowing multi p.e. resolution



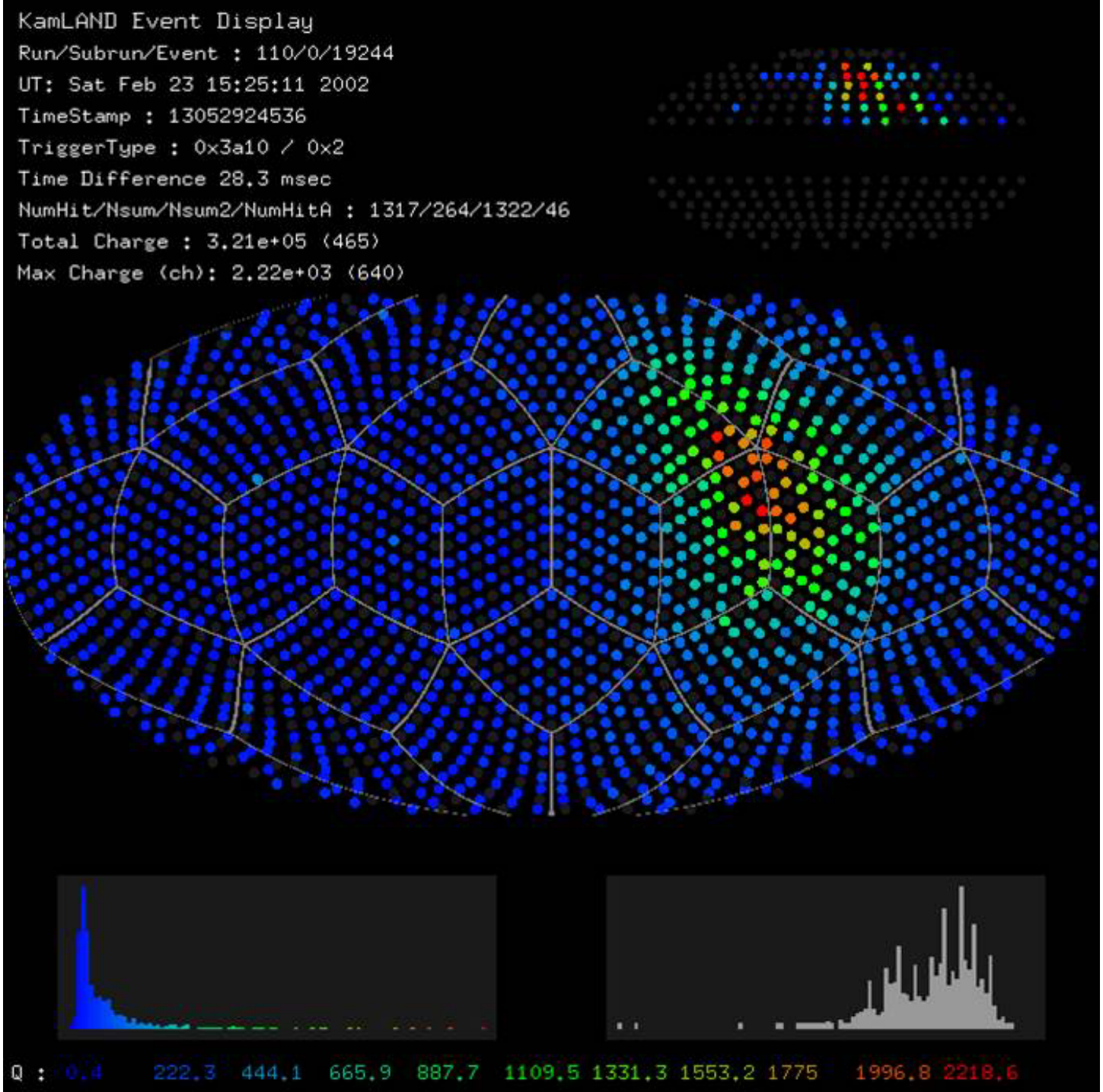
- The ATWDs are self launching with a threshold ~1/3 p.e.
- Each PMT is connected to 2 ATWDs, reducing deadtime
- Each ATWD has 3 gains (20, 4, 0.5), allowing a dynamic range of ~1mV- ~1V

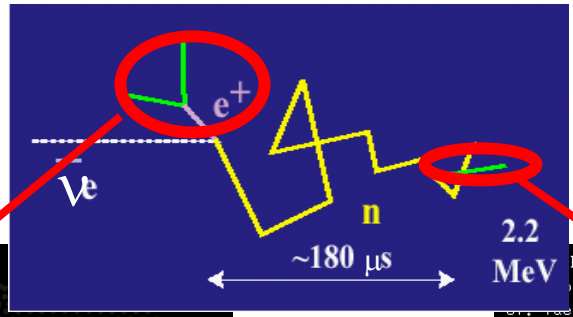
1235 fast 20" diameter PMTs masked to 17"

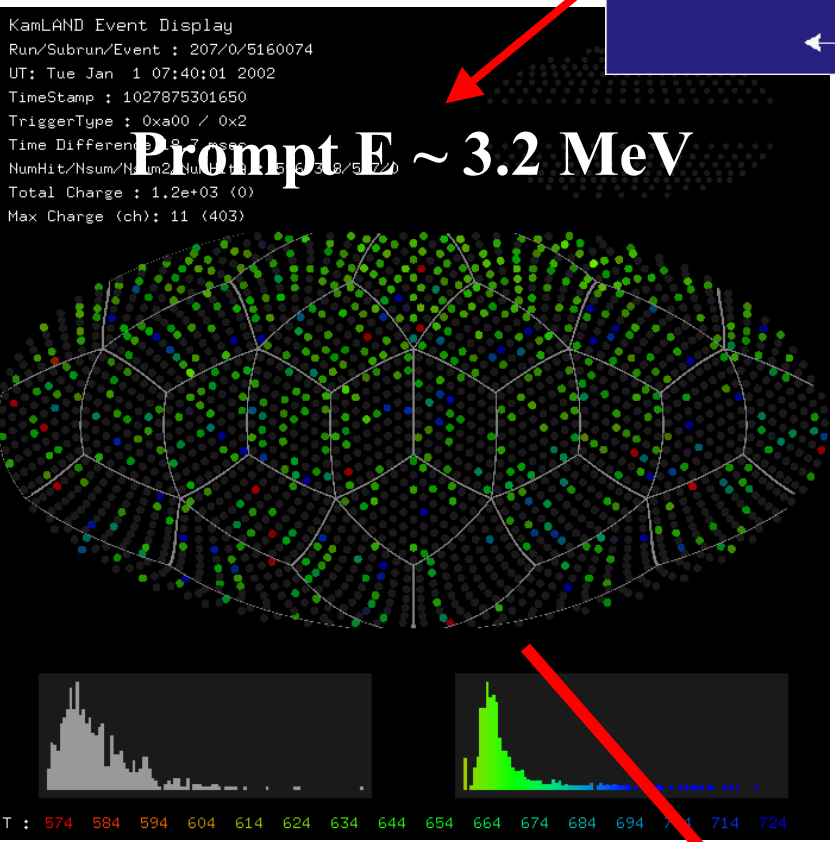
554 "previously owned" 20" PMTs



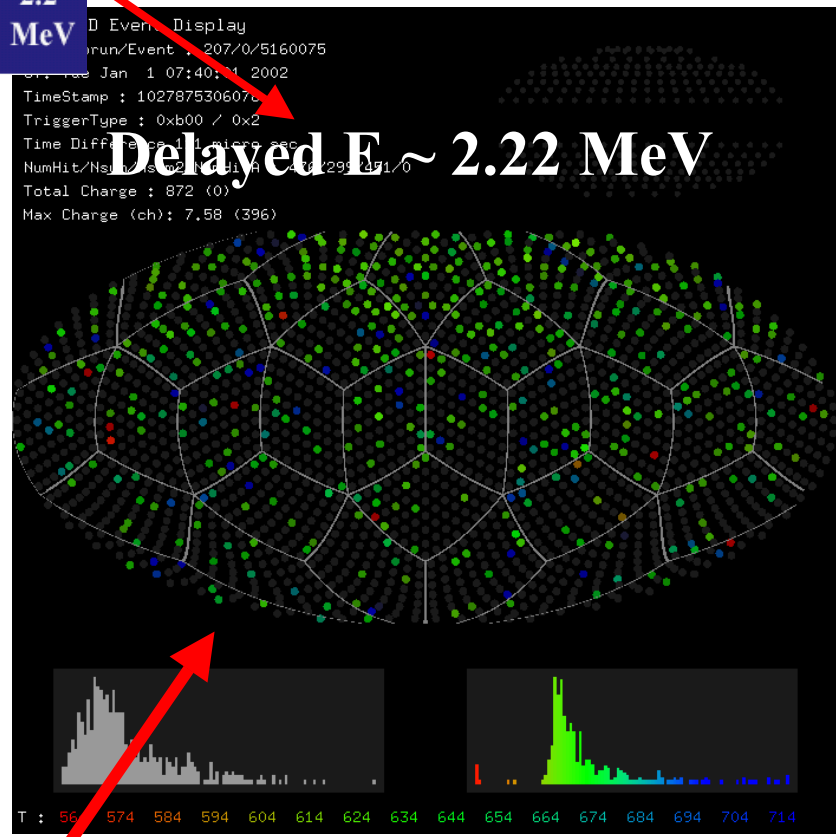
KamLAND Photodetectors


KamLAND Event Display
Run/Subrun/Event : 110/0/19244
UT: Sat Feb 23 15:25:11 2002
TimeStamp : 13052924536
TriggerType : 0x3a10 / 0x2
Time Difference 28.3 msec
NumHit/Nsum/Nsum2/NumHitA : 1317/264/1322/46
Total Charge : 3.21e+05 (465)
Max Charge (ch): 2.22e+03 (640)
Q : 0.4 222.3 444.1 665.9 887.7 1109.5 1331.3 1553.2 1775 1996.8 2218.6





Prompt E ~ 3.2 MeV

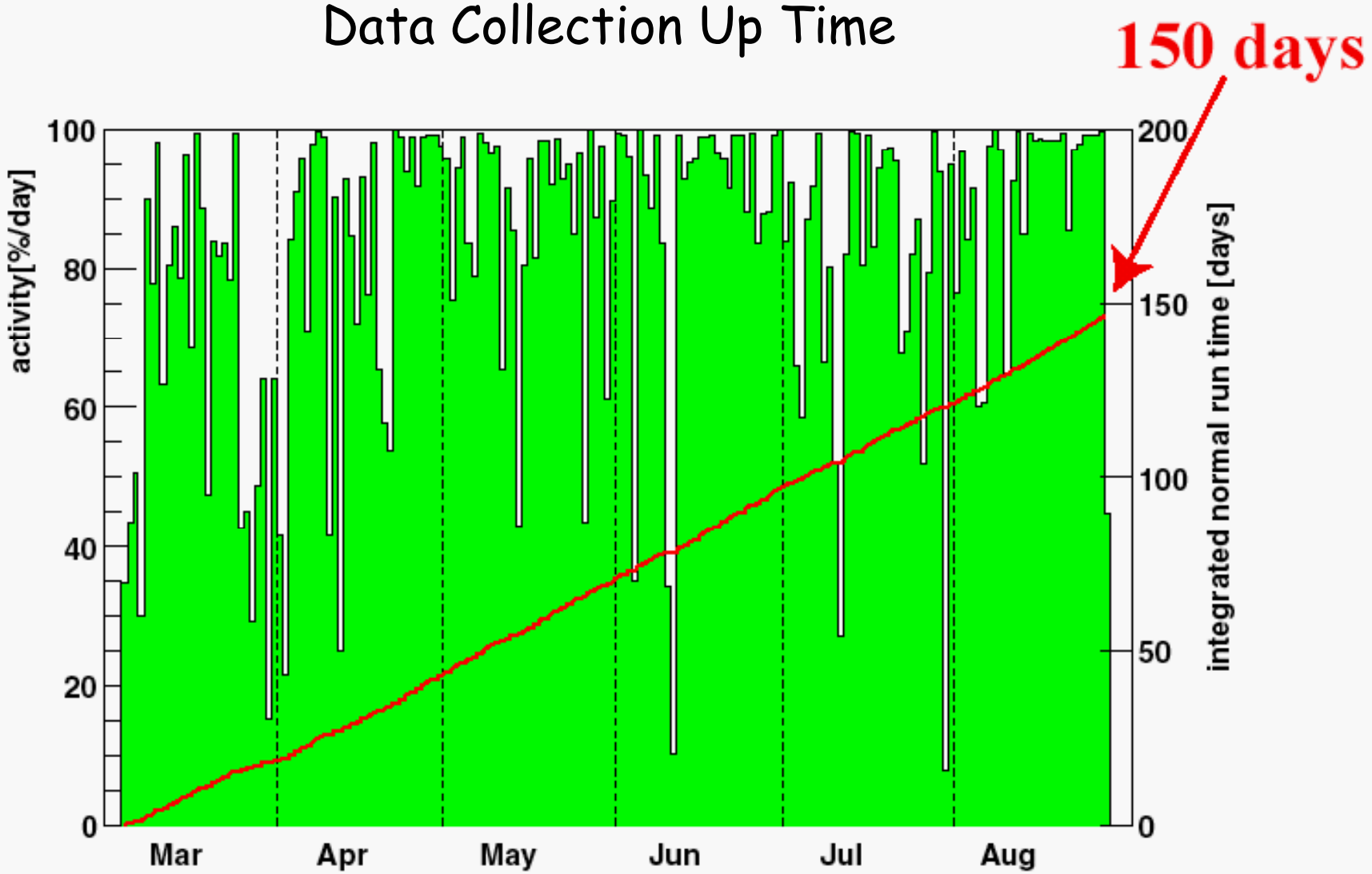


Delayed E ~ 2.22 MeV

Δt~110 μsec
ΔR~0.35 m

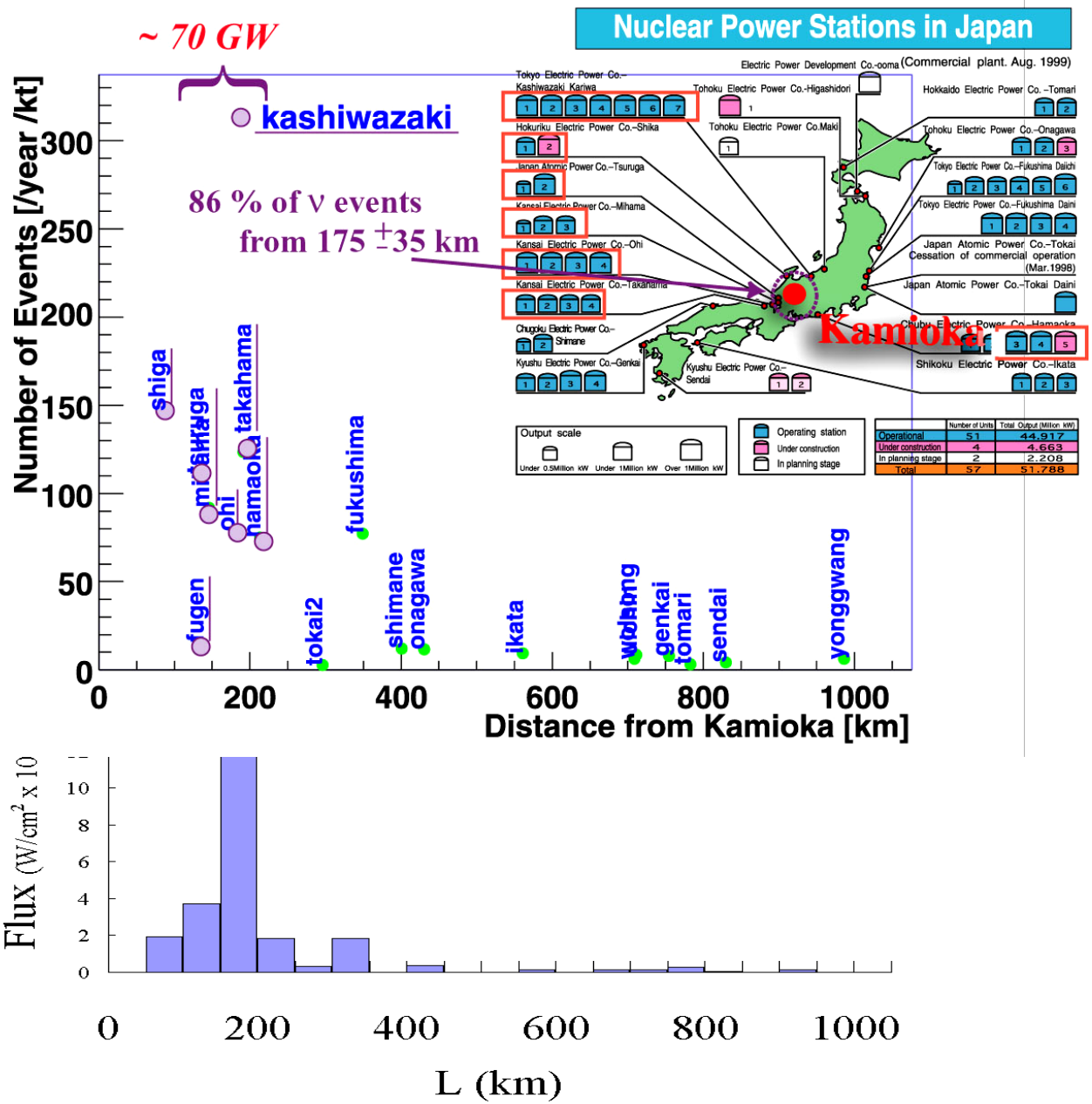
Candidate Neutrino Event

Data Collection Up Time

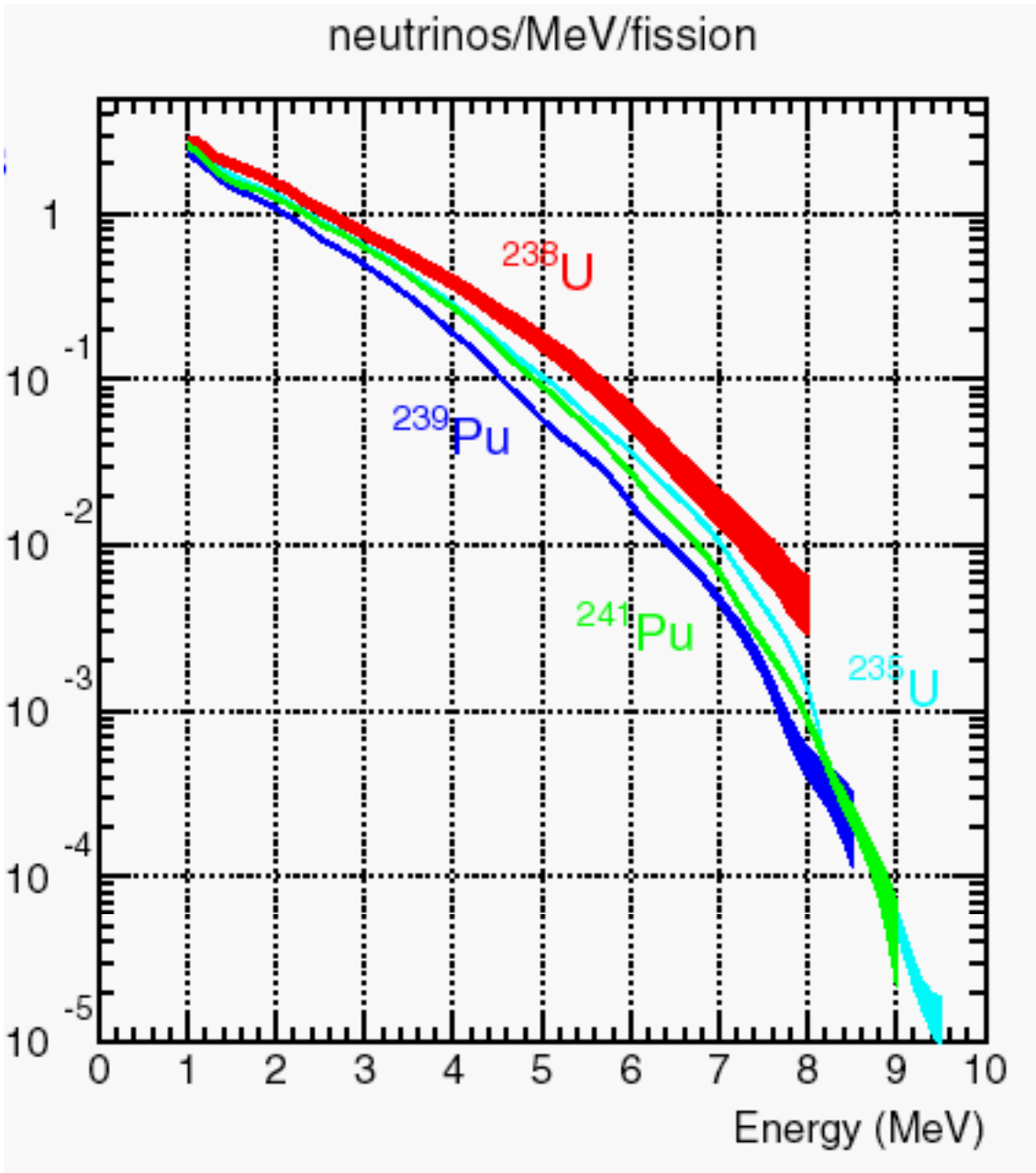


20 % of world nuclear power

~ 70 GW



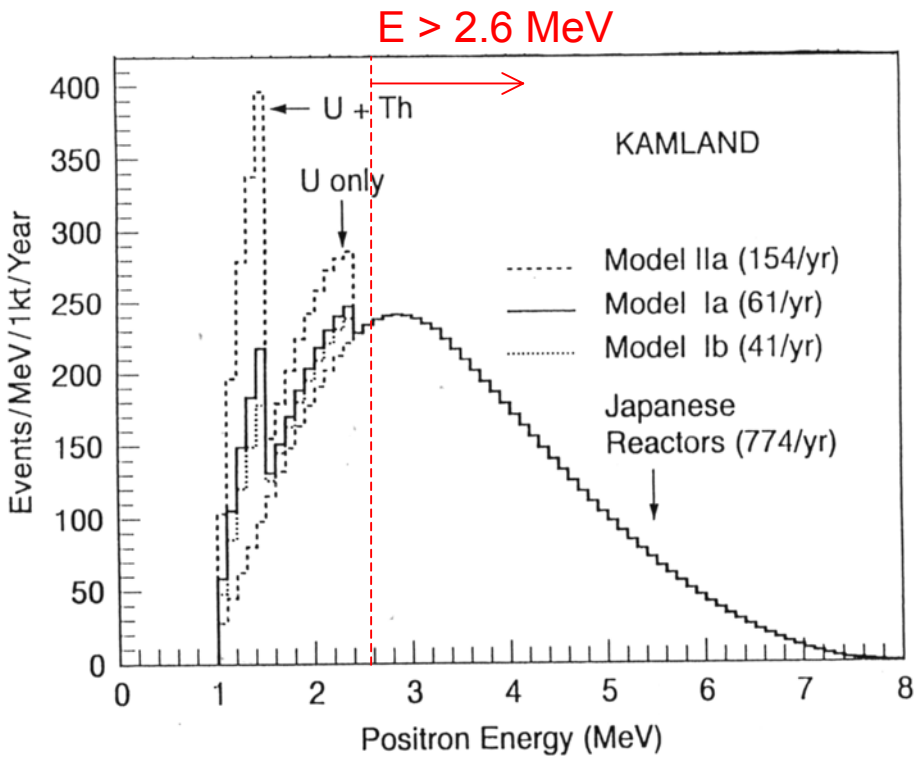
Neutrino Spectra from Principal Reactor Isotopes



Geo-Neutrino Signal (Background) from Earth

U/Th decays in crust and mantle

Produce radiogenic heat (40-60% of 40TW) from



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

Raghavan et al. PRL 80 (1998)

Data Processing and Analysis

US KamLAND Computing at NERSC

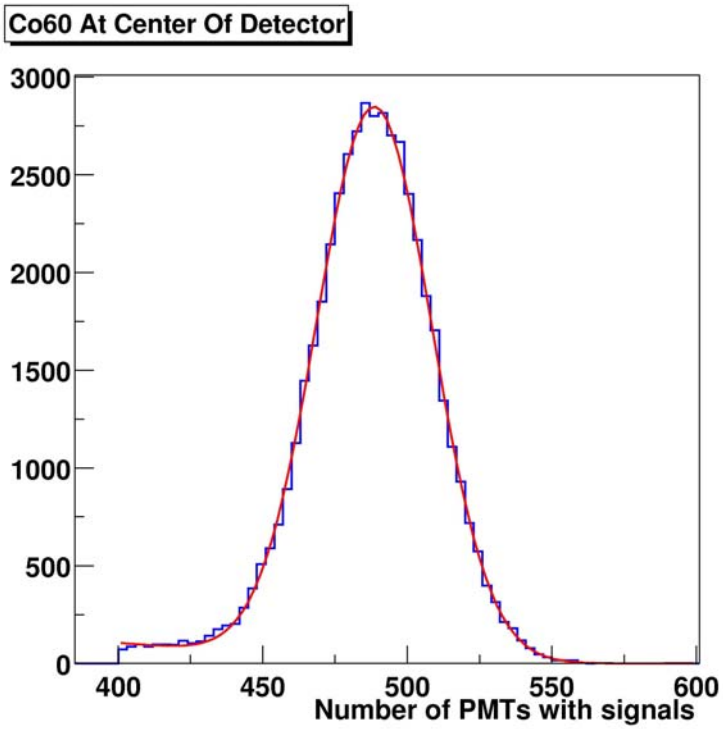
- KamLAND data taking ~ 300 GB/day

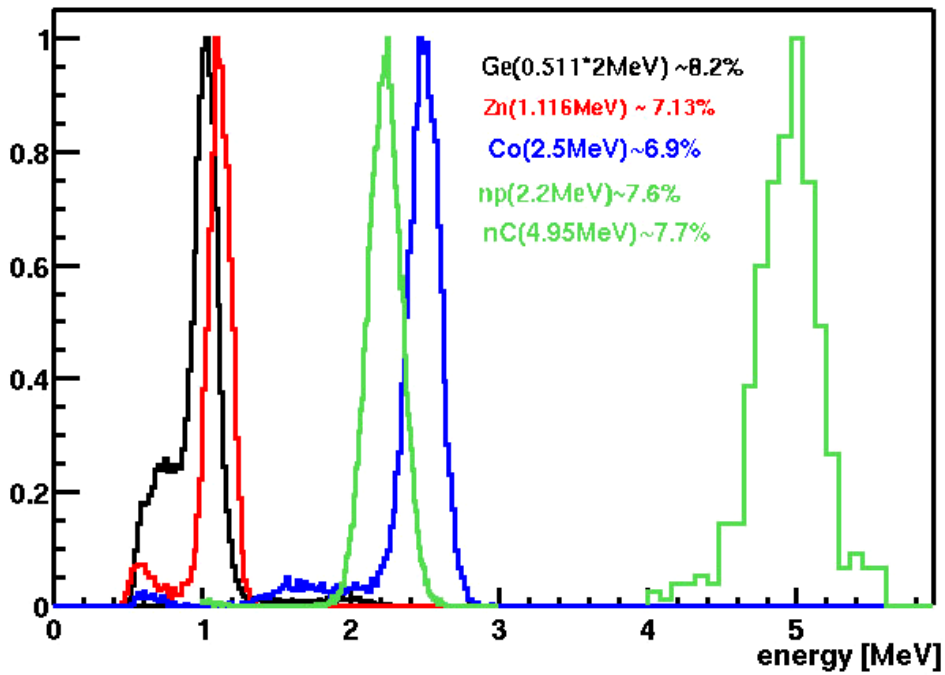
- HPSS (high performance storage system)

~2 TB/day input rate

- PDSF (parallel distributed systems facility)

Detector Energy Scale and Response





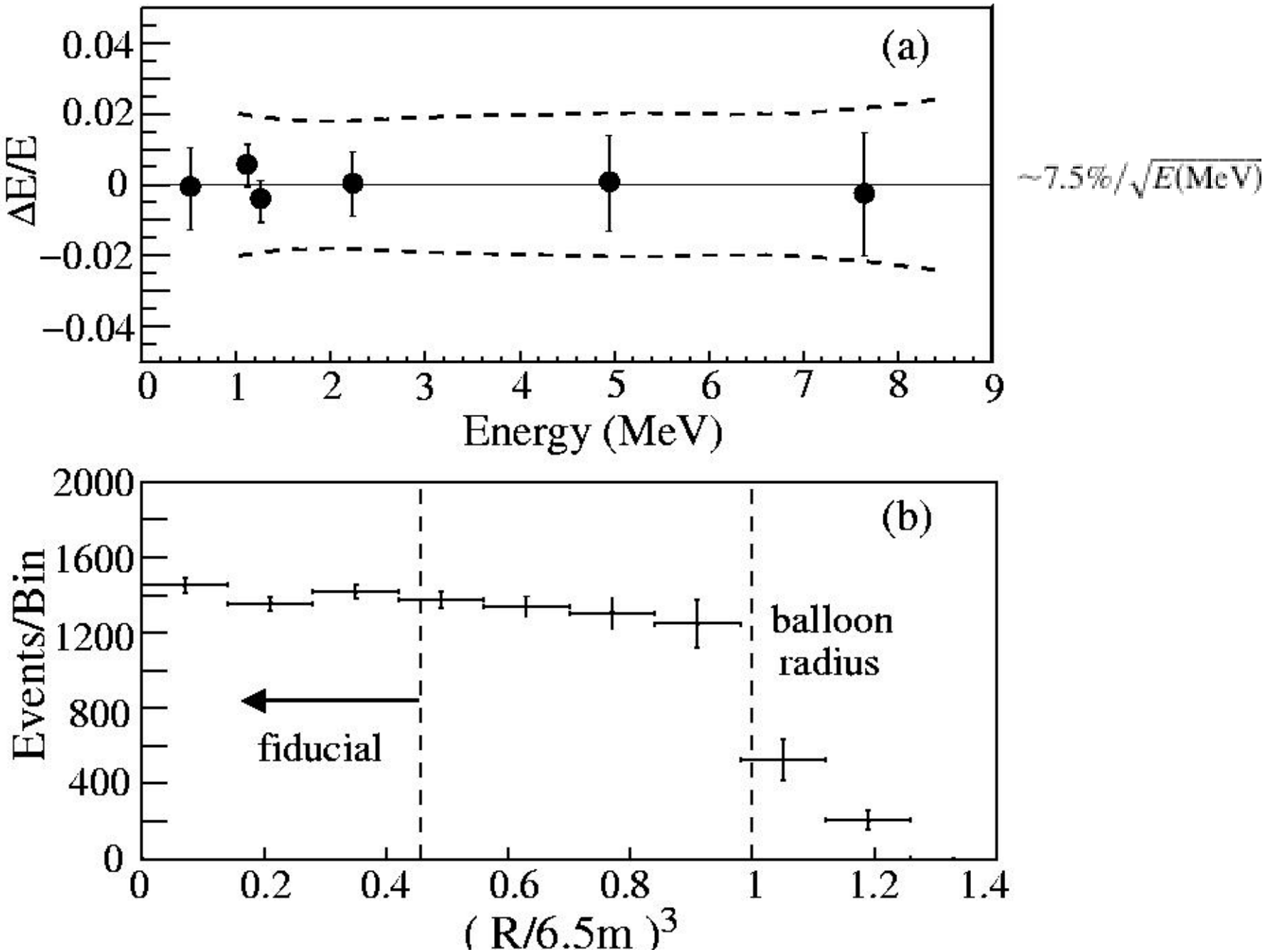
^{60}Co: 1.173+1.333 MeV

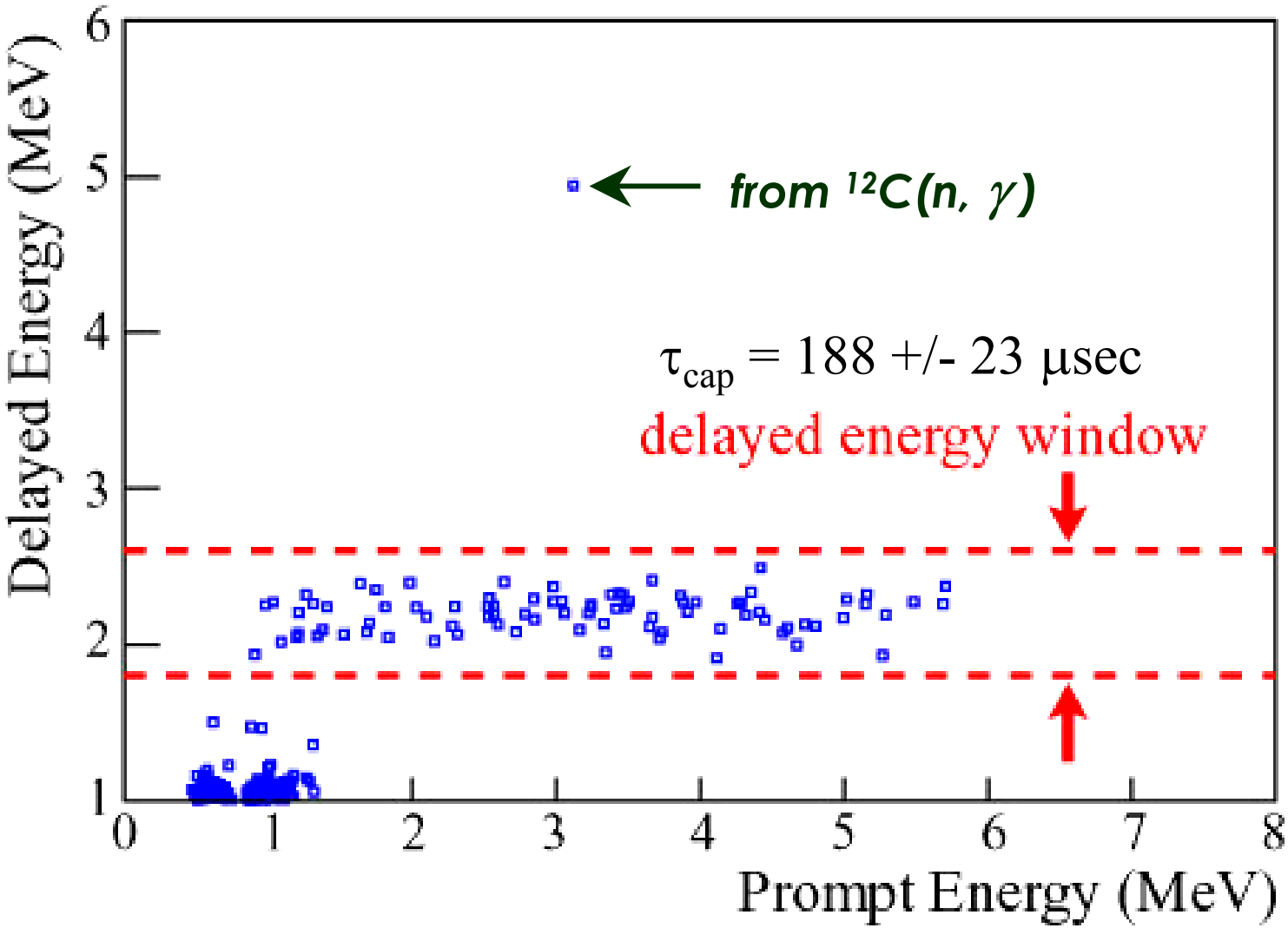
ΔE_{syst} = 1.91% at 2.6 MeV $\rightarrow$ 2.13 % for $\bar{\nu}_e$

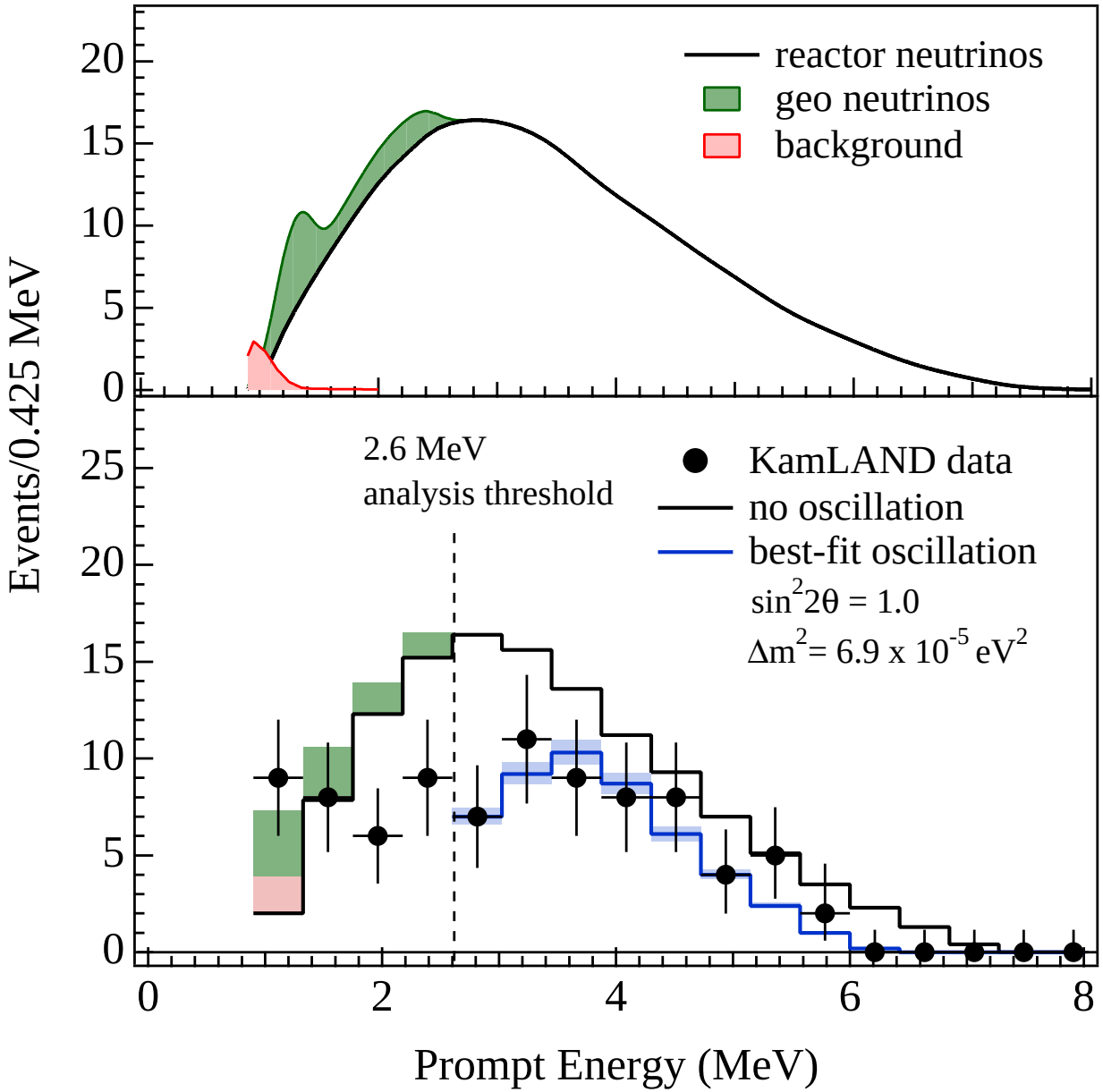
$\Delta E/E \sim 7.5\% / \sqrt{E}$

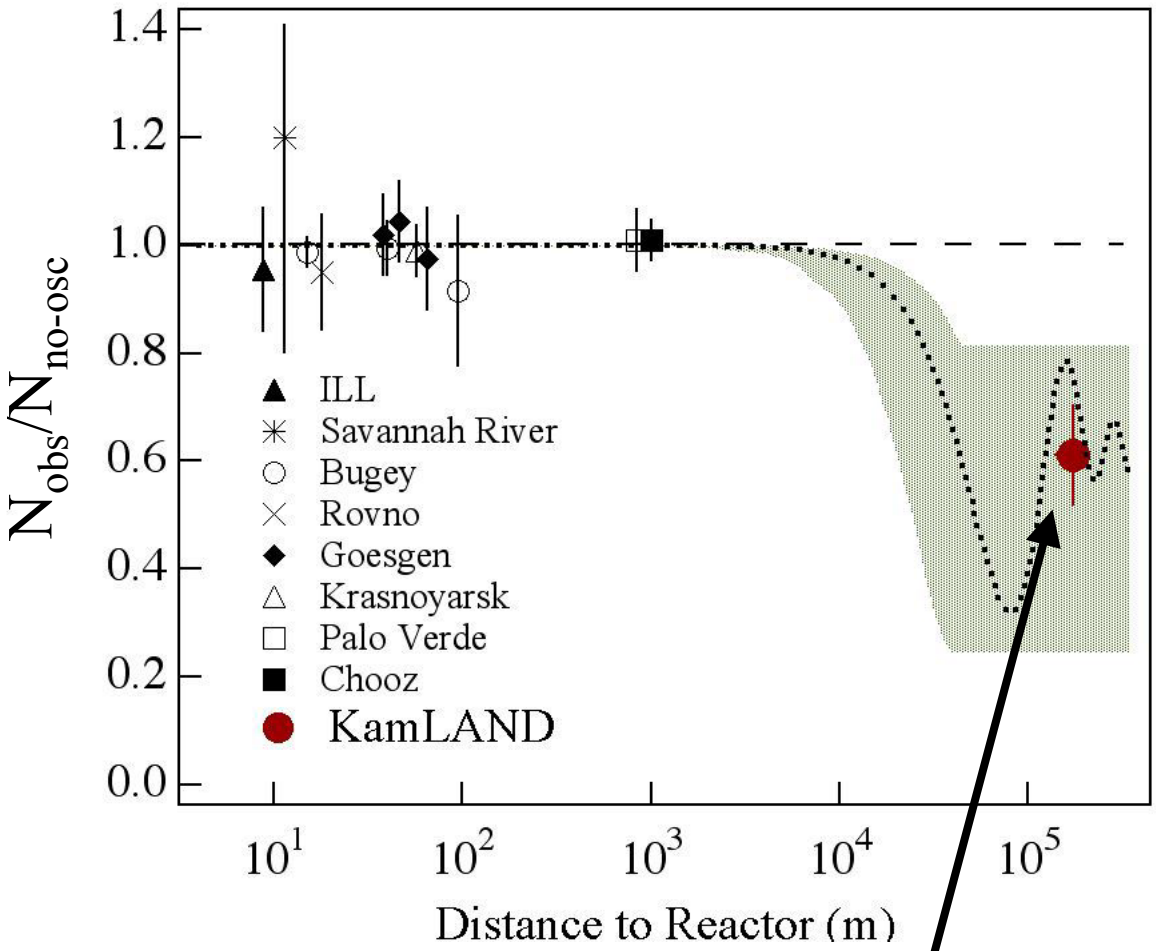
Light yield ~ 300p.e./MeV

Energy varies by < 0.5% within 10 m.


(a)
0.04
0.02
0
−0.02
−0.04
ΔE/E
0
1
2
3
4
5
6
7
8
9
Energy (MeV)
~7.5%/√E(MeV)
(b)
2000
1600
1200
800
400
0
Events/Bin
balloon
radius
fiducial
0
0.2
0.4
0.6
0.8
1
1.2
1.4
(R/6.5m)3


Delayed Energy (MeV)
Prompt Energy (MeV)
from $^{12}C(n, \gamma)$
τ_{cap} = 188 +/- 23 μsec
delayed energy window
0
1
2
3
4
5
6
7
8


reactor neutrinos
geo neutrinos
background
2.6 MeV
analysis threshold
KamLAND data
no oscillation
best-fit oscillation
sin²2θ = 1.0
Δm² = 6.9 x 10⁻⁵ eV²
Events/0.425 MeV
Prompt Energy (MeV)
0
5
10
15
20
25
0
2
4
6
8

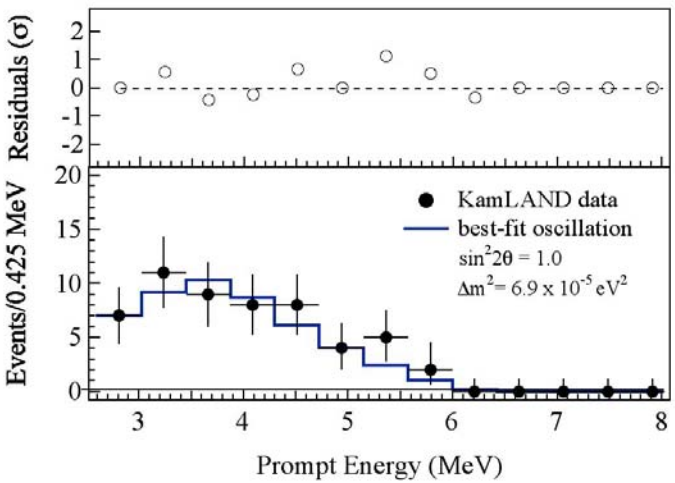


$$\frac{N_{obs}(-N_{BG})}{N_{expected}} = 0.611 \pm 0.085(stat) \pm 0.041(syst)$$

From $1/r^2$

Do we see a distorted spectrum?

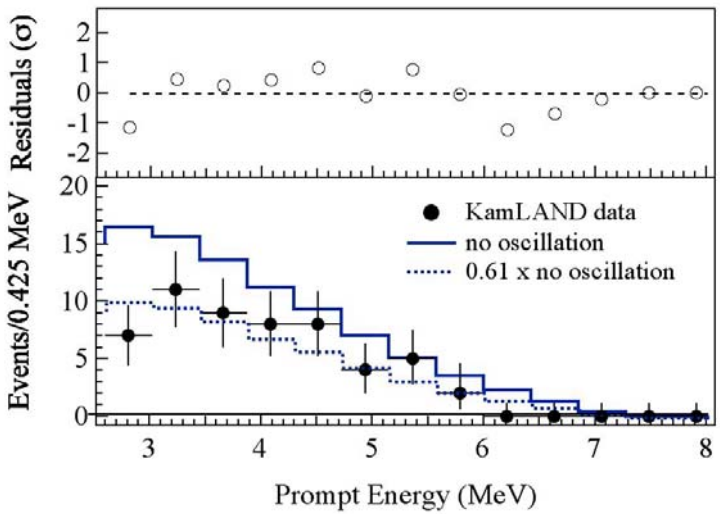
2-ν oscillation: best-fit



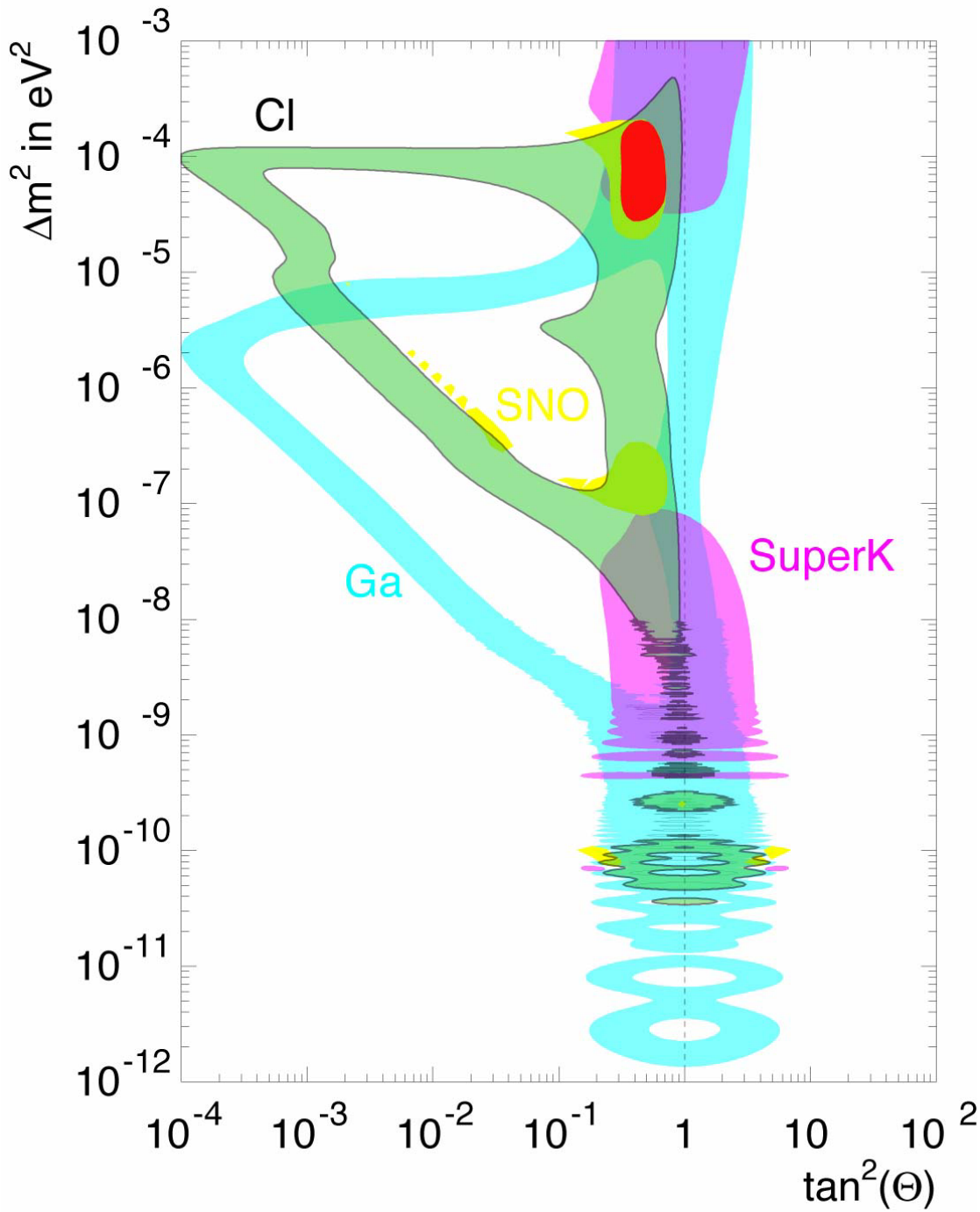
χ^2 / 8 d.o.f = 0.31

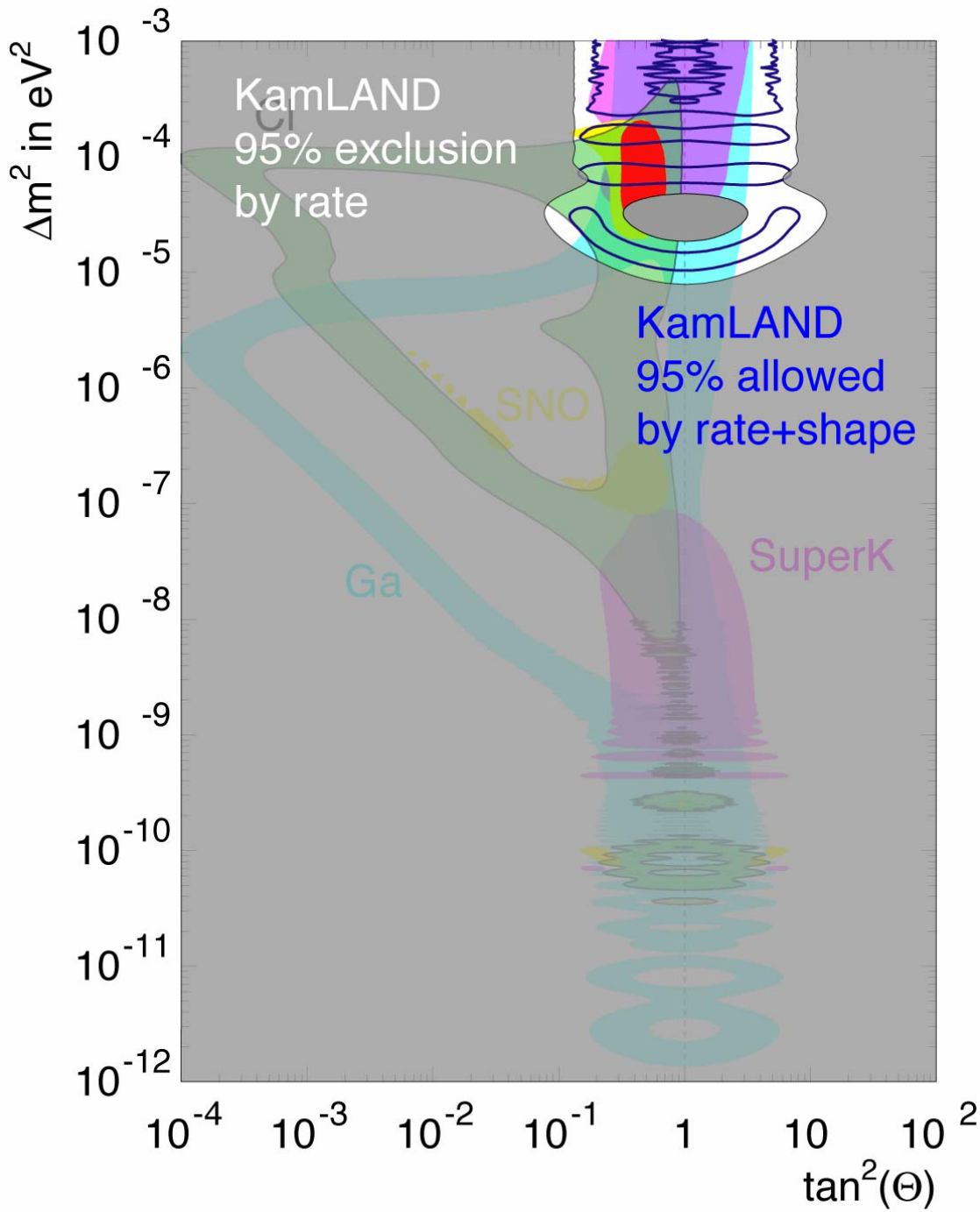
Data and best oscillation fit consistent at 93% C.L.

No oscillation, flux suppression

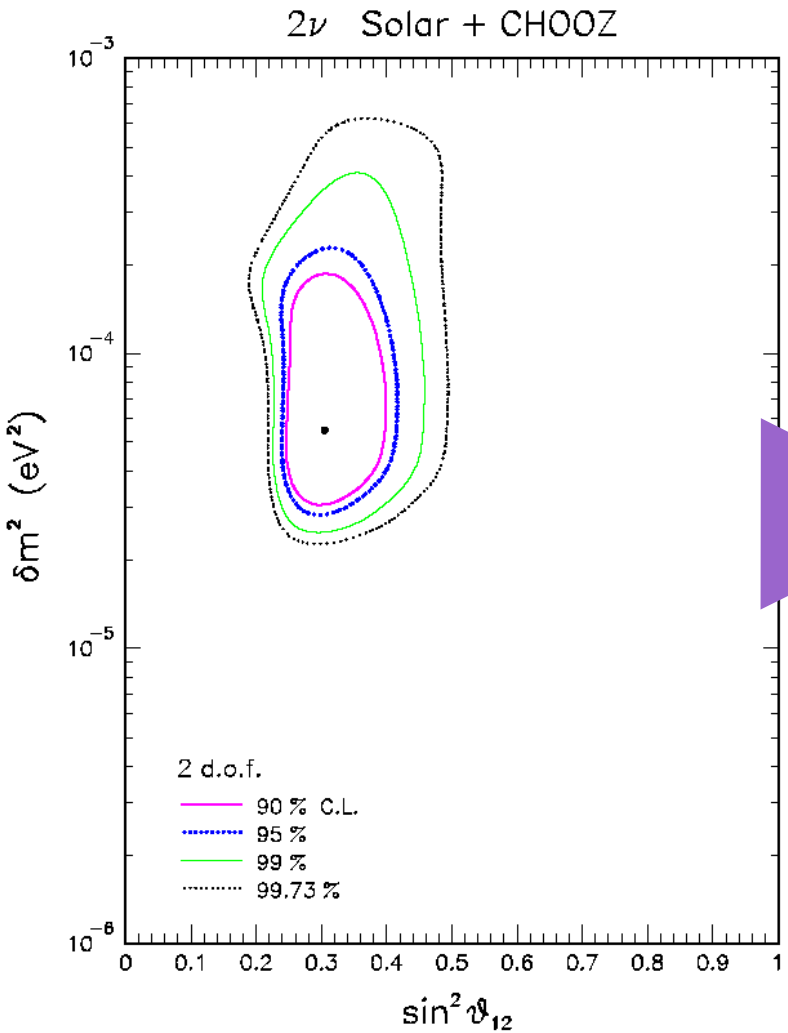


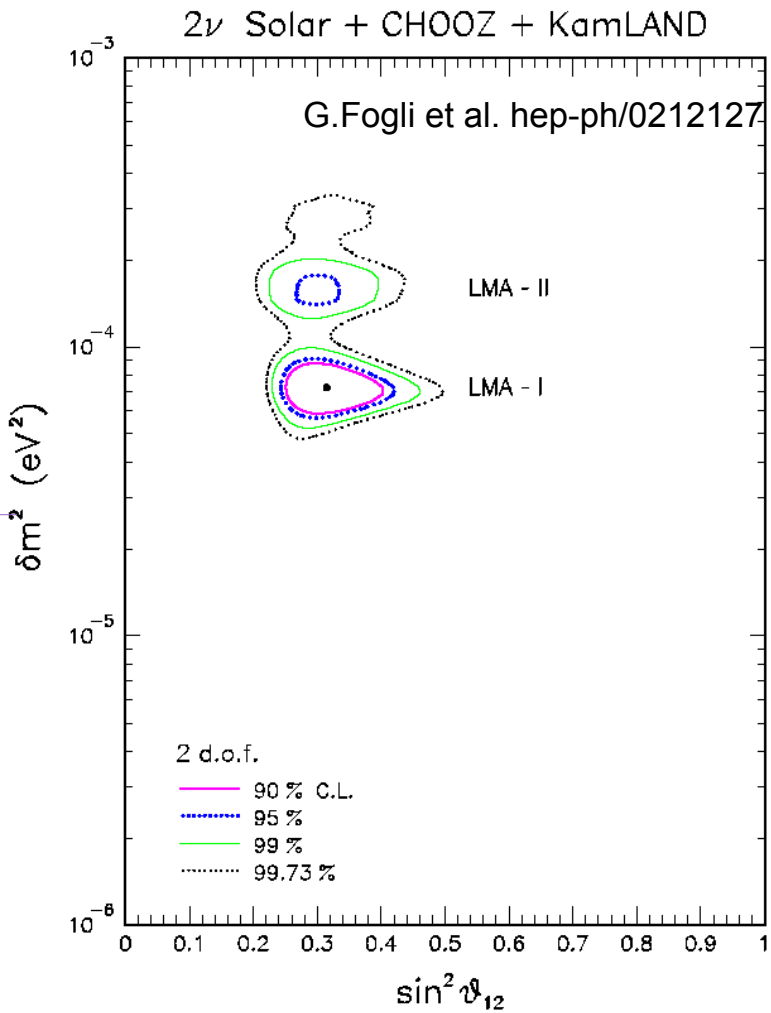
Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo


Cl
SNO
Ga
SuperK
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}
$\tan^2(\Theta)$


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}
$\tan^2(\Theta)$

Global Fit with KamLAND





LMA split into two regions...

U_{MNSP} Neutrino Mixing Matrix

MNSP Matrix $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

Solar $\theta_{12} = 30.3°$

Atmospheric $\theta_{23} = \sim 45°$

Chooz + SK $\tan^2 \theta_{13} < 0.03$ at 90% CL

In 3-ν scheme with Dirac neutrinos: $U_{MNSP} = U_{atm} * U_{e3} * U_{solar}$ δ =CP violating phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times \begin{pmatrix} \sim 1 & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \sim 1 \end{pmatrix} \times \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ν (SK)

reactor and accelerator ν (Chooz)

solar ν (LMA) KamLAND

Systematic Uncertainties

E > 2.6 MeV

	%	
Total LS mass	2.1	4.6%
Fiducial mass ratio	4.1	
Energy threshold	2.1	
Tagging efficiency	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	

PRL Total error	6.4 %
Next Publication	5% (?)

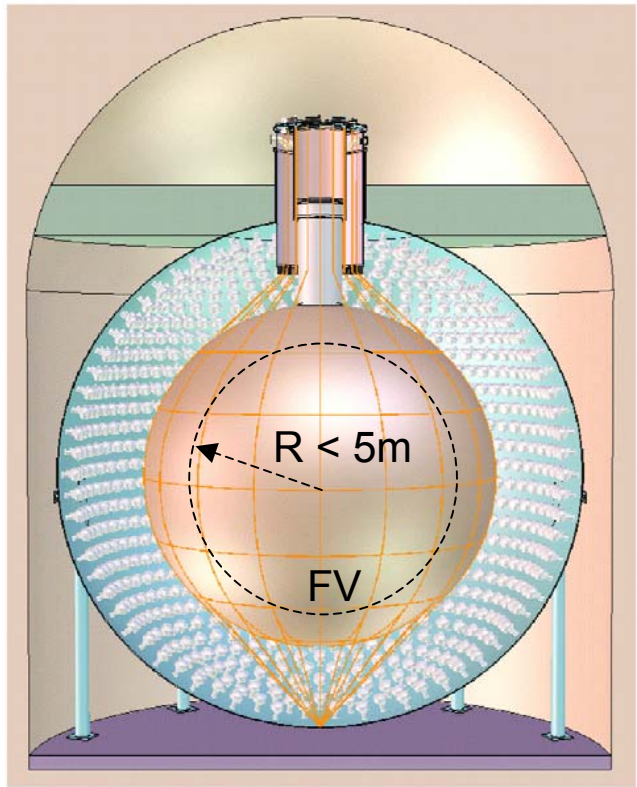
Statistical uncertainty: 13.6 %

$\rightarrow$ Need Off-Axis Clibration

Off-Axis Calibration

I. Increase the fiducial volume

54 $\overline{\nu}_e$ candidate events above 2.6 MeV for R < 5 m
[72] $\overline{\nu}_e$ candidate events for R < 5.5 m

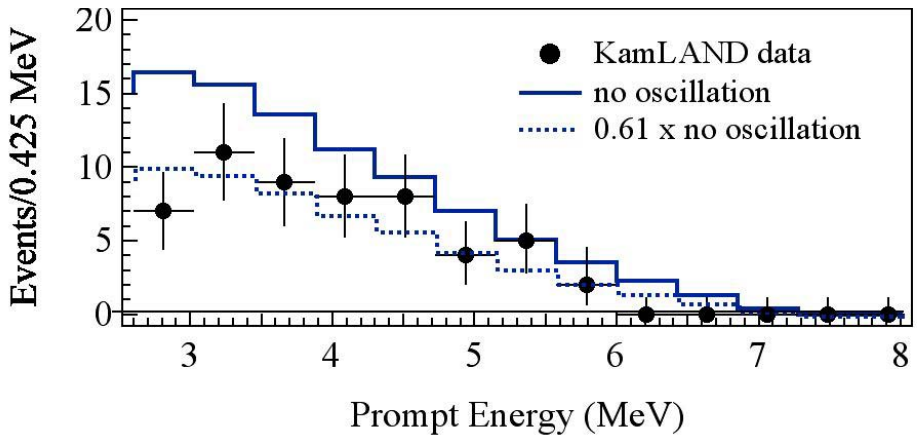


II. Reducing the systematic error

Fiducial volume error	4.6%
Total systematic error	6.4%
→ Goal for next analysis	~ 5%

III. Precision measurement of the detector response

→ search for spectral distortions as a *unique* signature of neutrino oscillations



KamLAND-II

Studies for the Solar Phase of KamLAND