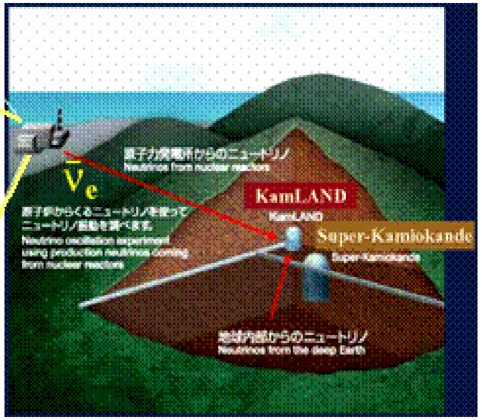
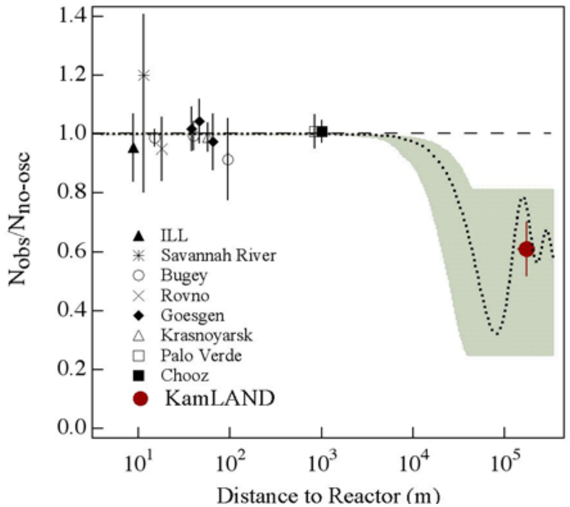


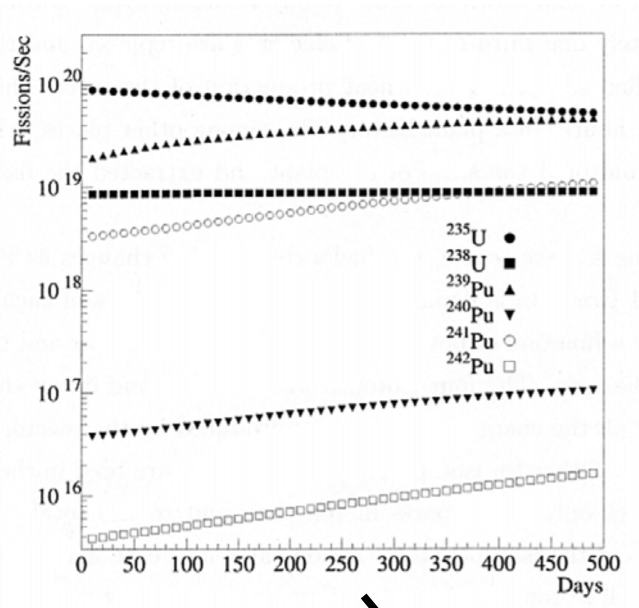


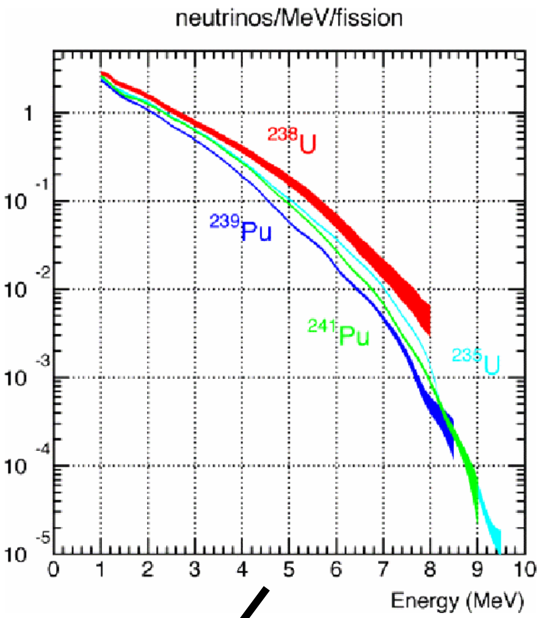
Evidence for Neutrino Oscillations from KamLAND

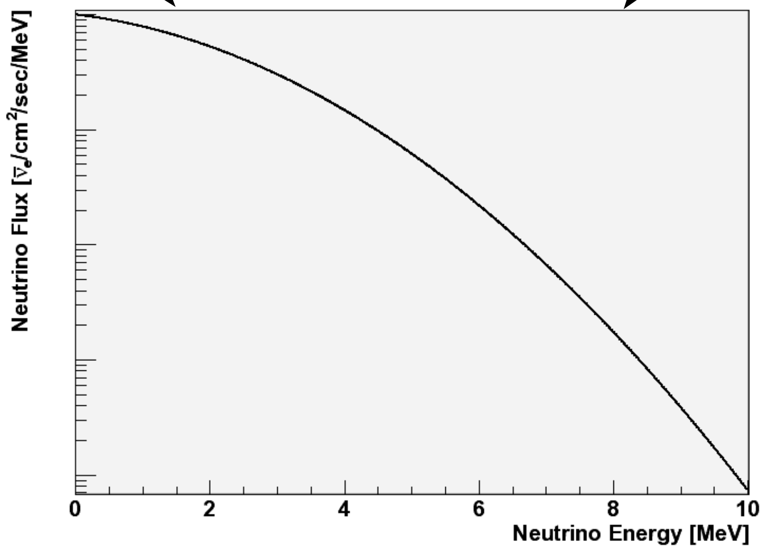
Brian Kurt Fujikawa for the KamLAND Collaboration

•Reactor Type
•Initial Fuel Composition
•Thermal Power
Uncertainty: ~ 1–2%

•Direct Measurement of β Spectrum
•Hypothetical β Decay Branches
Uncertainty: ~ 2%







Uncertainty: ~ 2.5%

Inverse Beta Decay

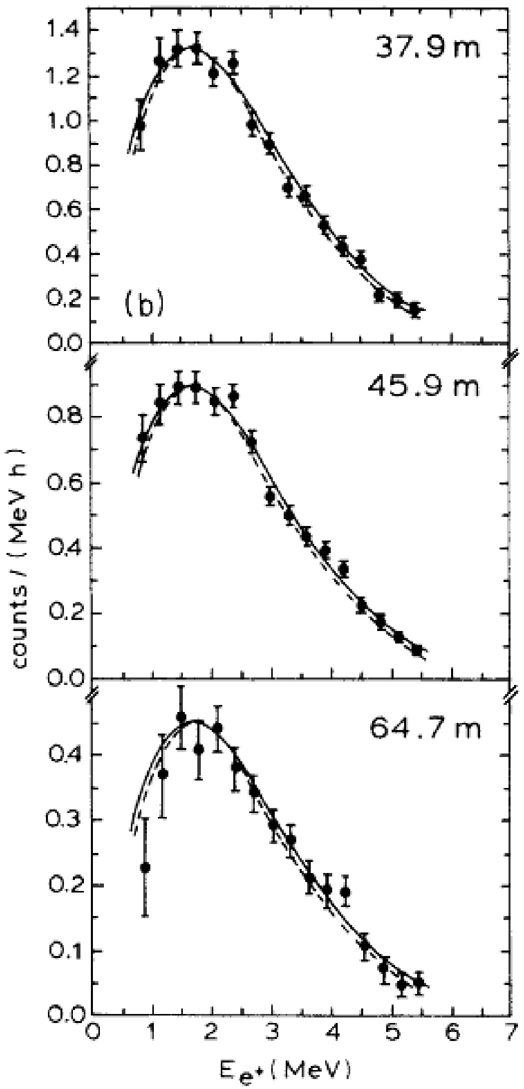
$$\overline{\nu_e} + p \rightarrow n + e^{+}$$ is inverse of $$n \rightarrow p + e^{-} + \overline{\nu_e}$$

$$\sigma_{tot} = \frac{2\pi^2/m_e^5}{f^R \tau_n} E_e p_e + (\mathit{Recoil} + \mathit{Radiative\ Corrections})$$

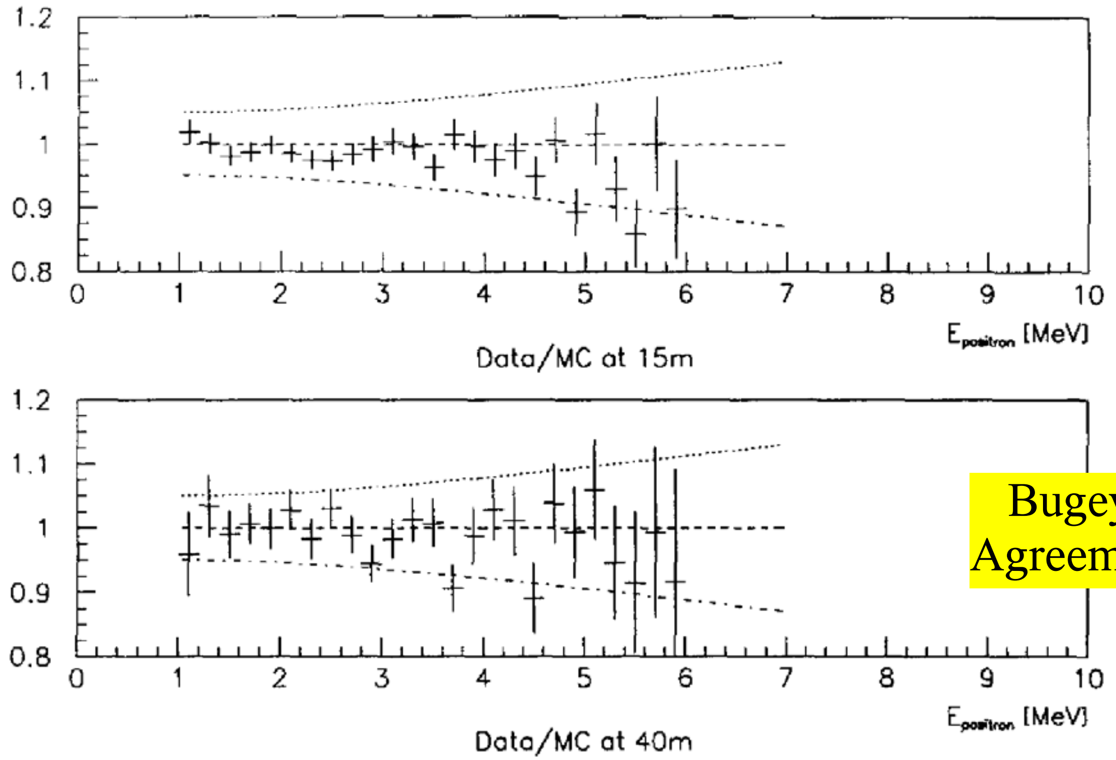
$$\tau_n = 885.7 \pm 0.8\,\text{sec.}$$ (neutron mean life)

$$E_e = E_\nu - M_n - M_p + O\left(\frac{E_\nu}{M_n}\right) \approx E_\nu - 1.29\ \text{MeV}$$

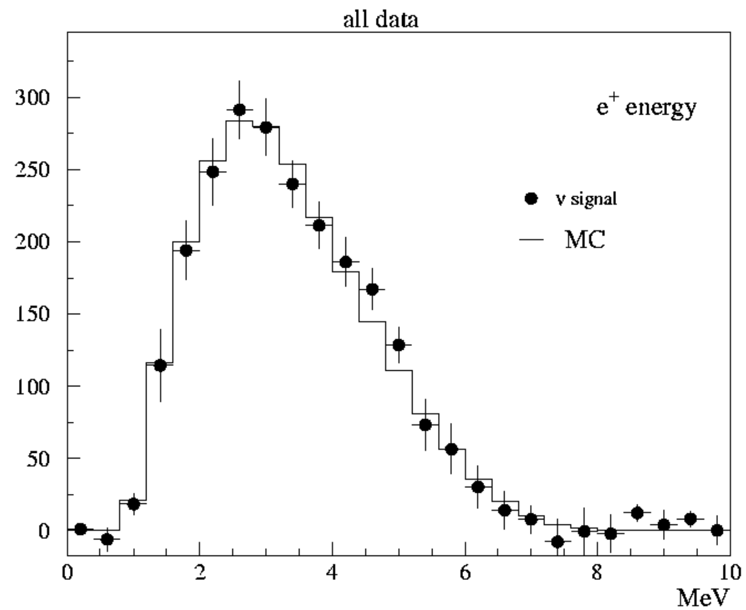
Uncertainty: 0.2%



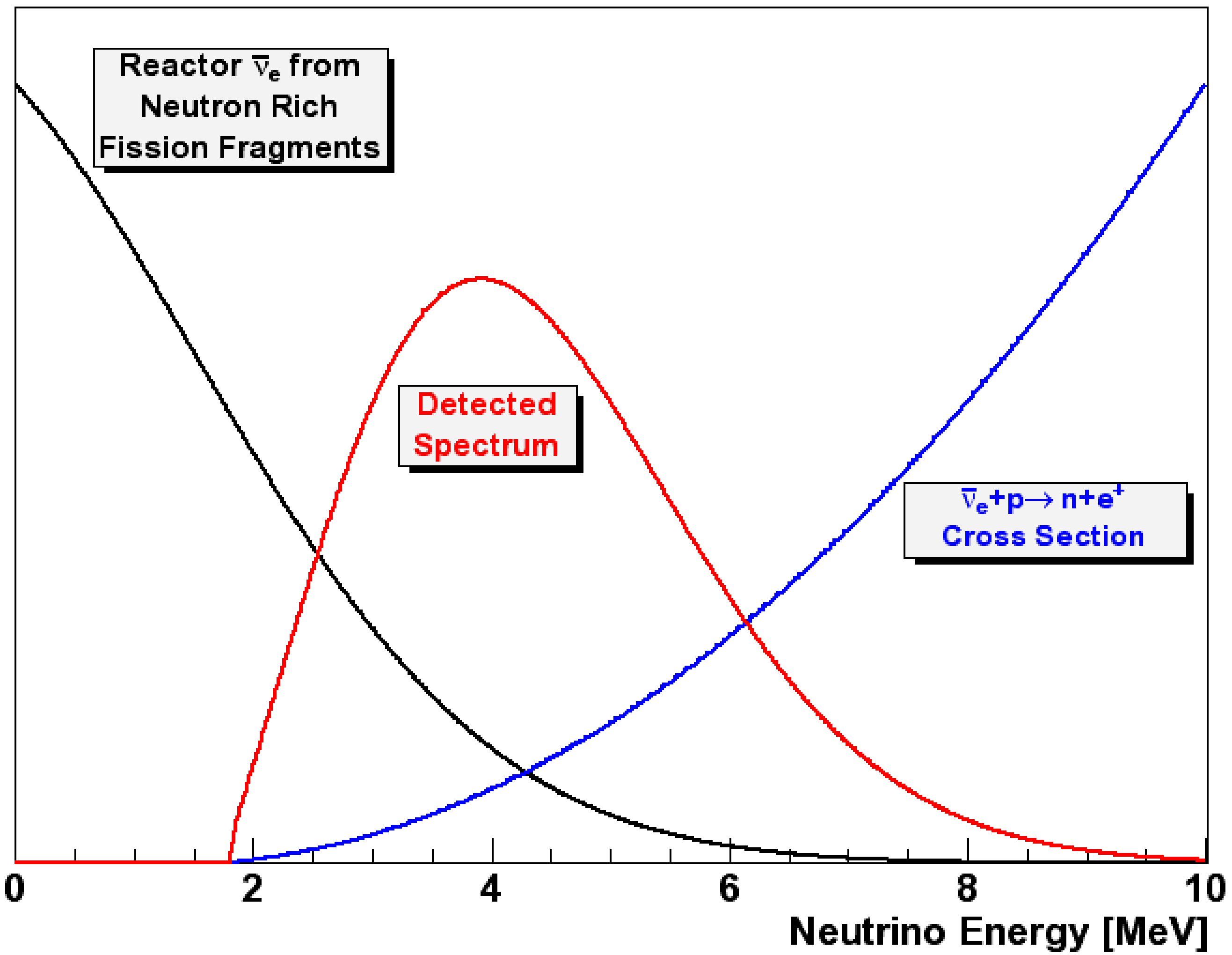
Gösgen (1986)
Agreement: ~ 2%



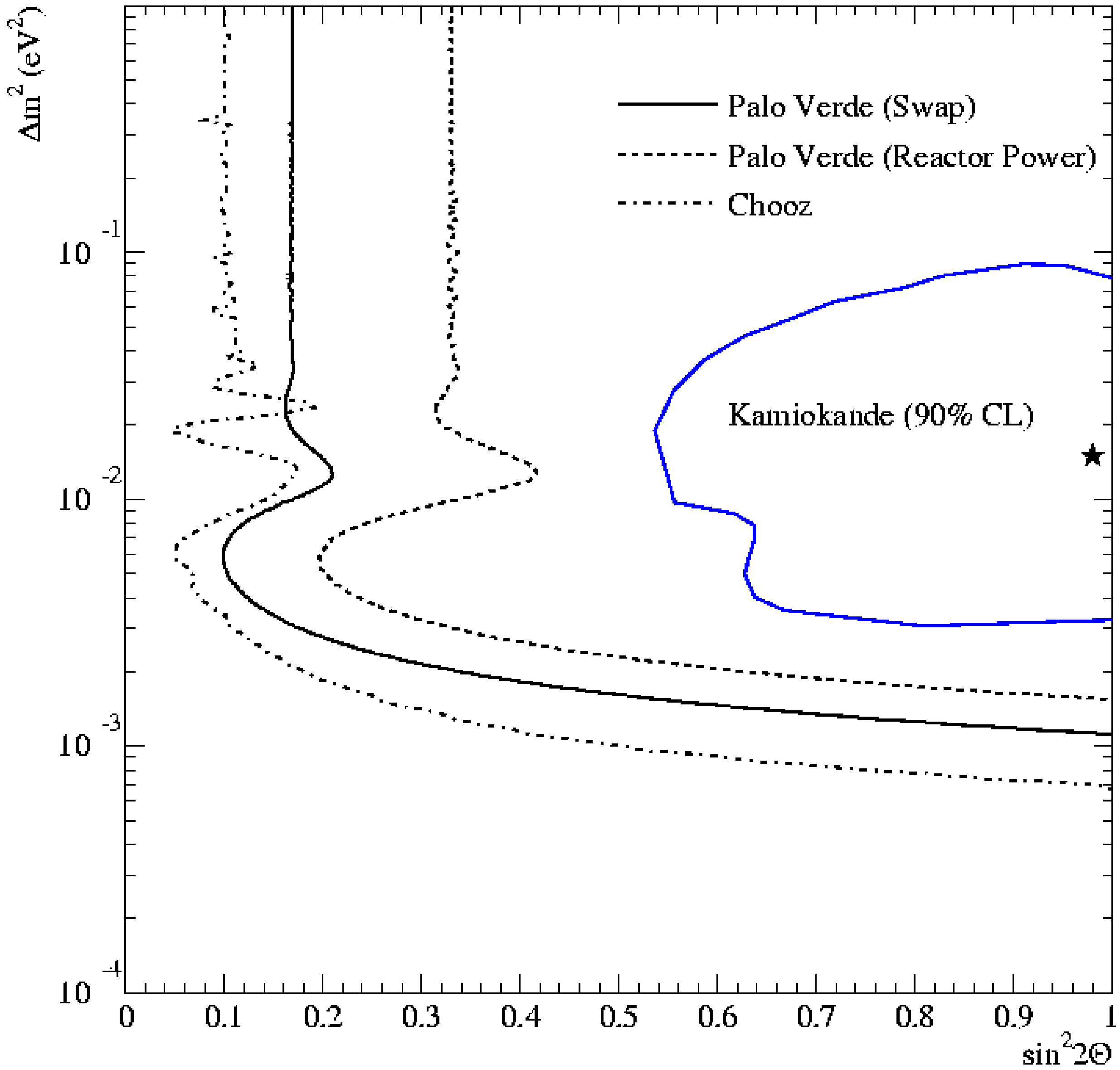
Bugey (1995)
Agreement: ~ 1%



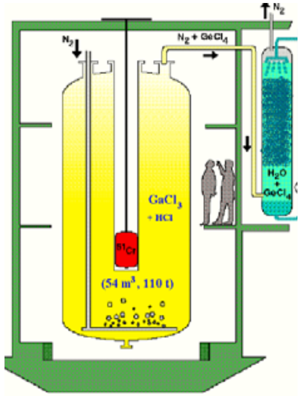
Chooz (1998)
Agreement: ~ 3%

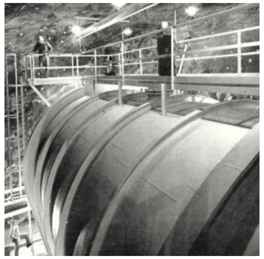


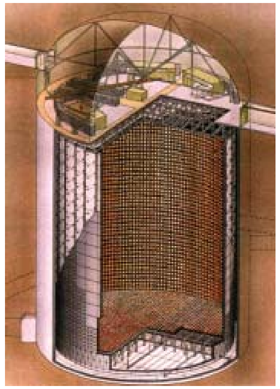
$$P(\overline{\nu}_e \rightarrow \nu_x) = 1 - \sin^2(2\theta)\sin^2\left(1.27\,\delta m^2 \frac{L}{E}\right)$$

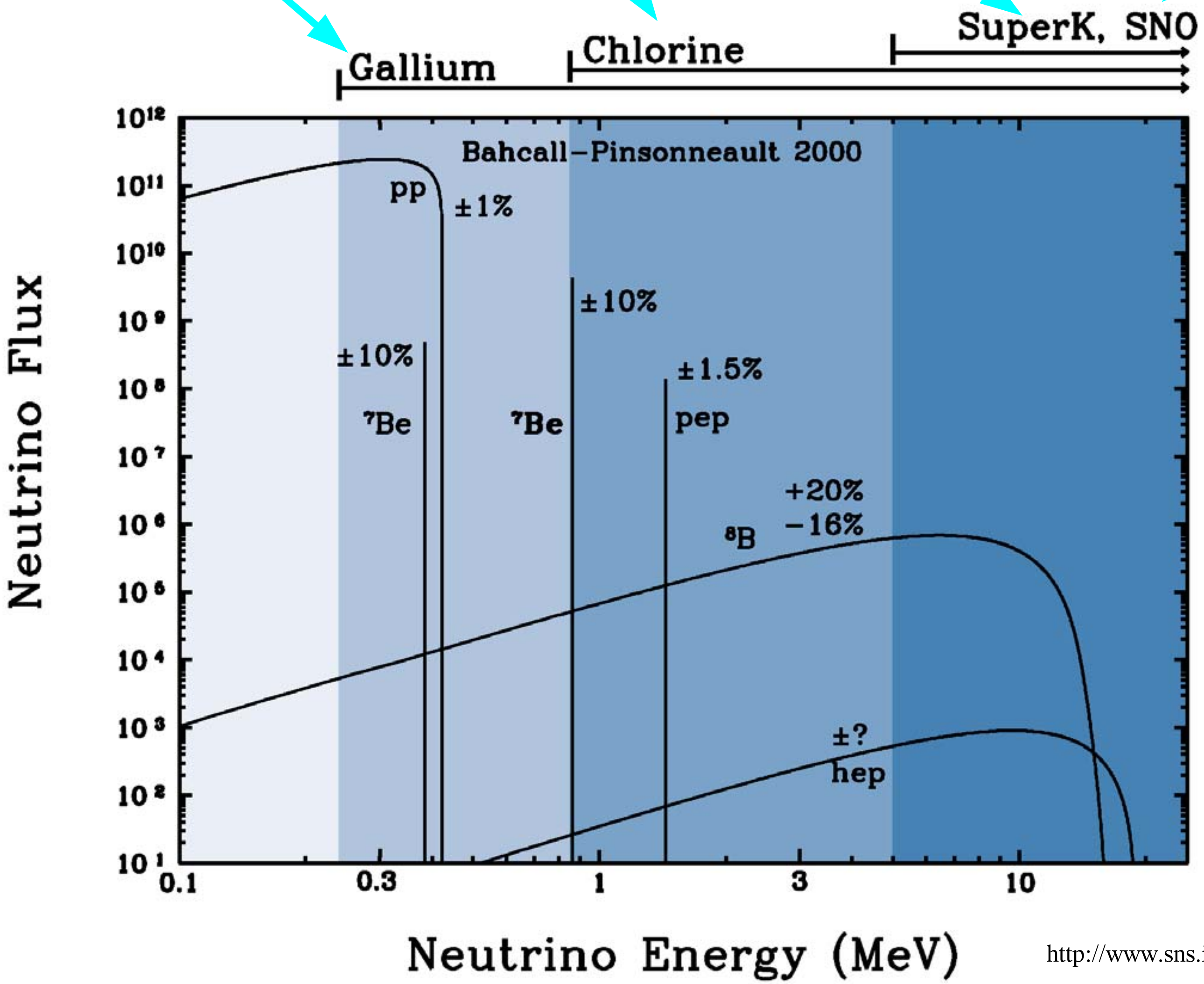


Palo Verde (Swap)
Palo Verde (Reactor Power)
Chooz
Kamiokande (90% CL)
$\Delta m^2 (eV^2)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\Theta$



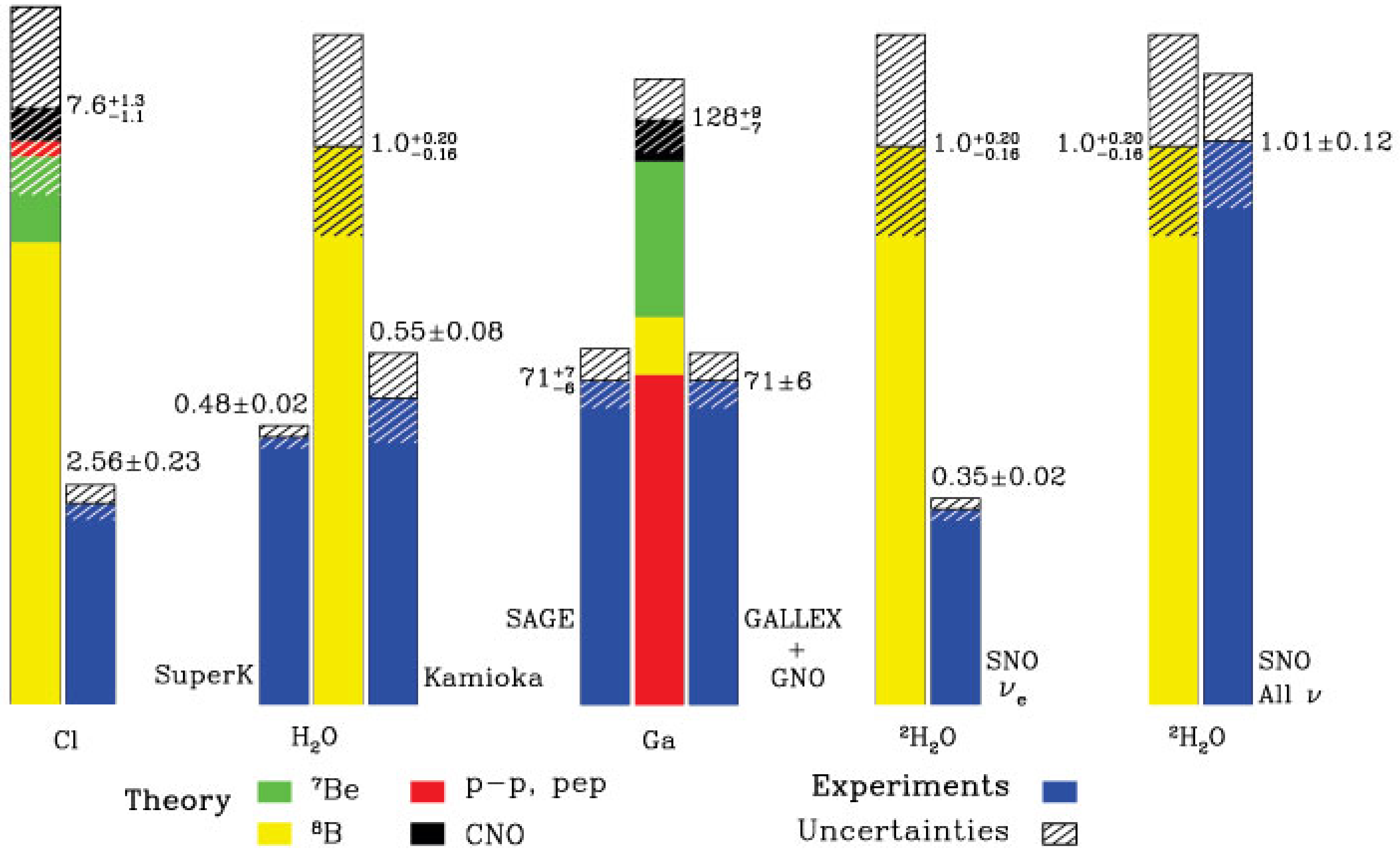




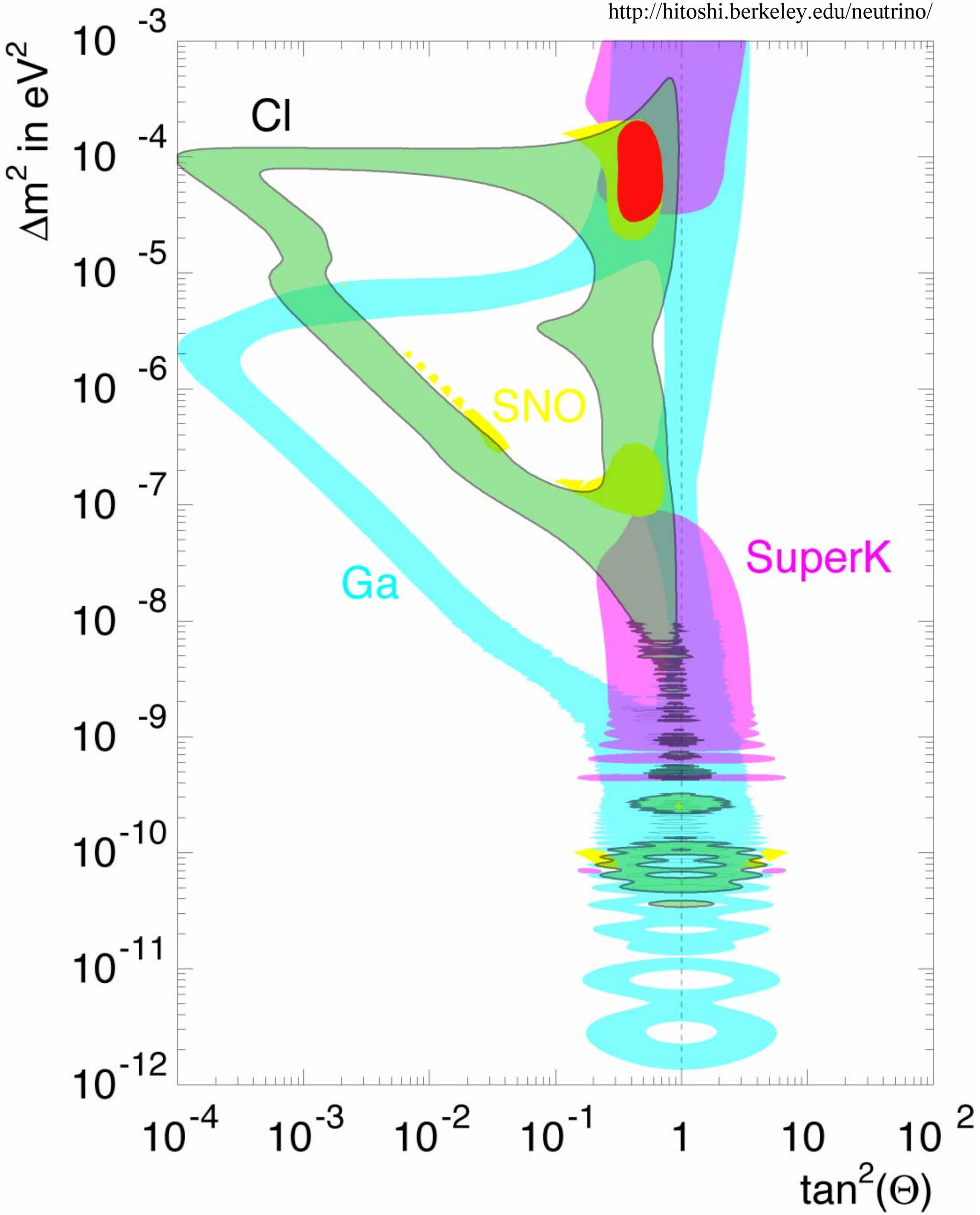


http://www.sns.ias.edu/~jnb/

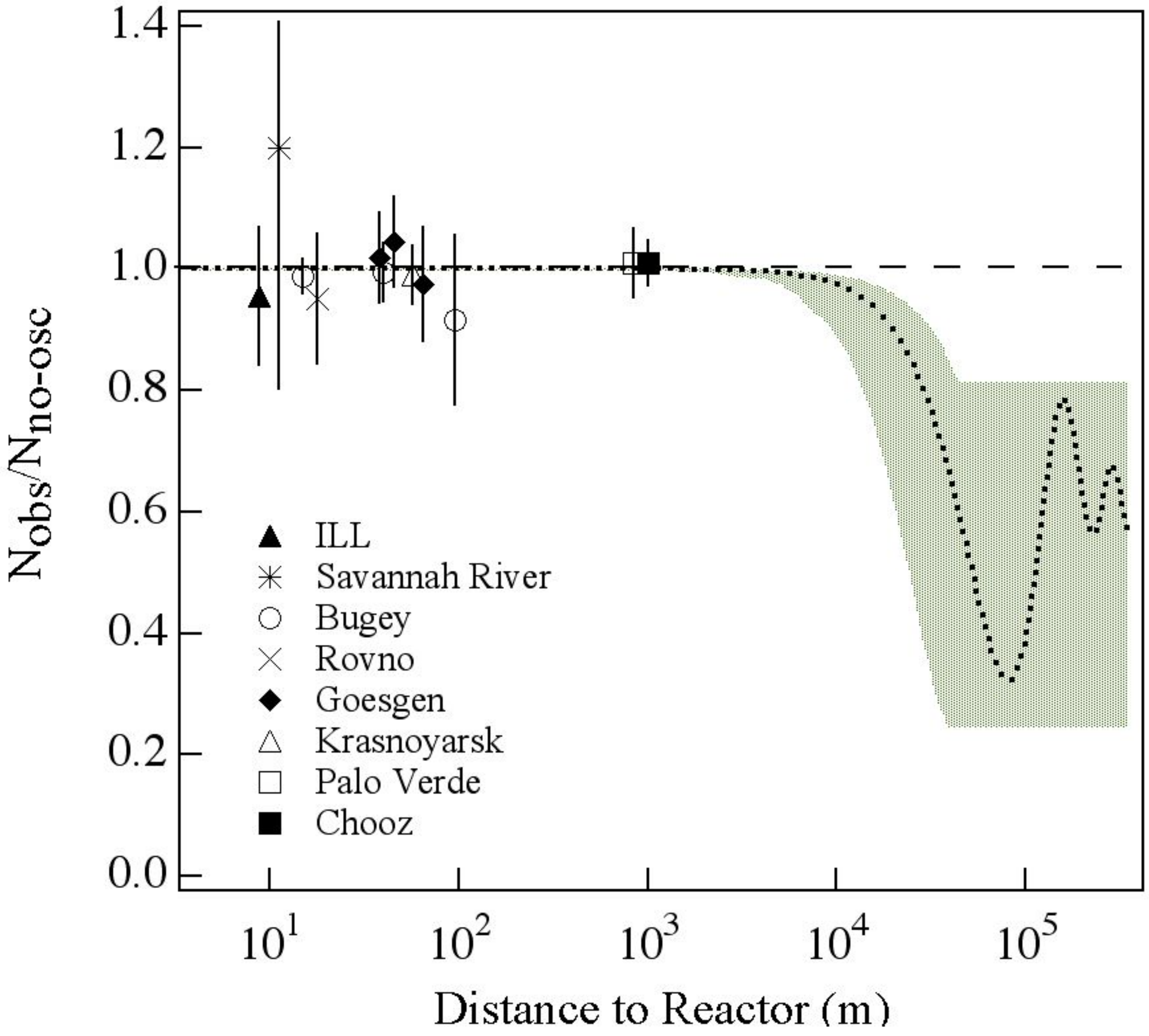
Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000

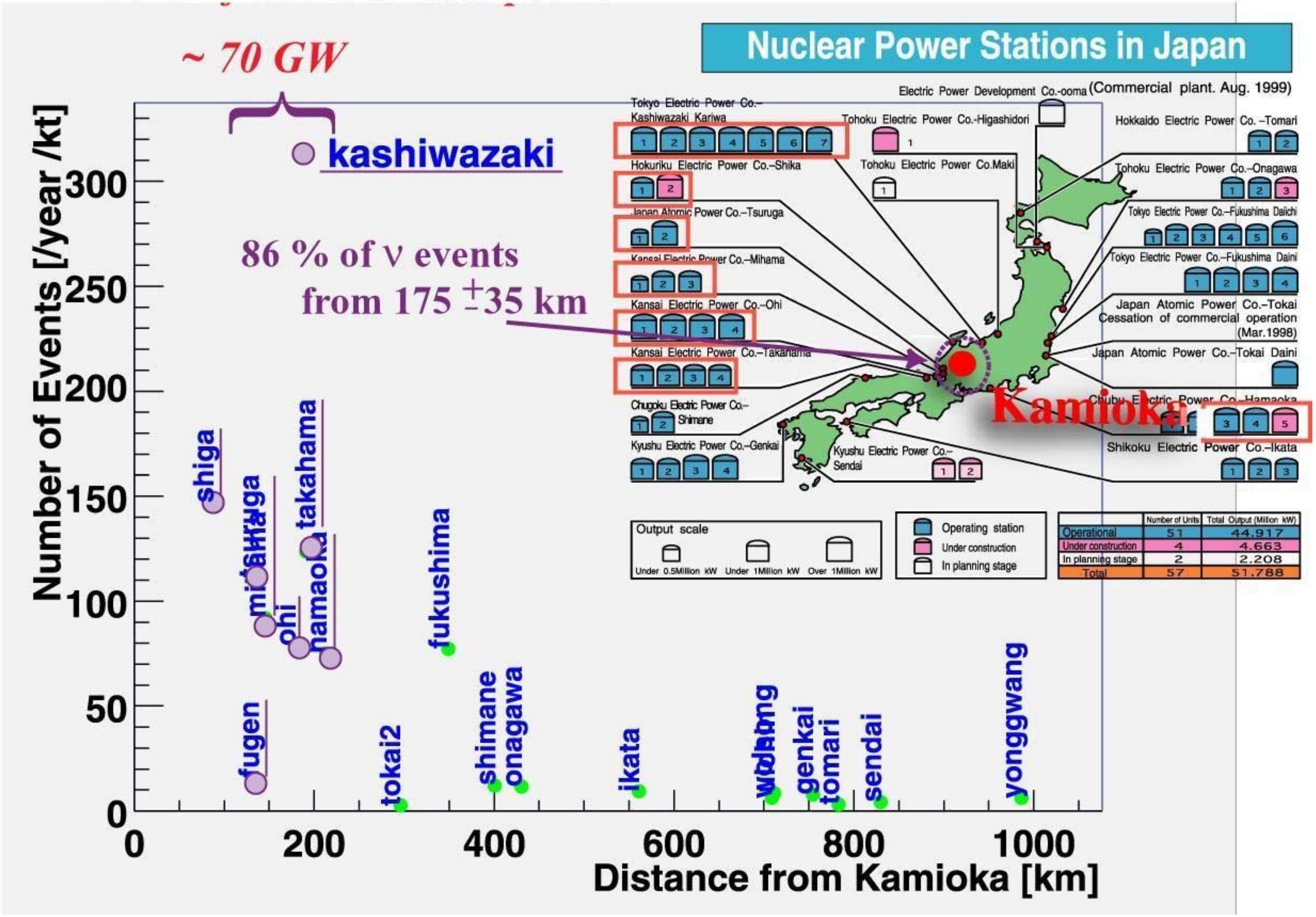


http://www.sns.ias.edu/~jnb/

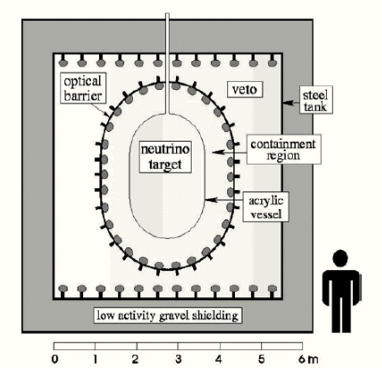


http://hitoshi.berkeley.edu/neutrino/
Δm² in eV²
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
10-10
10-11
10-12
Cl
SNO
SuperK
Ga
10-4
10-3
10-2
10-1
1
10
10 2
tan²(Θ)

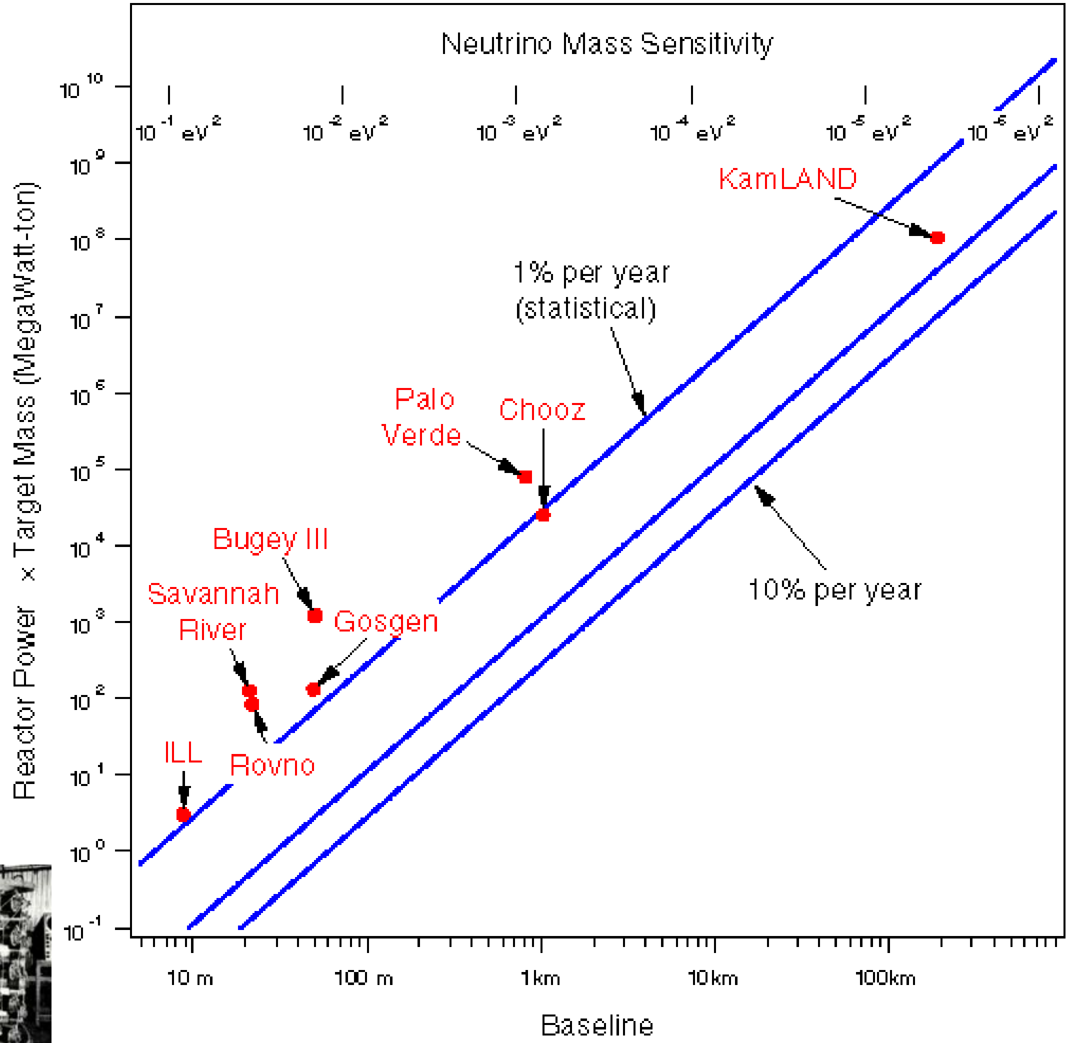

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nno-osc
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

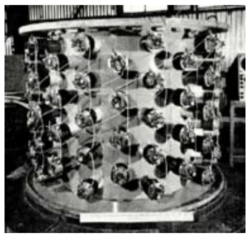


~ 70 GW
kashiwazaki
86 % of ν events
from 175 ±35 km
Nuclear Power Stations in Japan
Kamioka
Number of Events [/year /kt]
Distance from Kamioka [km]
shiga
fugen
takahama
ohi
hamaoka
tokai2
fukushima
shimane
onagawa
ikata
genkai
tomari
sendai
yonggwang
Output scale
Operating station
Under construction
In planning stage

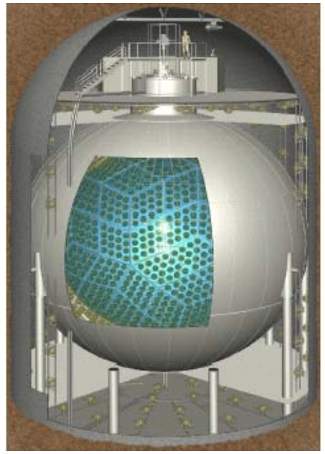


Chooz
(1998)

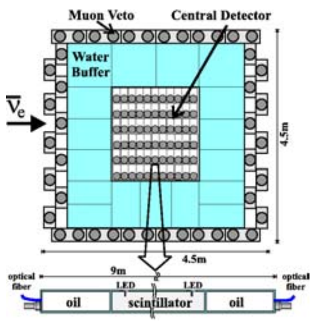




Poltergeist
(1955)



KamLAND
(2002)



Palo Verde
(2000)

The KamLAND Collaboration

K.Eguchi, S.Enomoto, K.Furuno, J.Goldman, H.Hanada, H.Ikeda, K.Ikeda, K.Inoue, K.Ishihara, W.Itoh, T.Iwamoto, T. Kawaguchi, T.Kawashima, H.Kinoshita, Y. Kishimoto, M.Koga, Y.Koseki, T.Maeda, T.Mitsui, M.Motoki, K.Nakajima, M.Nakajima, T.Nakajima, H.Ogawa, K.Owada, T.Sakabe, I.Shimizu, J.Shirai, F.Suekane, A.Suzuki, K. Tada, O.Tajima, T.Takayama, K.Tamae, H.Watanabe
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B.Berger, Y.D.Chan, M.P. Decowski, D.A. Dwyer, S.J.Freedman, Y.Fu, B.K.Fujikawa, K. Heeger, K.T.Lesko, K.-B.Luk, H.Murayama, D.R.Nygren, C.E.Okada, A.W.P.Poon, H.M.Steiner, L.A.Winslow
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Louisiana State University, USA

B.D.Dieterle, M.DiMauro
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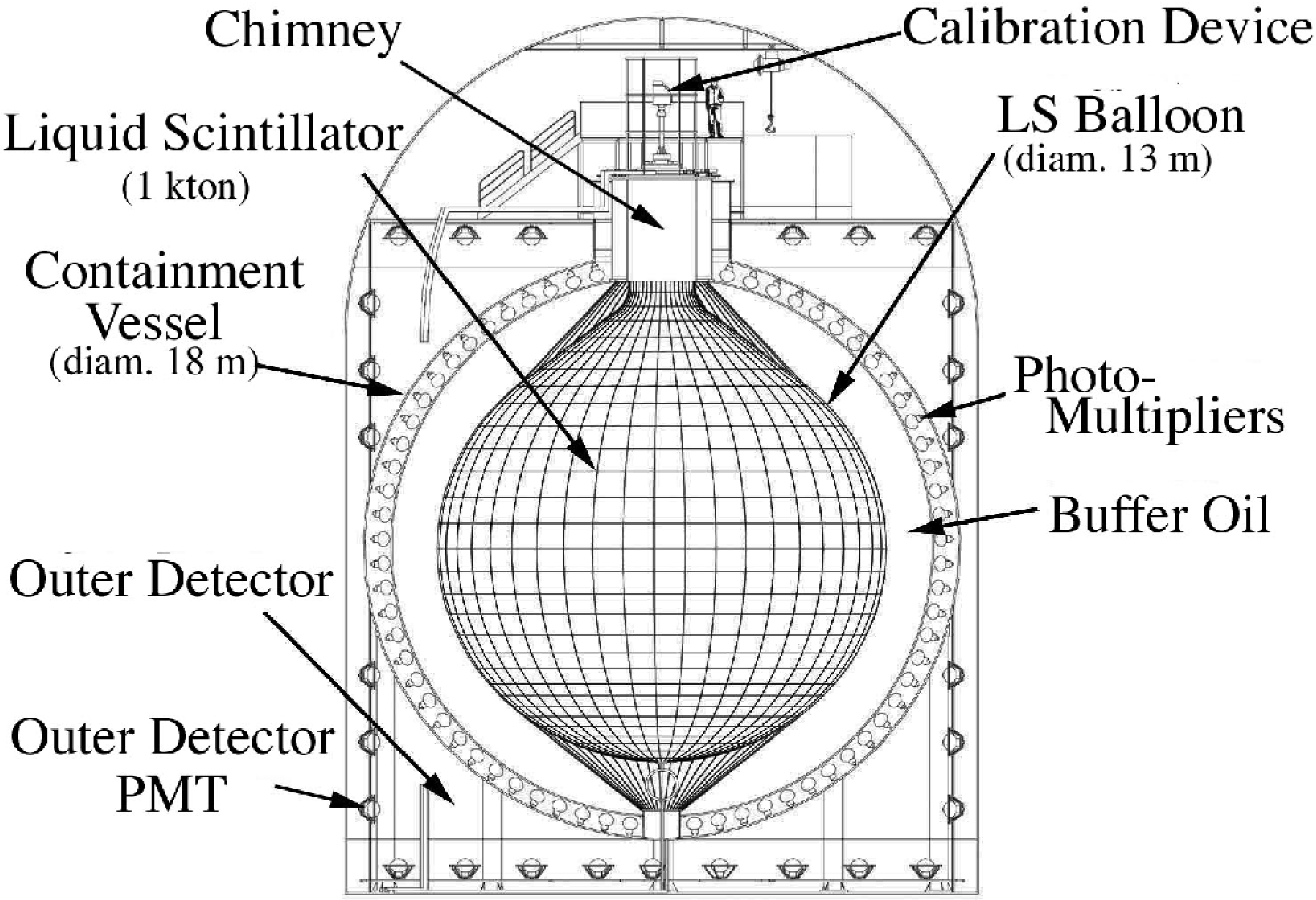
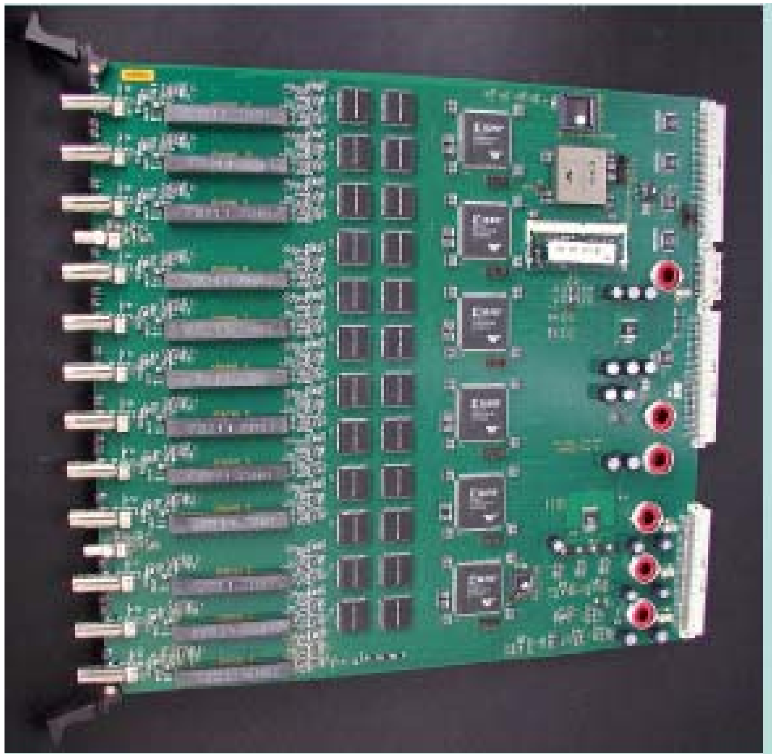
University of Tennessee, USA

L.Braeckeleer, C.R.Gould, H.J.Karwowski, D.M.Markoff, J.A.Messimore, K.Nakamura, R.M.Rohm, W.Tornow, A.R. Young
Triangle Universities Nuclear Laboratory, USA

Y-F.Wang
IHEP, Beijing, CHINA

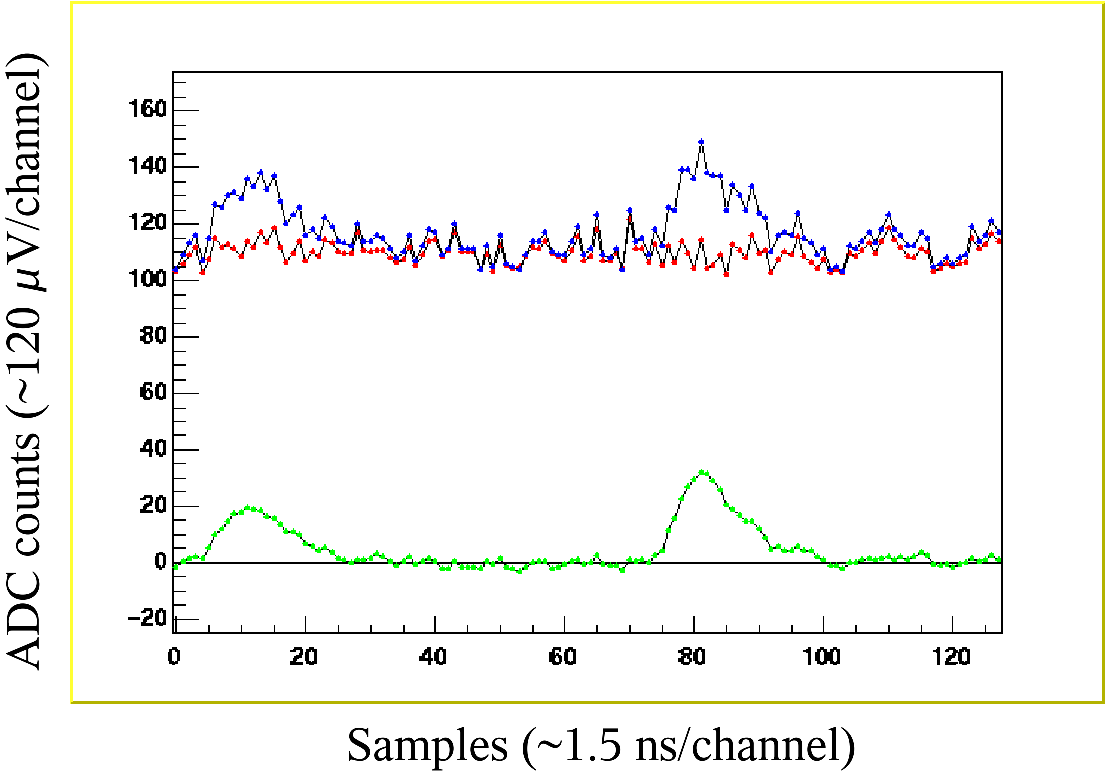

Chimney
Calibration Device
Liquid Scintillator
(1 kton)
LS Balloon
(diam. 13 m)
Containment
Vessel
(diam. 18 m)
Photo-
Multipliers
Buffer Oil
Outer Detector
Outer Detector
PMT

Frontend Berkeley Electronics (FBE)



12 channel KamLAND FBE Board

blue: raw data
red: pedestal
green: pedestal subtracted

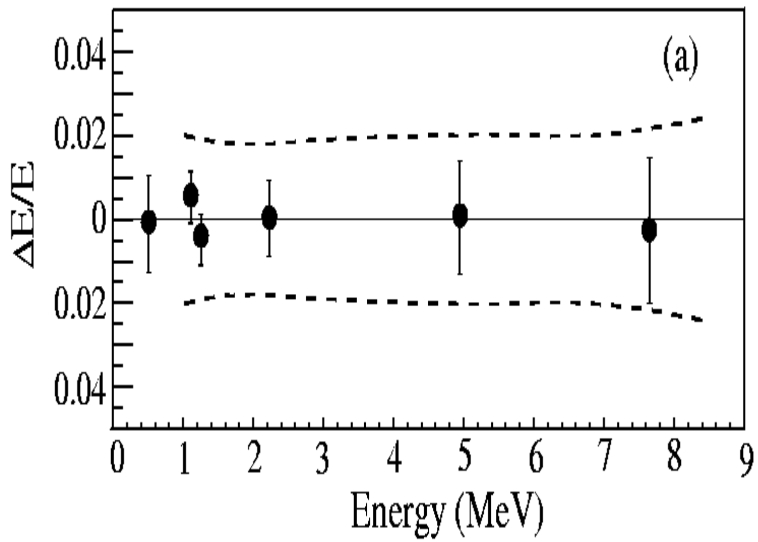


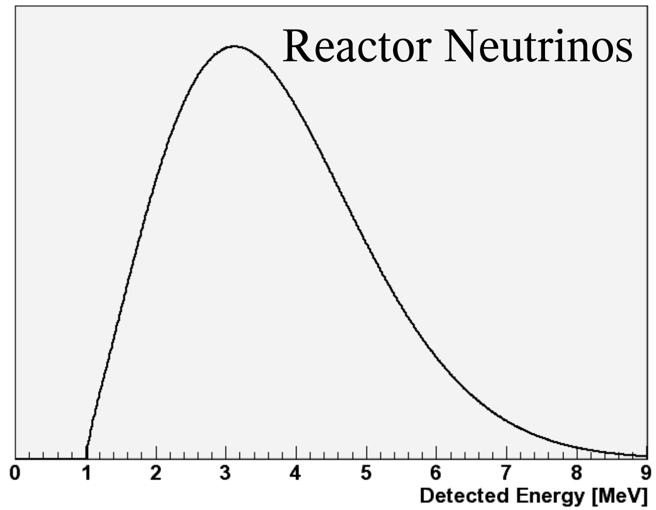
Energy Calibration

<u>Gamma Ray Sources</u>
- ^{68}Ge (2×0.511 MeV γ)
- ^{65}Zn (1.116 MeV γ)
- ^{60}Co (1.173 MeV γ + 1.332 MeV γ)
- AmBe (7.654 MeV γ)
- AmBe (4.439 MeV γ)
- AmBe (neutron)

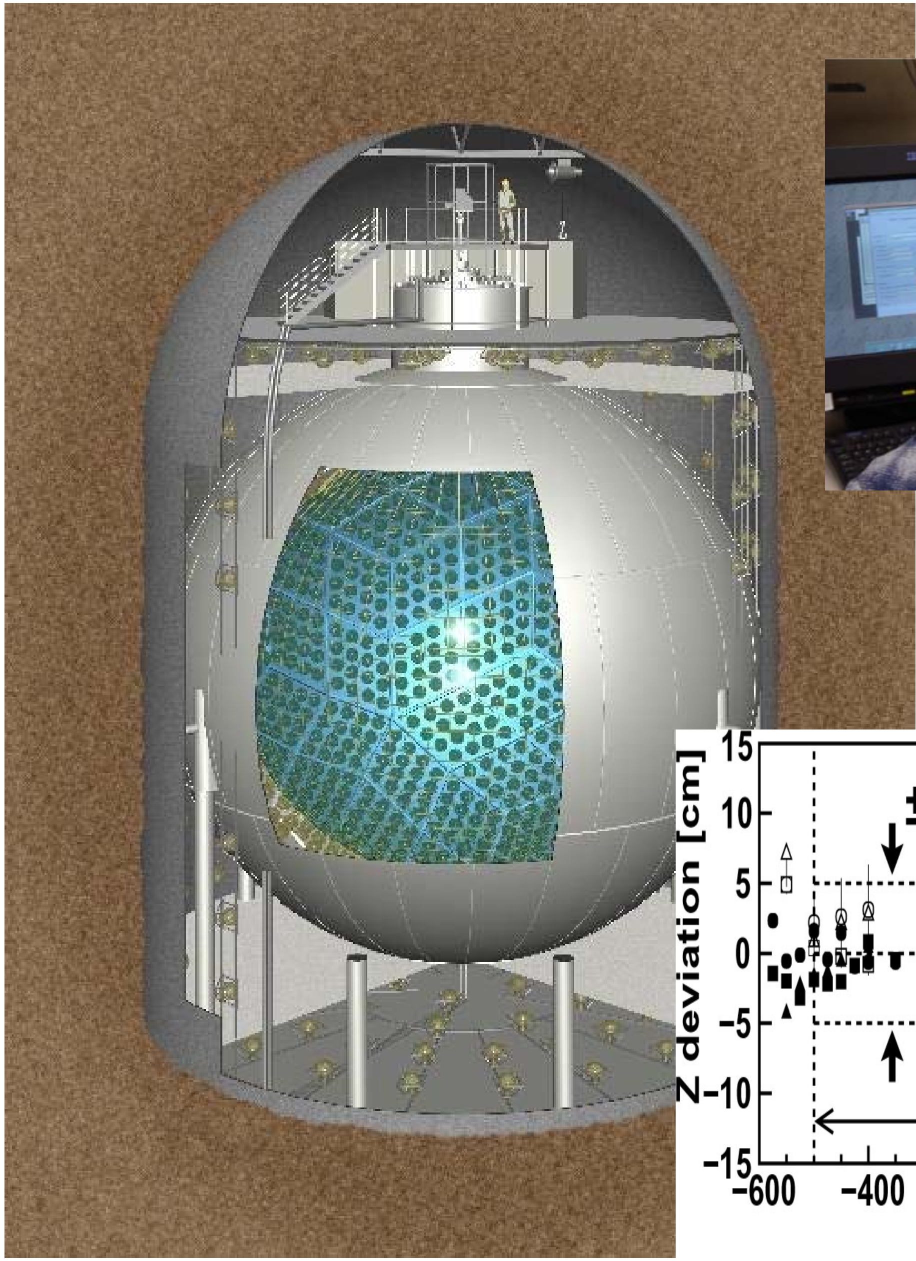
<u>Cosmic Ray Muon Spallation</u>
- n+^{1}H (2.225 MeV γ)
- n+^{12}C (4.946 MeV γ)
- ^{12}B (13.373 MeV β^-)
- ^{12}N (16.384 MeV β^+)

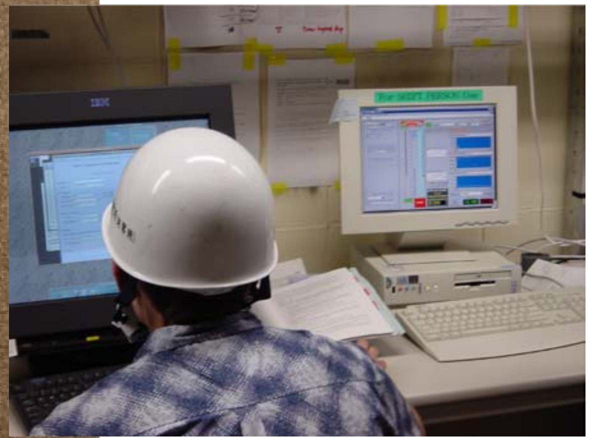
<u>Radioactive Contaminants</u>
- ^{40}K ($\beta\gamma$)
- ^{208}Tl ($\beta\gamma$)
- Bi-Po (α-decay)

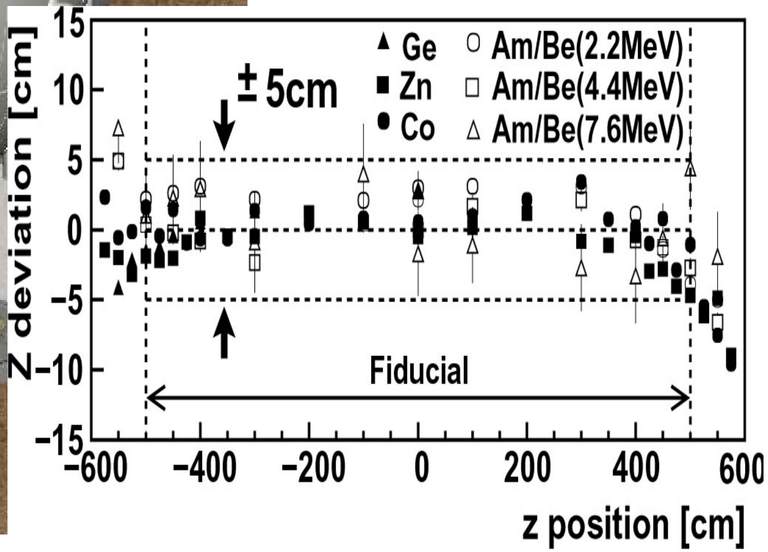




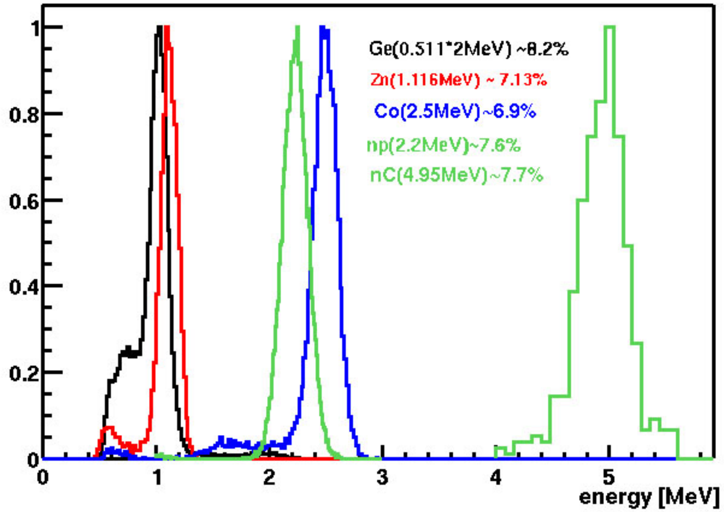
Calibration Source Deployment

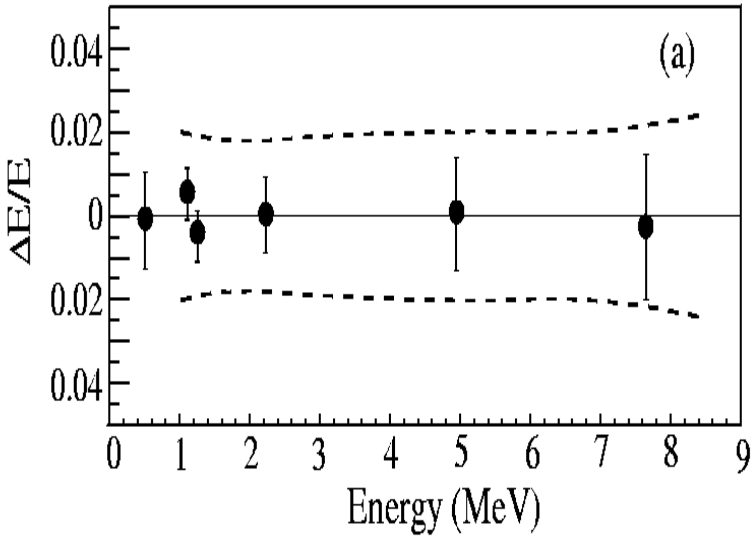






KamLAND Performance





$\Delta E/E \sim 7.5\text{‰}/\sqrt{E(\mathrm{MeV})}$ (~180 pe/MeV)

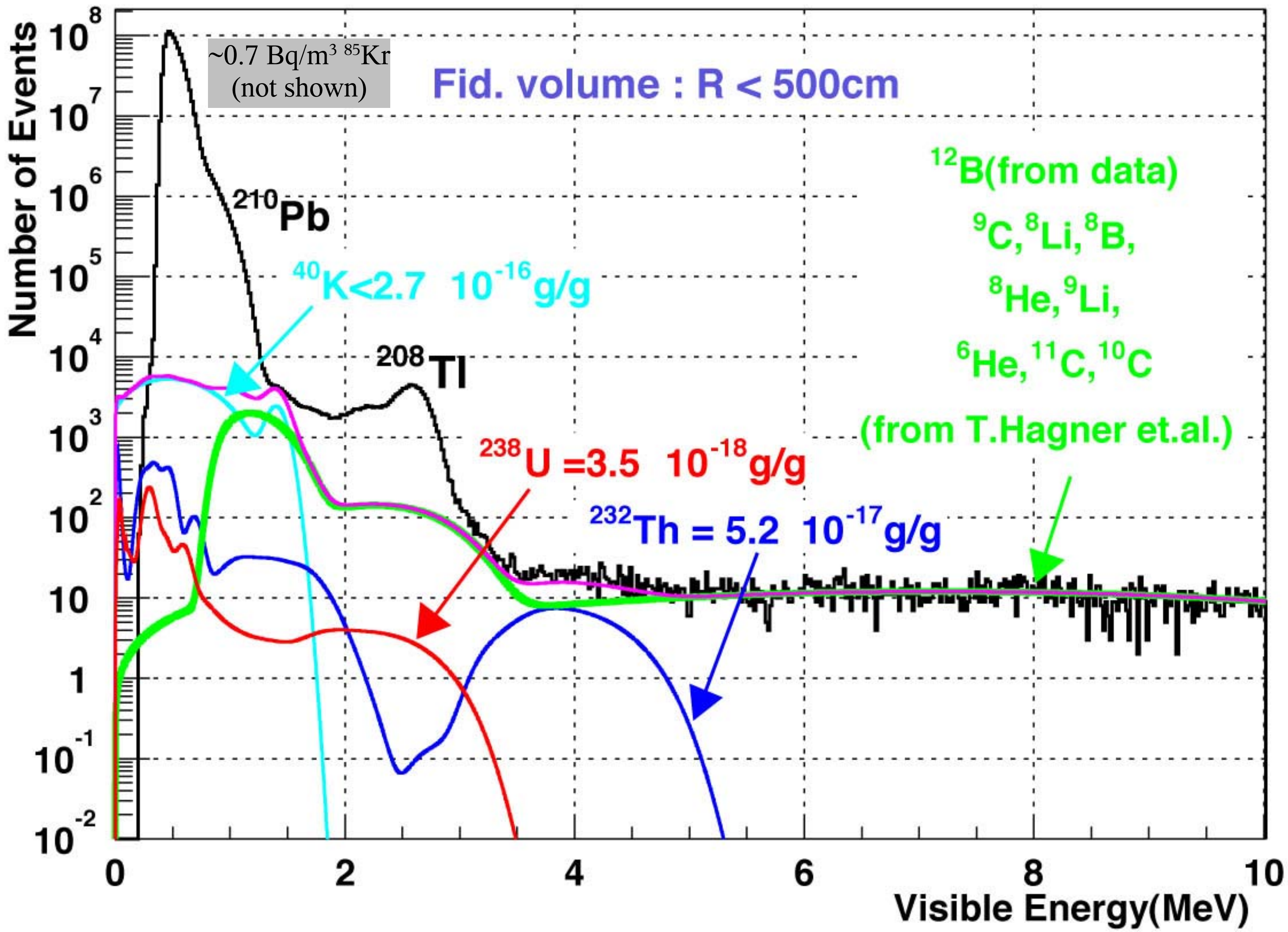
$\Delta E(\mathrm{syst})/E = 1.9\text{‰}$

Intrinsic Backgrounds

$$\overline{\nu}_e + p \rightarrow n + e^+$$
$$n + p \rightarrow d + \gamma$$

- Detected Prompt Energy > 2×0.511 = 1.022 MeV
- Delayed Coincidence Signal: 2.225 MeV γ

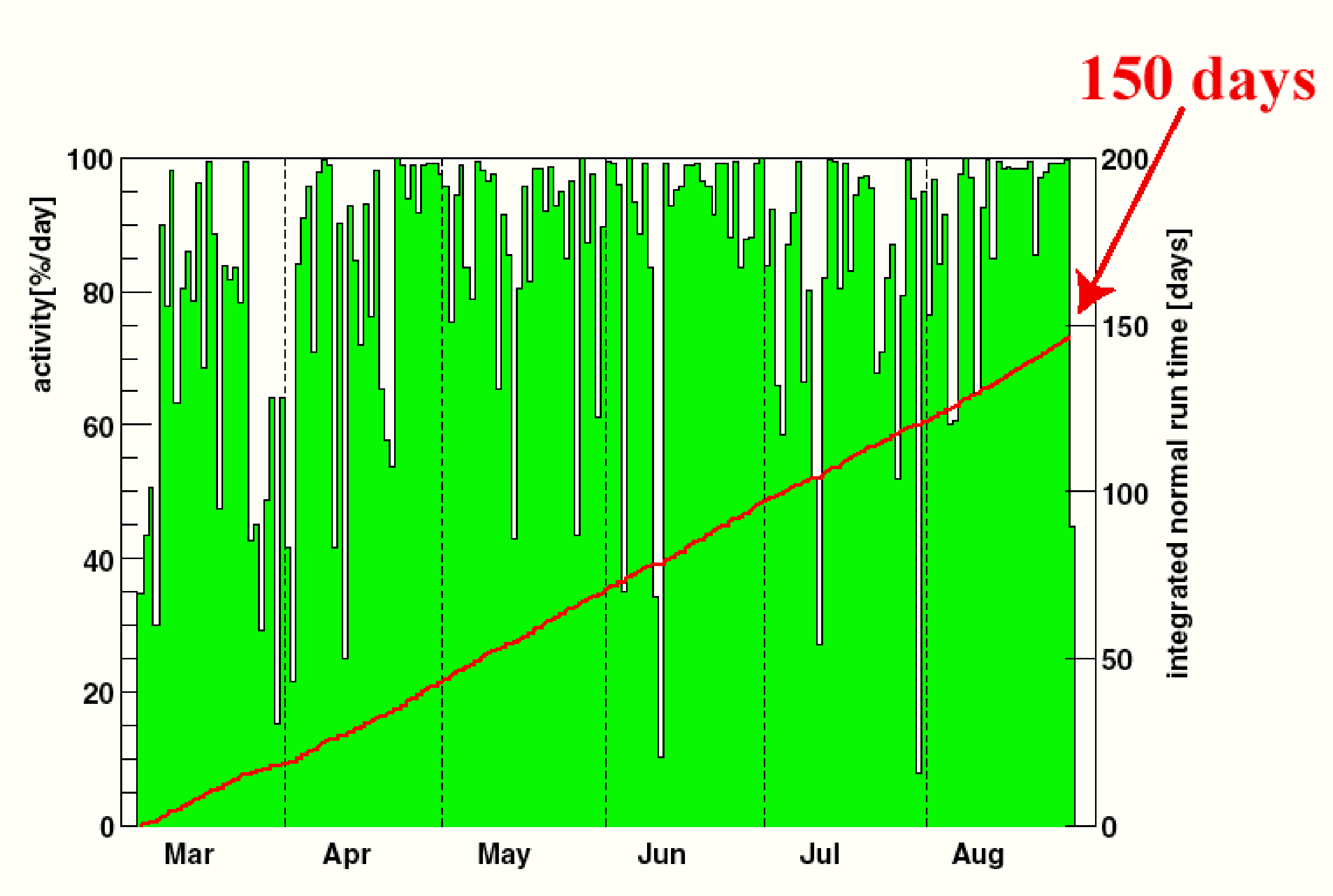
Background Requirements
- U,Th 10^{-13} g/g
- ^{40}K 10^{-14} g/g



Start of Normal Data Taking

January 21, 2002

KamLAND First Results Data Sample



- March 4 to October 6, 2002
- 145.1 Days of Live Time
- 0.7 MeV Primary Trigger Threshold
- ~ 30 Hz Trigger Rate
- 370×10^6 Events

Initial Cuts

$$\overline{\nu}_e + p \rightarrow n + e^+$$
$$n + p \rightarrow d + \gamma$$ Mean Capture Time ~ 215 μs

1) Cosmic Ray Muon Veto (2 ms)
2) Fiducial Volume (R < 5 m: 408 tons)
3) Time Correlation (0.5 μsec < ΔT < 660 μsec)
4) Vertex Correlation (ΔR < 1.6 m)
5) Prompt Energy (E > 0.9 MeV)
6) Delayed Energy (1.8 MeV < E_{delay} < 2.6 MeV)
7) Delayed Vertex Cylinder Cut (ρ_{delay} > 1.2 m)

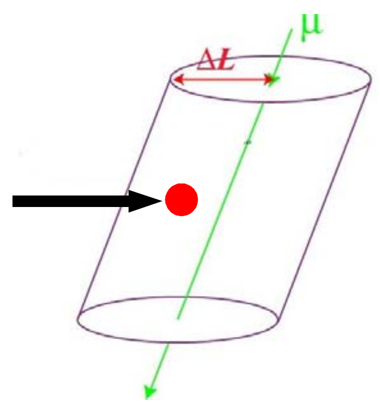
370×10^6 Events ⇨ 173 Events

Muon Spallation Cuts

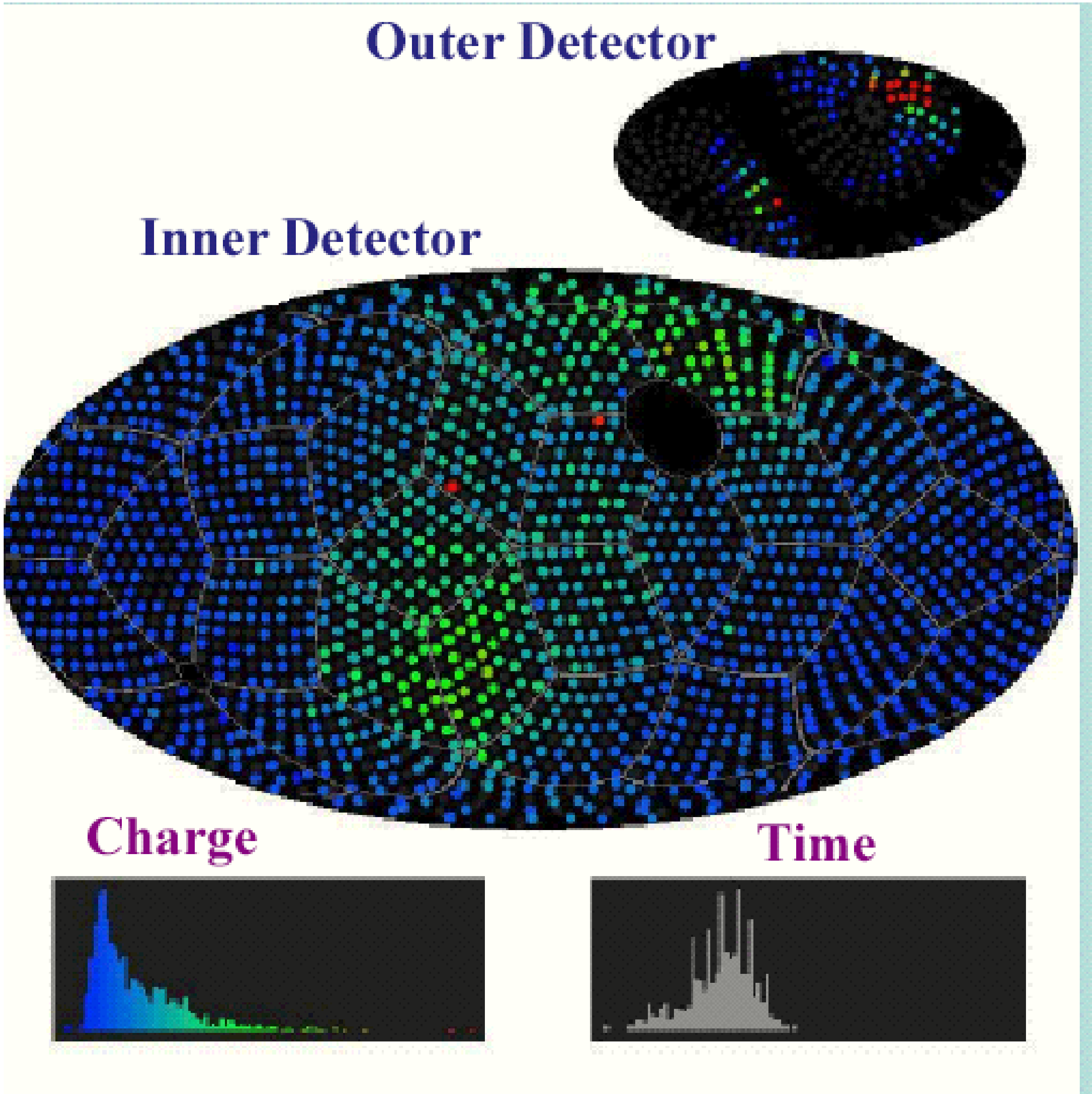
β -delayed neutron emitters: ^{8}He (119 ms) and ^{9}Li (178 ms)

1) 2 sec veto after "showering muon" (~3 GeV extra energy)
2) 2 sec and 3 meter veto after all muons

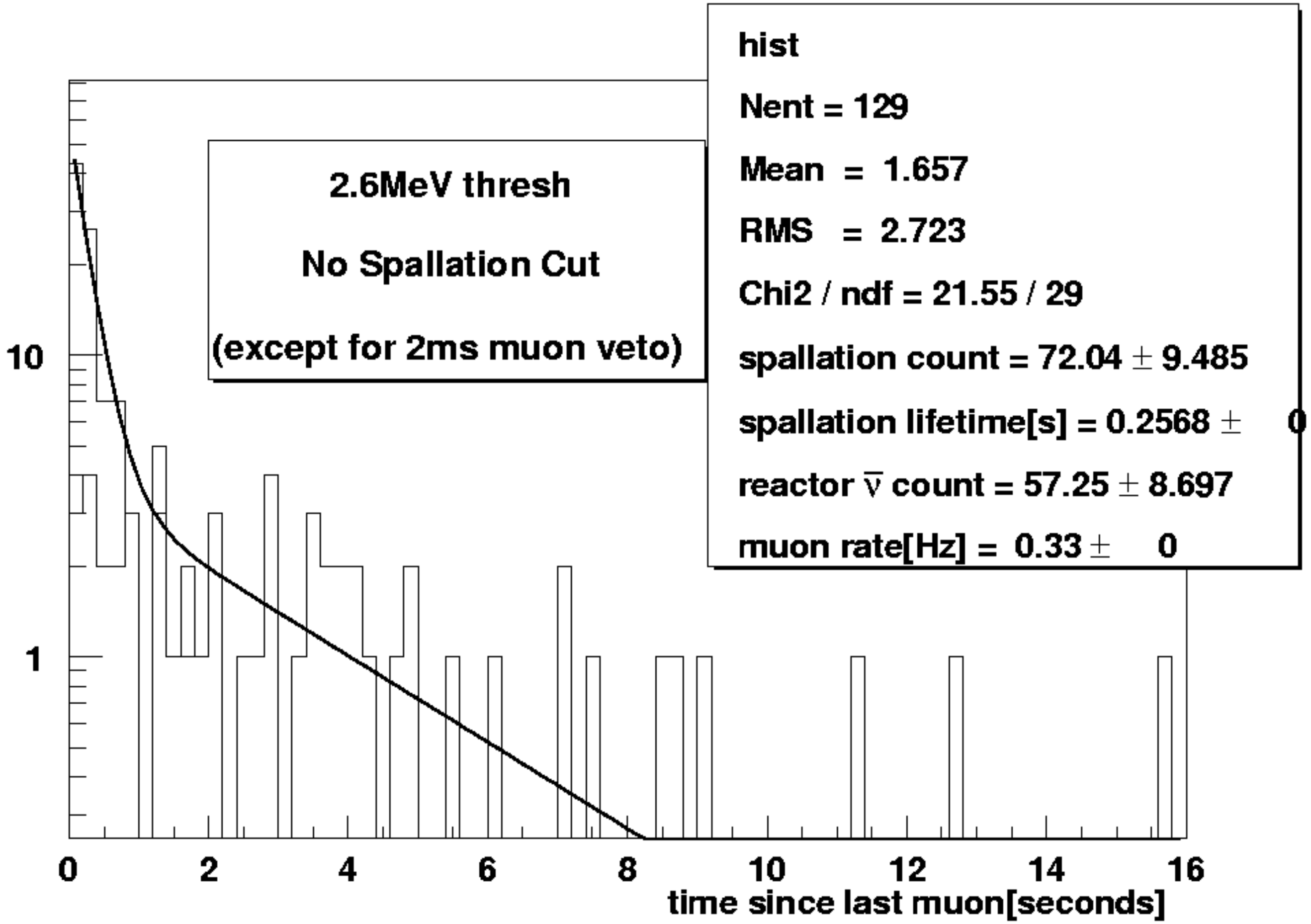
Vetoed Event

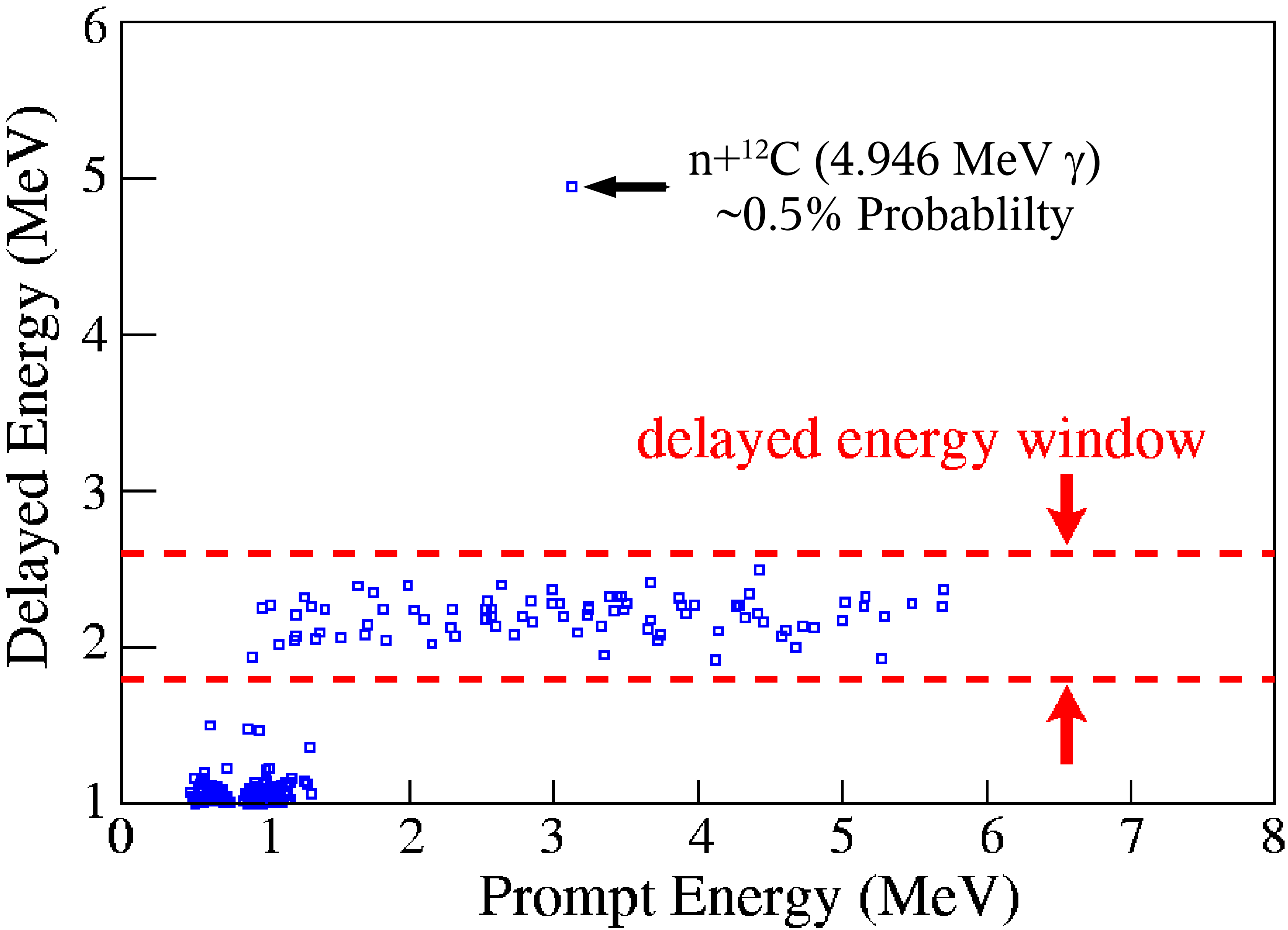


173 Events ⇨ 86 Events
54 Events with E > 2.6 MeV


Outer Detector
Inner Detector
Charge
Time

Confirmation of Spallation Cuts





n+^{12}C (4.946 MeV γ)
~0.5% Probablilty
delayed energy window
Delayed Energy (MeV)
Prompt Energy (MeV)
0
1
2
3
4
5
6
7
8
1
2
3
4
5
6

Remaining Backgrounds

Background	Number of Events
Accidental	0.0086 ± 0.0005
Muon Spallation Products ($^{9}Li/^{8}He$)	0.94 ± 0.85
Fast Neutrons (from surrounding rock)	< 0.5
Total Background	1 ± 1

Rate Analysis

$$P(\tan\theta, \delta m^2) = (\text{Neutrino Oscillation Probability})$$

$$1 - P = \frac{(\text{Number of Observed Events}) - (\text{Number of Background})}{(\text{Number of Expected Events with No Oscillations})}$$

$$(\text{Number of Expected Events with No Oscillatons}) = (\epsilon) \times (\Phi) \times (\sigma) \times (\text{N})$$

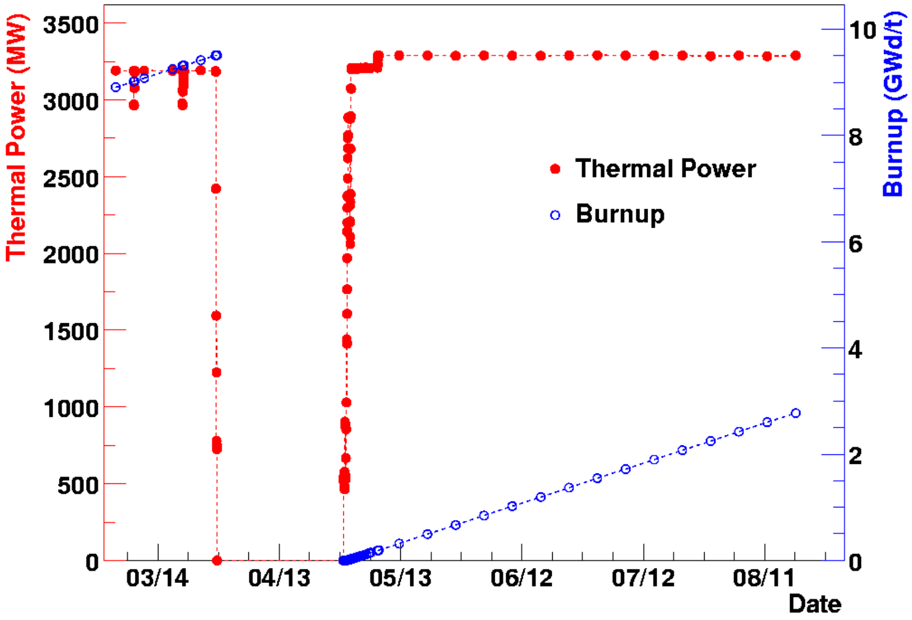
- ε = Trigger and Analysis Efficiency
- Φ= Reactor Neutrino Flux
- σ = Inverse Beta Decay Cross Section
- N = Number of Neutrino Targets

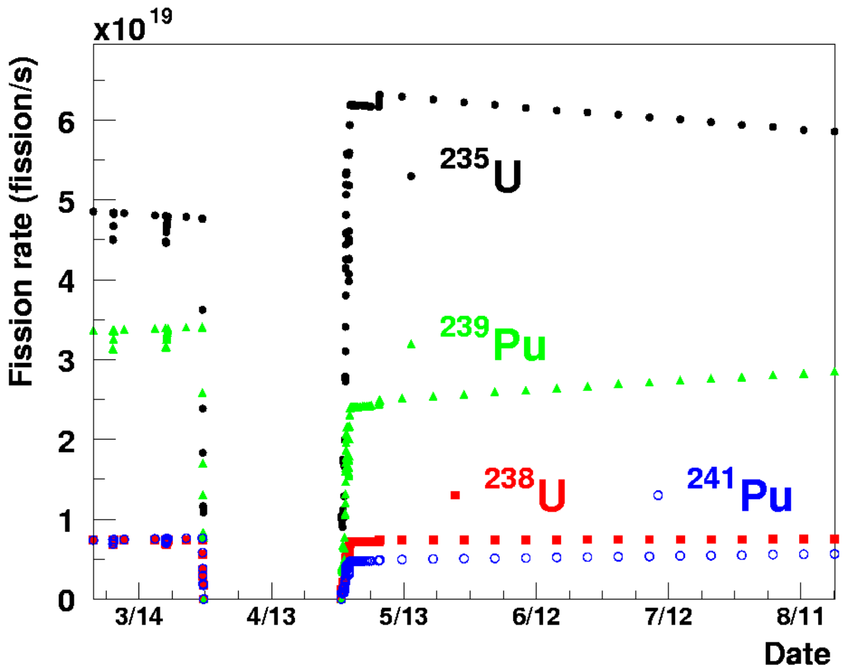
Efficiencies

Trigger, FBE, DAQ:	99.98%
Vertex Fitter:	> 99.9%
Event Selection:	(78.3 ± 1.6)%
Spallation Cuts:	88.6%

Reactor Neutrino Flux

Instantaneous Thermal Power, Burnup, and Fission Rates
for each of all 54 Nuclear Power Reactors in Japan



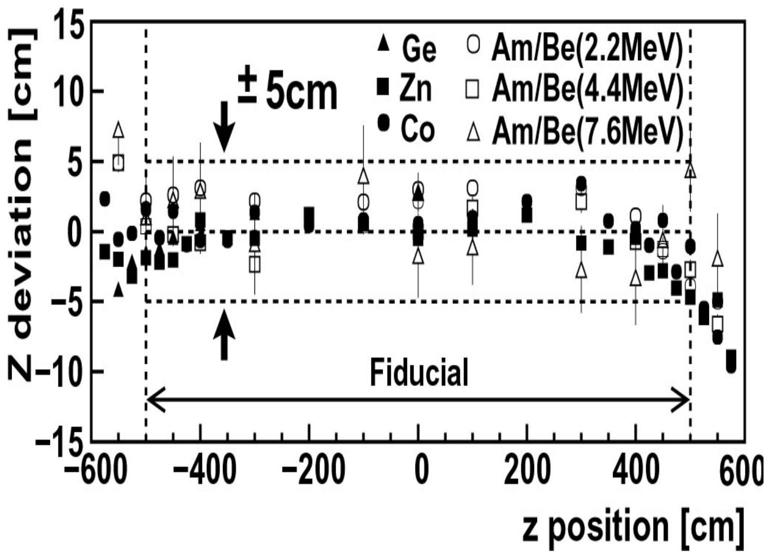


Include

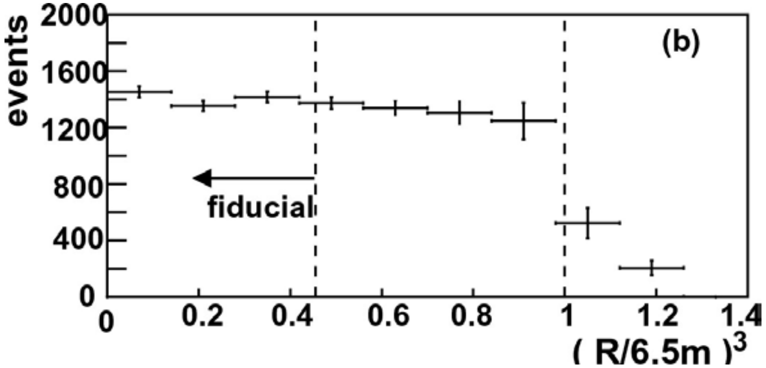
- Korean Reactors: (2.46 ± 0.25)%
- World Reactors: (0.70 ± 0.35)%

Reactor Power: 2.0%
Fuel Composition: 1.0%
Neutrino Spectra: 2.5%

z-axis Source Deployments

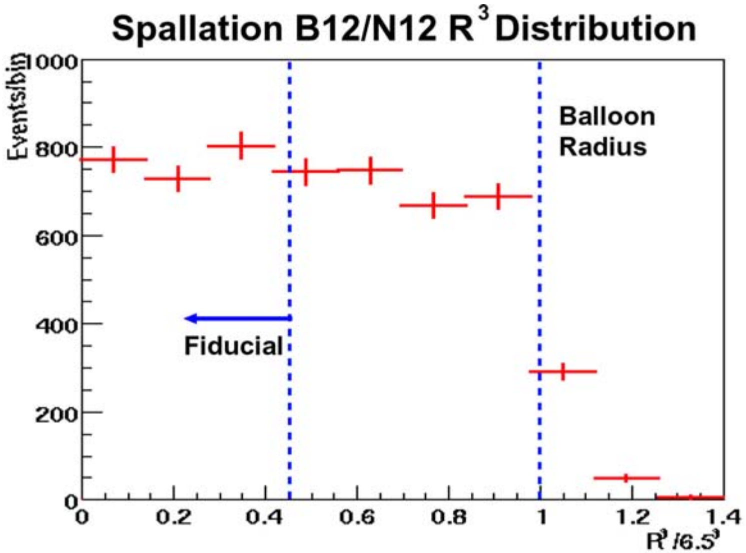


n+p→d+γ Uniformity



Fiducial Volume Uncertainty: 4.1%

$^{12}B/^{12}N$ Uniformity

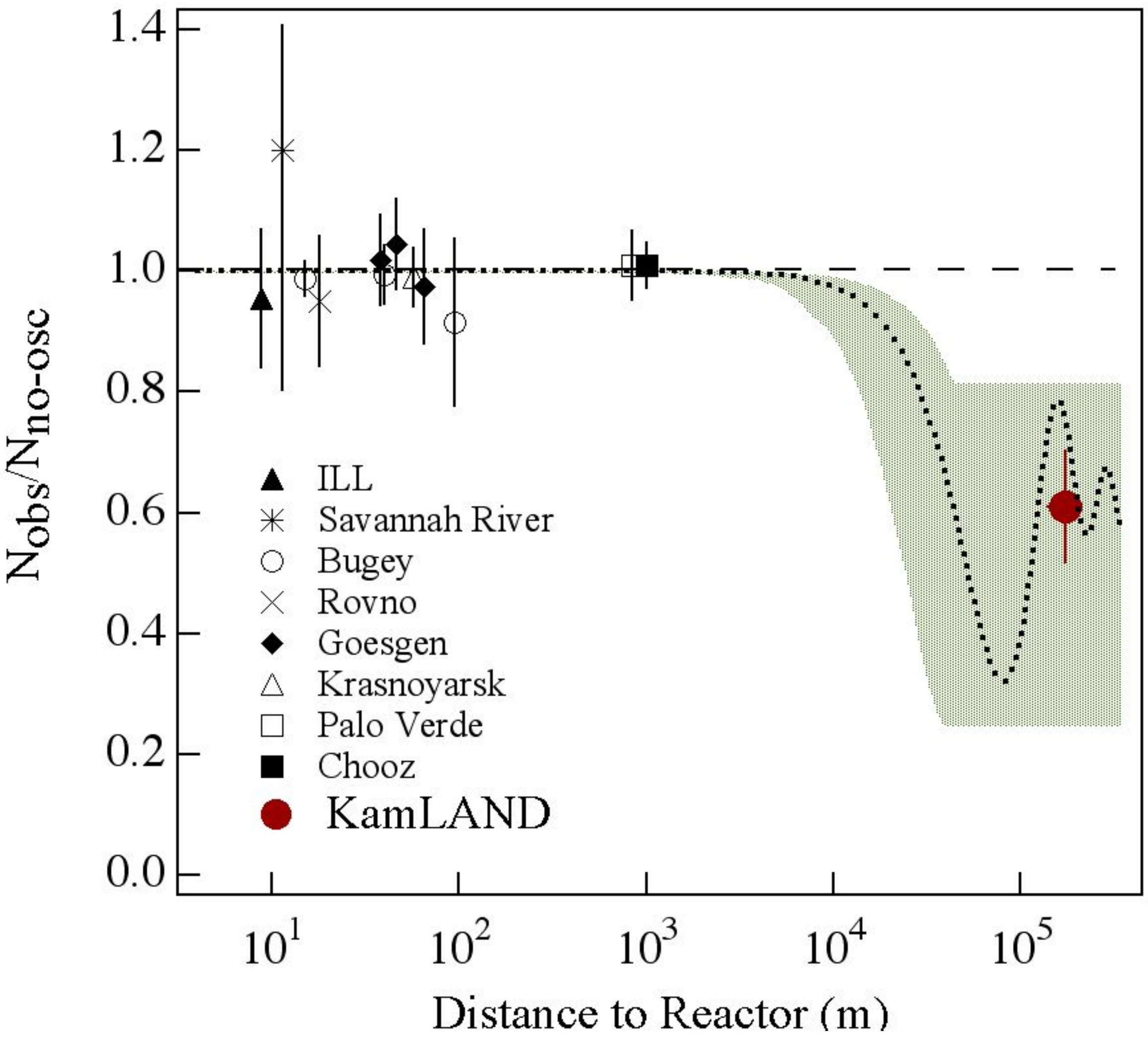


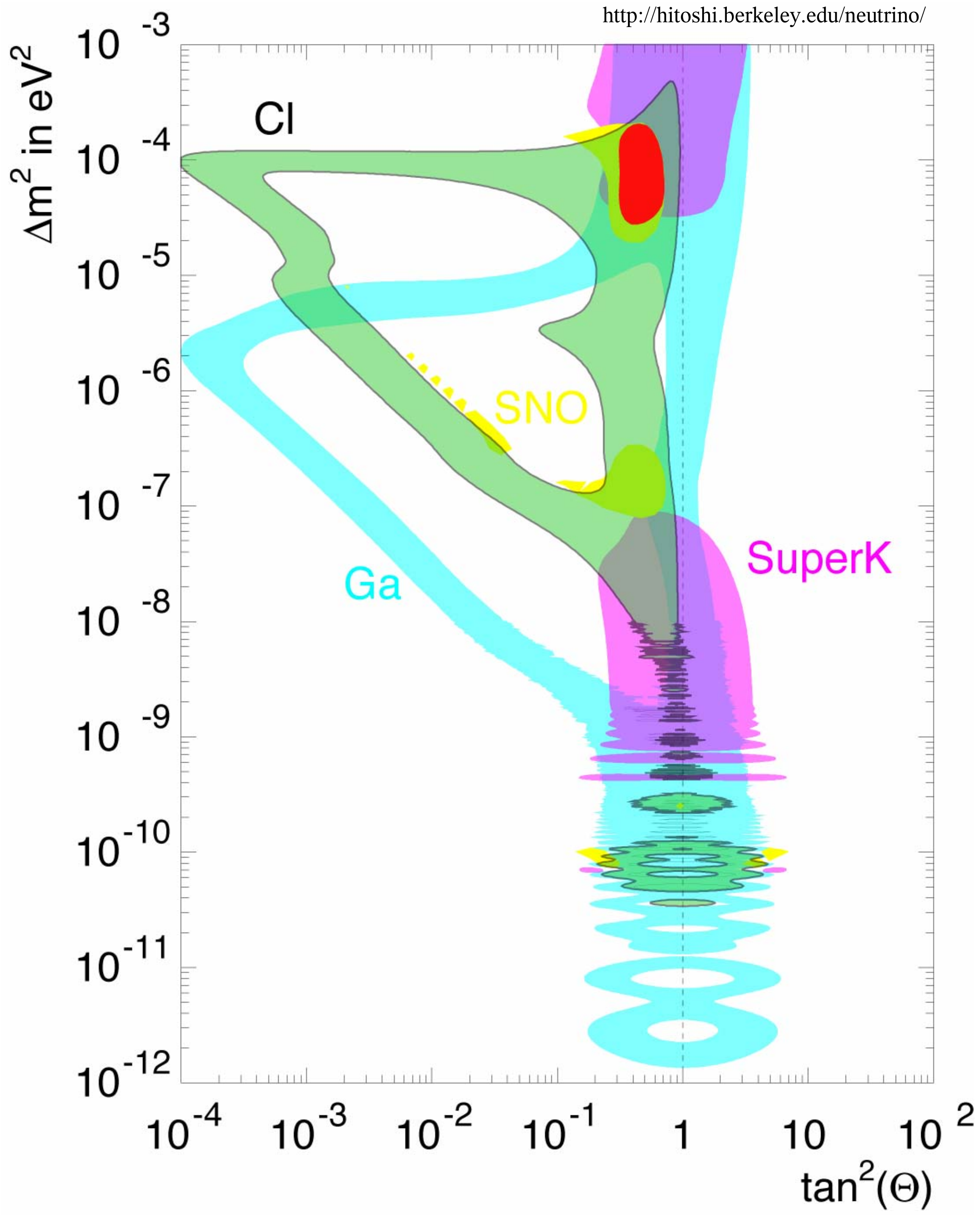
Rate Analysis Summary

Total LS 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%
Neutrino spectra	2.5%
Cross section	0.2%
Total	**6.4%**

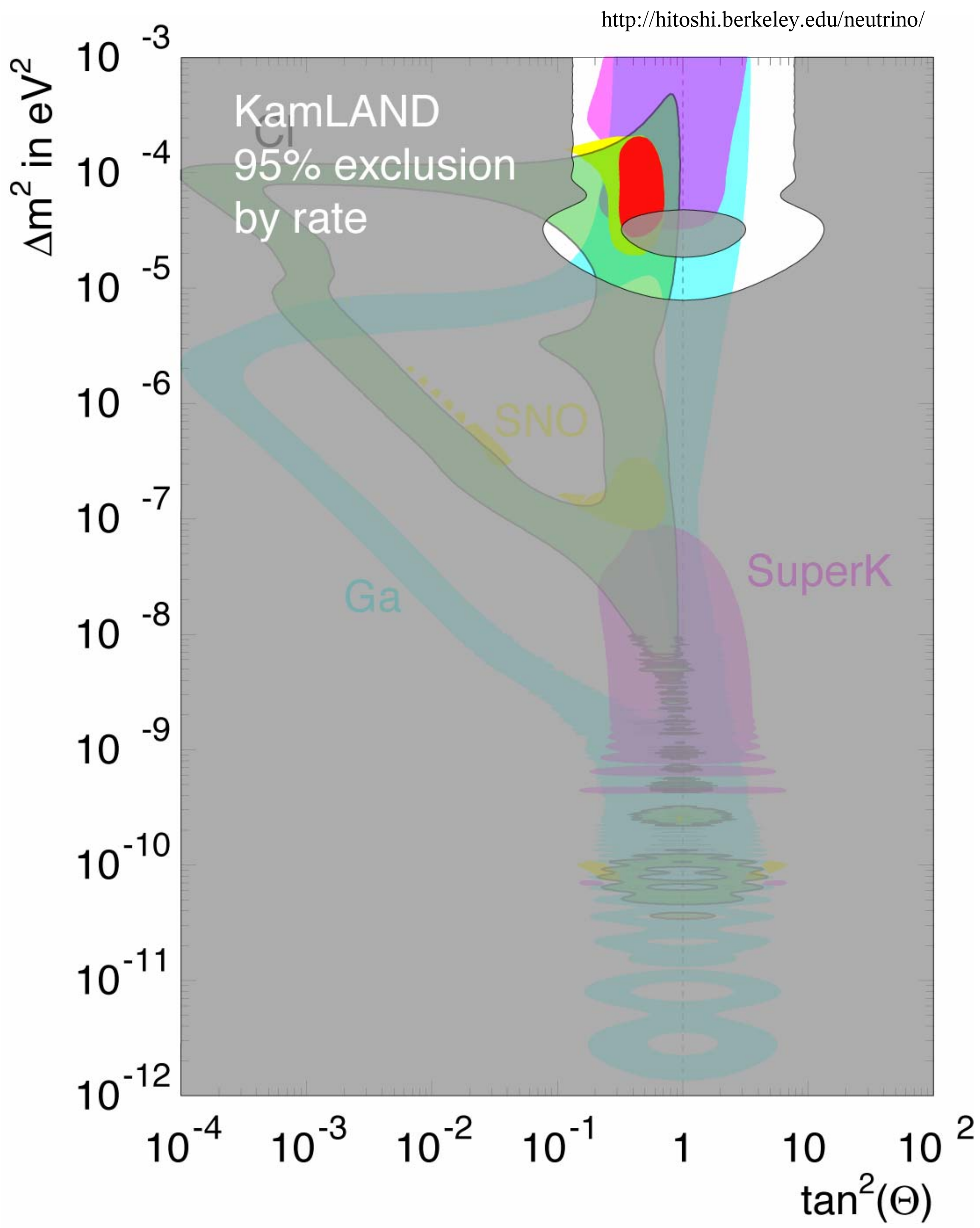
Number of Observed Events:	54
Expected Background Events:	1 ± 1
Number of Expected Events:	86.8 ± 5.6

$$\frac{N_{Observed} - N_{Background}}{N_{Expected}} = 0.611 \pm 0.085_{stat} \pm 0.041_{syst}$$

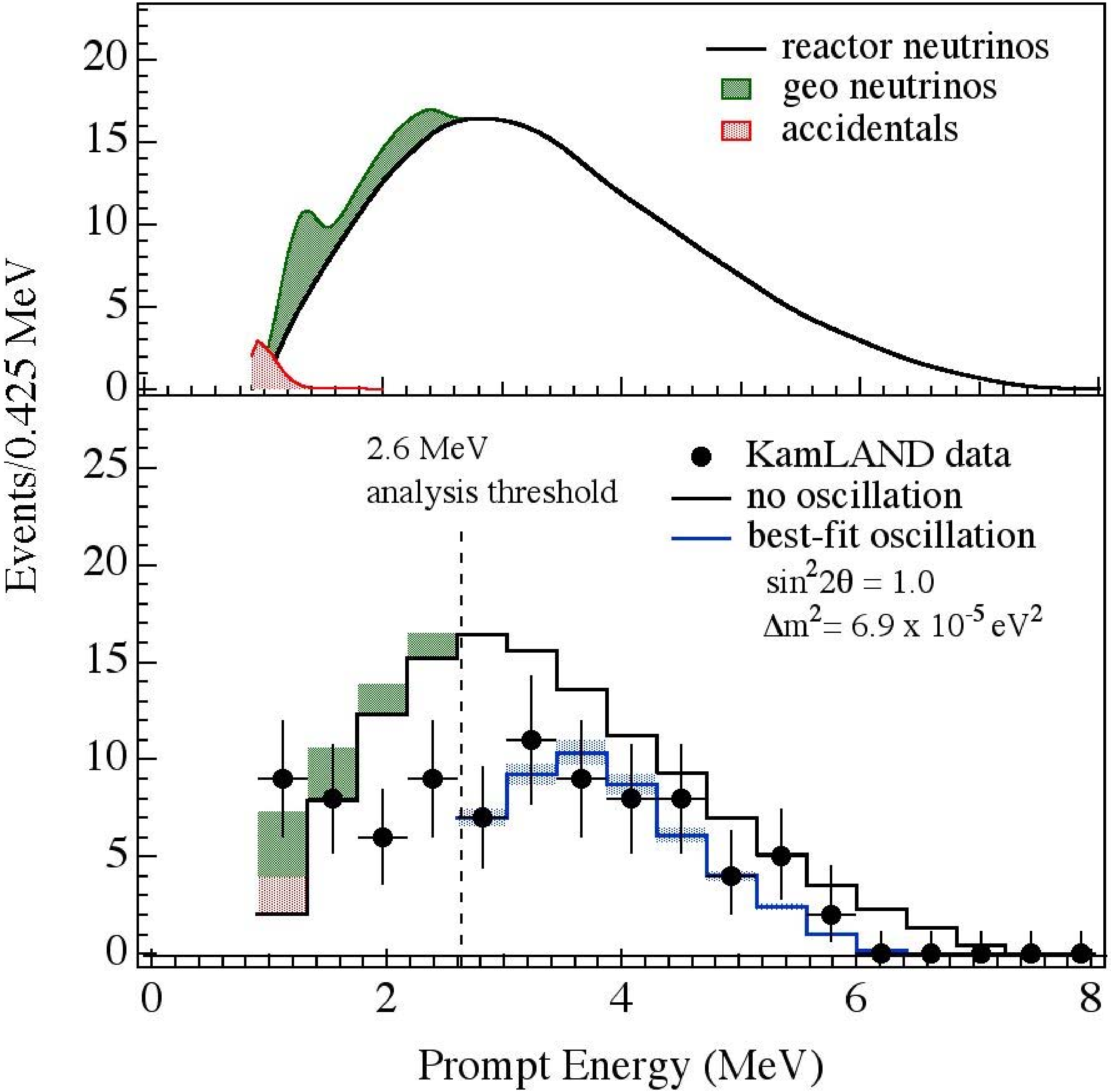


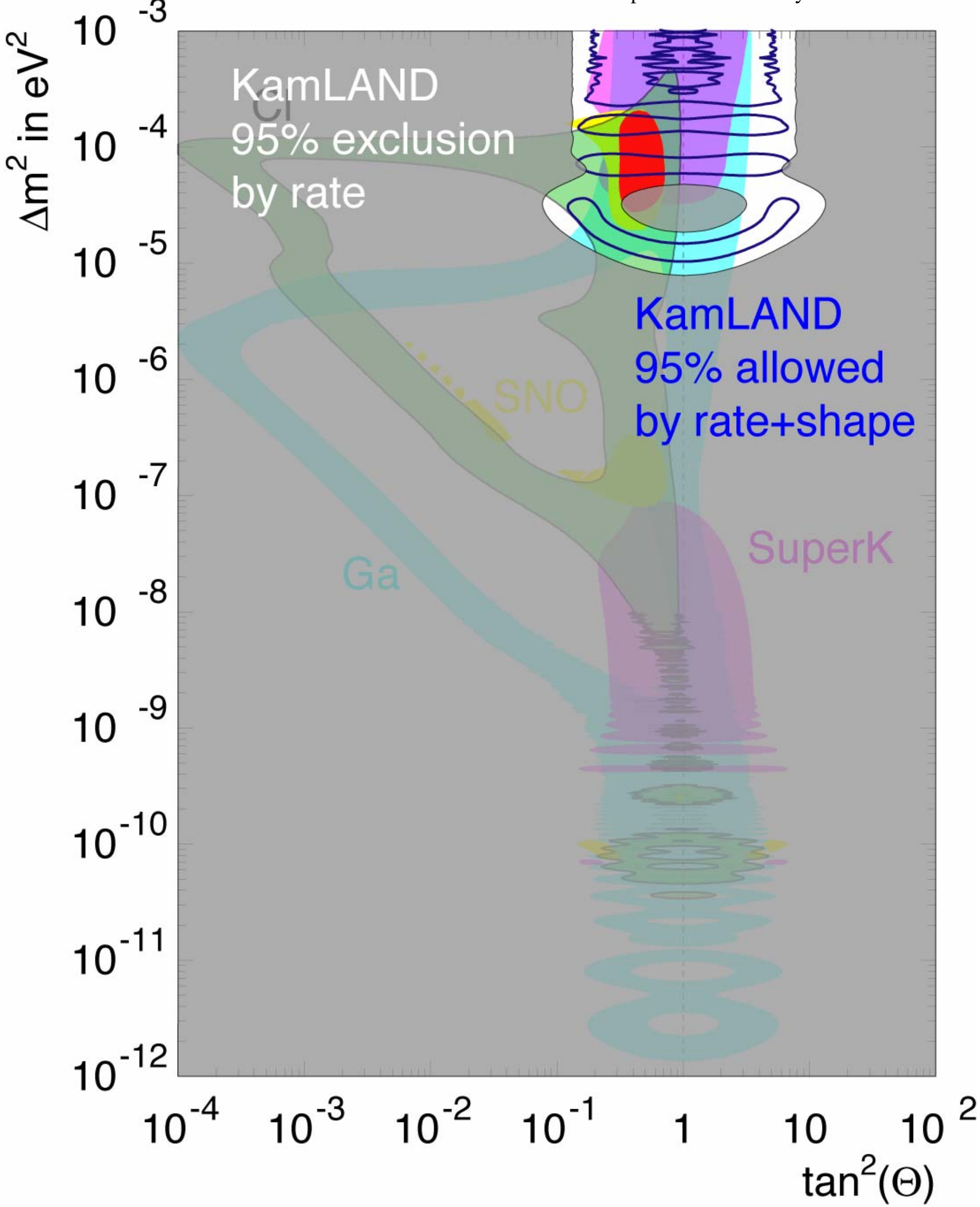


http://hitoshi.berkeley.edu/neutrino/
Δm^2 in eV^2
Cl
SNO
Ga
SuperK
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
$\tan^2(\Theta)$

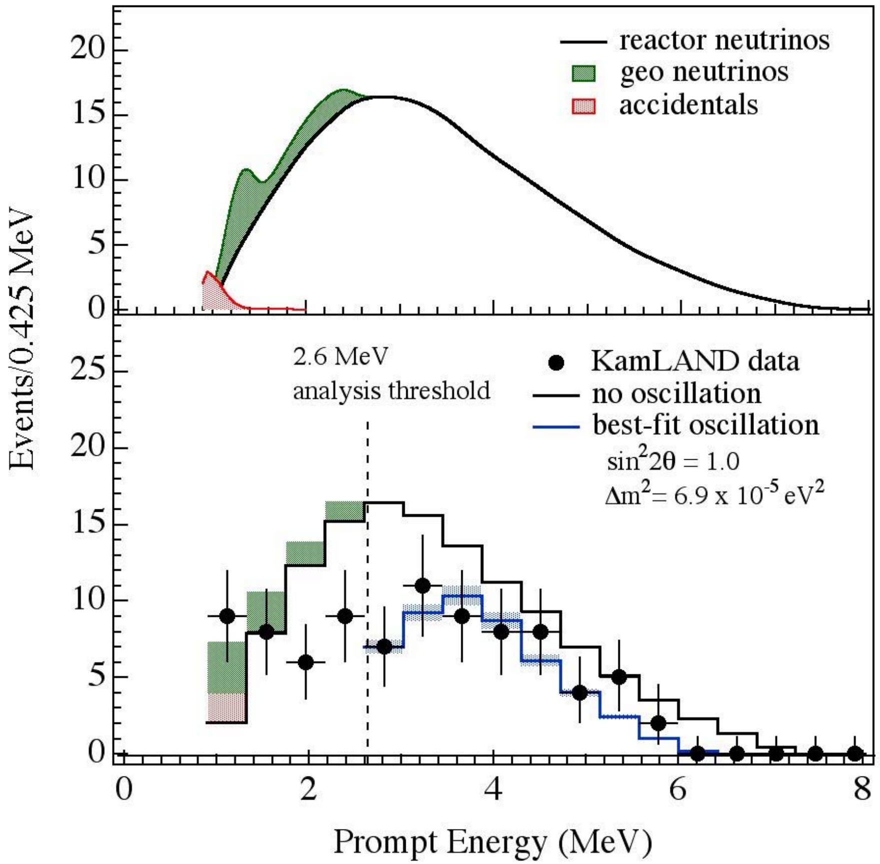


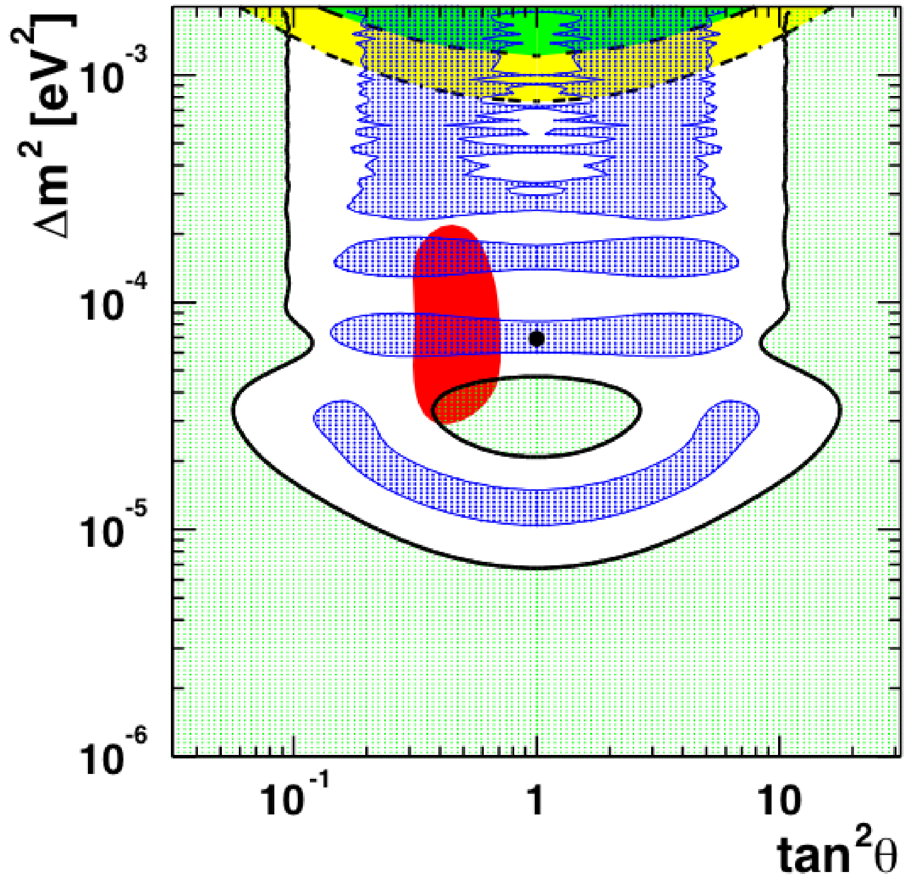
http://hitoshi.berkeley.edu/neutrino/
KamLAND
95% exclusion
by rate
Cl
SNO
SuperK
Ga
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
$\tan^2(\Theta)$


reactor neutrinos
geo neutrinos
accidentals
2.6 MeV
analysis threshold
KamLAND data
no oscillation
best-fit oscillation
$\sin^2 2\theta = 1.0$
$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$
Events/0.425 MeV
Prompt Energy (MeV)

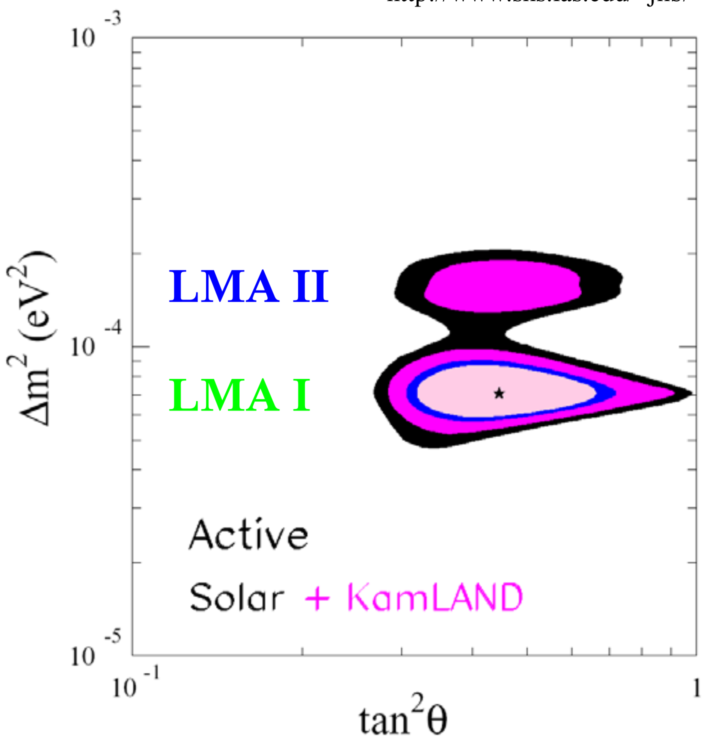

KamLAND
95% exclusion
by rate
Cl
SNO
KamLAND
95% allowed
by rate+shape
SuperK
Ga
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
tan^2(Θ)

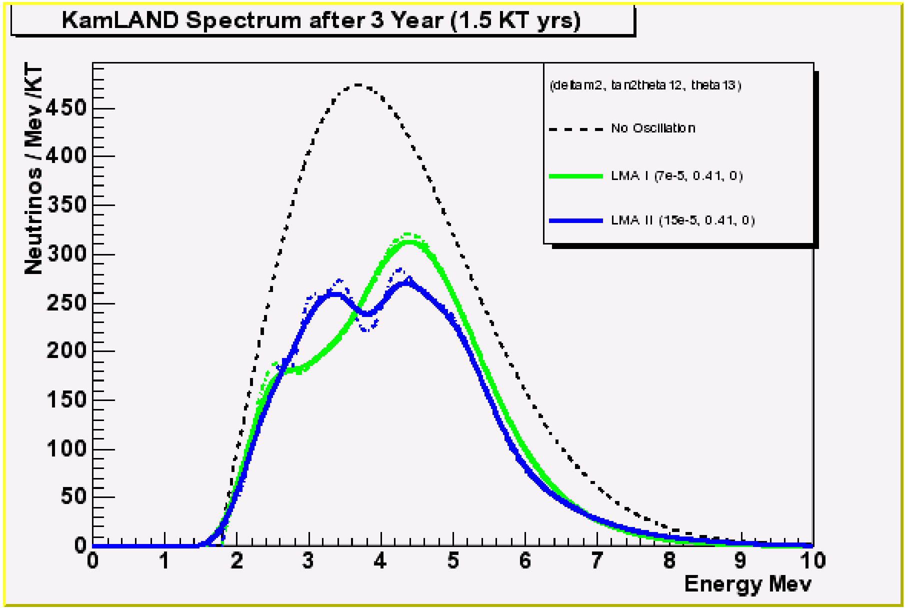
High Statistics Shape Analysis





http://www.sns.ias.edu/~jnb/





But...

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September 16, 2002, Monday

FOREIGN DESK

Safety Problems at Japanese Reactors Begin to Erode Public's Faith in Nuclear Power

By HOWARD W. FRENCH (NYT) 1320 words

TOKYO, Sept. 15 -- The reports of safety lapses, fraudulent repairs and cover-ups at Japan's largest nuclear power company began with a trickle but have resounded into an industry nightmare.

- Reactors at Kashiwazaki-Kariwa, Fukushima-Daiichi, and Fukushima-Daini are temporarily down for inspection.
- $\overline{\nu}_e$ Flux at KamLAND is reduced by ~ 50%.

world
Environment News

TEPCO reactor passes last test, ready for restart

TOKYO - Tokyo Electric Power Co Inc (TEPCO) (9501.T) said yesterday that one of its nuclear reactors was ready to begin operating after having passed a final test, although no restart date had been set.

The Japan Times ONLINE

Saturday, June 7, 2003

Hiranuma issues Tepco apology

Minister contrite over mishandling of defect coverups

KASHIWAZAKI, Niigata Pref. (Kyodo) Industry minister Takeo Hiranuma visited Niigata Prefecture on Friday to apologize for the mishandling of Tokyo Electric Power Co.'s coverup of defects at its nuclear reactors.

The Japan Times ONLINE

Thursday, June 12, 2003

Mayors OK restarting of Tepco reactor

NIIGATA (Kyodo) The mayors of two Niigata Prefecture municipalities hosting a nuclear power plant conveyed their approval Wednesday to Gov. Ikuo Hirayama to restart a reactor now that it has undergone repairs.

All reactors are expected to come back online during the summer, 2003.

KamLAND Future

- Shape Analysis
- Solar Electron Anti-Neutrinos
- Relic Supernova Electron Anti-Neutrinos
- Terrestial Electron Anti-Neutrinos
- Muon Spallation (Neutron Multiplicity)
- Supernova Watch
- Solar Phase (Detection of ^{7}Be Solar Neutrinos)

KamLAND Solar Phase

Background	Current	Goal	Method
^{238}U	3.5×10^{-18} g/g	OK	
^{232}Th	5.2×10^{-17} g/g	OK	
^{222}Rn	3.3×10^{-8} Bq/m^{-3}	OK	
^{40}K	$<2.7 \times 10^{-16}$ g/g	$<10^{-18}$ g/g	Water Extraction
^{210}Pb	$\sim 10^{-20}$ g/g	5×10^{-25} g/g	Water Extraction
^{85}Kr	0.7Bq/m^{-3}	10^{-6} Bq/m^{-3}	N_2 purge
^{222}Rn leak			N_2 purge/ air tight valves