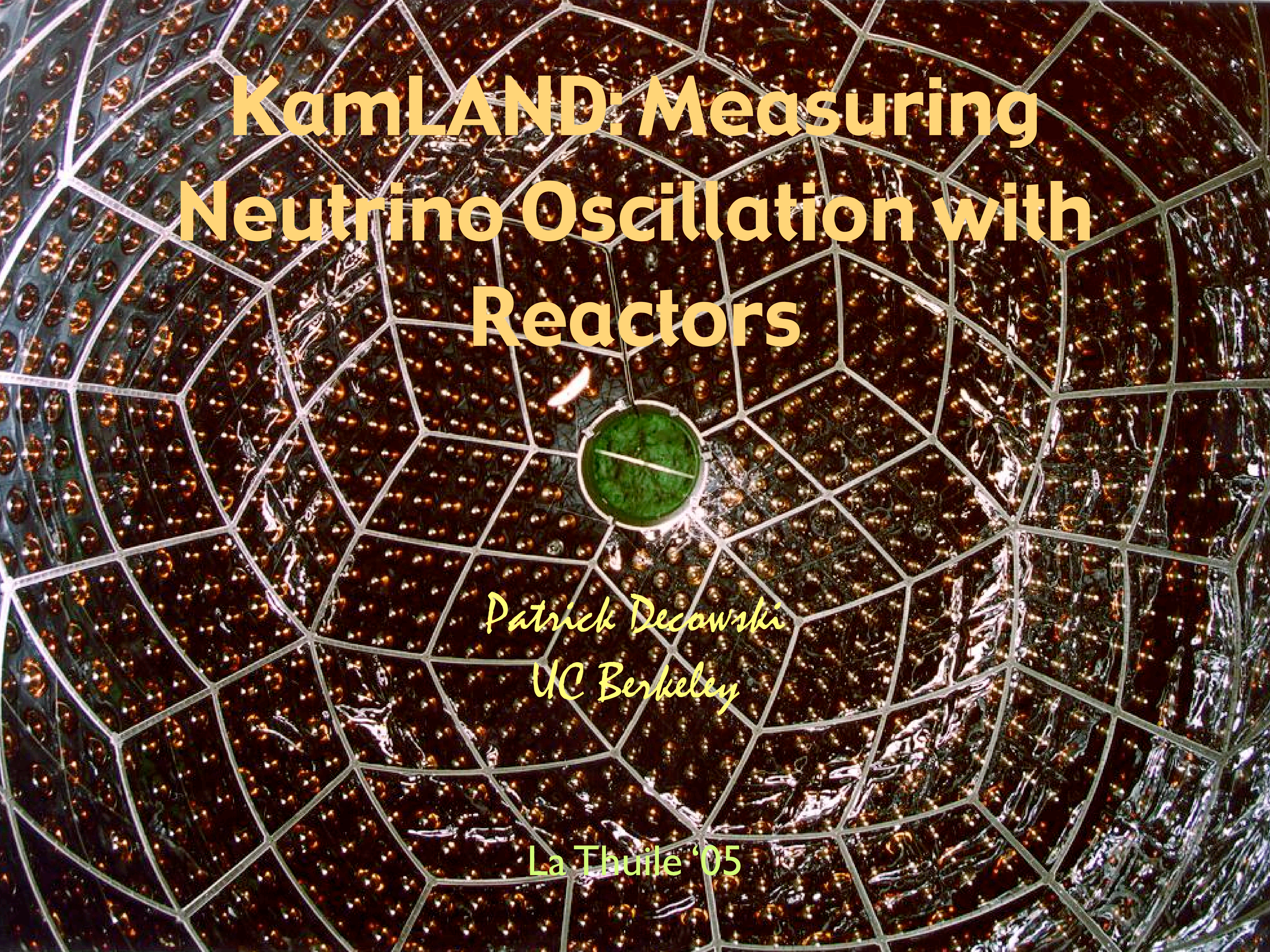
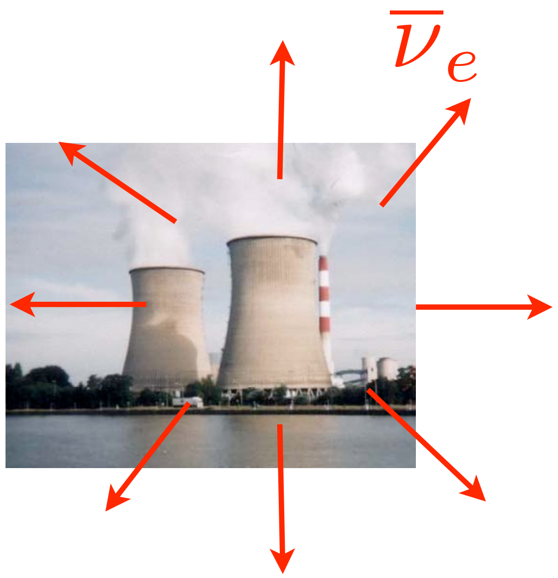


KamLAND: Measuring Neutrino Oscillation with Reactors

Patrick Decowski
UC Berkeley

La Thuile '05

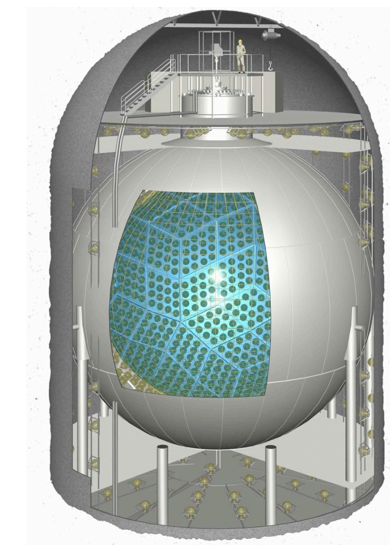
Reactor Neutrino Experiments



$\overline{\nu}_e$

$\overline{\nu}_e$**?** $\longrightarrow$

$\overline{\nu}_x$**?** $\longrightarrow$



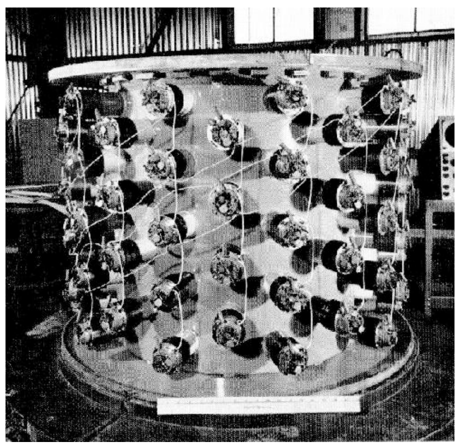
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

L

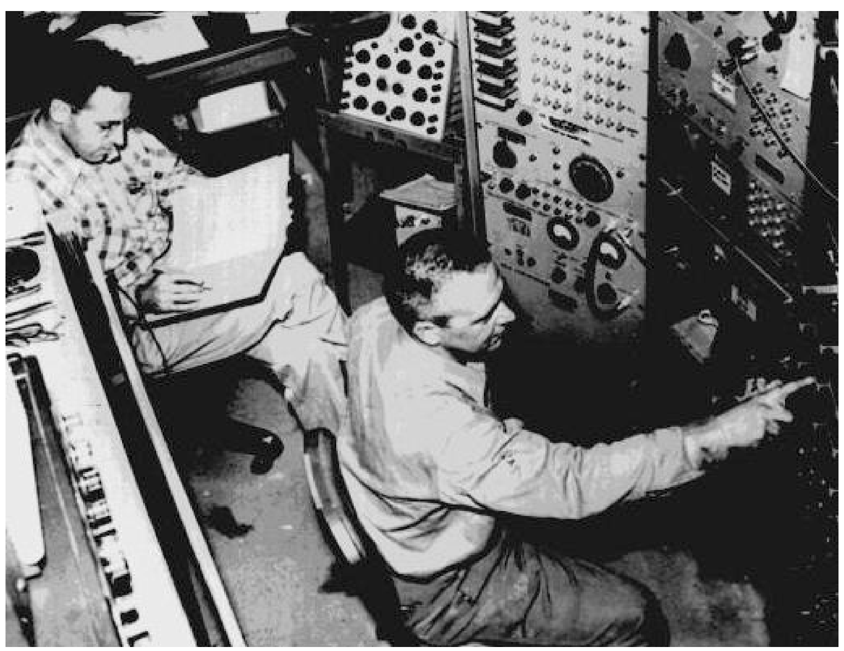
Few MeV anti-neutrinos, energy too low to produce μ or τ
➡ disappearance experiments

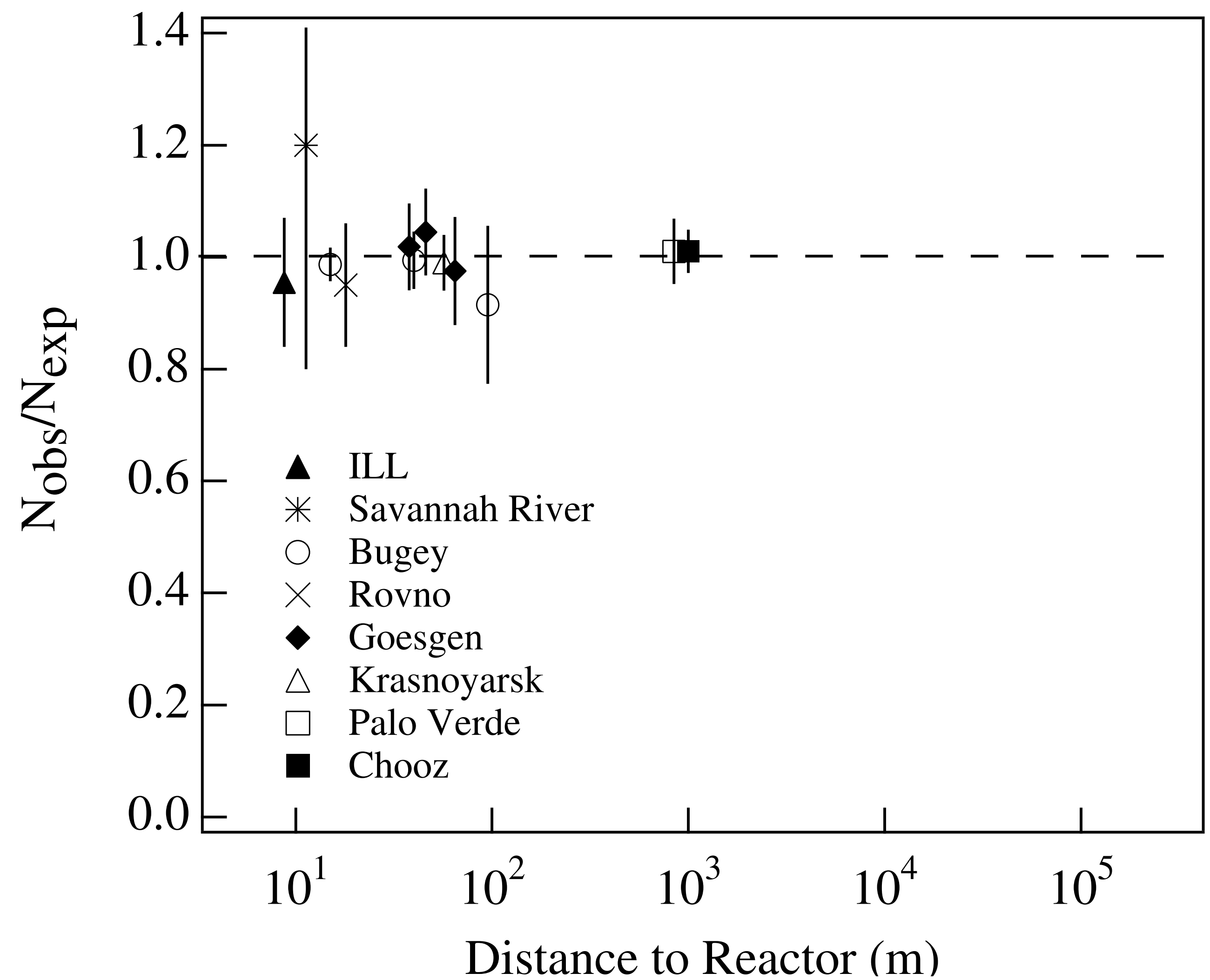
Oscillation searches with Reactors

Reactors have played an important role in the early history of neutrinos and in neutrino-oscillation searches: 1953 - Present



Poltergeist
(Reines & Cowan 1955)



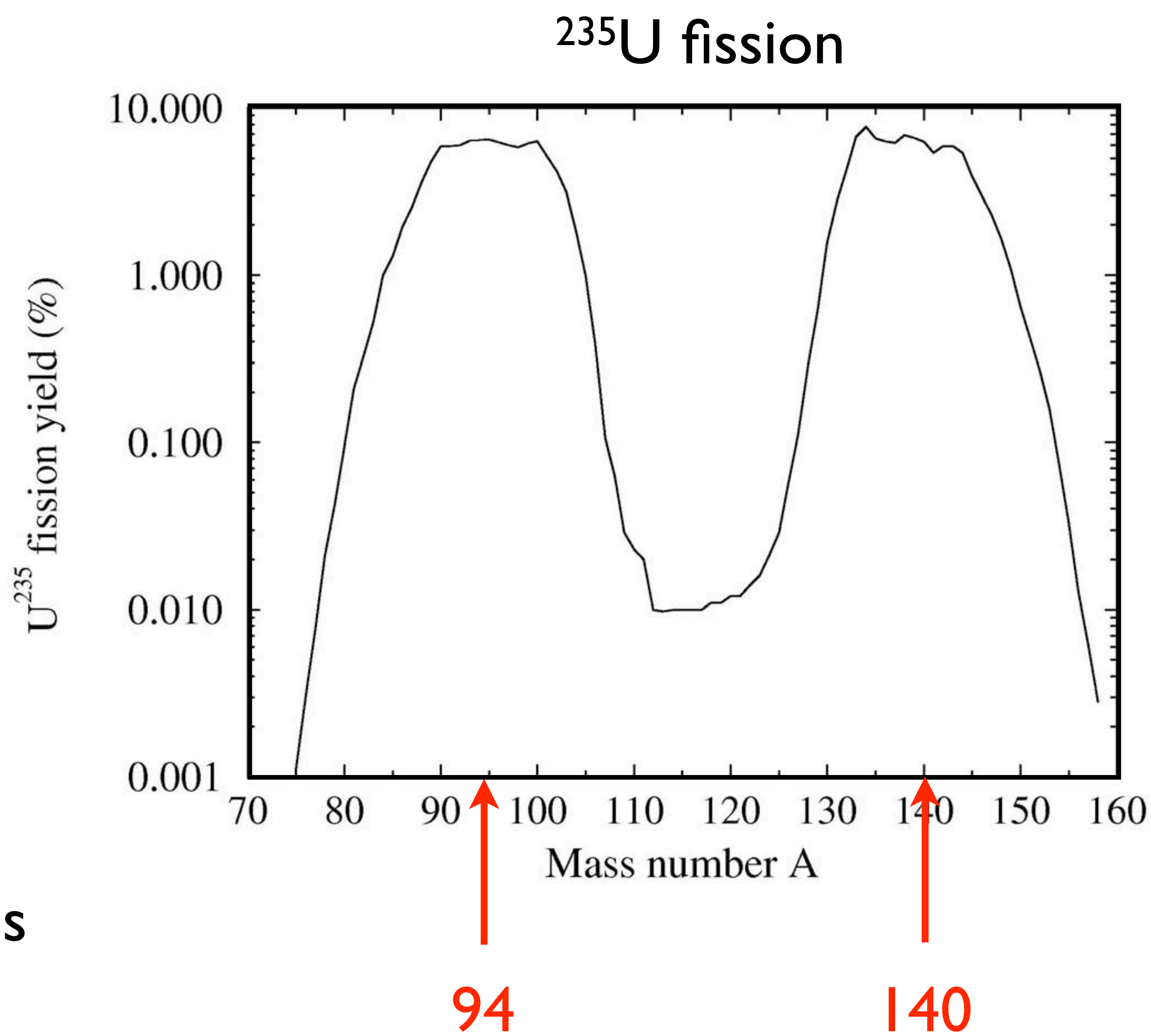


- Many different experiments
  - Baselines up to 1km
  - No evidence for $\overline{\nu}_e$ disappearance

Reactor Anti-Neutrinos

Reactor Neutrinos

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



The stable products most likely from Uranium fission:

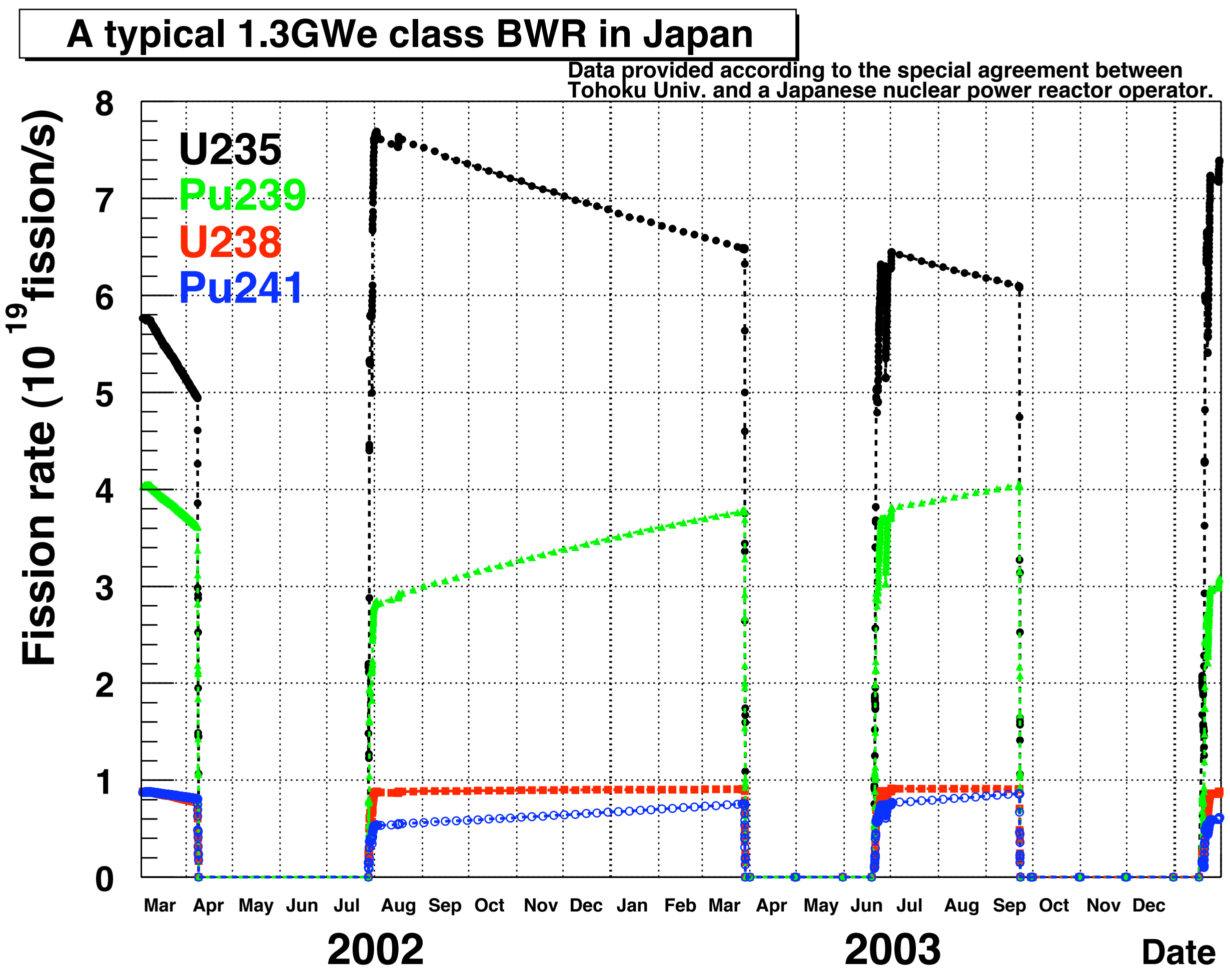
$^{94}_{40}Zr$ $\quad$ $^{140}_{58}Ce$

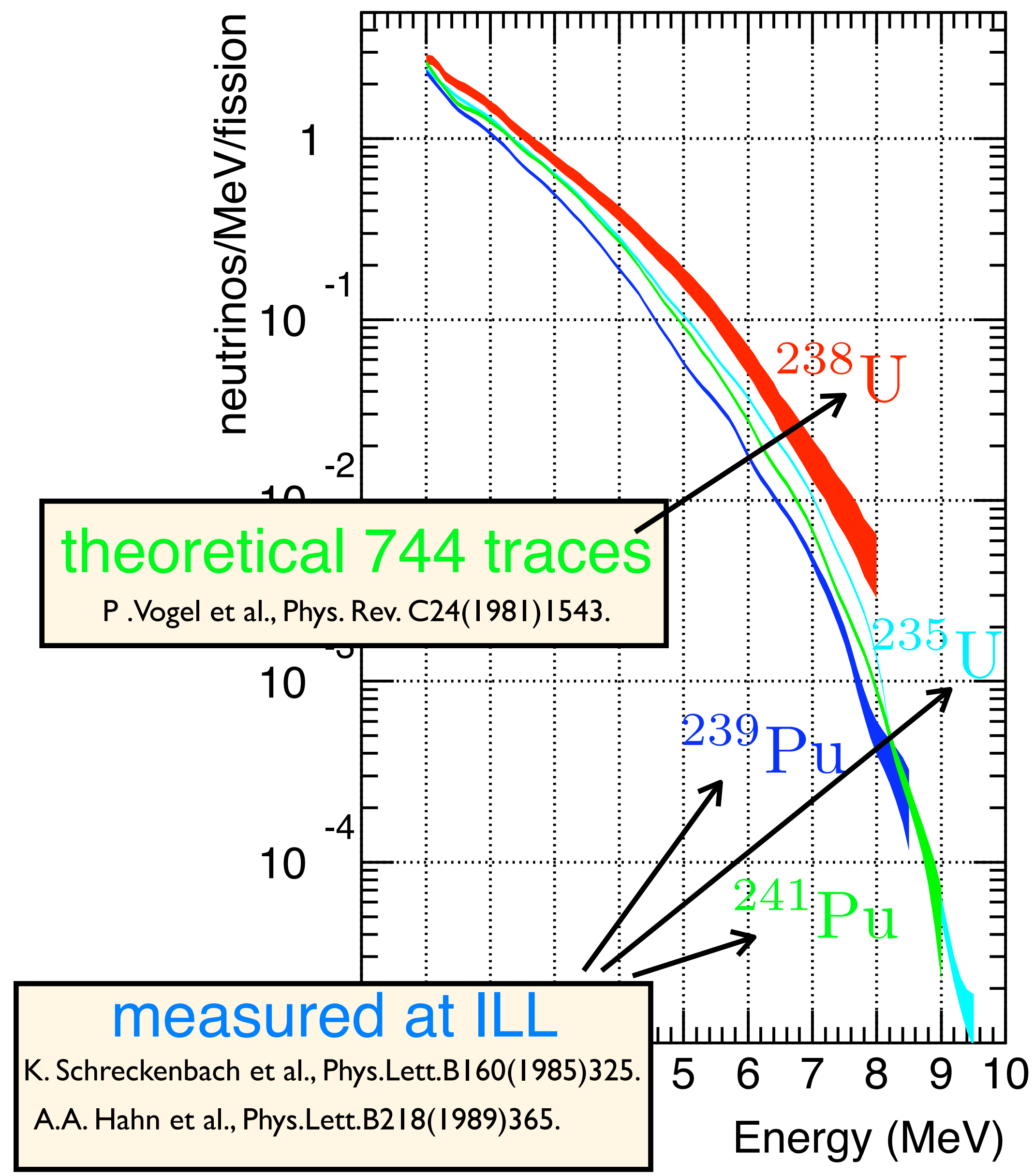
Together 98 protons and 136 neutrons

6 neutrons have to β-decay to reach stable matter, producing 6 $\overline{\nu}_e$ / fission

Calculating Neutrino Spectra

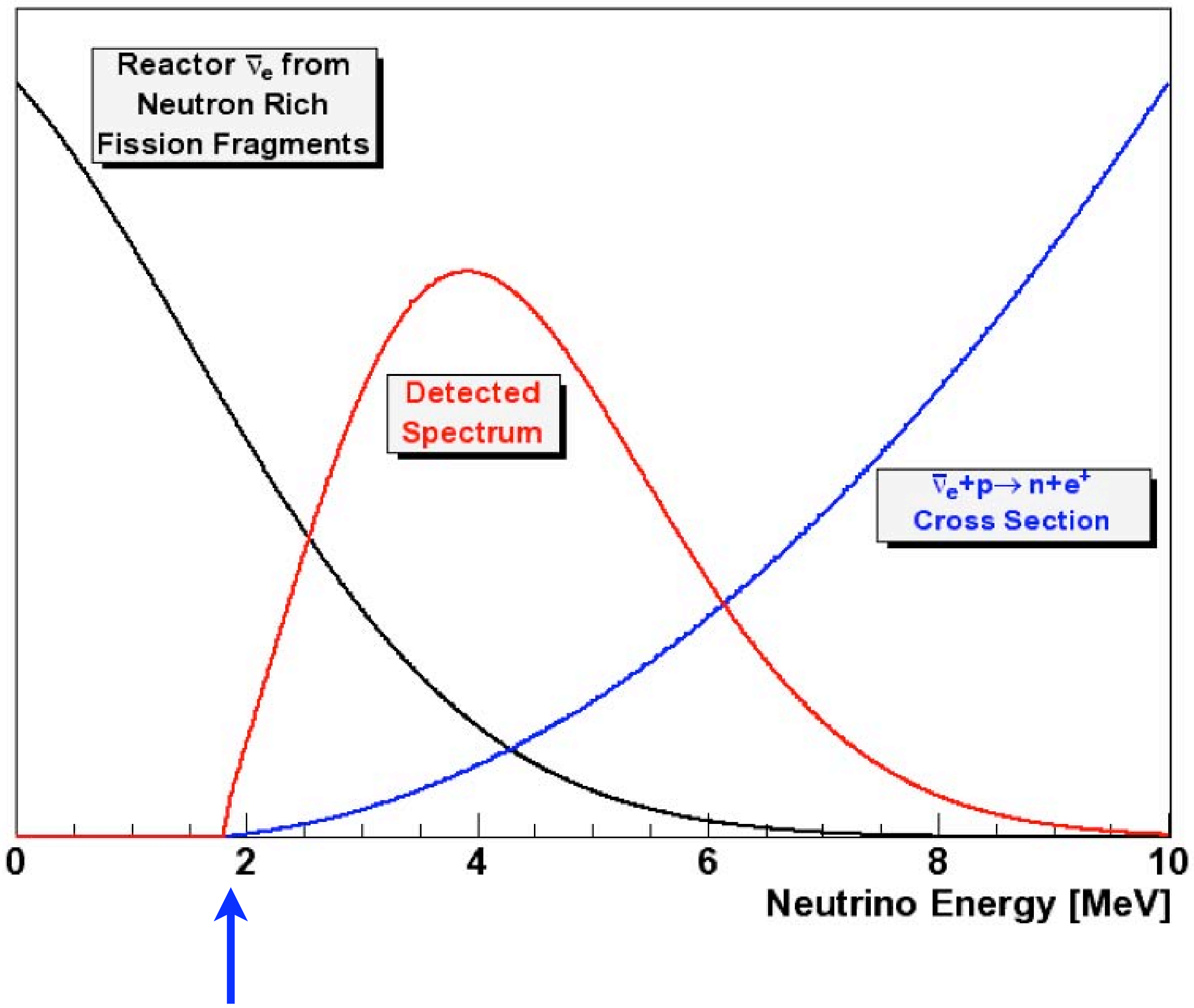
Only 4 isotopes relevant



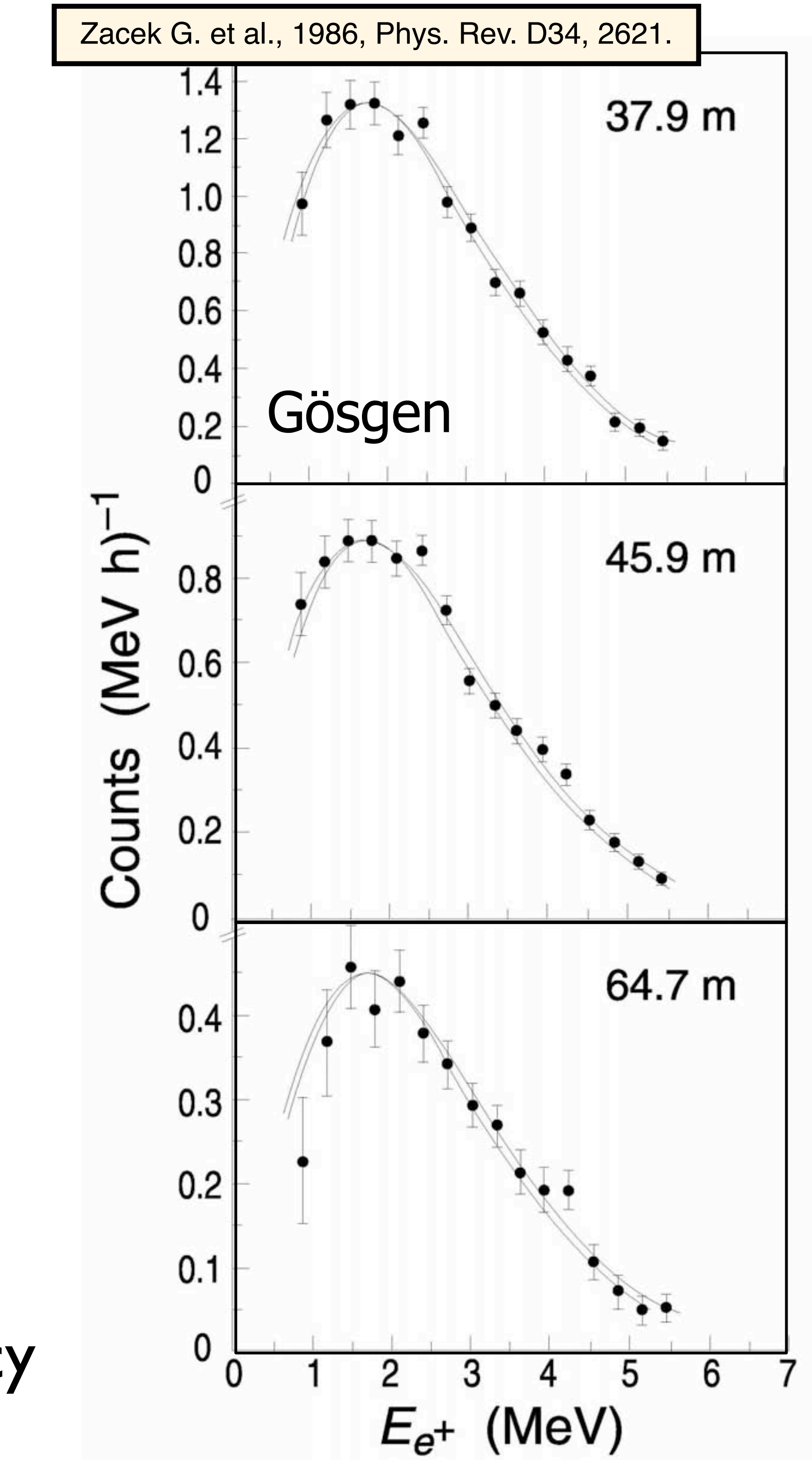


- Fission rates provided by reactor companies
  - Chiefly function of thermal power
  - Weak function of inlet T: 10% ➡ ~0.15% rate change

Detected Reactor Spectrum



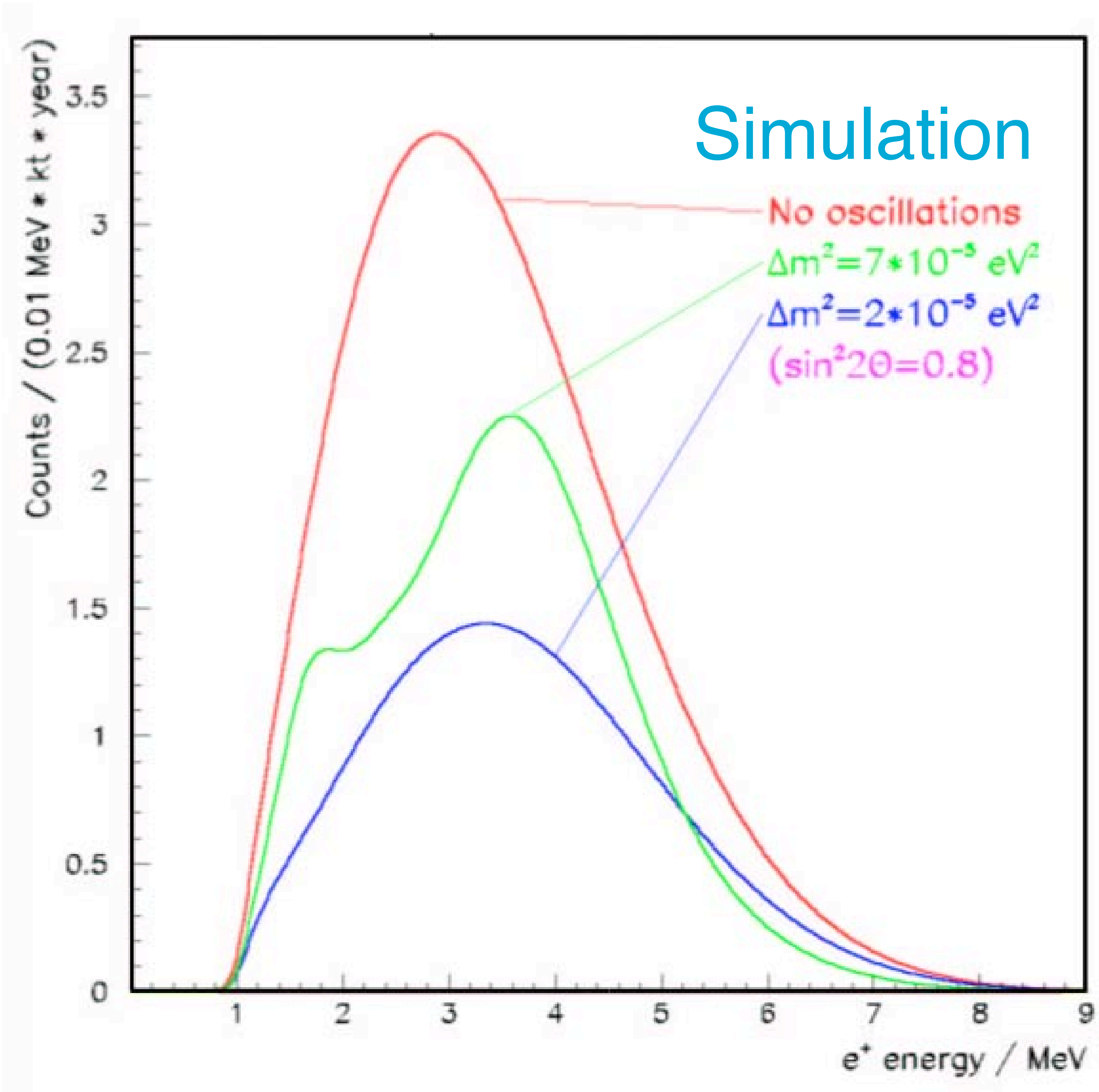
1.8MeV threshold in Inverse Beta Decay

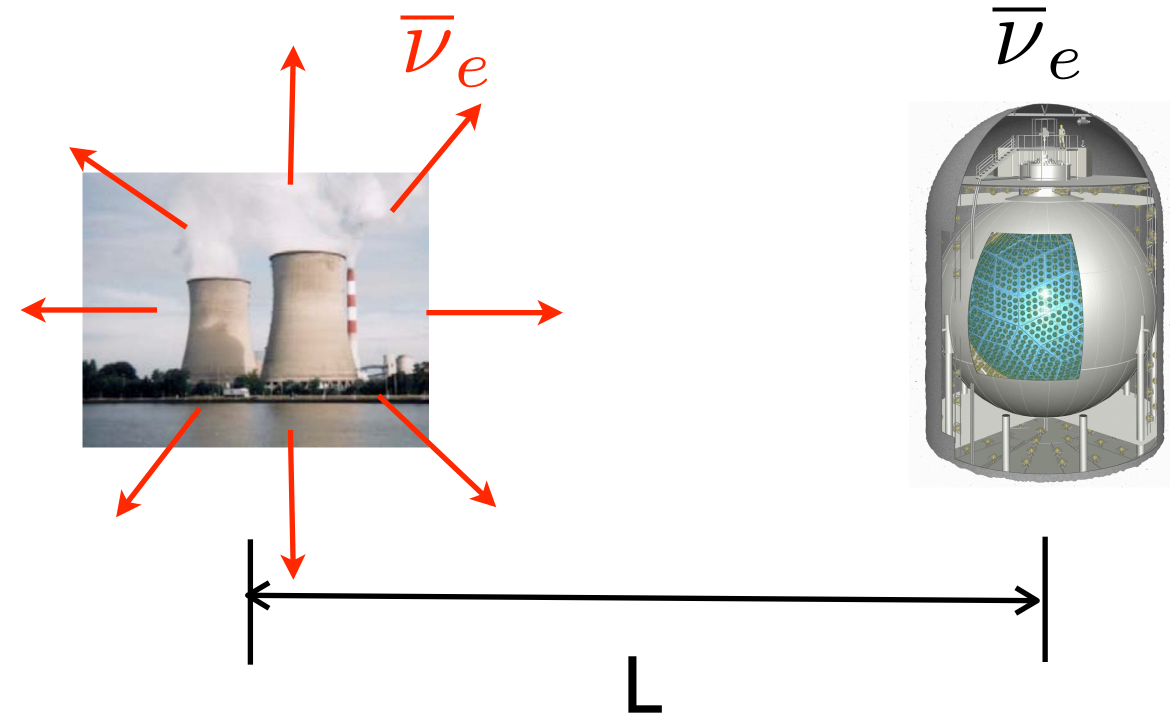


- In practice, only 1.5 neutrinos/fission detectable
- Calculated spectrum has been verified to 2% accuracy in past reactor experiments

No near detector necessary!

Distortion of Spectrum





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

Neutrino oscillation changes both the overall normalization and the shape of the spectrum

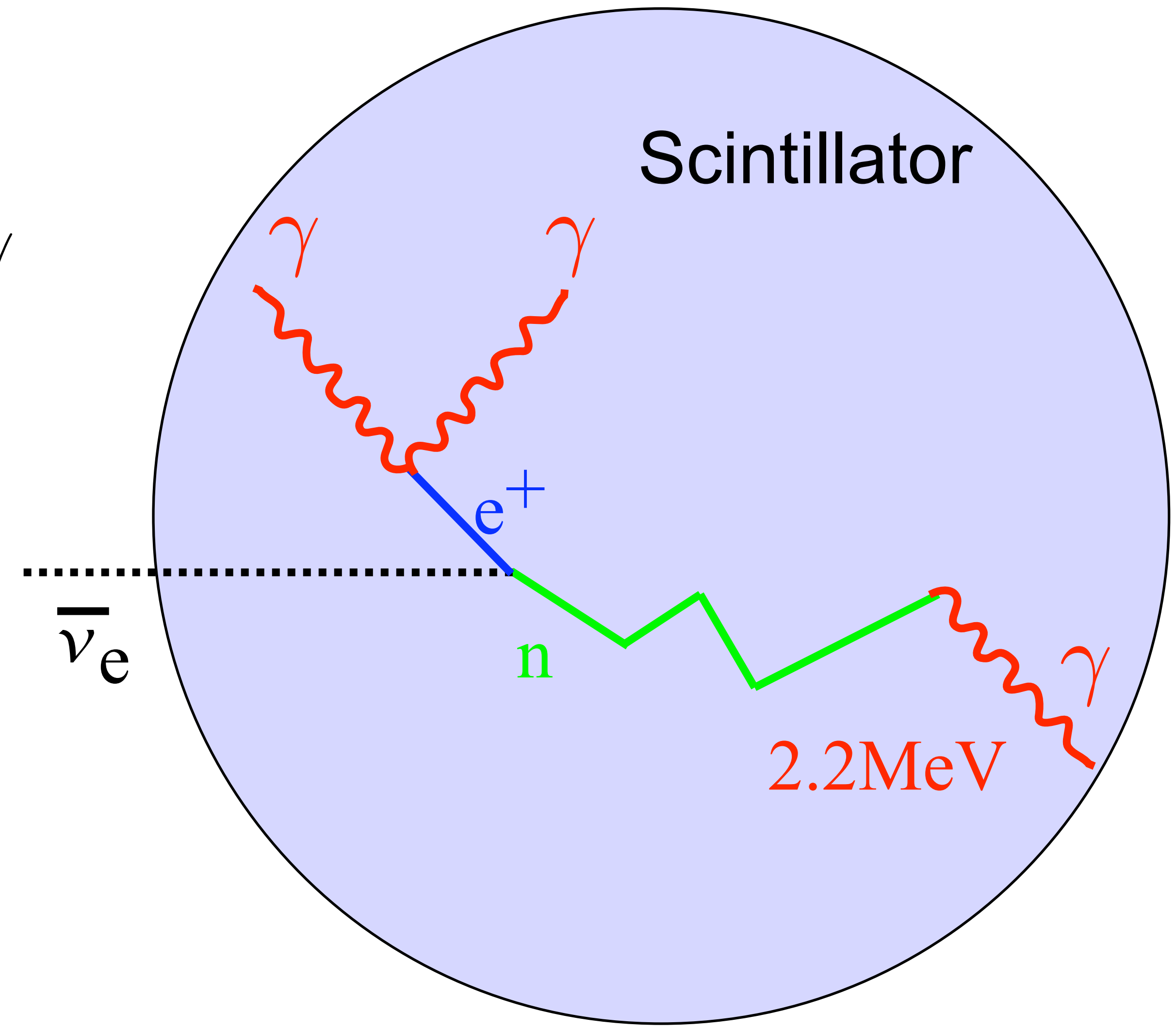
Anti-neutrino Detection Method

Reaction process: Inverse beta decay

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

$$n + p \rightarrow d + \gamma$$

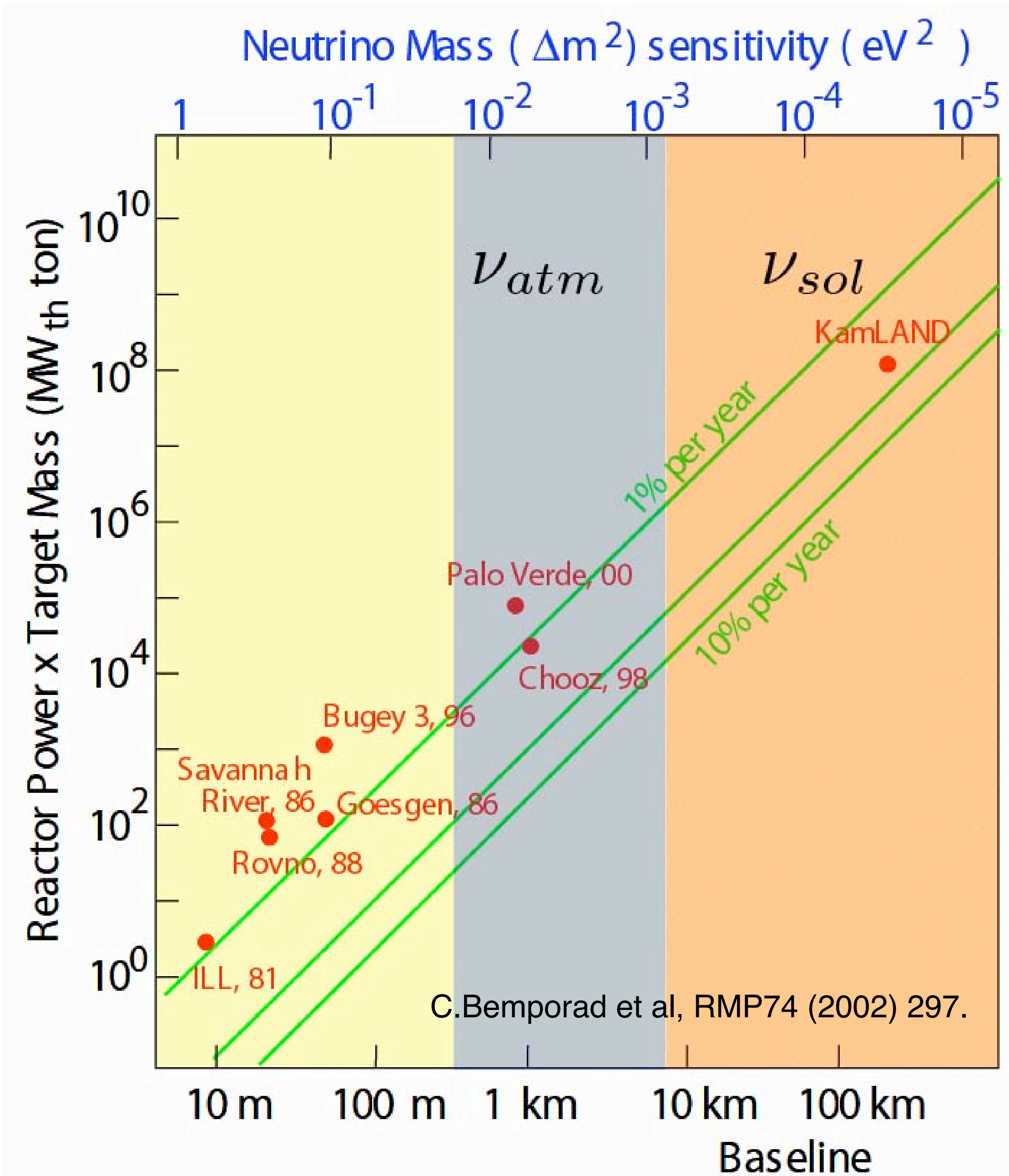
Scintillator is both target and detector



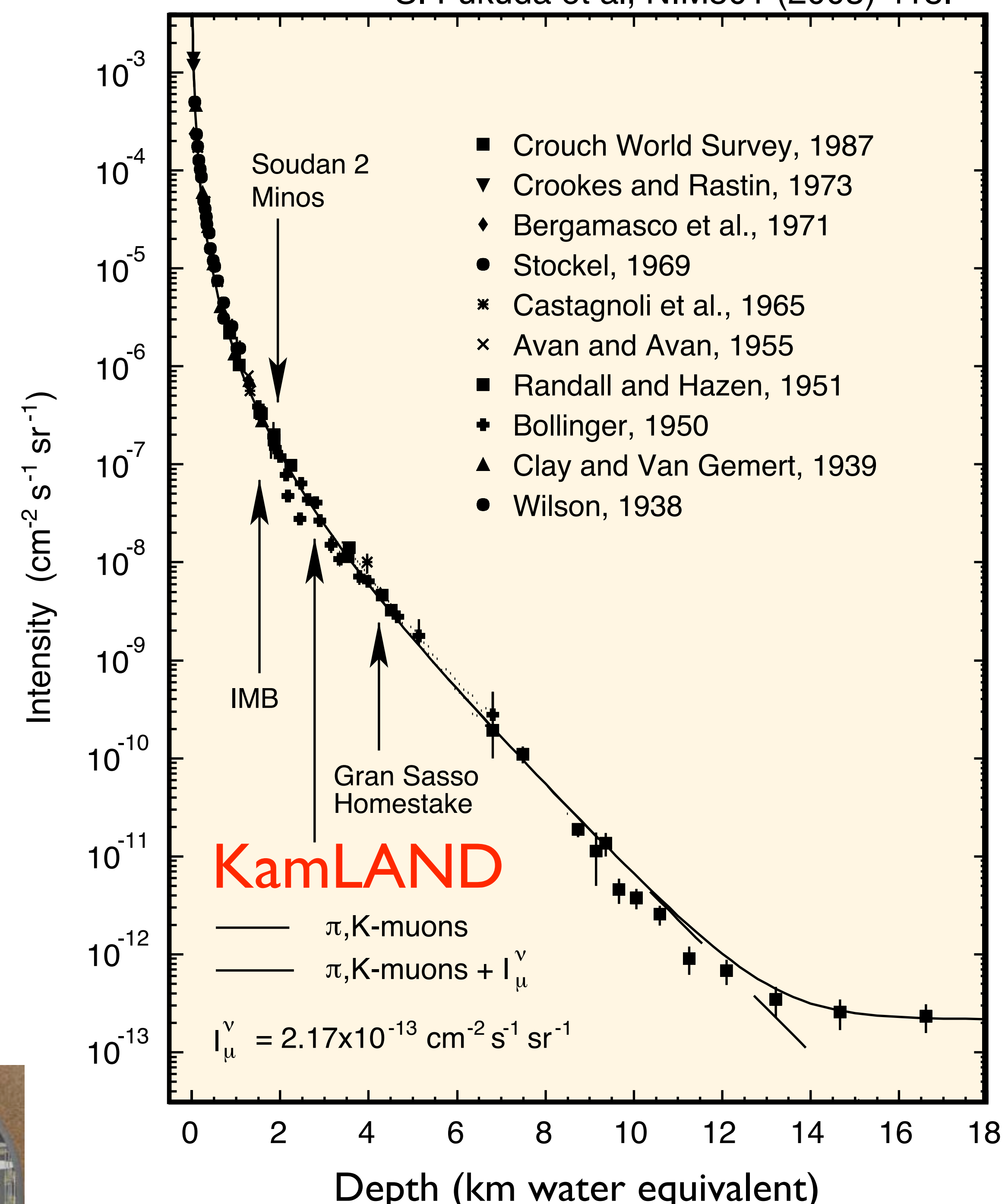
- Distinct two step process:
  - prompt event: positron
    $E_{\overline{\nu}_e} \simeq E_{prompt} + 0.8MeV$
  - delayed event: neutron capture after ~210μs
    - 2.2 MeV gamma

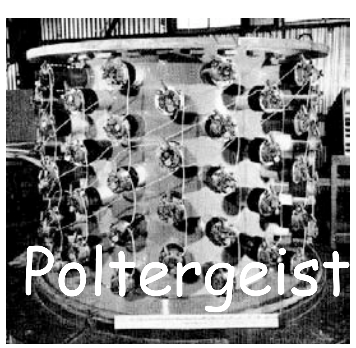
Delayed coincidence: good background rejection

Long Baseline Means Large Detectors

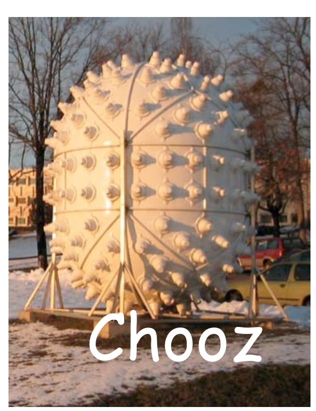


S. Fukuda et al, NIM501 (2003) 418.

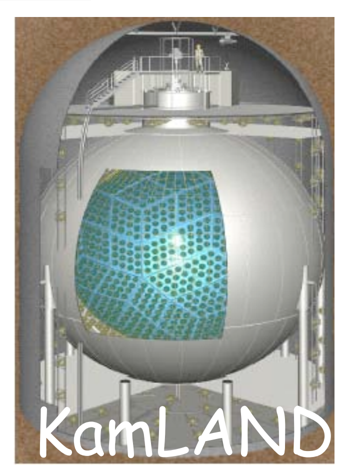




← 1m →



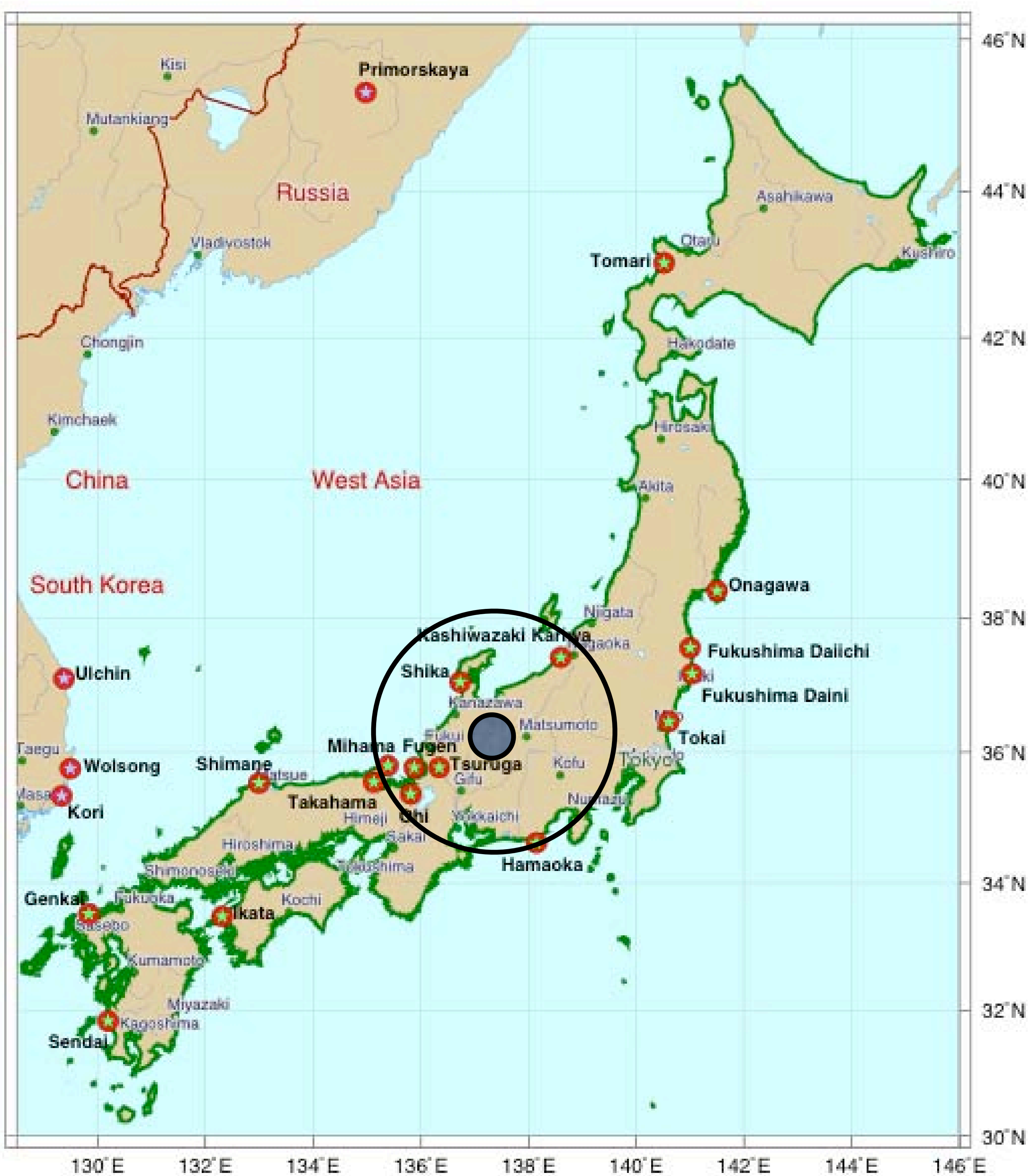
← 4m →



← 20m →

The KamLAND Experiment

$\overline{\nu}_e$ from 53 Reactor Cores in Japan

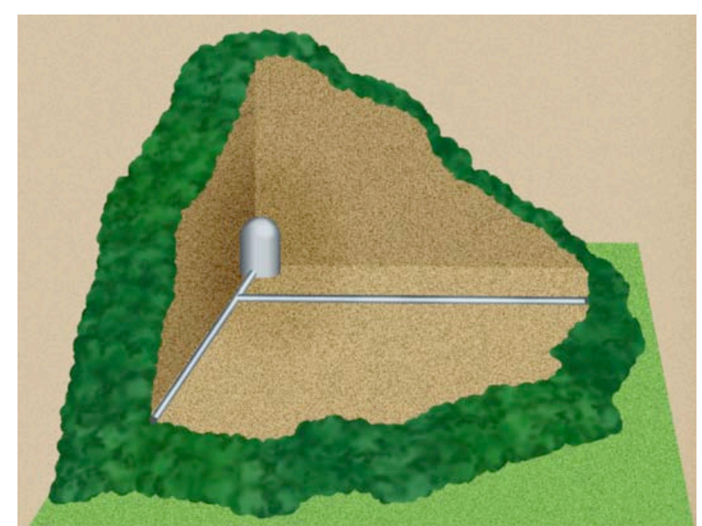


70 GW (7% of world total) is generated at 130-220 km distance from Kamioka.

Reactor neutrino flux, $\sim 6 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

95.5% from Japan
3.5% from Korea

Effective distance ~180km

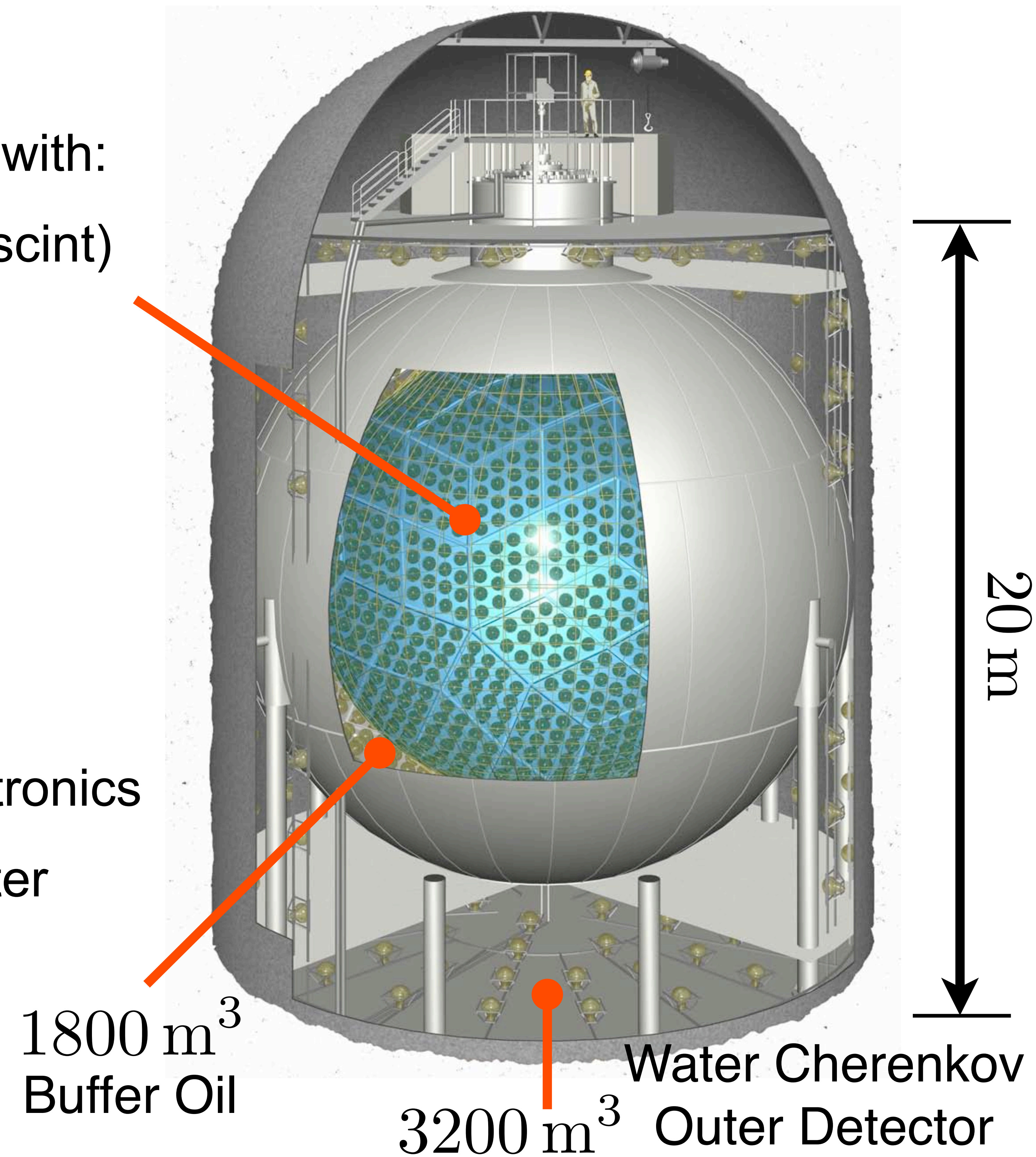


1000m rock
= 2700 mwe

long. $137°18'43.495''$
lat. $36°25'35.562''$
alt. $358\,\mathrm{m}$

KamLAND detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scint)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Multi-hit, deadtime-less electronics
- Water Cherenkov veto counter



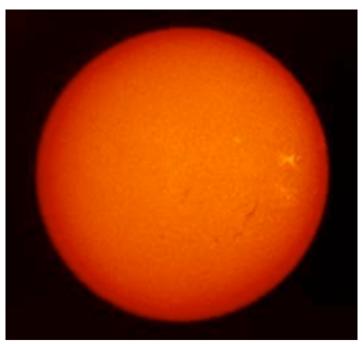
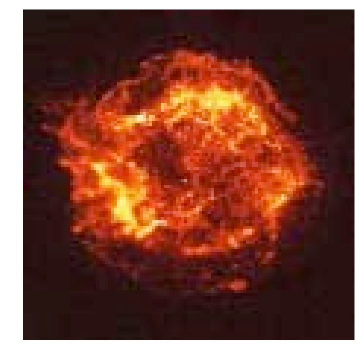
KamLAND Physics Capabilities

0.4 | 1.0 | 2.6 | 8.5 | Visible energy [MeV]

neutrino electron elastic scattering

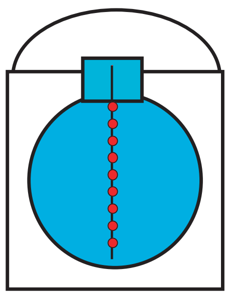
$\nu + e^- \rightarrow \nu + e^-$

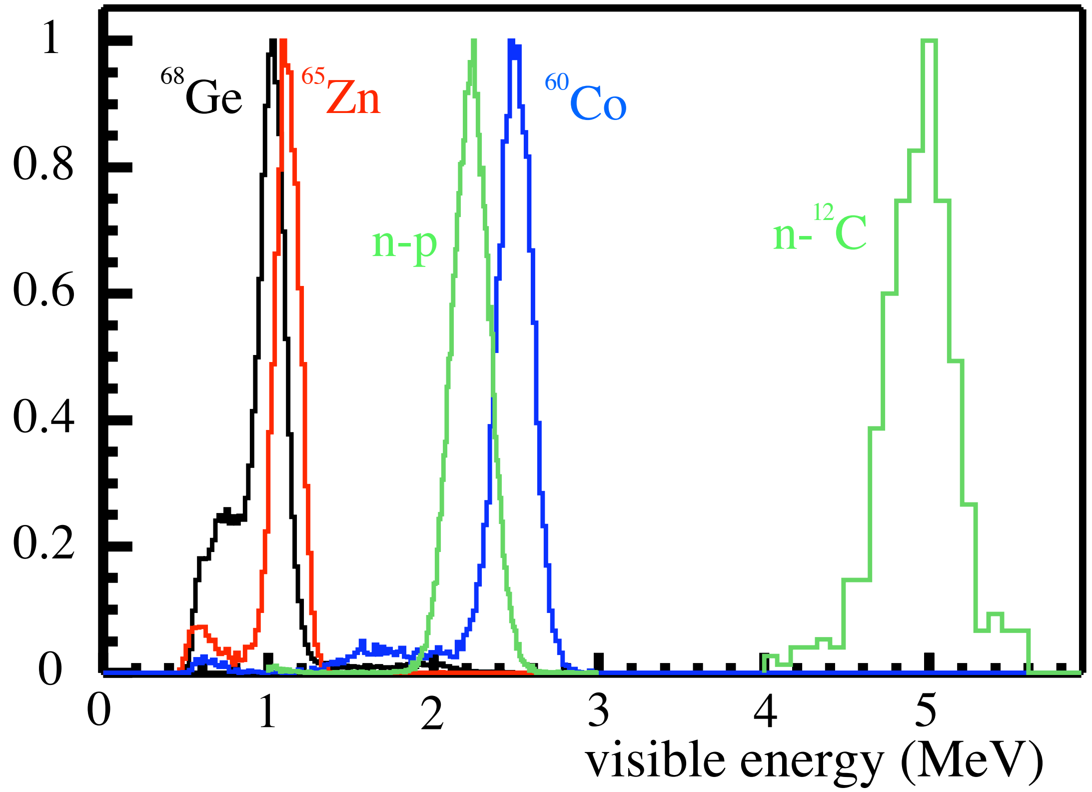
inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

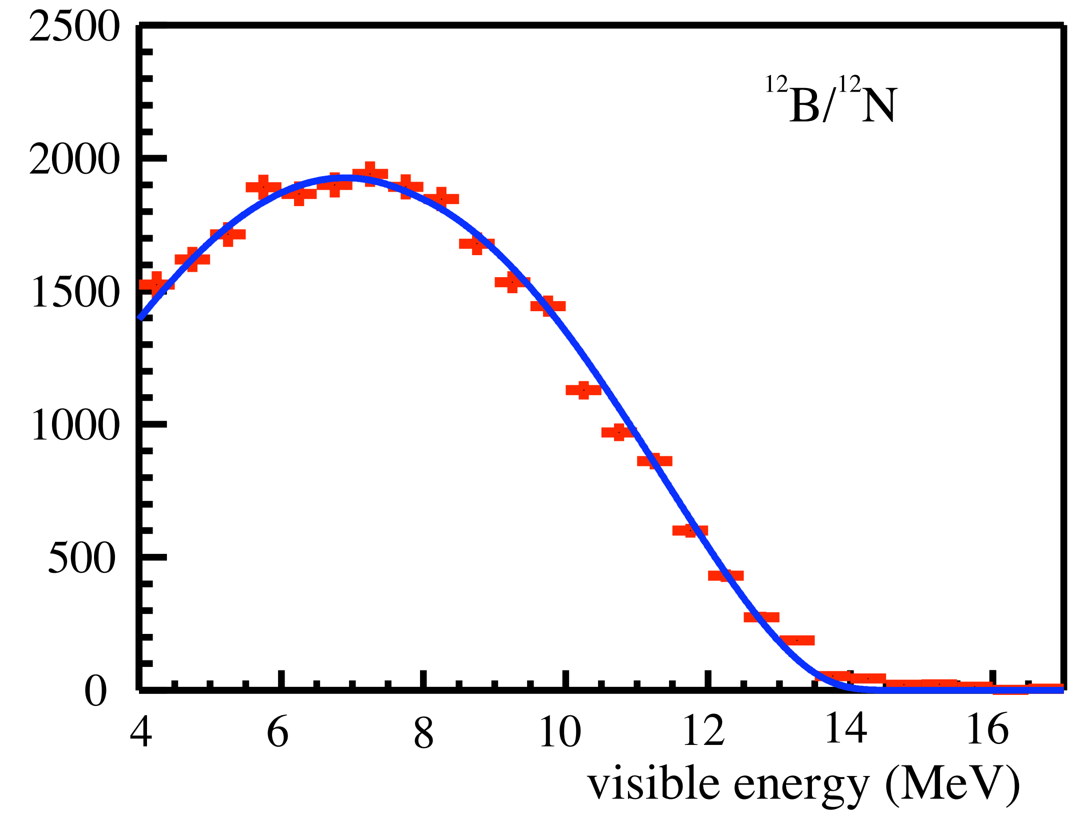
^{7}Be solar neutrino	geo-neutrino	reactor neutrino	supernova relic neutrino etc.
			
Neutrino Astrophysics	Neutrino Geophysics	Neutrino Physics	Neutrino Cosmology
verification of SSM	verification of earth heat model	Precision measurement of oscillation parameters	verification of universe evolution
future 2nd phase	“soon”	1st reactor result PRL 90 (2003) 021802.	Solar $\bar{\nu}_e$ PRL 92 (2004) 071301.

2nd reactor result
Accepted by PRL
hep-ex/0406035

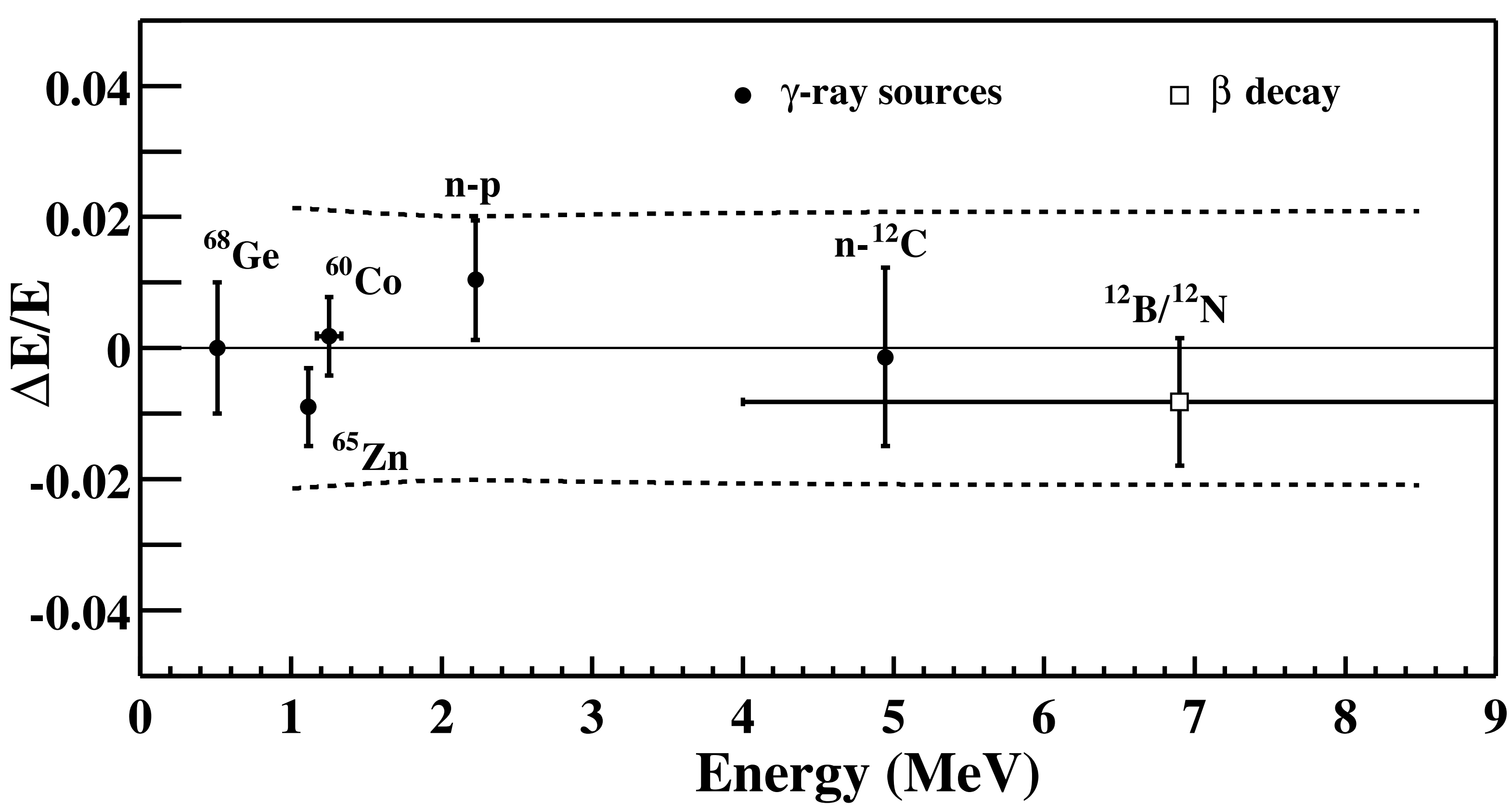
Detector Performance







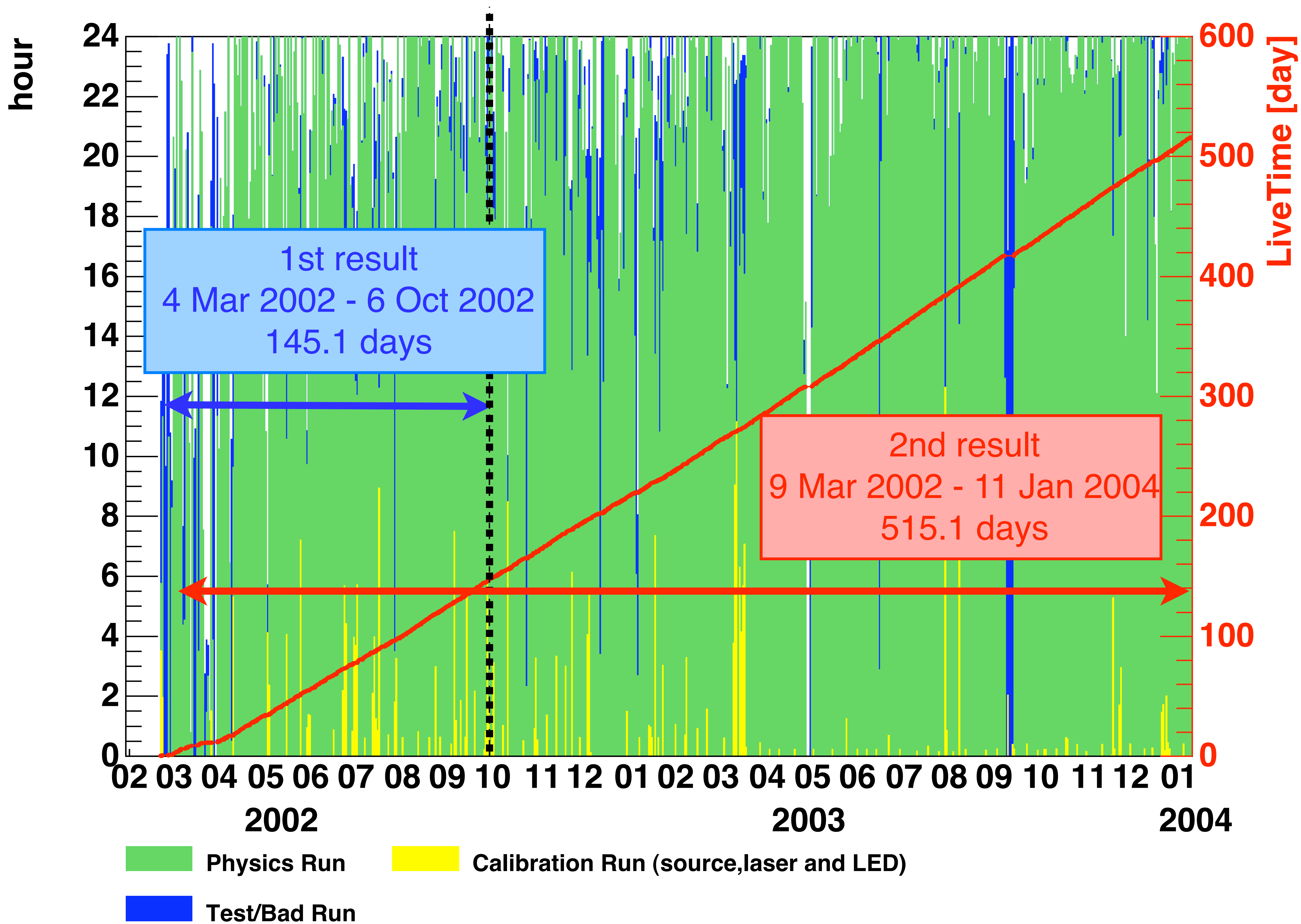
Energy Resolution: $\frac{\sigma}{E} \sim \frac{6.2\%}{\sqrt{E}}$



Energy scale error at 2.6 MeV

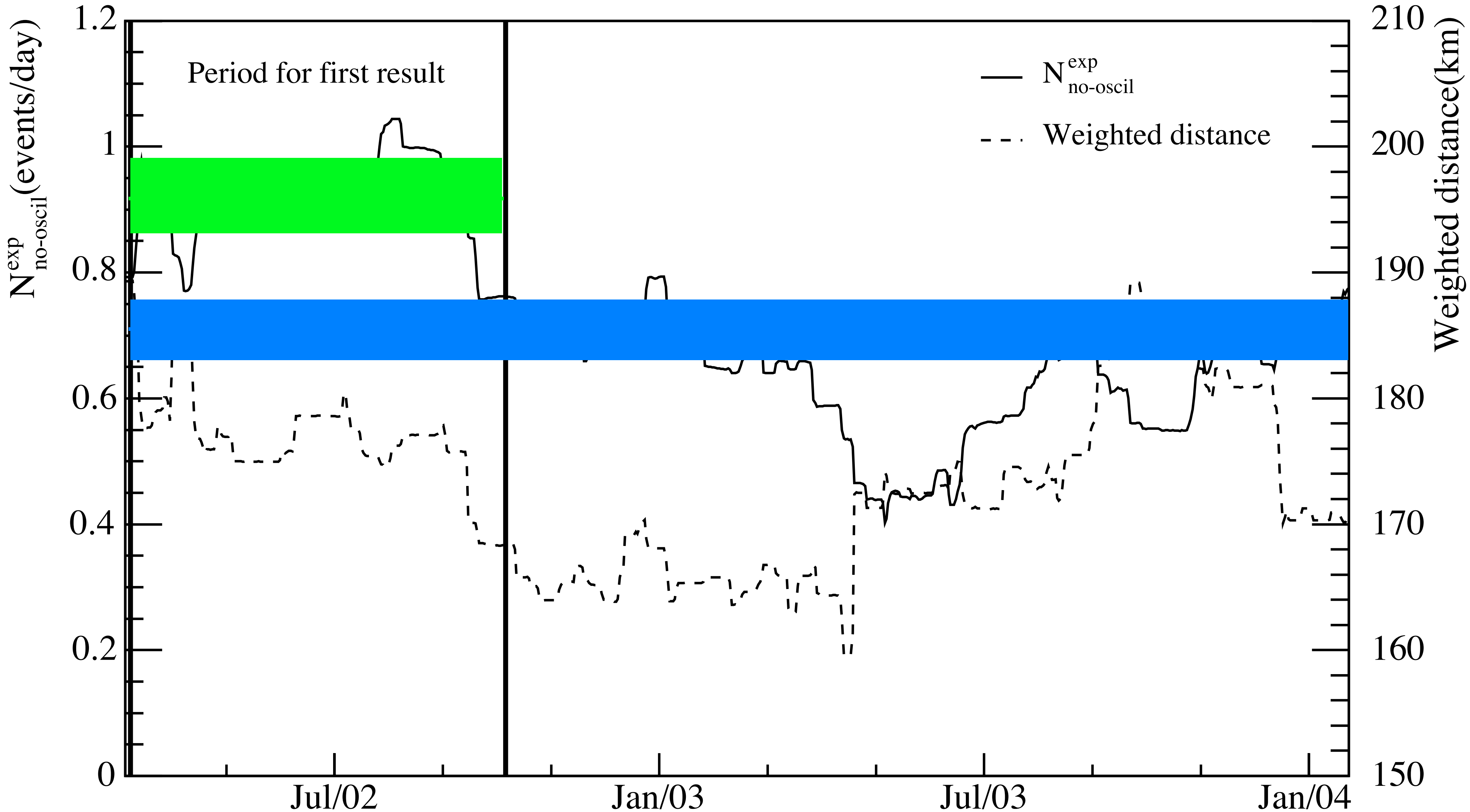
Cherenkov/Birks	1.0%
Time dependence	1.3%
Position dependence	1.0%
20” PMT non-linearity	0.8%
Total	2.0%

X 3.55 live time



Quite a few Reactors were Off

In 2002 it was discovered that some of the Japanese reactor companies had falsified safety records

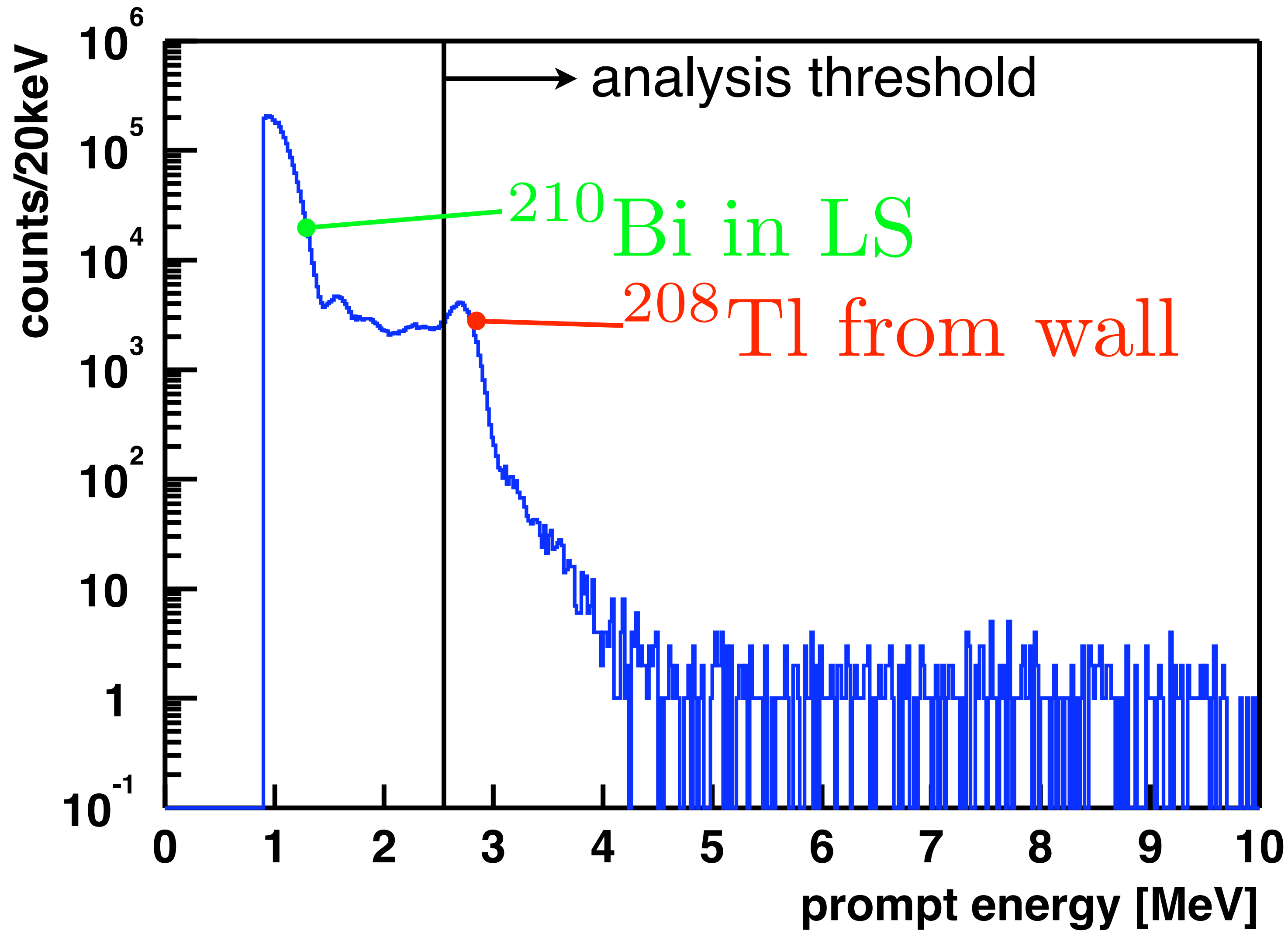


Anti-neutrino flux was 20% lower than in 1st result analysis

Backgrounds & Systematic Uncertainties

Accidental Backgrounds

Accidental prompt-delayed correlations from radioactivity (mainly on the balloon)



1st result (5m fiducial 162 ton-yr)

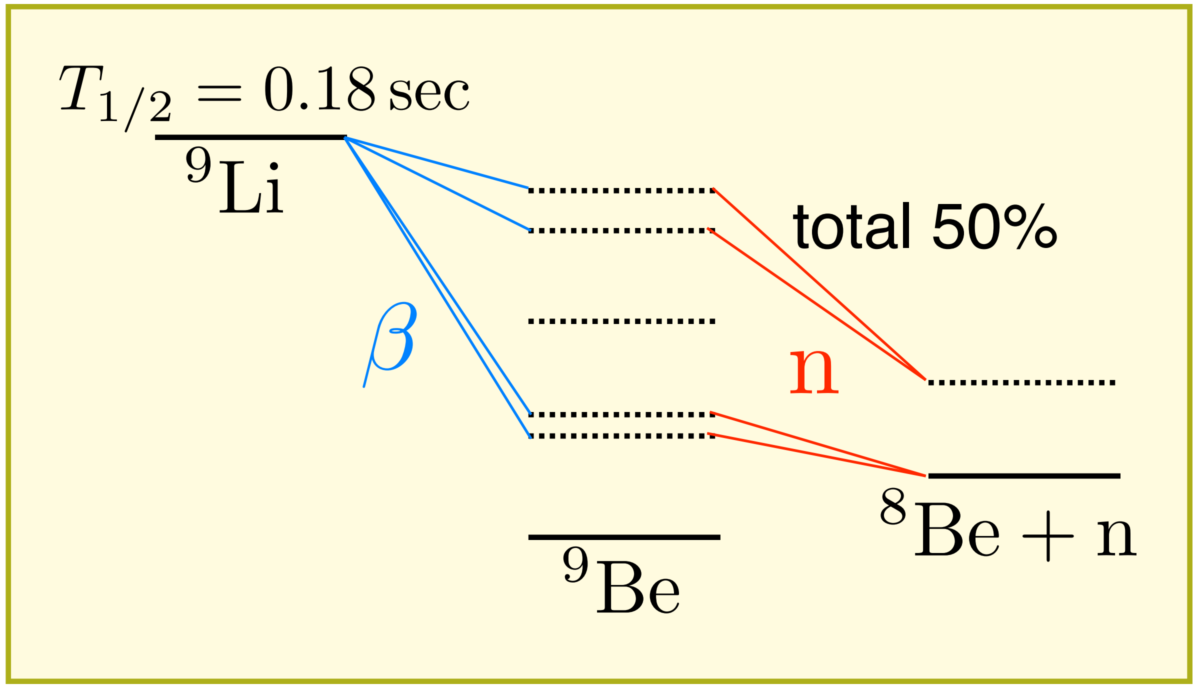
$$0.0086 \pm 0.00005$$

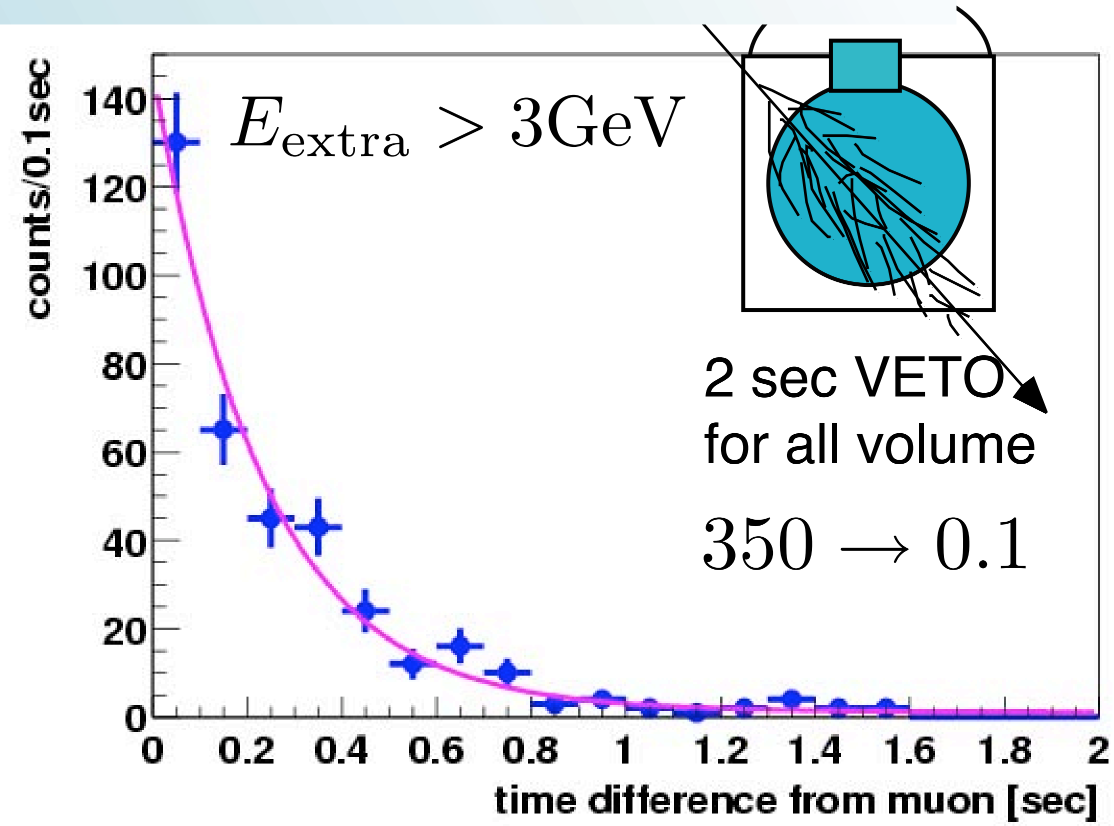
2nd results (5.5m fiducial 766.3 ton-yr)

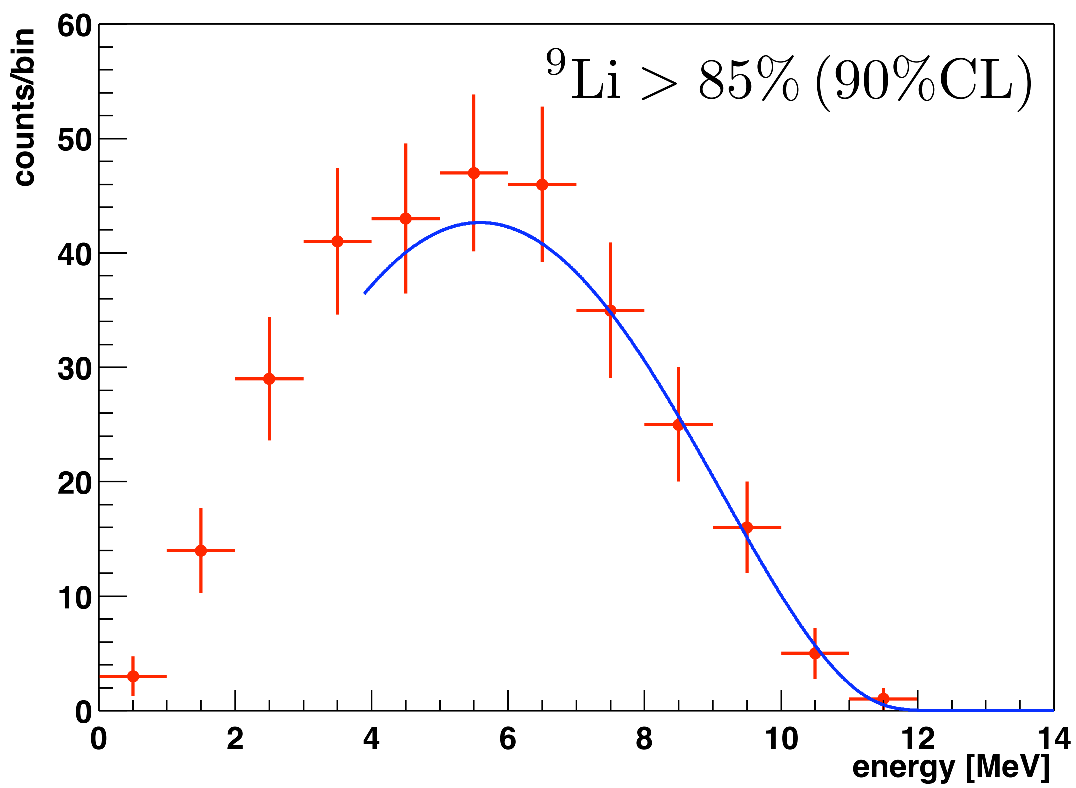
$$2.69 \pm 0.02$$

Fiducial volume is limited by accidental backgrounds.

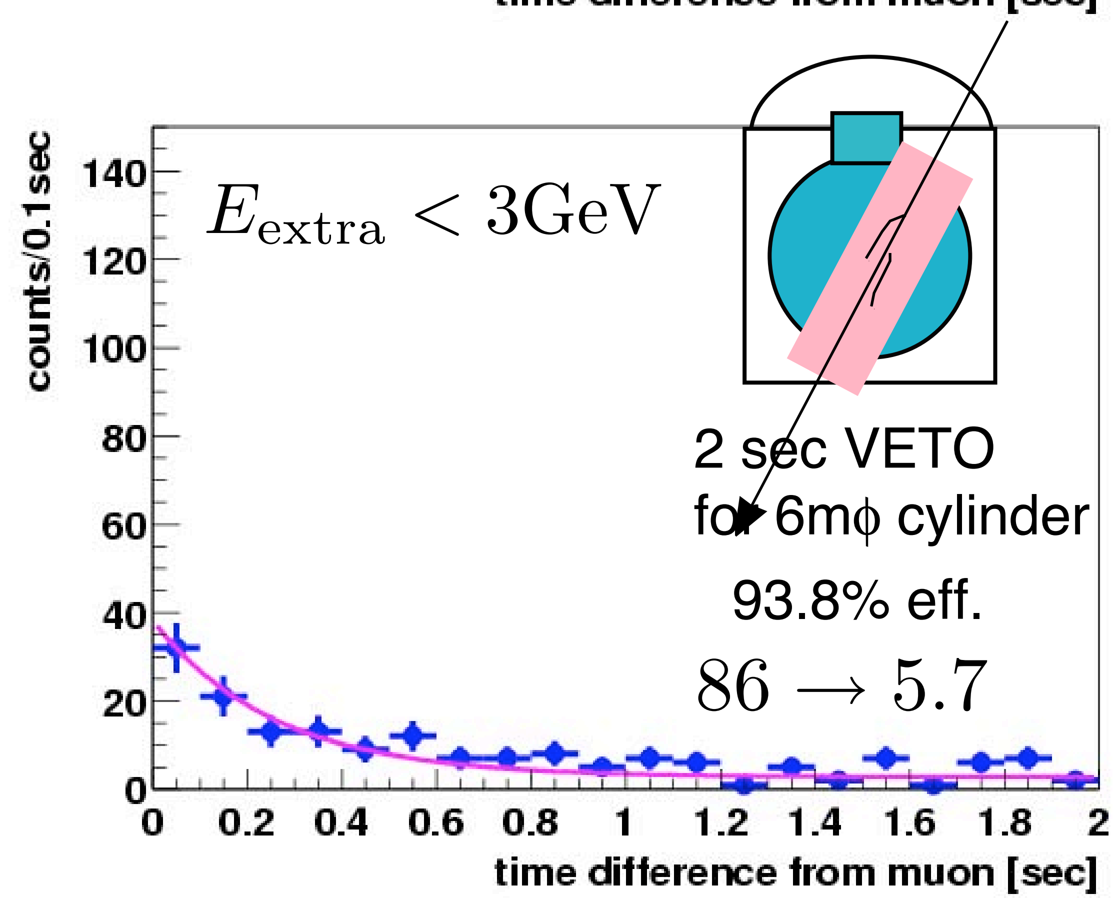
Muon Induced Spallation Events



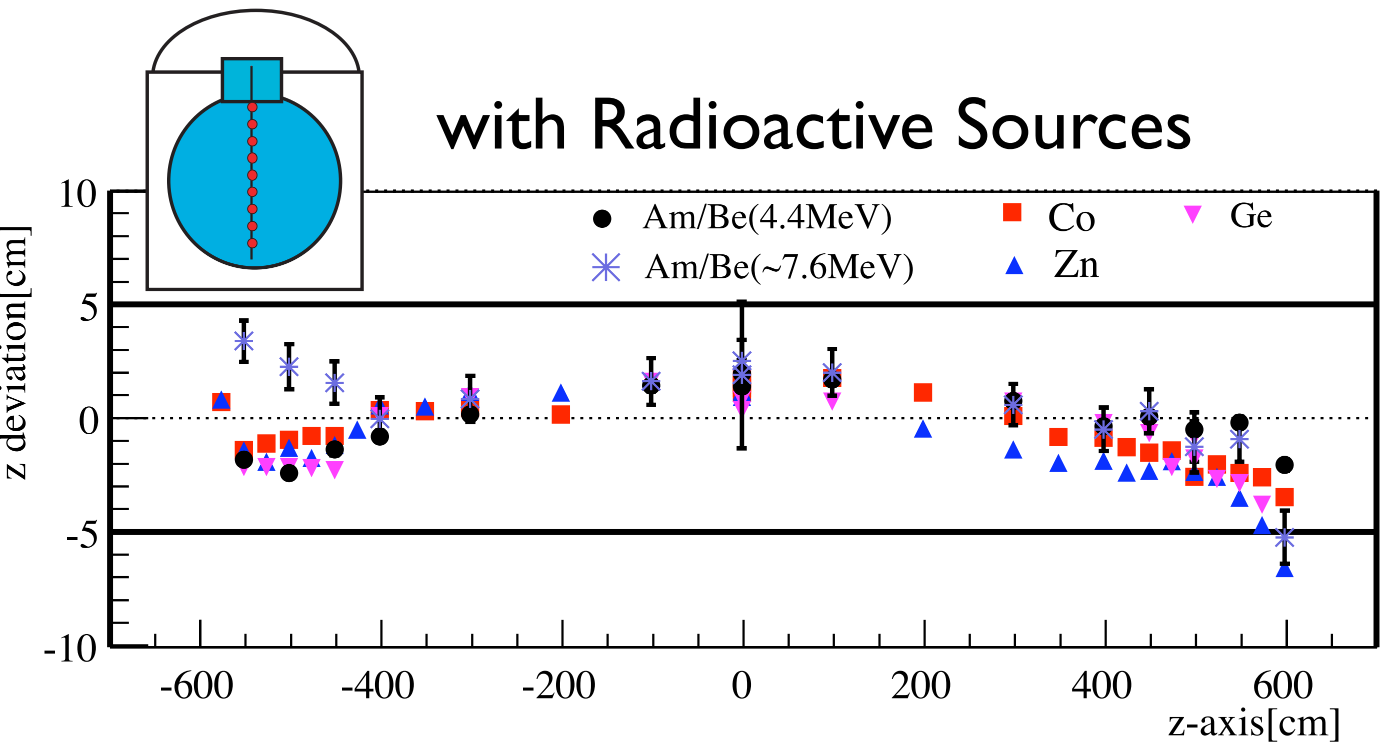


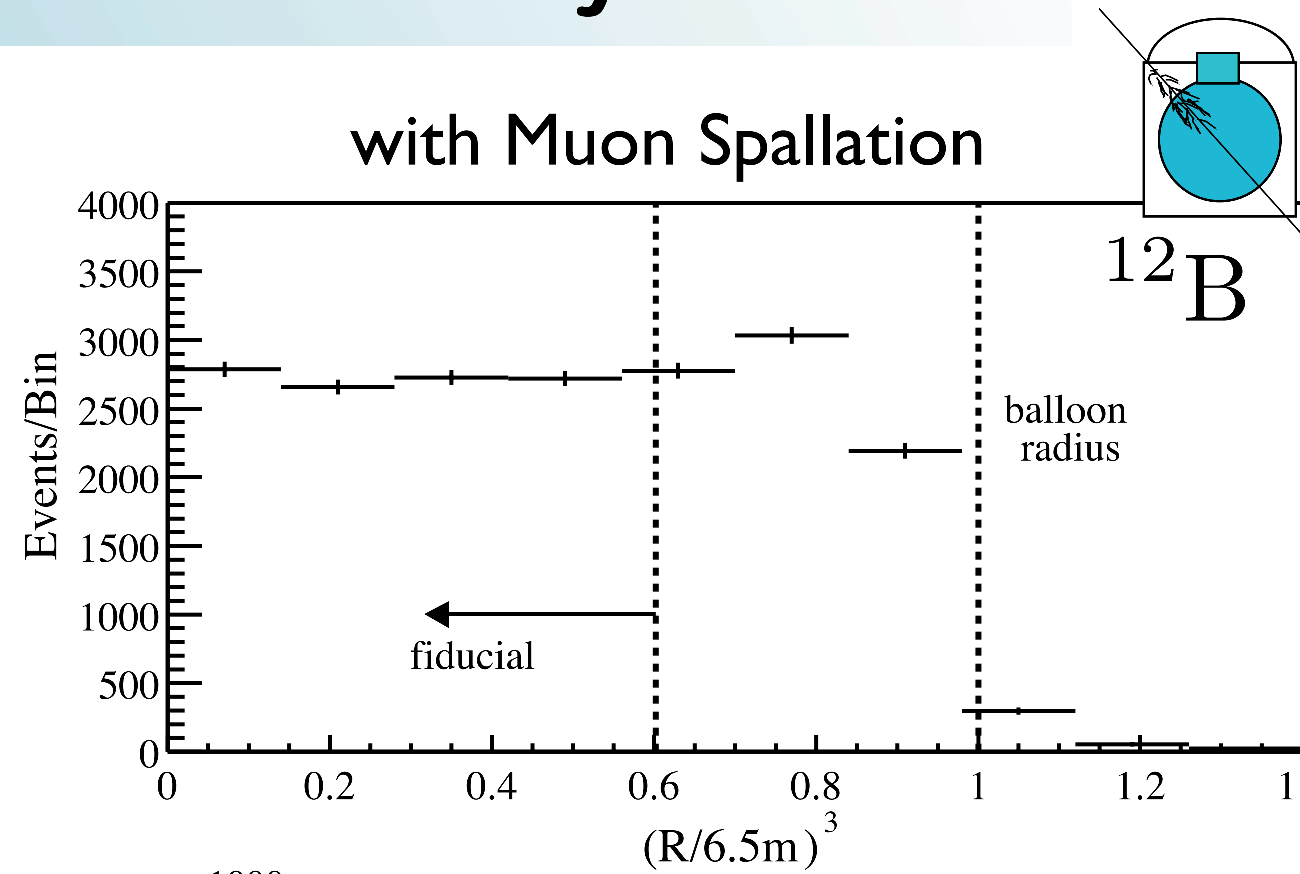


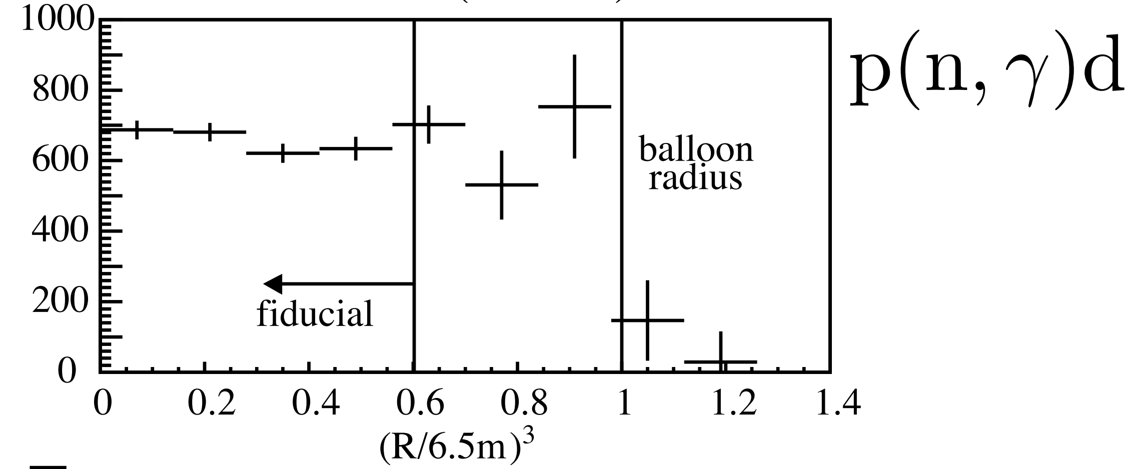
$$4.8 \pm 0.9 \text{ events } (E > 2.6\,\mathrm{MeV})$$

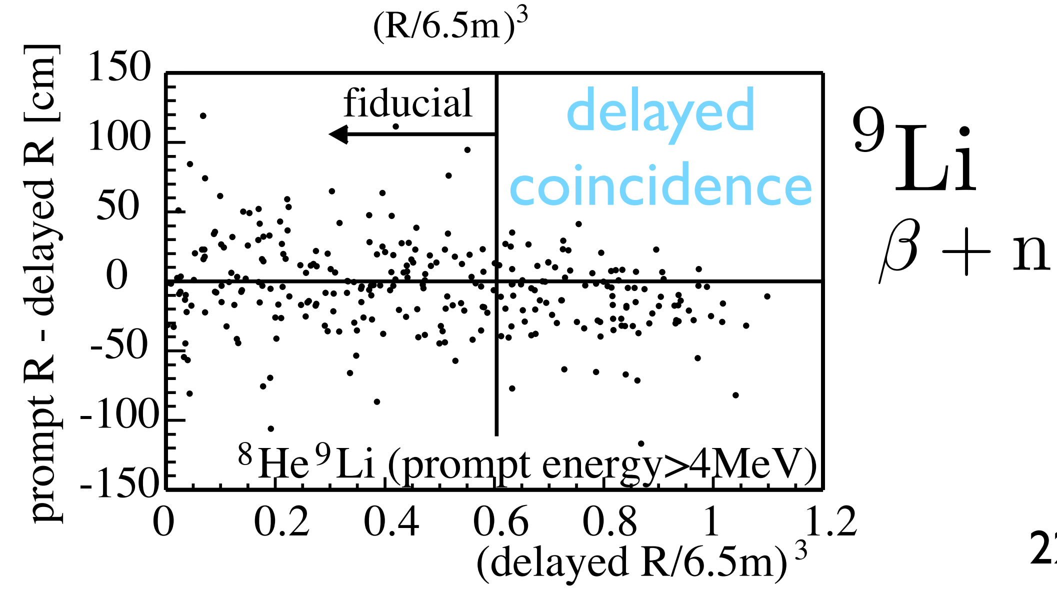


Fiducial Volume Uncertainty







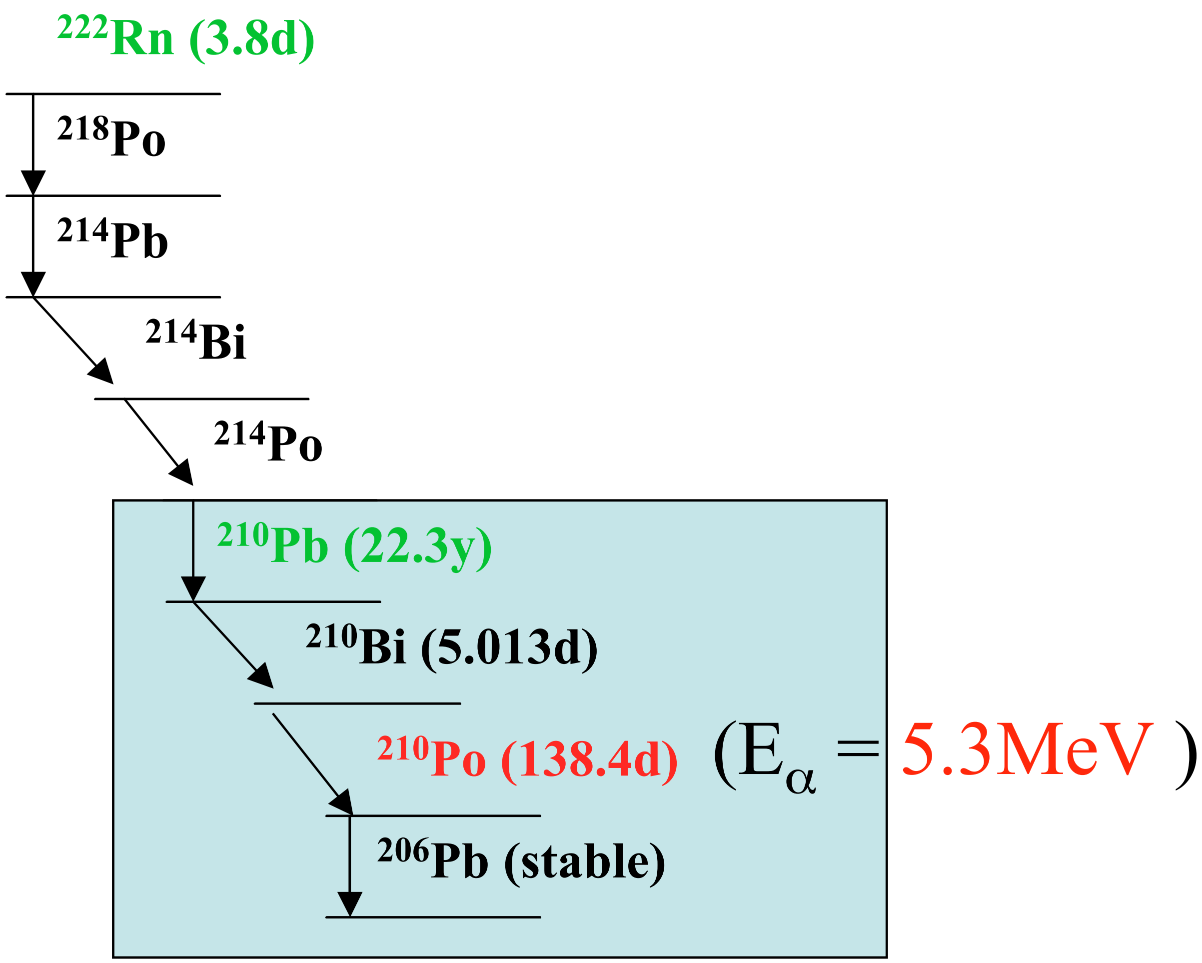


Fiducial/Total Volume Ratios

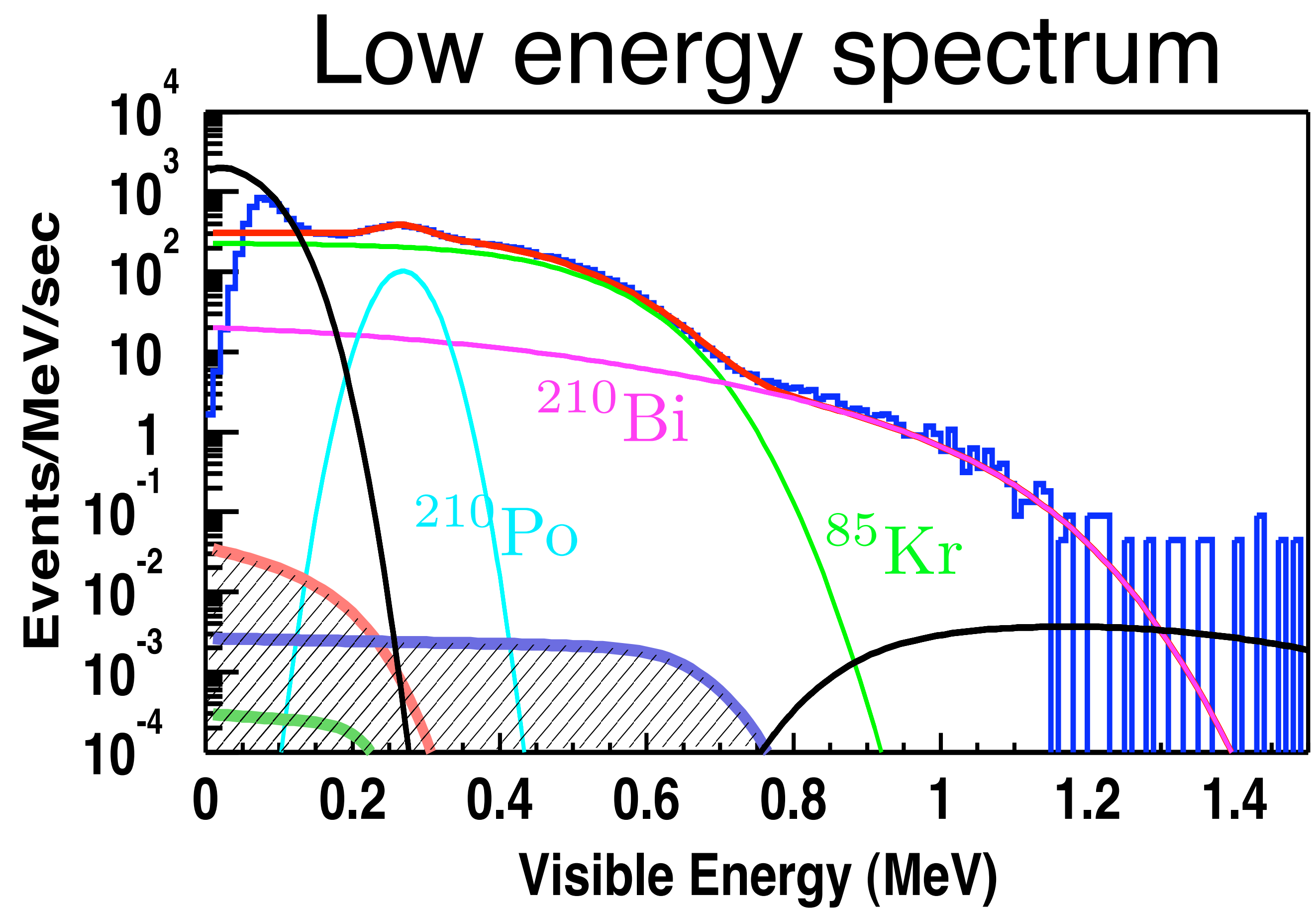
Geometrical	0.595 ± 0.013 $\left(= \frac{696.9\,\mathrm{m}^3}{1171 \pm 25\,\mathrm{m}^3}\right)$
$^{12}\mathrm{B}$	$0.607 \pm 0.006 \pm 0.006$
$\mathrm{p(n,\gamma)d}$	0.587 ± 0.013
$^{9}\mathrm{Li}$ relative	$< 2.7\%$

Fiducial Volume uncertainty 4.7%

(α,n) Background



equilibrium



$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O(g.s.)}$	low energy
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O(g.s.)}$ $\rightarrow^{12}\mathrm{C}(\mathrm{n},\mathrm{n}\gamma)^{12}\mathrm{C}$	~4.4 MeV
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}^*(6.13)$ $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}^*(6.05)$	~6 MeV

$$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O} \qquad P \sim 10^{-8}$$

1.1% abundance (measured)

10.6 events (E>2.6MeV)

Summary of Cuts

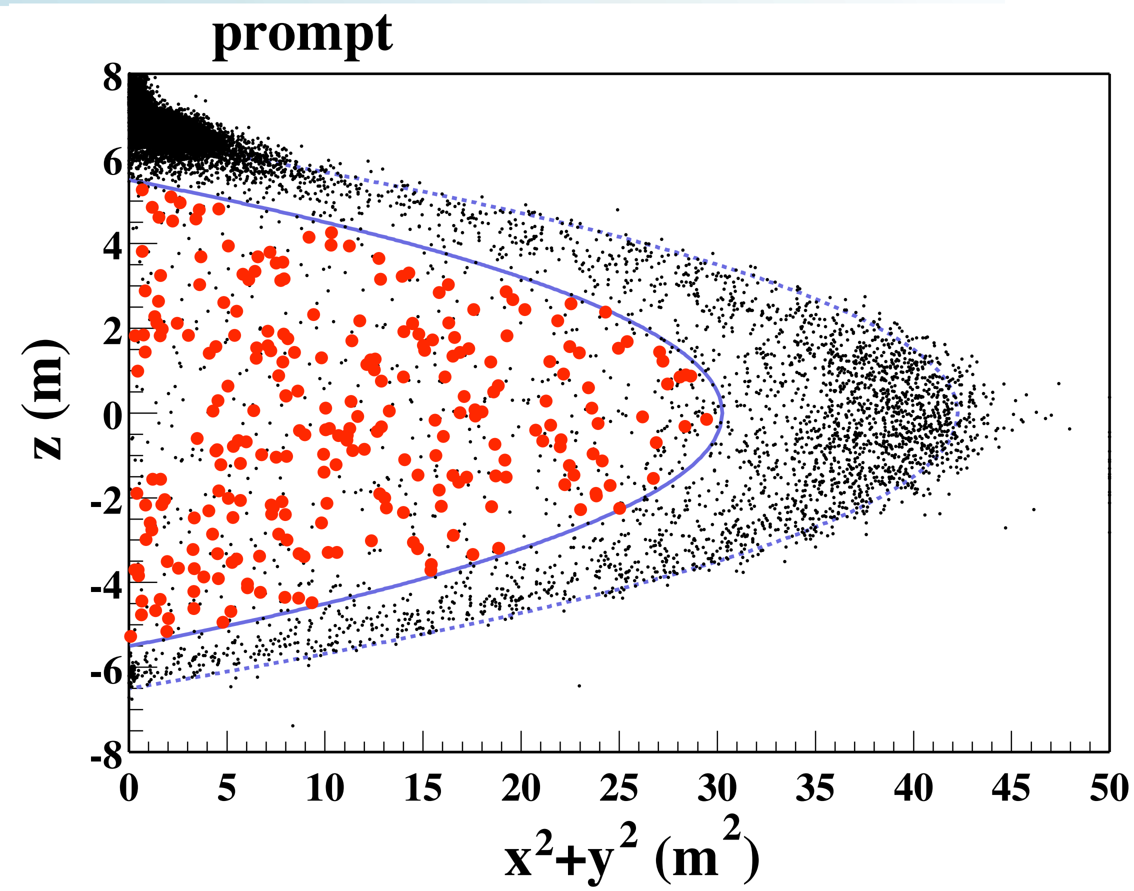
Inverse beta-decay selection:

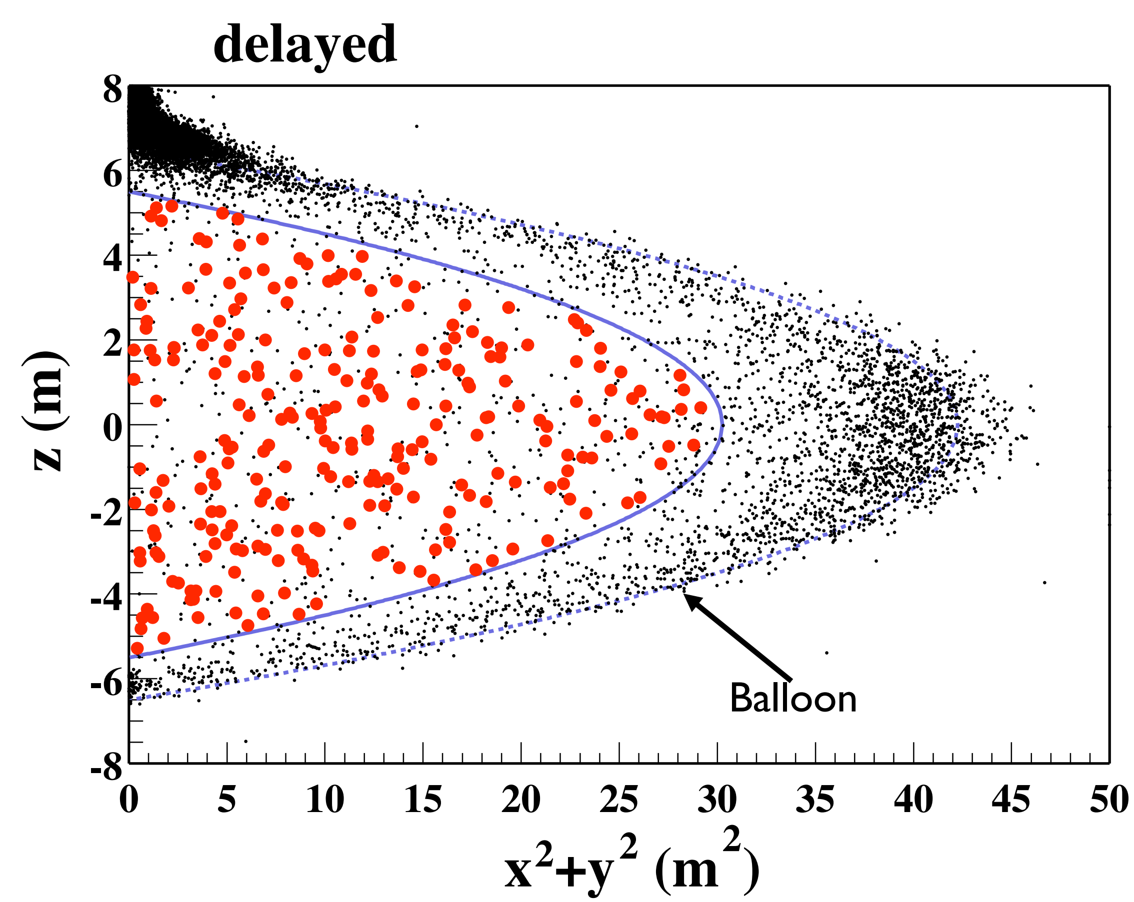
- $R_{prompt, delayed} < 5.5$ m
- $\Delta R < 2$ m
- $0.5\ \mu s < \Delta T < 1000\ \mu s$
- 1.8 MeV $< E_{delayed} < 2.6$ MeV
- 2.6 MeV $< E_{prompt} < 8.5$ MeV

Tagging efficiency 89.8%

- Muon-induced spallation event cuts:
  - 2 ms veto after every μ
  - 2 s veto for showering/bad μ
  - 2 s veto in a R = 3m tube along track

Dead time 9.7%





Systematic Uncertainties

Uncertainty	%
Fiducial volume	4.7
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.1
Reactor thermal power	2.1
Fuel composition	1.0
Antineutrino spectra	2.5
Cross section	0.2
Total uncertainty	6.5

} Future improvements

Results

2nd result

Data Summary

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure
×4.7 exposure (×3.55 live time, ×1.33 fiducial)

expected signal	365.2 ± 23.7
BG	17.8 ± 7.3
observed	258

Neutrino disappearance at 99.998% CL.

$R = 0.658 \pm 0.044(stat) \pm 0.047(syst)$

$R = 0.601 \pm 0.069(stat) \pm 0.042(syst)$
for Mar to Oct 2002
is consistent with first results

KamLAND collaboration, hep-ex/0406035;
coming out in the March 4, 2005 PRL issue

Caveat: ratio does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

1st result

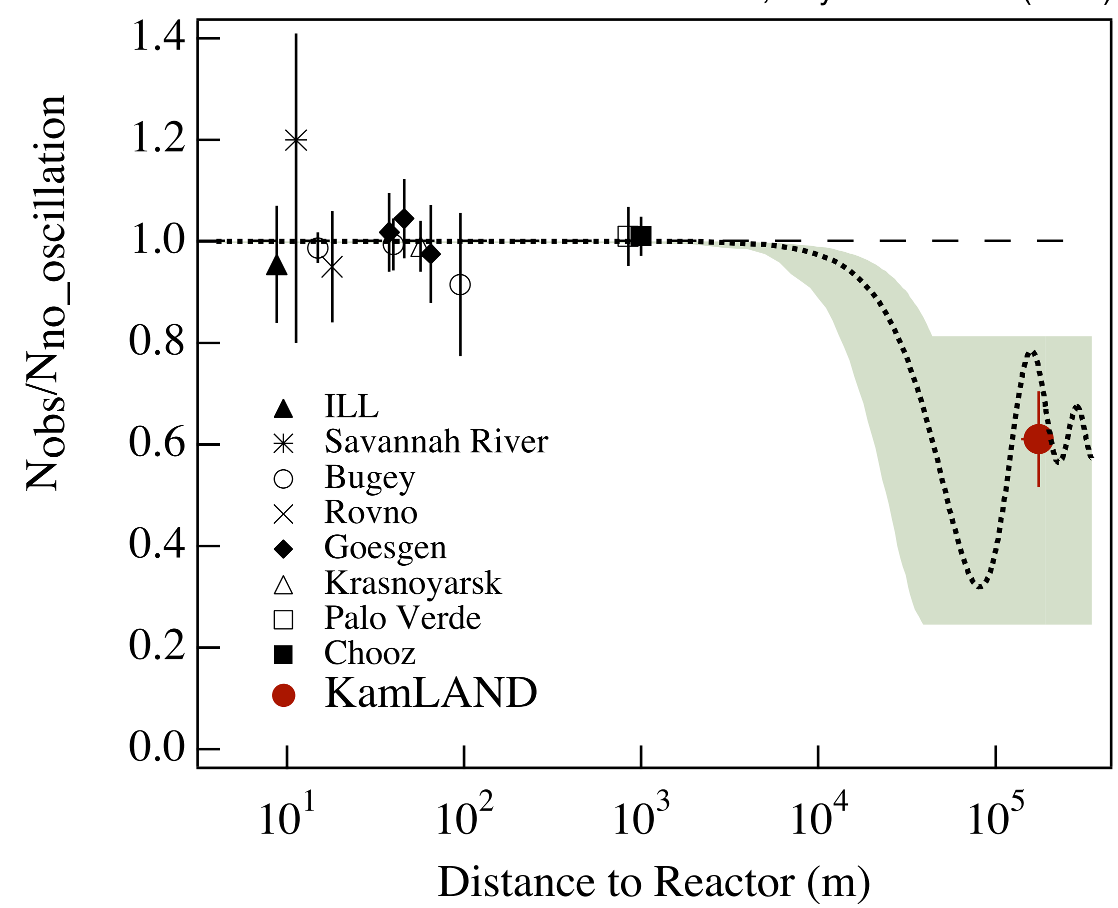
Data Summary

from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

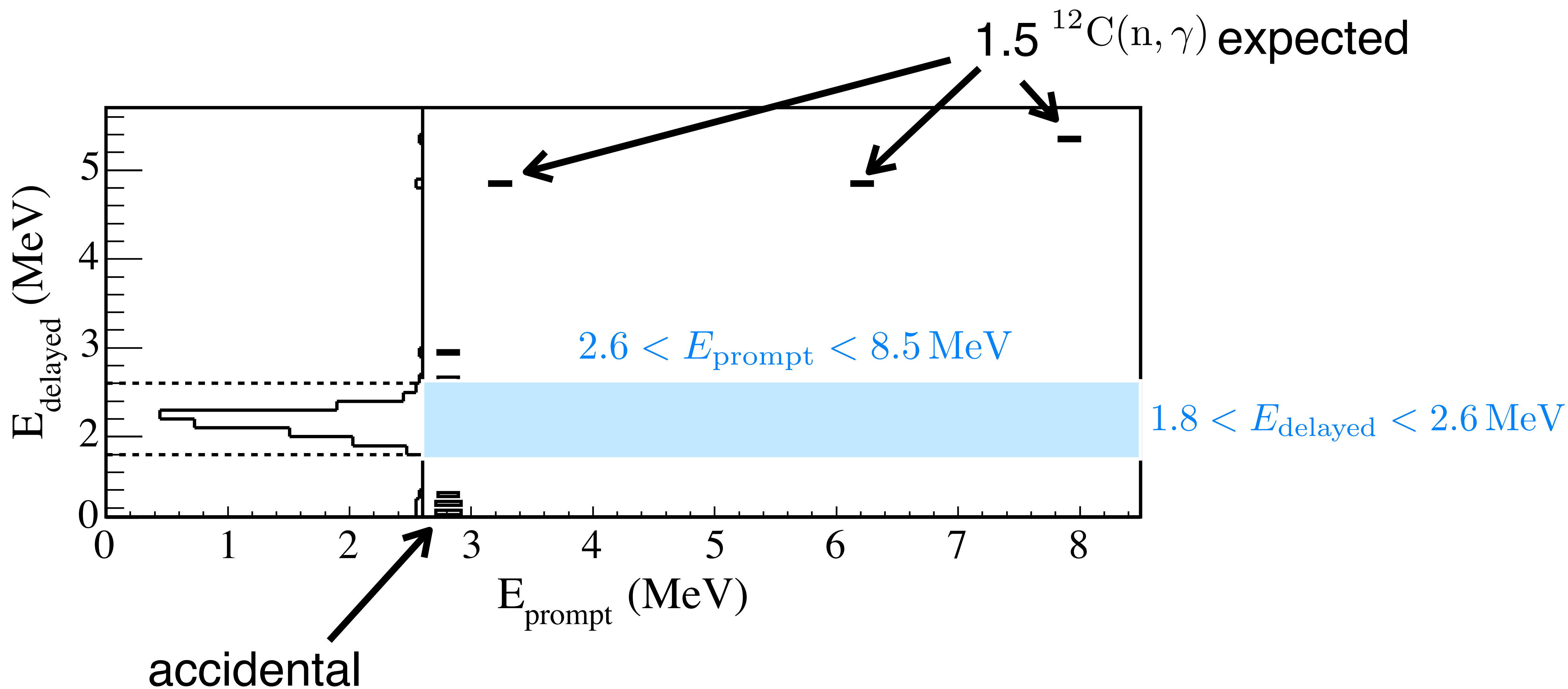
expected signal	86.8 ± 5.6
BG	1 ± 1
observed	54

Neutrino disappearance at 99.95% CL.
$R = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$

KamLAND collaboration, Phys.Rev.Lett.90(2003)021802

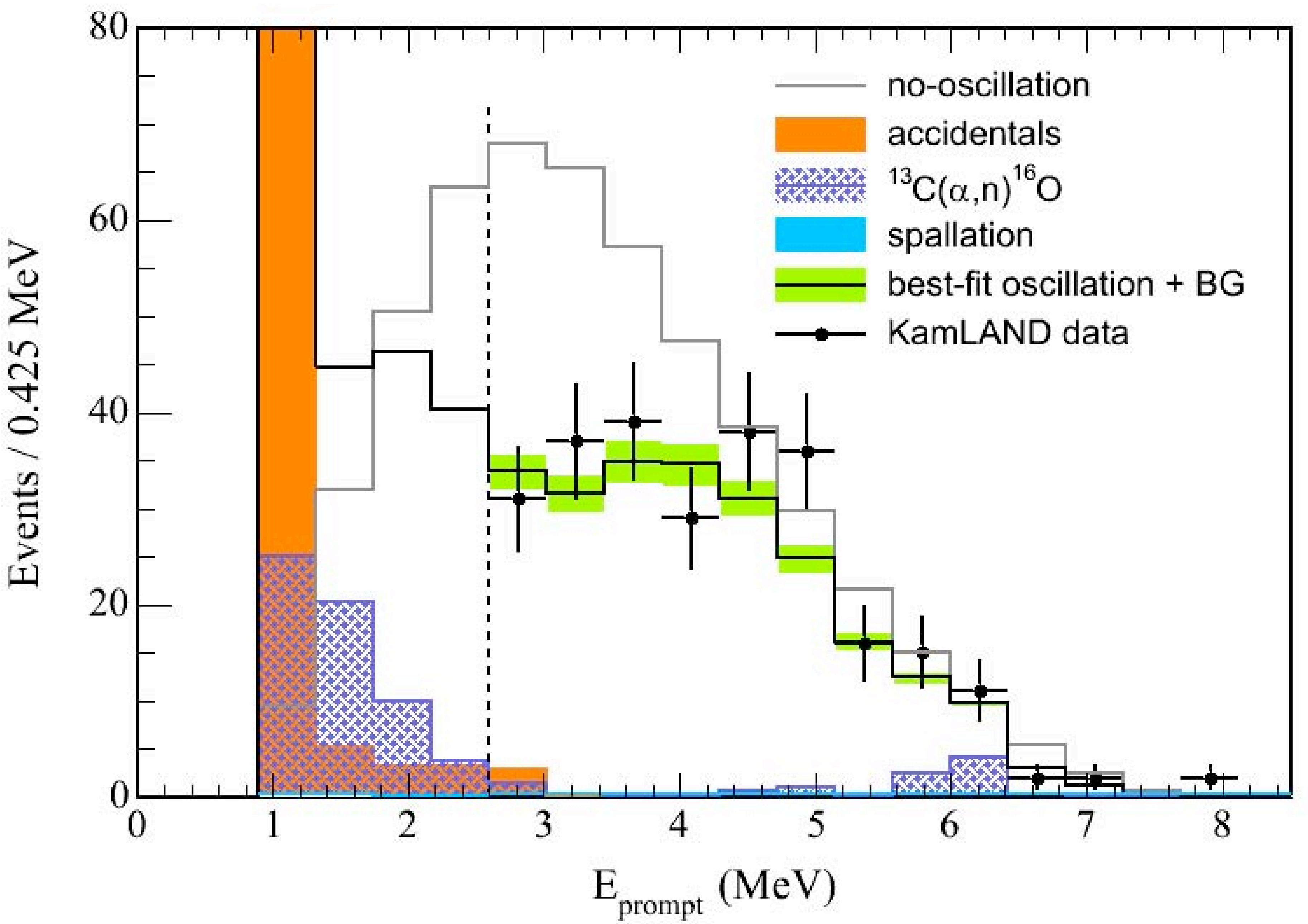


Delayed Coincidence



Clear delayed coincidence events

Energy Spectrum



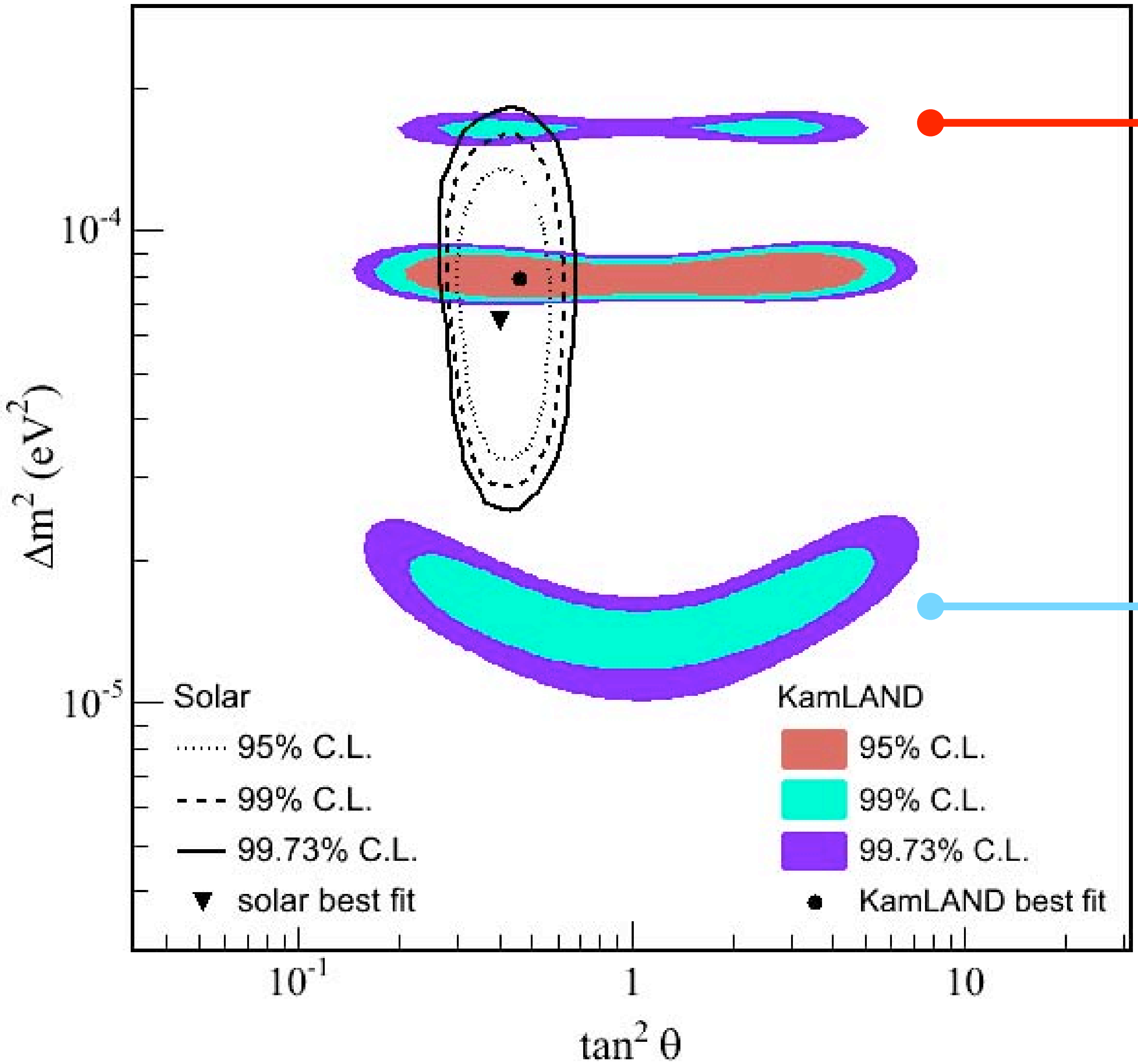
Best-fit oscillation:

$\tan^2\theta = 0.46$

$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$

A fit to a simple rescaled reactor spectrum is excluded at 99.6% CL

Unbinned Likelihood: 2 nu Oscillation



LMA2 is excluded at 98.0%

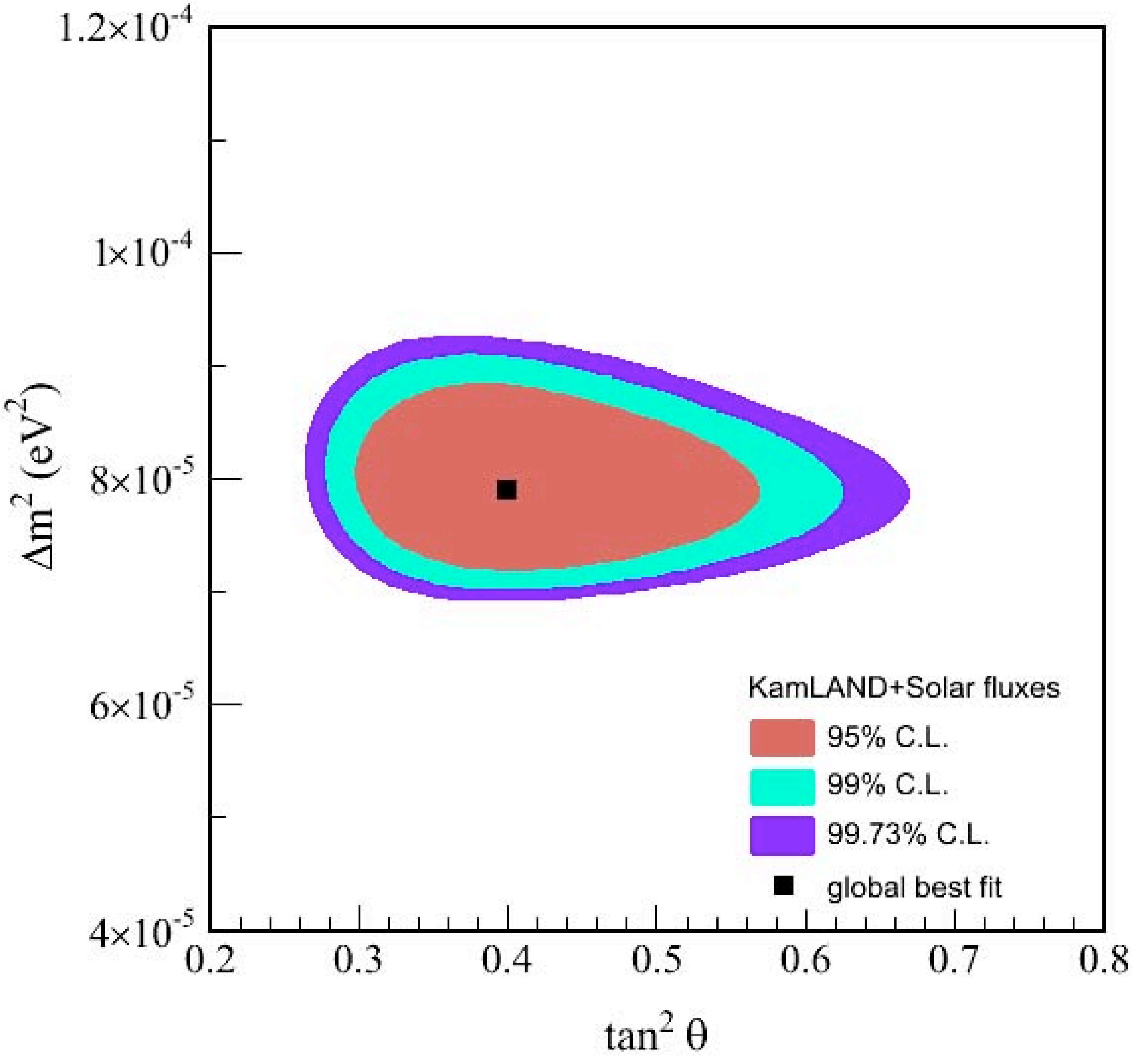
$$\tan^2\theta = 0.46$$
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

LMA0 is excluded at 97.5%

Global Analysis

Solar Experiments are sensitive to θ

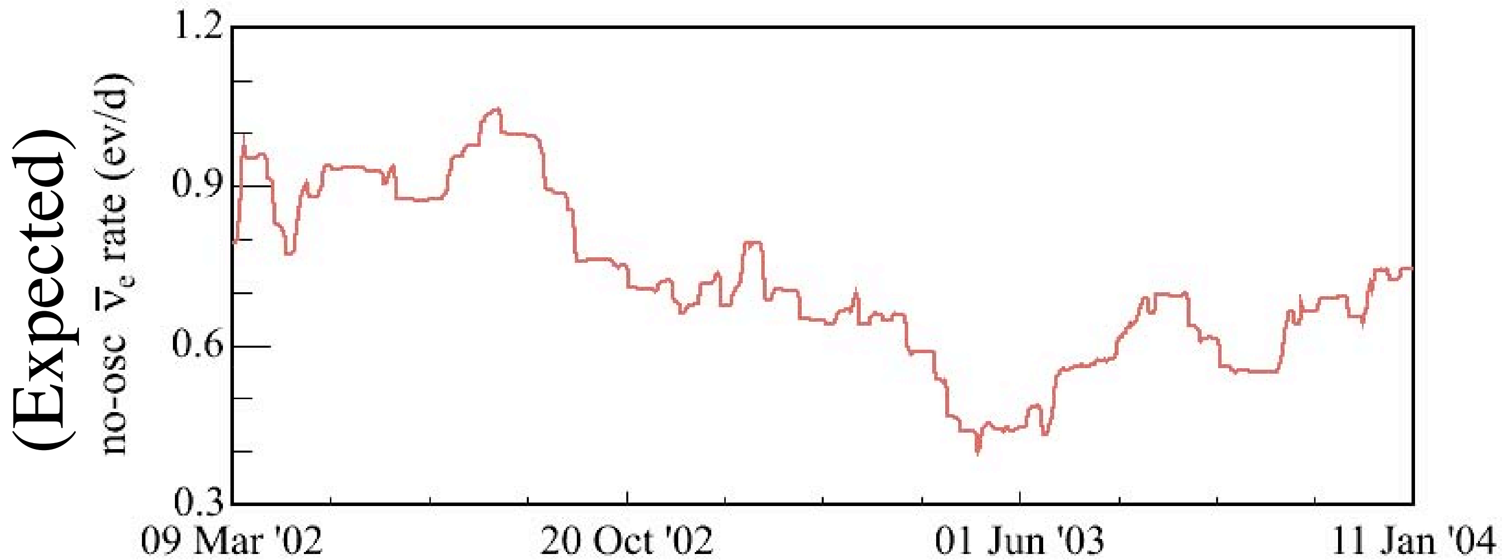
KamLAND is most sensitive to Δm^2



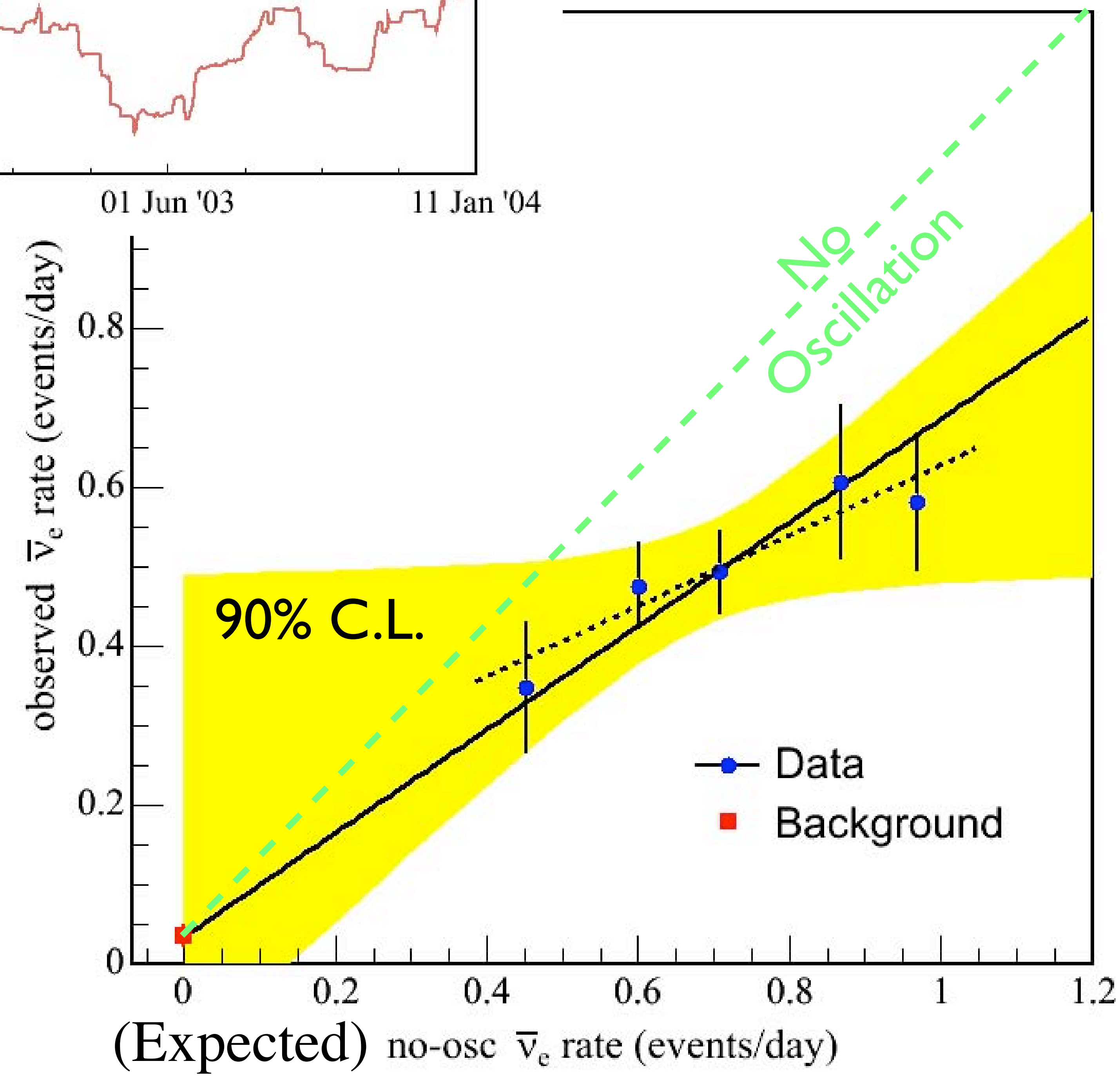
$$\tan^2\theta = 0.40^{+0.10}_{-0.07}$$
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

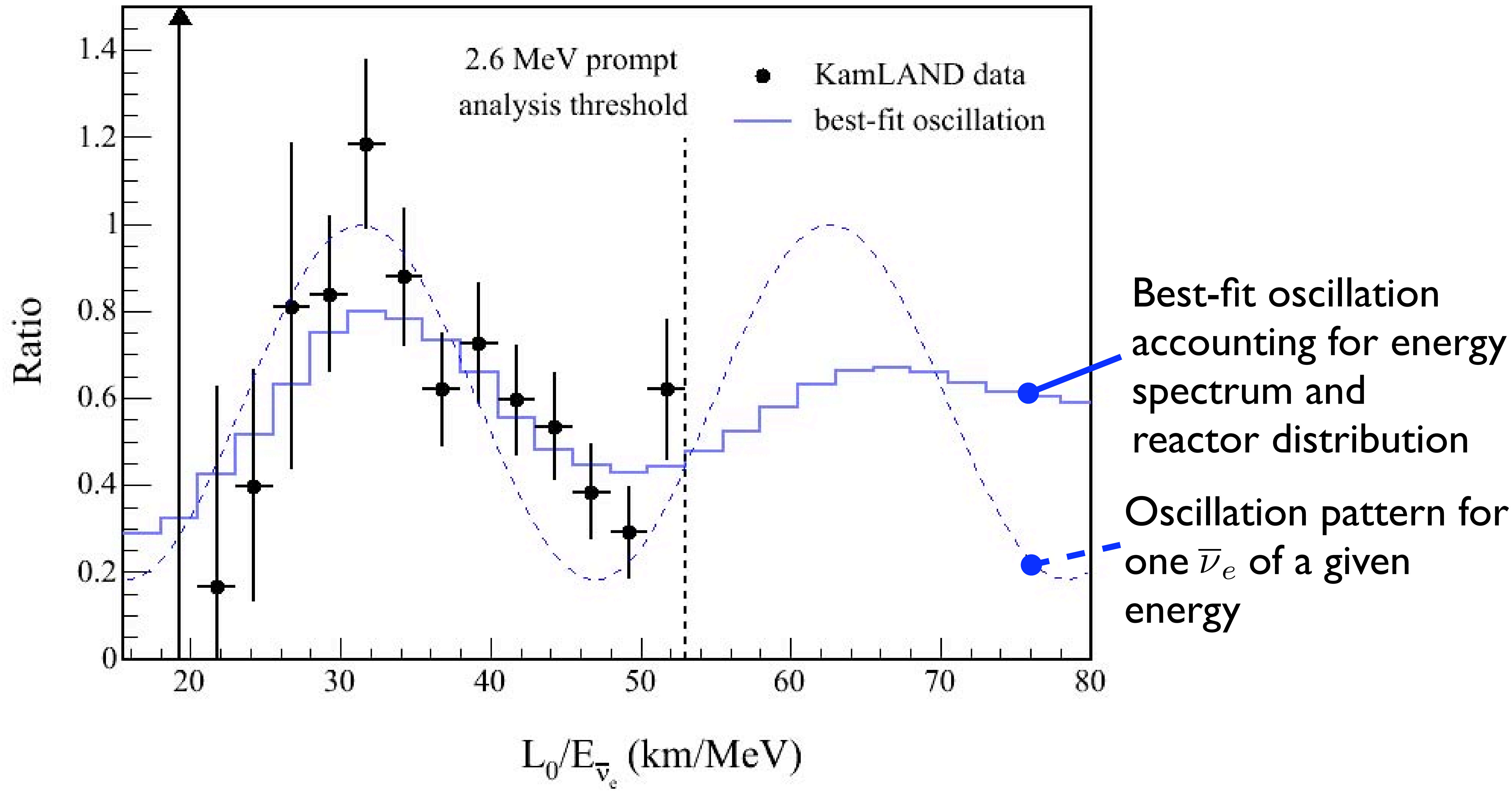
Most precise until the SNO results this morning....

Correlation with Reactor Power



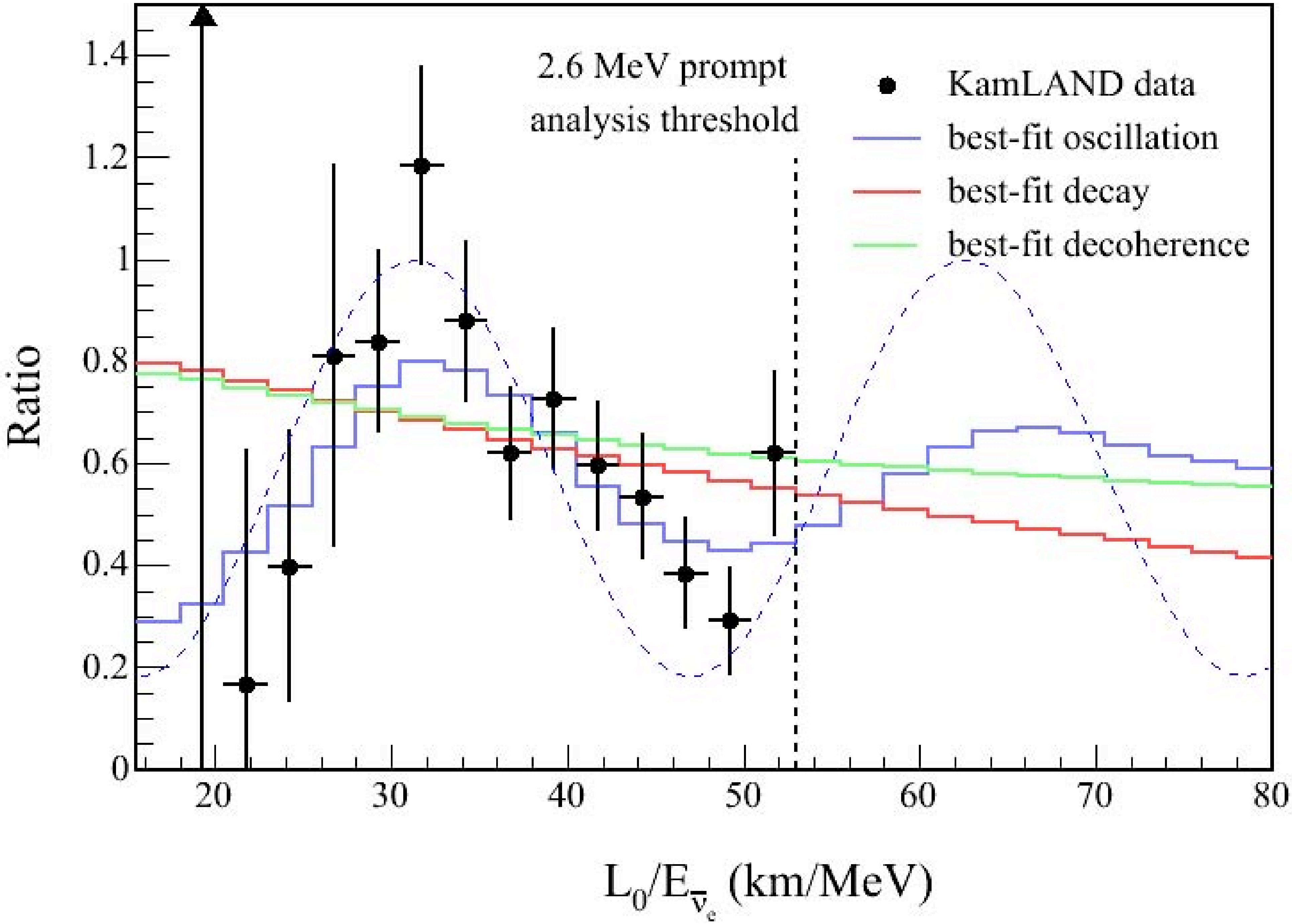
Current statistics not enough to make firm statements on correlation





Ratio of measured to expected spectrum

$$P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$$



Test alternative neutrino disappearance scenarios

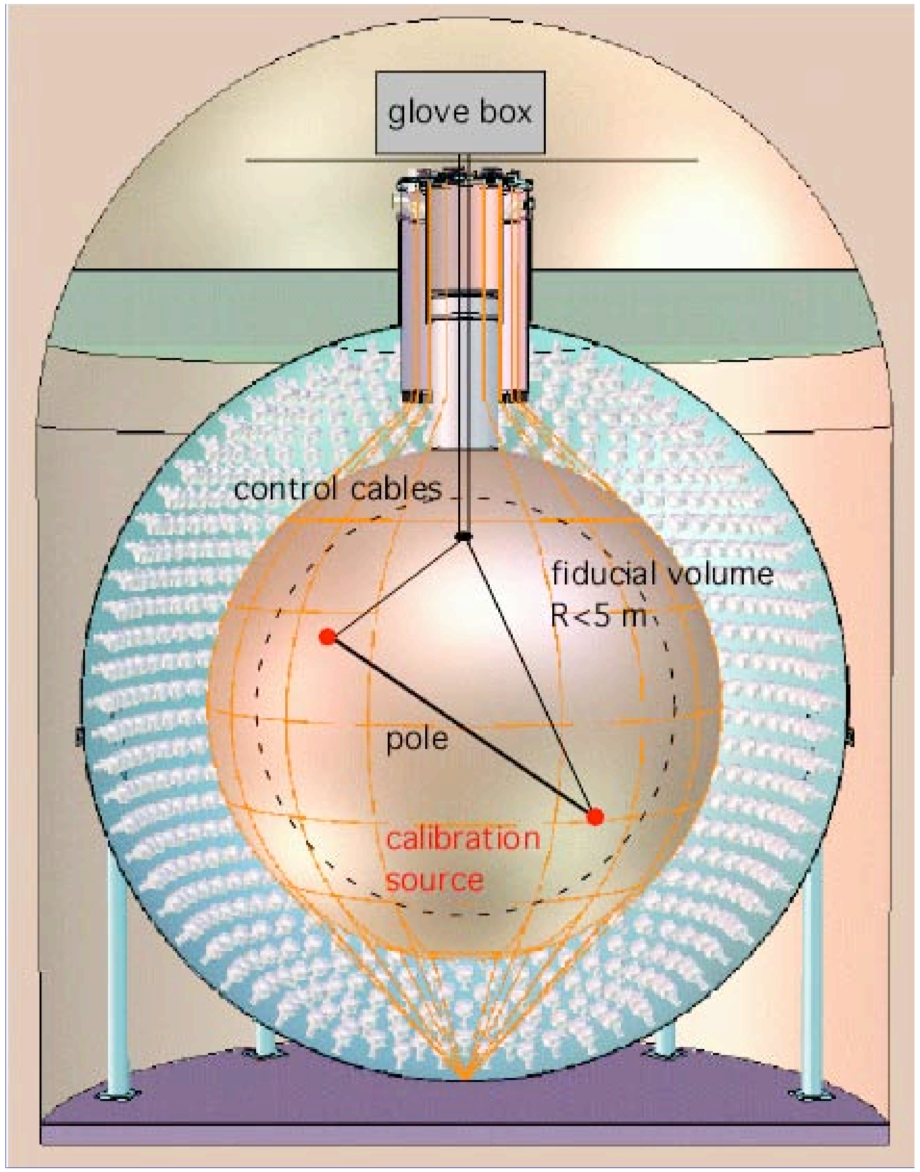
oscillation	$P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$
decay	$P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$
decoherence	$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$

V.D.Bager et al., PRL82 (1999) 2640.

E.Lisi et al., PRL85 (2000) 1166.

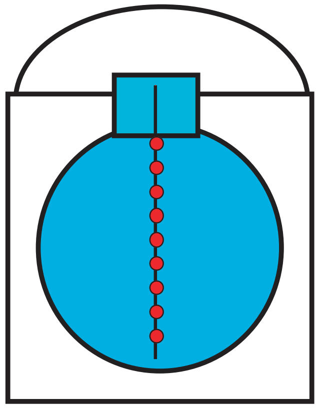
Future activities at KamLAND

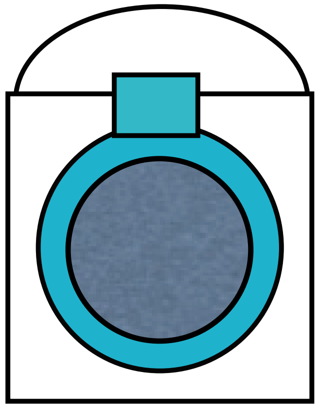
Future Improvements



z-axis calibration

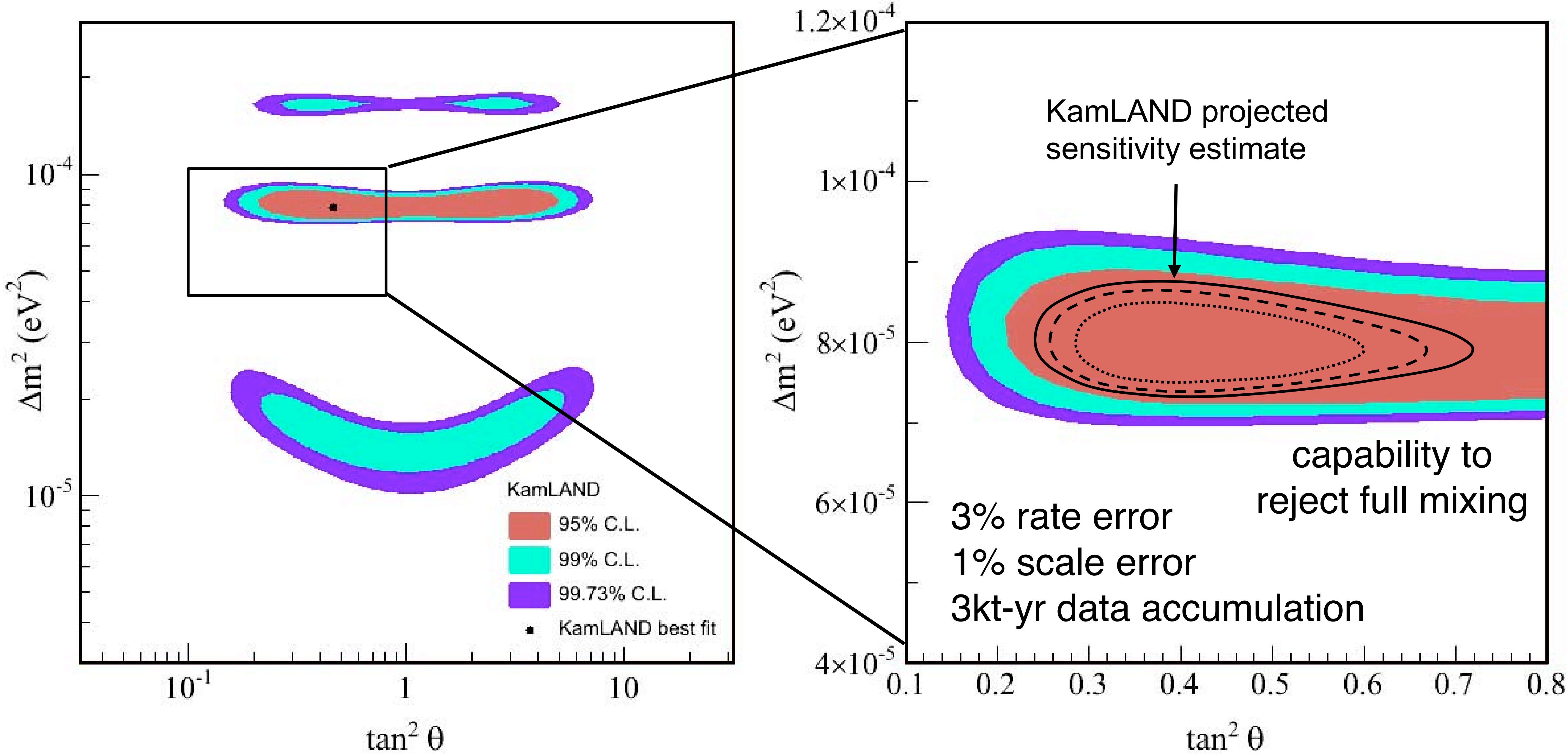
full volume calibration



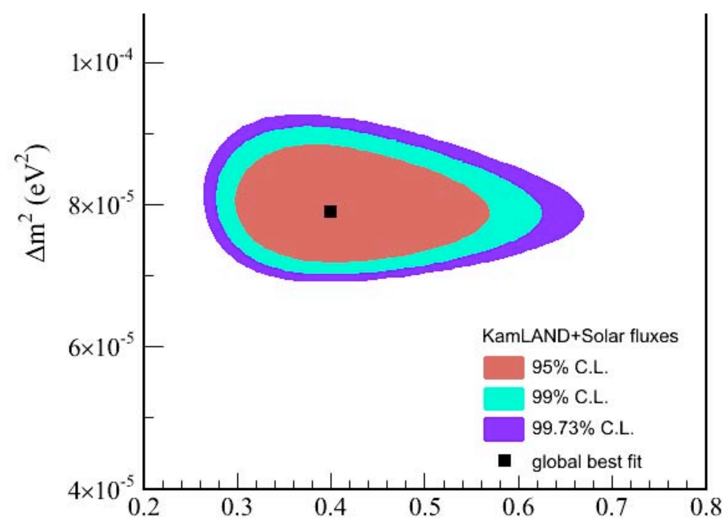


Reduce Fiducial Volume and Energy Uncertainty

KamLAND Future Sensitivity

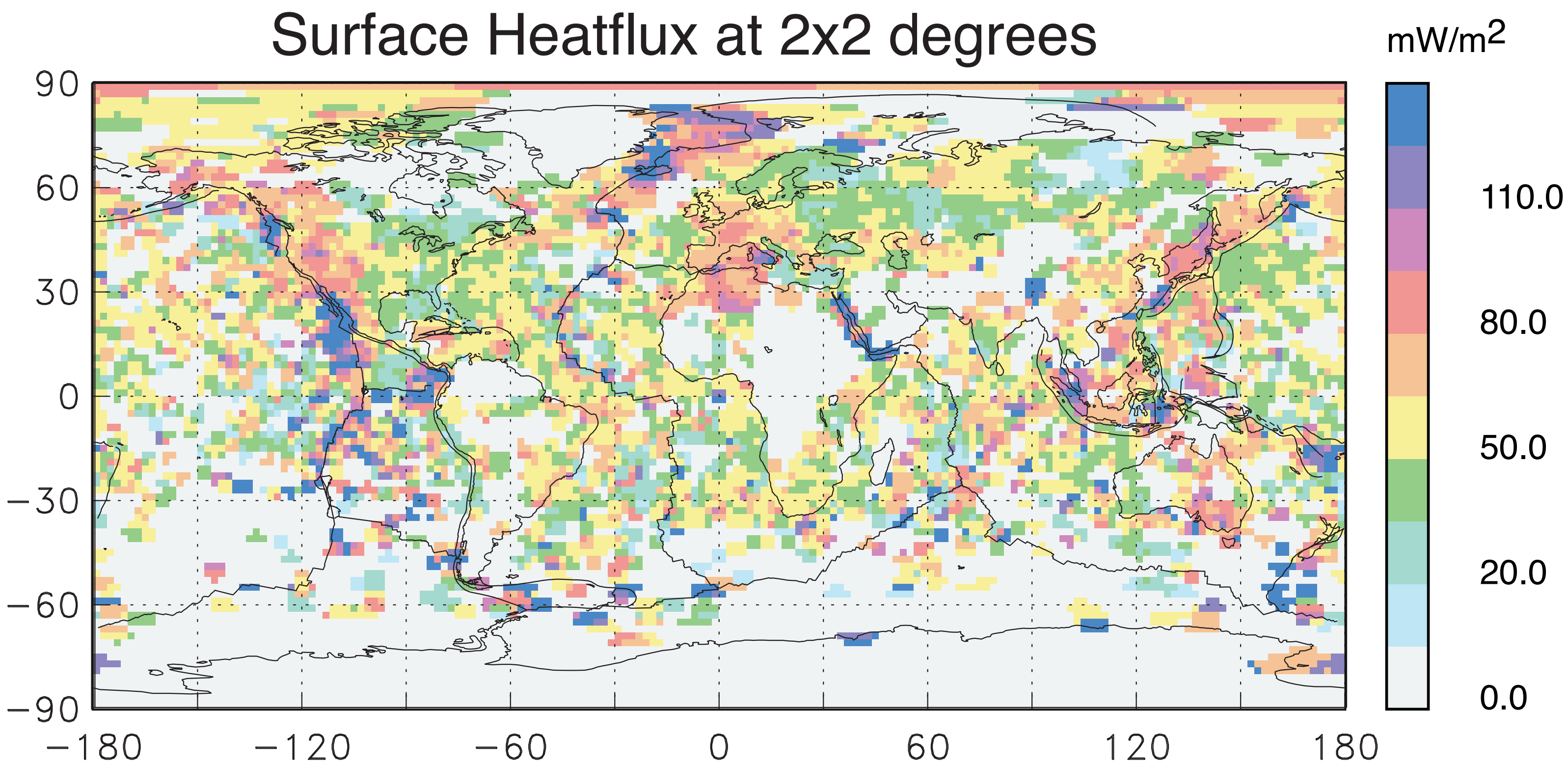


Mixing angle determination
comparable with current solar data



Looking for the source of the Earth's heat

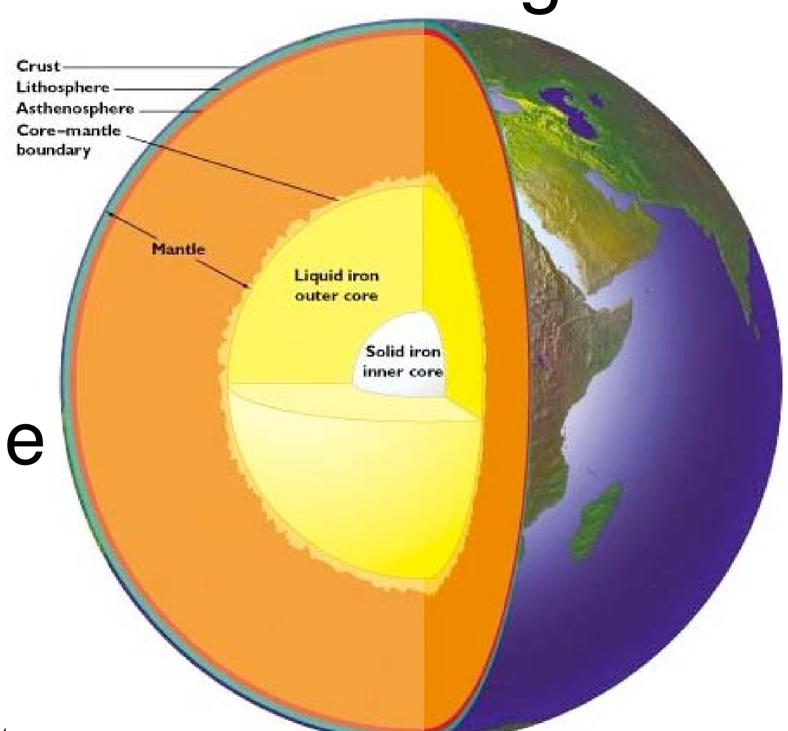
Surface heat flux measurements



Total flow of 44 TW is 40 times larger than total world reactor power.

Combining all the available geo-chemical knowledge:

U,Th are condensed in the crust



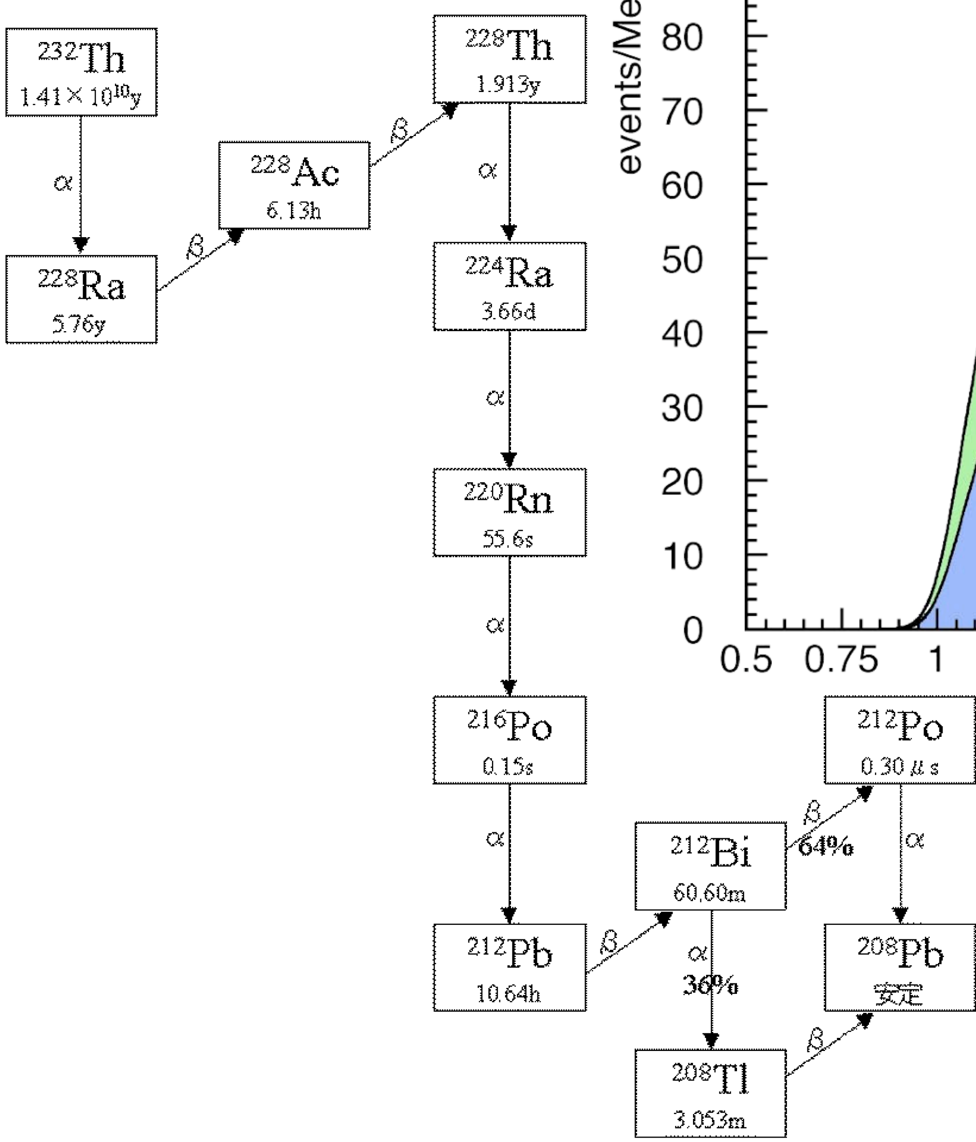
Radioactivity 20 TW

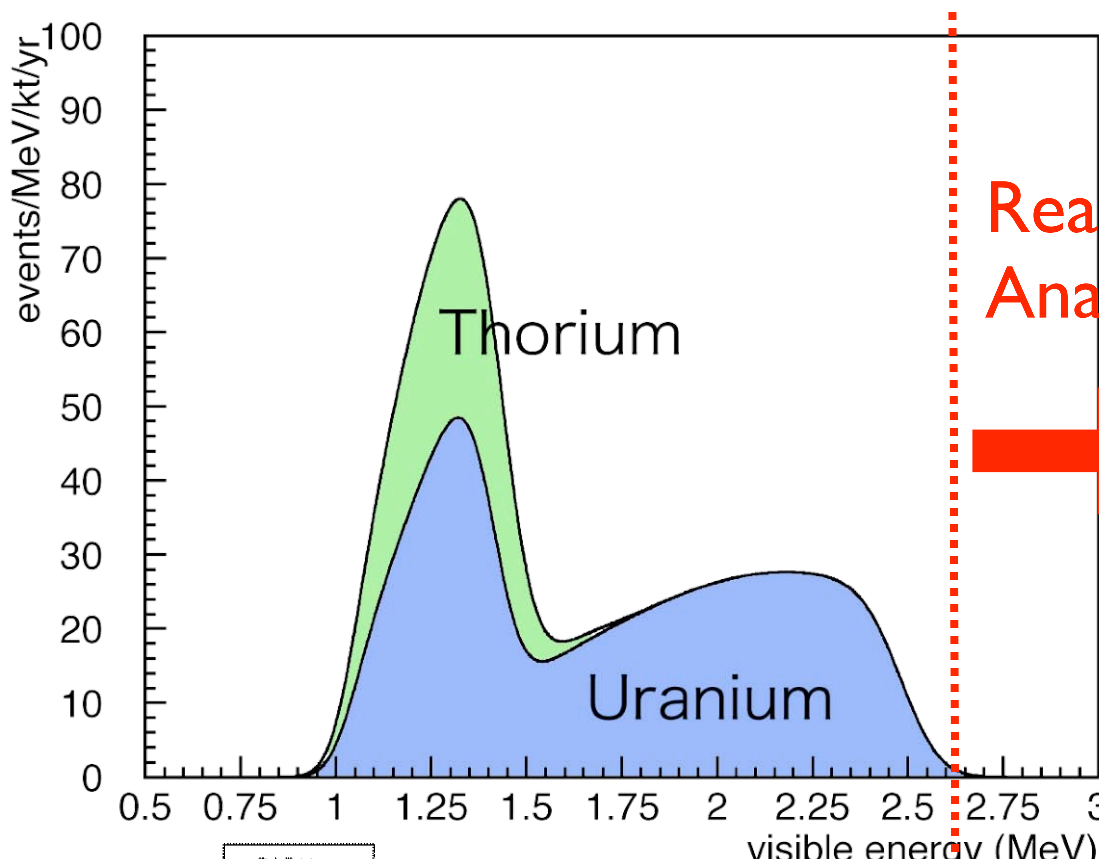
Uranium 8TW, Thorium 8TW,

Potassium 4TW

Neutrinos from radioactivity provide direct information on the earth's interior

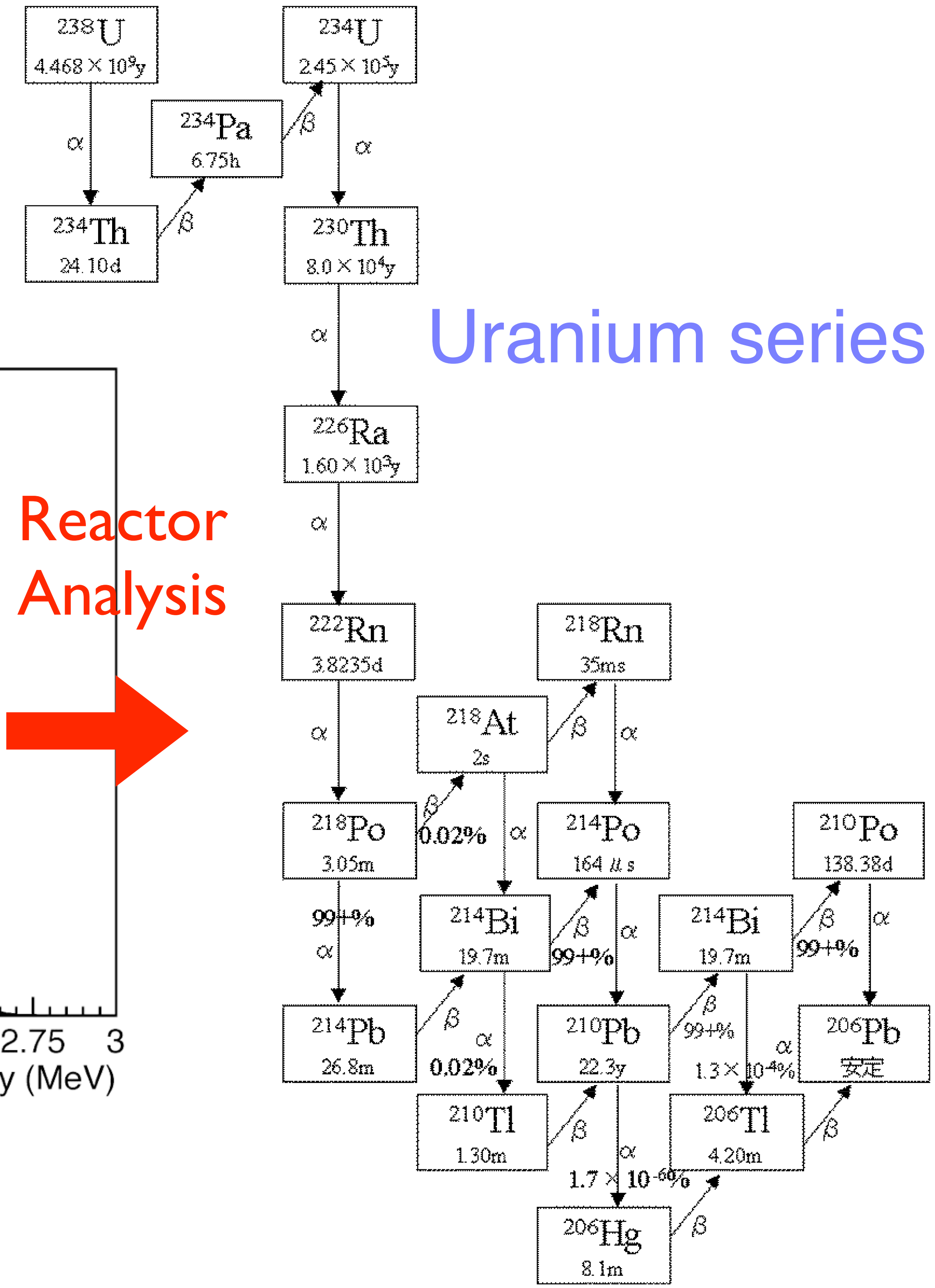
Thorium series





Reactor Analysis

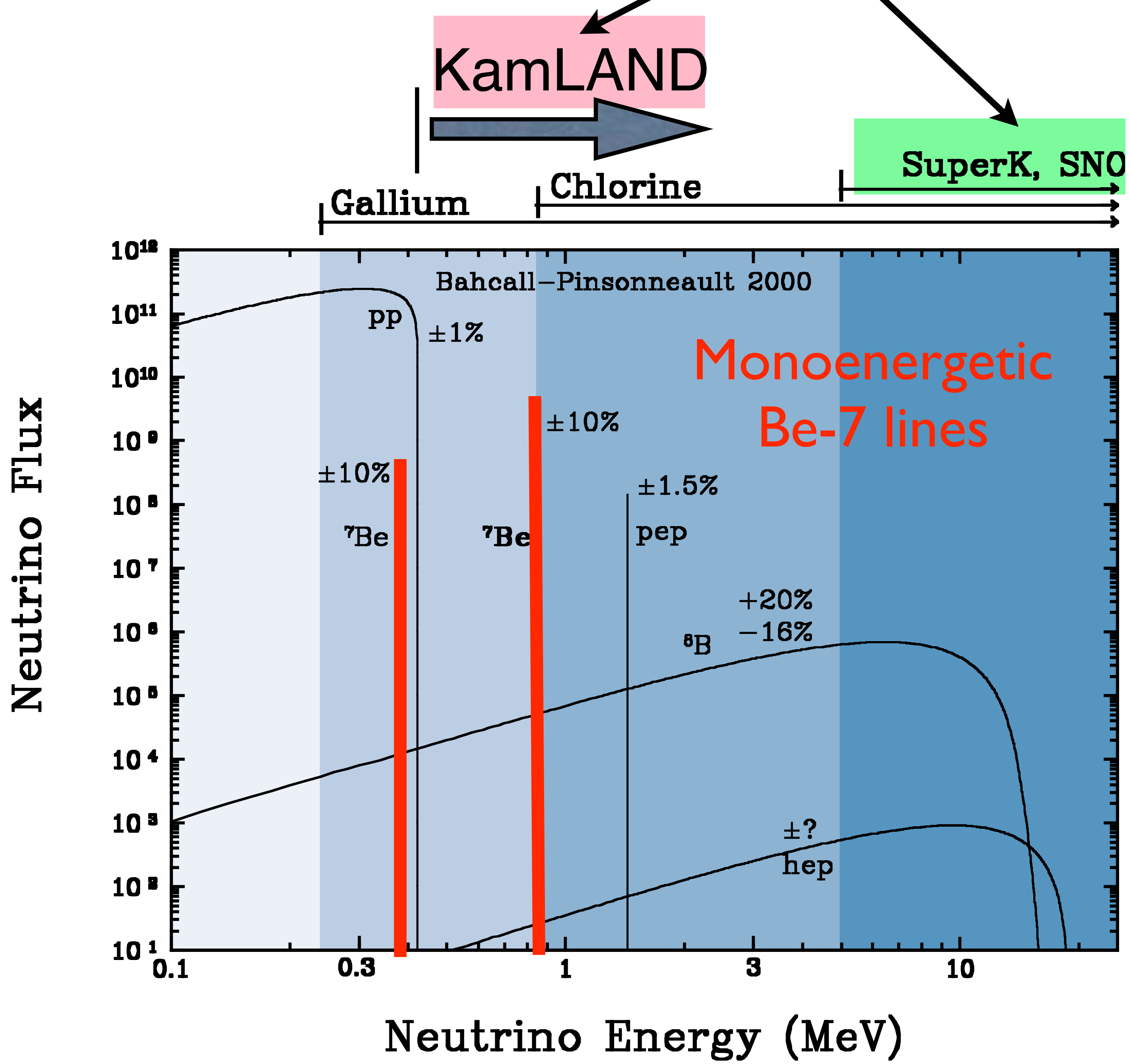
Uranium series



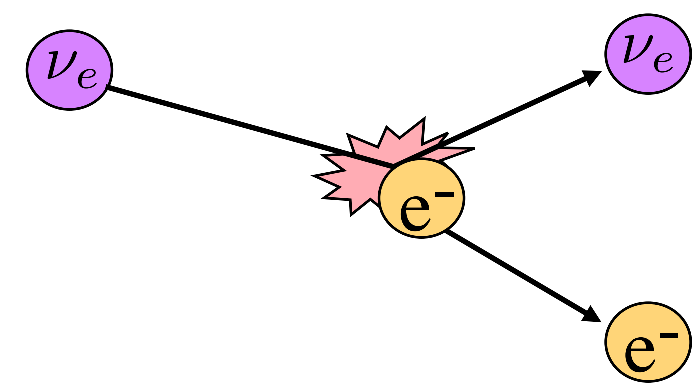
Analyzing data E< 2.6MeV, analysis forthcoming

Solar Be-7 Measurement

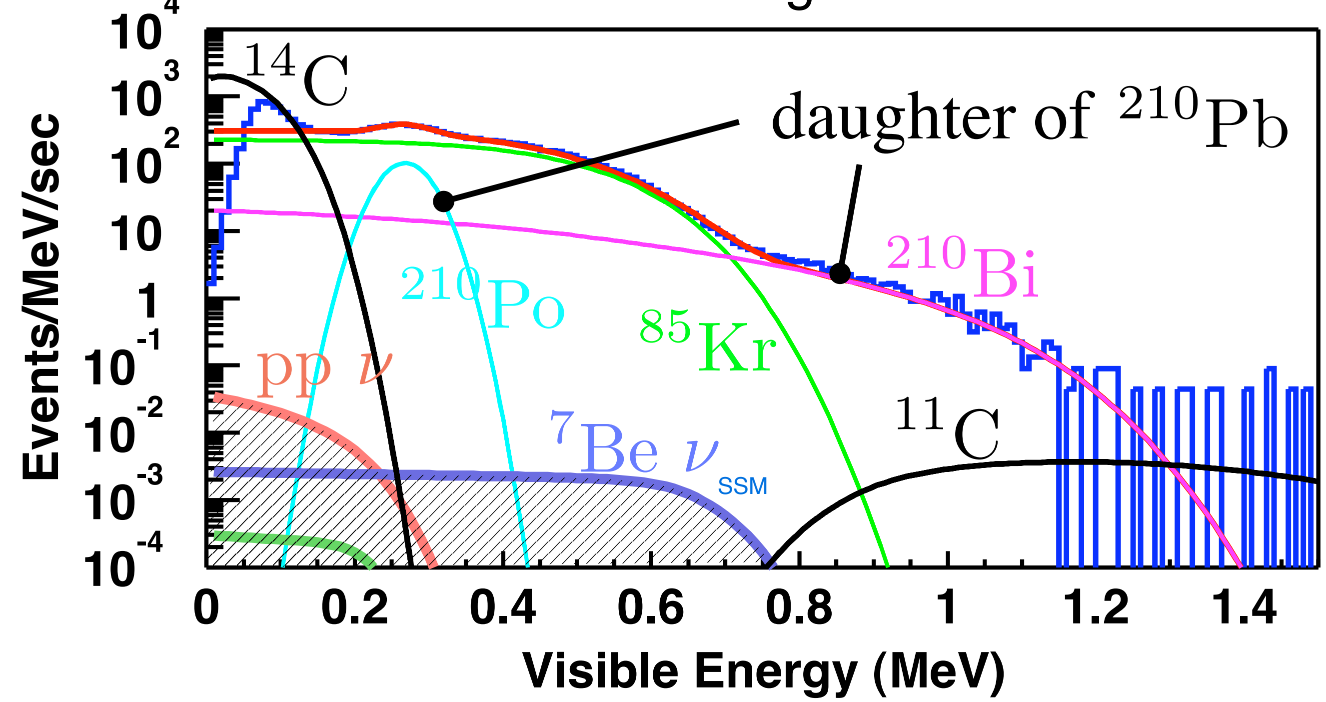
Real time measurements



Detect through elastic scattering:



Current background level



Measuring Theta13

The MNSP neutrino mixing matrix:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

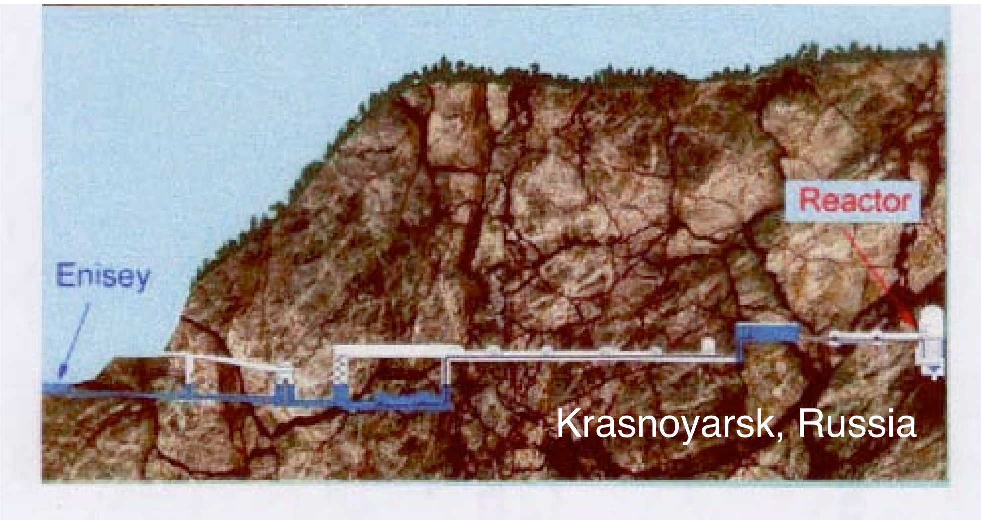
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

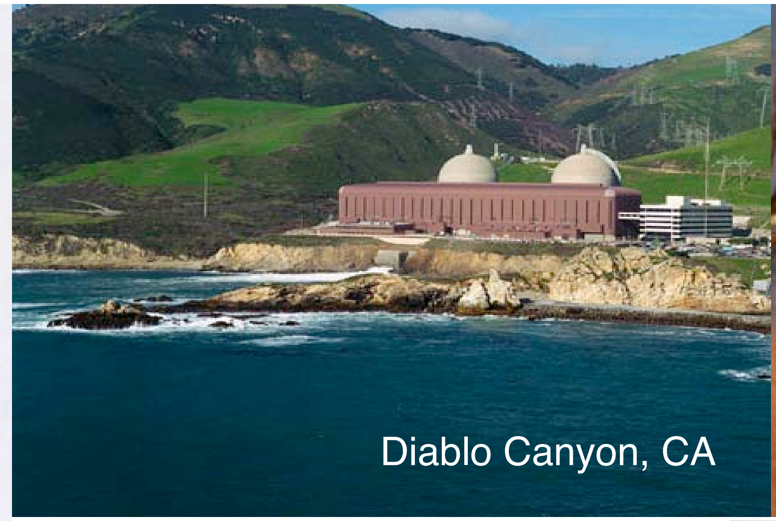
?

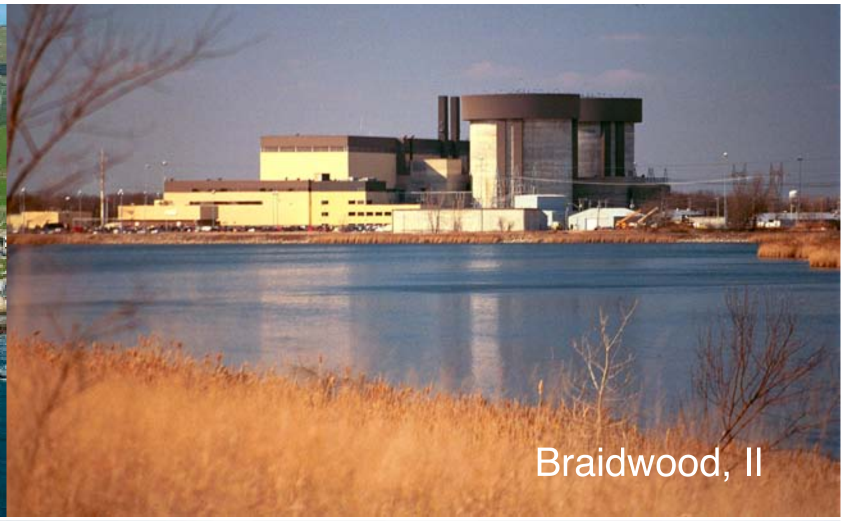
- atmospheric, K2K: $\theta_{23} = \sim 45°$
- reactor and accelerator: $\theta_{13} = ?$
- SNO, solar SK, KamLAND: $\theta_{12} \sim 32°$
- $0\nu\beta\beta$

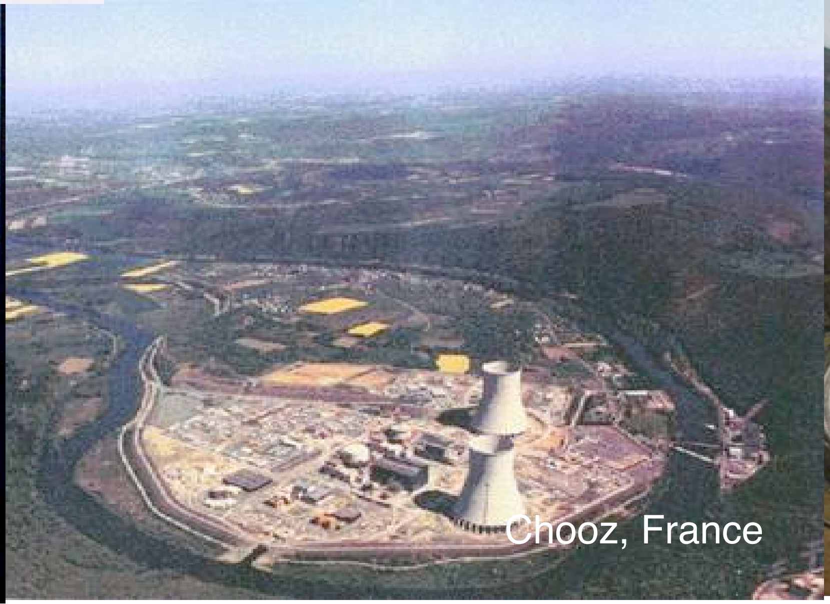
- Detectors near reactors are well suited to do this measurement
  - Need to do a ~1% measurement
  - Look for rate deviations from $1/r^2$ and spectral distortions
  - Observation of oscillatory signal with 2 or more detectors
  - Baseline *O(1km)*, no matter effects present

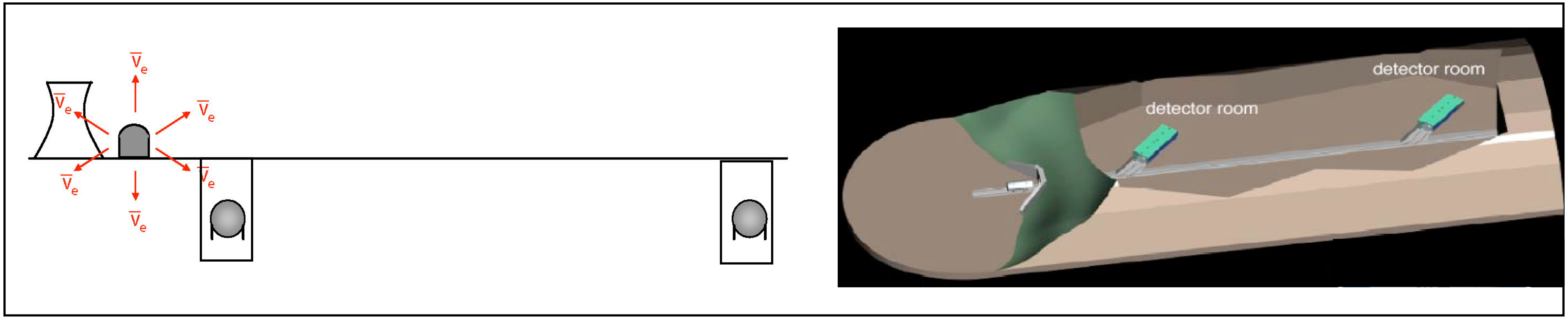
Several Proposals for Theta13 Experiments









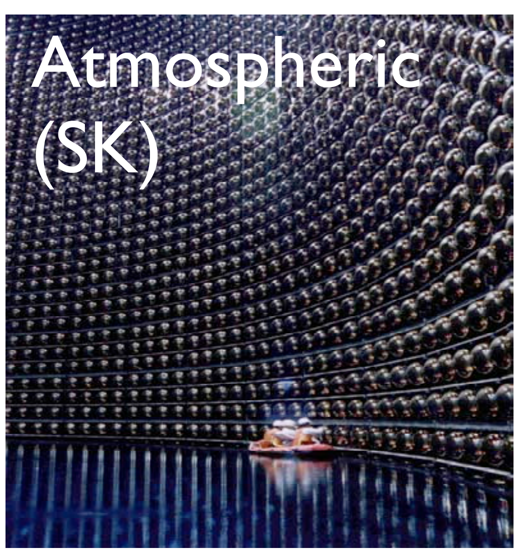


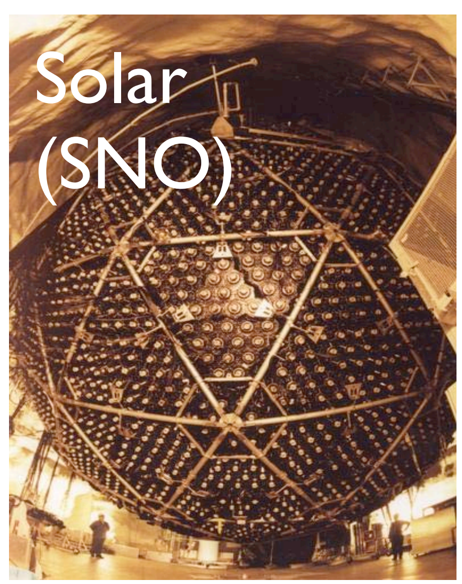
Summary

- KamLAND's updated results strengthen support for "neutrino disappearance"
- Best-fit KamLAND+Solar oscillation parameters are:

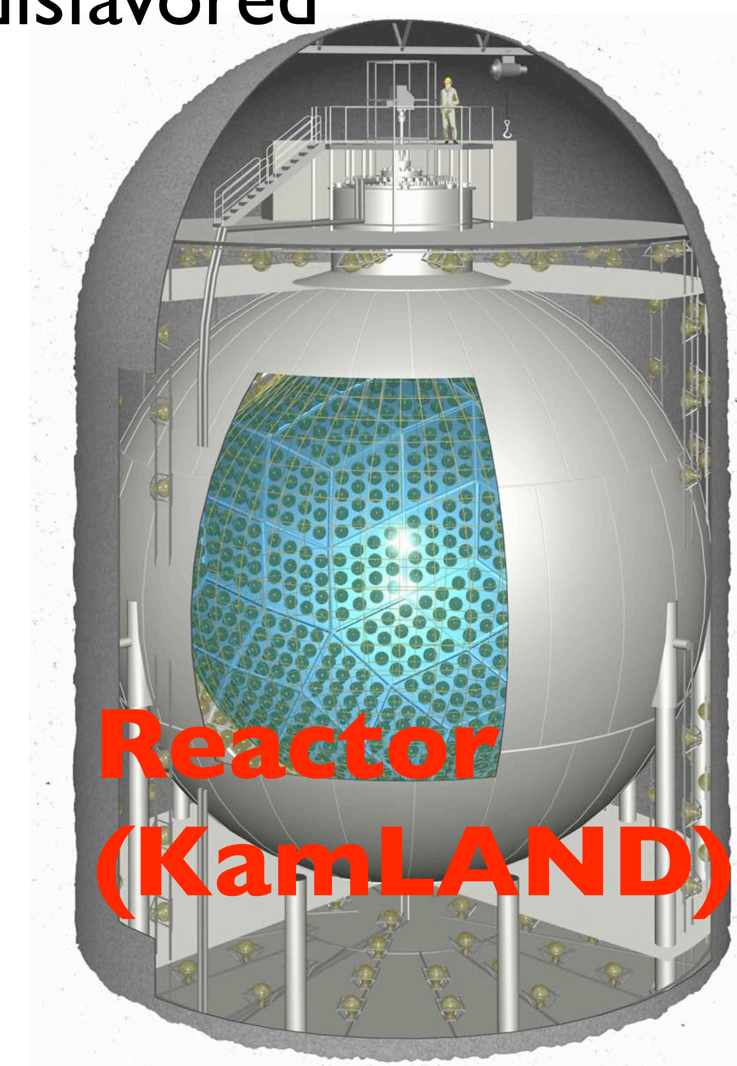
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2 \quad \tan^2\theta = 0.40^{+0.10}_{-0.07}$$

- No-oscillation hypothesis rejected at 99.6%
- Other disappearance mechanisms strongly disfavored
- Neutrino oscillation observed in:



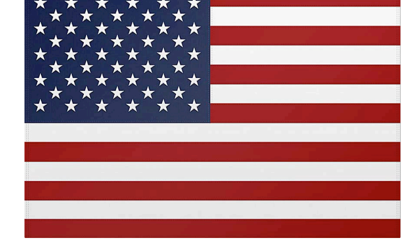


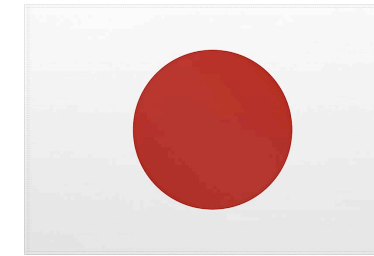
Accelerator
(K2K)



the End

KamLAND Collaboration



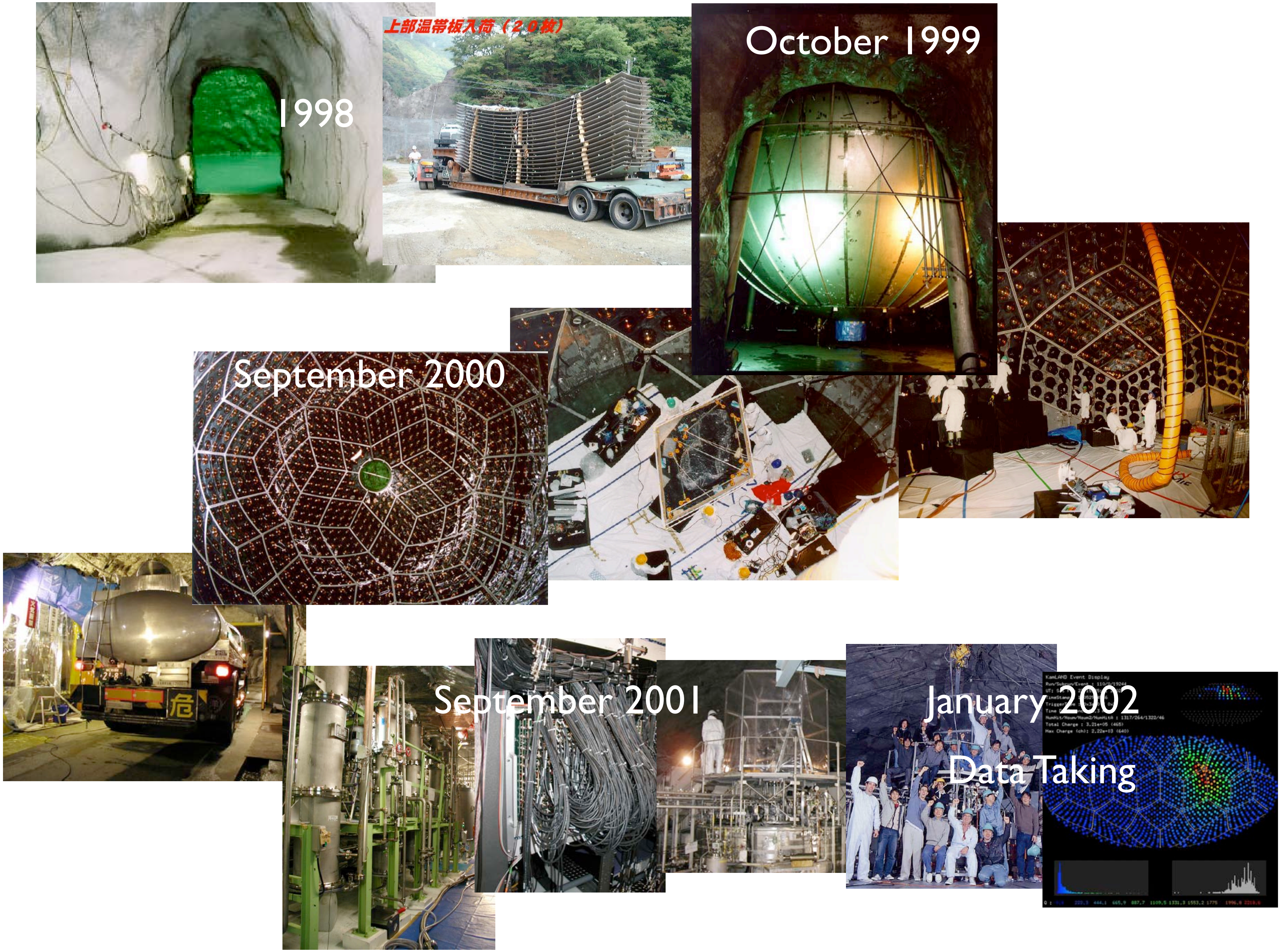


T. Araki,[1] K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1,*] T. Iwamoto,[1,†] T. Kawashima,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] J.-S. Ricol,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] K. Tamae,[1] Y. Tsuda,[1] H. Watanabe,[1] J. Busenitz,[2] T. Classen,[2] Z. Djurcic,[2] G. Keefer,[2] K. McKinny,[2] D.-M. Mei,[2,‡] A. Piepke,[2] E. Yakushev,[2] B.E. Berger,[3] Y.D. Chan,[3] M.P. Decowski,[3] D.A. Dwyer,[3] S.J. Freedman,[3] Y. Fu,[3] B.K. Fujikawa,[3] J. Goldman,[3] F. Gray,[3] K.M. Heeger,[3] K.T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3,§] A.W.P. Poon,[3] H.M. Steiner,[3] L.A. Winslow,[3] G.A. Horton-Smith,[4,¶] C. Mauger,[4] R.D. McKeown,[4] P. Vogel,[4] C.E. Lane,[5] T. Miletic,[5] P.W. Gorham,[6] G. Guillian,[6] J.G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] A. Rojas,[7] R. Svoboda,[7] B.D. Dieterle,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9,**] M. Batygov,[10] W. Bugg,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] C.R. Gould,[11] H.J. Karwowski,[11] D.M. Markoff,[11] J.A. Messimore,[11] K. Nakamura,[11] R.M. Rohm,[11] W. Tornow,[11] R. Wendell,[11] A.R. Young,[11] M.-J. Chen,[12] Y.-F. Wang,[12] and F. Piquemal[13]

(The KamLAND Collaboration)

[1] *Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan*
[2] *Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*
[3] *Physics Department, University of California at Berkeley and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4] *W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[5] *Physics Department, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[6] *Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA*
[7] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[8] *Physics Department, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[9] *Physics Department, Stanford University, Stanford, California 94305, USA*
[10] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[11] *Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA and Physics Departments at Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill*
[12] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[13] *CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I, F-33175 Gradignan Cedex, France*

Building KamLAND




KamLAND
Collaboration Meeting