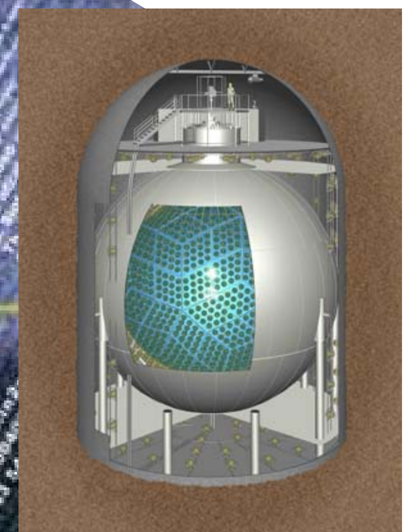
New Results from KamLAND



Neutrino 2004
Paris

The KamLAND Collaboration

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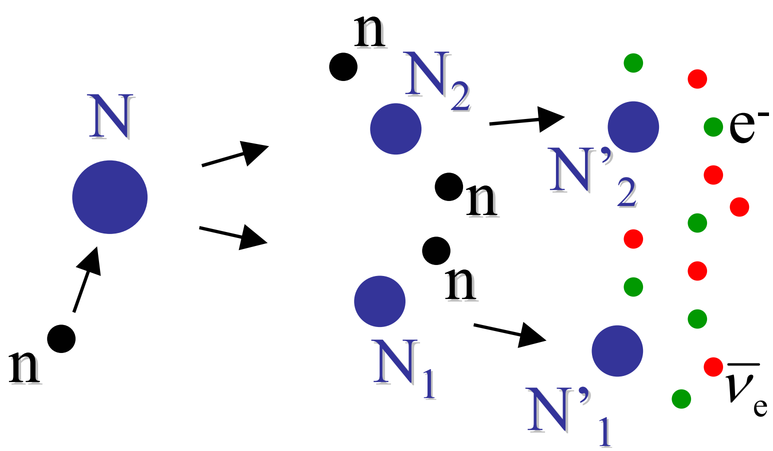
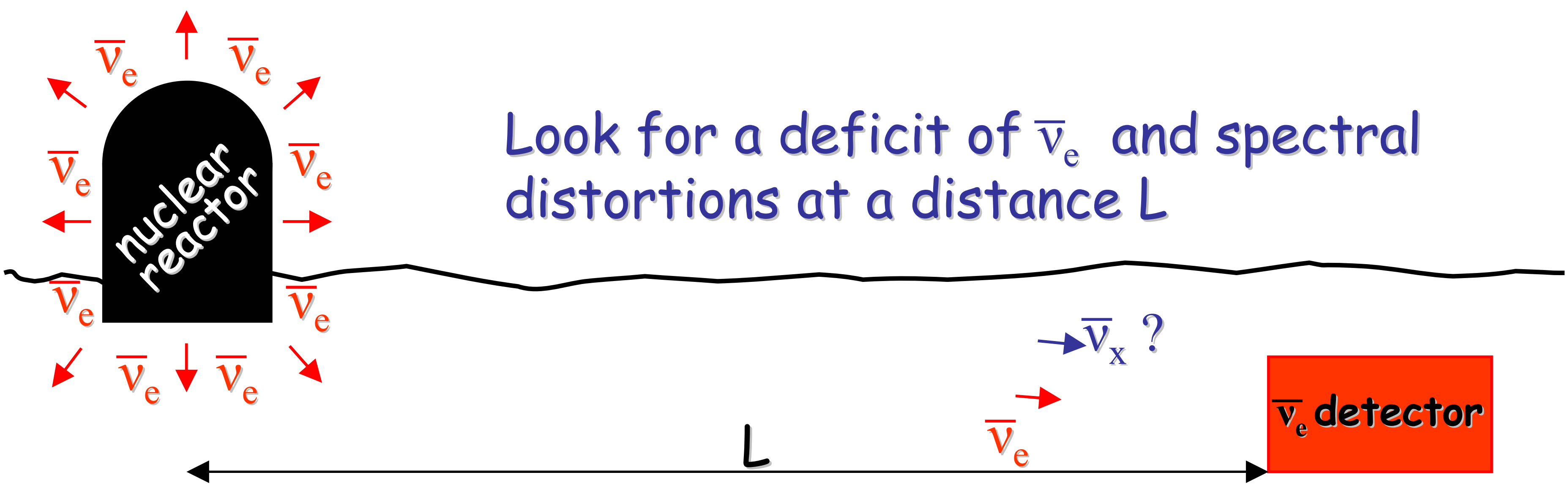
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments



$$Yield:$$
$$200 MeV / fission$$
$$6\bar{\nu}_e / fission$$

Look for a deficit of $\bar{\nu}_e$ and spectral distortions at a distance L



A specific signature is provided by the inverse-β reaction

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

$\tau \approx 200\ \mu s$

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

Event tagging by coincidence in time, space and energy of the neutron capture

E_ν measurement

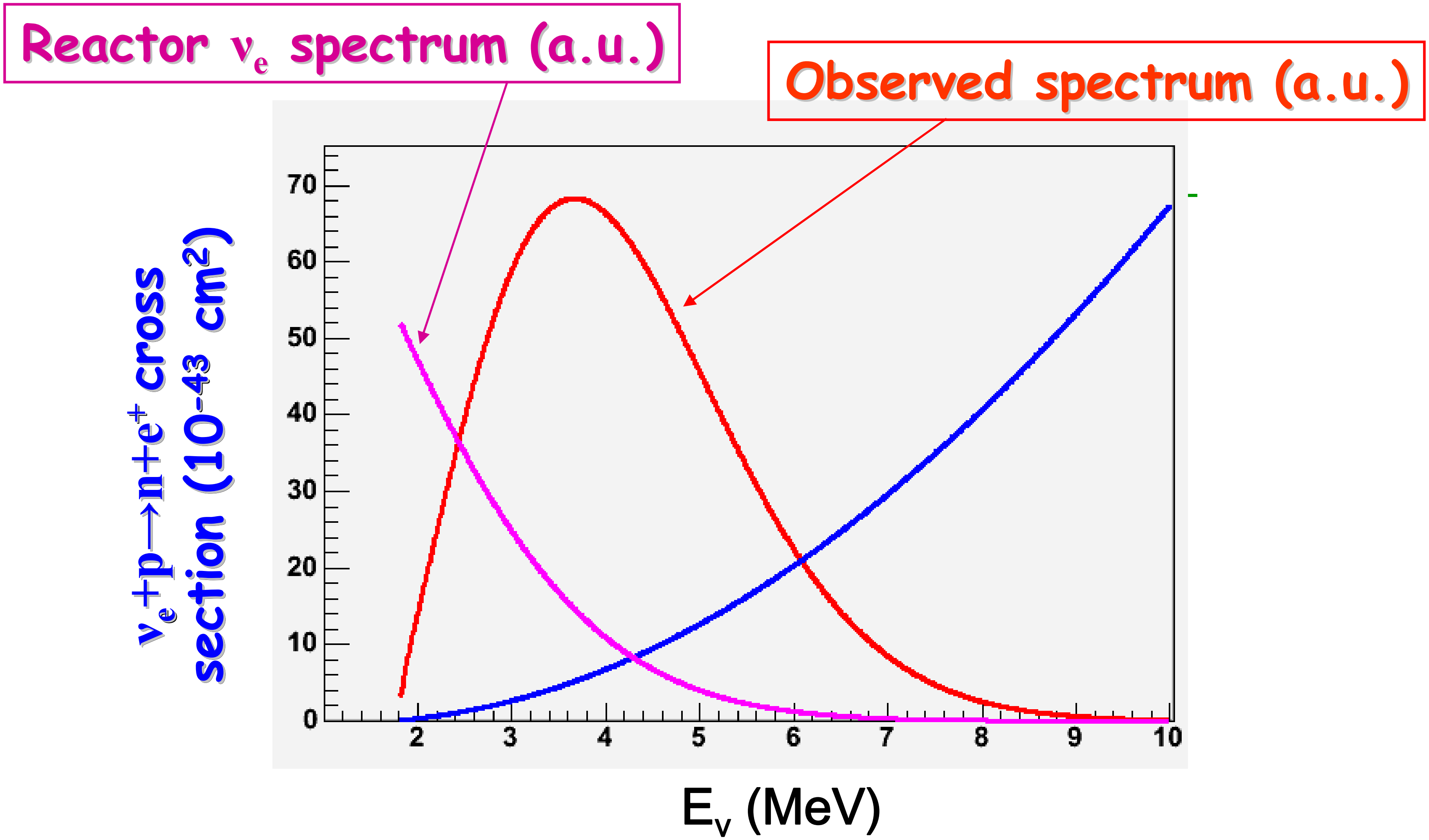
$$E_{\overline{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

T_n: *10-40 keV*; $(M_n - M_p) + m_{e^+}$: *1.8 MeV*

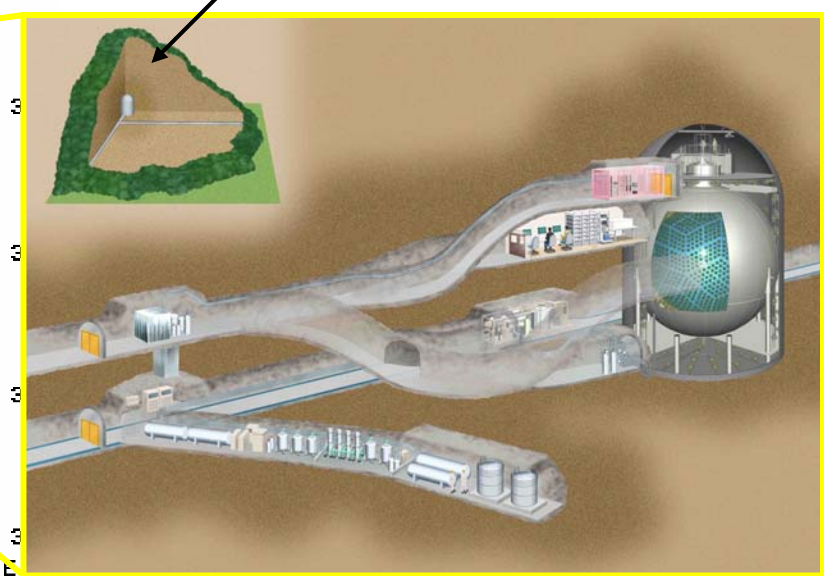
Threshold: $E_{\overline{\nu}} > 1.8 MeV$

→ only ~1.5 antineutrinos/fission can be detected

The $\bar{\nu}_e$ energy spectrum

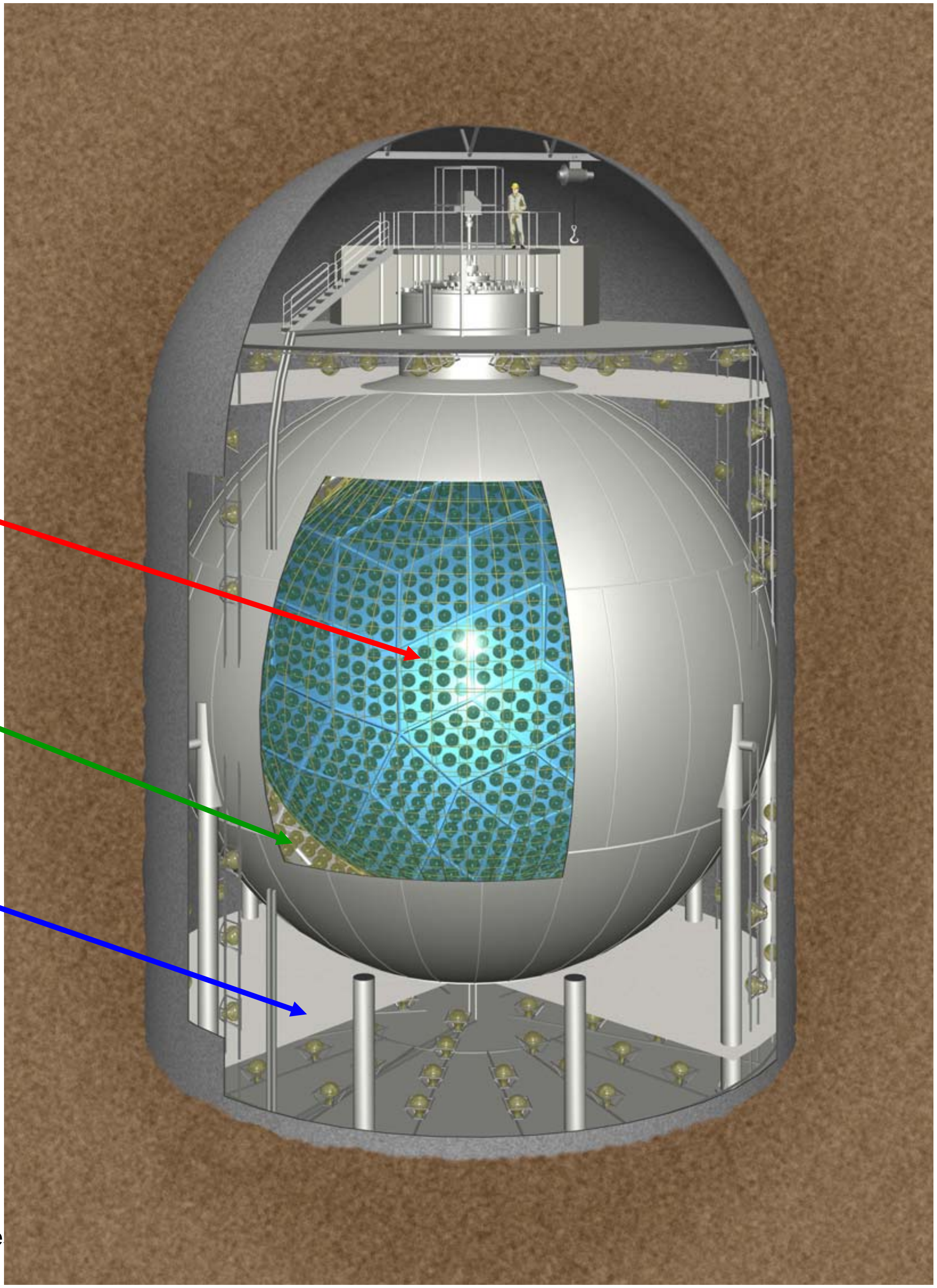


~1 km high
Mt Ikenoyama

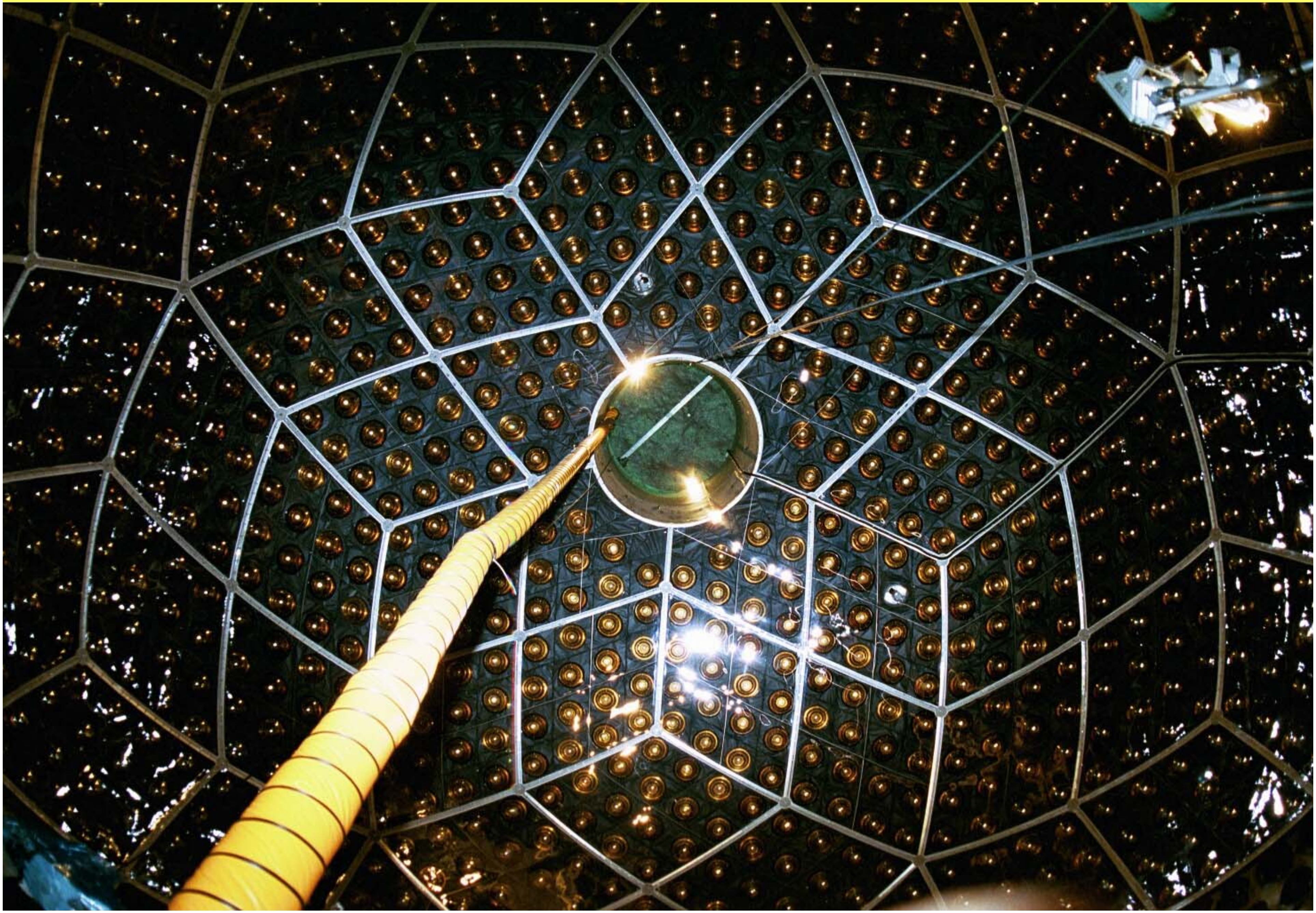


KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector
  in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



The completed detector, looking up



Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to $4 \cdot 10^{-4}$ of that of the scintillator

PPO concentration is 1.52 g/l in scintillator

Many reactors contribute to the 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**

*E_ν>3.4MeV (E_{prompt}>2.6MeV)

Japan: *Detailed power and fuel Composition calculation used*

South Korea: From electrical power Japanese average fuel used

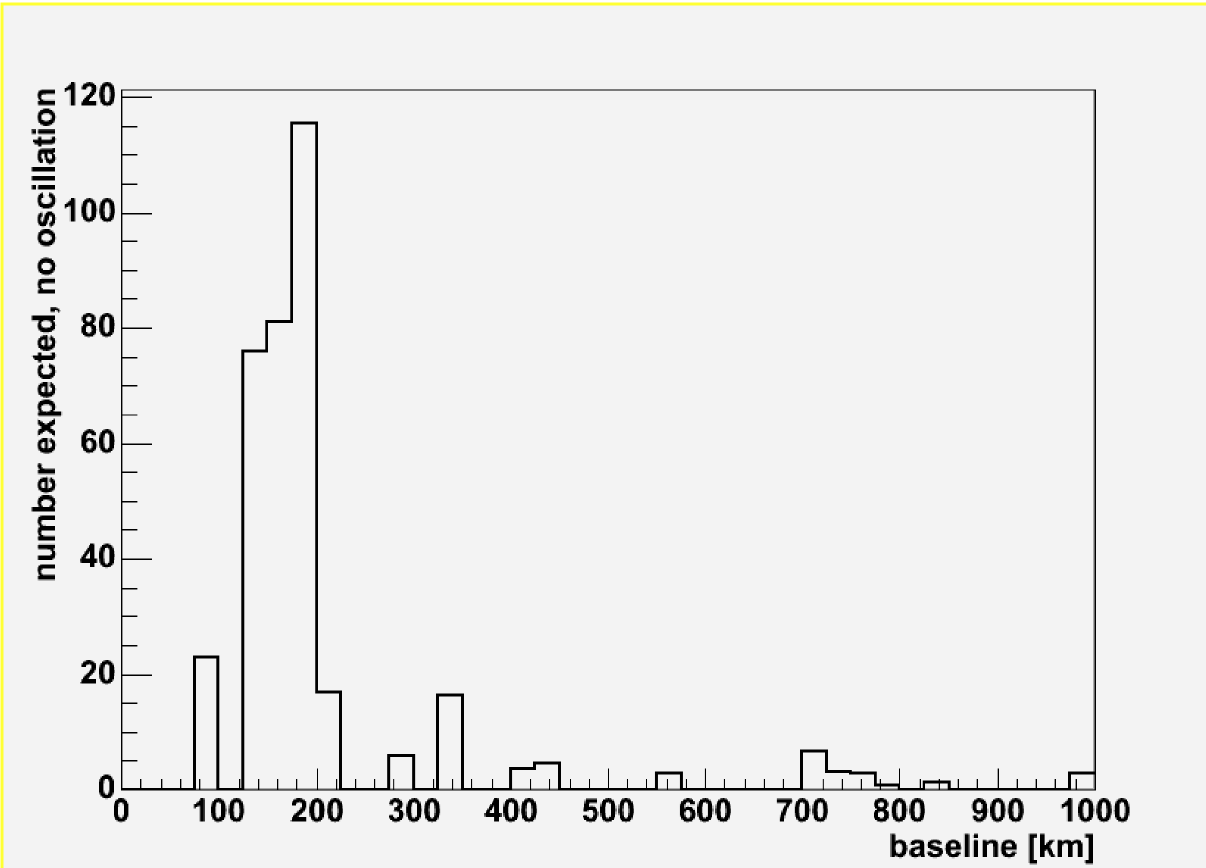
A brief history of KamLAND

	Dates	Live time (days)
Start data taking	Jan 2002	-
Run A (data-set of 1st paper)	Mar 9 – Oct 6 2002	145.4*
Electronics upgrade & 20" PMT commissioning	Jan/Feb 2003	-
Run B	Oct - Jan 11 2004	369.7
Data-set presented here†	Mar 9, 2002 – Jan 11, 2004	515.1

*Was 145.1 with old analysis

† T.Araki et al, arXiv:hep-ex/0406035 Jun 13, 04 submitted to Phys Rev Lett

A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka



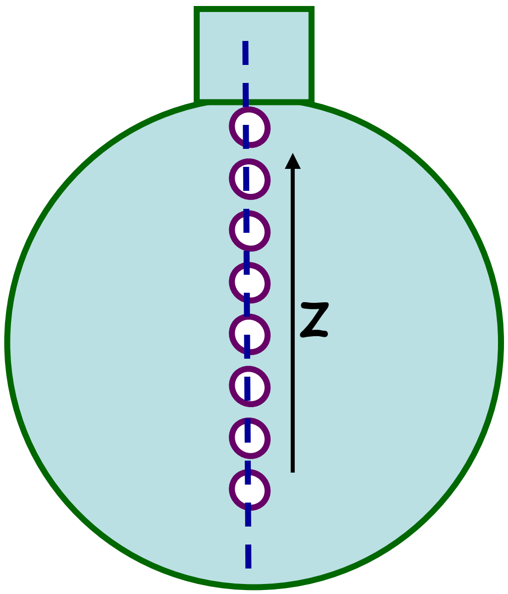
Over the data period Reported here

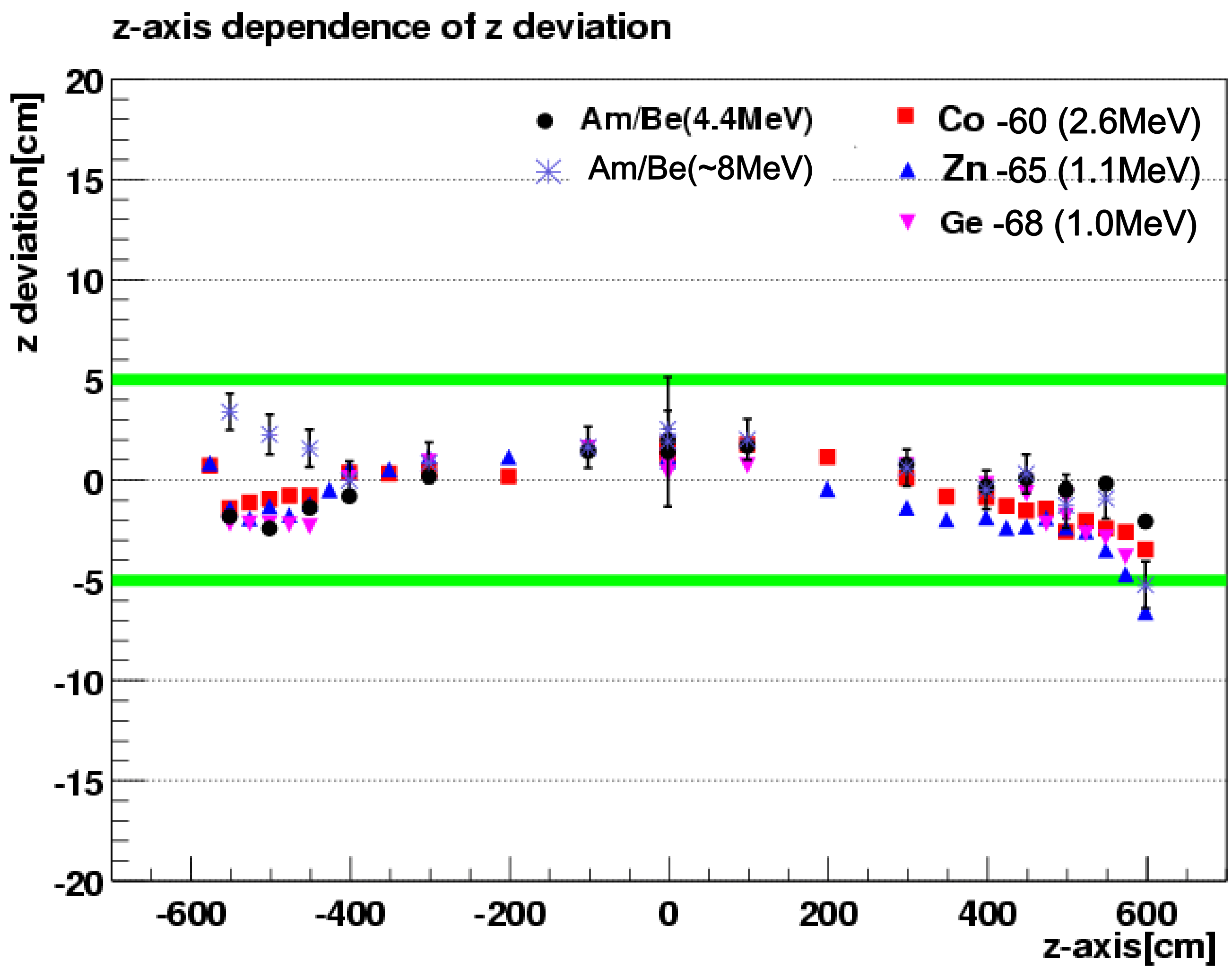
Korean reactors
3.4±0.3%

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

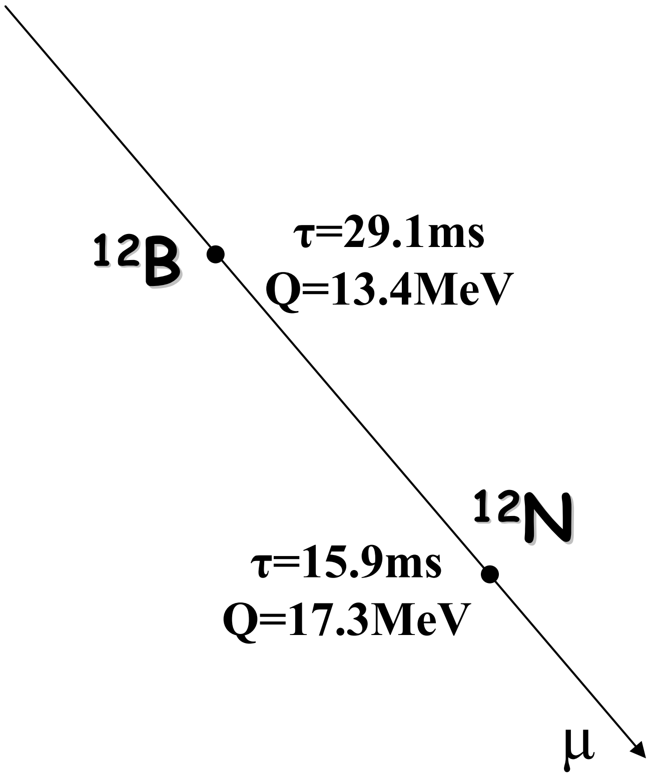
Japanese spent fuel
0.04±0.02%

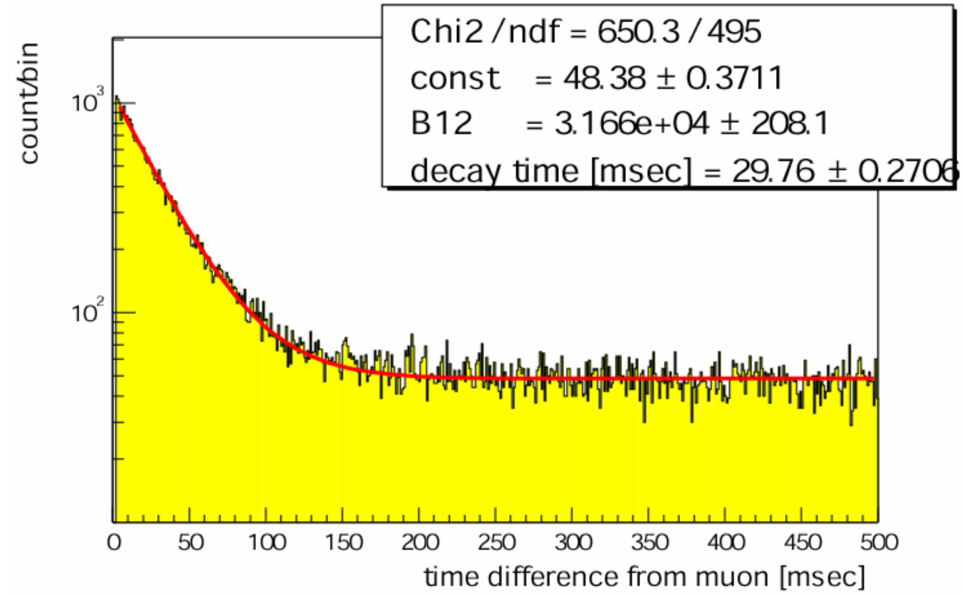
Vertexing is performed using timing from the 17” PMTs

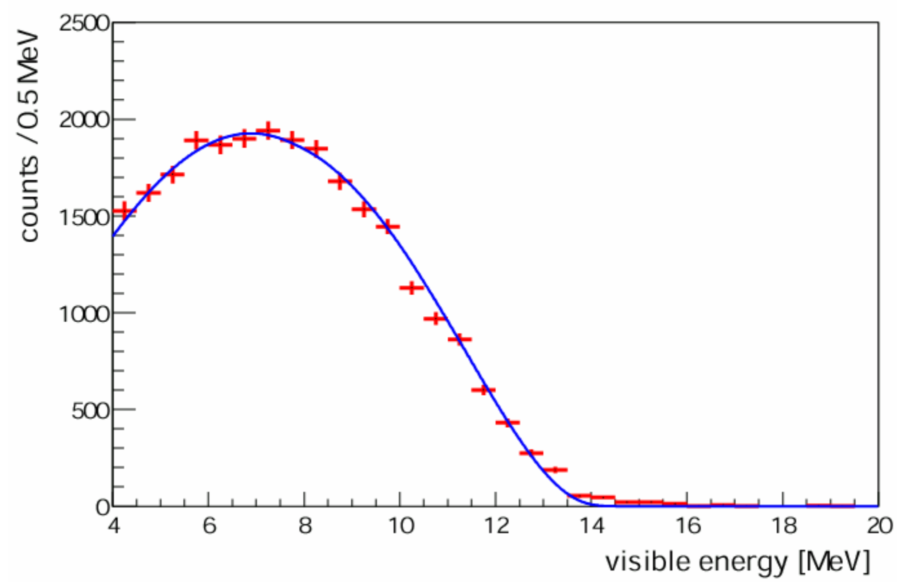




Tagged cosmogenics can be used for calibration



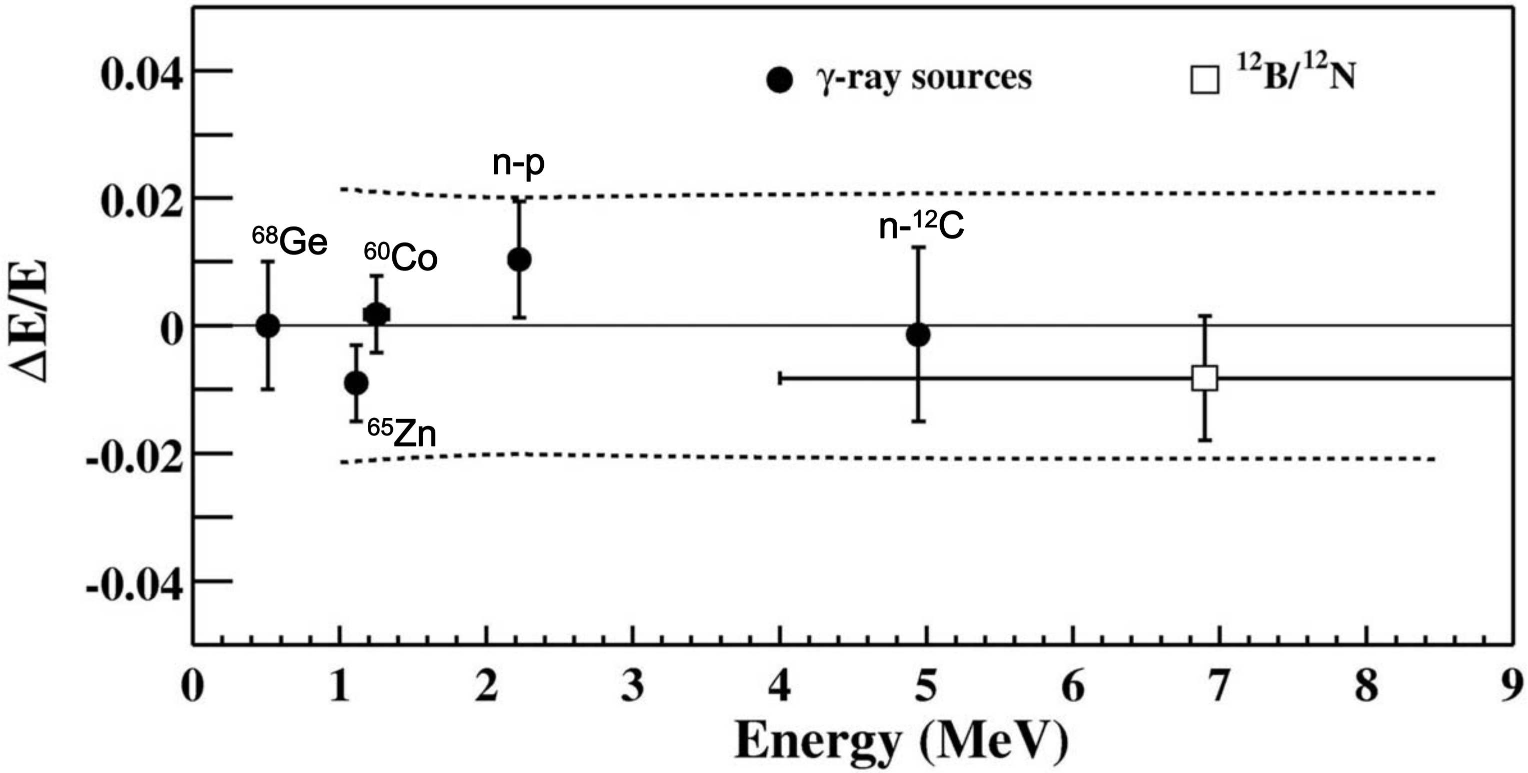




Fit to data shows that

^{12}B:^{12}N ~ 100:1

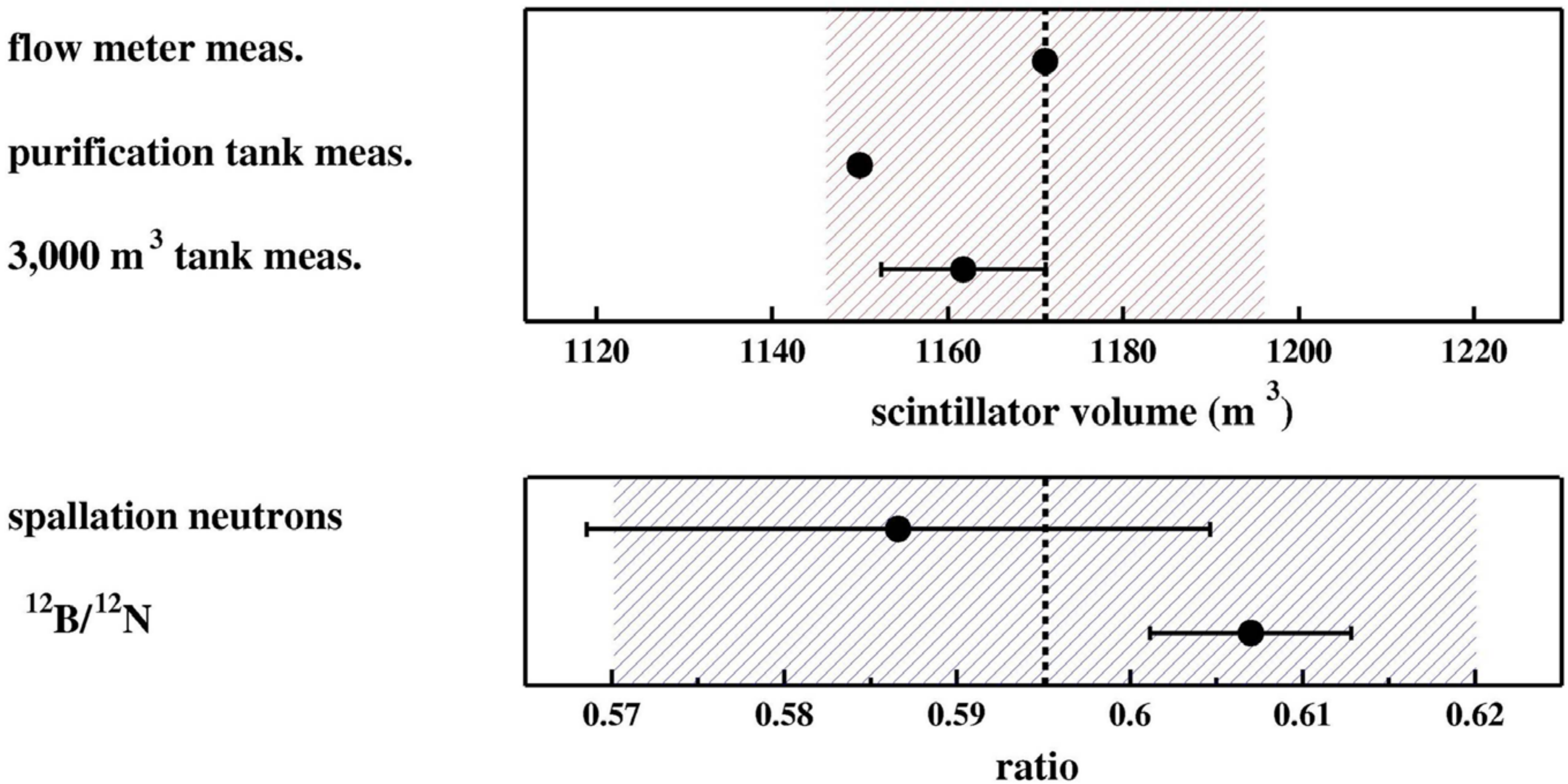
Energy calibration uses discrete γ and $^{12}B/^{12}N$



Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for γ and e–type depositions

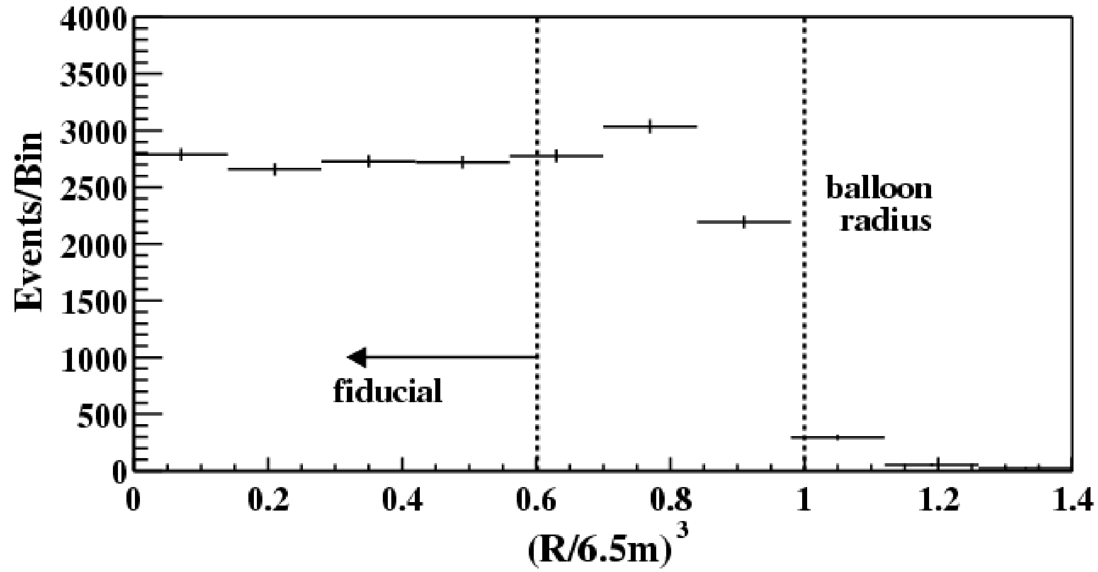
$\sigma/E \sim 6.2\%$ at 1MeV

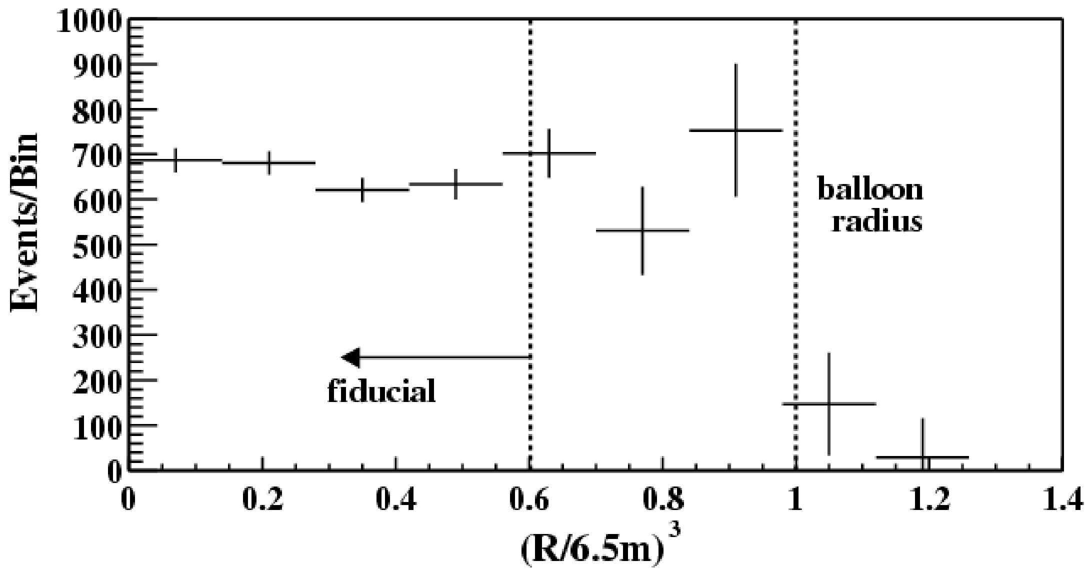
Estimate of total volume and fiducial fraction



Fraction of volume *inside* the fiducial radius verified using μ-produced $^{12}B/^{12}N$ and n (assumed uniform)

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





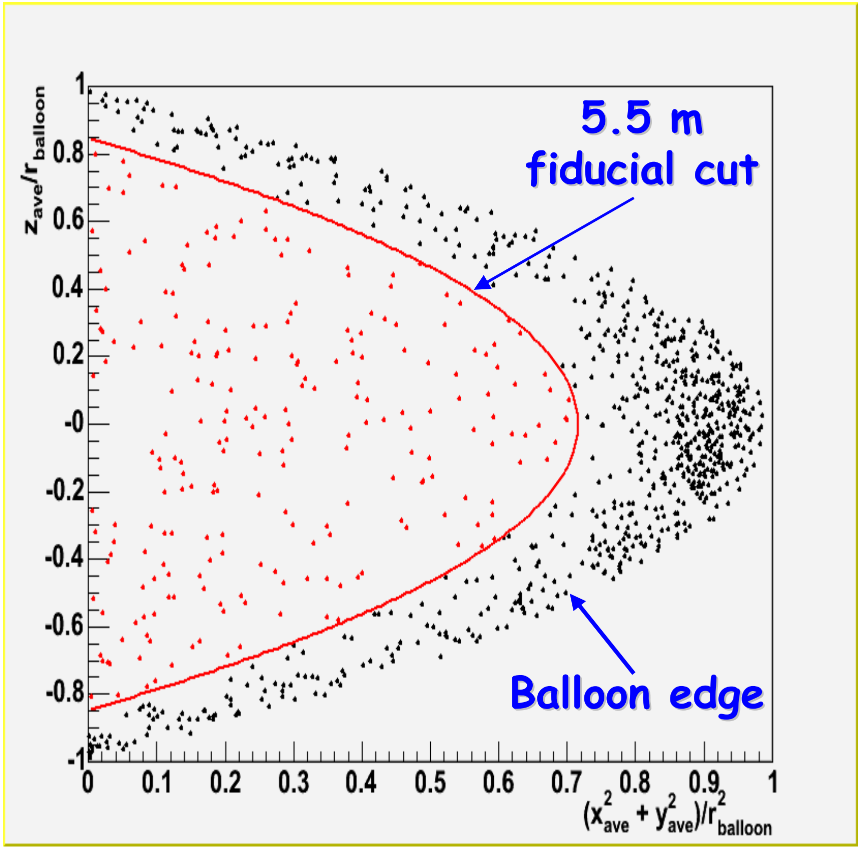
neutrons

Selecting antineutrinos, E_{prompt}>2.6MeV

- $R_{prompt,\ delayed}$ < 5.5 m
- ΔR_{e-n} < 2 m
- 0.5 μs < ΔT_{e-n} < 1 ms
- 1.8 MeV < $E_{delayed}$ < 2.6 MeV
- 2.6 MeV < E_{prompt} < 8.5 MeV

543.7 ton
33% increase

Tagging efficiency 89.8%



…In addition:

- 2s veto for showering/bad μ
- 2s veto in a R = 3m tube along track

Dead-time 9.7%

Systematic	%
Scintillator volume	2.1
Fiducial fraction	4.2
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.06
Reactor $P_{thermal}$	2.1
Fuel composition	1.0
Time lag	0.01
Antineutrino spectrum	2.5
Antineutrino x-section	0.2
Total	6.5

Results

(766.3 ton·yr, ~4.7× the statistics of the first paper)

Observed events 258
No osc. expected 365±24(syst)
Background 7.5±1.3

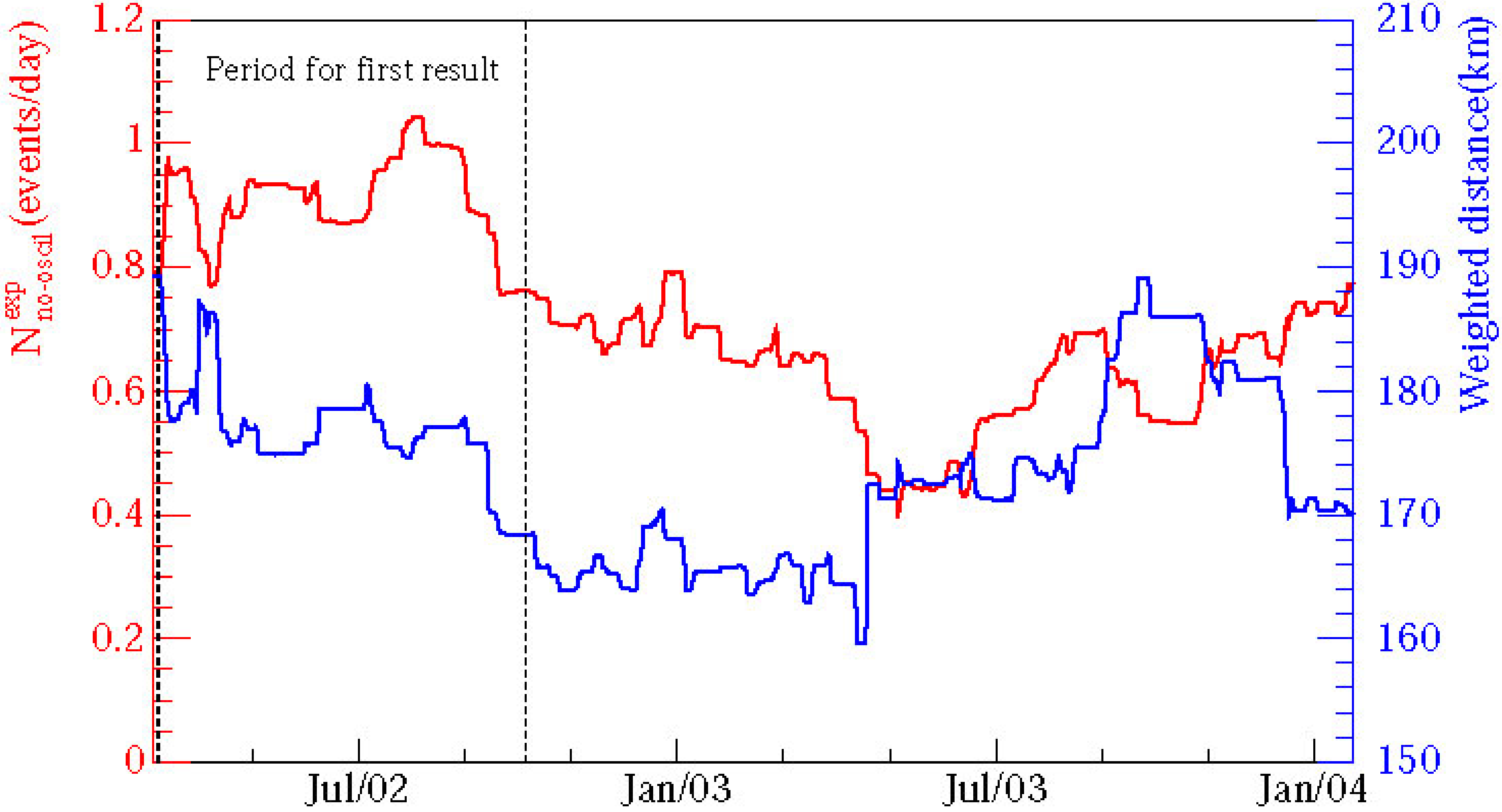
Background	Events
Accidentals	2.69±0.02
$^{8}He/^{9}Li$	4.8±0.9
μ-induced n	<0.89
Total	7.5±1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

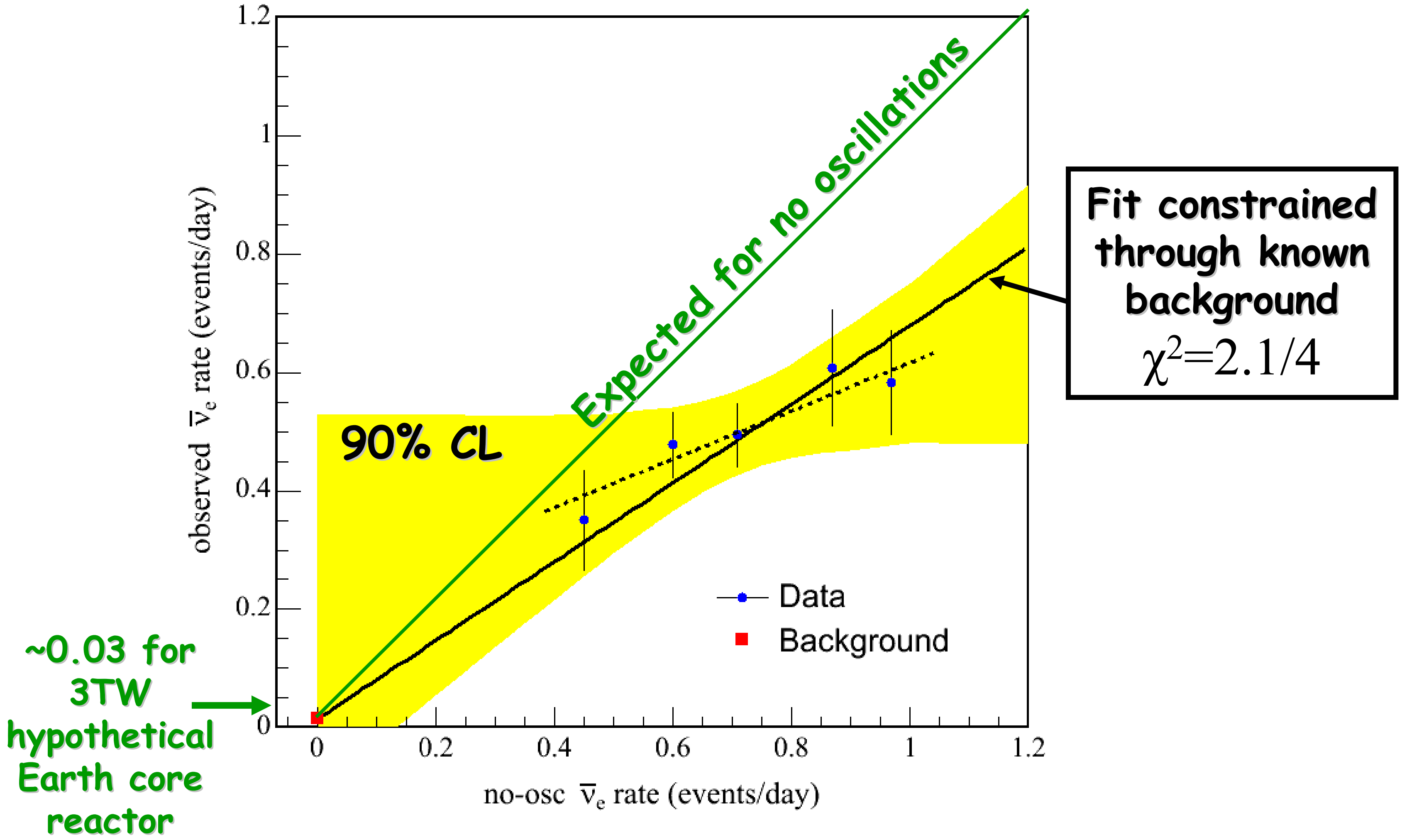
(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

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

2003 saw a substantial dip in reactor antineutrino flux

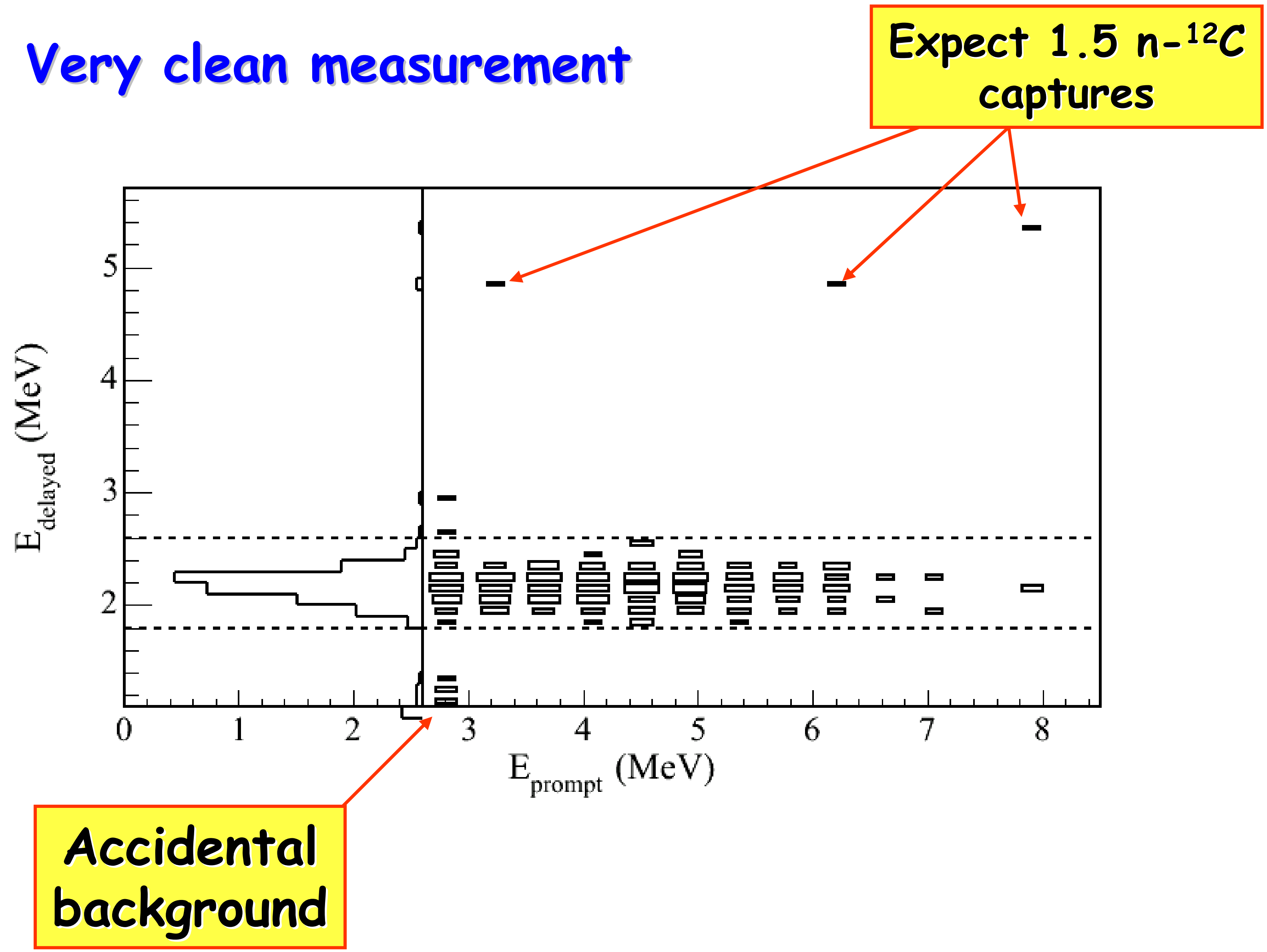


Good correlation with reactor flux

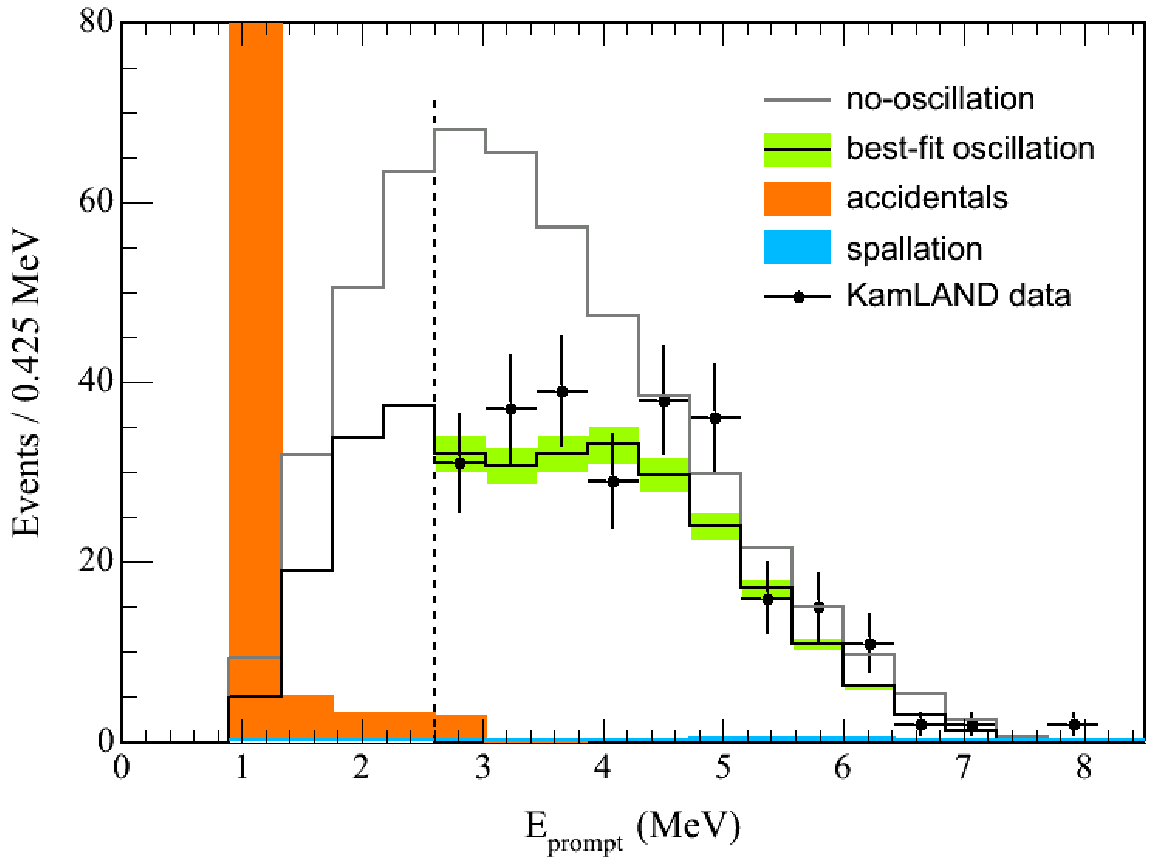


(But a horizontal line still gives a decent fit with χ^2=5.4/4)

Very clean measurement



Energy spectrum now adds substantial information



A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Best fit to oscillations:

$\Delta m^2 = 8.3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\theta = 0.83$

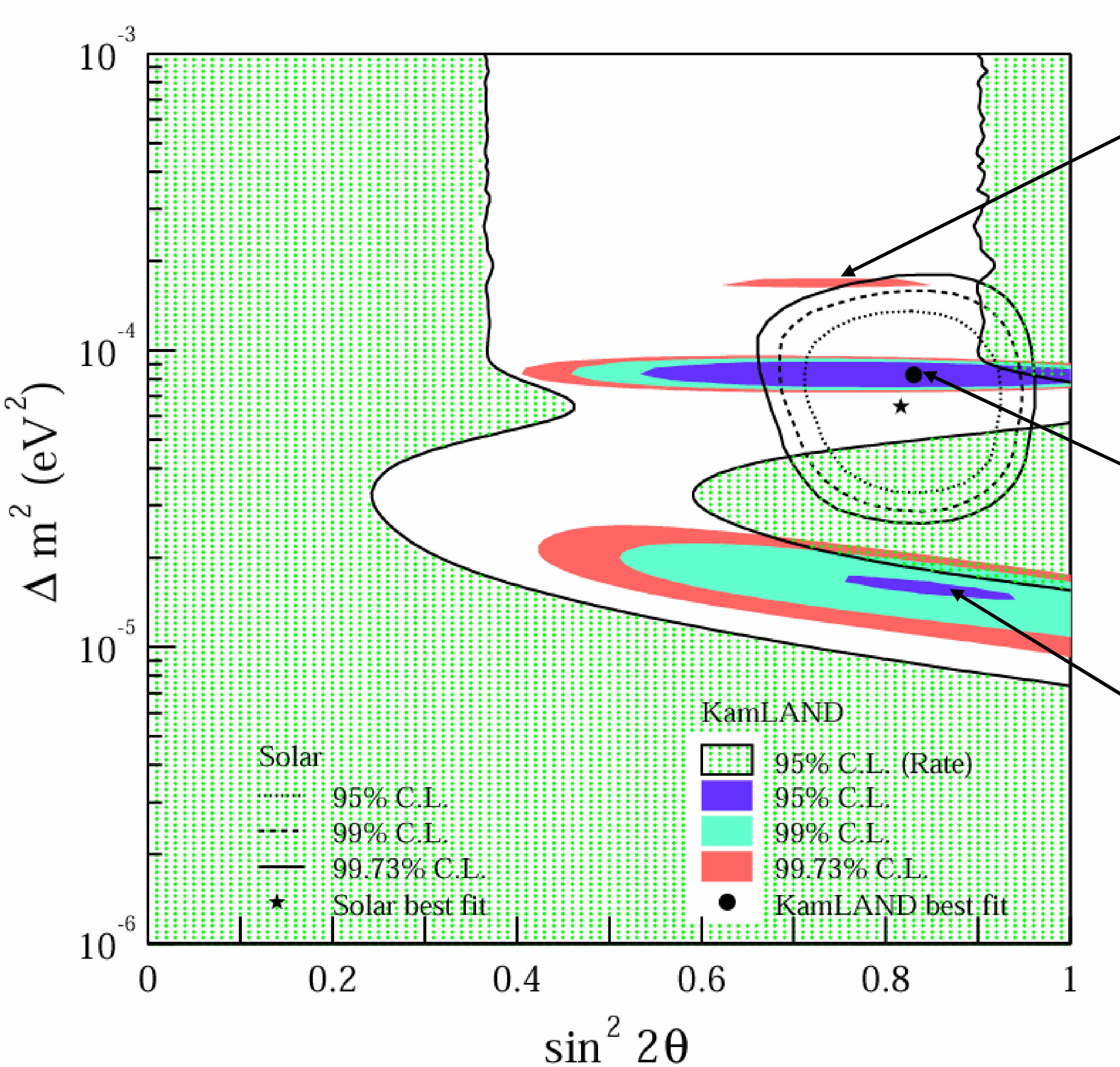
Straightforward χ^2 on the histo is 19.6/11

Using equal probability bins

$\chi^2/dof = 18.3/18$

(goodness of fit is 42%)

Un-binned likelihood fit to 2-flavor oscillations



LMA2 excluded at 99.6% CL

$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

$\sin^2 2\theta = 0.83$

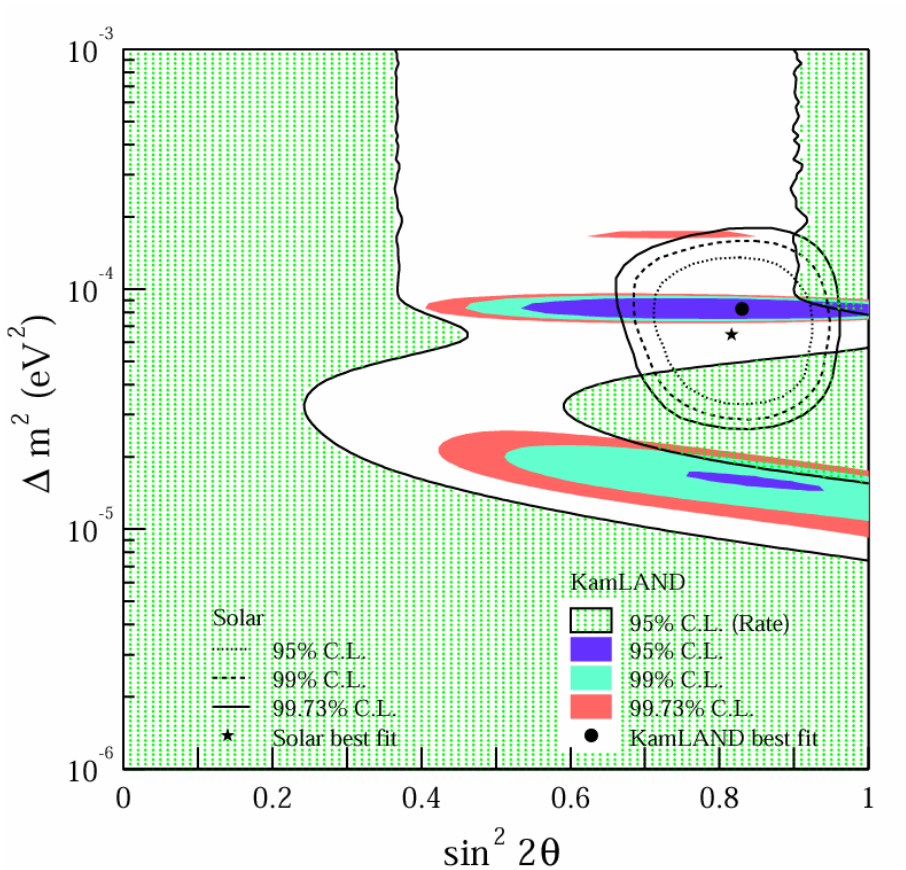
"LMA0" disfavored at 94% CL

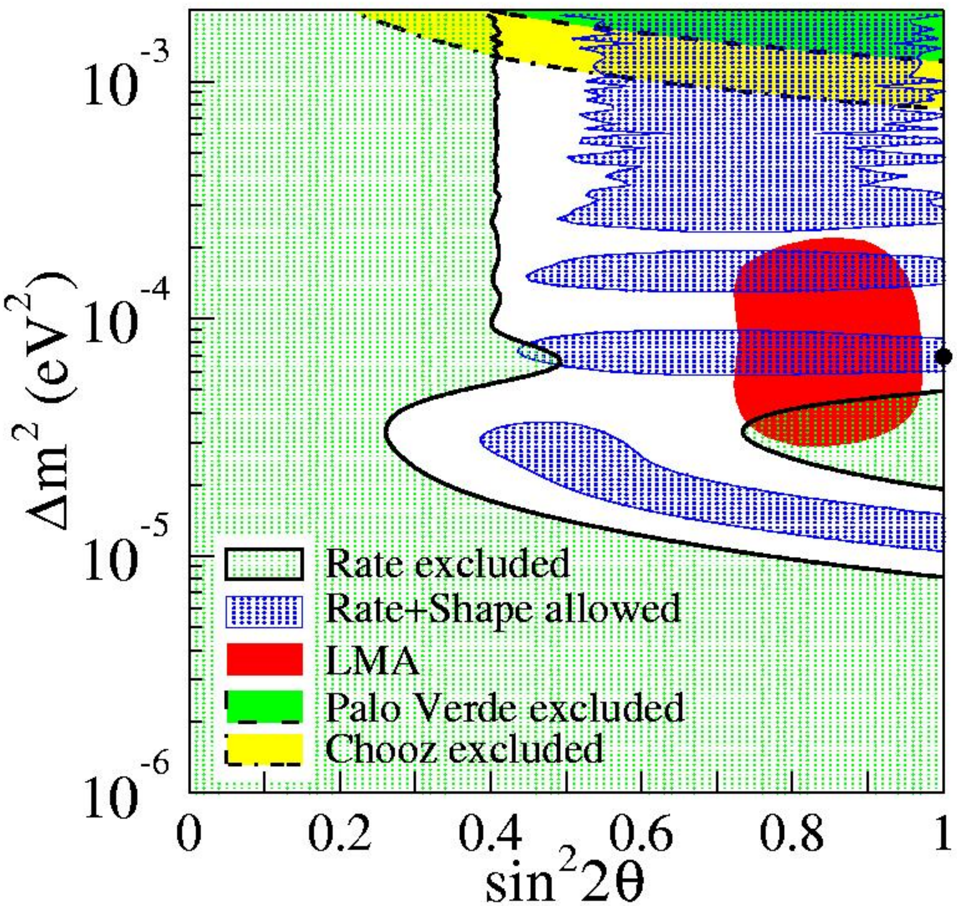
This result

$\Delta m^2=8.3\cdot10^{-5}\ eV^2$
$\sin^2 2\theta=0.83$

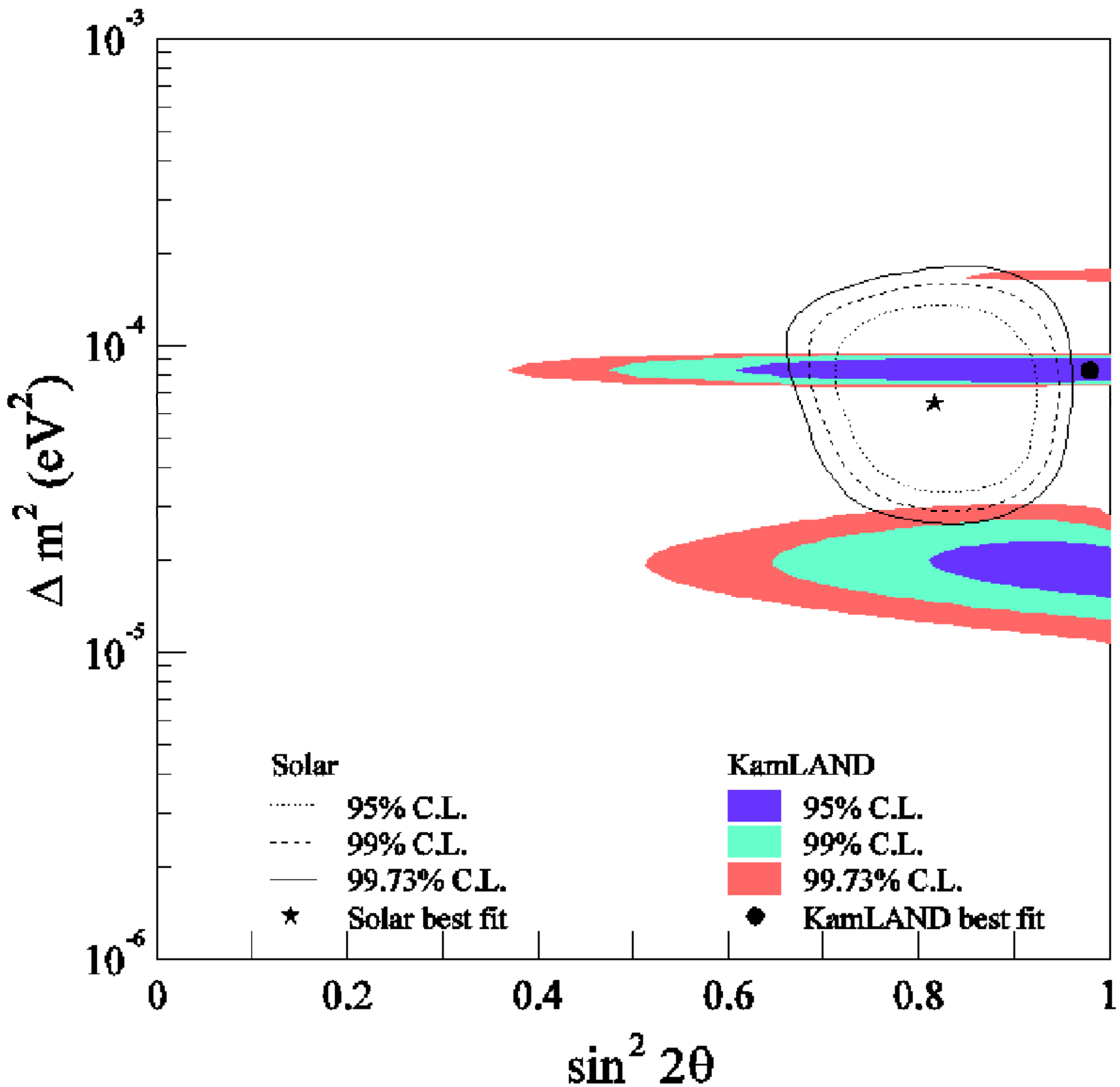
First KamLAND result

$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$
$\sin^2 2\theta = 1.0$





A shape-only fit gives similar results

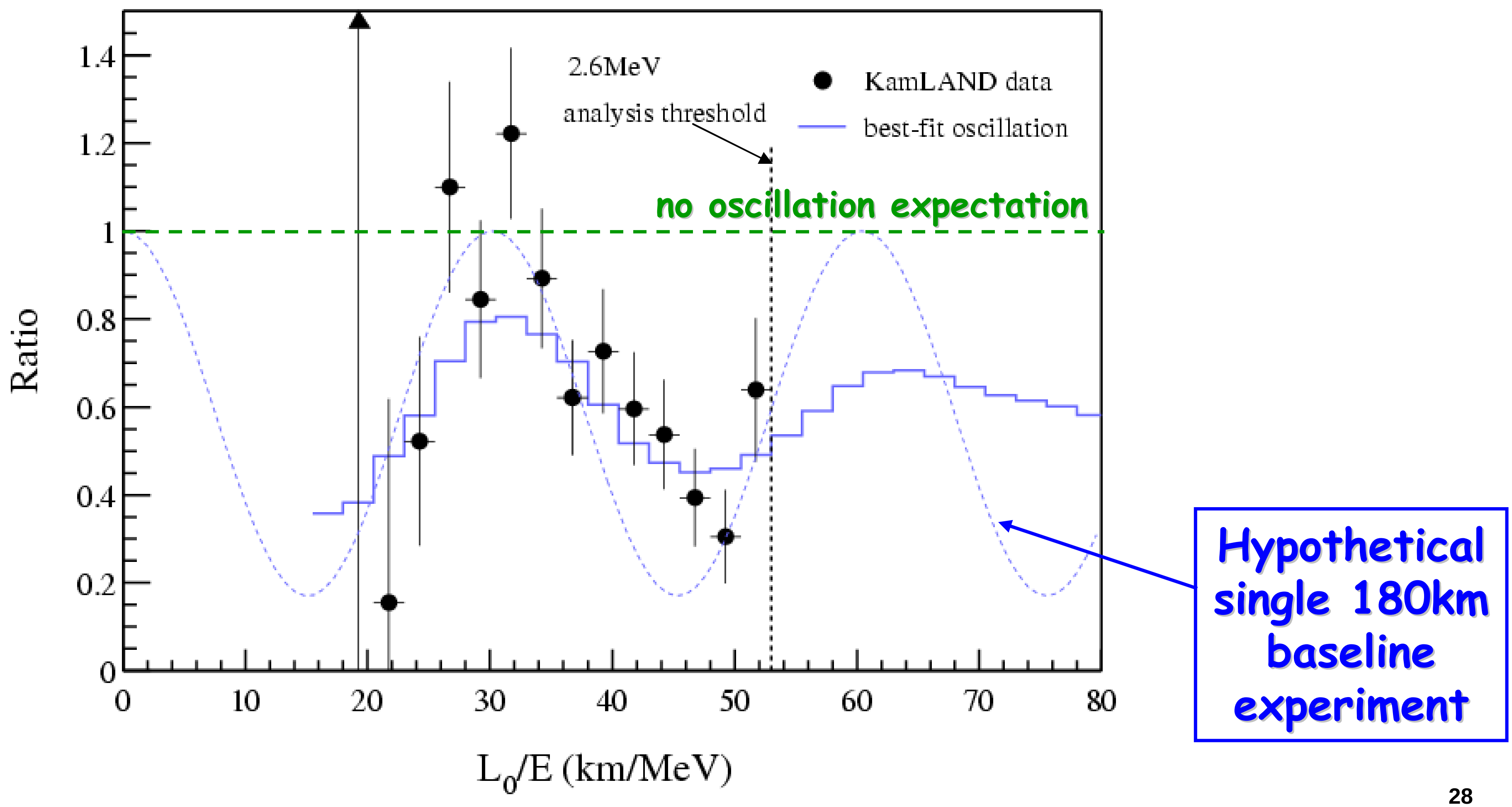


$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

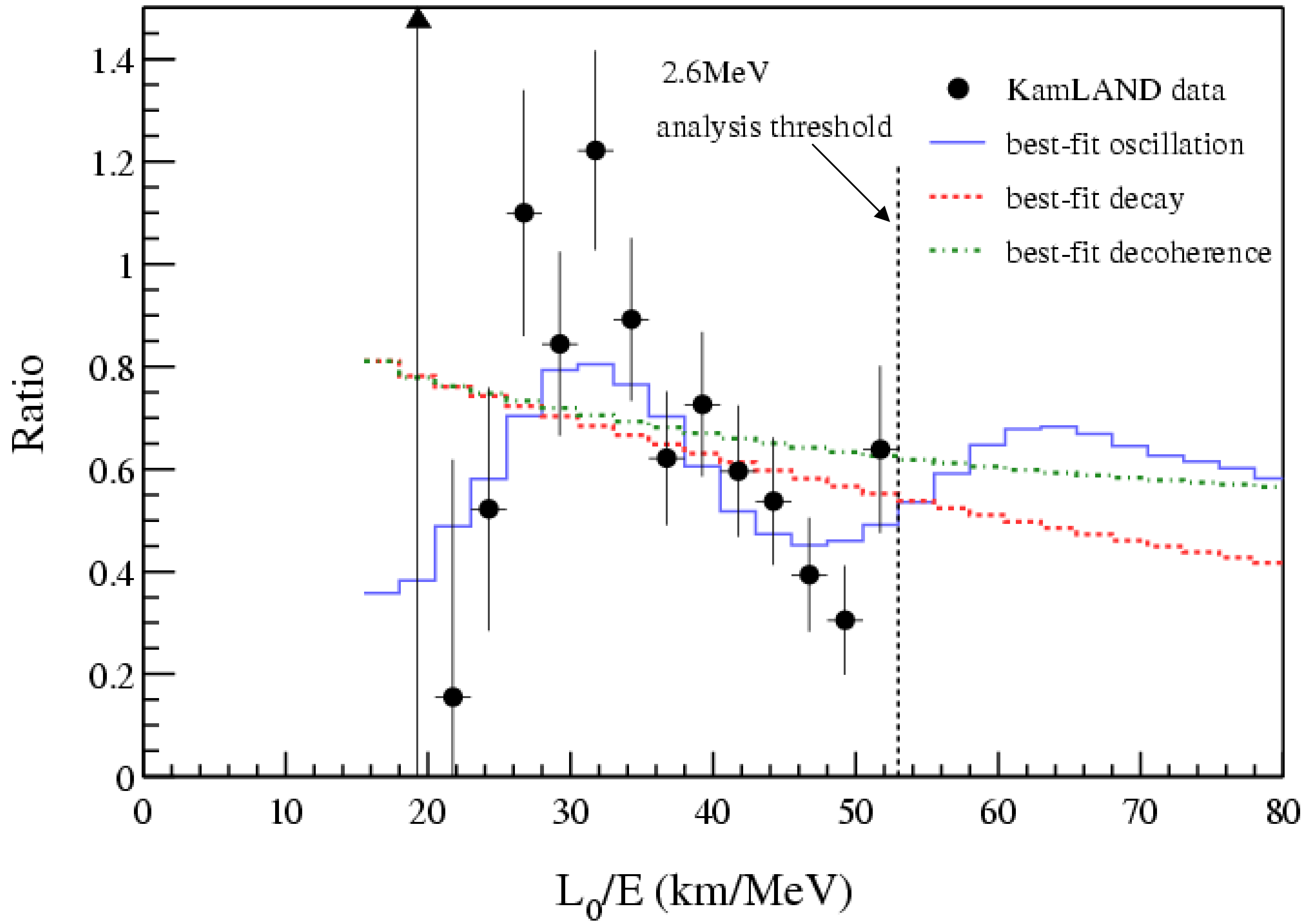
$\sin^2 2\theta = 0.98$

KamLAND uses a range of L and it cannot assign a specific L to each event

Nevertheless the ratio of detected/expected for L_0/E (or $1/E$) is an interesting quantity, as it decouples the ***oscillation pattern*** *from the reactor energy spectrum*



More exotic, non-oscillations models for the antineutrino channel start being less favored by data



Decay* excluded at 95% CL

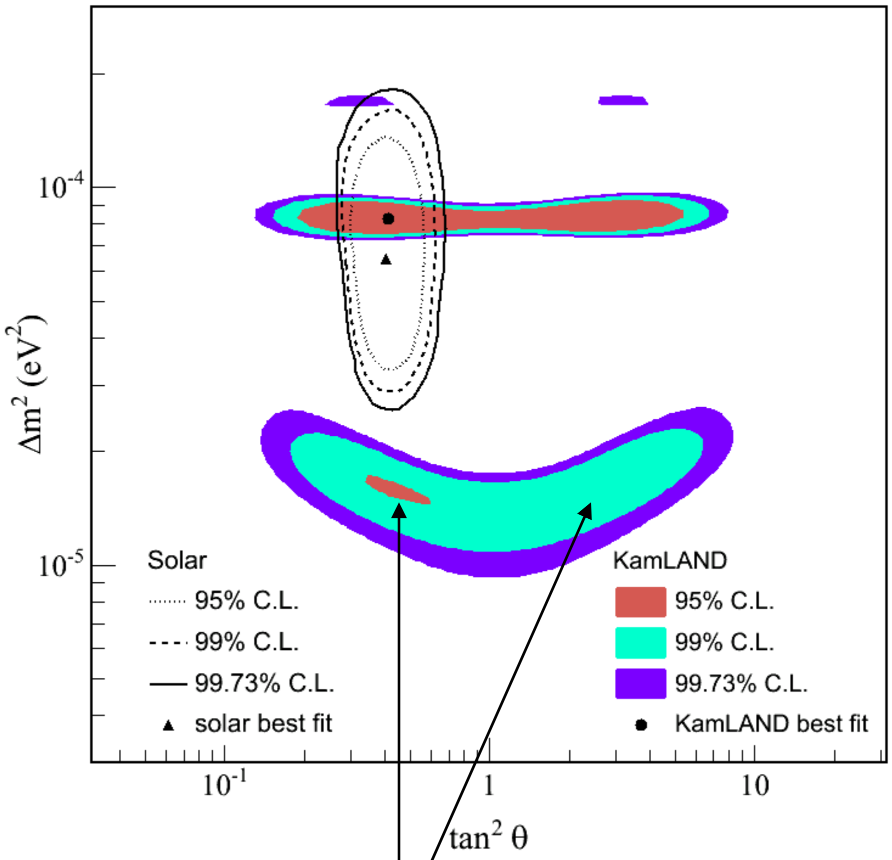
Decoherence† excluded at 94% CL

** V.Barger et al. Phys. Rev. Lett. 82 (1999) 2640*
†E.Lisi et al., Phys. Rev. Lett. 85 (2000) 1166

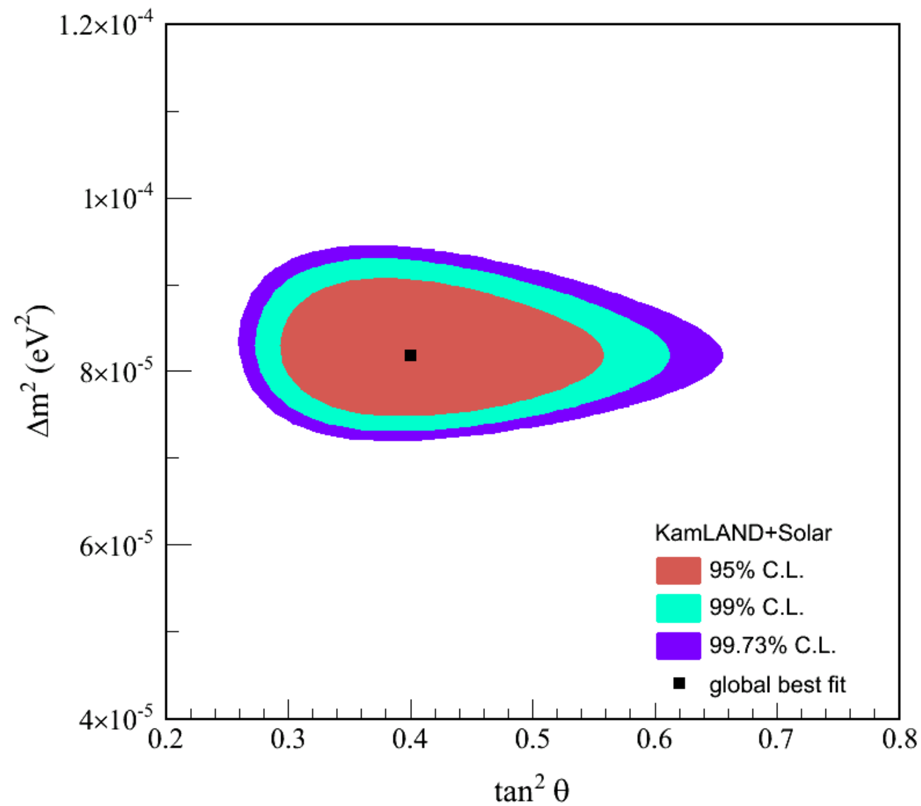
Combined solar ν – KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Includes (small) matter effects



Conclusions

KamLAND reactor exposure: 766.3 ton·yr (470% increase)

Data consistent with large flux swings in 2003

Spectrum distortions now quite significant, shape-only very powerful

Best KamLAND fit to oscillations $\Delta m=8.3\cdot 10^{-5}$ eV^2, $\sin^2 2\theta=0.83$
LMA2 is now excluded

Together with solar ν $\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5} eV^2; \tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$

Welcome to precision neutrino physics !