

**Measurement of Neutrino Oscillation with KamLAND:
Evidence of Spectral Distortion***

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Stanford University**

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***T.Araki et al. arXiv:hep-ex/0406035 June 13, 2004
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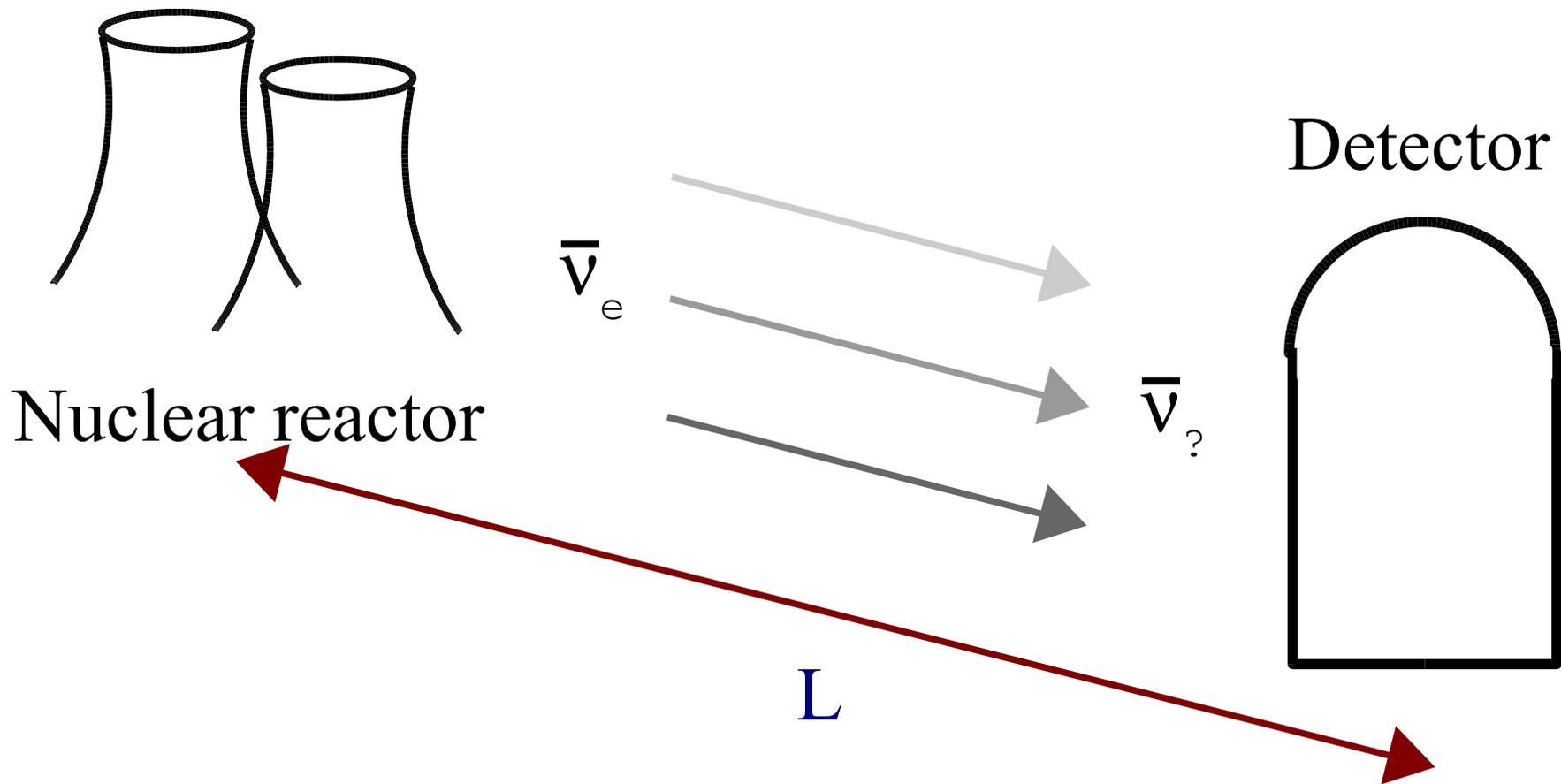
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Introduction

Reactor antineutrino experiments:
look for a flux deficit at a distance L



Neutrino Oscillations

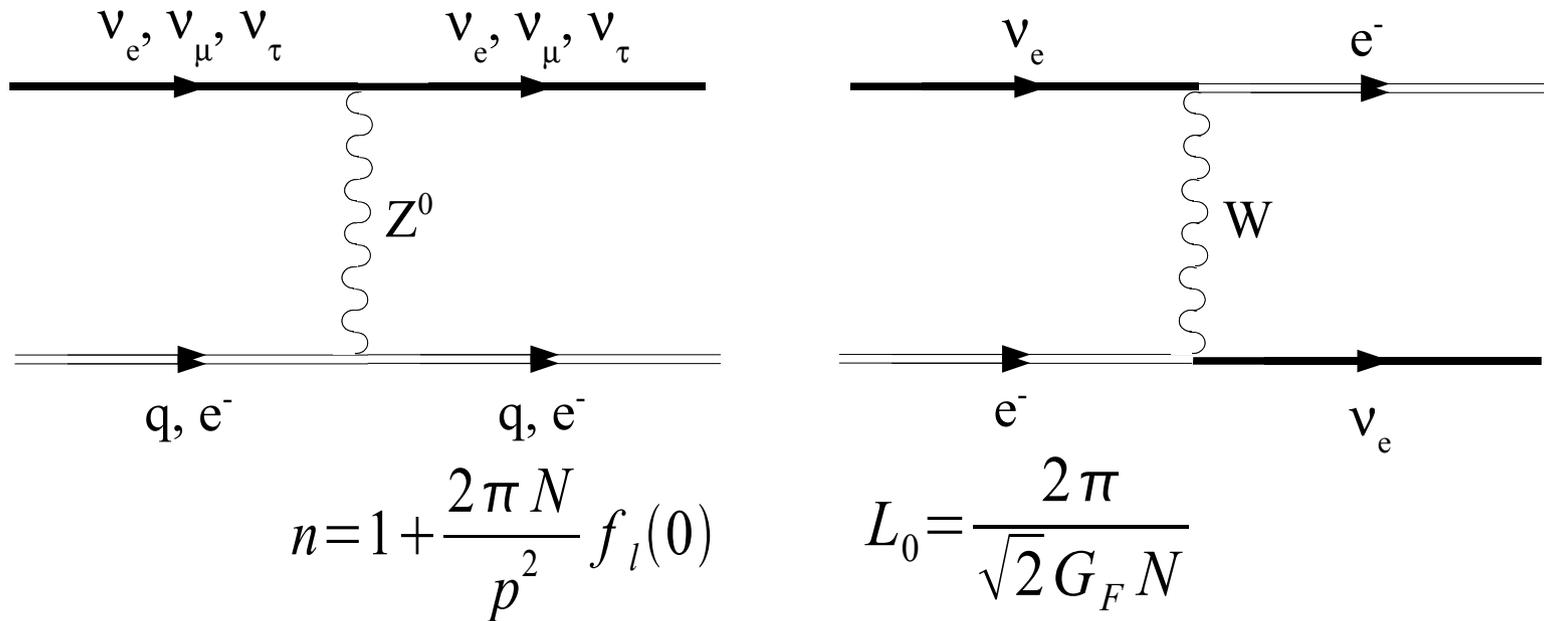
- Write the weak states ν_l as a linear combination of mass eigenstates ν_j :

$$\nu_l = \sum_j U_{lj} \nu_j$$

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

$$P(\nu_e \rightarrow \nu_e, L) = 1 - \sin^2 2\theta \sin^2 \frac{\pi L}{L_{osc}}; \quad L_{osc} \equiv \frac{\pi E}{1.27 \Delta m^2}$$

MSW Effect*



$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta_m \sin^2 \frac{\pi L}{L_m}$$

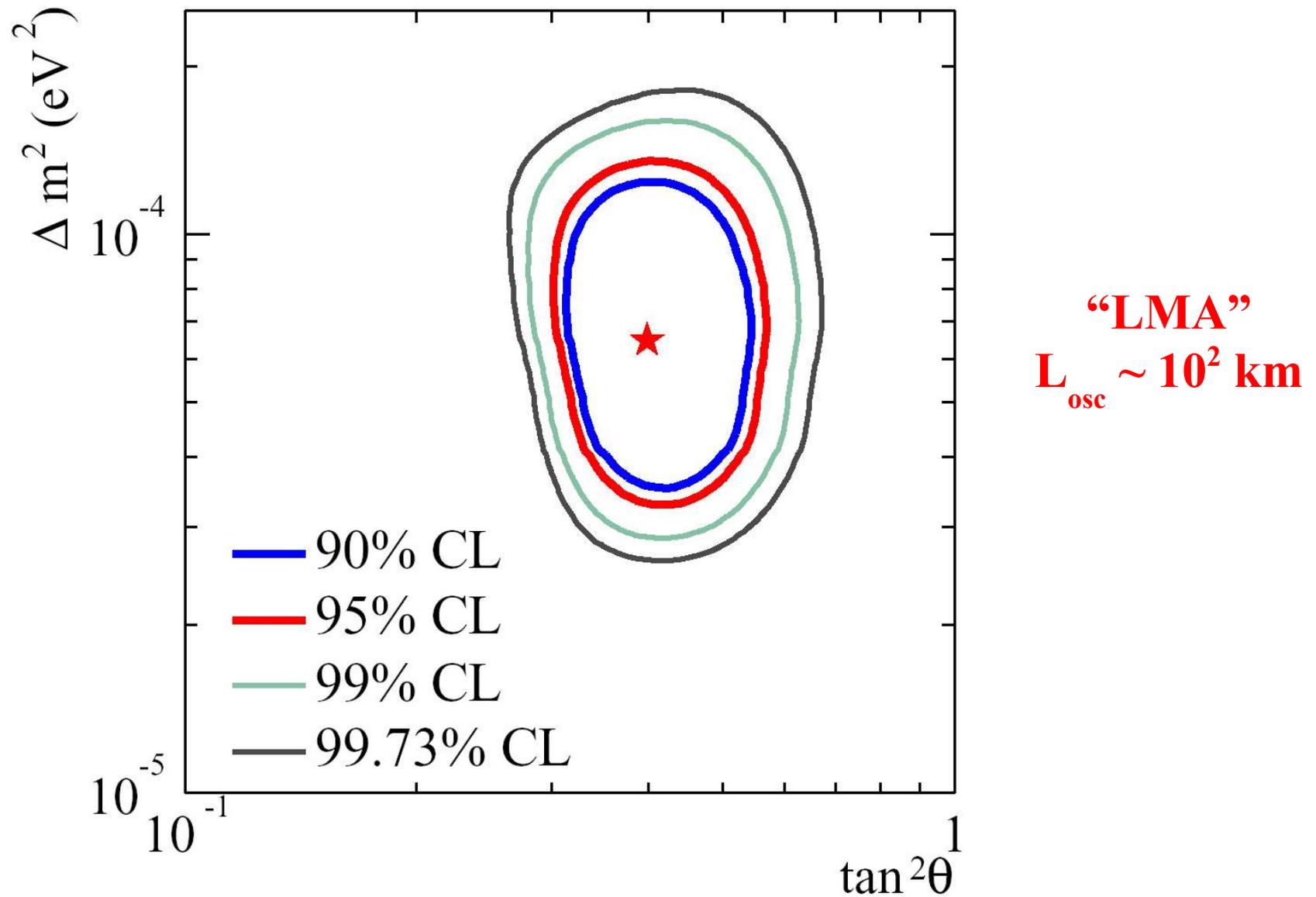
$$\tan 2\theta_m \equiv \tan 2\theta \left(1 + \frac{L_{osc}}{L_0} \sec 2\theta \right)$$

$$L_m \equiv L_{osc} \left[1 + 2 \frac{L_{osc}}{L_0} \cos 2\theta + \left(\frac{L_{osc}}{L_0} \right)^2 \right]^{-1/2}$$

* L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978)

S.P. Mikheev and A. Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985)

Solar Neutrino Oscillation Parameters



S.N. Ahmed *et al.* (SNO Collaboration), Phys. Rev. Lett. **92**, 181301 (2004)

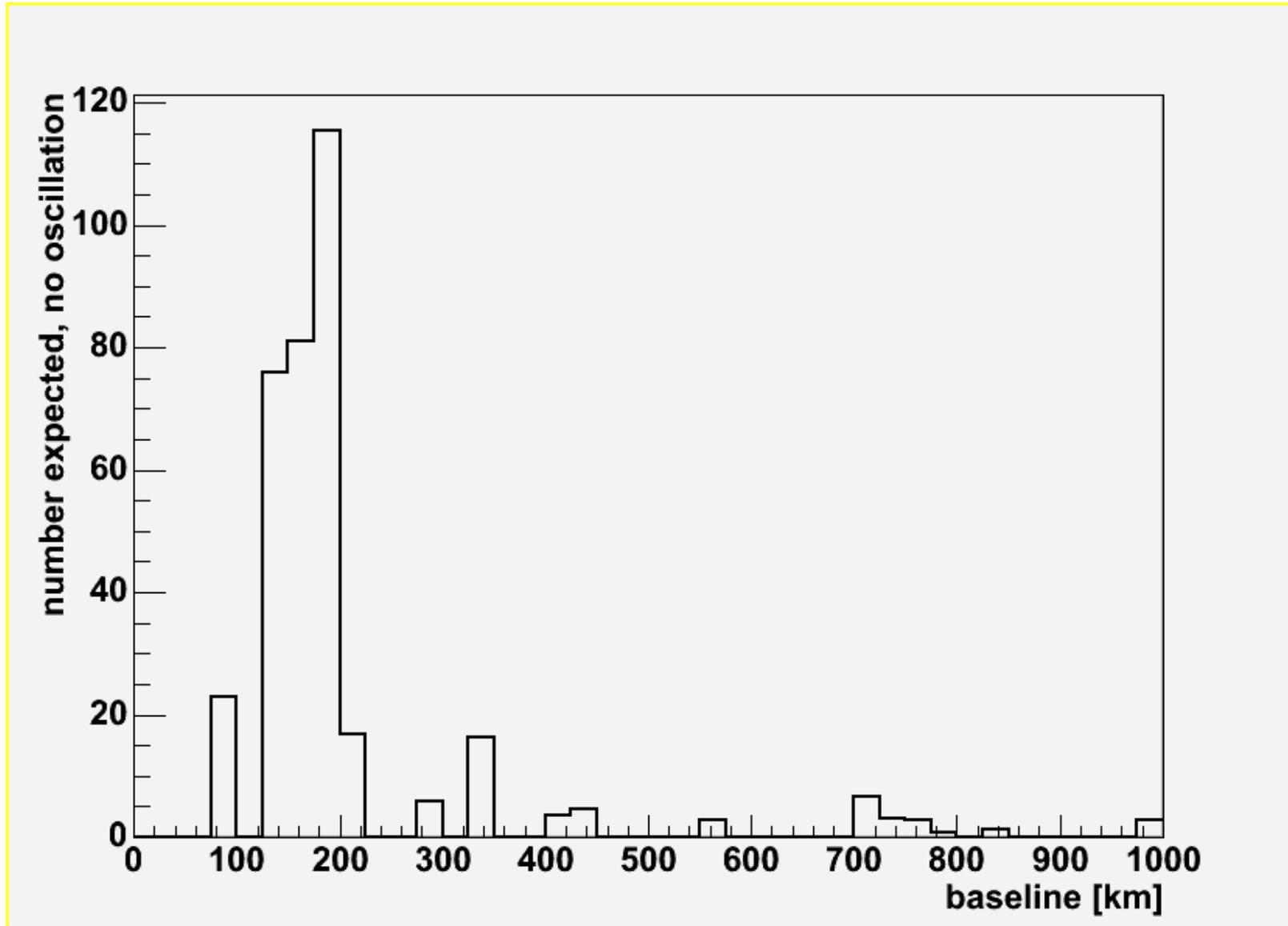
Reactor Experiments

- Control source and detector
- Rock has $L_0 > R_{earth} \rightarrow \frac{L_{osc}}{L_0} \ll 1$: Matter effects are negligible
- Detect *anti*-neutrinos instead of neutrinos

However...

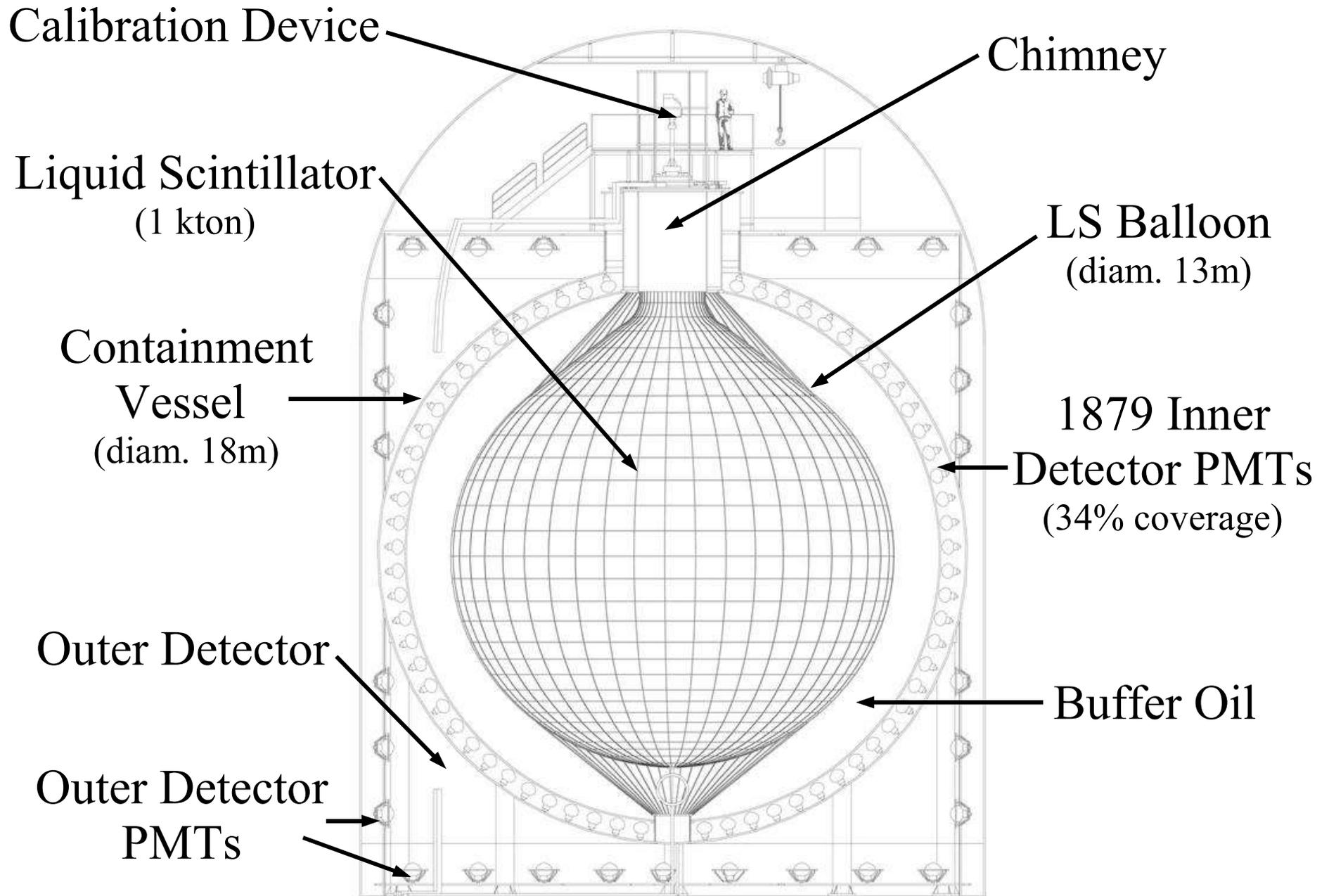
- Disappearance only \rightarrow limited θ sensitivity
- 4π source

Reactors In Japan

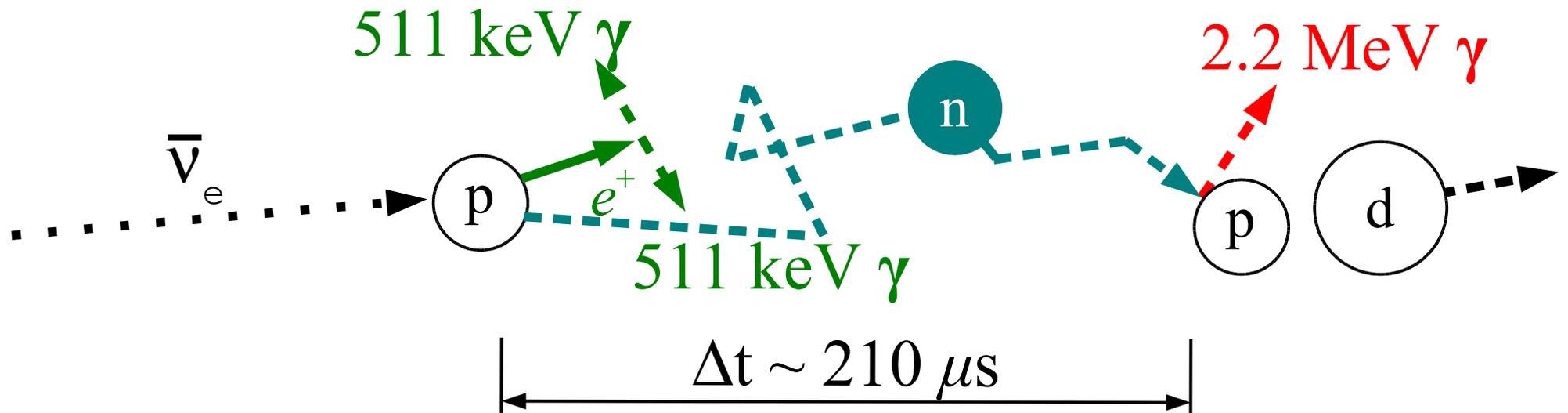
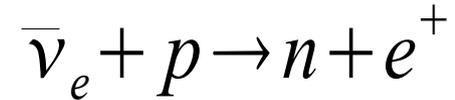


80% of total flux from baselines 140-210 km

The KamLAND Detector



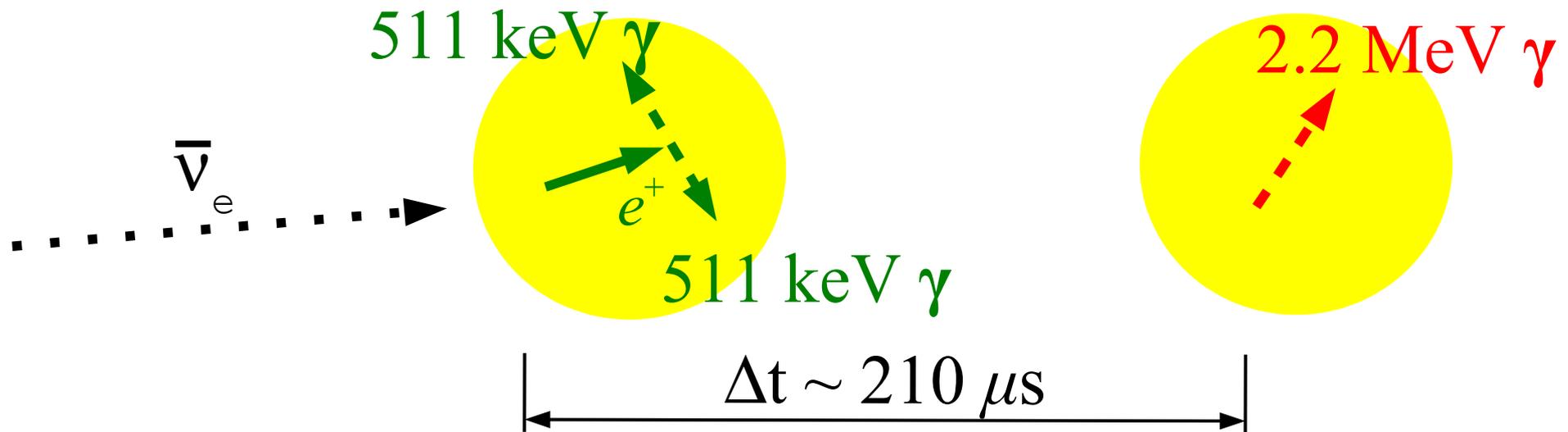
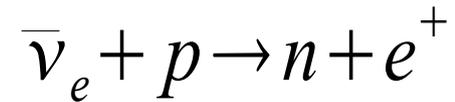
Event Signature



Coincidence signal: detect

- Prompt: e^+ energy + annihilation γ
- Delayed: n-capture γ

Event Signature

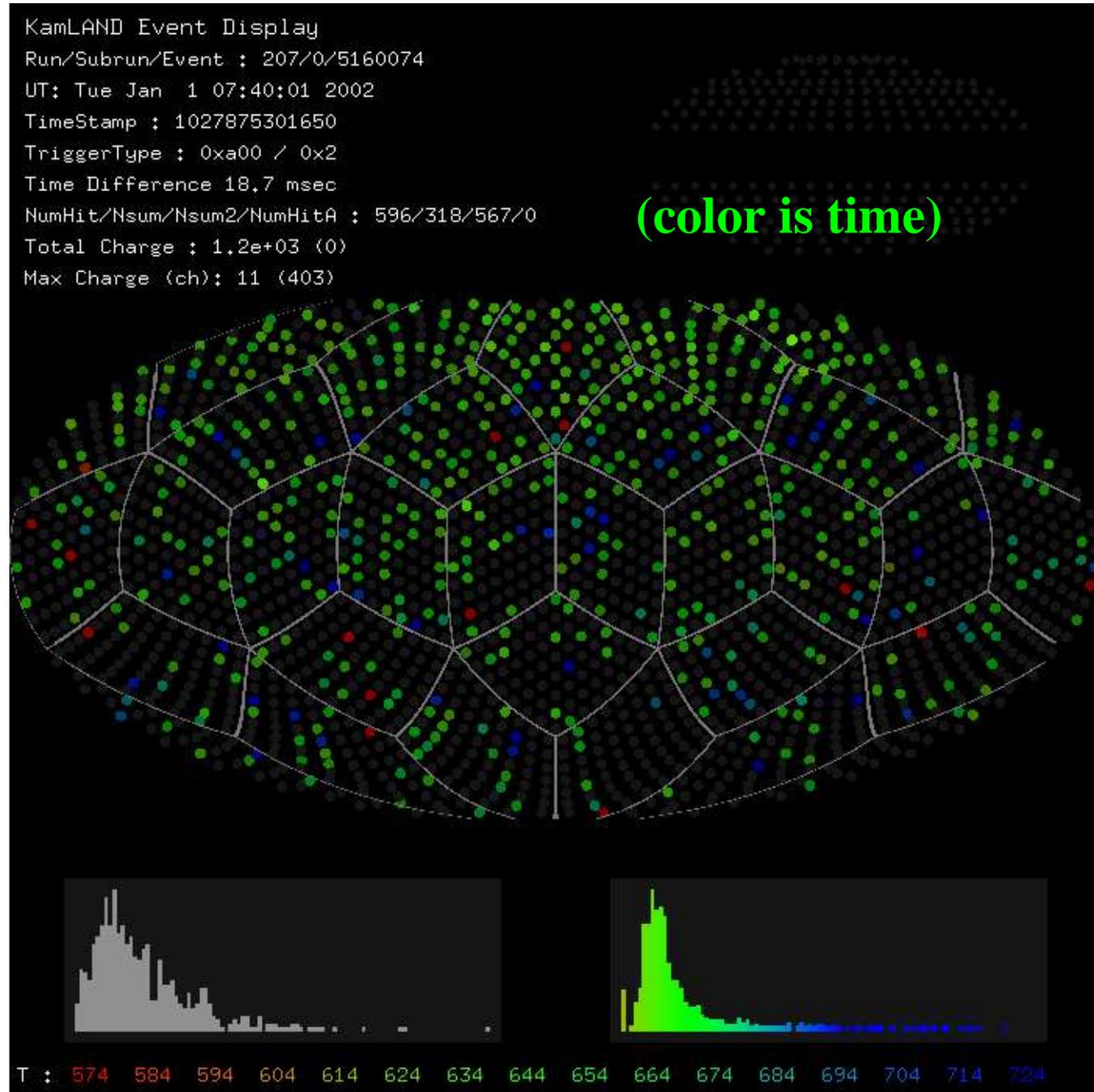


Coincidence signal: detect

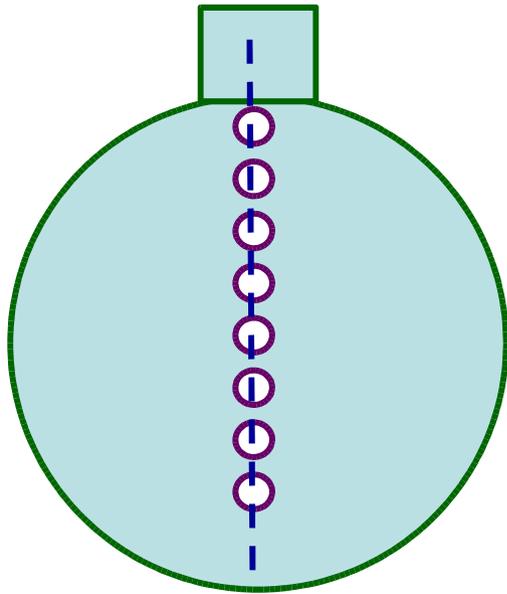
- Prompt: e^+ energy + annihilation γ
- Delayed: n-capture γ

Event Reconstruction

Reconstruct event
position and **energy**
from PMT-hit
timing and total
light collected

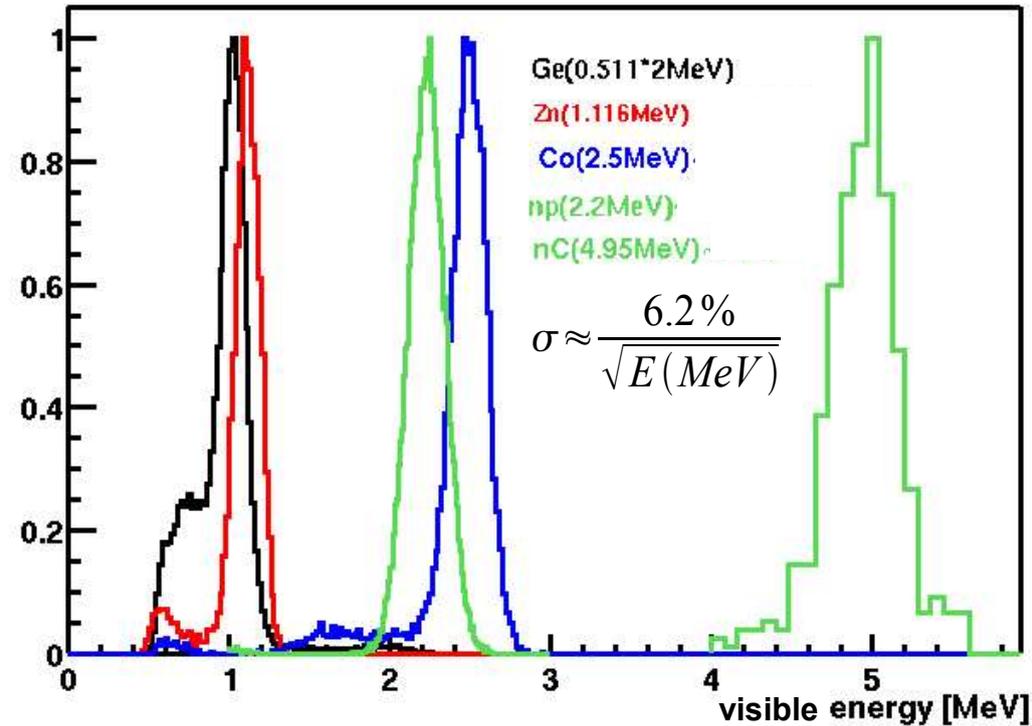
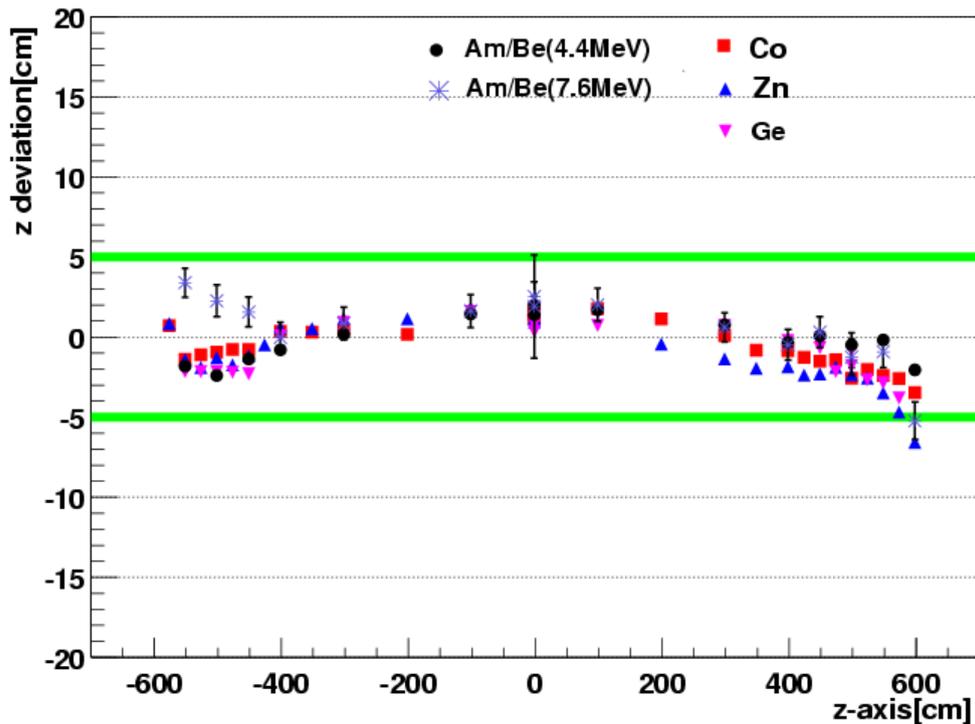


Calibration



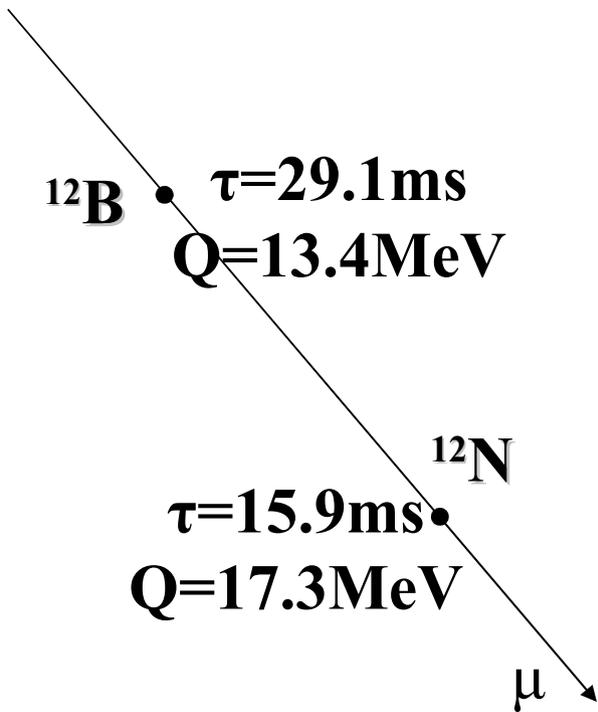
Calibrate energy and position reconstruction with radioactive gamma sources

z-axis dependence of z deviation

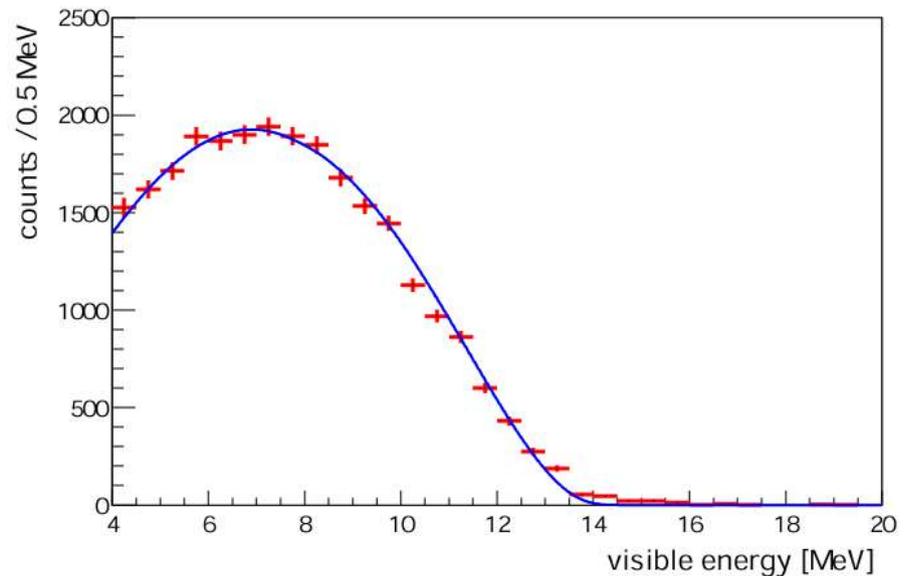
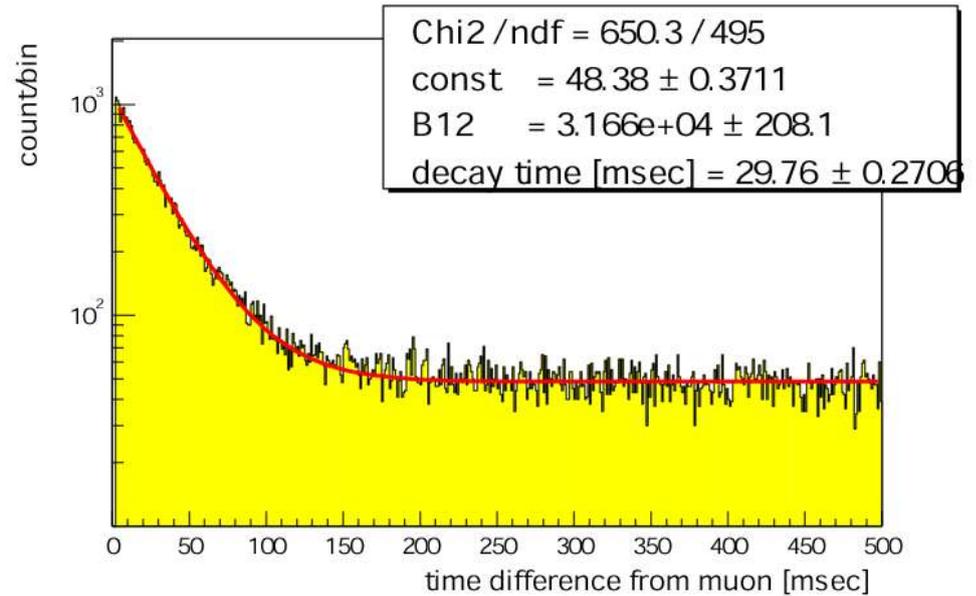


Calibration

Tagged cosmogenics are also used for calibration

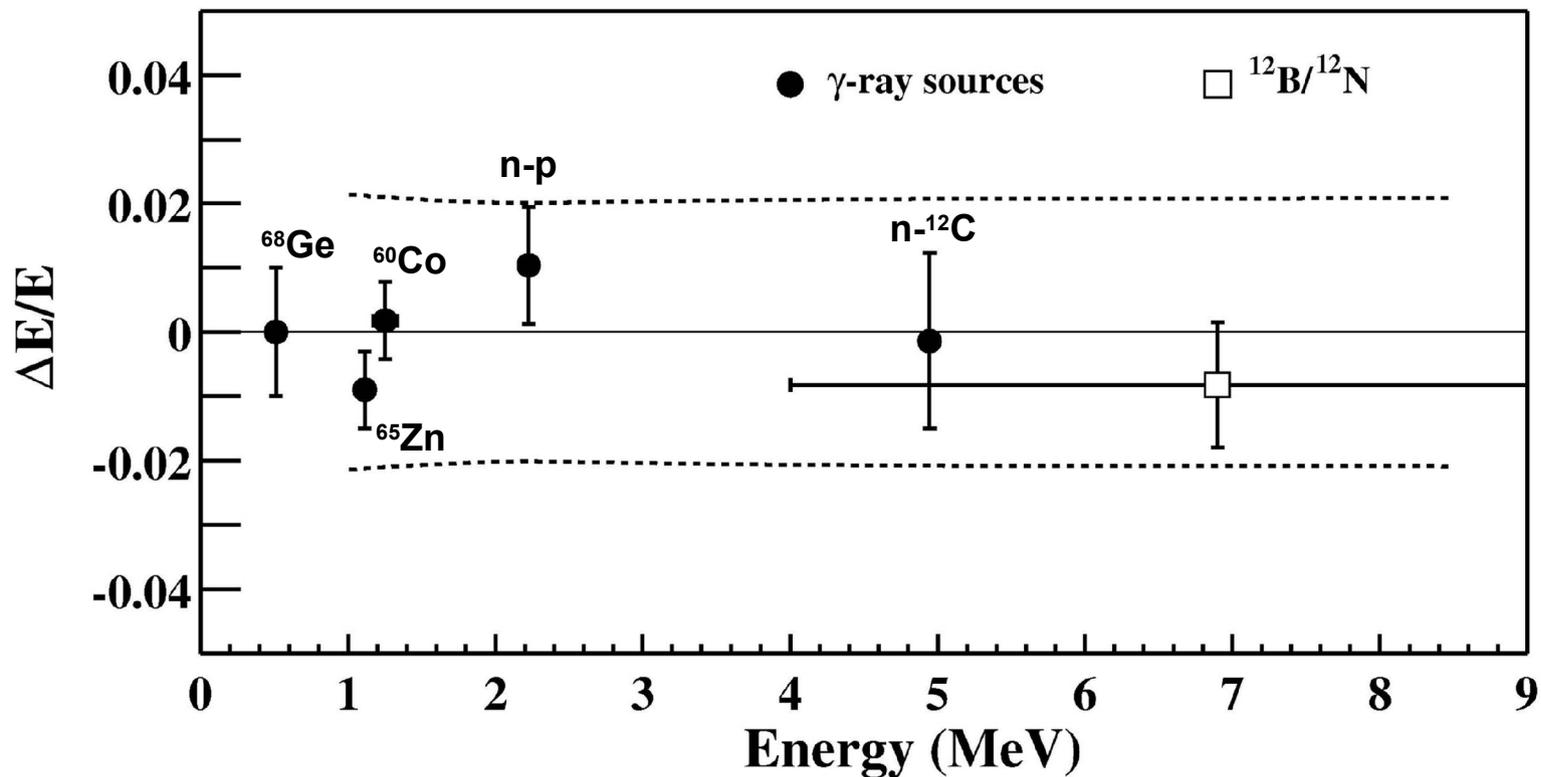


Fit to data gives $^{12}\text{B}:^{12}\text{N} \sim 100:1$

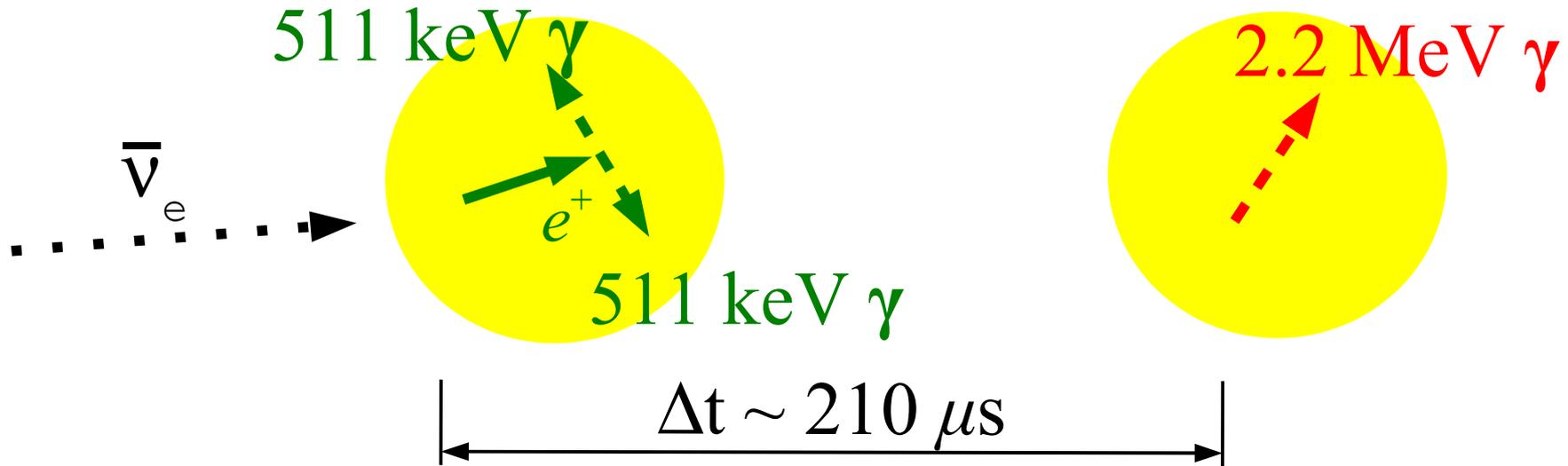


Energy Scale

Correct for Birk's quenching, Cherenkov emission, light absorption/optics



Event Selection



- Time correlation: $0.5 \mu s < \Delta t < 1 \text{ ms}$
- Vertex correlation: $\Delta R < 2 \text{ m}$
- Delayed event energy: $1.8 \text{ MeV} < E_d < 2.6 \text{ MeV}$
- Prompt event energy: $2.6 \text{ MeV} < E_p < 8.5 \text{ MeV}$
- Spherical fiducial volume: $R_p, R_d < 5.5 \text{ m}$

Total efficiency: $89.8 \pm 1.5 \%$

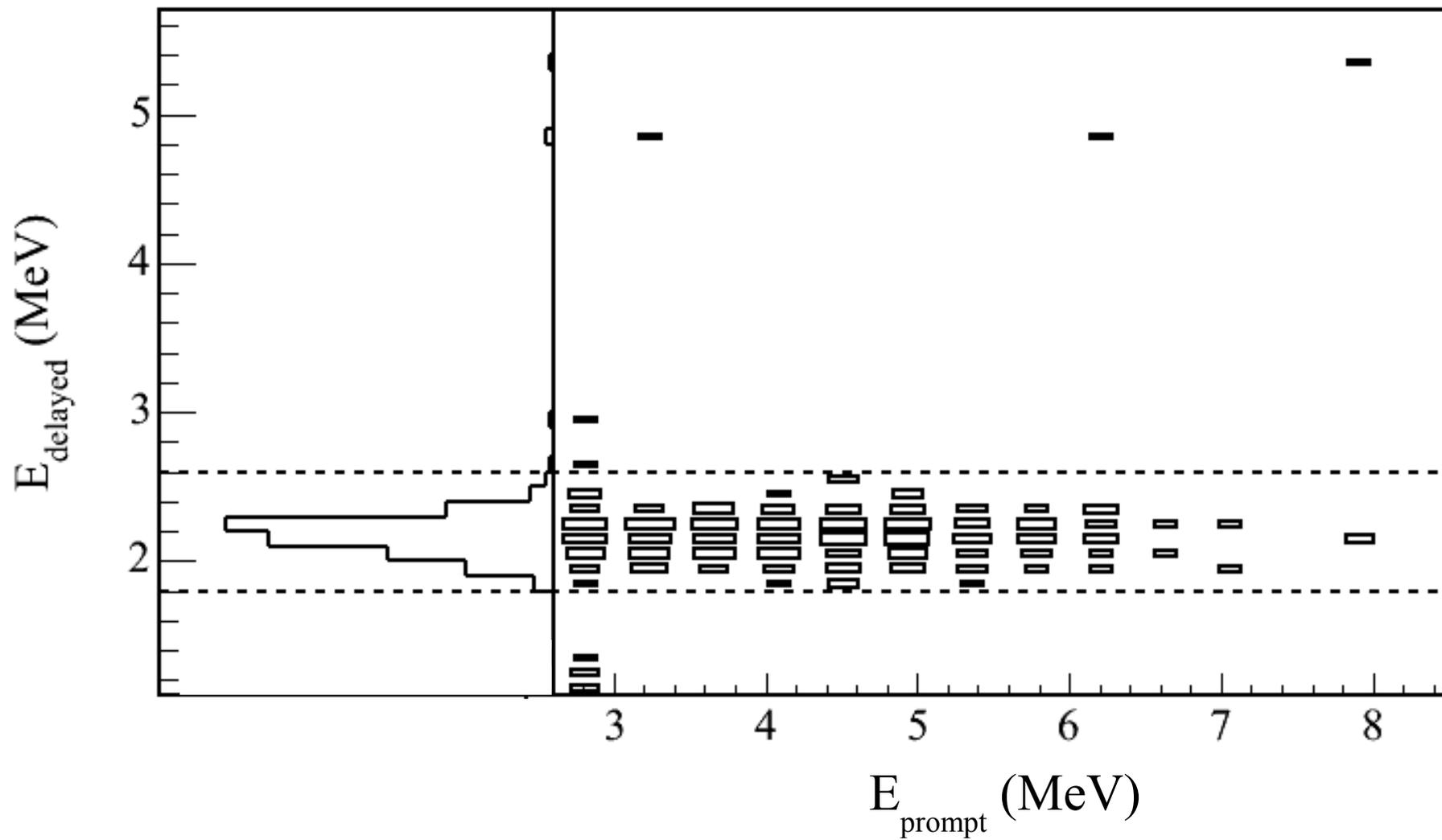
Data Collection

	Dates	Live time (days)
Start data taking	Jan 2002	-
Run A (data-set of 1 st 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

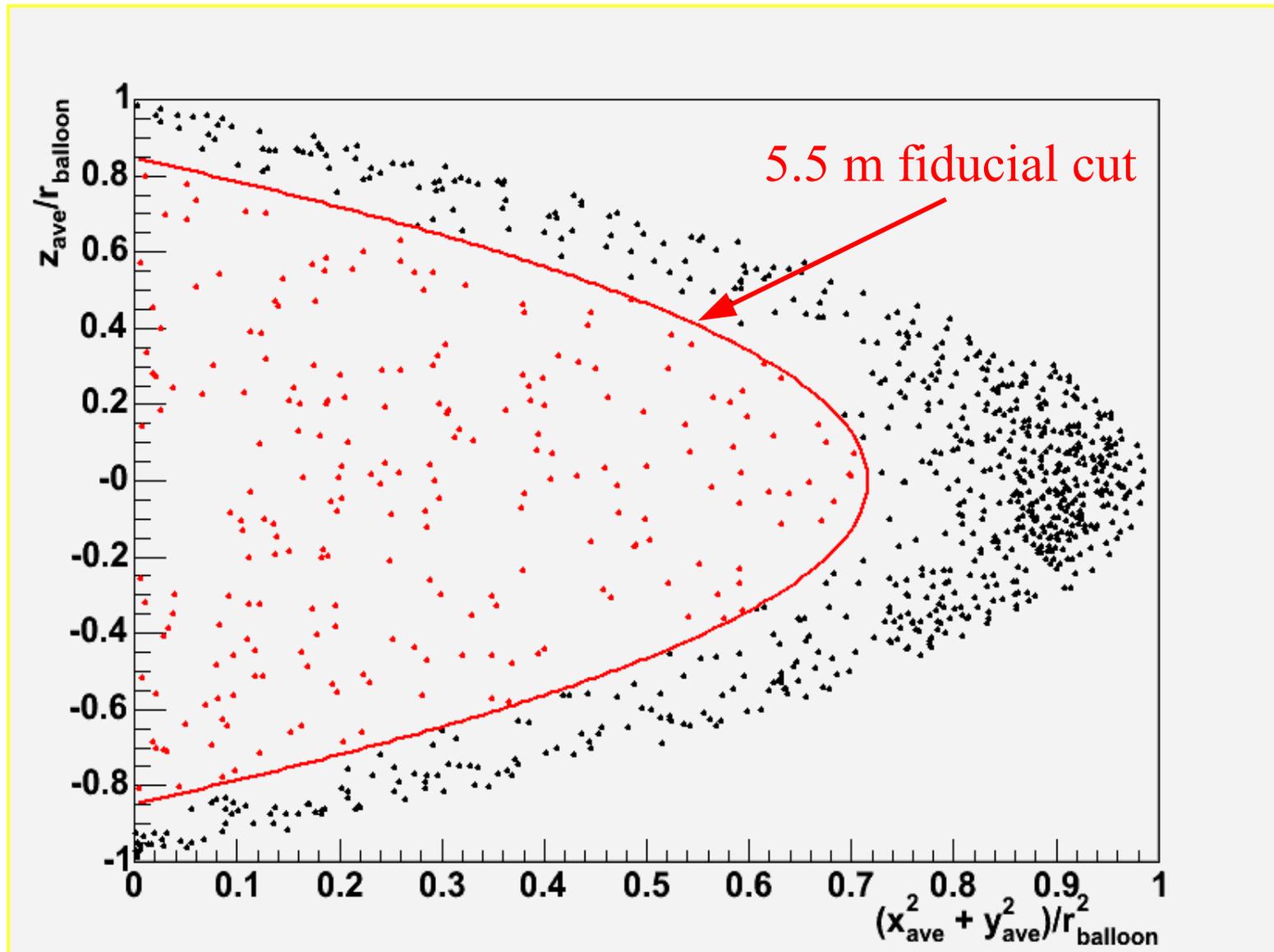
Exposure: **766.3 ton·yr** (4.7 times our previous result)

*K.Eguchi *et al.* (KamLAND Collaboration), Phys. Rev. Lett. **90**, 021802 (2003).

Prompt/Delayed Event Energies



Fiducial Cut

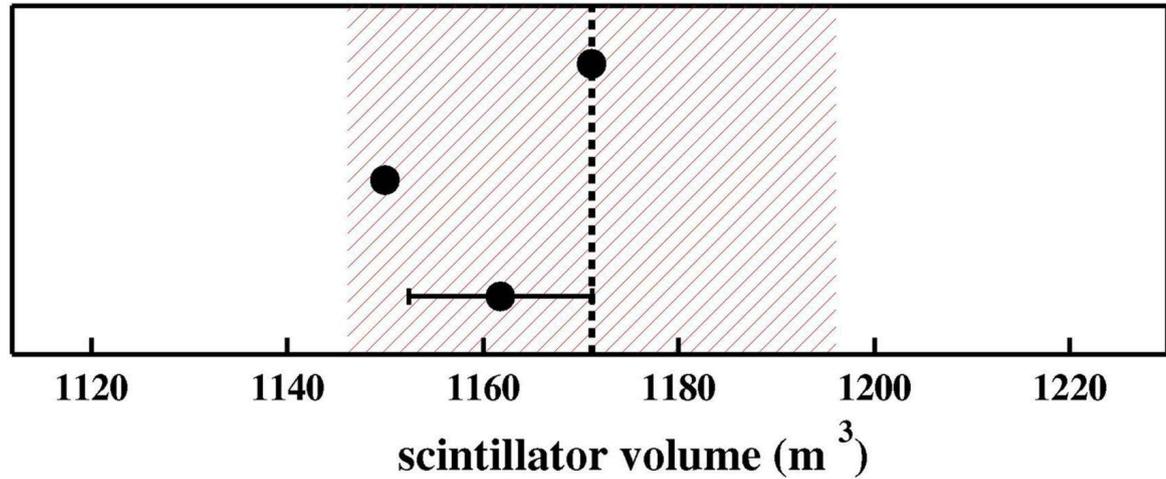


Fiducial Volume and Systematic

flow meter meas.

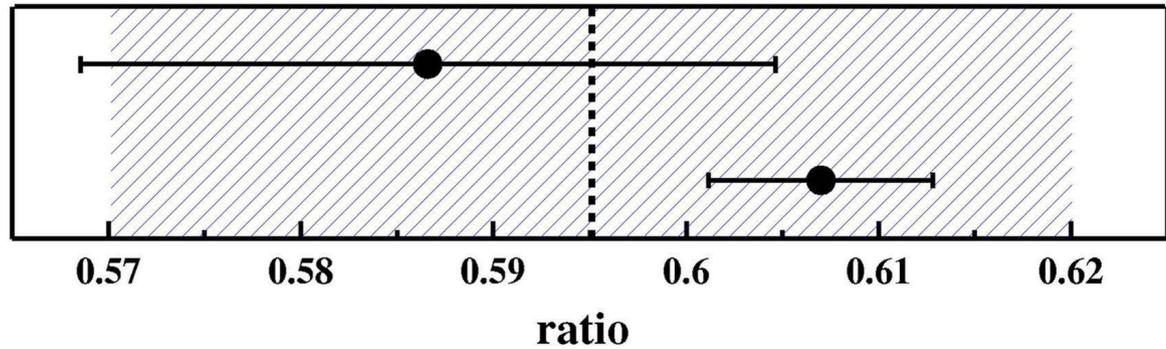
purification tank meas.

3,000 m³ tank meas.



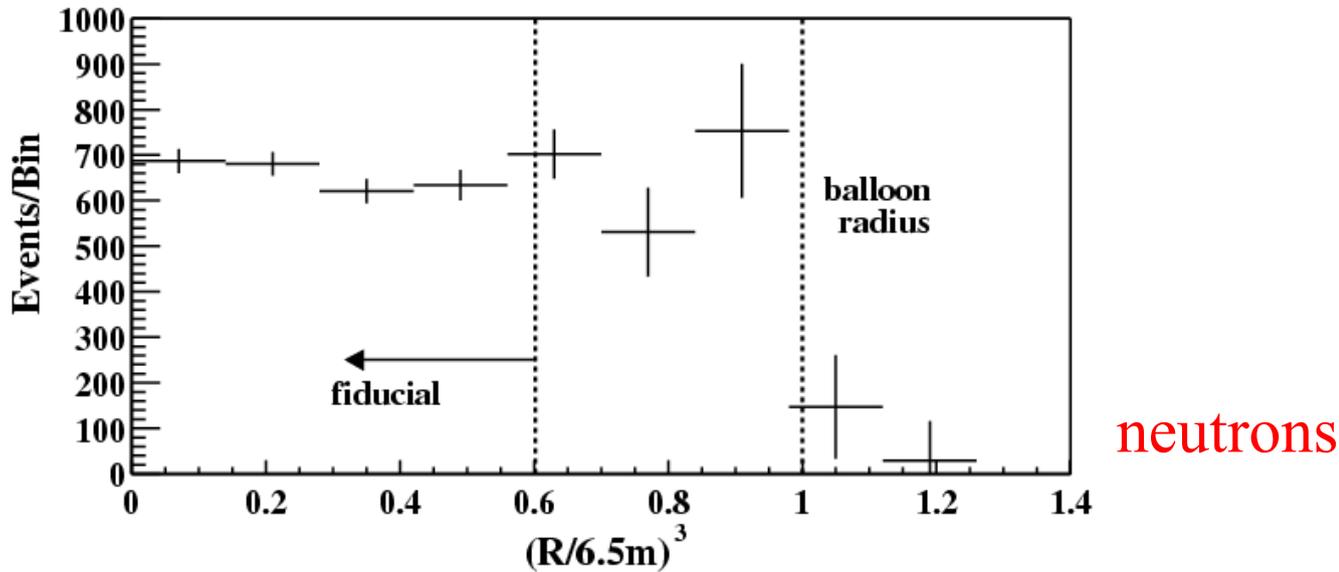
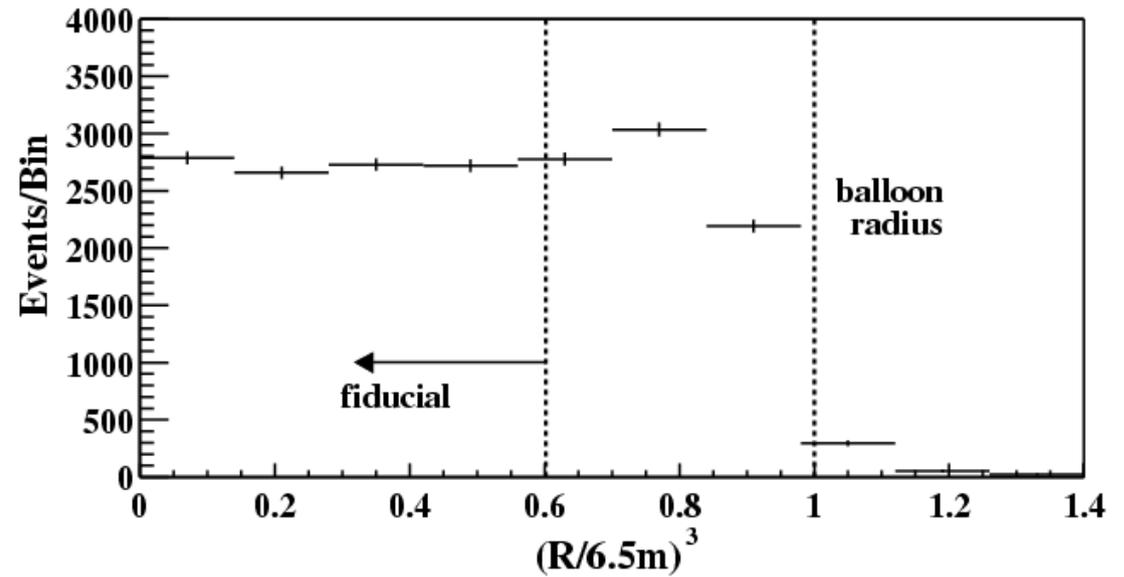
spallation neutrons

¹²B/¹²N



Fiducial Volume and Systematic

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



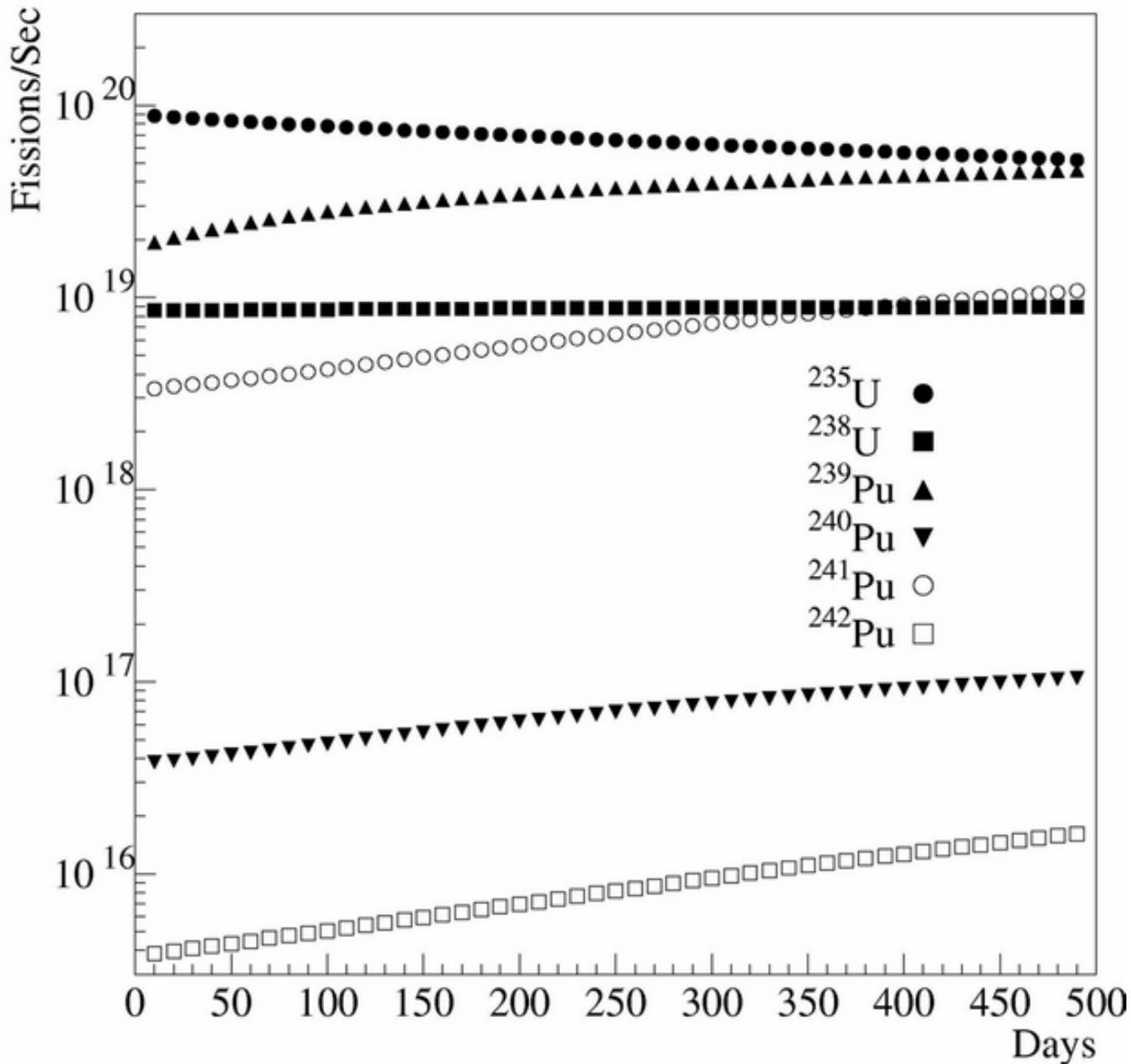
neutrons

Backgrounds

- Accidentals: 2.69 ± 0.02 events
 - off-time window selection
 - random event pairing
 - “swap” E_p/E_d cuts*
- Correlated backgrounds: spallation products
 - veto full detector for 2s after showering/bad- μ
 - apply 2s veto in 3m-radius tube along good- μ tracks
→ 9.7% correction to exposure
- Remaining correlated backgrounds:
 - $^8\text{He}/^9\text{Li}$: 4.8 ± 0.9 events
 - fast n: < 0.89 events
- Total Backgrounds: 7.5 ± 1.3 events

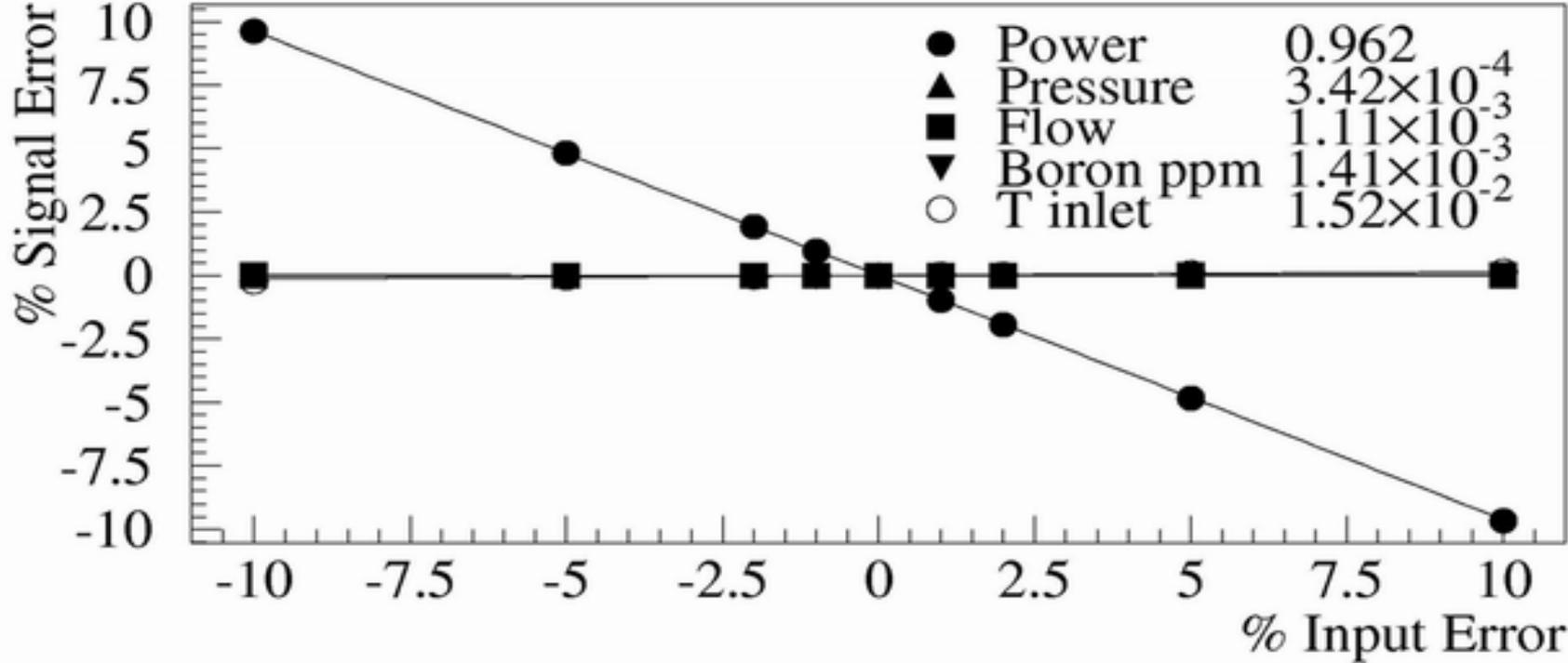
*Y.-F.Wang *et al.*, Phys. Rev. D **62**, 013012 (2000)

Reactor Fuel Cycle



$> 99.9\%$ of $\bar{\nu}_e$ are
produced by fissions of
 ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu

Simulation Inputs



Economics pushes the uncertainty on the power to < 1%

$\bar{\nu}_e$ Spectra

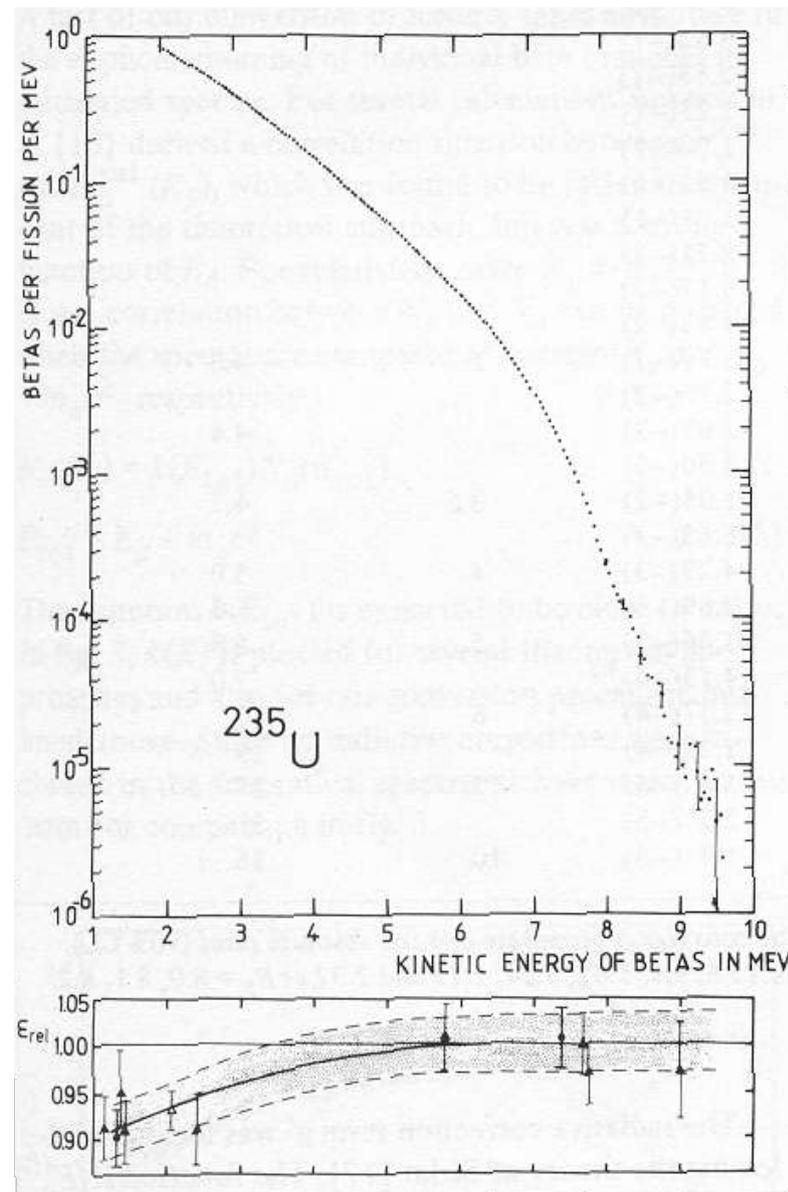
- ^{235}U , ^{239}Pu , and ^{241}Pu : $\bar{\nu}_e$ spectra are derived from β -spectra measurements

A. A. Hahn *et al.*, Phys. Lett. **B218**, 365 (1989)

K. Schreckenbach *et al.*, Phys. Lett. **B160**, 325 (1985)

- ^{238}U : no measurements are available, so we must rely on calculations

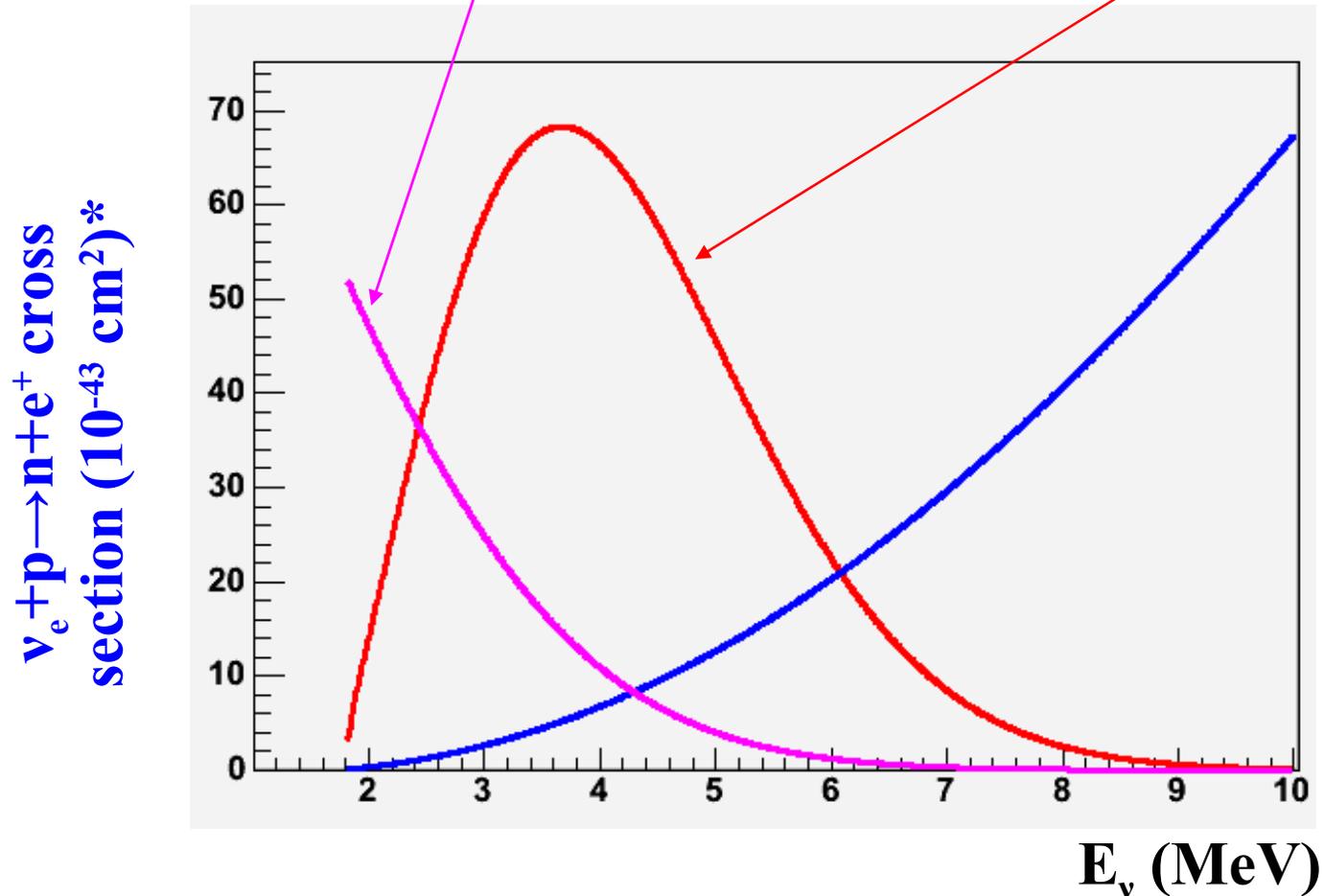
P. Vogel *et al.*, Phys. Rev. **C52** (2498)



The Detected $\bar{\nu}_e$ Spectrum

Reactor $\bar{\nu}_e$ spectrum (a.u.)

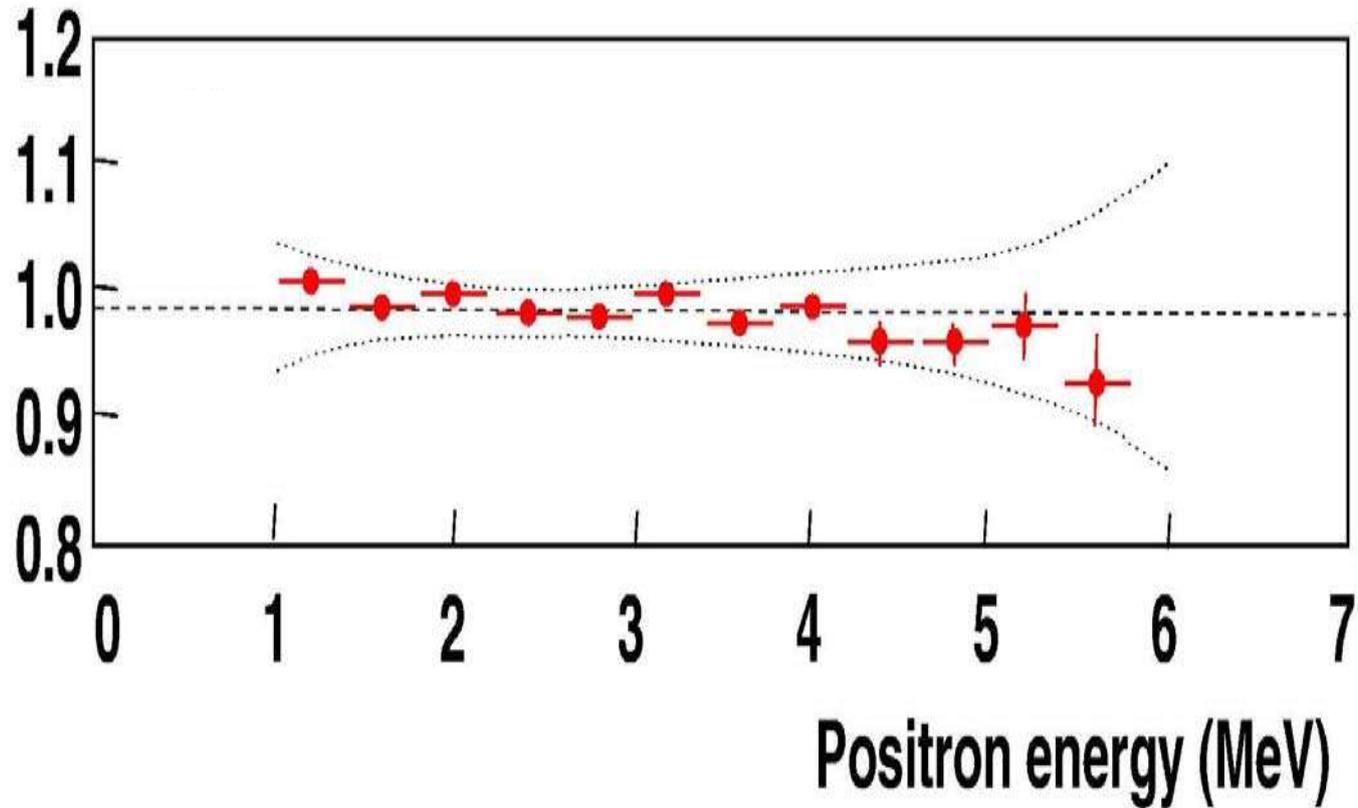
Observed spectrum (a.u.)



* P. Vogel and J. F. Beacom, Phys. Rev. **D60**, 053003 (1999)

Bugey 3

Short baseline ($L = 15$ m, 40 m), 1.5×10^5 events



B.Achkar *et al.*, Phys. Lett. B **374**, 243 (1996).

Bookkeeping...

Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($\text{cm}^{-2} \text{s}^{-1}$)	Rate noosc* ($\text{yr}^{-1} \text{kt}^{-1}$)	
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	

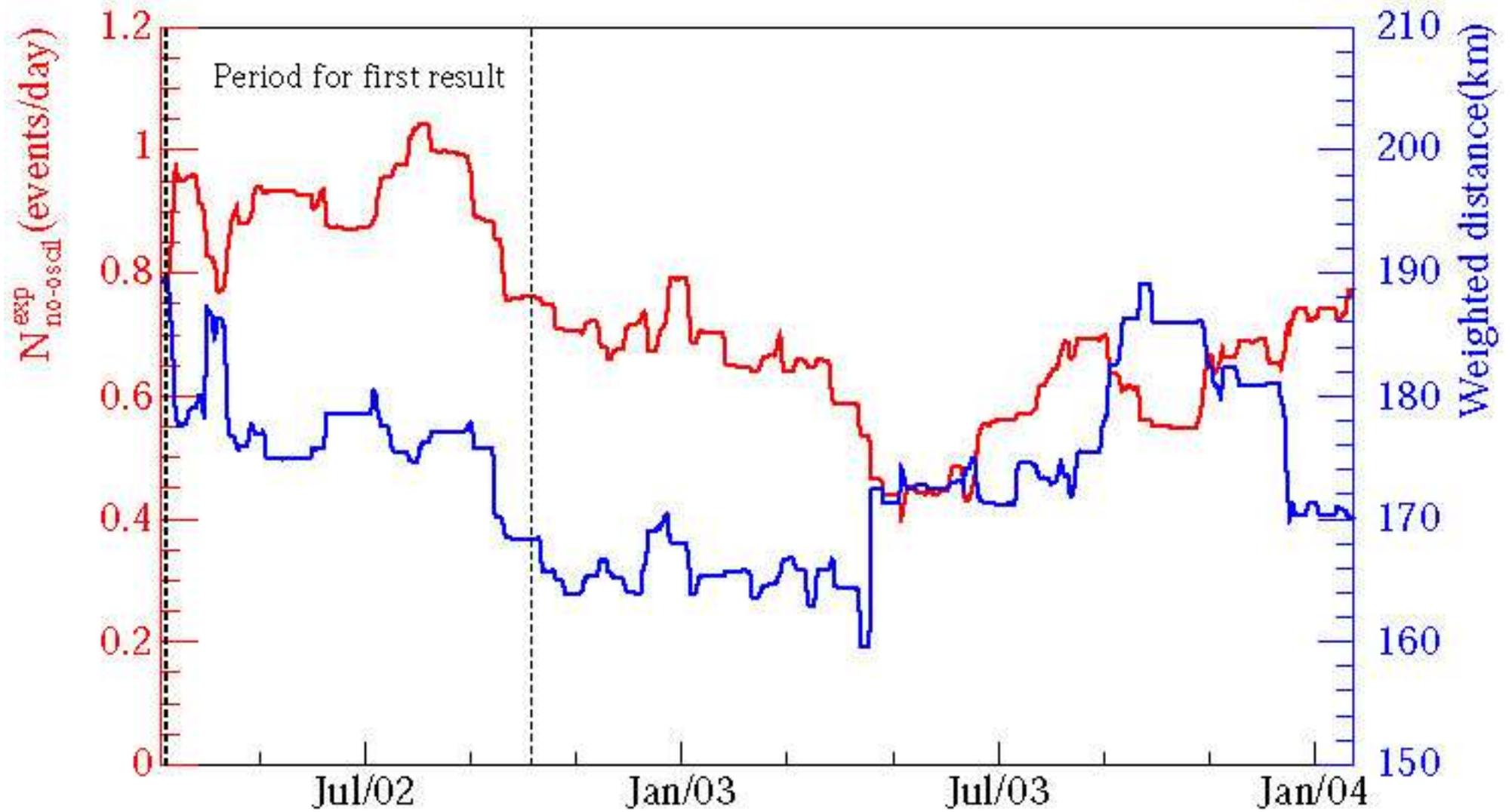
Japanese research reactors / spent fuel / rest of the world: $1.1 \pm 0.5\%$

Survival Probability

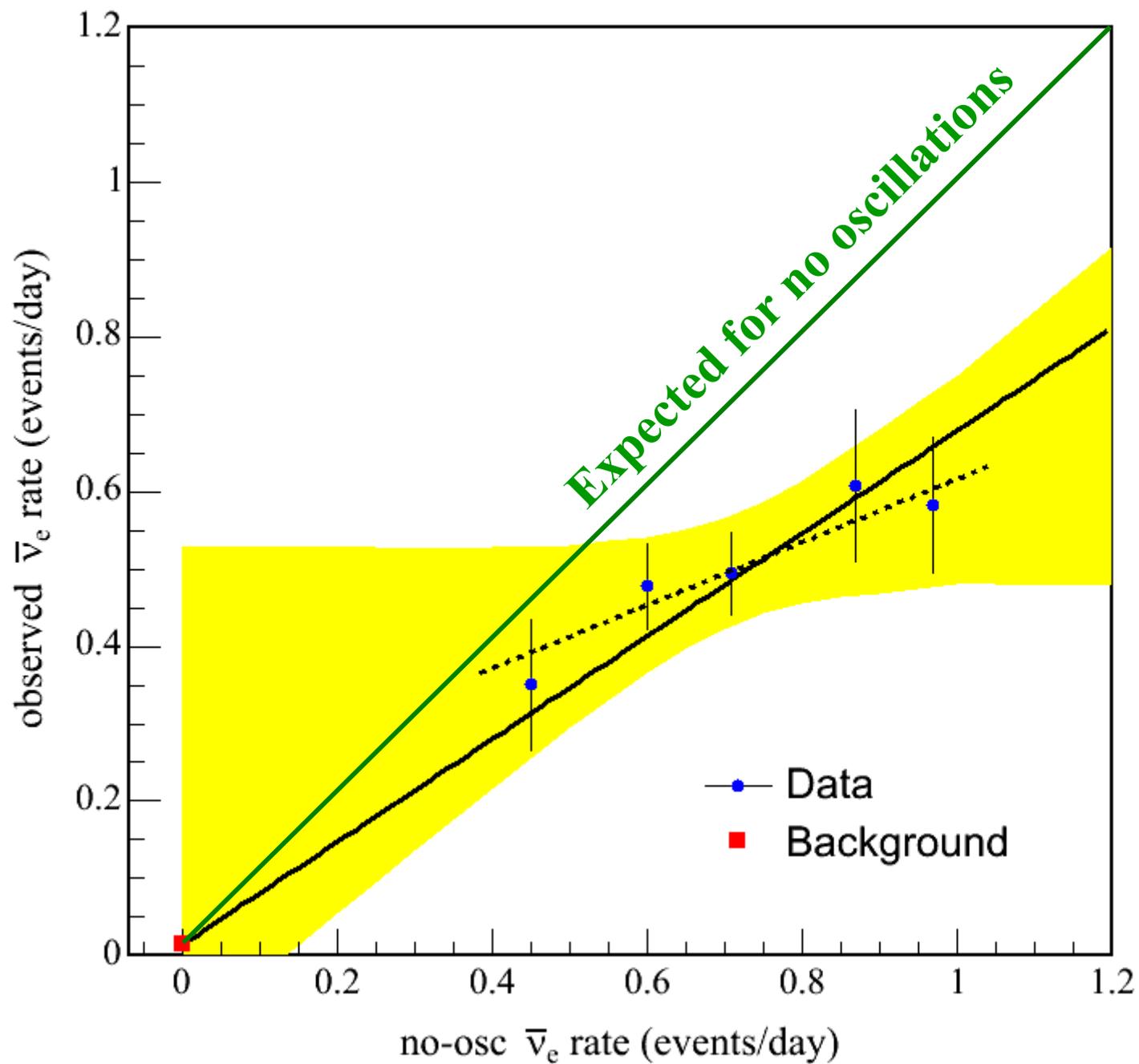
- Events observed: **258**
 - No oscillation expectation:
 365 ± 24 (syst)
 - Background: **7.5 ± 1.3**
 - Average survival probability:
 0.686 ± 0.044 (stat) ± 0.045 (syst)
- $\bar{\nu}_e$ disappearance at **99.995% C.L.**

Systematic	%
Scintillator volume	2.1
Fiducial fraction	4.2
Energy threshold	2.3
Efficiency of cuts	1.6
Live time	0.06
Reactor power	2.1
Fuel composition	1.0
Time lag	0.01
Antineutrino spectra	2.5
$\bar{\nu}_e$ - p cross section	0.2
Total systematic error	6.5%

Time Variation



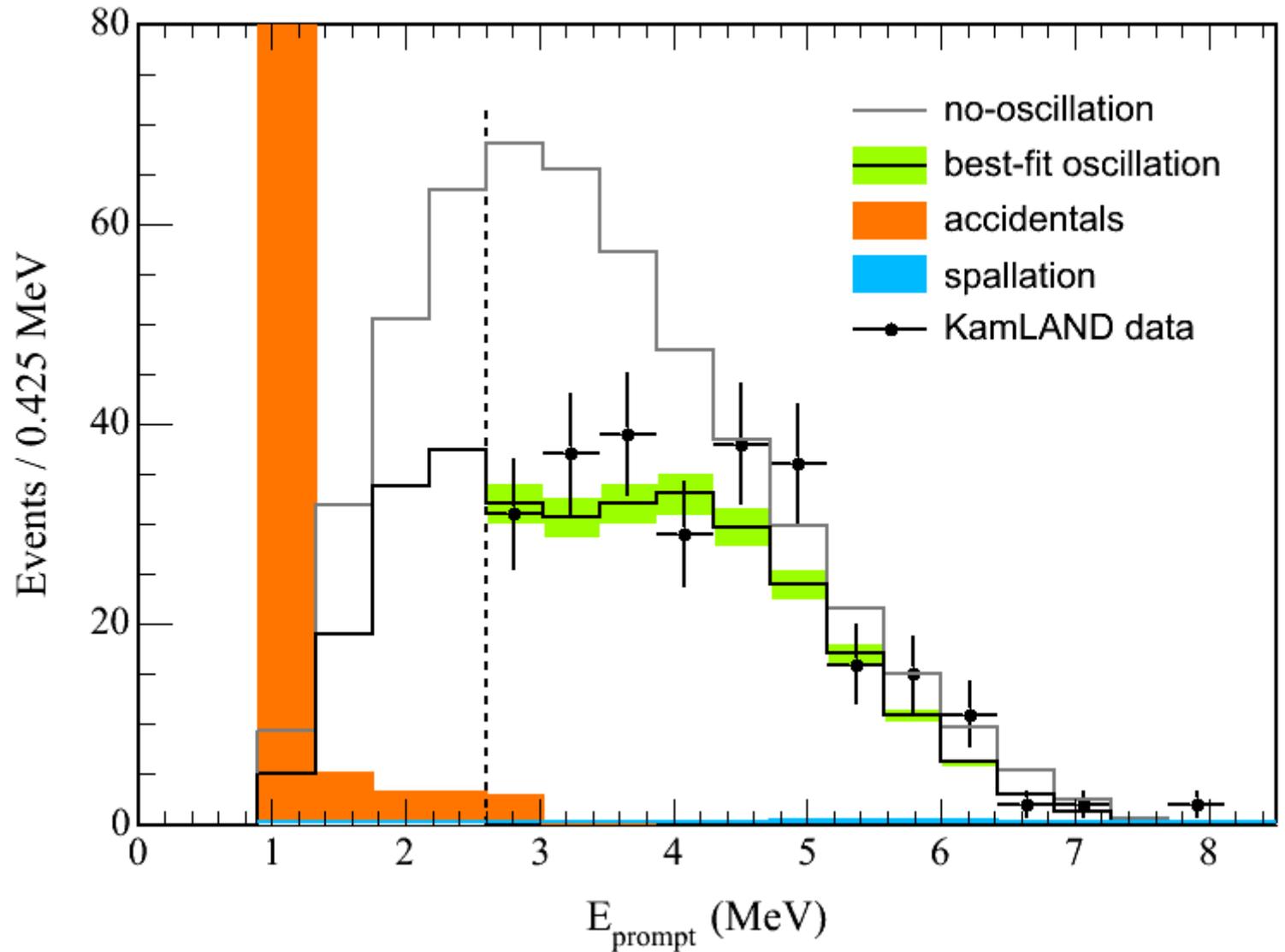
Source-Signal Correlation



Energy Spectrum

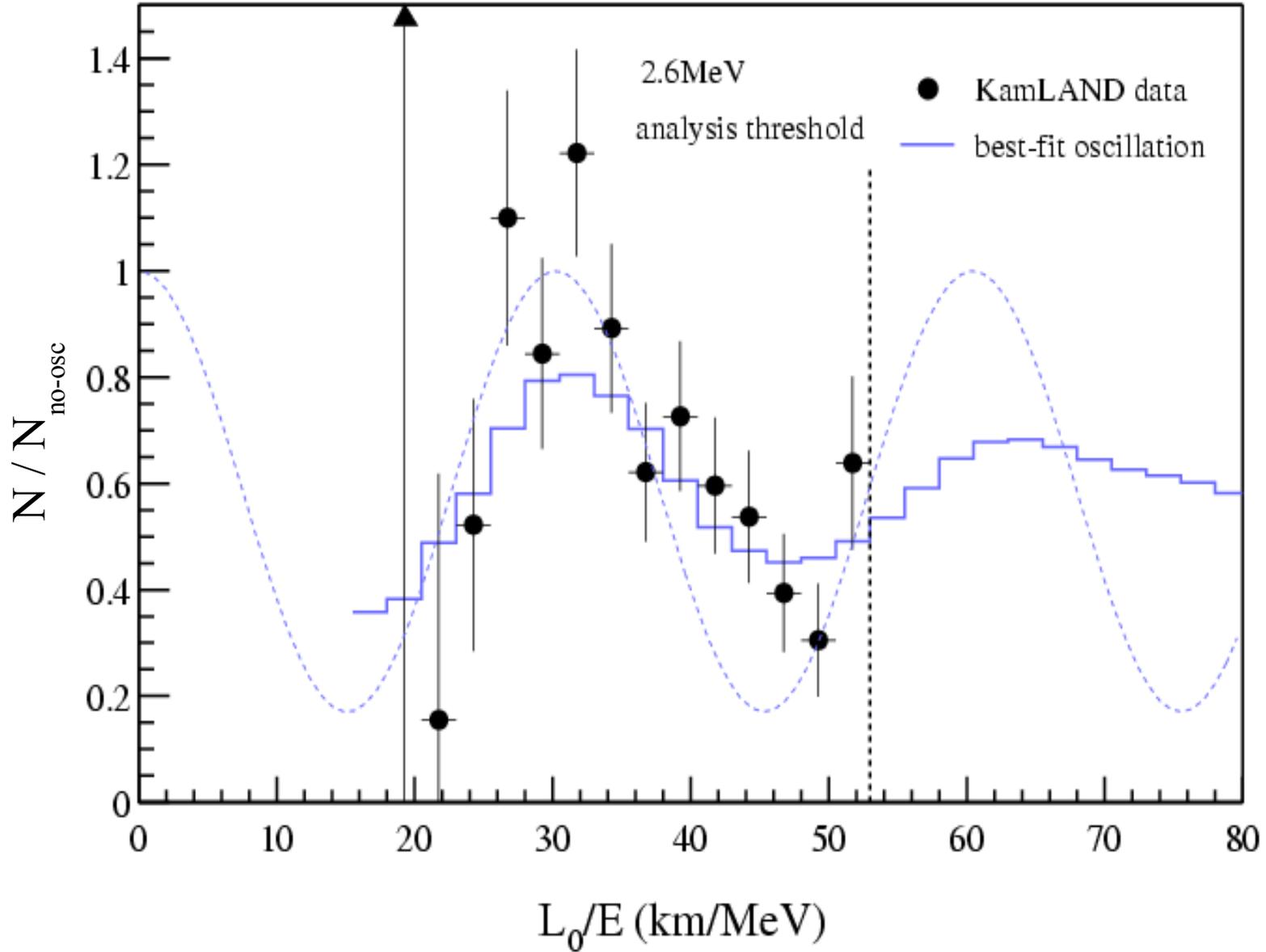
Best oscillation fit:
 $\Delta m^2 = 8.3 \times 10^{-5} \text{ eV}^2$
 $\sin^2 2\theta = 0.83$

χ^2 for 20 equal
probability bins:
18.3 (18 d.o.f.)

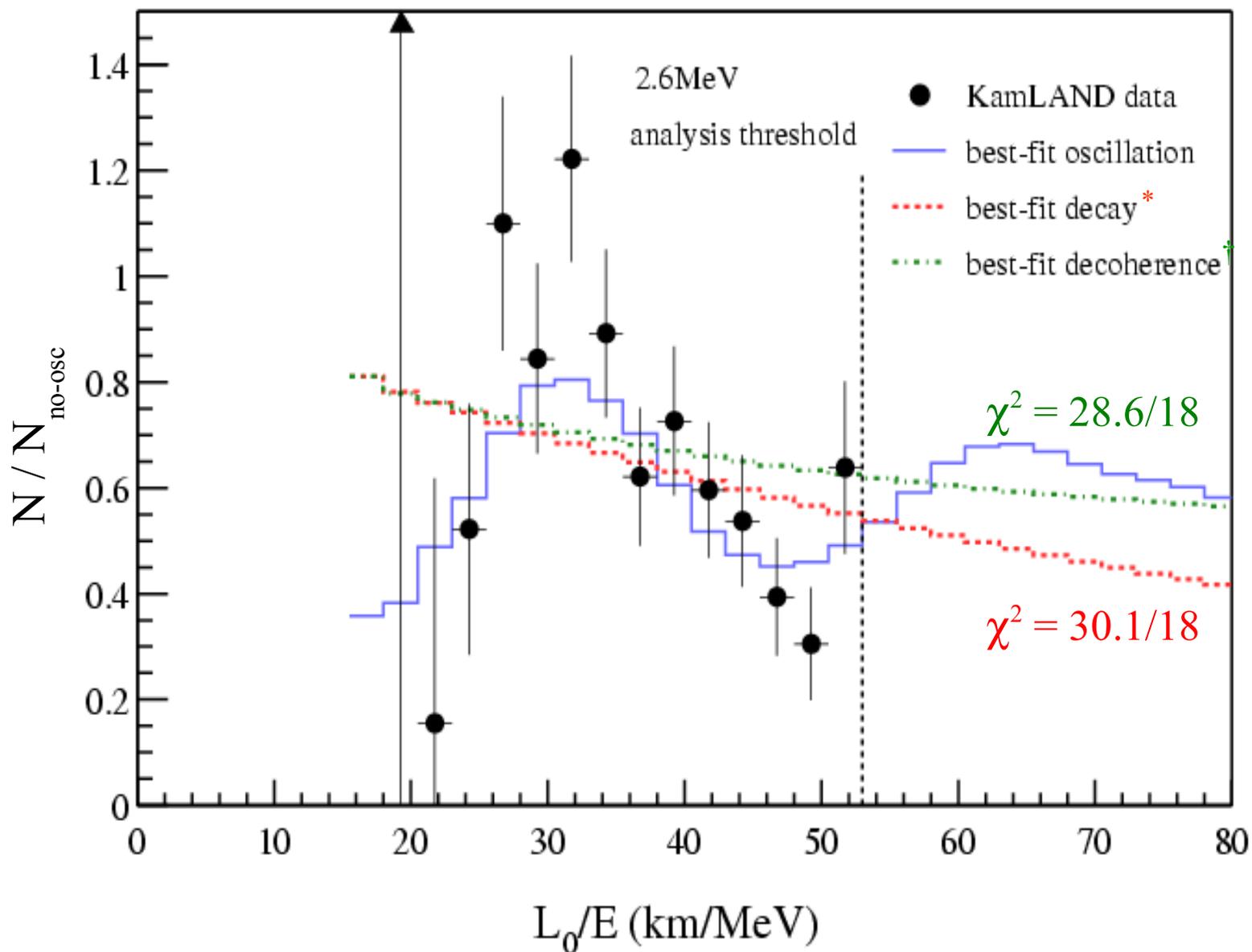


A rescaled no-oscillation spectrum is excluded at **99.89% C.L.**

L/E Spectrum



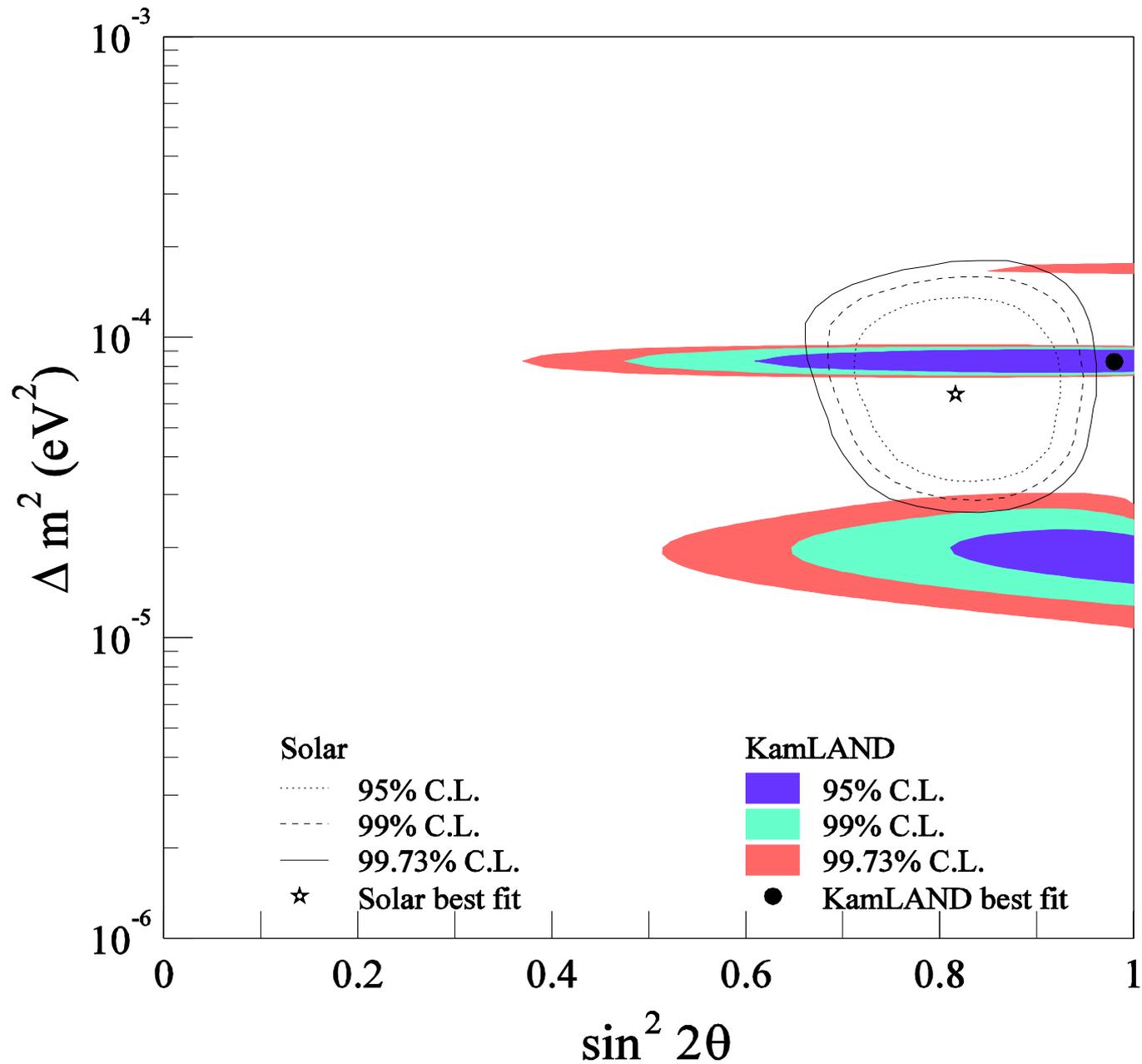
L/E Spectrum



*V.Barger et al. Phys. Rev. Lett. 82 (1999) 2640

†E.Lisi et al., Phys. Rev. Lett. 85 (2000) 1166

Shape-Only Contours



Best fit:
 $\Delta m^2 = 8.3 \times 10^{-5} \text{ eV}^2$
 $\sin^2 2\theta = 0.98$

Comparison with Previous Results

Previous result:

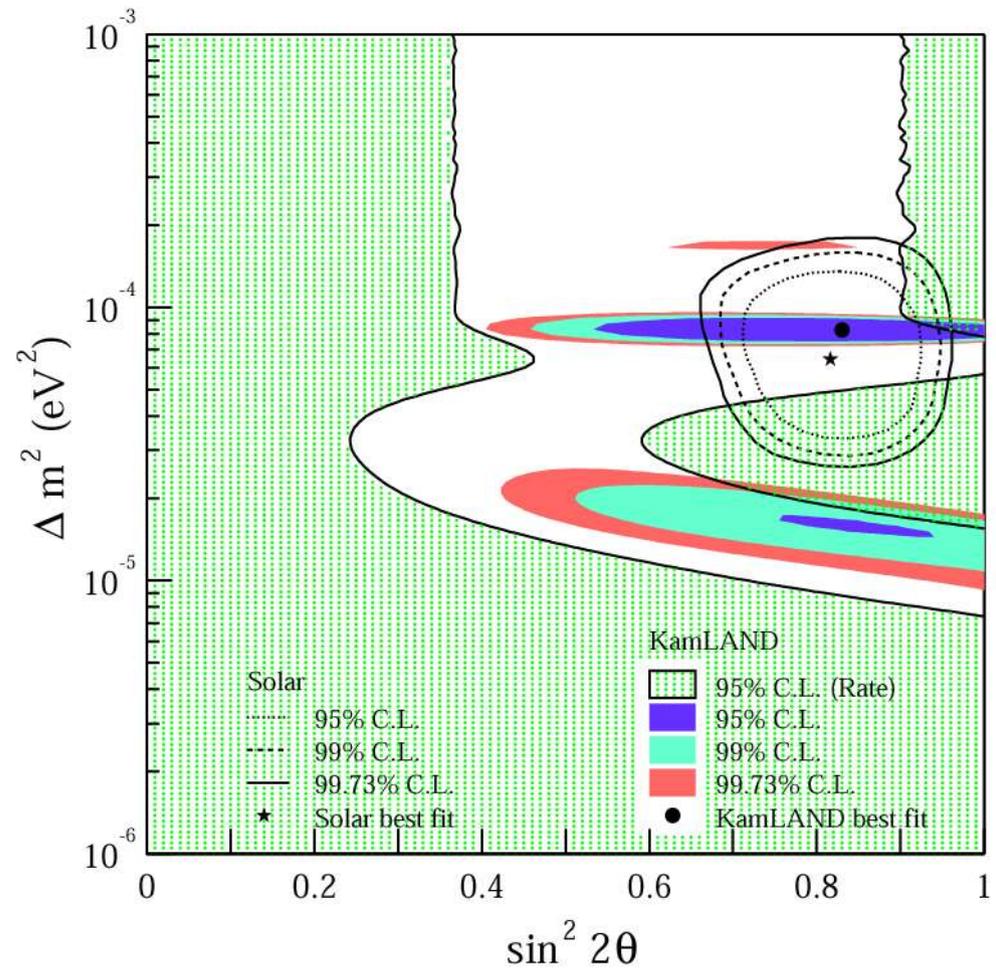
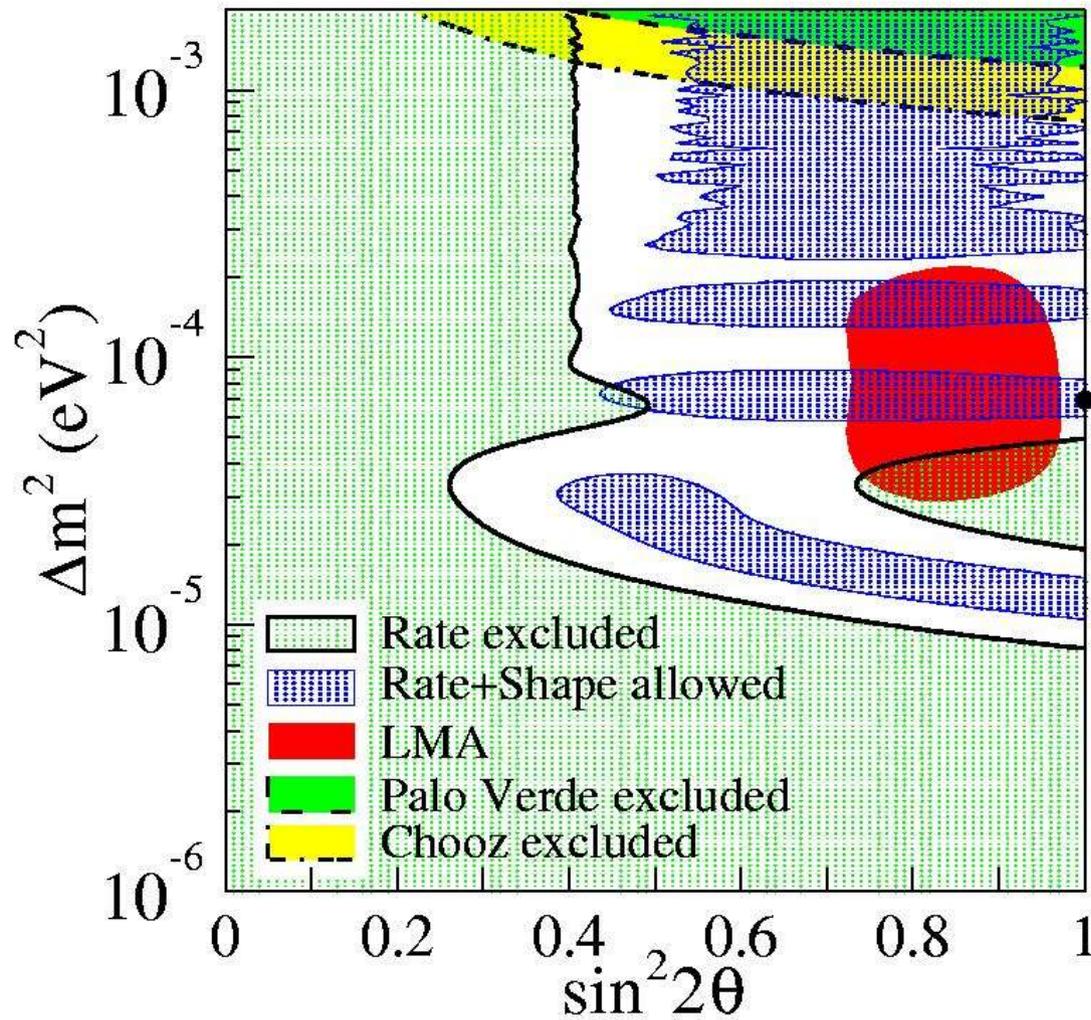
$$\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$$

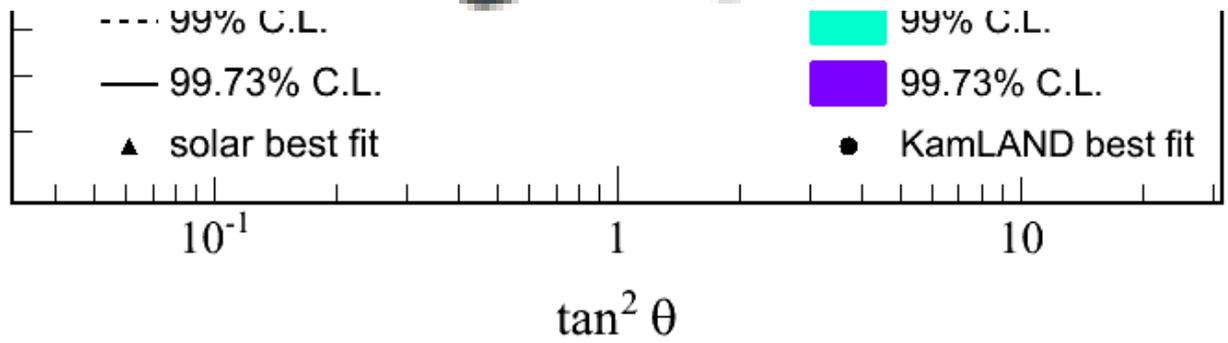
$$\sin^2 2\theta = 1.0$$

This result:

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

$$\sin^2 2\theta = 0.83$$

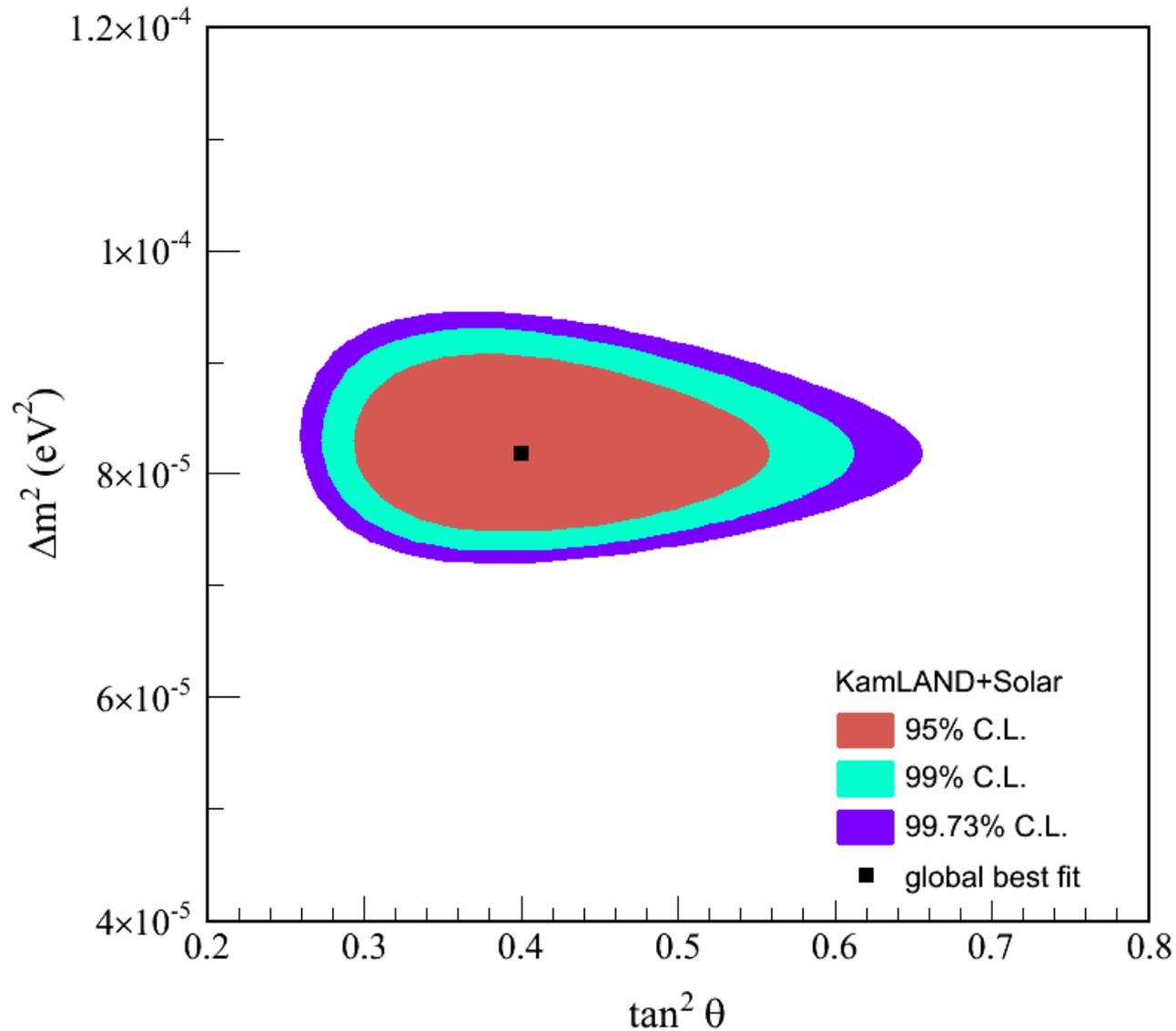




Global Solar + KamLAND Analysis

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

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



Conclusions

- Factor ~ 4.7 increase in exposure strengthens our previous findings of antineutrino disappearance
- Correlated variation of the signal with source modulations observed at a moderate C.L.
- Fit to neutrino oscillation is decent, while fits to no-oscillation, rescaled no-oscillation, decay, and decoherence are poor due to significant spectral distortion
- Global solar + KamLAND analysis excludes LMA II and gives a precision measurement of the oscillation parameters
- Statistics are on the same level as systematics; future work will focus on reducing systematics
- Stay tuned for more physics from KamLAND!