Recent Results from KamLAND

Jason Detwiler

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December 15, 2003

The KamLAND Collaboration

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University of Tennessee

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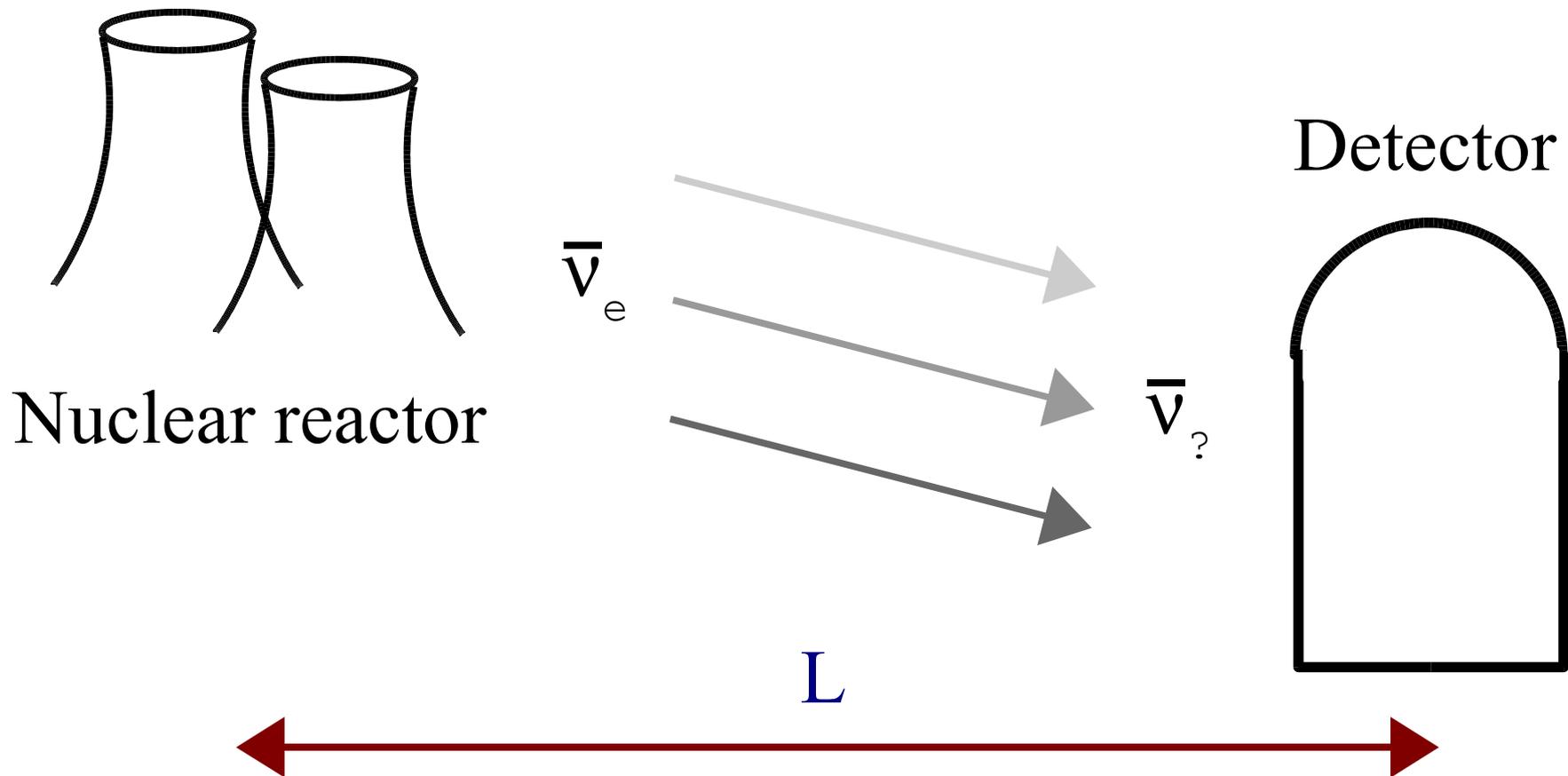
TUNL

Y-F.Wang

IHEP, Beijing

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

Detector

$\overline{\nu}_e$

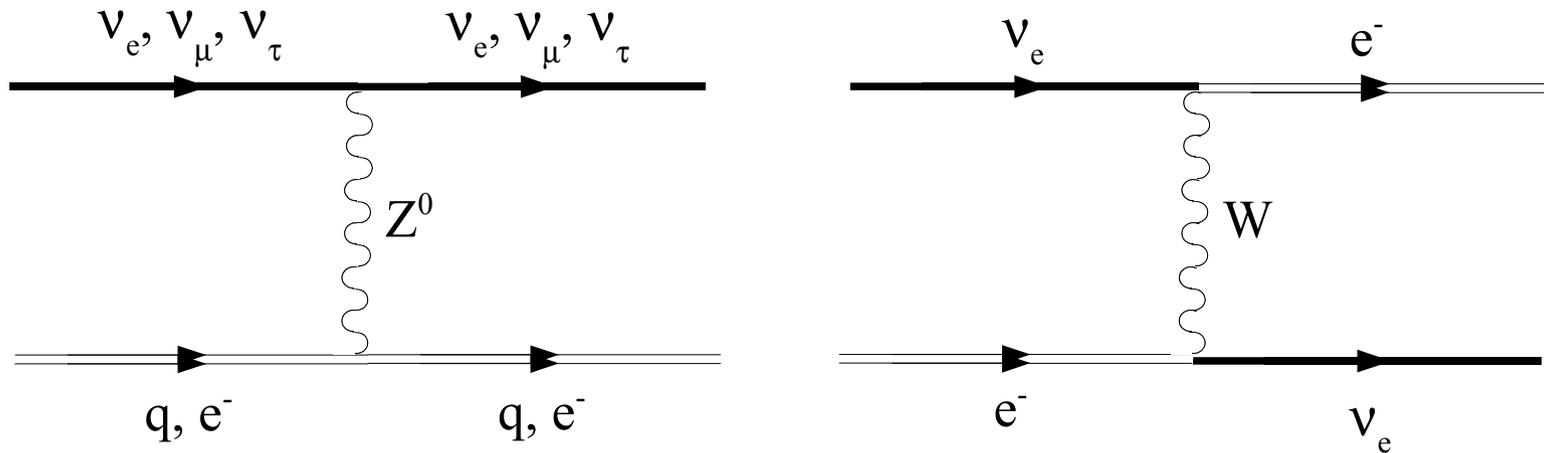Nuclear reactor

$\overline{\nu}_?$

L

Neutrino Oscillations

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

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

- Oscillation probability for 2 flavors (e.g. ν_e, ν_μ):

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

Jason Detwiler

Boston University, Dec 2003

MSW Effect[*]

$$n = 1 + \frac{2\pi N}{p^2} f_l(0) \qquad L_0 = \frac{2\pi}{\sqrt{2}\, G_F N_e}$$

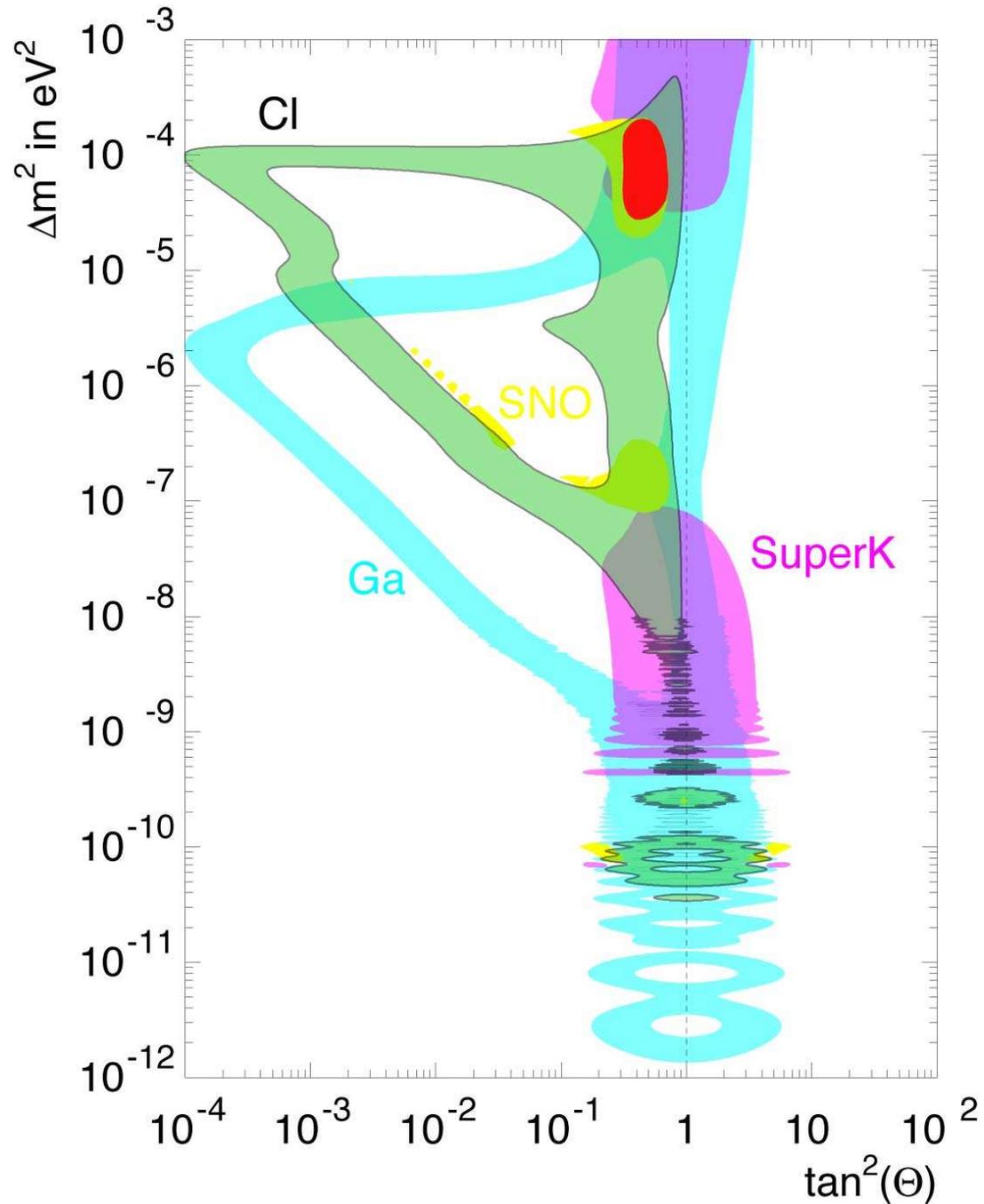$$\boxed{P(\nu_e \to \nu_\mu, L) = \sin^2 2\theta_m \sin^2 \frac{\pi L}{L_m}}$$

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

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

* L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978)
    S.P. Mikheev and A. Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985)

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Solar Neutrino Mixing Parameters

Neutrinos On Earth

- Control source and detector

- Sun: $L_0 \sim 200$ km $<< R_{sun}$; Rock: $L_0 \sim 10^4$ km $> R_{earth}$

  $\rightarrow$ Matter effects much less significant

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{1.27\,\Delta m^2 L}{E}$$
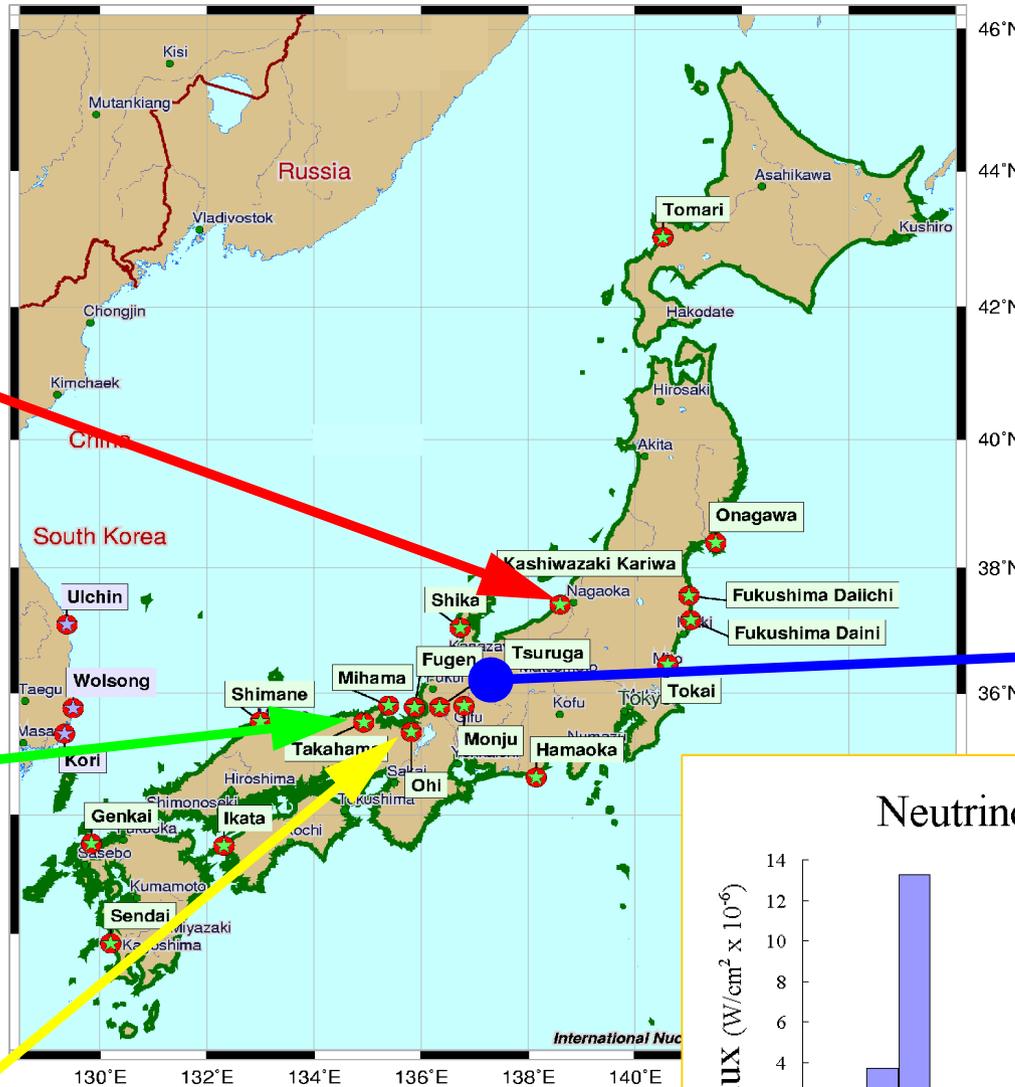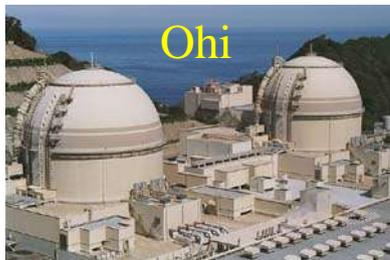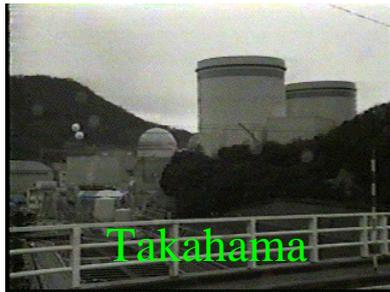
Neutrino beams

- sensitivity to small Δm^2 requires very large L

- appearance possible

- collimated source

Reactors

- sensitive to very small Δm^2

- disappearance only

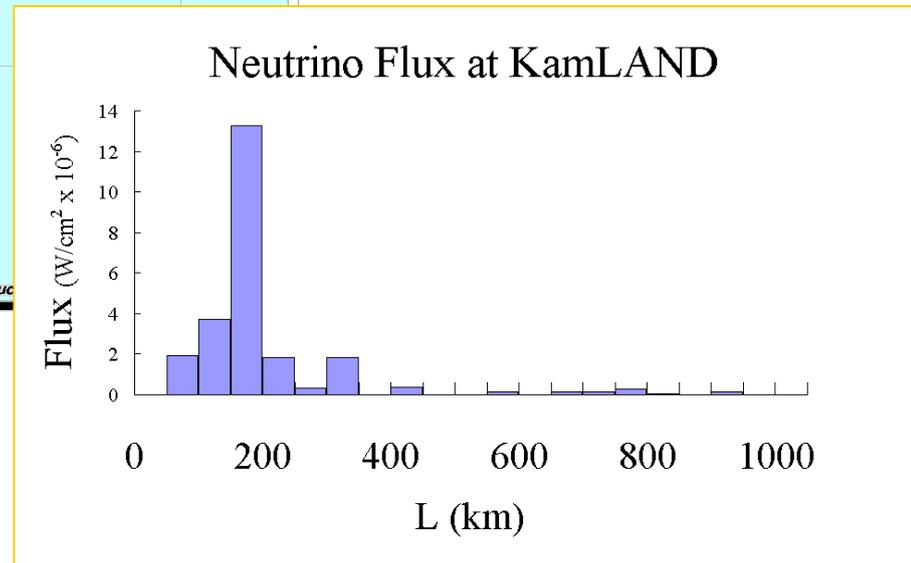 $\rightarrow$ limited $\sin^2 2\theta$ sensitivity

- 4π source

Reactors In Japan

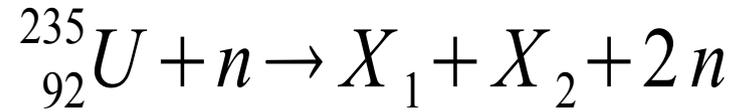
55% of total flux from:

Kashiwazaki

Takahama

Ohi

KamLAND uses the entire Japanese nuclear power industry as a 180 GW$_{th}$ long-baseline source!

KamLAND

80% of total flux from baselines 140-210 km

Neutrino Flux at KamLAND
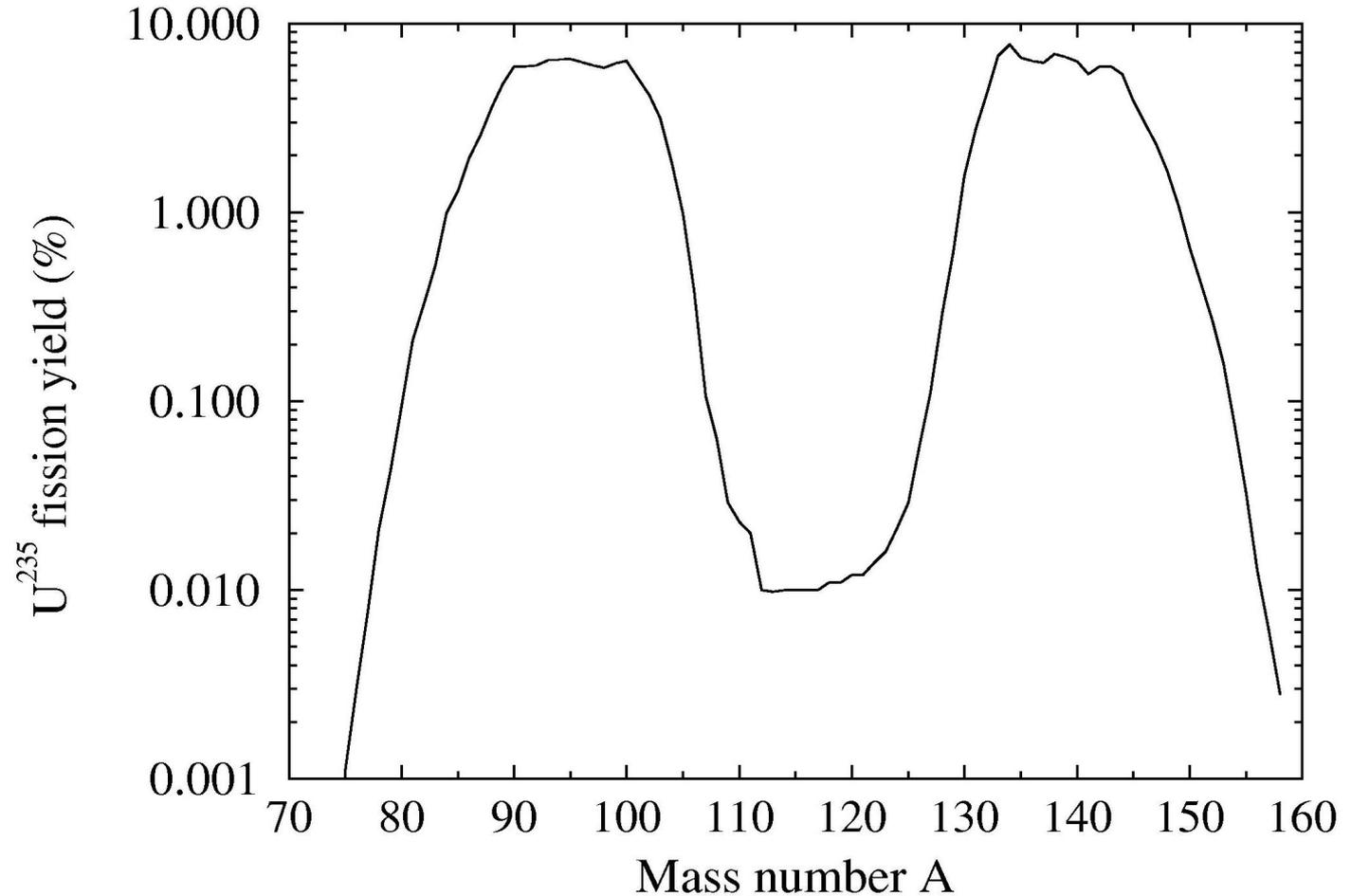
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

92 protons and 142 neutrons are shared between X_1 and X_2

Stable nuclei with A most likely from fission:

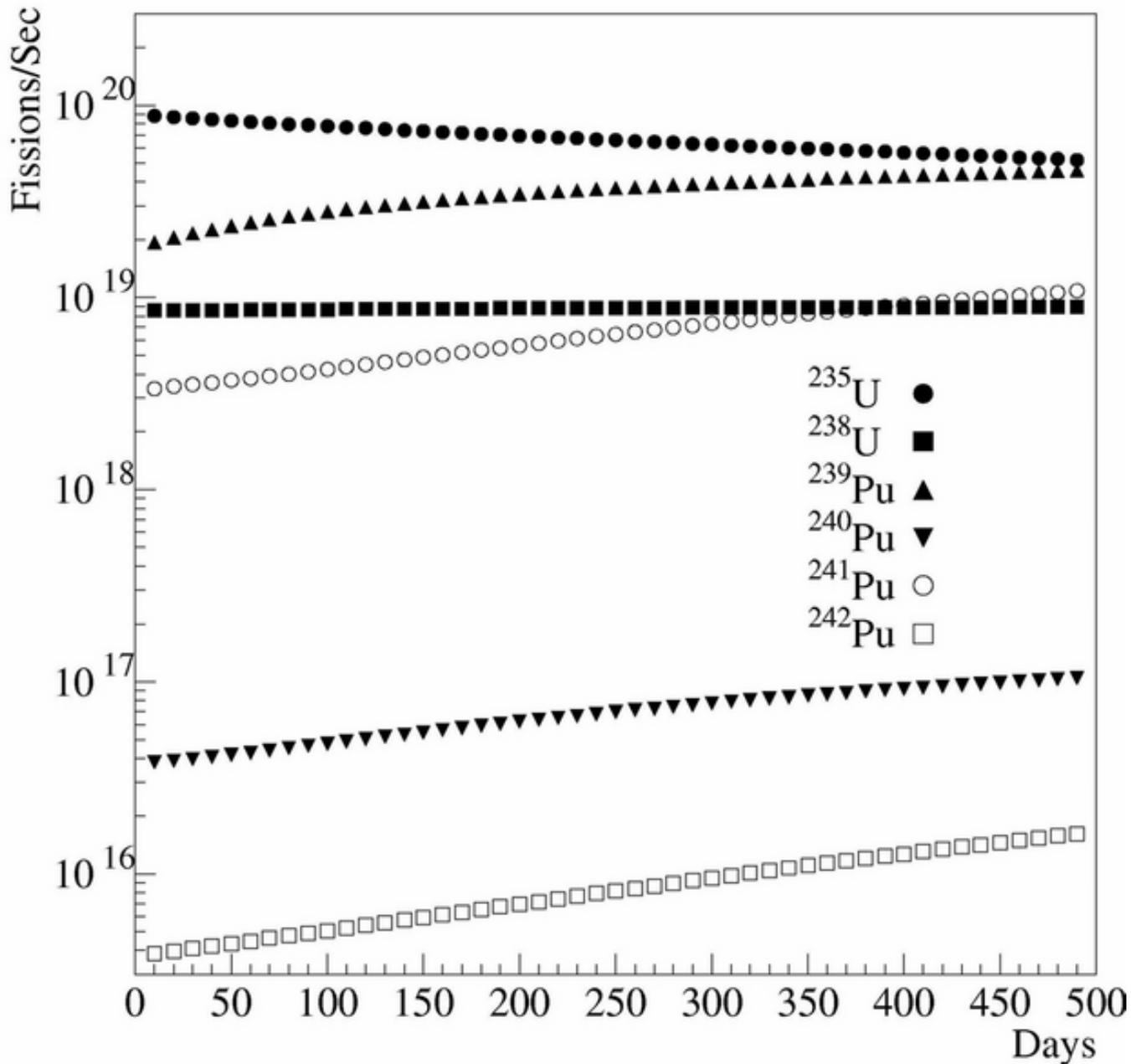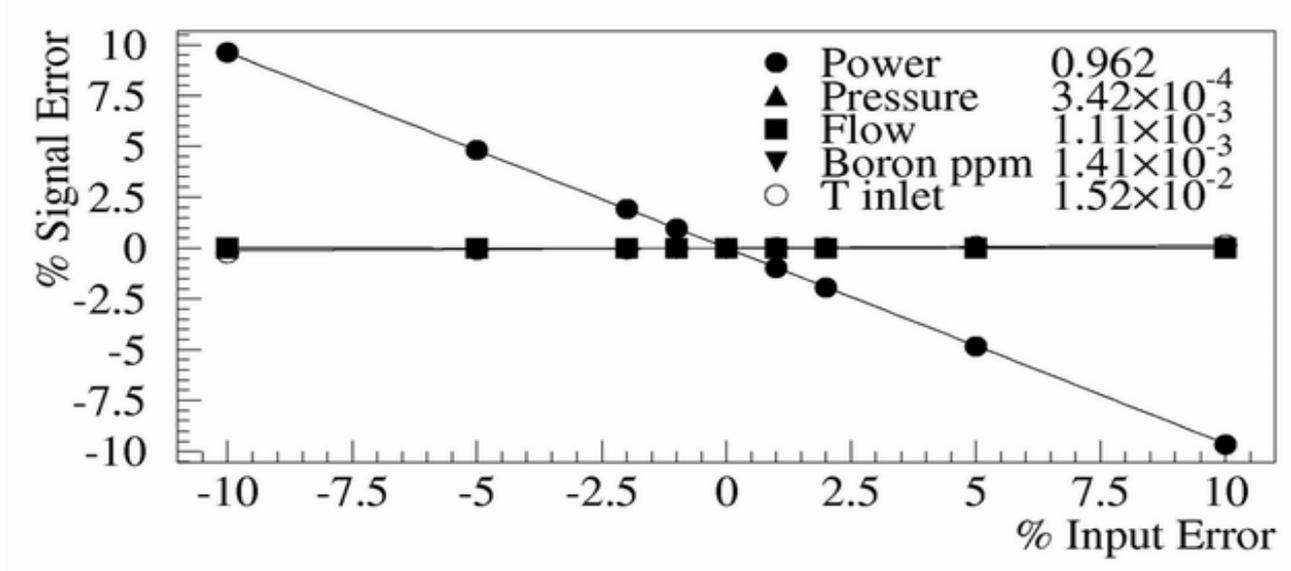$$^{94}_{40}Zr \quad \text{and} \quad ^{140}_{58}Ce$$

98 protons
136 neutrons

On average, 6 n must decay to 6 p to reach stable matter.

Reactor Fuel Cycle

> 99.9% of ν are produced by fissions of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Simulation Inputs

Economics pushes the uncertainty on the power to < 1%

$\overline{\nu}_e$ Spectra

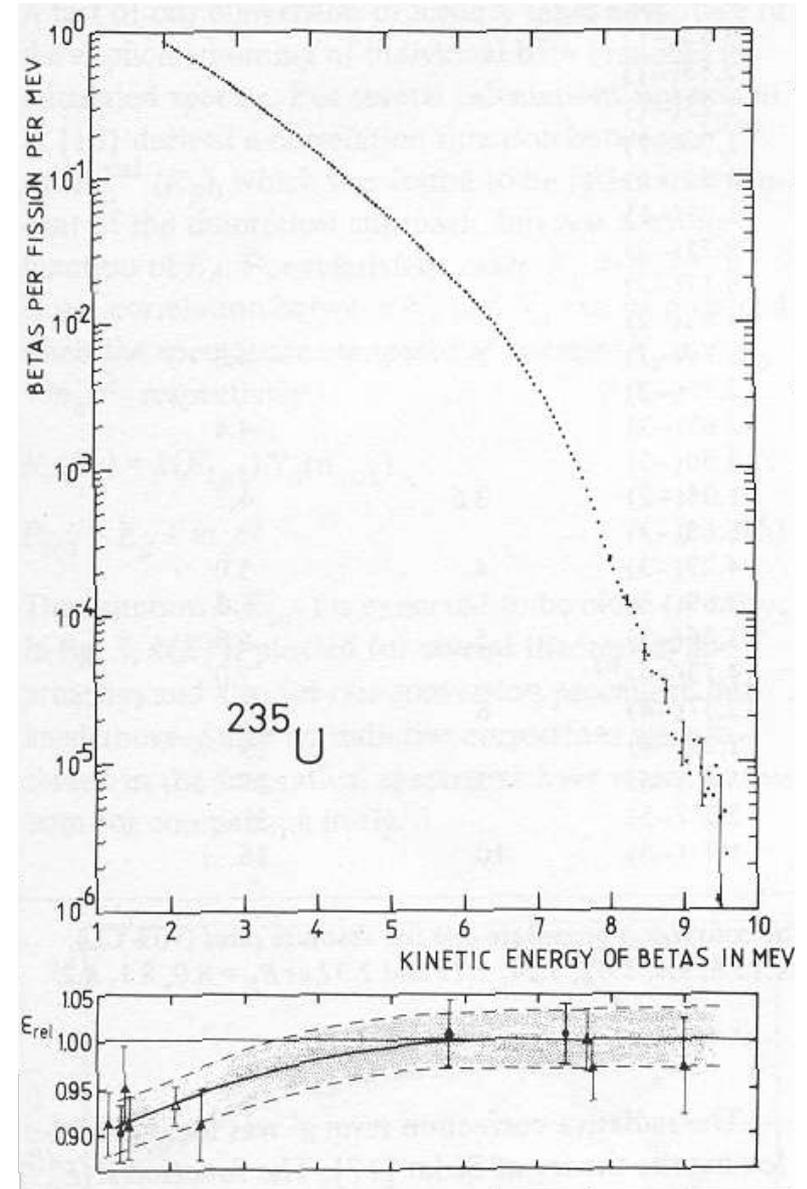- ^{235}U, ^{239}Pu, and ^{241}Pu: $\overline{\nu}_e$ spectra are derived from β-spectra measurements

A. A. Hahn *et al.*, Phys. Lett. **B218**, 365 (1989)
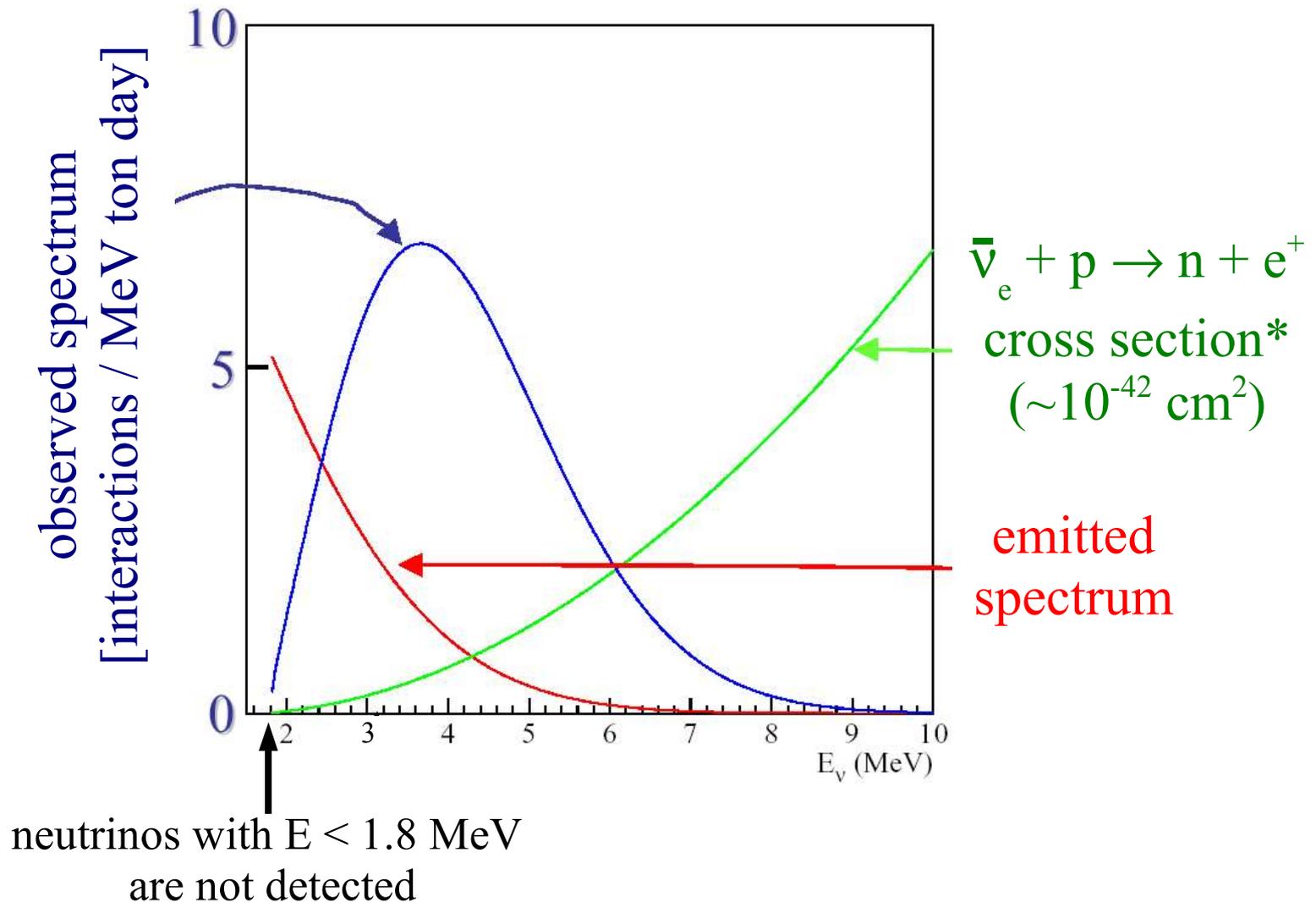K. Schreckenbach *et al.*, Phys. Lett. **B160**, 325 (1985)

- ^{238}U: no measurements are available, so we must rely on calculations
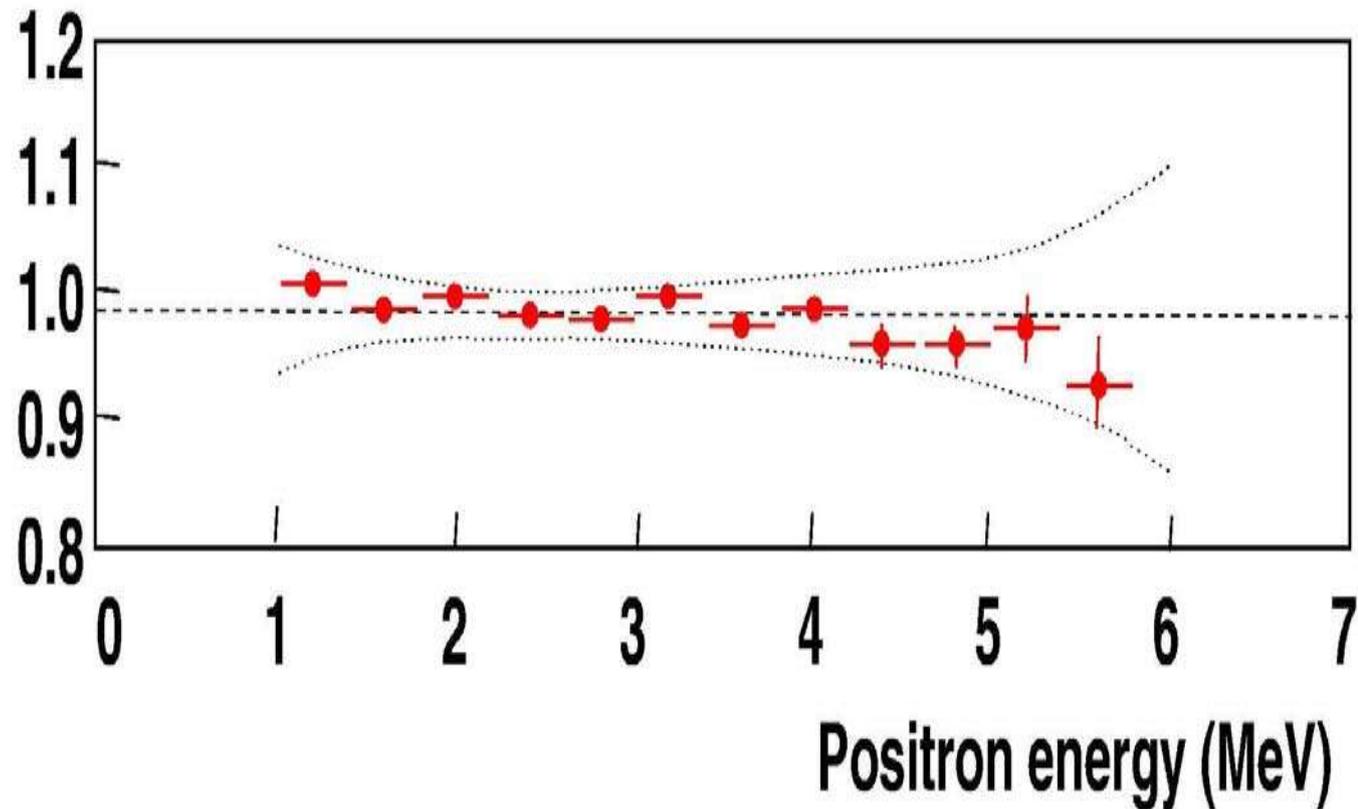
P. Vogel *et al.*, Phys. Rev. **C52** (2498)
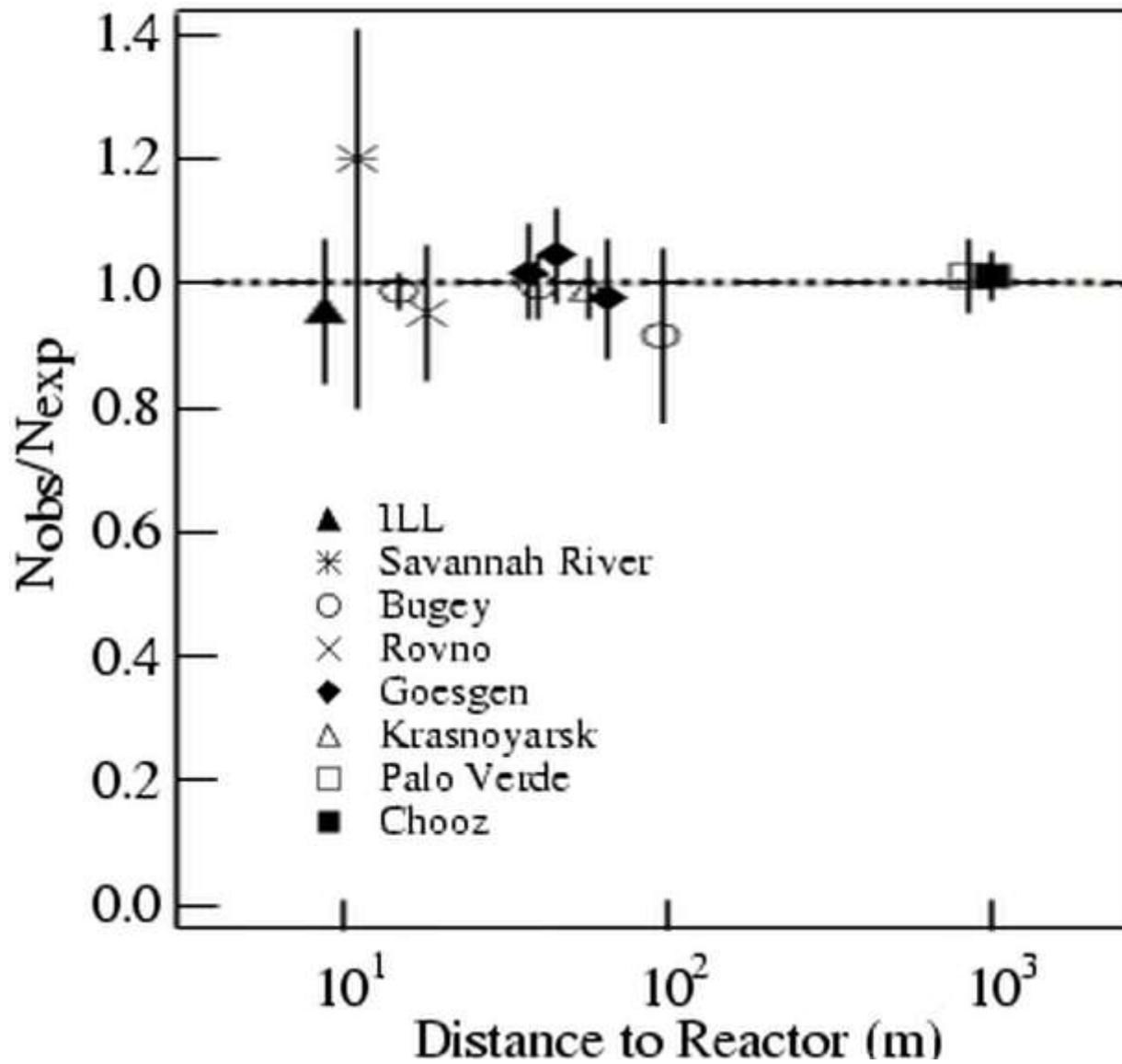
The Detected $\bar{\nu}_e$ Spectrum

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

cross section*
$(\sim 10^{-42} \text{ cm}^2)$

emitted spectrum

observed spectrum
[interactions / MeV ton day]

E_ν (MeV)

neutrinos with E < 1.8 MeV
are not detected

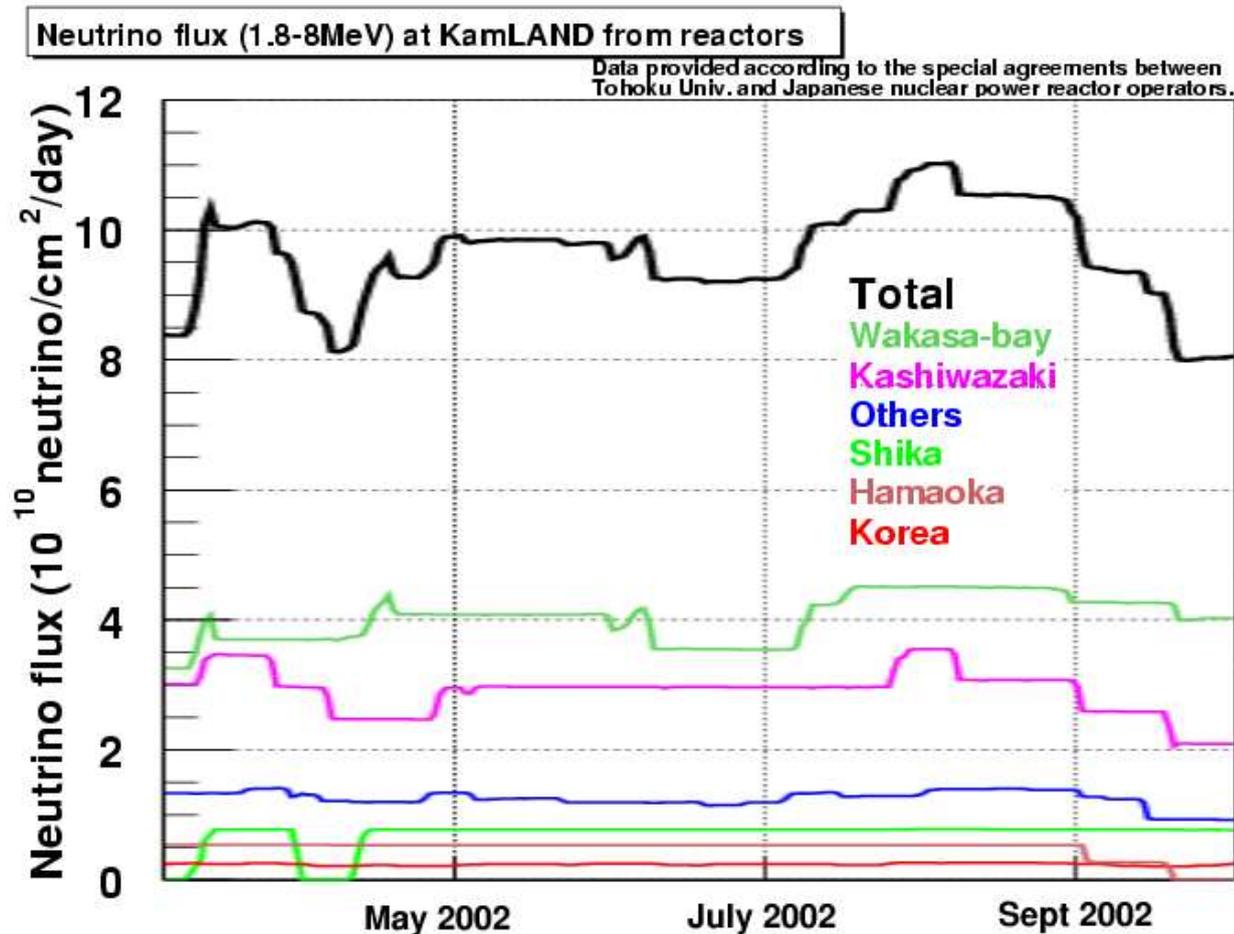* P. Vogel and J. F. Beacom, Phys. Rev. **D60**, 053003 (1999)

Previous Results

From Bugey 3: short baseline (L = 15 m, 40 m), 1.5×10^5 events

Previous Results

Antineutrino Flux at KamLAND

Neutrino flux (1.8-8MeV) at KamLAND from reactors

Data provided according to the special agreements between
Tohoku Univ. and Japanese nuclear power reactor operators.

Total
Wakasa-bay
Kashiwazaki
Others
Shika
Hamaoka
Korea

Flux Calculation Systematics (%)

Live time	0.07	Time lag	0.28
Reactor power	2.0	$\bar{\nu}_e$ spectra	2.5
Fuel composition	1.0	$\bar{\nu}_e$ - p cross section	0.2

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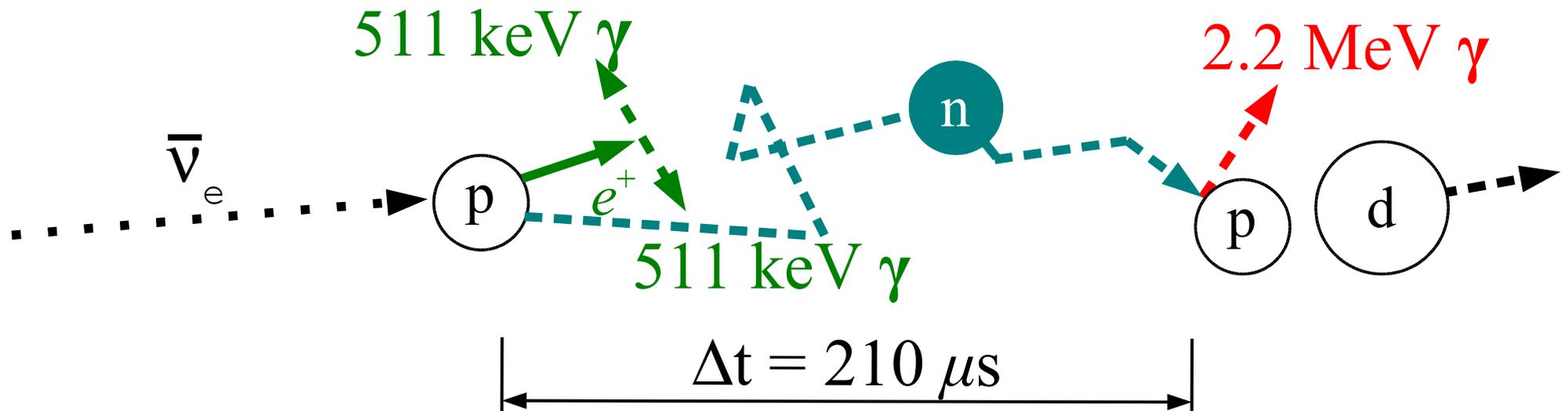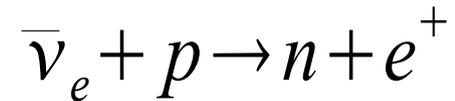
$$\bar{\nu}_e + p \rightarrow n + e^+$$

511 keV γ

2.2 MeV γ

$\bar{\nu}_e$

e^+

511 keV γ

n

p

p   d

$\Delta t = 210\ \mu s$
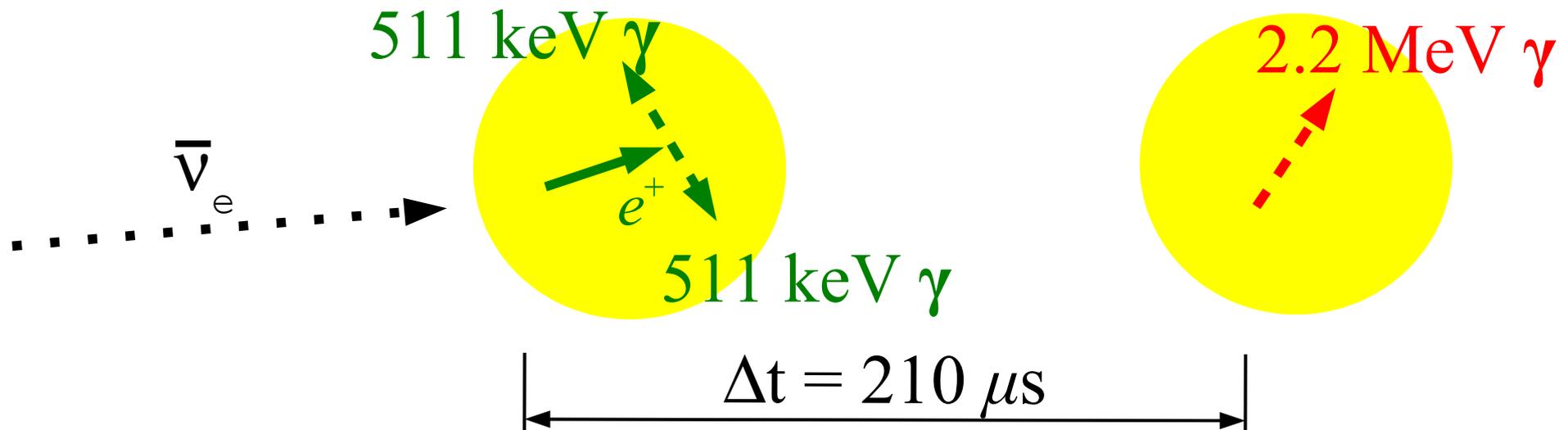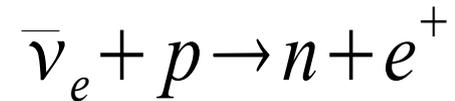
Coincidence signal: detect
- Prompt: e^+ energy + annihilation γ
- Delayed: n-capture γ

Event Signature

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

511 keV γ

$\overline{\nu}_e$

e^+

511 keV γ

2.2 MeV γ

$\Delta t = 210 \ \mu s$
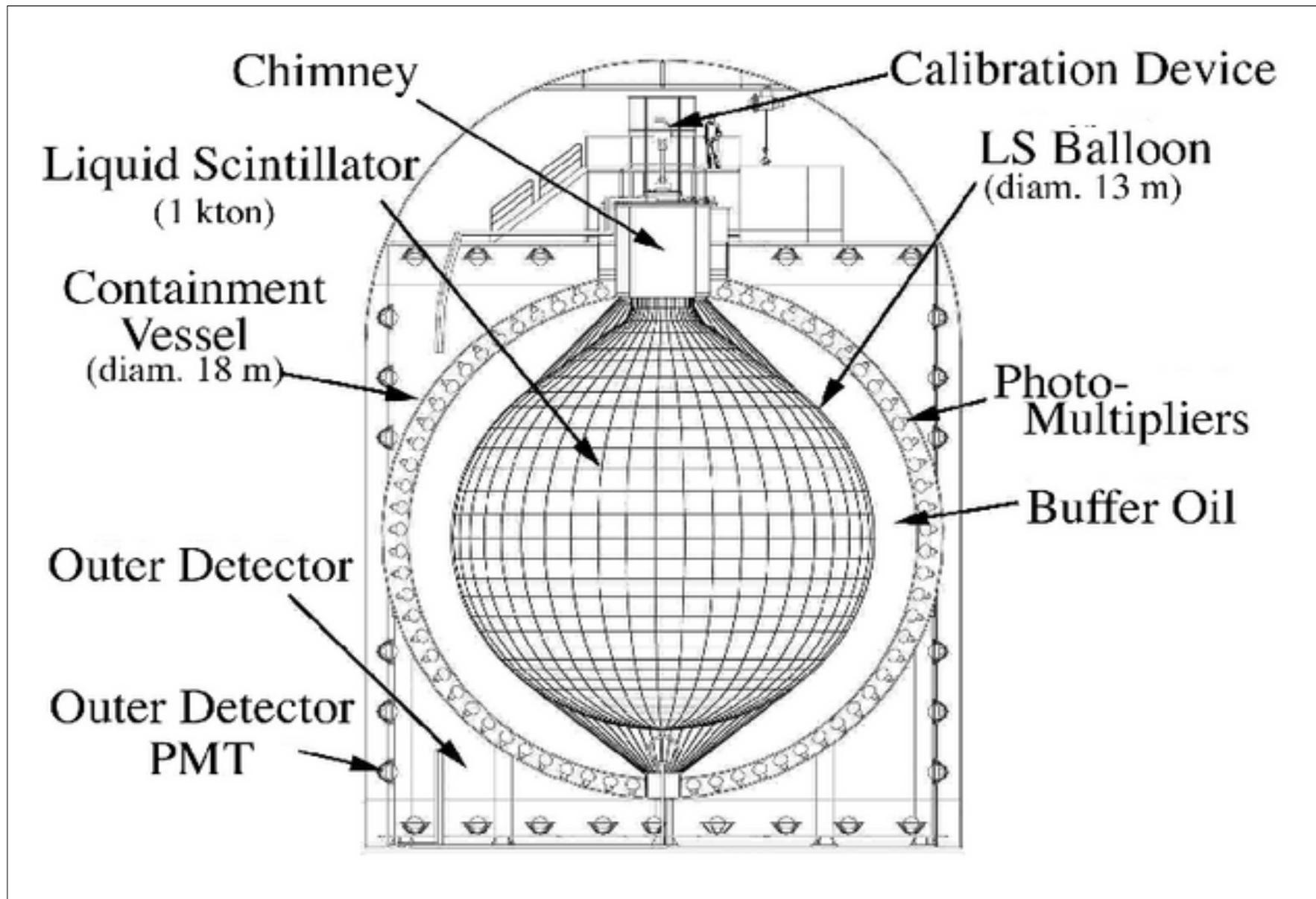
Coincidence signal: detect
- Prompt: e^+ energy + annihilation γ
- Delayed: n-capture γ

The KamLAND Detector

KamLAND Trigger

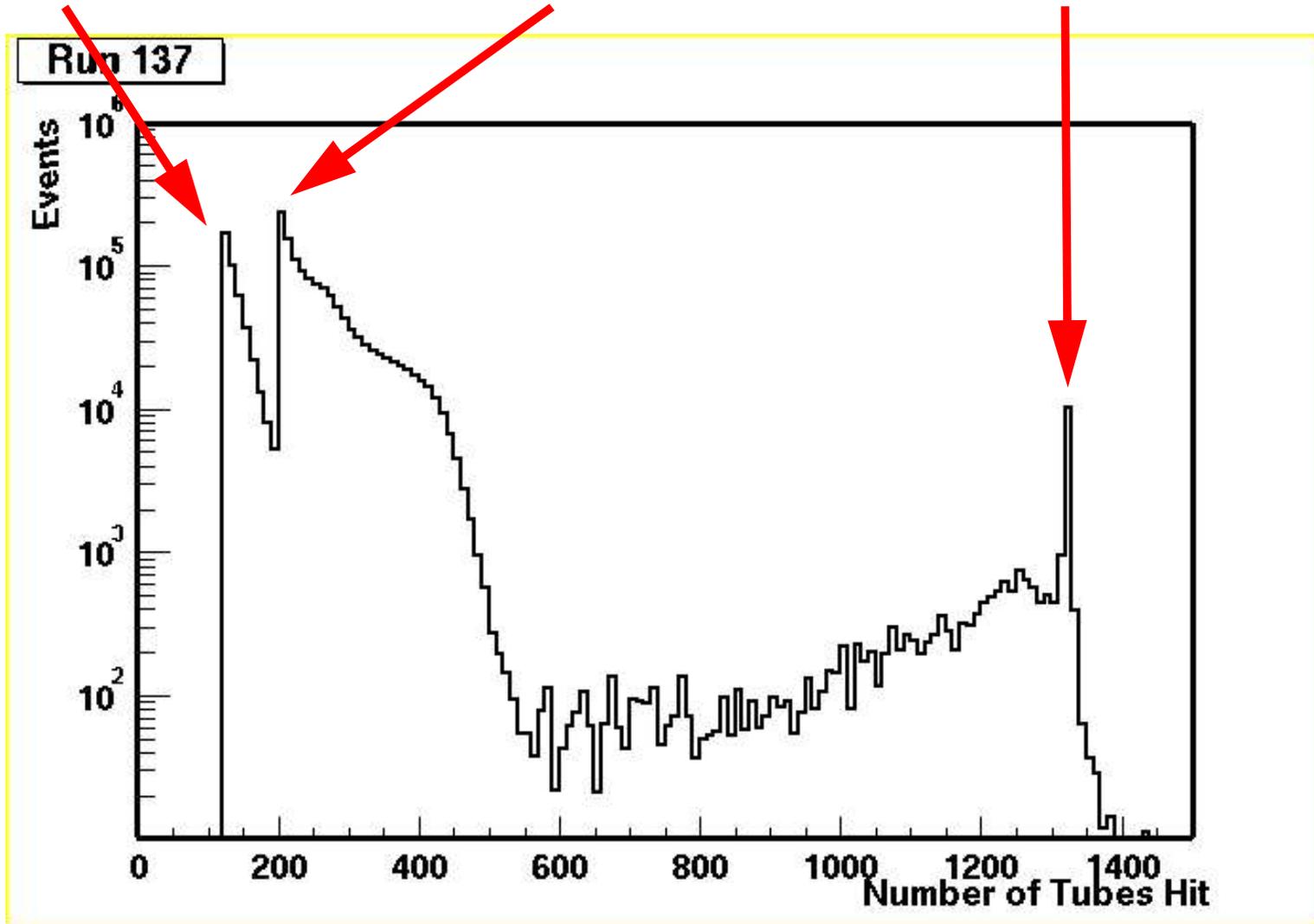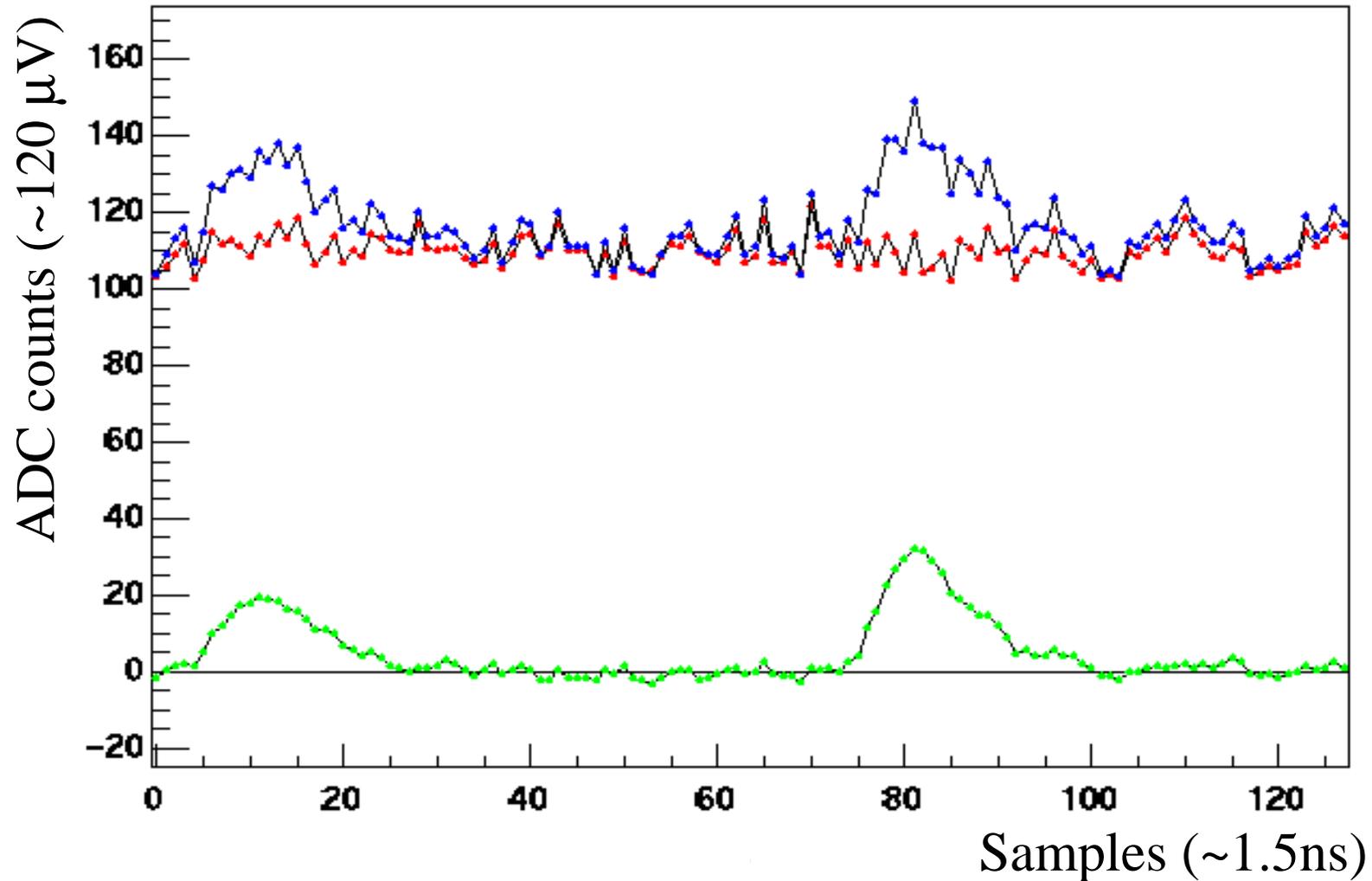Jason Detwiler   20   Boston University, Dec 2003

Waveform Analysis

Blue: raw data
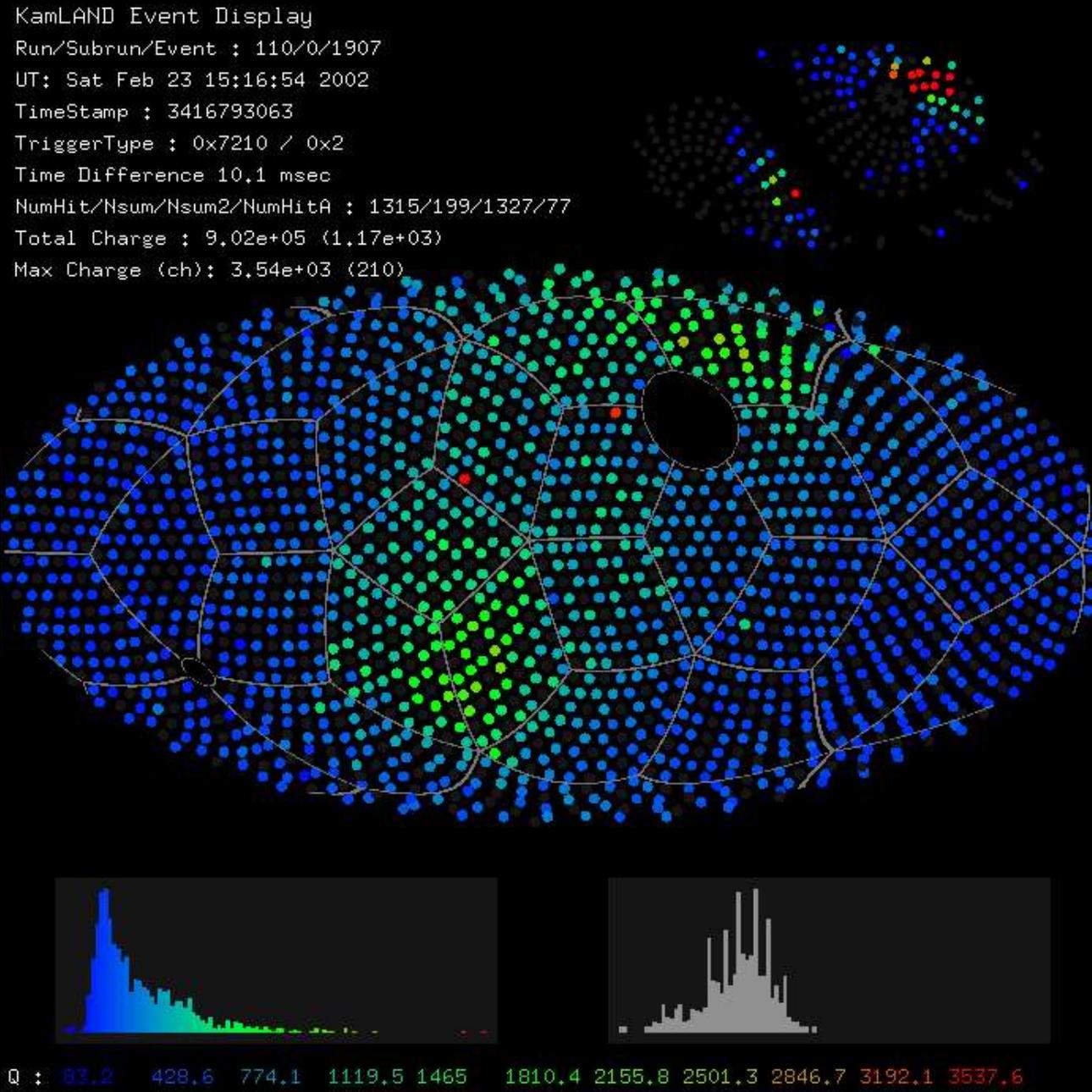**red**: pedestal
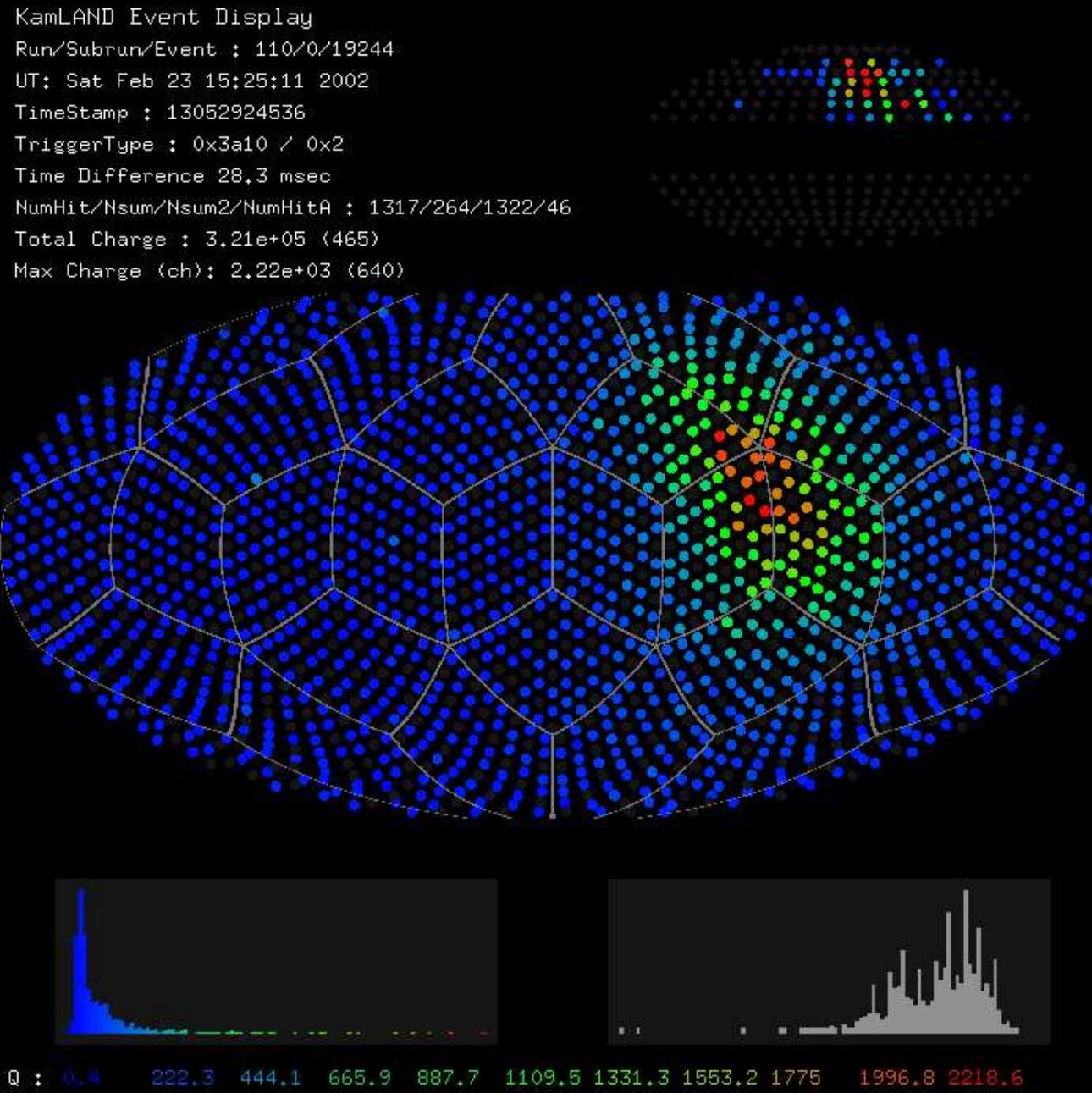**green**: pedestal subtracted

KamLAND Data

Event Display: through-going muon

color is pulseheight

all tubes illuminated

KamLAND Data

Stopped muon

KamLAND Data
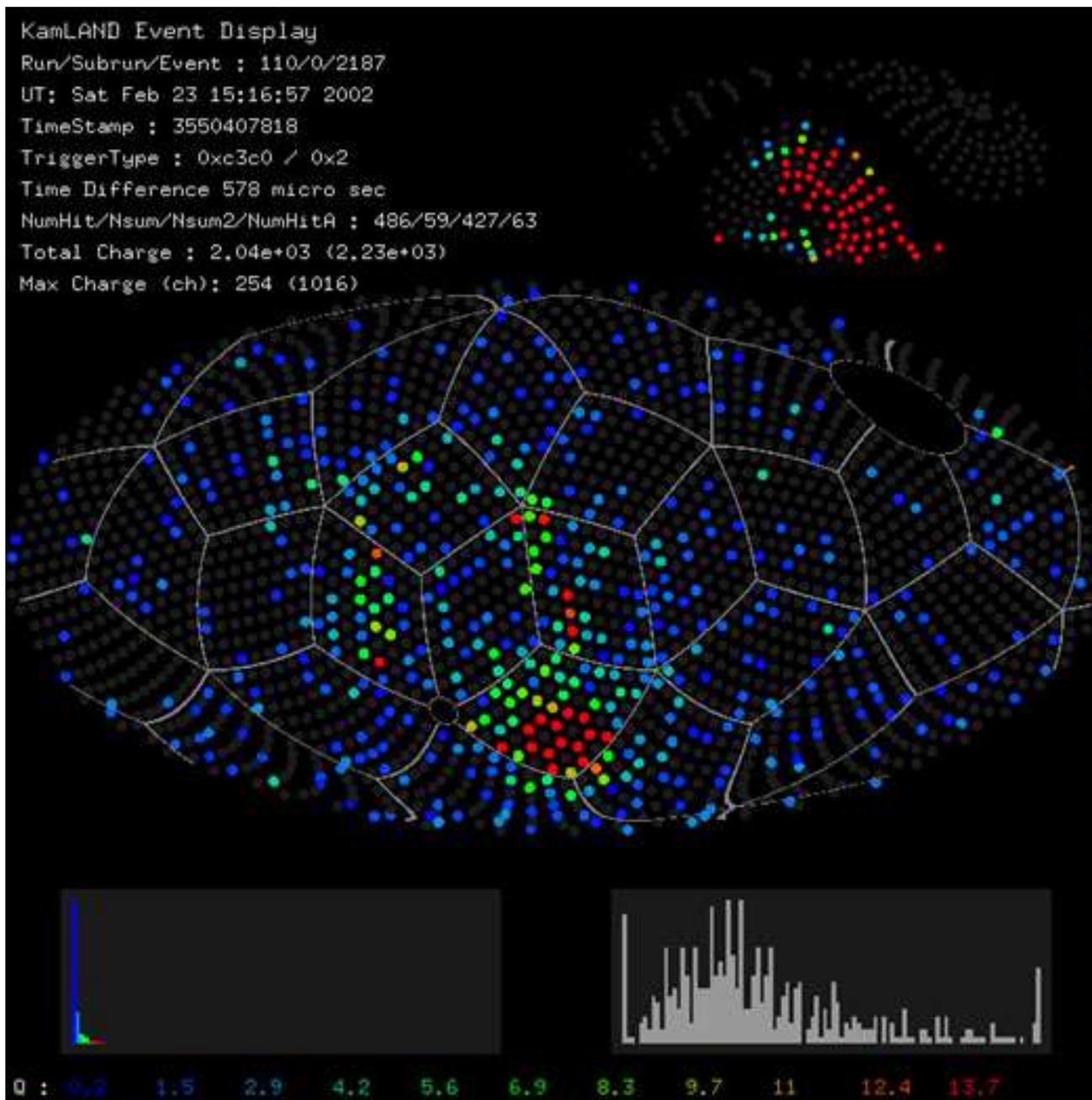
Cherenkov ring from "edge clipper"

Antineutrino Candidate
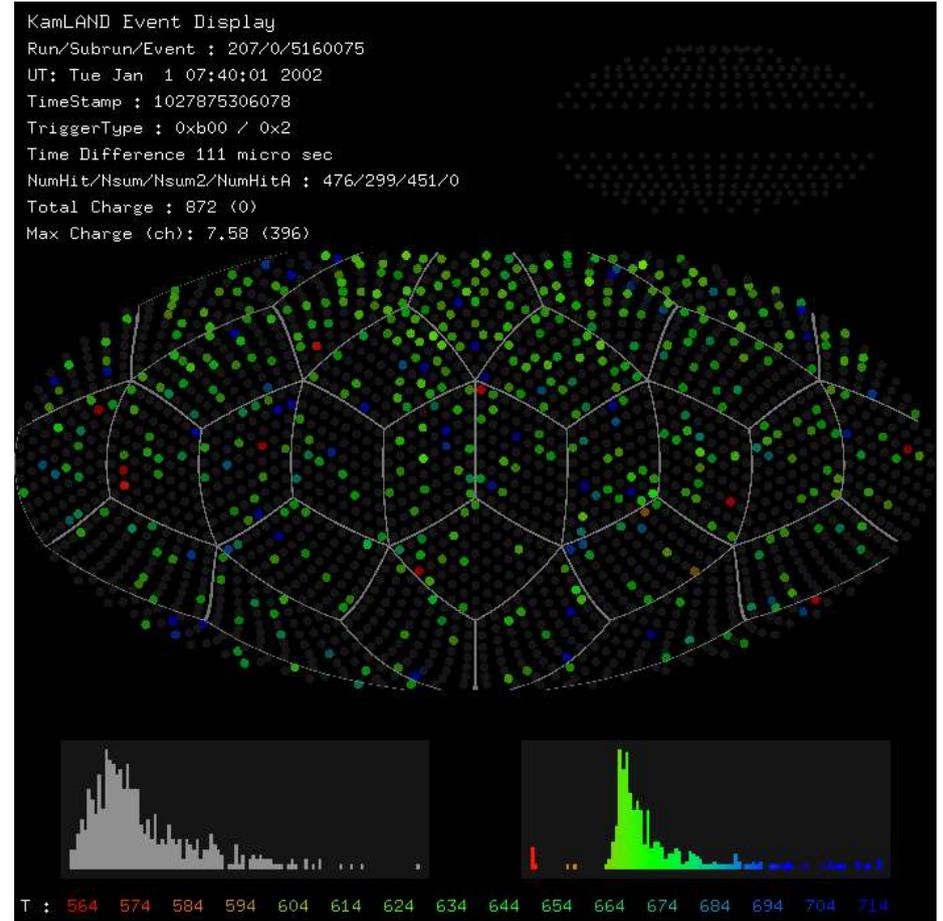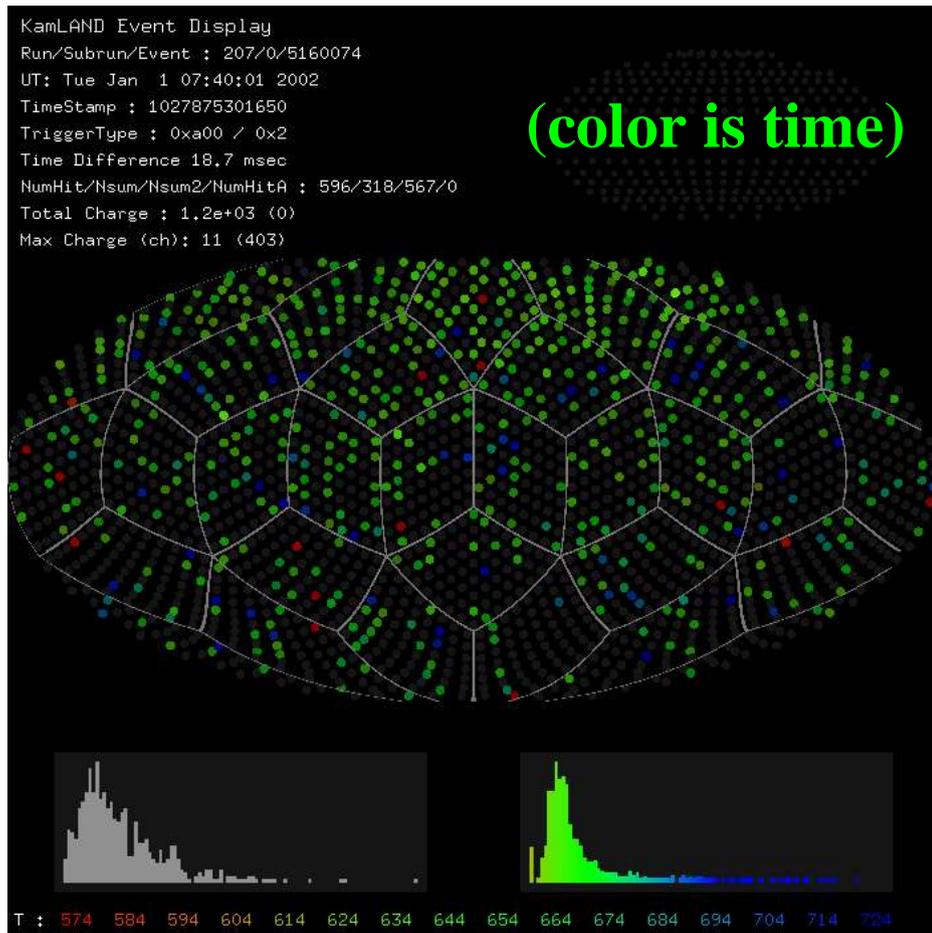
Prompt Signal
E = 3.20 MeV

Δt = 111 μs
ΔR = 34 cm

Delayed Signal
E = 2.22 MeV

Calibrations

Radioactive gamma sources inserted in detector to calibrate energy and position reconstruction

^{68}Ge(0.511*2MeV)

^{65}Zn(1.116MeV)

^{60}Co(2.5MeV)

np(2.2MeV)

nC(4.95MeV)

$\sigma \approx 7.5\% / \sqrt{E(MeV)}$
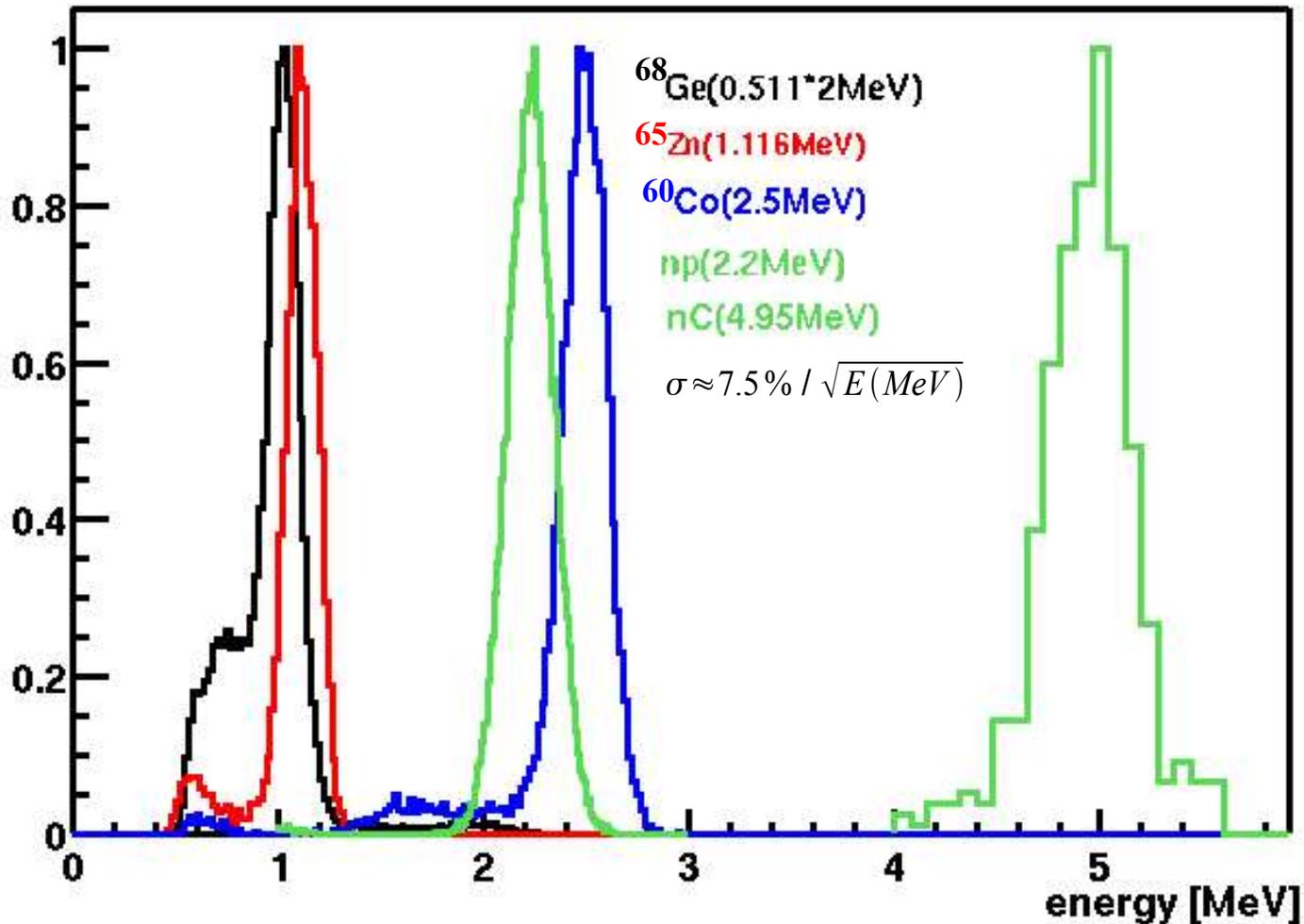
Autoradiography of KamLAND

$$^{238}U: \quad ^{214}Bi \xrightarrow[\substack{\beta + \gamma \\ E = 3.27\ MeV \\ \tau = 28.7\ min.}]{} {}^{214}Po \xrightarrow[\substack{\alpha \\ E = 7.69\ MeV \\ \tau = 237\ \mu s}]{} {}^{210}Pb$$

Chimney activity

Central thermometers

Balloon surface contamination

Bottom flange / plumbing

^{214}Bi Vertex Distribution

Z(m)

$X^2 + Y^2 (m^2)$
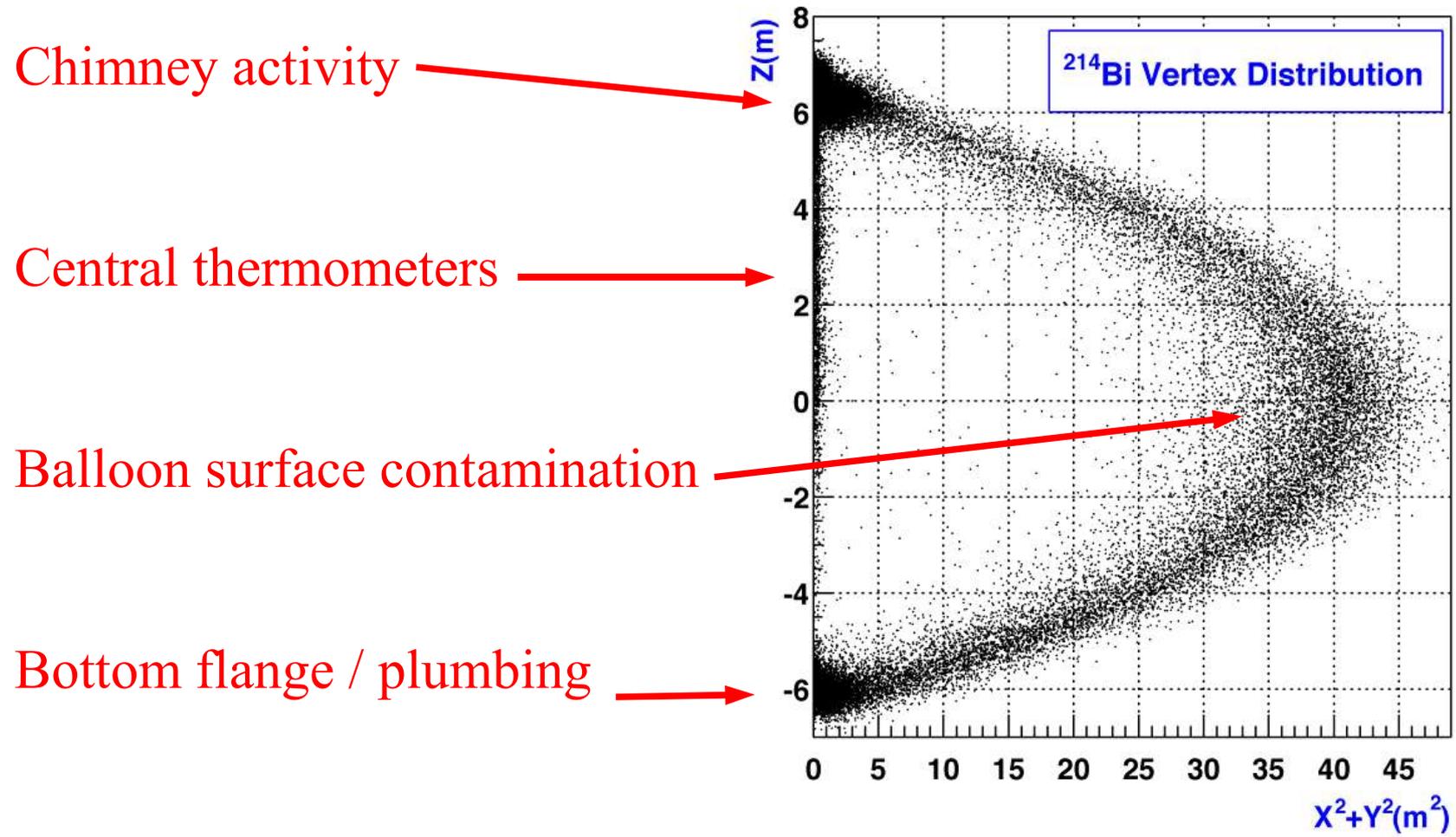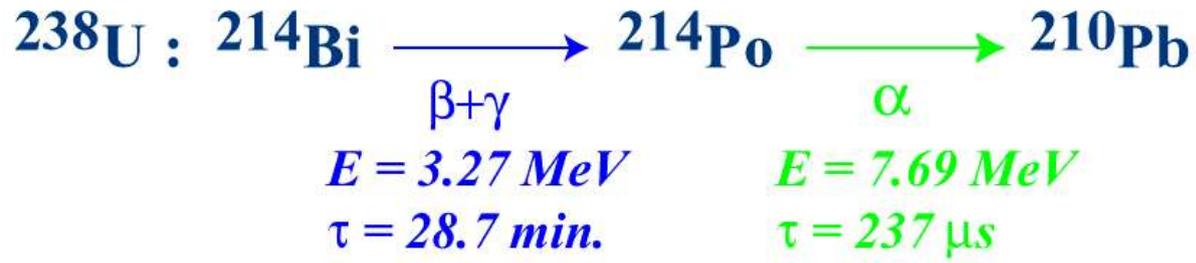
Reconstruction Performance

Energy scale
determined from
radioactive source
calibrations

R = 5.0 m radius
fiducial volume
estimation from
spallation neutron
uniformity

Event Selection

511 keV γ   2.2 MeV γ

$\overline{\nu}_e$

e^+

511 keV γ

$\Delta t = 210 \; \mu s$
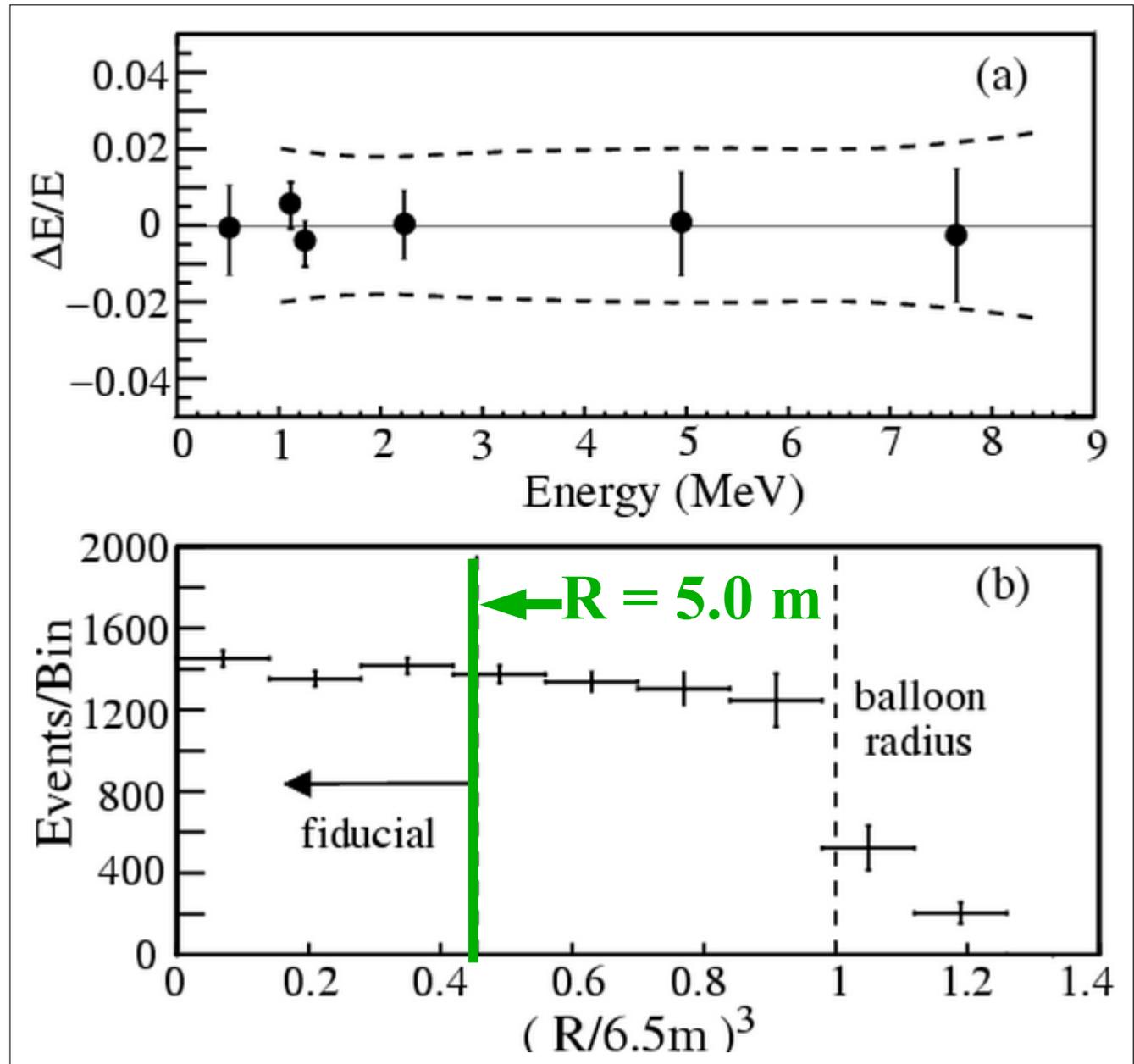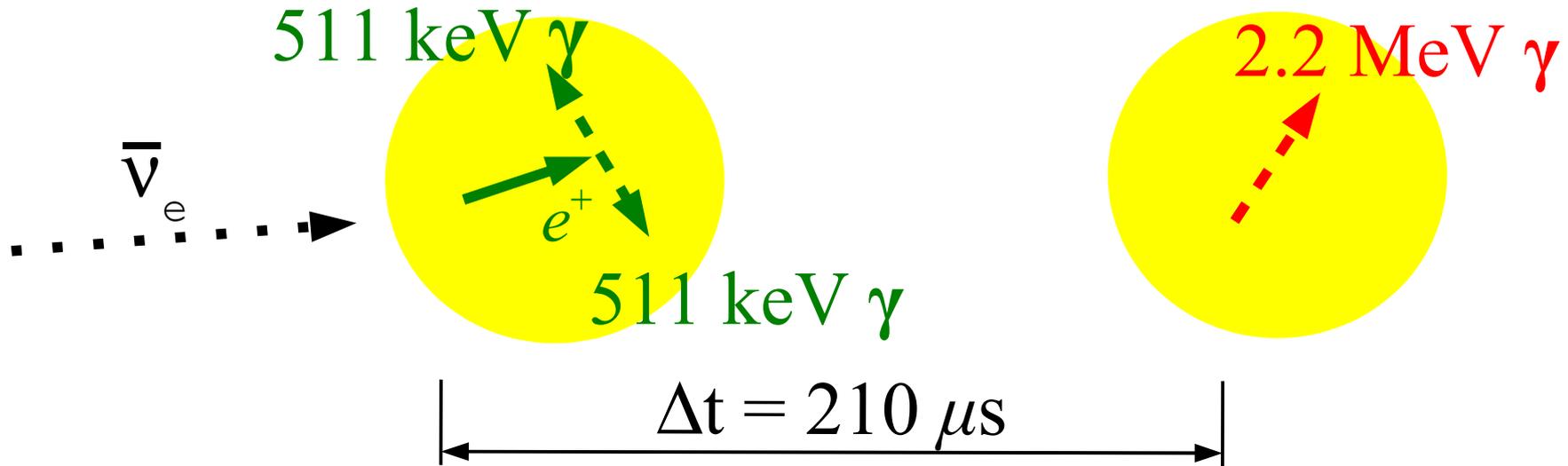
- Time correlation: $0.5 \; \mu s < \Delta t < 660 \; \mu s$
- Vertex correlation: $\Delta R < 1.6$ m
- Delayed event energy: $1.8 \; MeV < E_{del} < 2.6 \; MeV$
- Spherical fiducial volume: $R < 5$ m
- Z-axis: $\rho > 1.2$ m

Total efficiency: 78.3 ± 1.6 %

Backgrounds

Fid. volume : R < 500cm

^{210}Pb

^{40}K < 2.7 × 10^{-16} g/g

^{208}Tl

^{238}U = 3.5 × 10^{-18} g/g

^{232}Th = 5.2 × 10^{-17} g/g

^{12}B(from data)

^{9}C, ^{8}Li, ^{8}B,

^{8}He, ^{9}Li,

^{6}He, ^{11}C, ^{10}C

(from T.Hagner et.al.)
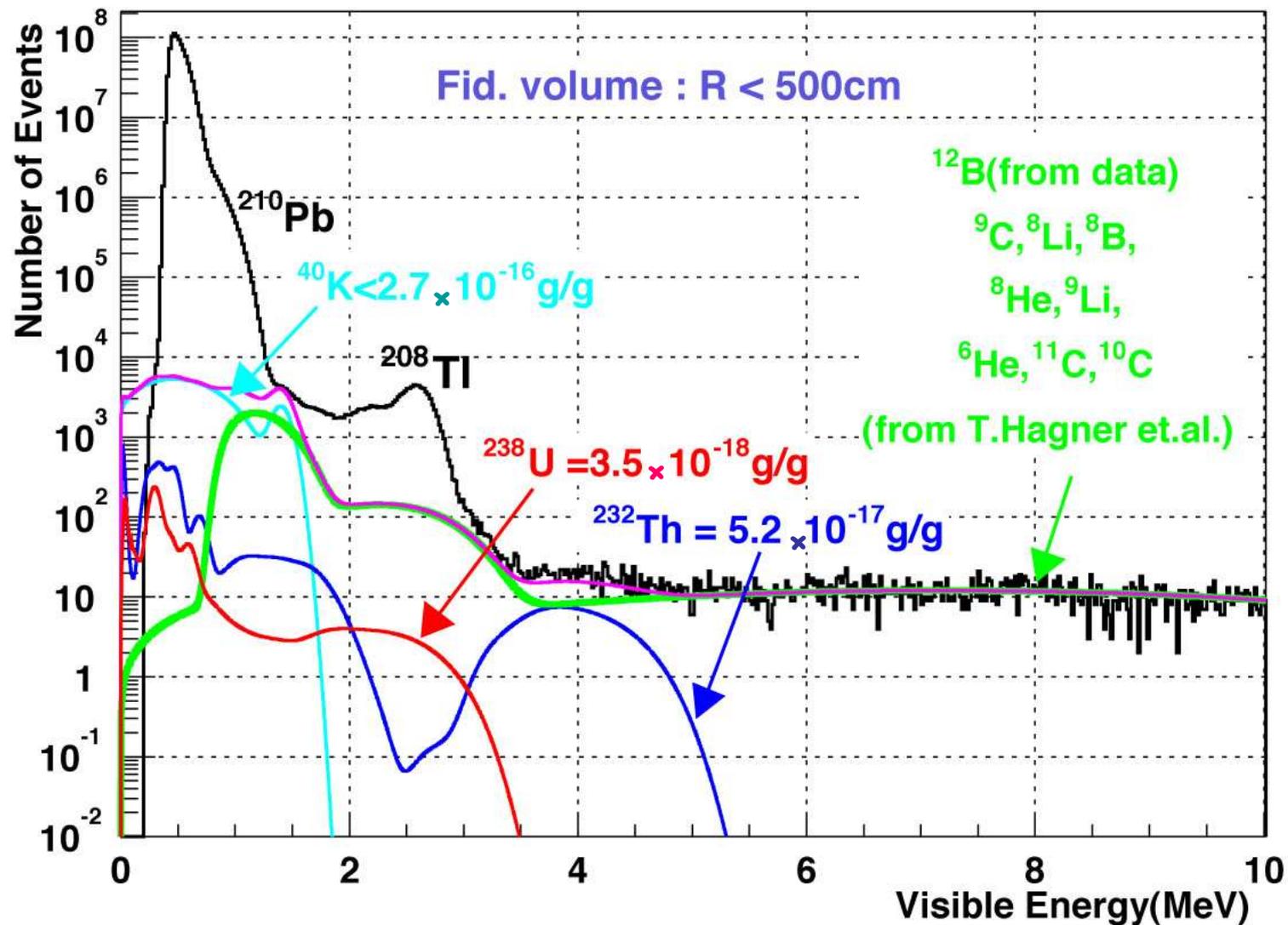
Accidental bg estimated from shifted time window 0.020-20 seconds

0.0086 ± 0.0005 events

Cosmogenic Backgrounds

2700 m.w.e. overburden cuts muon rate to ~0.3Hz

Muons leave neutrons which can fake the signal
• Veto detector for 2 ms after muons

Muons also create longer lived (> 100 ms) neutron emitters
• Veto 3m cylinder around muon track for 2 s
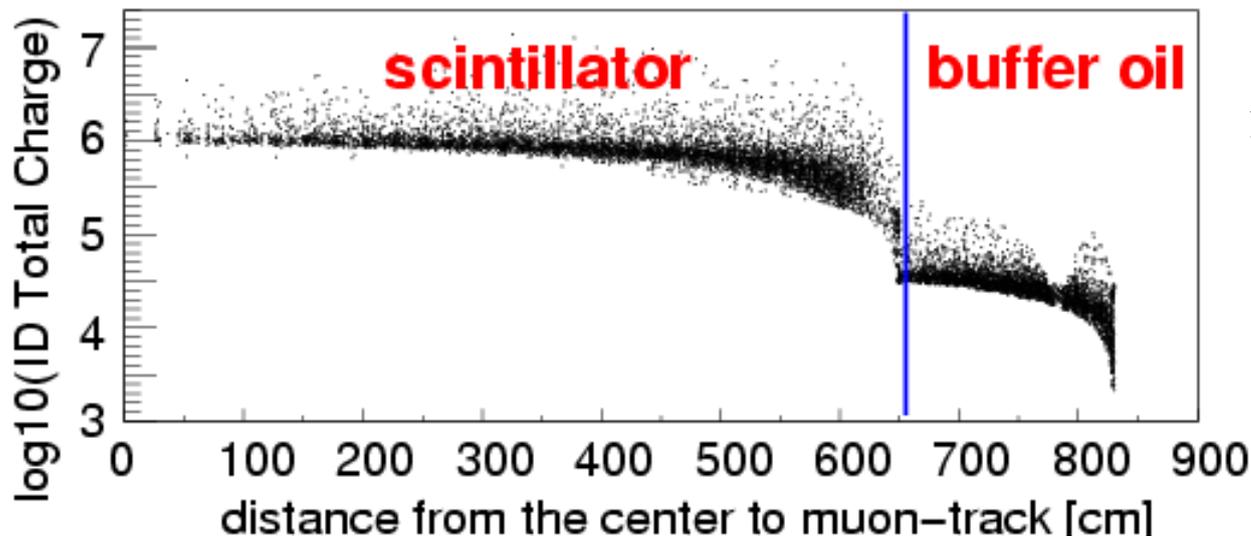• For high energy muons (> 3 GeV), veto entire detector for 2 s

Correction to livetime: 11.4%
Residual correlated background: 1 ± 1 event

Muon track reconstruction
reveals the balloon boundary

Jason Detwiler

Prompt/Delayed Event Energies
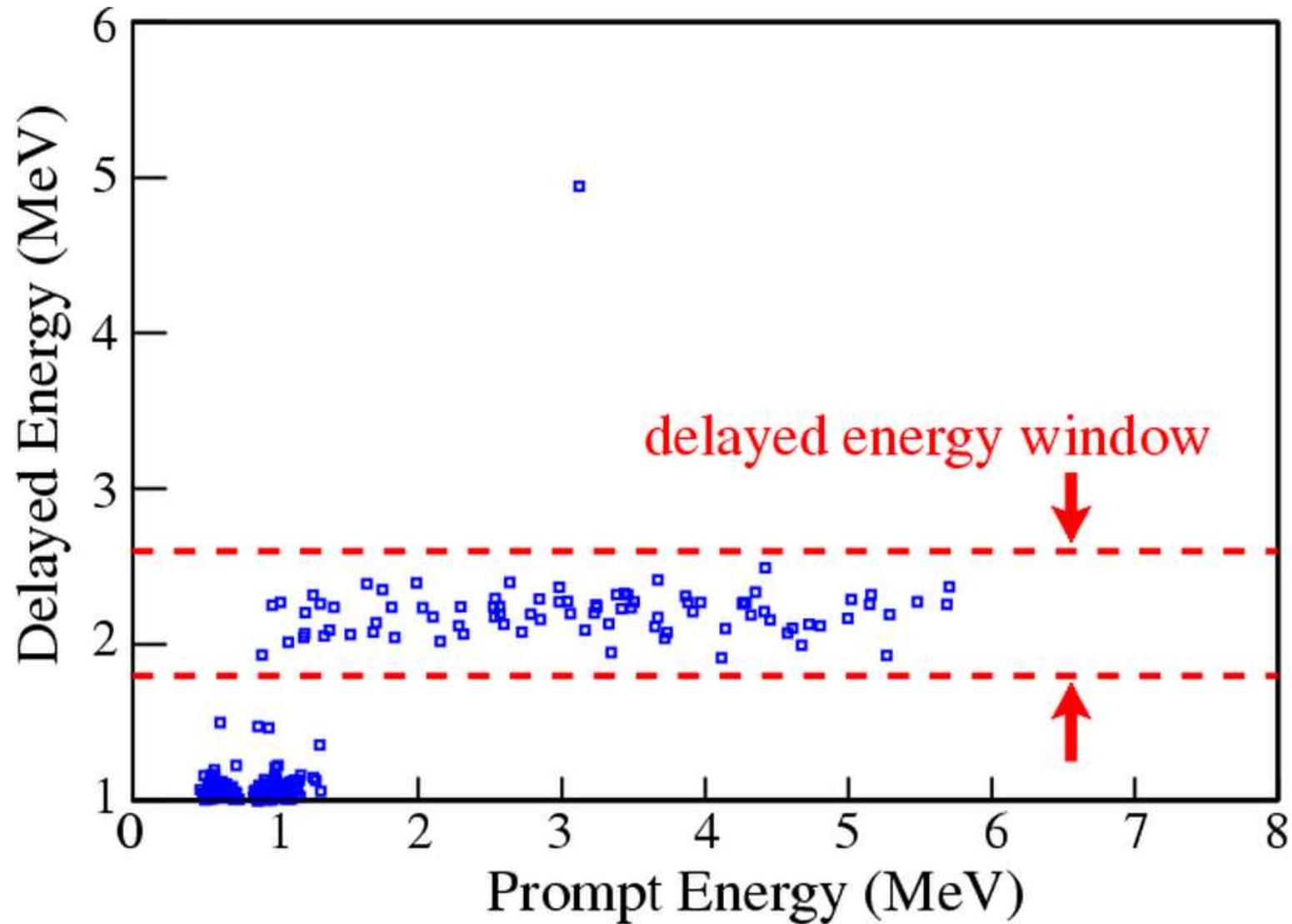
Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

Total Scintillator 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
Antineutrino spectra	2.5
$\overline{\nu}_e$- p cross section	0.2
Total systematic error	6.4%

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Boston University, Dec 2003

Measured Event Rate

For no oscillations, in 145.1 live-days we expect
86.8 ± 5.6 events (1 ± 1 bg)

We observe...

54

Measured Event Rate

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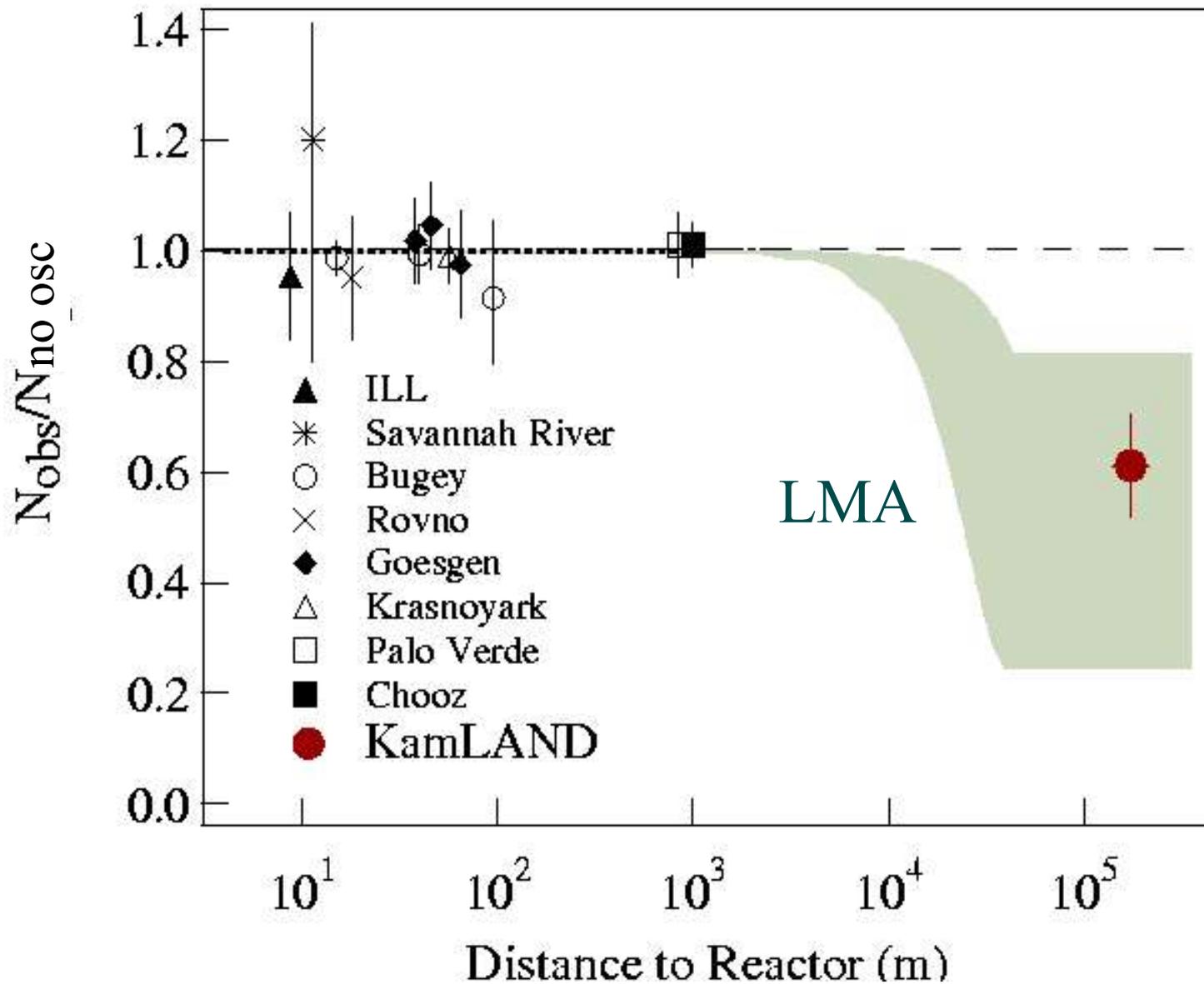
Solar Neutrino Mixing Parameters
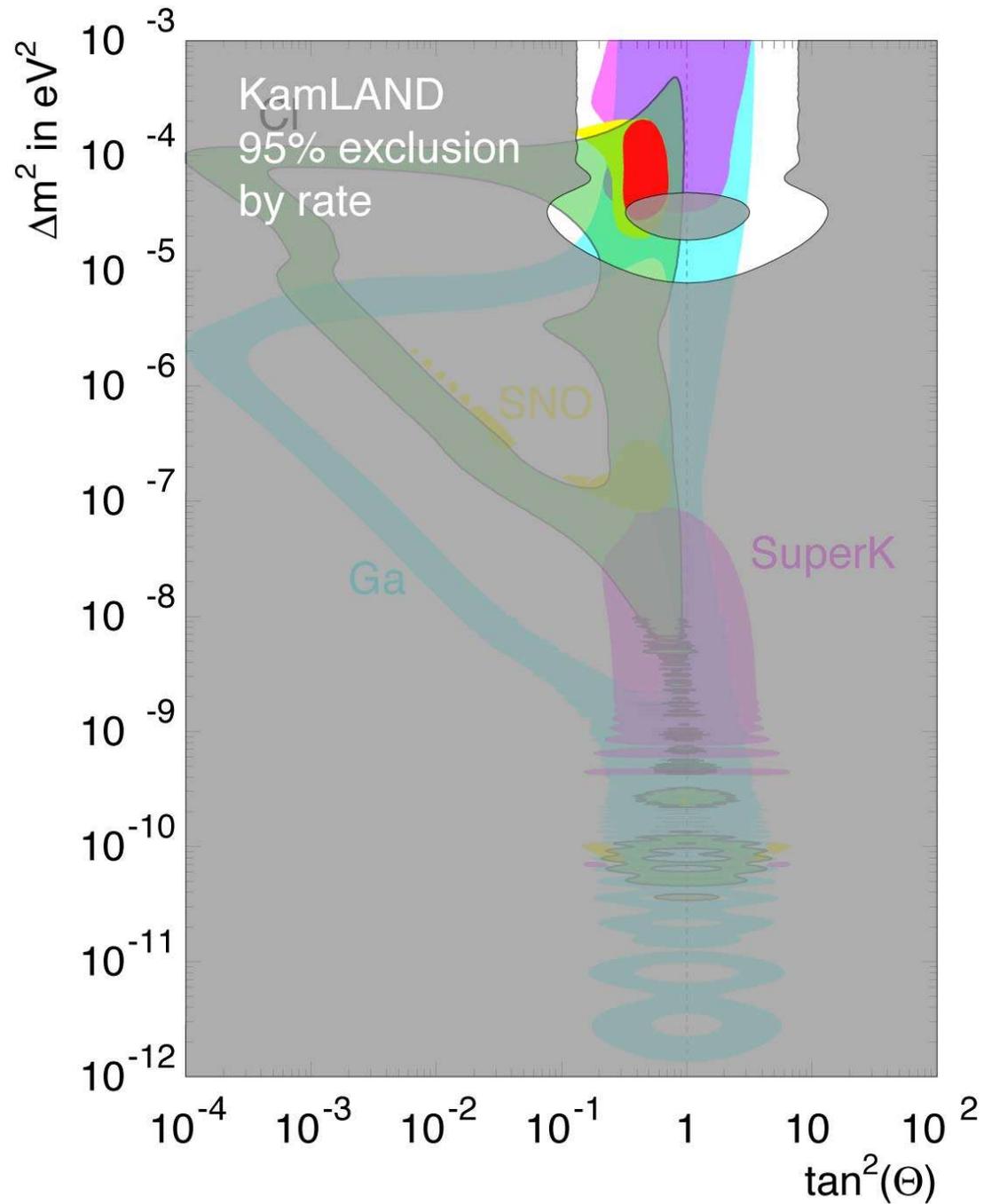
Event Spectrum
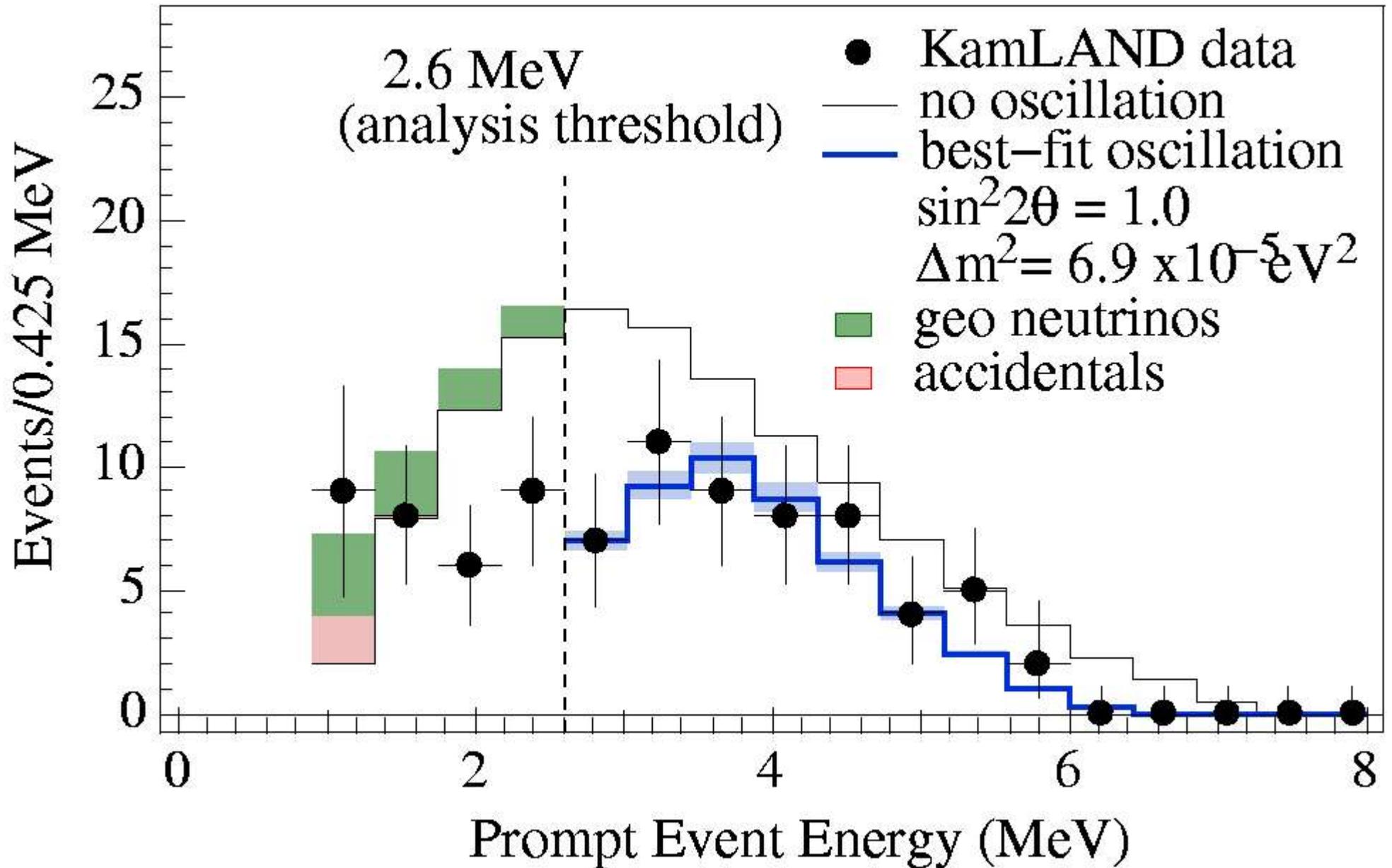
Fit to Oscillation Parameters

All contours at 95% CL

Best fit parameters:
$\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$
$\sin^2 2\theta = 1.0$

Legend:
- Rate excluded
- Rate+Shape allowed
- LMA
- Palo Verde excluded
- Chooz excluded

Axes: Δm^2 (eV^2) vs $\sin^2 2\theta$

Time Variation of Flux

Neutrino flux (1.8-8MeV) at KamLAND from reactors

Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.

Total
Wakasa-bay
Kashiwazaki
Others
Shika
Hamaoka
Korea
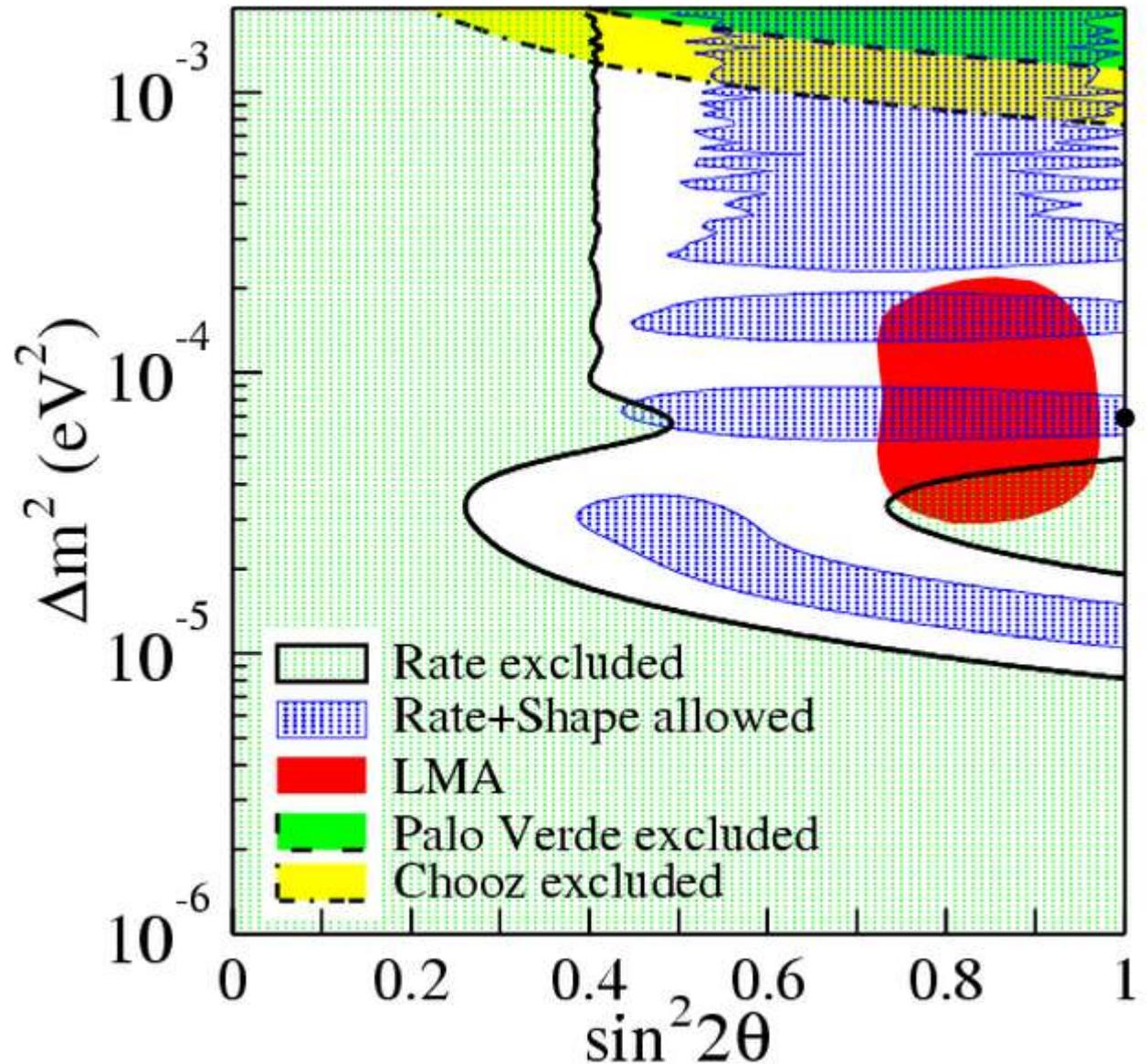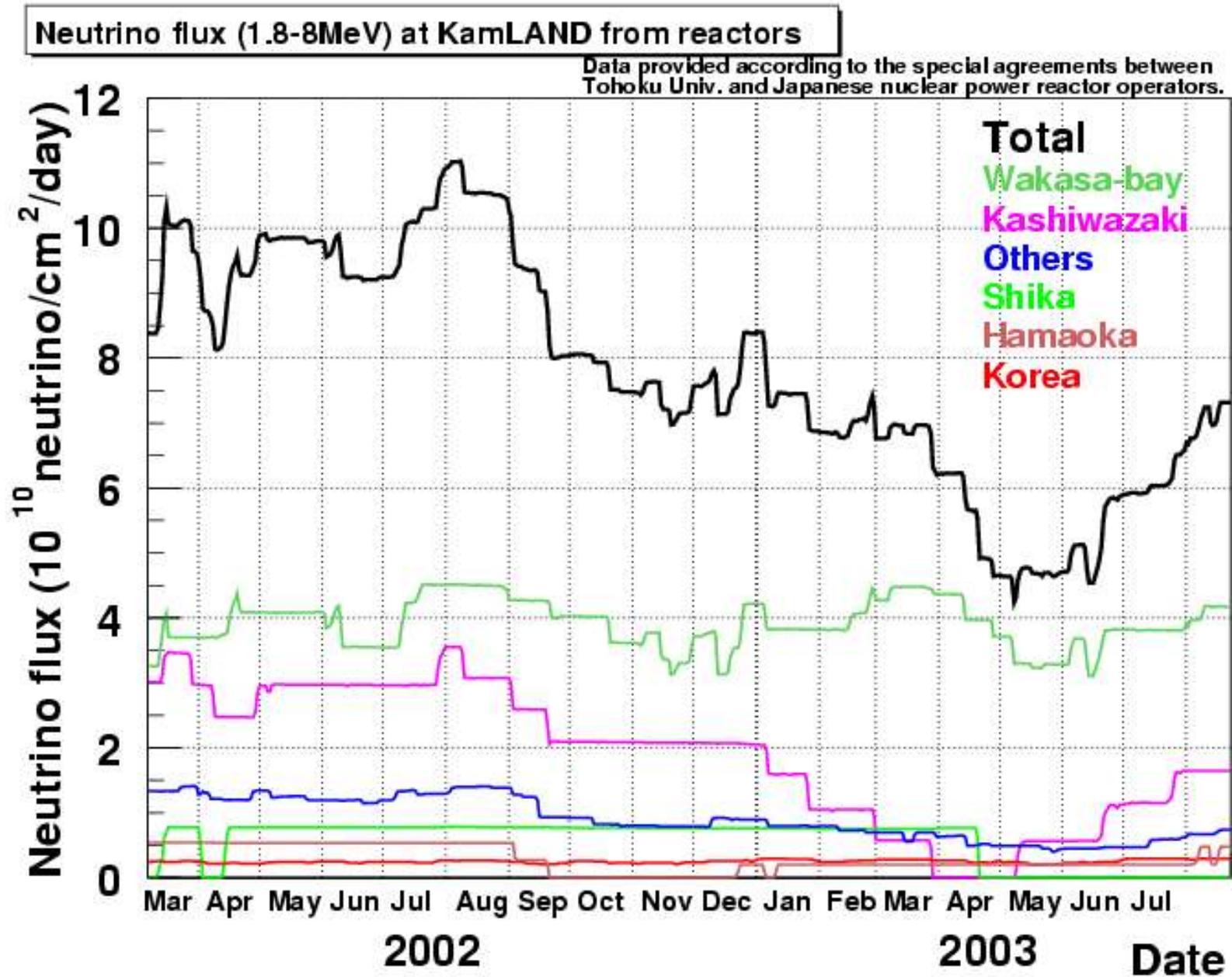
Expected Sensitivity
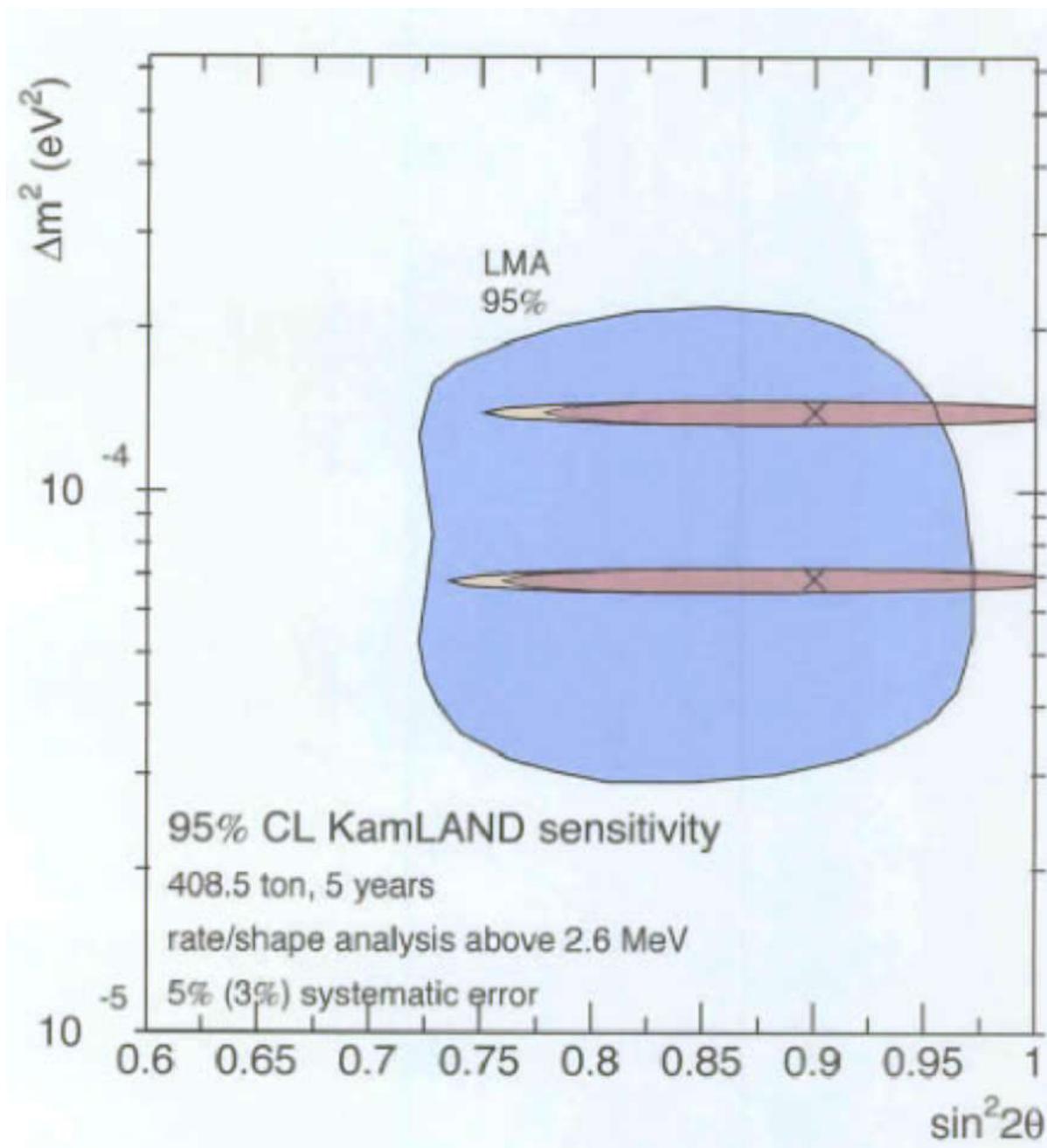
3-Flavor Mixing

$$m_1, m_2, m_3$$

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

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

solar + KamLAND:

$$\theta_{12} \sim 30°$$
$$\Delta m^2_{12} \sim 10^{-4} \text{ eV}^2$$

atmospheric ν:

$$\theta_{23} \sim 45°$$
$$\Delta m^2_{23} \sim 3 \times 10^{-3} \text{ eV}^2$$

$$\theta_{13} < 10°$$
$$\Delta m^2_{13} \sim \pm 3 \times 10^{-3} \text{ eV}^2$$

future accelerator/reactor

neutrinoless
double beta decay

High Energy $\bar{\nu}_e$ Sources

- Solar sources

  - spin flavor precession: $\nu_e \rightarrow \bar{\nu}_{\mu,\tau} \rightarrow \bar{\nu}_e$

  - ν_e decay to $\bar{\nu}_e$

- Other sources

  - WIMP annihilation

  - Supernova relic neutrinos

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Energy Scale Above 5 MeV

^{12}B decay spectrum

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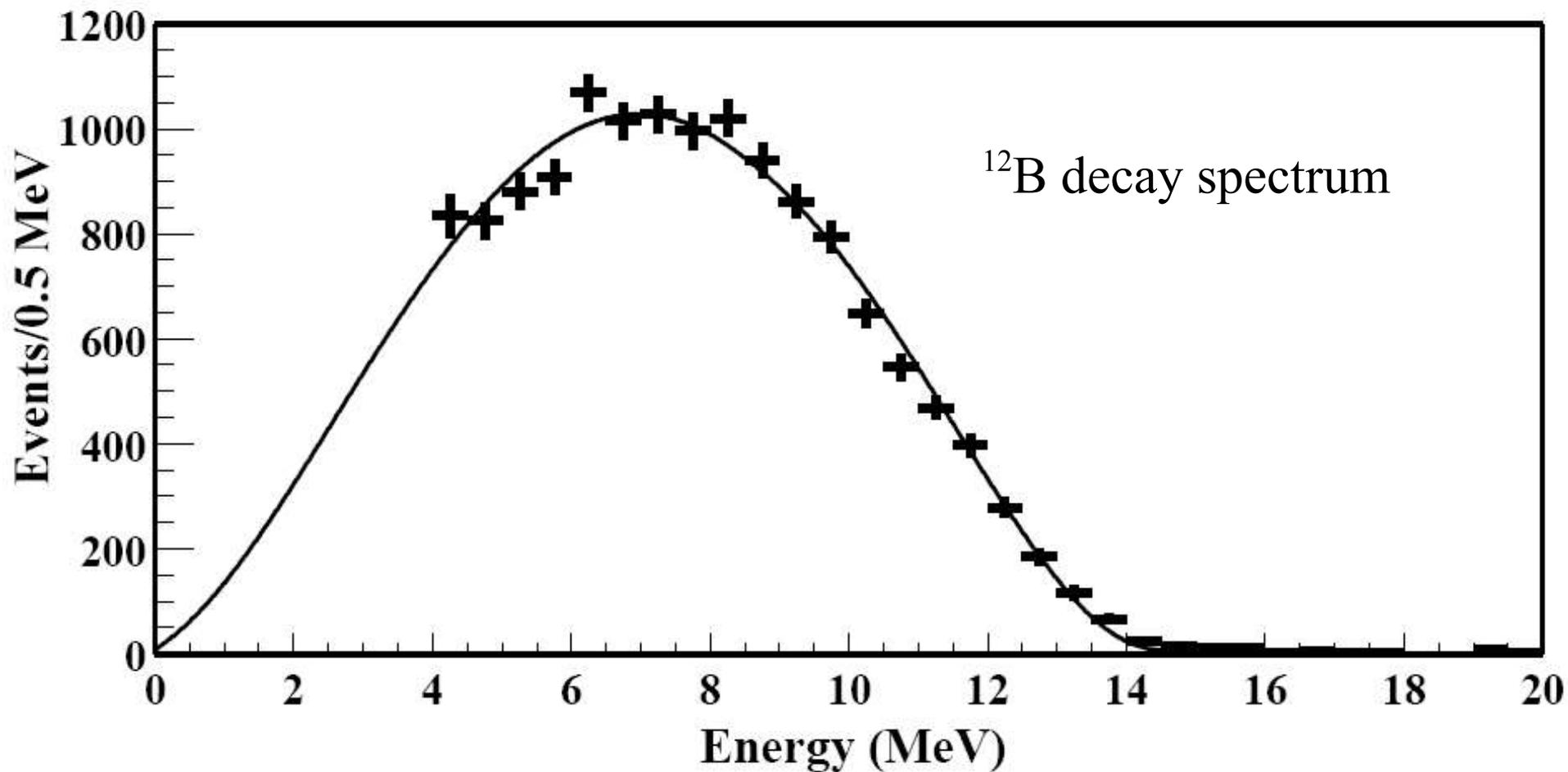
High Energy Backgrounds

Reactor $\bar{\nu}_e$	0.2 ± 0.2
Atmospheric neutrinos	0.001
Fast neutrons	0.3 ± 0.2
Accidentals	0.02
^{8}He and ^{9}Li	0.6 ± 0.2
Total	1.1 ± 0.4

High Energy Systematics

Detection efficiency	1.6
Cross section	0.2
Number of target protons	4.3
Energy threshold	4.3
Livetime	0.07
Total	6.3

High Energy Electron-Antineutrinos

energy region for
solar anti–neutrino
analysis
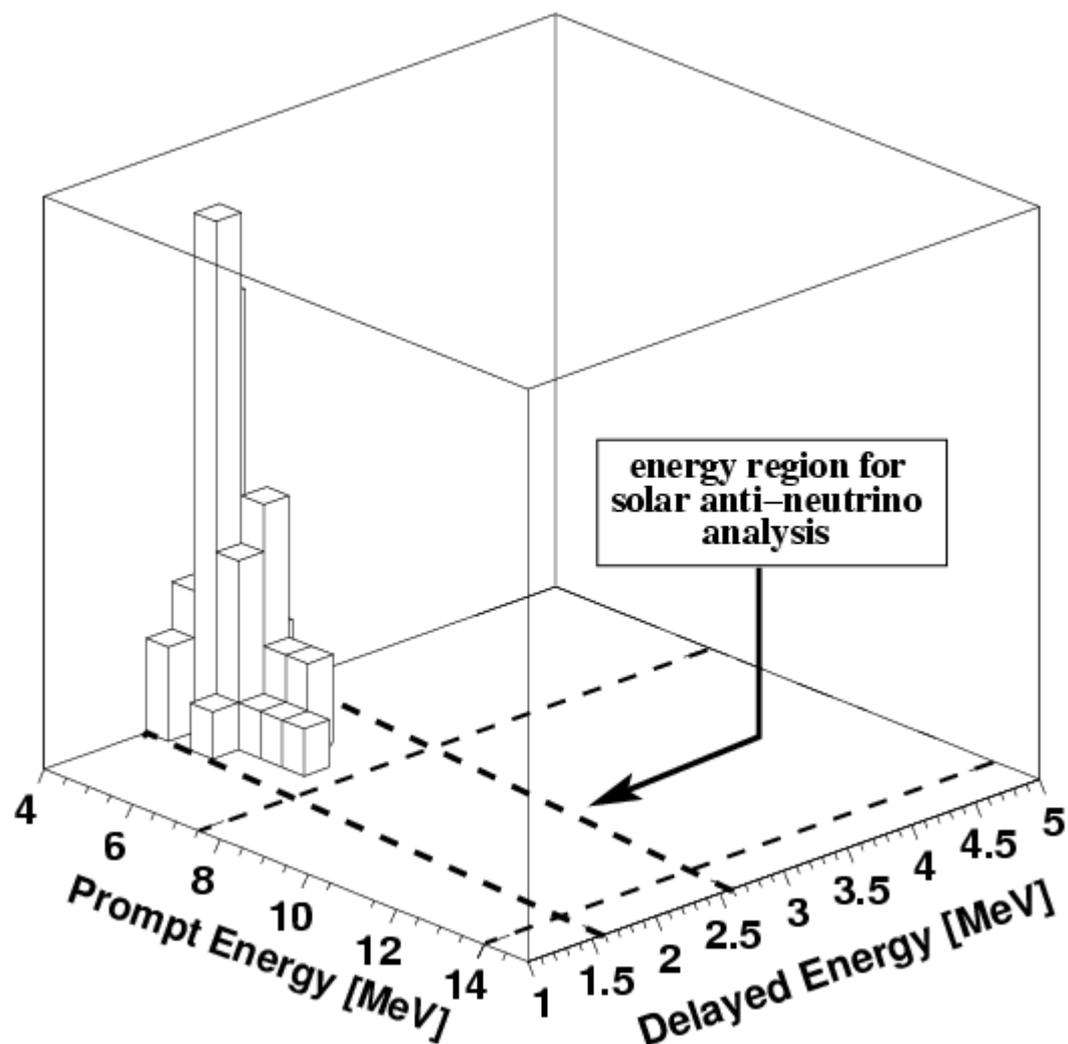
High Energy $\bar{\nu}_e$ Results

- No events detected in 0.28 kton-yr exposure with 1.1 ± 0.4 background expected

- ν_e flux $< 2.8 \times 10^{-4}$ times solar ^{8}B neutrino flux

  $\rightarrow$ improvement by a factor of ~30

- As a limit on spin flavor precession:

  $$\mu_\nu < 1.3 \times 10^{-10} \, \mu_B \times [100 \text{ kG} / B_{sT}(0.05 \, R_s)]$$

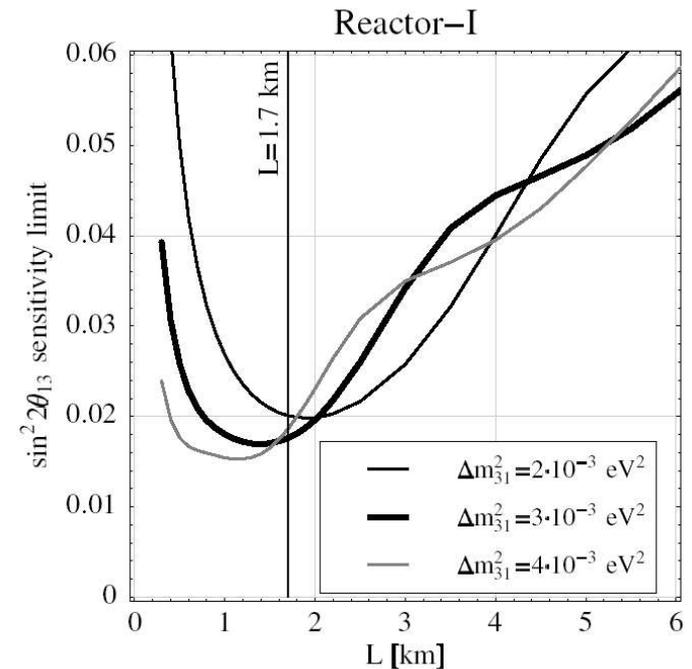 (best limit from MUNU: $\mu_\nu < 1.0 \times 10^{-10} \, \mu_B$)

Conclusions

- KamLAND observed, for the first time, disappearance of electron antineutrinos in a laboratory-style experiment

- Assuming CPT invariance, this result excludes solar neutrino oscillation solutions except LMA at > 99.95% CL

- No detected events between 8 - 15MeV puts a limit on *any* electron antineutrino flux at KamLAND in that energy range

- Limit on $\overline{\nu}_e$ from the sun improved by factor of ~30

- More results are on the way (updated reactor, geoneutrinos, neutron production...)

θ_{13} at Reactors

$\bar{\nu}_e$

Reactor

Near Detector
L ~ 100m

$\bar{\nu}_?$

Far Detector
L ~ 1000m
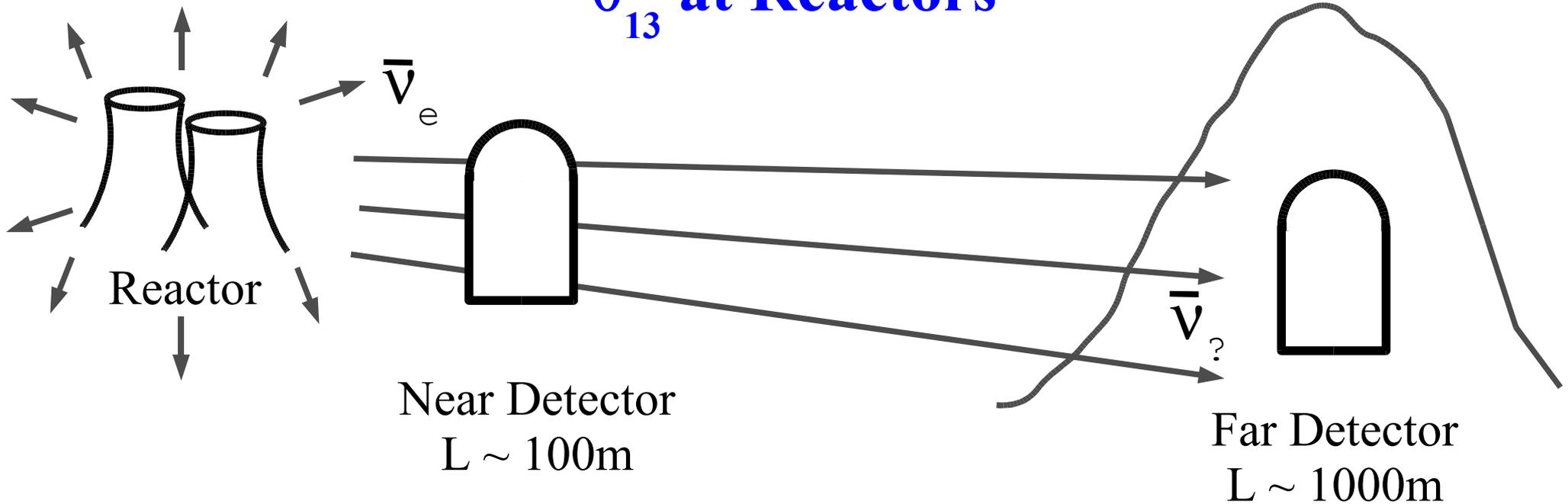
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{13}} \sin^2 \frac{1.27 \Delta m_{13}^2 L}{E} + O(\alpha^2)$$

- First discussed by L.A.Mikaelyan and V.V.Sinev, Phys. Atom. Nucl. **63**, 1002 (2001)
- Also see P. Huber et al., arXiv:hep-ph/0303232 and the more comprehensive list at http://kmheeger.lbl.gov/theta13/references.html

from Huber et al.