Reactor $\bar{\nu}_e$ Disappearance at KamLAND

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

Tohoku University

J.Busenitz, Z.Djurcic, K.McKinny, D-M.Mei, A.Piepke, E.Yakushev

University of Alabama

B.E.Berger, Y-D.Chan, M.P.Decowski, D.A.Dwyer, S.J.Freedman, Y.Fu, B.K.Fujikawa, K.M.Heeger, K.T.Lesko, K-B.Luk, H.Murayama, D.R.Nygren, C.E.Okada, A.W.Poon, H.M.Steiner, L.A.Winslow

LBNL/UC Berkeley

G.A.Horton-Smith, R.D.McKeown, J.Ritter, B.Tipton, P.Vogel

California Institute of Technology

C.E.Lane, T.Miletic

Drexel University

P.Gorham, G.Guillian, J.Learned, J.Maricic, S.Matsuno, S.Pakvasa

University of Hawaii

S.Dazeley, S.Hatakeyama, M.Murakami, R.C.Svoboda

Louisiana State University

B.D.Dieterle, M.DiMauro

University of New Mexico

J.Detwiler, G.Gratta, K.Ishii, N.Tolich, Y.Uchida

Stanford University

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

TUNL

M.Batygov, W.Bugg, H.Cohn, Y.Efremenko, Y.Kamyshkov, A.Kozlov, Y.Nakamura

University of Tennessee

Y-F.Wang

IHEP, Beijing

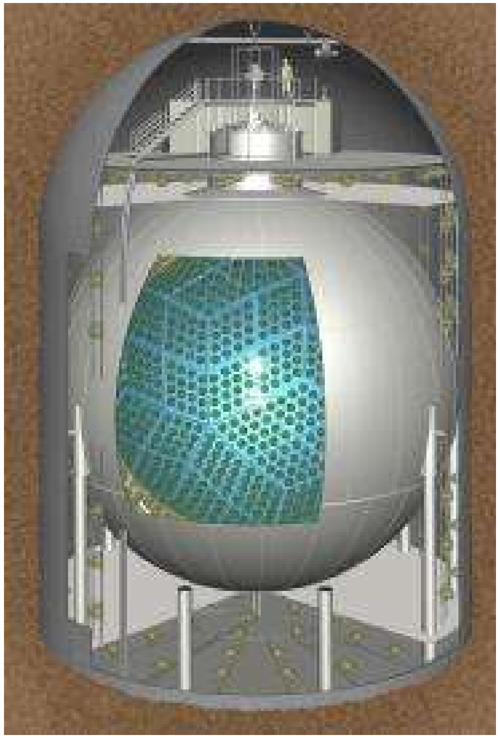
Introduction

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

Nuclear reactor

$\bar{\nu}_e$

Detector



L

Neutrino Oscillations

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

$$\nu_l = \sum$$

- the ν_j evolve in time as:

$$\nu_j(t) = e^{-i(p\cdot x)}\nu_j(0) \approx e^{-i(m_j^2/2E)L}\nu_j(0)$$

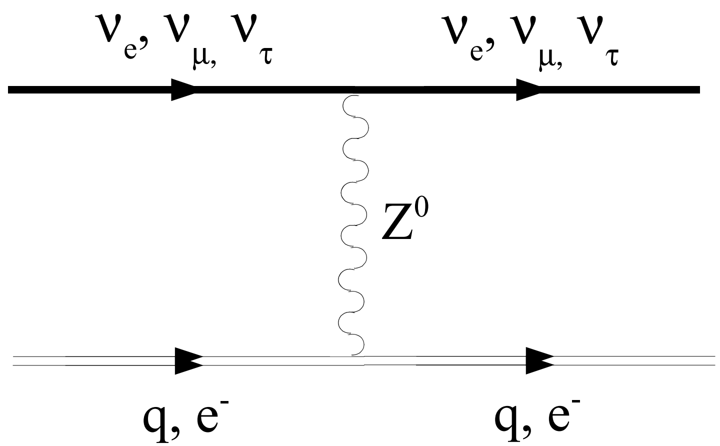
- The probability of detecting flavor $\nu_{l'}$ at distance L is:

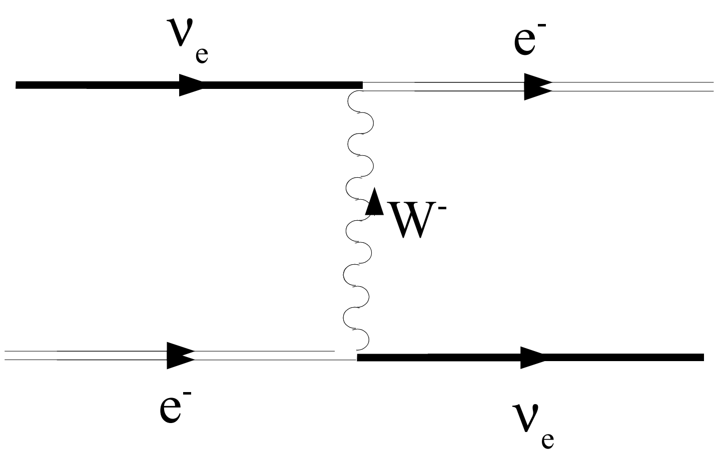
$$P(\nu_l \rightarrow \nu_{l'}, L) = |$$

- For 2 flavors (e.g. ν_e, ν_μ) this simplifies:

$$P(\quad L) \quad \sin^2 2$$

Matter Effects





$$n = 1 + \frac{2\pi N}{p^2} f_l(0)$$

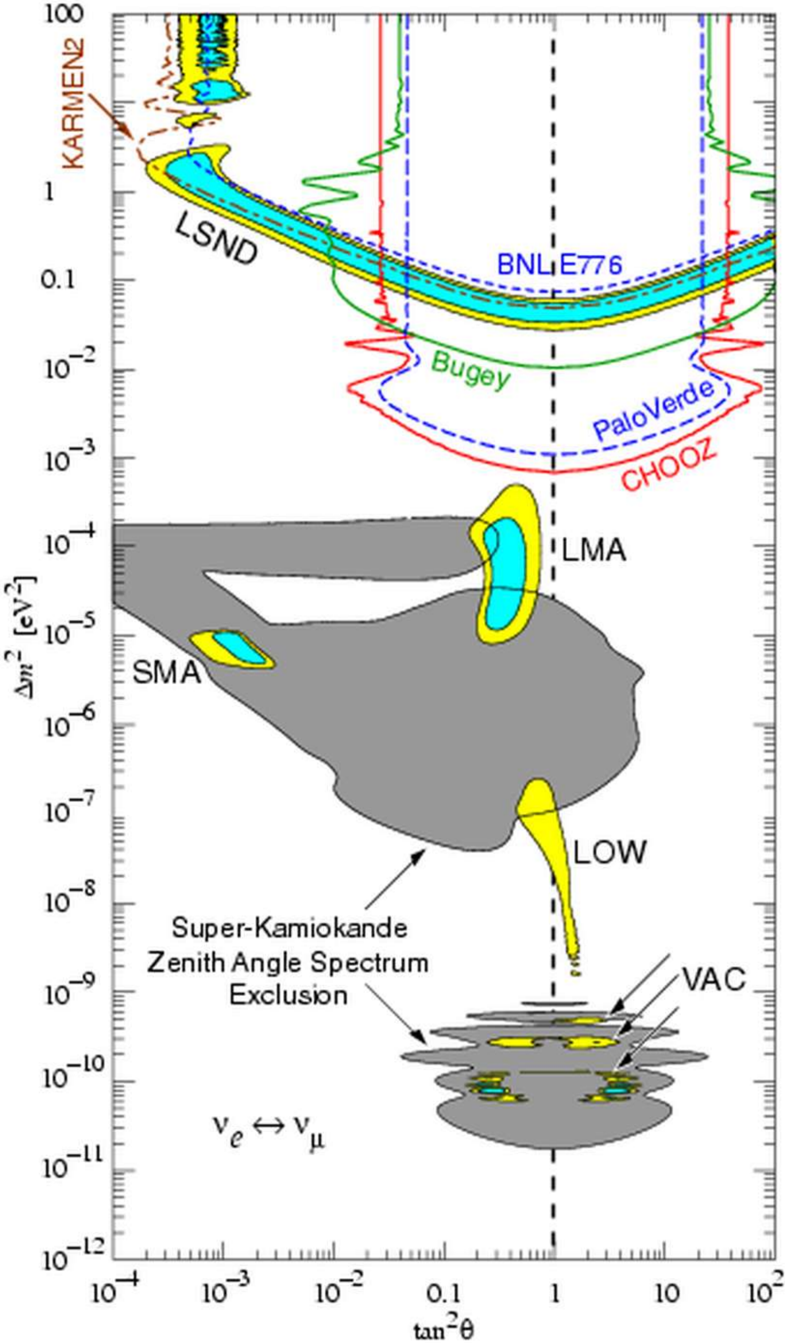
$$L_0 = \frac{2\pi}{\sqrt{2} G_F N_e}$$

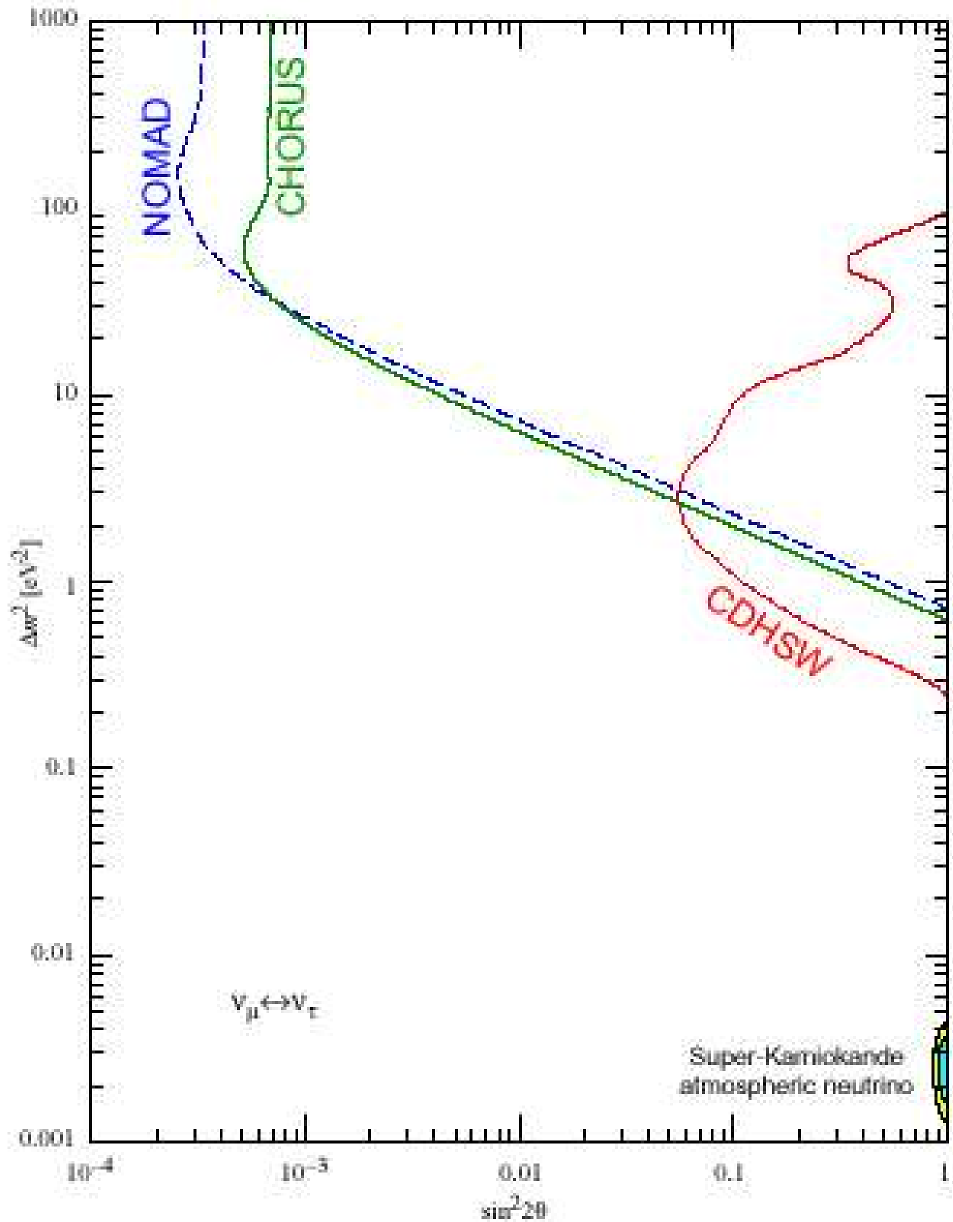
$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta_m \sin^2 \frac{\pi L}{L_m}$$

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

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

Neutrino Mixing Parameters

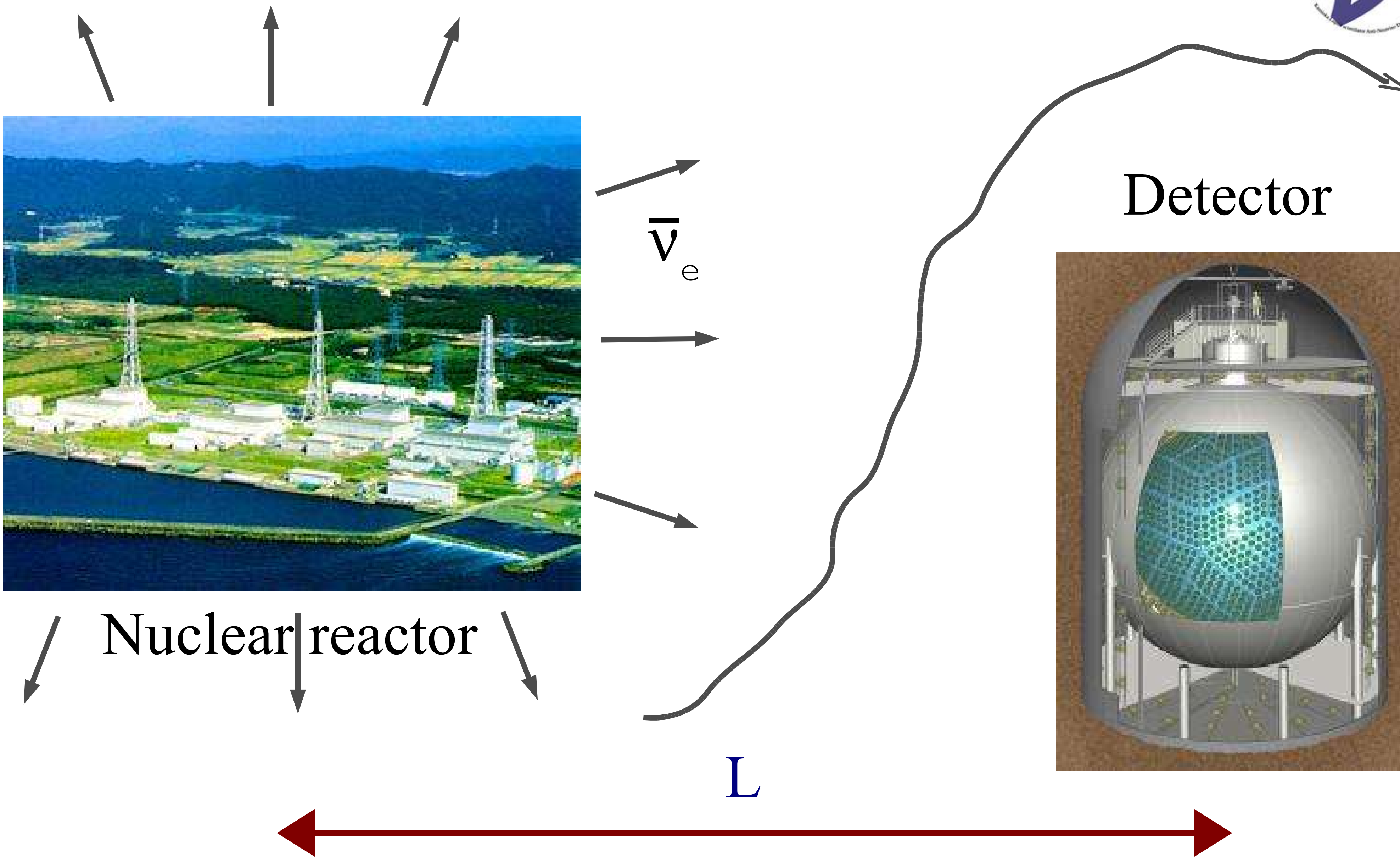




Neutrinos On Earth

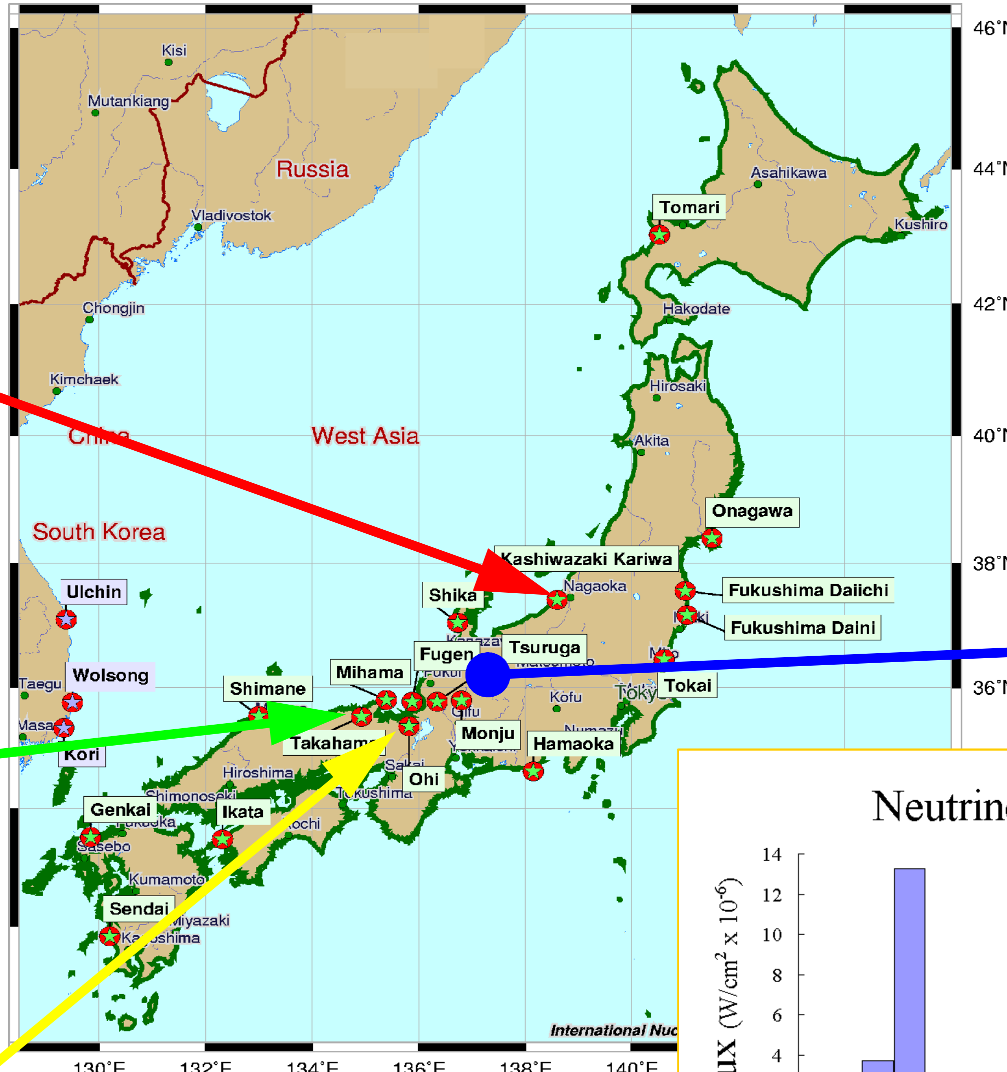
- Control source and detector
- Sun: $L_0 \sim 200$ km << R_{sun}; Rock: $L_0 \sim 10^4$ km > R_{earth}
  Matter effects much less significant
- Neutrino beams: E ~ 100 MeV: sensitivity to solar neutrino problem requires L ~ 1000km
- Reactors: antineutrinos with E ~ MeV: L can be smaller but 4π source

Reactor Experiments



Reactors In Japan

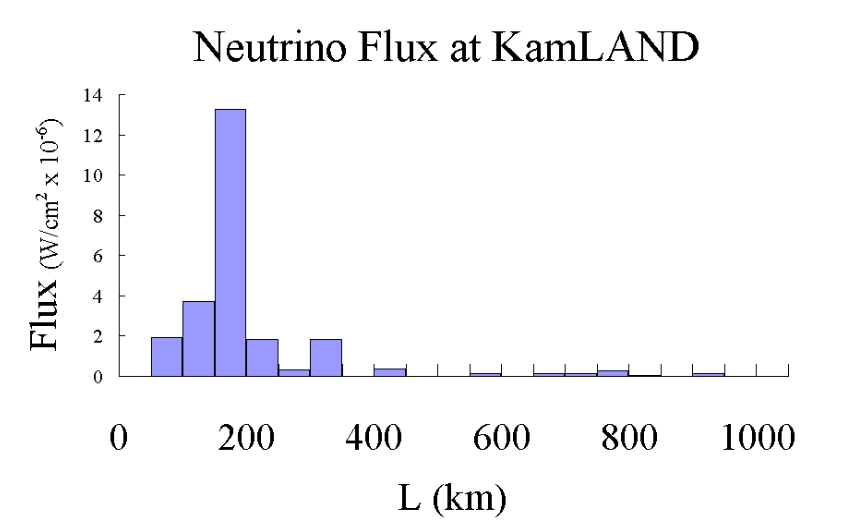
55% of total fl ux from:



KamLAND uses the entire Japanese nuclear power industry as a long-baseline source

KamLAND

80% of total flux from baselines 140-210 km



^{235}U Fission

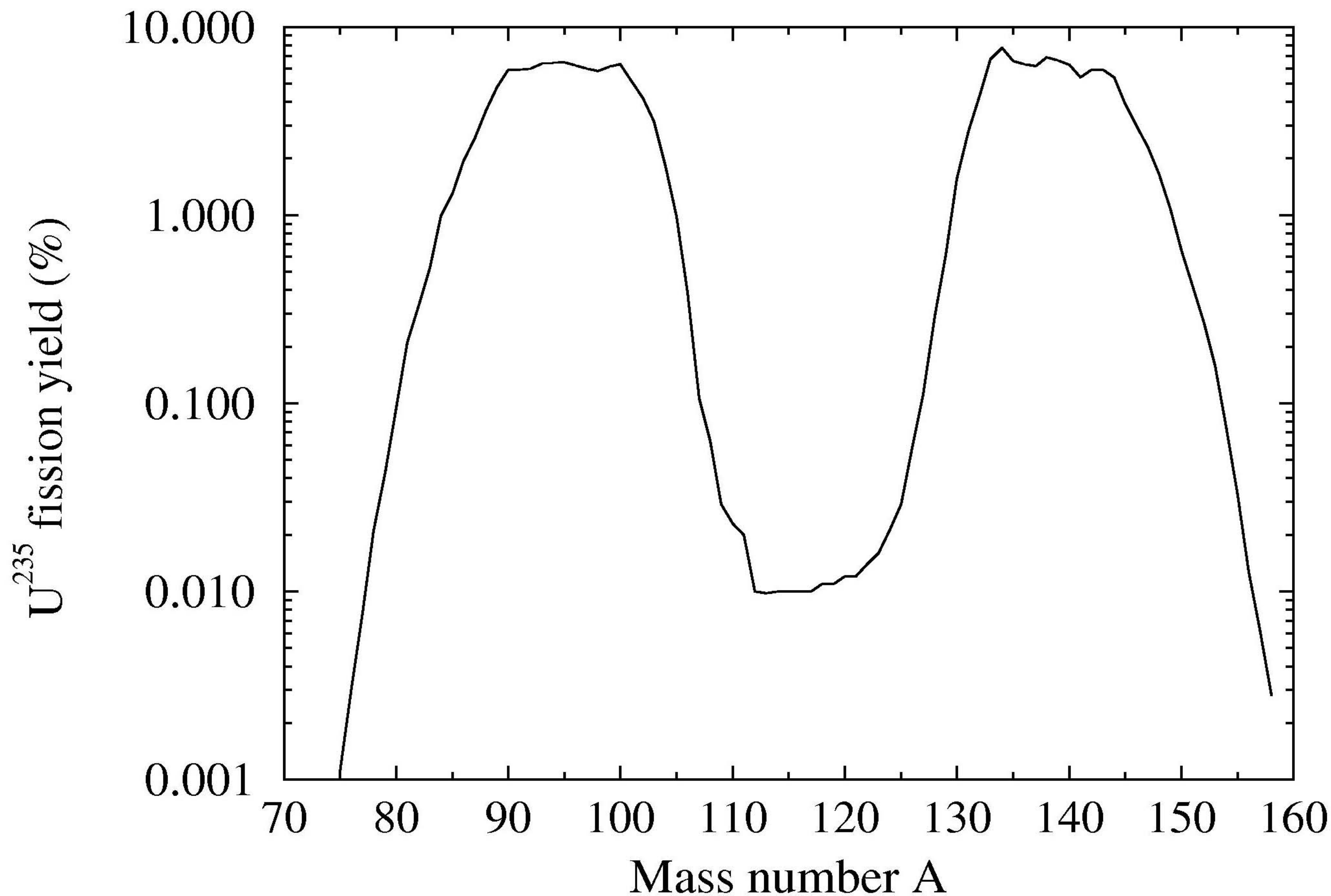
235 U

92 protons and 142 neutrons are shared between X_1 and X_2

Stable nuclei with A most likely from fission:

94 and 140

98 protons
136 neutrons



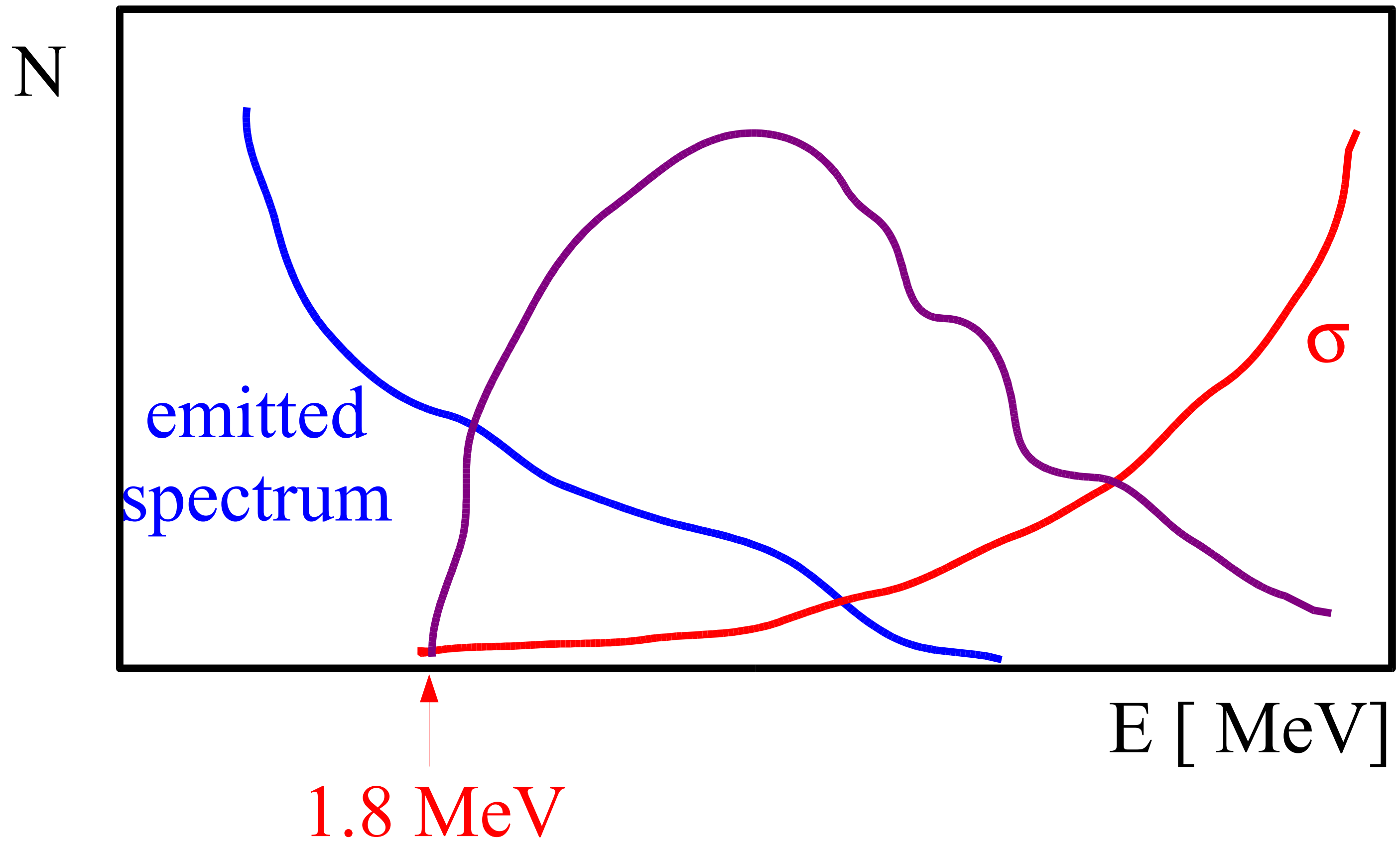
On average, 6 n must decay to 6 p to reach stable matter.

Reactor Output

- A typical large power reactor operates at ~3 GW_{th}
- At 200 MeV / fission and 6 ν_e / fission:

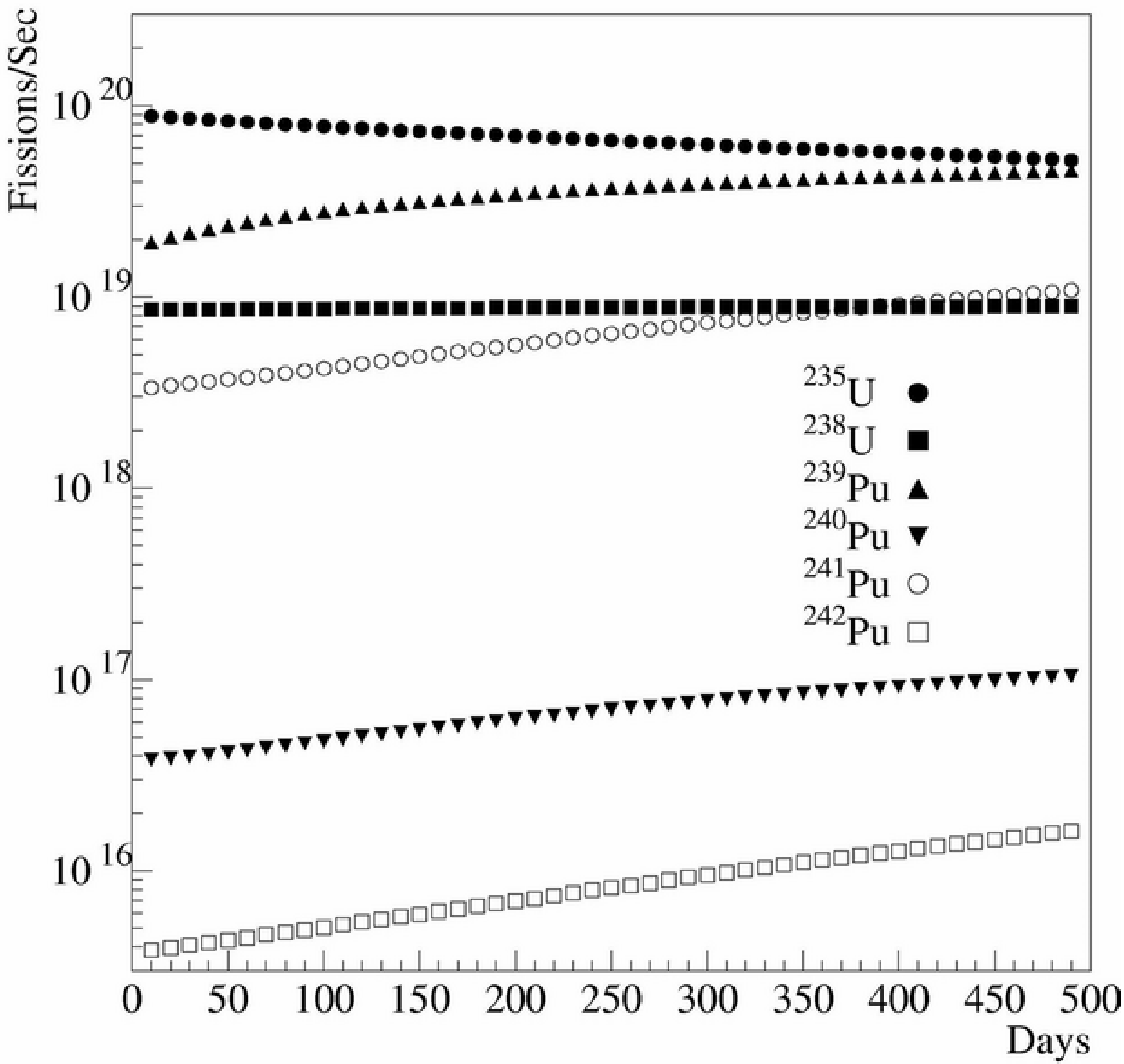
$$6 \times 10^{20}\ \bar{\nu}_e \text{ emitted into } 4\pi \text{ each second}$$

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



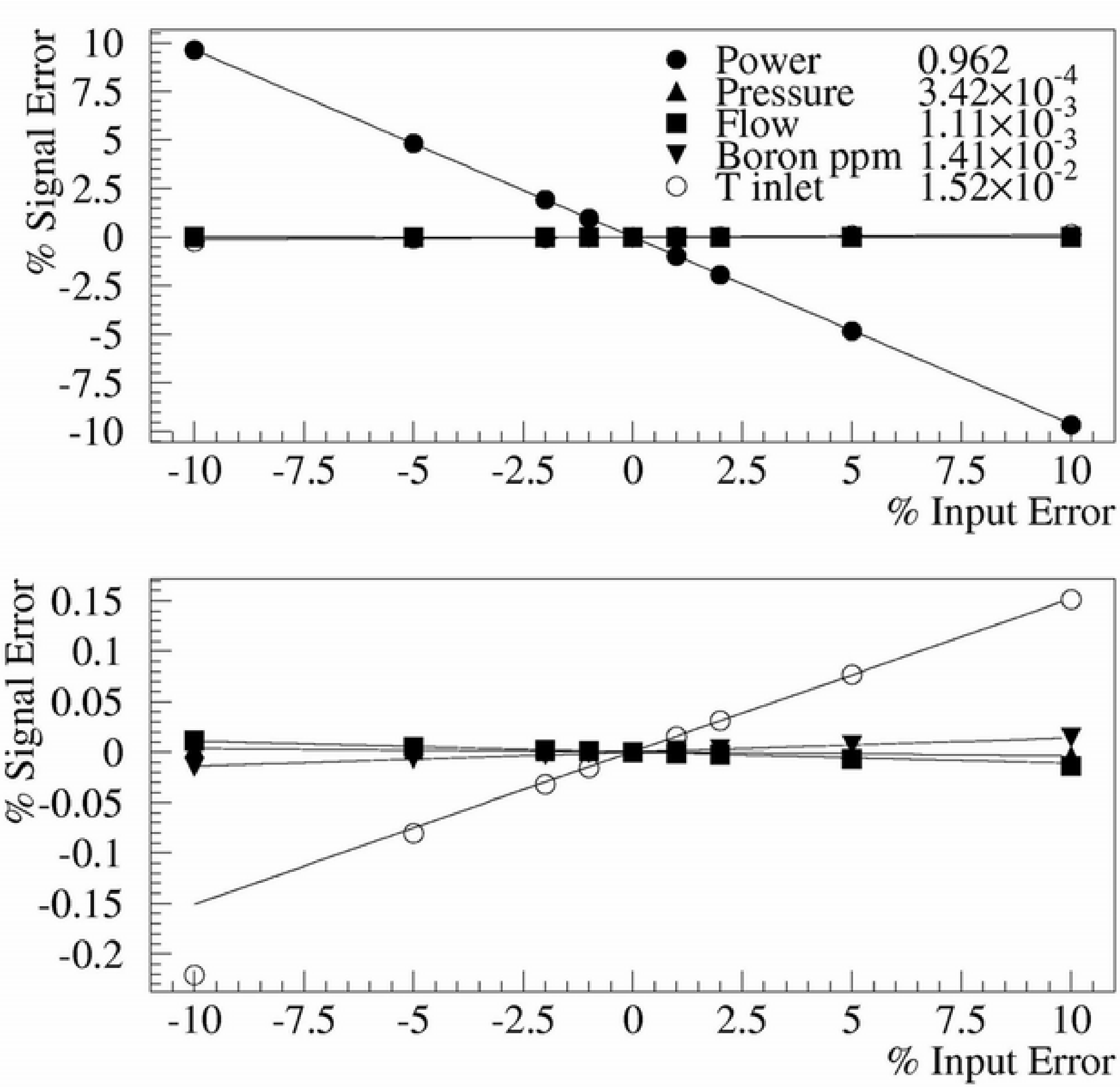
Only ~1.5 ν_e per fission are actually detected

Reactor Fuel Cycle



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

Simulation Inputs



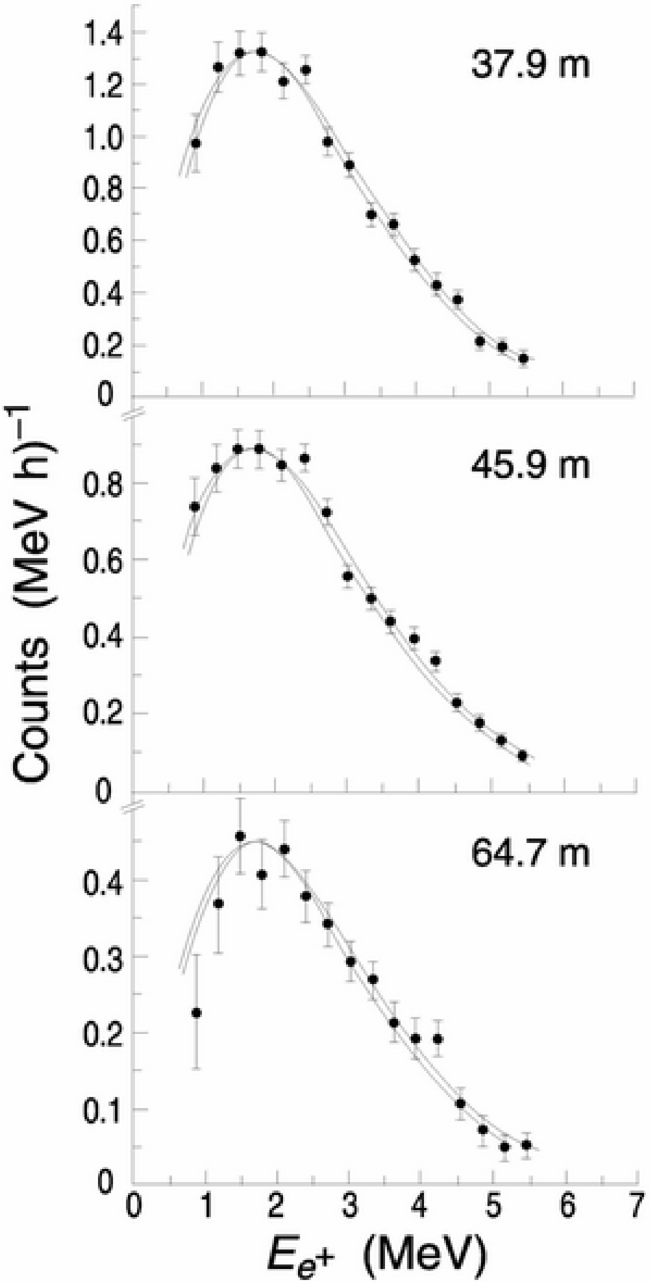
$\bar{\nu}_e$ Spectra

• For 235U, 239Pu, and 241Pu, nuebar spectra can be derived from β-spectrum measurements. This is not easy, since there are many fission branches, each with a variety of β-decay branches.

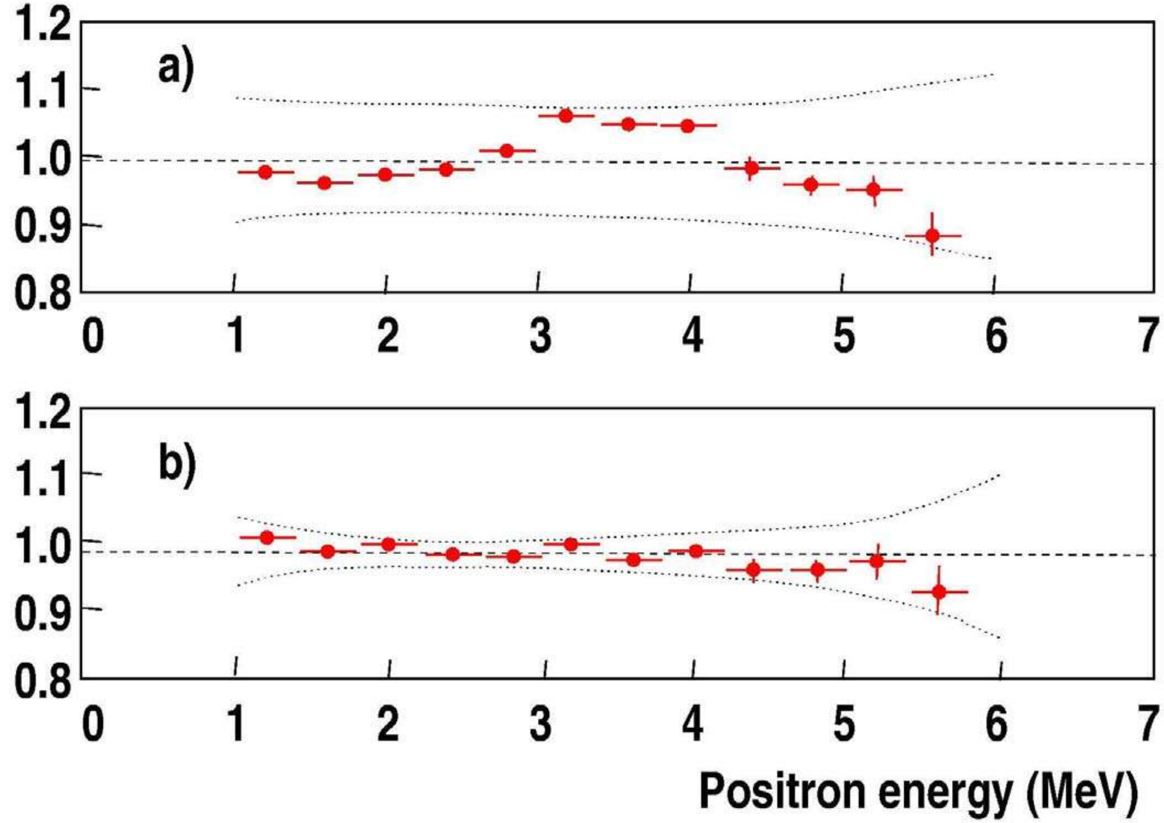
• For 238U, which makes up 11% of the yeild, no spectra are available, so we must rely on calculations, which are accurate to only 10%.

Previous Results

3 baselines at Goesgen



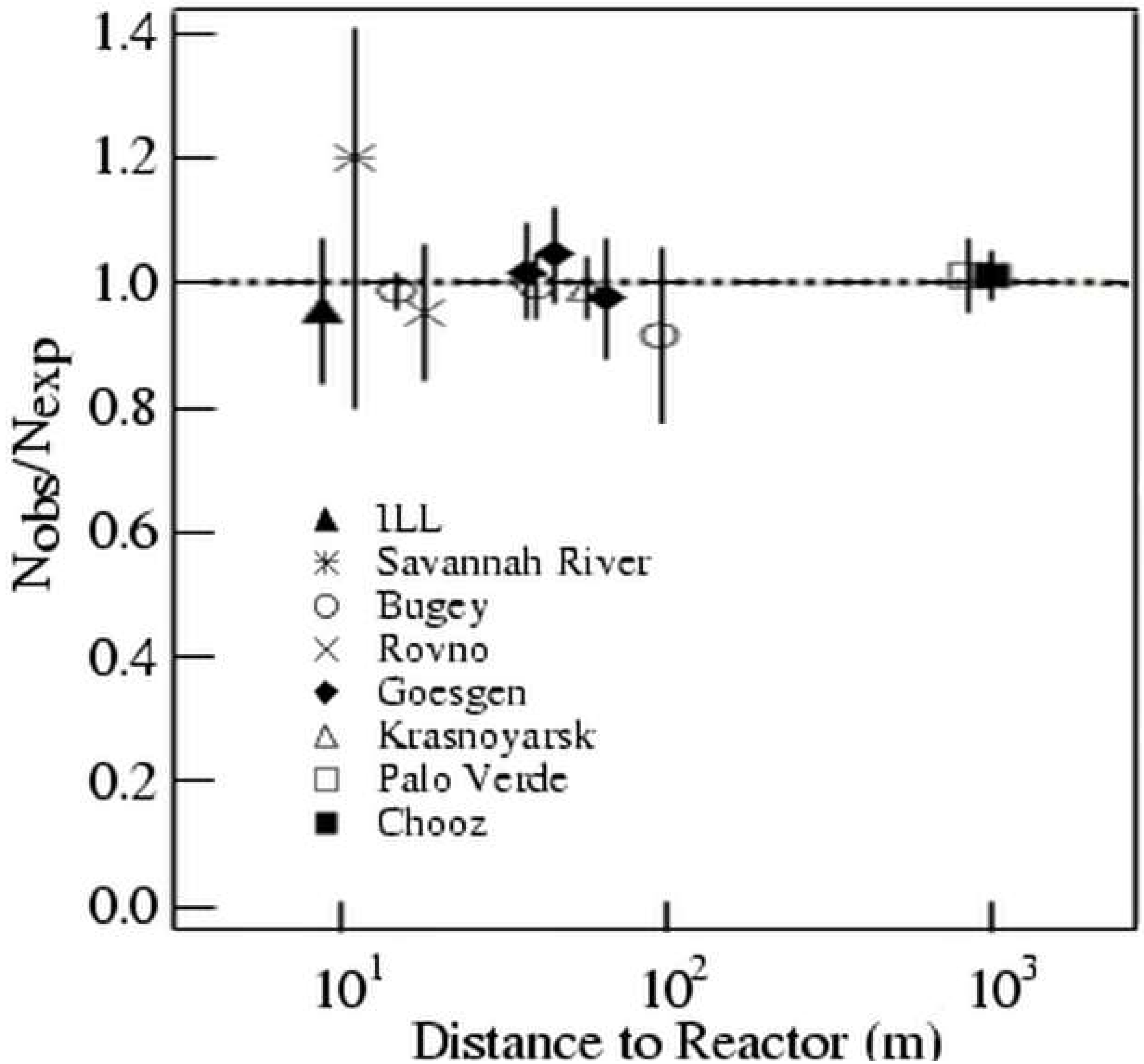
Bugey3 (short baseline)



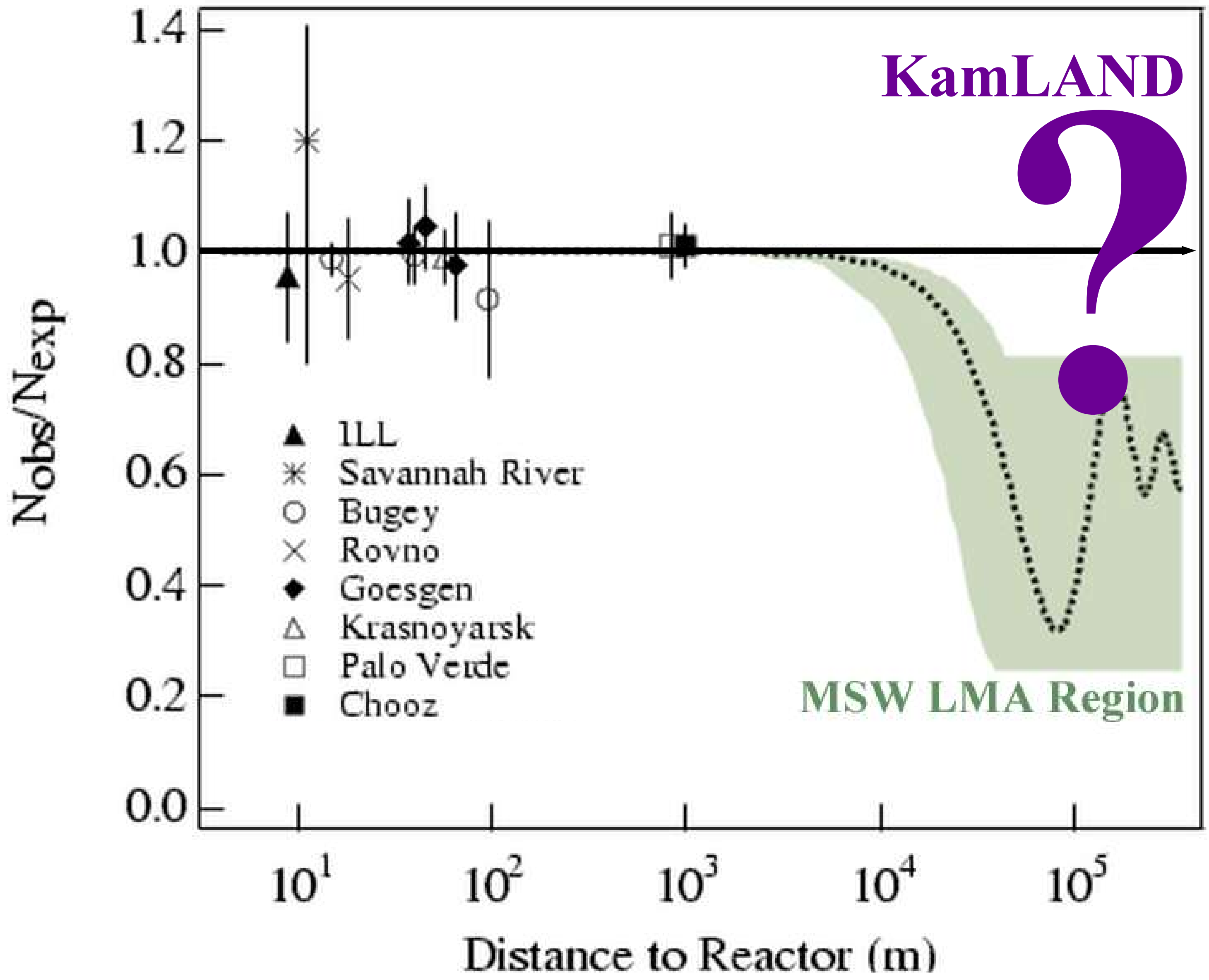
a) "first principles" calculation

b) best prediction (uses β-spectra where possible and calculation for U^{238})

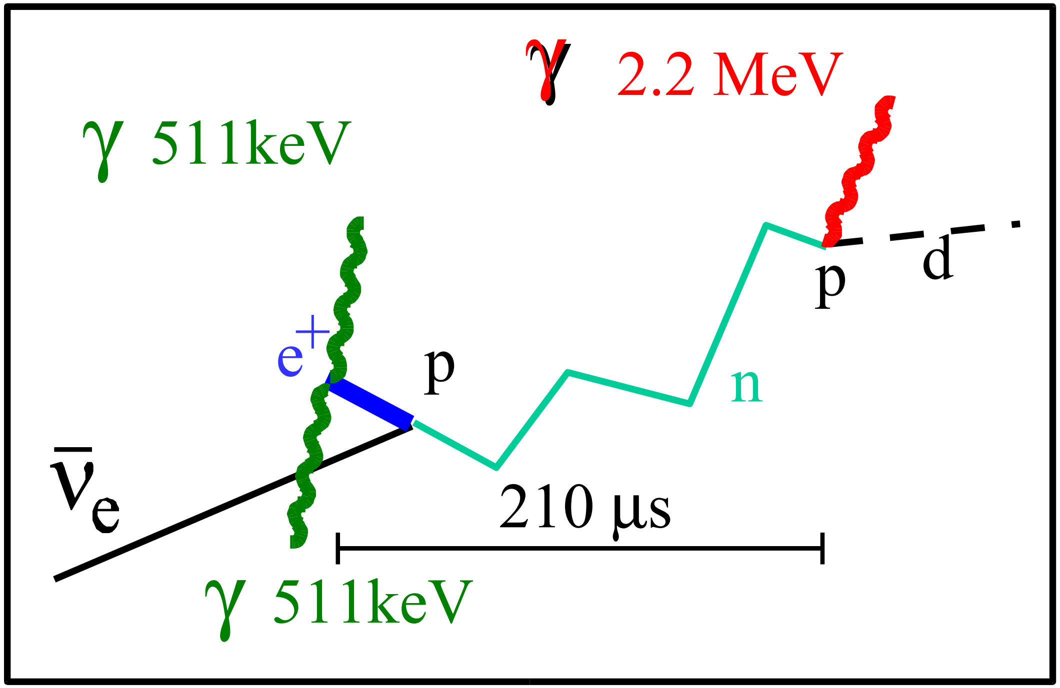
Previous Results



Previous Results



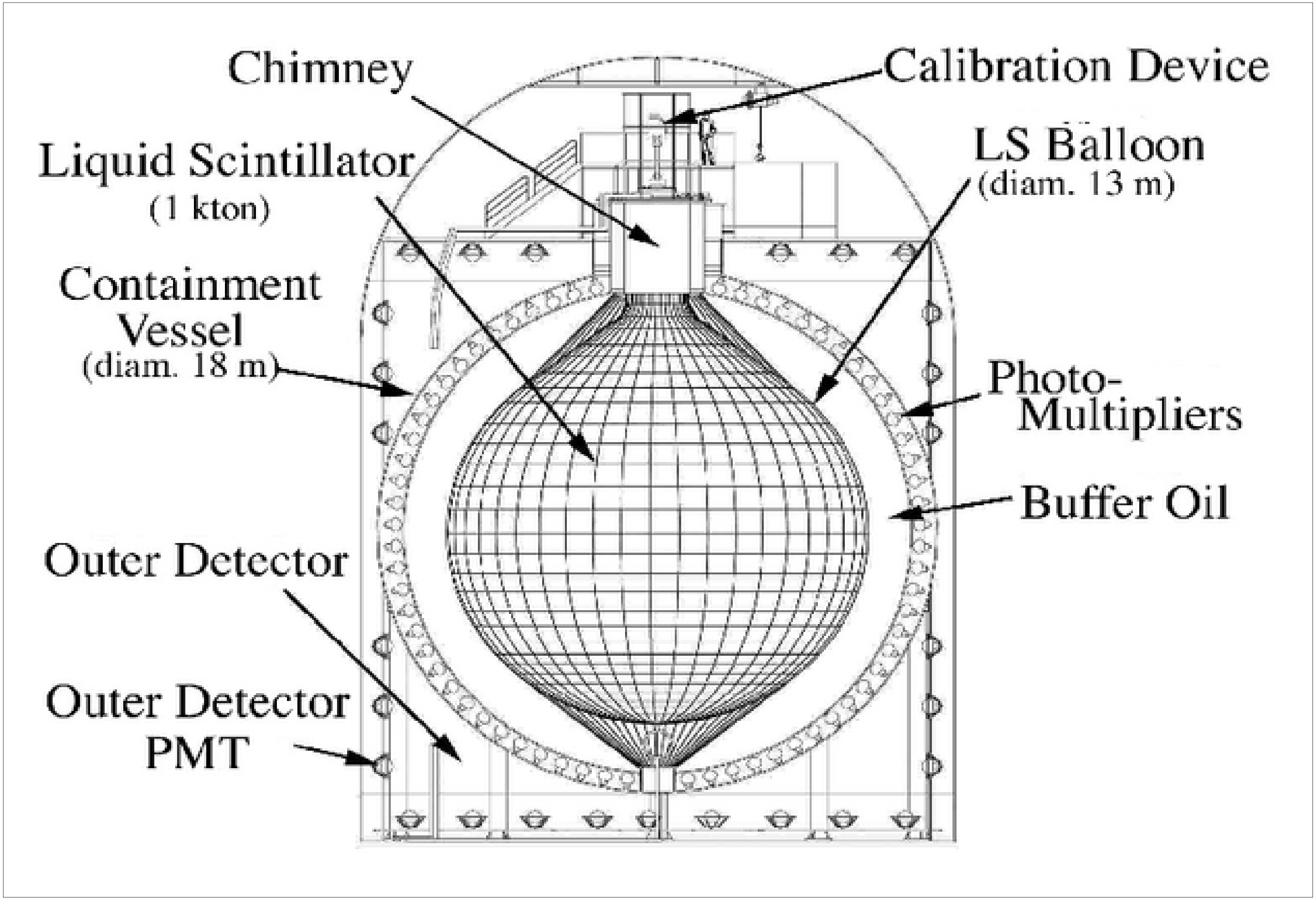
Event Signature



Coincidence signal: detect
- Prompt: e^+ energy + annihilation γ
- Delayed: **n**-capture γ

Average Δt = 210 μs

The KamLAND Detector



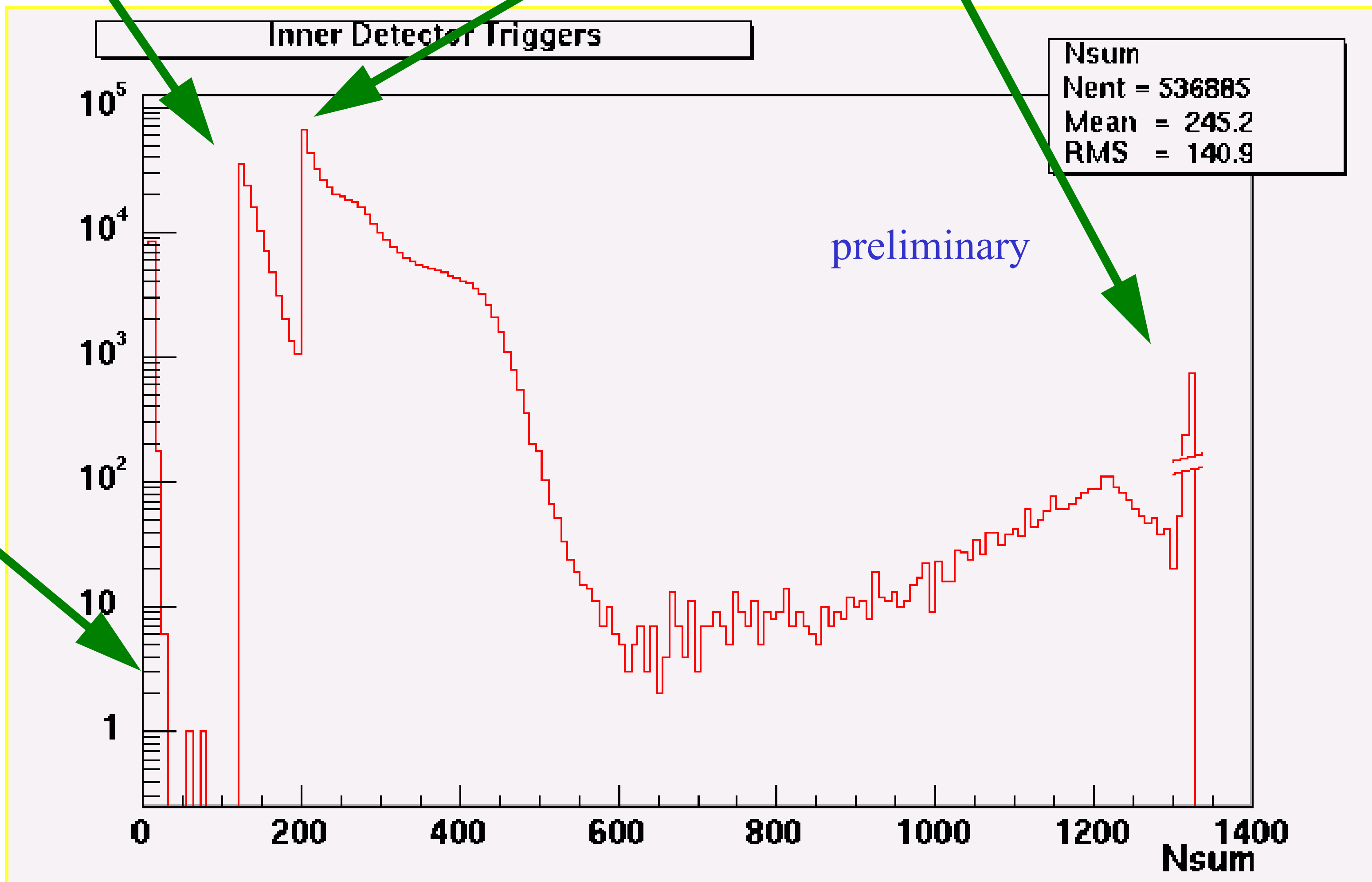
KamLAND Trigger

Coincidence, prescale threshold:
120 PMT's hit

Singles threshold:
200 PMT's hit

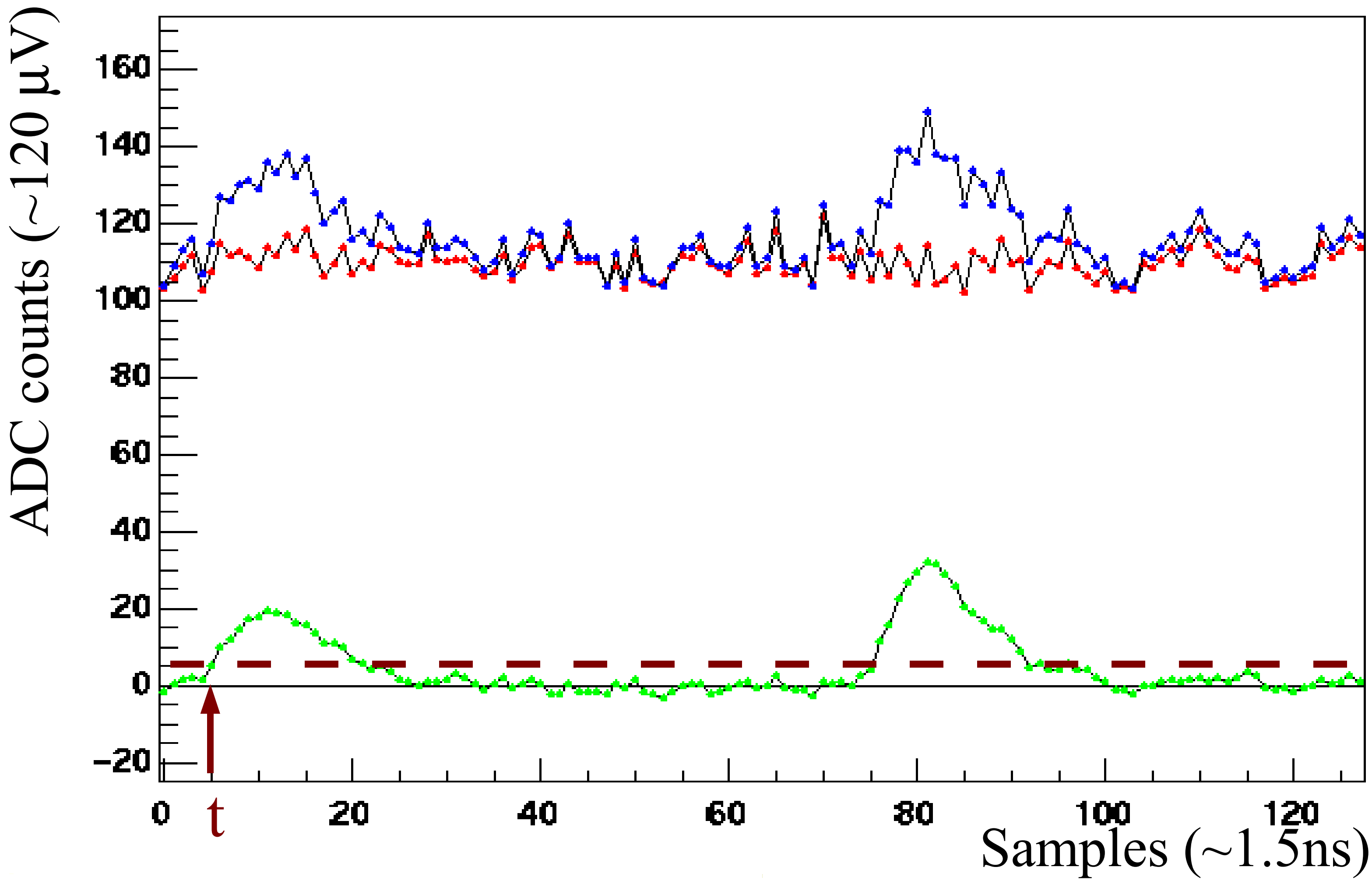
Muons:
all tubes hit

Calibration
triggers

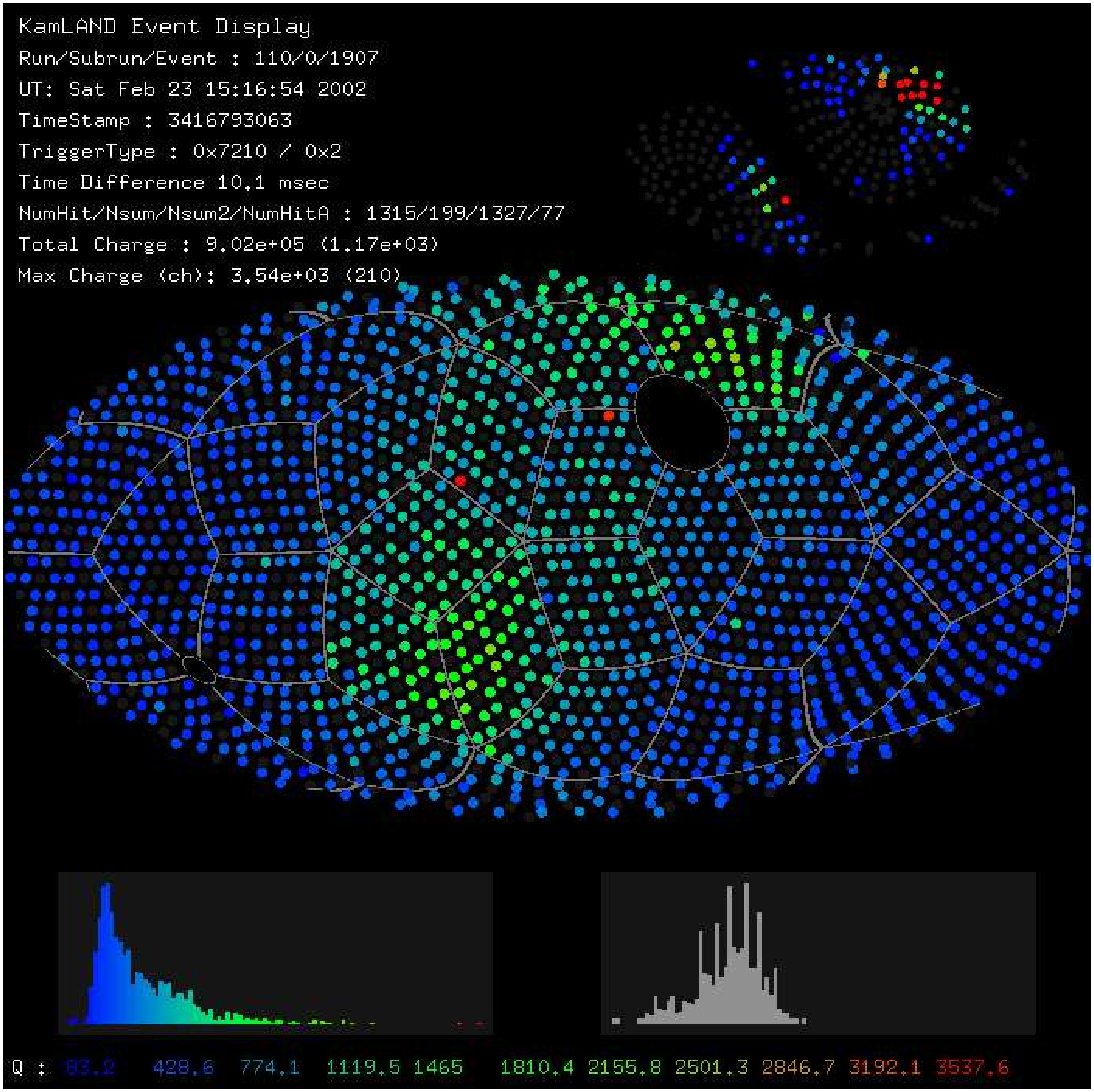


Waveform Analysis

Blue: raw data
red: pedestal
green: pedestal subtracted



KamLAND Data

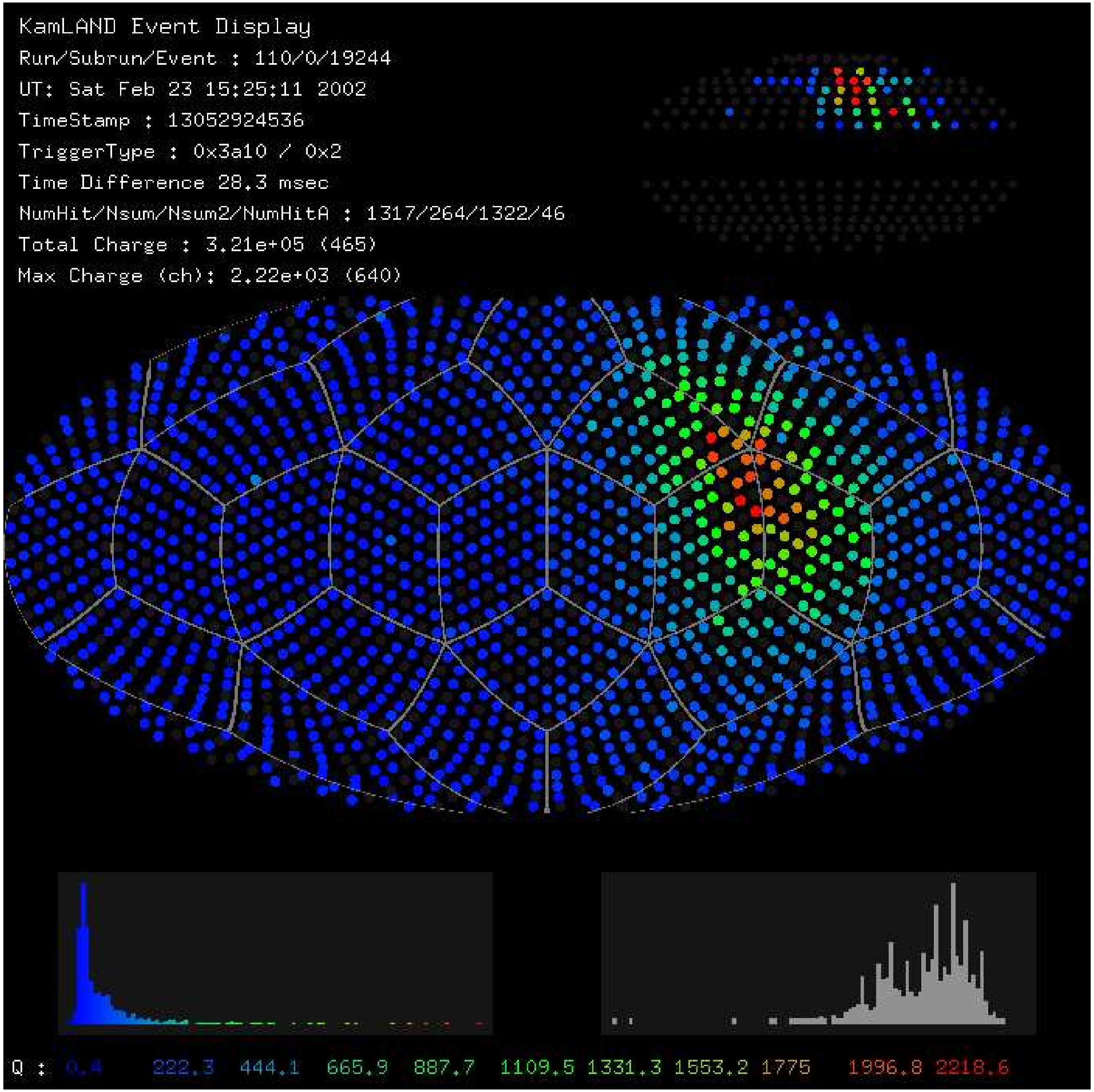


Event Display: through-going muon

color is pulseheight

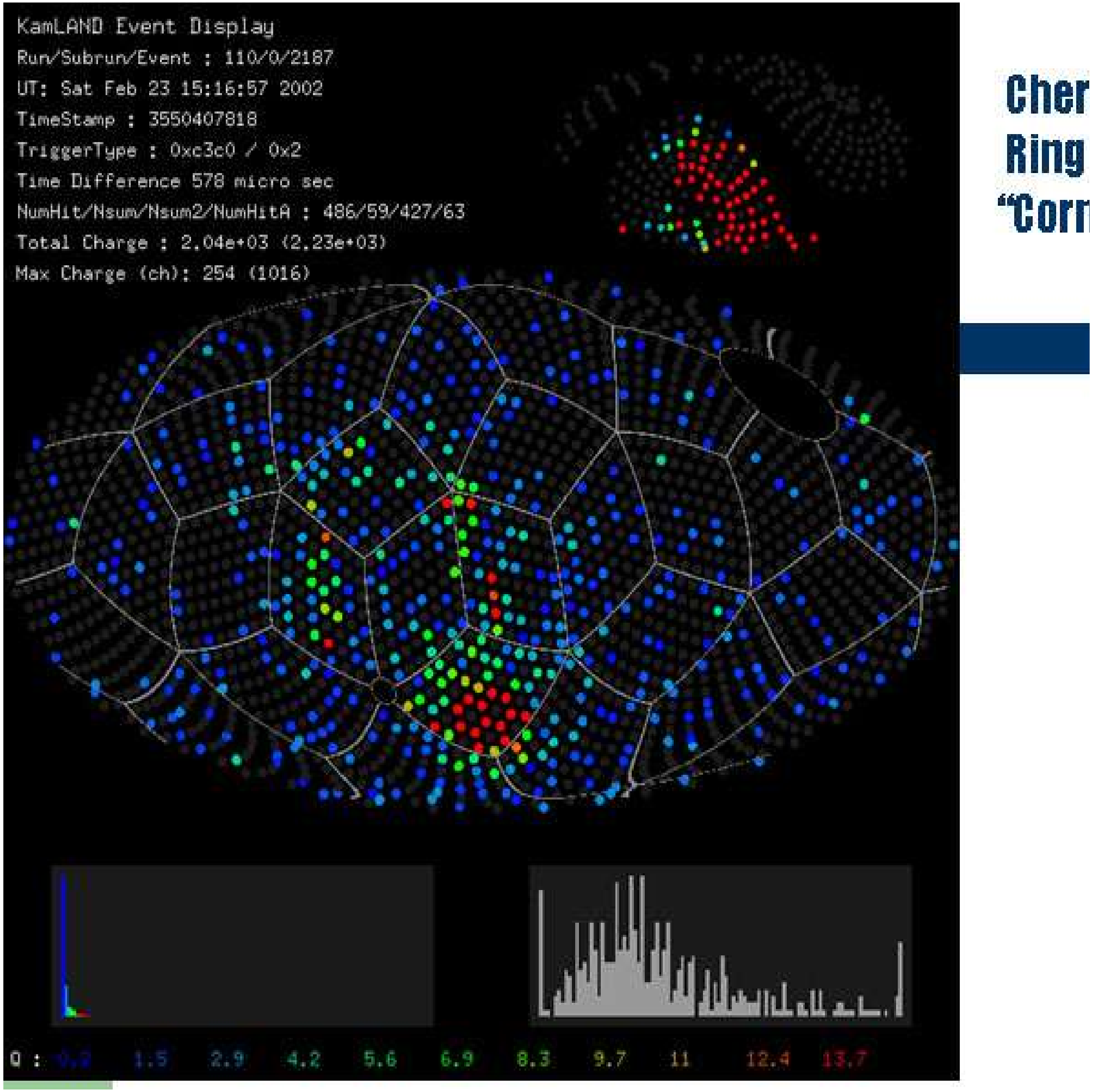
all tubes illuminated

KamLAND Data



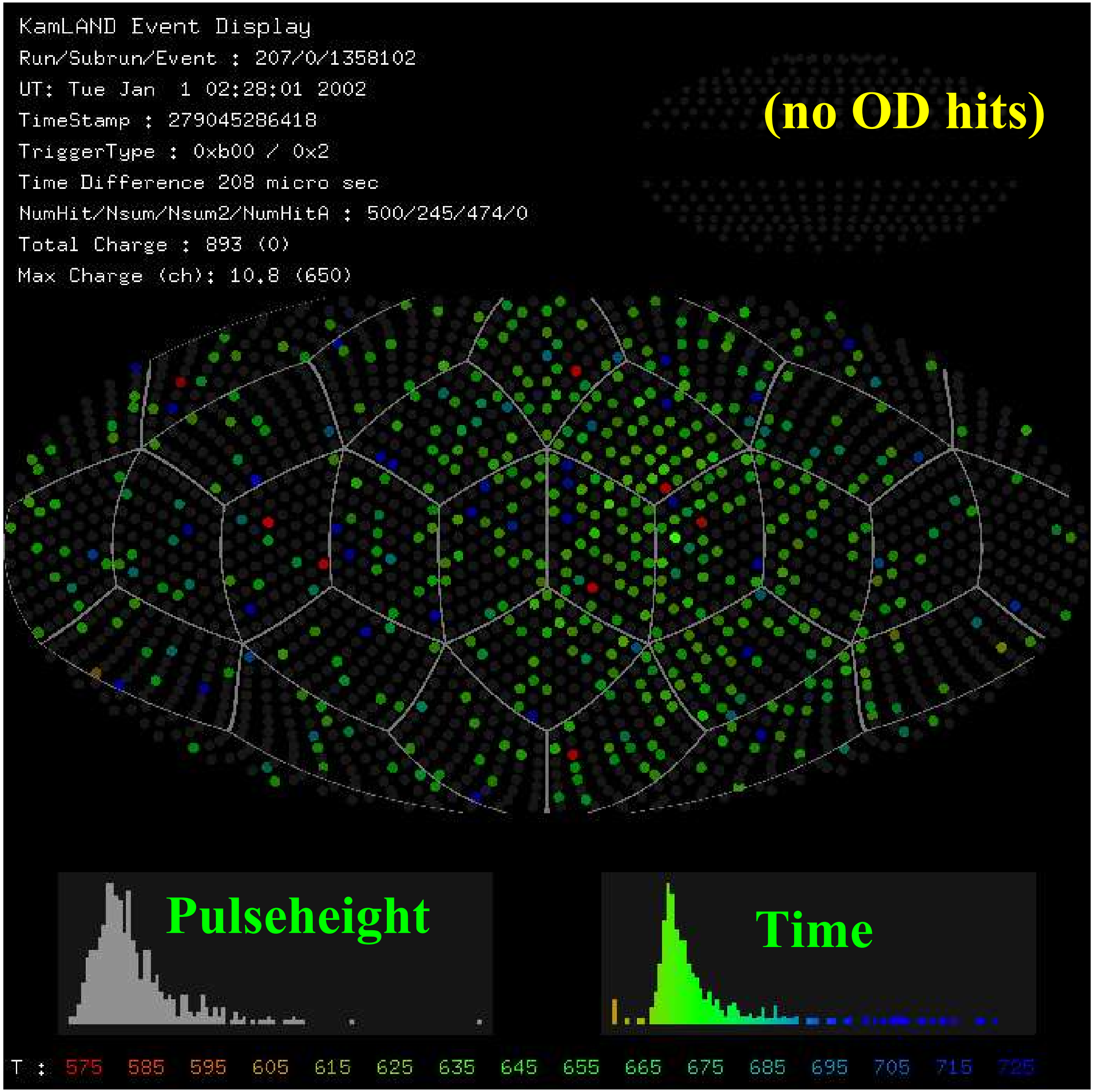
Stopped muon

KamLAND Data



Cherenkov ring from "edge clipper"

KamLAND Data

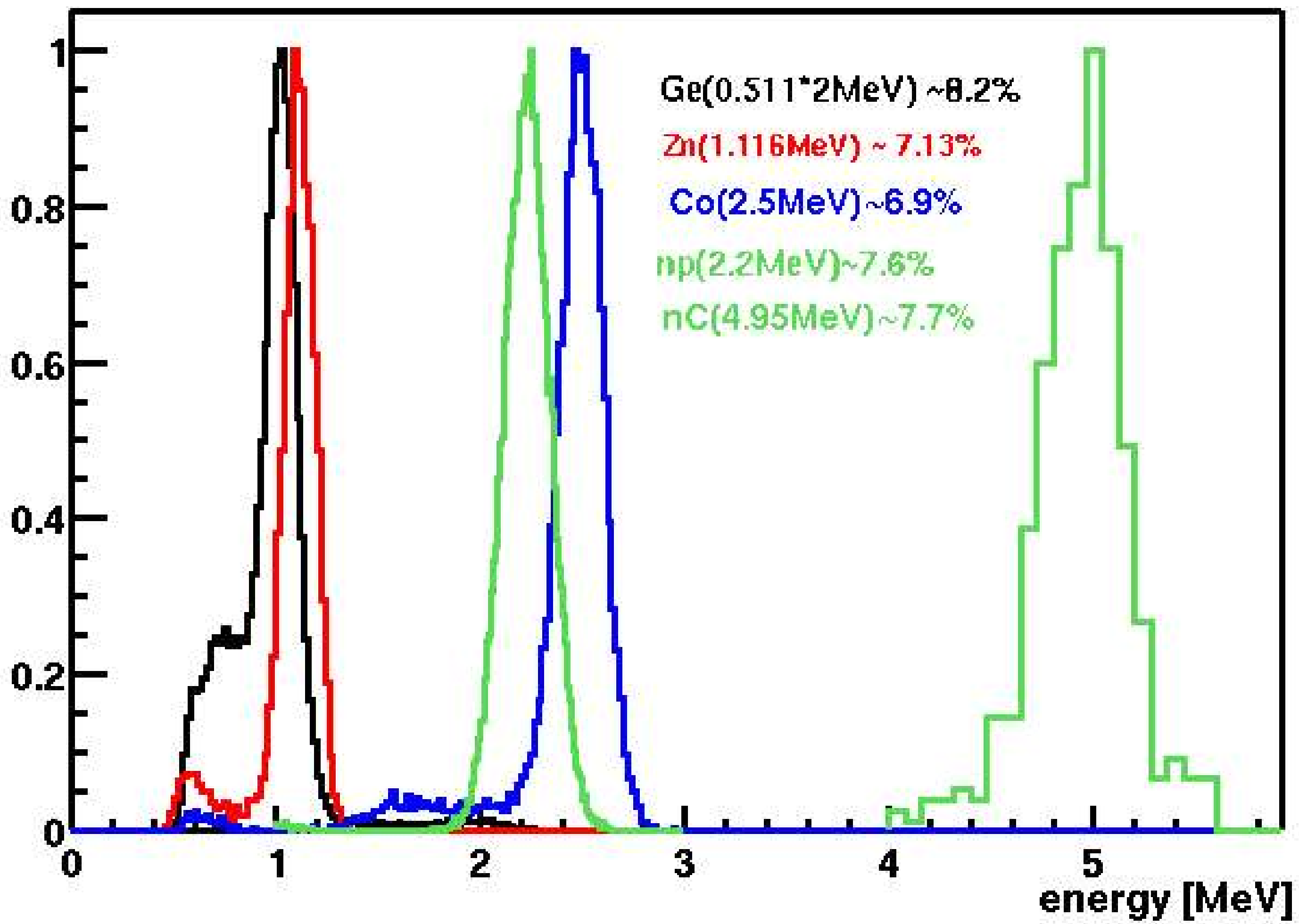


Low-energy event

color is time

Calibrations

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

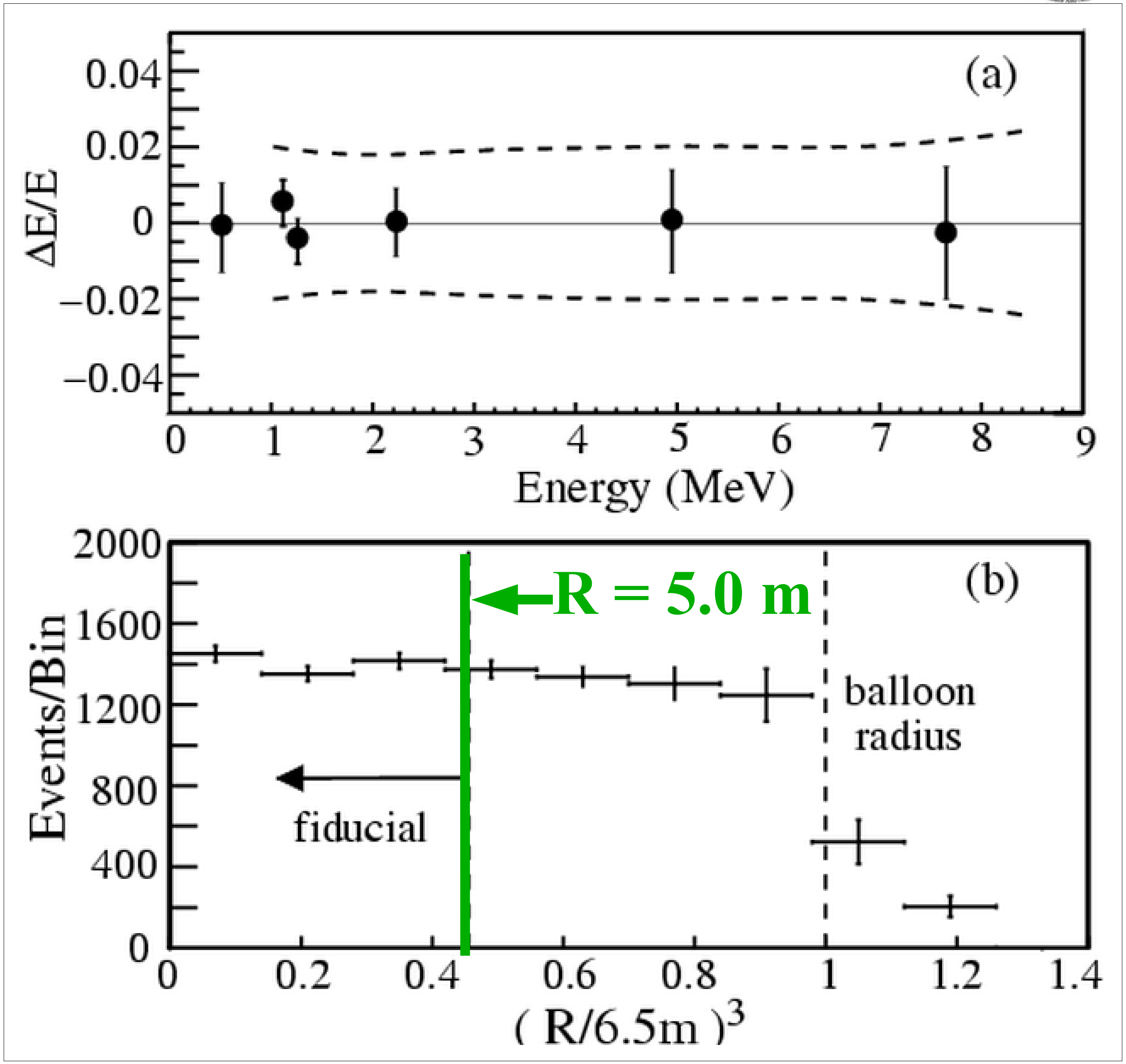


Reconstruction Performance

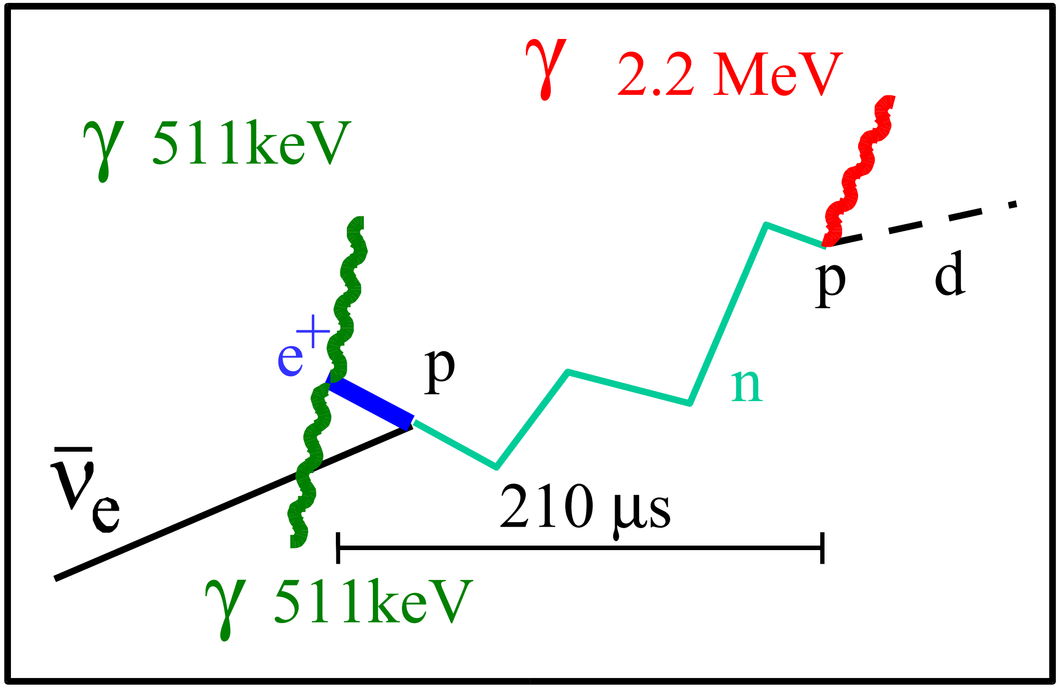
Energy estimation from from radioactive source calibrations

$\sigma = 7.5\% / \sqrt{E(MeV)}$

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



Event Selection



- Time correlation: $0.5\ \mu s < \Delta t < 660\ \mu s$
- Vertex correlation: $\Delta r < 1.6$ m
- Delayed event energy: $1.8\ \mathrm{MeV} < E_{del} < 2.6\ \mathrm{MeV}$
- Spherical fiducial volume: $R < 5$ m

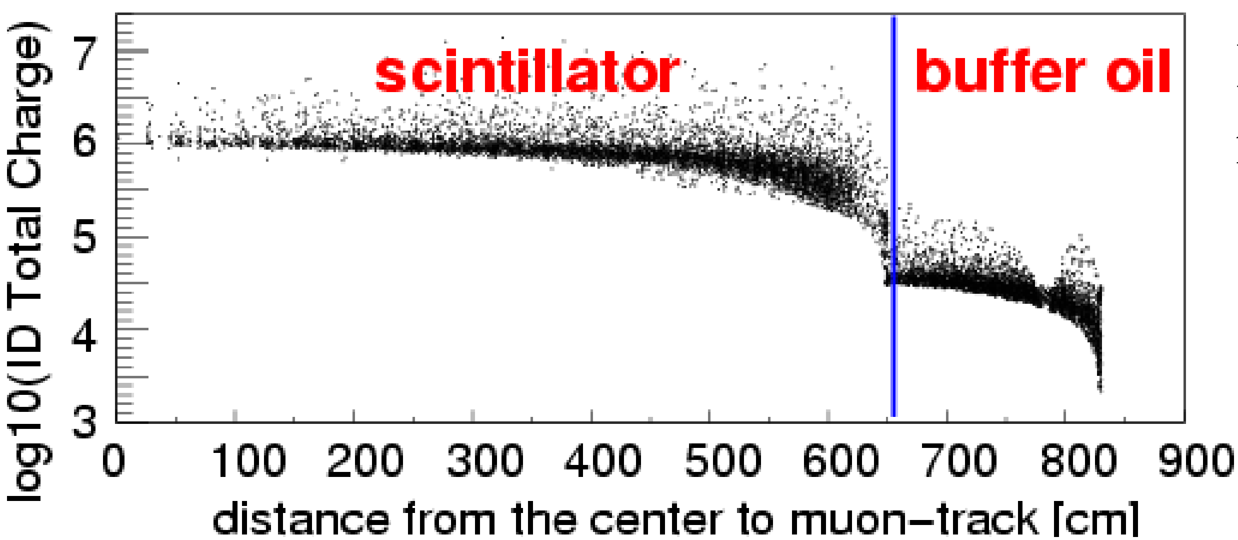
Total efficiency: 78.3 ± 1.6 %

Residual accidental background: $< 10^{-5}$ / day

Cosmogenic Backgrounds

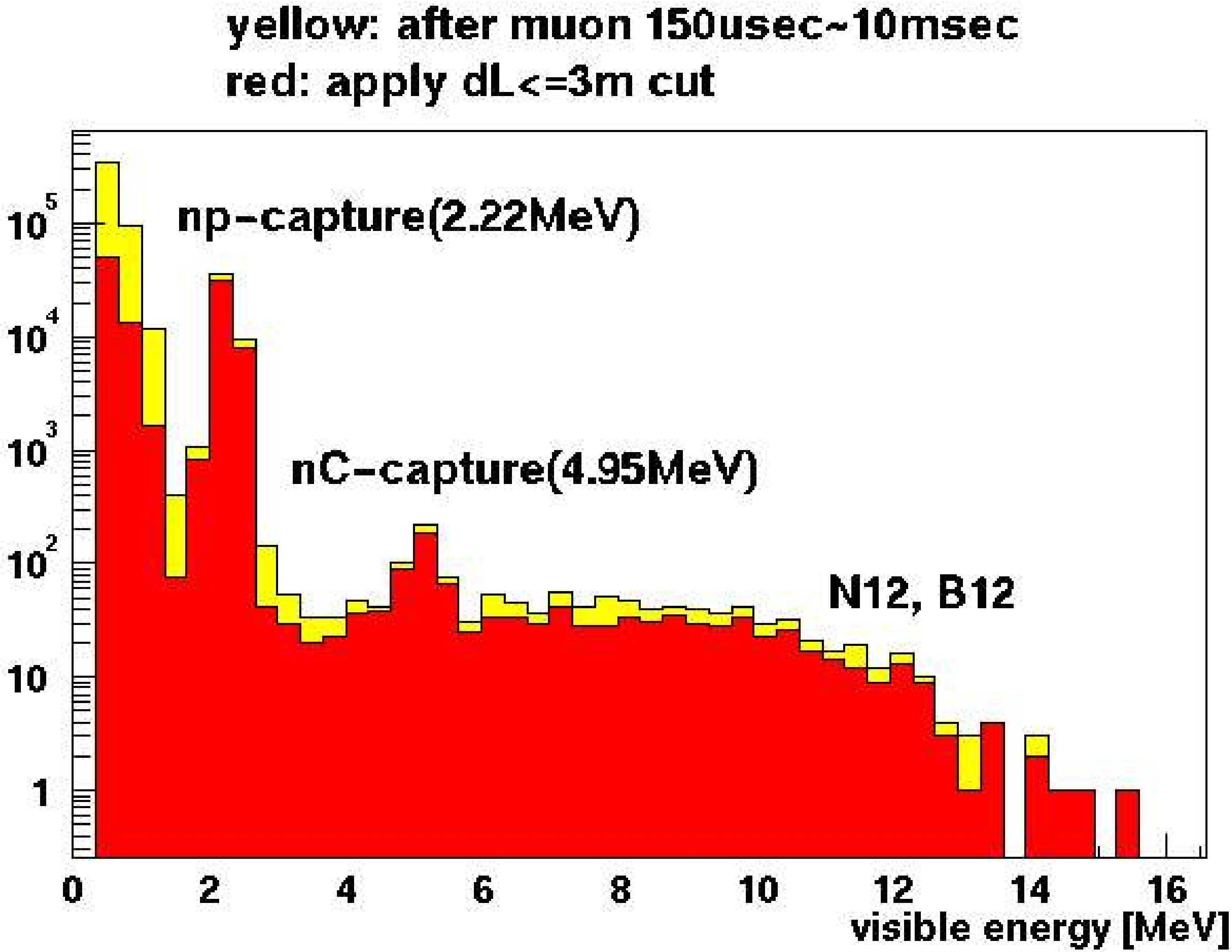
Muons leave neutrons which can fake the signal
- Veto detector for 2 ms after muons

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



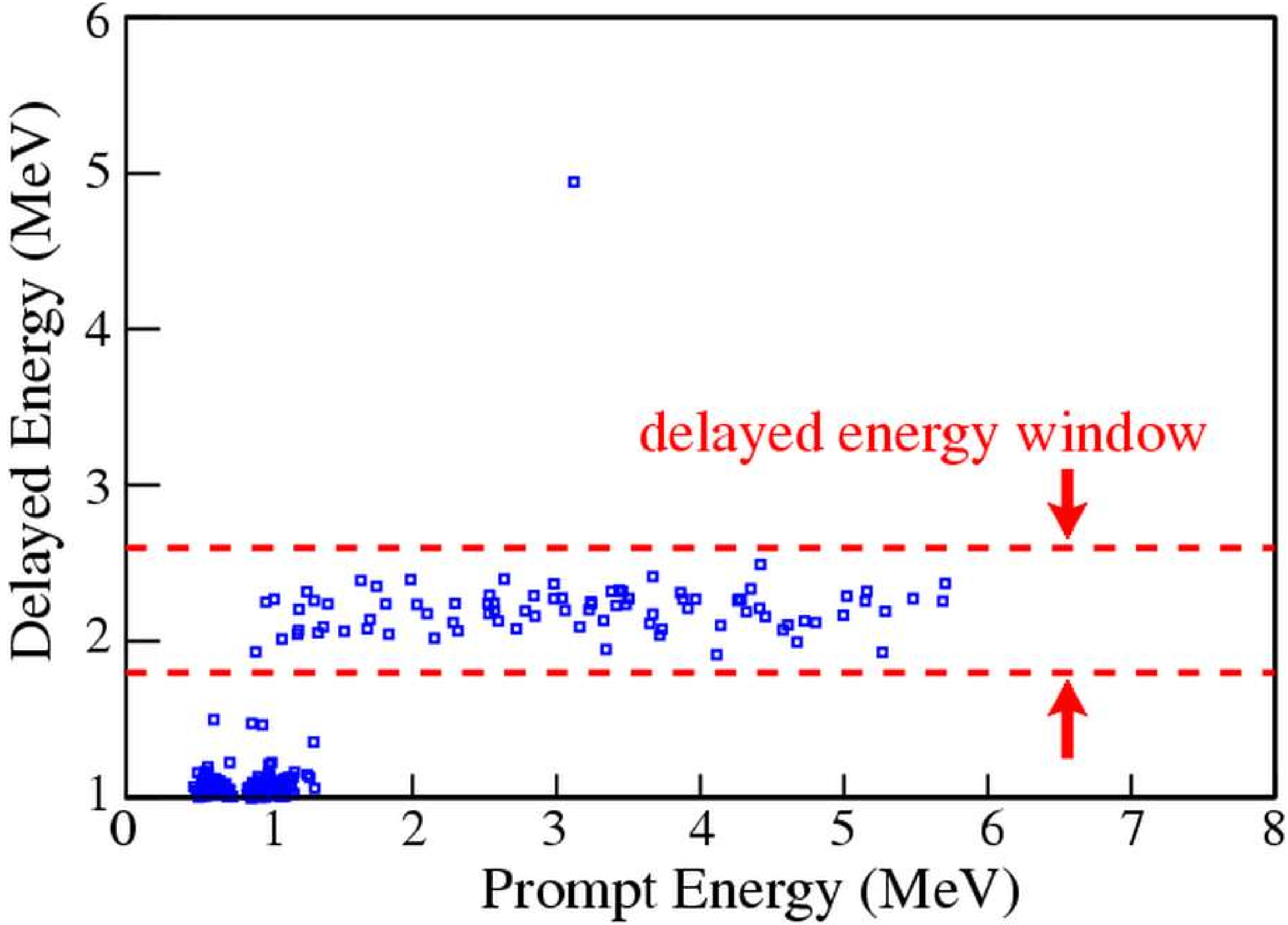
Muon track reconstruction reveals the balloon boundary

Cosmogenic Backgrounds

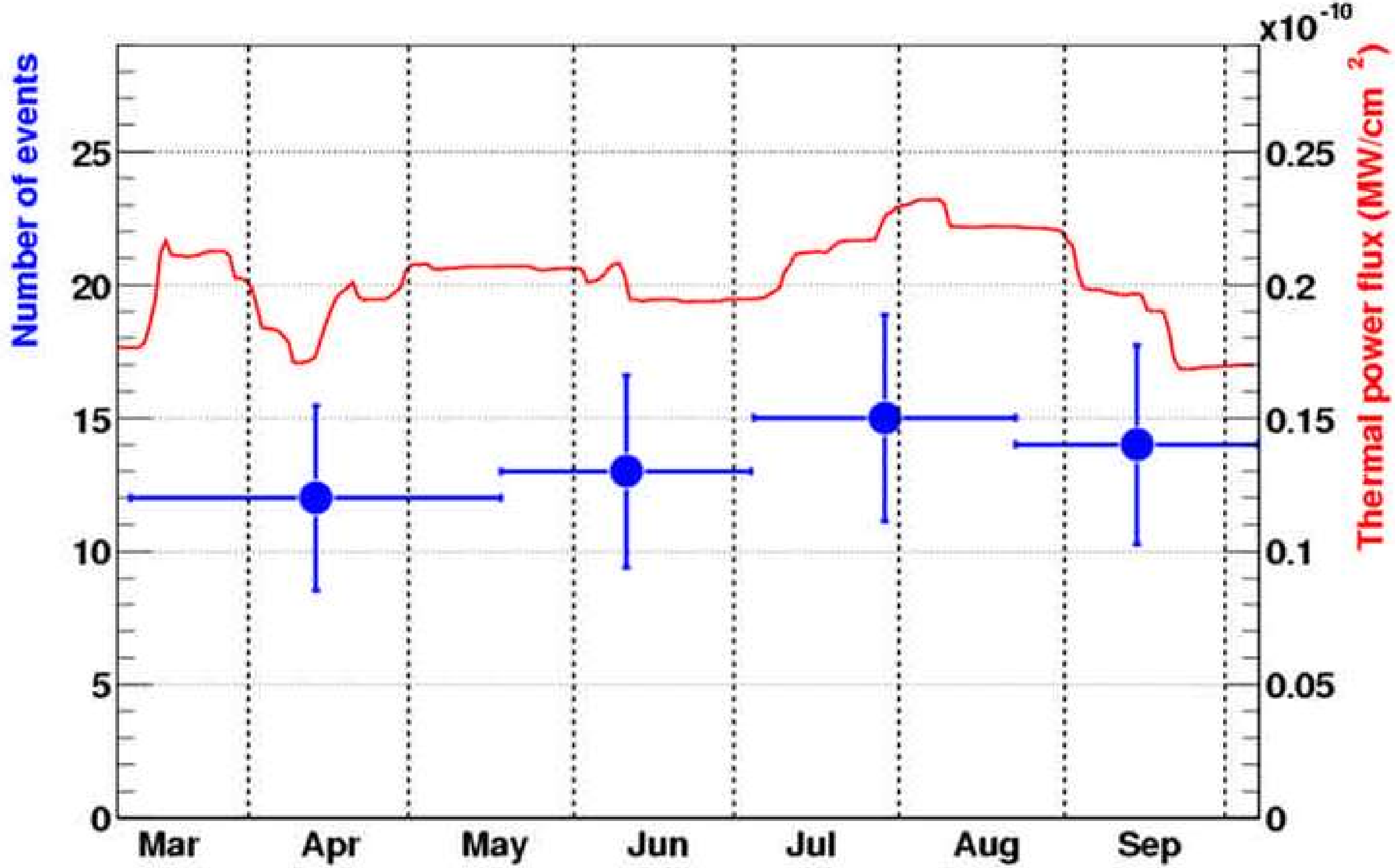


Residual correllated background: 0.0068 ± 0.0059 events/day

Prompt/Delayed Event Energies



Reactor Data



Livetime: 145.1 days (162 ton· yrs)
Expected signal (no osc.): 86.8 ± 5.6 events

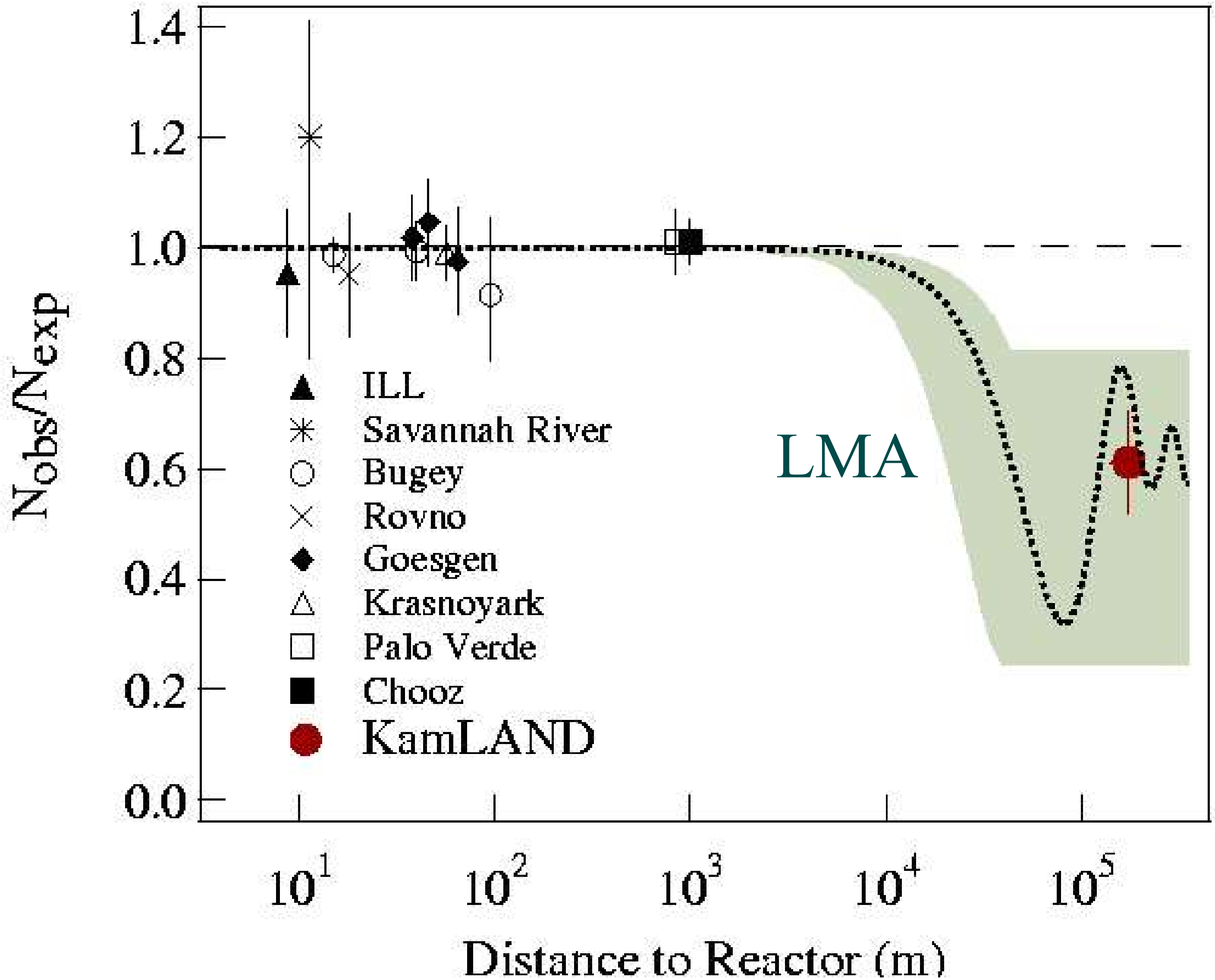
Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

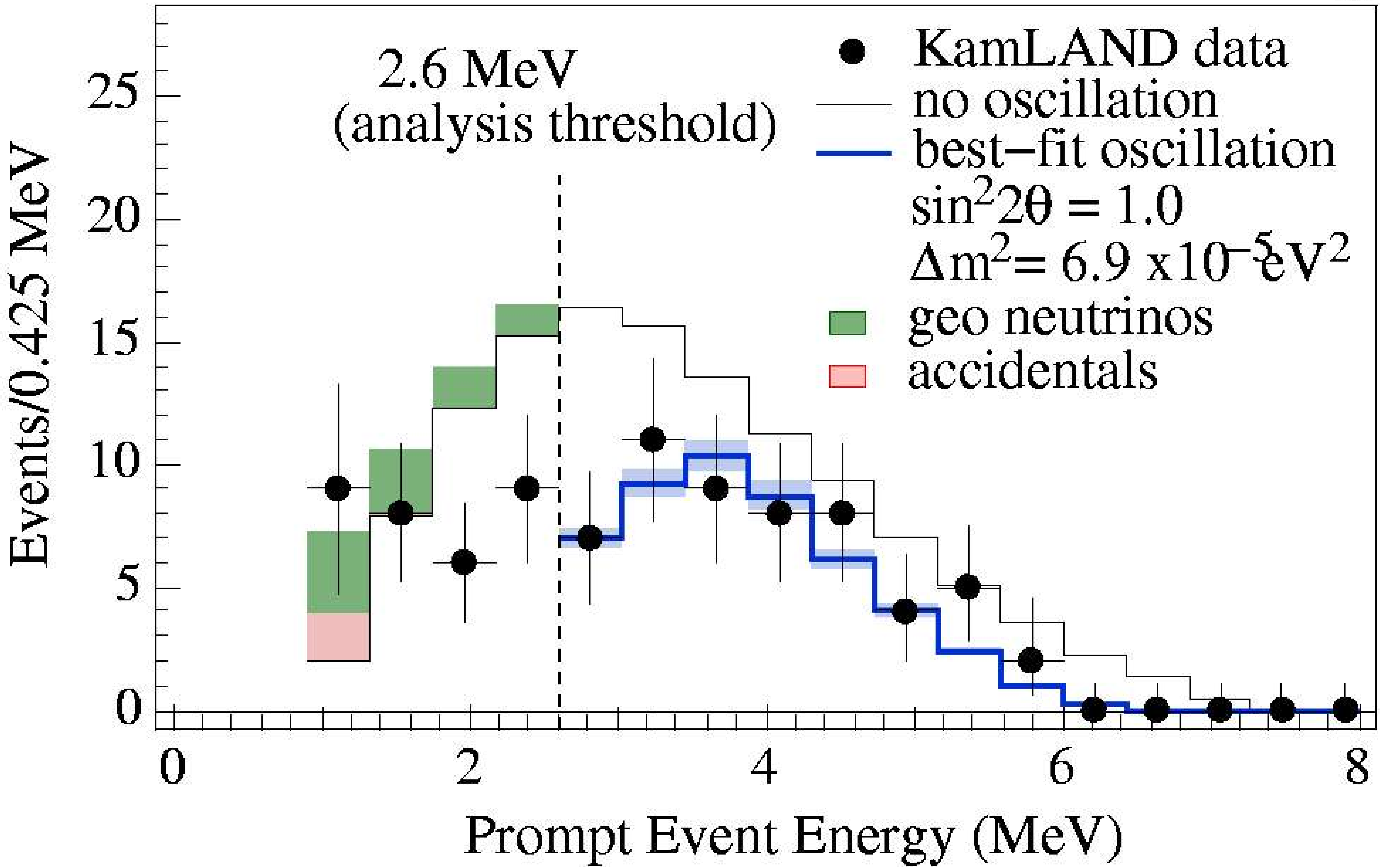
Total Scintillator Mass	2.13
Fiducial mass ratio	4.06
Energy threshold	2.13
Efficiency of cuts	2.06
Live time	0.07
Reactor power	2.05
Fuel composition	1.0
Time lag	0.28
Antineutrino spectra	2.48
$\bar{\nu}_e p$ cross section	0.2
Total systematic error	6.42%

Measured Event Rate

Expected 86.8 ± 5.6 (0.94 ± 0.85 bg), observed 54



Event Spectrum



Fit to Oscillation Parameters

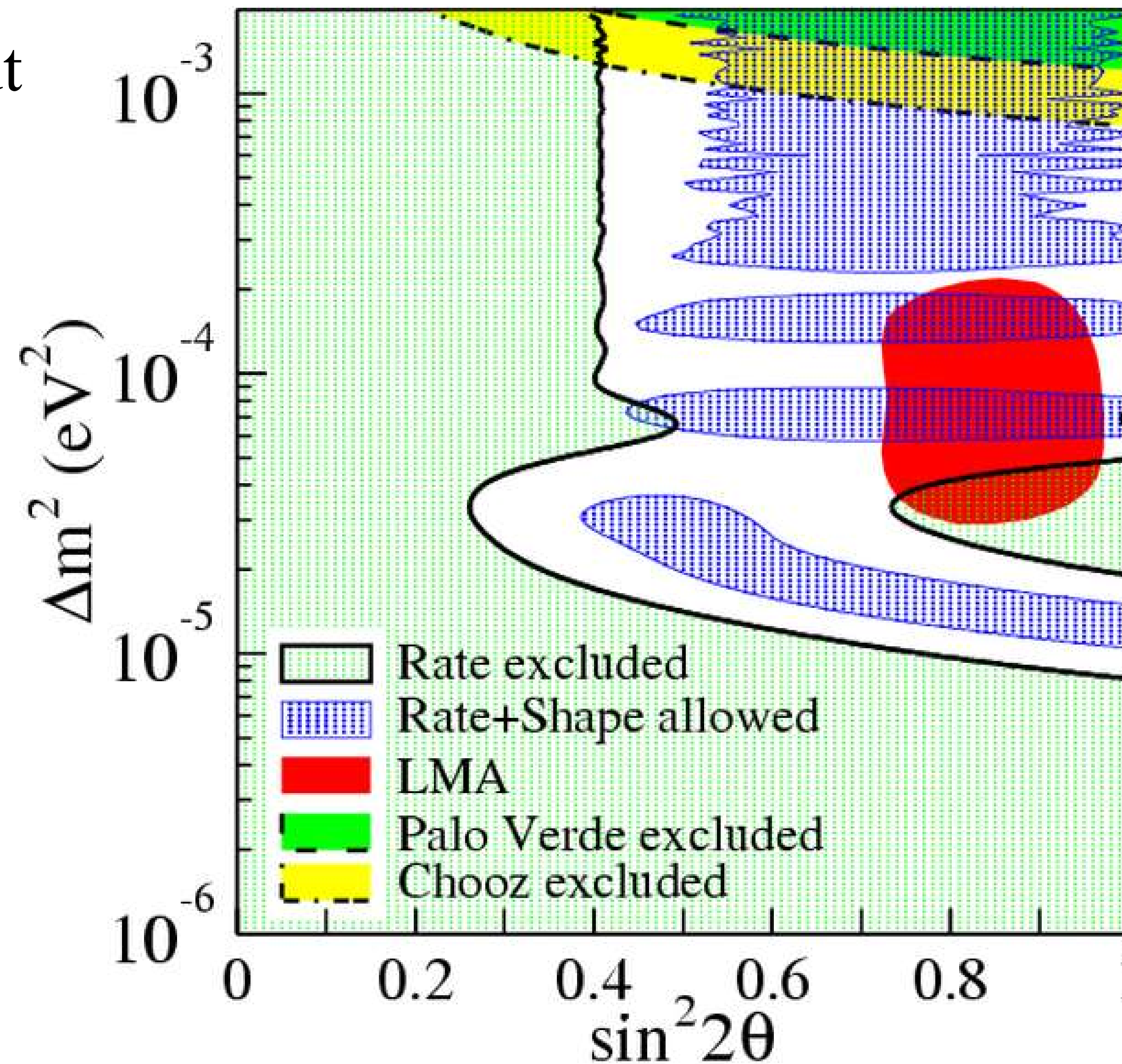
Backgrounds fixed but geoneutrino signal floated for fit

Best fit parameters:

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

$\sin^2 2\theta = 1.0$

All contours at 95% CL



Physics Interpretation

- KamLAND observed, for the first time, antineutrino disappearance at > 4σ

- Interpretted in terms of neutrino oscillations and assuming CPT invariance, this result

  – excludes all solar neutrino oscillation solutions except LMA

  – is in perfect agreement with LMA

Future Prospects

- Livetime has increased by a factor of ~2 since our first publication
- 50% reduction of flux in 2003 will allow for on-off analysis
- With any luck, KamLAND may observe spectral distortions, truly verifying neutrino oscillations
- Other physics results to come soon, including solar $\bar{\nu}_e$, geonuetrinos, neutron production...