G.Gratta
Neutrino 2000

Results from the Palo Verde Reactor Oscillation experiment

J. Busenitz, J. Kornis, K. McKinny, J. Wolf
University of Alabama

D. Lawrence, B. Ritchie
Arizona State University

F. Boehm, B. Cook, H. Henrikson, V. Novikov,
A. Piepke, P. Vogel, K.B. Lee
Caltech

G. Gratta, L. Miller, D. Tracy, Y-F. Wang
Stanford University

$$P_{x \to y} = \sin^2 2\theta \ \sin^2 \frac{1.27 \ \Delta m^2 \ L}{E_\nu}$$

Complementary Properties of Reactor and Accelerator Oscillation Experiments

Reactor	Accelerator
E_ν = few MeV	E_ν = few GeV
- Probe small Δm^2	- Good mass sensitivity requires very large L
- Disappearance only (fair $\sin^2 2\theta$ sensitivity)	- Appearence possible (produce μ and τ)
- 4π source (detector mass grows with L^2)	- (More) collimated beam

Reactors are good for exploring the very small Δm^2, large mixing region

Palo Verde (Arizona) optimized for the atmospheric ν region

- Baseline: 750 / 890 m
- 3 Reactors, total power: 11 GW (thermal)
- Shallow underground site: 32 mwe
- Segmented detector for active bkgnd suppression
- 12 ton Gd-loaded liquid scintillator
- Signal rate (no oscillation): 30 ν/day

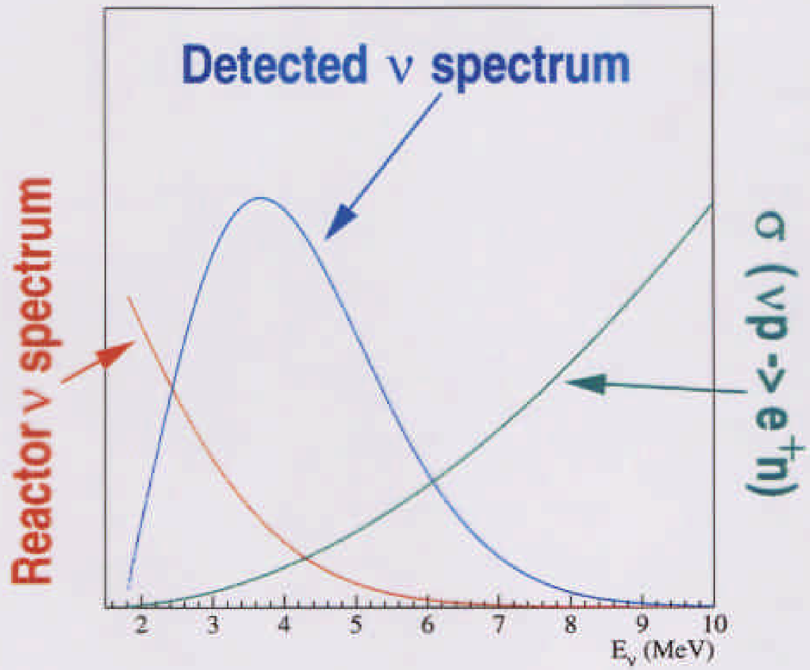
PALO VERDE APS

Gratta - 04

Gratta - 05

Reactor ν 's derive from β-decay of n-rich fission fragments

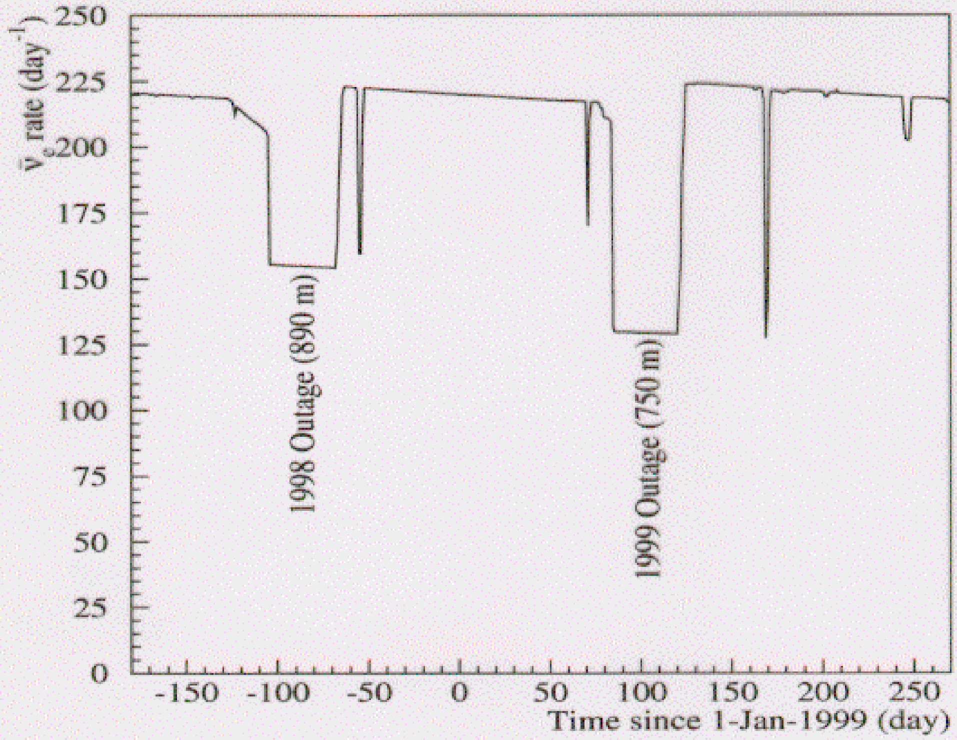
Most of ν 's are soft, deriving from long lived isotopes.



Only the high energy tail (from short lived isotopes) is above detection threshold for ν p -> e^+n [1.8 MeV]

Detected ν flux tracks closely reactor's power

Reactor power excursions (usually due to refueling) can be used to x-check background subtraction

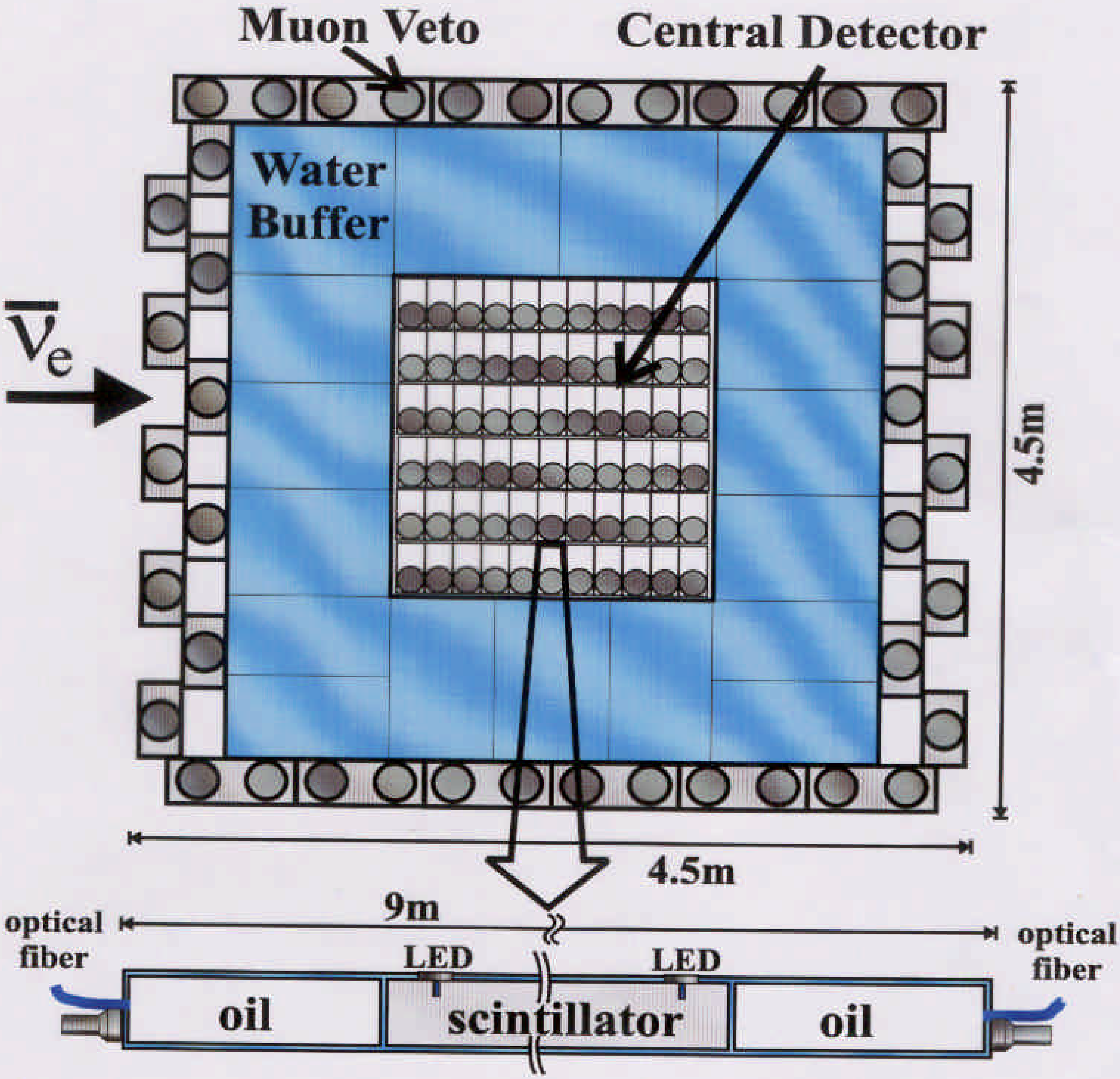


Data presented here collected in 98 and 99:

- 146.9 days full power
- 31.3 days with reactor at 890m off
- 23.4 days with reactor at 750m off

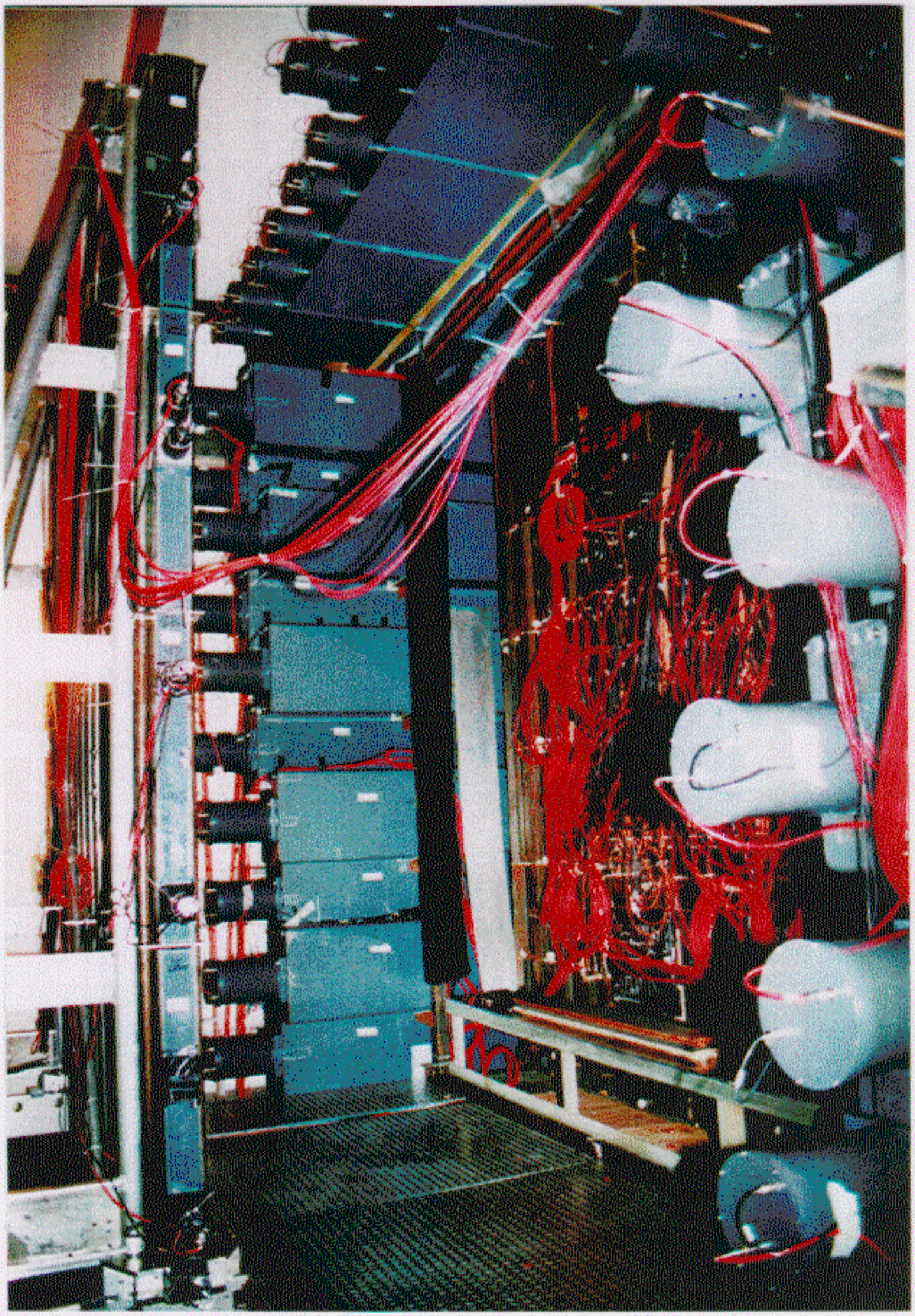
- *Phys. Rev. Lett. 84 (2000) 3764*
- *hep-ex/0003022 (Phys. Rev. D)*

Palo Verde detector



- Active target segmented in 66 cells
- 1m thick water buffer (n and γshield)
- Hermetic cosmic-ray veto

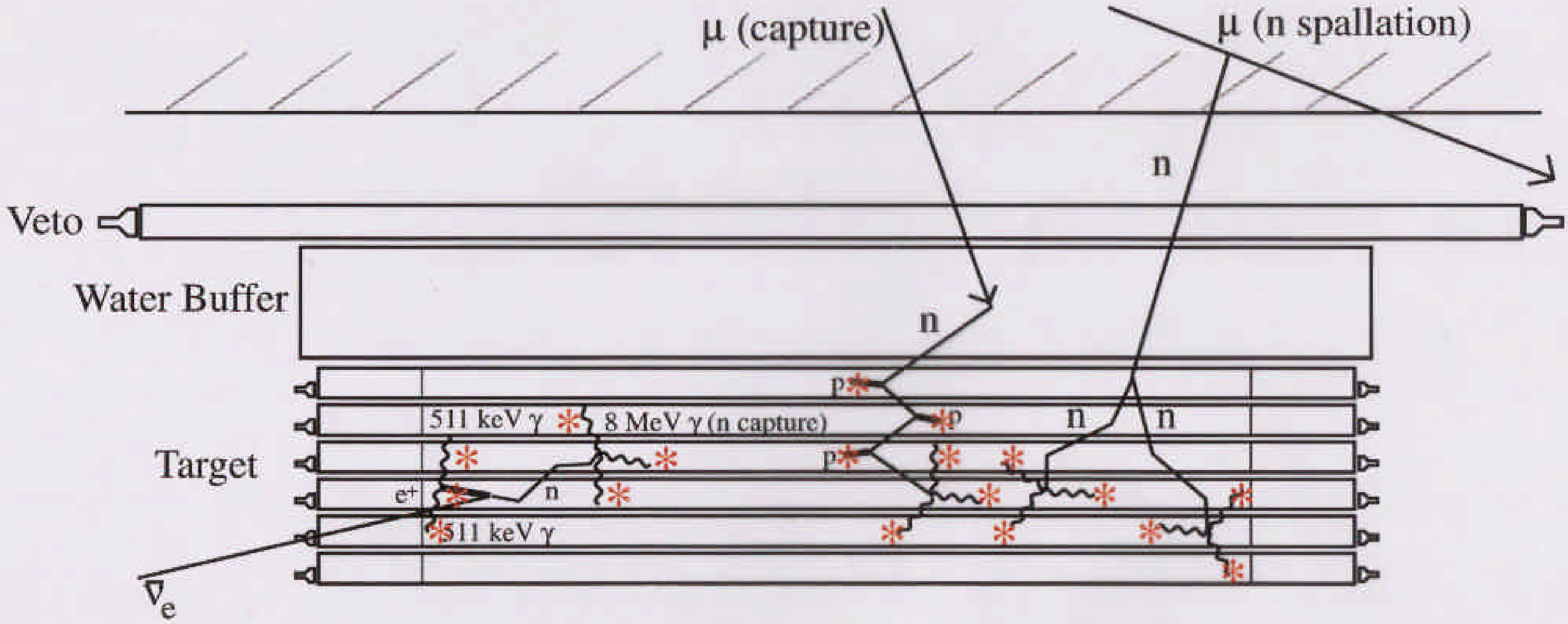
Endcap Veto-Detector open



Signal consists of 2 triples, separated by n-capture time

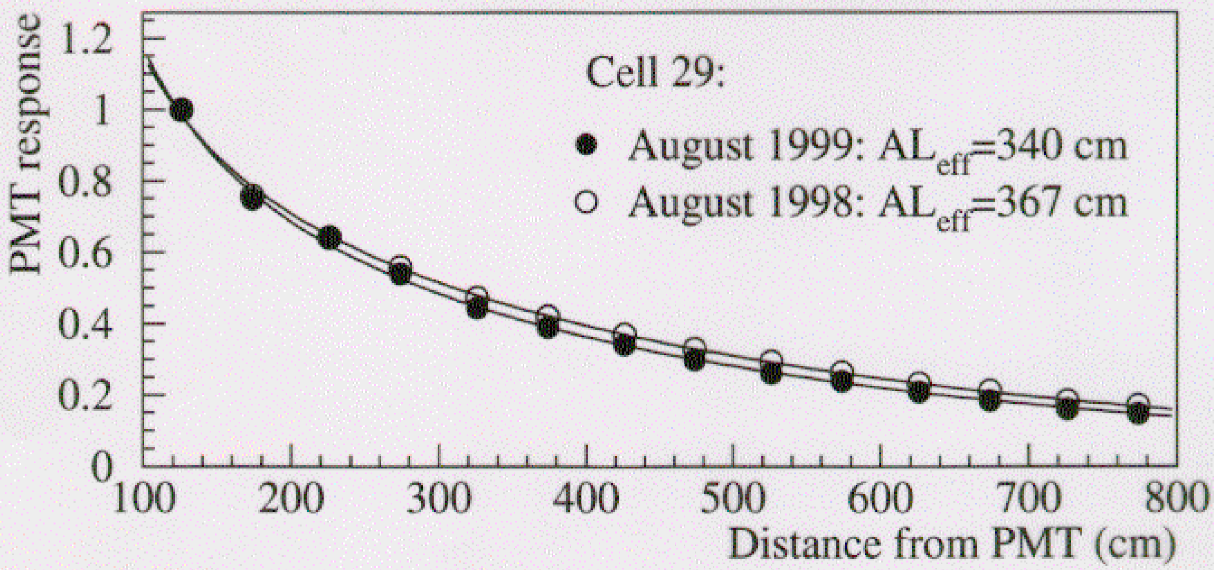
Gd-loading: - fast capture ($\gtrsim 30$ μs instead of $\gtrsim 200$ μs on p)

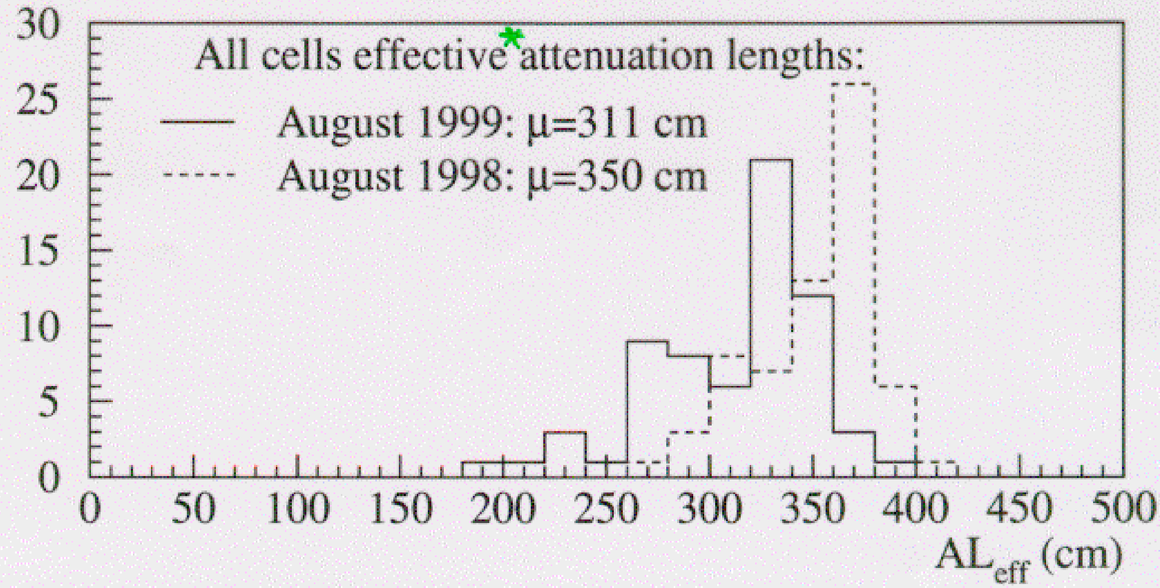
- 8 MeV (total) high mult. γ cascade at capture



$$E_\nu \simeq E_{e^+} + (M_n + M_p + m_{e^+}) + m_{e^+}$$

0.1% Gd-loaded liquid scintillator remarkably stable

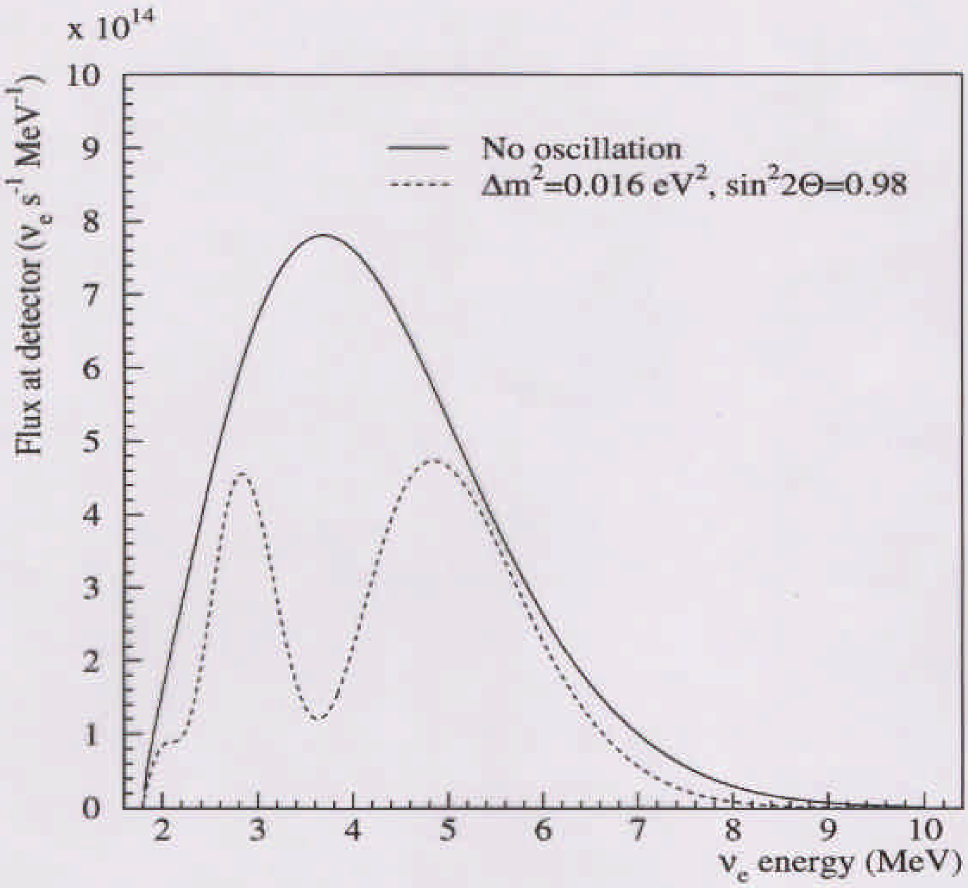




* Real attenuation length ≃ 12m

L_{att} degrades by less than 10%/year

Energy spectrum also is modified by oscillations....



....but the sensitivity limit is reached through an absolute rate measurment

Good calibration essential !

Detector Calibration

weekly

- Timing/position
  - Blue LEDs on cells ($\Delta t/Z$)
  - Fiberoptics for TDC walk

weekly

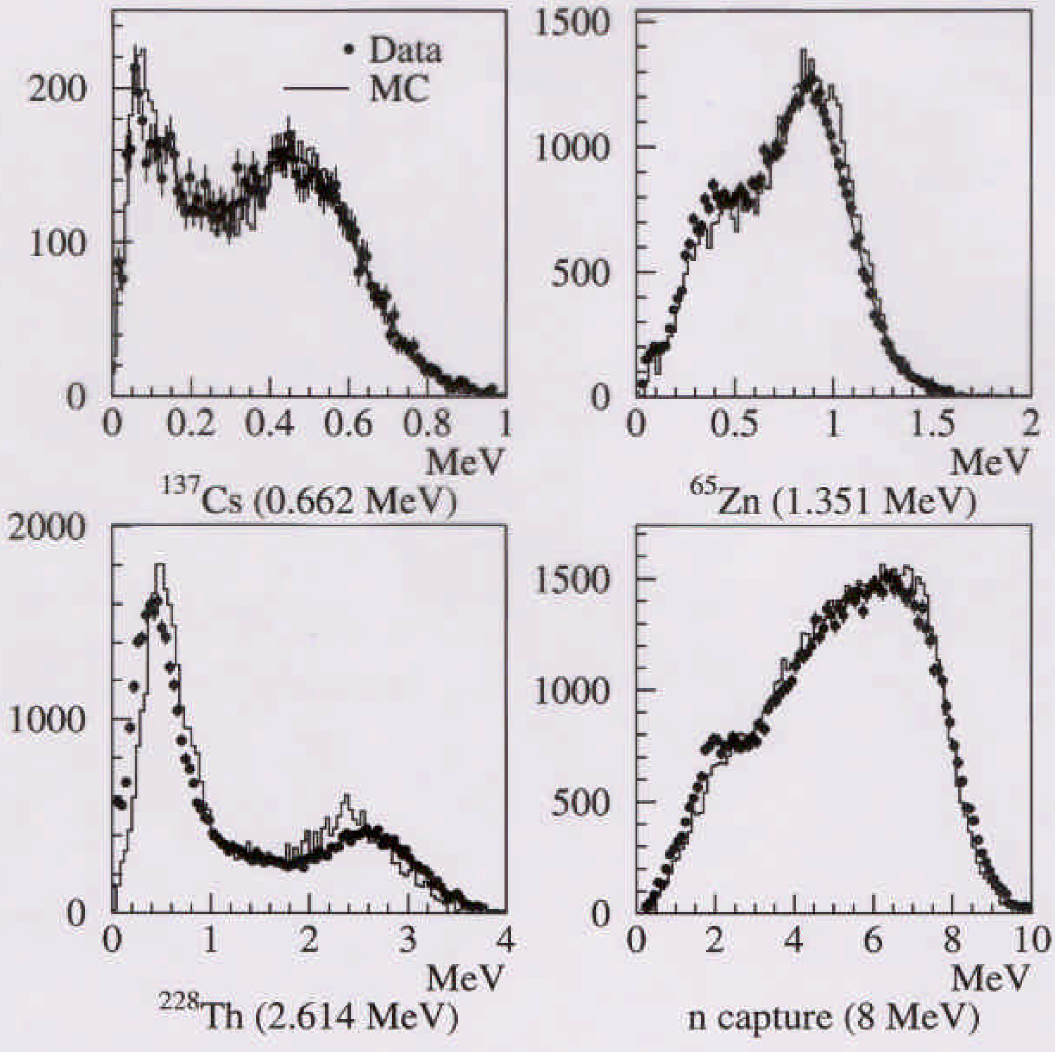
- Energy
  - PMT gain -> single p.e. peak
  - PMT non-lin. -> fiberoptics
  - Energy scale -> ^{137}Cs, ^{65}Zn, ^{228}Th sources
  - Scint. transparency -> ^{228}Th scan with Z

every few months

- Absolute effic.
  - Trigger thresholds -> ^{22} Na source
  - e^+ eff. -> Calibrated ^{22}Na source (-> ^{76} Ge source dissolved)
  - n eff. -> γ-tagged AmBe source

Monte Carlo simulation (based on GEANT 3, FLUKA and CALOR) tuned down to low energy

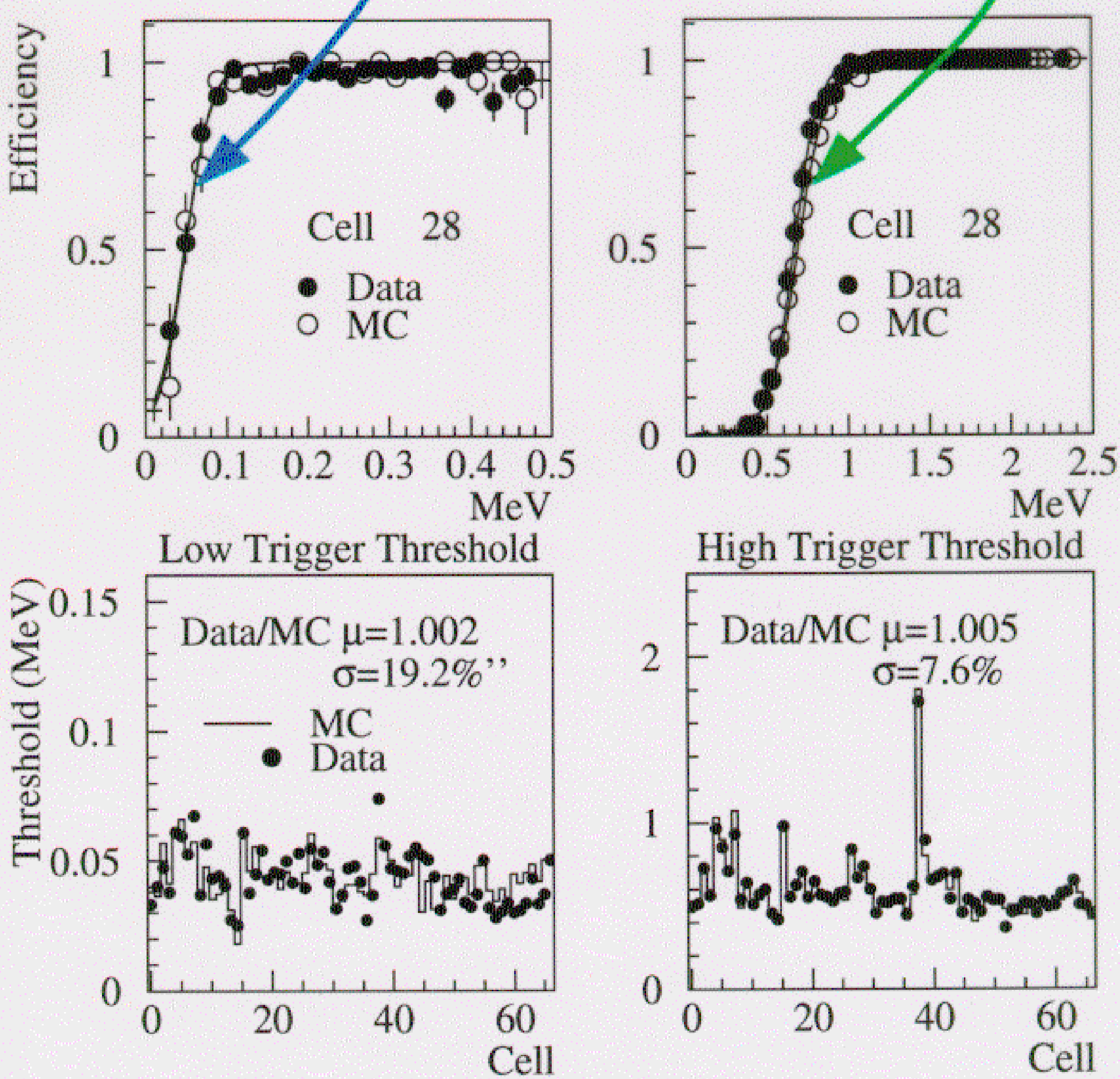
Energy calibration from different sources



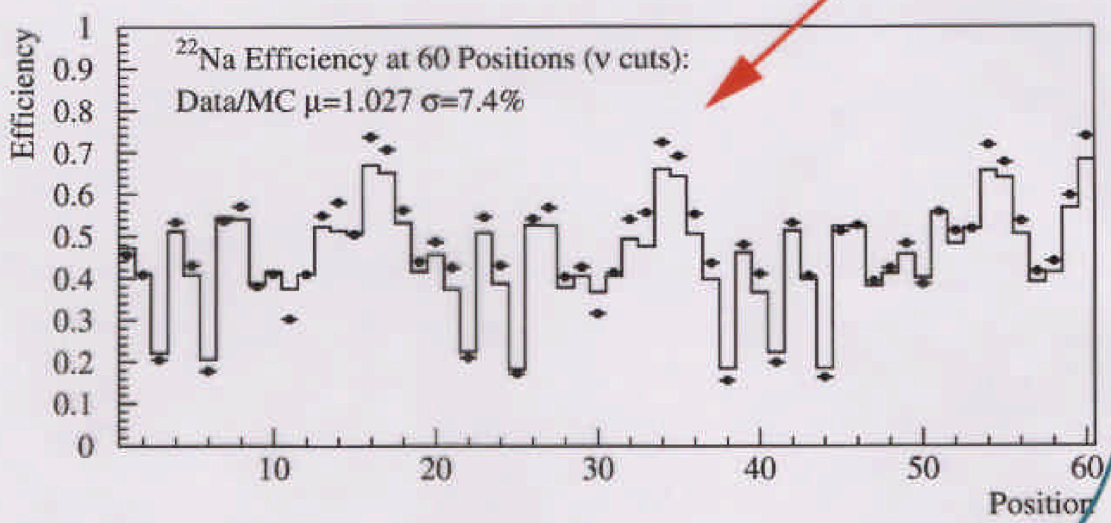
Trigger thresholds well simulated

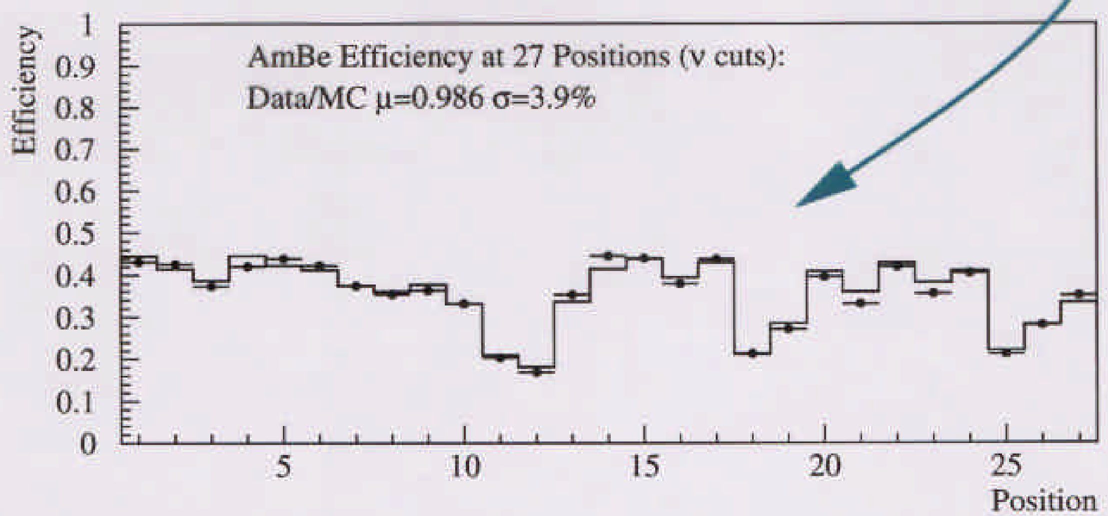
Lo threshold: 50 keV
- 1 p.e. from the middle
- annih. γ 's signal
- n γ -cascade edge

Hi threshold: 0.5 MeV
- seeds trigger cluster
- e^+ energy
- n γ-cascade core



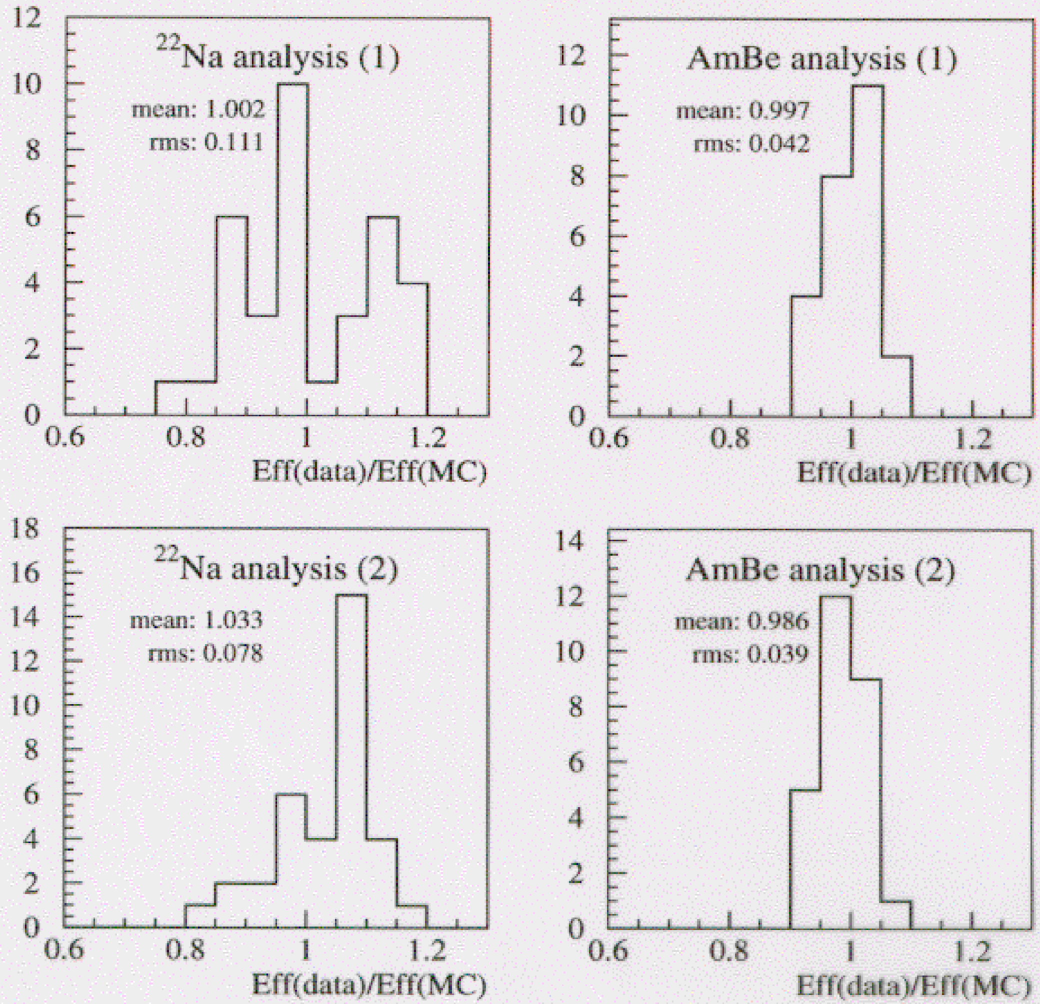
MC tracks well efficiency for e^+ and n in different regions of the detector





2 independent analyses used for calibrations, bkgnd and ν selection

Eff.(data) / Eff.(MC)



Analysis 1

Analysis 2

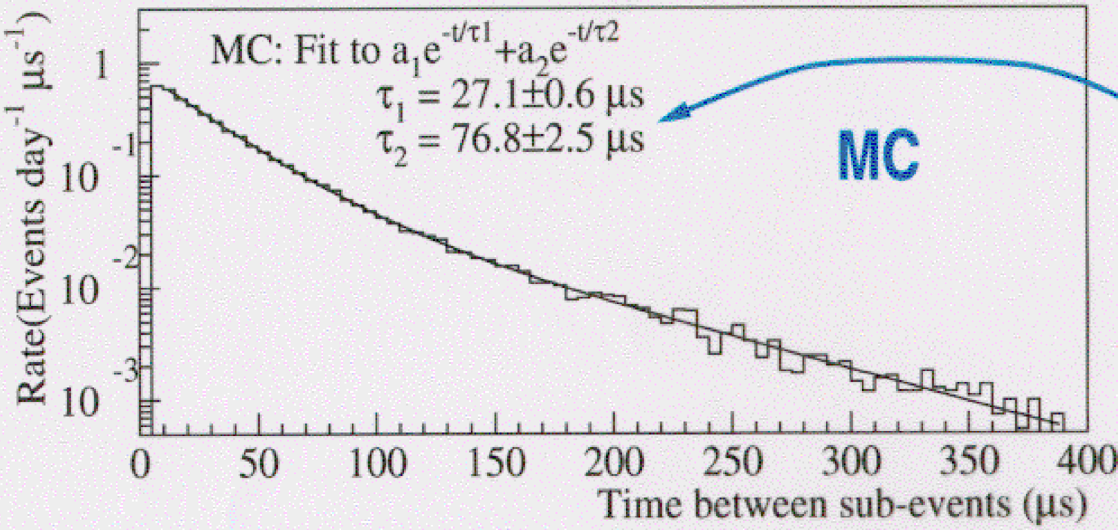
Spread used in systematics

$\bar{\nu}$ selection cuts

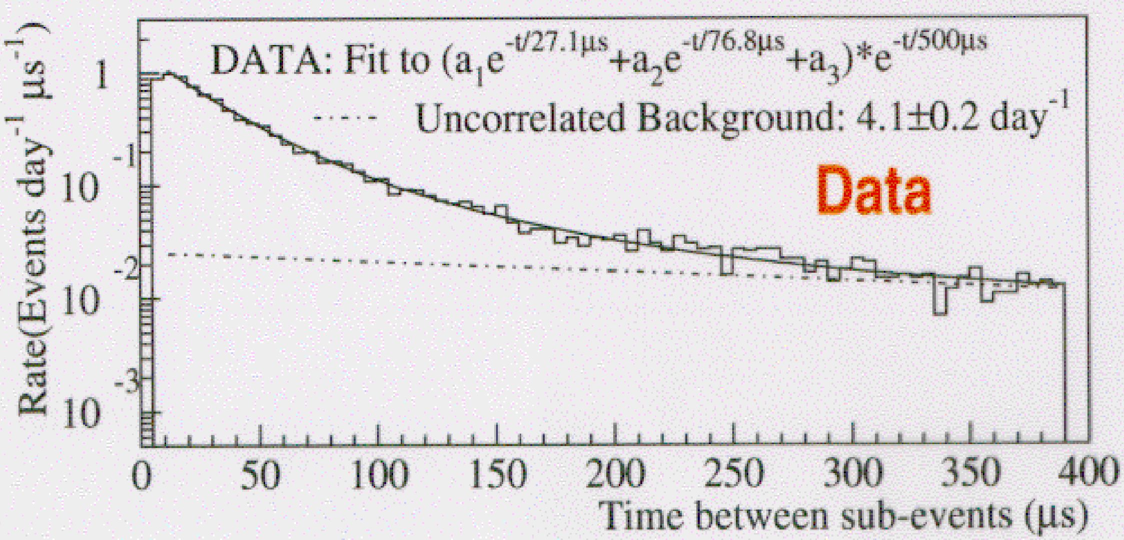
- e^+ and n same triple condition:
  - 1 hit with E > 1 MeV
  - 2 other hits with E > 30 keV
- 2 triples within $\Delta t < 200\ \mu s$
- 2 triples within $\Delta l < 1$ m
- reject is cosmic < 150 μs before
- for e^+ part only:

  annihilation γ's must have E < 0.6 MeV

Uncorrelated bkgnd from radioactivity and random neutrons is measured by studying the time between "e^+" and "n"



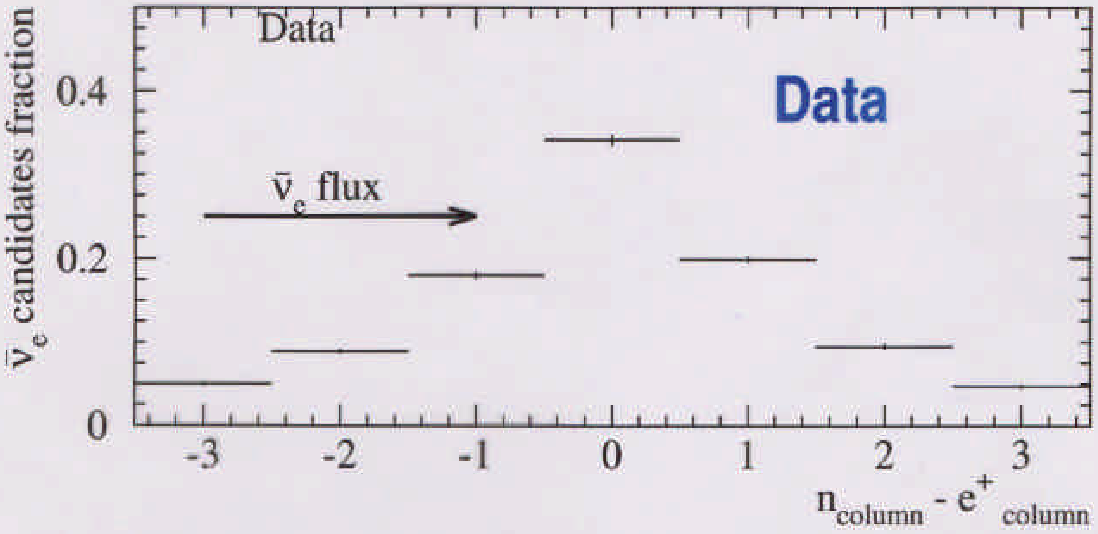
Note that n-capture has 2 time constant because the detector is non-homogeneous (22% acrylic)

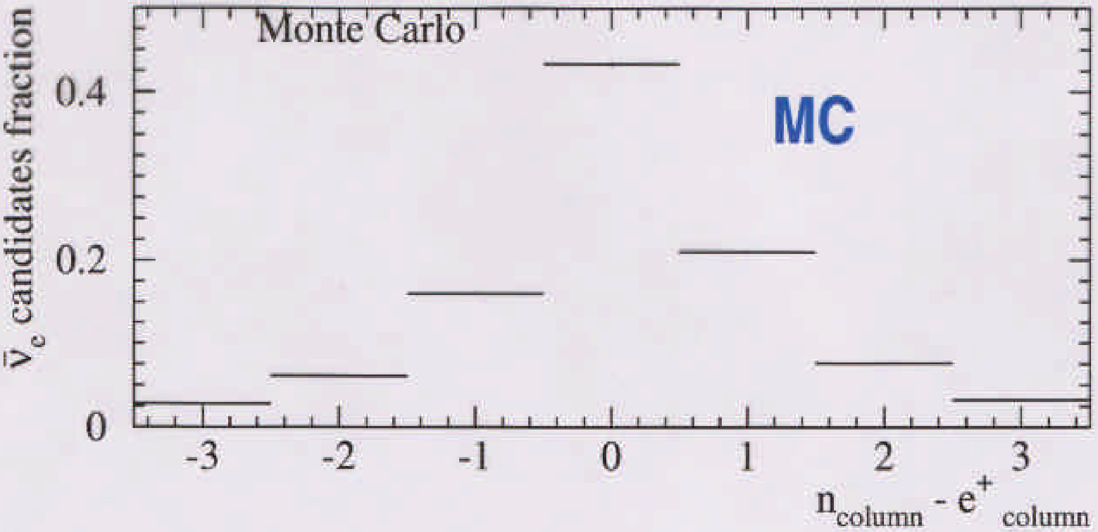


From DATA uncorr. bkgnd.
bkgnd. = 4.1 ± 0.2 ev/day
(10% of ν signal)

Note that uncorr. bckgnd is NOT flat because of 2kHz cosmic μ rate

An asymmetry results from the kinematic boost from the neutrino





$$A = \frac{R - L}{R + L}$$

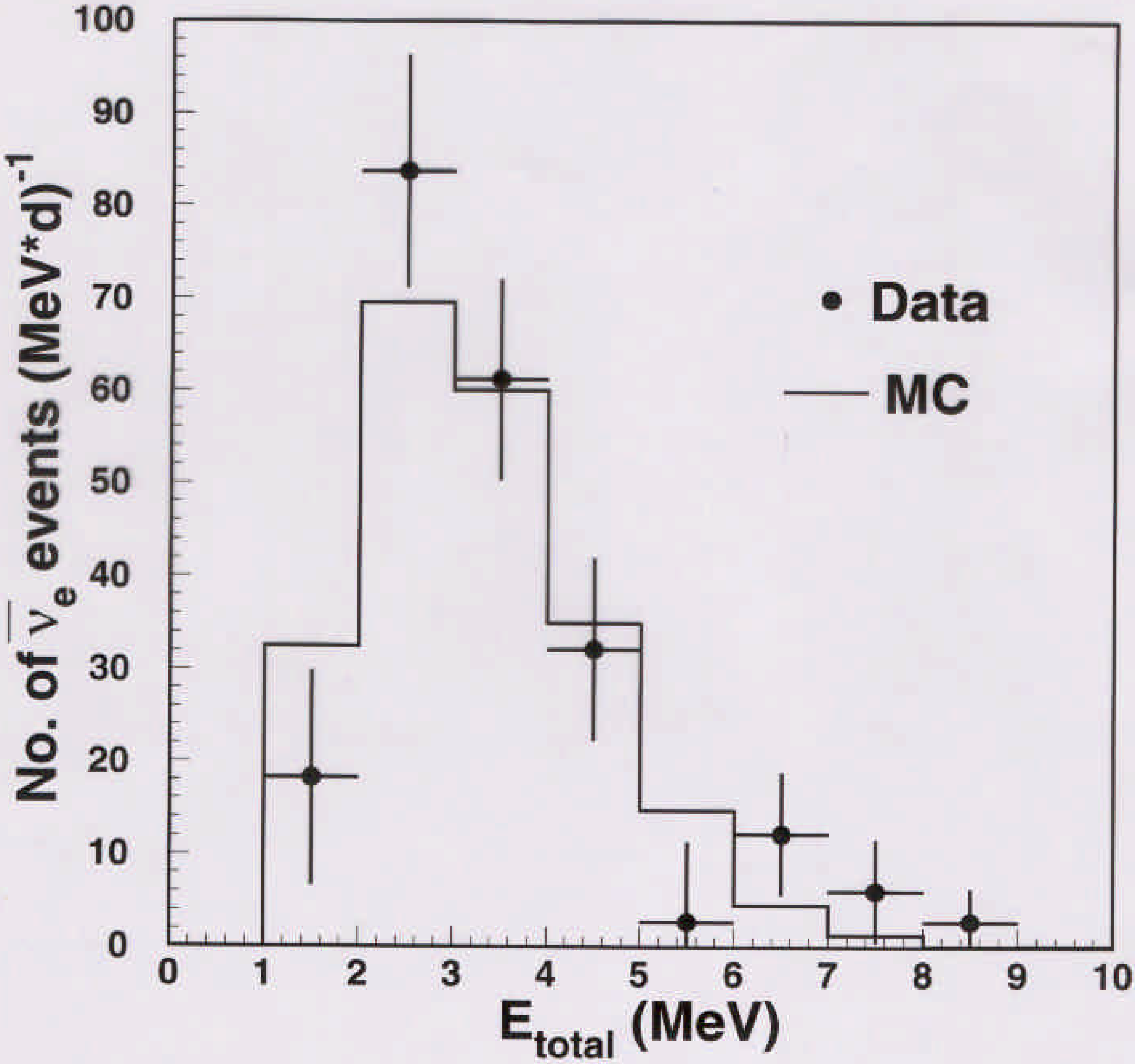
$$\frac{S}{N} = \frac{A_{data}}{A_{MC} - A_{data}} = 0.6^{+0.4}_{-0.3}$$

No evidence for oscillations with a simple "on-off" subtraction

	1998		1999	
	on	off 890 m	on	off 750 m
Days	35.97	31.35	110.95	23.40
$\overline{\nu}$ eff. (%)	7.46	7.72	11.2	11.1
Cand. $\overline{\nu}$ (/day)	38.2 ± 1.0	32.2 ± 1.0	52.9 ± 0.7	43.9 ± 1.4
After on-off				
$\overline{\nu}$ obs. (/day)	95 ± 19		77 ± 14	
$\overline{\nu}$ calc. (/day)	63		88	

Errors statistical only, sistematics 10% (more later...)

Good agreement with non-oscillation energy spectrum



"on - off" makes poor use of the data:
- **only 1 reactor out of 3 used for signal**
- **"off" periods limit statistical accuracy**

-> Develop alternate method to reject background based on symmetries of the events

hep-ex/0002050 (Phys. Rev. D Jul 2000)

Normal selection $N_1 = B_{unc} + B_{nn} + B_{np} + N_\nu$

e^+ and n swapped $N_2 = B_{unc} + B_{nn} + \varepsilon_1 B_{np} + \varepsilon_2 N_\nu$

$\varepsilon_1 \quad \varepsilon_2$ **efficiencies of swapped cuts for np bkgnd and ν**

Measure

$$N_1 - N_2 = (1 - \varepsilon_1) B_{np} + (1 - \varepsilon_2) N_\nu$$

Better variable since:
- B_{nn} is larger than B_{np}
- $\varepsilon_1 \simeq 1$
- $\varepsilon_2 \simeq 0$

Contains most of the ν but cancels most of bkgnd

Easy to find from MC

$$N_1 - N_2 = (1 - \varepsilon_1) B_{np} + (1 - \varepsilon_2) N_\nu$$

The hard part since there is no good MC

Main sources of fast neutrons:
- μ spallation
- μ capture

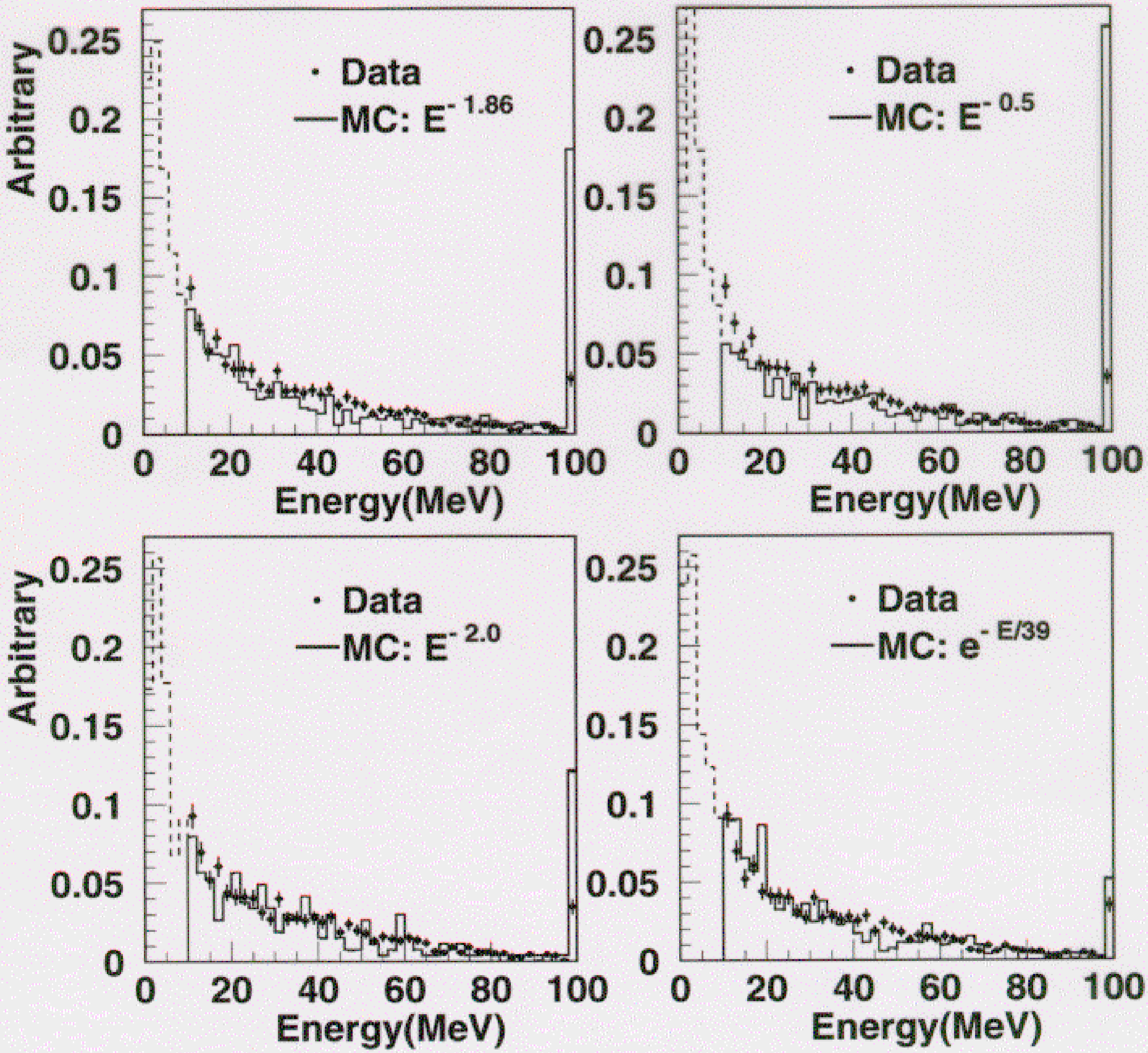
Measure B_{pn} from data for E > 10 MeV (no ν's)

Use MC to rescale in the region of interest below 10 MeV

wide range of spectra:

$E^{-1.86}$ $E^{-0.5}$ $E^{-2.0}$ $e^{-E/39}$

p-recoil spectra for the different n-spallation spectra used



$\varepsilon_1 = 0.159$ (84% of ν remain in $N_1 - N_2$)

$(1 - \varepsilon_2)\, B_{pn} = (0.5 \pm 0.8)$ events/day

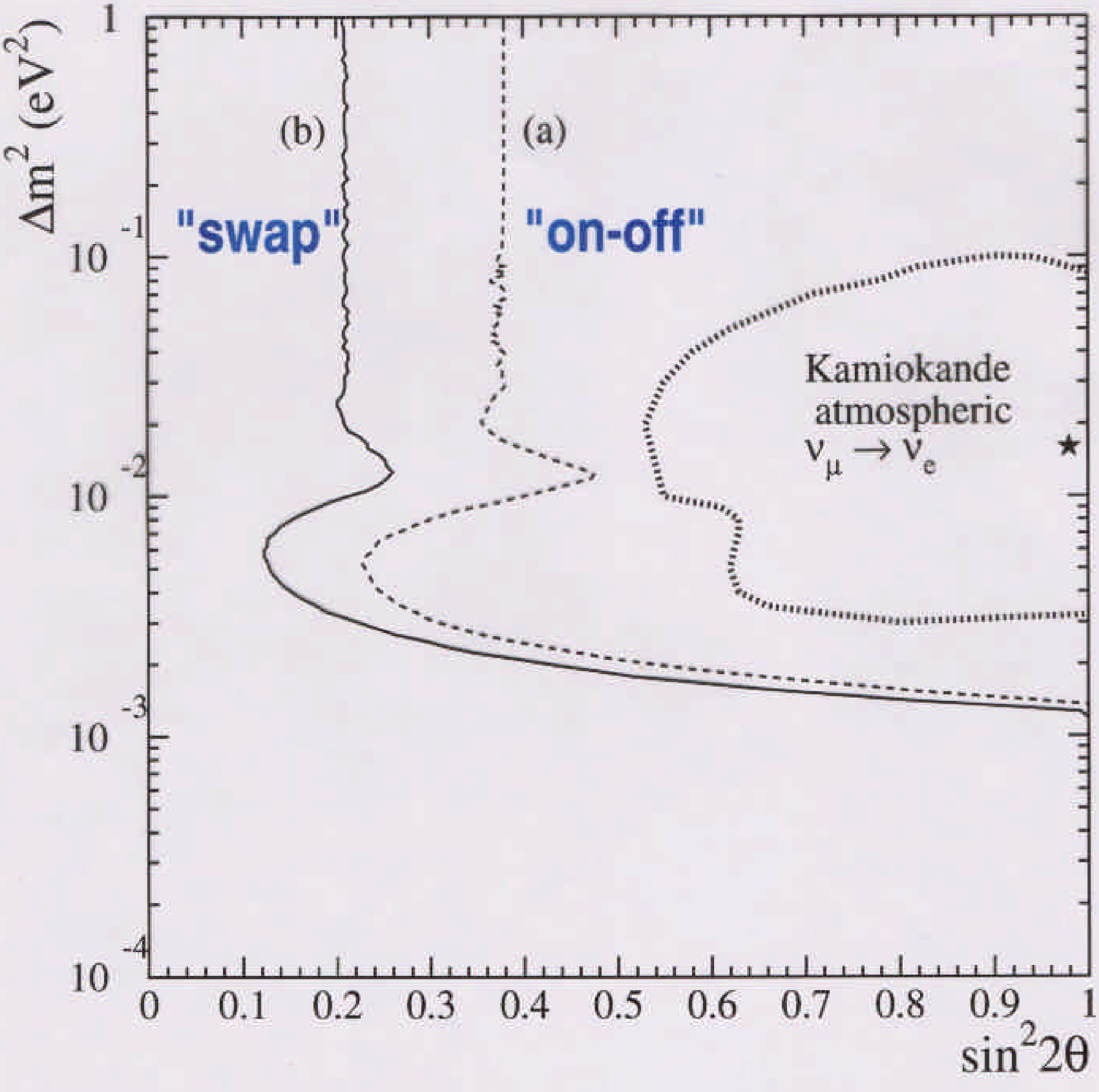
	1998		1999	
	on	off 980 m	on	off 750 m
Days	35.97	31.35	110.95	23.40
effic.	7.46	7.72	11.2	11.1
N_ν (/day)	16.5±1.4	13.5±1.4	25.5±0.9	15.0±1.9
Bkgnd (/day)	21.7±1.0	18.7±1.0	27.8±0.6	28.8±1.3
After eff. corr.				
ν observed	221±19	174±17	225±8	137±17
ν expected	218	155	218	130

$$\frac{\nu_{observed}}{\nu_{expected}} = 1.04 \pm 0.03\ (stat) \pm 0.08\ (syst)$$

Summary of systematics

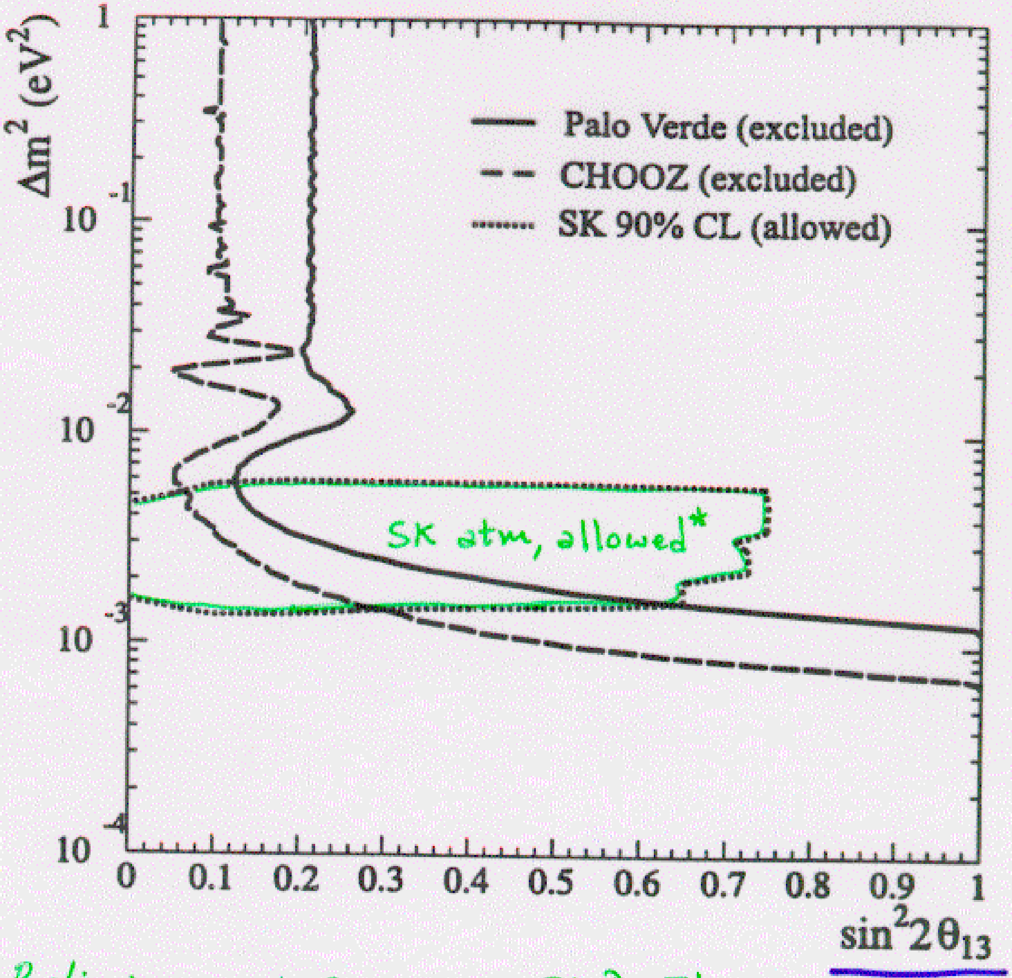
	"on-off"	"swap"
e^+ efficiency	4 %	4 %
n efficiency	3 %	3 %
ν flux prediction	3 %	3 %
ν selection cuts	8 %	4 %
B_{pn} estimate	-	4 %
Total	10 %	8 %

90 % CL, Feldman & Cousins



Assume $m_3^2 \gg m_1^2 \simeq m_2^2$

$\Delta m^2 \simeq \Delta m_{13}^2 \simeq \Delta m_{23}^2$, $\Delta m_{12} \simeq 0$

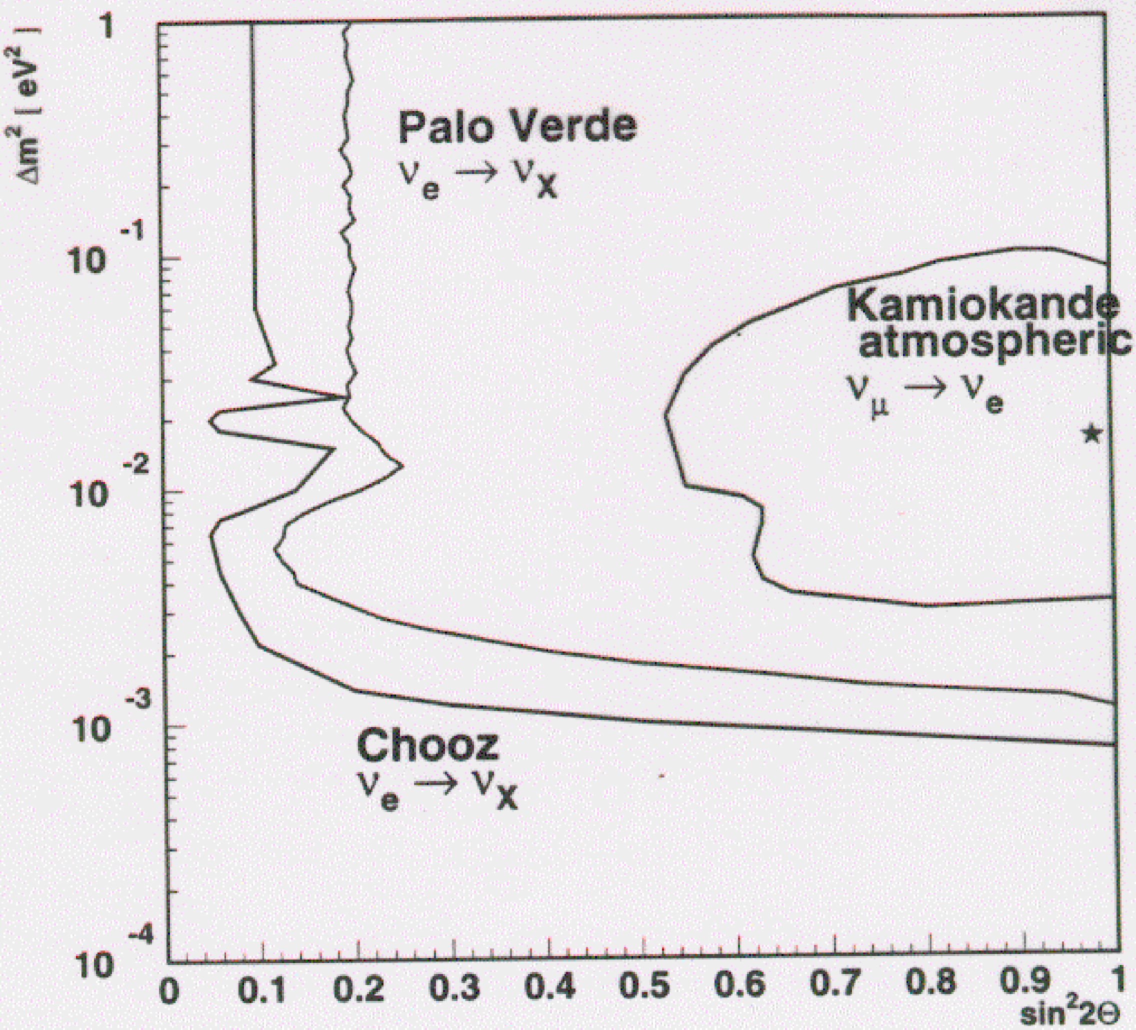


* Preliminary, K. Okumura PhD Thesis
U. of Tokyo

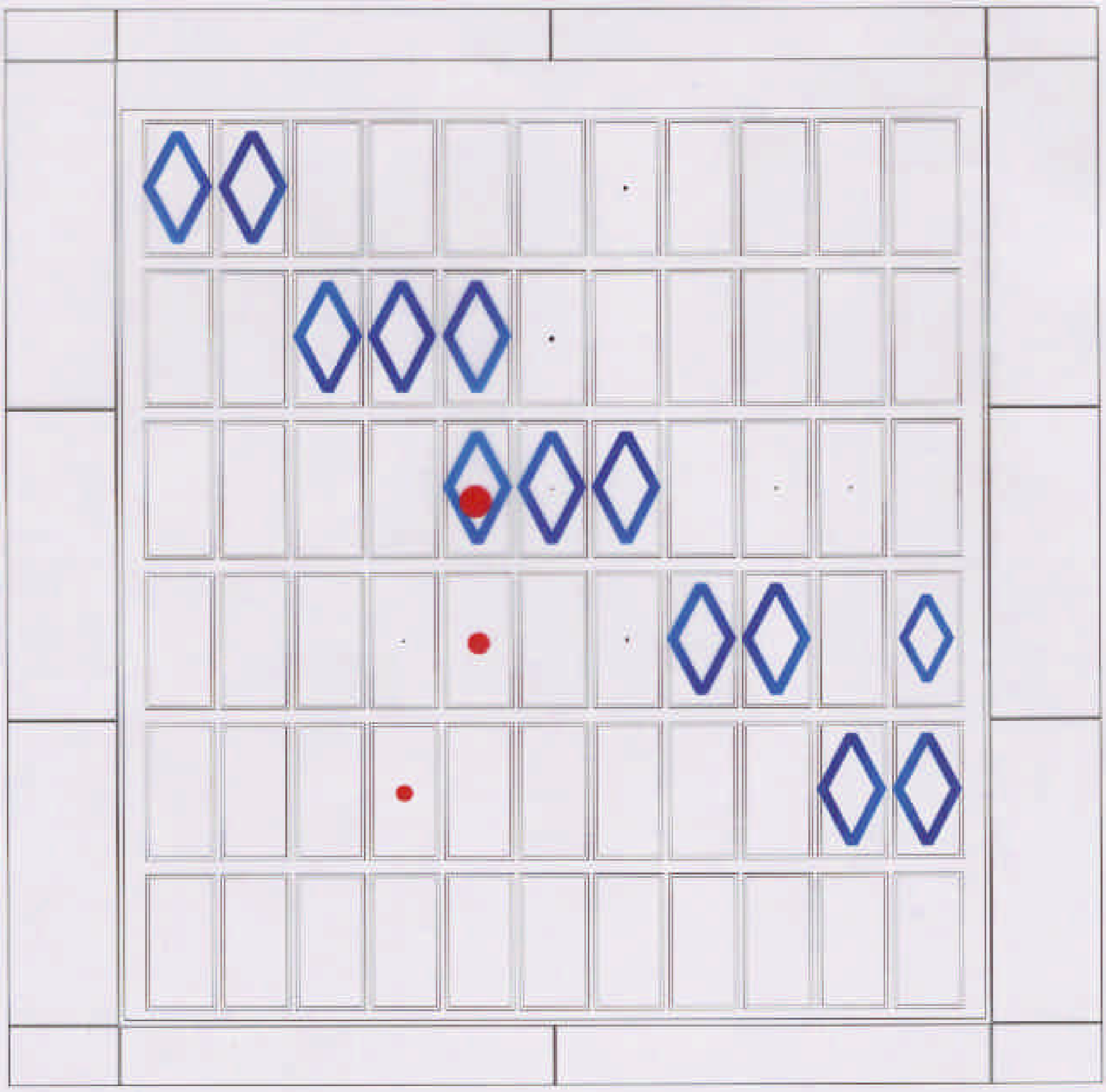
Palo Verde is due to stop data-taking

in July 2000

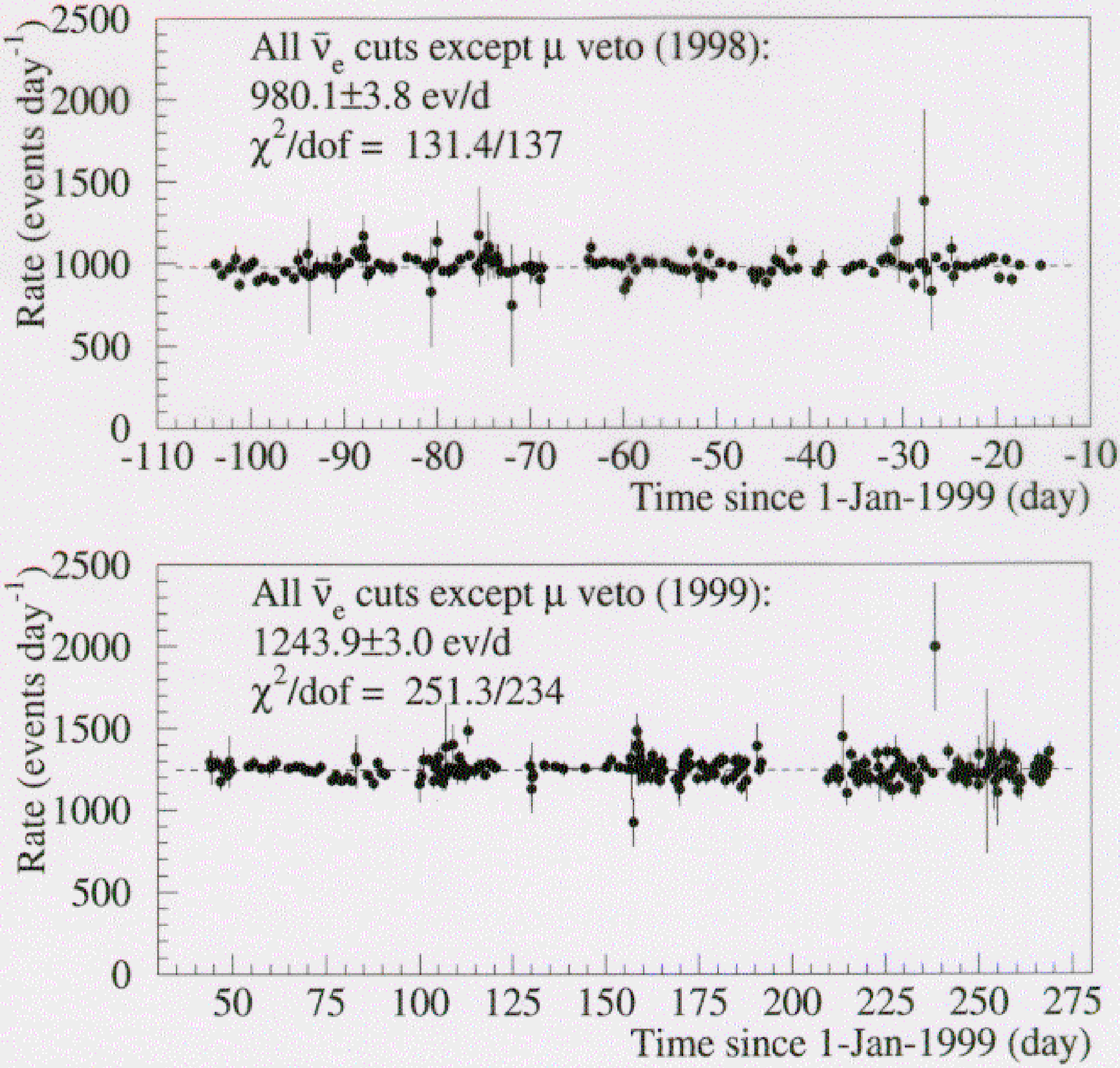
- Total data collected $\sim 2 \times$ data presented (both at full and low power)
- Final calibrations (including ^{76}Ge)
- Final results fall 2000


Palo Verde
$\nu_e \rightarrow \nu_X$
Kamiokande
atmospheric
$\nu_\mu \rightarrow \nu_e$
Chooz
$\nu_e \rightarrow \nu_X$
Δm^2 [eV^2]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\sin^2 2\Theta$

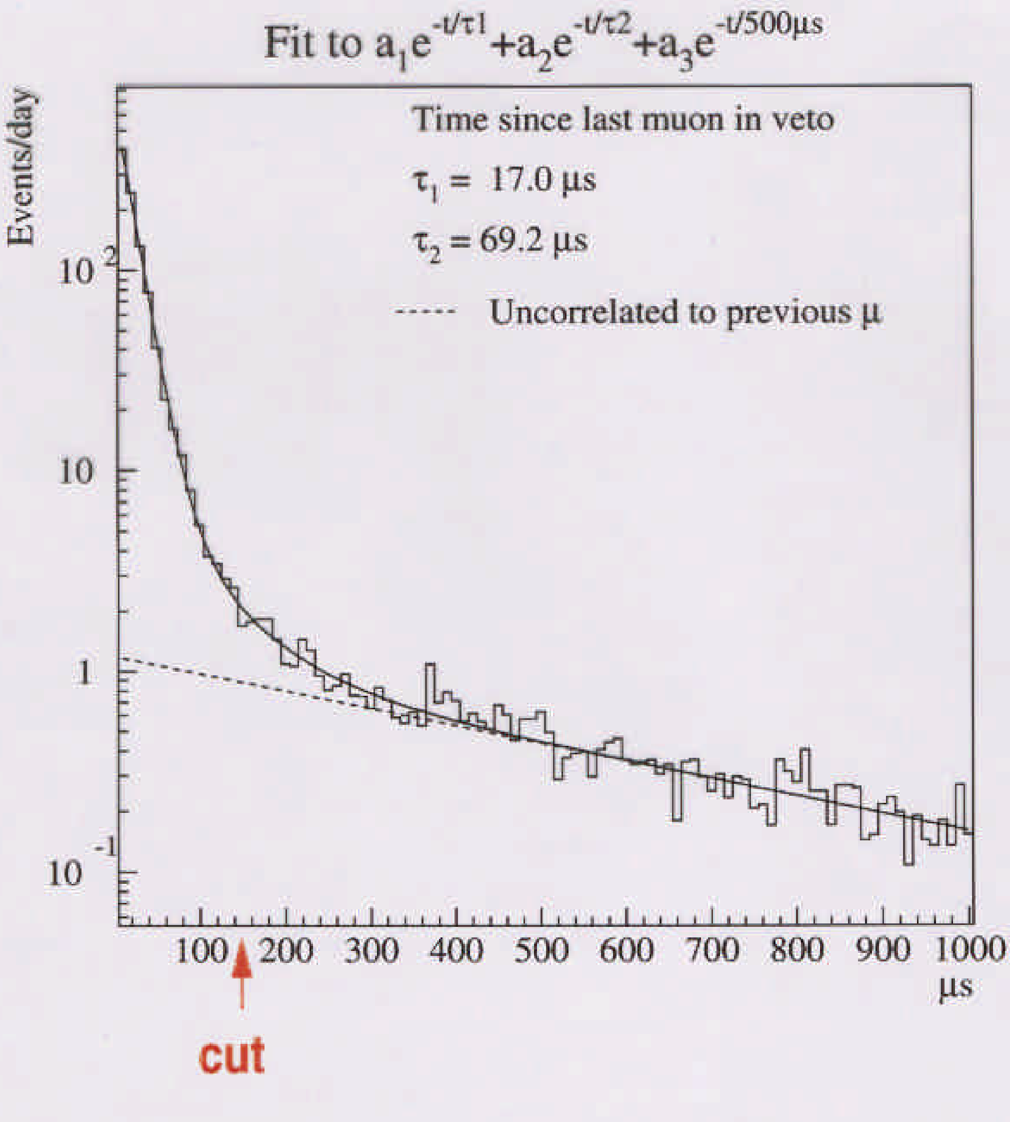
Single Event Display:
Muon track with possible spallation



Correlated background stability
(all cuts but Δ t of previous cosmic)



Time correlation between events and the previous activity in veto



Uncorrelated bkgnd stability

Trigger conditions changed